Diffuse neutrino fluxes and GZK neutrinos with IceCube

Aya Ishihara
for the IceCube collaboration
Chiba University, JAPAN

CHIBA UNIVERSITY

ICECUBE

VHEPA2014 Kashiwa
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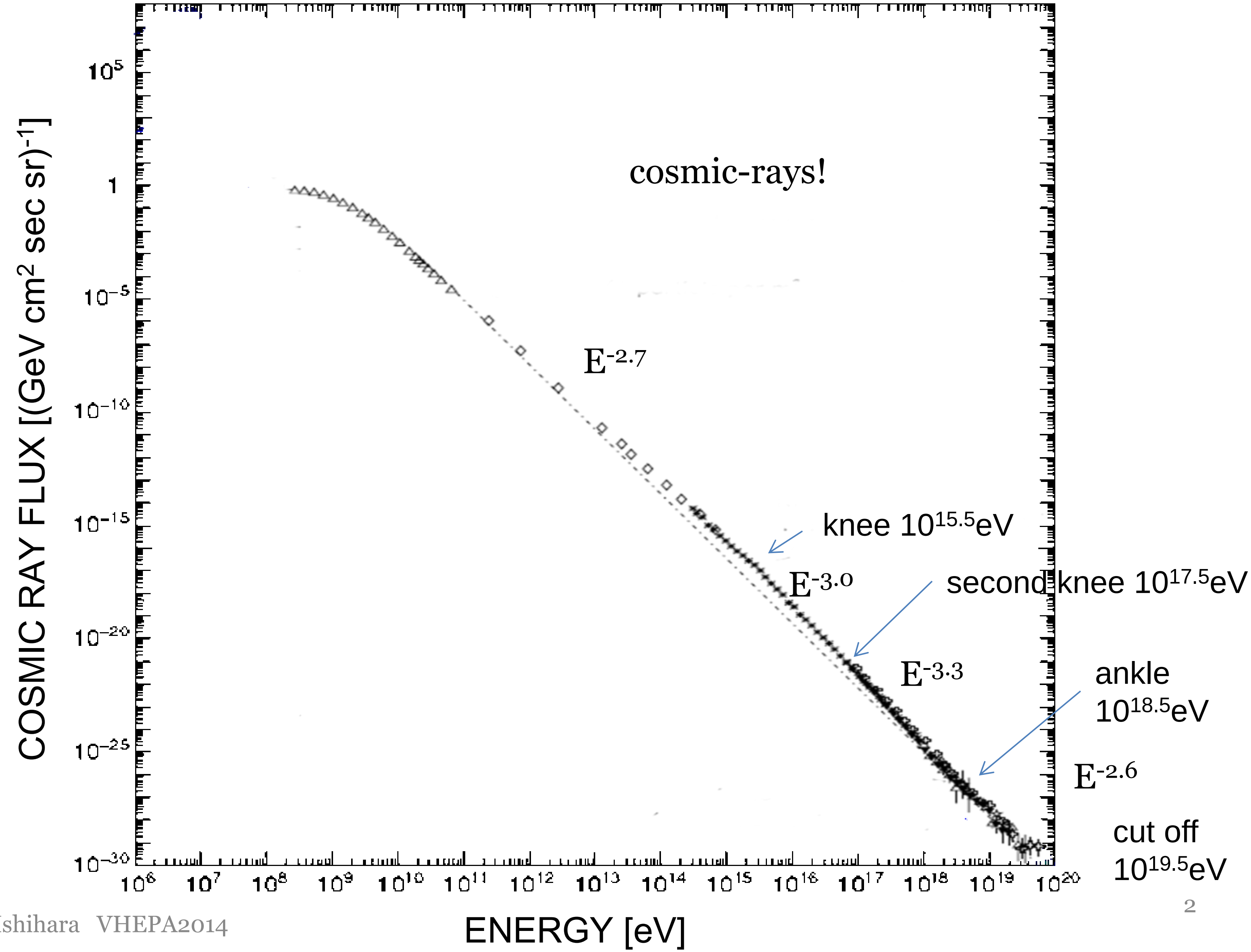
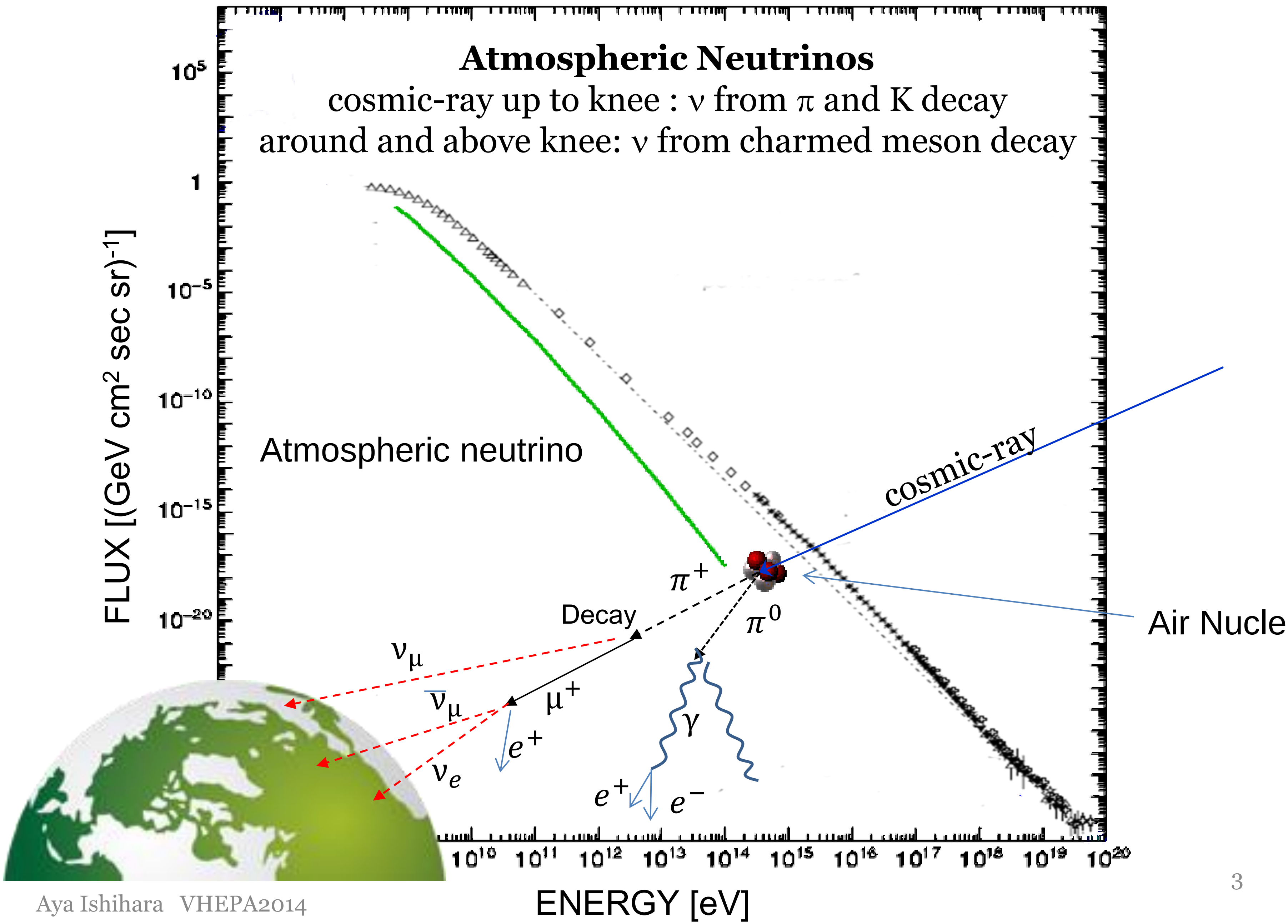
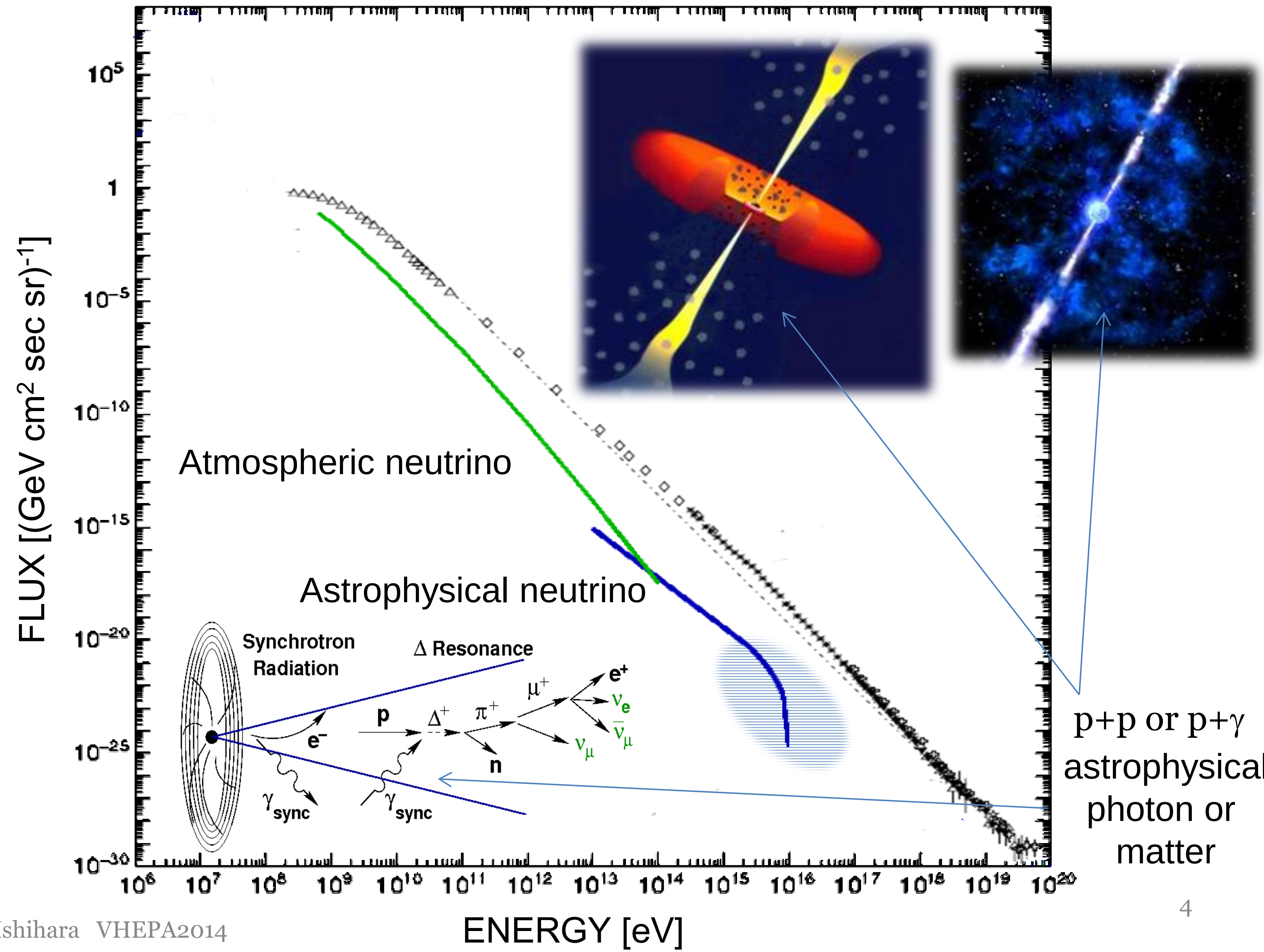
Extremely-high energy emission in the Universe



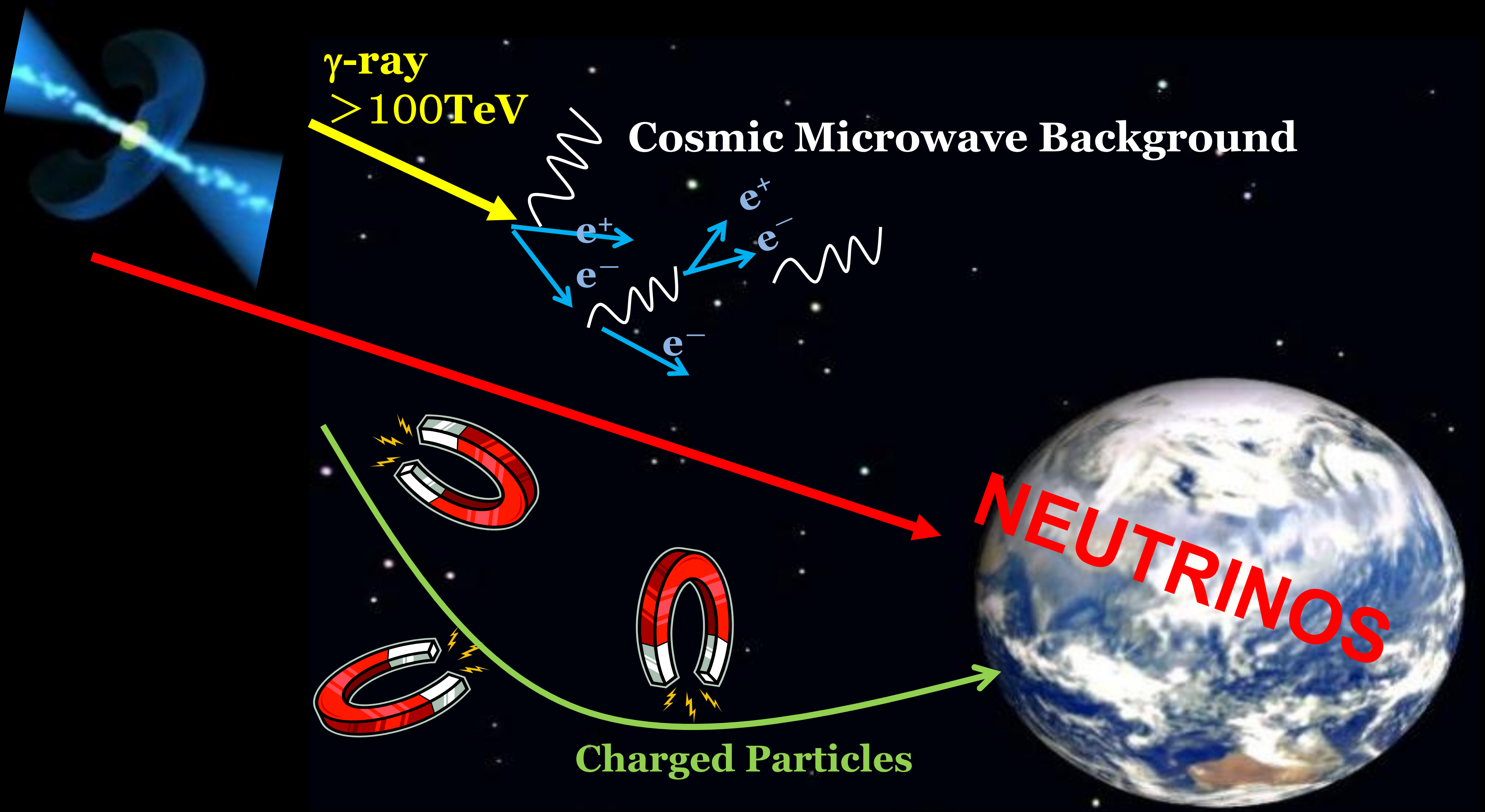
High energy emission in the Universe



Ultra-high energy neutrinos in the Universe



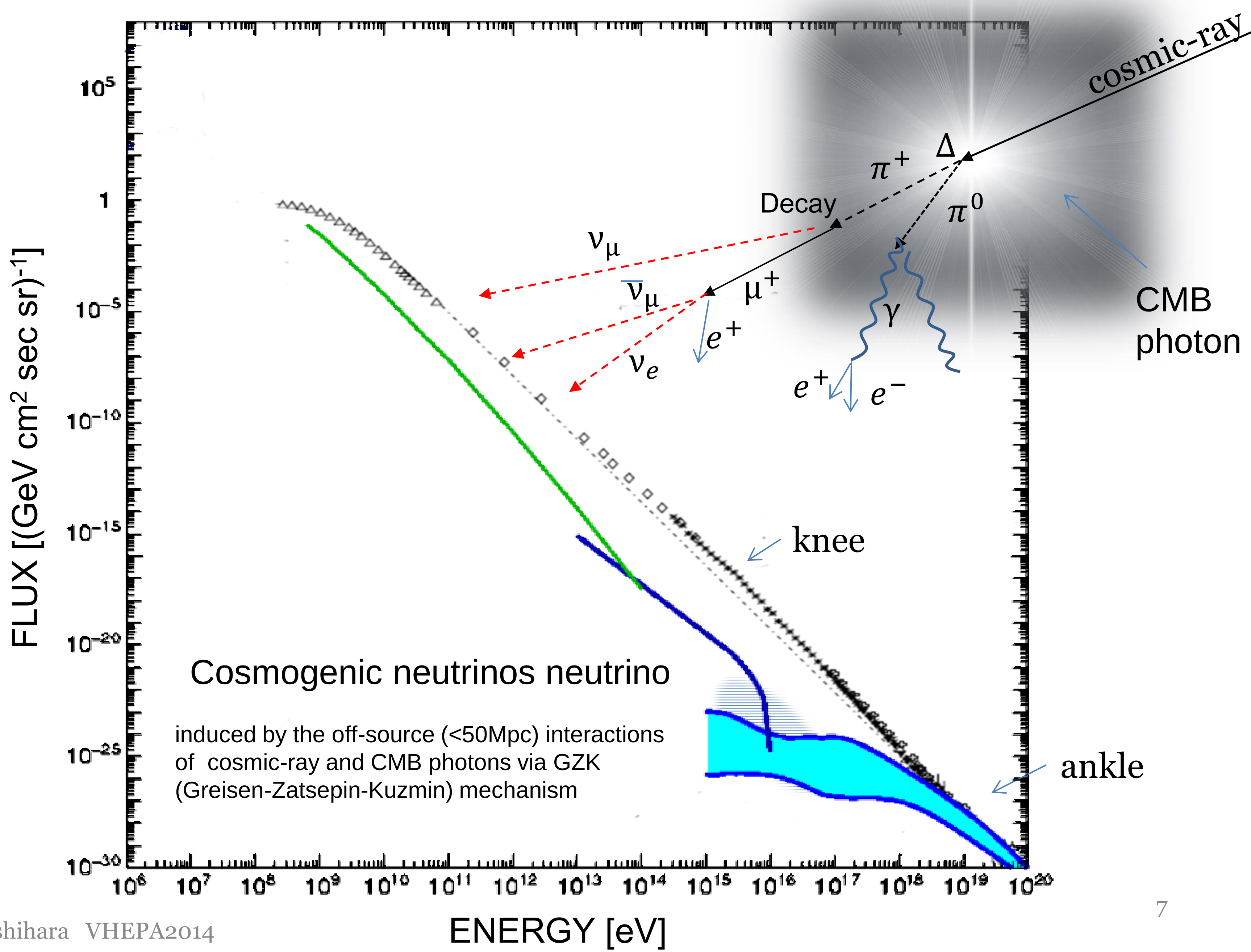
Questions for the ultra-high energy neutrinos



Questions for the ultra-high energy neutrinos

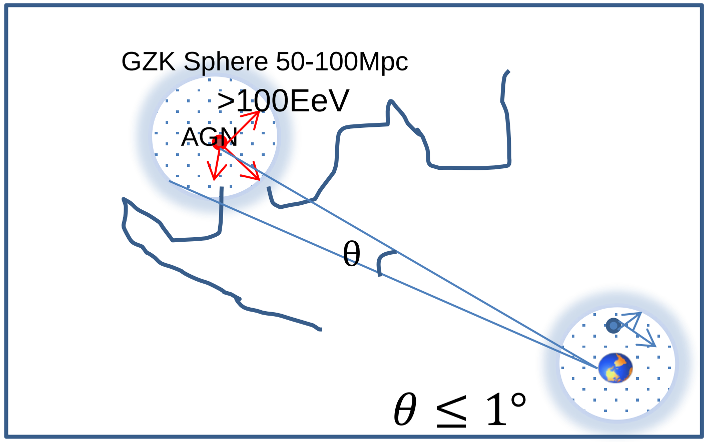
Where are the ultra-high energy cosmic-rays from?

