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Muon and Tau Neutrinos Spectra from Solar Flares

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Abstract Most power-full solar flare as the ones occurred on $23th$ February 1956, September $29th$ 1989, $28th$ October and on $2nd-4th$ November 2003 are sources of cosmic rays, X, gamma and neutrino bursts. These flares took place both on front or in the edge and in the hidden solar disk. The $4th$ November event was the most powerful X event in the highest known rank category $X28$ just at horizons. The observed and estimated total flare energy ($E_{\rm FL} \simeq 10^{31} \div 10^{33}\,$erg) should be a source of a prompt secondary neutrino burst originated, by proton-proton-pion production on the sun itself; a more delayed and spread neutrino flux signal arise by the solar charged flare particles reaching the terrestrial atmosphere. These first earliest prompt solar neutrino burst might be observed, in a few neutrino clustered events, in present or future largest neutrino underground detectors as Super-Kamiokande one, in time correlation with the X-Radio flare. The onset in time correlation has great statistical significance. Our first estimate on the neutrino number events detection at the Super-Kamiokande II Laboratory for horizontal or hidden flare is found to be few events: $N_{{\rm eV}_{\bar{\nu}_e}} \simeq 0.63\eta_e(\frac{\langle E_\nu\rangle}{35\ {\rm MeV}})(\frac{\langle E_{\rm FL}\rangle}{10^{31}\ {\rm erg}})$; and $N_{{\rm eV}_{\bar{\nu}_\mu}} \simeq 3.58(\frac{\langle E_{\nu_\mu}\rangle}{200\ {\rm MeV}})(\frac{\langle E_{\rm FL}\rangle}{10^{31}\ {\rm erg}})\eta_\mu$, where $\eta \simeq 1$, $E_{\nu_\mu} > 113\,$MeV. Our first estimates of neutrino signals in largest underground detectors hint for few events in correlation with X, gamma, radio onser. Our approximated spectra for muons and taus from these rare solar eruption are shown over the most common background. The muon and tau signature is very peculiar and characteristic over electron and anti-electron neutrino fluxes. The rise of muon neutrinos will be detectable above the minimal muon threshold $E_\nu \simeq 113\,$MeV energy, or above the pion and Δ° thresholds ($E_\nu \simeq 151$ and $484\,$MeV). Any large neutrino flare event record might also verify the expected neutrino flavour mixing leading to a few as well as a comparable, ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ energy fluence and spectra. The rarest tau appearence will be possible only for hardest solar neutrino energies above $3.471\,$GeV.

1 INTRODUCTION

The recent exceptional solar flares on October–November 2003 remind us the rarest the historical one on February 23th, 1956, (see Bachelet & Conforto 1956; Simpson 1957) and most power-full comparable event on September $29th$, 1989 at 11:30–12:00 UT, (see

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Alessio et al. 1991 and Miroshnichenko et al. 2000). These events were source of high energetic charged particles whose observed energies, E_p, range between the values: $15\,\mathrm{GeV} \geq E_p \geq 100\,\mathrm{MeV}$. Even higher proton solar energies $E_p \geq 500$ GeV have been reported (see Karpov, Miroshnichenko & Vashenyuk 1998). A large fraction of these *primary* particles, i. e. solar flare cosmic rays, became a source, on the Sun surface and later on the Earth atmospheres, of neutrons (Alessio et al. 1991) as well as *secondary* kaons, pions $K^{\pm}$, $\pi^{\pm}$ by their particle-particle spallation. Their following *secondary* rays, as muons $\mu^{\pm}$ and neutrinos and anti-neutrinos ν_μ, $\bar{\nu}_\mu$ as well as γ rays, and their final relic neutrinos ν_μ, $\bar{\nu}_\mu$, ν_e and relevant $\bar{\nu}_e$ were also released by the chain reactions $\pi^{\pm} \to \mu^{\pm} + \nu_\mu(\bar{\nu}_\mu)$, $\pi^0 \to 2\gamma$, $\mu^{\pm} \to e^{\pm} + \nu_e(\bar{\nu}_e) + \nu_\mu(\bar{\nu}_\mu)$. There are two different sites for these chain decays and consequently, two corresponding neutrino emissions (Fargion 1989):

(1) A first, brief and sharp solar flare *neutrino burst*;
(2) A later, diluted and delayed terrestrial *neutrino flux.*

The first is a prompt (few seconds-minutes on-set) neutrino burst due to charged particles scattering in the solar shock waves, associated with known prompt gamma-X neutron events. The largest event yet recorded was an $X28$ which occurred at $19:50$ UT Nov $4, 2003$. The consequent *solar* flare neutrinos reach the Earth laboratory with a well defined direction and within a narrow time gate. Their average energies are probably large (for given proton energy respect to an event on Earth atmosphere) because their associated primary rays ($\pi^{\pm}$, $\mu^{\pm}$) decay mainly in flight at low solar densities, i.e. where their primaries suffered negligible energy loss: > 50 MeV, $\simeq 100 \div 200$ MeV. The second delayed *neutrino flux* originated on the Earth's atmosphere, is due to the late arrival of prompt solar charged particles (nearly ten minutes later than the radio-X onset). These particles are not to be confused with lower energy ones in much later solar winds. These solar flare rays, even nearly relativistic (hundreds-thousand MeV), are charged and bent by inter-planetary particles and fields; therefore their arrival as well as their relic neutrino emission on Earth atmosphere takes place tens minute or even a few hours later the solar X-radio sharp event. Therefore their signal is widely spread and diluted in time. The terrestrial neutrino directions, at sea level are in this terrestrial case, nearly isotropic or even more clustered near the terrestrial magnetic poles. More over a large fraction of their low energy primary solar flare ray (protons, alpha) energies are dissipated by ionization in terrestrial atmosphere. Therefore *terrestrial* electronic neutrinos ν_e, $\bar{\nu}_e$, are originated by muons mostly at rest, (because of the dense terrestrial atmosphere) and are leading to a soft terrestrial neutrino flare spectra: their mean energy $E_{\nu\oplus}$ is on average smaller than the original *solar flare* ones: $\langle E_{\nu\odot} \rangle \simeq 100$ MeV and their total relic energy ratio (terrestrial neutrino over solar flare): $\frac{E_{\nu\oplus}}{E_{\nu\odot}} \leq 10^{-1}$ is also poor. Because of the cross section quadratic or linear growth with energy the terrestrial neutrino flux is harder to be detected respect to the solar ones. Finally the terrestrial diluted neutrino flux may be drown (out of exceptional cases and in present detectors) within the comparable steady atmospheric neutrino back-ground. For these reasons we may neglect, in the following approximation, the low energetic terrestrial *neutrino flux*, even if they are a certain and well defined source of secondaries neutrinos; statistically it will be hard to observe their signal in present Super-Kaimokande, SK detector, but they might be observable in new future larger underground detectors. We shall consider here mainly the observable consequences due to the first prompt solar flare *a solar neutrino burst.* Moreover, we shall consider two main proton-proton-neutrino relics origination: those particles scattering outward or inward the solar surface while pointing to the (Earth) observer, because of the very different consequent target solar atmosphere. Most of our present estimate of the solar flare *neutrino burst* is scaled on an integral flare energy E_{FL}, which is assumed to be of the order of $E_{\mathrm{FL}} \simeq 10^{31} \div 10^{32}$ erg, by comparison with the known largest solar flare event as the one in 1956, 1989. The recent solar flare spectra are unknown but their energies are extending well above a few GeV energy necessary to pion production. To appreciate the order of magnitude of a solar neutrino flare on the Earth, let us compare the total flare energy flux $\Phi_{\rm FL}$, at the Solar-Earth distance $d_{\odot}$ with the corresponding energy flux observed, by the well celebrated supernovæ explosion SN1987A, on February 23th, 1987, at a distance $d_{\rm SN}$:

