

Neutrinos Properties Beyond the Standard Model

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The present observational status of neutrino physics is sketched, with emphasis on the hints that follow from solar and atmospheric neutrino observations, as well as dark matter. I also briefly review the ways to account for the observed anomalies and some of their implications.

1. INTRODUCTION

One of the biggest drawbacks of the Standard Model (SM) is that the masslessness of neutrinos is not dictated by an underlying *grand principle*, such as that of gauge invariance in the case of the photon: the SM simply postulates that neutrinos are massless and, as a result, all their properties are trivial, e.g. magnetic and transition moments are zero, etc. Massless neutrinos would be exceptional particles, since no other such fermions exist. If massive, neutrinos would present another puzzle, of why are their masses so much smaller than those of the charged fermions. The fact that neutrinos are the only electrically neutral elementary fermions may hold the key to the answer, namely neutrinos could be Majorana fermions, the most fundamental ones. In this case the suppression of their mass could be associated to lepton number conservation, as actually happens in many extensions of the SM.

From the observational point of view non-zero neutrino masses now seem required in order to account for the data on solar and atmospheric neutrinos, as well as the (hot) dark matter in the universe. Detecting neutrino masses is one of the most outstanding chal-

lenges in particle physics, with far-reaching implications also for the understanding of fundamental issues in astrophysics and cosmology. Though very difficult, future experiments could shed light on the issue of neutrino masses and the conservation of lepton number. One interesting aspect of many models where neutrinos have non-vanishing masses is that they lead to effects that could be experimentally tested. Before over-viewing the present observational limits and hints in favour of massive neutrinos, let us make a few general remarks about the theoretical models.

2. THEORETICAL MODELS

One of the most attractive approaches to generate neutrino masses is from unification. Indeed, in trying to understand the origin of parity violation in the weak interaction by ascribing it to a spontaneous breaking phenomenon, in the same way as the W and Z acquire their masses in the SM, one arrives at the so-called left-right symmetric extensions such as $SU(2)_L \otimes SU(2)_R \otimes U(1)$ [1], $SU(4) \otimes SU(2) \otimes SU(2)$ [2] or $SO(10)$ [3], in some of which the masses of the light neutrinos are obtained by diagonalizing the following mass matrix in the basis ν, ν^c

$$\begin{bmatrix} 0 & D \\ D^T & M_R \end{bmatrix} \quad (1)$$

where $D = h_D \langle H \rangle / \sqrt{2}$ is the standard $SU(2) \otimes U(1)$ breaking Dirac mass term and $M_R = M_R^T$

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is the isosinglet Majorana mass. In the seesaw approximation, one finds

$$M_{eff} = -DM_R^{-1}D^T. \quad (2)$$

In general, however, this matrix also contains a $\nu\nu$ term [4] whose size is expected to be also suppressed by the left-right breaking scale. As a result one is able to explain naturally the relative smallness of neutrino masses. Even though it is natural to expect M_R to be large, its magnitude heavily depends on the model. As a result one can not make any real prediction for the corresponding light neutrino masses that are generated through the seesaw mechanism. In fact this freedom has been exploited in model building in order to account for an almost degenerate neutrino mass spectrum [5].

Although very attractive, unification is by no means the only way to generate neutrino masses. There is a large diversity of other possible schemes which do not require any new large mass scale. For example, it is possible to start from an extension of the lepton sector of the $SU(2) \otimes U(1)$ theory by adding a set of *two* 2-component isosinglet neutral fermions, denoted ν^c_i and S_i , to each generation. In this case there is an exact L symmetry that keeps neutrinos strictly massless, as in the SM. The conservation of total lepton number leads to the following form for the neutral mass matrix (in the basis ν, ν^c, S)

$$\begin{bmatrix} 0 & D & 0 \\ D^T & 0 & M \\ 0 & M^T & 0 \end{bmatrix} \quad (3)$$

This form has also been suggested in various theoretical models [6], including many of the superstring inspired models. In the latter case the zeros of eq. (3) naturally arise due to the absence of Higgs fields to provide the usual Majorana mass terms, needed in the seesaw model [7]. Clearly, one can easily introduce non-zero masses in this model through a μSS term that could be proportional to the VEV of a singlet field σ [8]. In contrast to the seesaw scheme, the neutrino masses are directly proportional to $\langle\sigma\rangle$. This model provides a conceptually simple and phenomenologically rich extension of

the Standard Model, which brings in the possibility that a wide range of new phenomena be sizeable. These have to do with neutrino mixing, universality, flavour and CP violation in the lepton sector [9,10], as well as direct effects associated with Neutral Heavy Lepton (NHL) production at high energy colliders [11]. A remarkable feature of this model is the possibility of non-trivial neutrino mixing despite the fact that neutrinos are strictly massless. This tree-level effect leads to a new type of resonant neutrino conversion mechanism that could play an important role in supernovae [12,13]. Moreover, there are loop-induced lepton flavour and CP non-conservation effects whose rates are precisely calculable [9,10,14]. I repeat that this is remarkable due to the fact that physical light neutrinos are massless, as in the standard model. This feature is the same as what happens in the supersymmetric mechanism of flavour violation [15]. Indeed, in the simplest case of SU(5) supergravity unification, there are flavour violating processes, like $\mu \rightarrow e\gamma$, despite the fact that in SU(5) neutrinos are protected by B-L and remain massless. The supersymmetric mechanism and that of eq. (3) differ in that the lepton flavour violating (LFV) processes are induced in one case by NHL loops, while in supersymmetry they are induced by scalar boson loops. In both cases the particles in the loops have masses at the weak scale, leading to branching ratios [9,10,14] [16,17] that are sizeable enough to be of experimental interest [18,19,20].

