Flavor revolution at ICECUBE horizons?

Daniele Fargion and Paolo Paggi

Physics Department, Rome University 1 and INFN – Pl. A. Moro 2, 00185, Rome, Italy

Abstract

Recently (May-November 2013) highest energy neutrino events have been presented by ICECUBE. Most (21) of all these (28) events are cascades shower whose flux exhibits a sharp hardening respect other lower energy atmospheric neutrino component, events suggesting an injection of extraterrestrial neutrino, mostly $\bar{\nu}_\mu$, $\nu_\tau$, making cascades. ICECUBE claimed that a component (10.6$^{+5.6}_{-3.0}$) of these events must be a trace of expected downward muons and-or atmospheric neutrinos (mostly muon track dominated): this imply that nearly all of the few observed muon tracks (at least 6 of the 7) must be themselves of atmospheric origin: therefore remaining 16 – 18 extraterrestrial events must be mostly of electron or of tau flavor (or rare neutral current events). The probability that this scenario occurs is very poor, about 0.1 – 0.5%. This $\bar{\nu}_\mu$, $\nu_\tau$ paucity paradox cannot be solved if part or even all the events are made by terrestrial prompt charmed signals, because, their probability to solve the puzzle is still below 1.31%. The paradox might be mitigate and somehow solved if nearly all of the 28 events are originated by extraterrestrial sources arriving to us in de-coherent states. At first sight a partial flavor solution may rise if highest energy events at $E_\nu > 60 TeV$ (17 showering versus 4 muon tracks) are mostly of extraterrestrial nature. This solution leaves nevertheless problematic the earlier 30 – 60 TeV energy region, whose 8 showers versus 3 tracks is in more in tension with most atmospheric neutrino signals, by a sharp difference at TeV energy ruled (as shown in Deep Core) by ten over one neutrino (muon) events over showers. This puzzling (fast) transition from atmospheric $\nu_\mu$, $\bar{\nu}_\mu$ flux at TeV to tens TeV has deep consequences: more abundant ten TeV extraterrestrial neutrino maps may better point to astronomical clustering or sky anisotropy; counting vertical versus horizontal (neutrino) muons crossing the whole ICECUBE , i.e. testing zenith anisotropy at tens TeV of muons up-going, may also better disentangle and confirm their mostly extraterrestrial (or atmospheric, respectively, more vertical and isotropic versus horizontal ones) neutrino nature. Few cascades shower events in early Antares yearly might also test the $\nu$ flavor changes above $10^{12} eV$ up to a rare one at $\simeq 3 \cdot 10^{13} eV$ signal. Additional EeV $\tau$ air-shower induced by UHE $\nu_\tau$ within mountains or Earth skin [5] while skimming [6], terrestrial ground as AUGER arrays [7] might be rare but the correlated horizontal upward PeVs $\tau$ air-shower may soon [8] shine into ASHRA crown telescopes at mountain edges by their Cherenkov flashes.

Keywords: Cosmic Rays, neutrino, muons, shower

1. Introduction: the $\nu_\mu$ fast flavor metamorphosis

Cosmic ray nuclei and nucleons scattering on top atmosphere makes (by pions, Kaons and late muons) a final persistent neutrino raining called atmospheric neutrinos, at high GeV-TeV energies by muon flavor. The parent charged cosmic rays are widely spread by solar, galactic magnetic fields. In the same way their secondaries, the atmospheric neutrinos, are commonly spread homogeneously in the sky. Therefore diffuse atmospheric neutrinos cannot offer any astronomy yet, as it has been shown by four hundred thousands neutrinos in ICECUBE. As observed and expected atmospheric neutrinos up to TeVs energies exhibit a muon flavor dominance, that suddenly (and somehow surprisingly) it is overthrown by recent 28 highest [1] energy ICECUBE events. Indeed the 28 ICECUBE events show a ruling cascade showering nature (21 events) and a rare muon (7 events) track signature. Therefore the new break is not just in the spectra hardening but mainly it is in the sudden and remarkable $\nu_\mu$, $\bar{\nu}_e$, $\nu_\tau$, $\bar{\nu}_\tau$ flavor ” sorpasso” or “surpassing over” $\nu_\mu$, $\bar{\nu}_\mu$. Let us remind that atmospheric neutrino are born mostly after nucleon scattering by pion and muon decays. These two way for a neutrino production (around GeVs energy) makes both lepton flavors, mostly muons (twice muon over electron ones). Along the vertical axis, at a few ten of GeV energy, there is also a narrow windows for muon neutrino oscillations and its average peculiar anisotropy that makes them halves the primary ones.

