Exploring some unconventional sources as the origin of TeV-PeV energy neutrinos at the IceCube detector

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Neutrino Astrophysics and Fundamental Properties

INT, Seattle

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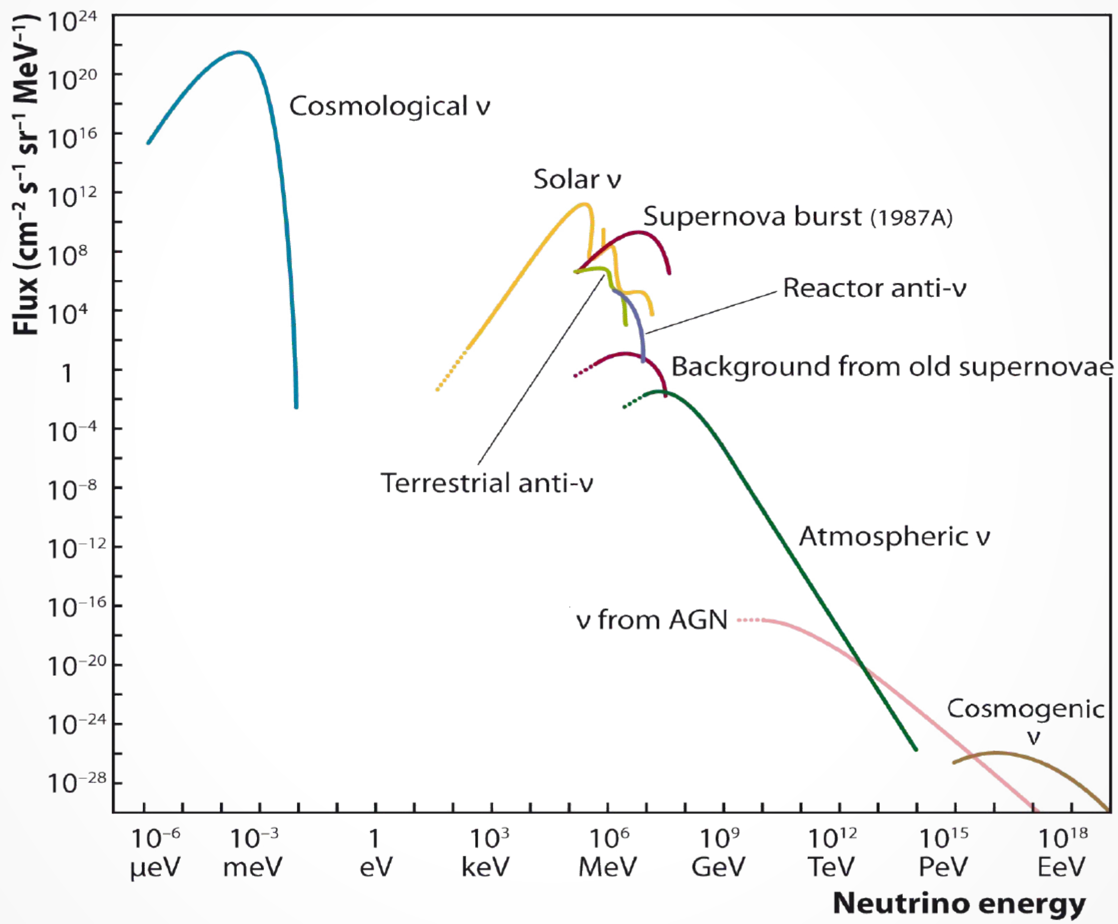
THE UNIVERSITY OF ARIZONA

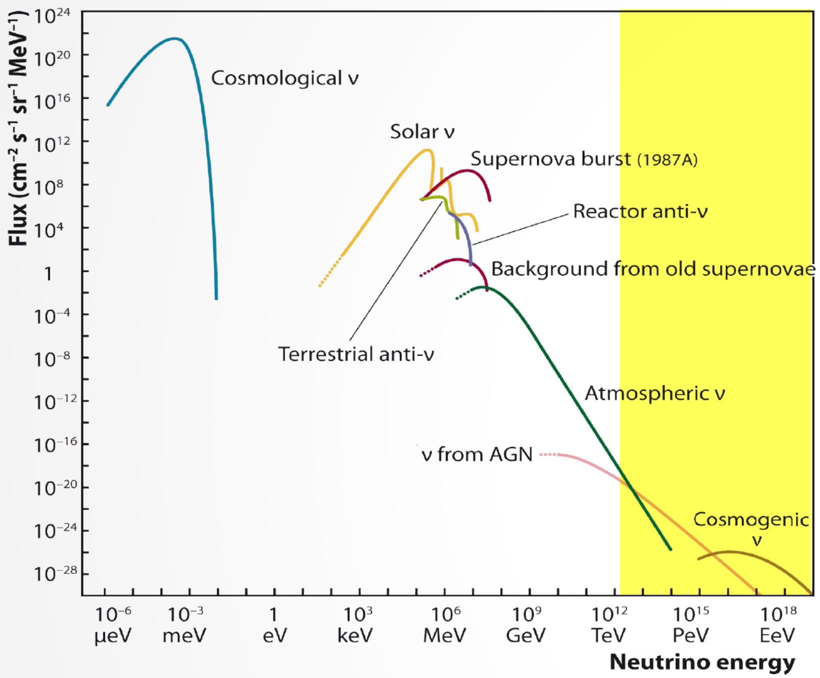
Plan

- **Ultra-High Energies** and the **IceCube** neutrino detector
  - The IC setup, aims and objectives
  - Recent results at IC
  - "Conventional" explanation and issues
- Search for heavy DM at IC?
- General prospects for heavy DM searches

