Neutrino Masses in Astrophysics and Cosmology

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Cosmology yields the most restrictive limits on neutrino masses and conversely, massive neutrinos would contribute to the cosmic dark-matter density and would play an important role for the formation of structure in the universe. Neutrino oscillations may well solve the solar neutrino problem and can have a significant impact on supernova physics. The neutrino signal from a future galactic supernova could provide evidence for cosmologically interesting neutrino masses or set interesting limits.

1. INTRODUCTION

Within the standard model of elementary particle physics, neutrinos play a special role in that they are the only fermions that appear with only two degrees of freedom per family, which are massless, and which interact only by the weak force apart from gravitation. If neutrinos had masses or anomalous electromagnetic interactions, or if right-handed (sterile) neutrinos existed, this would be the long-sought “physics beyond the standard model.” Hence the enthusiasm with which experimentalists search for neutrino oscillations, neutrinoless double-beta decay, a signature for a neutrino mass in the tritium beta decay spectrum, or for neutrino electromagnetic dipole or transition moments.

Over the years, many speculations about hypothetical neutrino properties and their consequences in astrophysics and cosmology have come and gone. I shall not pursue the more exotic of those conjectures such as strong neutrino-neutrino interactions by majoron and other couplings, small neutrino electric charges, the existence of low-mass right-handed partners to the established sequential flavors, and so forth. Any of them can be significantly constrained by astrophysical and cosmological methods [1,2], but currently there does not seem to be a realistic way to positively establish physics beyond the standard model on such grounds. Therefore, I will focus on the more conservative modifications of the standard-model neutrino sector, namely on neutrino masses and mixings. Surely the search for a nonvanishing mass is the quest for the holy grail of neutrino physics!

The most important astrophysical information about neutrino properties is the cosmological mass limit of about 40 eV which for \( \nu_\tau \) improves the direct experimental constraints by about six orders of magnitude. The only standard-model decay for mixed neutrinos that would be fast enough to evade this limit is \( \nu_\tau \to e^+ e^- \nu_e \) if \( m_{\nu_\tau} > 2m_e \). However, this channel is strongly constrained by the absence of \( \gamma \)-rays from the supernova 1987A and other arguments so that a violation of the cosmological limit requires fast invisible decays. Additional mass limits arise from big-bang nucleosynthesis. Evidence for a neutrino mass may well come from the neutrino signal of a future galactic supernova. Issues related to neutrino mass limits will be explored in Sec. 2.

Currently favored models for the formation of structure in the universe exclude neutrinos as a dark-matter candidate. Still, with a mass of a few eV they could play an important positive role in mixed hot plus cold dark matter scenarios and would leave an imprint in the power spectrum of cosmic microwave temperature fluctuations, topics to be discussed in Sec. 3.

The best hope for a positive identification of neutrino masses is to discover flavor oscillations. Current indications for this phenomenon include...
the solar neutrino problem, the atmospheric neutrino anomaly, and the LSND $\bar{\nu}_e$ excess counts. Because these matters have been widely discussed in the literature I will focus in Sec. 4 on neutrino oscillations in supernova physics. Apparently this is the only astrophysical site where flavor oscillations could play an important direct role.

2. MASS LIMITS

2.1. Cosmological Mass Limit

Arguably the most important contribution of cosmology to neutrino physics is the mass limit from the requirement that the universe not be “overclosed” \[^{[2,3]}\]. In the framework of the big-bang cosmogony one expects about as many background neutrinos as there are microwave photons. In detail, the cosmic energy density in massive neutrinos is found to be $\rho_\nu = \frac{3}{11} n_\gamma \sum m_\nu$ with $n_\gamma$ the present-day density in microwave background photons. The sum extends over all sequential flavors. In units of the critical density this is

$$\Omega_\nu h^2 = \frac{\sum m_\nu}{93 \text{eV}},$$ \hspace{1cm} (1)

where $h$ is the Hubble expansion parameter in units of $100 \text{km s}^{-1} \text{Mpc}^{-1}$. The observed age of the universe yields $\Omega h^2 \lesssim 0.4$ so that

$$m_\nu \lesssim 40 \text{eV}$$ \hspace{1cm} (2)

for any of the known flavors.

