Physics at the Ultra-high Energies

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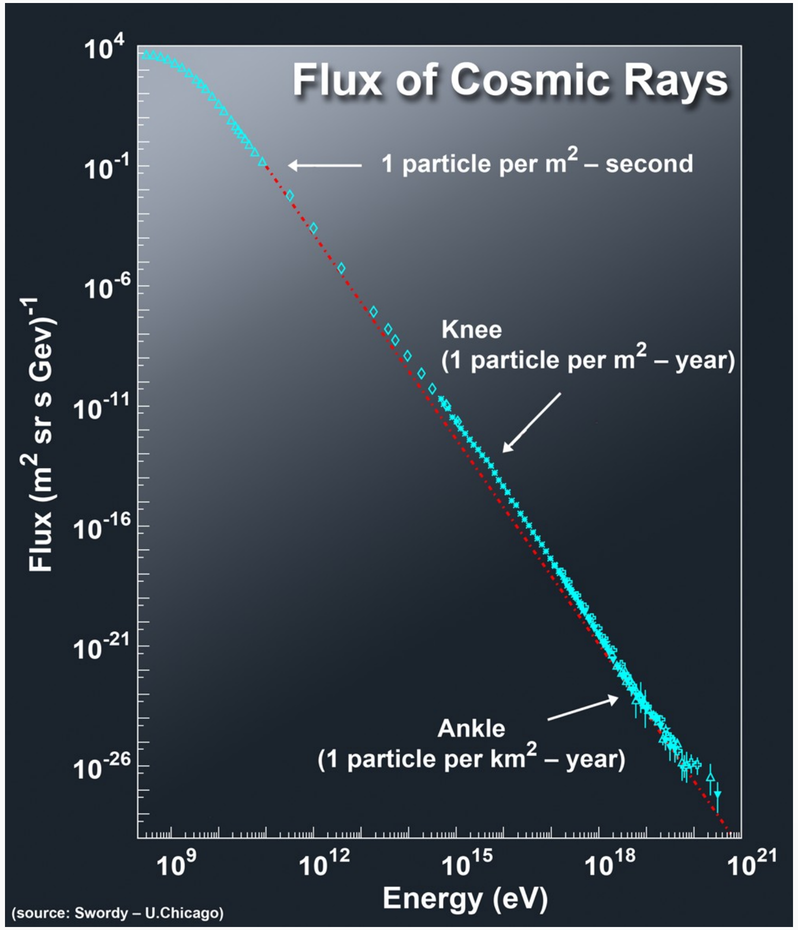
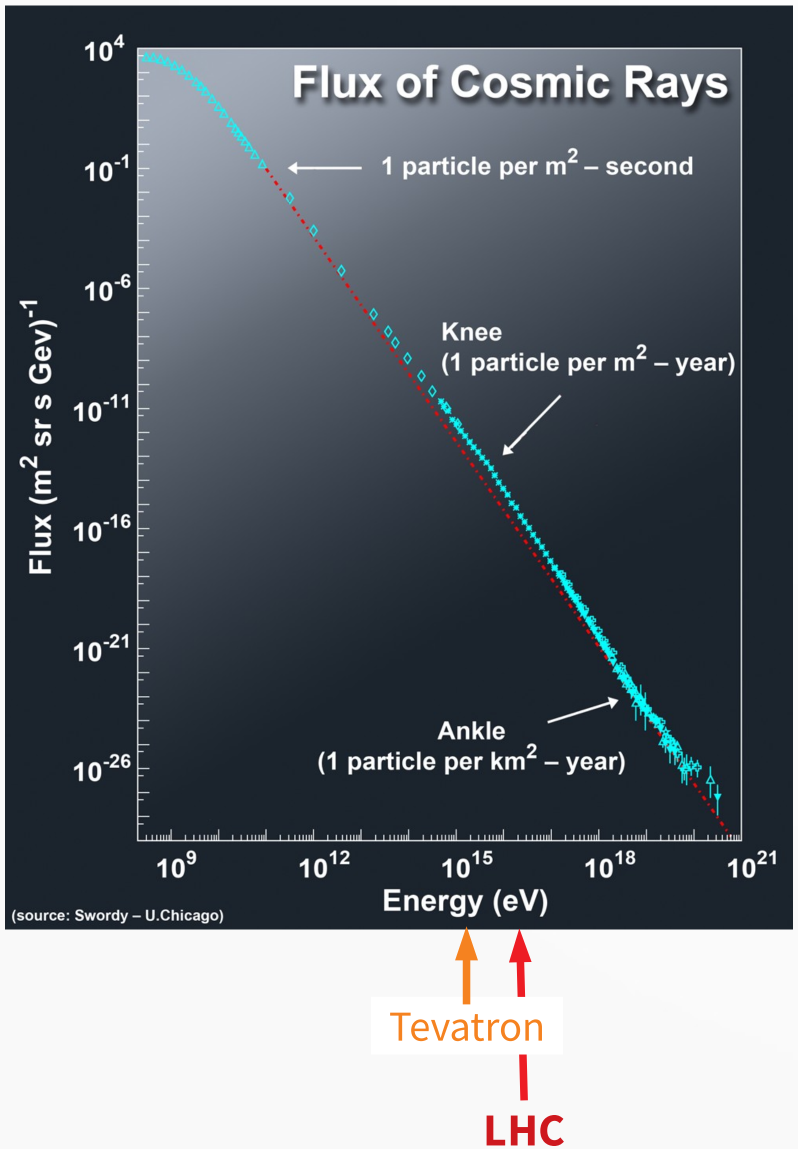
Postdoctoral fellow, IFPA (12/2015 –)

UHE & the Cosmic-Ray Connection



- First particles to be detected at UHE
- Combination of p^+, He^4 and heavy nuclei
- Ultra-high energy particles burning up in the atmosphere
- Debris detected at surface observatories
- Energy, direction reconstruction
- Higher up in energy $\Rightarrow$ More distant sources

