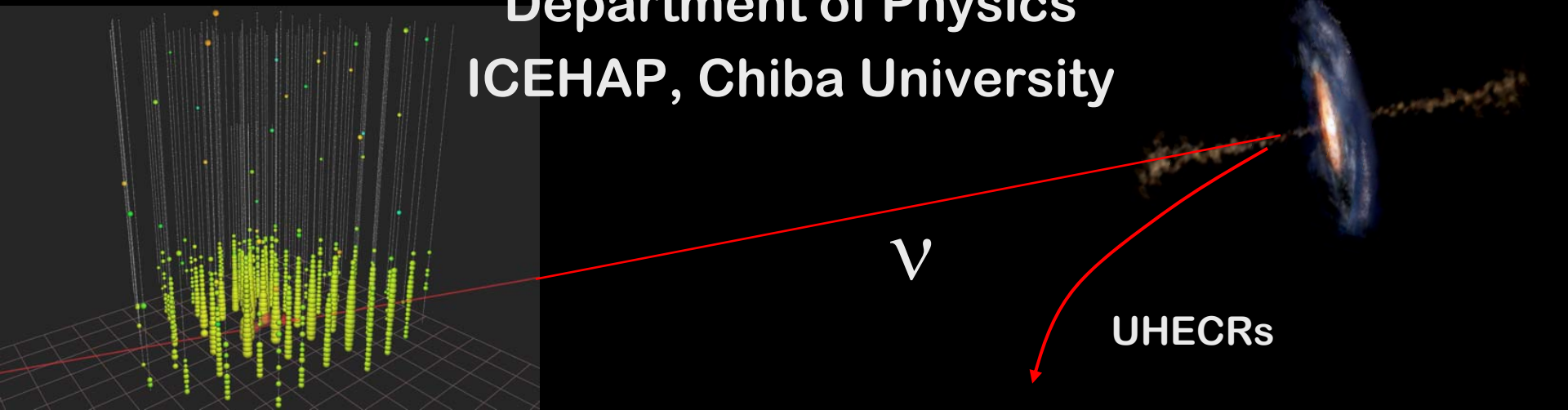
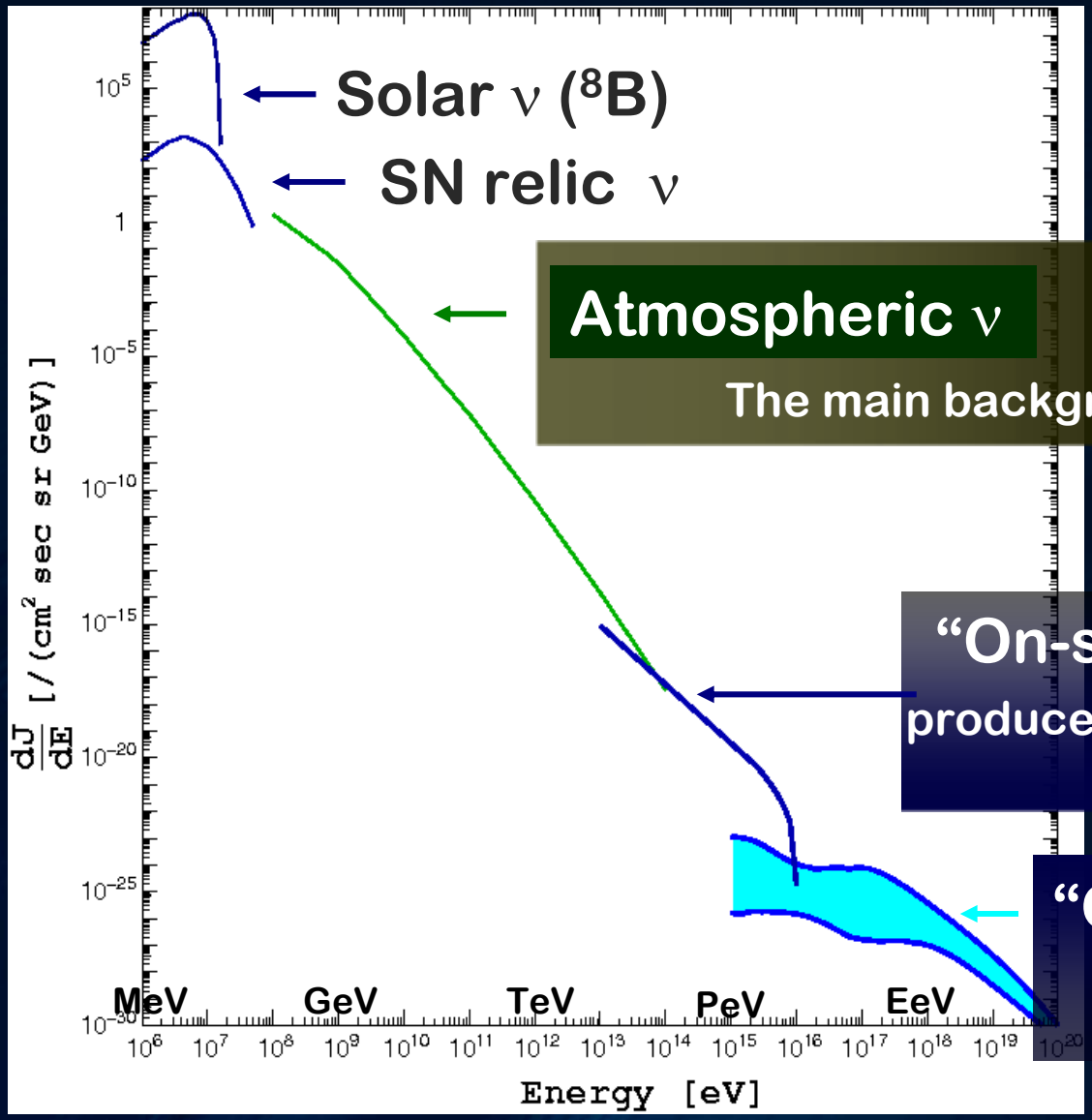
Exploring the origin of UHECRs with very-high energy neutrinos

The IceCube 7 year-long UHE ν searches and the connection of neutrinos to ultra-high energy cosmic rays

Shigeru Yoshida
Department of Physics
ICEHAP, Chiba University

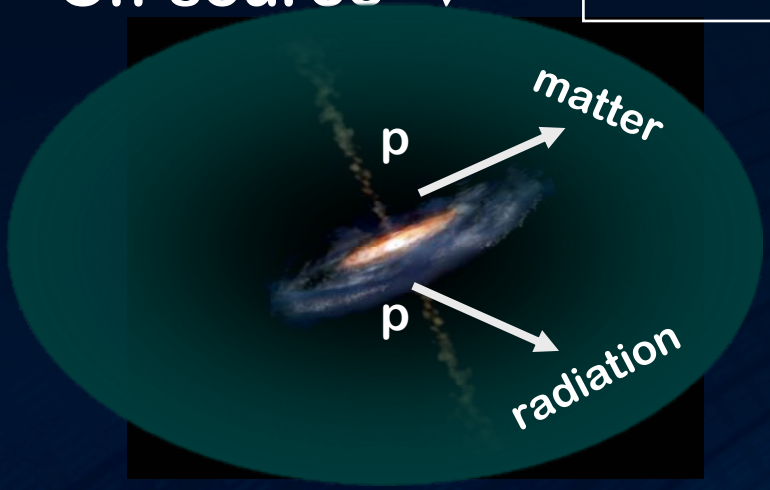


The Neutrino Flux: overview



The Cosmic Neutrinos
Production Mechanisms

"On-source" ν **TeV - PeV**

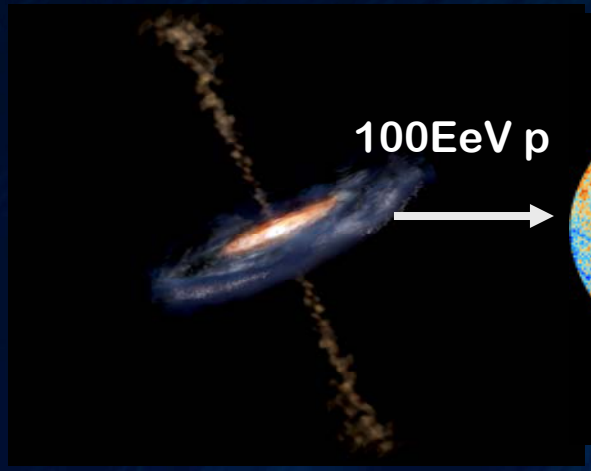


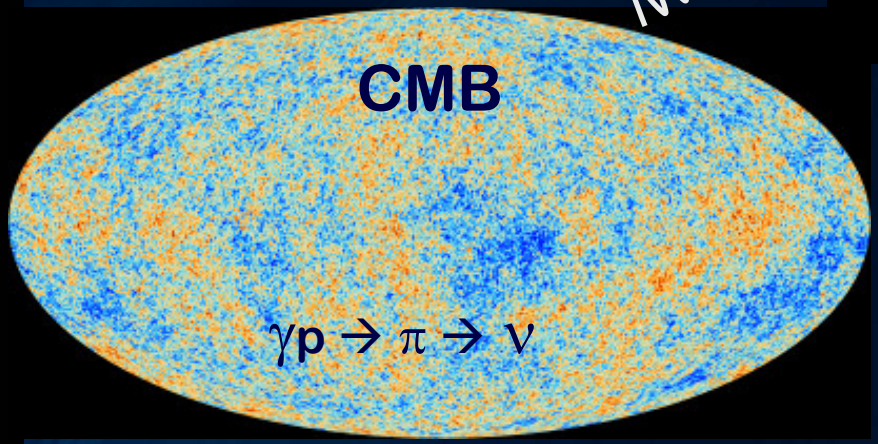
$pp \rightarrow \pi \rightarrow \nu$

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

photopion production

"GZK" cosmogenic ν **EeV**

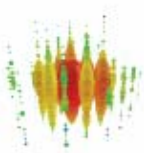




Bert & Ernie kicks off
the Discovery of Cosmic ν flux

Found by the IceCube UHE (GZK) ν searches

NEWSPAPER



Observation of a high-energy particle shower event from August 2011, identified as a PeV-energy neutrino. Each sphere represents a digital optical module sensor in the IceCube detector. Sphere size is a measure of the recorded number of photoelectrons. Colors represent arrival times of photons (red, early; blue, late). Selected for a Synopsis in *Physics* and an Editors' Suggestion. [M. G. Aartsen *et al.*, IceCube Collaboration, Phys. Rev. Lett. 111, 021103 (2013)]

IceCube collaboration
Phys. Rev. Lett. 111, 081801 (2013)

PHYSICAL REVIEW LETTERS

Contents

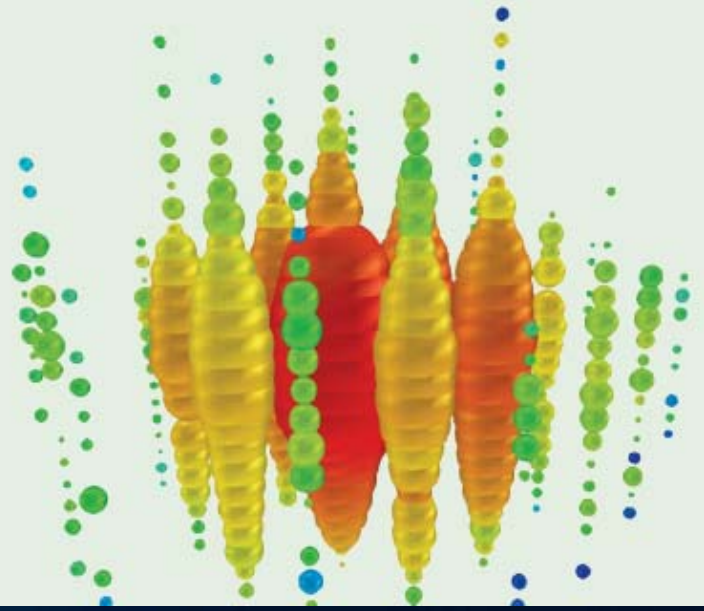
Articles published 6 July – 12 July 2013

VOLUME 111, NUMBER 2 — 12 July 2013

PHYSICAL REVIEW LETTERS

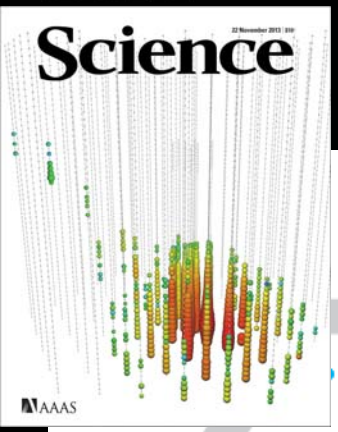
Articles published week ending 12 JULY 2013

PRL 111 (2), 020401–029902, 12 July 2013 (416 total pages)

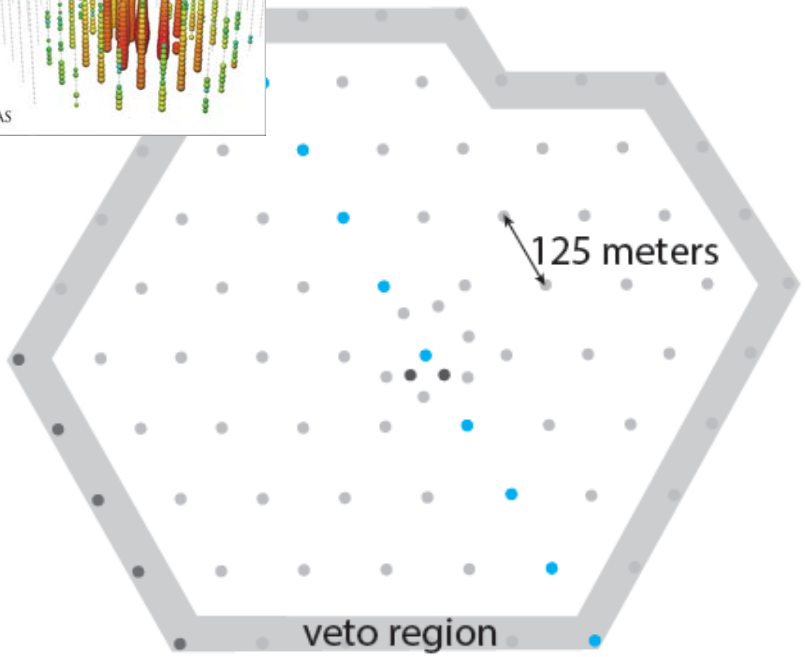


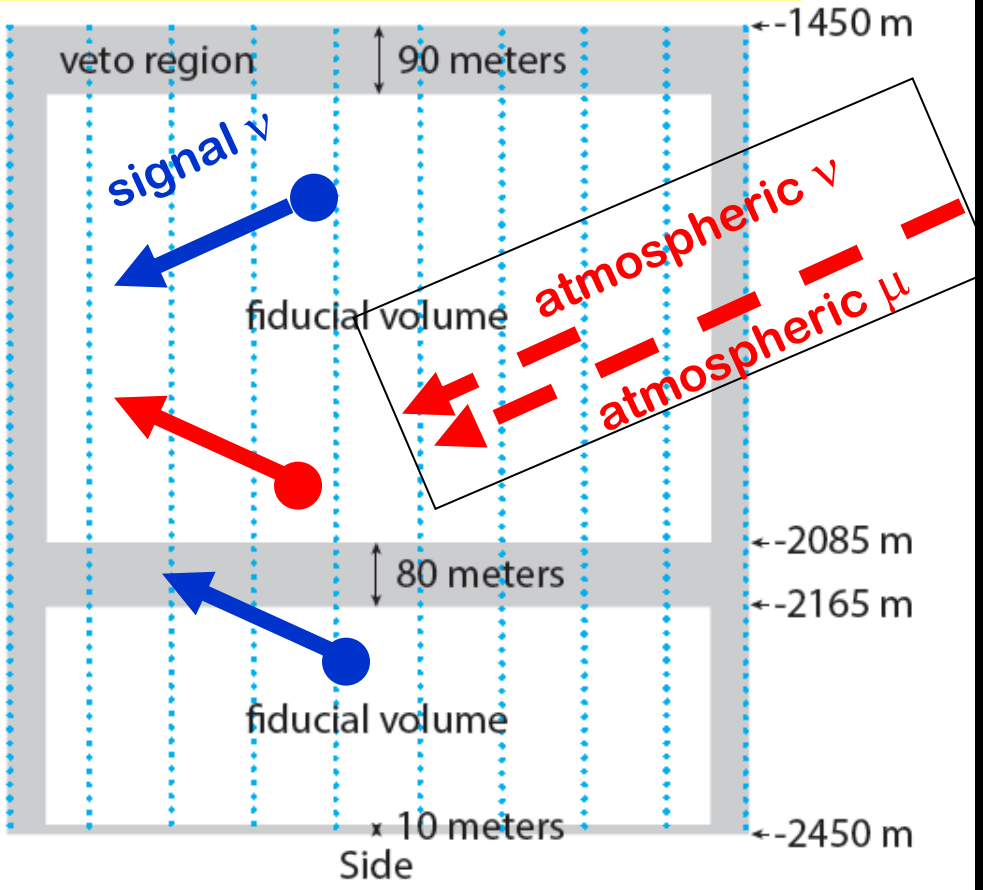
TeV PeV EeV

Mid Energy (60 TeV-)



