Direct Detection of Dark Matter and IceCubed

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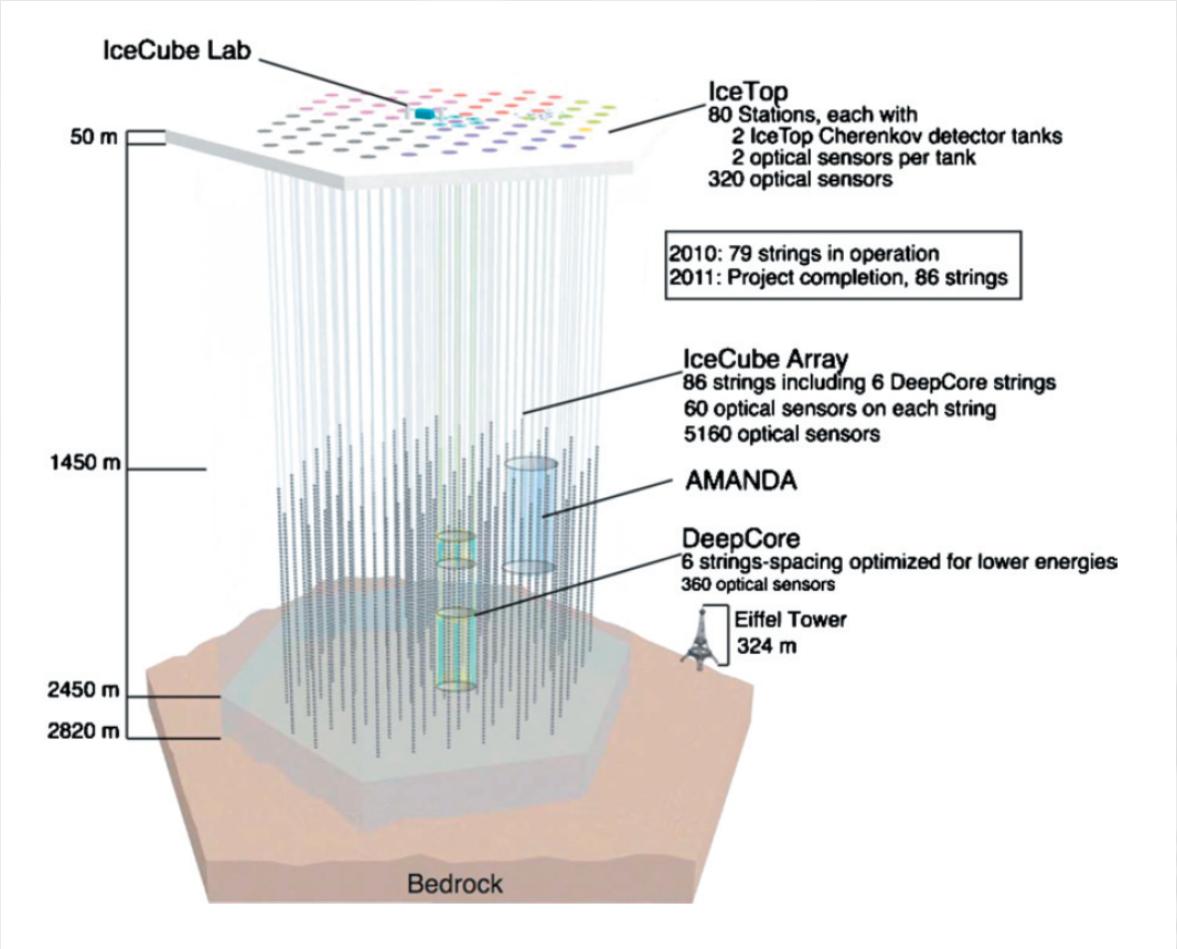
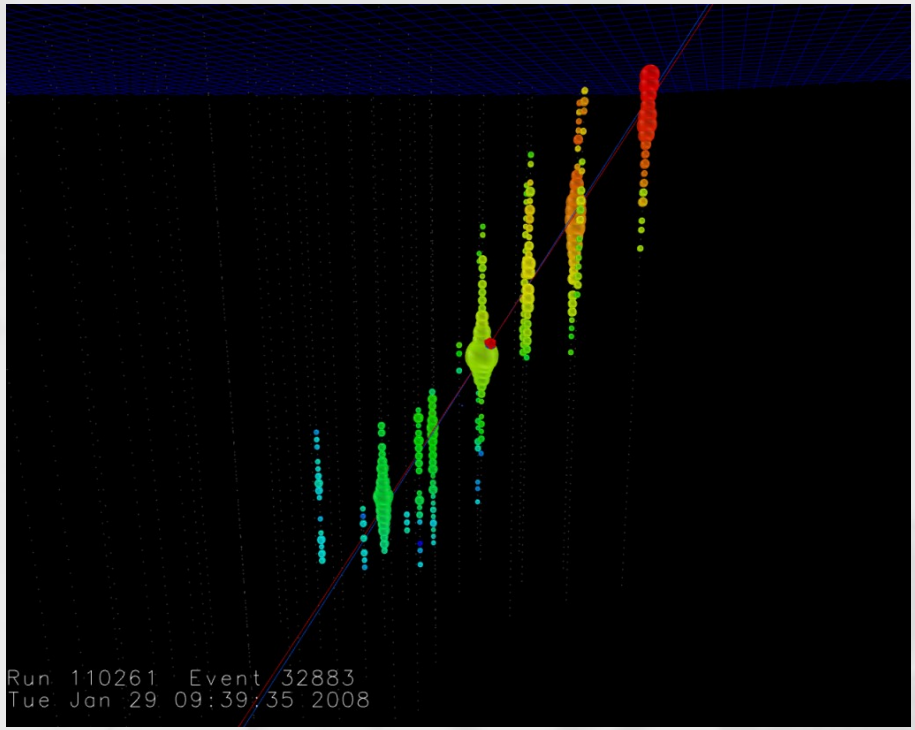
The IceCube Neutrino Detector and what it detects

- `IceCube : The Largest neutrino detector in the world.`

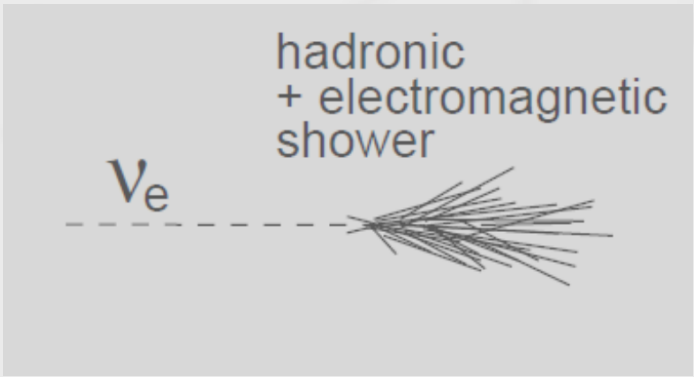


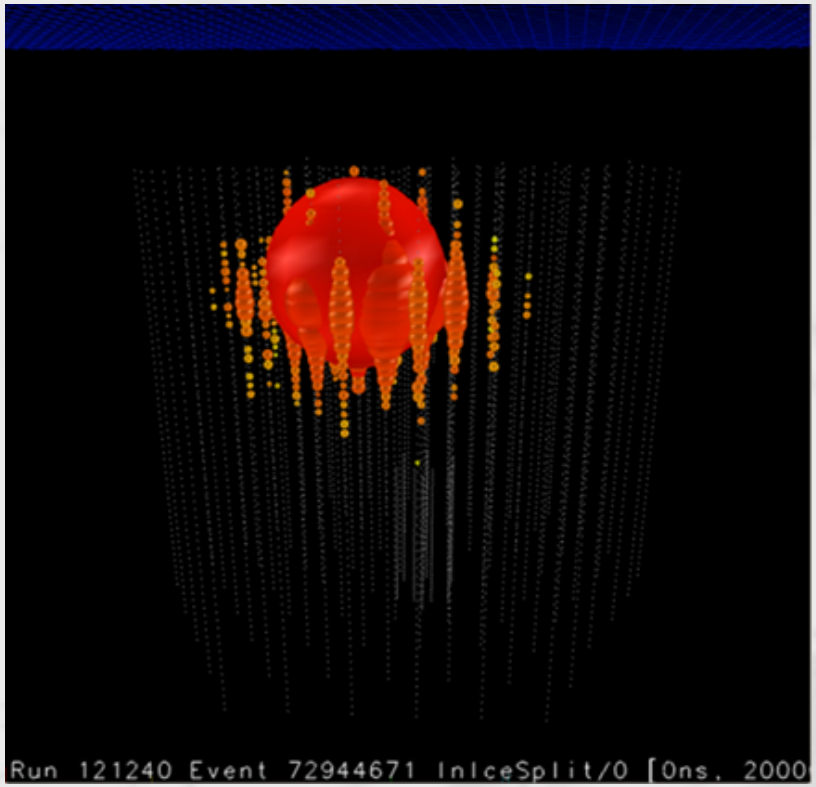
- Muons (produced from ν_μ interactions), are highly penepenetrating $\Rightarrow$ long *tracks* in the detector.
  (Track length $\sim$ 1 Km at TeV energies.)



