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# Neutrino Physics: an Update

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## Abstract

We update our recent didactic survey of neutrino physics, including new results from the Sudbury Neutrino Observatory and KamLAND experiments, and recent constraints from WMAP and other cosmological probes.

# 1 Introduction

Several years ago, we authored a paper in this journal entitled “Neutrino Physics,” hereafter called I[1], in order to encourage inclusion of material involving neutrinos into the introductory curriculum. We noted at the time that neutrinos, with new experiments about to provide first data, might continue to be a popular press item. This prediction has proven true:

- i) Ray Davis, the founder of the field of experimental solar neutrino physics, shared the 2002 Nobel Prize in physics with Mastoshi Koshiba, who led the Kamioka solar neutrino experiment, and Riccardo Giacconi [2].
- ii) Results from the Sudbury Neutrino Observatory (SNO) resolved the solar neutrino puzzle, showing that approximately two-thirds of these neutrinos oscillate into other flavors before reaching earth [3, 4].
- iii) The KamLAND experiment, in which antineutrinos from Japanese power reactors were detected, confirmed the SNO results and further narrow the allowed range of neutrino mass differences [5].
- iv) The Wilkinson Microwave Anisotropy Probe (WMAP) measured subtle temperature differences within the oldest light in the universe, from the epoch when atoms first formed 380,000 years after the Big Bang [6]. When combined with the results of large scale structure studies [7], a new bound on the sums of the neutrino masses is obtained.

In addition there has been published (and disputed) evidence for the existence of neutrinoless double beta decay which, if confirmed, would show that one of the standard model’s most important symmetries, the conservation of lepton number, is violated [8]. Thus we decided to bring our early paper up to date by explaining here the importance and implications of the new results.

In Section 2 we present a much abbreviated summary of the material presented in I. In Section 3 we discuss the SNO results and how they resolved the puzzling discrepancies Ray Davis first uncovered 30 years ago. In Section 4 we discuss KamLAND, the first terrestrial experimental to achieve the sensitivity to the small neutrino mass differences relevant to solar neutrino experiments. In Section 5 we describe marvelous new cosmological probes of large scale structure and of the time when atoms were first formed, and why the new data may soon challenge recent double beta decay claims. We

summarize where we stand in neutrino physics – including the new discoveries that may be soon be within reach – in Section 6.

## 2 The Two-Minute Review

In I we summarized the basics of neutrino physics, including neutrino history, properties, and implications for contemporary physics. For the purposes of the present work, we note that in the so-called standard model of particle/nuclear physics[9], which is consistent with nearly all present experimental information, there exist three massless neutrino types— $\nu_e, \nu_\mu, \nu_\tau$ —which are produced with purely left-handed helicity in weak interaction processes. If the neutrino were shown to have a nonvanishing mass, it would be the first clear failure of this 30-year-old standard model and the first proof of the existence of the “particle dark matter” that appears necessary to explain the structure and expansion of our universe. Nonzero neutrino masses were suggested by the results of experiments measuring the flux of solar neutrinos, which are produced as a byproduct of the thermonuclear reactions occurring in the high-temperature core of our sun [10]. Additional strong evidence comes from the study of atmospheric neutrinos, which are produced when high energy cosmic rays collide with the upper atmosphere, producing pions and other particles that then decay into neutrinos [11]. The largest of the various atmospheric neutrino experiments is SuperKamiokande, a detector in a mine in the Japanese alps that contains 50,000 tons of ultra-pure water. SuperKamiokande’s precise data show that the flux of muon-type atmospheric neutrinos arriving from the opposite side of the earth, which have travelled a long distance to reach the detector, is depleted.

Both the solar and atmospheric neutrino results can be explained quantitatively if neutrinos are massive and if the mass eigenstates are not coincident with the weak interaction eigenstates  $\nu_e, \nu_\mu, \nu_\tau$ , i.e., if the neutrinos produced in weak interactions are combinations of the various mass eigenstates. This is exactly what is known to occur in the analogous case of the quarks[9]. The relation between the neutrino mass and weak-interaction eigenstates is described by a unitary matrix: for three neutrinos, the mass and weak-interaction eigenstates can be viewed as two distinct 3D coordinate systems. The unitary matrix specifies the three rotations describing the orientation of one coordinate system relative to the other.

The reduced flux of atmospheric muon neutrinos (see Figure 1) is quan-

titatively explained by  $\nu_\mu \rightarrow \nu_\tau$  oscillations governed by maximal mixing,  $\theta_{23} \sim \pi/4$ : the relationship between the mass eigenstate  $\nu_2$  and  $\nu_3$  and the flavor eigenstates  $\nu_\mu$  and  $\nu_\tau$  involves a rotation of 45 degrees. The magnitude of the mass difference  $\delta m_{23} = m_3^2 - m_2^2$  between the two equal components making up the flavor eigenstates is  $\sim 2 \times 10^{-3} \text{ eV}^2$ . When I was written, the favored solution to the solar neutrino problem was also neutrino mixing, but was described by a much smaller mixing angle  $\theta_{12}$  specifying the relationship between mass eigenstates  $\nu_1$  and  $\nu_2$  and the flavor eigenstates  $\nu_e$  and  $\nu_\mu$ . The effects of this small mixing are magnified by matter effects in the sun. This is the so-called MSW effect and is described in I. But the results of the Sudbury Neutrino Observatory provided a bit of a surprise.