Supersymmetry with broken R-parity also provides a nice mechanism for the origin of neutrino mass [21,22]. For example, in a model where R-parity is broken by a bilinear term in the superpotential [21] the tau neutrino ν_τ acquires a mass, due to the mixing between neutrinos and neutralinos given in the matrix

$$\begin{bmatrix} M_1 & 0 & -\frac{1}{2}g'v_1 & \frac{1}{2}g'v_2 & -\frac{1}{2}g'v_3 \\ 0 & M_2 & \frac{1}{2}gv_1 & -\frac{1}{2}gv_2 & \frac{1}{2}gv_3 \\ -\frac{1}{2}g'v_1 & \frac{1}{2}gv_1 & 0 & -\mu & 0 \\ \frac{1}{2}g'v_2 & -\frac{1}{2}gv_2 & -\mu & 0 & \epsilon_3 \\ -\frac{1}{2}g'v_3 & \frac{1}{2}gv_3 & 0 & \epsilon_3 & 0 \end{bmatrix} \quad (4)$$

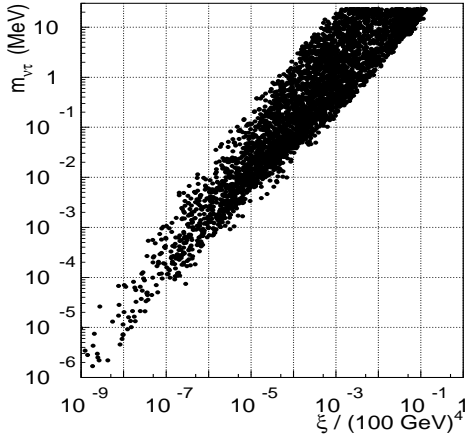


Figure 1. Tau neutrino mass versus ϵ_3

This mixing is proportional to the R-parity and lepton-number violating parameters ϵ_3 and v_3 . In the simplest unified supergravity model the ϵ_3 and the v_3 are related [21]. They lead to a non-zero Majorana ν_τ mass, which depends quadratically on an effective parameter ξ defined as $\xi \equiv (\epsilon_3 v_1 + \mu v_3)^2$. It is important to notice that the neutrino mass generated through R-parity violation in this model is not necessarily large, even though its implications can be observable. In Fig. (1) we display the allowed values of m_{ν_τ} (in the tree level approximation). As can be seen from the figure the m_{ν_τ} values can cover a very wide range, up to values in the MeV range, comparable to the present LEP limit [23]. The latter places a limit on the value of ξ . Notice that ν_e and ν_μ remain massless in this approximation. They get masses either from radiative corrections [24] or by mixing with singlets in models with spontaneous breaking of R-parity [25].

There is also a large variety of *radiative* schemes to generate neutrino masses. The prototype models of this type are the Zee model and the model suggested by Babu [26]. In these models lepton number is explicitly broken, but it is easy to realize them with spontaneous breaking of lepton number. For example in the version suggested in ref. [27] the neutrino mass arises from the diagram shown in

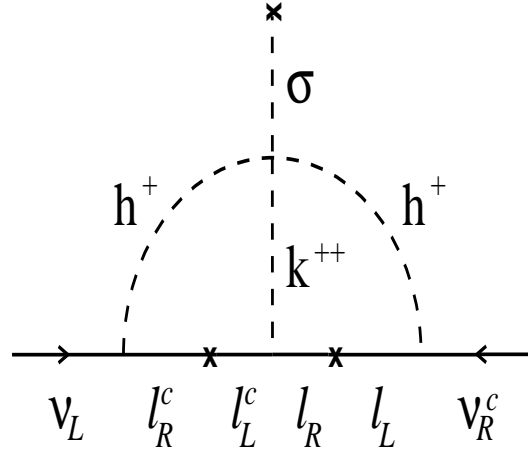


Figure 2. Two-loop-induced Neutrino Mass.

Fig. (2).

Other than the seesaw scheme, none of the above models requires a large mass scale. In all of them one can implement the spontaneous violation of the global lepton number symmetry leading to neutrino masses that scale **directly** proportional to the lepton-number scale or some positive power of it, in contrast to the original Majoron model [28]. Such low-scale models are very attractive and lead to a richer phenomenology, as the extra particles required have masses at scales that could be accessible to present experiments. One remarkable example is the possibility invisibly decaying Higgs bosons [29].

