THE ANNUAL BALZAN LECTURE

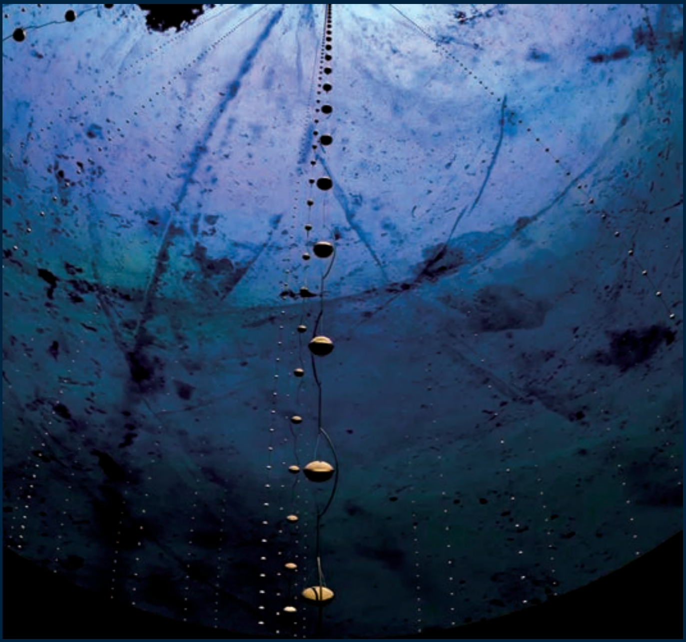
8

ICECUBE AND THE DISCOVERY OF HIGH-ENERGY COSMIC NEUTRINOS

by

FRANCIS HALZEN

2015 Balzan Prizewinner



LEO S. OLSCHKI
2018

Francis Halzen

IceCube and the Discovery of High-Energy Cosmic Neutrinos

11 October 2017, Accademia Nazionale dei Lincei, Palazzo Corsini, Rome

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FOREWORD

This year's International Balzan Prize Foundation Annual Balzan Lecture, delivered by Francis Halzen, marks another edition, and hence is an important manifestation of the Foundation's longstanding commitment to promoting the sciences and the humanities. This distinguished lecture series was born of a joint agreement between the Swiss Academies of Arts and Sciences, the Accademia Nazionale dei Lincei and the Balzan Foundation, and bears witness to their fruitful collaboration dedicated to providing venues for Balzan Prizewinners to present their achievements to the public and share with them issues and findings related to the Balzan Research Projects. Like another important initiative resulting from this collaboration, *IinteR-La$^+$B*,[1] an interdisciplinary research laboratory involving past Balzan Prizewinners and young researchers involved in the Balzan Research Projects, the Annual Balzan Lecture series also recalls the Foundation's principal aim of fostering communication between the sciences and the humanities at the highest level of international scholarship. Thus the Annual Balzan Lecture is also an opportunity for contemporary academic discourse and exchange, not only in the subject area of the lecturer, but in all disciplines as well.

It is both an honour and a great pleasure to write the foreword to this year's lecture by 2015 Balzan Prizewinner Francis Halzen, as it enables me to call attention to the unparalleled accomplishments

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[1] The acronym stands for International Interdisciplinary Research Laboratory. The second part combines an L for the Lincei, an a$^+$ for the Swiss Academies and a B for Balzan.

of all of the Balzan Prizewinners and increase knowledge of the Foundation among wider audiences.

The lecture series covers a wide range of subjects which, as the following short synopsis shows, reflects the interdisciplinary focus of the Balzan mission. In the first volume, the results of Peter and Rosemary Grant's research project involving young academics on the seminal topic of *The Evolution of Darwin's Finches, Mockingbirds and Flies* were presented. The second lecture by Anthony Grafton, *Humanists with Inky Fingers. The Culture of Correction in Renaissance Europe*, provided a detailed analysis of how these correctors influenced the meaning of the texts they worked on. The third lecture by Colin Renfrew illustrated the findings from his excavations on the Greek island of Keros in the project *Cognitive Archaeology from Theory to Practice*. Michael Marmot gave the fourth lecture, *Fair Society, Healthy Lives*, in which he examined the social determinants of health. Kurt Lambeck's lecture, entitled *Of Moon and Land, Ice and Strand: Sea Level during Glacial Cycles*, contributed to the debate on the consequences of human impact on the earth as well as on the very long cycles of changes in the world's physical structure. The sixth lecture, *'Far other worlds, and other seas': Thinking with Literature in the Twenty-First Century*, delivered by Terence Cave, analysed selected literary texts in light of issues encountered in adopting a cognitive approach to the study of literature, that is, literary study as it relates to cognitive science. Quentin Skinner gave the seventh Annual Balzan Lecture on *Thinking about Liberty: An Historian's Approach*, which defended a theoretical point of view of liberty based on a "neo-Roman", republican idea of freedom understood as freedom from arbitrary domination by others.

In today's lecture, *IceCube and the Discovery of High-Energy Cosmic Neutrinos*, Francis Halzen will present the accomplishments which have led to the construction of the large IceCube Neutrino Observatory in Antarctica that has given us a new view of the Universe through the study of cosmological high-energy neutrinos. After explaining why the construction of a kilometre-scale neutrino detector was necessary for this task, Halzen will show how IceCube functions. He will also deal with more general related topics like the discovery of cosmic neutrinos, how that discovery was applied to astronomy, and what the future may hold. I believe that Halzen's research and his discoveries have even started "IceCube Science" – a new branch of the Physical Sciences, so to speak.

WELCOME ADDRESS BY ENRICO DECLEVA

President of the International Balzan Foundation “Prize”

As always, it is an honour to be called upon to speak at the opening of the 2017 Annual Balzan Lecture by one of our recent Prizewinners. In this case, it is Professor Francis Halzen, 2015 Balzan Prize for Astroparticle Physics including neutrino and gamma-ray observation. Let me remind you that the Prize was awarded to him “for his unparalleled accomplishments which have led to the construction of the large IceCube Neutrino Observatory in the south polar ice, a facility that has opened up a new window into the universe through the study of cosmological high-energy neutrinos”.

In a little while, I will let Luciano Maiani, who is much more expert than I am in these matters, tell you about the importance of this prizewinner’s scientific work. It is, however, my job to formally thank Francis Halzen for accepting our invitation, and I must also add that it is a great pleasure to see him again after the awards ceremony in Berne two years ago, and to be able to listen to him speak once more.

I also thank Professor Quadrio Curzio, President of the Accademia dei Lincei, for being our host in this initiative. More importantly, my thanks to him for being the motivating force behind the collaboration between the Balzan Foundation, the Accademia Nazionale dei Lincei and the Swiss Academies of Arts and Sciences, because it enhances – while maintaining the traditional rotation of locations – the Italian-Swiss nature of the Balzan Prize and the multidisciplinarity that inspires it.

Olschki publishes the texts of the Lectures in a series that includes the question and discussion sessions following each Prizewinner’s contribution. The series bears witness to the amplitude of the programme, and of our progress over the years as we have gone into great depth in the humanities and experimental sciences alike, successfully interweaving diverse cultures and different disciplinary approaches, and always taking advantage of the excellent contributions of our laureates. The lecture by Professor Halzen that we are about to hear will certainly take its place among the others in this series, and hopefully it will be published in time for our return here next year for the 2018 Balzan Prize awards ceremony events.

Once again I would like to thank all of our speakers, and to express my gratitude to all of you who are here today. I now give the floor again to Alberto Quadrio Curzio.

OPENING REMARKS BY ALBERTO QUADRIO CURZIO

Thank you, Professor Decleva, for your kind words to myself as well as to the Accademia dei Lincei. The Annual Balzan Lecture was born of an agreement between the International Balzan Foundation, the Accademia dei Lincei and the Swiss Academies of Arts and Sciences, and this agreement is presently governed by a coordinating committee with two representatives from the Balzan Foundation, two from the Swiss Academies and two from the Lincei. The committee and the agreement concentrate on two initiatives that Professor Decleva already referred to, but I will expand upon what he said.

The Annual Balzan Lecture, which you are all here for this evening, takes place once a year. Before the current one, seven have already been published. Over the course of time, they have alternated on the one hand between the humanities and social sciences (or moral, historical and philological sciences as we call them at the Lincei), and natural, physical and mathematical sciences on the other. This is very important because the Balzan Prize is one of the few prizes that devotes a great deal of attention to the humanistic disciplines, and that has, in the course of its highly prestigious existence, enlightened the general public throughout the world about excellence not only in the natural, physical and mathematical sciences, but also in the humanities. Before today's lecture by Professor Halzen, the last time that the Annual Balzan Lecture was held at the Lincei, the outstanding English intellectual historian Quentin Skinner spoke on the theme of freedom in contemporary historical thought and in the modern and contemporary era. This evening, Professor Halzen will be presented by Professor Luciano Maiani, who is both a Lincei fellow and a member of the General Prize Committee of the Balzan Foundation. He will give a brief sketch of our speaker's distinguished scientific achievements.

Before giving the floor to Professor Maiani, I would like to underline one aspect of life at the Balzan Prize Foundation, the interdisciplinary nature of which is shared by Enrico Decleva (a historian) and myself (an economist) on the part of the Board, and by Salvatore Veca (a philosopher) and Luciano Maiani (a physicist) on the part of the General Prize Committee. Let us compare what I call "the Balzan Prize system" with perhaps the more widely recognized, world-famous Nobel Prize. There are some remarkable differences in the two prizes, but not in the quality of nominees as, in fact, a number of Nobel Prizewinners (like Alan J. Heeger, Shinya Yamanaka, the team Bruce Beutler and Jules Hoffman, and Karl von Frisch) first won the Balzan Prize!

The first difference lies in the variety of the subject areas in the sciences and the humanities chosen by the Balzan General Prize Committee. Two prizes are awarded in each of these broad categories each year. The Prize Committee members make an effort to recognize new, emerging fields and subject areas which do not always receive the attention of other renowned awards. In other words, the choice is on topics within disciplines as well as between two or more disciplines belonging either to sciences or humanities. The General Prize Committee's work choosing subjects and topics is difficult, but at the same time requires a great deal of investigation and evaluation on the part of its members.

The second difference is the initiative of the Annual Balzan Lecture, which has been a primary force in creating an interdisciplinary and inter-temporal community of Balzan Prizewinners, who keep in touch through the publication of these Lectures. This series of lectures has the merits of explaining the state of research and discovery on various subjects to a general public of cultured people.

The third difference is that half of the Balzan Prize must be devoted to a research project involving young scientists under the supervision of the Prizewinner, who must deliver progress reports regularly to the Balzan Prize Foundation. Again, the projects and the *Overview* that is published every two years create a strong link between the Prizewinners and the Foundation. In other words, a scientific community has been formed.

The fourth difference is *IinteR-La*$^{+}$*B*, an interdisciplinary seminar for young scholars who listen to lectures by a Balzan Prizewinner and then converse with the speaker and all of the others present. This year Federico Capasso gave the lecture, which was followed by a complex, wide-ranging debate, in which the "humanists" also had their say. Every year, what most strikes me about these meetings is that such outstanding personalities make these dialogues possible – even when encountering what might seem ingenuous or marginal questions from young people whose choice of career path does not necessarily fall within the speaker's field. Again we have here a scientific community that is connected and often overlaps with those formed at previous ones.

This is the "Balzan Prize system", which in my opinion is unique on the world scene of international prizes. Therefore, it is a pleasure for me to open today's lecture, also because this system has been established on the grounds of the Balzan Foundation agreement with the Accademia Nazionale dei Lincei and the Swiss Academies of Arts and Sciences. That said, on behalf of the Accademia dei Lincei, I thank Professor Halzen for coming to give us this lecture, and give the floor to Professor Maiani, who will introduce him and coordinate today's events.

PRESENTATION OF FRANCIS HALZEN
BY LUCIANO MAIANI

Member of the International Balzan Foundation General Prize Committee
and of the Accademia Nazionale dei Lincei

Thank you, President Quadrio Curzio. As Balzan President Decleva said, Francis Halzen is the 2015 Balzan Prizewinner for his work observing neutrinos from the IceCube detector located in Antarctica, as we will see when he gives his lecture.

I am very pleased to see that among our audience today is Professor Paolo de Bernardis, another Balzan Prizewinner, because the motivation for the Balzan Prize to both of these illustrious scientists comes from the fact that they observed messages from the cosmos: in Professor de Bernardis's case, the microwaves that come from the first 500,000 years of the universe's life; in Professor Halzen's instead, high-energy neutrinos whose origins we really do not know, but we think that the next stages of studying them will clear up the mystery. I would like to say a word or two on neutrinos before presenting Professor Halzen.

How do we see neutrinos? Of course, we don't see them, but every now and then – or better, very rarely – a neutrino, especially if it has very high energy, interacts with matter and this generates an electrically charged particle which emits light. This light is collected and analysed by photomultipliers; from the trajectory and the energy of this particle, we can go back to the energy and trajectory of its origin.

This is the central idea of the detectors under ice. However, one fact must be added, and this is precisely where one of Professor Halzen's important contributions lies: when the neutrino produces this particle, which in turn emits light, it happens that this phenomenon must take place in a transparent environment since if the light is not observed immediately, nothing can be detected. Thus the neutrinos produced charged particles in the ice, which are called muons, and we can see them. Halzen's first experiment as Principal Investigator was called project AMANDA (Antarctic Muon And Neutrino Detector Array), and aimed to reveal the interaction of neutrinos under the ice of the Antarctic. However, in the first installation, the ice had so many air bubbles that the multipliers could not reconstruct the trajectory. Fortunately Professor Halzen wagered that by going deeper into the ice, the air bubbles would disappear. This is what happened: by sinking the detectors deeper into the ice, as he will explain, it is transparent, and so we can detect these neutrinos in great volumes, on the order of one cubic kilometre.

That said, and so as not to take any more time from Professor Halzen's lecture, I would like to give you a brief account of Francis Halzen's life. Born in 1944, he earned his PhD at the University of Louvain in Belgium, his native country, but since the 1970s, he has been a Professor at the University of Wisconsin. At present, he is the Director of the Wisconsin IceCube Particle Astrophysics Center which, as you may imagine, is dedicated to this research.

As a researcher, Professor Halzen has led two lives: the first as a theoretical physicist and phenomenologist of elementary particles, and in this field we met various times in the 1980s. In particular, he was one of Carlo Rubbia's collaborators when intermediate bosons were discovered. We remember this well!

However, since the 1980s, Francis Halzen's interest has shifted towards very high-energy cosmic rays, in particular, very high-energy neutrinos. His idea of designing detectors in the Antarctic was born of this, after various attempts, since the Antarctic is the only place where there are kilometres of ice that is transparent enough to construct the ideal environment for carrying out this research.

In 1990, project AMANDA was the model used to establish the method, which is to say the disappearance of air bubbles with increasing depth of the ice. Then, in 1999, in a letter of intent, he submitted the proposal for IceCube, a detector on the order of one cubic kilometre of ice, to the National Science Foundation (NSF). In 2001, the project was approved; from 2004 to 2010 it was built, and then data taking began.

I must say that at the beginning of the first decade of the twenty-first century, I happened to go to the NSF and discuss scientific projects with them, and for relations between the NSF and CERN.

At that time, there were two projects that the NSF considered its flagships, so to speak: one was IceCube, the subject of today's lecture, and the other was LIGO (Laser Interferometer Gravitational-Wave Observatory).

