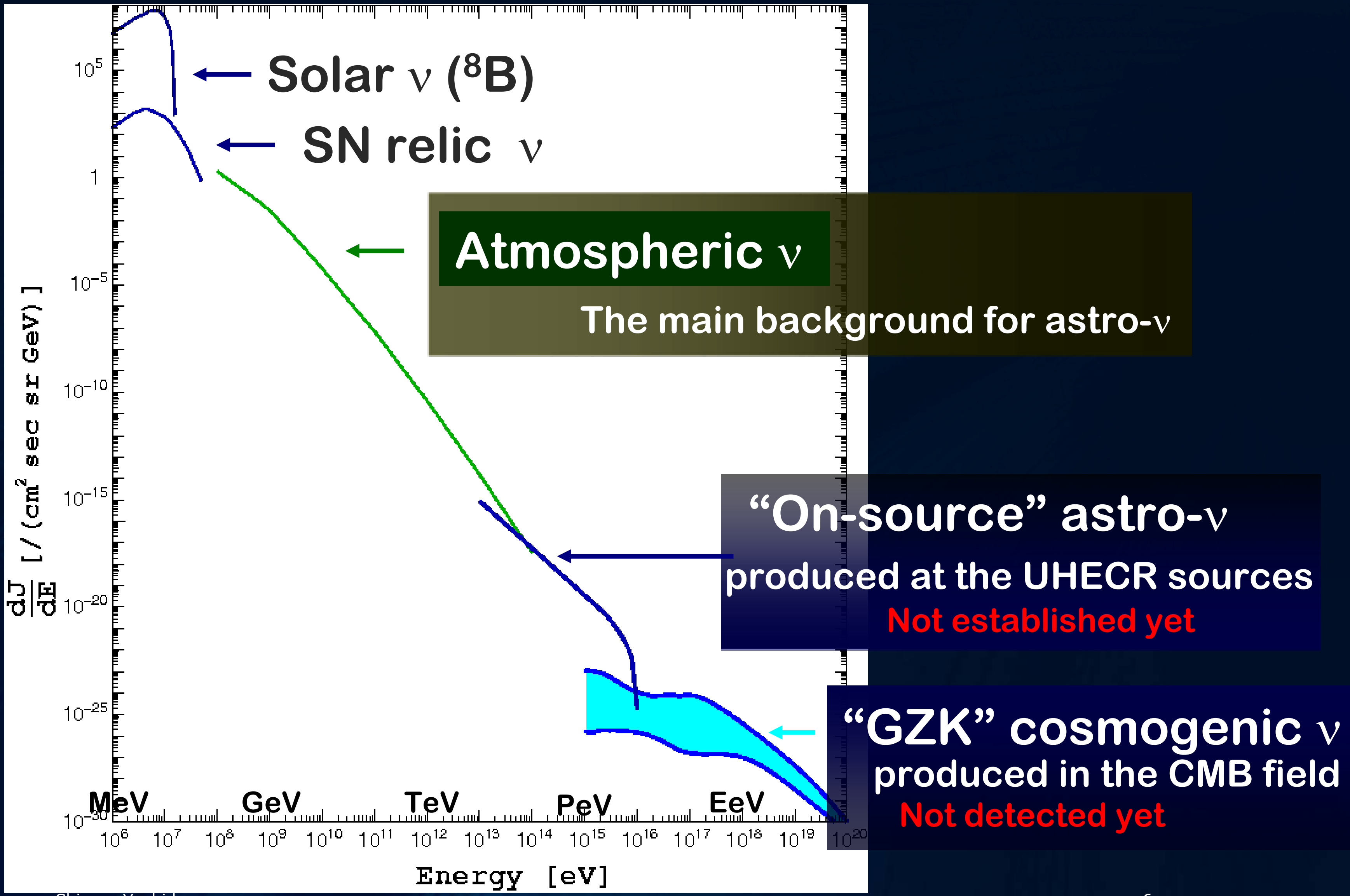
What the IceCube UHE ν results tell about the origin of UHE Cosmic Rays