1.1. Showering cascades surpassing $\nu_\mu$, $\bar{\nu}_\mu$ tracks

As soon as the muon energy increases their relativistic decay in flight (whose time life-distance corresponds to 0.6 km) may overcome at few GeV the $\simeq 12$ km atmosphere height of vertical terrestrial atmosphere, where shower develops. The average muon mixing suppression is leading to up-going events rate half of the primary muon $\nu_\mu$ ones while the $\nu_\tau$, $\bar{\nu}_\tau$ component rate decrease above GeVs because muons has not time to decay in flight, see Fig. 1[5] while pion and kaon may still do it. The marginal vertical $\nu_\mu$ suppression at GeVs energies is due to flavor mixing along the Earth that deplete muon neutrino converting them into nearly unobservable $\nu_\tau$ (hardly observable because of the large mass $\tau$ mass threshold). The same $\nu_\mu$ oscillation into $\nu_\tau$ become severe at 20 GeV at vertical axis, because
of a last complete oscillation; at higher energy $\nu_\mu$, $\bar{\nu}_\mu$ have no
time of flight to mix within Earth size; therefore $\nu_\mu$, $\bar{\nu}_\mu$ keep
their original flavor above hundreds GeV becoming soon twice
the electron flavor and even more at higher energy because of
suppression of muon decay.

Moreover at hundreds GeV muon neutrinos cannot oscillate
much into tau states because of longer and longer oscillation
distances (respect to Earth size). Therefore muon signals above
tens GeV dominates again over electron ones while electron
neutrino suffer as mentioned of the difficulty of energetic rela-
tivistic muons to decay. The pions and Kaons have a lifetime
two order of magnitude shorter than muons and the Kaon mass
makes the difference; therefore at two order of energy higher,
at TeVs, also $\nu_\mu$ begin to suffer of a pion-Kaon survival by a
linear (with energy) suppression, and both $\nu_\mu$, $\nu_e$ flavor follow
a harder spectra than parental cosmic rays with an experimen-
tal exponential index 3.7 as one would suggest, but at different
ratio among the two flavors with an enhanced for $\nu_\mu$ over $\nu_e$ by
nearly an order of magnitude. The atmospheric neutrino pro-
cess based on cosmic rays has been understood and tested from
GeV up to few tens TeV energy also by recent ICECUBE re-
results, see Fig.2. However, as we shall suggest, there is a possi-
ble overestimation of atmospheric neutrino flux at these highest
energies. The general average behavior of the muon (added to
its anti-muon) $\nu_\mu$ energy flux $\Phi_{\nu_\mu}$ between GeV up to PeV in
average, ignoring here the muon-tau flavor detailed oscillations
[10], may be approximated as follow to trace ICECUBE data :

$$\Phi_{\nu_\mu} = [(\Phi_{\nu_\mu})^{-1} + (\Phi_{2\nu_\mu})^{-1}]^{-1} + \Phi_{0\nu_\mu}$$

$$\Phi_{\nu_\mu} \equiv E_{\nu_\mu}^2 \frac{dN_{\nu_\mu}}{dE_{\nu_\mu}}$$

$$\Phi_{1\nu_\mu} = 5.0 \cdot 10^7 \cdot \left(\frac{E_{\nu_\mu}}{GeV}\right)^{-1} eVm^{-2} \cdot s^{-1} \cdot sr^{-1}$$

$$\Phi_{2\nu_\mu} = 9.0 \cdot 10^4 \cdot \left(\frac{E_{\nu_\mu}}{TeV}\right)^{-1.7} eVm^{-2} \cdot s^{-1} \cdot sr^{-1}$$

$$\Phi_{0\nu_\mu} = 12 \cdot e^{-\frac{E_{\nu_\mu}}{40} eVm^{-2} \cdot s^{-1} \cdot sr^{-1}}$$

