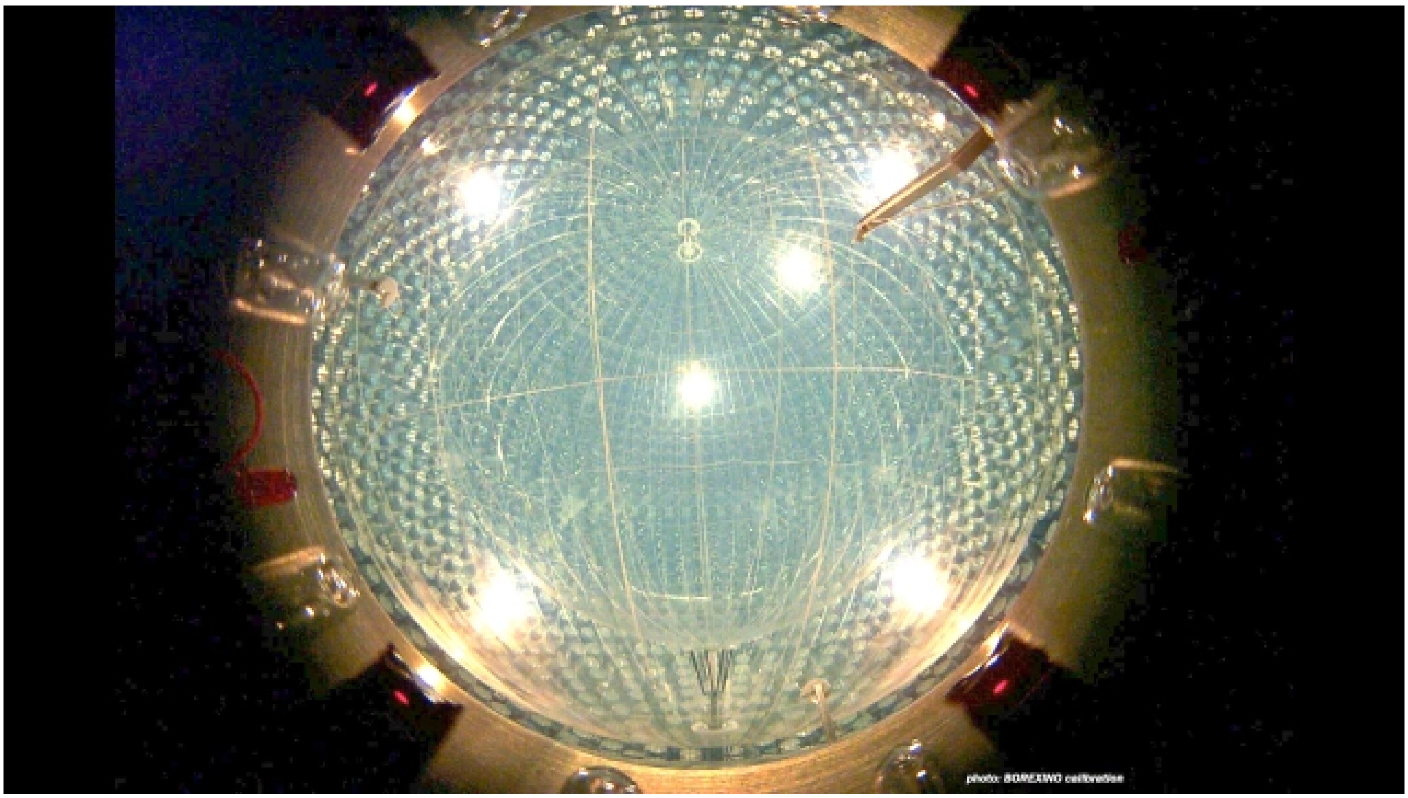
STARTS WITH A BANG — MARCH 1, 2023

If neutrinos have mass, where are all the slow ones?

If you're a massless particle, you must always move at light speed. If you have mass, you must go slower. So why aren't any neutrinos slow?



Neutrino detectors, like the one used in the BOREXINO collaboration here, generally have an enormous tank that serves as the target for the experiment, where a neutrino interaction will produce fast-moving charged particles that can then be detected by the surrounding photomultiplier tubes at the ends. However, slow-moving neutrinos cannot produce a detectable signal in this fashion.

(Credit: INFN/Borexino Collaboration)

