Nobel Lecture: Birth of neutrino astrophysics*

Masatoshi Koshiba

International Center for Elementary Particle Physics, University of Tokyo, 7-3-1, Hongo, Bunkyo, Tokyo, 13-0033 Japan

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In giving this talk I am very much helped by the preceding talk because I can skip some of the topics. If you want further information, please refer to my review article, "Observational Neutrino Astrophysics" (Koshiba, 1992).

I am to talk about the birth of neutrino astrophysics, but before the birth, there was a very important event, which was just described by Professor Davis (Nobel Lecture, Davis, 2003). It was the radiochemical work using the reaction $\nu_e + {}^{37}\mathrm{Cl}$ going to $e + {}^{37}\mathrm{Ar}$. He found that the observed neutrino flux was only one-third of what was theoretically expected. This could be considered as the conception of neutrino astrophysics and was in fact the impetus for us to begin seriously working on solar neutrinos.

I will talk about two experiments. The first was carried out at the original KamiokaNDE, which might be called an Imaging Water Cerenkov detector with 20% of its surface covered by photomultipliers. The total mass of the water inside this detector was 3000 tons. Its cost was about 3 million U.S. dollars. This, mind you, was meant to be the feasibility experiment on the astrophysical detection of solar neutrinos. The second experiment was carried out at Super-KamiokaNDE, the same type of detector but with a better light sensitivity, that is, 40% of the entire surface was covered by photocathodes and the total mass of the water was 50 000 tons. Its cost was about 100 million U.S. dollars. This was considered to be the full-scale solar neutrino observatory.

Both the facilities are situated about 1000 meters underground in the Kamioka Mine. The capital letters NDE at the end of the two names originally stood for Nucleon Decay Experiment. However, because of the detection of various neutrinos by these detectors, people started calling them Neutrino Detection Experiments. Figure 1 shows the interior of KamiokaNDE. You can see arrays of photomultipliers on the sidewalls as well as on the top and at the bottom. When we were preparing for this KamiokaNDE experiment, we heard that a much bigger experiment, but of similar type, was being planned in the United States (Bionta *et al.*, 1983). We had to think very seriously about the competition with this bigger detector. Both experiments aimed at the detection of a certain type of proton decay, i.e., the $e^+ + \pi^0$ mode. If we were aiming only for the detection of such a particular type of proton decay, certainly much bigger U.S. experiments would find it first. Then, what could we do with a smaller detector? We thought very seriously about this competition and we came to the conclusion that the only possible way to compete with this bigger detector would be to make our detector much more sensitive than that of our U.S. competitors, so that we could not only detect the easiest proton decay mode, but could also measure other types of proton decays. Then eventually we could say the proton decays into this mode with this branching ratio and into that mode with that branching ratio and so forth, so that our experiment would be able to point the way to the possible future, what is called the Grand Unified Theory, a new type of theory combining strong forces, weak forces, and electromagnetic forces.

Thanks to the cooperation of Hamamatsu Photonics Company, we jointly developed a very large photomultiplier tube (Kume *et al.*, 1983). I was very happy, as you can see in Fig. 2, that this tube was successfully developed.

Figure 3 shows the interior of Super-KamiokaNDE as viewed through a fish-eye lens. You can see many more phototubes, a total of about 11 000 big phototubes.

Since I suppose not many people are familiar with this type of detector, I want to illustrate the performance of

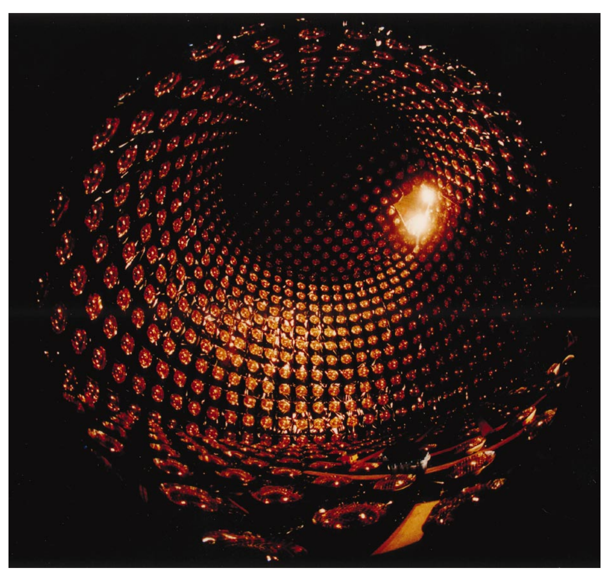

FIG. 1. (Color) The interior of KamiokaNDE.

*The 2002 Nobel Prize in Physics was shared by Raymond Davis, Jr., Riccardo Giacconi, and Masatoshi Koshiba. This lecture is the text of Professor Koshiba's address on the occasion of the award.

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FIG. 2. (Color) The newly developed large photomultiplier.

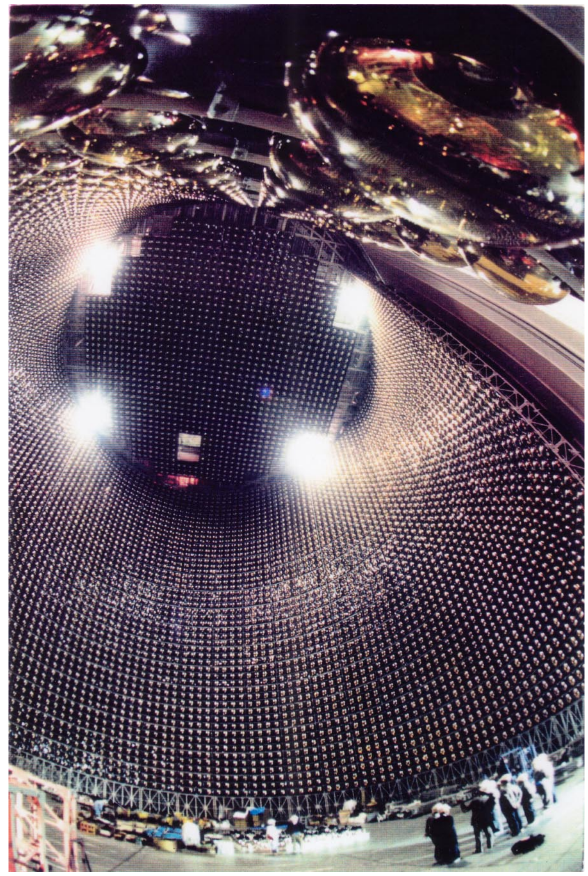

FIG. 3. (Color in online edition) The interior of Super-KamiokaNDE through a fish-eye lens.