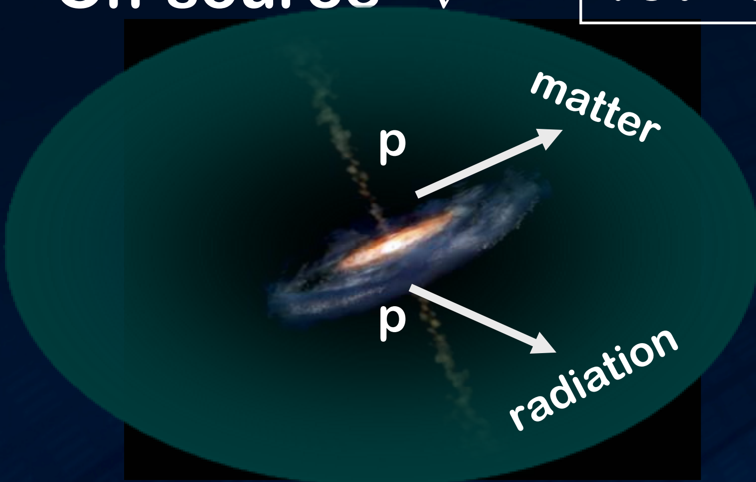
Shigeru Yoshida
Chiba University

The Neutrino Flux: overview



The Cosmic Neutrinos Production Mechanisms

"On-source" ν **TeV - PeV**

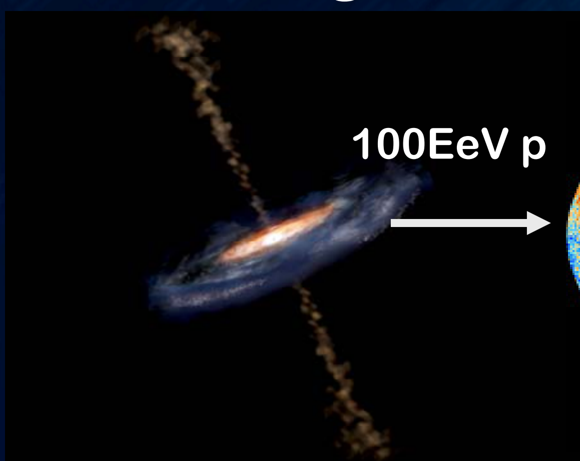


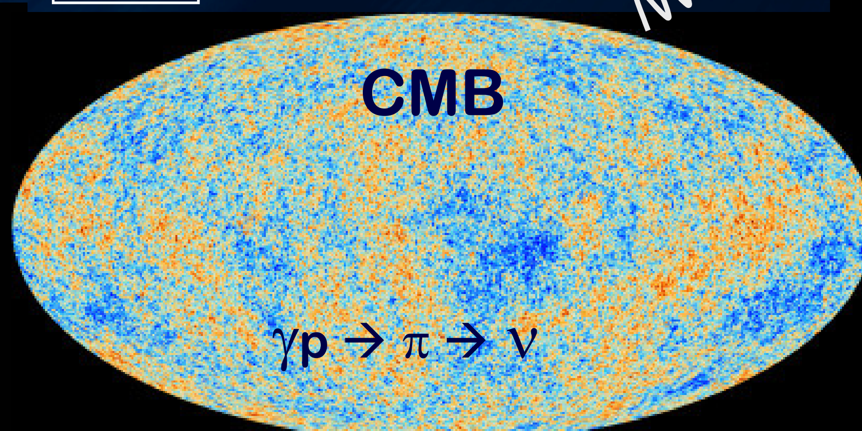
$pp \rightarrow \pi \rightarrow \nu$

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

photopion production

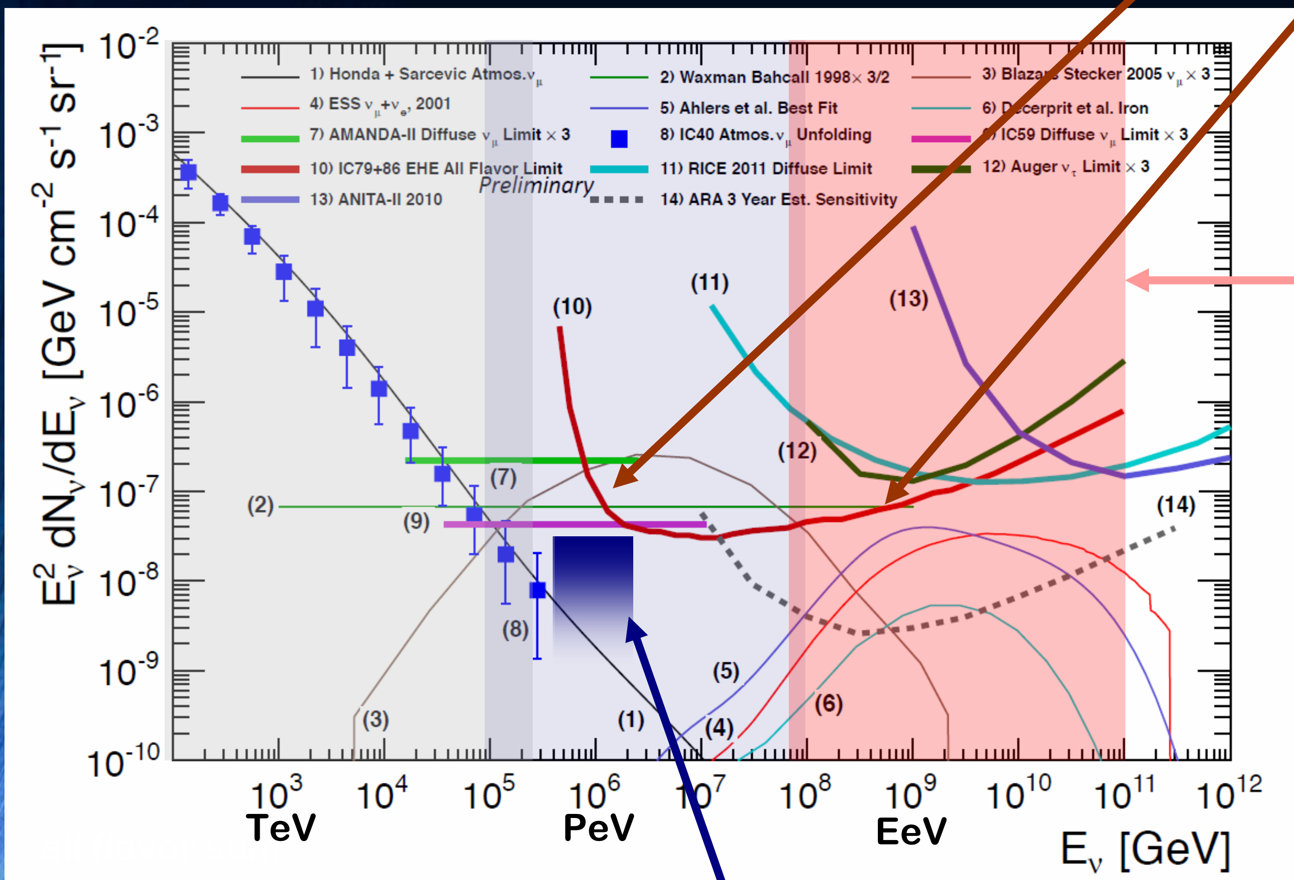
"GZK" cosmogenic ν **EeV**





The executive summary

The model-independent upper limit on flux in UHE



null observation in this regime

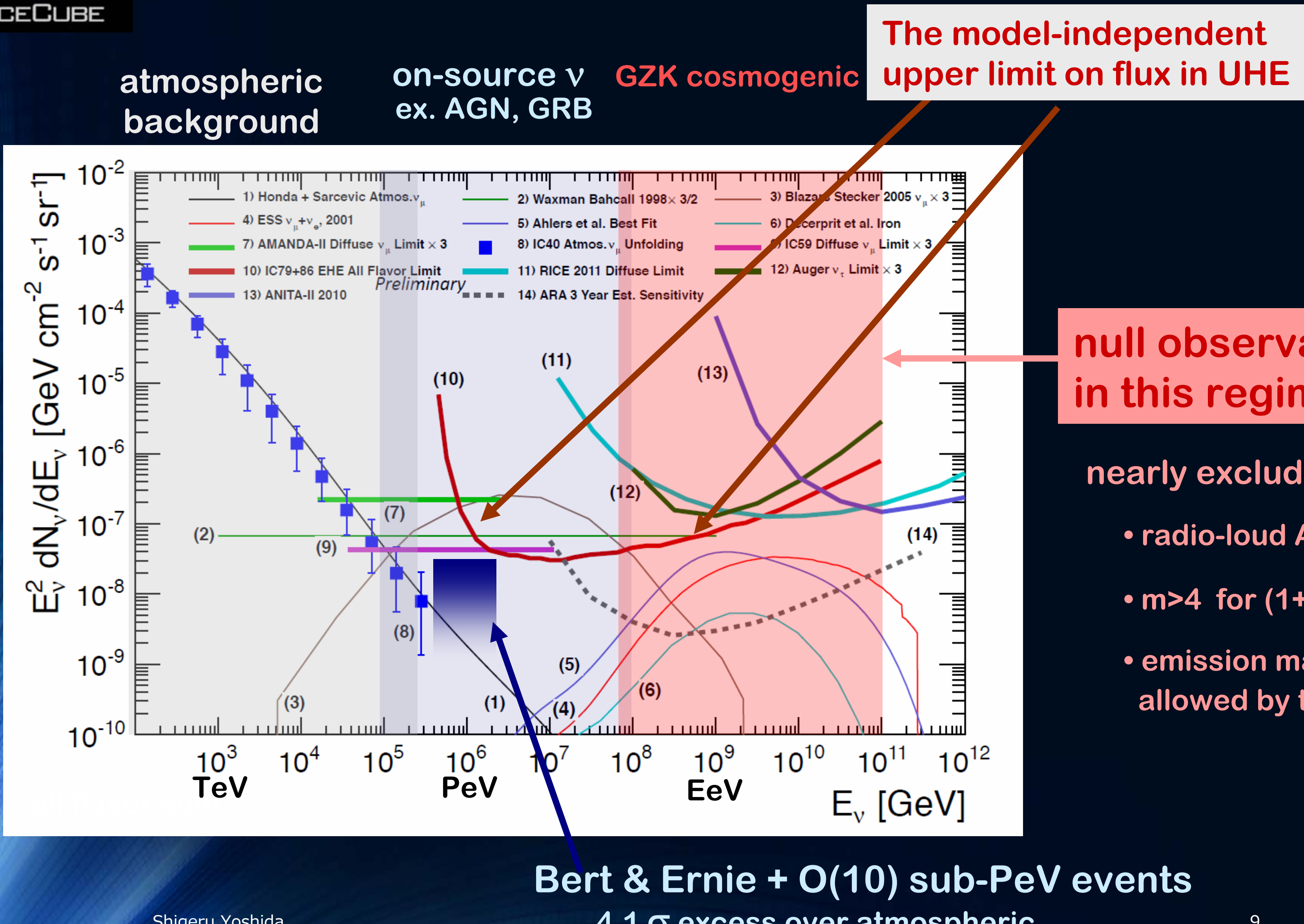
nearly exclude

- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

Bert & Ernie + O(10) sub-PeV events

4.1 σ excess over atmospheric

The executive summary



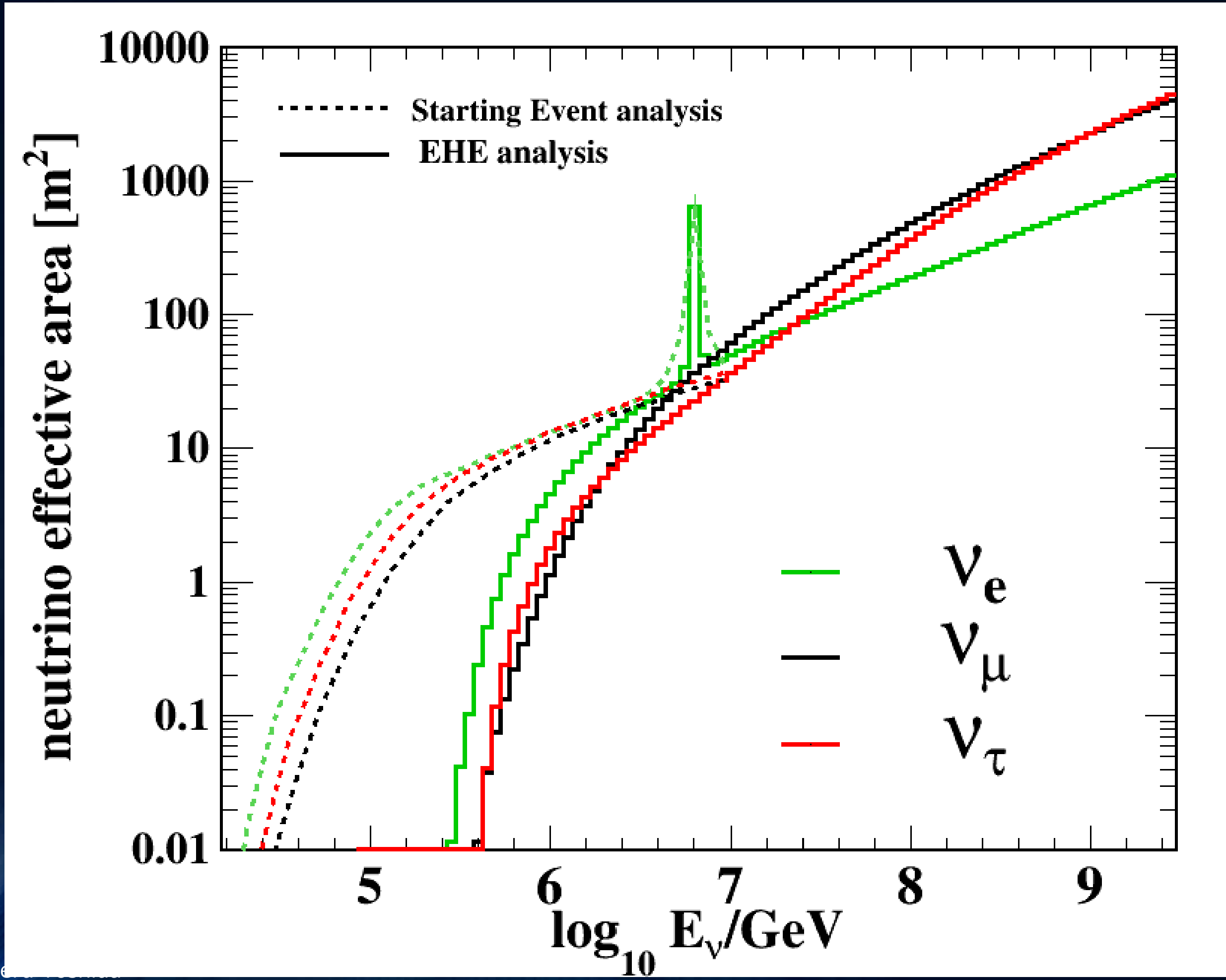
nearly exclude

- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

Effective Areas expanding down to 100 TeV's

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

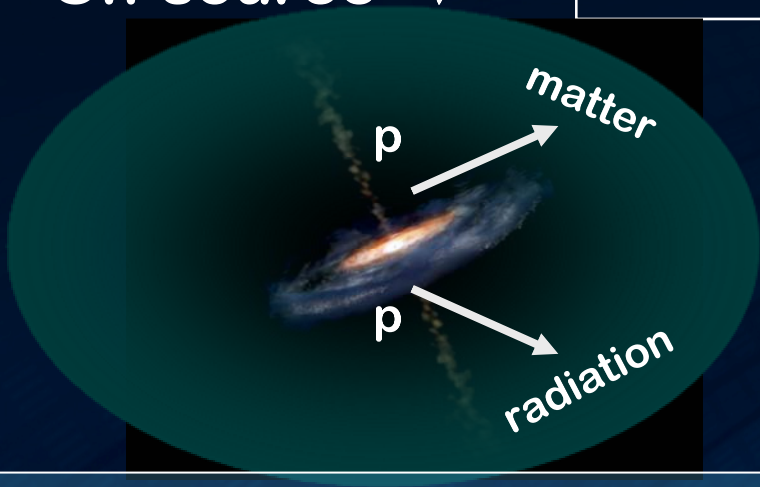
IC79+IC86 livetime 670.1 days



The Cosmic Neutrinos Production Mechanisms

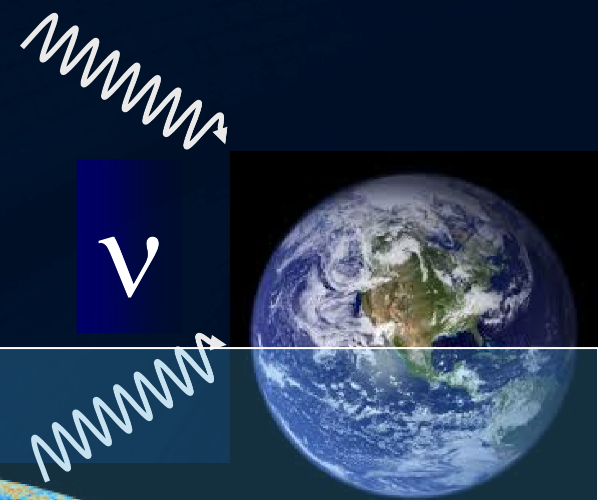
“On-source” ν

TeV - PeV



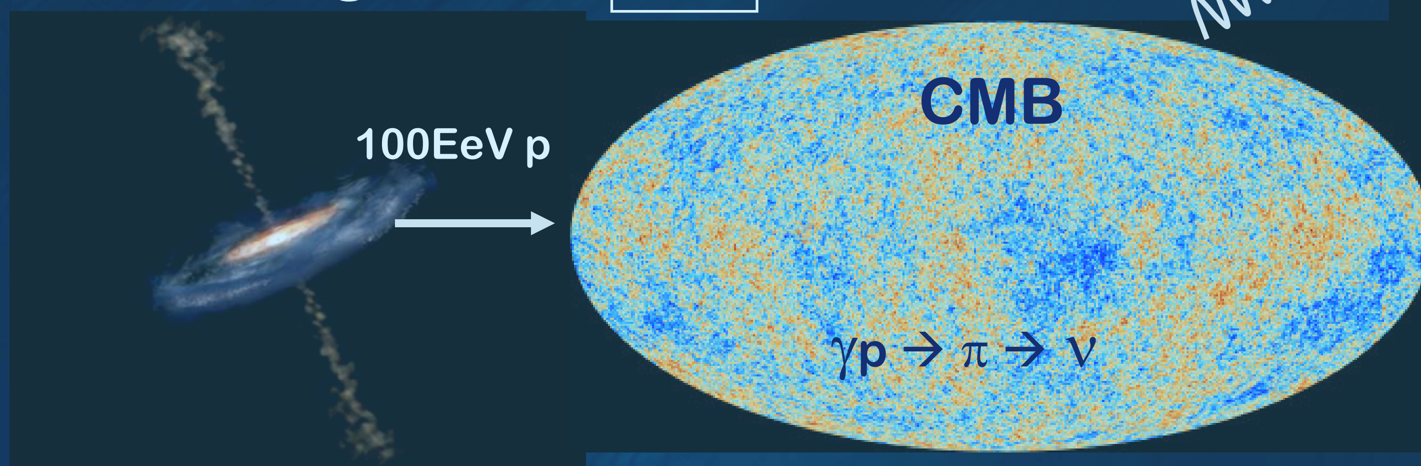
pp → π → ν

γp → π → ν
photopion production

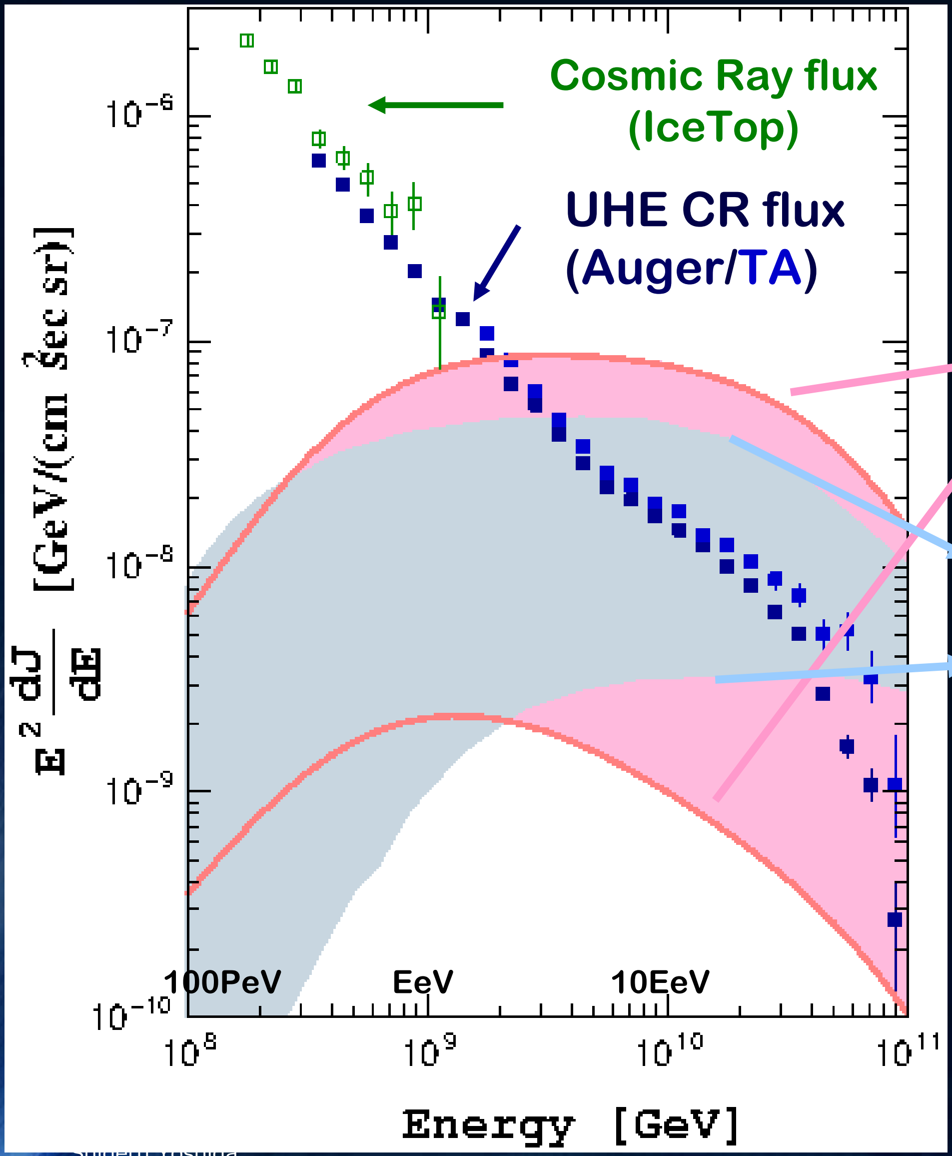


“GZK” cosmogenic ν

EeV



UHE cosmic ray and GZK ν fluxes



GZK cosmogenic ν's

allowed range of the ν flux

Ahlers et al, Astropart.Phys. **34** 106 (2010)

the ν fluxes from strongly evolved and no evolved sources

SY et al, Prog.Theo.Phys. **89** 833(1993)

Ranges more than an order of magnitude

why?

