Probing the origin of UHECRs with neutrinos

The connection of neutrinos to ultra-high energy cosmic rays

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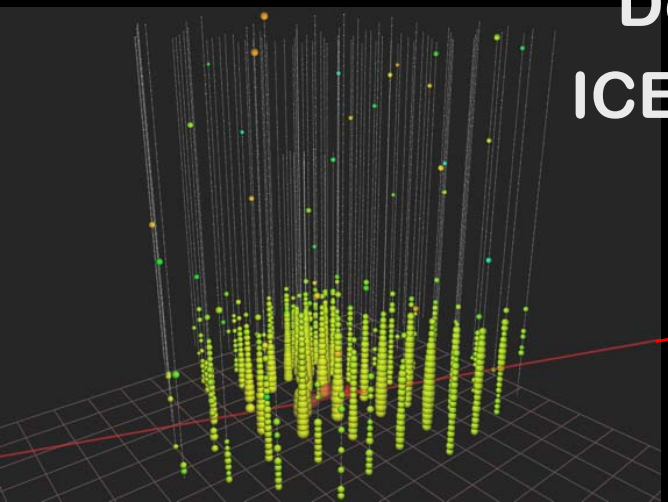
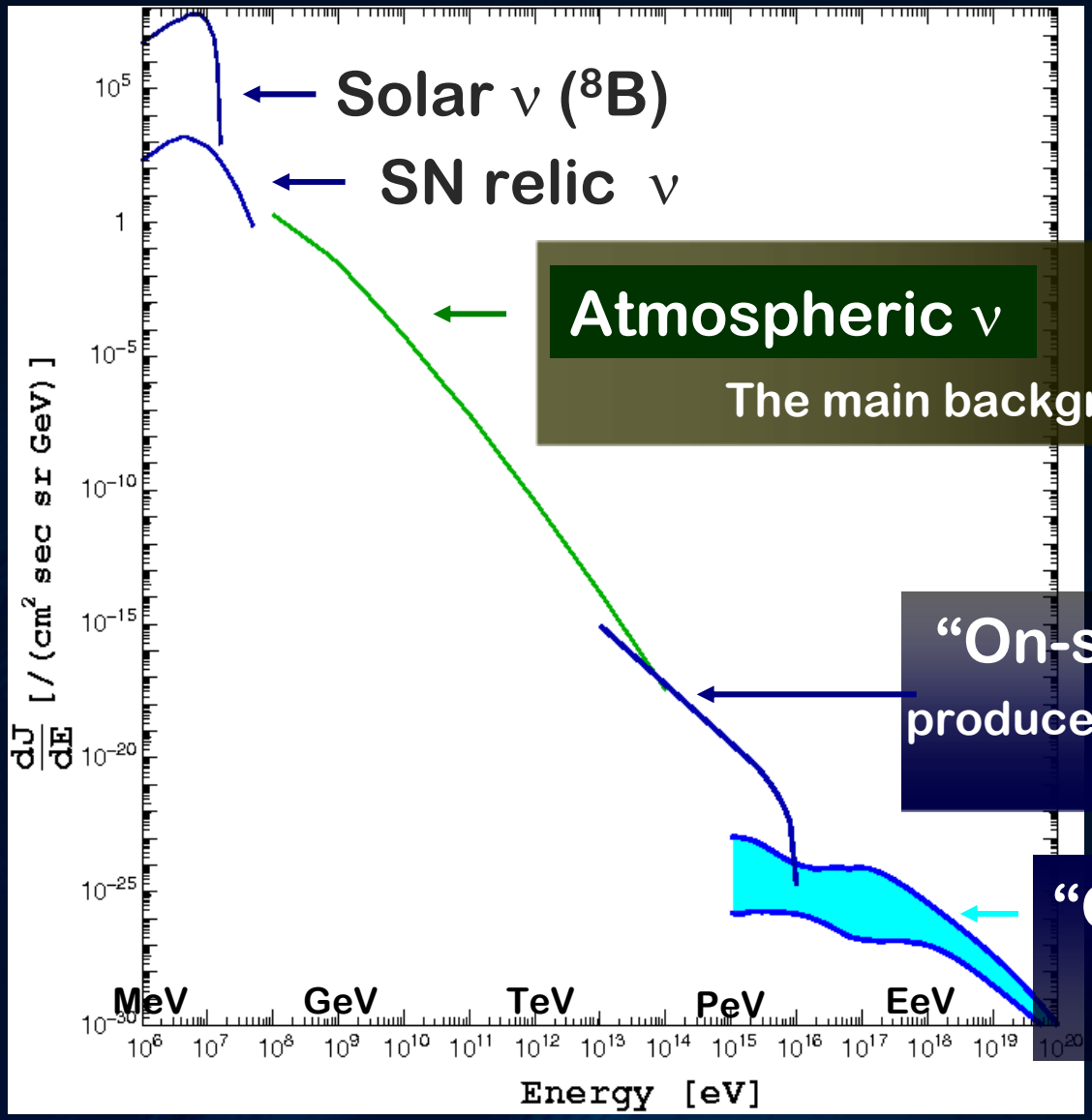
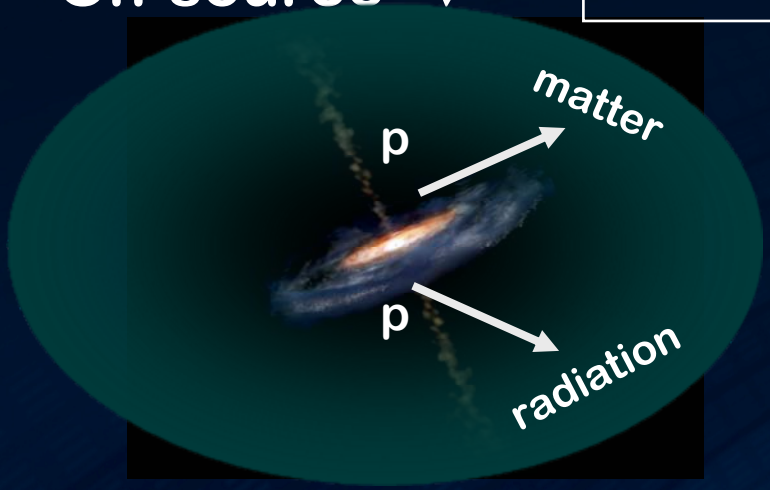