Super-KamiokaNDE. The first example is a very slow motion picture of a cosmic-ray muon passing through the detector.

As is well known, special relativity prohibits any particle from moving faster than the velocity of light in vacuum. However, in a medium such as water, the light velocity itself is reduced to three-quarters of its value in vacuum. Therefore, when the particle's energy is very high, its velocity can exceed the velocity of light in the water. Then, what happens is that such a high-energy, high-velocity, particle in water will generate what might be called a shock wave of light: the Cerenkov light. It is emitted in a cone shape with its axis on the trajectory of the moving electrically charged particle.

Figure 4-1 shows the response of Super-KamiokaNDE when a muon has just entered the detector. The Super-KamiokaNDE detector is exploded here. The sidewall is cut vertically at one point and is spread flat, the upper lid is opened up, and the bottom pulled down. Each dot represents a photomultiplier. Red light shows it received a large number of photoelectrons. The different colors indicate a different number of received photoelectrons. At the right below is the time profile of the total number of photons received. Figure 4-2 shows the pattern 50 nanoseconds later. Figure 4-3, another 50 nanoseconds later, shows that while the Cerenkov light is still on its way the muon has already reached the bottom. You can see that the particle is traveling faster than the velocity of light in water. Figures 4-4, 4-5, and 4-6 show the subsequent development of the event. You can see that with this detector an electrically charged particle can be observed in detail. The next figure, Fig. 5, shows two events, an e event above and a μ event below. Looking at these two examples, one with an electron and the other with a muon, you can see the difference in the distribution of the detected photons, especially in the radial distribution of photons. Electrons and muons are very similar particles except that their masses are different by a factor of about 200. This means that in traversing water, the heavier μ particle just slows down and stops, while the lighter electron emits γ rays, which in turn get converted into electrons and positrons. Those low-energy electrons and positrons get scattered violently. Therefore the Cerenkov light emitted by those low-energy particles is widely distributed, as you see in the upper event. By making a quantitative measurement of the radial distribution of those photons, you can make a very good discrimination between a μ event and an e event with an error probability of less than 1%. This is a very nice feature of this detector and led us eventually to discover what is called the atmospheric neutrino anomaly.

The old KamiokaNDE produced four significant results.

The first is the astrophysical observation of solar neutrinos by means of ν_e-e scattering on electrons in water (Hirata *et al.*, 1989). By "astrophysical observation" we

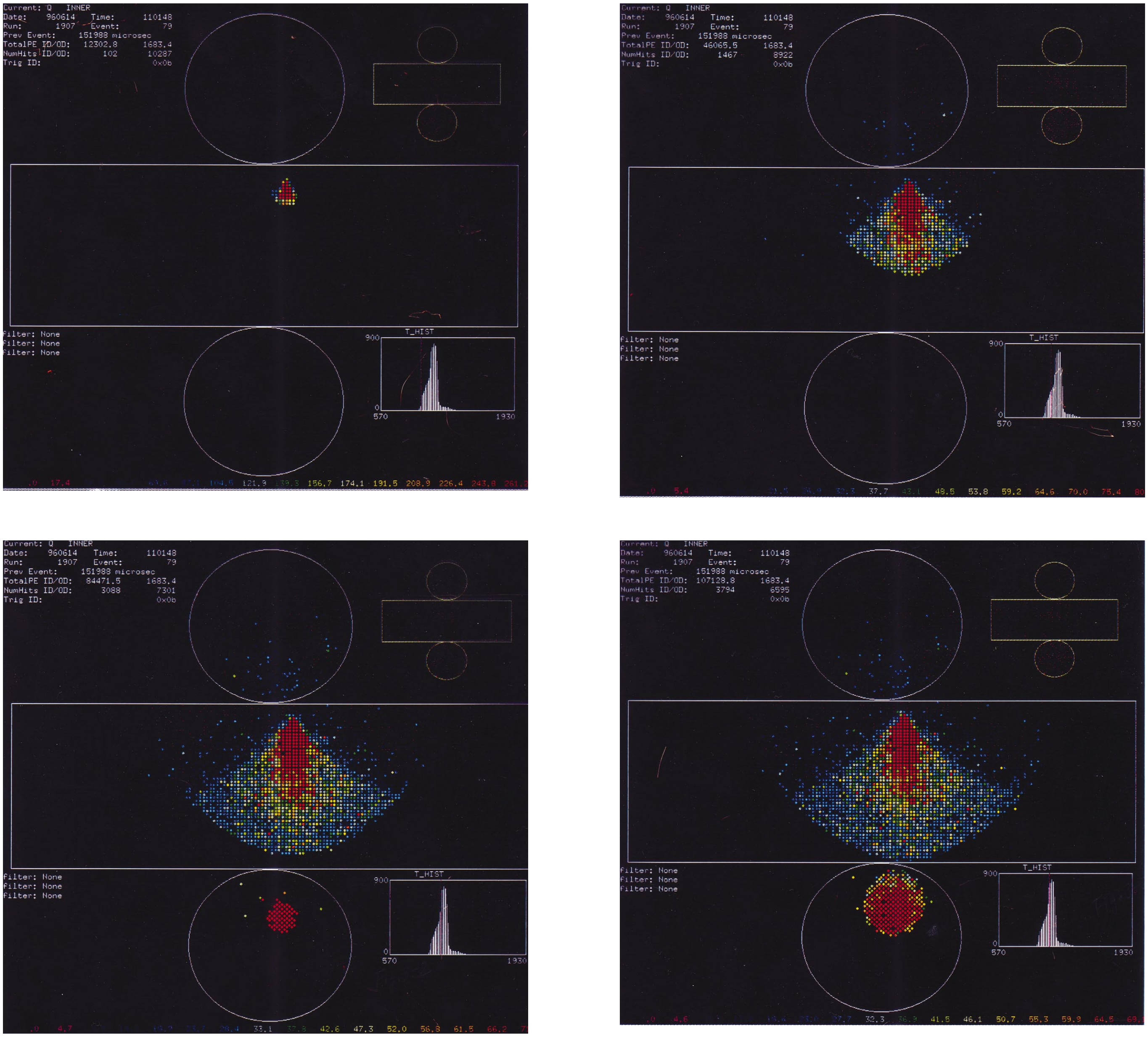

FIG. 4. (Color) Progress of a muon through the Super-KamiokaNDE detector: (4-1) Muon that has just entered Super-KamiokaNDE; (4-2) same muon 50 nanoseconds later; (4-3) muon has reached the bottom.

