日本の物理

OBSERVATIONAL NEUTRINO ASTROPHYSICS

Pioneering measurements of the solar neutrino flux and detailed observations of the neutrino burst from SN1987a and of solar boron-8 neutrinos have signaled the birth of observational neutrino astrophysics.

Masa-Toshi Koshiba

Neutrinos have been an important feature of theories of stellar processes for many decades. As a star forms from interstellar matter, its temperature gradually increases because of its gravitational contraction. However, this thermal energy is not sufficient to make it shine for long. We believe that the primary energy source of the Sun, and of stars in general, is a series of nuclear fusion reactions, occurring deep inside the star, in which energy is released as four protons are converted into a helium nucleus. In the process, two protons are converted into neutrons by each emitting a positron and an electron neutrino. Thus a star must emit electron neutrinos constantly.

As a star continues to generate energy in this way, it accumulates helium ashes in its inner region that eventually become hot enough through gravitational contraction to burn into carbon: Three helium nuclei fuse into a carbon nucleus by emitting gamma rays. As the star evolves further, the carbon ashes burn into heavier nuclei, thereby producing more energy. The process goes on until iron ashes accumulate in the core. The fusion reactions cannot continue further because the iron nucleus has the largest binding energy per nucleon; that is, reactions to produce heavier nuclei are endothermic. At this point, if the mass of the star is small and the mass of its iron core is less than 1.4 solar masses (the Chandrasekhar mass limit), the star is in its last years of life—it has become a white dwarf, supported against gravitational collapse by the pressure of the degenerate electron gas that surrounds the iron nuclei. If the star mass is large and the iron core mass reaches or surpasses the Chandrasekhar limit, the pressure due to the degenerate electrons cannot hold the iron ash in its shape, and the core collapses by its own gravitational force. The electrons are forced into iron nuclei, converting protons into neutrons by the emission of electron neutrinos. The result is a supernova explosion and the formation of a neutron star. (See the article by Adam Burrows in PHYSICS TODAY, September, page 28.)

As our nearest star, the Sun has been the subject of detailed theoretical studies based on optical observation data. The so-called standard solar model predicts, among other things, the solar neutrino flux corresponding to the various hydrogen-burning processes in the Sun. In his pioneering experimental work, Raymond Davis (Brookhaven National Laboratory) has monitored the solar neutrino flux for almost two decades—by measuring the number of argon atoms produced from chlorine in an underground C_2Cl_4 detector as a result of bombardment with high-energy solar neutrinos. His data have revealed that the observed neutrino flux is only one-third that predicted by the standard solar model. It is disconcerting to encounter such a discrepancy for the only stellar source we can study "up close," and a number of explanations for it have been proposed—for instance, the core temperature or helium content may be lower than predicted, or the emitted neutrinos may change to muon neutrinos as they pass through the Sun (the Mikeyev–Smirnov–Wolfenstein effect; see PHYSICS TODAY, June 1986, page 17). A definite conclusion has not yet been reached, and the possibility of a lower temperature or helium abundance in the solar core is now being extensively investigated by helioseismology.

Neutrino astronomy

The recent observation—by the Kamiokande II collaboration in Japan[1] and the Irvine–Michigan–Brookhaven collaboration in the United States[2]—of a neutrino burst from supernova 1987a in the Large Magellanic Cloud has opened up a new era in observational neutrino astrophysics. (See David Helfand's article in PHYSICS TODAY, August, page 24.) The two experiments, IMB and Kamiokande, were conceived at the end of 1978 to search for proton decay, based on the prediction from grand unified theories that the lifetime of the proton should be about 10^{29} years. Unlike the other nucleon decay experiments performed to date, IMB and Kamiokande detect particles by looking for Čerenkov radiation in a large tank of water. Both experiments have been running continuously for several years, except for some months spent in upgrading. IMB has the larger water mass, 7000 tons. The IMB group played a major role in discounting the original SU(5) theory by placing a lower limit well above 10^{32} years on the

