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

Sebastian Schoenen, Leif Rädel

III. Physikalisches Institut B – RWTH Aachen

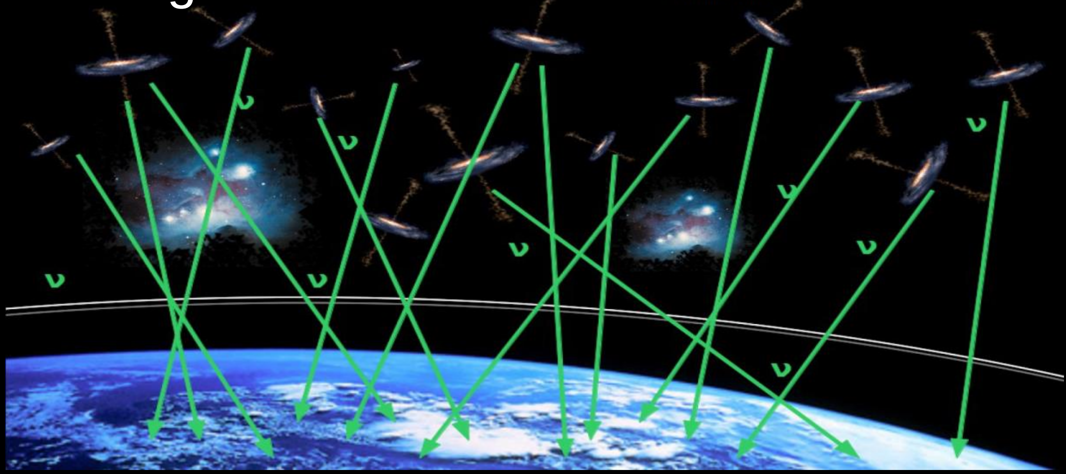
For the IceCube Collaboration

IceCube Particle Astrophysics Symposium 2015

Madison, Wisconsin, May 4th, 2015

What is a diffuse astrophysical muon neutrino flux?

Looking in all directions at the same time



Astrophysical neutrinos with energy spectrum:

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

<u>Promising candidate</u> → 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}
- <u>2 Questions:</u>

  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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<u>Detection principle:</u>

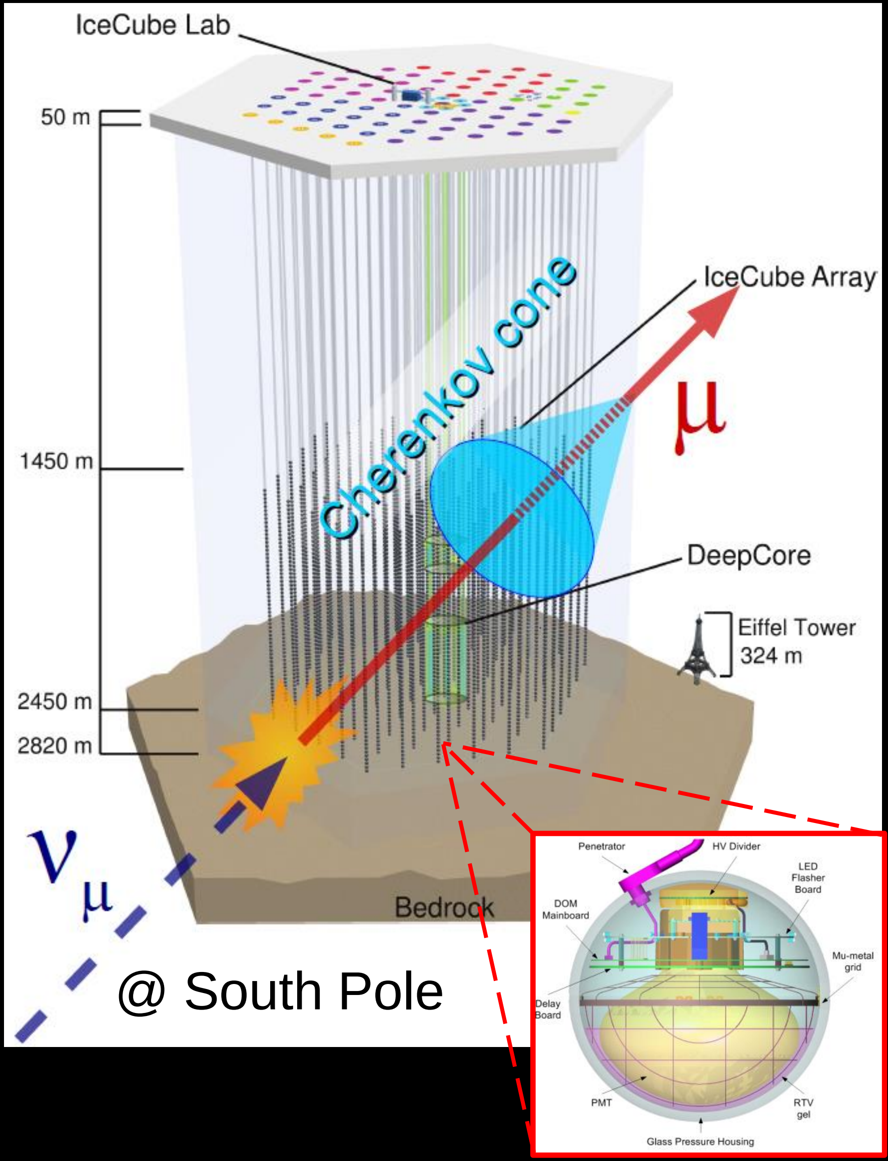
- ν_μ interaction <u>near</u> or inside the detector
- Detection of Cherenkov light produced by secondary relativistic, charged particles using optical sensors in ice