The neutrino sky… to the highest energies



Neutrinos @ highest energies: HowCatch'em



Main issues with detection

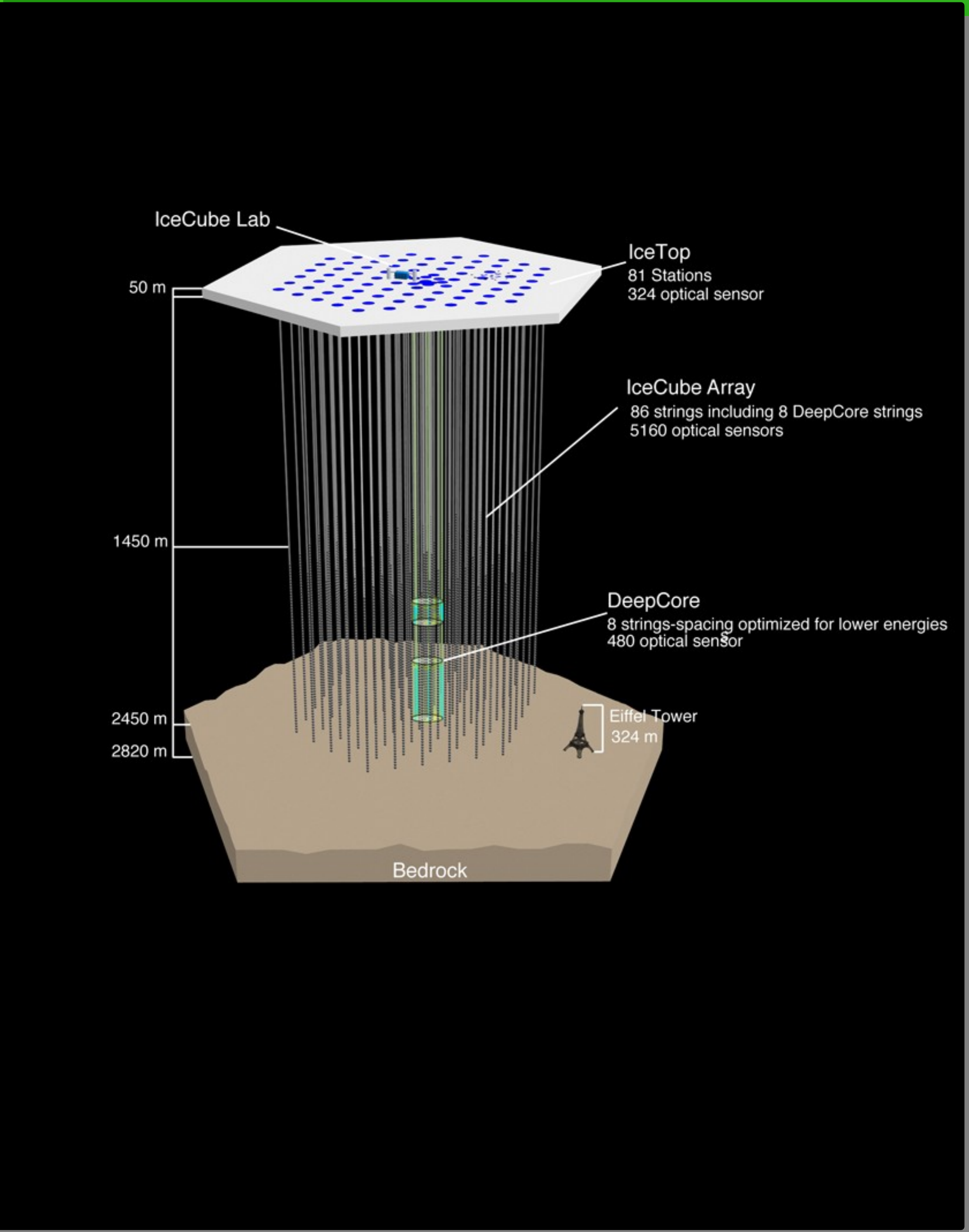
- Extremely low incident fluxes
- Huge incident energies – reconstruction requires voluminous detectors
- Flavour discrimination?

Solution?
Km³ Detectors

Km³ 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 ν_τ's

Present setup for UHE ν detection



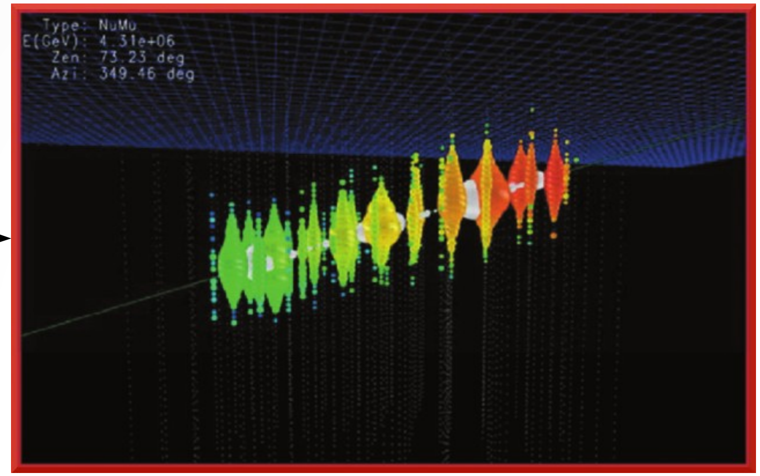
IceCube

- 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
- **37 UHE events in 998 days of run-time**
  - **3 events at PeV+ energies**

