Dark matter, sterile neutrinos and neutrinos at IceCube

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IceCube Discovery of VHE neutrinos.

3 years: 37 Events within 30 TeV - 2 PeV
29 Showers (which can be ν_e or ν_τ)
8 Tracks (ν_μ)

Not cosmogenic neutrinos.
Origin is unknown.

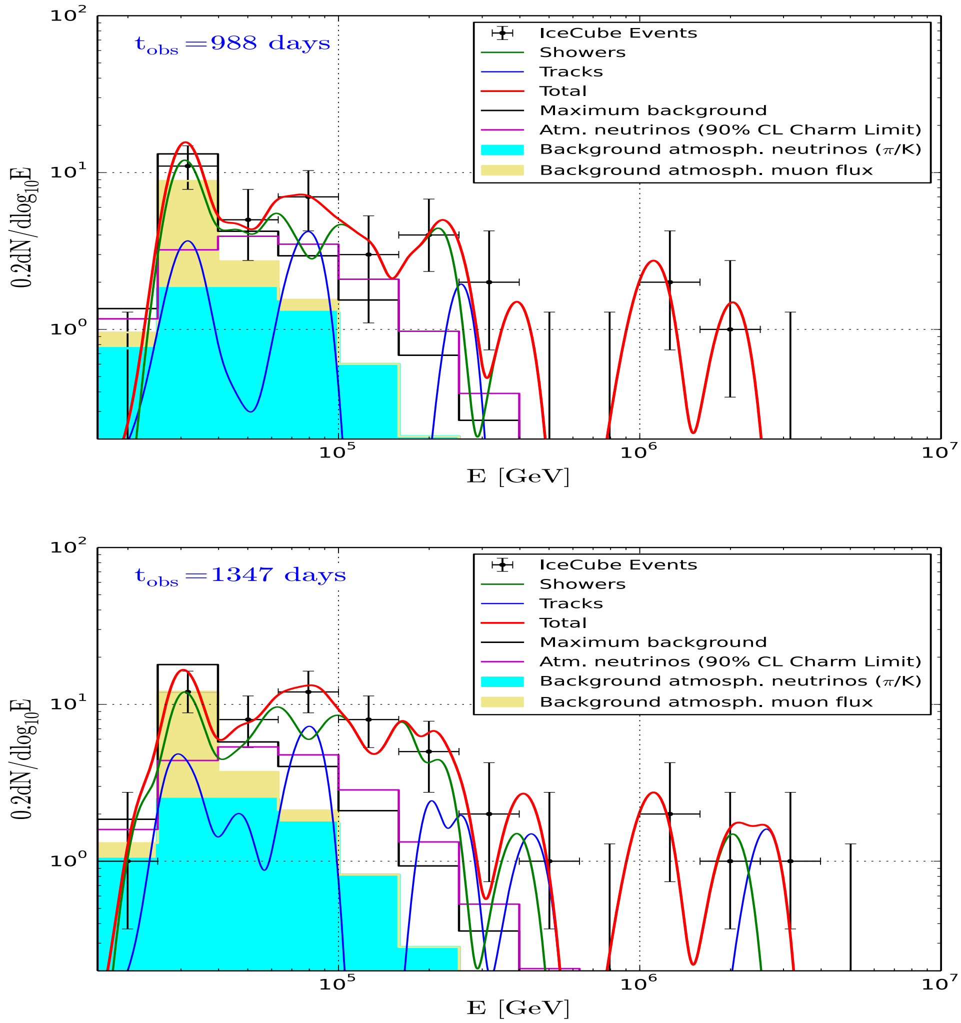

Figure 1: Spectral densities of the IC events for 988 and 1347 days.

$$\frac{dN_i(E)}{dE} = \frac{\exp\left[-(E-E_i)^2/2\sigma_i^2\right]}{\sigma_i\sqrt{2\pi}} \qquad \sigma_i/E_i = 0.1 - 0.15$$

Excess at higher energies: $E > 100$ TeV

Spectrum ends at few PeV PeV

Deficit between 400 TeV – 1 PeV

Can one explain all these feature (provided they are indeed true)

Our proposal

1. Heavy dark matter ($M \sim$ few PeV) which belongs to hidden gauge sector

2. It decays ($\tau_{\rm dec} \sim t_U$) into sterile neutrinos from the same gauge sector

3. Produced energetic sterile neutrinos oscillate into active neutrinos (with $P \sim 10^{-8} - 10^{-10}$)

How to get necessary necessary mass scale, lifetime, oscillation probabilities and bumpy energy spectrum of neutrinos ?

