# *Astrophysical neutrinos, PeV events at IceCube, and the Direct Detection of Dark Matter*

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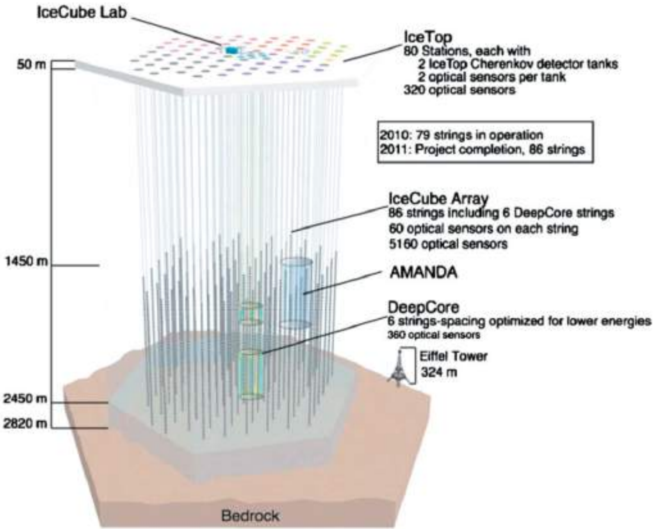
arXiv:1407.3280, with A. Bhattacharya and R. Gandhi

# Outline of the Talk

- The IceCube Neutrino Detector.
- Recently reported high energy events.
- Our interpretation of the events : Direct detection of Dark Matter ?
- Neutrino or Dark Matter? : Distinguishing features.
- Summary and Conclusions

# The IceCube Neutrino Detector and what it detects

- **IceCube : The largest neutrino detector in the world**



- In IceCube :

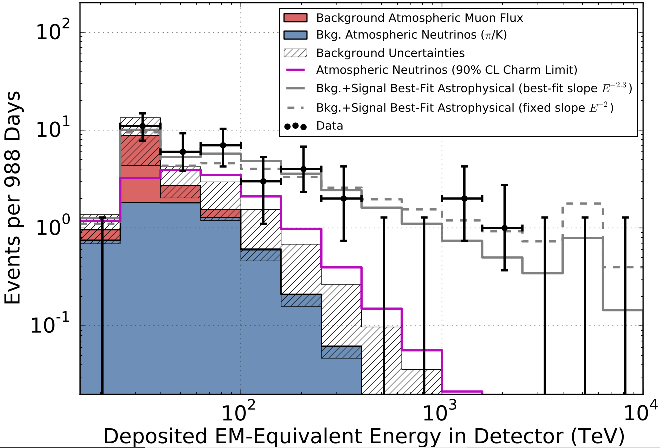
Track $\rightarrow$ $\nu_\mu$ CC and a subset of $\nu_\tau$ CC interactions.

Cascades $\rightarrow$ $\nu_e$ CC, a subset of $\nu_\tau$ CC and NC interactions of all three flavours.

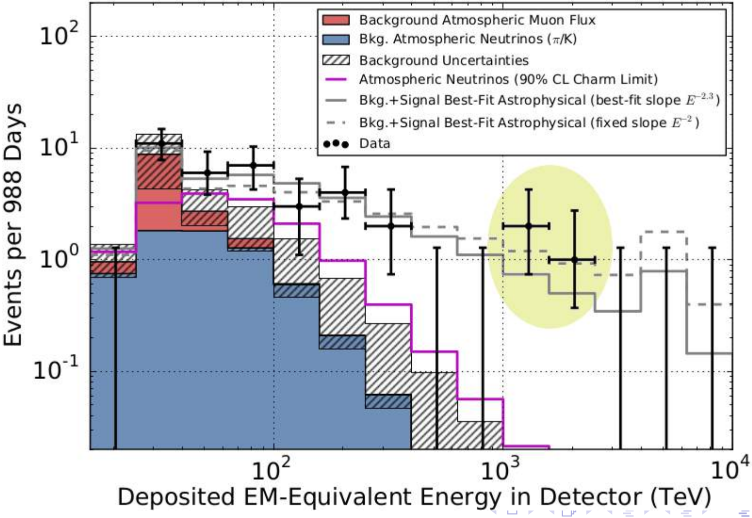
- Another important point is to note that IceCube measures the **energy deposited** i.e. $E_{final} - E_{initial}$ in a collision between a charged lepton and the ice nucleus.