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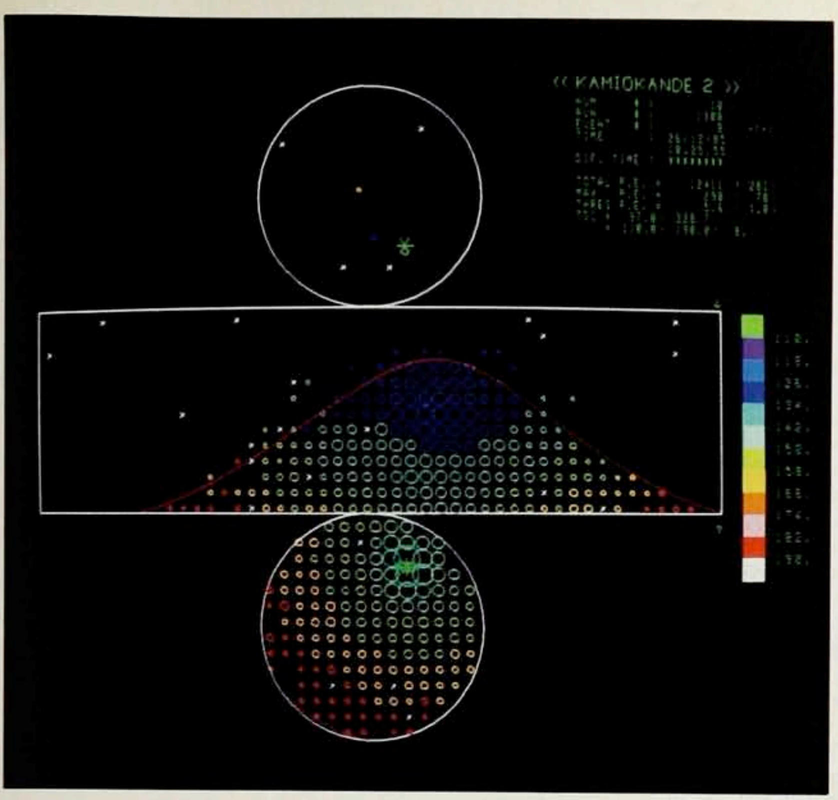


Čerenkov ring produced by a muon passing through the Kamioka detector. The cylindrical detector is slit along a vertical seam and unrolled to make the rectangular area; the detector's top and bottom surfaces are also shown. Each small circle is an excited photomultiplier tube. The color code indicates the time at which the tubes were struck by the incident Čerenkov radiation.

partial lifetime for one of the most probable proton decay modes, $p \to e^+ + \pi^0$.

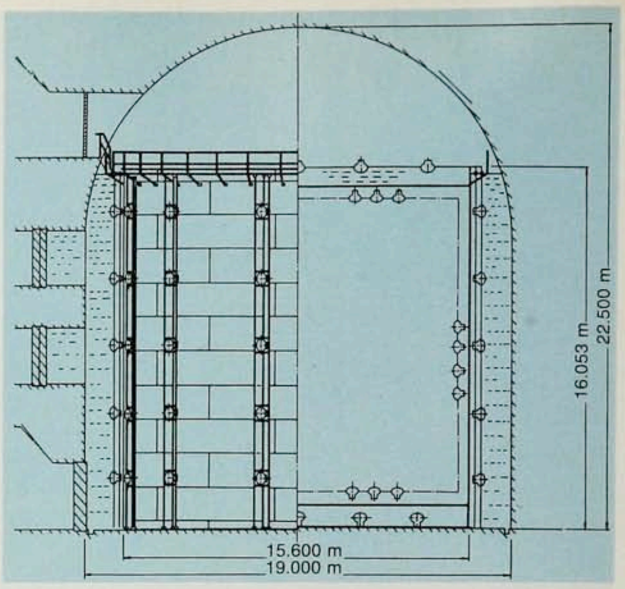
The Kamiokande detector, shown in figure 1, has a water mass of 3000 tons, but achieves better resolution than IMB's. The Kamiokande results have pushed up the lower limit on the partial lifetime for the decay $p \to \nu + K^+$, among others, thereby making the supersymmetric mass scale larger than was previously thought. As in IMB, the water is surrounded by a set of photomultipliers. An electrically charged particle moving faster than $^3\!/_4 c$ produces Čerenkov light in water; the observation of this light pattern gives the vertex of the Čerenkov light cone, and the direction of motion and the energy of the particle. If we at Kamiokande can collect a sufficient number of photons, we can identify the particle in most cases. For instance, the annular distribution of Čerenkov photons tells us whether it is due to a showering particle ($e^\pm$, γ) or a non-showering particle (μ, π). Our aim was not only to search for the existence of proton decays but also to determine the branching ratios into all the possible decay modes. To facilitate this achievement within our rather limited funding, we spent a little more than a year developing very large photomultipliers—50 cm in diameter—in collaboration with a Japanese firm, Hamamatsu Photonics. The detector was installed 1000 meters underground in a newly excavated cave of the Kamioka Mine, about 300 km west of Tokyo.