Let us do it in a best possible way !

At $E <$ few TeV best model is the Standard Model $SU(3) \times SU(2) \times U(1)$. What is best model at $E \gg$ TeV ? SUSY + GUT: $SU(5)$

Technical solution of Higgs hierarchy and D-T splitting problems, gauge constant unification, $b - \tau$ Yukawa unification, ...

Yet better candidate:
SUSY $SU(6)$ + GIFT Z.B., Dvali, 1989

Natural solution of hierarchy problem and μ-problem (Higgs as Pseudo-Goldstone boson), Naturally heavy top quark and natural $b - \tau$ unification, ν democracy, ...

Paradigm: At $M_G \sim 10^{16}$ GeV $SU(5)$ (or $SU(6)$) breaks down to $SU(3) \times SU(2) \times U(1)$.
At $M_S \sim$ TeV SUSY is broken.
Below TeV scale the theory is just the normal (one Higgs) Standard Model. $SU(2) \times U(1)$ breaks spontaneously at $M_Z \simeq 100$ GeV.
$SU(3)$ IR prisoned at $\Lambda \simeq 200$ MeV

Proton decay: $\tau_p \sim \frac{M_5^4}{\alpha_G^2 m_p^5} \sim 10^{30}$ **Gyr**

Now imagine that Dark sector is also described by same physics:

Two identical SUSY gauge factors
$SU(5) \times SU(5)'$ **(or** $SU(6) \times SU(6)'$**)**
Identical Lagrangians: $\mathcal{L}_{\rm tot} = \mathcal{L} + \mathcal{L}' + \mathcal{L}_{\rm mix}$
– Discrete symmetry $SU(5) \leftrightarrow SU(5)'$**.**

Both $SU(5)$ **or** $SU(5)'$ **breaks to SM and SM′ at** $M_G \sim 10^{16}$ **GeV**

But then in parallel sector SUSY is broken at $M'_S \sim 10^{11}$ **GeV.**

This induces SUSY breaking in our sector at $M_S \sim \frac{M'^2}{M_{Pl}} \sim 1$ **TeV, transmitted by gravity.**

