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

, 14th December, 2017.

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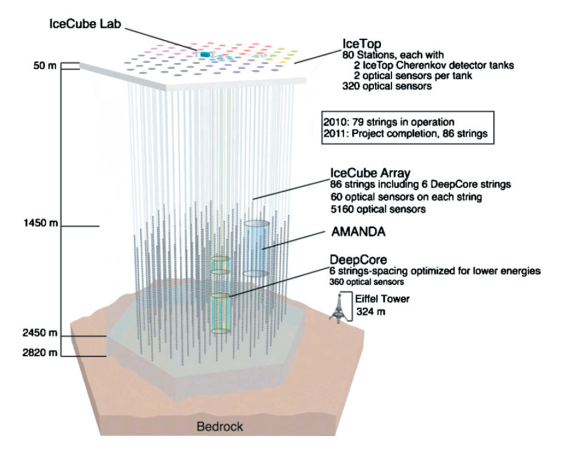
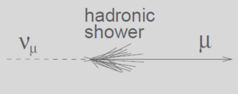
The IceCube Neutrino Detector and what it detects

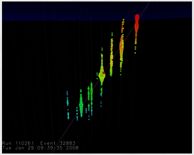
- IceCube : The Largest neutrino detector in the world.



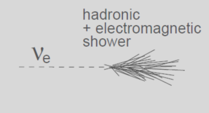
Event Topologies

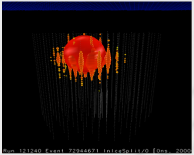
- **Track Type Events :**



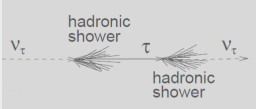


- **Cascade Type Events :**





- **Tau events :**



- In IceCube :

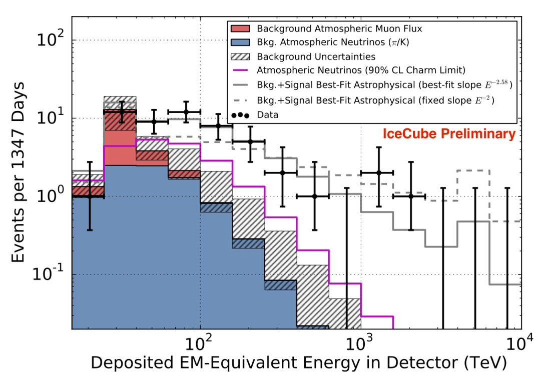
  Track $\rightarrow$ ν_μ CC and a subset of ν_τ CC interactions.

  Cascades $\rightarrow$ ν_e CC, a subset of ν_τ CC and NC interactions of all three flavours.

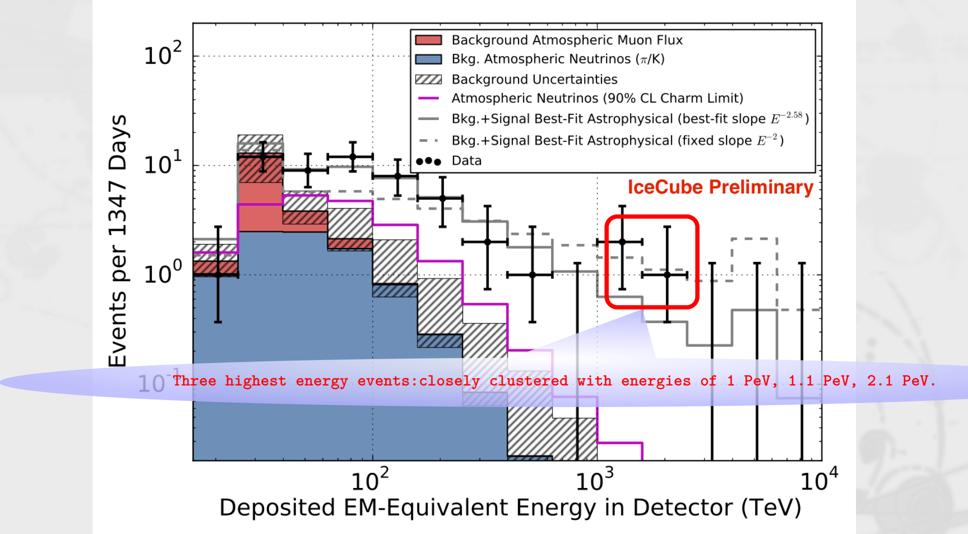
- IceCube measures the **deposited energy** i.e. $E_{\text{final}} - E_{\text{initial}}$.

