IceCube – High Energy Results

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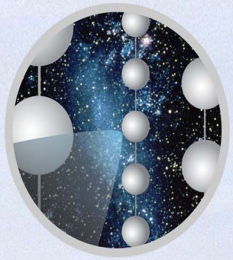
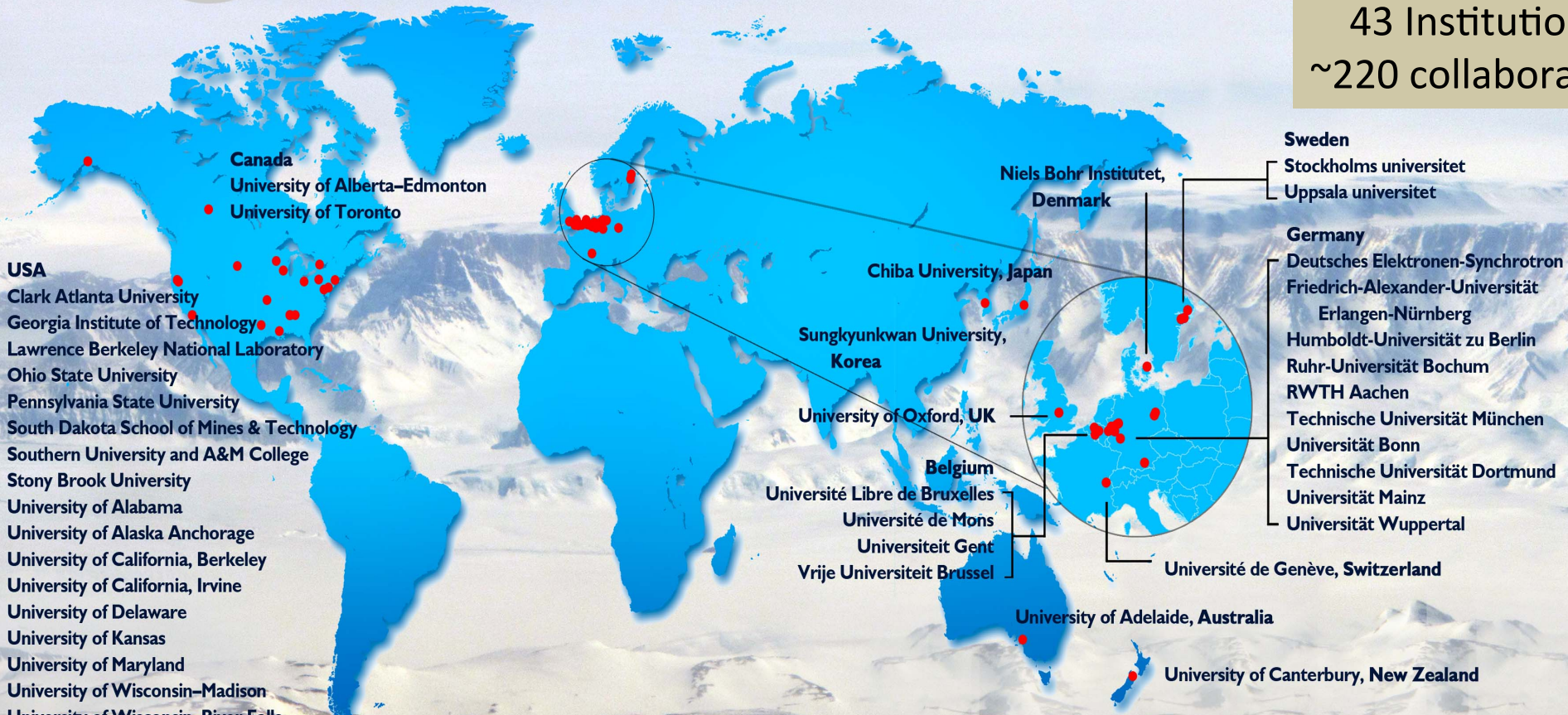
Neutrinos Beyond IceCube
24 April 2014



The IceCube Collaboration

43 Institutions
~220 collaborators

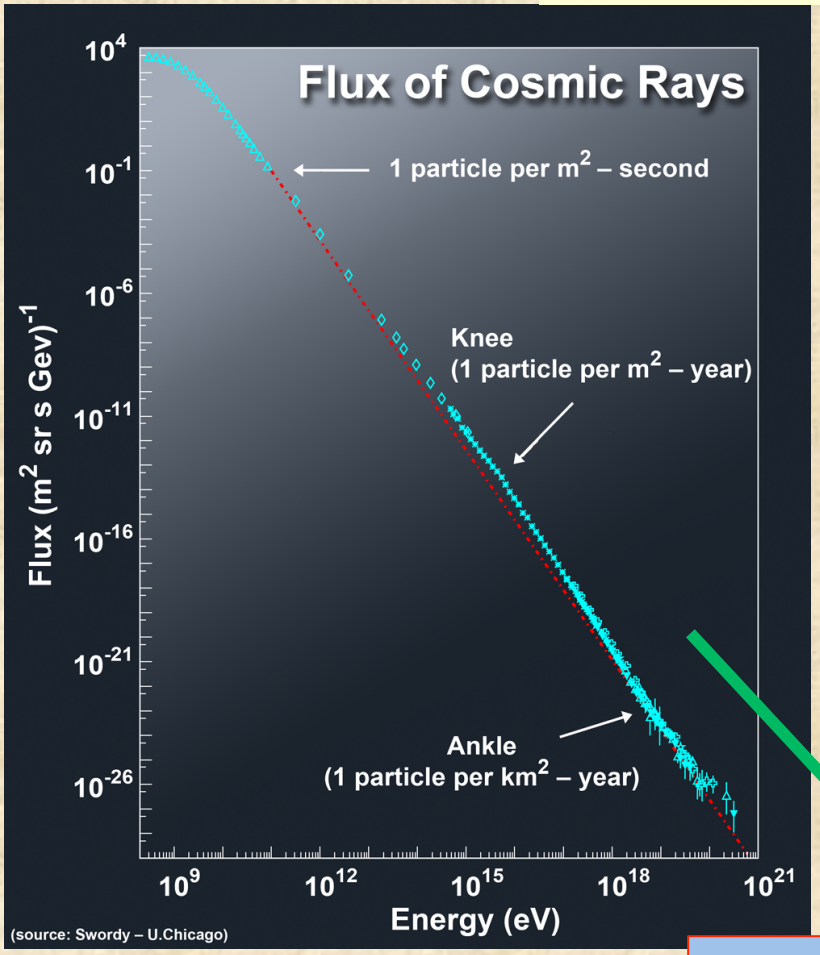


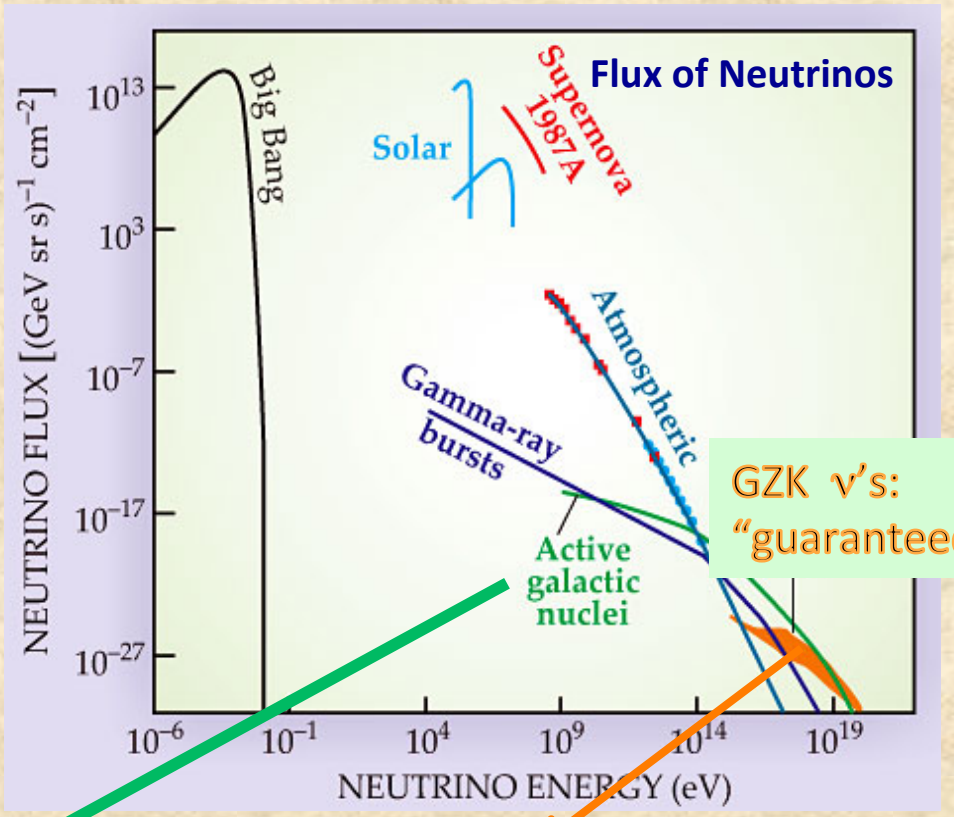
Funding Agencies

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)

Cosmic Rays and Neutrinos

Driving theme: Origin of Cosmic Rays



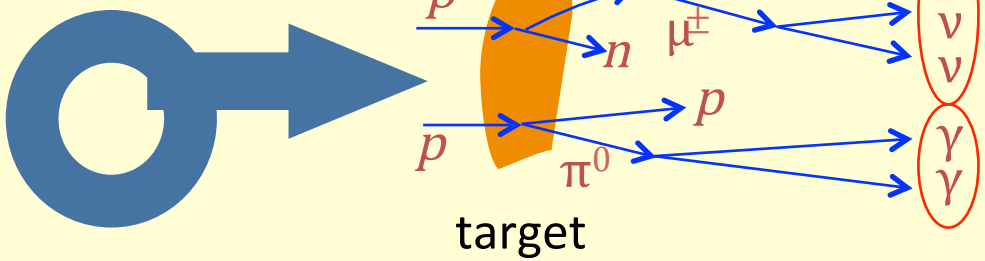


GZK ν's: "guaranteed"

$$\gamma_{cmb}\, p \rightarrow \Delta^{+} \rightarrow \begin{matrix} n\,\pi^{+} \rightarrow n\,\mu\nu \\ p\,\pi^{0} \rightarrow p\,\gamma\gamma \end{matrix}$$