In short, not bad, because this year as you know a Nobel Prize was awarded precisely for this reason – for the discovery of gravitational waves with LIGO (also with the support of our apparatus VIRGO in Pisa). Hence we hope that IceCube will evolve to the point of being able to furnish far more results than it has obtained in this past ten-year run. Halzen will speak on future projects, which involve detectors that might reach the size of 100 cubic kilometres. This will truly open the window onto an astronomy of cosmic neutrinos, which can be added to microwave astronomy of the primordial universe, to conventional astronomy of course, to optics, to the astronomy of high-energy cosmic rays and to the astronomy of gravitational waves. These present different ways of seeing the cosmos, from which we expect to obtain a multi-dimensional – hence realistic and complete – view of the universe that surrounds us.

I will stop here, and give the floor to Francis, whom I thank for coming and once again congratulate for the Balzan Prize that he so amply deserves.

Lecture by Francis Halzen

ICECUBE AND THE DISCOVERY OF HIGH-ENERGY COSMIC NEUTRINOS

IceCube: Building a New Window on the Universe

It is a great honour to be invited here to present this lecture. You have seen the topics involved (why a kilometre-scale neutrino detector should be built; IceCube; the discovery of cosmic neutrinos, from discovery to astronomy), and I am going to tell you a little bit about the history of the field, which is very old actually. It is not as though someone suddenly decided to build a neutrino detector of the size of a cubic kilometre. This concept has a long history, which I will try to describe. I will tell you about IceCube, then I will tell you about cosmic neutrinos, and I will conclude by telling you a little about what we want to do in the future. In fact, I will first explain – as a physicist – my vision of astronomy, and how it fits in with this subject.

Figure 1 shows the microwave background. The colour, or wavelength, of the light that you are looking at measures less than a millimetre. Since I am not an astronomer, I think of this in terms of photons that have an energy of ten to the minus four electronvolts. The history of astronomy in recent decades has been very successful in doing astronomy with different telescopes where the wavelength of the photon is changed. In fact, the sky can be studied in radio waves, or to go in the other direction, in wavelengths that are even smaller – a millionth of a metre – and that are photons of one electronvolt. This is the sky you see at night, although I doubt you can see it from Rome [Figure 2]. This is the galactic plane, but it is still the same sky, which can already illustrate the idea that if the sky is viewed in a different colour of light, or a different wavelength, or a different energy of

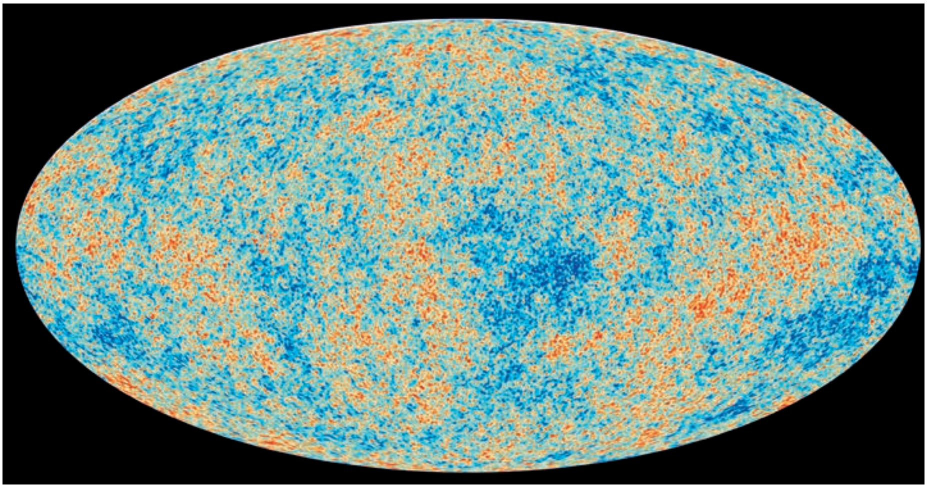


Fig. 1. Cosmic horizons – microwave radiation 380,000 years after the Big Bang (wavelength = 10^{-3} m <=> energy = 10^{-4} eV).

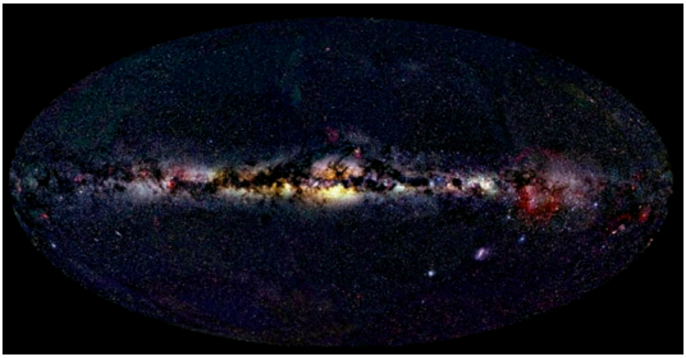


Fig. 2. Cosmic horizons – optical sky (wavelength = 10^{-3} m <=> energy = 10^{-4} eV).

the photon, different things can be seen. Continuing, with energies of one GeV – a gigaelectronvolt – the sky appears as in Figure 3, as observed by a satellite called the Fermi satellite. I will return to this because this is the highest-energy sky that telescopes study.

If the wavelength is made even shorter, or if the energy of the photon is increased, you see nothing [Figure 4]. The reason is interesting: you see nothing because if an object is far away, like a

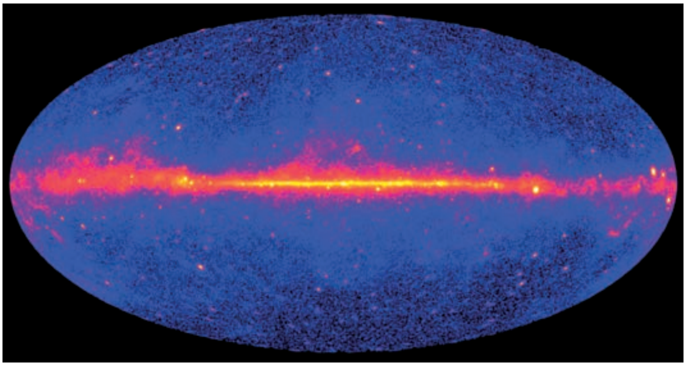


Fig. 3. Cosmic horizons – gamma radiation (wavelength = 10^{-15} m <=> energy = 1 GeV).

Fig. 4. Cosmic horizons – gamma radiation (wavelength = 10^{-21} m <=> energy = 10^{3} TeV).

galaxy, it will emit photons of this energy – we are rather sure of this fact [Figure 5]. However, they never get here because the universe is not an empty place. This should be remembered throughout this talk. In the universe, there is no vacuum: it is filled with stuff. In fact, it abounds with light of all kinds of wavelengths, including the cosmic microwave photons that I showed in Figure 1. Therefore, the universe is filled with 410 microwave photons in every cubic centimetre. When a photon of very high energy runs into one of these photons, it will make an electron and positron pair. That means it is gone, because once the photon is transformed into an electron and positron pair, a charged particle results, and with charged particles you cannot do

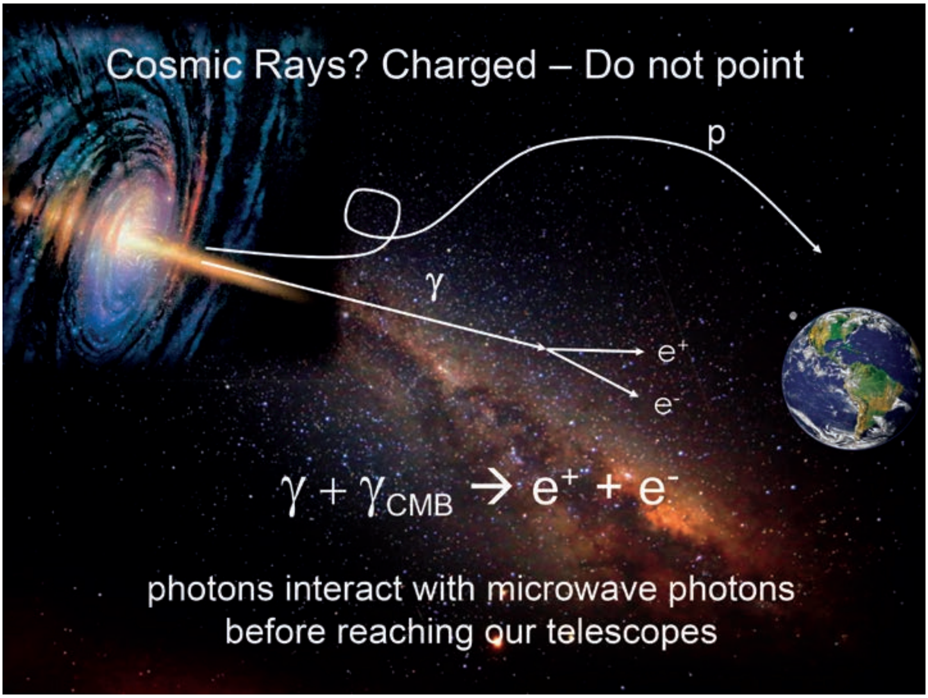


Fig. 5. Photons interacting with microwave photons to make an electron-positron pair.

astronomy. We detect charged particles of these energies as protons and nuclei. We have known about these particles for 105 years, but we have no idea where they come from. That is part of the subject of my talk today.

The particles are charged, so they are bent by the magnetic field of the galaxy before they reach your telescope. They can be produced there and you detect them from there. The same is true of this electron and positron pair. In fact, the photon is lost, but not completely, as I will tell you later. To make a long story short, here is the energy of the photons we study in the universe [Figure 6]. This is where the sky turns black. You might say, "How do we know something is out there? Maybe there simply is no astronomy anymore". But this is where we have discovered cosmic rays, and these cosmic rays are incredible objects, because we detect them with energies that are more than ten million times the energy of the particles we accelerate

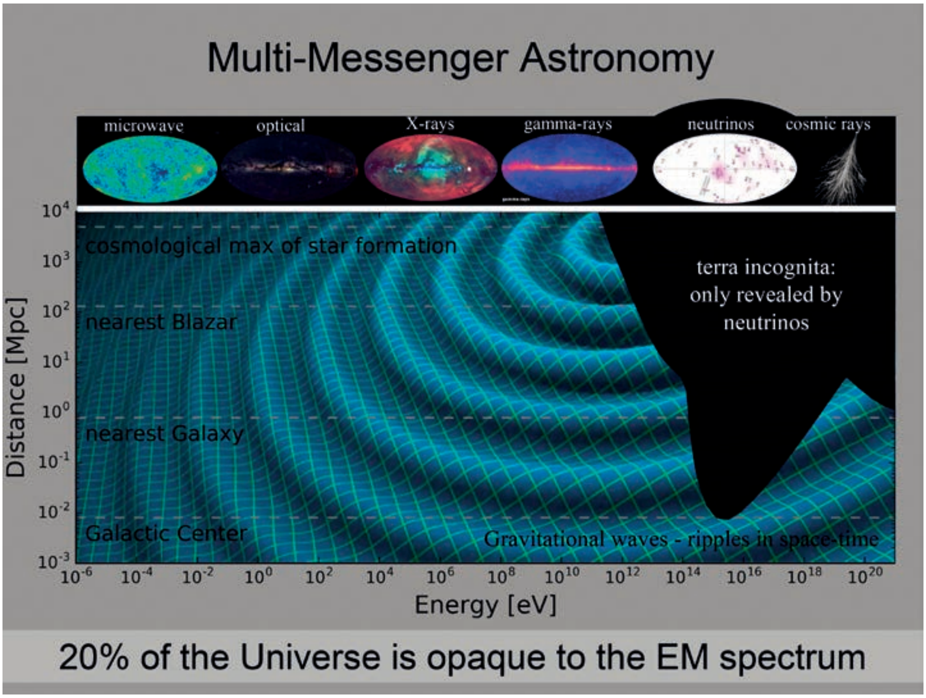
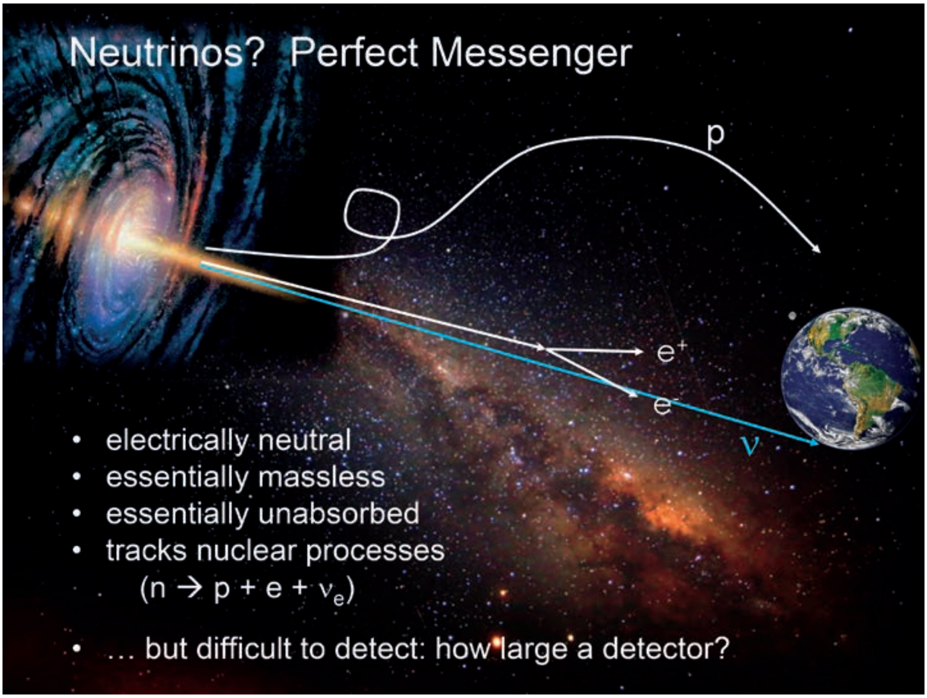


Fig. 6. Multi-messenger astronomy.

in Geneva at the LHC. Somehow and somewhere they are produced and accelerated in the sky. Moreover, even if we map them out, this is at least 20% of the universe that we have never seen. This could be compared to having explored the earth, but never having seen the Atlantic Ocean. How can you not look?

Of course, the idea was that in order to avoid this problem with photons, one other particle can be used: the neutrino – thus the idea to do astronomy with neutrinos [Figure 7]. I knew Frederick Reines, who discovered this particle in 1956 and stated that as soon as people realized that the neutrino was a real particle, everybody had the idea to do astronomy with it. Thus, the idea goes back to the 1950s, and by 1960 some very fundamental papers were written on this topic.

Although Professor Maiani mentioned this in his introduction to the subject, I have to tell you a little bit about what a neutrino is in my own way. In school, you have all learned that matter is



Neutrinos? Perfect Messenger

- electrically neutral
- essentially massless
- essentially unabsorbed
- tracks nuclear processes
  $(n \rightarrow p + e + \nu_e)$
- … but difficult to detect: how large a detector?

Fig. 7. Neutrinos are the perfect messenger, but difficult to detect.

made of three particles: protons and neutrons make nuclei, and when combined with electrons they make atoms. But that is not the whole story, because the neutron can actually change into a proton and back, and that is called nuclear physics. By switching neutrons and protons, different nuclei are created. People were studying this reaction in Cambridge in the 1930s. They noticed that, according to elementary mechanics, if a neutron decays, the proton goes one way, and the electron has to go another. However, they noticed that this was not always true. Occasionally, the proton and the electron would go in the same direction, which means that there is another particle balancing the momentum and the energy: that is the neutrino. You do not see it, but it has to be there. We now call this the missing energy experiment. C.D. Ellis and N.F. Mott actually discovered the neutrino (1933), but at the time they could not imagine a new particle when only three were known. They could not imagine that another particle would be discovered. Wolfgang Pauli, however, had already made this suggestion in 1930, along with the realization that this particle would probably be impossible to detect. If he had been right, I would not be here now.

