



# Neutrino masses in astroparticle physics

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## Abstract

The case for small neutrino mass differences from atmospheric and solar neutrino oscillation experiments has become compelling, but leaves the overall neutrino mass scale  $m_\nu$  undetermined. The most restrictive limit of  $m_\nu < 0.8$  eV arises from the 2dF galaxy redshift survey in conjunction with the standard theory of cosmological structure formation. A relation between the hot dark matter fraction and  $m_\nu$  depends on the cosmic number density  $n_\nu$  of neutrinos. If solar neutrino oscillations indeed correspond to the favored large mixing angle MSW solution, then big-bang nucleosynthesis gives us a restrictive limit on all neutrino chemical potentials, removing the previous uncertainty of  $n_\nu$ . Therefore, a possible future measurement of  $m_\nu$  will directly establish the cosmic neutrino mass fraction  $\Omega_\nu$ . Cosmological neutrinos with sub-eV masses can play an interesting role for producing the highest-energy cosmic rays (Z-burst scenario). Sub-eV masses also relate naturally to leptogenesis scenarios of the cosmic baryon asymmetry. Unfortunately, the time-of-flight dispersion of a galactic or local-group supernova neutrino burst is not sensitive in the sub-eV range.

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## 1. Introduction

Atmospheric and solar neutrino experiments provide rather compelling evidence for the phenomenon of flavor oscillations. The celebrated up-down-asymmetry of the atmospheric  $\nu_\mu$  flux measured by Super-Kamiokande is consistently explained by  $\nu_\mu \rightarrow \nu_\tau$  oscillations (Fukuda et al., 2000) with the mixing parameters that are summarized in Table 1. The K2K long-baseline experiment provides a first laboratory confirmation, albeit in a pure disappearance mode (Nishikawa, 2002). The recent results from SNO have largely established active–active flavor oscillations as a solution of the solar neutrino problem (Ahmad et al., 2002a,b). The LMA parameters are strongly favored, but the LOW case may still

be viable (Table 1). Neutrino mass differences that are small compared to the eV scale seem to be established.

The only spanner in the works of this beautiful interpretation is the persistence of the unconfirmed evidence for flavor transformations from the LSND experiment (Eitel, 2000). If interpreted in terms of neutrino oscillations, the mixing parameters from all three sources of evidence are mutually inconsistent. Even including a putative sterile neutrino no longer

Table 1  
Experimental evidence for neutrino flavor oscillations

Evidence	Channel	$\Delta m^2$ [eV <sup>2</sup> ]	$\sin^2 2\theta$
Atmospheric	$\nu_\mu \rightarrow \nu_\tau$	$(1.6-3.9) \times 10^{-3}$	0.92–1
Solar			
LMA	$\nu_e \rightarrow \nu_{\mu\tau}$	$(0.2-2) \times 10^{-4}$	0.2–0.6
LOW	$\nu_e \rightarrow \nu_{\mu\tau}$	$1.3 \times 10^{-7}$	0.92
LSND	$\bar{\nu}_\mu \rightarrow \bar{\nu}_e$	0.2–10	$(0.2-3) \times 10^{-2}$

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provides a good global fit because all three sources of evidence prefer active–active over active–sterile oscillations (Strumia, 2002). It is expected that MiniBooNE at Fermilab will confirm or refute LSND within the upcoming two years (Tayloe, 2002).

As there is no straightforward global interpretation of all indications for neutrino oscillations I will follow the widespread assumption that something is wrong with the LSND signature. If it is due to neutrino conversions after all, something fundamentally new is going on in the neutrino sector. In that case much of the current thinking in this field will have to be revised.

This is certainly the attitude that Dennis Sciama would have taken. He eloquently advocated a cosmological scenario of radiatively decaying dark-matter neutrinos which solves several astrophysical problems, but requires several flavors of light sterile neutrinos and anomalously large electromagnetic transition moments (Adams et al., 1998; Sciama, 1998). No doubt he would have challenged the more conservative approach taken here. The final verdict on neutrino masses and mixings is not yet in, let alone on the more exotic possibilities. The phenomenology of the neutrino sector may turn out to be far richer than envisaged in my presentation of a rather minimal scenario.