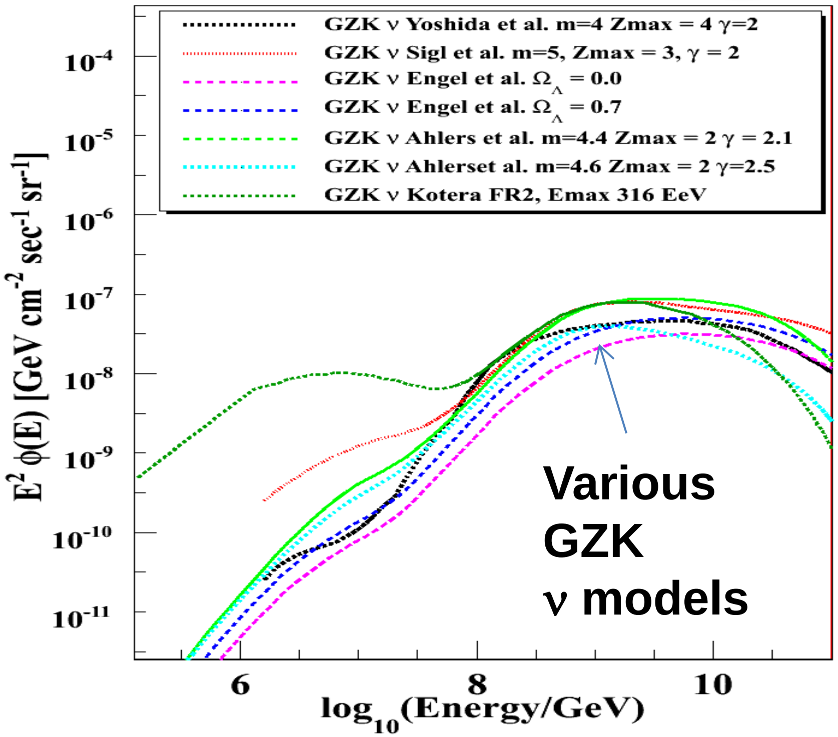
Extremely-high energy neutrinos in the Universe



What the EHE neutrinos tells about the Universe not accessible otherwise

Extremely high energy Universe beyond GZK sphere inaccessible with CR or gamma-rays





- (GZK or on source ν) Location of the cosmic-ray sources - EeVatron/ZeVatron!
- Cosmological evolution of the cosmic-ray sources; intensity reflects the contributions from the sources in a high redshift region
- Cosmic-ray spectra at sources: the highest energy of the cosmic-rays $\mathbf{E_{max}}$, spectral slope, extragalactic transition, cutoffs
- Composition of the cosmic-rays

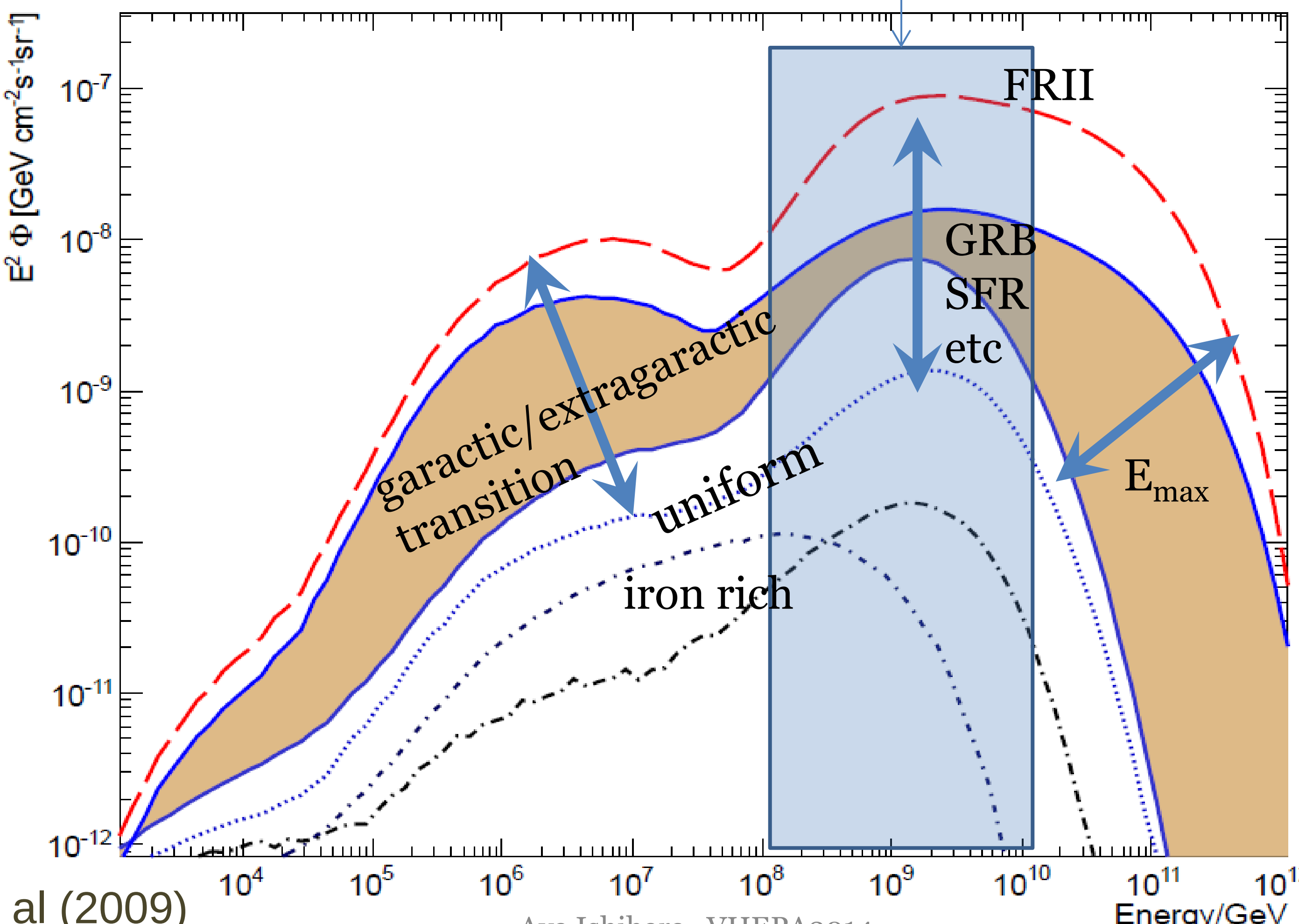
Plus

- Particle physics beyond the energies accelerators can reach!

Cosmological neutrino flux shape carry a lot of information about the cosmic-ray origin

However IceCube has a limited energy region sensitive to the cosmogenic neutrinos, we are sensitive to cosmological evolution not the other parameters

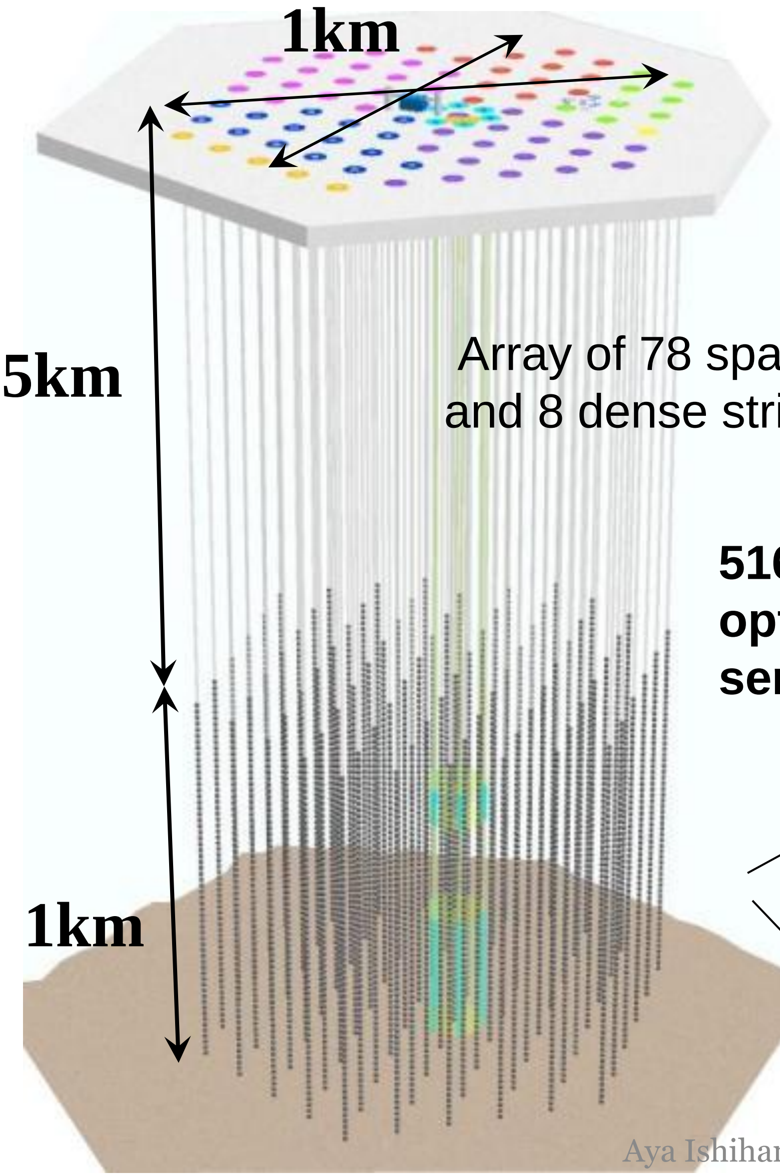
IceCube's view of the cosmogenic neutrinos
a robust estimator of the highest energy cosmic-ray source evolutions



Kotera et al (2009)

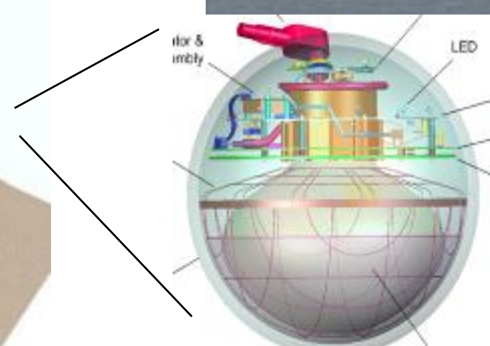
The Largest Neutrino Detector in the world:

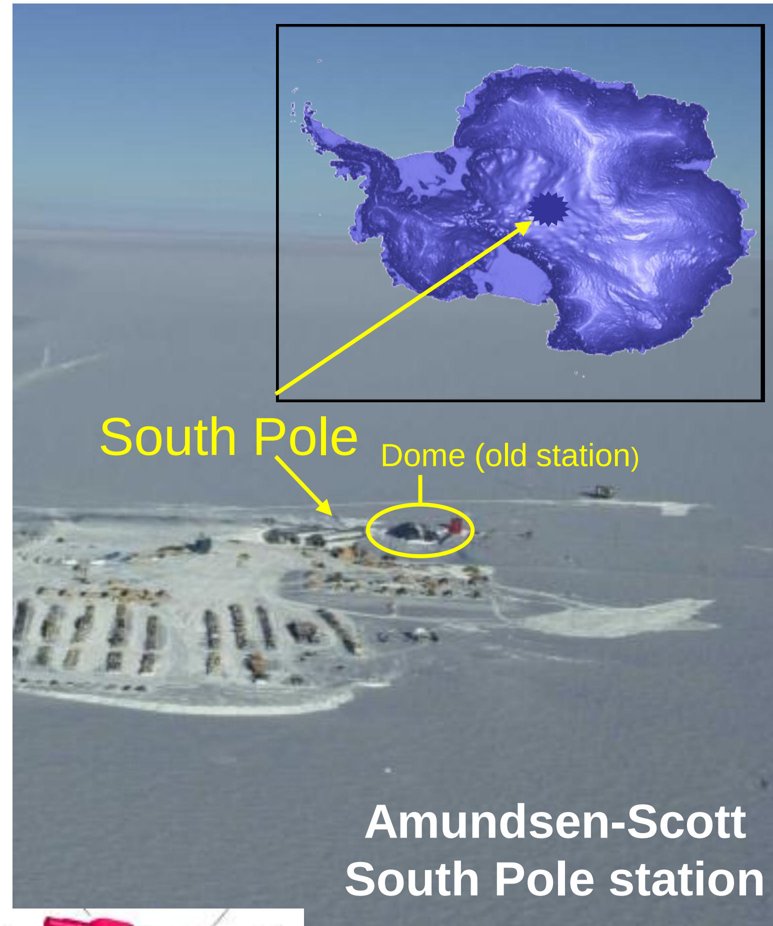
The IceCube Detector



Array of 78 sparse and 8 dense strings

5160 optical sensors





South Pole

Landing Strip
South Pole Station
IceCube Drill Head
& First Hole
IceCube Lab
Residential Build
IceCube Drill Camp

The IceCube LAB

60 photomultipliers/string

The IceCube Collaboration

http://icecube.wisc.edu

International Funding Agencies

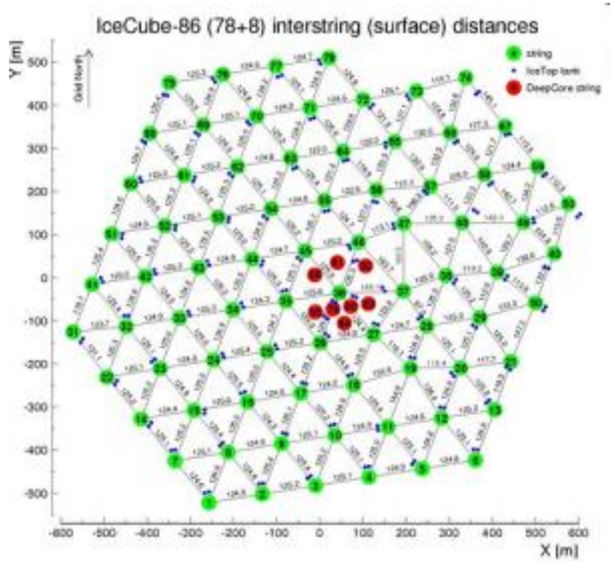
Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

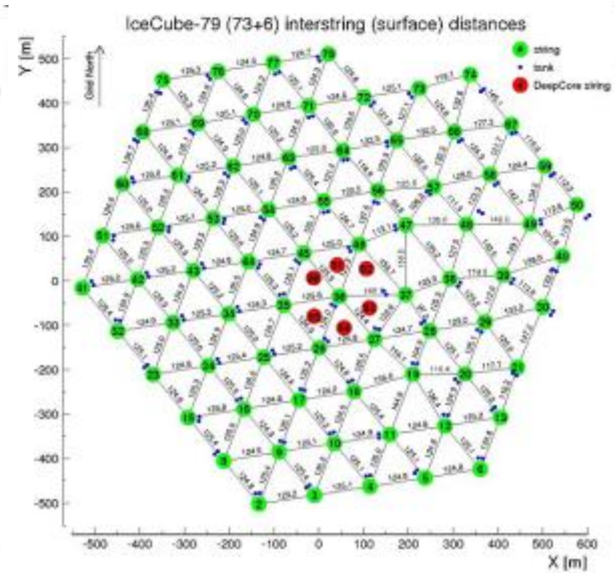
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

The IceCube Construction and Runs

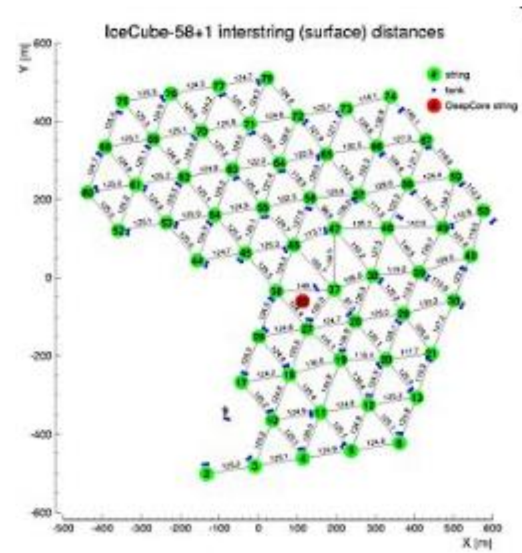
IC86 = full IceCube (2011~)



IC79 (2010-2011)

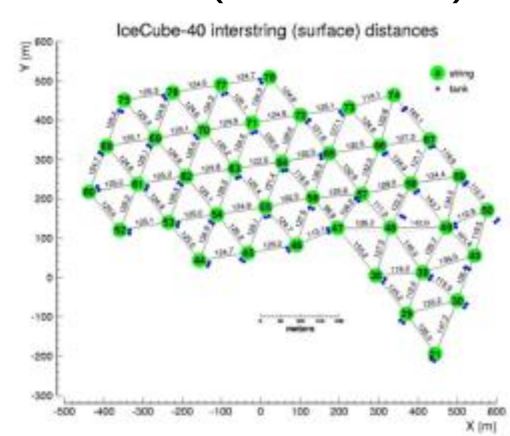


IC59 (2009-2010)



Strings	Data (year)	Livetime	trigger rate (Hz)	HE ν rate (per 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-I	2011- 2012	360 days	2700	~120/day
IC86-II	2012- 2013	360 days	2700	~120/day
IC86-III	2013-	TBD	2700	~120/day

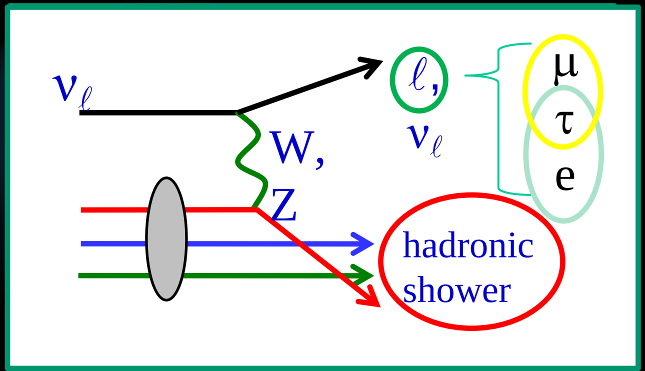
IC40 (2008-2009)



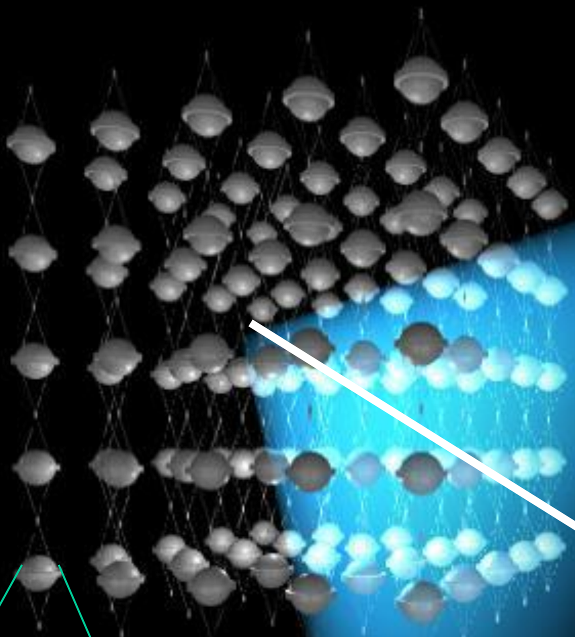
Very stable full operation since May 2011