mean all the necessary information is available, i.e., the arrival direction, the arrival time, and also the spectral information on the incoming neutrinos. In the case of ν_e-e scattering, since the electron rest mass is only 0.5 MeV, for an incoming neutrino of, say, 10 MeV, the struck electron goes almost in the dead forward direction. By observing this recoil electron, you can approximately infer the arrival direction of the neutrino. Also, the energy spectrum of the recoil electrons has a one-to-one relation to the original neutrino energy spectrum. The timing is accurate to better than ten nanoseconds.

The second is the observation of supernova neutrinos (Hirata *et al.*, 1987) by means of the reaction anti-ν_e on protons in water. This reaction produces an e^+ and a neutron. The e^+ is observed by the Cerenkov light it emits.

The third is the discovery of what is called the atmospheric neutrino anomaly (Hirata *et al.*, 1988). Since we can definitely separate μ events and e events, as I have shown before, we could measure the number ratio of ν_μ over ν_e very accurately by observing μ events and e events separately. KamiokaNDE claimed this anomaly at slightly more than four σ significance, but this result was later firmly confirmed at more than 9σ significance by the data of Super-KamiokaNDE.

Not many people are interested in proton decay any longer but the nonobservation of proton decays by the KamiokaNDE experiment was a fourth result, which killed the well-known Grand Unified Theory based on SU[5] symmetry (Hirata *et al.*, 1989).

The previous speaker showed this diagram, Fig. 6, and I am not going into the detail here but instead just

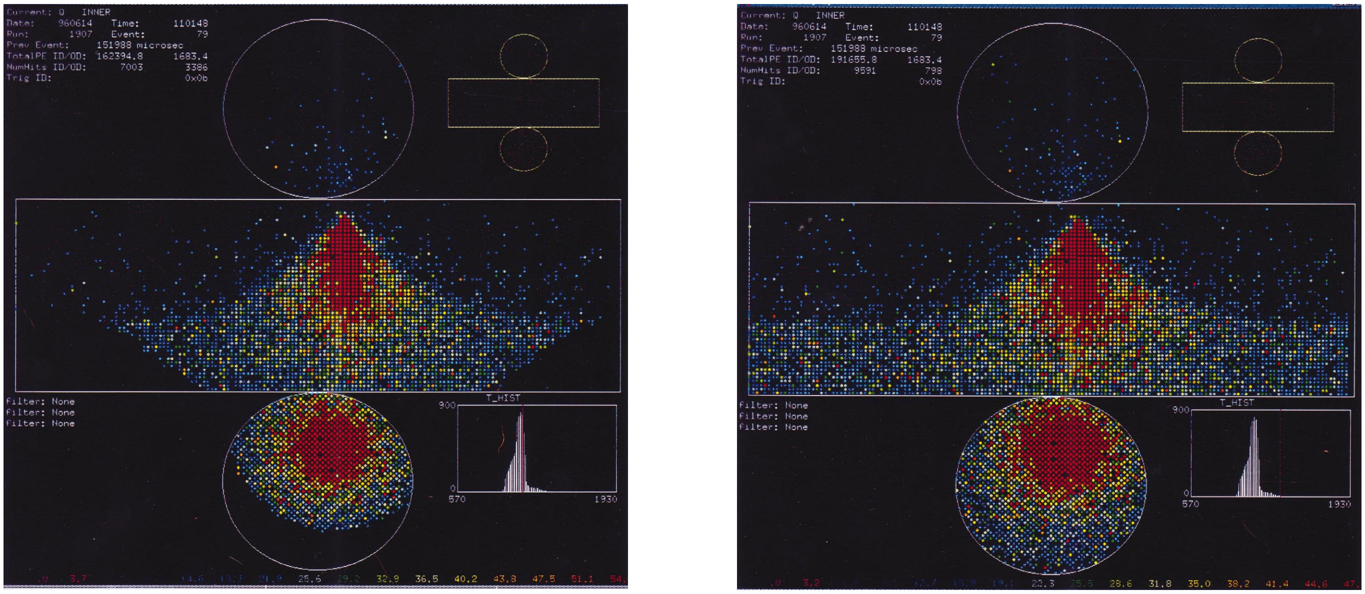

FIG. 4. (*Continued.*)

ask you to notice the threshold energies of various experiments. Figure 7 is to show the feasibility data by KamiokaNDE of observing a solar neutrino with its directional information. You can see, above the isotropic background, the accumulation of events in the direction from the sun to the earth.

The next one, Fig. 8, shows the observed energy spectrum as normalized to the theoretical one. From the figure you can see that the shape is not very different from