CR – ν connection

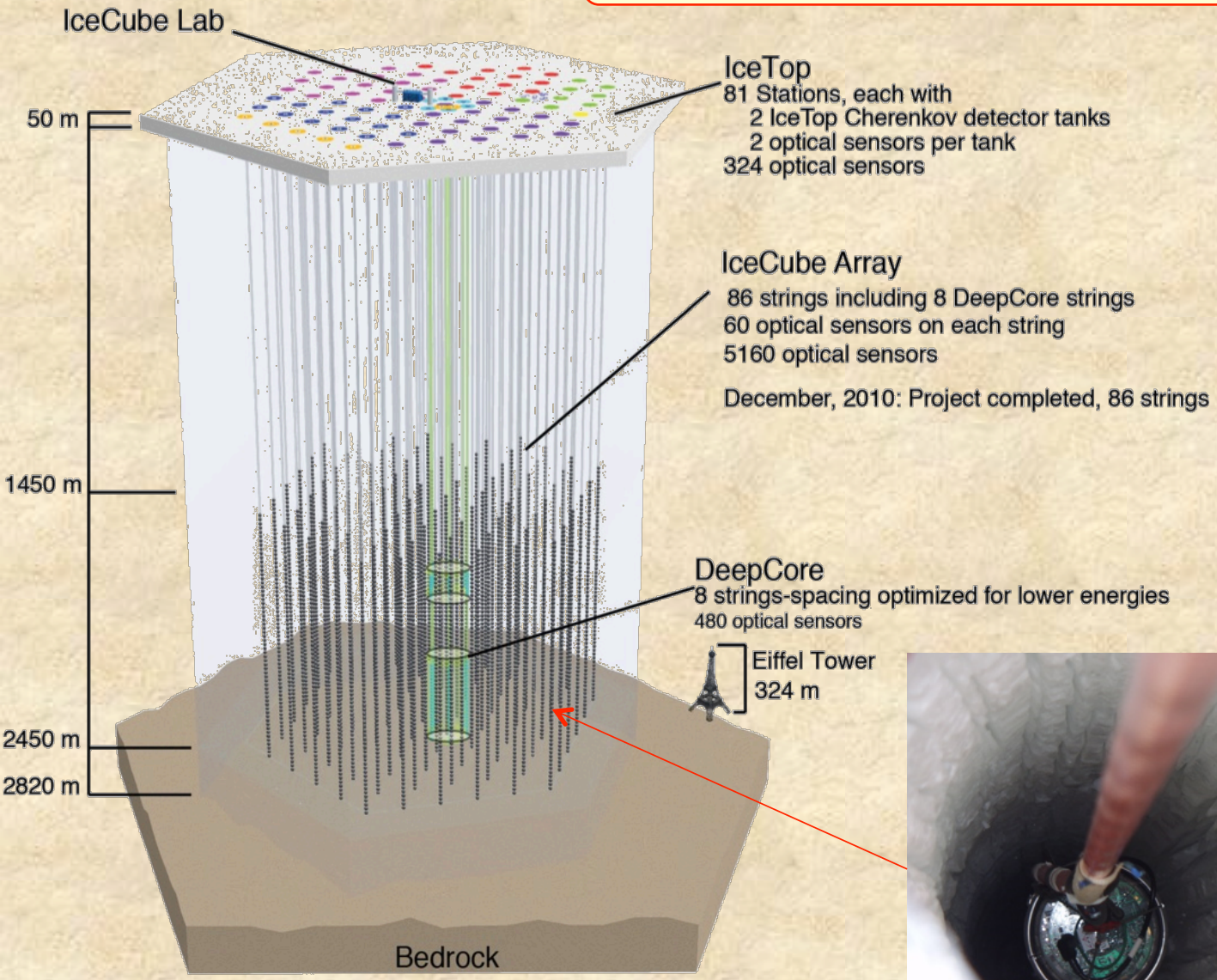
accelerator

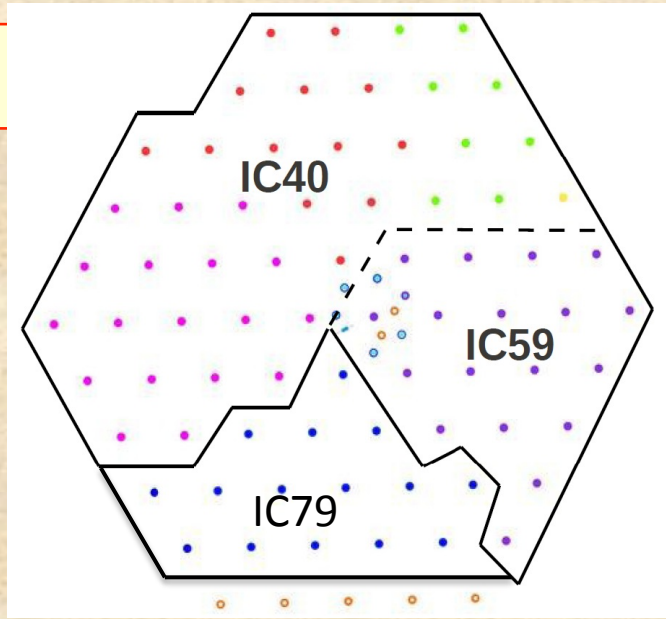


the **γ – ν** connection for hadronic accelerators

IceCube Detector

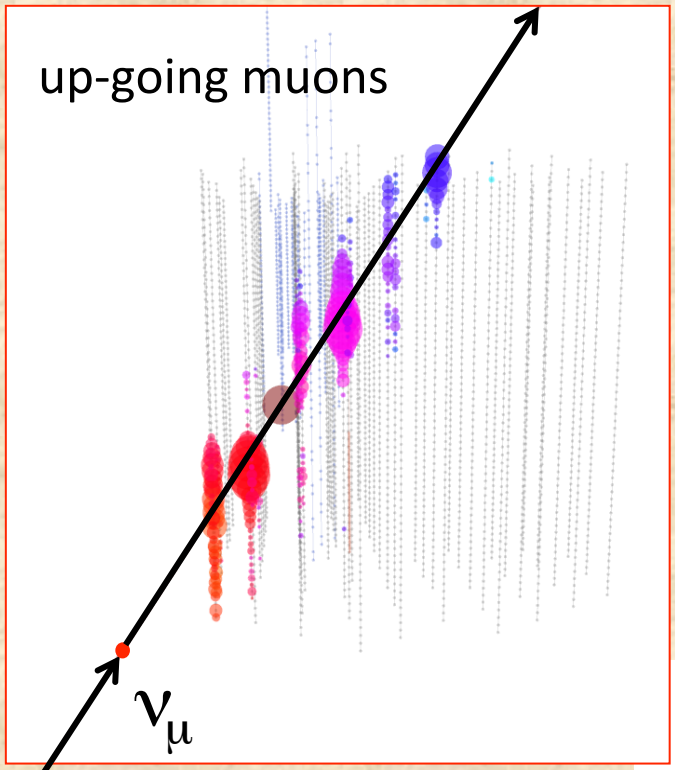
Detector Completion Dec 2010

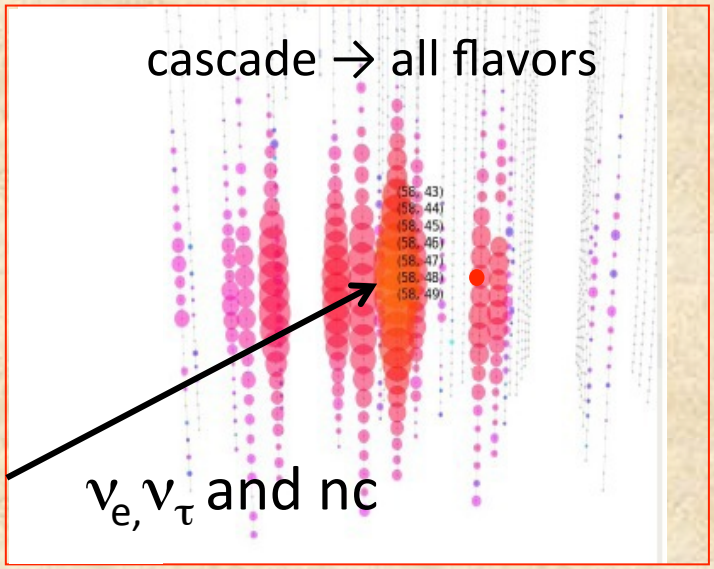


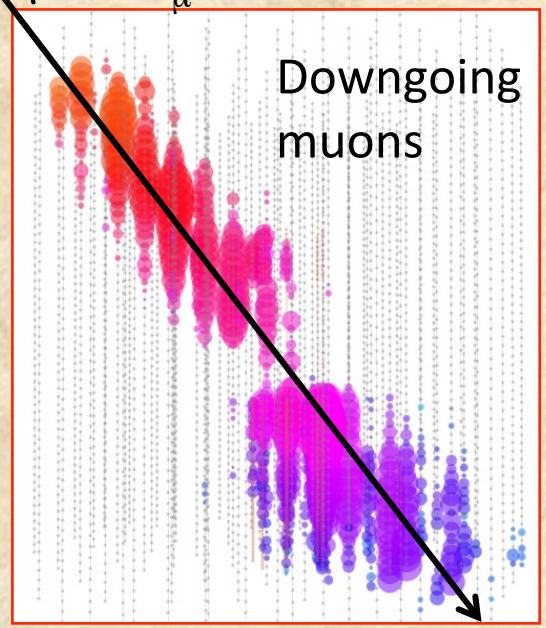


9 strings (2006)
22 strings (2007)
40 strings (2008)
59 strings (2009)
79 strings (2010)
86 strings (2011)

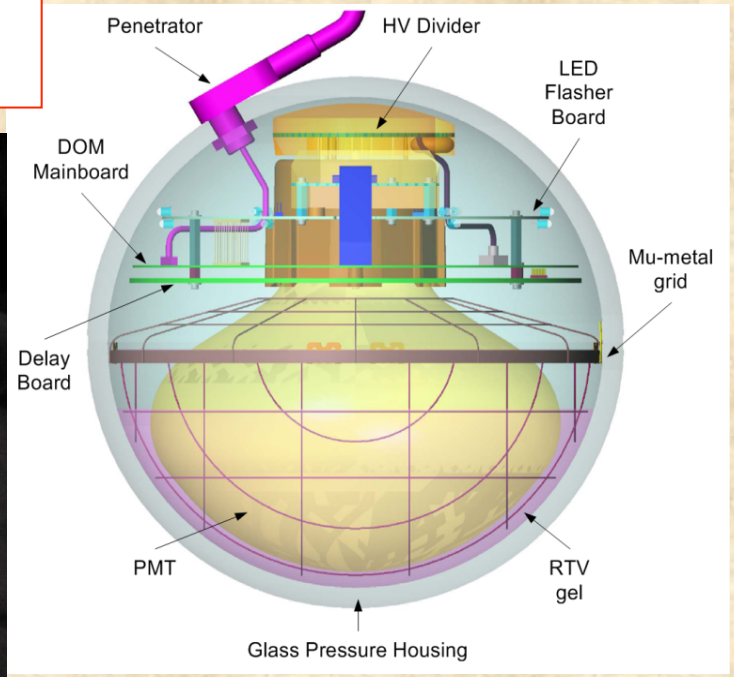
Detection Methods







light collection by DOMs

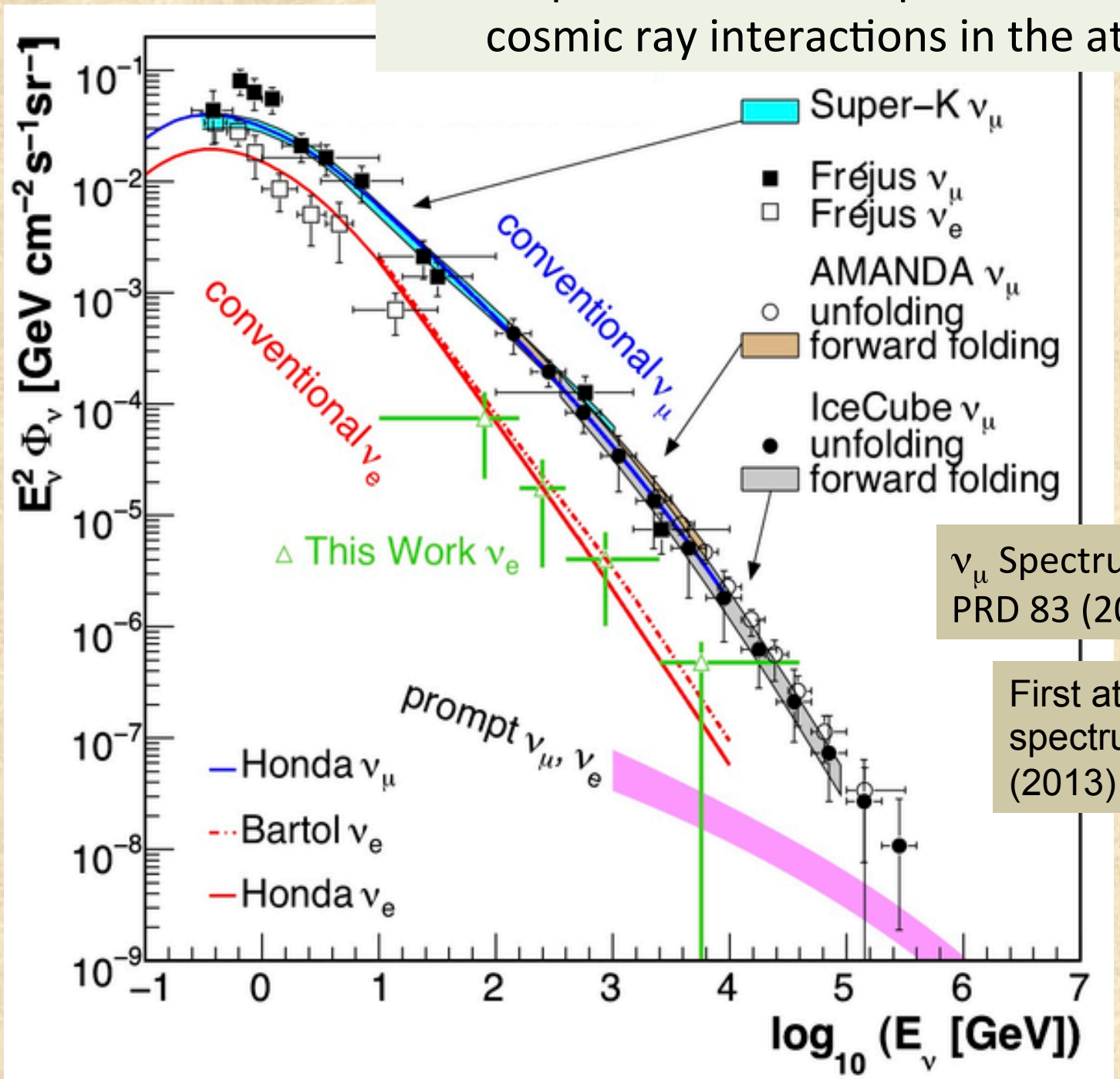


Digital Optical Module (DOM)