The above discussion should suffice to illustrate the enormous freedom and wealth of phenomenological possibilities in the neutrino sector. These reach well beyond the realm of conventional neutrino experiments, including also signatures that can be probed, though indirectly, at high energy accelerators. An optimist would regard as very exciting the fact that the neutrino sector may hold so many experimental possibilities, while a pessimist would be discouraged by the fact that one does not know the relevant scale responsible for neutrino mass, nor the underlying mechanism. Last but not least, one lacks a theory for the Yukawa couplings. As a consequence

neutrino masses are not predicted and it is up to observation to search for any possible clue. Given the theoretical uncertainties in predicting neutrino masses from first principles, one must turn to observation. Here the information comes from laboratory, astrophysics and cosmology.

3. OBSERVATIONAL LIMITS ON NEUTRINO MASSES AND MIXINGS

3.1. Laboratory Limits

The best limits on the neutrino masses can be summarized as [30]:

$$m_{\nu_e} \lesssim 5\text{eV}, \quad m_{\nu_\mu} \lesssim 170\text{keV}, \quad m_{\nu_\tau} \lesssim 18\text{MeV}(5)$$

These are the most model-independent of the laboratory limits on neutrino mass, as they follow purely from kinematics. The limit on the ν_e mass comes from beta decay, that on the ν_μ mass comes from PSI (90 % C.L.) [31], with further improvement limited by the uncertainty in the π^- mass. On the other hand, the best ν_τ mass limit now comes from high energy LEP experiments [23] and may be substantially improved at a future tau-charm factory [32]. In connection with tritium beta decay limit [33] even though the negative m^2 value has now been clarified, there are still un-understood features in the spectrum, probably of instrumental origin. Further results from the Mainz experiment are awaited.

Additional limits on neutrino masses follow from the non-observation of neutrino oscillations. The most sensitive searches have been performed at reactors [34] ($\bar{\nu}_e - \nu_x$ oscillations); at meson factories (KARMEN [35], LSND [36]) and at high-energy accelerators (experiments E531 and E776 [37]). A search for ν_μ to ν_e oscillations has now been reported by the LSND collaboration using ν_μ from π^+ decay in flight [38]. An excess in the number of beam-related events from the $C(\nu_e, e^-)X$ inclusive reaction is observed. The excess cannot be explained by normal ν_e contamination in the beam at a confidence level greater than 99%. If interpreted as an oscillation signal, the

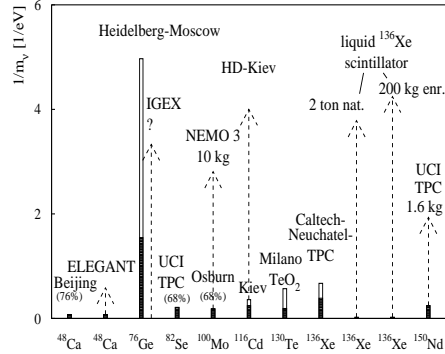


Figure 3. Sensitivity of $\beta\beta_{0\nu}$ experiments.

observed oscillation probability of $(2.6 \pm 1.0 \pm 0.5) \times 10^{-3}$ is consistent with the previously reported $\bar{\nu}_\mu$ to $\bar{\nu}_e$ oscillation evidence from LSND. Another recent result comes from NOMAD and rules out part of the LSND region. The future lies in searches for oscillations using accelerator beams directed to far-out underground detectors, with very good prospects for the long-baseline experiments proposed at KEK, CERN and Fermilab.

If neutrinos are of Majorana type a new form of nuclear double beta decay would take place in which no neutrinos are emitted in the final state, i.e. the process by which an $(A, Z - 2)$ nucleus decays to $(A, Z) + 2 e^-$. In such process one would have a virtual exchange of Majorana neutrinos. Unlike ordinary double beta decay, the neutrino-less process violates lepton number and its existence would indicate the Majorana nature of neutrinos. Because of the phase space advantage, this process is a very sensitive tool to probe into the nature of neutrinos.

Present data place an important limit on a weighted average neutrino mass parameter $\langle m \rangle \lesssim 1 - 2 \text{eV}$. The present experimental situation as well as future prospects is illustrated in Fig. (3), taken from ref. [39]. Note that this bound depends to some extent on the relevant nuclear matrix elements characterising this process [40]. The parameter $\langle m \rangle$ involves

both neutrino masses and mixings. Thus, although rather stringent, this limit may allow very large neutrino masses, as there may be strong cancellations between different neutrino types. This may happen automatically in the presence of suitable symmetries. For example, the decay vanishes if the intermediate neutrinos are Dirac-type, as a result of the corresponding lepton number symmetry [41].

Neutrino-less double beta decay has a great conceptual importance. It has been shown [42] that in a gauge theory of the weak interactions a non-vanishing $\beta\beta_{0\nu}$ decay rate requires neutrinos to be Majorana particles, *irrespective of which mechanism* induces it. This is important since in a gauge theory neutrino-less double beta decay may be induced in other ways, e.g. via scalar boson exchange.