The Neutrino Flux: overview



The Cosmic Neutrinos
Production Mechanisms

"On-source" ν **TeV - PeV**

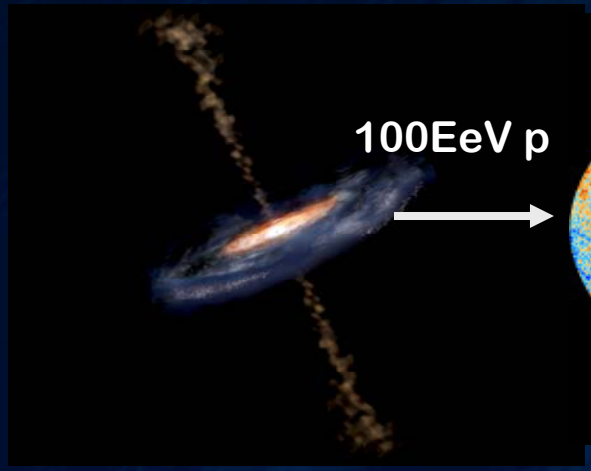


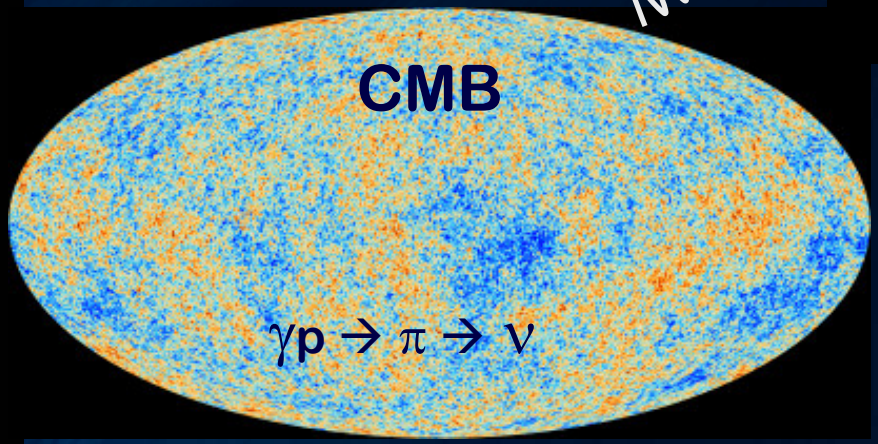
$pp \rightarrow \pi \rightarrow \nu$

$\gamma p \rightarrow \pi \rightarrow \nu$

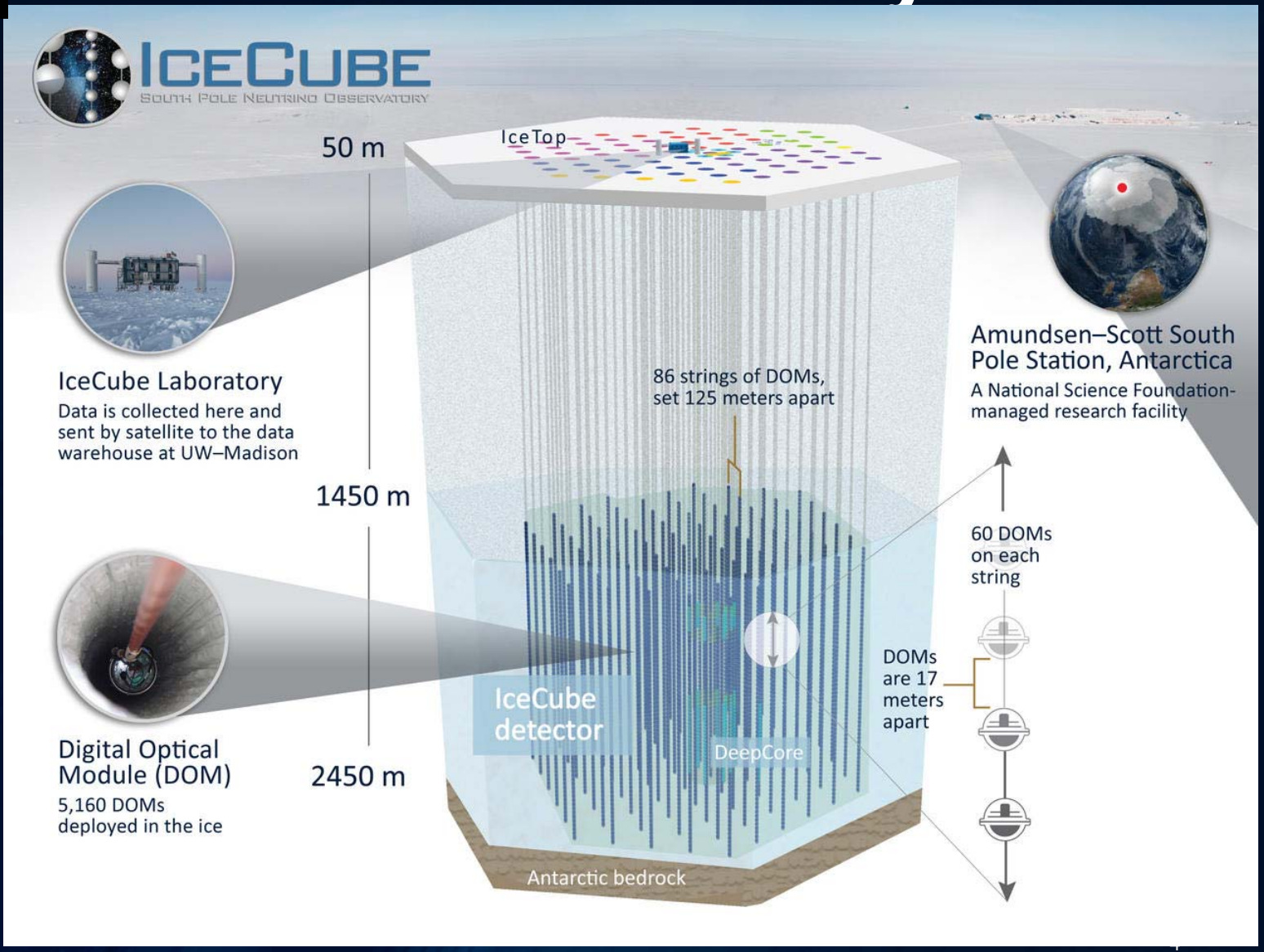
photopion production

"GZK" cosmogenic ν **EeV**





The IceCube Neutrino Observatory




The IceCube Collaboration
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University of Alberta–Edmonton
University of Toronto
USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
Michigan State University
Ohio State University
Pennsylvania State University
South Dakota School of Mines & Technology
Southern University and A&M College
Stony Brook University
University of Alabama
University of Alaska Anchorage
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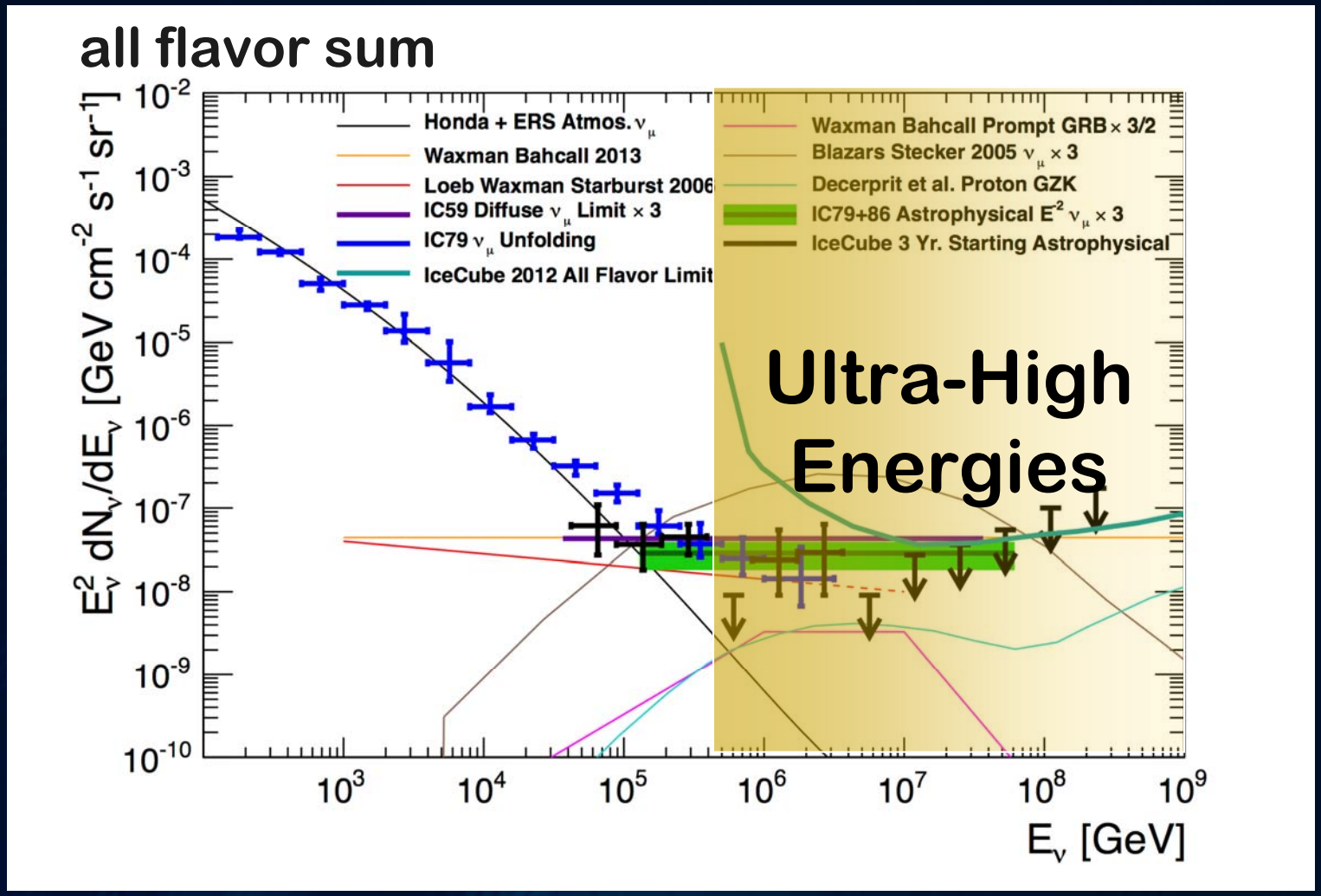
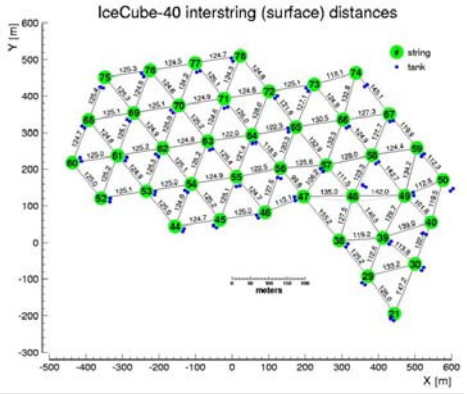
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

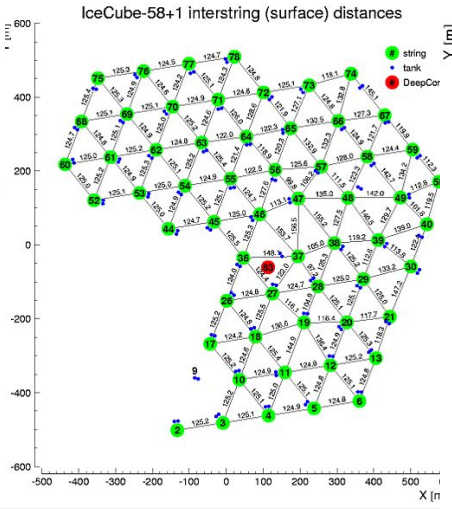
Summary of the IceCube Diffuse Flux measurements

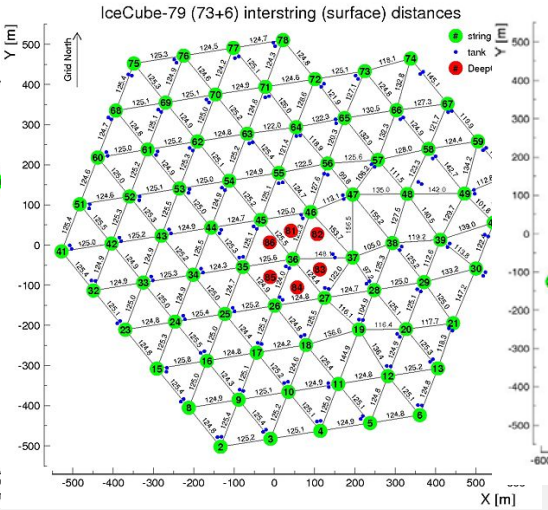


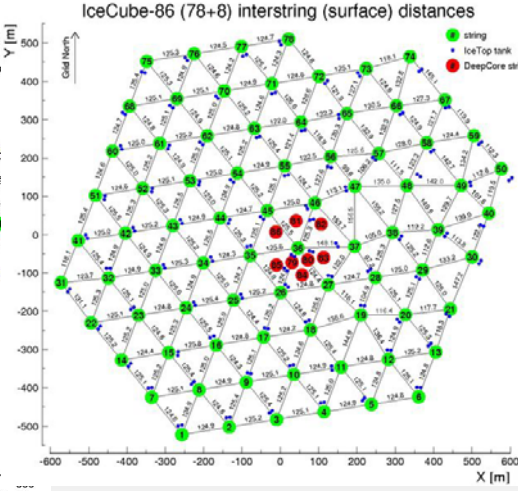
UHE ν search with 6 year long data

"IC40"	"IC59"	"IC79"	"IC86"
2008-2009	2009-2010	2010-2011	2011-2014
354.8 day	342.8 day	312.5 day	1031.8 day



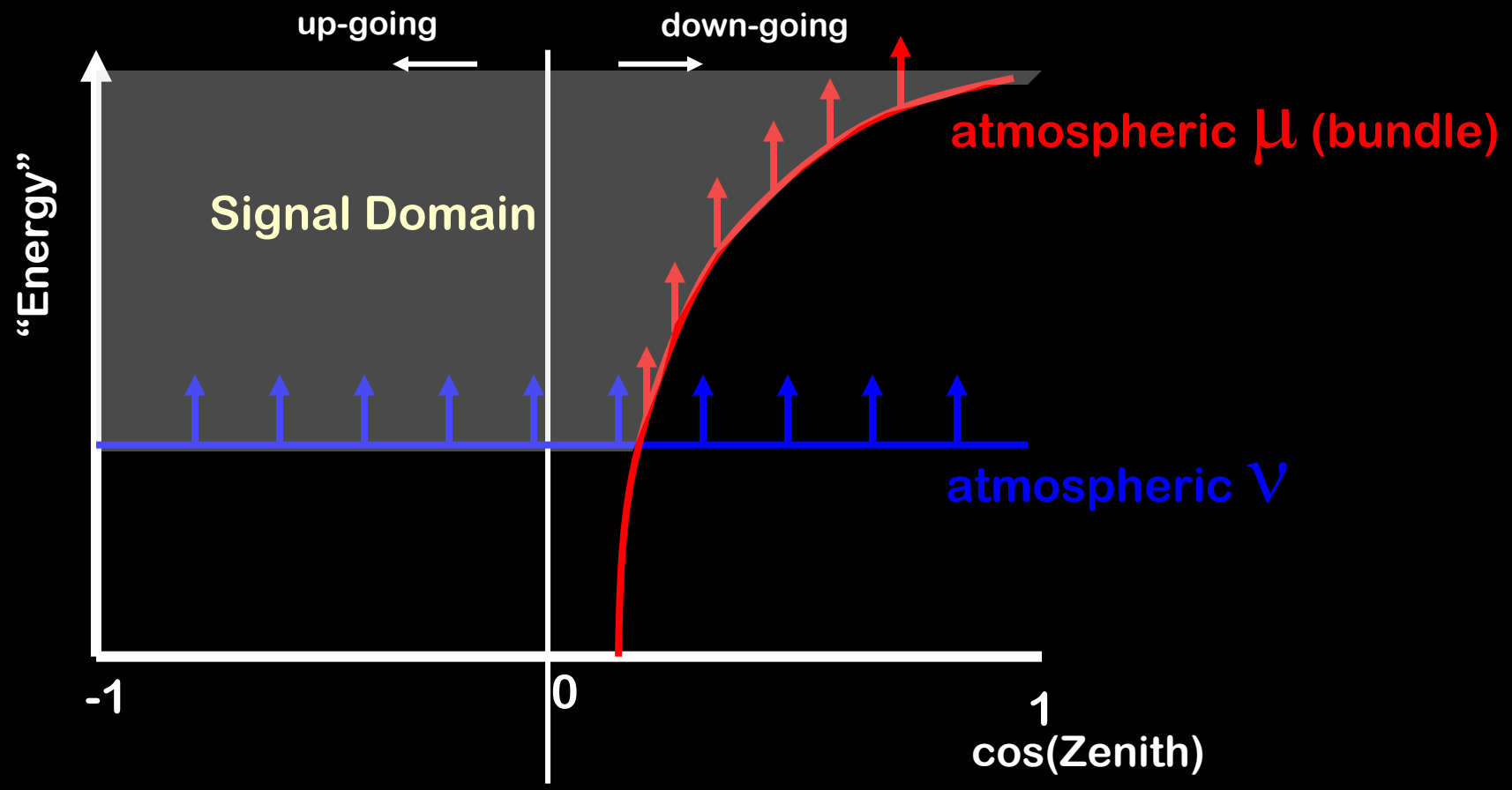






UHE (PeV-EeV)