look for only events with their interaction vertices within the fiducial volume

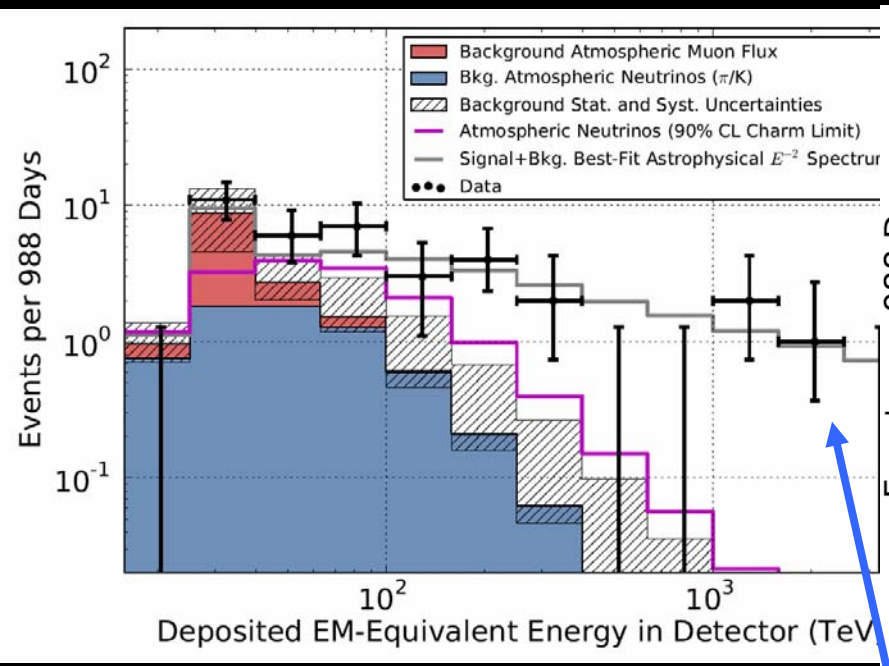


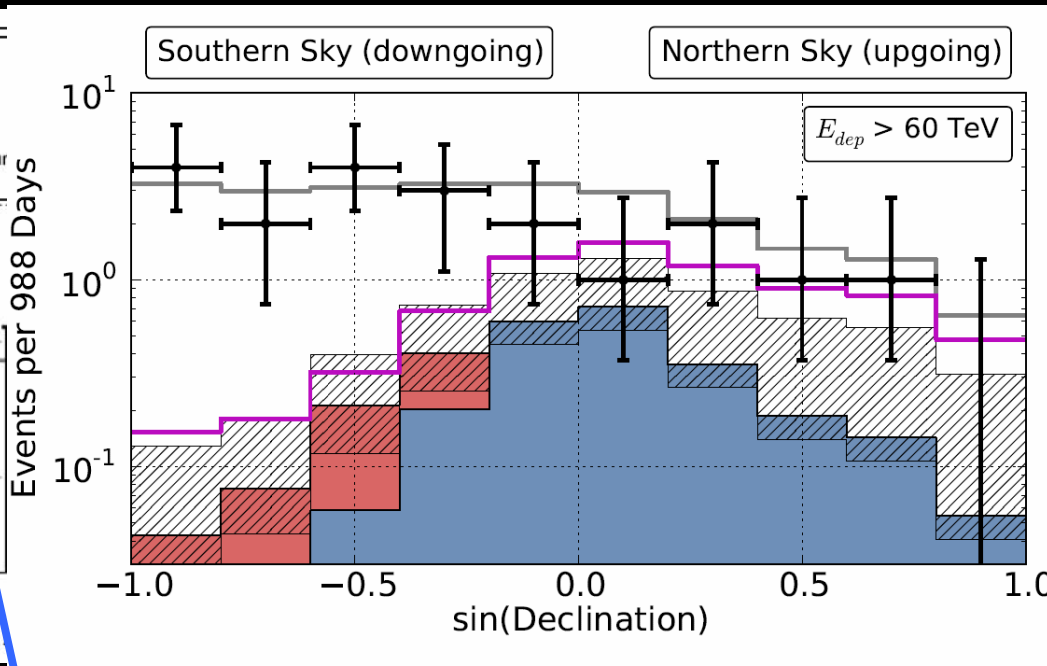


Mid Energy (60 TeV-)

IceCube 3 years data (2010-2013)

IceCube collaboration
Phys. Rev. Lett. 113, 101101

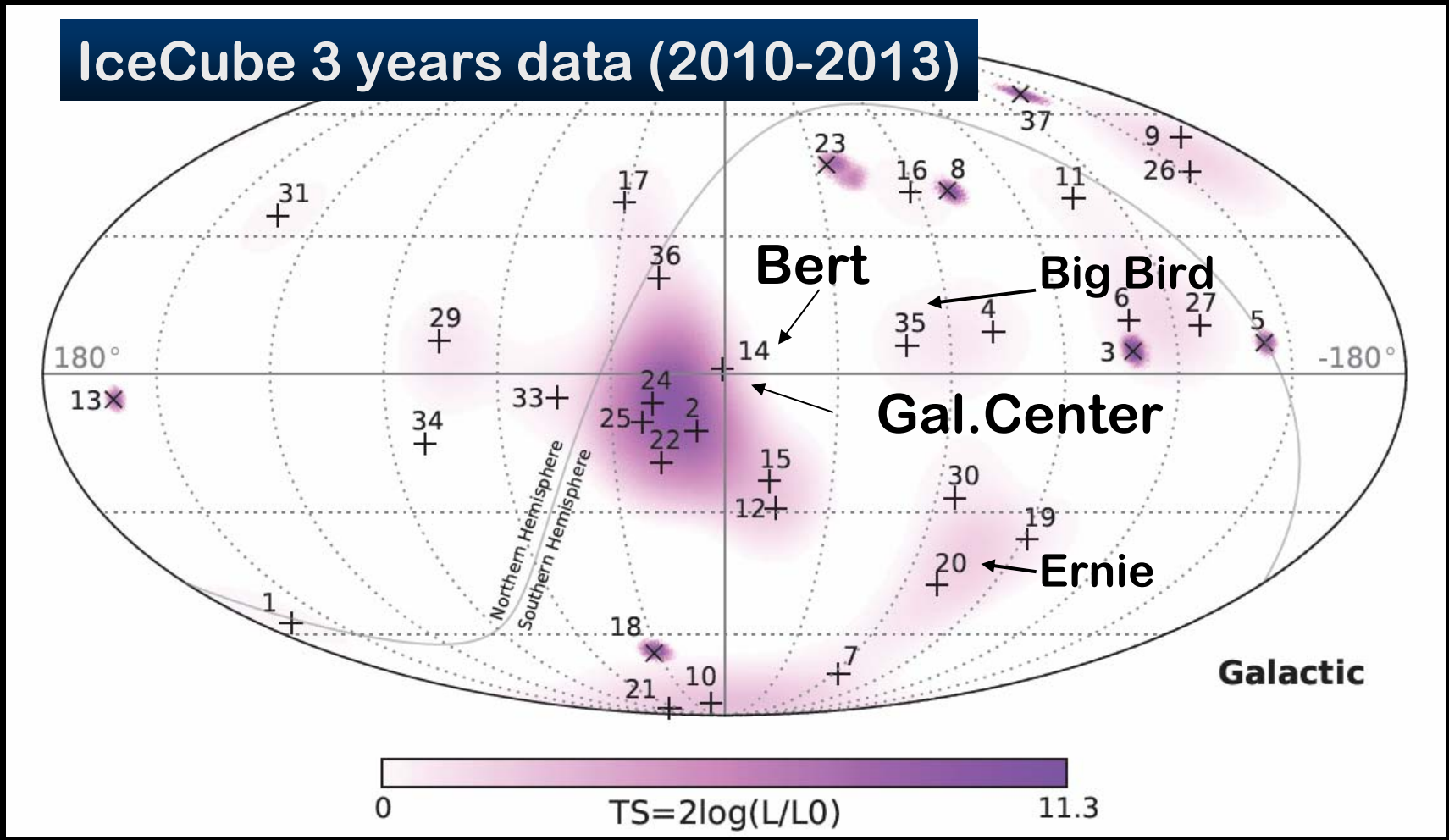




2PeV "Big Bird"

TeV PeV EeV

Mid Energy (60 TeV-)

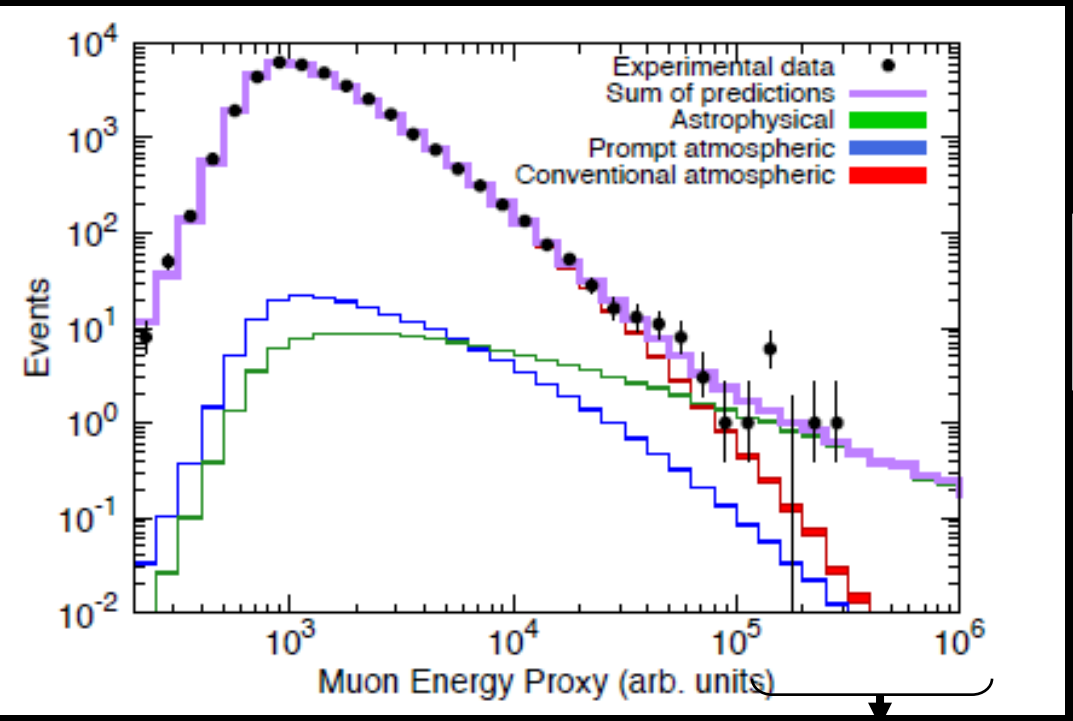


VHE (100 TeV-PeV)

The "traditional" ν_μ search looking into upgoing tracks

IceCube 2 years data (2010-2012)

$\nu_\mu \rightarrow \mu$ detected as up-going track



E_ν = O(100TeV)

IceCube collaboration
Phys. Rev. Lett. 115, 081102

3.9 σ excess over the atmospheric BG

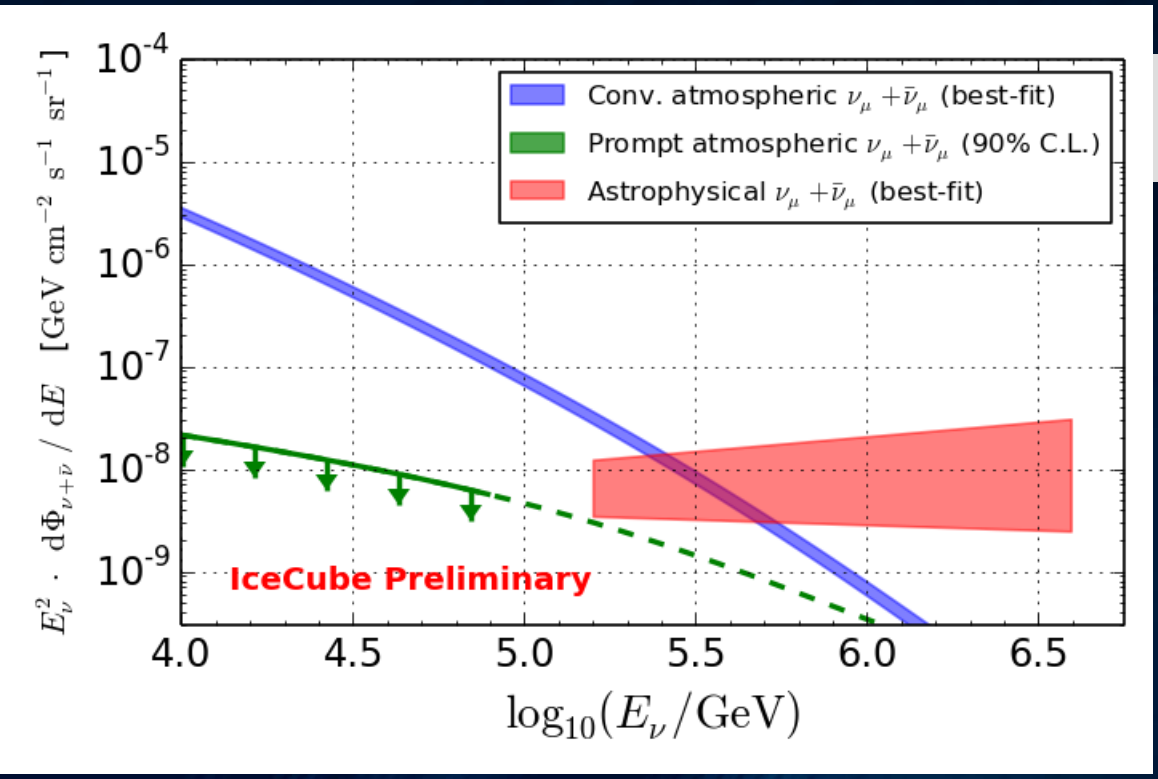
$E^2 \phi_{\nu_\mu}(E) \sim 9.9 \times 10^{-9}$ [GeV/cm^2 sec sr]

