Violation of Lorentz Invariance and IceCube Neutrinos

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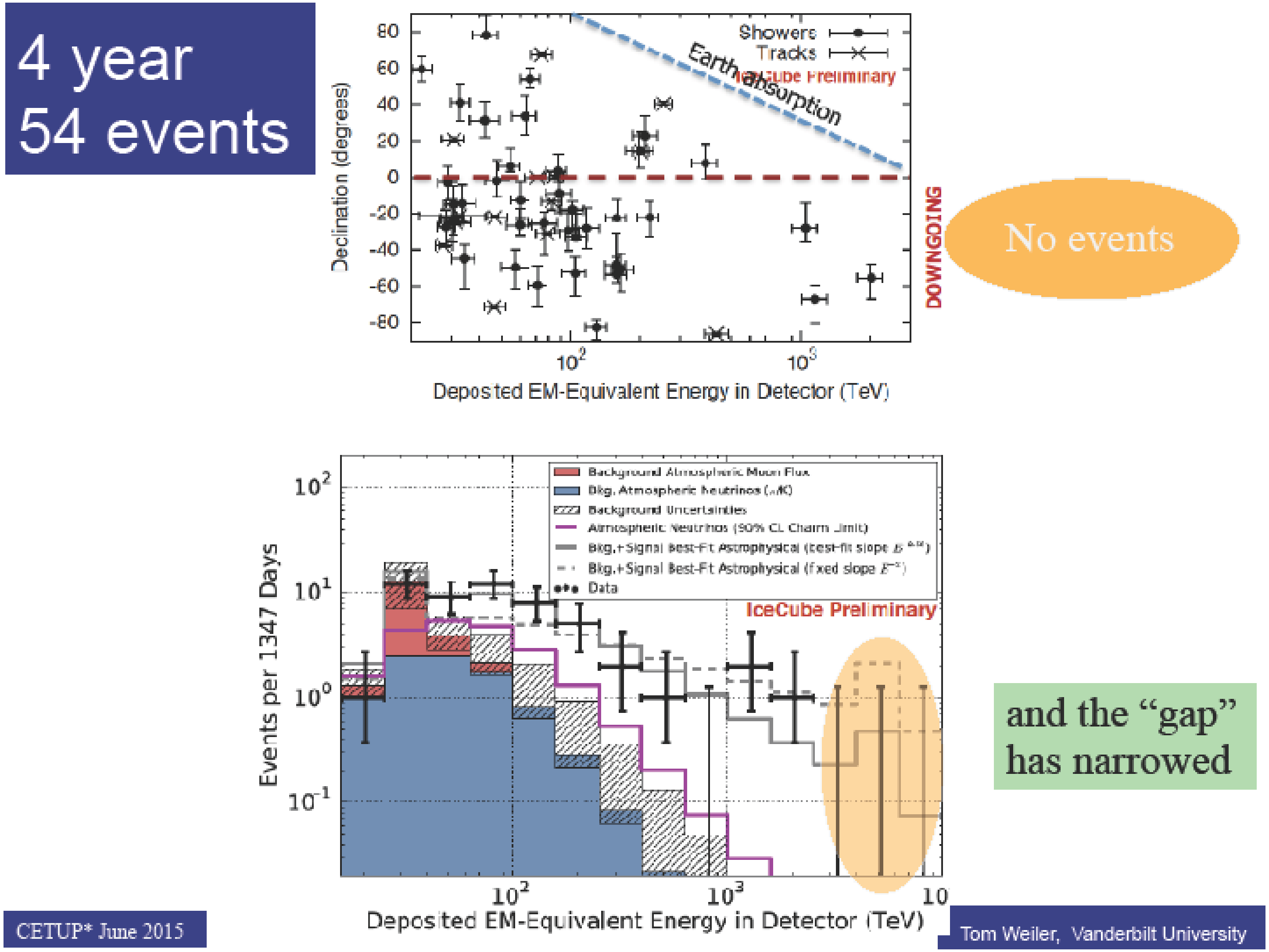


4 year
54 events

No events

and the “gap” has narrowed

CETUP* June 2015

Tom Weiler, Vanderbilt University

IceCube data

(See Weiler slides)

IceCube Neutrino events Flavor Mix:

IceCube: Consistent with (1:1:1)
also with (0:0.2:0.8)
arXiv:1502.03376

Palomares-Ruiz et al:(0.98:0.02:0)
also (0.01:0.01:0.98) and with
((0.75:0.25:0) depending on the energy
cuts, spectrum shape etc….
arXiv:1502.2645

There seem to be no events beyond 2 PeV
There are no Glashow Resonance events at 6.3 PeV

Possible Explanations ?