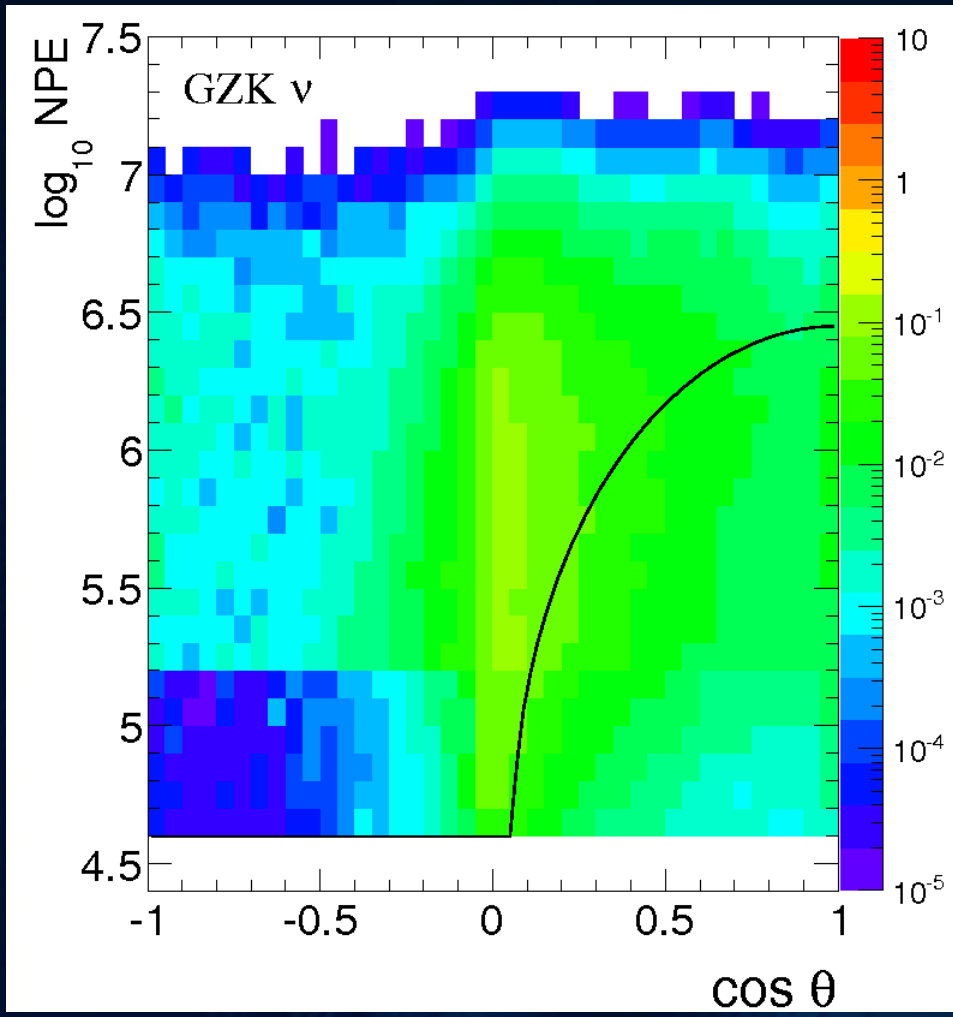
Detection Principle – All flavor sensitive

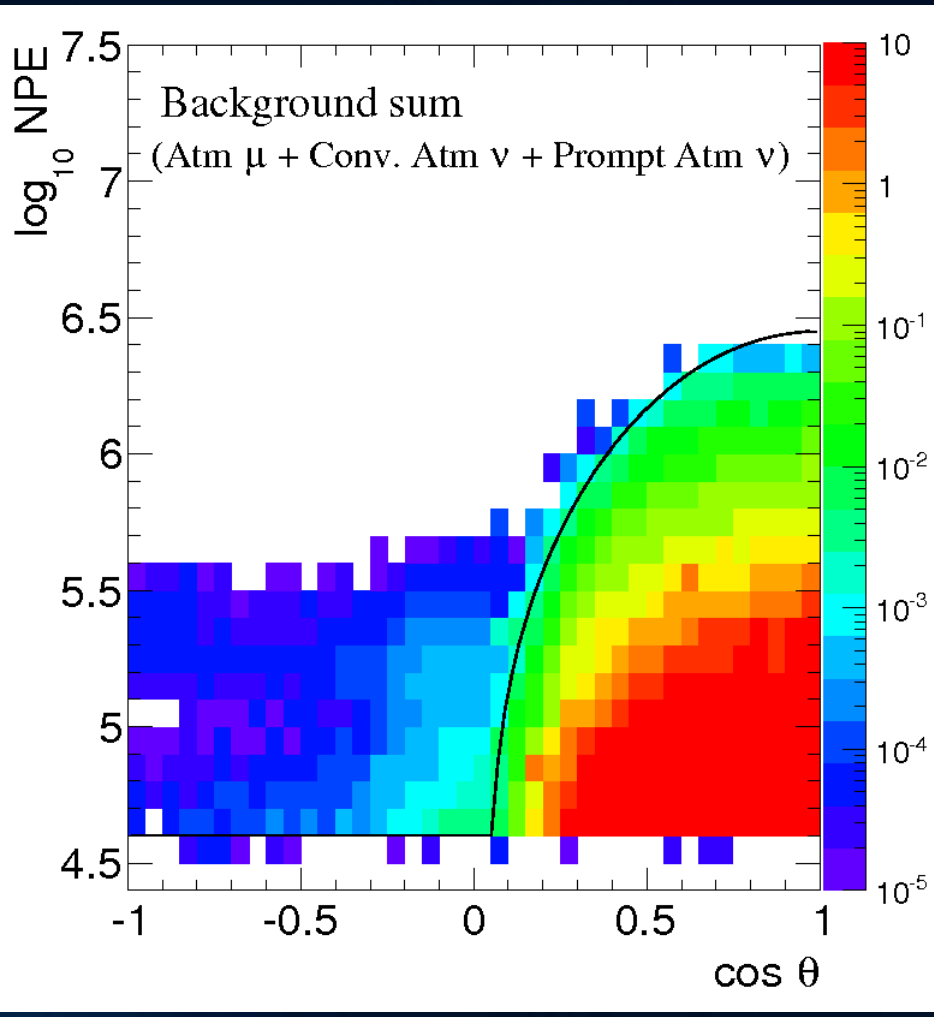


TeV PeV EeV

Event Distribution on

NPE("brightness" ~ "Energy") Vs cos(zenith) plane

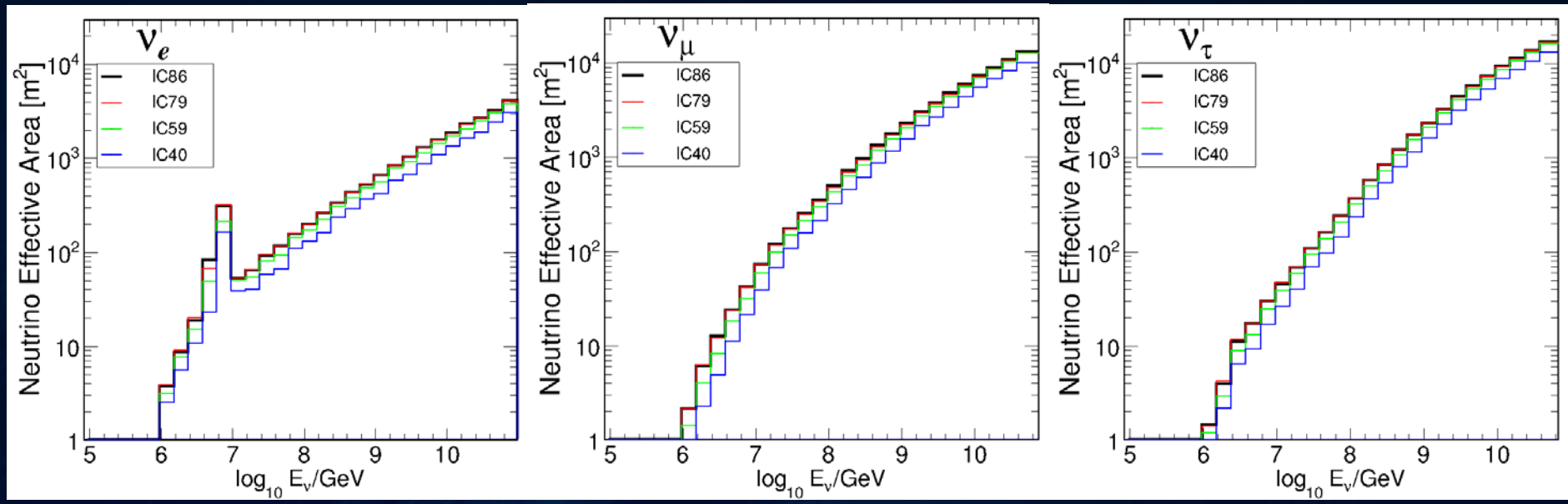




The ν detection effective area

PeV < E < 10 PeV ν_e sensitive

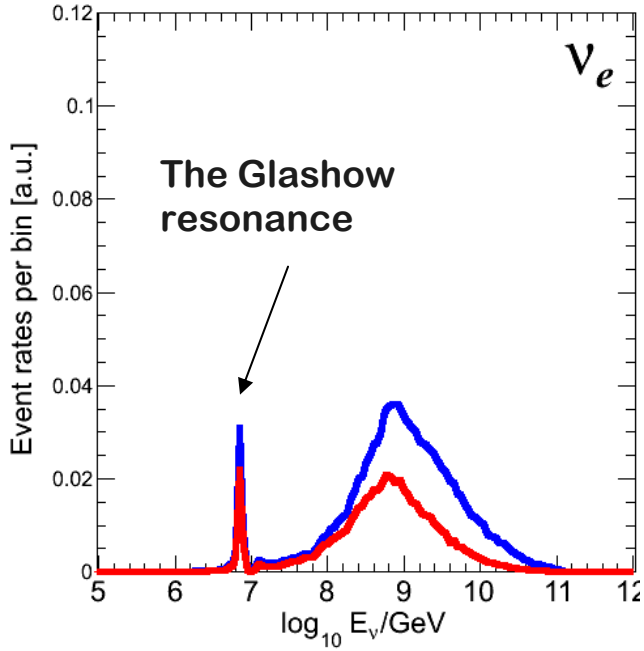
100PeV < E ν_μ ν_τ sensitive

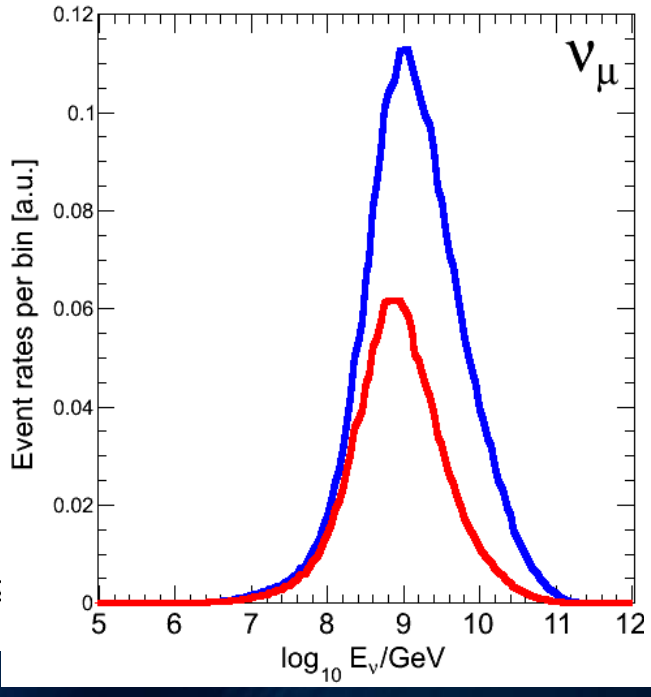


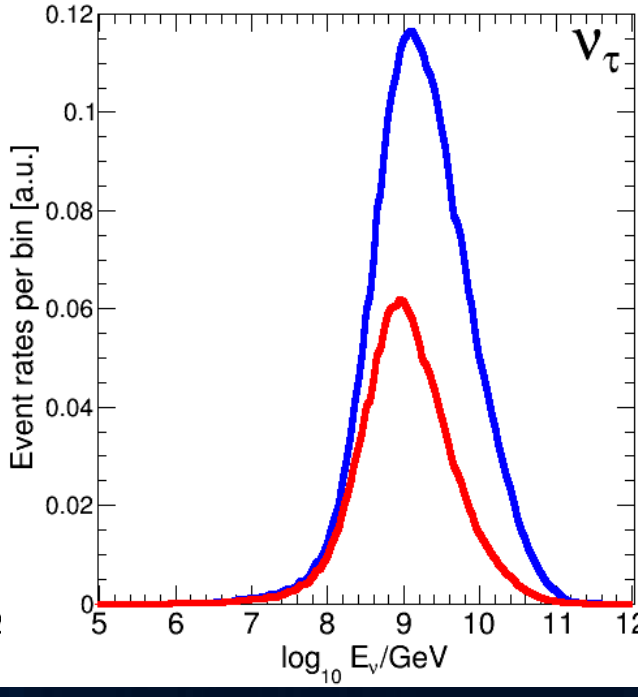
TeV PeV EeV

Expected Signal Event Distribution
with GZK-type of spectra

The main energies : EeV (=1000 PeV)