<u>Search strategy:</u>

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

<u>Previous IceCube analysis:</u>

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



Signal signature

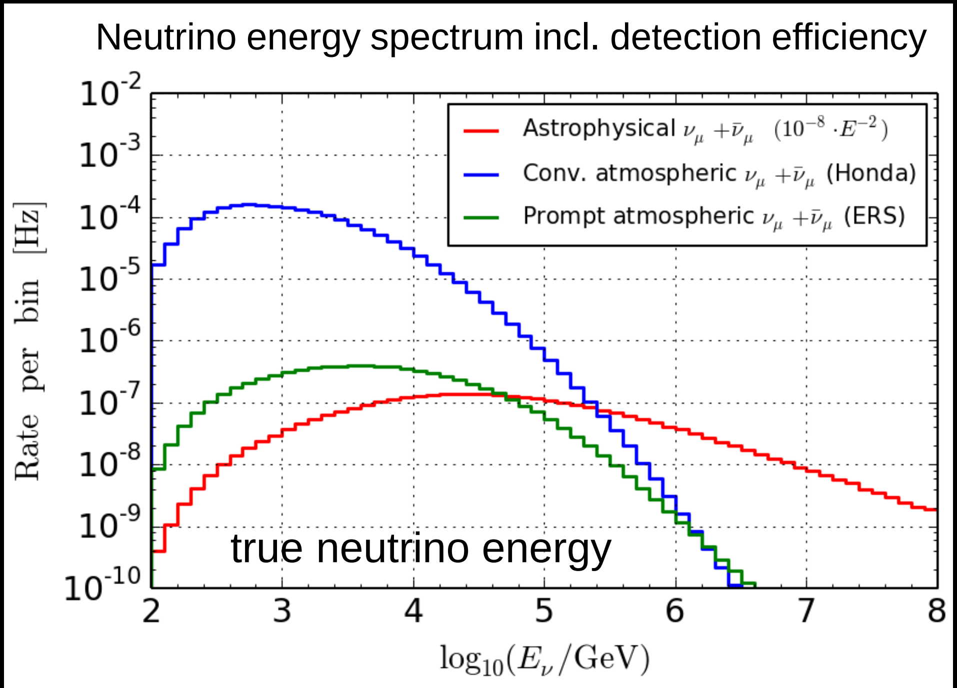
- Atmospheric neutrino background

  Conventional atmospheric neutrinos

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

  Prompt atmospheric neutrinos

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



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

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-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

Highest energy event in 2009-2012

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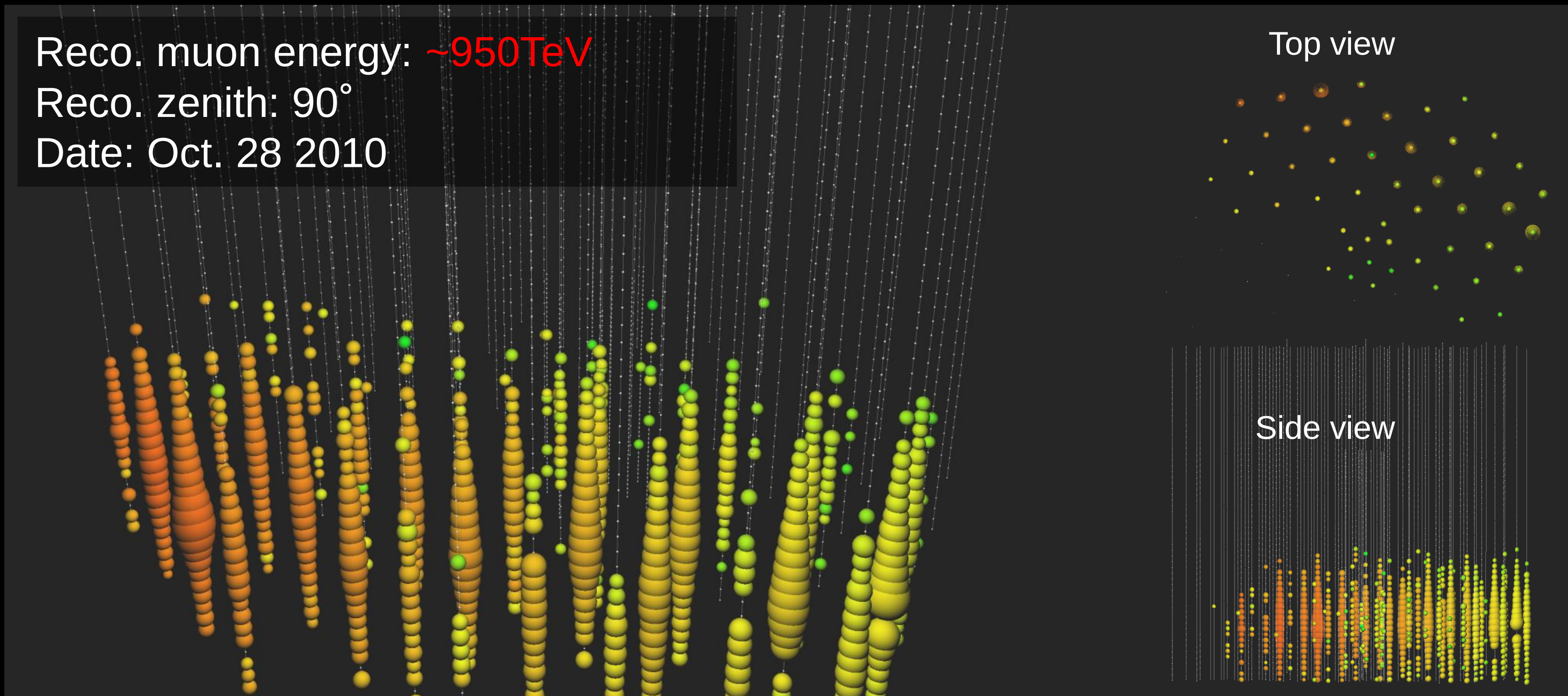
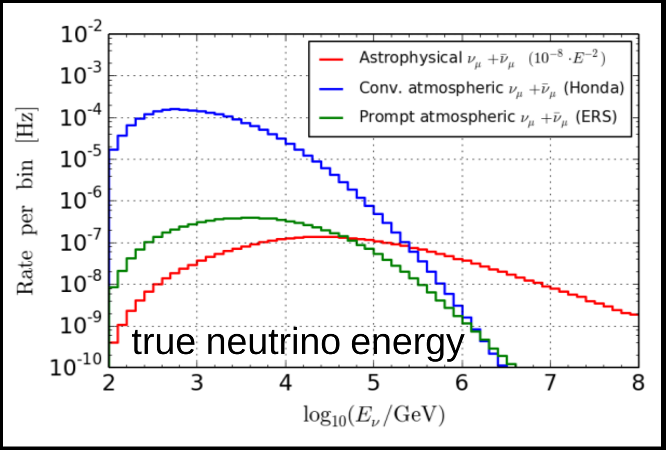


time scale

The analysis method

- Analyze 2-dimensional energy vs. zenith angle distribution



- Likelihood function: binned Poisson likelihood
  → Include systematic uncertainties as free continuous nuisance parameters