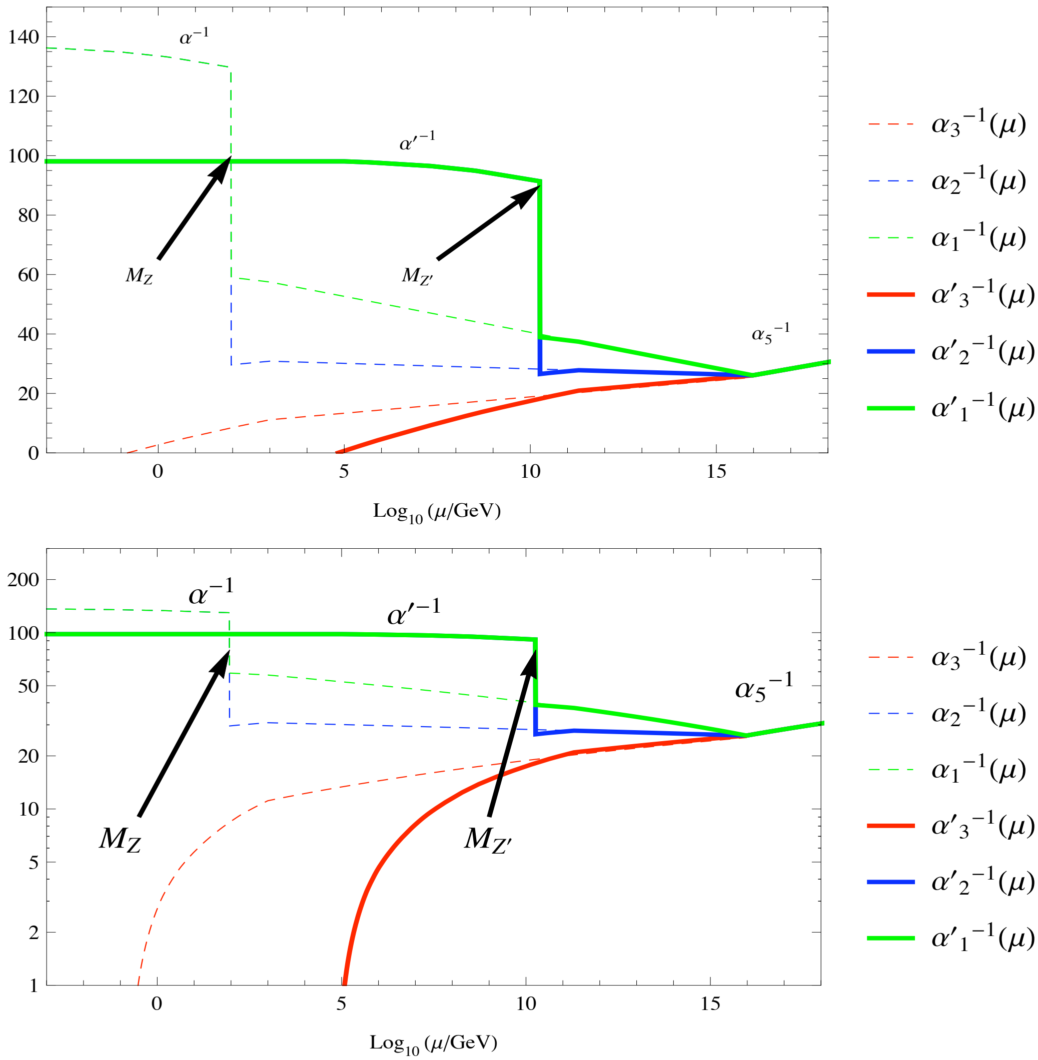

Figure 2: Running of gauge constants after breaking of $SU(5)$ and $SU(5)'$.

Our sector: SUSY broken at $M_S \sim 1$ TeV.
$SU(2)\times U(1)$ breaks at $v \simeq 100$ GeV.
$SU(3)$ is IR prisoned at $\Lambda \simeq 200$ MeV

Shadow sector: SUSY breaking $M'_S \sim 10^{11}$ GeV
$SU(2)'\times U(1)'$ breaks at $V \sim 10^{10}$ GeV.
$SU(3)'$ is IR prisoned at $\Lambda' \sim 100$ TeV

.... and miracles begin !!!

Quark and Lepton Masses

Below GUT scale 2 identical Standard Models, with identical fermion content and Yukawa couplings:

$$Y^e_{ij} l_i e^c_j h_1 + Y^d_{ij} q_i d^c h_1 + Y^u_{ij} q_i u^c_j h_2$$

$$Y^e_{ij} L_i E^c_j H_1 + Y^d_{ij} Q_i D^c H_1 + Y^u_{ij} Q_i U^c_j H_2$$

Fermion masses scale as $\propto V/v \simeq M'_Z/M_Z$ ...

But RG running must be taken into account:

$m_e = Y_e R_e \eta_e v_1, \quad m_d = Y_d R_d \eta_d v_1, \quad m_u = Y_u R_u \eta_u v_2 B_t^3$

$M_E = Y_e R_E \eta_E V_1$, $M_D = Y_d R_D \eta_D V_1$, $M_U = Y_u R_U \eta_U V_2 B_T^3$

RG in Susy SM:

$A_e \eta_e \approx 1.5, \;\; A_d \eta_d, A_u \eta_u \approx 8.5, \;\; B_t \approx 0.7$ (Y_t induced)

RG in Susy SM$'$:

$A_E \eta_E \approx 1.1$, $A_d \eta_d, A_u \eta_u \approx 1.3$, $B_T \simeq 1$

Our matter: we have $v \simeq 100$ GeV; $m_e = 0.5$ MeV, $m_u \approx 3$ MeV, $m_d \approx 5$ MeV ($\mu = 2$ GeV) – $m_{u,d} \ll \Lambda$.