# Recently reported high energy events at IceCube and some of its features

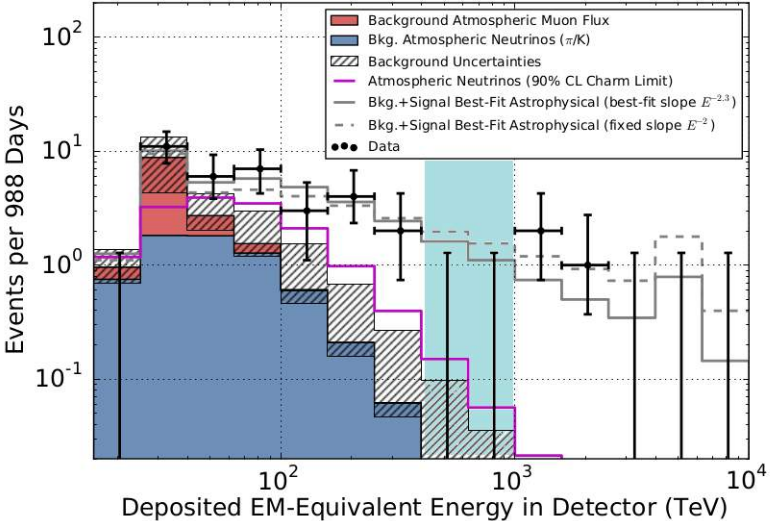
- The 988 days of data reveals 37 events (9 track and 28 cascades) with energies between 30 TeV and 3 PeV.



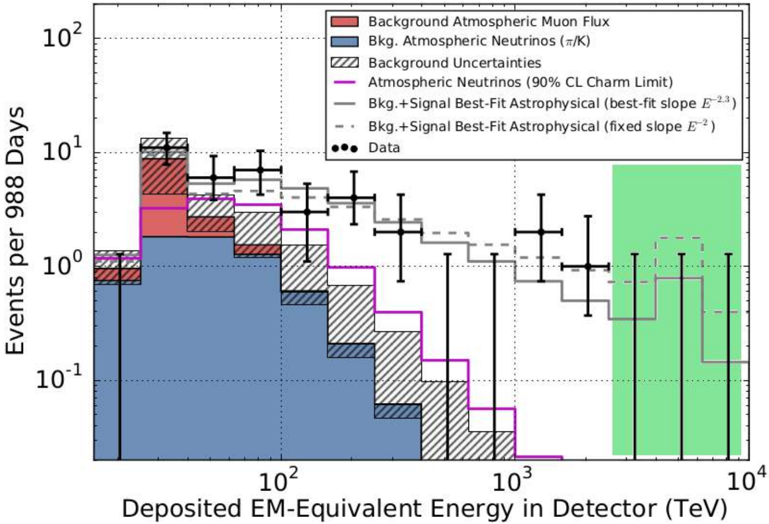
- First let us look at the three high-energy events in the PeV range. Some intriguing features to note are as follows :
- The three highest energy events are *closely clustered* with energies of 1 PeV, 1.1 PeV, 2.1 PeV.



- There are *no events* between 400 TeV and 1 PeV. Though this gap is believed to be statistical.