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

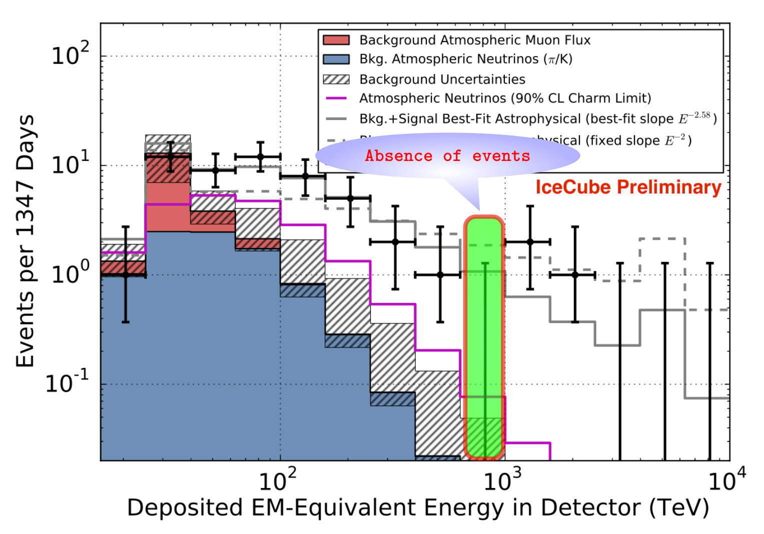
- **1347 days of data reveals 54 events (15 tracks and 39 cascades) with energies between 30 TeV and 3 PeV.**



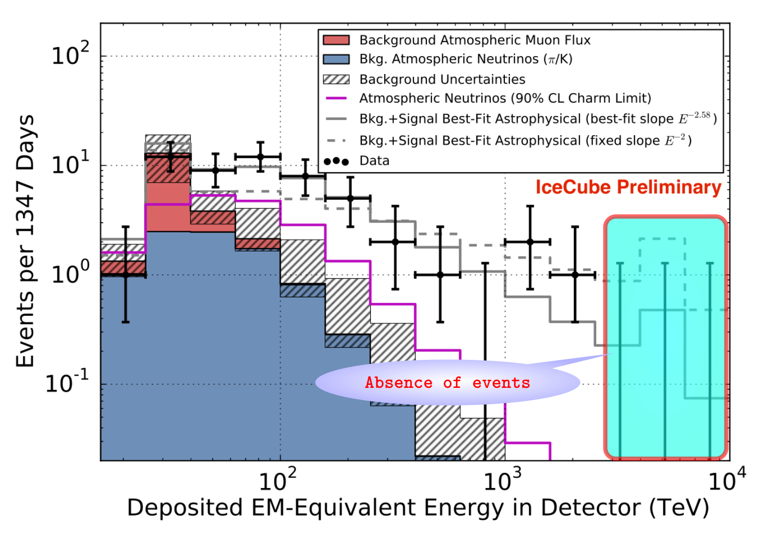
- The three highest energy events are **closely clustered**.



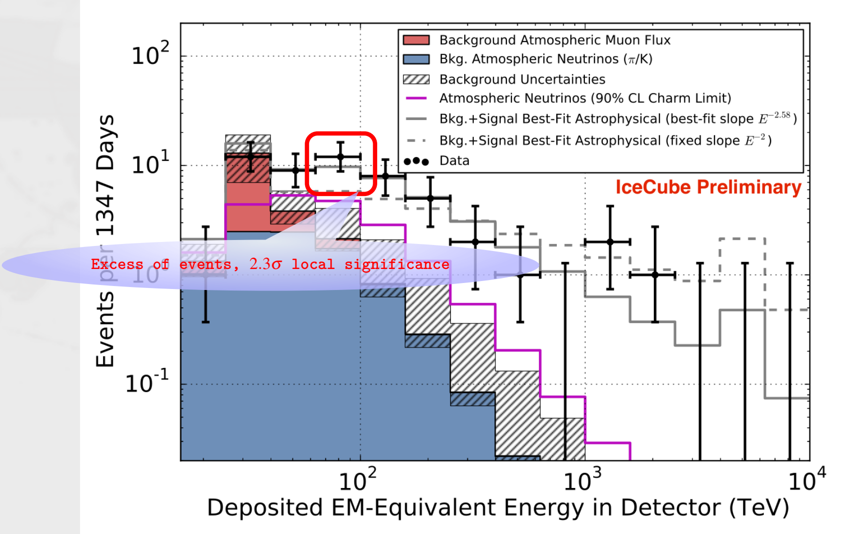
- **No events** between 400 TeV and 1 PeV.