$$\frac{\Phi_{\rm FL}}{\Phi_{\rm SN}} \simeq \frac{E_{\rm FL}}{E_{\rm SN}}\Big(\frac{d_{\rm SN}}{d_{\odot}}\Big)^2 \simeq \frac{1}{30}\Big(\frac{E_{\rm FL}}{10^{32}\ {\rm erg}}\Big)\Big(\frac{E_{\rm SN}}{3\cdot 10^{53}\ {\rm erg}}\Big)^{-1}. \quad (1)$$

The ratio, even being smaller than unity, it remarks the flare energy relevance. Naturally the SN neutrino fluence are certainly probed both experimentally and theoretically while the solar flare energy (10^{32} *erg*) conversion in neutrino has to be probed.However even in a more conservative frame where only a fraction η of the flare energy is partially converted $\eta <\sim 0.1$ into neutrinos, the flare energy flux on the Earth is:

$$\Phi_{\rm FL} = 3.5\cdot\eta\cdot 10^4\ {\rm erg\ cm^{-2}}\Big(\frac{E_{\rm FL}}{10^{32}\ {\rm erg}}\Big). \quad (2)$$

We know that Kamiokande detectors observed 11 neutrino events from the 1987A supernovæ explosion. The Super-Kamiokande, because its larger volume may observe a signal 22 time as large. Therefore, in this low energy $\eta <\sim 10\%$ conversion the signal ($\geq\sim 0.8$) is near or above unity and it may be reached. Moreover the expected pion-muon neutrino flare mean energy $\langle E_{\nu{\rm FL}}\rangle \geq kT_{\nu{\rm SN}} \simeq 10$ MeV is much larger $E_{\nu{\rm FL}} \simeq 0.1 - 1$ GeV, than the corresponding one for thermal supernovæ neutrinos; the consequent neutrino cross section with nucleons grows square with the energies; therefore the event number in present first approximation is larger (by a factor ten or more) than ten MeV energy. In conclusion, if a realistic fraction ($\simeq 0.001$) of the total flare energy ($E_{\rm FL} \simeq 10^{32}$ erg) was emitted, by proton-pion-muon chain, into neutrino relics, as we shall show in more details, their arrival on Earth might be nearly detectable ($\sim 1\div 5$ events) and it would be much worth checking the Super-Kamiokande records at a the X-radio precursor flare times corresponding, for instance to X-ray maximum on $28th$ October and during $2nd - 4th$ November (edge), 13 November (hidden) solar flare 2003. Of course also gamma signals are expected by similar event: there are very limited gamma data (OSSE-EGRET) on solar flare and only a very surprising evidence of hard gamma events (Lin et al. 2003) on recent July 2002 solar flare where hard X-gamma events have been followed in details by RHESSI gamma detector; the gamma energy on 2002 flare output is smaller than our neutrino estimate. Incidentally it is worth-full to remind that the absence of large gamma solar flare have been used to infer a bound on anti-meteorite and anti-matter presence in our solar system and galaxy (Fargion & Khlopov 2003). But downward gamma flare and-or higher X flare energy, beaming and hidden flare, might play a key role in enhancing neutrino signal over gamma flare. We therefore consider the total flare energy (kinetic, X) as a main meter to foresee the neutrino signal.

2 THE SOLAR FLARE ENERGY

The energy released during the largest known flares is mainly in the form of inter-planetary shock waves $E_{\rm FL} \geq 10^{32}$ erg (see Dryer 1974) up to $E_{\rm FL} \leq 10^{33}$ erg, (see Miroshnichenko et al. 2000). Another large fraction of energy is found in optical emission $E_{\rm FLop} \simeq 8\cdot 10^{31}$ erg. A considerable energy fraction is also observed in soft and hard X-rays (by electromagnetic or nuclear bremsstrahlung) as well as energetic cosmic rays ($2\div 5\cdot 10^{31}$ erg). The flares might be on Earth front or just beyond, as the one on September 1989 located behind the West limb of the Sun (105° West) and last event on $4th$ November 2003; the 1989 flare was observable $first$ by 8.8 Gigahertz radioburst, (because of the refractive index of solar atmosphere), at time

11:20 UT and, later it reached a higher (visible) height from where it was observable in X-ray (see Alessio et al. 1991).Is there any *hidden* underground flare whose unique faithful trace is in a powerful (unobserved) neutrino burst? Gamma rays secondaries, due to common neutral pion decay, positron annihilations and neutron capture, have a very small cross section and there must also be as observed a trace on the Sun surface of such a powerful hidden flare. Nevertheless observed gamma ray flares from known ones, are not in favor of any extreme $E_{\rm FL} \gg 10^{33}$ erg underground flares (see Berezinsky, Castagnoli & Galeotti 1985). However it must be kept in mind that the rarest event on February $'56$ was not observed in gamma band, because of the absence of such satellite detector at that epoch, while the Sept. 29th 1989 flare was not detected in gamma rays because it occurred on the opposite solar side. Nevertheless lower power-full solar flare as the 4th June 1991 have been experienced in all radio-X-gamma energy up to tens MeV energy band also by OSSE detector in CGRO satellite. Therefore there are no real severe direct bounds on a larger *hidden* underground flare. One may suspect that too large flare event should be reflected somehow into electromagnetic cascade which may influence the continuous solar energy spectrum ($E_{\odot} \simeq 3.84 \cdot 10^{33}$ erg s^{-1}), even in the observable solar side. Moreover recent accurate helio seismography might be able to reveal any extreme hidden flare energy. Therefore we may restrict our most powerful solar flare energy in range:

$$10^{32} \text{ erg} \sim\geq E_{\rm FL} \geq 10^{31} \text{ erg}\,, \tag{3}$$

keeping the lowest energy as the flare energy threshold.