Shadow matter: For $V \sim 10^{10}$ GeV,
shadow electron mass $M_E \simeq 0.5$ PeV, lightest quark masses $M_D \simeq 1$ PeV, $M_U \simeq 2$ PeV – $M_{U,D} \gg \Lambda'$

Hadron masses

Our sector:

Pions ($\pi^0, \pi^\pm$) are PGB's: $m_\pi \simeq \frac{m_q^{1/2}\langle \bar{q}q\rangle^{1/2}}{f_\pi} \sim (m_q \Lambda^3)^{1/2}$

lightest (stable) baryon: proton with $m_p \simeq 1$ GeV.

But in SUSY $SU(5)$ it decays: $\tau_p \sim \frac{M_5^4}{\alpha_G^2 m_p^5} \sim 10^{30}$ Gyr

Shadow: $M_E = 0.5$ PeV, $M_D = 1.1$ PeV, $M_U = 1.9$ PeV

Shadow quark is similar to our heavy quark sector (b, c).
Pions (lightest pseudoscalars) are not PGB's:
$M_D^0 \simeq 2.2$ PeV, $M^\pm \simeq 3$ PeV, $M_U^0 \simeq 3.8$ PeV,
lightest (stable) shadow baryon is $\Delta \sim DDD$ (spin 3/2
with $M_\Delta \simeq 3.3$ GeV.

in Susy $SU(5)$ it decays: $\tau_\Delta \sim \frac{M_G^4}{\alpha_G^2 M_\Delta^2 \Lambda'^3} \sim 10 - 100$ Gyr,

$\Delta_{(DDD)} \to \rho^-(D\overline{U}) + \nu'_x \qquad (M_\rho \simeq 3.1 \text{ PeV}),$
producing monoenergetic shadow neutrinos with
$E_x = \frac{1}{2} M_\Delta \left(1 - \frac{M_\rho^2}{M_\Delta^2}\right) \simeq 200$ TeV – Miracle No. 1 !

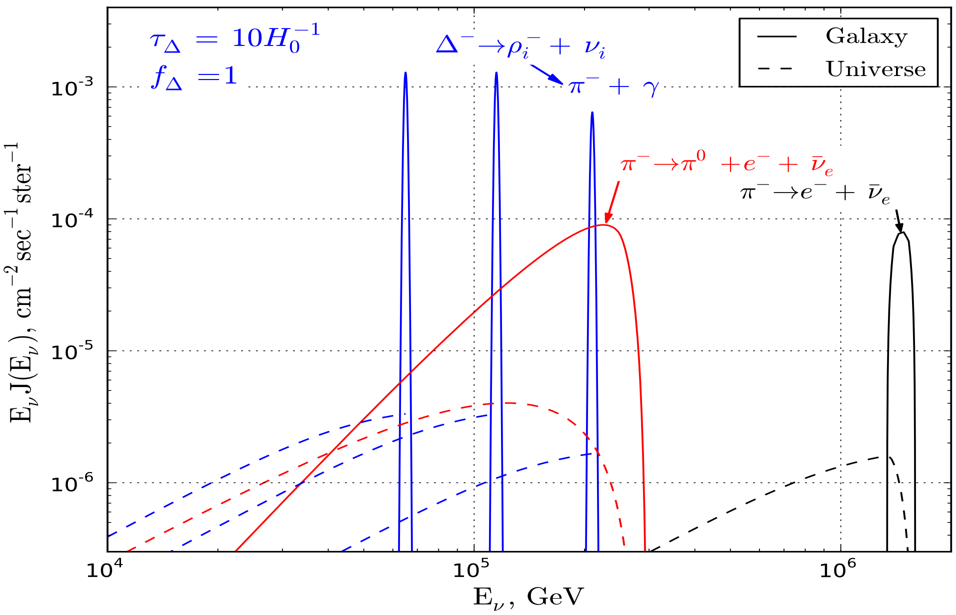

Figure 3: Shadow neutrino spectrum produced by Δ-baryon decay.

$\rho^-(D\overline{U})$ meson as well as its excited states can be produced, with masses say $3.1, 3.2, 3.25$ PeV ...
producing monoenergetic neutrinos ν_x' with

$$E_{xi} = \frac{1}{2} M_\Delta \left(1 - \frac{M_{\rho i}^2}{M_\Delta^2}\right) \simeq 200, 100, 60 \text{ TeV}$$

ρ_i bearing energies $E_{\rho i} = \frac{1}{2} M_\Delta \left(1 + \frac{M_{\rho i}^2}{M_\Delta^2}\right) \simeq 3.3$ PeV.

