A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data

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For the IceCube Collaboration

34th International Cosmic Ray Conference

The Hague, Netherlands, August 4th, 2015

What is a diffuse astrophysical muon neutrino flux?

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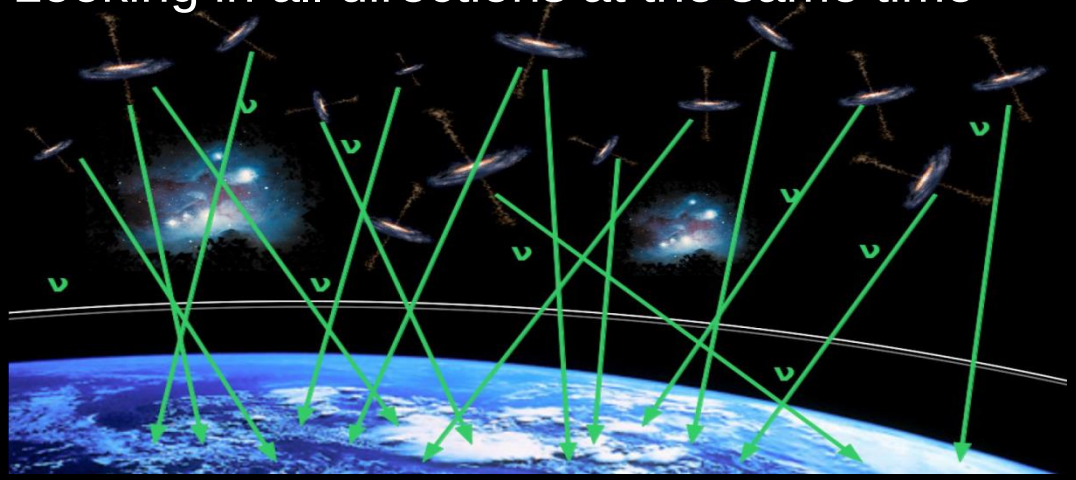
Looking in all directions at the same time



Astrophysical neutrinos with energy spectrum:

$$\frac{d\phi}{dE} \propto E^{-2}$$

Promising candidate → abundant extragalactic sources (e.g. AGN)

- A cosmic neutrino flux can be detected even if the individual source flux is below the detection threshold
- IceCube starting event measurement: ν flux per flavor ~1 x 10^{-8} GeV cm^{-2} s^{-1} sr^{-1}
- 2 Questions:
  1) Is the flux from the Northern Sky for the muon neutrino channel the same?
  2) What are the properties of this flux?

IceCube detector

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Detection principle:

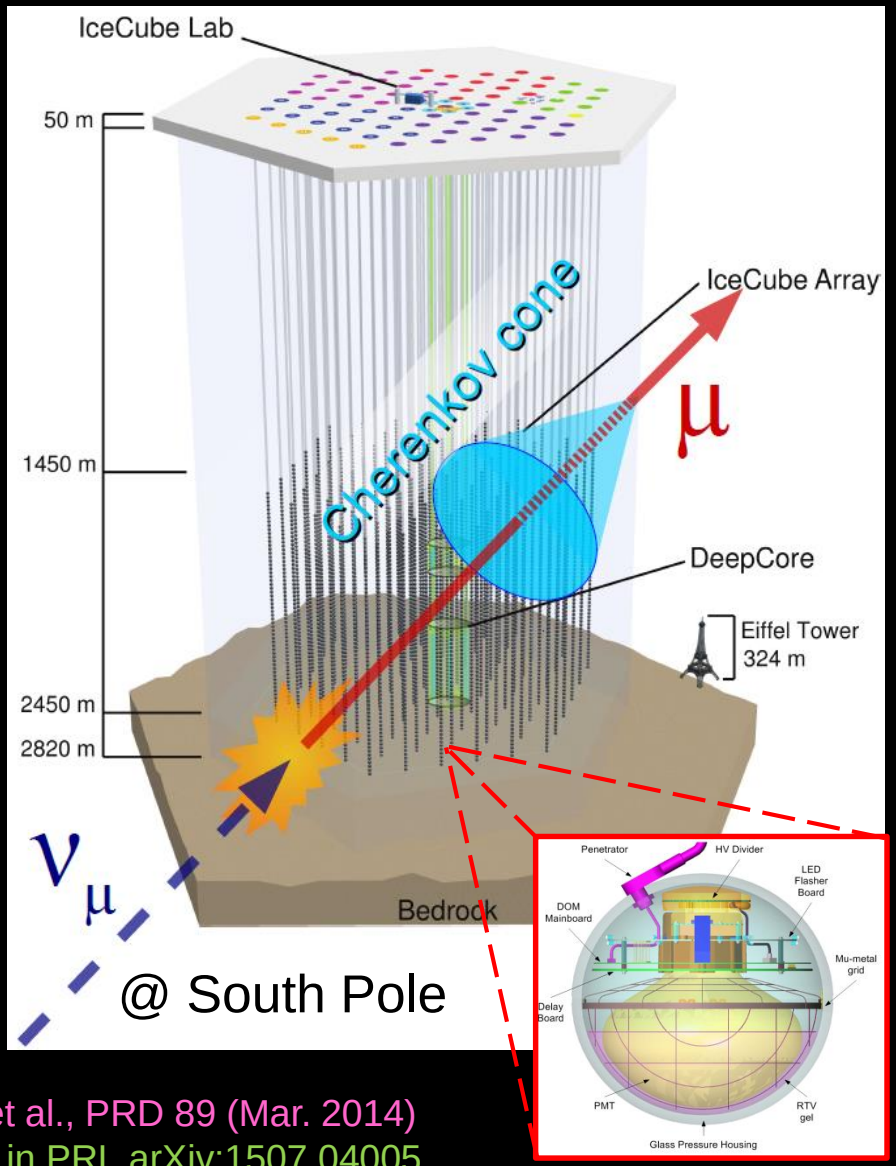
- ν_μ interaction near or inside the detector
- Detection of Cherenkov light produced by secondary relativistic, charged particles using optical sensors in ice

Search strategy:

- Select high-energy up-going muon track
- ➢ Northern sky neutrino sample: High purity and high efficiency

Previous IceCube analysis:

- IC59: from 2009 – 2010 (~20,000 neutrinos, excess 1.8σ)
- IC79 + IC86: from 2010-2012 (~35,000 neutrinos, excess 3.7σ)