Flavour @ IC

$\nu_\mu N \, CC$

Muon Track

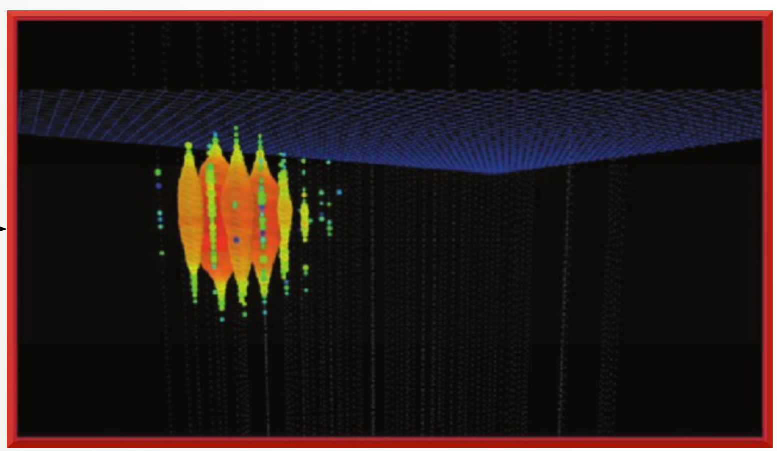


$\nu_{e,\tau} N \, CC$

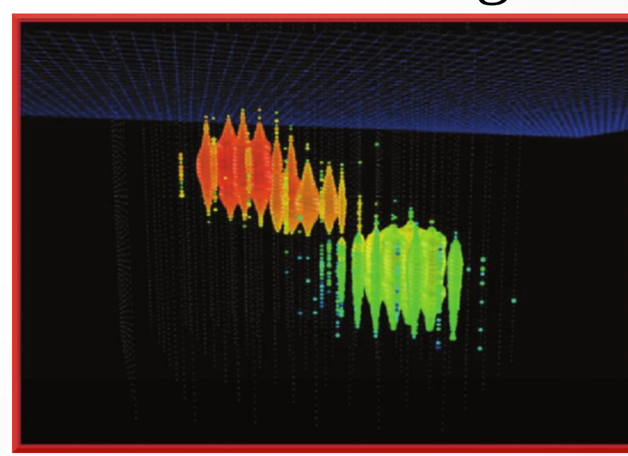
$\nu N \, NC$

$\nu_\tau N \, CC (\geqslant 1 \text{ PeV})$

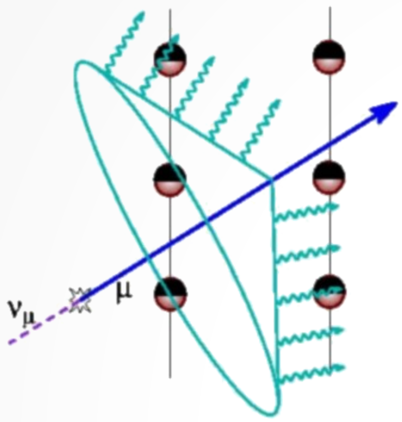
Cascades

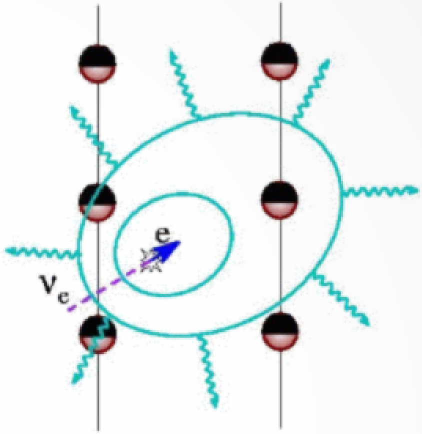


Double Bang



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

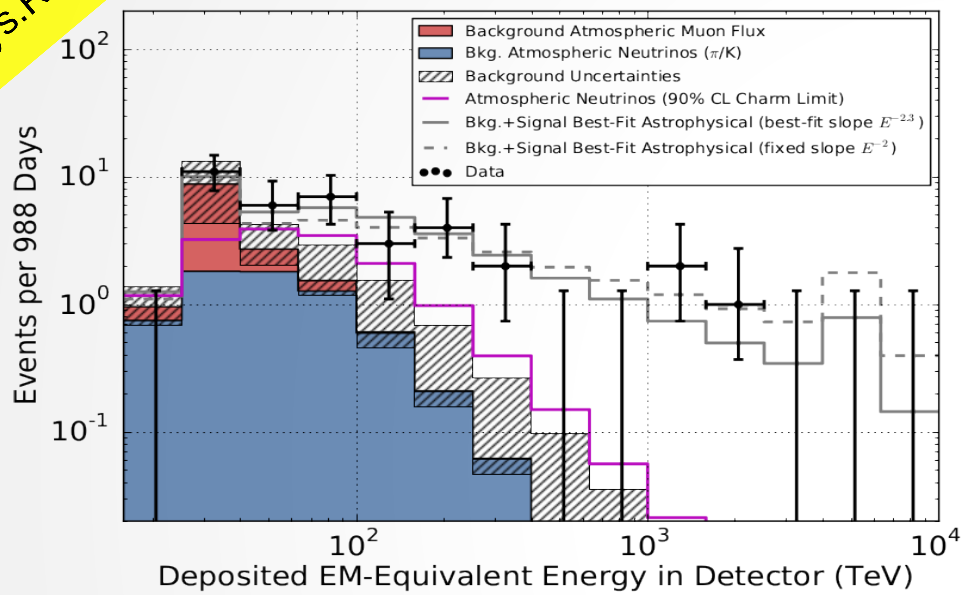
Charged current interaction of the electron-neutrino and tau-neutrino

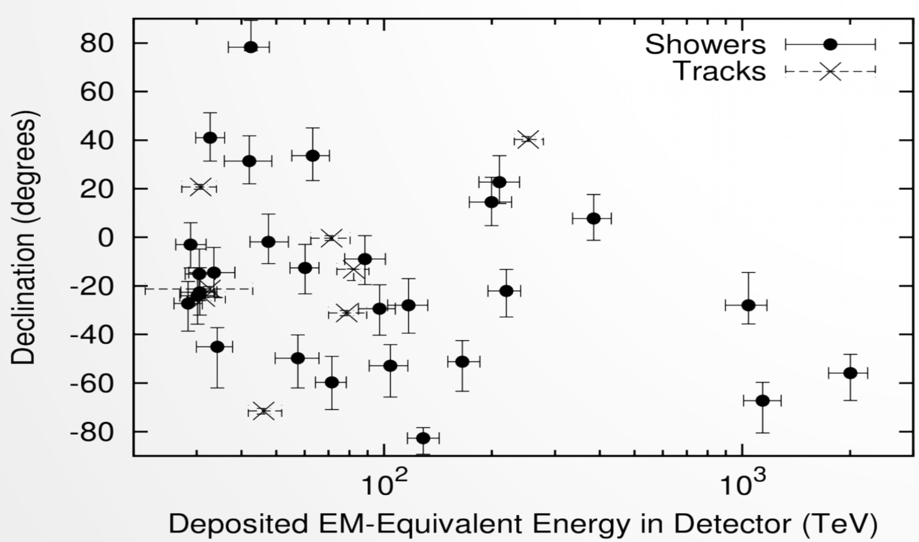
Neutral current interactions of all flavours

