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

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For the IceCube Collaboration

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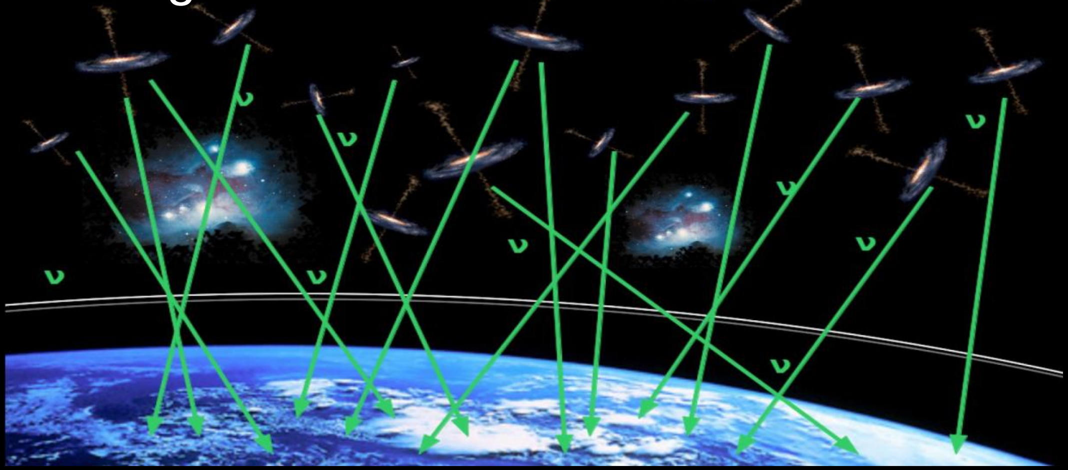
What is a diffuse astrophysical muon neutrino flux?

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

Detection principle:

- ν_μ interaction near or inside the detector
- Detection of Cherenkov light produced by secondary relativistic, charged particles

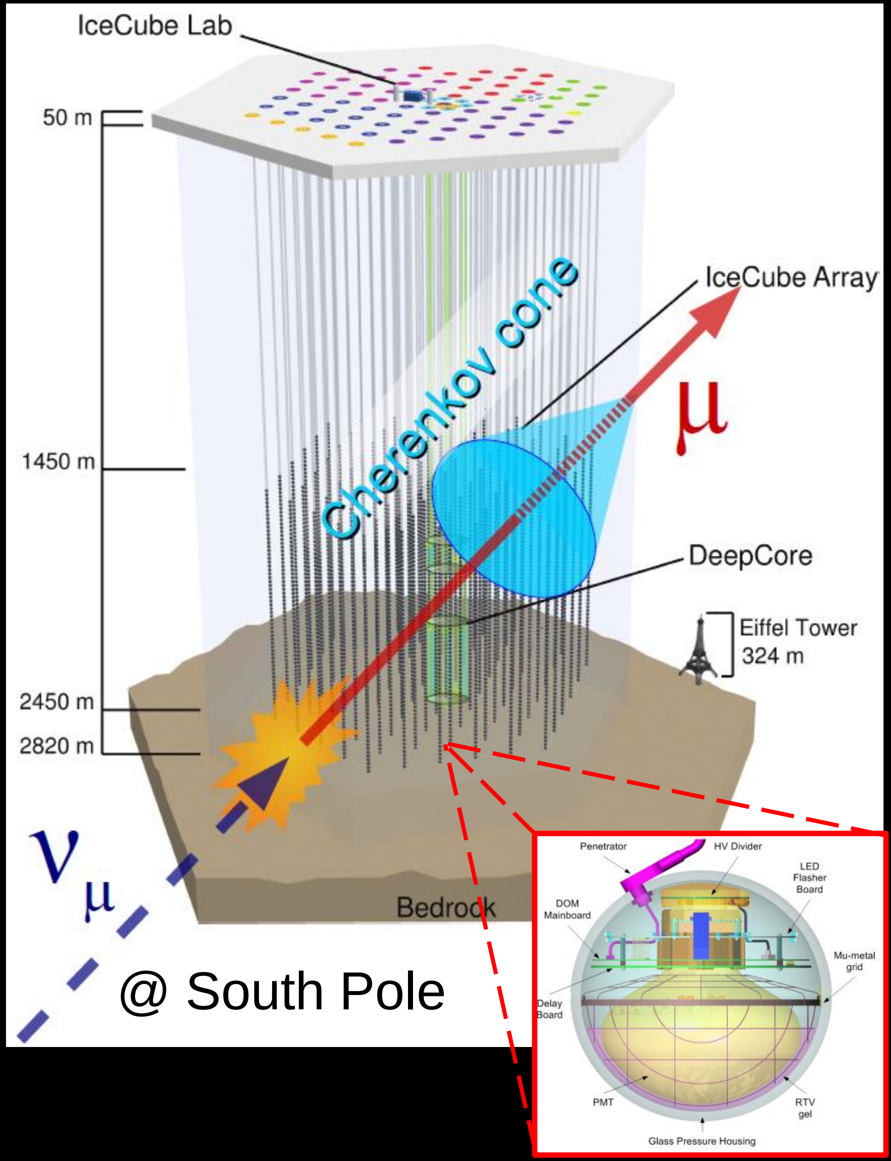
Search strategy:

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

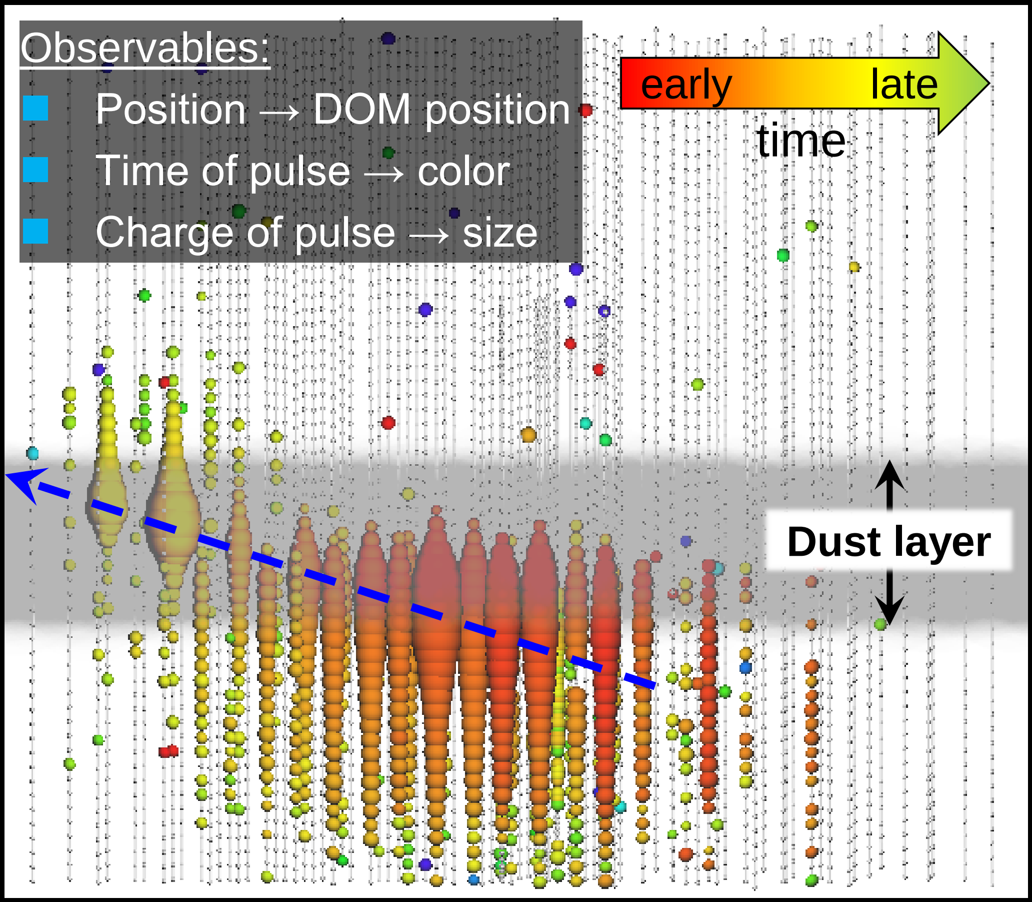
Previous IceCube analysis:

- 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)
Aartsen et al., PRL 115 (Aug. 2015)



Multi-PeV track event
June 11th 2014



track-like neutrino event
E_{dep} = 2.6 ± 0.3 PeV

- Muon and neutrino energy are at least 2.6 PeV
- angular uncertainty (stat. + sys.): ~0.27°
- p-value < 0.01% to be of atmospheric origin
- No closeby source candidate in TeVCat, Fermi‘s 2FGL & 3FGL
  - ➢ ATEL #7856

→ Through-going neutrino induced muon

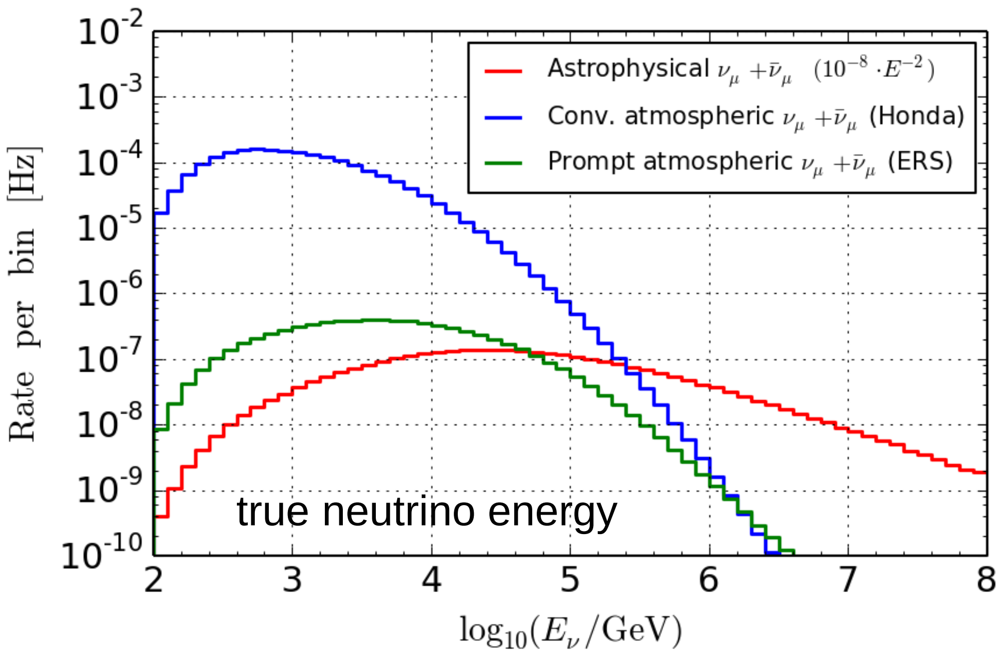
Signal signature

- 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: $\frac{d\phi}{dE} \propto E^{-2.7}$

Neutrino energy spectrum incl. detection efficiency



- 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

- 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 neutrino efficiency: ~ 340,000 neutrinos (2009 - 2015)
  - → High signal efficiency: ~ 550 astrophysical neutrinos (2009 - 2015)
- ➢ Large statistics used to constrain the systematic uncertainties from non-signal region

