Neutrinos ultra energéticos y física más allá del modelo estándar

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CINVESTAV

25 de Septiembre 2013

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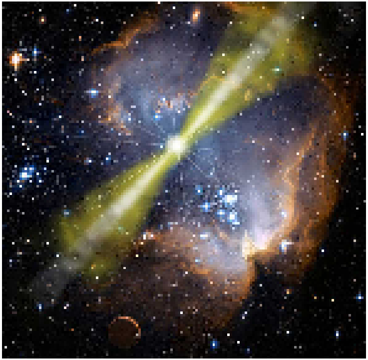
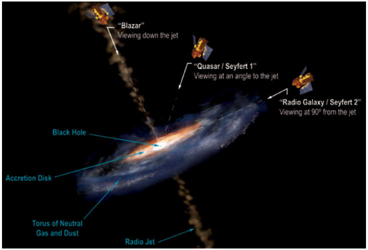
Cosmic rays and neutrinos

GRB



AGN



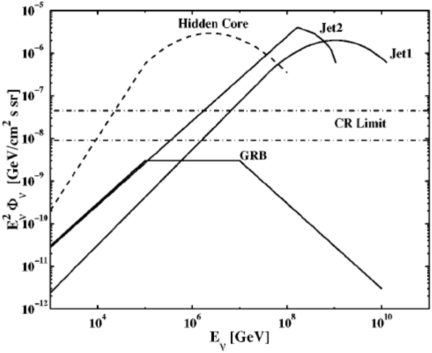
Cosmic rays and neutrinos

The interaction of high energy protons with photons would produce an UHE neutrino flux

$$\begin{aligned} p + \gamma &\rightarrow \Delta^+ \rightarrow p + \pi^+, \quad p + \pi^0 \\ \pi^+ &\rightarrow \mu^+ + \nu_\mu \\ \mu^+ &\rightarrow e^+ + \nu_e + \bar{\nu}_\mu \end{aligned}$$

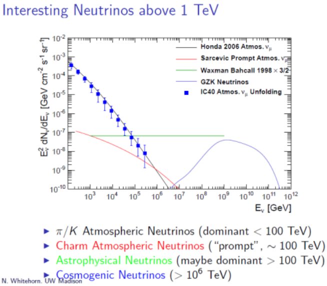
UHE neutrinos may be detected on earth (IceCube)

Cosmic rays and neutrinos



E. Waxman and J. Bahcall, Physical Review Letters **78**, 12 (1997).

Cosmic rays and neutrinos



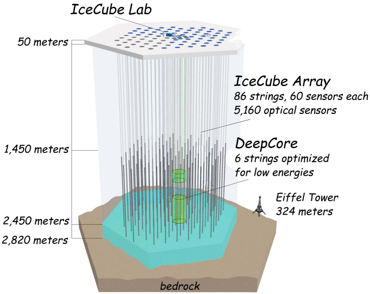
Interesting Neutrinos above 1 TeV

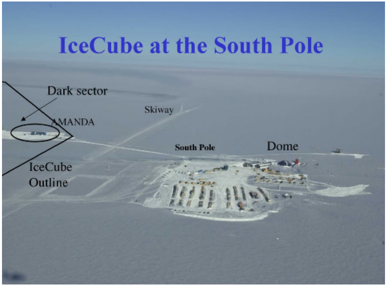
- π/K Atmospheric Neutrinos (dominant $<$ 100 TeV)
- Charm Atmospheric Neutrinos ("prompt", $\sim$ 100 TeV)
- Astrophysical Neutrinos (maybe dominant $>$ 100 TeV)
- Cosmogenic Neutrinos ($> 10^6$ TeV)

