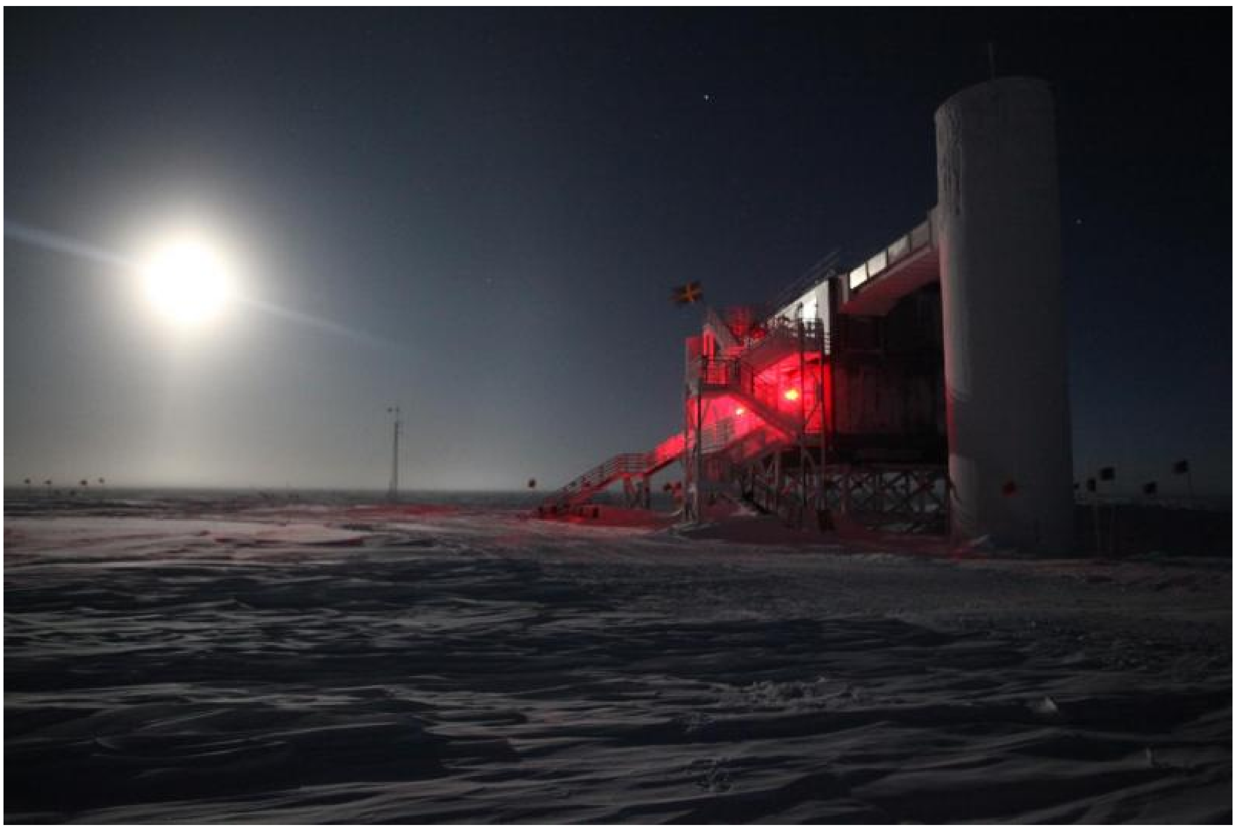
Scientists give 'outlaw' particles less room to hide

October 21 2015, by Francis Reddy



The IceCube Laboratory at Amundsen-Scott South Pole Station, Antarctica, sits atop a cubic kilometer of clear ice instrumented with thousands of sensors designed to catch flashes of light from neutrino interactions. Credit: Dag Larsen, IceCube/NSF

Studying the highest-energy particles in the cosmos provides scientists with a way to test how well they understand the cutting edge of physics. Recently, scientists using a giant particle detector at the South Pole have set records for the highest-energy observations of mysterious subatomic entities called neutrinos. If neutrinos happen to be traveling faster than light, a feat that violates Einstein's relativity theory but is allowed by some newer rival theories, these measurements provide a way to determine how far they're pushing the speed limit.

"A foundational tenet of relativity is what physicists call Lorentz invariance," explained Floyd Stecker, a theorist in the Astrophysics Science Division at NASA's Goddard Space Flight Center in Greenbelt, Maryland. "This includes the notion that light traveling in a vacuum sets a cosmic speed limit that cannot be exceeded by any matter or information."

But some versions of theories designed to replace general relativity, such as string theory and loop quantum gravity, predict possible exceptions. The highest-energy neutrinos offer a way to determine how big any faster-than-light loophole may be.