### 3 The SNO Experiment

Because both charged and neutral currents contribute to the reaction important to SuperKamiokande,

$$\nu_x + e^- \rightarrow \nu_x + e^-, \quad (1)$$

the experimentalists cannot easily distinguish  $\nu_e$ s from the  $\nu_\mu$ s and  $\nu_\tau$ s: the detector records both fluxes, though with a reduced sensitivity (0.15) for the heavy-flavor types. The reaction produces energetic recoil electrons which generate Cerenkov radiation that is recorded in an array of phototubes surrounding the detector. As the cross section is sharply forward peaked, the correlation with the position of the sun can be used to “cut” background contributions associated with cosmic rays and radioactivity in the rock walls surrounding the detector. Because the threshold for electron detection is  $\sim 6$  MeV, only the high energy portion of the  $^8\text{B}$  solar neutrino flux is measured. These are the same neutrinos that dominate the radiochemical measurements of Ray Davis: Superkamiokande confirmed that this flux was substantially below that predicted by the standard solar model (SSM)[12]

$$\phi_{SSM}(\nu_x) = 5.44 \times 10^6 \text{ cm}^{-2} \text{ sec}^{-1} \quad (2)$$

When the Davis and SuperKamiokande results were combined with those from the gallium experiments SAGE and GALLEX, the resulting three constraints on the three principal solar neutrino sources ( $^8\text{B}$ ,  $^7\text{Be}$ , and the low-energy pp fluxes) produced a surprising result. No combination of these

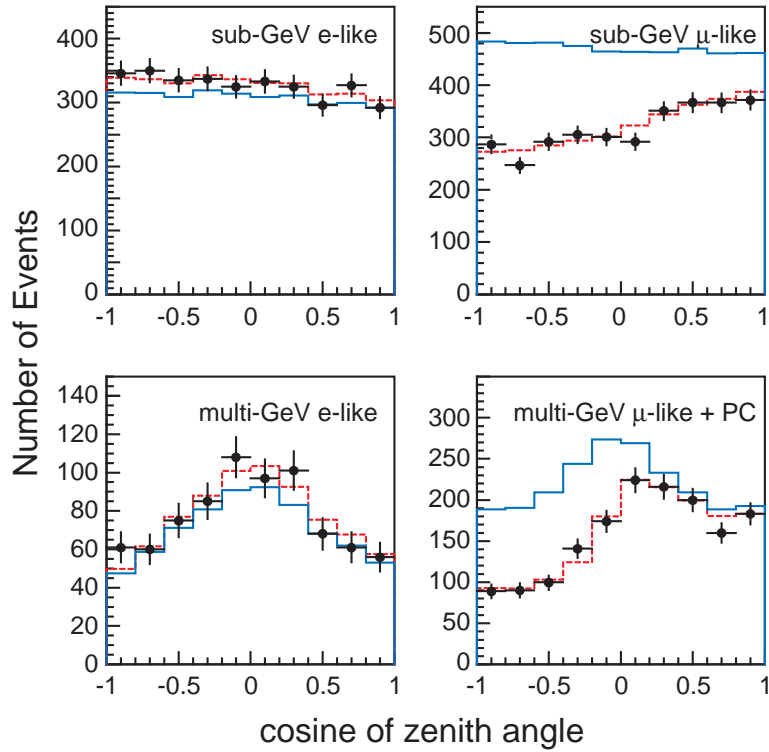


Figure 1: The SuperKamiokande atmospheric neutrino results showing excellent agreement between the predicted (blue lines) and observed electron-like events, but a sharp depletion in the muon-like events for neutrinos coming from below, through the earth. The results are fit very well by the assumption of  $\nu_\mu \rightarrow \nu_\tau$  oscillations with maximal mixing (red lines).

fluxes could reproduce the combined data well. Though circumstantial, this evidence indicated that the solution to the solar neutrino problem would not be found in the SSM, but instead would require new particle physics.

The favored explanation became neutrino oscillations which, as we have just summarized, occur for massive neutrinos when the weak and mass eigenstates do not coincide. The SuperKamiokande discrepancy, a solar neutrino rate less than half that expected from the SSM, would require that approximately two-thirds of the high energy electron neutrinos generated in the solar interior oscillate into other species –  $\nu_\mu, \nu_\tau$  – before reaching earth. Low-energy  $\nu_\mu$ s and  $\nu_\tau$ s are invisible to the Davis and SAGE/GALLEX detectors and scatter electrons in the SuperKamiokande detector with a reduced cross section, as we noted previously.

