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Cosmological Implications of Neutrino Mass

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Abstract In this paper the interplay between cosmology, astrophysics, accelerator and non-accelerator experiments, aimed to understand the properties and ultimately the nature of the elusive neutrino, as known in the mid A. D. 2004 is summarized.

Key words: Cosmology: early universe – cosmological parameters – observations – elementary particles

1 INTRODUCTION

The existence of a neutral almost undetectable particle was proposed in 1930 by W. Pauli in an apologetic briefcard sent to the "Radioactive Ladies and Gentlemen" participating to a nuclear physics workshop held in Tübingen, as a "*verzweifelten Ausweg*" (desperate way out) to save energy conservation and statistics in beta decay. After the discovery of the neutron by J. Chadwick in 1932, Fermi nicknamed the Pauli particle "neutrino", that is actually an italian word which means "little neutron". Not only Fermi gave the name to the neutrino but also understood its role in physics (Fermi 1934) originating the theory of weak interactions. In the original Fermi's theory beta-decay was a process that converts a proton into a neutron with the emission of an electron and a neutrino. The electron is coupled with the proton by Coulomb interaction while the neutrino couples to the electron and the heavy components of the nucleus by weak force only.

The first evidence that free neutrinos were actually emitted by nuclear reactors has been obtained by Reines & Cowan (1953), exploiting the inverse beta decay $\overline{\nu}+p \rightarrow e^{+}+n$ occurring in hydrogenous liquid scintillator. As shown in the timeline of neutrino physics progress, reported in Figure 1, we are living in very exciting times, for this type of physics. It is remarkable that cosmology, astrophysics and accelerator experiments have so effectively cooperated in answering the more fundamental questions about neutrinos. In this paper I will address some of these questions, focalizing on the more relevant results obtained by the three type of techniques.

2 NUMBER OF NEUTRINO SPECIES

2.1 Limits from Big Bang Nucleosynthesis

The prediction on the limit to the number of light neutrino species is one of the most remarkable contribution of cosmology to neutrino physics. In fact extra neutrino species would have contributed to the total energy density, speeding up the expansion of the universe (see *e.g.* Steigman, Schramm & Gunn 1977), regulated by the Friedmann-Lemaitre equation:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\,\pi}{3} G_{\rm N}\, \rho, \tag{1}$$

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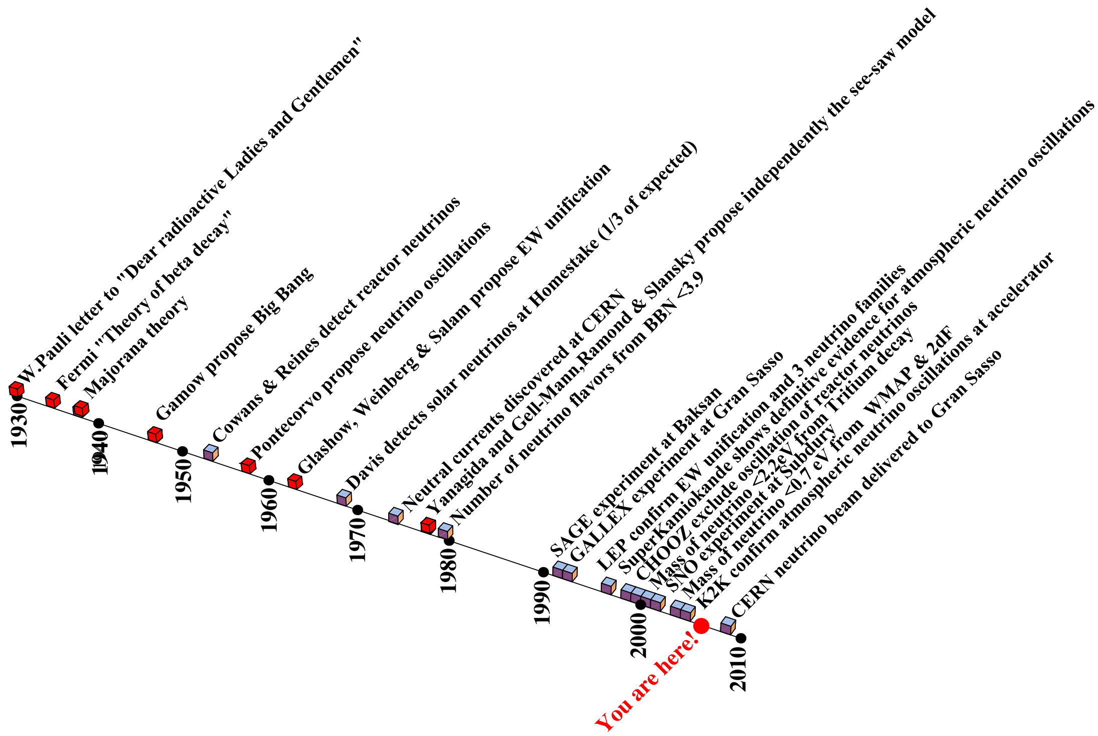

Figure 1 Neutrino timeline.