In what follows I will always assume that there are three neutrino mass eigenstates separated by the atmospheric and solar mass differences. In this scenario, a number of obvious questions remain open. The 12 and 23 mixing angles are large, the 13 mixing angle is small, but how small? Are there CP-violating phases in the mixing matrix? Are the neutrino masses of Dirac or Majorana nature? Is the ordering of the masses “normal” with  $m_2^2 - m_1^2$  corresponding to the solar and  $m_3^2 - m_2^2$  to the atmospheric splitting, or is it inverted? And finally, what is the overall neutrino mass scale? Are the masses hierarchical with  $m_1 \ll m_2 \ll m_3 \approx 50$  meV or degenerate with  $m_1 \approx m_2 \approx m_3 \gg 50$  meV?

I will focus on these last questions and review the implications of neutrino masses in astrophysics and cosmology. Traditionally, cosmology has provided the most restrictive limits on neutrino masses, and this is again the case using large-scale galaxy redshift surveys in conjunction with the standard

theory of structure formation. Conversely, if the solar LMA solution is indeed correct, the cosmic neutrino number density is well constrained by big-bang nucleosynthesis so that a laboratory measurement of the absolute neutrino masses, for example in the KATRIN tritium experiment (Osipowicz, 2001), would directly establish the cosmic neutrino mass fraction. Moreover, neutrino masses can have a number of other interesting implications in astroparticle physics in the context of cosmic-ray physics, cosmological baryogenesis, and supernova physics.

In Section 2 this review begins with neutrino dark matter and the latest  $m_\nu$  limits from large-scale redshift surveys. Section 3 turns to the related question of how many neutrinos there are in the universe and how this issue connects with the solar neutrino problem. Section 4 deals with  $Z$ -burst scenarios for producing the highest-energy cosmic rays, Section 5 with leptogenesis scenarios for producing the baryon asymmetry of the universe. Section 6 is devoted to the time-of-flight dispersion of supernova neutrinos caused by a non-vanishing  $m_\nu$ . Finally, Section 7 summarizes the status of neutrino masses in astroparticle physics.

## 2. Neutrino dark matter and cosmic structure formation

The cosmic number density of neutrinos and anti-neutrinos per flavor is  $n_\nu = 3/11 n_\gamma$  with  $n_\gamma$  the number density of cosmic microwave photons, and assuming that there is no neutrino chemical potential. With  $T_\gamma = 2.728$  K this translates into  $n_\nu = 112 \text{ cm}^{-3}$ . If neutrinos have masses one finds a cosmic mass fraction

$$\Omega_\nu h^2 = \sum_{\text{flavors}} \frac{m_\nu}{92.5 \text{ eV}}, \quad (1)$$

where as usual  $h$  is the Hubble constant in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ . The requirement that neutrinos do not overclose the universe then leads to the traditional mass limit  $\sum m_\nu \lesssim 40$  eV, an argument that was first advanced in a classic paper by Gershtein and Zeldovich (1966).

Later Cowsik and McClelland (1973) speculated that massive neutrinos could actually constitute the

dark matter of the universe. However, it soon became clear that neutrinos were not a good dark matter candidate for two reasons. The first argument is based on the limited phase space for neutrinos gravitationally bound to a galaxy (Tremaine and Gunn, 1979). As a consequence, if massive neutrinos are supposed to be the dark matter in galaxies, they must obey a *lower* mass limit of some 30 eV for typical spirals, and even 100–200 eV for dwarf galaxies.

Today the most restrictive laboratory limits on the overall neutrino mass scale arise from the Mainz (Weinheimer et al., 1999) and Troitsk (Lobashev et al., 1999) tritium end-point experiments. The current limit is (Weinheimer, 2002)

$$m_\nu < 2.2 \text{ eV} \quad \text{at 95\% CL.} \quad (2)$$

This limit applies to all mass eigenstates if we accept that the mass differences are as small as indicated by the atmospheric and solar oscillation interpretation. This limit is so restrictive that neutrinos as galactic dark matter are completely out of the question, even without any further appeal to cosmic structure formation arguments.