The analysis method

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

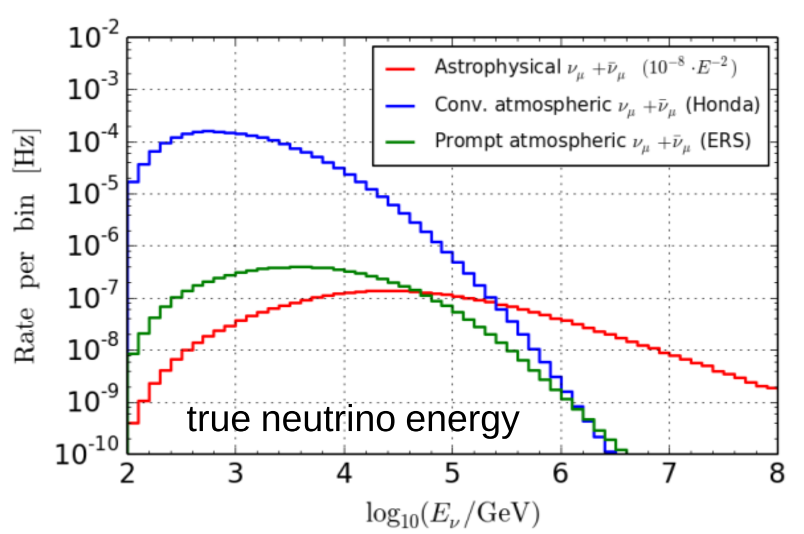
signal and nuisance parameters

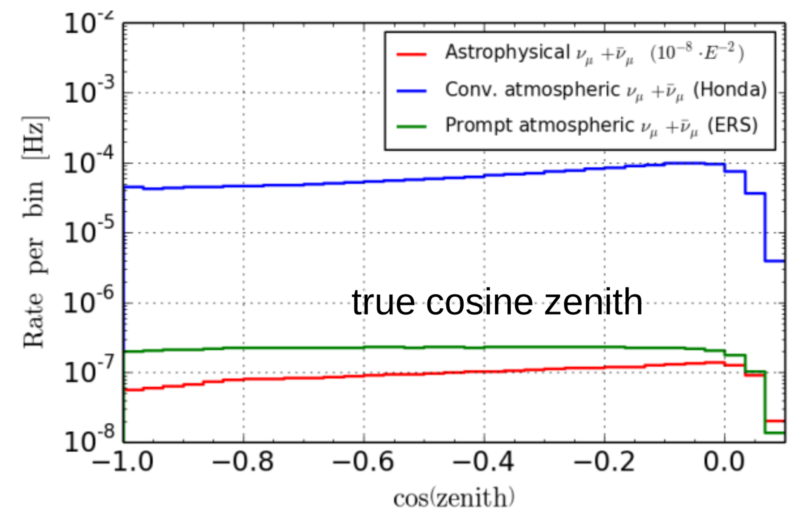
$$L(\boldsymbol{n}|\boldsymbol{\mu}(\boldsymbol{\theta},\boldsymbol{\xi})) = \prod_{i=1}^{N} \frac{(\mu_i(\boldsymbol{\theta},\boldsymbol{\xi}))^{n_i}}{n_i!} \exp(-\mu(\theta,\xi))$$

measurement and expectation

- Expectation:

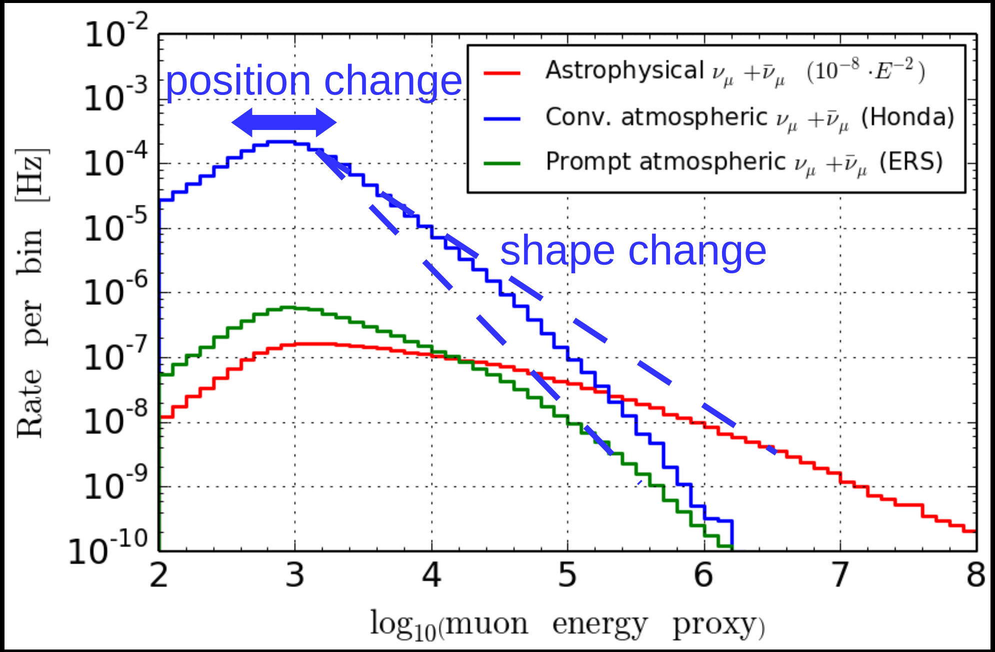
$$\mu_i(\boldsymbol{\theta},\boldsymbol{\xi}) = \mu_i^{conv} + \mu_i^{prompt} + \mu_i^{astro}$$





The challenge:
Systematic uncertainties

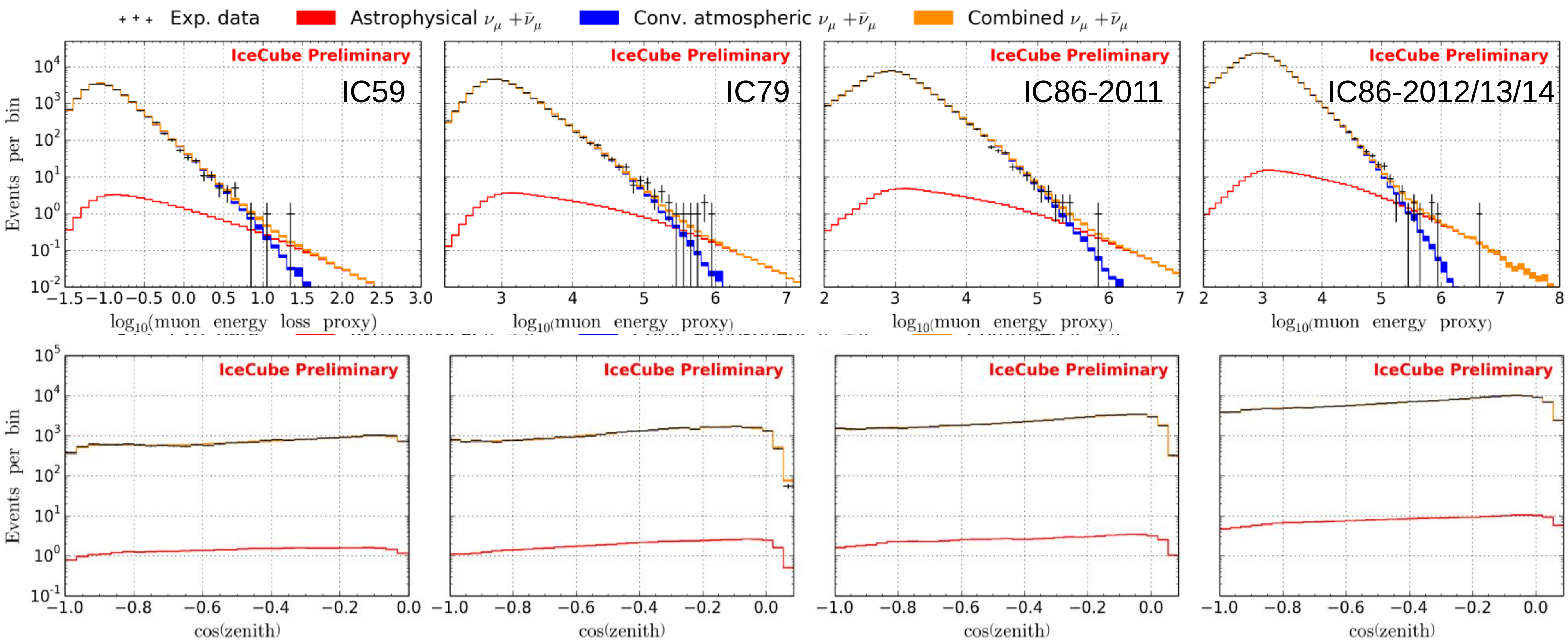
- <u>Detection uncertainties:</u>
  e.g. optical sensor efficiency, optical ice properties at South Pole, neutrino interaction cross section, muon energy loss cross section
- <u>Atmospheric ν_μ prediction uncertainties:</u>
  e.g. rate, shape and composition of the primary cosmic ray spectrum, ratio of pion to kaon decay in air showers