2.2. Decaying Neutrinos

The cosmological mass limit assumes that neutrinos are stable which most likely they are not if they have masses. Early decays into light daughter particles would allow the energy stored in the massive neutrinos to be redshifted enough so that the universe would not be overclosed after all. In Fig. 1 the range of neutrino masses and lifetimes that remains forbidden is shown by the shaded area marked “Mass Density.” A detailed construction of this plot is found in Ref. \[^{[4]}\].

A decaying-neutrino cosmology actually has attractive features for cosmic structure formation. Standard cold dark matter produces too much power in the density-fluctuation spectrum on small scales (Sec. \[^{[2]}\]). With decaying neutrinos the universe would become matter-dominated when the massive neutrino becomes non-relativistic, would return to radiation domination when it decays, and would become matter-dominated again at a later time. As structure grows by gravitational instability only in phases of matter domination, one has two more parameters at hand (the neutrino mass and lifetime) to tune the final density fluctuation spectrum. In the shaded band marked “Structure Formation” in Fig. 1 this mechanism could help to solve the problems of the cold dark matter cosmology \[^{[5]}\].

The snag with this scenario is that within the particle-physics standard model even massive mixed neutrinos cannot decay fast enough because the absence of flavor-violating neutral currents prevents processes of the sort $\nu_\tau \rightarrow \nu_\tau \bar{\nu}_e \nu_e$. What remains are radiative decays like $\nu_\tau \rightarrow \nu_e \gamma$ which are of higher order and thus too slow unless one postulates interactions beyond the standard model. Moreover, the final-state photons would

\[\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Cosmological bounds on neutrino masses and lifetimes. The experimental mass limits are shown above the main panel. The dashed line is the lifetime for $\nu_\tau \rightarrow \nu_e \gamma$ and $\nu_\tau \rightarrow \nu_e e^+ e^-$ under the assumption of maximum $\nu_e - \nu_\tau$ mixing.}
\end{figure}
appear as contributions to the cosmic photon backgrounds, excluding a large range of neutrino masses and radiative lifetimes independently of theoretical predictions [2]. Therefore, decaying-neutrino cosmologies as well as a circumvention of the cosmological mass bound require “fast invisible decays,” i.e., fast decays with final-state neutrinos or with new particles such as majorons. Turning this around, a violation of the cosmological mass bound of 40 eV would imply physics “far beyond” the standard model.

There is one apparent exception if $m_{\nu_e} > 2m_e$ so that $\nu_e \rightarrow \nu_e e^+ e^-$ is kinematically possible. Assuming maximum $\nu_e/\nu_e$ mixing the lifetime of $\nu_e$ is plotted in Fig. 3 as a dashed line. However, there are numerous laboratory limits on the $\nu_e/\nu_e$ mixing angle. Moreover, it is thought that in a supernova (SN) collapse the gravitational binding energy of about $3 \times 10^{53}$ ergs is emitted almost entirely in neutrinos of all flavors. The positrons from the subsequent $\nu_e \rightarrow \nu_e e^+ e^-$ decay would be trapped in the galactic magnetic field for about $10^5$ yr so that the positron flux from all galactic supernovae, integrated over this time, yields further restrictions on the decay rate [3]. Finally, the absence of a $\gamma$-ray burst in conjunction with the neutrino signal from SN 1987A yields very restrictive limits on radiative neutrino decays and in particular on the inner bremsstrahlung process $\nu_e \rightarrow \nu_e e^+ e^- \gamma$ [2]. Altogether, even heavy $\tau$ neutrinos cannot escape the cosmological mass limit if masses and mixings are the only extensions of the standard model.