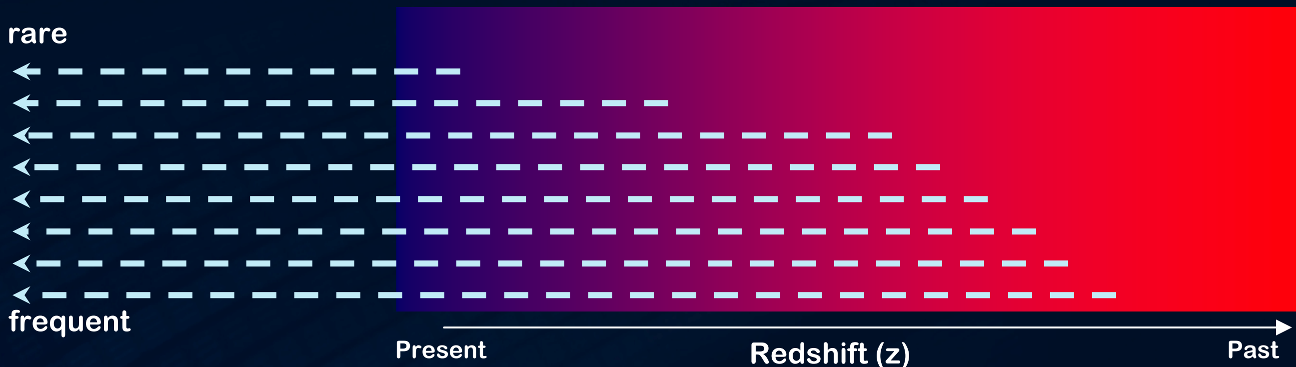
Tracing *history* of the particle emissions with ν flux

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

ν

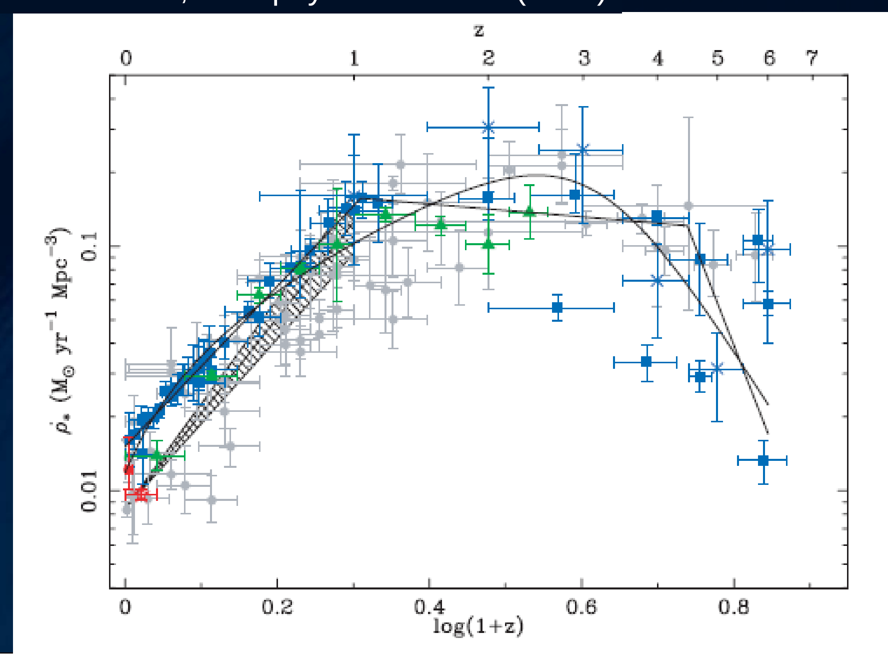


The cosmological evolution

Many indications that the past was more active.

Star formation rate→

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



The spectral emission rate

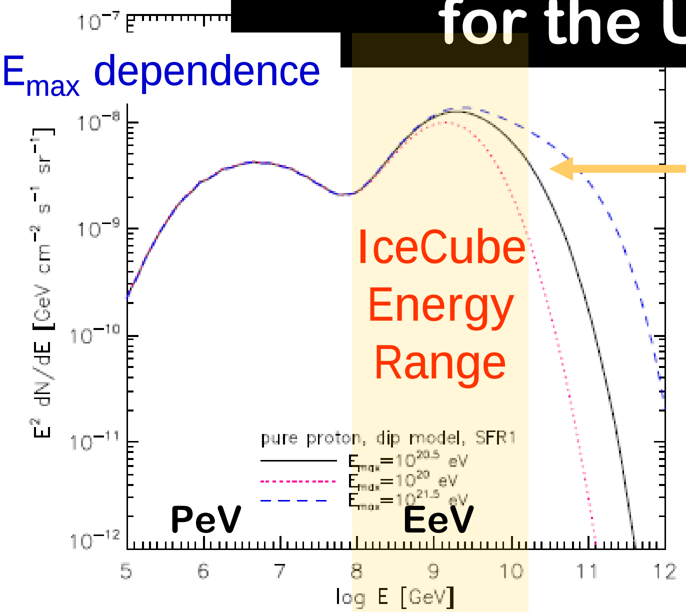
$$\rho(z) \sim (1+z)^m$$

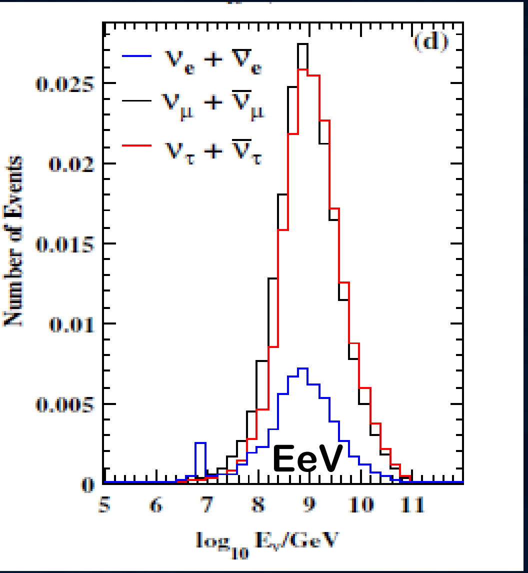
m= 0 : No evolution

Shigeru Yoshida

I^{GZK}_{ν} @ 1EeV is an excellent indicator for the UHECR emission history

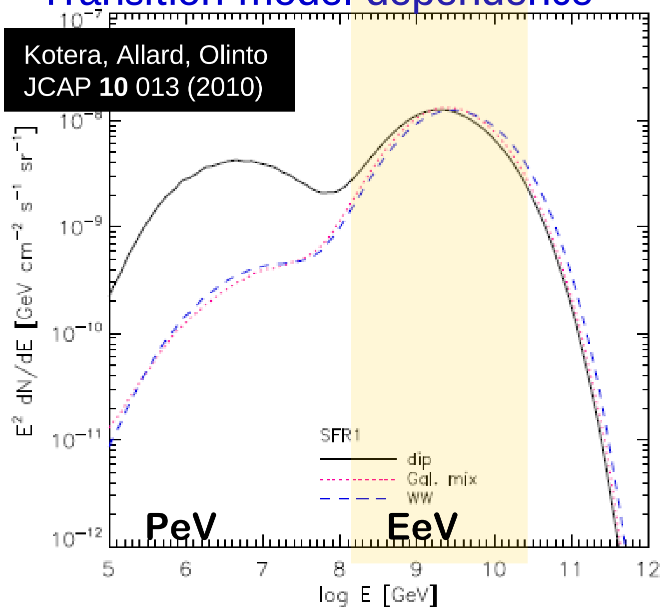
E_{max} dependence





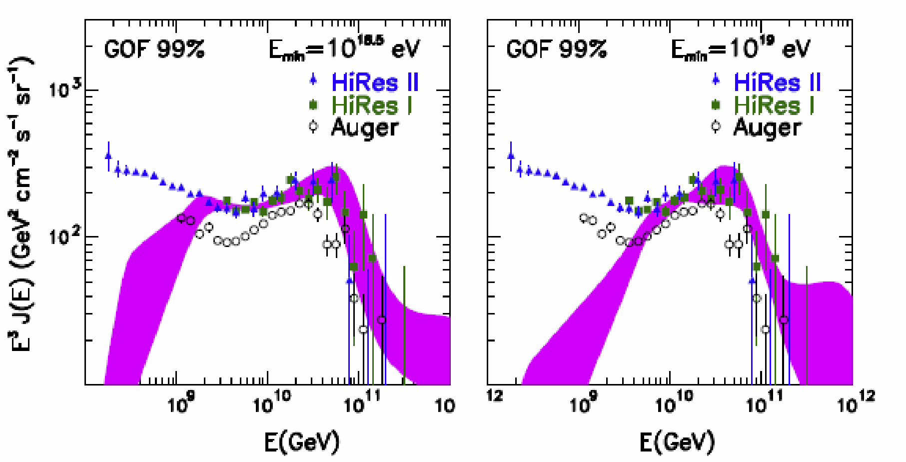
IceCube collaboration
PRD **83** 092003 (2011)

Transition model dependence



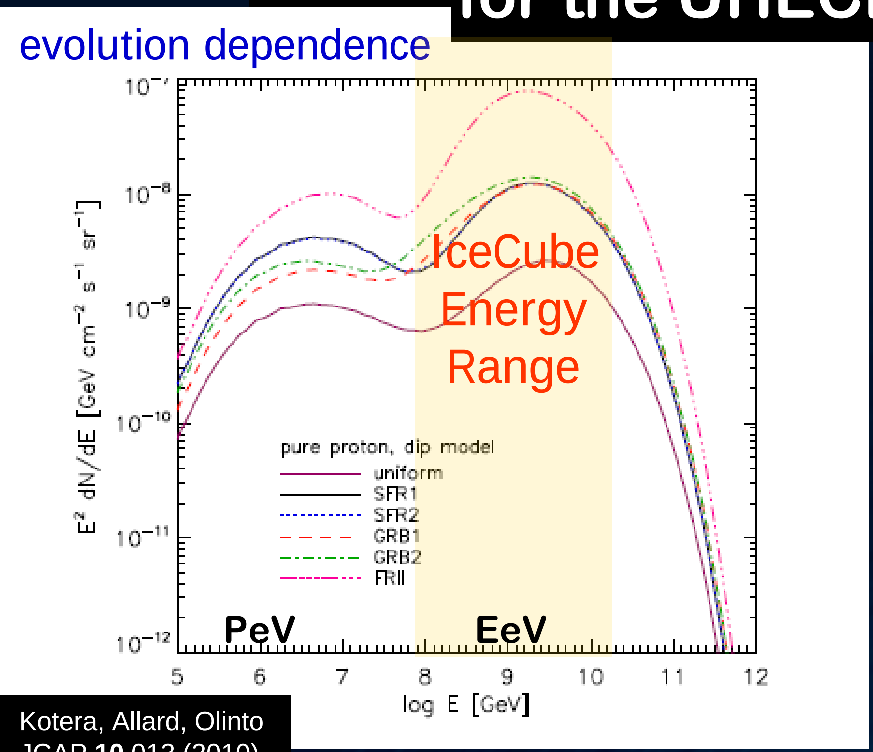
Kotera, Allard, Olinto
JCAP **10** 013 (2010)

Ahlers et al, Astropart.Phys. **34** 106 (2010)

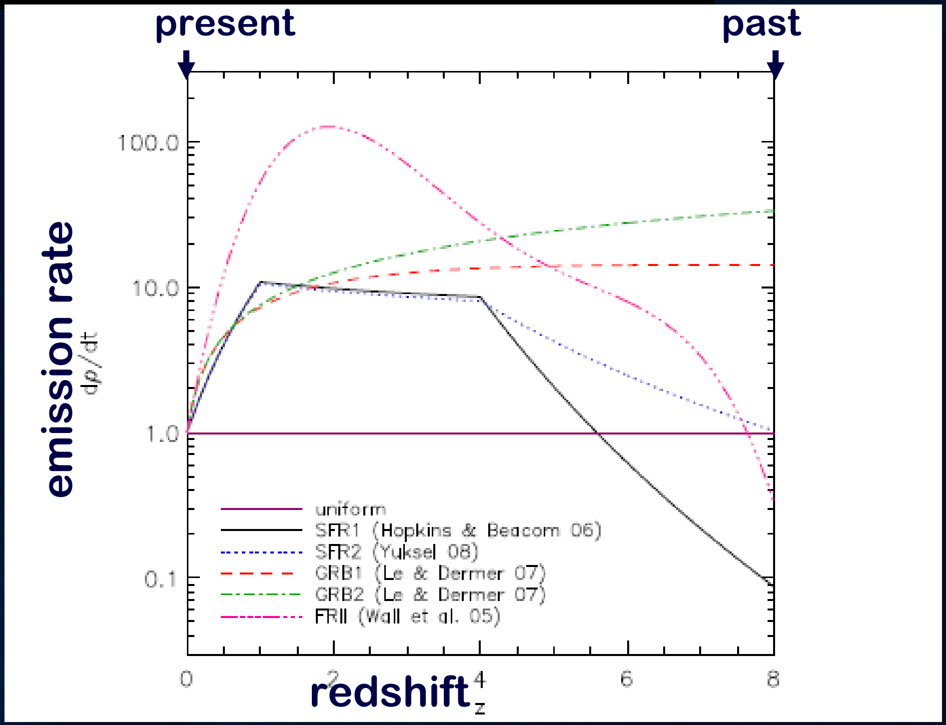


"Dip" model "Ankle" model

I^{GZK}_{ν} @ 1EeV is an excellent indicator for the UHECR emission history



Kotera, Allard, Olinto
JCAP **10** 013 (2010)



ν = early history of cosmic radiation!

GZK cosmogenic ν flux estimates: model-independent analytical approach

Yoshida and Ishihara, PRD 85, 063002 (2012)

Adding up contribution from sources at z

$$\frac{dJ_\nu}{dE_\nu} = \frac{c}{H_0} n_0 \int_0^{z_{max}} dz \frac{\psi(z)}{(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\lambda}}$$

$$\int_0^{z} dz_\nu \frac{dN_{p\to\nu}}{dE_\nu^{\rm GEN} dL}(E_\nu(1+z_\nu), z_\nu, z) \frac{dt_\nu}{dz_\nu}.$$

Emission rate per comoving volume

$\sim(1+z)^m$

ν yield in the CMB field with $E^{GEN}=E_\nu(1+z_\nu)$ from UHECR proton emitted from sources at $z>z_\nu$. z_ν; redshift when generates ν

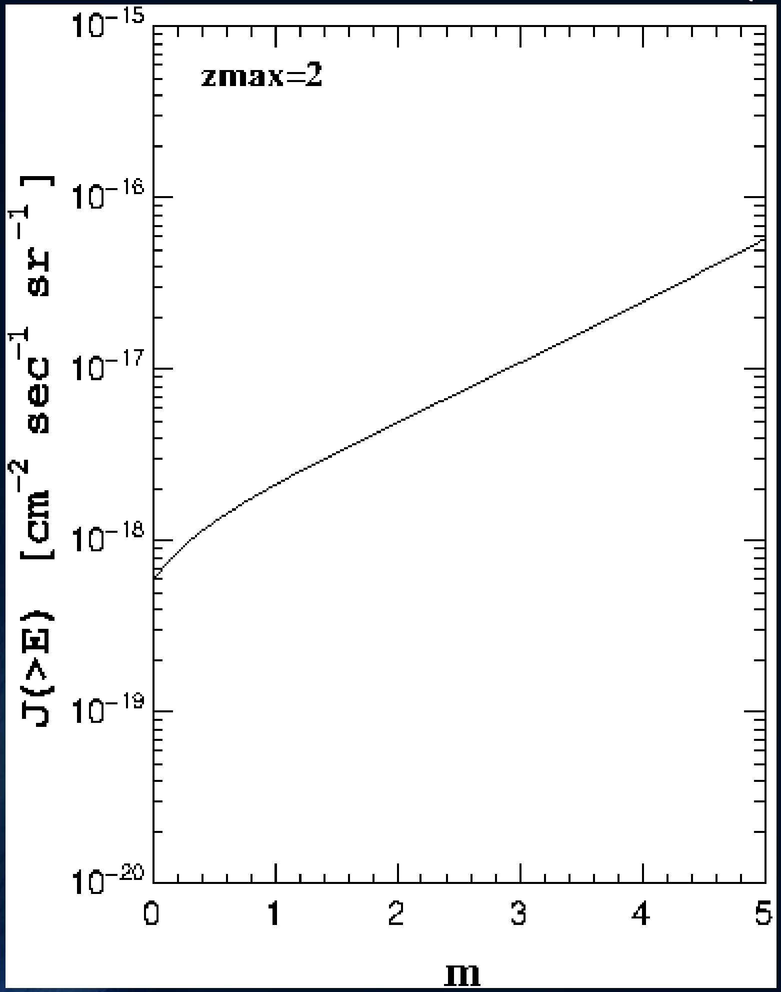
Semi-analytically computable when

1. neglect IR/O background – ν is generated only by $p\gamma_{CMB}$
2. photo-pion production only via Δ-resonance
3. simplify the pγ collision kinematics as a single pion production
4. approximate UHECR energy attenuation length as a constant above 10^{20} eV