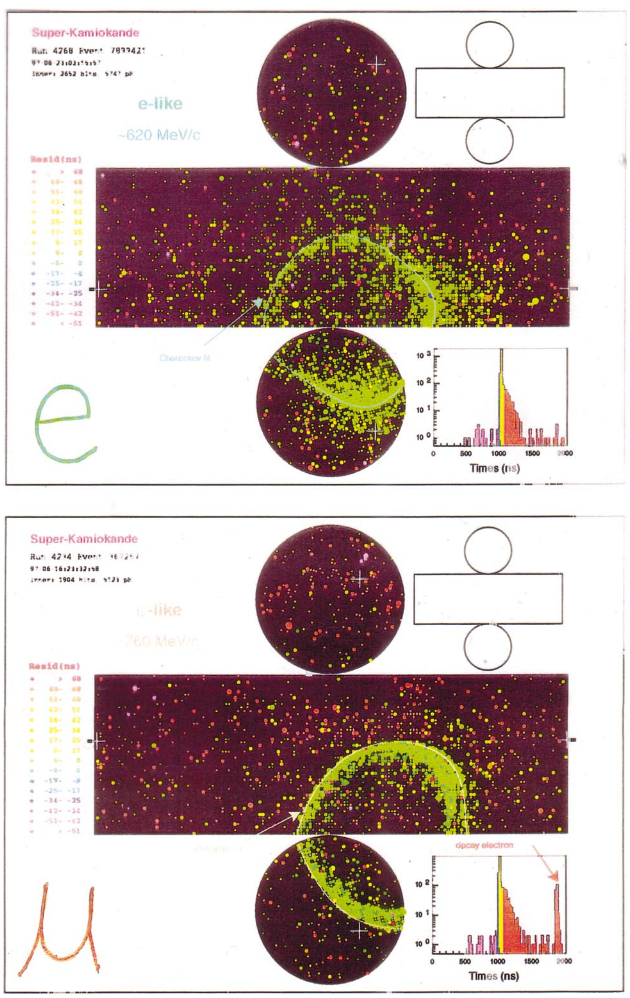

FIG. 5. (Color) An e event above and an μ event below.

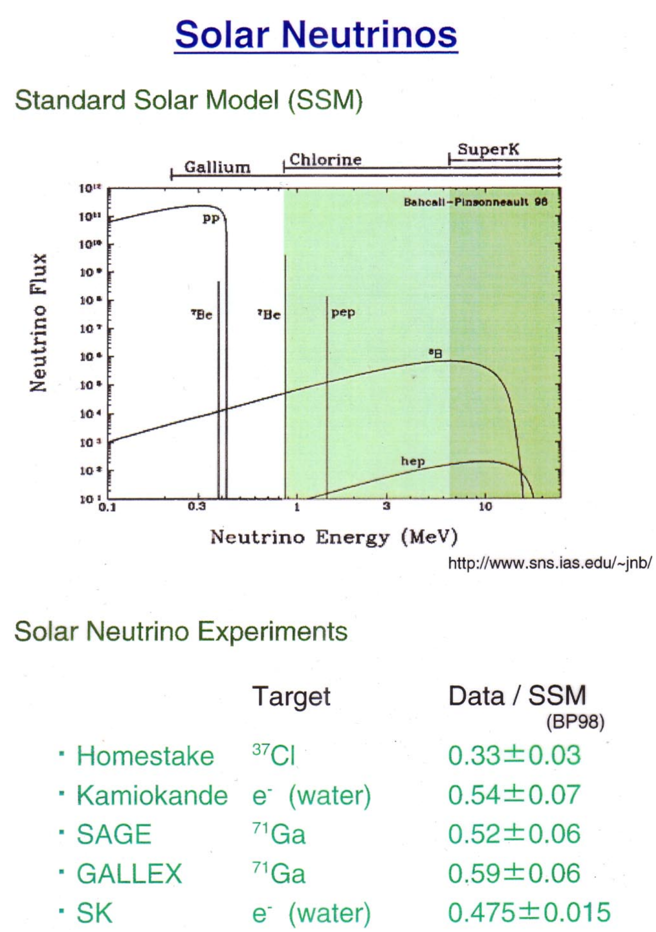

FIG. 6. (Color in online edition) The standard solar model and solar neutrino experiments.

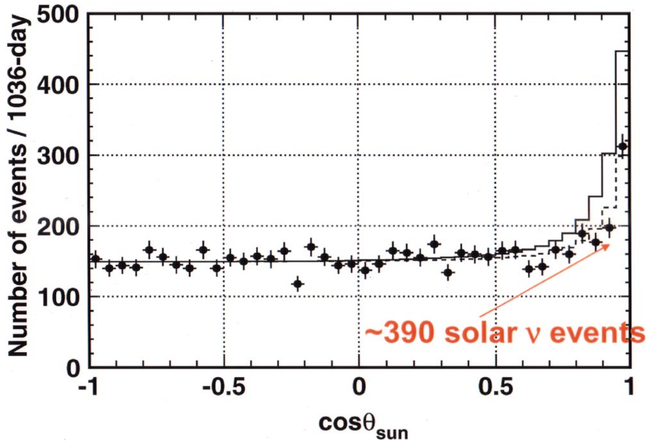

FIG. 7. (Color in online edition) The directional observation of solar neutrinos.

the expected theoretical anticipation, but the intensity is almost one-half.

I now go on to the observation of supernova neutrinos. Thanks to a collaboration with the group of A. K. Mann at Pennsylvania State University, we were able to greatly improve the performance of our detector by reducing the background, purifying the water, and so forth. At the very beginning of 1987, our detector was already calm enough to start taking data on the solar neutrinos. Two months later, we heard that there was a supernova explosion in the southern sky. So we immediately looked at our data and found the supernova neutrino signal very easily because our detector was already capable of taking solar neutrino data. Solar neutrinos are much more difficult to observe than supernova neutrinos, because the supernova neutrinos have considerably higher energies and are bunched in a short period of time. The data we found are shown in Fig. 9. You can clearly see the supernova neutrino signal above the background events of about 17 photoelectrons. This observation confirmed theoretical ideas on the triggering of supernova explosions by a gravitational collapse of iron core. For instance, not only did the average energy and the estimated total number of emitted neutrinos agree with the theoretical expectations, but the time duration of about ten seconds implied that those neutrinos were emitted from very, very dense matter, such as that of a nucleus. If they were emitted from a tenuous stellar body, the time duration of the signal would have been less than one millisecond. But those neutrinos had to get diffused out of very dense, nucleuslike matter, so that it took ten seconds to emerge from this surface; probably a protoneutron star is responsible.

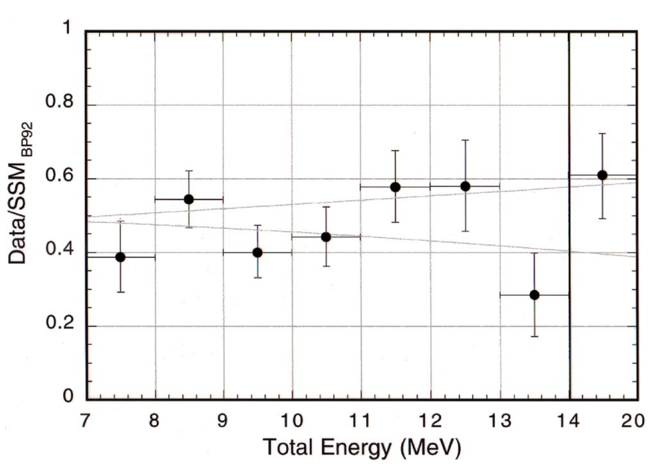

FIG. 8. The normalized energy spectrum.

