High-energy neutrinos at IceCube: A global picture

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AG Annual Meeting 2013
Splinter Meeting – “The High-Energy Universe”

Eberhard Karls Universität Tübingen – September 26, 2013

Introduction to neutrino astronomy and IceCube

Searches for high-energy neutrinos in IceCube

Characterization of the IceCube high-energy excess

A note on neutrino astronomy

- **"Astronomy is a natural science that is the study of celestial objects (such as moons, planets, stars, nebulae, and galaxies) […]."**
  – Wikipedia

- **Complete list of confirmed extraterrestrial neutrino sources:**
  - The Sun
  - Supernova 1987a

- **Neutrino astronomy is yet to begin**
  But maybe it is just about to start...

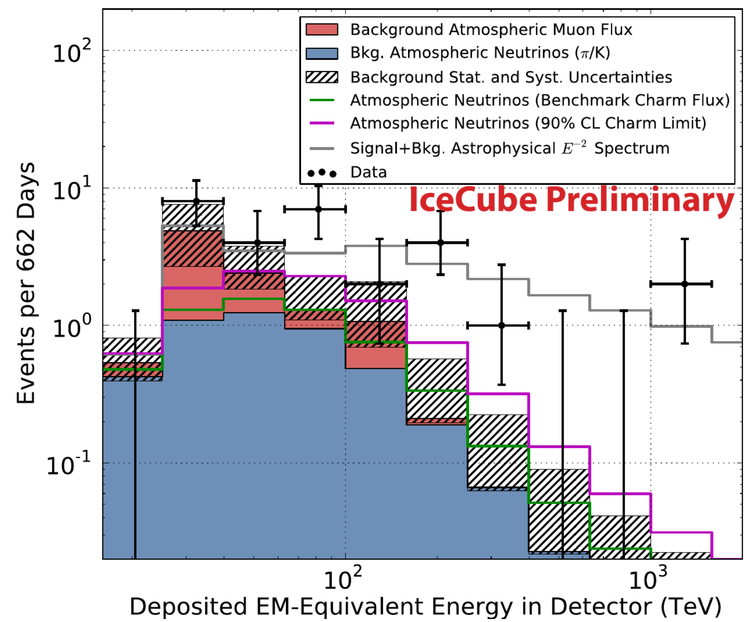
The dawn of neutrino astronomy?

PRL **111,** 021103 (2013) PHYSICAL REVIEW LETTERS week ending 12 JULY 2013

First Observation of PeV-Energy Neutrinos with IceCube

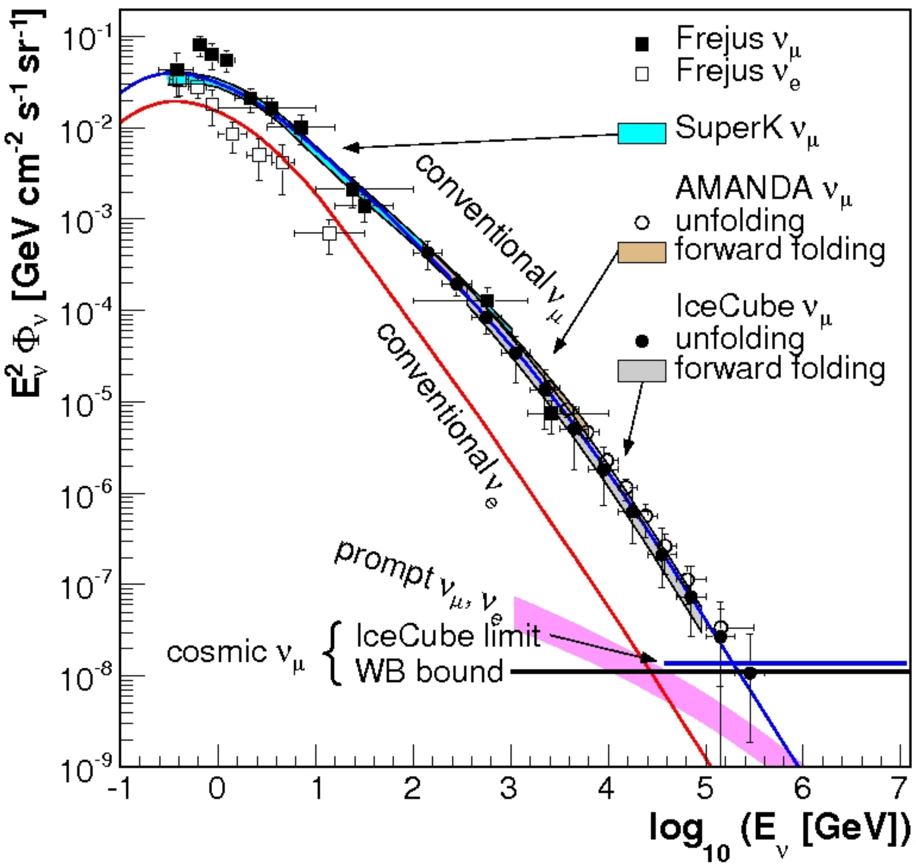
Observation of PeV Neutrinos in IceCube

Very high energy events in the 2010/2011 IceCube data



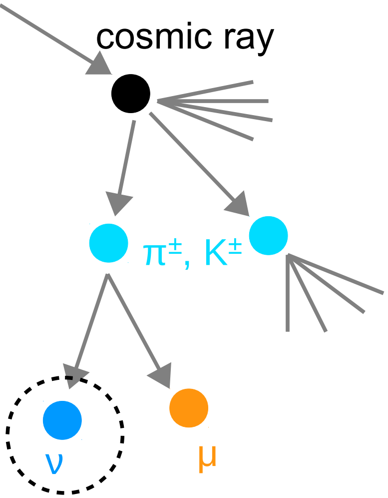
Why are high-energy neutrinos so interesting?

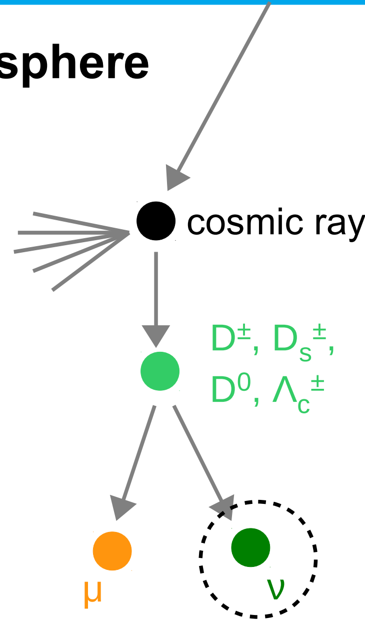
- Atmospheric neutrino spectrum is steeply falling
- Any excess at high energies is a sign for a new source of neutrinos



What are the possible sources of high-energy neutrinos?

Earth's atmosphere

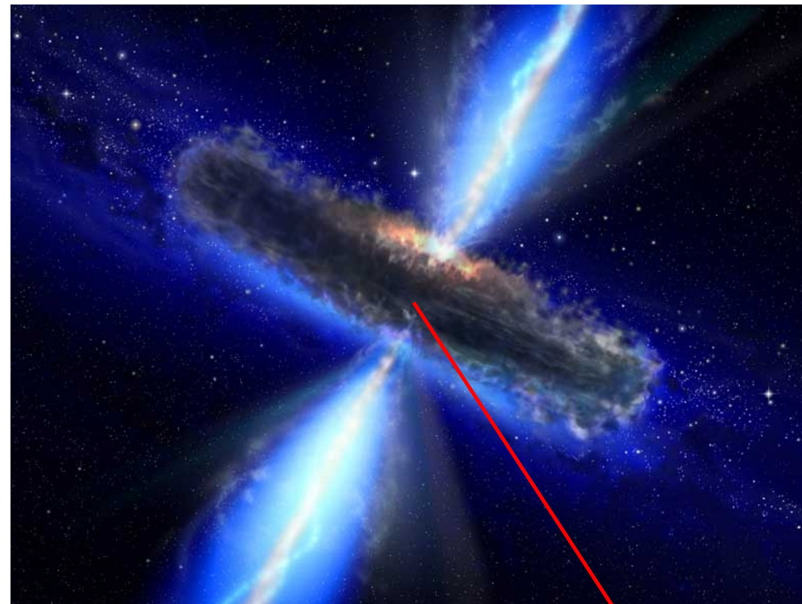




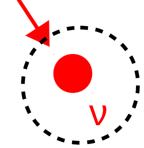
- **“Conventional”**
- From π / K decay
- $\Phi \sim E^{-3.7}$

- **“Prompt”**
- From charmed meson decay
- $\Phi \sim E^{-2.7}$
- Undetected so far

Astrophysical sources



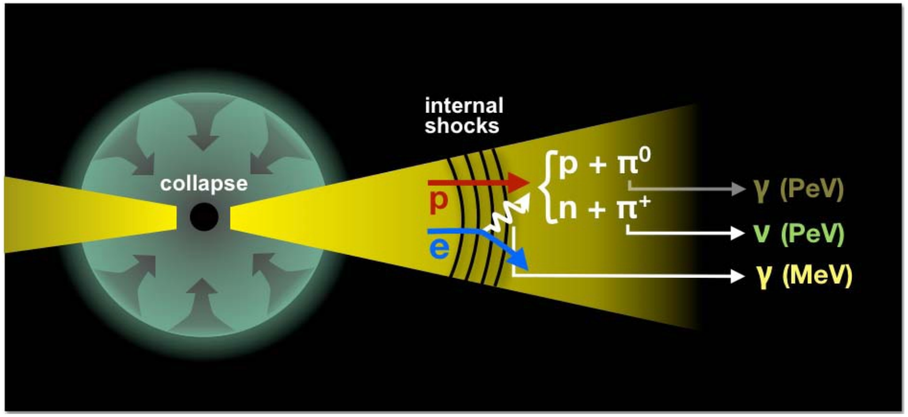
http://www.nasa.gov



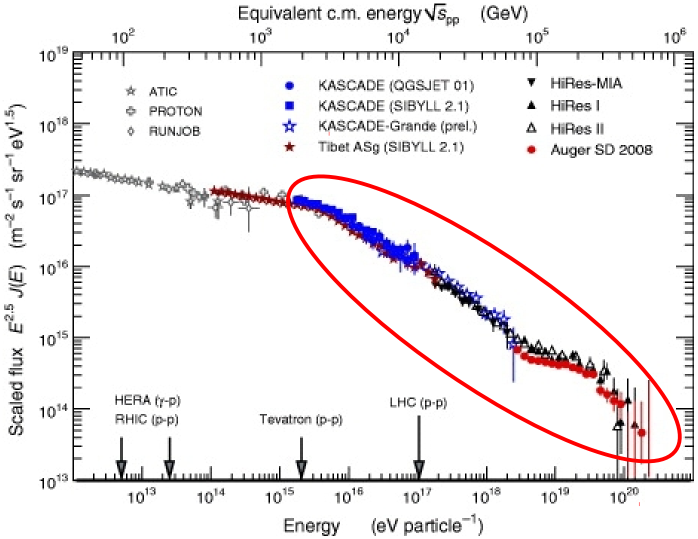
- **Astrophysical**
- Benchmark scenario:
  - $\Phi \sim E^{-2}$
  - Flavor ratio $\nu_e : \nu_\mu : \nu_\tau$ = 1 : 1 : 1
- The truth could be very different!

What can neutrinos tell us about astrophysical sources?

- Neutrinos are tracers of hadronic interactions



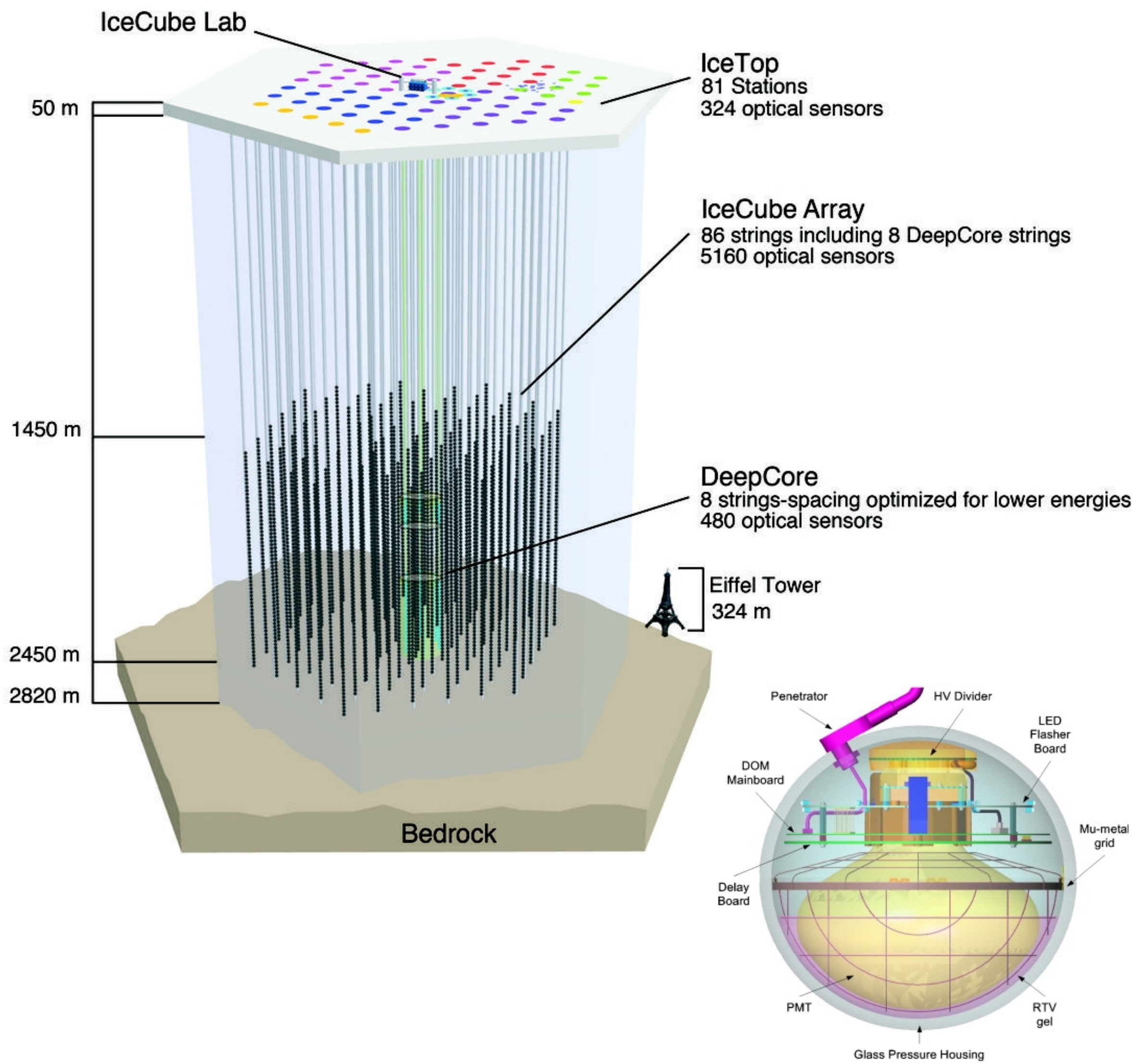
- They could help us to identify the acceleration sites of UHE cosmic rays