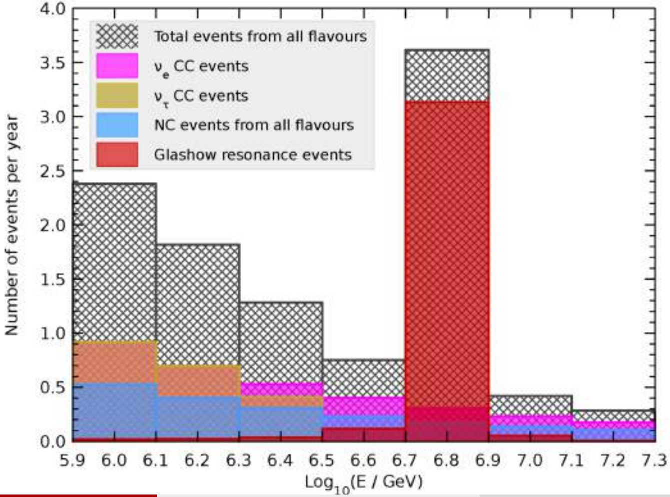


- There are again *no events* beyond 2 PeV, although 3 events are expected between 2 - 10 PeV for an unbroken $E^{-2}$ spectrum.



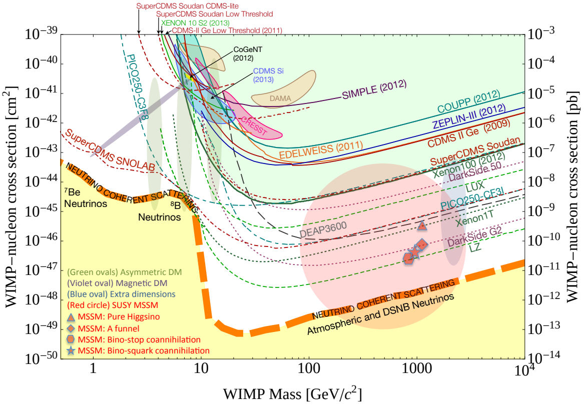
- Events were also expected at these PeV energies due to Glashow Resonance ($\bar{\nu}_e e^- \to W^-$). We will exploit these absence of events later.

(A. Bhattacharya, R. Gandhi et al. arXiv : 1108.3163)



# Our interpretation of the events : Direct detection of Dark Matter?

- From the direct detection experiments done so far we see that the neutrino nucleon cross-section at these (low) energies forms a background.
  $\rightarrow$ Indicates similar nature of interaction of neutrino and DM.



- We interpret that the PeV events (i.e. the ones with deposited energies of 1 PeV, 1.1 PeV, 2.1 PeV) are due to relativistic dark matter particles (*not neutrinos*) produced from late time decay of another heavier dark matter species.

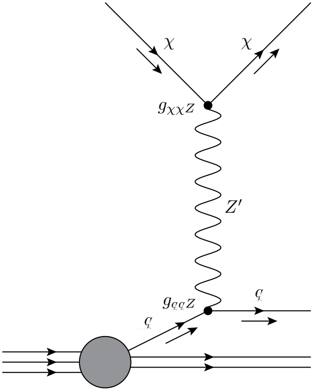
- So we hypothesize of a minimal Dark Sector which consists of :

  1) A co-moving, non-relativistic real scalar dark matter species $\phi$ with mass $m_\phi$ which decays with a life-time $\tau_\phi$.

  2) A much lighter fermionic dark matter species $\chi$ with mass $m_\chi$ which is produced from the decay of the heavier species $\phi$.

# Phenomenological determination of $m_\phi$ :

- The $\chi$ interacts (*vector-like interaction*) *with the ice nucleus via neutral current interaction mediated by a (heavy) beyond SM gauge boson $Z'$.*



- Under these assumptions we have :

$$\frac{d^2\sigma}{dxdy} = \frac{G^2 s}{8\pi} \frac{(1+(1-y)^2)}{(xys + m_{Z'})^2} \sum_p x f_p(x) \tag{1}$$

