Constraints on UHECR Sources with 9 Years of the IceCube EHE Data

AYA ISHIHARA (CHIBA UNIVERSITY)

FOR THE ICECUBE COLLABORATION

Selected results from

Constraints on ultra-high-energy cosmic ray sources from a search for neutrinos above 10 PeV with IceCube

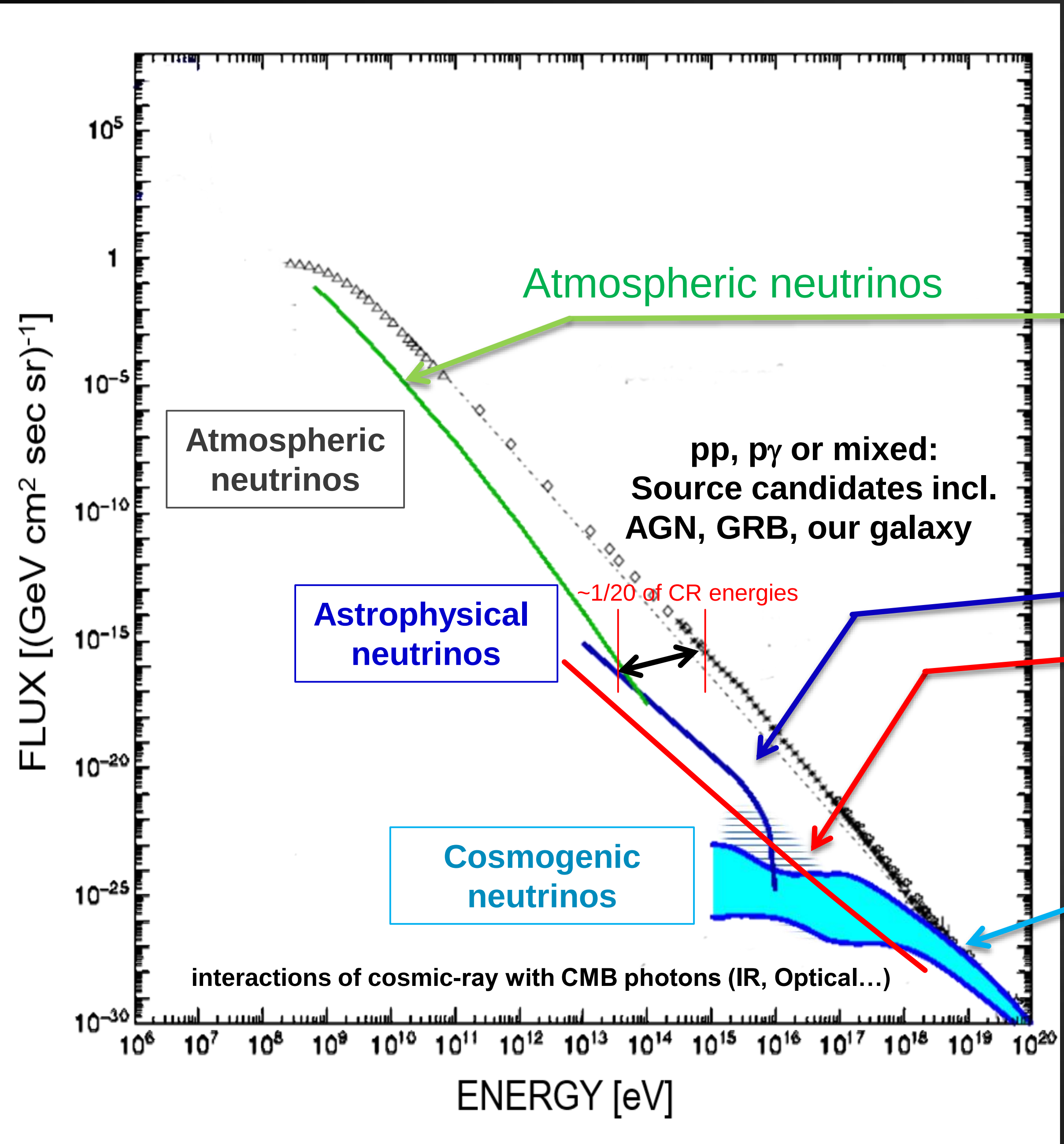
- Phys. Rev. Lett. **117**, 241101 (2016); Erratum/Phys. Rev. Lett. 119, 259902 (2017)

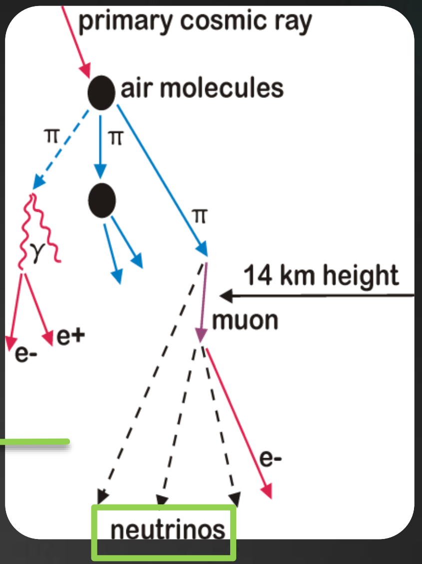
and

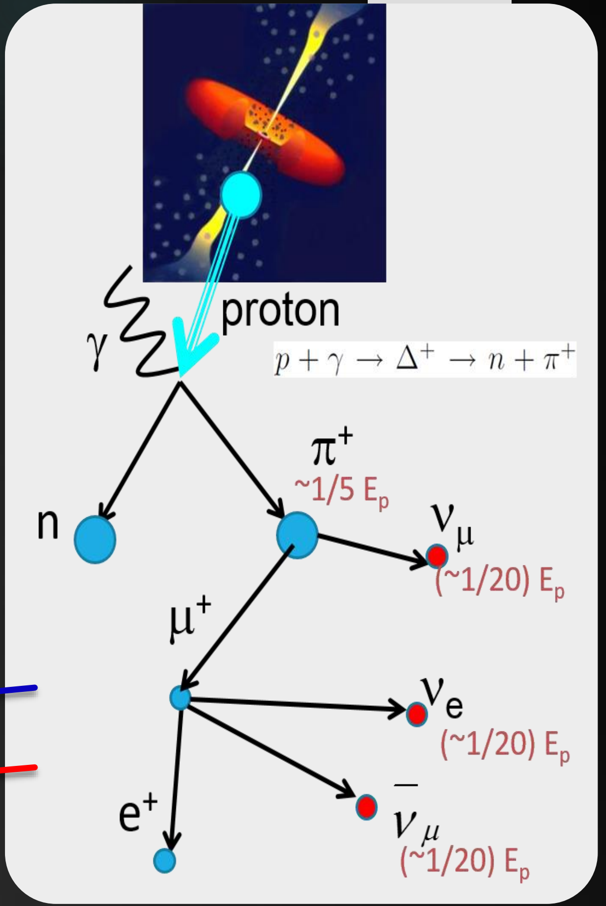
Differential limit on the extremely-high-energy cosmic neutrino flux in the presence of astrophysical background from nine years of IceCube data

- Phys Rev D **98** 062003 (2018)

Cosmic-rays creates neutrinos







"IceCube neutrino flux"

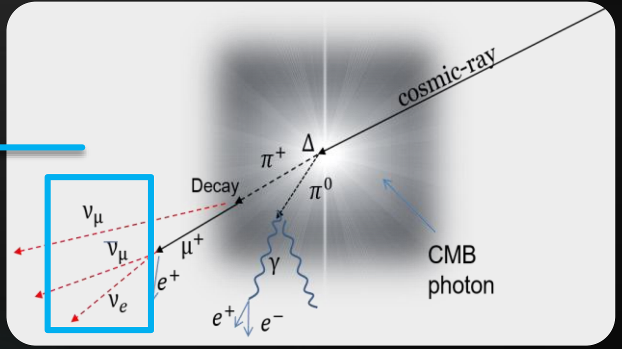
10 TeV - PeV

"Astrophysical neutrinos"

UHECR source may produce detectable fluxes above 10 PeV!

"Cosmogenic neutrinos"