However, cosmic structure formation does place powerful limits on the neutrino mass. The observed structure in the distribution of galaxies is thought to arise from the gravitational instability of primordial density fluctuations. The small masses of neutrinos imply that they stay relativistic for a long time after their decoupling (“hot dark matter”), allowing them to stream freely, thereby erasing the primordial density fluctuations on small scales (Doroshkevich et al., 1980). While this effect does not preclude neutrino dark matter, it implies a top-down scenario for structure formation where large structures form first, later fragmenting into smaller ones. It was soon realized that the predicted properties of the large-scale matter distribution did not seem to agree with observations and that neutrino dark matter was apparently ruled out (White et al., 1983).

Today it is widely accepted that the universe has critical density and that its matter inventory sports several nontrivial components. Besides some 5% baryonic matter (most of it dark) there are some 25% cold dark matter in an unidentified physical form and some 70% of a negative-pressure component (“dark

energy”). And because neutrinos do have mass, they contribute at least 0.1% of the critical density. This fraction is based on a hierarchical mass scenario with  $m_3 = 50 \text{ meV}$ , the smallest value consistent with atmospheric neutrino oscillations.

An upper limit on the neutrino dark matter fraction can be derived from the measured power spectrum  $P_M(k)$  of the cosmic matter distribution. Neutrino free streaming suppresses the small-scale structure by an approximate amount (Hu et al., 1998)

$$\frac{\Delta P_M}{P_M} \approx -8 \frac{\Omega_\nu}{\Omega_M} \quad (3)$$

where  $\Omega_M$  is the cosmic mass fraction in matter, i.e. excluding the dark energy. This effect is illustrated in Fig. 1 where  $P_M(k)$  measured by the 2dF Galaxy Redshift Survey is shown and compared with the predictions for a cold dark matter cosmology with neutrino fractions  $\Omega_\nu = 0, 0.01, \text{ and } 0.05$ , respectively (Elgaroy et al., 2002). When the theoretical curves are normalized to the power at large scales, neutrinos indeed suppress  $P_M(k)$  at large  $k$ .

Based on the 2dFGRS data, Elgaroy et al. (2002) and Hannestad (2002) find limits on  $\Sigma m_\nu$  in the range 1.8–3.0 eV, depending on the assumed priors for other cosmological parameters, notably the Hubble constant, the overall matter fraction  $\Omega_M$ , and the tilt of the spectrum of primordial density fluctuations. For a reasonable set of priors one may adopt

$$\sum_{\text{flavors}} m_\nu < 2.5 \text{ eV} \quad (4)$$

at a statistical confidence level of 95%. This limit corresponds approximately to the dot-dashed ( $\Omega_\nu = 0.05$ ) curve in Fig. 1, i.e. neutrinos may still contribute as much as 5% of the critical density, about as much as baryons.

Within the framework of the standard theory of structure formation, the largest systematic uncertainty comes from the unknown biasing parameter  $b$  which relates the power spectrum of the galaxy distribution to that of the true underlying matter distribution,  $P_{\text{Gal}}(k) = b^2 P_M(k)$ . The biasing parameter is one of the quantities which must be taken into account when fitting all large-scale structure data to observations of the galaxy distribution and of the temperature fluctuations of the cosmic microwave background radiation. In the future the Sloan Digital