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

- <u>Advantage of high statistics</u> of conventional atmospheric ν_μ:
  → Strong constraints on systematic uncertainties from non-signal region

Experimental data from 2009 - 2015



- Excellent data/mc agreement for all six years
- Clear excess @ high reconstructed muon energies

Unfolded astrophysical muon neutrino spectrum

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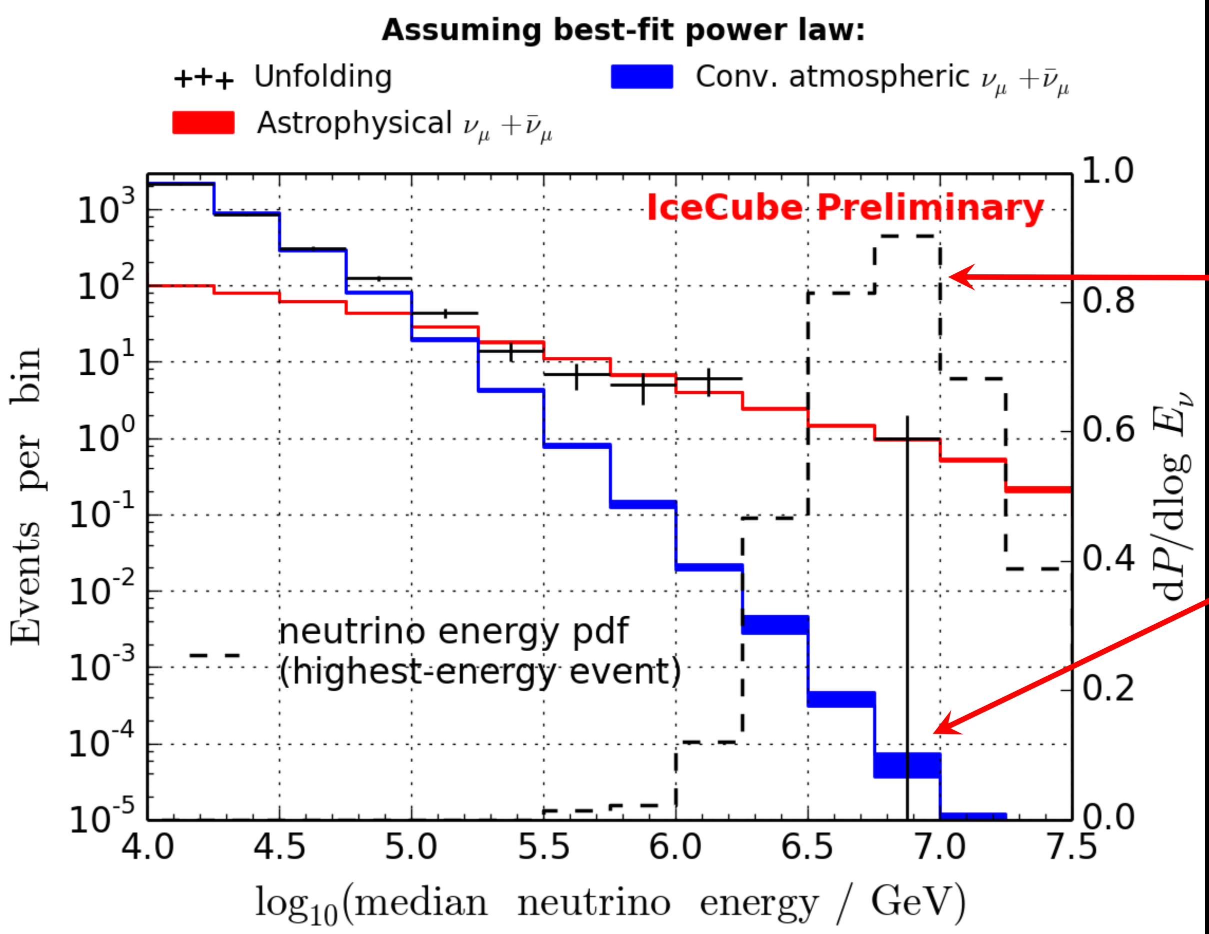
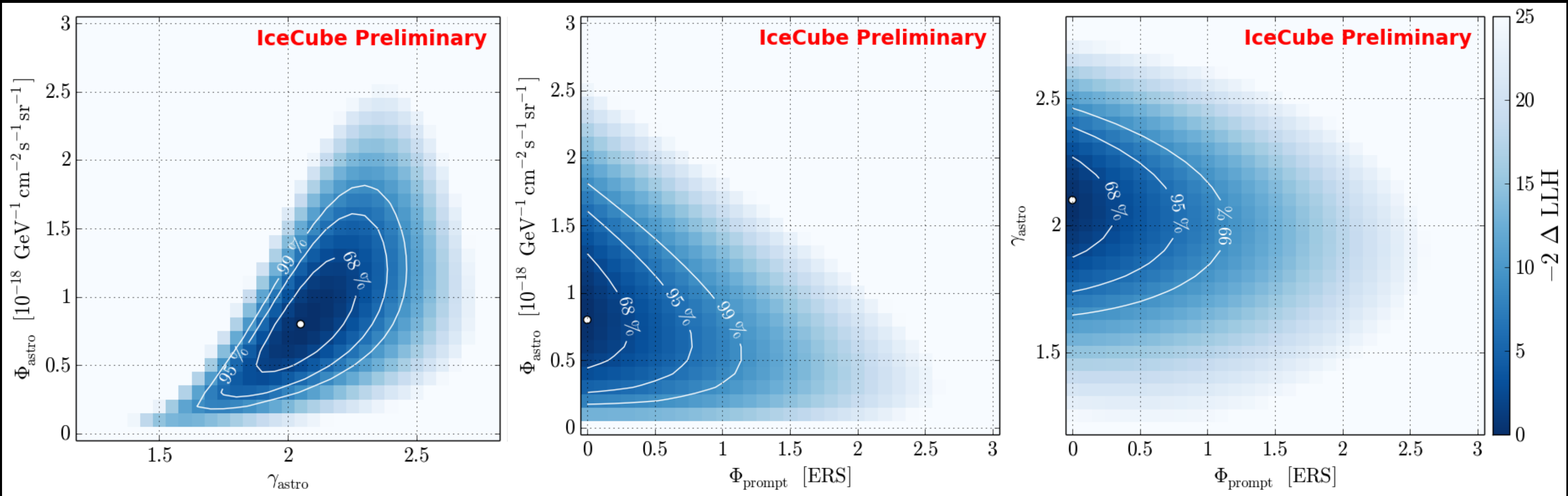