When we began taking data on 4 July 1983, we immediately realized that the energy spectrum of μ–e decay electrons can be observed down to about 12 MeV, where the background sets in. This implied that it was possible to make real-time, directional and spectral observations of solar boron-8 neutrinos having energies up to 14.06 MeV by detecting their elastic scattering off the electrons in water—if the background could be sufficiently reduced to bring the detection threshold down to several MeV. We announced this possibility at the 1984 international conference on baryon nonconservation, which was held in Park City, Utah. Alfred K. Mann (University of Pennsylvania) showed keen interest in our work, and we decided to form an international collaboration, Kamiokande II, to demonstrate the feasibility of the experiment. The American team was to provide the new electronics, ADC + TDC with multihit capability, to reduce the dead time of the detector practically to zero. The Japanese team was to provide an additional anticounter, a 1.4-m or more layer of water completely surrounding the inner detector. The anticounter not only verifies that the event is indeed confined, but also works as an absorber of environmental soft radiation. Both sides kept to the agreement, and Kamiokande II began operation in January 1986. The detector performed as expected, and the trigger rate for low-energy events dropped drastically compared with the early-1985 run. At the beginning of 1987, the trigger rate at a threshold of 7.5 MeV was 0.6 Hz, of which 0.36 Hz was due to cosmic ray muons. So the detector was ready to receive a neutrino burst from a supernova explosion at any time. The supernova neutrinos are expected to have considerably higher energy than the solar neutrinos and also to be bunched in a short time interval. These two factors make the detection of supernova neutrinos much easier than that of solar neutrinos.

The neutrino burst from supernova 1987a, shown in figure 2, was detected via the Čerenkov light from positrons created in the reaction $\bar{\nu}_e + p \to n + e^+$; the conclusion that electron antineutrinos were involved was based on the near isotropy of the event directions. We estimated the event energy from the number of photomultipliers hit, and the zero time of the burst from the more accurate clock of the IMB experiment—assuming that the IMB burst (open circles in figure 2) corresponds tentatively to the second, high-energy subcluster of the Kamiokande burst (filled circles). At the time of detection, IMB had a fiducial mass of 5000 tons, while Kamiokande II had a fiducial mass of 2140 tons.

It should be noted that the Kamiokande II data of figure 2 are essentially the raw data as printed out by a laser printer, and hence if the computer had been at the site, it could have given an advance warning of the supernova explosion before the optical sighting.

The observed time structure, flux and average energy of the neutrinos from SN1987a confirmed decisively the predictions of theoretical neutrino astrophysics. In particular, the data verified that electron antineutrinos, presumably together with neutrinos and antineutrinos of other flavors, are produced in the hot plasma by neutral-current processes, and that the gravitational potential energy of the iron core (with a mass of about 1.4 solar masses) was released in the form of a neutrino burst. The temperature, as estimated from the observed average event energy, is in good agreement with the theoretical expectation. The time lapse between the neutrino burst and the optical luminosity growth is also in line with the theoretical estimate for the blue giant progenitor star. The data have not only supplied the astrophysical results; they have also elicited scores of theoretical papers in particle physics: on the mass, the electric charge, the lifetime, the magnetic moment and the possible flavor oscillations of the neutrino.



Kamiokande II detector is lined along its inner surface with 50-cm-diameter photomultipliers, at a density of one tube per square meter. It is surrounded by a 4π anticounter, which has a water thickness of at least 1.4 m and a coarser array of photomultipliers. The detector, in its present configuration, has been observing solar boron-8 neutrinos since January 1986. **Figure 1**