- Low Noise rate (500 Hz)
- High reliability, very few sensor issues per year.
- Gains very stable to <0.3%.
- Digital communication from DOM

Search Strategies for Astrophysical Neutrinos

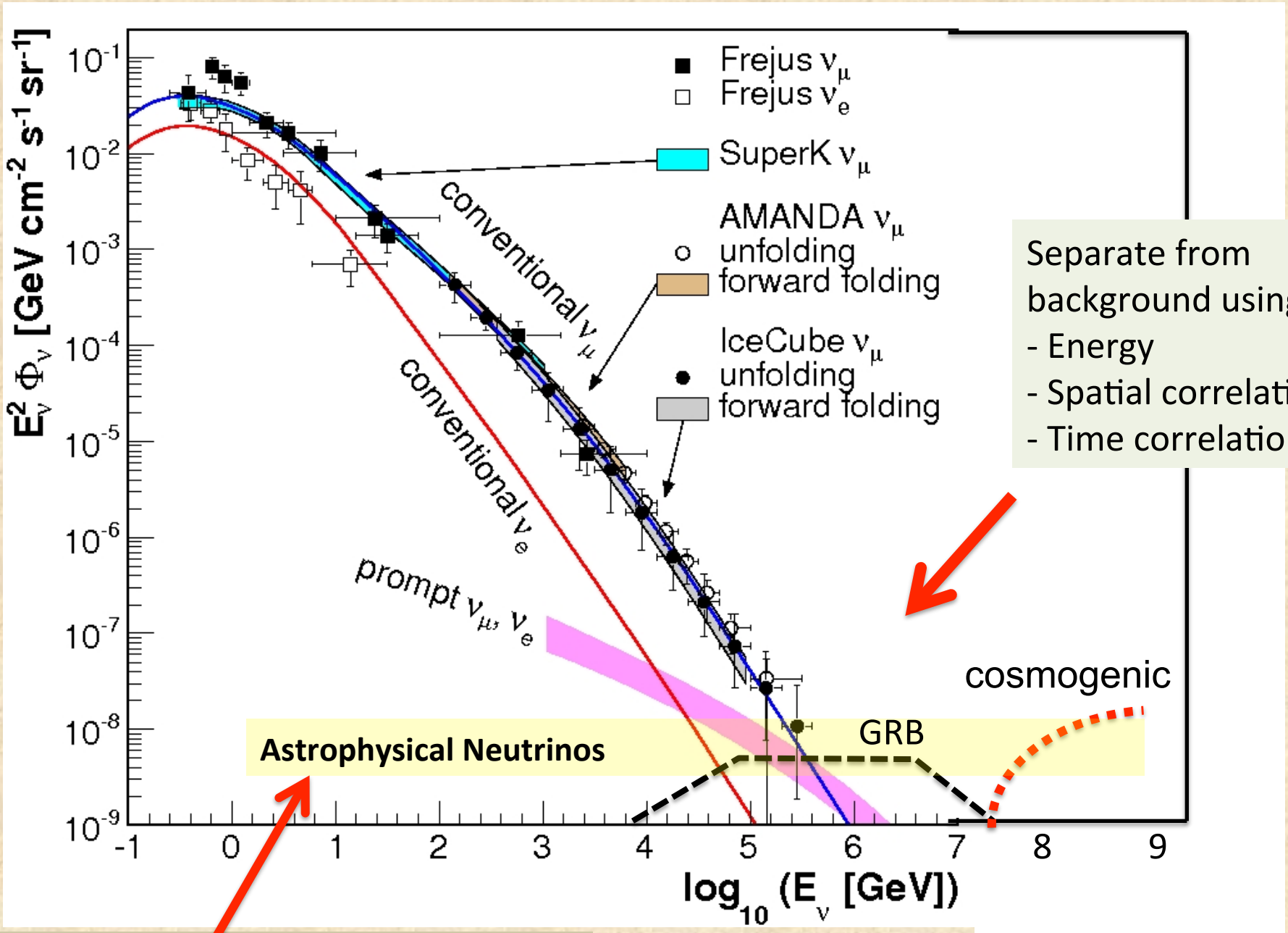
Atmospheric Neutrinos produced terrestrially by cosmic ray interactions in the atmosphere



ν_μ Spectrum
PRD 83 (2011) 012001

First atmospheric ν_e spectrum (green) PRL 110 (2013) 151105

Search Strategies for HE Astrophysical Neutrinos



Separate from background using:
- Energy
- Spatial correlation
- Time correlation

Motivates requirement of at least 1 km^3

IceCube Detector Data Runs

Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per day)
AMANDAII(19)	2000-2006	3.8 years	100	~5 / day
IC40	2008-09	375 days	1100	~40/ day
IC59	2009-10	350 days	1900	~70/ day
IC79	2010-11	320 days	2250	>100/day
IC86-1	2011- 2012	~ year	2700	~200/day
IC86-2	2012-2013	~year	2700	~200/day
IC86-3	5/13 – 5/14	running	2700	

DeepCore Installed

Run transition near May 1

IC86 achieving > 99% uptime

Outline

- Impact of High Energy Neutrinos with IceCube and implications for "Neutrinos Beyond IceCube"
  - High Energy Diffuse Neutrinos
    - Frist evidence for high energy astrophysical neutrinos (Science 2013) → opens the era of HE ν astrophysics!
    - Consistent with projections based upon the flux of high energy cosmic rays… many questions arise… know science is possible
    - ***Opens the era of neutrino astrophysics – neutrinos are there!***
  - High Energy Gamma Ray Burst (GRB) Neutrinos
    - IceCube's 2012 Nature Paper using IC40/59 data has ruled out GRB as the source of high energy cosmic rays!
    - And… Stimulated a reevaluation of the astrophysical models for neutrino production in GRB fireball model
    - now at sensitivity of these "new" models → observation(?) would open ***another*** exciting era of particle physics and astrophysics

IceCube diffuse EHE astrophysical neutrino searches

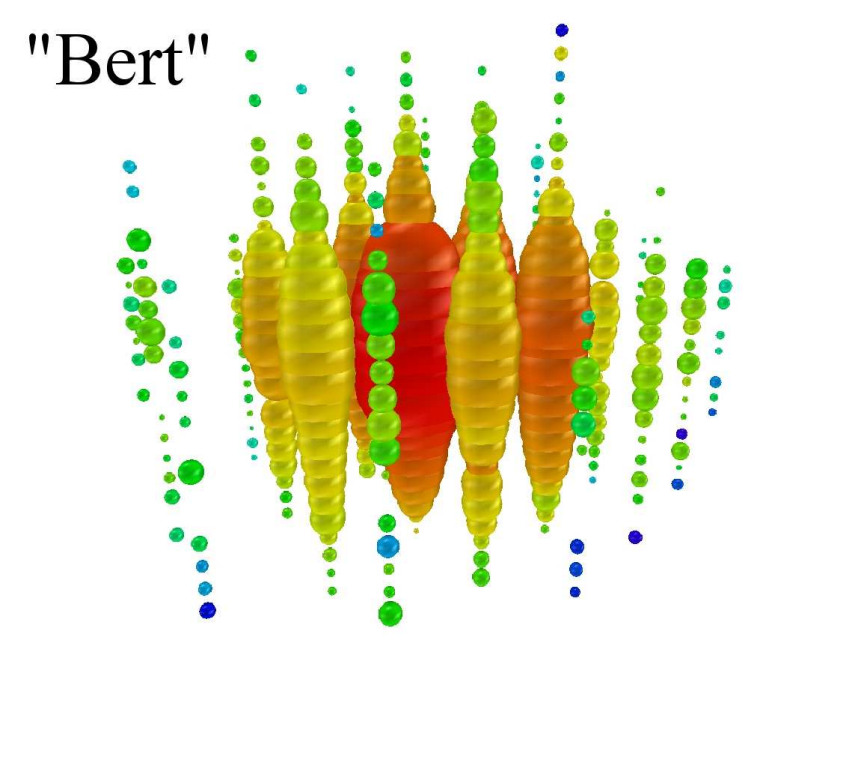
- At Neutrino 2012
  - IceCube had achieved sensitivity to diffuse neutrinos at about Waxman-Bahcall flux with data from partial detector
  - Upward fluctuation in 59-string ν_μ data (1.8σ)
  - **IC79, IC86-1 EHE (GZK neutrino) Search**
    - **2 events at ~ 1 PeV found in data (2.8σ)**
    - **Low energy threshold for GZK search**
- Motivated the High Energy Starting Event search (HESE)
  - Extend sensitivity to events below EHE search low energy threshold
  - All flavor search uses tracks and cascades
  - 2 years data from → IC79, IC86-1 (662 days live time)
    - **Found 4σ excess** → evidence for HE astrophysical neutrinos published in 2013

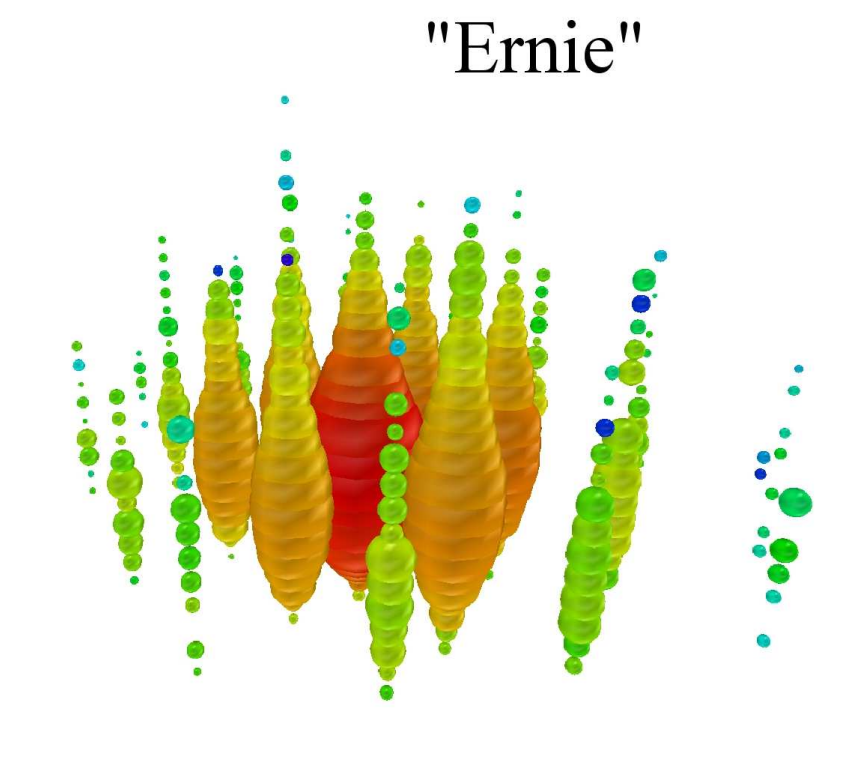
Updated here

  - Add IC86-2 as third year to HESE data (988 days live time)
  - IC79,86-1 ν_μ diffuse neutrino search as supporting evidence

