The Neutrinos Saga

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Wolfgang Pauli (1900-1958) considered physics so complicated that he almost wished he had never come across it. The Swiss physicist expressed this when faced with the problems posed by the radioactive decay of atomic nuclei. This revelation came only a few months before Pauli's letter to his physicist colleagues, which in part had to do with neutrinos, which are evasive particles that continuously bombard the Earth and which transverse our bodies every second by the billion.

***Figure 1:* Nicknamed "The Scourge of God" for his critical but inspired mind, physicist Wolfgang Pauli received the Nobel Prize in Physics in 1945.**

Shortage of Energy

The history of the neutrino begins at the turn of the last century, shortly after Henri Bacquerel discovered radioactivity in 1896. Radioactive nuclei decay spontaneously into a more stable nucleus thanks to the ejection of a particle: particle α (helium nucleus) in the case of radioactivity α, or an electron in the case of radioactivity β[1]. However, while particle α carries all of the energy released by the reaction, the electrons, which are ejected with a wide range of different speeds, only carry part. The experiments conducted by Germany's Lise Meitner and Otto Hahn from 1911, and then England's James Chadwick after 1914, with a primitive version of the Geiger counter, demonstrated that their energy takes any value between zero and the expected value.

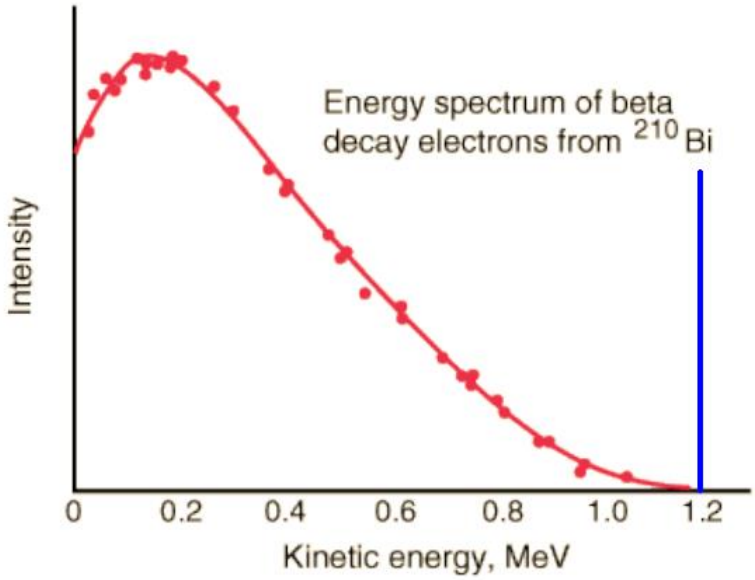

Figure 2: ***Distribution spectrum of electrons observed during the radioactivity β of a bismuth nucleus.*** *The electrons emitted by radioactivity β carry variable energies, between zero and the expected value: on the X-axis is the observed kinetic energy; on the Y-axis is the number of electrons emitted (image: G. Neary, Roy. Phys. Soc, A175, 71, 1940). The blue bar (which has been added to the original image) represents the "expected" energy, i.e., the difference of the energies between point of departure Bi210 (formerly radium E) and point of arrival Po210 (radioactive family of uranium 238 and radium).*

This continuous energy spectrum has caused problems for physicists. Lise Meitner initially blamed the inhomogeneous deceleration of electrons in the radioactive source. In her view, the lost energy was converted into heat. However, highly precise measurements of heat in 1927 revealed that this was not the case. Leading figures like Sweden's Niels Bohr therefore reassessed the principle of conservation of energy, at least at the atomic level.

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1. In light of current knowledge, radioactivity α can be expressed by this equation: ${}^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$. Radioactivity β^- (for nuclides with excess neutrons) is written as the following: ${}^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + e^{-} + \bar{\nu}$, where e^- is an electron and $\bar{\nu}$ an antineutrino.

PAULI'S IDEA

Only he who dares wins. Wolfgang Pauli

The Austrian-born Swiss Wolfgang Pauli, and professor at the Polytechnic institute in Zürich, did not share the views of Bohr. Godson of Ernst Mach and spiritual song of Einstein, Pauli had already established a solid reputation for himself in the field of quantum mechanics in 1925, by formulating the Pauli exclusion principle that two electrons of the same atom cannot coexist in the same state.

In order to save the conservation of energy and rescue physics from the situation it was in, Pauli came up with an original solution: what if the missing energy was carried by a small neutral particle, of infinitesimal mass, if at all, and therefore almost impossible to detect through normal channels? Not wishing to communicate this bold hypothesis officially, Pauli slipped it into a letter dated the 4th December 1930 and addressed to "Radioactive Ladies and Gentlemen", in other words, his fellow physicists who were to meet up in Tübingen, Germany. And to show the lack of seriousness that he himself gave this idea, Pauli even addressed his absence at the congress. The following year, in June 1931, during a lecture in Pasadena, California, Pauli ventured to publicly exhibit his idea of the ghost particle, which he termed "neutron" because of its lack of electric charge – what we know as neutron nowadays was to be discovered the following year. Nevertheless, he categorically refused that the text of his speech be printed and distributed.

SAVING STATISTICS AT ALL COSTS

As well as protecting the principle of energy conservation, the introduction of Pauli's ghost particle solved the problem of statistics, i.e., the laws of quantum mechanics describing the behaviour of microscopic particles. Protons and electrons, the sole components of the atom known at the time, were classified as fermions because they obeyed Fermi-Dirac statistics – their spin kinetic moment[2] could only be half full. Photons, which formed light, followed Bose-Einstein statistics thus assigning them their full spin. A consensus was also established

2. The spin is a form of rotation specific to quantum objects. The spin of the electron, for example, plays an important role in the macroscopic physical properties of magnetism.

around the atomic model of New Zealand's physicist Ernest Rutherford: negative *Z* electrons moving around a dense nucleus consisting of positive *A* protons and *(A-Z)* electrons, in order to protect their electrical neutrality. The electrons present in the nucleus do not collide; radioactivity β precisely releases electrons!

The problem: by adding spin magnetic moments of *A* protons and *(A-Z)* electrons, the total spin of the nucleus was to be half full when *2A-Z* was an odd number. And yet, a nucleus such as nitrogen, which contains 14 protons and (14-7) electrons, or 21 particles in total, has a full spin! As does lithium-6, whose nucleus was supposed to have 6 protons and 3 electrons! The addition to the nucleus of one of Pauli's termed "neutrons", which were classified as fermions and therefore have a half-full spin, solved the problem by getting round the "incorrect" statistics.