Now I come to a discussion of the atmospheric neutrino anomaly. When cosmic-ray particles enter the atmosphere, they interact with the N and O nuclei to produce π mesons and K mesons. These mesons decay in tenuous air into μ and ν_μ, so you get one muon and one ν_μ there. If the secondary μ also decays into e then you get additional ν_μ and ν_e. If everything proceeded this way, you would have two ν_μ's against one ν_e. The number ratio, $N(\nu_\mu)/N(\nu_e)$, is thus 2. When you go to higher energy, muons of longer lifetime than a π meson cannot decay. Indeed, some μ's do reach our detector, as you have seen before. In this case, you do not get additional ν_μ or ν_e. So at high energies, this ratio becomes larger than 2. In Fig. 10 are shown the above number ratio observed by KamiokaNDE together with the results of other experiments.

Let us turn now to the discussion of neutrino oscillations (Maki *et al.*, 1962). This may be the most difficult part of my talk. I will try to make it understandable to the first-year undergraduate student. For the sake of simplicity, let us say there are only two kinds of neutrinos in nature. Then, for instance, the wave function describing the state of a neutrino can be described by a linear combination of two independent base functions. For instance, you can take the mass matrix to be diagonal and then choose the two basic vectors of mass m_1 and mass m_2, respectively. So any neutrino state can be described by a combination of Ψ_{m1} and Ψ_{m2}. $\Psi_{\nu\mu} = \cos\phi\Psi_{m1} + \sin\phi\Psi_{m2}$. This is like two-dimensional geometry, where a vector can be described by its x and y components. So the ν_μ state is a linear combination of an m_1 state and an m_2 state with an angle parameter ϕ. The two states, Ψ_{m1} and Ψ_m, oscillate with their characteristic frequencies. This frequency is proportional to the total energy of the state. If the mass m is small, then for a given momentum one can make the following approximation. Namely, $E \sim p + m^2/2p$. E_1 minus E_2, which is proportional to the frequency difference of these two states, is then, using this approximation, proportional to $(m_1^2 - m_2^2)$. This m-square difference between the two states is designated by Δm^2. When two oscillations of nearly equal frequencies coexist, there occurs a phenomenon known as a "beat," in which the amplitudes of the two oscillations change slowly with the difference frequency. This change of the component amplitudes, Ψ_{m1} and $\Psi_{m\_}$, induces the appearance of a ν_τ state in the original pure ν_μ state.

By using these two parameters, Δm^2 and ϕ, you can describe the oscillation of neutrinos from one type to the other. In Fig. 11 is shown the result obtained by KamiokaNDE (Hatakeyama *et al.*, 1998), on the atmospheric neutrino oscillation.

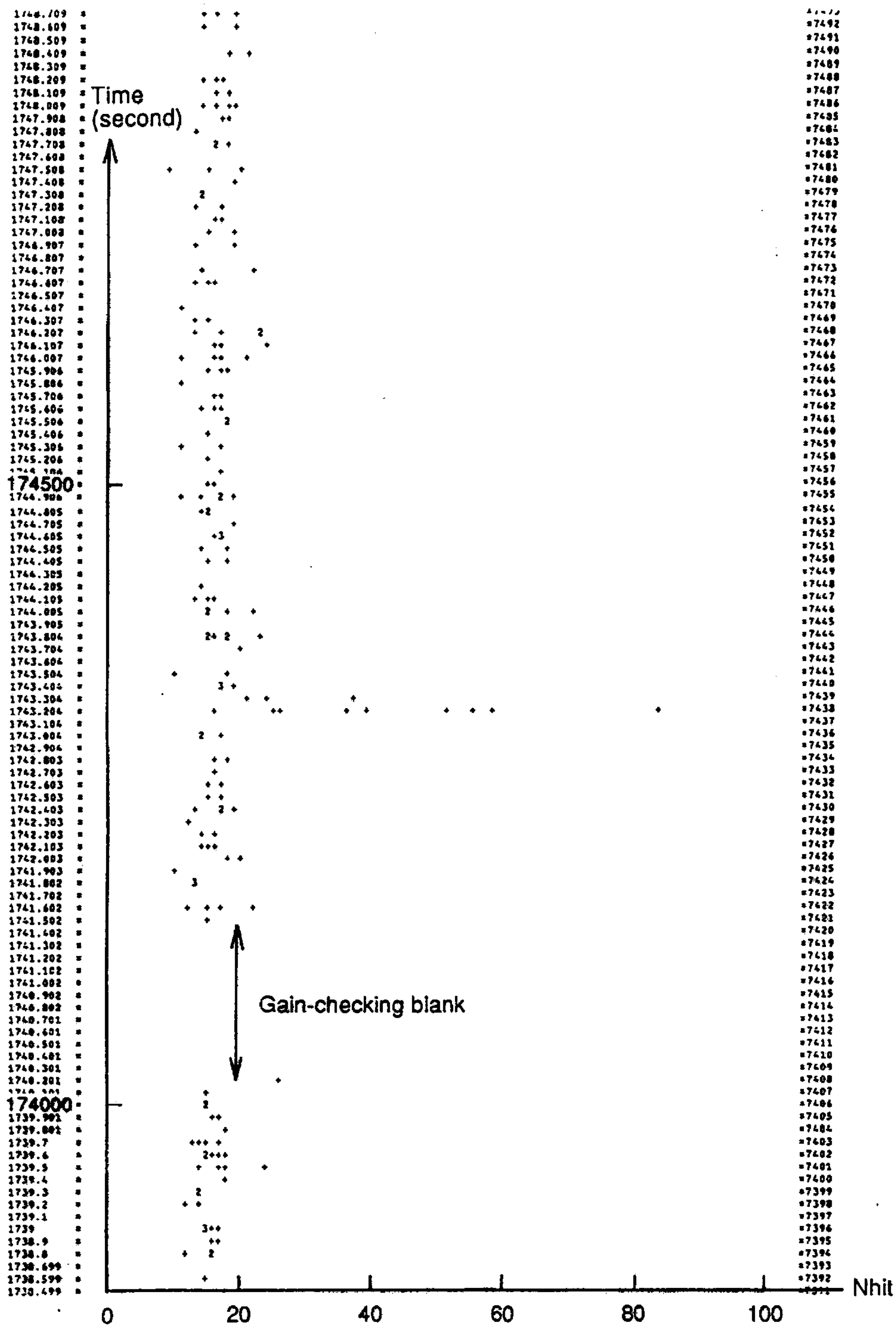

FIG. 9. The SN1987A neutrino "signal" in the computer printout.

