# Detecting TeV-PeV scale dark matter signatures at the IceCube neutrino detector

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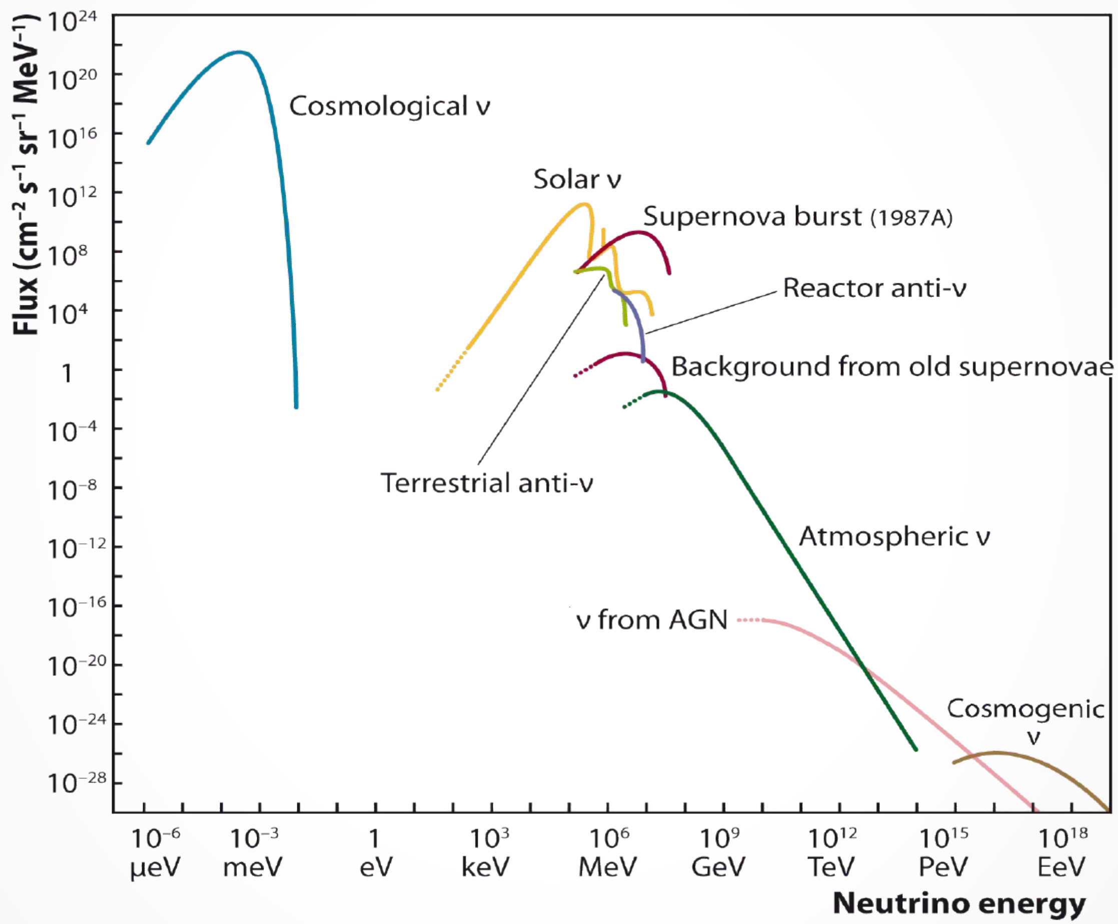
THE UNIVERSITY OF ARIZONA

# Plan

- **U**ltra-**H**igh **E**nergies and the **I**ce**C**ube neutrino detector
  - The IC setup, aims and objectives
  - Recent results at IC
  - Issues with standard explanations
- **D**ark **M**atter decay and neutrinos at IC
- Direct search for heavy DM at IC
- General prospects for heavy DM searches

# The neutrino sky… to the highest energies

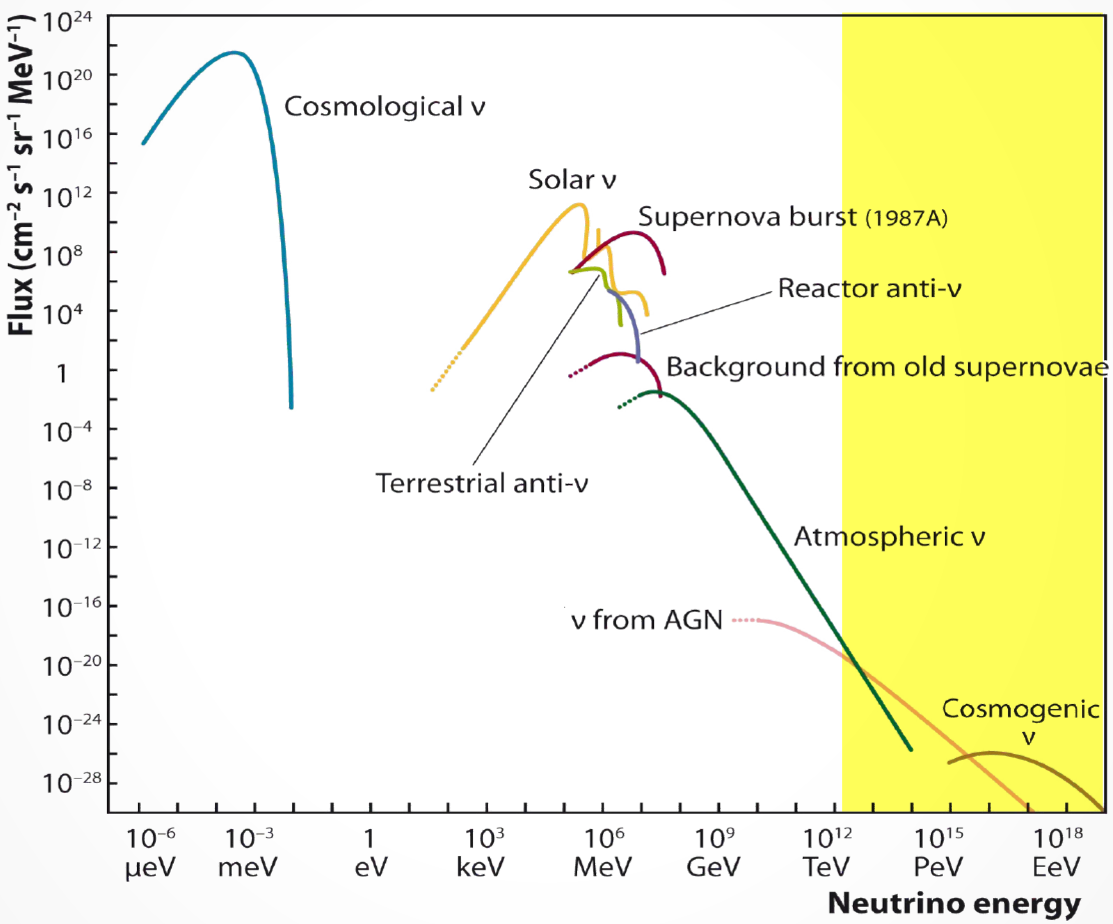


# The neutrino sky… to the highest energies

Probe highest energy neutrino production mechanisms

Existence of tiny non-std physical effects (LV, etc.)