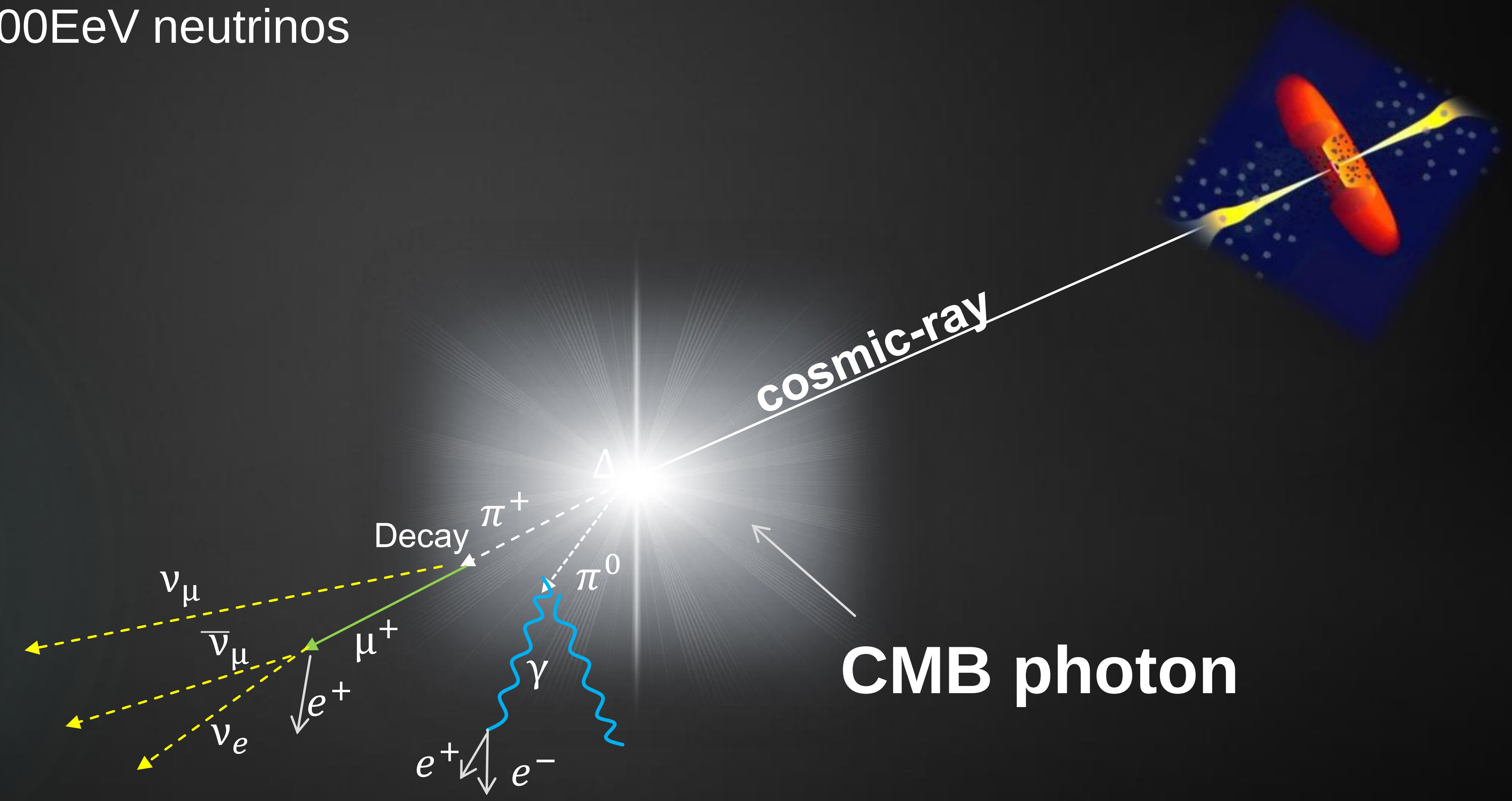
dominates above 10PeV



Cosmogenic Neutrinos

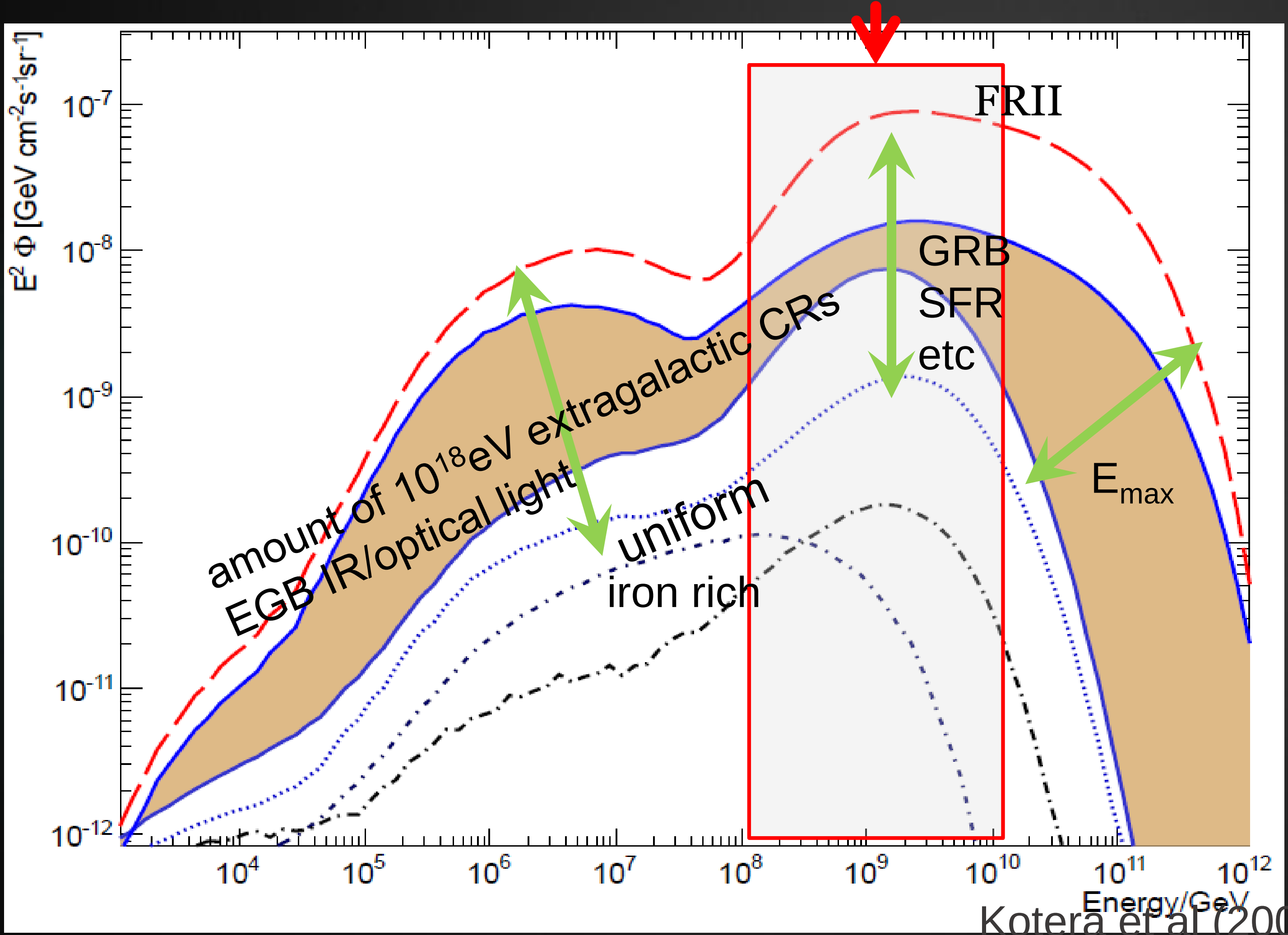
Induced by the off-source (<50Mpc) interactions of UHE cosmic-rays (>$10^{19.5}$eV) and CMB photons via GZK (Greisen-Zatsepin-Kuzmin) mechanism

⇒PeV-100EeV neutrinos



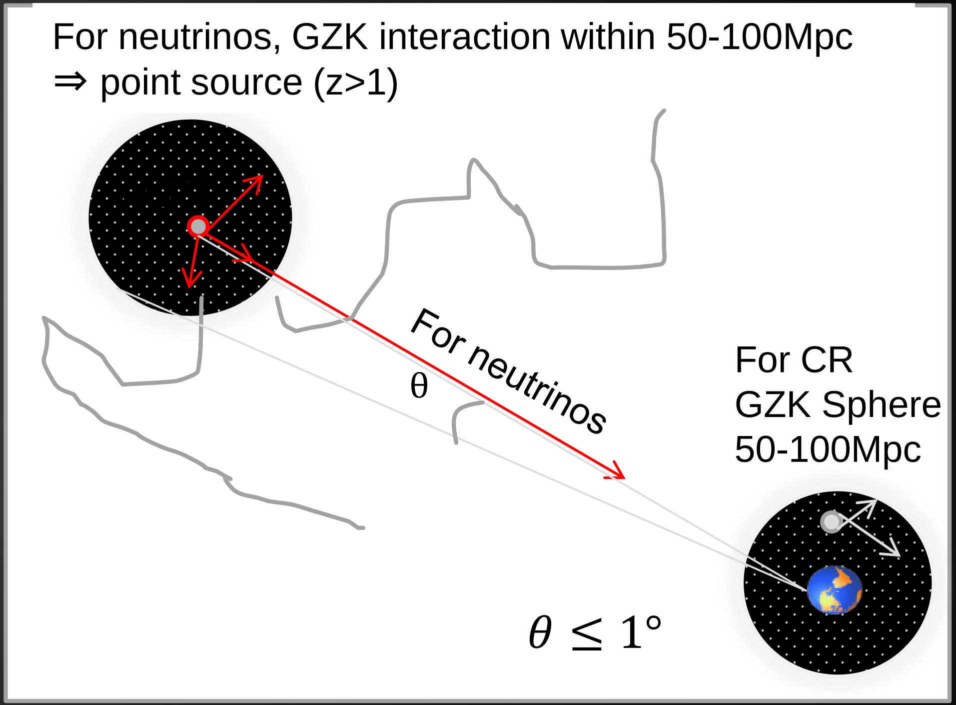
Messenger from beyond GZK sphere

IceCube's event rates ⇒ cosmic-ray source evolutions and composition

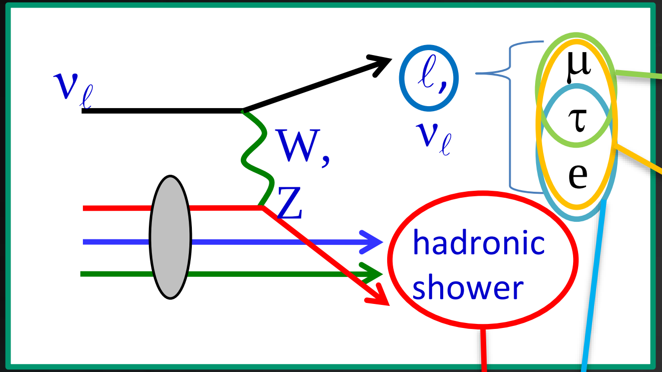


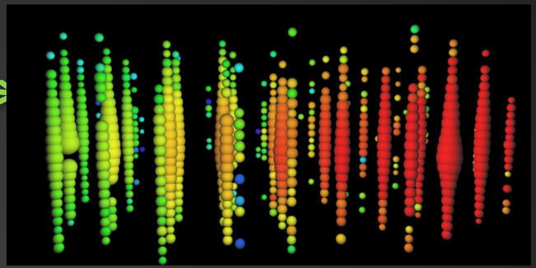
Kotera et al (2009)

Location of the UHE cosmic-ray sources



High Energy Neutrino Detection Channels



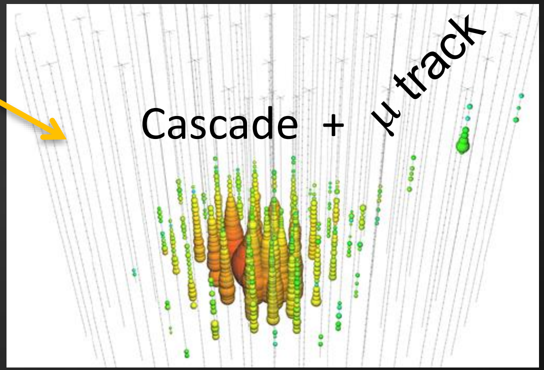


ν_μ CC only

~880TeV upward through-going muon track event

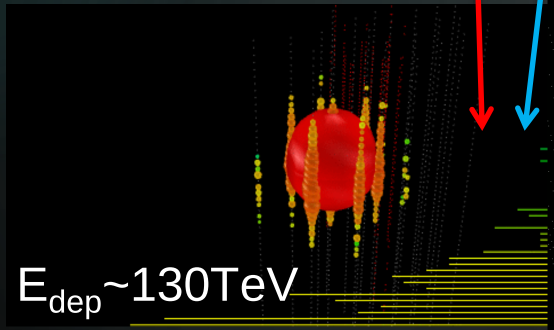
Phys. Rev. Lett. 115, 081102

Starting event inside detector sensitive to all flavor CC/NC

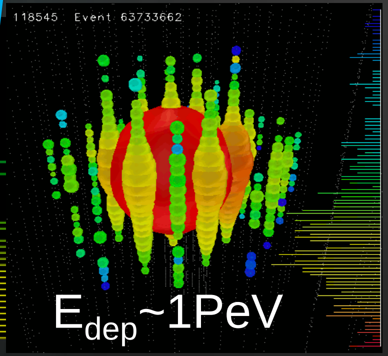


Science 22 Vol. 342 (2013)
PRL 113, 101101 (2014)