"NEUTRON" BECOMES *NEUTRINO*

In January 1932, some months after the intervention of Pauli, Frédéric and Irène Joliot-Curie subjected a beryllium target to a bombardment of particles α, and obtained radiation so penetrating that it could extract protons from hydrogenated substances. The two physicists had meant to find the presence of photos γ but that same year James Chadwick showed that the radiation from beryllium nuclei consisted of neutral particles, of a mass similar to that of protons[3]. The existence in the atomic nuclei of these new entities, known as neutrons too, lead to a complete overhaul of the atomic model. Inspired by an idea of Italy's Ettore Majorana (1906-1938), German physicist Werner Heisenberg suggested the nucleus was composed of *Z* protons and *A-Z* neutrons. The charge of *Z* electrons moving around the nucleus was offset by that of *Z* protons. Consequently, there was no reason to suppose the existence of electrons in the nucleus to guarantee an atom's electrical neutrality. Nor was there any reason to introduce Pauli's ghost particle to obtain a whole spin and "save statistics": the nitrogen and lithium nuclei indeed had an even number of fermions, 14 in the former (7 protons and 7 neutrons) and 6 in the latter (3 protons and 3 neutrons).

3. Beryllium reacts with helium according to the reaction: ${}^{9}_{4}Be + {}^{4}_{2}He \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$

***Figure 3:* The Solvay Conference of 1933 (22-29 October 1933, Brussels).** *This would be the last conference before the Second World War. To name a few of the scientists mentioned in this article: to the left, Irène Joliot-Curie is seated between Schrödinger and Bohr, her husband stands behind her, and her mother Marie Curie is seated at the table's angle. The other woman present, to the right, is Lise Meitner, between Louis de Brogie and Chadwick (to the very right, seated). Enrico Fermi stands to the right of Bohr (and to Bohr's left is Heisenberg, standing). Wolfgang Pauli is stood in the centre, slightly to the left, wearing a light grey three-piece suit.*

In 1933, the Solvay Conference in Brussels, which was devoted to the discovery of the neutron, ratified the identity of the nucleus. The Italian physicist Enrico Fermi, who was asked on this occasion if Chadwick's neutron was the same as Pauli's, responded: "No. Pauli's neutron is much smaller: it is a neutrino. " Pauli's "neutron" therefore became the neutrino, which means "little neutron" in Italian. The following year, Fermi, who had immediately supported the views of Pauli, wrote an article in which he detailed and developed a theory explaining radioactivity β by the intervention of a new nuclear force, of low intensity and reduced scope: weak interaction. This meant the conversion of a neutron into proton via the emission of an electron and neutrino. Fermi's article, rejected by the British journal *Nature* on the grounds that it contained speculations too remote from physical reality, appeared in a less famous Italian journal before being published in Germany in the March 1935 issue of *Zeitschrift für Physik*.

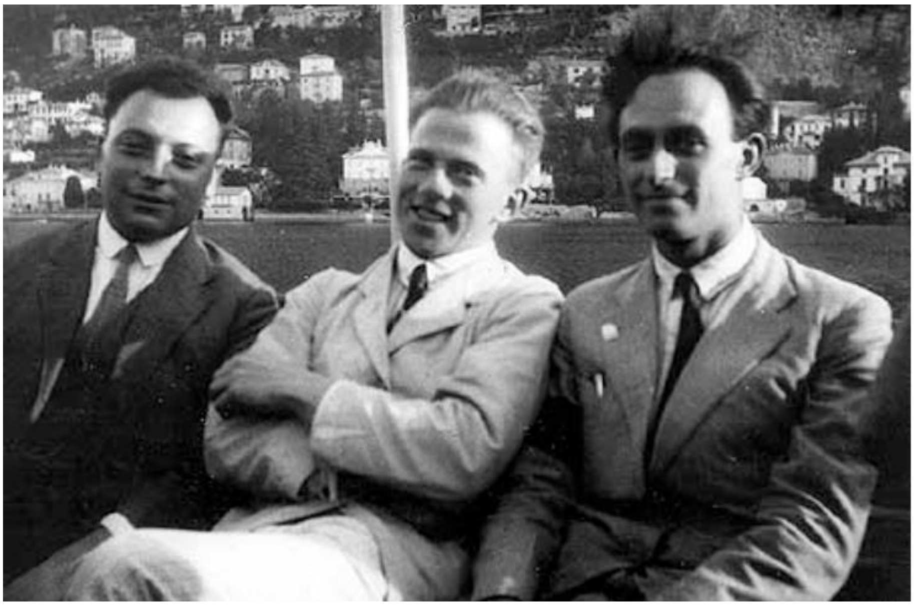


***Figure 4:* Wolfgang Pauli, Werner Heisenberg, Enrico Fermi, on Lake Como.** *(© Usual Archives, F.D. Rasetti, AIP Emilio Segré)*

On the Hunt for Neutrinos

The most tiny quantity of reality ever imagined by a human being.
Fred Reines

Why were we so slow to highlight these neutrinos "that we ought to have seen if they actually existed"? Their low mass, if at all, made them difficult to be interpreted. Their electrical neutrality made them insensitive to the action of electric or magnetic fields, so much so that they would go everywhere. Calculations established that neutrons with medium energy were able to traverse sizes of hundreds of light years with only a 50% chance of being absorbed.

To capture some, major sources of neutrinos were a requirement. Things only began to change in the 50s with the first nuclear tests. After some time trying to detect neutrons emitted in abundance during the explosion of atomic bombs, American physicists Clyde Cowan (1919-1974) and Frederick Reines (1918-1998) turned to civilian nuclear reactions. After a first attempt in Hanford, Washington in 1953, project "Poltergeist" become a reality with the installation of a tank of 400 litres of water containing cadmium chloride, in the immediate vicinity of the nuclear power plant in the Savannah River, South Carolina. According to the calculations made by Cowan and Reines, collision between a neutrino and a proton of a water molecule produced a positive electron, or positron, and a neutron. The positron was destroyed immediately with an electron producing two gamma photons. Meanwhile, the neutron endured collusions on light nuclei before being captured by a cadmium atom, a large absorber of neutrons, commonly used in the control rods of nuclear reactors. After a few microseconds, cadmium in turn emitted a gamma photon, de-exciting. In total, liquid organic scintillators, sensitive to gamma radiation, produced three tiny flashes; the photomultiplier tubes transformed into electrical impulses. To the great satisfaction of Reines and Cowan, the new version of the device, which was less sensitive to background noise than Hanford's, detected neutrinos at a rate of 2 to 3 per hour. A telegram bearing the good news was thus sent to Paul and Fermi. In 1956, Pauli had won, but still nothing was known about the neutrino's mass.