Usable as GZK ν version of *Waxman-Bahcal* Formula

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 <u>85</u>, 063002 (2012)

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

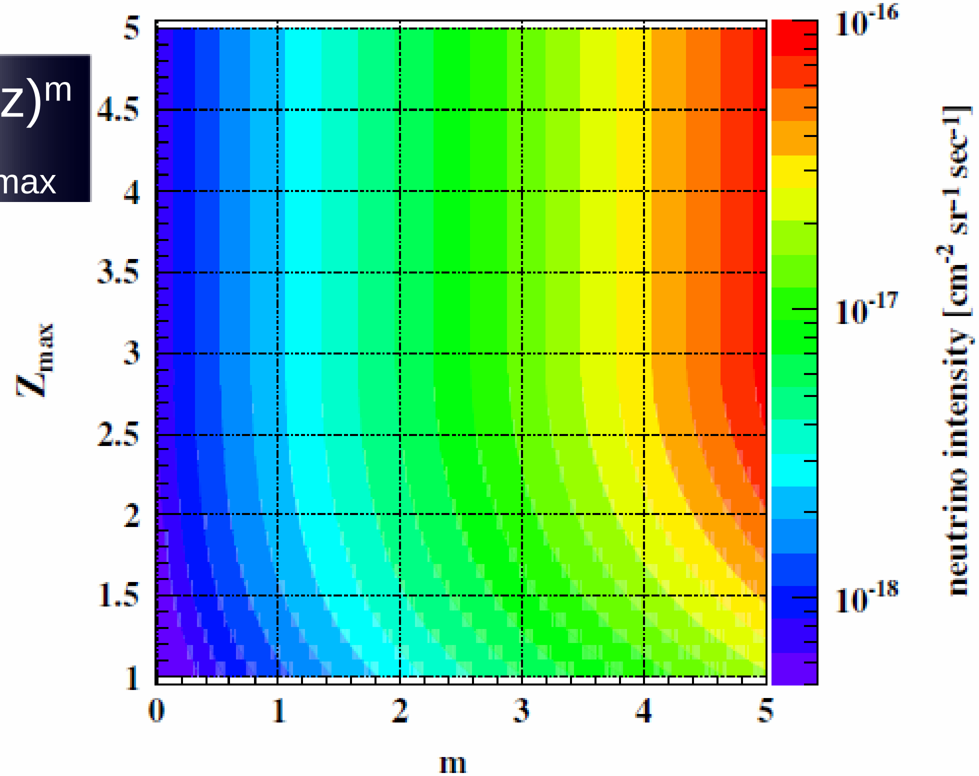


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [$cm^{-2}\ sec^{-1}\ sr^{-1}$], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

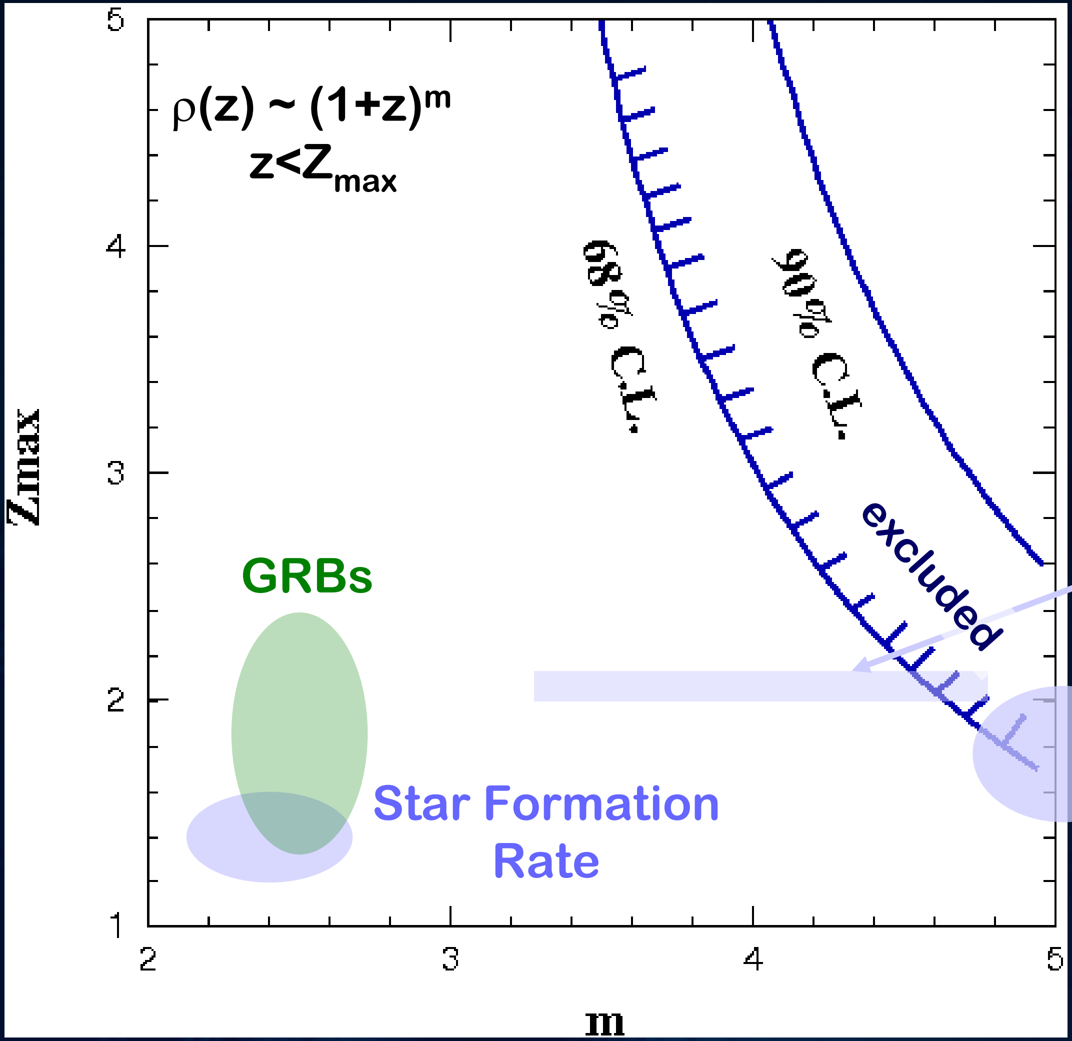
x IceCube Exposure

Number of events we should have detected

↕

We have seen null events

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

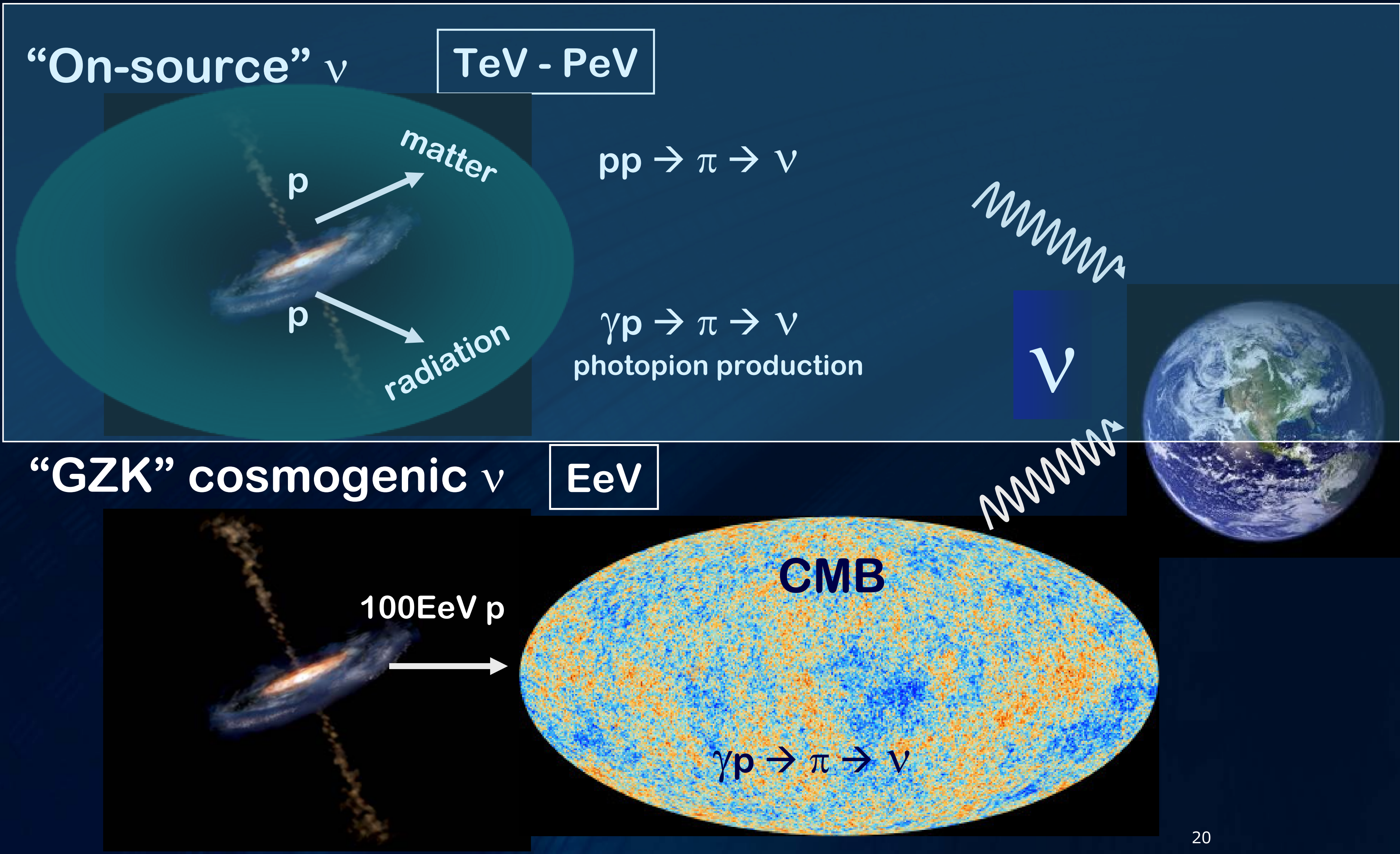


Ahlers et al, Astropart.Phys. **34** 106 (2010)

The best guess from the cosmic ray spectrum

AGNs with radio-loud jets

The Cosmic Neutrinos Production Mechanisms



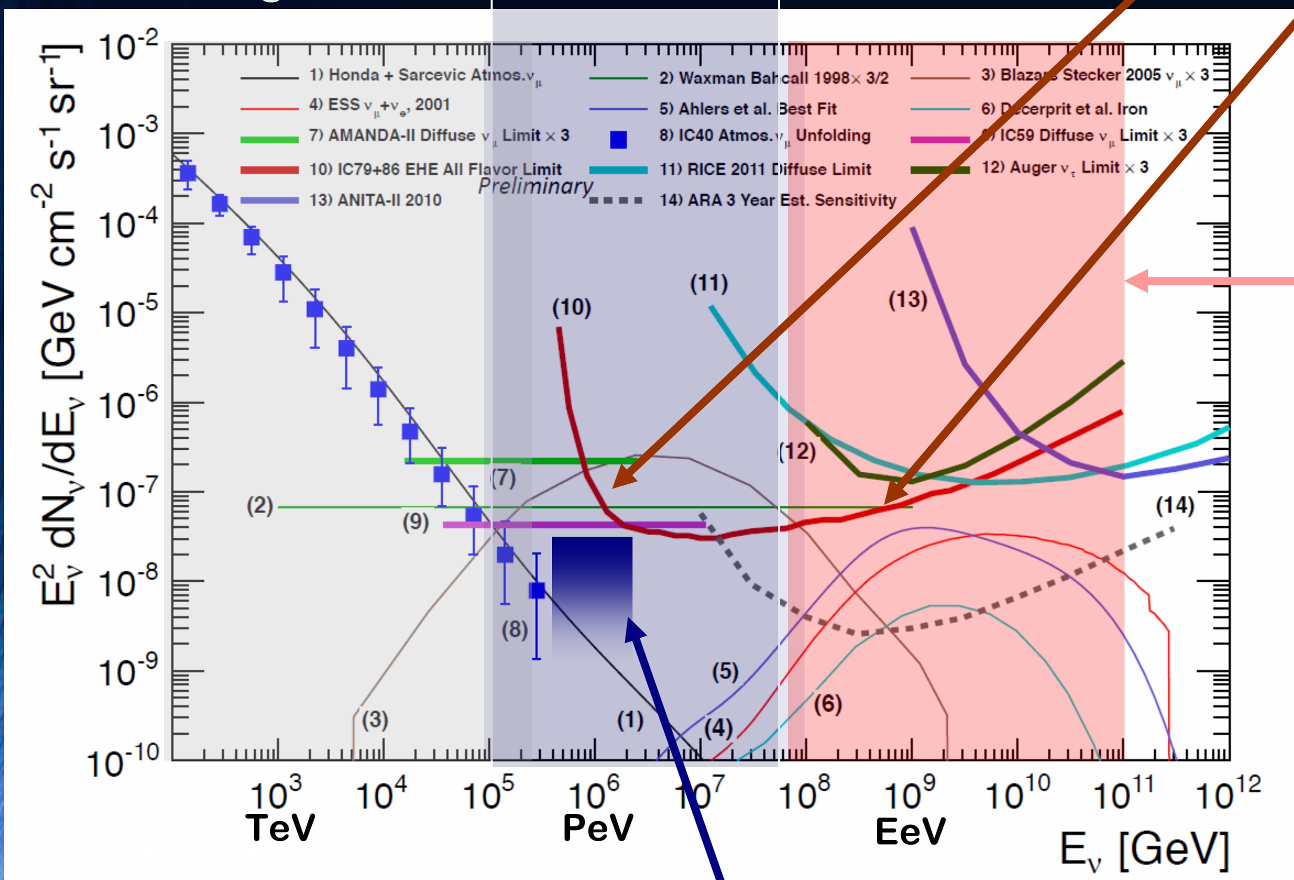
The executive summary

atmospheric background

on-source ν ex. AGN, GRB

GZK cosmogenic

The model-independent upper limit on flux in UHE



null observation in this regime

nearly exclude

- radio-loud AGN jets
- m>4 for $(1+z)^m$
- emission maximally allowed by the Fermi γ

