Dark Matter, Sterile Neutrinos and IceCube Events

Hot topics in Modern Cosmology - Spontaneous Workshop IX

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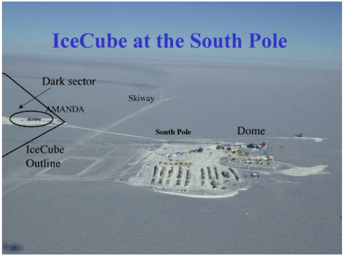
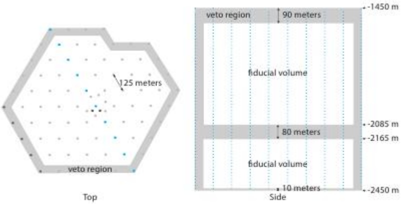
Contents

IceCube

- Large Volume Cherenkov Detector(1 km^3)
- South Pole
- 1450 – 2450 m under Antarctic Ice
- 5160 PMT's (DOM)
- Energy Range: TeV- PeV





The Detector

All neutrinos Charged Current interactions (CC) deposits its energy into a charged lepton and an hadronic shower

$\Rightarrow$ Energy resolution: 15% beyond i 10 TeV.

Two topologies:

Tracks:

- ν_μ CC interaction
- Angular resolution $\leq 1^\circ$

Showers:

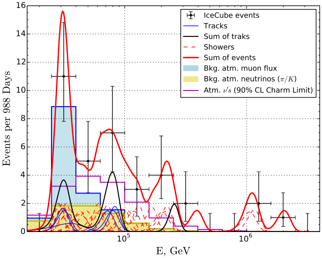
- ν_e o ν_τ CC interaction
- Angular resolution $\sim 15^\circ$

Background:
Neutrinos and Muons from cosmic rays (Atmospheric)

Event selection:
Interaction vertex in the fiducial volume, muon veto (external layers) and deposited charge in PMT $>$ 600 (E $\gtrsim$ 30 TeV)

Events

After three years of data taking: 35 events from 30 TeV to 2 PeV, over an expected background of 8.4 $\pm$ 4.2 for cosmic muons and $6.6^{+5.9}_{-1.6}$ from atmospheric neutrinos $\Rightarrow$ exess di 5.7 σ



- Gap $400\ TeV - 1\ PeV$
- Isolated events at $E \sim 1 PeV$
- Cut-Off at $E > 2PeV$
- Abundance of showers (28) over tracks (7)

$\Rightarrow$ Tracks are compatible with the expected background
$\Rightarrow$ From 100 TeV to 2 PeV only one track and 11 Showers

$\Rightarrow$ Cosmic neutrinos component dominating at E $>$ 60 TeV which for some reason prefers ν_e and/or ν_τ over ν_μ.

Standard Neutrinos

$\Rightarrow$ Can we understand something on the origin of this neutrinos studying their flavor content?

$\Rightarrow$ Suppose that this neutrinos come from some distant Astrophysical source (Cosmic Ray, Dark Matter decay ...)

$\Rightarrow$ Can we explain the fraction of tracks $F(E, E')$ detected at IceCube in some model or production mechanism thats take into account only the three standard neutrinos?

$\Rightarrow$ Starting from different flavor composition at the source we will compute $F(E, E')$ expected at IceCube considering different power-law spectra and the effective area of the detector

$\Rightarrow$ We will also take into account the experimental uncertainties on the parameters of the standard neutrinos mixing matrix

Expected ν_μ Fraction

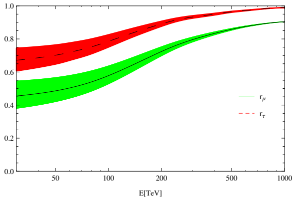
Expected tracks fraction in certain energy range can be expressed:

$$F(E,E') = \frac{N_t}{N_t + N_s} = \frac{\int_E^{E'} dE \;\; \phi_\mu(E)\; A_\mu(E)}{\int_E^{E'} dE \;\; \sum_\alpha \phi_\alpha(E)\; A_\alpha(E)}$$