1. The Energy Spectrum has a steeper slope or a break and hence the number of events is much smaller than expected.
2. Neutrinos decay away sompletely and none are left?
3. There is a genuine cut-off in neutrino energy entailng Violation of Lorentz Invariance(at a few PeV)

1. The spectrum index has to be drastically different from 2 to get significant reduction in event rate….

2. Decays are severely constrained by bounds on lifetimes from SN1987A.

Incidentally, Only decays possible are into invisible channels such as $\nu + \chi$ where χ is a spin 0 almost massless particle. The severe constraints from SN1987A restrict these .

- For example, with normal hierarchy , ν_1 as the lightest neutrino must survive till reaching earth, in order to give rise the events seen from SN1987A whereas the other two can decay away . This makes the lifetime longer than 10^5 sec/eV. Since L/E for SN1987A is at least 100 times larger than for PeV neutrinos from GRB's and other potential sources, those neutrinos cannot have decayed before reaching IceCube.
- For inverted hierarchy, even though the lightest state is ν_3 , it has a very low content of ν_e . Hence, survival of a significant fraction of ν_1 or ν_2 is still needed to ensure enuf flux for seeing SN1987A signal.
- In either case arrival of neutrinos of PeV energies at IceCube is guaranteed…. In other words, decay cannot explain absence of events above 2 PeV.

Proposals to explain energy cut-off with LIV:

L. Anchordoqui et al., arXiv:1404.0622; J. G. Learned and T. J. Weiler, arXiv:1409.0739; J.Diaz et al., arXiv:1308.6344;

F. Stecker et al, arXiv:1411.5889; etc…

Coleman and Glashow, 1997, A. Kostelecky et al, 1997 onwards…

The choice of Neutrino dispersion relation suggested by some theories such as :P. Horava, arXiv.0901.3775. These have higher derivatives, try to make gravity renormalisable, and suggest dispersion relation for neutrinos of the type we employ.

(Gaurav Tomar, Subhendra Mohanty, SP)

(See also recent works by Kostecky and Mewes, J. Diaz et al., Myers and Pospelov….)

(Calculations done in the frame in which CMB is isotropic.)

$$E^2 = p^2 + m^2 - \frac{\xi_n}{M_{pl}^{n-2}}\, p^n$$

$$v = \frac{\partial E}{\partial p} = 1 - \frac{n-1}{2}\,\frac{\xi_n}{M_{pl}^{n-2}}\, p^{n-2}$$

n chosen to be 3

Decay width

$$d\Gamma = (2\pi)^4 \delta^{(4)}(p - \sum_i p_i)\, \frac{1}{2E_p} |\mathcal{M}_{fi}|^2 \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)}\,,$$

- We assume energy-momentum conservation and modified dispersion relation for neutrinos only.

Sum over spins for neutrinos:

$$E(p) = F(p)p,$$

$$F(p) \equiv \frac{E}{p} = 1 - \frac{\xi_n p^{n-2}}{2M_{pl}^{n-2}},$$

$$(\gamma^0 E - F(p)\vec{\gamma} \cdot \vec{p})u(p) = 0.$$

$$\sum_{s=1,2} u^s(p)\bar{u}^s(p) = F(p)\gamma^\mu p_\mu$$

Pion decay rate

$$\pi^-(q) \to \mu^-(p)\bar{\nu}_\mu(k)$$

$$M = f_\pi V_{ud}\; q^\mu \bar{u}(p)\frac{G_F}{\sqrt{2}}\gamma_\mu(1-\gamma_5)v(k)$$