Aartsen et al., PRD 89 (Mar. 2014)
accepted in PRL arXiv:1507.04005

Signal signature

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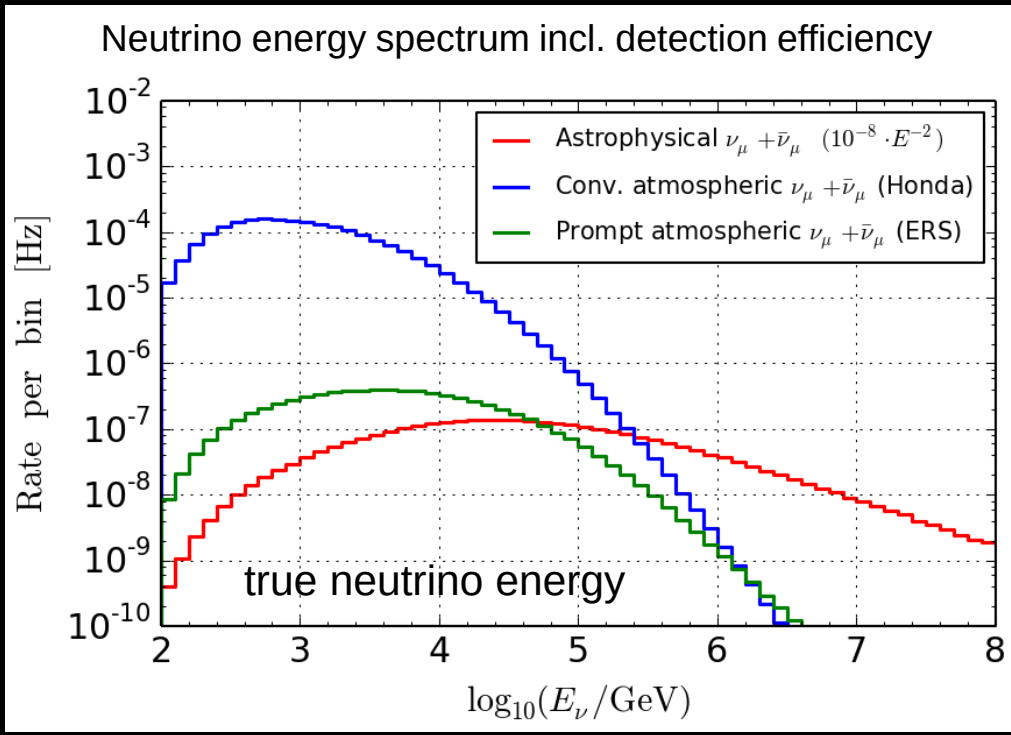
- Atmospheric neutrino background

  Conventional atmospheric neutrinos

  - From pion and kaon decays produced by cosmic ray interactions with the atmosphere
  - Energy spectrum: $\frac{d\phi}{dE} \propto E^{-3.7}$

  Prompt atmospheric neutrinos

  - From heavy meson decays produced by cosmic ray interactions with the atmosphere (not measured yet)
  - Energy spectrum: $\frac{d\phi}{dE} \propto E^{-2.7}$



- Astrophysical neutrino signal
  - Energy spectrum: $\frac{d\phi}{dE} \propto E^{-2}$

Honda: Honda et al., Phys. Rev. D 75 (Feb, 2007)
ERS: Enberg et al., Phys. Rev. D 78 (Aug, 2008)

Analysis strategy

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- Combined likelihood fit using multiple years
  - → Analyze 6 years of IceCube data (2009 – 2015)
  - → All systematic uncertainties are parameterized continuously
- Neutrino sample properties:
  - → High-purity: > 99.9%
  - → High-efficiency: ~ 70,000 neutrinos / year
- ➢ Improved constraints of systematic uncertainties from non-signal region due to larger statistics

First step:

- Apply combined likelihood fit on IceCube data from 2009 – 2012 (IC59+IC79+IC86)
- ➢ Results will be presented in this talk

The analysis method

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- Analyze 2-dimensional energy vs. zenith angle distribution
- Likelihood function: binned Poisson likelihood
  - → Include systematic uncertainties as free continuous nuisance parameters

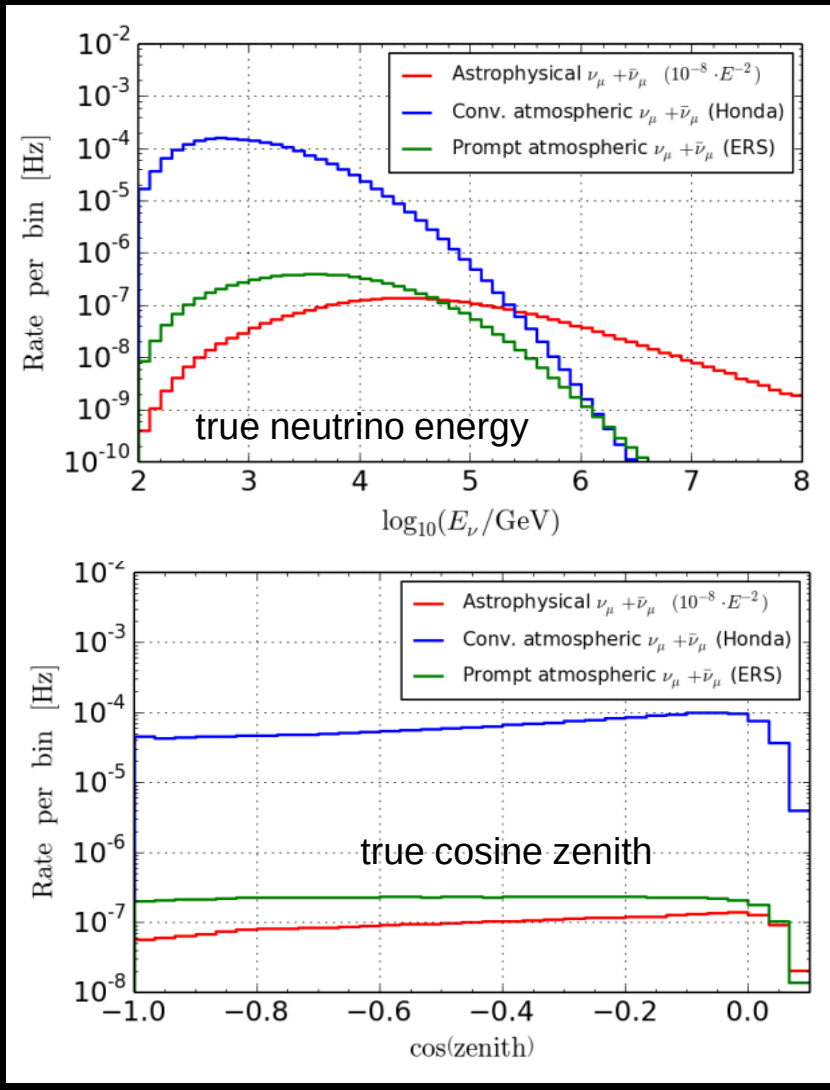
signal and nuisance parameters

$$L(\boldsymbol{n}|\boldsymbol{\mu}(\boldsymbol{\theta},\boldsymbol{\xi})) = \prod_{i=1}^{N} \frac{(\mu_i(\boldsymbol{\theta},\boldsymbol{\xi}))^{n_i}}{n_i!} \exp(-\mu(\theta,\xi))$$

measurement and expectation

- Expectation:

$$\mu_i(\boldsymbol{\theta},\boldsymbol{\xi}) = \mu_i^{conv} + \mu_i^{prompt} + \mu_i^{astro}$$