They all decay into $\rho^-(D\overline{U}) \to \pi^-(D\overline{U}) + \gamma'$
(pseudoscalar bound state is ligtest! $M_\pm = 3$ PeV)
Pions decay in two channels: 2-body $\pi^- \to E + \bar{\nu}_e$ and 3-body $\pi^- \to \pi_D^0 + E + \bar{\nu}_e$, with comparable branchings
$\frac{\Gamma_2}{\Gamma_3} \simeq 5 \left(\frac{F_\pi}{1 \text{ PeV}}\right)^2$ ($F_\pi \sim \Lambda' \sim 100$ TeV) – Miracle No. 2!

Neutrino masses, active-sterile mixing

We assume:

1. neutrino masses emerge by Planck scale operators
Akhmedov, ZB, Senjanovic, 1992

2. two sectors, ordinary and shadow, have a common gauge factor, $U(1)_{B-L}$ (Bento, ZB, 2005) or local flavor symmetry $SU(3)_H$ between families (ZB, 1983, 1998). It is spontaneously broken by some scalar (or scalars) χ, near GUT scale.

All Possible operators

$$\frac{Y\chi}{M_{Pl}^2}\bar{5}\bar{5}h_5h_5 + \frac{Y\chi}{M_{Pl}^2}\bar{5}'\bar{5}'H_5H_5 + \frac{Z}{M_{Pl}}\bar{5}\bar{5}'h_5H_5$$

2-nd operator generates shadow neutrino Majorana masses

$$M'_\nu = \frac{Y\chi V^2}{M} = Y\chi_{15}V_{10}^2 \times 10^3 \text{ keV}$$

3-rd operator generates mixing (Dirac) masses between active and shadow neutrinos

$m_D = \frac{ZvV}{M} = ZV_{10}\times 1$ keV ... and active-sterile mixing:
$\Theta = \frac{m_D}{M'_\nu} = \frac{ZvM_{Pl}}{YV\chi} \sim (Z/Y)(V_{10}/\chi_{15}) \times 10^{-4}$.
This "seesaw" induces Majorana mass terms of ordinary neutrinos $m_\nu = \frac{m_D^2}{M'_\nu} = \frac{Z^2v^2}{Y\chi} = (Z^2/Y) \times 10^{-2}$ eV.
First operator is practically irrelevant: $\delta m_\nu \sim 10^{-10}$ eV

Oscillation probability $\sim 10^{-8} - 10^{-10}$ suits for transmission of right amount of shadow neutrino flux to ordinary VHE neutrinos

– Miracle No. 3 !

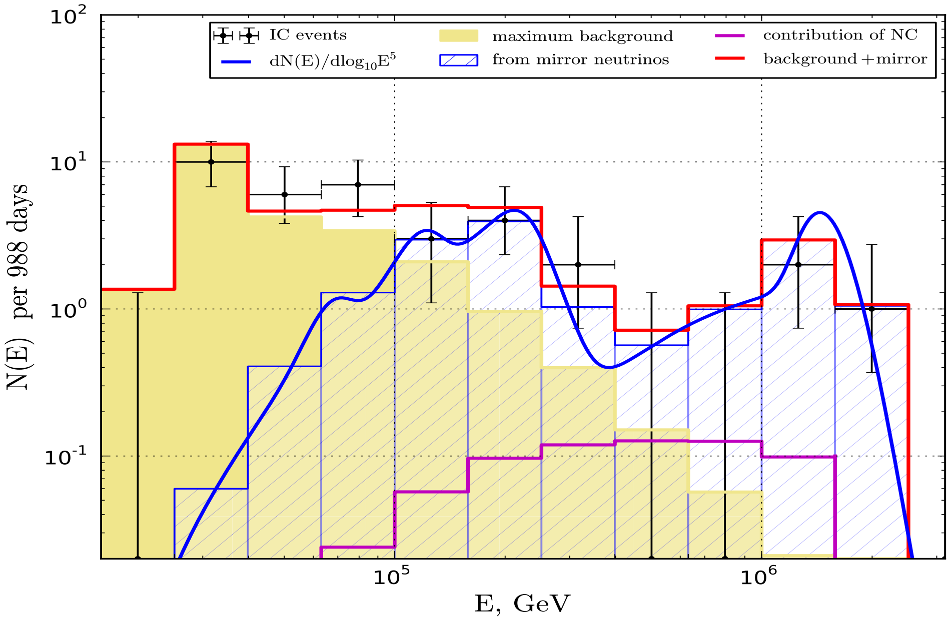

Figure 4: Spectrum of VHE neutrino events as predicted in our model.