These functions keep care of the observed atmospheric $\nu_\mu$, $\bar{\nu}_\mu$
behavior in GeV- PeV range, trying to fit the 28 events hard-
eining at hundreds TeV and the needed cut off of events at PeV
(because of the absence of additional events with higher energy

Figure 1: A fluency energy spectra overview $\frac{dN}{dE}$ for all photons, cos-
mic rays and neutrinos in the Universe sky, in log-log scale as a function of
the energy. The the atmospheric neutrino oscillation flux in the vertical axis
suffer a shrinkage oscillation due to the log scale, for tau neutrino appearance;
we overlap the ICECUBE observed average atmospheric $\nu_\mu$, $\bar{\nu}_\mu$, neutrino flux, shown better in next figures.

Figure 2: Reinterpretation of each ICECUBE (see [I]) neutrino event nature:
the hard dashed red boxes are too inclined to be atmospheric; a group of less
inclined dashed downward events in square box might be also extraterrestrial;
the very horizontal muon track in a green circle is very probably the unique
guaranteed atmospheric event, very probably (7) made by $K^\pm$ than by $\pi^\pm$
decline in flight.

It should remind that at GeVs energies the $\mu$ pairs are widely
deflected by geomagnetic fields; therefore there is also a local
zenith and azimuth anisotropy somehow related to the histor-
ical geomagnetic (B.Rossi) cut-off in cosmic rays. Moreover
the atmosphere width depend on the zenith angle geometry as
well as on the muon-pion-Kaon decay distances: therefore at
TeVs energies the zenith anisotropy is remarkable. We shall
concentrate to the average flux value.

Figure 3: The needed forecast flavor ratio variability, to fit cascades and track
ICECUBE events, a ratio between the number of ($\nu_\mu$, $\nu_e$) tracks over cascade events
(due to both flavor ($\nu_\mu$, $\nu_e$)) derived from ICECUBE data for low and highest
energy events, for the most realistic fitting model considered in the text.
in PeV region events and in particular of $\bar{\nu}_e + e \to W$, the enhanced Glashow resonance at $E_{W} = \frac{m_{W}^{2}}{2m_{e}} \approx 6.3\,\text{PeV}$.

As mentioned, $\nu_e$ flux as being secondary of muons becomes suppressed at higher energy (GeV-TeV), i.e. the initial flavor ratio $R_{\nu} = \frac{\sum N_\nu}{\sum N_{\bar{\nu}}} \approx 2$ for atmospheric terrestrial neutrinos becomes larger leading to a factor

$$R_{\nu} = \frac{\sum N_\nu}{\sum N_{\bar{\nu}}} \approx 20$$

at TeV energies as shown in Fig.3.

This occurs because we begin from a flavor $\nu_e \nu_\mu \nu_\tau$ equal $1 : 2 : 0$ and we end (see Fig.3) at TeVs to a flavor ratio $\nu_e \nu_\mu \nu_\tau$ equal $\frac{1}{20} : 1 : 0$ (we neglect here the rare $\nu_\tau$ appearance by mixing at those energies). Therefore muon atmospheric neutrinos are ruling over electron (cascade showers) at high (TeV) energies. At higher energies, where the 28 events occur, (hundred TeV), Pion and Kaon decays (as well as muon late decay) are all too boosted and long life to take place; they mostly interact with nucleons leading to an additional suppression in the spectra for both muons and electron $\nu_e$, $\bar{\nu}_e$, $\nu_\mu$, $\bar{\nu}_\mu$, $\nu_\tau$, $\bar{\nu}_\tau$; at horizons their signal is crossing longest distances and they may survive enhanced by nearly an order of magnitude respect vertical events. At highest (hundred TeV or few PeV) energies the rare very unstable charmed mesons may decay faster, with little absorption in atmosphere, decaying equally into $\nu_\mu \bar{\nu}_e$ and $\nu_e \bar{\nu}_\mu$, flavors, shining nearly isotropically (out, of the upward Earth opacity): they may be the best source of terrestrial highest energy neutrino; however these signals may provide only a small fraction (1.5) among the 28 ICECUBE events $\bar{\nu}_e$. To describe in the following these observed $\nu_\mu, \bar{\nu}_\mu$ and $\nu_e, \bar{\nu}_e$ flux we assumed an averaged $\Phi_{\nu_\mu}$ shown in Fig.2, Fig.4, Fig.5, Fig.6.