Event Topologies

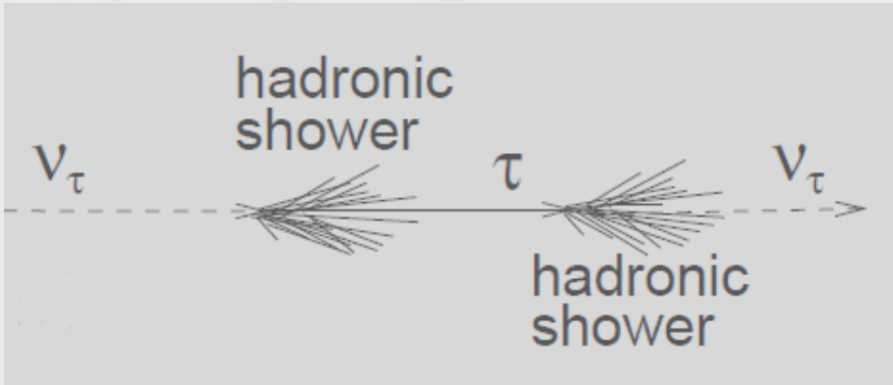
- e^- resulting from a ν_e event loses energy much faster. Hence these events are more spherical, or *cascade*-like.
  (A few meters in diameter.)





- τ (produced from ν_τ) can also create track events but decays quickly before travelling far (50m at PeV energies) $\Rightarrow$ usually indistinguishable from electron cascades.

- τ-event could be distinguished from an e^- with a *double bang* event.



To summarize...

- In IceCube :

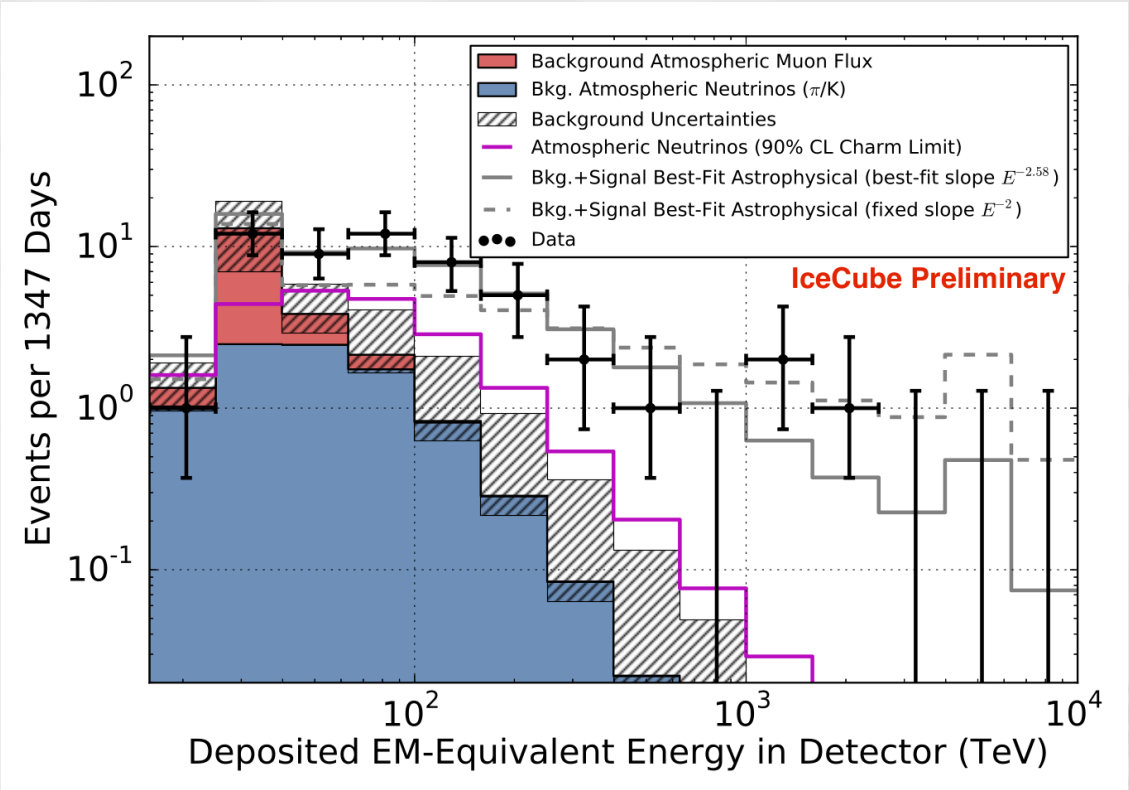
  Track $\rightarrow$ ν_μ CC and a subset of ν_τ CC interactions.

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

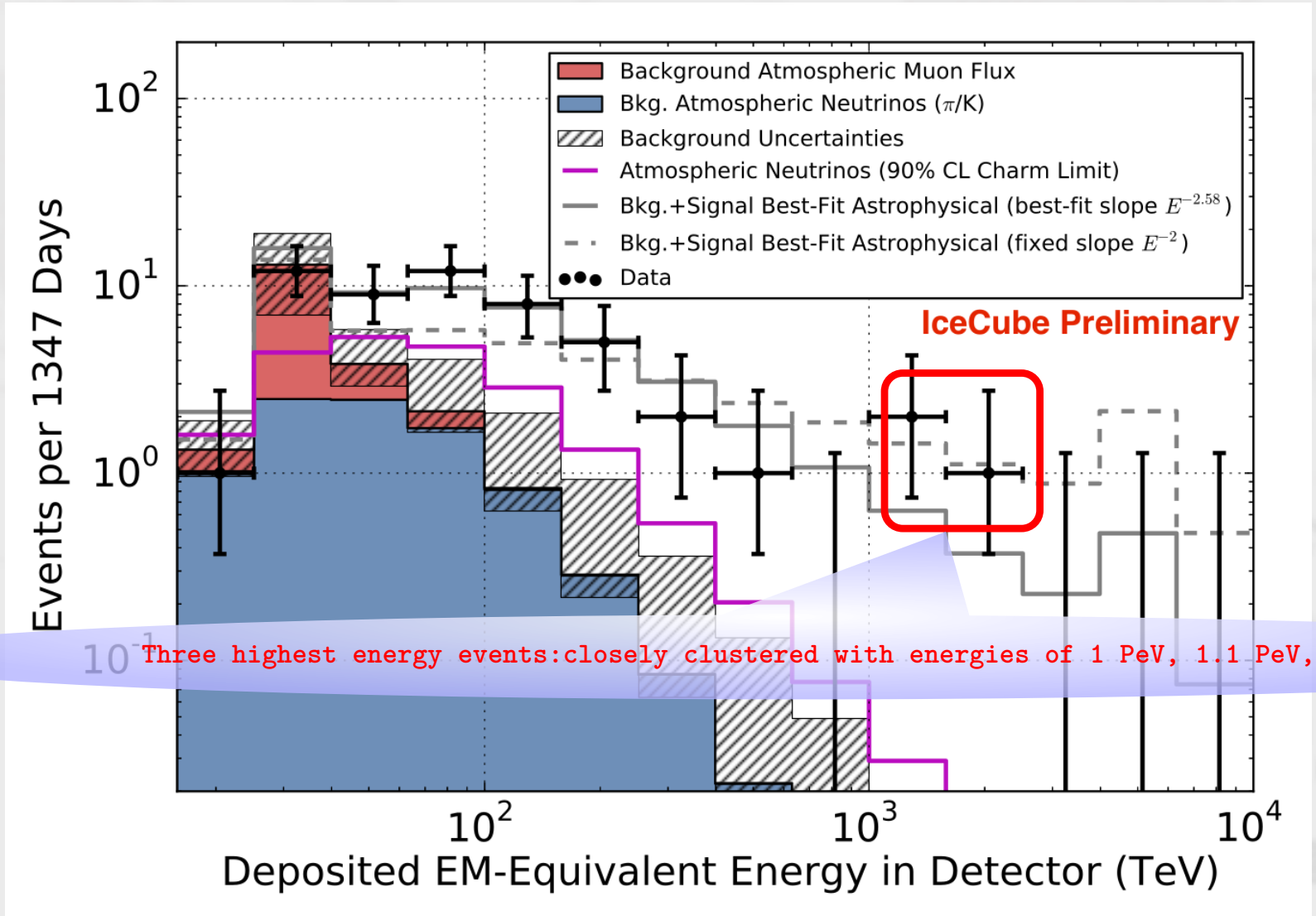
- IceCube measures the **deposited energy** i.e. $E_{\text{final}} - E_{\text{initial}}$.