TeV PeV EeV

VHE (100 TeV-PeV)

up-going ν_μ flux detected by IceCube

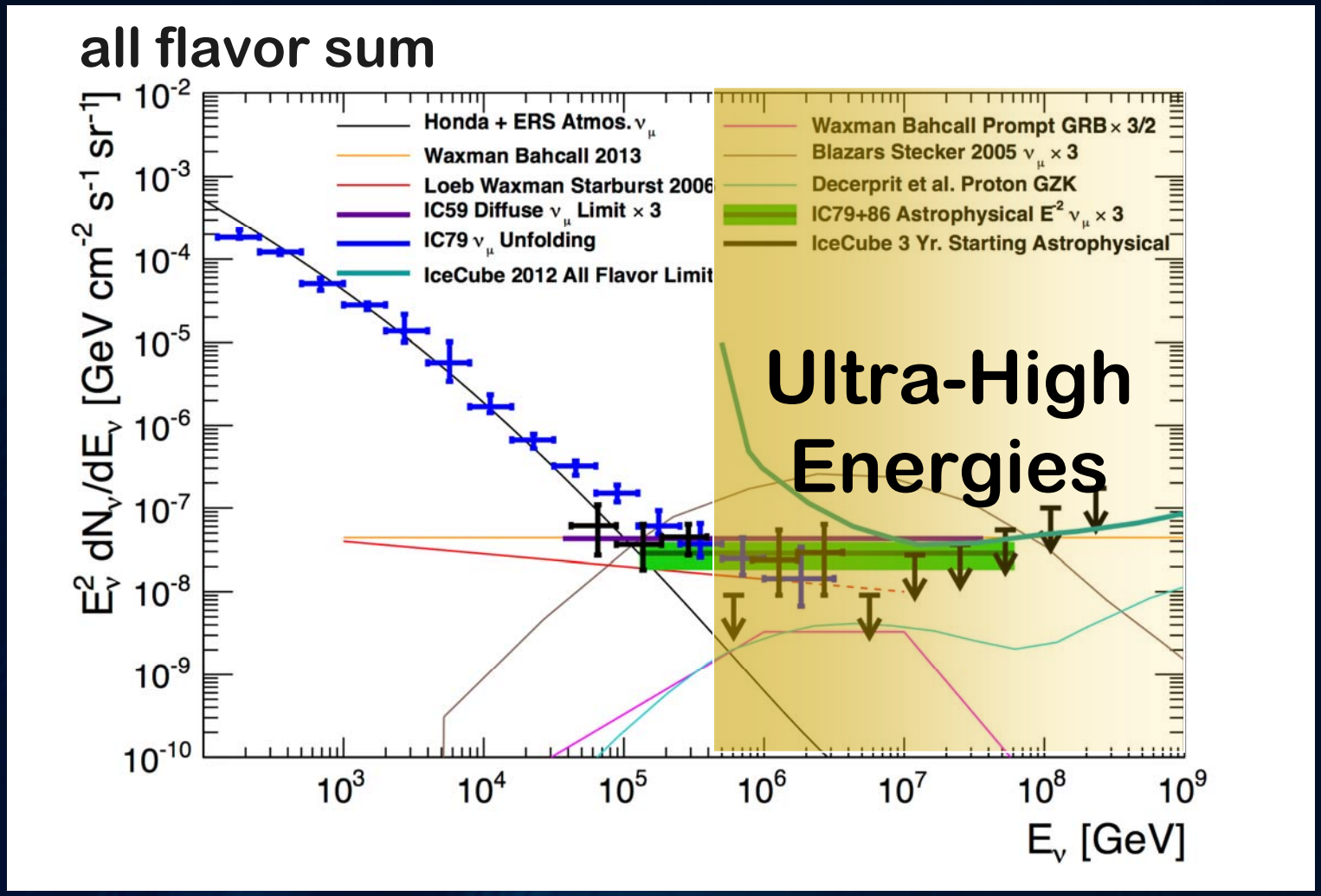
With 6 year-long data (2009-2015)



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

per flavor flux

Summary of the IceCube Diffuse Flux measurements

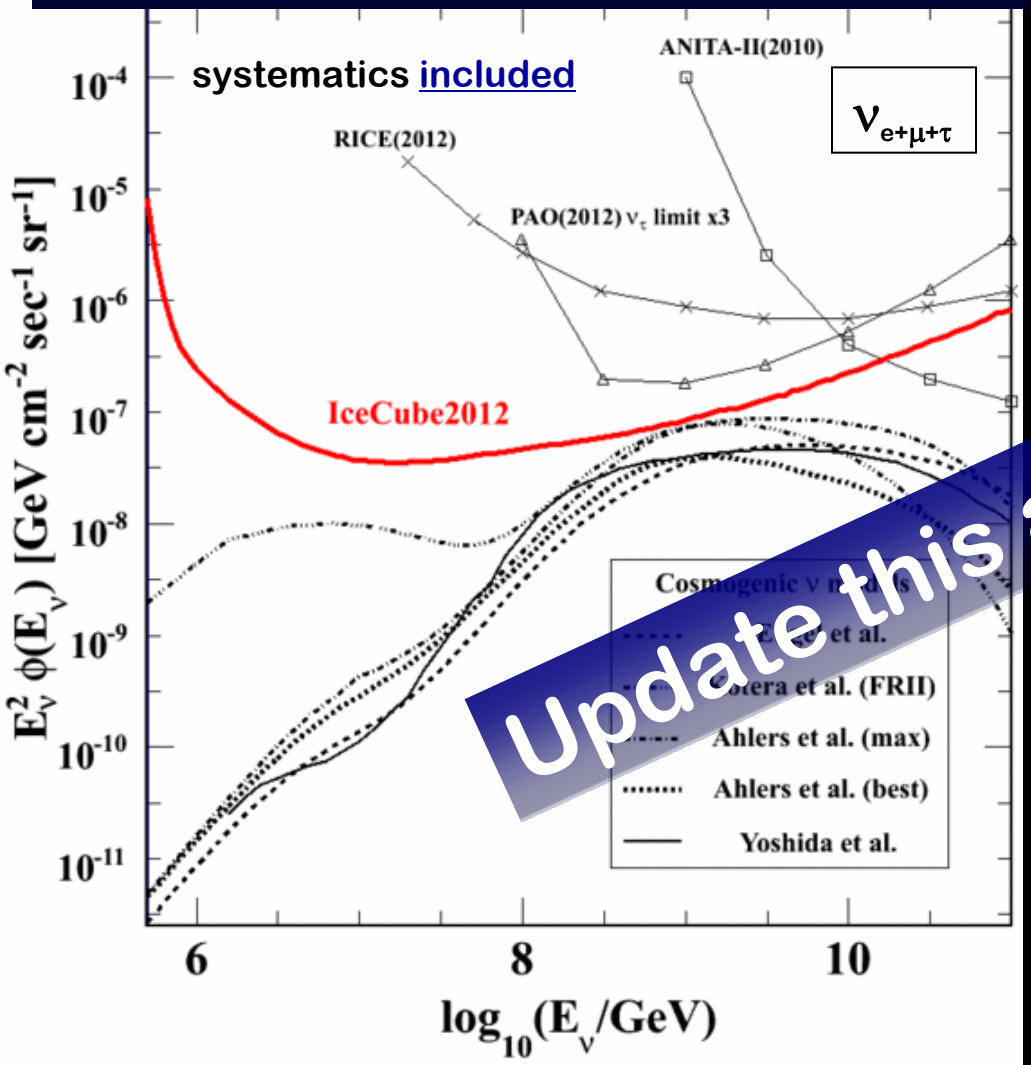


TeV PeV EeV

UHE (PeV-EeV)

The model-independent upper limit on flux

IceCube 2 years data (2010-2012)



IceCube collaboration
Phys. Rev. D 88, 112008 (2013)

any model adjacent to the limit is disfavored by the observation

Effective $\nu_{e+\mu+\tau}$ detection exposure

6×10^7 m² days sr @ 1EeV

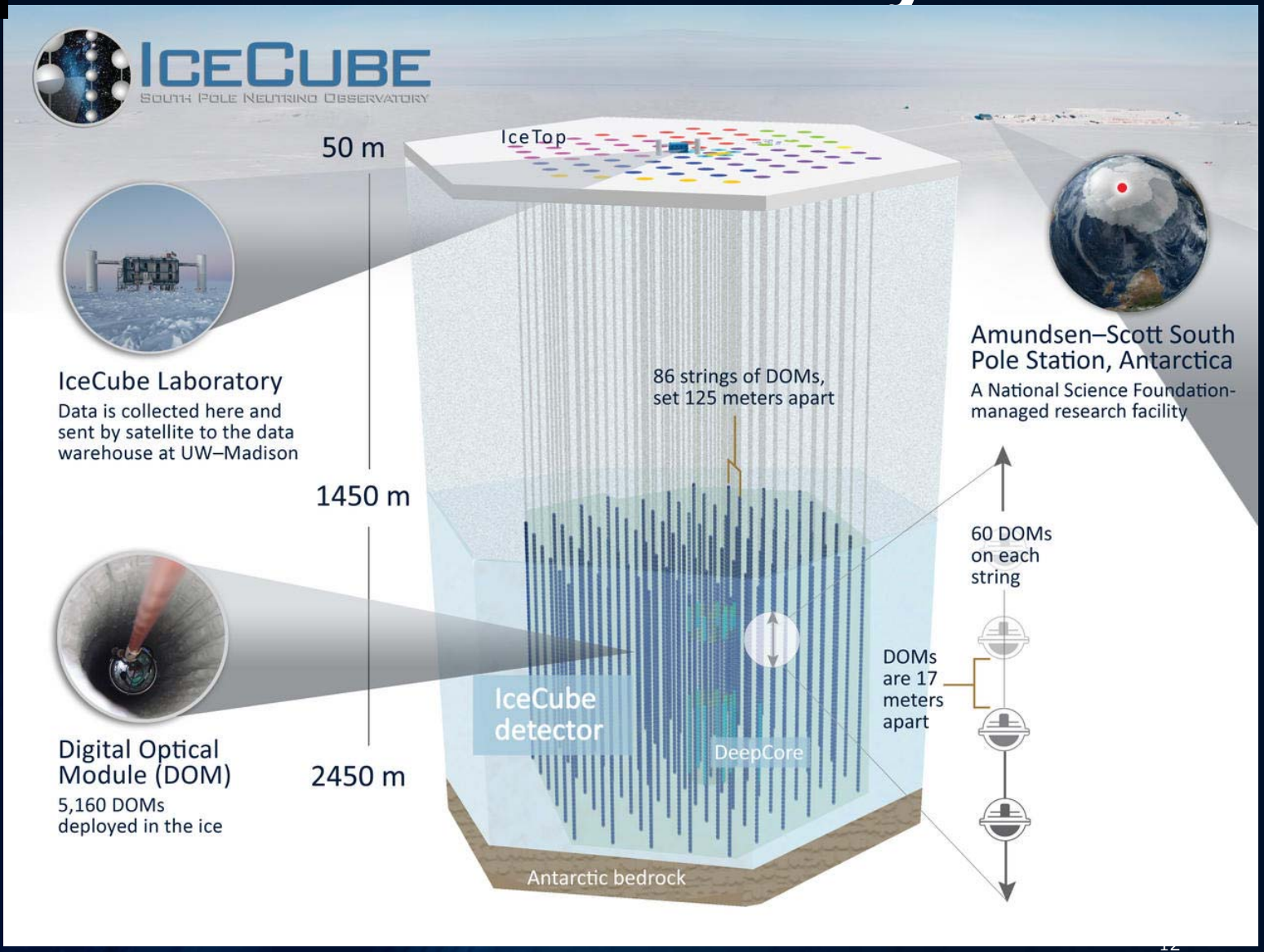
= 0.2 km² sr year

Update this analysis

Note: ϕ_{CR}(>1EeV) ~ 20/km² sr year

ν with CR comparable flux should have been detected

The IceCube Neutrino Observatory




The IceCube Collaboration
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University of Toronto
USA
Clark Atlanta University
Drexel University
Georgia Institute of Technology
Lawrence Berkeley National Laboratory
Massachusetts Institute of Technology
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Southern University and A&M College
Stony Brook University
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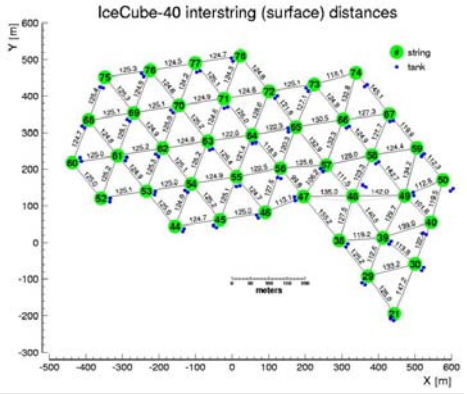
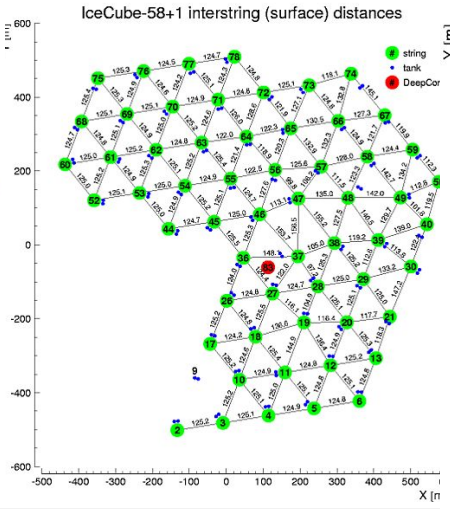
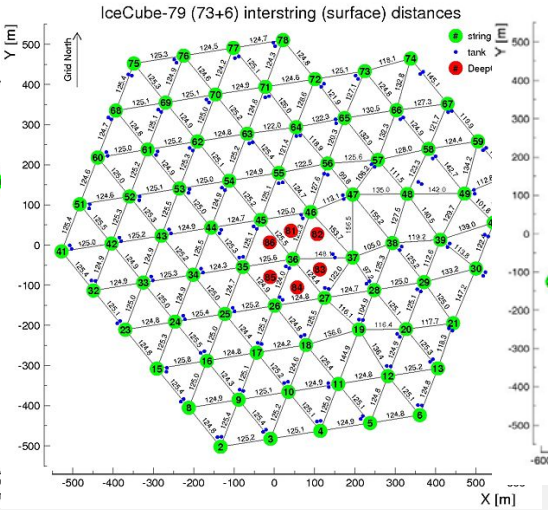
The Swedish Research Council (VR)
University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)