2.1 The pion production in solar flare

The kaon-pion-muon chain reactions and their consequent neutrino relics spectrum in solar atmosphere may be evaluated in detail if the energetic particle (protons, alpha nuclei, ...) energy spectra is known, as well as the solar density and magnetic configuration. Indeed magnetic screening may reduce high energy particle scattering in the solar flare regions. Successful description for terrestrial atmospheric neutrinos, and their primary relic of cosmic rays, has been obtained. Our approach, ignoring the exact spectrum for protons in recent solar flare and the detailed magnetic configuration, will force us to consider only averaged values, neglecting the (higher energetic) Kaon production. In order to find the interaction probability for an energetic proton ($E_p \simeq 2$ GeV) to scatter un-elastically with a target proton at rest in solar atmosphere, we must assume an exponential solar density function following well known solar density models (Machado & Linsky 1975).

$$n_{\odot} = N_0 e^{\frac{-h}{h_0}};\; N_0 = 2.26 \cdot 10^{17} \text{ cm}^{-3},\; h_0 = 1.16 \cdot 10^{7} \text{ cm}\,, \tag{4}$$

where h_0 is the photosphere height where flare occurs.

2.2 Upward protons interactions in solar flare

The unelastic proton-proton cross section for energetic particles ($E_p > 2$ GeV) is nearly constant: $\sigma_{pp}(E > 2 \text{ GeV}) \simeq 4 \cdot 10^{-26}$ cm^2. Therefore the scattering probability P_{up} for an orthogonal up-ward energetic proton p_E, to produce by nuclear reaction, pions (or kaons) is:

$$P_{up} = 1 - e^{-\int_{h_0=0}^{\infty} \sigma_{pp} n_{\odot} dh} \simeq 0.1\,. \tag{5}$$

A terrestrial Observatory in direct line of sight with a solar flare would observe only 10% (or much less, if, as it is well possible $h_0 > 10^7$ cm) of the primordial proton flare number, converted into pions and relic muons, neutrinos and electron-positron pairs. Moreover, because of the kinematics, only a fraction smaller than 1/2 of the energetic proton will be released to pions (or kaons) formation. In the simplest reaction, source of pions, ($p + p \to \Delta^{++} n \to p\pi^+ n$; $p + p \to \Delta^+ p \begin{smallmatrix}\nearrow p+p+\pi^0 \\ \searrow p+n+\pi^+\end{smallmatrix}$) at the center of mass of the resonance Δ (whose mass value is $m_\Delta = 1232$ MeV), the reaction $R_{\pi p}$ between the pion to the proton energy is:

$$R_{\pi p} = \frac{E_\pi}{E_p} = \frac{{m_\Delta}^2 + {m_\pi}^2 - {m_p}^2}{{m_\Delta}^2 + {m_p}^2 - {m_\pi}^2} = 0.276\,. \tag{6}$$

Therefore the total pion flare energy due to upward proton is:

$$E_{\pi_{\mathrm{FL}}} = P R_{\pi p} E_{\mathrm{FL}} = 2.76 \cdot 10^{-2} E_{\mathrm{FL}}\,. \tag{7}$$

Because of the isotopic spin the probability to form a charged pion over a neutral one in the reactions above: $p + p \to p + n + \pi^+$, $p + p \to p + p + \pi^0$, is given by the Clebsh Gordon coefficients, (3/4), and by the positive-negative ratio (1/2):

$$C_{\frac{\pi^-}{\pi^0}} \simeq C_{\frac{\pi^+}{\pi^0}} \simeq \frac{3}{4}\,. \tag{8}$$

The ratio of the neutrino of the muon energy in pion decay is also a small adimensional fraction $R_{\nu_\mu \mu}$

$$R_{\nu_\mu \mu} = \frac{E_{\nu_\mu}}{E_\mu} = \frac{{m_\pi}^2 - {m_\mu}^2}{{m_\pi}^2 + {m_\mu}^2} = 0.271\,. \tag{9}$$

In a first approximation one may assume that the total pion energy is equally distributed in all its final remnants: ($\bar{\nu}_\mu$, e^+, ν_e, ν_μ) or (ν_μ, e^-, $\bar{\nu}_e$, $\bar{\nu}_\mu$):

$$\frac{E_{\bar{\nu}_\mu}}{2} \simeq \frac{E_{\nu_\mu}}{2} \simeq E_{\nu_e} \simeq E_{\bar{\nu}_e} \simeq \frac{1}{4} E_{\pi^+}\,. \tag{10}$$

Actually the correct averaged energy (by Michell parameters) for neutrino decay $\mu^\pm$ at rest are: $E_{\bar{\nu}_e} = E_{\nu_e} = \frac{3}{10} m_\mu \simeq \frac{1}{4} m_\pi; E_{\bar{\nu}_\mu} = E_{\nu_\mu} \simeq \frac{7}{20} m_\mu \simeq \frac{1}{3} m_\pi$. Similar reactions (at lower probability) may also occur by proton-alfa scattering leading to: ($p + n \to \Delta^+ n \to n\pi^+ n$; $p + n \to \Delta^o p \begin{smallmatrix}\nearrow p+p+\pi^- \\ \searrow p+n+\pi^o\end{smallmatrix}$). Here we neglect their additional role due to the flavor mixing and the dominance of previous reactions at soft flare spectra. Therefore $E_{\nu_\mu} > E_{\nu_e}$; however muon neutrino from pions $\pi^\pm$ decays have a much lower mean energy and the combined result in eq.(10) is a good approximation. We must consider also the flavour mixing (in vacuum) that it is able to lead to an averaged neutrino energy along the neutrino flight making a final mix-up and average neutrino flavour energy and flux intensity. In a first approximation the oscillation will lead to a 50% decrease in the muon component and it will change mainly the electron neutrino component making it harder. We will keep this flavor mixing into account by an efficient conversion term $\eta_\mu \simeq \frac{1}{2}$ re-scaling the final muon neutrino signal and increasing the electron spectra component. Because in π-μ decay the μ neutrinos relic are twice the electron ones, the anti-electron neutrino flare energy is, at the birth place on Sun:

$$E_{\bar{\nu}_e \mathrm{FL}} \simeq E_{\nu_e \mathrm{FL}} \simeq \frac{E_{\nu_\mu \mathrm{FL}}}{2} \simeq P_{up} R_{\pi p} C_{\frac{\pi^-}{\pi^0}} E_{\mathrm{FL}} R_{\nu_\mu \mu} \simeq 2.6 \cdot 10^{28} \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big)\ \mathrm{erg}\,. \tag{11}$$