The muon and electron flavor ratio $R_{\nu}$ metamorphosis as a function of the neutrino energy $E_{\nu}$, in GeV unity, is shown in Fig.7 approximated by a simple analytical law that may meet at best the flavor behavior and ICECUBE records. The main functions structure are three: $R_{1}$ function that describes the rise of the extraterrestrial neutrino component, whose cascades (by one $\nu_e$ or by two $\nu_\mu + \nu_\tau$) fit the ICECUBE data, $R_{2}$ keep memory of largest flavor difference, $R_{3}$ describes the fast extraterrestrial appearance: $R_{1} = 100 \cdot E_{\nu}^{-1}$, $R_{2} = A \cdot E_{\nu}^{-2}$, $R_{3} = \frac{1}{2} \cdot (1 - e^{-\frac{A}{E_{\nu}}})$

$$R_{\nu} = [R_{1}^{-1} + R_{2}^{-1} + R_{3}^{-1}]^{-1}$$

$$R_{\bar{\nu}} = [R_{1}^{-1} + R_{2}^{-1} + 2 \cdot R_{3}^{-1}]^{-1}$$

Where the constant $A = 20$, the neutrino energy $E_{\nu_{\text{min}}}$ is in GeV unity. The last two laws are for one showering flavor or for two, namely the unique $\nu_e$ or both $\nu_\mu$ and $\nu_\tau$, as long as the $\nu_e$ energy is below the few PeV where double bang signature might be noticed. We wish to remind that up to now there are not yet any evidence of such twin event due to $\nu_e$ first nuclear interaction and later on $\tau$ decay. Surprisingly, possibly, also for the third announced PeV event. Anyway the exponential decay term in $R_{3}$ stand for a rapid change of flavor at hundred TeV. Finally

$$\Phi_{\nu_{e}} \approx \Phi_{\nu_{\mu}} \cdot [R_{\nu}]^{-1}$$

This flavor ratio evolution with energy $R_{\nu}$ is shown in (see Fig.3) for one (dashed) or two flavors) where both muon and electron atmospheric neutrino evolution is derived from the data (see Fig.2) combined in the model above for the fluency in the following figure (see Fig.4). The model and the data are combined in (see Fig.5) and in more detail are shown in last Fig.6. The dashed curve stand for one electron shower, the combined electron and tau are described by the continuous line.

Figure 4: Energy Fluency for $\nu_{e}, \nu_{\mu}, \nu_{\tau}$ flavor $\Phi_{\nu_{e}}, \Phi_{\nu_{\mu}}, \Phi_{\nu_{\tau}}$ in $eVcm^{-2}s^{-1}sr^{-1}$ unity, as a function of the neutrino energy in GeV within a log-log graph. Note that the horizontal twin dashed lines stand for the observed fluency at highest ICECUBE energy for one or two flavor. The thin dashed curve describe the role of one (of the two) showering flavor fluency by present description model

Figure 5: Energy fluency $\frac{dN_{\nu}}{d\Omega dE}$ for $(\nu_{e}, \nu_{\mu})$ showering cascades (green crosses) respect to same fluency for $(\nu_{\tau})$ tracks (blue continues curve) for old SK, Frejus and AMANDA as well as the recent ICECUBE (green crosses by Deep Core detector) results, as a function of the energy in logarithmic-logarithmic scale. The last 28 highest energy event are somehow displayed. All data fit $\Phi_{e}, \Phi_{\mu}$ followed by our curve model to explain the ICECUBE neutrino events. In the same figure at low figure area it is shown the flavor ratio as a function of the energy; near hundred TeV the soppasso takes place.

2. An atmospheric prompt neutrino role?

The energetic prompt atmospheric neutrinos cannot oscillate much inside the terrestrial size and therefore they may keep the
same primary ratio $N_\nu / N_\mu = 1$; $\nu_e$ flavor flux is an order of magnitude smaller and maybe neglected. The expected prompt neutrino flavor ratio is $\nu_\tau : \nu_\mu : \nu_e \approx 0 : 1 : 1$. This ratio is much more suitable in explaining the sudden muon reduction than conventional ones. Therefore one may wonder if the present flavor paradox maybe solved at best within a total prompt atmospheric neutrino scenario; the probability that among 28 events only 7 are muon track is $P_{\text{Prompt}} = \left( \frac{1}{3} \right) \cdot \left( \frac{1}{2} \right)^7$, where $p = q = \frac{1}{2}$ and $n = 28$, $k = 7$, or just $P_{\text{Prompt}} = 0.44\%$, while the cumulative probability that among 28 events only 7 or less are muon tracks is just $P_{\text{Prompt}} \leq 1.3\%$. Therefore a global prompt atmospheric neutrino role for ICECUBE events cannot solve much the flavor paradox.