Assuming a power-law spectra: $\phi_\alpha(E) \propto E^{-\gamma}$

$$F(E,E') = \frac{r_\mu \; f_\mu}{f_e + r_\mu \; f_\mu + r_\tau \; f_\tau}$$

with: $r_{\mu,\tau} = \frac{\int_E^{E'} \; dE \;\; E^{-\gamma} \;\; A_{\mu,\tau}(E)}{\int_E^{E'} \; dE \;\; E^{-\gamma} \;\; A_e(E)}$



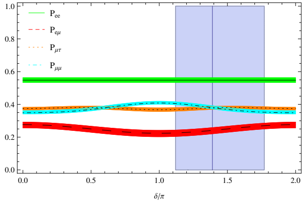
$$\gamma = 2.4 + \delta\gamma \qquad -0.4 < \delta\gamma < 0.4$$

Uncertainties on Mixing Parameters

Source Flavor Composition: $\Longrightarrow \tilde{f}_\alpha$
Averaged Oscillation Probability: $\Longrightarrow \; P_{\alpha\beta} = \sum_i |V_{\alpha i}|^2 |V_{i\beta}|^2$
Composition ad Earth: $\Longrightarrow f_\alpha = P_{\alpha\beta} \, \tilde{f}_\beta$

- 6 Independent Elements
- 3 Bounds: $\sum_\alpha P_{\alpha\beta} = 1$

$\Longrightarrow$ 3 Independent Elements
We choose: $P_{ee}, P_{e\mu}$ e $P_{\mu\tau}$



If $r_\mu = r_\tau = 1 \Longrightarrow F = f_\mu \simeq P_{e\mu} - (P_{e\mu} - P_{\mu\tau}) \left(1 - \tilde{f}_e\right)$

$P_{e\mu}$ is the key parameter!

To take into account experimental uncertanties on neutrino mixing angles we choose to marginalize every $P_{\alpha\beta}$ matrix elements with the combination of 1 σ interval extremes that maximize or minimize $P_{e\mu}$.

$$P^{\pm}_{\alpha\beta} = P_{\alpha\beta}(\theta^{\pm}_{23}, \theta^{\mp}_{13}, \theta^{\mp}_{12})$$

Source Composition $\tilde{f}_\alpha$ I

Many possibilities:

- Most common scenario: (π and μ decay) $(1/3 : 2/3 : 0)$
- Depending on E_{Meson} we can also have: $(0 : 1 : 0)$ or $(1 : 0 : 0)$
- Neutron Decay:$(1 : 0 : 0)$
- Symmetric case $(1/3 : 1/3 : 1/3)$
- Only ν_τ production $(0 : 0 : 1)$ (DM decay)

Oscillation Effects: $\tilde{f}_\alpha \rightarrow P_{\alpha\beta}\tilde{f}_\alpha$

$$\begin{aligned}
(1/3 : 1/3 : 1/3) &\rightarrow (1/3 : 1/3 : 1/3)\\
(1/3 : 2/3 : 0) &\rightarrow (0.34 : 0.33 : 0.33)\\
(1 : 0 : 0) &\rightarrow (0.55 : 0.24 : 0.21)\\
(0 : 1 : 0) &\rightarrow (0.24 : 0.38 : 0.38)\\
(0 : 0 : 1) &\rightarrow (0.21 : 0.38 : 0.41)
\end{aligned}$$

After oscillation the Atmospheric case reduces to the Symmetric one

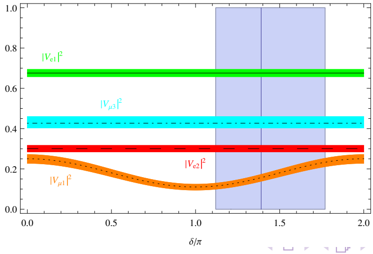
Source Composition $\tilde{f}_\alpha$ II

We can also think at more exotic production mechanism such as neutrinos from Dark Matter direct decay