Multi-PeV track neutrino energy pdf

Multi-PeV track p-value < 0.01% to be of atmospheric origin

- Atmospheric-only hypothesis excluded by 5.9σ

Measurement of the astrophysical flux



- <u>Best-fit astrophysical normalization @ 100TeV:</u>

$$(0.82^{+0.30}_{-0.26}) \times 10^{-18}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

- <u>Best-fit spectral index:</u>

$$\gamma_{astro} = 2.08 \pm 0.13$$

- <u>Best-fit prompt normalization:</u>

$$0 \times \mathrm{ERS}$$

- ➢ Astrophysical flux cannot be explained by only a prompt flux
- ➢ Spectral index nearly independent of a prompt flux

The measured astrophysical flux

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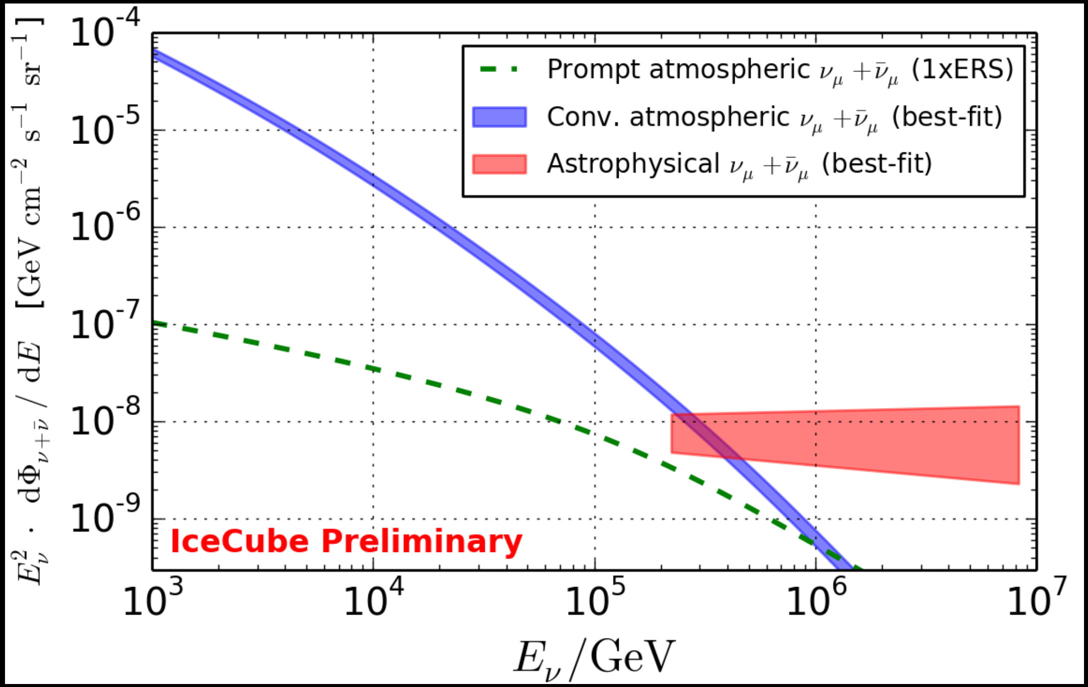


- Atmospheric-only hypothesis excluded by 5.9σ
- Best-fit astrophys. norm. @ 100 TeV:

$$(0.82^{+0.30}_{-0.26}) \times 10^{-18} \frac{1}{\text{GeV cm}^2\text{ s sr}}$$

- Best-fit spectral index:

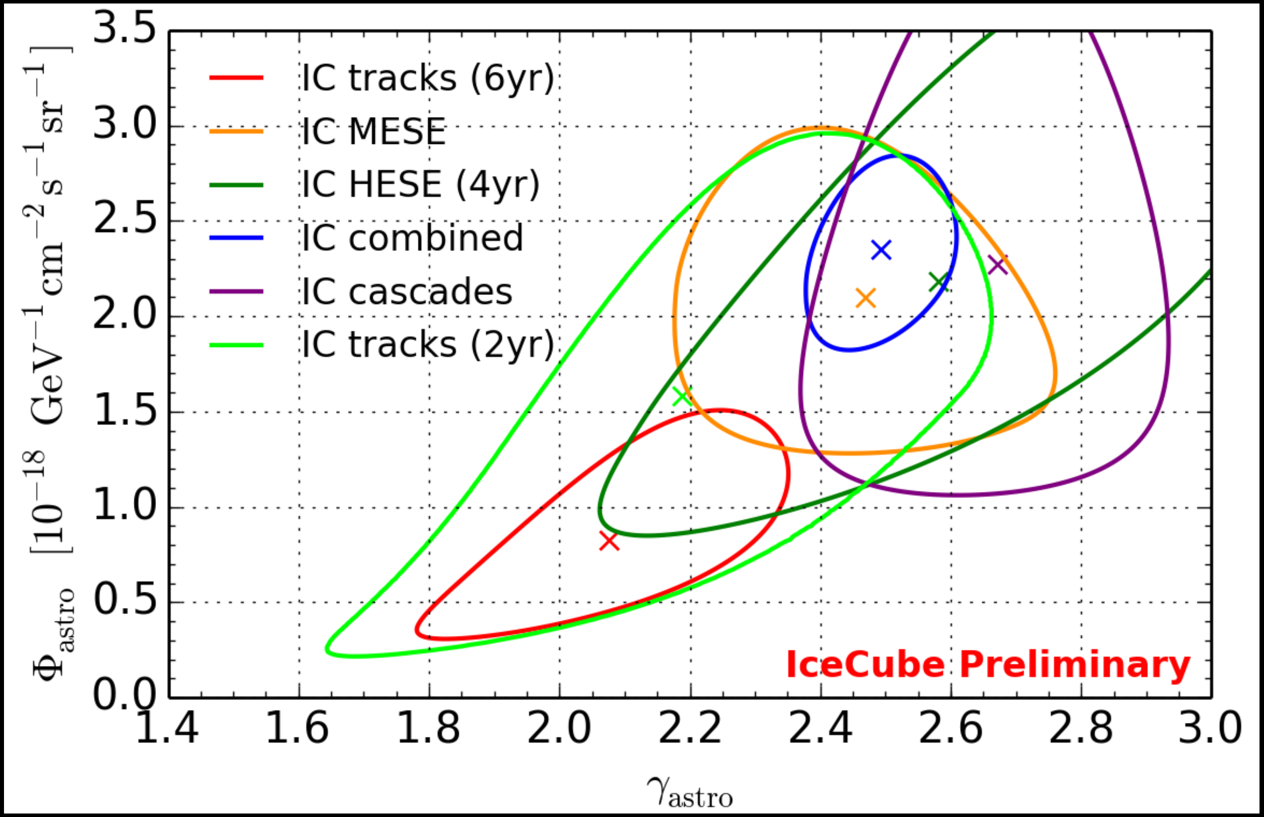
$$\gamma_{\text{astro}} = 2.08 \pm 0.13$$