Detection Principle

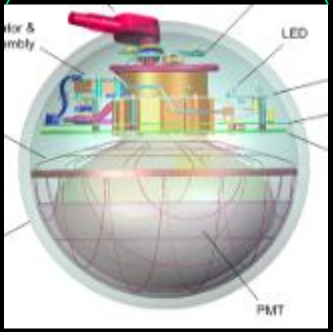
Dark and transparent material



μ, τ or cascades



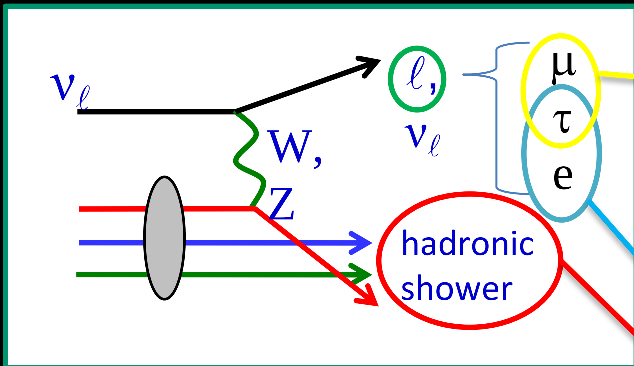
Cherenkov light



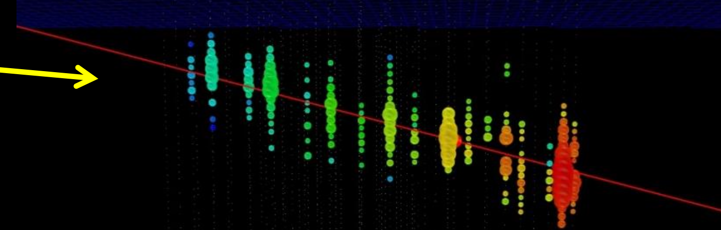
An array of photomultiplier tubes

ν

IceCube event topological signatures

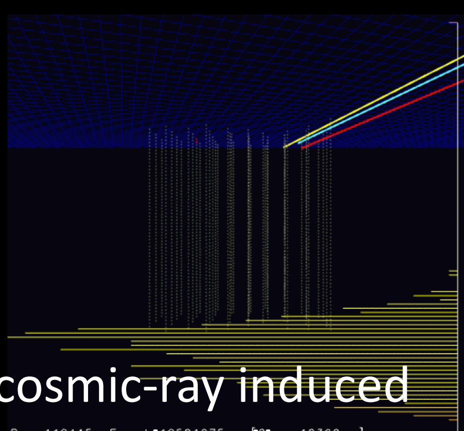


With 59 strings 2009



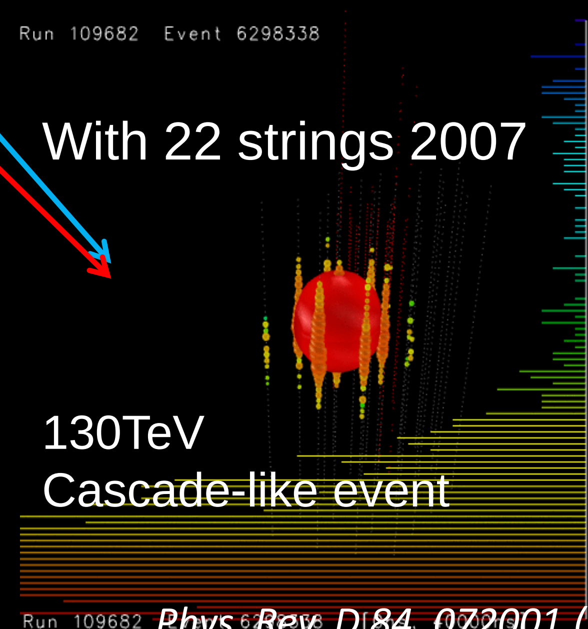
～100TeV up-going muon track event

With 40 strings, 2008 Dec



high energy cosmic-ray induced atmospheric muon bundle event

With 22 strings 2007



130TeV
Cascade-like event

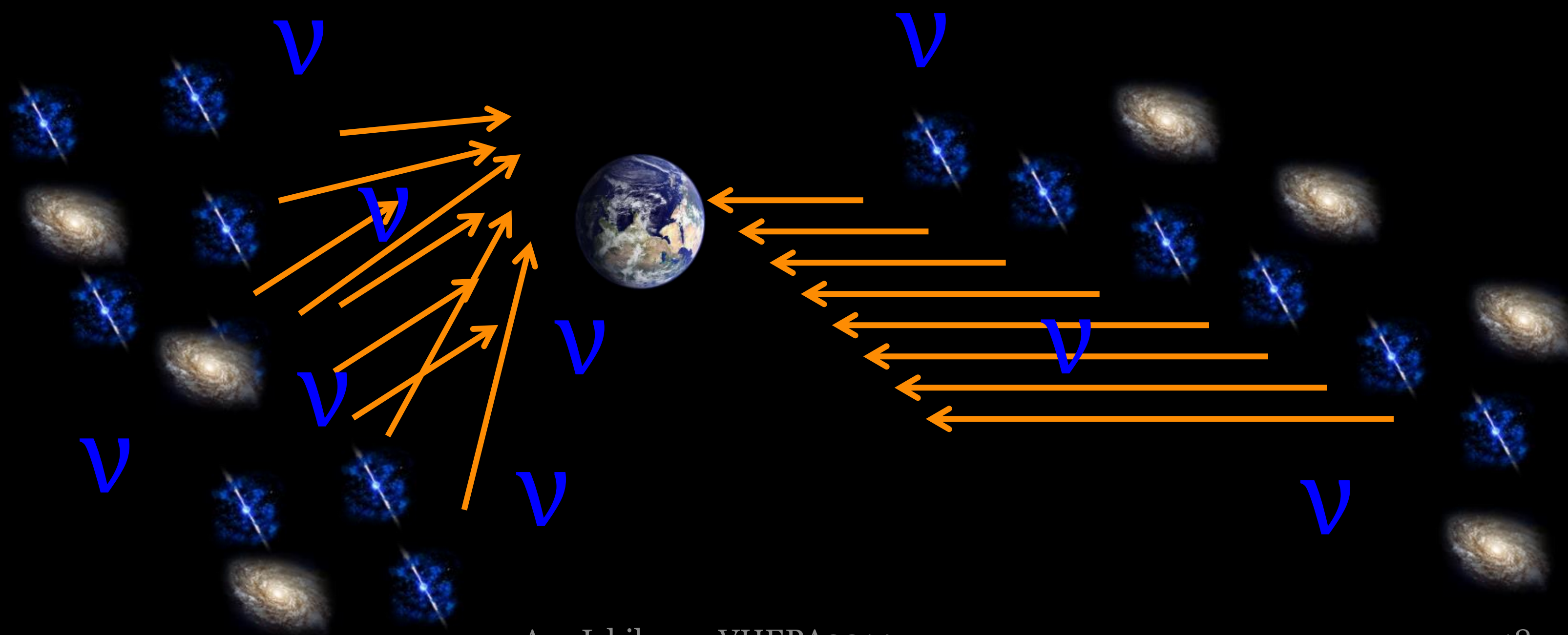
Phys. Rev. D 84, 072001 (2011)

Searches for Diffuse neutrinos

$$\phi_{\mathrm{diffuse}}\left(E|L,z\right) = \int\int\int \phi_{\mathrm{single}}\left(E|L,z\right) \frac{d^2 n(L,z)}{dz\,dL} dz\,dL\,d\Omega$$

Diffuse neutrino fluxes: Powerful tool to search abandant sources

- Advantage: Accumulate neutrinos from many many sources even at very far Universe, different direction, and of different types
- Disadvantage: Accumlate background from all the direction and time (good understanding needed), indirect identification of sources



Expected signals in diffuse ν search

Conventional Atm. neutrinos → **Prompt Atm. neutrinos** → **Astrophysical neutrinos**

- **Conventional Atm. neutrinos**
  - neutrinos from decays of pions and kaons in atmosphere
- **Prompt Atm. neutrinos**
  - neutrinos from decays of short-lived mesons in atmosphere
- **Astrophysical neutrinos**
  - neutrinos from decays of pions in astrophysical sources

"Features" in the energy spectra

steepening of neutrino spectra: $\phi \propto E^{-\gamma}$, conventional γ~3.7(+Δ*) ⇒ prompt γ~2.7(+Δ*) ⇒ astrophysical γ~2.0(+α**)

*Δ is due to cosmic-ray steepening (knee), **α is possible softening at CR acceleration site

Neutrino "flavor"

flavor changes with energy: conventional ν_μ ⇒ prompt $\nu_\mu + \nu_e$ ⇒ astrophysical $\nu_\mu + \nu_e + \nu_\mu$ (?)

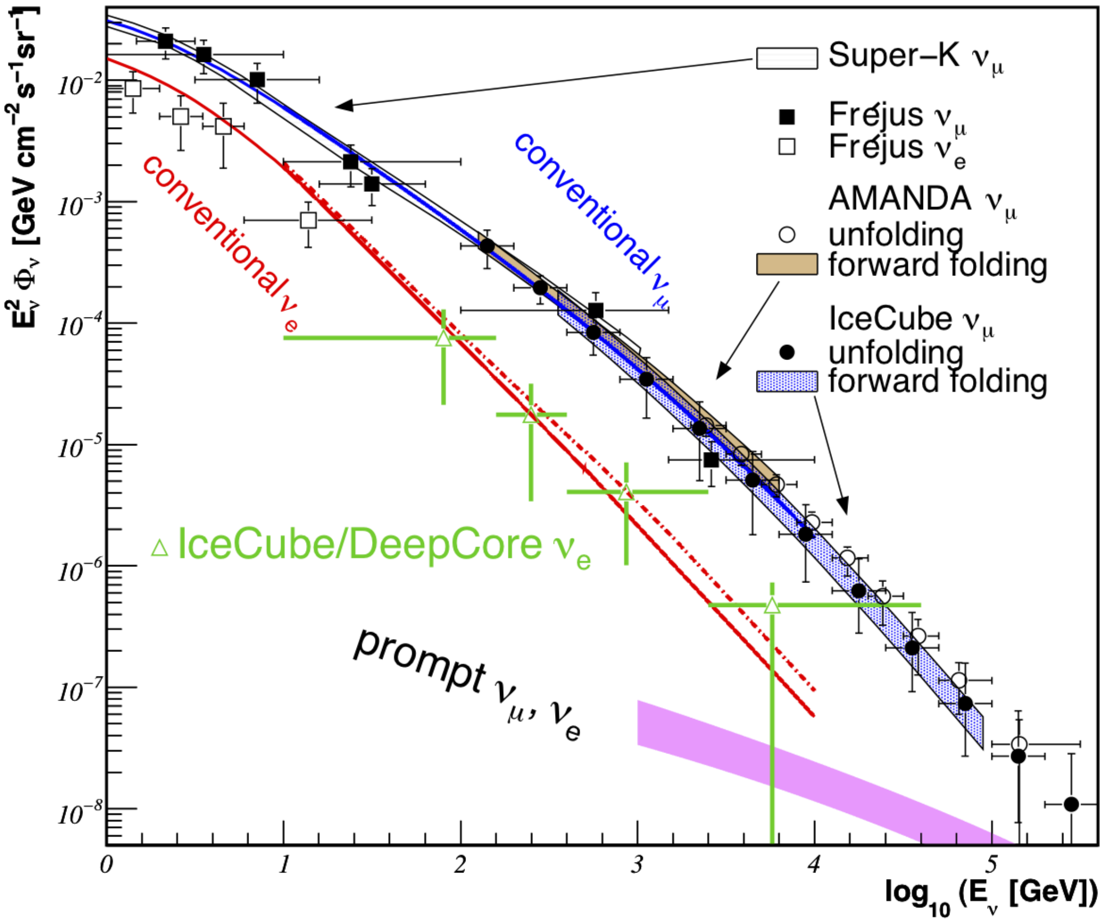
Event "directions"

zenith angle distribution changes with energy:

conventional horizontal enhanced ⇒ prompt isotropic ⇒ astrophysical isotropic (?)

This is true at surface, after propagation in Earth, high energy ν is highly reduced in the upward-going region

Atmospheric ν measurements



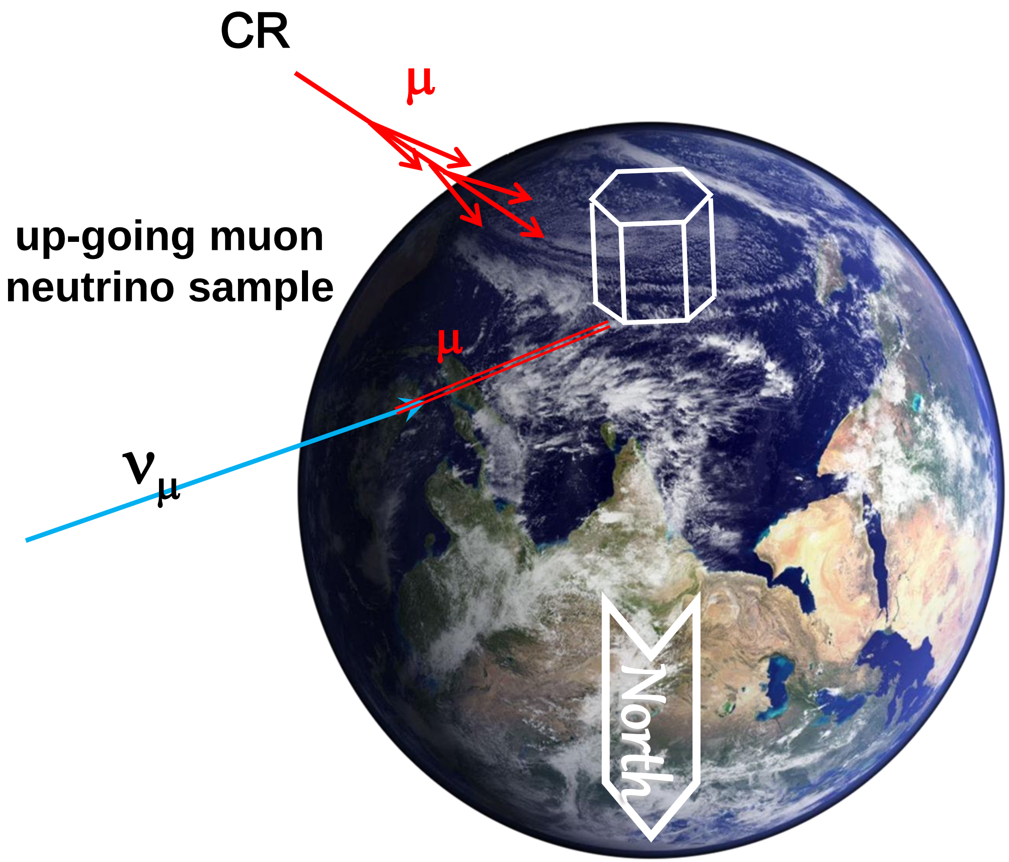
- ν_μ
- Data: 2008-2009
- ***100 GeV to 400 TeV***

Phys. Rev. D 83, 012001 (2011) by IceCube

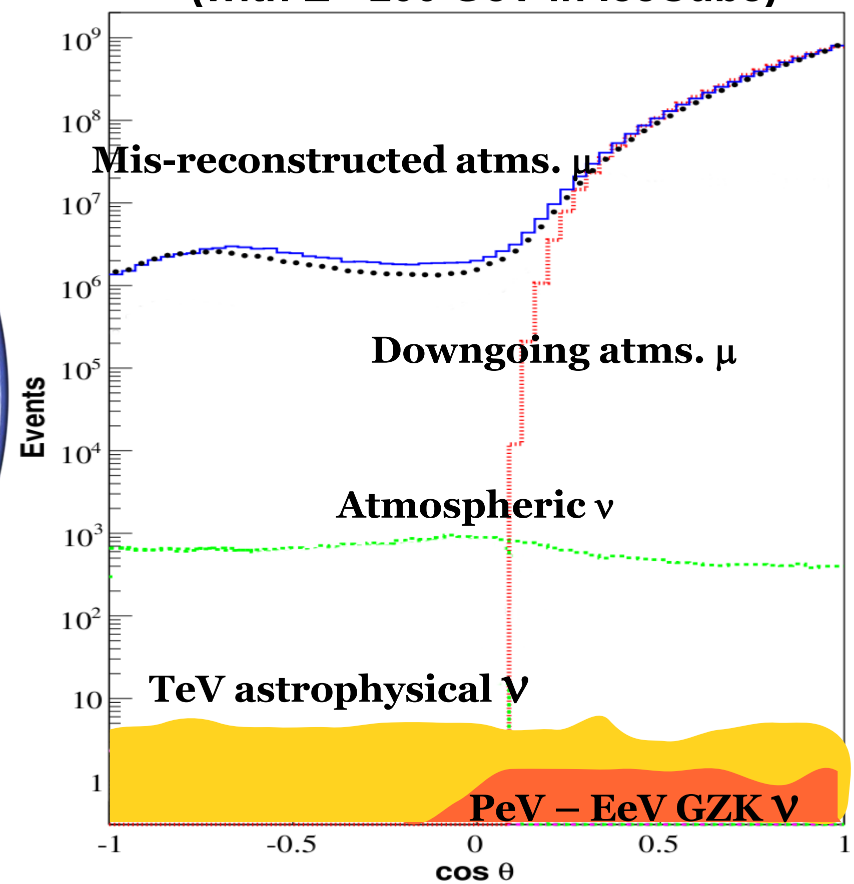
- ν_e
- Data: 2010-2011
- DeepCore
- ***80 GeV to 6 TeV***

Phys. Rev. Lett. 110, 151105 (2013) by IceCube

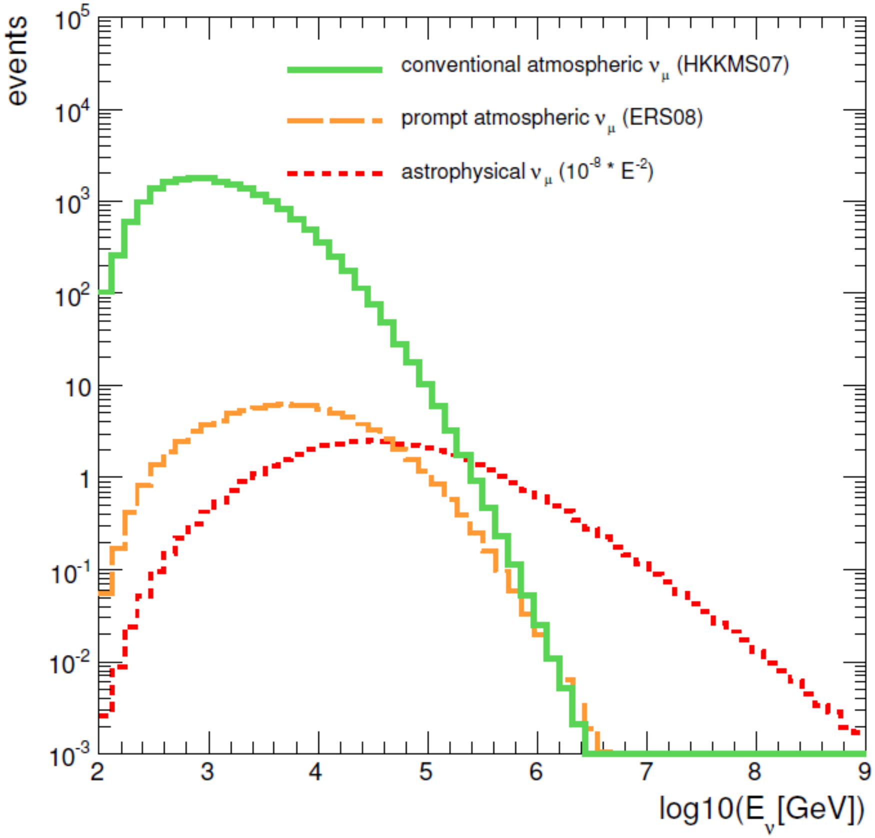
Up-Track astrophysical ν_μ search

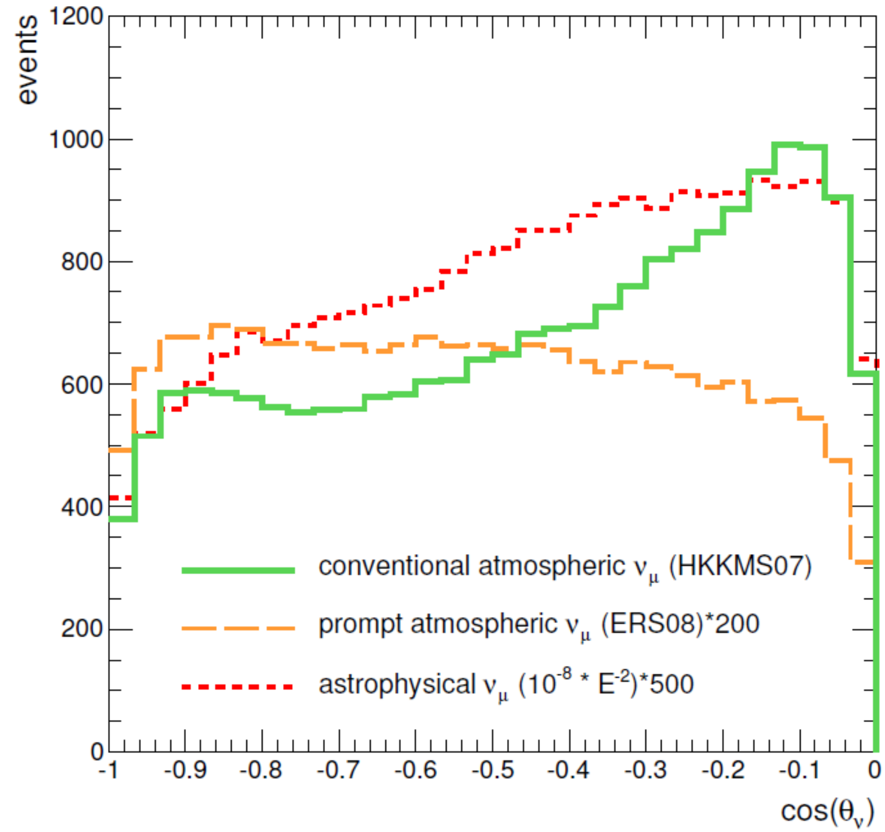


Trigger rates:
Atm. muons: ~3 kHz,
~200 atm. ν /day
(with E >100 GeV in IceCube)