Nuclear physics can only happen because there is a fourth particle. In fact, there are almost as many neutrinos as photons in the universe, and there are roughly a billion neutrinos for every proton, thus they are the most common particle. They exist everywhere that nuclear physics happens. In the Big Bang, when a star explodes it emits neutrinos – I will come back to this point. The sun is a nuclear reactor. The sun would not shine without neutrinos. I think that brings my point home. We accelerate neutrinos; you emit neutrinos from the salt decaying in your body; the earth is radioactive in neutrinos. Consider the nuclear reactor. To avoid radiation, nuclear reactors are covered with water, and this water is always blue, which is an important point in this lecture. When charged particles come out of the reactor and travel through the water, they emit blue light. We call this Cherenkov radiation. It has been known for a long time, and is going to play a big role.

The other aspect of this astronomy is that when you look up at the sky, it is actually incredibly easy to see neutrinos. IceCube sees one neutrino every 3 to 4 minutes, depending on how data is collected. Neutrinos are made by cosmic rays, the very high-energy particles previously mentioned. They enter the atmosphere, and about 20 km above our head, interact with nitrogen and oxygen nuclei and make pions. Pions decay into neutrinos and muons. The pion first decays into a muon neutrino and a muon, and then the muon decays, making two more neutrinos and an electron. These neutrinos reach the earth, so when we point IceCube at the sky we see neutrinos all the time, but they are neutrinos produced in the atmosphere. Imagine that you are doing astronomy, but there are clouds overhead that prevent you from seeing the universe. Of course, these clouds never disappear; they are there all the time.

Figure 8 is a bit more technical, but illustrates the core of the problem. In the same way, it shows all the wavelengths of light that I was talking about: the microwave background, visible gamma rays, and so on. In Figures 2-4, I showed the sky in these three wavelengths. Figure 8 also tells you how many photons there are. For the ones

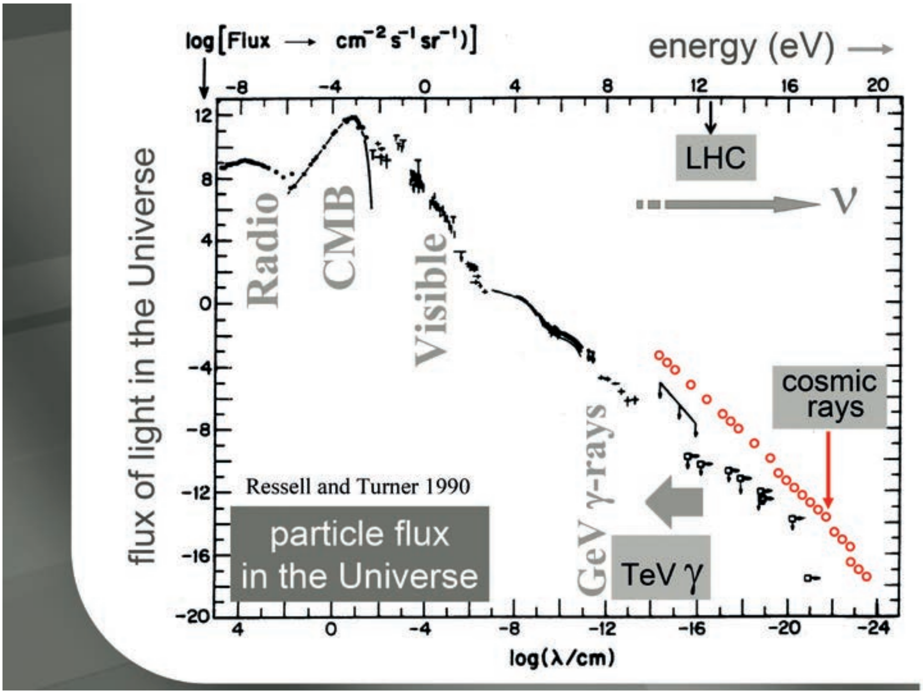


Fig. 8. Particle flux in the universe.

labelled CMB, there are 410 per cubic centimetre. Here you also see where astronomy stops, in the multi-GeV to TeV region. What you see on the right on the side are just upper limits: nobody has ever seen photons in the sky of Figure 4. The idea is to do neutrino astronomy in that region. The problem with this argument is that it does not tell you how big a detector you need. You do not detect neutrinos with a mirror – you know that, and you know from the Cambridge story how difficult it is to detect them. But as I already said, there are cosmic rays in the sky, so we know there are things going on there. The sky is not empty; there must be pretty fantastic things going on.

Figure 9 tells us what the 1960s idea was: to study those wavelengths with neutrinos instead of light. But in 1969 Veniamin Berezinski, a theoretician who is now at Gran Sasso, and G.T. Zatsepin did the calculation. They realized that the universe is not empty. The cosmic rays circled on the lower right-hand side of the plot fill the whole

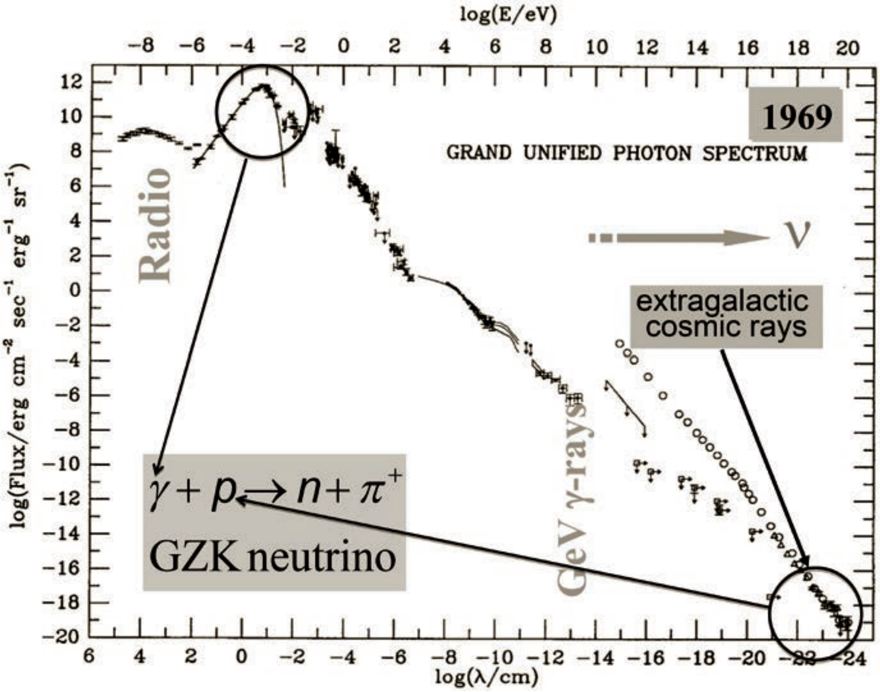


Fig. 9. Idea from 1960s of using neutrinos instead of light.

galaxy. We only confirmed this a few weeks ago, when the Auger experiment published a paper showing convincingly that these cosmic rays do not come from our own galaxy. We knew this, but it had never been proved convincingly and measured and demonstrated; the Auger experiment did this. Therefore, the cosmic rays live in the same place as the microwave photons, so you can do the simple calculation that Berezinski and Zatsepin did. These protons will meet microwave photons, interact, produce pions, and the pions will decay into neutrinos. This is the physics that Enrico Fermi was doing in the 1950s in Chicago just before he died, so it is particle physics that is very well understood. Since the number of protons and gamma rays are known, and Fermi's work in Chicago supplied the physics, you can calculate how many neutrinos are produced. At the bottom of Figure 10, the calculation shows that if you build a fully efficient one-kilometre cube detector, you will see one neutrino per year. That is a

$$p+\gamma \rightarrow n+\pi^{+} \text{ and } p+\pi^{0}$$

$$\pi \rightarrow \mu+\upsilon_{\mu} \rightarrow \{e+\overline{\upsilon_{\mu}}+\upsilon_{e}\}+\upsilon_{\mu}$$

Fig. 10. Cosmic rays interact with the microwave background in the first equation, while in the second, cosmic rays disappear and neutrinos with EeV (10^{6} TeV) energy appear.

bit disappointing, but at least it was the first time we heard about the concept of a kilometre cube detector.

The good news is that the energy of the neutrinos is one million TeV. Remember that one TeV will be my unit of energy; the LHC accelerates particles in Geneva to 13 TeV, and the old Fermilab collider accelerated particles to one TeV. My unit is the energy of a proton circulating in the Fermilab collider. The energy of that neutrino is one million TeV, so if it hits your detector, you do not have to do anything fancy: you will know about it. You cannot miss it.

Why Build a Kilometre-Scale Neutrino Detector?

So, good and bad news. For many decades people tried to be more and more imaginative, trying to find reasons to build a detector that would have more optimistic predictions than one neutrino per year. This was a long task, and to introduce the calculations, it is helpful to consider the solar flare, whose filaments are accelerated particles that move close to the speed of light, as in Figure 11.

If you have a moving charged particle, you make magnetic fields; if you make magnetic fields, you have an accelerator. This goes under the magic word of shockwaves, or magnetic reconnection, but the point is that to accelerate a particle to a certain energy, you have to have a large magnetic field and your accelerator has to be big, as can be seen in the equation in Figure 12. In fact, the way you derive this equation is to say that the gyroradius of the particle has to be trapped in the accelerator in order to be accelerated. This is dimensional analysis. You would think that these energies might never be reached, but in fact they can be. If you look at a solar flare and wait one day, you will see protons of 10 GeV arrive on earth. This is exactly the

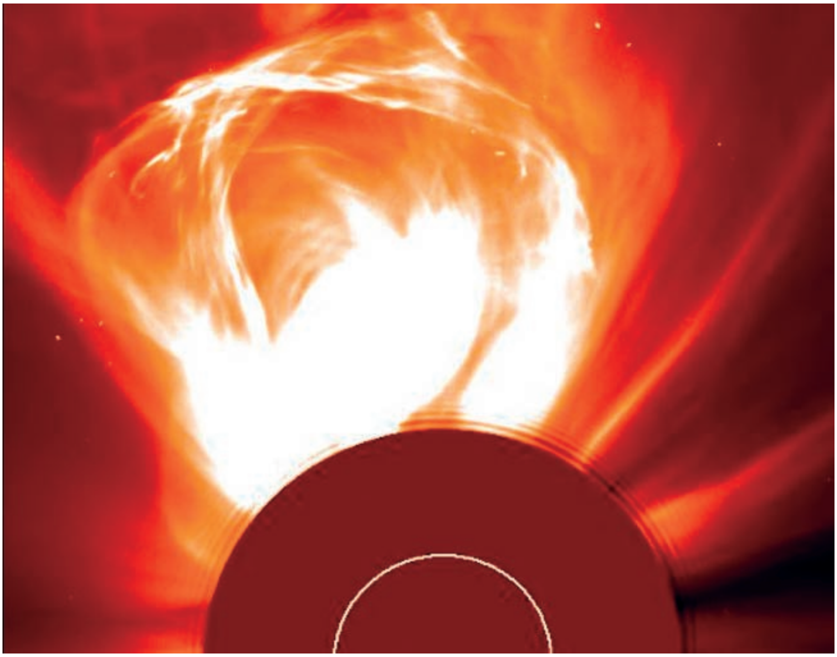


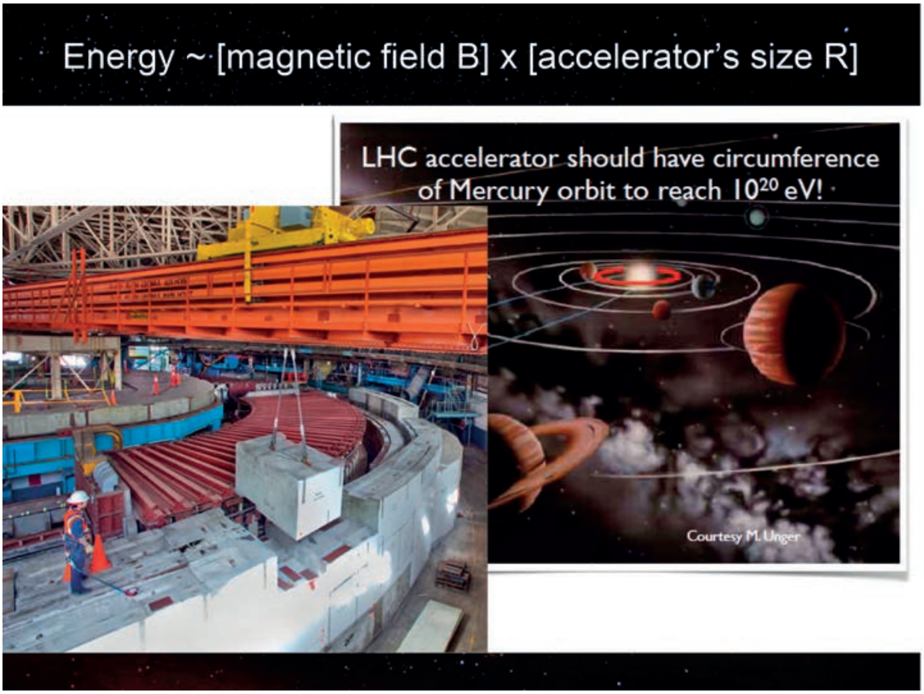
Fig. 11. Solar flare.

$$R_{gyro}\,(=\frac{E}{\mathrm{v}qB})\leq R$$
$$E\leq \mathrm{v}\,qBR$$

Fig. 12. The accelerator must contain the particles; challenges of cosmic ray astrophysics are that dimensional analysis is difficult to satisfy and accelerator luminosity is high.

amount of energy you get when you just plug in the magnetic field in the flare and the size of the flare. It's fascinating.

Hence the question arises: what accelerator is necessary to accelerate the highest-energy cosmic rays? If LHC magnets filled the orbit of the planet Mercury, the highest-energy cosmic rays would be accelerated, as shown in Figure 13. However, that is not how it happens. It is amazing that there are objects in the sky that do this, but we do not know what they are, or how they can do it. That partially



Energy ~ [magnetic field B] x [accelerator's size R]

LHC accelerator should have circumference of Mercury orbit to reach 10^{20} eV!

Courtesy M. Unger

Fig. 13. Required LHC circumference to accelerate highest-energy cosmic rays.

explains our interest in this energy region: to figure out what these accelerators are.

