ν

NEUTRINO ASTRONOMY

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2016 Aspen Winter Conference on Particle Physics

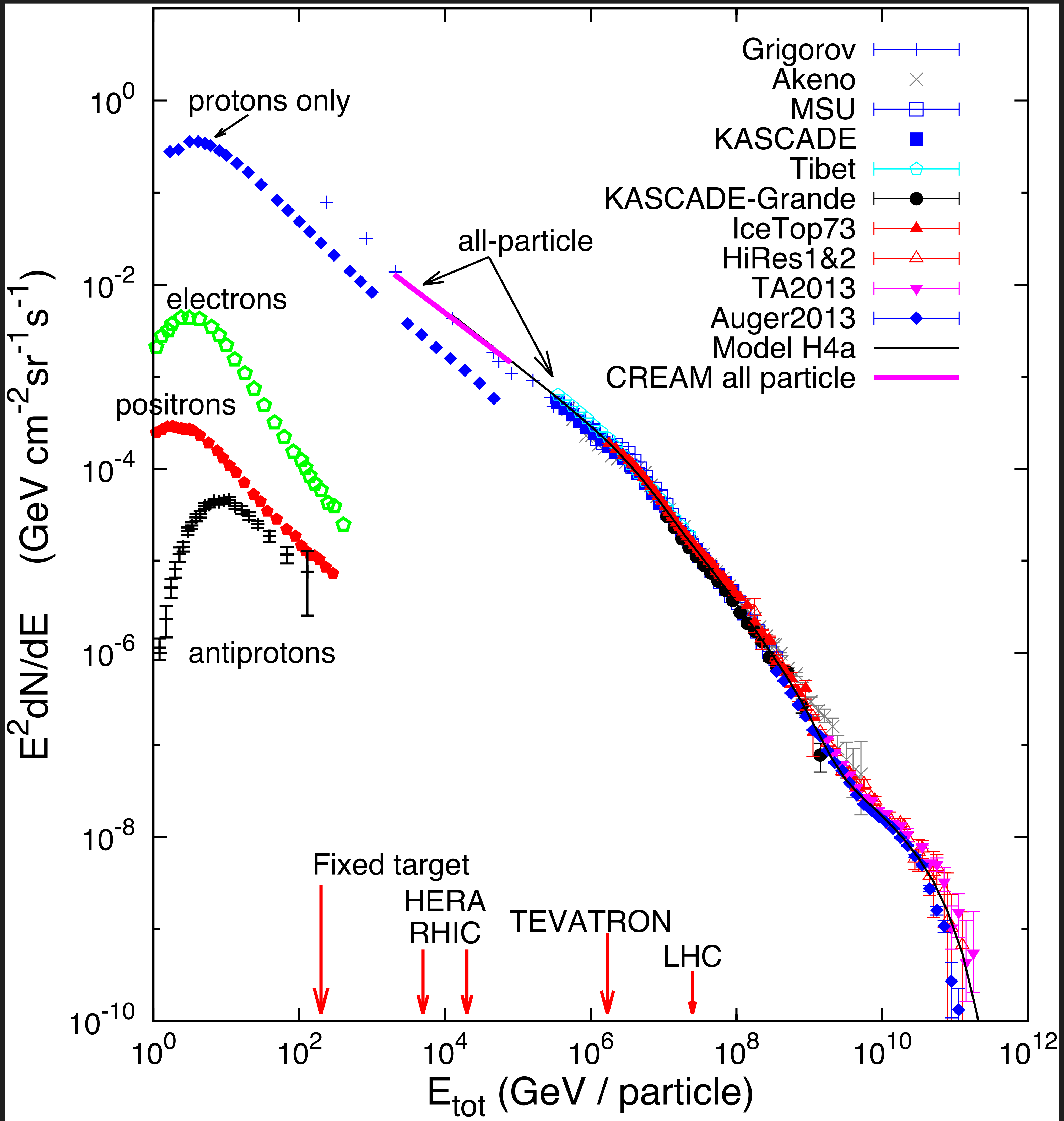
UNIVERSITY OF ALBERTA

COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays

COSMIC RAYS

where (and how) are they accelerated?

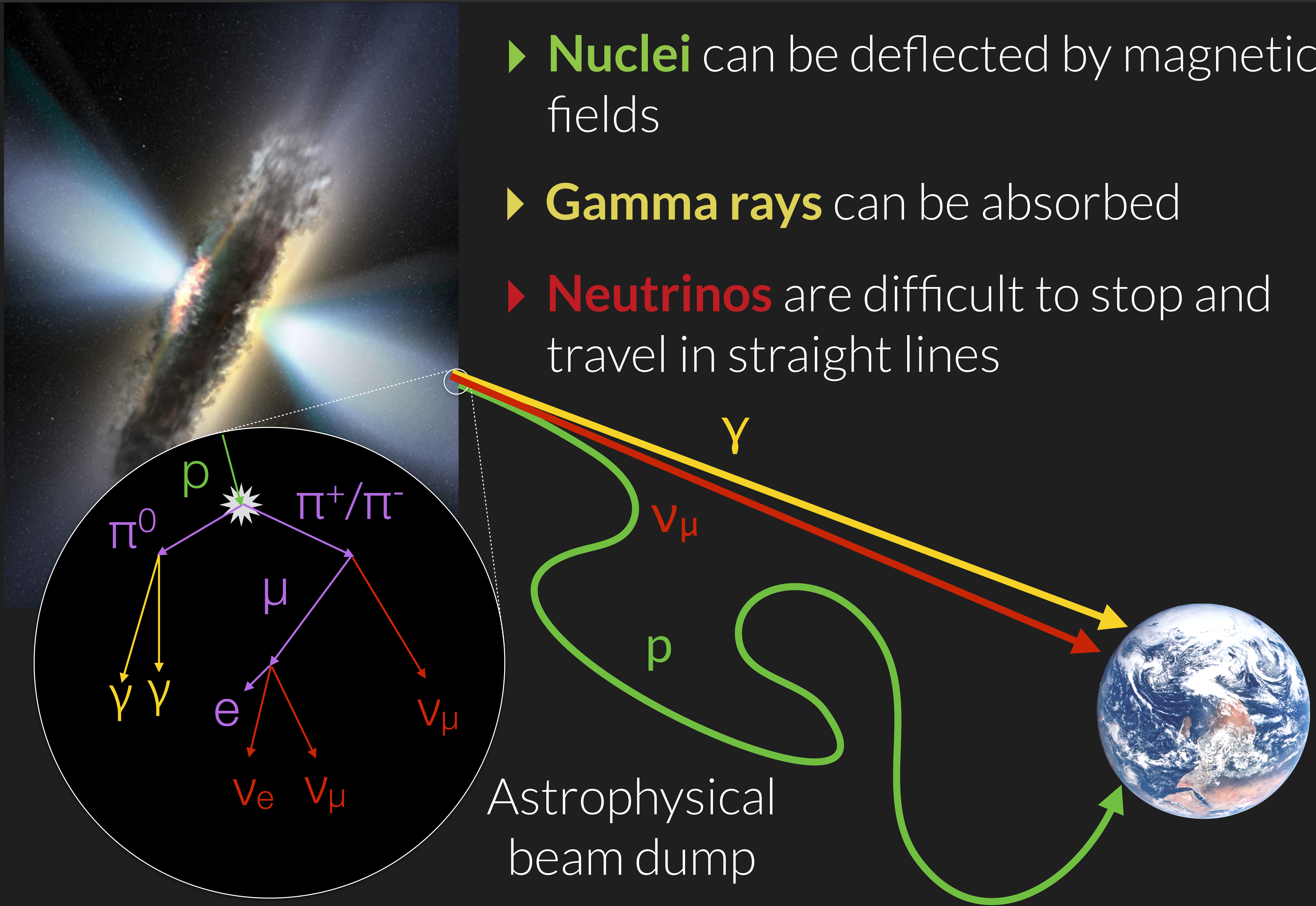


We know their energy spectrum over 11 orders of magnitude

Their sources (especially at the highest energies) are still mostly unknown

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS

- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines



Astrophysical beam dump

TEV NEUTRINOS

Observing astrophysical neutrinos allows conclusions about the acceleration mechanism of Cosmic Rays

$$p + \gamma \;\text{(or p, …)} \rightarrow \pi^0 + p$$
$$\hookrightarrow \gamma + \gamma + p$$
$$\rightarrow \pi^+ + n$$
$$\hookrightarrow \mu^+ + \nu_\mu + n$$
$$\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n$$

(can also be from leptonic processes…)

TeV gamma rays

Cosmic rays?

TeV neutrinos

NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components

ATMOSPHERIC NEUTRINOS (π/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

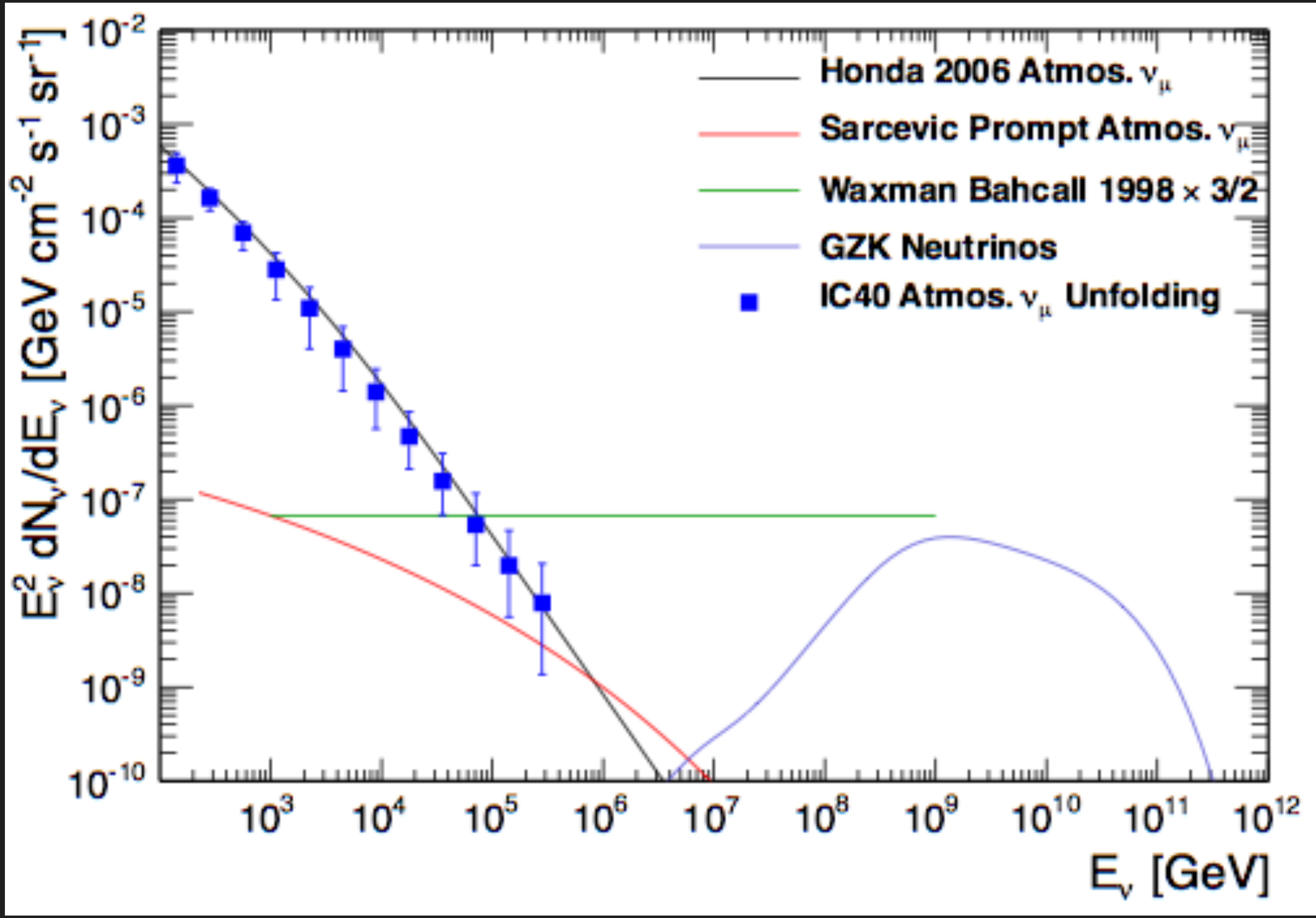
"prompt" ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

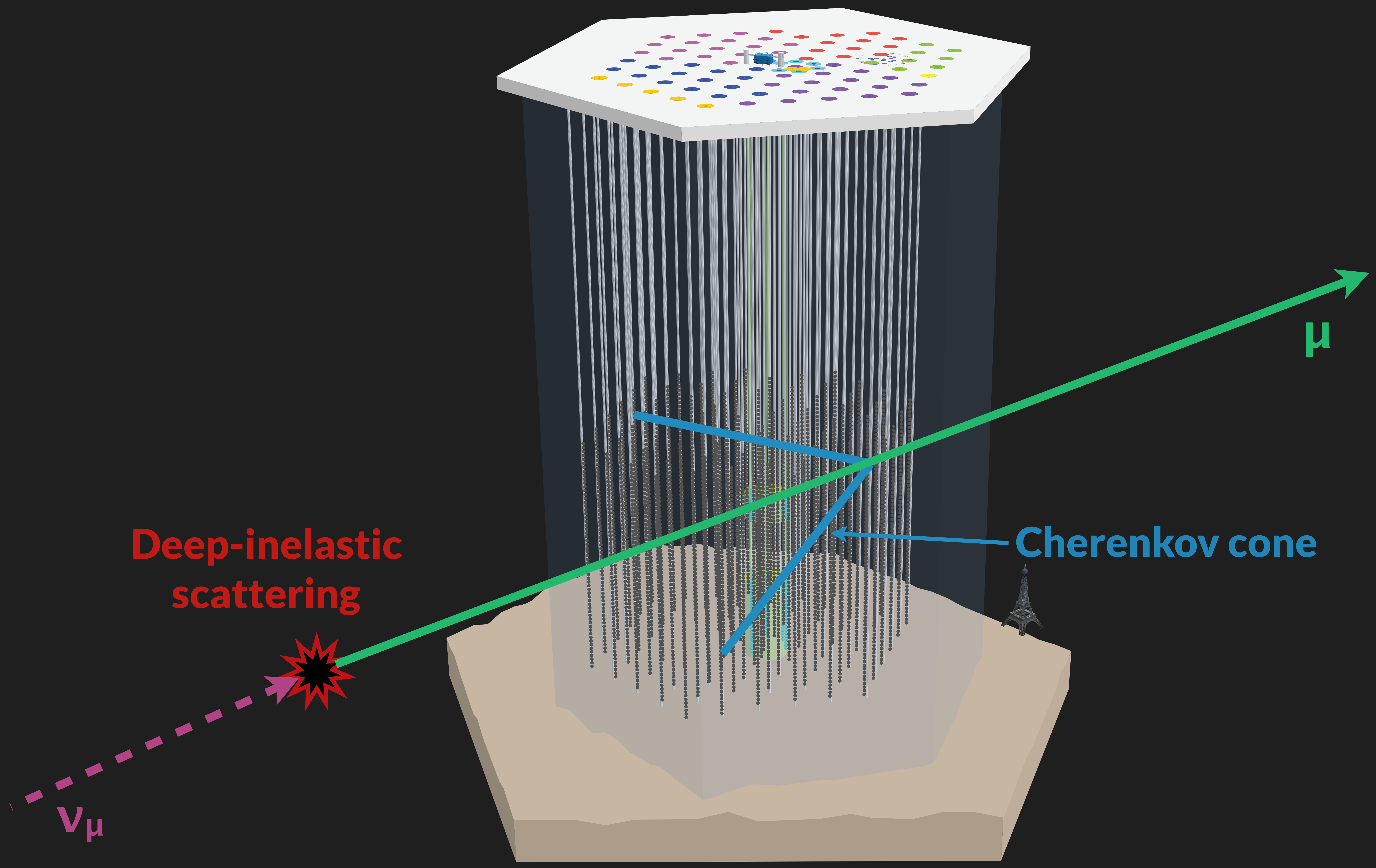
COSMOGENIC NEUTRINOS

$>10^6$ TeV



DETECTING NEUTRINOS

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



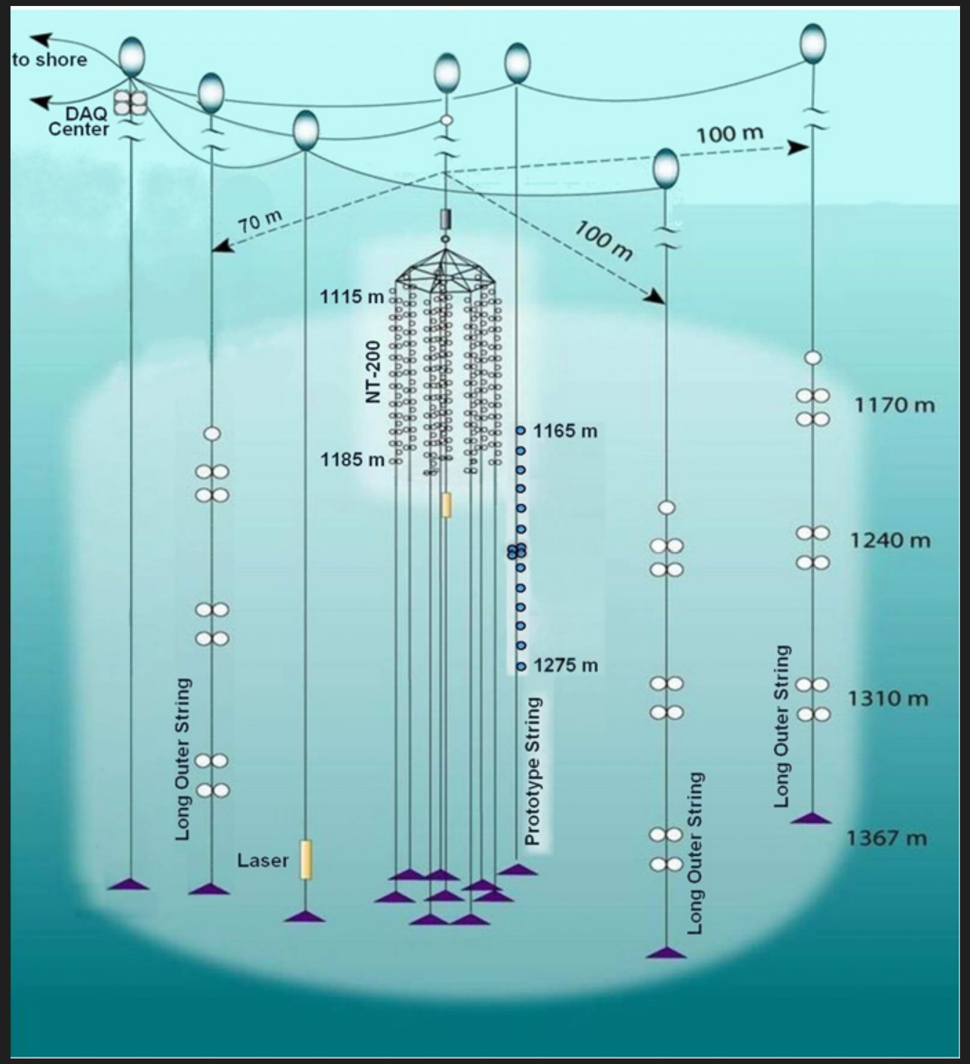
NEUTRINO TELESCOPE SITES

deep natural sites with water/ice (deep sea, lakes, glaciers)