2 events found at threshold
~ 1 PeV

2.8σ excess over backgrounds from terrestrial sources





"Bert"
~1050 TeV

"Ernie"
~1150 TeV

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

arXiv:1304.5356

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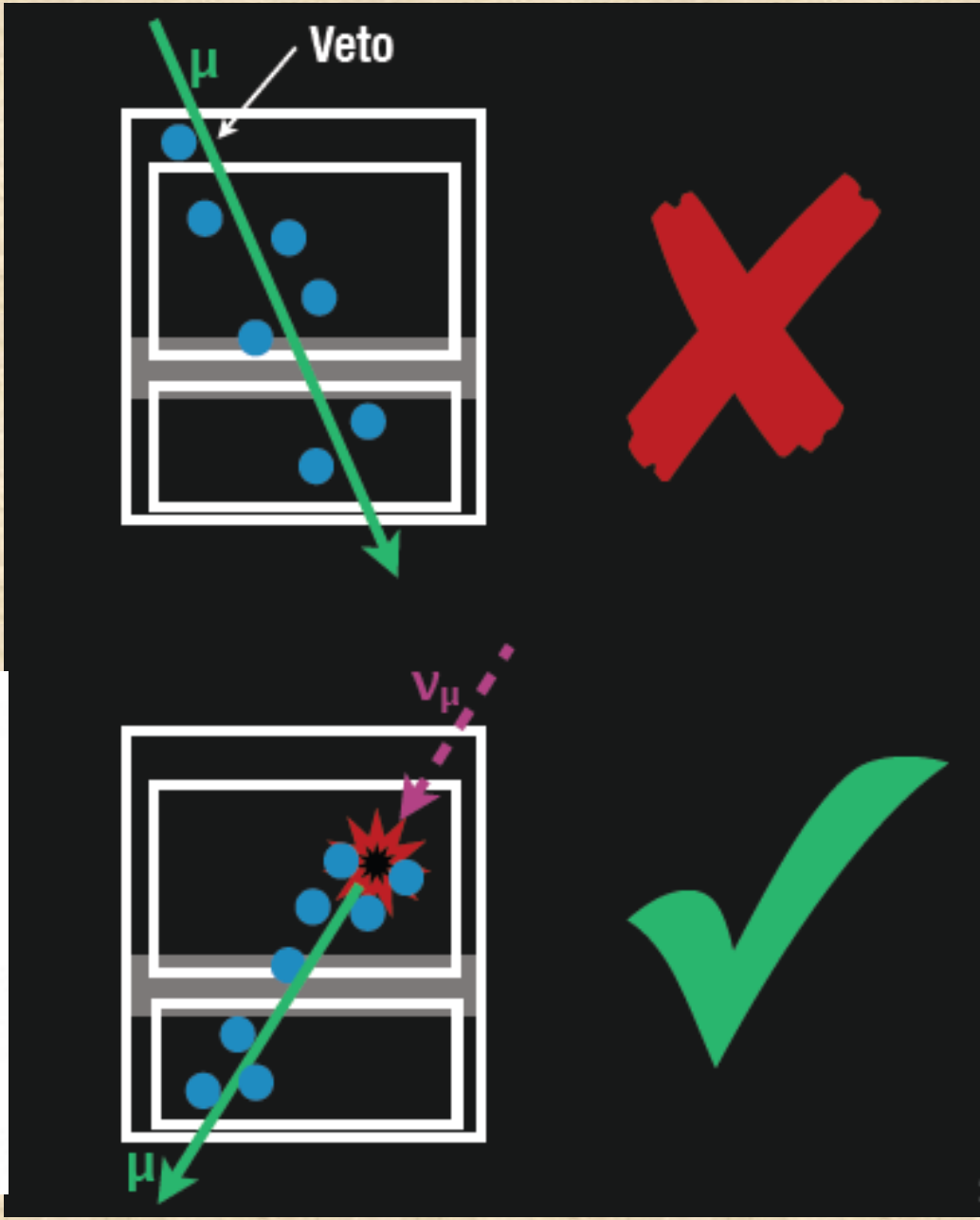
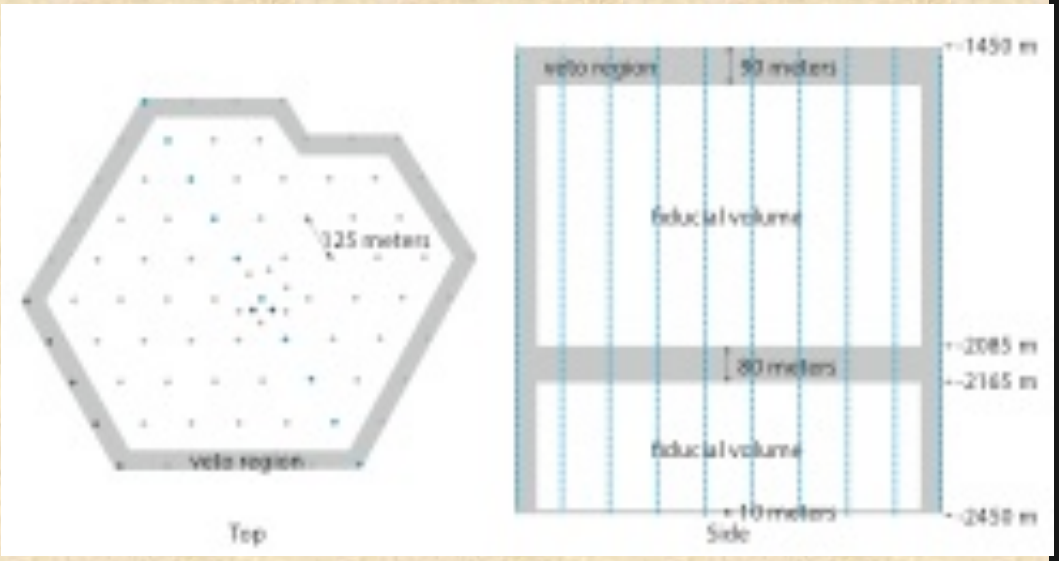
High Energy Start Event (HESE) search

- find more contained events
- total calorimetry
- complete sky coverage
- flavor determined
- some will be muon neutrinos with good angular resolution

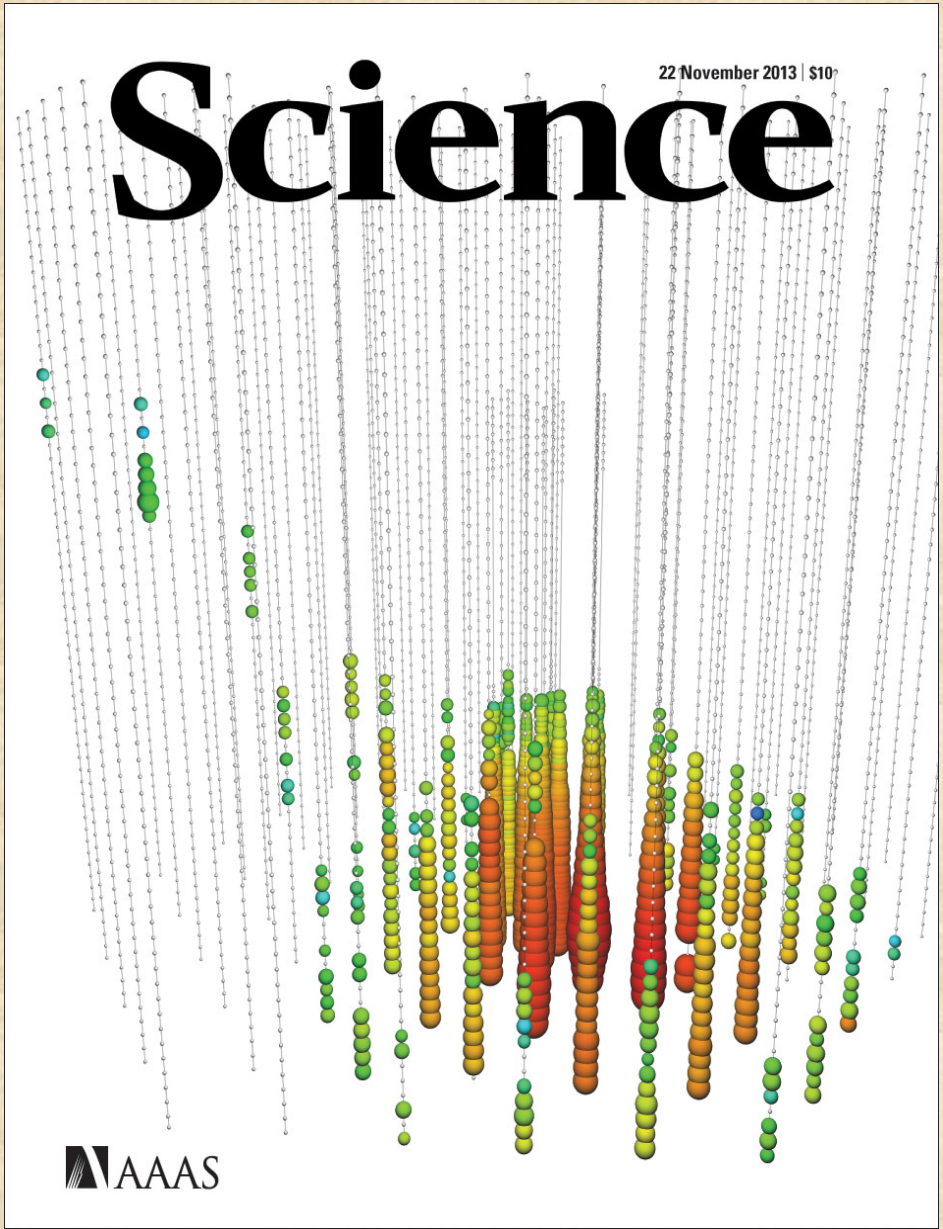




HE Neutrino Diffuse Results

- *Last year IceCube published the first evidence for high energy astrophysical neutrinos using 2 years of data*
  - IC79,86-1 "HESE" analysis
  - 28 events detected
  - Evidence at the 4σ level