Bert & Ernie + O(10) sub-PeV events

4.1 σ excess over atmospheric

The on-source PeV ν : many scenarios.
involving lots of uncertain parameters

extra-galactic **galactic** **exotic**

- AGN cores, Stecker, arXiv:1305.7404
- Distant AGNs + EBLs, Kalashev et al PRL 111, 041103 (2013)
- Low-Power GRB jets, Murase and Ioka, arXiv:1306.2274
- Extragalactic pp collisions, Murase, Ahlers, Lacki, arXiv:1306.3417
- Galactic diffuse with the interstellar matter, Gupta, arXiv:1305.4123
- Galactic TeV UnID sources, Fox et al arXiv:1305.6606
- Dark matter with PeV mass, Esmaili and Serpico, arXiv:1308.1105

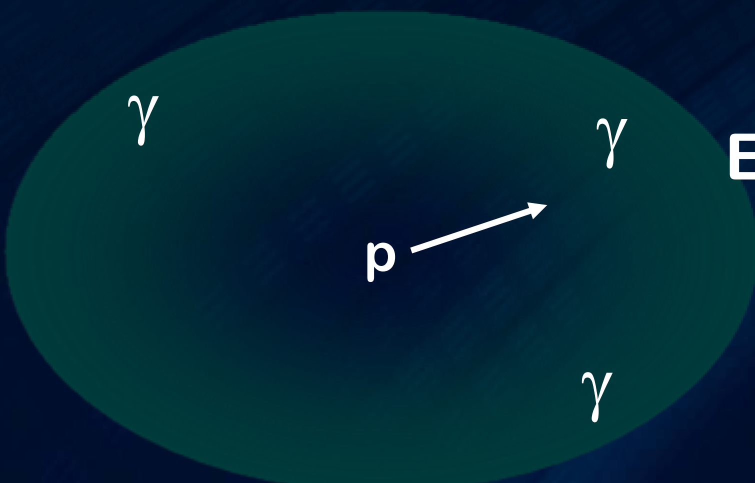
and many more!!

(My) Assumptions on the “on-source” TeV-PeV ν

- They are extra-galactic
- $\gamma p \rightarrow \pi$’s (*not* $pp \rightarrow \pi$’s)

for pp, see Murase, Ahlers, Lacki (2013)

The generic consequence – you need γ target



$$E_\nu \lesssim \Gamma^2 \frac{(E_\pi/E_p)(1-m_\mu^2/m_\pi^2)\,(m_\Delta^2-m_p^2)/4}{E_\gamma}$$

$$E_\gamma \gtrsim 1\,\Gamma^2 \left(\frac{E_\nu^{max}}{10PeV}\right)^{-1} \text{ [eV]}$$

consistent with AGN(Γ~1) or GRBs (Γ~1000)

What else can we say in general ?

On-source ν flux estimates: model-independent analytical approach

Adding up contribution from sources at z

$$\frac{dJ_\nu}{dE_\nu} = \frac{c}{H_0} n_0 \int_0^{z_{max}} dz \frac{\psi(z)}{(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\lambda}} \int_0^z dz_\nu \frac{dN_{p\to\nu}}{dE_\nu^{\rm GEN} dL}(E_\nu(1+z_\nu), z_\nu, z)\frac{dt_\nu}{dz_\nu}.$$

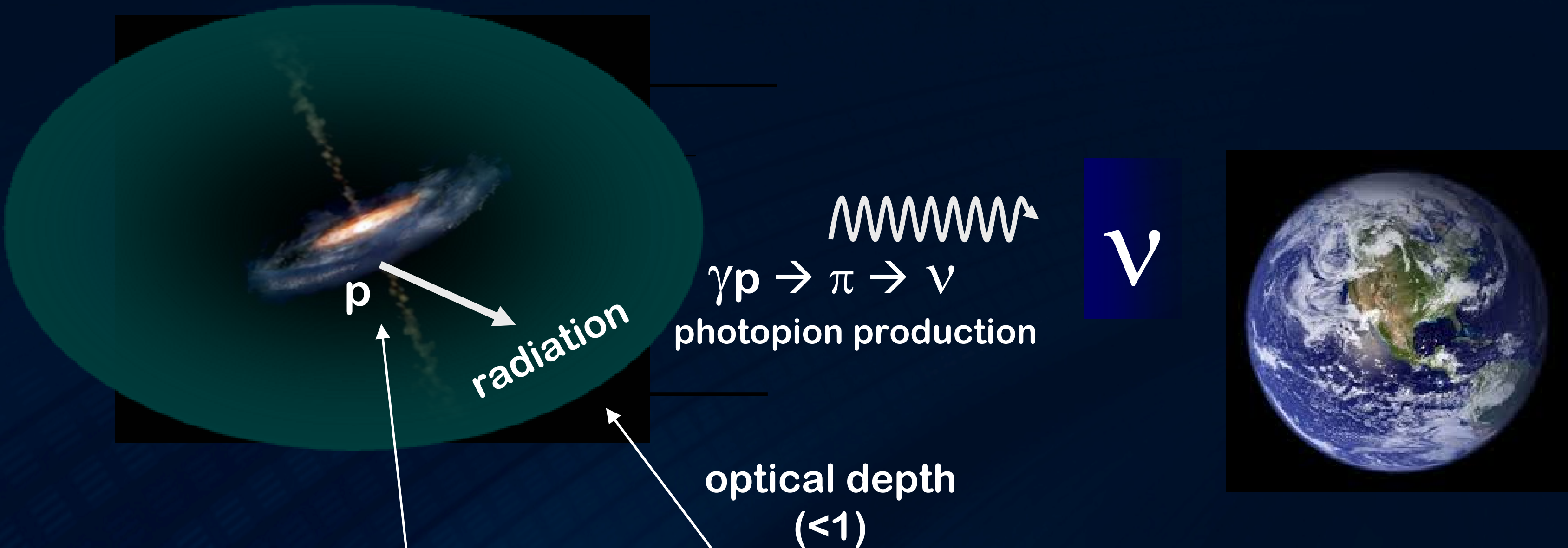
Emission rate per comoving volume

$\sim(1+z)^m$

ν yield with $E^{GEN}=E_\nu(1+z_\nu)$ from UHECR proton emitted from sources at $z>z_\nu$. z_ν; redshift when generates ν

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

On-source ν flux estimates: model-independent analytical approach



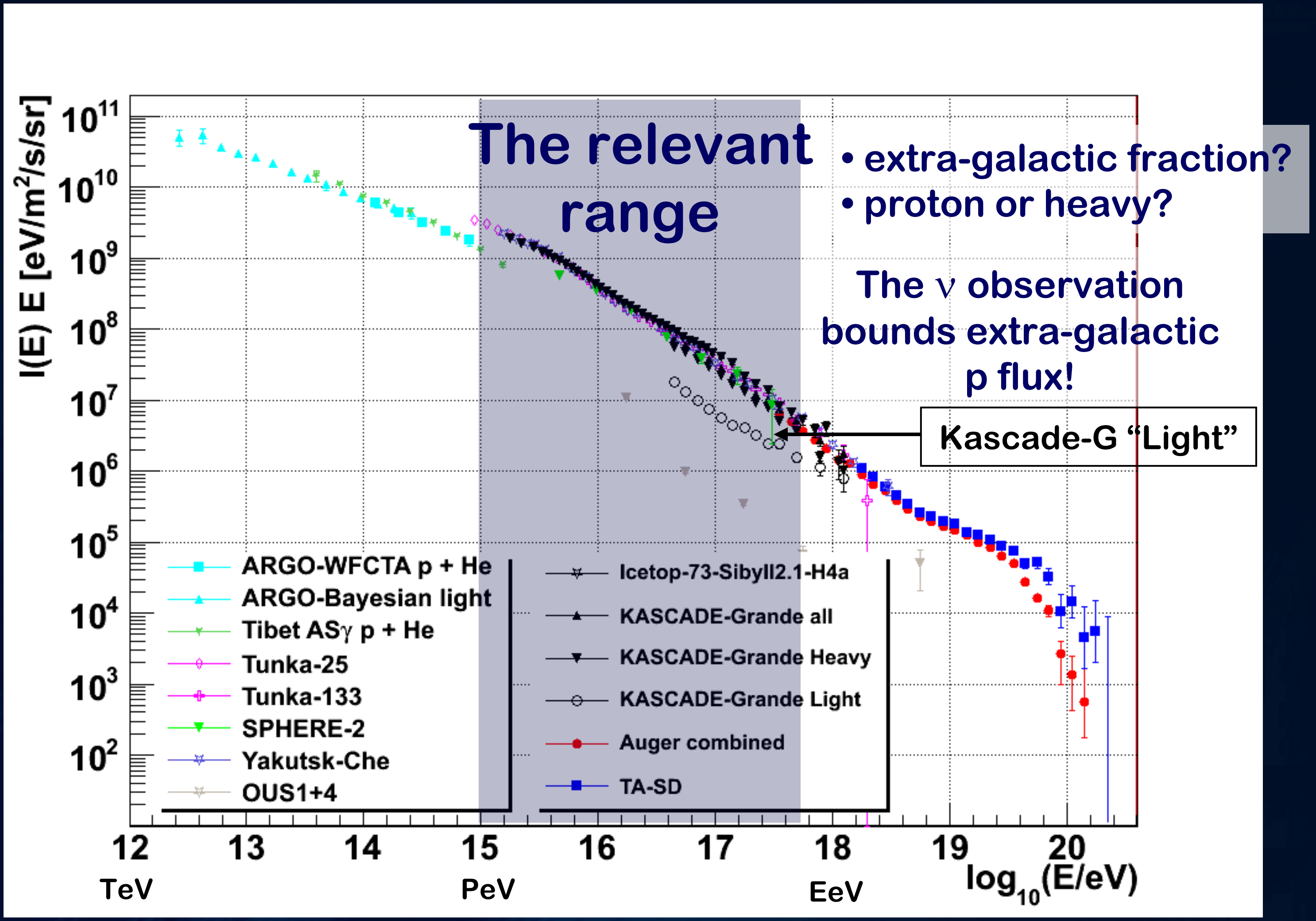
$$\frac{dJ_\nu}{dE} \sim F_{GZK\ CR} \frac{R_{cosmic}}{R_{GZK}} E^{-\alpha} \; \tau(E) \; \zeta(z, m, z_{max}, E)$$

Primary Extragalactic CR proton flux $\sim E^{-\alpha}$

The cosmological term to account the source evolution

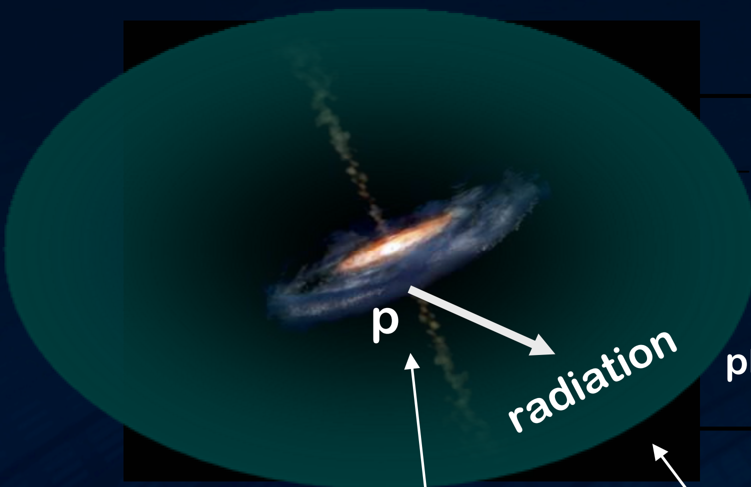
We do NOT know how large: strongly depends on α

The Cosmic Ray Spectrum



Recompiled from the ICRC 2013 Rapporteur talk (Y.Tsunesada)

Constraints on the optical depth and extra-galactic CR flux



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

photopion production

ν

optical depth (<1)