Cascade-like
NC and ν_e ν_τ CC events

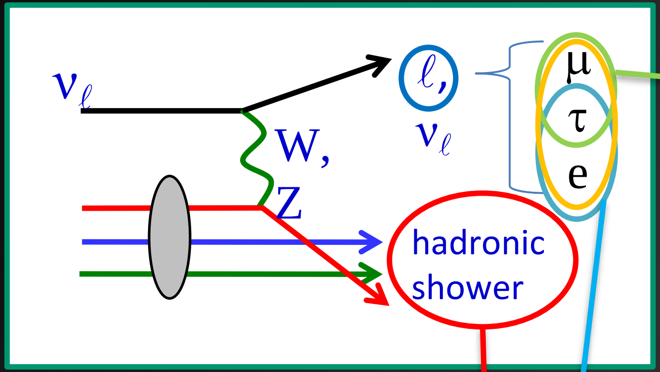


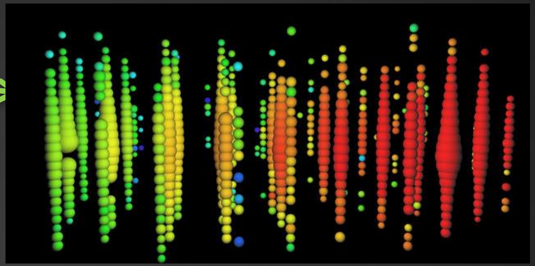
Phys. Rev. D 84, 072001 (2011)



PRL 111 (2013) 021103

Extremly-high Energy Neutrino Detection Channel





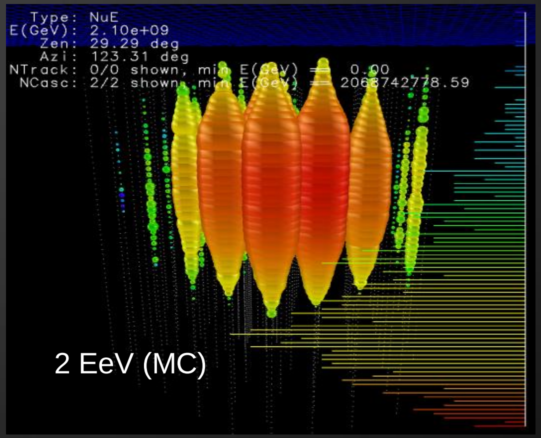
ν_μ CC only

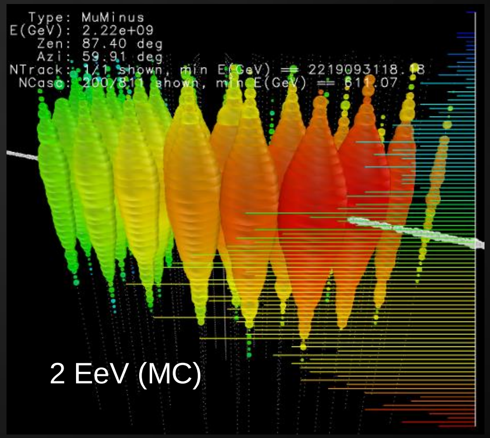
~880TeV upward through-going muon track event

Phys. Rev. Lett. 115, 081102

EHE signals: All flavors

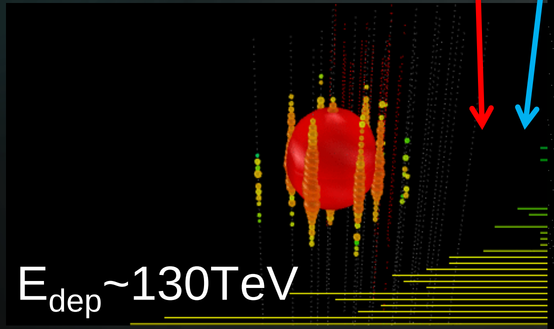
elongated cascades and highly stochastic tracks



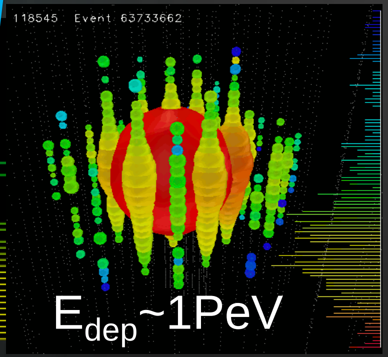


Cascade-like

NC and ν_e ν_τ CC events



Phys. Rev. D 84, 072001 (2011)

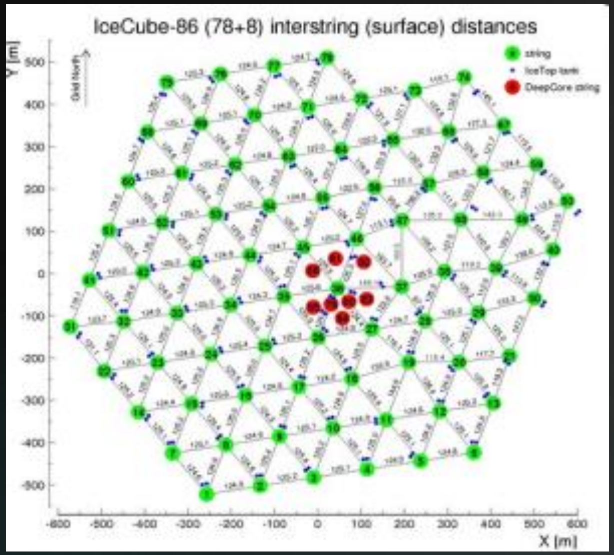


PRL 111 (2013) 021103

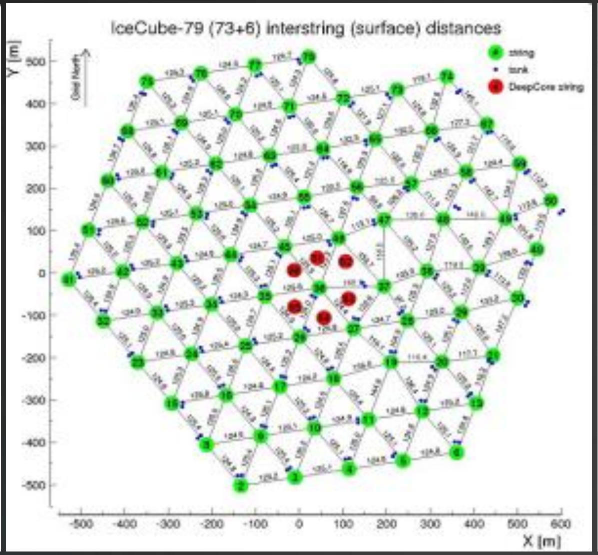
IceCube 9 year EHE Sample

- **Data from IC40-2008 to IC86-2016 runs (9 years)**

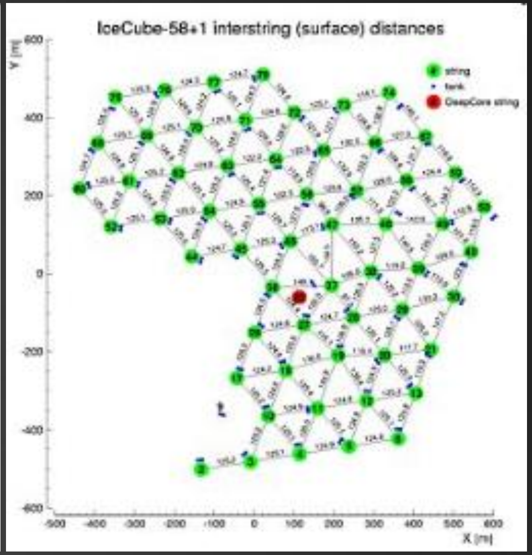
IC86 = full IceCube (2011/5~2017/5)



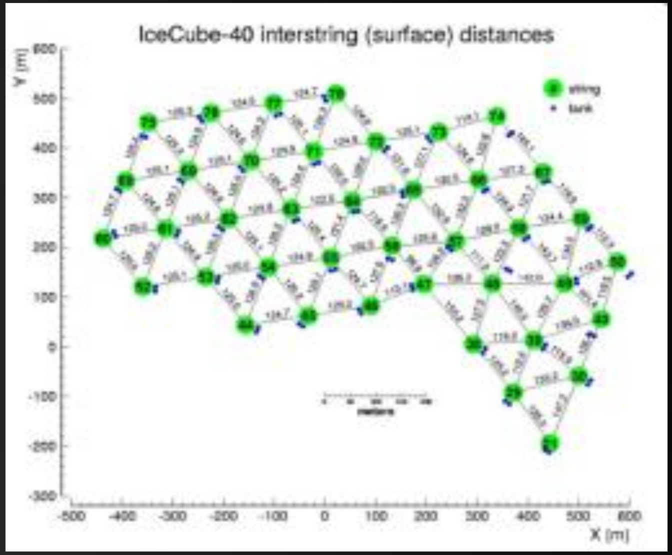
IC79 (2010-2011)



IC59 (2009-2010)



IC40 (2008-2009)



- 22 strings results

The first search for extremely-high energy cosmogenic neutrinos with the IceCube Neutrino Observatory - IceCube Collaboration (Abbasi, R. *et al.*) Phys.Rev. D82 (2010) 072003 arXiv:1009.1442

- 40 strings results

Constraints on the Extremely-high Energy Cosmic Neutrino Flux with the IceCube 2008-2009 Data - IceCube Collaboration (Abbasi, R. *et al.*) Phys.Rev. D83 (2011) 092003, Erratum: Phys.Rev. D84 (2011) 079902 arXiv:1103.4250 [astro-ph.CO]

- 79 strings and the first full IceCube results ⇒ Observation of the first PeV events

First observation of PeV-energy neutrinos with IceCube - IceCube Collaboration (Aartsen, M.G. *et al.*) Phys.Rev.Lett. 111 (2013)

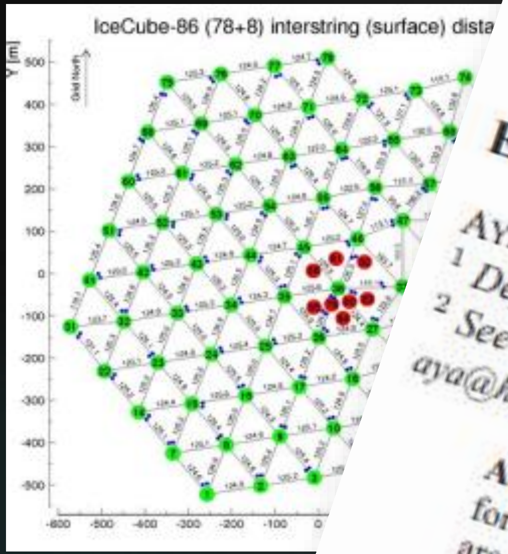
- 79 strings and the first full IceCube results ⇒ The first constraints on realistic cosmogenic neutrino models