UHE & the Cosmic-Ray Connection



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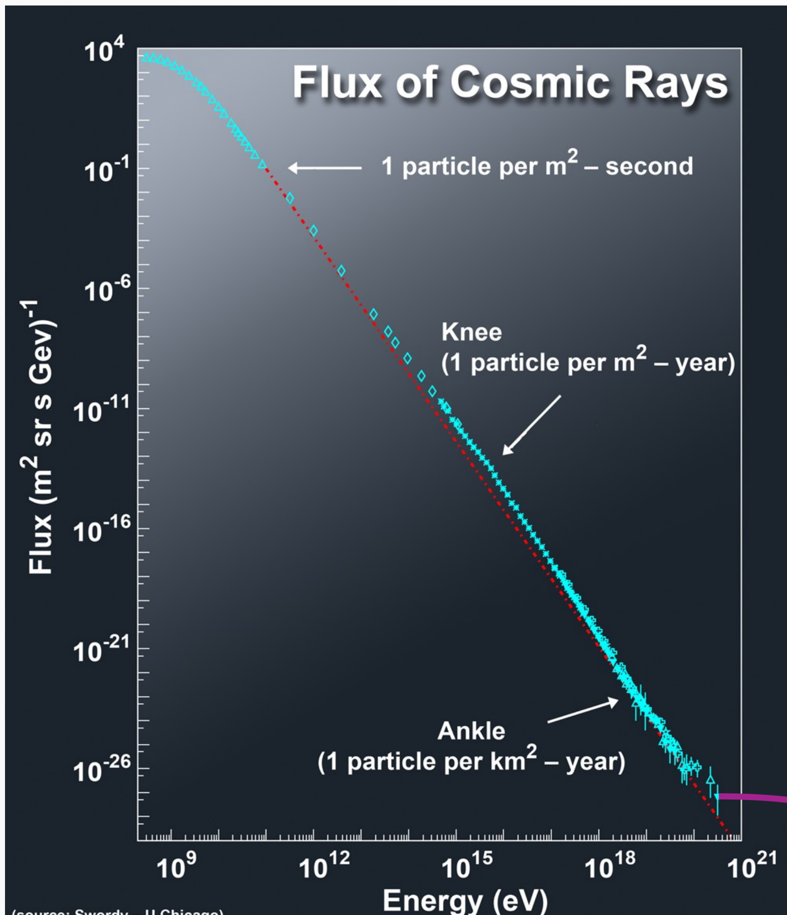
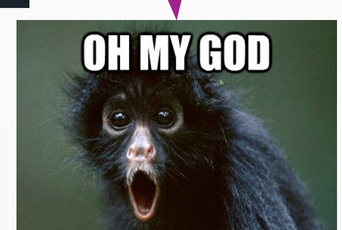