Solar neutrinos

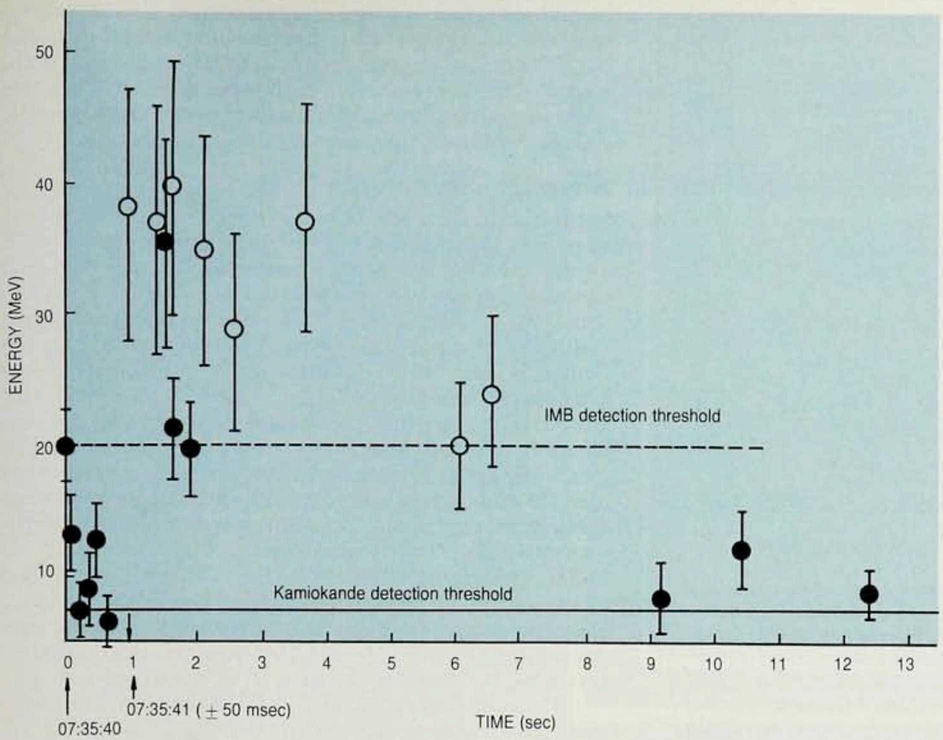
Furthermore, Kamiokande II produced the first real-time, directional and spectral observations of solar neutrinos.[3] Figure 3 shows data on solar neutrinos presented at the international symposium on high-energy lepton and photon interactions held in Hamburg in July. The integral energy spectrum of recoil electrons produced in water by neutrinos coming from the direction of the Sun is shown after subtraction of the background counts, based on 127.8 live days of data taken this year.

Minimizing background radiation is the most difficult part of carrying out this kind of observation. There are three major sources of background radiation. First, the rocks surrounding the detector emit low-energy radiation—gamma rays and neutrons. Even after we completely encased the experiment with an anticounter water layer 1.5 meters thick, we still had to restrict the fiducial volume to the innermost 680 m^3, where the volume distribution of low-energy events was statistically checked to be uniform. Second, the detector water itself contains radioactive trace elements, such as uranium and radium. We have installed special ion-exchange columns to remove these elements. Radon in air also caused considerable trouble, and we had to make the entire inner circulating water system airtight. At the same time, we kept the water in this system very transparent by circulating it through a series of fine filters and an ultraviolet irradiator; we achieved a light attenuation length of 50 m. Third, the nuclear interaction of muons with the oxygen nuclei in the water sometimes results in a variety of long-lived (milliseconds to seconds) radioactive nuclear fragments. We eliminated this type of background in our off-line analysis by noting the temporal, as well as spatial, correlations with the preceding muon event.

Even after these background eliminations, our overall signal-to-noise ratio was still about 1:10, and it was only after making use of the directional correlation with respect to the Sun that we can hope to extract the solar neutrino signal; our present signal-to-noise ratio around the Sun–Earth direction is 2:1 for the signal expected from the standard solar model. The result shown in figure 3 was obtained in this way; namely, the raw data for the low-energy contained events were checked if they were within the fiducial volume (about $\frac{1}{10}$ reduction), if they were not associated with the preceding muon interaction (about $\frac{1}{5}$ reduction) and if they were due to neutrinos from the direction of the Sun (about $\frac{1}{20}$ reduction).

Figure 3 also demonstrates that the bare standard solar model is negated at a 90% confidence level, confirming Davis's result. This means either that the resonance flavor flipping of finite-mass neutrinos in matter is actually taking place, or that the lowering of the temperature or helium abundance in the solar core is responsible. The situation will be clarified in about a year's time, when Kamiokande II produces quantitative solar neutrino results to be analyzed jointly with the helioseismological data.