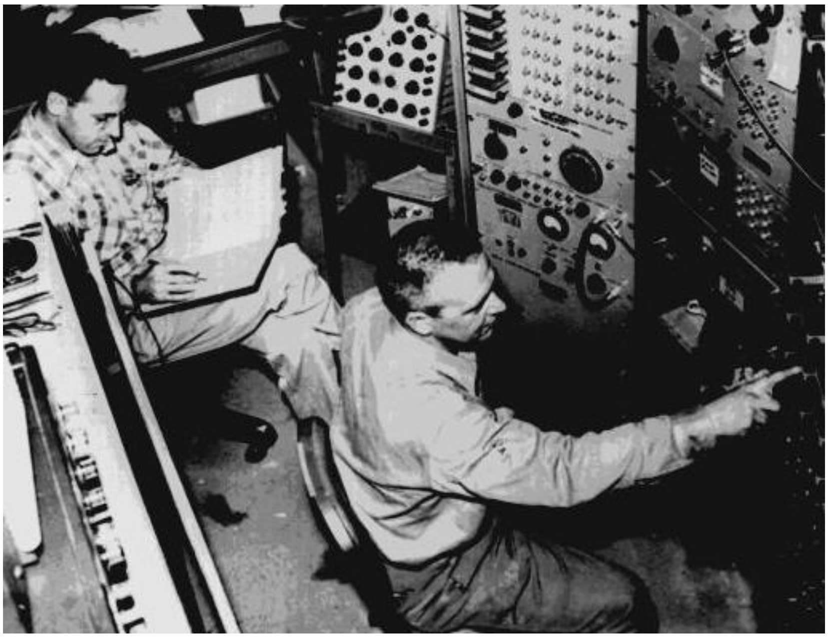


Figure 5:* Fred Reines (left) and Clyde Cowan (right), Hanford Experiment in 1953(photo: University of California at Irvine). Reines received the Nobel Prize in Physics in 1995 for discovering the neutrino (Cowan had died in 1974).*

Neutrino and Antineutrino

I cannot believe God is a weak left hander (Wolfgang Pauli)

In the 1930s, English physicist Paul Dirac suggested the existence of antimatter as well as matter. In his view, all particles have antimatter, with the same mass as themselves but opposite spin and charge. As soon as a particle meets its antiparticle, they annihilate each other, producing radiation in the form of two gamma photons, emitted back-to-back. The antiparticle of e^- electron is the e^+positron, discovered in 1932 by American physicist Carl Anderson. The antiparticle of the neutrino ν is the antineutrino $\bar{\nu}$.

Natural radioactivity β^-, which concerns nuclei with too many neutrons, occurs when a neutron transforms into a proton via the emission of an electron and an antineutrino. Artificial radioactivity[4] β^+, discovered in 1934 by Irène and Frédéric Joliot-Curie, and which affects nuclei with excess protons, occurs when a proton transforms into a neutron via the emission of a positron and a neutrino. In his experiments, Reines highlighted the antineutrino, which differs from the neutrino by its spin or helicity, i.e., the direction of rotation of the moving particle.

So far we have observed left-handed neutrinos and right-handed antineutrinos, which violates the principle of parity according to which every physical phenomenon exists in two versions, each a "mirror" image. Unless the neutrino is its own antiparticle, suggested by enigmatic Italian physicist Ettore Majorana. To be sure, particle physicists have studied a rare type of radioactivity: double decay β, which occurs when two electrons and two antineutrinos are emitted. If the neutrino were its own antiparticle, there would be cases where the two antineutrinos would annihilate each other. The NEMO Experiments, of which the latest, NEMO3 in Modane, stopped on 11th January 2011, have examined hundreds of millions of outcomes. Yet, to no avail!

The Neutrinos Family Expands

Although he supposed the existence of the neutrino, Pauli had no idea whatsoever that it could exist in several versions. In 1936, four years after the discovery of the positive electron, or positron, America's Carl Anderson discovered the muon in particles generated by cosmic rays in the upper atmosphere. The muon was classified in the family of leptons, with the electron of which it is a heavier and less stable variant.

Radioactivity β^- produces electron neutrinos, associated with the electron. The disintegration of cosmic muons therefore suggested the existence of a new variety of neutrinos, associated with the muon. In 1962, the muon neutrino was discovered at the Brookhaven laboratory, New York. It was not until 2000 at the Fermi laboratory in Chigago that the tau neutrino was discovered, whose existence had been suspected following the discovery of a third lepton, the tau, a superheavy electron. The tau neutrino is the twelfth and final elementary particle of the standard model of the architecture of matter. According to this theory,

4. See analysis *BibNum* by Pierre Radvanyi (April 2009) of the Nobel Conference in 1935 (F. Joliot).

matter consists of twelve fundamental parts: six quarks and six leptons (the electron, the muon, the tau and their associated neutrinos). Neutrinos are involved mainly in the reactions of production and destruction of leptons, via weak interaction.

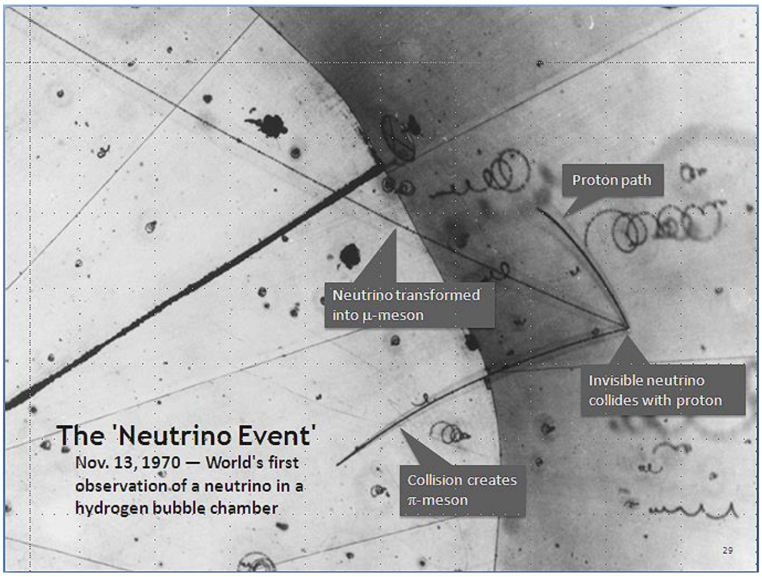


***Figure 6:* First world observation of a neutrino in a liquid hydrogen bubble chamber, at the Argonne Laboratory, southwest of Chicago in 1970.** *A (muon) neutrino is involved in the reaction of the production of a muon when collided with a proton (© Argonne, National Laboratory).*

THE ENIGMA OF SOLAR NEUTRINOS

Not content with being divided into three varieties (or *flavours*, electron, muon and tau), neutrinos can mutate and change from one form to another, a property revealed thanks to solar neutrinos, the shortage of which has annoyed the scientific community for a good thirty years.