2.3. Big-Bang Nucleosynthesis

Another mass limit arises from big-bang nucleosynthesis (BBN). The agreement between the predicted and observed primordial light-element abundances shows that the expansion rate in the early universe must have been roughly the standard value, leaving little room for new contributions. This argument excludes $1 \text{MeV} \lesssim m_{\nu_e} \lesssim 30 \text{MeV}$ if neutrinos live longer than about $10^3$ s, the time of BBN [3]. If some extension of the standard model allows them to decay on this time scale or faster one can still derive limits in the parameter space of the mass and the couplings which allow for the decay [4,5]. If the daughter particles involve electron neutrinos they will modify the $\beta$ reactions between protons and neutrons and thus change the cosmic baryon fraction which is compatible with the observed light-element abundances [10]. All of this requires new physics beyond neutrino masses and mixings and thus shall not be pursued here any further.

2.4. Supernova Mass Limits

Two mass limits deserve mention which were derived from the SN 1987A neutrino signal. First, the absence of a discernible time-of-flight dispersion of the observed $\bar{\nu}_e$ burst gave rise to $m_{\nu_e} \lesssim 20 \text{eV}$ [6]. There remains some interest in this result because the laboratory limits from the tritium $\beta$ decay endpoint spectrum seem to be plagued with unidentified systematic errors [12].

Second, if neutrinos had Dirac masses, helicity-flipping collisions in the dense inner core of a SN would produce right-handed (sterile) states which are not trapped and thus carry away the energy directly rather than by diffusing to the neutrino sphere. This new energy-loss channel leads to a shortening of the expected SN 1987A $\bar{\nu}_e$ burst. The observed burst duration thus leads to a bound $m_{\nu} (\text{Dirac}) \lesssim 30 \text{keV}$ [6].

Such a large mass violates the cosmological limit and is thus excluded anyway unless there are nonstandard decays. Even “invisible” channels typically involve left-handed final-state neutrinos which are visible to the detectors which registered the SN 1987A signal. Because the sterile neutrinos which escape directly from the SN core are more energetic than those emitted from the neutrino sphere, these events would stick out from the observed SN 1987A signal, leading to additional limits on some decay channels [13].

A future galactic SN would lead to much better mass limits. A detector like the proposed OMNIS [6], which has evolved from the former SNBO concept [5], could measure neutrinos of all flavors by a coherently enhanced neutral-current nuclear dissociation reaction of the type $\nu + (Z,N) \rightarrow (Z,N - 1) + n + \nu$. One could measure time-of-flight signal dispersion effects corresponding to neutrino masses of a few $10 \text{eV}$ for $\nu_\mu$ or $\nu_\tau$, especially in conjunction with the charged-current $\bar{\nu}_e p \rightarrow ne^+$ signal expected
for Superkamiokande. This detector alone would be sensitive to $m_{\nu_e} \lesssim 1 \text{ eV}$ on the basis of the rapid rise time of the expected neutrino burst. Alas, galactic supernovae are rare—one expects at most a few per century. It would still be of utmost importance to run a supernova burst observatory for however long it takes to capture a galactic SN neutrino signal!

3. NEUTRINOS AS DARK MATTER

3.1. Galactic Phase Space

Massive neutrinos would seem to be natural candidates for the dark matter which dominates the dynamics of the universe. However, they fare poorly in this regard for two main reasons. The first is a well-known problem with the phase space available to neutrinos in the dark-matter haloes of galaxies ("Tremaine-Gunn limit"). Neutrinos bound to the galaxy naturally must move slower than the escape velocity $v_{\text{esc}}$ so that their momentum is bounded by $p_{\text{max}} = m_{\nu} v_{\text{esc}}$ and their density by $n_{\text{max}} = p_{\text{max}}^3 / 3 \pi^2$ due to the Pauli exclusion principle. The maximum local mass density in dark-matter neutrinos is then $\rho_{\nu_{\text{max}}} = m_{\nu} n_{\text{max}} = m_{\nu}^4 (v_{\text{esc}}^3 / 3 \pi^2)$, leading to a lower limit on the required mass for galactic dark-matter neutrinos of a few $10 \text{ eV}$ for normal spiral galaxies, and a few $100 \text{ eV}$ for dwarf galaxies. Therefore, neutrinos cannot be the dark matter on all scales where it is known to exist.