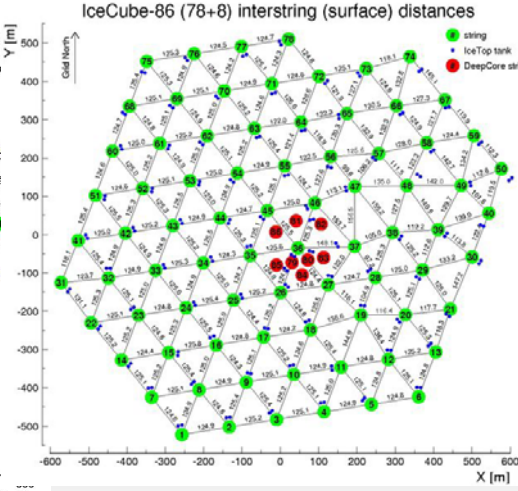
UHE ν search with 7 year long data

"IC40"	"IC59"	"IC79"	"IC86"
2008-2009	2009-2010	2010-2011	2011-2015
354.8 day	342.8 day	312.5 day	1406.2 day



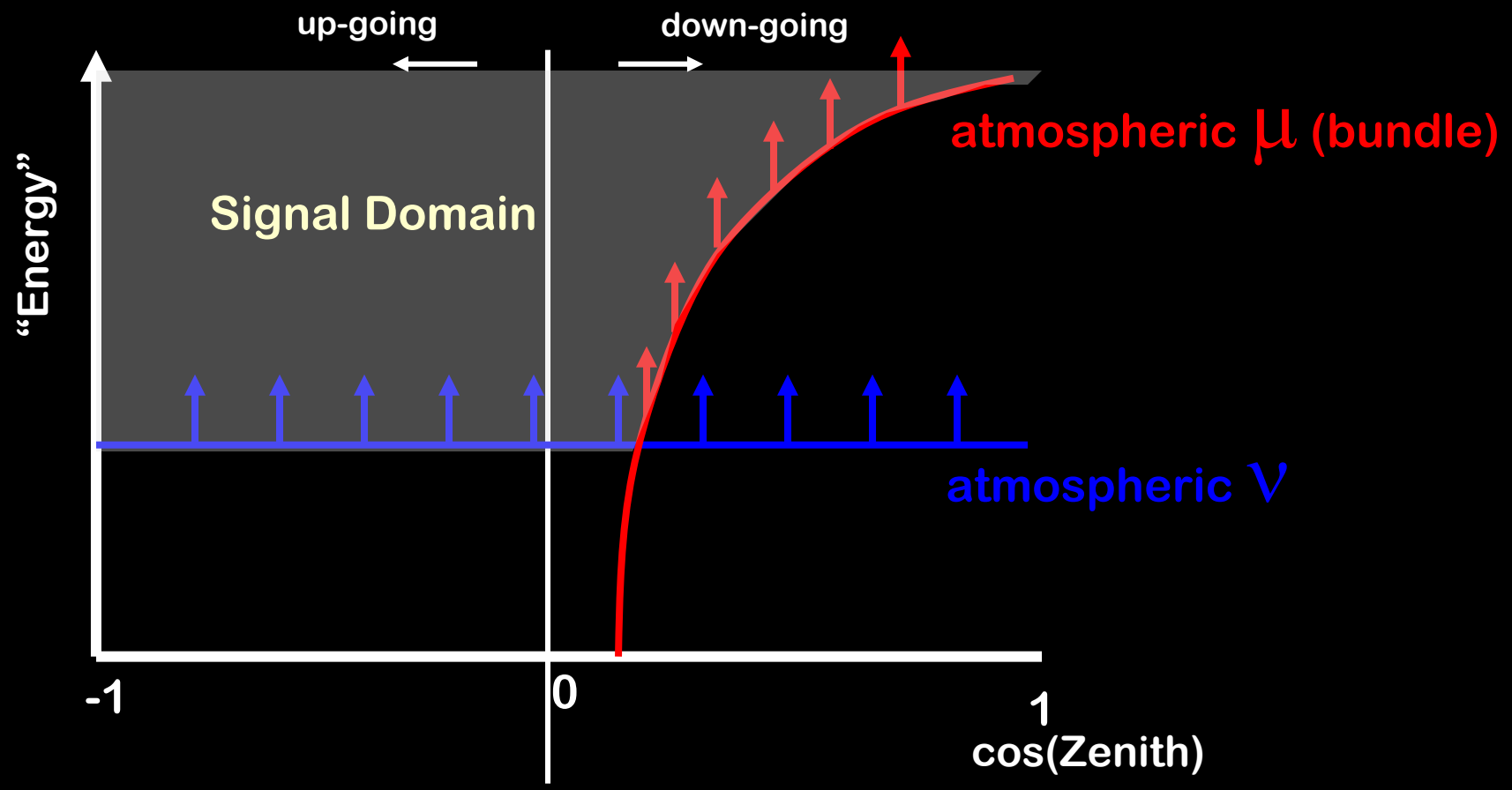






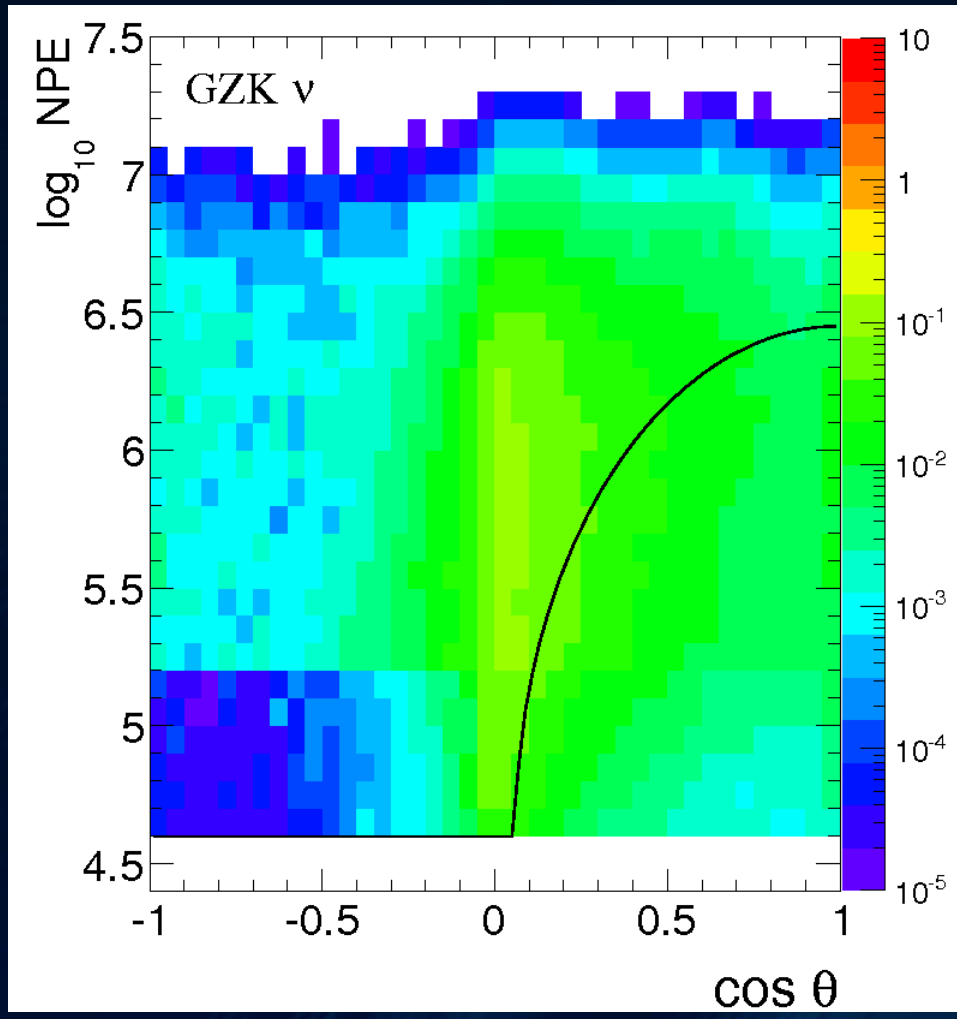
UHE (PeV-EeV)

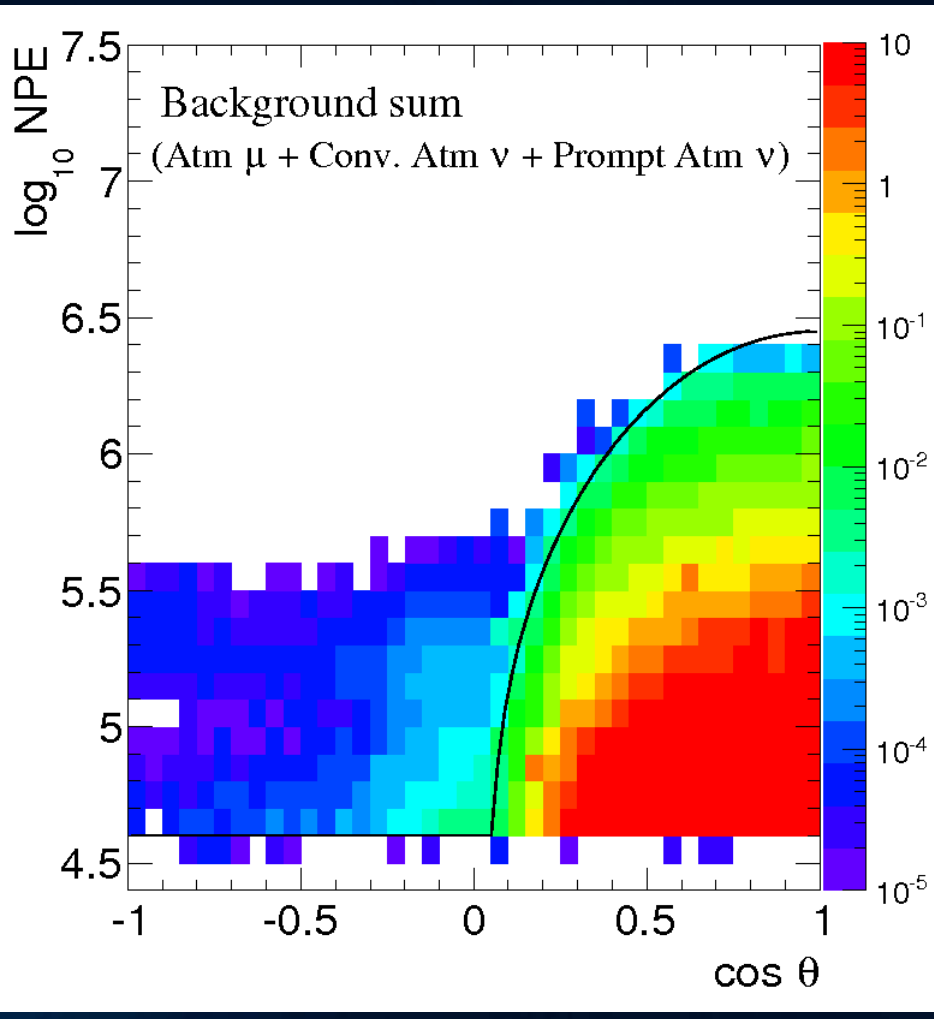
Detection Principle – All flavor sensitive



Event Distribution on

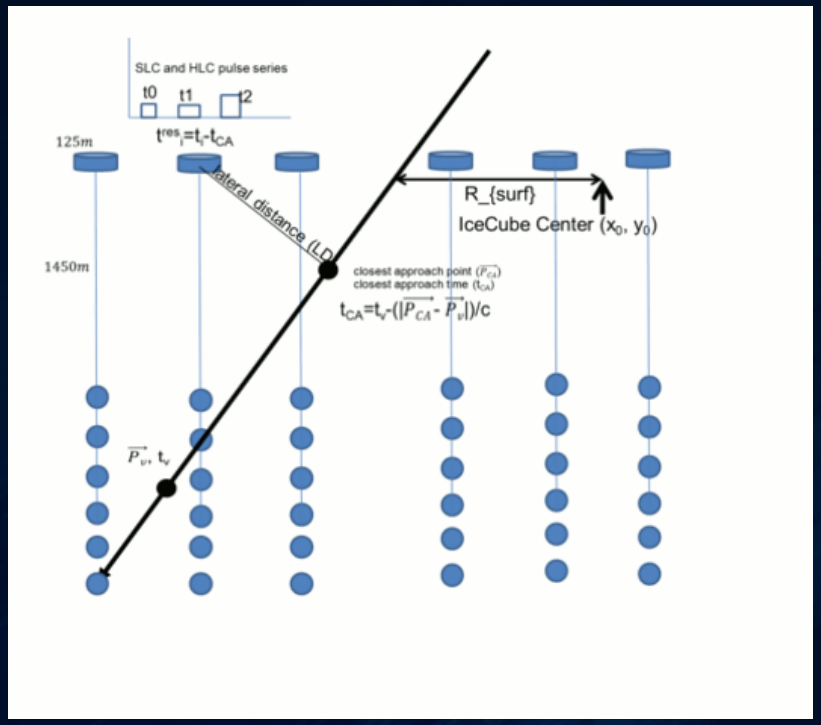
NPE("brightness" ~ "Energy") Vs cos(zenith) plane