Hunting for astrophysical point objects (AGN, etc.) using neutrinos




Probe neutrino oscillation at highest energies

DM annihilation at the galactic centre

Indirect search for very heavy DM decay

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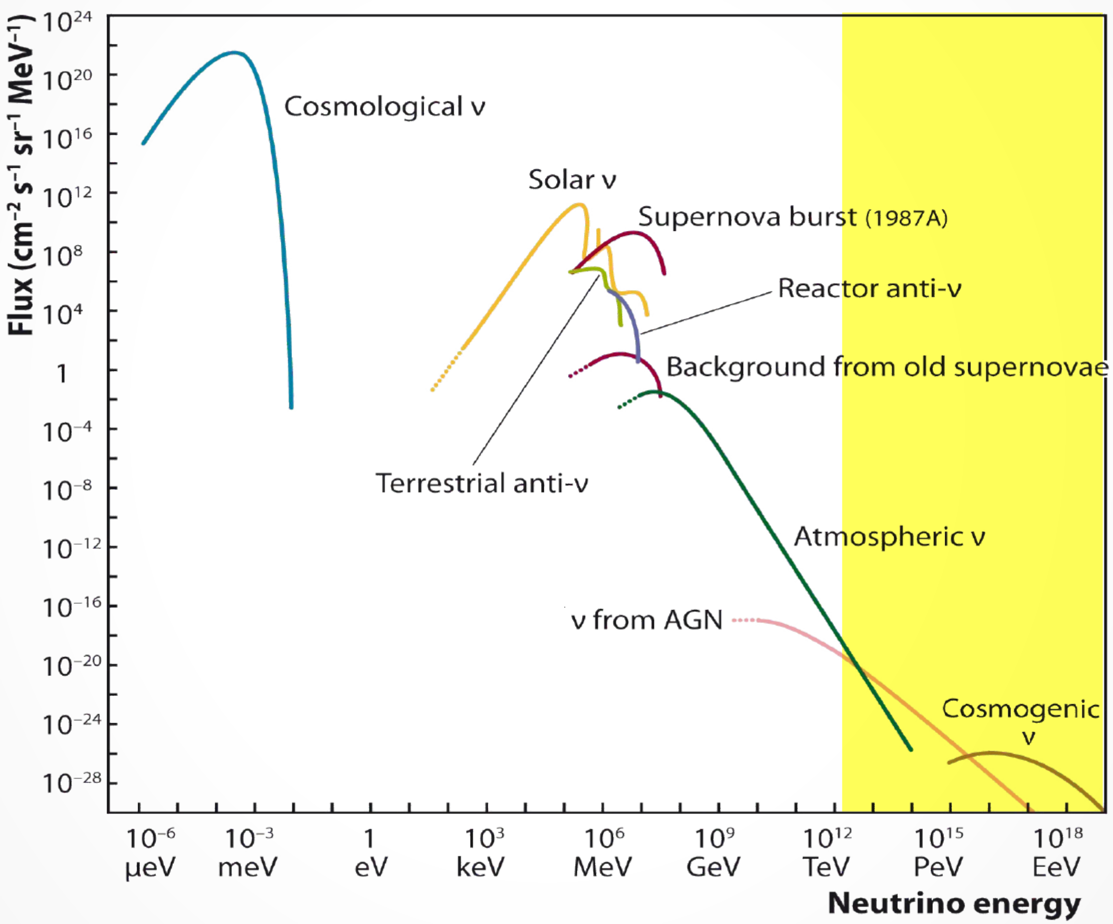


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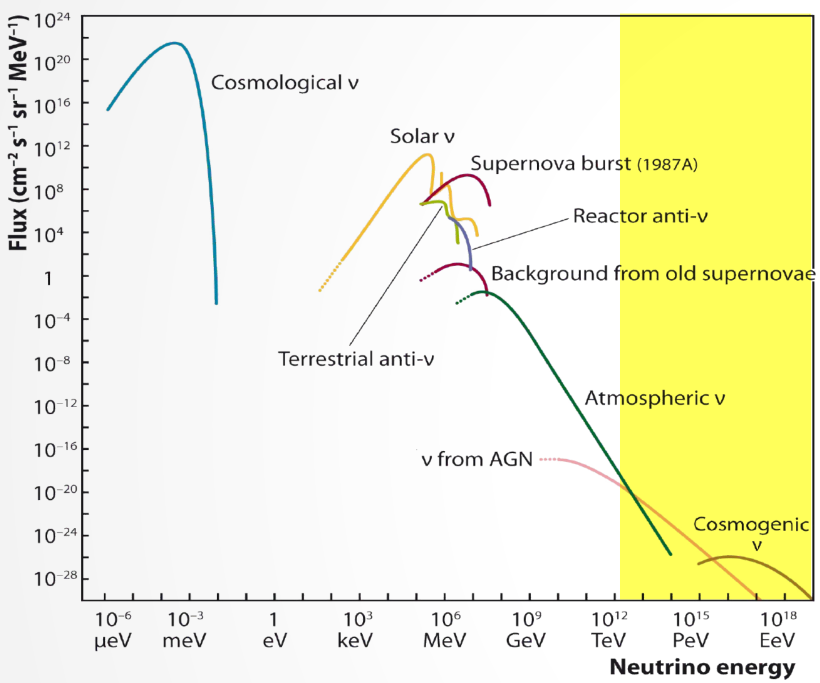
# Neutrinos @ highest energies: HowCatch'em




## Main issues with detection

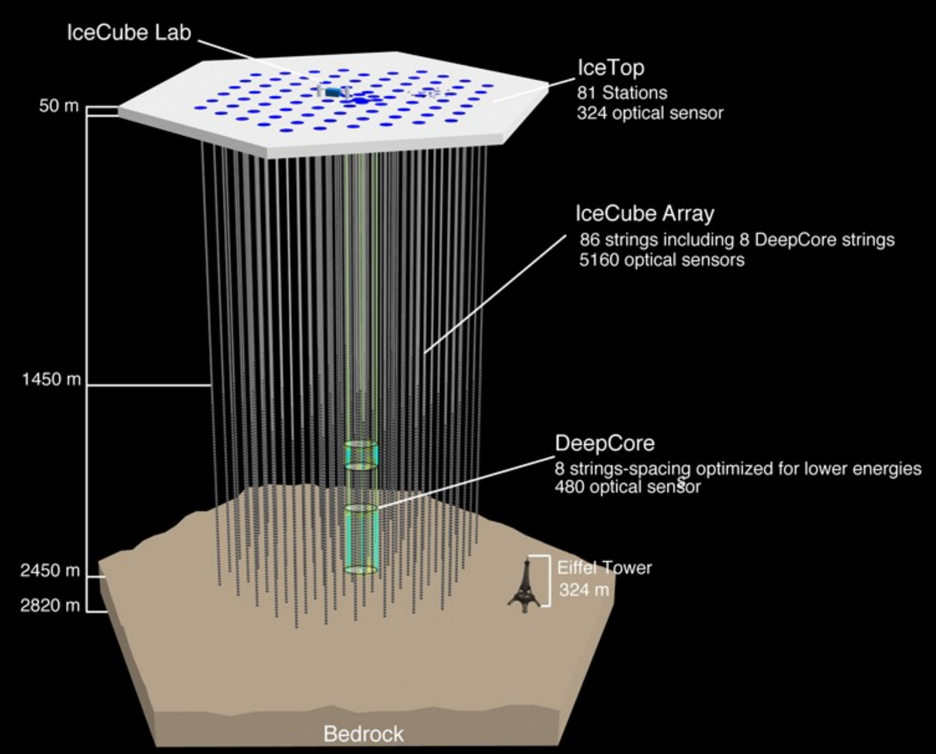
- Extremely low incident fluxes
- Huge incident energies – reconstruction requires voluminous detectors
- Flavour discrimination?