The key idea behind the Sudbury Neutrino Observatory (SNO) was construction of a detector that would have multiple detection channels, recording the  $\nu_e$ s by one reaction and the total flux of all neutrinos ( $\nu_e$ s +  $\nu_\mu$ s +  $\nu_\tau$ s) by another. This was accomplished by replacing the ordinary water in a water Cerenkov detector with heavy water – D<sub>2</sub>O instead of H<sub>2</sub>O. The charged-current (CC) channel that records the  $\nu_e$ s is analogous to the reaction used in the Davis detector



As the electron produced in this reaction carries off most of the neutrino energy, its detection in the SNO detector (by the Cerenkov light it generates) allows the experimentalists to determine the spectrum of solar  $\nu_e$ s, not just the flux. A second reaction, the neutral current (NC) breakup of deuterium, gives the total flux, independent of flavor (the  $\nu_e$ ,  $\nu_\mu$ , and  $\nu_\tau$  cross sections are identical),



The only signal for this reaction in a water Cerenkov detector is the neutron, which can be observed as it captures via the  $(n, \gamma)$  reaction. SNO is currently operating with salt added to the water, as Cl in the salt is an excellent  $(n, \gamma)$  target, producing about 8 MeV in  $\gamma$ s.

While the strategy may sound straightforward, producing such a detector was an enormous undertaking. The needed heavy water – worth about \$300M – was available through the Canadian government because of its CANDU reactor program. The single-neutron detection required for the neutral current reaction is possible only if backgrounds are extremely low. For this reason the detector had to be placed very deep underground, beneath approximately two

kilometers of rock, so that cosmic-ray muon backgrounds would be reduced to less than 1% of that found in the SuperKamiokande detector. The experimentalists found the needed site in an active nickel mine, the Sudbury mine in Ontario, Canada, where they worked with the miners to carve out a 10-story-high cavity on the mine's 6800-ft level. Trace quantities of radioactivity were another background concern: if a thimblefull of dust were introduced into the massive cavity during construction, the resulting neutrons from U and Th could cause the experiment to fail. Thus, despite the mining activities that continued around them, the experimentalists constructed their detector to the strictest cleanroom standards. The detector also provided a third detection channel, neutrino elastic scattering (ES) off electrons (Eq. (1)), which we have noted is sensitive to  $\nu_e$ s and, with reduced sensitivity,  $\nu_\mu$ s and  $\nu_\tau$ s.

The ES reaction, of course, provides SNO a direct cross check against SuperKamiokande. SNO's threshold for measuring these electrons is about 5 MeV. Assuming no oscillations, SNO's detection rate is equivalent to a  $\nu_e$  flux of

$$\phi_{SNO}^{ES} = 2.39 \pm 0.34(\text{stat}) \pm 0.15(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}, \quad (5)$$

a result in excellent accord with that from SuperKamiokande,

$$\phi_{SK}^{ES} = 2.32 \pm 0.03(\text{stat}) \pm 0.06(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}. \quad (6)$$

The greater accuracy of the SuperKamiokande result reflects the larger mass (50 kilotons) and longer running time of the Japanese experiment. (SNO contains, in addition to the one kiloton of heavy water in its central acrylic vessel, an additional seven kilotons of ordinary water that surrounds the central vessel, helping to shield it.)

The crucial new information provided by SNO comes from the two reactions on deuterium. The CC current channel is only sensitive to  $\nu_e$ s. Under the assumption of an undistorted  $^8\text{B}$  neutrino flux, SNO experimentalists deduced

$$\phi_{SNO}^{CC}(\nu_e) = 1.75 \pm 0.07(\text{stat}) \pm 0.12(\text{sys}) \pm 0.05(\text{theory}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}. \quad (7)$$

The CC flux is less than that deduced from the ES rate, indicating that  $\nu_\mu$ s and  $\nu_\tau$ s must be contributing to the later. From the difference between the SuperKamiokande ES and the SNO CC results

$$\delta\phi = 0.57 \pm 0.17 \times 10^6 \text{ cm}^{-2}\text{sec}^{-1} \quad (8)$$



and recalling that the  $\nu_\mu/\nu_\tau$  ES cross section is only 0.15 that for the  $\nu_e$ , one deduces the heavy-flavor contribution to the solar neutrino flux

$$\phi(\nu_\mu/\nu_\tau) = 3.69 \pm 1.13 \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}. \quad (9)$$

That is, approximately two-thirds of the solar neutrino flux is in these flavors.

While the first SNO analysis was done in the manner described above, a second publication gave the long awaited NC results. This allowed a direct and very accurate determination of the flavor content of solar neutrinos, without the need for combining results from two experiments. The published NC results were obtained without the addition of salt to the detector: the neutron was identified by the 6.25 MeV  $\gamma$  ray it produces by capturing on deuterium. The resulting total flux, independent of flavor, is

$$\phi_{SNO}^{NC}(\nu_x) = 5.09 \pm 0.44(\text{stat}) \pm 0.45(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1}. \quad (10)$$

Combining with the CC signal yields

$$\begin{aligned} \phi_{SNO}(\nu_e) &= 1.76 \pm 0.05(\text{stat}) \pm 0.09(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1} \\ \phi_{SNO}(\nu_\mu/\nu_\tau) &= 3.41 \pm 0.45(\text{stat}) \pm 0.46(\text{syst}) \times 10^6 \text{ cm}^{-2}\text{sec}^{-1} \end{aligned} \quad (11)$$

The presence of heavy-flavor solar neutrinos and thus neutrino oscillations is confirmed at the  $5.3\sigma$  level! Furthermore the total flux is in excellent agreement with the predictions of the SSM—Eq. 2, an important vindication of stellar evolution theory.