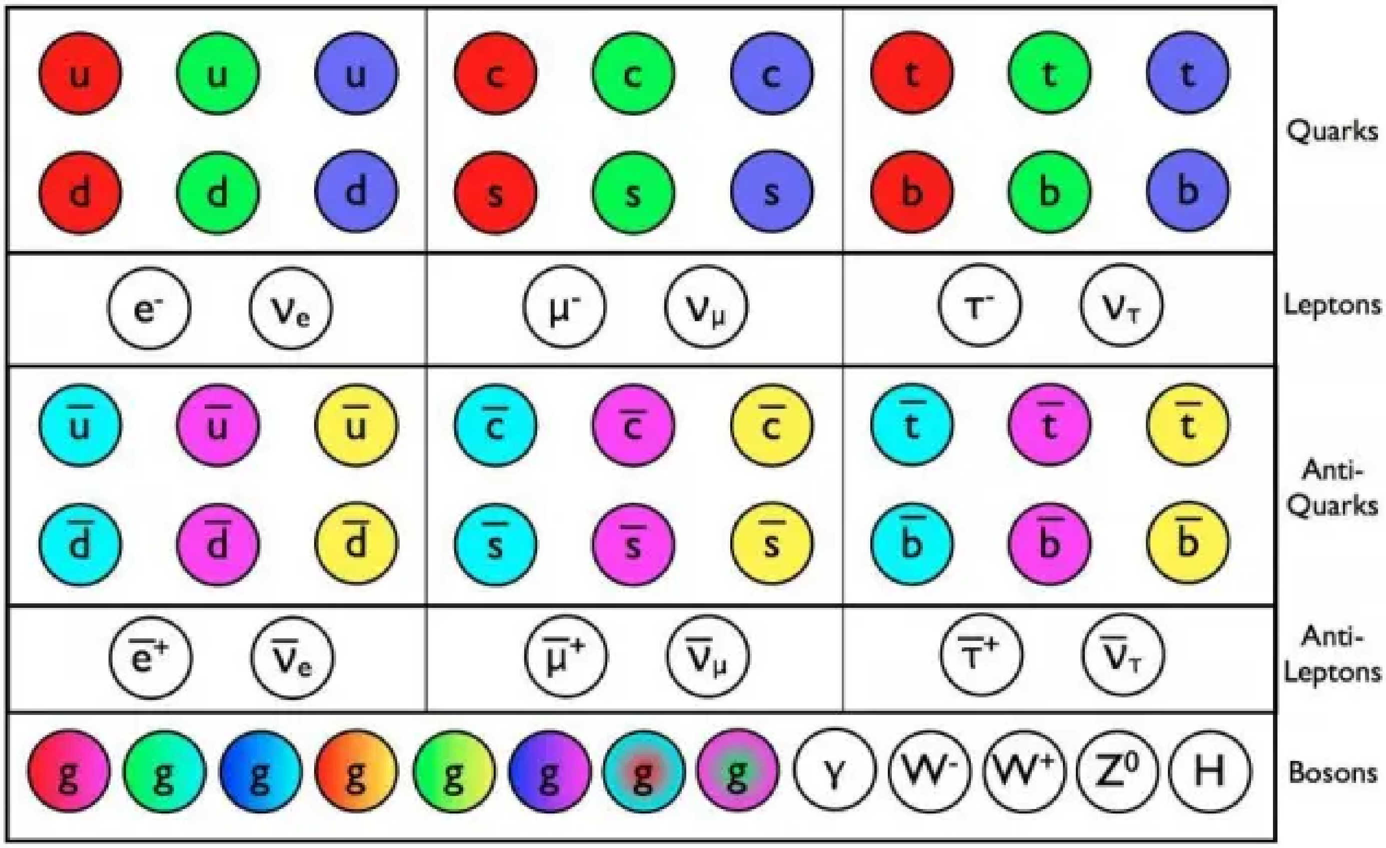
KEY TAKEAWAYS

When neutrinos were first theorized, they were introduced to have no charge and to carry energy and momentum away from certain nuclear decays. However, when we first started detecting them, they appeared to be completely massless, always moving indistinguishably from the speed of light. Yet more recent experiments have revealed that neutrinos oscillate, or change flavor, implying they must have mass. So if they have mass, where are all the slow ones?

Ethan Siegel

For many years, the neutrino was among the most puzzling and elusive of cosmic particles. It took more than two decades from when it was first predicted to when it was finally detected, and they came along with a bunch of surprises that make them unique among all the particles that we know of. They can "change flavor" from one type (electron, mu, tau) into another. All neutrinos always have a left-handed spin; all anti-neutrinos always have a right-handed spin. And every neutrino we've ever observed moves at speeds indistinguishable from the speed of light.

But must that be so? After all, if neutrinos can oscillate from one species into one another, that means they must have mass. If they have mass, then it's forbidden for them to actually move at the speed of light; they must move slower. And after 13.8 billion years of cosmic evolution, surely some of the neutrinos that were produced long ago have slowed down to a reasonably accessible, non-relativistic speed. Yet, we've never seen one, causing us to wonder where are all the slow-moving neutrinos? As it turns out, they're probably out there, just at levels well-below what current technology can detect.



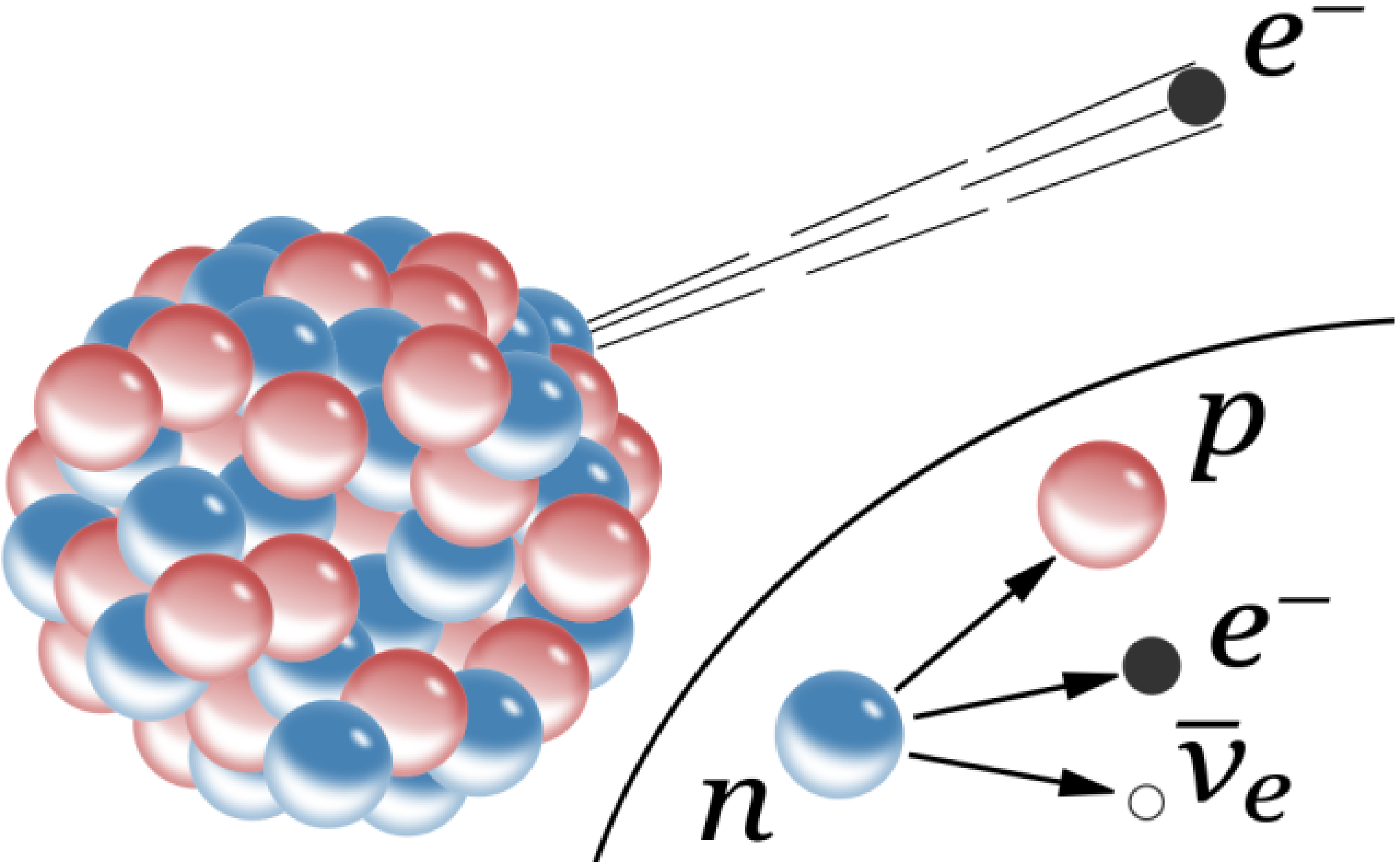
(Credit: E. Siegel/Beyond the Galaxy)

According to the Standard Model, the leptons and antileptons should all be separate, independent particles from one another. But the three types of neutrino all mix together, indicating they must be massive and, furthermore, that neutrinos and antineutrinos may in fact be the same particle as one another: Majorana fermions.