**Solution? Km$^3$ Detectors**

### Km$^3$ detectors

- Trap high fraction of incident neutrino fluxes
- Proper energy and direction (for tracks) reconstruction of large event signature tracks
  - Big enough to contain hadronic/em cascades
  - Possibility of detection of double-bang signatures from incident $\nu_\tau$'s

# Present setup for UHE ν detection



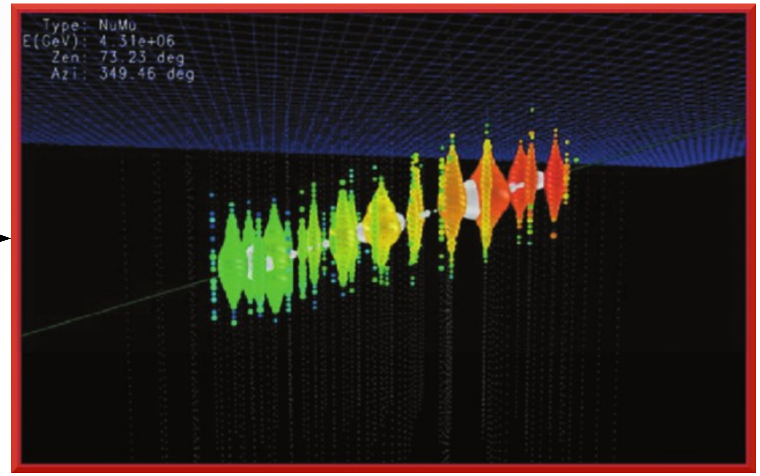

## IceCube

- Operational since 2010
  - Full exposure since Dec. 2011
- Capable of flavour discrimination
  - Limited to detection of three distinct event signatures
- Excellent energy reconstruction
  - < 10% for contained cascades
  - ~ 30% for tracks with contained vertices
- Good direction reconstruction
  - Up to 1° for tracks
  - ~30° for cascades
- Designed to run (minimal op. cost) for 10+ yrs
- **28 UHE events in 662 days of run-time**
  - **2 events at PeV+ energies**
  - **Recently reported 9 more events, making total event number 37 over 988 days**

# Flavour @ IC

## Muon Track

$\nu_\mu N\ CC$

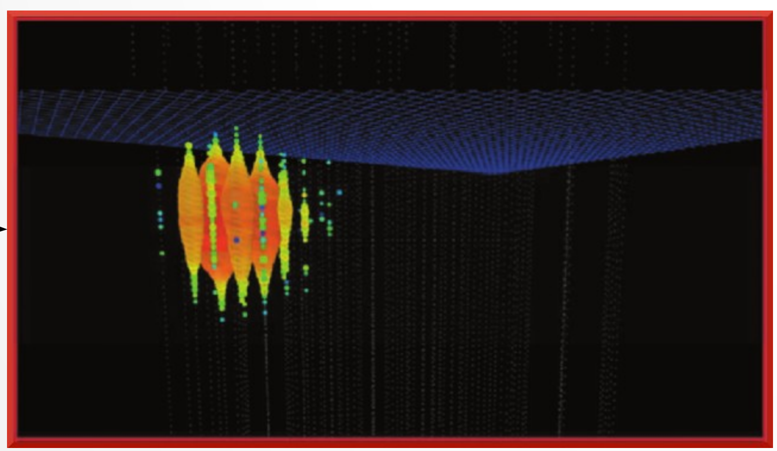



$\nu_{e,\tau} N\ CC$

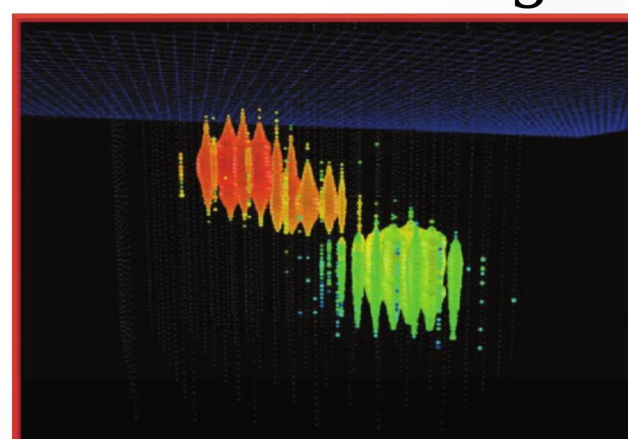
$\nu N\ NC$

$\nu_\tau N\ CC (\gtrsim 1\ \mathrm{PeV})$

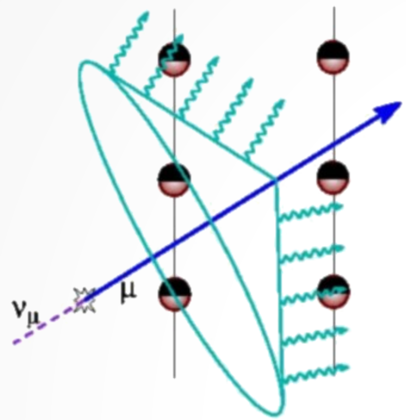
## Cascades

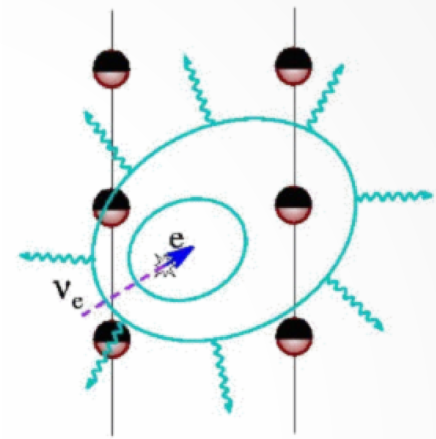


## Double Bang



# Reconstructing events @ IceCube




**Muon Tracks**

Charged current interaction of the muon-neutrino

Clear tracks and excellent direction reconstruction

Energy reconstruction is indirect – energy loss along track

**Cascades**

Charged current interaction of the electron-neutrino and tau-neutrino

Neutral current interactions of all flavours

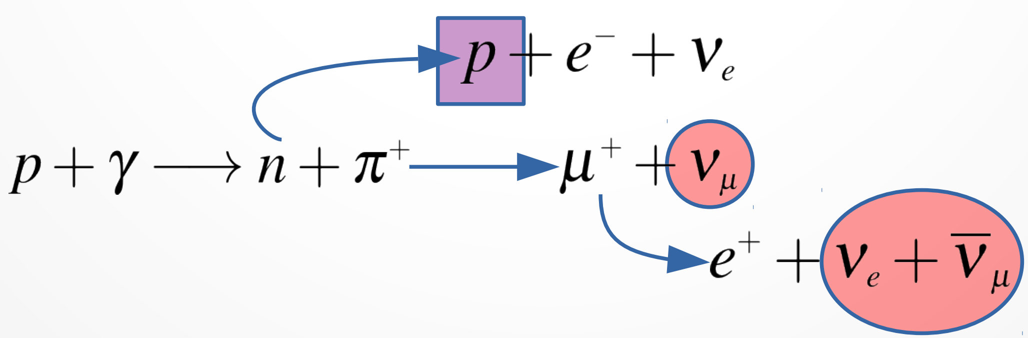
Excellent energy but poorer direction reconstruction