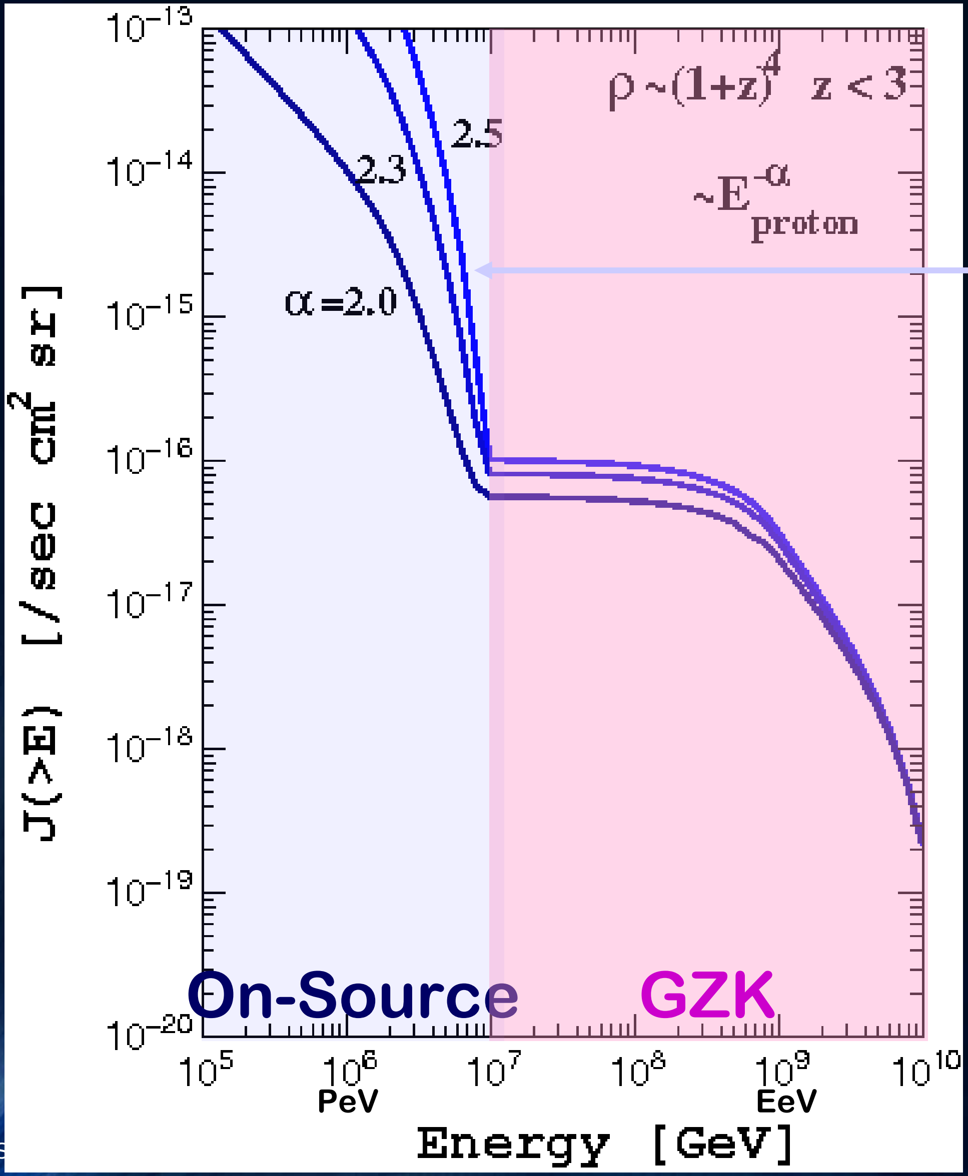
$$\frac{dJ_\nu}{dE} \sim F_{GZK\ CR} \frac{R_{cosmic}}{R_{GZK}} \mathbf{E}^{-\alpha} \; \tau(E) \; \zeta(z, m, z_{max}, E)$$

Fixed to the Star Formation Rate

Constrain them by the IceCube 100TeV-PeV observation

The "on-source" ν fluxes

Integral flux

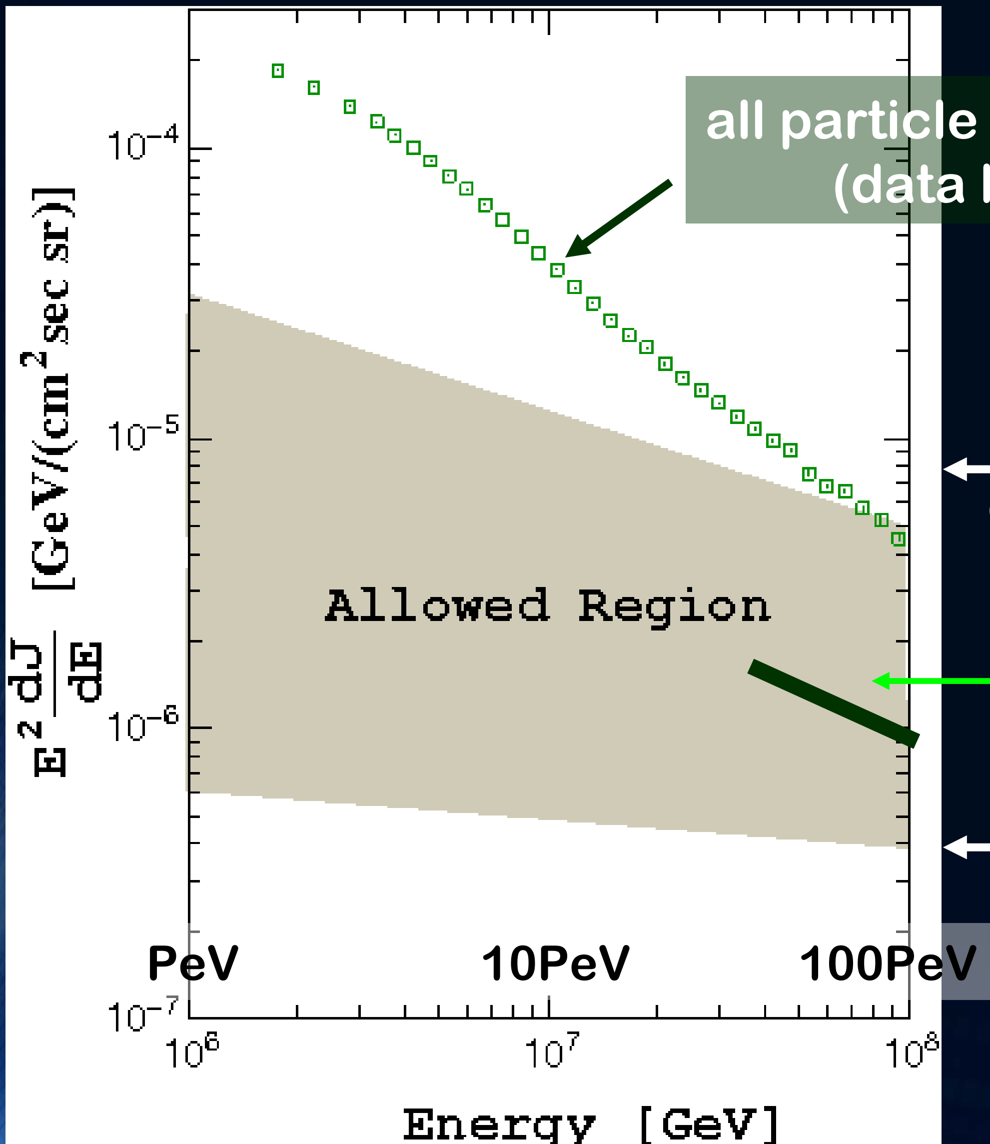


α dependences

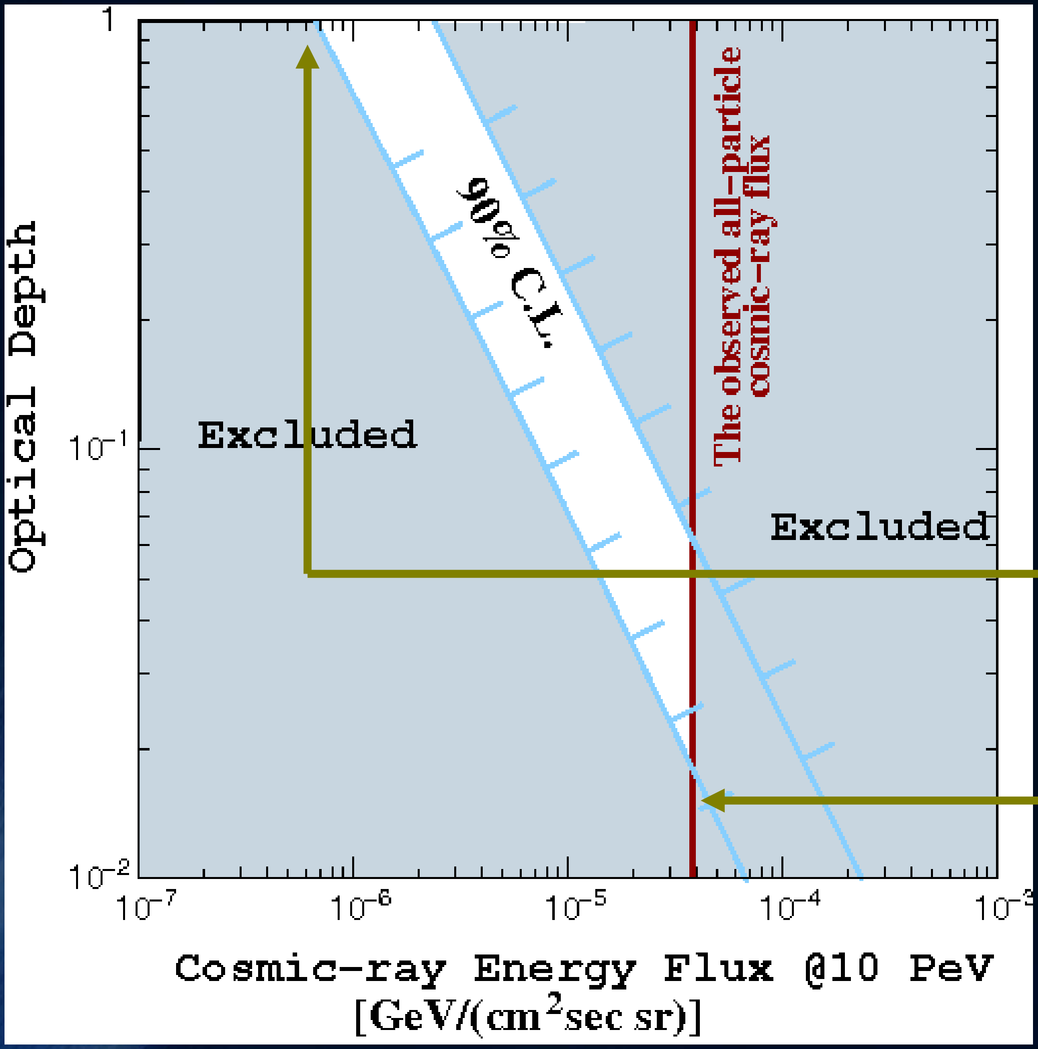
=

(unknown) extra-galactic proton flux dependences

Constraints on the optical depth and extra-galactic CR flux



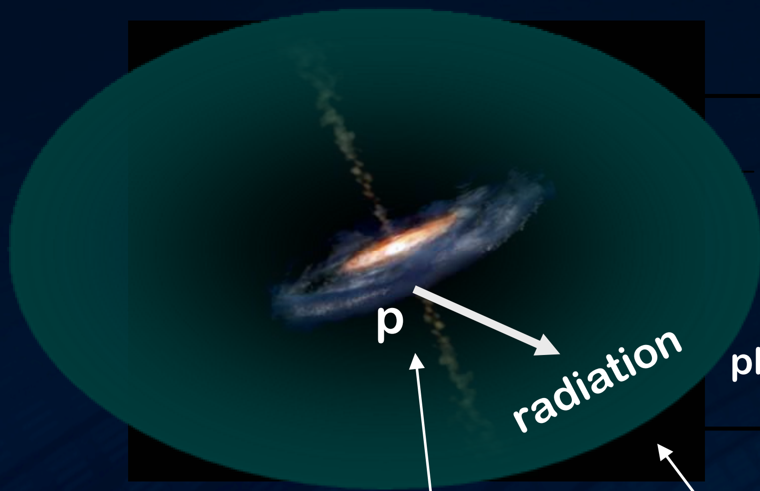
Constraints on the optical depth and extra-galactic CR flux



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

optical depth must be $\gtrsim 10^{-2}$

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



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

photopion production

ν

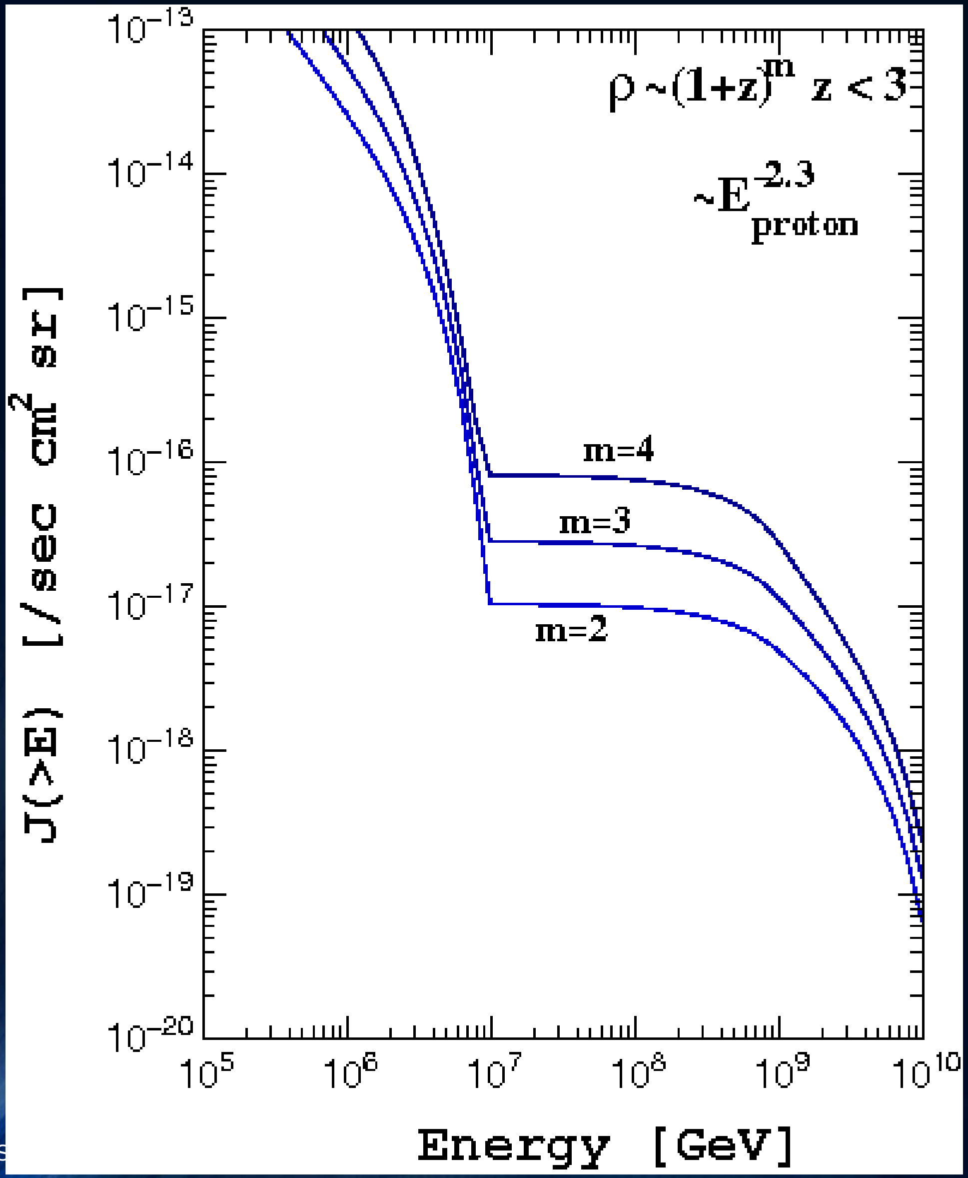
optical depth (<1)