There is a simple idea that in principle works. When a star collapses, an enormous amount of gravitational energy is released. If you convert a few percent of that energy into accelerating particles, which is achieved by the magic shockwaves or magnetic reconnection, then you can actually explain the cosmic rays that we see. To give you an idea, Figure 14 shows a star that exploded a few hundred years ago. It leaves behind a neutron star, and with filaments that are basically the same as what can be seen in a solar flare. If the star collapses to a black hole, you can actually generate – in principle by the formula of Figure 12 – the highest-energy cosmic rays we see. Another idea suggests that galaxies with an active black hole at the centre are the sources of cosmic rays. In the inflows of charged particles on the black hole, or in the outflows, particles are accelerated. These outflows are

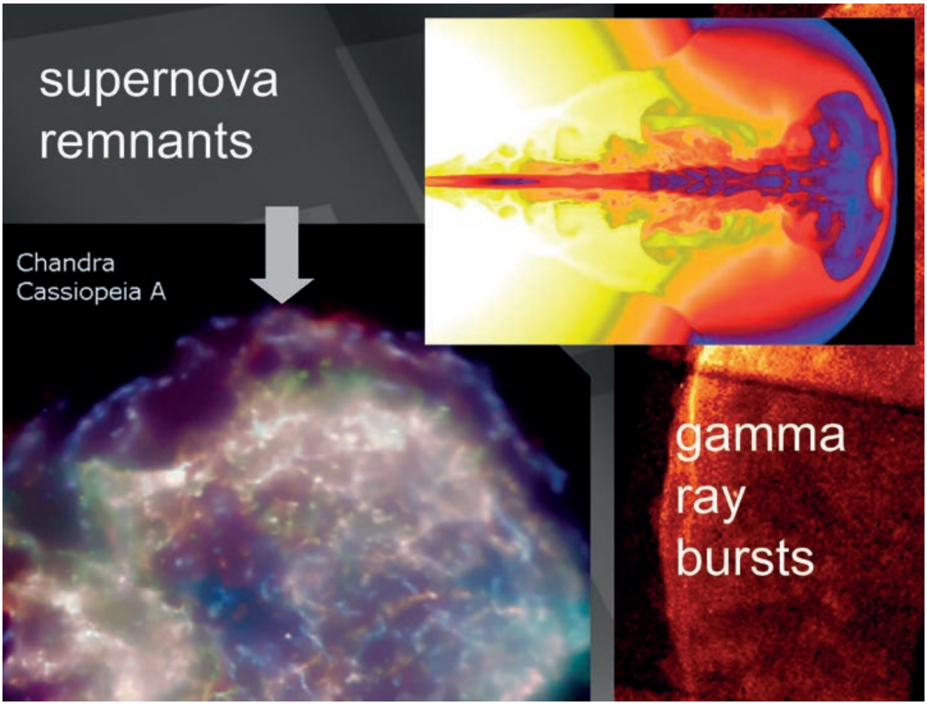


Fig. 14. Supernova remnants; gamma-ray bursts.

similar to jets because the black hole is spinning, and these particles remember the spin direction, as illustrated in Figure 15. Hence, we have another possible theory.

At this point, I would like show how neutrinos come into the story. If you accelerate protons, for instance, in the beam emitted from the black hole, they will interact with light that is radiated by the galaxy. Then you have again the $p\gamma$ interaction that produces pions, and the pions produce neutrinos. At CERN, this is what we call a beam dump [Figure 16]. You have an accelerator, you dump your beam into a target, you produce pions, and neutrinos come out at the other end.

If you go back to a 1950s physics textbook, you will see that whenever you produce a charged pion that makes neutrinos, you produce a π^0. That is inevitable; it is not negotiable. For every neutrino you see, there has to be a gamma ray, because the π^0 decays into two gamma rays. This is worrisome from the start, because no

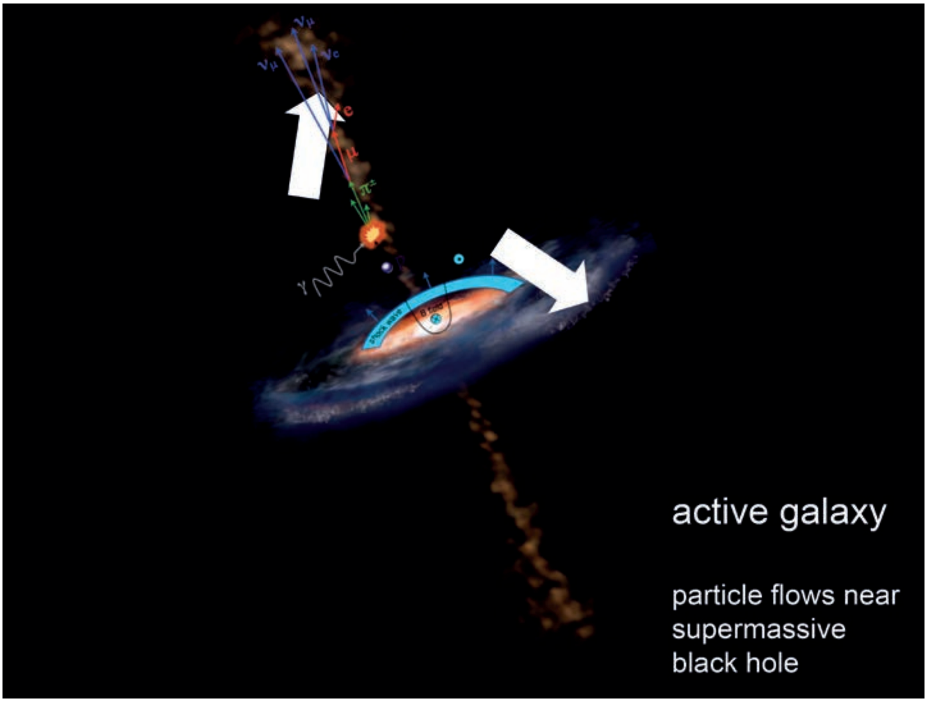
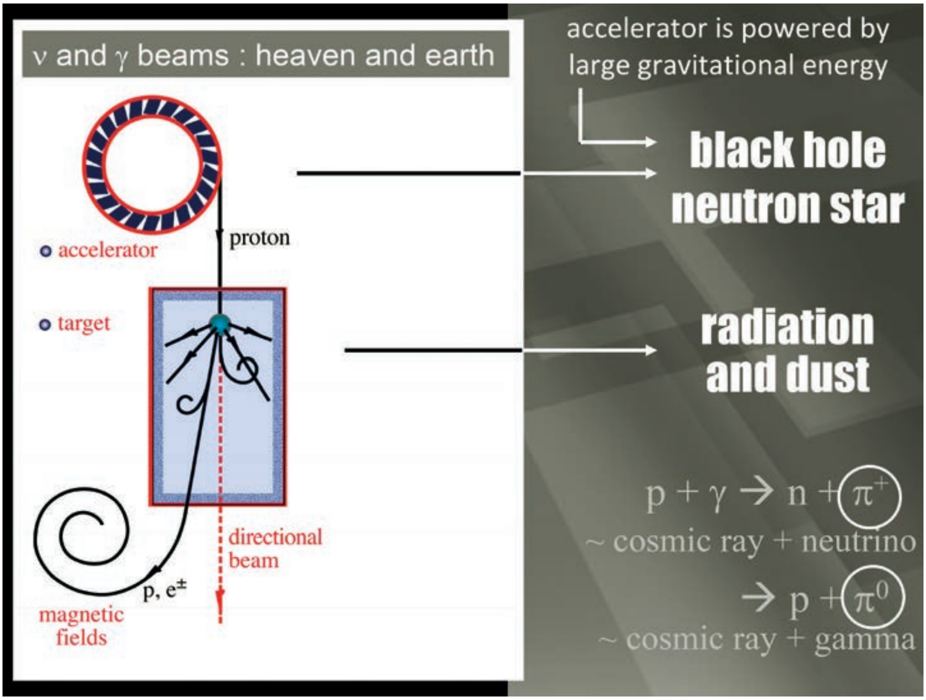


Fig. 15. Particle flows near supermassive black hole.



ν and γ beams : heaven and earth

accelerator is powered by large gravitational energy

black hole
neutron star

radiation and dust

$p + \gamma \rightarrow n + \boxed{\pi^+}$
~ cosmic ray + neutrino

$\rightarrow p + \boxed{\pi^0}$
~ cosmic ray + gamma

Fig. 16. The beam dump.

astronomer has ever seen a thousand-TeV gamma ray in the place where we want to go and look for neutrinos. In any event, to make a long story short again, all the predictions are lined up in Figure 17: galactic supernovae, gamma-ray bursts, and GZK, which refers to the neutrino flux calculated by Berezinski and Zatsepin. It is a beam where the flux of the particles falls as the energy squared. It has to do with shockwaves; it is a prediction. If I plot E squared times the flux, all these predictions form a horizontal line. You see the idea now. If you build a fully efficient cubic kilometre detector, you will see 10-100 events per year from these objects: ten if you are unlucky; one hundred if you are lucky. But given the nature of these estimates, this was at best a hope.

The huge flux on the left of Figure 17 shows atmospheric neutrinos, which have already been introduced. Thus, there is the bad news, because these fluxes are enormous. These are logarithmic

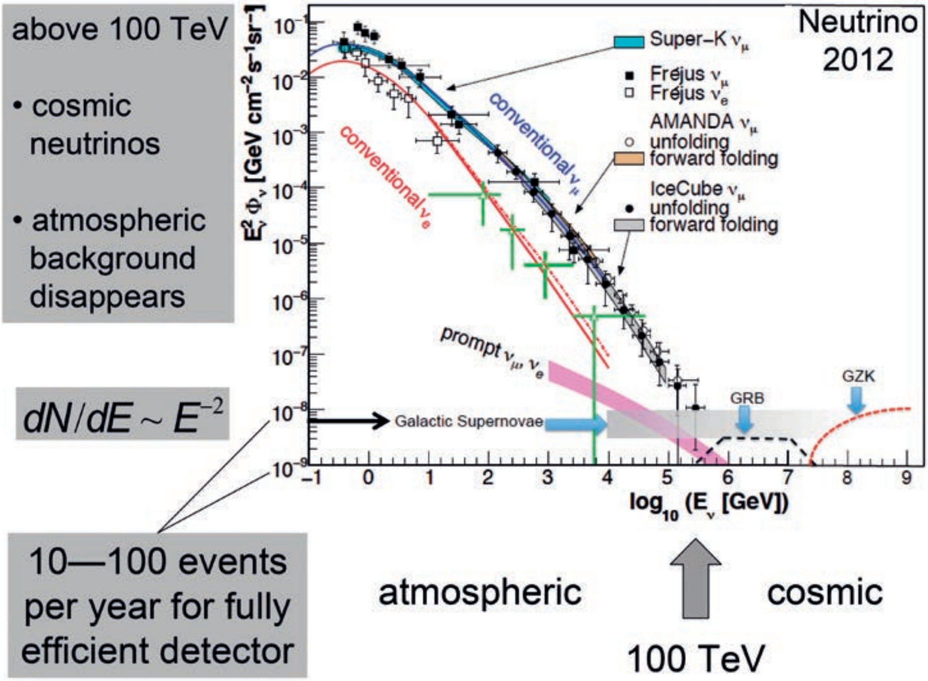


Fig. 17. Summary plot of atmospheric neutrino fluxes.

scales, so when you come to the point where the five is, that is 10^5 GeV, which is to say 100 TeV, or 100 times the energy of the Fermilab accelerator. Once that level is reached, the atmosphere no longer produces neutrinos of such high energy, and the sky is open. Thus, one neutrino is a discovery, if you are well above this magic hundred-TeV transition line. It is important to point out that IceCube and AMANDA – as can be seen on both of the plots in Figure 17 – have measured this flux over many orders of magnitude. It is an annoying background, but our experiment is very well calibrated by measuring it. We know how to measure energy, and that is very important for the rest of this story.

How is such a detector built? That has also been known since 1960. I like to recall a photograph [Figure 18] of Markov, who had the idea, together with Pontecorvo, because Pontecorvo had basically every idea in neutrino physics – except this one. This one was Markov's idea, and the idea is explained in Figure 19. What you do is build a Cherenkov detector. You go deep in the ocean, or in the case of Russia, you go deep into Lake Baikal. It is dark. You install light sensors, filling a kilometre cube of water with them. You take your imaginary kilometre, and you detect particles coming through the earth. If a particle comes through the earth, it is a neutrino. No other particle comes through the earth. What does this neutrino do? It goes through the detector, and you do not see anything. However, about one time in a million, in the region we are interested in and where IceCube operates, the neutrino will crash into a proton. Then you get a nuclear reaction and the water turns blue, precisely as it does in a nuclear reactor, as I pointed out before. Thus, we are measuring the blue light that is made by the nuclear interaction of one neutrino exciting a proton in the water, or an oxygen nucleus. Moreover, if this is a muon neutrino, it makes muons. In the final state, there are lots of particles – a spray of particles – but the muons travel through the water for kilometres, so you can even detect a neutrino when it interacts far outside your detector.

The muon moves at the speed of light, or very close to it. But in water, light moves at about three quarters of the speed of light. It is like a speed boat that leaves water waves behind. You get a shockwave – a bow wave – like a boat. With the bow wave, you do not have to see the neutrinos. The bow wave tells you which direction the muon is

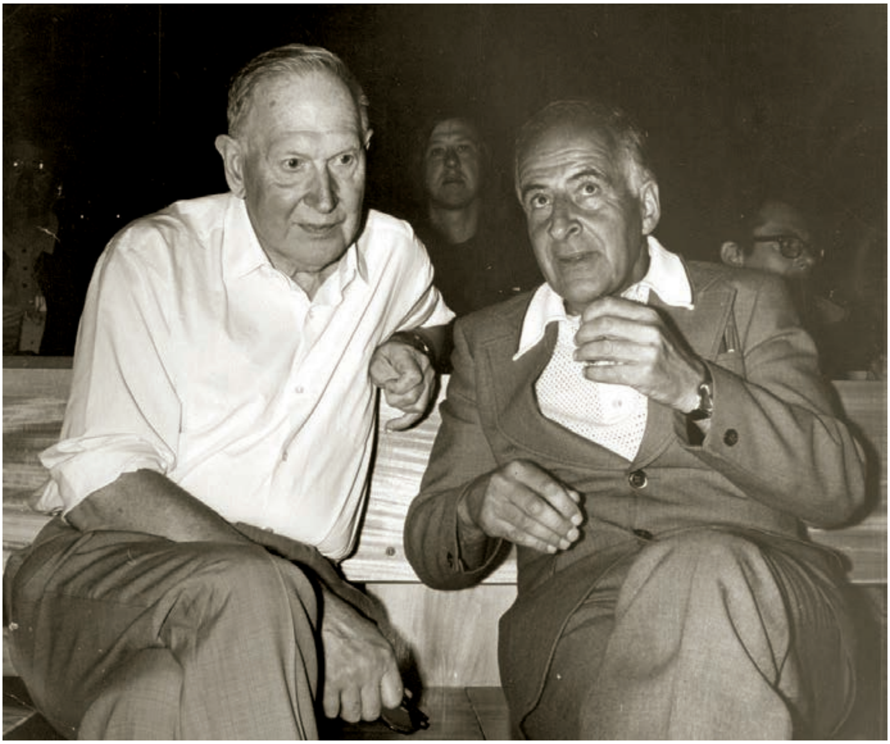


Fig. 18. Markov and Pontecorvo in 1960.

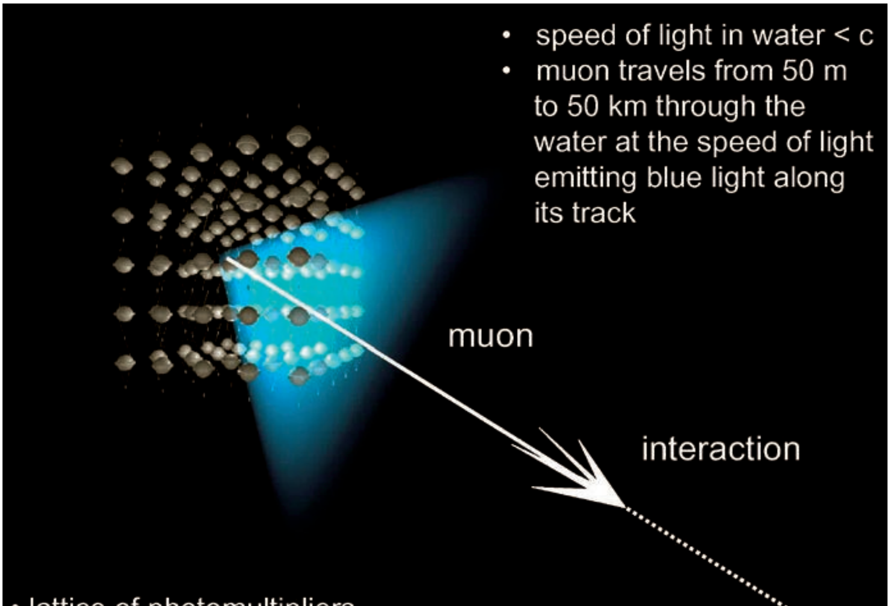


Fig. 19. Depiction of array of sensors as a Cherenkov detector.

going, and the muon tells you the direction of the neutrino. Thus, you also have a telescope; you do not just detect neutrinos.