Tevatron

LHC



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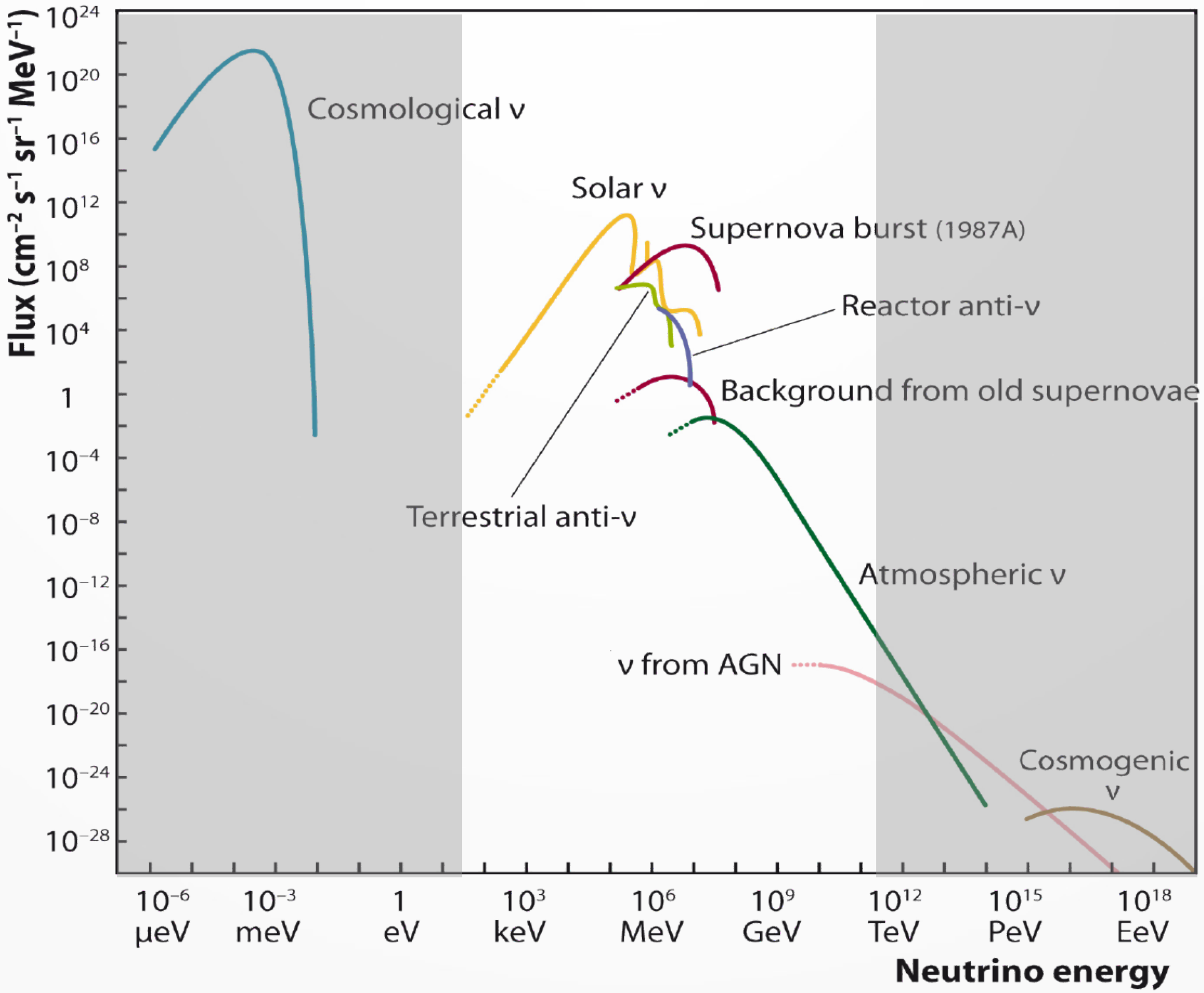
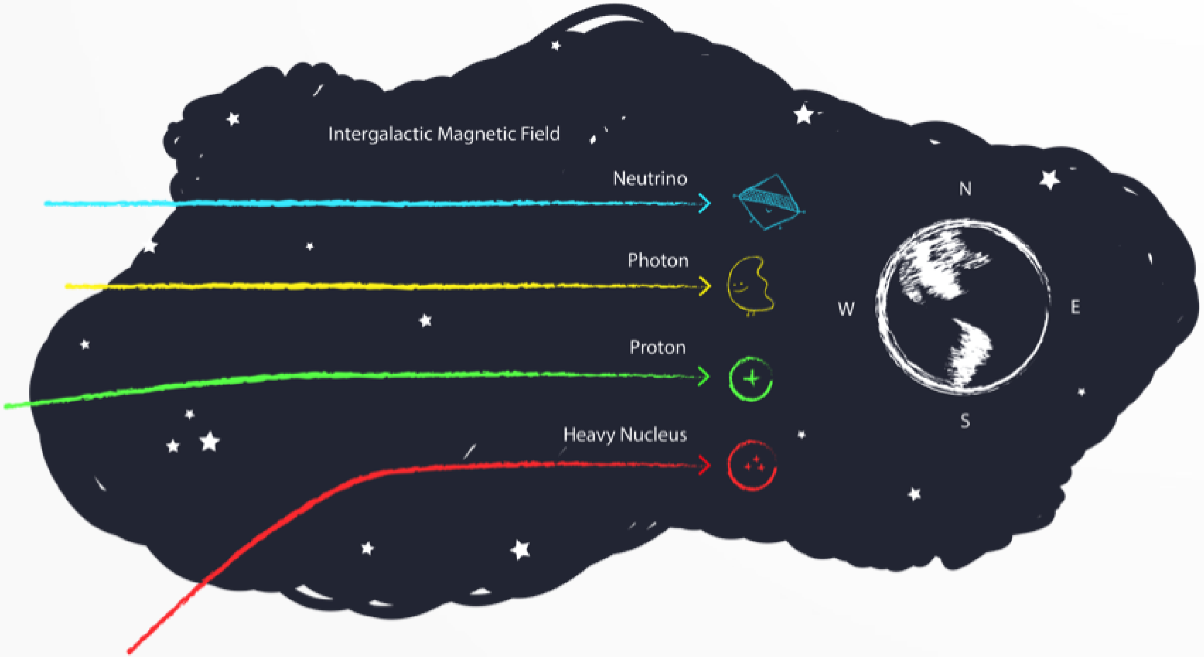
Neutrinos across different energies