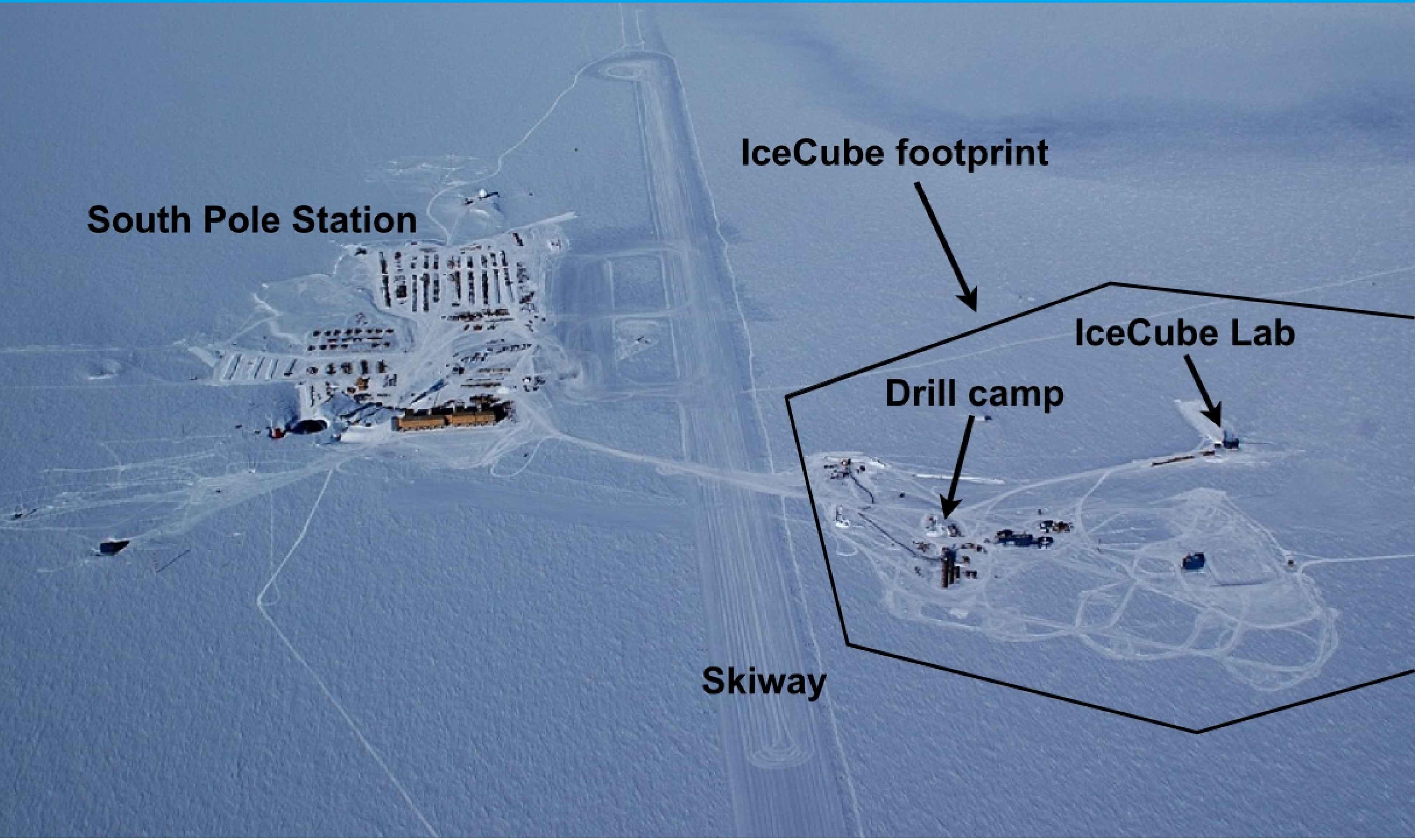
The Pierre Auger Collaboration, New J. Phys. 12, 035001 (2010)

The IceCube Neutrino Observatory

- **1 km^3** of South Pole Ice instrumented with **5160 PMTs**
- Detect neutrino interactions via **Cherenkov radiation** of secondary particles
- Full detector with **86 strings** completed in **2010** → **IC86**
- Previous configurations:
  - **IC79**
  - **IC59**
  - **IC40**



The IceCube Neutrino Observatory

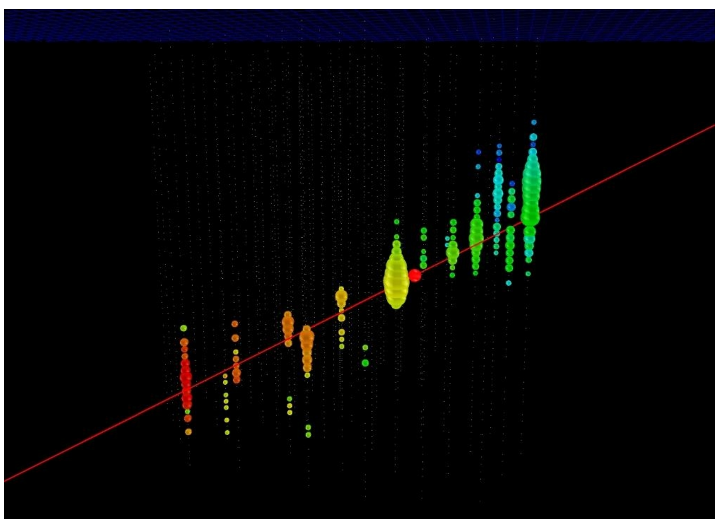


Neutrino event signatures in IceCube

Tracks

- ν_μ charged-current interaction

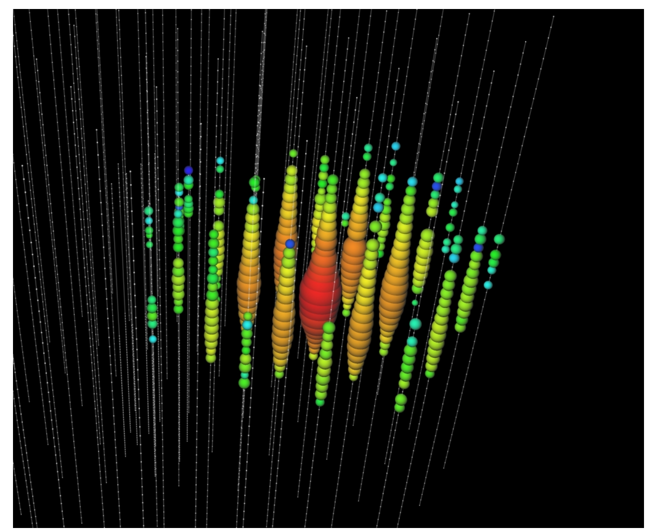
- Angular resolution < 1°
- Can measure muon dE/dx only

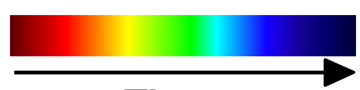


Showers

- ν_e + ν_τ charged-current interaction +
  ν_e + ν_μ + ν_τ neutral-current interaction

- Angular resolution > 10°
- Energy resolution ≥ 15%
  (on deposited energy)





Time

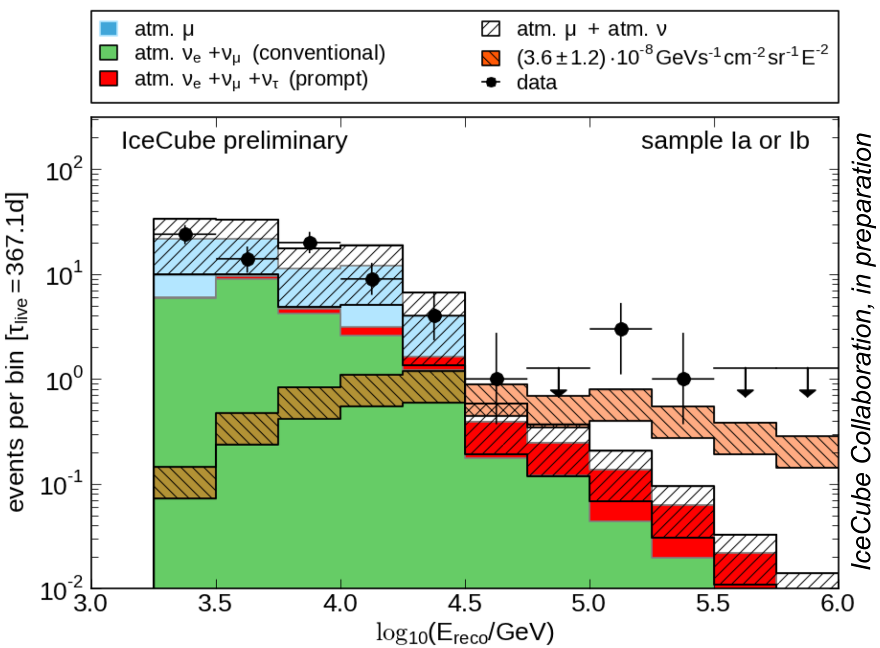
Introduction to neutrino astronomy and IceCube

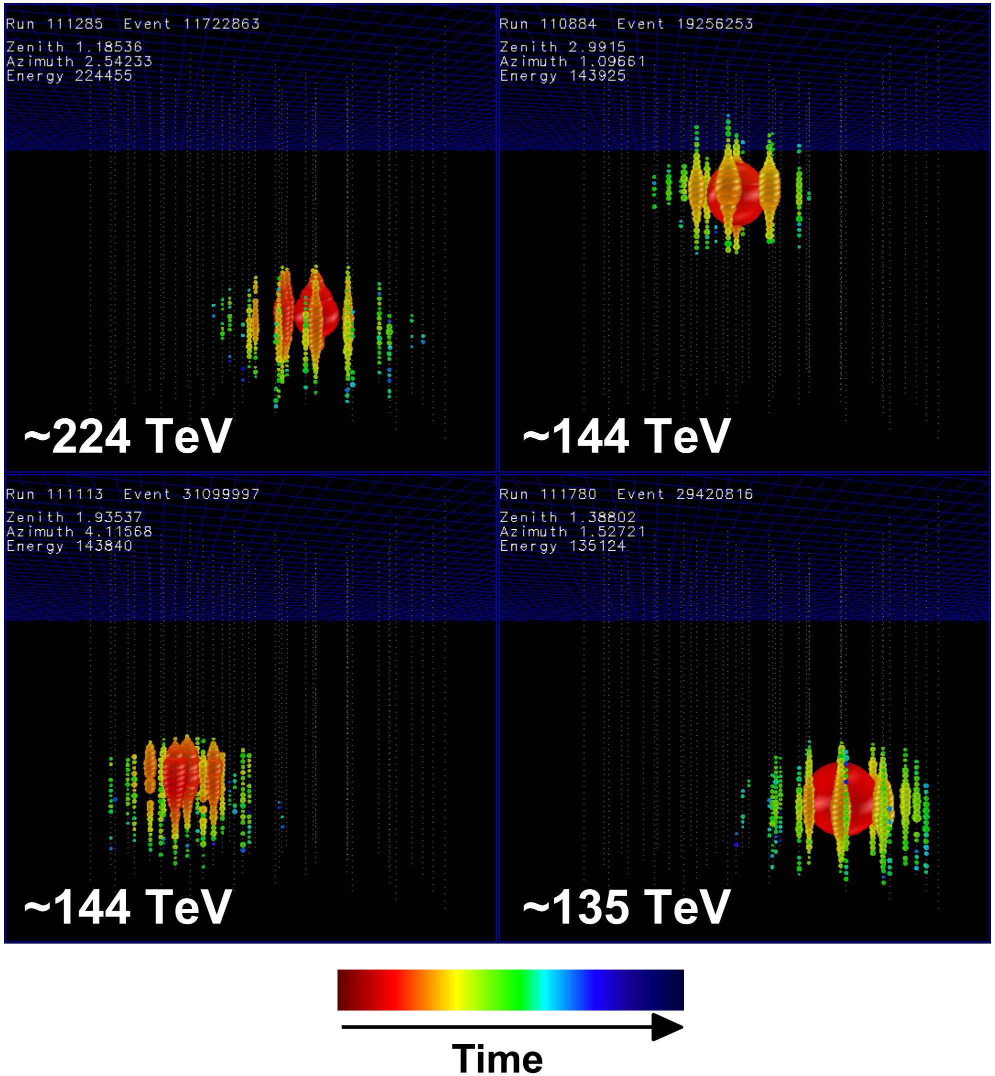
Searches for high-energy neutrinos in IceCube

Characterization of the IceCube high-energy excess

Search for contained showers with IC40

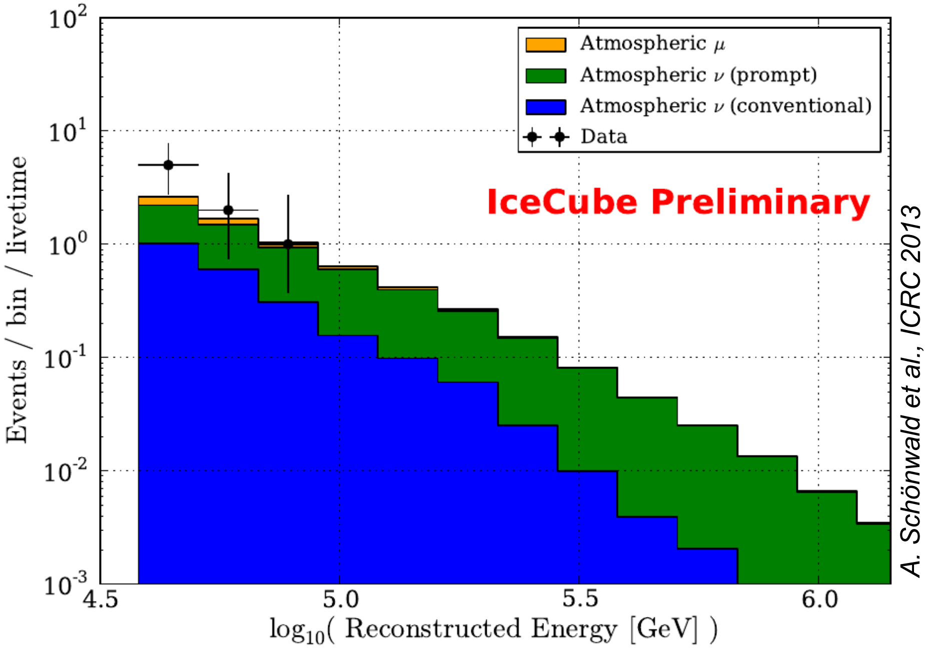
- **IC40 – contained showers**
- **Excess over background: 2.7 σ**