# Incident fluxes from std. theory

- Diffuse flux from all-sky astrophysical sources
  - Expected to follow a power-law spectrum
    - Fermi 1st order shocks → α = 2.0
    - Normalisation fixed by observational best-fits

$$\Phi_\nu \propto E^{-\alpha}$$

  - Neutrinos in sources predominantly from pion decays
    - Std. oscillation → incident flavour 1:1:1 at earth



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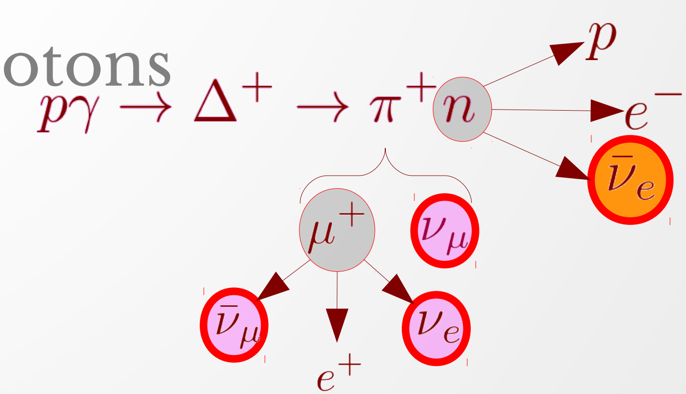
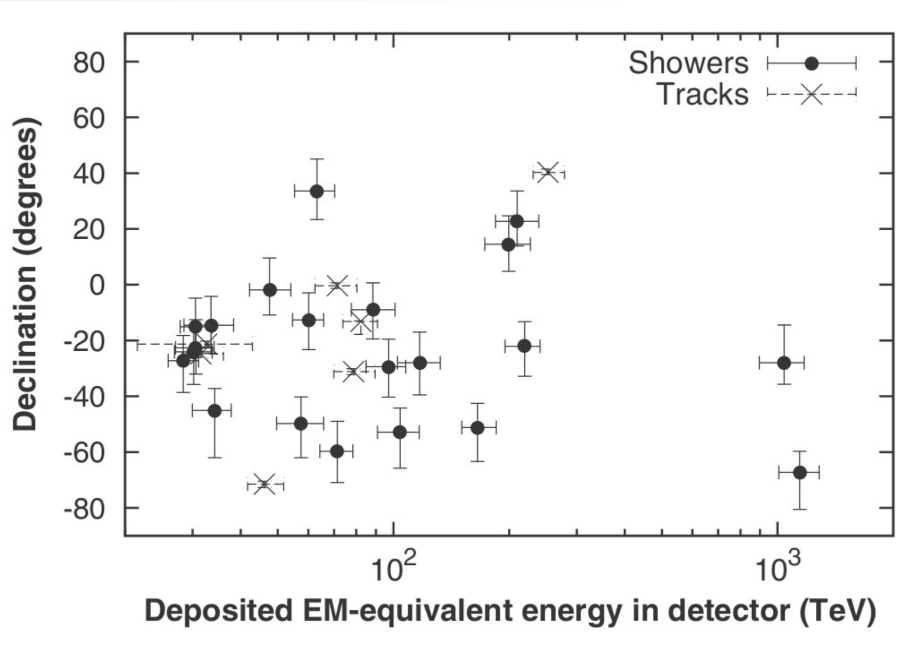
    $$\Phi_\nu \propto E^{-\alpha}$$
  - Neutrinos in sources predominantly from pion decays
    - Std. oscillation → incident flavour 1:1:1 at earth
- Cosmogenic neutrinos (E ⩾ 100 PeV)
  - Cosmic rays interacting with CMBR photons



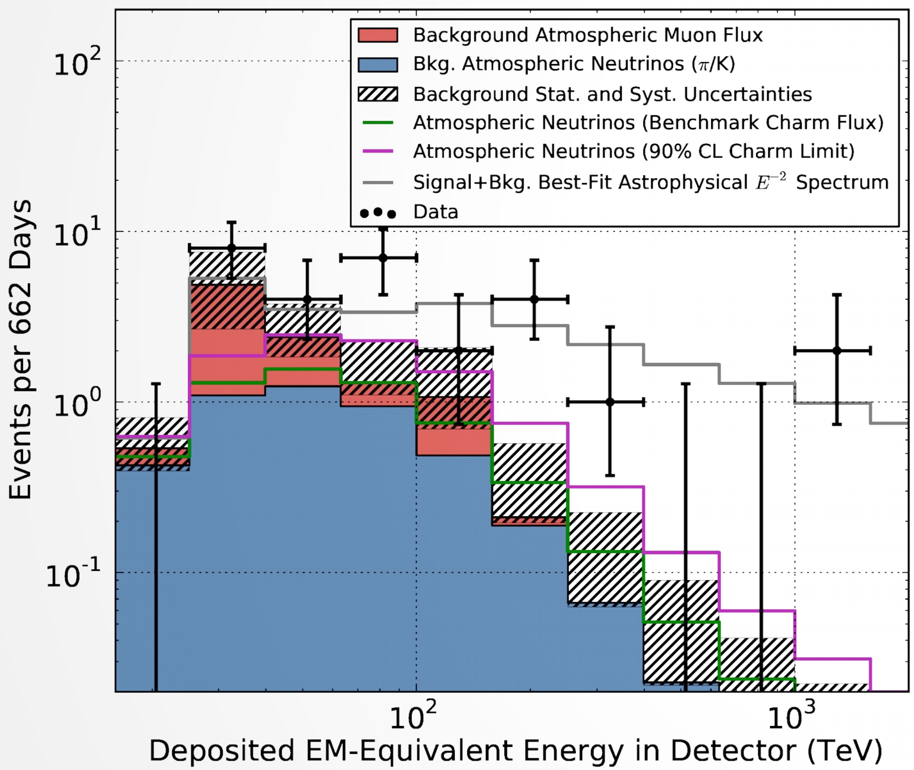
# Observations @ IC [662 days]




**28 total events**

- **Two PeV+ cascades**
  - Highest energy neutrino events ever observed
- Additional 19 lower energy cascades
- 7 track events
- Events from 4π sky
- No event from 300 TeV–1 PeV

# Observations @ IC [662 days]




**At least 4.7σ signal over atmospheric neutrino background with 90% c.l. charm estimates**

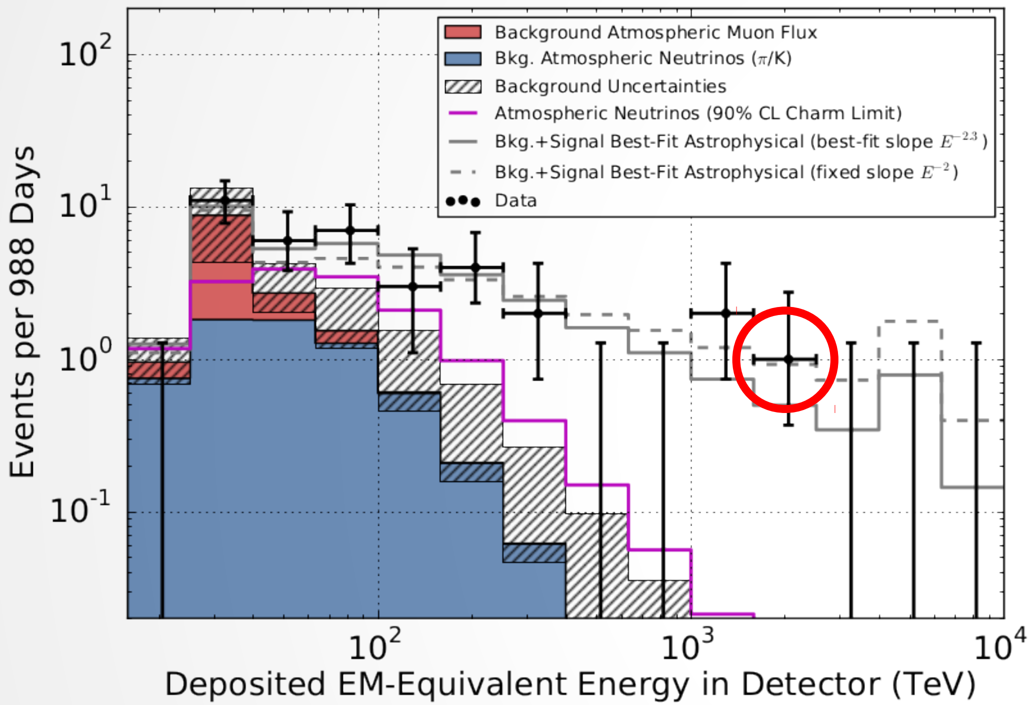
Best-fit largely consistent with $E^{-2}$ power flux up to 1.1 PeV…