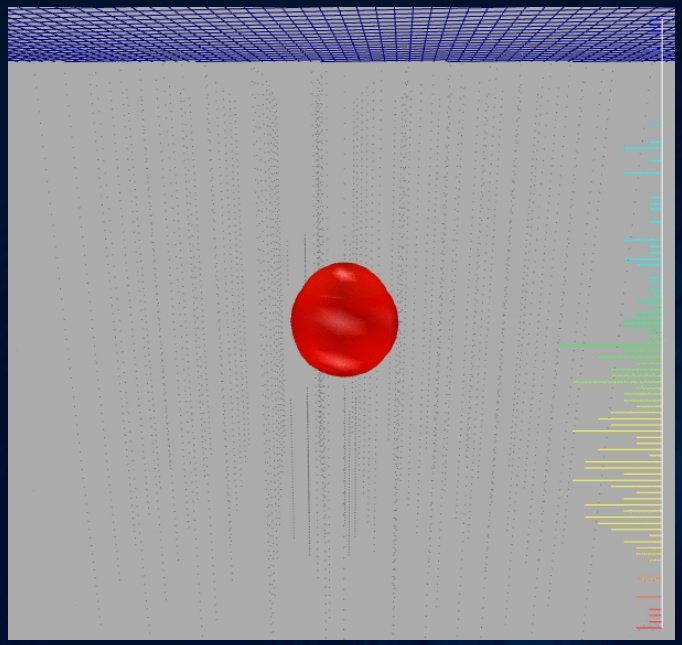


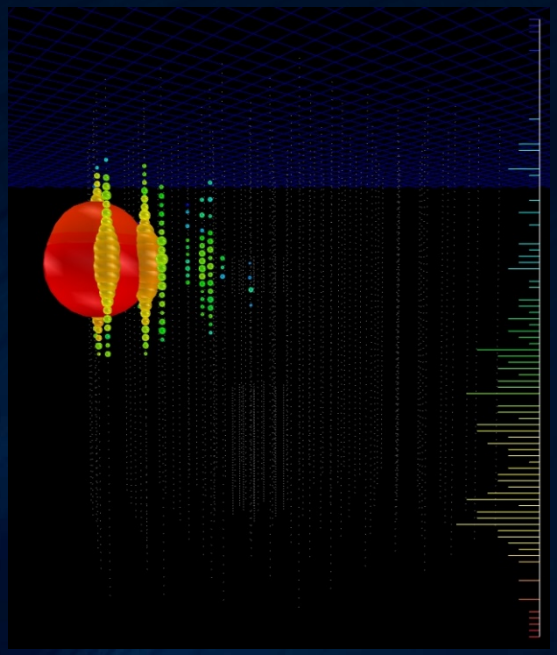
TeV PeV EeV

Open the box : What we found

No EeV events

but a ~ PeV-Energy cascade





Preliminary

Reconstructed Parameters

Diposited Energy

808 TeV

zenith angle

174 deg

~20 deg uncernt.

(Probably) the most energetic upgoing event detected by IceCube

What is this event?

The preliminary analysis tells..

This is not the atmospheric background

The background-only hypothesis rejected by ~2.45 σ

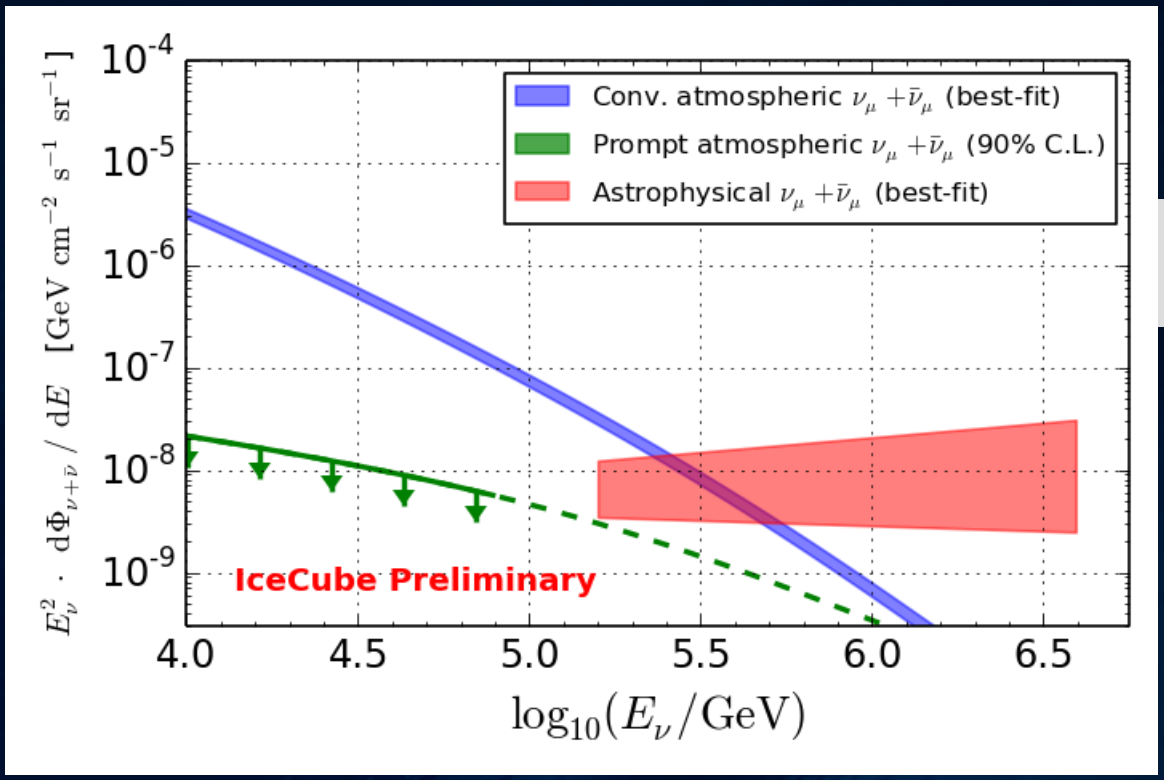
This is not the GZK cosmogenic ν

The GZK hypothesis rejected by ~2.41 σ
favoring ~ E^{-2} type of spectrum

A sort of similar situation when the UHE search found two PeV-Energy events in 2012

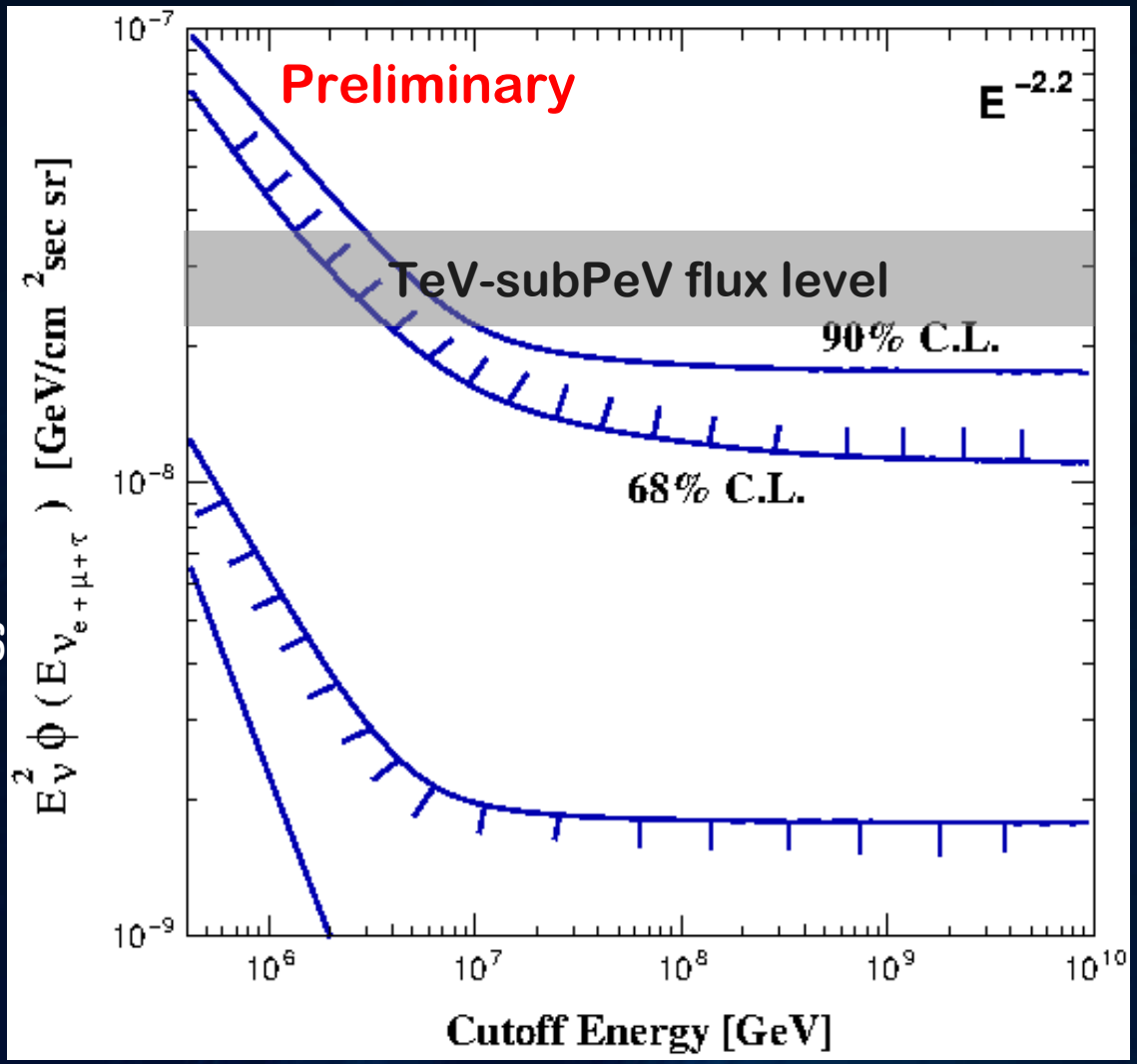
A part of the sub PeV cosmic neutrino bulk?

up-going ν_μ flux detected by IceCube



$$E^2 \phi(E) \approx 8 \times 10^{-9}\ \mathrm{GeV/cm^2 sec\,sr}$$

A part of the sub PeV cosmic neutrino bulk?



consistent
but must have
a cutoff energy

TeV PeV EeV

The Score Board

Preliminary

Many EeV-energy ν models are excluded

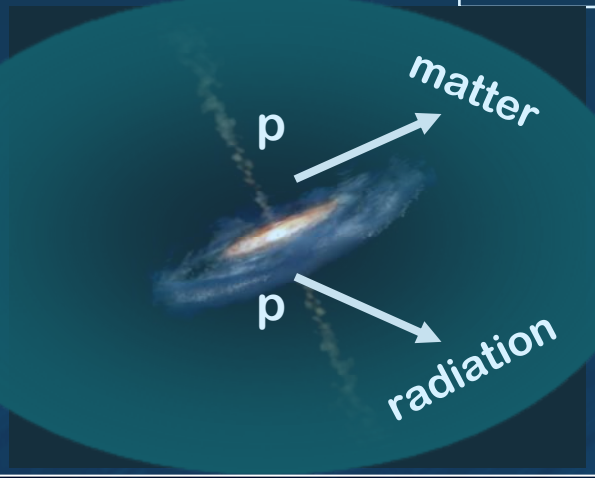
ν Model	GZK Y&T m=4,zmax=4	GZK Ahlers Best Fit 10EeV	GZK Ahlers Best Fit 1EeV	GZK Kotera SFR	GZK Aloisio SFR	AGN Murase γ=2.0 Load.fac 10	Young Pulsar Ke+ Uniform
Expect. # of events	5.8	4.4	2.3	3.0	3.9	12.3	3.6
Model Rejection Factor	0.38	0.51	1.01	1.15	0.81	0.29	0.90
p-value	4.0×10^{-3}	1.4×10^{-2}	1.2×10^{-1}	1.6×10^{-1}	5.1×10^{-2}	$<1.0\times10^{-3}$	7.9×10^{-2}