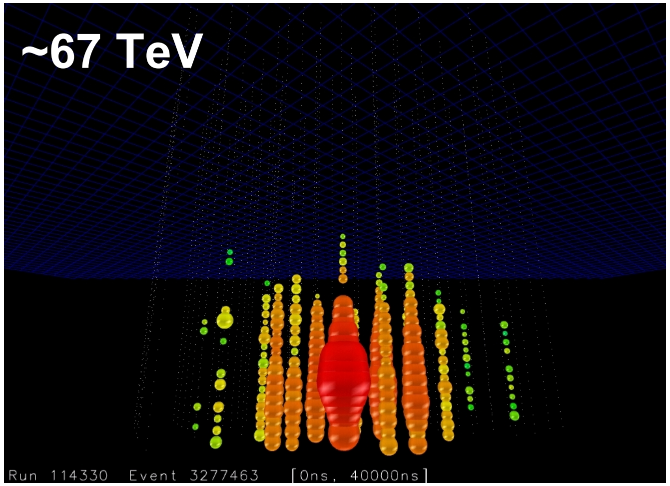


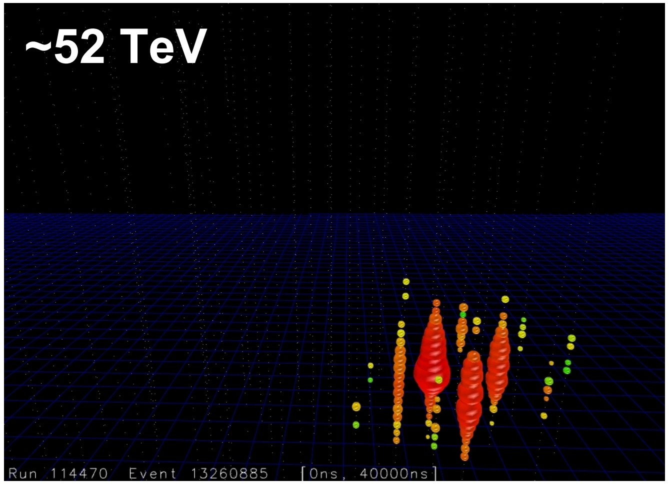


Search for contained showers with IC59

- IC59 – contained showers
- Excess not significant



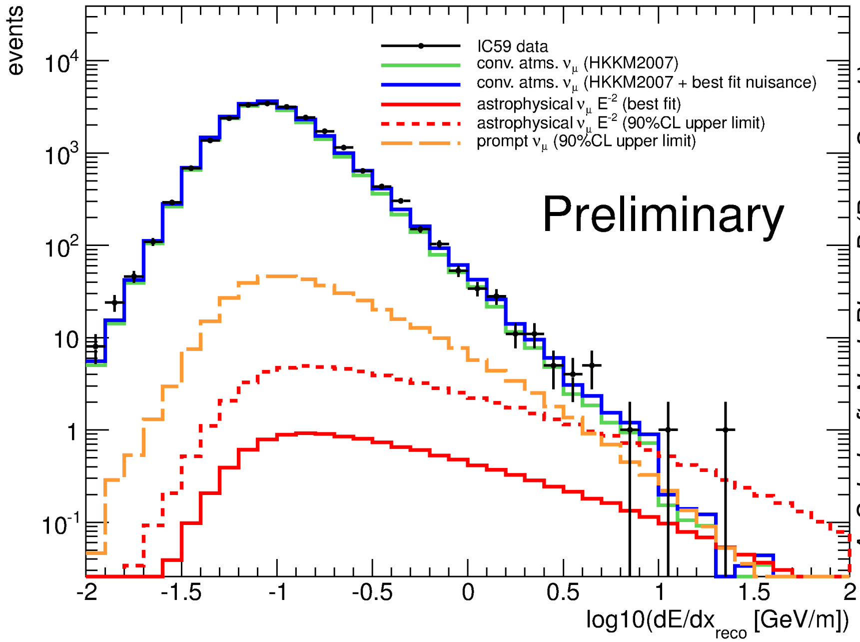




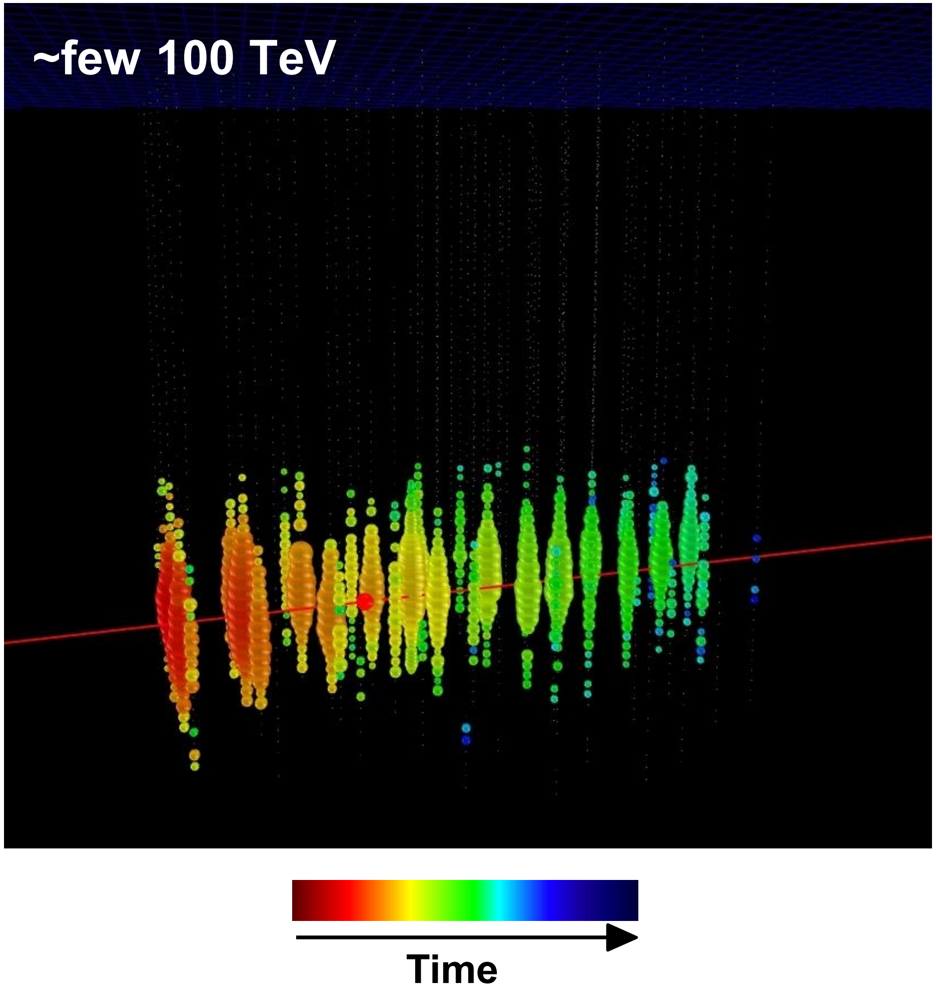
Time

Search for high-energy muon neutrinos with IC59

- **IC59 – throughgoing tracks**
- **Excess over background: 1.8 σ**

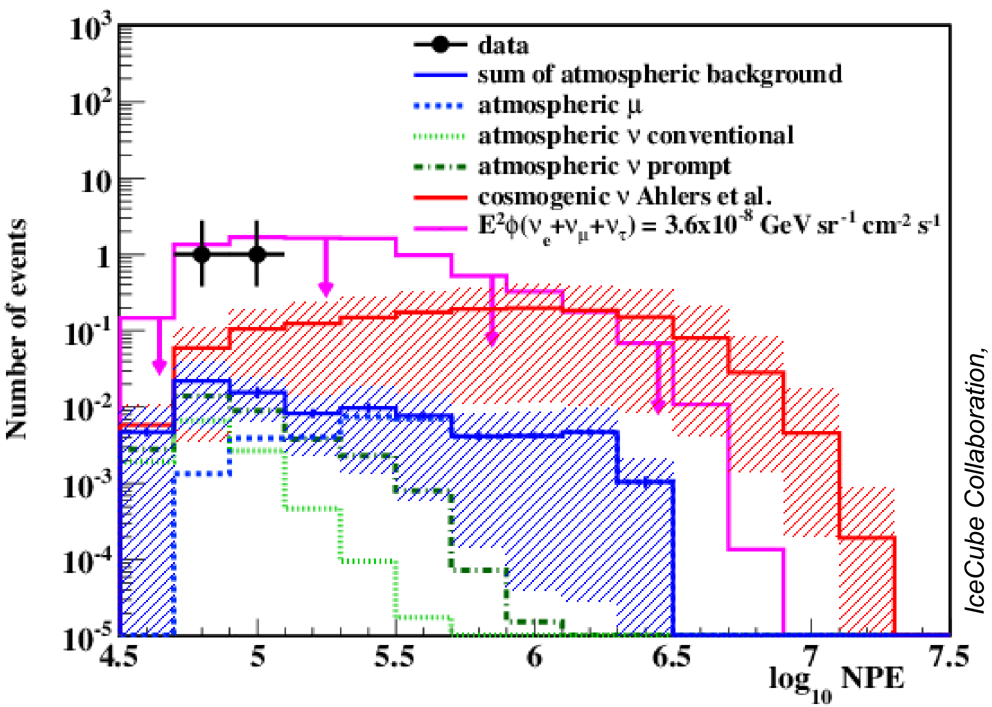


A. Schukraft, Nucl. Phys. B (Proc. Suppl.) 237-238, 266 (2013)

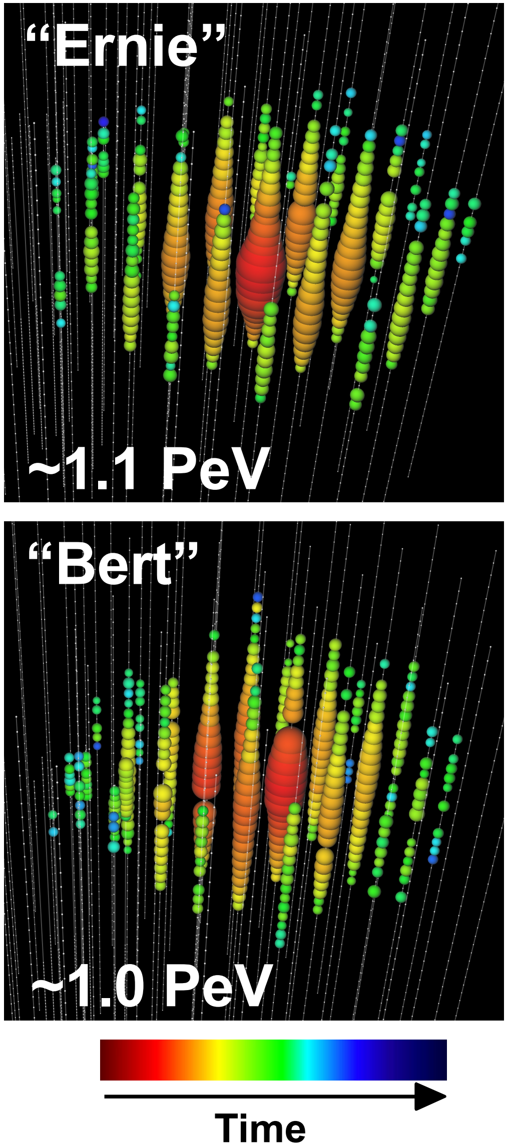


First analysis of data from the full IceCube detector

- **IC79 + IC86 – very bright events**
- **Found 2 events at energy threshold**
- **Excess over background: 2.8 σ**