$$E^2\Phi = 1.2^{1.6}_{0.8} \times 10^{-8} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

**…BUT**

- Unexplained sharp drop above 1 PeV
- Lack of events within 300 TeV – 1 PeV
- Sub-100 TeV energy event numbers consistently higher than prediction from $E^{-2}$ flux

# Updated Observations @ IC [988 days]




**At least 5.7σ signal over atmospheric neutrino background with 90% c.l. charm estimates**

Best-fit E$^{-2}$ power flux now given by

$$E^2\Phi = 0.95^{1.25}_{0.65} \times 10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

**...AND YET**

- Unexplained sharp drop above 2.1 PeV
- Gap: 400 TeV – 1 PeV
- Sub-100 TeV event numbers consistently higher than prediction from E$^{-2}$ flux

**Plausible astro explanation**

$$E^2\Phi_{\mathrm{astro}} = 1.51 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

# Issues with uniform power-law explanation

- Diffuse neutrino flux follows a uniform power law

$$\Phi_\nu = A E_\nu^{-\alpha}\Big|_{\alpha=2}$$

- Gap in events between 400 TeV to 1 PeV **unexplained**
- Small but **notable excess** in observed low-energy events (~ 100 TeV)
- **Event rate drops to zero beyond 2.1 PeV**
  - $\Phi \propto E^{-2}$ predicts 3-6 events from 3—10 PeV

# Proposition I

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**Diffuse neutrino flux incident at IC as combination of astro and DM-decay neutrinos**

# Decay of Dark Matter

- For neutrino events in IC range, need DM species of mass ≈ 100 TeV —2 PeV
  - Probably non-thermal in nature
  - Heavier than the typical WIMP
- Slow decays of DM to Std. Model (SM) particles possible
  - Relic abundance requirements force $\tau_{\mathrm{DM}} \gtrsim 10^{16}\mathrm{s}$
  - Further constraints on life-time from observational astronomy
- Two-body decays to various SM channels possible
  - Charged lepton pairs ($e^+e^-$, etc.)
  - Neutrinos
  - Quark pairs ($u\bar{u}$, etc.)
  - Gauge boson pairs ($W^+W^-$, $Z^0Z^0$)

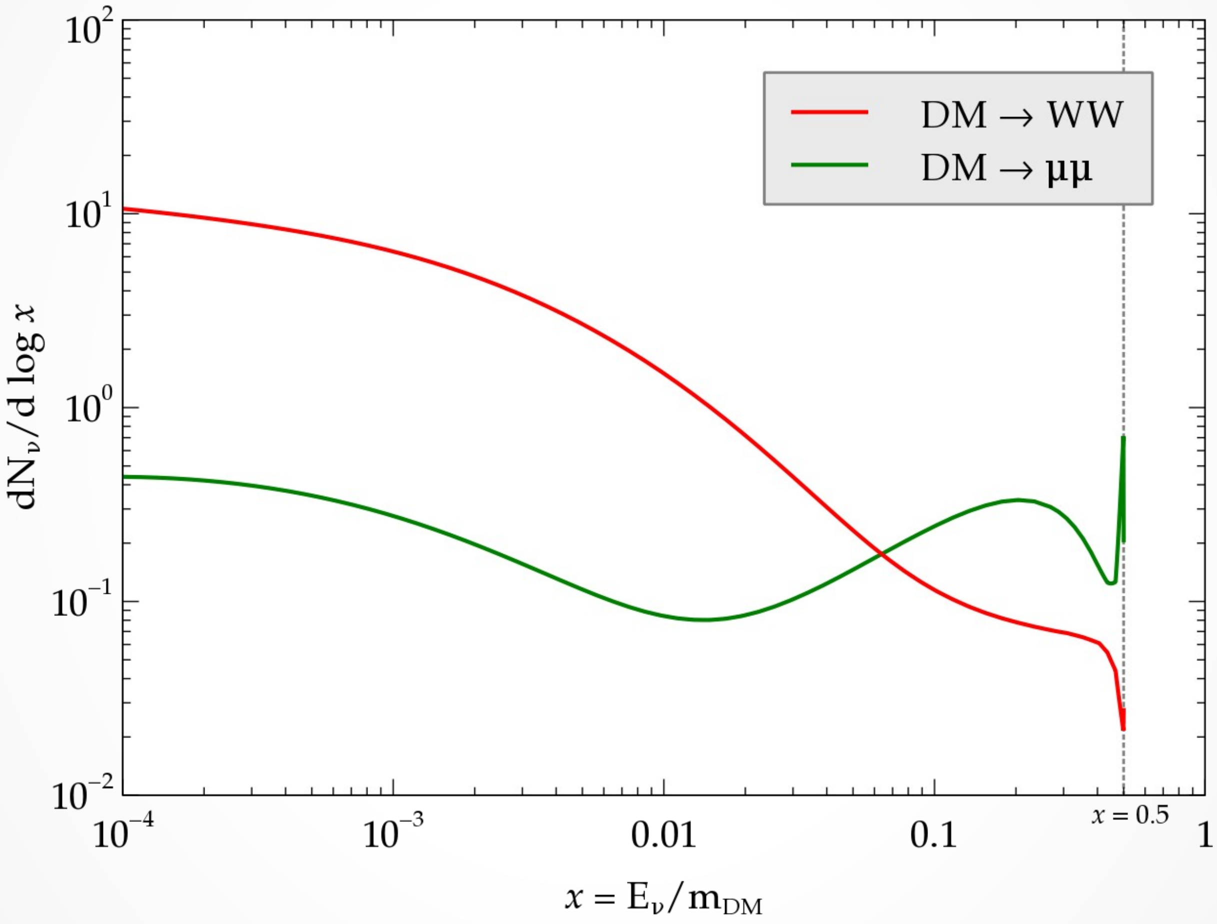
# Objective: IC events as combination of astro and DM-decay neutrinos

- Main motivation: **Explain low-energy excess**
- Reasoning
  - Secondary neutrinos from ~100 TeV massive DM decays to different SM primaries augment diffuse astrophysical neutrino spectrum
  - The astro flux itself can be then significantly lower, providing a natural explanation for the depletion in event rates beyond 1.1 PeV