where ρ is the total energy density. In the radiation dominate era we have

$$\rho \simeq \frac{\pi^2}{30}\left(\sum_b g_b + \frac{7}{8}\sum_f g_f\right)\, T^4 = \frac{\pi^2}{30}\, g_*(T)\, T^4\,, \tag{2}$$

where the sums are extended to all the particle species with mass $m \ll T$. Inserting Eq. (2) into the Eq. (1), we have

$$H(T) = \sqrt{\frac{8\pi}{3} G_{\rm N}\, \rho} \simeq 1.66\, \sqrt{g_*(T)}\, \frac{T^2}{M_{\rm P}}\,, \tag{3}$$

where $M_{\rm P} = \sqrt{G_{\rm N}} = 1.22 \times 10^{19}$ GeV is the Planck mass. The neutron to proton ratio will conserve the equilibrium value $n/p = \exp[-\Delta m/T]$, being Δm the mass difference between neutron and proton, if the reaction $n \leftrightarrows p + e^- + \nu_{\rm e}$ proceeds faster then the expansion of the Universe. In the temperature range $m_{\rm e} \leq T \leq m_\mu$ we expect

$$g_*(T) = \left[g_\gamma + \frac{7}{8}\,(g_{\rm e} + N_\nu\, g_\nu)\right]. \tag{4}$$

The statistical weights are obtained counting two polarization states for the photon, four helicity state for the electron and two for the neutrino. In conclusion we have that the expansion will be speed-up by a factor

$$\xi = \frac{H}{H(N_\nu = 3)} = \left[1 + \frac{7}{43}(N_\nu - 3)\right]^{\frac{1}{2}}\,, \tag{5}$$

where N_ν is the number of neutrino species with mass $m_\nu \leq 1$ MeV. The effect of this speed-up is to produce a higher abundance of ^{4}He. The observational limits to the primordial abundance of ^{4}He known in 1977 lead to the constraint $N_\nu \leq 5$. Burles *et al.* (1979) have refined this limit obtaining $N_\nu \leq 3.2$ (95%

C.L.). It is worth noticing that this limit holds if one exclude large neutrino degeneracy and large magnetic fields. On the other side the fact that the number of light neutrino species is 3 allows to set limits on this possible perturbations of on the cosmological production of light elements.

2.2 Limits from SN Explosion

The number of neutrino species is also limited by the direct observation of neutrinos from SN explosion (for a review see *e.g.* Denegri, Sadoulet & Spiro 1990), that until now has been possible only for the SN1987A in the Large Magellanic Cloud (Hirata *et al.* 1987, Bionta *et al.* 1987).

The total energy released during the collapse of the iron core will be

$$\Delta E = \zeta G_{\rm N}\, M_{\rm NS}^2 \left(\frac{1}{R_{\rm NS}} - \frac{1}{R_{\rm IC}}\right) \simeq G_{\rm N}\,\frac{M_{\rm NS}^2}{R_{\rm NS}}\,, \tag{6}$$

where $M_{\rm NS}$ is the mass of the collapsed object, $R_{\rm NS}$ its final radius and $R_{\rm IC} \gg R_{\rm NS}$ the initial radius of the iron core and ζ a prefactor of the order of 1 which depends from the stratification of the mass distribution. After the $\nu_{\rm e}$ neutronization peak, emitted during the initial rapid cooling (timescale ≈ 1 s), the thermalization neutrinos are produced by neutral current reaction $e^+e^- \leftrightarrows \nu_i\,\overline{\nu}_i$, where $i = e, \mu, \tau, ..., N_\nu$ (Burrows & Lattimer 1986; Mayle, Wilson & Schramm 1987). If on the Earth we detect only $\overline{\nu}_e$, we have

$$\Delta E \geq N_\nu \int_0^\infty 2\, L_{\overline{\nu}_e}\, dt\,, \tag{7}$$

where $L_{\overline{\nu_e}}$ is the inferred antineutrino luminosity at the source. Bahcall *et al.* (1987) have fitted the angular and energy distributions of the neutrinos from SN1987A detected by Kamiokande and IMB with a single temperature $T_{\overline{\nu}_e} = 4.1^{+1.0}_{-0.4}$ MeV and a fluency $\Phi_{\overline{\nu}_e} = 0.5^{+0.2}_{-0.35} \times 10^{10}$ cm^{-2} (Bahcall, Piran,Press & Spergel 1987). Using the "short distance" of the LMC estimated by Stanek, Zaritsky & Harris (1998) $R_{\rm LMC} = 41.2 \pm 0.6 \pm 1.7$ kpc, we derive an upper limit to the antineutrino luminosity integrated over time $\int L_{\overline{\nu}_e}\, dt \geq 4.2 \times 10^{52}$ erg. Therefore assuming $\Delta E \simeq 1.5 \times 10^{53}$ erg we have the limit $N_\nu \leq 3.6$ (95% C.L.).

2.3 Limits from Accelerators

After 1989 the limits to the number of light neutrino flavor obtained from cosmology and astrophysics have only an historical interest. In fact in 1989 after the runs of Large Electron and Positron collider (LEP) at CERN the number of types of neutrino with mass $m < M_Z/2 \simeq 45.5$ GeV has been determined from the width of the Z^0 vector boson. The most precise measurements of the number of light neutrino types N_ν come from studies of Z^0 production. The invisible partial width, $\Gamma_{\rm inv} = \Gamma_Z - \Gamma_{\rm had} - \Gamma_{\ell\ell}(3-\delta\tau)$ ($\delta\tau$ corrects for the τ mass effect), is determined by subtracting the measured visible partial widths, corresponding to Z^0 decays into quarks and charged leptons, from the total Z^0 width. The invisible width is assumed to be due to N_ν light neutrino species each contributing the neutrino partial width $\Gamma_{\nu\nu}$ as given by the Standard Model

$$(\Gamma_{\nu\nu})_{\rm SM} = G_F \frac{M_Z^3}{12\pi\sqrt{2}} \simeq 180 \text{ MeV}, \tag{8}$$

while the predicted value of $\Gamma_{\ell\ell}$ is

$$(\Gamma_{\ell\ell})_{\rm SM} = (\Gamma_{\nu\nu})_{\rm SM}\left[(2\sin^2\theta_W)^2 + (2\sin^2\theta_W - 1)^2\right] \simeq 90 \text{ MeV}. \tag{9}$$