Excellent energy but poorer direction reconstruction

Observations @ IC [988 days]

IceCube Collab.
Phys.Rev.Lett. 113 (2014) 101101





- 37 HE events
- 3 PeV+ events, max. energy 2.1 PeV
  Highest energy ν observed
- 28 cascades, 9 tracks
- Near uniform distribution of events over declination

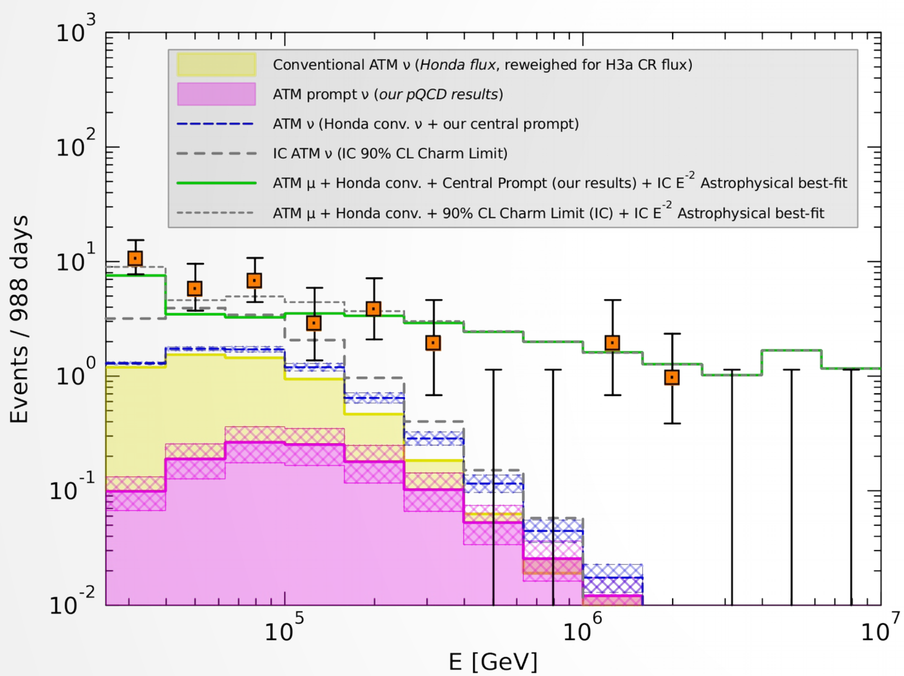
Understanding the background

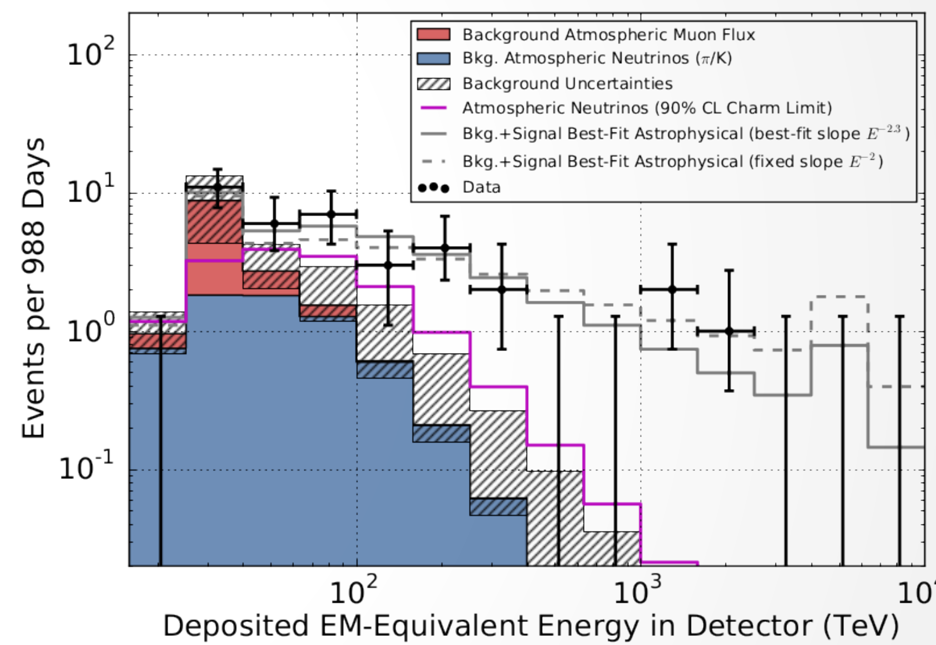
Revised prompt ν background

- Present IC estimates of prompt ν flux predictions based on Enberg et al, 2009
  - QCD parameters for pp σ strongly disfavoured from LHC measurements
  - LO QCD computation scaled to mimic NLO results
  - Cosmic-ray proton flux estimated as power-law
- Revise
  - Constrain QCD parameters (m_c, M_F, μ_R) from LHC results ↓
  - Updated proton content estimates in cosmic-ray flux at high energies ↓
  - Full NLO computation
  - Recent pdf's: **CT10nlo** [vs CTEQ3]