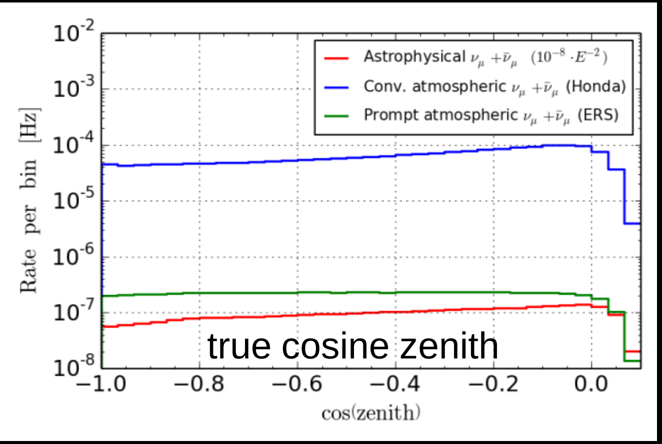
signal and nuisance parameters

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

measurement and expectation

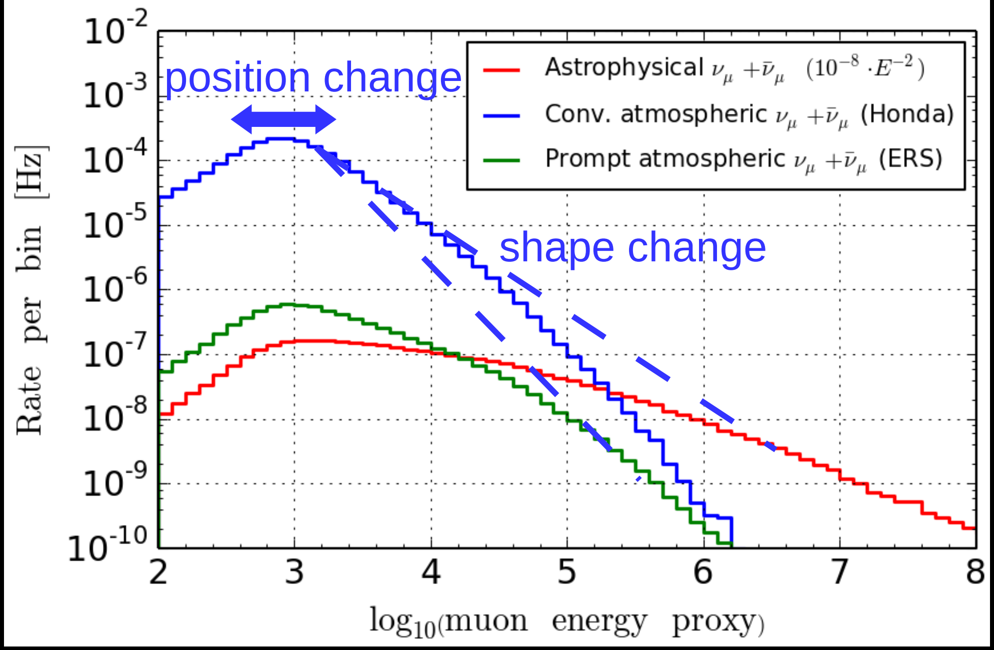
- Expectation:

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



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 2009 – 2012

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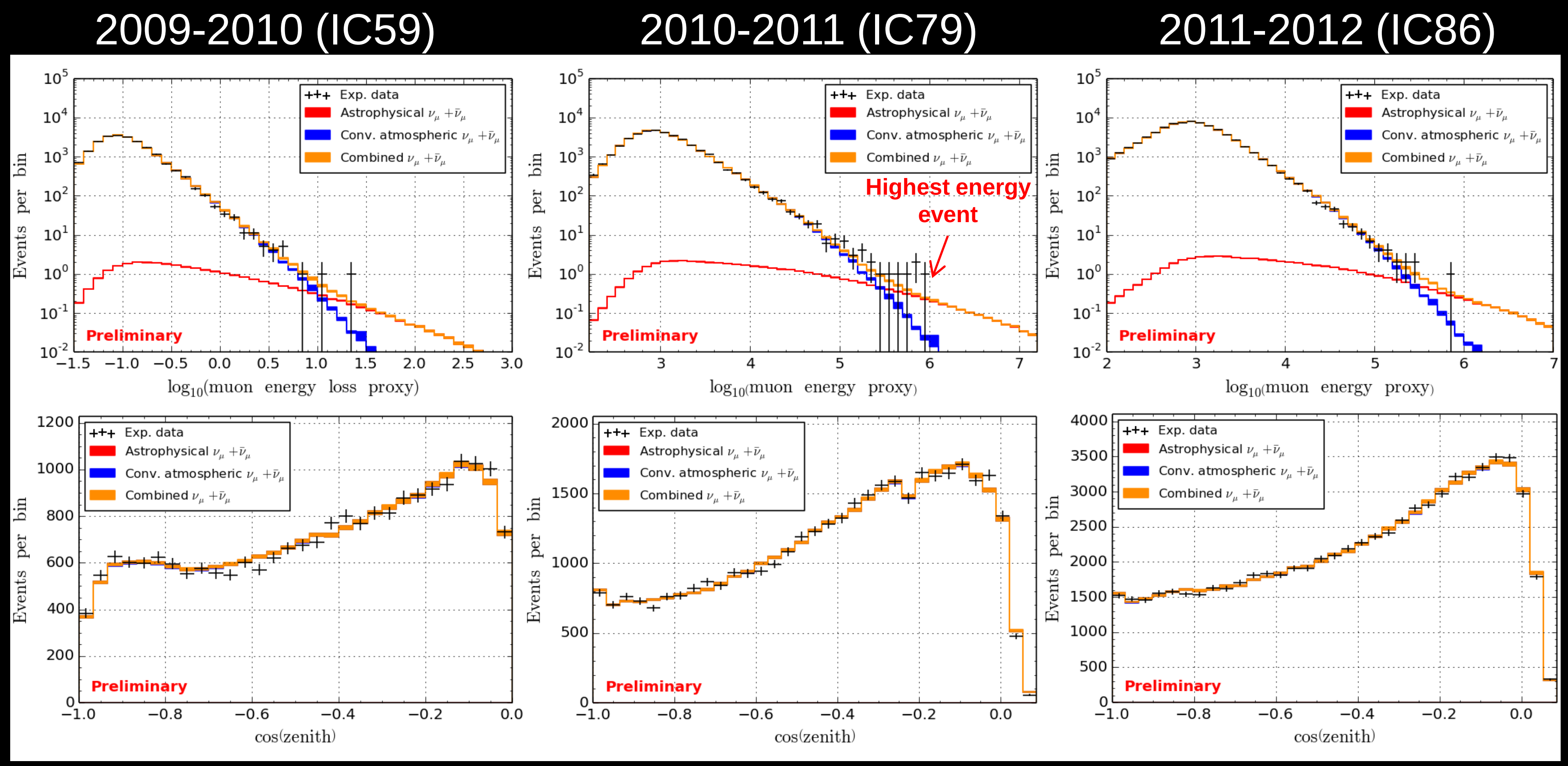
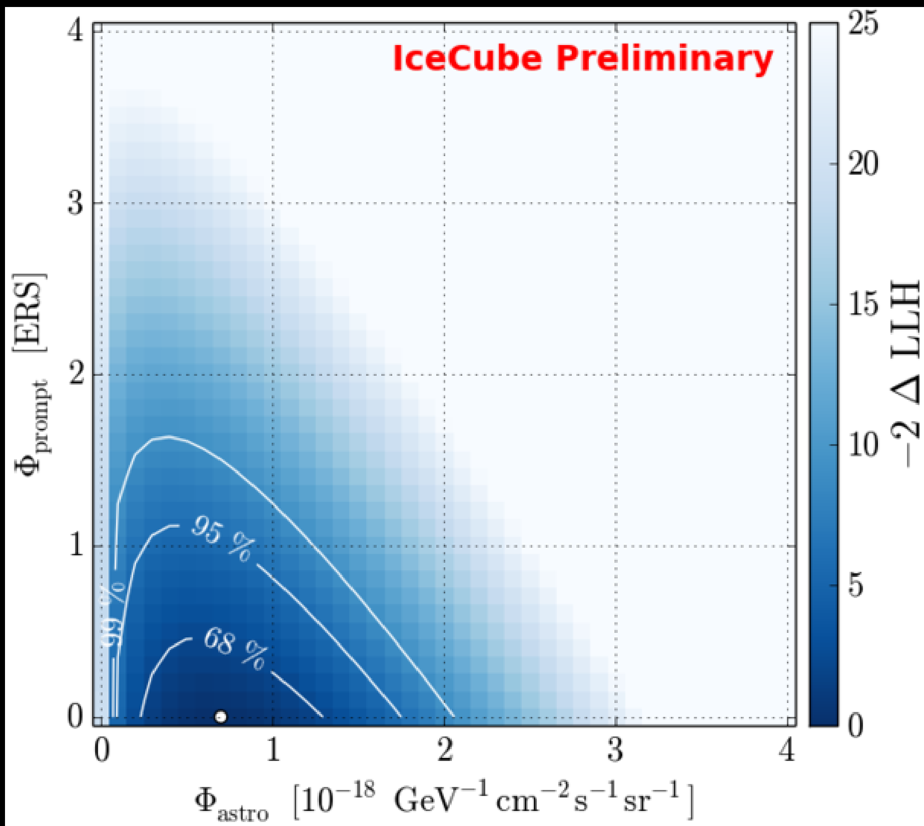


- Excellent data/mc agreement for all three years

#neutrinos ≈ 130,000

Analysis results
Astrophys. and prompt normalization



- 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 prompt normalization:

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

- Upper limit on the prompt ERS flux:

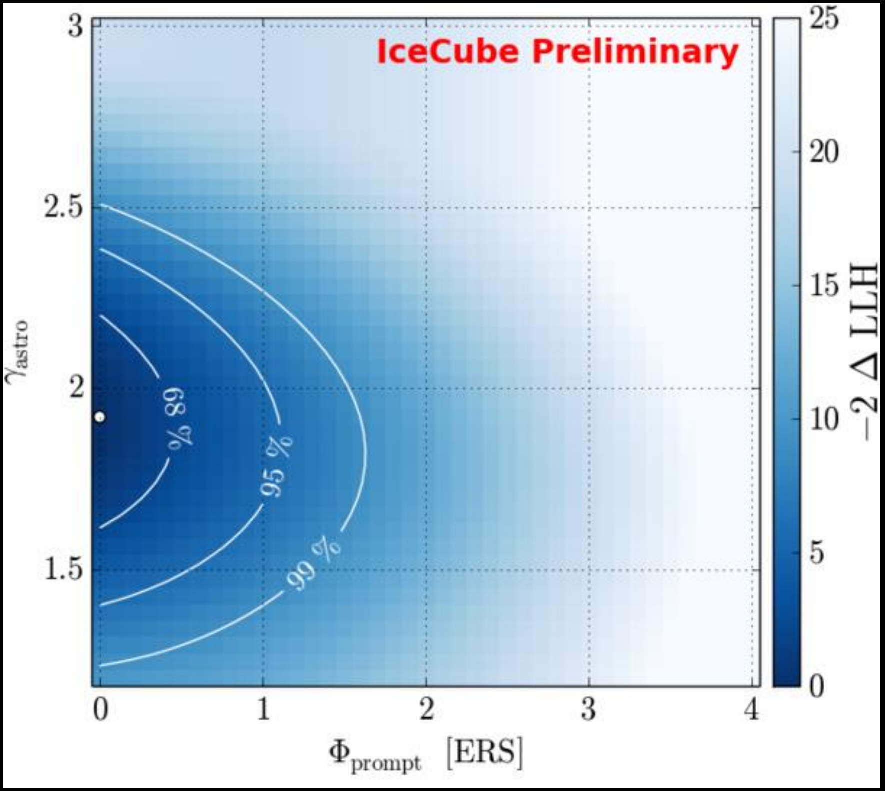
$$0.54 \times \mathrm{ERS}\ @90\%\ \mathrm{C.L.}$$