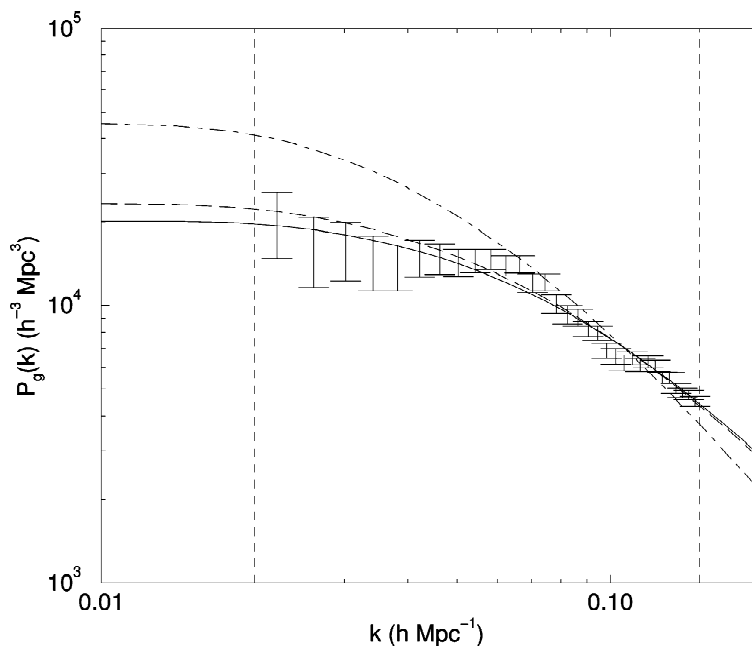


Fig. 1. Power spectrum of the galaxy distribution function measured by the 2dF Galaxy Redshift Survey. The solid line is the theoretical prediction without neutrino dark matter ( $\Omega_\nu = 0$ ), the dashed line for  $\Omega_\nu = 0.01$ , and dot-dashed for  $\Omega_\nu = 0.05$ . The other cosmological parameters are  $\Omega_M = 0.3$ ,  $\Omega_\Lambda = 0.7$ ,  $h = 0.70$ , and  $\Omega_B h^2 = 0.02$ . [Figure from Elgaroy et al. (2002) with permission.]

Sky Survey will have greater sensitivity to the overall shape of  $P_{\text{Gal}}(k)$  on the relevant scales, allowing one to disentangle more reliably the impact of  $b$  and  $\Omega_\nu$  on  $P_M(k)$ . It is foreseen that one can reach a sensitivity of  $\Sigma m_\nu \sim 0.65$  eV (Hu et al., 1998).

For a degenerate neutrino mass scenario the limit of Eq. (4) corresponds to a limit on the overall mass scale of  $m_\nu < 0.8$  eV, far more restrictive than the laboratory limit Eq. (2). However, the KATRIN project for improving the tritium endpoint sensitivity is foreseen to reach the 0.3 eV level (Osipowicz, 2001), similar to the anticipated sensitivity of future cosmological observations. If both methods yield a positive signature, they will mutually re-enforce each other. If they both find upper limits, again they will be able to cross-check each other's constraints.

### 3. How many neutrinos in the universe?

The laboratory limits or future measurements of  $m_\nu$  and the cosmological limits or future discovery of

a hot dark matter component can be related to each other if the cosmic neutrino density  $n_\nu$  is known. However, the cosmic neutrino background cannot be measured with foreseeable methods so that one depends on indirect arguments for determining  $n_\nu$ . Even if we accept that there are exactly three neutrino flavors as indicated by the  $Z^0$  decay width and that they were once in thermal equilibrium does not fix  $n_\nu$ . Each flavor is characterized by an unknown chemical potential  $\mu_\nu$  or a degeneracy parameter  $\xi_\nu = \mu_\nu/T$ , the latter being a quantity invariant under cosmic expansion. While the observed baryon-to-photon ratio suggests that the degeneracy parameters of all fermions are very small, for neutrinos this is an assumption and not an established fact.

In the presence of a degeneracy parameter  $\xi_\nu$ , the number and energy densities of relativistic neutrinos plus anti-neutrinos in thermal equilibrium are

$$n_\nu = T_\nu^3 \frac{3\zeta_3}{2\pi^2} \left[ 1 + \frac{2\ln(2)}{3\zeta_3} \xi_\nu^2 + \frac{\xi_\nu^4}{72\zeta_3} + O(\xi_\nu^6) \right], \quad (5)$$

$$\rho_\nu = T_\nu^4 \frac{7\pi^2}{120} \left[ 1 + \frac{30}{7} \left( \frac{\xi_\nu}{\pi} \right)^2 + \frac{15}{7} \left( \frac{\xi_\nu}{\pi} \right)^4 \right]. \quad (6)$$

Therefore, if chemical potentials are taken to be the only uncertainty of the cosmic neutrino density,  $n_\nu$ , can only be larger than the standard value. In this sense the structure formation limits on the hot dark matter fraction provide a conservative limit on the neutrino mass scale  $m_\nu$ . Conversely, a laboratory limit on  $m_\nu$  does not limit the hot dark matter fraction while a positive future laboratory measurement of  $m_\nu$  provides only a lower limit on  $\Omega_\nu$ .