Excluded

Mildly Excluded

The Cosmic Neutrinos
Production Mechanisms

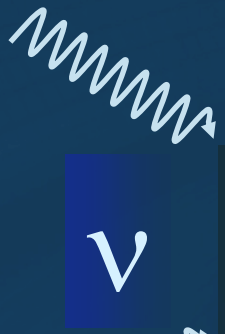
"On-source" ν **TeV - PeV**



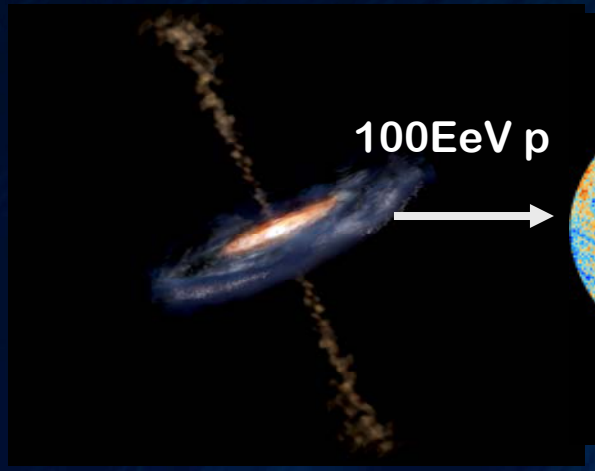
$pp \rightarrow \pi \rightarrow \nu$

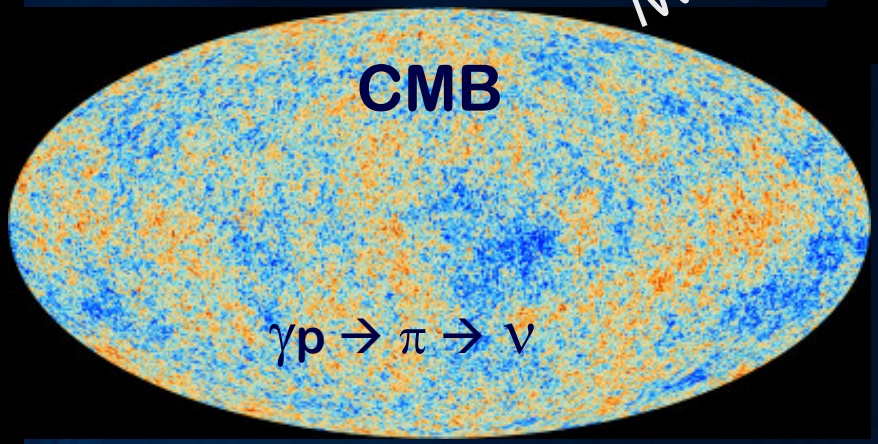
$\gamma p \rightarrow \pi \rightarrow \nu$

photopion production

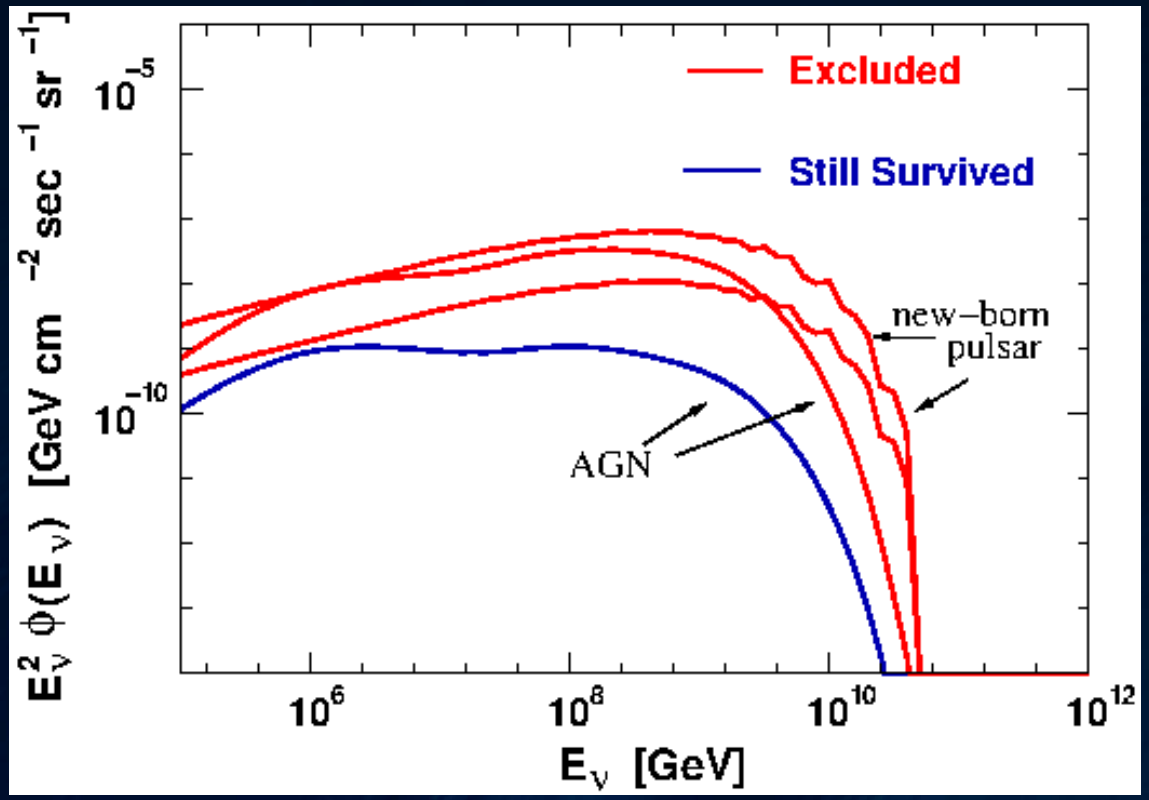


"GZK" cosmogenic ν **EeV**





On-source ν models



ν flux upper limit

AGN can only contribute 0.1-0.5 of the observed UHECR bulk *at most*

Neither AGN or pulsar is the UHECR origin

AGN model: Murase, Inoue, Dermer, PRD 2014

Pulsar model : Ke, Kotera, Olinto, Murase, PRD 2014

The Cosmic Neutrinos
Production Mechanisms

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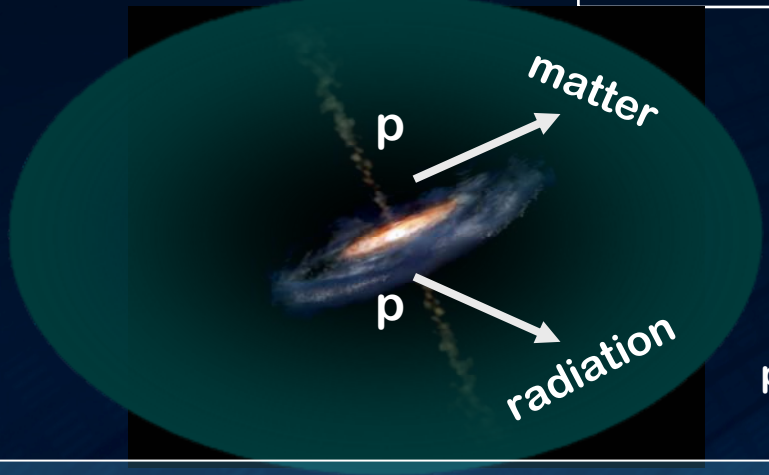

$pp \rightarrow \pi \rightarrow \nu$

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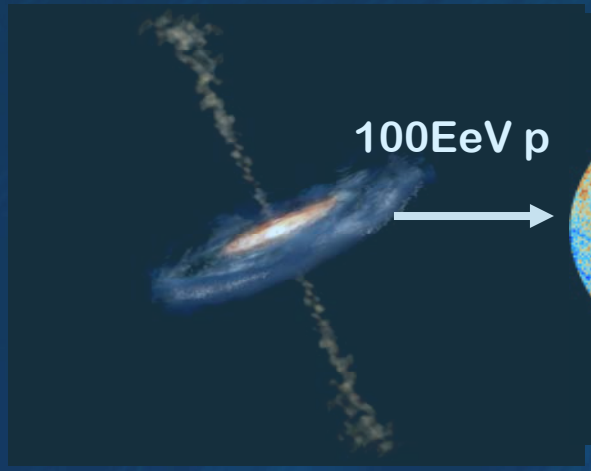
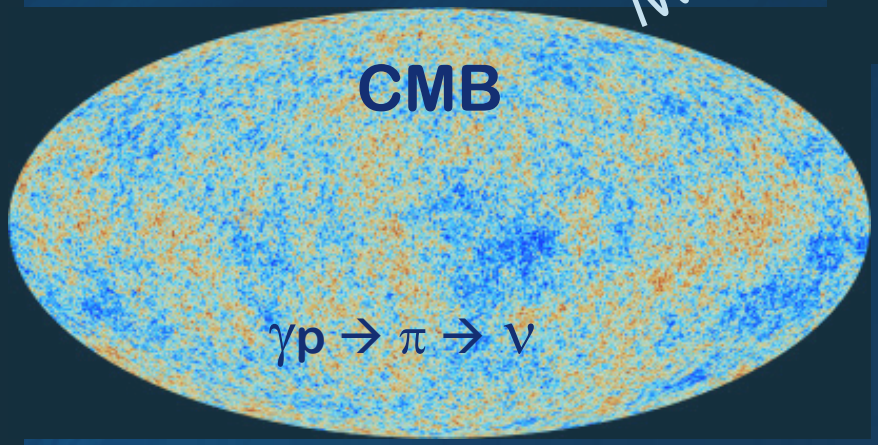
photopion production