Neutrinos as Cosmic Messengers – Pros & Cons



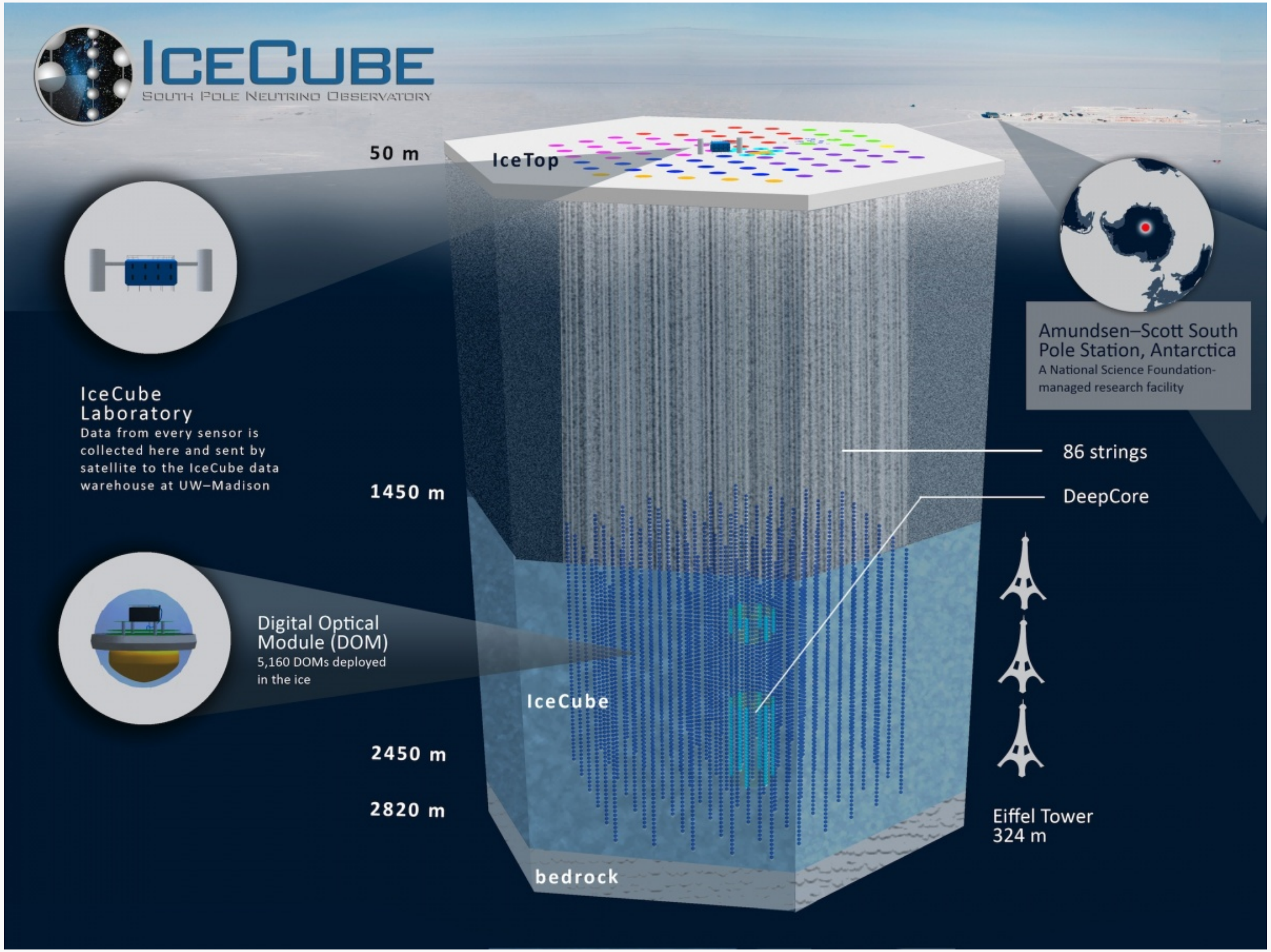
As cosmic messengers

- Feeble interactions
  - **Unimpeded propagation**
  - **Unaltered direction**
- Expected to be produced in the **same interactions propelling cosmic-ray protons**

Detection issues

- **Feeble** interactions
- Extremely **low flux**
- High incident energies require **very large detectors**

Catching UHE neutrinos – IceCube



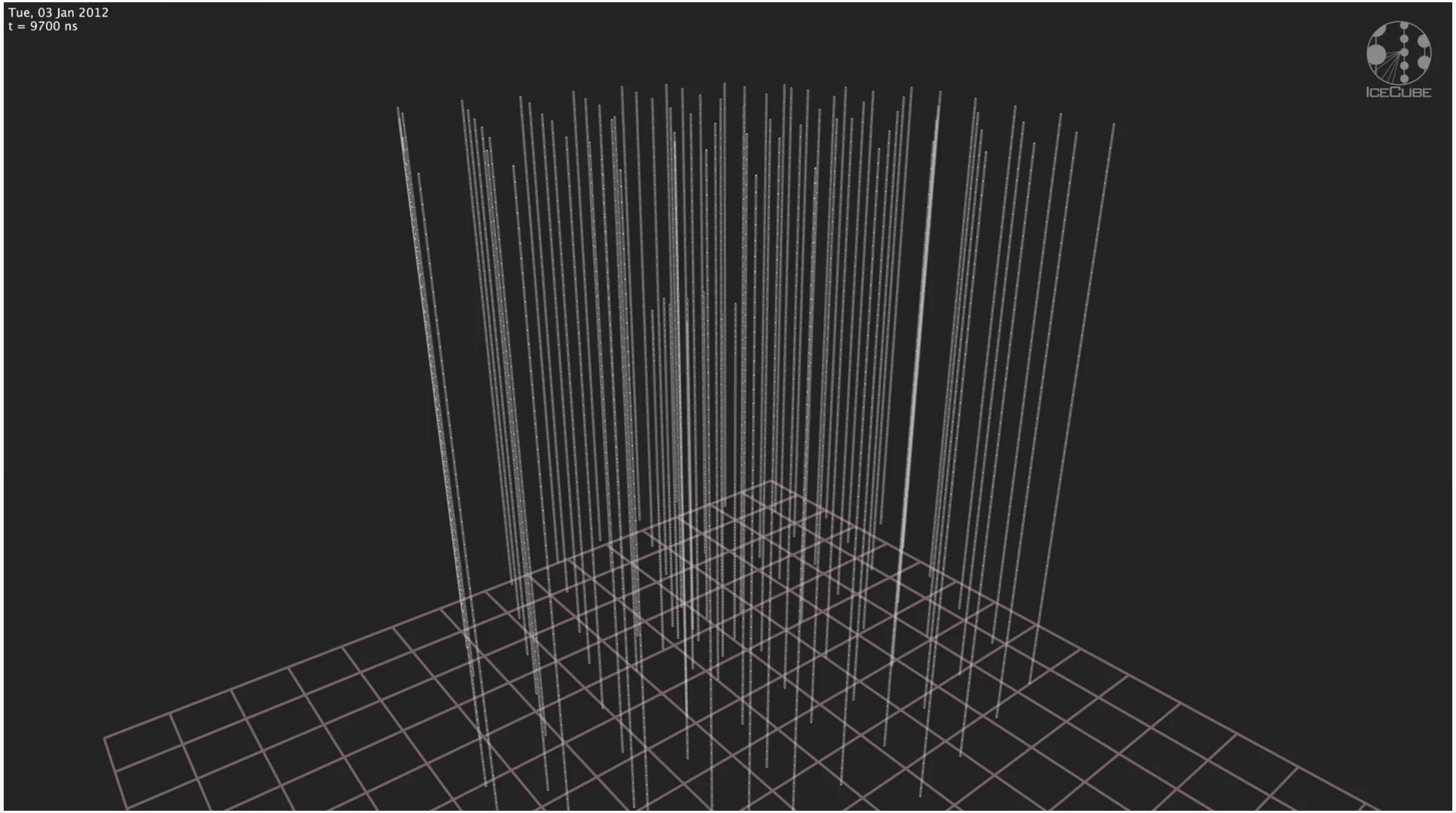
IceTop + 1 km rock

- Background veto
- Correlating arrival directions of bkg. μ and ν
- Gamma-ray observations at IceTop