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

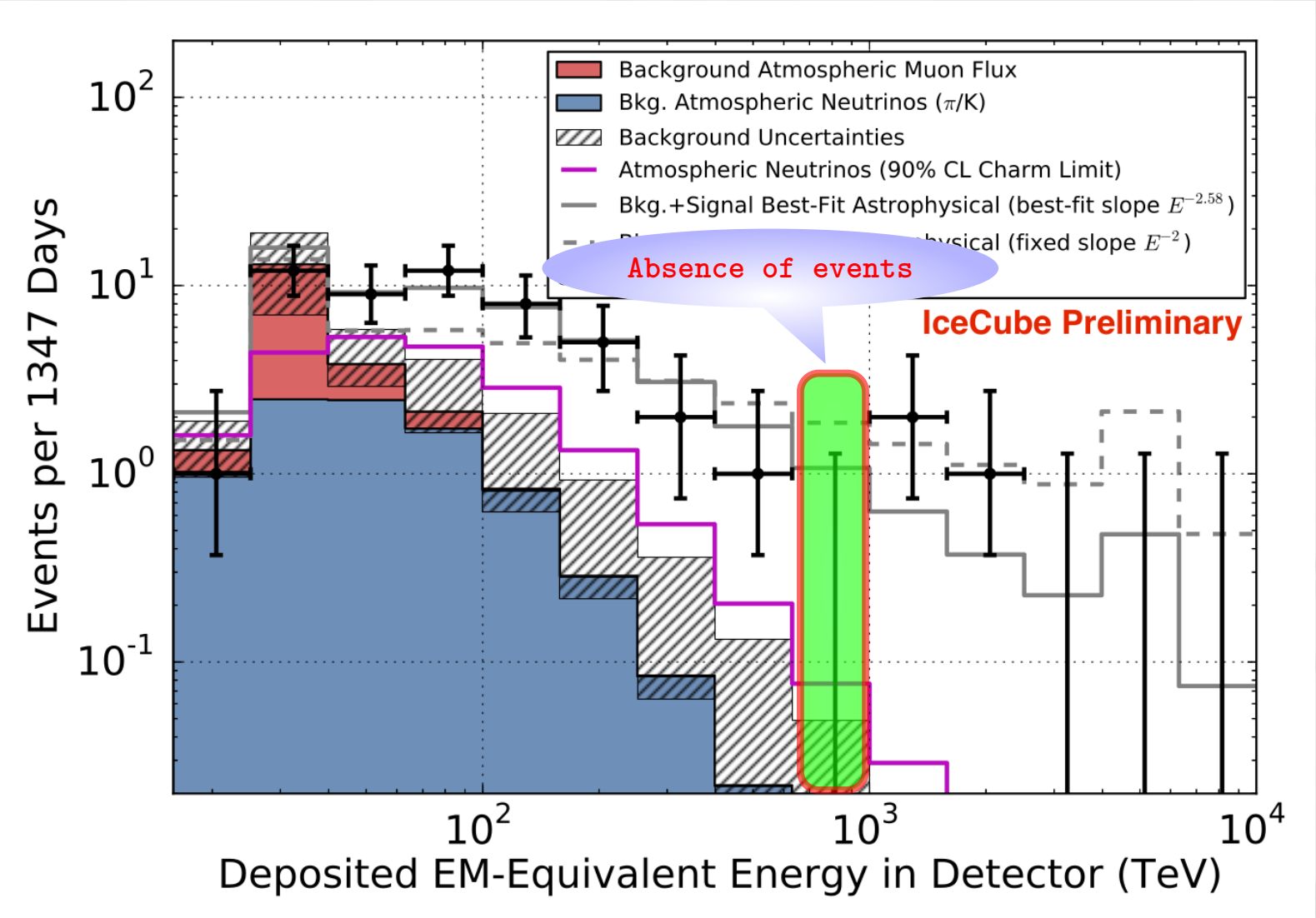
- 1347 days of data reveals 54 events (15 tracks and 39 cascades) with energies between 30 TeV and 3 PeV.



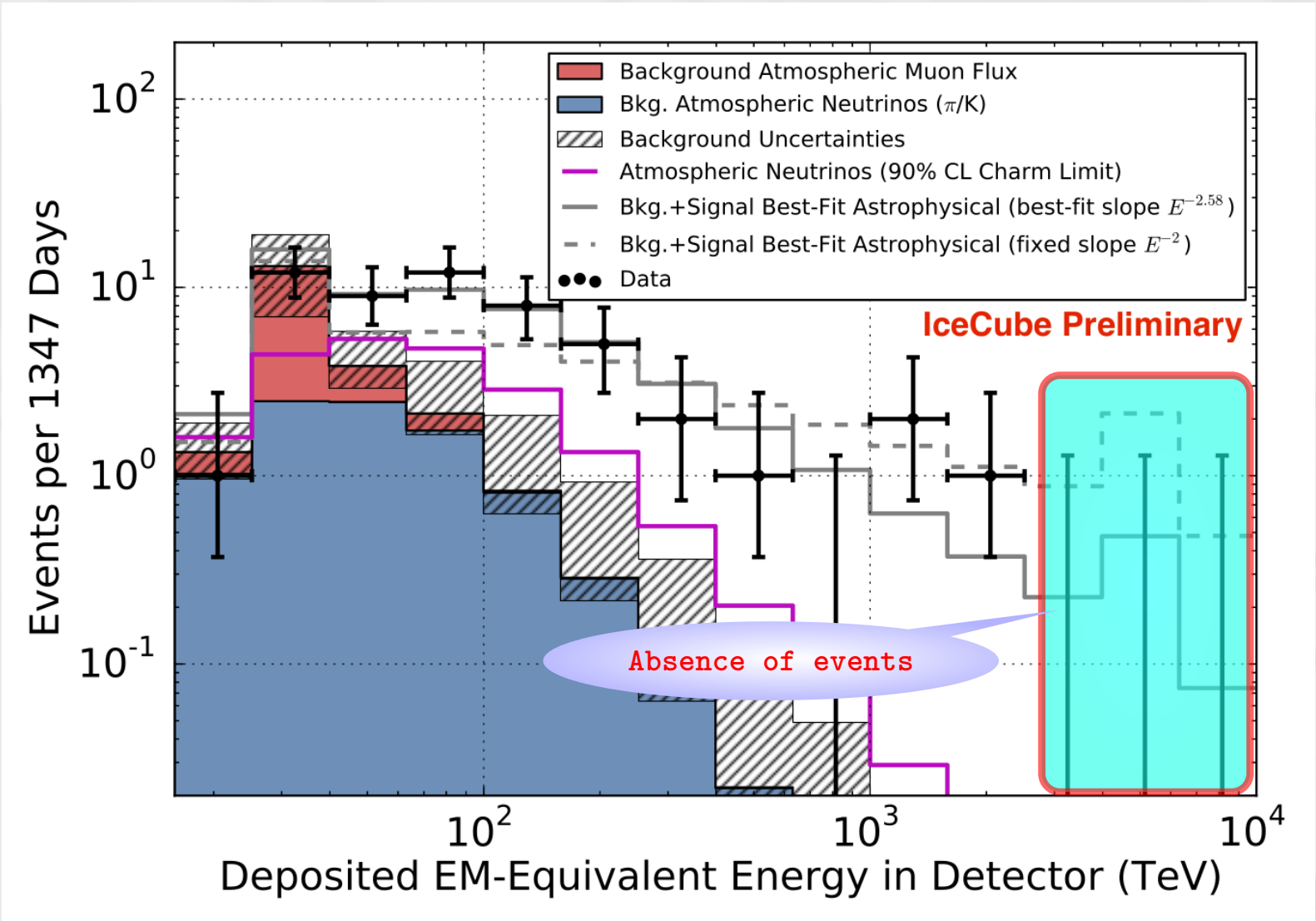
- The three highest energy events are **closely clustered**.