- Energy ranges:

$$220\text{ TeV} - 8.3\text{ PeV}$$

- Best fit astrophysical neutrino flux and conventional atmospheric neutrino flux predicted by Honda
- ERS prediction for a prompt atmospheric neutrino flux (best-fit prompt norm. is zero)

Summary of the diffuse IceCube results



- 90% C.L. contours of the different IceCube analyses
- Results of IC tracks (6yr) and IC combined analysis (3 yr tracks slightly correlated) not compatible within > 3.6σ (two sided significance)

Comparison to HESE 4 year

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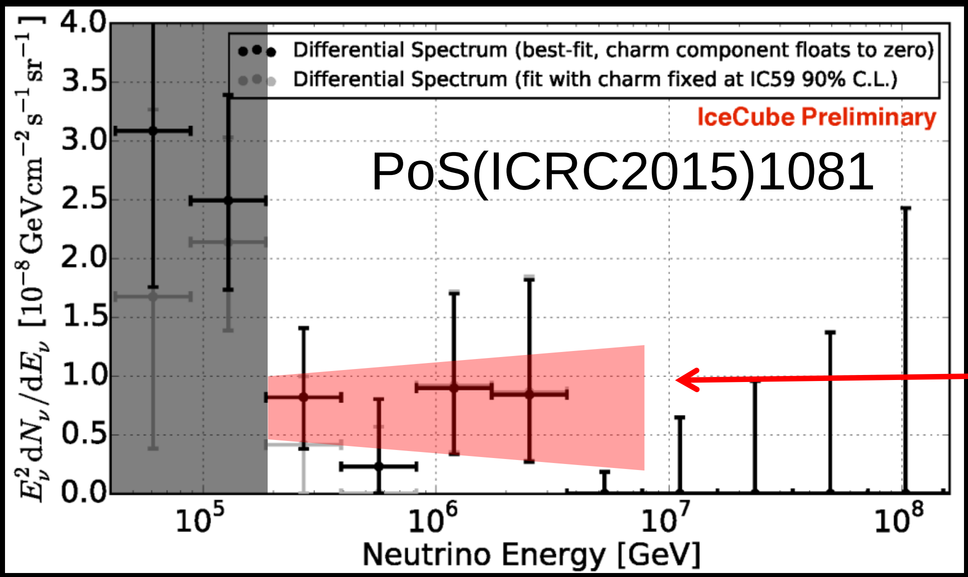
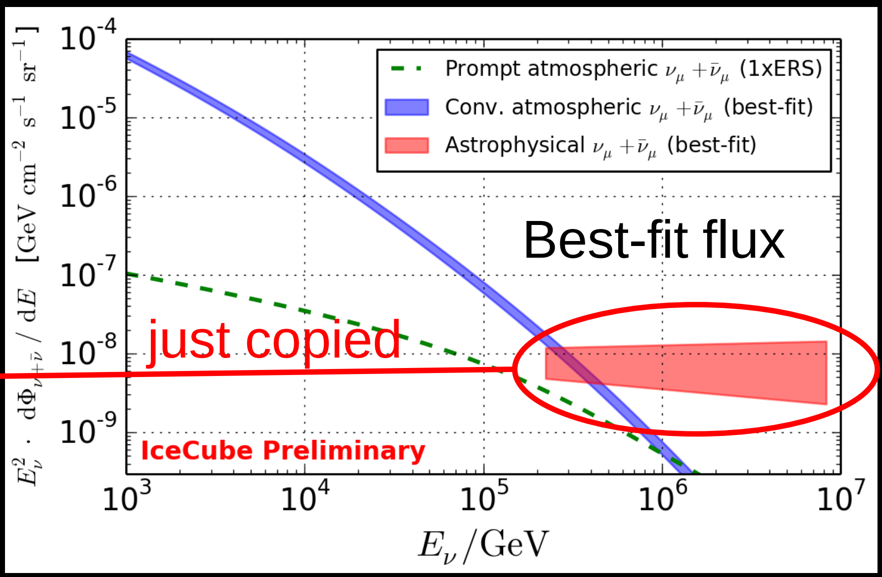
HESE 4 year unfolding
(→ dominated by shower-like events)