The challenge: Systematic uncertainties

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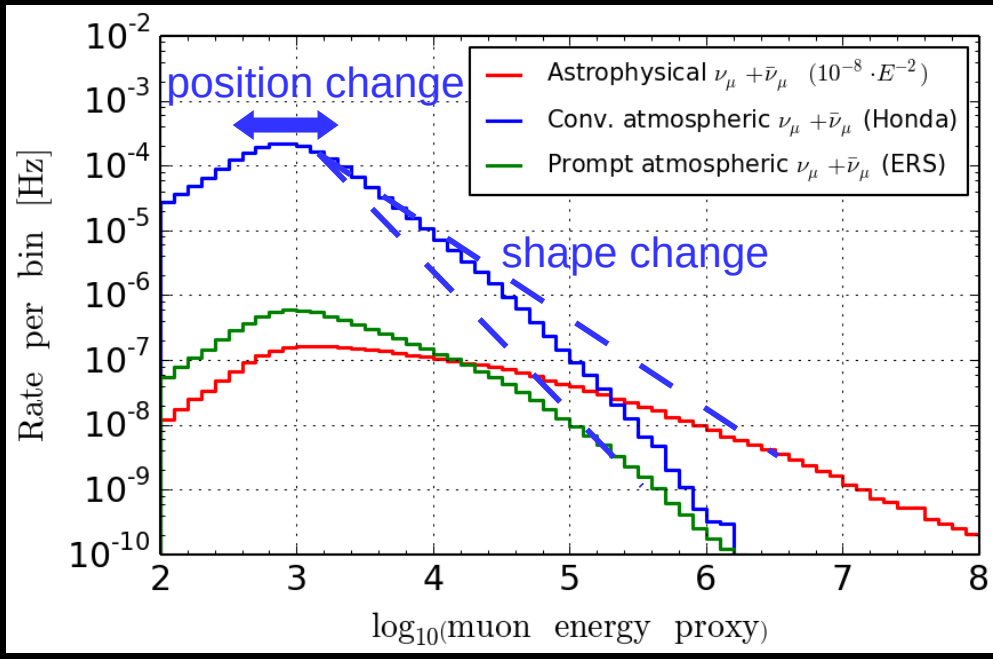
- Detection uncertainties:

  e.g. optical sensor efficiency, optical ice properties at South Pole, neutrino interaction cross section, muon energy loss cross section

- Atmospheric ν_μ prediction uncertainties:

  e.g. rate, shape and composition of the primary cosmic ray spectrum, ratio of pion to kaon decay in air showers



- Systematic effects on observables are continuously parameterized and included in the likelihood fit

- Advantage of high statistics of conventional atmospheric ν_μ:

  → Strong constraints on systematic uncertainties from non-signal region

Experimental data 2009 – 2012

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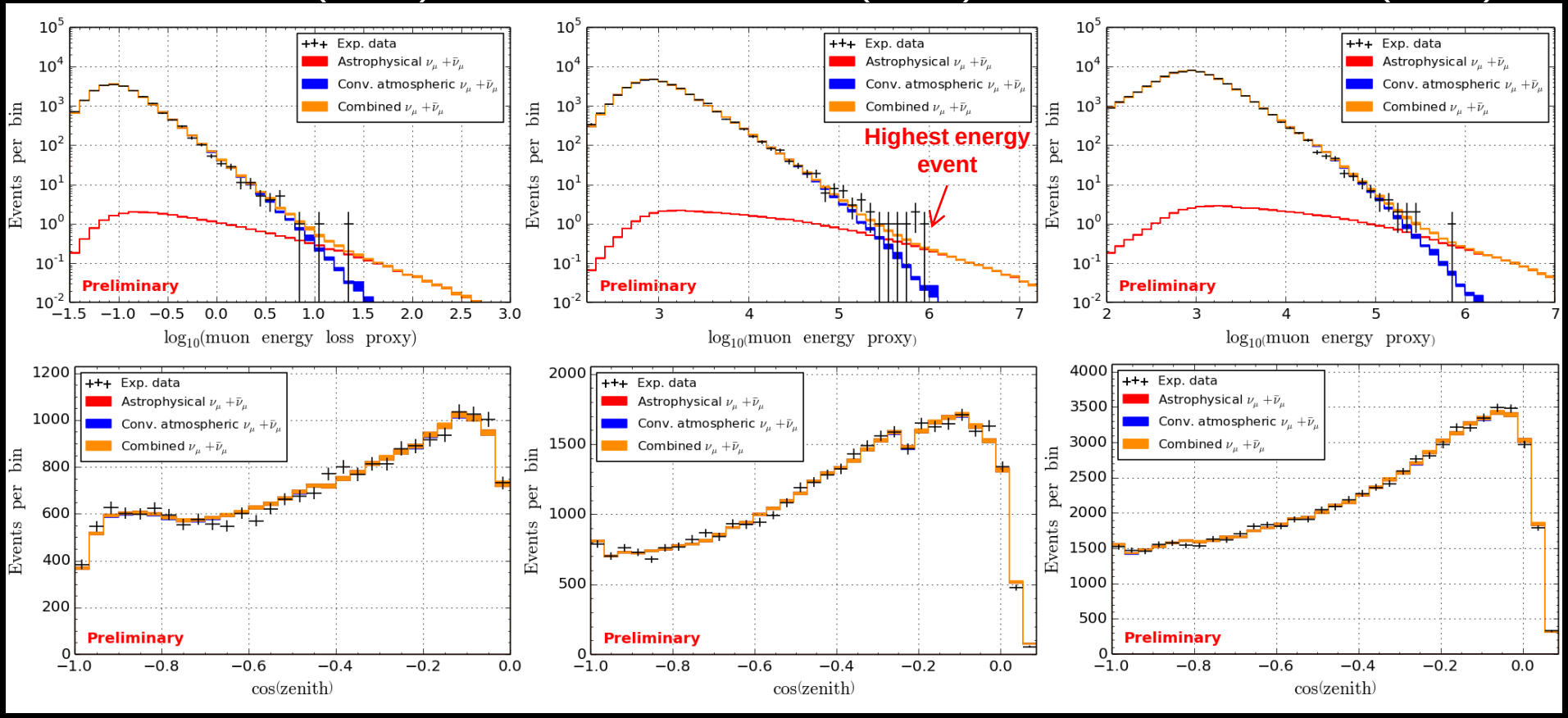
2009-2010 (IC59) | 2010-2011 (IC79) | 2011-2012 (IC86)