$\Rightarrow$ Which can product neutrino Mass Eigenstate: ν_1, ν_2 and ν_3

$\Rightarrow$ Mass Eigenstate are are not Affected by oscillation

Flavor composition at earth is given by projecting mass eigenstate in the flavor eigenstate base: $f_\alpha = |V_{\alpha i}|^2$



Results I

Now we can compute $F(E, E')$:

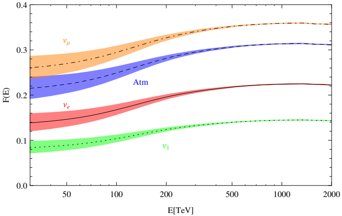
We are interested in the area above 60 TeV and expecially in the two sub-region where $60TeV < E < 100TeV$ (Low Background) and $100TeV < E < 2PeV$ (No Background)

E [Tev]	$60 < E < 2000$	$60 < E < 100$	$100 < E < 2000$
$\tilde{f}_e : \tilde{f}_\mu : \tilde{f}_\tau$	$F_{IC} = 0.2$	$F_{IC} = 0.375$	$F_{IC} = 0.083$
$1/3 : 1/3 : 1/3$	$.229 + .045\,\delta\gamma$	$.153 + .0012\,\delta\gamma$	$.249 + .031\,\delta\gamma$
$1/3 : 2/3 : 0$	$.235\,^{-.005}_{+.015} + .045\,\delta\gamma$	$.150\,^{-.005}_{+.013} + .0012\,\delta\gamma$	$.245\,^{-.005}_{+.016} + .031\,\delta\gamma$
$(1 : 0 : 0)$	$.156\,^{+.029}_{-.032} + .035\,\delta\gamma$	$.096\,^{+.019}_{-.020} + .0012\,\delta\gamma$	$.174\,^{+.032}_{-.035} + .029\,\delta\gamma$
$(0 : 1 : 0)$	$.264\,^{-.025}_{+.046} + .046\,\delta\gamma$	$.185\,^{-.021}_{+.039} + .0012\,\delta\gamma$	$.284\,^{-.025}_{+.047} + .032\,\delta\gamma$
$(0 : 0 : 1)$	$.279\,^{-.009}_{-.005} + .045\,\delta\gamma$	$.200\,^{-.004}_{-.007} + .0012\,\delta\gamma$	$.298\,^{-.011}_{-.004} + .031\,\delta\gamma$
ν_1	$.106\,^{+.058}_{-.052} + .029\,\delta\gamma$	$.062\,^{+.035}_{-.031} + .001\,\delta\gamma$	$.120\,^{+.065}_{-.058} + .021\,\delta\gamma$
ν_2	$.278\,^{-.054}_{+.044} + .056\,\delta\gamma$	$.191\,^{-.039}_{+.034} + .001\,\delta\gamma$	$.300\,^{-.057}_{+.046} + .036\,\delta\gamma$
ν_3	$.341\,^{-.021}_{+.031} + .037\,\delta\gamma$	$.275\,^{-.019}_{+.028} + .001\,\delta\gamma$	$.355\,^{-.022}_{-.031} + .026\,\delta\gamma$

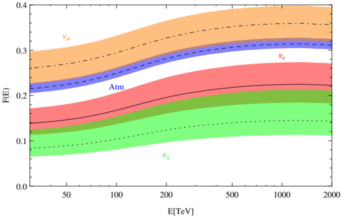
Results II

Cumulative: $(E' = 2PeV)$

Spectral Index



Oscillation Parameters



$\Rightarrow$ None of this scenarios can explain the flavor content observed at IceCube in both the Interesting Energy region.

$\Rightarrow$ Signal of New Physics ?!?

Sterile Neutrinos

What if this cosmic neutrinos were created in some Hidden Gauge Sector as Sterile Neutrinos?