Science 22 November 2013:
Vol. 342 no. 6161



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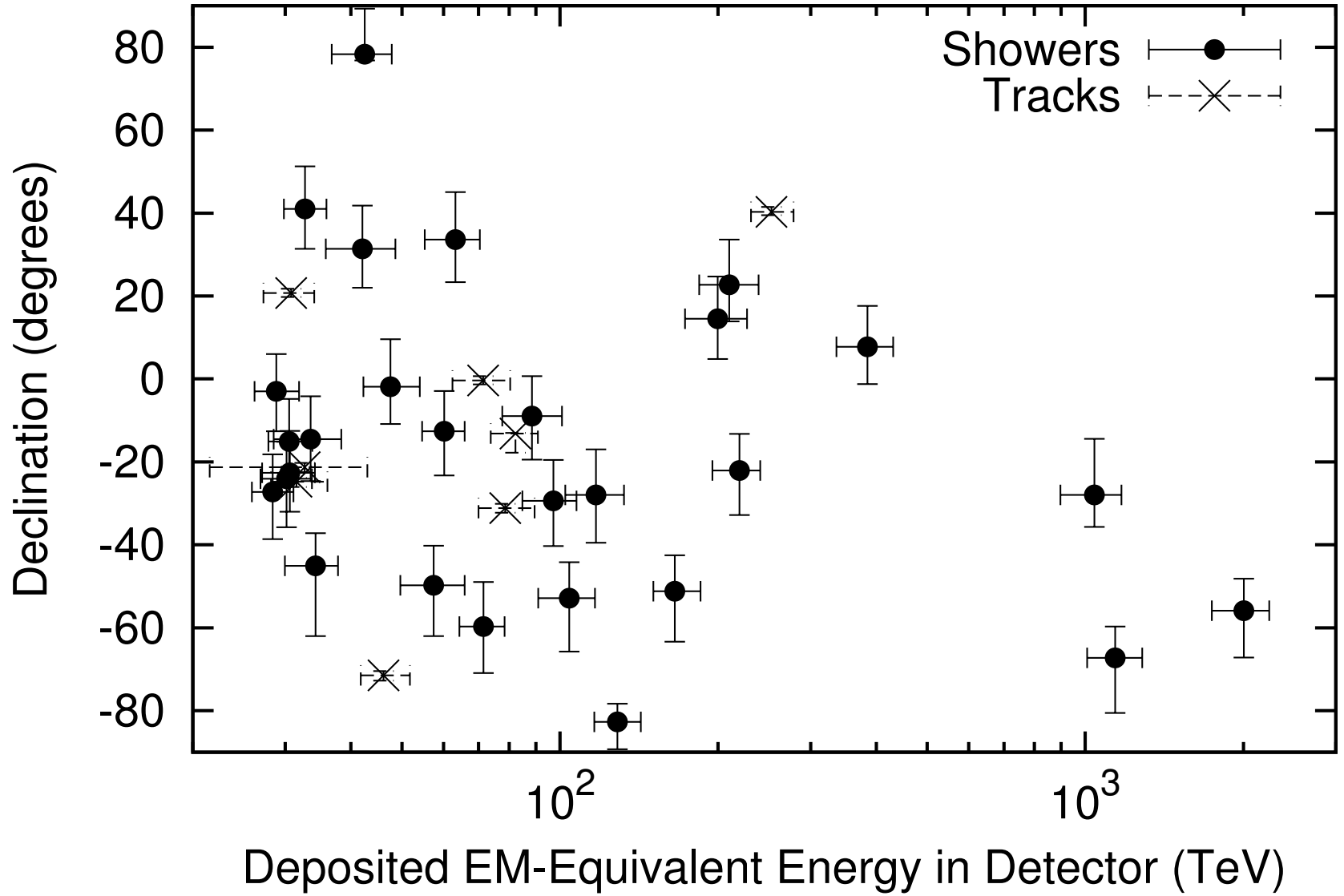
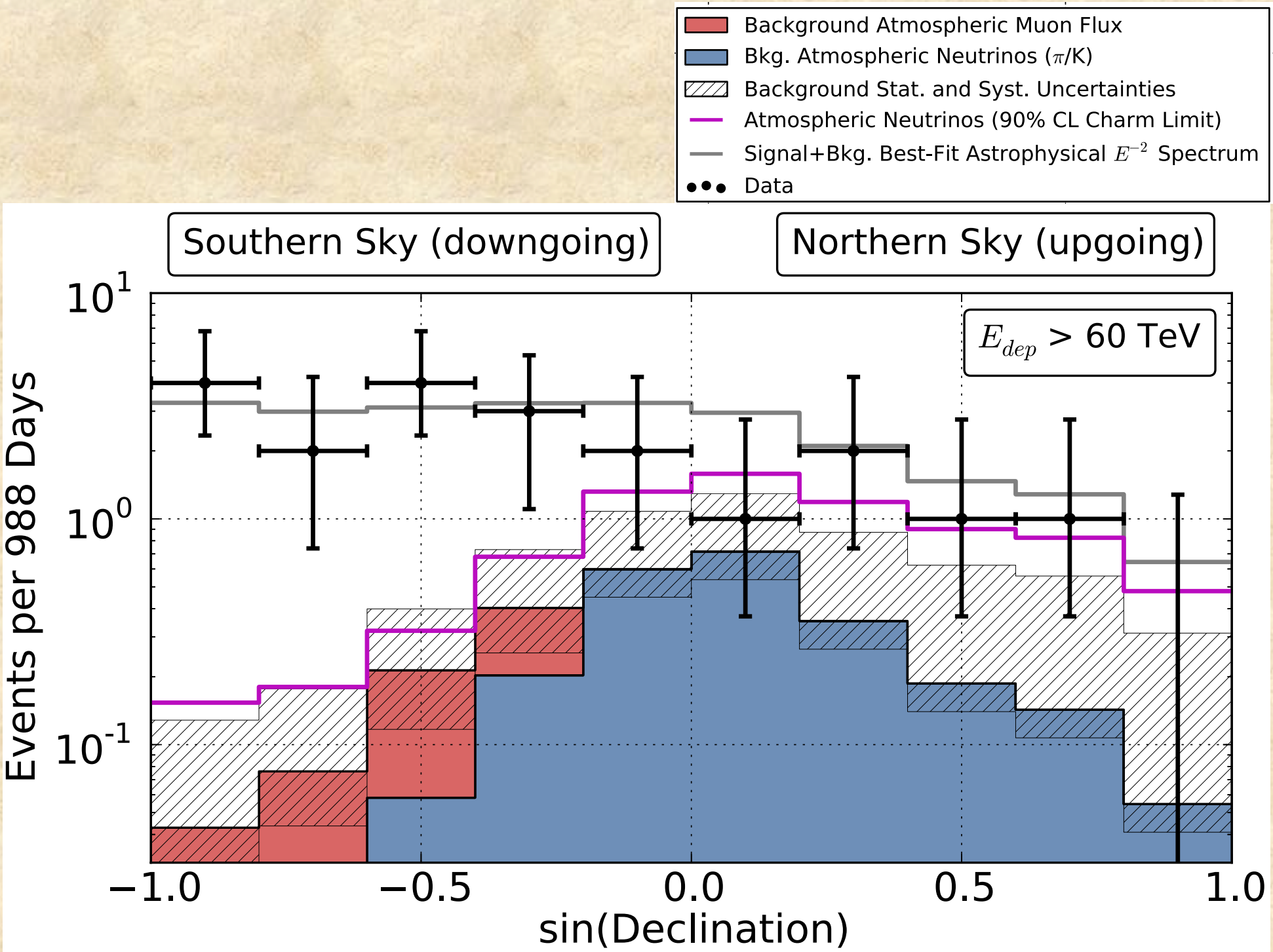
Updated HESE Results (3 Year)

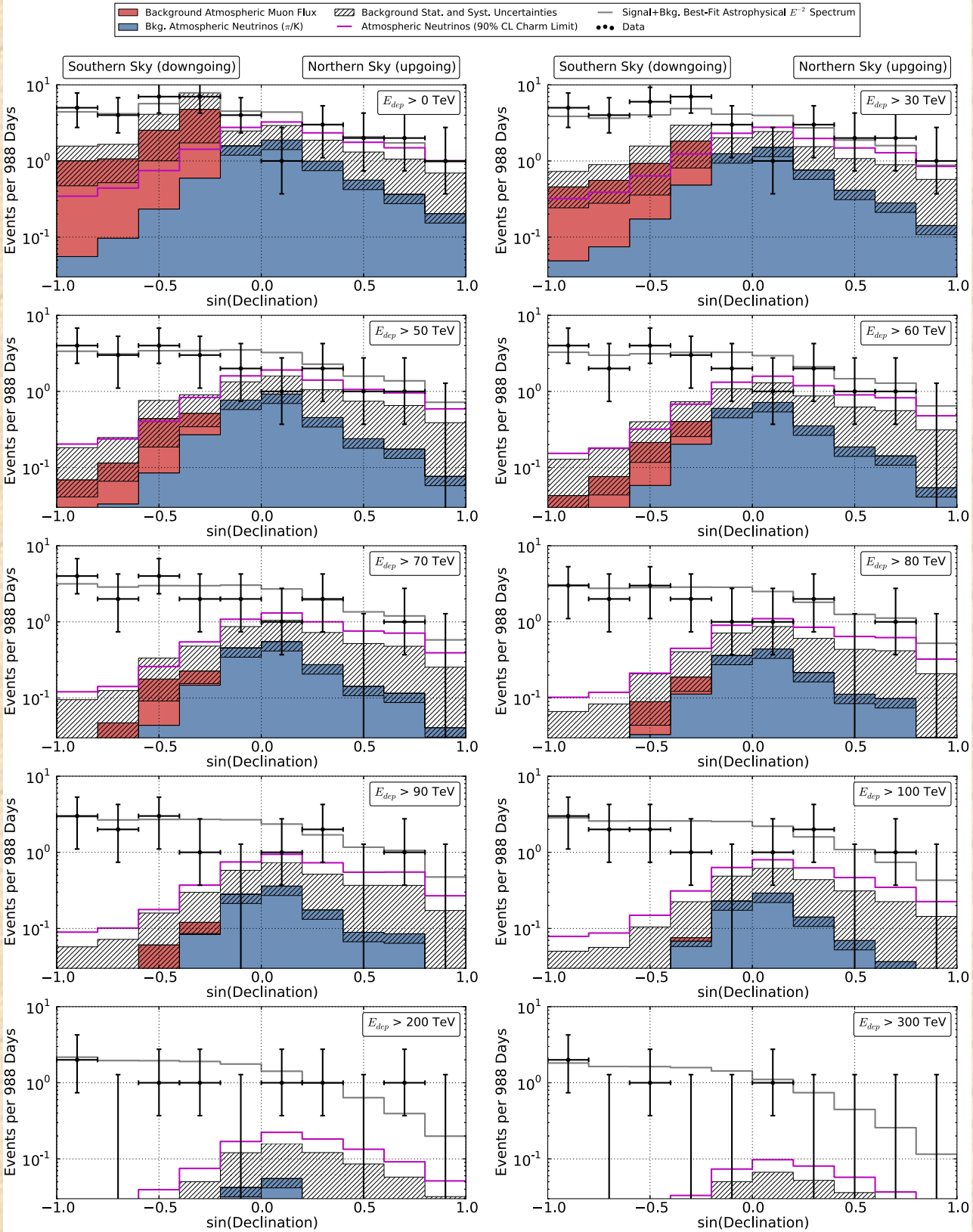
- 988 day sample
- detected 37 events
- expected background of 8.4 ± 4.2 cosmic ray muon events and 6.6+5.9 atmospheric neutrinos.

→ 5.7σ



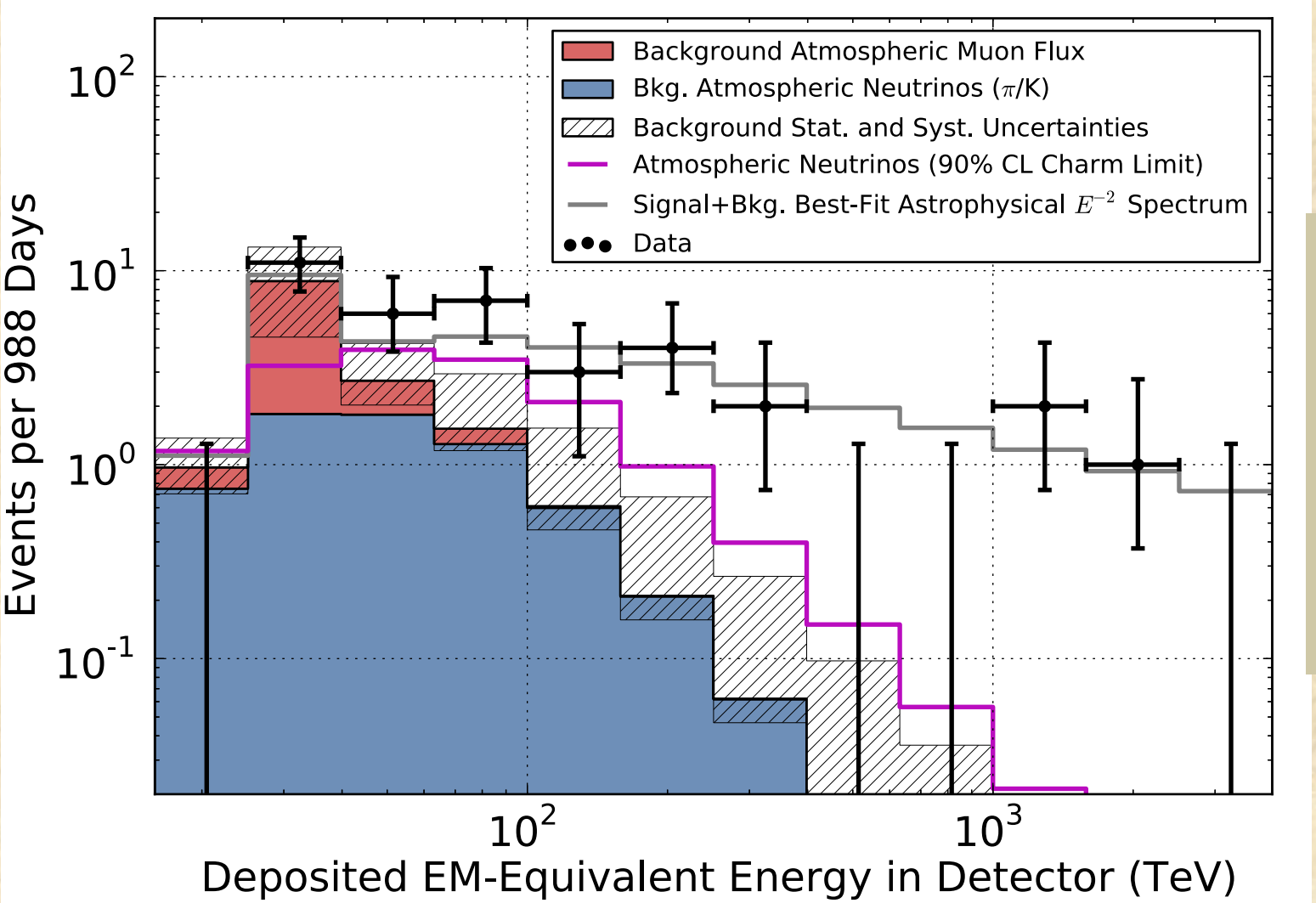
HESE 3 Year Results




Background Atmospheric Muon Flux
Bkg. Atmospheric Neutrinos (π/K)
Background Stat. and Syst. Uncertainties
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^-2 Spectrum
Data
Southern Sky (downgoing)
Northern Sky (upgoing)
E_dep > 0 TeV
E_dep > 30 TeV
E_dep > 50 TeV
E_dep > 60 TeV
E_dep > 70 TeV
E_dep > 80 TeV
E_dep > 90 TeV
E_dep > 100 TeV
E_dep > 200 TeV
E_dep > 300 TeV
Events per 988 Days
sin(Declination)

