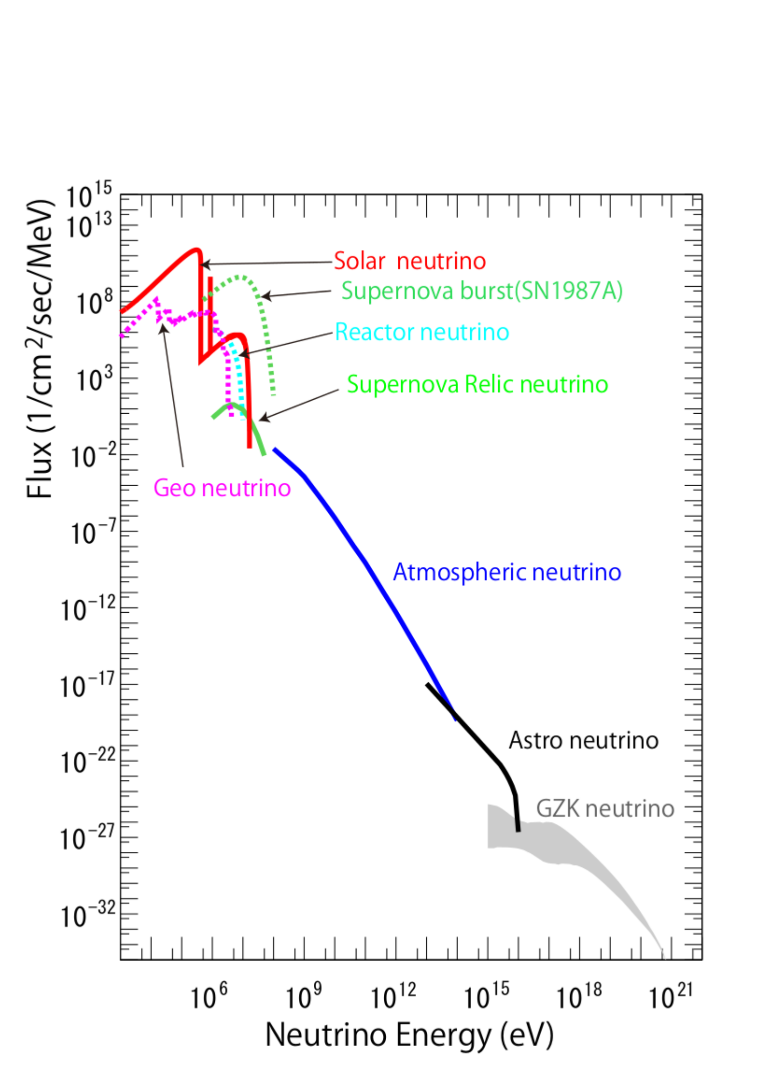
High Energy ν Astronomy
The recent progress by IceCube

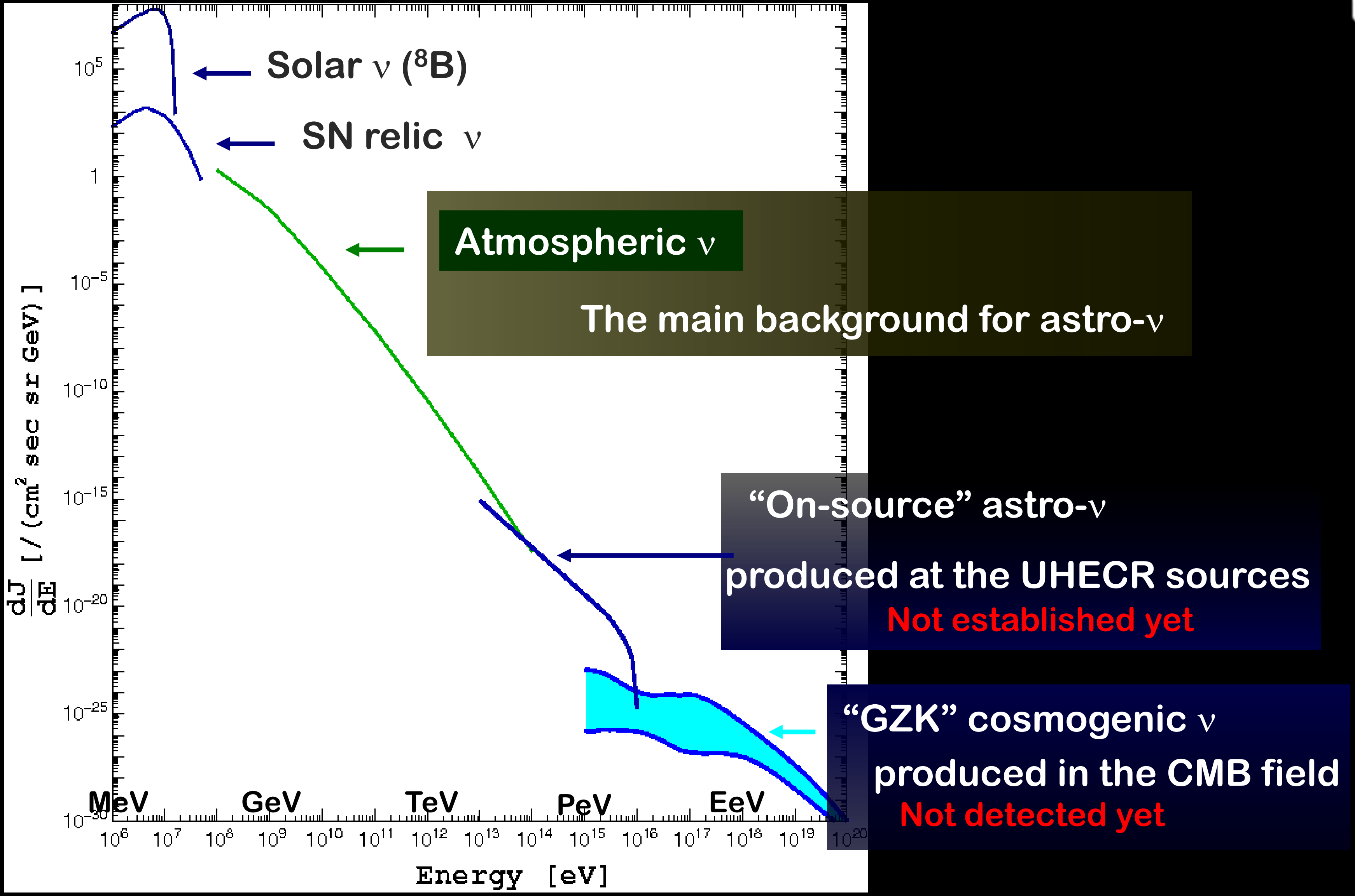
Shigeru Yoshida
ICEHAP
Chiba University

The Neutrino Flux
from Geo Neutrino to GZK neutrino

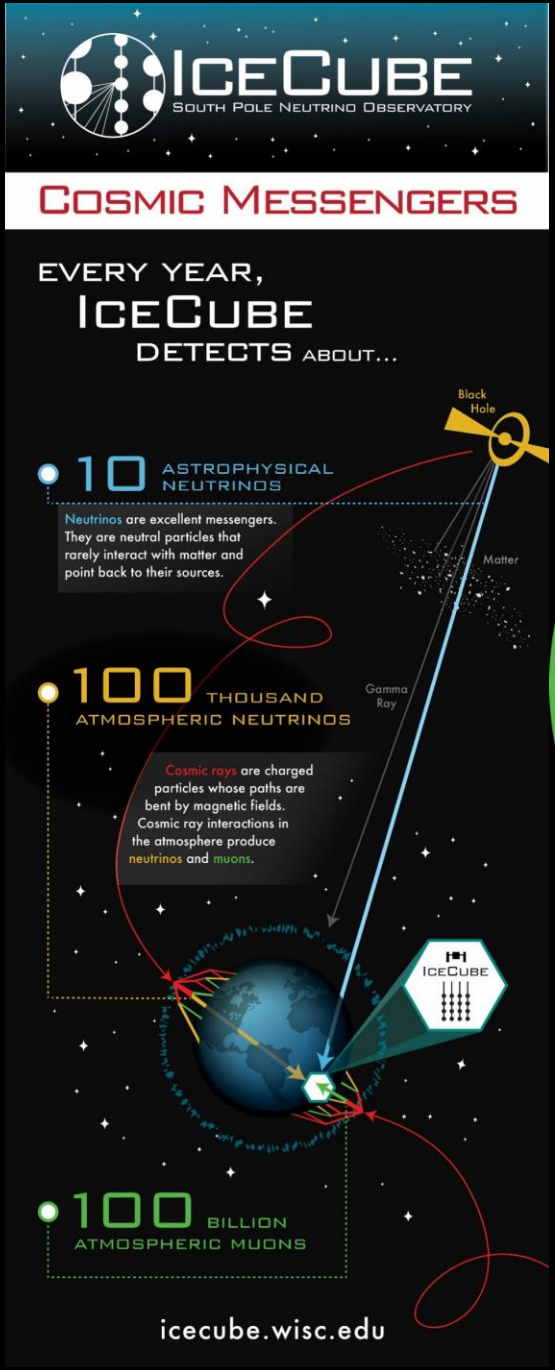


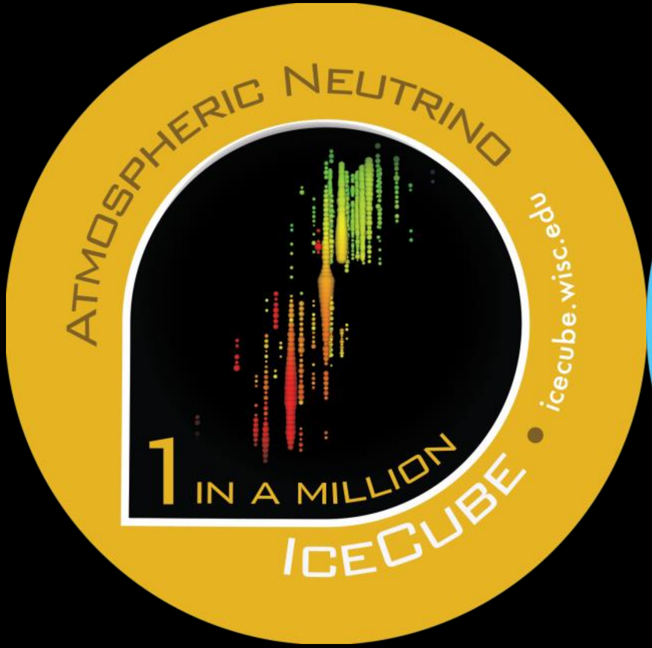
Extending to 18 orders of magnitude in Energy

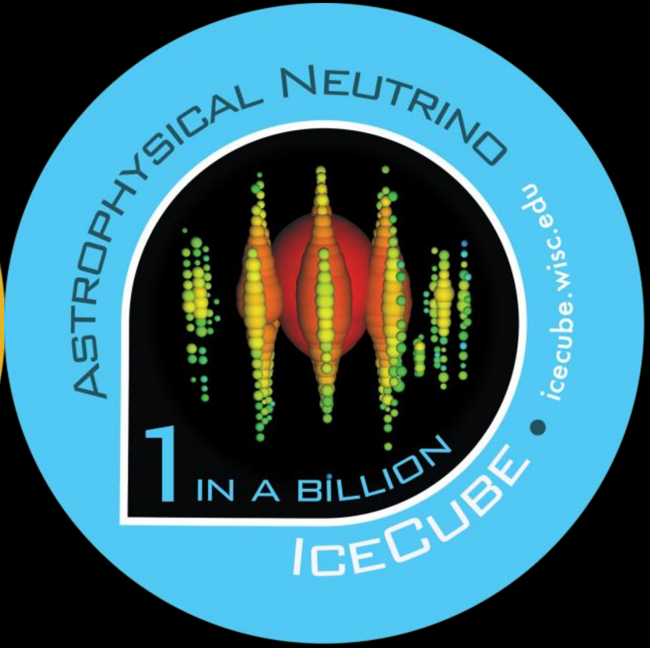
The Neutrino Flux: overview



ν as cosmic messengers







The Cosmic Neutrinos
Production Mechanisms

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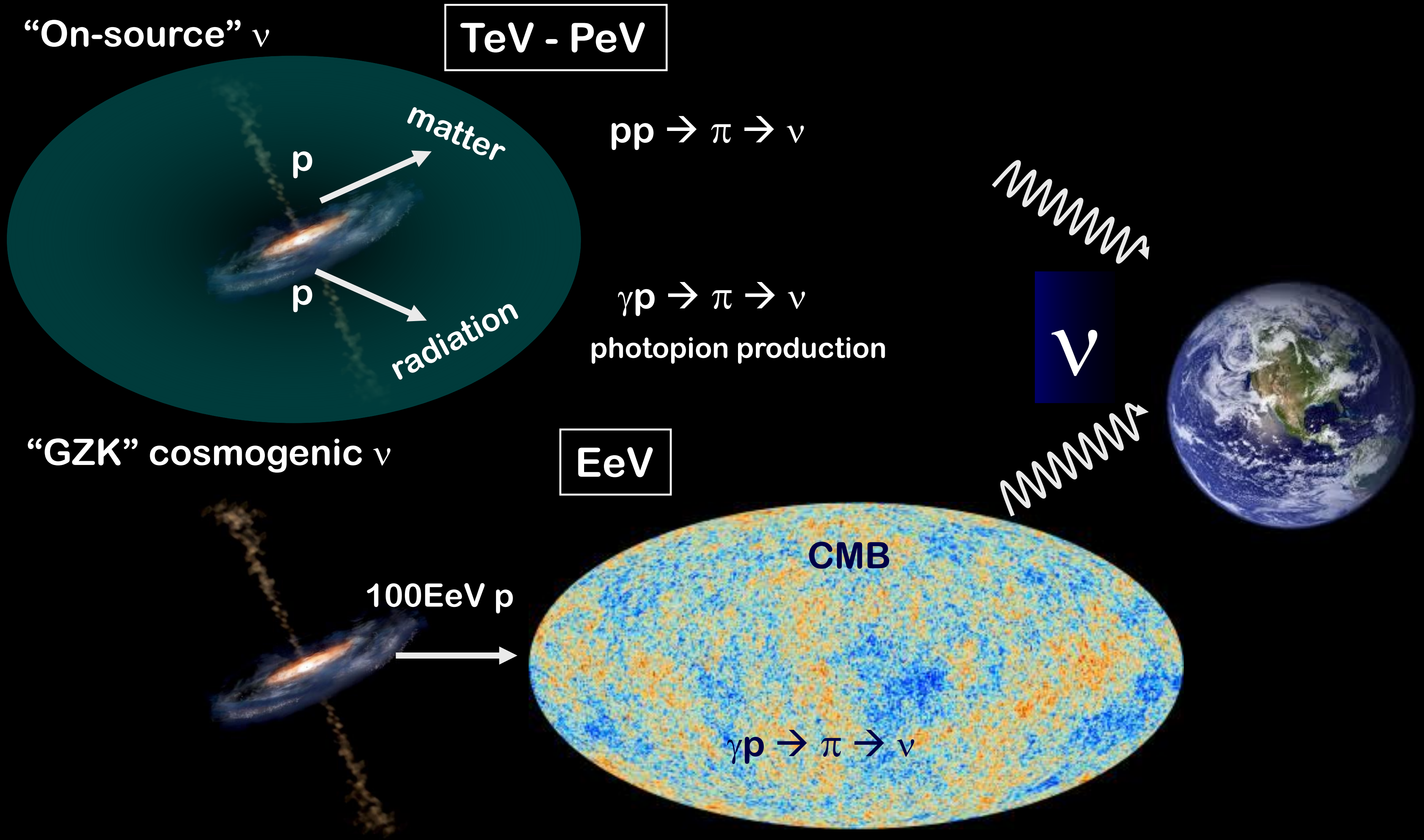
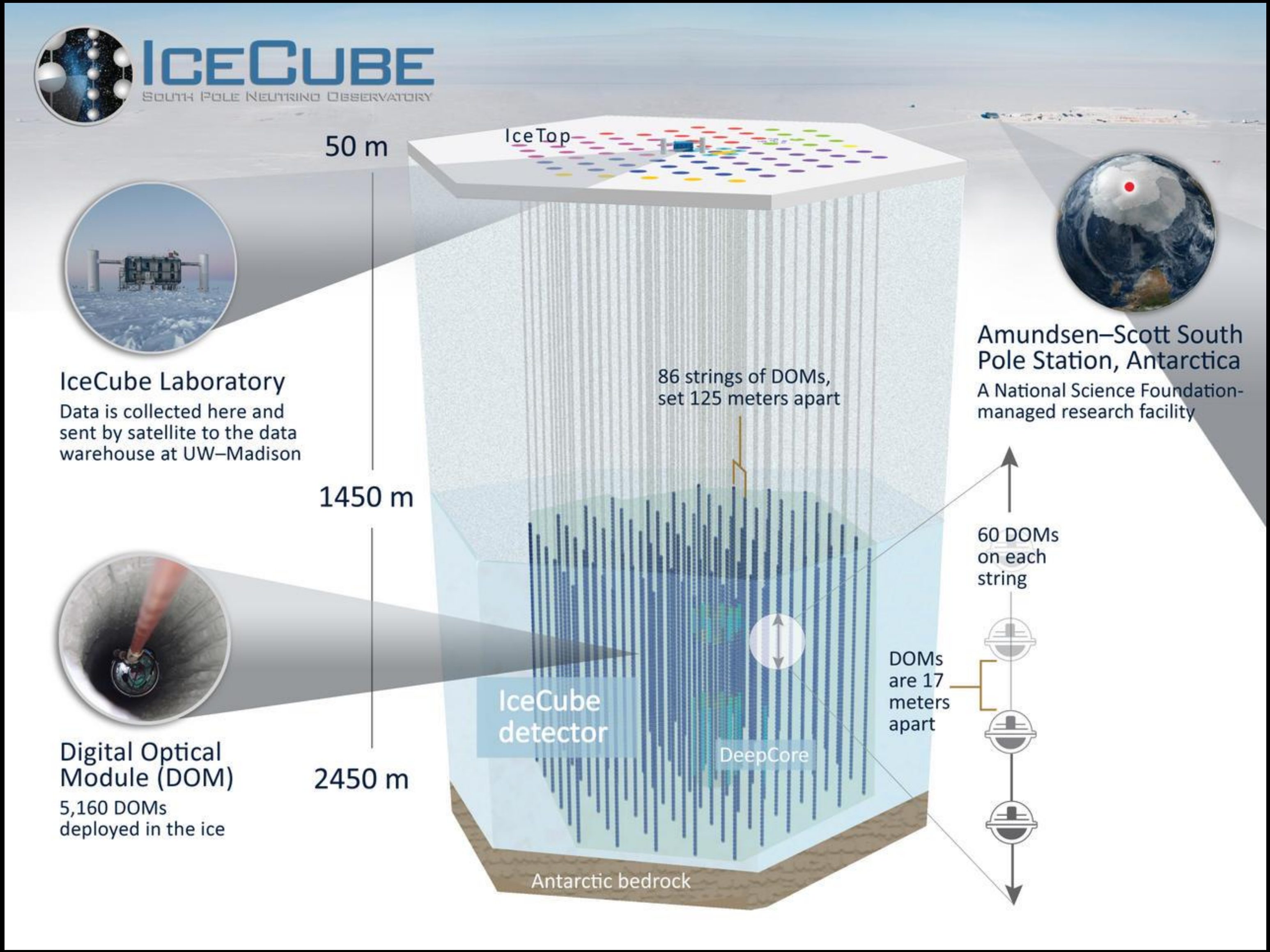


IceCube Neutrino Observatory



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ICECUBE SOUTH POLE NEUTRINO OBSERVATORY
icecube.wisc.edu

IceCube Event Topology

Track

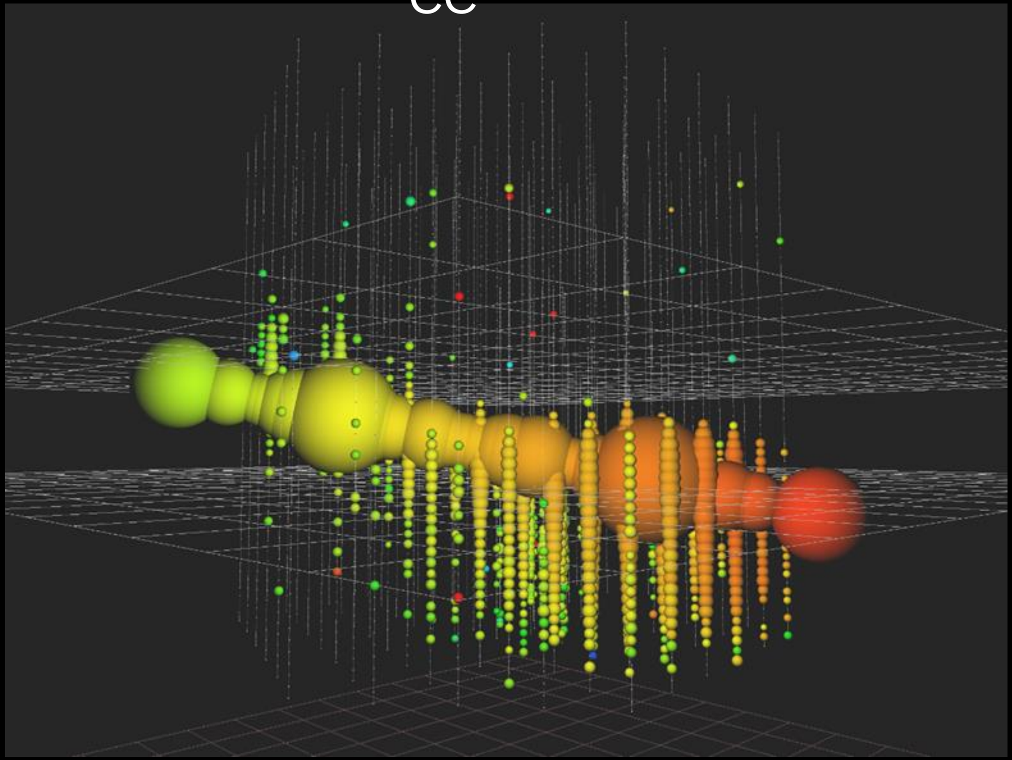
$\nu_\mu \xrightarrow[CC]{} \mu$

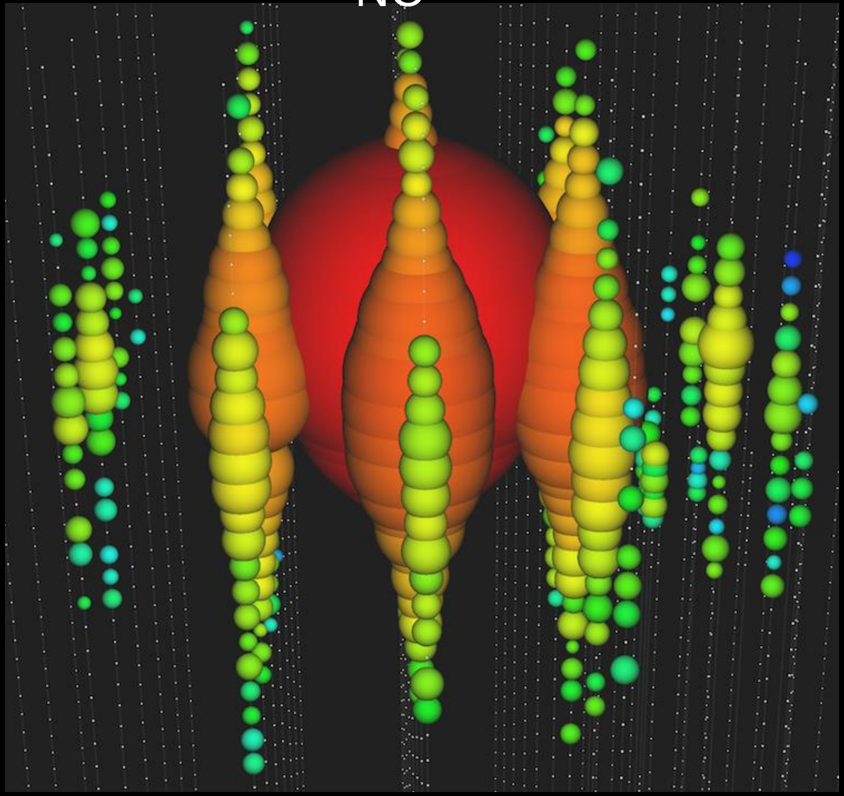
$\nu_\tau \xrightarrow[CC]{} \tau$ (only at ultra-high energies)

Cascade (shower)