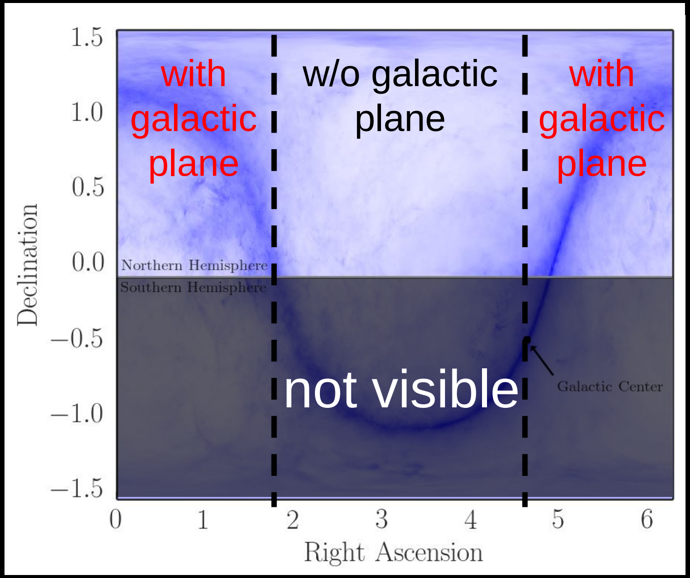
6 year up-going numu analysis

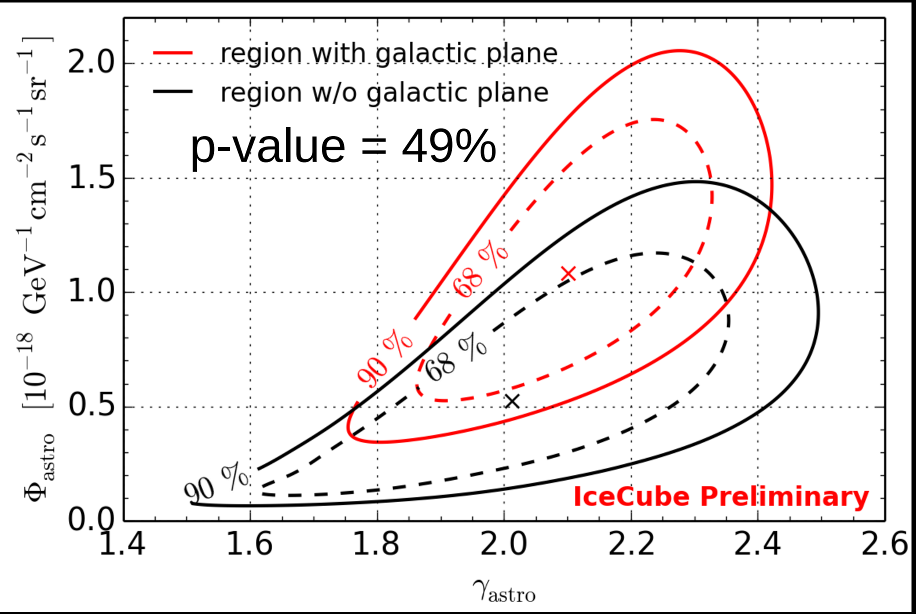


- Energy threshold @ about 60TeV
  → Softer spectral index currently driven by low energy bin
- Energy threshold @ about 200TeV
- @ high energies ($\gtrsim$ 200 TeV) HESE 4 year analysis (left) compatible with E^{-2}

Results of a simple galactic plane analysis

- <u>Question:</u> Could a dominant galactic component be the reason for the tension?
- ➤ Split data into two right ascension regions with similar amount of statistics





- Fits compatible: p-value = 49%
  - → No evidence for a dominant flux from the galactic plane
- Fit of region with galactic plane has slightly higher norm. and softer spectral index
  - → Hint for a galactic component?

Summary and Outlook

- Presented the currently most precise measurement of a diffuse flux of astrophysical muon neutrinos
  - → Astrophysical flux @ 5.9σ level:
    $0.82 \cdot (E/100\text{TeV})^{-2.08}\ [10^{-18}\text{GeV}^{-1}\text{cm}^{-2}\text{s}^{-1}\text{sr}^{-1}]$
  - → No evidence for a dominant flux from the galactic plane
- Tension of 3.6σ between up-going track and all-sky cascade analysis
  - → Indication of a spectral break

The IceCube Collaboration

Canada
University of Alberta–Edmonton
University of Toronto

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Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
Michigan State University
Ohio State University
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South Dakota School of Mines & Technology
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Thank you for your attention!

Backup slides

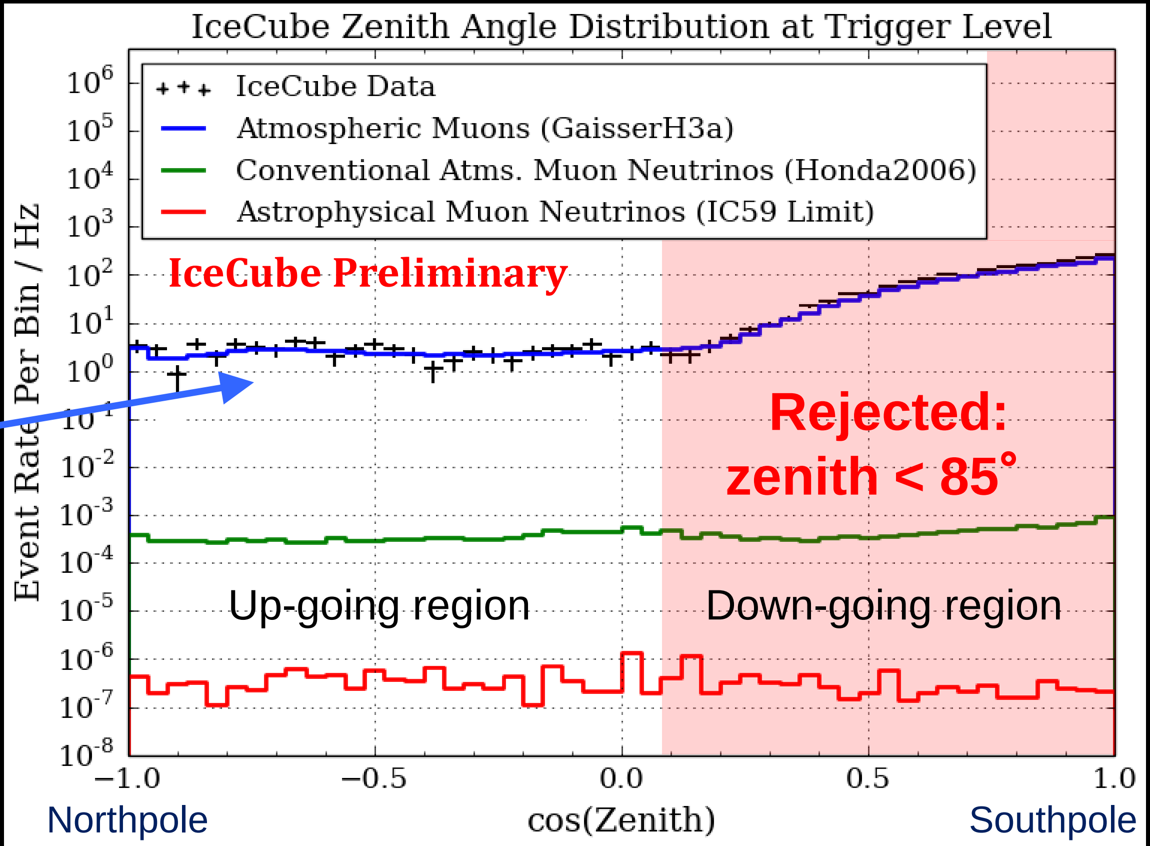
Discussion

- The diffuse muon analysis is …
  - → sensitive only at high energies (above ~200 TeV)
  - → sensitive only in the Northern Hemisphere