The corresponding neutrino flare energy and number fluxes at sea level are:

$$\Phi_{\bar{\nu}_e \mathrm{FL}} \simeq 9.15 \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big)\ \mathrm{erg\ cm}^{-2}\,, \tag{12}$$

$$N_{\nu_e} \simeq N_{\bar{\nu}_e} \simeq 5.7 \cdot 10^4 \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big) \Big(\frac{\langle E_{\bar{\nu}_e} \rangle}{100\ \mathrm{MeV}} \Big)^{-1} \mathrm{cm}^{-2}\,. \tag{13}$$

The flux energy in eq. (12) is nearly 4000 times smaller than the energy flux in eq. (2) and, as we shall see, it maybe nevertheless nearly observable by present detectors. This flux at GeV energy may correspond approximately to a quarter of a day atmospheric neutrino integral fluence (for each flavor specie). Therefore it may lead to just a half of an event as on out-ward event on 28th. October 2003. The largest neutron and gamma flare energies should be (and indeed are) comparable or even much larger (February 1956) than the upward neutrino flux energy in eq.(12). The exceptional solar flare on Sept. 29th, 1989 as well as the most recent on 2nd -4th November 2003 took place in the nearly hidden disk side and we may look now for their horizontal or down-ward secondary neutrinos. Their scattering are more effective and are offering more pion production. The processes we describe here are analogous to the one considered for horizontal and upward neutrino induced air-showers inside the Earth Crust (see Fargion 2002) and nearly ultra high horizontal showers (detectable by EUSO). The solar neutrino flare production is enhanced by a higher solar gas density where the flare beam occurs. Moreover a beamed X-flare may suggest a corresponding beamed pion shower whose mild beaming naturally increase the neutrino signal. Most of the down-ward neutrino signal to be discussed below is generated at mild relativistic regime as well as their pion and muon secondaries; therefore there maybe also a mild outburst outside with some anisotropy suppression, back toward the Earth.

2.3 Downward, proton interactions in solar flare

High energetic protons flying downward (or horizontally) to the Sun center are crossing larger (and deeper) solar densities and their probability of interaction P_d, is larger than the previous one (P_{up}). The proton energy losses due to ionization, at the densities where most of their reaction take place, are low in respect to the nuclear ones and most of the proton flare energy is converted into pion-Kaon nuclear productions with few losses.

If the energetic proton direction is tangent or downward to the solar core, the probability interaction is even larger than one. Unstable and short lived pions of few GeV will decay in flight because nuclear reaction at those solar atmosphere densities, are small; the pion number density n_π is described by an evolution equation of the form:

$$\begin{aligned}\frac{dn_\pi}{dt} &= \iint \Big[\frac{d^2 n_{pE}}{dEd\Omega} n_{pT}\sigma_{pp}v_{pE} - \frac{d^2 n_{pE}}{dEd\Omega} n_\pi \sigma_{p\pi} v_\pi - \frac{d^2 n_\pi}{dEd\Omega} n_\pi \sigma_{\pi\pi} v_\pi\Big] dE d\Omega + \\ &- \int_{m_\pi}^{\infty} \frac{d^2 n_\pi}{dE}\Gamma_\pi \Big(\frac{m_\pi}{E_\pi}\Big) dE_\pi; \qquad (14)\end{aligned}$$

where n_{pE}, n_{pT}, n_π are the number density of the flare energetic and target protons, $\sigma_{pp}(E)$, $\sigma_{p\pi}(E)$, $\sigma_{\pi\pi}(E)$, are the p-p, p-π, π-π cross sections. The velocities v_{pE}, v_π are near the velocity of light and $\Gamma_\pi = 3.8 \cdot 10^7 s^{-1}$. The last term in eq.(14), due to the relativistic pion decay, at solar densities as in eq.(4) and at an energy $E_\pi \simeq$ GeV, is nearly six order of magnitude larger than all other terms. Therefore the pion number density n_π should never exceed the corresponding proton number density n_{pE}; however the integral number of all pion stable relics ($\bar{\nu}_\mu$, ν_μ, ν_e, $\bar{\nu}_e$, e^-) may exceed, in principle, the corresponding number of proton flare, because each proton may be a source of more than one pion chain. The proton number density, below the photosphere ($h < 0$), is described by a polytropic solution, but it can be also approximated by a natural extrapolation of the low in the eq.(4) with a negative height h. It is easy to show that the interaction probability for a relativistic proton ($E_{pE} \gg$ GeV) reaches unity at depth $h = -278$ km which is the interaction length. At the corresponding density ($n\odot \sim 2.2 \cdot 10^{18}$ cm^{-3}) the proton ionization losses, between any pair of nuclear reactions are negligible (few percent). Unstable relic pions decay (almost) freely are after a length $L_\pi \simeq (\frac{E_\pi}{m_\pi}){\Gamma_\pi}^{-1} C \simeq 7.8 \cdot 10^2 (\frac{E_\pi}{m_\pi})$