IceCube

- Actual detector at ~1.5 km depth
- Neutrinos collide against ice-nuclei producing e, μ, τ and hadrons
- Photo-multiplier tubes lit up by Cerenkov radiation from these super-fast charged particles
- Cascades *(spheres of ~200 m diameter)* & tracks *(lines over ~km)* allow flavour distinction

Catching UHE neutrinos – IceCube



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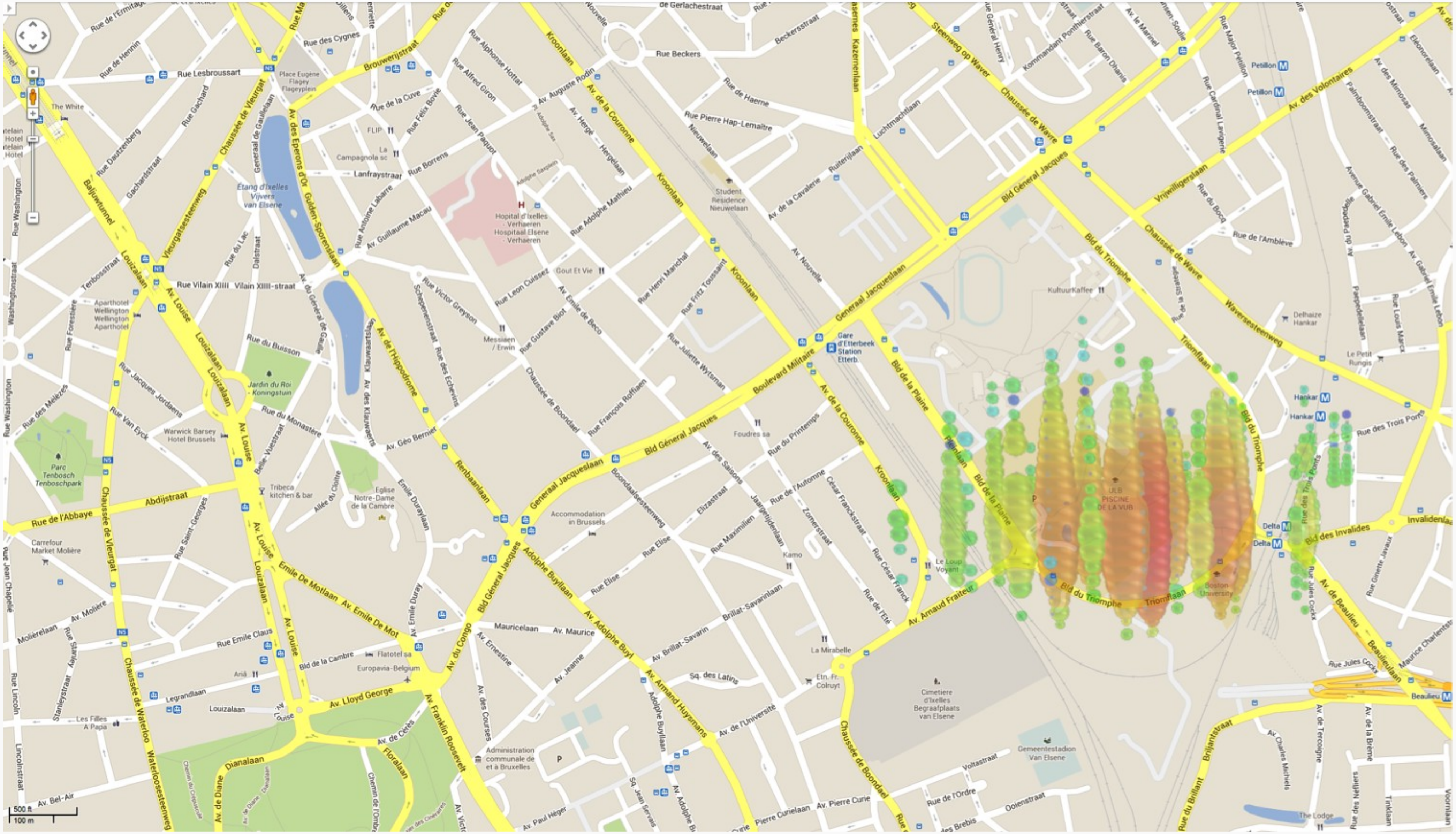
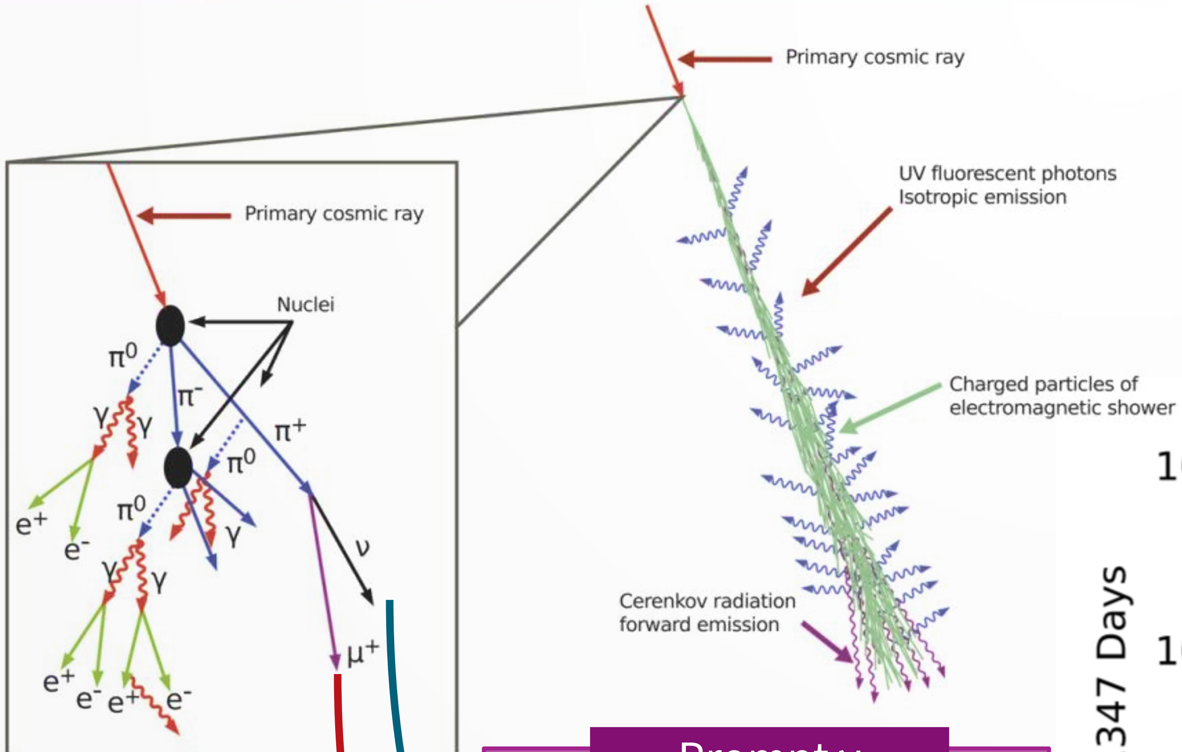
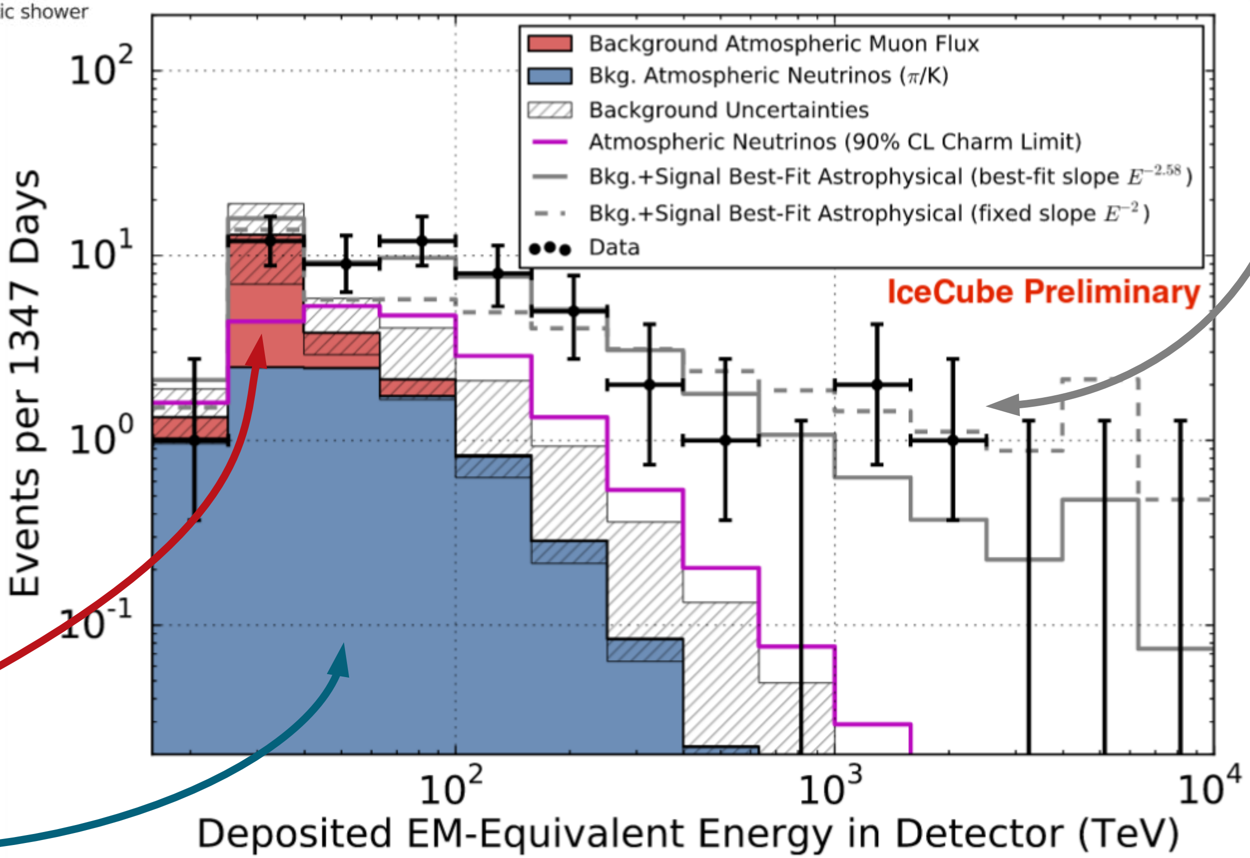