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

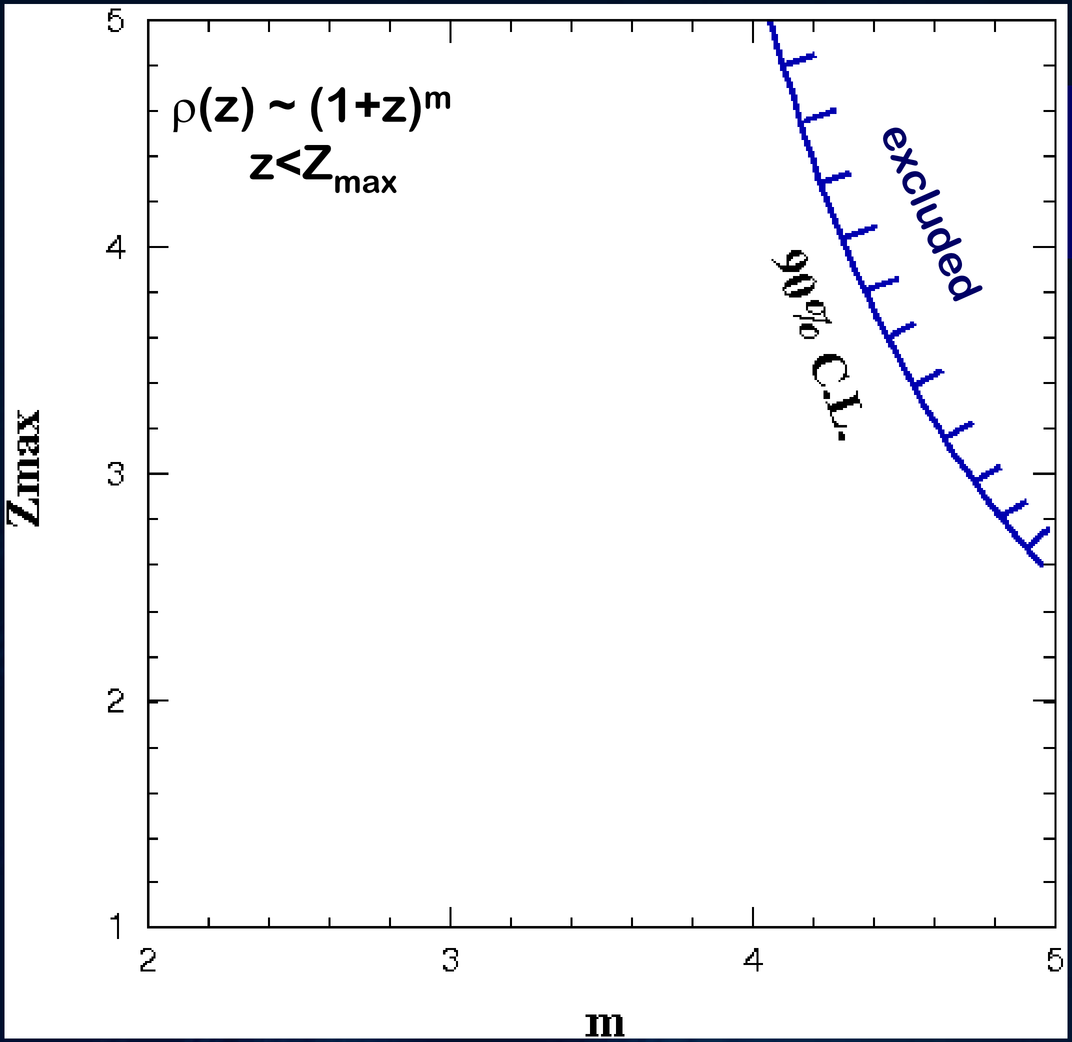
Fixed to $E^{-2.3}$

Constrain them by the IceCube 100TeV-PeV observation

The “on-source” ν fluxes

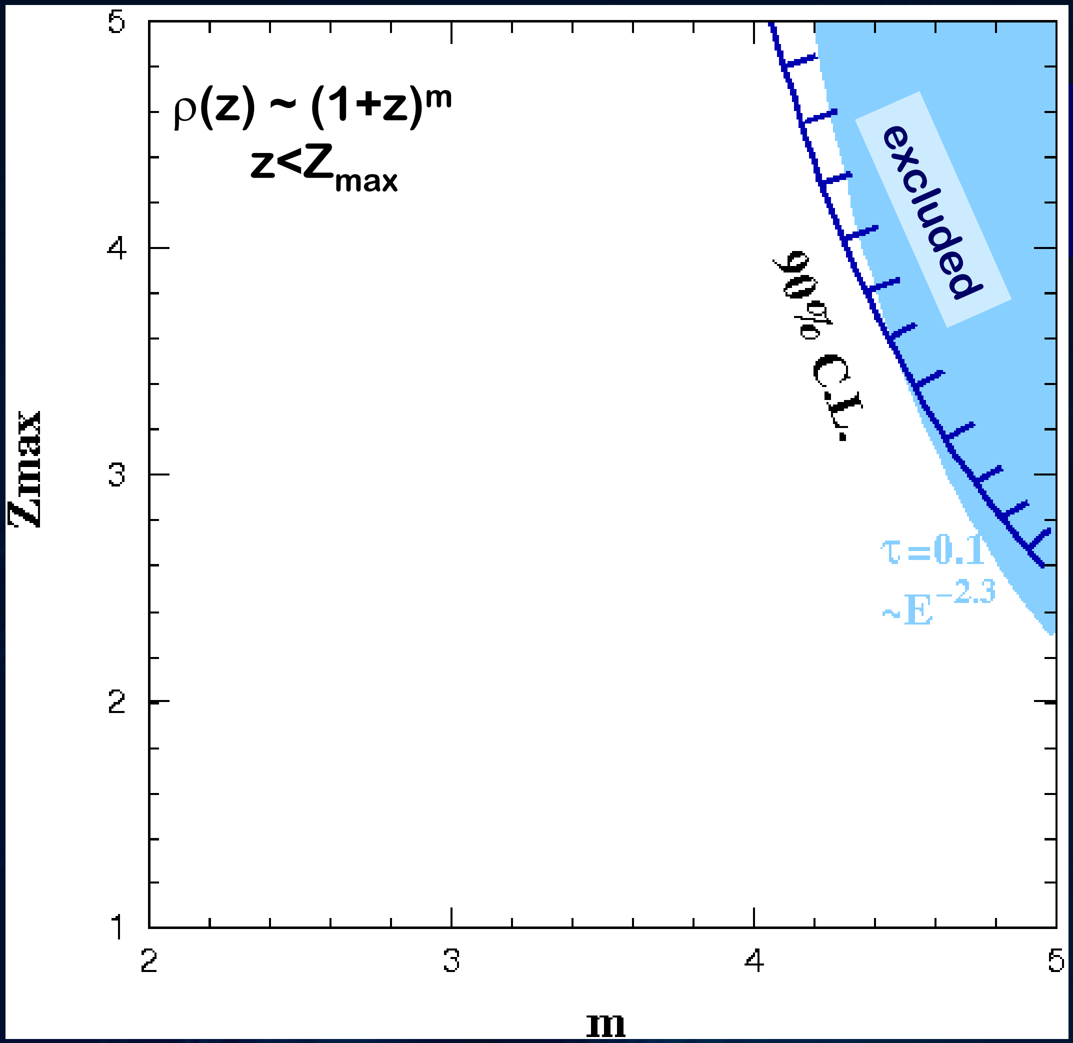


The Constraints on evolution (=emission history) of UHE cosmic ray sources



The solid bound by the GZK ν

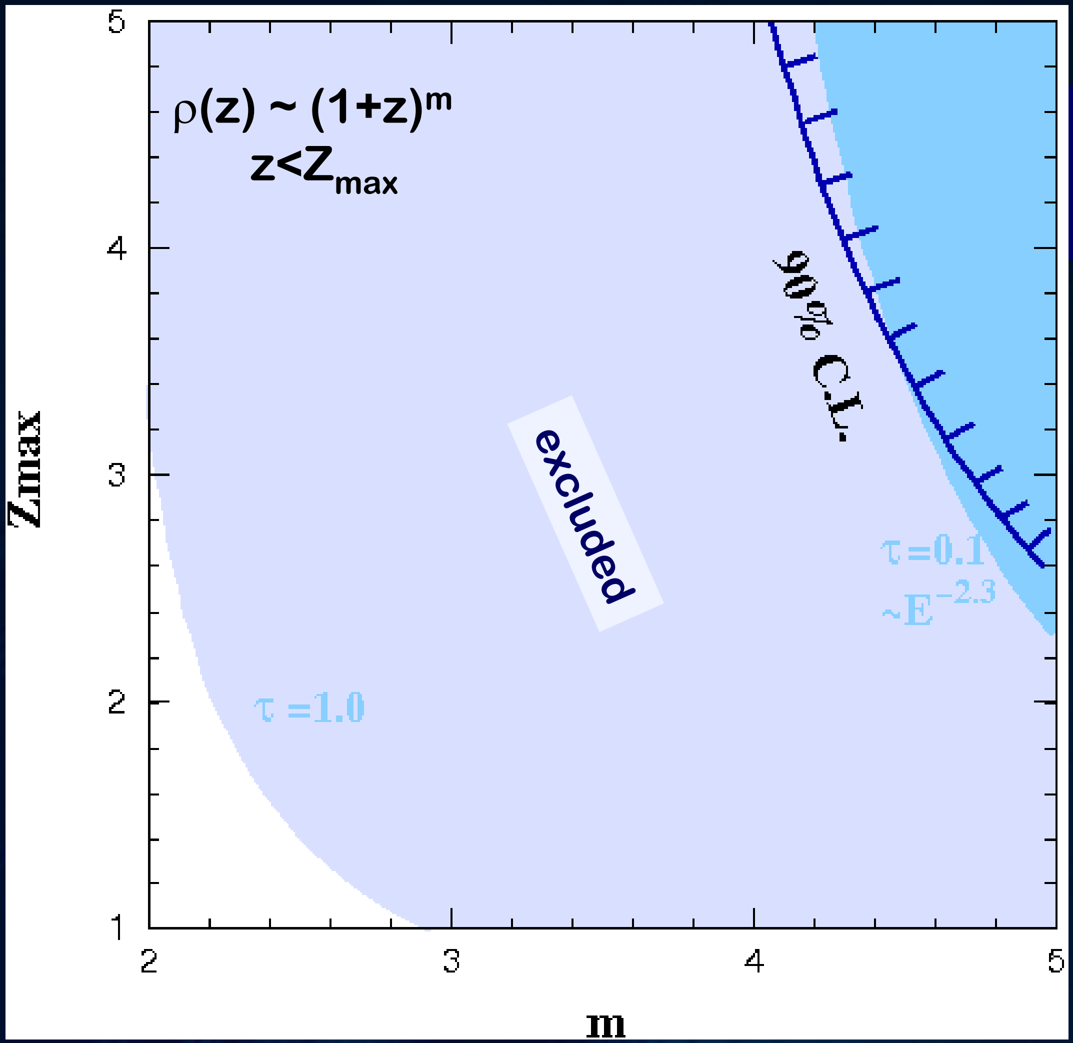
The Constraints on evolution (=emission history) of UHE cosmic ray sources



The solid bound by the GZK ν

+ by the on-source ν

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



The solid bound by the GZK ν

+ by the on-source ν

+ by the on-source ν if optical depth ~1

no high-redshift emission

consistent with the star formation rate

Conclusion: The ν has indicated that...

IF the extra-galactic UHE cosmic rays are protons

The cosmic ray sources (whatever they are) are not strongly evolving with cosmic time.

- disfavors far sources like quasars and radio-loud AGNs
- *may* still OK GRBs – we need to know their rate better.

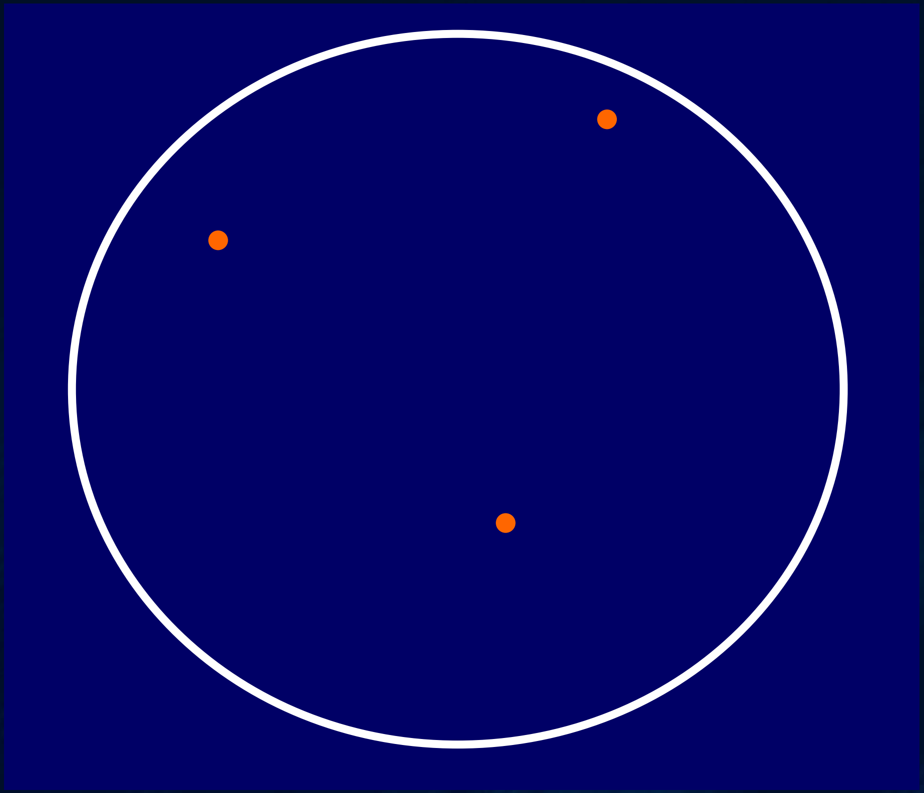
If they are also effective PeV neutrino emitters (i.e., τ~1), must be no sizable evolution – the emission is mostly at z<<2