The SNO analysis is summarized in Figure 2, which shows the three bands corresponding to the CC, NC, and ES measurements coinciding in a single region. These results can now be combined with other solar neutrino measurements to determine the parameters – the mixing angle and mass-squared difference – governing the oscillations. At the time I was written, there were several contending solutions, though the data favored one characterized by a small mixing angle (thus called the SMA solution). Figure 3 shows that the SNO result has determined an oscillation solution that, at 99% confidence level, is unique – and as in the atmospheric neutrino case, it has a large mixing angle,  $\theta_{12} \sim 30$  degrees. This LMA oscillation is clearly distinct from that seen with atmospheric neutrinos, with  $\delta m_{12}^2 = m_2^2 - m_1^2$  centered on a region  $\sim 8 \times 10^{-5} \text{ eV}^2$ .

The discovery that the atmospheric and solar neutrino problems are both due to neutrino oscillations has provided the first evidence for physics beyond the standard model. That neutrinos provided this evidence is perhaps

not unexpected: if the standard model is viewed as an effective theory, one largely valid in our low-energy world but missing physics relevant to very high energies, beyond the reach of current accelerators, then a neutrino mass term is the lowest-order correction that can be added to that theory. But a surprise is the large mixing angles characterizing the neutrino oscillations – which contradicts the simple prejudice that neutrino mixing angles might be similar to the small angles familiar from quark mixing. Perhaps this simply reinforces something that should have been apparent at the outset: with their small masses and distinctive mixings, neutrinos likely have an underlying mechanism for mass generation that differs from that of the other standard model fermions.

## 4 The KamLAND Experiment

One remarkable aspect of the solar and atmospheric neutrino discoveries is that the derived oscillation parameters are within the reach of terrestrial experiments. This did not have to be the case – solar neutrinos are sensitive to neutrino mass differences as small as  $10^{-12}$  eV<sup>2</sup>, for which terrestrial experiments would be unthinkable.

The first terrestrial experiment to probe solar neutrino oscillation parameters, KamLAND, very recently reported first results. The acronym KamLAND stands for Kamioka Liquid scintillator Anti-Neutrino Detector. The inner detector consists of one kiloton of liquid scintillator contained in a spherical balloon, 13m in diameter. The balloon is suspended in the old Kamioka cavity (where SuperKamiokande’s predecessor was housed) by Kevlar ropes, with the region between the balloon and an 18m-diameter stainless steel containment vessel filled with additional scintillator (serving to shield the target from external radiation). Several Japanese power reactors are about 180 km from the Kamioka site, and the electron antineutrinos emitted by nuclear reactions in the cores of these reactors can be detected in KamLAND via the inverse beta decay reaction

$$\bar{\nu}_e + p \rightarrow e^+ + n, \tag{12}$$

where the  $e^+$  is seen in coincidence with the delayed 2.2 MeV  $\gamma$  ray produced by the capture of the accompanying neutron on a proton. This coincidence allows the experimentalists to distinguish  $\bar{\nu}_e$  reactions from background.

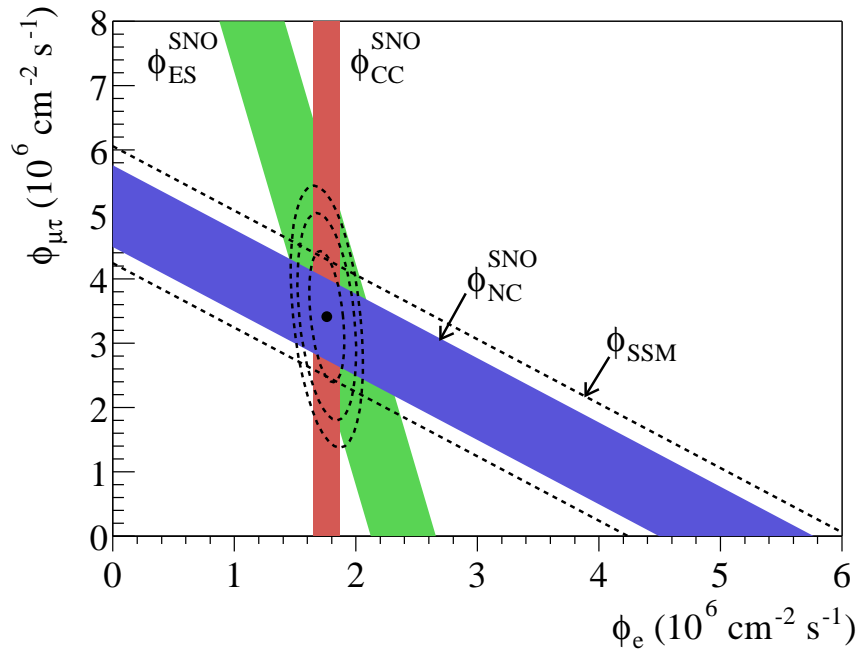


Figure 2: Flux of  ${}^8\text{B}$  solar neutrinos is divided into  $\nu_\mu/\nu_\tau$  and  $\nu_e$  flavors by the SNO analysis. The diagonal bands show the total  ${}^8\text{B}$  flux as predicted by the SSM (dashed lines) and that measured with the NC reaction in SNO (solid band). The widths of these bands represent the  $\pm 1\sigma$  errors. The bands intersect in a single region for  $\phi(\nu_e)$  and  $\phi(\nu_\mu/\nu_\tau)$ , indicating that the combined flux results are consistent with neutrino flavor transformation assuming no distortion in the  ${}^8\text{B}$  neutrino energy spectrum.