3.2. Structure Formation

The main argument against neutrino dark matter arises from our current understanding of how the observed structure forms in the cosmic matter distribution. One pictures a primordial distribution of low-amplitude density fluctuations which are later amplified by the action of gravity. The final distribution of galaxies depends on both the nature of the dark matter and the original fluctuation spectrum. This reasoning leads to pictures like Fig. 2 where the power spectrum of the matter distribution is shown as a function of wavenumber or length scale. The data are derived from the observed galaxy distribution.

Rather general arguments as well as inflationary models of the early universe predict a roughly scale-invariant primordial fluctuation spectrum (Harrison-Zeldovich-spectrum). One normalizes its amplitude to the COBE observations of the spectrum of cosmic microwave background temperature fluctuations. Fig. 2 reveals that with this normalization a standard cold dark matter scenario predicts more power in the small-scale galaxy distribution than is observed.

Neutrinos, on the other hand, represent "hot dark matter" (HDM) because they stay relativistic until very late. This implies that their collisionless streaming erases the primordial fluctuation spectrum on small scales, suppressing the formation of small-scale structure (Fig. 2). One way out is that the original seeds for structure formation are not provided by initial density fluctuations but rather by something like cosmic strings or textures which cannot be erased by free streaming. Such scenarios may or may not be excluded at present, but they surely have been deserted by all cosmologists apart from a few dedicated cosmic-string aficionados.
The problem of a standard CDM cosmology depicted in Fig. 2 can be patched up in a variety of ways. One may tinker with the primordial fluctuation spectrum which may have been almost, but not quite, of the Harrison-Zeldovich form. One example of such a “tilted cold dark matter” (TCDM) result is shown in Fig. 2.

Another patch-up is to invoke a mixed hot plus cold dark matter (MDM or CHDM) cosmology (Fig. 2) where the hot component erases enough of the initial power on small scales to compensate for the overproduction by pure CDM [22]. In a flat universe (Ω = 1) the best fit is obtained with a total mass in neutrinos corresponding to \( \sum m_\nu = 5 \) eV with an equipartition of the masses among the flavors.

3.3. Cosmic Microwave Background

Granted that something like a CDM cosmology describes our universe, how will we ever know if it contains a small component of neutrino dark matter? One crucial source of information will be the precision sky maps of the cosmic microwave background from the future MAP and Planck Surveyor (formerly COBRAS/SAMBA) satellites [24]. Such sky maps are usually interpreted in terms of the multipole expansion of their power spectrum. For a pure CDM cosmology the expected power as a function of the multipole order \( l \) is shown in Fig. 3 as a solid line. The modified power spectra for three versions of a mixed hot plus cold dark matter cosmology are also shown.

The first ambition of current cosmic microwave experiments is to identify the first of the “Doppler peaks” in the power spectrum. However, with the high angular resolution planned for the satellite experiments one will be able, in principle, to distinguish between the CDM and the MDM curves of Fig. 3. Of course, there are other unknown cosmological parameters such as the overall mass density, the Hubble constant, the cosmological constant, the baryon fraction, and so forth, which all affect the expected power spectrum. All of them have to be determined by fitting the power spectrum to the observations. Therefore, it remains to be seen if a small neutrino component of the overall dark matter density can be identified in future cosmic microwave data.

![Figure 3. Power spectrum of the temperature sky map for the cosmic microwave background in a cold dark matter cosmology, and three variants of mixed dark matter [23].](image)

In summary, neutrinos as a universal dark matter particle are strongly disfavored, but with a mass of a few eV they could play a very useful role for structure formation and as a dark matter component which is less clustered than CDM. One may be able to identify the imprint of this component in future cosmic microwave sky maps.