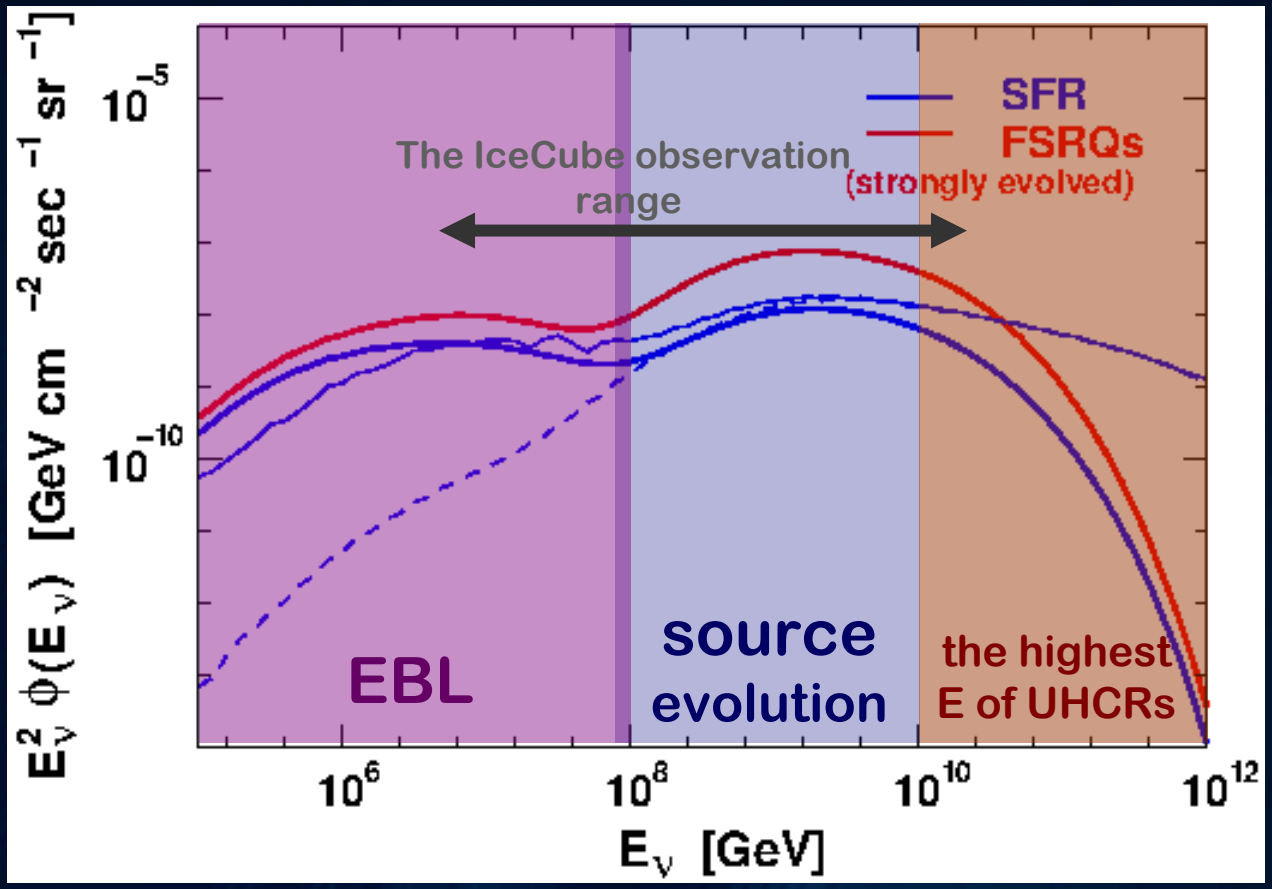
"GZK" cosmogenic ν **EeV**



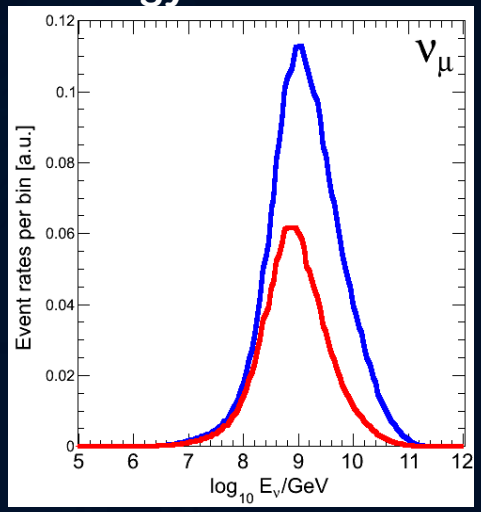


GZK cosmogenic ν models

- Kotera, Allerd, Olinto 2010
- Ahlers et al 2010
- Aloisio et al 2014



IceCube signal event energy distribution

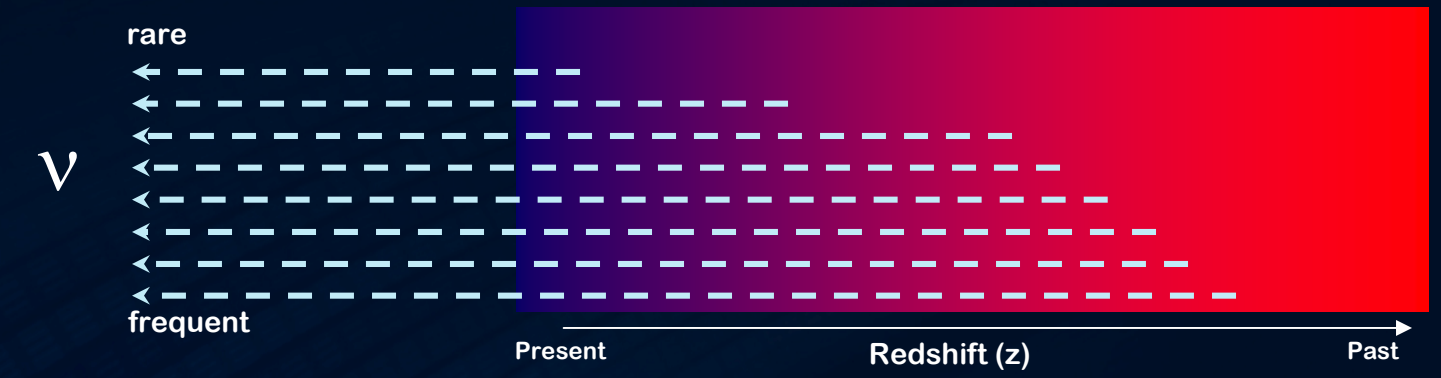


Tracing *history* of the particle emissions with ν flux

color : emission rate of ultra-high energy particles

Intensity gets higher if the emission is more active in the past

because ν beams are penetrating over cosmological distances

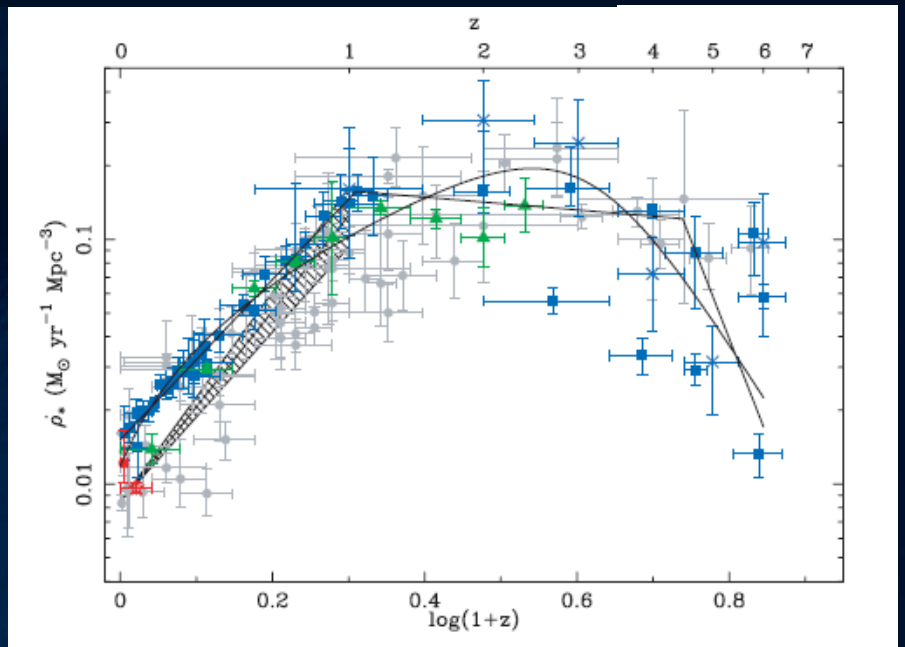


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→



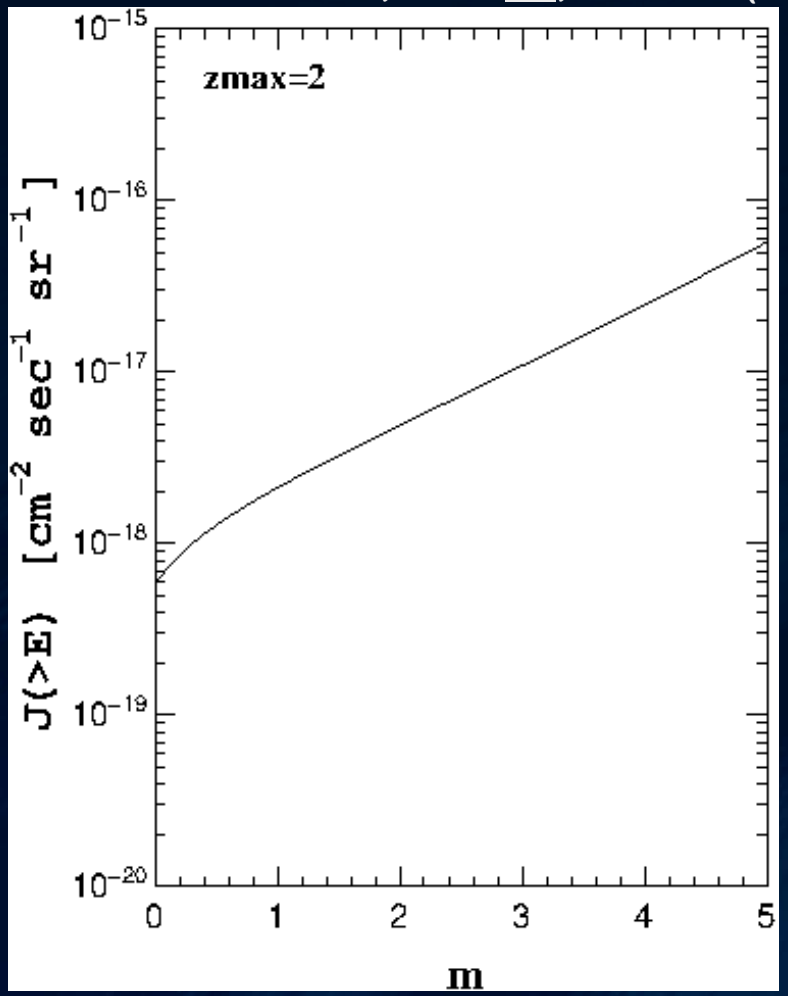
The spectral emission rate

$\rho(z) \sim (1+z)^m$

m= 0 : No evolution

Ultra-high energy ν intensity depends on the emission rate in far-universe

Yoshida and Ishihara, PRD 85, 063002 (2012)



intensity above 1 EeV(=10^{18} eV)

more than an order of magnitude difference

$\rho(z) \sim (1+z)^m$

"quiet" ← → "dynamic"

particle emissions in far-universe

GZK cosmogenic ν intensity @ 1EeV in the phase space of the emission history

Yoshida and Ishihara, PRD 85, 063002 (2012)