3.2. Limits from Cosmology

There are a variety of cosmological arguments that give information on neutrino parameters. In what follows I briefly consider the critical density and the primordial Nucleosynthesis arguments.

3.2.1. The Cosmological Density Limit

The oldest cosmological bound on neutrino masses follows from avoiding the overabundance of relic neutrinos [43]

$$\sum m_{\nu_i} \lesssim 92 \nu h^2 eV, \quad (6)$$

where $\nu h^2 \leq 1$ and the sum runs over all species of isodoublet neutrinos with mass less than $O(1MeV)$. Here $\nu = \rho_\nu/\rho_c$, where ρ_ν is the neutrino contribution to the total density and ρ_c is the critical density. The factor h^2 measures the uncertainty in the present value of the Hubble parameter, $0.4 \leq h \leq 1$, and νh^2 is smaller than 1. For the ν_μ and ν_τ this bound is much more stringent than the laboratory limits eq. (5).

Apart from the experimental interest [32], an MeV tau neutrino also seems interesting from the point of view of structure formation [44]. Moreover, it is theoretically viable as the constraint in eq. (6) holds only if neutrinos are

stable on the relevant cosmological time scale. In models with spontaneous violation of total lepton number [28] there are new interactions of neutrinos with the majorons which may cause neutrinos to decay into a lighter neutrino plus a majoron, for example [45],

$$\nu_\tau \rightarrow \nu_\mu + J. \quad (7)$$

or have sizeable annihilations to these majorons,

$$\nu_\tau + \nu_\tau \rightarrow J + J. \quad (8)$$

The possible existence of fast decay and/or annihilation channels could eliminate relic neutrinos and therefore allow them to have higher masses, as long as the lifetime is short enough to allow for an adequate red-shift of the heavy neutrino decay products. These 2-body decays can be much faster than the visible modes, such as radiative decays of the type $\nu' \rightarrow \nu + \gamma$. Moreover, the Majoron decays are almost unconstrained by astrophysics and cosmology (for a detailed discussion see ref. [43]).

A general method to determine the Majoron emission decay rates of neutrinos was first given in ref. [46]. The resulting decay rates are rather model-dependent and will not be discussed here. Explicit neutrino decay lifetime estimates are given in ref. [25,45,47]. The conclusion is that there are many ways to make neutrinos sufficiently short-lived and that all mass values consistent with laboratory experiments are cosmologically acceptable.

3.2.2. The Nucleosynthesis Limit

There are stronger limits on neutrino lifetimes or annihilation cross sections arising from cosmological nucleosynthesis. Recent data on the primordial deuterium abundance [48,49] have stimulated a lot of work on the subject [50,51,52]. If a massive ν_τ is stable on the nucleosynthesis time scale, (ν_τ lifetime longer than ~ 100 sec), it can lead to an excessive amount of primordial helium due to their large contribution to the total energy density. This bound can be expressed through an effective number of massless neutrino species

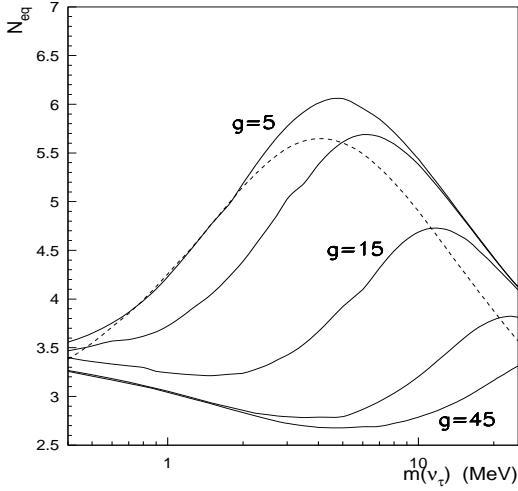


Figure 4. A heavy ν_τ annihilating to majorons can lower the equivalent massless-neutrino number in nucleosynthesis.

(N_ν). If $N_\nu < 3.4 - 3.6$, one can rule out ν_τ masses above 0.5 MeV [53,54]. If we take $N_\nu < 4$ the m_{ν_τ} limit loosens accordingly. However it has recently been argued that non-equilibrium effects from the annihilations of the heavy ν_τ 's make the constraint a bit stronger in the large m_{ν_τ} region [55]. In practice, all ν_τ masses on the few MeV range are ruled out. One can show, however that in the presence of new ν_τ annihilation channels the nucleosynthesis m_{ν_τ} bound is substantially weakened or eliminated [56]. Fig. 4 gives the effective number of massless neutrinos equivalent to the contribution of a massive ν_τ Majoron model with different values of the coupling g between ν_τ 's and J 's, expressed in units of 10^{-5} . For comparison, the dashed line corresponds to the SM $g = 0$ case. One sees that for a fixed N_ν^{max} , a wide range of tau neutrino masses is allowed for large enough values of g . No ν_τ masses below the LEP limit can be ruled out, as long as g exceeds a few times 10^{-4} .