In order to reduce the model dependence, the Standard Model value for the ratio of the neutrino to charged leptonic partial widths $(\Gamma_{\nu\nu}/\Gamma_{\ell\ell})_{\rm SM} = 1.991 \pm 0.001$ is used instead of $(\Gamma_{\nu\nu})_{\rm SM}$ to determine the number of light neutrino types, with the formula

$$N_\nu = \frac{\Gamma_{\rm inv}(\text{meas})}{\Gamma_{\ell\ell}(\text{meas})} \left(\frac{\Gamma_{\nu\nu}}{\Gamma_{\ell\ell}}\right)^{-1}_{\rm SM}. \tag{10}$$

The combined result from the four LEP experiments is $N_\nu = 2.984 \pm 0.008$ (Drees 2001). It is worth noticing that this constraints exclude also neutrinos with mass in the range $2 \text{ GeV} \leq m \leq 45.5$ GeV that is not excluded by cosmological arguments (see discussion above in §2.1).

3 ABSOLUTE NEUTRINO MASSES

3.1 Limit from End Point of Beta Spectrum

In his original 1934 paper Fermi predicted the momentum distribution of the emitted β ray, showing how the higher tail of the spectrum would be affected by a finite mass of the neutrino. His estimate was that the existing data allowed to state that the neutrino was at least 500 times lighter then the electron.

The high energy tail of the beta-decay spectrum $^3\mathrm{H} \rightarrow ^3\mathrm{He} + \mathrm{e}^+ + \overline{\nu}_\mathrm{e}$ with the emission of a massive neutrino with mass m_{ν_e} is predicted to be in case of V-A coupling

$$\frac{dN_\mathrm{e}}{dE} = R(E)\,(E_0 - E)\sqrt{(E_0 - E)^2 - m_{\overline{\nu}_e}^2}\,, \tag{11}$$

where $E = p^2/2m_e$ is the kinetic energy of the electron and E_0 will be the effective end point of the spectrum for $m_{\overline{\nu}_e} = 0$, namely $E_0 = M_{^3\mathrm{H}} - (M_{^3\mathrm{He}} + m_e) - \Delta E$, being ΔE a correction which should take into account of 1) the energy of the final states of the daughter $(^3\mathrm{He}\,^3\mathrm{H})^+$ molecule, 2) the energy loss by the electron in the ^{3}H film, 3) the excitation of neighbor ^{3}H molecules and 4) the self-charging of ^{3}H film due to electron escape.

The two more recent experiments (Kraus *et al*. 2004, Lobashev *et al*. 2001) gives values of neutrino masses consistent with zero. However unphysical best-fitted values $m_{\overline{\nu}_e}^2 < 0$ of both experiments, due to an excess of counts at the end point, makes the interpretation of tritium beta decay experiments not without ambiguity (see e.g. Eidelman *et al*. 2004).

3.2 Cosmological Limit to Neutrino Masses

Copious numbers of neutrinos were produced in the early universe. As the rapporteur of the "APS Multi-Divisional Neutrino Study Committee" said *"We live within a matrix of neutrinos, which number far exceed that of all the atoms in the Universe"*. Luckily enough neutrinos have a very small mass otherwise they could have shortened the life of the Universe and we could not be here today. The reason why neutrinos are so copious today is that, due to the weakness of the weak interactions, they decoupled very early from any other particle and field. Before that neutrinos were in thermal equilibrium with the electrons by charged and neutral current scattering $\overset{(-)}{\nu}_i + e^\pm \leftrightarrows \overset{(-)}{\nu}_i + e^\pm$ and neutral current annihilations $\nu_i + \overline{\nu}_i \leftrightarrows e^+ + e^-$, where $i = e, \mu, \tau$ will be the neutrino flavor, as long as the collision rate Γ_ν will be larger then the expansion rate of the Universe H. Therefore the neutrino will be also in equilibrium with the photon bath because the e.m. annihilation of electrons $e^+ e^- \rightleftarrows \gamma\gamma$ will proceed very fast. The thermal averaged cross can be parameterized, for $T \ll M_\mathrm{W}$

$$\left\langle \sigma_{\overset{(-)}{\nu}_i} v \right\rangle_T \simeq \beta_i(T) \frac{\alpha_\mathrm{W}^2 T^2}{M_\mathrm{W}^4}, \tag{12}$$

where $\alpha_\mathrm{W} \approx 1/30$ is the weak coupling constant, $M_\mathrm{W} = 83$ GeV the mass of the vector boson, and $\beta_i(T)$ is a threshold function that saturates to the value $\beta_i(T) \rightarrow \mathcal{O}(10^{-1})$ for $T \gg m_\mathrm{e}$, being $\beta_\mathrm{e} > \beta_{\mu,\tau}$. The freeze-out of neutrinos with flavor i and negligible mass, will take place when $n_{\overset{(-)}{\nu}_i} \langle \sigma\, v \rangle_{T_{d_i}} = H(T_{d_i})$, where $n_{\overset{(-)}{\nu}_i} \sim T^3$, therefore assuming $N_\nu = 3$ we obtain

$$T_{d_i} \simeq \left(\frac{1.66\,\sqrt{g_*(T_{d_i})}\,M_\mathrm{W}^4}{\beta_i(T_{d_i})\,M_\mathrm{P}} \right)^{\frac{1}{3}}\,, \tag{13}$$