The neutrino was first proposed in 1930, when a special type of decay — beta decay — seemed to violate two of the most important conservation laws of all: the conservation of energy and the conservation of momentum. When an atomic nucleus decayed in this fashion, it:

- increased in atomic number by 1,
- emitted an electron,
- and lost a little bit of rest mass.

When you added up the energy of the electron and the energy of the post-decay nucleus, including all the rest mass energy, it was always slightly less than the rest mass of the initial nucleus. In addition, when you measured the momentum of electron and the post-decay nucleus, it didn't match the initial momentum of the pre-decay nucleus. Either energy and momentum were being lost, and these supposedly fundamental conservation laws were no good, or there was a hitherto undetected additional particle being created that carried that excess energy and momentum away.



(Credit: Inductiveload/Wikimedia Commons)

Schematic illustration of nuclear beta decay in a massive atomic nucleus. Beta decay is a decay that proceeds through the weak interactions, converting a neutron into a proton, electron, and an anti-electron neutrino. Before the neutrino was known or detected, it appeared that both energy and momentum were not conserved in beta decays.

It would take approximately 26 years for that particle to be detected: the elusive neutrino. Although we couldn't quite see these neutrinos directly — and still can't — we can detect the particles they collide or react with, providing evidence of the neutrino's existence and teaching us about its properties and interactions. There are a myriad of ways the neutrino has shown itself to us, and each one provides us with an independent measurement and constraint on its properties.

We've measured neutrinos and antineutrinos produced in nuclear reactors.

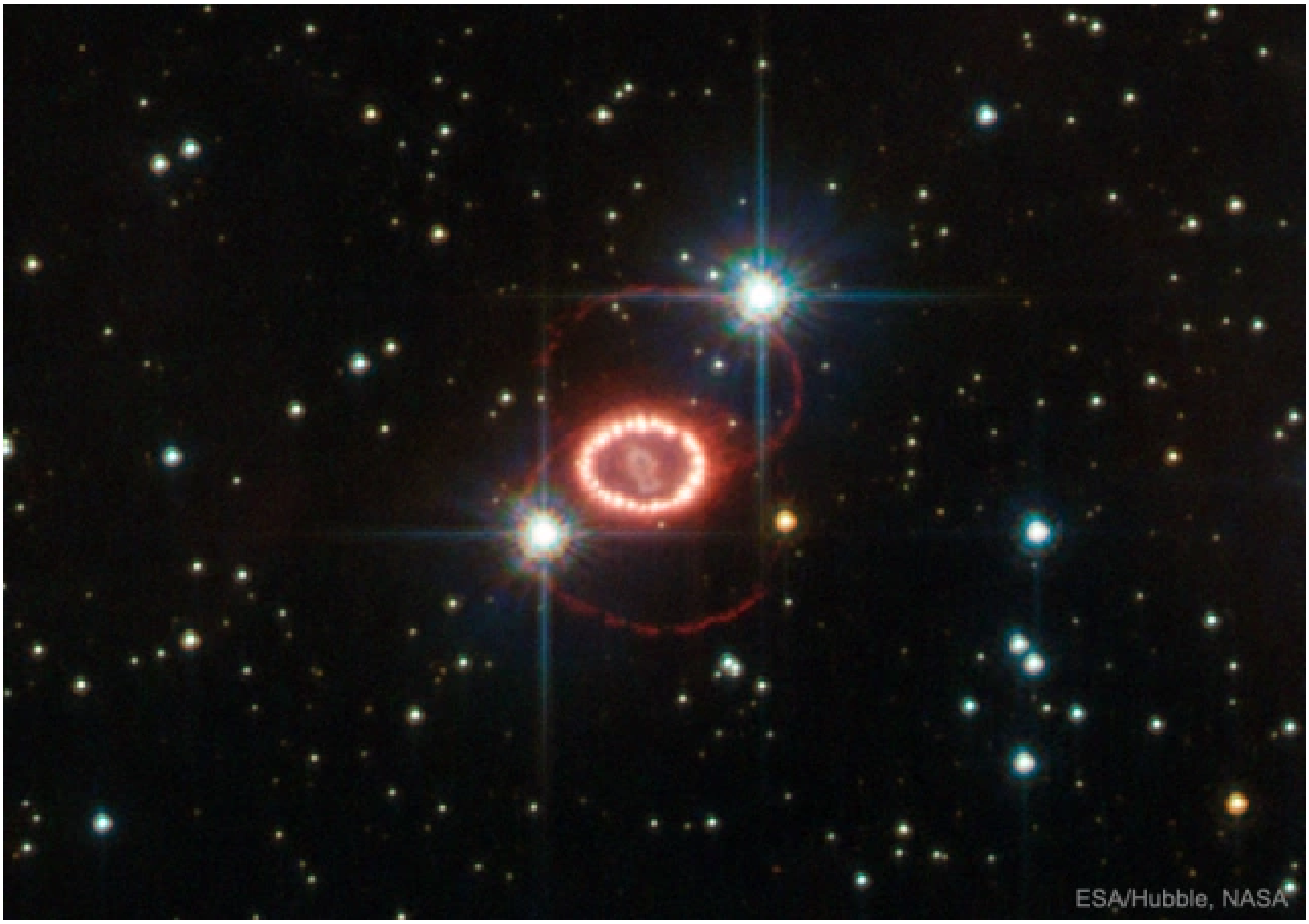
We've measured neutrinos produced by the Sun.

We've measured neutrinos and antineutrinos produced by cosmic rays that interact with our atmosphere.

We've measured neutrinos and antineutrinos produced by particle accelerator experiments.

We've measured neutrinos produced by the closest supernova to occur in the past century: SN 1987A.

And, in recent years, we've even measured a neutrino coming from the center of an active galaxy — a blazar — from under the ice in Antarctica.



