# What have we learnt about UHECRs via neutrino astronomy?


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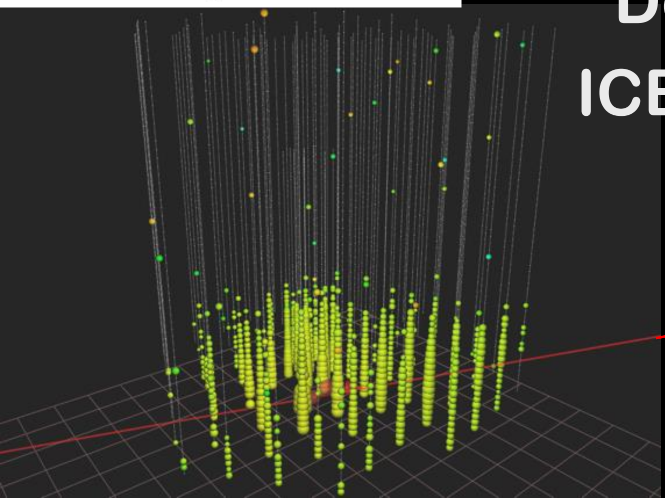
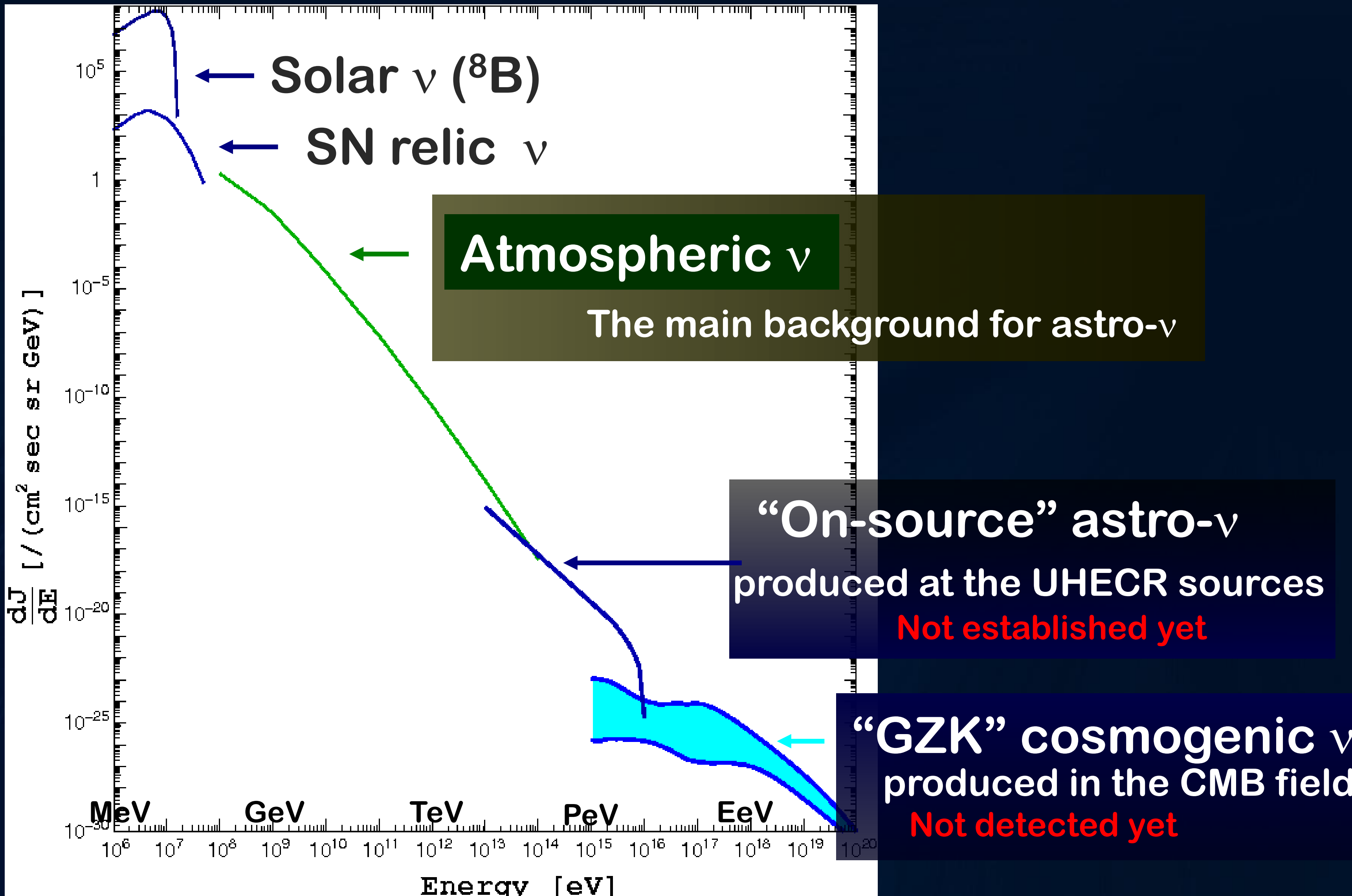


ν

UHECRs

CRIS2016 07.07.2016

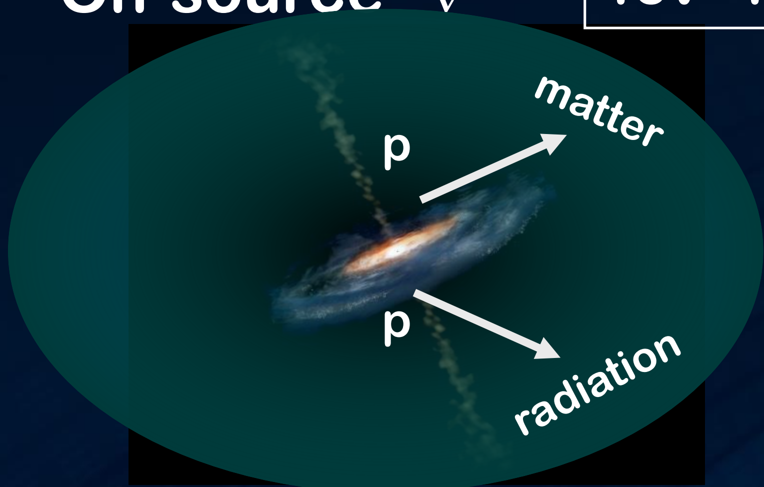
# The Neutrino Flux: overview



# The Cosmic Neutrinos Production Mechanisms

“On-source” ν

TeV - PeV

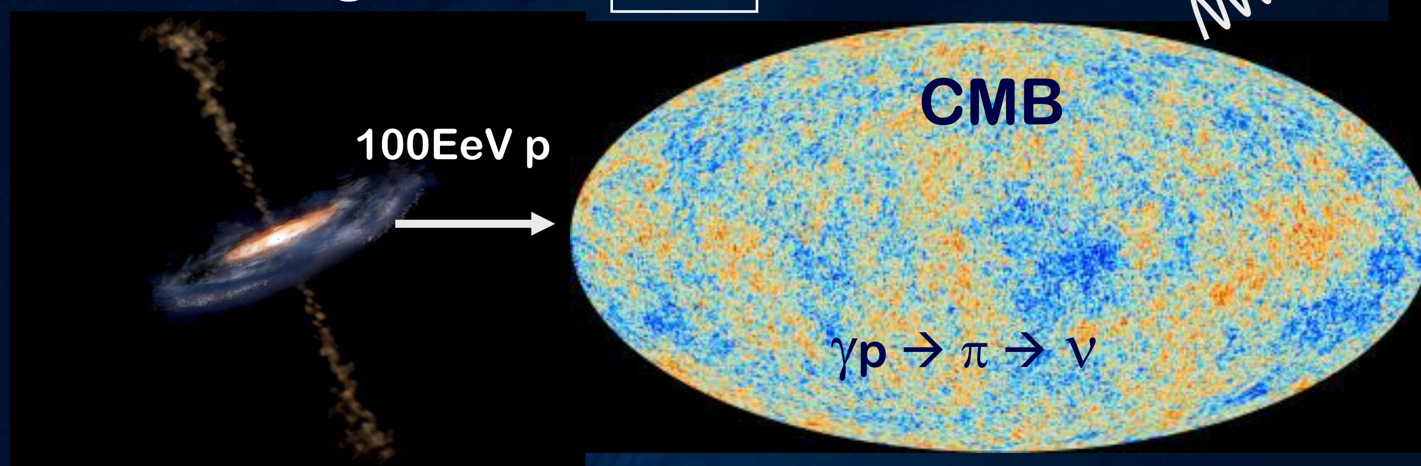



pp → π → ν

γp → π → ν
photopion production

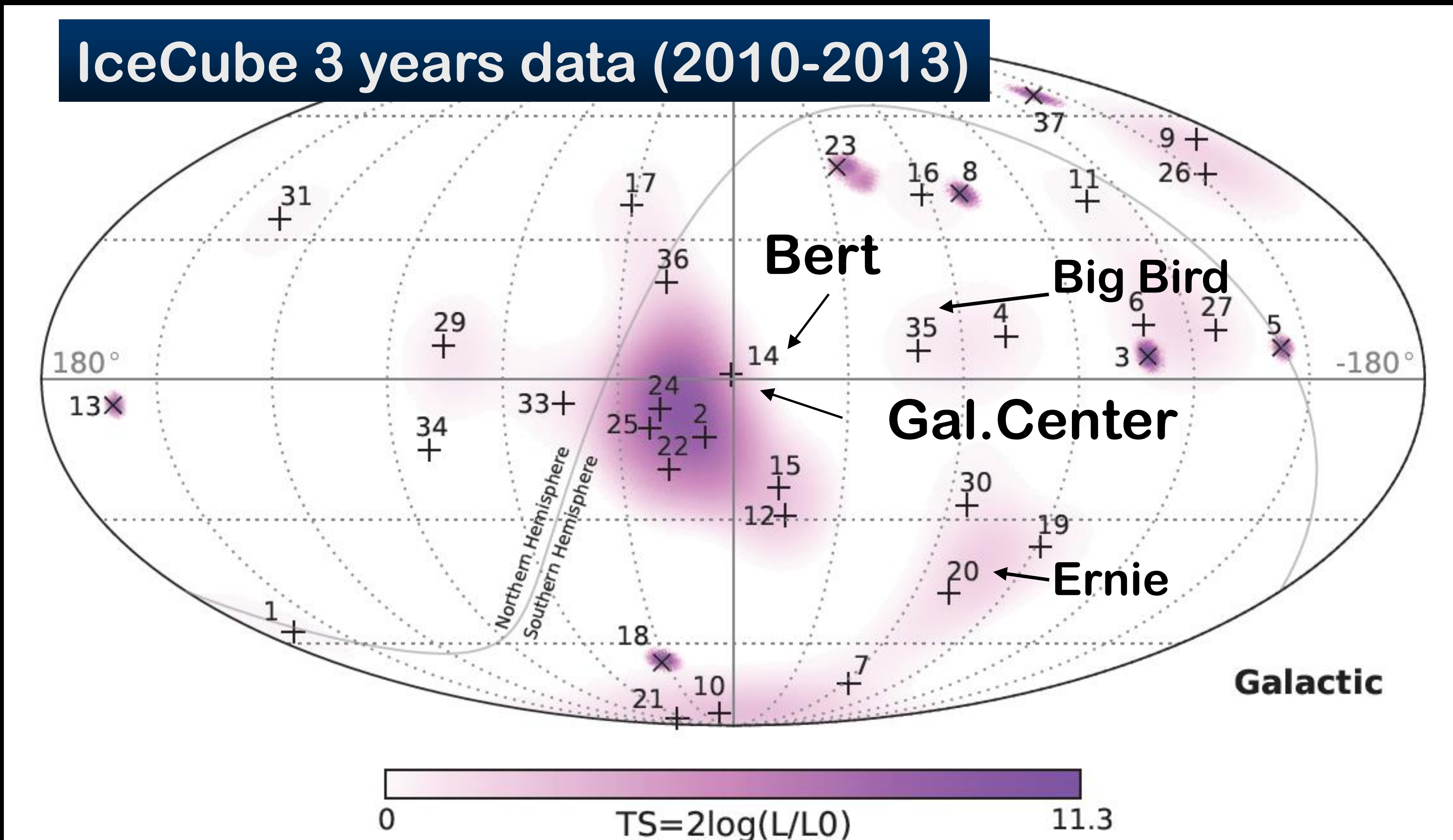

“GZK” cosmogenic ν

EeV



TeV PeV EeV

# Mid Energy (60 TeV-)



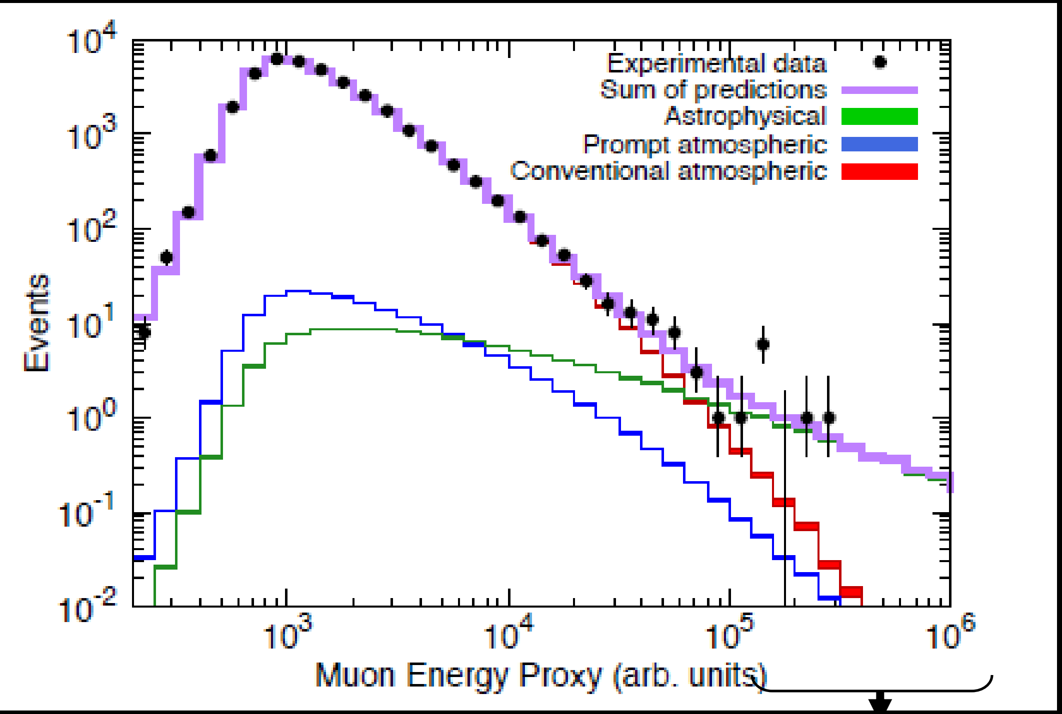
TeV PeV EeV

# VHE (100 TeV-PeV)

**The "traditional" $\nu_\mu$ search looking into upgoing tracks**

IceCube 2 years data (2010-2012)

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




$E_\nu = O(100TeV)$

IceCube collaboration
Phys. Rev. Lett. 115, 081102

**3.9 $\sigma$ excess over the atmospheric BG**

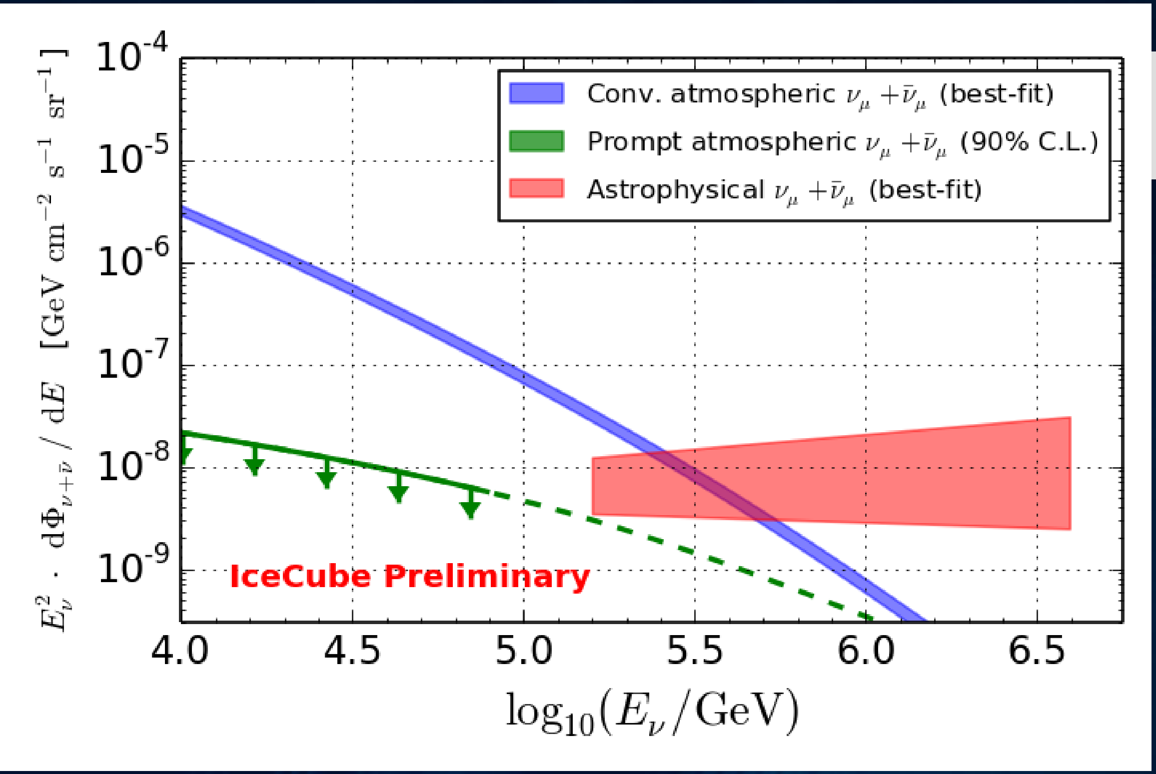
$E^2\ \phi_{\nu_\mu}(E) \sim 9.9 \times 10^{-9}$ [GeV/cm$^2$ sec sr]