THE WORLD'S NEUTRINO TELESCOPES

lakes, sea, glaciers

NT-200+

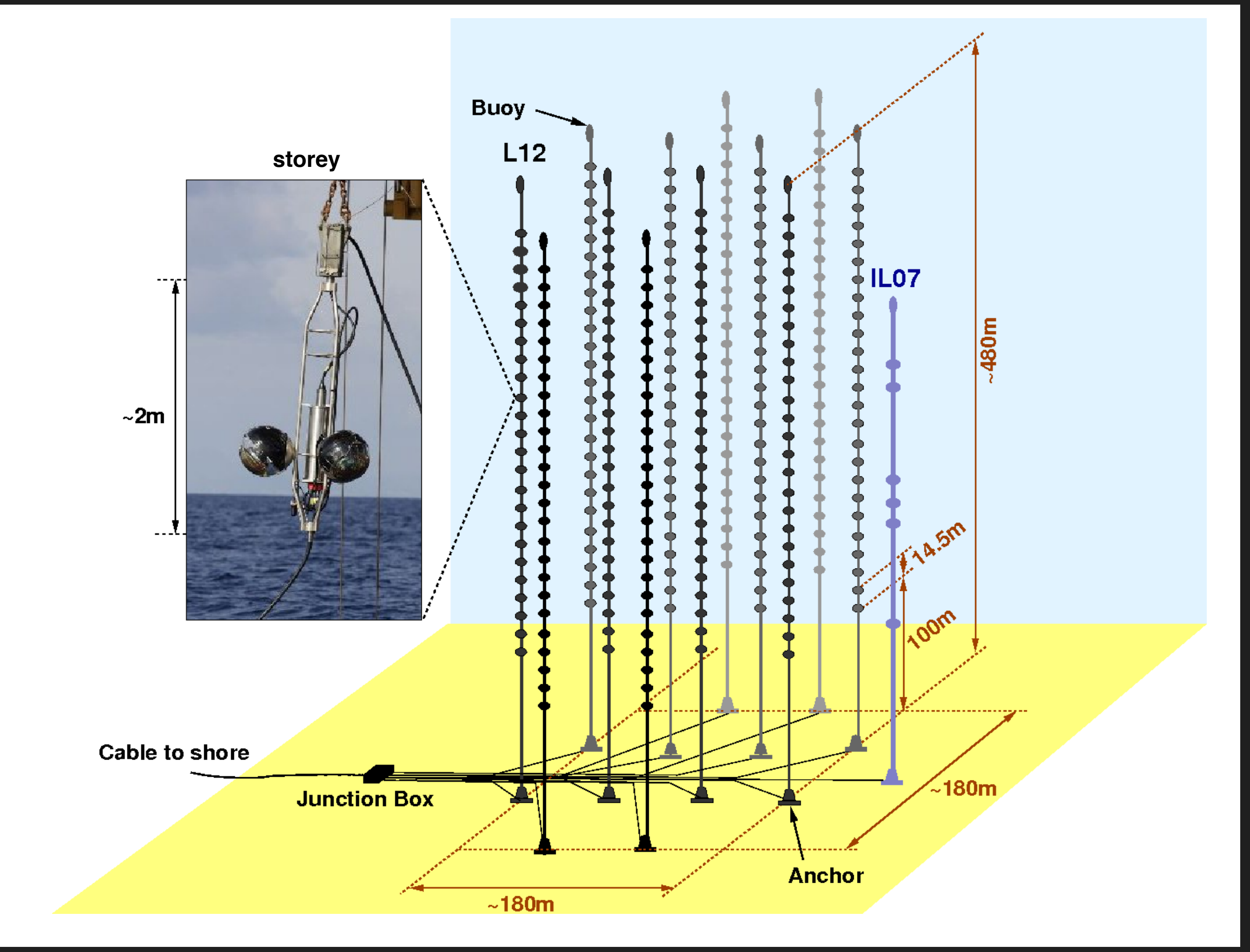


Lake Baikal

1/2000 km^3

228 PMTs

Antares

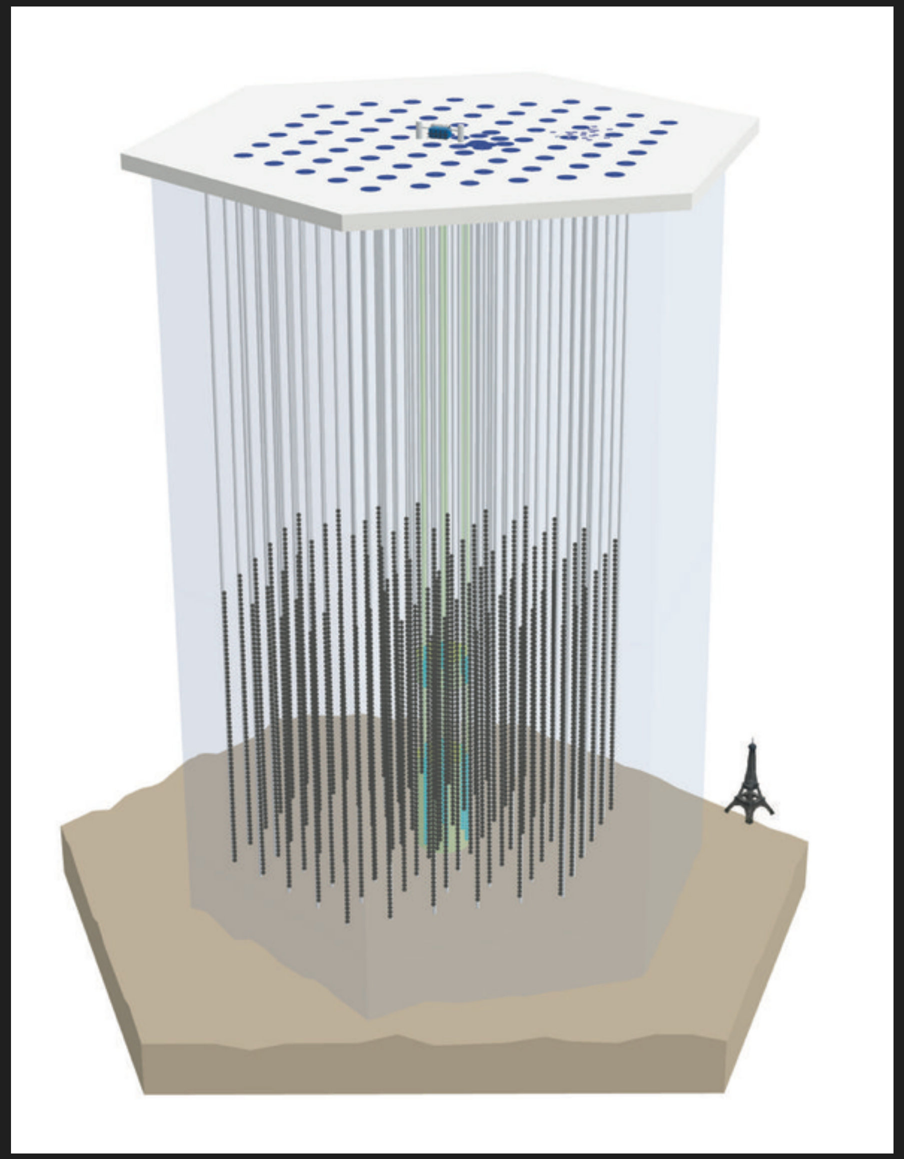


Mediterranean Sea

1/100 km^3

885 PMTs

IceCube



South Pole glacier

1 km^3

5160 PMTs

Larger, sparser → higher energies

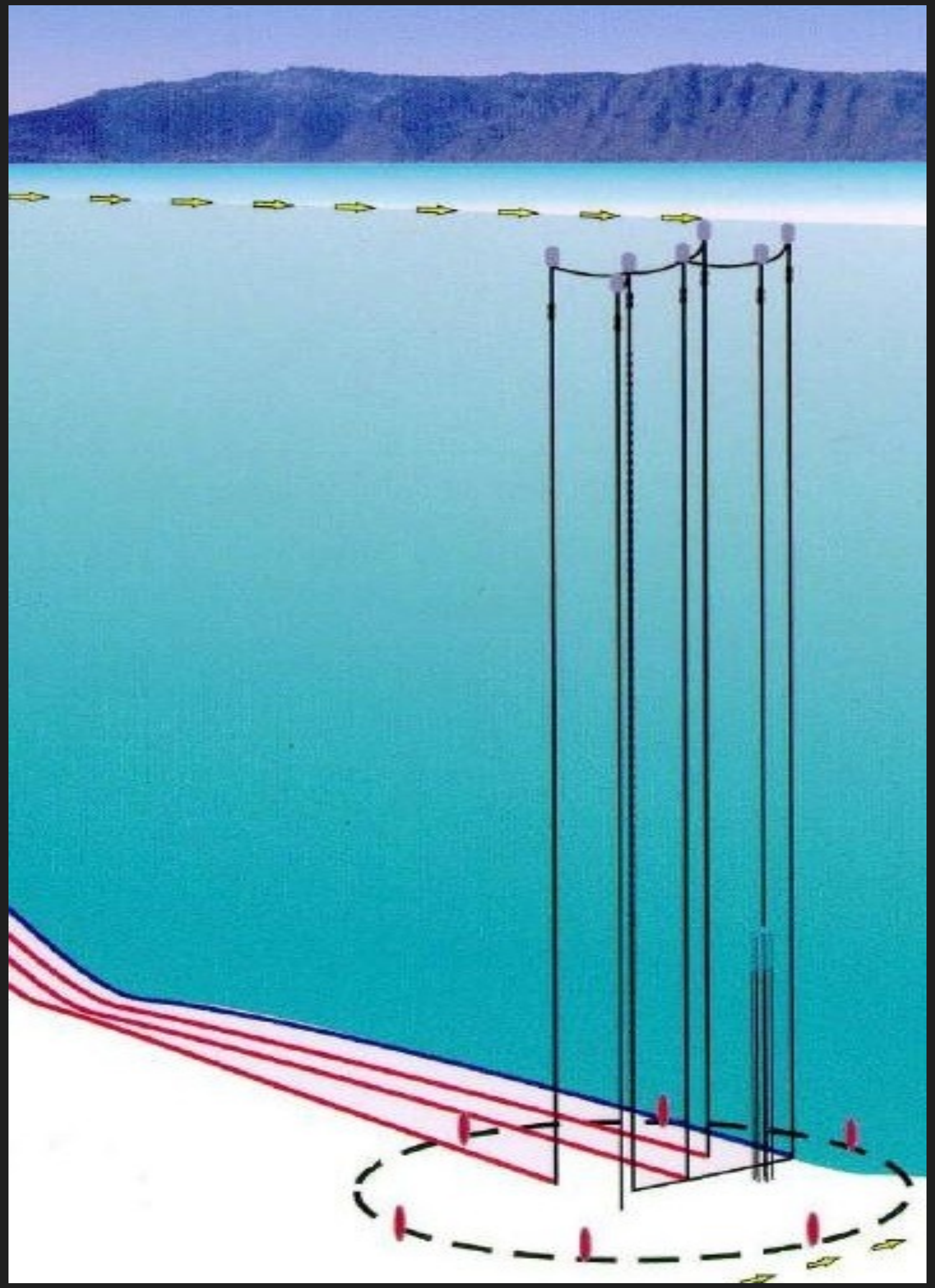

Lake Baikal

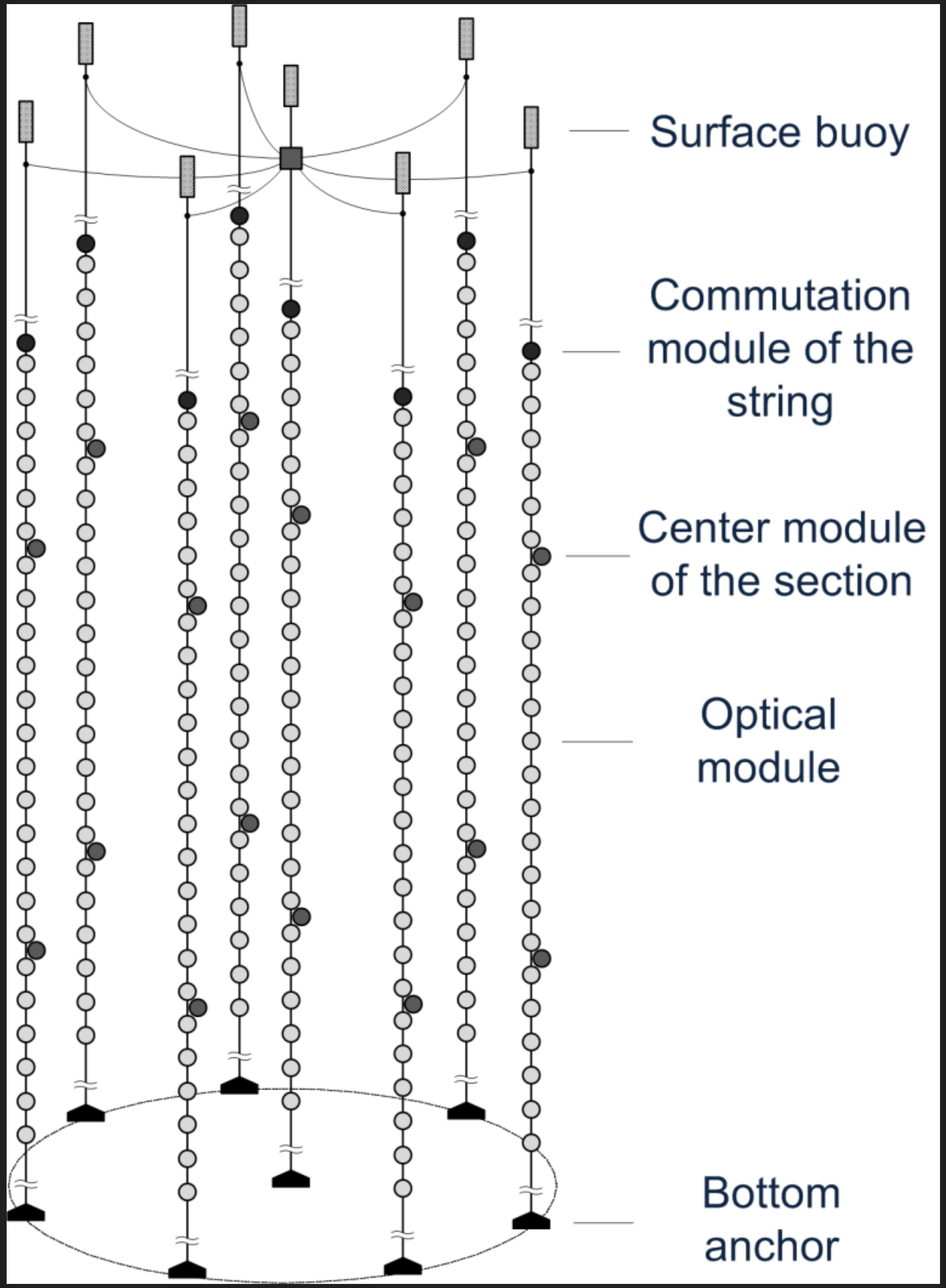
BAIKAL / BAIKAL-GVD

Neutrino telescope deployed in Lake Baikal

First cluster of the gigaton detector deployed in April 2015

Plan: 8-12 such arrays

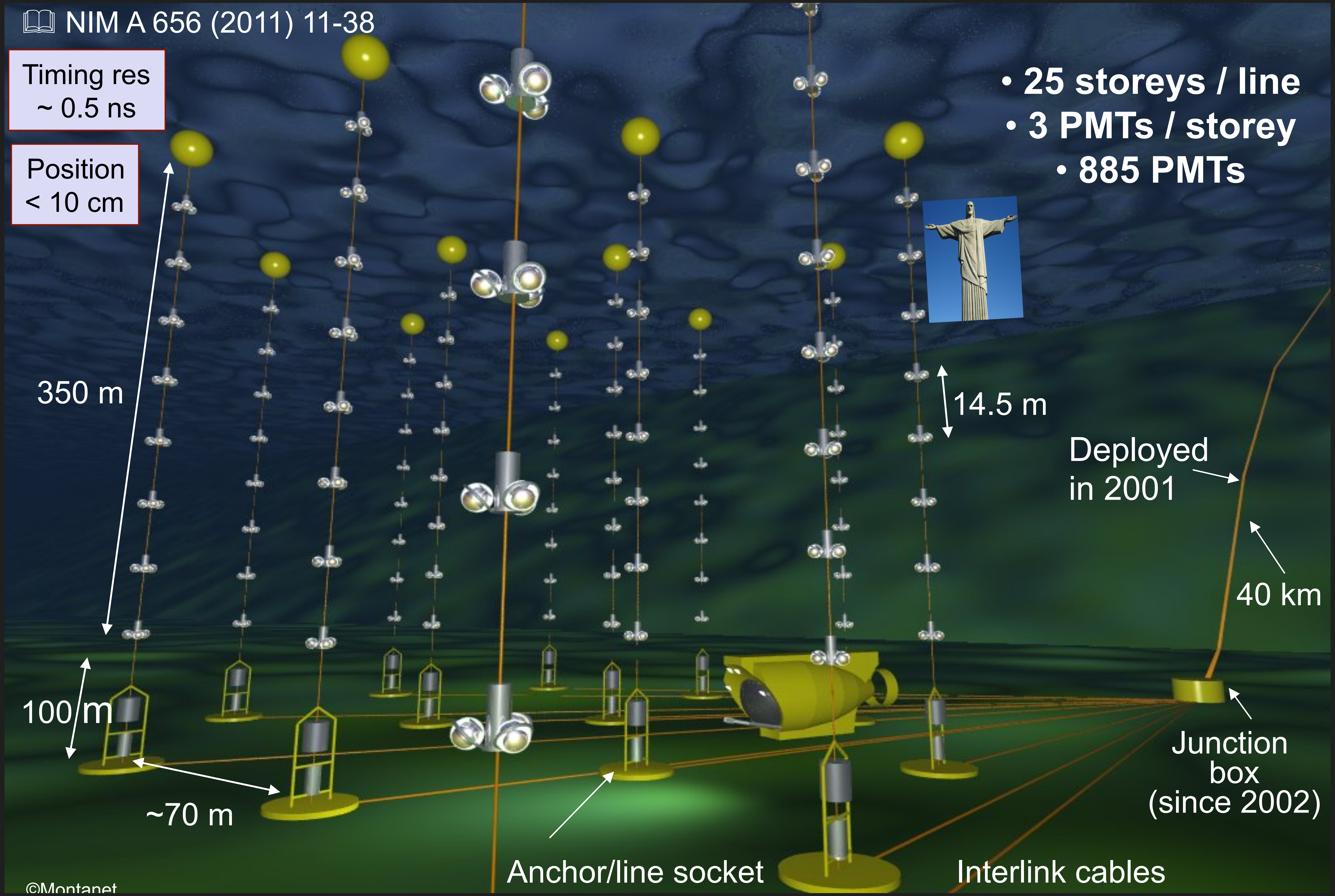


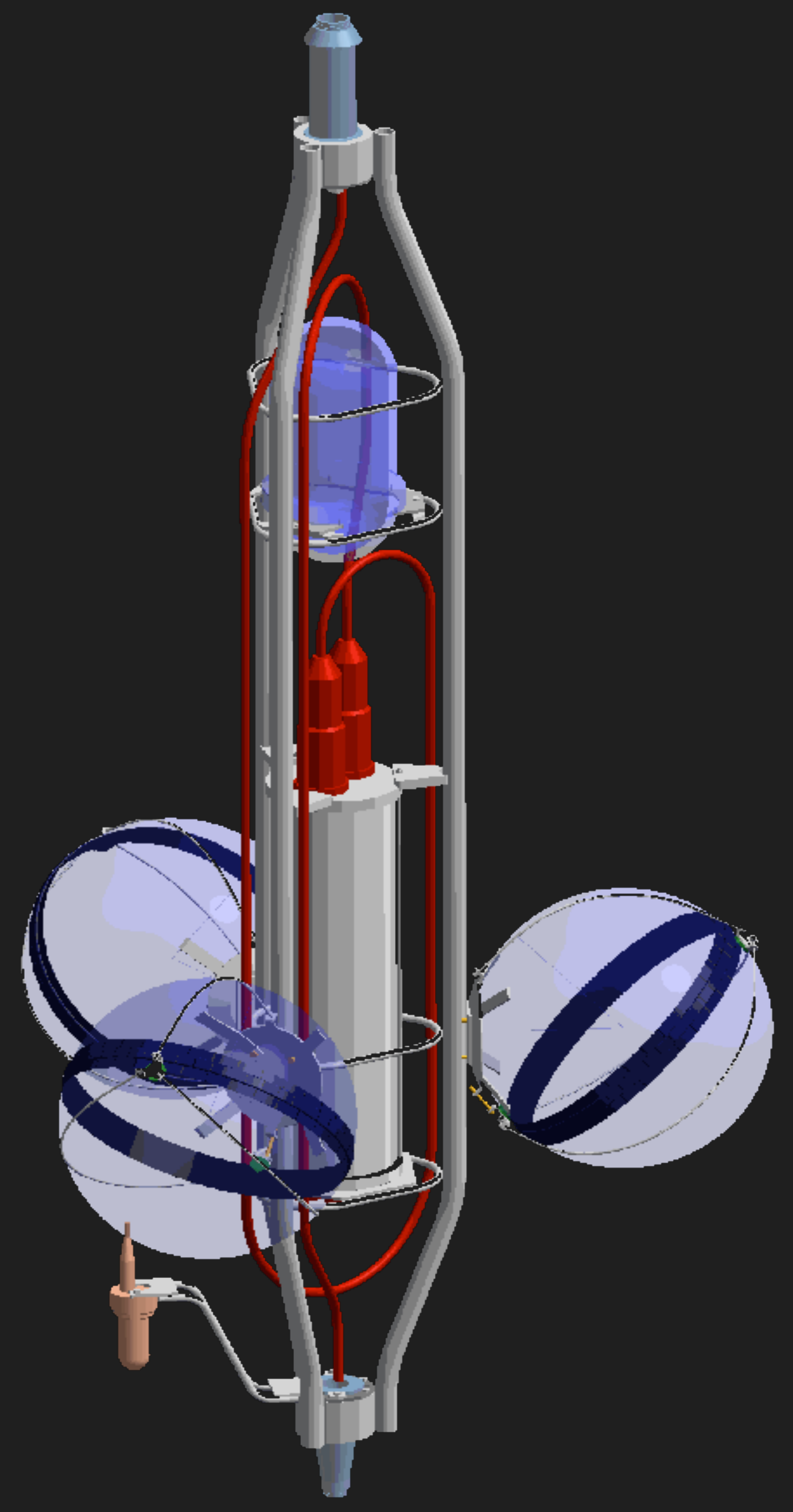


Mediterranean Sea

THE ANTARES NEUTRINO TELESCOPE

In the Mediterranean Sea near Toulon, France





"storey" with 3 OMs


South Pole Glacier
IceCube's footprint
South Pole station
IceCube Lab (ICL)
Drill camp
Skiway

THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

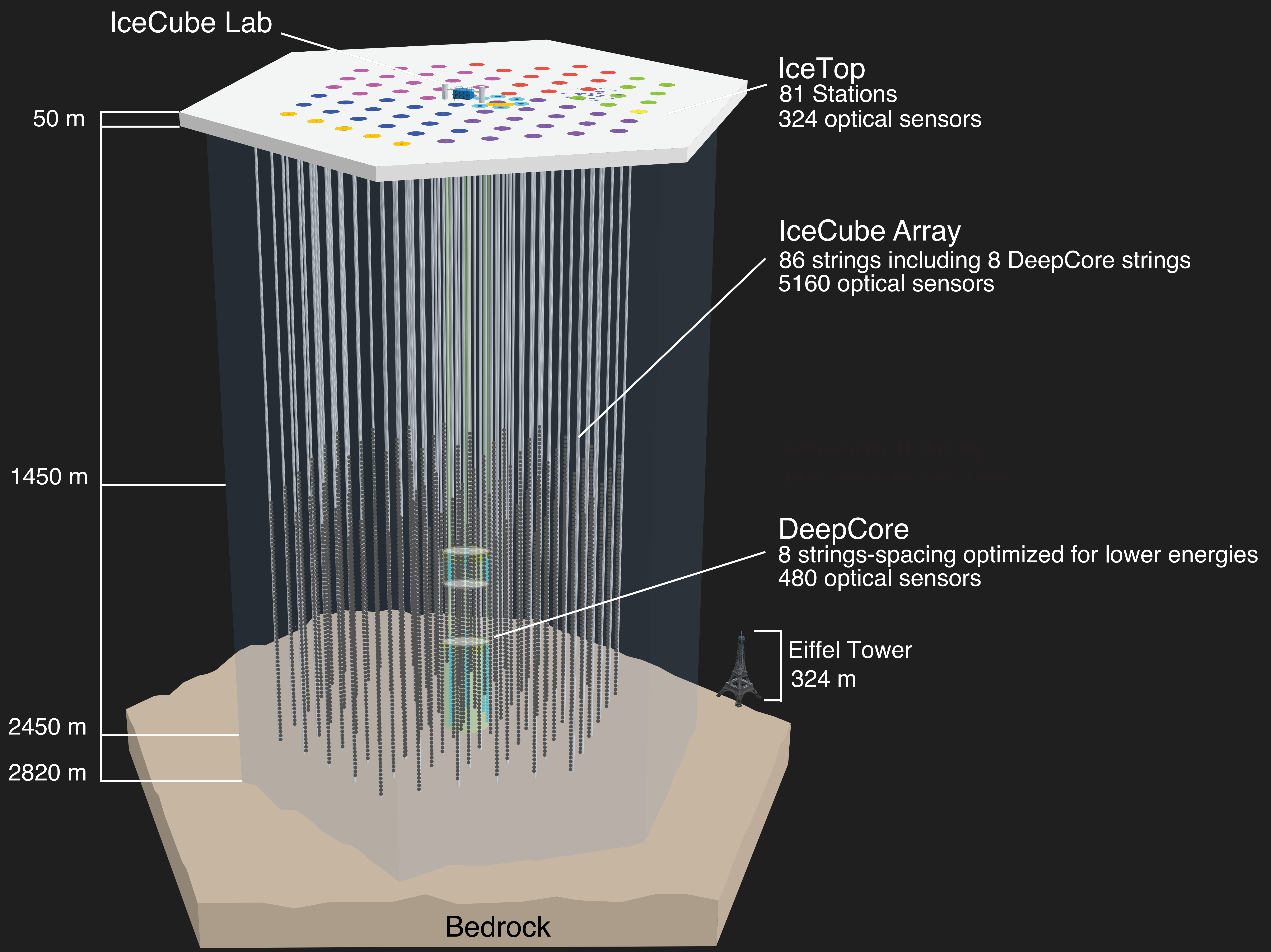
1 km^3 volume

86 strings

17 m vertical spacing

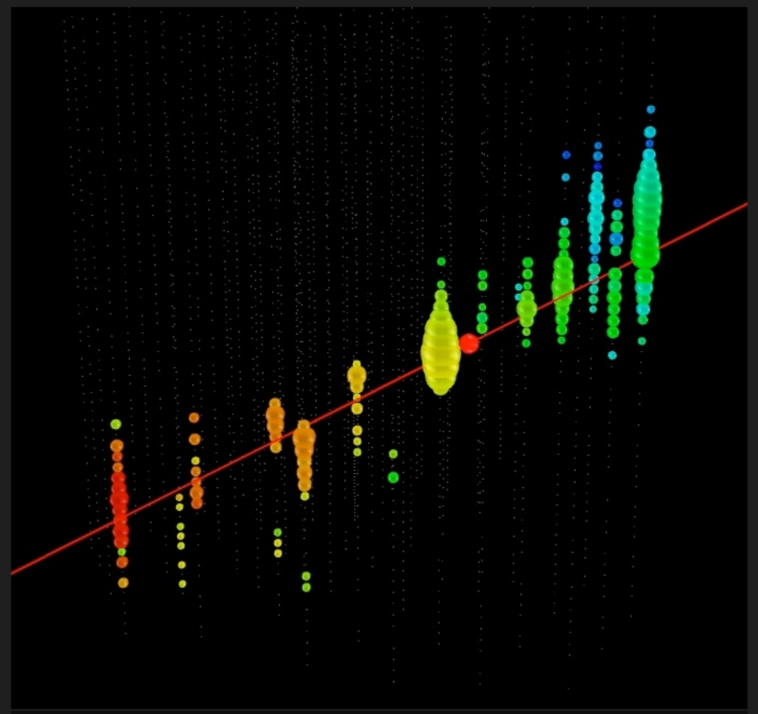
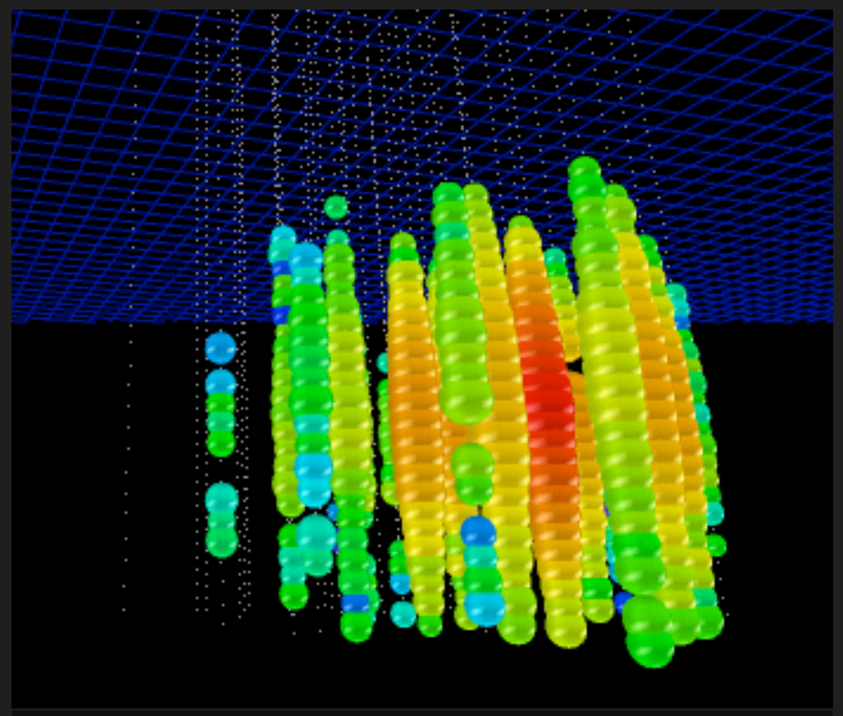
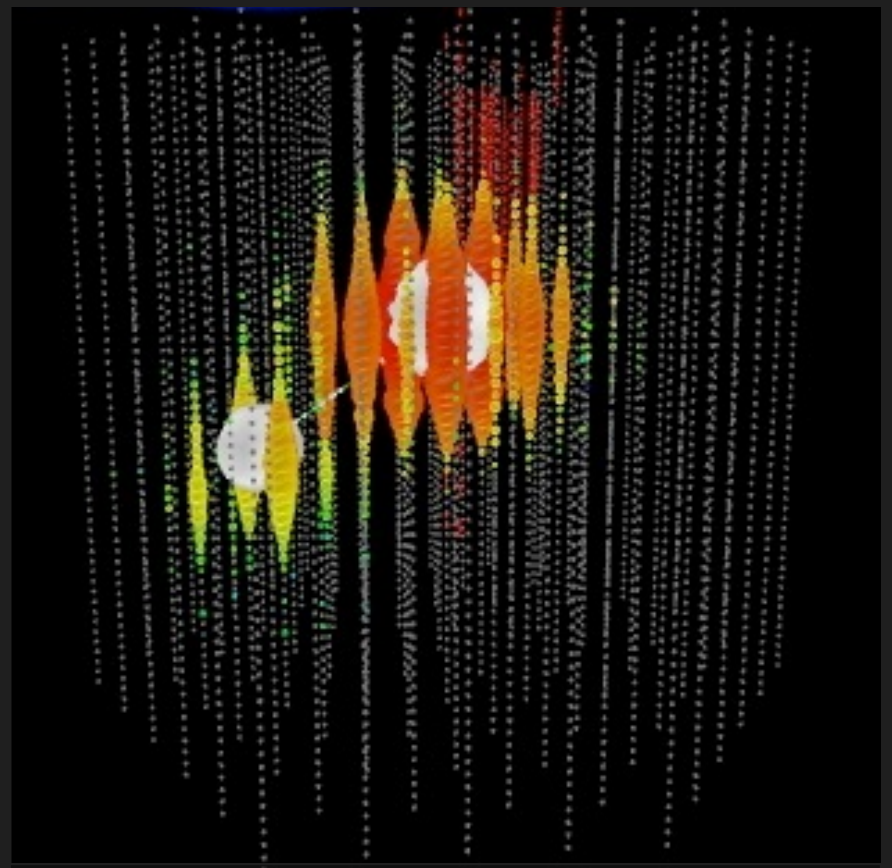
125 m string spacing

Completed **2010**



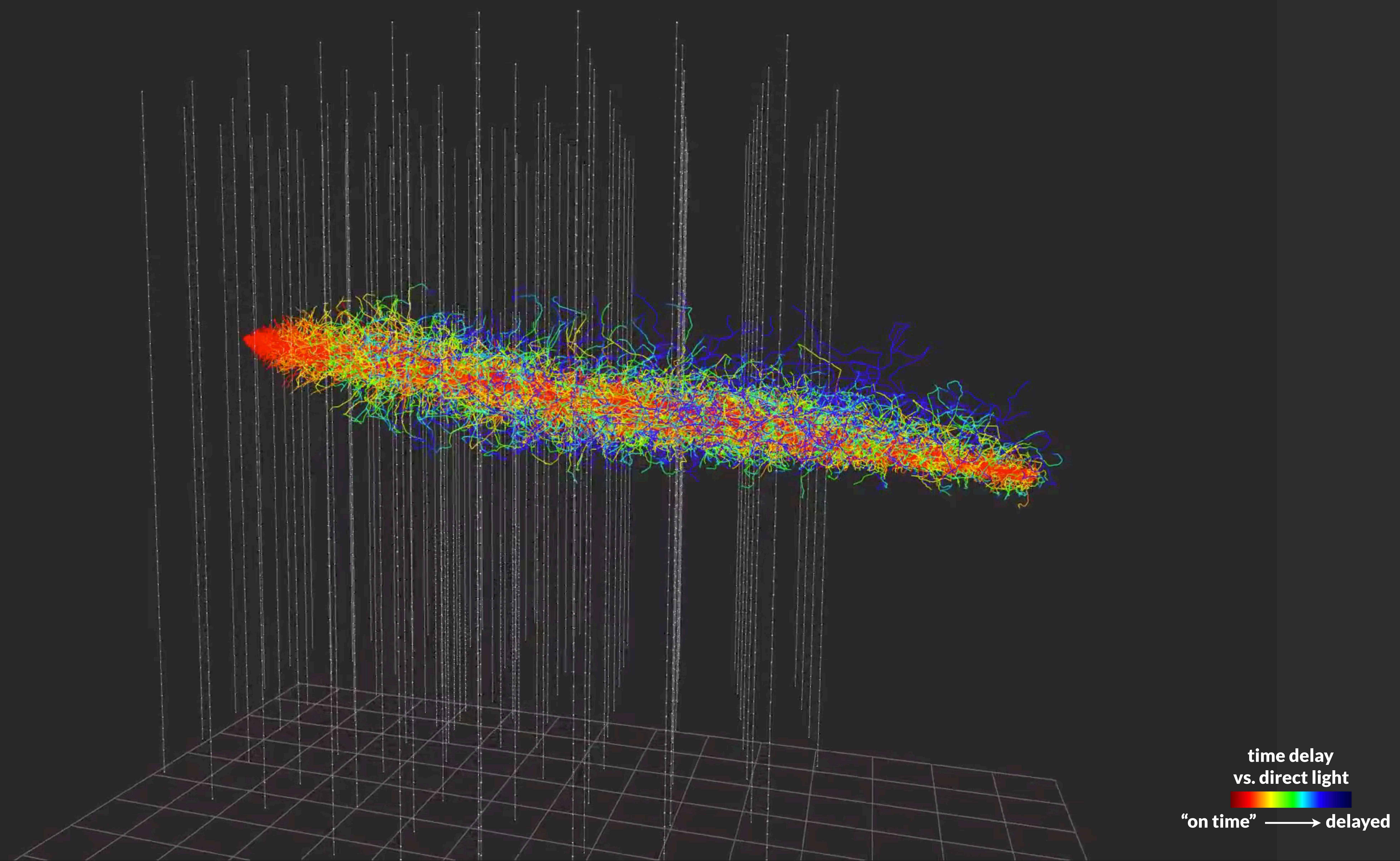
NEUTRINO EVENT SIGNATURES

Signatures of signal events

CC Muon Neutrino	Neutral Current / Electron Neutrino	CC Tau Neutrino
		
$\nu_\mu + N \rightarrow \mu + X$	$\nu_e + N \rightarrow e + X$ $\nu_x + N \rightarrow \nu_x + X$	$\nu_\tau + N \rightarrow \tau + X$
track (data)	cascade (data)	“double-bang” (≳10PeV) and other signatures (simulation)
factor of ≈ 2 energy resolution < 1° angular resolution at high energies	≈ ±15% deposited energy resolution ≈ 10° angular resolution (in IceCube) (at energies ≳ 100 TeV)	(not observed yet: τ decay length is 50 m/PeV)

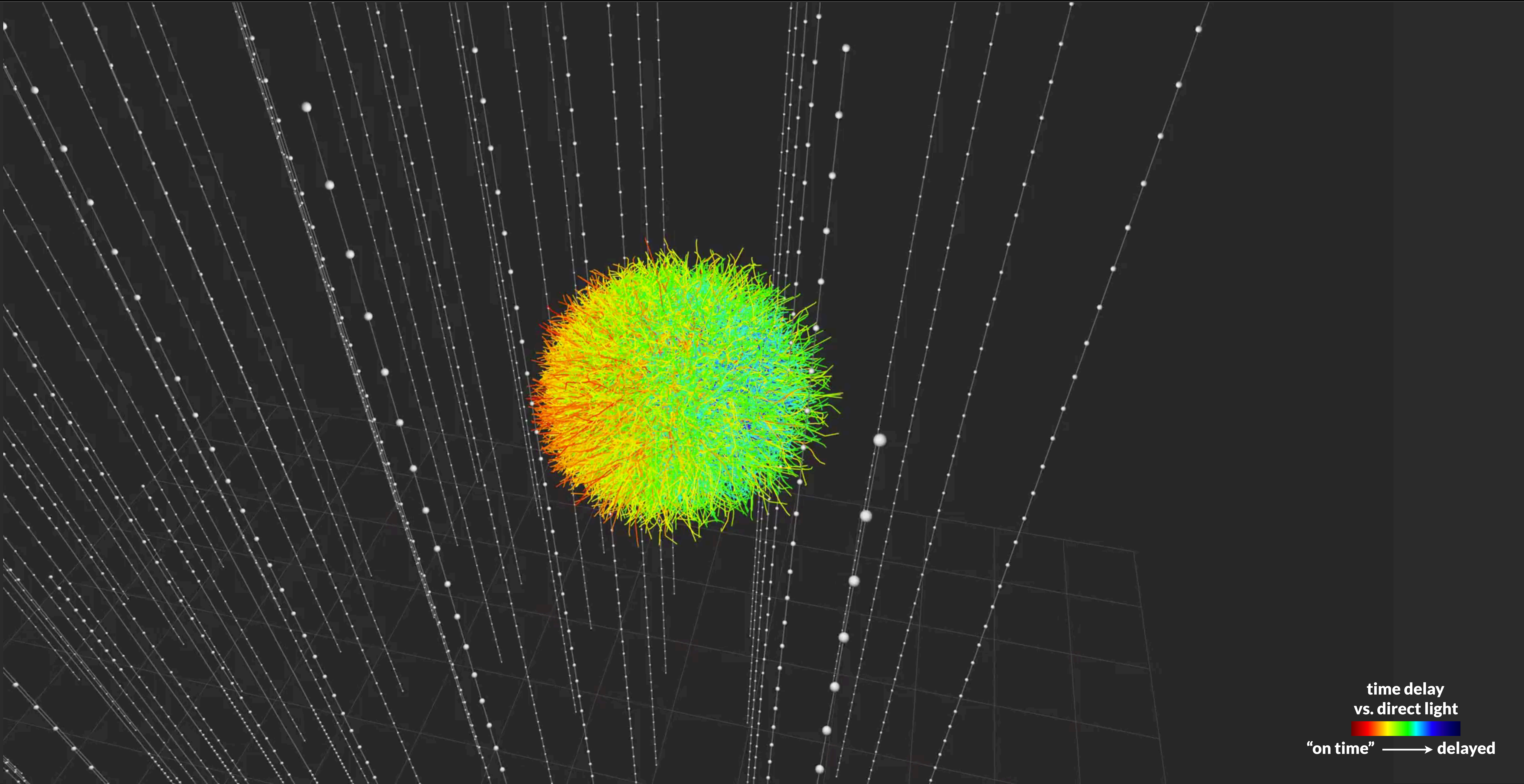
DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles



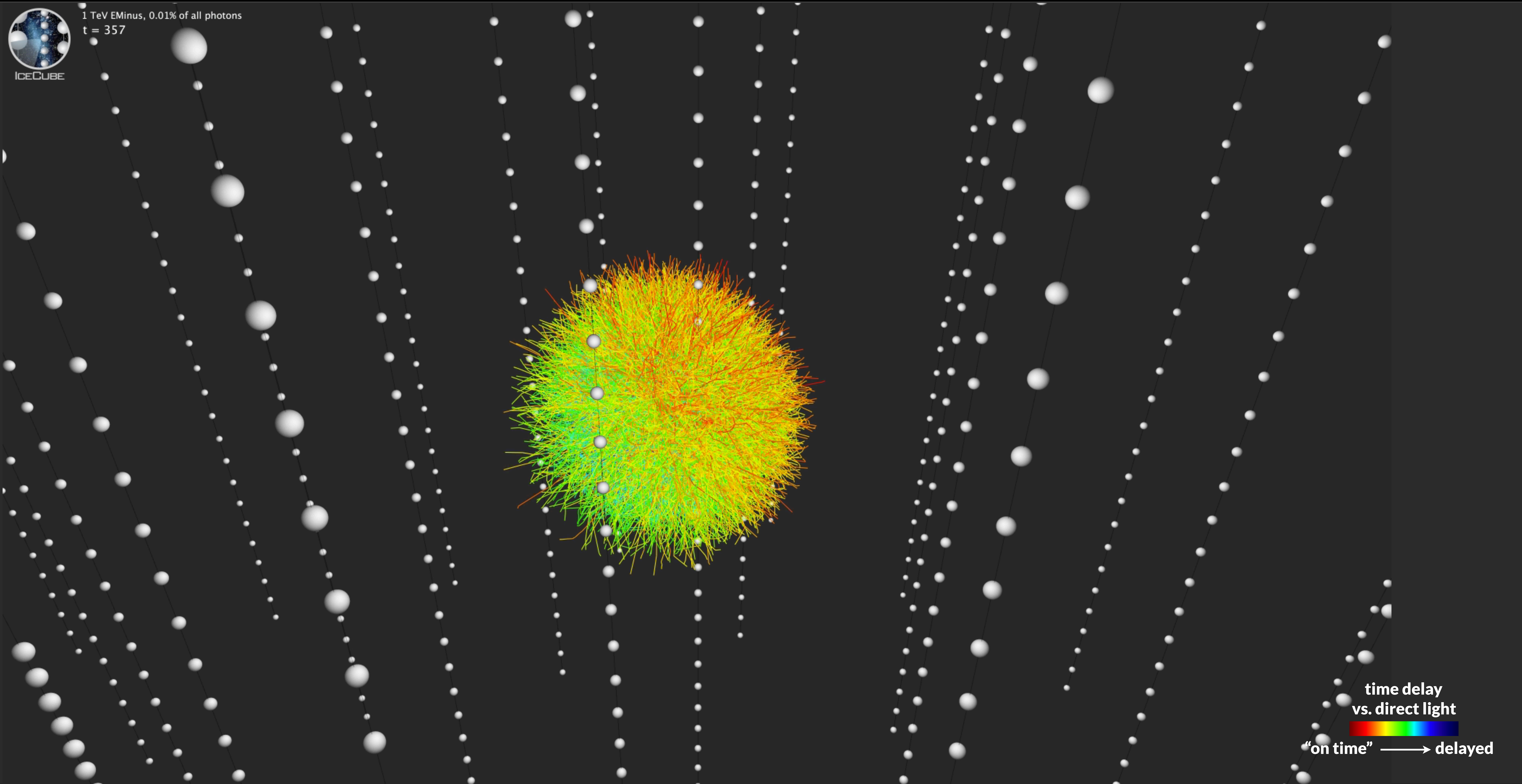
DETECTION PRINCIPLE (CASCADE IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles



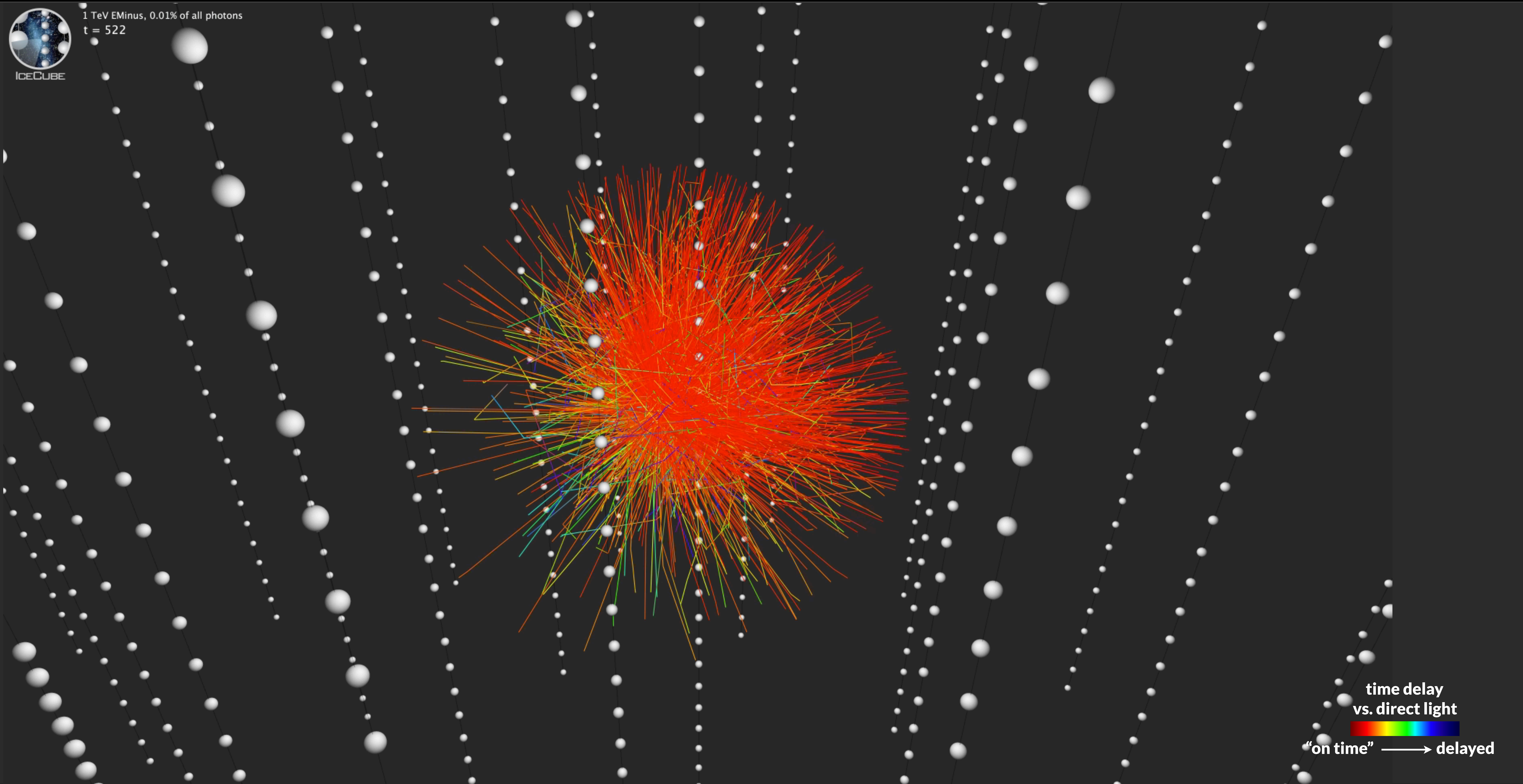
DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower



DETECTION PRINCIPLE (CASCADE IN WATER)

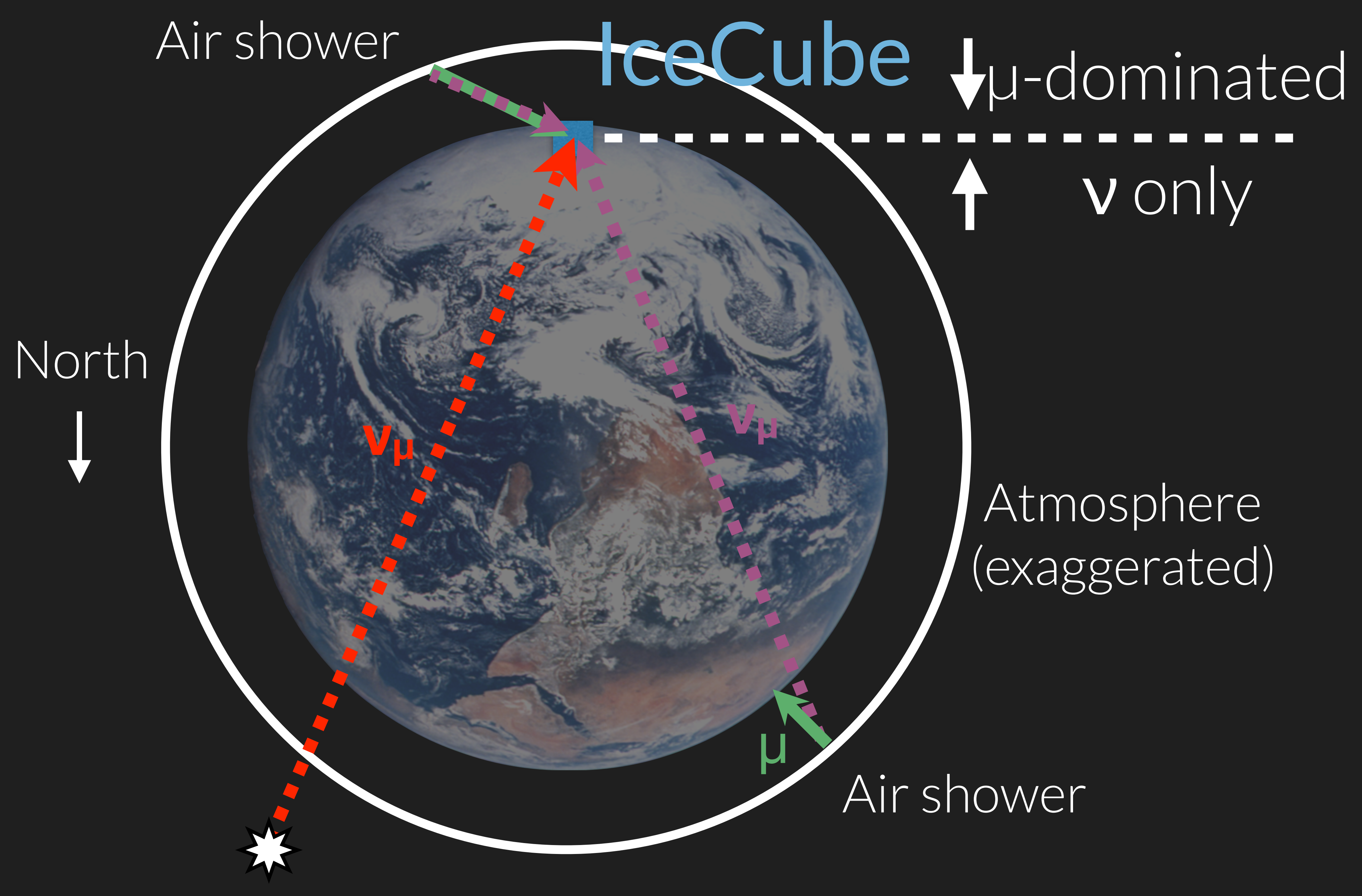
This is how it would look in sea water (KM3NeT|ANTARES)



ISOLATING NEUTRINO EVENTS

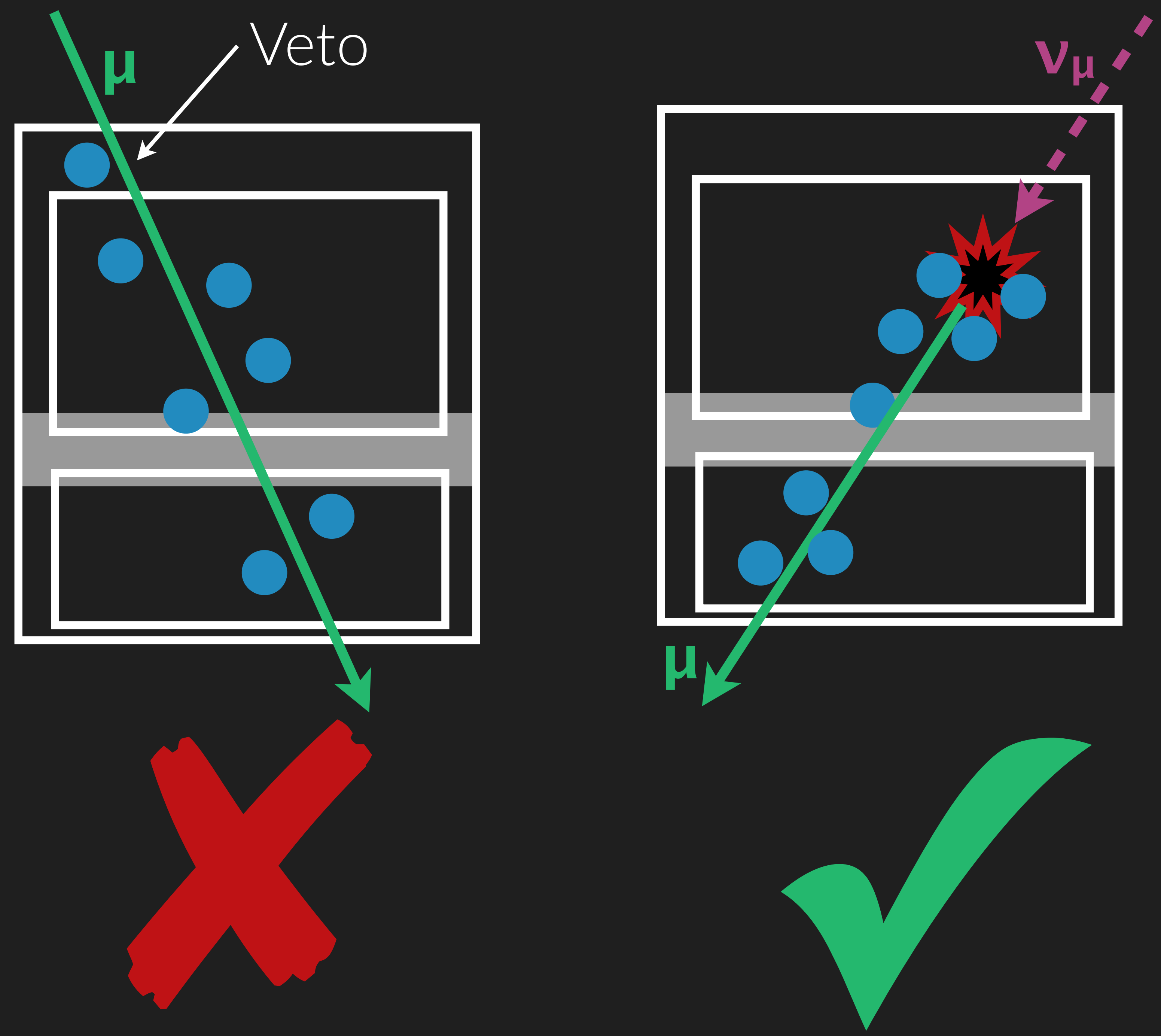
two strategies

Up-going tracks



Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to “half” the sky

Active veto



Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

STUDYING NEUTRINOS

Many different analyses

High-energy:

- Point-source searches looking for clustering in the sky
- Diffuse fluxes above the atmospheric neutrino background
- Gamma-ray bursts/transient searches (GRB models excluded by IceCube: Nature 484 (2012))
- Ultra-high energy "GZK" neutrinos from proton interactions on the CMB

Low energy:

- Neutrino oscillations + more with PINGU/ORCA upgrades

Others:

- Dark Matter / WIMPs
- …

THE (VERY) HIGH-ENERGY TAIL

Update of the high-energy astrophysical flux discovery analysis

SIGNALS AND BACKGROUNDS

Signal

Dominated by showers (~80% per volume) from oscillations

High energy (benchmark spectrum is typically E^{-2})

Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth

Background

Track-like events from Cosmic Ray muons and atmospheric ν_μ

Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)

Muons in the Southern Sky, neutrinos from the North

"STARTING EVENT" ANALYSIS

Specifically designed to find contained events.

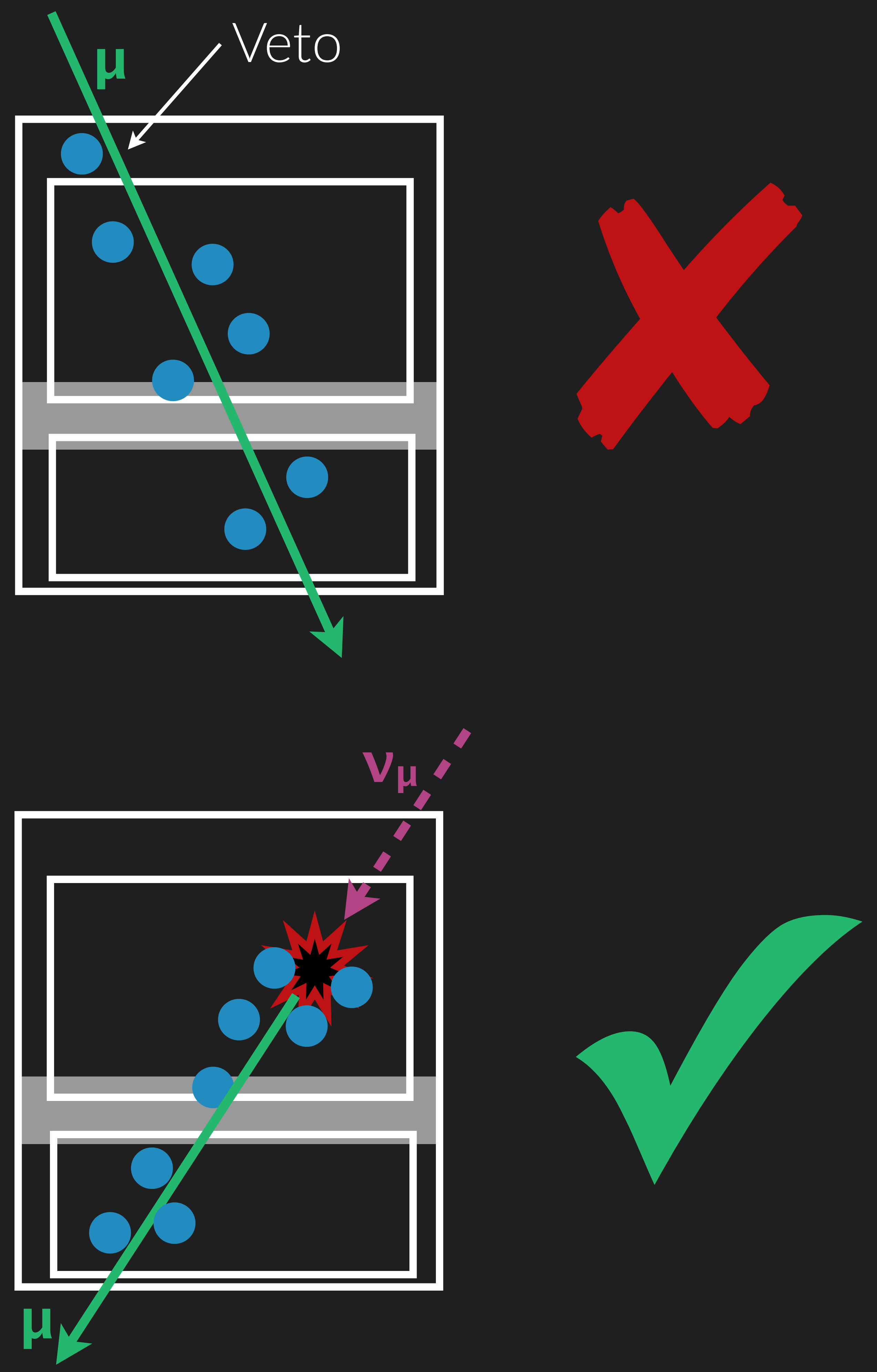
Explicit contained search at high energies (cut: Qtot>6000 p.e.)

400 Mton effective fiducial mass

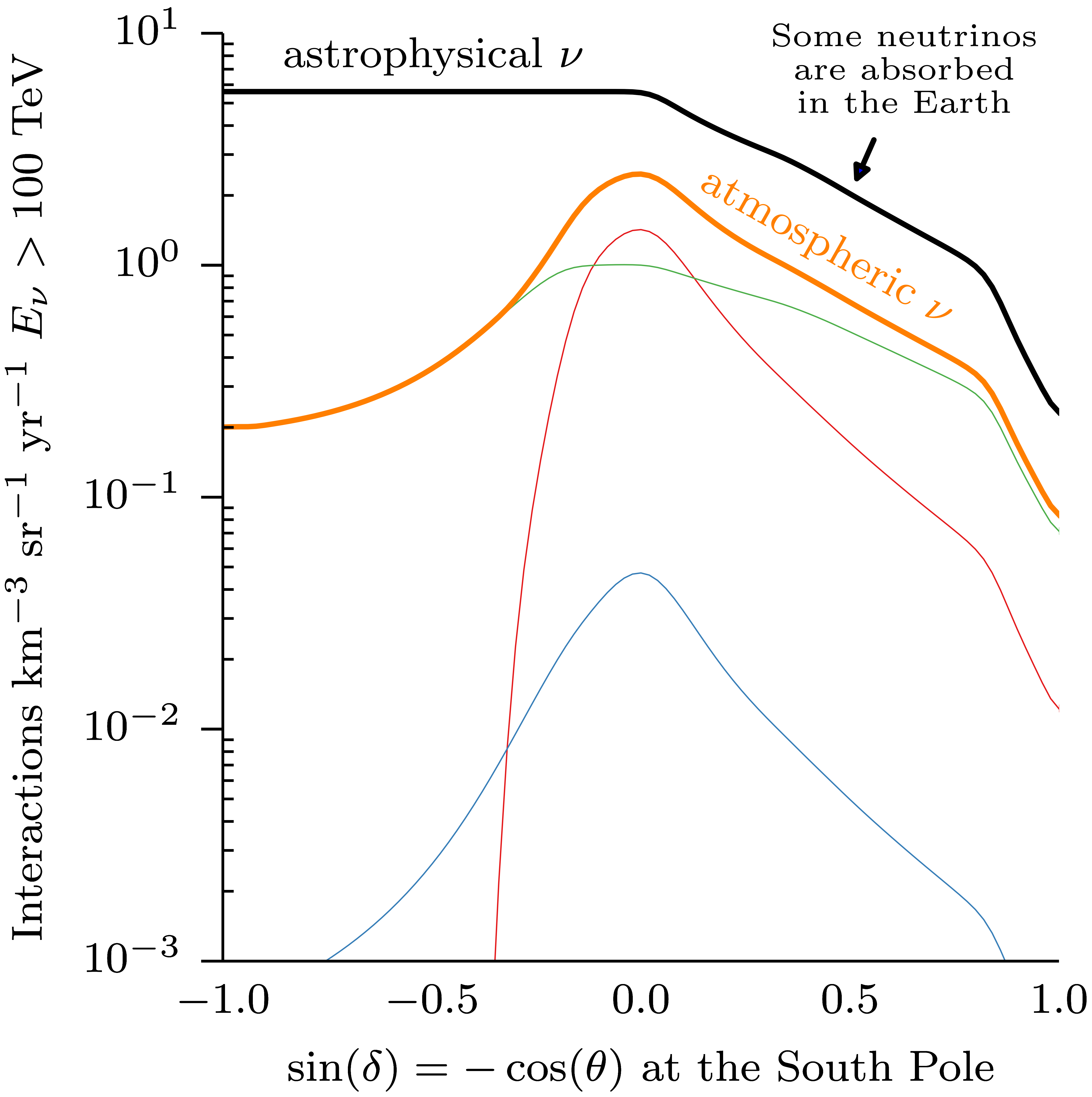
Use atmospheric muon veto

Sensitive to all flavors in region above 60TeV deposited energy

Estimate background from data



Atmospheric neutrino self-veto



The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

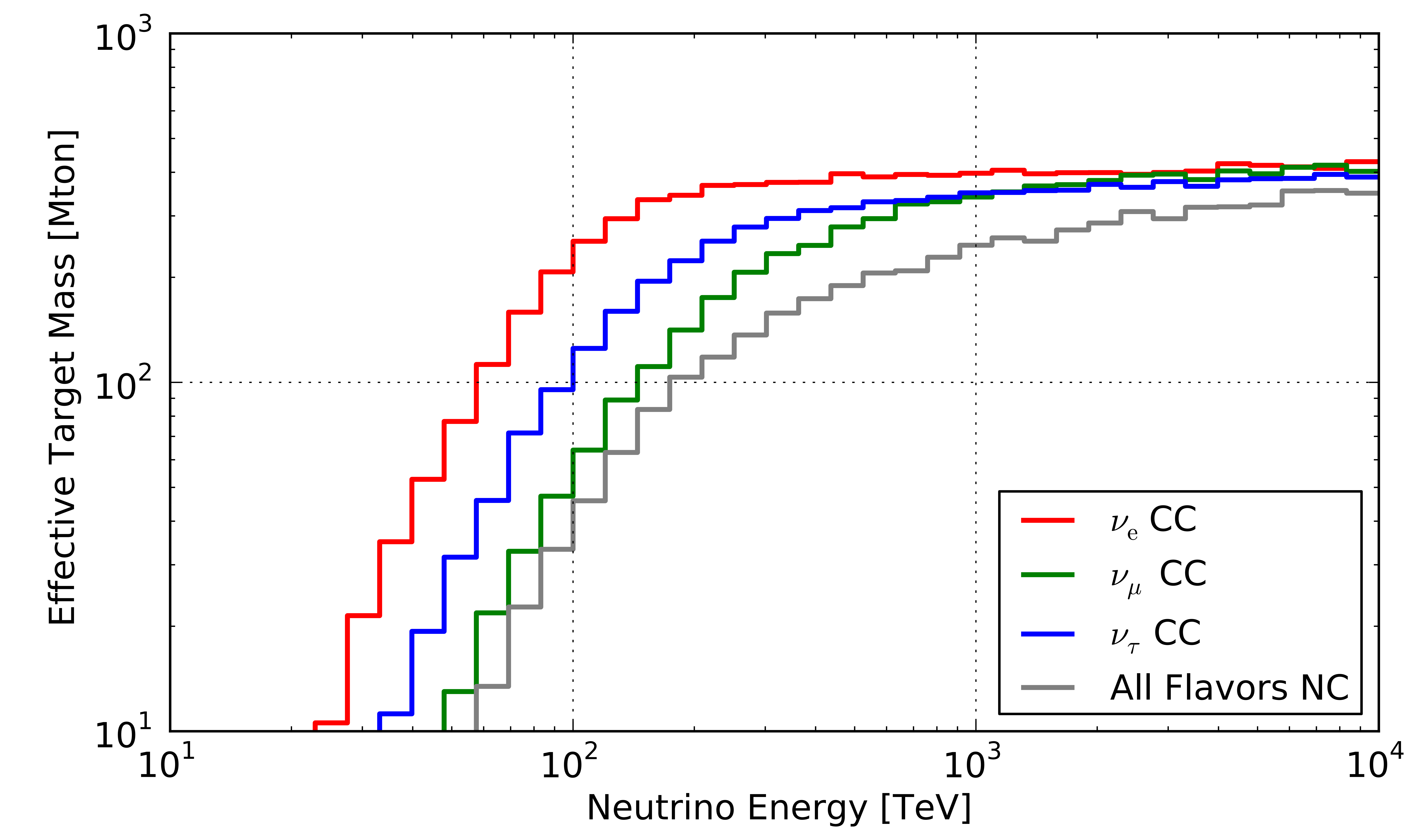
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

slide courtesy of J. van Santen

EFFECTIVE VOLUME / TARGET MASS

Fully efficient above 100 TeV for CC electron neutrinos



WHAT DID ICECUBE FIND? (3 YEARS)

37 events!

36(+1) events observed!

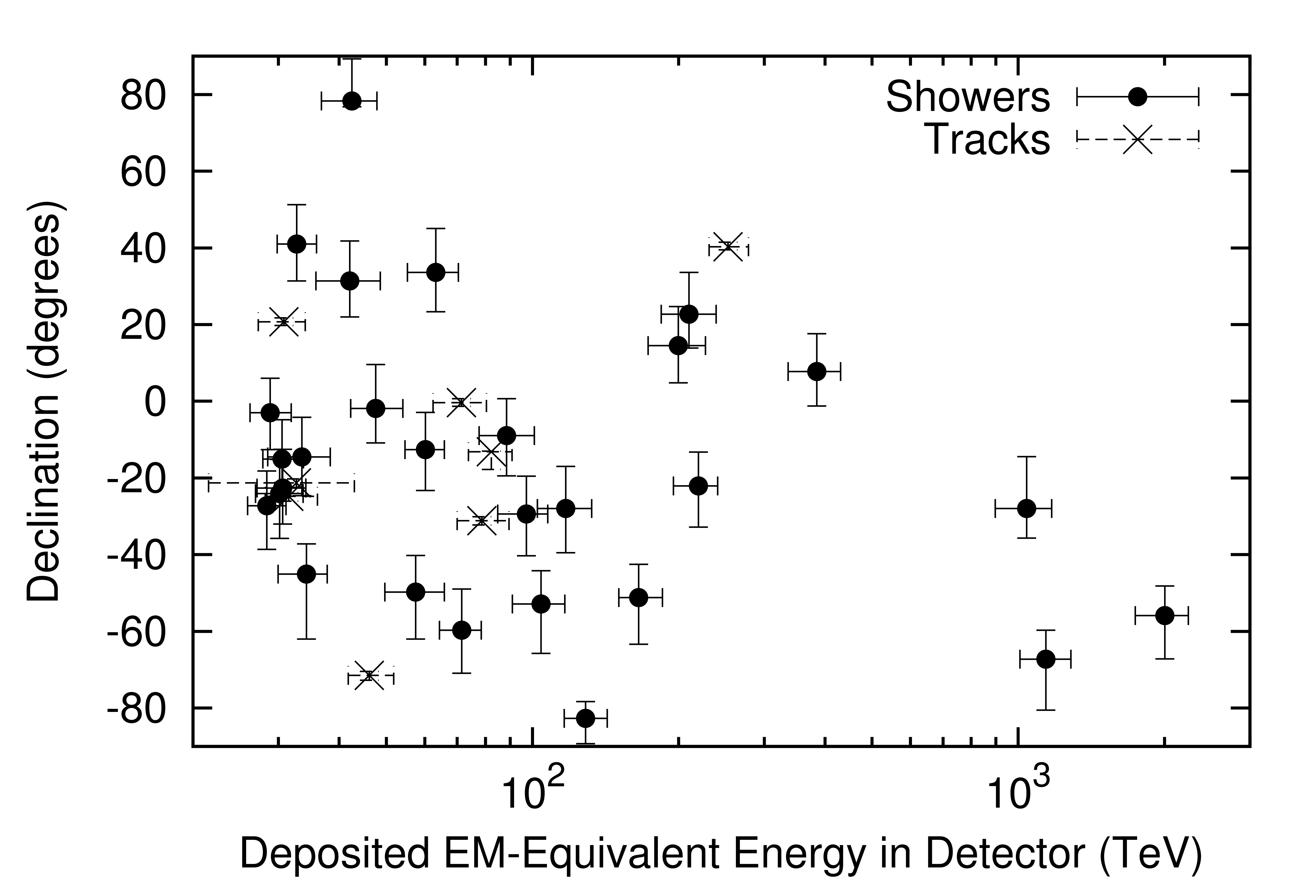
Estimated background:

$6.6^{+5.9}_{-1.6}$ atm. neutrinos

8.4±4.2 atm. muons

One of them is an obvious (but expected) background

coincident muons from two CR air showers



full likelihood fit of all components: 5.7σ for 36(+1) events

PRL 113, 101101

WHAT DID ICECUBE FIND? (4 YEARS)

54 events!

53(+1) events observed!