- Excellent data/mc agreement for all three years

#neutrinos ≈ 130,000

Analysis results
Astrophys. and prompt normalization

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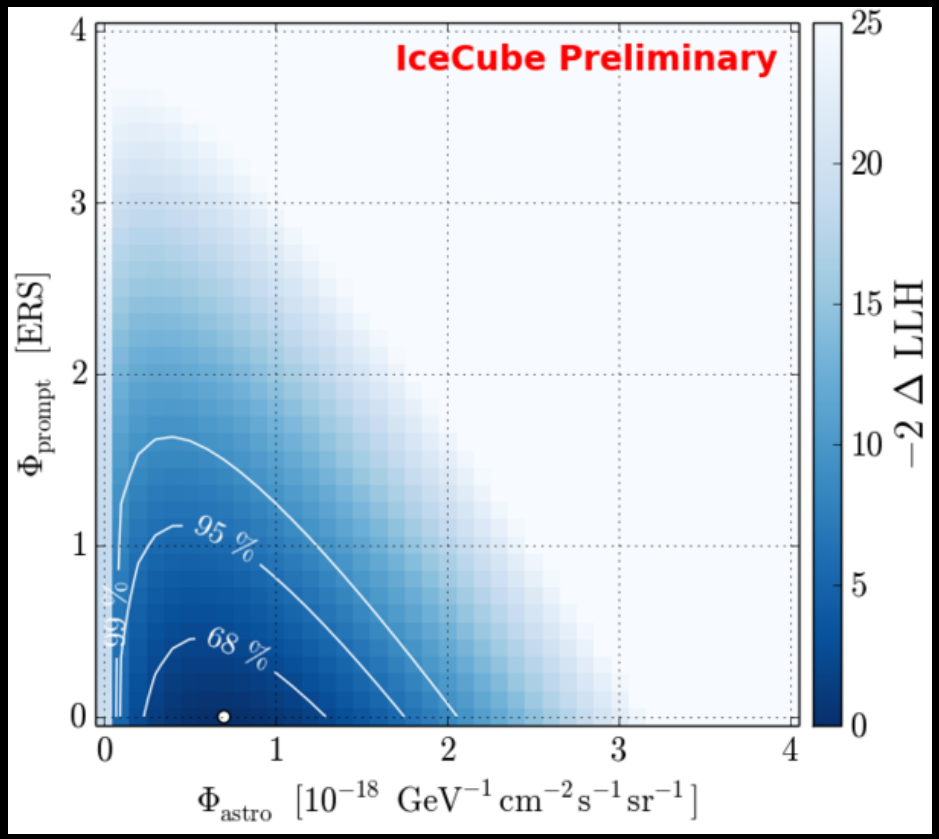

- Best-fit astrophysical normalization:

$$(0.66^{+0.40}_{-0.30}) \times 10^{-18}\ \text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}$$

- Best-fit prompt normalization:

$$0 \times \text{ERS}$$

- Measured astrophysical flux cannot be explained by only a prompt flux

- Atmospheric-only hypothesis excluded by 4.3σ with three years already

ERS: Enberg et al., Phys. Rev. D 78 (Aug, 2008)
BERSS: Bhattacharya et al., accepted in JHEP 194 (2015) [arXiv:1502.0107] ~ 0.5 ERS

Analysis results
Astrophysical spectral index

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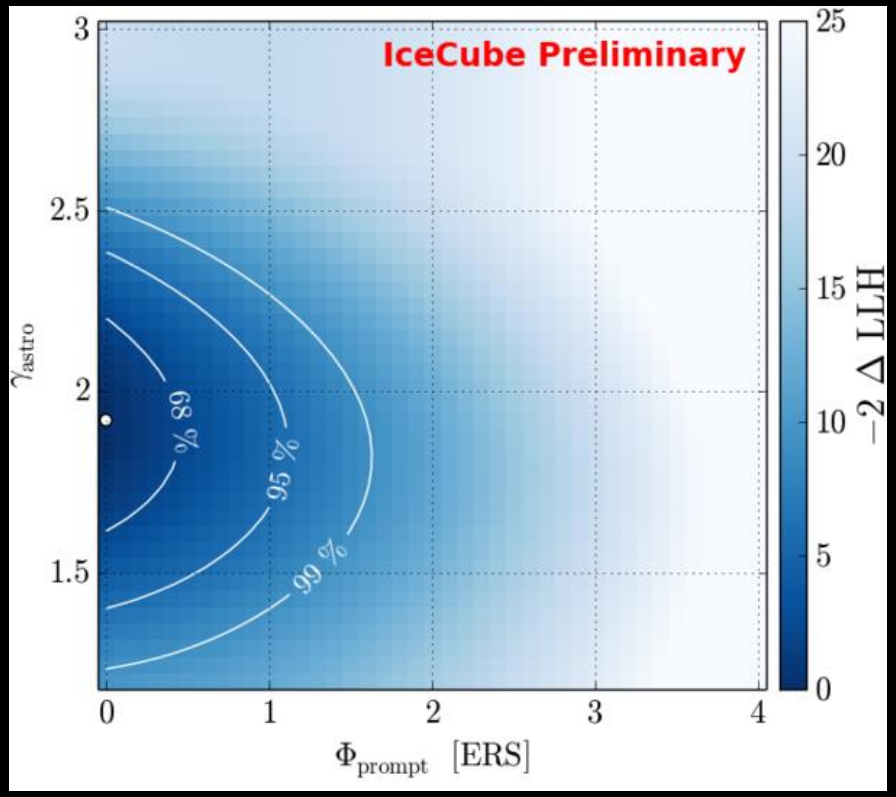
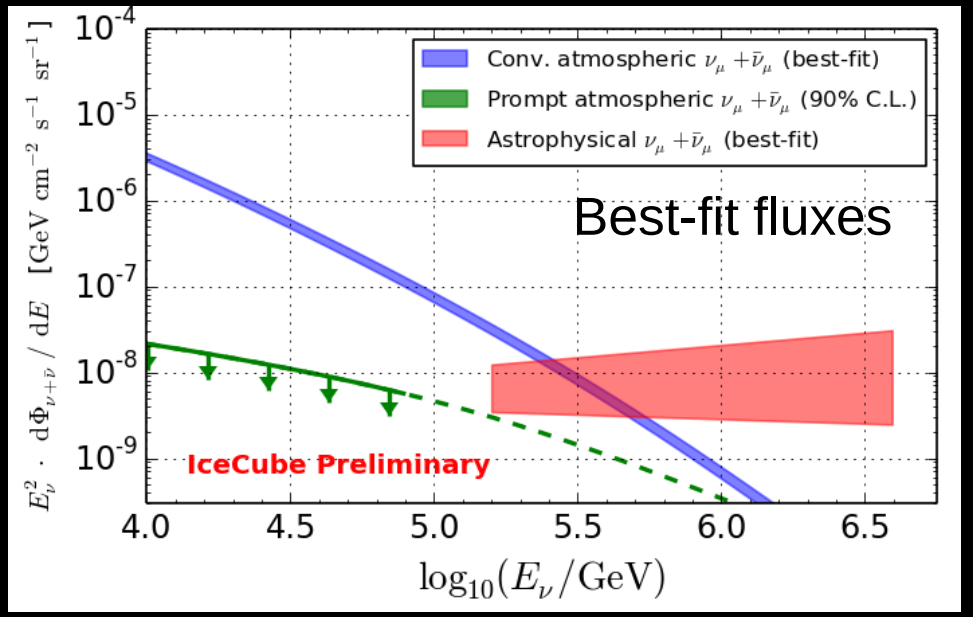


- Best-fit spectral index:

$$\gamma_{\mathrm{astro}} = 1.91 \pm 0.20$$

- Measured astrophysical spectral index nearly independent of the prompt normalization

