REVEALING THE UNSEEN UNIVERSE

Astronomy is entering an era in which gravitational waves and neutrinos will be used to complement existing techniques and to uncover the hidden features of our Universe.

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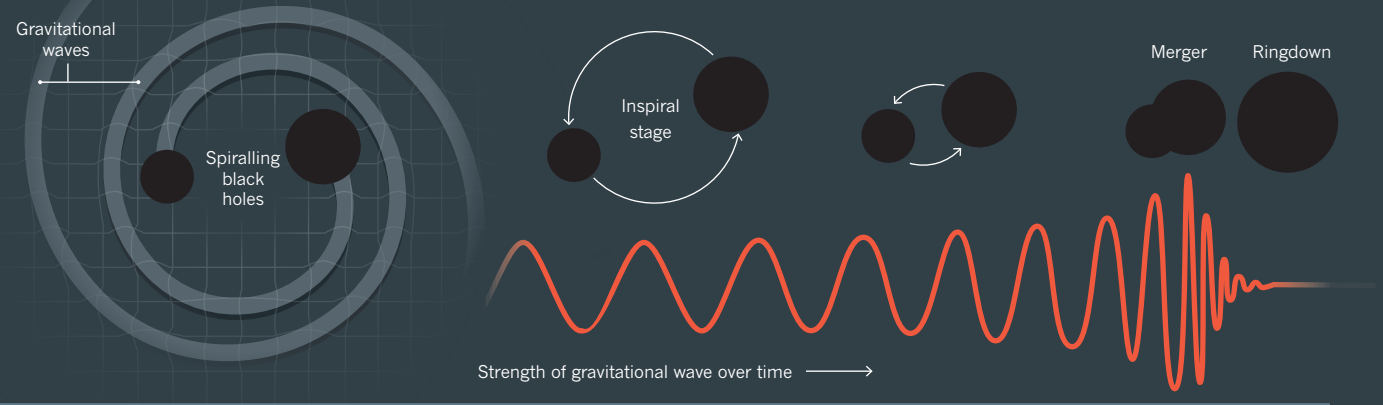
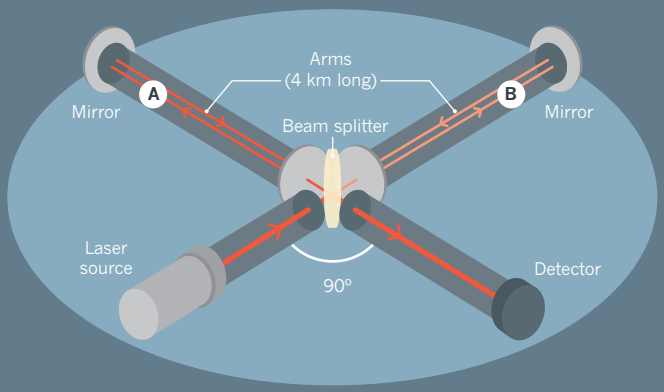
GRAVITATIONAL WAVES

When two black holes or neutron stars in a binary system spiral towards each other, their massive size causes ripples in space-time known as gravitational waves. The strength of these waves increases as the black holes revolve faster, spiralling towards each other until they merge and there is a fall off in the signal (ringdown). The Universe seems to be awash with these cataclysmic collisions, which astronomers expect to tell them how many black holes and neutron stars there are.



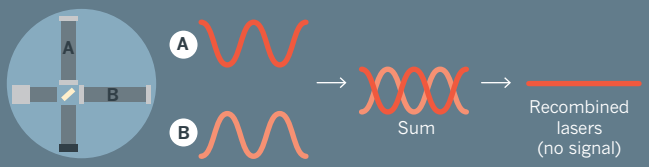
How to detect gravitational waves

In the Laser Interferometer Gravitational-Wave Observatory (LIGO), which detected gravitational waves for the first time in 2015, a laser beam is split in two, and each sent down a 4-kilometre tunnel. The beams are reflected back and forth by mirrors at the end of each tunnel, before being recombined at a detector[1].