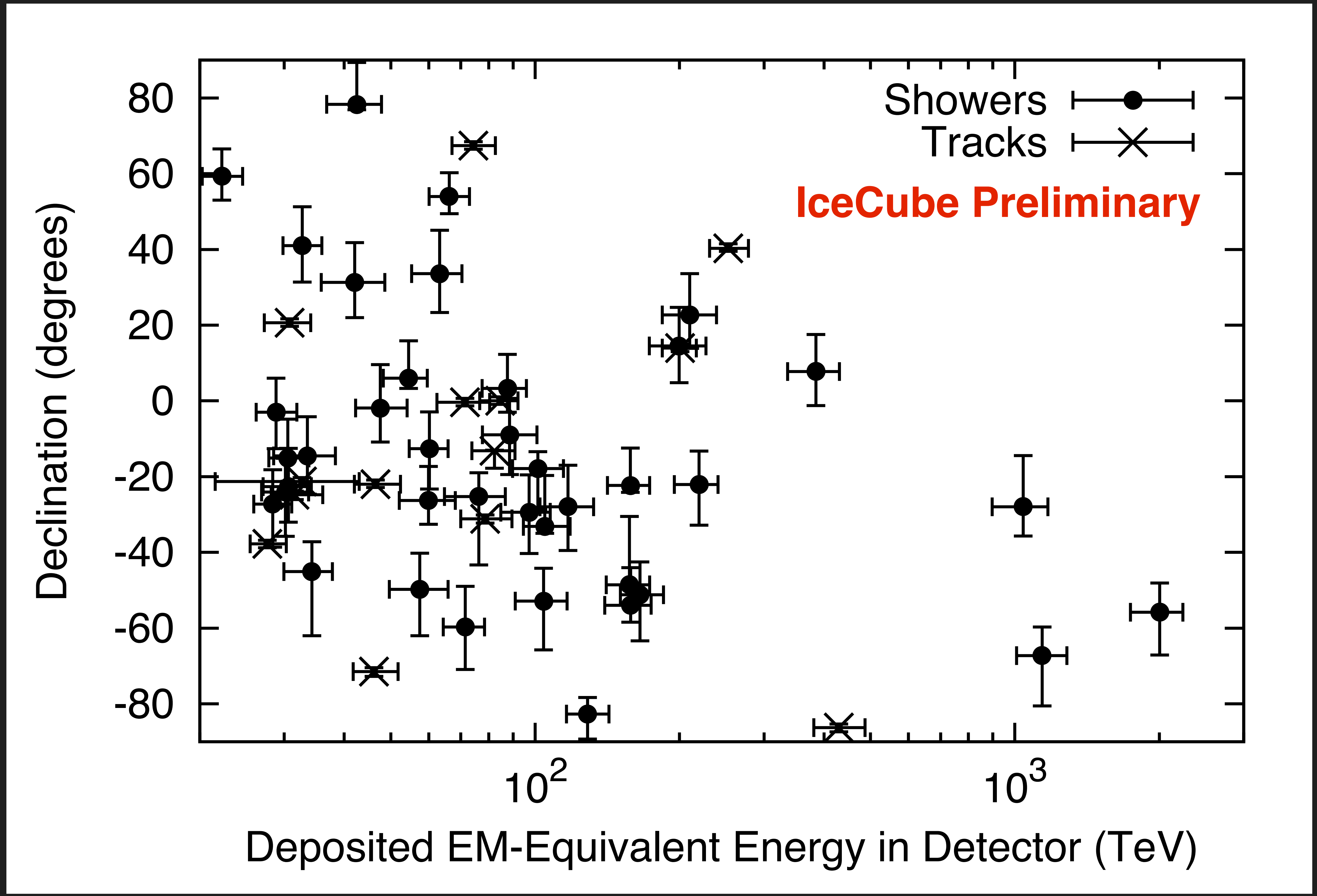
Estimated background:

$9.0^{+8.0}_{-2.2}$ atm. neutrinos

12.6±5.1 atm. muons

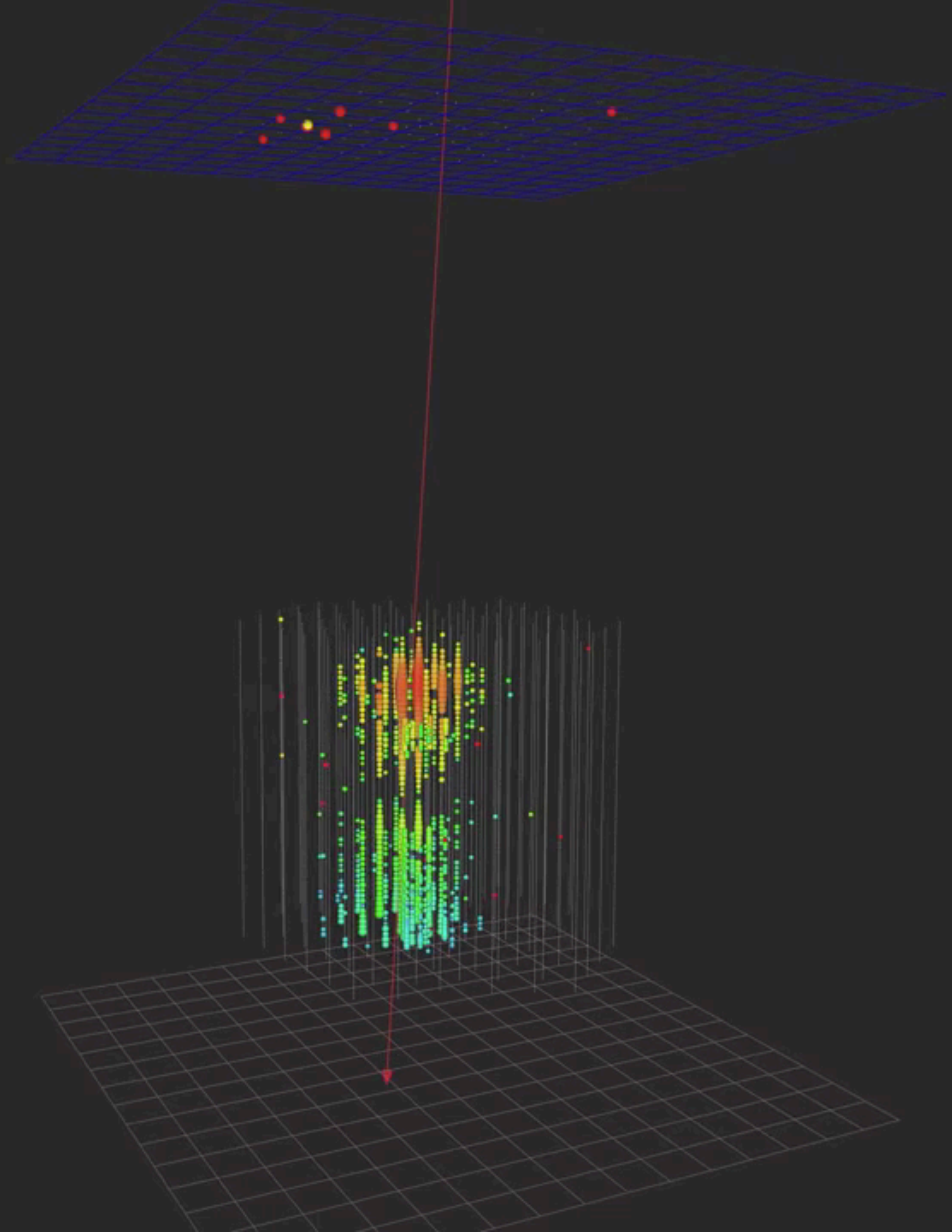
One of them is an obvious (but expected) background

coincident muons from two CR air showers



full likelihood fit of all components: 6.5σ for 53(+1) events

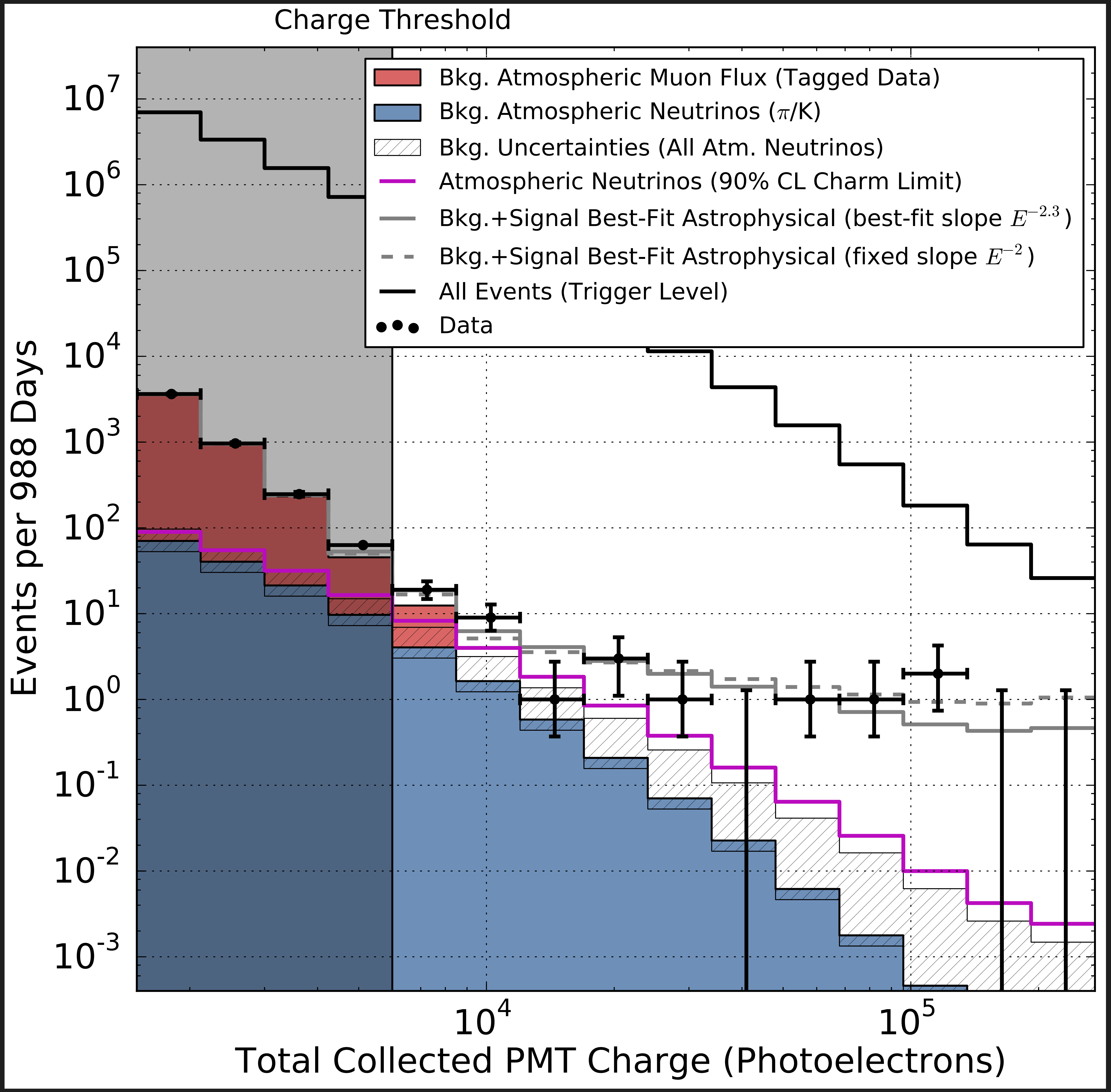
presented at ICRC2015 / PoS(ICRC2015)1081



CHARGE DISTRIBUTION

Fits well to tagged background estimate from atmospheric muon data (red) below charge threshold (Qtot>6000)

Hatched region includes uncertainties from conventional and charm atmospheric neutrino flux (blue)



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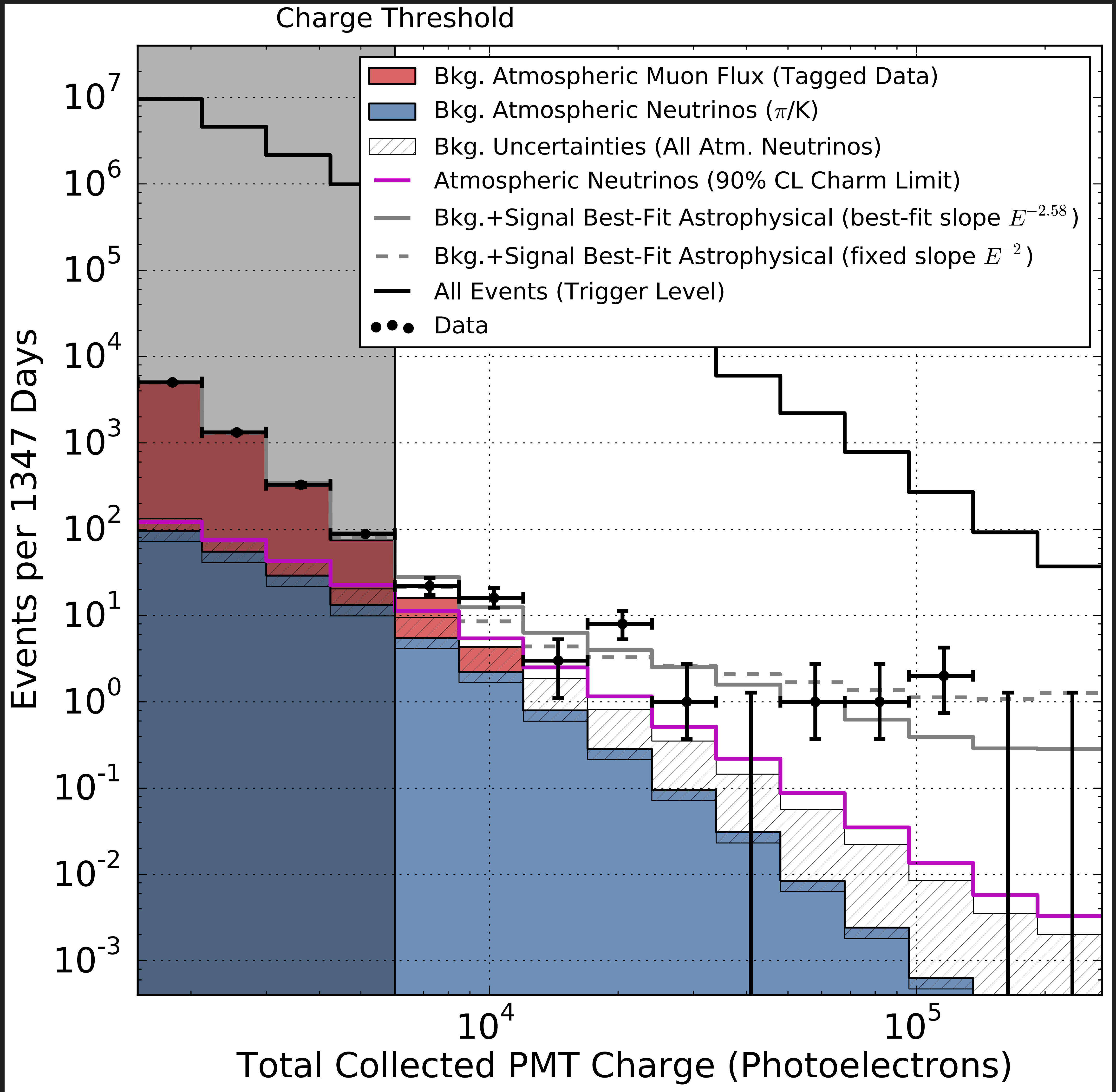


ENERGY SPECTRUM (3 YEARS)

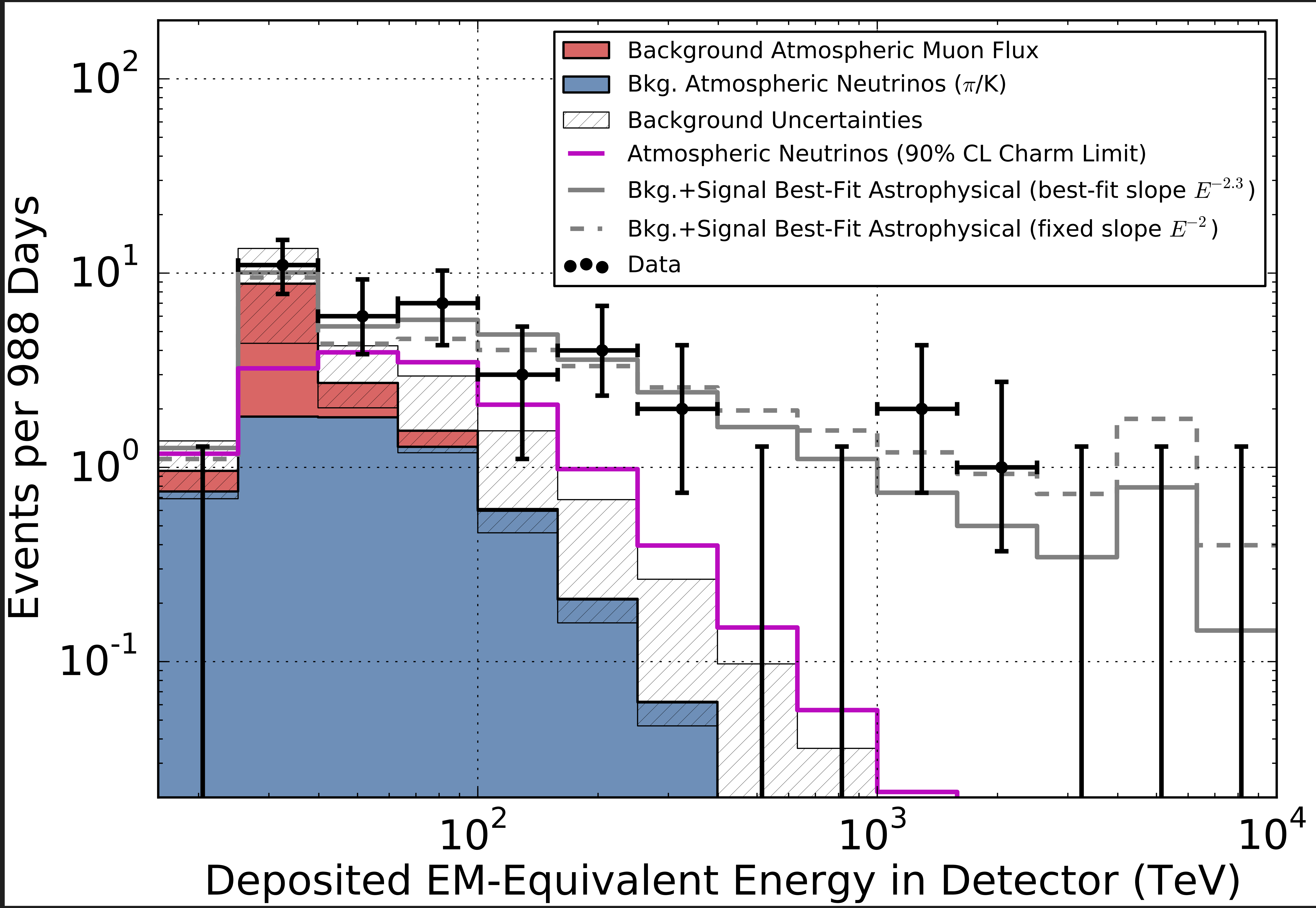
energy deposited in the detector (lower limit on neutrino energy)

Harder than any expected atmospheric background

Merges well into background at low energies

Potential cutoff at about 2-5 PeV (or softer spectrum)

Best fit spectral index: $E^{-2.3}$



ENERGY SPECTRUM (4 YEARS)

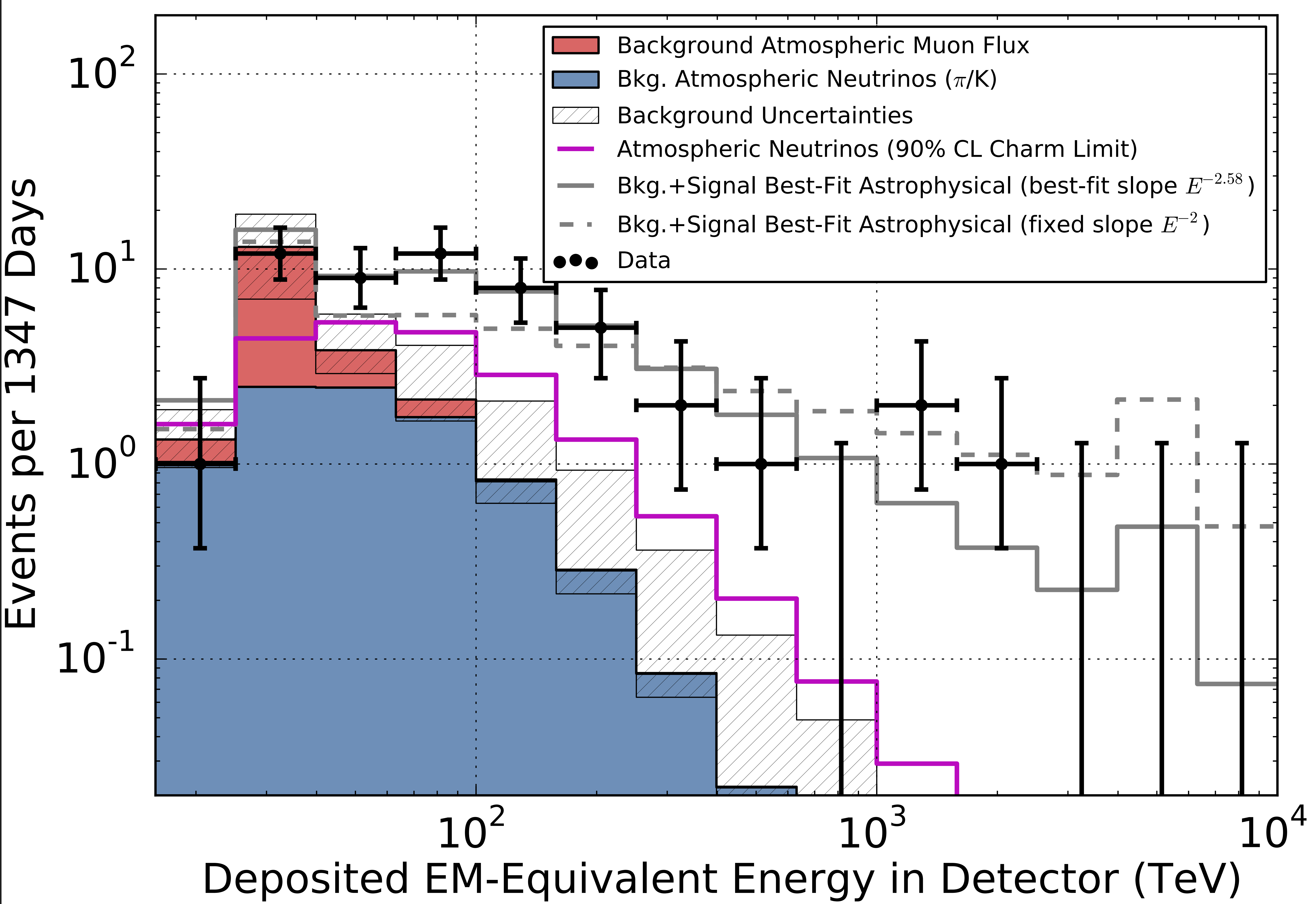
energy deposited in the detector (lower limit on neutrino energy)

Somewhat compatible with benchmark E^{-2} astrophysical model or single power-law model, but looks like things are more complicated

Best fit assuming E^{-2} (not a very good fit anymore):

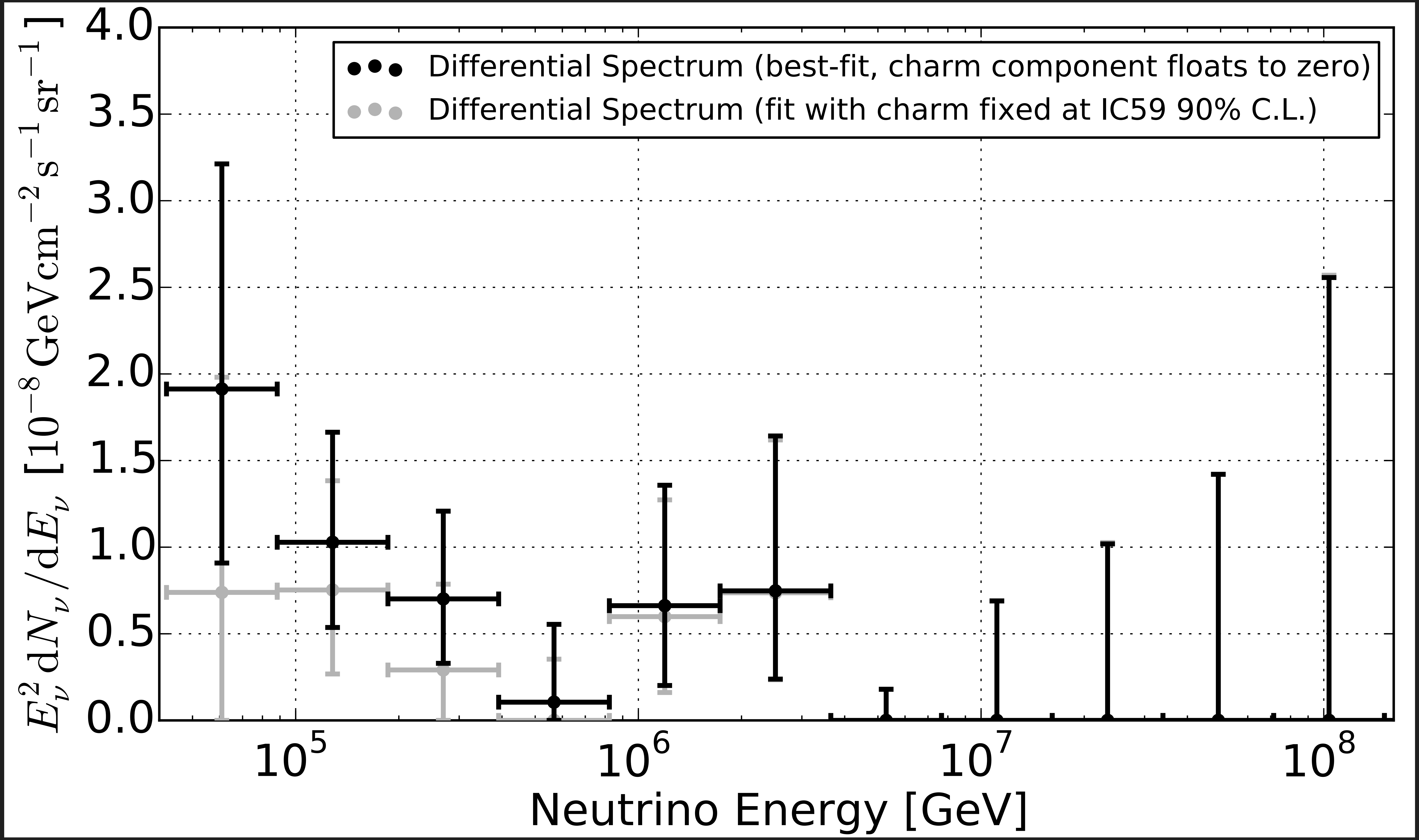
$0.84 \pm 0.3\ 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

Best fit spectral index: $E^{-2.58}$



UNFOLDING TO NEUTRINO ENERGY

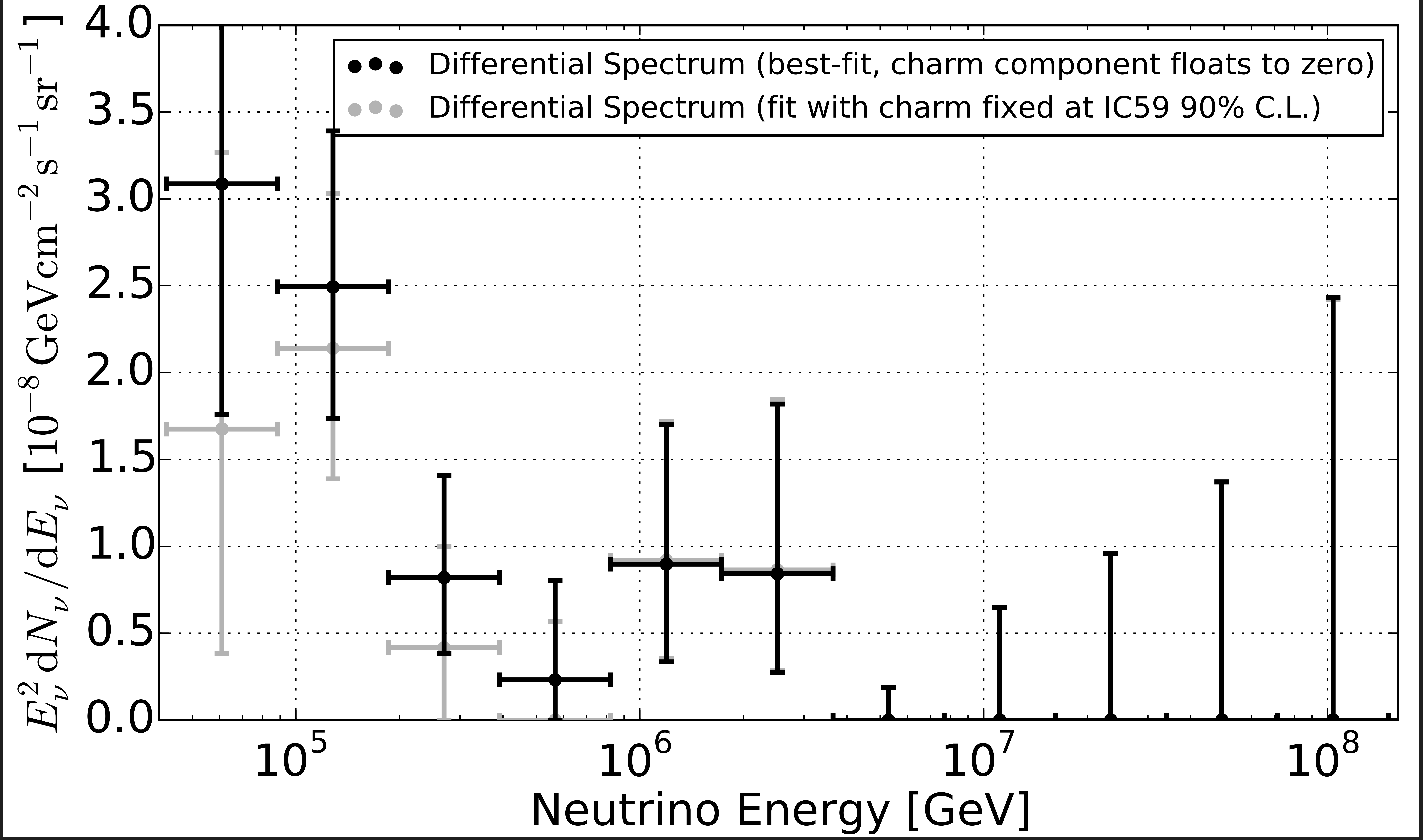
updated from PRL plot version with priors for backgrounds - 3 years



assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

UNFOLDING TO NEUTRINO ENERGY

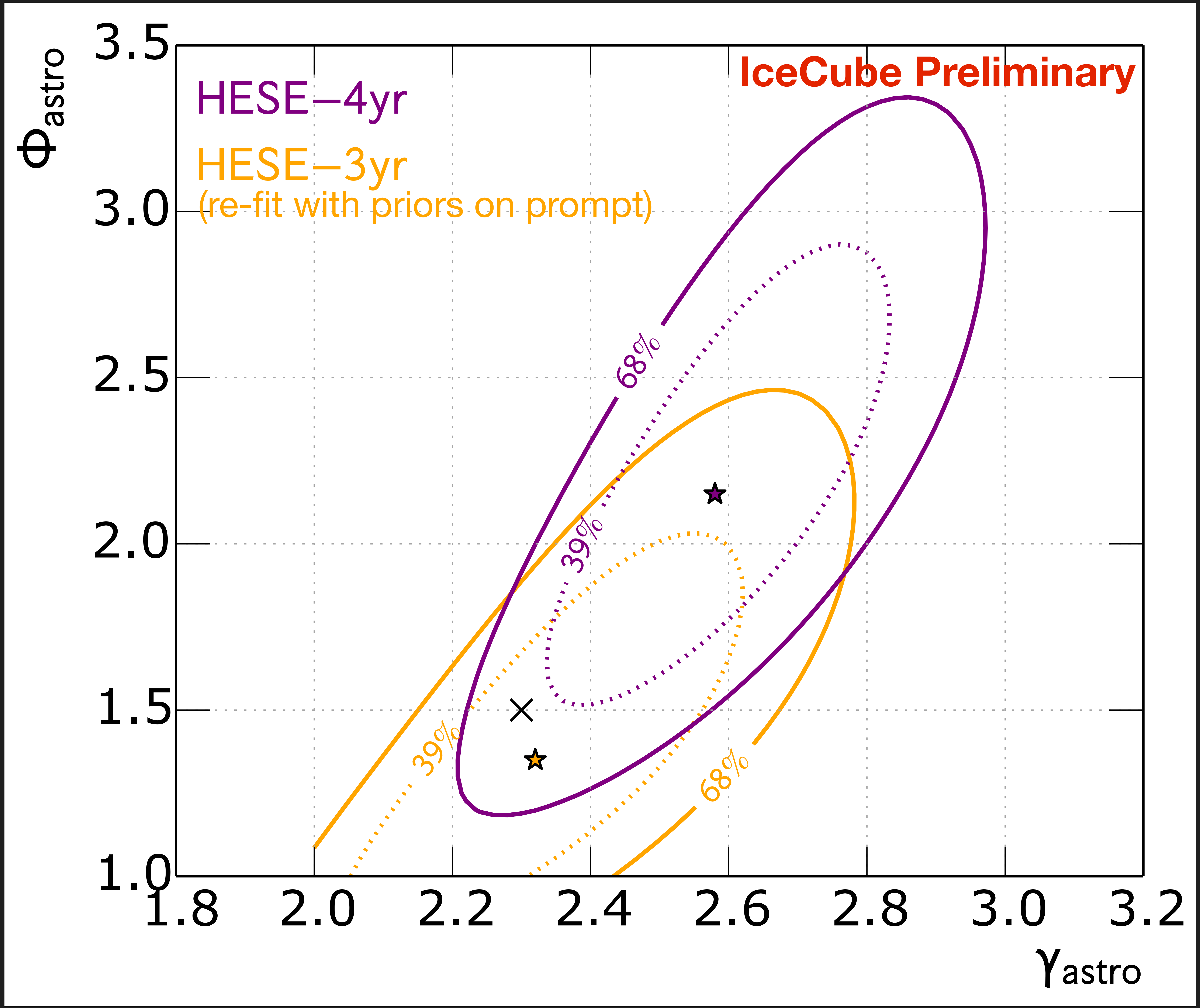
updated from PRL plot version with priors for backgrounds - 4 years



assumption: 1:1:1 flavor ratio, 1:1 neutrino:anti-neutrino

SPECTRAL FIT

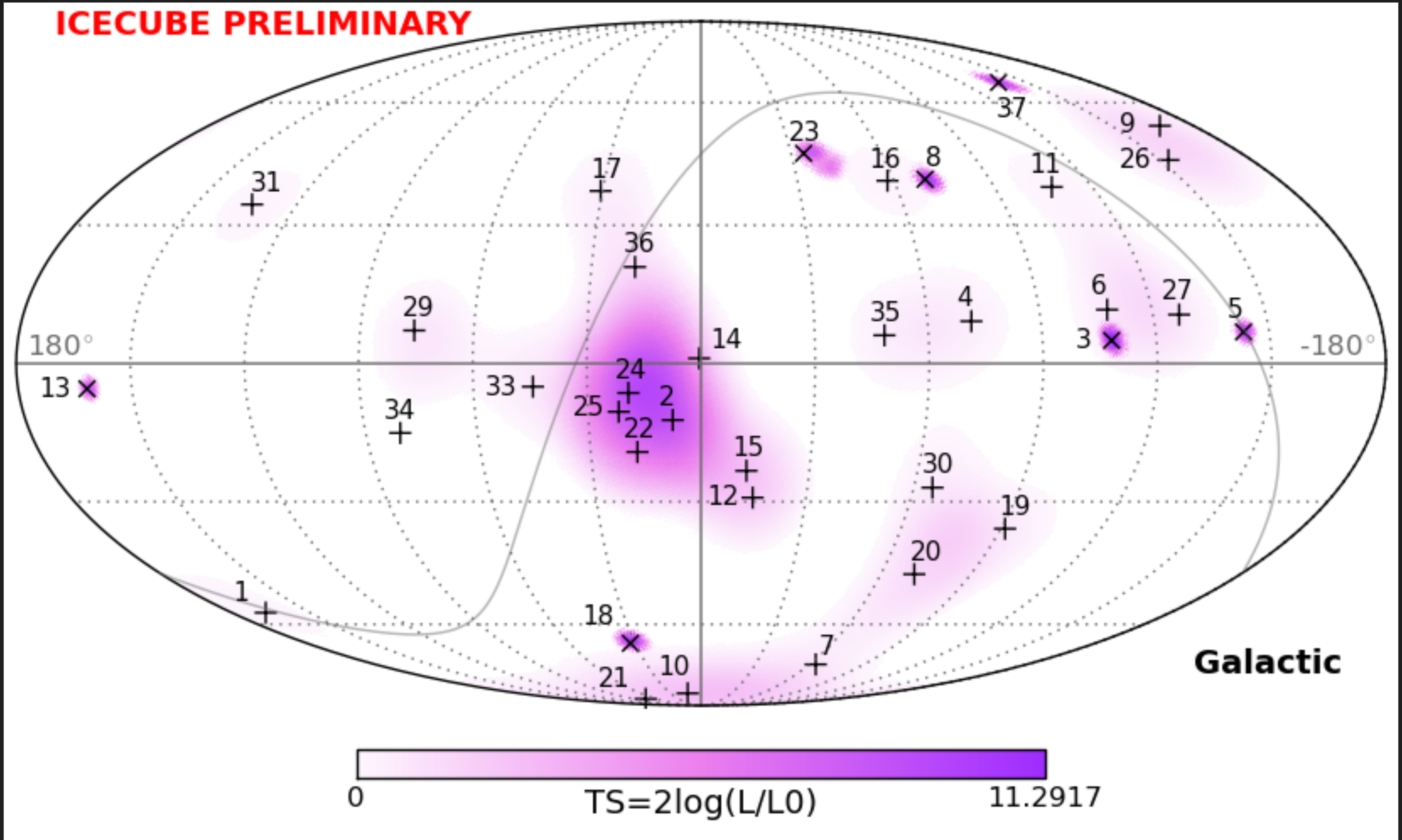
Normalization vs. spectral index contour plot