$$\overline{|M|^2} = 2G_F^2 f_\pi^2 |V_{ud}|^2 m_\mu^2 F(k)\left[m_\pi^2 - m_\mu^2 - \xi_3' k^3\left(\frac{m_\pi^2}{m_\mu^2}+2\right)\right]$$

$$\Gamma = \frac{G_F^2 f_\pi^2 |V_{ud}|^2 m_\mu^2 F(k)}{8\pi E_\pi} \int \frac{k^2\, dk\, d\cos\theta}{E_\nu \sqrt{|\vec{q}-\vec{k}|^2 + m_\mu^2}} \delta(E_\nu - E_\pi + \sqrt{|\vec{q}-\vec{k}|^2 + m_\mu^2}) \\ \times \left[m_\pi^2 - m_\mu^2 - \xi_3' k^3 \left(\frac{m_\pi^2}{m_\mu^2} + 2 \right) \right]$$

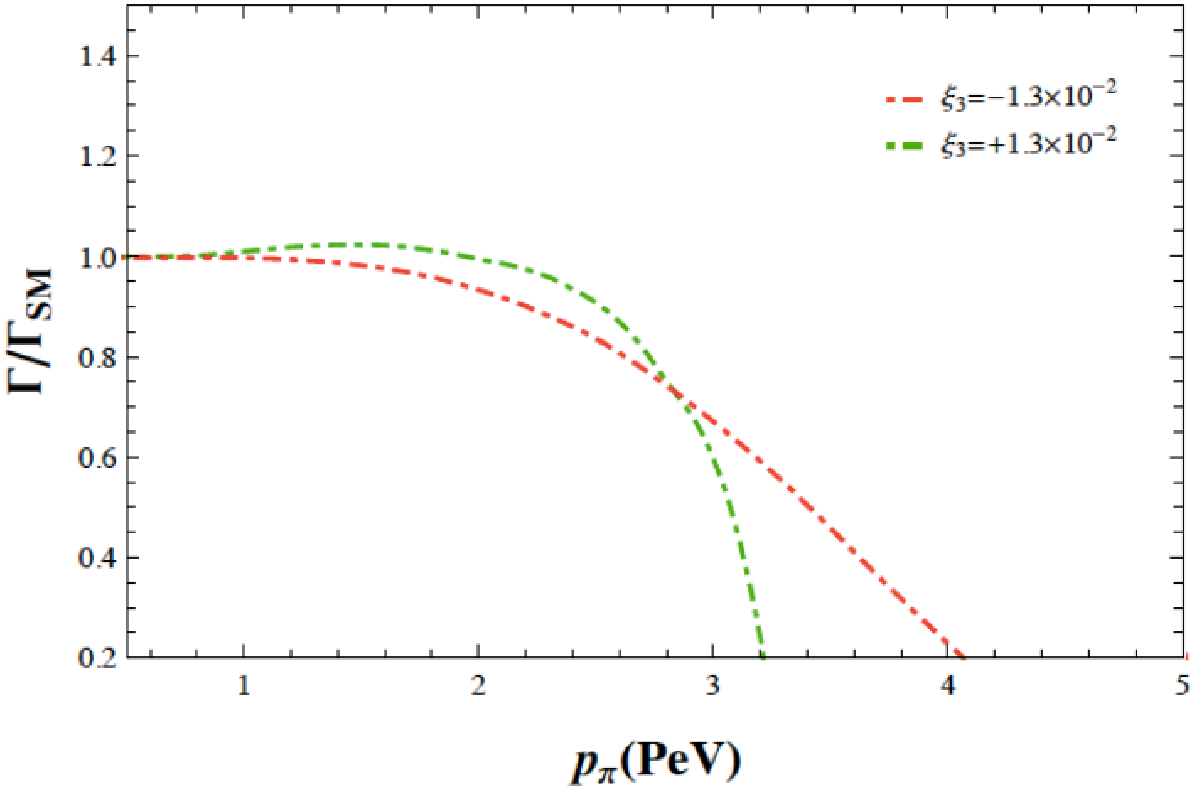
$$\cos\theta = \frac{\left(m_\mu^2 - m_\pi^2 + 2E_\pi k - E_\pi k^2 \xi_3' + k^3 \xi_3'\right)}{2kq}.$$