IceCube

Our idea was to do exactly what physicists trying to do this experiment in the ocean off Hawaii were doing, but we decided instead to put these light sensors in ice. After a lot of R&D, we found that the ice below 1.5 kilometres should be clear enough for our purposes. Figure 20 shows the geographic South Pole, where the National Science Foundation research station is, which was essential to do this experiment. It is also where the IceCube project is, and you can see the runway where planes land.

The depth of the glacier is 3 km at the South Pole. Below 1.5 km, as mentioned by Professor Maiani, we found that the ice is clear. I'll

Fig. 20. Aerial view of the IceCube site.

come back to this data at the end of my lecture. There is about 0.5 km left between the bottom of the detector and the bedrock. To build the cubic-kilometre neutrino detector, you do exactly what I described: just take a cubic kilometre of ice and fill it with light sensors [Figure 21]. The light sensors are similar to basketball-size light bulbs that can be purchased in Japan for about one thousand dollars each. When light strikes them, they create a little electric current, which is then amplified and sent to a computer. The computer can tell you which sensors detect light. Then electronics comes into play. These sensors are deployed deep in the ice, so they have to be placed in a glass pressure vessel. Electronics convert the light signals into digital signals, and after this point, the whole experiment is totally digital. You can run it from my computer in this room. The sensor will tell you in detail whenever it detects a photon. It will count the photons and tell you exactly when they arrived. Aboveground, there is a

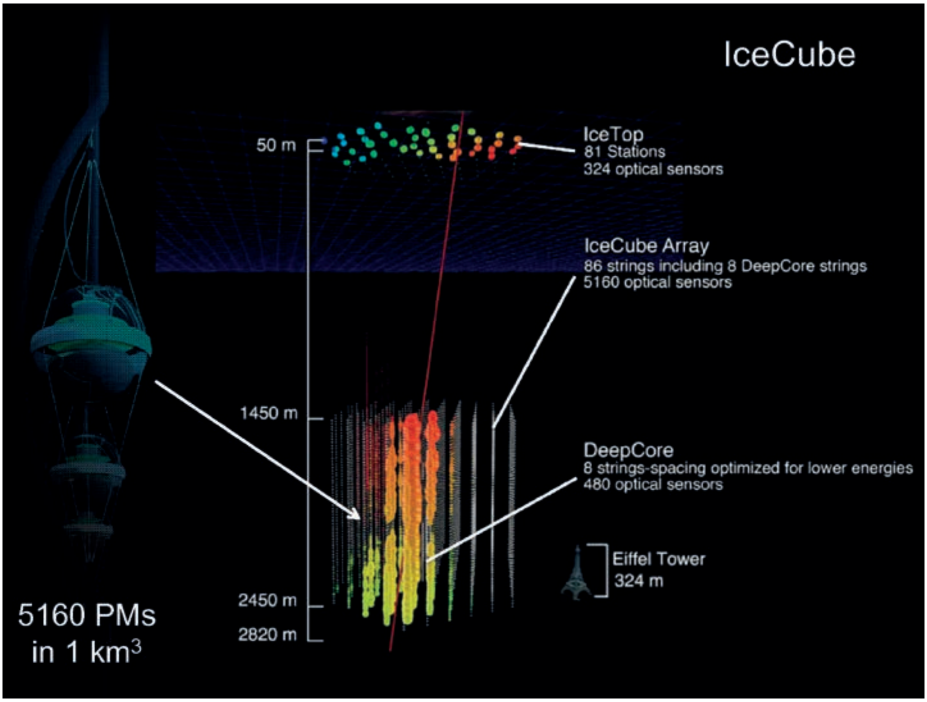


Fig. 21. IceCube schematic.

computer that simply collects all the information from more than 5,000 light sensors and puts it together in light patterns, from which we can determine the energy, the direction, and the "flavour" of the neutrino, which I will return to later. By now you must wonder, "How do you put these light sensors a kilometre and a half deep in ice?". In fact, the bottom is even deeper, at a depth of 2.5 kilometres.

At the South Pole, the first hundred metres are snow, so you just melt the snow. Then, in comes what we call the hot water drill, which is just a nozzle that ejects hot water under pressure, and it just falls. After two days, the ice has been transformed into water, over a hole that is about 0.5 m in diameter. For this operation, 200 gallons of water per minute must go through this nozzle at boiling temperatures. A 4.8 MW heating plant is required, which is basically 40 carwash heaters. That's it – and so you have a cubic-kilometre neutrino detector. All of this equipment is mounted on sleds, like a circus train, but with runners instead of wheels. In fact, this hose was constructed near Venice in Italy, the only company that can do this. It is 2.5 km long and 10 cm in diameter and brings down the hot water. The car wash heaters are run by normal generators with fuel that is brought in by airplanes.

At this point ice has been transformed into water. Since ice is an insulator, the water stays liquid for quite some time. The drill is pulled out, and then the whole "circus" moves on to a different place. Sixty of these light sensors stand waiting to be deployed in this hole, with one of the light sensors attached to a cable every 17 metres and plugged in. After this operation, you have a 1-km-long cabled instrument, with a 600-pound weight at the bottom, that can simply be dropped in the hole and allowed to sink. Thus, the sensors sit at a depth of 1.5-2.5 km. If you could go inside the detector, you would see a kilometre-long string which has a sensor every 17 metres, and then you would see another string 125 metres away. If you deploy 86 of these strings, which we deployed on a hexagonal pattern, you have a kilometre cube detector.

You can drill at the South Pole for only two months a year. The cables bring up the signals, which go into a two-storey building filled with computers that collect all of the information and put it together in neutrino events. In a typical event [Figure 22], you would see a muon entering the detector, the light it emits, and all of the activated

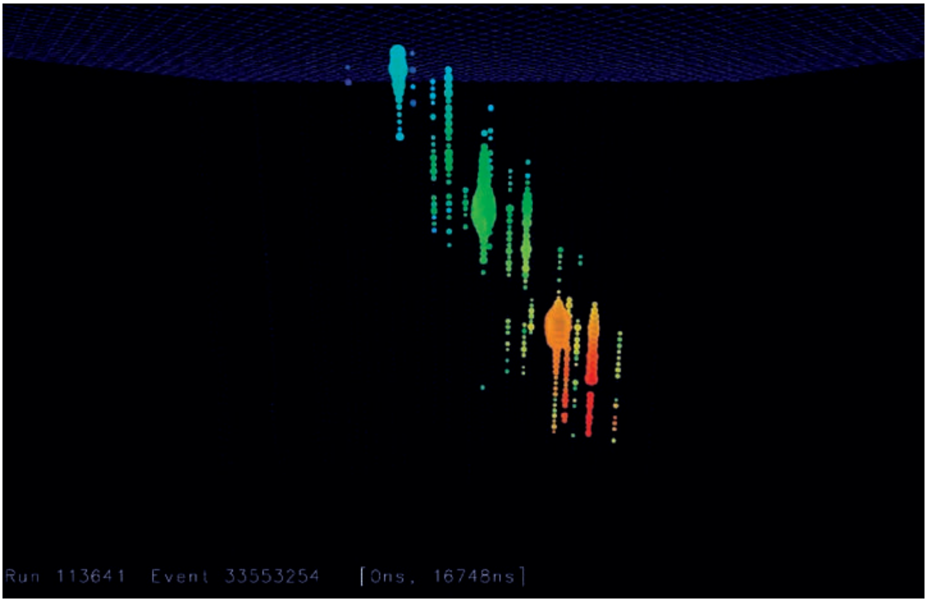


Fig. 22. Reconstruction of a typical muon neutrino event.

light sensors. These light sensors can detect a single photon, but if they appear big, they may be detecting ten to a hundred photons. In any event, all of this information is stored in the computer that reconstructs the muon. However, you can see where the muon went with the naked eye. Even during construction of the detector, we saw muons like this one. The colour indicates the direction of time, and follows the rainbow from red to blue. Thus, this muon came through the earth, and we now strongly suspect it is a cosmic neutrino.

What does the detector detect [Figure 23]? It detects cosmic ray neutrinos, including muons, from the Southern Hemisphere, and then it detects neutrinos produced in the atmosphere everywhere on earth, not just at the South Pole. As explained above, we are looking for 10-100 cosmic neutrinos. As the detector takes in data, it continuously reconstructs muons. In the case of cosmic ray muons produced in the atmosphere, you occasionally see bundles of muons going through the detector. We detect about a hundred billion muons per year, by now something like 200,000 neutrinos per year – but these

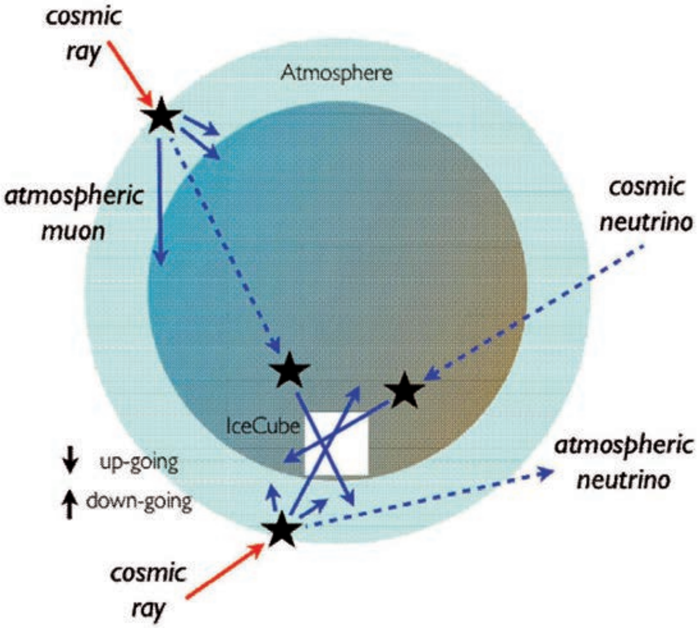


Fig. 23. Drawing of IceCube at the South Pole and the types of particles it detects.

are atmospheric neutrinos, our background, and so we are trying to extract the ten cosmic events from these.

Again, to make an even longer story short, in one of the cosmic neutrino events that we observed, a neutrino pointing 11 degrees below the horizon moved through the earth, and up through the detector [Figure 24]. What is special about this event is that it actually deposited 2.6 PeV of energy inside the detector. PeV stands for one thousand TeV – remember that one hundred TeV is where things become interesting. This event deposited 2600 TeV inside the detector, hence an example of a singular event representing a five-sigma discovery.

Figure 25 presents the status of this measurement, showing – as a function of energy – the number of events we measured. The blue line is what we expect from background, and the red is what we measured. This is exactly what was predicted, which is amazing because as will emerge at the end of this talk, we have not actually seen any of the sources that were predicted. We have not seen

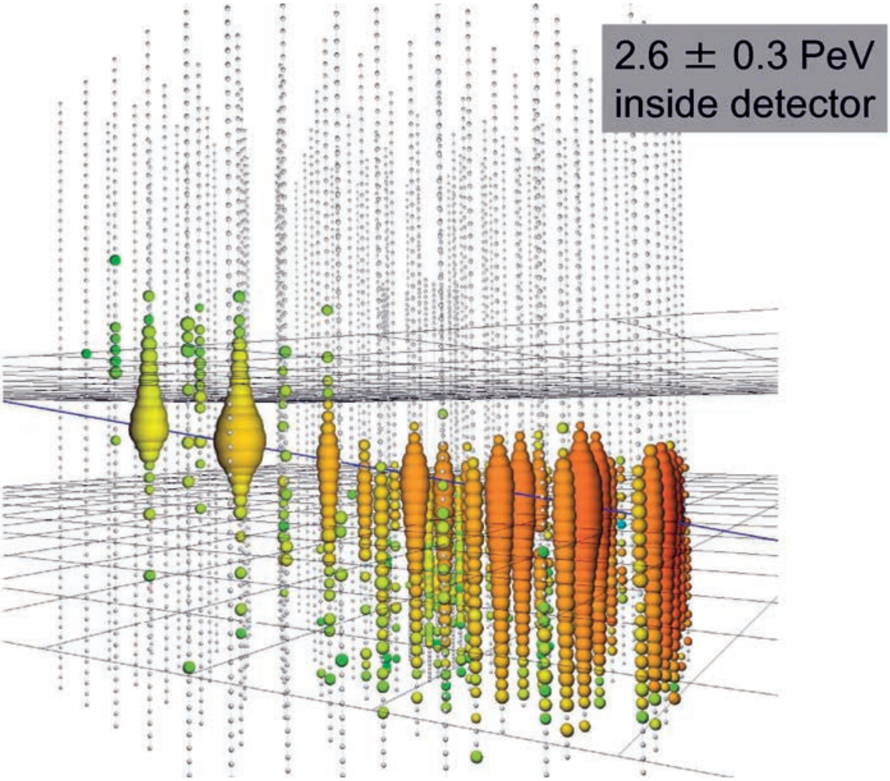


Fig. 24. Muon track from 2.6 PeV parent neutrino.

gamma-ray bursts, and we have not seen supernova remnants, but somehow the prediction that the neutrinos would appear at the level that can be detected by IceCube happens to be correct, as shown in Figure 17. This makes it possible to create sky maps, but I'll come back to that later.

The Discovery of Cosmic Neutrinos

Actually, we did not discover cosmic neutrinos this way. Some lonely graduate student somewhere was doing an analysis, which we had already given up on, and made this discovery, but unfortunately too late. We were looking for events of one million TeV, because that

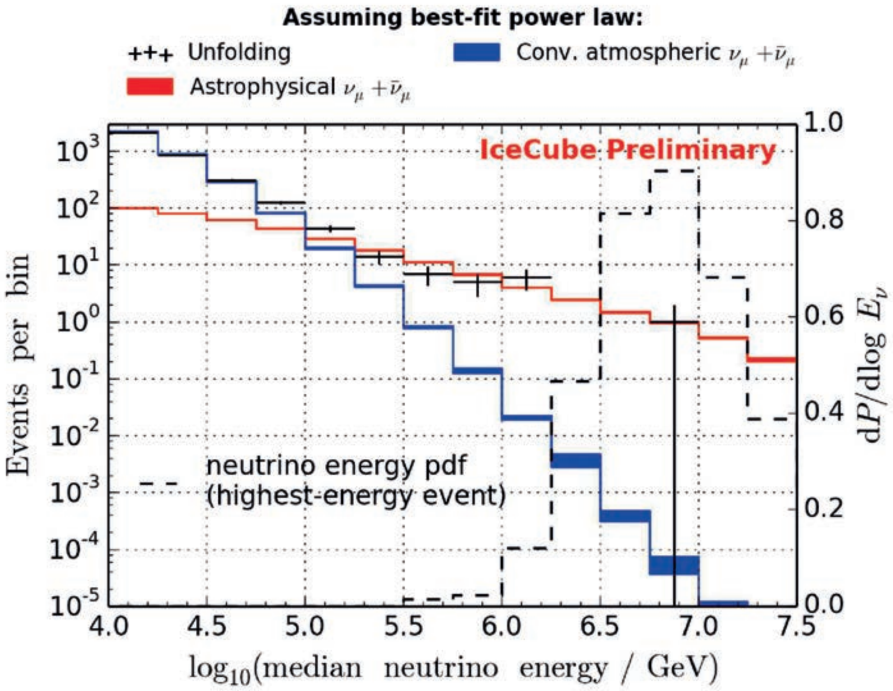


Fig. 25. Calculated median neutrino energies assuming best-fit power law spectrum.

was easy [see Figure 10]. You find one of these and you just publish. We looked at the first two years of data and didn't see what we were looking for. Instead, we found two events: one of them is shown in Figure 26 and is totally different from what you saw before.