TeV PeV EeV

# VHE (100 TeV-PeV)

## up-going $\nu_\mu$ flux detected by IceCube

**With 6 year-long data (2009-2015)**




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

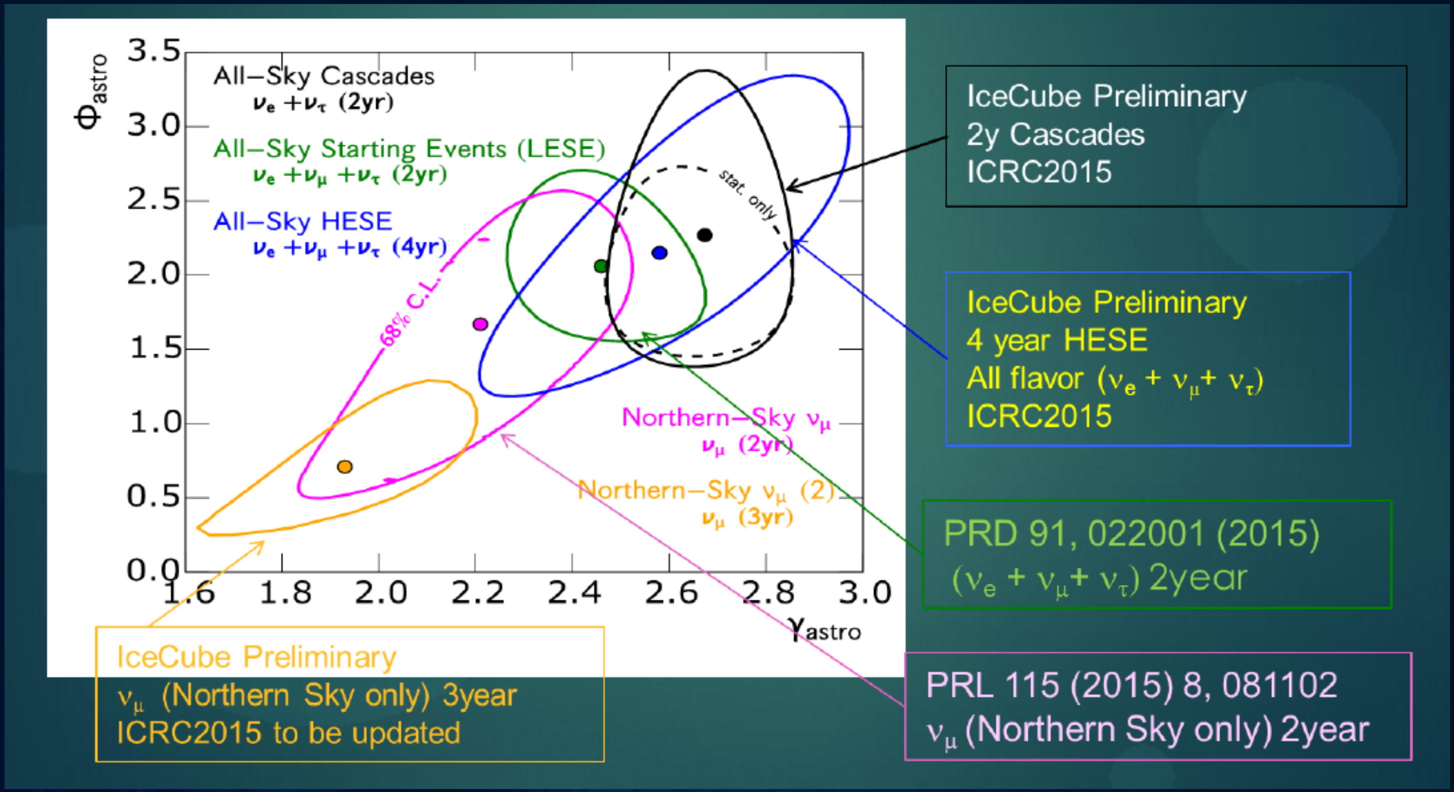
**per flavor flux**

TeV PeV EeV

# Global Picture of TeV-PeV ν fluxes

from ICRC Rapporteur talk/ TeVPA 2015(2015) by A.Ishihara

## Consistent, but ~ 2 σ tension between Cascade and upward $\nu_\mu$



# The Cosmic Neutrinos Production Mechanisms

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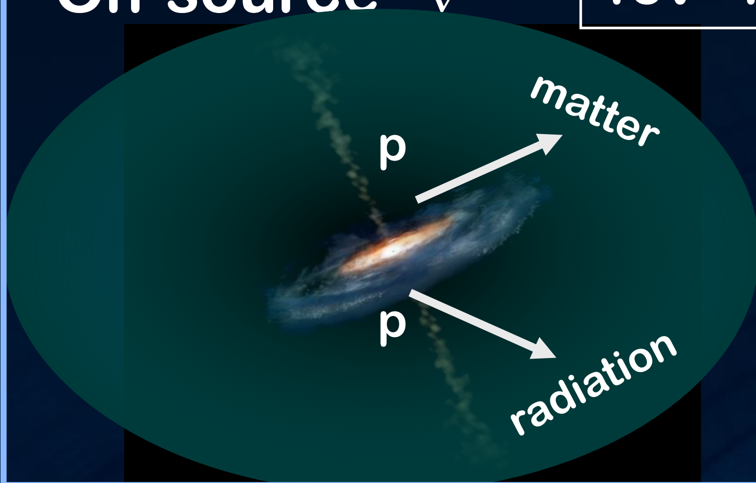



pp → π → ν

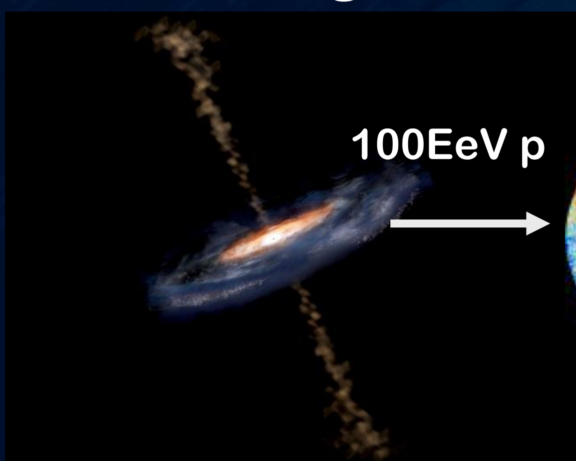
γp → π → ν

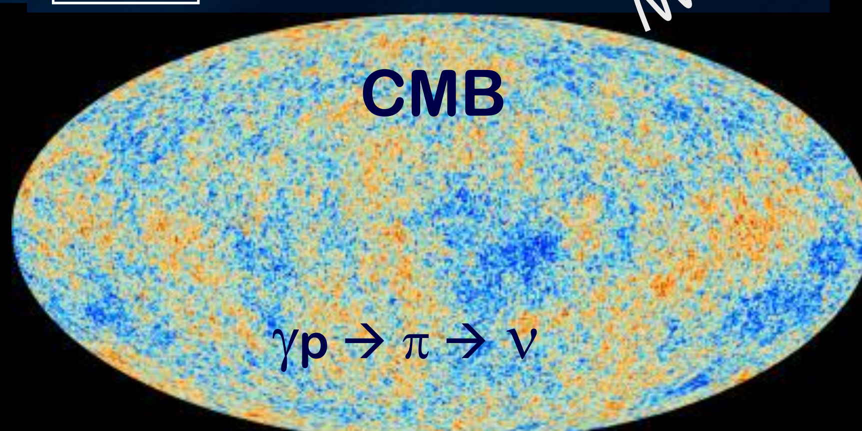
photopion production

ν

"GZK" cosmogenic ν

EeV

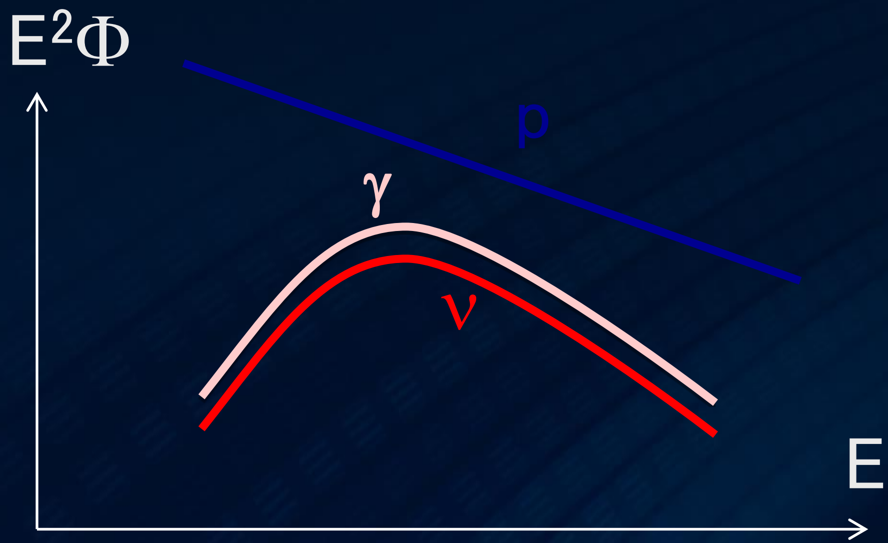


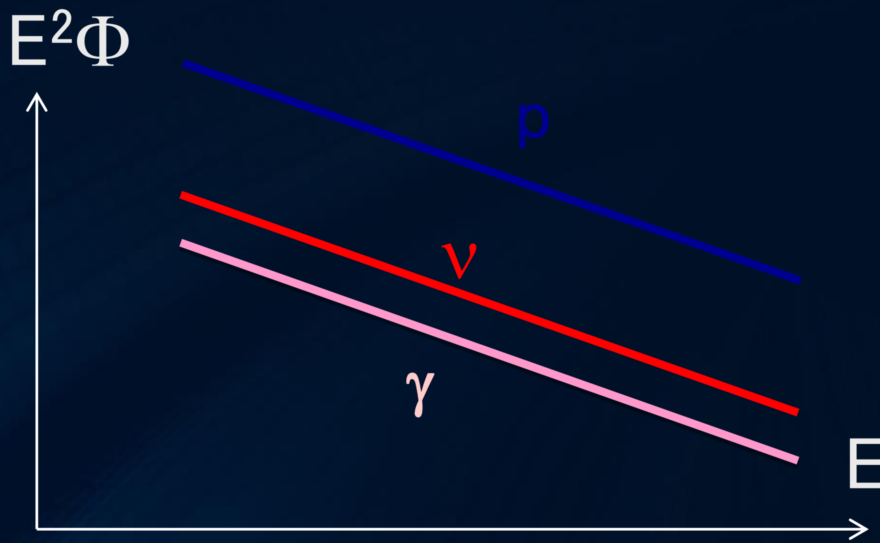



# $\gamma$p? or pp?

$$p + \gamma \rightarrow N\pi + X$$

$$p + p \rightarrow N\pi + X$$



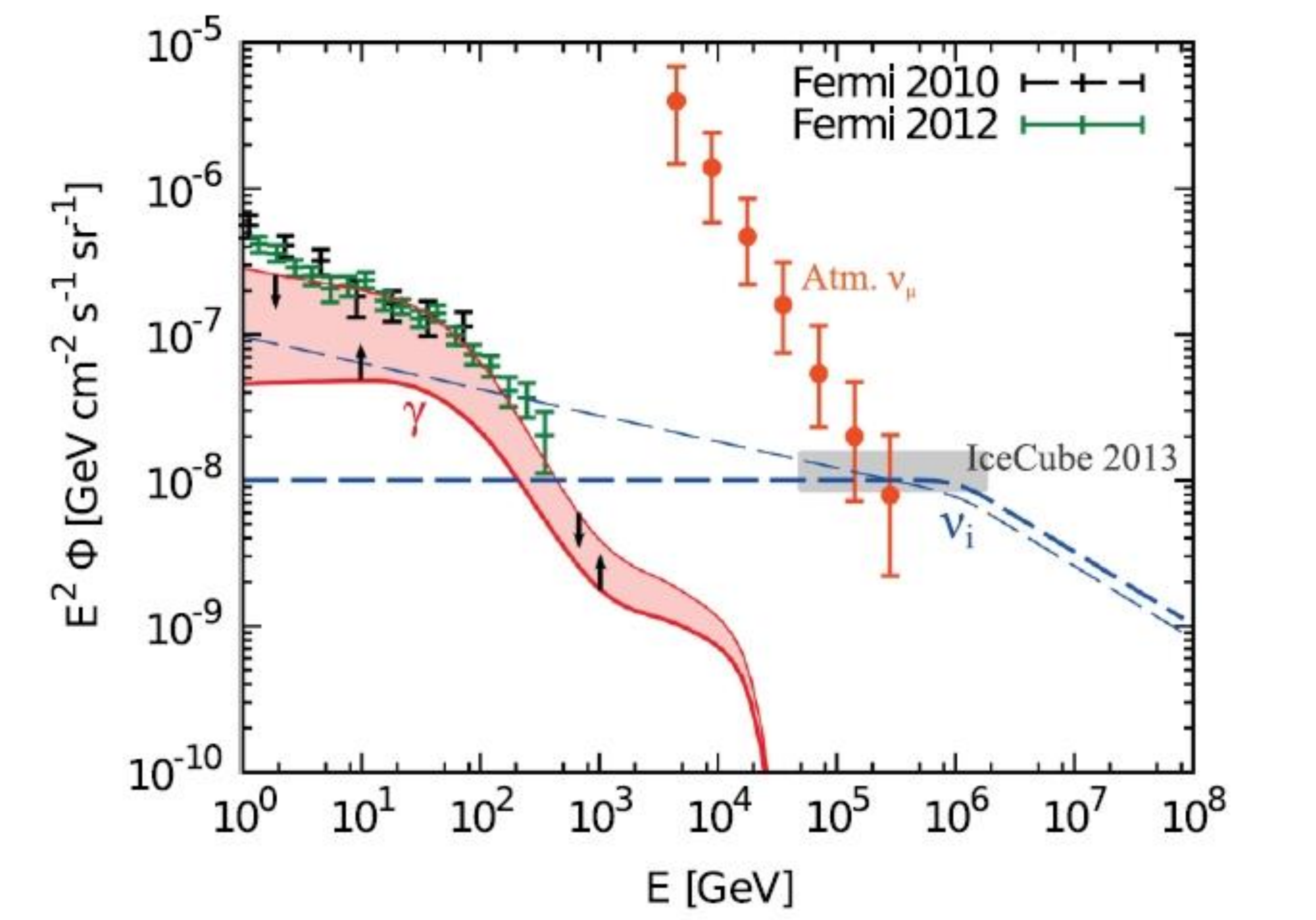

$\varepsilon'_p \, \varepsilon'_\gamma \sim 0.16$ GeV$^2$

**Convolute target $\gamma$ spectrum**

**Copy p spectrum**

# Bounds on pp→ν by Fermi

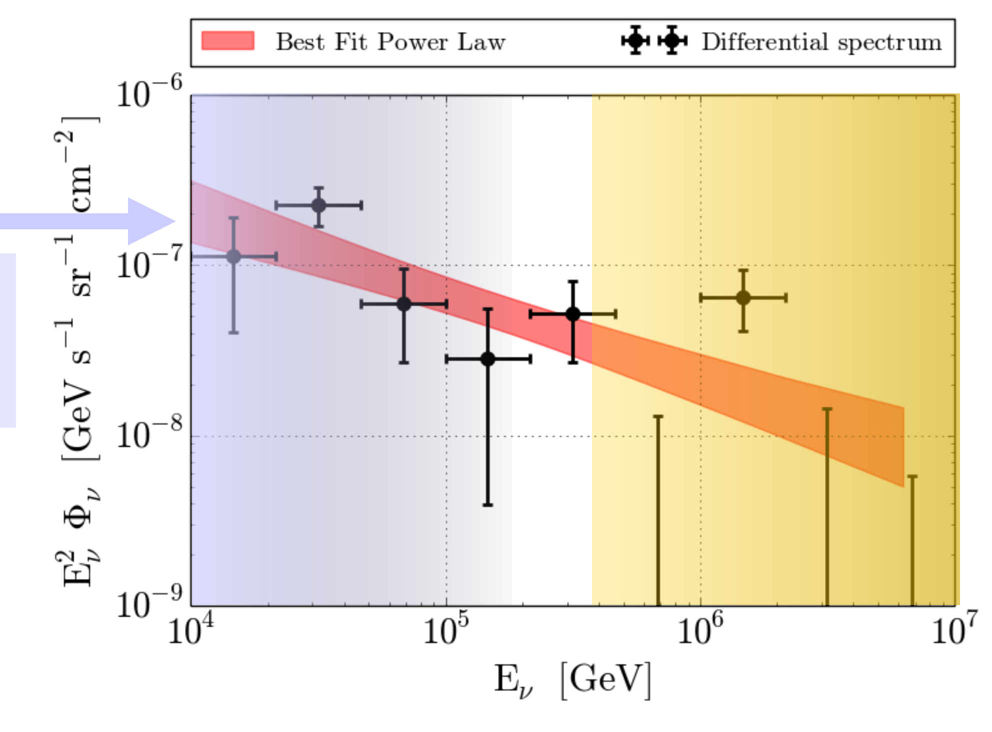
Murase, Ahlers, Lacki, PRD 2013



# A possible scenario

if pp→$\nu$

a tension with Fermi



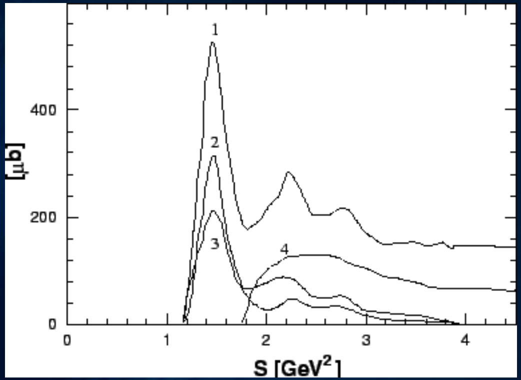

if p$\gamma$→$\nu$

no rich target photons (~ X-rays) to yield TeV $\nu$'s

$$E_\nu \sim 10\mathrm{TeV}\left(\frac{E_\gamma}{1\mathrm{keV}}\right)^{-1}$$

@ obs. frame

threshold effect of the p$\gamma$ reaction



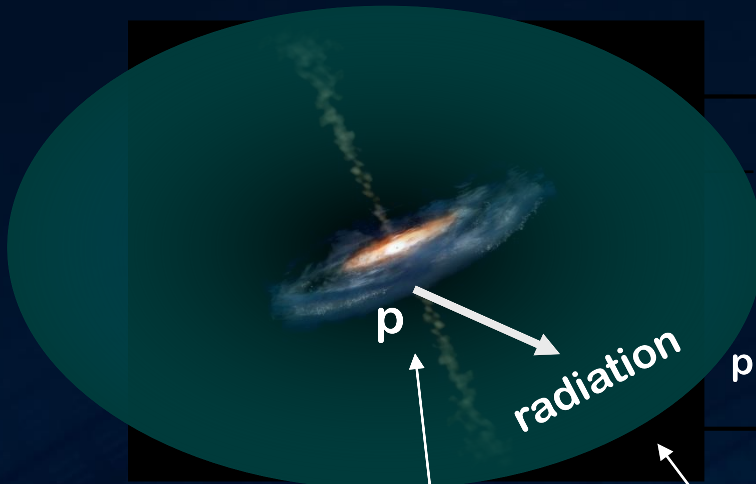

p$\gamma$→$\nu$

$$E_\nu \sim 1\ \mathrm{PeV}\left(\frac{E_\gamma}{10\mathrm{eV}}\right)^{-1}$$

target $\gamma$ visible light/IR

Ly $\alpha$

# Constraints on the optical depth and extra-galactic CR flux




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

photopion production

$\nu$

optical depth
(<1)