Dark Sector $\leftrightarrows$ Standard Model

We can think to some kind of Heavy Dark Matter $M_{DM} \sim$ PeV that decade into neutrinos of that sector which are Sterile for us.

$$DM \to DM_{stable} + \nu_s + \ldots$$

Then they oscillate with small probabilities ($P \sim 10^{-10}$) in our neutrinos [1]

$$\nu_s \to \nu_e,\ \nu_\mu,\ \nu_\tau$$

Which are then detected by IceCube.

[1] BBN $\to \delta m_s^2 \sin^4\theta_s < 10^{-6} eV^2$

Mixing Matrix

Extra sterile neutrino with small mixing angles s_i

$$R_S(s_i) = \begin{pmatrix} 1 & 0 & 0 & s_1 \\ 0 & 1 & 0 & s_2 \\ 0 & 0 & 1 & s_3 \\ -s_1 & -s_2 & -s_3 & 1 \end{pmatrix} + O(s_i^2)$$

So, the mixing matrix is given by:

$$U = \left(\begin{array}{ccc|c} V_{e1} & V_{e2} & V_{e3} & V_{e4} \\ V_{\mu 1} & V_{\mu 2} & V_{\mu 3} & V_{\mu 4} \\ V_{\tau 1} & V_{\tau 2} & V_{\tau 3} & V_{\tau 4} \\ \hline V_{s1} & V_{s2} & V_{s3} & 1 \end{array}\right) + O(s_i^2)$$

$|V_{si}| \ll 1 \Rightarrow P_{\alpha\beta}$ Between the three ordinary neutrinos remain the same
On the other hand:

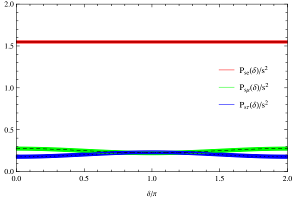
$$P_{s\alpha} = |V_{\alpha 4}|^2 + \sum_{i=1}^{3} |V_{si}|^2 |V_{\alpha i}|^2$$

Different Scenarios:

One can think about different mixing pattern between active and sterile neutrinos.

As an example we can choose: $s_2 = s_3 = 0$ e $s_1 = s$

$$P_{se} = s^2 \left[1 + P_{ee}\right]$$
$$P_{s\mu} = s^2 P_{e\mu}$$
$$P_{s\tau} = s^2 P_{e\tau}$$



So we have:

$$F(E, E') = \frac{s^2\, r_\mu\ (1 + P_{e\mu})}{s^2\,(1 + P_{ee} + r_\mu\ P_{e\mu} + r_\tau\ P_{e\tau})}$$

$F(E, E')$ is independent from s! (if $s \ll 1$)

Results I

$\Rightarrow$ Initial composition: $\tilde{f} = (0:0:0:1)$

$\Rightarrow$ Power-Law Spectra: $\phi_s(E) \propto E^{-\gamma}$

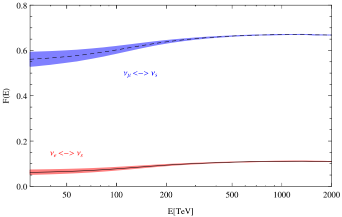
$\Rightarrow$ Three different scenarios: when the sterile neutrino is mixed with only one of the standard neutrinos: $\mathcal{M}_{s\alpha} : \nu_s \leftrightarrows \nu_\alpha$

E [Tev]	$60 < E < 2000$	$60 < E < 100$	$100 < E < 2000$
	$F_{IC} = 0.2$	$F_{IC} = 0.375$	$F_{IC} = 0.083$
$\mathcal{M}_{se}$	$.071\,^{+.012}_{-.014} + .021\,\delta\gamma$	$.040\,^{+.007}_{-.008} + .001\,\delta\gamma$	$.080\,^{+.014}_{-.016} + .016\,\delta\gamma$
$\mathcal{M}_{s\mu}$	$.572\,^{-.019}_{+.032} + .058\,\delta\gamma$	$.457\,^{-.023}_{+.038} + .002\,\delta\gamma$	$.596\,^{-.017}_{+.031} + .039\,\delta\gamma$
$\mathcal{M}_{s\tau}$	$.137\,^{-.005}_{-.002} + .022\,\delta\gamma$	$.101\,^{-.003}_{-.002} + .001\,\delta\gamma$	$.145\,^{-.005}_{-.001} + .016\,\delta\gamma$