- **No events** beyond 2 PeV.



- **Excess** around 100 TeV.



PeV events : Direct detection of Dark Matter?

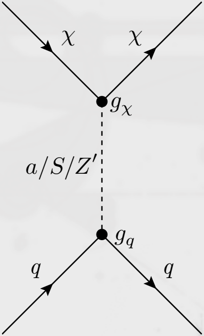
- PeV events are due to relativistic dark matter particles (χ) produced from late time decay of another heavier dark matter species ϕ ($\phi \rightarrow \chi\bar{\chi}$).

- $\Rightarrow$ A minimal Dark Sector which consists of :

  1) A co-moving, non-relativistic real scalar dark matter species ϕ with mass m_ϕ which decays with a life-time τ_ϕ.

  2) A much lighter fermionic dark matter species χ with mass m_χ which is produced from the decay of the heavier species ϕ.

- The χ interacts with the ice nucleus via a BSM mediator.



- Highly energetic χ $\Rightarrow$ Deep Inelastic Scattering.
- Define : $G_q \equiv g_\chi \times g_q$ = product of couplings.

- For definiteness let us take the Pseudoscalar mediator :

$$\frac{d^2\sigma}{dxdy} = \sum_q \frac{1}{32\pi} \frac{E_\chi}{xM_N(E_\chi^2 - m_\chi^2)} \frac{G_q^2\,(Q^2)^2}{(Q^2+m_a^2)^2} f_q(x,Q^2)$$

- Define inelasticity parameter y :

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

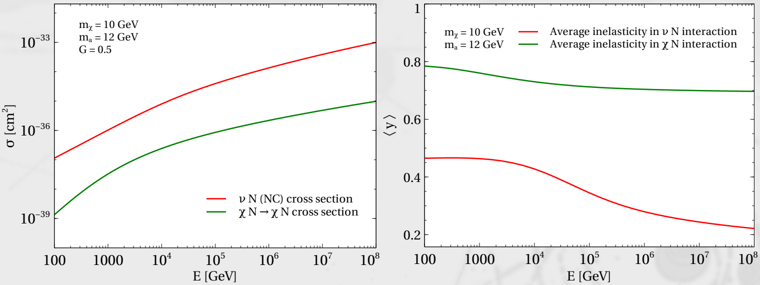
- $Q^2 = 2xyM_N E_\chi$.

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

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

- Using the above, and CT10 PDFs we find $\sigma(E_{Lab})$ and $\langle y(E_{Lab})\rangle$.

  G is arbitrarily fixed at 0.5. Note however $\langle y(E_{Lab})\rangle$ does not depend on G.



- We find that around the PeV energy scale $\langle y \rangle \simeq 0.7$.

- $E_{\rm dep} \sim 1.1$ PeV $\Rightarrow$ an incident energy of 1.57 PeV and which in turn gives $m_\phi \simeq 3.14$ PeV.

Regarding PeV Event rates ...

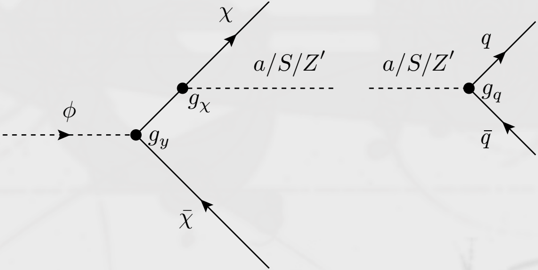
- Cross-section $\times$ flux $\Rightarrow$ number of PeV events.

- Flux $\sim f_\phi/\tau_\phi$ and cross-section $\sim G_q^2$

- Hence, PeV event rate $\sim (G_q^2 \times f_\phi)/\tau_\phi$.