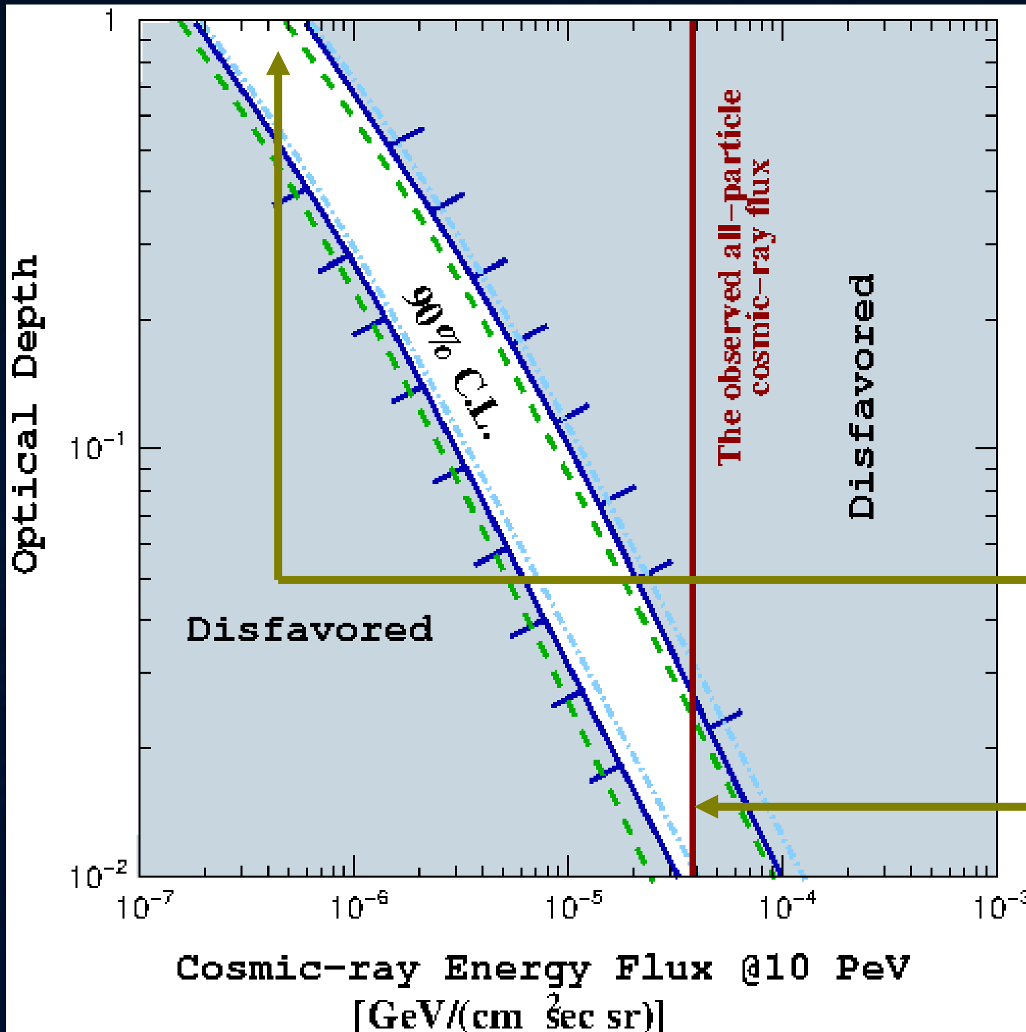
$$\frac{dJ_\nu}{dE} \sim F_{GZK\,CR} \frac{R_{cosmic}}{R_{GZK}} E^{-\alpha} \; \tau(E) \; \zeta(z, m, z_{max}, E)$$

Fixed to the Star Formation Rate

**Constrain them by the IceCube 100TeV-PeV observation**

# Constraints on the optical depth and extra-galactic CR flux

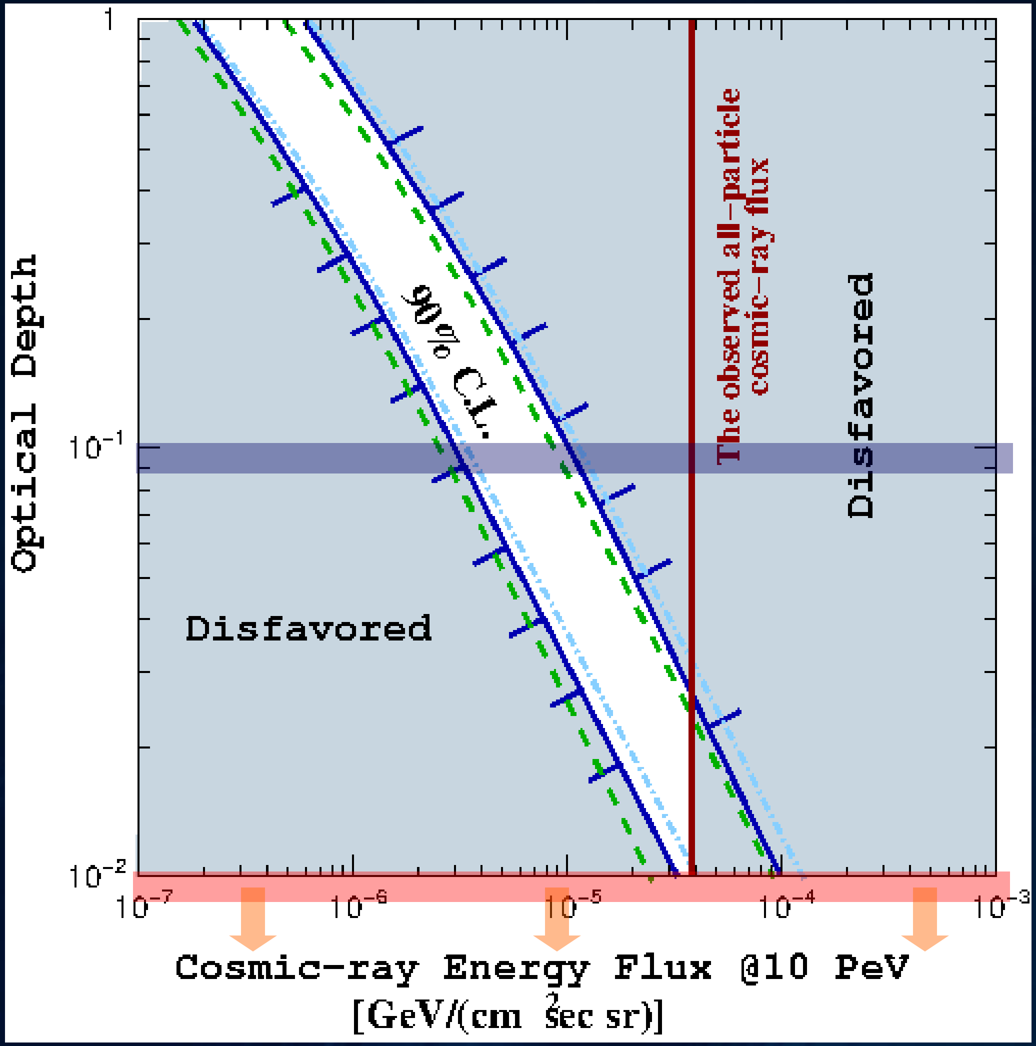
Yoshida, Takami
PRD (2014)




extra-galactic proton flux must be > $10^{-2}$ of the all-particle CR flux @ 10 PeV

optical depth must be > $10^{-2}$

# Constraints on the optical depth and extra-galactic CR flux




Quasars/FR-II

GRBs (internal shock)

energetics

BL Lac/FR-I

GRBs (external shock)

TeV PeV EeV

# subPeV-Energy ν origin

Probably pγ, but not so many candidates

**GRB** $10^{43\text{-}44}$ erg/Mpc$^3$ year

<< 10PeV-CR $10^{46}$ erg/Mpc$^3$ year

**BL Lac**

Leptonic model

τ <<1 → needs a plenty of protons to explain the IceCube flux, would *exceed* the CR flux

Hadronic model

strongly constrained by the trans-PeV to EeV ν observation (will discuss later)

**FSRQ**

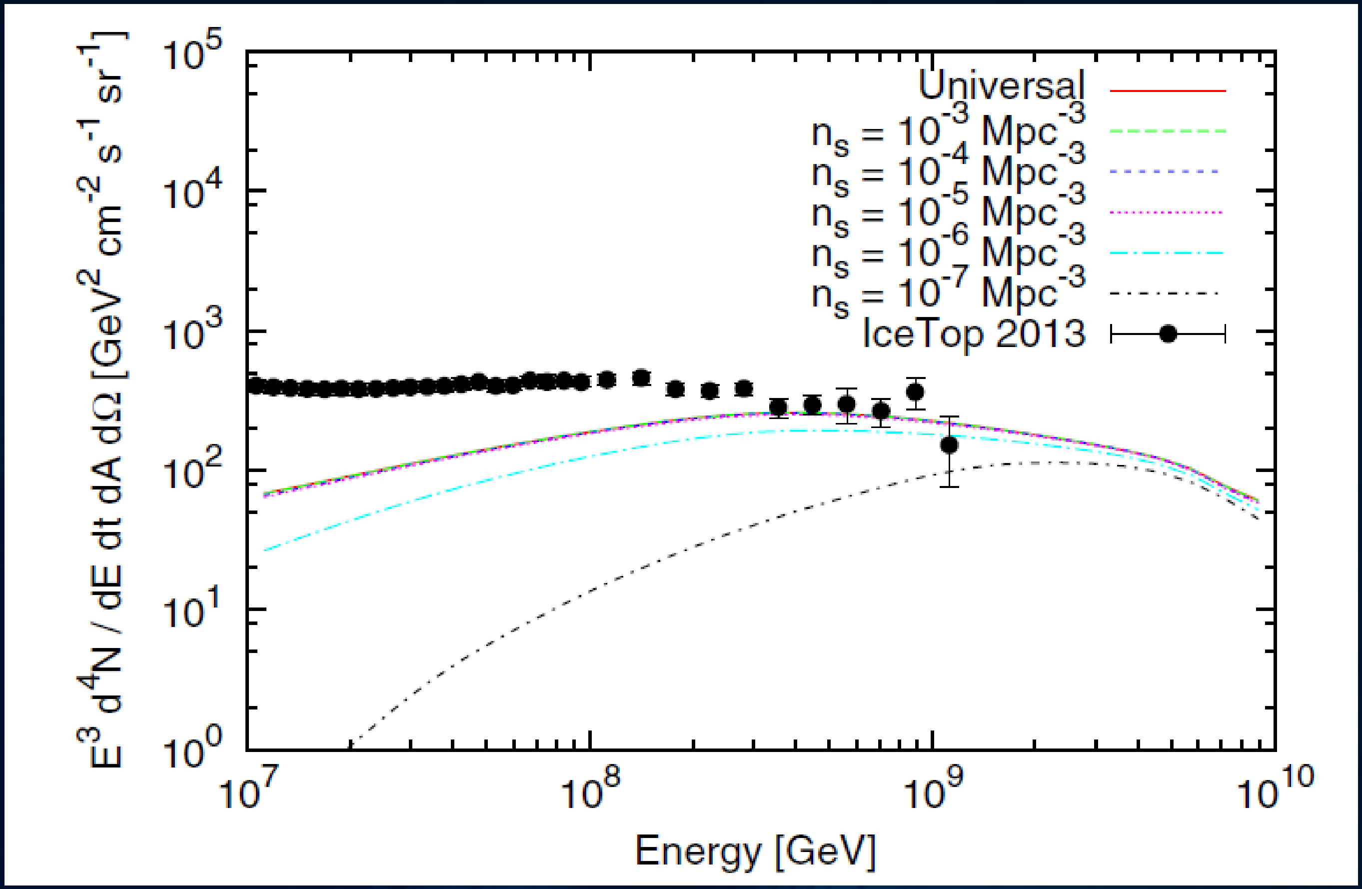
**Sources NOT to emit protons**

GRB choked jet etc.


# subPeV-Energy ν origin

## Decouple ν from CR protons by the magnetic horizon effect?

**works for only rare objects with density < $10^{-6}$ Mpc$^{-3}$**

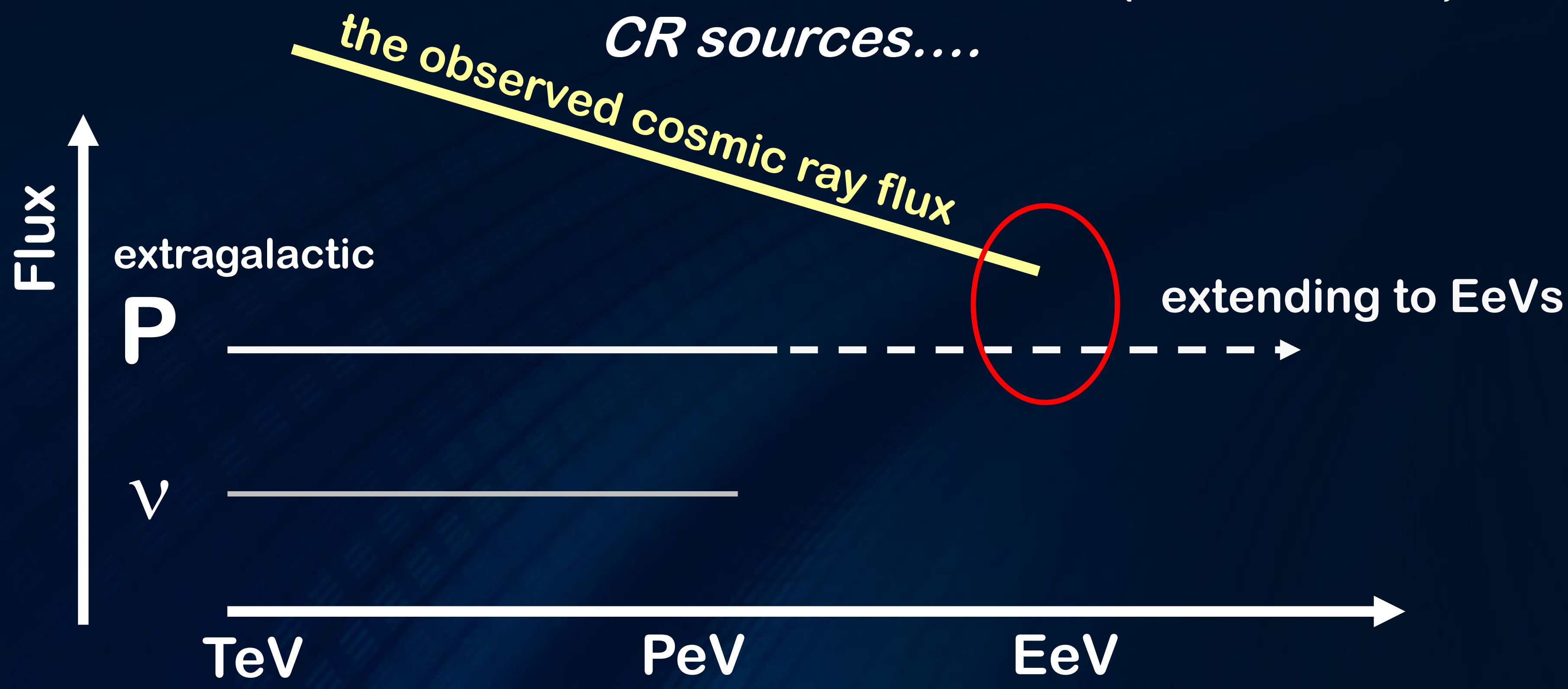



**Yoshida, Takami PRD (2014)**

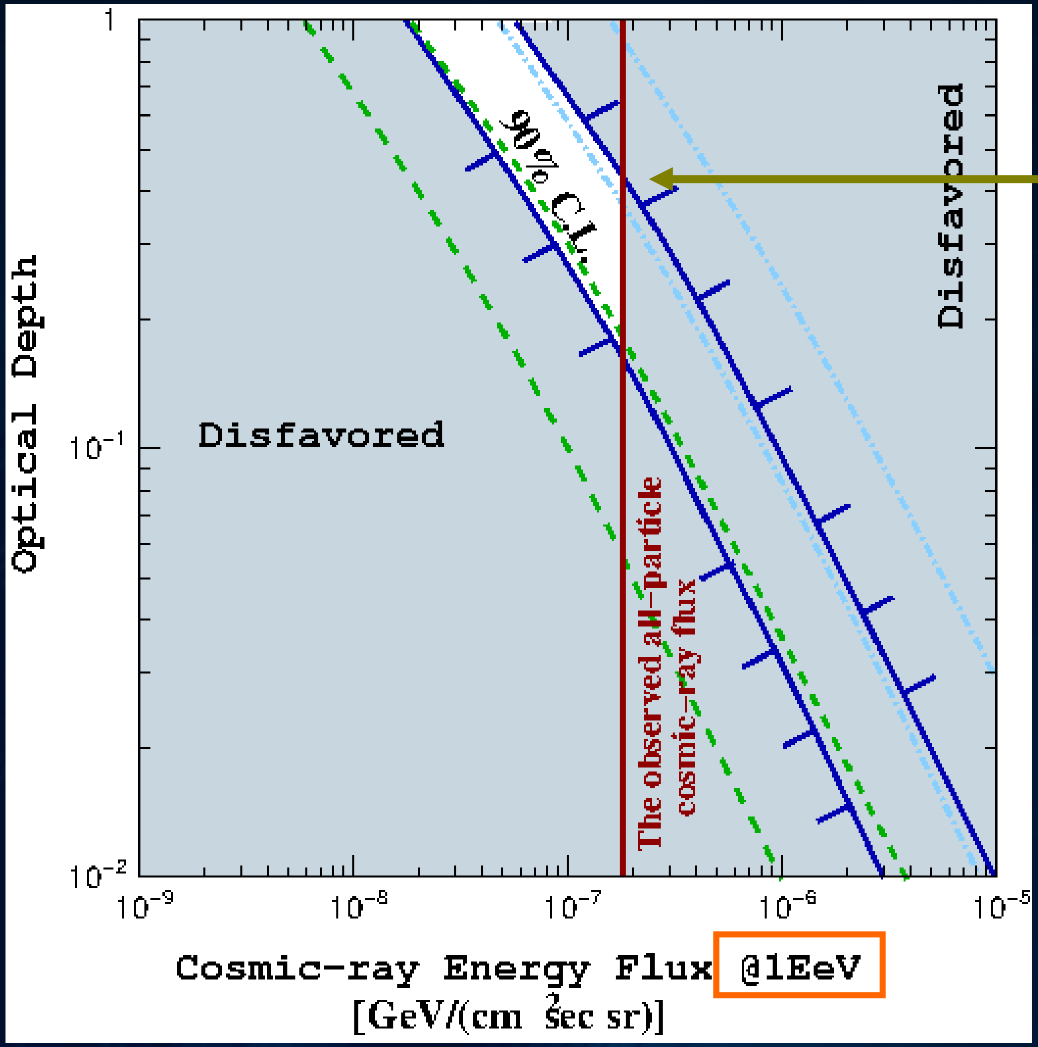
TeV PeV EeV

# The sub-PeV ν emitters = UHECR origin?

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

# The sub-PeV ν emitters = UHECR origin?

**None** of the known objects can realize this

needs optical depth ~ 1!