$\rho \sim (1+z)^m$
$0<z<z_{max}$

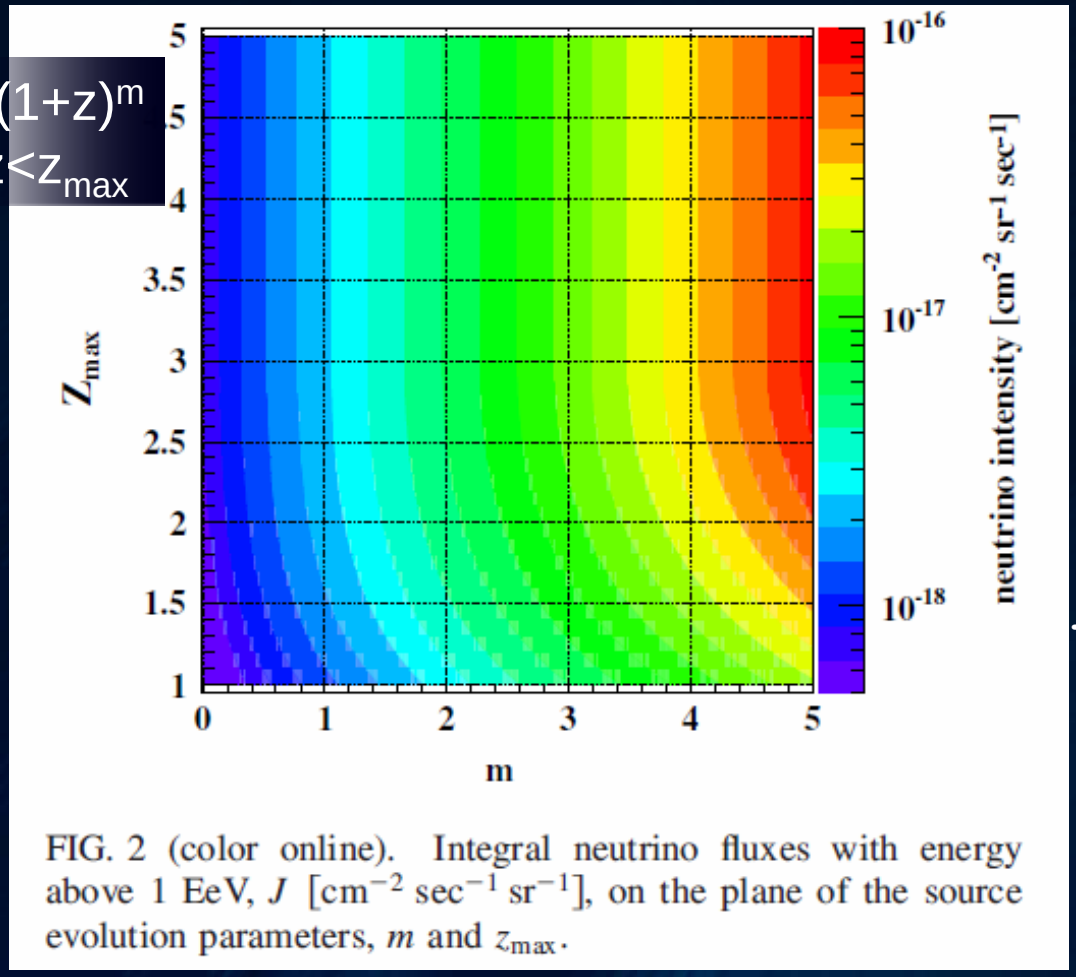


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

↓ x IceCube Exposure

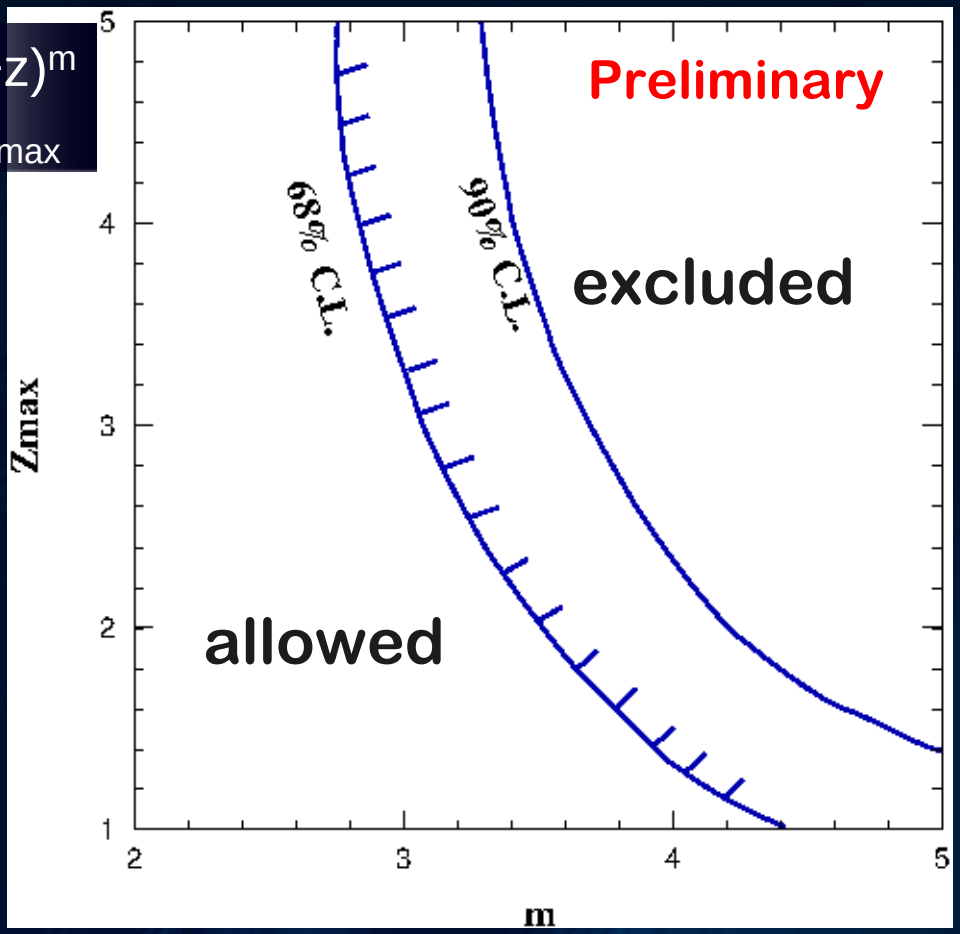
Event distribution on plane of (E, cos(zenith)

↕

The *observed* event distribution

The Constraints on evolution (=emission history) of UHE cosmic ray sources

$\rho \sim (1+z)^m$
$0<z<z_{max}$

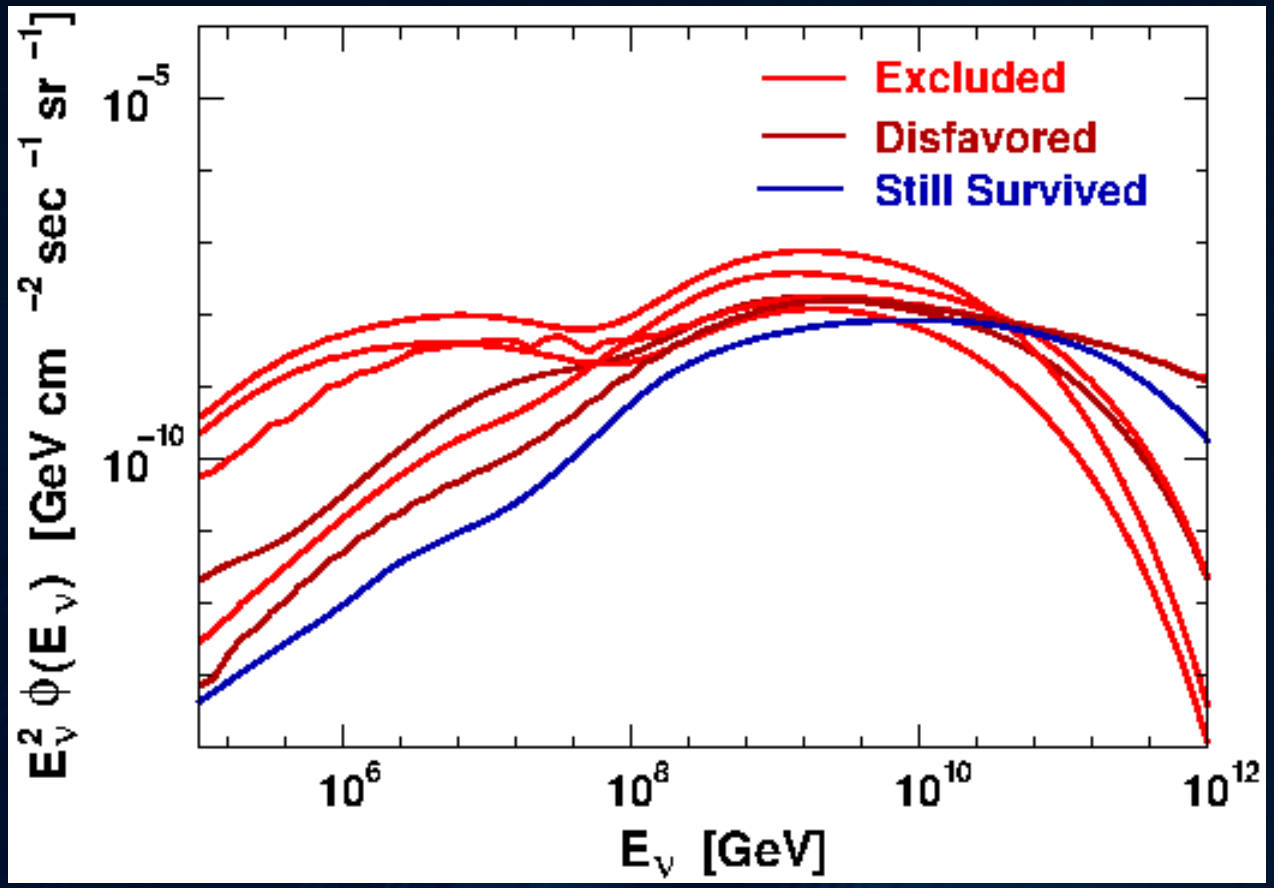


UHECR source is cosmologically LESS evolved

even SFR history is more evolved than UHECR emission

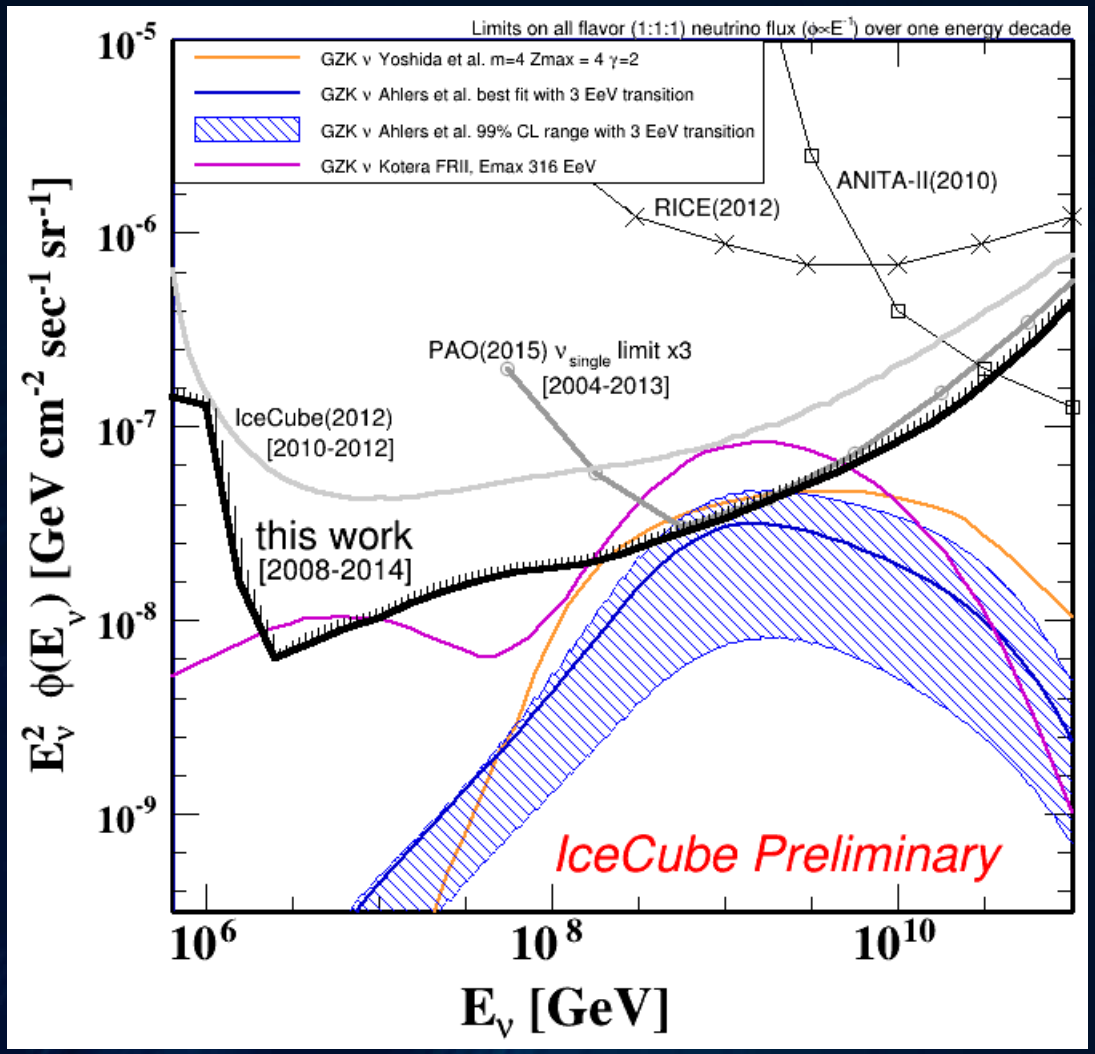
Model dependent constraints

The GZK ν models assuming proton-dominated CRs



only very weak evolution scenario is allowed

The model-independent upper limit on flux



Conclusion

No EeV ν's, only a (sub-)PeV-energy event
seen in IceCube 6 year data

- AGNs are NOT the UHECR origin
- Pulsars are NOT the UHECR origin
- Any sources following SFR or stronger evolution are NOT the UHECR origin (ex GRB) unless EBL is dimmer than we think

Theorists, tell me what!