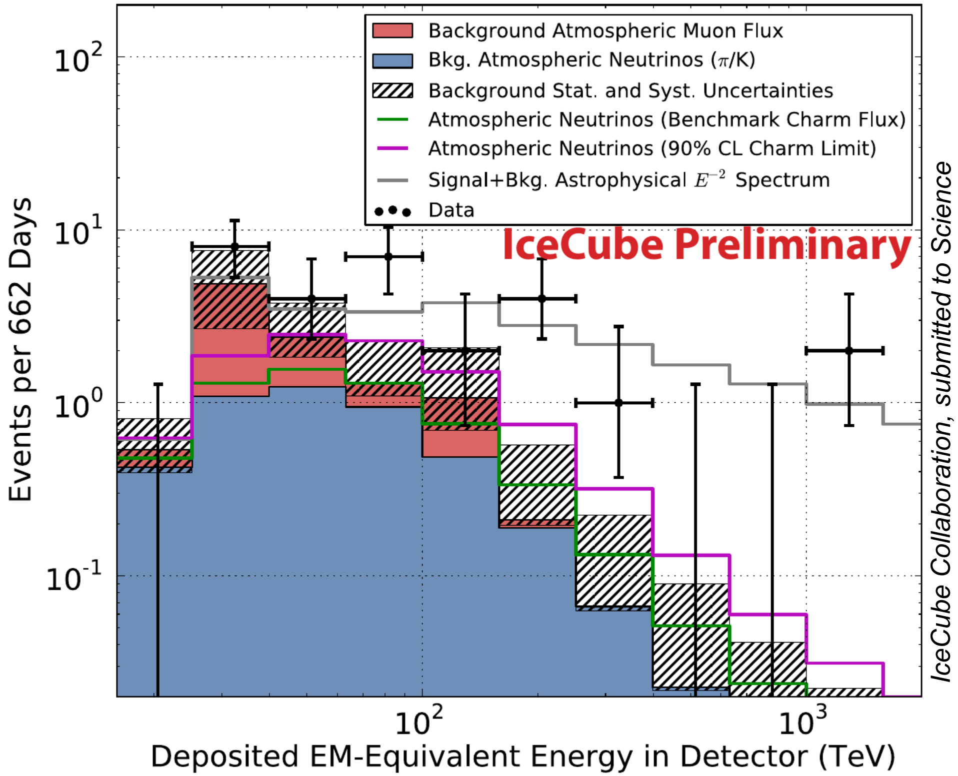


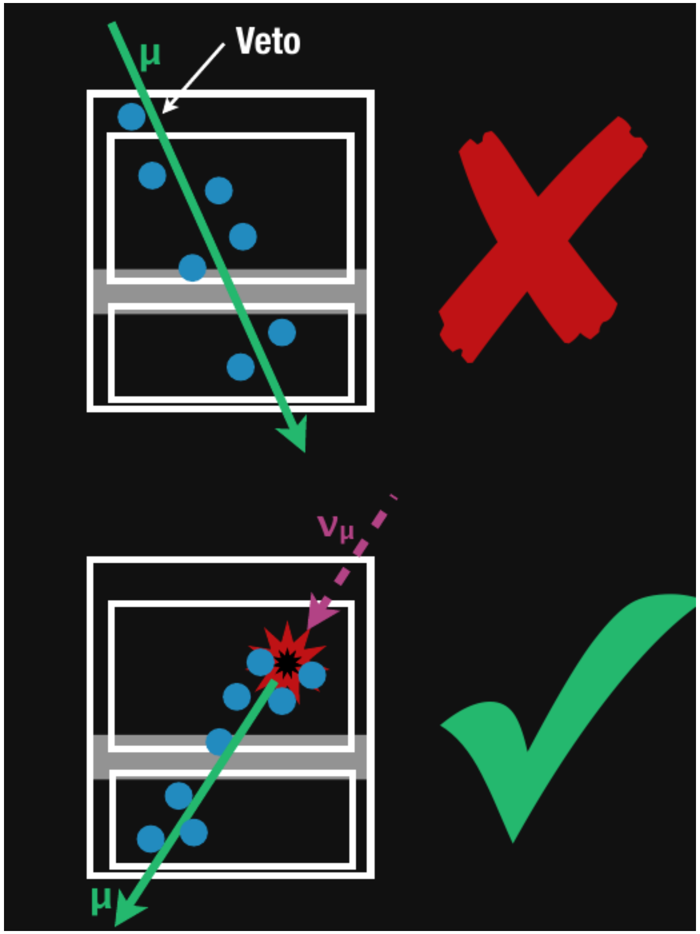
IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)



Follow-up analysis using the same data set

- IC79 + IC86 – contained showers + tracks
- 2 PeV-events + 26 new events (30 – 300 TeV)
- Combined significance of excess: 4.1 σ





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Searches for high-energy neutrinos in IceCube

Characterization of the IceCube high-energy excess

Interpretation of the IceCube excess by the community

An incomplete collection...

[ ] = arXiv reference

Extragalactic sources

On the origin of IceCube's PeV neutrinos
– Cholis, Hooper [1211.1974]

Diffuse PeV Neutrinos from Gamma-ray Bursts
– Liu, Wang [1212.1260]

Cosmic PeV Neutrinos and the Sources of Ultrahigh Energy Protons
– Kistler, Stanev, Yuksel [1301.1703]

PeV Neutrinos from Intergalactic Interactions of Cosmic Rays Emitted by Active Galactic Nuclei
– Kalashev, Kusenko, Essey [1303.0300]

Diffuse PeV neutrino emission from ultraluminous infrared galaxies
– He, Wang, Fan, Liu, Wei [1303.1253]

PeV neutrinos observed by IceCube from cores of active galactic nuclei
– Stecker [1305.7404]

TeV-PeV neutrinos from Low-Power Gamma-ray Burst Jets inside Stars
– Murase, Ioka [1306.2274]

Testing the Hadronuclear Origin of PeV Neutrinos Observed with IceCube
– Murase, Ahlers, Lacki [1306.3417]

Photohadronic Origin of the TeV-PeV Neutrinos Observed in IceCube
– Winter [1307.2793]

Long-lived PeV-EeV Neutrinos from GRB Blastwave
– Razzaque [1307.7596]

Galactic sources

Galactic PeV Neutrinos
– Gupta [1305.4123]

Sub-PeV Neutrinos from TeV Unidentified Sources in the Galaxy
– Fox, Kashiyama, Meszaros [1305.6606]

Pinning down the cosmic ray source mechanism with new IceCube data
– Anchordoqui et al. [1306.5021]

The Galactic Pevatron
– Neronov, Semikoz, Tchernin [1307.2158]

The Galactic Center Origin of a Subset of IceCube Neutrino Events
– Razzaque [1309.2756]

Probing the Galactic Origin of the IceCube Excess with Gamma-Rays
– Ahlers, Murase [1309.4077]

Lorentz invariance tests

Stringent constraint on neutrino Lorentz invariance violation from the two IceCube PeV neutrinos
– Borriello et al. [1303.5843]

Constraining Superluminal Electron and Neutrino Velocities using the 2010 Crab Nebula Flare and the IceCube PeV Neutrino Events
– Stecker [1306.6095]

Testing Relativity with High-Energy Astrophysical Neutrinos
– Diaz, Kostelecky, Mewes [1308.6344]

Exotic

Neutrino decays over cosmological distances and the implications for neutrino telescopes
– Baerwald, Bustamante, Winter [1208.4600]

Explanation for the Low Flux of High-Energy Astrophysical Muon Neutrinos
– Pakvasa, Joshipura, Mohanty [1209.5630]

Neutrinos at IceCube from heavy decaying dark matter
– Feldstein et al. [1303.7320]

Superheavy Particle Origin of IceCube PeV Neutrino Events
– Barger, Keung [1305.6907]

Pseudo-Dirac neutrinos via mirror-world and depletion of UHE neutrinos
– Joshipura, Mohanty, Pakvasa [1307.5712]

Are IceCube neutrinos unveiling PeV-scale decaying dark matter?
– Esmaili, Sercipo [1308.1105]

Two source populations

TeV-PeV neutrinos over the atmospheric background: originating from groups of sources?
– He, Yang, Fan, Wei [1307.1450]

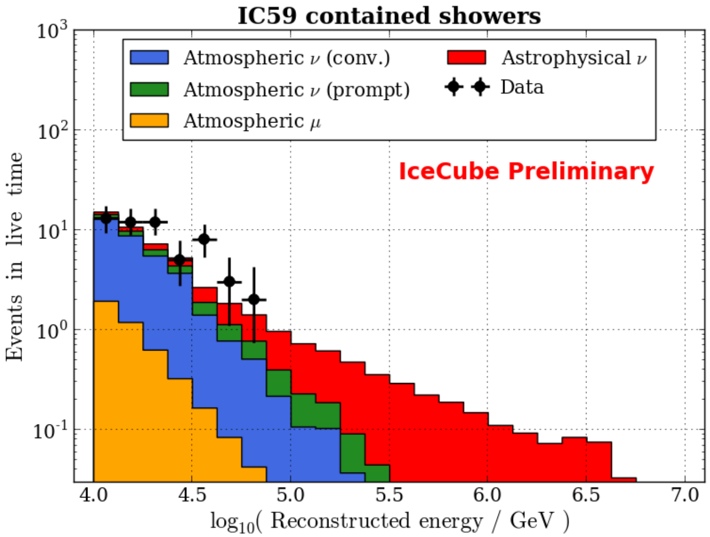
> 30 papers in total

Global likelihood fit

- **Characterize** the excess by fitting a **generic model** to the data of **multiple analyses**
- Perform **Poisson-likelihood fit** of **energy distributions**

Global likelihood fit

- **Goal:** Characterize the excess by using information from all analyses at the same time
- **Method:** Global Poisson-likelihood fit of energy distributions
- **Components:**
  - Atmospheric μ – CORSIKA simulation / from data
  - Atmospheric ν (conventional) – Honda et al.[1] + Gaisser[3] (H3a)
  - Atmospheric ν (prompt) – Enberg et al.[2] + Gaisser[3] (H3a)
  - Astrophysical ν – $E^2\Phi = 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}



[1]Honda et al., Phys. Rev. D 75, 043006 (2007)
[2]Enberg et al., Phys. Rev. D 78, 043005 (2008)
[3]Gaisser, Astropart. Phys. 35, 801-806 (2012)

Global likelihood fit

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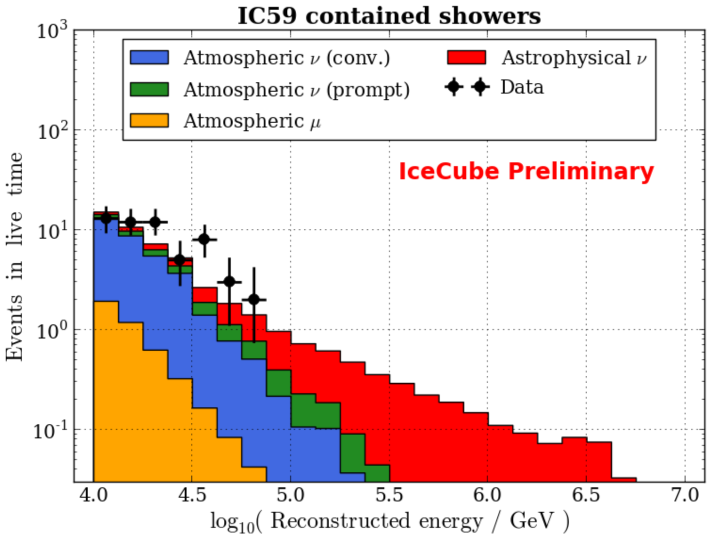
  - Astrophysical ν



- **Parameters:**
  - Normalization (μ)* + (ν) + (ν) + (ν)
  - * Nuisance parameters
    → absorb systematic effects

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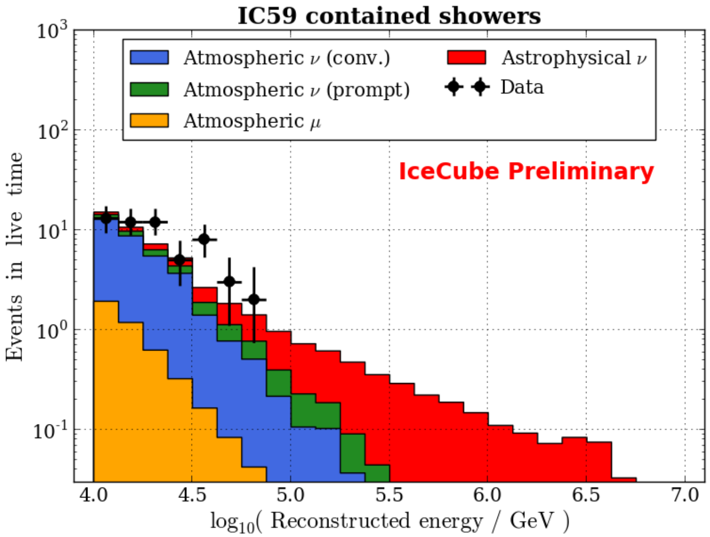

- **Parameters:**
  - Normalization (μ)* + (ν) + (ν) + (ν)
  - Cosmic ray spectral index (μ, ν, ν)*
  - * Nuisance parameters
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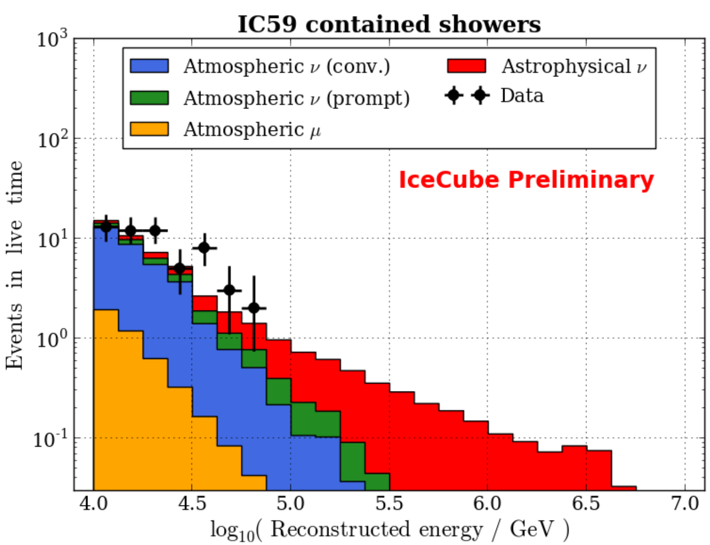

- **Parameters:**
  - **Normalization (μ)* + (ν) + (ν) + (ν)**
  - **Cosmic ray spectral index (μ, ν, ν)***
  - **Kaon-to-pion ratio (ν)***
  - *** Nuisance parameters**
    → absorb systematic effects

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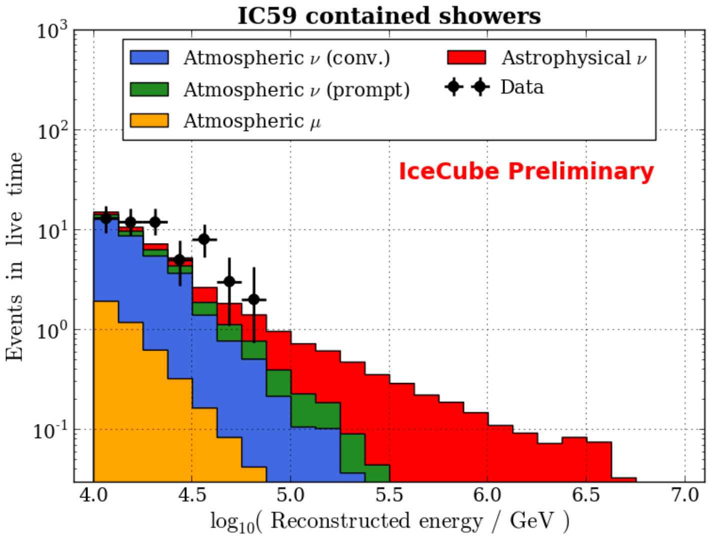