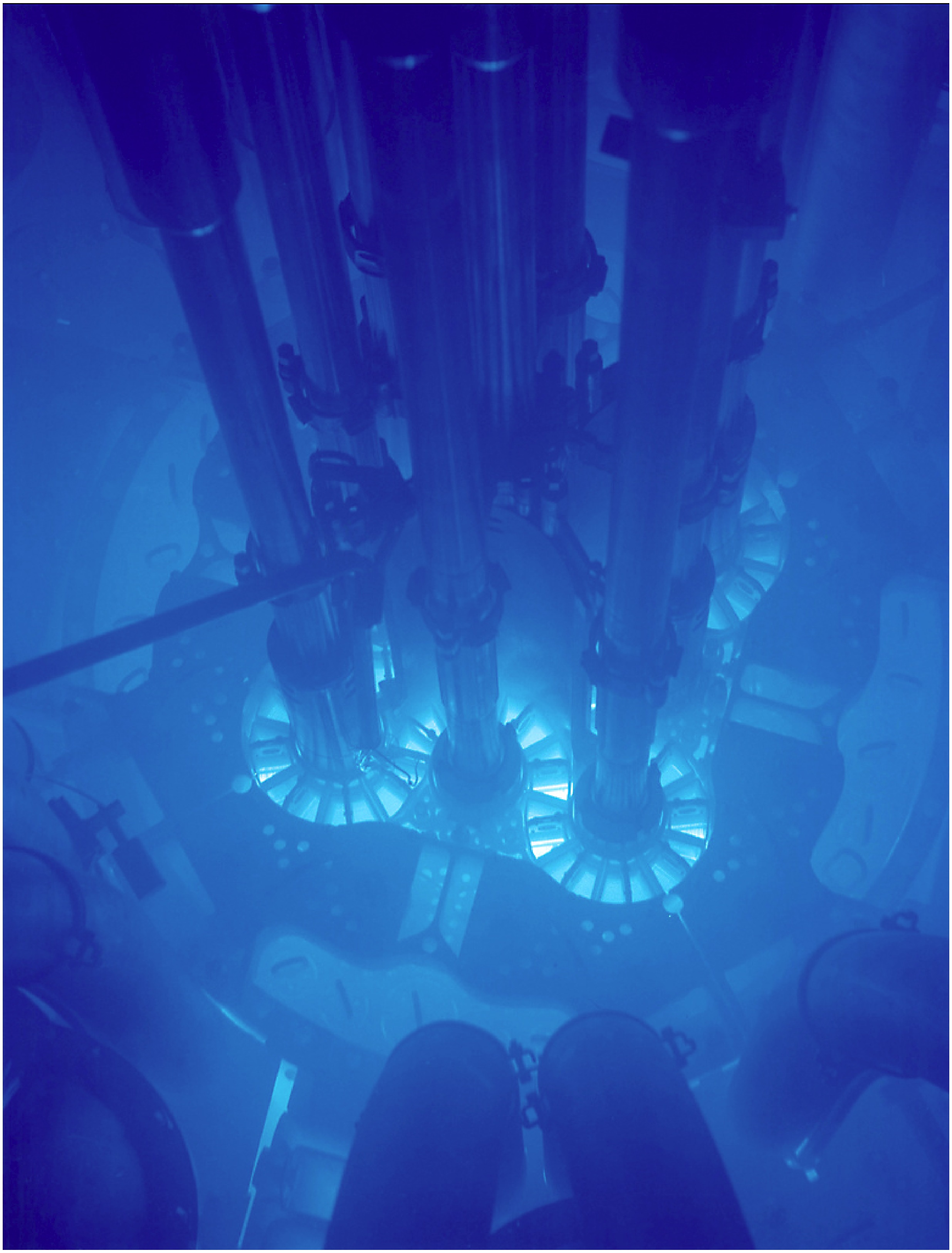
Neutrinos are among the least understood fundamental particles. Each second, about 100 trillion of them pass through our bodies, but they interact with matter so infrequently that even at this rate catching a single event in a human-sized detector would take decades. Neutrinos are produced in Earth's atmosphere by the impact of cosmic rays and through nuclear reactions in the center of the sun. They were produced in the big bang and are emitted by exploding stars, pulsars, black holes and other astrophysical phenomena. Unlike charged particles, such as protons in cosmic rays, neutrinos are not deflected by interstellar magnetic fields. They easily escape places light cannot, such as the core of a collapsing star, and they are rarely absorbed or scattered by intervening matter, zipping through the universe almost completely unimpeded.