$\nu_e \xrightarrow[CC]{} e + X$

$\nu_x \xrightarrow[NC]{} x + X$ x=e, μ, τ





IceCube ν search channels

ν_e

TeV PeV EeV

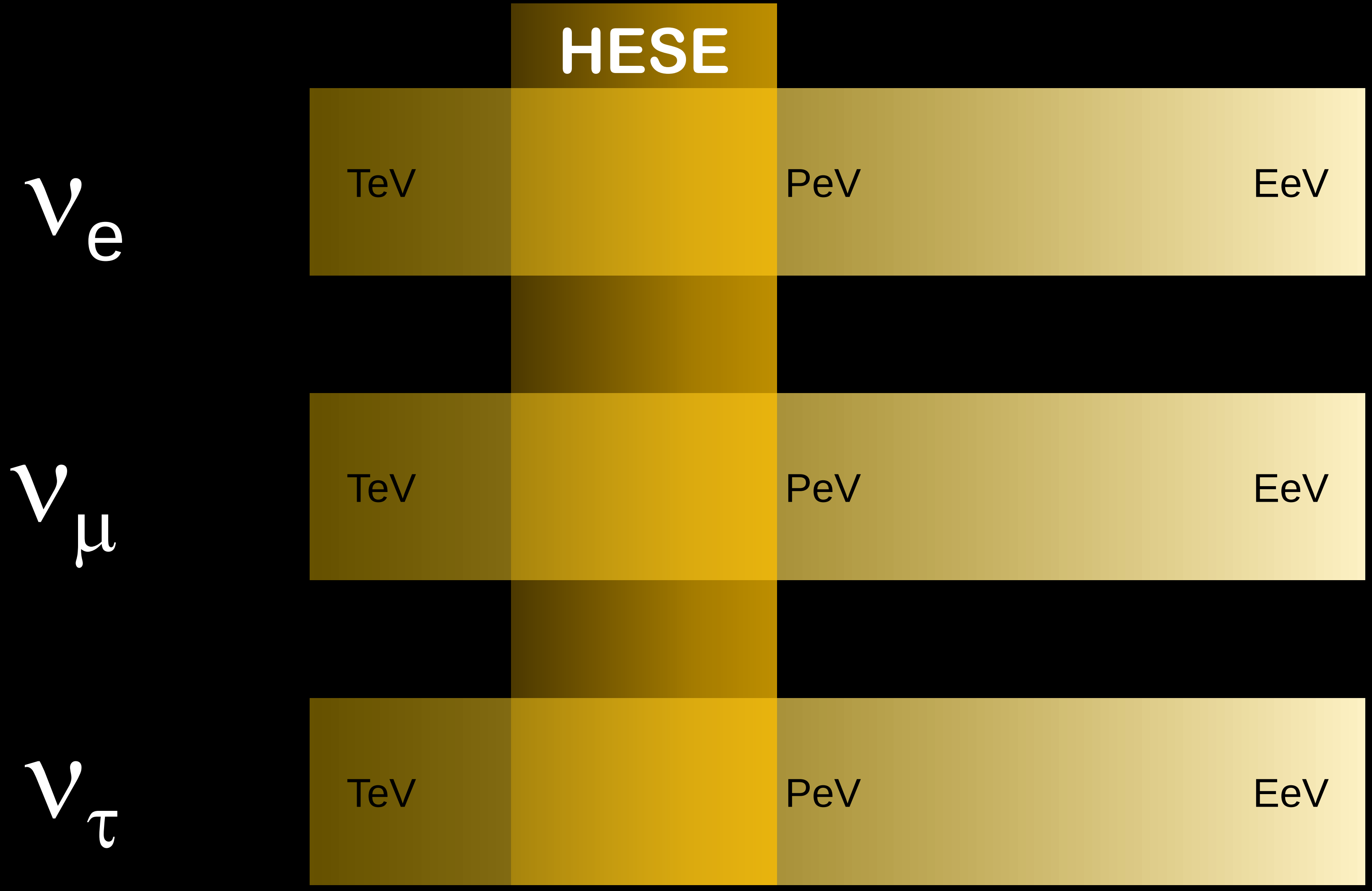
ν_μ

TeV PeV EeV

ν_τ

TeV PeV EeV

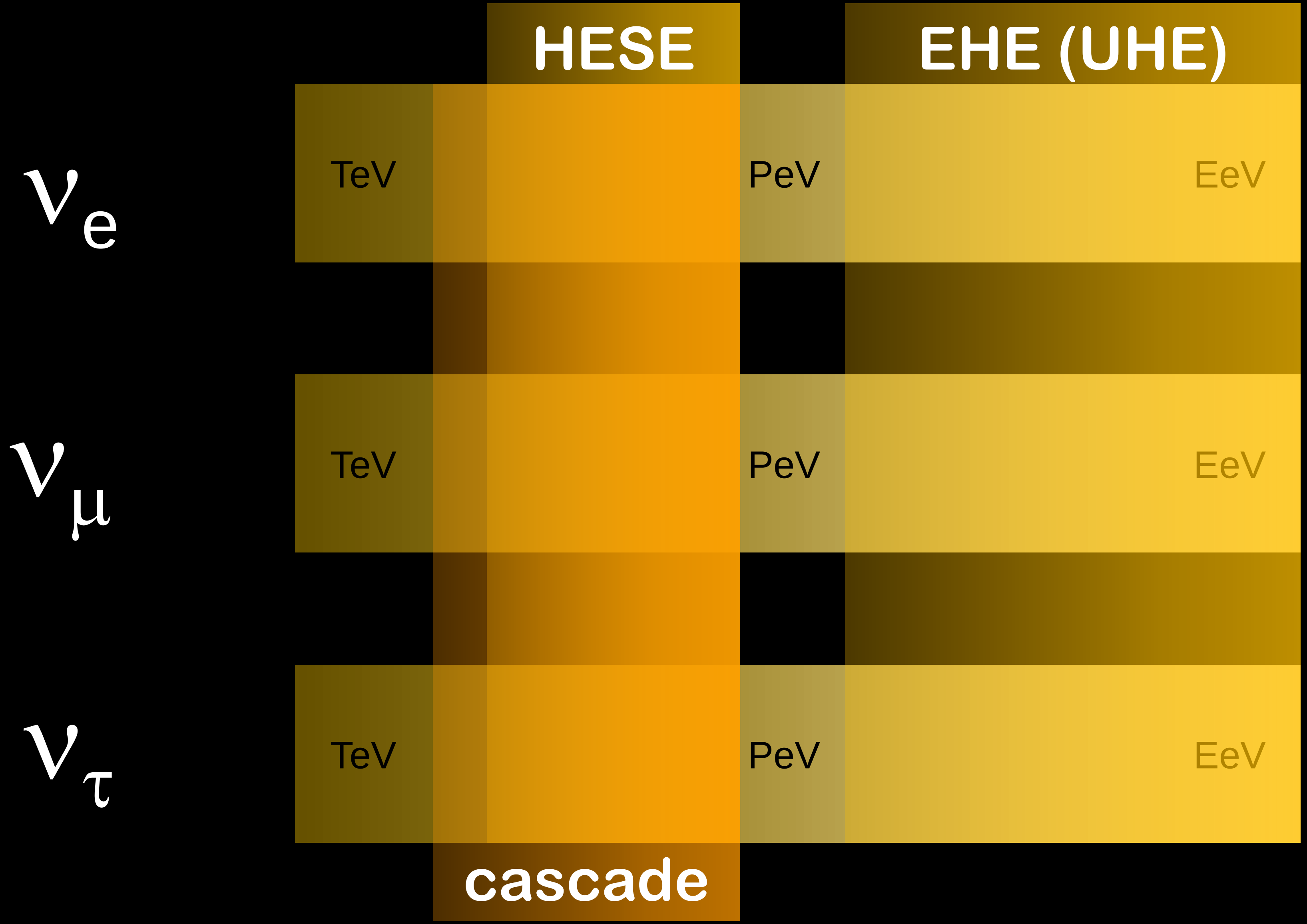
IceCube ν search channels



IceCube ν search channels

		HESE		EHE (UHE)
ν_e	TeV		PeV	EeV
ν_μ	TeV		PeV	EeV
ν_τ	TeV		PeV	EeV

IceCube ν search channels



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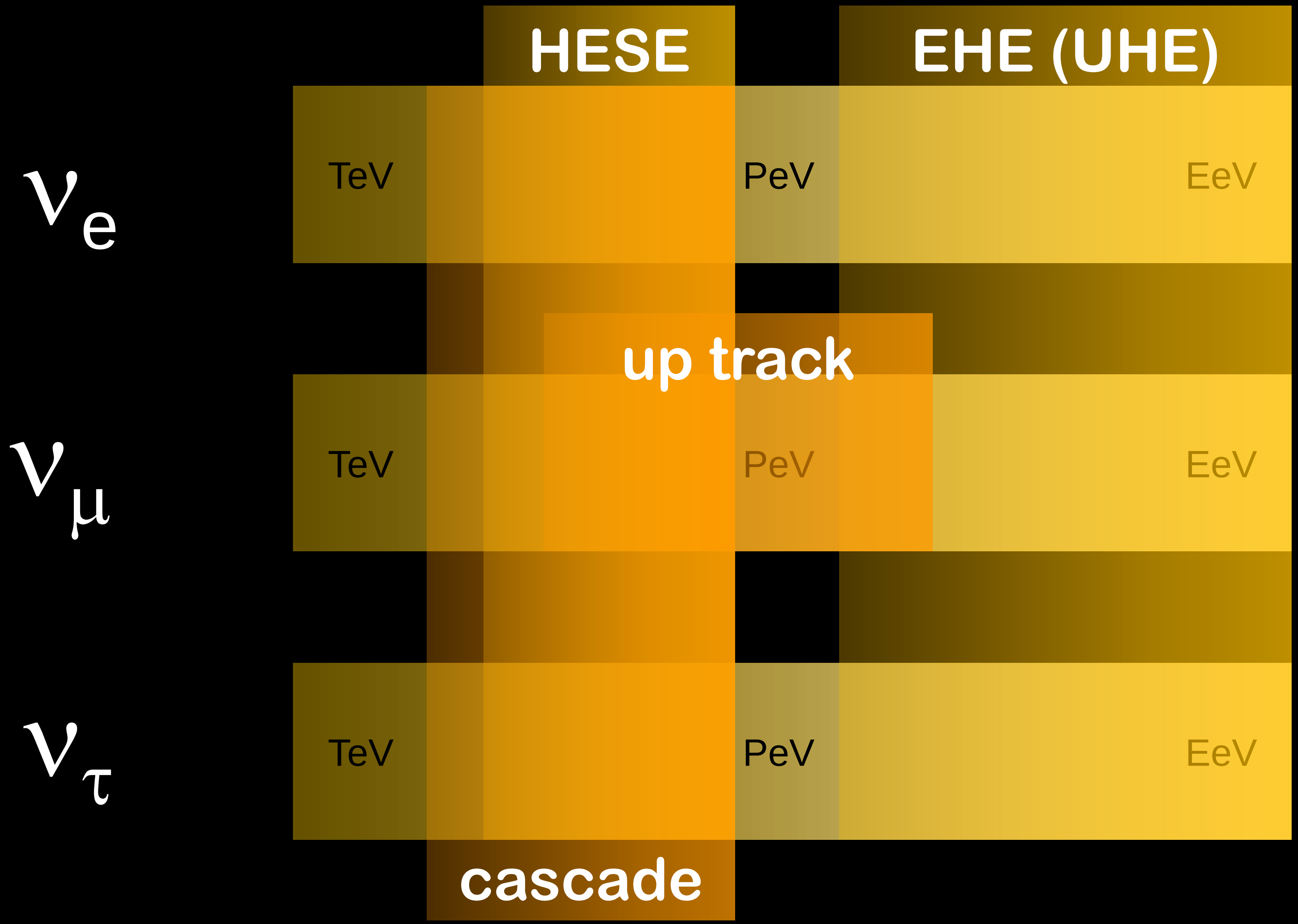

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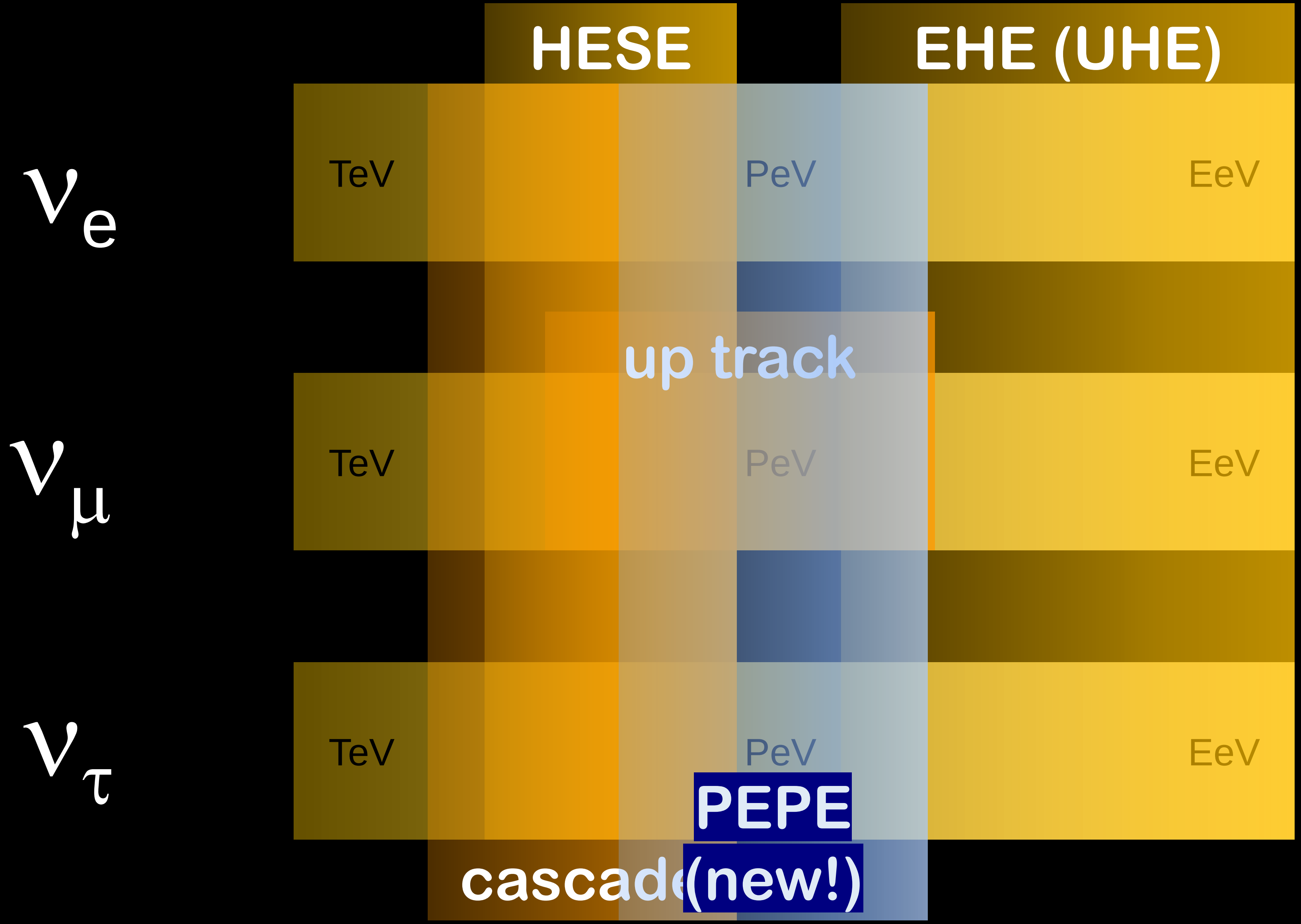

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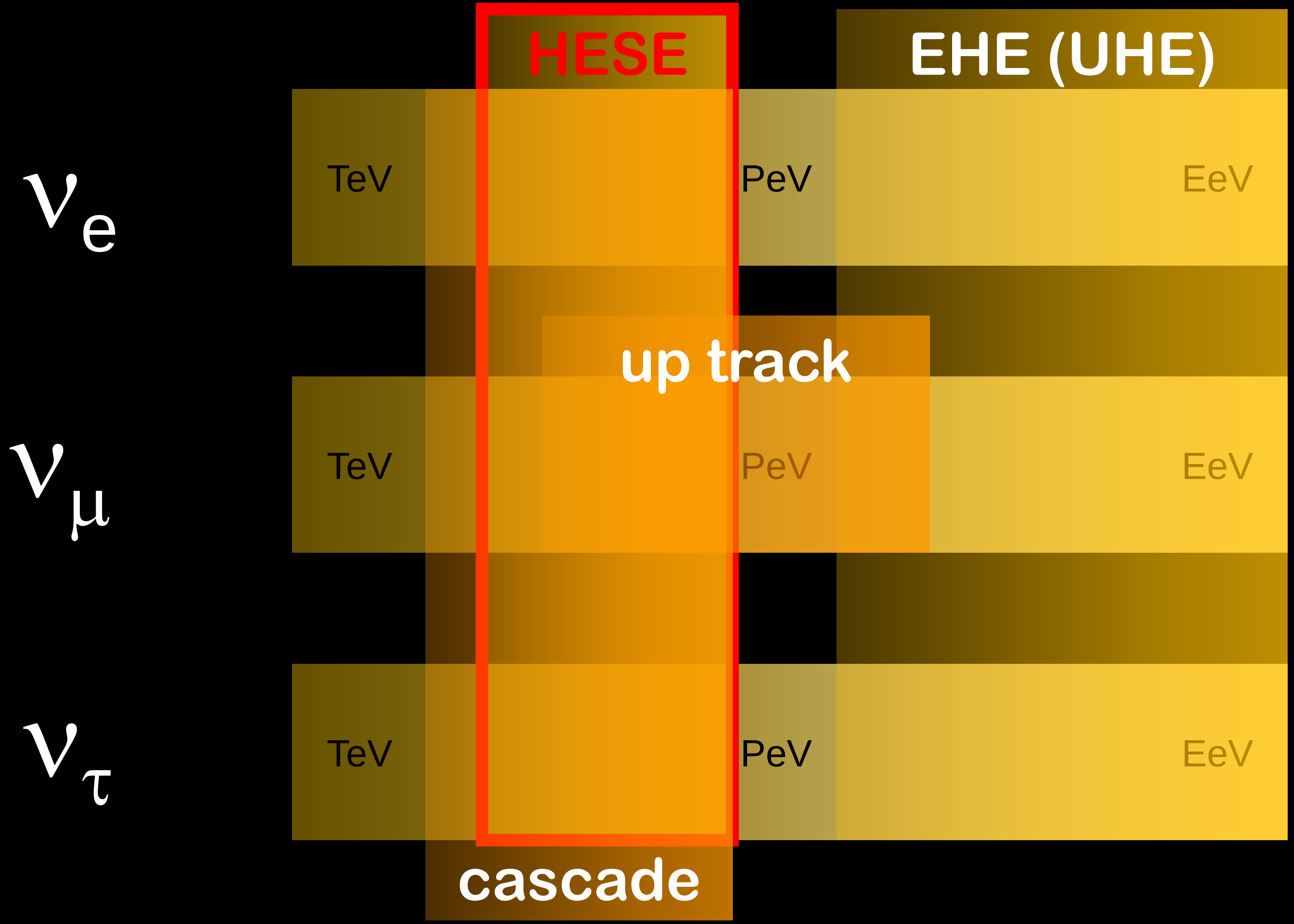

TeV PeV EeV

Mid Energy (60 TeV-)

HESE

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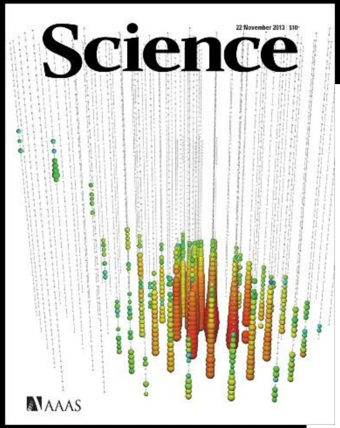
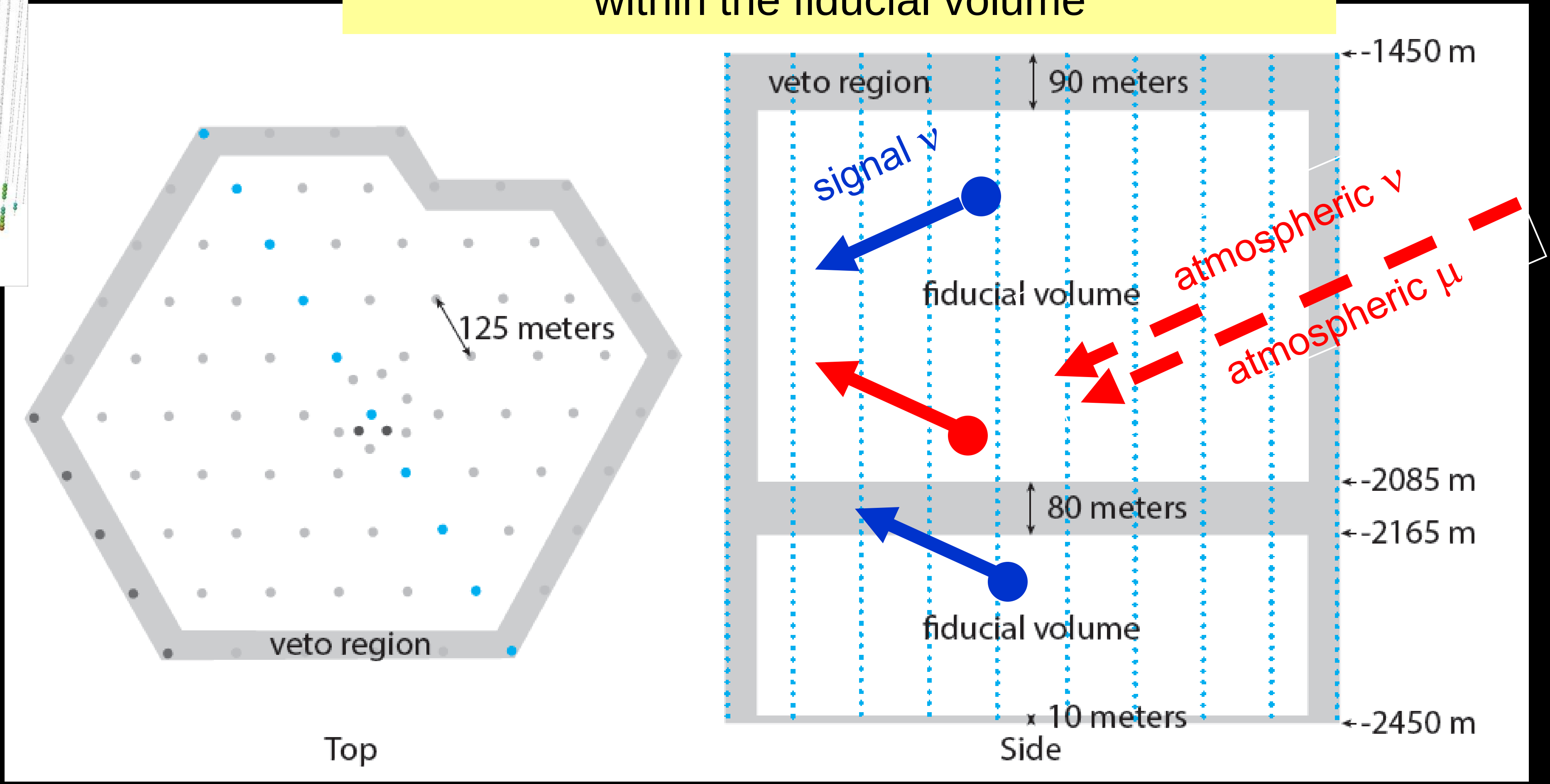
look for only events with their interaction vertices within the fiducial volume

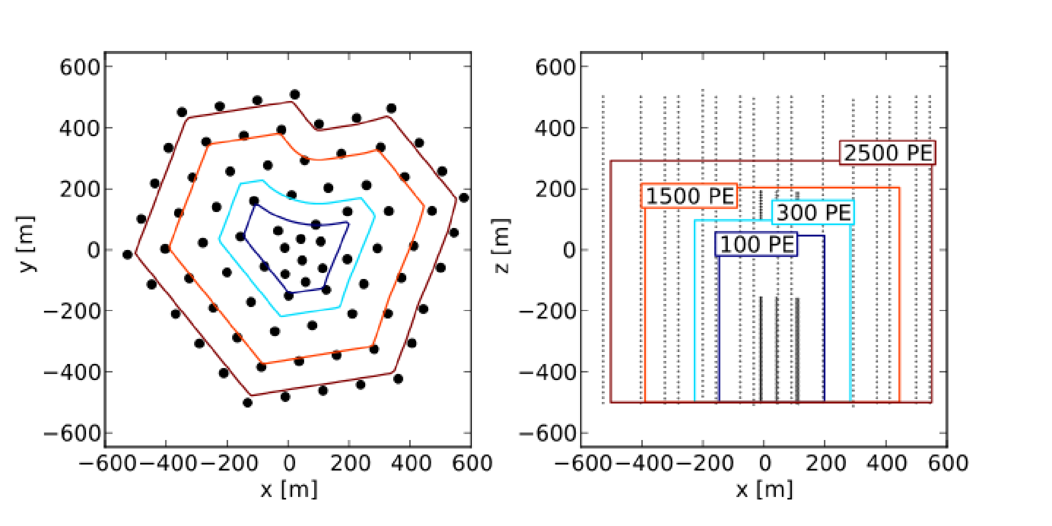


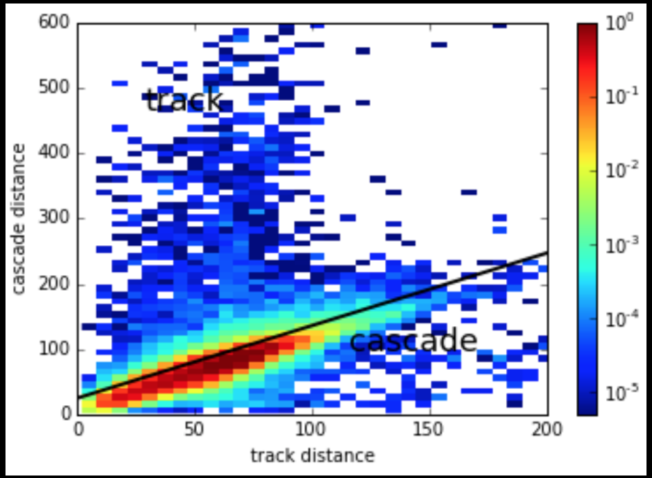


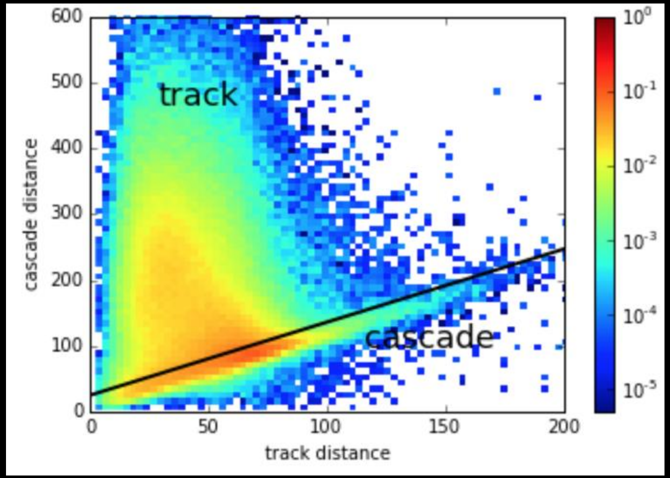
TeV PeV EeV

HESE + MESE (low energy extended)

7 years of data (IC79, IC2011-IC2016)

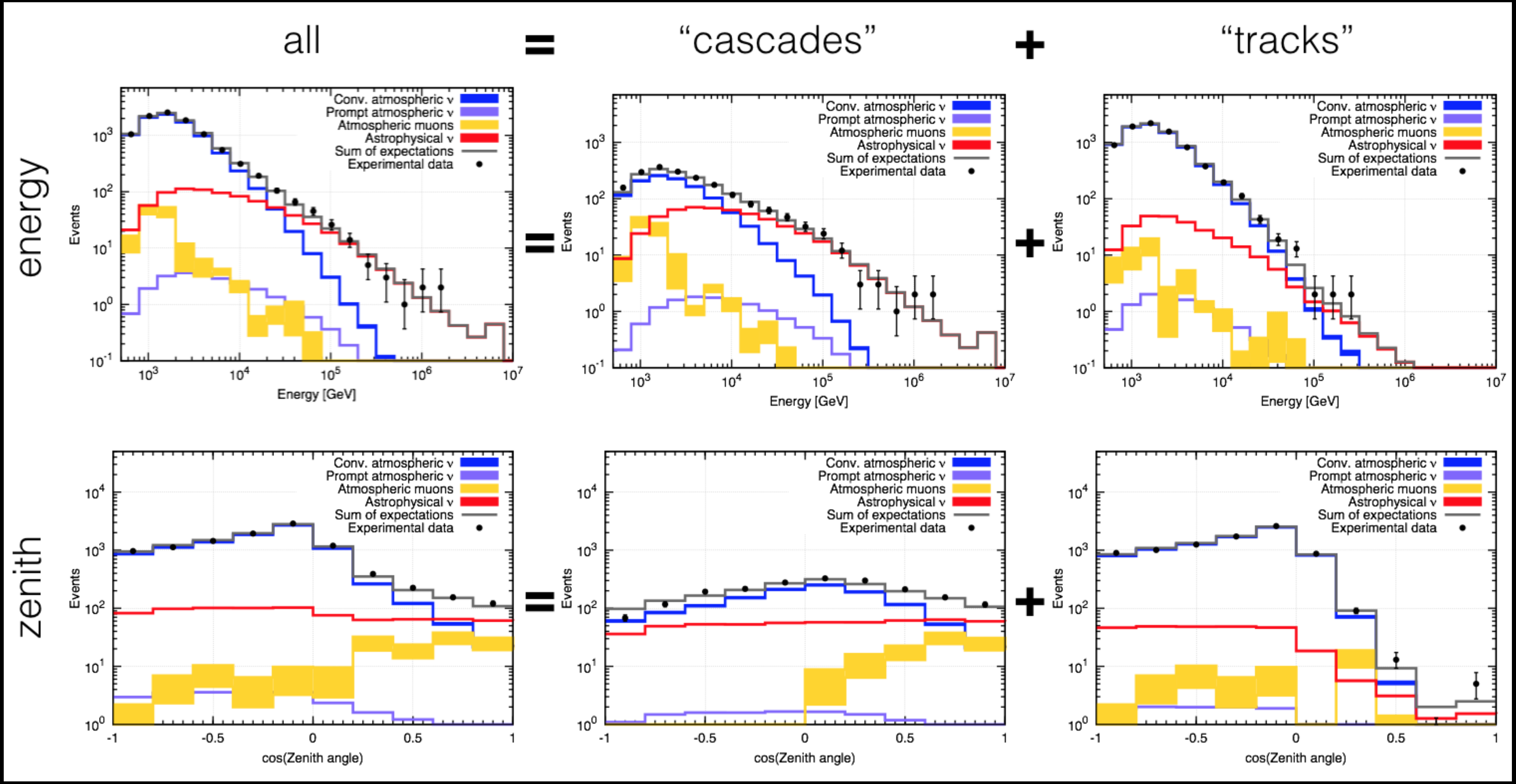






TeV PeV EeV

HESE + MESE (low energy extended)