Note on neutrino Flavor composition

$$\nu_\alpha = V_{\alpha i}\nu_i, \qquad \alpha = e, \mu, \tau, \quad i = 1, 2, 3$$

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} V_{e1} & V_{e2} & V_{e3} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix} \tag{1}$$

$$\begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} = \begin{pmatrix} |V_{e1}|^2 & |V_{\mu 1}|^2 & |V_{\tau 1}|^2 \\ |V_{e2}|^2 & |V_{\mu 2}|^2 & |V_{\tau 2}|^2 \\ |V_{e3}|^2 & |V_{\mu 3}|^2 & |V_{\tau 3}|^2 \end{pmatrix} \begin{pmatrix} \tilde{f}_e \\ \tilde{f}_\mu \\ \tilde{f}_\tau \end{pmatrix} \tag{2}$$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix} = \begin{pmatrix} |V_{e1}|^2 & |V_{e2}|^2 & |V_{e3}|^2 \\ |V_{\mu 1}|^2 & |V_{\mu 2}|^2 & |V_{\mu 3}|^2 \\ |V_{\tau 1}|^2 & |V_{\tau 2}|^2 & |V_{\tau 3}|^2 \end{pmatrix} \begin{pmatrix} f_1 \\ f_2 \\ f_3 \end{pmatrix} \tag{3}$$

$$\begin{pmatrix} f_e \\ f_\mu \\ f_\tau \end{pmatrix} = \begin{pmatrix} P_{ee} & P_{e\mu} & P_{e\tau} \\ P_{\mu e} & P_{\mu\mu} & P_{\mu\tau} \\ P_{\tau e} & P_{\tau\mu} & P_{\tau\tau} \end{pmatrix} \begin{pmatrix} \tilde{f}_e \\ \tilde{f}_\mu \\ \tilde{f}_\tau \end{pmatrix} \tag{4}$$