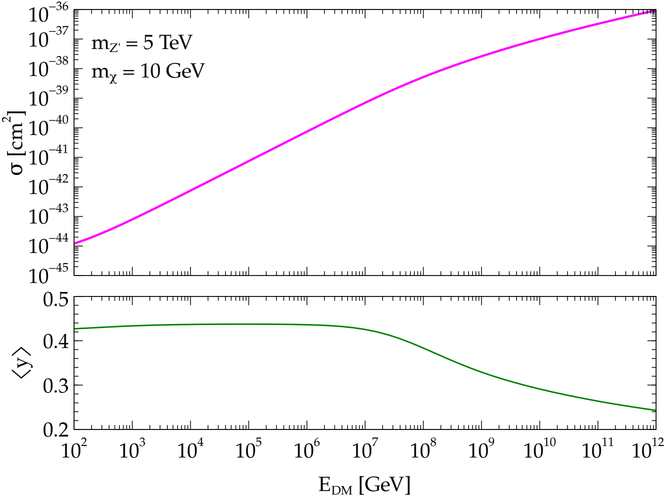
- Since IC can only detect deposited energy, it is important to determine the nature of the inelasticity parameter y, where

$$y = \frac{E_\chi^{in} - E_\chi^{out}}{E_\chi^{in}} \equiv \frac{E^{dep}}{E_\chi^{in}} \tag{2}$$

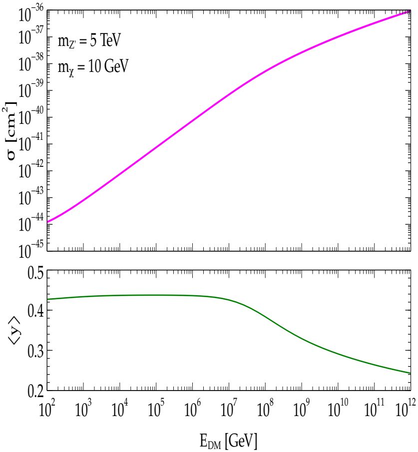
- An useful quantity to calculate is the mean inelasticity parameter :

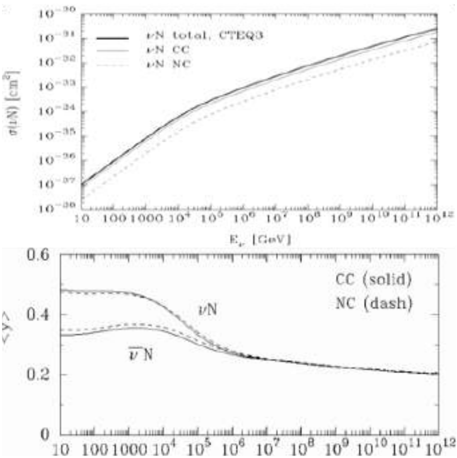
$$\langle y(E) \rangle \equiv \frac{1}{\sigma(E)} \int_0^1 \int_0^1 y \frac{d^2\sigma}{dxdy} dxdy \tag{3}$$

- Using the above, and CT10 PDFs we find $\sigma(E_{Lab})$ and $\langle y(E_{Lab})\rangle$.
  G is *arbitrarily* fixed at 0.05. Note however $\langle y(E_{Lab})\rangle$ does not depend on G.



- Contrasting with the well understood neutrino-nucleon DIS :




- We find that around the PeV energy scale $\langle y \rangle \simeq 0.42$.
  A deposited energy of say 1.1 PeV (one of the observed UHE event) implies an incident energy of 2.53 PeV and which in turn gives $m_\phi = 5.06$ PeV.

# Phenomenological determination of G $(= g_{\chi\chi Z'} \times g_{\chi\chi q})$ :

- Cross-section times the flux gives the number of events and we can adjust G to obtain the presently observed 3 UHE events in IceCube.

- A careful analysis will show however that the actual independent parameter is $\dfrac{G}{\tau_\phi}$. We can only estimate G only after we have fixed a value of $\tau_\phi$.

- But we have to calculate the flux first.

- The flux $\Phi$ of $\chi$ particles consists of both galactic ($\Phi^G$) and extra-galactic component ($\Phi^{EG}$).
- For the Galactic component we have :

$$\boxed{\Phi^G = \int_{E_{min}}^{E_{max}} D_G \frac{dN_\chi}{dE_\chi} dE} \tag{4}$$

where,

$$D_G = \frac{1}{4\pi m_\phi \tau_\phi} \int_0^\infty \rho_{Halo}[r(s,l,b)]ds \tag{5}$$

with the usual,

$$r(s,l,b) = \sqrt{s^2 + R_\odot^2 - 2sR_\odot cos(b)cos(l)} \tag{6}$$

$\rightarrow$ We have taken the usual NFW profile in calculating $\rho_{Halo}$.