TeV PeV EeV

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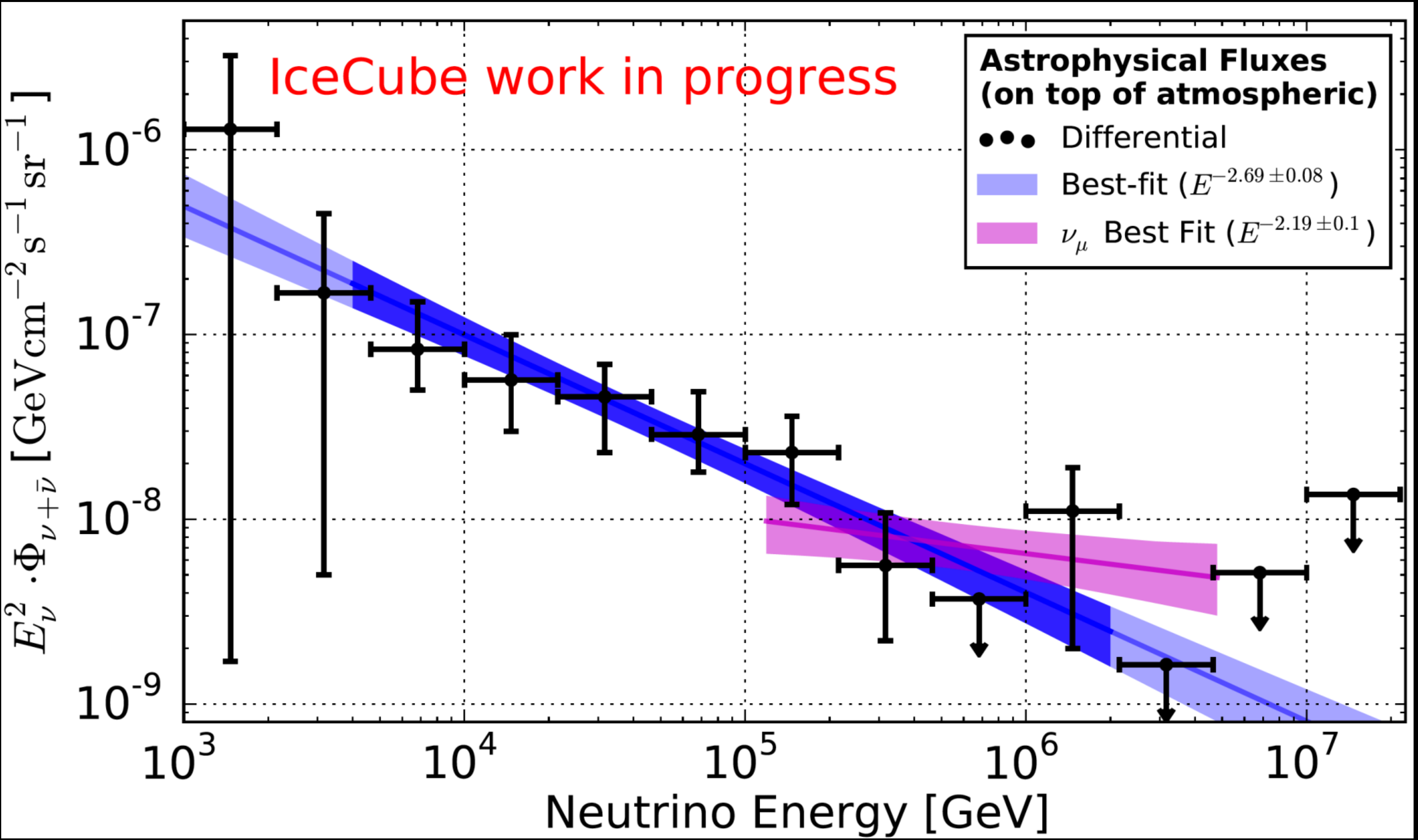
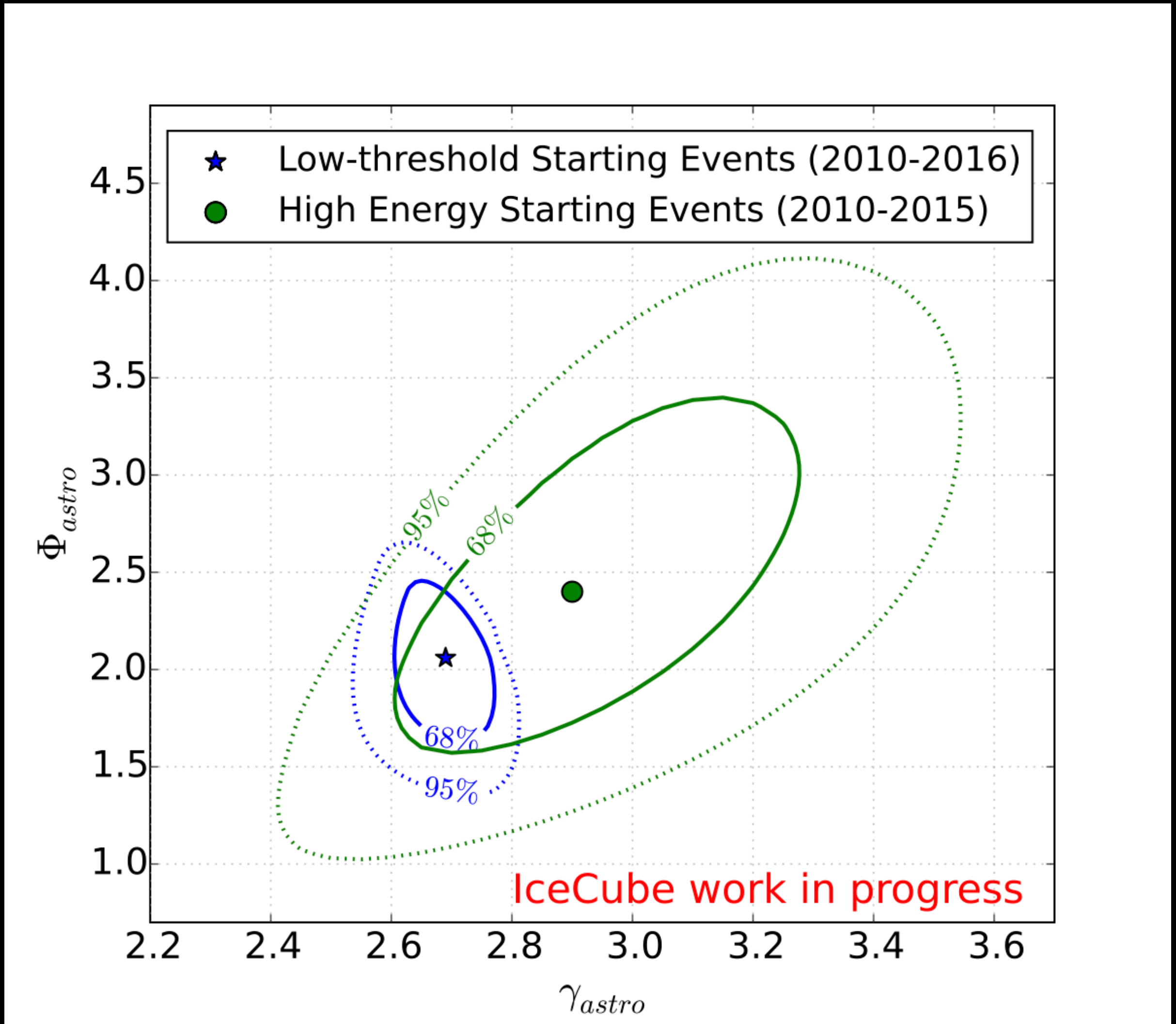
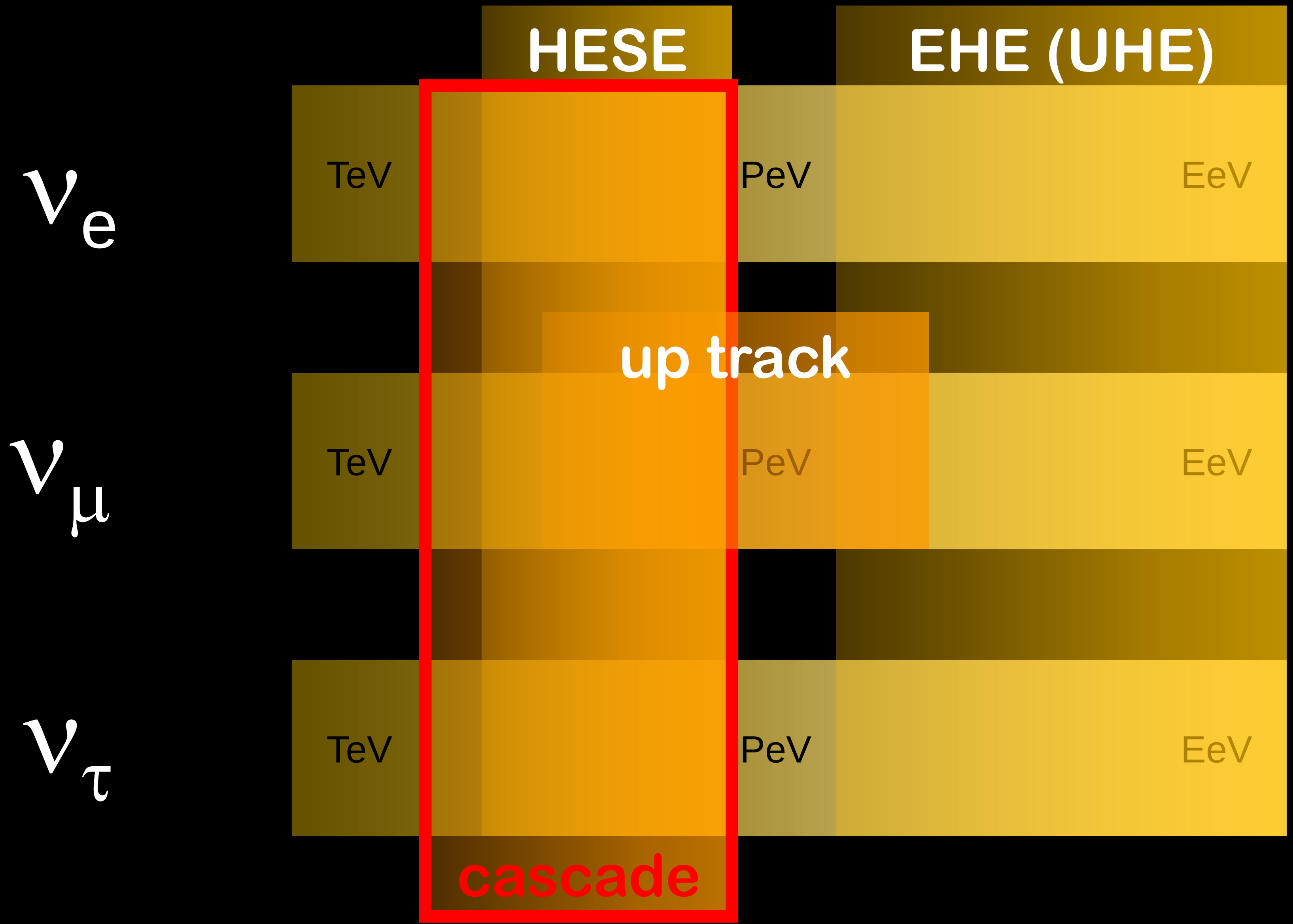


TeV PeV EeV

HESE + MESE (low energy extended)



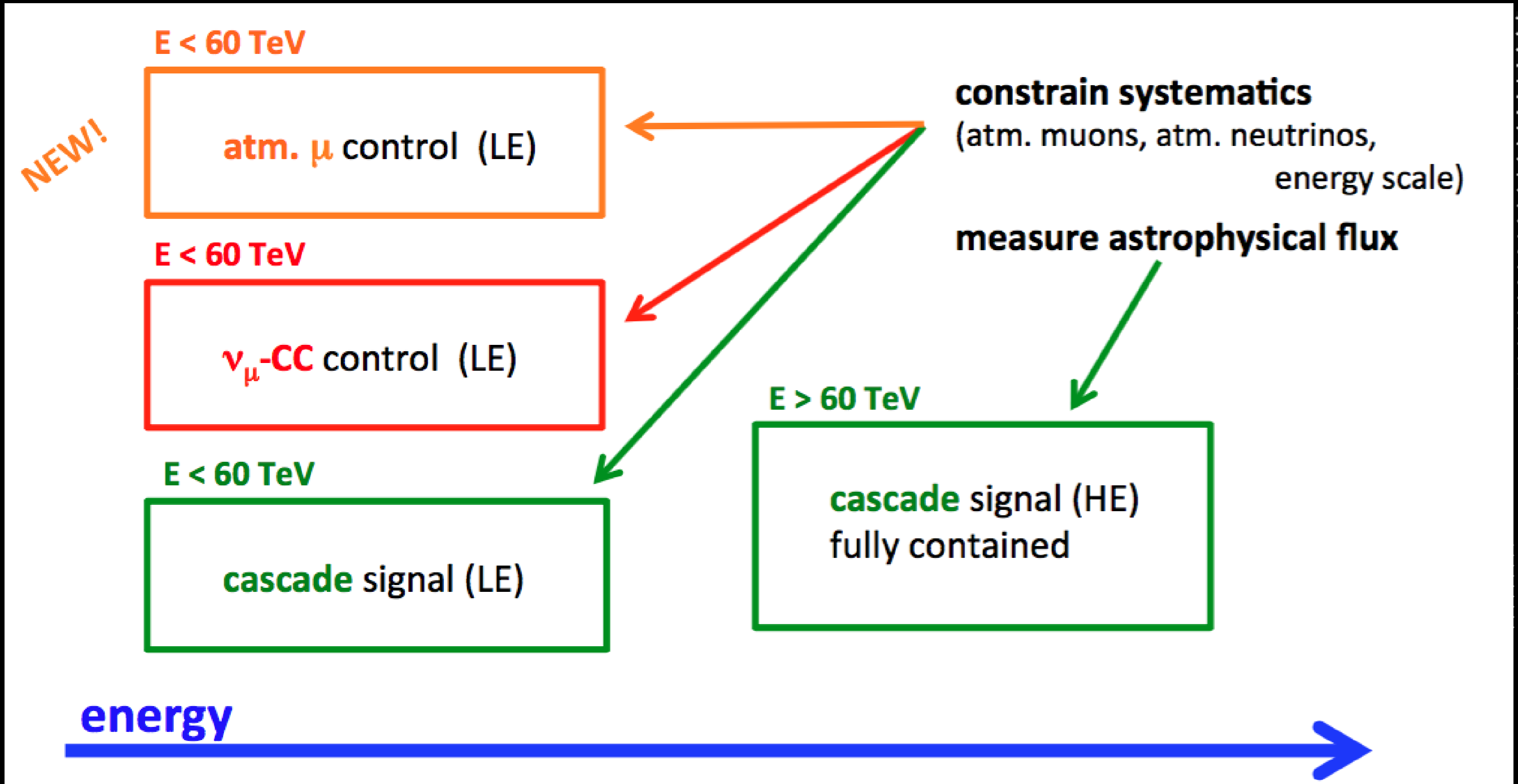
IceCube ν search channels

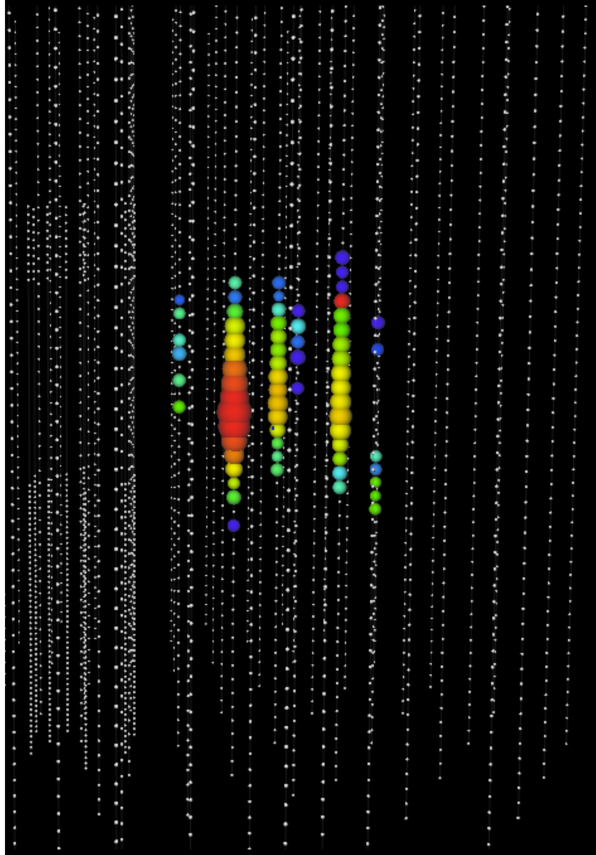


TeV PeV EeV

Search with Cascade Events

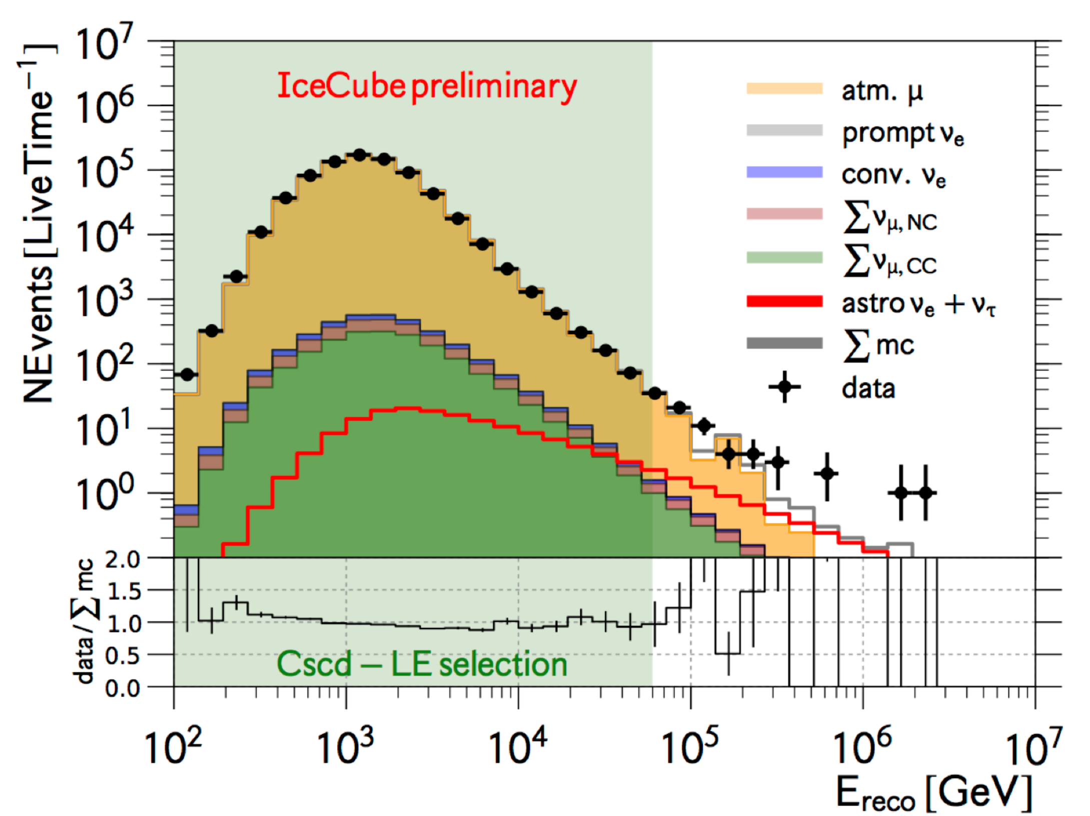
4 years of data (IC2012-IC2015)