  - Currently the best limit on the prompt flux

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

- Atmospheric-only hypothesis excluded by 4.3σ

Analysis results
Astrophysical spectral index



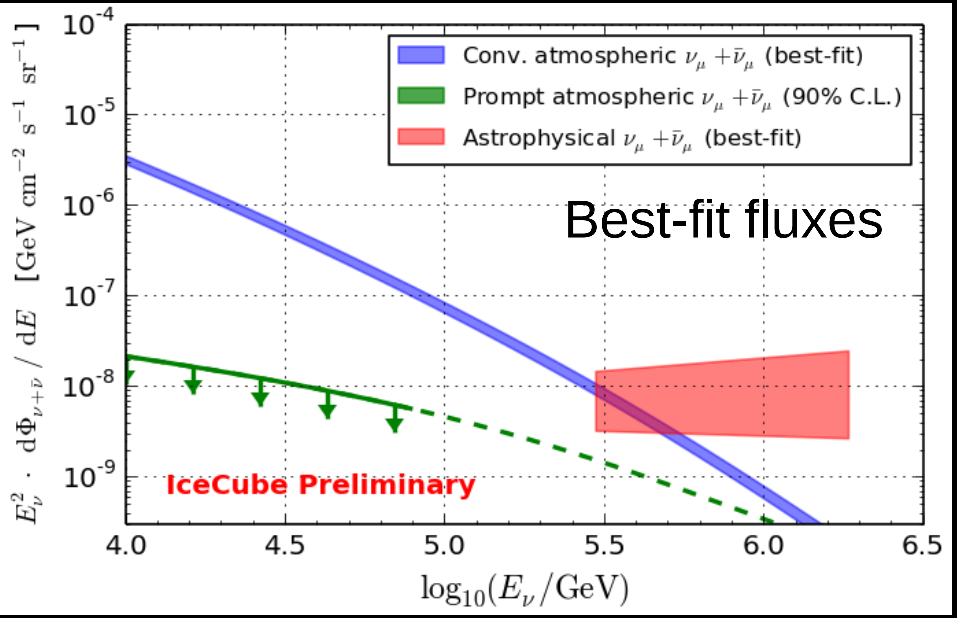
- Best-fit spectral index:

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

- Measured astrophysical spectral index nearly independent of the prompt normalization

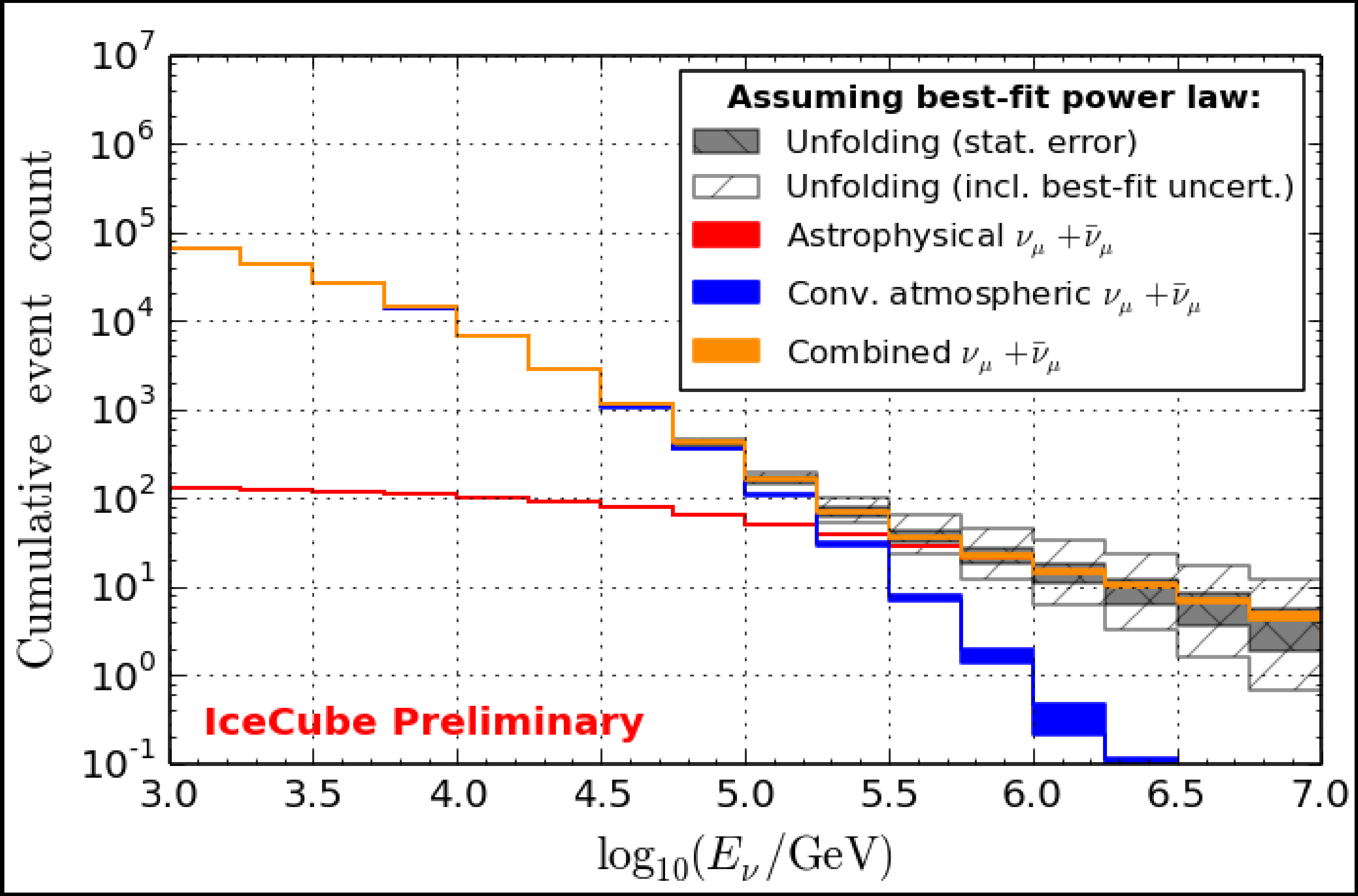
- Energy region:

$$300\mathrm{TeV} < E_\nu < 2\mathrm{PeV}$$



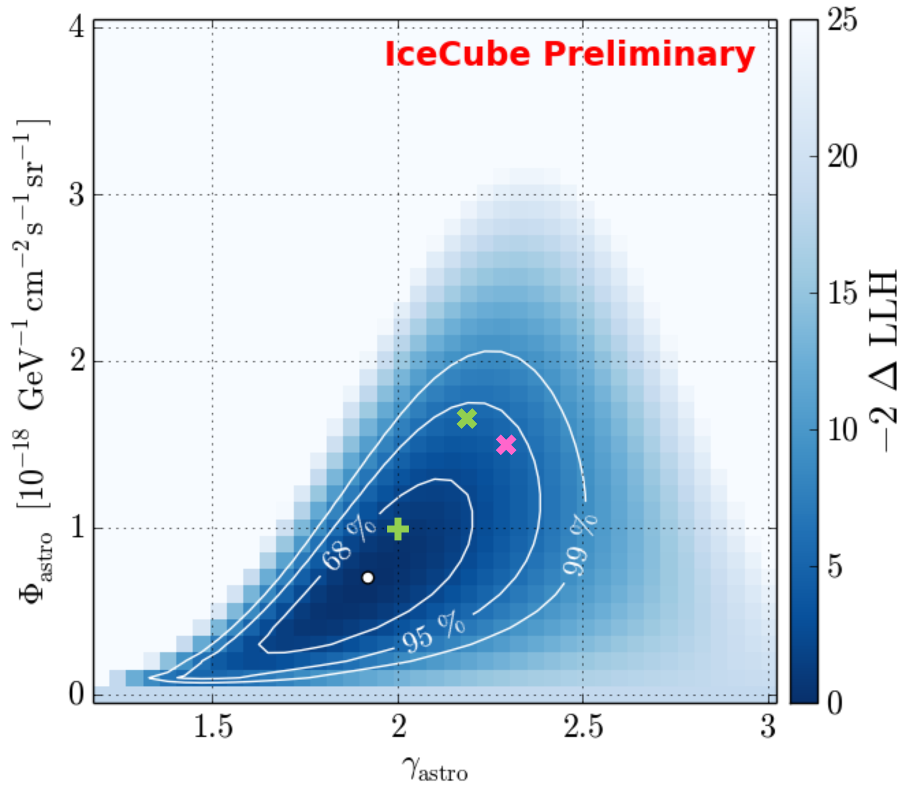
Measured best-fit energy spectrum

Unfolded astrophysical muon neutrino spectrum



Disclaimer: The unfolded neutrino spectrum assumes the best-fit unbroken power law!

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 (will be published in Phys. Rev. Lett. soon)

Comparison to analysis dominated by shower-like events

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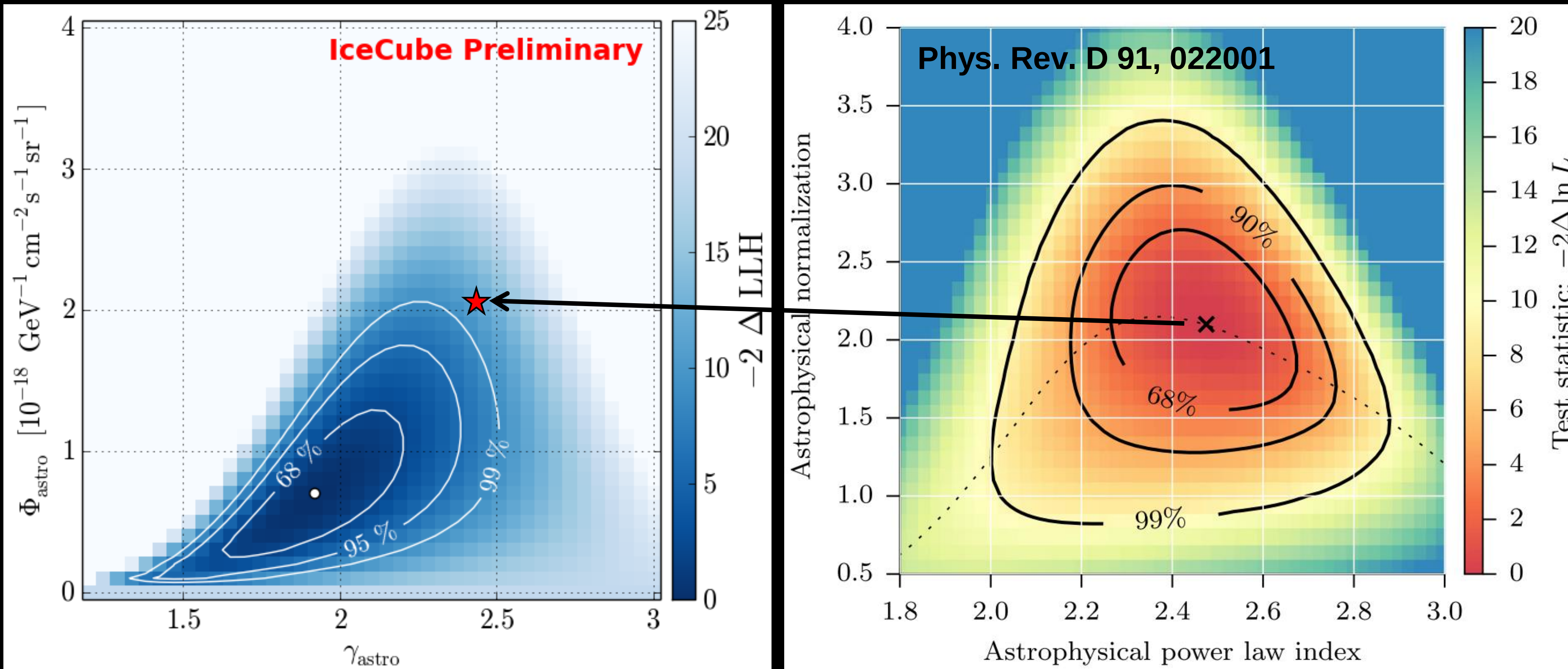

- Right: IceCube result reported in Phys. Rev. D 91, 022001
  - → Sensitive to shower-like events and therefore much lower energy threshold (~10TeV)
  - → Sensitive to neutrino events from the Southern Sky
- Some tension (~2σ) between the result present here and the reported result (right)