IceCube Results – Signal vs Background



Prompt ν

Decays of heavy mesons
QCD modeling uncertain
Unseen in 6-yr data



Refining the Background Analysis: Prompt Neutrinos

- Modeling the QCD of heavy meson ($D^{\pm,0}$) production
  - Perturbative analysis to NLO involving up to date constraints, including from LHCb, ATLAS
  - Diffractive production involving Regge dipoles, *kT* factorisation,…
  - Nuclear effects during CR–N^{14} collisions in atmosphere
- Uncertainties from modeling of p^+-content in CR

AB, R. Enberg, M.H. Reno, et al
JHEP 1506 (2015) 110
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- Uncertainties from modeling of p^+-content in CR
- Unusual QCD: Intrinsic charm in p^+, non-perturbative models of $D^{\pm,0}$ production

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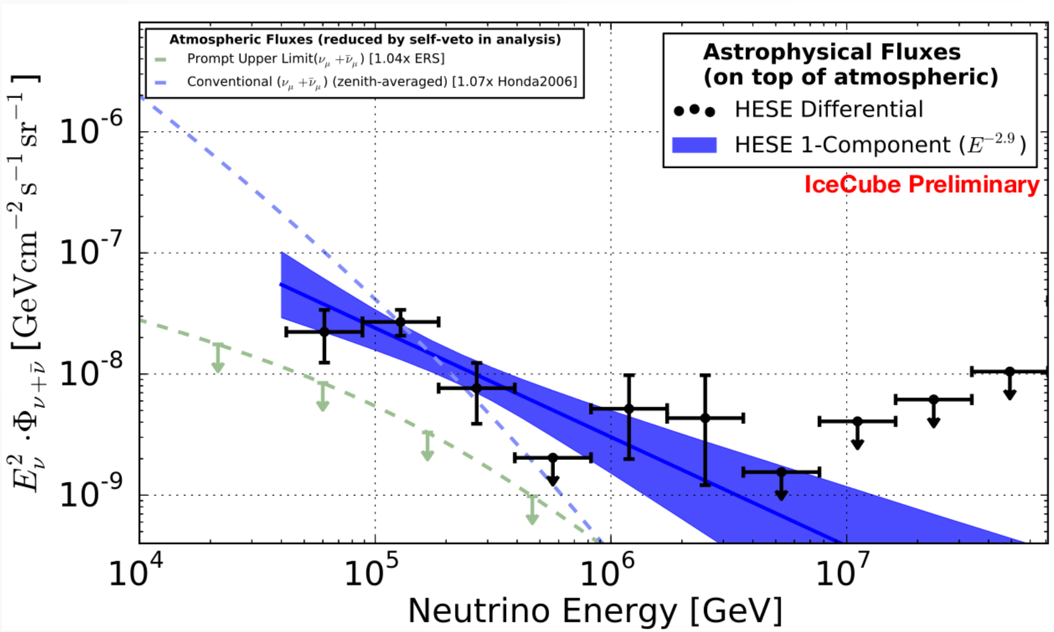
AB, J.R. Cudell
Work-In-Progress

Interpreting the Signal



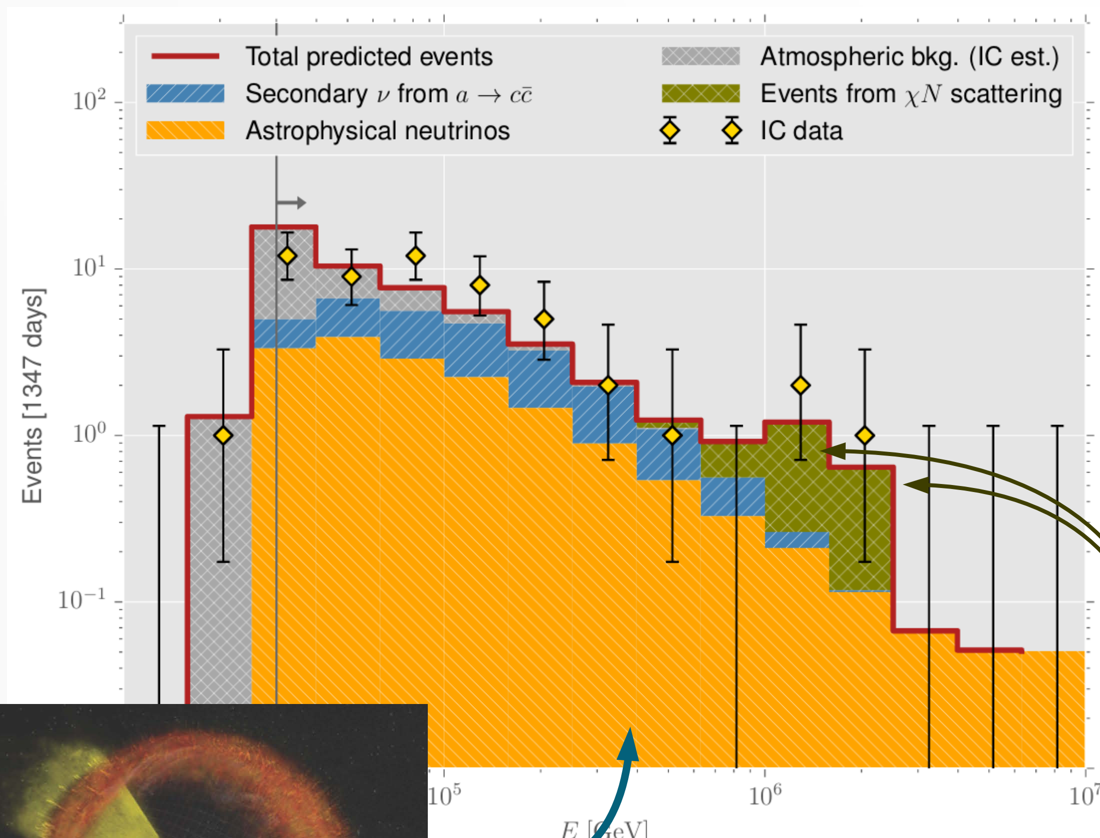
- Diffuse flux from a class of **extragalactic sources**
- Uniform power-law ∝ $E^{-2.9}$
- Equiflavoured: $\boldsymbol{\nu_e:\nu_\mu:\nu_\tau = 1:1:1}$

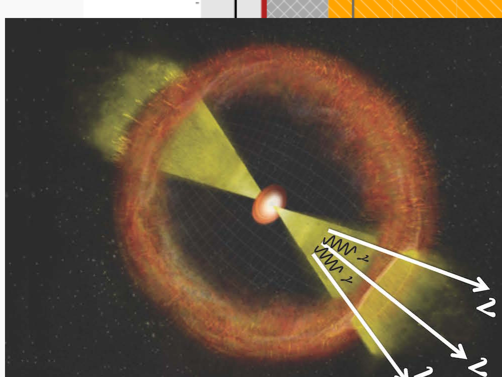
- ✓ Definite **new component of UHE ν flux**
- ✓ **> 5σ above** maximum expected **background**
- ✓ **Highest energy ν**, up to 2×10^{15} eV

- Discrepancy between sub-PeV and super-PeV spectra
- Gap ~400 TeV – 1 PeV
- Softer flux than theory ~2.0–2.2
- No events between 3–10 PeV? GR!