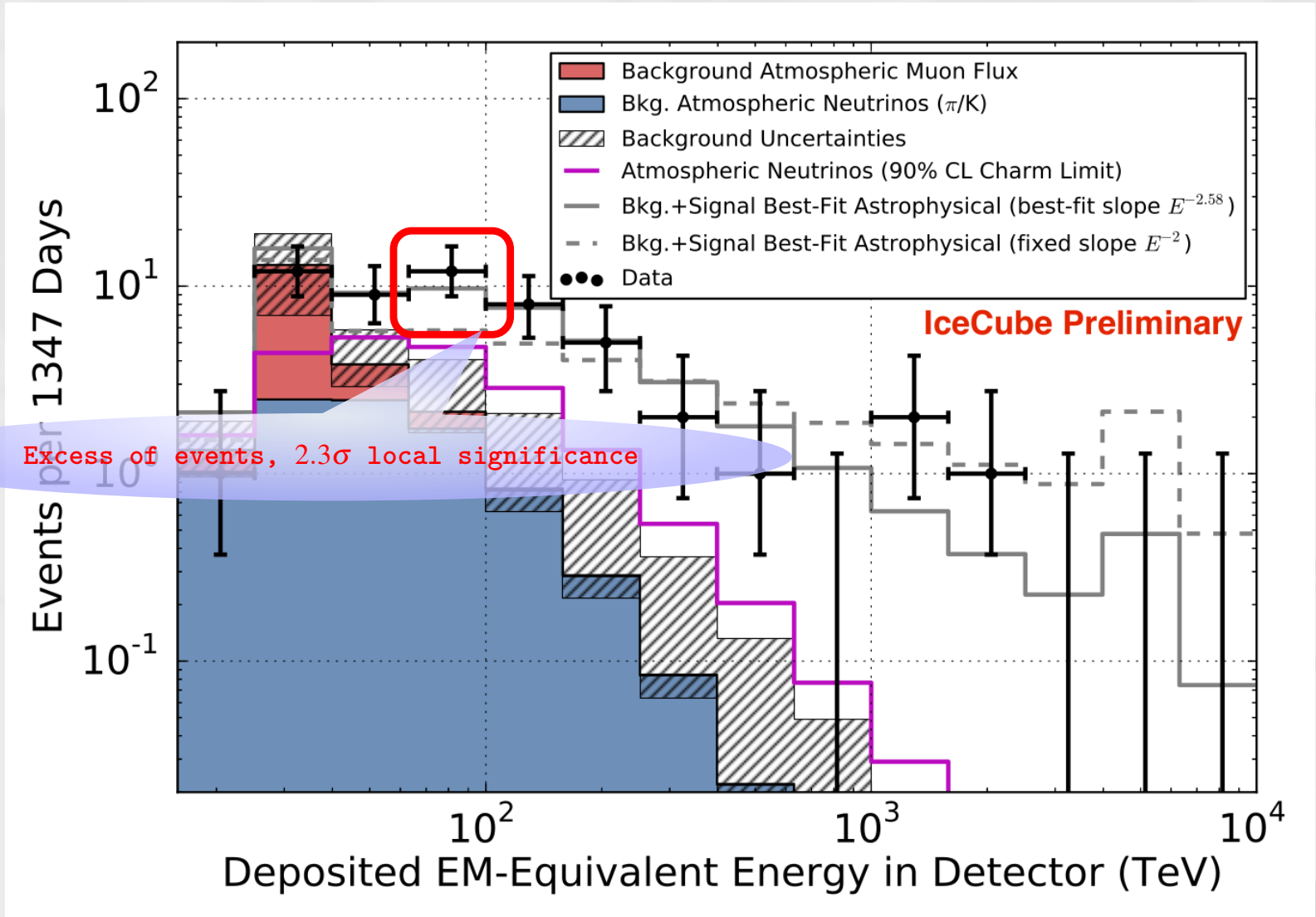
- **No events** between 400 TeV and 1 PeV.



- **No events** beyond 2 PeV.

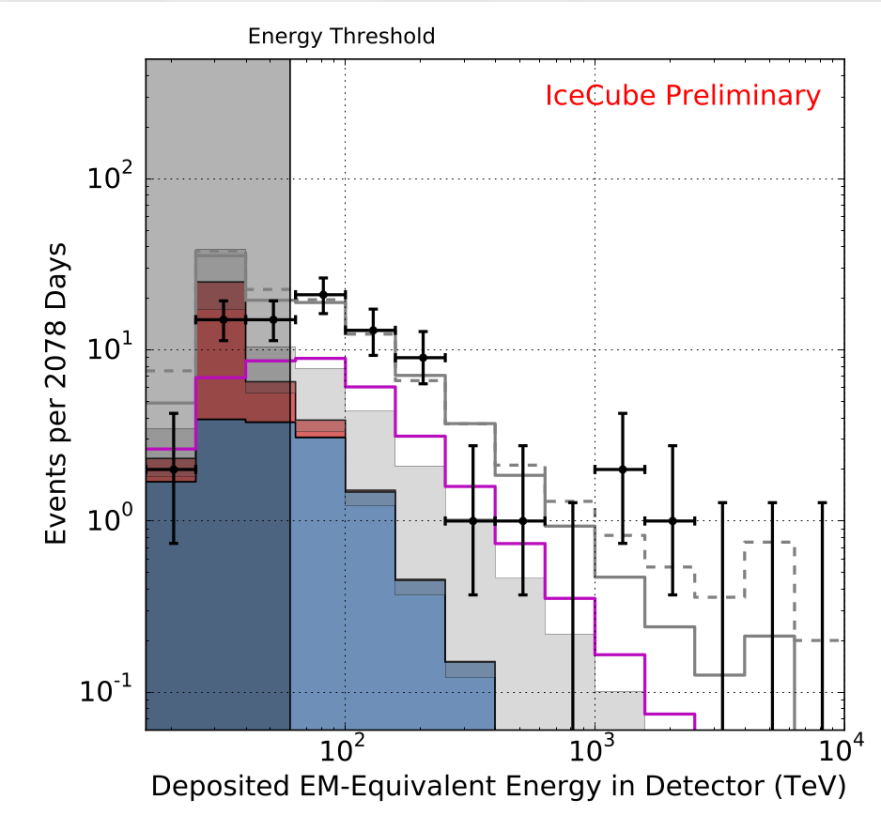


- **Excess** around 100 TeV.



Latest Results (2078 days)

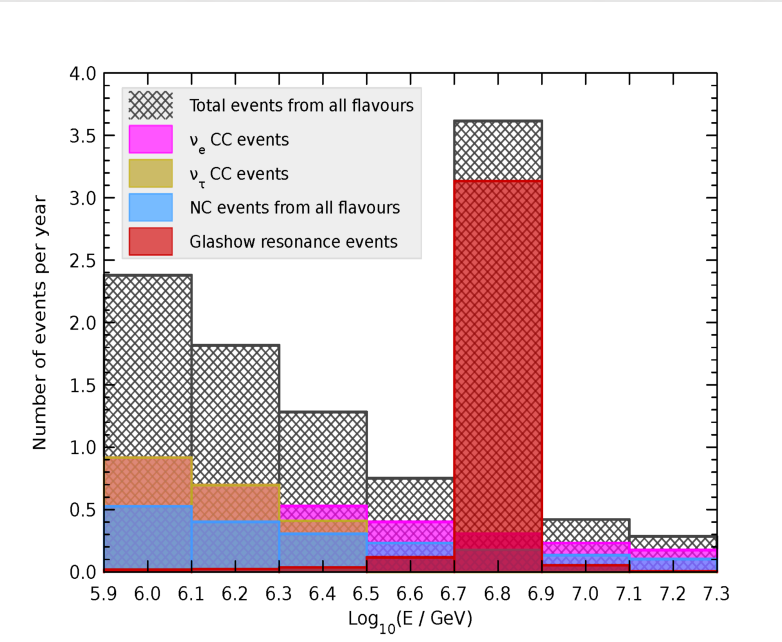
- 27 more events (energies around 200 TeV), 19 cascades and 8 tracks.
- Spectral index increased to 2.92 from the previous 2.58.