N. Whitehorn, UW Madison

Cosmic rays and neutrinos

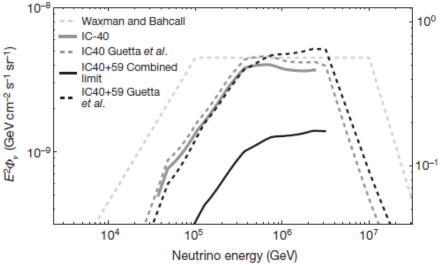
The IceCube detector





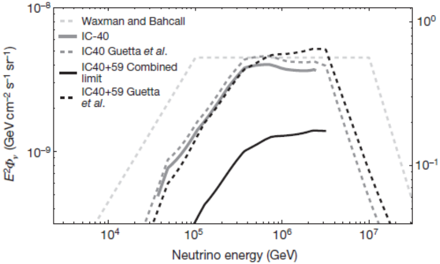
Cosmic rays and neutrinos

IceCube

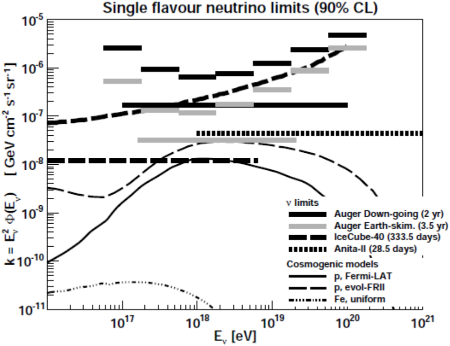


Cosmic rays and neutrinos

IceCube



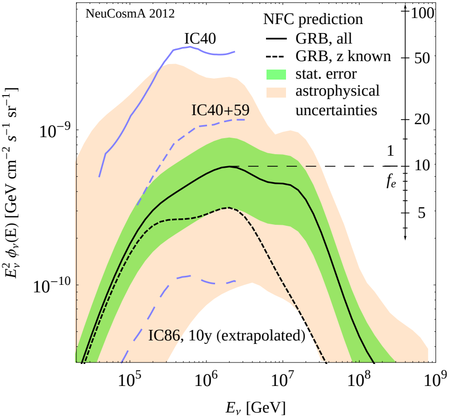
Pierre Auger



IceCube Collaboration, Nature **484**, 351 (2012

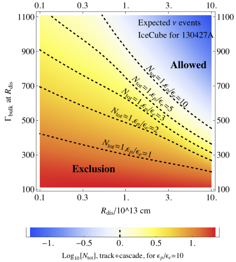
The Pierre Auger Collaboration, arXiv: 1304.1630v1 (2013)

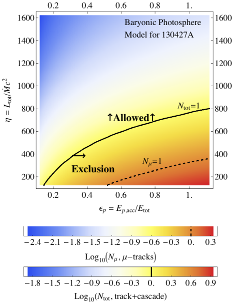
Cosmic rays and neutrinos

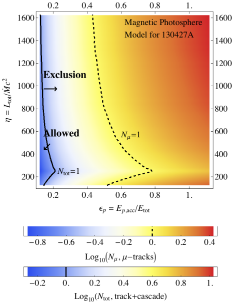


Hummer, Baerwald, Winter, PRL **108**, 231101 (2012)

Cosmic rays and neutrinos

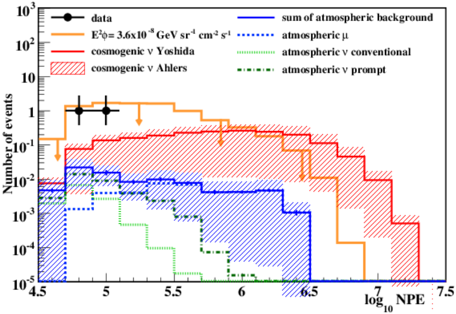




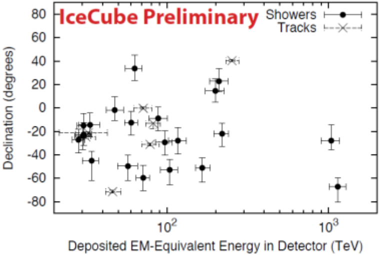


Gao, Kashiyama, Meszaros, Astrophys. J. **772** (2013) L4

Cosmic rays and neutrinos



Results of Contained Vertex Event Search (4.3σ)



28 events (7 with visible muons, 21 without) on background of $10.6^{+4.5}_{-3.9}$ (12.1 ± 3.4 with reference charm model)

N. Whitehorn, UW Madison

IceCube Phys. Rev. Lett **111** 021103 (2013)