One can express the above results in the $m_{\nu_\tau} - g$ plane, as shown in figure 5. One sees that the constraints on the mass of a Majorana ν_τ from primordial nucleosynthesis can be sub-

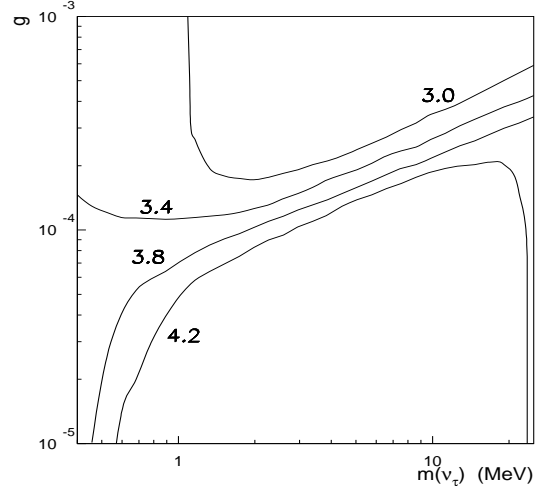


Figure 5. The region above each curve is allowed for the corresponding N_{eq}^{max} .

stantially relaxed if annihilations $\nu_\tau \bar{\nu}_\tau \leftrightarrow JJ$ are present. Moreover the required values of $g(m_{\nu_\tau})$ are reasonable in many majoron models [45,56,58]. Similar depletion in massive ν_τ relic abundance also happens if the ν_τ is unstable on the nucleosynthesis time scale [57] as will happen in many Majoron models.

3.3. Limits from Astrophysics

There are a variety of limits on neutrino parameters that follow from astrophysics, e.g. from the SN1987A observations, as well as from supernova theory, including supernova dynamics [59] and from nucleosynthesis in supernovae [60]. Here I briefly discuss three recent examples of how supernova physics constrains neutrino parameters.

It has been noted a long time ago that, in some circumstances, *massless* neutrinos may be *mixed* in the leptonic charged current [12]. Conventional neutrino oscillation searches in vacuo are insensitive to this mixing. However, such neutrinos may resonantly convert in the dense medium of a supernova [12,13]. The observation of the energy spectrum of the SN1987A $\bar{\nu}_e$'s [61] may be used to provide very stringent constraints on *massless* neutrino mixing angles, as seen in Fig. (6). The regions to the right of the solid curves are for-

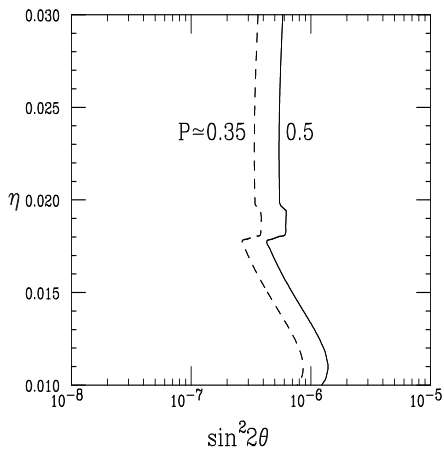


Figure 6. SN1987A bounds on massless neutrino mixing.

bidden, those to the left are allowed. Massless neutrino mixing may also have important implications for r -process nucleosynthesis in the supernova [60]. For details see ref. [13].

Another illustration of how supernova restricts neutrino properties has been recently considered in ref. [62]. There flavour changing neutral current (FCNC) neutrino interactions were considered. These may induce resonant massless-neutrino conversions in a dense supernova medium, both in the massless and massive case. The restrictions that follow from the observed $\bar{\nu}_e$ energy spectra from SN1987A and the supernova r -process nucleosynthesis provide constraints on supersymmetric models with R parity violation, which are much more stringent than those obtained from the laboratory. In Fig. (7) we display the constraints on explicit R -parity-violating FCNCs in the presence of non-zero neutrino masses in the hot dark matter eV range. As seen from Fig. (7) they disfavour a leptoquark interpretation of the recent HERA anomaly.

As a final example of how astrophysics can constrain neutrino properties we consider the case of resonant $\nu_e \rightarrow \nu_s$ and $\bar{\nu}_e \rightarrow \bar{\nu}_s$ conversions in supernovae, where ν_s is a *sterile* neutrino [63], which we assume to be in the hot dark matter mass range. The implications

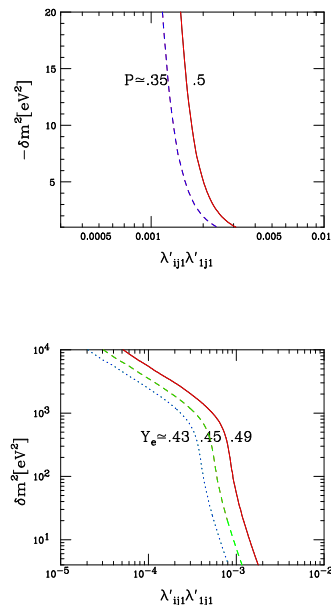


Figure 7. Supernovae and FCNC neutrino interactions.

of such a scenario for the supernova shock reheating, the detected $\bar{\nu}_e$ signal from SN1987A and for the r -process nucleosynthesis hypothesis have been recently analysed [63]. In Fig. (8), taken from [63], we summarize the resulting constraints on mixing and mass difference for the $\nu_e - \nu_s$ system that follow from these arguments. Notice that for the case of r -process nucleosynthesis there is an allowed region for which the r -process nucleosynthesis can be enhanced. In fact, strictly speaking, only SN1987A can yield real bounds on sterile neutrino parameters.