- We should keep in mind that ...
  - → the energy spectrum need not be a single power law
  - → there could be more than one component (e.g. one galactic and one extragalactic)

IceCube data @ trigger level
Downgoing muon rejection

- Rejection of muon events from cosmic ray air showers by restriction to Northern hemisphere
- Mis-reconstructed muon events in the upgoing region
  - ➢ Can be removed by quality criteria on track reconstruction

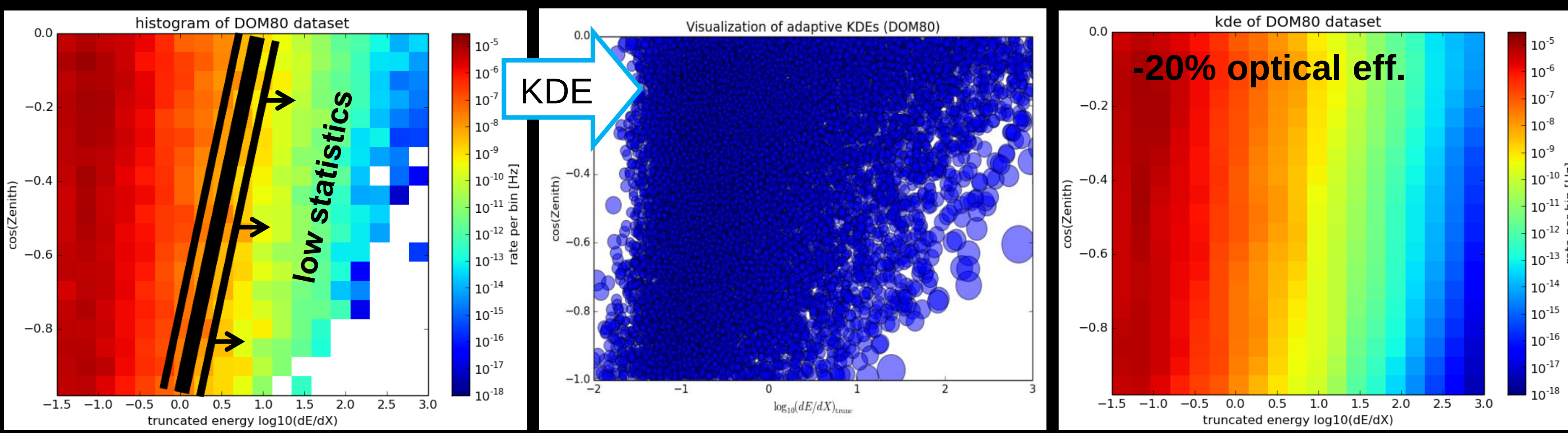


Use a Boosted Decision Tree (BDT → machine learning algorithm)

➢ High-purity neutrino sample (> 99.9%) with high neutrino efficiency (~ 70,000 neutrino events per year)

Parameterization of systematic uncertainties
Example: Optical sensor efficiency

- Simulation of datasets with different optical sensor efficiencies (e.g. ±10%, ±20%)
  → BUT datasets have low statistics especially at higher energies (signal region)
- Use Kernel Density Estimation (KDE) to approximate pdfs in regions of low statistics (arXiv:0709.1616)



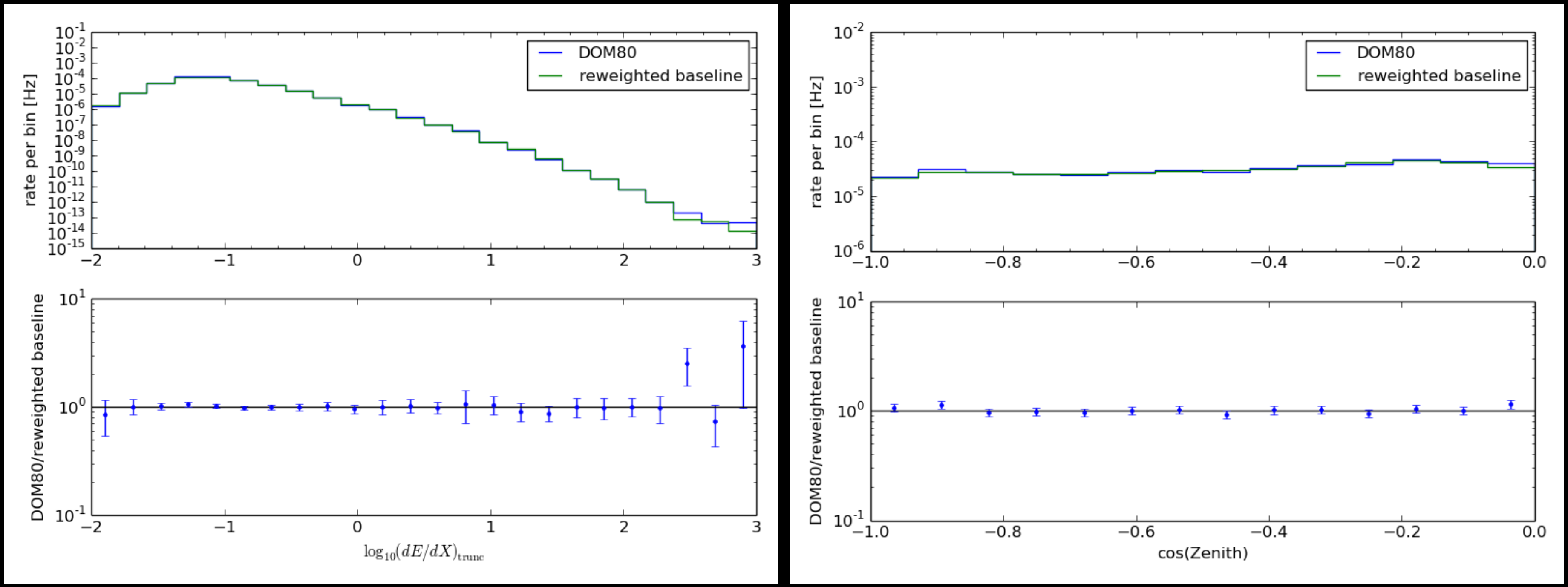
- Reweight the high-statistics baseline dataset to a dataset with different optical efficiencies by reweighting each event

$$w_i = w_i^{baseline} \cdot f_i^{DOM}$$

Parameterization of systematic uncertainties

Example: Optical sensor efficiency

- Comparison between systematic dataset (here: opt. eff. 80%) and reweighted baseline dataset (here: opt. eff. 100% → 80%) by using the KDE method



- No differences within statistical uncertainties between systematic dataset and reweighted baseline dataset

Simple galactic plane analysis

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