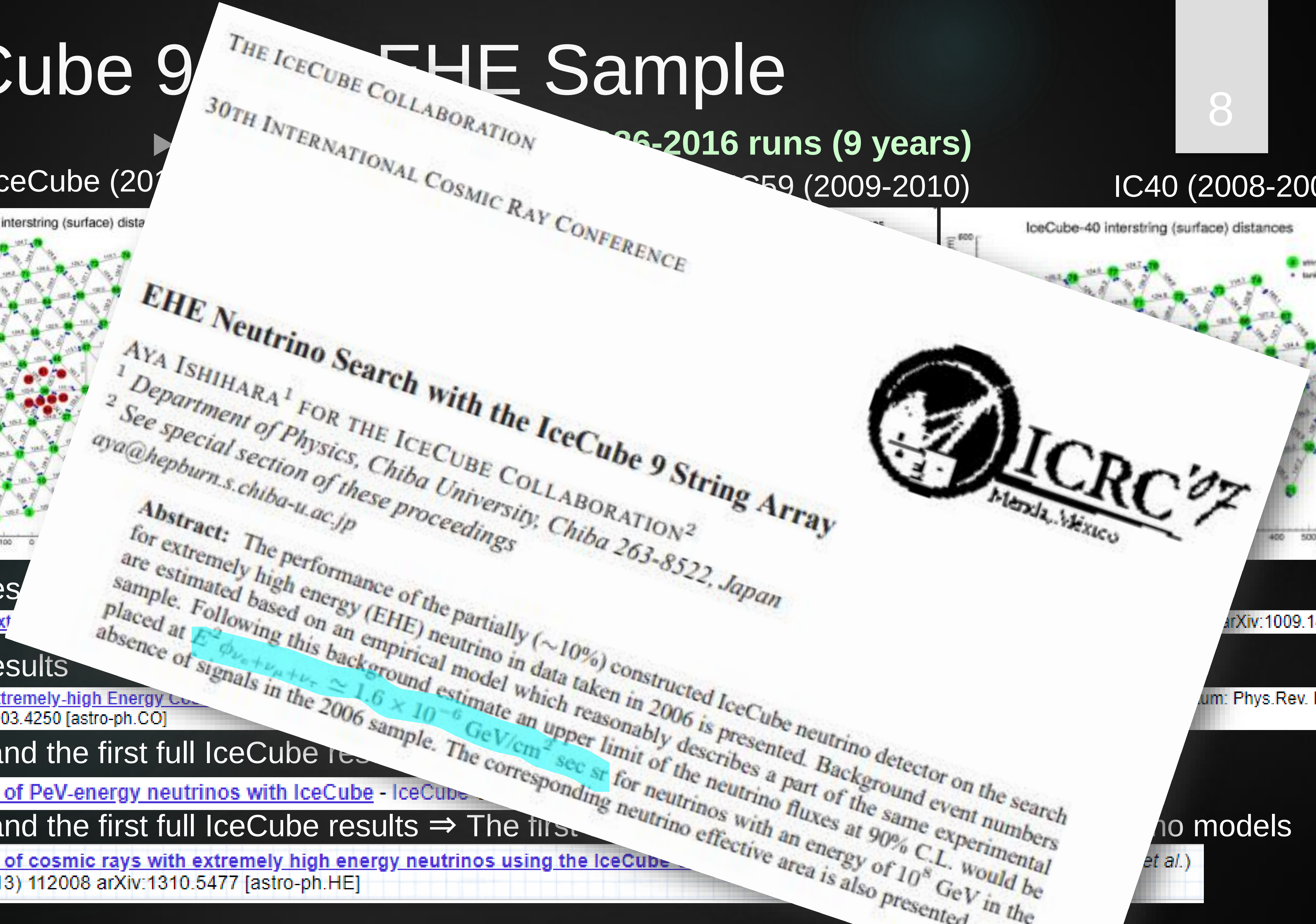
Probing the origin of cosmic rays with extremely high energy neutrinos using the IceCube Observatory - IceCube Collaboration (Aartsen, M.G. *et al.*) Phys.Rev. D88 (2013) 112008 arXiv:1310.5477 [astro-ph.HE]

IceCube 9 ... EHE Sample

▶ ...86-2016 runs (9 years)

IC86 = full IceCube (20... | ...C59 (2009-2010) | IC40 (2008-2009)





THE ICECUBE COLLABORATION

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Merida, Mexico

EHE Neutrino Search with the IceCube 9 String Array

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Abstract: The performance of the partially (~10%) constructed IceCube neutrino detector on the search for extremely high energy (EHE) neutrino in data taken in 2006 is presented. Background event numbers are estimated based on an empirical model which reasonably describes a part of the same experimental sample. Following this background estimate an upper limit of the neutrino fluxes at 90% C.L. would be placed at $E^2\phi_{\nu_e+\nu_\mu+\nu_\tau} \simeq 1.6 \times 10^{-6}$ GeV/cm^2 sec sr for neutrinos with an energy of 10^8 GeV in the absence of signals in the 2006 sample. The corresponding neutrino effective area is also presented

22 strings res...

The first search for ext... ...arXiv:1009.1442

40 strings results

Constraints on the Extremely-high Energy Co... ...um: Phys.Rev. D84 (2011) 079902 arXiv:1103.4250 [astro-ph.CO]

79 strings and the first full IceCube re...

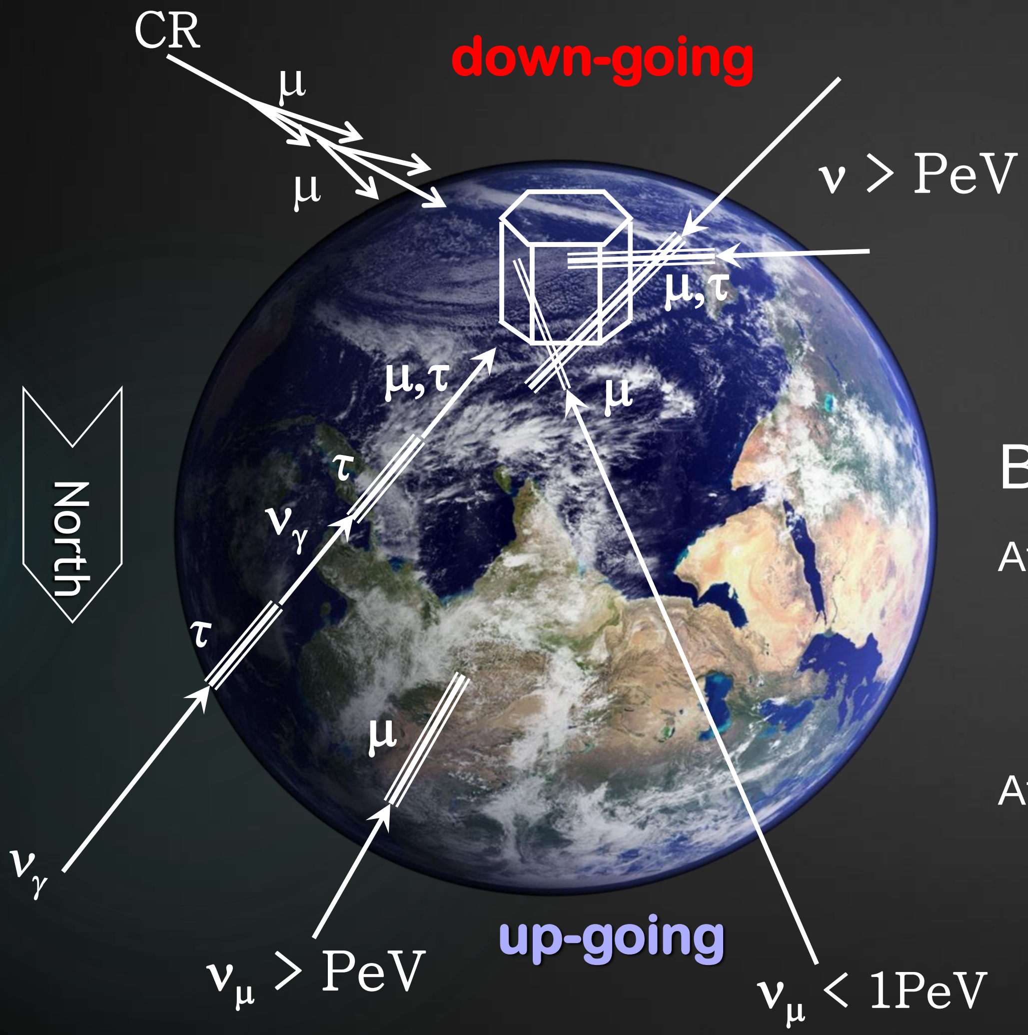
First observation of PeV-energy neutrinos with IceCube - IceCube ...

79 strings and the first full IceCube results ⇒ The first ... no models

Probing the origin of cosmic rays with extremely high energy neutrinos using the IceCube ... et al.)

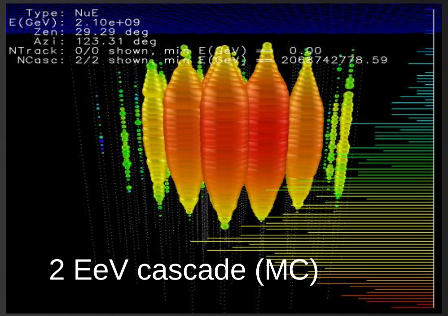
Phys.Rev. D88 (2013) 112008 arXiv:1310.5477 [astro-ph.HE]

Extremly-high Energy (EHE) Events

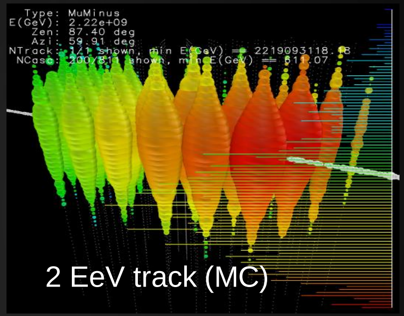


Signal: **above 10 PeV**

elongated cascades and highly stochastic tracks



2 EeV cascade (MC)



2 EeV track (MC)

Background:

Atmospheric muons

- vertical down-going a large number of muons in a bundle
- inclined down-going a few high energy muons

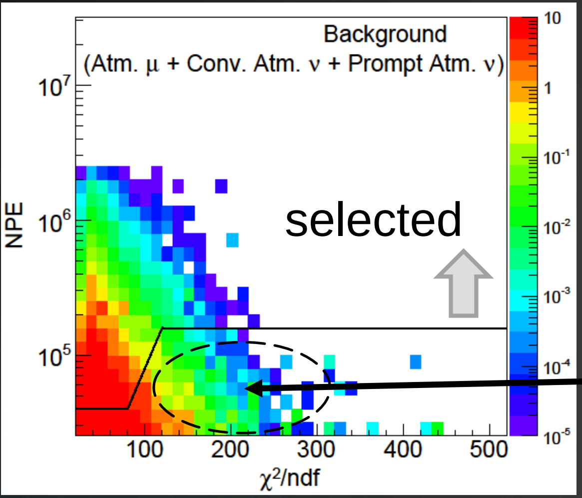
Atmospheric neutrinos

- from pion and kaon decay: dominant below ~PeV
- from charmed meson decay: above ~PeV, large uncertainty