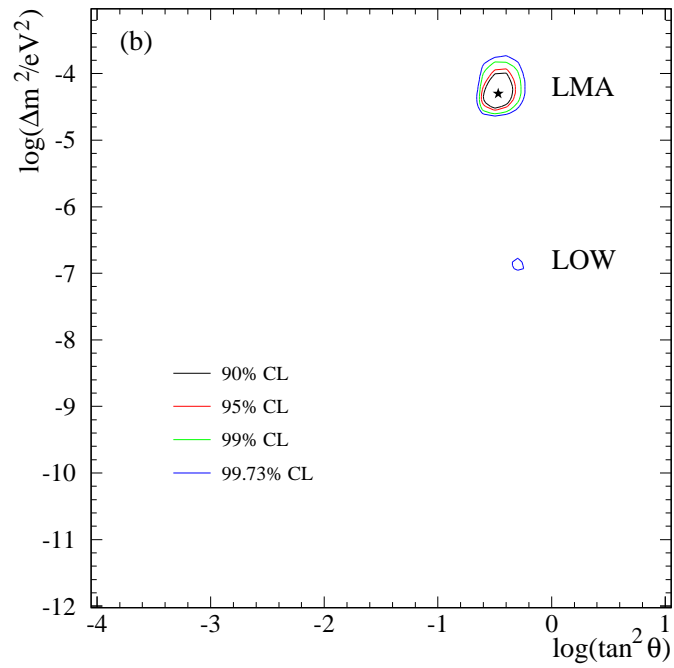


Figure 3: For two-flavor mixing, the values of the mass difference and mixing angle consistent with the world's data on solar neutrinos, post SNO. At 99% confidence level the addition of SNO data isolates a unique, large-mixing angle solution.

From the reactor operations records, which the power companies have made available, KamLAND experimentalists can calculate the resulting flux at Kamiokande to a precision of  $\sim 2\%$ , in the absence of oscillations. Thus, if a significant fraction of the reactor  $\bar{\nu}_e$ s oscillate into  $\bar{\nu}_\mu$ s or  $\bar{\nu}_\tau$ s before reaching the detector, a low rate of  $e^+$ /capture- $\gamma$ -ray coincidences will be evident: this is an example of the “disappearance” oscillation technique we described in I. For the 162 ton/yr exposure so far reported by the KamLAND collaboration, the number of events expected in the absence of oscillations is  $86.8 \pm 5.6$ . But the number measured is 54 – just 61% of the no-oscillation expectation. From the two-neutrino-flavors oscillation survival probability

$$P(\bar{\nu}_e \rightarrow \bar{\nu}_e) \simeq 1 - \sin^2 2\theta_{12} \sin^2 \frac{\delta m_{12}^2 L}{4E_\nu} \quad (13)$$

one obtains the oscillation parameters of Figure 4. KamLAND confirms the LMA solution and significantly narrows SNO’s allowed region (the red area in Figure 4). KamLAND has excellent sensitivity to  $\delta m_{12}^2$  but less sensitivity to  $\sin^2 2\theta_{12}$  (due to uncertainties in the shape of the reactor  $\bar{\nu}_e$  spectrum). The result is the separation of the SNO LMA allowed region into two parts, with the best-fit  $\delta m_{12}^2 \sim 7 \times 10^{-5} \text{ eV}^2$ , but with a larger mass difference  $\sim 1.5 \times 10^{-4} \text{ eV}^2$  also fitting well. KamLAND is an excellent example of complementary terrestrial and astrophysical measurements: solar neutrino experiments provide our best constraints on  $\theta_{12}$ , but KamLAND places the tightest bounds on  $\delta m_{12}^2$ .

## 5 WMAP, Double Beta Decay, and Neutrino Mass

Despite the wonderful recent discoveries in neutrino physics, there remain quite a number of open questions. Several have to do with the pattern of neutrino masses. All of the experiments described above probe mass *differences*, not absolute neutrino masses. Furthermore the atmospheric neutrino experiments only constrain the magnitude of  $\delta m_{23}^2$ , and not its sign. As a result, there exist several mass patterns fully consistent with all known data. One choice would assign  $m_3$  to be the heaviest neutrino, split by the atmospheric mass difference  $\delta m_{23}^2 \sim 2 \times 10^{-3} \text{ eV}^2$  from a lighter, nearly degenerate pair of neutrinos responsible for solar neutrino oscillations. (This pair is split