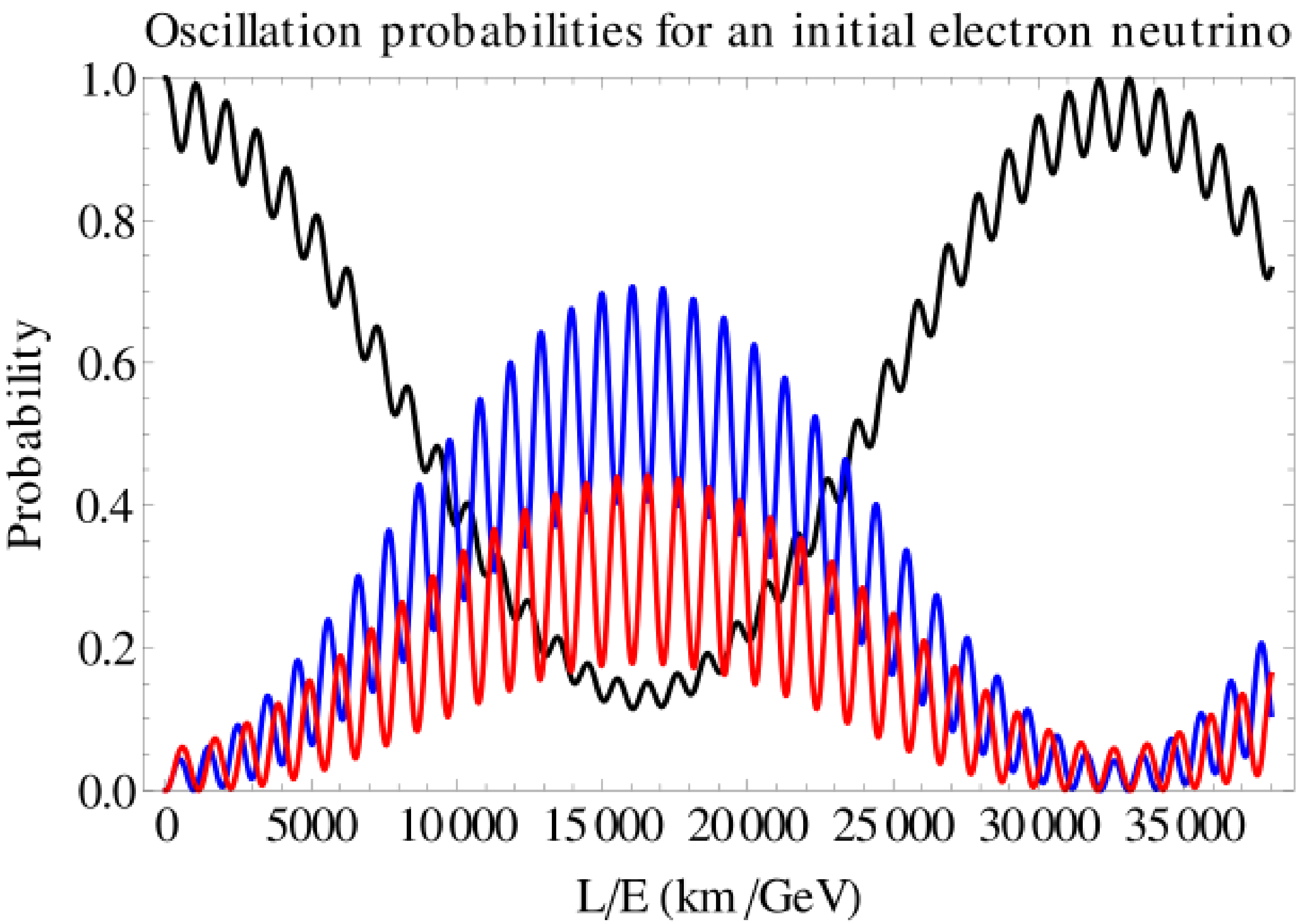
(Credit: ESA/Hubble & NASA)

The remnant of supernova 1987a, located in the Large Magellanic Cloud some 165,000 light years away, is revealed in this Hubble image. It was the closest observed supernova to Earth in more than three centuries, and has the hottest known object, at its surface, currently known in the Local Group. Its surface temperature now is estimated at around ~600,000 K, and it was the first neutrino source ever detected beyond our own Solar System. The neutrinos that arrived from it came in a burst lasting about ~10 seconds: equivalent to the time that neutrinos are expected to be produced.

With all of this information combined, we've learned an incredible amount of information about these ghostly neutrinos. Some particularly relevant facts are as follows:

- Every neutrino and antineutrino we've ever observed moves at speeds so fast they're indistinguishable from the speed of light.
- Neutrinos and antineutrinos both come in three different flavors: electron, mu, and tau.

- Every neutrino we've ever observed is left-handed (if you point your thumb in its direction of motion, your left hand's fingers "curl" in the direction of its spin, or intrinsic angular momentum), and every anti-neutrino is right-handed.
- Neutrinos and antineutrinos can oscillate, or change flavor, from one type into another when they pass through matter.
- And yet neutrinos and antineutrinos, despite appearing to move at the speed of light, must have a non-zero rest mass, otherwise this "neutrino oscillation" phenomenon would not be possible.