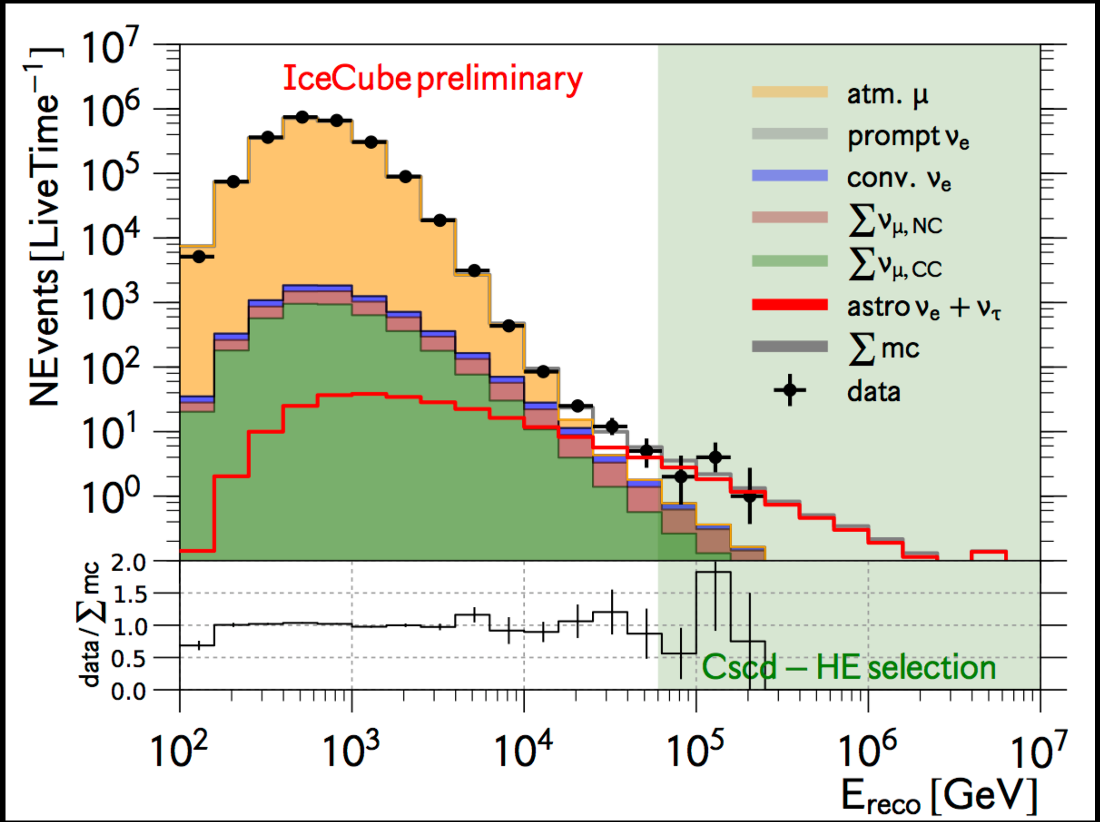


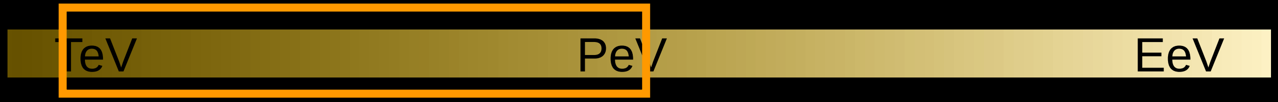


TeV PeV EeV

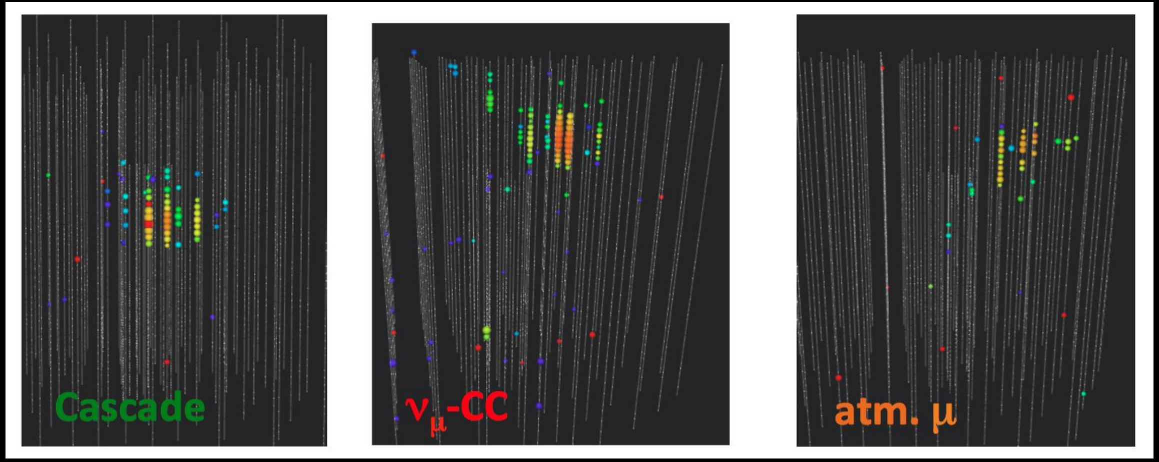
Search with Cascade Events

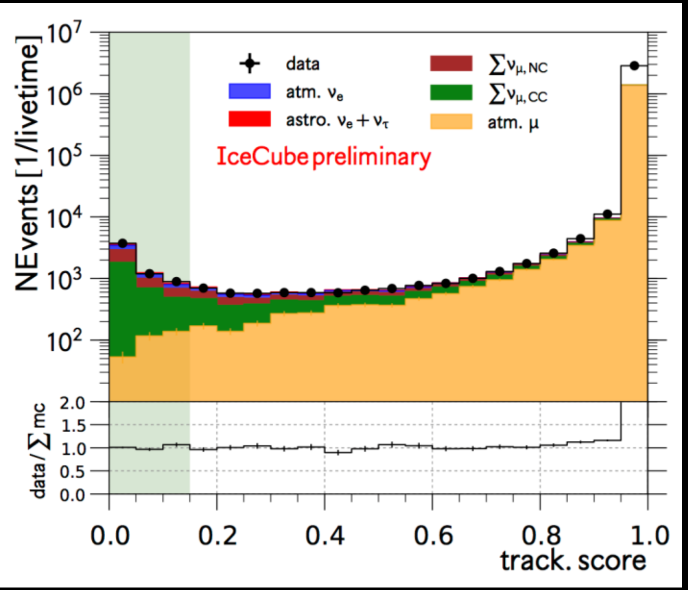


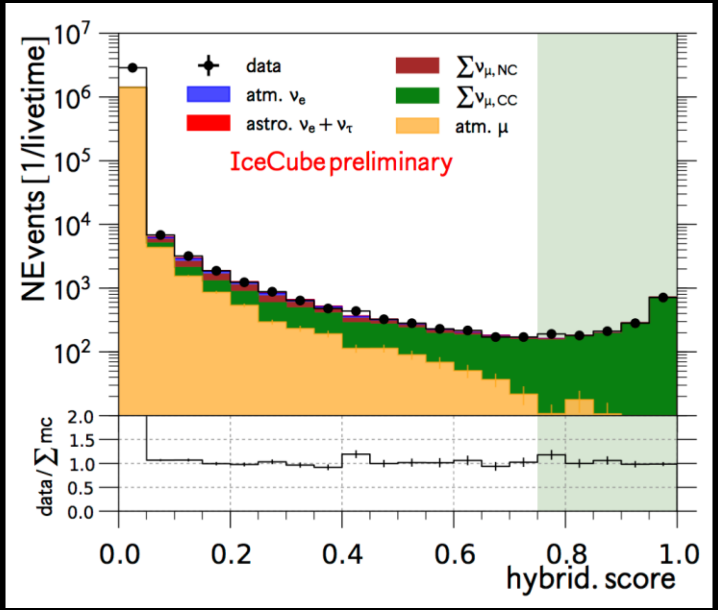


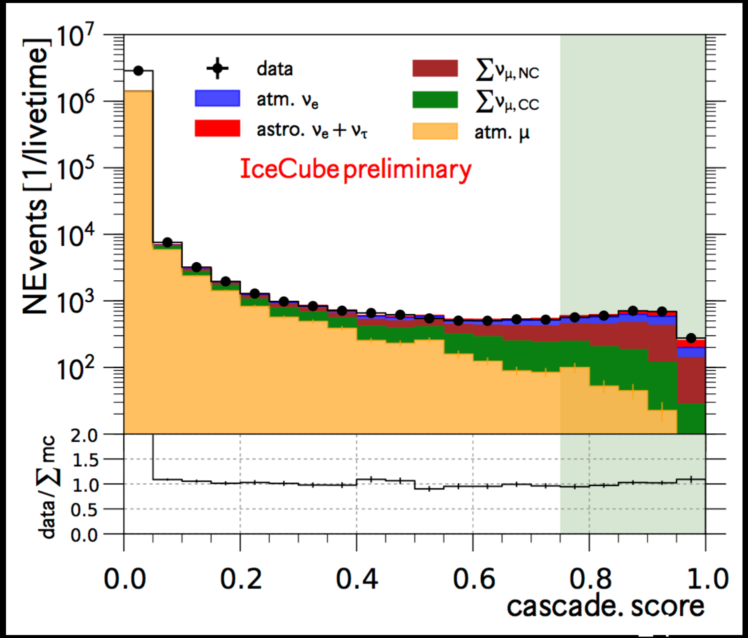


Search with Cascade Events



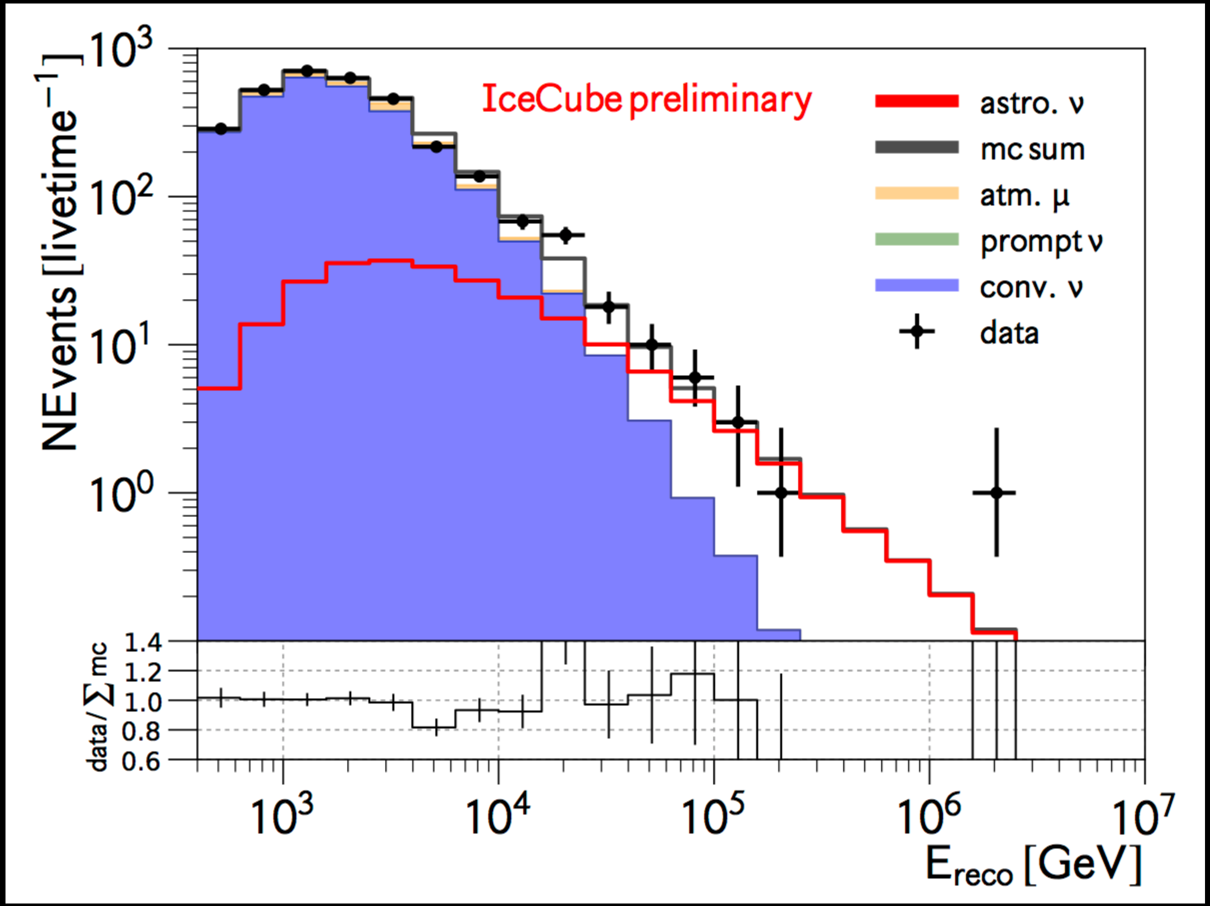




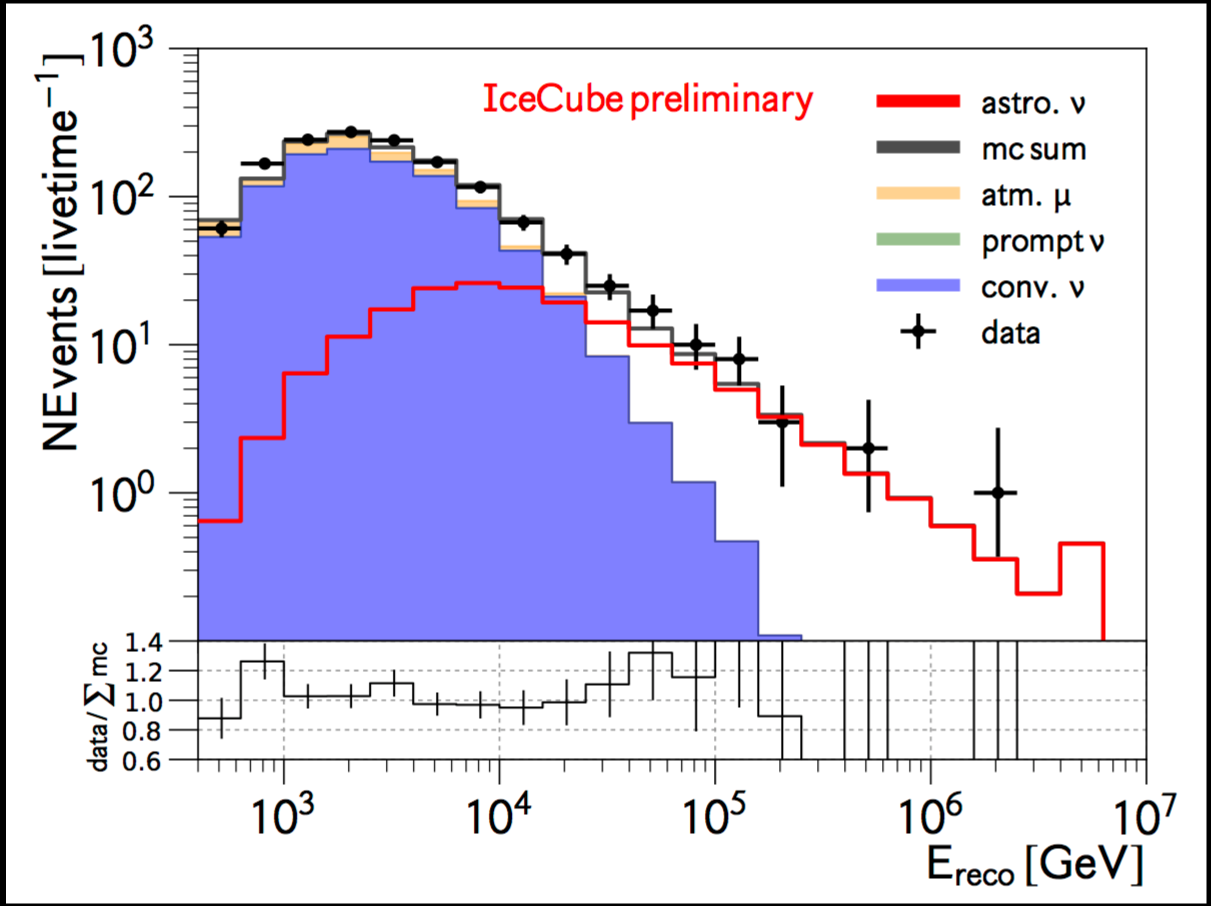


Search with Cascade Events

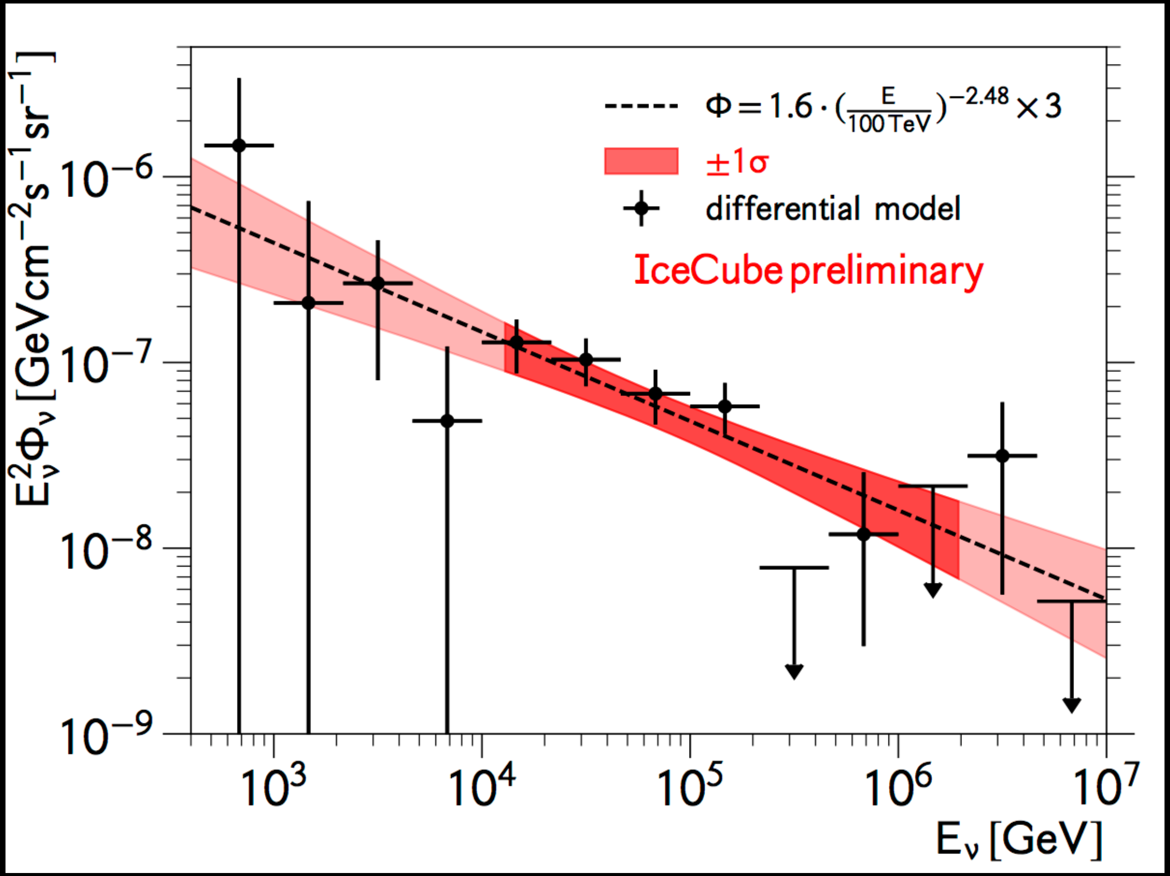
Upward events

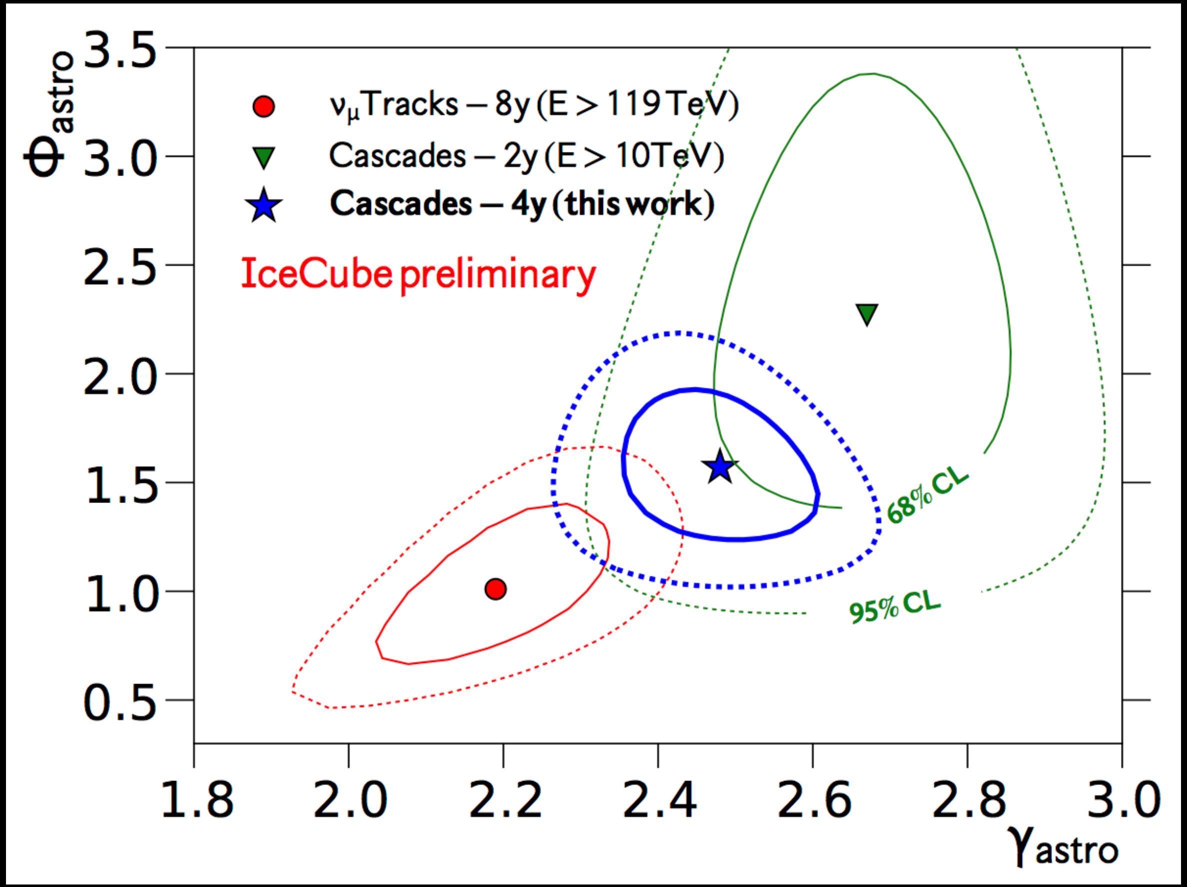


Downward events



Search with Cascade Events

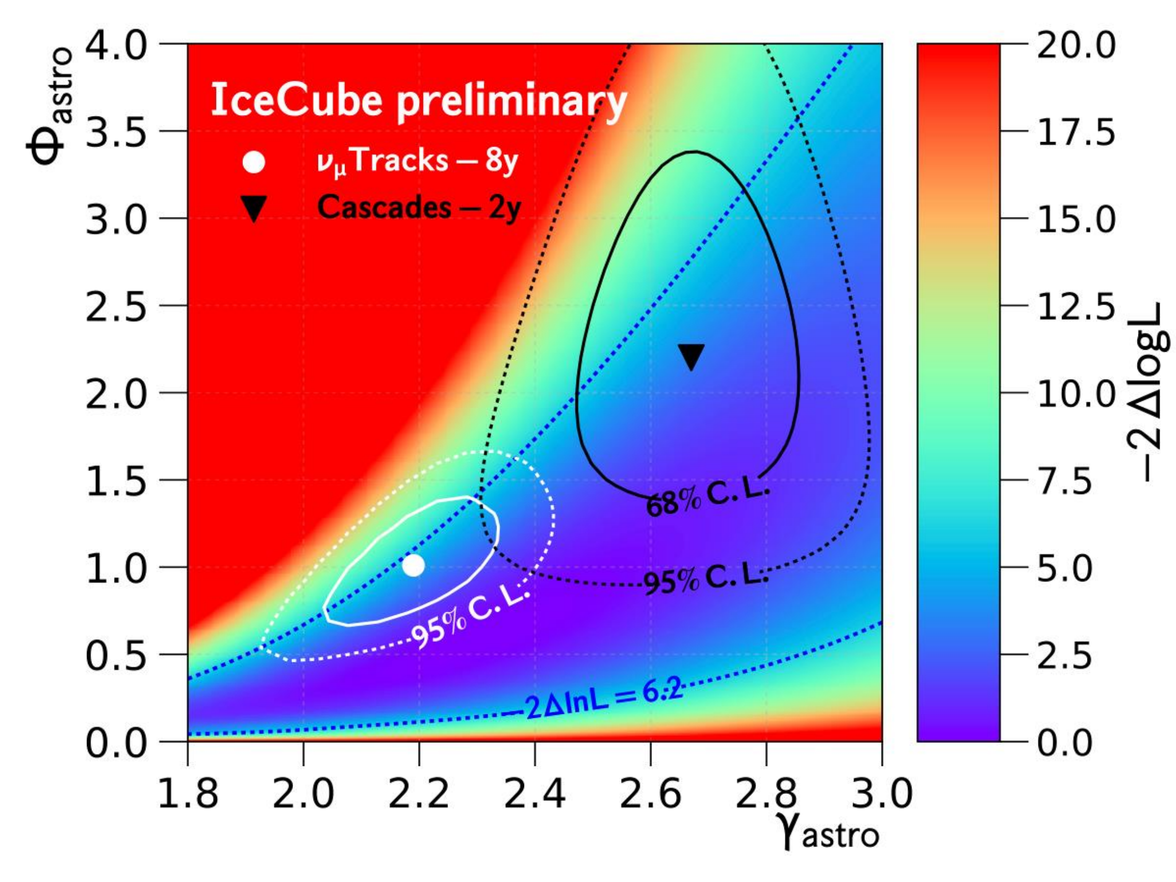


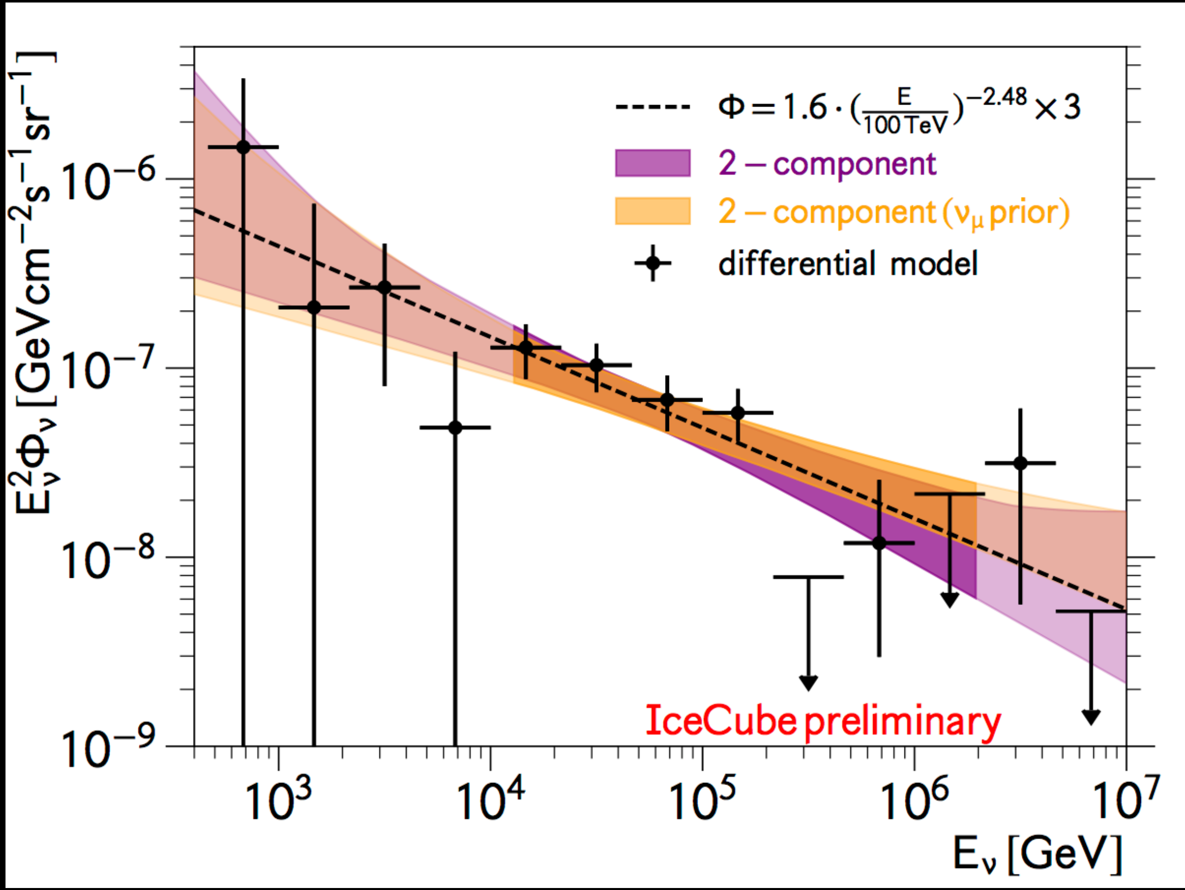


TeV PeV EeV

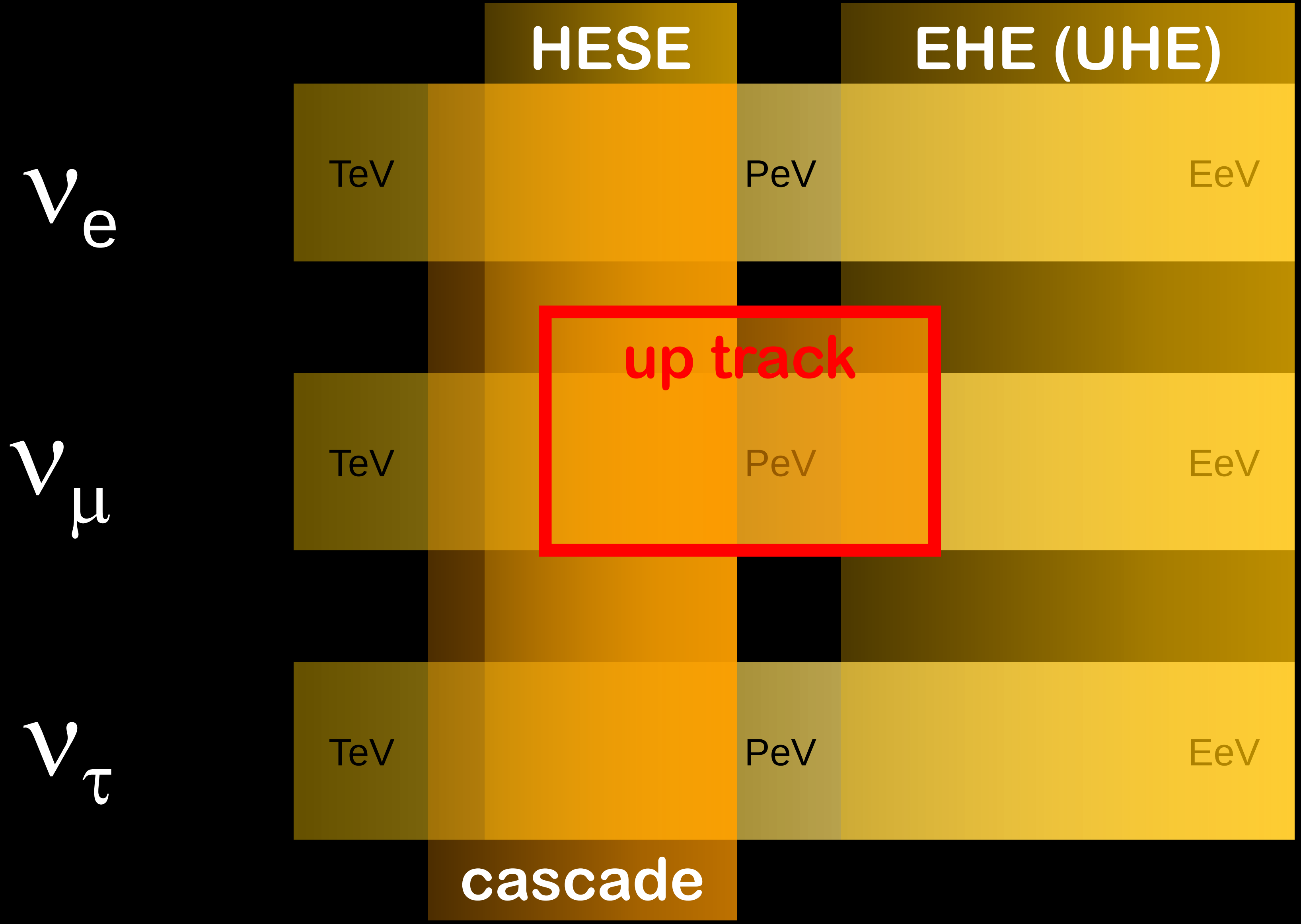
Search with Cascade Events

Fit in E > 200 TeV : overlapping with upgoing track (ν_μ) analysis





IceCube ν search channels



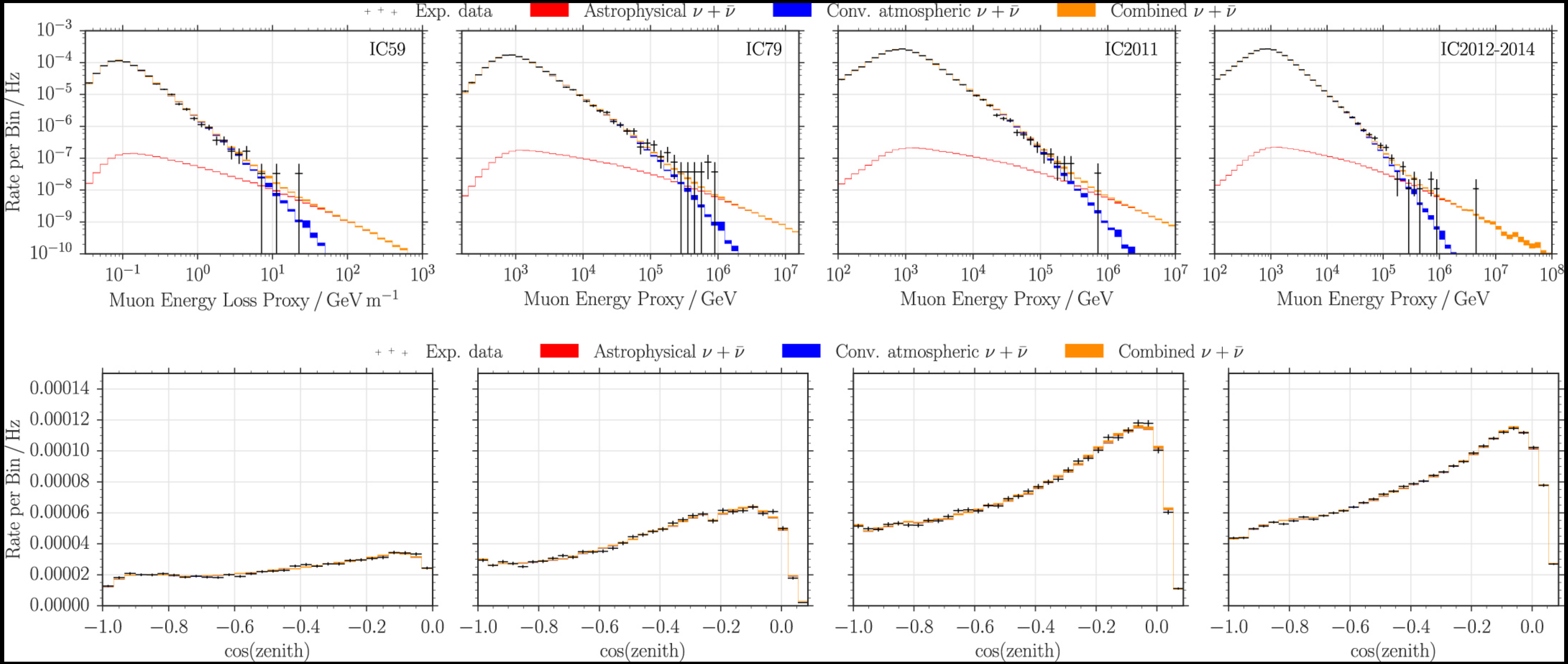
TeV PeV EeV

Upward track (~300 TeV-)

The “traditional” ν_μ search

IceCube collaboration Astrophys. J. **833** 3 (2016)

6 years of IceCube data (2009-2014)