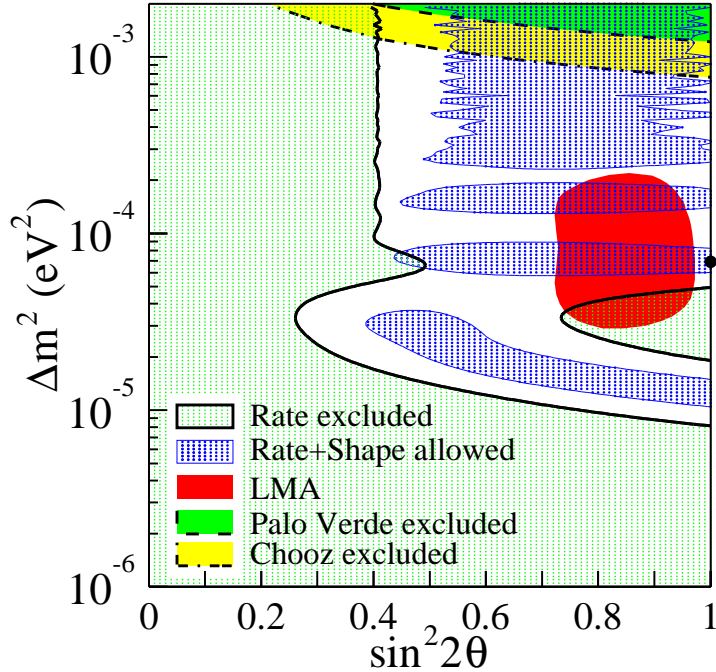


Figure 4: The 95% c.l. LMA allowed region of SNO and other solar neutrino experiments is shown in red. The regions marked “Rate and Shape allowed” show the 95% c.l. KamLAND allowed solutions. The thick dot indicates the best fit to the KamLAND data, corresponding to  $\sin^2 2\theta_{12} \sim 1.0$  and  $\delta m_{12}^2 \sim 6.9 \times 10^{-5} \text{ eV}^2$ .

by solar neutrino mass difference  $\delta m_{12}^2 \sim 10^{-5} \text{ eV}^2$ .) However, as the sign of  $\delta m_{23}^2$  is not known, it is also possible that  $m_3$  is the lightest neutrino, with the nearly degenerate  $m_1$  and  $m_2$  heavier. Finally, the best direct laboratory constraint on absolute neutrino masses comes from studies of tritium beta decay, as described in I. Studies of the tritium spectrum near its endpoint energy places a bound of 2.2 eV [13] on the  $\bar{\nu}_e$  mass (or more properly, on the principal mass eigenstate contributing to the  $\bar{\nu}_e$ ). Consequently, one can add an overall scale of up to 2.2 eV to the mass splittings described above. That is, no terrestrial measurement rules out three nearly degenerate neutrinos, each with a mass  $\sim 2.2 \text{ eV}$ , but split by requisite  $\delta m_{atmos}^2$  and  $\delta m_{solar}^2$ .

As discussed in I, the absolute neutrino mass is crucial in cosmology, as a sea of neutrinos produced in the Big Bang pervades all of space. If

these neutrinos carry a significant mass, they would constitute an important component of particle dark matter, invisibly affecting the structure and expansion of our universe. Light neutrinos, such as those we have been discussing, decouple from the rest of the matter as relativistic particles, about one second after the Big Bang. Their number density and temperature can be calculated at the time of decoupling and today. Their contribution to the universe’s mass-energy budget is now dominated by their masses,

$$\rho_\nu = 0.022\rho_{crit} \sum_i \frac{m_\nu(i)}{\text{eV}}, \quad (14)$$

where  $\rho_{crit}$  is the critical density that will just close the universe. A variety of cosmological probes suggest that our universe is very close to the critical density— $\rho/\rho_{crit} = 1.0 \pm 0.04$ .

From the discussion above, we know that at least one neutrino must have a mass of at least  $\sqrt{\delta m_{atmos}^2}$ . Similarly, the tritium beta decay limit places an upper bound on the sum of the masses of 6.6 eV (corresponding to three nearly degenerate neutrinos of mass 2.2 eV). It follows that the neutrino contribution to dark matter is bounded above and below

$$0.0012 \lesssim \rho_\nu/\rho_{crit} \lesssim 0.15. \quad (15)$$

This broad range implies that the amount of mass in neutrinos could easily exceed all the familiar baryon matter – stars, dust, gas clouds, and us – visible or invisible: big-bang nucleosynthesis and precision measurements of the cosmic microwave background (CMB) both indicate that  $\rho_{baryons}/\rho_{crit} \sim 0.042$ .

However, in the past few years a series of extraordinarily precise measurements have been made in cosmology. One of these is the recent WMAP full-sky map of the CMB and its subtle (few millionths of a degree) temperature anisotropies. This is the oldest light in the universe, the photons that decoupled from matter at the time atoms formed, about 380,000 years after the Big Bang. The CMB temperature anisotropies tell us about the structure of the universe – its clumpiness – at this very early epoch. Measurements of distant SNIa supernovae – a sort of “standard candle” by which astronomers can measure cosmological distances – have constrained the expansion rate and mass/energy budget of the universe. Large-scale surveys, such as the 2dF Galaxy Redshift Survey, have mapped the distribution of visible matter in the universe today and in recent times. The result from combining these

and other cosmological probes is a rather sharp constraint on the amount of hot dark matter – in particular, the mass density in neutrinos – that can be allowed, given that our universe has evolved to its present state. One finds

$$\rho_\nu/\rho_{crit} \lesssim 0.022, \quad (16)$$

that is, an upper bound on the sum of neutrino masses of about 1.0 eV. (Some analyses claim even tighter upper bounds.) This bound is significantly tighter than that of Eq. (14), derived from laboratory data only.