Details: Hallsie Reno's talk at workshop

Revised prompt ν background





At the level of central flux predictions, reduction by a factor of 3—5

The Signal Over Background

A new source of neutrino flux

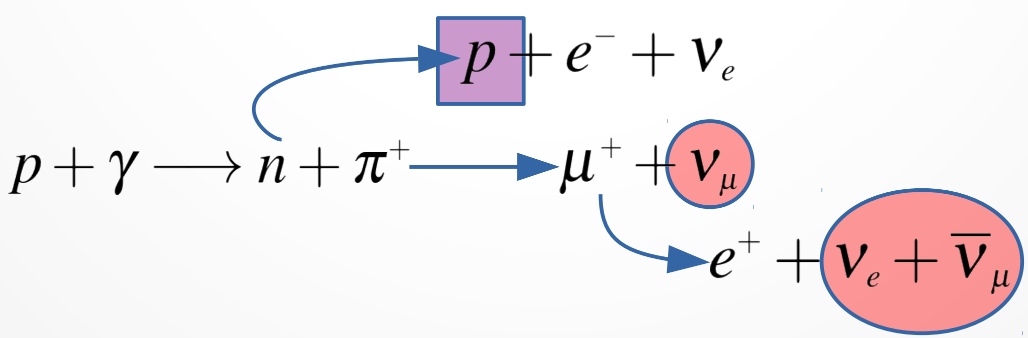
- Definite component of flux over and above the total atmospheric background visible as signal
- Statistical significance now at 5.7σ
  A new source of neutrino flux exists!
- Total expected background: 8.4±4.2 muons, 6.6 (+5.9,-1.6) atm. neutrinos (w/o prompt)
- Above ~ 200 TeV, backgrounds are tiny
  Almost all observed events (8 in total) between 200 TeV – 2.1 PeV from "new" source

Std. explanation for new component

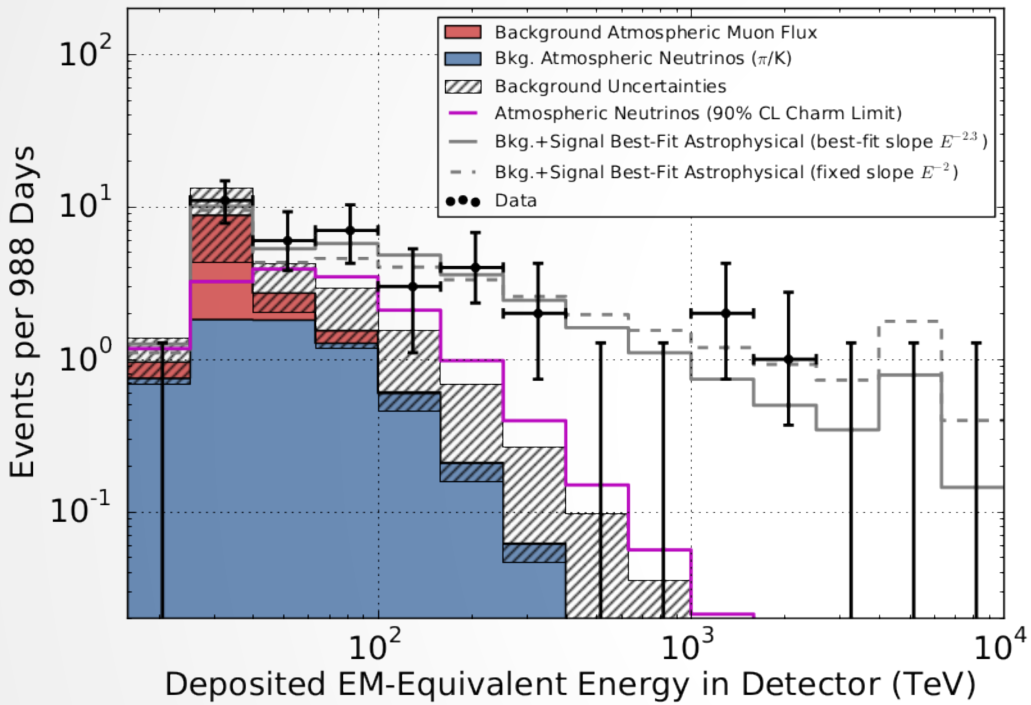
- Diffuse flux from all-sky astrophysical sources
  - Expected to follow a power-law spectrum
    - Fermi shock acceleration → α ≥ 2.0
    - Normalisation fixed by observational best-fits

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

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



Std. astro flux vs IC observations [988 days]



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

Best-fit E^{-2} astro flux

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

Issues with uniform power-law explanation

- Gap in events between 400 TeV to 1 PeV
  "unexplained"
  Realised in ~ 43% of uniform power-law predictions
- **Event rate drops to zero beyond 2.1 PeV**
  - $\Phi \propto E^{-2}$ predicts 4—6 events from 3—10 PeV
  - Glashow resonance predicts 3—4 events in the 6—7 PeV window
- B.f. flavour ratio appears to be ≈1:0:0, rather than 1:1:1

Plausible astro explanation

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

An alternate proposition

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PeV events from scattering of relativistic DM against ice-nucleon

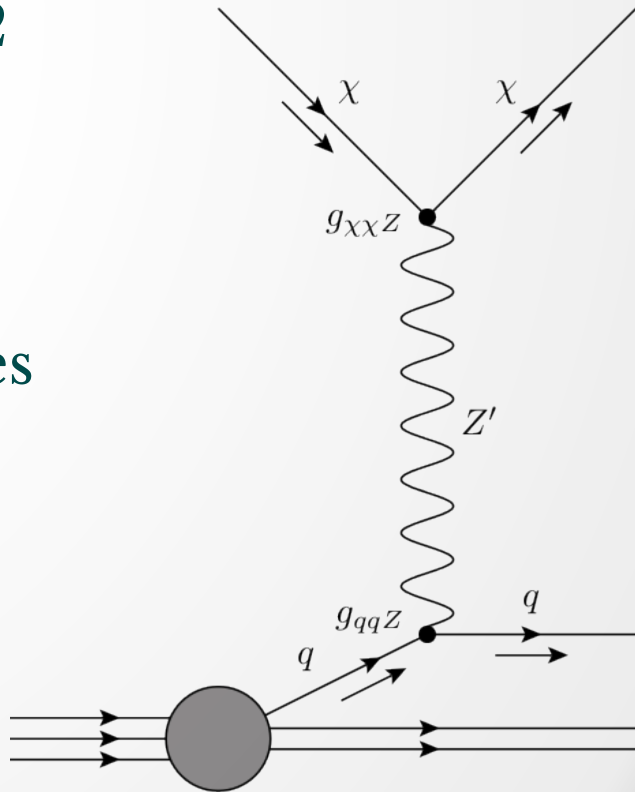
AB, Raj Gandhi, Aritra Gupta
JCAP 1503 (2015) 03, 027
e-Print: arXiv:1407.3280 [hep-ph]