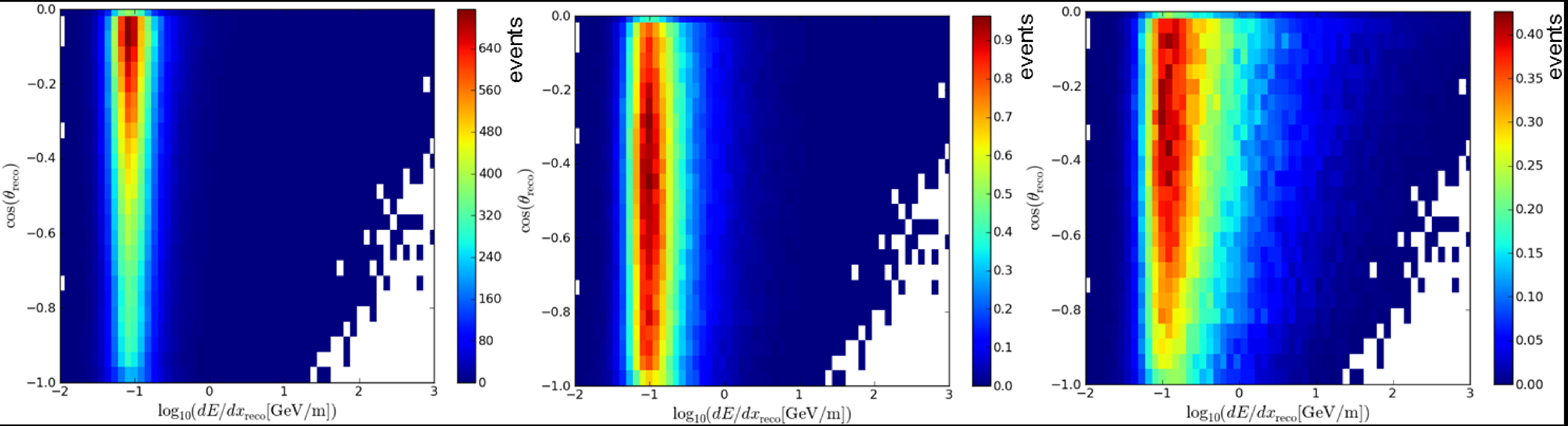
TeV PeV EeV

Upward track (~300 TeV-)

The “traditional” ν_μ search

IceCube collaboration Astrophys. J. **833** 3 (2016)

conventional atmospheric ν_μ prompt atmospheric ν_μ astrophysical atmospheric ν_μ



TeV PeV EeV

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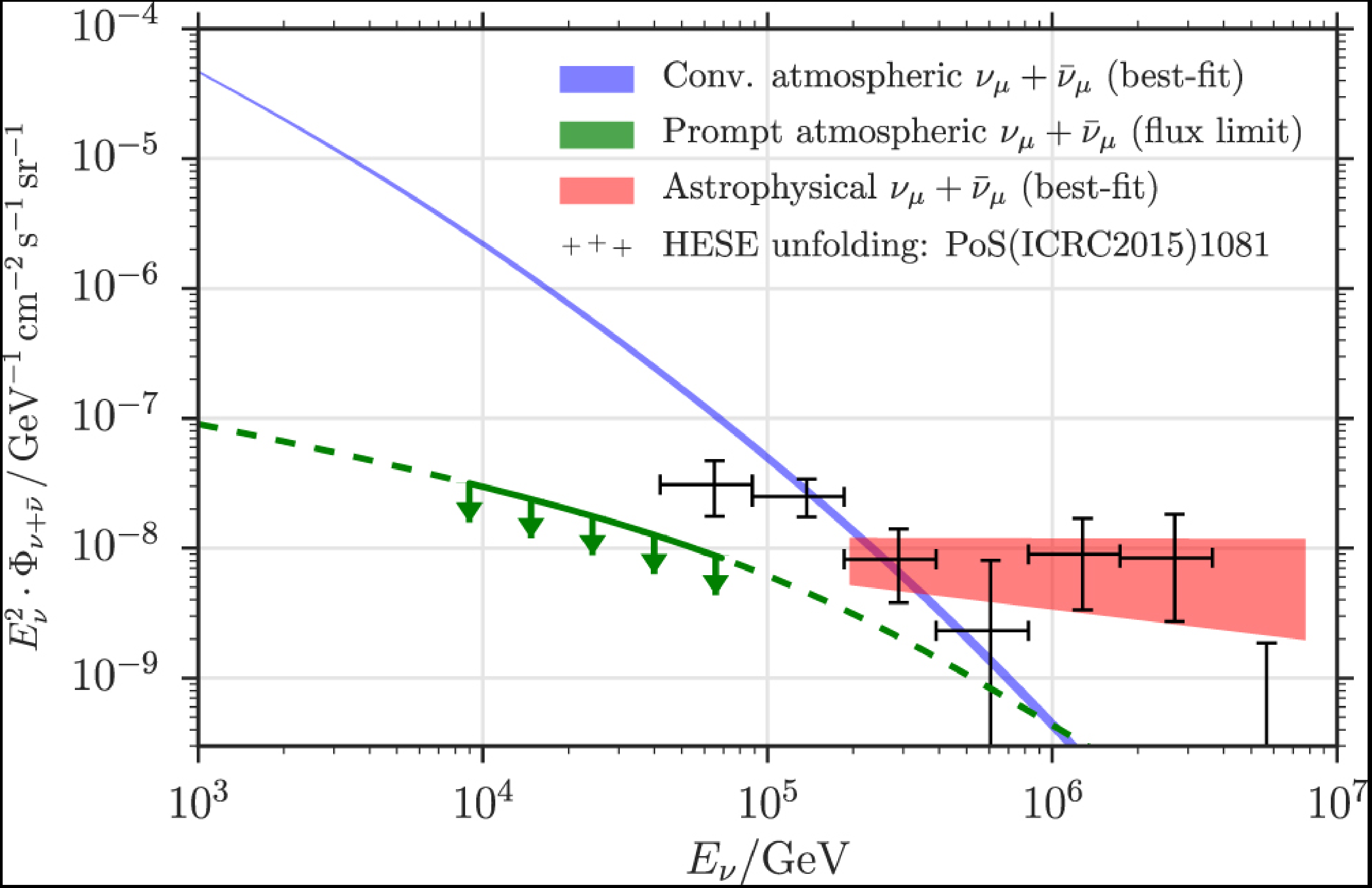
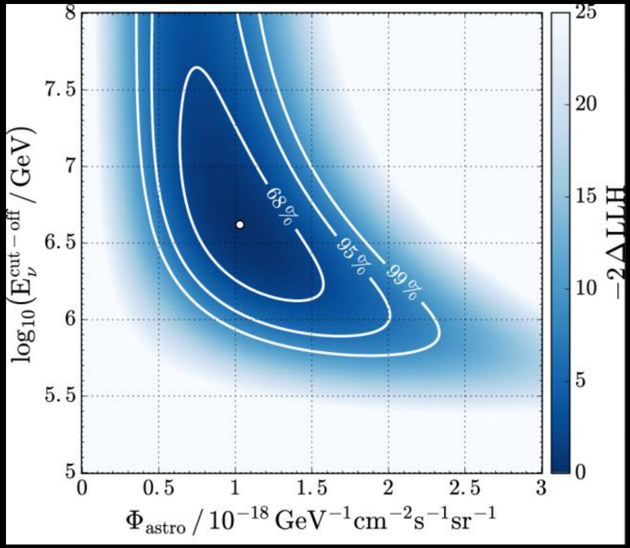
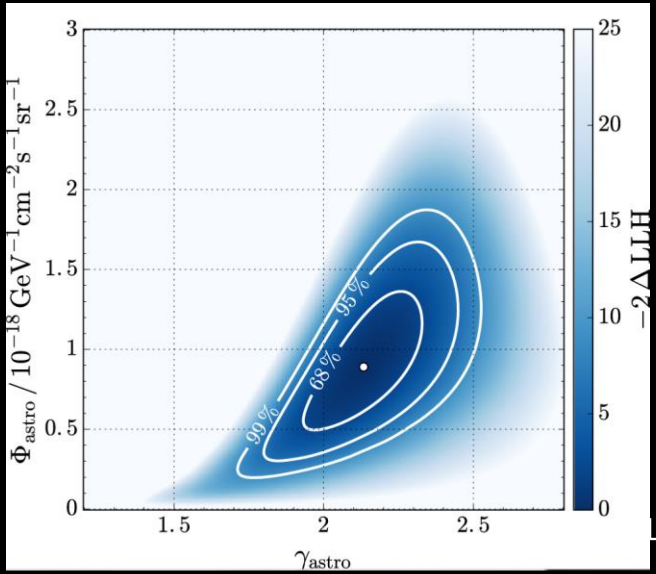
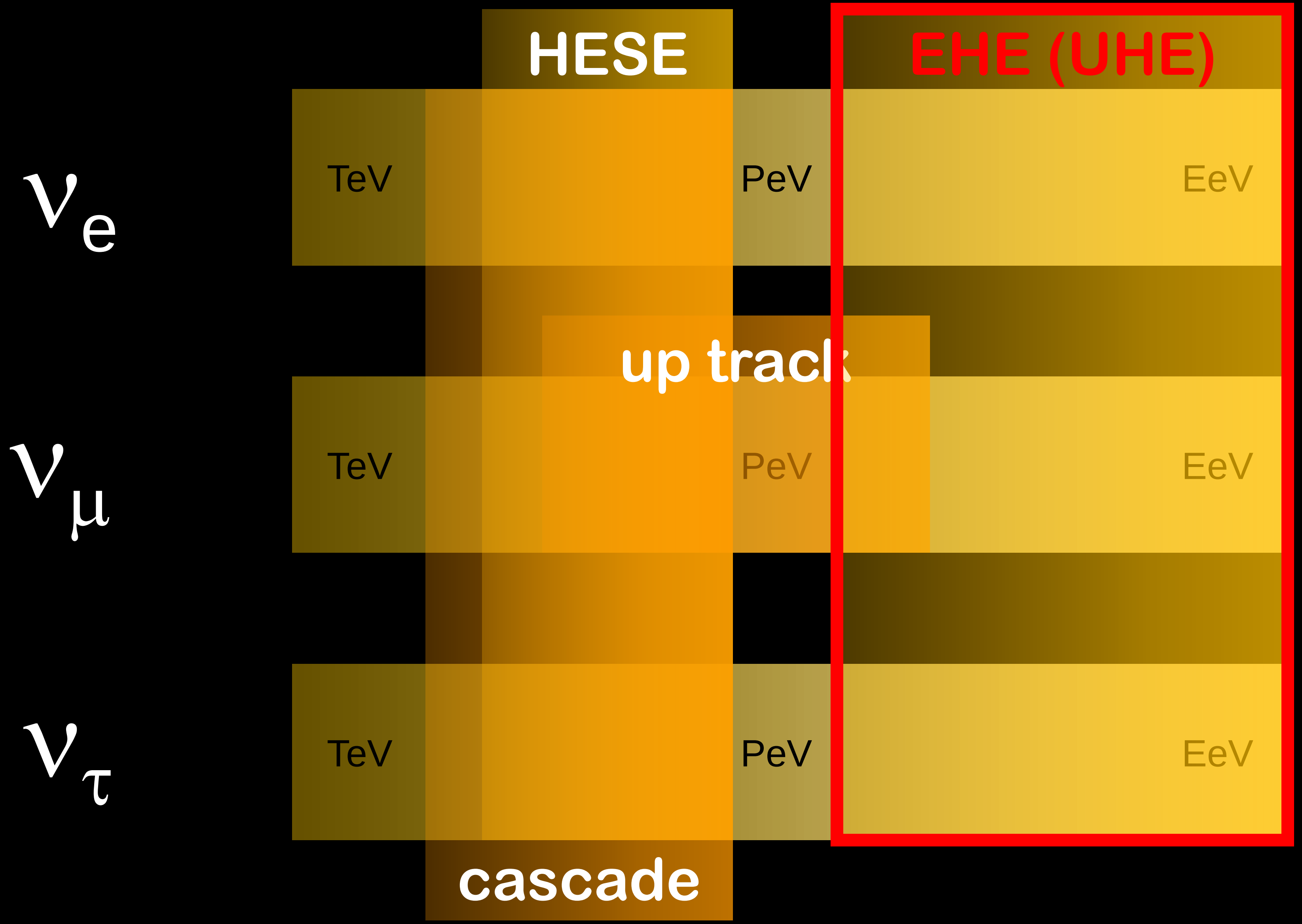






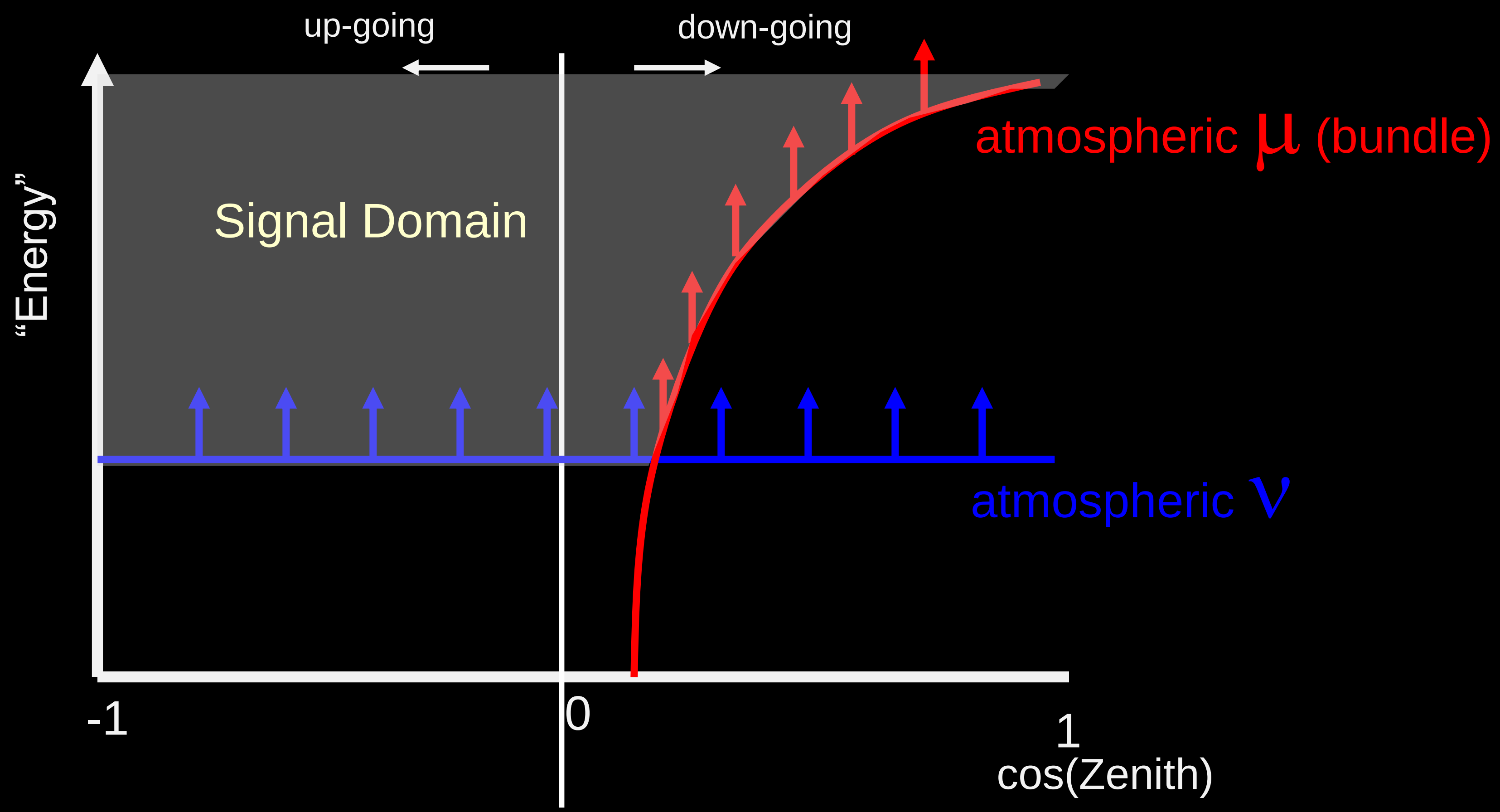
IceCube ν search channels



TeV PeV EeV

UHE (PeV-EeV)

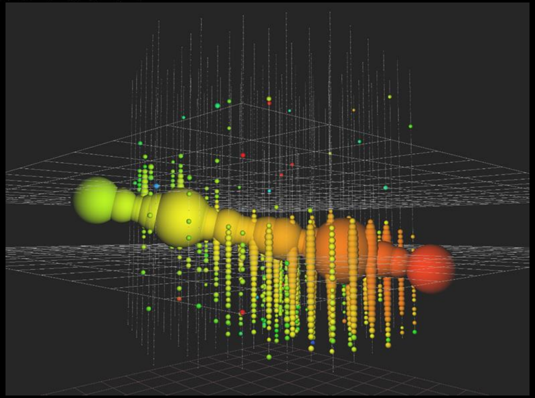
Detection Principle – All flavor sensitive



TeV PeV EeV

Two PeV events found in the 9yr data sample

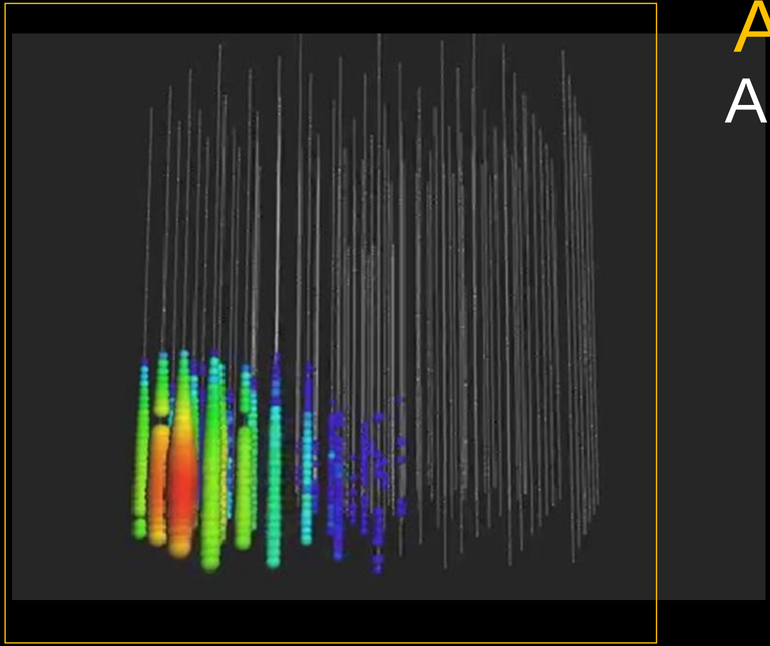
April 2008 – May 2017



A track event in June 2014 Deposited energy 2.6 PeV

The event found in the previous EHE neutrino search

Of the two background events published in PRL 117 241101,
one was discovered to be a detector artifact and has been removed



A new event in December 2016

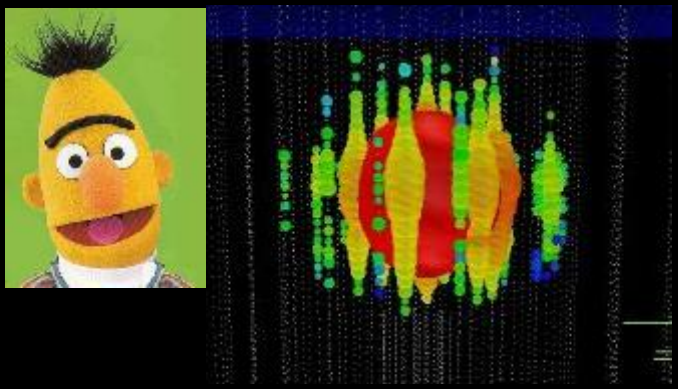
An uncontained shower event

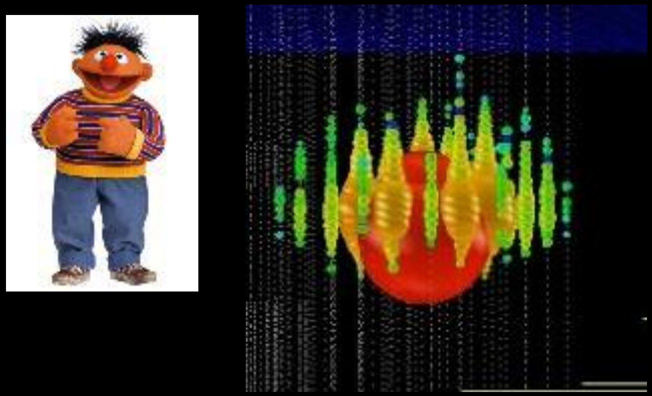
Preliminary deposited energy 6 PeV

Uncontained nature of this event indicates large uncertainty on energy estimate

- Investigations ongoing to see if a prompt atmospheric muon could be responsible for this event

Why the other (well-known) PeV ν events are missed?





The 1st two events were identified by the 2012's GZK ν search

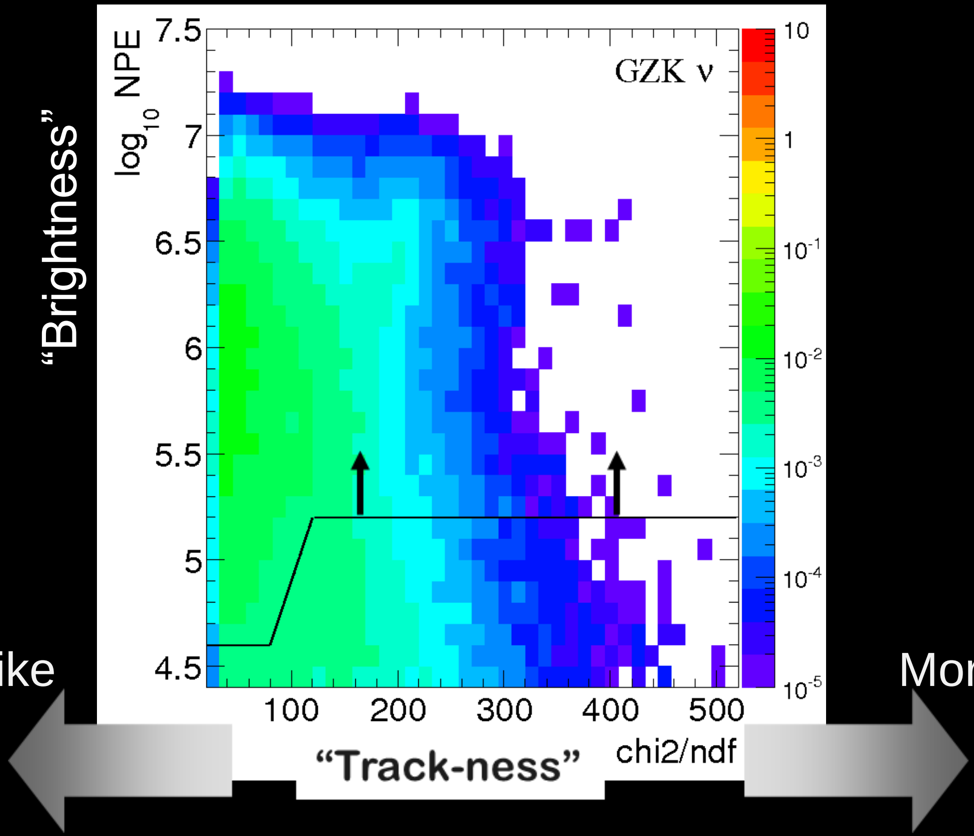
We tightened the cuts for shower-like events

For reduction of atmospheric background events

more than 2000 days of live time requires stronger BG reduction

"Brightness"

More track-like



More shower-like

TeV PeV EeV

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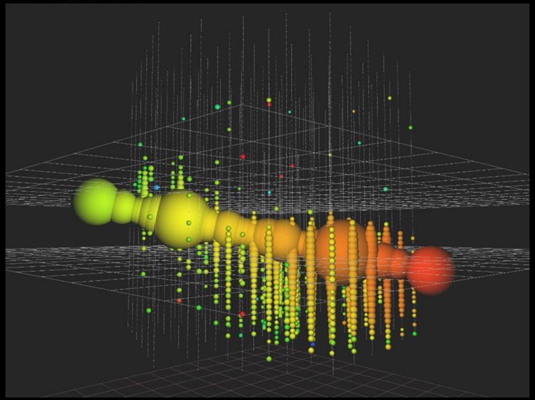

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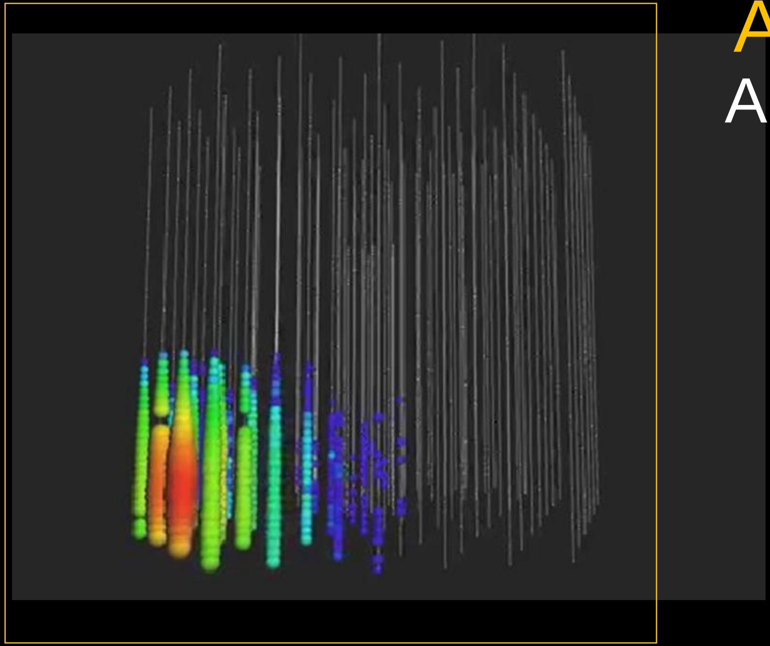

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An uncontained shower event

Preliminary deposited energy 6 PeV

Uncontained nature of this event indicates large uncertainty on energy estimate

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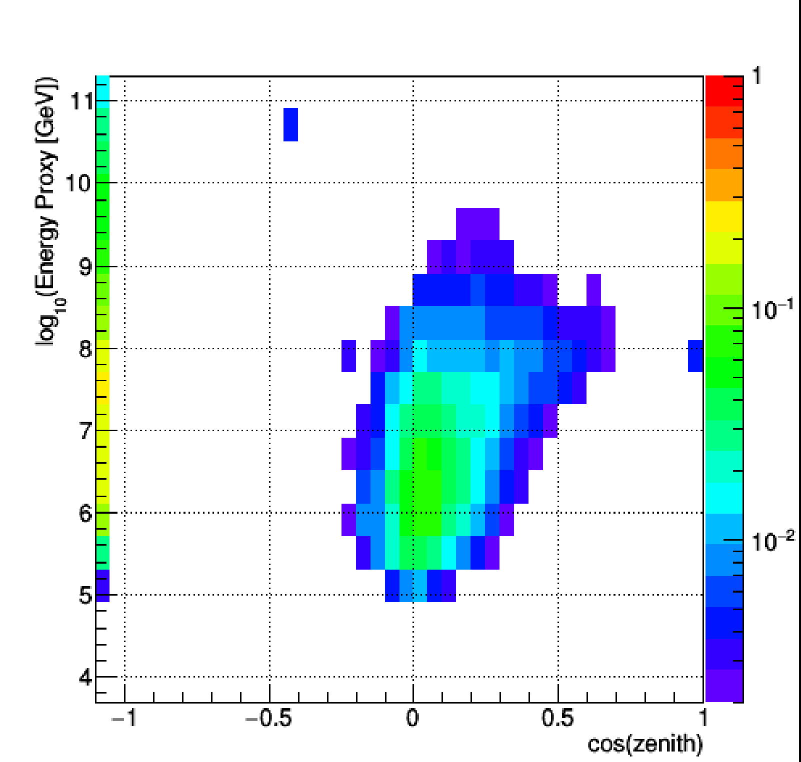
The detected 2 events are *not* GZK cosmogenic ν's

- p-value to support GZK ν hypothesis 2.47%
- compatible with a generic astrophysical E^{-2} power-law flux

Expected GZK ν event distribution



p-value 78.8%

TeV PeV EeV

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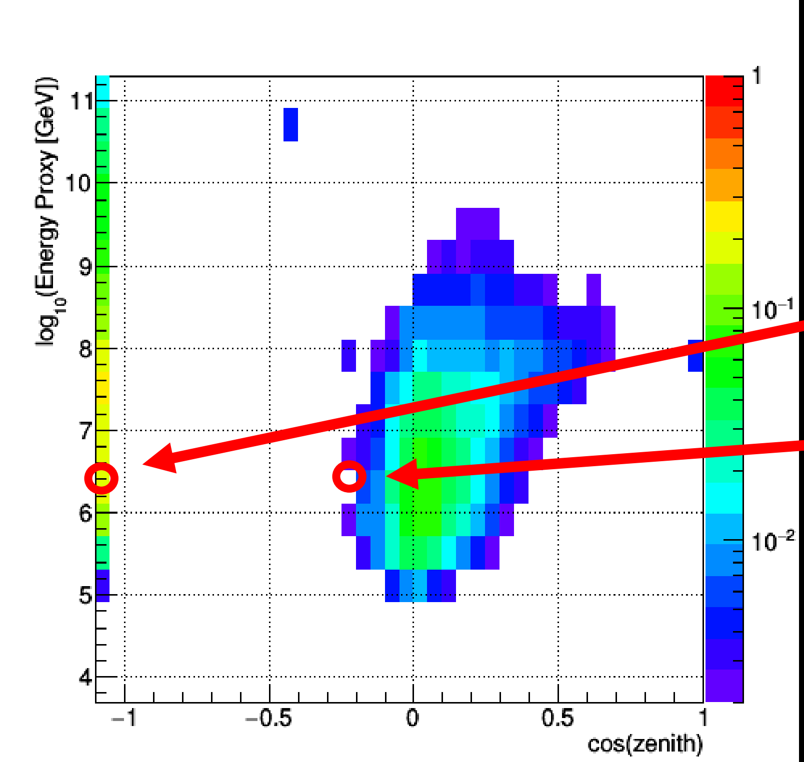