which gives a value $T_{d_e} \simeq 2.4$ MeV, being $T_{d_e} < T_{d_\mu} = T_{d_\tau} \simeq 3.7$ MeV. The exact value of the decoupling temperature is not relevant if one neglects the electron mass. The important fact is that neutrinos were largely relativistic at decoupling, therefore their number density evolves as $n_\nu \sim T_\nu^3$. Taking into account the reheating of the photon bath, due to annihilations of electrons when $T \ll m_e$ we have that at present is $T_\nu = (4/11)^{1/3}\,T_0$. If neutrino have a small mass $m \ll 1$ MeV the energy density today would be $\rho_\nu = n_\nu \Sigma m_\nu$ where Σm_ν is the sum of the mass eigenstates of the neutrino (see §5 below). In order to compare with observables it is convenient to normalize the densities to the critical density. In this case we have

$$\Omega_\nu\, h_0^2 = \frac{\Sigma m_\nu}{93.3\ \mathrm{eV}}\,. \tag{14}$$

Including the effect of electron mass and solving the Boltzmann-Vlasov equation (Hannestad & Madsen 1995) introduces only corrections of the order of few percent to this estimate.

From the small scale fluctuations as measured by WMAP (Spergel *et al.* 2003) a value of the matter density $\Omega_m\, h^2 = 0.14 \pm 0.02$ has been derived, while the density of ordinary baryonic matter is $\Omega_b\, h^2 = 0.024 \pm 0.01$. If we make the implausible hypotheses that the dark matter is entirely composed of neutrinos, we set the upper limit $\Omega_\nu \leq \Omega_m$, we obtain the not too compelling limit $\Sigma m_\nu < 13$ eV.

However it has been shown by Bond, Efstathiou & Silk (1980) that even a very small neutrino mass $\Sigma m_\nu = \mathcal{O}(10\ \mathrm{eV})$ could practically forbid the formation of galaxies. The reason is that relativistic particles smooth out small scale fluctuations of the gravitational field, the so called "free streaming effect". Therefore the fluctuations could start to grow only after the slowing down of neutrinos to sub relativistic velocities, or in other words when the average momentum becomes $\langle p_\nu \rangle \ll m_\nu$. The momentum distribution of neutrinos after decoupling was a relativistic frozen distribution (Irvine & Humphreys 1983) also when $\langle p_\nu \rangle \ll m_\nu$, because neutrinos no longer interact. Therefore we can estimate that the distance spanned by neutrinos with mass m_ν in the free-streaming regime was twice the size of the horizon at the redshift $z_{\rm nr} \simeq m_\nu / (\pi T_{0\nu}) \simeq 1900\,(m_\nu/1\ \mathrm{eV})$, where we have used the fact that $\langle p_\nu \rangle \simeq \pi\, T_\nu$. From the well know relation, valid in the matter dominated era $D_H = 6\,000/\sqrt{\Omega_m\, z}\ h^{-1}\,\mathrm{Mpc}$ (Eidelman *et al.* 2004), we have finally

$$k_{\rm nr} = \frac{\pi}{D_H} \simeq 0.023\,\sqrt{\Omega_m}\,\left(\frac{m_\nu}{1\ \mathrm{eV}}\right)^{1/2} h\,\mathrm{Mpc}^{-1}\,. \tag{15}$$

It is evident that the part of the fluctuations of the power spectrum $P(k)$ with $k > k_{\rm nr}$ will be suppressed by the effect of neutrinos. The amount of suppression is calculated by Hu, Eisenstein, & Tegmark (1988) to be

$$\frac{\Delta P}{P} \simeq -8\frac{\Omega_\nu}{\Omega_m}\,. \tag{16}$$

Until now eight different fit to the power spectrum aimed to the detection of neutrino mass has been published (see Table 1).

Table 1 Various recent limits on the neutrino mass from cosmology and the data sets used in deriving them.

Reference	Σm_ν (eV)	Data set used
Tegmark *et al.* (2004)	≤ 1.74 (95% C.L.)	1, 5
Hannestad (2003)	≤ 1.01 (95% C.L.)	1, 2, 3, 6
Crotty, Lesgourgues & Pastor (2004)	≤ 1 (≤ 0.6) (95% C.L.)	1, 2, 3, 5 (6)
Spergel *et al.* (2003)	≤ 0.69 (95% C.L.)	1, 2, 3, 4a, 6, 7
Barger, Marfatia & Tegre (2003)	≤ 0.75 (95% C.L.)	1, 2, 3, 5, 6
Hannestad (2004)	≤ 0.65 (95% C.L.)	1,5,6,7
Seljak *et al.* (2004)	≤ 0.42 (95% C.L.)	1, 2, 4c, 5, 6, 7
Melchiorri *et al.*(2005)	≤ 0.47 (95% C.L.)	1, 2, 4c, 5, 6, 7
Allen, Smith & Bridle (2003)	$0.56^{+0.30}_{-0.26}$	1, 2, 3, 4b, 6

1: WMAP data, 2: Other CMB data, 3: 2dF data, 4: Constraint on σ_8 (different in 4a, 4b, and 4c),
5: SDSS data, 6: Constraint on H_0, 7: Constraint from Lyman-α forest. (Adapted from Hannestad 2004)

Oscillation experiments (see below §4) are sensitive not to the absolute neutrino mass but to the difference of the square of the mass between different neutrino states. In any case these experiments imply that the mass difference between the three neutrino mass eigenstates is small. Assuming in CMBR analysis that there are three mass degenerate light neutrino species the limit becomes (Spergel et al. 2003):

$$\Omega_\nu\, h_0^2 \leq 0.0076 \qquad (95\%\ \mathrm{C.L.}) \tag{17}$$

and using (14) we have $\sum m_\nu \leq 0.23$ eV.