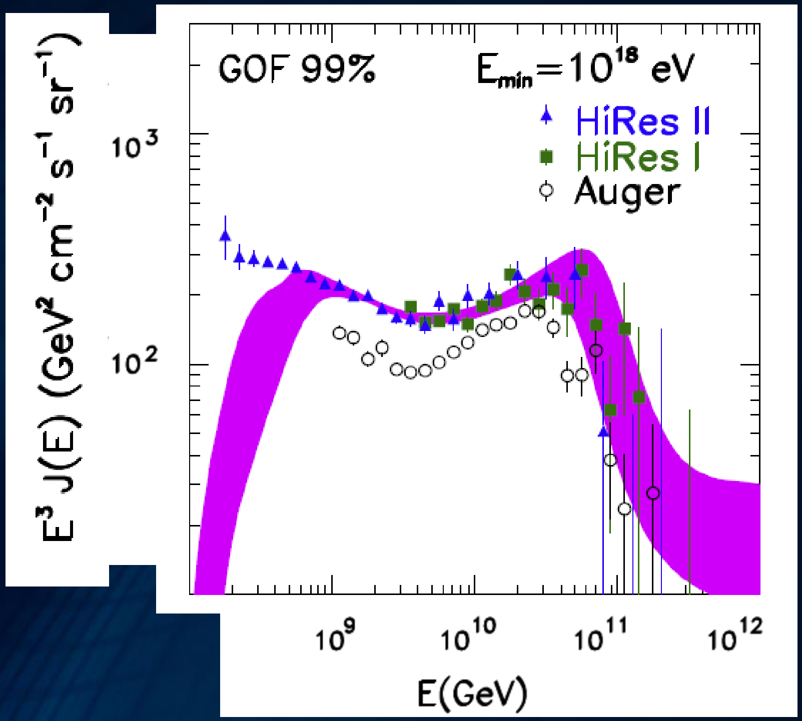
**Unknown** completely new object?

then EeV-energy CRs must be protons!

The “dip” model
of galactic to extragalactic
transition of UHECRs

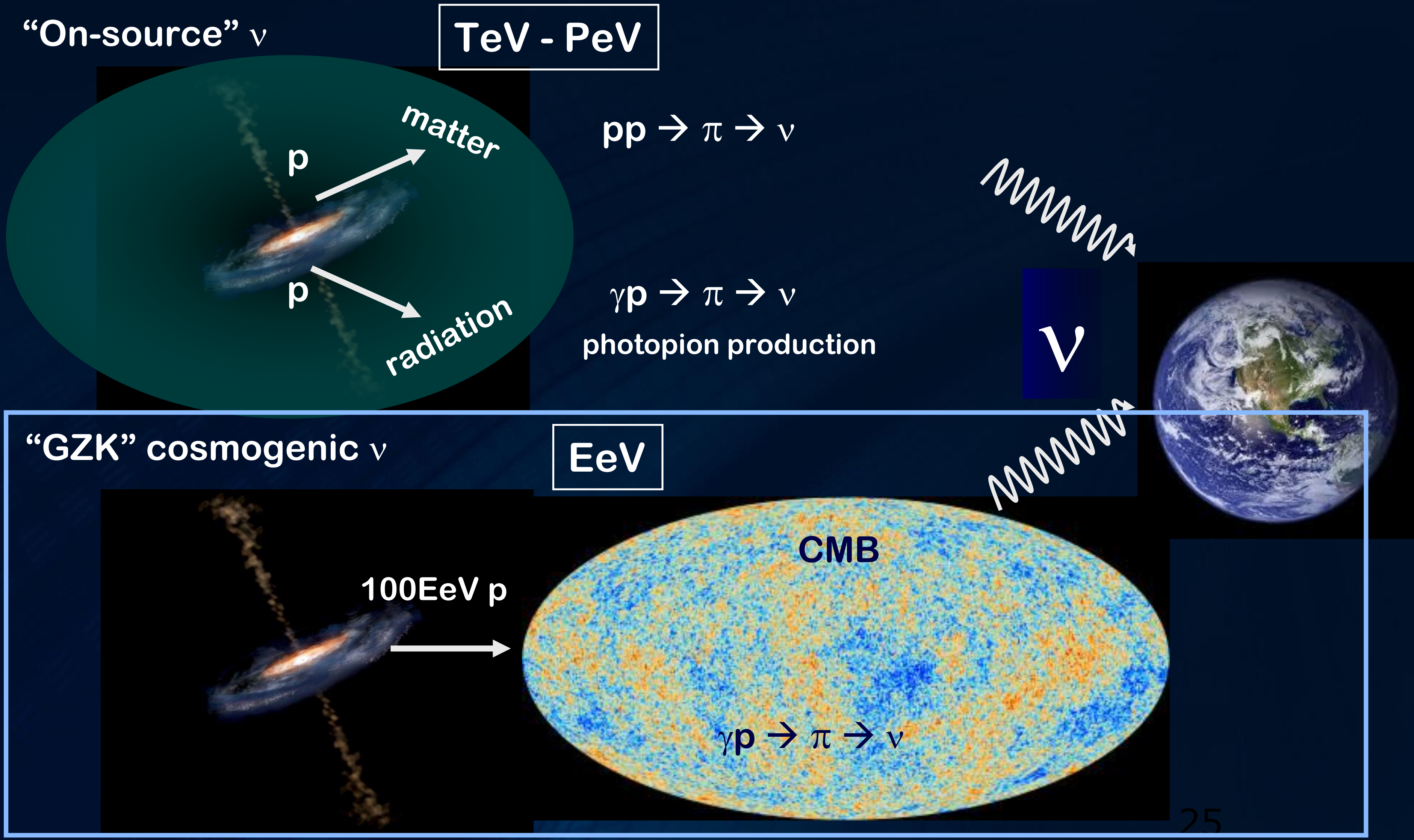
But disfavored by
the IceCube UHE ν observation

(will discuss next)

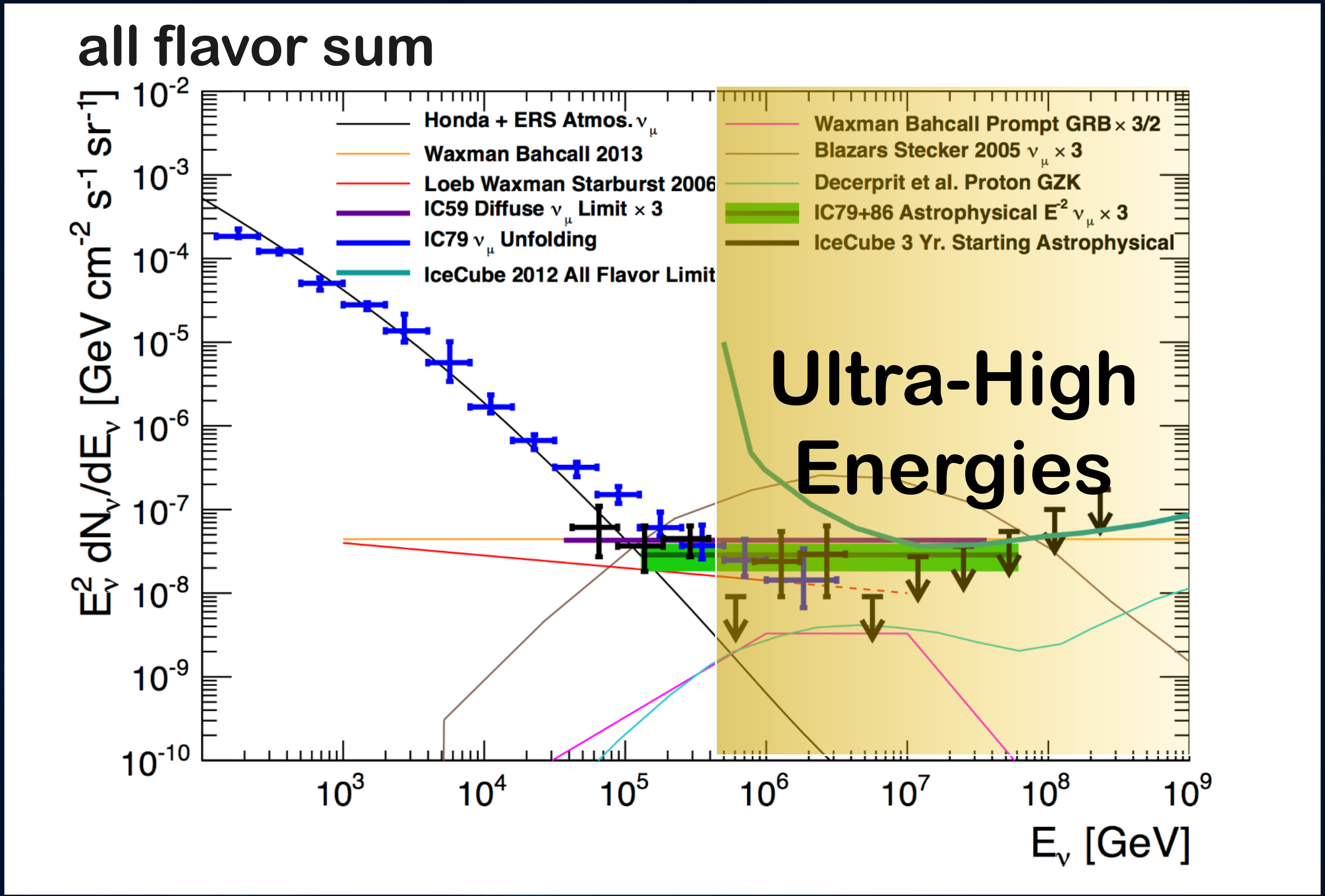



Ahlers et al
2010

# The Cosmic Neutrinos Production Mechanisms



# Summary of the IceCube Diffuse Flux measurements

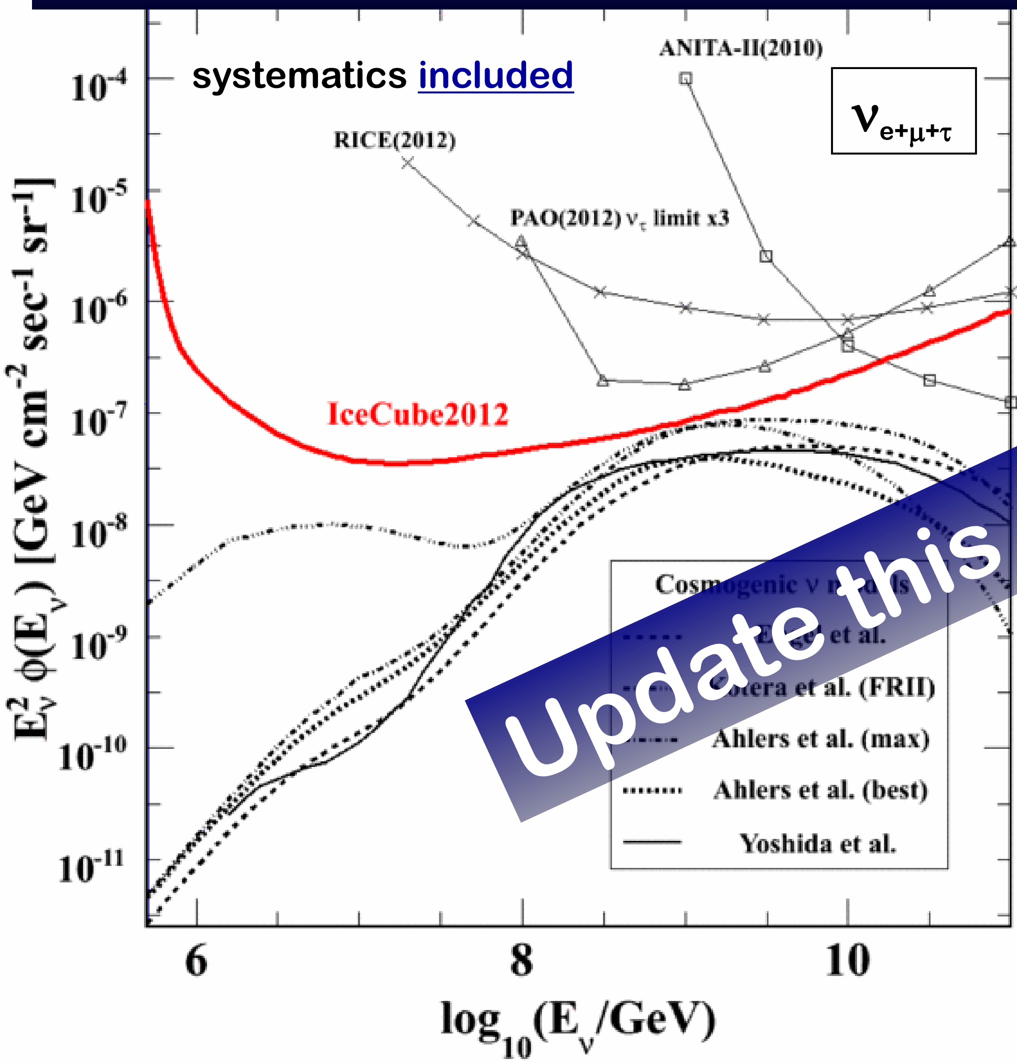


TeV PeV EeV

# UHE (PeV-EeV)

## The model-independent upper limit on flux

### IceCube 2 years data (2010-2012)




**Update this analysis**

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

$6\times10^{7}$ m$^2$ days sr @ 1EeV

= 0.2 km$^2$ sr year

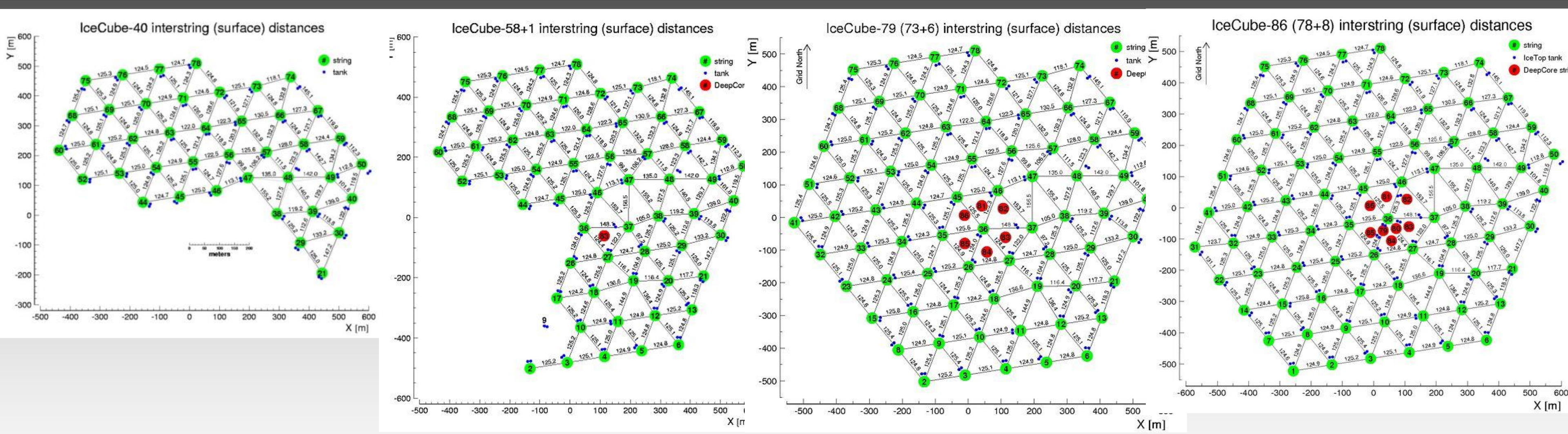
Note: $\phi_{CR}$(>1EeV) ~ 20/km$^2$ sr year