3. Hiding atmospheric role within a 30-60 TeV band?

One may imagine, following a referee suggestion, that most atmospheric neutrino are hidden in the lower range, within 30-60 TeV energy band; among the higher energy 17 events (4 tracks, 13 showers) above 60 TeV only 4 events are muons tracks, implying a negligible or none atmospheric pollution.

However a more carefull analysis of each event seem still to disfavor this new interpretation even above 60 TeV: among the 17 events two (event ID 5, ID 5 23) 2, seem very probable atmospheric ones because low energetic and very horizontal, leaving just 13 showers versus 2 tracks to be explained. The probability for such situation to occur is below 22\% (assuming a probability of $\frac{1}{3}$ for track/shower ratio ) or below 7.7\% (assuming a more realistic probability of $P \leq \frac{1}{4}$ for track/shower ratio due to the negligible role of NC) 11.

Indeed the event n. 5 23, a clear muon neutrino track, is nearly horizontal (-0.4 degree) and low energetic therefore it is very probably of atmospheric nature; also events 23 (-13.2 degree) is like that. But, once again, the puzzle survive even more remarkable for those events at lower energies (60 TeVs-30TeV) hidden into a limbo: (11) events that (in principle) should be mostly polluted by atmospheric muons and their atmospheric neutrinos (10.6\%). In this view this region (30TeVs-60 TeV) one observe an unexpected (8) showers and 3 tracks versus a characteristic (in early TeV-10 TeV range by Deep Core) negligible showering rate (1 over 3 assuming NC ); for well known reasons it is better to say that the expected shower versus tracks in atmospheric dominated range is nearly 1 over 10 11. The discontinuity in the flavor metamorphosis inside such a narrow energy range is even more surprising in view of the fast flavor variability (from $\text{TeV} \sim \text{30TeV}$) while showing in the same range a steady muon neutrino flux decay. Therefore if the paradox is reduced in the high energy range it is strongly enhanced in lowest ones.

In conclusion to solve the puzzle there may be a growing role of extra-terrestrial neutrino all along the 30-TeV-PeV energy, leaving a marginal atmospheric $\nu_e$ role; such transition should be ruling more and more (1 over ten) on atmospheric ones, suggesting that the dominance occurs already at earlier energies, around 10 TeV, as suggested in our articles; Otherwise, as the new proposal and the connected question marked in the title, a sudden flavor change at 30-60 TeV seem unexplained: $P(k=8, n=11) = 7.45 \cdot 10^{-3}$ assuming a ratio 1/3 for NC over a complete CC rate for most neutrino; assuming a more realistic probability $P = \frac{9}{10}$ for NC (at given energy) over $P = \frac{9}{10}$ for CC interactions by atmospheric muon neutrino 11, the probability to occur is almost vanishing: $P(k = 8, n = 11) = 1.2 \cdot 10^{-6}$: there is no room for an atmospheric hidden role in a 30 – 60 TeV energy band. Otherwise the puzzle is even greater.