# Properties of DM Decay

- Assume scalar DM
- Restrict to two-body decays
  - Simplicity
  - Decay spectrum well-known (e.g. PYTHIA8, PPPC, etc.)
- Consider all possible SM channels:
  - Lepton pairs: ~~$e^+e^-$~~, $\mu^+\mu^-$, $\tau^+\tau^-$
  - Gauge boson pairs: $W^+W^-$, $Z^0Z^0$
  - ~~Quark pairs~~

# Secondary Neutrino Spectrum



# Fluxes from heavy DM decay

**Total Flux = Galactic Flux + Extra-Galactic Flux**

- Galactic
  - $$\frac{\mathrm{d}\Phi^{\mathrm{G}}}{\mathrm{d}E_\nu} = \frac{1}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \int_0^\infty \rho(r(s,l,b))\, \mathrm{d}s$$
- Extragalactic
  - $$\frac{\mathrm{d}\Phi^{\mathrm{EG}}}{\mathrm{d}E} = \frac{\Omega_{\mathrm{DM}}\, \rho_c}{4\pi\, m_{\mathrm{DM}}\, \tau_{\mathrm{DM}}} \int_0^\infty \frac{1}{H(z)} \frac{\mathrm{d}N_\nu}{\mathrm{d}E_\nu} \left[(1+z)E_\nu\right] \mathrm{d}z$$
- Comparable contributions from G and EG fluxes, flux obtained from 4π sky
  - High energy neutrinos attenuated by earth ⇨ more downgoing neutrinos than up-going

# Total DM + Astro flux at IC

- Assume astrophysical flux to be unbroken power-law:

$$\frac{\mathrm{d}\Phi_{\mathrm{Astro}}}{\mathrm{d}E} \equiv \frac{\mathrm{d}}{\mathrm{d}E}\Phi_{\mathrm{Astro}}(k,\alpha) = kE^{-\alpha}$$

- Total flux incident at IC:

$$\frac{\mathrm{d}}{\mathrm{d}E}\Phi^{\lambda}_{\mathrm{Total}}(m_{\mathrm{DM}},\tau_{\mathrm{DM}},k) = \frac{\mathrm{d}}{\mathrm{d}E}\Phi^{\lambda}_{\mathrm{DM}}(m_{\mathrm{DM}},\tau_{\mathrm{DM}}) + \frac{\mathrm{d}}{\mathrm{d}E}\Phi^{\lambda}_{\mathrm{Astro}}(k,\alpha)\Big|_{\alpha=2}$$

- Best-fit IC power-law:

$$E^2\frac{\mathrm{d}\Phi_{\mathrm{IC}}}{\mathrm{d}E} = 1.2\times10^{-8}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$$

# Determining Best-fit to Observed Events

- Use bin-by-bin event rates observed at IC
- Determine total incident flux by varying parameters:

$$100 \leqslant \left(\frac{m_{\mathrm{DM}}}{1\ \mathrm{TeV}}\right) \leqslant 1000 \qquad 1 \leqslant \left(\frac{\tau_{\mathrm{DM}}}{10^{26}\ \mathrm{s}}\right) \leqslant 1000 \qquad 10^{-10} \leqslant \frac{k}{\mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}} \leqslant 10^{-7}$$

- Compare with predicted event rates from total incident flux by evaluating total $\chi^2$
  - Lower $\chi^2$/d.o.f indicates better fit
- Use IC best-fit as null-statistic to determine goodness of fit from model flux by **F-test**

# Best-fits and goodness-of-fit

| Decay mode | $m_{\rm DM}^{\rm b.f.}$ (TeV) | $\tau_{\rm DM}^{\rm b.f.}/10^{27}$s | $\frac{E^2\Phi^{b.f.}_{\rm Astro}}{(10^{-9}\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}})}$ | $\chi^2$ | p-value |
|---|---|---|---|---|---|
| DM $\to Z^0Z^0$ | 191.82 | 1.27 | 5.86 | 4.209 | 0.061 |
| DM $\to W^+W^-$ | 199.32 | 1.18 | 5.82 | 4.209 | 0.061 |
| DM $\to \tau^+\tau^-$ | 176.61 | 3.11 | 6.29 | 4.188 | 0.060 |
| DM $\to \mu^+\mu^-$ | 197.97 | 5.01 | 6.14 | 4.445 | 0.072 |

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The low values of the p-value indicate that the fit to the data in the DM + Astro model with a reduced astrophysical flux improves upon the IC best-fit significantly.

Conventionally, p <= 0.05 indicates strong presumption against the null hypothesis, which in this case refers to the hypothesis that the fit does not improve statistically significantly.

# "Hidden" component: ν from DM decay?

$\chi^2$ = 4.209
*p-value* = 0.061

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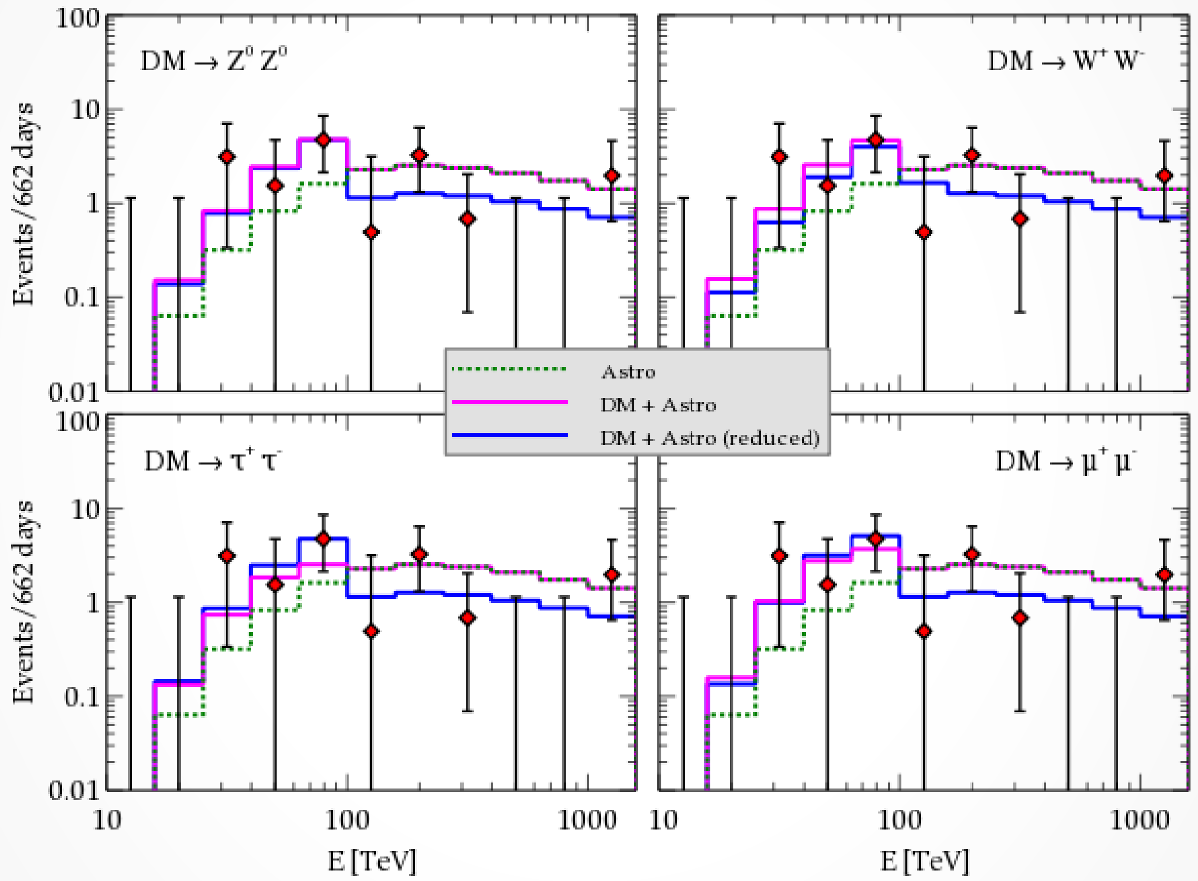