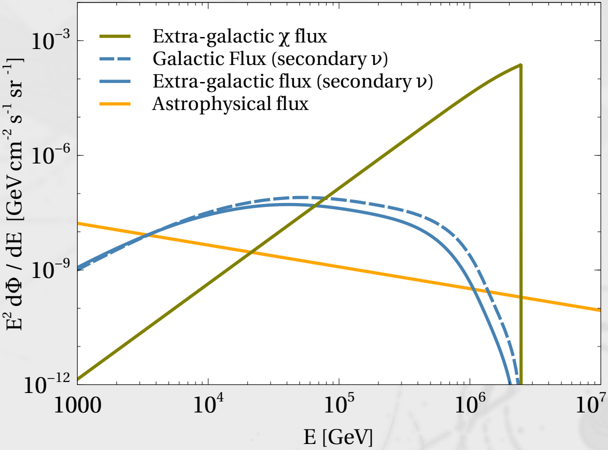
Sub-PeV events

- Let us look at the following three body decay :



- Quarks hadronize further to give a neutrino spectrum $\Rightarrow$ source of the sub-PeV (neutrino) excess.
- Differential Flux of χ or ν particles $\equiv d\Phi/dE$ has both galactic and extra-galactic contributions.

- **Different Fluxes in action :**



Regarding sub-PeV events ...

- ν-cross-section $\times$ flux $\Rightarrow$ number of sub-PeV events.
- flux $\sim$ 3-Body branching ratio$\times f_\phi/\tau_\phi \sim (g_\chi^2 f_\phi)/\tau_\phi$
- Hence, sub-PeV event rate $\sim (g_\chi^2 f_\phi)/\tau_\phi$

  $\Rightarrow$ Fitting the sub-PeV events along with the PeV ones fixes g_q uniquely.
- Set of parameters we are interested in our analysis thus turns to be :

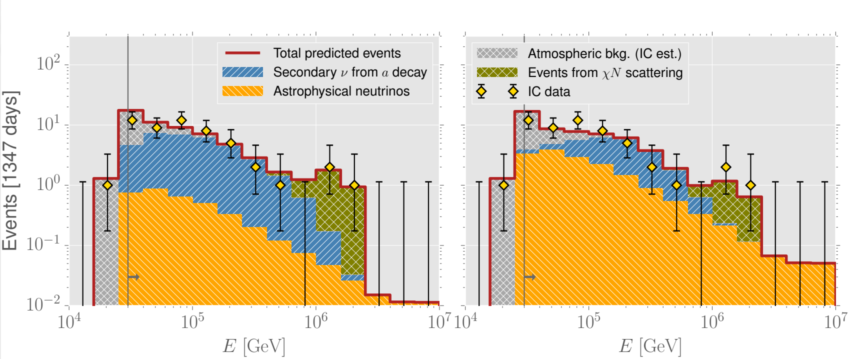
$$m_\phi,\, m_a,\, (G_q^2 f_\phi)/\tau_\phi,\, (g_\chi^2 f_\phi)/\tau_\phi,\, \tilde{N}_{ast},\, \gamma.$$

$\Rightarrow$ m_ϕ is fixed around $\mathscr{O}$(PeV), all others are varied (randomly).

Results

- **Best fit values :**

Parameter	m_a [GeV]	g_q	$f_\phi g_\chi^2/\tau_\phi$ [s^{-1}]	γ	$\tilde{N}_{ast}$ (all flavour)
$a \to b\bar{b}$	12.0	0.32	1.23×10^{-26}	2.57	1.21×10^{-9}
$a \to c\bar{c}$	5.3	0.50	5.02×10^{-27}	2.61	5.40×10^{-9}



Summary and conclusions

- We have managed to explain both the PeV and the sub-PeV events under a single phenomenological scheme.
- Although is g_q is known exactly but we only have information on $(f_\phi\, g_\chi)^2/\tau_\phi \equiv R_1$ (say).
- However, with $\tau_\phi \geq t_{\rm universe}$ and $0 \leq f_\phi \leq 1$, $g_\chi^2 \geq t_{\rm universe} \times R_1$.
- For our benchmarks, this translates to $g_\chi \geq 10^{-5}$.

THANK YOU