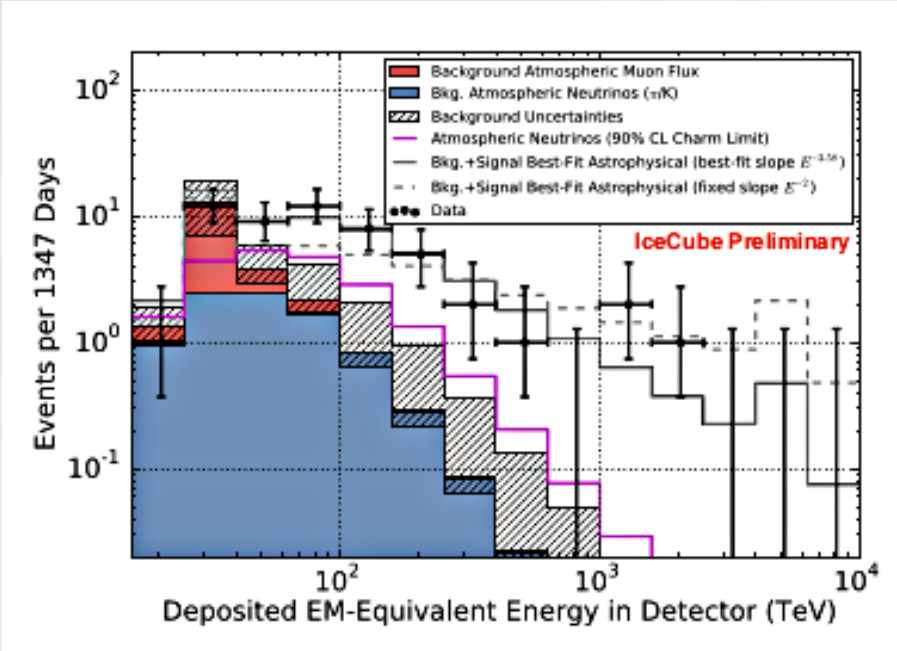


Are they *all* neutrinos ?

- A purely *atmospheric* explanation of these events is strongly disfavoured (at 6.7σ level).
- Explanation in terms of neutrinos from AGN and GRB's.
- Others interpret these high energy events as neutrinos coming from Dark Matter decay or annihilation (Esmaili and Serpico, JCAP 1311 (2013) 054).
- But ...

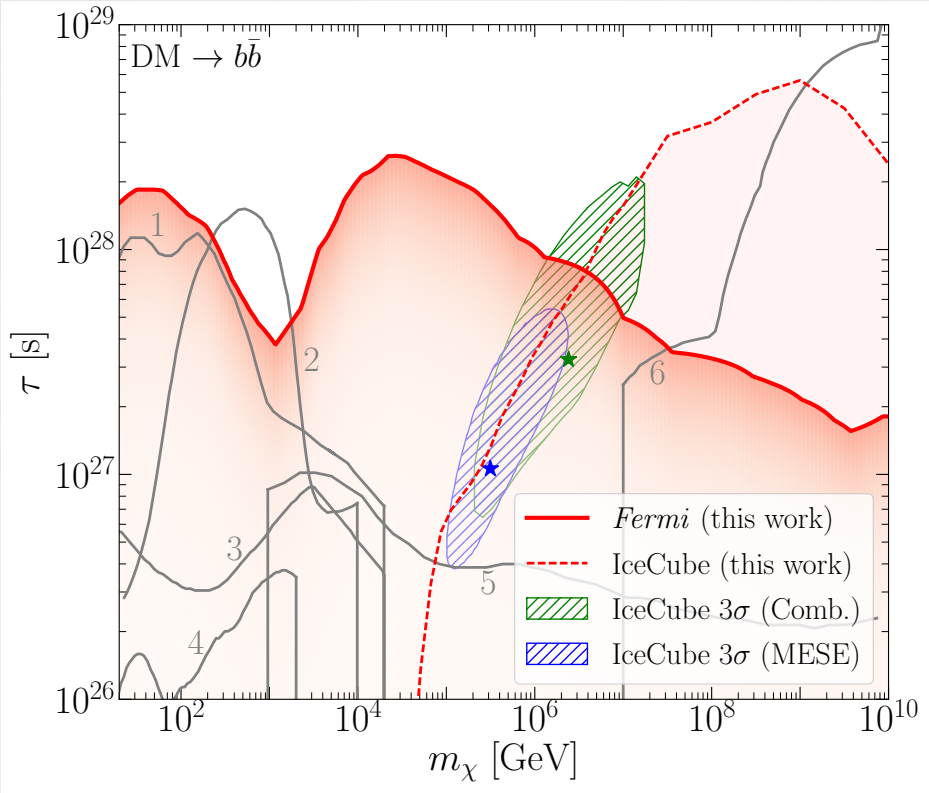
- No events corresponding to Glashow Resonance till now ...





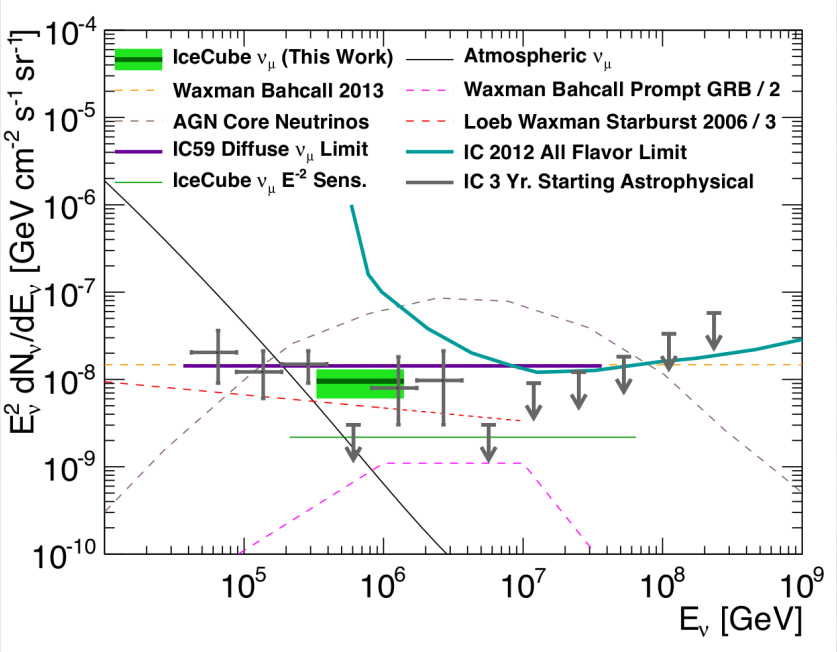
R. Gandhi, A. Bhattacharya et. al, arXiv:1108.3163

- **Constraints from diffuse γ-ray flux ...**



Murase et. al, Phys. Rev. Lett. 119, 021102 (2017)

- Closeness to Waxman-Bahcall bound ...