4. NEUTRINO OSCILLATIONS

4.1. Current Evidence

While neutrino masses would play a very important role in cosmology, it appears unlikely that cosmological arguments or observations alone will be able to prove or disprove this hypothesis anytime soon. Therefore, the most realistic and systematic path is to search for neutrino oscillations. Unsurprisingly, a vast amount of experimental effort is dedicated to this end. While there is yet no uncontestable positive signature for oscillations, there exist a number of experimental “anomalies” that are best explained by this phenomenon.

The most recent example is an experiment at Los Alamos where neutrinos are produced in a
proton beam dump. The secondary positive pions decay according to $\pi^+ \rightarrow \mu^+ + \nu_\mu$ and the muons according to $\mu^- \rightarrow e^+ + \bar{\nu}_e + \nu_\tau$. In the Liquid Scintillator Neutrino Detector (LSND) about 30 meters downstream, a significant number of excess $\bar{\nu}_e$ counts was obtained which cannot be due to the primary source but which can be interpreted as the appearance of oscillated $\bar{\nu}_\mu$'s. If this interpretation were correct, the $\nu_e$-$\nu_\mu$ mass difference could be of order 1 eV or more, pointing to cosmologically significant neutrino masses. At the present time one has to wait and see if more LSND data and other experiments, notably KARMEN, will confirm this claim.

Another indication for oscillations arises from atmospheric neutrinos. Their production is very similar to the LSND experiment, except that the higher-energy cosmic-ray protons produce both positively and negatively charged pions and kaons in roughly equal proportions so that one expects about equally many neutrinos as antineutrinos, and a $\nu_\mu$:$\nu_e$ flavor ratio of about 2:1. Some measurements agree with this prediction, but several detectors have observed a flavor ratio more like 1:1 (“atmospheric neutrino anomaly”). Further, Kamiokande has seen an angular dependence of the flavor ratio as expected for oscillations due to the different path lengths through the Earth from the atmosphere to the detector and most recently Superkamiokande had made a similar case. These observations can be explained by $\nu_e$-$\nu_\mu$ or $\nu_\mu$-$\nu_\tau$ oscillations, but the former possibility is now ruled out by the CHOOZ reactor experiment. The $\nu_\mu$-$\nu_\tau$ oscillation interpretation requires nearly maximum mixing with a mass difference of about 0.1 eV.

The longest-standing hint for oscillations arises from solar neutrinos. The masses and mixing angles which are required to explain the measured flux deficits in terms of oscillations have been updated in Ref. but they remain close to the textbook values. The two MSW solutions indicate a mass difference around 0.003 eV while the vacuum solution would require about $10^{-5}$ eV.

It is well known that these indications for oscillations require three different mass differences which are not compatible with each other. Therefore, not all of the oscillation interpretations can be correct unless one appeals to neutrino degrees of freedom beyond the sequential flavors, i.e. to the existence of sterile neutrinos.

4.2. Early Universe

Meanwhile it remains of interest to look for astrophysical effects where neutrino oscillations could be important. Neutrinos dominate the dynamics of the early universe and so it is natural to wonder if oscillations could be important there. However, because all flavors are in thermal equilibrium with each other the usual flavor oscillations would not change anything. Oscillations into sterile neutrinos can have nontrivial and interesting effects, but following the philosophy of this presentation of mostly ignoring everything other than masses and mixings for the sequential flavors I will not discuss these matters here.

4.3. Supernova Physics

Concentrating on flavor oscillations between sequential neutrinos, supernovae are natural sites to look for nontrivial consequences. A type II SN occurs when a massive star ($M > 8 M_\odot$) has reached the end of its life. It consists of a degenerate iron core, surrounded by several shells of different nuclear burning phases. Iron cannot gain energy by nuclear fusion so that no further burning phase can be ignited. As the iron core grows in mass it eventually reaches its Chandrasekhar limit of about $1.4 M_\odot$, i.e. the maximum mass that can be supported by electron degeneracy pressure. The subsequent collapse is halted only at nuclear densities where the equation of state stiffens, causing a shock wave to form at the edge of the inner core. It advances outward and eventually expels the mantle and envelope, an event which is observed as the SN explosion. The implosion of the core is transformed into an explosion of the outer parts of the star by this “shock and bounce” mechanism.