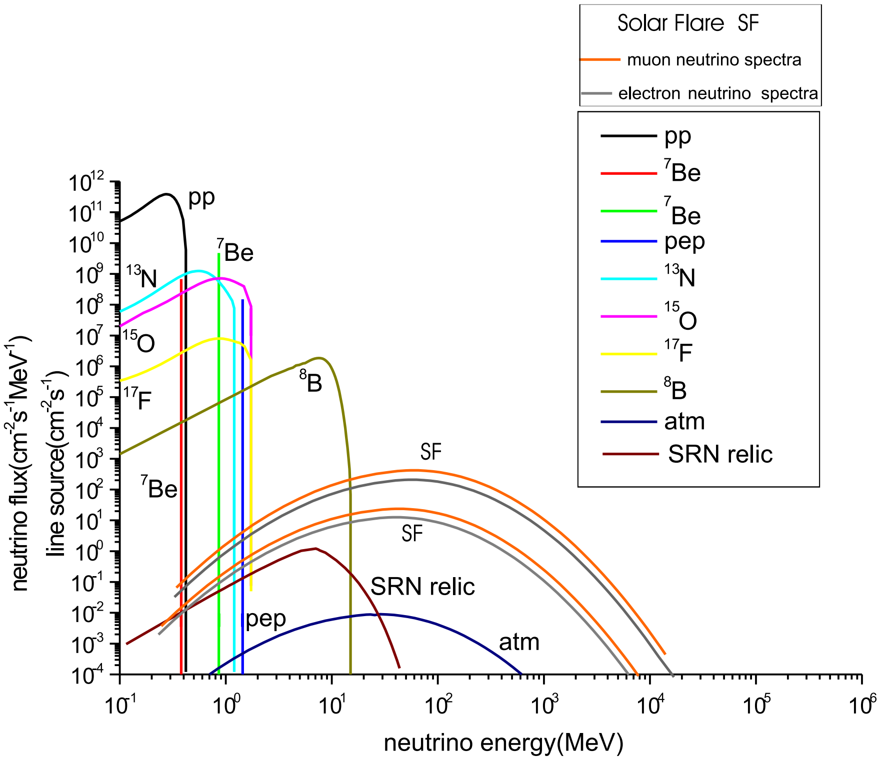

Fig. 1 Solar neutrino Flare fluxes over known neutrino background: solar neutrinos by known nuclear activities as well as the expected Supernova Relic fluxes and the atmospheric noises. The Solar flare are estimated on the Earth at peak activity of the flare supposed to held 100 s. The two primordial flavour ν_e, $\overline{\nu}_e$ and their correspondent ν_μ, $\overline{\nu_\mu}$ are shown before their oscillation while flying and mixing toward the Earth. Their final flavour are nearly equal in all states ν_e,ν_μ, ν_τ and are not shown for sake of simplicity; however each final ν_e,ν_μ, ν_τ, $\overline{\nu_e}$,$\overline{\nu_\mu}$,$\overline{\nu_\tau}$ fluxes are almost corresponding to the lower curve for the electron neutrino spectra. Both highest and lowest activities are described following an up-going (poor flux) or down-going (richer flux) scenario. The primary solar flare spectra is considered like the atmosphere one at least within the energy windows $E_{\nu_\mu} \simeq 10^{-3}$ GeV up to 10 GeV.

cm. The secondary muons μ do not loose much of their energy ($\leq 1\%$) in ionization, ($E_\mu \leq 0.1 - 1$ GeV) during their nearly free decay: the muon flight distance is $L_\mu = \frac{E_\mu}{m_\mu}{\Gamma_\mu}^{-1}C = 6.58 \cdot 10^4 (\frac{E_\mu}{m_\mu})$ cm, and the ionization losses are: $\frac{dE_\pi}{dx} \simeq \frac{dE_\mu}{dx} \simeq 10^{-5}$ MeV cm^{-1}. In conclusion most of the solar flare energy will contribute to downward muon energy, with an efficiency η near unity. At deeper regions, near $h < -700$ km where the solar density is $n_\odot \geq 10^{20}$ cm^{-3}, a GeV-muon will dissipate most of its energy in ionization before decaying. In that case the energy ratio between muon relics and primary protons is much smaller than unity. Only a small fraction of inward protons will reach by a random walk such deeper regions and we may conclude that, in general, the flare energy relations are:

$$E_{\pi FL} \equiv \eta E_{\rm FL} \leq E_{\rm FL}$$

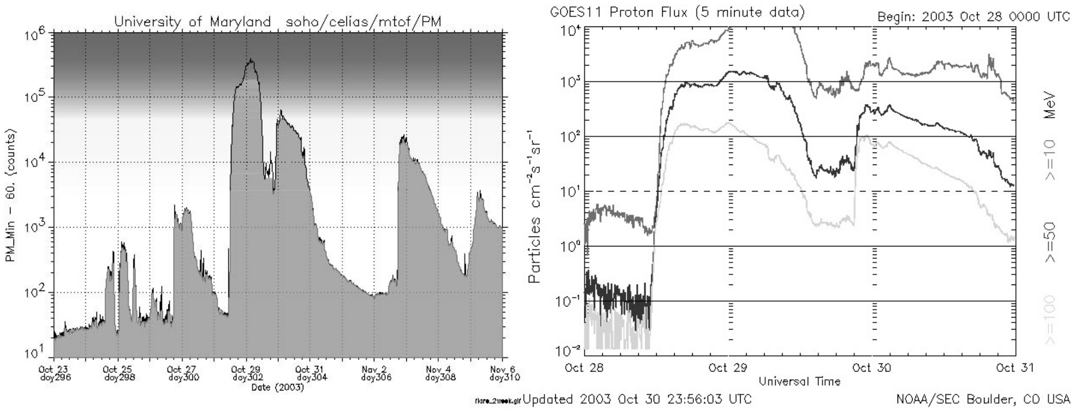

Fig. 2 Proton solar flare flux (left: all the events during 23 October-6 November 2003 at lowest energies); (right: detail of part (10-100 Mev) energy the spectra); the data are respectively from SOHO and GOES11 satellite experiments

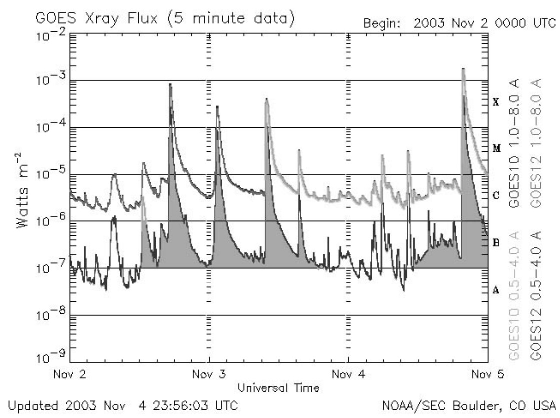

Fig. 3 Left:X Solar Flare on-set 2nd-4th November 2003 by GOES satellite: readable are the X-peak outburst

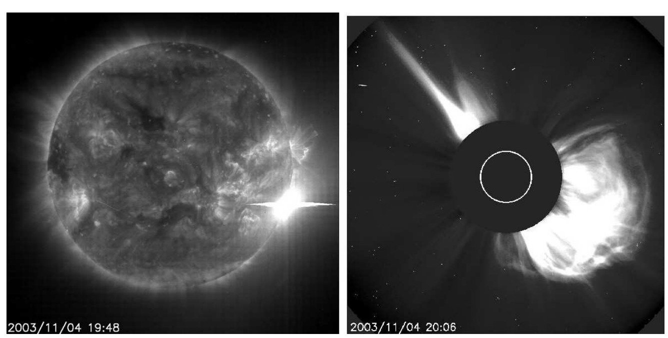

Fig. 4 X Solar Flare on 4th November 2003 observed by GOES and SOHO satellites: note the sharp outburst at 19:48-20:08 UT

$$E_{\bar{\nu}_e\mathrm{FL}} \simeq E_{\nu_e\mathrm{FL}} \simeq \frac{E_{\nu_\mu\mathrm{FL}}}{2} \simeq \frac{E_{\bar{\nu}_\mu\mathrm{FL}}}{2} \simeq \frac{\eta C_{\frac{\pi^-}{\pi_0}} E_{\mathrm{FL}}}{4} \simeq 9.4 \cdot 10^{30} \eta \Big(\frac{E_{\mathrm{FL}}}{10^{32}\ \mathrm{erg}} \Big)\ \mathrm{erg}\,. \tag{15}$$