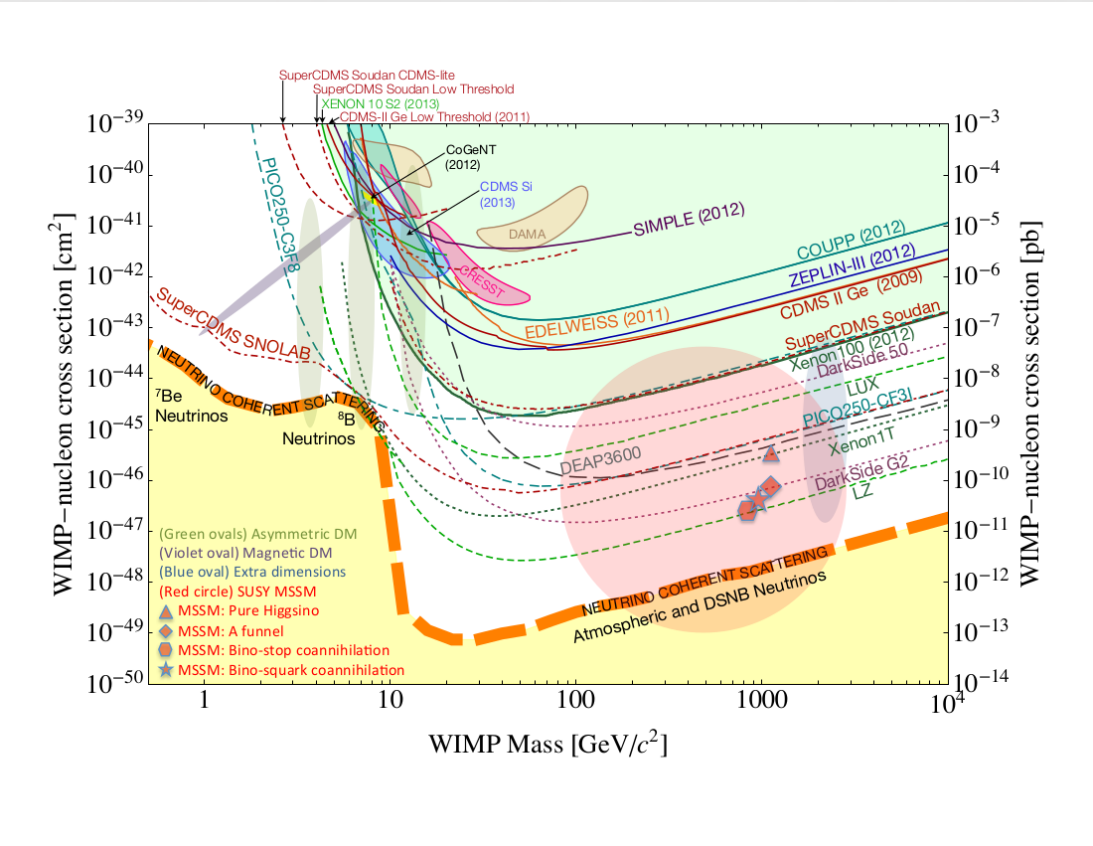


- Applicable to neutrinos produced from AGN and GRB's (p-p / p-γ interaction).

Waxman & Bahcall, Phys.Rev.D59:023002,1999

Neutrino Dark matter analog

- At lower energies we know that dark matter can *mimic* the neutrino signal.



PeV events : Direct detection of Dark Matter?

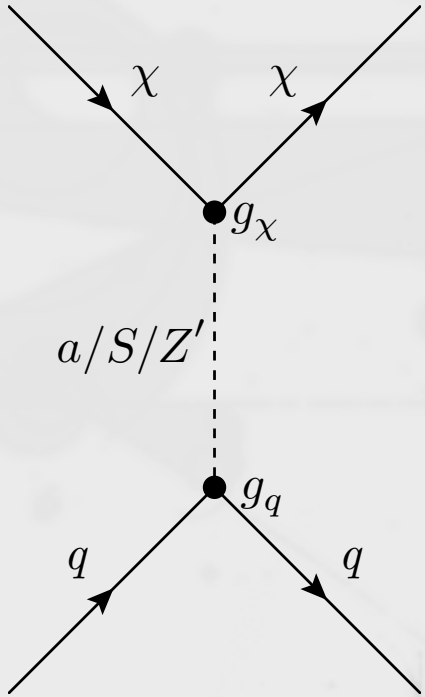
- PeV events are due to relativistic dark matter particles (χ) produced from late time decay of another heavier dark matter species ϕ ($\phi \to \chi\bar{\chi}$).

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

- For definiteness let us take the Pseudoscalar mediator :

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

- Define inelasticity parameter y :

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

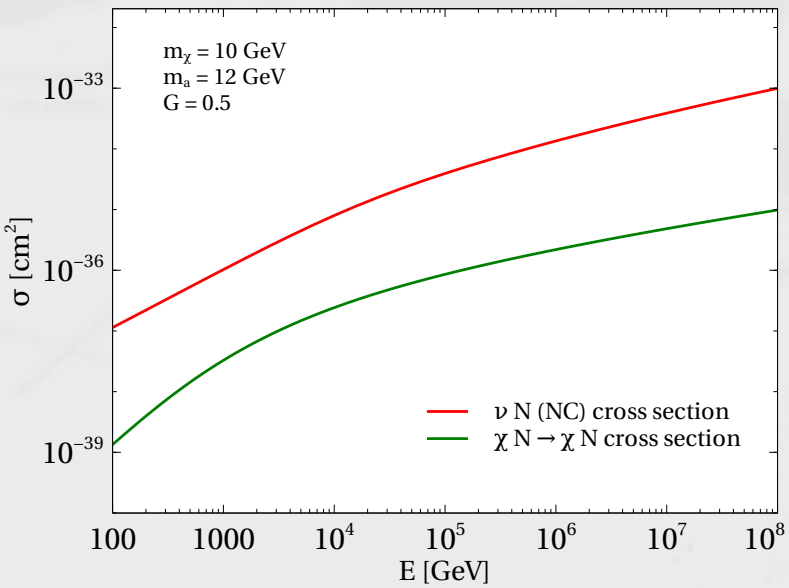
- $Q^2 = 2xyM_N E_\chi$.

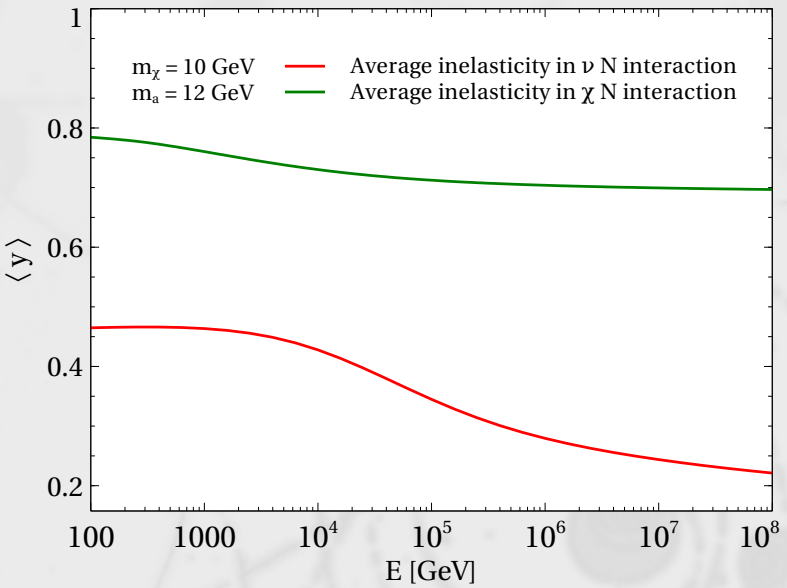
- An useful quantity to calculate is the mean inelasticity parameter :

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

- 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 ...