In 1920, English astrophysicist Arthur Eddington suggested that the energy of stars was nuclear. In 1938 Hans Bethe proposed a model for fusion reactions converting hydrogen into helium. This cycle of reactions, called "proton-proton" because it began with the fusion of two hydrogen nuclei, produces an impressive number of neutrinos that pass through the solar matter undamaged, unlike photons which deteriorate when passed through from the inside to the outside of a star, thus forgetting their origin. Neutrinos give us an intact message concerning the physical conditions, particularly temperature, from the sun's core. However, while our planet receives sixty-six billion per square centimetre every second, the absence of interaction they have with matter makes them difficult to catch. To detect solar neutrinos, Raymond Davis (1914-2006, Nobel Prize in

Physics in 2002), from the Brookhaven National Laboratory in New-York and John Bahcall (1934-2005), from the Princeton Institute, in the 60s placed a giant cistern underground in an abandoned gold mine at Homestake, South Darkota, 1.5 kilometres deep, far from the background noise of cosmic particles. The tank, surrounded by water in order to absorb interference emitted from the radiation, was filled with 400,000 litres of perchloroethylene, a cleaning liquid rich in chlorine atoms. Around once per day, one neutrino would interact with a chlorine-37 atom, transforming one of its neutrons into a proton, according to the process ${}^{37}_{17}Cl + \nu \rightarrow {}^{37}_{18}Ar + e^-$, creating argon-37, which could be detected by its gamma radioactivity. However, after more than 20 years of operation, the device would only give a third of the neutrinos predicted by the model of the sun's internal structure. To everyone's dismay, two thirds of the neutrons were missing! In the 1990s, the "Alsace-Lorraine" detectors, in which gallium-71 were transforming into germanium-71, an operation requiring less energy than the passage of chlorine to argon, showed a deficit of 40% for solar neutrinos with low energy, created during the first stage of the "proton-proton" cycle. Cherenkov detectors followed suit. Unlike their predecessor, which were limited to counting neutrinos, these new generation detectors gave access to the energy of the neutrinos and their incident direction, and therefore making it possible to verify their origin. Solar neutrinos interacted with the water protons by emitting an electron with a speed greater than that of light in water. This phenomenon, called the Cherenkov effect, occurred with the emission of a blue light cone, an optical equivalent of the Mach cone produced by a supersonic aircraft in flight.

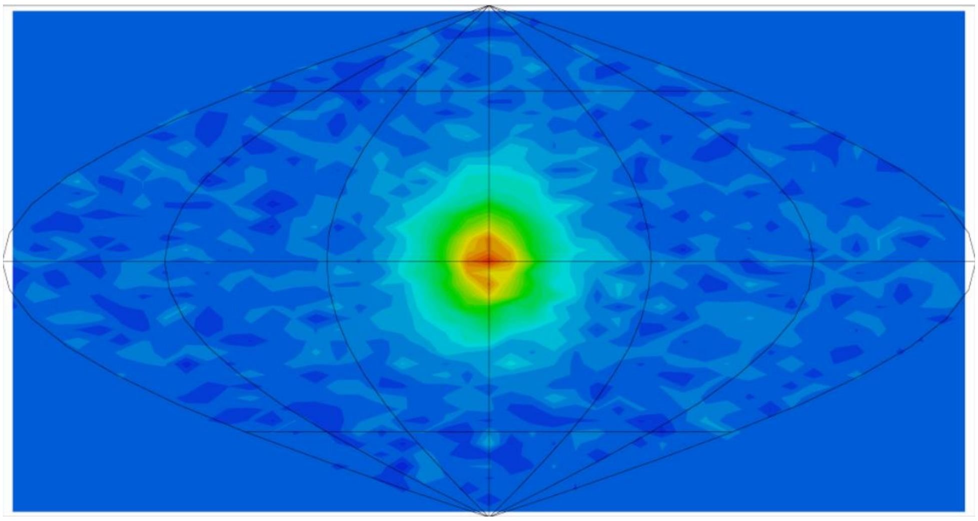


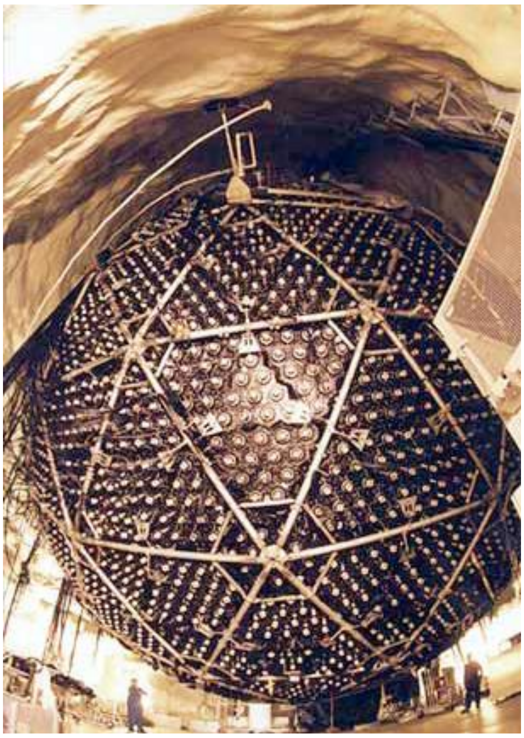
Figure 7: ***Image of the sun in neutrinos, taken across Earth, with an exposure time of 503.8 days*** *(Institute for Cosmic Ray Research, Tokyo). While it takes several thousands years for photons to escape from the core of the sun, neutrinos take no more*

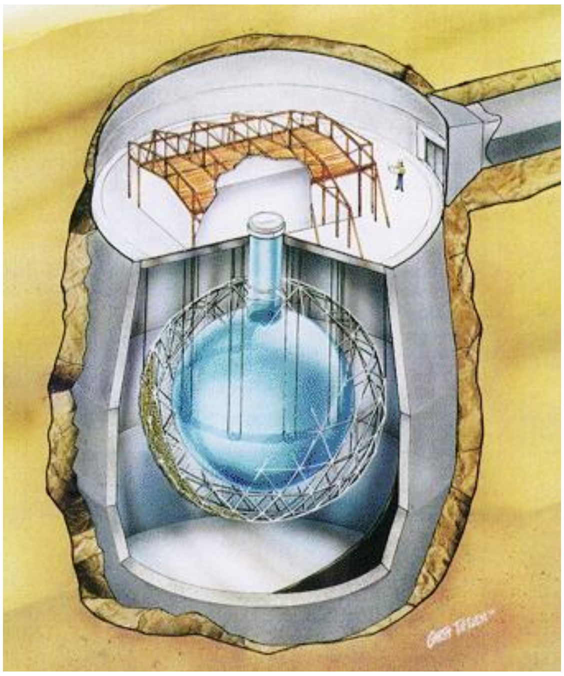
than two seconds to emerge from the star, revealing in real time, or about, the physical conditions of the centre. The flux of neutrinos increases from blue to red, highlighting the intense production of neutrinos from the thermonuclear fusion reactions at the core of the sun. The low resolution of the image, covering one-eighth of the sky, makes the sun appear significantly larger than in photonics.