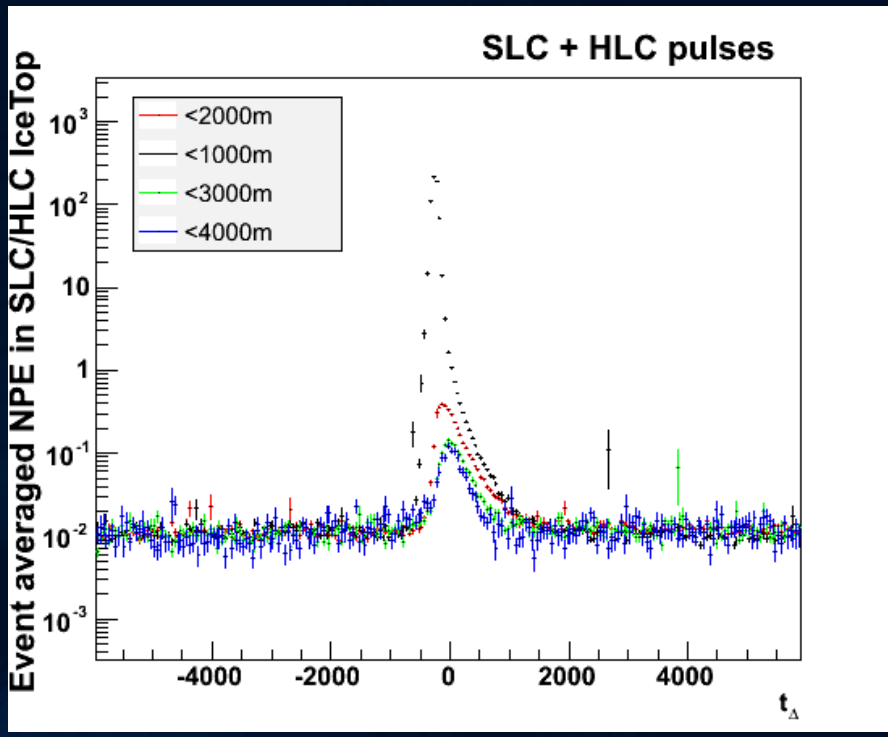




vetoed by the air-shower array

We have the IceTop array on the IceCube ice surface



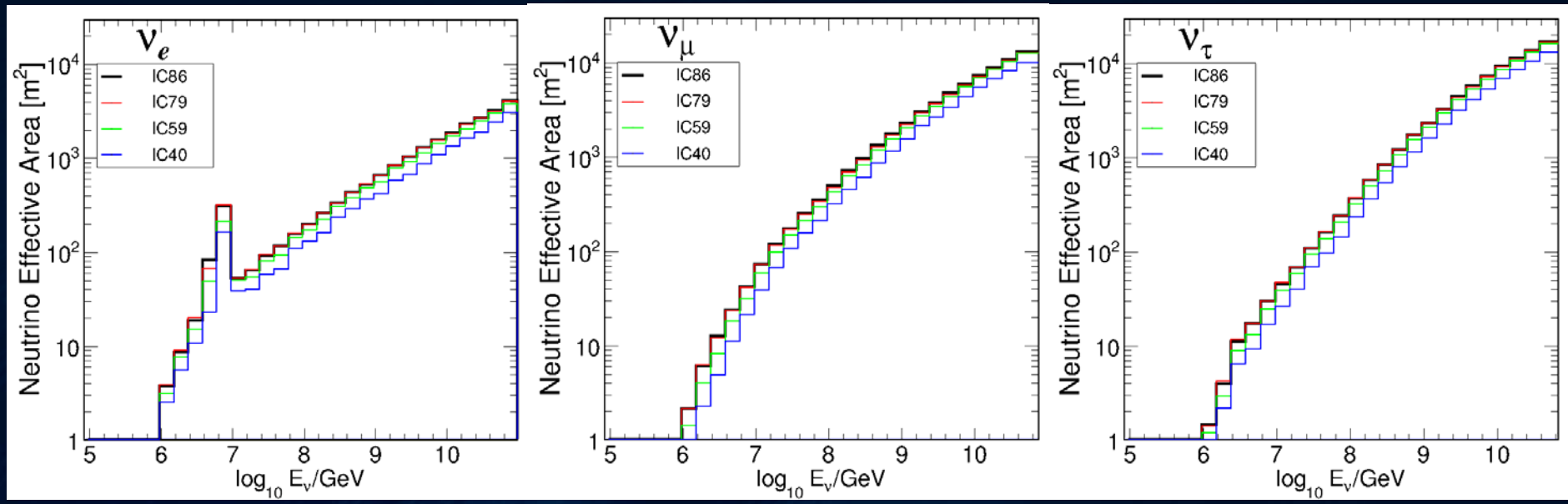


If more than 2 IceTop hits occurs in 1.2 usec window → Label as backgrounds

The ν detection effective area

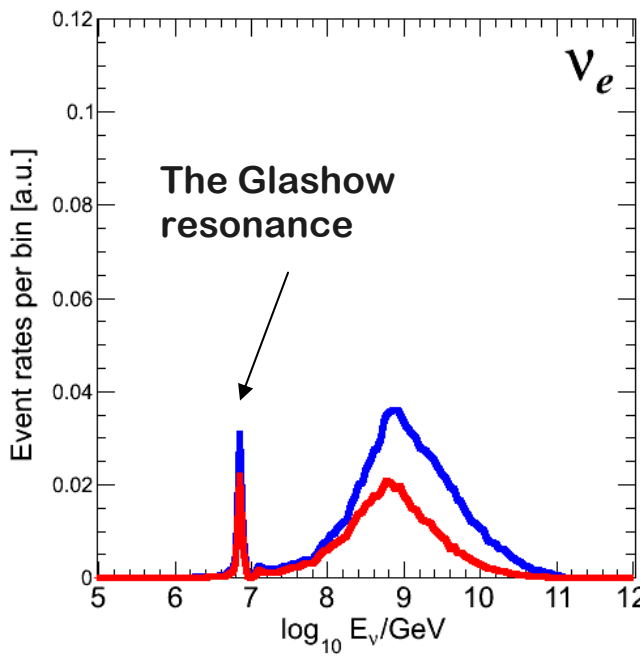
PeV < E < 10 PeV ν_e sensitive

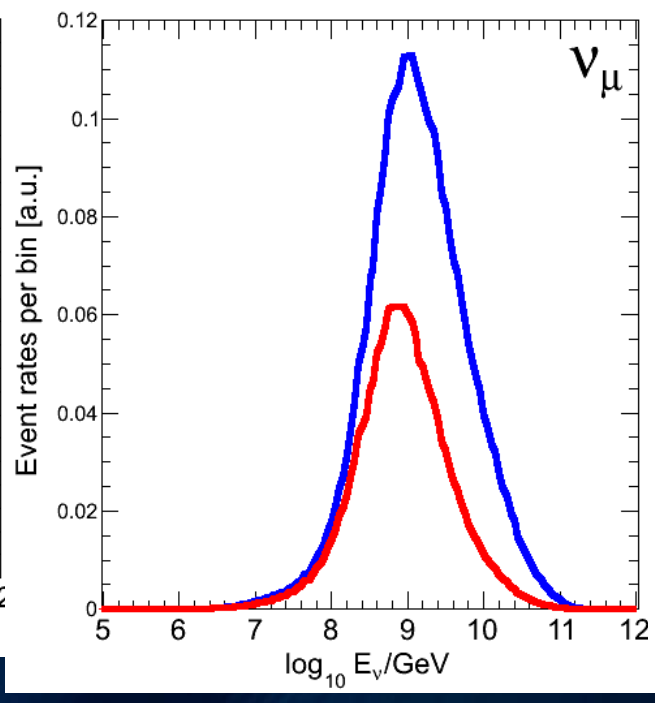
100PeV < E ν_μ ν_τ sensitive

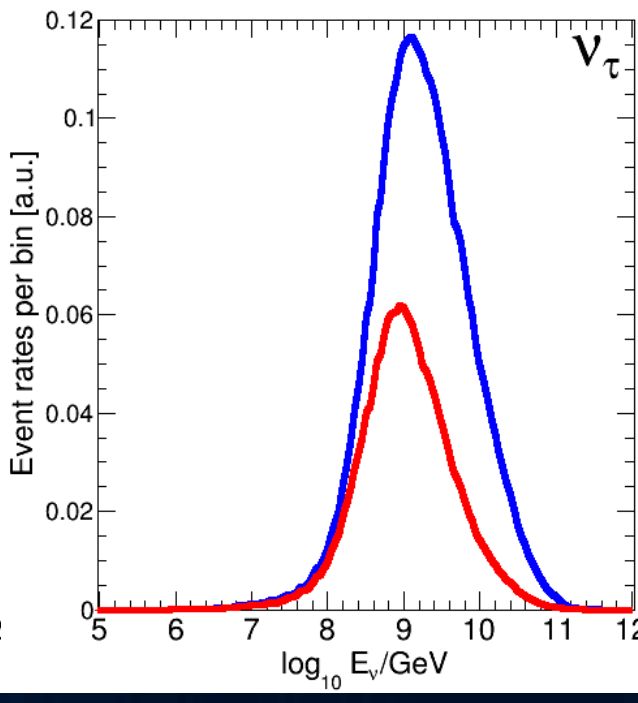


Expected Signal Event Distribution
with GZK-type of spectra

The main energies : EeV (=1000 PeV)



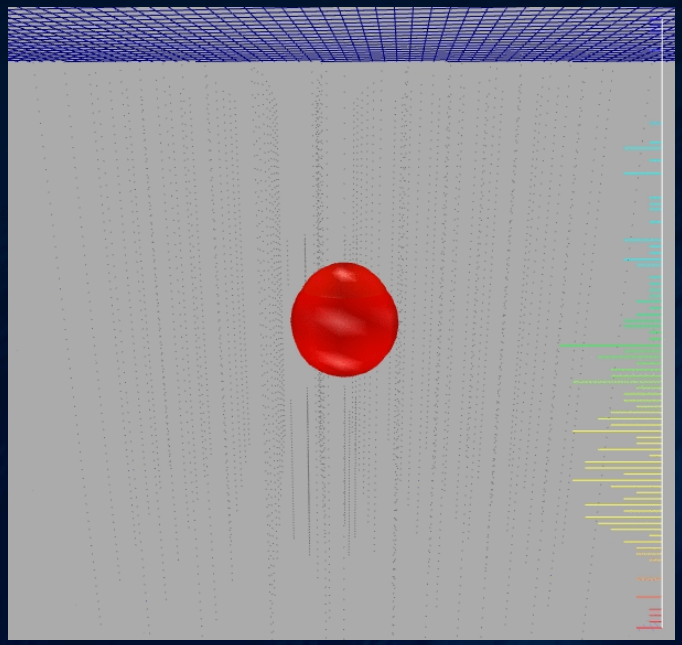


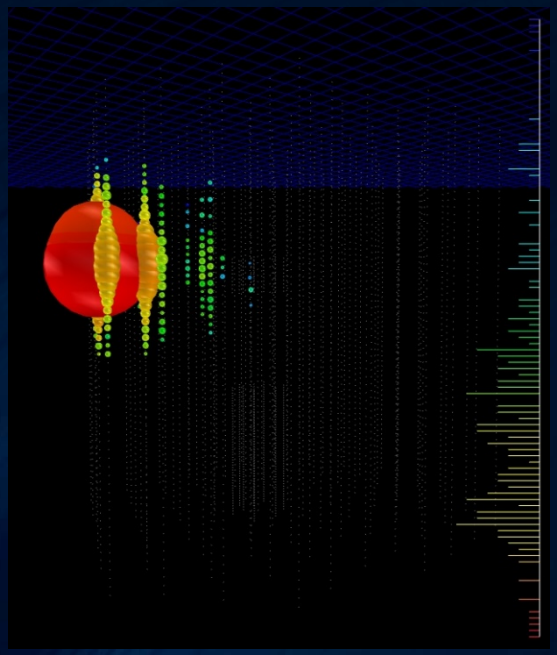


Open the box : What we found

Two PeV-ish events

1st event: shower (cascade) event in 2013 sample





Preliminary

Reconstructed Parameters

Diposited Energy

808 TeV

zenith angle

174 deg

~20 deg uncernt.

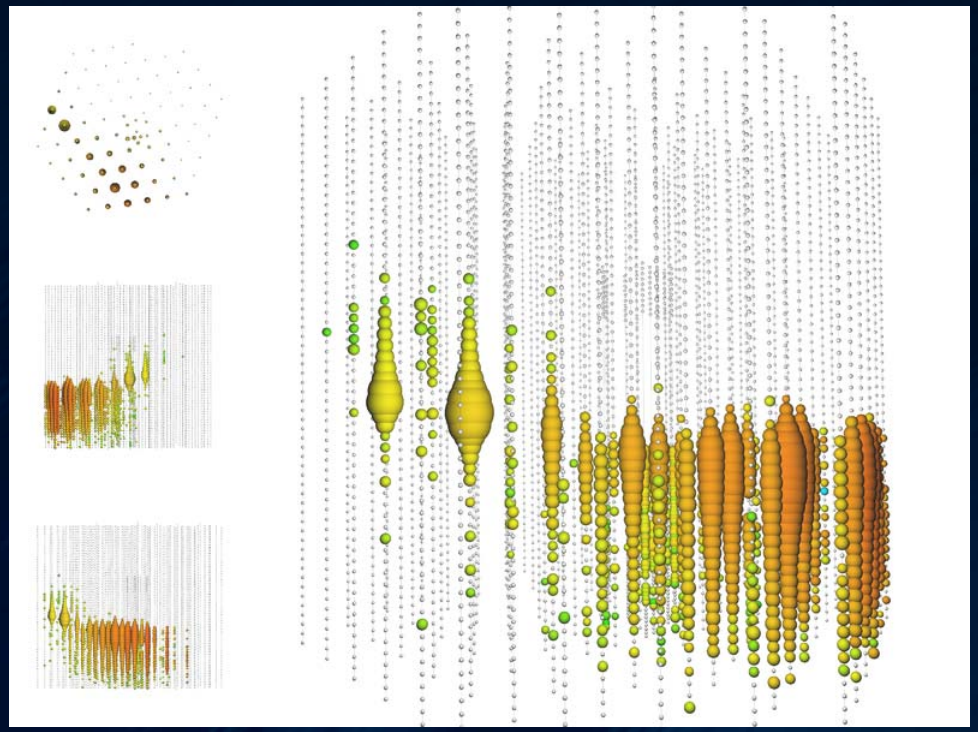
(Probably) the most energetic upgoing event detected by IceCube

TeV PeV EeV

Open the box : What we found

Two PeV-ish events

2nd event: track event in 2014 sample



Preliminary
Reconstructed Parameters

Diposited Energy
2.6 +- 0.3 PeV

8 deg off TeVCat
3 deg off 2-3FGL
~0.5deg uncernt.

the most energetic event ever detected by IceCube

TeV PeV EeV

What are these events?