Cosmology now demands that neutrino dark matter can make up no more than 2-3% of the universe’s mass-energy budget and, in particular, is less important than other forms of matter we know about (e.g., nucleons). (We will not go into the disconcerting fact that at least 93% of the universe’s mass-energy budget appears to be dark energy and cold dark matter that we have not yet adequately characterized!) It also tells us that neutrino mass at the  $\sim 1$  eV level now effects cosmological analyses: such analyses would constrain other cosmological parameters more tightly if neutrino masses were measured, rather than being free parameters that one must dial in cosmological models until unacceptable deviations are found. (The one eV bound was derived in this way.) This underscores how important it is to significantly improve laboratory mass limits.

One possibility is a new-generation tritium experiment: there is a serious effort underway to improve the current bound on the  $\bar{\nu}_e$  mass to about 0.3 eV, which would then place an upper bound on the sum of the masses of about 0.9 eV [13]. Another possibility – less definitive, perhaps, but with even greater reach – is offered by new-generation neutrinoless double beta decay experiments.

The phenomenon of neutrinoless double beta decay, described in I, tests not only mass, but also whether a standard model symmetry called lepton number conservation is violated. In neutrinoless double beta decay a nucleus spontaneously decays by changing its charge by two units while emitting two electrons,

$$(A, Z) \rightarrow (A, Z + 1) + e^- + \bar{\nu}_e \rightarrow (A, Z + 2) + e^- + e^-, \quad (17)$$

where the intermediate nuclear state  $(A, Z + 1)$  is virtual. The emitted electrons carry off the entire nuclear energy release, allowing this process to be distinguished from the standard-model-allowed process of two-neutrino double beta decay (where the energy is shared between two electrons and



two  $\bar{\nu}_e$ s in the final state). The neutrinoless process clearly violates lepton number, as two leptons (the electrons) are spontaneously produced. (By contrast, as the  $e^-$  carries  $l = +1$  and the  $\bar{\nu}_e$   $l = -1$ , two-neutrino double beta decay conserves lepton number.)

What conditions will lead to neutrinoless double beta decay? The necessary lepton number violation is present if the neutrino is a Majorana particle—*i.e.*, is identical to its antiparticle. Most theoretical models include Majorana neutrinos: this is part of the mechanism that allows us to understand why neutrinos have masses much smaller than those of the other standard-model fermions, such as electrons and quarks. But the existence of a Majorana neutrino alone is not sufficient because of the exact handedness of neutrinos, which we discussed in I. In the neutrinoless double beta decay reaction written above, the  $\bar{\nu}_e$  appearing in the intermediate nuclear state was produced in the nucleus by the neutron  $\beta$  decay reaction  $n \rightarrow p + e^- + \bar{\nu}_e$ . To complete the decay, the antineutrino must be reabsorbed on a second neutron,  $\nu_e + n \rightarrow p + e^-$ . At first glance, if  $\bar{\nu}_e = \nu_e$ , *i.e.*, if the neutrino is its own antiparticle, this reabsorption looks possible. However, this conclusion overlooks the neutrino handedness. In the first step, the  $\bar{\nu}_e$  produced is righthanded, while the second reaction only proceeds if the  $\nu_e$  is lefthanded. Thus it would appear that the neutrinoless process is forbidden, even if  $\bar{\nu}_e = \nu_e$ .

This argument, however, overlooks the effects of neutrino mass: a small neutrino mass breaks the exact neutrino handedness, allowing neutrinoless  $\beta\beta$  decay to proceed, though the amplitude is suppressed by the factor  $m_\nu/E_\nu$ , where  $E_\nu \sim 30$  MeV is the typical energy of the exchanged neutrino. It follows that neutrinoless double beta decay measures the neutrino mass – at least the Majorana portion of that mass. (Making this statement more precise, unfortunately, takes us beyond the limits of this paper.)