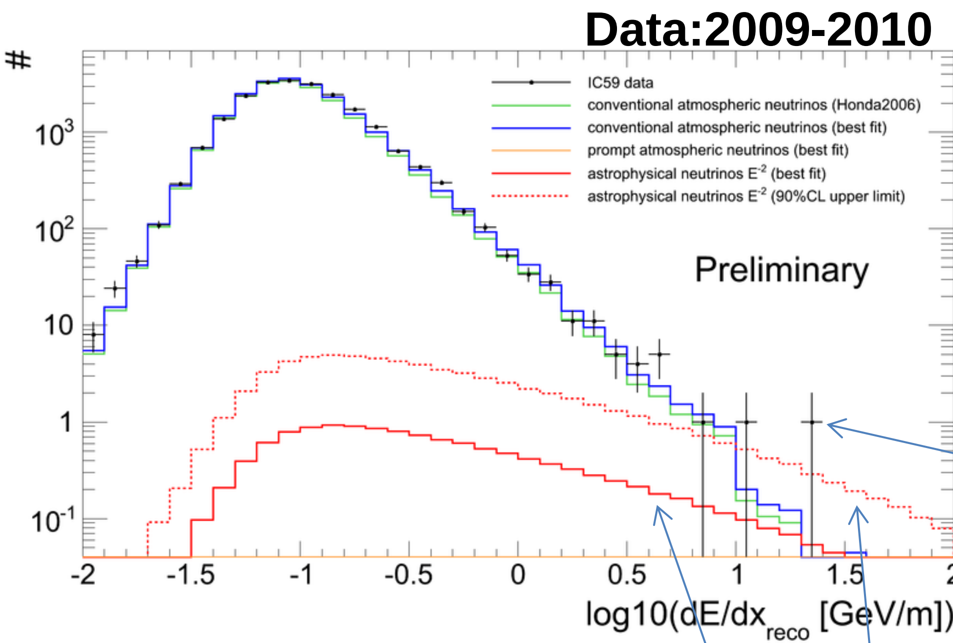
Astrophysical and Atmospheric ν_μ



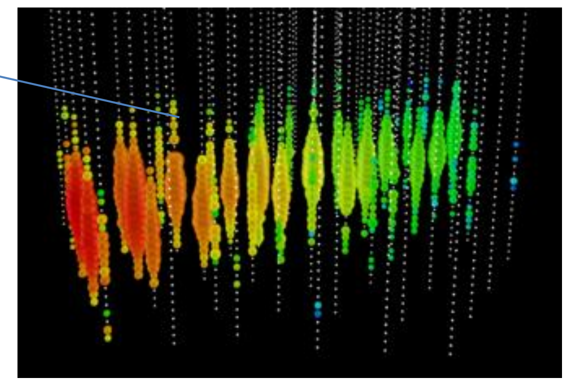


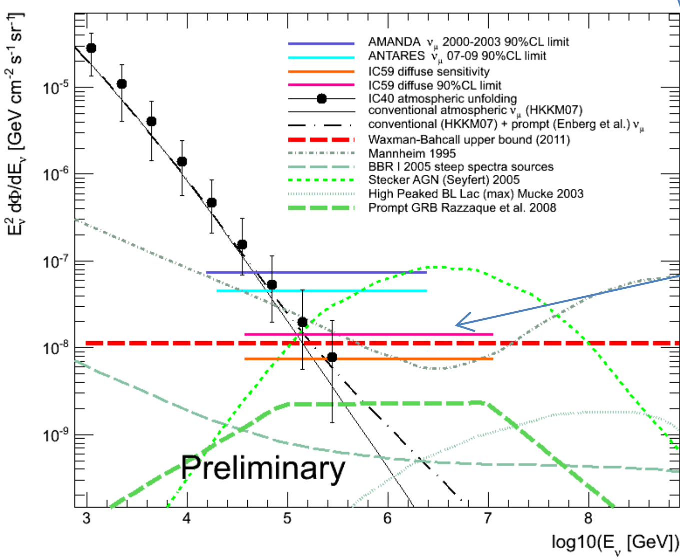
Extraterrestrial neutrino search with ν_μ

arXive:1302.0127
Accepted by Phys. Rev. D



The found highest energy event





Upperlimit on $\phi_{astro} \propto E^{-2}$ for ν_μ

$E^2\phi$=1.4x10^{-8} [GeV cm-1 s-1 sr-1]

Best fit results of $\phi_{astro} \propto E^{-2}$ for ν_μ

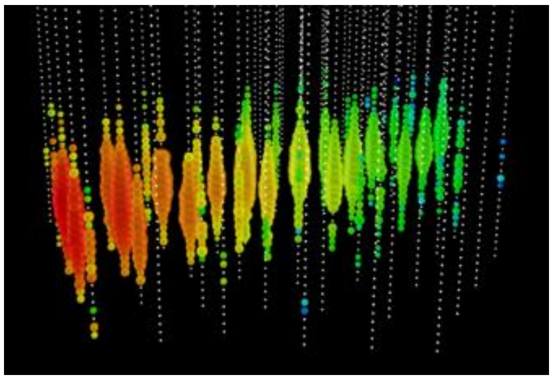
$E^2\phi$=(2.7±5.9)x10^{-9} [GeV cm-1 s-1 sr-1]

Energy estimate of the highest energy track event

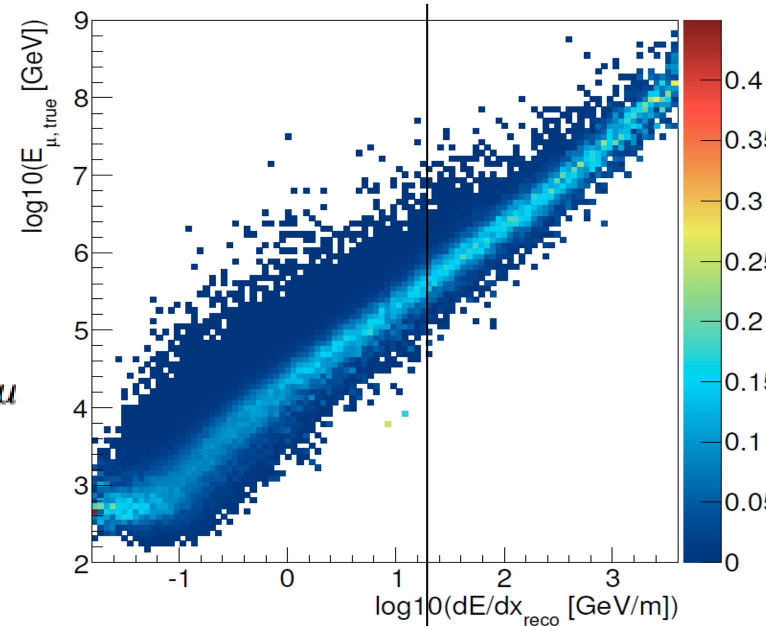
IceCube: NIMA Volume 703 (2013)190

muon energy

Peak energy: 400TeV
Median energy: 500TeV

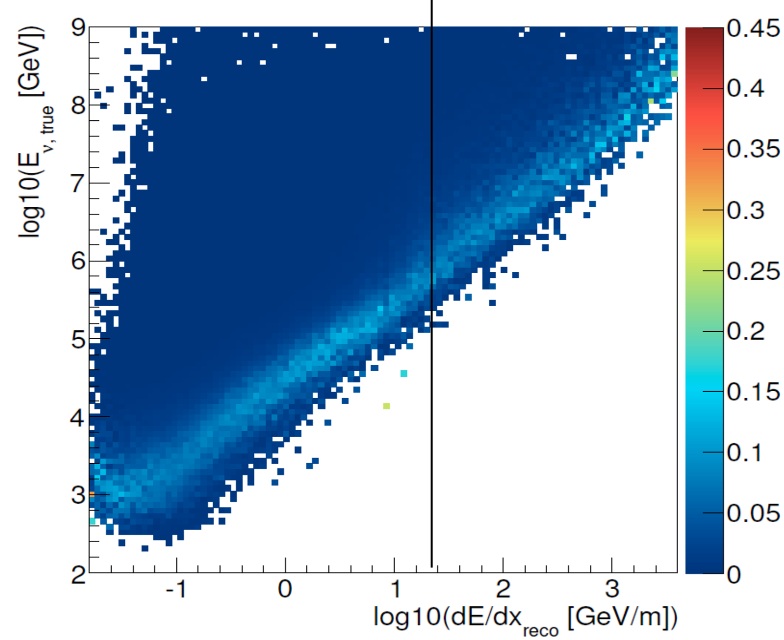


$$\frac{dE_\mu}{dx} = A + BE_\mu$$



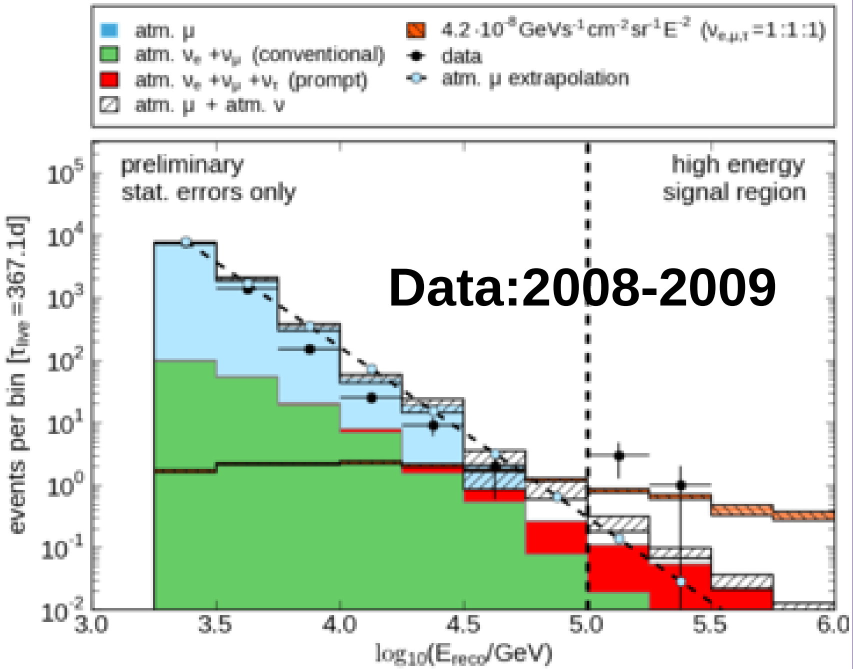
ν_μ energy

Peak energy: 560TeV
Median energy: 1.1PeV

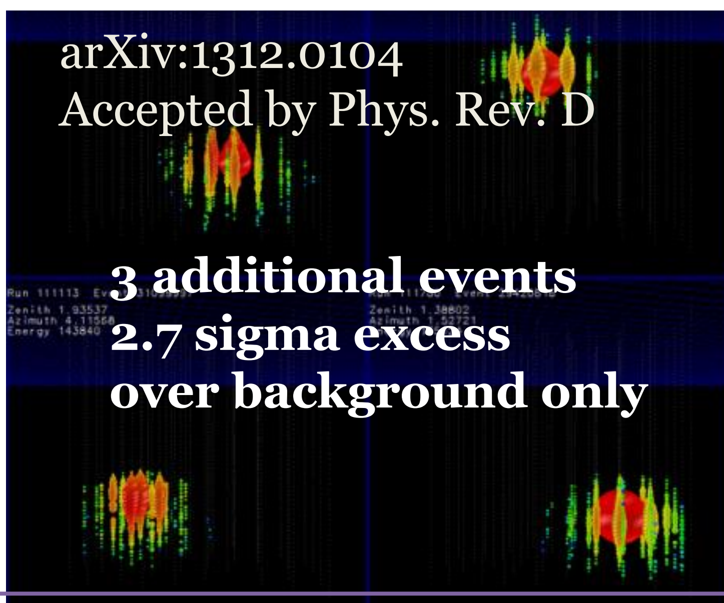


IceCube: arXiv:1311.4767
Accepted by Journal of Instrumentation

Extraterrestrial neutrino search with cascades

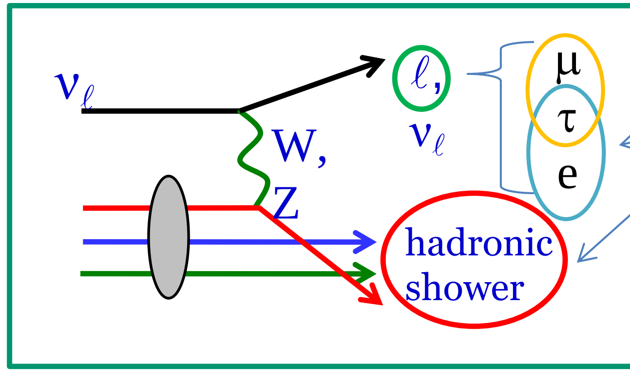


Data:2008-2009

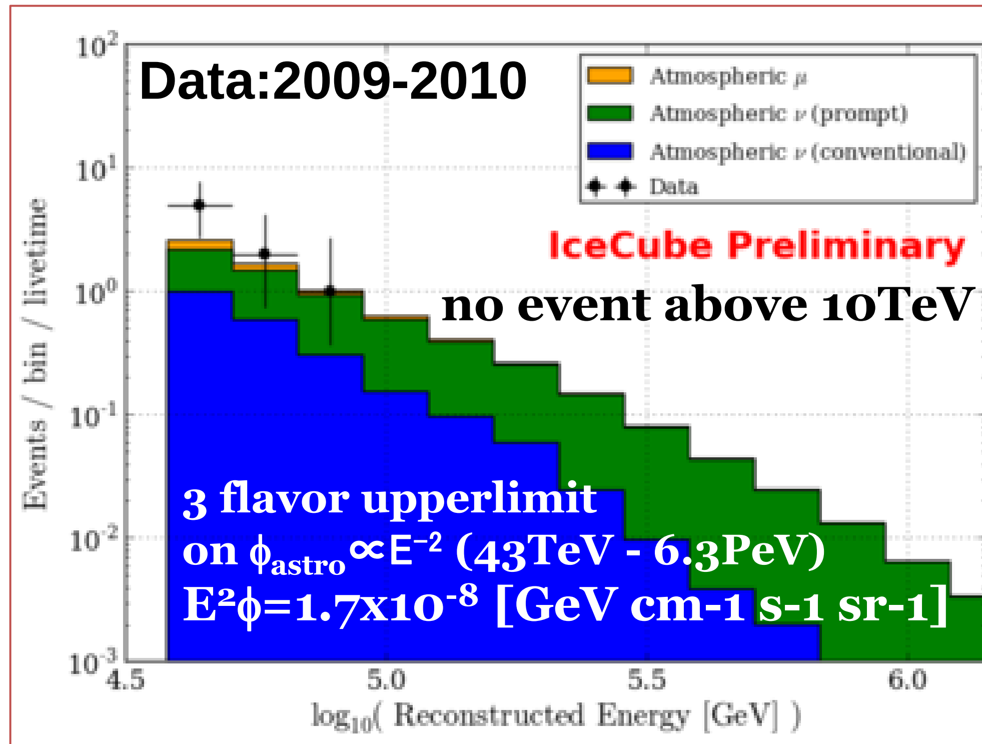


arXiv:1312.0104
Accepted by Phys. Rev. D

3 additional events
2.7 sigma excess
over background only



cascade-like signatures



Data:2009-2010

IceCube Preliminary

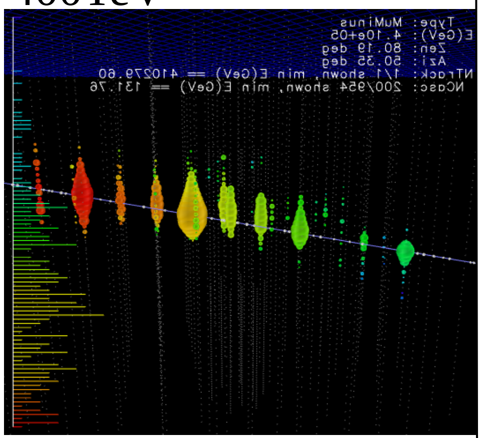
no event above 10TeV

3 flavor upperlimit
on $\phi_{astro} \propto E^{-2}$ (43TeV - 6.3PeV)
$E^2\phi=1.7\times10^{-8}$ [GeV cm-1 s-1 sr-1]