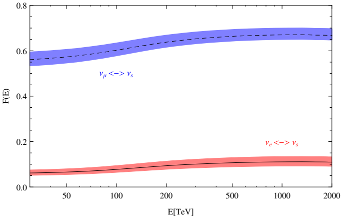
Results II

Cumulative: $(E' = 2PeV)$

Spectral Index



Oscillation Parameters



$\Rightarrow$ In the No Background region: IceCube $\sim \mathcal{M}_{se} : \nu_s \leftrightarrows \nu_e$

$\Rightarrow$ In the Low Background region: IceCube $\sim \mathcal{M}_{s\mu} : \nu_s \leftrightarrows \nu_\mu$

Can this be a Clue?

Idea

The ideal scenario to explain this flavor content is a mechanism that creates ν_s mixed with ν_e over 100 TeV and ν_s mixed with ν_μ below.

We can think at two different species of Dark Matter with different masses and different decay modes whose as decay product have two different kind of sterile neutrinos.

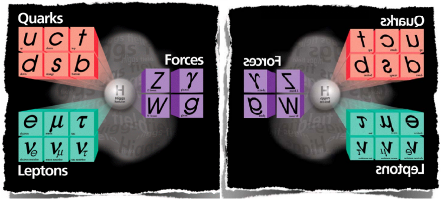
$$DM_e \to \ldots + \nu_s \leftrightarrows \nu_e$$

$$DM_\mu \to \ldots + \nu_s \leftrightarrows \nu_\mu$$

But... What fixes DM decay time? and What defines oscillation probabilities?

All of this can be naturally obtained in the framework of Asymmetric Mirror Dark Matter

Mirror Universe



Particle physics will is described by such a Lagrangian:

$$\mathcal{L}_{tot} = \mathcal{L}_{SM} + \mathcal{L}'_{SM} + \mathcal{L}_{mix}$$

- Invariant under two identical gauge groups: $G \times G'$
- Identical field contents
- Mirror Parity $P(G \leftrightarrow G')$ (no new parameters)

Gravity is not the only common interaction! $\rightarrow \mathcal{L}_{\text{mix}}$

History Of Mirror World

Ideas of Mirror Matter:

- 1956 Left-Right symmetry can be restored in nature (Lee and Yang)
- 1966 Mirror fermions cannot have common Interactions EM, Weak and Strong but only common Gravity (Kobzarev, Okun, Pomeranchuk)
- 1991 Two Standard Models : SM and SM' (Foot et al.)
- 1995 Lepton number violation in ordinary and mirror matter (Berezhiani, Mohapatra)
- 1995 Asymmetric Mirror Universe (Berezhiani, Dolgov, Mohapatra)
- 2001 MM as a viable candidate for DM if $T'/T \ll 1$ (Berezhiani, Comelli, Vilante)
- 2006 Baryon number violation in ordinary and mirror matter (Berezhiani)

Mirror Particle Physics

For Ordinary particles we have the **Standard Model**:

- Gauge Symmetry: $G = SU(3) \times SU(2) \times U(1)$
- Particles: quarks, leptons, photon, gluons, $W^{\pm}$, Z, Higgs.
- Interactions: long-range EM forces, Strong interaction confinement (Λ_{QCD}), Weak scale M_W

In the Mirror Sector we have the same:

- Mirror Gauge Symmetry: $G' = SU(3)' \times SU(2)' \times U(1)'$
- Mirror Particles: quarks′, leptons′, photon′, gluons′, $W'^{\pm}$, Z', Higgs′.
- Mirror Interactions: long-range EM forces, Strong interaction confinement (Λ'_{QCD}), Weak scale M'_W