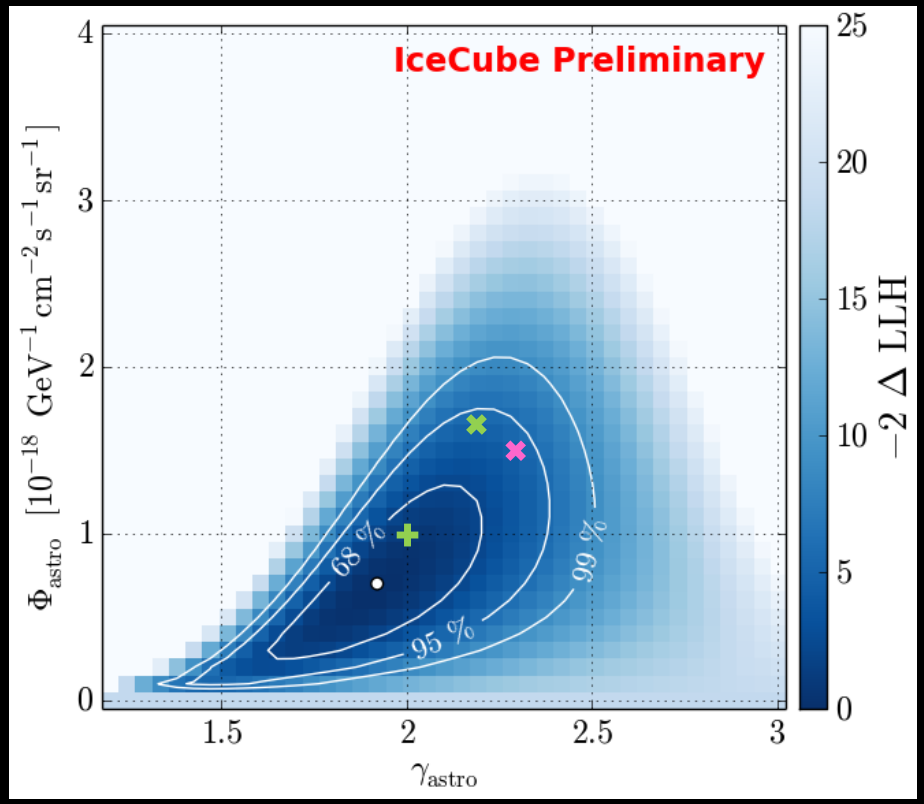


Measured best-fit energy spectrum

- Energy region:

$$170\mathrm{TeV} < E_\nu < 3.8\mathrm{PeV}$$

Analysis result
Astrophys. norm. & spectral index



- Correlation between astrophysical normalization @100TeV and the spectral index
- Best-fit astrophysical normalization:

$$(0.66^{+0.40}_{-0.30}) \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- Best-fit spectral index:

$$\gamma_{\mathrm{astro}} = 1.91 \pm 0.20$$

- Atmospheric-only hypothesis excluded by 4.3σ

- Compatible with the best-fit of high-energy starting event analysis (Phys. Rev. Lett. 113, 101101 (2014))
- Compatible with best-fit result of the current up-going muon neutrino analysis (accepted in Phys. Rev. Lett. arXiv:1507.04005)

Comparison to analysis dominated by shower-like events

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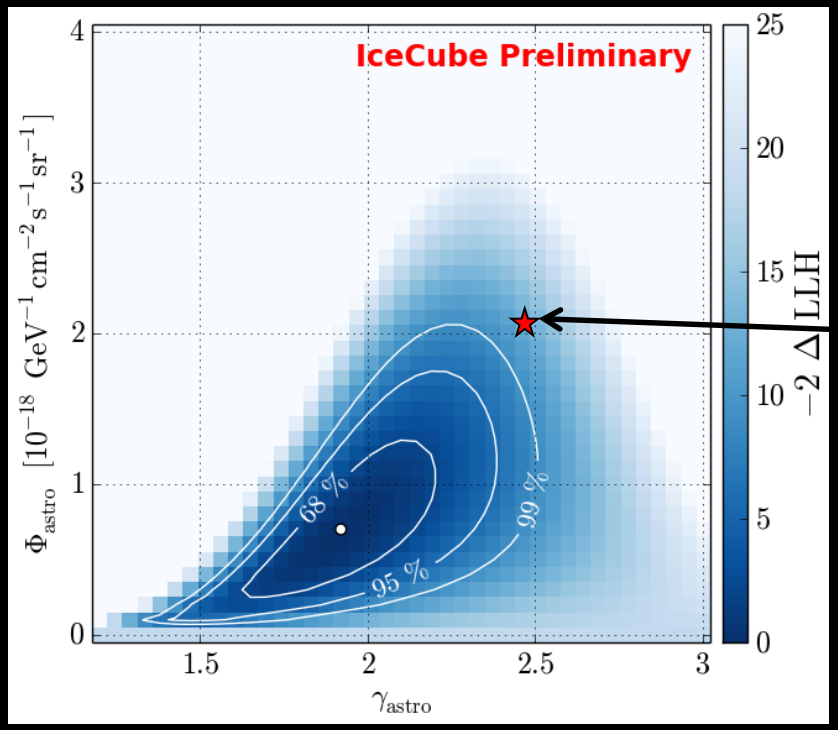

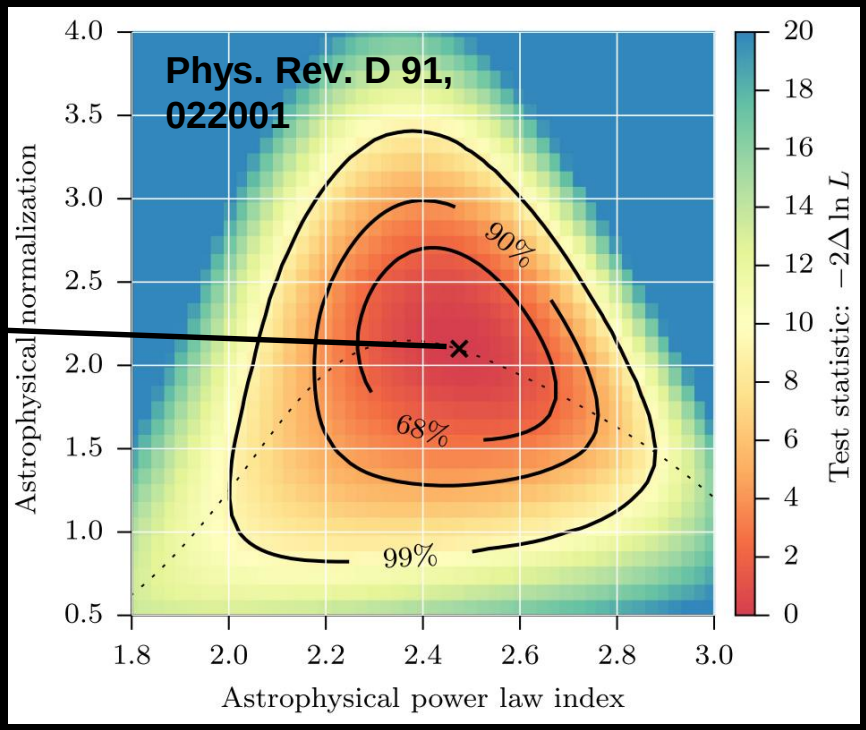

- Right: IceCube result reported in Phys. Rev. D 91, 022001
  - → Sensitive to shower-like events and therefore much lower energy threshold (~10TeV)
  - → Sensitive to neutrino events from the Southern Sky
- Some tension (~2σ) between the result presented here and the reported result (right)
  - → Calculated comparing the 2d llh contours in gauss approximation