Big-bang nucleosynthesis (BBN) is affected by  $\rho_\nu$ , in that a larger neutrino density increases the primordial expansion rate, thereby increasing the neutron-to-proton freeze-out ratio  $n/p$  and thus the cosmic helium abundance. Therefore, the observed helium abundance provides a limit on  $\rho_\nu$  which corresponds to some fraction of an effective extra neutrino species. In addition, however, an electron neutrino chemical potential modifies  $n/p \propto \exp(-\xi_{\nu_e})$ . Depending on the sign of  $\xi_{\nu_e}$  this effect can increase or decrease the helium abundance and can compensate for the  $\rho_\nu$  effect of other flavors (Kang and Steigman, 1992). If  $\xi_{\nu_e}$  is the only chemical potential, BBN provides the limit

$$-0.01 < \xi_{\nu_e} < 0.07. \quad (7)$$

Including the compensation effect, the only upper limit on the radiation density comes from precision measurements of the power spectrum of the temperature fluctuations of the cosmic microwave background radiation and from large-scale structure measurements. A recent analysis yields the allowed regions (Hansen et al., 2002)

$$-0.01 < \xi_{\nu_e} < 0.22, \quad |\xi_{\nu_{\mu,\tau}}| < 2.6, \quad (8)$$

in agreement with similar results of Hannestad (2001) and Kneller et al. (2001).

However, the observed neutrino oscillations imply that the individual flavor lepton numbers are not conserved and that in true thermal equilibrium all neutrinos are characterized by one single chemical potential  $\xi_\nu$ . If flavor equilibrium is achieved before  $n/p$  freeze-out the restrictive BBN limit on  $\xi_{\nu_e}$  applies to all flavors, i.e.  $|\xi_\nu| < 0.07$ , implying that the cosmic number density of neutrinos is fixed to

within about 1%. In that case the relation between  $\Omega_\nu$  and  $m_\nu$  is uniquely given by the standard expression Eq. (1).

The approach to flavor equilibrium in the early universe by neutrino oscillations and collisions was recently studied by Lunardini and Smirnov (2001), Dolgov et al. (2002), Wong (2002), and Abazajian et al. (2002). Assuming the atmospheric and solar LMA solutions, an example for the cosmic flavor evolution is shown in Fig. 2. The detailed treatment is rather complicated and involves a number of subtleties related to the large weak potential caused by the neutrinos themselves as they oscillate. The intriguing phenomenon of synchronized flavor oscillations (Samuel, 1993; Pastor et al., 2001) plays an important and subtle role.

The practical bottom line, however, is rather simple. Effective flavor equilibrium before  $n/p$  freeze-out is reliably achieved if the solar oscillation parameters are in the favored LMA region. In the LOW region, the result depends sensitively on the value of the small but unknown third mixing angle  $\theta_{13}$ . In the SMA and VAC regions, which are now heavily disfavored, equilibrium is not achieved. Therefore, establishing LMA as the correct solution of the solar neutrino problem amounts in our context to counting the number of cosmological neutrinos and thus to establishing a unique relationship between the neutrino mass scale  $m_\nu$  and the cosmic neutrino density  $\Omega_\nu$ . A final confirmation of LMA is expected by the Kamland reactor experiment (Shirai, 2002) within the next few months of this writing.

#### 4. Z-burst scenario for the highest-energy cosmic rays

The number density and mass of cosmic background neutrinos is also relevant for the propagation of extremely high-energy (EHE) neutrinos that may be produced by hitherto unknown astrophysical sources at cosmological distances. Assuming that neutrinos with energies in the  $10^{21}$ – $10^{22}$  eV range are somewhere injected in the universe, and assuming that the cosmic background neutrinos have masses in the neighborhood of 1 eV, the center-of-momentum energy is in the neighborhood of the  $Z^0$  boson mass.