4 NEUTRINO OSCILLATIONS

4.1 Solar Neutrinos

Pontecorvo proposed in 1946 to exploit the reaction $Cl^{37} + \nu \rightarrow Ar^{37} + e^{-}$ for detecting neutrinos emitted by the Sun. The first attempt to use this method for the detection of solar neutrinos was accomplished by Davis (1964) using as detector about 4 000 liters of perchlorethylene $C_2\,Cl_4$. The result of the search was negative, while current calculations of the expected solar neutrino capture rate (Bahcall 1964) predicted about one order of magnitude larger signal. In 1967 the experiment was upgraded to 390 000 liters of $C_2\,Cl_4$, still with negative results (Davies, Harmer & Hoffmann 1968). Only in runs starting from April 1970, after several improvements of the detection technique, neutrino capture rate above background has been recorded, but corresponding to about 30% of the rate predicted by solar standard model. This surprising result was nicknamed by Bachall & Davis (1976) the "solar neutrino puzzle".

Gribov & Pontecorvo (1968) proposed that the apparent deficit of neutrinos could be due to the conversion during the long travel from the Sun to the Earth of the electron neutrinos into neutrinos of different flavor undetectable in the chlorine experiment. This is possible if neutrinos are massive and the eigenstate of flavor mix different eigenstate of mass. For example, if the electron neutrino is a mixed state, its state can be expressed as the combination $|\nu_e\rangle = \cos\theta\,|\nu_1\rangle + \sin\theta\,|\nu_2\rangle$ where θ is the mixing angle. The time evolution of this state is given by a Schrödinger equation whose solution in free space will be

$$|\nu_e\rangle_t = \cos\theta\, e^{-iE_1\,t}\,|\nu_1\rangle + \sin\theta\, e^{-iE_2\,t}\,|\nu_2\rangle\,. \tag{18}$$

Therefore the probability that an electron neutrino does not change flavor after traveling a distance L will be in practice

$$P_{\nu_e}(t) = \langle\nu_e|\nu_e\rangle_t^2 \approx 1 - \sin^2 2\theta\,\sin^2 1.27\frac{\Delta m^2\,L}{E_\nu}\,, \tag{19}$$

where L is the distance in meters, $\Delta m^2 = |m_1^2 - m_2^2|$ in eV^2 and $E_\nu = \sqrt{p_\nu^2 - m_\nu^2}$ the neutrino energy in MeV. Eq. (19) is an approximation which holds for $m_1 \neq m_2 \ll p_\nu$. It is clear from this equation that the fraction of surviving electron neutrinos has an oscillatory behavior, that's why this phenomenon is nicknamed "neutrino oscillations". In presence of matter Eq. (19) should be modified to take into account the MSW effect (see e.g. Auriemma *et al.* 1988).

In the last 35 years several experiments have measured the flux of neutrinos from the Sun using different experimental techniques (for a detailed history see e.g. Bahcall & Davis 2000), whose results are summarized in Table 2. The direct evidence for the neutrino flavor transformation has been given by the SNO experiment (McDonald et al. 2003). The particularity of this Canadian experiment is the use of heavy water as detecting medium in which two different type of neutrino interactions could take place: 1) charged current interactions $\nu_e + d \rightarrow p + p + e^-$ in which a neutron is converted into a proton with the emission of an electron and 2) neutral current scattering's $\nu + d \rightarrow n + p + \nu$ by which the deuteron is split into a neutron and a proton. The important fact is that while the process 2) is insensitive to neutrino flavor, process 1) is possible by flavor conservation only for electron neutrinos. The results shown in Table 2 prove that a deficit of neutrinos is observed only for the process 1), while process 2) gives a flux of neutrinos in very good agreement with the predictions. This demonstrate that muon and or tau neutrinos are detected on the Earth which cannot have been produced by low energy nuclear reactions in the Sun.

If we assume that solar neutrino deficit is due to oscillations, the neutrino parameters appearing in Eq. (19) are (Ahmed et al. 2004):

$$\Delta m^2_{\rm sol} = 7.1^{+1.2}_{-0.6} \times 10^{-5}\ {\rm eV}^2 \quad {\rm and} \quad \tan^2\theta_{\rm sol} = 0.41^{+0.08}_{-0.07}\,. \tag{20}$$

An important independent confirmation of the neutrino oscillations has been obtained by the KamLAND experiment (Eguchi et al. 2003). The active part of this detector is 1000 tons of liquid scintillator in which antineutrinos are detected via the charged current reaction $\overline{\nu}_e + p \rightarrow e^+ n$ with a threshold $E_{\overline{\nu}_e} \geq 2.6$ MeV. There are 52 commercial power reactor which produce copiously antineutrinos distributed in 16 sites in Japan, around the Kamioka mine, where KamLAND is located with a total nominal thermal power output 152 GW, namely 15% of the world total. The reactor complex located at about 160 km from Kamioka site, including Kashiwazaki Kariwa, that is the world's strongest reactor with full thermal power