We now proceed to the discussion of Super-KamiokaNDE.

The Super-KamiokaNDE facility has so far produced three significant results.

The first is the astrophysical observation of the solar neutrinos with comfortable statistics. In Fig. 12 you can see the peak of neutrinos in the direction from the sun to the earth above the isotropic background. When you break a bone in your hand you go to the doctor and get an x-ray picture taken. You then can see inside of your hand to determine whether the bone is broken. When you use neutrinos, with a much larger penetrability, you can see inside of the sun. In Fig. 13 is shown the first neutrinograph, rather than photograph, of the sun. Below is the orbit of the sun in the galactic coordinates as seen by the neutrinos.

This sounds very nice, but if you look at this neutrinograph carefully, you find the size of sun is much bigger than the size of sun you see with your own eyes. The reason is, of course, that the directional accuracy of a neutrino observation is much worse than that of visible light. But you have to be patient. Neutrino astrophysics has only just been born. It is still in its infantile stage.

Figure 14 shows the observation of the solar neutrino energy spectrum as compared to the theoretically expected spectrum from the Solar Standard Model. De-

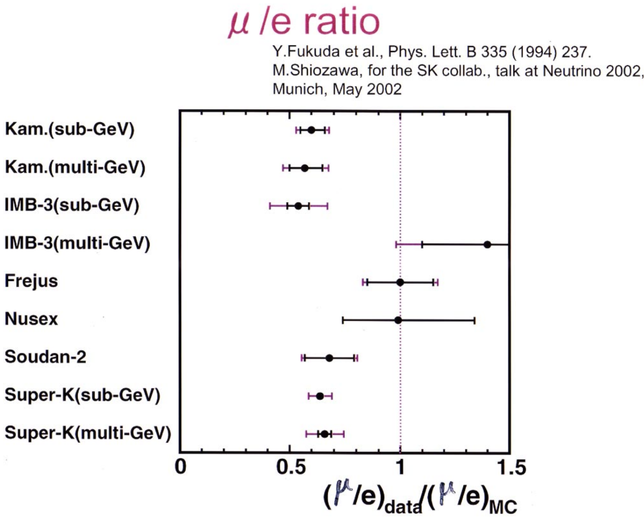

FIG. 10. The number ratio $N(\nu_\mu)/N(\nu_e)$.

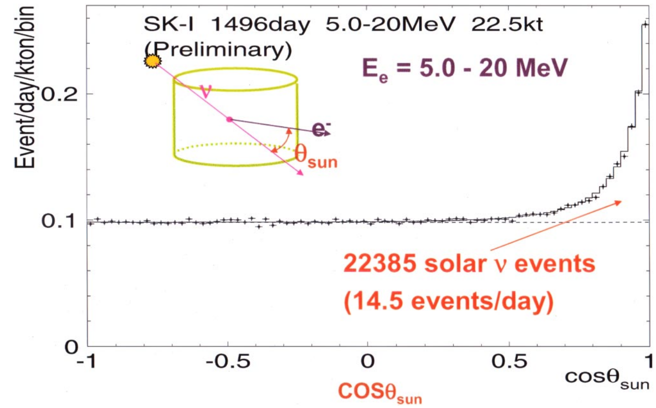

FIG. 12. (Color in online edition) Directional observation.

tailed comparison of these two energy spectra gives us better information on solar neutrino oscillation.

If the observed anomaly in the $N(\nu_\mu)/N(\nu_e)$ is indeed due to neutrino oscillation, then the degree of oscillation would be different depending on the path lengths the neutrino had to traverse from its generation to our detector. When it comes from vertically above, the distance is only 20 kms. When it comes horizontally, it has traveled some 1000 km. If it comes from the bottom, it was produced 13 000 km away. There is a big difference in the path lengths.

One sees in Fig. 15 that in the case of e events, due to ν_e, there is no deviation from the expectation of no oscillation. Only in the case of μ events, due to ν_μ, does one see a large reduction from the bottom up. Figure 16 shows six allowed regions for solar neutrino oscillation (two are very small) and one region—in the upper right corner—for atmospheric neutrino oscillation, in red in the online version, as determined by the data of Super-KamiokaNDE (S. Fukuda *et al.*, 2002).

With the oscillation data described above, from KamiokaNDE and Super-KamiokaNDE, we go on to combine them with other available data. The next figure, Fig. 17, shows only one possible oscillation region for solar neutrino oscillation. This was accomplished by combining all the solar neutrino experiments—Super-KamiokaNDE, SNO, and other radio-chemical results

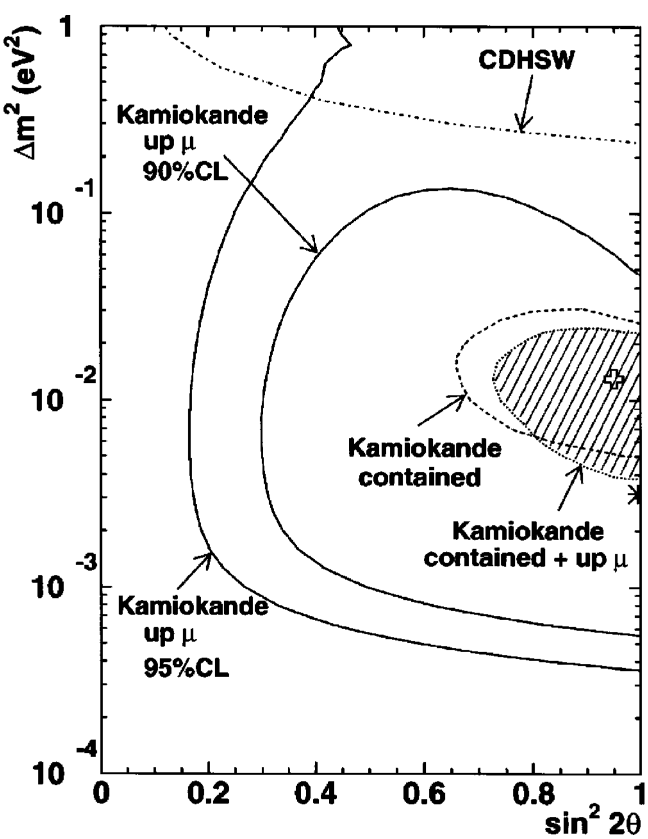

FIG. 11. The allowed parameter region.