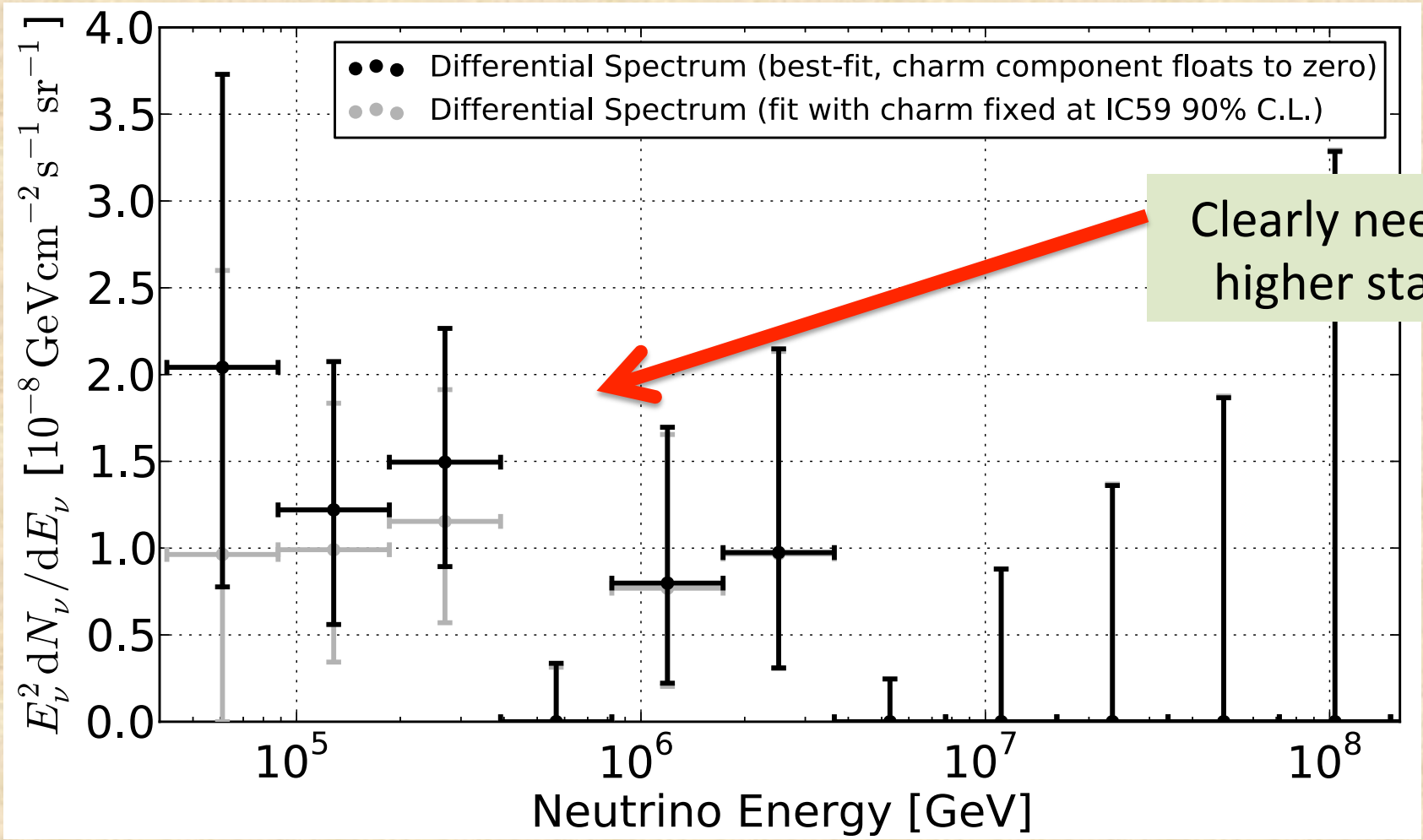
HESE 3 Year Results

best-fit per-flavor astrophysical(E^{-2}) flux
in the energy range of 60 TeV – 3 PeV
$E^2\phi(E) = 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$



- consistent with E^{-2}
- indication of a cutoff around 2 PeV above which 4.1 events would be expected from a flux at our best-fit level
- The range of best fit slopes of -2.0 to -2.3.

HESE 3 Year Results

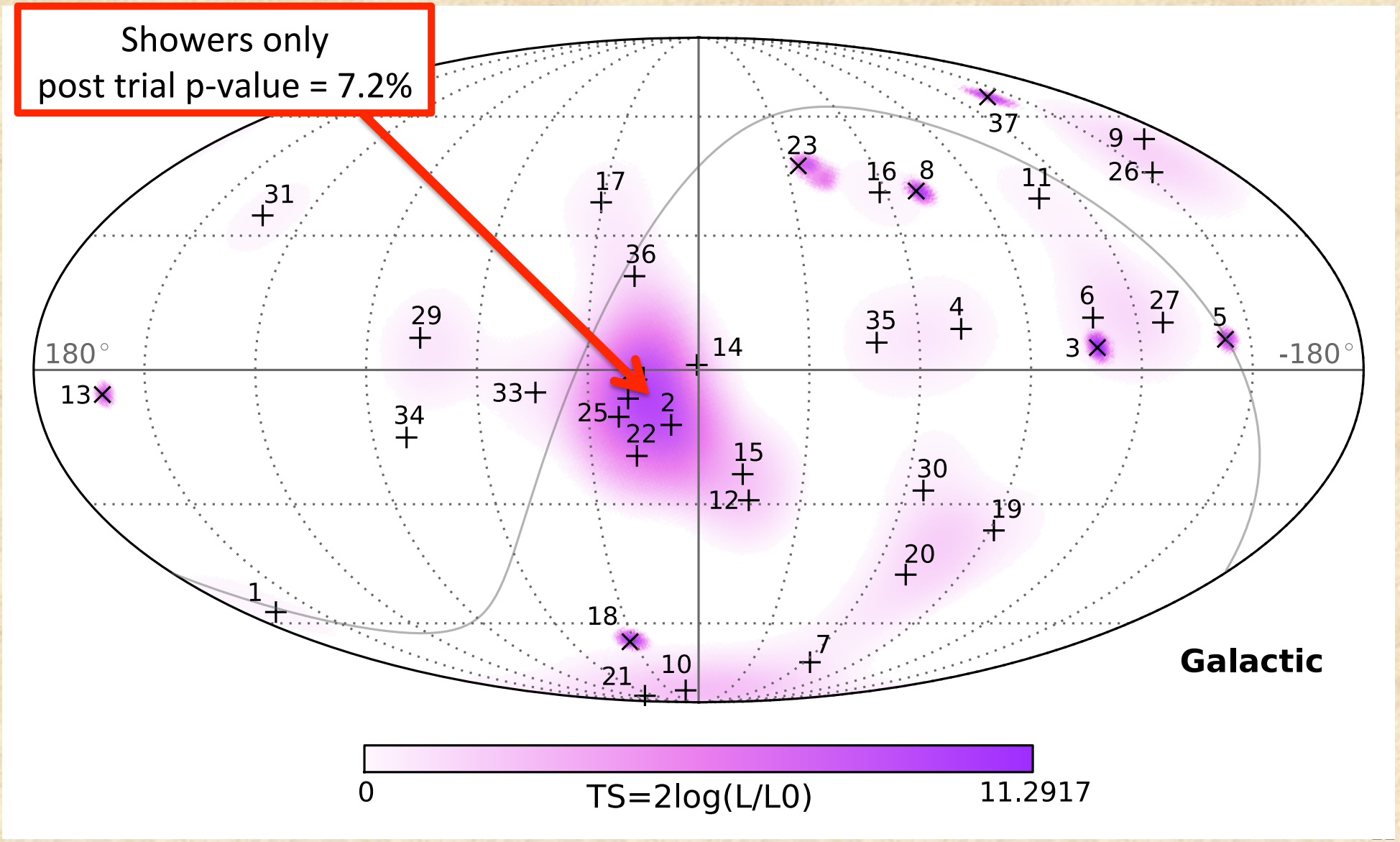


Clearly need much higher statistics!

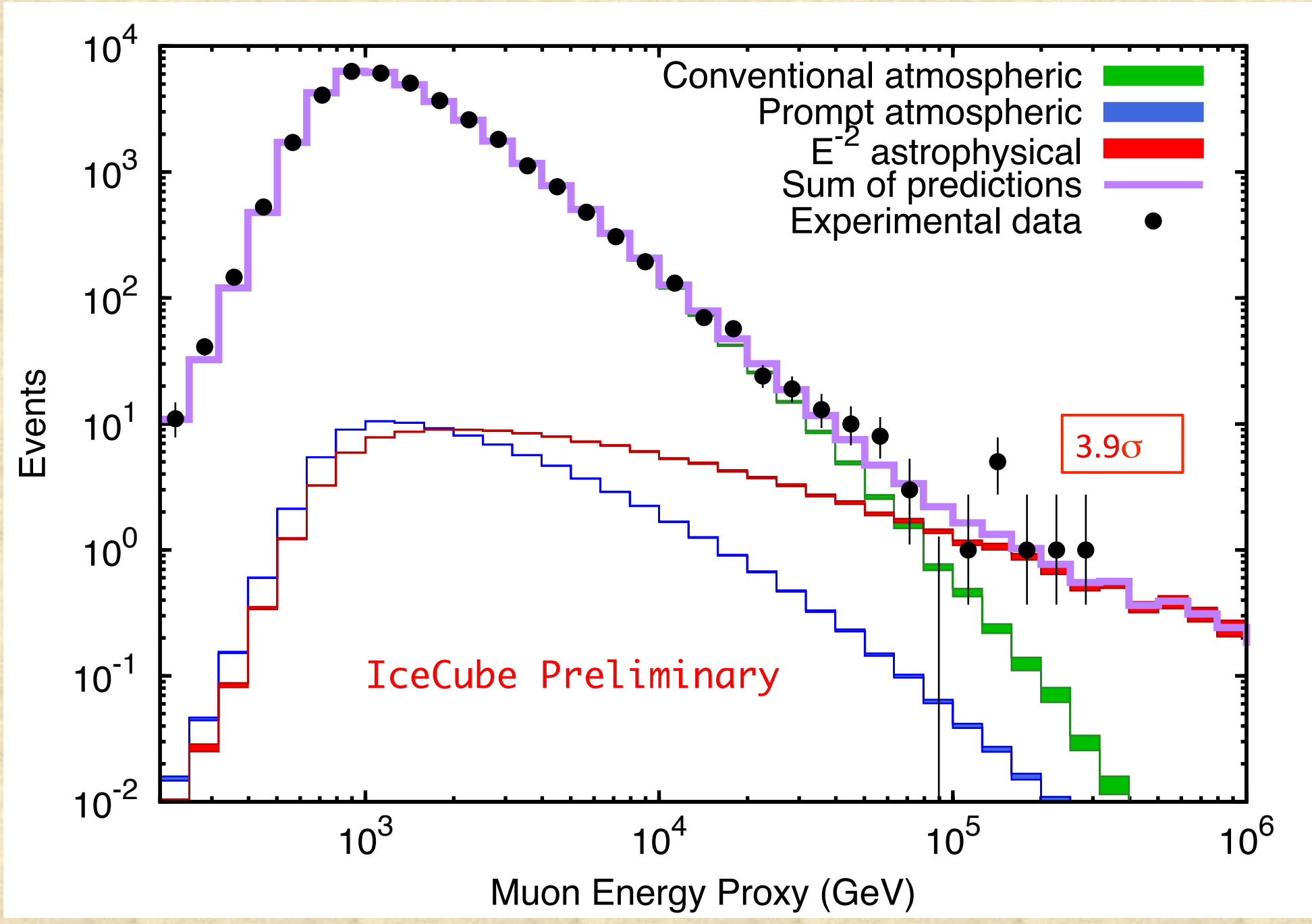
The best-fit power law is:

$E^2\phi(E) = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}$ GeV cm^{-2} s^{-1} sr^{-1}