Most of the binding energy of the newly formed compact star is radiated away by neutrinos. The collapsed core is so hot and dense that even neutrinos are trapped. The cooling takes several seconds which corresponds to a neutrino diffusion time scale from the center to the “neutrino sphere” where these particles can escape. It is
thought that the energy is roughly equipartitioned between all (anti)neutrino flavors, but the spectra are different. Various studies find for the average expected neutrino energy

\[ \langle E_{\nu} \rangle = \begin{cases} 
10 - 12 \text{ MeV for } \nu_e , \\
14 - 17 \text{ MeV for } \bar{\nu}_e , \\
24 - 27 \text{ MeV for } \nu_{\mu,\tau} \text{ and } \bar{\nu}_{\mu,\tau} . 
\end{cases} \]  

The differences arise from the main trapping reactions, namely \( \nu_e n \rightarrow p e^- , \bar{\nu}_e p \rightarrow n e^+ , \) and \( \nu N \rightarrow N \nu \) with \( N = n \) or \( p \). The charged-current reactions have larger cross sections than the neutral-current ones and there are more neutrons than protons so that the \( \nu_e \)'s have the hardest time to escape. They emerge from the largest radii and thus from the coldest layers.

In detail the spectra formation depends subtly on the neutrino transport near the neutrino sphere. A recent scrutiny of the neutrino interaction rates suggests that the spectral energies may be less different between the flavors than had been thought, but a self-consistent implementation is not yet available.

It is conceivable that (resonant) oscillations occur outside of the neutrino sphere so that the spectra between two flavors are swapped. This would affect the explosion mechanism itself which does not work quite as simple as described above. Because the shock wave forms within the core it has to move through a layer of iron before reaching the stellar mantle. By dissociating iron it loses energy and stalls after a few 100 ms in typical calculations. The deposition of energy by neutrinos which emerge from the inner core is thought to revive the shock so that it resumes its outward motion. However, this “delayed explosion mechanism” still does not seem to work in typical calculations because the transfer of energy to the shock wave is not efficient enough.

If neutrinos follow a “normal” mass hierarchy with \( \nu_e \) dominated by the lightest mass eigenstate one can have MSW oscillations between, say, \( \nu_e \) and \( \nu_\tau \). If this occurs between the neutrino sphere and the stalling shock wave the \( \nu_e \)'s arriving there really are oscillated \( \nu_\tau \)'s and thus have the higher spectral energies characteristic for that flavor, leading to a more effective energy transfer to the shock wave.

Because the MSW transition must occur close to the neutrino sphere where the matter densities are large, neutrino mass differences in the 10 eV regime are required (Fig. 4).

Oscillations may also affect the r-process synthesis of heavy elements (neutron capture) which may well occur in the high-entropy “hot bubble” in a SN between the neutron star and the advancing shock wave a few seconds after collapse. Because \( \langle E_{\nu_e} \rangle < \langle E_{\nu_\tau} \rangle \) the \( \beta \) processes shift the neutrino-driven wind to the required proton-rich phase. However, if oscillations cause a spectral swap between, say, \( \nu_e \) and \( \nu_\tau \) this energy hierarchy is inverted and the wind is shifted to a proton-rich phase, preventing the occurrence of the r-process. Because this argument applies to a later phase than the explosion argument above, the neutron star has thermally settled so that the matter gradients at its surface are much steeper. This makes it harder to meet the adiabaticity condition, reducing the range of mixing angles where the MSW effect operates.

At the present time it is not certain if r-process nucleosynthesis indeed occurs in supernovae so
that the hatched are in Fig. 4 cannot be taken as an exclusion plot. More importantly, there is a range of mixing parameters below the hatched region where the spectral swap is only partial and causes an increase of the neutron fraction, actually helping the r-process.