Limits of neutrino momentum

$$k_{max} = \frac{m_\pi^2 - m_\mu^2 + \xi_3' k_{max}^2 (E_\pi - k_{max})}{2(E_\pi - q)}$$

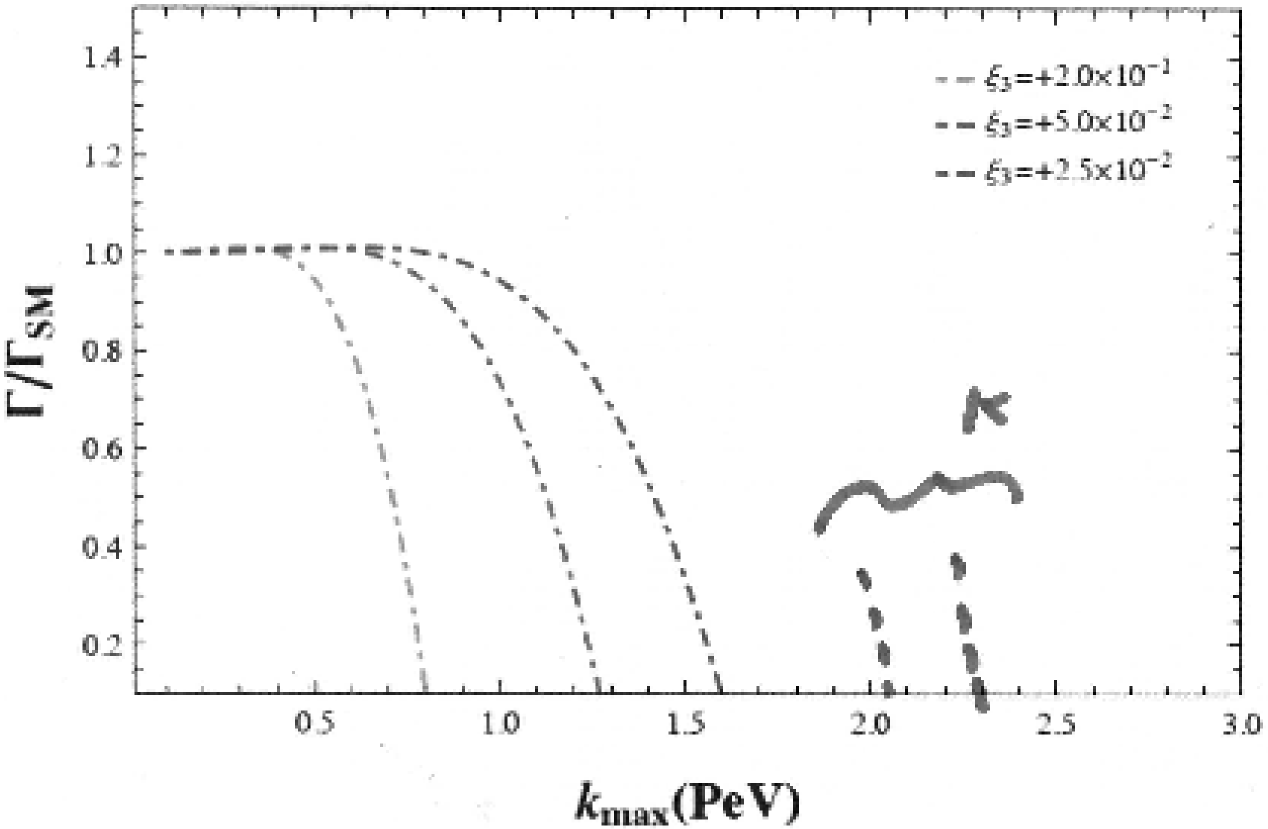
$$k_{min} = \frac{m_\pi^2 - m_\mu^2 + \xi_3' k_{min}^2 (E_\pi - k_{min})}{2(E_\pi + q)}$$

$$\Gamma = \frac{G_F^2 f_\pi^2 |V_{ud}|^2 m_\mu^2}{8\pi E_\pi} \int \frac{dk}{q} \left[m_\pi^2 - m_\mu^2 - \xi_3' k^3 \left(\frac{m_\pi^2}{m_\mu^2} + 2 \right) \right]$$