Here, a muon track is not seen. Rather, it is as if someone turns on a light bulb in the detector, and then the light dissipates and stops. This is a fantastic event. We found two of them. A neutrino interacting inside the detector makes an electron, and the electron makes an electromagnetic shower that radiates Cherenkov light as shown in Figure 27.

The shower is only about five metres long – the size of this room, or even smaller. However, in a kilometre cube detector, this room is like a light bulb – it's a point source of light, which is exactly what you saw. In fact, the size of this ball of light indicates its energy. When I saw this event for the first time, I immediately understood how much

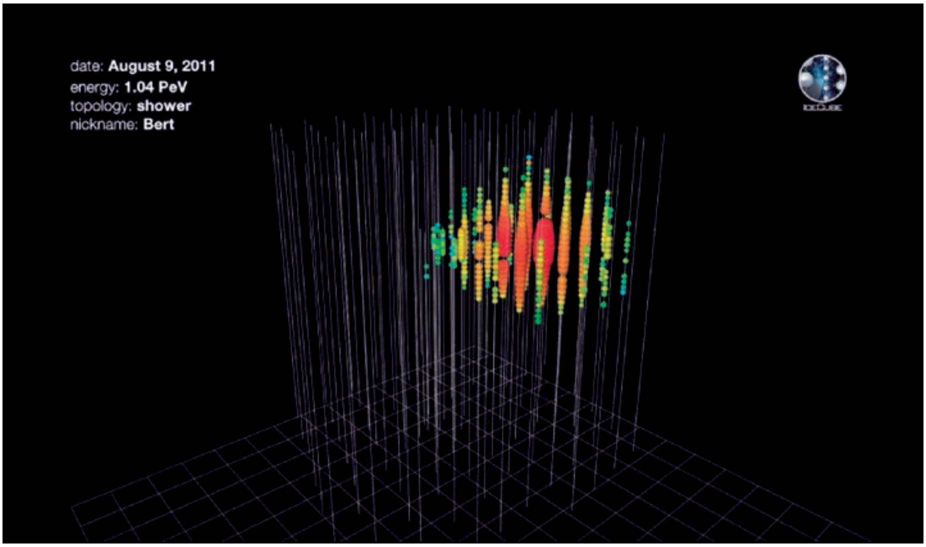


Fig. 26. GZK neutrino search: two neutrinos with energy > 1,000 TeV.

energy it released just by eyesight alone; a computer was not necessary. In fact, we understand these events very well. In a simulation of the event, which is totally isotropic, the colour of the photons – red, yellow, and then green and blue – in the sensors indicates the neutrino direction. I like to show this event superimposed on the Data Center in Madison, Wisconsin, with the lakefront view, as in Figure 28. If this event were superimposed on Rome, it would have the size of about five city blocks. There are 100,000 photons in this event, and we know where each of them is, down to two nanoseconds, which is about 60 cm. With all of this information, the energy is measured, as in a real CERN

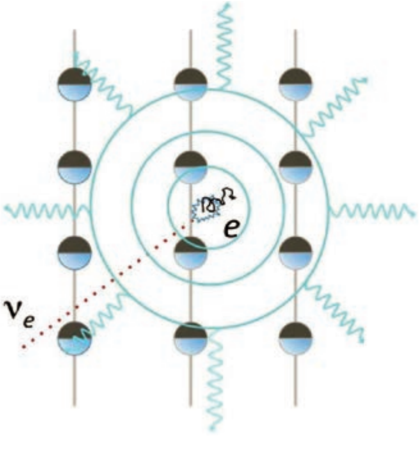


Fig. 27. Electron showers versus muon tracks. PeV ν_e and ν_τ showers are 10m long, with a volume ~ 5 m^3, and are isotropic after 25~50m.

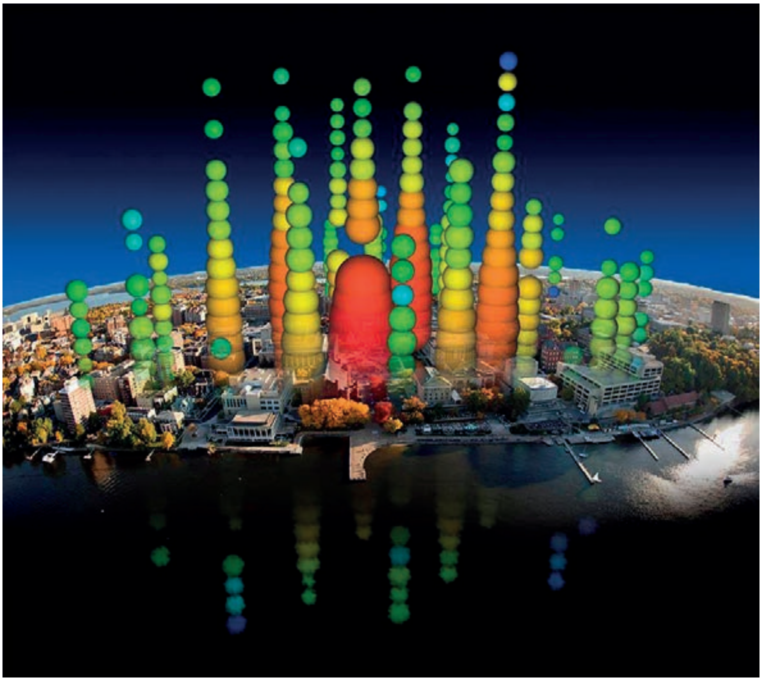


Fig. 28. The detector superimposed on the Data Center in Madison, Wisconsin: >300 sensors; >100,000 pe reconstructed to 2 nsec.

detector, to 10%. Therefore, there is no doubt about what the energy of these events is.

Thus, we decided to look at our first two years of data again, selecting only neutrinos that start inside the detector – unlike what we were told to do by Markov in 1960 – and we built a veto. That means we allowed no light to come in. The light sensors are employed to guarantee that no light enters the detector, thus the event starts inside. We did a very sophisticated, complicated blind analysis, but after a while we realized that the events could simply be plotted for the signal to be seen. Figure 29 shows one year of data, the z axis contains the number of events – this is the integral number – and the x and the y axes contain the number of photons in the event, so from low to high energy, and how many photons there are in the veto layer, which is supposed to be zero: no light, as can be seen in the signal sticking out. These are very high-energy neutrinos; there is no light entering the detector.

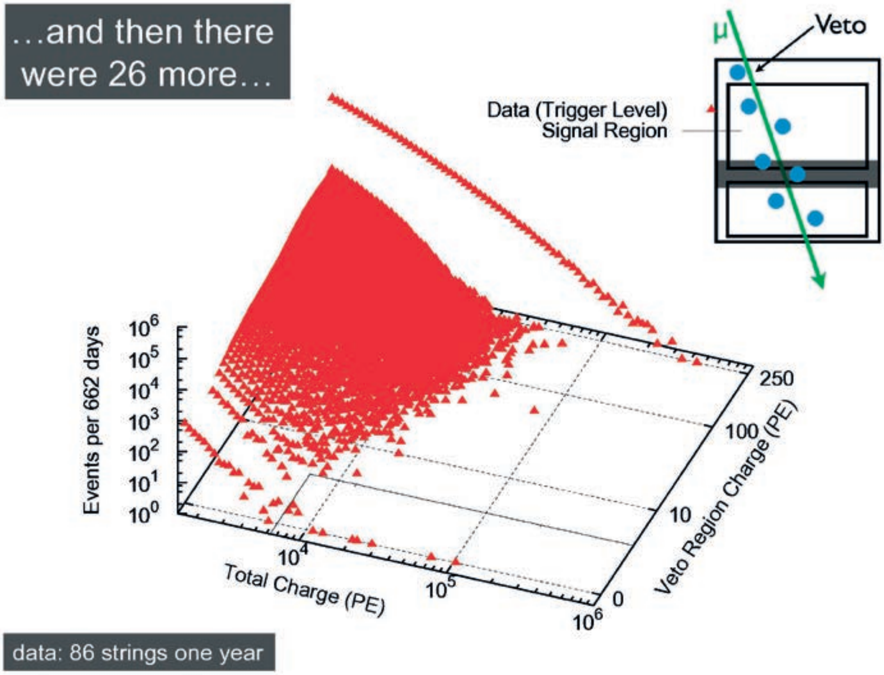


Fig. 29. One year of data: the z axis contains the number of events; the x and the y axes contain the number of photons in the event.

After seven years of data, every year looks exactly the same. We actually published our findings in *Science*; we have tripled the data since then, as shown in the left-hand plot in Figure 30. It is again a chart where the atmospheric neutrino flux is plotted as the coloured histogram, and the excess can also be seen. Figure 31 shows the highest-energy event we have found, just recently, and in fact it has an energy of 6000 TeV inside the detector.

Two immediate questions arise. There are two totally different ways of determining the flux. Are they consistent? The answer is yes. In Figure 32, the black data are, as a function of energy, the number of neutrinos starting in the detector, and the purple overlay are the numbers of muon neutrinos coming up through the earth, and they are perfectly consistent. There is a very interesting problem: we see more neutrinos than we expect to see below a hundred TeV, and that is under investigation since it concerns sources that have never been

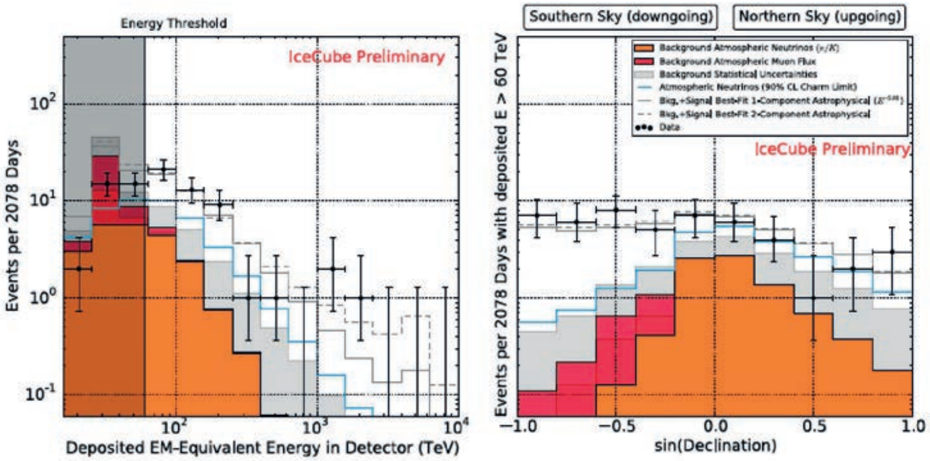
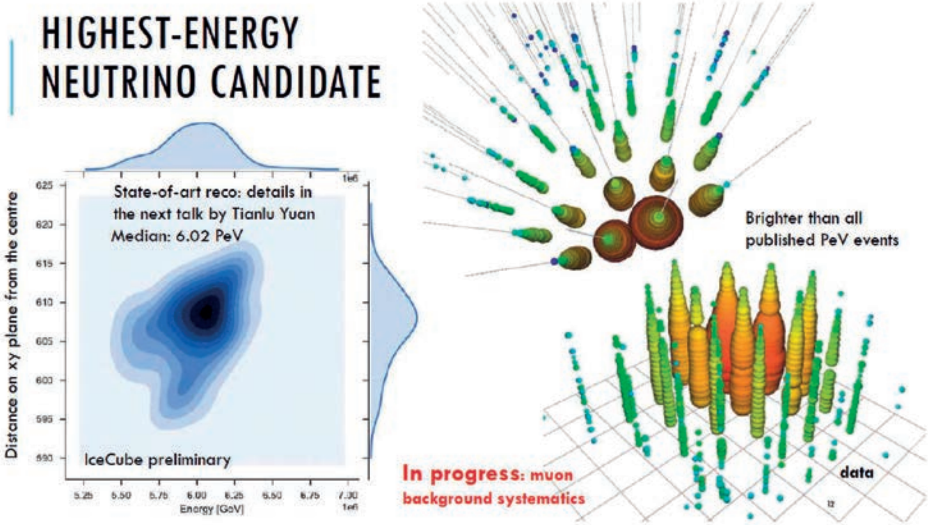


Fig. 30. Seven years of data.



HIGHEST-ENERGY NEUTRINO CANDIDATE

State-of-art reco: details in the next talk by Tianlu Yuan

Median: 6.02 PeV

Brighter than all published PeV events

In progress: muon background systematics

Fig. 31. Highest-energy neutrino candidate found to date.

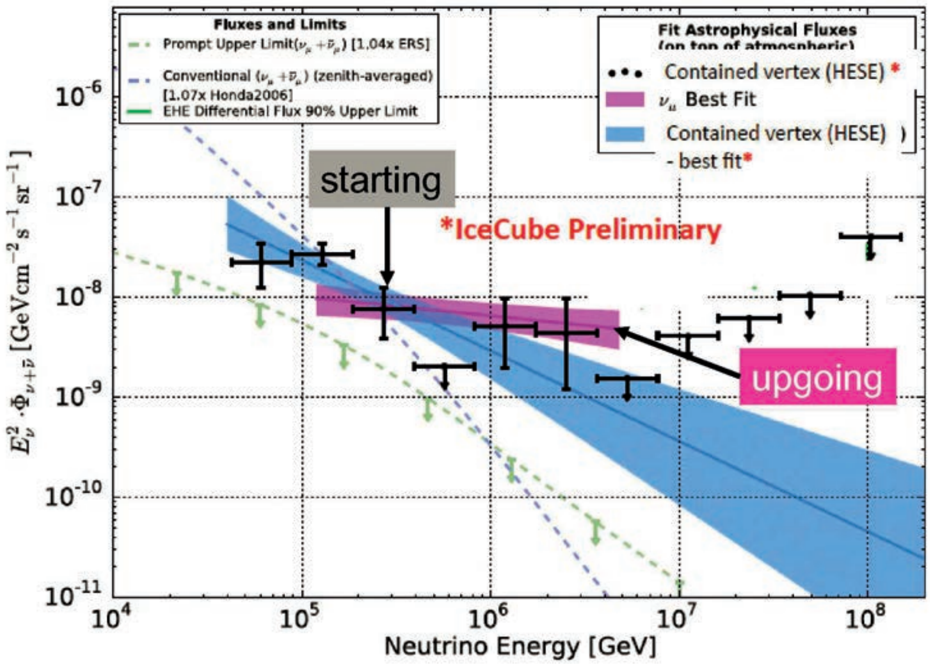


Fig. 32. Plot showing consistency in the two ways of determining the flux.

seen by astronomers, as will be further explained below. However, this also assumes that you have equal flavours of neutrinos, which is expected.

Then there is the second question: where do they come from? You just make a sky map. Figure 33 shows the first sky map with two years of neutrinos starting in the detector. I always warn people about small statistics. The first event we ever measured came within one degree from the centre of our galaxy. It now turns out that, after six years of data, there is absolutely no correlation to the centre of our galaxy. The purple spot in Figure 33 is something close to the centre of the galaxy. After six years of data, it is clear that there is no preferred arrival direction for the neutrinos. If we were seeing neutrinos from our own galaxy, they would all have to line up on the horizontal line in the figure, which is not the case. You saw the galactic plane in light, and here, there is no galactic plane.