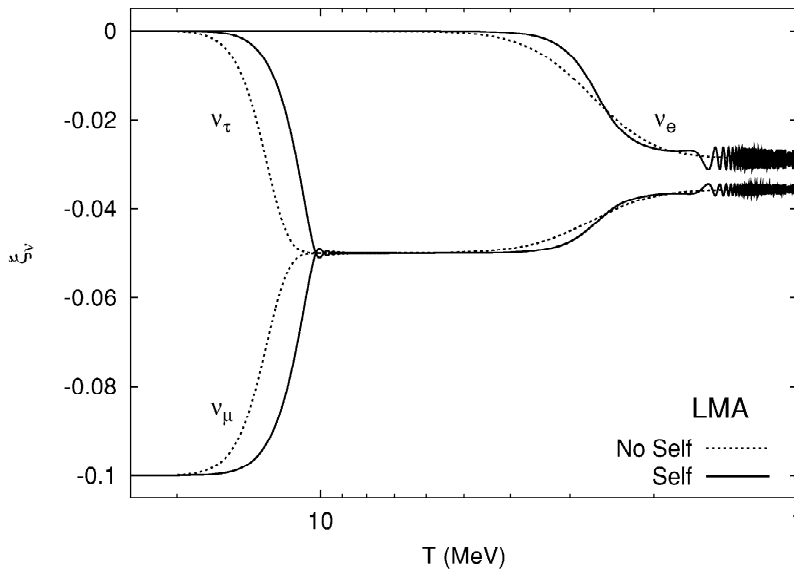


Fig. 2. Cosmological evolution of neutrino degeneracy parameters assuming the initial values  $\xi_{\nu_e} = \xi_{\nu_\tau} = 0$  and a non-zero value for  $\xi_{\nu_\mu}$ . The neutrino mixing parameters were chosen according to the atmospheric and solar LMA solutions, and taking  $\theta_{13} = 0$ . [Figure from Dolgov et al. (2002) with permission.]

Put another way, the required neutrino energy for the  $Z^0$ -resonance is

$$E_\nu = \frac{m_Z^2}{2m_\nu} = \frac{4.2 \times 10^{21} \text{ eV}}{m_\nu/\text{eV}}. \quad (9)$$

The subsequent decay of the  $Z^0$ -bosons on average produces two nucleons, 10  $\pi^0$  mesons which subsequently decay into photons, and 17  $\pi^\pm$  mesons which subsequently decay into  $e^\pm$  and neutrinos. These Z-bursts would be a source for cosmic rays at the upper end of the observed spectrum, i.e. with energies at and above  $10^{20}$  eV (Weiler, 1999; Fargion et al., 1999; Fodor et al., 2002).

The motivation for considering this sort of scenario is the difficulty of explaining the observed highest-energy cosmic rays which exceed the Greisen–Zatsepin–Kuzmin (GZK) cutoff, i.e. which cannot reach us from large distances because the cosmic microwave background renders the universe opaque for protons around and above  $10^{20}$  eV. No compelling explanation for the super-GZK cosmic rays exists, leaving much room and motivation for speculations and exotic scenarios (Sigl, 2001). Of course, the Z-burst scenario is not a real explanation

because it appeals to unknown EHE neutrino sources producing huge fluxes and with rather exotic properties (Kalashev et al., 2002).

However, one should view this scenario as an opportunity. The required EHE neutrino fluxes are below current limits, but are accessible to future experiments such as the IceCube neutrino telescope at the South Pole or the Auger air shower array in Argentina (Fig. 3). Therefore, if such fluxes are detected they provide a handle on sub-eV masses of the cosmic background neutrinos by virtue of the Z-burst production of super-GZK cosmic rays. This would be the only evidence for the cosmic neutrino background and its properties other than provided by big-bang nucleosynthesis.

## 5. Leptogenesis

Neutrino masses in the sub-eV range can play an interesting albeit indirect role for creating the baryon asymmetry of the universe (BAU) in the framework of leptogenesis scenarios (Fukugita and Yanagida, 1986). The main ingredients are those of the usual see-saw scenario for small neutrino masses. Restrict-

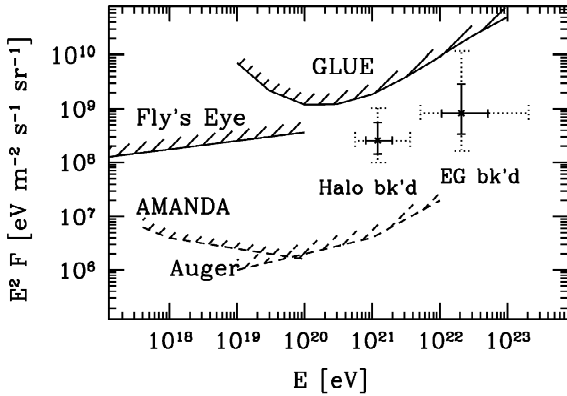


Fig. 3. Extremely high-energy neutrino fluxes. The crosses represent two scenarios for explaining the highest-energy cosmic rays by Z-bursts. The upper hatched curves are the current experimental limits, the lower ones the foreseen sensitivity of future experiments. [Figure from Fodor et al. (2002) with permission.]