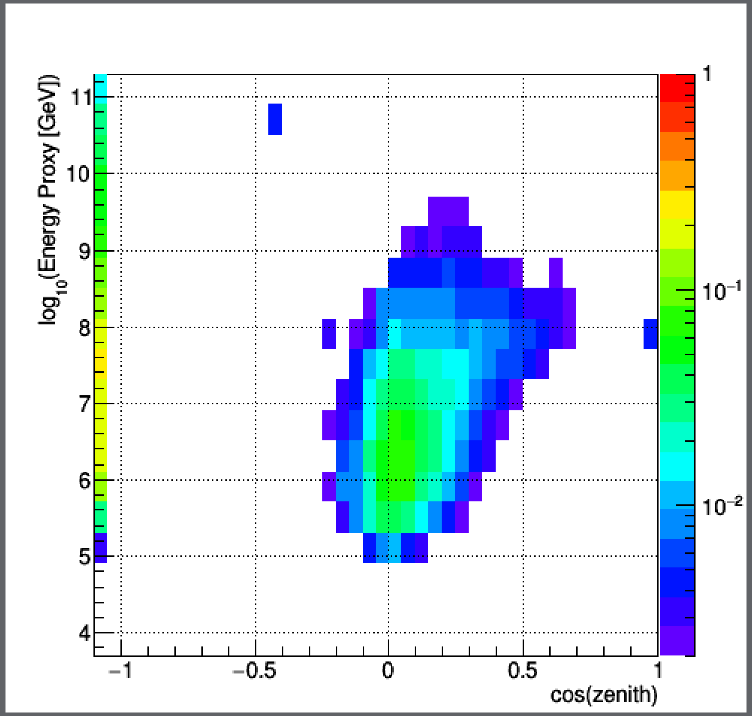
p-value 78.8%

The uncontained shower event

The track event

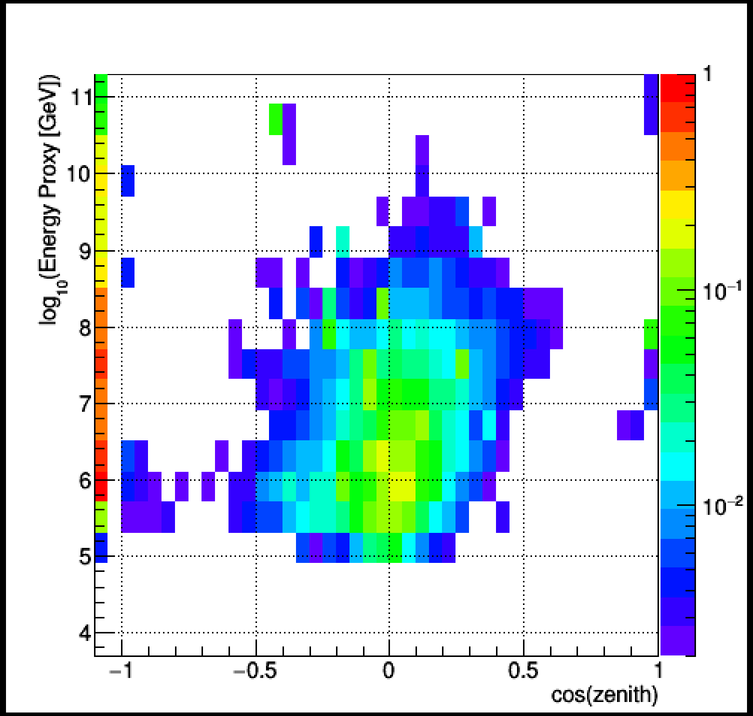
The method to test your UHE ν model

Binned Poisson Likelihood construction by
the expected event distribution on Energy-proxy and cos(zenith)

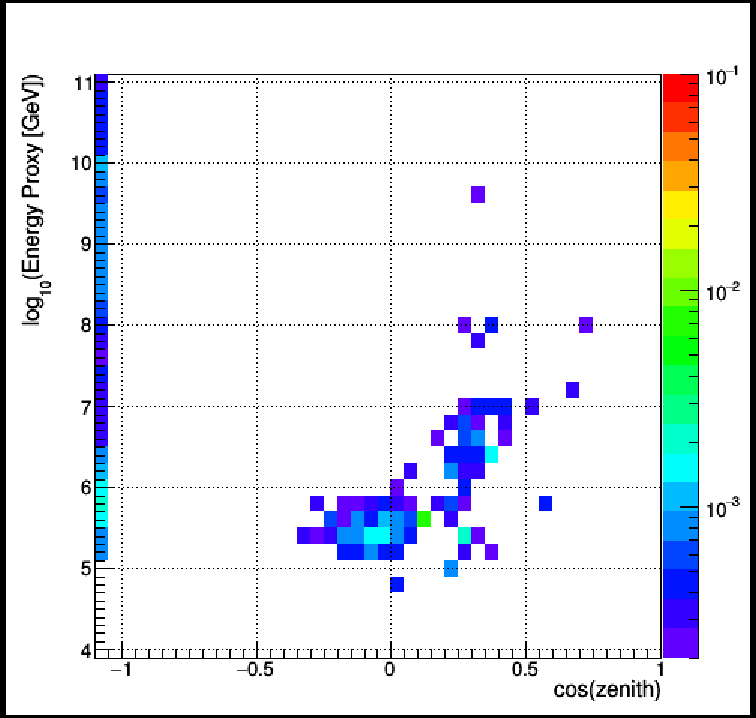


GZK cosmogenic (Ahlers + 2010)

The model to test



Astrophysical BG : E^{-2}



Atmospheric ν and μ BG

float the norm. to fit the data

+

TeV PeV EeV

UHE (PeV-EeV)

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	0.43	0.63	1.33	1.04	0.80	0.62	0.87
p-value	1.0×10^{-3}	1.1×10^{-2}	1.3×10^{-1}	6.0×10^{-2}	3.2×10^{-2}	3.0×10^{-3}	1.6×10^{-2}

Excluded

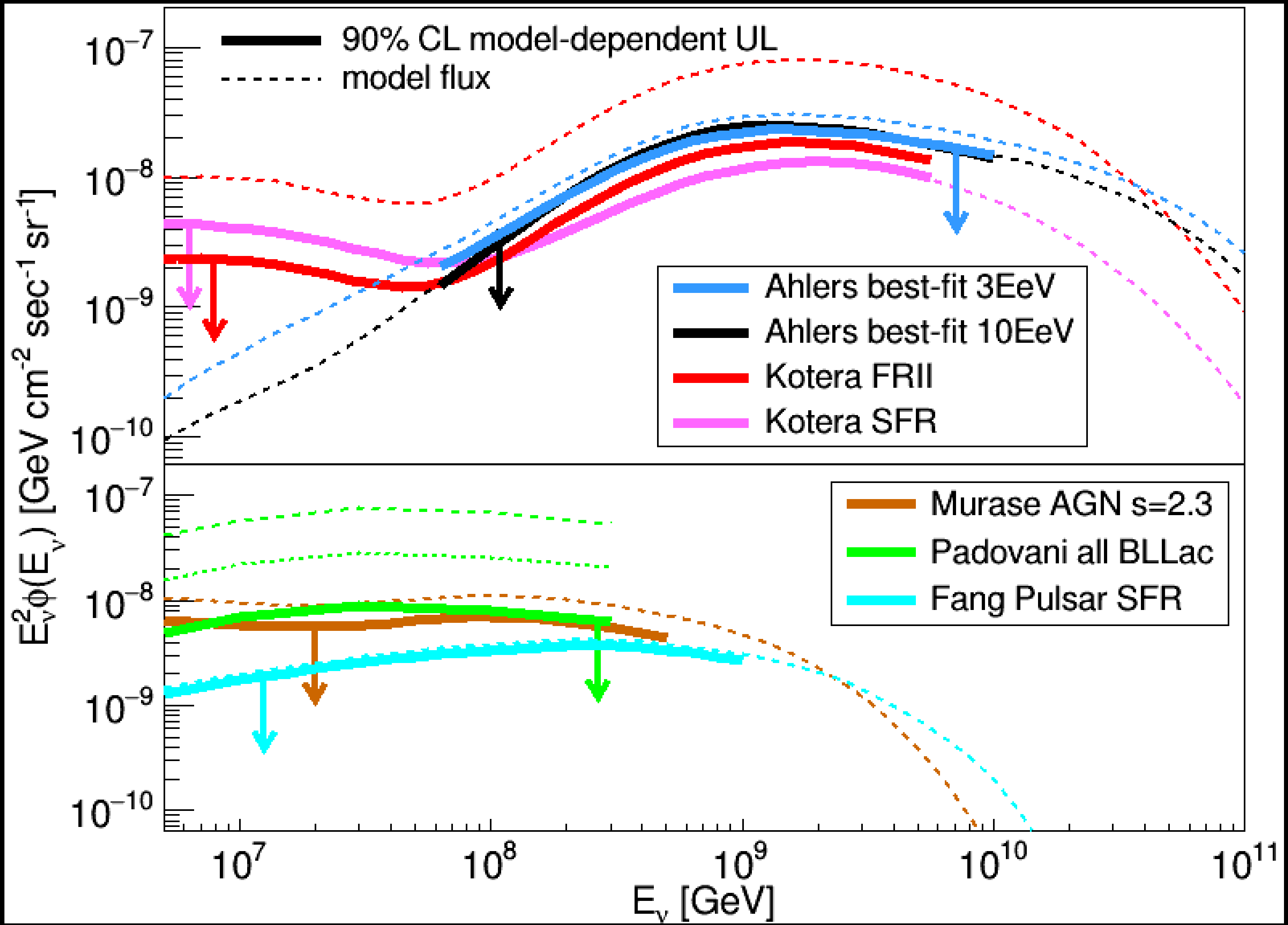
Mildly Excluded

IceCube collaboration
Phys.Rev.Lett.**117** 241101(2016)

TeV PeV EeV

UHE (PeV-EeV)

all flavor sum



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

CHIBA UNIVERSITY

Yoshida and Ishihara, PRD **85**, 063002 (2012)

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

$0<z<z_{max}$

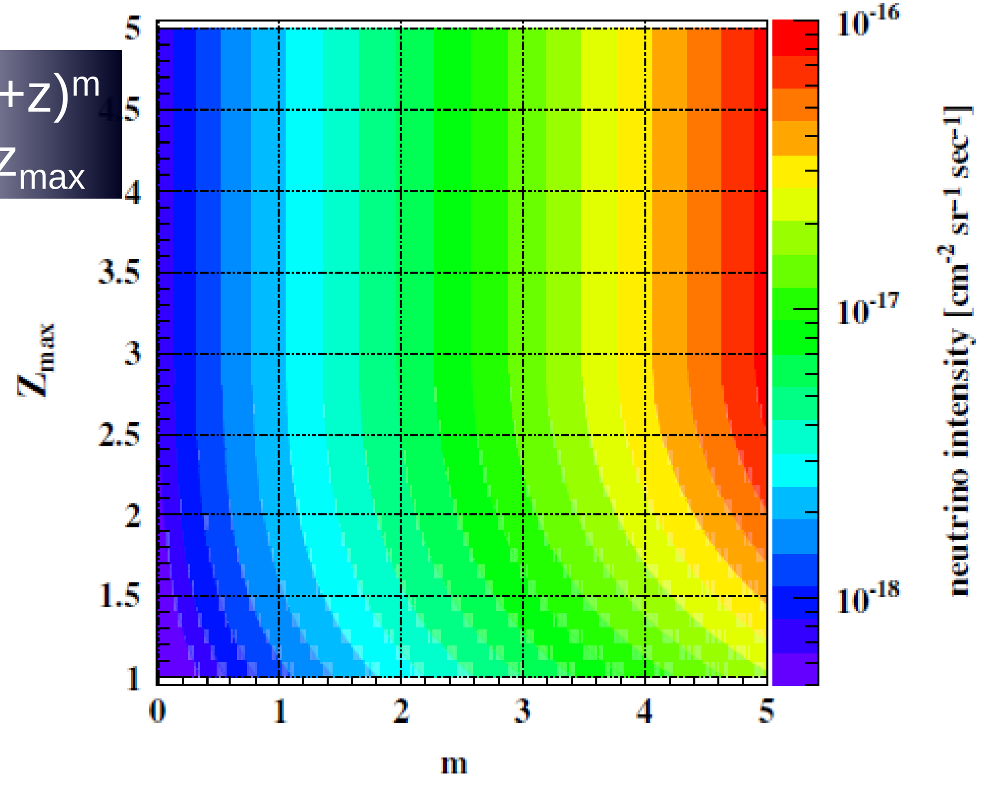


FIG. 2 (color online). Integral neutrino fluxes with energy above 1 EeV, J [cm^{-2} sec^{-1} sr^{-1}], on the plane of the source evolution parameters, m and z_{max}.

GZK ν flux $\phi = (m, z_{max})$

x IceCube Exposure

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

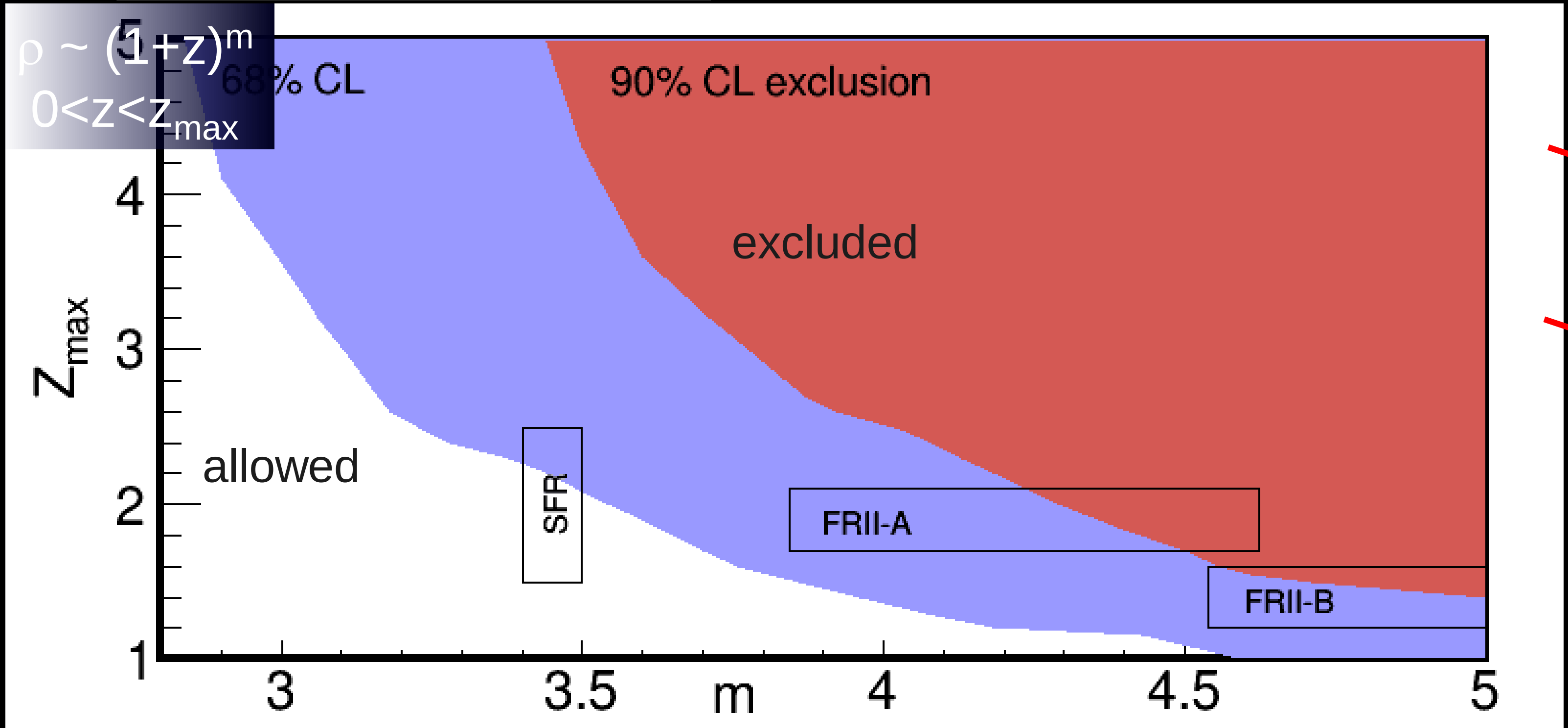
The *observed* event distribution

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

IceCube collaboration
Phys.Rev.Lett.**117** 241101(2016)

UHECR source is cosmologically LESS evolved

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



~~Radio-loud AGNs~~

~~GRBs~~

TeV PeV EeV

What IceCube tells
if UHECRs are not proton-dominated?

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

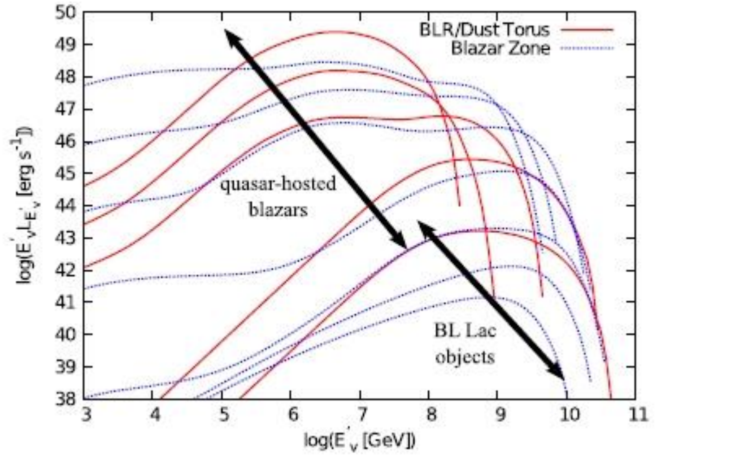
Example: AGN(Blazar) inner jets taking into account the Blazar sequence
(Murase, Inoue, Dermer, PRD 2014)

FSRQs (QHB) → ν

middle class → γ

BL Lac → UHECRs

ν luminosity from a Blazar



The highest energy CRs
are HEAVY nuclei

TeV PeV EeV

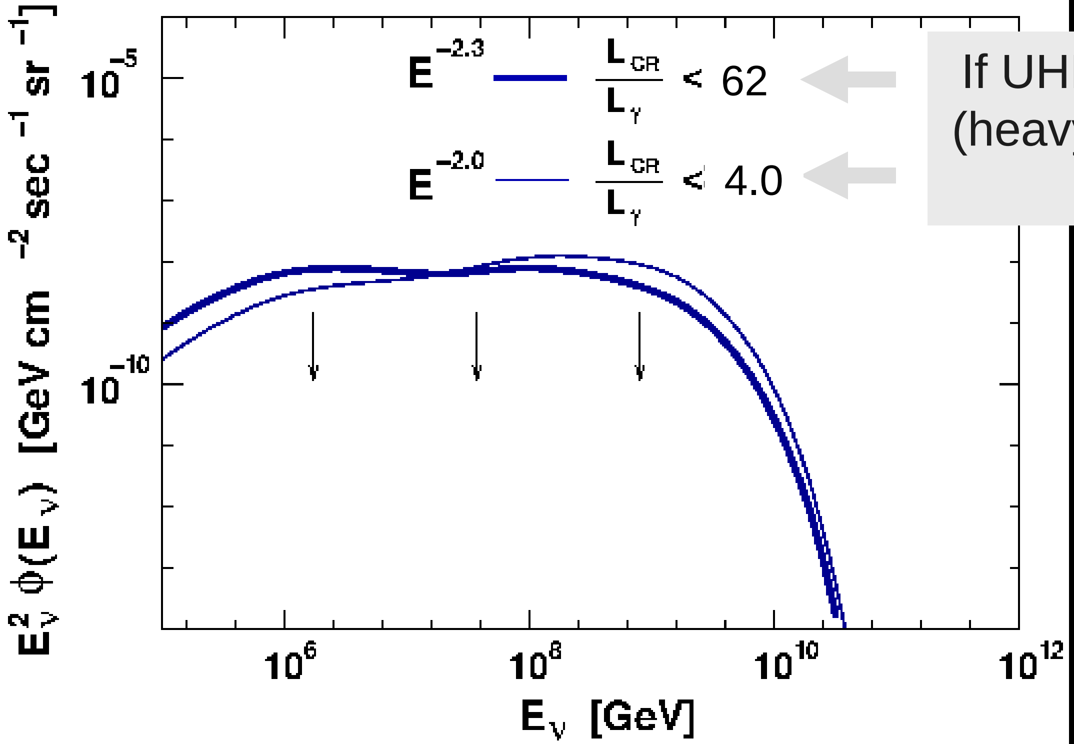
IceCube tests on *on-source* ν models

AGN (Blazar) Inner Jet

Murase, Inoue, Dermer, PRD 2014

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

ν flux upper limit by IceCube

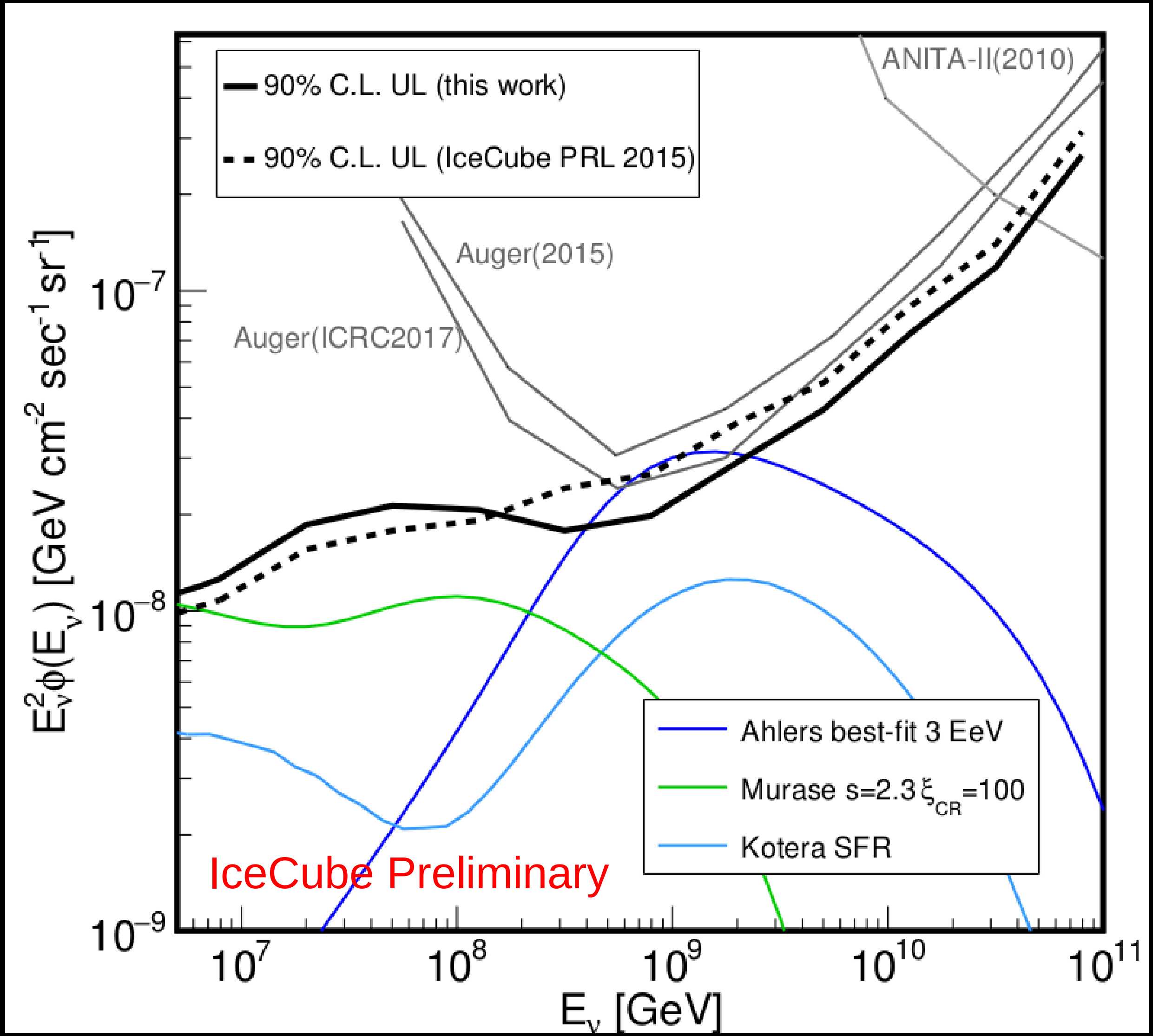


If UHECRs are 100% AGN-originated (heavy) nuclei, we would have already seen EeV neutrinos

AGN unlikely

though not completely ruled out

Model Independent Differential Limit



The obtained limit at 1 EeV

$\boxed{\sim 2 \times 10^{-8}\ \mathrm{GeV/cm^2\ s\ sr}}$

≈

Energy flux of UHECRs

TeV PeV EeV

Summary in UHE ν

Two PeV-ish events detected. No EeV events in the IceCube 9 year-long data

IF UHECRs are proton-dominated

(consistent with the TA's claim)

UHE sources are not populated at far universe

radio-~~loud~~ 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

No GRBs

100 TeV ~ 10 PeV

No neutrinos associated from GRBs

Based on 807 GRBs

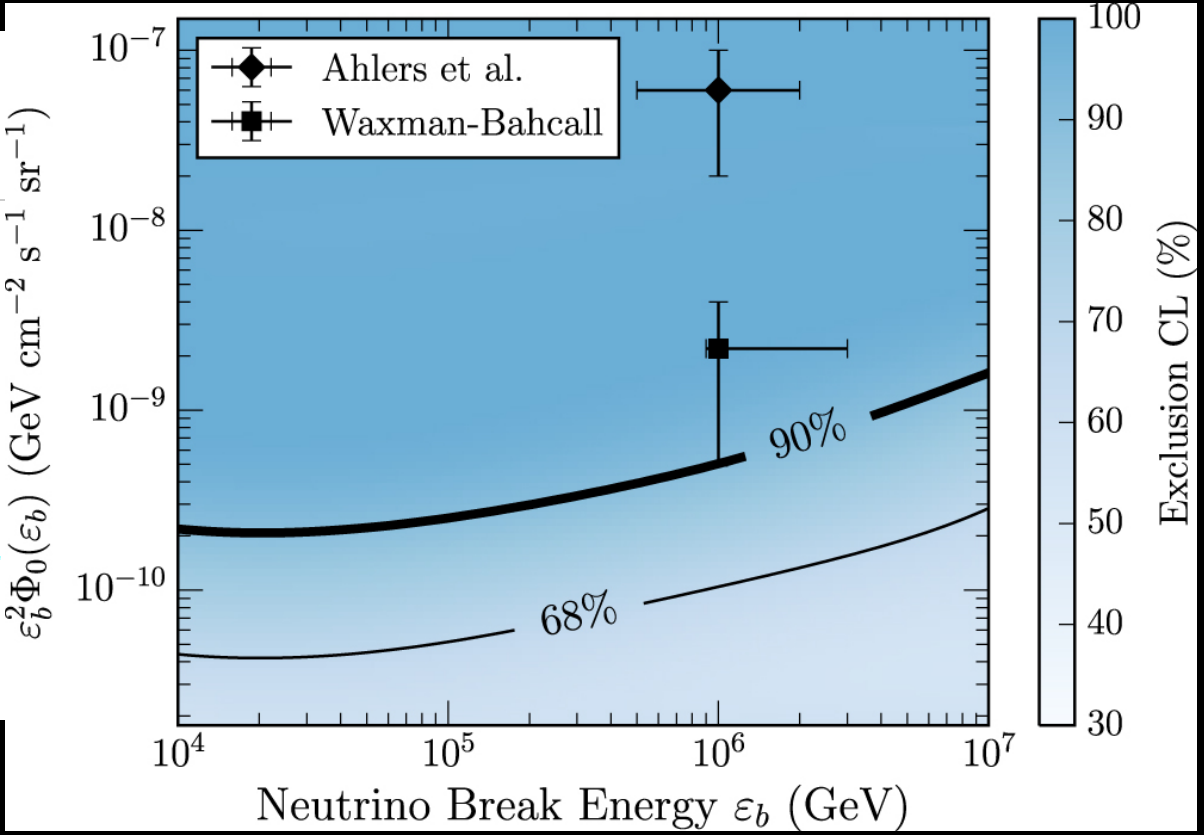
THE ASTROPHYSICAL JOURNAL

AN ALL-SKY SEARCH FOR THREE FLAVORS OF NEUTRINOS FROM GAMMA-RAY BURSTS WITH THE ICECUBE NEUTRINO OBSERVATORY

M. G. Aartsen[1], K. Abraham[2], M. Ackermann[3], J. Adams[4], J. A. Aguilar[5], M. Ahlers[6], M. Ahrens[7], D. Altmann[8], T. Anderson[9], I. Ansseau[5] Show full author list