ν with CR comparable flux should have been detected

TeV PeV EeV

# UHE ν search with 7 year long data

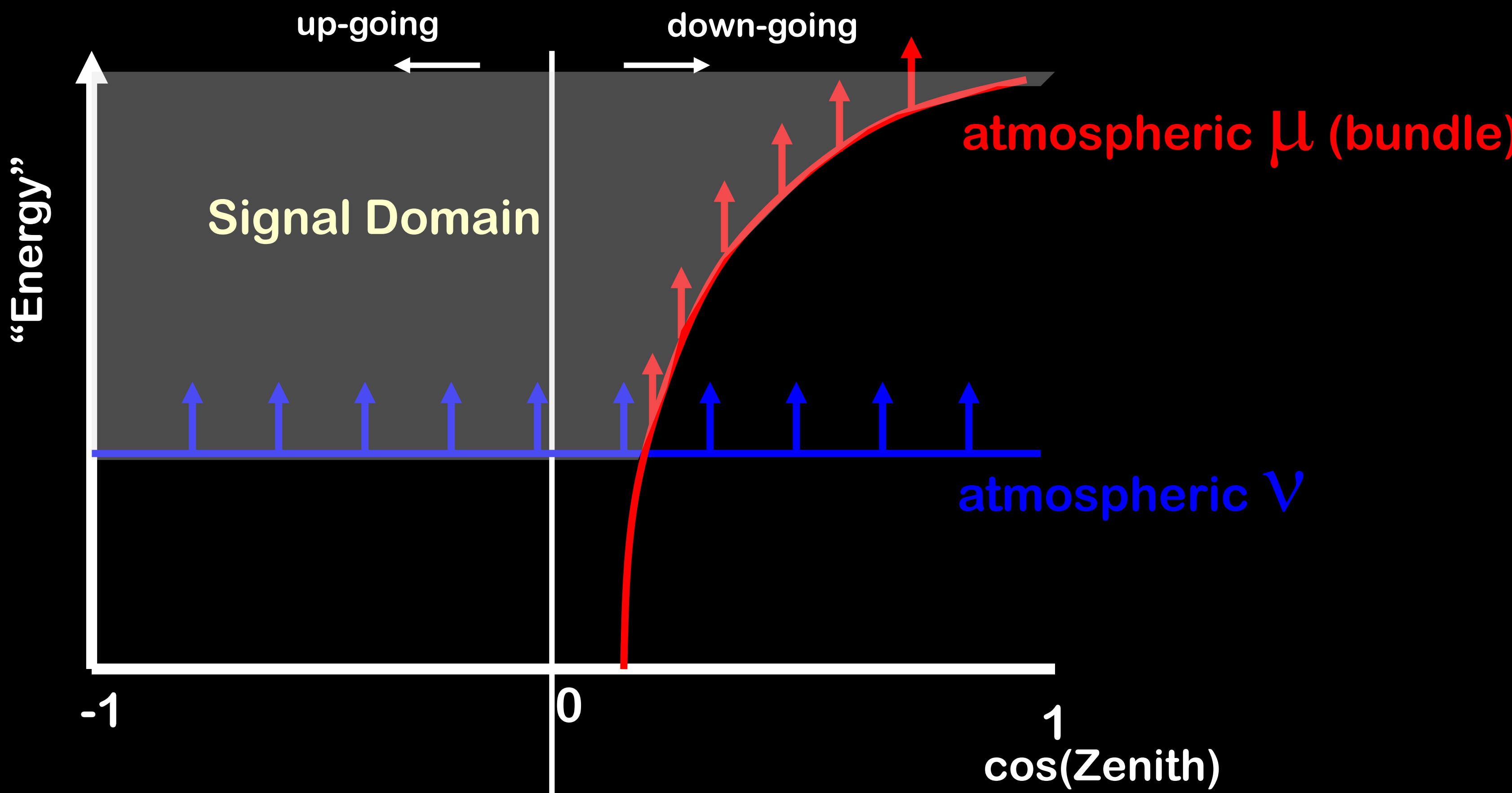
| “IC40” | “IC59” | “IC79” | “IC86” |
|---|---|---|---|
| 2008-2009 | 2009-2010 | 2010-2011 | 2011-2015 |
| 354.8 day | 342.8 day | 312.5 day | 1406.2 day |



TeV PeV EeV

# UHE (PeV-EeV)

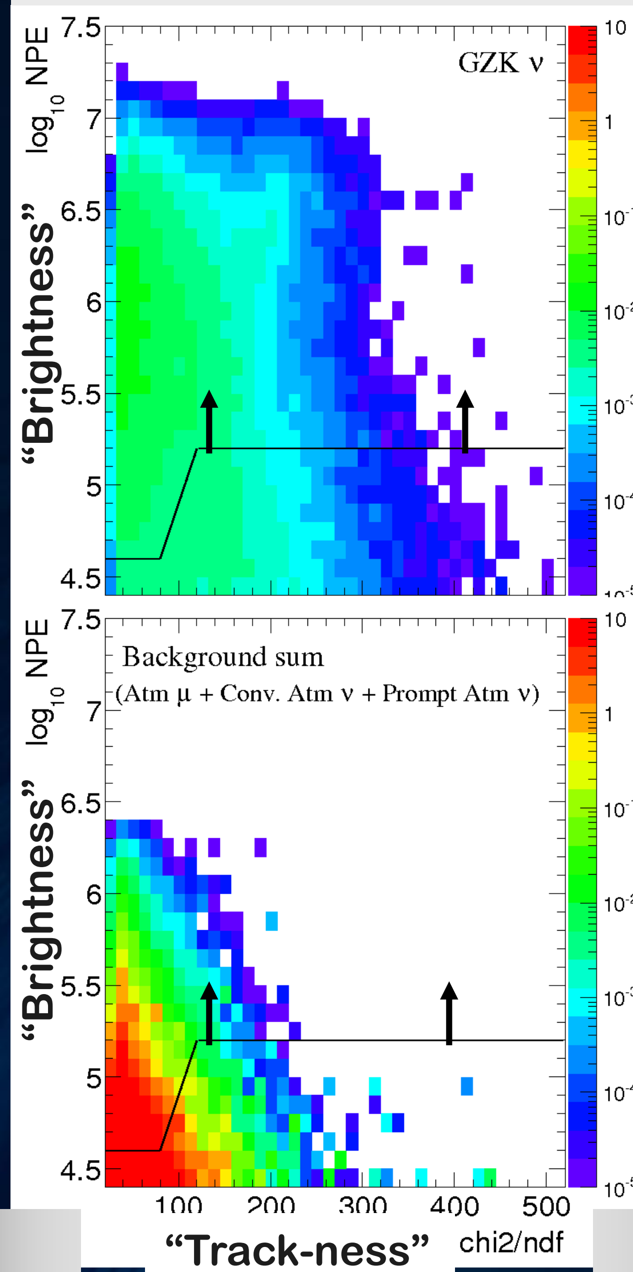
## Detection Principle – All flavor sensitive