The experimental results of Davis and of the IMB and Kamiokande groups may signal the birth of observational neutrino astrophysics, but the field is still very much in its infancy. We do not yet really have any direct knowledge about the interior of the Sun, and it is very encouraging that a variety of experiments throughout the world are being prepared or planned with the aim of looking into the solar core by observing neutrinos. These are the Italian project at the Gran Sasso Underground Laboratory, which includes Icarus (a large liquid argon drift chamber), LVD (a large liquid scintillator), and GALLEX (a gallium–germanium experiment); the joint Canadian–United States plan for a Kamiokande-type experiment using D_2O



Neutrino burst from supernova 1987a in the Large Magellanic Cloud, as observed by Kamiokande II in Japan (filled circles) and by IMB in the United States (open circles). The zero time was adjusted to make the IMB burst coincide with the second subcluster of the Kamiokande II burst. **Figure 2**

instead of H_2O in the Sudbury Mine; and a gallium–germanium experiment at Baksan, USSR. The groups will look at neutrinos of different energies using different physical processes, and their work should be considered complementary.

The advantages of using Čerenkov radiation in water for neutrino detection lie in the capability for real-time, directional and spectral observation of electron neutrinos by means of their elastic scattering off electrons in the water, and for real-time and spectral observation of electron antineutrinos, as exemplified in figure 2. Neutrinos of other flavors can also be detected through their interactions with electrons in the water, albeit with smaller cross sections.

Furthermore, the Čerenkov method is at present the only way, both technically and economically, to realize the next-generation detectors of much larger mass, say tens of thousands of tons. This, of course, is keenly desired if we are to arrive at a quantitative understanding of the solar interior or supernova explosions.

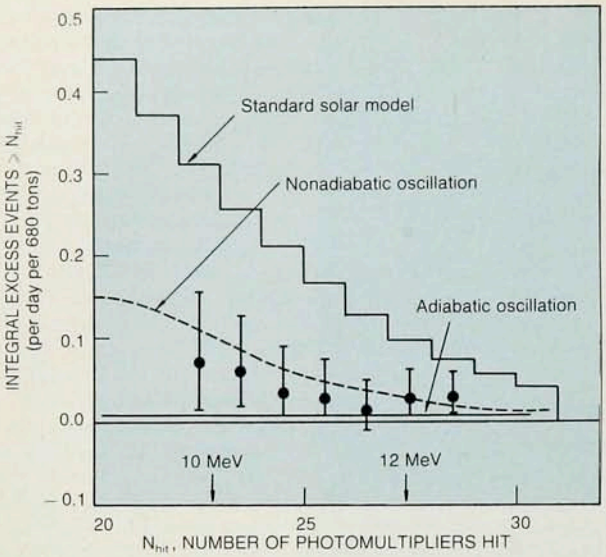
A super-Kamiokande plan was first announced at the ICOBAN '84 meeting.[4] It would scale up Kamiokande II by a linear factor of 2.5, as well as double the photomultiplier density on the surface. With a total of 32 000 tons of water, this detector not only will serve as a thermometer for registering the variation of the solar core temperature to better than 1% accuracy over a week, but also will give about 4000 events for a supernova explosion occurring in the center of the Galaxy, which is not accessible to optical observation because of the large amount of intervening matter.

These 4000 events could certainly provide us with detailed information on the dynamics of the gravitational collapse of a star (about 200 events in the first few milliseconds due to electron neutrinos from the initial neutronization would also yield directional information, with 2° accuracy), changes in the neutrino energy spectrum with time, and so forth. For better directionality data, we should have a network of such detectors—not only Čerenkov-type detectors, but also liquid scintillator and liquid argon instruments. A 10-microsecond timing accuracy for a worldwide network would yield a minute-of-arc directional accuracy. Such detectors could also explore proton decay if the lifetime is on the order of 10^{34} years.