In the simplest case – a single Majorana mass eigenstate dominating the  $\beta\beta$  decay – the neutrinoless amplitude is proportional to  $U_{ei}^2 m_i$ , where  $U_{ei}^2$  is the mixing probability of the  $i$ th mass eigenstate in the  $\nu_e$  and  $m_i$  is the mass. Currently the best neutrinoless  $\beta\beta$  decay limits are those obtained by the Heidelberg-Moscow and IGEX enriched (86%)  $^{76}\text{Ge}$  experiments, which are both probing lifetimes beyond  $10^{25}$  years – corresponding to roughly one decay per kg-year! These experiments employ Ge crystals – the Ge is both source and detector – containing about 10 kg of active material. Next-generation experiments, using a variety of double beta decay sources ( $^{76}\text{Ge}$ ,  $^{136}\text{Xe}$ ,  $^{100}\text{Mo}$ ), have been proposed at the one ton scale. These have as

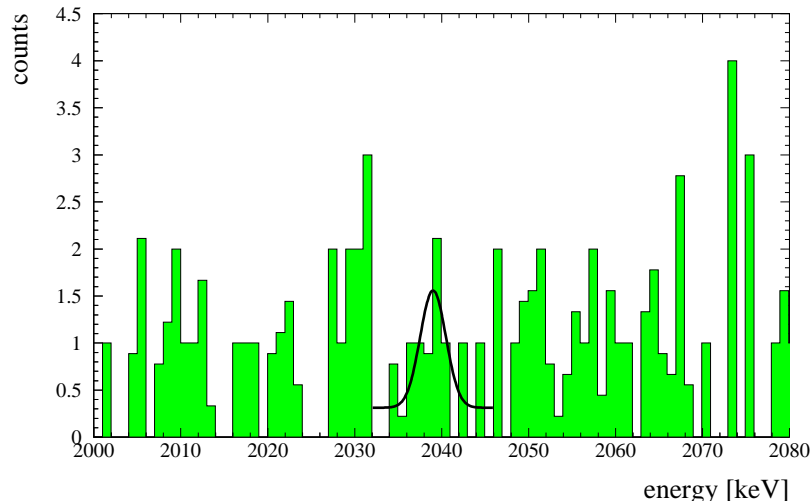


Figure 5: Spectrum found in ref. [8]. The claimed signal is as shown.

their goals sensitivities to neutrino masses of 10-50 milli-eV, corresponding to lifetimes well in excess of  $10^{27}$  y. One important motivation for these heroic proposals is the number  $\sqrt{\delta m_{atmos}^2} \sim 55$  milli-eV: in several scenarios accommodating the solar and atmospheric oscillation results, this scale plays a role in determining the level at which neutrinoless  $\beta\beta$  decay might be observed.

A few members of the Heidelberg-Moscow collaboration have claimed that their present results are not a limit, but rather a detection of neutrinoless  $\beta\beta$  decay, with a best value for the Majorana neutrino mass of  $\sim 0.4$  eV [8]. This claim has also been strongly criticized by a group that argues that the claimed peak, shown in Figure 5, is not statistically significant. Regardless, this claim will clearly be tested soon, in other  $\beta\beta$  decay experiments and in future cosmological tests, which promise to soon be probing masses  $\sim 0.3$  eV.

## 6 Conclusion

In the three years since the publication of I, several very significant neutrino discoveries have been made:

- i) SNO has shown that approximately two-thirds of the  ${}^8\text{B}$  neutrinos that arrive on earth have oscillated into  $\nu_{\mu\text{S}}$  or  $\nu_{\tau\text{S}}$ , thus demonstrating that new neutrino physics is responsible for the solar neutrino puzzle first uncovered by Ray Davis, Jr. Together with the atmospheric neutrino discoveries of SuperKamiokande, this discovery of an effect requiring massive neutrinos and neutrino mixing is the first evidence for physics beyond the standard model. The SNO results for the total solar neutrino flux, independent of flavor, are in excellent agreement with the predictions of the standard model – despite the challenge of calculating a flux that varies as  $T_c^{22}$  (!), where  $T_c$  is the solar core temperature. The SNO results, when added to other solar neutrino data, isolate a single oscillation scenario, the LMA solution.
- ii) The first terrestrial experiment to probe solar neutrino oscillation parameters, KamLAND, has confirmed the SNO results and further narrowed the LMA range of allowed  $\delta m_{12}^2$ .
- iii) Both the absolute scale of neutrino masses and the detailed pattern of the masses remain unknown, as the results in hand measure only mass differences (and leave the sign of  $\delta m_{23}^2$  undetermined). The most stringent current bound on the absolute scale of neutrino mass comes from recent precision tests of cosmology (notably WMAP and the 2dF Galaxy Redshift Survey). This limit, a bound of about 1 eV for the sum of neutrino masses, is likely to improve as new surveys are done. In addition, much improved tritium  $\beta$  decay and neutrinoless  $\beta\beta$  decay experiments are being planned. There is one controversial claim of an observation of neutrinoless  $\beta\beta$  decay that must be checked soon.

We stress, as we did in I, that this field is producing many new results that promise to impact physics broadly. The most common mechanisms for explaining neutrino mass suggest that current experiments are connected with phenomena far outside the standard model, residing near the Grand Unified energy scale of  $10^{16}$  GeV. Thus there is hope that, by fully determining the properties of neutrinos – a few of the unresolved problems have

been mentioned here – we may equip theorists to begin constructing the next standard model. Neutrino physics is also crucial to astrophysics – not just the standard solar model, but also in supernovae and in high-energy astrophysical environments – and to cosmology. We now have identified the first component of particle dark matter, though the significance of neutrino mass is still unclear due to our ignorance of the overall scale. Neutrinos could prove central to one of cosmology’s deepest questions, why our universe is matter dominated, rather than matter-antimatter symmetric. But this is a story for another paper and another time.

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