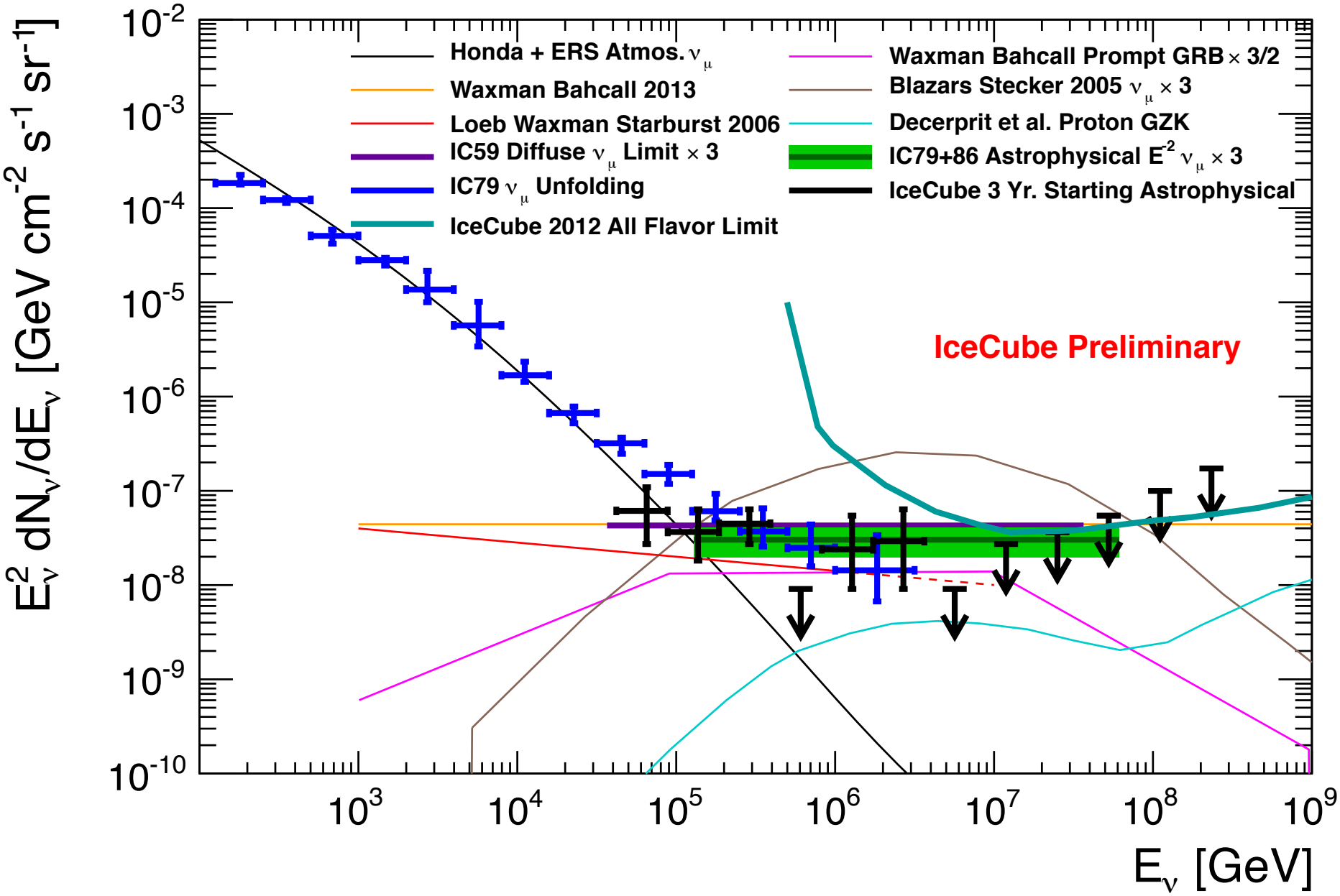
HESE 3 Year Results



IC79,86-1 ν_μ diffuse neutrinos



High Energy Neutrinos



HE Astrophysical Neutrinos?

- High energy astrophysical neutrinos are detected
  - *astrophysics and particle physics within reasonable reach!*
- Many questions about the HE Neutrinos with astrophysics and particle physics implications
  - What are the unknown sources and the origin of cosmic rays?
    - Clustering and point source searches
    - Tracks events with better angular resolution
  - What are the high energy production mechanisms?
    - Spectral Index, spectral cutoff, Glashow resonance
    - Flavor content
- We know the flux is there
  - Need more data to answer these questions

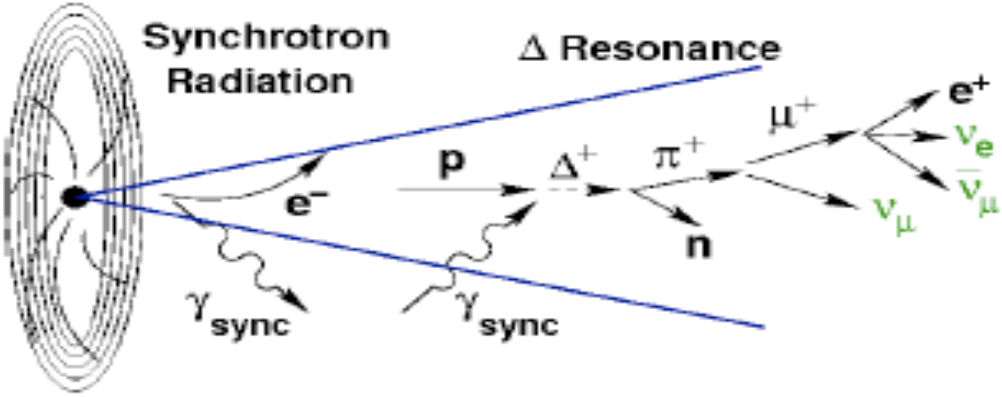
Implications for Neutrinos Beyond IceCube

- Scaling the number of HESE events with E > 500 TeV = 3 (>1.1 at 90% c.l.)
  - +7 years ≈ 10 events
    - (> 3.7 at 90%)
  - x5 (50 years equivalent) ≈ 50 events
    - (>18.3 at 90%)
- Muons above 300 TeV (~20% of total), which give good pointing!
  - +7 years → N_μ≈ 2 events
    - (> 0.74 at 90%)
  - x5 = 50 years equivalent → N_μ ≈ 10 events
    - (> 3.7 at 90%)

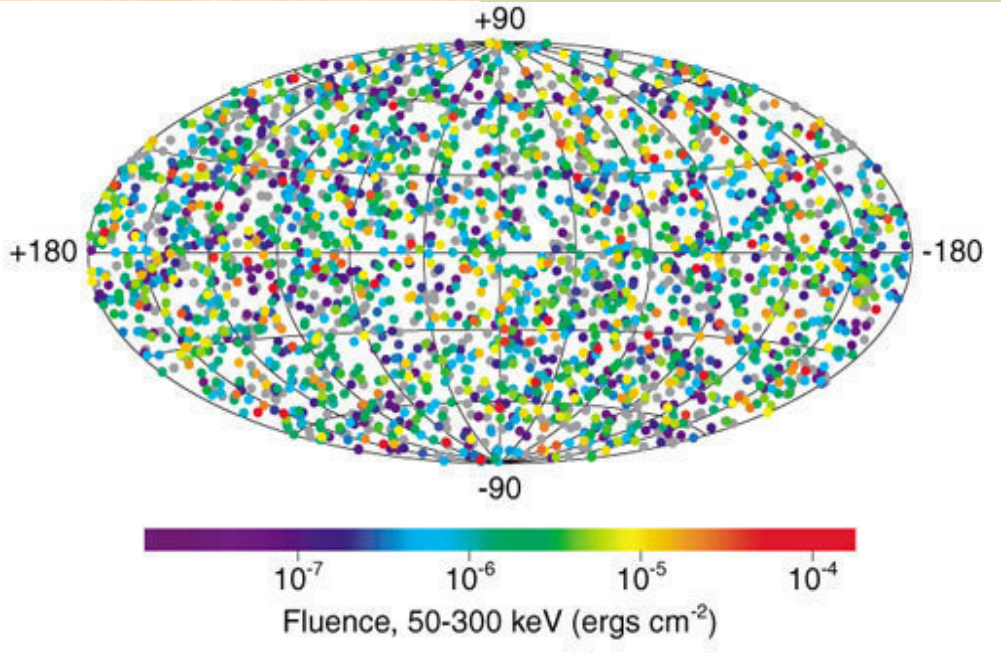
Gamma Ray Bursts

- Gamma-Ray Bursts are short bursts of gamma rays, few-100 seconds in duration
- Brighter than rest of gamma ray sky
  - Afterglow lasting much longer
- Several generations of satellite-based observations have shown:
  - Extra-galactic origin
  - Gamma-ray emission beamed
- Internal shocks in GRBs were a compelling candidate for the source of acceleration for UHECRs.

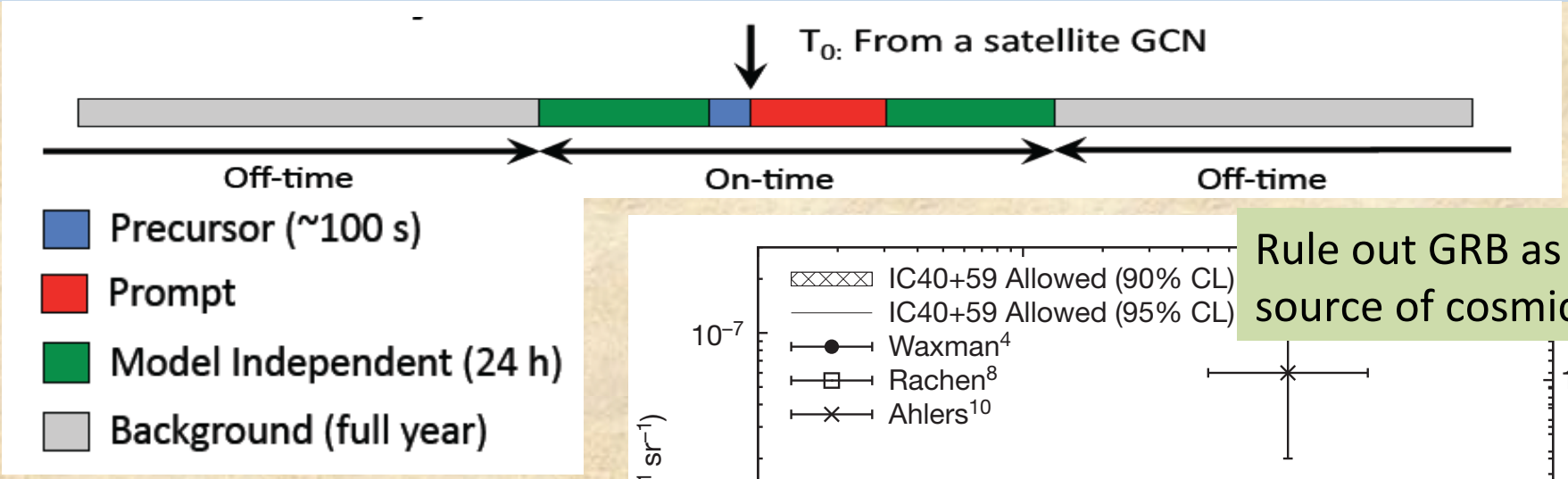
Beamed emission in Jet

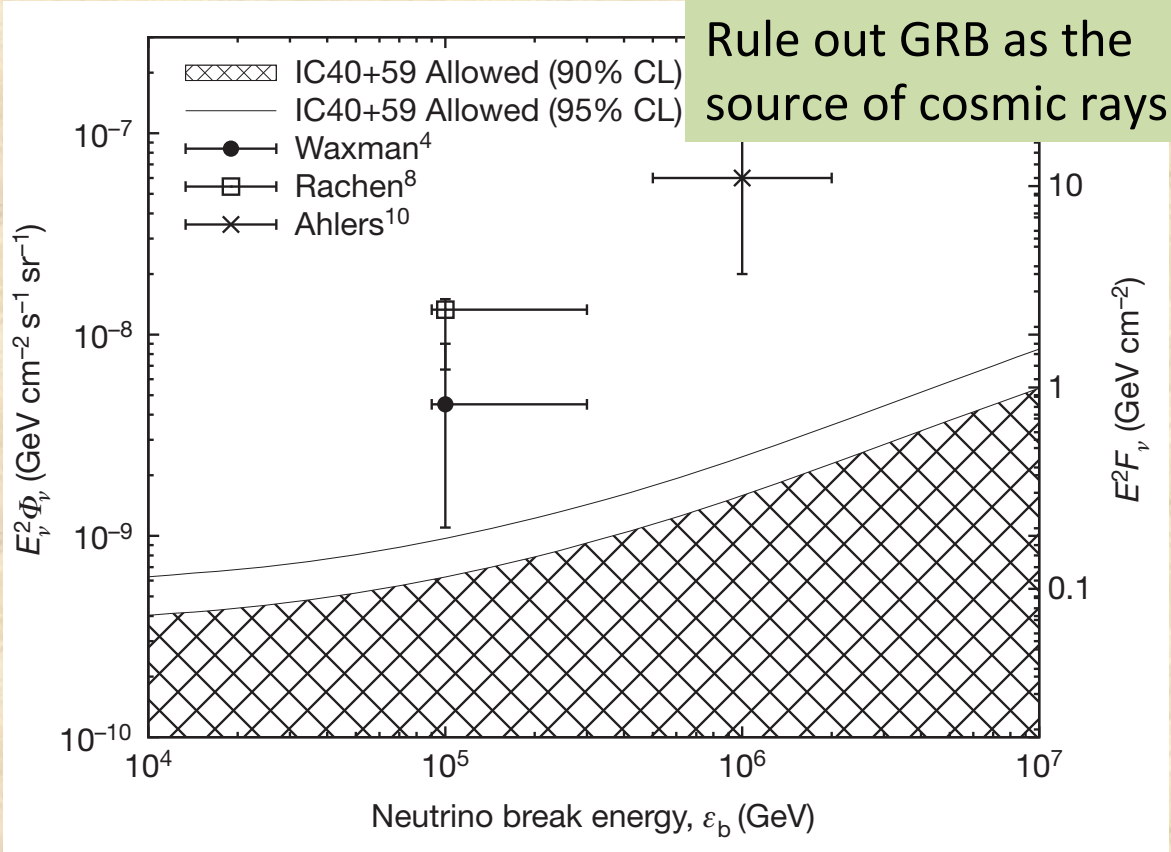


GRB in Gamma-Rays



- Model dependent stacked search for a neutrino signal in coincidence with observed GRB gamma signals
  - Northern hemisphere GRB bursts are considered.
  - Spatial & time correlation yields very low background ***(~Background Free Search)***
- Model independent search more generic on wider time-scale
  - Up to ± 1 day and with generic (E^{-2}) spectrum