4. HINTS FOR NEUTRINO MASSES

So far the only indications in favour of nonzero neutrino rest masses have been provided by astrophysical and cosmological obser-

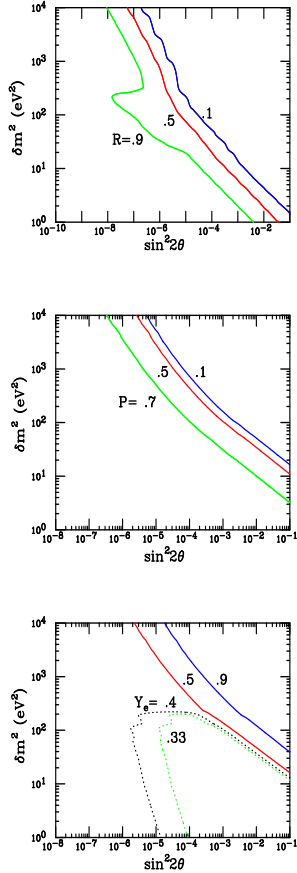


Figure 8. Supernovae and sterile neutrinos.

variations, with a varying degree of theoretical assumptions. We now turn to these.

4.1. Dark Matter

Considerations based on structure formation in the Universe have become a popular way to argue in favour of the need of a massive neutrino [64]. Indeed, by combining the observations of cosmic background temperature anisotropies on large scales performed by the COBE satellite [65] with cluster-cluster correlation data e.g. from IRAS [66] one finds that it is not possible to fit well the data on all scales within the framework of the simplest cold dark matter (CDM) model. The simplest

way to obtain a good fit is to postulate that there is a mixture of cold and hot components, consisting of about 80 % CDM with about 20 % **hot dark matter** (HDM) and a small amount in baryons. The best candidate for the hot dark matter component is a massive neutrino of about 5 eV. It has been argued that this could be the tau neutrino, in which case one might expect the existence of $\nu_e \rightarrow \nu_\tau$ or $\nu_\mu \rightarrow \nu_\tau$ oscillations. Searches are now underway at CERN [67], with a similar proposal at Fermilab. This mass scale is also consistent with the hints in favour of neutrino oscillations reported by the LSND experiment [36].

4.2. Solar Neutrinos

The averaged data collected by the chlorine [68], Kamiokande [69], as well as by the low-energy data on pp neutrinos from the GALLEX and SAGE experiments [70,71] still pose a persisting puzzle, now re-confirmed by the first 200 days of Super-Kamiokande (SK) data. The most recent data can be summarised in Fig. (9) where the theoretical predictions refer to the BP95 SSM prediction of ref. [72]. For the gallium result we have taken the average of the GALLEX [70] and the SAGE measurements [71].

The totality of the data strongly suggests that the solar neutrino problem is real, that the simplest astrophysical solutions are ruled out, and therefore that new physics is needed [73]. The most attractive possibility is to assume the existence of neutrino conversions involving very small neutrino masses. In the framework of the MSW effect [74] the required solar neutrino parameters m^2 and $\sin^2 2\theta$ are determined through a χ^2 fit of the experimental data. In Fig. (10), taken from ref. [75], we show the allowed two-flavour regions obtained in an updated MSW analysis of the solar neutrino data including the the recent SK 200 days data, in the BP95 model for the case of active neutrino conversions. The analysis of spectral distortion as well as day-night effect plays an important role in ruling out large region of parameters. Compared with previously,

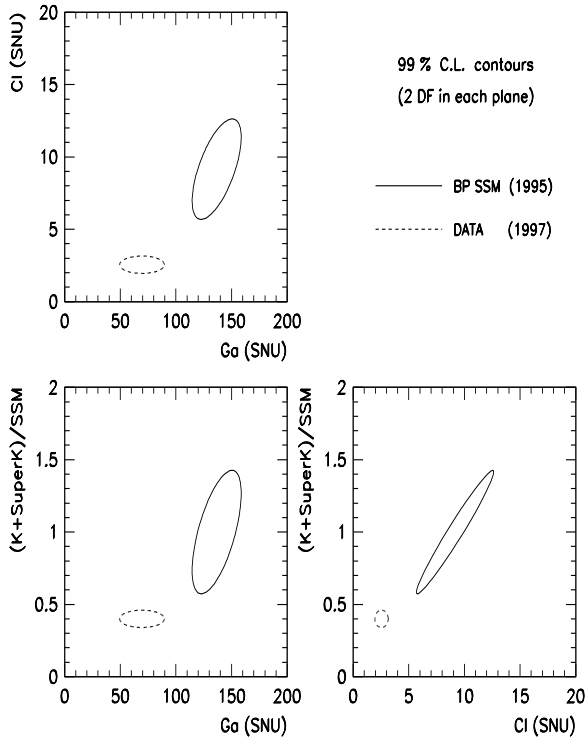


Figure 9. Solar neutrinos: theory versus data.