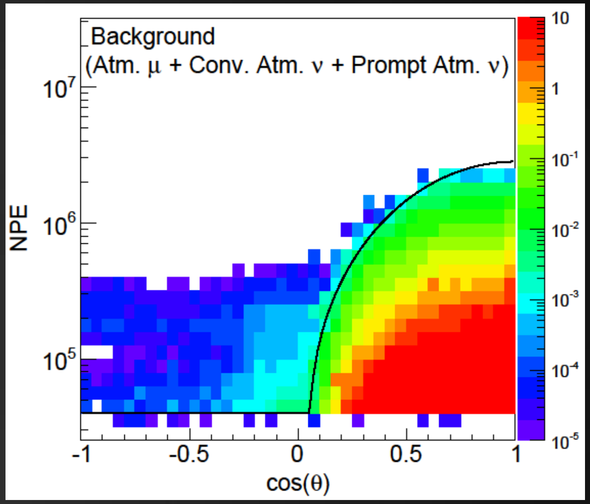
EHE Event Selection

track-like ⟷ cascade-like

up-going ⟷ down-going



Background

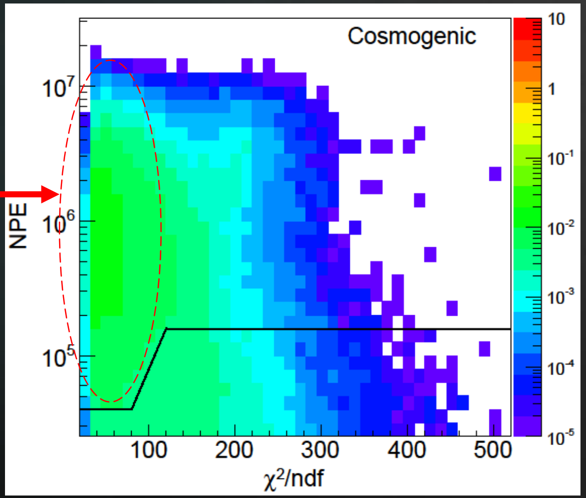


$\lesssim$ PeV cascades (prompt ν)

+

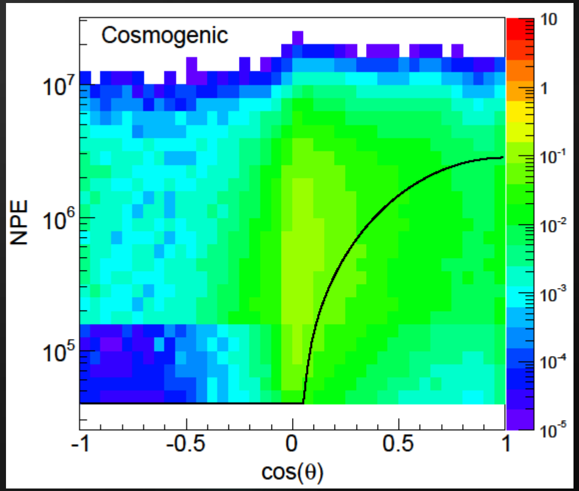
mis-reconstructed muons

well reconstructed track events (muon and taus)



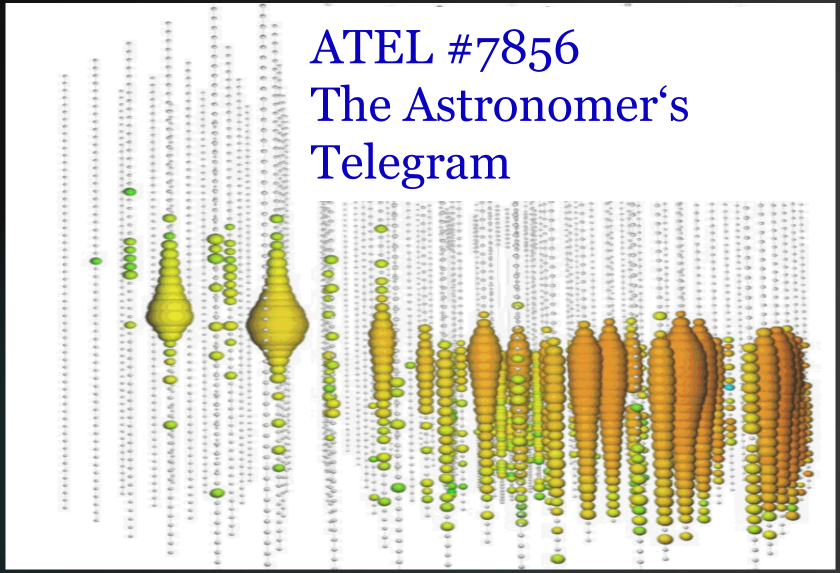
more than 100,000 photo electrons per event

Signal



Neutrino events above PeV (=10^{15}eV)

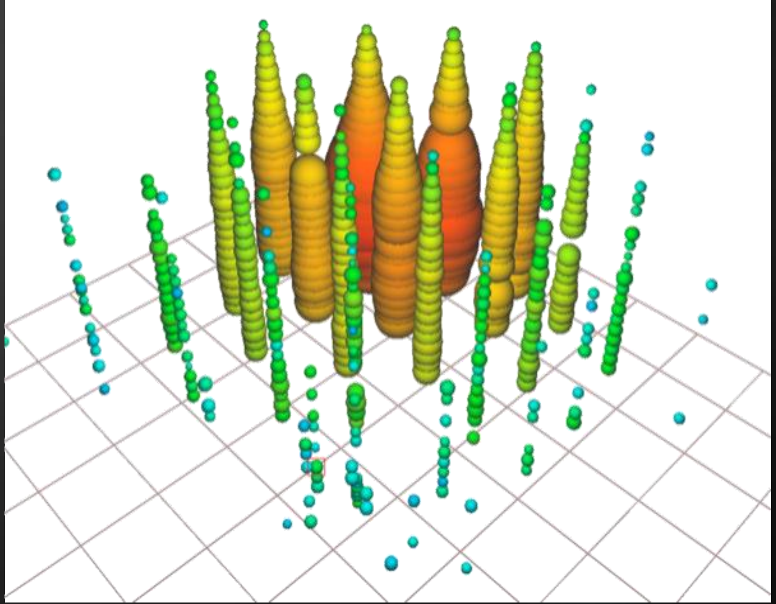
- two events observed in 9 year data of extremely-high event selection



A upward-going track with the highest energy deposit
2014 data
reconstructed energy deposits **2.6±0.3 PeV**
number of photo electrons 130,000pe

- Only 1 event observed in 7 year data

particle shower event in December 2016
Reconstructed energy deposit **5.9±0.18 (stat) PeV**
Number of photoelectrons 200,000pe (the brightest to date)
Glashow resonance event cadidate



Binned Poisson LLH analysis

$$L(\lambda) = \prod_{i=1}^{N} Poisson(n_i, \mu_i(\lambda))$$ (n_i observation and μ_i expectation in i_{th} bin)

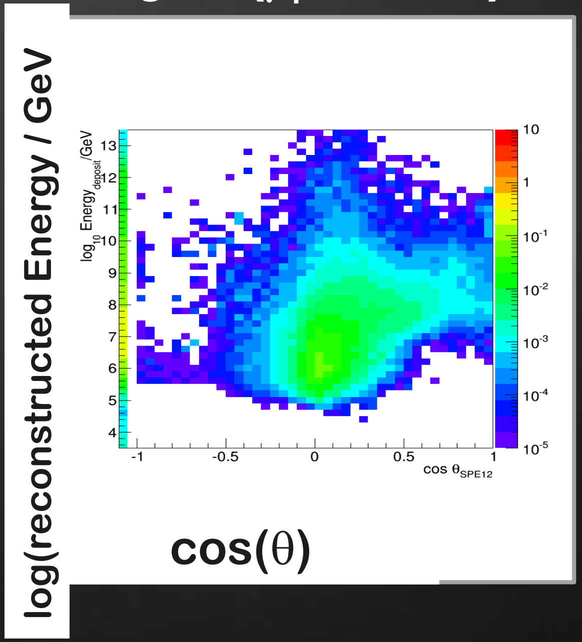
Ex) a case of atmospheric background only hypothesis test

$$\begin{cases} H_0: \mu_i(\lambda_0 = 0) = \mu_i^{BG} \\ H_1: \mu_i(\lambda^{max}) = \mu_i^{BG} + \lambda^{max} \mu_i^{cosmogenic} \end{cases}$$ (λ^{max} maximizes L_1)

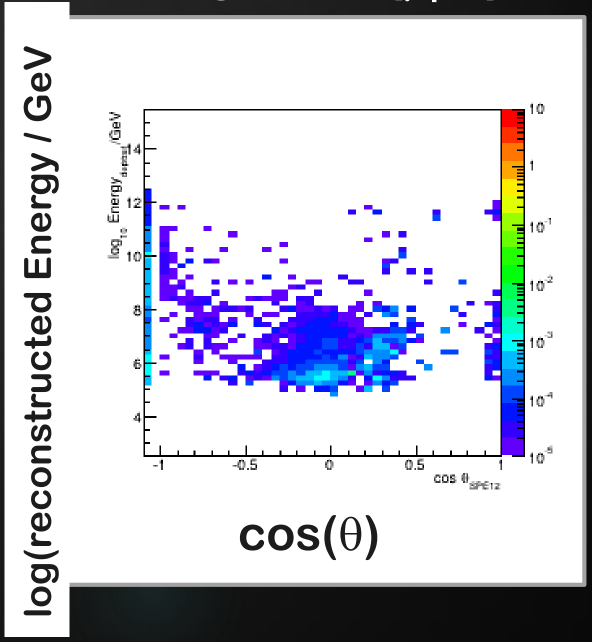
test statistic

$$\Lambda = \ln \frac{L(\lambda^{max})}{L(\lambda_0)}$$

signal ($\mu_i^{cosmogenic}$)



Background (μ_i^{BG})



Tests on the Observed Events

Is the observed event explained by atm. background?

No. Hypothesis of observed event being of atmospheric origin rejected at 3.5σ.
Background only hypothesis test resulted a p-value of 0.024%

Is the observed event astro or cosmogenic origin?

(1) Observation is inconsistent with cosmogenic hypothesis with p-value of 2.5%	**(2) On the other hand, E^{-2} power-law signal model is compatible with p-value of 78.8%**

(1)

$$\mathrm{H}_0: \mu_i(\lambda^{max}) = \mu_i^{BG} + \lambda^{\max}\mu_i^{cosmogenic}$$

$$\mathrm{H}_1: \mu_i(\lambda'^{max}) = \mu_i^{BG} + \lambda^{\max}\mu_i^{power-law}$$

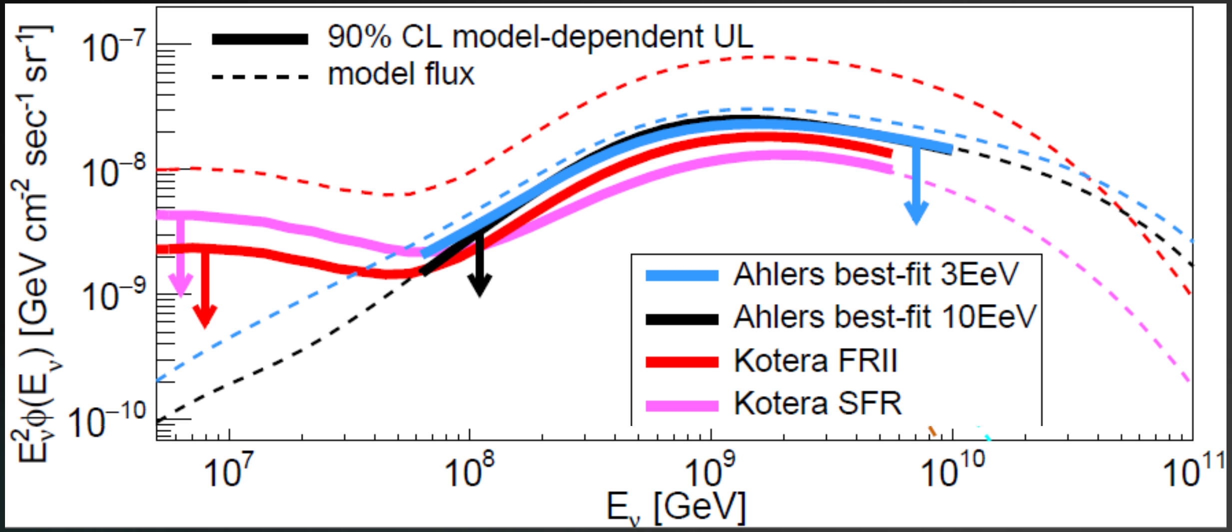
(2)

$$\mathrm{H}_0: \mu_i(\lambda'^{max}) = \mu_i^{BG} + \lambda^{\max}\mu_i^{power-law}$$

$$\mathrm{H}_1: \mu_i(\lambda^{max}) = \mu_i^{BG} + \lambda^{\max}\mu_i^{cosmogenic}$$