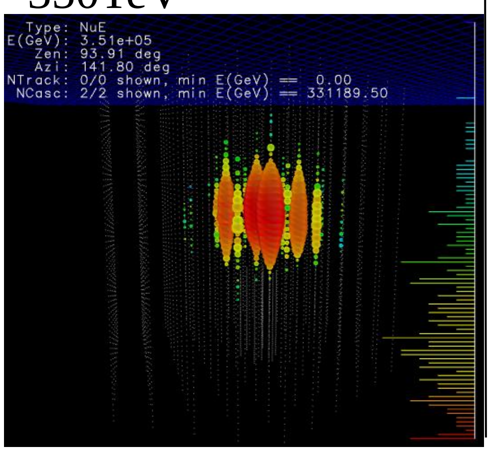
The extremely high energy neutrino search

below ~PeV, upward-going tracks and cascade-like topology is important

400TeV

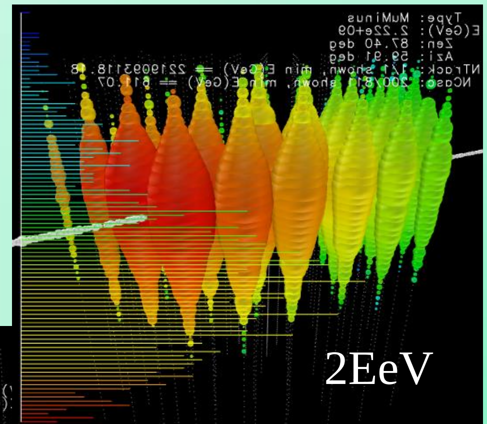


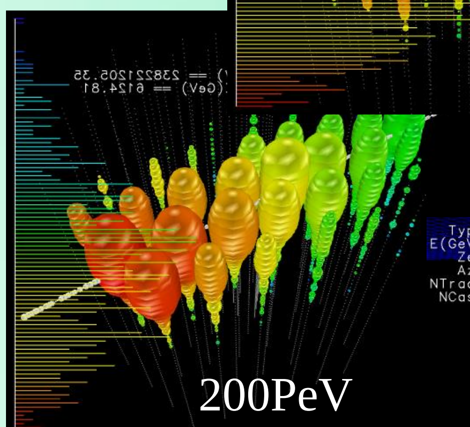
350TeV

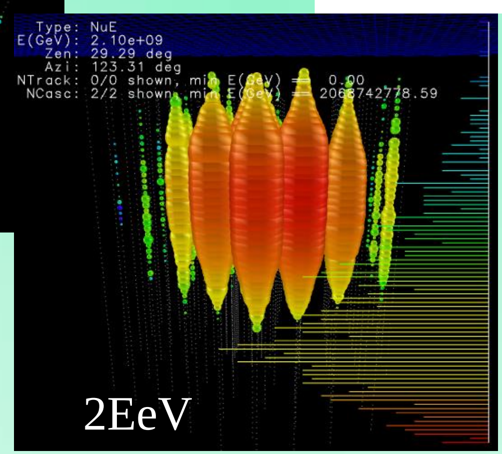


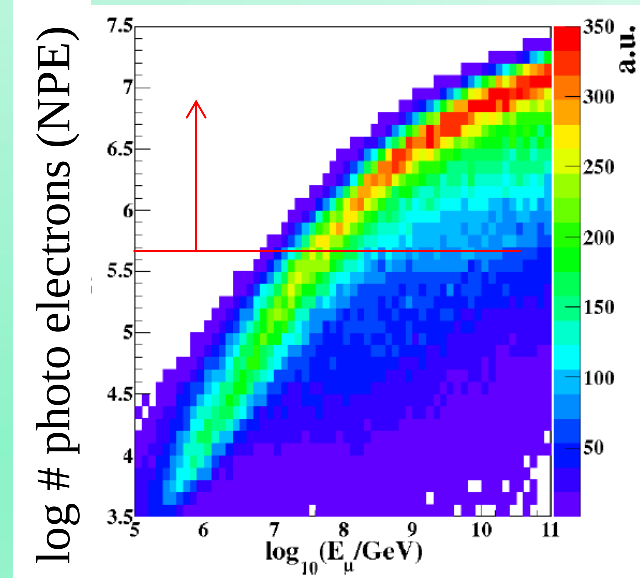
'Very bright' is an important condition

Select both type of events with a 'brightness' of events







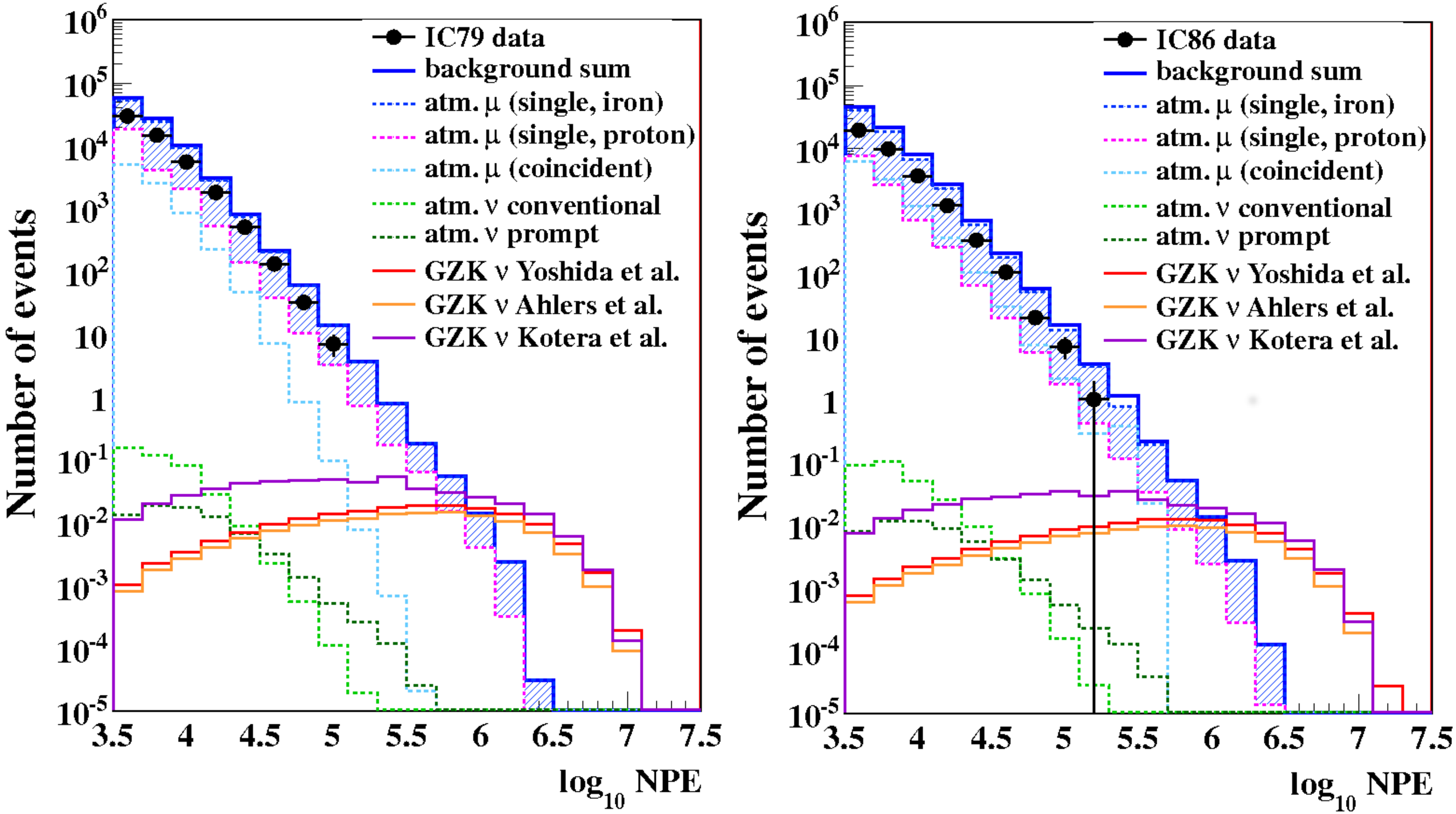


from MC simulation

IceCube EHE Event NPE Distributions

NPE > 3000

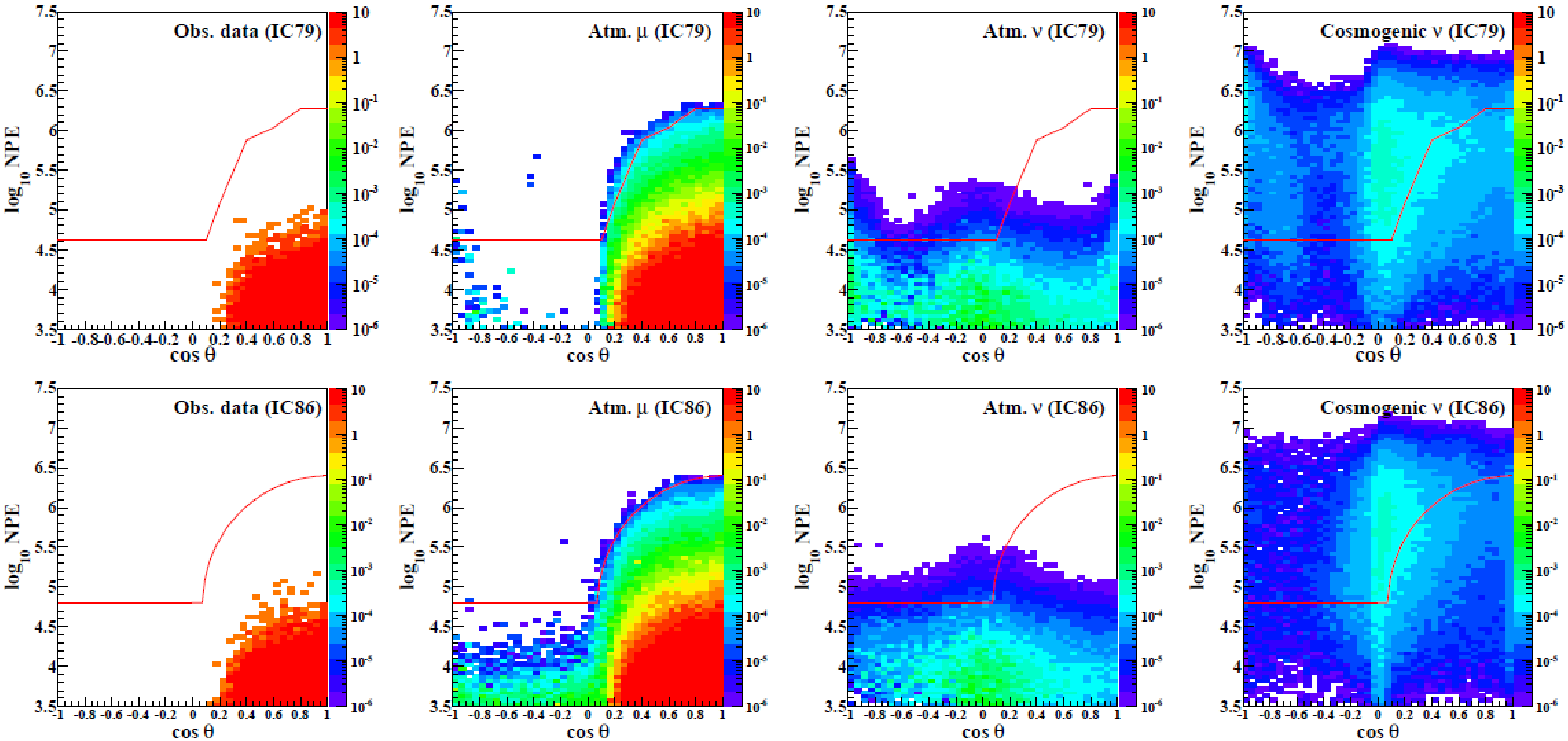
PhysRevD.88.112008



Zenith angle dependent NPE threshold

PhysRevD.88.112008

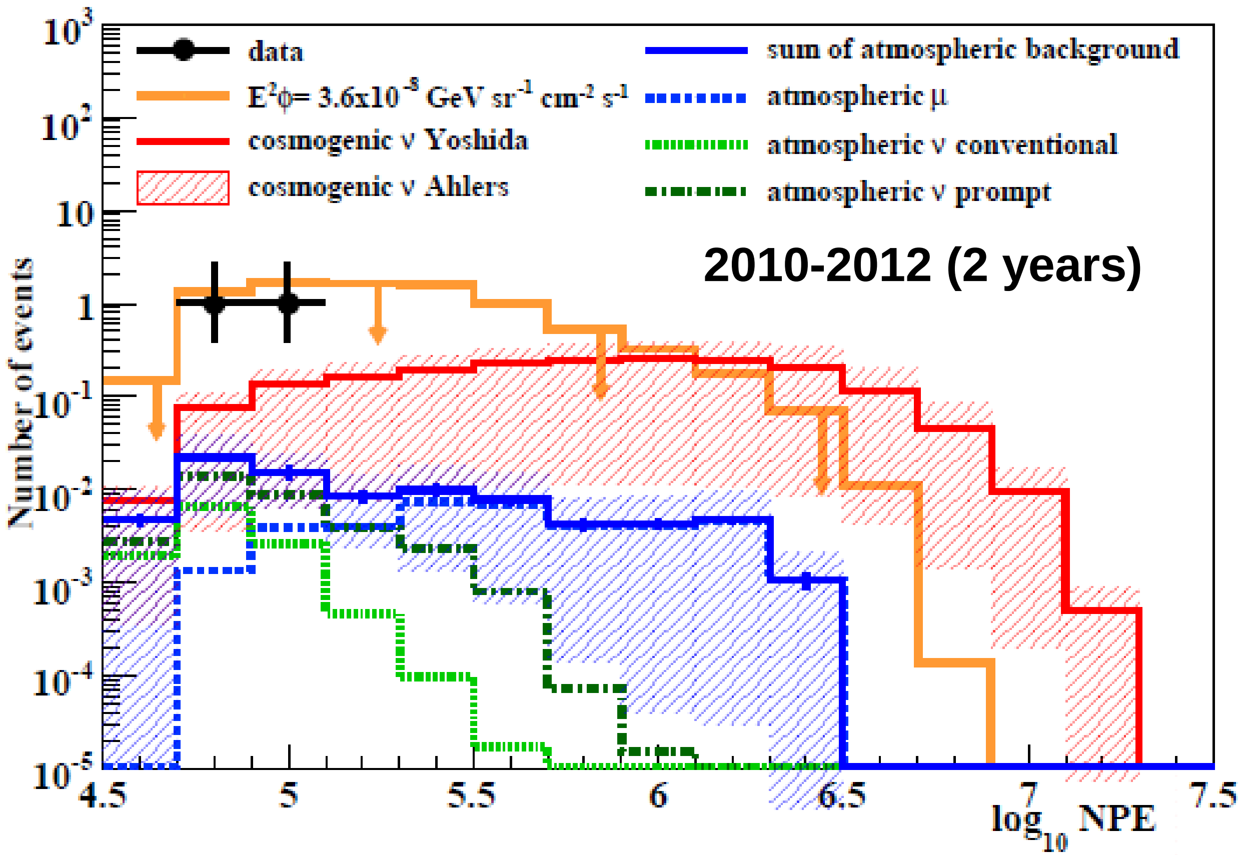
Data | Background | Signal

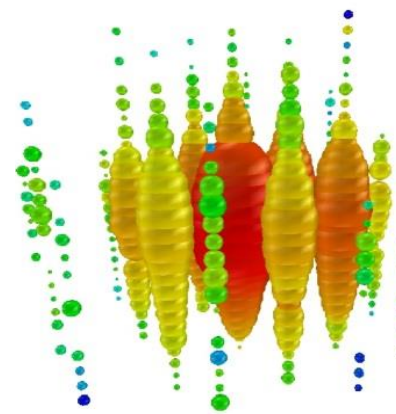


Extremely high energy neutrino search above PeV

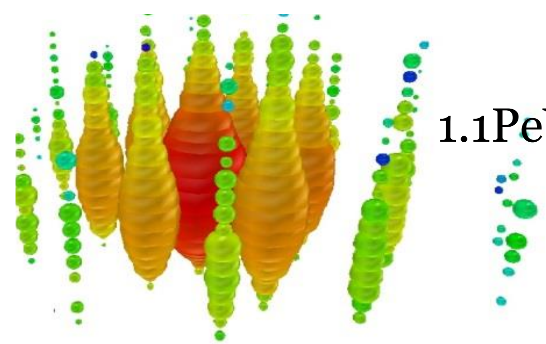
Phys. Rev. Lett. 111, 021103 (2013)

- **$\nu_e:\nu_\mu:\nu_\tau$=6:1:2 at 1PeV, 3:4:2 at 10PeV, 2:5:3 at 100PeV**
- **2..8sigma excess over $0.08^{+0.04}_{-0.06}$ events of default atmospheric background**





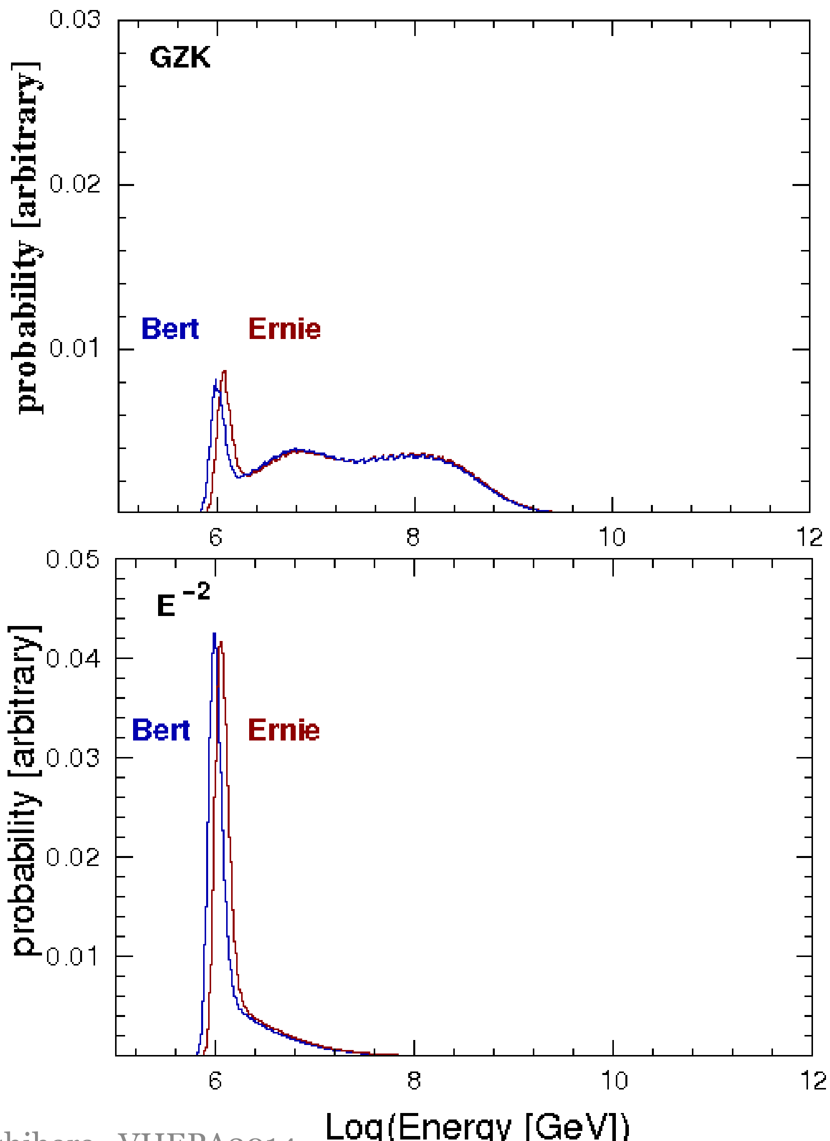
1.0PeV



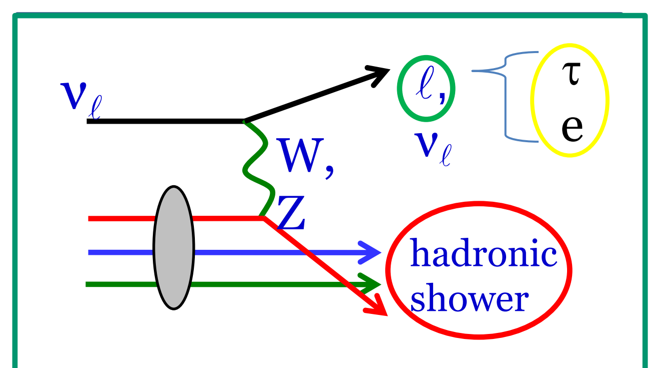
1.1PeV

Number of photoelectrons: NPE ∝ Visible Energy

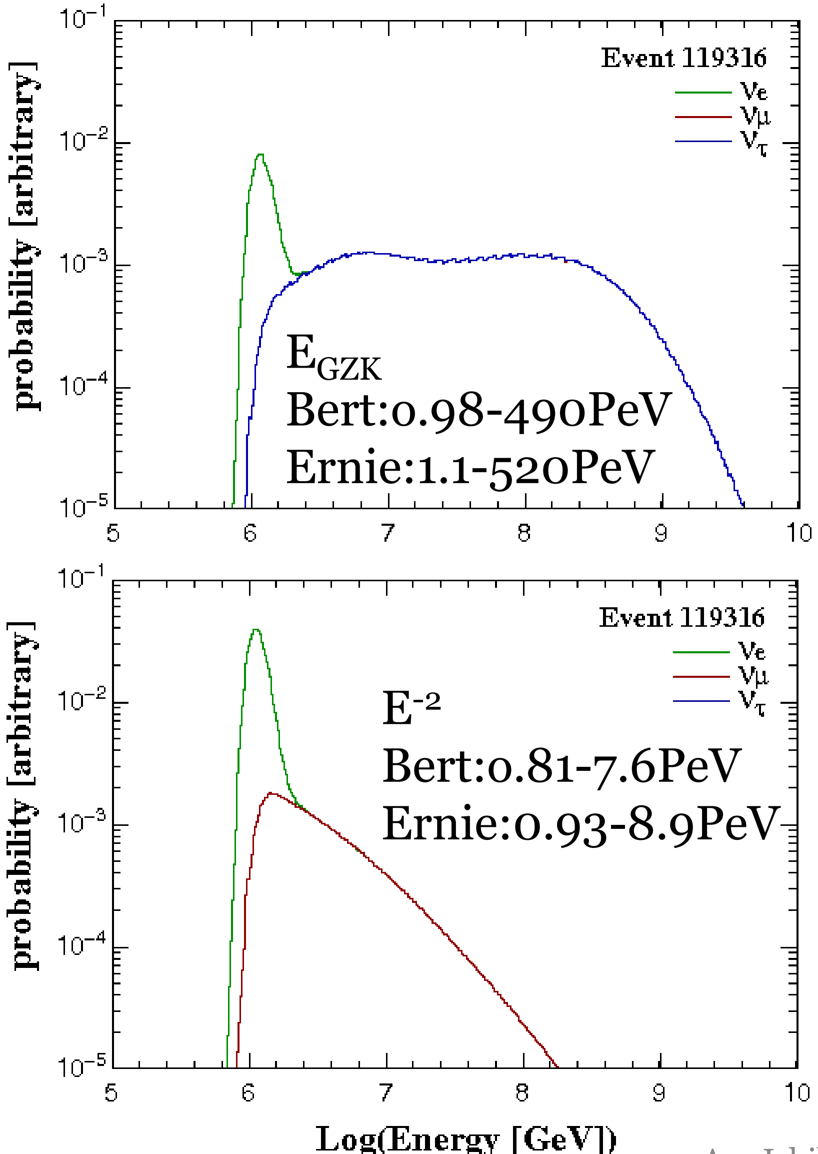
Neutrino energy at the IceCube depth



- Parent neutrino energies of these events depend on the charged current to neutral current interaction probability
- The higher energy neutrinos, the more contribution from neutral-current interactions
- The harder parent ν spectra, the more likely to be high energy ν induced