the impact of the recent SK data is felt mostly in the large mixing solution which, however, does not give as good a fit as the small mixing solution, due mostly to the larger reduction of the ${}^7\text{Be}$ flux found in the later. The most popular alternative solutions to the solar neutrino anomaly include the MSW sterile neutrino conversions, as well as the just-so or vacuum oscillation solution. Recent fits have also been given including the recent SK data [75].

A theoretical point of direct phenomenological interest for Borexino is the study of the possible effect of random fluctuations in the solar matter density [76]. The existence of noise fluctuations at a few percent level is not excluded by the SSM nor by present helioseismology studies. They may strongly affect the ${}^7\text{Be}$ neutrino component of the solar neutrino spectrum so that the Borexino experiment should

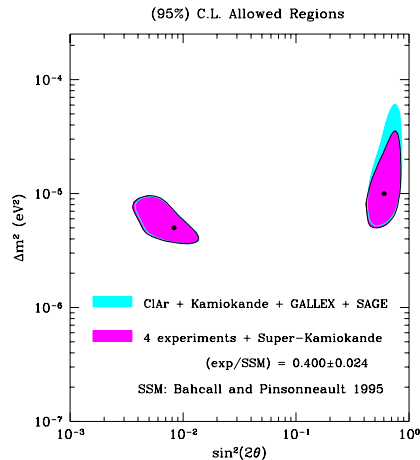


Figure 10. Allowed solar neutrino oscillation parameters for active neutrino conversions.

provide an ideal test, if sufficiently small errors can be achieved. The potential of Borexino in "testing" the level of solar matter density fluctuations is discussed quantitatively in ref. [77].

4.3. Atmospheric Neutrinos

Two water Cerenkov underground experiments, Kamiokande and IMB, and possibly also Soudan2, have indications which support an apparent deficit in the expected flux of atmospheric ν_μ 's relative to that of ν_e 's that would be produced from conventional decays of π 's, K 's as well as secondary muon decays [78]. Although the predicted absolute fluxes of neutrinos produced by cosmic-ray interactions in the atmosphere are uncertain at the 20% level, their ratios are expected to be accurate to within 5%. While some of the experiments, such as Frejus and NUSEX, have not found a firm evidence, it has been argued that there may be a strong hint for an atmospheric neutrino deficit that could be ascribed to neutrino oscillations. Kamiokande data on higher energy neutrinos strengthen the case for an atmospheric neutrino problem. In ref. [79] the impact of recent experimental results on atmospheric neutrinos from experiments such as Superkamiokande and Soudan on the

determinations of atmospheric neutrino oscillation parameters is considered, both for the $\nu_\mu \rightarrow \nu_\tau$ and $\nu_\mu \rightarrow \nu_e$ channels. In performing this re-analysis theoretical improvements in flux calculations as well as neutrino-nucleon cross sections have been taken into account. The relevant oscillation parameters can be determined from a fit and the allowed regions of parameters are found in ref. [79]. One of the features is that the best fit value of the m^2 is somewhat lower than previously obtained.

5. RECONCILING PRESENT HINTS

5.1. Almost Degenerate Neutrinos

The above observations from cosmology and astrophysics do seem to suggest a theoretical puzzle. As can easily be understood just on the basis of numerology, it seems rather difficult to reconcile the three observations discussed above in a framework containing just the three known neutrinos. The only possibility to fit these observations in a world with just the three known neutrinos is if all of them have nearly the same mass ~ 2 eV [80]. This can be arranged, for example in general seesaw models which also contain an effective triplet vacuum expectation value [1,4] contributing to the light neutrino masses. This term should be added to eq. (2). Thus one can construct extended seesaw models where the main contribution to the light neutrino masses (~ 2 eV) is universal, due to a suitable horizontal symmetry, while the splittings between ν_e and ν_μ explain the solar neutrino deficit and that between ν_μ and ν_τ explain the atmospheric neutrino anomaly [5].

5.2. Four-Neutrino Models

A simpler alternative way to fit all the data is to add a fourth neutrino species which, from the LEP data on the invisible Z width, we know must be of the sterile type, call it ν_s . The first scheme of this type gives mass to only one of the three neutrinos at the tree level, keeping the other two massless [81].