Experiments have shown neutrinos come in at least three varieties, called "flavors," and that they switch from one flavor to another as they travel, a discovery that won this year's Nobel Prize in physics. Recent findings based on cosmological observations estimate the combined mass of all three flavors at less than a millionth the mass of a single electron. Yet, according to relativity, having even a small amount of mass means neutrinos should travel slower than light speed. But do they?

In 2011, an experiment designed to measure the speed of neutrinos erroneously suggested they traveled slightly faster than light. The incident intrigued Stecker, who began thinking about the physical consequences of faster-than-light, or superluminal, neutrinos and how their effects could be observed in planned and existing experiments, such as the IceCube Neutrino Observatory in Antarctica.

Built into a cubic kilometer of clear glacial ice at the South Pole, IceCube detects about 100,000 atmospheric neutrinos a year. When a neutrino interacts with other matter in the ice, it produces a cascade of charged particles that emit a faint glow called Cerenkov light, which is detected by thousands of optical sensors strung throughout IceCube. Scientists determine the total energy of the incoming neutrino by the amount of Cerenkov light detected.

In November 2013, the scientific collaboration operating IceCube announced strong evidence the facility had detected dozens of very high-energy neutrinos coming from beyond the solar system. These included two events, nicknamed Bert and Ernie, with energies of about 1 quadrillion electron volts (PeV). In 2014, another extreme event, dubbed Big Bird, arrived with an energy of about 2 PeV.



Nuclear fuel glows blue in a submerged reactor core. The light, called Cerenkov radiation, arises from high-energy electrons that are moving faster than light can travel through the water. Similarly, IceCube detects flashes of Cerenkov light when neutrinos interact within the detector and produce charged particles that move through the ice faster than light does. Credit: Argonne National Laboratory

"That's about the energy needed to lift a roll of postage stamps a foot off the ground," Stecker said, "yet it's contained in a subatomic particle with the smallest mass known."

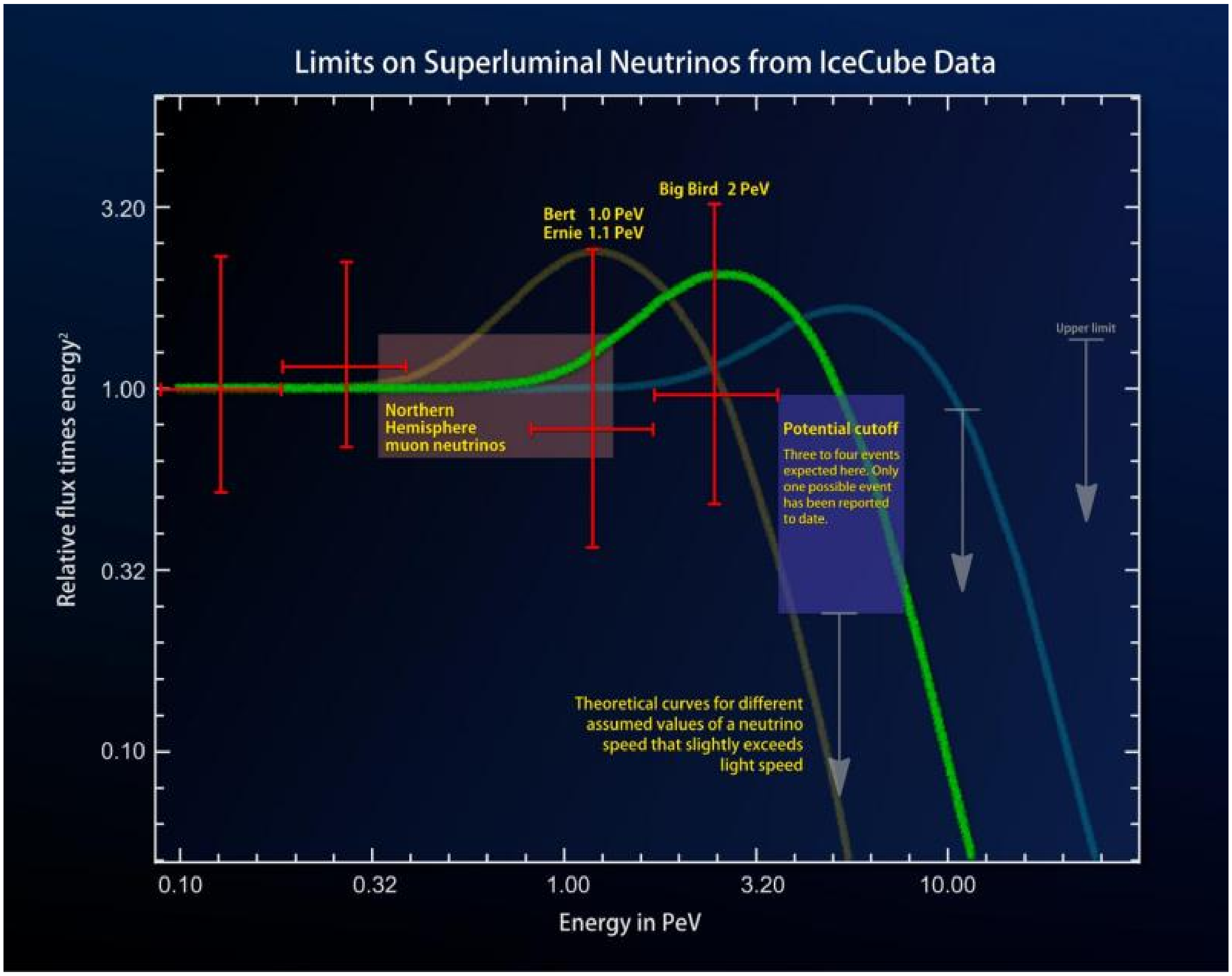
Big Bird was followed in July 2015 by a neutrino with an estimated energy of 2.6 PeV. These are the highest-energy neutrinos ever detected. They appear to originate outside our galaxy, but the astronomical objects producing them are presently unknown.