Neutrino energy on the Earth surface



Then we take account of the effect of the neutrino absorption and regeneration effect in the Earth to obtain the energy pdf of neutrinos on the Earth surface

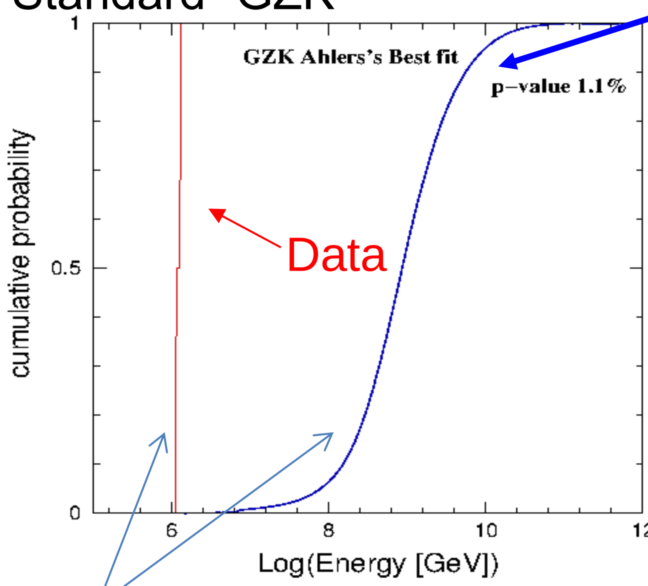
Are these 2 events cosmogenic in origin?

the Kolmogonov-Smirnov test implies that the estimated energies (assuming GZK spectra on surface) can not be explained by the cosmogenic neutrino models

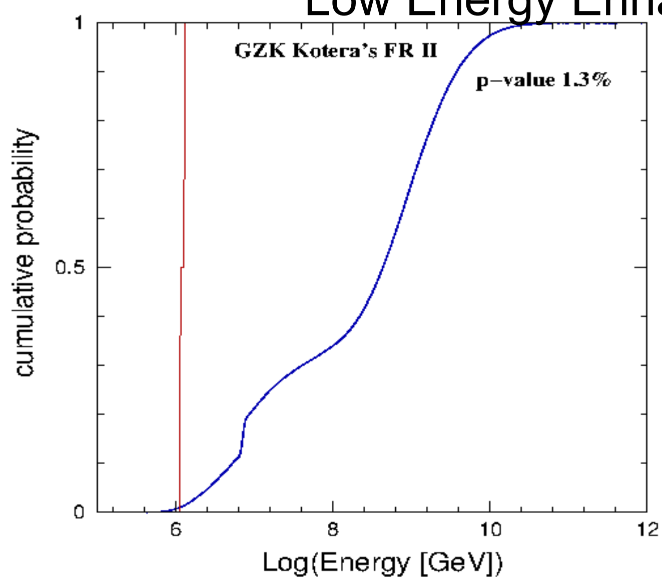
No!

The predicted E_{ν} cumulative probability

“Standard” GZK

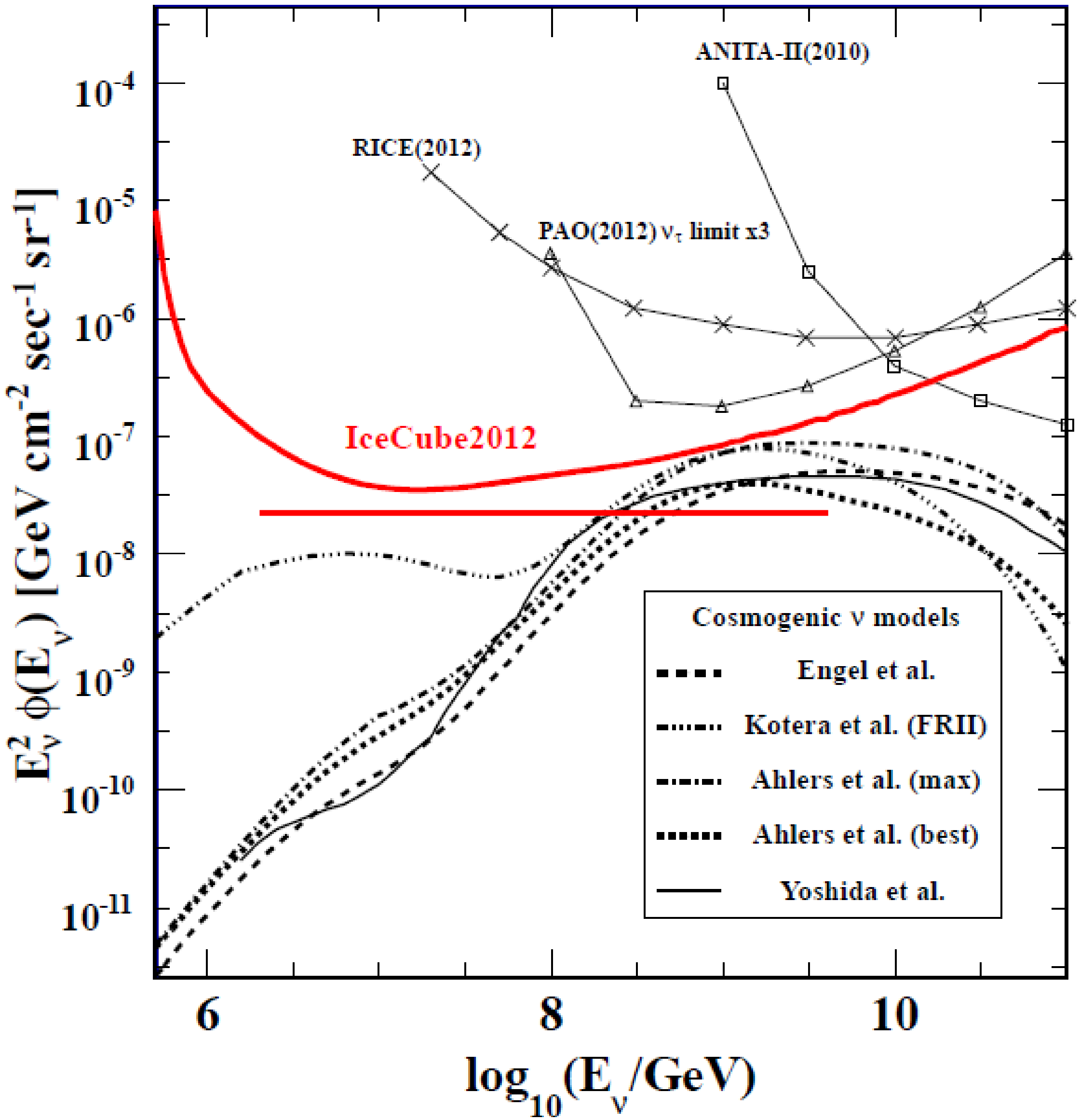


“Low Energy Enhanced” GZK



The test tells that they are very (at 95%CL) inconsistent

Model independent quasi-differential upper limit



- Including Energy PDF of the two events
  - PeV region upperlimits are weaken by the 2 event observation
- Significantly improved from the previous upperlimits
- IceCube becoming more and more sensitive to cosmogenic fluxes above ***100 PeV (10^8 GeV)*** and started to constrain the highest energy comsic-ray source evolutions
- E^{-2}flux integrated limit taking into 2 observations

$E^2\varphi(\nu e+\nu\mu+\nu\tau)= 2.5\times10^{-8}$GeV cm^{-2}s^{-1}sr^{-1}(1.6 PeV – 3.5 EeV)

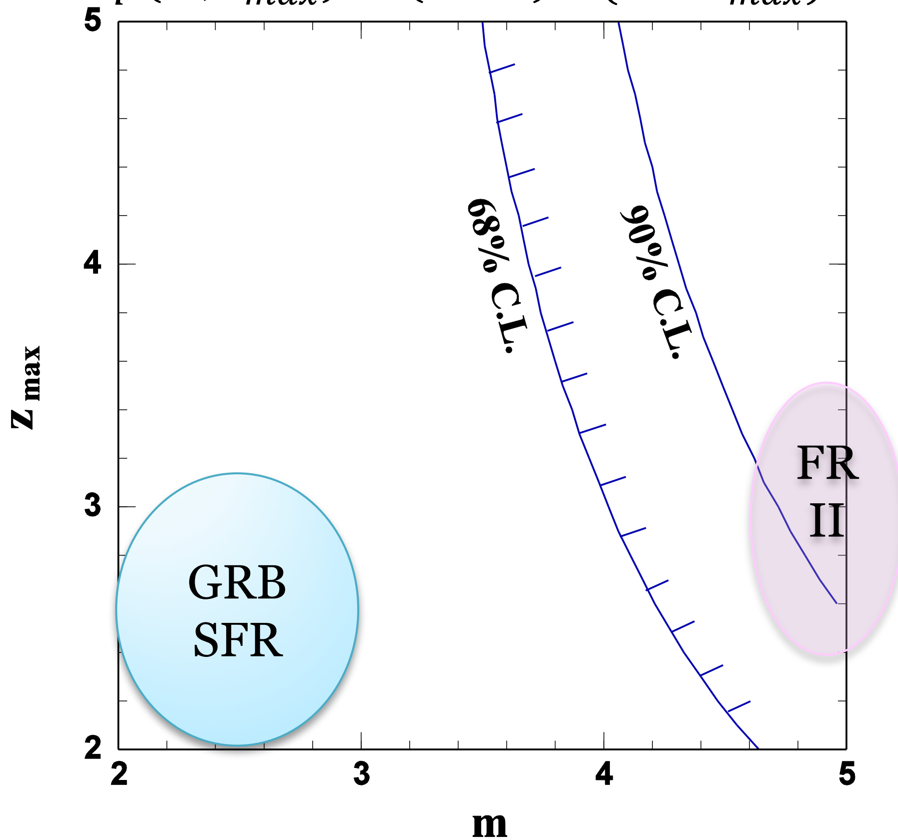
Event rates and p-values from the extremely high energy neutrino search (proton CR model)

Neutrino models	Event rate above 100PeV 2008, 2010, 2011 data	p-value of ~null observation above 100PeV
Yoshida and Teshima m=4.0, z_{max}=4.0	2.0	0.14
Kalashev et al (Phys. Rev. D 66, 063004) m=5.0, z_{max}=2.0	3.1	0.045
Yoshida and Ishihara (Phys. Rev. D 85, 063002) m=5.0, z_{max}=2.0	1.5	0.22
Ahlers et al (best fit) M=4.0, z_{max}=2.0	1.5	0.22
Ahlers et al (the maximal flux model)	3.1	0.044
Kotera et al GRB, z_{max}=8, alpha=2.4	0.48	0.66
Kotera et al SFR, z_{max}=8, alpha=2.5	0.46	0.67
Kotera et al FRII, z_{max}=8, alpha=2.3	2.9	0.052

We will more than double the rates with 2009, 2012, 2013 data soon

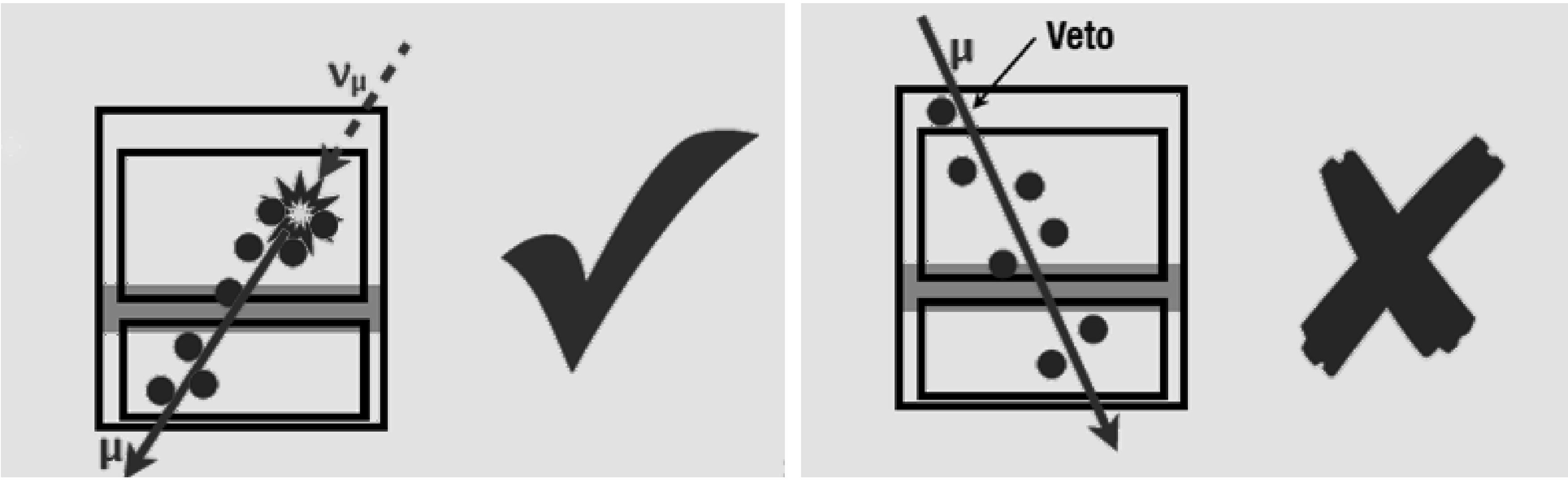
Constraint on the highest energy neutrino fluxes and cosmic-ray sources

$$p(m, z_{max}) = (1+z)^m \ (z < z_{max})$$



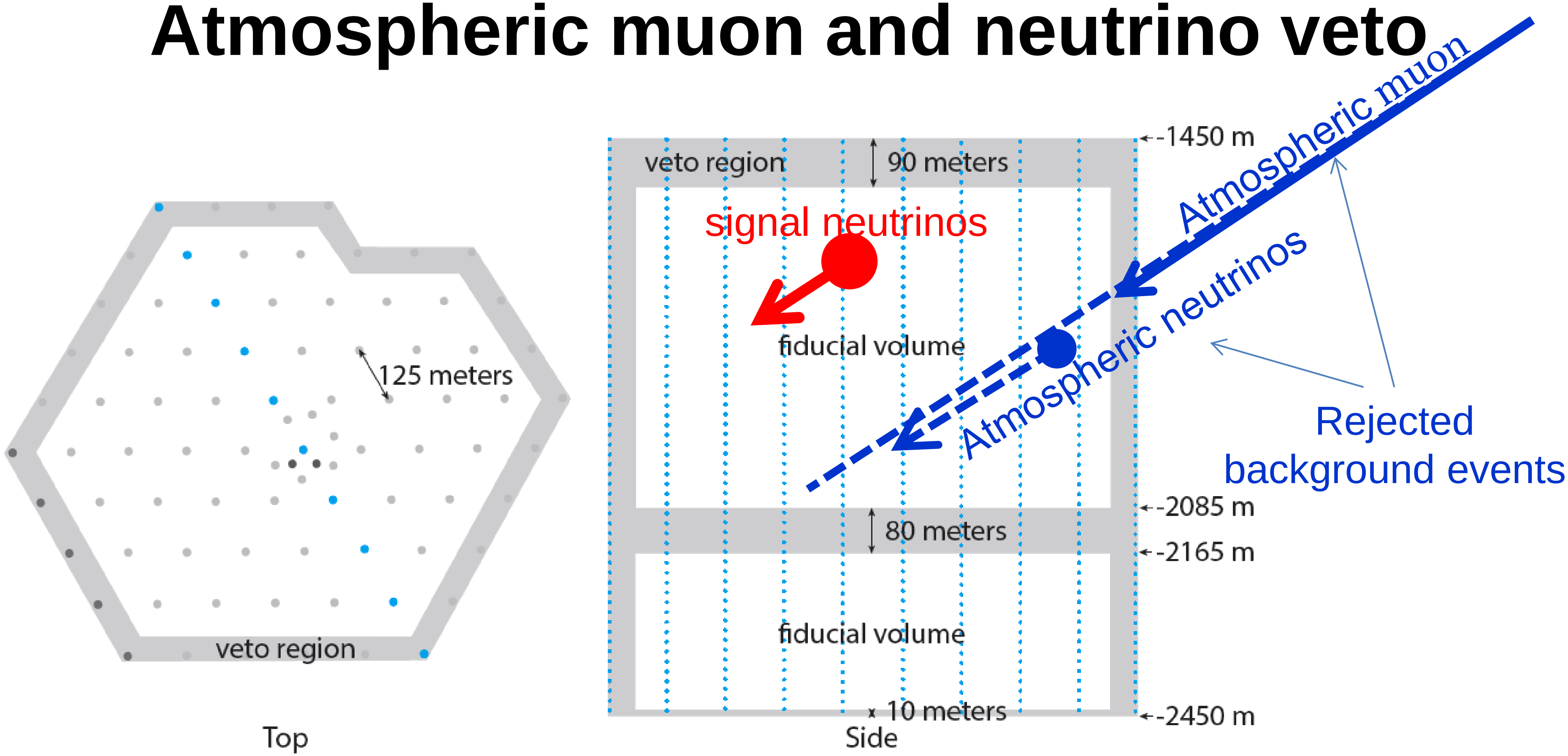
- Highly evaluating source models of the highest energy cosmic-ray protons can be excluded
- Disfavoring a generic expression of the evolution parameter m larger than ~4 which includes radio loud active galaxies (FRII)

Starting Event Search (cascade+starting track)



- Followup analysis on the UHE cascade-like events
- Atmospheric muon/neutrino background largely reduced by vetoing events with initial photons in outer layers
- Events with NPE > 6000 (the case for EHE, NPE > 60000), sensitivity extended down to 30TeV