METAMORPHOSES OF NEUTRINOS

The only neutrinos detectable in radiochemical experiments at first were electron neutrinos. Yet, with the neutrinos from the thermonuclear reactions of the sun precisely belonging to this category, it was unclear how to explain the recorded deficit. Did the dispute therefore have to do with the imperfection of theoretical solar models or with unknown properties of neutrinos? Bahcall summarised the situation, stating that there was something wrong either with the sun or with the neutrinos, or with what researchers thought they knew about them.

Italian-born Soviet physicist Bruno Pontecorvo (1913-1993), who cut his teeth in the United States and then England where he was suspected of being a KGB agent, was among the first to suggest neutrinos could change in nature. In 1969, under the leadership of Pontecorvo, a group of physicists at the Academy of Sciences of the USSR developed a theory that, during their journey to Earth, a number of high-energy electron neutrinos had transformed into muon neutrinos, of lower energy and therefore undetectable in experiments like at Homestake. Neutrinos can oscillate from one state to another: the probability of metamorphosis depended on their mass, energy and distance travelled since their formation. In 1985, Stanislas Mikheyev and Alexei Smirnov went even further. Drawing on the work of America's Lincoln Wolfenstein, the two claimed that the oscillations were amplified in the presence of matter. According to their theory (which is known as the SMW theory), the density at the centre of the sun was enough for two thirds of the electron neutrinos produced to change into muon neutrinos in the half second spent in the star's core. Sensitive to all types of neutrinos, the detectors at the Sudbury Observatory, in Ontario, Canada, confirmed this metamorphosis in 2001.





***<u>Figure 8:</u>* The Sudbury detector, 12m- diameter sphere.** *Thanks to the heavy water tank, the 9600 detectors of the Sudbury Observatory, Canada, detected the three flavours of neutrinos. To the right: artist's impression of the physical environment: the sensor is protected from cosmic rays by surrounding rock (@SNO Observatoire de Sudbury).*

Detection of Neutrinos, Sudbury

Sudbury detected all solar neutrinos, thanks to heavy water, i.e., water where the hydrogen is replaced by deuterium whose nucleus contains not only a proton but a neutron as well. Some thousand litres of heavy water were buried in the abandoned Creighton mine, more than two kilometres deep, in an acrylic sphere, five centimetres thick and twelve metres in diameter. The tank was immersed in a bath of ultrapure light water, charged to absorb the radiation emitted by the nearby rock, which served as a shield against the cosmic rays.

The charged current interaction (see figure 9), specific to electron neutrinos, and the electron distribution occur when the Cherenkov light cone is emitted, recorded by thousands of photomultipliers inserted into the plastic of hexagonal cells.

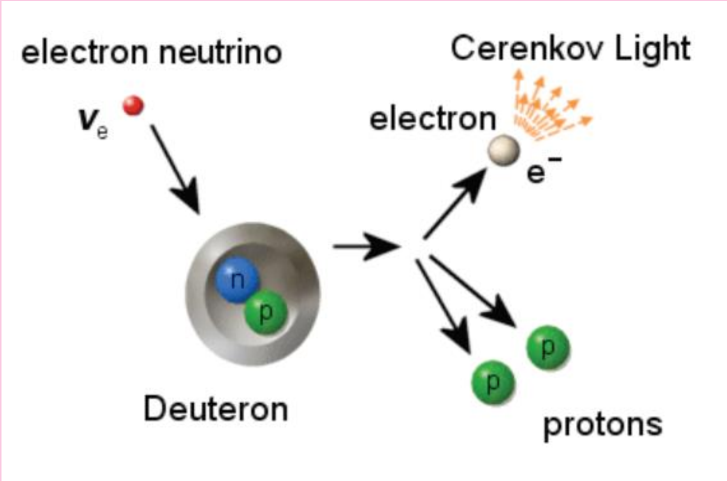
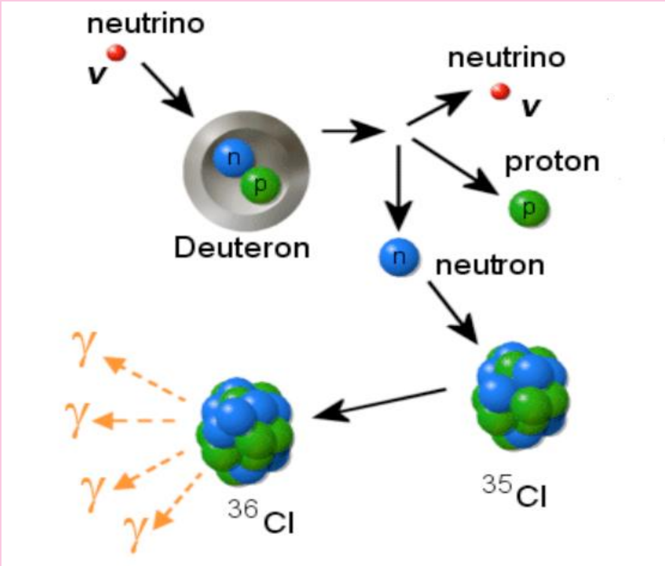


***Figure 9:* Detection of the electron neutrino (charged current method).** *The neutrino meets the deuterium; the neutron is transformed into a proton, and the neutrino into an electron - therefore it becomes detectable by the Cherenkov effect (image: Sudbury, Carleton University, Ottawa, Canada[5])*

The neutral current interaction (see figure 9.1) of the three kinds of neutrinos with deuterium releases the proton and neutron thereof. Captured by chlorine-35, the neutron leads to the formation of a chlorine-36 nucleus which emits gamma radiation.

5 . To read more on the explanations of these reactions (in English), see page from Carleton University (Ottawa, Canada).



<u>Figure 9.1:</u> Detection of the neutrino (neutral current method). *The neutrino meets the deuterium and, by another mediator of weak interaction (the Z boson and not the W boson like before), separates the proton and neutron from the deuterium. The neutron interacts with the ^{35}Cl producing gamma photons (image: Sudbury, Carleton University, Canada)*

The system determined the rate of energy and direction of the neutrinos emitted at the core of the sun. It runs almost continuously and has gathered data since November 1999. Because the detection frequency hardly exceeds once per hour, several days are required to get data for analysis.