- Observed events are unlikely atmospheric background, nor cosmogenic neutrino event…
- Consistent with HE neutrinos from flux following power-law (e.g. previously observed IceCube flux)

Cosmogenic Model Constraints



- Expect 3.6-4.8 events from SFR models
- UHECR sources evolve more slowly than SFR
- Or heavier/mixed composition

⇒Constraints on proton component

- Models to describe the origin of observed diffuse gamma-ray as cosmogenic from observed UHECRs constrained

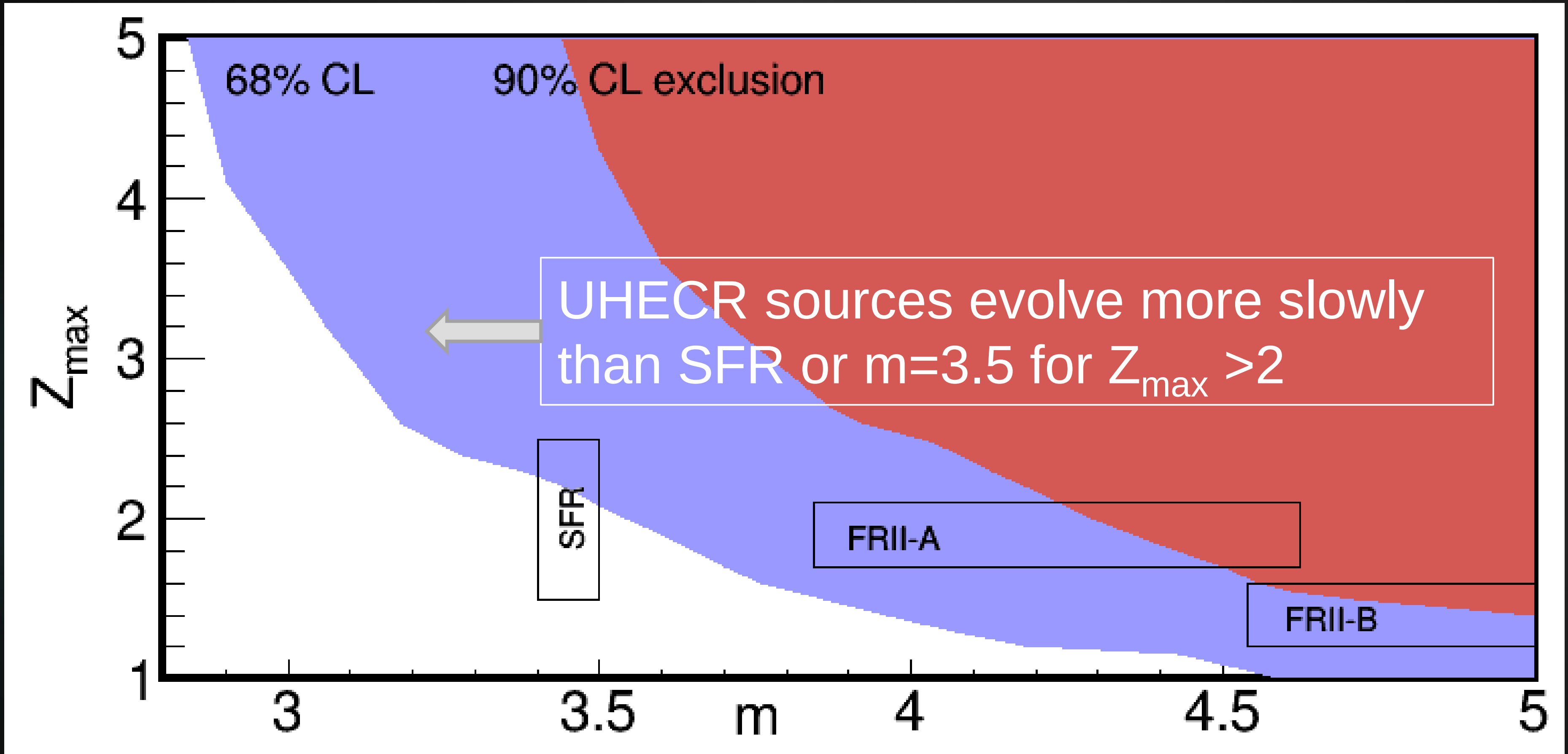
7 year sample PRL(2016)

ν Model	Event rate per livetime	p-value	MRF
Kotera *et al.* SFR	$3.6^{+0.5}_{-0.8}$	$6.0^{+2.9}_{-1.0}\%$	1.04
Kotera *et al.* FRII	$14.7^{+2.2}_{-2.7}$	<0.1%	0.23
Aloisio *et al.* SFR	$4.8^{+0.7}_{-0.9}$	$3.2^{+2.8}_{-0.7}\%$	0.80
Aloisio *et al.* FRII	$24.7^{+3.6}$	<0.1%	0.15
Yoshida *et al.* $m = 4.0, z_{max} = 4.0$	$7.0^{+1.0}_{-1.0}$	$0.1^{+0.4}_{-0.1}\%$	0.43
Ahlers *et al.* best fit, 1 EeV	$2.8^{+0.4}_{-0.4}$	$13.4^{+9.2}_{-2.2}\%$	1.33
Ahlers *et al.* best fit, 3 EeV	$4.4^{+0.6}_{-0.7}$	$3.2^{+1.8}_{-1.4}\%$	0.76
Ahlers *et al.* best fit, 10 EeV	$5.3^{+0.8}_{-0.8}$	$1.1^{+2.5}_{-0.3}\%$	0.63

Generic Constraints on Source Evolution

Evolution function of UHECR source parameterized as $\psi(z)=(1+z)^m$ for $z \le z_{max}$

An analytical relation between flux and m and z_{max} : Yoshida and AI Phys.Rev.D 85 063002 (2012)



Assumptions

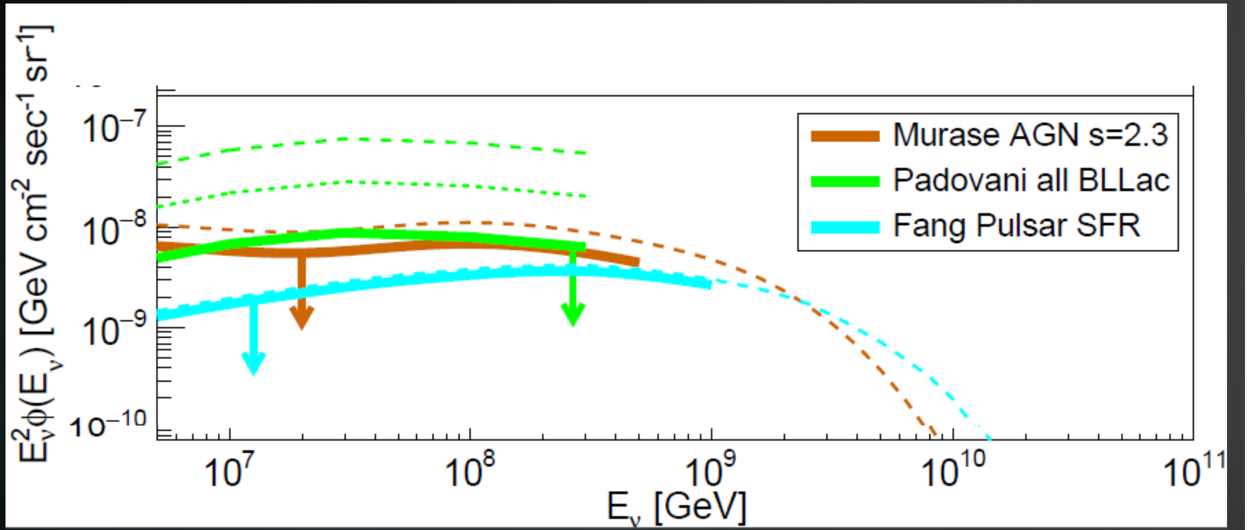
- only CMB is target field (small IR/O contribution in the current energy range)
- the photo-pion production is single pion from Δ-resonance only

➡ Underestimates flux below 100 PeV

SFR: Hopkins and Beacom 2006
FRII-A: Inoue and Totani 2009
FRII-B: Ajello et al 2012

Astrophysical neutrino model tests

- ✓ **Astrophysical model test can tests heavy-/mixed-composition models**
- ✓ **AGN and pulser models predicts hard spectra**



$$\xi_{\rm cr} \equiv \frac{L_{\rm cr}}{L_{\rm rad}}$$

$\xi_{\rm cr} = 100$ and $s = 2.3$, the CR energy generation rate 10^{19} eV is comparable to the UHECR energy budget

7 year sample PRL(2016)