# The pre-cuts

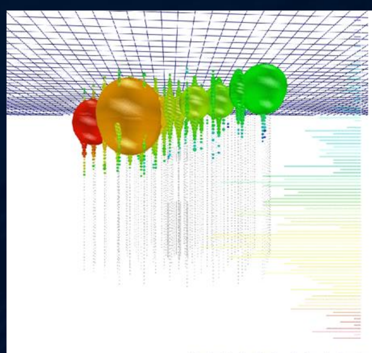
TeV — EeV

$\nu_\mu$ $\nu_\tau$ Charged current



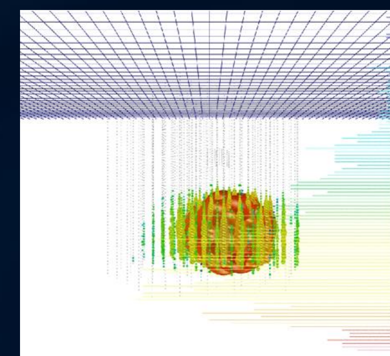

$\nu_e$ → Charged current

$\nu_e$, $\nu_\mu$, $\nu_\tau$ → Neutral current



Track-like events

Softer cuts



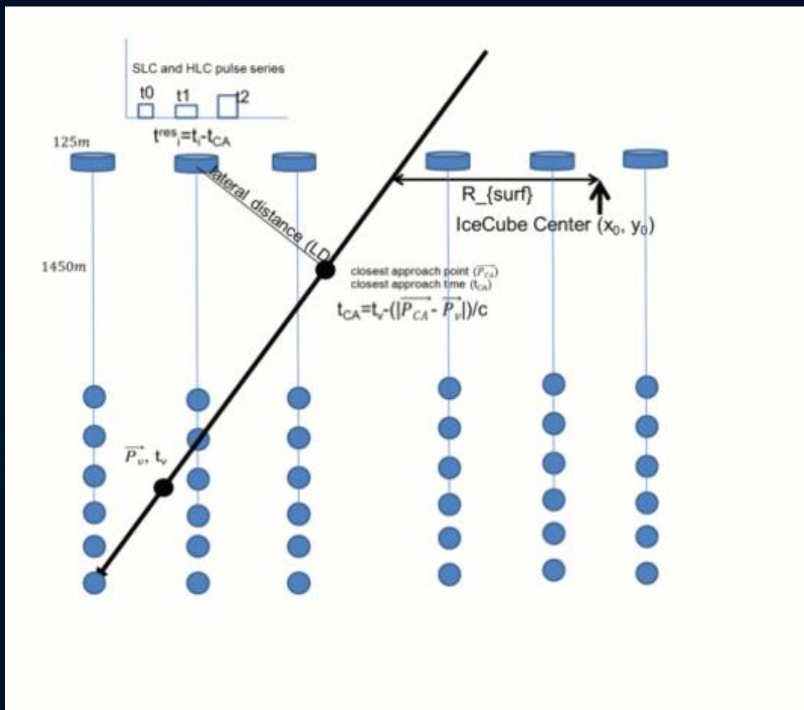
Shower-like events

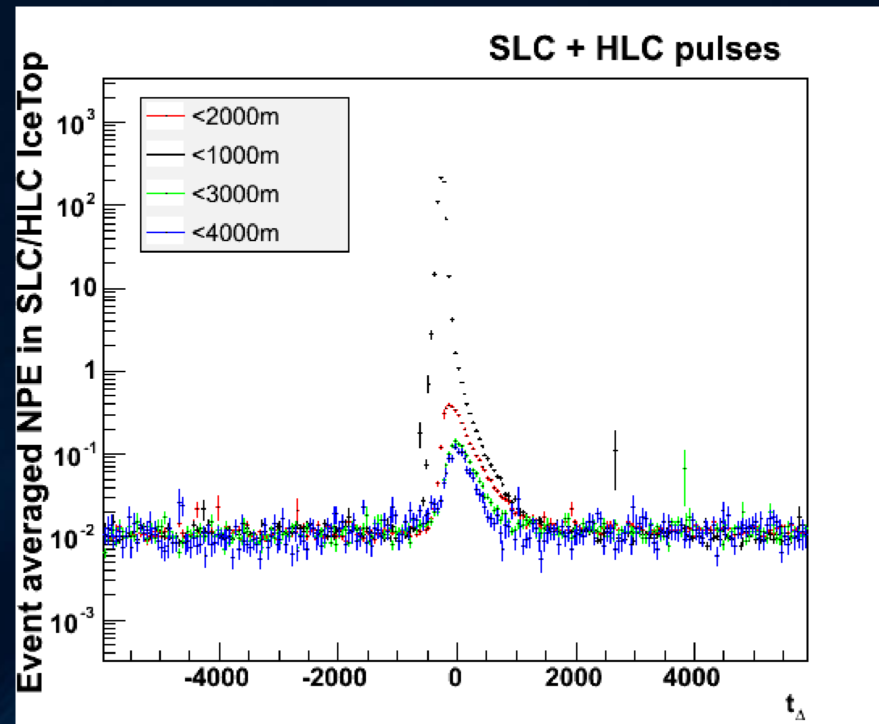
Tighter cuts

TeV PeV EeV

# vetoed by the air-shower array

## We have the IceTop array on the IceCube ice surface



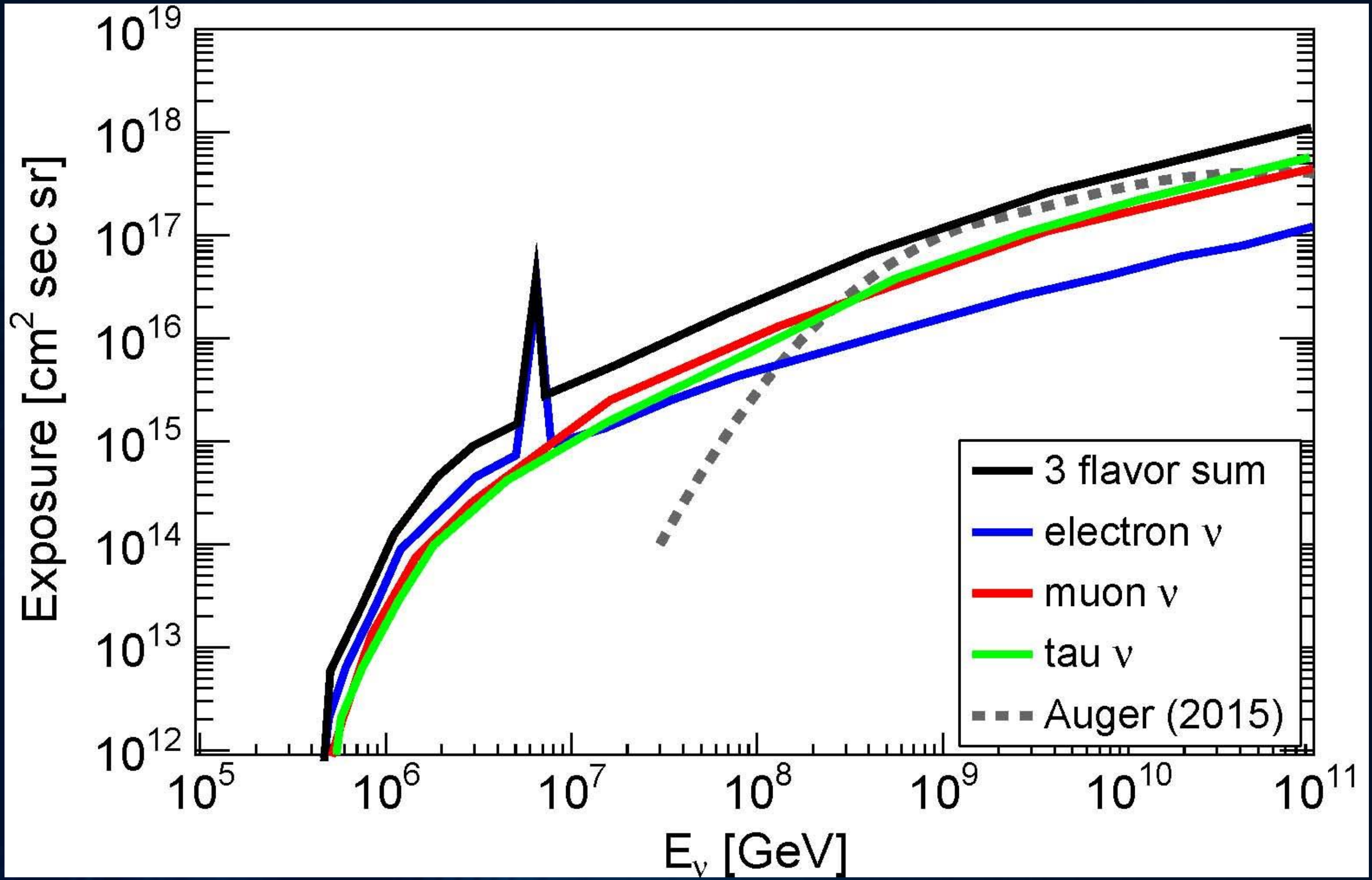

If more than 2 IceTop hits occurs in 1.2 usec window → Label as backgrounds

TeV PeV EeV

# The ν detection effective area

PeV < E < 10 PeV $\nu_e$ sensitive

100PeV < E $\nu_\mu$ $\nu_\tau$ sensitive

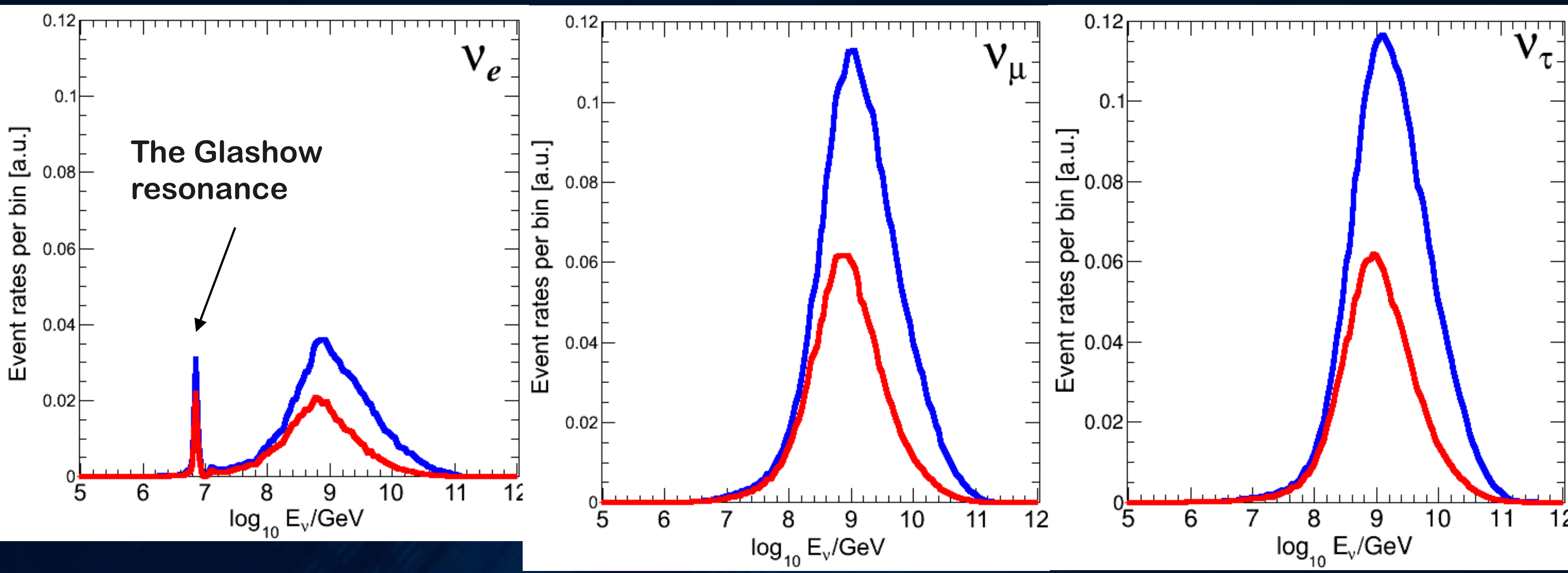


TeV PeV EeV

# Expected Signal Event Distribution

## with GZK-type of spectra

**The main energies : EeV (=1000 PeV)**

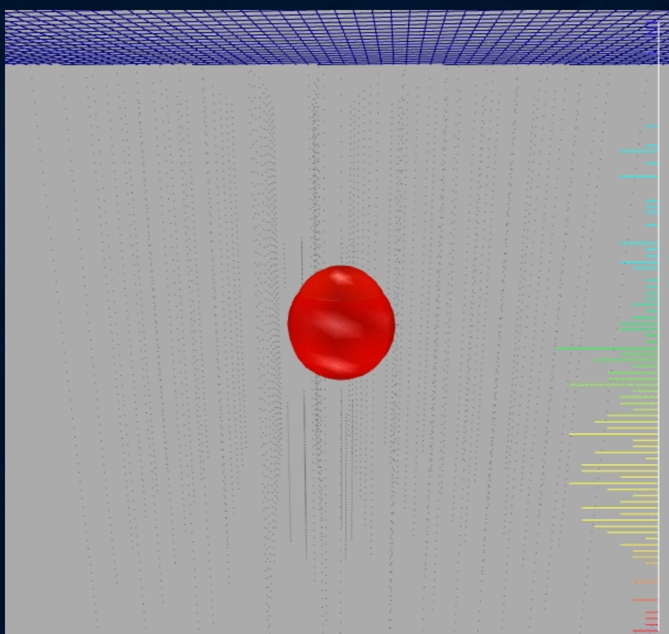


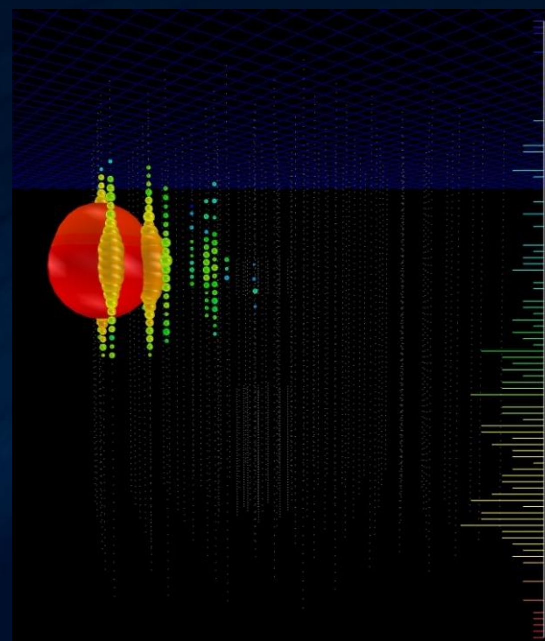
TeV PeV EeV

# Open the box : What we found

## 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.

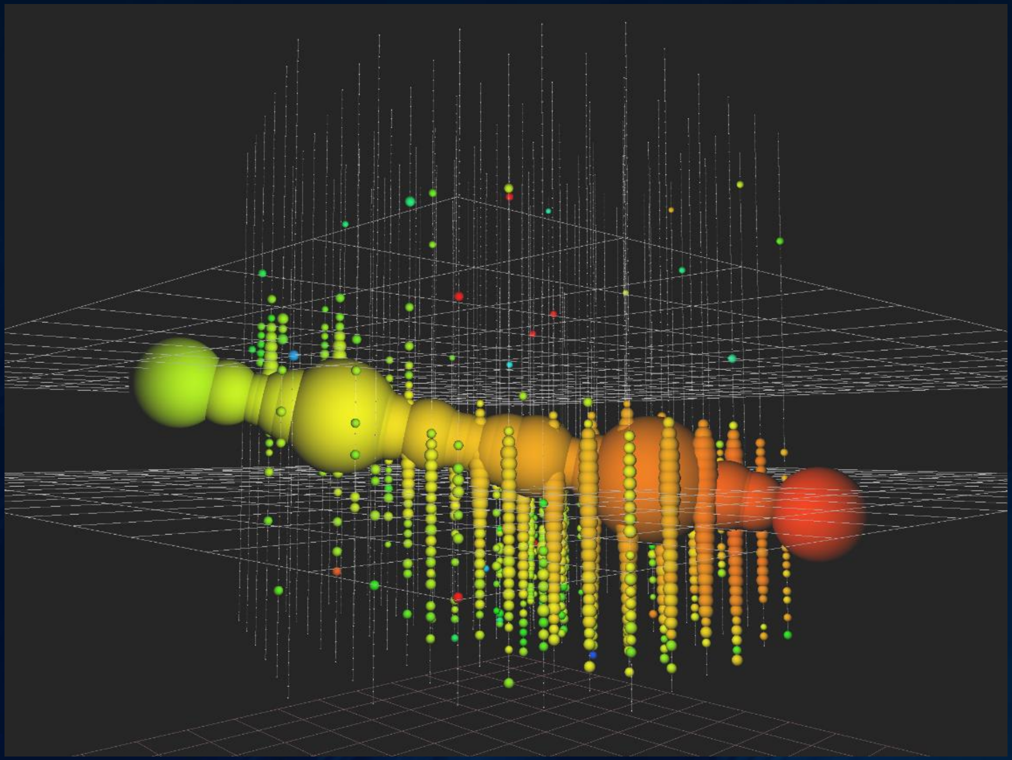
(Probably) the most energetic upgoing event detected by IceCube

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 $\sigma$**
**(expected background rate 0.064)**

**They are not the GZK cosmogenic $\nu$**

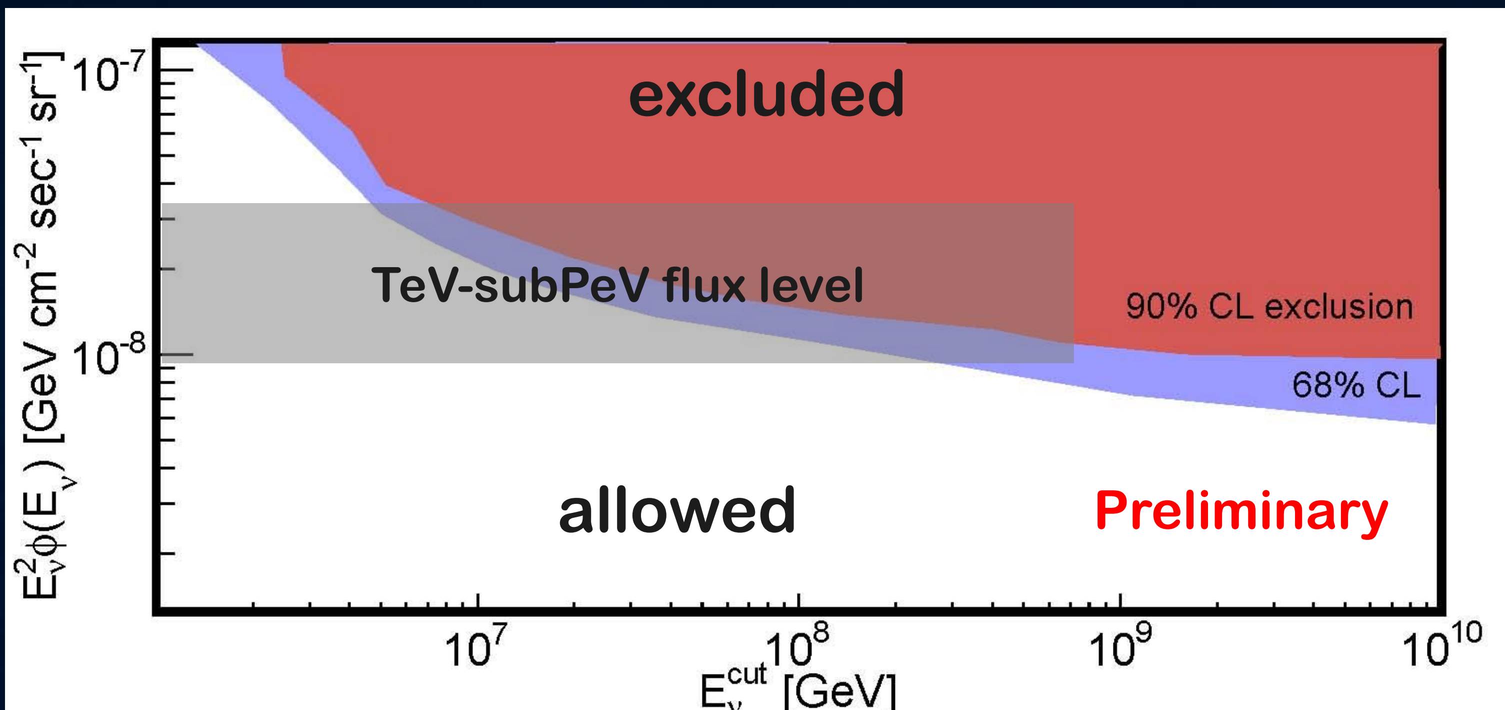
**The GZK hypothesis rejected by ~2.75 $\sigma$**
**favoring ~ $E^{-2}$ type of spectrum**

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

TeV PeV EeV

# A part of the sub PeV cosmic neutrino bulk?

Energy flux




consistent
but <u>must have</u>
<u>a cutoff energy</u>

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 $\nu$ models to constrain UHECR sources**

Robust and solid constraints,
but UHECR composition limited

(Only sensitive to proton-dominated case)

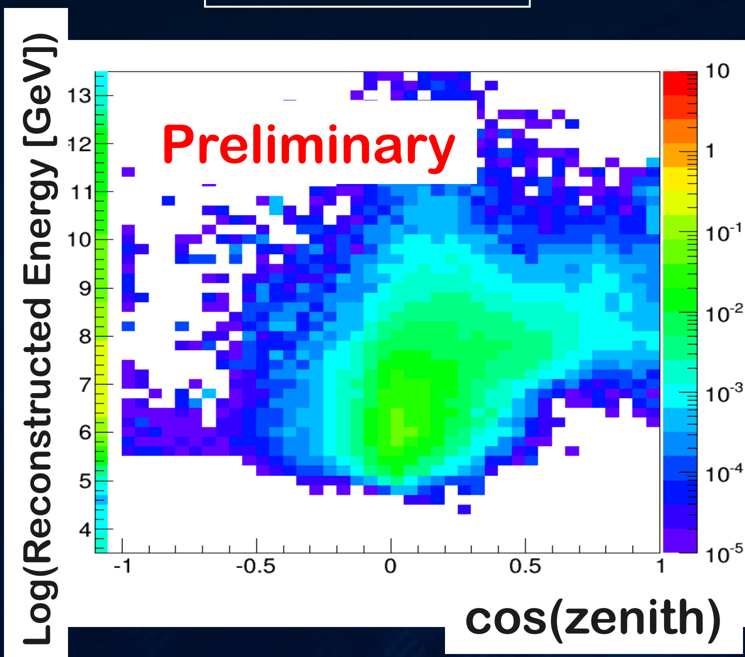
**Test on the on-source PeV-EeV-energy $\nu$ models (ex AGN jets)**

model-dependent arguments
but mixed-composition case reachable

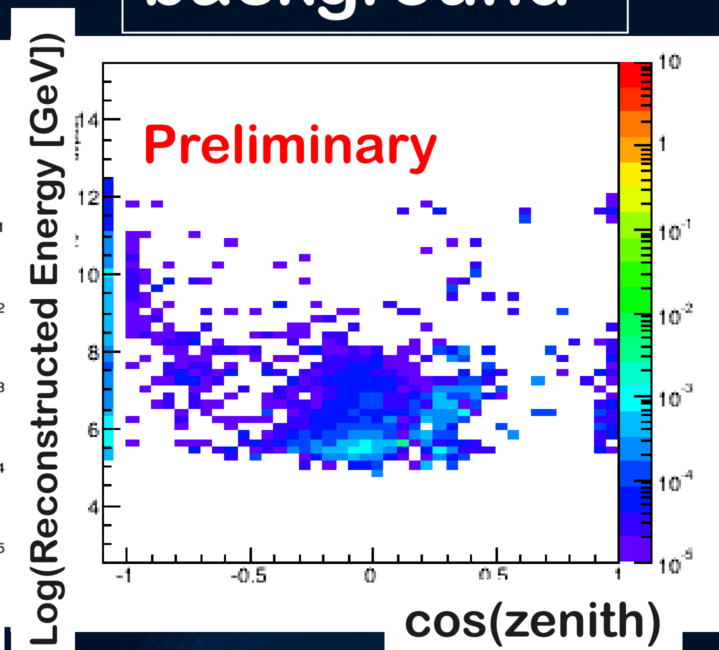
TeV PeV EeV

# 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=2.3 Load.fac 100 | Young Pulsar Ke+ SFR |
|---|---|---|---|---|---|---|---|
| Expect. # of events | 7.0 | 5.3 | 2.8 | 3.6 | 4.8 | 7.4 | 5.5 |
| Model Rejection Factor | 0.37 | 0.48 | 1.17 | 1.44 | 1.09 | 0.96 | 1.34 |
| p-value | $1.0\times10^{-3}$ | $7.0\times10^{-3}$ | $9.5\times10^{-2}$ | $2.2\times10^{-1}$ | $7.8\times10^{-2}$ | $2.2\times10^{-3}$ | $7.8\times10^{-2}$ |

Excluded

Mildly Excluded

TeV PeV EeV

# Implications to UHECR origin with the IceCube PeV-EeV data

Two PeV-ish events

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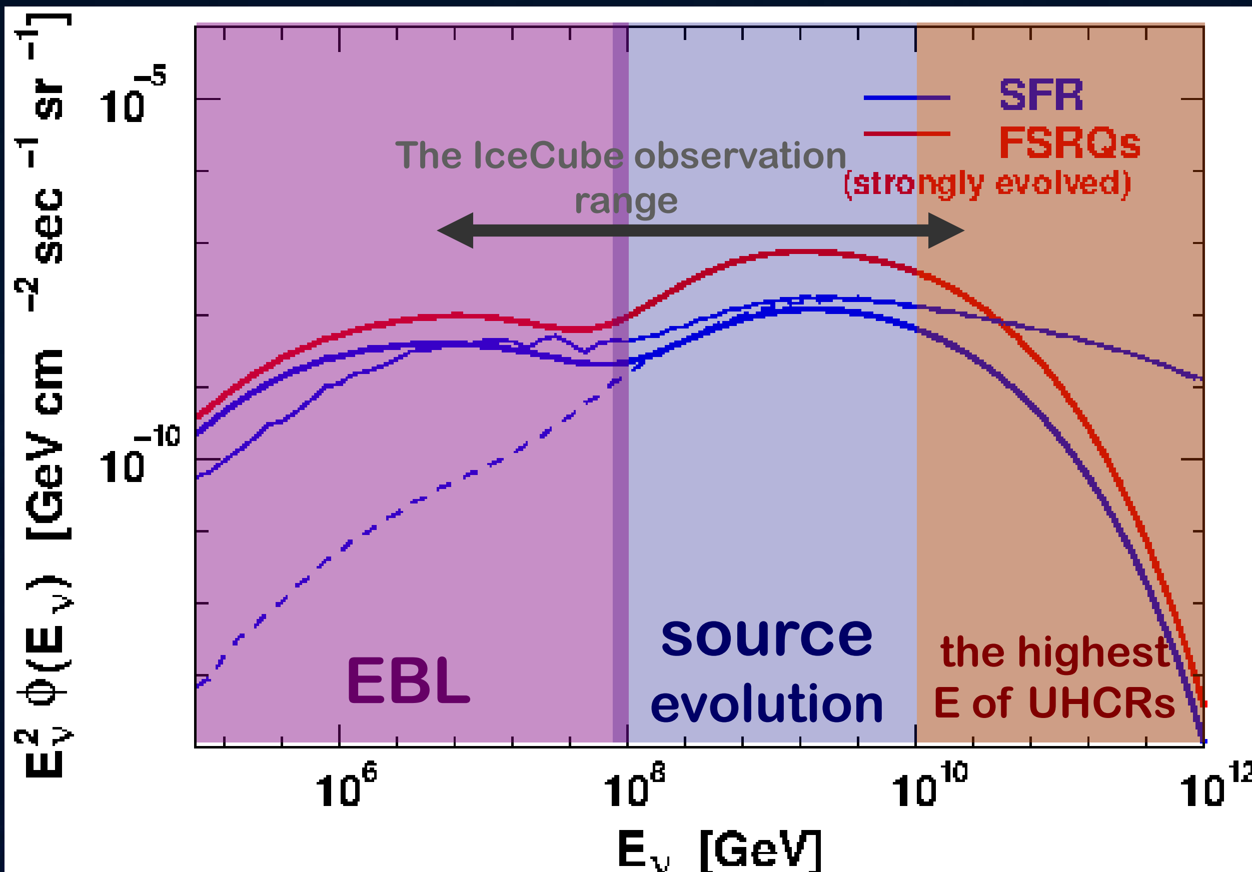
Robust and solid constraints,
but UHECR composition limited
(Only sensitive to proton-dominated case)

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

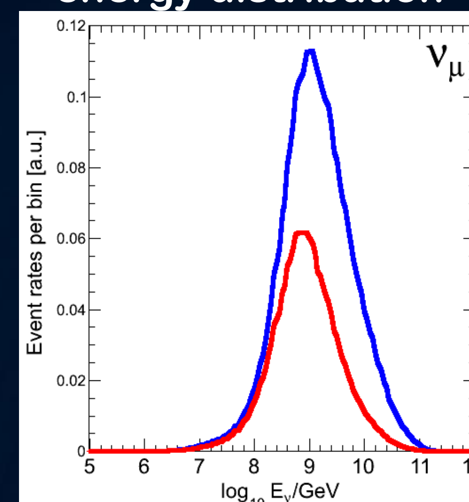
model-dependent arguments
but mixed-composition case reachable