Cosmic rays and neutrinos

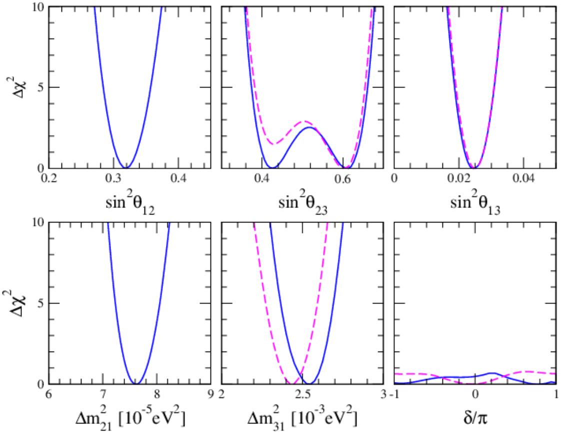
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix} \cdot \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

$$P(\nu_l \to \nu_{l'}) = \left| \sum_i U_{li} U^*_{l'i} e^{-i(m_i^2/2E)L} \right|^2$$

Cosmic rays and neutrinos

$$\begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Cosmic rays and neutrinos



Spin precesion

current constraints on the neutrino magnetic moment are of the order of $\mu_\nu \sim 10^{-12}\mu_B$. Magnetic field in a GRB or AGN are expected to be very strong.

Evolution equation

$$i\begin{pmatrix} \dot{\nu}_{l_L} \\ \dot{\nu}_{l_R} \end{pmatrix} = \begin{pmatrix} 0 & \mu_\nu B_\perp \\ \mu_\nu B_\perp & 0 \end{pmatrix}\begin{pmatrix} \nu_{l_L} \\ \nu_{l_R} \end{pmatrix}$$

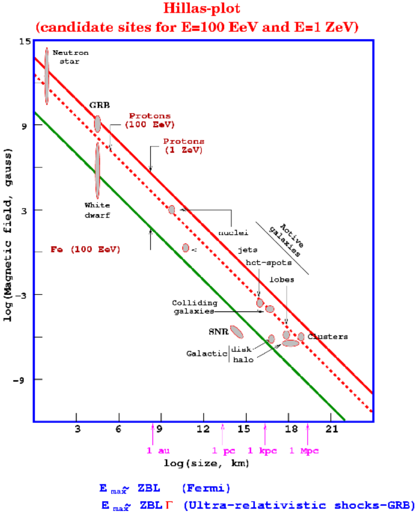
Conversion probability

$$P(\nu_{l_L} \to \nu_{l_R}; r) = \sin^2\left(\int_0^r \mu_\nu B_\perp(r')dr'\right)$$

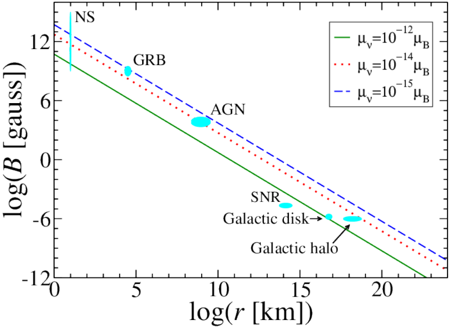
$$\mu_\nu B_\perp r \approx \frac{\pi}{2}$$

A. Cisneros, Astrophysics and Space Science 10 (1971) 87-92.

Spin precesion

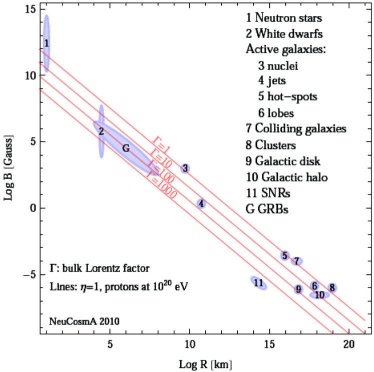


A. M. Hillas, Ann.Rev.Astron.Astrophys. 22(1984)

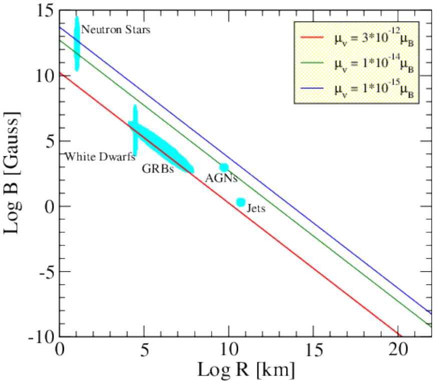


J. Barranco, O.G.Miranda, C.A. Moura, A. Parada,
Phys. Lett. B 718 (2012) 26

Spin precesion



P.Mehta and W.Winter,arXiv:1101.2673v2 (2011)