Rule out GRB as the source of cosmic rays!

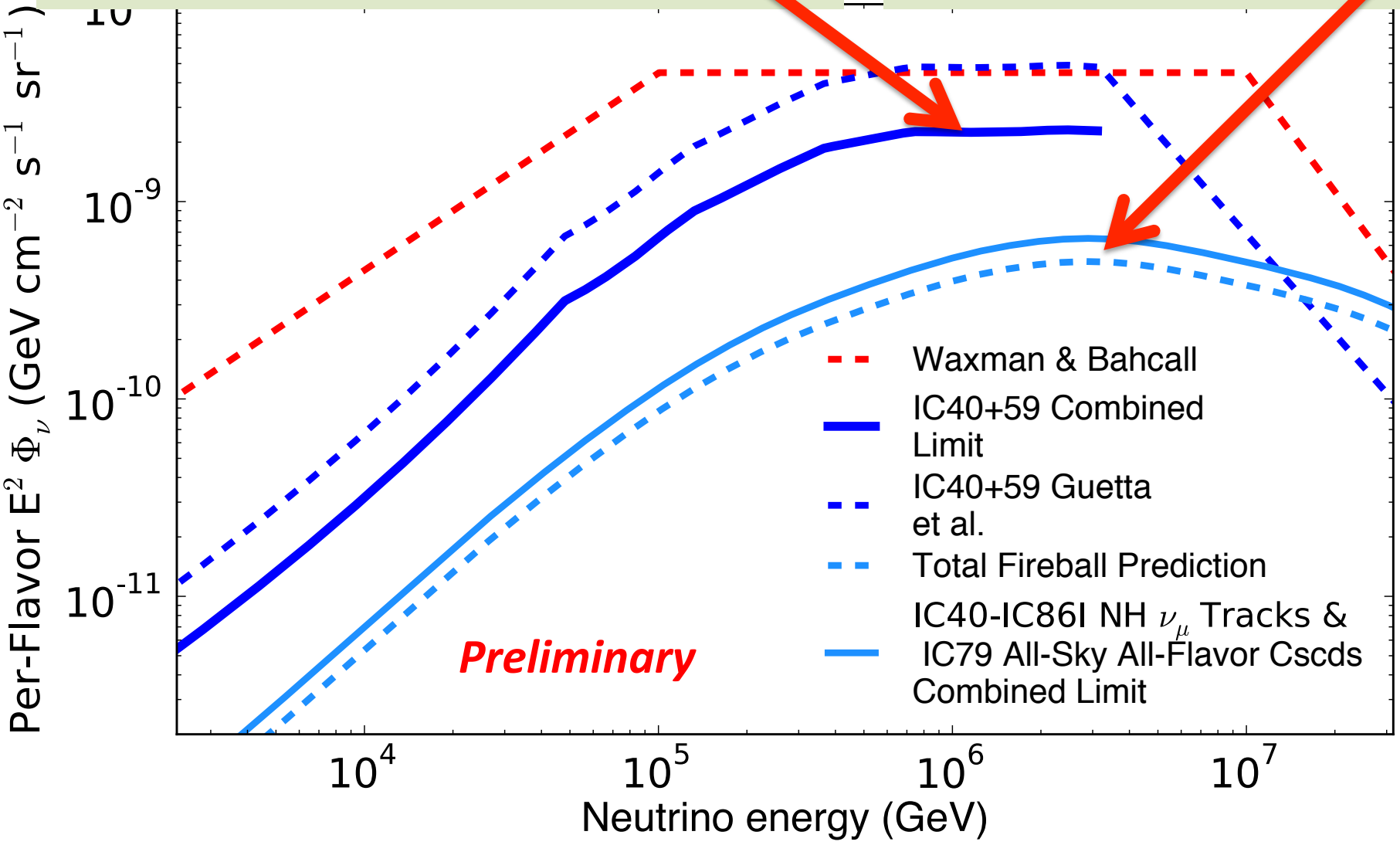
Nature **Vol 484**, 351 (2012)

Using IC40/IC59 ν_μ data

GRB Neutrinos a brief history

IC40/59 model dependent result (2011-2012)
- Ruled out GRB as the UHCR source
- Set limit below fireball models

Models reevaluated (after Nature Paper)
- Current data now approaching models (2014)



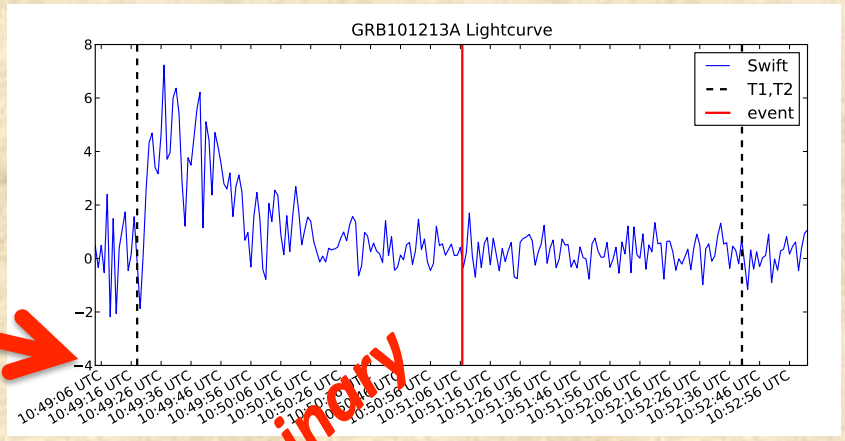
Are We Starting to See GRB neutrino flux?

IC79 Cascade GRB search

- Expected signal events per search, season:
  - **NH Track Searches:**
    0.27 (IC40), 0.66 (IC59), 0.23 (IC79), 0.34 (IC86)
  - **All-Sky Cascade Search:**
    0.26 (IC79)
- IC40-86 NH track search:
  - **Total expected ν events:** 1.5
  - **Total events seen:** 0
  - **90% UL:** 1.54 x model flux
- IC40-86 NH track + IC79 All-Sky cascade search:
  - **Total expected ν events:** 1.76
  - **Total events seen:** 1
  - **90% UL:** 1.31 x model flux

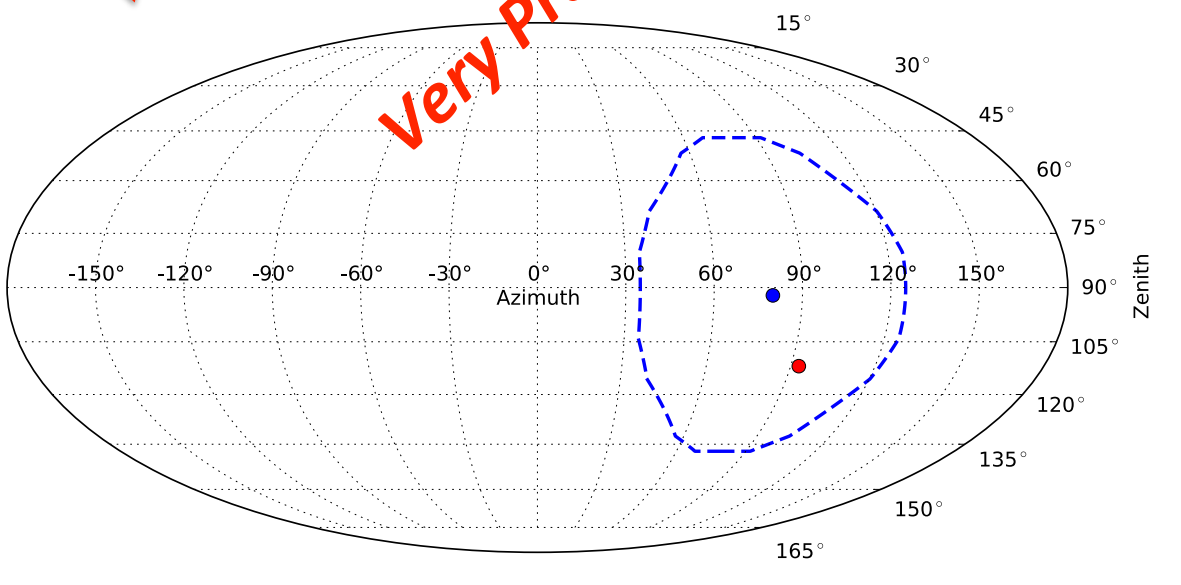
T100

time



space

Very Preliminary



Not yet significant...

- **Resulting Test Statistic:**

$\mathcal{T}$	0.17
p	11.4%
p (sigmas)	1.2

IceCube HE GRB Summary

- Combined (IC40, IC59) search results → *Nature Paper*
  - *Rule out GRB as THE source of HE cosmic rays*
  - *Stimulated new astrophysical modeling of neutrino production*
    - *Resulted in lowering of prediction for neutrino flux*
- IC79, 86-1 Track search *Preliminary*
  - No observation of signal
  - Sensitivity near the new predictions
- Added IC79 Cascade search *Very Preliminary*
  - See one event with expected 1.7 from current models
    - Not significant (1.2σ)
- Will soon add IC86-2,3 to track search and IC86-1,2,3 to Cascades
  - Very soon go from 4yr (track) + 1yr Cascade to 6 yr (track)+4 yr (cascade) → doubled exposure
  - 1 event now → … *wait and see?*

Implications for Neutrinos Beyond IceCube

- ***assumption*** that current models are about accurate and use the 1 event we have as the mean rate
  - Have 1 event in 4yr of mu and 1yr cascade = 5 "GRB-yr" or 2.5 years of combined (track+cascade) exposure
  - Soon add 2 years track and 3 years cascade = 5 years
    - Doubled exposure and reach limit setting potential below current models
  - Double that with 5 more years by around 2020?
    - ~few events with large uncertainty.
  - ***caveat*** (still theory based), Low statistics
    - Even if assumption is accurate may have only small number of events
- Beyond IceCube detector assuming X5 I3 equivalent
  - ~20 events (~2-4 GRB events per year depending on detector)
  - Would represent another breakthrough in HE neutrinos
    - Astrophysics
    - Particle physics

Summary

- IceCube was designed as a discovery instrument
  - The first 1 km^3 detector. Volume required to reach the sensitivity of W-B flux motivated by cosmic ray flux
- IceCube was successfully constructed as an NSF MREFC, on time and on budget, with a performance exceeding the approved baseline requirements.
- IceCube has discovered diffuse astrophysical neutrinos!
  - We know the flux → opens questions on sources and mechanisms, and provides us with a basis on what we need to make astrophysical measurements and to maximize the science output
- The IceCube observatory represents an existing and well operated infrastructure within the NSF South Pole Facility.
  - Provides an ideal platform to leverage for the next generation detector for HE astrophysical neutrino precision measurements