OR

UHECRs are not proton-dominated

Auger is right

We still have a clue

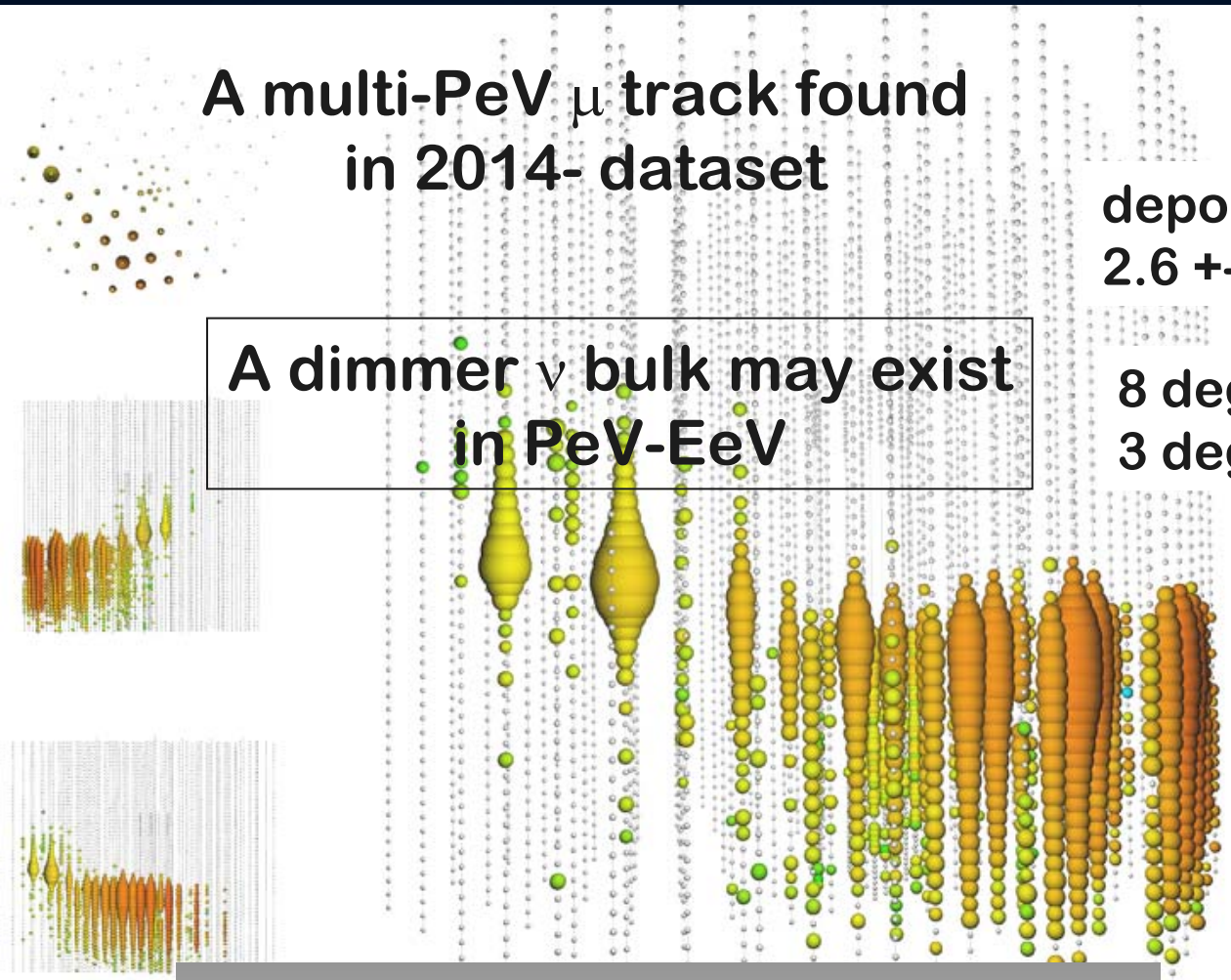
Beyond-PeV ν sky is not completely dark

A multi-PeV μ track found in 2014- dataset

deposited energy
2.6 +- 0.3 PeV

A dimmer ν bulk may exist in PeV-EeV

8 deg off TeVCat
3 deg off 2-3FGL



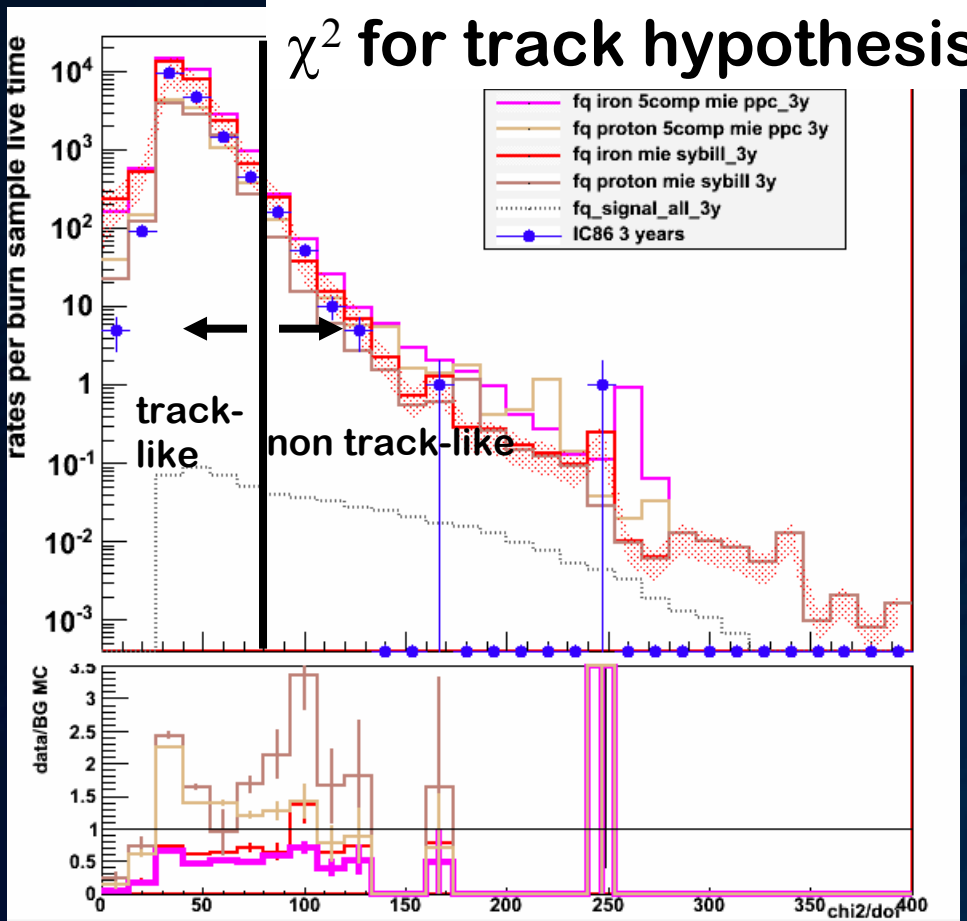
UHE ν analysis with 7 year data including this event is on-going

UHE (PeV-EeV)

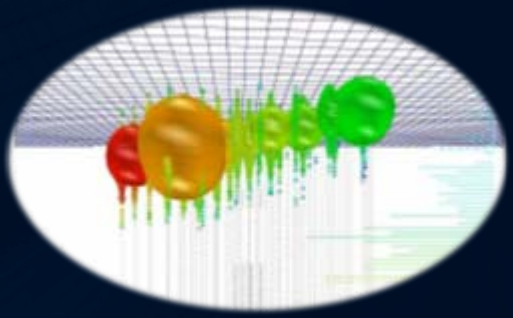
Online Analysis for γ-ray/optical follow-up

new

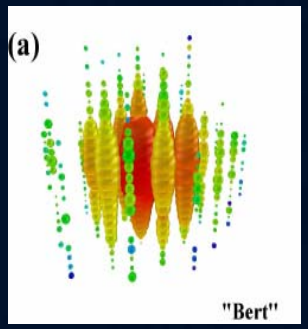
event topology separation



track



cascade (non track-like)

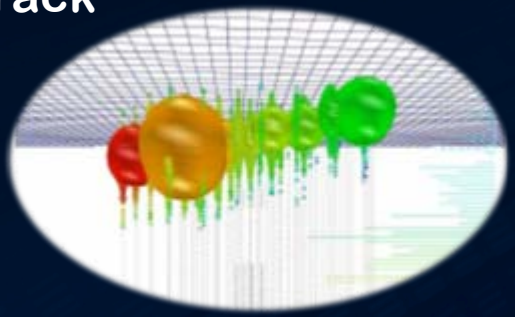


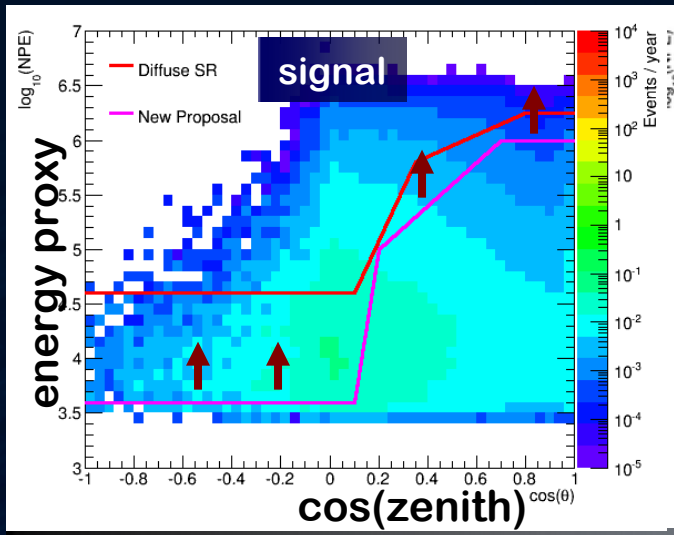
TeV PeV EeV

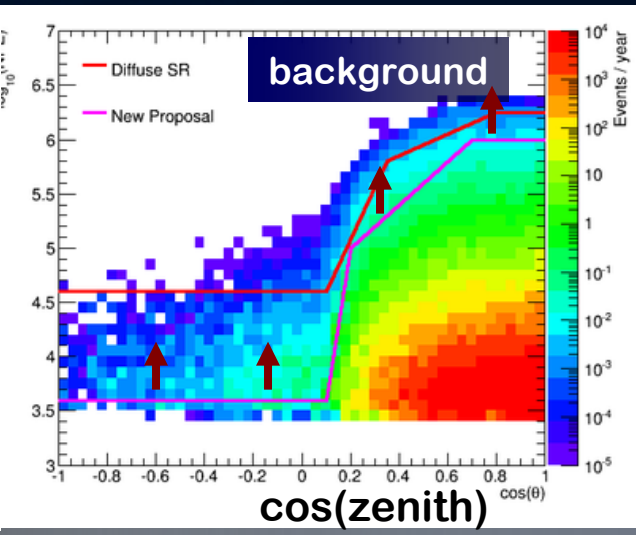
UHE (PeV-EeV)

Online Analysis for γ-ray/optical follow-up

track





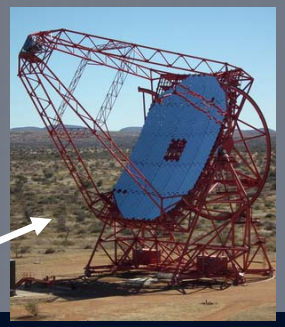


0.7 event/year for $\nu_{e+\mu+\tau}$ of

$E^2\phi = 5\times10^{-9}\,GeVm^{-2}sec^{-1}sr^{-1}$

GZK: ~ 0.3-0.9 event/year

BG: ~ 2.76 event/year



We will send you:

- direction
- Energy (proxy)
- rating of signal-likelihood

$\Delta\theta$~0.25 deg

IceCube Realtime Analysis Chain

muon singlet

good angular resolutions
muon neutrino sensitive
large background chance

veto-based HESE

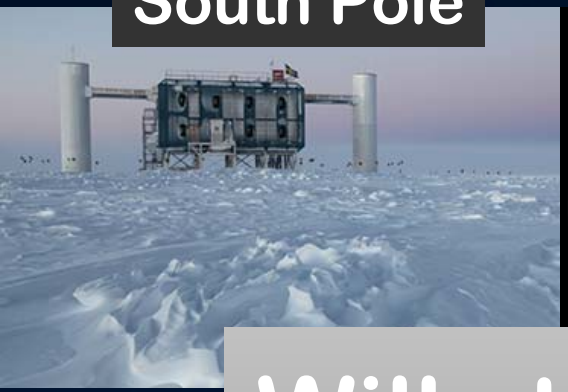
high chance of real cosmic neutrino signals
all neutrino flavor sensitive
angular resolutions mostly poor

Ultra-High Energies

high chance of real cosmic neutrino signals
all neutrino flavor sensitive
good angular resolutions
signal flux highly uncertain

IceCube Realtime Analysis Chain

South Pole



O(hrs)

Quick results

Will start sending ν alerts to the MoU-singed observatory this year!

Northe

WIPAC
Wisconsin IceCube Particle Astrophysics Center

O(1-2days)

refined results
from iterated reconstructions