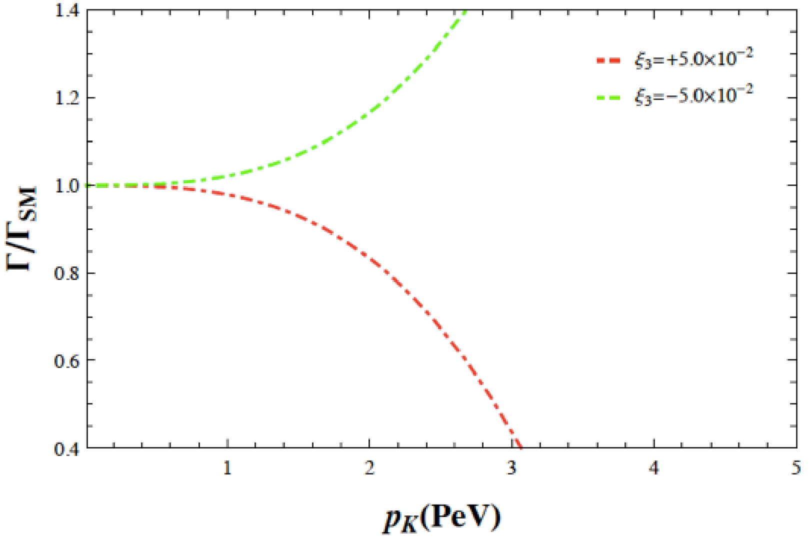
Pion decay is suppressed for both subluminal and superluminal neutrinos.

Limiting neutrino energy from $\begin{Bmatrix}\text{pion}\\ K\end{Bmatrix}$ decay neutrinos



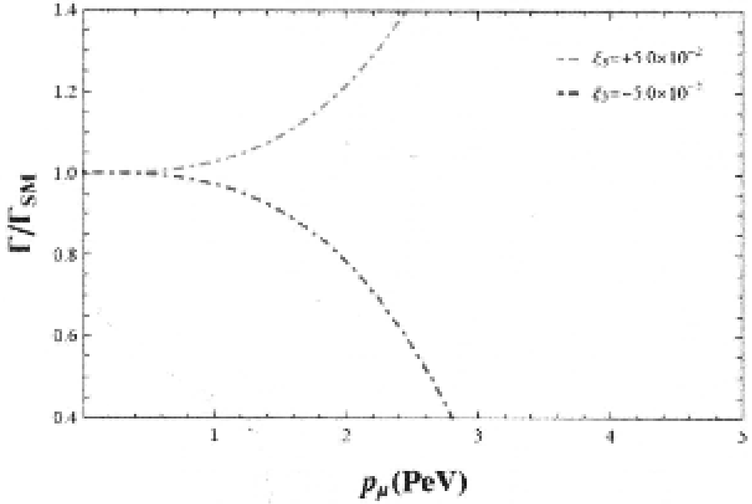
$$K^- \to \pi^0 e^- \bar{\nu}_e$$

$$\Gamma \simeq \frac{G_F^2 |V_{us}|^2 f_+^2 m_K^4}{768\pi^3 E_K}\left[m_K^2\left(1-\frac{8m_\pi^2}{m_K^2}\right)-\frac{4}{9}p_K^3\xi_3'\left(1-\frac{m_\pi^4}{m_K^4}\right)\right]$$



Three body decays $\mu^- \to e^- \bar{\nu}_e \nu_\mu$

$$\Gamma = \frac{G_F^2 m_\mu^4}{192\pi^3 E_\mu}\left(m_\mu^2 + \frac{2}{27}\xi_3' p^3\right)$$



Similarly for

$n \to p e^- \bar{\nu}_e$

To summarize: with our choice of dispersion relation for the neutrinos, and choice of the parameter ξ in a certain range ,

$\pi \to \mu\nu$ decay has a cutoff at a few PeV

so does $K \to \mu\nu$, $K \to \pi e \nu$, radiative decays etc.

But decay modes $\mu \to e\nu\nu$, and

$n \to p e \nu$ do NOT!