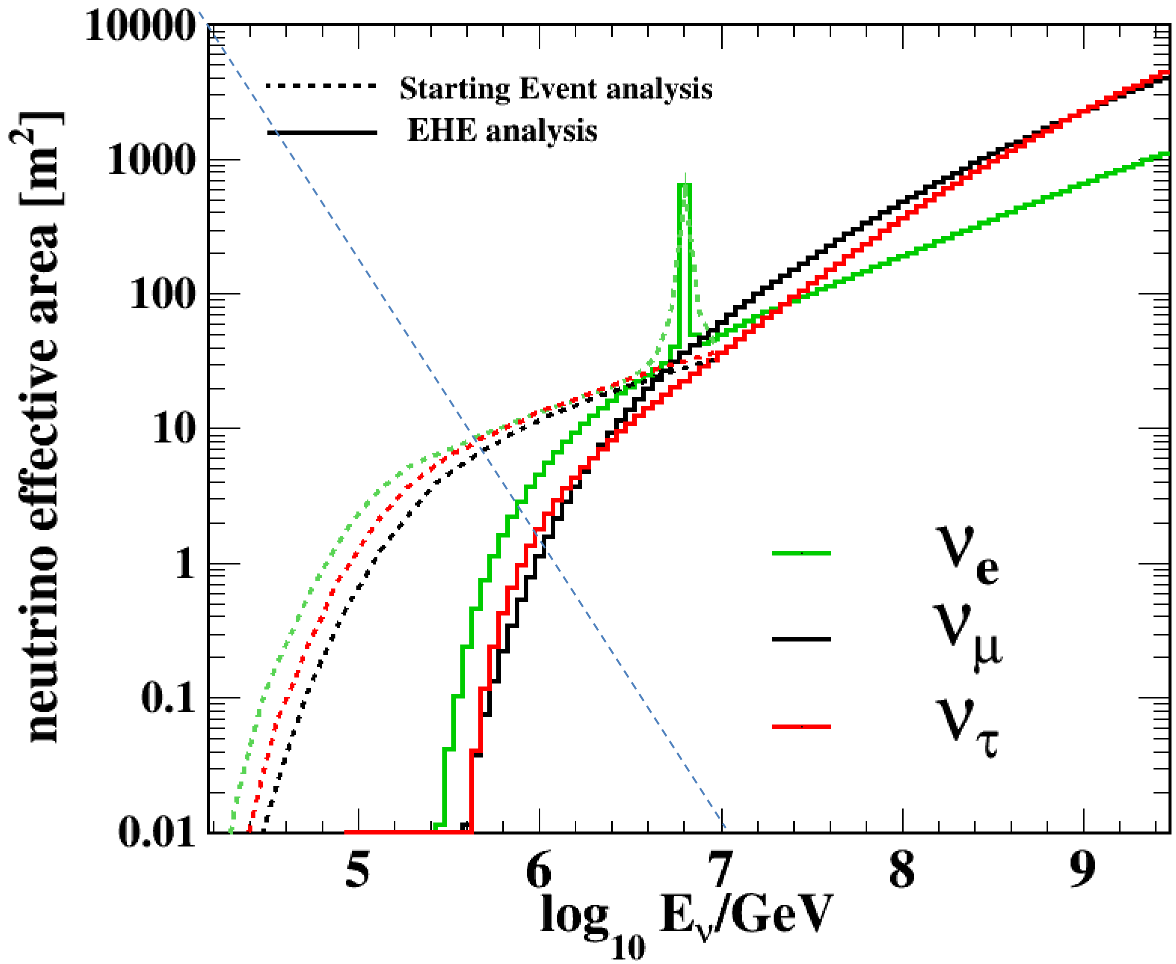
Atmospheric muon and neutrino veto



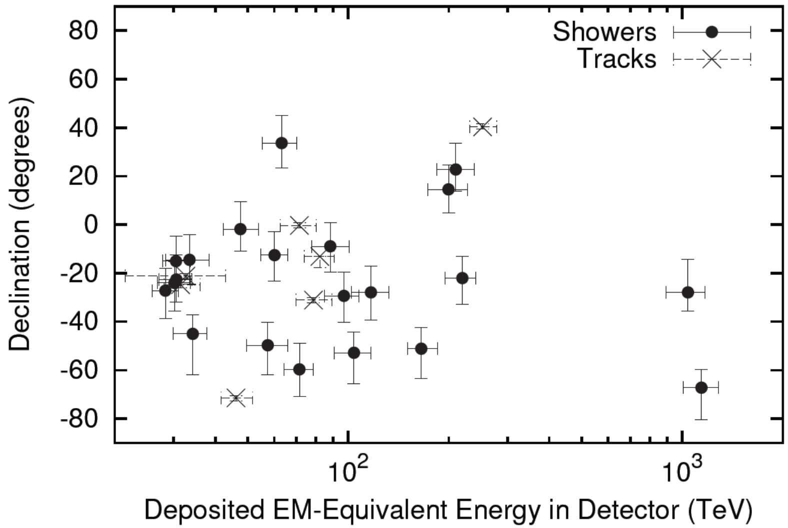
- Down-going atmospheric neutrinos are also reduced by vetoing atmospheric muon events
- **This changes atmospheric neutrino zenith angle distributions to upward-going dominated**

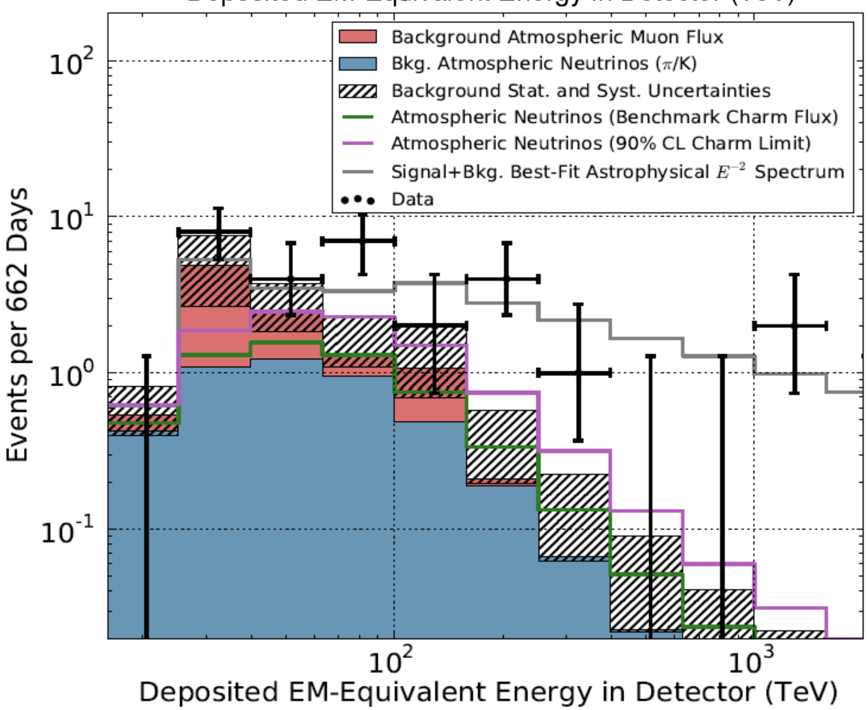
Effective Areas
Propositional to expected event rates

Area x ν flux x 4π x livetime = event rate



Starting event energy distribution





IceCube:
Science 342, 1242856 (2013)

2010-2012 (2 years) results

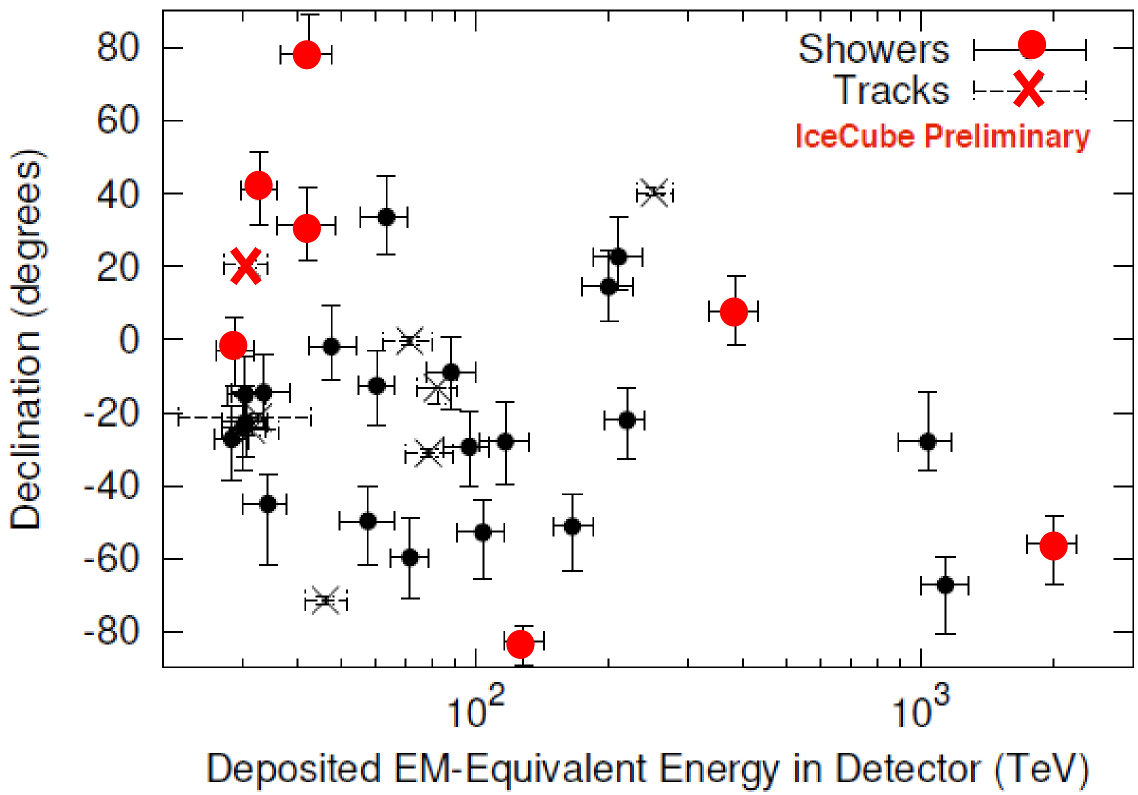
- 26 new events found
  (19 cascades, 7 with tracks)

- over background expectation of $10.6_{-3.6}^{+5}$ total atmospheric muons (6.0 ± 3.4) and atmospheric neutrinos ($4.6_{-1.2}^{+3.7}$)

- **Best fit results**
  $E^2\phi=(1.2\pm0.4)\text{x}10\text{-}8$ [GeV cm^{-2} s^{-1} sr^{-1}] with a hard cut off at 1.6PeV

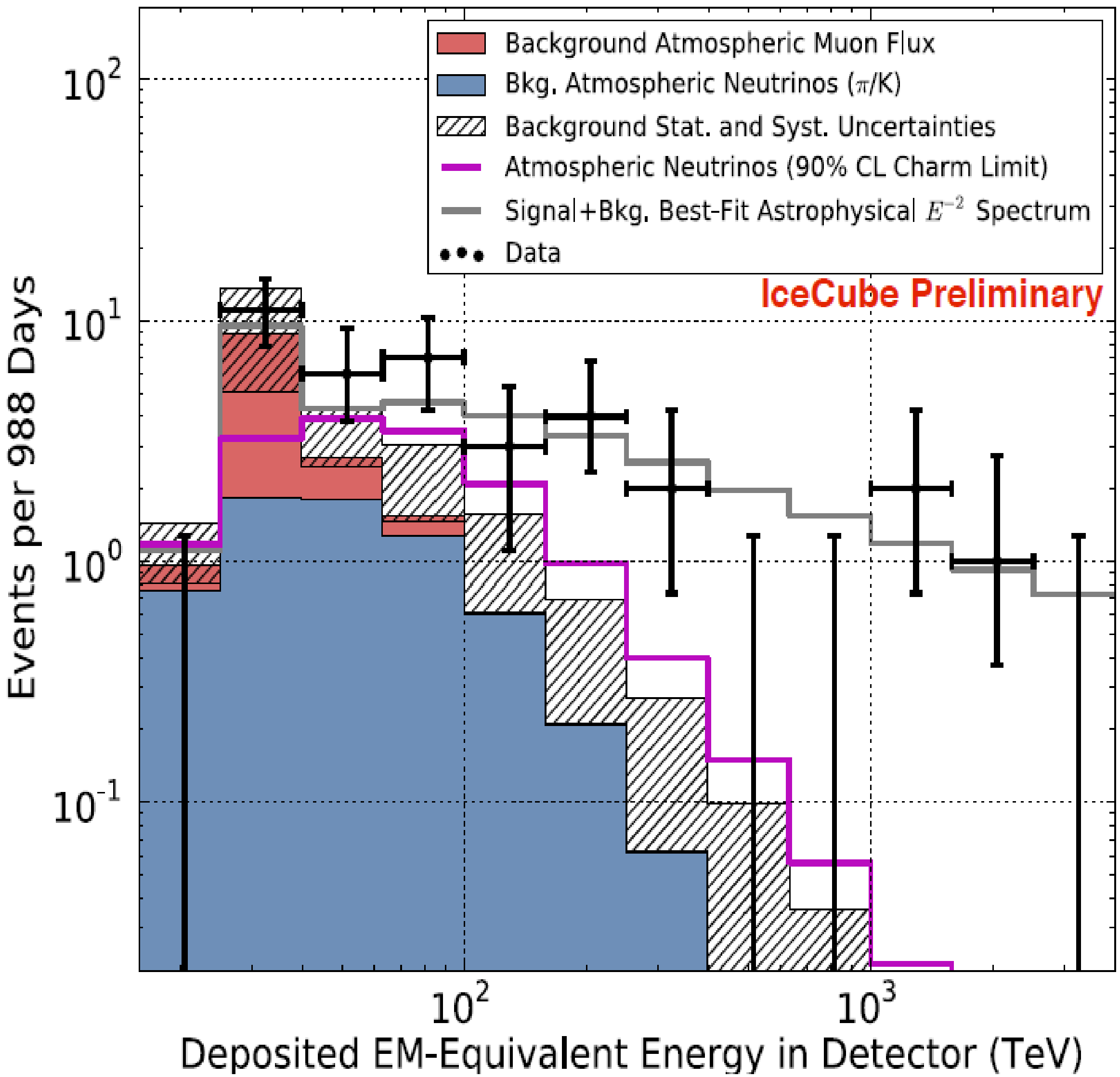
Starting Events in 3 year sample

2010-2013 (3 years)



- 9 new events found
- 7 cascades, 1 with tracks, and 1 coincident muon event (not plotted)
- 5 from southern sky and 3 from northern sky
- the highest energy 2PeV event in the test sample
- 28+9 over background expectation of $15.0^{+7.2}_{-4.5}$ atmospheric muons 8.4 ± 4.2 and atmospheric neutrinos $6.6^{+5.9}_{-1.6}$

Extraterrestrial neutrino search with starting events



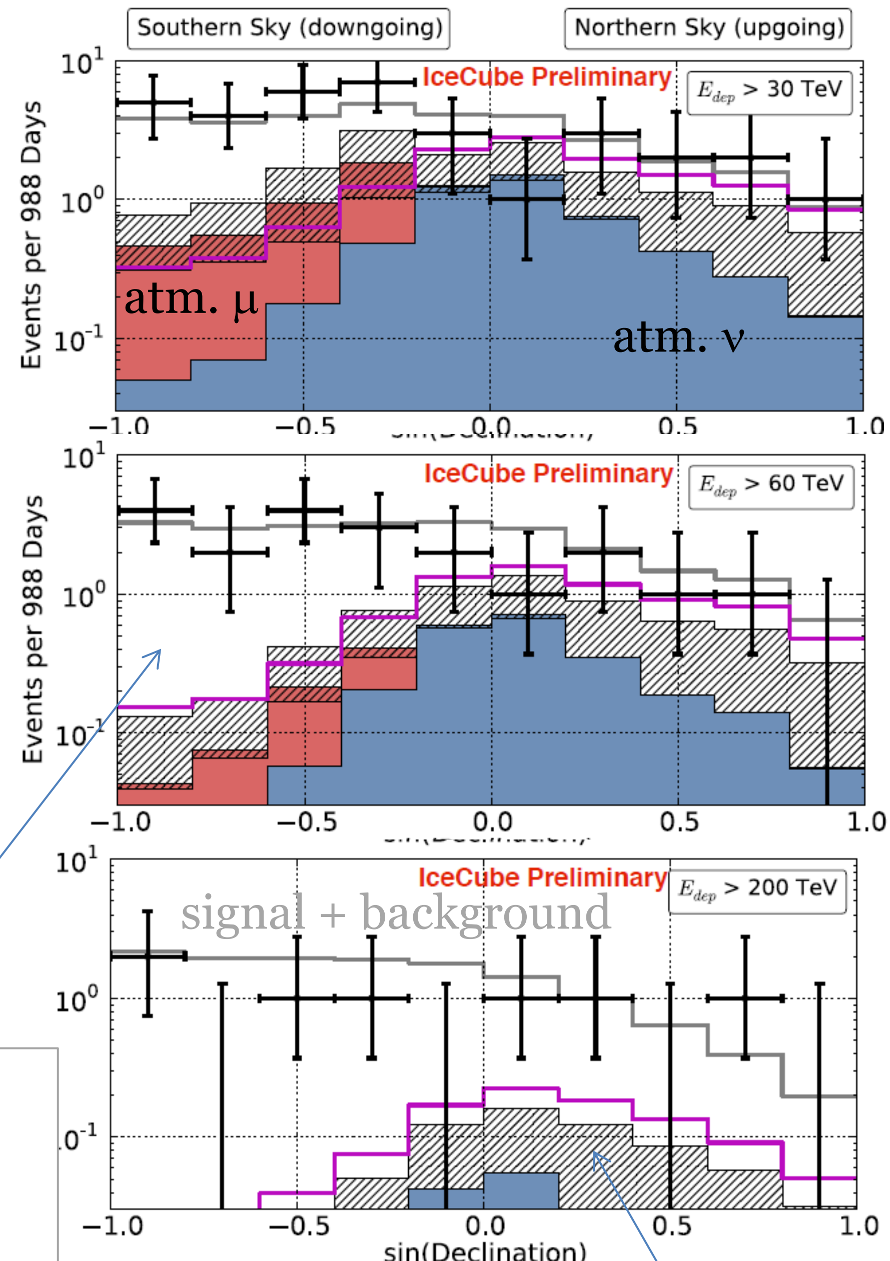
- atmospheric background $13.0^{+7.2}_{-4.5}$
- **Inconsistent with background only model** at 4.1σ with 28 events (science 2013) and 5.7σ with additional 7 events (preliminary)
- Event features (reconstructed energy, zenith angle and topology) **consistent with background + astrophysical ($\phi_{astro} \propto E^{-2}$) fluxes**

- **Best fit flux** $E^2\phi = (0.95 \pm 0.3) \times 10^{-8}$ [GeV cm^{-2} s^{-1} sr^{-1}] with a hard cut off around 2.0 PeV or a softer spectra with a spectral index $\gamma = 2.3 \pm 0.3$

Zenith angle distributions

- Low energy atmospheric muons in downward-going geometry
- Atmospheric neutrinos in horizontal to upward-going region
- High energy astrophysical component dominant in the downward-going region

Veto method suppress a large fraction of southern atmospheric neutrino background but not the astrophysical neutrinos



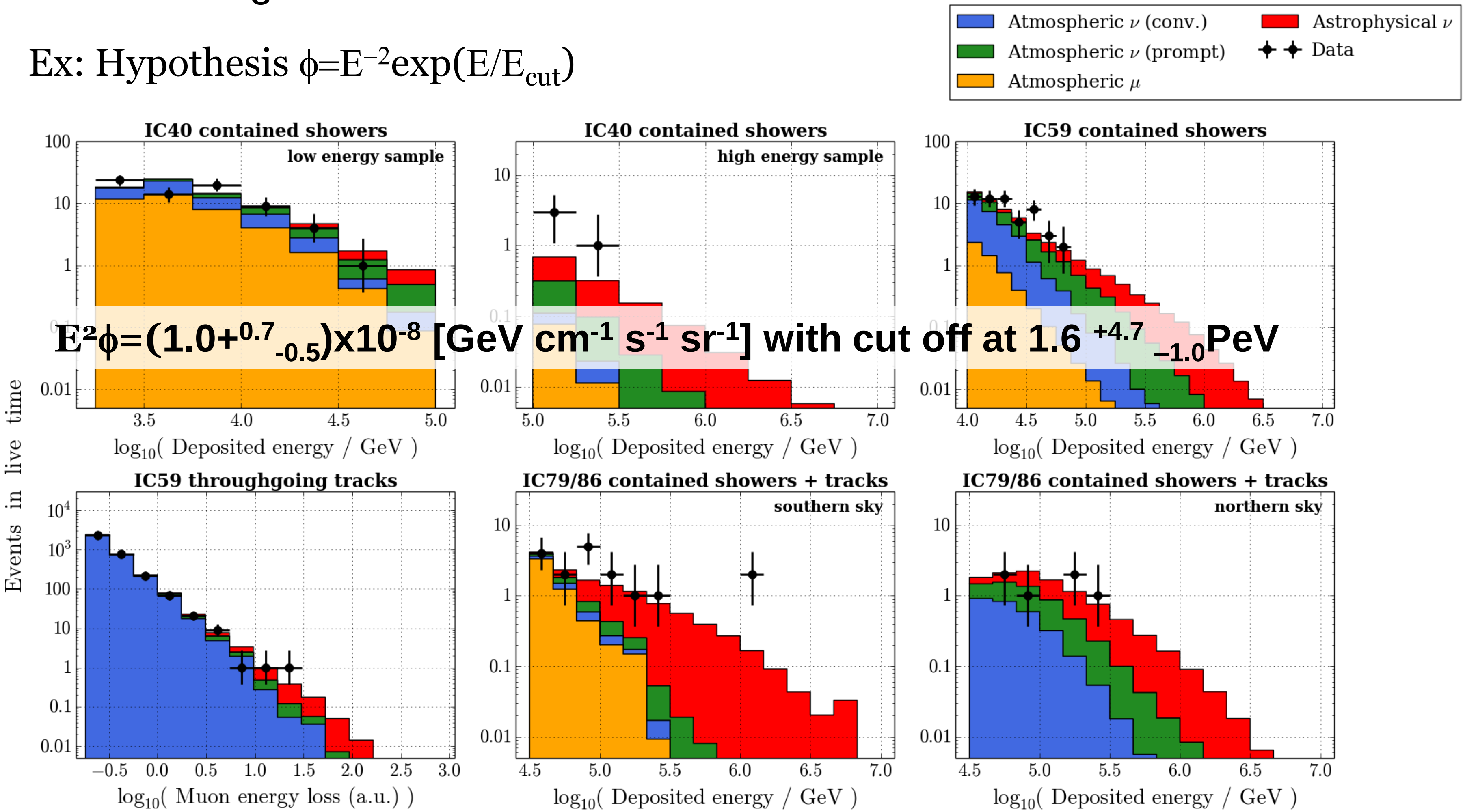
background systemic uncertainty

Global fit with multiple channel samples from multiple years

Global fit on the multiple channels and samples from different year - IC40 cascade, IC59 cascade, IC59 upgoing muon, and the IC79 and IC86 starting events included