# GZK cosmogenic ν models



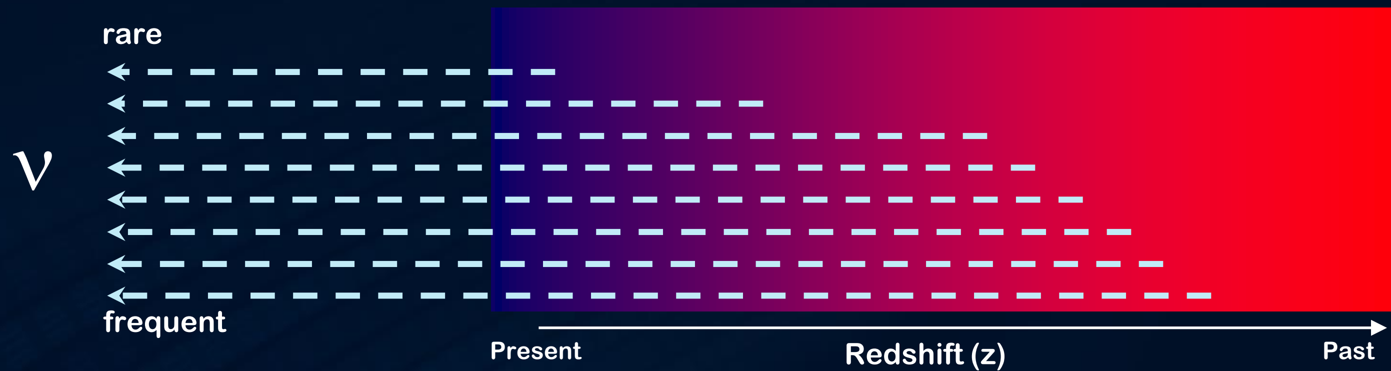

- Kotera, Allerd, Olinto 2010
- Ahlers et al 2010
- Aloisio et al 2014

IceCube signal event energy distribution



# Tracing *history* of the particle emissions with ν flux

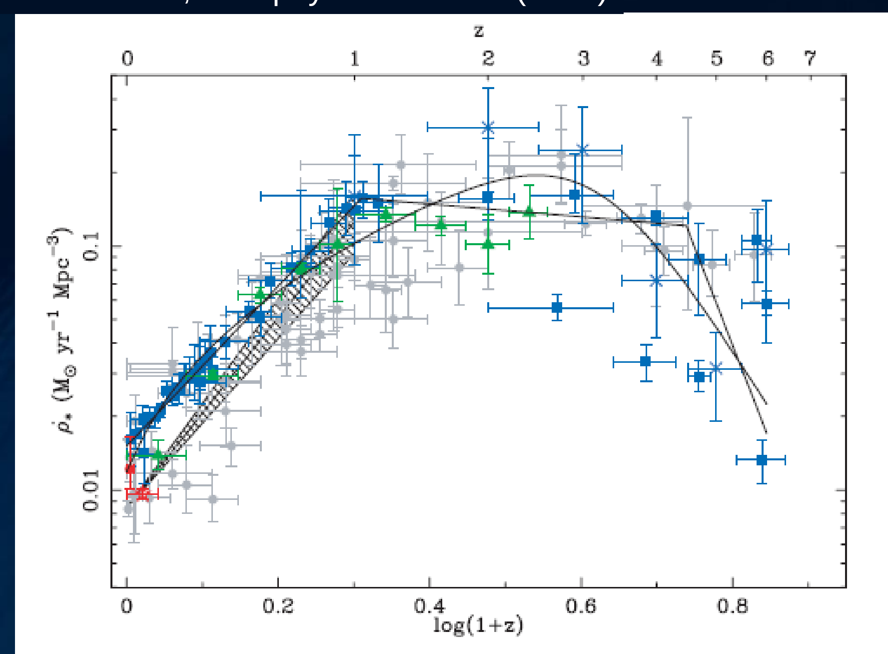
color : emission rate of ultra-high energy particles




Intensity gets higher if the emission is more <u>active</u> 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→

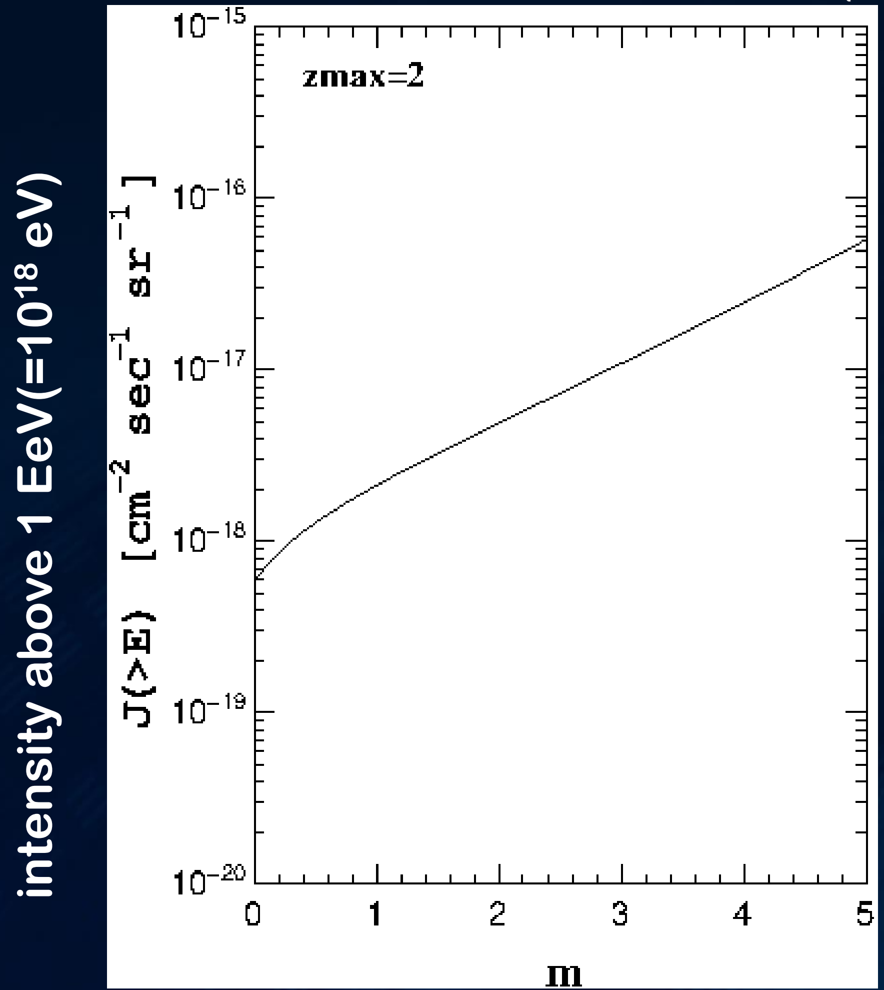
The spectral emission rate

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

m= 0 : No evolution

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

Yoshida and Ishihara, PRD 85, 063002 (2012)




more than an order of magnitude difference

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

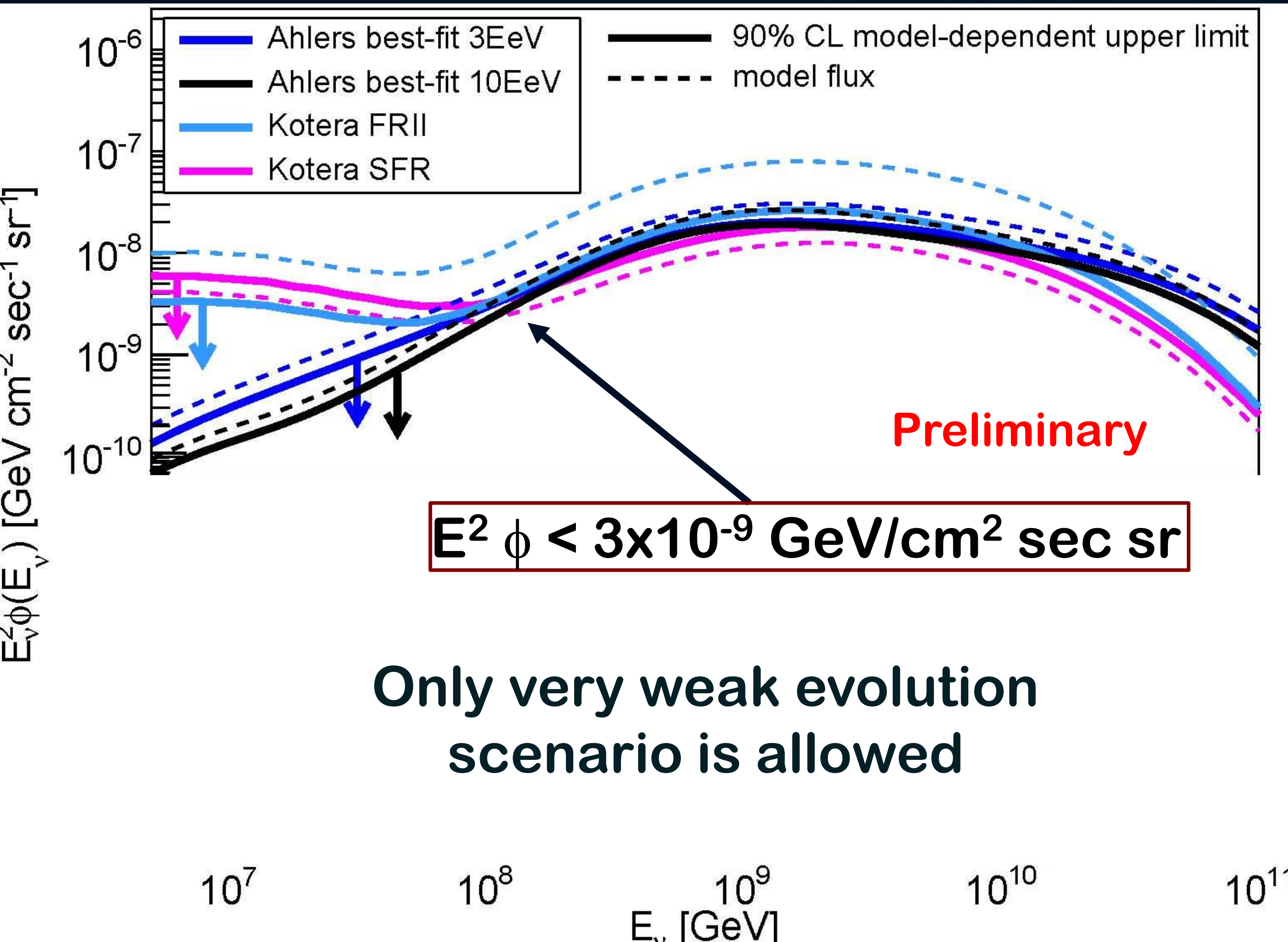
"quiet" "dynamic"

particle emissions in far-universe

TeV PeV EeV

# IceCube Tests on the GZK ν model

## The GZK ν models assuming proton-dominated CRs




$E^2\ \phi < 3\times10^{-9}$ GeV/cm$^2$ sec sr

**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)

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

$0<z<z_{max}$

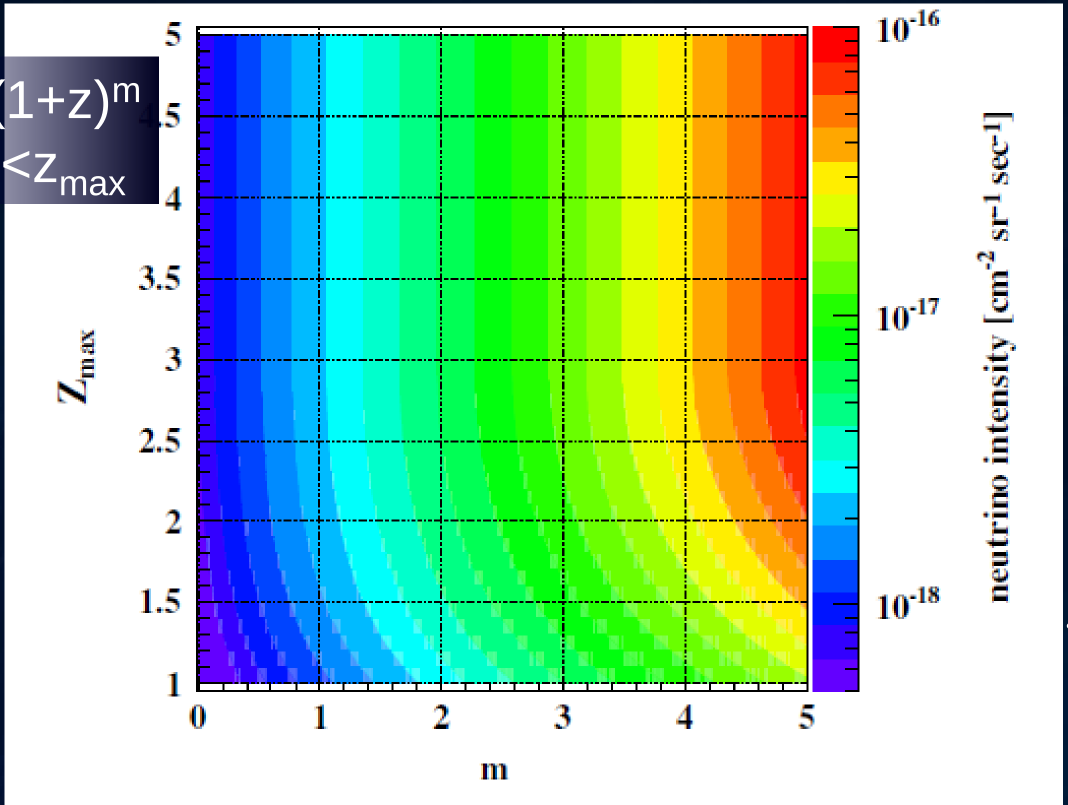



FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, $J$ [$\mathrm{cm}^{-2}\,\mathrm{sec}^{-1}\,\mathrm{sr}^{-1}$], on the plane of the source evolution parameters, $m$ and $z_{\mathrm{max}}$.