- For the extragalactic component we have :

$$\boxed{\Phi^{EG} = \frac{\Omega_{DM}\rho_c}{4\pi m_\phi \tau_\phi}\int_{E_{min}}^{E_{max}} dE \int_0^\infty dz \frac{1}{H(z)}\frac{dN_\chi}{dE_\chi}[(1+z)E_\chi]} \quad (7)$$

where,

$$H(z) = H_0\sqrt{\Omega_\Lambda + \Omega_m(1+z)^3} \quad (8)$$

and define,

$$D_{EG} \equiv \frac{\Omega_{DM}\rho_c}{4\pi m_\phi \tau_\phi H_0} \quad (9)$$

- For the two body decay of $\phi$ we have :

$$\frac{dN_\chi}{dE_\chi} = 2\delta(E_\chi - \frac{1}{2}m_\phi) \quad (10)$$

- Using all these we calculate the total flux ($\Phi = \Phi^G + \Phi^{EG}$) of $\chi$.
  $\tau_\phi$ is set to be $10^{24}$ secs.

- With this value of $\tau_\phi$ the value of G can be ascertained by normalising the number of events predicted due to flux of the $\chi$ particles against those seen in IceCube.

- We find that we need to set $G^2 = 0.45$ (instead of the previous *arbitrarily* chosen value of 0.05) to obtain the three UHE events in the PeV range over 988-days of data accumulation.

# Sub-PeV events :

- While the events corresponding to deposited energies $\geq 1$ PeV are accounted for the $\chi$ dark matter particles, the sub-PeV events up to 400 TeV are consistent with astrophysical neutrinos.

- IceCube uses *all* the events to derive the spectral behaviour of the astrophysical neutrinos. They give the flux as :

$$\Phi_\nu = 0.95 \pm 0.3 \times 10^{-8} E^{-2} \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \tag{11}$$

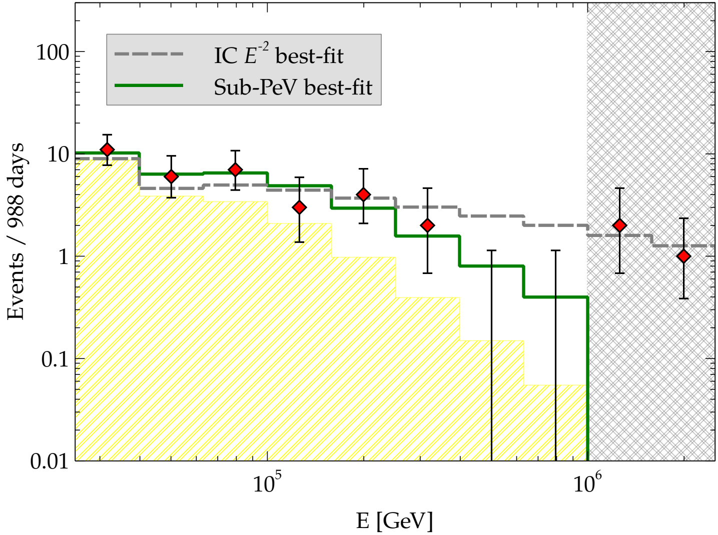
  They predict events in the 1-10 PeV range, while we see none above 2.1 PeV.

- Using only the sub-PeV, we get a steeper spectrum :