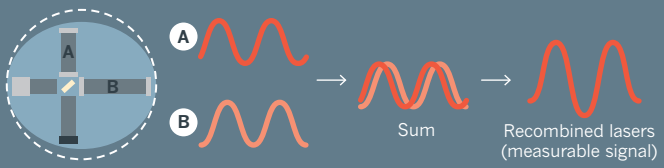
Normal operations

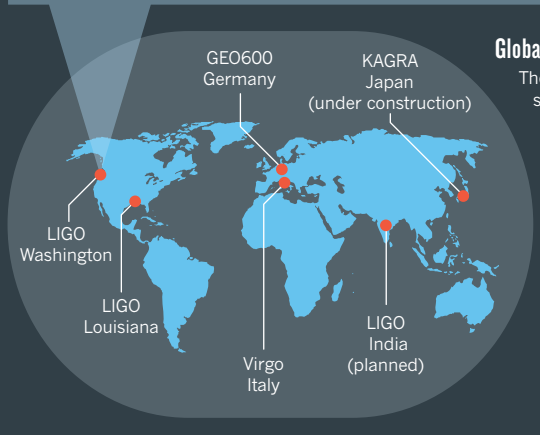
Laser beams travel identical paths and cancel each other out when they recombine at the detector.



Effect of gravitational waves

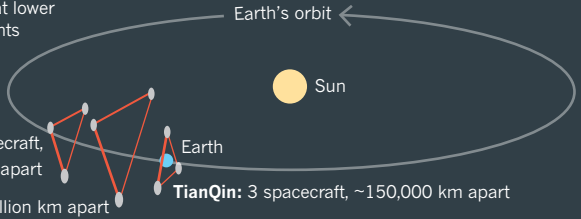
The waves warp the region of space-time that the tunnels sit in so that the beams seem to have travelled different distances when they merge. The difference is very small — about the width of an atomic nucleus for the first detection.





Global network of detectors

There are three operational gravitational wave detectors around the world: two LIGO arrays and Germany's smaller GEO600 facility. Kamioka Gravitational Wave Detector (KAGRA) and Virgo are due to come online in 2018 and 2016, respectively, and a third LIGO detector in India is planned. Combining data from multiple detectors will allow scientists to locate the origin of the waves much more precisely. The laser arms of proposed space-based observatories, such as Europe's eLISA and China's Taiji and TianQin, would be much longer. They could detect gravitational waves at lower frequencies and reveal events from weaker sources than can be felt on Earth[2].



Sources: 1. LIGO Scientific Collaboration; 2. *Nature* **531,** 150 (2016); 3. IceCube/Univ. Wisconsin–Madison

HIGH-ENERGY NEUTRINOS

Particles known as neutrinos flood the Universe and are so small that they can zip straight through most matter, making them the ideal cosmic messenger. By studying neutrinos, scientists hope to piece together details of the events that made the particles.

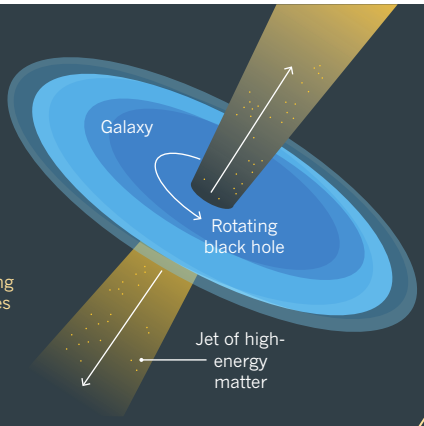
Neutrinos produced by the Sun or in nuclear reactors on Earth have energies of

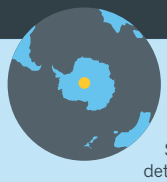
1,000,000 ELECTRONVOLTS

Neutrinos from outside the Solar System can be a billion times more energetic, at

1,000,000,000,000,000 ELECTRONVOLTS

The sources of high-energy neutrinos are shrouded in mystery, but the jets of matter streaming from supermassive black holes at the core of active galaxies are a prime suspect.