Table 2 Summary of Solar Neutrino Results

Experiment	Reaction	$E_\nu^{\rm min}$ (MeV)	Meas. Flux	SSM
Homestake	$^{37}Cl + \nu_e \rightarrow ^{37}Ar + e^-$	0.814	$2.56 \pm 0.16 \pm 0.16$	8.5 ± 1.8
SAGE			$75 \pm 7 \pm 3$	
GALLEX	$^{71}Ga + \nu_e \rightarrow ^{71}Ge + e^-$	0.233	$78 \pm 6 \pm 5$	131^{+12}_{-10}
GNO			$66 \pm 10 \pm 3$	
Kamiokande	$\nu + e^- \rightarrow \nu + e^-$ (E.S.)	7.5	$2.80 \pm 0.19 \pm 0.33$	
SK		5.5(6.5)	$2.35 \pm 0.02 \pm 0.08$	
	$\nu_e + d \rightarrow p + p + e^-$ (C.C.)		$1.68 \pm 0.06^{+0.08}_{-0.09}$	$5.82^{+1.1}_{-0.9}$
SNO	$\nu + e^- \rightarrow \nu + e^-$ (E.S.)	6.75	$2.35 \pm 0.22 \pm 0.15$	
	$\nu + d \rightarrow n + p + \nu$ (N.C.)		$4.94 \pm 0.21^{+0.38}_{-0.34}$	

generation of 24.3 GW. A fortunate characteristic of the Kamioka site is that 80% of neutrino contribution comes from 130 to 220 km, a distance relevant for the solar neutrino oscillations parameter. A deficit of antineutrino of the order of 40% is observed also in this experiment, that can be explained very well by the antineutrino oscillations. Incidentally it is worth noticing that this experiment was able to detect for the first time antineutrinos produced by long lived radioactive components in the Earth interiors (Araki et al. 2005a), that could yield important geophysical information.

A best fit of the neutrino oscillations parameters for the disappearence of reactor antineutrinos is (Araki et al. 2005b):

$$\Delta m^2_{\rm reac} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ {\rm eV}^2 \quad \text{and} \quad \tan^2\theta_{\rm reac} \approx 0.46, \tag{21}$$

with a large uncertainty on the fit of the mixing angle. Assuming CPT theorem, which states that neutrino and antineutrino must have the same mass Bahcall & Peña-Garay (2003) have derived a combined fit

$$\Delta m^2_{\rm sol+reac} = 7.9^{+0.6}_{-0.5} \times 10^{-5}\ {\rm eV}^2 \quad \text{and} \quad \tan^2\theta_{\rm sol+reac} = 0.40^{+0.10}_{-0.07}. \tag{22}$$

4.2 Atmospheric Neutrinos

Neutrinos are produced in the upper atmosphere by CR interactions mainly via the chain of decays:

$$\begin{array}{lll} \pi^+ \rightarrow & \mu^+ + \nu_\mu & \\ & \downarrow & \\ & e^+ + \nu_e + \bar\nu_\mu & \end{array} \quad \text{and} \quad \begin{array}{lll} \pi^- \rightarrow & \mu^- + \bar\nu_\mu & \\ & \downarrow & \\ & e^- + \bar\nu_e + \nu_\mu\ . & \end{array} \tag{23}$$

Therefore the ratio $\nu_\mu/\nu_e = N_{\nu_\mu+\bar\nu_\mu}/N_{\nu_e+\bar\nu_e}$. is expected to be $\nu_\mu/\nu_e \approx 2$ and the energy distribution for any type of neutrinos is similar in the laboratory frame, due to the Lorentz boost.

Atmospheric neutrinos have been observed in underground detectors exploiting different techniques since the 60's. In order to reduce systematic uncertainties, more recent results are usually expressed in terms of the ratio $R = (\nu_\mu/\nu_e)_{\rm exp}/(\nu_\mu/\nu_e)_{MC}$ Atmospheric neutrinos have been detected in underground laboratories with controversial results, as can be seen from Tables 3 and 4, that summarize the Particle Data Group compilations (Caso *et al.* 1998). The recent data from SuperKamiokande and MACRO seems to converge on the evidence for atmospheric neutrino oscillations.

Neutrinos are produced in the upper atmosphere by CR interactions principally via the chain of decays:

$$\pi^\pm \rightarrow \bar\nu_\mu(\nu_\mu) + \mu^\pm \rightarrow e^\pm + \bar\nu_e(\nu_e) + \nu_\mu(\bar\nu_\mu).$$

Therefore one expects naïvely $\nu_e + \bar\nu_e \approx \frac{1}{2}(\nu_\mu + \bar\nu_\mu)$. Detailed MC calculations have been performed by several groups, with results that are estimated to be uncertain near ±20%. In underground detectors atmospheric neutrinos originates four type of events:

Fully contained (FC) events	$\nu_e, \bar\nu_e, \nu_\mu, \bar\nu_\mu$	$E_\nu \approx 0.1 - 1$ GeV
Partially contained (PC) events	$\nu_e, \bar\nu_e, \nu_\mu, \bar\nu_\mu$	$E_\nu \approx 1 - 10$ GeV
Stopping muons (STμ's)	only $\nu_\mu, \bar\nu_\mu$	$E_\nu \approx 5 - 20$ GeV
Through going muons (TGμ's)	only $\nu_\mu, \bar\nu_\mu$	$E_\nu \geq 20$ GeV

Table 3 Ratio (ν_μ/ν_e)

Year	Exp.	$kt \cdot y$	Ratio/MC	Type
1989	NUSEX	0.7	$0.96^{+0.32}_{-0.28}$	PC+FC
1994	Kamiokande	7.7	$0.60^{+0.06}_{-0.05} \pm 0.05$	FC
			$0.57^{+0.08}_{-0.07} \pm 0.07$	PC
1995	Frejus	2.0	$1.00 \pm 0.15 \pm 0.08$	PC+FC
1997	Soudan II	1.57	$0.72 \pm 0.19^{+0.05}_{-0.07}$	PC+FC

Table 4 Flux ν_μ/MC

1978	Crouch	0.62 ± 0.17	TG μ's
1981	Baksan	0.95 ± 0.22	TG μ's
1995	MACRO	$0.73 \pm 0.09 \pm 0.06$	TG μ's

The evidence for oscillations in atmospheric neutrinos can be searched in two ways. At low energies the ratio ν_μ/ν_e could be examined, while at higher energies only the zenith angle modulation of the ν_μ could be compared to the MC predictions.