They are not the atmospheric background

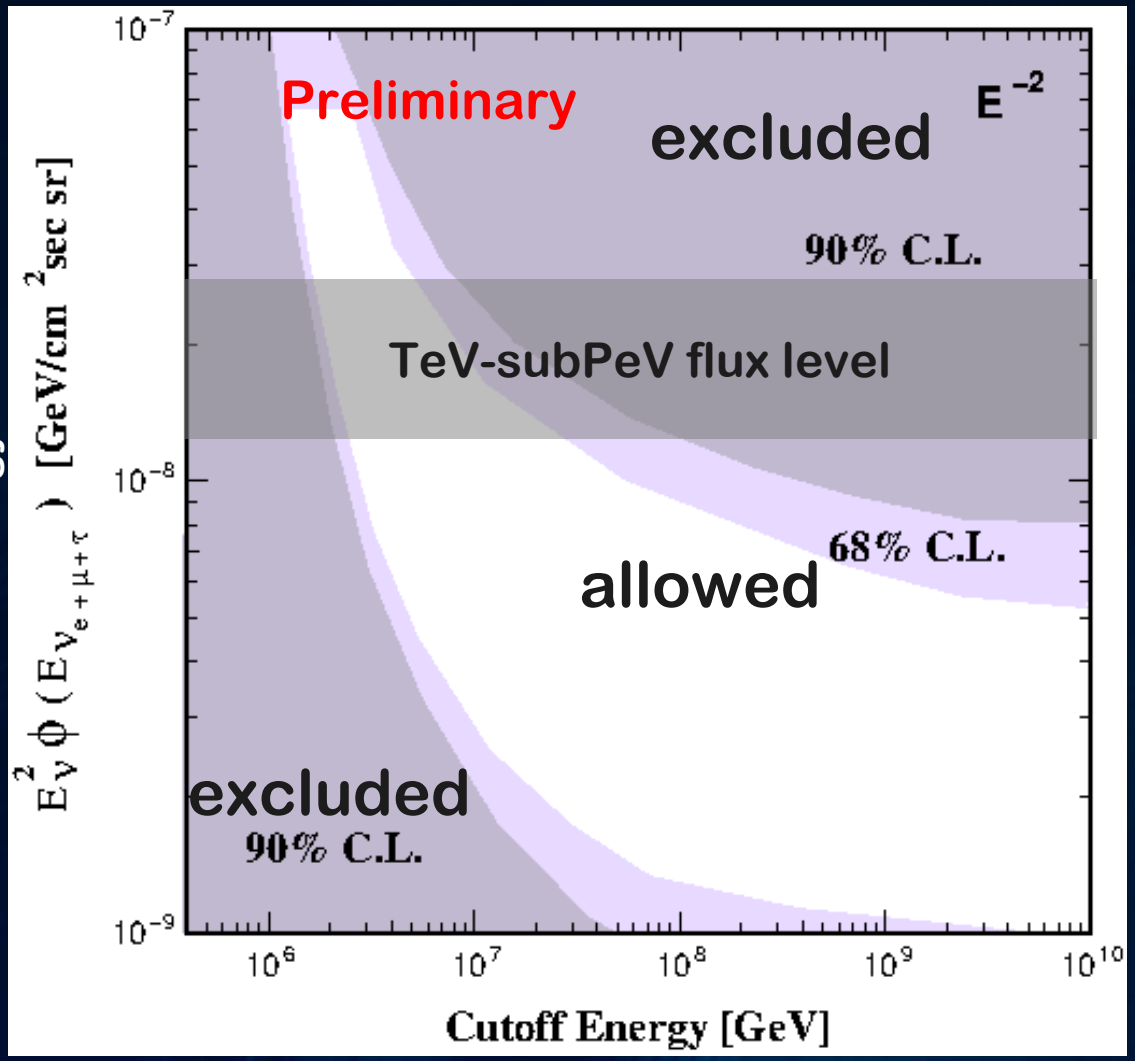
The background-only hypothesis rejected by ~3.66 σ
(expected background rate 0.064)

They are not the GZK cosmogenic ν

The GZK hypothesis rejected by ~2.75 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?



consistent
but must have
a cutoff energy

TeV PeV EeV

Implications to UHECR origin with the IceCube PeV-EeV data

Two PeV-ish events

No EeV-ish events

Test on the GZK ν models to constrain UHECR sources

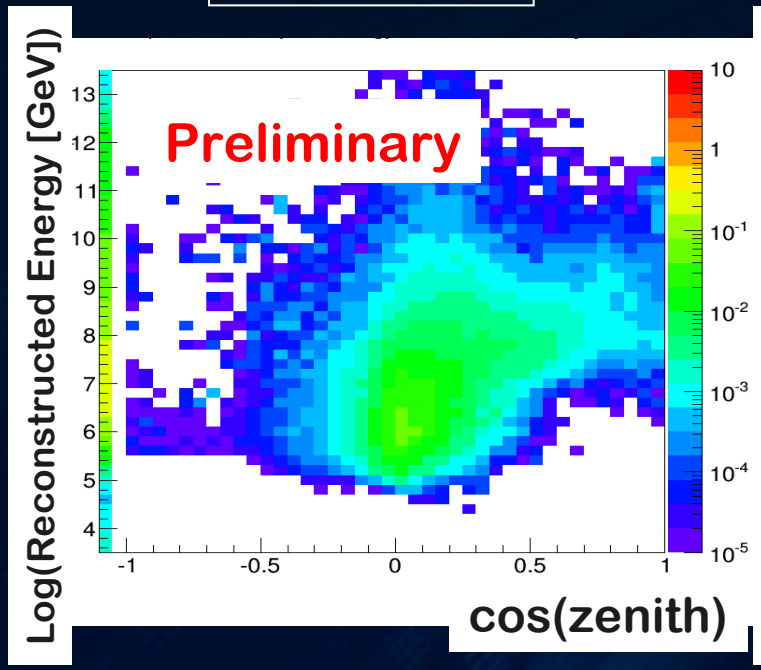
Robust and solid constraints,
but UHECR composition limited
(Only sensitive to proton-dominated case)

Test on the on-source PeV-EeV-energy ν models (ex AGN jets)

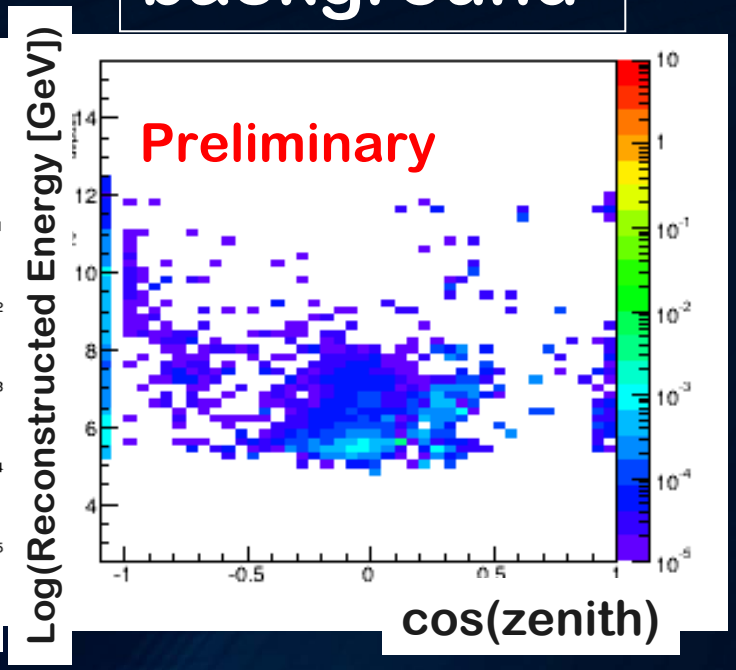
model-dependent arguments
but mixed-composition case reachable

Testing PeV-EeV cosmic ν models

ν Signal



Atmospheric background



Data

No events except

Two PeV events

Likelihood Ratio Test

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+ SFR
Expect. # of events	6.9	5.3	2.9	3.6	4.8	15.0	5.5
Model Rejection Factor	0.34	0.41	0.99	1.2	0.93	0.36	0.99
p-value	1.0×10^{-3}	2.0×10^{-3}	9.5×10^{-2}	2.2×10^{-1}	7.8×10^{-2}	2.8×10^{-5}	7.8×10^{-2}

Excluded

Mildly Excluded

TeV PeV EeV

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Test on the GZK ν models to constrain UHECR sources

Robust and solid constraints,
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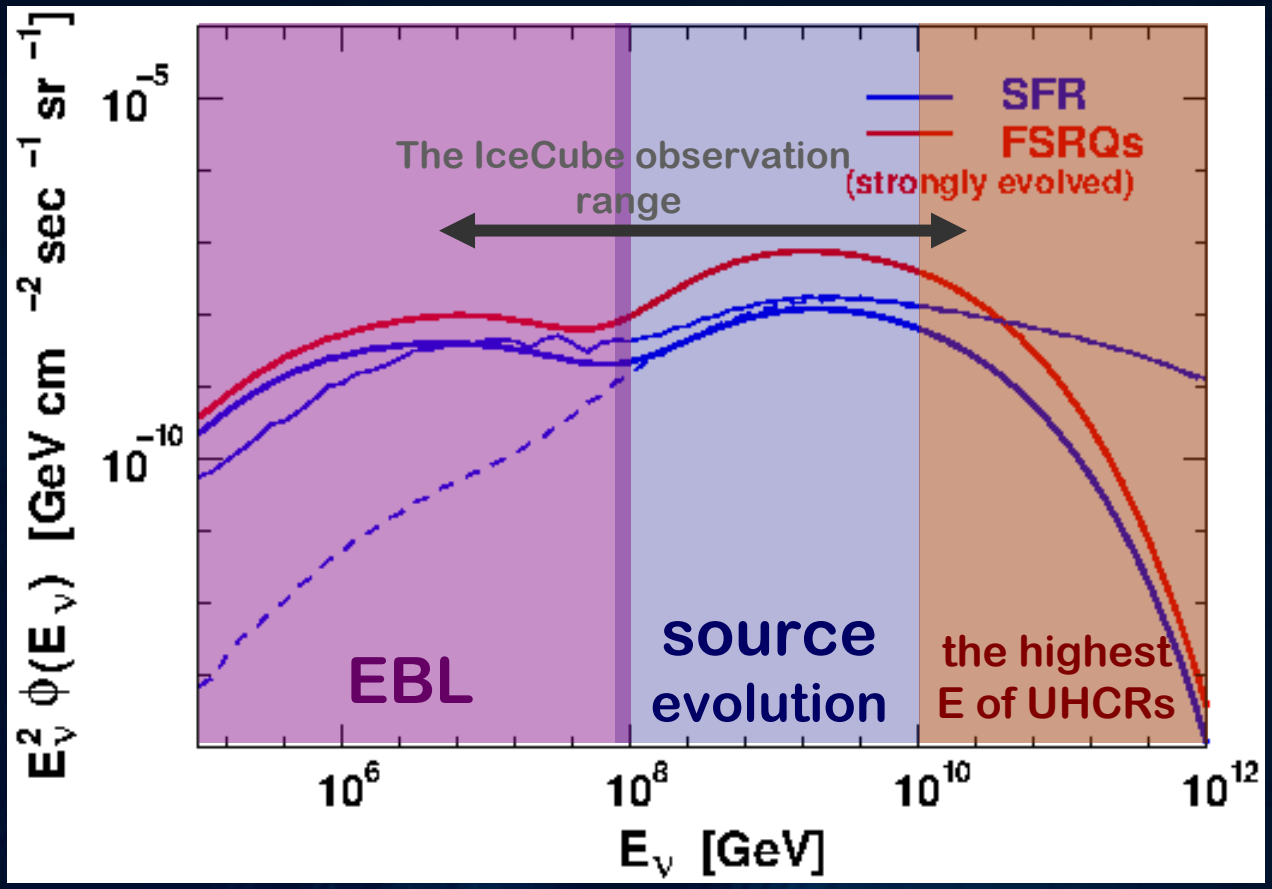
(Only sensitive to proton-dominated case)

Test on the on-source PeV-EeV-energy ν models (ex AGN jets)

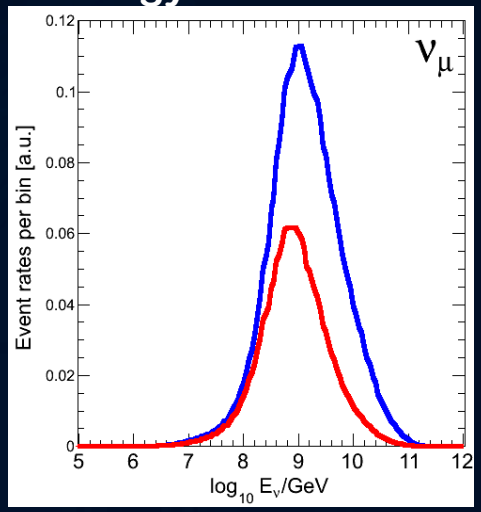
model-dependent arguments
but mixed-composition case reachable

GZK cosmogenic ν models

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



IceCube signal event energy distribution

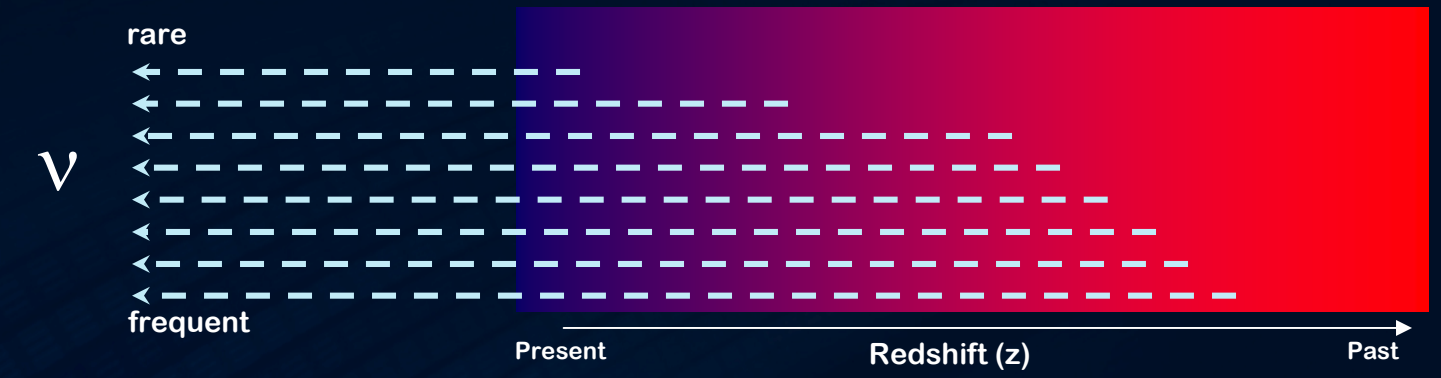


Tracing *history* of the particle emissions with ν flux

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

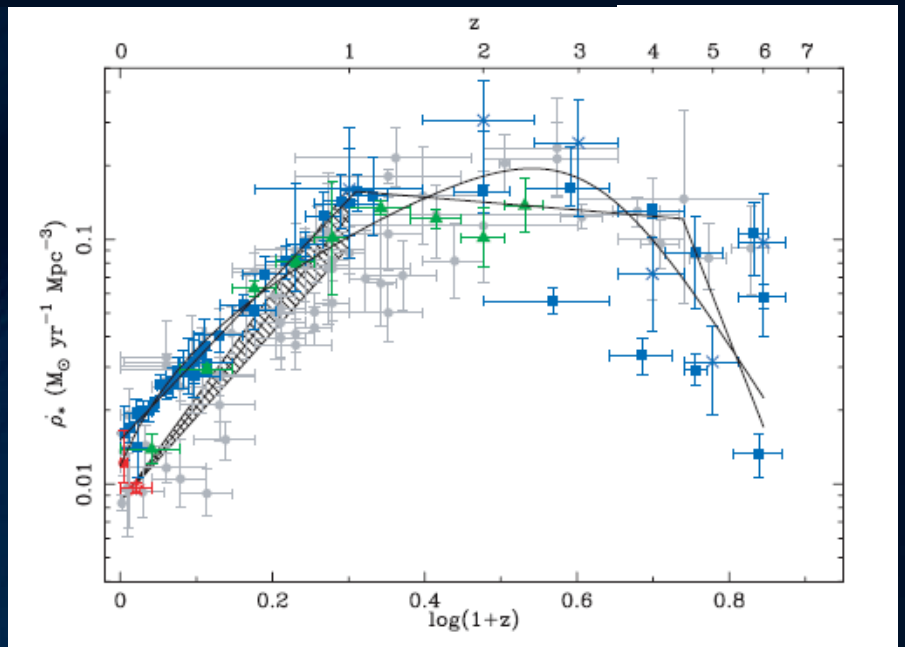


Hopkins and Beacom, Astrophys. J. **651** 142 (2006)

The cosmological evolution

Many indications that the past was more active.