1. So it is possible to explain a cutoff in energy of a few PeV in IceCube neutrino events. Since μ’s only come from π decay which have the cutoff, so do the μ’s.
2. If μ’s are produced say by e^+ e^- collisions, those muons will show the increase in decay rate with energy expected in this model.
3. Since there is no energy cutoff for neutron β-decay, and hence for beta-beam neutrinos , it implies interesting outcomes for B-Z neutrinos: the existence of neutrinos from neutron β-decay at energies above 10 PeV via GZK-BZ process is a prediction of our proposal!

Neutrinos from “GZK” process: BZ neutrinos:

- Berezinsky and Zatsepin pointed out the existence/inevitability of neutrinos acompanying GZK cutoff from :
- $P_{CR} + \gamma_{CMB} \rightarrow \Delta^+ \rightarrow n + \pi^+$
- Flavor Mix: below 100 Pev: (n decays)pure Beta-Beam: e:μ:τ = 1:0:0 (leading to 5:2:2)
- Above 100 PeV: conventional(π decays) :e:μ:τ =1:2:0 (Leading to 1:1:1)

(due to Engel et al. PRD64,(2001),

also Stanev(2009))

This is for primaries being mostly protons

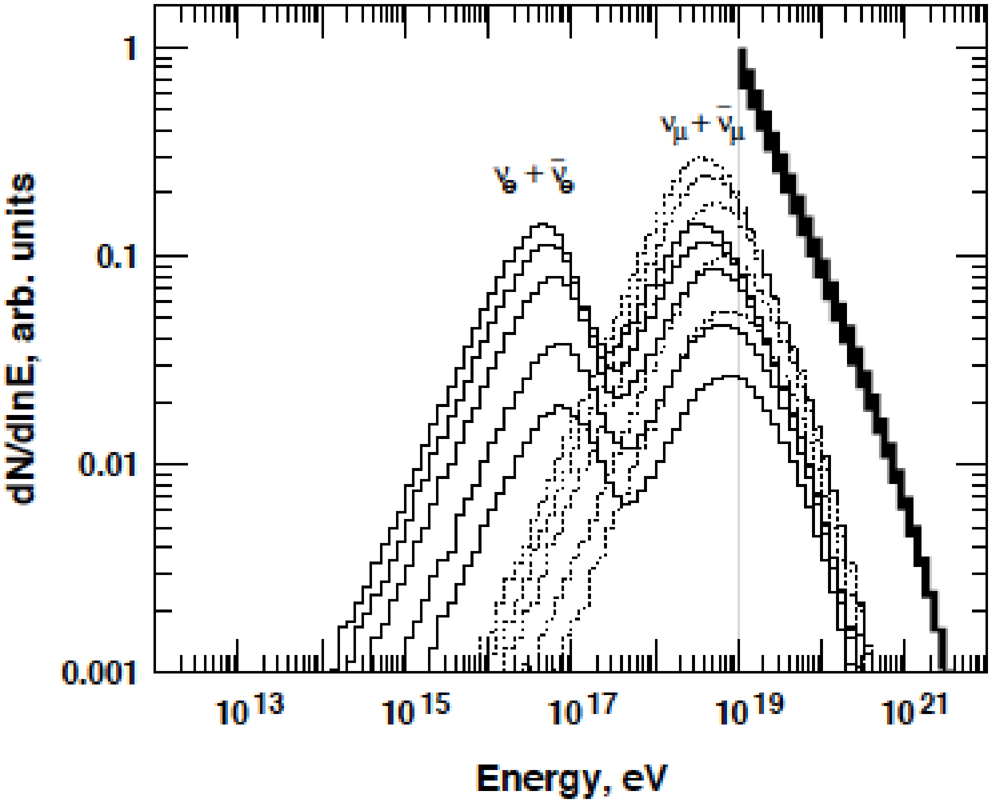


FIG. 2. Neutrino fluxes produced during the propagation of protons over 10, 20, 50, 100, and 200 Mpc (from bottom up) in a 1 nG random magnetic field. The heavy histogram shows the proton injection spectrum defined in Eq. (1).

With our model, the first peak survives, and the second one is gone!