- **Parameters:**
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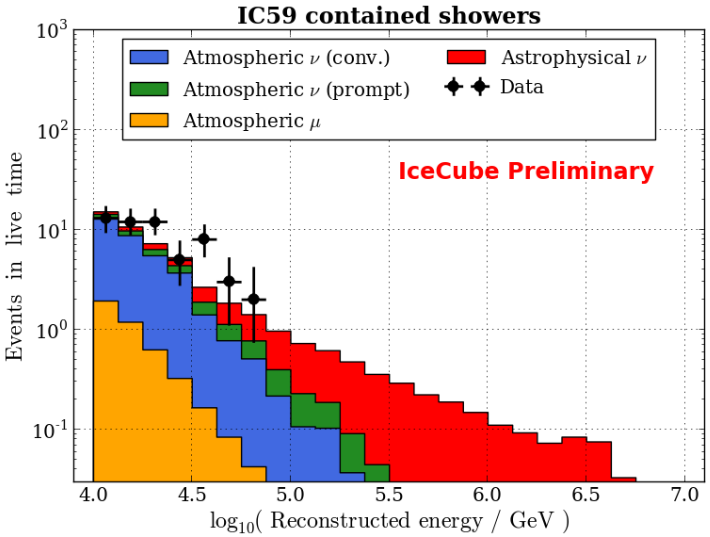

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  - **Cosmic ray spectral index (μ, ν, ν)***
  - **Kaon-to-pion ratio (ν)***
  - **Energy scale (μ, ν, ν, ν)***
  - **Power law index (ν)**
  - *** Nuisance parameters**
    → absorb systematic effects

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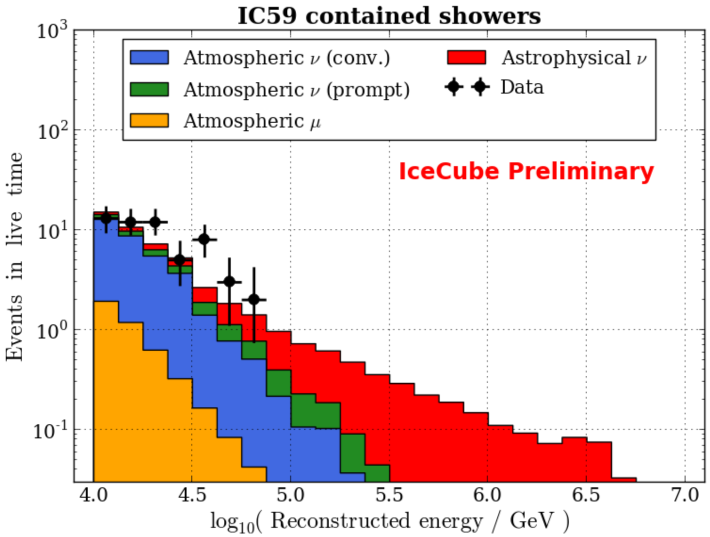
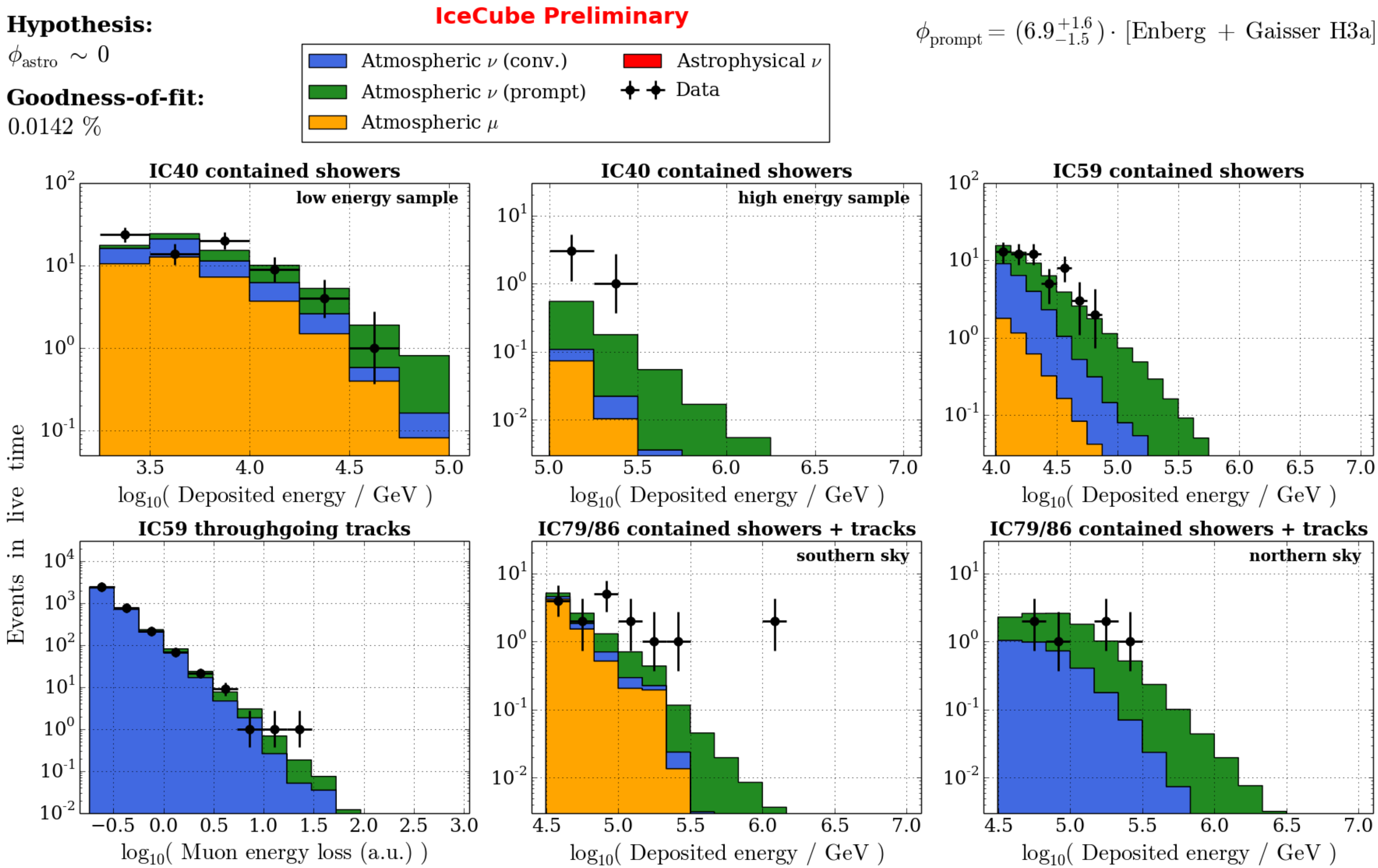


- **Parameters:**
  - Normalization (μ)* + (ν) + (ν) + (ν)
  - Cosmic ray spectral index (μ, ν, ν)*
  - Kaon-to-pion ratio (ν)*
  - Energy scale (μ, ν, ν, ν)*
  - Power law index (ν)
  - Exponential cut-off (ν)
  - * Nuisance parameters
    → absorb systematic effects

Fit result – background-only hypothesis

Hypothesis:
$\phi_{\mathrm{astro}} \sim 0$

Goodness-of-fit:
0.0142 %



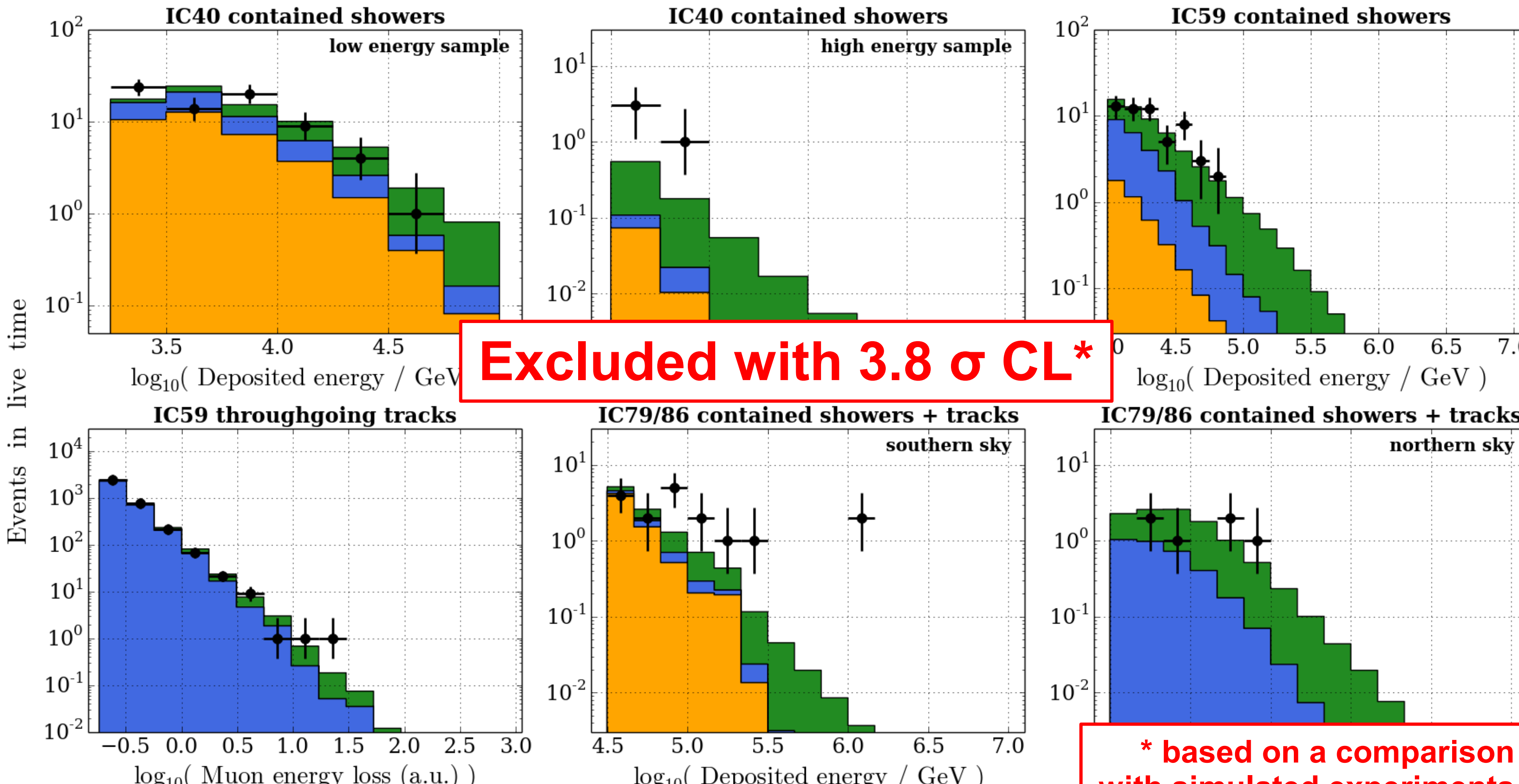
Fit result – background-only hypothesis

IceCube Preliminary

Hypothesis:
$\phi_{\text{astro}} \sim 0$

Goodness-of-fit:
0.0142 %

$\phi_{\text{prompt}} = (6.9^{+1.6}_{-1.5}) \cdot$ [Enberg + Gaisser H3a]



Excluded with 3.8 σ CL*

*** based on a comparison with simulated experiments**

Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-2}$)

Hypothesis:

$\phi_{\text{astro}} \sim E^{-2}$

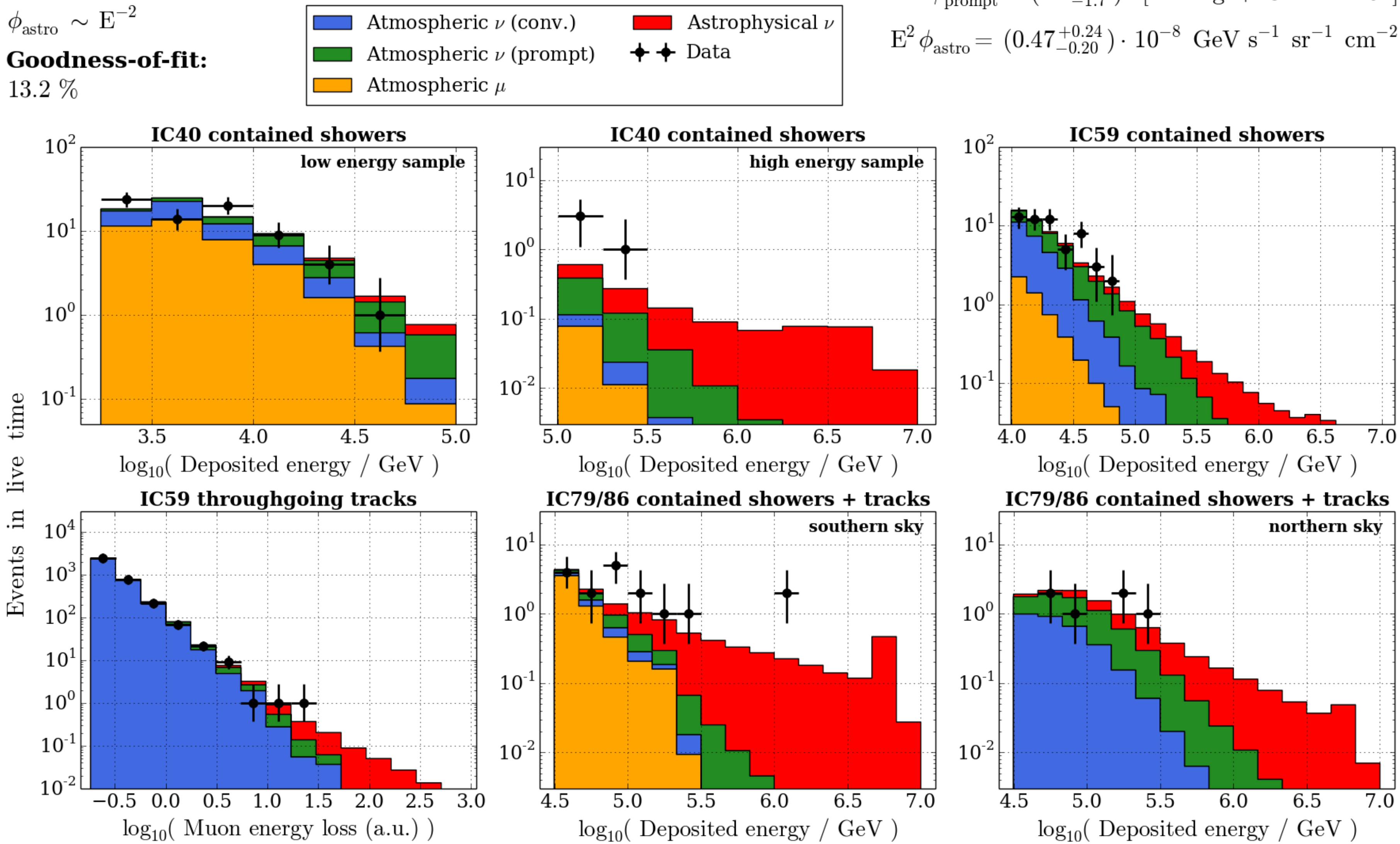
Goodness-of-fit:

13.2 %

IceCube Preliminary

$\phi_{\text{prompt}} = (4.2^{+1.8}_{-1.7}) \cdot [\text{Enberg} + \text{Gaisser H3a}]$

$E^2\,\phi_{\text{astro}} = (0.47^{+0.24}_{-0.20}) \cdot 10^{-8}\ \text{GeV s}^{-1}\ \text{sr}^{-1}\ \text{cm}^{-2}$



Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-2} \cdot e^{E/Ecut}$)

Hypothesis:

$\phi_{astro} \sim E^{-2} \cdot \exp(E/E_{cut})$

Goodness-of-fit:

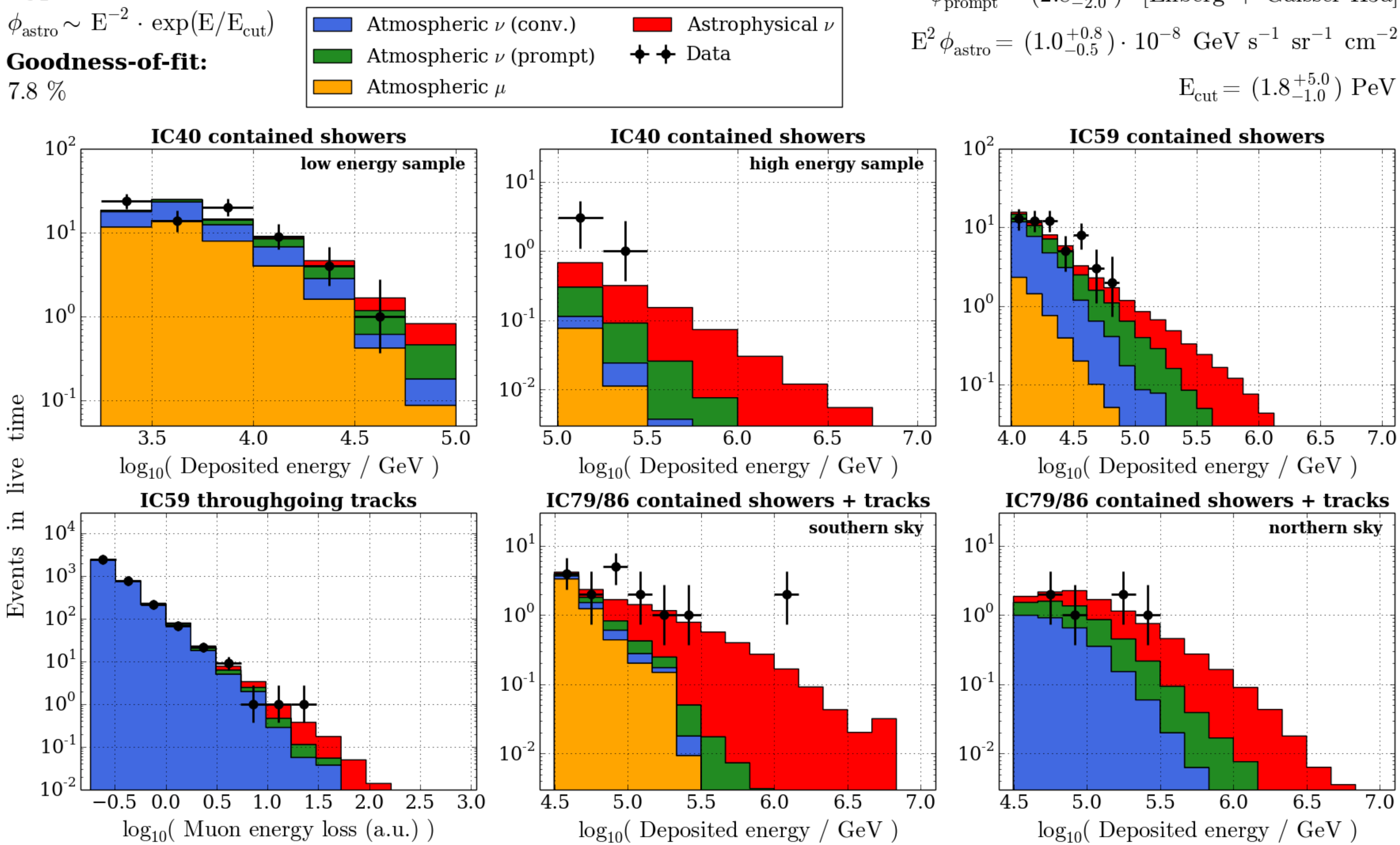
7.8 %

IceCube Preliminary

$\phi_{prompt} = (2.8^{+2.0}_{-2.0}) \cdot$ [Enberg + Gaisser H3a]

$E^2 \phi_{astro} = (1.0^{+0.8}_{-0.5}) \cdot 10^{-8}$ GeV s^{-1} sr^{-1} cm^{-2}

$E_{cut} = (1.8^{+5.0}_{-1.0})$ PeV



Fit result – with astrophysical signal ($\Phi_{astro} \sim E^{-\gamma}$)

Hypothesis:
$\phi_{astro} \sim E^{-\gamma}$

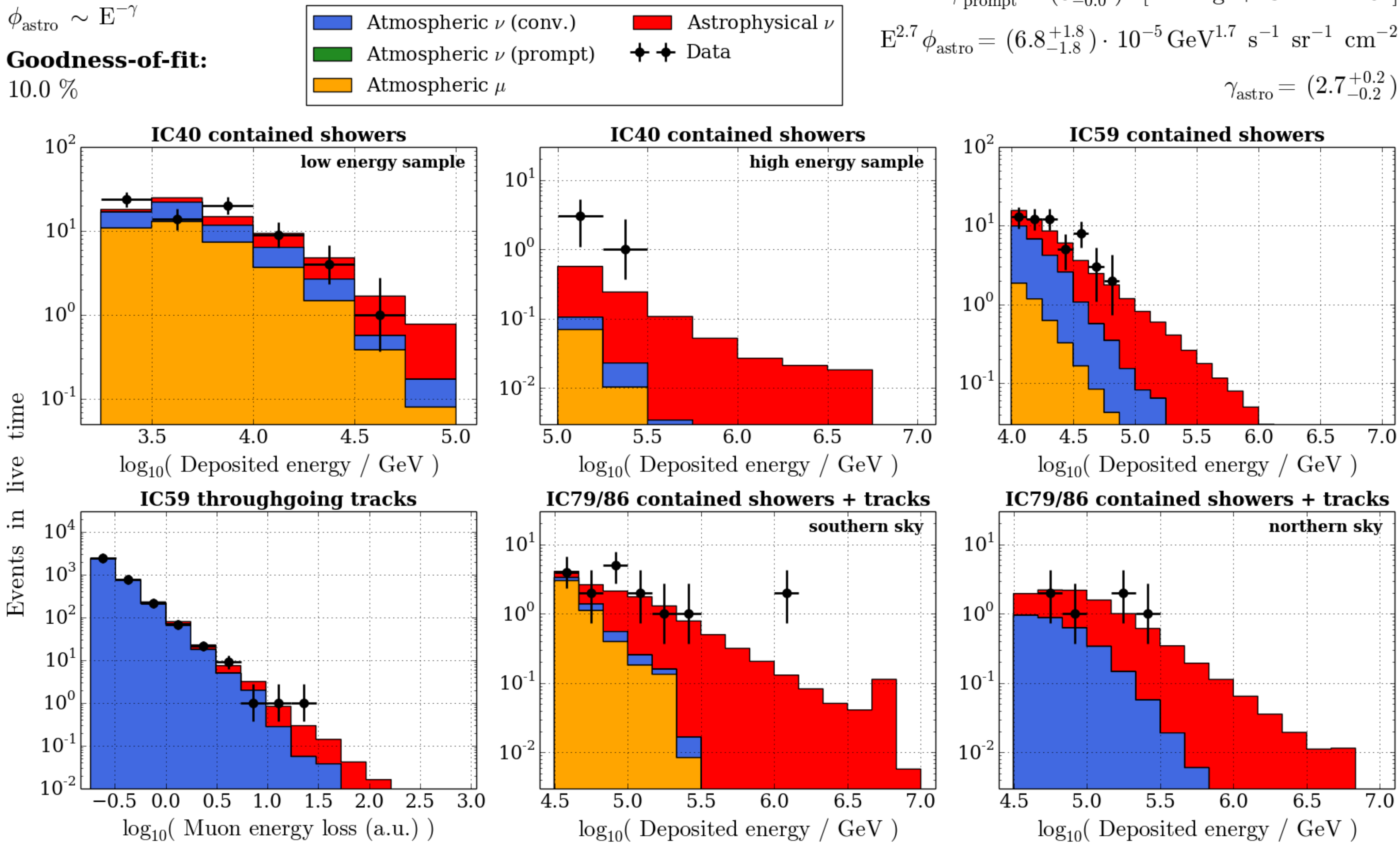
Goodness-of-fit:
10.0 %

IceCube Preliminary

$\phi_{prompt} = (0^{+1.6}_{-0.0}) \cdot$ [Enberg + Gaisser H3a]

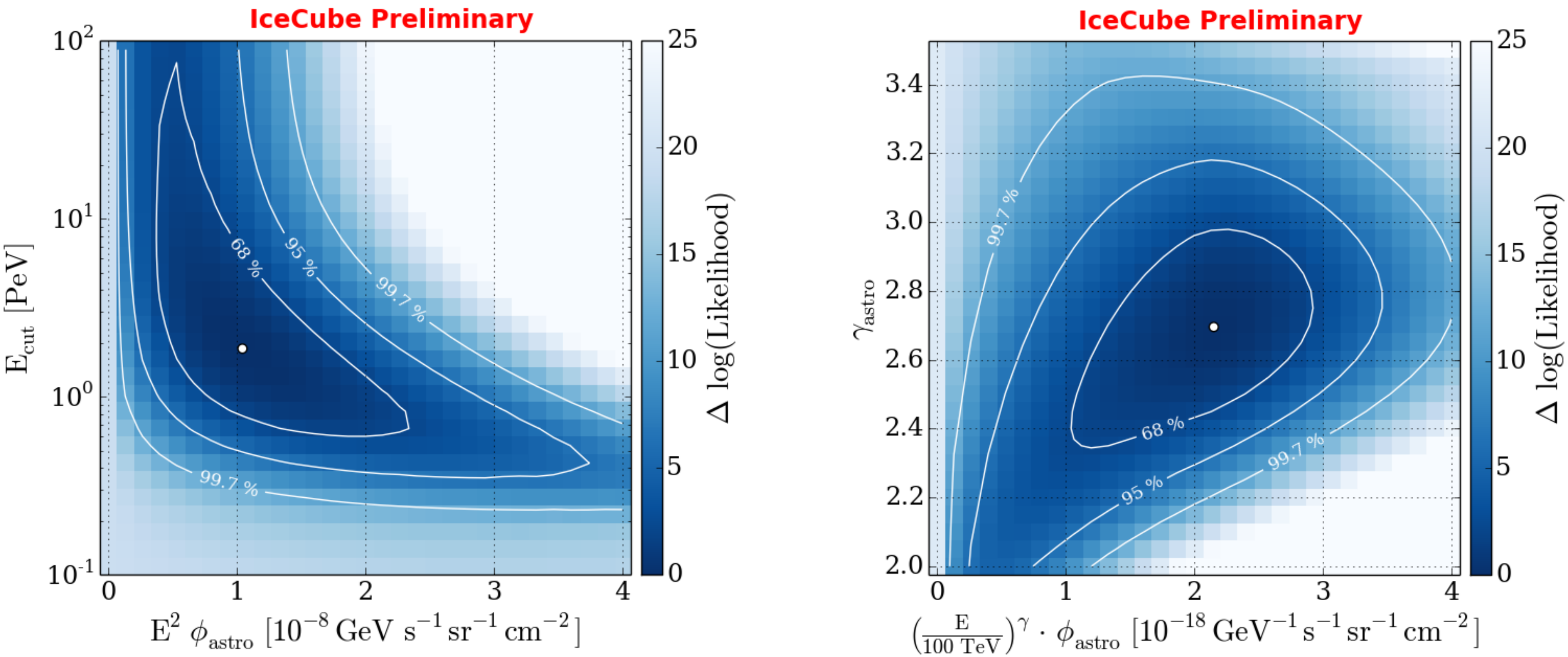
$E^{2.7}\phi_{astro} = (6.8^{+1.8}_{-1.8}) \cdot 10^{-5}\,\mathrm{GeV}^{1.7}\ \mathrm{s}^{-1}\ \mathrm{sr}^{-1}\ \mathrm{cm}^{-2}$

$\gamma_{astro} = (2.7^{+0.2}_{-0.2})$



Likelihood landscapes

- Scan of **likelihood landscape** shows **correlation of parameters**
- **Normalization** of astrophysical spectrum is **correlated with index / cut-off parameter**