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The electron neutrinos are not the only ones that can change in nature along the way. Since 1998, the Super-Kamiokande detector in Japan has recorded a deficit of atmospheric muon neutrinos. Muon neutrinos are produced when photons of cosmic rays collide with nitrogen or oxygen nuclei from the upper layers of the atmosphere. The shock produces, among other things, particles called pions, or mesons π, which decay into a muon and a muon neutrino: $\pi^+ \rightarrow \mu^+ + \nu_\mu$ or $\pi^- \rightarrow \mu^- + \overline{\nu_\mu}$. Unstable, the muon decays in turn, producing an electron, an electron neutrino and a muon neutrino (or their antiparticles): $\mu^- \rightarrow e^- + \overline{\nu_e} + \nu_\mu$ or $\mu^+ \rightarrow e^+ + \nu_e + \overline{\nu_\mu}$. In the end, two times more muon neutrinos than electron neutrinos are produced.

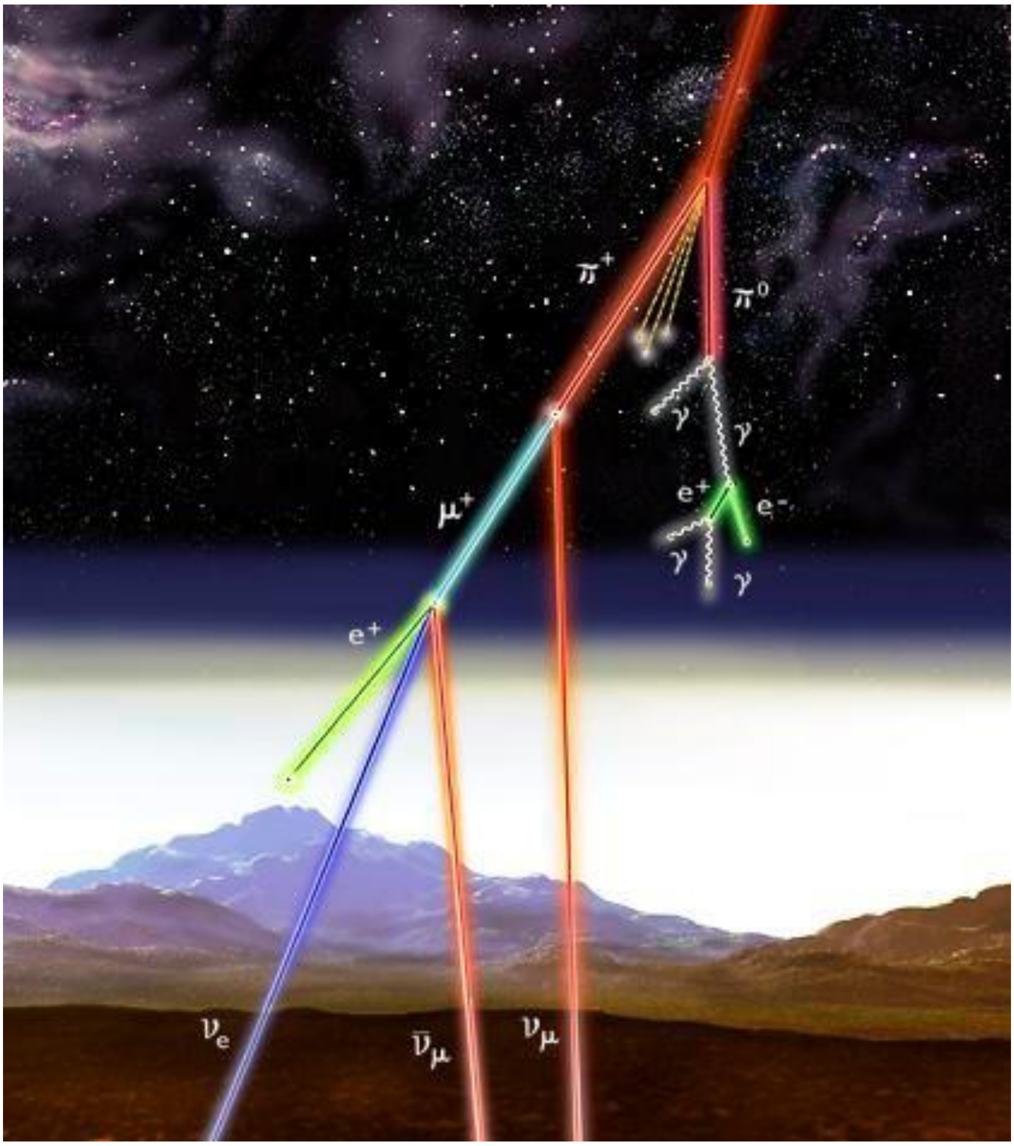

***Figure 10:* A proton from a comic ray collides with an air molecule.** *Here appears a pion π^+, which decays into a muon μ^+ and a muon neutrino ν_μ. The muon μ^+ in turn produces an electron neutrino ν_e along with a muon antineutrino (© Instituto nazionale di Fisica nucleare INFN -Notizie).*

Since Earth is transparent to neutrinos, the detectors record not only the downward neutrinos, produced in the atmosphere immediately above the detector, but also upward neutrinos, produced poles apart. The Super-Kamiokande detectors reported a ratio of two between muon neutrinos and downward electrons, but a ratio of only one between muon neutrinos and upward electrons. Again a transformation had taken place, interpreted as the oscillation from muon neutrino to tau neutrino. The upward muon neutrinos, which had travelled a thousand times more than their counterparts, turned into tau neutrinos, undetected at Kamiokande.

The possibility of this transformation was confirmed on 31st May 2010, by the OPERA detector, installed in the Gran Sasso tunnel, near Rome. OPERA, which gathers neutrinos from the CERN accelerators in Geneva, managed to discover a rapidly changing muon neutrino, showing its direct transformation into a tau neutrino. This occurrence, which crowned more than three years of work and the sending of billions of neutrinos from CERN to Gran Sasso, confirmed that the mass of the neutrino was not zero. The standard model of particle physics actually prohibits particles of zero mass from oscillating between states. A particle of zero mass moves at the speed of light. Time stops for it, implying that it cannot change, the duration of possible mutation at infinity. The likelihood of oscillation between two flavours of neutrinos depends on the difference in the squares of their masses, which establishes a lower limit for the mass of each.

NEUTRINOS: COSMIC MESSENGERS

Particles of cosmic radiation are quickly stopped or deviated by intergalactic magnetic fields. Meanwhile, electromagnetic radiation avoid, with difficulty, dense regions of the Universe. Neutrinos, however, can move all around. Witnesses of the life and death of stars, they are emitted not only in the thermonuclear reactions within stars, but also during violet cataclysmic processes: death of stars, swallowed by giant black holes, exchanges of matter in binary star, jets of active galactic nuclei. It was on 23rd February 1987, in Japan and the USA, that neutrino traps detected a short burst of 19 neutrinos from the supernova explosion SN1987A, a blue supergiant from the Large Magellanic Cloud, a galaxy located 170,000 light-years from Earth. This neutrino shower (11 in 12.5 seconds at Kamiokande and 8 in 6 seconds at IMB Cleveland) preceded the visual observation by a few hours.