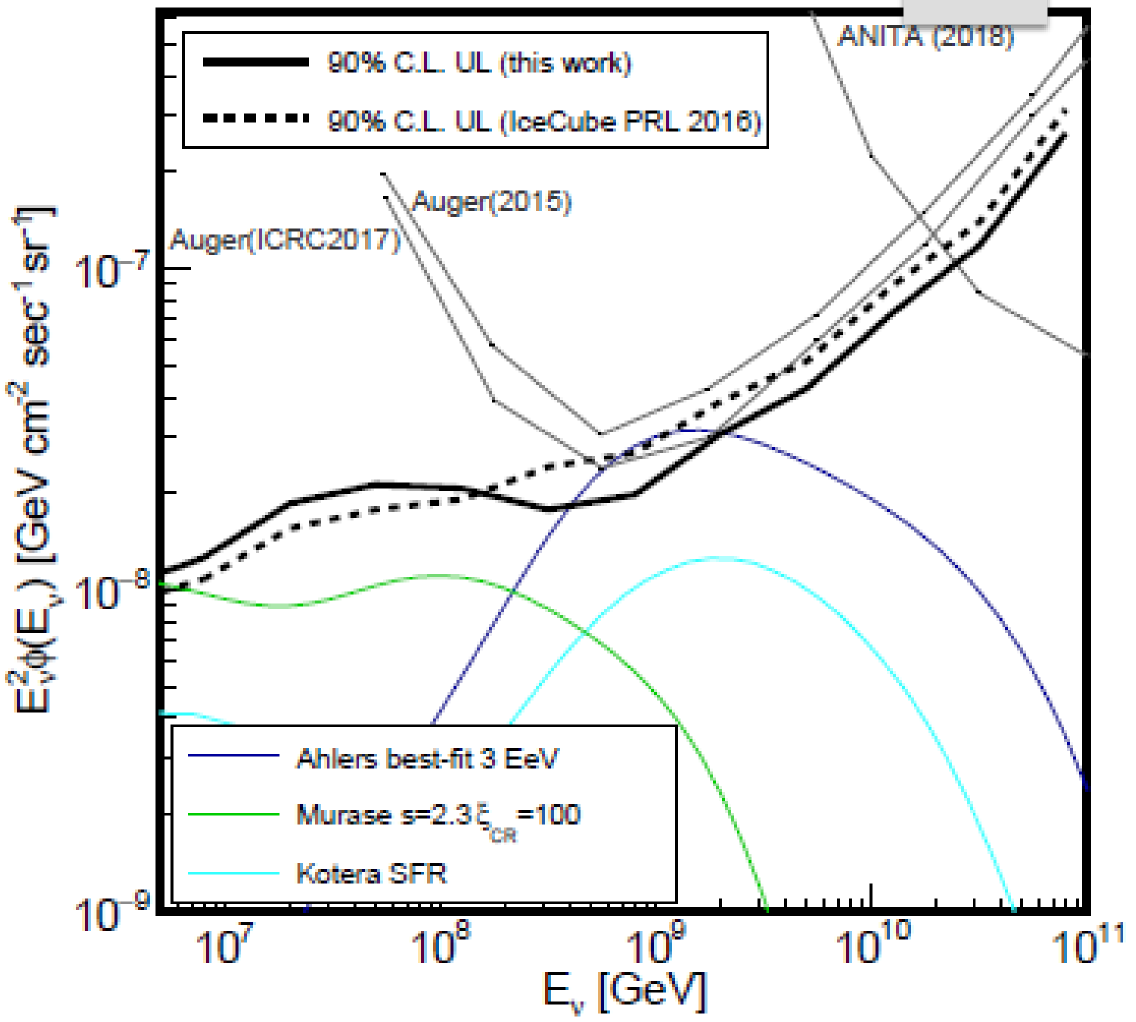
ν Model	Event rate per livetime	p-value	MRF
Murase *et al.* $s = 2.3$, ξ_{CR}=100	$7.4^{+1.1}_{-1.8}$	$0.3^{+1.3}_{-0.2}$%	0.62 ($\xi_{CR} \leq$62)
Murase *et al.* $s = 2.0$, ξ_{CR}=3	$4.5^{+0.7}_{-0.9}$	$4.8^{+4.9}_{-2.2}$%	1.32 ($\xi_{CR} \leq$4.0)
Fang *et al.* SFR	$5.5^{+0.8}_{-1.1}$	$1.6^{+3.0}_{-0.8}$%	0.88
Fang *et al.* uniform	$1.2^{+0.2}_{-0.2}$	$78.2^{+2.4}_{-3.9}$%	4.0
Padovani *et al.* $Y_{\nu\gamma} = 0.8$	$37.8^{+5.6}_{-8.3}$	<0.1%	0.12 ($Y_{\nu\gamma} \leq$0.13)

Murase et al: Phys.Rev.D 90 (2014) 023007
Fang et al: Phys. Rev. D 90, 103005 (2014)
Padvani et al MNRAS 452 1877 (2015)

Differential limits

- Differential limit is comparable to UHECR energy density at 1EeV (～$2x10^{-8}$ GeV/cm^2 sec sr)
- 100 times better limit compared to 2007 !

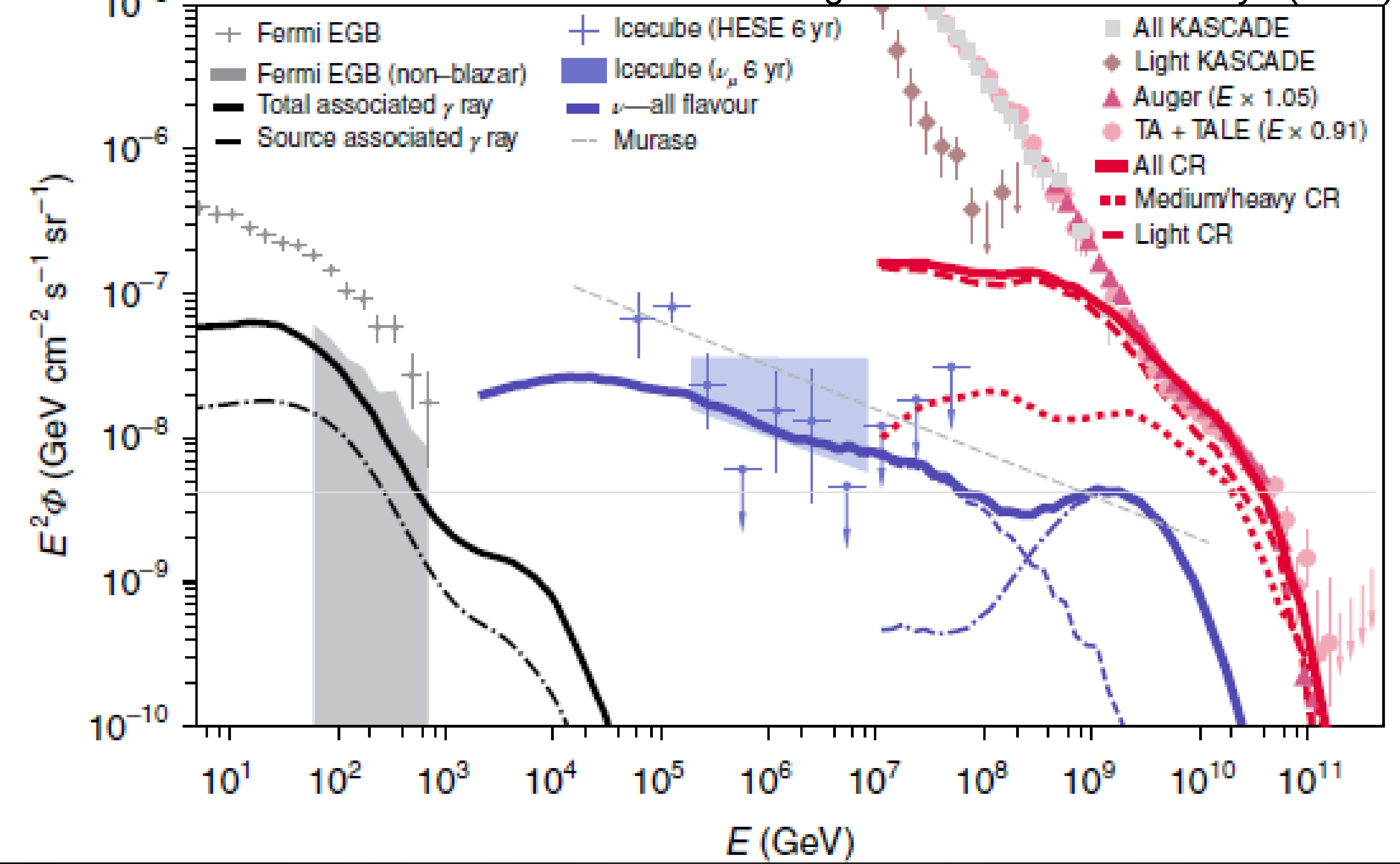
9 year sample PRD(2018)



Prospects to IceCube-Gen2

- Stronger constraints on proton fraction of highest energy cosmic-rays

Fang and Murase Nature Phys (2018)



Also:
AGN in the large scale cluster model: consistent with Auger composition, Kascade-Grande light composition, fermi EGB fluxes
...and IceCube neutrino flux

A factor of ～two better sensitivity than the current IceCube sensitivity allow us to reach

Summary

- Analyzed events with **large energy deposits** in 7 years and 9 years of IceCube data
- Two observed events are consistent with IceCube astrophysical neutrino flux
- The binned LLH ratio analysis places constraints on cosmogenic models for proton UHECR sources and astrophysical mixed composition models
- **Disfavoring** cosmological evolution stronger than the **SFR** if proton dominant UHECRs
- **Constraining AGN** models as the dominant UHECR sources – independent of their composition
- **Neutrinos' pointing capability** is also important in this energy region! A few events above 10 PeV – either cosmogenic or source - could be detected by IceCube-Gen2

Backup

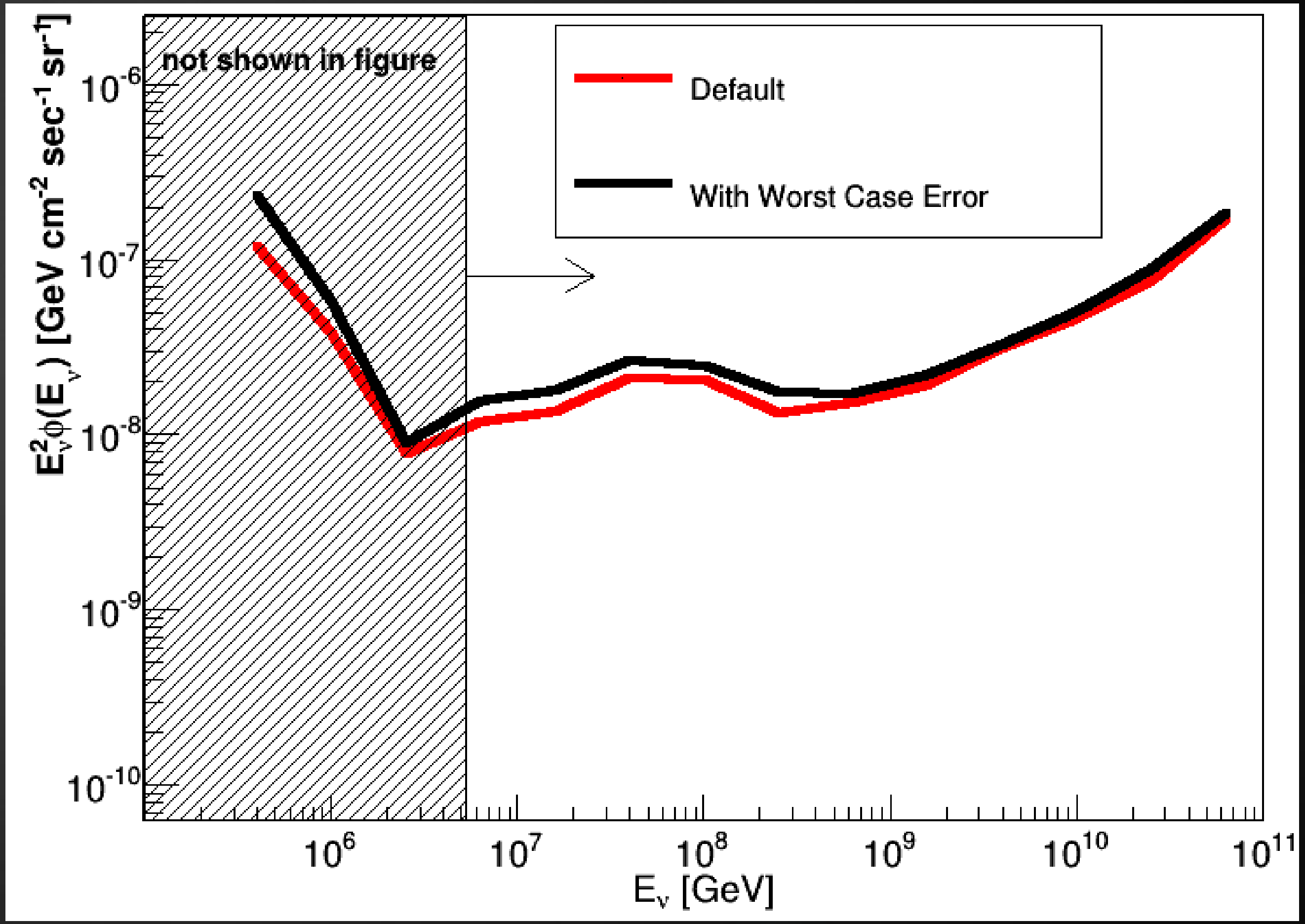
Systematical errors on quasi differential upper-limits