The preliminary results of SuperKamiokande 535 day run (33.0 kton y) of $PC + FC$ events show a ratio $(\nu_\mu/\nu_e)/MC = 0.65 \pm 0.05 \pm 0.08$ that cannot be explained by experimental bias or MC uncertainty. The ratio (ν_μ/ν_e) is modulated with the zenith angle and with the energy of the neutrino.

Results of the analysis of the full MACRO detectors runs from April 1994 to December 1997 (2.89 years of live time) show that the ratio of observed TG μ's over expected is $\phi(\nu_\mu)/MC = 0.74 \pm 0.0036 \pm 0.046$, and it is modulated with the zenith angle. The probability of no-oscillations (GOF test) $\leq 0.1\%$ for $E_\mu \geq$ 1 GeV, $\langle E_\nu \rangle \approx 100$ GeV.

Both SuperKamiokande and MACRO data can be interpreted as $\nu_\mu \not\to \nu_\mu$ oscillations with $\Delta m^2 \approx 10^{-2} - 10^{-3}$ eV^2 and $\sin^2 2\theta \geq 0.8$.

What is extremely important for underground physics is that the range of mass square difference suggested by the atmospheric neutrino anomaly can be accessed by long baseline oscillation experiments with artificial neutrino beams, because

$$L_{\rm osc} = 1270 \text{ km} \left(\frac{E}{1\,\text{GeV}}\right)\left(\frac{10^{-3}\,\text{eV}^2}{\Delta m^2}\right)$$

is within the reach of possible experiments. At least three experiments, from which we can expect a direct laboratory confirmation of the effect, and a better determination of the oscillations parameters, are going to be operated in the world:

- KEK $\longrightarrow$ SuperKamiokande (Distance: 225 km)
- Fermilab $\longrightarrow$ MINOS, Soudan (Distance: 774 km)
- CERN $\longrightarrow$ Gran Sasso Laboratory (Distance: 770 km).

5 MODELS OF NEUTRINO MASSES

The lagrangian of a free massive fermion (for a review see Gelmini & Roulet 1994) is

$$\mathcal{L}_{\rm free} = \frac{i}{2}\left(\overline{\psi}\gamma^\mu\partial_\mu\psi - \psi\gamma^\mu\partial_\mu\overline{\psi}\right) - m\,\overline{\psi}\,\psi, \tag{24}$$

where ψ is a four component Dirac spinor and $\overline{\psi}$ its adjoint (not to be confounded with the antiparticle spinor). A Dirac spinor can be expressed as the combination of two Weyl spinors $\psi = \psi_{\rm L} + \psi_{\rm R}$, each one represents in the limit $m \to 0$ the two possible helicity state. The mass term in the lagrangian (24) will be written in matricial form

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} \left(\psi_{\rm L} \;\; \overline{\psi}_{\rm R} \right) \begin{pmatrix} 0 & m_{\rm D} \\ m_{\rm D} & 0 \end{pmatrix} \begin{pmatrix} \psi_{\rm L} \\ \overline{\psi}_{\rm R} \end{pmatrix} + {\rm h.c.}\,, \tag{25}$$

which mix the left-handed components with the right-handed one. In the Standard Model only left-handed neutrinos and right-handed antineutrinos do exist, therefore in this model the neutrino is massless.

As a matter of fact neither cosmology nor experiments can exclude the existence of an heavy right-handed neutrino with mass much greater than $M_Z/2$. This type of particle is predicted in SO(10) Grand Unified Theories, for example. In this case we can have a mass term of the type

$$\mathcal{L}_{\rm mass} = -\frac{1}{2} \left(\psi_{\rm L} \;\; \overline{\psi}_{\rm R} \right) \begin{pmatrix} 0 & m_{\rm D} \\ m_{\rm D} & M \end{pmatrix} \begin{pmatrix} \psi_{\rm L} \\ \overline{\psi}_{\rm R} \end{pmatrix} + {\rm h.c.}. \tag{26}$$

If $M \gg m_{\rm D}$ the eigenvalues of the mass matrix are $\{-m_{\rm D}^2/M, M\}$. This is a simple example of the so called "seesaw mechanism", suggested independently by Yanagida and Gellmann, Ramond & Slansky in 1980, that provides a very natural and attractive explanation of the smallness of the neutrino mass.

Since lepton number is violated the right-handed neutrinos can be majorana type particles, which means in practice particles that are indistinguishable from their anti-particles, such as happens for the neutral pion. The The smallness of left-handed neutrino masses as inferred from the oscillations of solar and atmospheric neutrinos masses, being the mass matrix of left-handed neutrinos

$$m_{\rm L} = -m_{\rm D}\, M_{\rm R}^{-1}\, m_{\rm D}^T\,, \tag{27}$$

where $m_{\rm D}$ is the ordinary mass matrix of Dirac particles, and $M_{\rm R}$ the mass matrix of right-handed majorana particles.

Assuming a minimal extension of the SM the quark sector will be unchanged, while to the lepton sector will be added three singlet right-handed neutrinos N_i. The terms of of the mass matrix will be of the order $m_{\rm L} \approx m^2/M$ where m are the eigenvalues of the dirac mass of the charge $2/3$ quarks and M the typical mass of right-handed neutrinos. The largest mass of left-handed neutrinos should be of the order of m_t^2/M.