$\chi^2$ = 4.188
*p-value* = 0.060

$\chi^2$ = 4.445
*p-value* = 0.072

Compare with IC best-fit

$\chi^2_{IC}$ = 10.7

# IC events as neutrinos from DM + Astro

- **MORE DATA REQUIRED**
- Within the purview of limited statistics, reduced astrophysical flux + low energy neutrinos from DM decay fits observed data significantly better than the IC best-fit with a power-law astrophysical flux alone
  - Consistency with lack of events in the “well”
  - Better match to the sub-100 TeV events
- Event spectrum favours TeV scale DM, and astro $E^{-2}$ flux at roughly half that of IC 662-day best-fit.

# Proposition II

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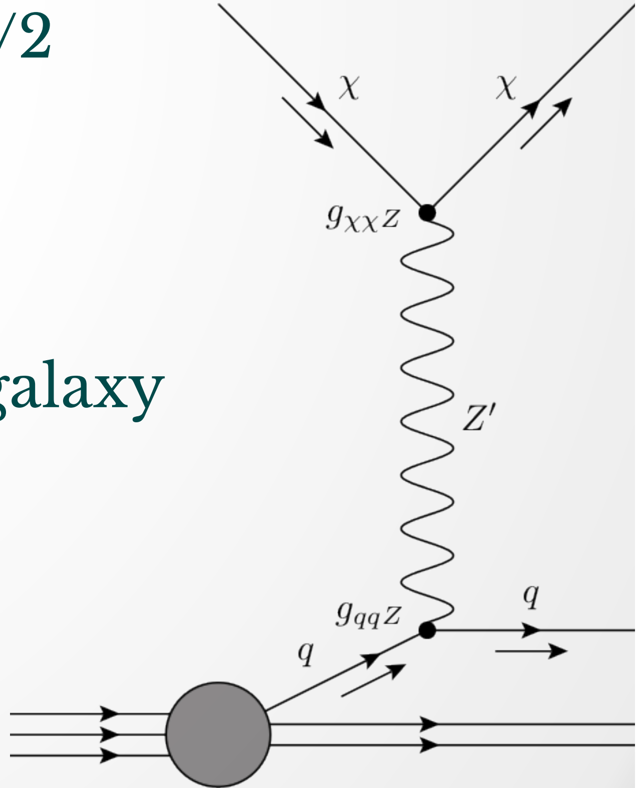
# PeV events from scattering of relativistic DM against ice-nucleon

# Motivation and Model

- Main motivation: **Explain PeV events and cut-off**
- Hypothesise existence of a two-component DM sector
  - Very heavy scalar DM species (φ, PDM), $m_\varphi$ ~ 5 PeV
    - Non-thermal in origin
    - Frozen out of interactions with SM particles completely
    - Only decays to a lighter DM within the sector
  - Lighter DM species (χ, TDM), $m_\chi$ (~ TeV) ≪ $m_\varphi$
    - Stable, Fermionic
    - Predominantly produced via two-body decay of PDM: $\varphi \rightarrow \chi\bar{\chi}$
    - Weak interactions with nuclei mediated by heavy (BSM) neutral gauge boson Z'

# Properties of DM species

- PDM
  - Large decay lifetime, $\tau > 10^{20}$ s
  - Makes up almost entire relic abundance of universe
- TDM
  - Produced monochromatically, energy of $m_\varphi/2$
  - Neutral current interaction with nuclei, mediated by Z'
    - Analogous to νN neutral current interaction
  - Does not contribute to co-moving DM, e.g. galaxy rotation curves, etc.



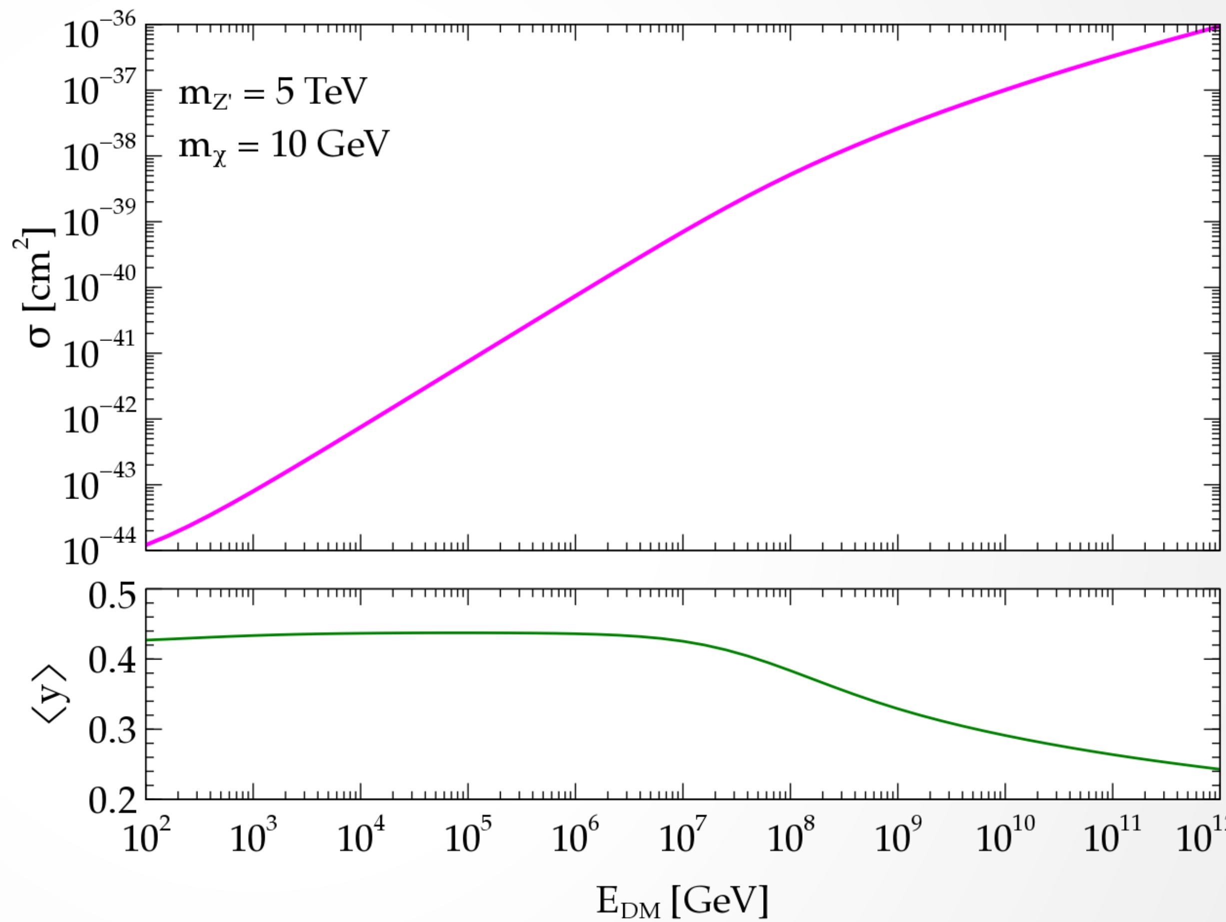
# Cross-section and Avg. y

$$\frac{\mathrm{d}\sigma}{\mathrm{d}y}(E_\chi^{\mathrm{in}}, y) = G^2 f(E_\chi^{\mathrm{in}}, y)$$

$$G = g_{\chi\chi Z} g_{qqZ}$$

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

Assume arbitrary normalisation
$G^2 = 0.05$



# DM Parameters Fixed by Observations

- **PDM mass determined by high-energy cutoff**
  - Requires event rates peaking at ~ 1.1 PeV, therefore peak TDM flux at

$$E_{\text{peak}} = 1.1/\left[\langle y\rangle\big|_{E=1.1\text{ PeV}}\right] = 2.53 \text{ PeV}$$