Note: 3-year data re-fit since PRL with priors for backgrounds

SKYMAP / CLUSTERING

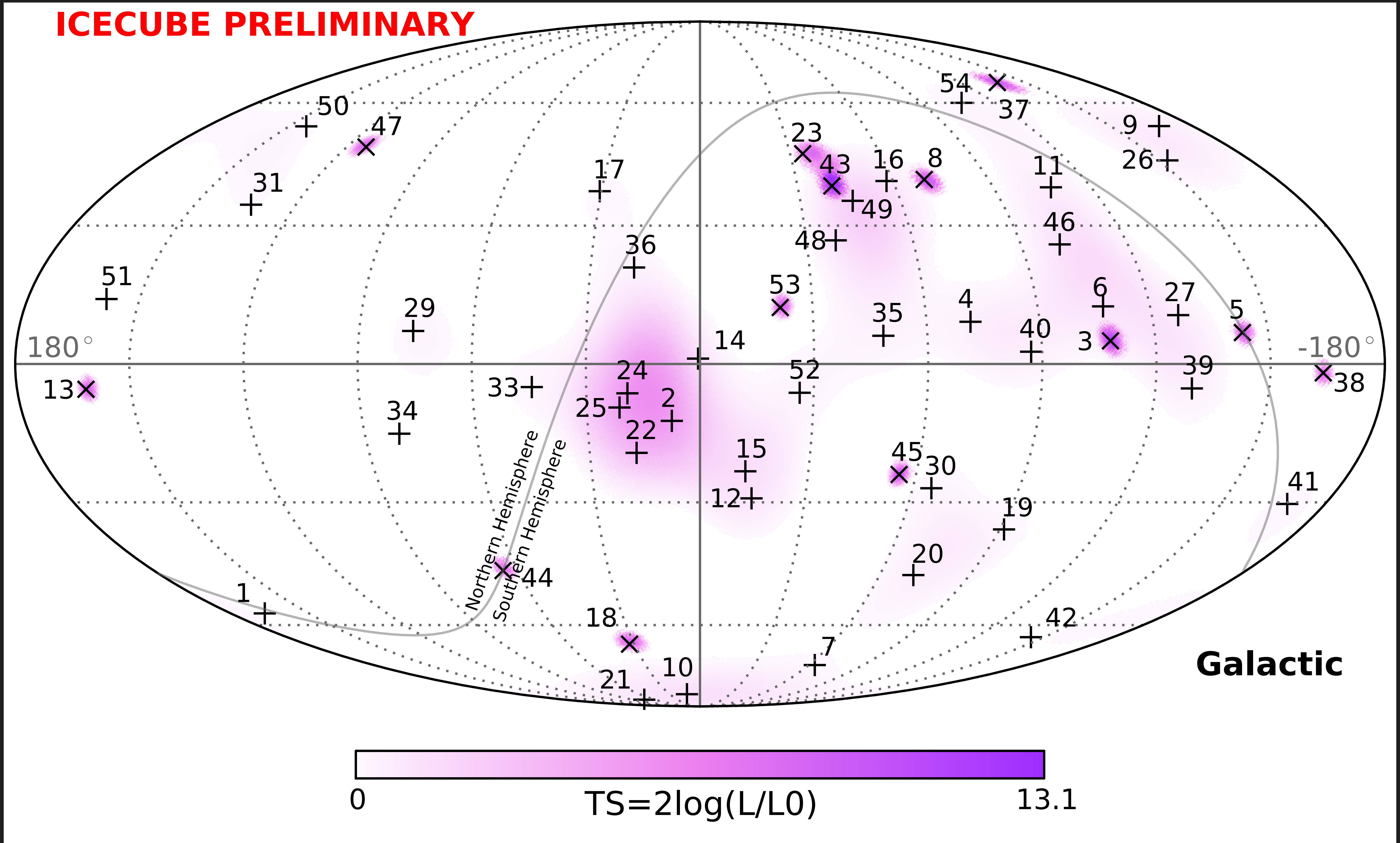
No significant clustering observed (three years)



(all p-values are post-trial)

SKYMAP / CLUSTERING

No significant clustering observed (four years)



(all p-values are post-trial)

SKYMAP / CLUSTERING

No significant clustering observed

Analyzed with a variant of the standard PS method (w/o energy) (i.e. scrambling in RA)

Most significant excess close to (but not at!) the Galactic Center

Significance: **44%** (not significant)

Other searches (multi-cluster, galactic plane, time clustering, GRB correlations) not significant either

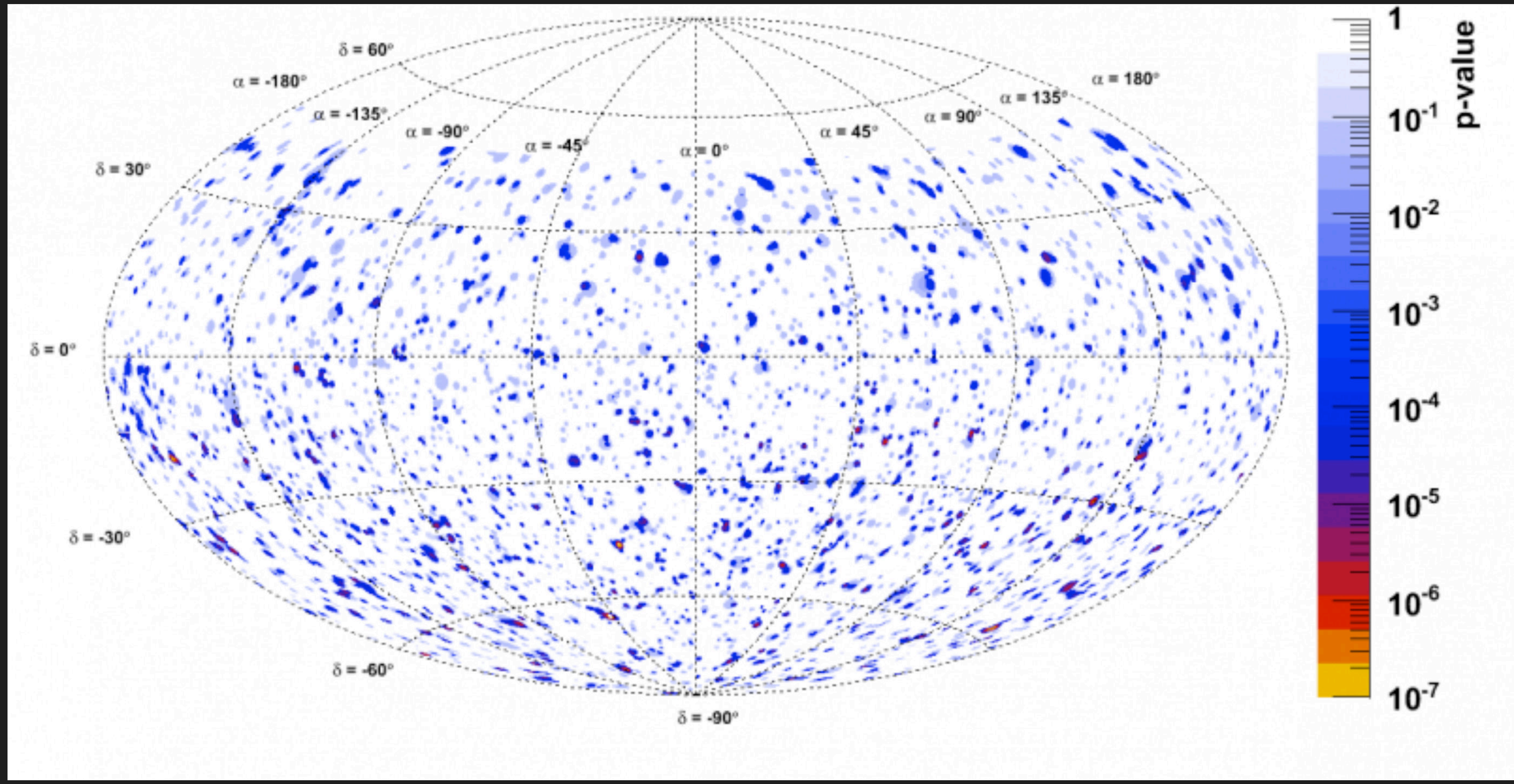
WHAT CAN ANTARES SAY?

Analysis of the galactic center "excess" (only limit)

No hint of neutrino point source as of now (in either detector), flux confirmation needs bigger detector (KM3NeT!)

WHERE ARE THE SOURCES?

There is still no evidence for point sources of high-energy neutrinos.

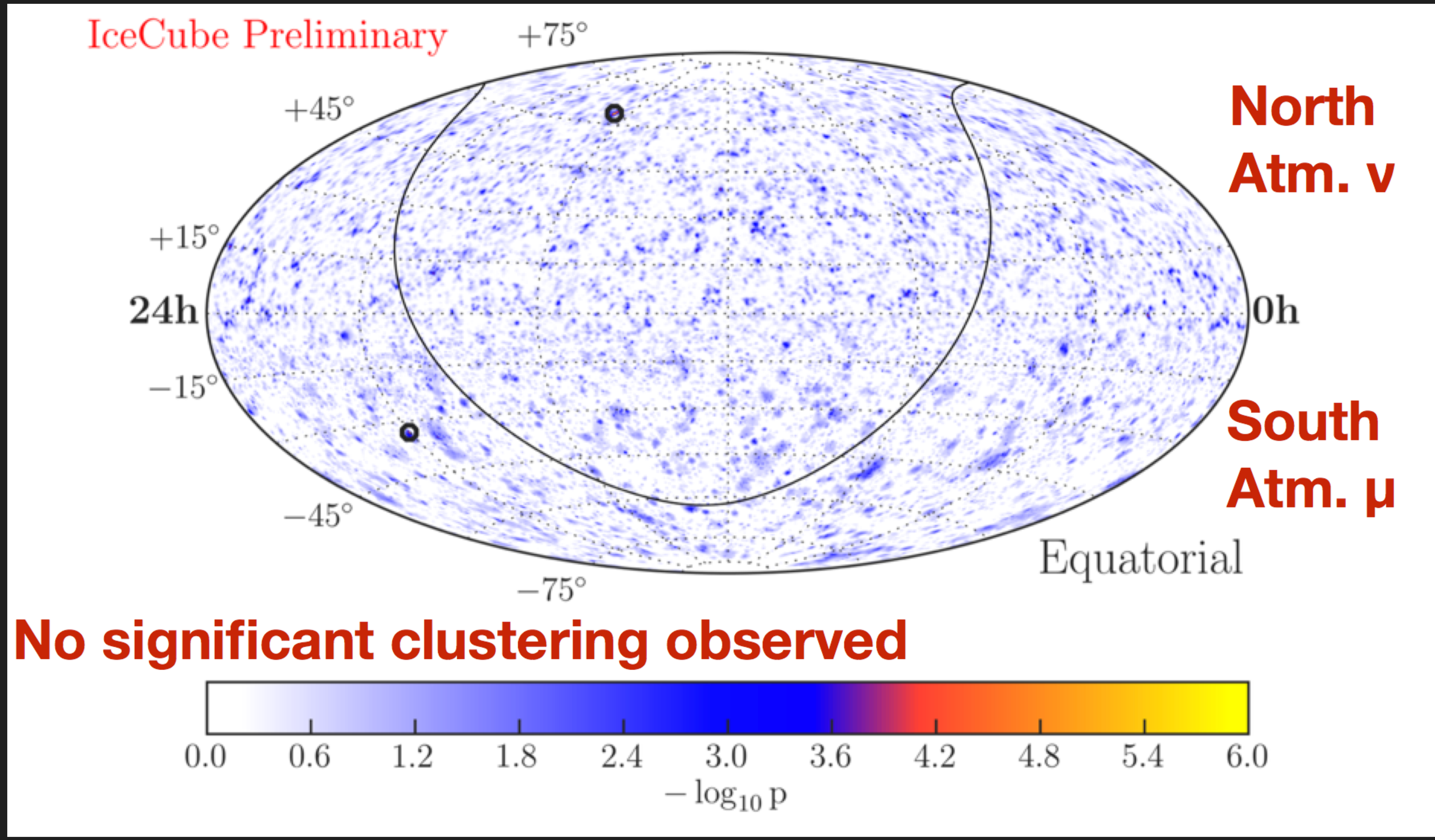


ApJ Lett, 786, L5 (2014)

ANTARES 4-year up-going muon point source search: **~2%** chance probability (post-trial)

IceCube 6-year though-going muon point source search
Northern-sky muons: **35%** chance probability
> PeV southern-sky muons: **87%**

PoS(ICRC2015)1047

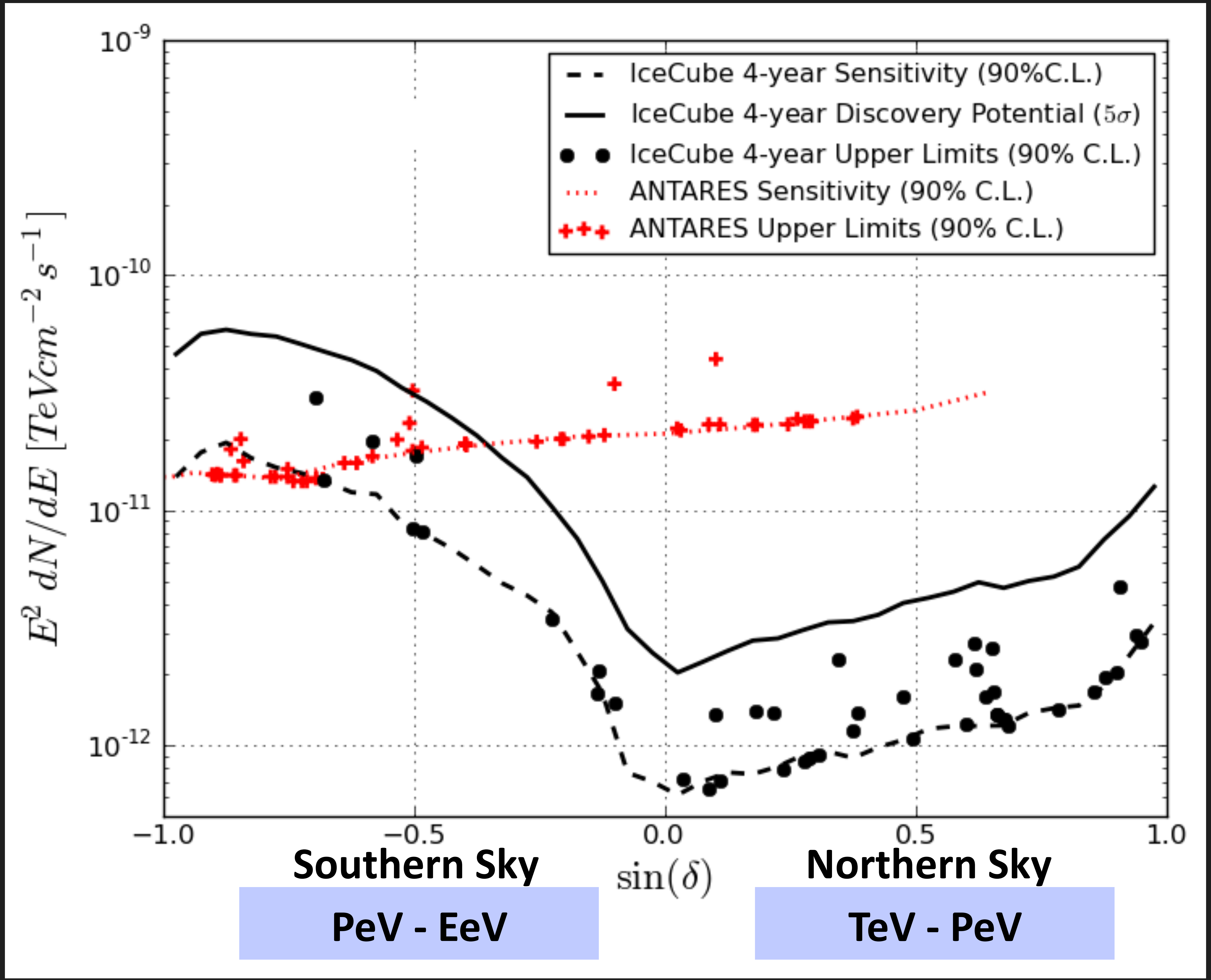


CONSTRAINTS ON POINT SOURCES

ANTARES can observe the southern sky through the Earth → lower threshold, better limits in the south

IceCube has a larger effective area → more events, better limits in the north

New: combined IceCube/ ANTARES search



IMPROVED VETO TECHNIQUES

PRD 91, 022001

What happens to the astrophysical flux below 60 TeV?

How large is the neutrino flux from atmospheric charm?

→ Need to observe lower-energy neutrinos, especially from the southern sky.

IMPROVED VETO TECHNIQUES

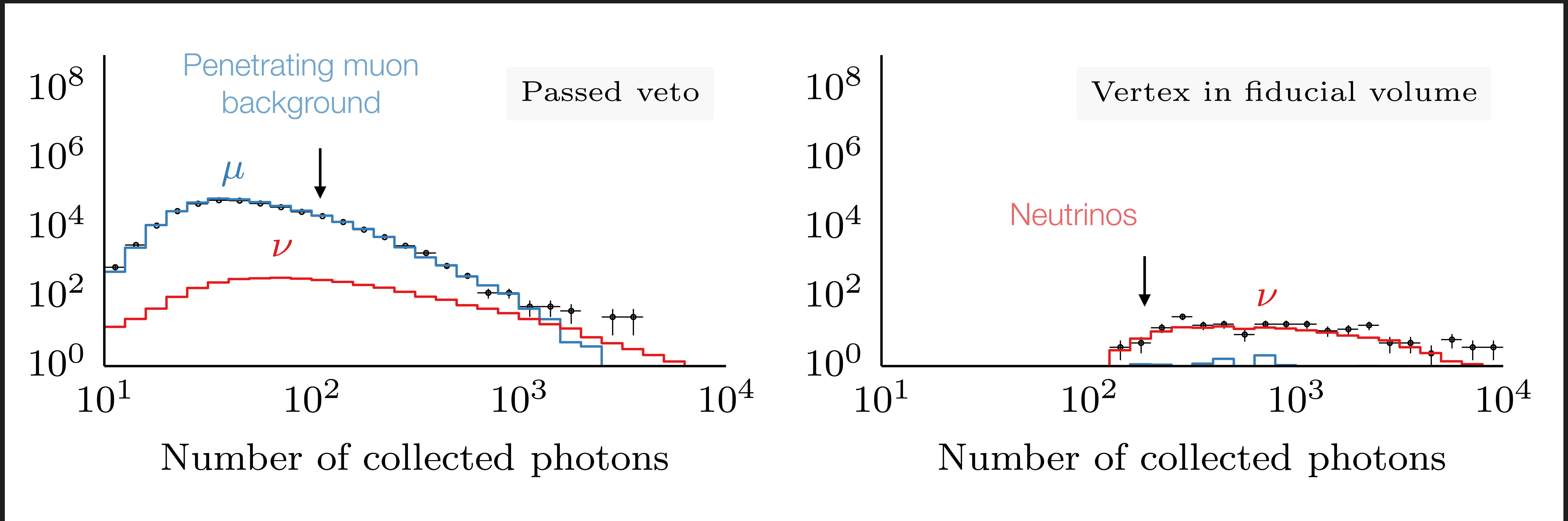
What happens to the astrophysical flux below 60 TeV?

PRD 91, 022001

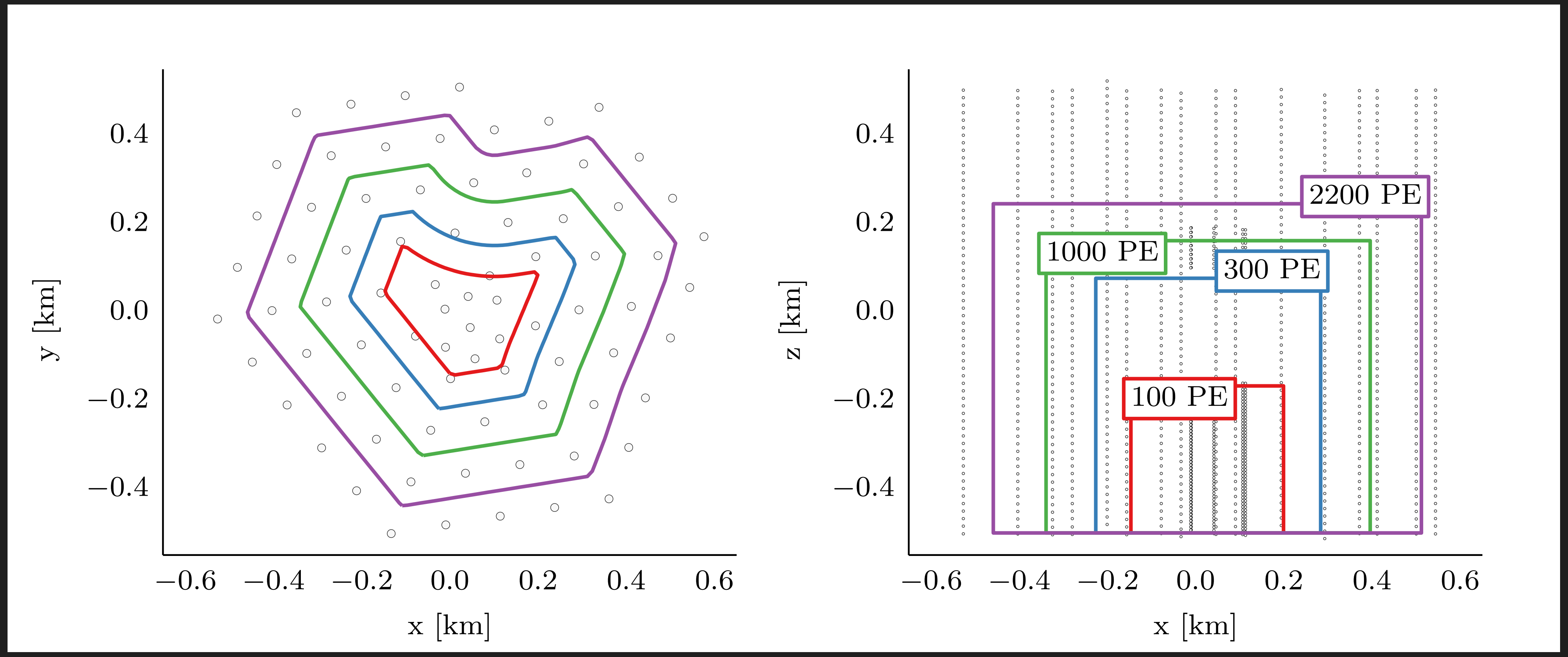
Outer-layer veto → Energy-dependent veto

Neutrino-dominated for E_{dep} > 60 TeV

Neutrino-dominated for E_{dep} > 1 TeV



Thicker veto at low energies suppresses penetrating muons without sacrificing high-energy neutrino acceptance



IMPROVED VETO TECHNIQUES

What happens to the astrophysical flux below 60 TeV?

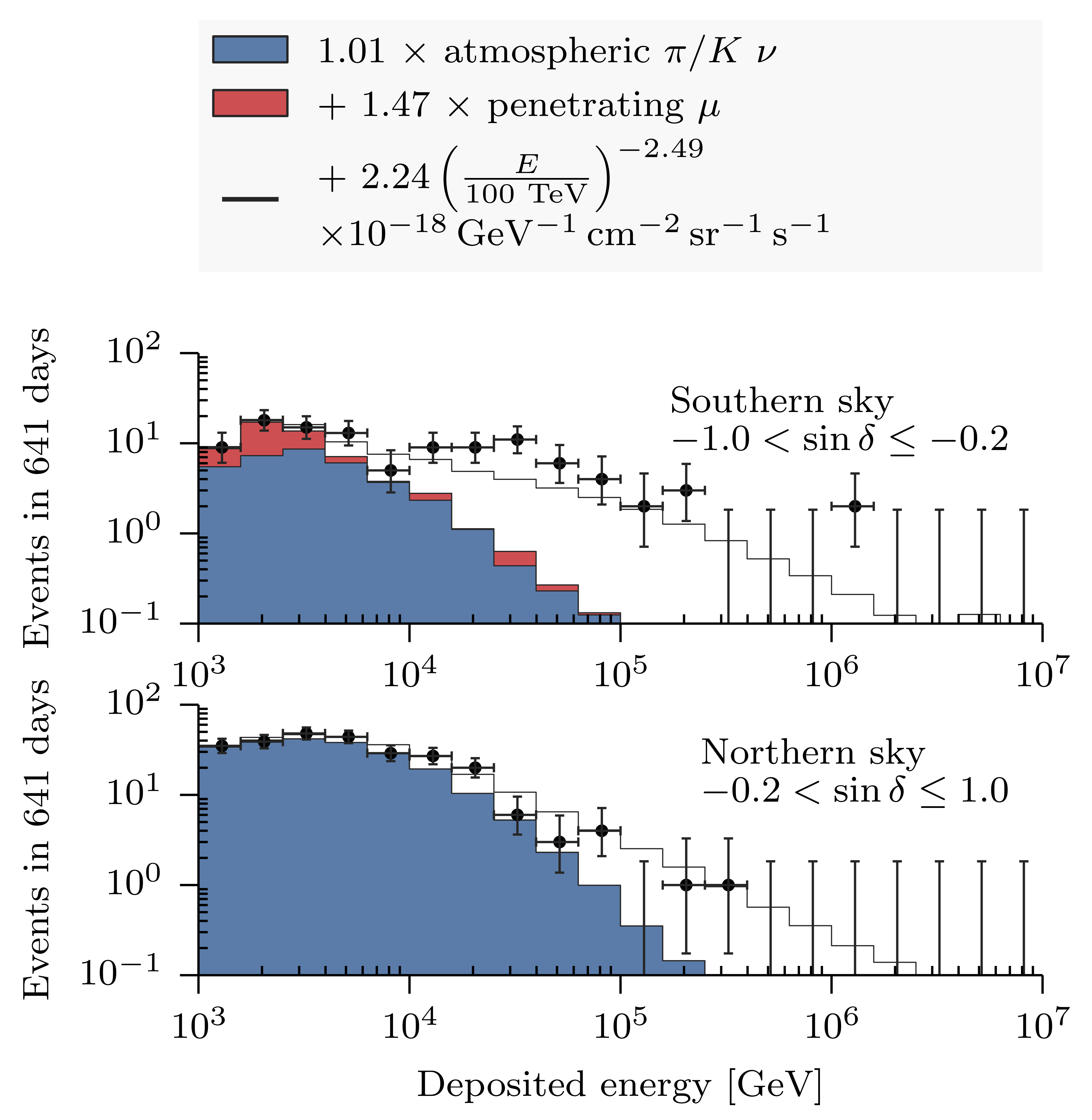
106 events > 10 TeV, 9 events > 100 TeV (7 of those in high-energy starting event sample)

Conventional atmospheric neutrino flux observed at expected level with starting events

Astrophysical excess continues down to 10 TeV in the southern sky

Deviation from model at 30 TeV (statistical fluctuation)

Model-dependent upper limit on flux from charmed meson decay: 1.4 x ERS prediction

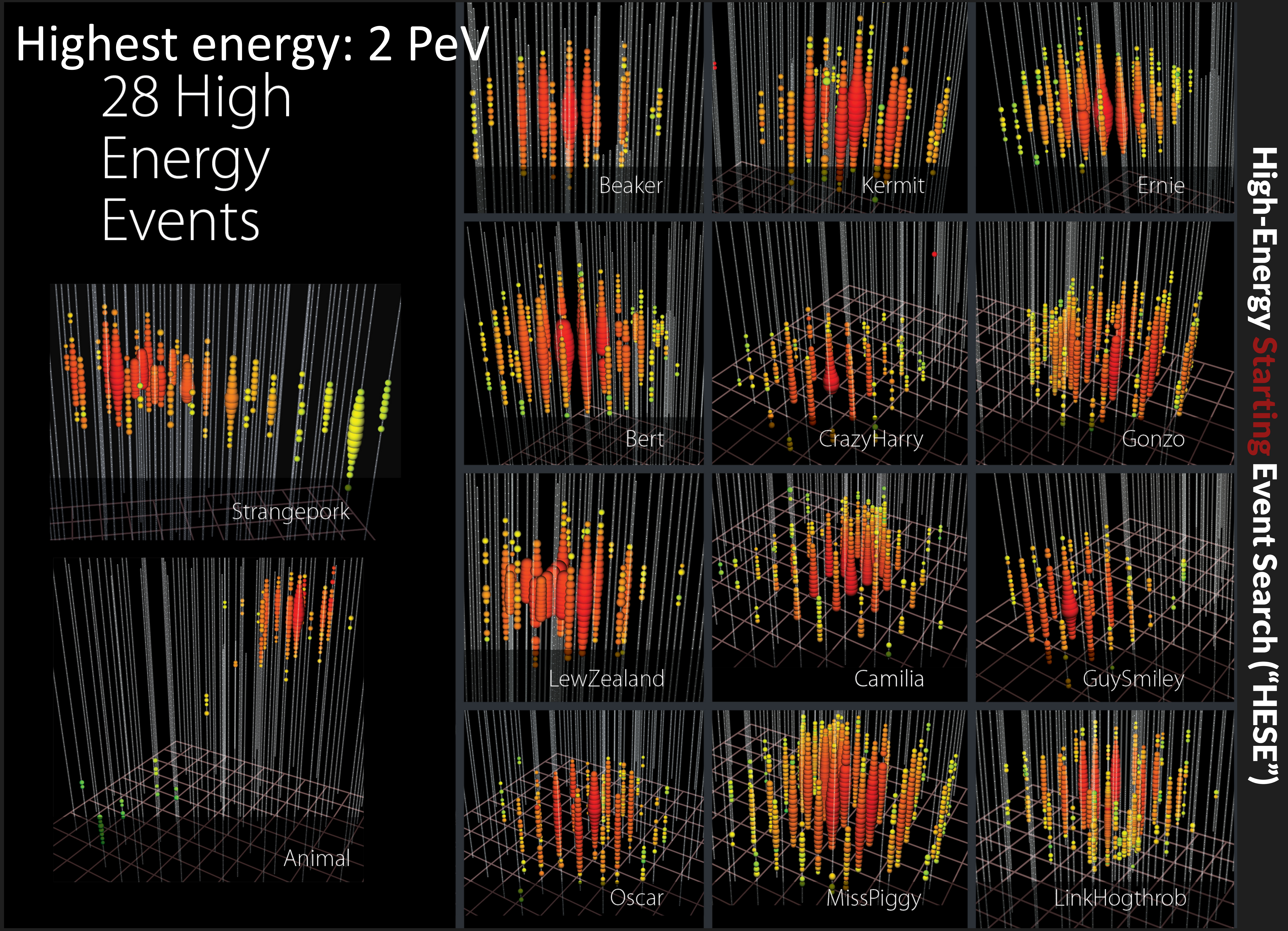


OTHER CHANNELS

Most of the “starting” sample consists of showers, with a high acceptance in the southern sky