Errors are energy dependent. Estimated by taking the ratio between default upperlimit and UL with the worst case error (worst signal reduction and background, in addition to NPE uncertainty)

These estimate include statistical fluctuations

Below 400 PeV, uncertainty is about 30% and 11% error

The threshold region (not shown in the differential limit) has larger uncertainty because of the uncertainty associated with the absolute efficiency (incl. from detector response and ice model)

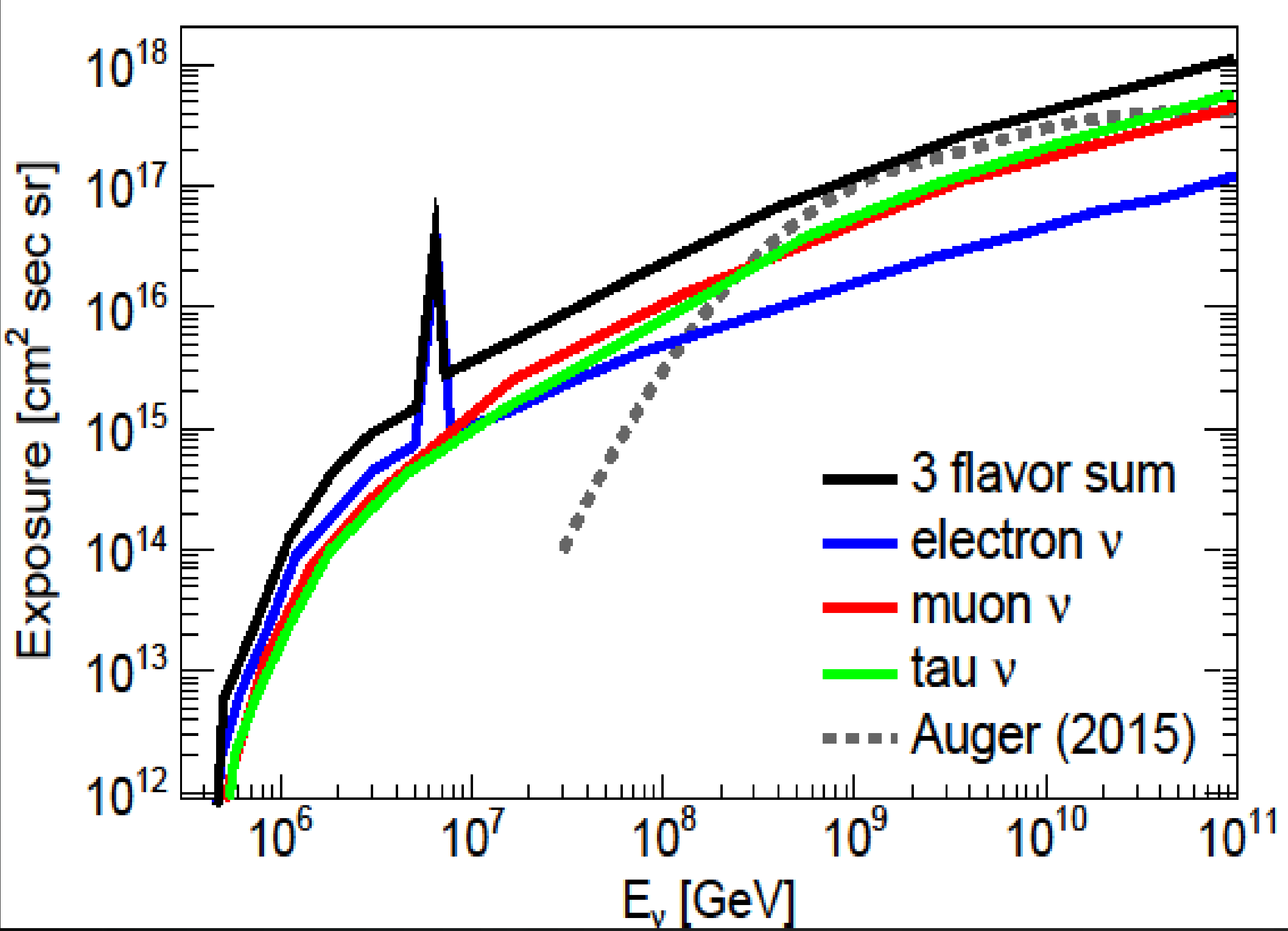


The Estimation of maximam systematic error

- Upperlimit is worsen when signal is reduced.
- Observed photo-electron charges (NPE) are shifted by -16.5% (due to uncertainties in absolute DOM efficiency and ice model), signal rate is decreased by -7%, while background is also reduced by -43%.
- At the same time, background is increased by $\sqrt{16^2+30^2}=34\%$ in the worst case, signal is additionally reduced by -9%, when excluding the components included into the NPE shift.
- We then calculate the worst case upperlimit with -16.5% shifted charge with worst case increased background error (+34%) and worst case signal reduction (-9%)

Exposure and Background

Effective livetime: 2426 days



Expected background rates in 2426 days

atm. muon (iron CR)	atm. ν (π, K)	atm. ν (heavy meson)	TOTAL
0.021	0.022	0.021	0.064

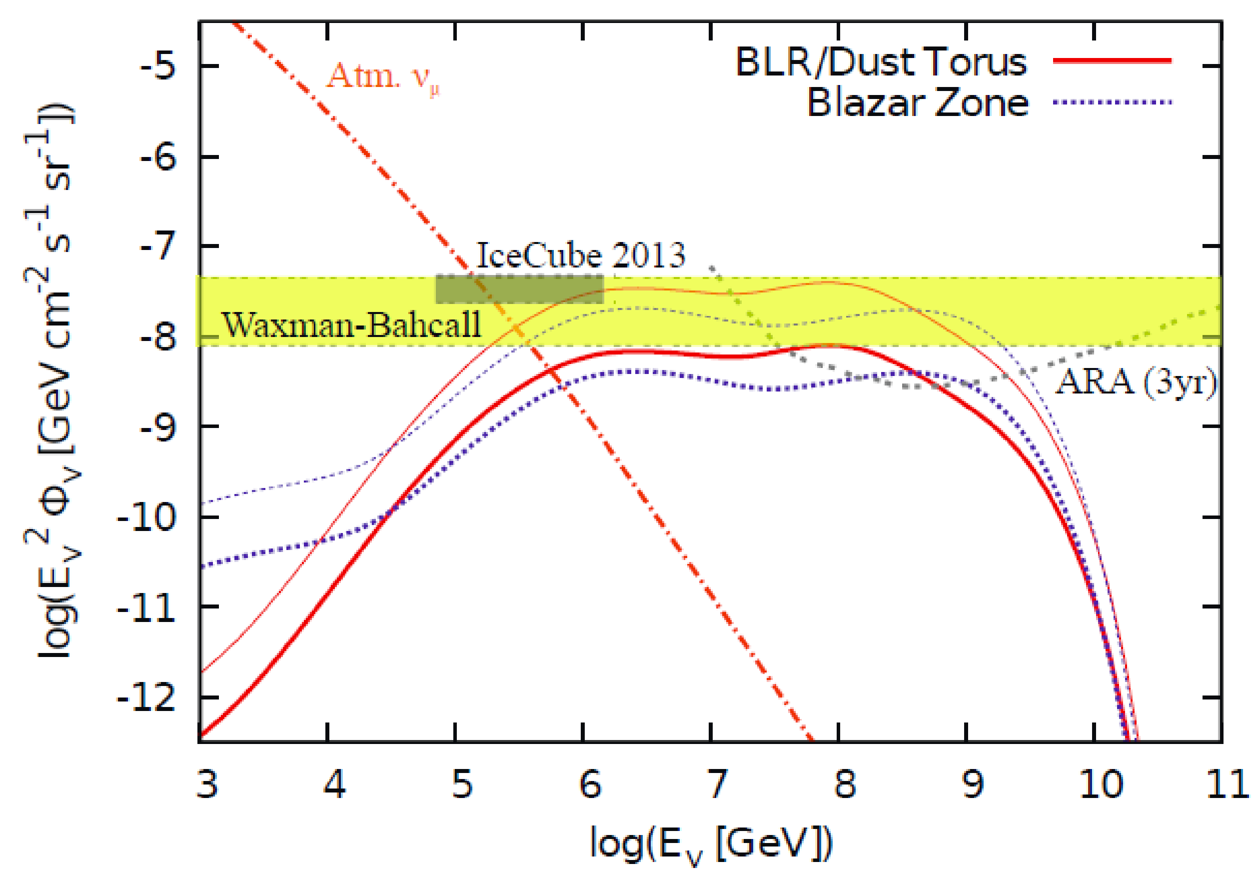


FIG. 13: Cumulative neutrino background from radio-loud AGN in the blazar sequence model. The CR spectral index $s = 2.3$, and the CR loading factor $\xi_{cr} = 100$ (thick) and 500 (thin). Note that the former value is motivated by the AGN-UHECR hypothesis, where the CR energy injection rate is normalized by the observed UHECR energy generation rate. The atmospheric muon neutrino background is also shown (dot-dashed).

Systematics in Event Rates

contribution	cosmogenic ν (%)	atm. μ (%)	conventional atm ν (%)	prompt atm ν (%)	BG sum (%)
Energy scale	-6, +13	-45, +22	-43, +8	-33, +9	-39, +13
ice model + detector responses	-3	-14	-24	-16	-17
hadronic interactions (sibyll 2.1 and qgsjet-II-03)	na	+4	na	na	+2
CR composition (pure p and Fe)	na	-79	na	na	-26
CR flux measurements	na	±30	±30	±30	±30
prompt model (charm)	na	na	na	-40, +32	-19, +16
neutrino cross section	±9	na	na	na	na
photonuclear interaction	+10	na	na	na	na
LPM effect	±1	na	na	na	na
SUM	-13, +14	-97, +37	-58, +31	-62, +45	-61, +36
energy scale + ice + detector	-7, +13	-48, +22	-49, +8	-37, +9	-43, +13

**energy scale + ice model is based on in-situ calibration data with artificial light source