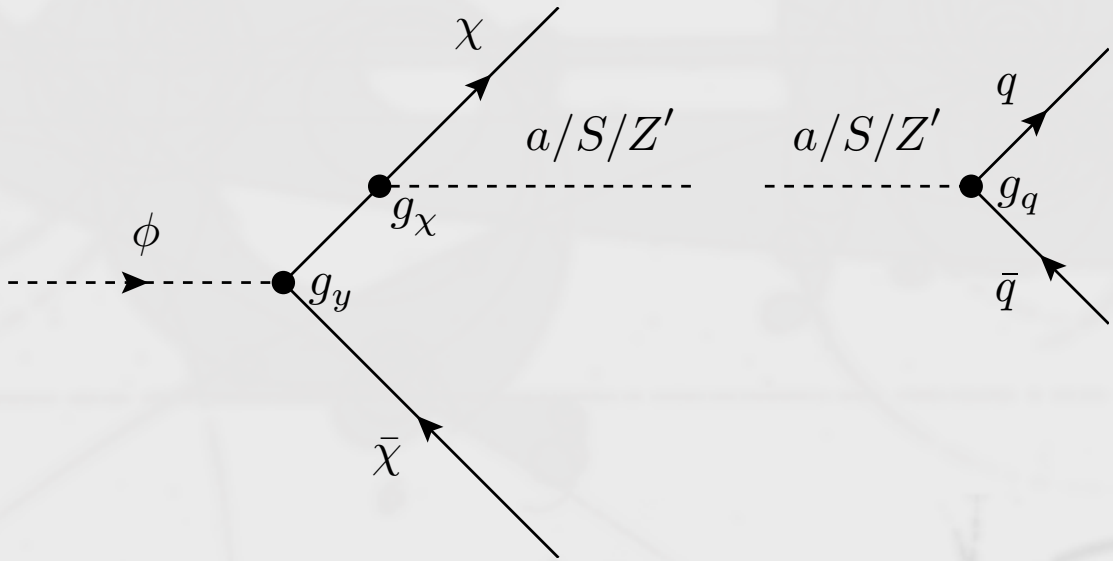
- Cross-section $\times$ flux $\Rightarrow$ number of PeV events.

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

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

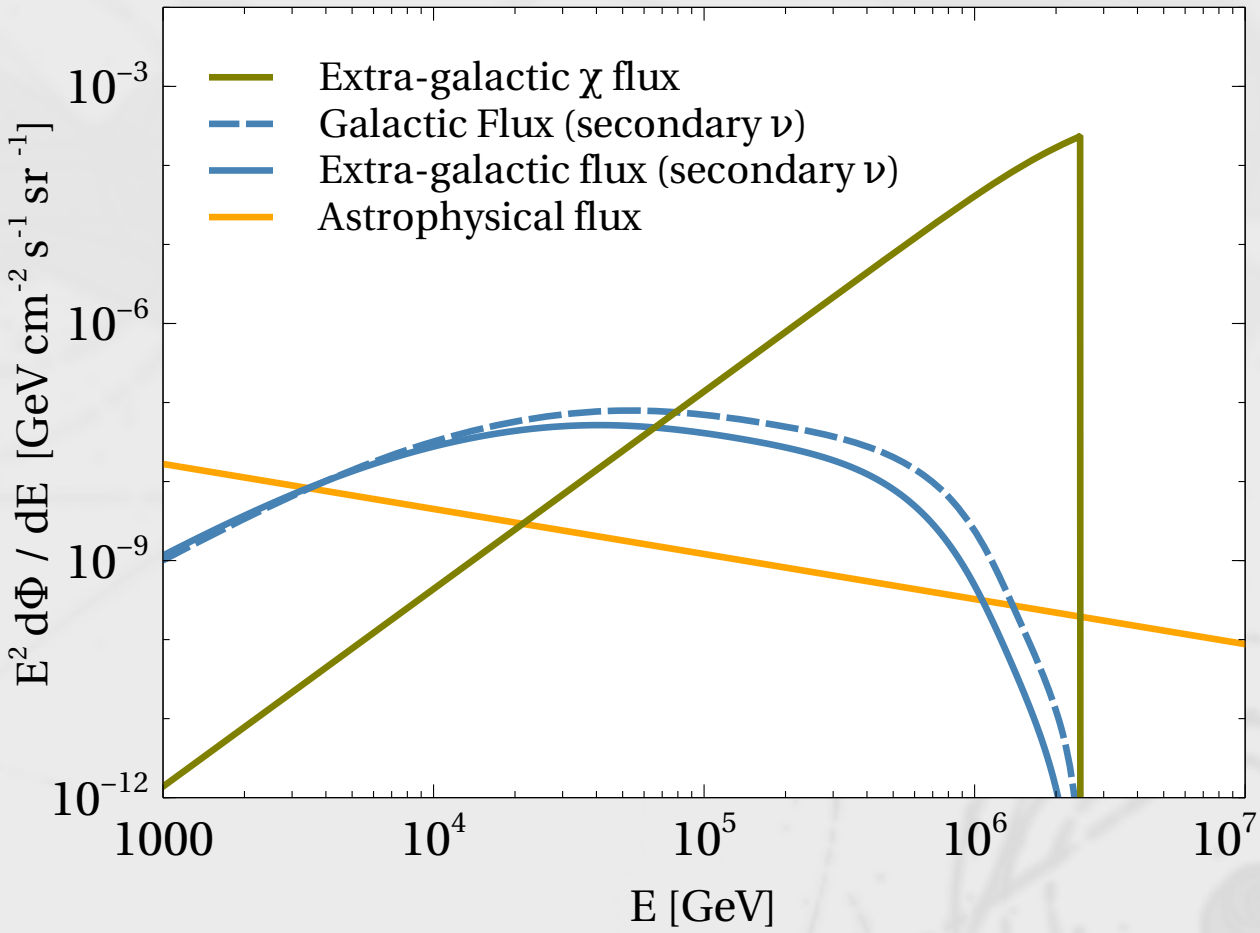
Sub-PeV events

- 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 :**



- **Astrophysical ν Flux** $\sim \tilde{N}_{ast}\, E^{-\gamma}$

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 :

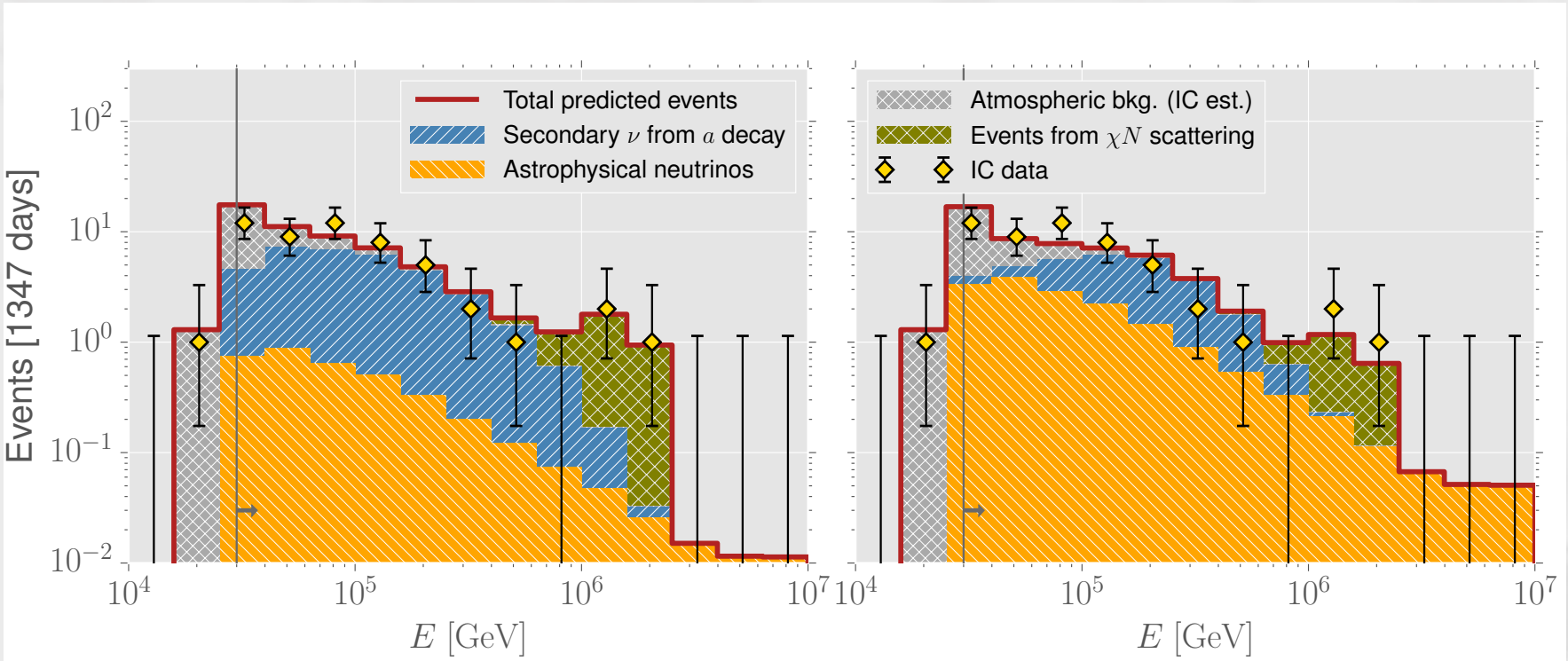
$$m_\phi,\ m_a,\ (G_q^2 f_\phi)/\tau_\phi,\ (g_\chi^2 f_\phi)/\tau_\phi,\ \tilde{N}_{ast},\ \gamma.$$