IceCube Preliminary

Ex: Hypothesis $\phi = E^{-2}\exp(E/E_{cut})$



$E^2\phi = (1.0{+}^{0.7}_{-0.5}) \times 10^{-8}$ [GeV cm^{-1} s^{-1} sr^{-1}] with cut off at 1.6 $^{+4.7}_{-1.0}$ PeV

Summary from diffuse neutrino searches

- IceCube has been fully operational since 2011, accumulated 2-full year samples + 4 years of partial operation data (22, 40, 59, and 79 strings)

- Observed extraterrestrial diffuse neutrinos from different analysis methods as an excess from background only hypothesis – more than 5sigma level achieved with the starting event search with muon veto technique

- Best fit results to E^{-2} power-law type of astrophysical neutrino fluxes indicates the diffuse neutrino fluxes of the level of 10^{-8} [GeV cm^{-1} s^{-1} sr^{-1}] with a cut off around 2 PeV or softer spectra without cut off

- Access to further properties of the astrophysical neutrino flux requires more statistics as well as consistent picture from different search channels

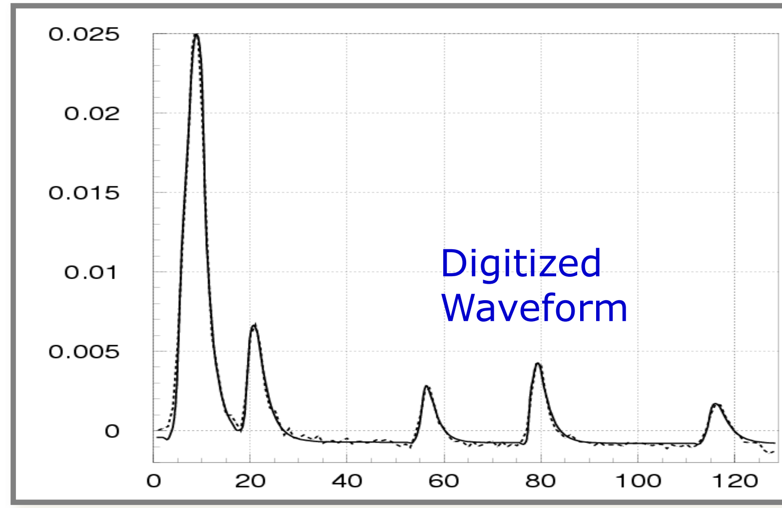
- The tightest upperlimit on the cosmogenic (GZK) neutrino fluxes starts to constrain on the highest energy cosmic-ray origin

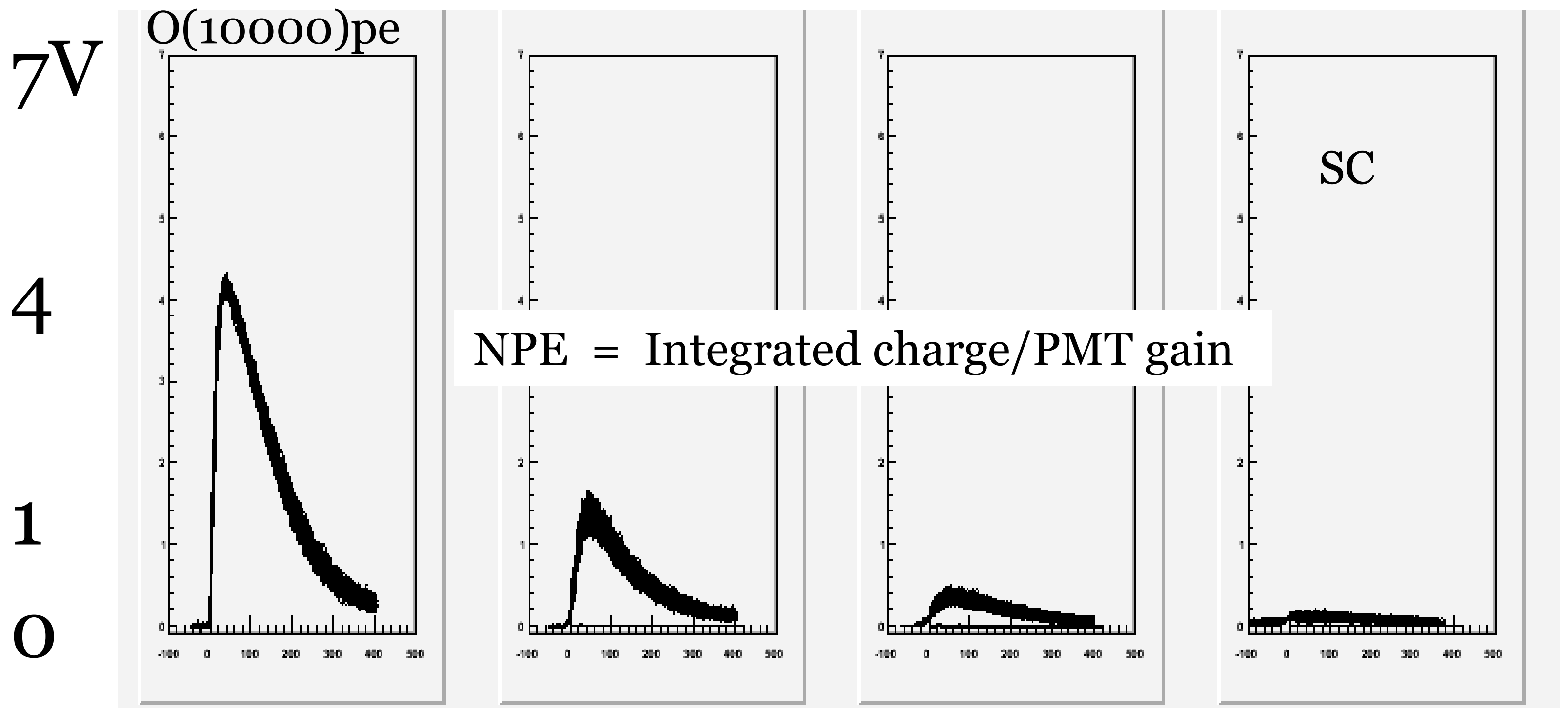
- strongly evolving sources such as FRII type distribution disfavored IceCube's cosmogenic neutrino study. Newly obtained samples will tell about more closer sources such as GRB or star forming region

Waveform examples from spe to 10,000 pe

25 cm PMT

single pe level

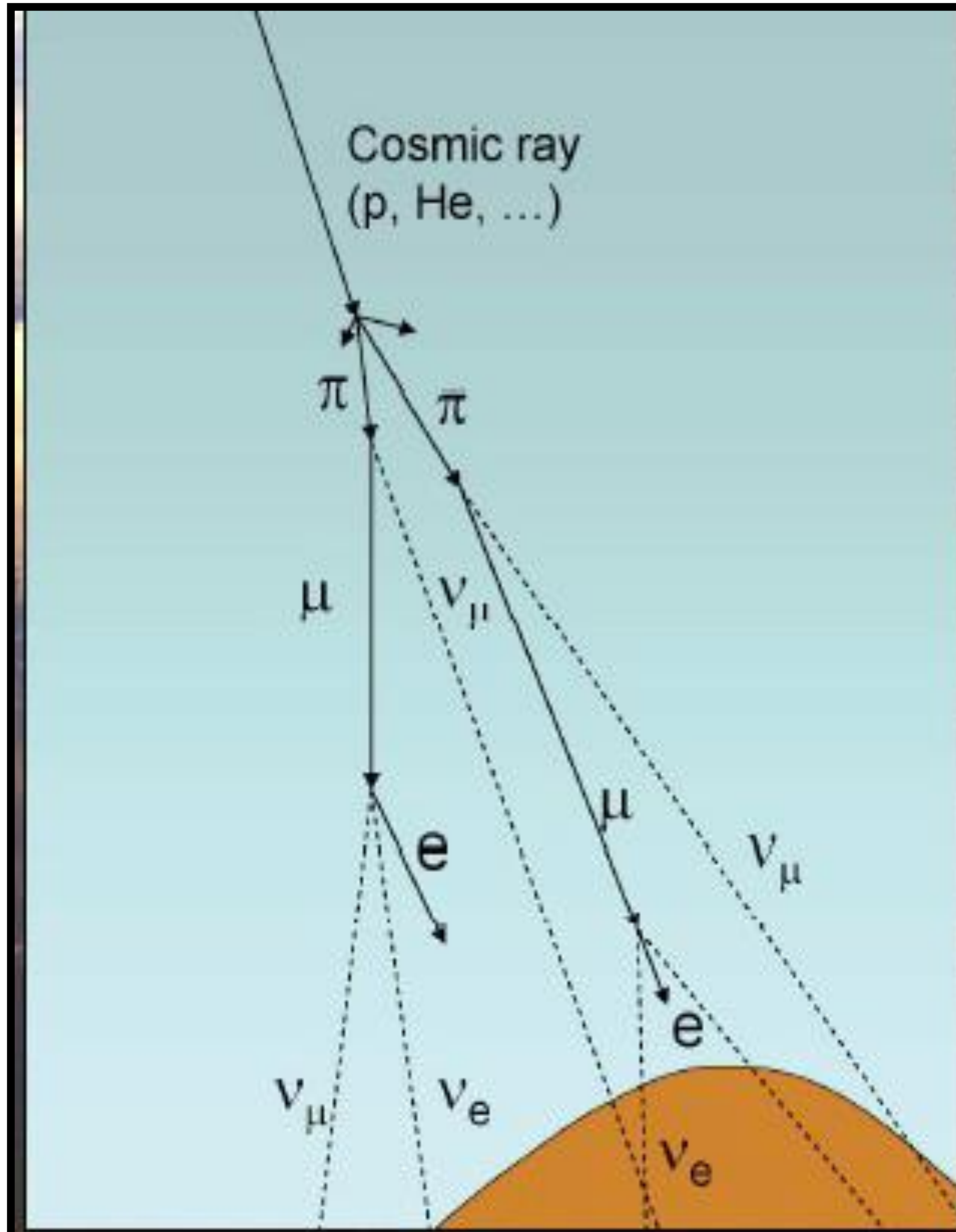


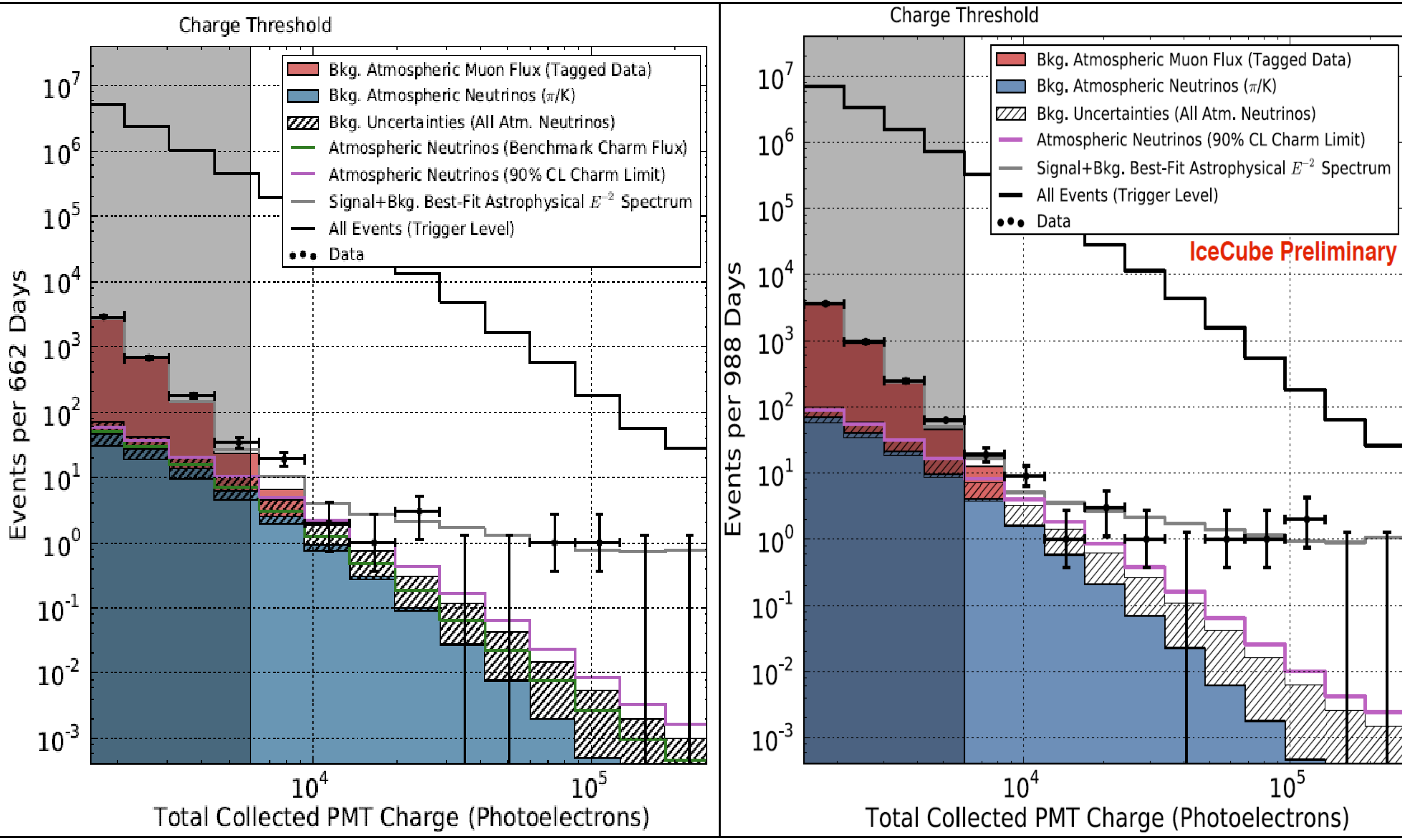


NPE = Integrated charge/PMT gain

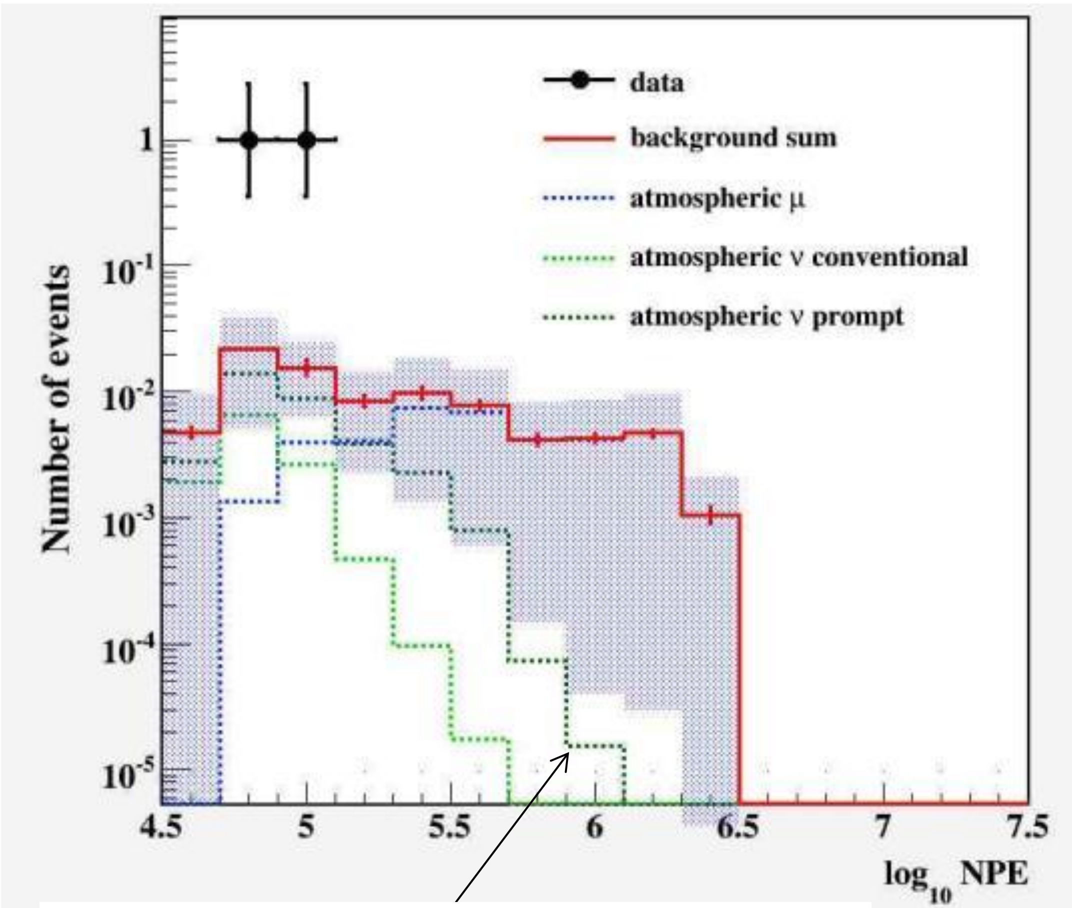
Background

Atmospheric muons
(downward going,
more energetic and
dominant in number)
and
Atmospheric
neutrinos
(full angle, less
energetic, smaller in
rate)




Charge Threshold
Bkg. Atmospheric Muon Flux (Tagged Data)
Bkg. Atmospheric Neutrinos (π/K)
Bkg. Uncertainties (All Atm. Neutrinos)
Atmospheric Neutrinos (Benchmark Charm Flux)
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
All Events (Trigger Level)
Data
Events per 662 Days
Total Collected PMT Charge (Photoelectrons)
Charge Threshold
Bkg. Atmospheric Muon Flux (Tagged Data)
Bkg. Atmospheric Neutrinos (π/K)
Bkg. Uncertainties (All Atm. Neutrinos)
Atmospheric Neutrinos (90% CL Charm Limit)
Signal+Bkg. Best-Fit Astrophysical E^{-2} Spectrum
All Events (Trigger Level)
Data
IceCube Preliminary
Events per 988 Days
Total Collected PMT Charge (Photoelectrons)

Background Errors



The largest uncertainty is on the prompt (charm) ν model (a factor of 2 in pQCD model, up to a factor of 5 from nonpQCD)

Sources	conventional Atm. μ, ν(%)	prompt (%)
Statistical error	±7.3	±1.1
DOM efficiency	+63.7, −30.8	+21.3, −18.9
Ice property and detector responses	−48.0	−29.8
Cosmic-ray flux variation	+24.0, −39.0	±30.0
Cosmic-ray composition	−61.0	
Hadronic interaction	+13.5	
nu yield from cosmic-ray nucleon	± 3.5	
Total	±7.3(stat) +69.5−92.5(sys)	±1.1(stat) +36.8−46.4(sys)

Test Including energy PDF of the two events

Use the Kolmogorov-Smirnov statistics

$$\text{p-value} = \int d\log E_{Bert}\, \rho_{Bert}(\log E_{Bert}) \int d\log E_{Ernie}\, \rho_{Erine}(\log E_{Ernie})\, P_{KS}(\log E_{Bert}, \log E_{Ernie})$$

p-values are found to be 4~8x10^{-2} dependent on the models

- >90% CL the two events can not be explained by cosmogenic neutrinos
- Let us leave the question of "then what are they?" to dedicated follow up analyses
- Here, we focus on the fact that **we have not seen the cosmogneic neutrinos flux so far with IceCube**