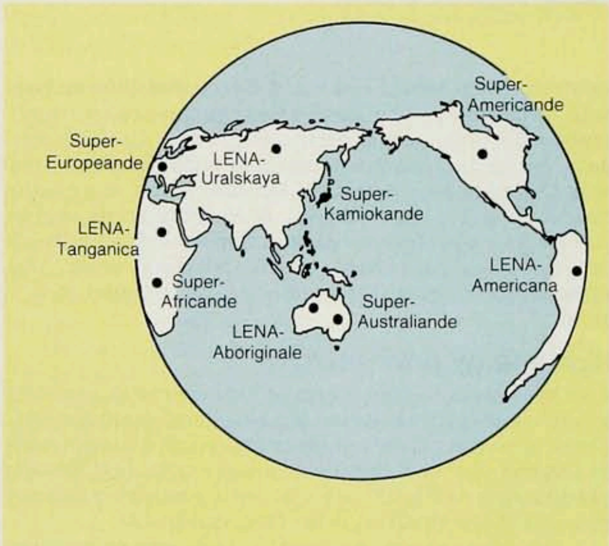
High-energy point sources

Another very interesting type of experiment in neutrino astrophysics is the detection of high-energy point sources. There have been claims of observing point sources—such as Cygnus X-3 and the Vela pulsar—with high-energy gamma rays (10^{12}–10^{15} eV) or with neutrino-produced muons, but the situation is far from conclusive.

The physical process used in high-energy neutrino astronomy is the charged-current interaction of neutrinos with nucleons. The leptons produced in the interaction—muons and electrons—give the direction of the incident neutrino. The success of such an experiment depends on the size of the sensitive area and the angular resolution attained. One would need a sensitive area of at least 10^4 m^2 and an angular resolution better than 1°. The Lake Experiment on Neutrino Astronomy was proposed along these lines.[5] It is a two-dimensional expansion of the super-Kamiokande by a linear factor of 4. A water mass 150 meters in diameter and 30 meters deep would be surrounded by an array of 50-cm-diameter photomultipliers on a 5-m lattice. There is an outer layer on the top and sides of the $5\times5\times5$-m^3 Čerenkov modules, each of which contains one 50-cm-diameter photomultiplier. These outer photomultipliers serve as



Integral energy spectrum of recoil electrons from the elastic scattering of electron neutrinos by electrons in the Kamiokande II detector's water. The Kamiokande team expects to reach some conclusions about the existence of the Mikeyev–Smirnov–Wolfenstein effect in about a year; the predictions of that theory are also schematically shown in the figure. **Figure 3**



The author's dream—a world network of super-neutrino detection experiments and Lake Experiments on Neutrino Astronomy. **Figure 4**

anticounters and at the same time act as energy-flow detectors for γ-ray showers. Thanks to the directionality of the Čerenkov light, we do not have to install this gigantic detector deep underground—a part of a natural lake or a surface pit could be used to observe the upward-moving muons produced by neutrinos. About 4000 such muons per year, plus some electrons, could be expected for a 10^4-m^2 sensitive area, and the angular resolution would be about 0.8°.

Because this detector could differentiate between muon events and electron events, it would also be possible to study the Mikeyev–Smirnov–Wolfenstein effect in the Earth by using the cosmic ray neutrinos. The large inner volume (300 000 m^3) would make this detector 100 times more sensitive than existing experiments to heavy relic supersymmetric particles annihilating in the Sun.

A worldwide network

Let me describe a dream of mine for the future, which I have depicted in figure 4. It now seems clear that a world network of neutrino astronomical observatories with good timing accuracy, say 10 microseconds, is to be installed. Along with the super-Kamiokande and LENA, now being seriously considered in Japan, the observatories in the United States ("super-Americande"), in Europe ("super-Europeande") and in Australia ("super-Australiande") not only would serve as a real-time thermometer for the center of our Sun, with 1% accuracy daily, but could also give warnings of supernova explosions, with minute-of-arc directional information, to optical, radio or space stations throughout the world. In high-energy neutrino astronomy, the network of "LENA-Andes," "LENA-Uralskaya," "LENA-Aboriginale," "LENA-Tibet," "LENA-Africa" and so on would cover the entire sky continuously. This network could observe the high-energy gamma rays simultaneously with the high-energy neutrinos from an active stellar object at the time of its radio outburst.

The cost—about 40 million US dollars for the super-neutrino detection experiment and about 5 million US dollars for LENA—is, of course, very substantial, but in view of the endeavor's potential impact on particle physics, astronomy, space physics and nuclear physics, perhaps these neighboring disciplines could each contribute 1% of their total budgets. The project is ideally suited for a peaceful international collaboration, and as such could be an item to be considered in a summit conference of international leaders.

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