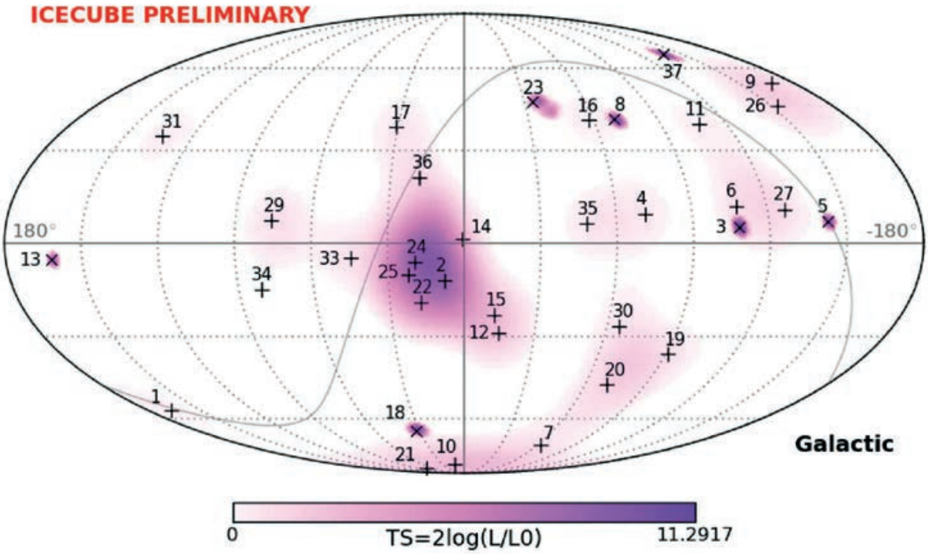


Fig. 33. Two-year results plotted on a sky map.

Actually, the important discovery is that we see neutrinos apparently coming from the whole universe – not from our galaxy – although we cannot rule out a small subdominant galactic flux. In fact, we have some evidence of galactic sources that is now approaching the 3-sigma level, and we are at the point of studying them more carefully. Sometimes 3-sigma comes true, so we will see.

From Discovery to Astronomy

In any event, the big question is – as shown earlier in Figure 8 – why have astronomers never seen thousand-TeV gamma rays? 1950s physics tells you that you have to, which is an interesting question. Although gamma rays would not make it to the earth, and once you have an electron-positron pair – charged particles – you can no longer do astronomy, that is not the end of it. Remember that, as in Figure 6, the electron will emit a photon; this photon will make a pair of electron positrons again, and so an electromagnetic cascade develops. These thousand-TeV photons will end up as many lower energy photons that do reach the earth. The Fermi satellite can see them, and you can calculate – even by counting on your fingers – how many there are: 2 neutrinos for every 2 gamma rays. The neutrino data on the right in Figure 34 can be fitted together with the photons, which can be dumped into the microwave background and its standard electromagnetism to calculate what comes out, which is shown by the red line, and the data points are what the Fermi satellite sees. This was a true shock, because what it tells you is that, at some qualitative level, we are seeing the same energy in the universe in neutrinos as in light. This was certainly not expected, and I think that this is the most important result in this field up to now. You may say, "You build a kilometre cube detector, and run it for six years. So why did you need to do that if the flux is so large?". But the problem is that for every neutrino we detect, there are a million that just go through the detector, and that's what you have to remember.

This is interesting, but the next question is, "Are you actually seeing the same objects in neutrinos as in gamma rays?". That is

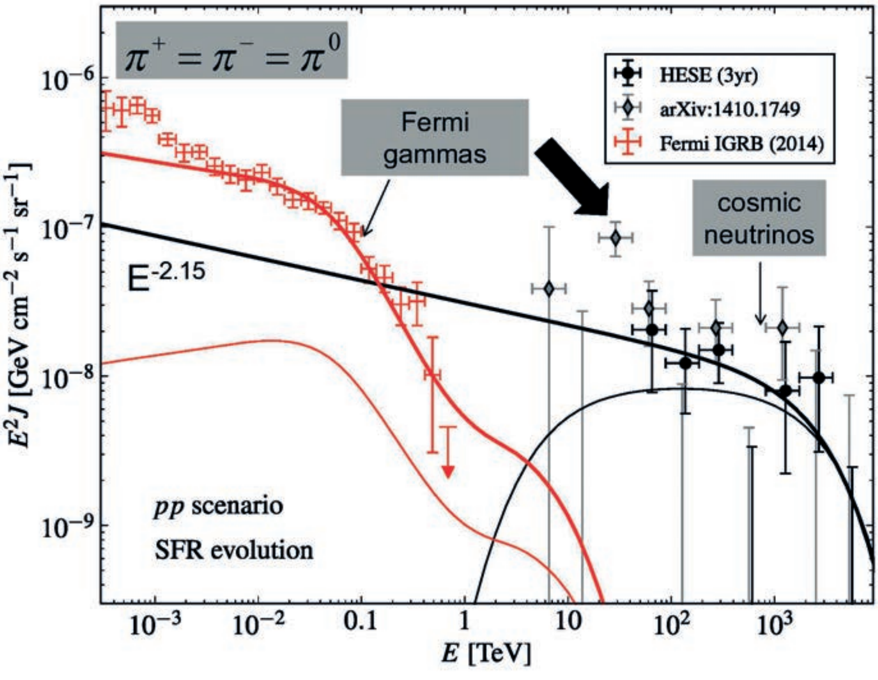


Fig. 34. Comparison of IceCube data and Fermi satellite data.

more complicated, because I cannot tell you the answer. The Fermi satellite sees mostly blazars; IceCube mostly does not see blazars, but it's hard to really know because we do see different skies with light and neutrinos. And with neutrinos, you look much deeper in space, for instance. With Fermi, a lot of the sources they see in this energy range – maybe 80% – are objects where the beam of the accelerator is pointing at the earth. That is called a blazar, an active galaxy where the beam points at you. There are maps that show all the sources, but in examining them closely, there is not a strong correlation.

Better results come from what we call multi-messenger astronomy, which we have been doing even since AMANDA. For instance, when astronomers detect a gamma-ray burst, the star collapsing to a black hole that I talked about and that theorists love as a theory for the extragalactic cosmic rays, they tell us its direction, where it is happening, and at what time. During that short time there is no background, so you see neutrinos or you do not.

After more than 1,100 bursts, we have never seen a neutrino, so we can put an upper limit on this theory, with a flux that is less than 1% of the flux that is actually seen. For the past few months, we have been doing the reverse. When we see a neutrino, we quickly measure, typically within less than 60 seconds, where it comes from, and send an alert to the astronomers, and they point their telescopes there. This has just started. We have sent approximately ten alerts. One was observed by AGILE as a flare of light, which may have been connected to one of these blazars. You can read the paper, whose authors claimed a 4-sigma effect, to see how convincing this is.[1] A few weeks ago, in fact, on September 22, we detected an event of over 100 TeV, so it was almost certainly a cosmic neutrino. We sent the direction to telescopes, and Fermi, the same instrument I have been talking about, not only saw one of their galaxies, but even saw one of their galaxies flare. These galaxies produce particles, not in a steady beam like the CERN accelerator, but in bursts, which has to do with

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[1] F. Lucarelli, C. Pittori, F. Verecchia, I. Donnarumma, M. Tavani, A. Bulgarelli, A. Giuliani, L.A. Antonelli, P. Caraveo, P.W. Cattaneo, S. Colafrancesco, F. Longo, S. Mereghetti, A. Morselli, L. Pacciani, G. Piano, A. Pellizzoni, M. Pilia, A. Rappoldi, A. Trois, S. Vercellone. AGILE Detection of a Candidate Gamma-Ray Precursor to the ICECUBE-160731 Neutrino Event. The Astrophysical Journal, vol. 846, no. 2 (Sept. 2017).

the variability of the flows into the black hole. This galaxy changes its flux, the amount of light it emitted, by a factor of 6, and during that flare, we detected this neutrino.

We later found out that MAGIC, which only detects TeV gamma rays – the interesting region for us – also observed it. One point is the muon direction, and this is the superposition of MAGIC [Figure 35]. There was other activity, too, with 5-6 telescopes that have discovered this blazar by now. Thus, we are desperately trying to calculate the probability of this phenomenon happening accidentally, which is not going to be very large. Certainly, our neutrino is very unlikely to be atmospheric background. The problem with this, of course, is trying to predict things ahead of time, and a posteriori statistics is always very dangerous.

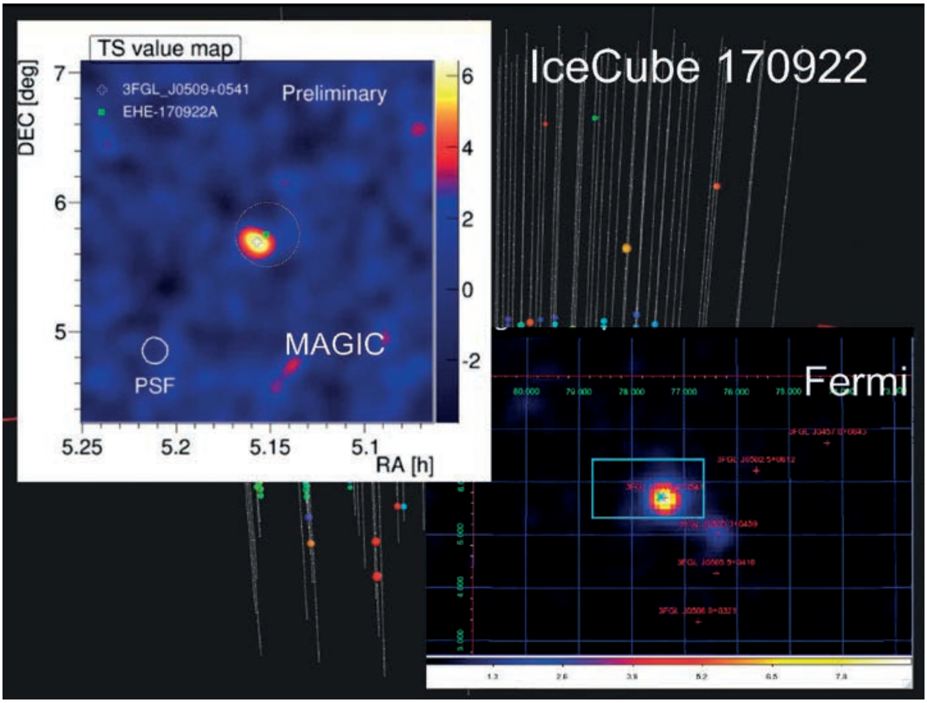

Fig. 35. MAGIC and Fermi detection results following an IceCube alert.

CONCLUSIONS

I will wrap up by asking, "What are we going to do next?". One wishes for 10 times more events, which means a detector that is 10 times bigger, and a budget with 10 times more money. Procuring that sum is almost impossible these days, but it is possible if you build a detector that is well motivated. If a detector that is an order of magnitude larger is built, multiple muons from the same direction can be seen, and then you will not have to work out a posteriori statistics, and the sky can be mapped using neutrinos only. What makes this dream realistic is that our ice is made out of layers of snow. By building this detector, which was of course crucial, we discovered how far this blue light travels through the ice [Figure 36]. We actually found out that it travels 100 metres when at the top, but 220 metres when close to the bottom. To give you an idea, the equivalent – what we called absorption length – of water is 2 metres, which if distilled is 8 metres. Water can be purified to reach 80 metres, which I think is the limit of technology. The water in neutrino detectors underground has this purity.

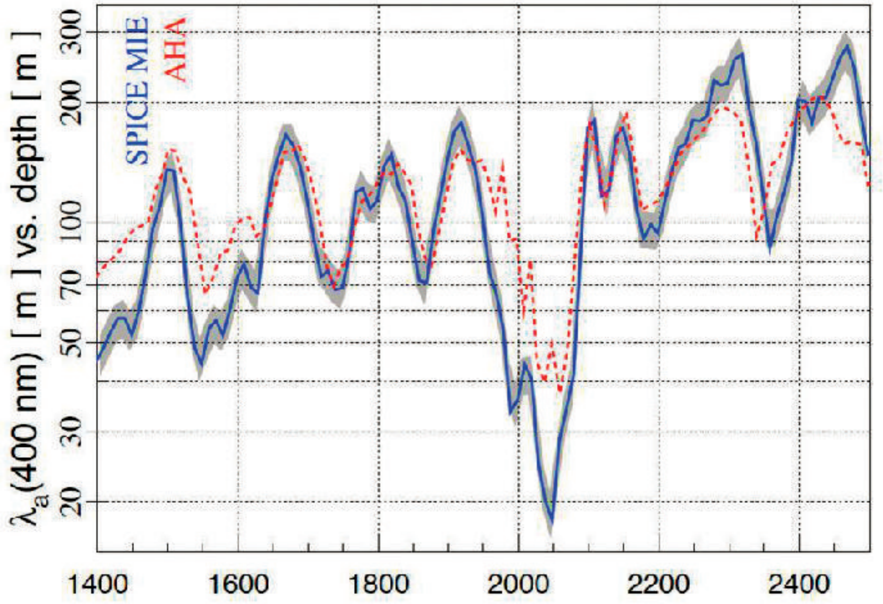

Fig. 36. Absorption length of Cherenkov light.

This means that we can collect this light from 200 metres away or more, and so we would not have to put our strings under 125 metres apart. Of course, there is a problem: if you collect light from far away, it begins to scatter [Figure 37]. There is dust in the ice, and the dust varies according to when the snow condensed. I like this graph because it shows how well we understand this problem – this peak was snow that fell 74,000 years ago. That was the time of the Toba eruption, two notches before 2150 on the graph, which geologists know very well. It was a huge volcanic eruption that deposited dust in the atmosphere. Some of it was carried to Antarctica, and this was never seen in ice cores. It was controversial, but we see this clearly.

We resolve concentrations of dust of less than a centimetre. Then it is just a computing problem; if you collect photons from far away, you have to propagate them through this dust. We are already doing this, and so we are ready to design this detector. In fact, this detector has been designed through the funding from my Balzan Prize, because in the US you cannot develop your future proposals with money from the National Science Foundation. The Balzan money funds a postdoc, who is actually Dutch and has worked with KM3Net. He is working on designing and optimising this detector [Figures 38 and 39].

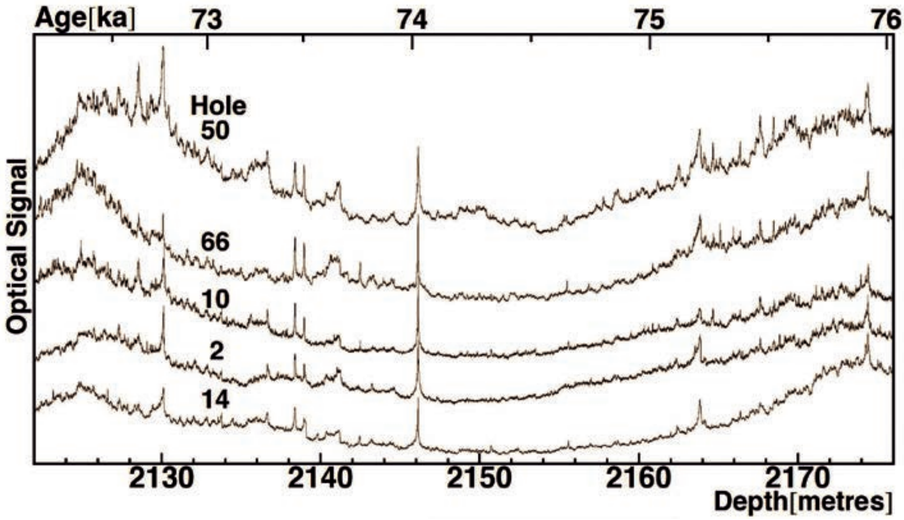

Fig. 37. Optical signal variation by depth.