4. Conclusions: Extraterrestrial neutrino at tens TeV

Extraterrestrial neutrinos (by AGN,GRBs by jets or by UHECR via GZK cut off or their decay in flight, by prompt charmed interaction and decoherence) may also rise at highest energy. Their rate, almost comparable in each flavor after oscillations and mixing may pollute or even rule the neutrino highest energy edges. Let us remind that the de-coherence of the $\nu$ flavors after oscillation depends on the primary rate and the flavor matrix discussed in recent articles 9, 10 $P_{\nu_{\mu}} = \sum_{\alpha=1}^{3} U_{\alpha\mu}^{2} U_{\alpha\nu}^{2}$. For instance, for the GZK neutrinos, due to UHECR scattering on relic photons, their flavors $\nu_e : \nu_\mu : v_\tau$ are born by photo-pion decays usually as $\nu_e : 2 : 1$; because oscillation they reach us as $\nu_e : 1 : 1$. The consequent probability to occur as observed by ICECUBE by 21 cascades and 7 tracks is $P_{1:1:1} = 10.8\%$, a realistic range. Moreover the astrophysical neutrinos may also rise by proton proton scattering leading once again to a comparable final flavor population; also astrophysical UHE neutrino maybe also be born as a prompt ones within $\nu_\tau : \nu_\mu : \nu_e \rightarrow 0 : 1 : 1$ reaching us after decoherence, at a ratio $\nu_\tau : \nu_\mu : \nu_e \rightarrow 0.283 : 0.311 : 0.406$; therefore $\nu_e, \nu_\tau$ showering will already rule (ignoring the neutral current role) at 68.9\% ratio over all the events (the muon tracks take place within a probability of 31.1\%), more consistently with the observed ICECUBE showering-tracks 3 : 1 ratio. If one takes into account also the neutral current (leading to additional one third cascades at lower energies), the final ratio become: $\nu_\tau: \nu_\mu: \nu_e \rightarrow 0.323 : 0.323 : 0.354 = 3.28$, a value even more consistent with data (if at least one or two muons are indeed atmospheric ones). The probability that ICECUBE events are born within such a prompt extraterrestrial originiation
is even more favorite because \(P_{0:1:1} \mapsto 0.406 : 0.311 : 0.283\) while previous \(\approx 1 : 1 : 1\) democratic flavor distribution: \(P_{1:1:1} = 10.8\%\), \(P_{\text{prompt}} = 13.34\%\). Finally we considered also a beta decay role where UHECR are radioactive heavy or lightest nuclei whose secondaries neutrino feed also astrophysical neutrino flux. The flavor ratio in such a beta decay flux scenario, is originally \(\nu_\tau : \nu_\mu : \nu_e \approx 0 : 0 : 1\) but the final flavor abundance after de-coherence becomes \(\nu_\tau, \nu_\mu, \nu_e \approx 0.1883 : 0.2643 : 0.5473\). In this case the final rate probability for an electron or a tau whole showering is as large as 73.5\% for cascade over a much rarer 26.4\% muon track signature; if one takes into account also NC cascades this ratio become slightly larger, \(\frac{P_{\text{Cascade}}}{P_{\text{track}}} \mapsto 0.799\).\(\frac{0.799}{1.00} = 4.03\) a ratio at best compatible with the observed ones in ICECUBE assuming just 5 extraterrestrial event are muons: \(\frac{N_{\text{shower}}}{N_{\text{all}}} \approx \frac{1}{5}\).

In conclusion contrary to present ICECUBE understanding the recent 28 highest energy neutrinos [1] might be mostly all of extraterrestrial origin; atmospheric ones must have, we believe, a softer spectra than expected [1], even a factor ten. A few (one-two) may be real atmospheric \(\nu_\mu\) one as the horizontal ones (see Fig[3] Fig[2]), the other \(\nu_\tau, \nu_\mu, \nu_e\) should be already extraterrestrial signals showering cascades more than tracing muon tracks. Their flavor revolution require a transition from atmospheric to extraterrestrial ones already about ten TeV. This imply a relevance in clustering and correlation map at a few ten TeV energies. The muons crossing flux by \(\nu_\mu\) at horizons or at vertical (where Earth opacity is still negligible) may be a key meter to verify the expected overabundance of horizontal atmospheric neutrinos versus vertical ones (at least an order of magnitude) within 5\(^o\) of the upward horizons respect vertical ones, contrary to our foreseen mostly isotropic extraterrestrial flux. The number of such crossing events should be about few or several tens a year. The tens TeV neutrino sky and clustering with the its flavor revolutions is a crucial cornerstone to solve ICECUBE muon paucity puzzle. With more events a sharper sky map may better address us to the eventual galactic or extragalactic origination. Antares, as large as twice Deep Core, might contain also rare cascades at few and tens TeVs testing somehow the early flavor metamorphosis.

4.1. Dedicated to 16 October 1943

This article is devoted to the memory of all the Jew deported to Auschwitz 70 years ago, on 16 October 1943, from Rome.

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