Star formation rate→



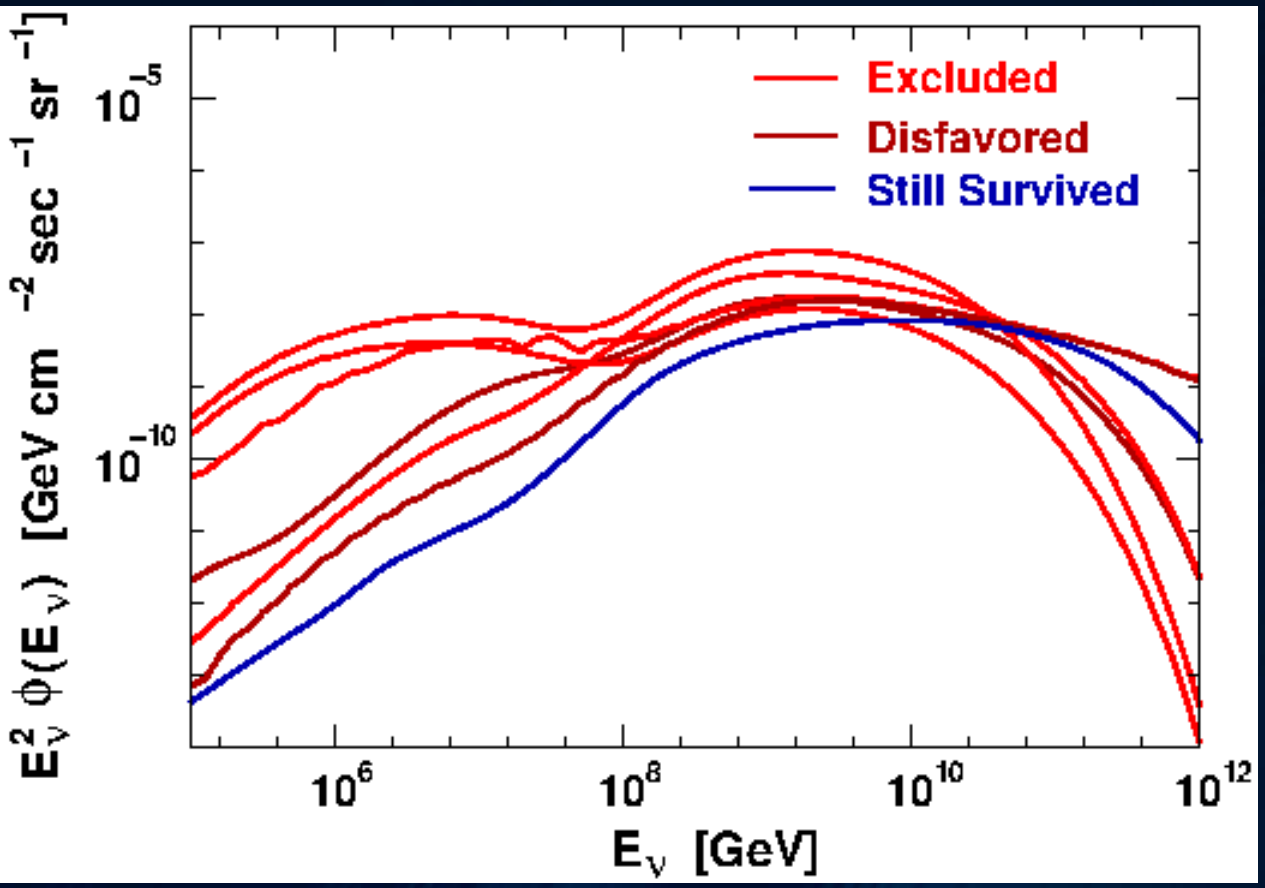
The spectral emission rate

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

m= 0 : No evolution

IceCube Tests on the GZK ν model

The GZK ν models assuming proton-dominated CRs



only very weak evolution scenario is allowed

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

Yoshida and Ishihara, PRD 85, 063002 (2012)

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

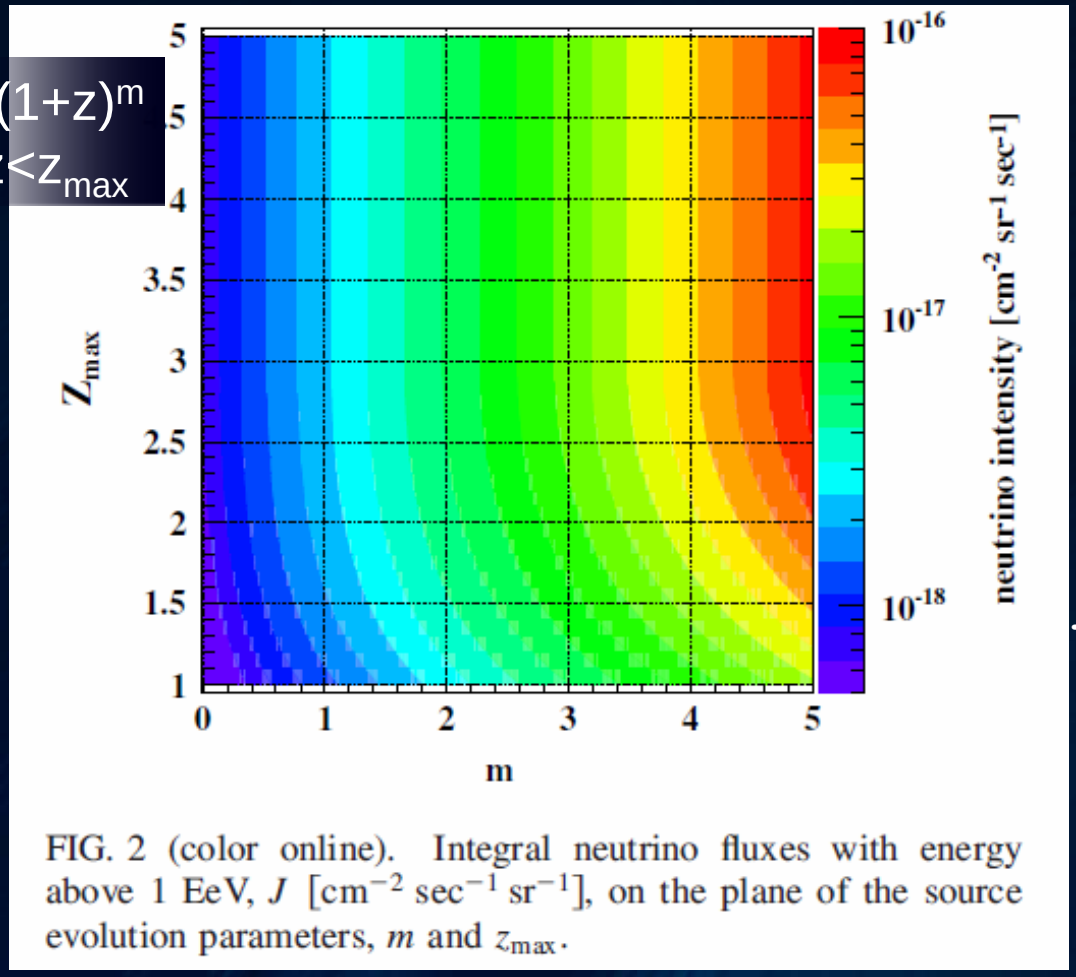


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

↓ x IceCube Exposure

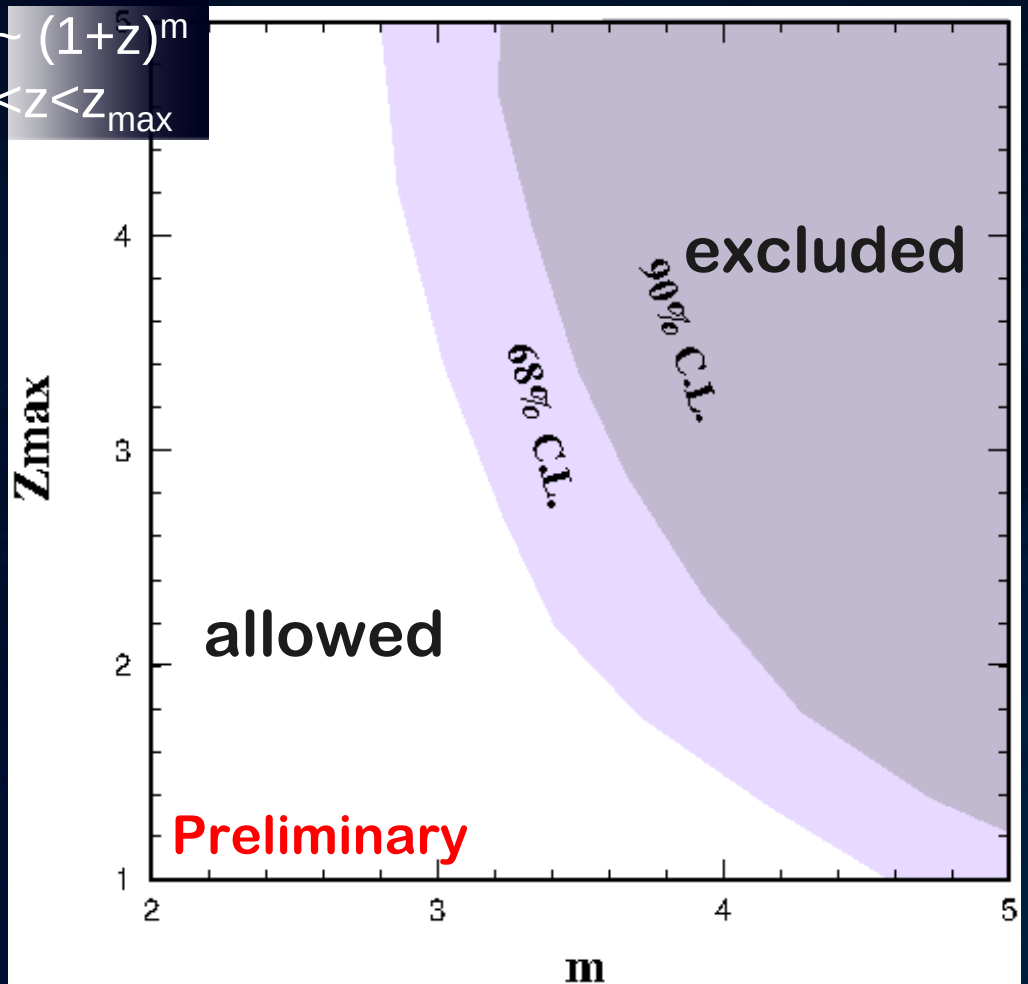
Event distribution on plane of (E, cos(zenith))

↕

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

Any sources with evolution compatible or stronger than star formation rate are disfavored

~~AGNs~~

~~GRBs~~

What IceCube tells if UHECRs are not proton-dominated?

Move on to the on-source ν model-dependent constraints

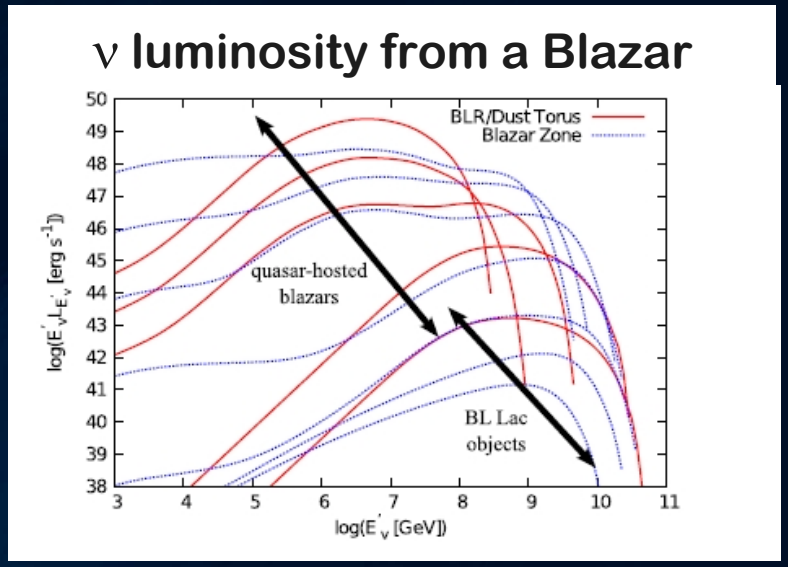
Example: AGN(Blazar) inner jets taking into account the Blazar sequence
(Murase, Inoue, Dermer, PRD 2014)

FSRQs (QHB) ⟷ middle class ⟷ BL Lac

FSRQs (QHB) → ν

middle class → γ

BL Lac → UHECRs



The highest energy CRs are HEAVY nuclei

TeV PeV EeV

IceCube tests on *on-source* ν models

AGN (Blazar) Inner Jet

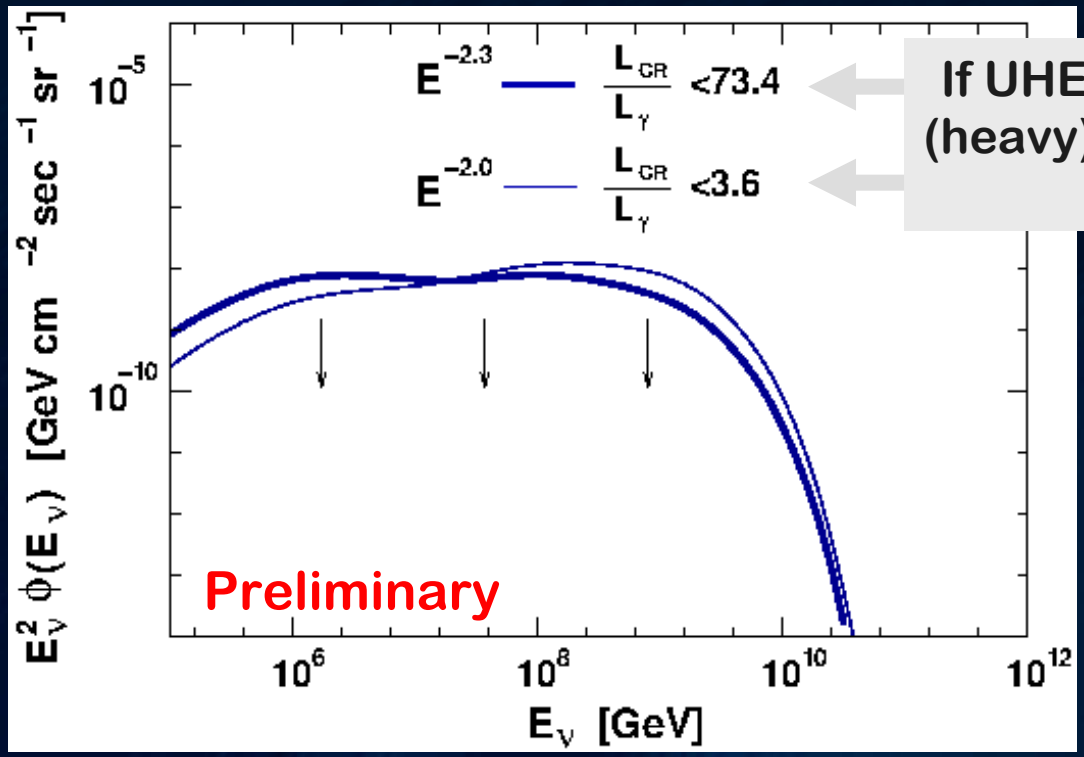
Murase, Inoue, Dermer, PRD 2014

$$\nu \text{ flux} \propto \frac{L_{CR}}{L_\gamma} \approx \begin{cases} 100 & \text{if } E^{-2.3} \\ 4 & \text{if } E^{-2.0} \end{cases}$$