$$P_{\beta\alpha} = P_{\alpha\beta} = \sum_i |V_{\alpha i}|^2 |V_{\beta i}|^2$$

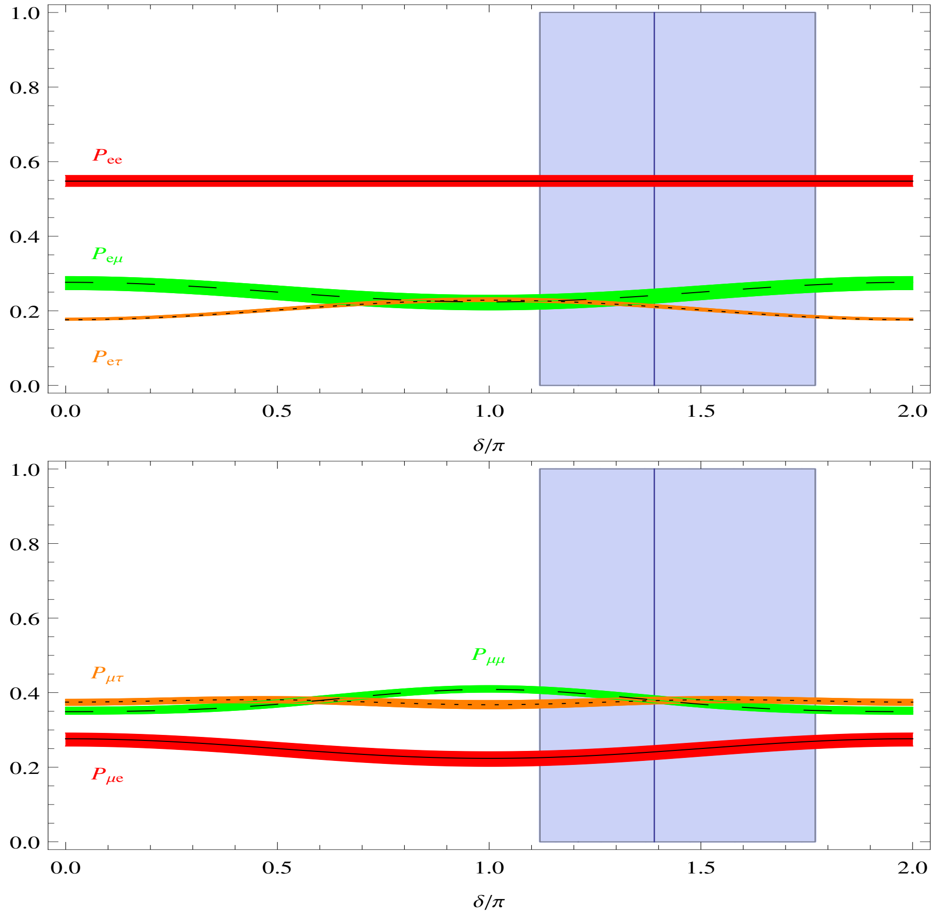

Figure 5: Flavor composition obtained from ν_e and ν_μ

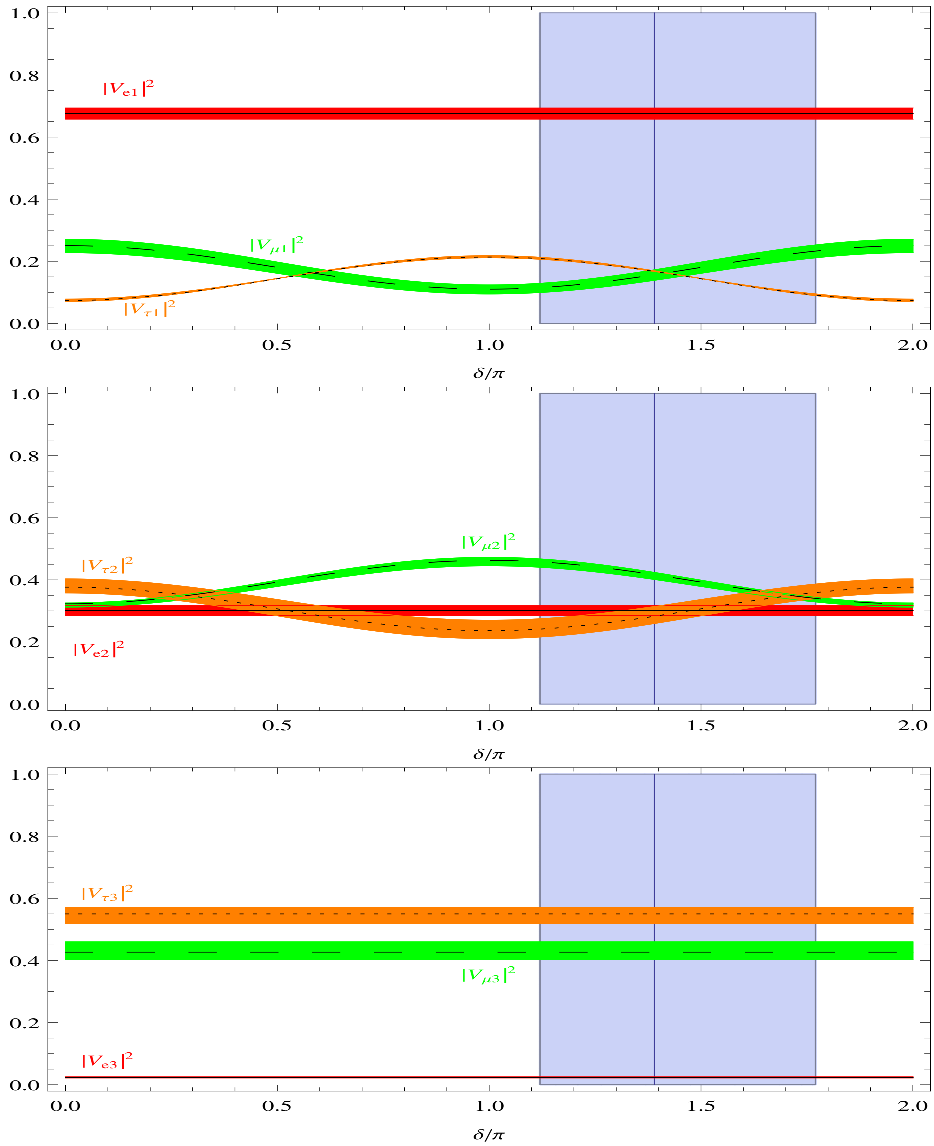

Figure 6: Flavor composition of mass eigenstates $\nu_{1,2,3}$