$\mathcal{L}_{mix} \longrightarrow$ O-M Interactions

Mirror Cosmology

Same Physics Different Stories:

$\Rightarrow$ Mirror Matter: $\Delta N_\nu \simeq 6.14$ (BBN limit: $\Delta N_\nu \lesssim 0.5$)

But if after Inflation $\rightarrow T' < T$ Mirror Matter can full-fit BBN bounds and also we obtain for free:

$\Rightarrow \eta'_B \gtrsim \eta_B \rightarrow$ Mirror Matter is a natural candidate for Dark Matter

$\Rightarrow$ Mirror BBN: $\sim 75\%$ of He and $\sim 25\%$ of H

How Mirror Universe would look like?

- Mirror stars are older than ordinary ones; some populate the galaxy halo as MACHOs; many has exploded as Super Novae.
- Like for OM most of MM is in the form of gas clouds rather than stars and planets.
- MM clouds consists of interacting gas at different temperatures and density.

Mirror Phenomenology

Are there any Window to the Mirror World?

$$\mathcal{L}_{mix}$$

is responsible for many O-M Interactions

We can build up higher dimension operator that generate interactions such as:

- Photon Kinetic Mixing: $-\epsilon F^{\mu\nu}F'_{\mu\nu}$
- $n - n'$ Oscillation: $\frac{1}{M}(uud)(u'u'd')$
- $\nu - \nu'$ Oscillations: $\frac{1}{M}(\phi l)(l'\phi')$
- $\pi^0 - \pi'^0$ and $K^0 - K'^0$ Mixing (with common Gauge or Higgs Boson) $\frac{1}{M}(\bar{q}\gamma^\mu q)(\bar{q}'\gamma_\mu q')$

$\Rightarrow n - n'$ and $\nu - \nu'$ Oscillation Violate B-L Symmetry in both sector

$\Rightarrow$ Baryon and Lepton Asymmetry in the Early Universe

Distorted Mirror

What if Mirror Parity is broken for some reason?

$\Rightarrow$ In can be done in many ways, the most intriguing one is to have a mechanism that make different the Higgs VEV of the two sectors

$$\frac{v'}{v} \neq 1$$

$\Rightarrow$ This introduces only one Extra Parameter: $\zeta = \frac{v'}{v}$

$\Rightarrow$ Elementary mirror fermions and gauge bosons will have different masses from the Ordinary ones.

$\Rightarrow$ It will also affect the Running of Coupling constants

$\Rightarrow$ Depending on the value of ζ we can have many different scenarios

We will show that an highly Asymmetric Mirror Matter scenario can give an explenation of what is observed at IceCube

Breaking of Mirror Parity

We choose a SUSY + GUT scenario:

$\Rightarrow$ Below GUTs scale ($M_G \sim 10^{16} GeV$) both sectors are given by identical SUSY GUTs groups such as $SU(5) \times SU(5)'$ or $SU(6) \times SU(6)'$ and Mirror Parity in conserved.

$\Rightarrow$ $M_G \sim 10^{16} GeV$: SSB of GUTs group in both sectors:

- $SU(5) \rightarrow SU(3) \times SU(2) \times U(1)$
- $SU(5)' \rightarrow SU(3)' \times SU(2)' \times U(1)'$

$\Rightarrow$ $M'_S \sim 10^{11} GeV$: Soft Breaking of SUSY in the Mirror Sector due to a non zero F or D Term of some Auxiliary Field

$\Rightarrow$ This induces SUSY Breaking in our sector at $M_S \sim \frac{M'^2_S}{M_{Pl}} \sim 1 TeV$ (Transmitted by Gravity or Planck Scale Mediator)

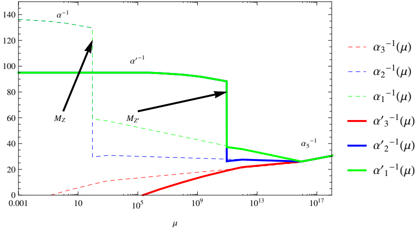
$$M_S \ll M'_S \longrightarrow v \ll v'$$