6 BARYOGENESYS THROUGH LEPTOGENESIS

Among the many baryogenesis scenario (see e.g. Auriemma 2004) that have been proposed in order to find an explanation to the observed baryon asymmetry, Fukugita & Yanagida (1986) proposed that baryon over antibaryon excess could be produced not directly but by lepton number violating GUT processes. This approach is very interesting in the light of present evidence for small neutrino masses, naturally explained by the see-saw mechanism (as we have discussed in the previous §5) if one (or likely more) heavy righthanded Majorana neutrinos should exist. In this model one can guess that neutrino masses scales as quark masses, therefore the difference of the squared masses measured by neutrino oscillations should be $\Delta m_\nu^2 \approx (\Delta m_q^2)^2/M^2$. From this *ansatz*, an upper value for $M \sim 10^{15}$ GeV c^{-2} is obtained, taking $\Delta m_\nu^2 = \Delta m_{\rm atm}^2$ and $\Delta m_q^2 \sim m_t^2 - m_c^2$, while a lower value of $M \sim 10^{12}$ GeV c^{-2} corresponds to $\Delta m_\nu^2 = \Delta m_{\rm sol}^2$ and $\Delta m_q^2 \sim m_c^2 - m_s^2$. Therefore if heavy right-handed neutrinos do exist, their Majorana mass must be in the range $10^{12} - 10^{15}$ GeV c^{-2} and their decay at $T \approx T_{\rm max}$ should take place when they are not in thermodynamical equilibrium, respecting the third Sakharov's condition for the generation of a baryon asymmetry.

In this situation an initial lepton asymmetry will be originated by CP violation which makes the two decay channel of the right handed neutrinos $N \to l^- + h^+$ and $N \to l^+ + h^-$ asymmetrical with

$$\Gamma[N \to l^- + h^+] = \frac{1}{2}\,(1+\epsilon)\,\Gamma \quad \text{and} \quad \Gamma[N \to l^+ + h^-] = \frac{1}{2}\,(1-\epsilon)\,\Gamma, \tag{28}$$

where Γ is the total width and $\epsilon \ll 1$ the amount of CP violation.

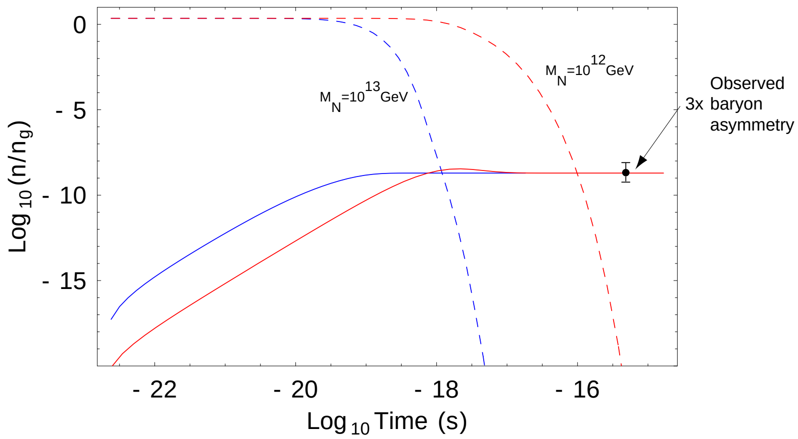

Figure 2 Solution of the Boltzmann-Vlasov equation for an initially baryon and lepton symmetric Universe. The dashed lines represents the equilibrium density, while solid lines are the L-asymmetry originated by the decay of heavy majorana neutrinos.

The thermodynamics of these decays is very similar to the one done for the decay of the GUT bosons (see e.g. Pilaftsis 1999, Buchmüller *et al*. 2003). Typical numerical solutions of the Boltzmann-Vlasov coupled equations is shown in Figure 2. Also in this case we have that the lepton asymmetry will be

$$\eta_{\rm L} \approx \mathcal{O}(10^{-2})\,\epsilon. \tag{29}$$

Even if the initial baryon number $B = 0$ initially at $T > T_{\rm max}$ we have $B - L = -L_{\rm ini}$, then the fast sphaleron baryon number violating transitions can produce excess baryons, in order to keep $B - L$ constant. Taking into account the conservation of chemical potentials, of charge and of hypercharge (see e.g. Pilaftsis 1999) we arrive to the conclusion that the baryon number at the end of the EW phase transition will about $1/3$ of the conserved $B-L$ initial value, which secure the result that this mechanism can produce the observed asymmetry if the CP violation amount is $\epsilon \approx \mathcal{O}(10^{-8})$.

However in order to establish that the observed baryon asymmetry was produced in this way, it is necessary to demonstrate that both the sign and the absolute value of the CP violations are the correct ones (Frampton, Glashow & Yanagida 2002). What is interesting about this mechanism is the fact that it could be tested using low energy observables. For example it appear possible to establish a link between the amount of CP violations required by successful leptogenesys and the difference $P(\nu_\mu \to \nu_e) - P(\overline{\nu}_\mu \to \overline{\nu}_e)$ in the probability the oscillation of low energy neutrinos (Endoh *et al*. 2003), which can be tested in long-baseline accelerator experiments.

7 CONCLUSIONS

The existence of 3 neutrino flavor, with a mass smaller then 0.4 eV, is the coherent indication of cosmology, astrophysics and laboratory experiments. The Standard Model fails to explain: why different flavors do exist in Nature, why neutrino has mass, why the mass of neutrino is so small and why different neutrino flavors are strongly mixed; A minimal extension of the SM with the inclusion of a heavy right-handed Majorana neutrino with mass in the range $10^{12} - 10^{13}$ GeV, could shed some light on the issues of neutrino mass and mixing, but does not appear to be able to give the full picture. Two second generation long baseline neutrino oscillations experiments are on the line CERN-Gran Sasso (OPERA, ICARUS) FermiLab-Homestake (MINOS) Both have the capabilities for showing the appearance of tau neutrinos and perhaps give the first hint for CP violation in the leptonic sector, which is important for baryogenesis.

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