Conclusion

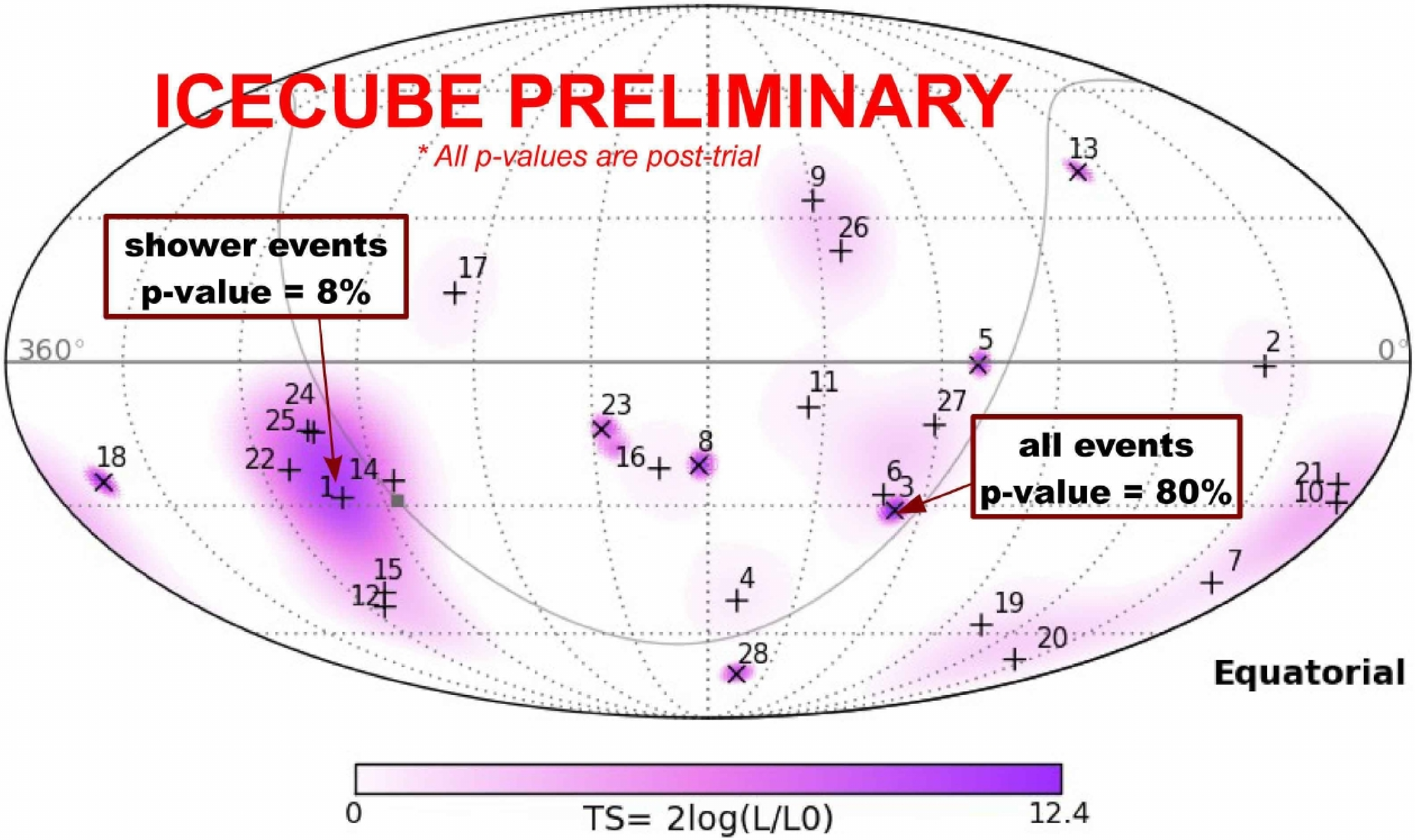
- **IceCube** measures an **excess of high-energy neutrino events**
  → this could be the **dawn of neutrino astronomy...**

- Presented **first global interpretation** of IceCube results
  - Results of individual analyses are **consistent**
  - The **prompt component** of the atmospheric neutrino flux is **not well constrained**
  - However, an **astrophysical component is needed** to explain the excess
  - **Different hypotheses** for the astrophysical flux yield **similar results**

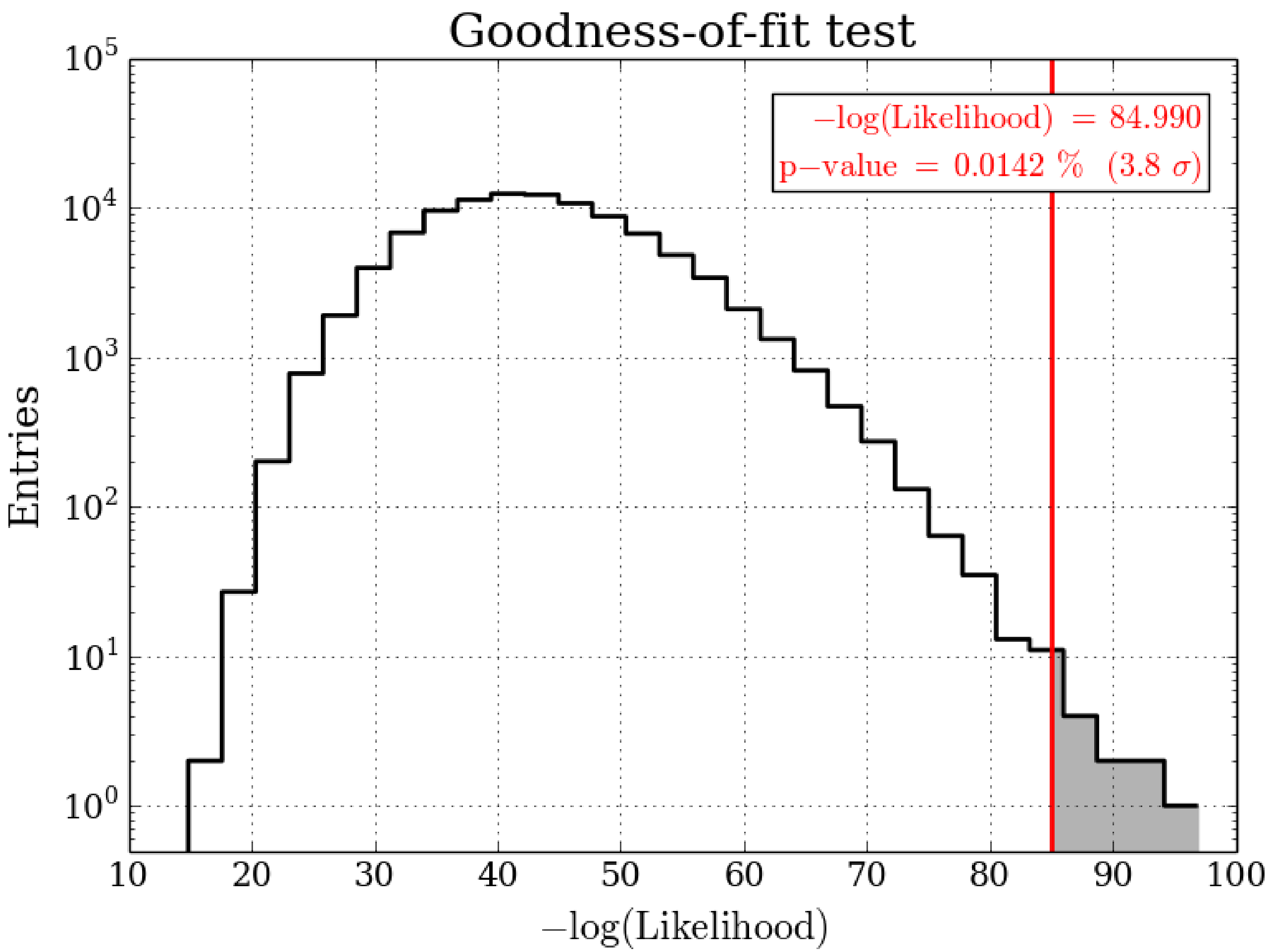
- Results of **new analyses** expected soon
  → **global analysis** will become more powerful

Backup slides

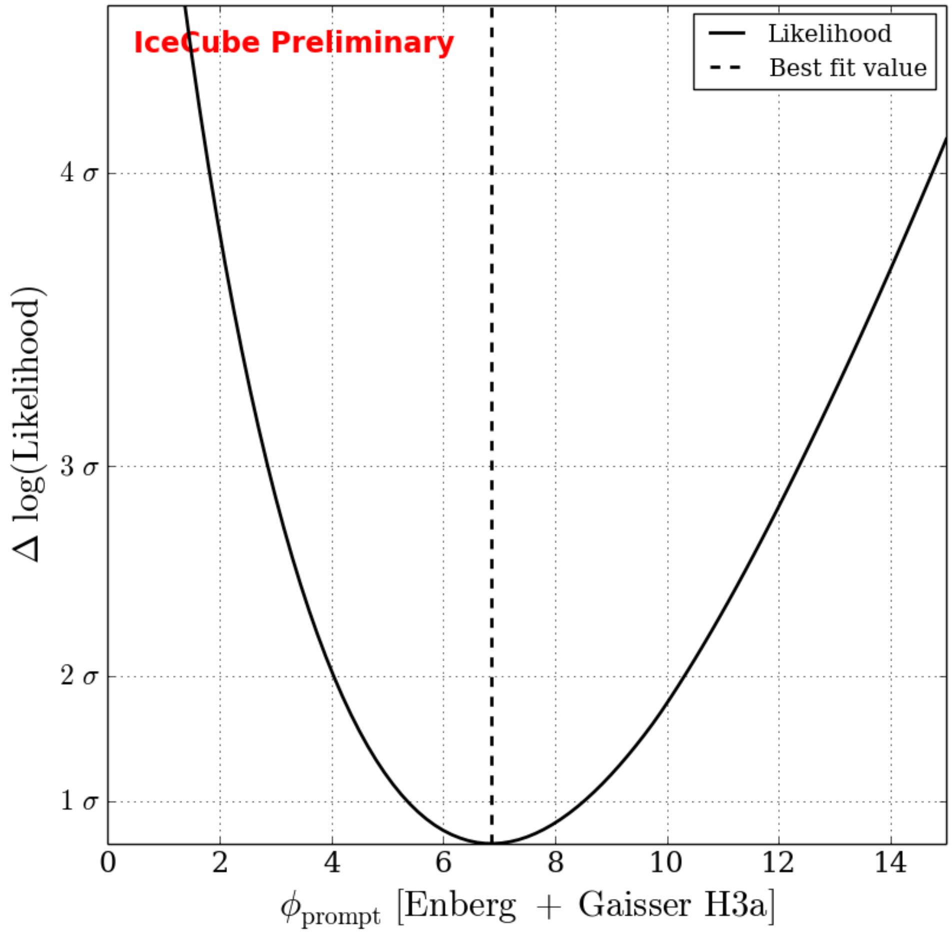
Skymap of the 28 high-energy events



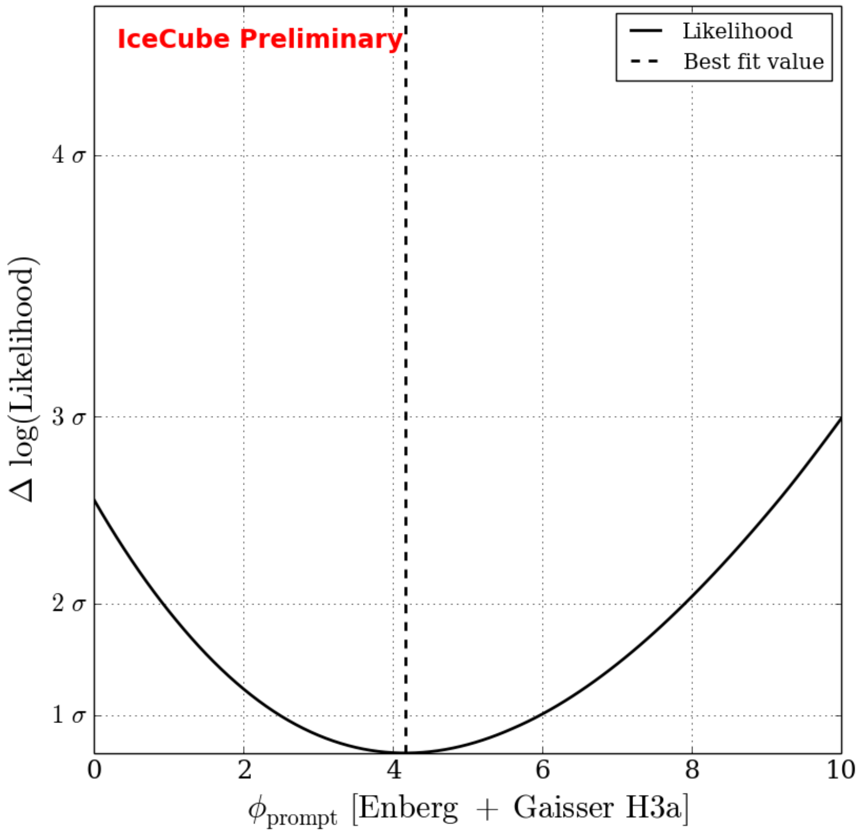
Goodness-of-fit for background-only hypothesis