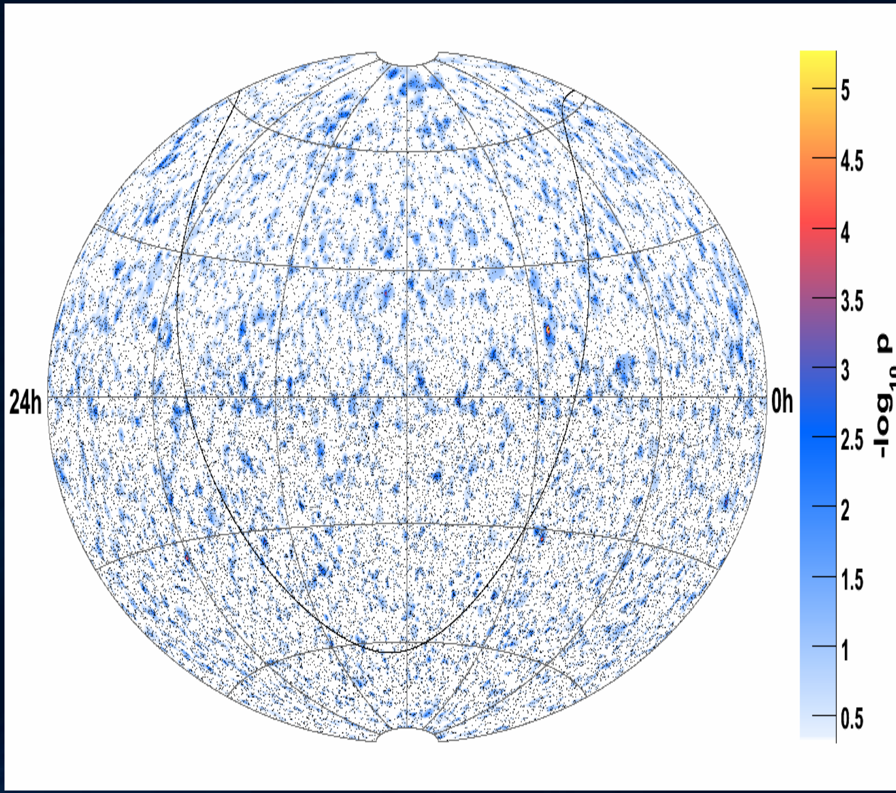
- just like a (boring) standard star following the star formation rate

The PeV ν emitters, if via pγ, are responsible for only ~O(1 %) of the observed cosmic ray bulk at O(10 PeV) or must be optically very thin (τ<<1), otherwise

- extra-galactic proton spectrum is likely harder than the observed all particle cosmic ray spectrum beyond knee

A Personal View: Diffuse Search Vs. Point Sources





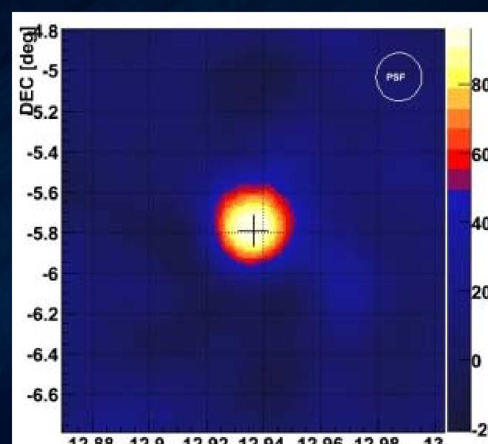
- Looks *boooooooooring*
- But the intensity and even its limit would provide rich implications
- ν is sensitive to (unresloved) dim emission

- Looks *cooooooooooool!*
- But doesn't mean anything
- ν 's are NOT local messengers – no good at resolving sources

A Personal View:
Diffuse Search Vs. Point Sources

But we want to ID a source(s) in the end!

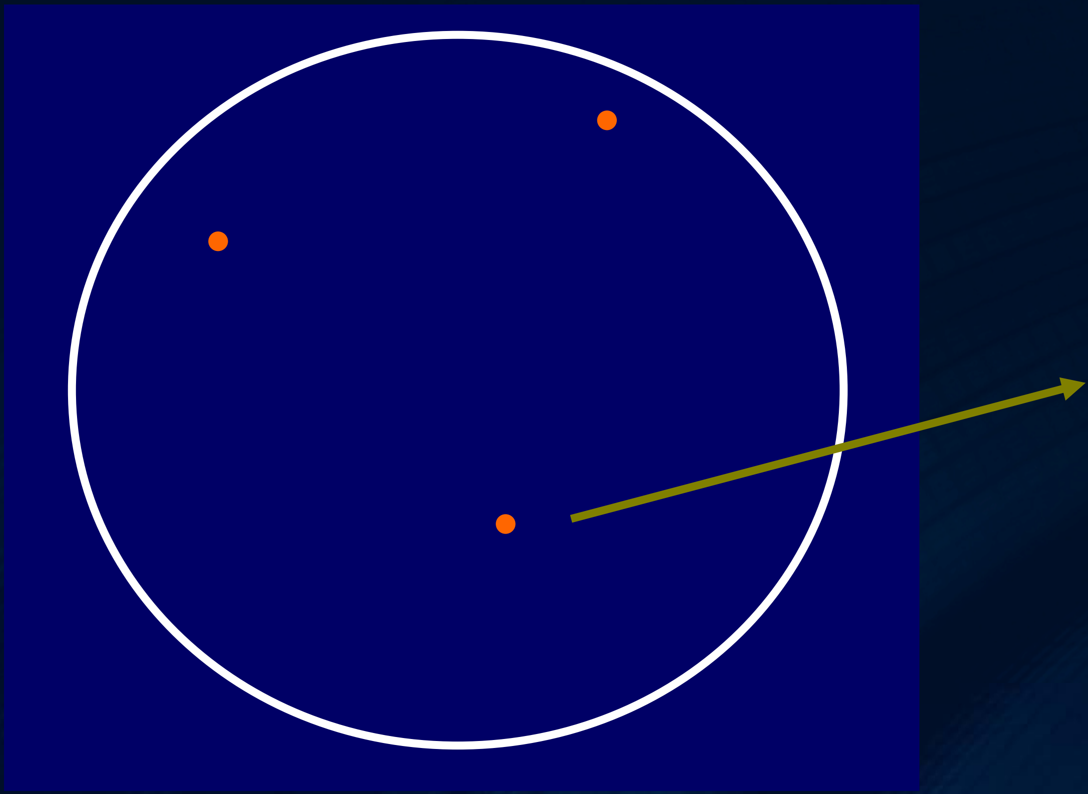
This is
THE UHECR SOURCE!



PKS0XYZ+0xy

(ICECUBE J1XYZ-3xy)

The Multi Messengers: UHE $\nu \rightarrow \gamma$

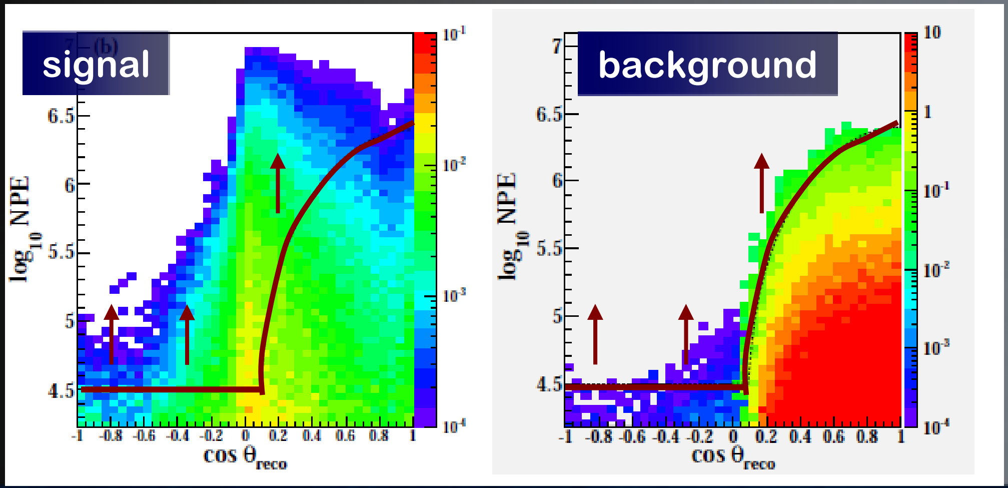


look up this direction!

ν "GFU" γ

The Multi Messengers: UHE $\nu \rightarrow \gamma$

The IceCube UHE ν search



- sensitive to ν > O(10PeV)
- the robust algorithm

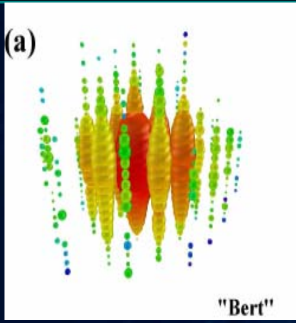
~ 2 events/year for $\nu_{e+\mu+\tau}$ of $E^2\phi = 3 \times 10^{-8} GeVm^{-2}sec^{-1}sr^{-1}$

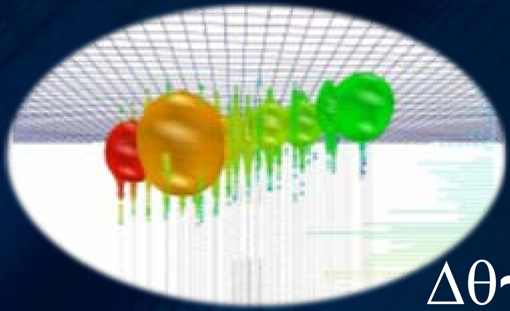
BG: ~ 0.1 event/year

cascade | track

new

event topology separation



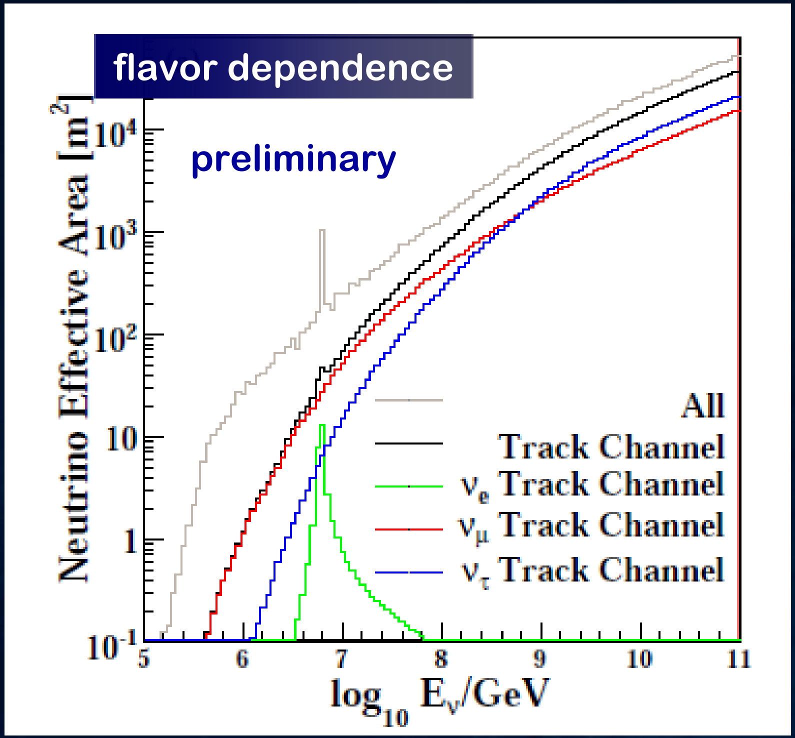


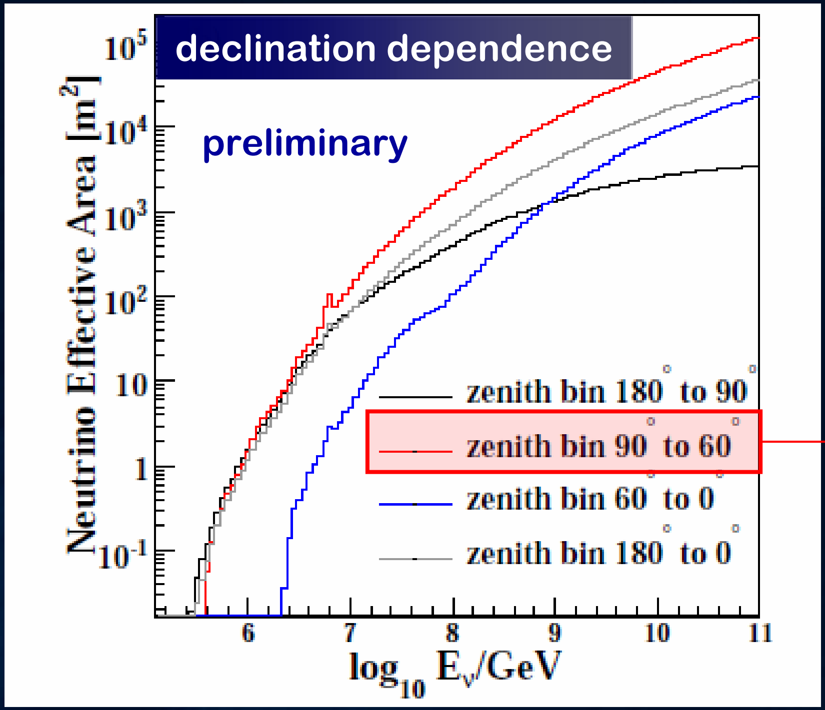
$\Delta\theta$~1deg

The Multi Messengers: UHE $\nu \rightarrow \gamma$

This is the next move of the Japan's IceCube group

the detection sensitivity





dec. -30~0 = southern sky!

→ H.E.S.S.

→ VERITAS with Large Zenith

→ MAGIC?

科研費新学術「ニュートリノ」の公募研究が開始されます。(H26年度)

- 150-300 万
- ２年間
- 今年から学振PDも応募できます！
- 「ニュートリノ」が少しでもからんでいればよし

たとえば(あくまで例えばです)

- ああ旅費がほしいなあという理論屋さん
- **ASIC** のテストキットがあればなあという実験屋さん
- しょうがないから吉田とマルチメッセンジャーやってやるから旅費よこせという観測屋さん