JCAP 1705 (2017) no.05, 002
JCAP 1503 (2015) no.03, 027

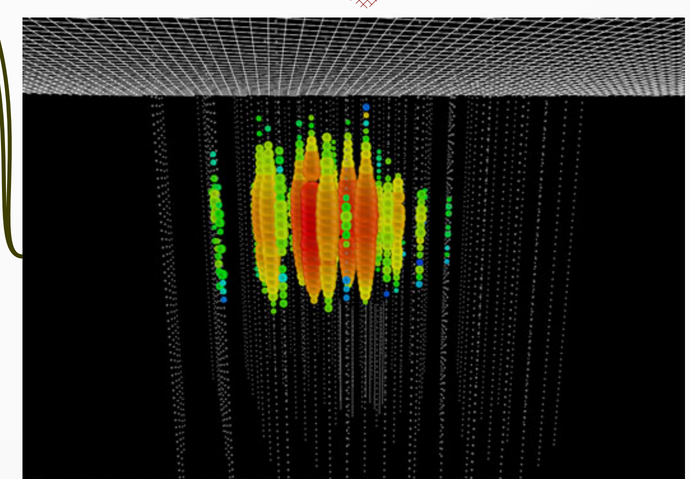
Decaying Dark Matter Interpretations





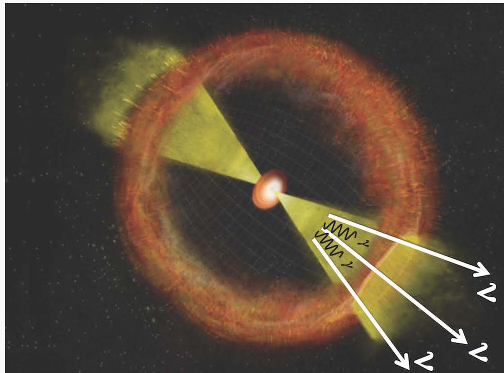
mDM ≲ 1 TeV,
Ultra-Boosted,
Weak interactions with SM,
monochromatic

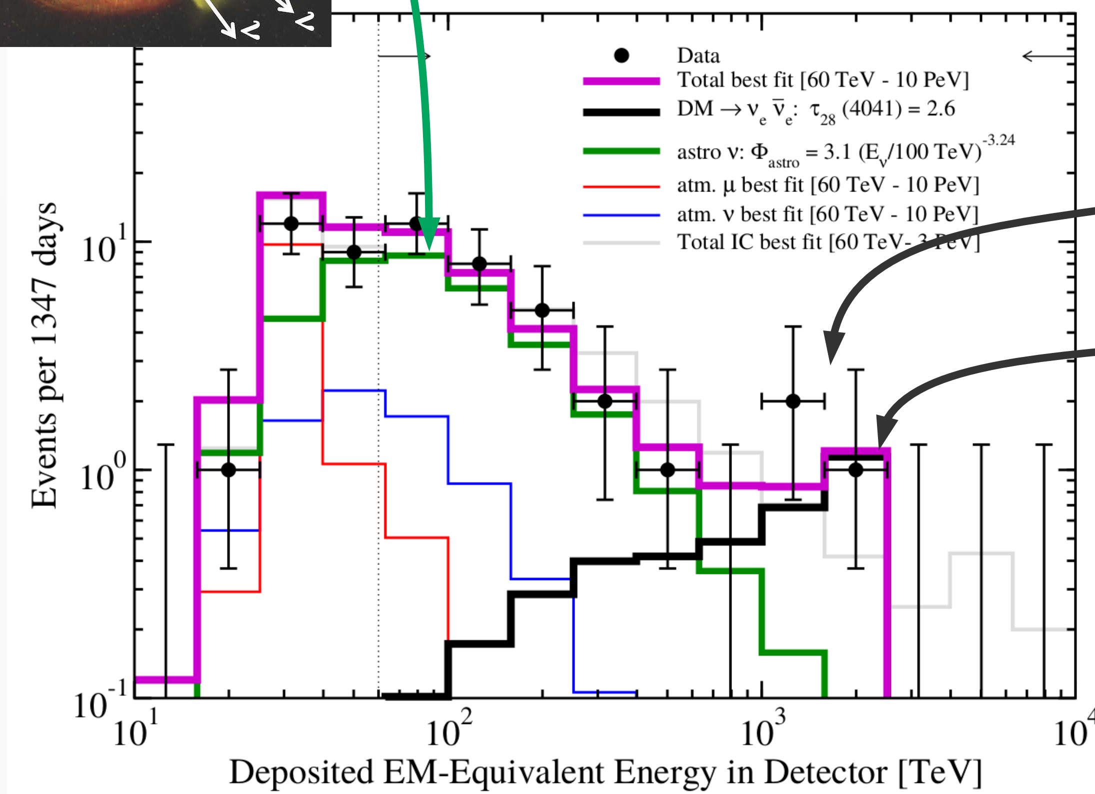
$m_{\rm DM} \approx 5$ PeV
~ 97% relic
Inert, clumpy



AB, A. Esmaili,
S. Palomares-Ruiz, I. Sarcevic
JCAP 1707 (2017) no. 07, 027

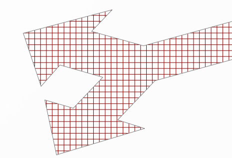
Decaying Dark Matter Interpretations





ν

ν



$m_{DM} \approx 5$ PeV,
Non-relativistic,
100% of
DM abundance

- Observations prefer multicomponent explanations.
- DM decays to SM or within DM sector work!
- Compatible with other IC results

IceCube is a window to the UHE universe
A new path to looking at astrophysical sources

Results over 6 years prove the existence of at least one *new* ν flux

What produces this flux?
Standard explanations in tension
Multi-component preferred – Dark Matter?

Improved modeling of bkg important