Two basic schemes of this type that keep

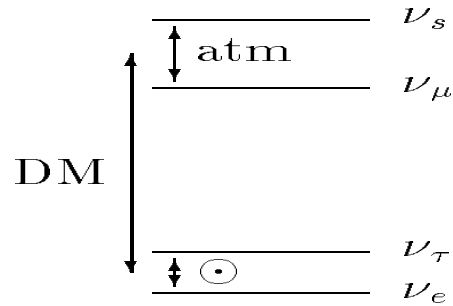


Figure 11. **"Heavy"** Sterile 4-Neutrino Model

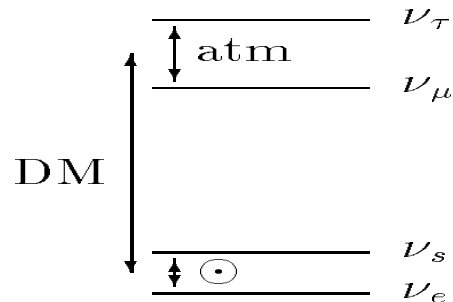


Figure 12. **Light** Sterile 4-Neutrino Model

the sterile neutrino light due to a special symmetry have been suggested. In addition to the sterile neutrino ν_s , they invoke additional Higgs bosons beyond that of the standard model, in order to generate radiatively the scales required for the solar and atmospheric neutrino conversions. In these models the ν_s either lies at the dark matter scale [82] as illustrated in Fig. (12) or, alternatively, at the solar neutrino scale [83]. In the first case the atmospheric neutrino puzzle is explained by ν_μ to ν_s oscillations, while in the second it is explained by ν_μ to ν_τ oscillations. Correspondingly, the deficit of solar neutrinos is explained in the first case by ν_e to ν_τ oscillations, while in the second it is explained by ν_e to ν_s oscillations. In both cases it is possible to fit all observations together. However, in the first case there is a clash with the bounds from big-bang nucleosynthesis. In the latter case the ν_s is at the MSW scale so that nucleosynthesis limits are satisfied. They nicely agree

with the best fit points of the atmospheric neutrino parameters from Kamiokande [79]. Moreover, it can naturally fit the hints of neutrino oscillations of the LSND experiment [36]. Another theoretical possibility is that all active neutrinos are very light, while the sterile neutrino ν_s is the single neutrino responsible for the dark matter [84].

5.3. MeV Tau Neutrino

An MeV range tau neutrino is an interesting possibility to consider for two reasons. First, such mass is within the range of the detectability, for example at a tau-charm factory [32]. On the other hand, if such neutrino decays before the matter dominance epoch, its decay products would add energy to the radiation, thereby delaying the time at which the matter and radiation contributions to the energy density of the universe become equal. Such delay would allow one to reduce the density fluctuations on the smaller scales purely within the standard cold dark matter scenario, and could thus reconcile the large scale fluctuations observed by COBE [65] with the observations such as those of IRAS [66] on the fluctuations on smaller scales.

In ref. [85] a model was presented where an unstable MeV Majorana tau neutrino naturally reconciles the cosmological observations of large and small-scale density fluctuations with the cold dark matter model (CDM) and, simultaneously, with the data on solar and atmospheric neutrinos discussed above. The solar neutrino deficit is explained through long wavelength, so-called **just-so** oscillations involving conversions of ν_e into both ν_μ and a sterile species ν_s , while the atmospheric neutrino data are explained through $\nu_\mu \rightarrow \nu_e$ conversions. Future long baseline neutrino oscillation experiments, as well as some reactor experiments will test this hypothesis. The model assumes the spontaneous violation of a global lepton number symmetry at the weak scale. The breaking of this symmetry generates the cosmologically required decay of the ν_τ with lifetime $\tau_{\nu_\tau} \sim 10^2 - 10^4$ seconds,

as well as the masses and oscillations of the three light neutrinos ν_e , ν_μ and ν_s required in order to account for the solar and atmospheric neutrino data. One can verify that the big-bang nucleosynthesis constraints [53,54] can be satisfied in this model.

6. CONCLUSION

Although unpredicted, neutrino masses, are strongly favoured by present models of elementary particles. On the other hand, they seem to be required to account for present astrophysical and cosmological observations. Neutrino mass effects could show up as spectral distortions in many weak decays, such as nuclear β decays and $\pi\ell 2$ decays. Searches for $\beta\beta_{0\nu}$ decays with enriched germanium could test the quasi-degenerate neutrino scenario that accounts for the hot dark matter, solar and atmospheric neutrino anomalies. Underground experiments Superkamiokande, Borexino, and Sudbury will shed more light on the solar neutrino issue. Oscillation searches with long-baseline experiments both at reactors and accelerators show good prospects for testing the regions of oscillation parameters presently suggested by the atmospheric neutrino anomaly. Finally, new satellite experiments will test different models of structure formation, and shed light on the possible role of neutrinos as dark matter.

Despite all the limits from laboratory experiments, both at accelerators and reactors, as well as the limits from cosmology and astrophysics, there is considerable room for interesting new effects in the neutrino sector. These cover an impressive range of energies and could be probed in experiments performed at underground installations as well as particle accelerators such as LEP and LHC.

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