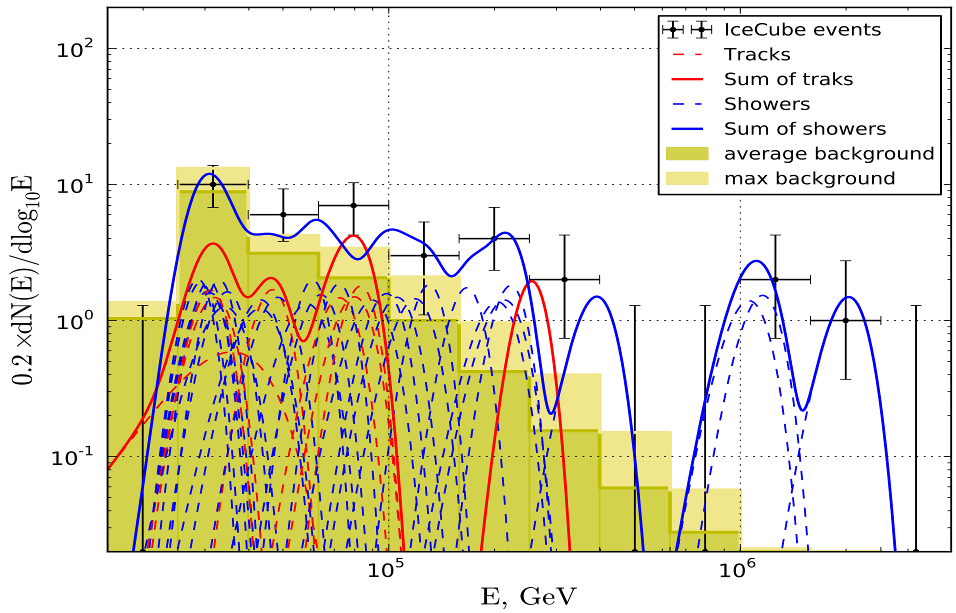

Figure 7: Spectrum of VHE VHE neutrino spectrum as observed by IceCube.

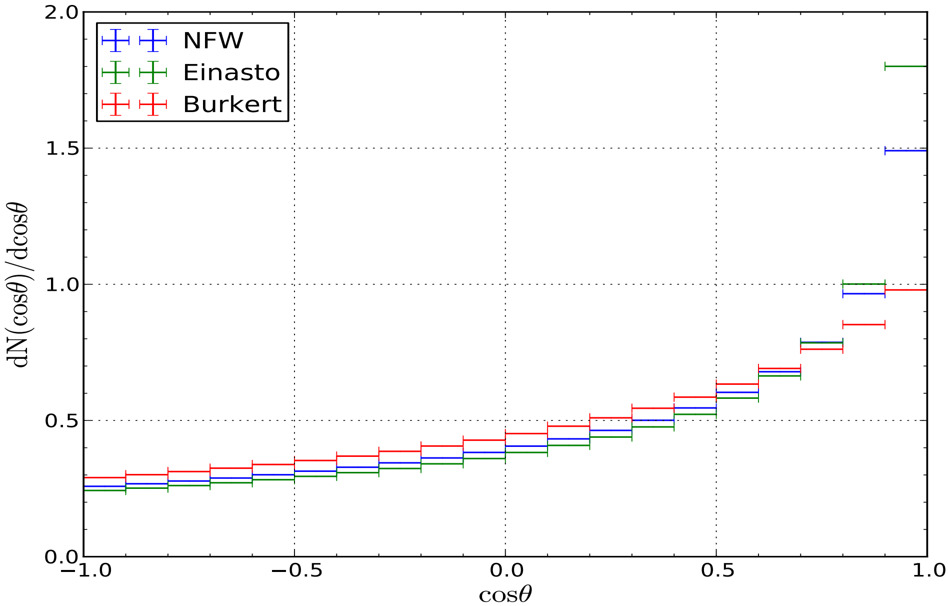

Figure 8: Directional asymmetry of VHE neutrinos produced in Galaxy.