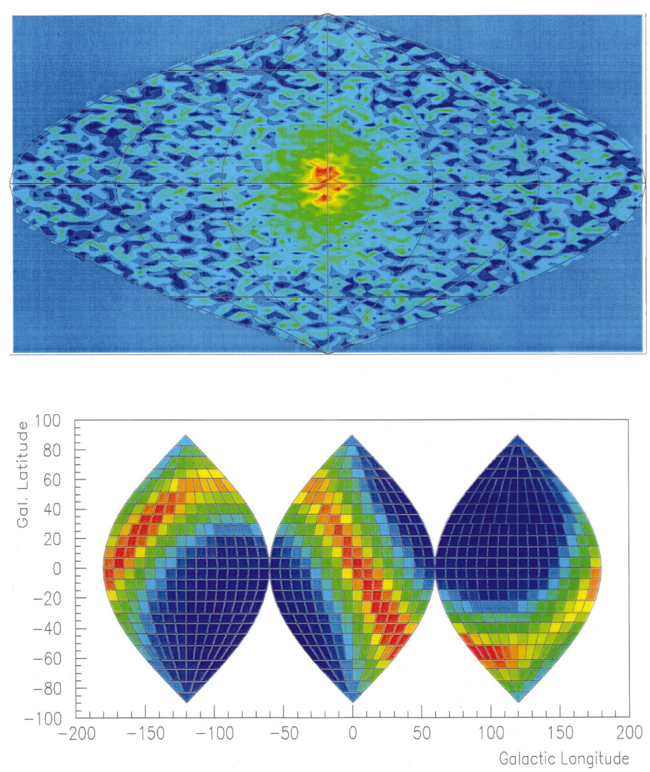

FIG. 13. (Color) Neutrinograph of the sun.

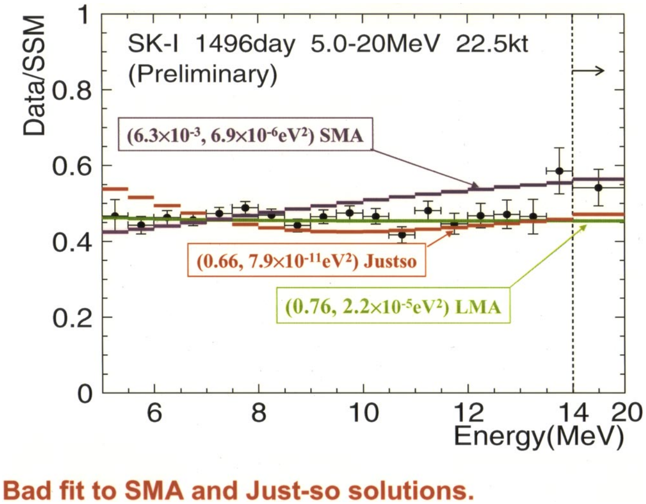

FIG. 14. (Color in online edition) The energy spectrum.

(Cleveland *et al.*, 1998; Hampel *et al.*, 1999; Altmann *et al.*, 2000; Abdurashitov *et al.*, 2002).

Now that the observed Δm^2's are definitely not zero we have to admit some nonzero masses for neutrinos. This implies that the Standard Theory of elementary particles has to be modified. For the sake of giving proper credit, I include the whole author list of the article on supernova neutrino detection (Hirata *et al.*, 1987) and that of the atmospheric neutrino paper (Y. Fukuda *et al.*, 1998).

Lastly I show you the latest result from Kamioka. In Kamioka, there is a third-generation experiment now underway. This KamLAND experiment is installed in the old cave of the original KamiokaNDE and uses a liquid scintillator to measure the anti-ν_e's from the reactors about 200 km away. The authors of the experiment published their first result (Eguchi *et al.*, 2003) recently and I got this by email. The experiment is measuring the

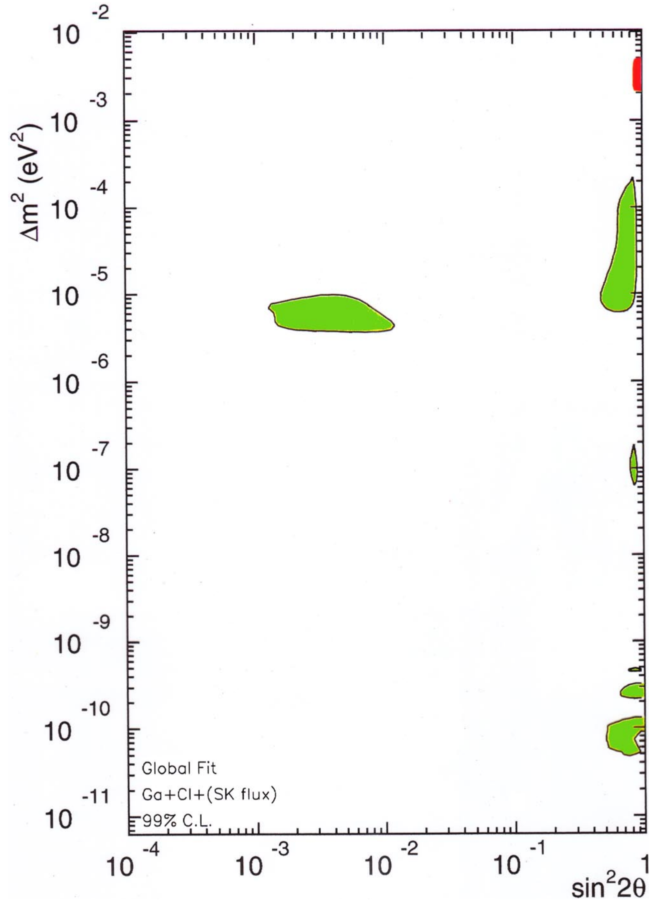

FIG. 16. (Color in online edition) The allowed regions of oscillations.

antineutrino flux as well as the energy spectrum. The result is shown in Fig. 18. The obtained oscillation parameters, $\sin 2\phi = 0.833$ and $\Delta m^2 = 5.5 \times 10^{-5}\,(\mathrm{eV})^2$, are in good agreement with the solar neutrino result of Fig. 17.