Deposited (i.e. measured) energies closely related to neutrino energies

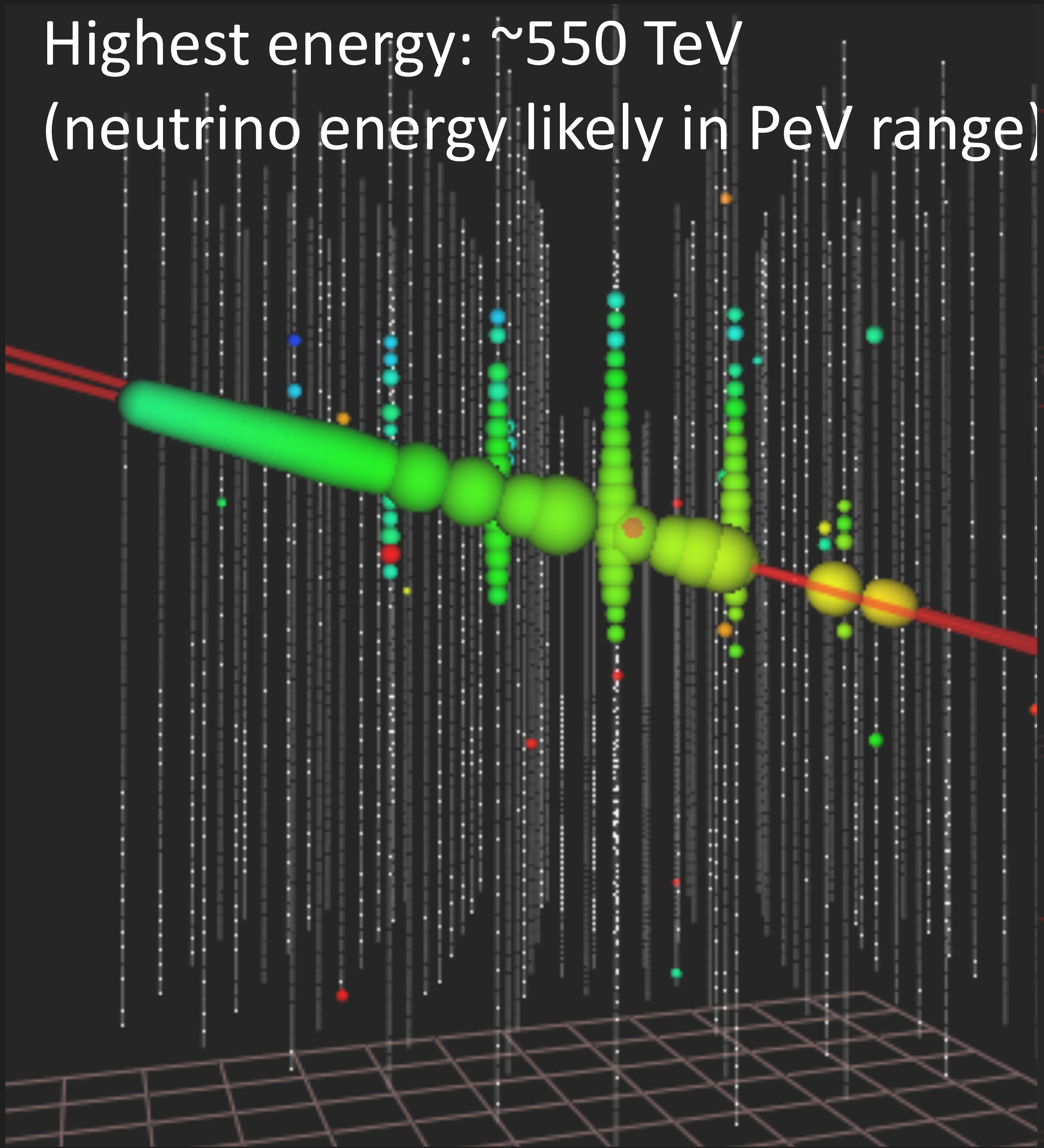
Great for discovering a signal

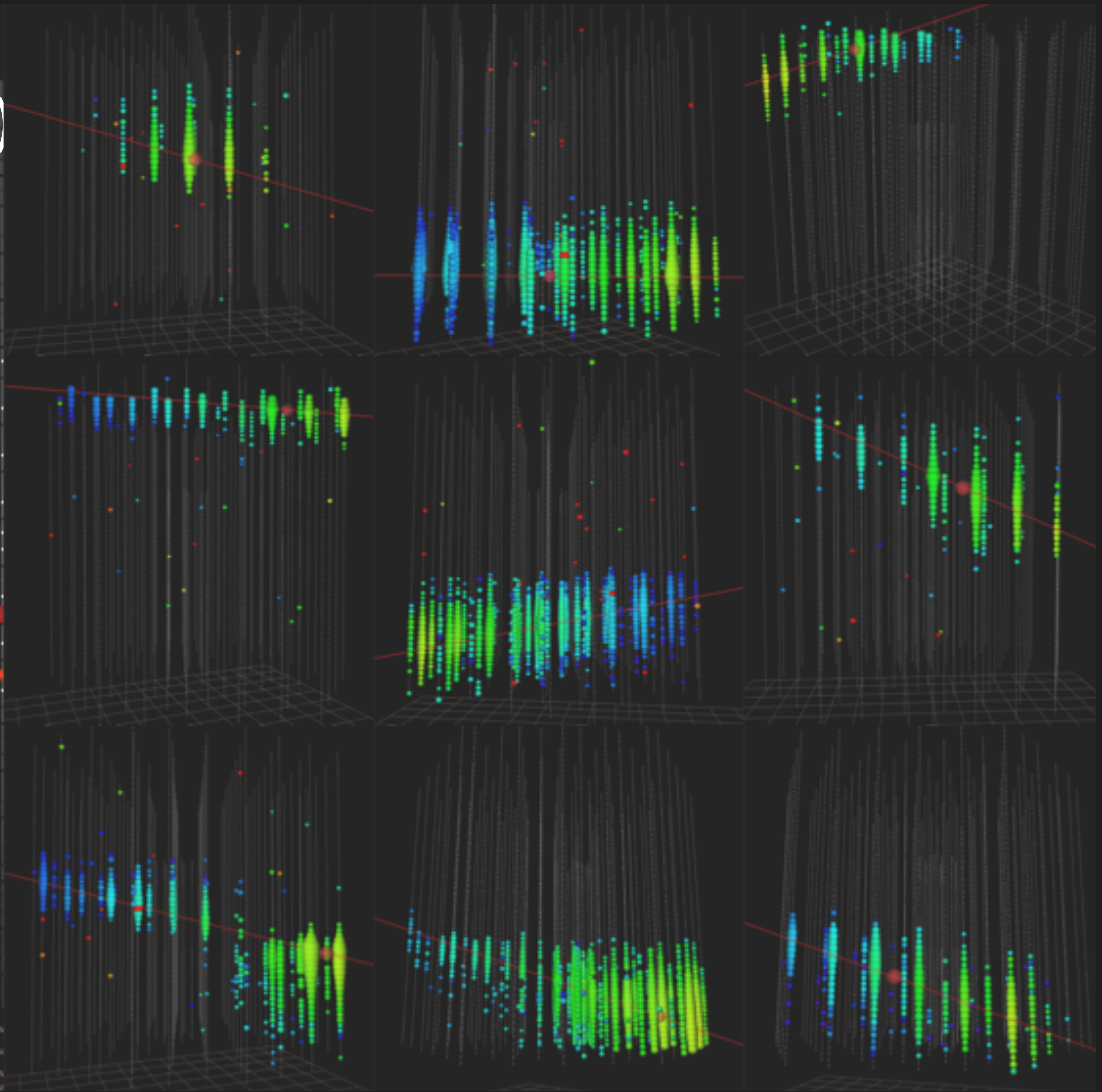


OTHER CHANNELS

Two years of data

IceCube has now seen a similar flux in the muon channel (**3.7σ in 2 years**)





Throughgoing **Muons**

PRL 115, 081102 (2015)

UPGOING MUONS - SPECTRAL COMPONENTS

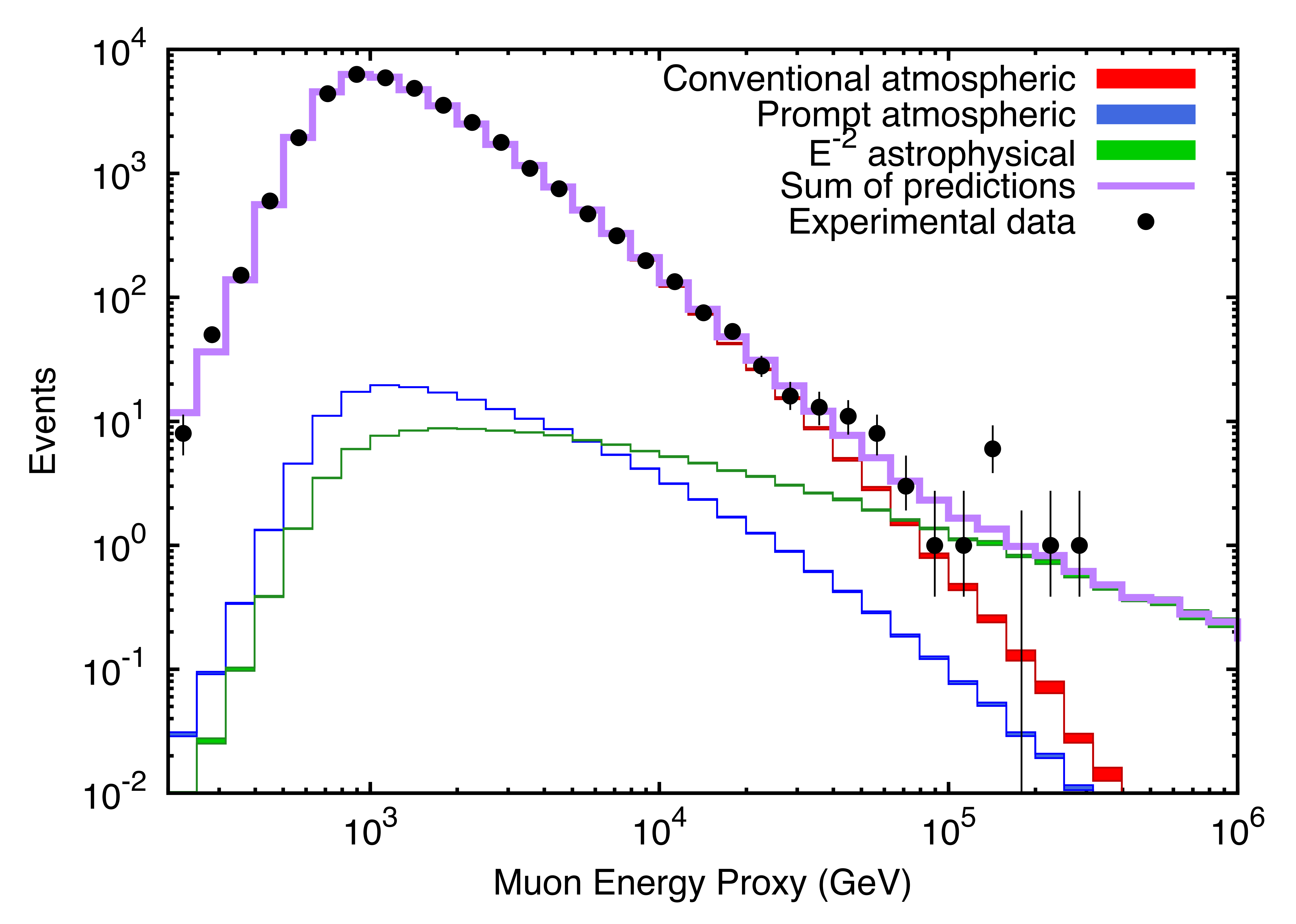
Two years of data

first significant ν_μ -based and northern sky-dominated measurement of the astrophysical neutrino flux

for E^{-2} spectral assumption - (best fit is $E^{-2.2}$)

Normalization for E^{-2}:
$0.99^{+0.4}_{-0.3}\ 10^{-8}\ E^{-2}\ \mathrm{GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}$

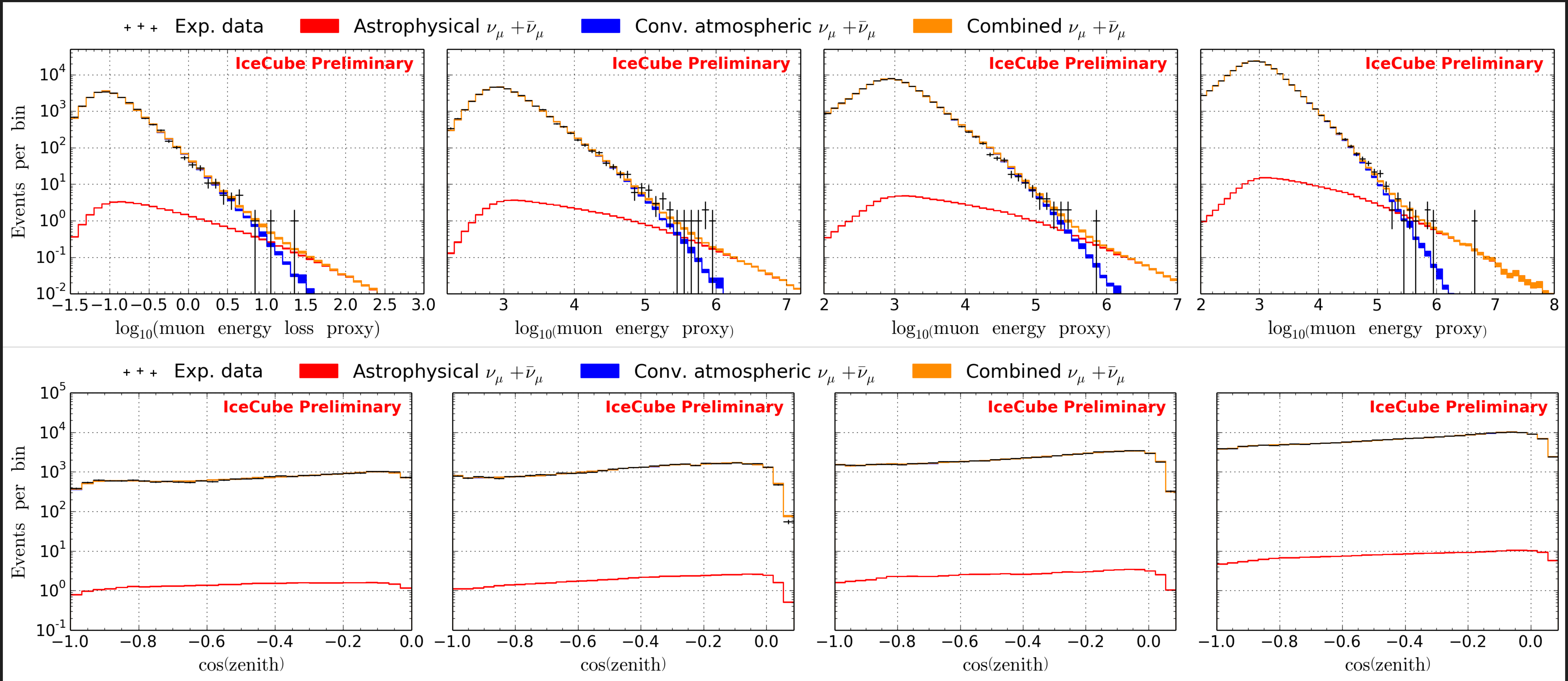
PRL 115, 081102 (2015)



UPGOING MUONS - SPECTRAL COMPONENTS

Six years of data - (previous two years re-analyzed)

Now looking at up to 6 years of muon data (2009-2015) - good data/MC agreement

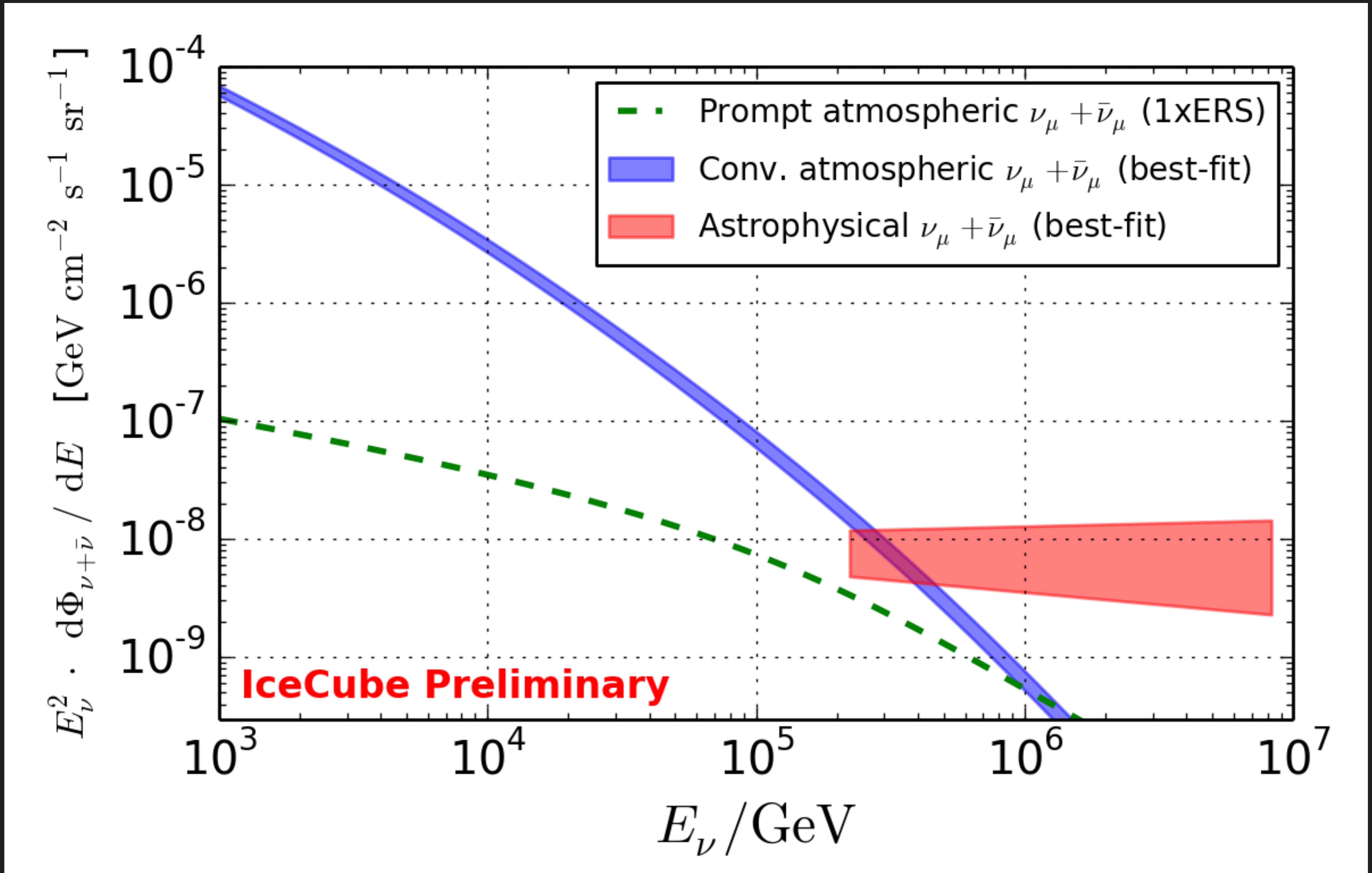


UPGOING MUONS - SPECTRAL COMPONENTS

Six years of data

Preliminary fit: $\Phi(E_\nu) = 0.82^{+0.30}_{-0.26}\ 10^{-18}\ \mathrm{GeV^{-1}cm^{-2}sr^{-1}s^{-1}}\ (E_\nu/100\mathrm{TeV})^{-(2.08\pm0.13)}$

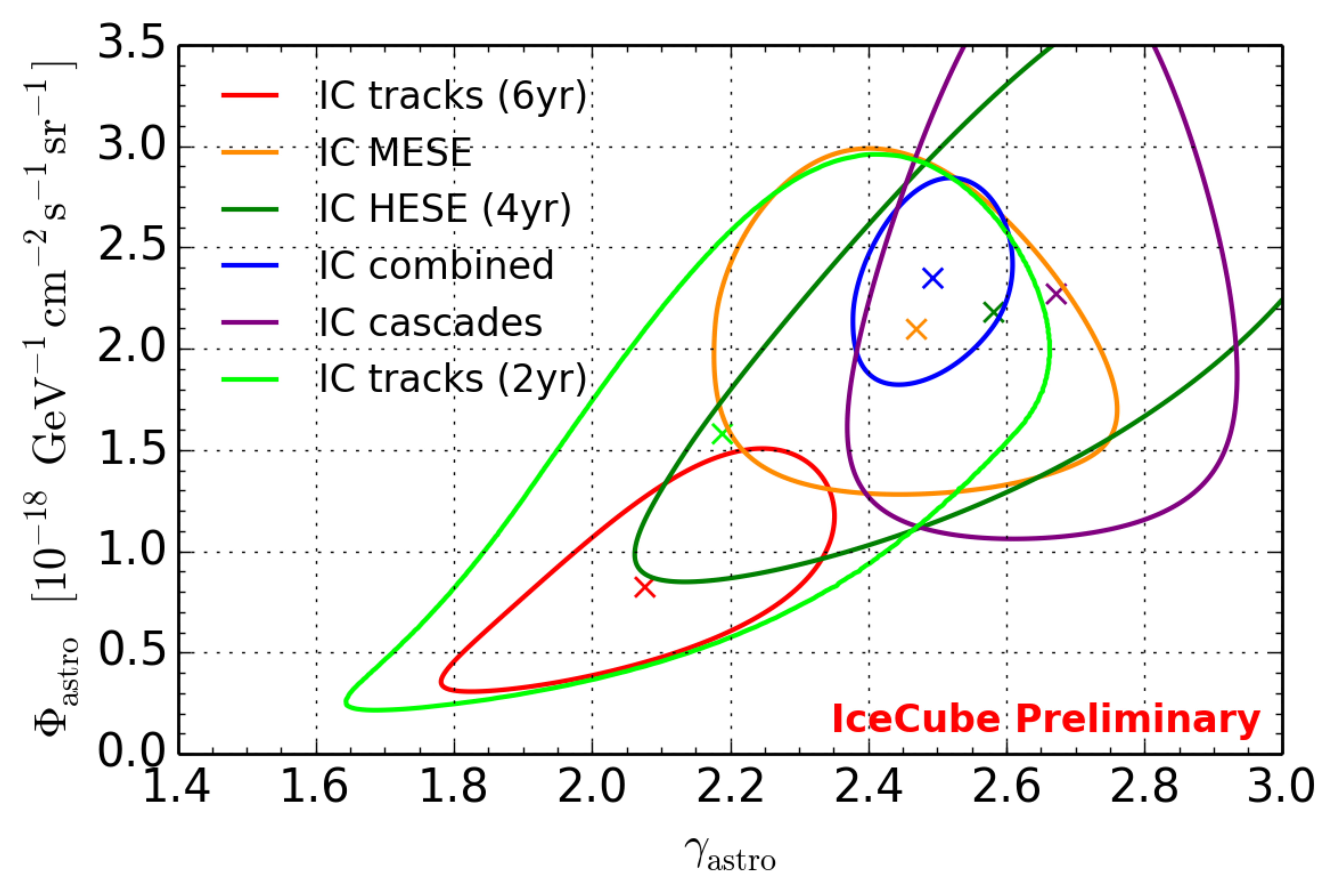
prompt fits to 0, upper limit details under study



SUMMARY OF VARIOUS ICECUBE DIFFUSE RESULTS

all astrophysical fits shown are single unbroken power-laws

90% C.L. contours of various IceCube analyses - all single unbroken power-law fits
some tension between **6-year track** sample and **global fit** of previous results



6-year tracks
(previous slides, ν_μ, Northern Sky)

PRD 91, 022001 (2015)
(all-flavor)

PoS(ICRC2015)1081
(all-flavor, previous slides)

PoS(ICRC2015)1066
(combined fit, all-flavor)

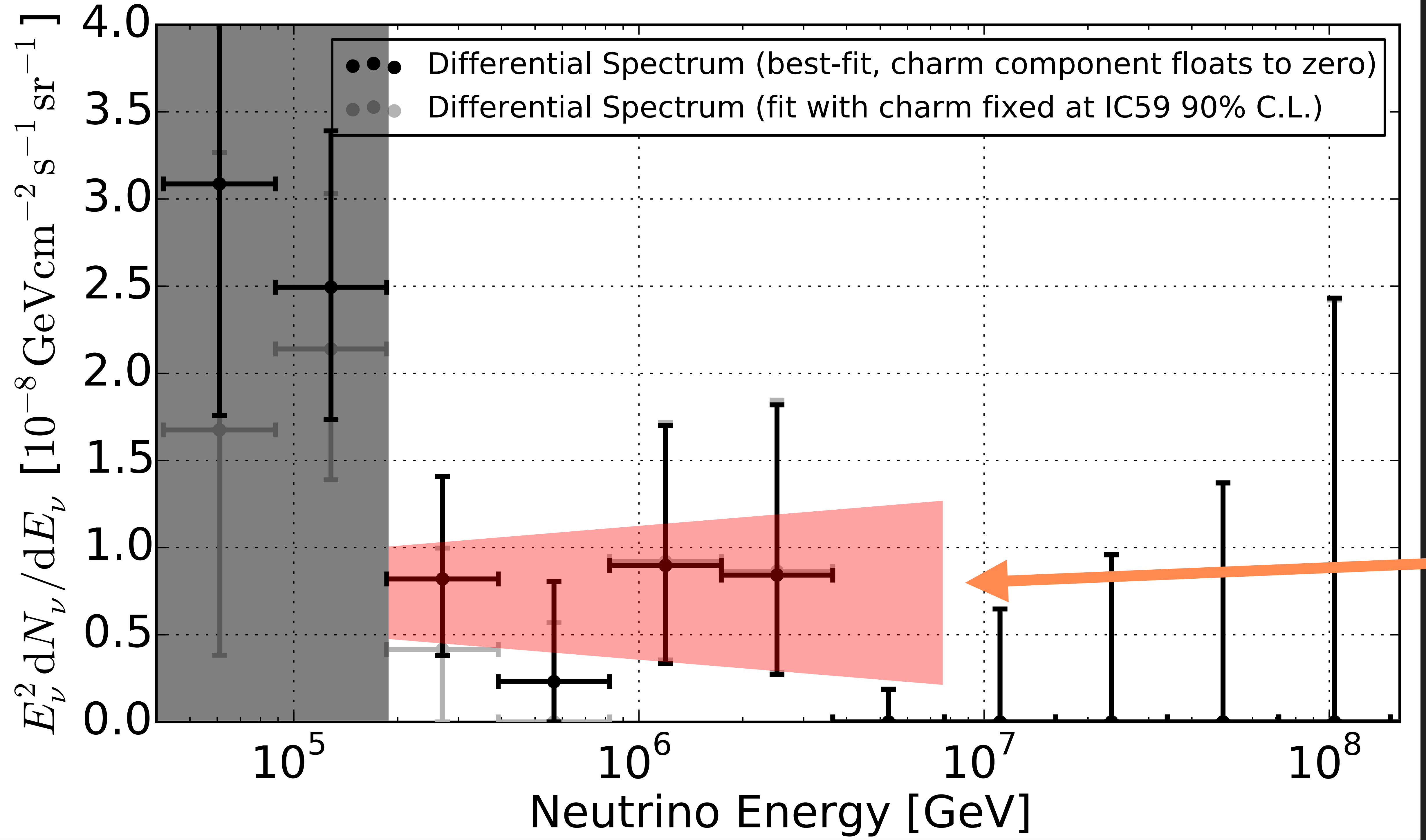
PoS(ICRC2015)1109
(cascades)

PRL 115, 081102 (2015)
(ν_μ, Northern Sky)

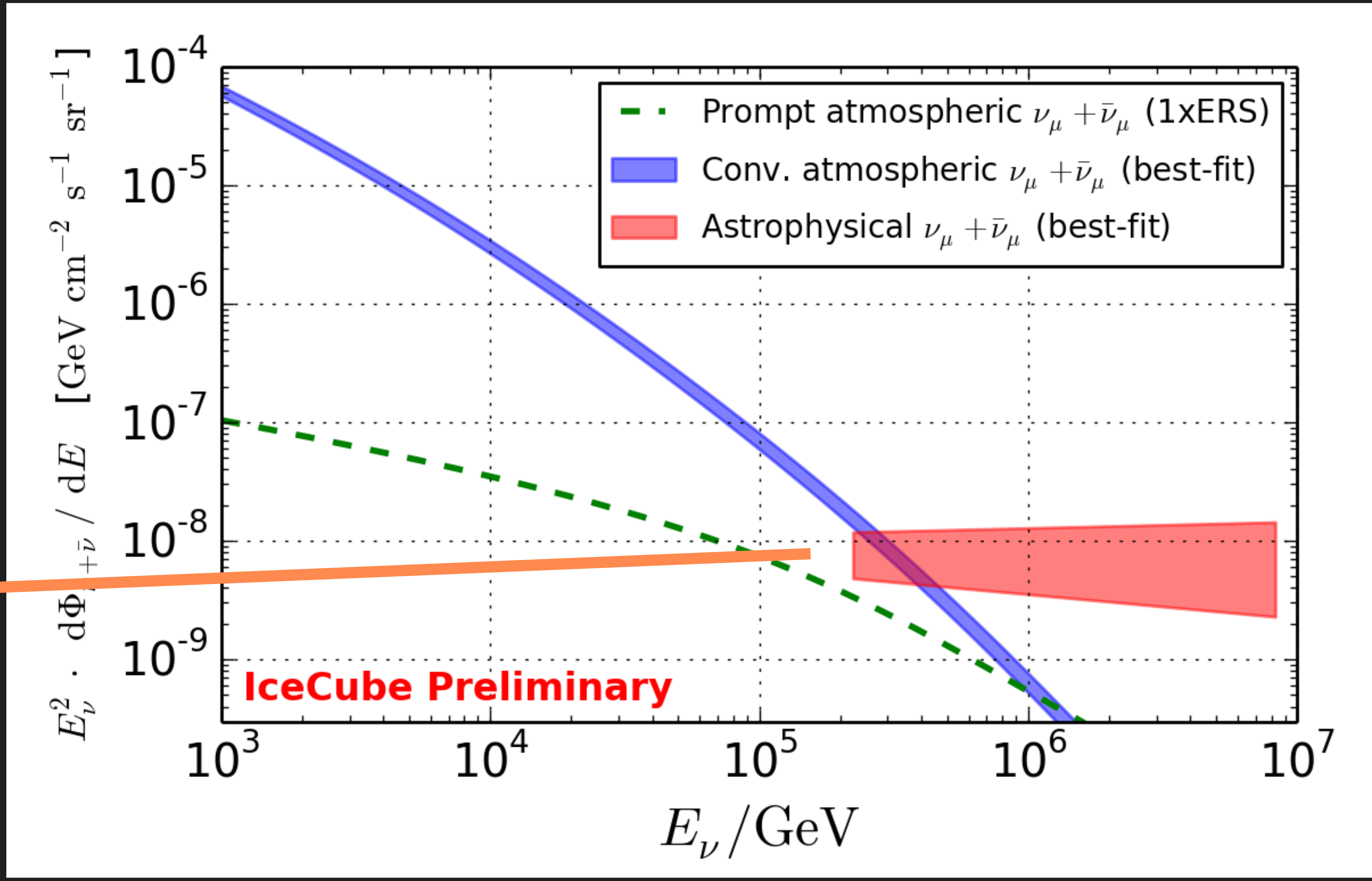
COMPARISON WITH STARTING EVENT RESULTS

we start to see that simple power laws for the whole sky are probably not enough...

starting events (unfolding)
(dominated by showers)