ing ourselves to a single family, the relevant parameters are the heavy Majorana mass  $M$  of the ordinary neutrino's right-handed partner and a Yukawa coupling  $g_\nu$  between the neutrinos and the Higgs field  $\Phi$ . The observed neutrino then has a Majorana mass

$$m_\nu = \frac{g_\nu^2 \langle \Phi \rangle^2}{M} \tag{10}$$

that can be very small if  $M$  is large, even if the Yukawa coupling  $g_\nu$  is comparable to that for other fermions. Here,  $\langle \Phi \rangle$  is the vacuum expectation value of the Higgs field which also gives masses to the other fermions.

The heavy Majorana neutrinos will be in thermal equilibrium in the early universe. When the temperature falls below their mass, their density is Boltzmann suppressed. However, if at that time they are no longer in thermal equilibrium, their abundance will exceed the equilibrium distribution. The subsequent out-of-equilibrium decays can lead to the net generation of lepton number. CP-violating decays are possible by the usual interference of tree-level with one-loop diagrams with suitably adjusted phases of the various couplings. The generated lepton number excess will be re-processed by standard-model sphaleron effects which respect  $B - L$  but violate  $B + L$ . It is straightforward to generate the observed BAU by this mechanism.

The requirement that the heavy Majorana neut-

rininos freeze out before they get Boltzmann suppressed implies an upper limit on the combination of parameters  $g_\nu^2/M$  that also appears in the see-saw formula for  $m_\nu$ . The out-of-equilibrium condition thus implies an upper limit on  $m_\nu$ . Detailed scenarios for generic neutrino mass and mixing schemes have been worked out, see Buchmüller and Plümacher (2000) for a recent review and citations of the large body of pertinent literature.

The bottom line is that neutrino mass and mixing schemes suggested by the atmospheric and solar oscillation data are nicely consistent with plausible leptogenesis scenarios. Of course, it is an open question of how one would go about to verify or falsify leptogenesis as the correct baryogenesis scenario. Still, it is intriguing that massive neutrinos may have a lot more to do with the baryons than with the dark matter of the universe!

### 6. Time-of-flight dispersion of supernova neutrinos

In principle, neutrino masses can be measured by the dispersion of a neutrino burst from a pulsed astrophysical source, notably a supernova (SN). The time-of-flight delay of massive neutrinos with energy  $E_\nu$  is

$$\Delta t = \frac{m_\nu^2}{2E_\nu^2} D \tag{11}$$

where  $D$  is the distance to the source. Therefore, if a neutrino burst has the intrinsic duration  $\Delta t$  and the energies are broadly distributed around some typical energy  $E_\nu$ , one is approximately sensitive to masses

$$m_\nu > 10 \text{ eV} \left( \frac{E_\nu}{10 \text{ MeV}} \right) \left( \frac{\Delta t}{\text{s}} \right)^{1/2} \left( \frac{10 \text{ kpc}}{D} \right)^{1/2} . \tag{12}$$

The measured  $\bar{\nu}_e$  burst of SN 1987A was characterized by  $E \approx 20 \text{ MeV}$ ,  $\Delta t \approx 10 \text{ s}$ , and  $D \approx 50 \text{ kpc}$ , leading to the well-known limit  $m_\nu \lesssim 20 \text{ eV}$  (Loredo and Lamb, 1989). In a recent re-analysis Loredo and Lamb (2002) find a somewhat more restrictive limit. Either way, these results are only of historical interest because the tritium and cosmological limits are now much more restrictive.

The neutrino burst from a future galactic SN could yield more restrictive limits because one would expect up to 8000 events in a detector like Super-Kamiokande for a typical galactic distance of around 10 kpc. With such a high-statistics signal the relevant time-scale  $\Delta t$  is the fast rise-time of around 100 ms rather than the overall burst duration of several seconds. Therefore, one is sensitive to smaller masses than the SN 1987A burst, despite the shorter baseline. From detailed Monte-Carlo simulations Totani (1998) infers that Super-Kamiokande would be sensitive to about  $m_\nu \gtrsim 3$  eV, almost independently of the exact distance. (At a larger distance one gains baseline but loses statistics, two effects that cancel for a given detector size.)