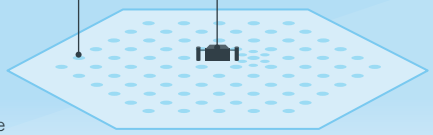
IceCube neutrino observatory

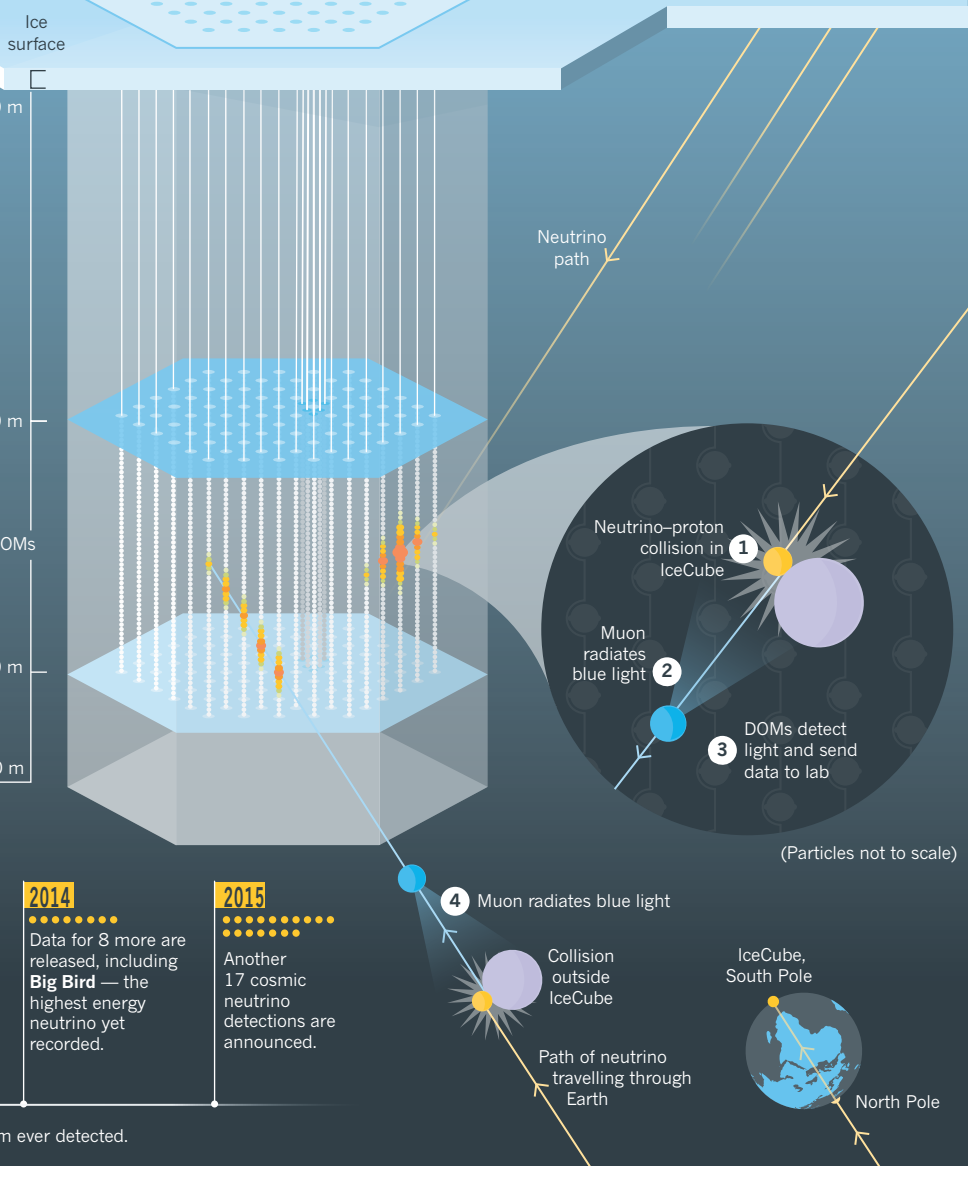
Located beneath the Amundsen–Scott South Pole Station, a US research facility, the detector of the IceCube neutrino observatory is arranged over one cubic kilometre of ice. IceCube's sensitivity is partly due to the fact that ice in the region is one of the purest and most transparent solids on Earth[3].

The IceTop air-shower detectors filter out some particle 'noise' from cosmic-ray interactions in the atmosphere.

The IceCube laboratory collects and analyses data.

Around 80 steel cables in the ice hold **5,160 digital optical modules (DOMs),** which are sensitive to light and allow researchers to track the paths of neutrinos.





How IceCube works

1. On rare occasions, a neutrino will collide with another particle, such as a proton or neutron, in IceCube's ice.
2. The collision creates a shower of particles that radiate blue light. Most fizzle out after a few metres, creating a bloom of light. But one particle — a muon — continues through the ice on the neutrino's original path.
3. Optical sensors send data about light intensity to the surface. The pattern (indicated by the colour, size and distribution) of the activated modules allows scientists to determine the neutrino's energy and rough direction.
4. IceCube can also spot the trails of light left as the muons, produced by neutrino collisions outside the detector, pass through it. But these tracks are also produced by muons from other sources, including cosmic rays. To combat this, IceCube uses Earth as a noise filter, looking only for muons that have passed through the planet.

Timeline of high-energy neutrino discovery

1987
Two detectors in Japan and Ohio spot 19 neutrinos from a nearby supernova in the Large Magellanic Cloud, about 51,000 parsecs away.

2013
IceCube detects 28 neutrinos, including two monsters above 1 petaelectronvolt named **Bert** and **Ernie**.

2014
Data for 8 more are released, including **Big Bird** — the highest energy neutrino yet recorded.

2015
Another 17 cosmic neutrino detections are announced.

- Every neutrino from outside the Solar System ever detected.