J. Barranco, O.G.Miranda, C.A. Moura, A. Parada, Phys. Lett. B 718 (2012) 26

Spin precesion

Evoution equation:

$$i\begin{pmatrix} \dot{\nu}_{l_L} \\ \dot{\nu}_{l_R} \end{pmatrix} = \begin{pmatrix} 0 & \mu_\nu B_\perp \\ \mu_\nu B_\perp & V_e \end{pmatrix} \begin{pmatrix} \nu_{l_L} \\ \nu_{l_R} \end{pmatrix}, \qquad V_e = \sqrt{2} G_F (N_e - N_n/2)$$

Conversion probability:

$$P(\nu_{l_L} \to \nu_{l_R}; r) = \frac{(2\mu_\nu B_\perp)^2}{V_e^2 + (2\mu_\nu B_\perp)^2} \sin^2\left(\frac{1}{2}\sqrt{V_e^2 + (2\mu_\nu B_\perp)^2}\, r\right).$$

Source	V_e (eV)	μB (eV)
GRBs	2×10^{-34}	10^{-13}
AGNs	10^{-27}	6×10^{-20}
SNRs	10^{-37}	10^{-28}
Galactic Disk	5×10^{-39}	5×10^{-29}

Spin precesion

Evolution equation:

$$i\begin{pmatrix}\dot{\nu}_{l_L}\\ \dot{\nu}_{x_R}\end{pmatrix}=\begin{pmatrix}V_e-\delta & \mu_\nu B\\ \mu_\nu B & \delta\end{pmatrix}\begin{pmatrix}\nu_{e_L}\\ \nu_{x_R}\end{pmatrix}$$

conversion probability

$$P_{\nu_{eL}\to\nu_{xR}}=\frac{(2\mu_\nu B_\perp)^2}{(2\delta-V_e)^2+(2\mu_\nu B_\perp)^2}\times\sin^2\left(\frac{1}{2}\sqrt{(2\delta-V_e)^2+(2\mu_\nu B_\perp)^2}\,r\right)$$

where:

$$\delta=(\Delta m^2/4E_\nu)\cos 2\theta,\qquad V_e=\sqrt{2}G_F(N_e-N_n/2)$$

for GRBs, $V_e\sim 10^{-34}eV$.
where $E_\nu=10^{16}eV$, $\Delta m^2\sim 10^{-18}eV^2$

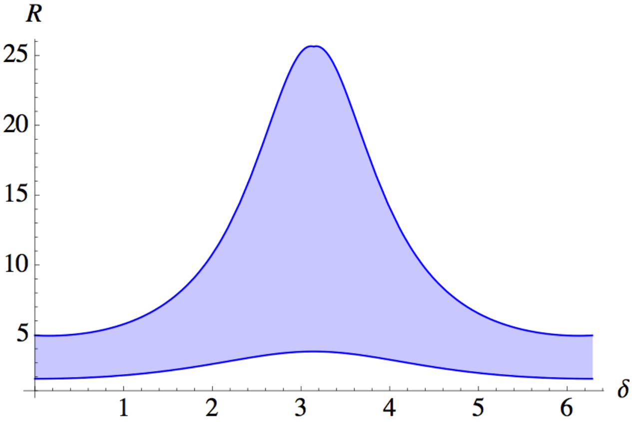
Neutrino decay

$$\phi_{\nu_\alpha}(E) = \sum_{i\beta} \phi^{\text{source}}_{\nu_\beta}(E) |U_{\beta i}|^2 |U_{\alpha i}|^2 e^{-L/\tau_i(E)}$$

$$R_{\nu_e:\nu_\mu} = \left(\frac{\cos\theta_{12}\cos\theta_{13}}{|-\sin\theta_{12}\cos\theta_{23} - \sin\theta_{13}\sin\theta_{23}\cos\theta_{12} e^{\imath\delta}|} \right)^2, \qquad (1)$$