$\Rightarrow$ m_ϕ is fixed around $\mathcal{O}$(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}



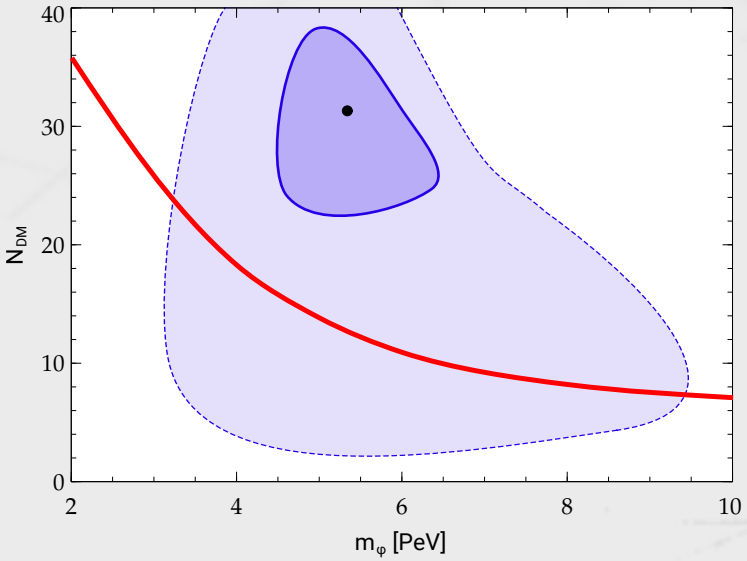
Points to note ...

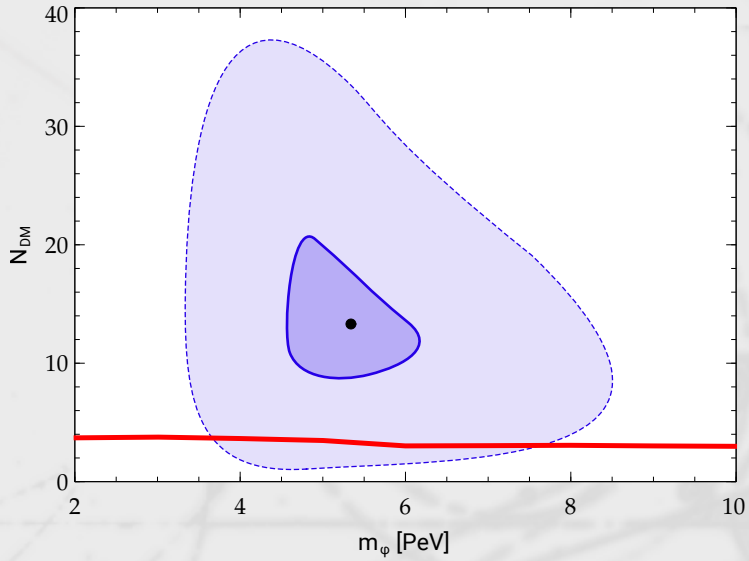
- Both the PeV and the sub-PeV events (along with their different *features*) can be explained under a single phenomenological scheme.
- g_q is known exactly but we only have information on $f_\phi \, (g_\chi)^2 / \tau_\phi \equiv R_1$ (say).
- However, with $\tau_\phi \geq t_{\text{universe}}$ and $0 \leq f_\phi \leq 1$, $g_\chi^2 \geq t_{\text{universe}} \times R_1$.
- For our benchmarks, this translates to $g_\chi \geq 10^{-5}$.
- This scenario is however tightly constrained by diffuse gamma ray bounds.

Gamma-ray constraints

- The 3-body decay that gave rise to the neutrino flux $\Rightarrow$ gives rise to diffuse γ-ray flux as well.

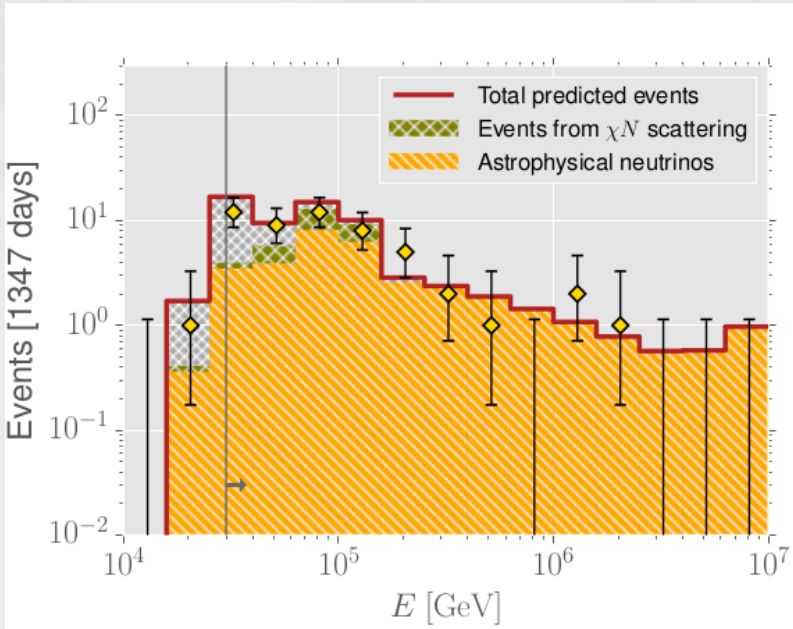
- The controlling factor is already fixed $(R_1 = f_\phi \, (g_\chi)^2 / \tau_\phi)$.





Need for a new scenario ...

- Let us not *assume* that $\phi \to \bar{\chi}\chi$ is restricted to explain only the PeV events.
- Hence, m_ϕ is no more constrained to PeV range.



- Controlling parameter is only $f_\phi \, (g_q \, g_\chi)^2 / \tau_\phi \equiv R_2$(say) [no R_1!!].

- No dependence on $R_1 \Rightarrow$ Unconstrained from diffuse gamma ray flux (however, we can put upper limit).

- We have :

$$R_1 \leqslant 5.2 \times 10^{-27}\, s^{-1} \qquad \text{for the pseudo-scalar case}$$

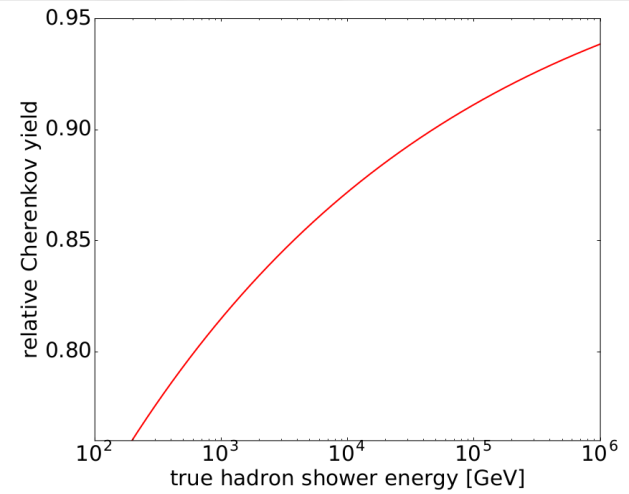
- The best fit values turn out to be :

Parameter	m_a [GeV]	m_ϕ [TeV]	$R_2\,[\mathrm{s}^{-1}]$	γ
Pseudoscalar	16.1	680	1.15×10^{-27}	2.31

Smoking Gun signatures

- According to IceCube collaboration, our scenario can be verified if it is possible to distinguish between the hadronic and electromagnetic showers
  $\Rightarrow$ we expect no electromagnetic showers.

- IC expects to do so by comparing the Cherenkov light emanating from the two types of shower.



IceCube Collaboration, arXiv:1710.01197

THANK YOU