6 year up-going ν_μ analysis



threshold order of 60 TeV
softer index driven by lower energy bins

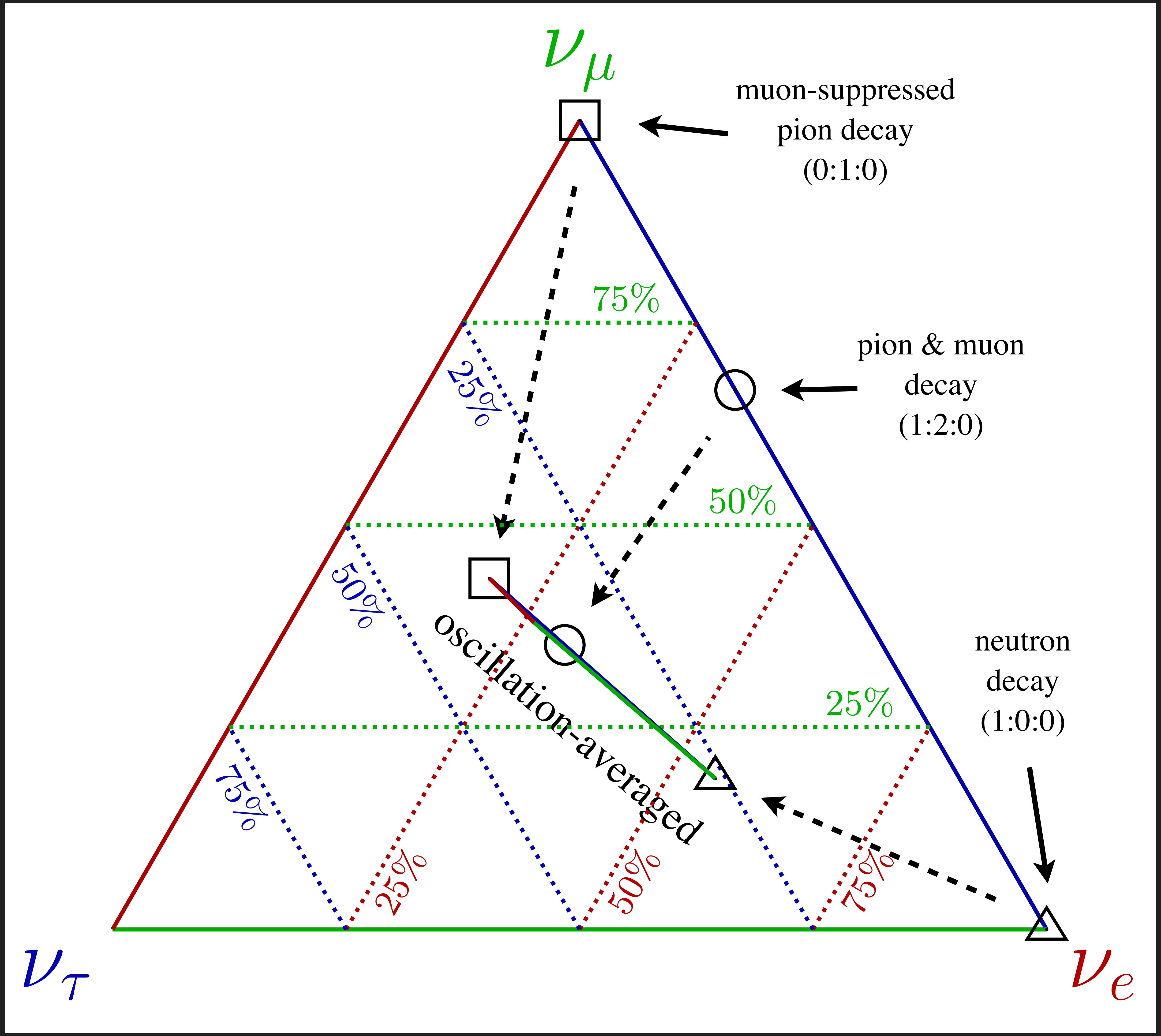
threshold of about 200 TeV
compatible at higher energies

FLAVOR COMPOSITION

Flavor ratio at Earth contains information about source ratio after oscillations en route to Earth

For standard oscillations, only a small region of flavor ratios is allowed at Earth

	at source		⟶	at Earth		
	ν_e	ν_μ	ν_τ	ν_e	ν_μ	ν_τ
pion decay	1	2	0	1	1	1
muon-damped	0	1	0	0.2	0.39	0.39
neutron decay	1	0	0	0.56	0.22	0.22



GLOBAL FIT OF ICECUBE ANALYSES

interesting results such as flavor ratio

fit for flavor ratio, spectral shape and cutoff

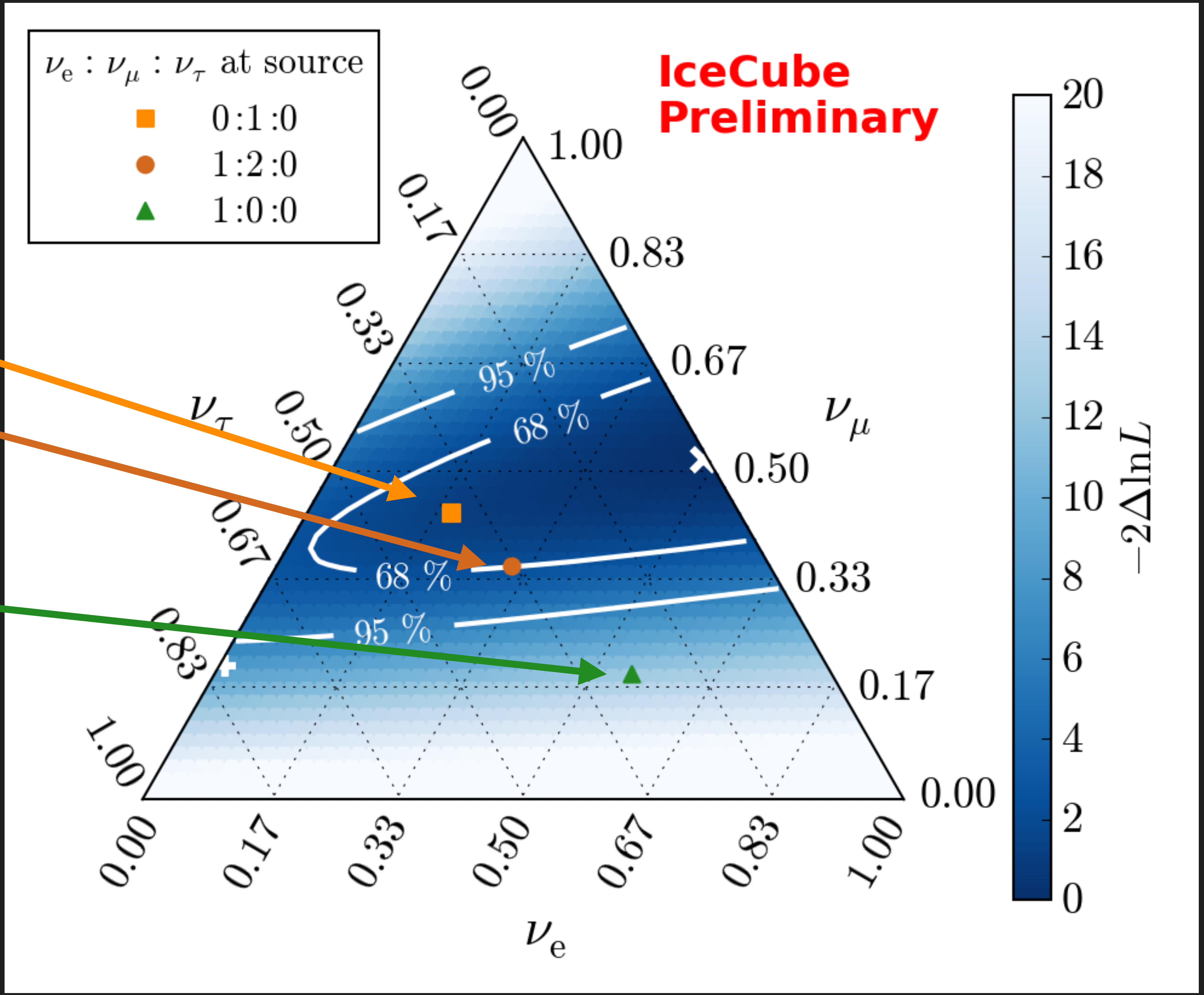
muon-damped (0:1:0)

pion decay (1:2:0)

→ compatible

neutron decay (1:0:0)

→ excluded at 3.7σ

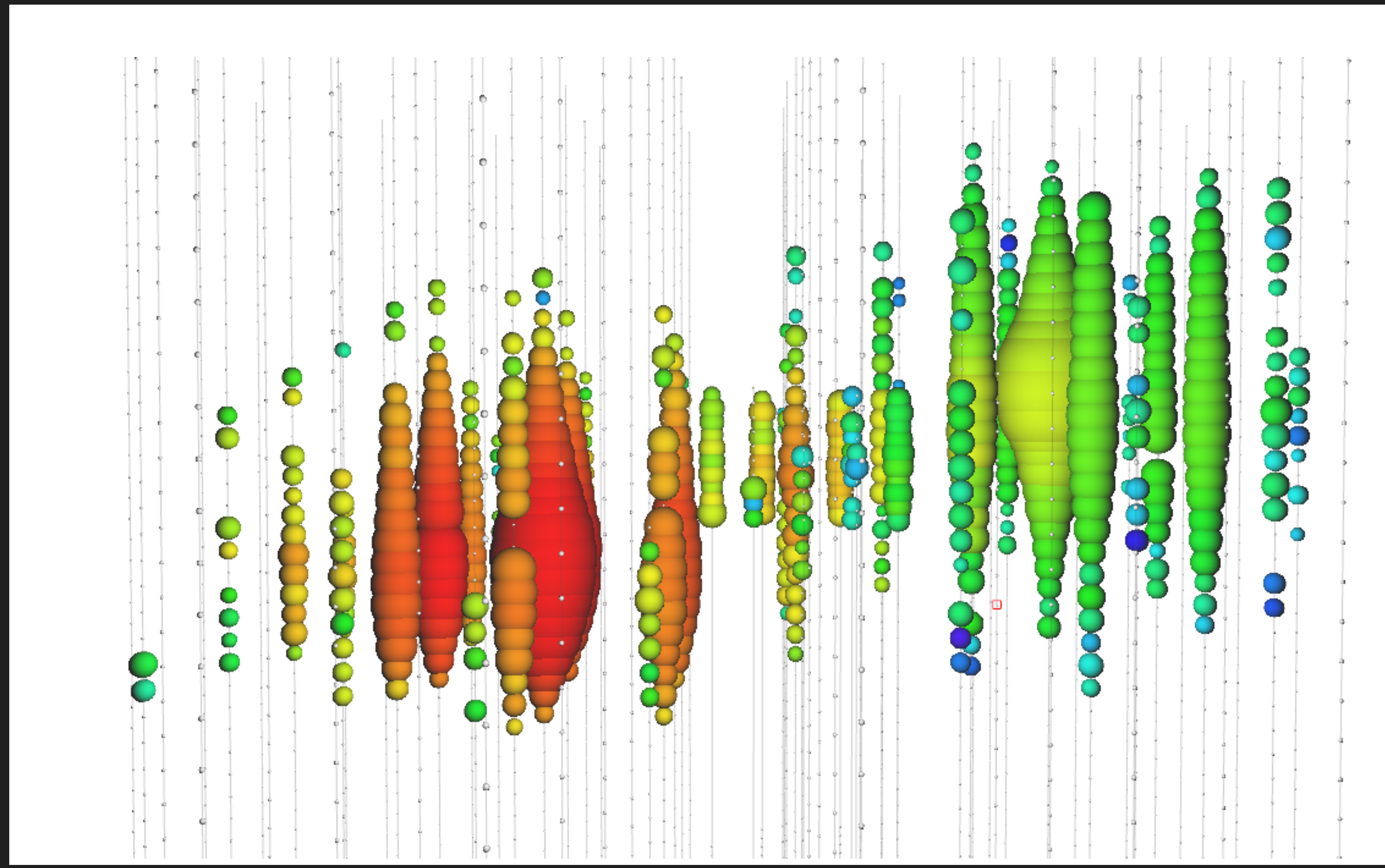


ApJ 809, 98 (2015)/ PoS(ICRC2015)1066

TAU NEUTRINOS

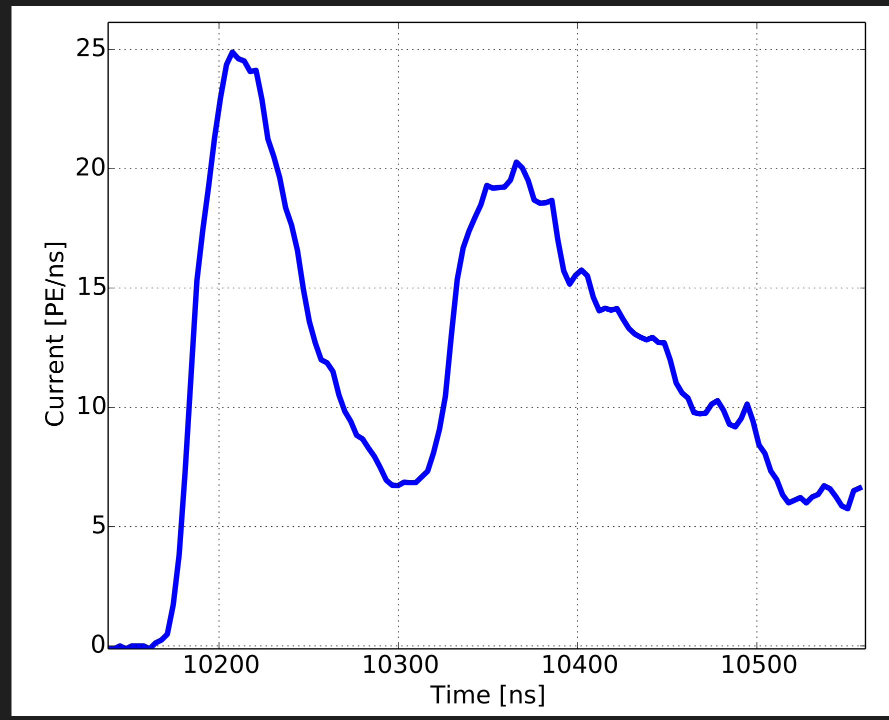
should see the first taus soon

should be able to identify a “double-bang” signature above ~PeV - not observed yet!



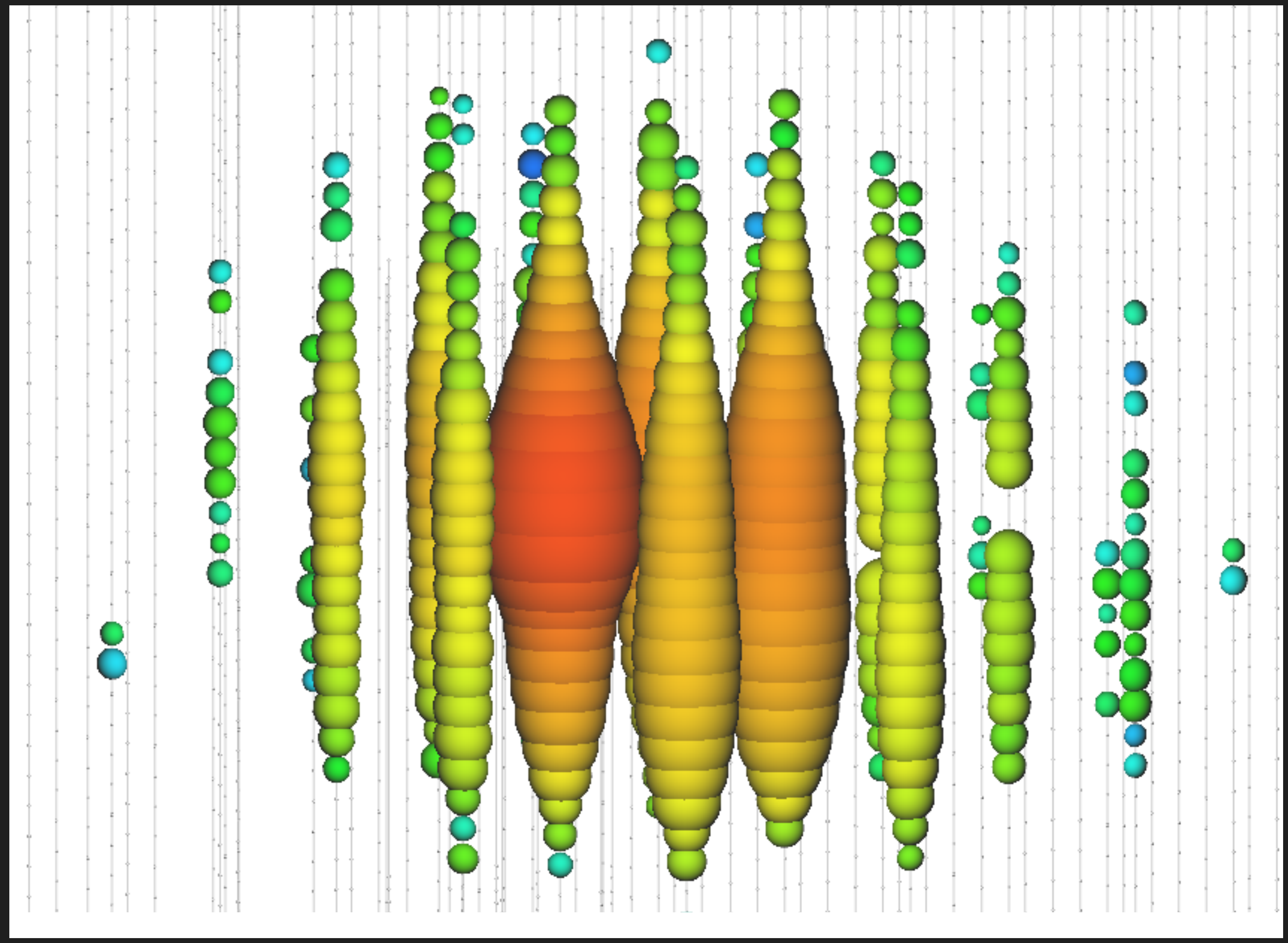
event with longer decay length

at lower energies identification is more challenging - IceCube just set new limits!

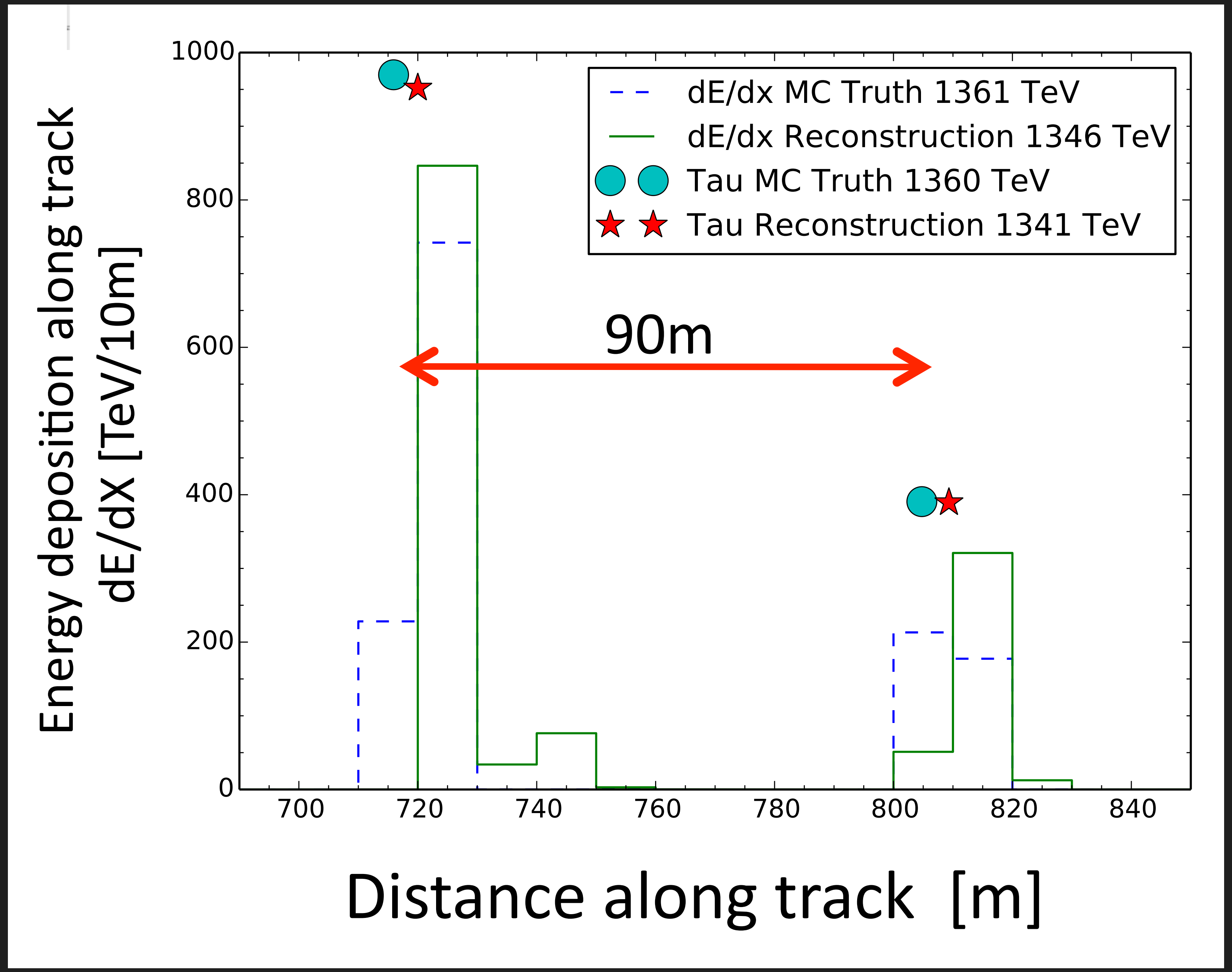


lower energy tau study

PRD 93, 022001 (2016)

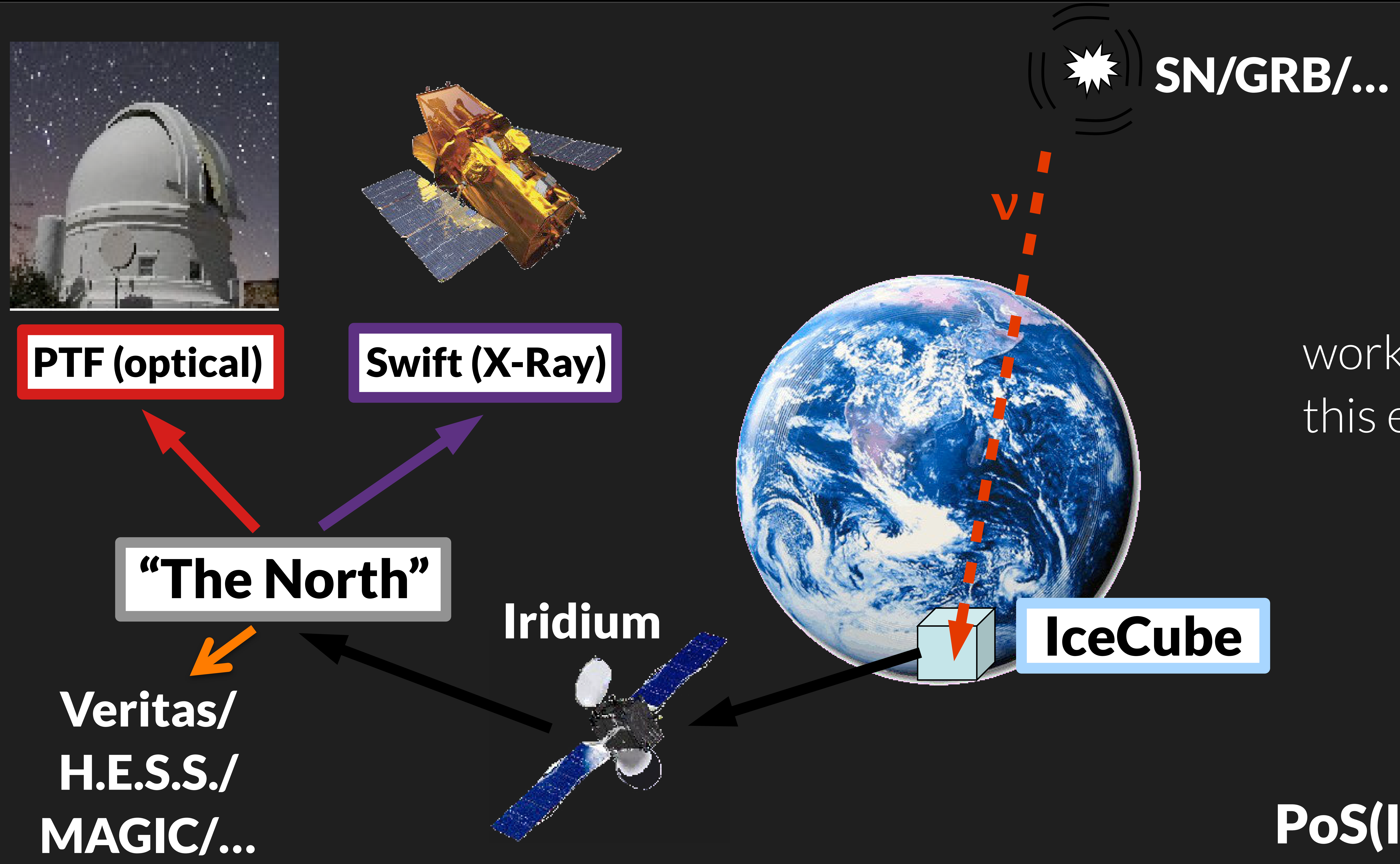


simulated event, 1.36PeV
(no data event identified yet)



ALERTS/FOLLOW-UPS

we try to alert other experiments as soon as we see an interesting event



working on extending this effort significantly!

PoS(ICRC2015)1069

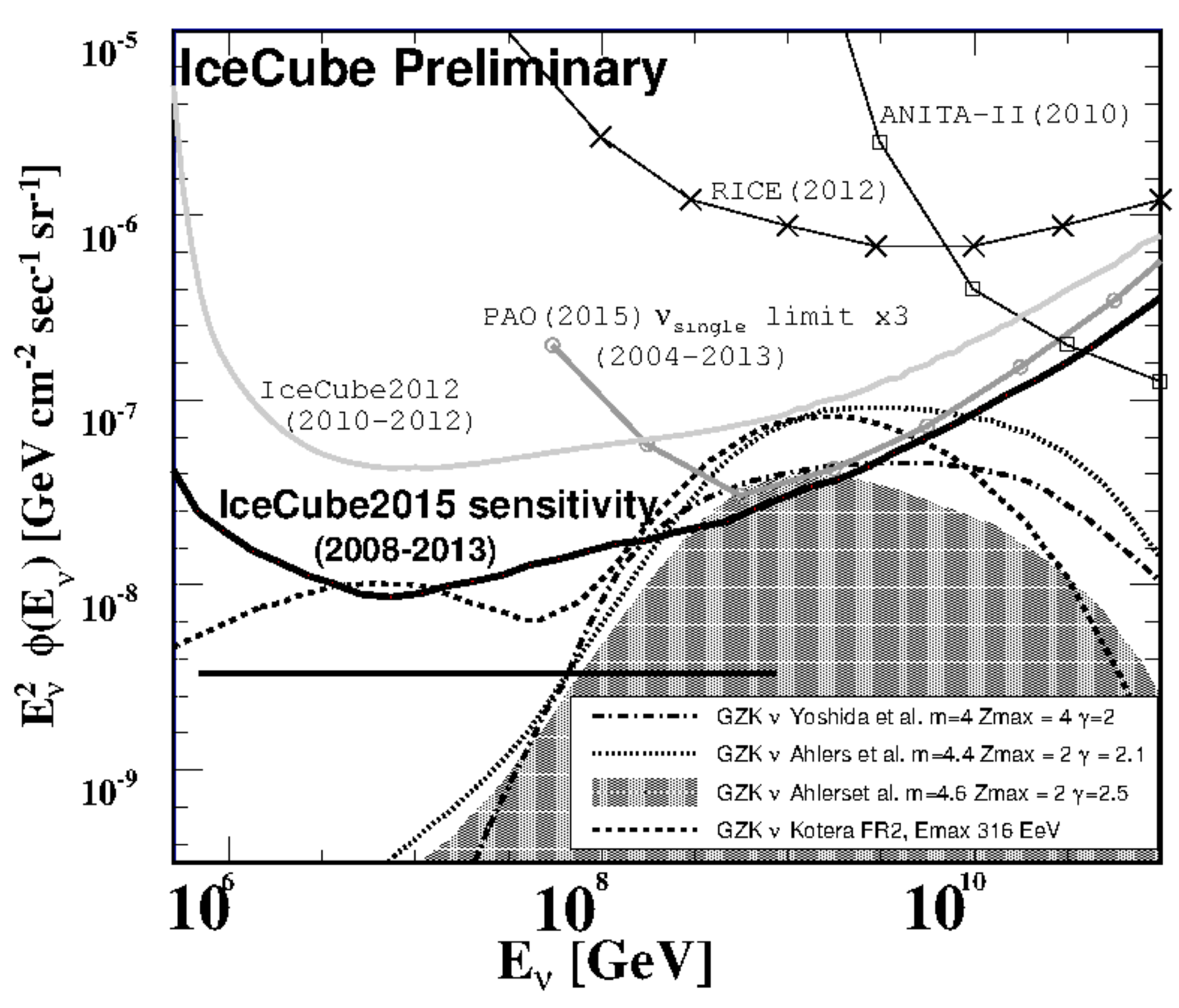
COSMOGENIC (GZK) NEUTRINOS

updated limit with even larger data set

IceCube searches for extremely high-energy events from neutrinos generated by interactions of CR particles on the CMB

Updated to 6 years of data

PoS(ICRC2015)1064



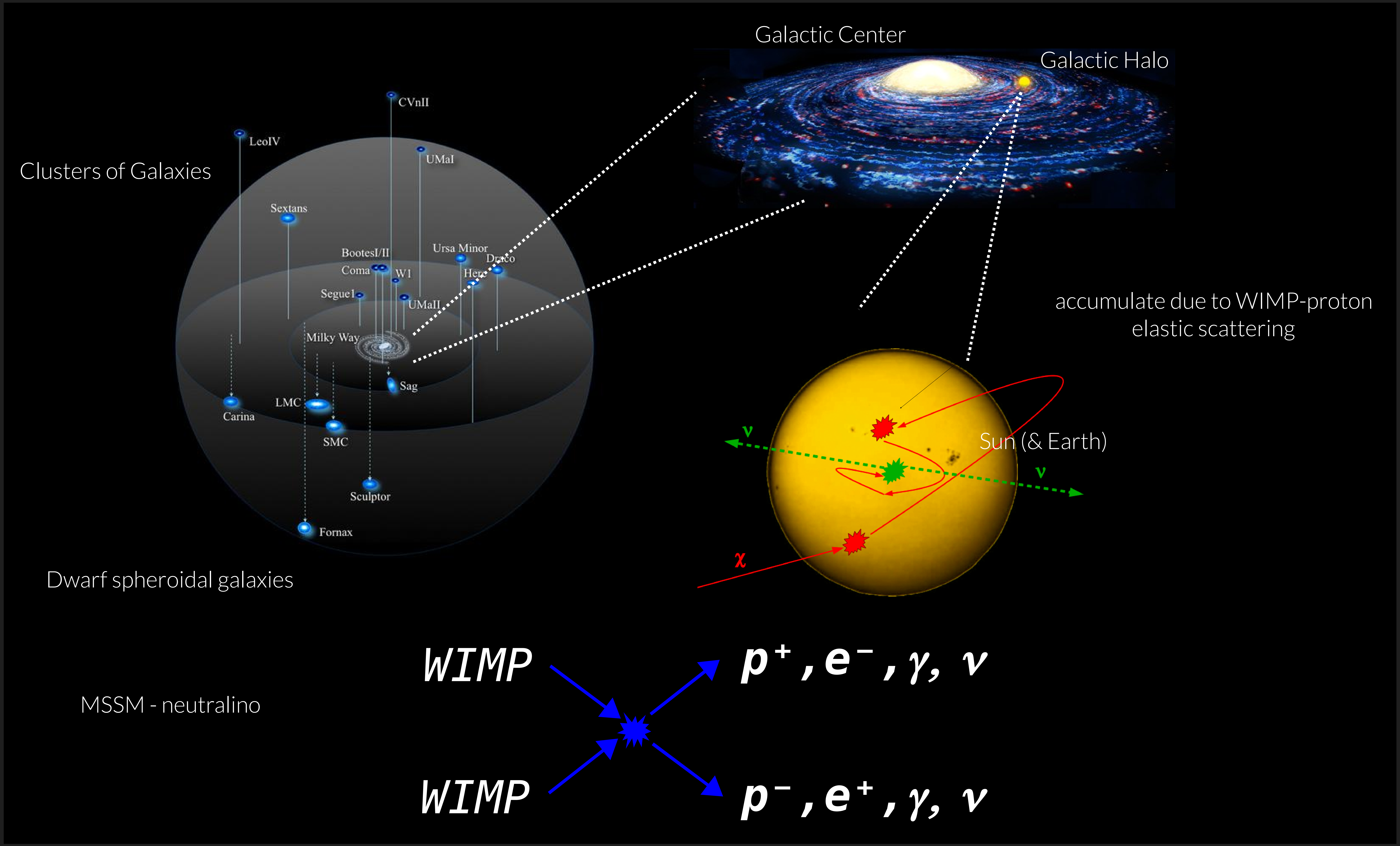
ν

DARK MATTER

(High-Energy) Neutrino Signals from the Sun, the Galactic Center, Halo and more!