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_φ ~ 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_χ (~ TeV) $\ll m_\varphi$
    - 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
  - Explains the 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 features
    - E.g. galaxy rotation curves, etc.



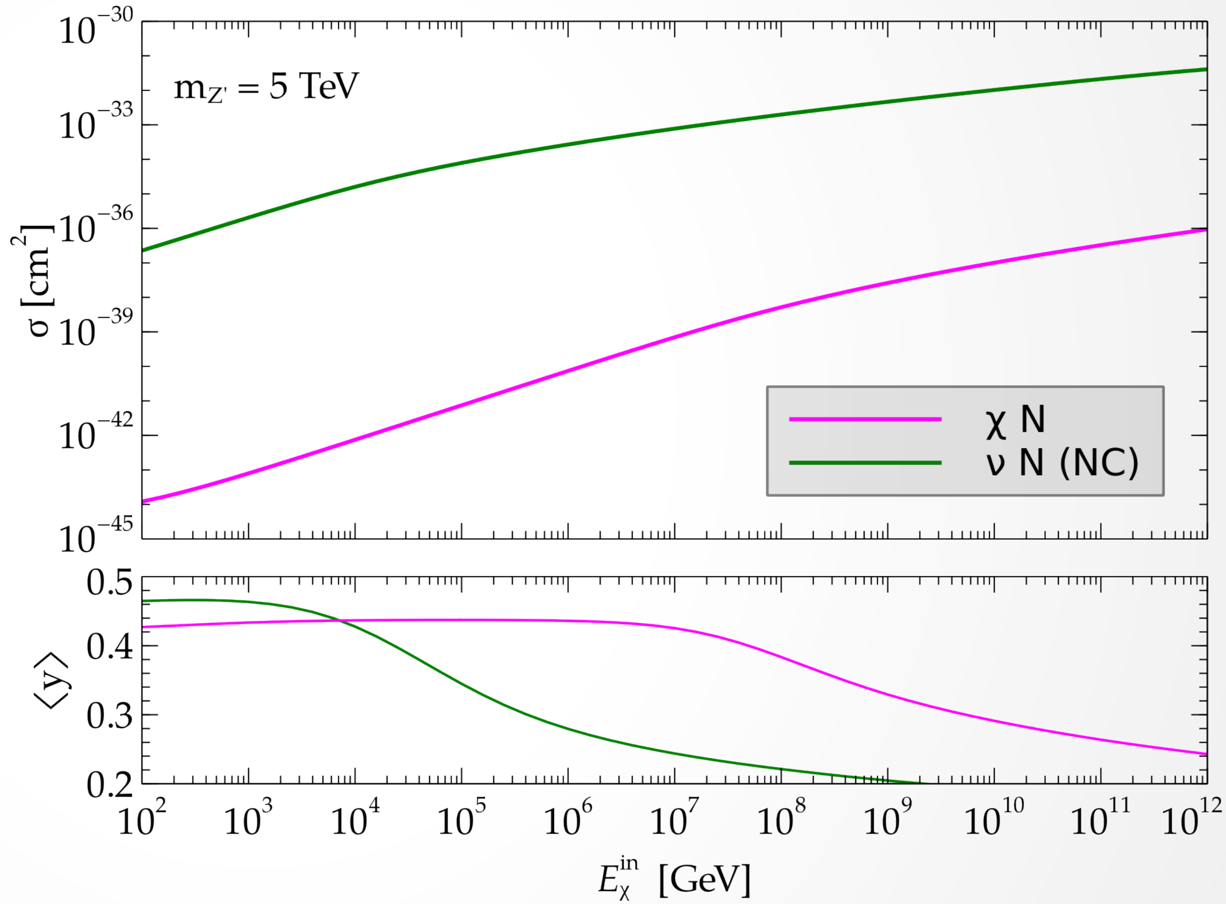
Cross-section and Avg. y

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

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

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

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

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

  - Fixes PDM mass at $2E_{peak}$ = 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 $\propto G^2/\tau_\phi$