Comparison to analysis dominated by shower-like events

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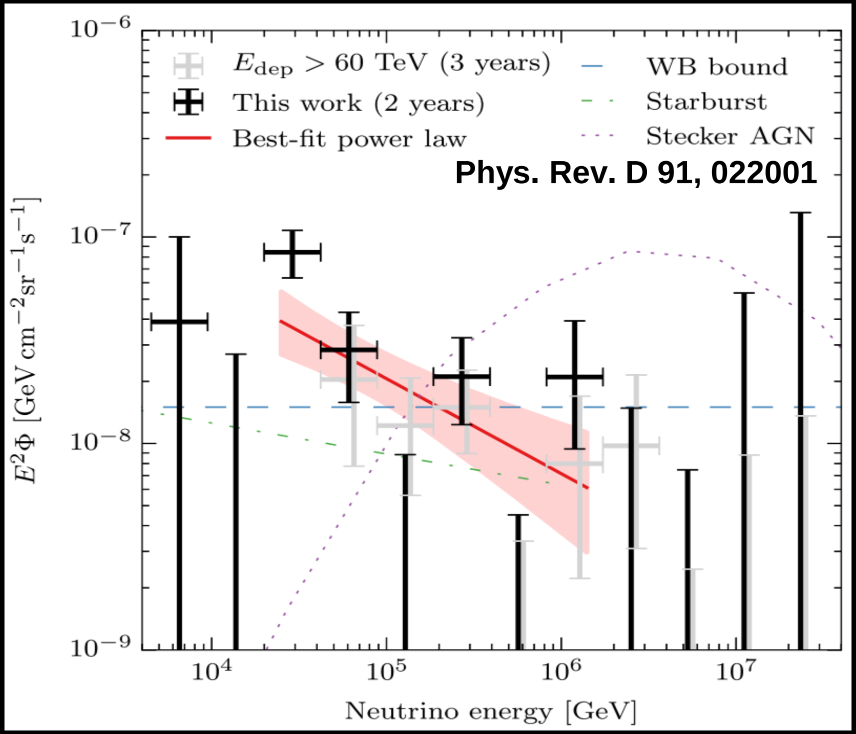
Unfolding (dominated by shower-like events)



- 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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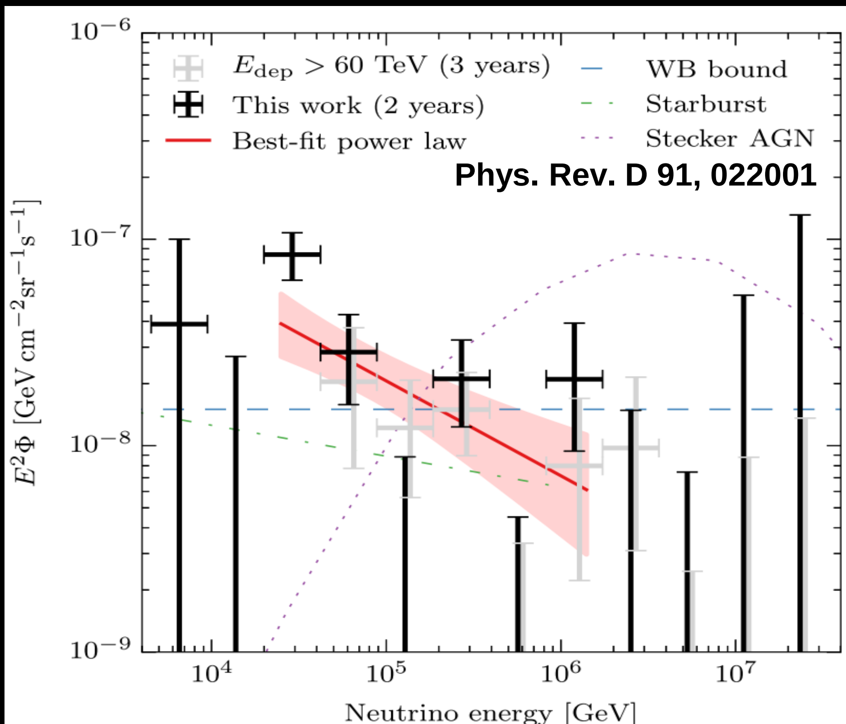
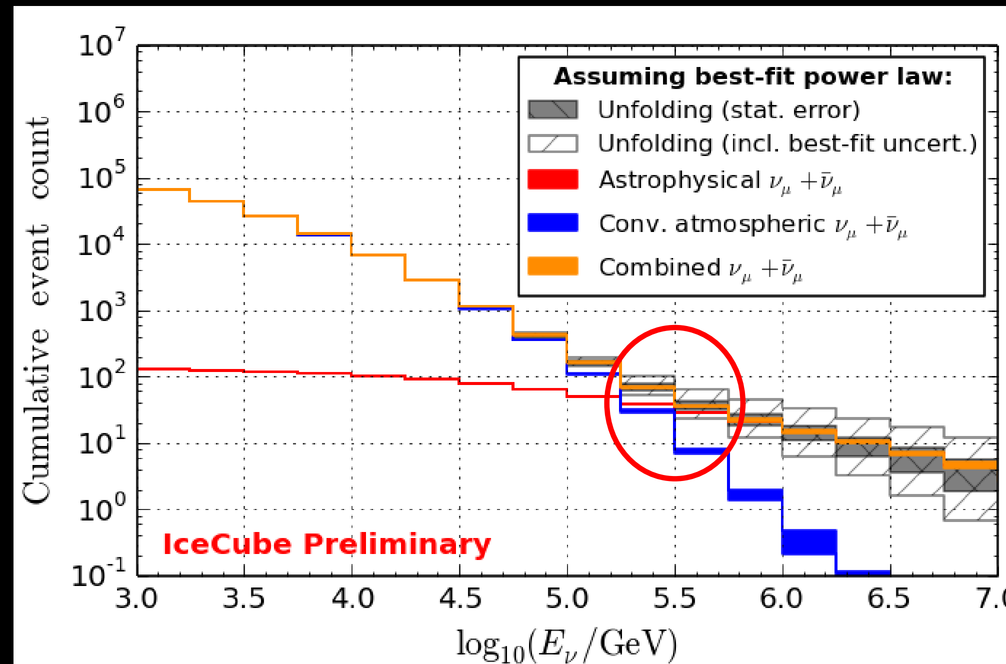
Unfolding (dominated by shower-like events)