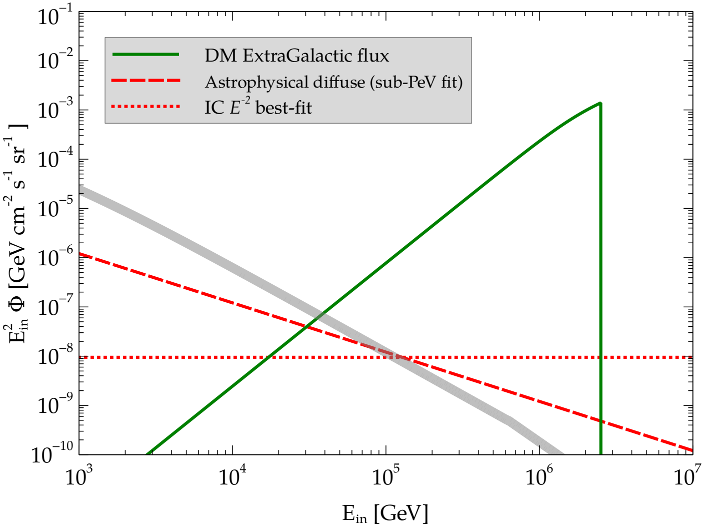
$$\Phi_\nu = 1.21 \times 10^{-3} E^{-3} \text{GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \tag{12}$$

  (They predict no events above 2 PeV.)

- The prediction of events from the two best fits in Eqn(11) and Eqn(12) :



- Different relevant fluxes :



# Neutrino or Dark Matter? : Smoking Gun signature

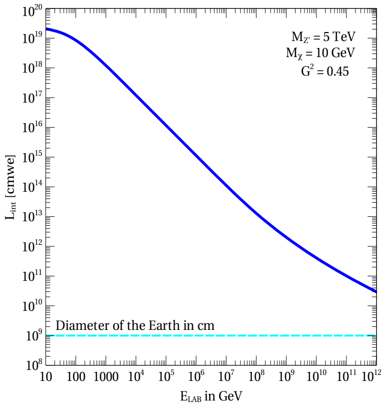
- If the high energy events be indeed Dark matter induced then IceCube is expected to see both up and down going tracks because earth is transparent to the dark matter due to low cross-section.

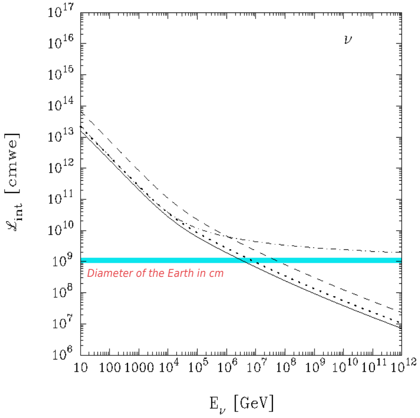
  But to the neutrinos the earth is opaque at these PeV energies, hence only down going events are expected for them.

  A relevant quantity to calculate is :

$$L_{int}^{water-equivalent} = \frac{18}{\sigma(E) N_A} \tag{13}$$

- The last point is depicted in the following figure :



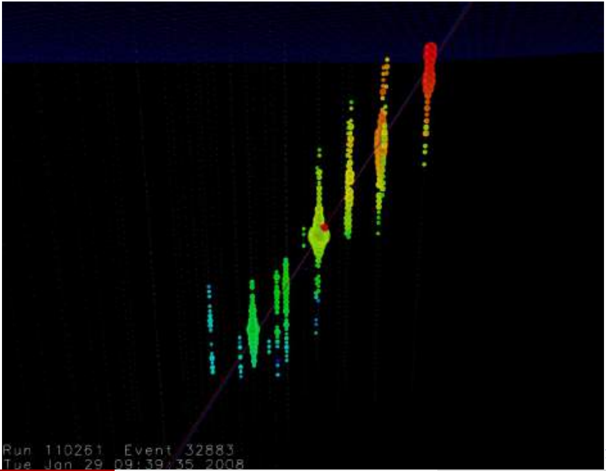
# Summary and conclusions

- We have hence shown that the PeV events in IceCube can come from relativistic dark matter particles ($\chi$) produced from decay of a heavier species $\phi$, while the latter forms the bulk of DM energy density.
- The Sub-PeV events come from astrophysical neutrinos with $E^{-3}$ spectrum.
- This can be claimed as a Direct Detection of Dark Matter, but different from the known direct detection techniques which focusses on *low energy coherent* scattering off nuclei. On the contrary, our detection technique relies DIS.
- So direct detection bounds on dark matter nucleon cross-section is not applicable to our case.
- We should wait for more and more data for confirmation of this explanation. Let us hope for the best.