Published 2016 June 20 •

The Astrophysical Journal, Volume 824, Number 2



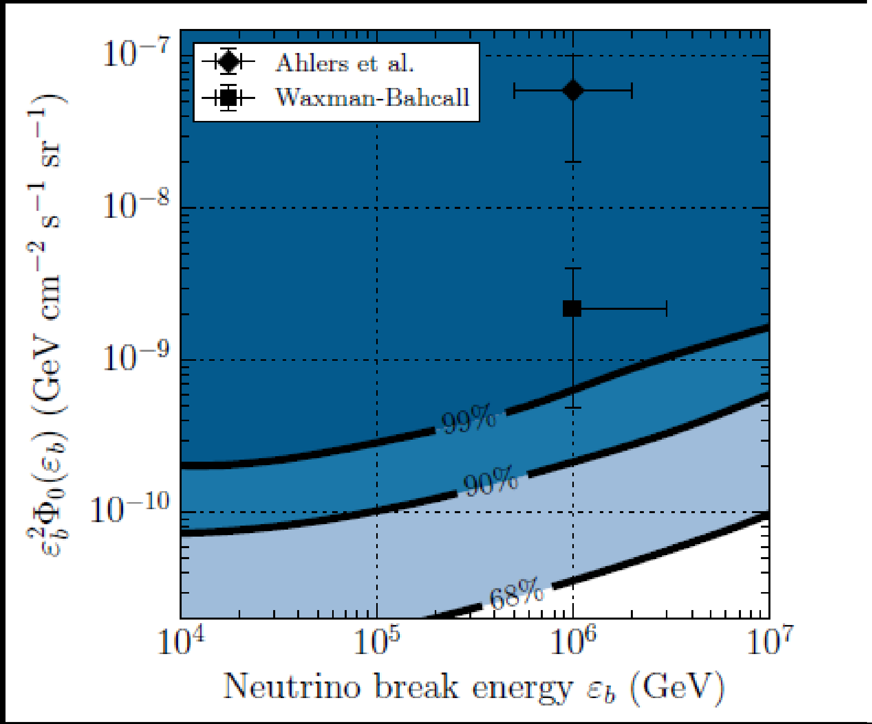
TeV PeV EeV

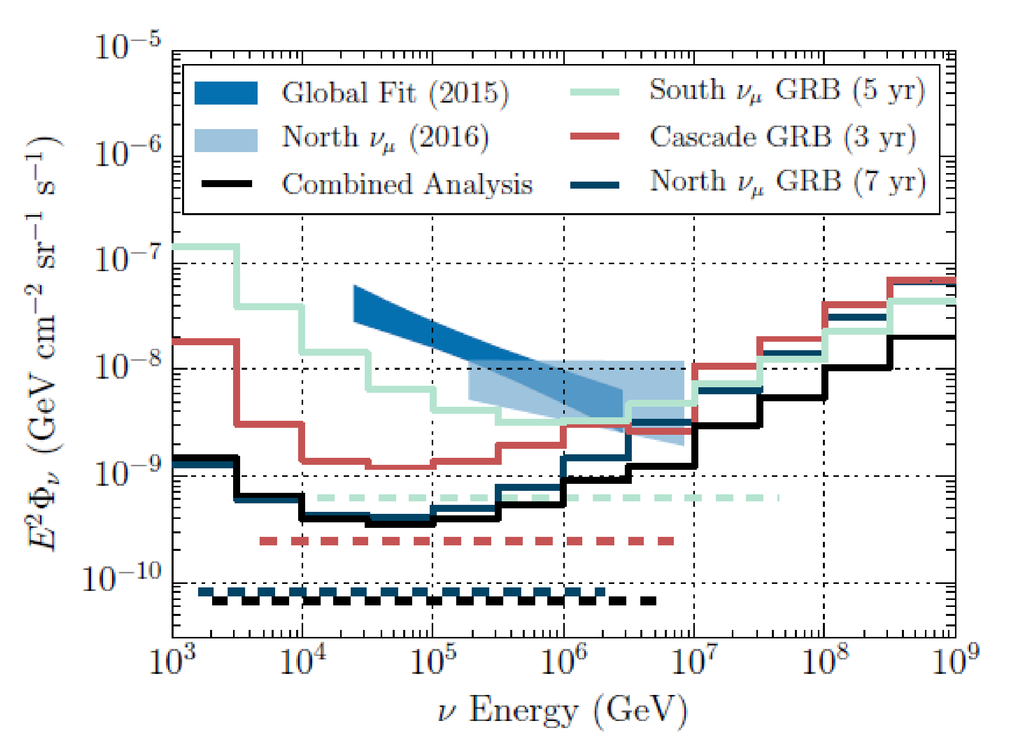
No GRBs

No neutrinos associated from GRBs

Based on 1172 GRBs

Arxiv:1702.06868





Significant constraints on single-zone fireball models of GRB neutrino and UHECR production

TeV PeV EeV

No Blazars

Blazar stacking analysis

THE CONTRIBUTION OF *FERMI*-2LAC BLAZARS TO DIFFUSE TEV–PEV NEUTRINO FLUX

M. G. Aartsen[1], K. Abraham[2], M. Ackermann[3], J. Adams[4], J. A. Aguilar[5], M. Ahlers[6], M. Ahrens[7], D. Altmann[8], K. Andeen[9], T. Anderson[10]

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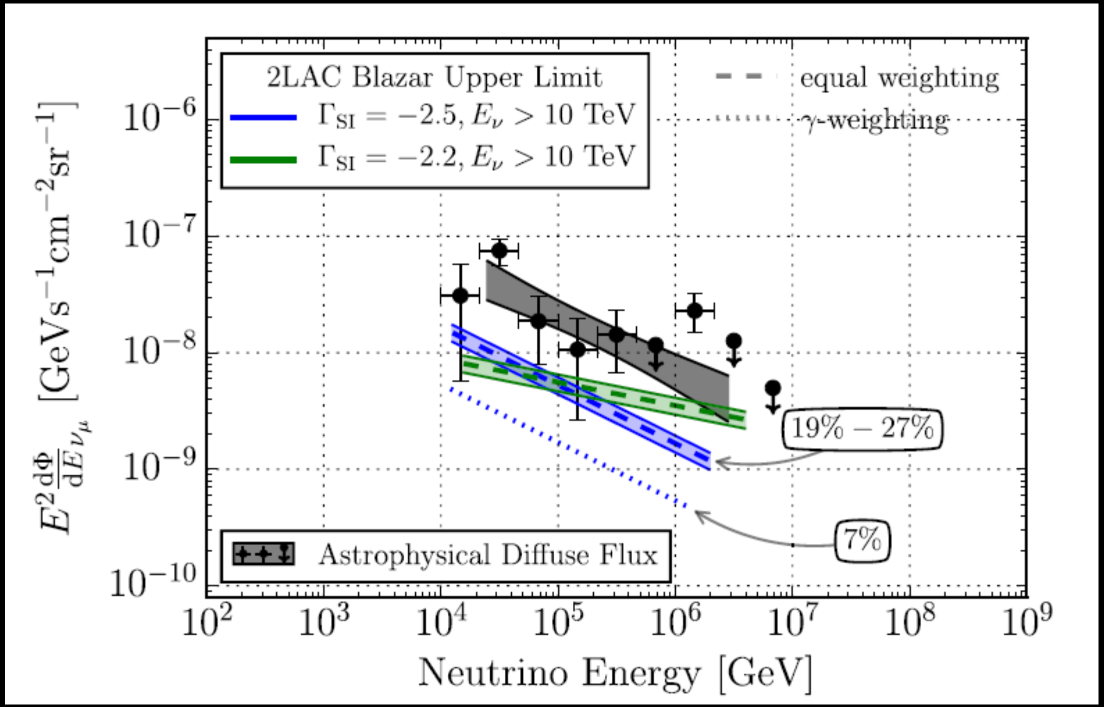
Published 2017 January 17 •

The Astrophysical Journal, Volume 835, Number 1

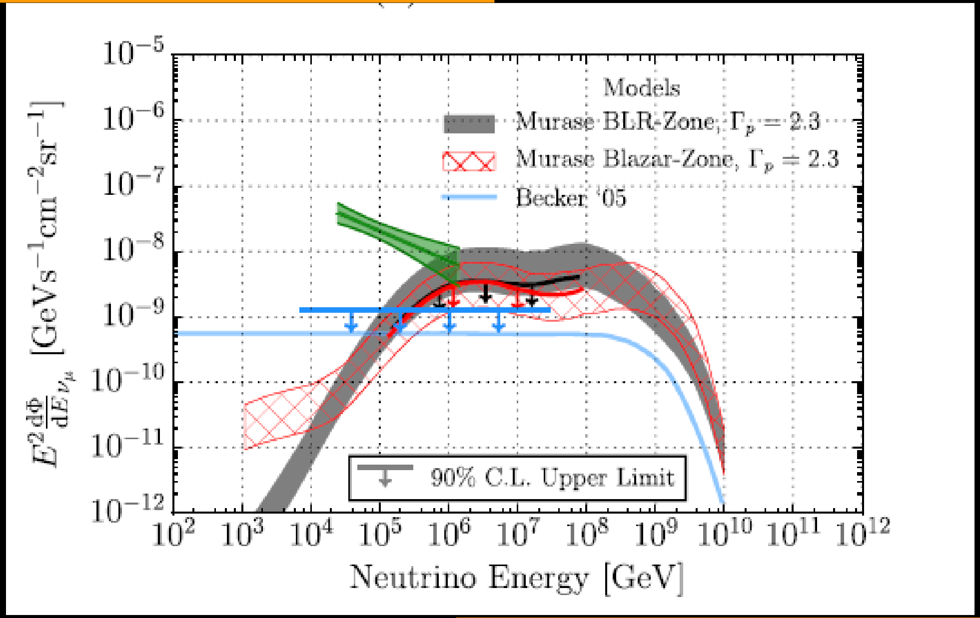


Search for a cumulative ν excess from 862 2LAC blazars

Model dependent constraints on Blazars

TeV PeV EeV

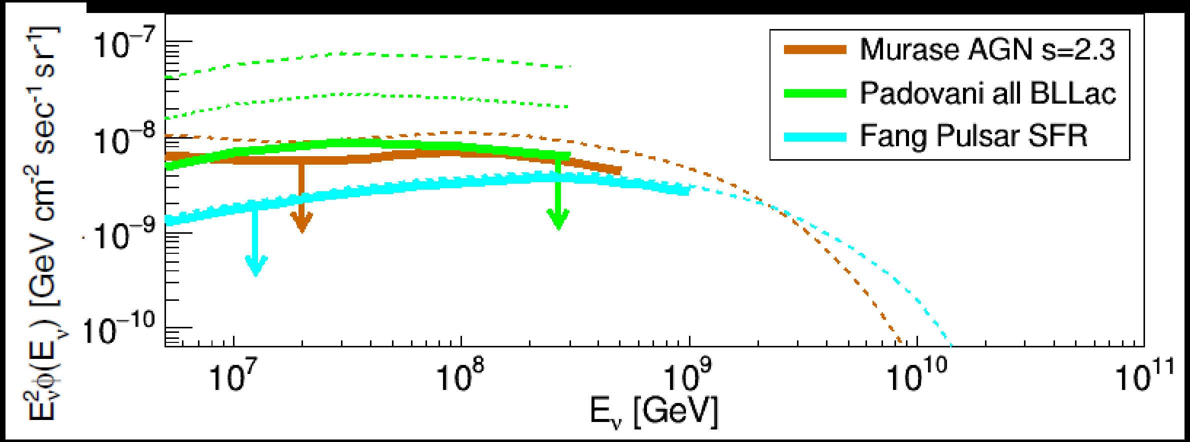
IceCube Collaboration
ApJ 835 no.1 45 (2017)



ν_μ only

TeV PeV EeV

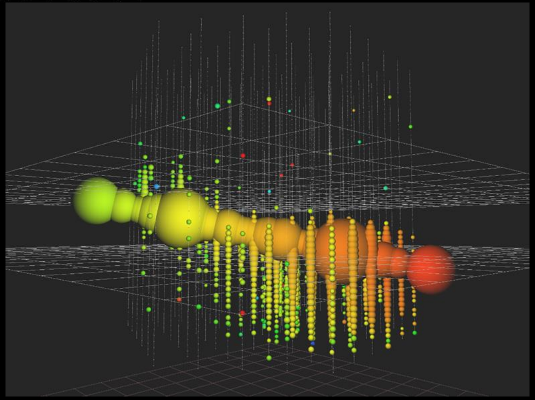
IceCube Collaboration
PRL 117 241101 (2016)



all flavor sum

Two PeV events found in the 9yr data sample

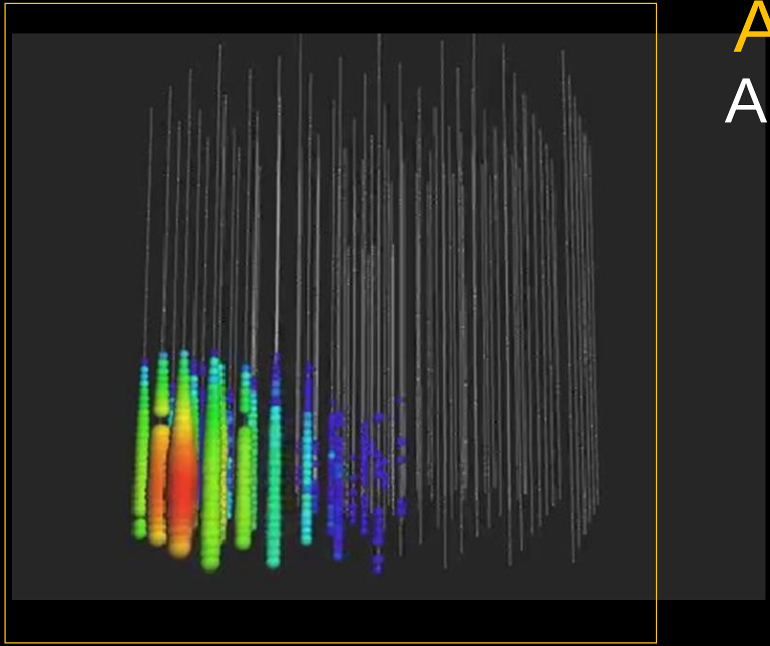
April 2008 – May 2017



A track event in June 2014 Deposited energy 2.6 PeV

The event found in the previous EHE neutrino search

Of the two background events published in PRL 117 241101, one was discovered to be a detector artifact and has been removed



A new event in December 2016

An uncontained shower event

Preliminary deposited energy 6 PeV

Uncontained nature of this event indicates large uncertainty on energy estimate

- Investigations ongoing to see if a prompt atmospheric muon could be responsible for this event

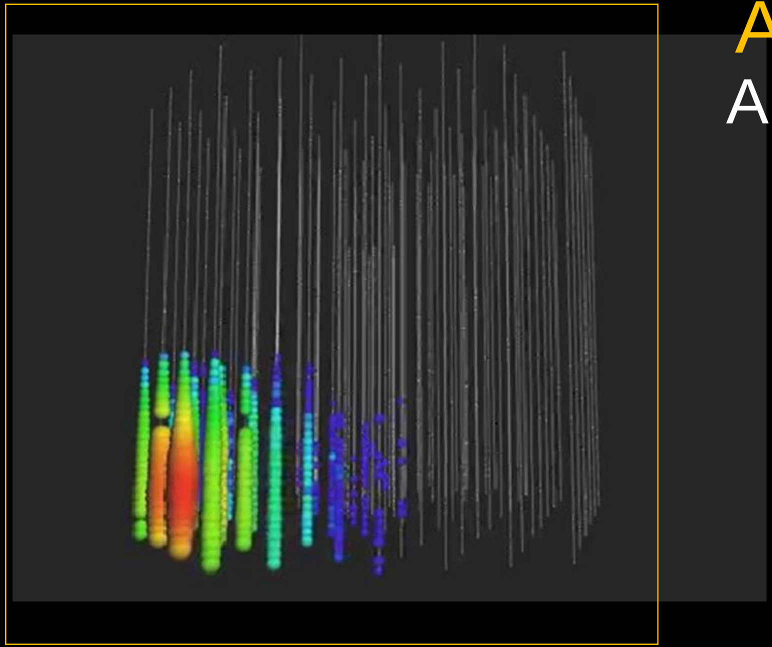
TeV PeV EeV

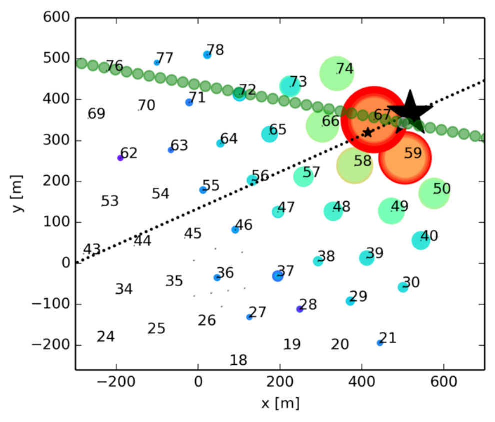
UHE (PeV-EeV)

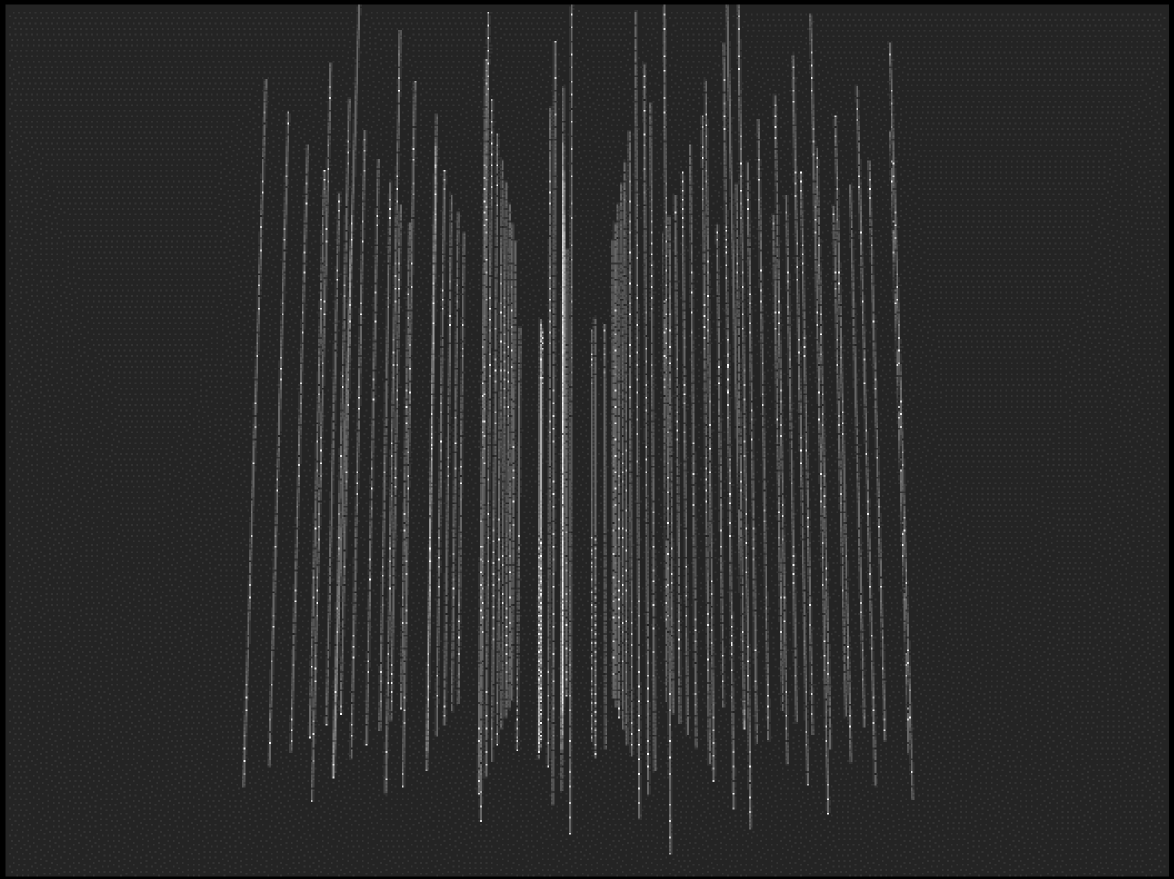
A new event in December 2016

An uncontained shower event

Preliminary deposited energy 6 PeV







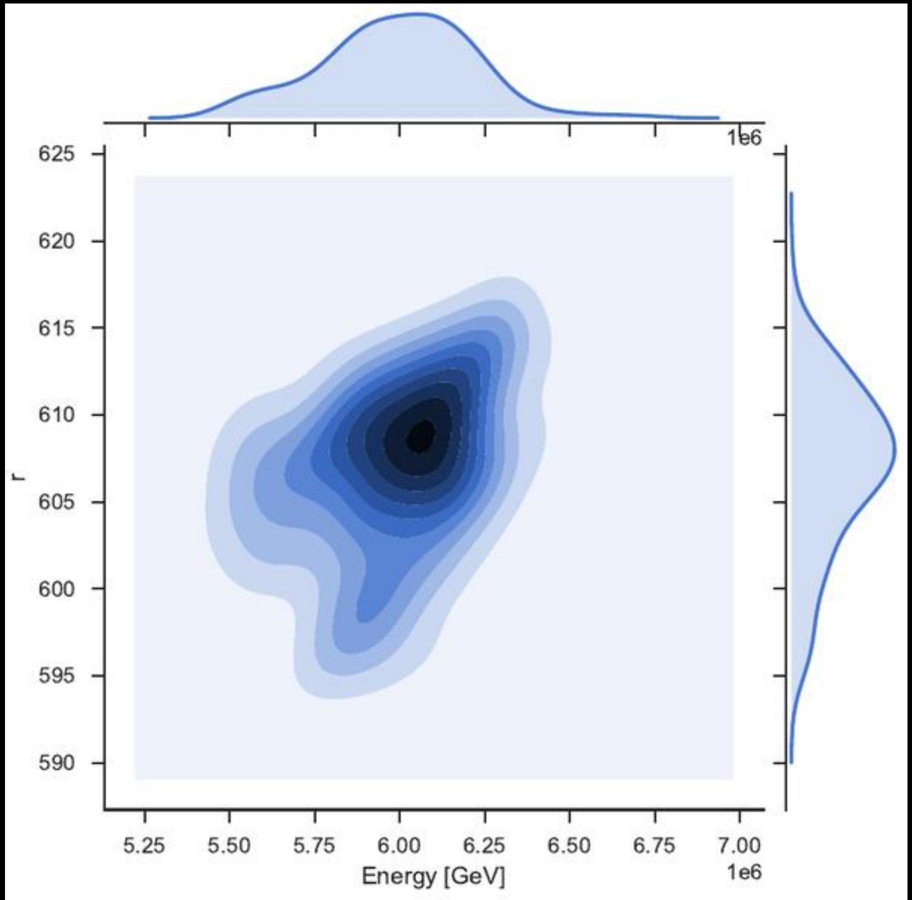
A new event in December 2016

An uncontained shower event

Preliminary deposited energy 6 PeV

Event "Hydrangea"

Energy Reconstruction



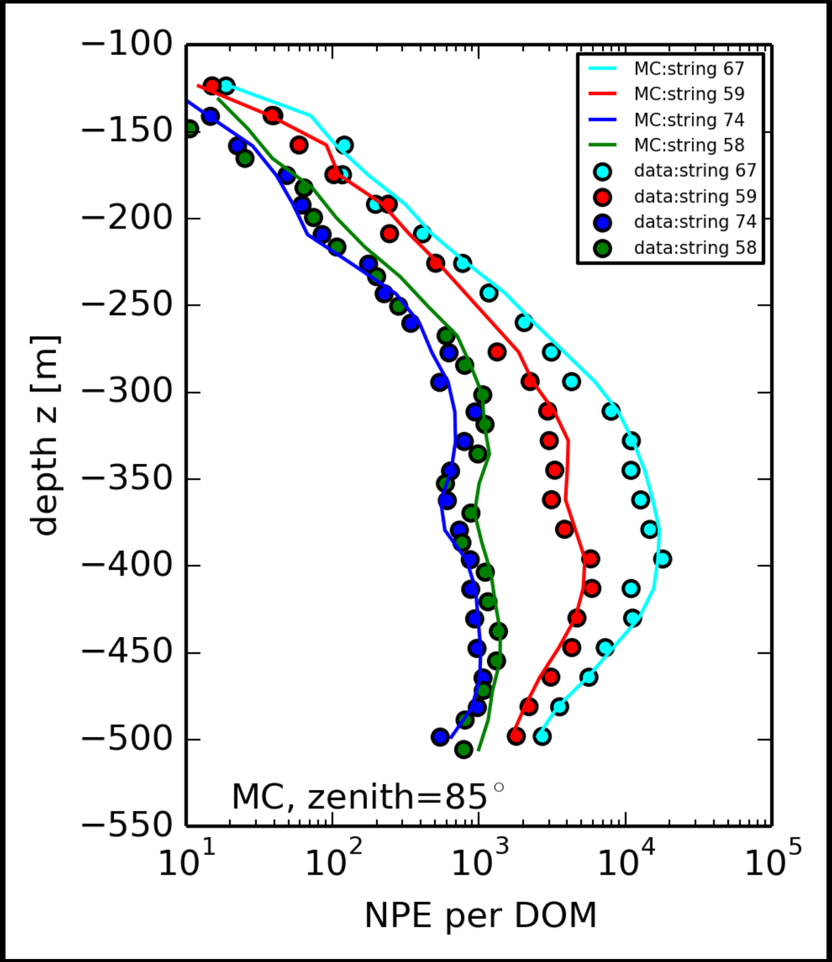
A new event in December 2016

An uncontained shower event

Preliminary deposited energy 6 PeV

Event "Hydrangea"