4.4. Pulsar Recoils
Neutron stars (pulsars) usually have strong magnetic fields. They cause the neutrino refractive index to be anisotropic so that the MSW resonance would not occur at precisely the same radius everywhere in the SN core. As a result the total neutrino luminosity may not be precisely isotropic, causing a small recoil of the newborn neutron star [41]. It is not clear, however, if one can actually achieve the 1–2% anisotropy which is required to explain the observed pulsar velocities of around 500 km s$^{-1}$ [42].

4.5. SN 1987A Signal Interpretation
Oscillations would modify the SN 1987A neutrino signal, notably the "prompt $\nu_e$ burst" which precedes the main cooling phase. It arises when the shock wave breaks through the surface of the iron core, suddenly releasing $\nu_e$'s by the reactions $e^- p \rightarrow n \nu_e$ from a layer encompassing perhaps a few $0.1 M_\odot$. In the IMB and Kamiokande water Cherenkov detectors which registered the SN 1987A signal the $\nu_e$-e scattering reaction could have produced forward-peaked electrons as a signature for this burst, in agreement with the first event in Kamiokande, although one would have expected only a fraction of an event.

Resonant oscillations would have transformed the $\nu_e$ burst into $\nu_\mu$'s or $\nu_\tau$'s which have a much smaller scattering cross section on electrons. In Fig. 4 the shaded triangle shows the mixing parameters for which the oscillation probability in the stellar mantle and envelope would have exceeded 50%. The small-angle MSW solution is not in conflict with the interpretation that the first SN 1987A Kamiokande event was indeed from $\nu_e$-e scattering. Of course, this single event does not lead to the opposite conclusion that the large-angle MSW solution was ruled out.

Most of the 19 events must have been due to the $\bar{\nu}_e p \rightarrow n e^+$ reaction. For a normal mass hierarchy resonant oscillations cannot swap the $\bar{\nu}_e$ spectra with another flavor; they can affect only the $\nu_e$ spectrum. Therefore, the observed events represent the original $\bar{\nu}_e$ source spectrum unless the mixing angle is large enough to allow for significant nonresonant oscillations. Large mixing angles are motivated by the large-angle MSW and the vacuum solution to the solar neutrino problem as well as the oscillation interpretation of the atmospheric neutrino anomaly.

One way of interpreting the observed SN 1987A events is to derive best-fit values for the total binding energy $E_b$ and the spectral temperature of the observed $\bar{\nu}_e$'s which is defined by $T_{\bar{\nu}_e} = \frac{1}{2} (E_{\bar{\nu}_e})$. For certain mixing parameters and relative spectral temperatures $\tau = T_{\nu_\mu}/T_{\nu_e}$ the results from such an analysis [44] are shown in Fig. 5. For $\tau = 1$ oscillations have no effect; this is identical to the no-oscillation scenario.

Figure 5. Mixing parameters between $\nu_e$ and $\nu_\mu$ or $\nu_\tau$ where the prompt $\nu_e$ burst would have resonantly oscillated into another flavor (after Ref. [43]). A normal mass hierarchy is assumed where $\nu_e$ is dominated by the lightest mass eigenstate. For orientation, the Kamiokande solar MSW triangle and the MSW solutions to the solar neutrino problem are also shown.
According to Eq. (3) a typical value for the relative spectral temperature is $\tau = 1.7$. This is inconsistent with the vacuum solution to the solar neutrino problem (Fig. 6). The expected event energies in the detector would have been even larger than in the standard case, contrary to the relatively low energies that were actually observed. Put another way, if the vacuum solution to the solar neutrino problem is borne out by future experiments, there is a serious conflict between the SN 1987A observations and current theoretical predictions.