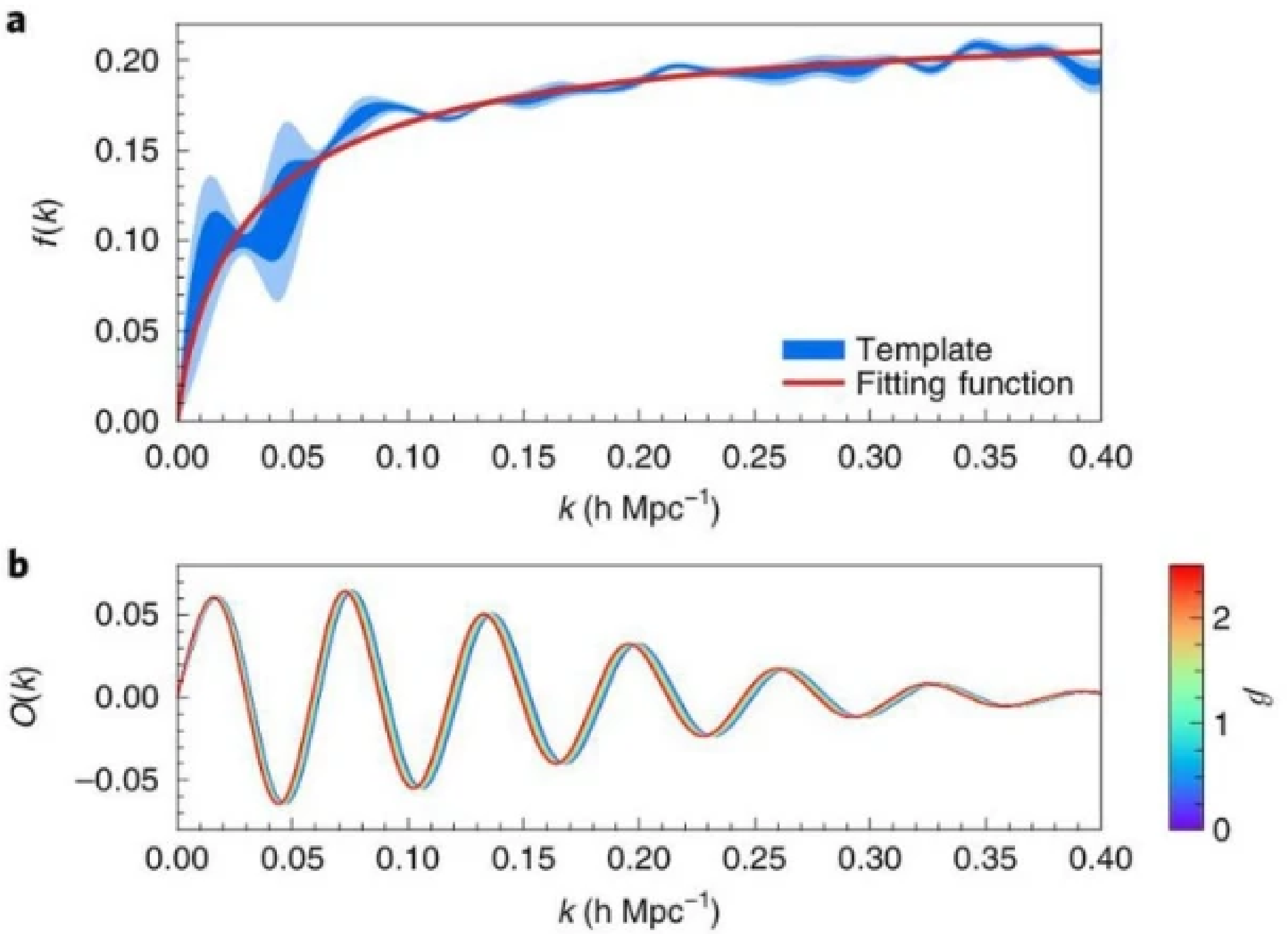


(Credit: Strait/Wikimedia Commons)

Vacuum oscillation probabilities for electron (black), muon (blue) and tau (red) neutrinos for a chosen set of mixing parameters, beginning from an initially produced electron neutrino. An accurate measurement of the mixing probabilities over different length baselines can help us understand the physics behind neutrino oscillations, and could reveal the existence of any other types of particles that couple to the three known species of neutrino. If additional particles (such as dark matter particles) carry energy away, the overall neutrino flux will show a deficit.

Neutrinos and antineutrinos come in a wide variety of energies, and the odds of having a neutrino interact with you increase with a neutrino's energy. In other words, the more energy your neutrino has, the more likely it is to interact with you. For the majority of neutrinos produced in the modern Universe, through stars, supernovae, and other natural nuclear reactions, it would take about a light-year worth of lead to stop approximately half of the neutrinos fired upon it.

All of our observations, combined, have enabled us to draw some conclusions about the rest mass of neutrinos and antineutrinos. First off, they cannot be zero. The three types of neutrino almost certainly have different masses from one another, where the heaviest a neutrino is allowed to be is about 1/4,000,000th the mass of an electron, the next-lightest particle. And through two independent sets of measurements — from the large-scale structure of the Universe and the remnant light left over from the Big Bang — we can conclude that approximately one billion neutrinos and antineutrinos were produced in the Big Bang for every proton in the Universe today.

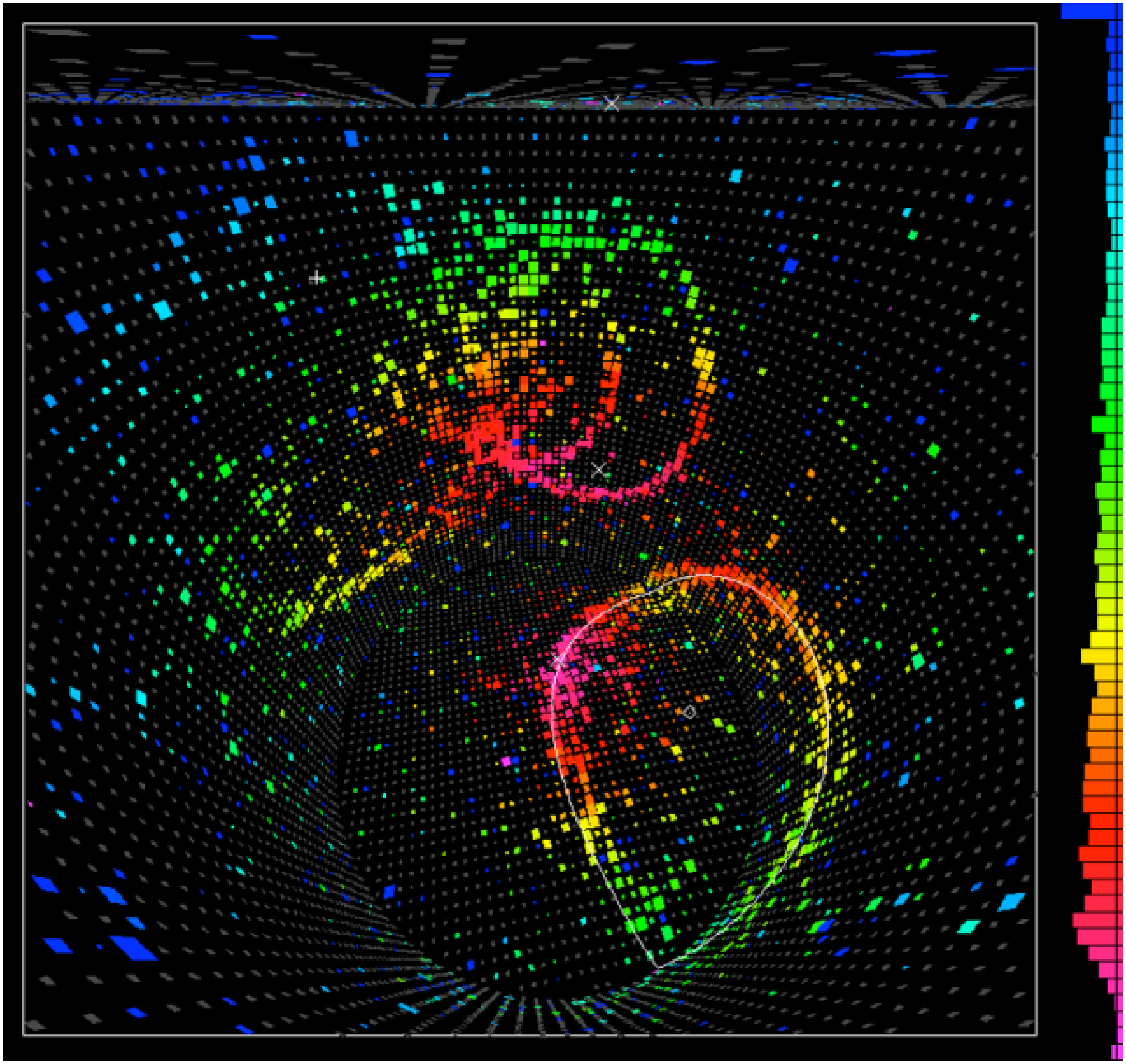


(Credit: D. Baumann et al., Nature Physics, 2019)

If there were no oscillations due to matter interacting with radiation in the Universe, there would be no scale-dependent wiggles seen in galaxy clustering. The wiggles themselves, shown with the non-wiggly part subtracted out (bottom), are dependent on the impact of the cosmic neutrinos theorized to be present by the Big Bang. Standard Big Bang cosmology corresponds to β=1. Note that if there is a dark matter/neutrino interaction present, the acoustic scale could be altered.