Using IceCube observations, Stecker and his colleagues—Sean Scully at James Madison University, in Harrisonburg, Virginia; Stefano Liberati at the International School for Advanced Studies in Trieste, Italy; and David Mattingly at the University of New Hampshire Durham—were able to place strong limits on how much faster than light any superluminal neutrinos can be.

That's because faster-than-light neutrinos will lose energy in their intergalactic travels through several exotic mechanisms. This results in a characteristic "bump" of lower-energy neutrinos and a sharp cutoff at higher energies. "Above a certain threshold energy, which depends on their velocity, faster-than-light neutrinos will emit pairs of subatomic particles, including other neutrinos," explained Stecker. This creates a pileup of neutrinos around the threshold energy—the bump—and an absence of neutrinos at higher energies—the cutoff.

In a paper published in the journal *Physical Review D* in February, the researchers calculated "bump-and-cutoff" curves for slightly different superluminal neutrino speeds and compared them to the most energetic IceCube events. Stecker has since refined this analysis by including additional detections announced in August.

"There is evidence for a cutoff at energies above 3 PeV, where three or four events are expected but where only one has been seen to date," Stecker explained. "If that cutoff is indeed caused by superluminal neutrinos, then they're exceeding light speed by only about 5 parts in a billion trillion." Put in terms of distance, this is equivalent to a difference in Earth's diameter hundreds of times smaller than a single hydrogen atom.



An apparent cutoff (purple box) in the highest-energy neutrinos detected by the IceCube Neutrino Observatory (red error bars and box) could be a result of energy losses incurred by faster-than-light neutrinos. If so, the neutrinos are exceeding the speed of light by only 5 parts in a billion trillion. Detections at higher energies will provide even tighter limits. Credit: NASA's Goddard Space Flight Center

It would take the discovery of many more extragalactic neutrinos to reveal a pronounced pileup. But if both features ultimately are observed, they would provide strong evidence that neutrinos violate Lorentz invariance.

"Even with no observed pileup below the cutoff, the very existence of high-energy neutrinos can be used to determine the strongest upper limit on their velocity yet found," Stecker said. "So our results allow for either only a very, very small violation of relativity or give strong indications that Einstein's theory is upheld."

The value Stecker and colleagues obtained, 5 parts in a billion trillion, gives the relative amount by which the velocity of neutrinos can exceed the speed of light. This relative excess is more than 100 billion times lower than that found from studying the arrival of neutrinos from SN 1987A, a supernova in the nearby galaxy known as the Large Magellanic Cloud. Stecker also notes that if the IceCube experiment detects neutrinos at even higher energies, it would leave even less wiggle room for neutrinos having superluminal velocities.

Francis Halzen, the principal investigator of IceCube at the University of Wisconsin–Madison, is intrigued by the study. "I find it amazing that each time we detect a higher-energy event, we actually improve the precision on a fundamental measurement," he said.

Whether or not neutrinos are breaking Einstein's cosmic speed limit, they're definitely ushering in a new astronomical era. Historically, light has been astronomy's only courier. Now neutrinos deliver information about the most extreme events in the universe completely independent of the electromagnetic spectrum.

"It's the dawn of extragalactic neutrino astronomy," said Stecker, "and we're only now learning how to decipher the message."

More information: journals.aps.org/prd/abstract/ … 3/PhysRevD.91.045009

Provided by NASA's Goddard Space Flight Center