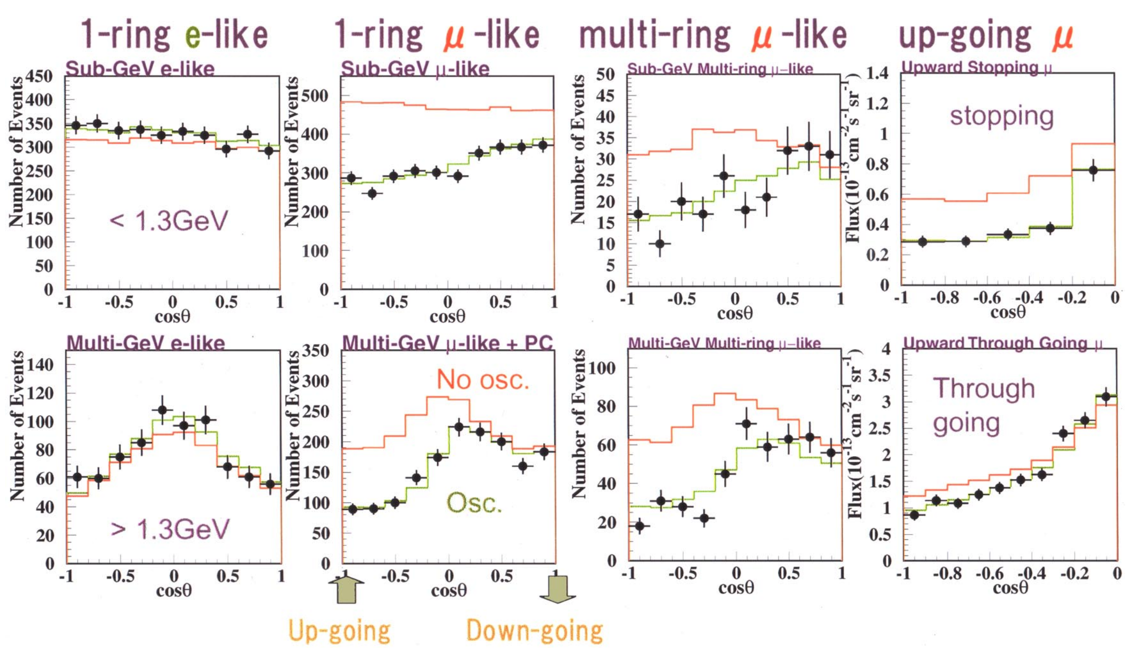

FIG. 15. (Color in online edition) The change of oscillation as a function of path length.

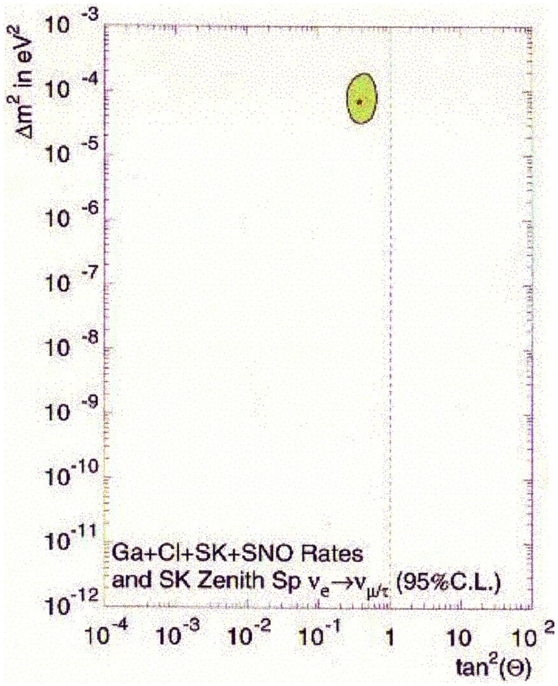

FIG. 17. (Color in online edition) The allowed region for solar neutrino oscillation.

Since this is a confirmation of neutrino oscillation not for the electron neutrino but for the antielectron neutrino, the fact that it is giving the same oscillation parameters implies that the *CPT* theorem is not violated. Further data accumulation may lead to some interesting insight into the *CP* problem within the framework of *CPT* invariance (Eguchi *et al.*, 2003). The interesting thing is that about two-thirds of the collaborators are from the United States. Some say Kamioka is now considered the Mecca for neutrino research, and this pleases me very much.

Now that neutrino astrophysics is born, what should we do next? Of course the plan depends on whom you ask. There is a move to build a megaton Hyper-KamiokaNDE. A world network of at least three Super-KamiokaNDEs may be a good choice for supernova watching. The most challenging problem will be the observation of the cosmic neutrino background of 1.9 K, which would tell us the state of our universe one second after its birth. The nonzero masses of neutrinos imply total reflection at the low temperatures of low-energy neutrinos. This is a wonderful gift providing the possibility of a parabolic mirror for focusing the cosmic neutrino background. The detection however, of such low-energy neutrinos is really a formidable task.

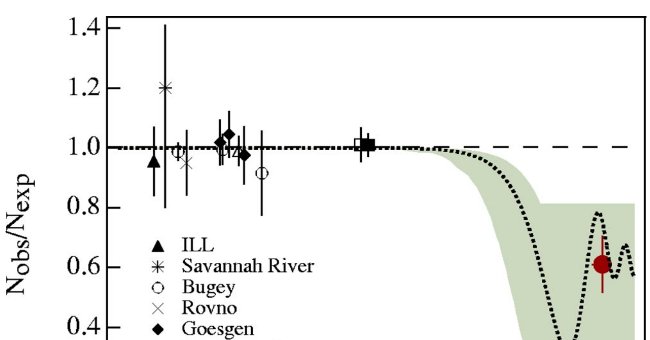

FIG. 18. (Color in online edition) Results from KamLAND.

ACKNOWLEDGMENTS

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