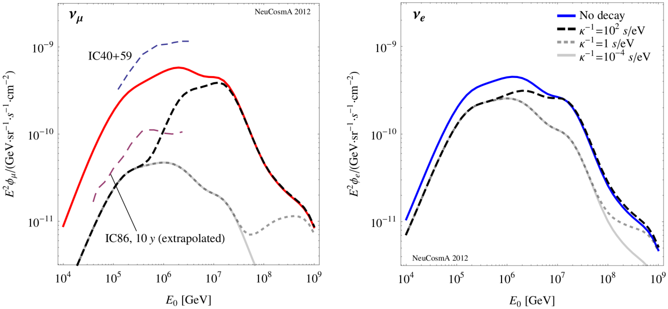
Pakvasa, Joshipura, Mohanty, 1209.5630

Neutrino decay



Dorame, Miranda, Valle, 1303.4891

Neutrino decay



Baerwald, Bustamante, Winter, JCAP 10(2012)020

Neutrino decay

	$\overline{L_e}$	$\overline{L_\mu}$	$\overline{L_\tau}$	ν_{R_e}	ν_{R_μ}	ν_{R_τ}	h	S_1	S_2	S_3	σ
$SU(2)$	2	2	2	1	1	1	2	1	1	1	1
$U(1)_H$	-2	-2	-4	2	2	4	0	0	0	-2	-2

Table: Model field content and transformation properties

$$\mathcal{L}_\nu = Y_{m_{D_{ij}}} \bar{L}_i \nu_{R_j} h + M_{ij} \nu_{R_i} S_j + \\ Y_{M_{\sigma_{ij}}} \nu_{R_i} S_j \sigma + Y_{\mu_{ij}} S_i S_j + \mu_{\sigma_{ij}} S_i S_j \sigma, \tag{2}$$

Dorame, Miranda, Valle, 1303.4891

Neutrino decay

$$\Gamma(\nu_i \to \nu_j + J) = \frac{g_{ij}^2}{16\pi}\frac{(m_i+m_j)^2}{m_i^3}(m_i^2 - m_j^2) \quad ,$$

where

$$J = \sqrt{2}\ \mathrm{Im}\sigma.$$

Neutrino decay

$$M_\nu = \begin{bmatrix} 0 & m_D^T & 0 \\ m_D & 0 & M^T \\ 0 & M & \mu \end{bmatrix},$$

$$m_D = \begin{bmatrix} m_a & m_b & 0 \\ m_c & m_d & 0 \\ 0 & 0 & m_e \end{bmatrix}, M = \begin{bmatrix} 0 & 0 & M_1 \\ 0 & 0 & M_2 \\ 0 & 0 & 0 \end{bmatrix}, \mu = \begin{bmatrix} M_8 & M_9 & 0 \\ M_{10} & M_{11} & 0 \\ 0 & 0 & 0 \end{bmatrix}$$

Neutrino decay

Can we relate this process with a neutrinoless double beta decay search?

$$(A, Z) \to (A, Z+2) + 2\,e^- + J$$

$$\Gamma^{0\nu} = |\langle g_{ee}\rangle|^2\,|\mathcal{M}_J|^2\; G_J(Q, Z)$$

Neutrino decay

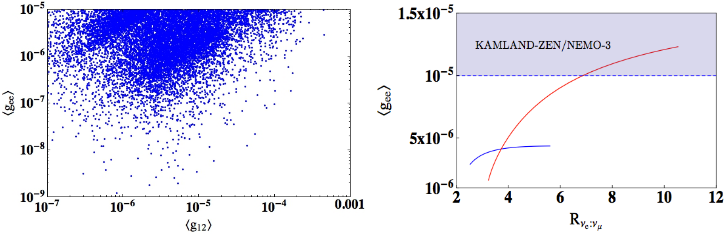


Figure: Left panel: Correlating majoron-emitting $J0\nu\beta\beta$ coupling $\langle g_{ee} \rangle$ to $\langle g_{12} \rangle$. Right panel: Correlating $R_{\nu_e:\nu_\mu}$ to $\langle g_{ee} \rangle$

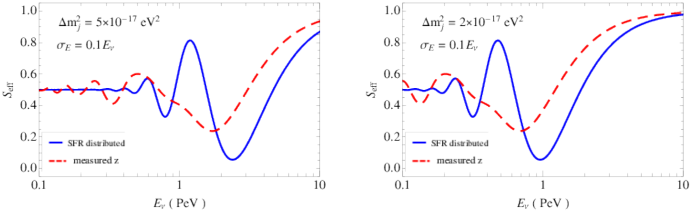
Sterile neutrinos, dark matter and resonant effects

$$P_{\alpha\beta} = \frac{1}{4}\left|\sum_{j=1}^{3} U_{\alpha j}\left\{e^{i\Phi_j^+} + e^{i\Phi_j^-}\right\} U_{\beta j}^*\right|^2$$

$$P_{\alpha\beta} = \sum_{j=1}^{3} |U_{\alpha j}|^2 |U_{\beta j}|^2 \cos^2\left(\frac{\Delta m_j^2 L}{4E_\nu}\right)$$