Mirror Parity is Broken

Running of Coupling Constant

All elementary fermions and gauge bosons in the Mirror Sector are rescaled by the factor: $\zeta = v'/v = 10^9$

$\Rightarrow$ We can compute the running of the three gauge coupling constant:



$\Rightarrow$ $\Lambda'_{QCD} \sim 100TeV$: There are no Light Quarks in the Mirror World

$\Rightarrow$ No confinement effects in Hadrons

$\Rightarrow$ M-Hadrons are Bound States of Heavy Quark : $M_{Hadr} = \sum M_{q'}$

Asymmetric Mirror World

How this Asymmetric Mirror World would look like?

Our sector:

- SUSY scale: $M_S \sim 1TeV$
- EW SSB: $v \simeq 100GeV$
- confinement: $\Lambda \simeq 200MeV$

Mirror sector:

- SUSY scale: $M_S \sim 10^{11}GeV$
- EW SSB: $v \lesssim 10^{11}GeV$
- confinement: $\Lambda \simeq 100TeV$

Mirror Universe is popolated by Neutrinos, Photons, lightest Leptons and the lightest Mirror Baryon

Quark and Lepton Masses

At GUT scale we have two Identical sector, with identical fermions and Yukawa couplings:

$$\mathcal{L}_Y = (Y^e_{ij} l_i e^c_j h_1 + Y^d_{ij} q_i d^c h_1 + Y^u_{ij} q_i u^c_j h_2)$$
$$\mathcal{L}'_Y = (Y^e_{ij} l'_i e'^c_j h'_1 + Y^d_{ij} q'_i d'^c h'_1 + Y^u_{ij} q'_i u'^c_j h'_2)$$

But, down to lower energies we have to take into account RG running:

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

$$m_{e'} = Y_e R_{e'} \eta_{e'} v'_1 \quad m_{d'} = Y_d R_{d'} \eta_{d'} v'_1 \quad m_{u'} = Y_u R_{u'} \eta_{u'} v'_2 B_{t'}^3$$

RG in SUSY SM: $R_e \eta_e \sim 1.5$, $R_d \eta_d \sim R_u \eta_u \sim 1.5$ and $B_t \sim 0.7$

RG in SUSY SM': $R_{e'} \eta_{e'} \sim 1.1$, $R_{d'} \eta_{d'} \sim R_{u'} \eta_{u'} \sim 1.3$ and $B_{t'} \sim 1.$

Our sector:

- $m_e \simeq 0.5 MeV$
- $m_d \simeq 4.8 MeV$
- $m_u \simeq 2.3 MeV$

Mirror sector:

- $m_{e'} \simeq 0.4 PeV$
- $m_{d'} \simeq 1.1 PeV$
- $m_{u'} \simeq 1.9 PeV$

Mirror Neutrinos

We Assume that neutrino masses emerge by Plack Scale Operators and a $U_{l-l'}(1)$ Symmetry

$$\mathcal{L}_{m_\nu} = \frac{Y\chi}{M_{Pl}^2}(\bar{5}H)(\bar{5}H) + \frac{Y\chi}{M_{Pl}}(\bar{5}'H')(\bar{5}'H') + \frac{Z}{M_{Pl}^2}(\bar{5}H)(\bar{5}'H')$$

$U_{l-l'}(1)$ Symmetry is broken by the χ field ($V_\chi \sim 10^{15}GeV$)

- 1-st Op: practically irrelevant $\delta m \simeq \frac{V_\chi v^2}{M_{Pl}^2} \sim 10^{-10}eV$
- 2-nd Op: ν' Majorana Masses: $M_{\nu'} = \frac{Y V_\chi v'^2}{M_{Pl}} \sim MeV$
- 3-rd Op: Mixing Dirac Masses between ν and ν' $m_D = \frac{Zvv'}{M_{Pl}} \sim KeV$
- 3-rd Op: Active-Sterile Mixing $\Theta = \frac{m_D}{M_{\nu'}} \sim 10^{-4}$