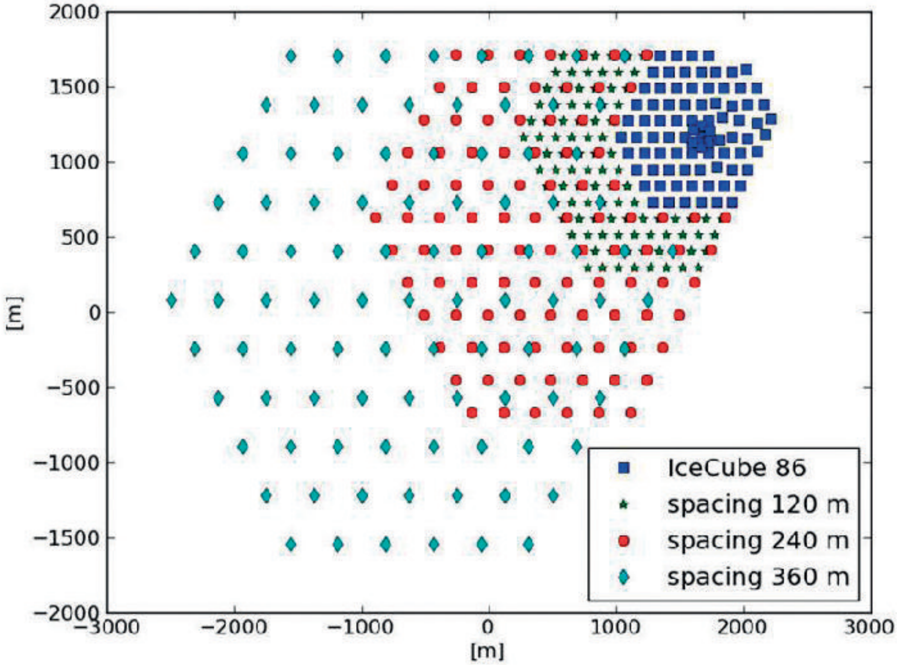

Fig. 38. Comparison of string spacing designs for future detector.

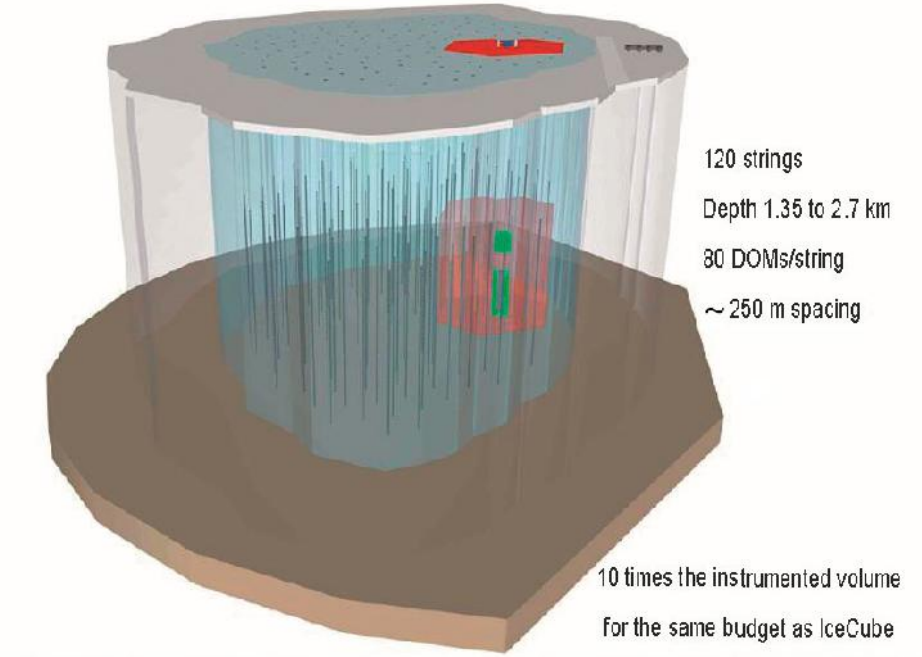

Fig. 39. Potential configuration for future detector.

IceCube is also doing other things. I have only talked about the astrophysics part. Figure 40 is not a wish list. We have published a paper, or are about to submit one, on every box in this table. That is the beauty of this experiment. Whatever you are interested in, you can come and do something useful.

I will conclude with our most important results. Astronomers thought that cosmic rays were some exotic phenomena, and that all of the universe could be explained with electrons and gamma rays. That idea is gone. We have to start over, and we have to study neutrinos. We are upgrading IceCube, our first project, which is still going on. Rather than doing science, we are stopping for a while to recalibrate and improve the detector. We have kept all of our data, so we can apply these improvements to 10 years of data once we get there. However, in order for this to really be astronomy, you have to have many telescopes, and certainly bigger ones. I think that my talk will have convinced you of this. This is also happening off the coast

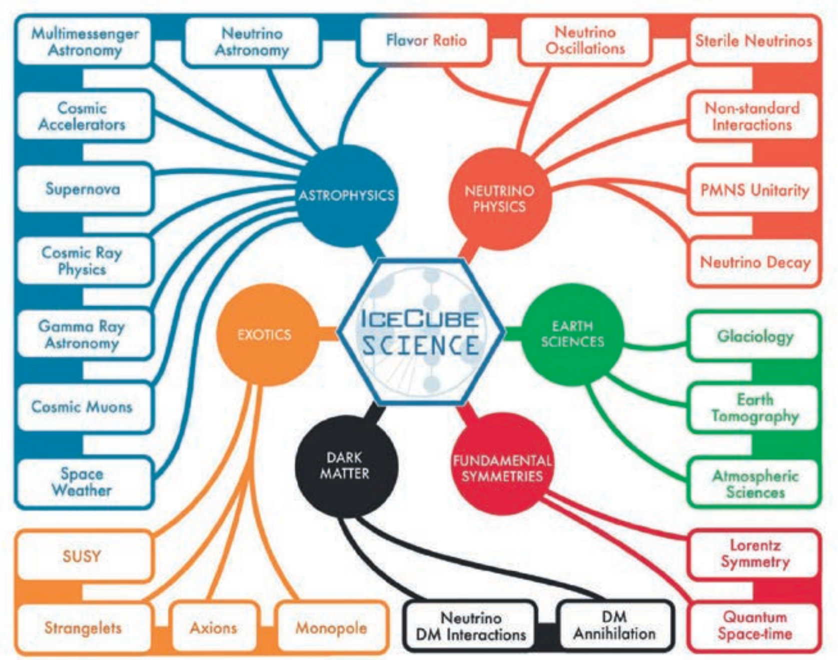

Fig. 40. Wide range of science topics covered by IceCube.

of Catania, where a similar detector, KM3Net, is being built. It will not only be larger, but it will also be complementary, observing a different sky. A detector is being built in Lake Baikal, too. Thus, there is much more data to come in this field, and that is what is really needed rather than "reading the tea leaves" in the 100 events or 200 events that we have thus far. Stay tuned: this is going to be exciting!

Acknowledgement of sources

ESA and the Planck Collaboration (Figure 1)
Axel Mellinger (Figure 2)
NASA/DOE/Fermi/LAT Collaboration (Figure 3)
n/a (Figures 4, 10)
IceCube Collaboration (Figures 5-9, 12, 16-17, 19-40)
Solar and Heliospheric Observatory - SOHO (Figure 11)
M. Unger (Figure 13)
NASA/Zhang and Stan Woosley (Figure 14)
Aurore Simonnet (Figure 15)
Christian Spiering (Figure 18)

DISCUSSION AND QUESTIONS

Luciano Maiani: We have time for some questions and comments, or requests for information.

You mentioned the deep underwater projects. How far are we from that, from seeing neutrinos?

Francis Halzen: Earlier, you mentioned the AMANDA detector, which was absolutely necessary to figure out what we are doing. People have been trying to build these experiments in water for a long time. In fact, the most ambitious effort was off the coast of Hawaii. It failed, but in the Mediterranean, a European collaboration has built an experiment about the size of the AMANDA detector, and has made a lot of improvements on the technology, which remedied the problems that the experiment in Hawaii had.

They are now at the point of initial construction. You know that the Sapienza is involved in this, and the principal investigator is sitting in the audience, so it's strange for me to explain this. They are now constructing this detector. When we had to construct our detector, we did it in six seasons, but each season was only two months long. This limitation doesn't exist in water, so this one could go faster.

Luciano Maiani: I have another question. You mentioned matter in your beautiful talk, your "metropolitan subway chart". I remember that one of the main scopes of AMANDA was to see dark matter. Are you on that now?

Francis Halzen: Yes. We actually – for the experts in the audience – have the world's best limit on dark matter particles that interact with the spin of the nucleus, spin-dependent. We are still working on that. In fact, we are going to bring out a paper which more than doubles our data. So, expect more results soon.

Francis Halzen

BIOGRAPHICAL AND BIBLIOGRAPHICAL DATA

Francis Halzen, born in Belgium on 23 March 1944, is a US citizen.

He is currently Hilldale and Gregory Breit Distinguished Professor at the University of Wisconsin-Madison and Director of its Institute for Elementary Particle Physics.

He earned his Master's degree (1966), his PhD (1969) and his Agrégé de l'Enseignement Supérieur from the Université de Louvain, Belgium.

He is currently the Principal Investigator for the IceCube project, the world's largest neutrino detector, and has served on various advisory committees, including those for the SNO, Telescope Array and Auger-upgrade experiments, the Max Planck Institutes in Heidelberg and Munich, the ICRR at the University of Tokyo, the US Particle Physics Prioritization Panel and the ApPEC particle astrophysics advisory panel in Europe.

Among his recent honours are the European Physical Society Prize for Particle Astrophysics and Cosmology in 2015; the *Smithsonian* American Ingenuity Award for Physical Sciences in 2014; the *Physics World* Breakthrough of the Year Award for making the first observation of cosmic neutrinos, the American Physical Society Highlights of the Year, and the University of Wisconsin Hilldale Award in 2013; and the International Hemholtz Award of the Alexander von Humboldt Foundation in Germany in 2006. He was the International Franqui Professor, VUB-ULB-UGent-UMons-UA-ULg-KULeuven, Belgium (2013-14), and Affiliated Professor at Technical University Munich, Germany (2012), and holds honorary degrees from Ghent University in Belgium (doctor honoris causa, 2013) and Uppsala University (doctor of philosophy honoris causa, 2005). He became a Fellow of the American Physical Society in 1996.

Francis Halzen has a most impressive list of publications among which we would mention:

- Determining neutrino oscillation parameters from atmospheric muon neutrino disappearance with three years of IceCube DeepCore data (with the IceCube Collaboration), *Phys. Rev.* D91 072004 (2015).
- Search for dark matter annihilations in the Sun with the 79-string IceCube detector (with the IceCube Collaboration), *Phys. Rev. Lett.* 110, 131302 (2013).
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- Optical properties of deep glacial ice at the South Pole (M. Ackermann, J. Ahrens, X. Bai, M. Bartelt, S.W. Barwick, R.C. Bay, T. Becka, ...). *Journal of Geophysical Research: Atmospheres* (1984-2012) 111 (D13) (2006).
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- Neutrino fluxes from active galaxies: A model-independent estimate (with E. Zas), *Astrophys.J.* 488 (2), 669 (1997).

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- Observation of muons using the polar ice cap as a Čerenkov detector (with D.M. Lowder, T. Miller, R. Morse, P.B. Price and A. Westphal), *Nature* 353, 331 (1991).
- Delta *r* beyond one loop (with B. Kniehl), *Nucl. Phys.* B 353, 567 (1991).
- *High-energy neutrino detection in deep polar ice* (with J.G. Learned), Proceedings of the 5th International Symposium on Very High-Energy Cosmic Ray Interactions, Lodz, Poland (1988).
- "Soft" hard scattering in the teraelectronvolt range (with T. Gaisser), *Phys. Rev. Lett.* 54 (16), 1754 (1985).
- *Quark & Leptons: An Introductory Course in Modern Particle Physics* (with A.O. Martin), John Wiley & Sons (1983).
- Testing QCD in the hadroproduction of real and virtual photons (with D. Scott), *Phys. Rev. Lett.* 40, 1117 (1978).

For his full CV and bibliography, see: http://icecube.wisc.edu/~halzen/.

Balzan Research Project

BALZAN FELLOWSHIP
FOR A POSTDOCTORAL RESEARCHER

Advisers for the General Prize Committee: Bengt Gustafsson and Luciano Maiani

The Wisconsin IceCube Particle Astrophysics Center (WIPAC) at the University of Wisconsin-Madison has created the "Balzan Fellowship" for an outstanding postdoctoral candidate to work with the IceCube neutrino experiment, with special emphasis on future technologies and/or multi-wavelength campaigns to advance the future of neutrino astronomy.

The IceCube Neutrino Observatory is the first detector of its kind, designed to observe the cosmos from deep within the South Pole ice. It does so by recording the interactions of a nearly massless subatomic particle called the neutrino. IceCube is also the world's largest neutrino detector, encompassing a cubic kilometre of ice. The neutrinos come from the most violent astrophysical sources, like exploding stars, gamma-ray bursts, and cataclysmic phenomena involving black holes and neutron stars. Thus, the IceCube telescope is a powerful tool to search for dark matter, and could reveal the physical processes associated with the enigmatic origin of the highest-energy particles in nature. Moreover, by exploring the background of neutrinos produced in the atmosphere, IceCube studies the neutrinos themselves; their energies far exceed those produced by accelerator beams.

After an extensive international search, Daan Van Eijk was selected as the Balzan fellow. Van Eijk was previously employed as a scientist at NIKHEF, Amsterdam, where he was coordinating the integration of KM3NeT digital optical modules. The DOM, which is shorthand for digital optical module, is the basic detection element of the KM3NeT neutrino detector. Van Eijk is a member of the KM3NeT Steering

Committee. He contributes to the commissioning and data analysis of the first deployed DOMs, and his goal is to eventually work on the KM3NeT physics program to determine the neutrino mass hierarchy using atmospheric neutrino oscillations. His PhD research was performed at CERN, studying CP-violating decays using data from the LHC-B detector.

Van Eijk joined WIPAC in July 2017. Before taking up his position, his research program was planned and KM3NeT was under construction in the Mediterranean. Like IceCube, KM3NeT is a kilometre-scale neutrino detector, but the design of its photosensors is different. The same design is now being considered for the next-generation IceCube detector, and Van Eijk's expertise will be valuable for future decisions on sensors.

Telescopes evolve. AMANDA, an experiment preceding IceCube, provided proof of concept for a kilometre-scale detector by observing atmospheric neutrinos using natural ice as a particle detector. IceCube's discovery of a large flux of cosmic neutrinos has triggered the development of a next-generation instrument capable of observing thousands rather than hundreds of events in several years. It would turn discovery into astronomy. The experience gained with IceCube has augmented the capability to instrument a ten-times-larger volume of ice on a budget similar to the one for IceCube. Daan Van Eijk presently participates in completing the design of the instrument. He has already completed an extensive study of novel photomultipliers that are considered for the next-generation detector. A publication covering the research is in preparation. In the same context, novel technologies that do not necessarily involve the IceCube technique will also be researched, such as radio detectors and horizontal cosmic ray air shower arrays. With Van Eijk as a Balzan fellow at the lead institution of the IceCube project, there are hopes to further the excellent support and coordination that characterize the current collaboration between IceCube and the European KM3NeT.