  - Fixes PDM mass at $2E_{\text{peak}}$ = 5.06 PeV
- **Normalisation determined by number of PeV+ events**
  - $\Phi \propto \tau_\phi^{-1}$, $\mathrm{d}\sigma/\mathrm{d}y \propto G^2$ implies, event rate at IC $\propto G^2/\tau_\phi$

3 PeV+ events in 988-day data

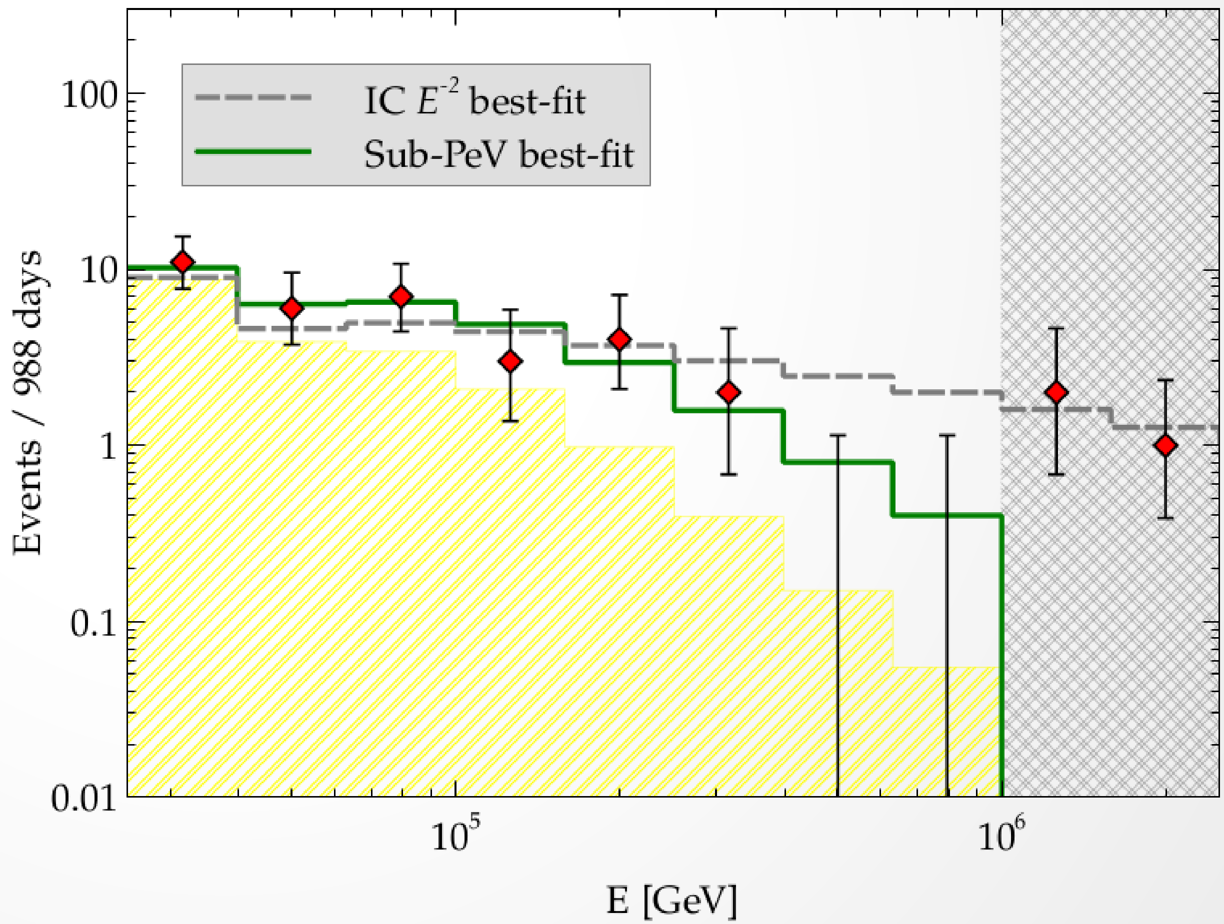
Fix $\tau_\varphi$ = $10^{24}$ s, $G^2$ = 0.45

# The Sub-PeV Event Spectrum

- Steeply falling $E^{-3}$ spectrum explains sub-PeV events

$$\Phi_{\text{astro}} = 1.21\times10^{-3}E^{-3.0}\ \text{GeV}^{-1}\ \text{cm}^{-2}\ \text{s}^{-1}\ \text{sr}^{-}$$

- Source of neutrinos: extra-galactic objects like GRB's, AGN's, etc.
- Consistent with 400—1000 TeV "gap"
- Softer flux naturally drops below threshold above PeV's



## Putting the two together

# The Full Event Spectrum

- PeV+ events exclusively from TDM scattering on ice-nucleus within IC
  - Soft astrophysical neutrino spectrum ensures no contribution at PeV+
- Hard-cutoff at 2.5 PeV expected
  - Max energy set by PDM mass
- Soft $E^{-3}$ diffuse astrophysical flux spectrum ensures compatibility with 20—400 TeV event rates
  - Also explains gap from 400—1000 TeV

# Probable Tell-tale Signatures

## ...or definite falsifiability?

- IC expects to run for the next decade
  - Event rates of about 10 $yr^{-1}$
- With statistically significant data (say, 5 yrs), **if**
  - Complete lack of events persists above some PeV+ threshold
    - **Definite pointer to a hard cutoff, DM-like?**
  - Gap between 400—1000 TeV persists
    - Power-law flux cannot explain
    - **Probably points to two different components in the neutrino flux**
  - Some galactic bias expected in PeV+ events
    - Pure astro flux would be strongly isotropic

# Generalisation & Side-effects

- Different interactions for different natures of TDM
  - Scalar or fermionic?
  - Additional symmetries?
- Prospective method to discover existence of ultra-fast DM in next-gen neutrino telescopes
  - Complementary to DM direct searches sensitive to lower energy DM
  - Probably only currently viable way to look for fast (non-comoving) DM
- TDM contributes additional light degrees of freedom in the early universe
  - $N_{\text{rel}}$ from PLANCK (3.34 ± 0.32) vs $N_{\text{eff}}$ from SM (3.04)

# Conclusions

# Conclusions

- IC events a window to interesting possibilities
- **MORE DATA REQUIRED**
  Present event rates (37 over 988 days) too low
- Possibility of being explained by std. astrophysical phenomena...
- ...but tantalising **hints of non-conformity**
- If non-std. features persist, will call for innovative suggestions for explanations
- **Possibility of flux coming from disparate sources**
  - **DM-decay contributing one component**
  - **Astrophysical sources the other**