- 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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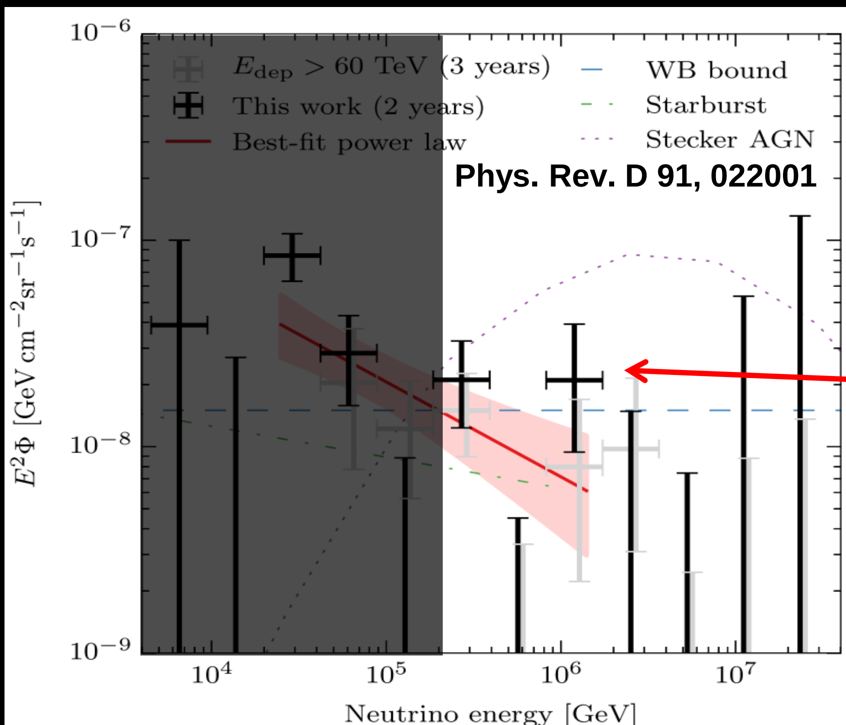
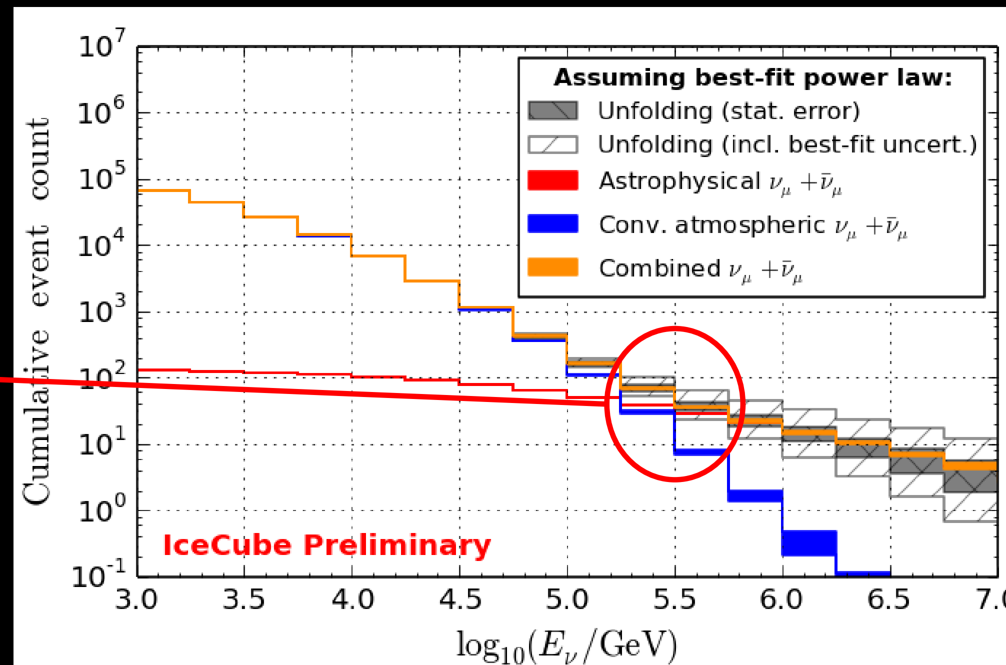
Unfolding (dominated by shower-like events)



This analysis (up-going track-like events)



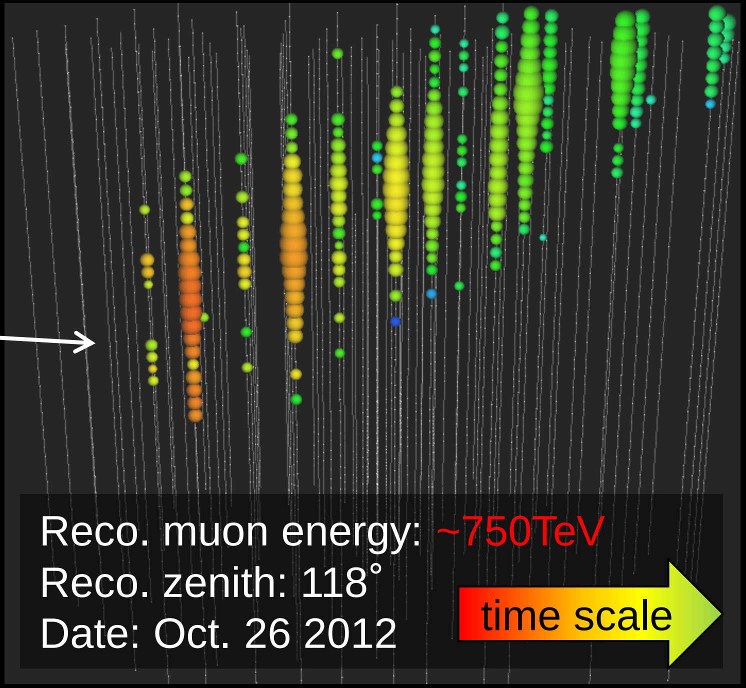
- Energy threshold @ about 10TeV
  - → Softer spectral index currently driven by low energy bin

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

Summary and Outlook

- 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):
    $0.66 \cdot (E/100\mathrm{TeV})^{-1.91}\ [10^{-18}\mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}]$
  - → Current best upper limit on the prompt flux: ~0.54 x ERS @90% C.L.

- By summer three more years of data will be added to the analysis
  - → Highest energy burnsample event in 2012-2014



The IceCube Collaboration

Thank you for your attention!

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)