Comparison to analysis dominated by shower-like events

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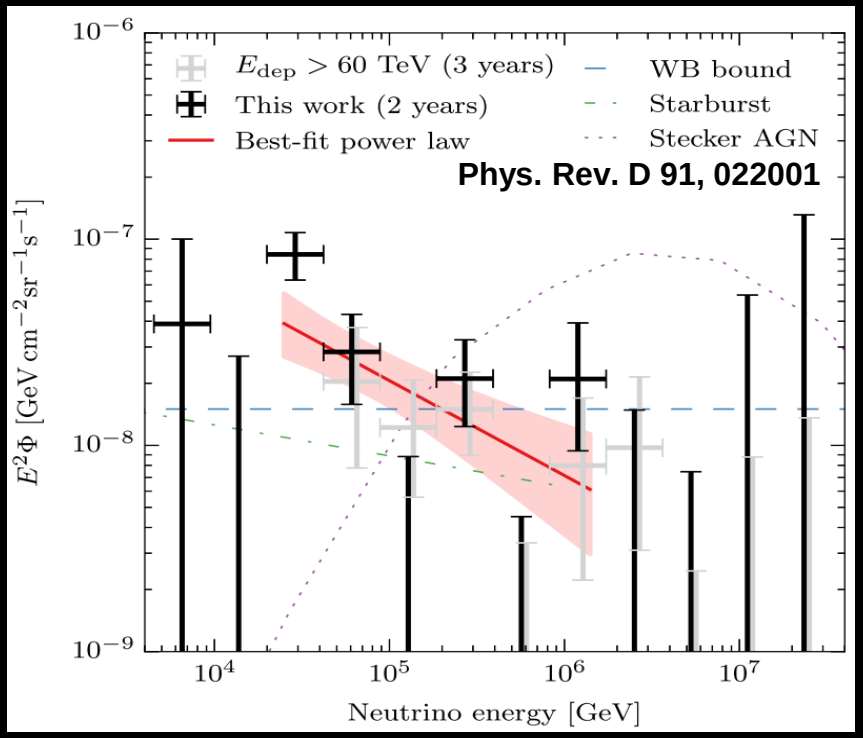
Unfolding (dominated by shower-like events)



- Energy threshold @ about 10TeV
  - → Softer spectral index currently driven by low energy bin

Comparison to analysis dominated by shower-like events

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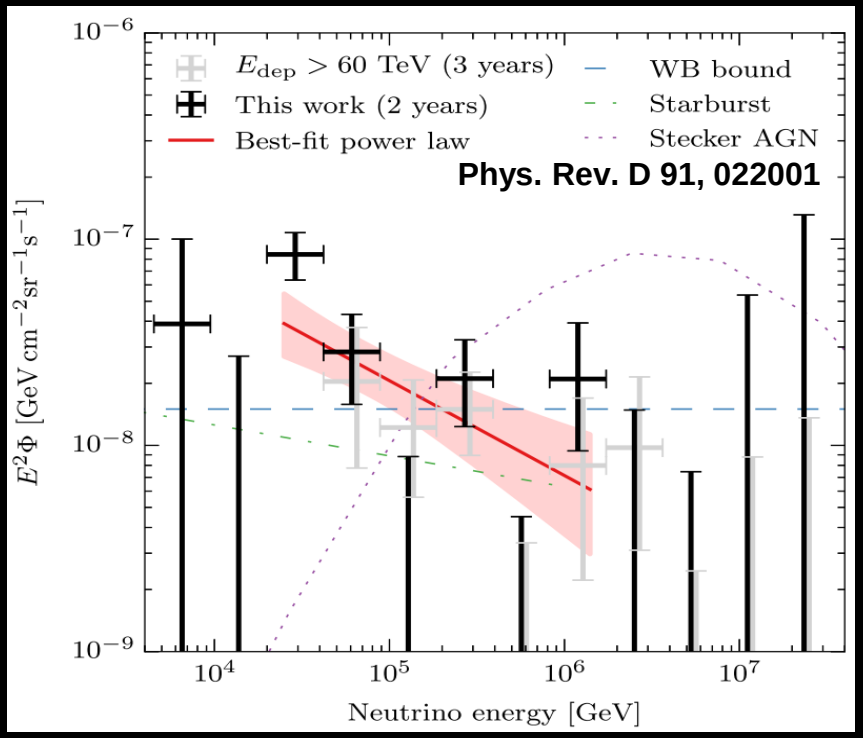
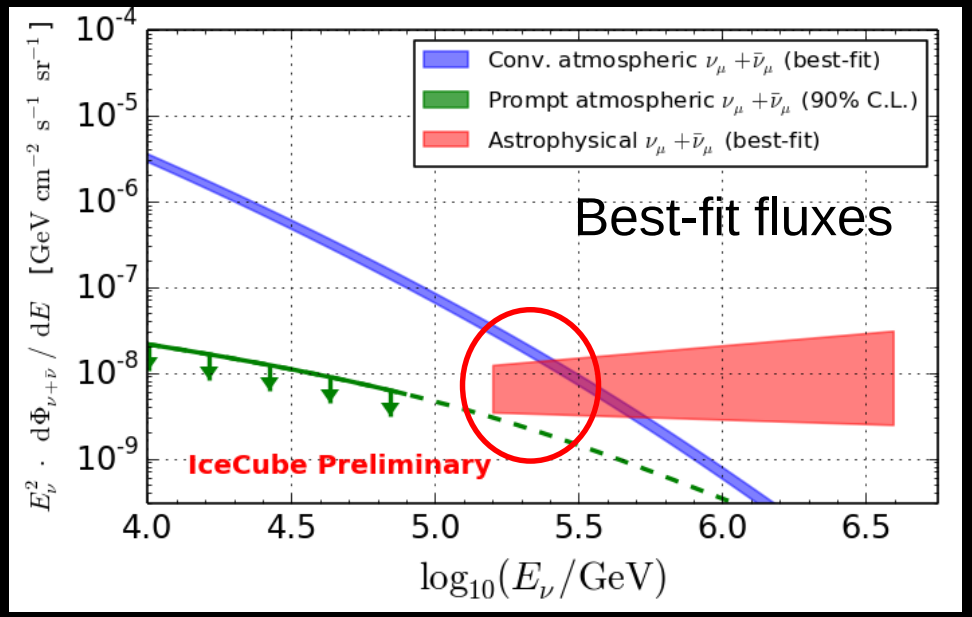
Unfolding (dominated by shower-like events)



- Energy threshold @ about 10TeV
  - → Softer spectral index currently driven by low energy bin

This analysis (up-going track-like events)