The explosion, which occurred at the dawn of humanity, had produced a total of 10^{58} neutrinos, of which 30 million billion crossed the Cleveland detector. A real godsend for astrophysicists, the occurrence crowned twenty years of theoretical research on the role of neutrinos in stellar explosions. It strengthened the understanding of the phenomenon of the core-collapse of massive stars which, at the end of their lives, running low on fuel, contract until the protons and electrons merge into neutrons with an emission of neutrinos according to the reaction $p + e^- \rightarrow n + \overline{\nu_e}$. The falling matter then rebounds, creating a shock wave which, accompanied by the first emitted neutrinos, tries to make its way through the still collapsing inner layers. When the wave reaches the surface of the star, light energy is released, but most of the lost gravitational energy is converted into heat energy inside the neutron star that is formed. When it cools, the energy is carried by neutrinos and antineutrinos, notably from converted electron-positron pairs into neutrino-antineutrino pairs: $e^- + e^+ \rightarrow \nu_e + \overline{\nu_e}$. The first neutrinos reach us even before the light, with speeds depending on their mass and energy. The spread in time of the neutrino signal observed at Cleveland and Kamiokande made it possible to fix an upper limit of 15 eV to the mass energy $E = mc^2$ of neutrinos. Although subject to much uncertainty, if only because of the low number of detected neutrinos, the method procured for this time an interesting order of magnitude.

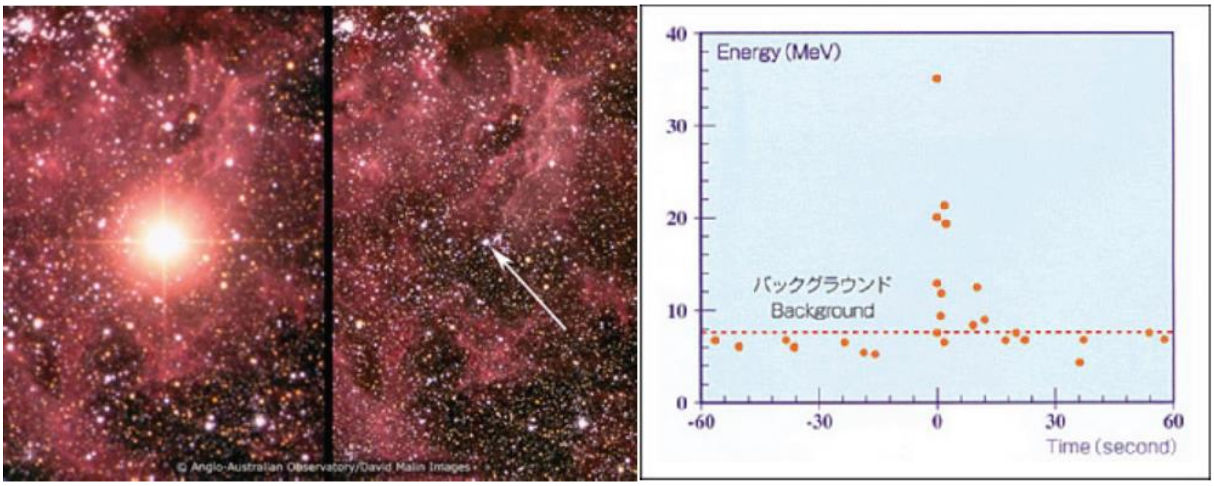

***Figure 11:* End of a superstar.** *The massive star Sanduleak (20 times the mass of the sun) before (middle image) and after (image to the left) its explosion into supernova SN1987A (© Anglo-Australian Observatory, Eastwood, Australia, images David Malin). Some massive stars end their lives as supernovae, before evolving into neutron stars or black holes. Most of the gravitational energy released during the star's core-collapse is carried by neutrinos. On the image to the right (Kamiokande, Japan), you can see the peak of neutrinos (at 0 sec.) from the explosion. The red line marks the lower limit of retaining energy, showing that eleven neutrinos were recorded. The spread in time of the signal recorded made it possible, considering their energy, to fix an upper limit to the neutrinos' mass.*

Upside-Down Telescopes

Lurking in the depths of the sea, 40 kilometres off the coast of Toulon, 2500 metres deep, the ANTARES neutrino telescope's mission is to detect high energy neutrinos (of the order of PeV, read further) emitted during stellar cataclysms. In operation since 2006, ANTARES is not a real telescope, in that it does not have an optical mirror, but only a battery of Cherenkov detectors, coupled with photomultipliers. A network of 900 photodetectors equip 12 lines (350 metres high) and define a volume of 20 million tons of water. The sensors scan the sky in the southern hemisphere across the Earth which serves as a target for high-energy muon neutrinos from the cosmos. Most of them had to cross the globe from side to side, but some of them could interact with atoms in the Earth's crust just before arrival in the marine environment, creating visible muons by Cherenkov effect. As for the atmospheric muons, they were filtered by the Earth, which acts as a natural shield.

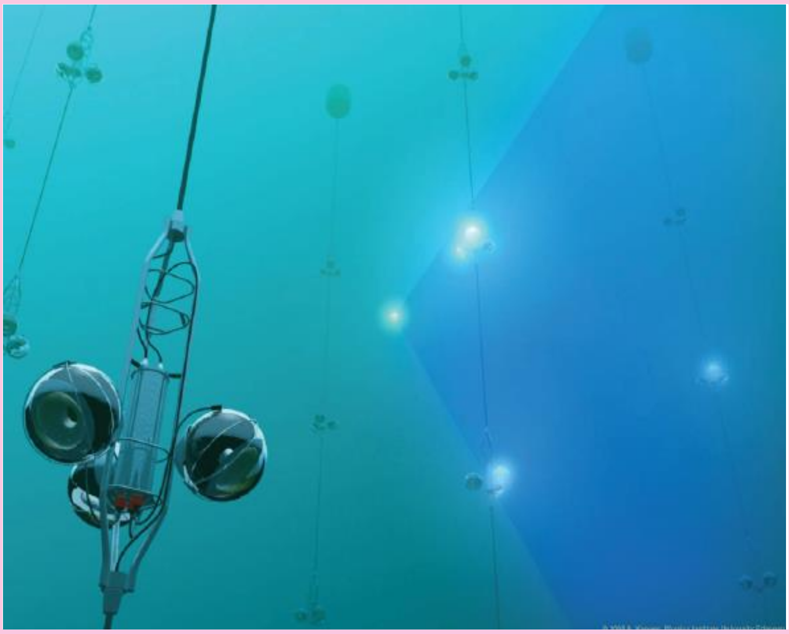

***Figure 12:* ANTARES Observatory at Toulon harbour.** *One level (the basic unit) of a detection line with its three optical modules and associated electronics. The glass spheres each contain a photomultiplier which detects Cherenkov light from the particles. You can see the blueish cone which is joined to the passage of one.*