Here's where the disconnect between theory and experiment lies. In theory, because neutrinos have a non-zero rest mass, it should be possible for them to slow down to non-relativistic speeds. In theory, the neutrinos left over from the Big Bang should have already slowed down to these speeds, where they'll only be moving at a few hundred km/s today: slow enough that they should have fallen into galaxies and galaxy clusters by now, making up approximately ~1% of all the dark matter in the Universe.

But experimentally, we simply don't have the capabilities to detect these slow-moving neutrinos directly. Their cross-section is literally millions of times too small to have a chance at seeing them, as these tiny energies wouldn't produce recoils noticeable by our current equipment. Unless we could accelerate a modern neutrino detector to speeds extremely close to the speed of light, these low-energy neutrinos, the only ones that should exist at non-relativistic speeds, will remain undetectable.

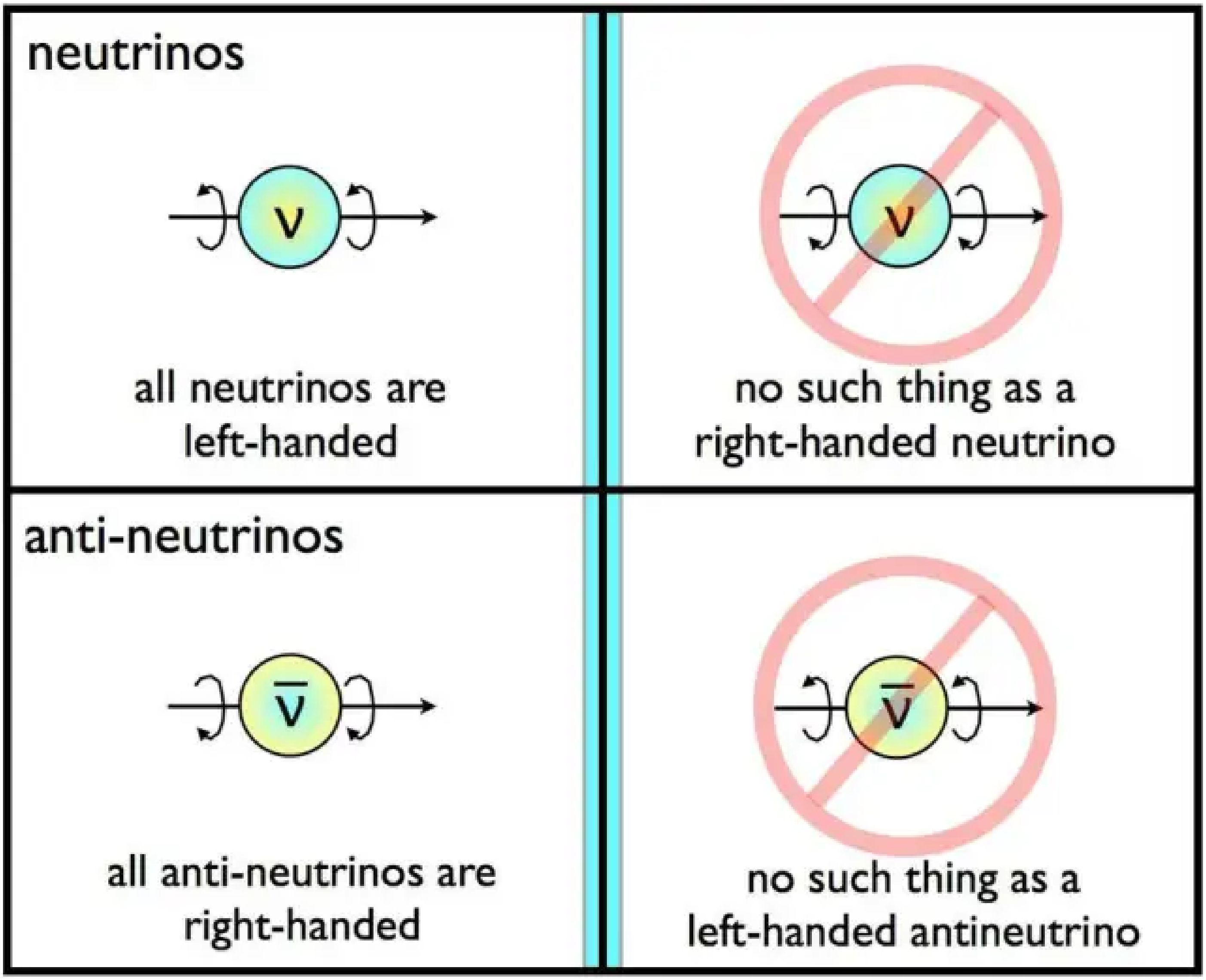


(Credit: Super-Kamiokande Collaboration)

A neutrino event, identifiable by the rings of Cherenkov radiation that show up along the photomultiplier tubes lining the detector walls, showcase the successful methodology of neutrino astronomy. This image shows multiple events, and is part of the suite of experiments paving our way to a greater understanding of neutrinos.

And that's unfortunate, because detecting these low-energy neutrinos — the ones that move slow compared to the speed of light — would enable us to perform an important test that we've never performed before. Imagine that you've got a neutrino, and you're traveling behind it. If you look at this neutrino, you'll measure it moving straight ahead: forward, in front of you. If you go to measure the neutrino's angular momentum, it will behave as though it's spinning counterclockwise: the same as if you pointed your left hand's thumb forward and watched your fingers curl around it.

If the neutrino always moved at the speed of light, it would be impossible to move faster than the neutrino. You'd never, no matter how much energy you put into yourself, be able to overtake it. But if the neutrino has a non-zero rest mass, you should be able to boost yourself to move faster than the neutrino is moving. Instead of seeing it move away from you, you'd see it move toward you. And yet, its angular momentum would have to be the same, in the counterclockwise direction, meaning you'd have to use your *right* hand to represent it, rather than your left.