Fix τ_φ ~ 10^{21} s, G^2 ~ 0.05

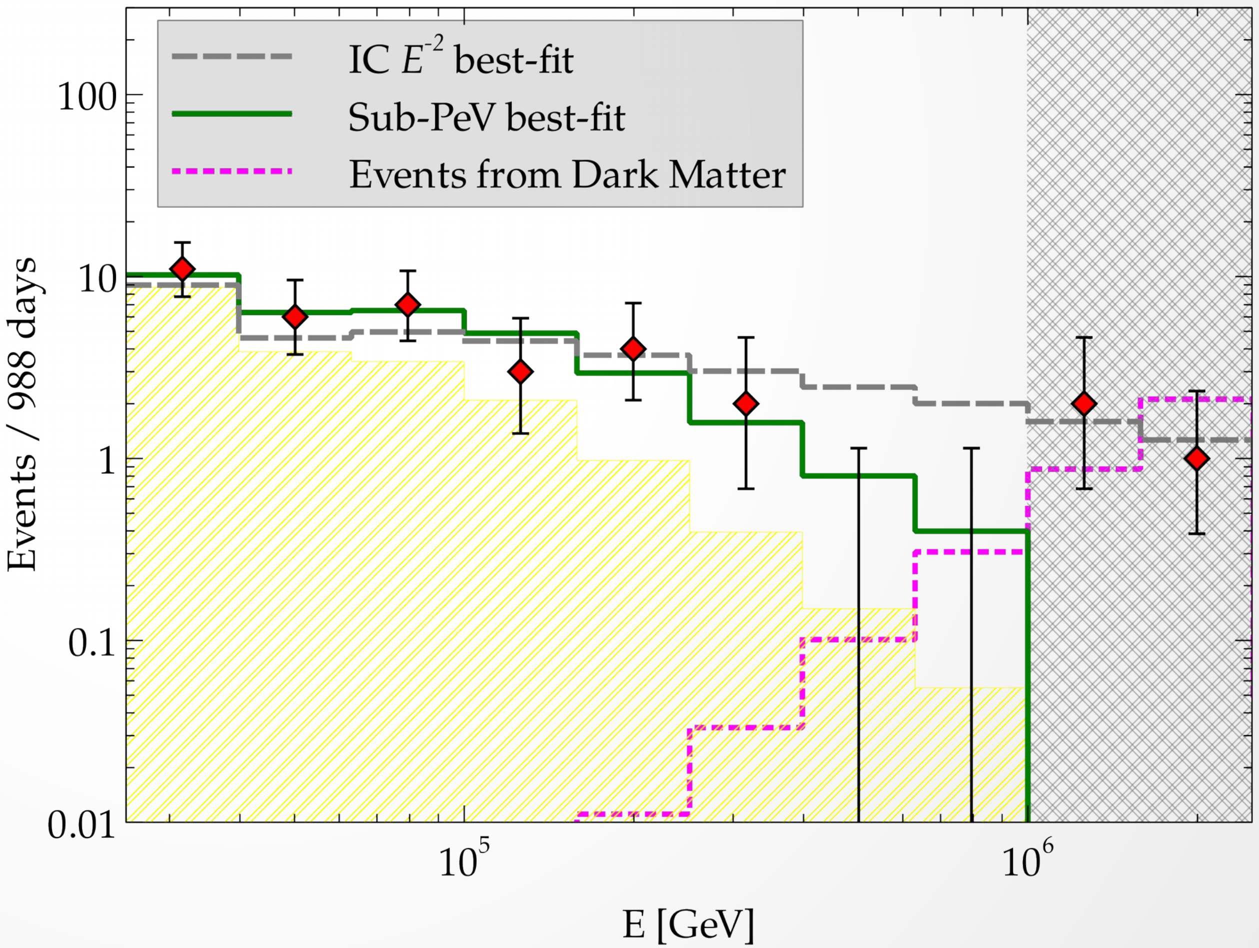
3 PeV+ events in 988-day data

The Sub-PeV Event Spectrum

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

$$\mathrm{d}\Phi_{\mathrm{astro}}/\mathrm{d}E = 1.21 \times E^{-3.0} \mathrm{GeV}^{-2}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}$$

- 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 (*or trough*) 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

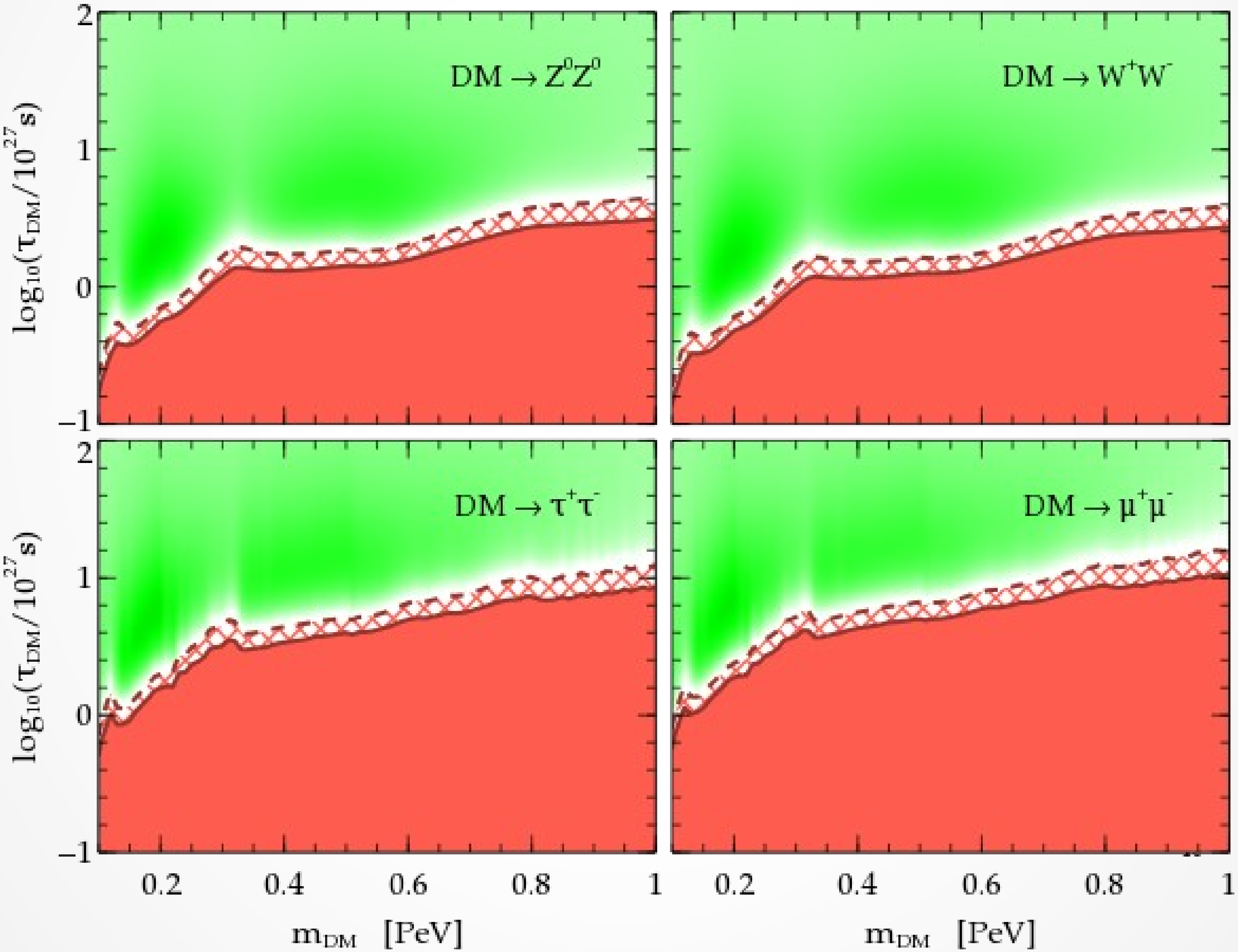
- Different interactions for different natures of TDM
  - Scalar or fermion?
  - Additional symmetries?
- Prospective method to discover existence of ultra-fast DM in next-gen neutrino telescopes
  - Complementary to DM direct searches sensitive to lower mass DM
  - Viable way to look for fast (*not comoving*) DM
- Additional light degrees of freedom in the early universe from dark sector
  - N_{rel} from PLANCK (3.34 ± 0.32) vs N_{eff} from SM (3.04)