- Energy threshold @ about 200TeV

Comparison to analysis dominated by shower-like events

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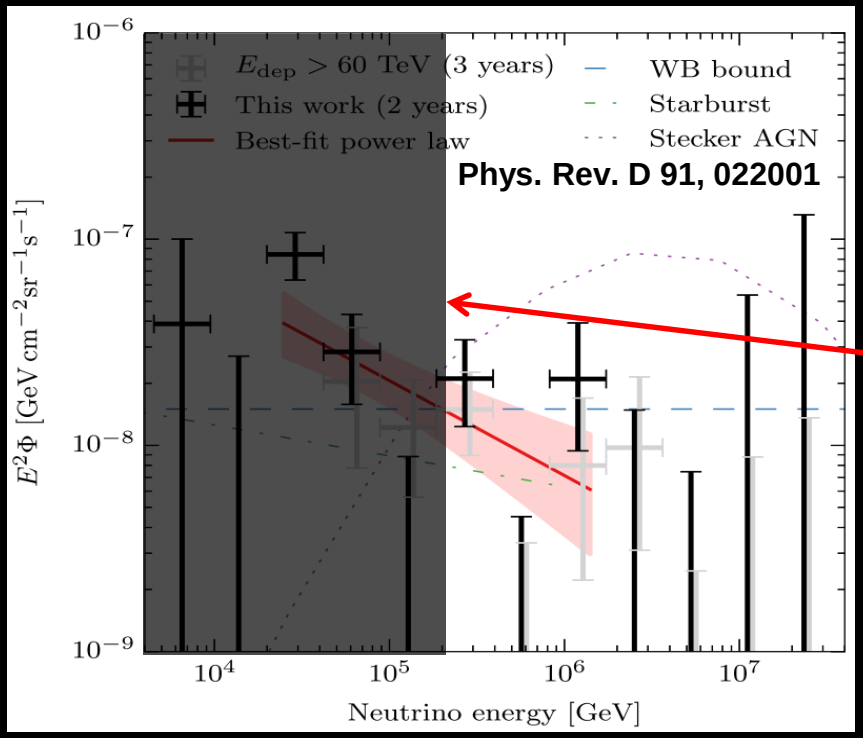
Unfolding (dominated by shower-like events)



- Energy threshold @ about 10TeV
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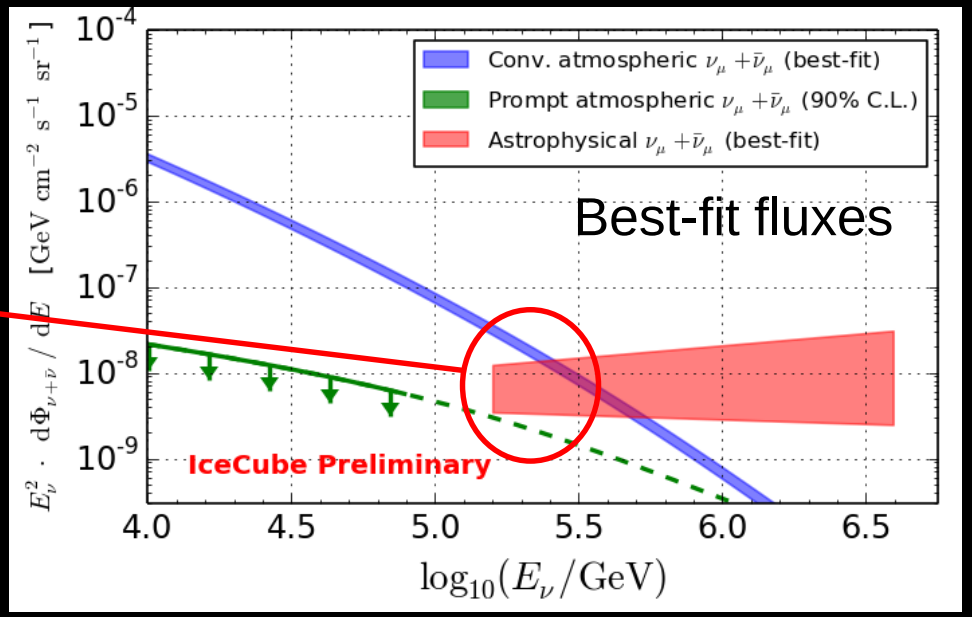
This analysis (up-going track-like events)



- Energy threshold @ about 200TeV
- @ high energies ($\gtrsim$ 200 TeV) analysis dominated by shower-like events (left) compatible with E^{-2}

Summary and outlook

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- Presented the currently most precise measurement of a diffuse flux of astrophysical muon neutrinos
  - → Reject atmospheric-only hypothesis by 4.3σ
  - → Best fit astrophysical flux (normalized @100TeV):

    $0.66 \cdot (E/100\text{TeV})^{-1.91}$ $[10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$
  - → Some tension with cascade dominated analyses. Currently compatible with statistical fluctuation

Looking at the additional three years of data!

Multi-PeV track event: Event views

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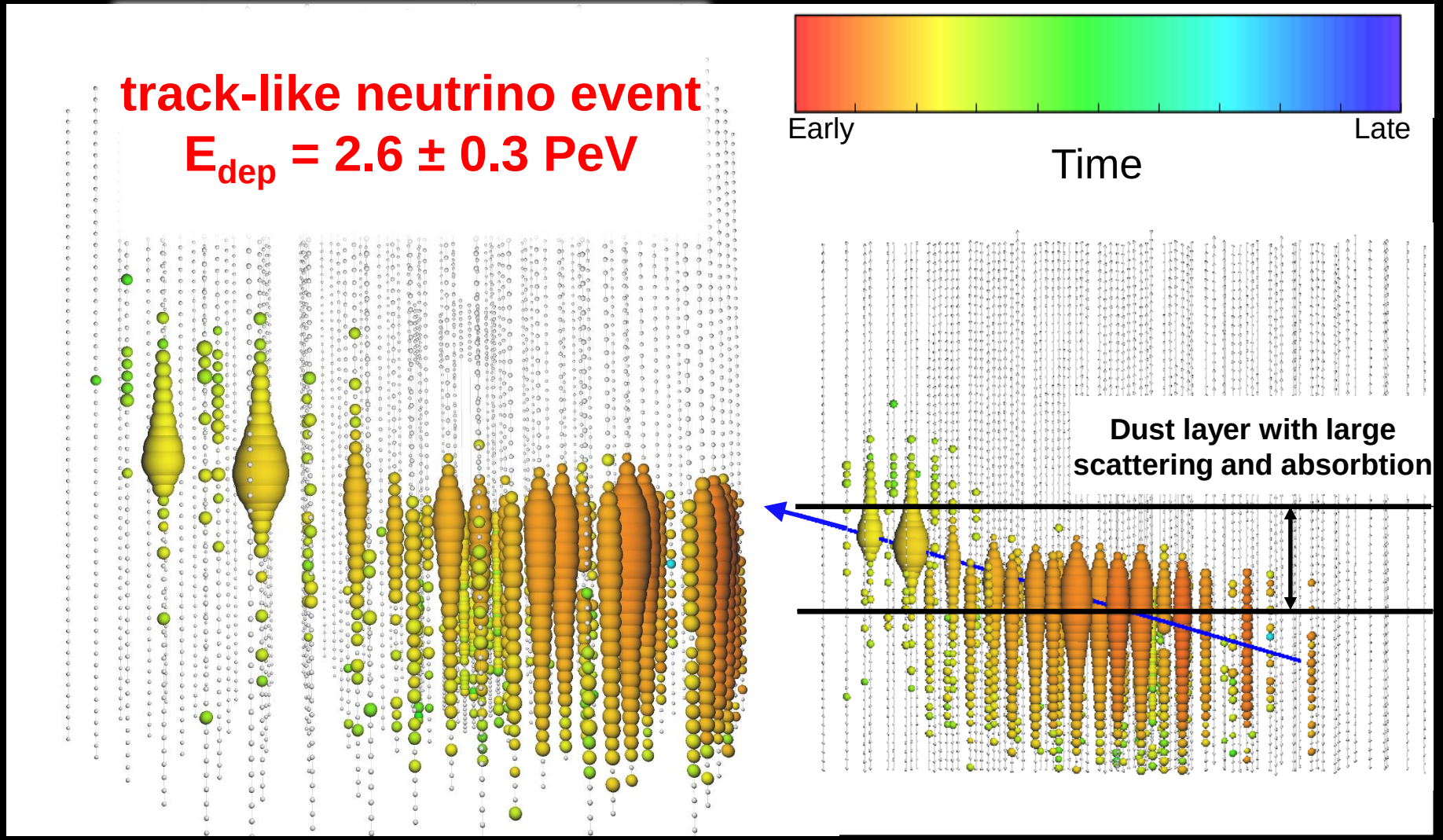