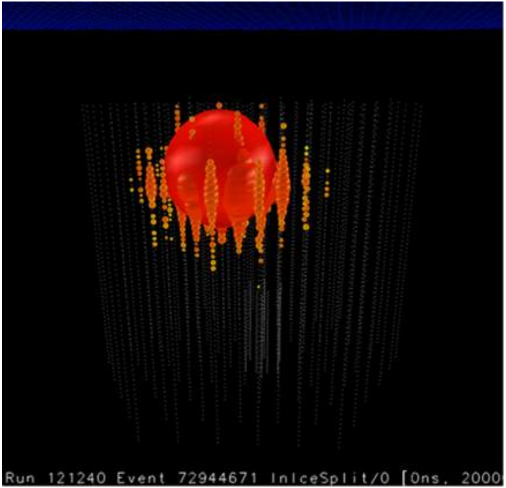
**THANK YOU**

# Back-Up slides

- IceCube is most sensitive to muons (produced from $\nu_\mu$) than other charged leptons, because they are the most penetrating and thus have the longest *tracks* in the detector. (Track length $\sim$ 1 Km at TeV energies.)



- An electron resulting from a $\nu_e$ event typically loses energy much faster. Hence these events are more spherical, or *cascade* -like. (A few meters in diameter.)



# Attempts so far in explaining the events : A brief summary

- A purely *atmospheric* explanation of these events is strongly disfavoured (at $5.7\sigma$ level), because with these atmospheric fluxes the very high energy events are not expected.

- The flux is more or less isotropic and hence possible astrophysical sources from within (for e.g. from Fermi Bubble) as well as outside our galaxy (for e.g. AGN cores, GRBs) are considered as a origin of these high energy neutrino events.

- Some other class of explanations involve interpreting the high energy events as neutrinos coming from Dark Matter decay or annihilation.

- We note however that in all these explanations, the high-energy events have been assumed to be *neutrino* events.

# Properties of $\phi$ :

- This dark matter species is *assumed* to comprise of the bulk of the present day dark matter. Hence $\tau_\phi \gg$ life-time of the universe.

- $\phi$ decays further into a much lighter species of dark-matter $\chi$ :

$$\phi \to \chi\bar{\chi}$$

  Energy of each of this $\chi$ particles (if produced from late time decay of $\phi$) is nearly $m_\phi/2$. Since we are assuming these $\chi$ particles to produce the PeV events in IceCube, $m_\phi \simeq$ PeV.

- $\phi$ is a non-thermal dark matter $\to$ Griest-Kamionkowski Bound.

- $\phi$ has no decay channels to any standard model particles.

# Properties of $\chi$ :

- $\chi$, produced from the decay of $\phi$, is *assumed* to be fermionic.
- Since at production, from the decay of $\phi$, $\chi$ is relativistic, it is much lighter than $\phi$ i.e. $m_\chi \ll m_\phi$.
- $\chi$ interacts with the standard model particles via the exchange of a heavy neutral gauge boson which connects the DM and SM sectors.
- $\chi$ is also a non-thermal dark matter.
- It does not form the major component of the dark matter energy density of the universe.

# Galactic Bias :

- From the earlier mentioned expressions for the galactic and the extra-galactic fluxes we can have the following:

$$D_G = 1.7 \times 10^{-8} \left(\frac{1\ \text{TeV}}{m_\phi}\right) \left(\frac{10^{26}\ \text{secs}}{\tau_\phi}\right) \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \qquad (14)$$

and

$$D_{EG} = 1.4 \times 10^{-8} \left(\frac{1\ \text{TeV}}{m_\phi}\right) \left(\frac{10^{26}\ \text{secs}}{\tau_\phi}\right) \text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1} \qquad (15)$$

Hence the galactic and extra-galactic fluxes are of the same order.

- So for the PeV events we would expect half of the total flux contribution to be coming from the galactic center.

- Of the three PeV events detected so far in IceCube, two of them come from the galactic center.