Conclusions

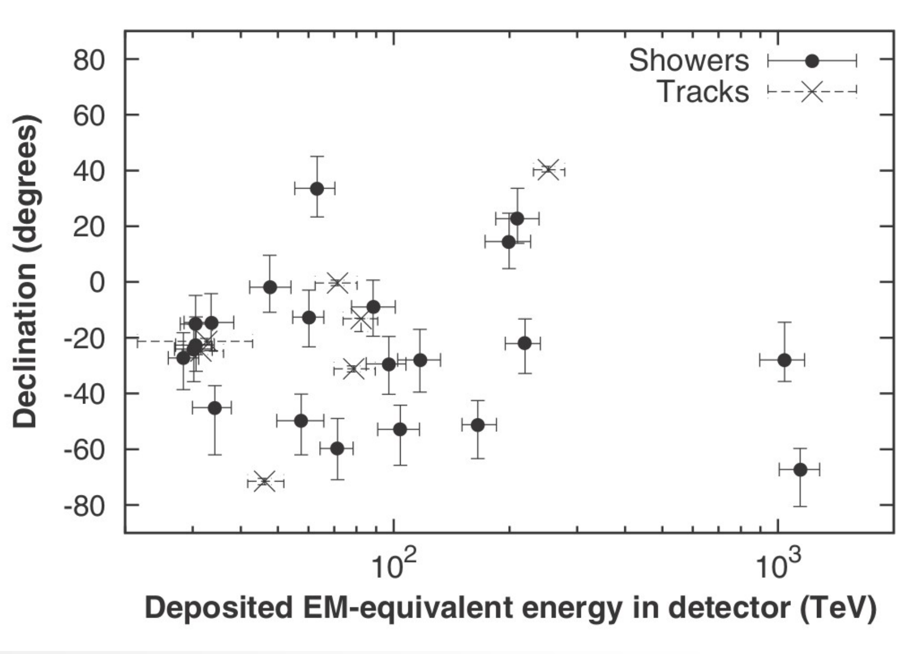
Conclusions

- IC events a window to interesting possibilities
- **MORE DATA REQUIRED**
  Present statistics (37 over 988 days) *not enough*
- 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**

Backup Slides



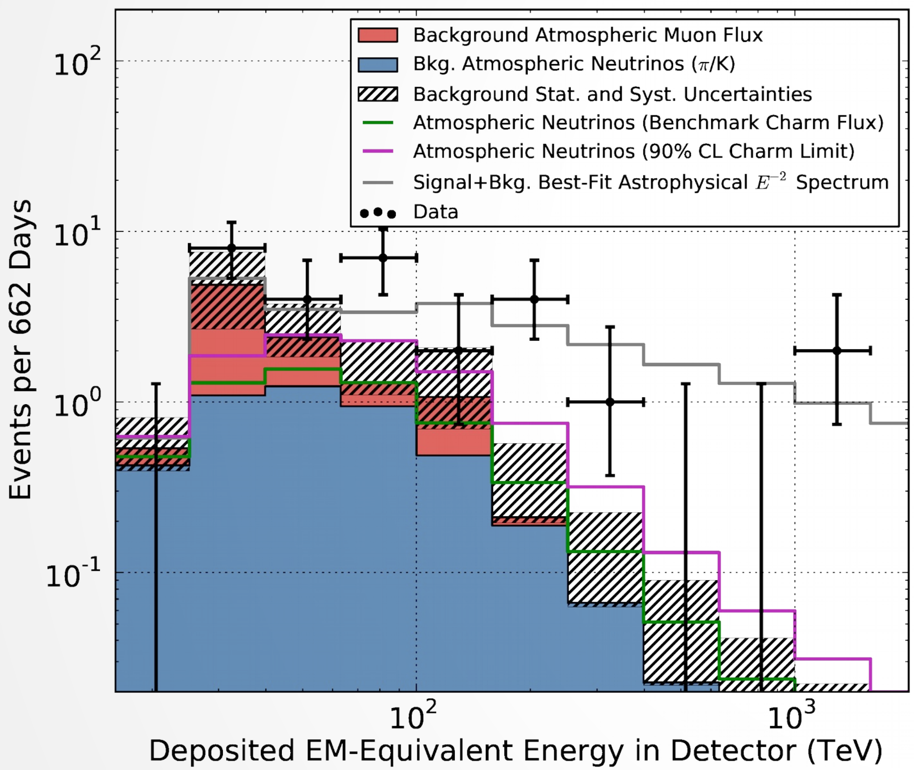
Observations @ IC [662 days]



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...

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

...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

Proposition I

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

AB, Mary Hall Reno, Ina Sarcevic
JHEP 1406 (2014) 110