GZK ν flux $\phi = (m, z_{max})$

↓ x IceCube Exposure

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

↕

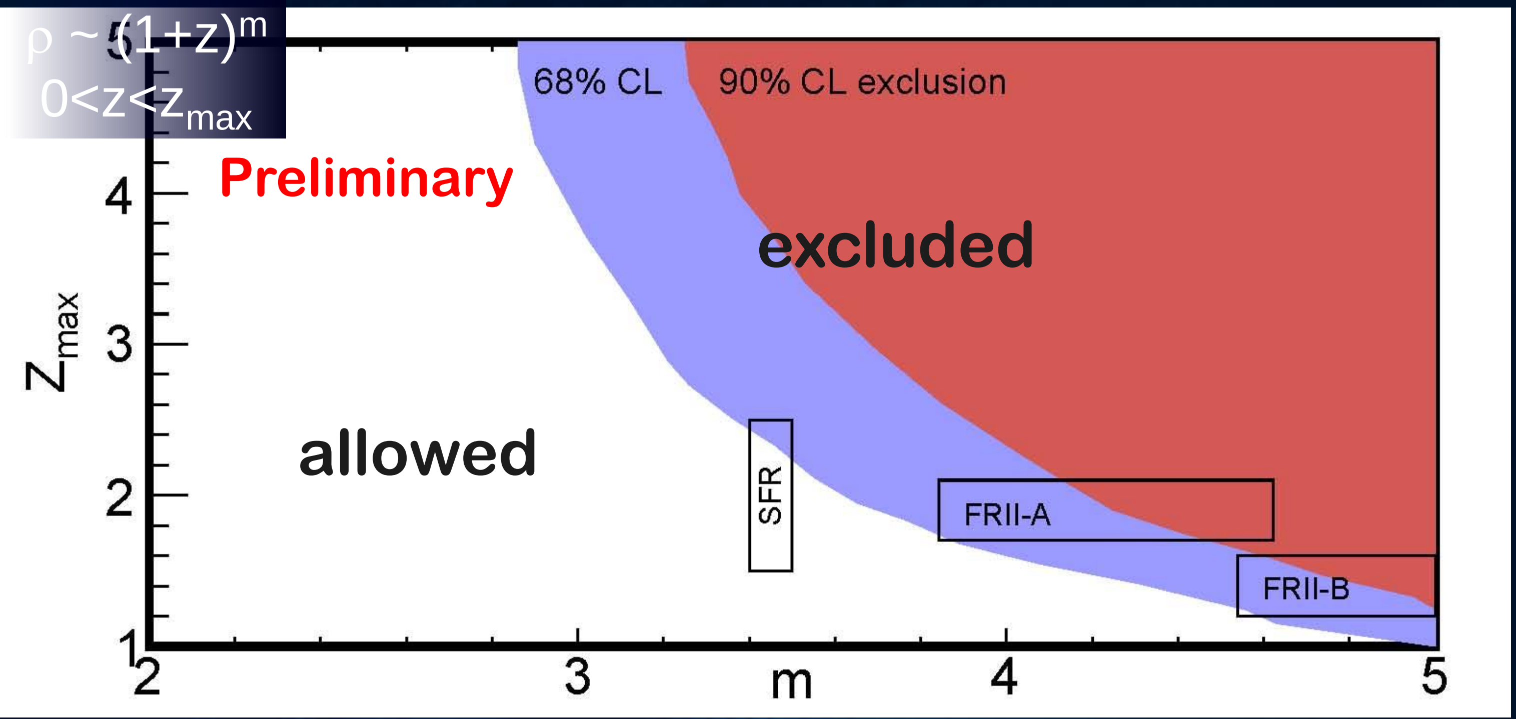
The *observed* event distribution

TeV PeV EeV

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

UHECR source is cosmologically **LESS evolved**

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




~~AGNs~~

~~GRBs~~

TeV PeV EeV

# 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)** ⟶ ν

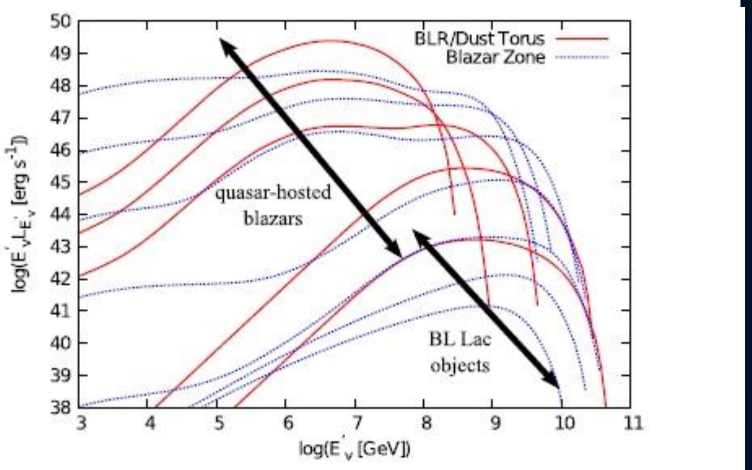
↕

**middle class** ⟶ γ

↕

**BL Lac** ⟶ **UHECRs**

**ν luminosity from a Blazar**




**The highest energy CRs are HEAVY nuclei**

TeV PeV EeV

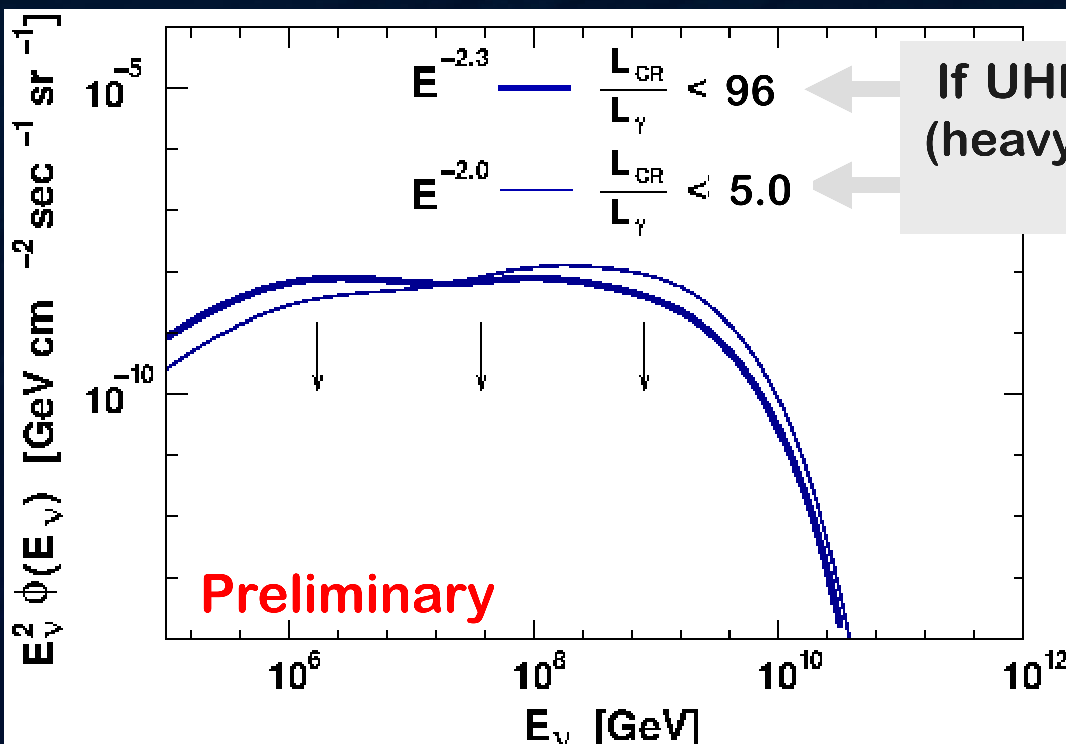
# IceCube tests on *on-source* ν models

## AGN (Blazar) Inner Jet

Murase, Inoue, Dermer, PRD 2014

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

**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

# IceCube tests on *on-source* ν models

## AGN (Blazar) Hadronic model

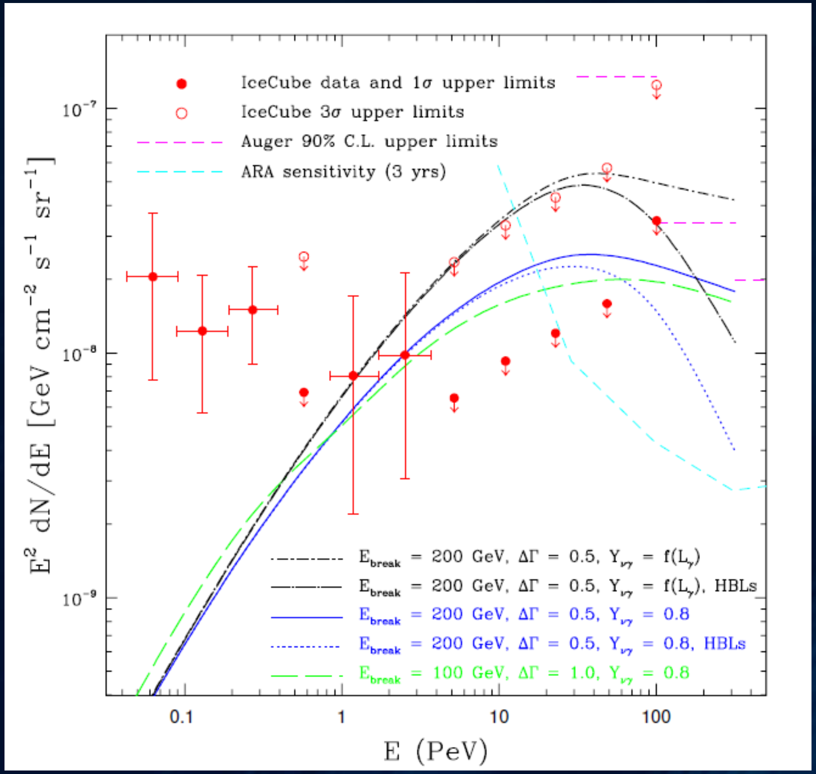
Padovani et al MNRAS (2015)

$$\nu \text{ flux} \propto \frac{L_\nu}{L_\gamma}$$

$L_\nu$ ⟵ IceCube

$L_\gamma$ ⟵ TeV γ observation

≈ **0.8**




ν flux upper limit by IceCube **0.15**

**BL-Lac hadronic unlikely**

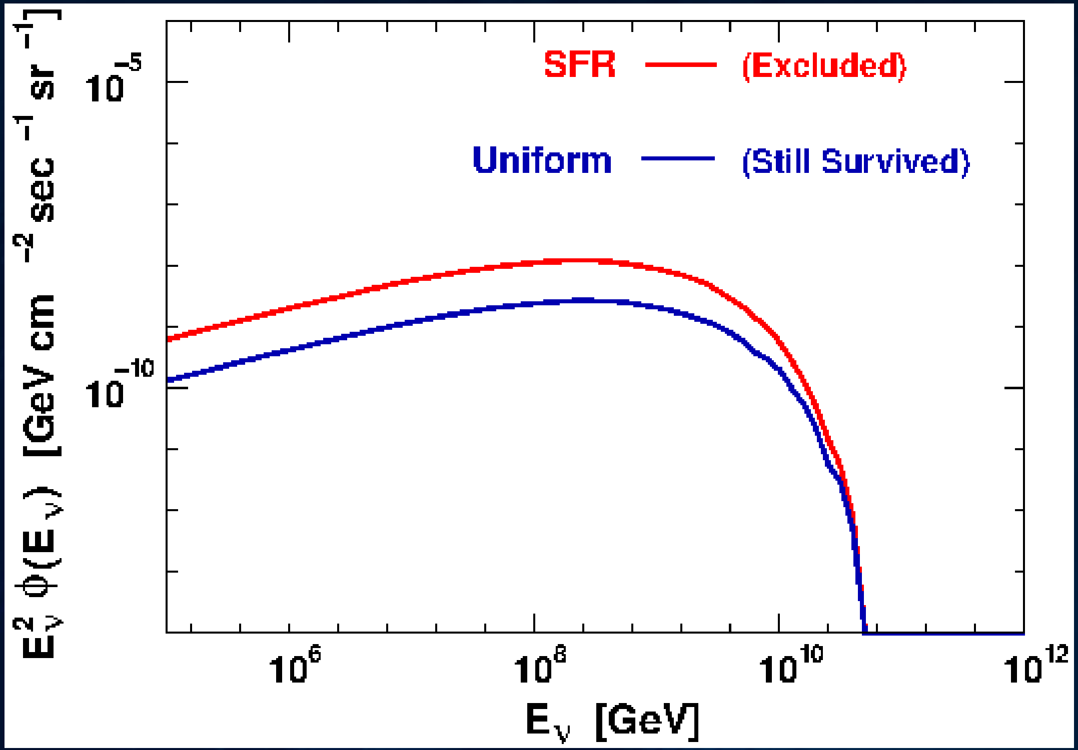
TeV PeV EeV

# 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**

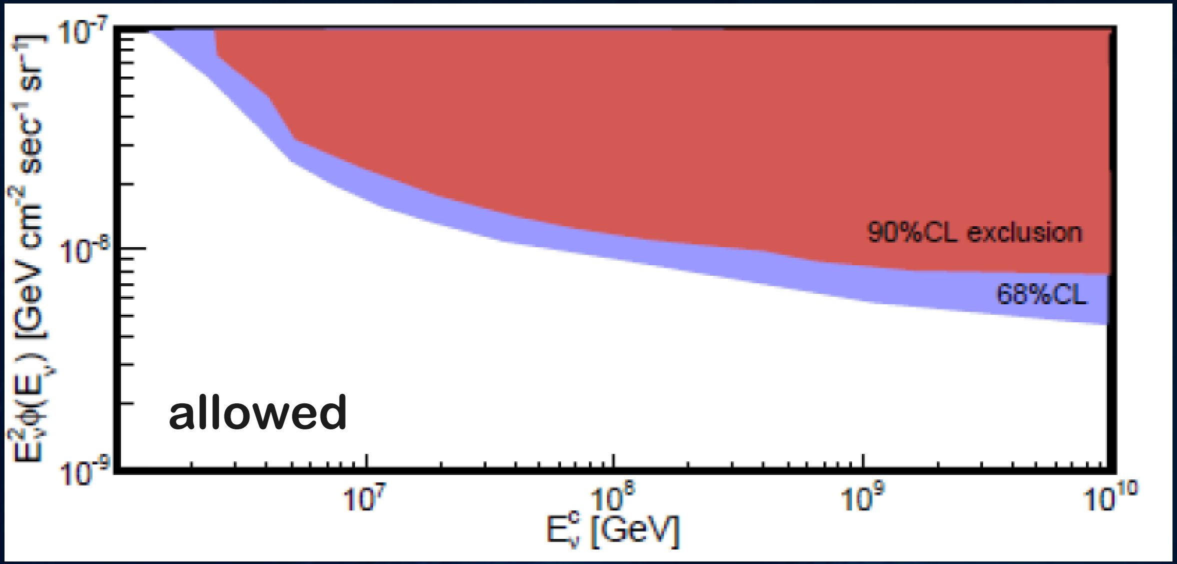
though not completely ruled out

TeV PeV EeV

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

excluded

**Preliminary**




$E^2\phi(E)$ ~ a few x$10^{-9}$

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

TeV PeV EeV

# Summary in UHE ν

**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

# Grand Summary

- (sub-)PeV $\nu$ origin

  FSRQs (or any p accelerators with optical depth >0.01)

  $\nu$-bright, proton dim sources (ex. Magnetic horizon)

  $n_s < 10^{-6}$ /Mpc$^3$

  unlikely to associate with UHECR of E>EeV

- EeV $\nu$ observation indicates on UHECRs

  GRBs /major AGNs unlikely if protons

  Model-dependent constraints

  if mixed- or heavy composition

# Next move

## Multi messenger astronomy

IceCube triggers ToO/follow-up observations in various wavelengths

# IceCube Realtime Analysis Chain

**muon multiplet for Gamma-ray/Optical followup**

TeV PeV EeV

good angular resolutions

muon neutrino sensitive

large background chance

**veto-based HESE**

TeV PeV EeV

high chance of real cosmic neutrino signals

all neutrino flavor sensitive

angular resolutions so-so

**Ultra-High Energies**

TeV PeV EeV

high chance of real cosmic neutrino signals

all neutrino flavor sensitive

good angular resolutions

signal flux highly uncertain

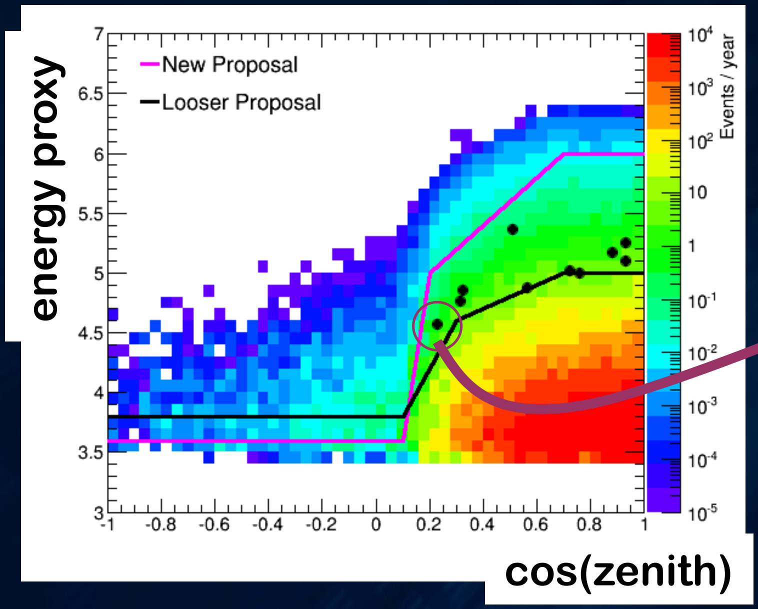
TeV PeV EeV

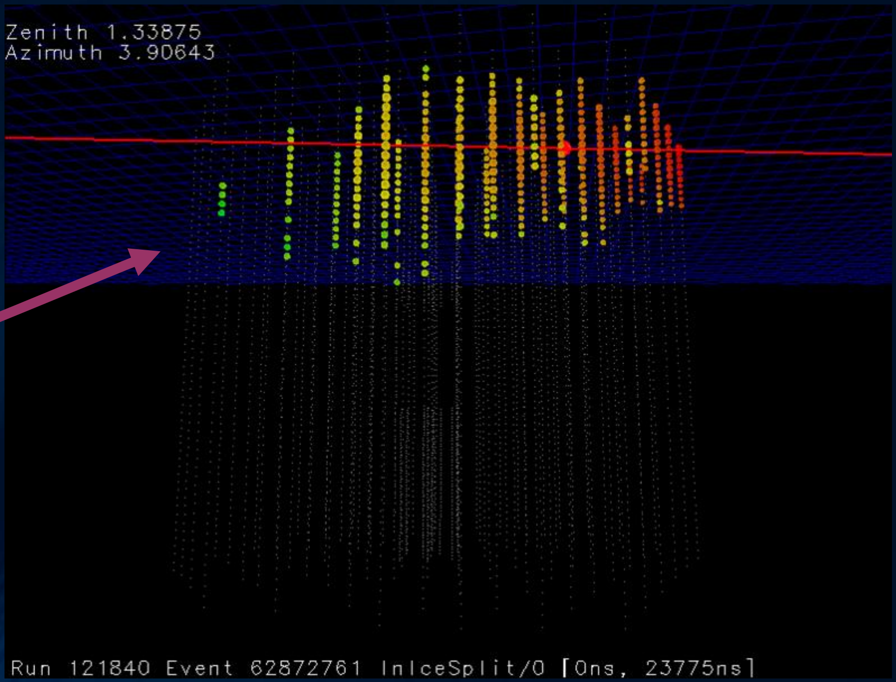
# UHE (PeV-EeV)

## Online Analysis for γ-ray/optical follow-up

new

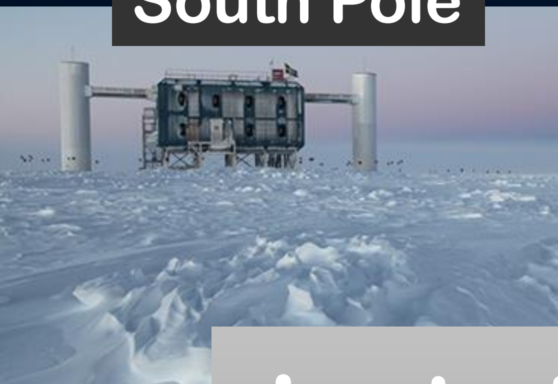
an event from “heart-beat” run

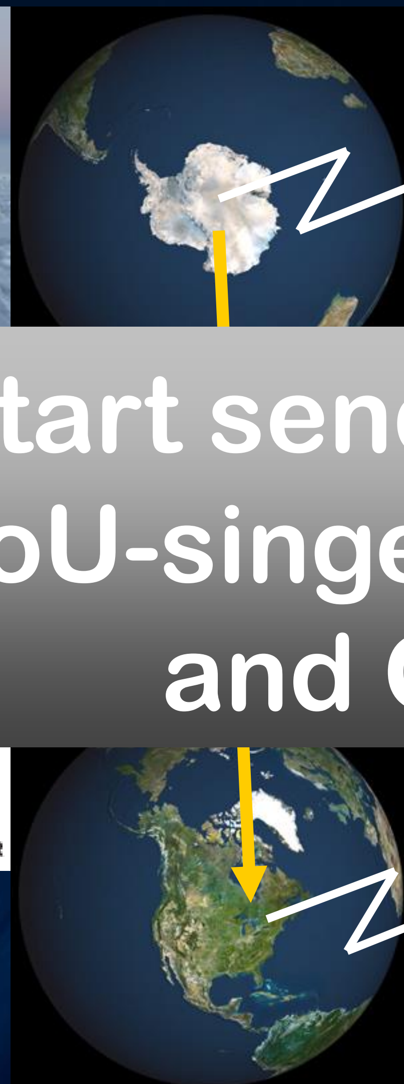


# IceCube Realtime Analysis Chain

South Pole





< 3 minitues

Quick results

**Just start sending ν alerts to the MoU-singed observatory and GCN !**

Northe

O(hrs)

refined results
from iterated reconstructions

TeV PeV EeV

# First GCN event from HESE

**April 27, 2016 at 5:52 UTC** **~ 150 TeV**

~0.6 deg uncert.