Multi-PeV track event
Event information

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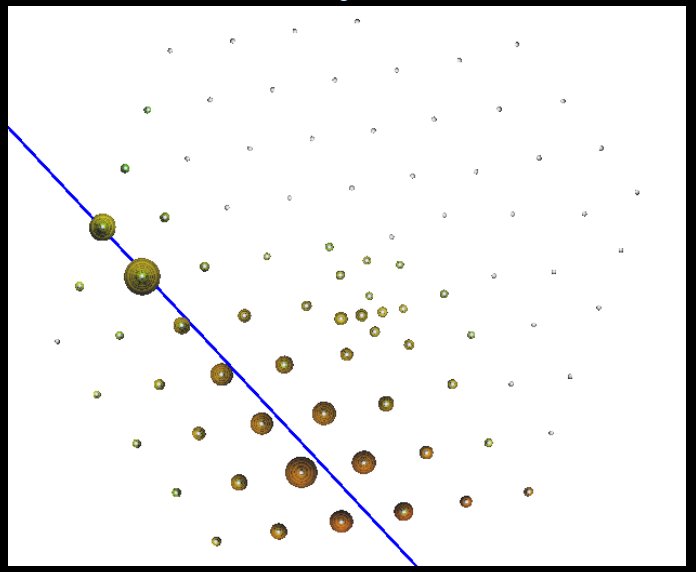
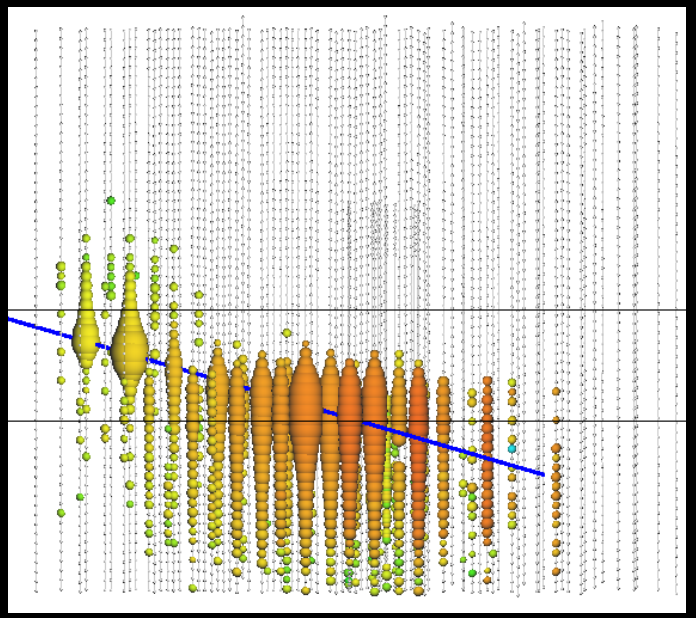
- Date
  - → June 11th 2014 (56819.20444852863 MJD)
- Arrival direction
  - → Declination 11.48 deg
  - → Right Ascension 110.34 deg
  - → Angular resolution < 1 deg
- Energy loss inside the detector
  - → 2.6 ± 0.3 PeV
- Muon energy and neutrino energy are at least that
- Reference
  - → ATEL #7856





Multi-PeV track event

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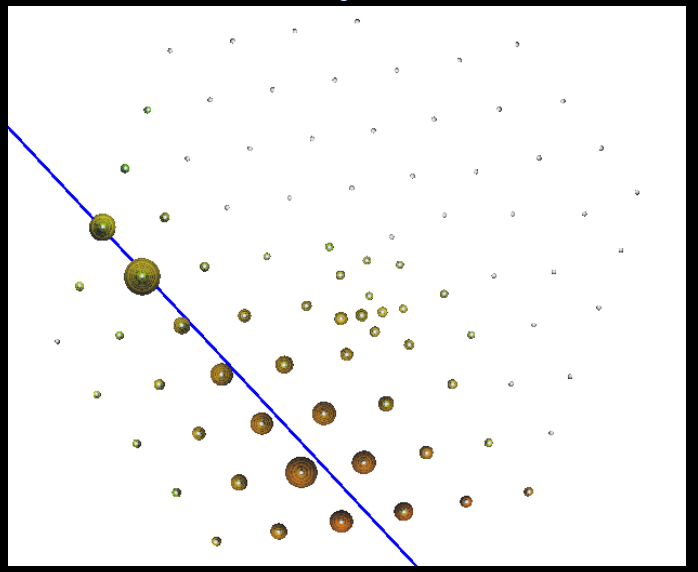
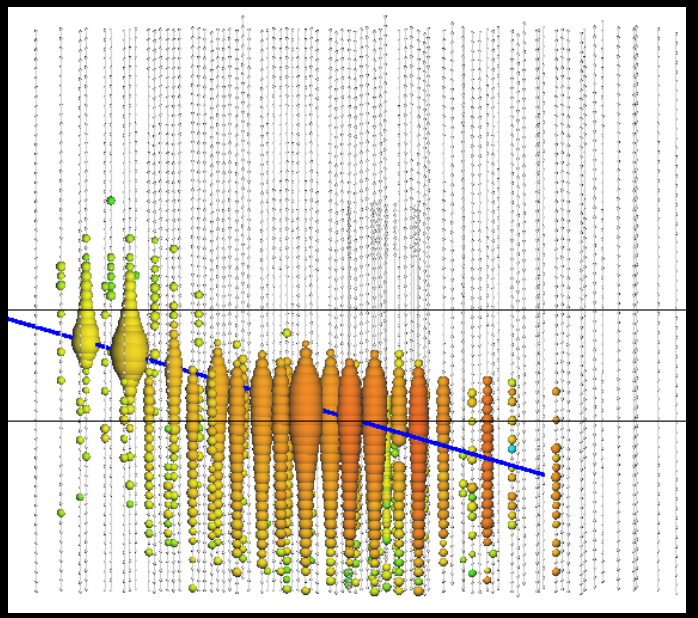
- IceCube
  - → No hot spot in IceCube PS skymap within 0.5 deg
- Source catalogues
  - → TeVCat closest source ~8deg away
  - → Fermi‘s 2FGL & 3FGL closest source ~3deg away
- ~12deg off the Galactic Plane
- No coincident GRB
- ACTs
  - → Sky location remains close to the Sun until September
- HAWC
  - → No evidence for gamma-ray emission
  - → ATEL #7868





The IceCube Collaboration

Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)
Deutsches Elektronen-Synchrotron (DESY)
Japan Society for the Promotion of Science (JSPS)
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

Thank you for your attention!