Cherenkov photon distribution

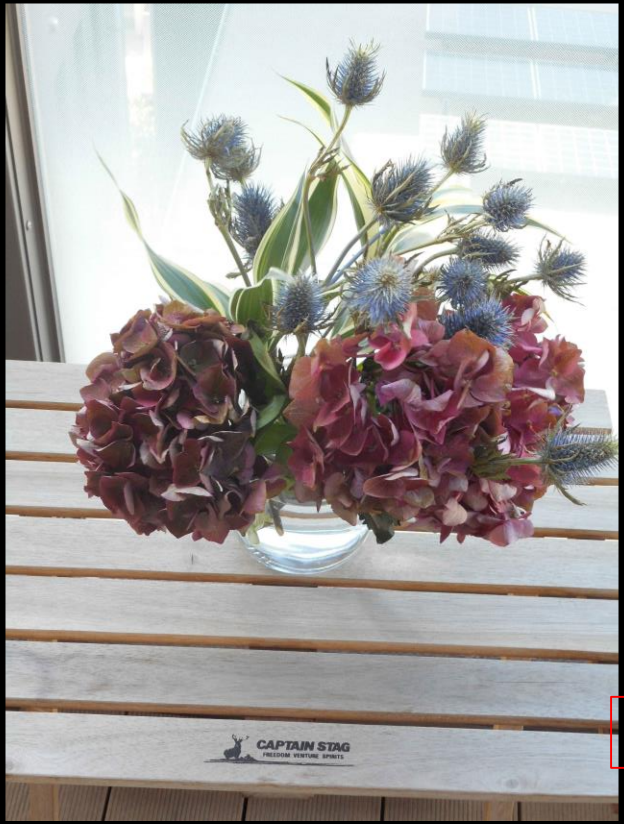


A new event in December 2016

An uncontained shower event

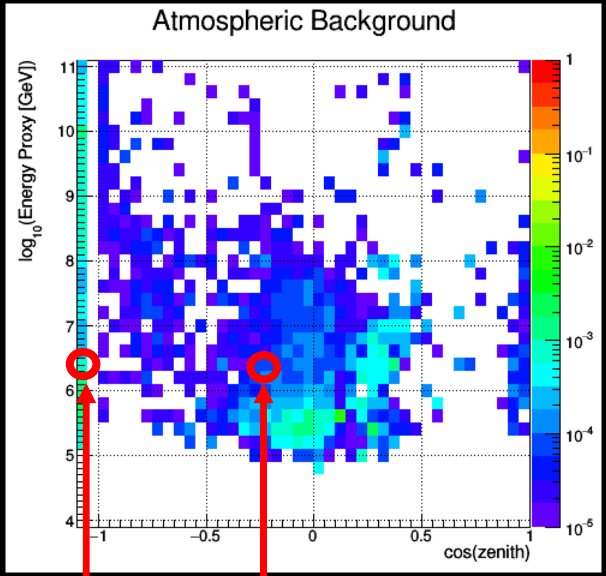
Preliminary deposited energy 6 PeV

Event "Hydrangea"

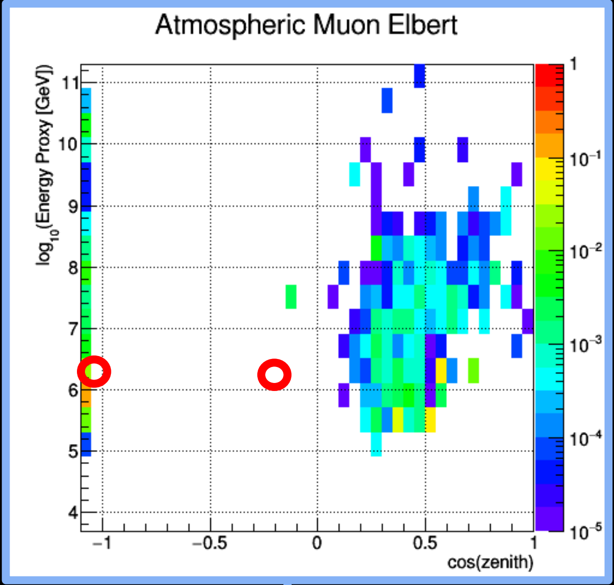


Energy – Zenith PDF

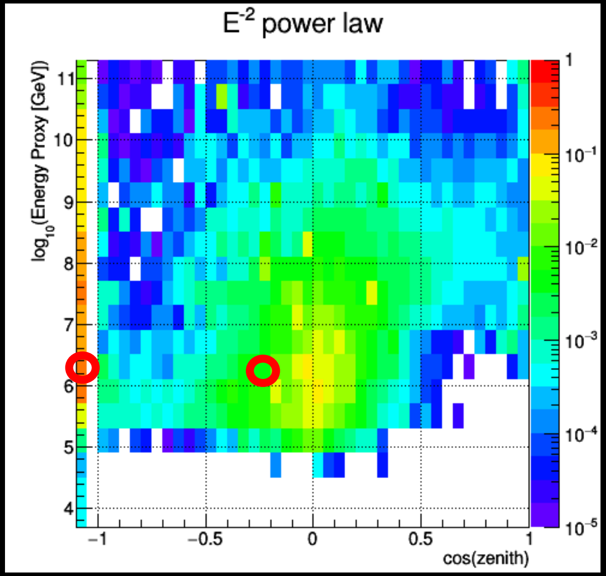
Conventional BG



Uncertain prompt μ



Astrophysical ν



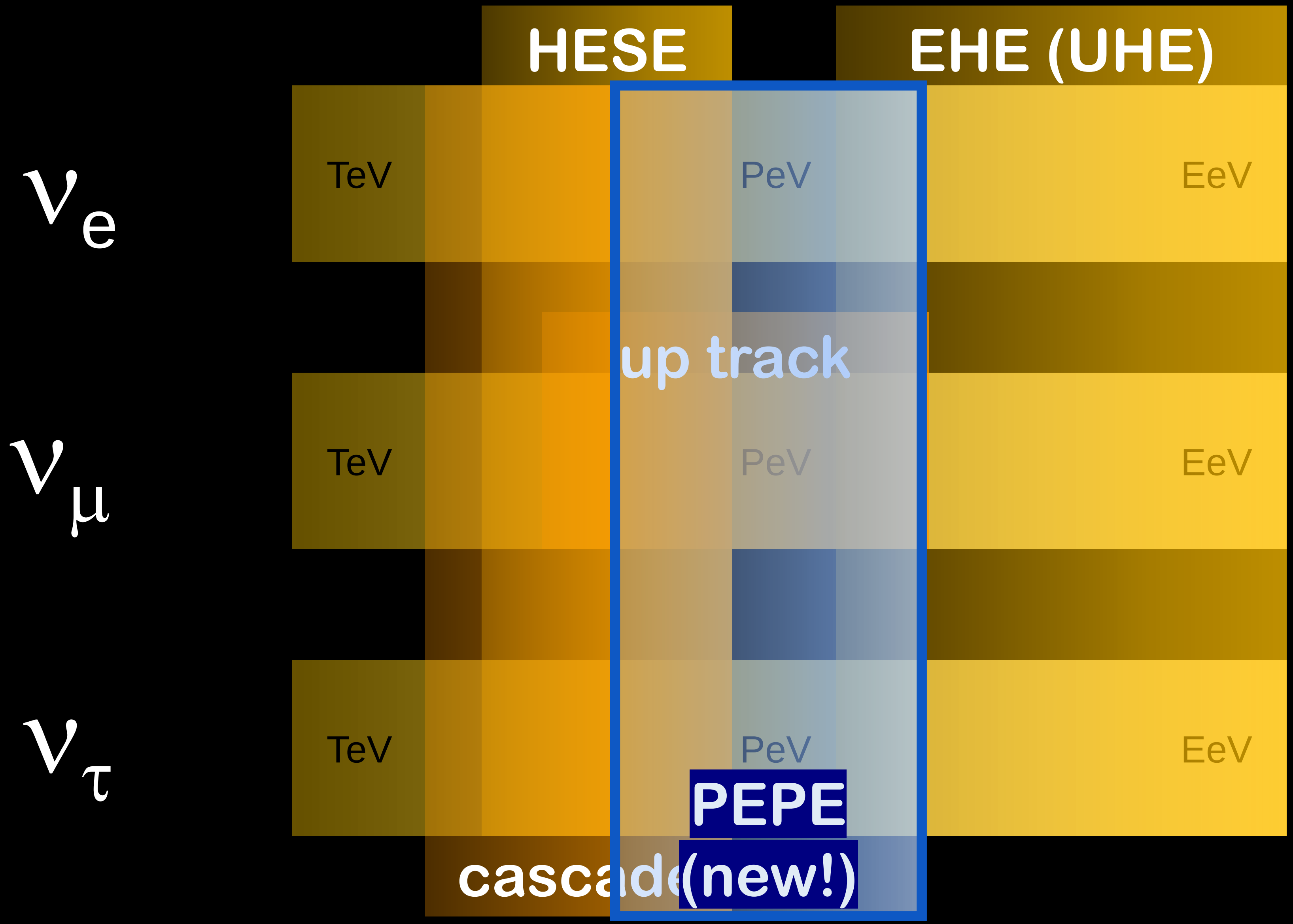
Hydrangea

The another detected track event

unlikely: the best fit=0

More work on progress

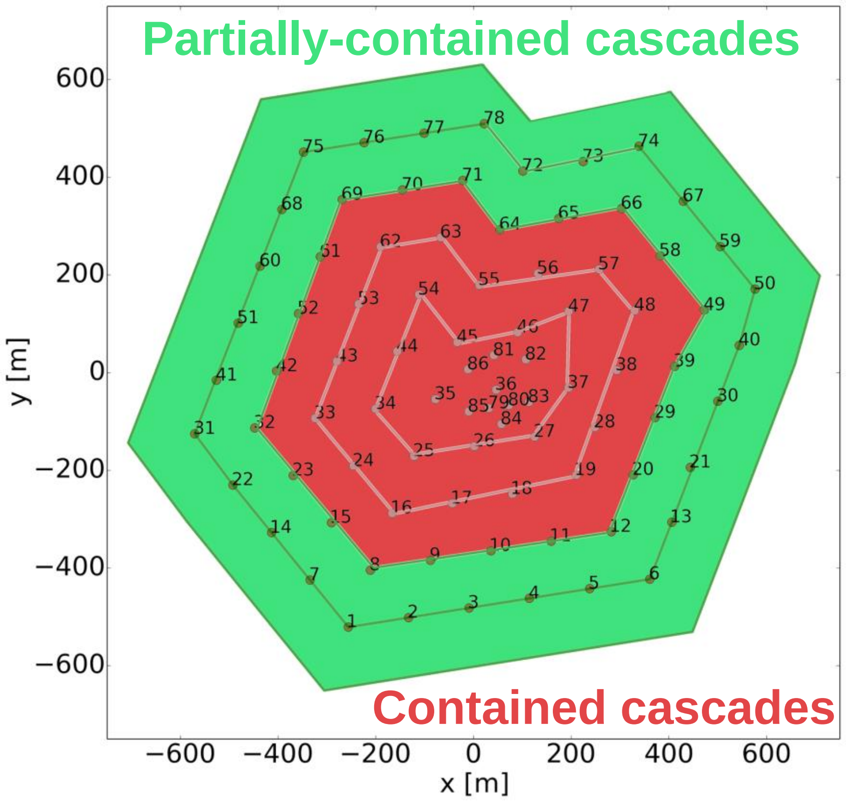
Investigate **PeV**-energy ν sky

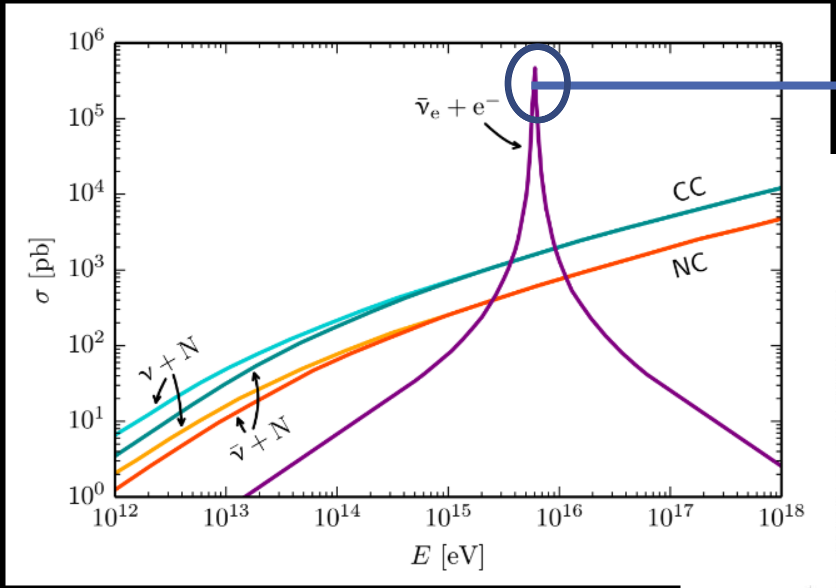


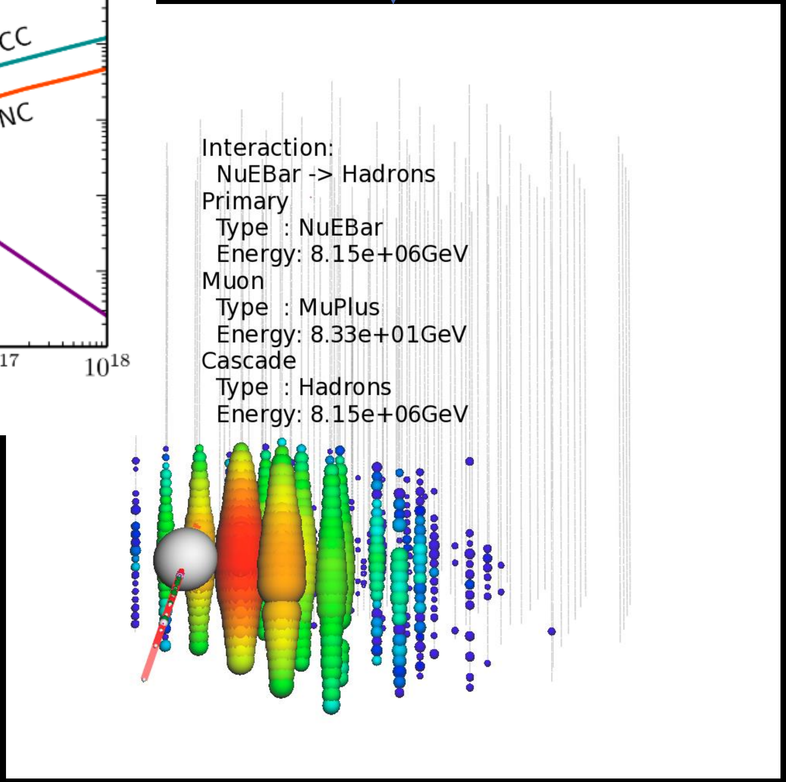
TeV PeV EeV

Multi-flavor PeV search

PEPE = PeV Energy Partially-contained Events





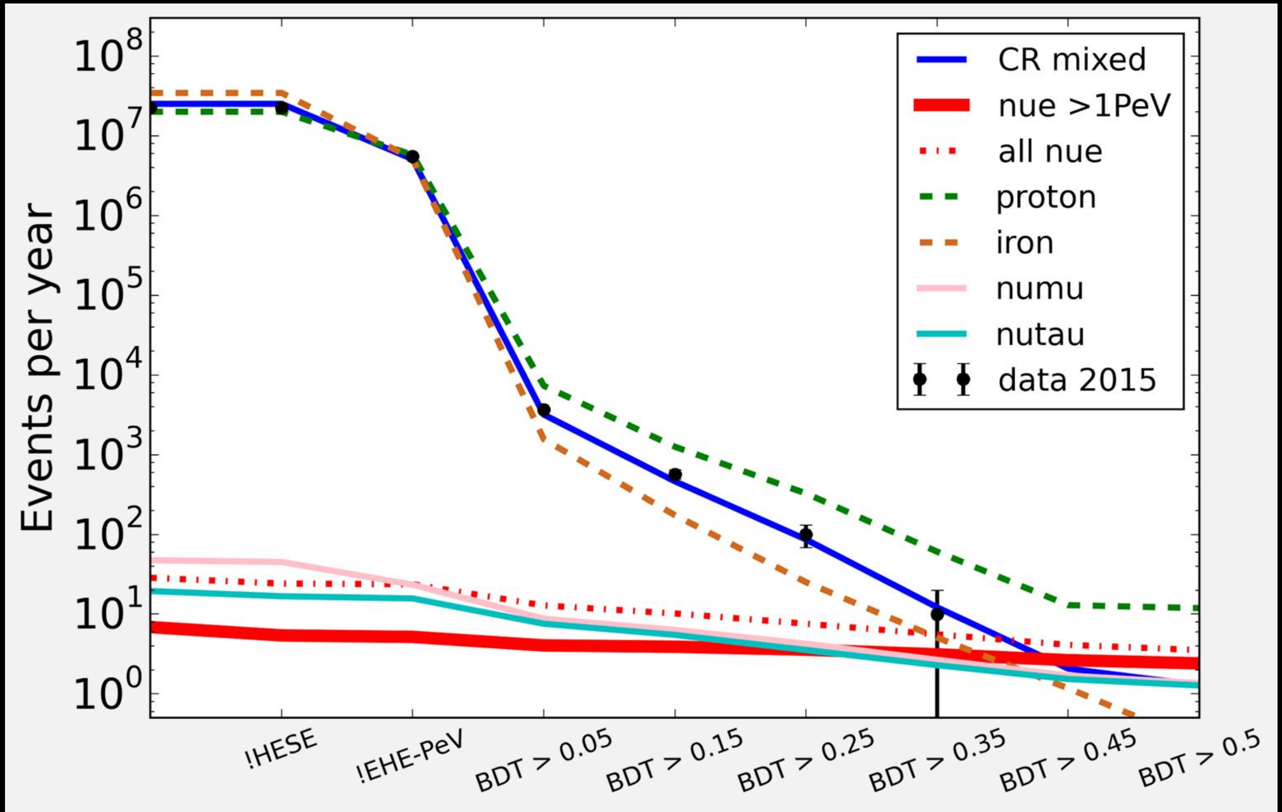


TeV PeV EeV

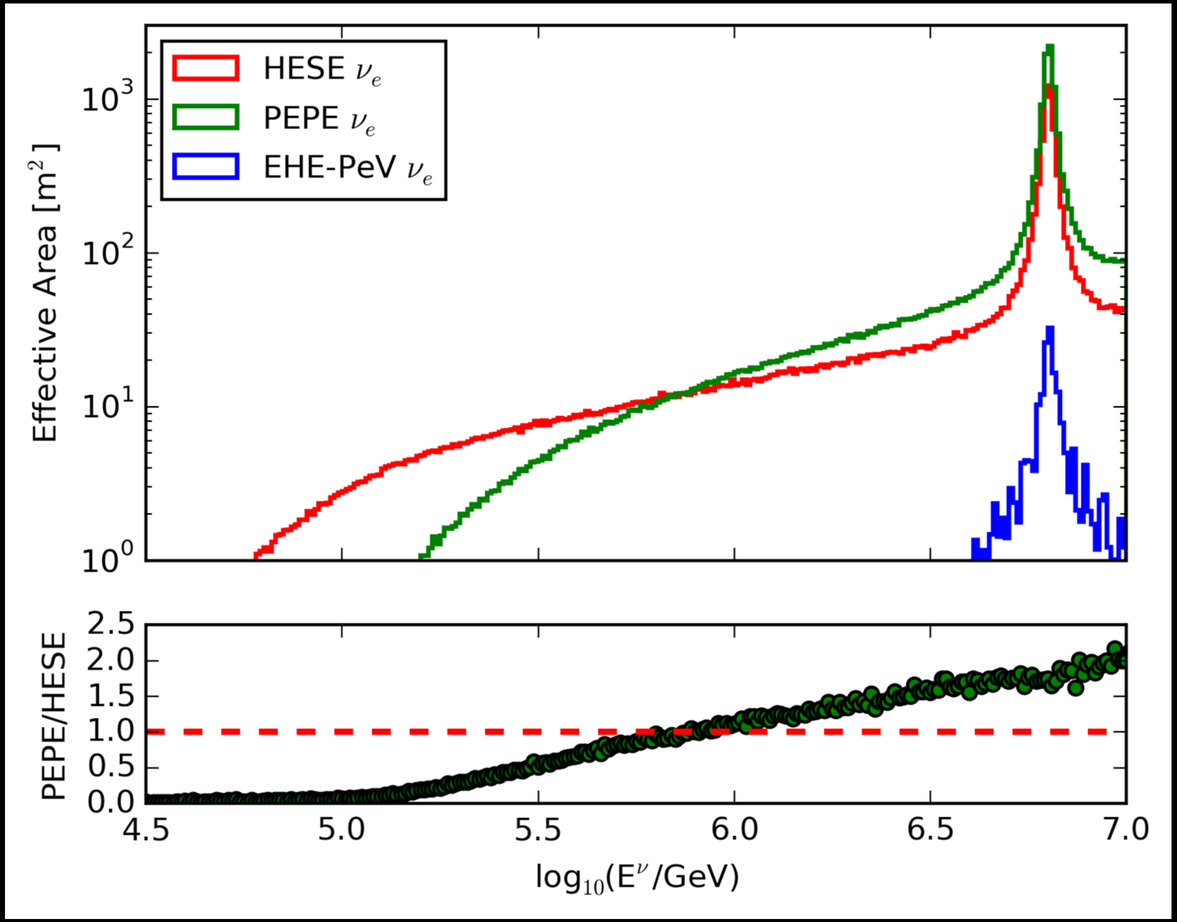
Multi-flavor PeV search

PEPE = PeV Energy Partially-contained Events

Background rejection after each cut



Effective Area for ν_e : a factor of 2 higher than HESE



TeV PeV EeV

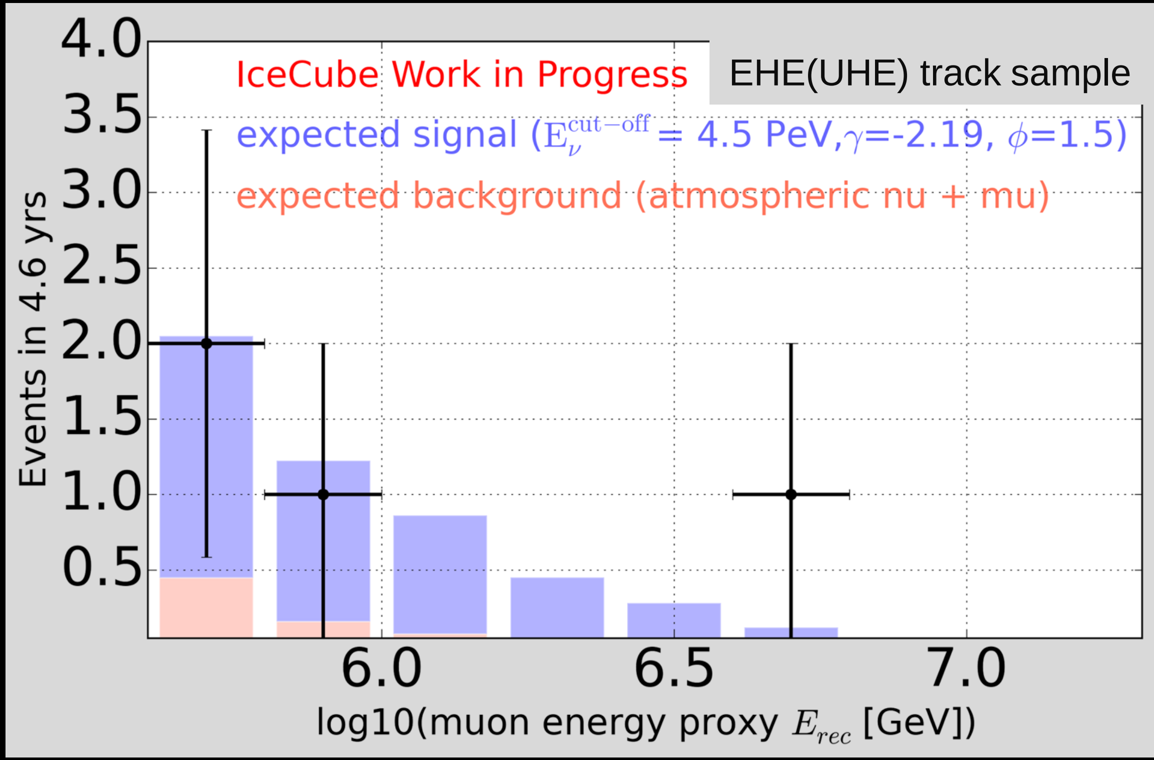
Multi-flavor PeV search

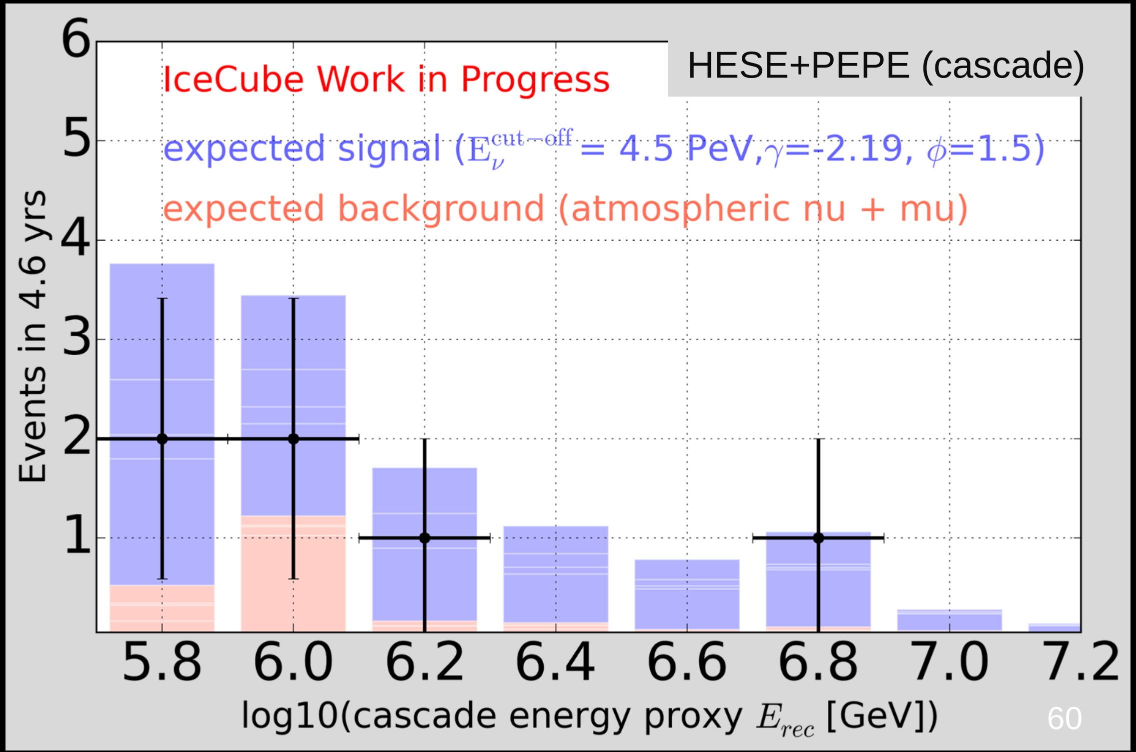
PEPE = PeV Energy Partially-contained Events

With 4.6 year of IceCube Data (2012-2015)

10 Events found in E>400 TeV. One event found in E> PeV (Hydrangea)

Global Event distribution in E > 500 TeV $\Phi = 10^{-18} \times 1.5 \times \left(\frac{E}{100\mathrm{TeV}}\right)^{-2.19} e^{-E/4.5\mathrm{PeV}} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$





TeV PeV EeV

Multi-flavor PeV search

PEPE = PeV Energy Partially-contained Events

Preliminary conclusion at the moment

PeV ν exists, but less luminous

(Tentative) Summary

TeV PeV EeV

$E^{-2.3\sim2.8}$

TeV PeV EeV

$E^{-2.1\sim2.3}$

Significance of the statistical tension

~ 2 σ

suggestive but not conclusive

TeV PeV EeV

only 4 events

Less luminous

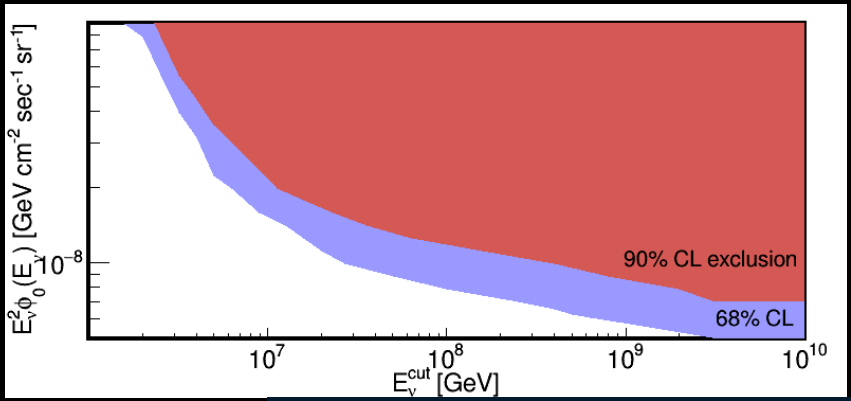
TeV PeV EeV

Upper limit only

Suggesting weakly evolved UHECR sources or mix composition

constraints on the power law flux (intensity Vs cutoff E)

all flavor ν intensity



Phys.Rev.Lett.**117** 241101(2016)

Other remark

No clearly identified ν_τ events yet with the current IceCube discrimination power

still consistent with 1:1:1 flavor ratio at ~90% CL