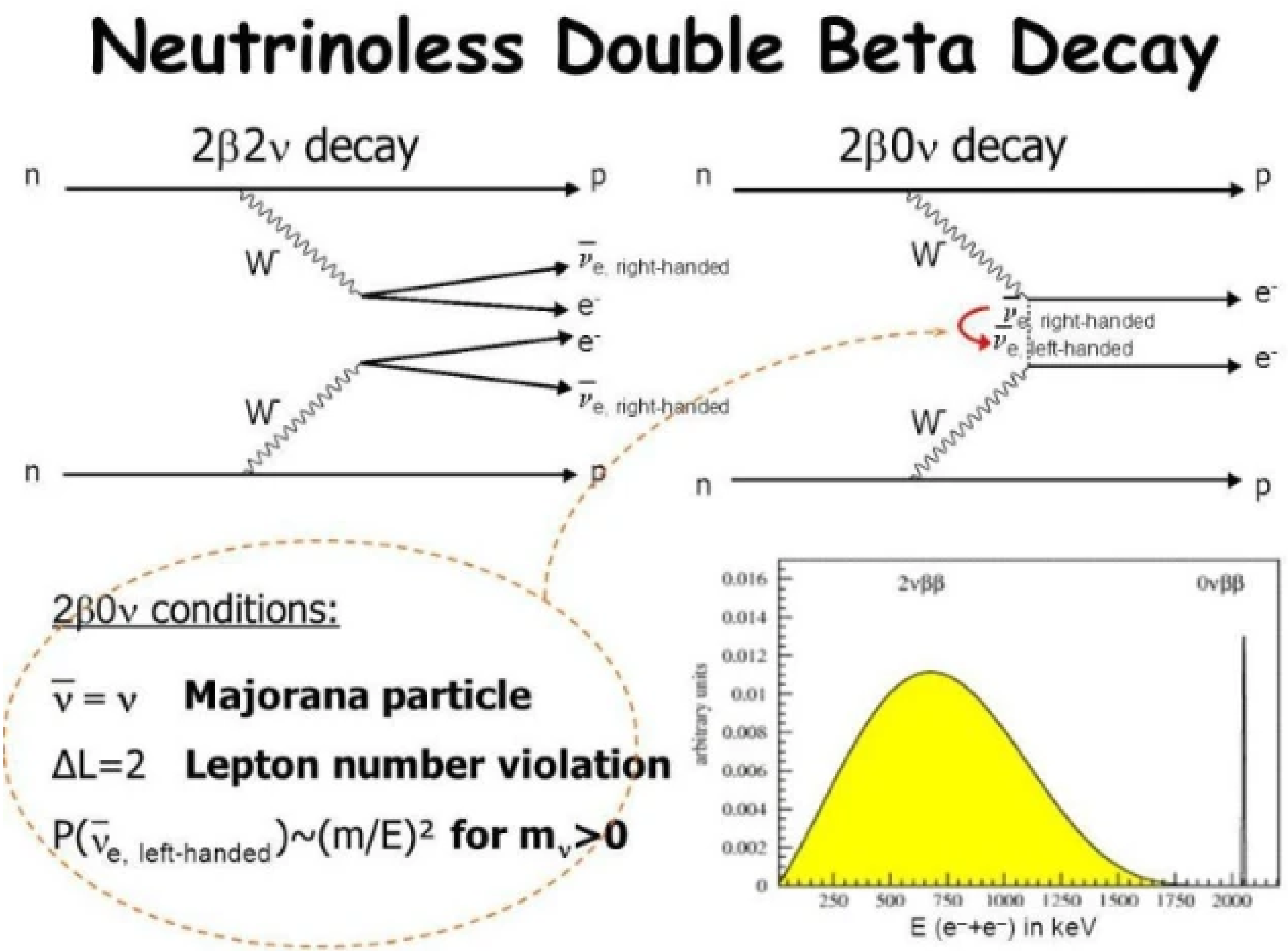


(Credit: E. Siegel/Beyond the Galaxy)

Nature is not symmetric between particles/antiparticles or between mirror images of particles. (Or, for that matter, both mirror reflection and charge conjugation symmetry combined.) Prior to the detection of neutrinos, which clearly violate mirror-symmetries even without decays, as all neutrinos are left-handed and all anti-neutrinos are right-handed, weakly decaying particles offered the only potential path for identifying P-symmetry violations.

This is a fascinating paradox. It seems to indicate that you could transform a matter particle (a neutrino) into an antimatter particle (an antineutrino) simply by changing your motion relative to the neutrino. Alternatively, it's possible that there really could be right-handed neutrinos and left-handed antineutrinos, and that we've just never seen them for some reason. It's one of the biggest open questions about neutrinos, and the capability to detect low-energy neutrinos — the ones moving slow compared to the speed of light — would answer that question.

But we can't really do that in practice. The lowest-energy neutrinos we've ever detected have so much energy that their speed must be, at minimum, 99.99999999995% the speed of light, which means that they can move no slower than 299,792,457.99985 meters-per-second. Even over cosmic distances, when we've observed neutrinos arriving from galaxies other than the Milky Way, we've detected absolutely no difference between a neutrino's speed and the speed of light.



(Credit: K-H. Ackermann et al., Eur. Phys. J. C, 2013)