This result is nearly 36 times larger than the corresponding one for *up-ward* neutrinos in eq.(10). Terrestrial neutrino relics from cosmic rays, related to analogous pion chain reaction, lead to a predicted and observed asymmetry (see Gaisser, Stanev & Barr 1989) between $\bar{\nu}_e$, ν_e, due to the positive proton charge predominance either in target and incident beam:

$$\frac{N_{\nu_e}}{N_{\bar{\nu}_e}} = \frac{N_{\mu^+}}{N_{\mu^-}} \simeq 1.2\,,$$

at energies 10 GeV $> E_\nu >$ 100 MeV. Therefore the energy component of the observable flare should be marginally reduced in eq.(15), even assuming a low flare (10^{31} erg) output:

$$E_{\bar{\nu}_e} \simeq 7.8 \cdot 10^{-2} \eta E_{\mathrm{FL}} = 7.8 \cdot 10^{29} \eta \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big)\ \mathrm{erg}\,. \tag{16}$$

3 DETECTABLE SOLAR FLARE NEUTRINOS IN SK-II

We cannot say much about the solar flare neutrino spectrum because of our ignorance on the recent primordial proton flare spectra. The solar flare are usually very soft. We may expect a power spectrum with an exponent equal or larger than the cosmic ray proton spectrum. Therefore we consider here only averaged neutrino energy $\langle E_\nu \rangle$ at lowest energies (below near GeV) and we scale the result above, eq. (16), for the anti-neutrino numbers at sea level:

$$\langle E_{\bar{\nu}_e} \rangle \simeq 1.72 \cdot 10^6 \eta \Big(\frac{\langle E_{\bar{\nu}_e} \rangle}{100\ \mathrm{MeV}} \Big)^{-1} \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big)\ \mathrm{cm}^{-2}\,, \tag{17}$$

$$\langle E_{\bar{\nu}_\mu} \rangle \simeq 4.12 \cdot 10^6 \eta \Big(\frac{\langle E_{\bar{\nu}_\mu} \rangle}{100\ \mathrm{MeV}} \Big)^{-1} \Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}} \Big)\ \mathrm{cm}^{-2}\,. \tag{18}$$

We now consider the neutrino events due to these number fluxes at Super-Kamiokande II; other detectors as SNO (and AMANDA if the spectra was extremely hard) might also record a few events but at much lower rate. The observable neutrino events, due to inverse beta decay ($\bar{\nu}_e + p \to n + e^+$; $\bar{\nu}_\mu + p \to \mu^+ + n$), at Super-Kamiokande detectors are:

$$N_{ev} = \sum_i \int \frac{dN_{\bar{\nu}_i}}{dE_i} \sigma_{\bar{\nu}_i p}(E_{\nu_i}) N_{p_{\mathrm{SK}}} dE_i\,, \tag{19}$$

$i = e, \mu$. A comparable neutrino events, due to stimulated beta decay ($\nu_e + n \to p + e^-$; $\nu_\mu + n \to \mu^- + p$), must also take place (see Bodek, Budd & Arrington 2003). We may approximate this number with an averaged one due to an effective neutrino energy $\bar{E}_\nu$:

$$N_{\mathrm{eV}} = \sum_i \sigma_{\bar{\nu}_i p}(\bar{E}_{\nu_i}) N_{p_{\mathrm{SK}}}\,. \tag{20}$$

Where $N_{p_{\mathrm{SK}}}$ is the proton number in the Super-Kamiokande detector $N_{p_{\mathrm{SK}}} = \frac{N_p}{N_{\mathrm{H_2O}}} N_{\mathrm{nucl}}$; $N_{\mathrm{nucl}} = 22KT \cdot N_A = 3.33 \cdot 10^{34}$; $\frac{N_p}{N_{\mathrm{H_2O}}} = \frac{10}{18}$; $N_{p_{\mathrm{SK}}} = 7.38 \cdot 10^{33}$. The cross section is an elaborated analytical formula (see Strumia & Vissani 2003) is possible. This expression is in agreement with full result within few per-mille for $E_\nu \leq 300$ MeV is

$$\sigma(\bar{\nu}_e p) \approx 10^{-43}\,\mathrm{cm}^2\ p_e E_e\ E_\nu^{-0.07056 + 0.02018 \ln E_\nu - 0.001953 \ln^3 E_\nu}\,, \qquad E_e = E_\nu - \Delta\,, \tag{21}$$

where $\Delta = m_n - m_p$; E_e is the energy of the escaping electron. In the simplest low-energy approximation (see Bemporad, Gratta & Vogel 2002)

$$\sigma \approx 9.52 \times 10^{-44} \frac{p_e E_e}{\mathrm{MeV}^2}\ \mathrm{cm}^2, \qquad E_e = E_\nu \pm \Delta \text{ for } \bar{\nu}_e \text{ and } \nu_e\,. \tag{22}$$

In a more simple and direct form (see Fargion 1989), at low energy (10 MeV $\leq E_{\bar{\nu}_e} \leq$ GeV)

$$\sigma_{\bar{\nu}_e p} \simeq 7.5 \cdot 10^{-44} \Big(\frac{E_{\bar{\nu}_e}}{\mathrm{MeV}}\Big)^2 \mathrm{cm}^2\,. \tag{23}$$

The expected neutrino event, during the flare may be two fold as we mentioned above: a solar burst and a terrestrial flux; for the terrestrial neutrino flux (during the recent 28/29 Oct. 2003 flare) we expect from the solar proton hitting the atmosphere and leading to neutrinos at least:

$$N_{\mathrm{eV}} \cong 1.7 \cdot 10^6 \cdot 7.38 \cdot 10^{33} \cdot 6 \cdot 10^{-40} \simeq 7.5 \cdot \eta\,. \tag{24}$$