Conceivably this sensitivity could be improved if a gravitational wave signal could be detected preceding the neutrinos, signifying the instant of the stellar collapse (Fargion, 1981; Arnaud et al., 2002). In this case one may be sensitive to about 1 eV.

It is also conceivable that a SN collapses to a black hole some short time after the original collapse. In this case the neutrino signal would abruptly terminate (within  $\Delta t \lesssim 0.5$  ms), thereby defining a very short time scale. Beacom et al. (2000, 2001) found that Super-Kamiokande would be sensitive to  $m_\nu \gtrsim 1.8$  eV.

In the foreseeable future megatonne neutrino detectors may be constructed to search for proton decay and to perform precision long-baseline oscillation measurements with neutrino beams. Such detectors would have about 30 times the fiducial volume of Super-Kamiokande. The exact  $m_\nu$  sensitivity for such an instrument has not been worked out. With a megatonne detector one could measure SN neutrinos throughout the local group of galaxies. From Andromeda at a distance of 750 kpc one would get around 50 events. Using the overall signal duration for  $\Delta t$  yields a sensitivity in the few eV range.

The only conceivable time-of-flight technique that could probe the sub-eV range involves Gamma-Ray Bursts (GRBs) which have been speculated to be strong neutrino sources. If the neutrino emission shows time structure on the millisecond scale, and assuming a cosmological distance of 1 Gpc, one would be sensitive to neutrino masses  $m \gtrsim 0.1$  eV  $E/\text{GeV}$ . Therefore, observing millisecond time structure in sub-GeV neutrinos from a GRB would be sensitive

to the sub-eV mass scale (Halzen and Jaczko, 1996; Choubey and King, 2002).

## 7. Discussion and summary

The compelling detection of flavor oscillations in the solar and atmospheric neutrino data have triggered a new era in neutrino physics. In the laboratory one will proceed with precision experiments aimed at measuring the details of the mixing matrix. Future tritium decay experiments may well be able to probe the overall neutrino mass scale down to the 0.3 eV range, but if the absolute masses are smaller, it will be very difficult to measure them, and the overall mass scale may remain the most important unknown quantity in neutrino physics for a long time to come.

Unfortunately, it is unlikely that astrophysical time-of-flight methods will help much. Foreseeable SN neutrino detectors are sensitive to eV masses, but not the sub-eV range. On the bright side this means that the measured neutrino light-curve of a future galactic SN will faithfully represent the source without much modifications by neutrino dispersion.

Cosmological large-scale structure data at present provide the most restrictive limit on neutrino masses of  $\Sigma m_\nu < 2.5$  eV, corresponding to  $m_\nu < 0.8$  eV in a degenerate mass scenario. A rigorous relationship between the cosmic hot dark matter fraction  $\Omega_\nu$  and  $m_\nu$  depends on the cosmic neutrino density  $n_\nu$ . If the solar LMA solution is correct, big-bang nucleosynthesis constrains  $n_\nu$  without further assumptions about the neutrino chemical potentials. In the LMA case neutrinos reach de-facto flavor equilibrium before the epoch of weak-interaction freeze out.

While neutrinos do not play a dominant role for dark matter or structure formation, the mass and mixing schemes suggested by the oscillation experiments are nicely consistent with leptogenesis scenarios for creating the cosmic baryon asymmetry. Therefore, massive neutrinos may be closely related to the baryons in the universe, not the dark matter.

If extremely-high energy neutrinos will be observed in future, the Z-burst scenario provides a handle on the cosmic background neutrinos and their mass through the observed cosmic rays near the GZK cutoff.

The great advance in our knowledge of neutrino



properties together with the cosmological precision information has rendered the question of neutrino masses in astrophysics and cosmology far more subtle than it looked only a few years ago. We will not know if the accumulation of new results would have persuaded Dennis Sciama that nature has used massive neutrinos perhaps in different ways for cosmology than he himself had imagined for so long. Either way, the connection between neutrino properties and astroparticle physics remains of fundamental interest.

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