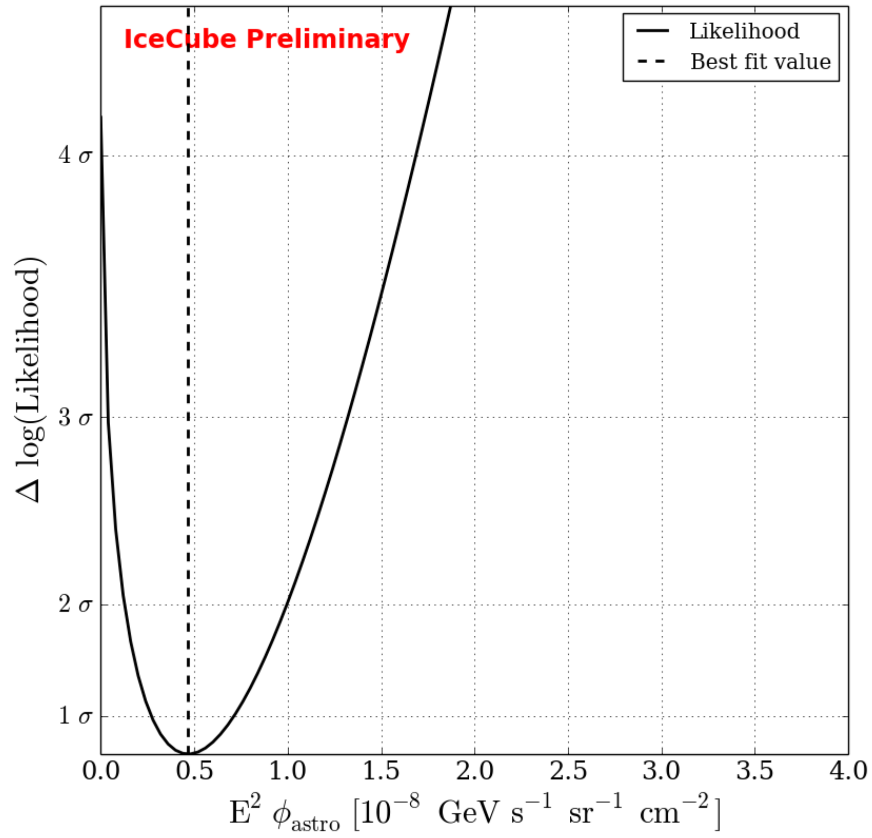


1-D profile likelihood for background-only hypothesis

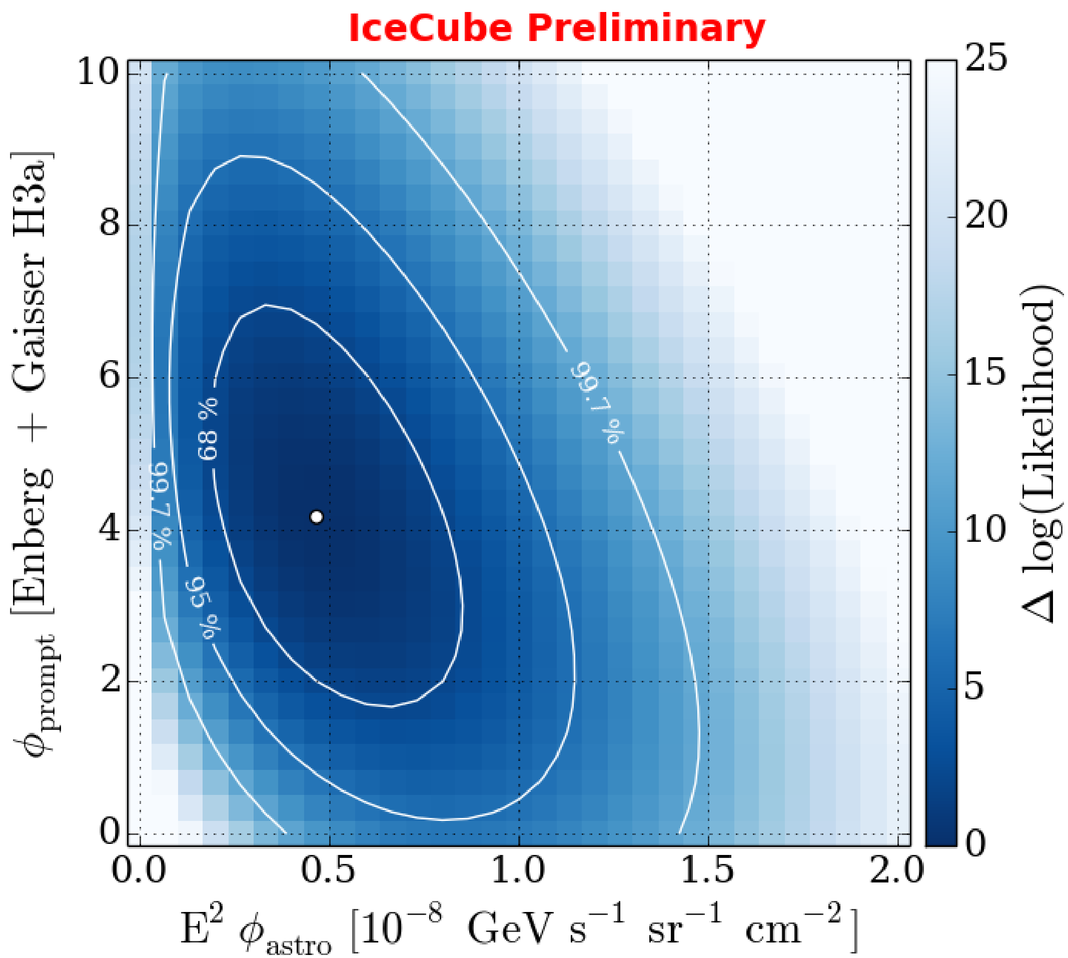


1-D profile likelihood for signal hypothesis (E^{-2})

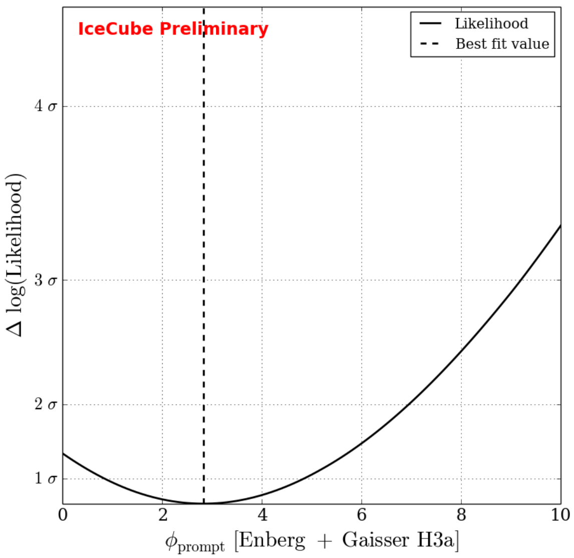


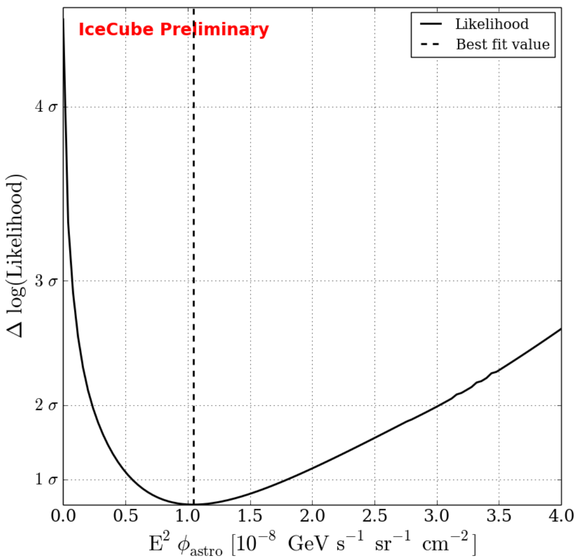


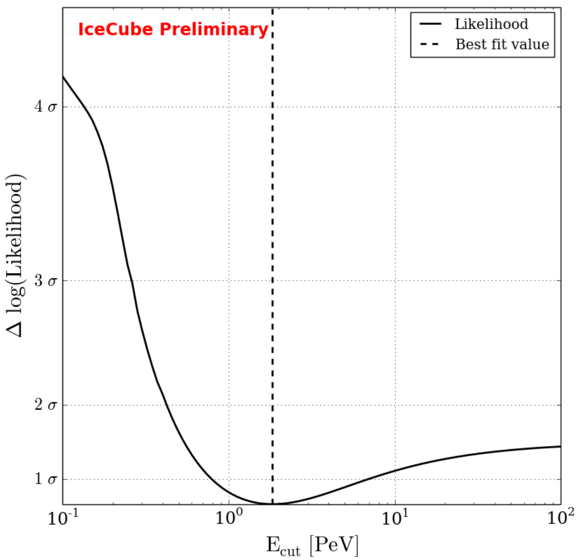
2-D profile likelihood for signal hypothesis (E^{-2})



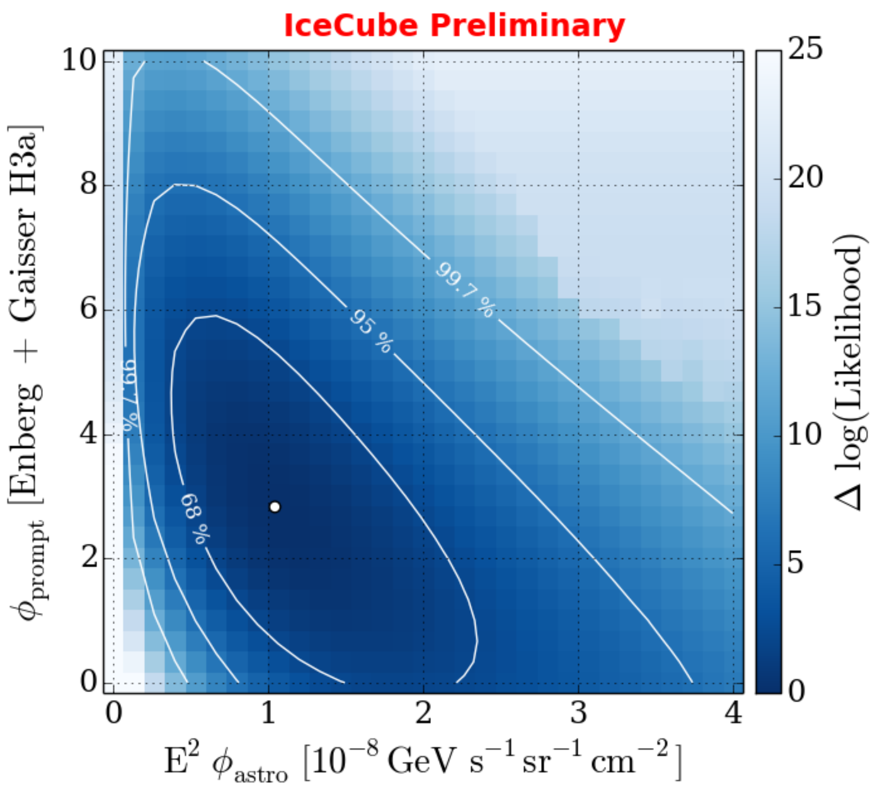
1-D profile likelihood for signal hypothesis ($E^{-2} \cdot e^{E/Ecut}$)

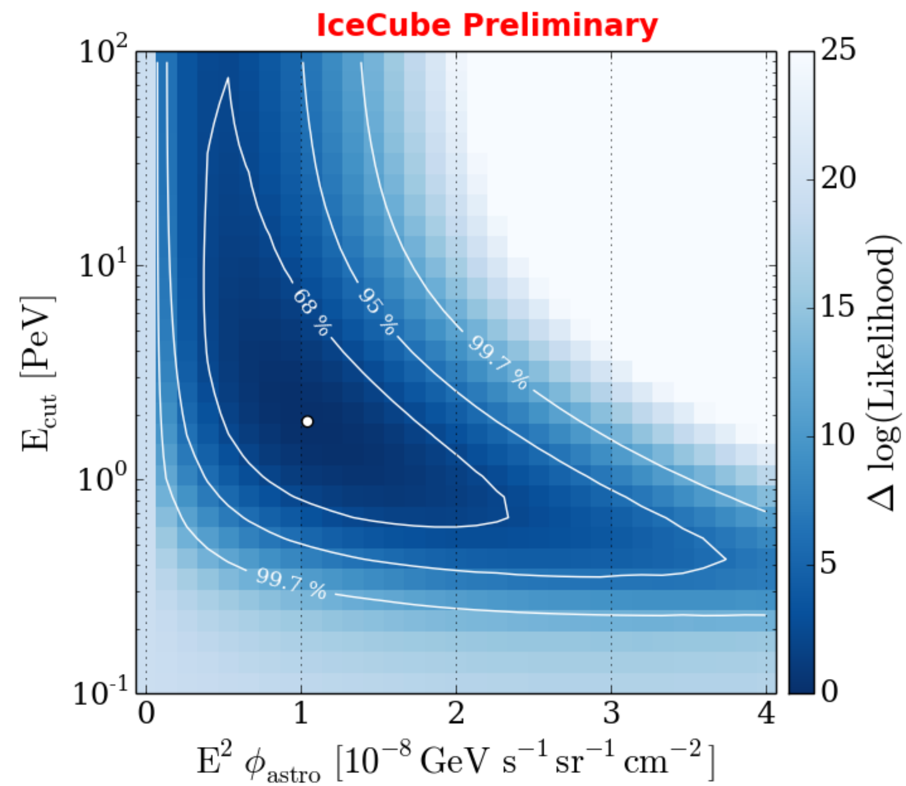




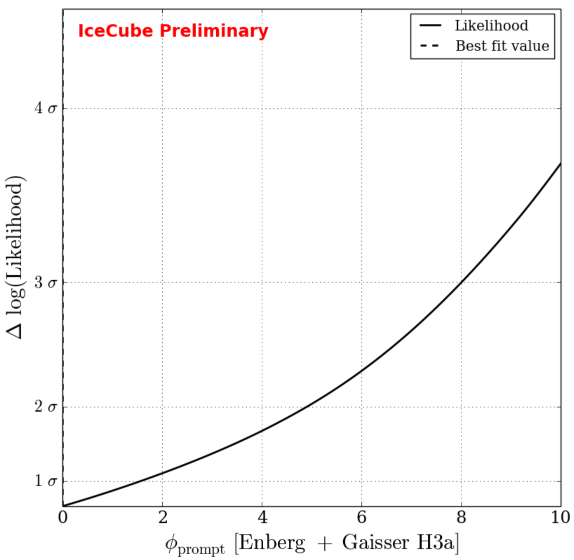


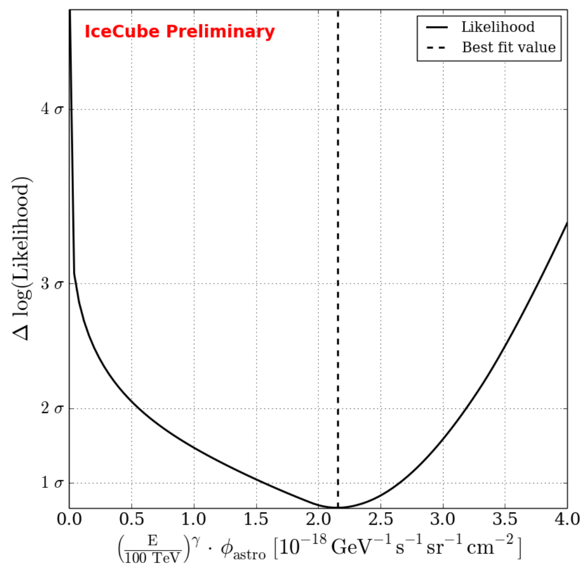
2-D profile likelihood for signal hypothesis ($E^{-2} \cdot e^{E/Ecut}$)

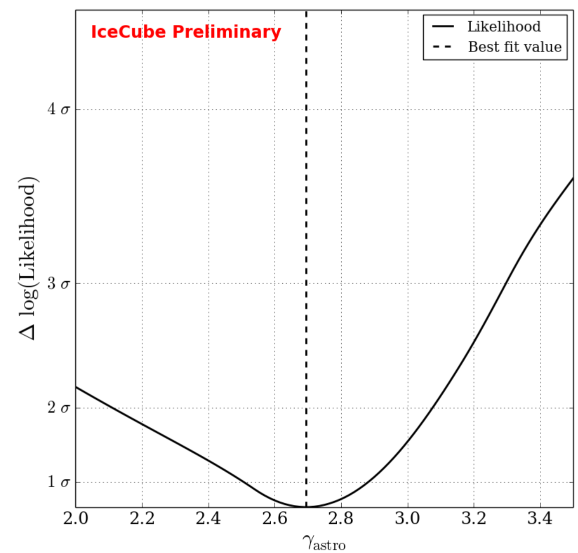




1-D profile likelihood for signal hypothesis ($E^{-\gamma}$)







2-D profile likelihood for signal hypothesis ($E^{-\gamma}$)