Less unstable than the ocean, ice floe is also used to trap neutrinos. In the South Pole, the IceCube Neutrino telescope, put in operation on 18th December 2010, has 5000 photomultipliers. This structure (significantly made from one cubic kilometres) is placed in an ice cap, one kilometre deep. The ice contains no bioluminescent organisms or natural radioactive isotopes. Furthermore, it has the clarity and transparency of crystal because the pressure there is so great that all air bubbles have been expelled. Aimed at the northern sky, IceCube can also detect WIMPs, hypothetical massive particles which are sensitive to weak interaction, like all neutrinos.

Dark Matter and Neutrino Mass

Since the 30s, Swiss astronomer Fritz Zwicky had suspected the existence of huge amounts of dark matter in the Universe. The rotational speeds of the

Coma Berenices Cluster, determined by the Doppler effect, were shown to be unusually high. The visible mass of the luminous disks was clearly too low to ensure the stability of the whole and avoid the escape of galaxies. Hence, there came about the hypothesis of an abundant amount of hidden matter (i.e., dark matter), concentrated in the dark halo which surrounds galaxies In the 70s, American astrophysicist Vera Rubin reached a similar conclusion by measuring the rotational speed of stars in the Andromeda Galaxy. Instead of decreasing as they moved away from the centre, the stars' speed remained constant while the gravitational field created by the visible matter density got smaller.

According to the latest estimates, the mass-energy content of the Universe consists of 26% matter (of which 83% is dark matter, 17% ordinary matter) and 74% dark energy, which is a major component of the Universe whose nature still eludes physicists. This latent energy, introduced in 1998 to explain the recent acceleration of the expansion of the Universe, is said to oppose the collapse of the Universe. In the 80s, neutrons were considered possible components of dark matter. According to estimations, their contribution would not exceed a few percent. Moreover, far from boosting the concentration of matter clusters, neutrons are said to have a tendency to make the Universe more homogeneous, by a friction effect linked to their high speed. The Mega Z mapping of the distribution of galaxies, made in 3D at the Apache Point Observatory, New Mexico, has allowed astrophysicists to better understand neutrino mass, via relatively important concentrations of the observed matter.

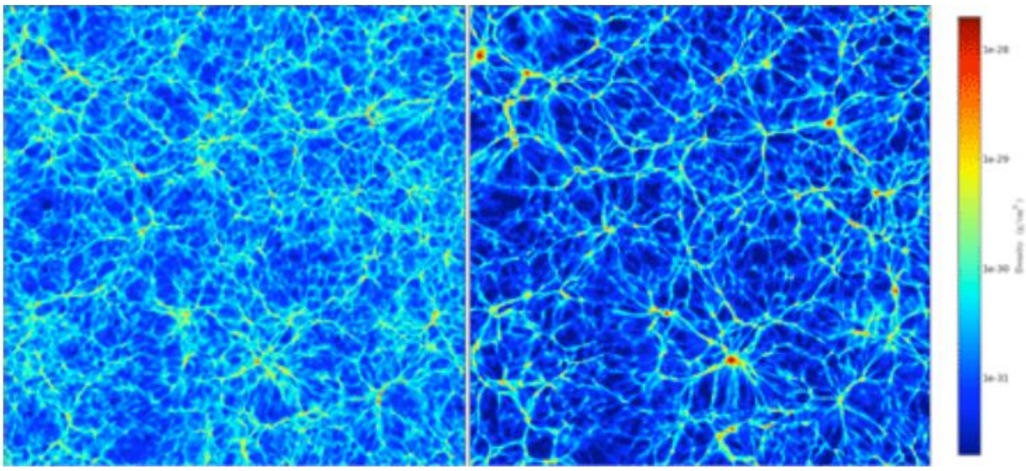

***Figure 13:* Simulations of the distribution of baryonic matter (ordinary matter) in the Universe** *(image: Shankar Agarwal & Hume Feldman,University of Kansas, 2010). Neutrinos of mass 1.9 eV (image to the left – this very high value was chosen in this numerical simulation to increase the visual contrast), and neutrinos of zero mass (to the right). Matter is distributed more uniformly to the left and the contrast of density is less. From blue to orange, matter density increases from 10^{-31} à 10^{-28} g/cm^3.*

Without Forgetting Fossil Neutrinos

Calculations have suggested a cosmic neutrino background from the hot and dense period after the Big Bang. As fossils of the Universe, these neutrinos are said to have escaped one second after the Big Bang. All categories of them are said to have filled the Universe, 330 per cubic centimetre. Their low energy, of the order of meV, means that they have not yet been detected: neutrino temperature is said to be 1.9 K, compared with 2.9 K of microwave background radiation detected by Penzias and Wilson in 1965.

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Thanks to the analysis of the large scale distribution of 700,000 galaxies, Shaun Anthony Thomas, Ofer Lahav and Filipe Abdalla, of University College London, announced in June 2010 a new limit on the sum of neutrino mass. This has been reduced to 0,28eV, or more than two million times less than the electron and four billion times more than the proton. With 0.01 times the mass of the proton, Pauli was far from reality!

This is difficult to beat even if Project KATRIN (Karlsruhe Tritium Neutrino Experiment), which was scheduled for 2012, aims to get the direct measurement of the electron neutrino mass via the study of the tritium beta emission spectrum decaying into helium-3. The final form of the energy spectrum of electrons depends on the mass of the neutrinos emitted. KATRIN therefore should be quite capable of reducing the upper limit of the mass energy of the electron neutrino to 0.2 eV. The experiment, nevertheless, is still tricky and requires highly sophisticated apparatus. For this reason, Mark Raizen and his colleagues at the University of Austin, Texas, have suggested an alternative, based on ultra-cold atoms of tritium. At a very low temperature, the electron emitted by decayβ^- remains trapped on an electron shell of the helium-3 atom, instead of escaping. Consequently, the difference between the mass energy of the tritium atom and the helium atom created would give direct access to the neutrino's mass energy. Unfortunately, laboratories do not yet have the technology to cool tritium to the few millionths Kelvin necessary to complete KATRIN. No doubt the neutrino will hold onto the secret of its mass for many more years!

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(April 2009)

(English translation by John Moran, published December 2015)