This *"see-saw"* mechanism induces Majorana Mass term to Ordinary neutrinos: $m_\nu = \frac{m_D^2}{M_{\nu'}} \sim 10^{-2}eV$

$\Rightarrow$ Oscillation probabilities: $P \propto \Theta^2 \sim 10^{-8} - 10^{-10}$

Hadron Masses and Decays

Lightest and Stable Mirror Baryon: $\Delta'^{-} \sim (d'd'd')$ with $M_{\Delta} \simeq 3.3PeV$

In SUSY SU(5) in decays $\Delta'^{-} \to \rho'^{-} + \bar{\nu}'_x$ $(M_{\rho'} \simeq 3.1PeV)$

with: $\tau_{\Delta'} \sim M_G^4(\alpha_G^5 m_{\Delta'}^5)^{-1} \sim 10 - 100Gyr$ $(\sim \tau_U)$

instead of: $\tau_P \sim M_G^4(\alpha_G^5 m_P^5)^{-1} \sim 10^{31}Gyr$

$\Rightarrow \nu'_x$: Mono-energetic M-Neutrinos: $E_x = \frac{1}{2}M_{\Delta'}\left(1 - \frac{M_{\rho'}^2}{M_{\Delta'}^2}\right) \simeq 200TeV$

$\Rightarrow$ Also resonance of $\rho'^{-}(d'\bar{u}')$ can be produced giving rise to several lines in the spectra

$\Rightarrow \nu'_x$ Superposition of Mirror Neutrino Flavor Eigenstates.

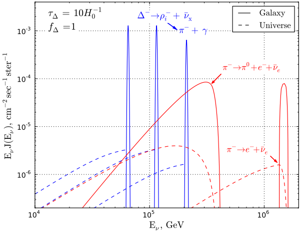
Neutrino Energy Spectrum

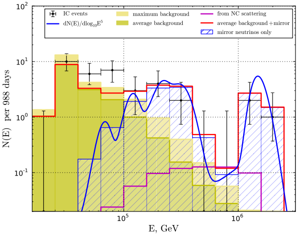
All ρ' decay into pions $\rho'^- \to \pi'^-(d'\bar{u}') + \gamma'$ with $M_{\pi^\pm} \simeq 3PeV$

$\Rightarrow \pi'^- \to e' + \bar{\nu}'_e \quad or \quad \pi'^- \to \pi'^0 + e' + \bar{\nu}'_e \qquad \Gamma_2 \simeq \Gamma_3$

$\Rightarrow \nu'_e$ is the Mirror Electron Neutrino

$\Rightarrow$ Now we can reconstruct the spectra that would be observed in IceCube taking into account Galactic $(z = 0)$ and Cosmic $(z > 0)$ contributions:





And Compare it with what IceCube Observe

Flavor Content

Assuming that:

$\Rightarrow$ ν'_e Is mixed only with our Electron Neutrino

$\Rightarrow$ ν'_x Superposition prefers to Oscillate in our Muon Neutrino

$\Rightarrow$ We can compute the Tracks Fraction using the spectra from Asymmetric Mirror Dark Matter decay:

E [Tev]	$60 < E < 100$	$100 < E < 2000$
	$F_{IC} = 0.375$	$F_{IC} = 0.083$
Asym-MM	$.456\,^{-.022}_{+.036}$	$.122\,^{+.021}_{-.024}$

Conclusions

It is hard to explain IceCube neutrino events in the framework of known Neutrino Physics and Astrophysics

- A better agreement it's possible if we take into account Sterile Neutrinos
- This Neutrino could be produced from Dark Matter decay in an Hidden Gauge Sector
- Then they Oscillate into our active neutrino with small probabilities $P \sim 10^{-10}$
- Using the paradigm of Asymmetric Mirror Dark Matter we can have a model that naturally explain all the features of neutrino observed at IceCube

The validity of our model will be tested with increasing statistics by IceCube Collaboration