L_{CR} ← Auger

L_γ ← Radio

ν flux upper limit by IceCube



If UHECRs are 100% AGN-originated (heavy) nuclei, we would have already seen EeV neutrinos

AGN unlikely

though not completely ruled out

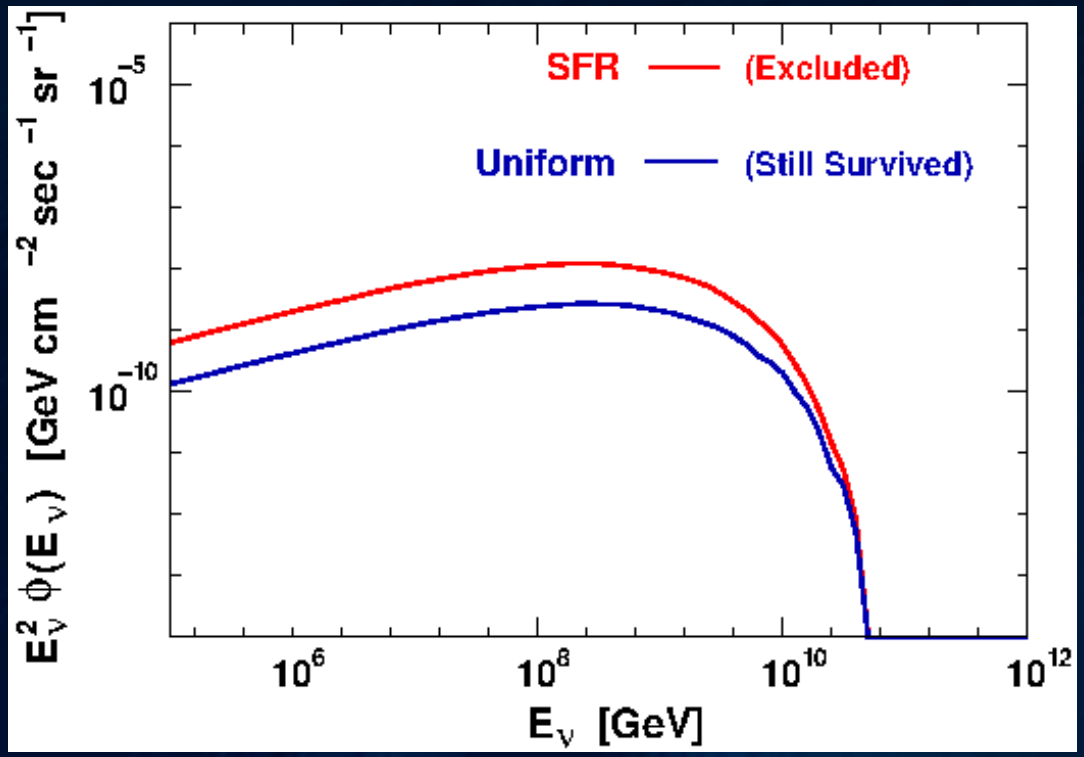
TeV PeV EeV

IceCube tests on *on-source* ν models

New-Born young pulsars

Ke, Kotera, Olinto, Murase, PRD 2014

The highest energy CRs
are HEAVY nuclei



If the fast-spinning pulsars evolves with cosmic time like the standard star formation, we would have EeV seen ν s

Pulsars unlikely

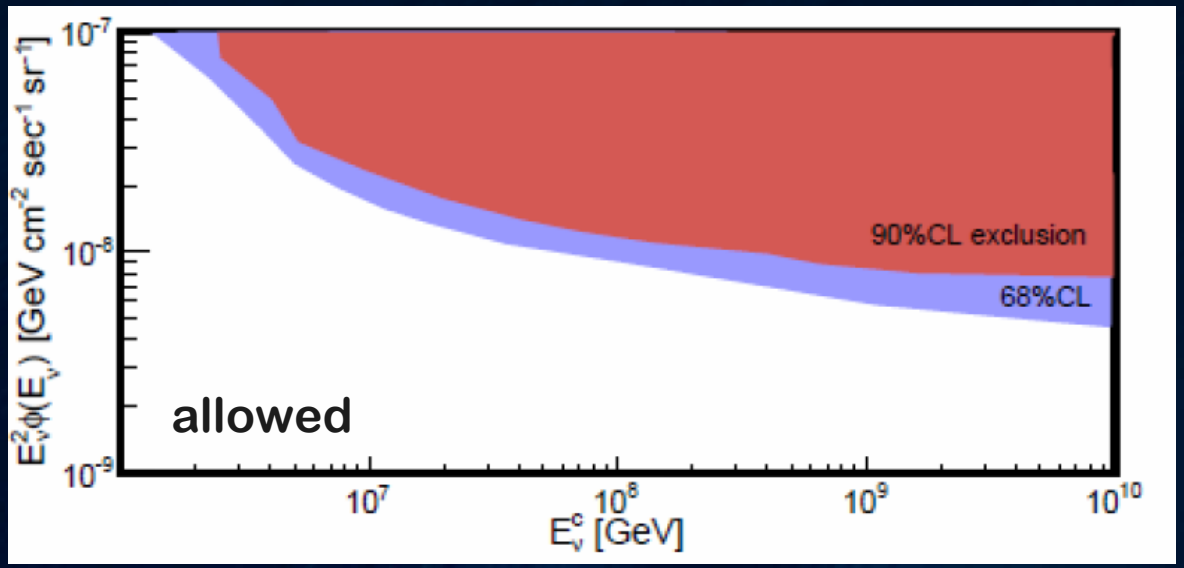
though not completely ruled out

TeV PeV EeV

IceCube generic constraints on *on-source* EeV ν models

excluded

Preliminary

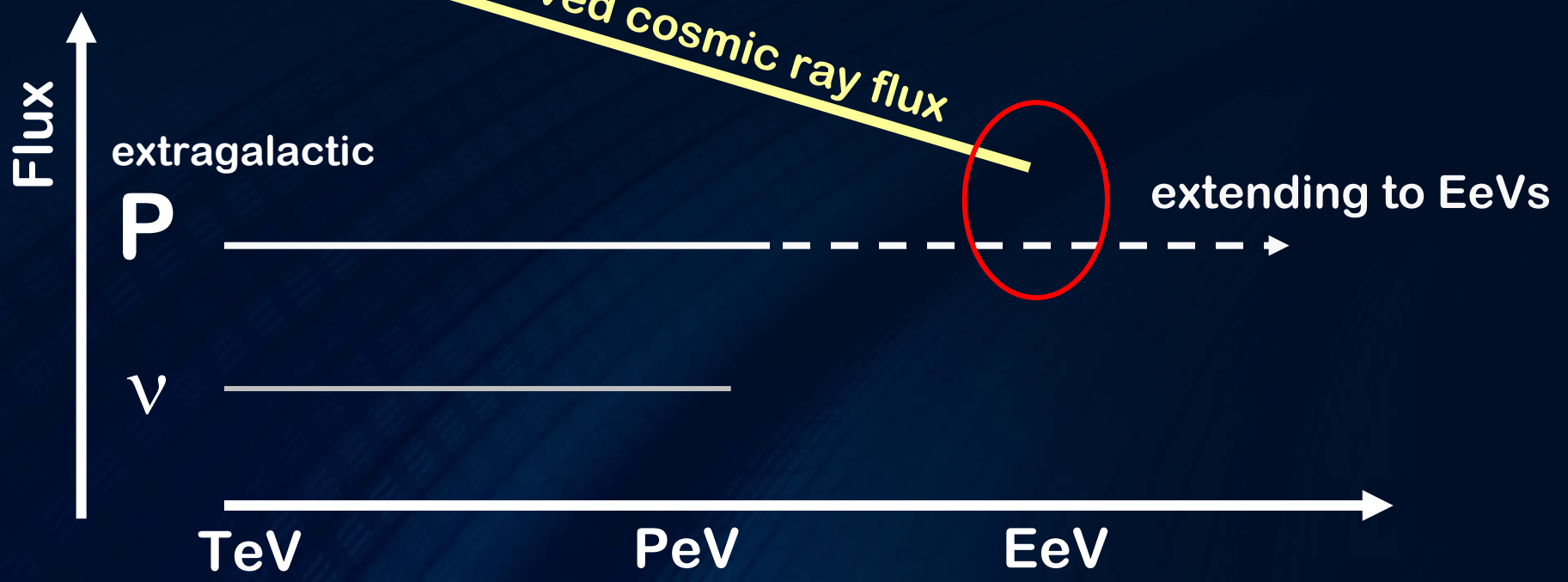


$E^2\phi(E) \sim$ a few $\times 10^{-9}$

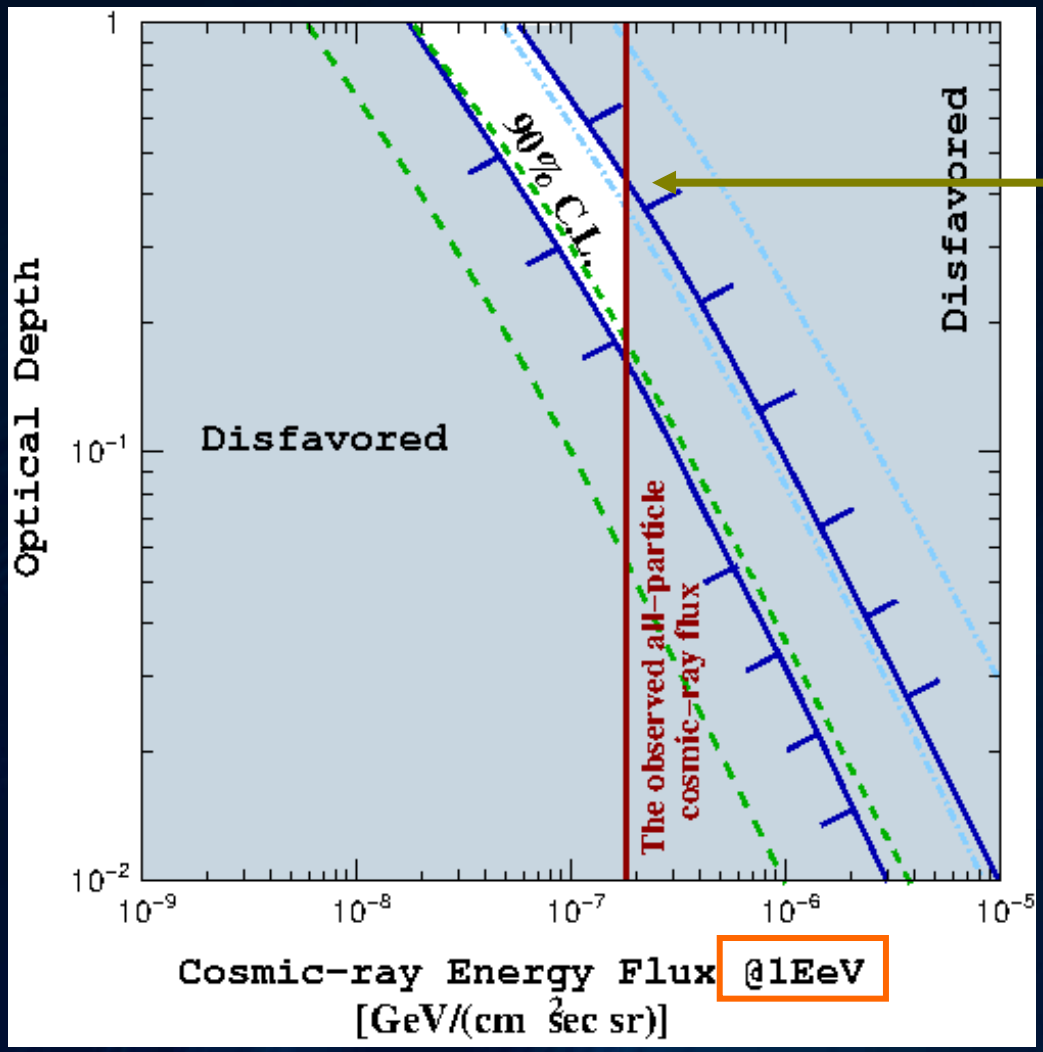
[GeV cm^2 s^{-1} sr^{-1}]

Connections between the observed TeV-PeV ν flux and UHECRs

If the TeV-PeV ν emitters are *also EeV (not 100EeV)-CR sources….*



Extra-galactic protons must dominate in the EeV-energy Cosmic Rays



Yoshida, Takami
PRD (2014)

- extra-galactic proton flux must *dominate* in the all-particle CR flux @ 1 EeV(=1000PeV)
- optical depth must be ~1

TeV PeV EeV

Summary

Two PeV-ish events detected. No EeV events in the IceCube 7 year-long data

IF UHECRs are proton-dominated
(consistent with the TA's claim)

UHE sources are not populated at far universe

~~AGN~~

~~GRB~~

The "standard" UHRCR models are dead

IF UHECRs are nuclei-dominated

(Auger is right !)

Exclusion of some on-source ν models started to constrain popular sites for UHECR production

Blazar jets may no longer be a plausible UHECR source candidate

TeV PeV EeV

Next move

Multi messenger astronomy

IceCube triggers ToO/follow-up observations in various wavelengths

IceCube Realtime Analysis Chain

muon singlet

good angular resolutions
muon neutrino sensitive
large background chance

veto-based HESE

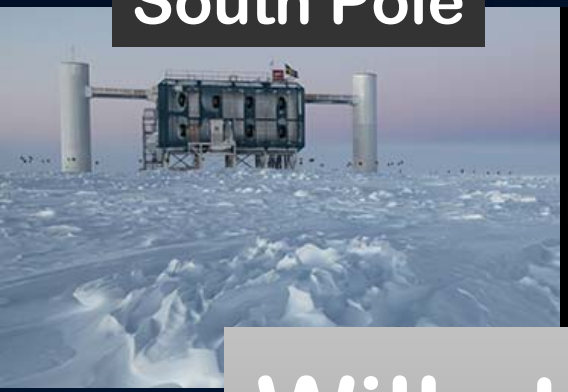
high chance of real cosmic neutrino signals
all neutrino flavor sensitive
angular resolutions mostly poor

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 next year!

Northe

WIPAC
Wisconsin IceCube Particle Astrophysics Center

O(1-2days)

refined results
from iterated reconstructions