Esmaili, Farzan, 12(2012)014

Sterile neutrinos, dark matter and resonant effects



Esmaili, Farzan, 12(2012)014

Sterile neutrinos, dark matter and resonant effects

Evolution equation,

$$i\frac{\mathrm{d}}{\mathrm{d}t}\begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix} = \frac{1}{4E}\mathrm{M}_\alpha\begin{pmatrix}\nu_\alpha\\ \nu_s\end{pmatrix}, \tag{3}$$

where,

$$\mathrm{M}_\alpha = \begin{pmatrix} -\Delta m_{i4}^2\cos 2\theta + V_{\nu_\alpha f} + V_{\nu_\alpha\chi} & \Delta m_{i4}^2\sin 2\theta \\ \Delta m_{i4}^2\sin 2\theta & \Delta m_{i4}^2\cos 2\theta + V_{\nu_s\chi} \end{pmatrix}, \tag{4}$$

Sterile neutrinos, dark matter and resonant effects

$$\Delta m_{i4}^2 \cos 2\theta = 2E(V_{\nu_\alpha f} + V_{\nu_\alpha \chi} - V_{\nu_s \chi}) . \tag{5}$$

With

$$\begin{aligned} V_{\nu_\alpha f} &= \frac{1}{4}\frac{g^2}{m_W^2}(N_\alpha - N_n/2) = \sqrt{2}G_F(N_\alpha - N_n/2) ; && (6) \\ V_{\nu_\alpha \chi} &\sim \frac{g_{\nu_\alpha} g_\chi}{m_I^2} N_\chi = G'_{\nu_\alpha} N_\chi = \varepsilon_{\nu_\alpha \chi} G_F N_\chi ; && (7) \\ V_{\nu_s \chi} &\sim \frac{g_{\nu_s} g_\chi}{m_I^2} N_\chi = G'_{\nu_s} N_\chi = \varepsilon_{\nu_s \chi} G_F N_\chi . && (8) \end{aligned}$$

As a result,

$$\Delta m_{i4}^2 \cos 2\theta = 2EG_F[\sqrt{2}(N_\alpha - N_n/2) + (\varepsilon_{\nu_\alpha \chi} - \varepsilon_{\nu_s \chi})N_\chi] . \tag{9}$$

Sterile neutrinos, dark matter and resonant effects

Ref	$\frac{(g_\chi)(g_\nu)}{(m_I/MeV)^2}$	$\varepsilon_{\nu_e\chi}$	$\varepsilon_{\nu_s\chi}$	m_χ (eV)
Aarssen	$\frac{(0.7)(10^{-6}-10^{-1})}{10^{-2}-10^{0}}$	0	$10^5 - 10^{15}$	10^{12}
Mirror	$\frac{(1)(1)}{(30M_W)^2}$	0	10^{-3}	10^9
Fayet	$< \frac{10^{-6}}{(10^0)^2}$	$< 10^5$	0	10^7
Mangano	$< \frac{10^{-3}}{10^0}$	$< 10^8$	0	10^7

Sterile neutrinos, dark matter and resonant effects

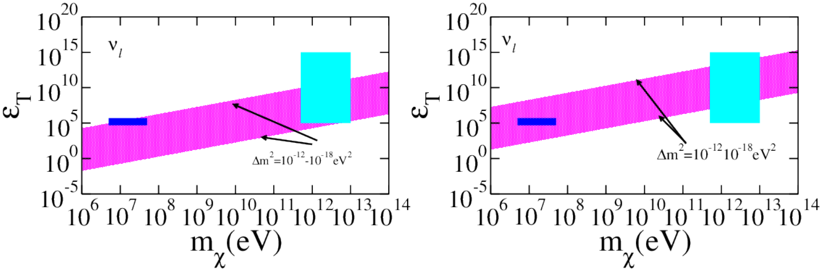


Figure: Fayet(dark blue box) and Aarssen et al (light blue box). The dark matter density value was considered as to coincide with the estimate for the halo region ($\rho_\chi = 0.3$ GeV cm $^{-3}$). $E = 10^{18}$ eV (left panel) and $E = 10^{15}$ eV (right panel).

Conclusions

IceCube has detected the first neutrino events in the energy region of PeV. However, more events, especially muon neutrino events are necessary to have a better picture, both from the astrophysical as well as from the particle physics point of view.