These events should increase (almost doubling its flux) the common atmospheric neutrino flux background (5.8 event a day). For the prompt neutrino solar burst in the Sun we expect (if covered or horizontal) a similar number in a very narrow time window. Naturally this result might be over-optimistic. In order to obtain a more severe and more pessimistic result we now tune our expectation with the event number due to the well known supernovæ SN1987A where we know (or we hope to know) the primordial neutrino energy: $\sum E_{\nu_{\mathrm{SN}}} \simeq 3 \cdot 10^{53}$ erg and $\bar{E}_{\bar{\nu}_e} \simeq 10$ MeV. We know (by cosmology and Z_0 width decay in LEP) that the possible neutrino flavours states are $N_F = 6$ ($\nu_e, \bar{\nu}_e, \nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$). The Earth-SN1987A distance $d_{\mathrm{SN}} = 1.5 \cdot 10^{23}$ cm lead to:

$$N_{\mathrm{eV}\,\bar{\nu}_e} = \frac{N_{\nu_{\mathrm{SN}}}}{N_F} \sigma_{\bar{\nu}_e p}(\bar{E}_{\nu_{\mathrm{SN}}}) N_{\mathrm{pSK}} = 11 \Big(\frac{E_{\mathrm{SN}}}{3 \cdot 10^{53}\ \mathrm{erg}}\Big)\Big(\frac{\bar{E}_\nu}{10\ \mathrm{MeV}}\Big)\,. \tag{25}$$

It should be noted that the quadratic energy $\bar{E}_\nu$ dependence of the cross section $\sigma_{\bar{\nu}_e p}$ and the inverse energy $\bar{E}_\nu$ relation of the neutrino flux number leads to the linear dependence in eq.(23). However, the inverse beta decay processes increases linearly with energy $\bar{E}_\nu$ up to a value smaller than $m_p \sim$ GeV. Above it the cross section in eq.(20) becomes flat and only at higher energies it grows linearly with the energy: $\bar{\nu}_e + p \to e^+ + n$; $\quad \bar{\nu}_\mu + p \to \mu^+ + n$; $\nu_e + n \to e^- + p$; $\quad \nu_\mu + n \to \mu^- + n$;

$$\sigma_{\bar{\nu}_e p} \simeq 6.2 \cdot 10^{-39}\ \mathrm{cm}^2 \Big(\frac{\bar{E}_{\bar{\nu}_e}}{\mathrm{GeV}}\Big); \qquad \sigma_{\nu_e n} \simeq 3.5 \cdot 10^{-39}\ \mathrm{cm}^2 \Big(\frac{\bar{E}_{\nu_e}}{\mathrm{GeV}}\Big) \mathrm{cm}^2\,. \tag{26}$$

The formulas above are approximation only within an energy window $E_{\nu_\mu}, E_{\bar{\nu}_\mu}, E_{\nu_e}, E_{\bar{\nu}_e} \simeq 100 - 1000$ MeV. As we shall see, we may neglect the prompt neutrino-electron scattering processes due to charged or neutral currents cross sections:

$$\sigma_{\nu_e e} \simeq 9 \cdot 10^{-45} \Big(\frac{\bar{E}_\nu}{\mathrm{MeV}}\Big) \mathrm{cm}^2;\ \sigma_{\nu_\mu e} \simeq 1.45 \cdot 10^{-45} \Big(\frac{\bar{E}_\nu}{\mathrm{MeV}}\Big) \mathrm{cm}^2\,,$$

$$\sigma_{\bar{\nu}_e e} \simeq 3.7 \cdot 10^{-45} \Big(\frac{\bar{E}_\nu}{\mathrm{MeV}}\Big) \mathrm{cm}^2;\ \sigma_{\bar{\nu}_\mu e} \simeq 1.24 \cdot 10^{-45} \Big(\frac{\bar{E}_\nu}{\mathrm{MeV}}\Big) \mathrm{cm}^2\,. \tag{27}$$

Indeed these values are nearly 100 times smaller (at $\bar{E}_\nu \sim 100$ MeV) than the corresponding nuclear ones in eq.(23, 26). We consider the neutrino flare signals at Super-Kamiokande due to either $\bar{\nu}_e + p \to n + e^+$ and $\bar{\nu}_\mu + p \to \mu^+ + n$, $\nu_e + n \to e^- + p$; $\quad \nu_\mu + n \to \mu^- + n$; keeping in mind, for the latter, the threshold energy E_{ν_μ},$E_{\bar{\nu}_\mu} > 113$ MeV. We may summarize from eq.(17) the expectation event numbers at Super-Kamiokande as follows: $N_{ev\bar{\nu}_e} \simeq 0.63\eta(\frac{\bar{E}_{\bar{\nu}_e}}{35\ MeV})\Big(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}}\Big)$; $\bar{E}_{\bar{\nu}_e} \leq 100$ MeV; $N_{ev\bar{\nu}_e} \simeq 1.58\eta(\frac{E_{\mathrm{FL}}}{10^{31}\ \mathrm{erg}})$; $\bar{E}_{\bar{\nu}_e} \geq 100 - 1000$ MeV;

$N_{ev\bar{\nu}_\mu} \simeq 3.58\eta(\frac{E_{\rm FL}}{10^{31}\ {\rm erg}})$; $\bar{E}_{\bar{\nu}_\mu} \geq 200 - 1000$ MeV; where $\eta \leq 1$. The neutrino events in Super-Kamiokande may be also recorded as stimulated beta decay on oxygen nuclei. Indeed such reactions exhibit two possible channels: $\nu_e + O \to F + e^-$, $\bar{\nu}_e\ O \to N + e^+$; they have been analyzed by W. C. Haxton (see Haxton 1987). For this reason our preliminary estimate is just a lower bound for any high energetic ($E_{\nu_e} > 100$ MeV) neutrino spectrum.