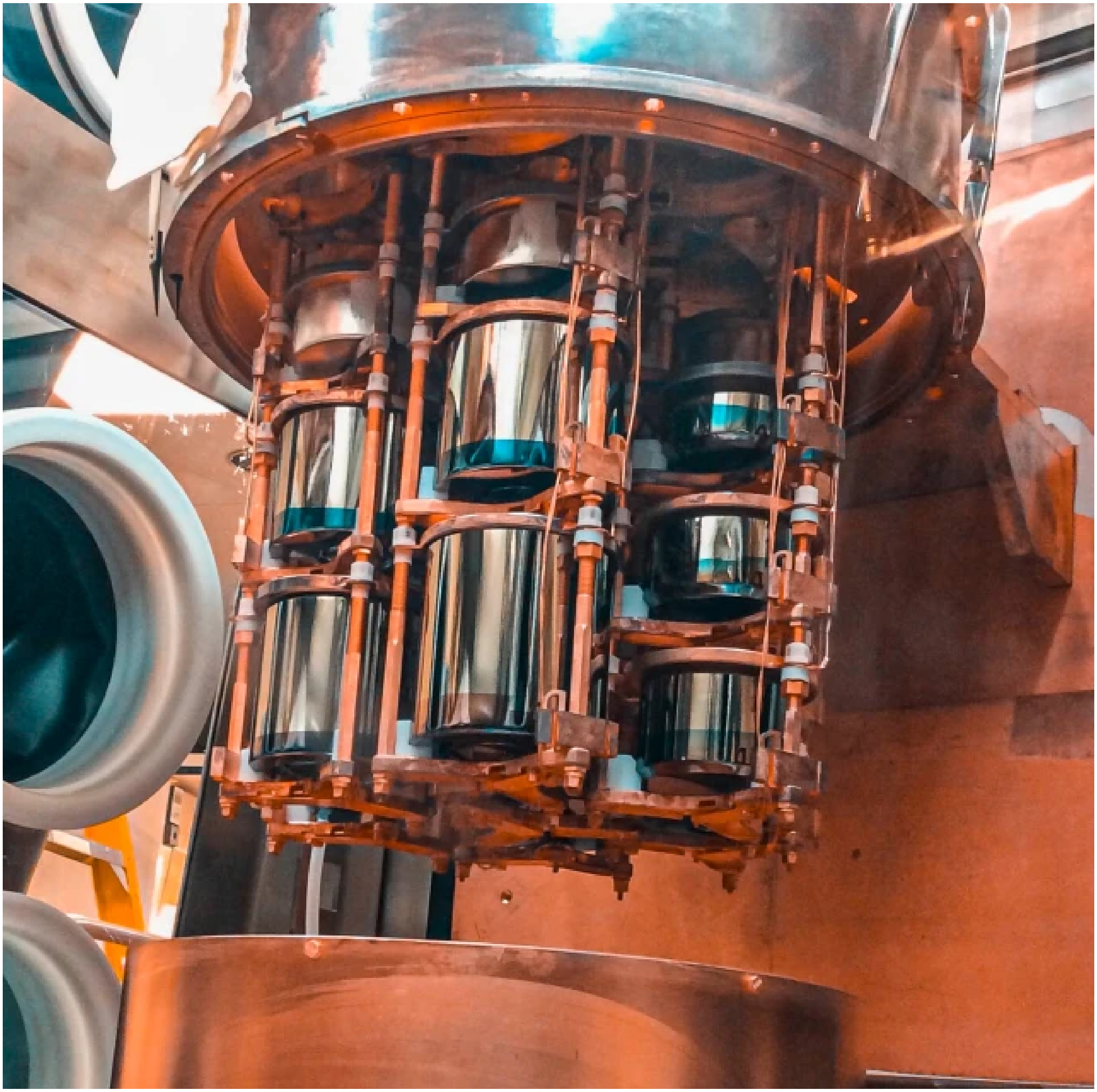
When a nucleus experiences a double neutron decay, two electrons and two neutrinos get emitted conventionally. If neutrinos obey this see-saw mechanism and are Majorana particles, neutrinoless double beta decay should be possible. Experiments are actively looking for this.

Nevertheless, there's a tantalizing chance we have to resolve this paradox, despite the difficulty inherent to it. It's possible to have an unstable atomic nucleus that doesn't just undergo beta decay, but double beta decay: where two neutrons in the nucleus simultaneously both undergo beta decay. We've observed this process: where a nucleus changes its atomic number by 2, emits 2 electrons, and energy and momentum are both lost, corresponding to the emission of 2 (anti)neutrinos.

But if you could transform a neutrino into an antineutrino simply by changing your frame-of-reference, that would mean that neutrinos are a special, new type of particle that exists only in theory thus far: a Majorana fermion. It would mean that the antineutrino emitted by one nucleus could, hypothetically, be absorbed (as a neutrino) by the other nucleus, and you'd be able to get a decay where:

- the atomic number of the nucleus changed by 2,
- 2 electrons are emitted,
- but 0 neutrinos or antineutrinos are emitted.

There are currently multiple experiments, including the MAJORANA experiment, looking specifically for this neutrinoless double beta decay. If we observe it, it will fundamentally change our perspective on the elusive neutrino.



(Credit: Majorana Demonstrator collaboration/Sanford Underground Research Facility)

The GERDA experiment, a decade ago, placed the strongest constraints on neutrinoless double beta decay at the time. The MAJORANA experiment, whose demonstrator is shown here, has the potential to finally detect this rare decay. It will likely take years for their experiment to yield robust results, but any events at all in excess above the expected background would be groundbreaking.

But for right now, with current technology, the only neutrinos (and antineutrinos) we can detect via their interactions move at speeds indistinguishable from the speed of light. Neutrinos might have mass, but their mass is so small that of all the ways the Universe has to create them, only the neutrinos made in the Big Bang itself should be moving slow compared to the speed of light today. Those neutrinos might be all around us, as an inevitable part of the galaxy, but we cannot directly detect them.

In theory, however, neutrinos can absolutely travel at any speed at all, so long as it's slower than the cosmic speed limit: the speed of light in a vacuum. The issue we have is twofold:

- slow moving neutrinos have very low probabilities of interactions,
- and those interactions that do occur are so low in energy that we cannot presently detect them.

The only neutrino interactions we see are the ones coming from neutrinos moving indistinguishably close to the speed of light. Until there's a revolutionary new technology or experimental technique, this will, however unfortunate it is, continue to be the case.

In this article

particle physics

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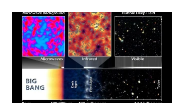

Without colliding with anything since the Universe was 1 second old, these neutrinos still pack a punch! "When you see how fragile and delicate life can be, all else fades [...]

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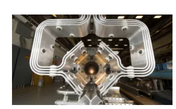

The neutrino is the most ghostly, rarely-interacting particle in all the Standard Model. How well can we truly make "beams" out of them?

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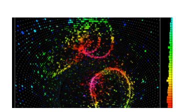
A failed proton decay search accidentally birthed neutrino astronomy



Before we discovered gravitational waves, multi-messenger astronomy got its start with light and particles arriving from the same event.

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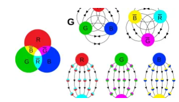

Protons and neutrons are held together by the strong force: with 3 colors and 3 anticolors. So why are there only 8 gluons, and not 9?

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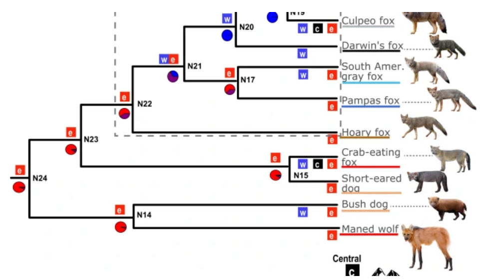

Darwin missed an amazing example of evolution.

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