For the large-angle MSW solution the conflict is less severe (Fig. 6). In this case the flavor evolution is adiabatic in the SN envelope so that propagation eigenstates emerge from the surface. On the path through the Earth to the detectors matter-induced "regeneration effects" partly restore the original source spectra, reducing the overall impact of neutrino oscillations.

In summary, the SN 1987A neutrino observations disfavor the large-angle solutions to the solar neutrino problem, even though the data are too sparse to reach this conclusion "beyond reasonable doubt."

5. DISCUSSION AND SUMMARY

In the absence of any compelling theoretical reason for neutrinos to be strictly massless it is commonplace to assume that they do carry small masses and that the flavors mix. Cosmology provides by far the most restrictive limit of about 40 eV on the mass of all sequential flavors. This limit cannot be circumvented by decays unless neutrinos interact by new forces which allow for "fast invisible" (i.e. nonradiative) channels. Therefore, a neutrino mass in excess of the cosmological limit would signify that either the particle-physics or the cosmological standard model require nontrivial revisions.

Neutrinos are unfavored dark matter candidates because of the well-known problems of a hot dark matter cosmology. The cold dark matter picture works impressively well even though it appears to overproduce structure on small scales. This problem can be patched up by a number of different modifications, one of them being a hot plus cold dark matter scenario with a neutrino component corresponding to $m_{\nu_e} + m_{\nu_\mu} + m_{\nu_\tau} \approx 5$ eV. However, it looks unlikely that this sort of scenario can be unambiguously identified by cosmological methods alone. Even the most ambitious future cosmic microwave sky maps will have a hard time to identify this model unambiguously in view of the remaining uncertainty in other cosmological parameters.

Figure 6. Confidence contours (95%) for the neutron star binding energy and temperature of the primary $\bar{\nu}_e$ spectrum for the given values of $\tau = T_{\bar{\nu}_e}/T_{\bar{\nu}_e}$ [4]. The hatched area is the range of theoretical predictions. Upper Panel: Neutrino mixing parameters of the solar vacuum solution ($\Delta m^2 = 10^{-10}$ eV$^2$, $\sin^2 2\Theta = 1$). Lower Panel: Large-angle MSW solution ($\Delta m^2 = 10^{-8}$ eV$^2$, $\sin^2 2\Theta = 0.8$).
Depending on the exact mixing parameters, neutrino oscillations have severe consequences for supernova physics and the signal interpretation of SN 1987A or a future galactic supernova. Especially for neutrino masses in the cosmologically interesting regime, oscillations can affect the explosion mechanism and r-process nucleosynthesis. However, the current understanding of SN physics is too uncertain and the SN 1987A data are too sparse to tell if neutrino oscillations are either required or excluded. Still, it remains fascinating that a neutrino mass as small as a few eV has any significant consequences outside of cosmology.

Even though massive neutrinos may play an important role in cosmology and supernova physics, realistically we will know if this is indeed the case only by more direct measurements. The most promising approach is by oscillation experiments. Already, oscillations can explain the atmospheric neutrino anomaly, the LSND $\bar{\nu}_e$ excess counts, and the solar neutrino problem even though a simultaneous explanation of all three phenomena is not possible by flavor oscillations between sequential neutrinos alone.

If neutrinos do have masses and if their mass differences are as small as suggested by solar and atmospheric neutrinos, then a cosmological role is only possible if all three mass eigenvalues are in the eV range and almost equal. The common scale of these quasi-degenerate masses cannot be determined in oscillation experiments. Therefore, it remains of utmost importance to push tritium $\beta$ decay and neutrinoless $\beta\beta$ decay experiments below the 1 eV threshold for $m_{\nu_e}$. Moreover, it remains of utmost importance to measure the neutrino light curve from a future galactic supernova with a high-statistics experiment such as Superkamiokande or the proposed OMNIS. Besides a wealth of other information one would be sensitive to an eV mass for $\nu_e$ and to the 10 eV scale for $m_{\nu_\mu}$ and $m_{\nu_\tau}$. Galactic supernovae may be rare, but the scientific harvest would be worth the wait!

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