4 CONCLUSIONS: THE SOLAR MUON AND TAU NEUTRINO

The Earth-Sun distance $D_{\oplus\odot}$ is large enough to guarantee a complete flavor mixing even for hundred MeV or GeV neutrino energies. Indeed the oscillation distance in vacuum: $L_{\nu_\mu-\nu_\tau} = 2.48 \cdot 10^9\ {\rm cm}\left(\frac{E_\nu}{10^9\ {\rm eV}}\right)\left(\frac{\Delta m_{ij}^2}{(10^{-2}\ {\rm eV})^2}\right)^{-1} \ll D_{\oplus\odot} = 1.5 \cdot 10^{13}$ cm. The consequent flavor mixing will increase the average energy of the anti neutrino electron component respect to its birth one. This will increase also the neutrino electron component while it will reduce the corresponding muon component leading to: $\frac{\eta_\mu}{\eta_e} \simeq \frac{1}{2}$ and to $N_{{\rm eV}_{\bar{\nu}_\mu}} \simeq N_{{\rm eV}_{\bar{\nu}_e}} \simeq 2(\frac{\langle E_{\nu_\mu}\rangle}{200\ {\rm MeV}}(\frac{\langle E_{\rm FL}\rangle}{10}^{31}\ {\rm erg})$; $N_{{\rm eV}_{\nu_\mu}} \simeq N_{{\rm eV}_{\nu_e}}$ as well as a comparable, ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ energy fluence and spectra. The rise of muon neutrinos will be detectable above the minimal muon threshold $E_\nu \simeq$ 113 MeV energy, or better above the pion and Δ° thresholds ($E_\nu \simeq$ 151 and 484 MeV). Its presence is unexpected by standard solar physics. The prompt muon neutrino burst will inaugurate a novel solar muon neutrino astronomy. Any large neutrino flare event record might also verify the expected neutrino flavour mixing leading to a few as well as a comparable ν_e, ν_μ, $\bar{\nu}_e$, $\bar{\nu}_\mu$ energy fluence and spectra. The rarest tau appearance will be possible only for hardest solar neutrino energies above 3.471 GeV, but this require a hard ($E_{\nu_\mu} \to E_{\nu_\tau} \simeq 4$ GeV) flare spectra. At highest neutrino energies above 4.357 GeV the τ appearance by Δ° resonance will be most favorite.

Any positive evidence for such events will mark a new road to Neutrino Astrophysics, to be complementary to lower neutrino energy from Sun and Supernovæ. New larger generations of neutrino detectors will be more sensitive to these less power-full, but more frequent and energetic solar flares, than sensitive to rarest extragalactic supernovæ (as the one from Andromeda) whose time delay might give insight of neutrino mass, (Fargion 2002). In conclusion therefore the recent solar flare on October-November 2003 as large as the one on Sept. $29th$, 1989 might be an exceptional source of cosmic, gamma, neutron rays and neutrinos as well. Their minimal event number at Super-Kamiokande $N_{{\rm eV}_{\bar{\nu}_\mu}} \simeq N_{{\rm eV}_{\bar{\nu}_e}} \simeq 2(\frac{\langle E_{\nu_\mu}\rangle}{200\ {\rm MeV}}(\frac{\langle E_{\rm FL}\rangle}{10^{31}\ {\rm erg}})$; $N_{{\rm eV}_{\nu_\mu}} \simeq N_{{\rm eV}_{\nu_e}}$ is near or above unity. The noise signal of energetic atmospheric neutrinos at the Japanese detector is nearly 5.8 event a day time corresponding to a rate $\Gamma \simeq 6.710^{-5} s^{-1}$. The minimal and the largest predicted event number $(1 \div 5)\ \eta$, $(\eta \leq 1)$ within the narrow time gate defined by the sharp X burst onset (100 s), are above the noise. Indeed the probability to find by chance one neutrino event within a $1 - 2$ minute $\Delta t \simeq 10^2$ s in that interval is $P \simeq \Gamma \cdot \Delta T \simeq 6.7 \cdot 10^{-3}$. For a Poisson distribution the probability to find $n = 1, 2, 3, 4, 5$ events in a narrow time window might reach extremely small values: $P_n \cong \frac{P^n}{n!} = (6.7 \cdot 10^{-3}, 2.25 \cdot 10^{-5}, 5 \cdot 10^{-8}, 8.3910^{-11}, 1.1 \cdot 10^{-13})$. Therefore the very possible presence of one or more high energetic (tens-hundred MeVs) positron (or better positive muons) as well as any negative electron or muon, in Super-Kamiokande at X-flare onset time may be a well defined and most brilliant signature of the solar neutrino flare. A surprising discover by τ appearance of the complete mixing may occur by hard ($E_{\nu_\mu} \to E_{\nu_\tau} \simeq> 4$ GeV) flare spectra. Its most recognizable signature occurs by a rare π^o production, (by the common hadronic τ decay), and its pion consequent decays into mono-cromatic γ whose relics are consequent e^+,e^- relativistic pairs production. Any steep proton flare spectrum, where a large flare energy fraction is at a low proton energies may reduce σ_{pp} un-elastic cross-sections and increase the elastic ones, reducing the pion-neutrino creations. A low flare energy $E_{\rm FL} < 10^{32}$ erg, any neutrino muon spectra where $\bar{E}_{\bar{\nu}_\mu}$ <100 MeV, or any proton-magnetic field interaction may suppress somehow our estimates. Therefore our considerations are only preliminary and they must be taken with caution (also in view of the delicate chain of assumptions and simplification). We hope to stimulate with our work correlated research in gamma-optical-neutron rays observations and neutrino underground detectors in view of additional solar activity. In particular we suggest to control the very Super-Kamiokande data records on $October - November$ solar flare X-radio peak activity, namely on $26 - 28 - 30th$ October and $2nd - 4th$ and 13 November X-ray onset (see figures below for time details). We like to point the attention to the hard X on set at $19 : 48$ UT on $4th$ November 2003.

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References

Alessio M., Allegri L., Fargion D., Improta S. et al., 1991, Il Nuovo Cimento, 14C, 53

Bachelet F., & Conforto A.M., 1956, Nuovo Cimento, 3, 1153

Barr G., Gaisser T.K., Stanev T., 1989, Phys. Rev. D, 39, 3532

Bemporad C., Gratta G., & Vogel P., 2002, Rev. Mod. Phys., 74, 297

Berezinsky V.S., Castagnoli C., & Galeotti P., 1985, Il Nuovo Cimento, 8C, 185

Bodek A., Budd H., and Arrington J., 2003, hep-ex/0309024

Dryer M., 1974, Space Science Reviews, 15, 403-468

Fargion D., 1989, preprint INFN n.721, see http://adsabs.harvard.edu/abs/1989STIN...9023331F; Fargion D., 2004, JHEP 0406, 045

Fargion D., 2002 Ap. J. 570, 909-925

Fargion D., & Khlopov M., 2003, Astrop. Phys., vol. 19, 3, 441-446

Haxton W.C., 1987, Phys. Rev. D, 36, 2283

Karpov S.N., Miroshnichenko L.I., Vashenyuk E.V., 1998, Il Nuovo Cimento, 21C, 551

Lin R.P., et al., 2003, Ap.J, 595, L69.

Machado M.E., & Linsky J. L., 1975, Solar Phys., 42, 395

Miroshnichenko L.I., De Koning C.A., Perez-Enriquez R., 2000, Space Science Reviews, 91, 615

Simpson J., 1957, Proc.National Acad. of Sc.of USA, 43, 42

Strumia A., & Vissani F., 2003, astro-ph/0302055