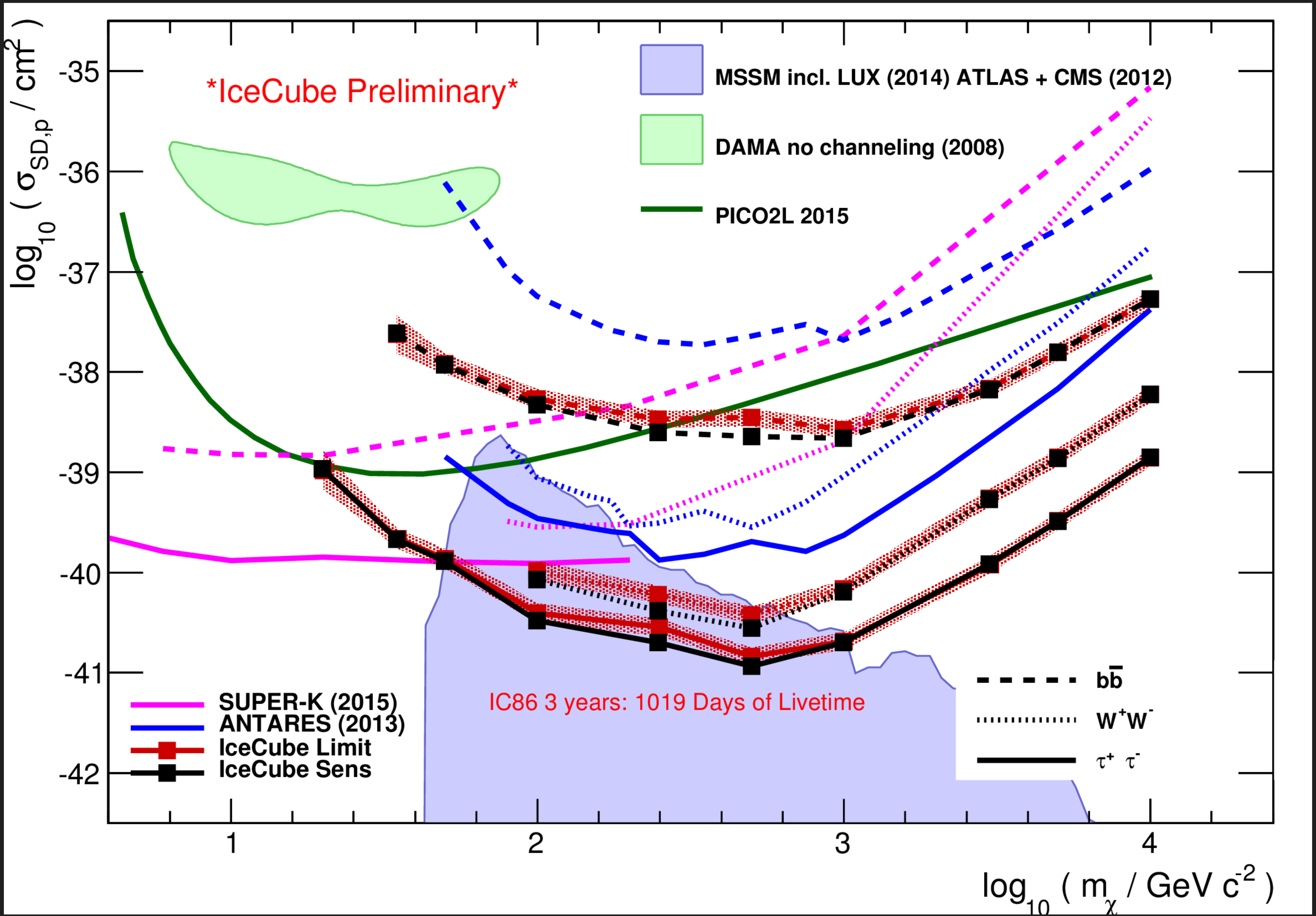
INDIRECT DARK MATTER SEARCHES

Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe



SOLAR WIMP RESULTS - ICECUBE 3 YEARS

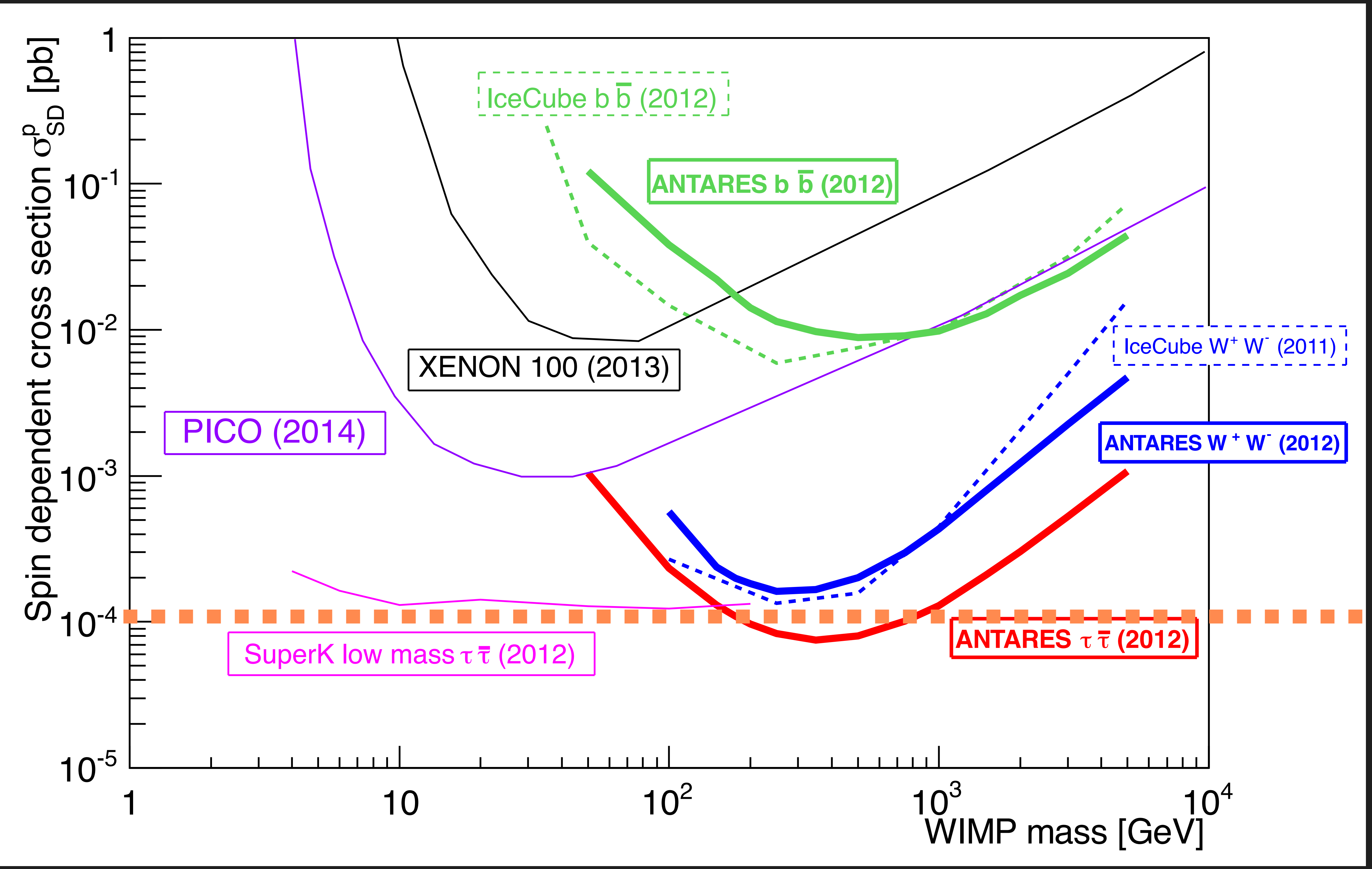
example of one channel where IceCube sets competitive limits



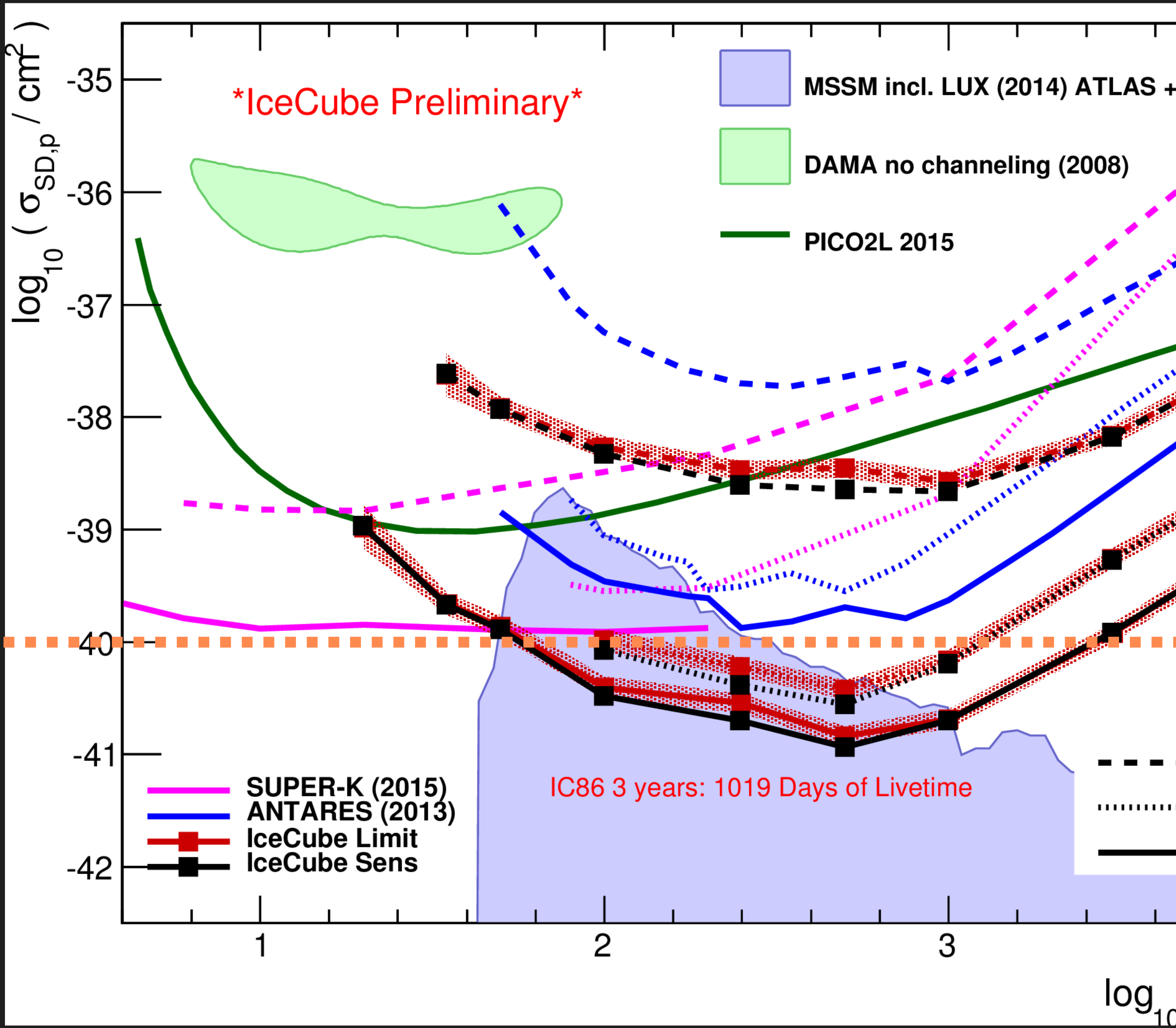
SOLAR WIMP RESULTS - ANTARES

compared to similar limits from ANTARES

ANTARES



PoS(ICRC2015)024



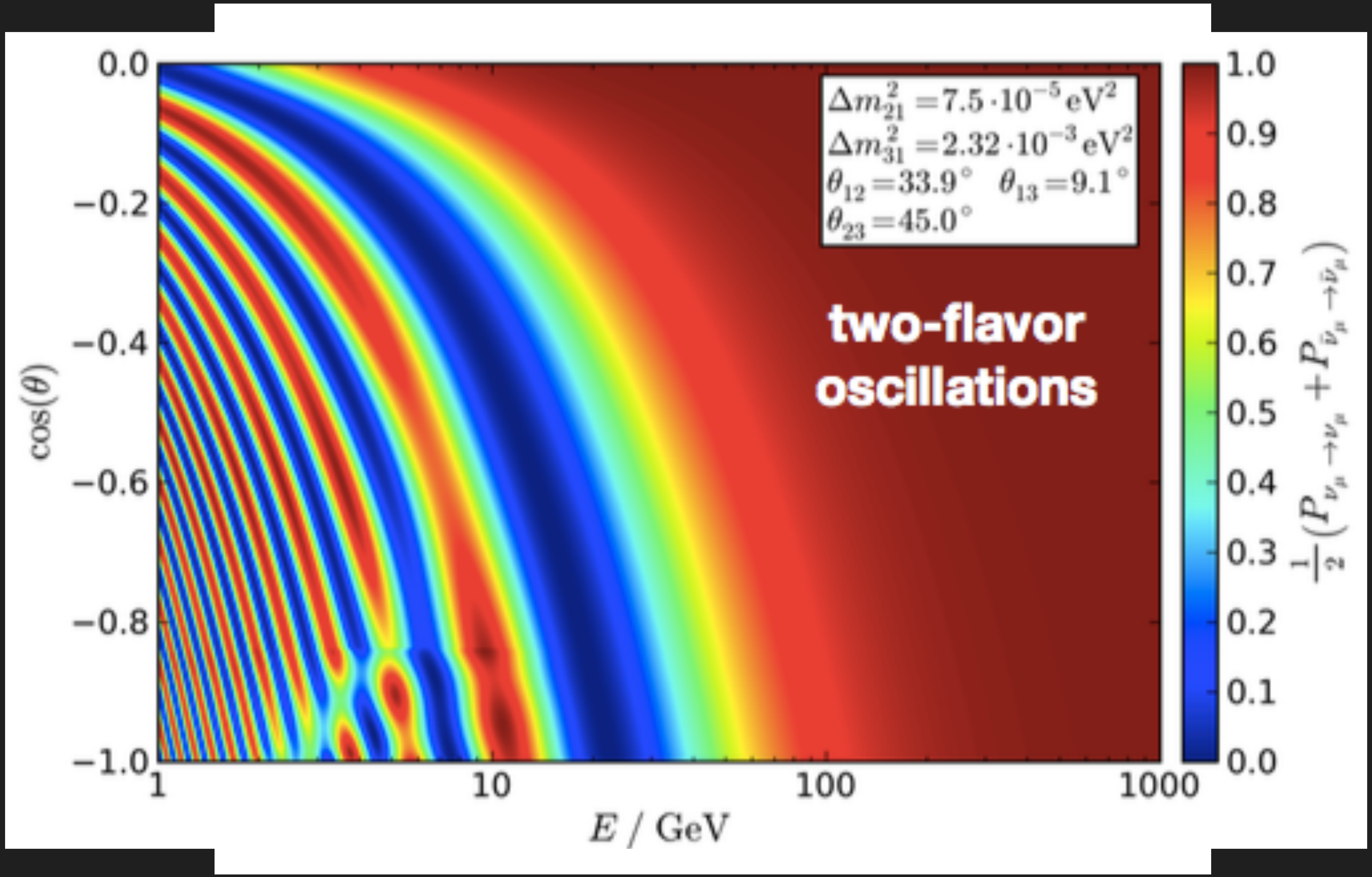
NEUTRINO OSCILLATIONS

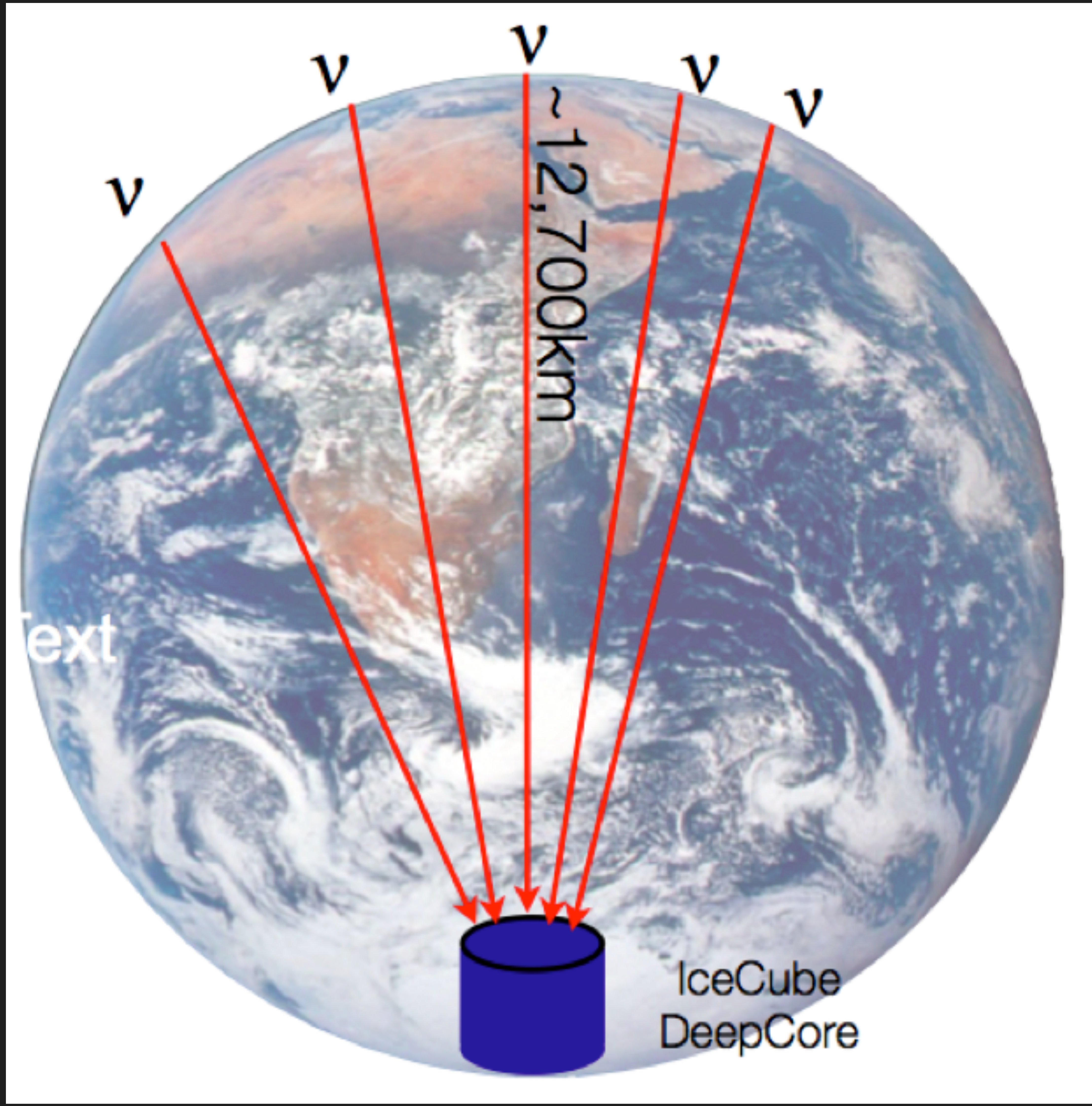
Using the atmospheric neutrino "background" to study neutrino physics

NEUTRINO OSCILLATIONS WITH ATMOSPHERIC NEUTRINOS

neutrino oscillations through Earth's diameter are accessible by IceCube/DeepCore

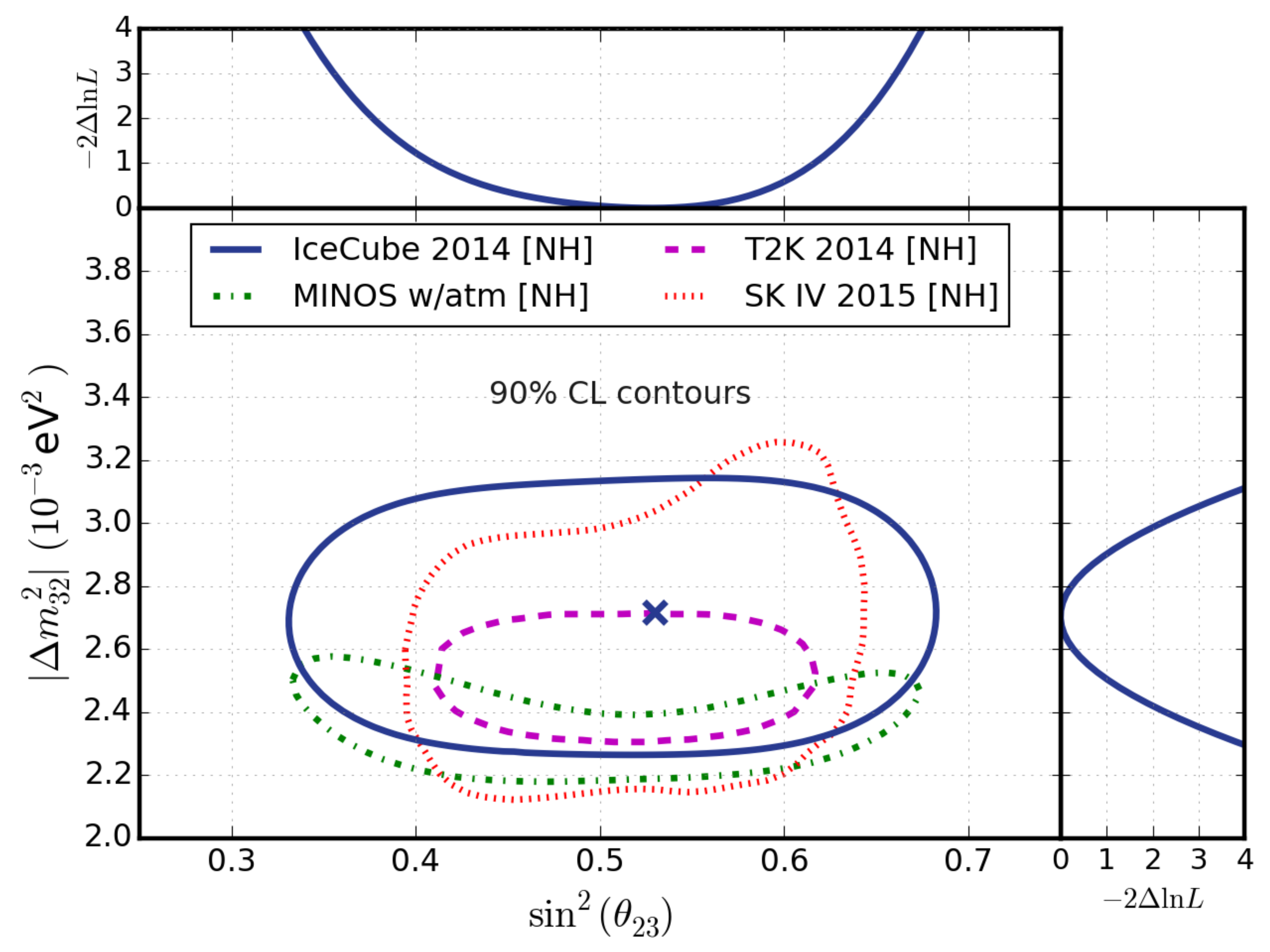
First oscillation maximum at 24 GeV, accessible with DeepCore

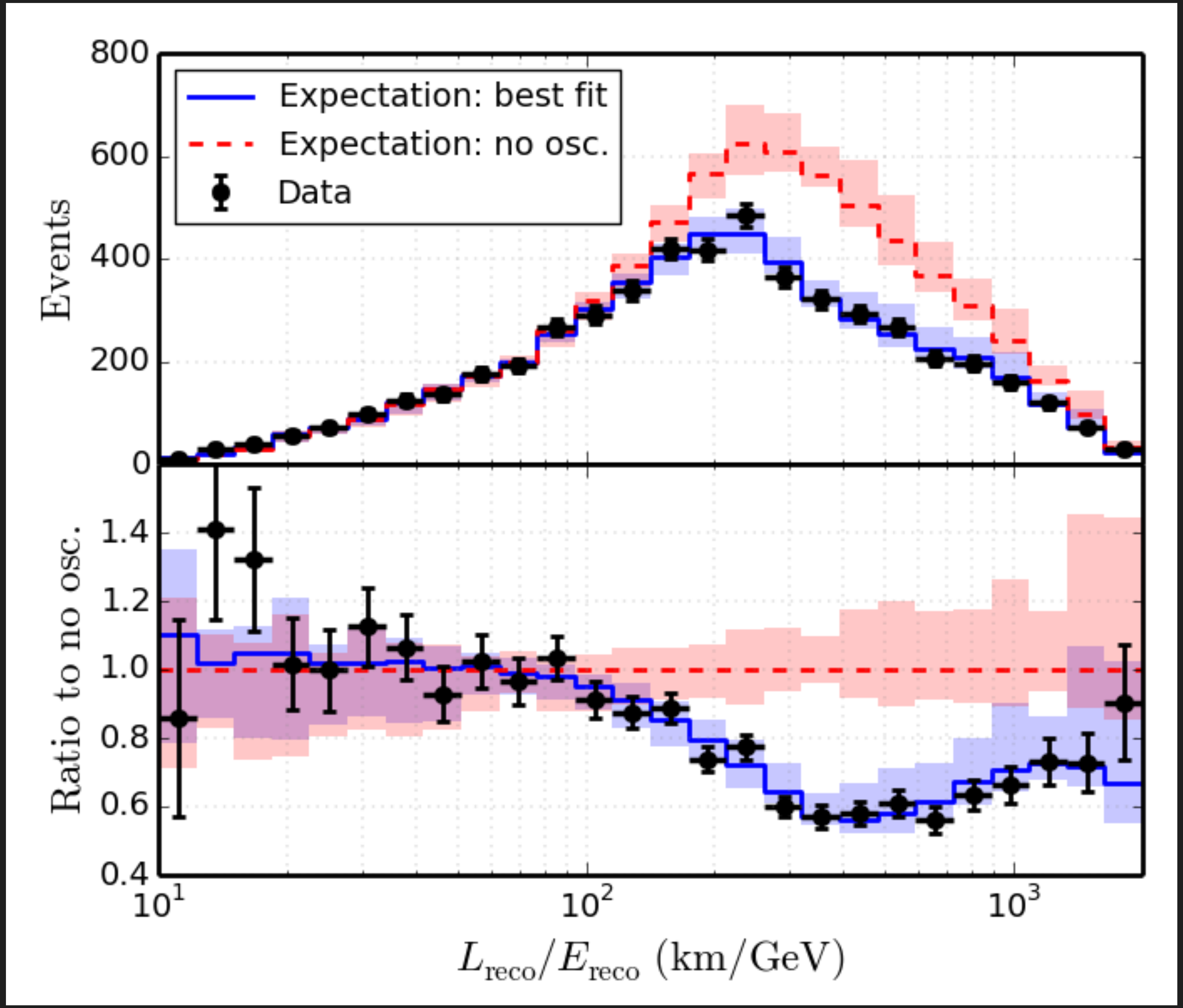




3-YEAR MUON DISAPPEARANCE STUDY

3 years of data (2011-2014, 953 days) - competitive with other experiments





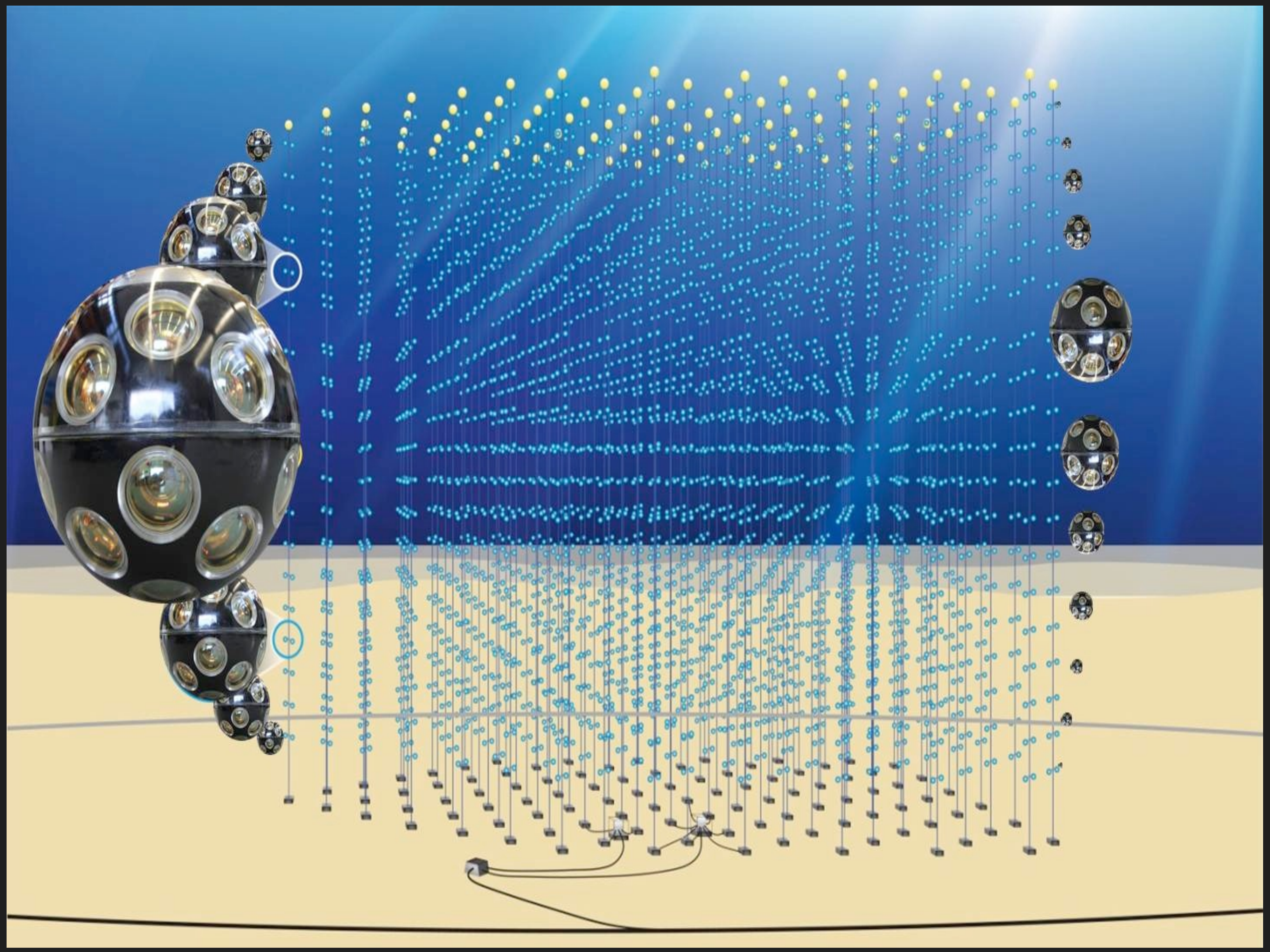
PRD 91, 072004 (2015)

THE FUTURE

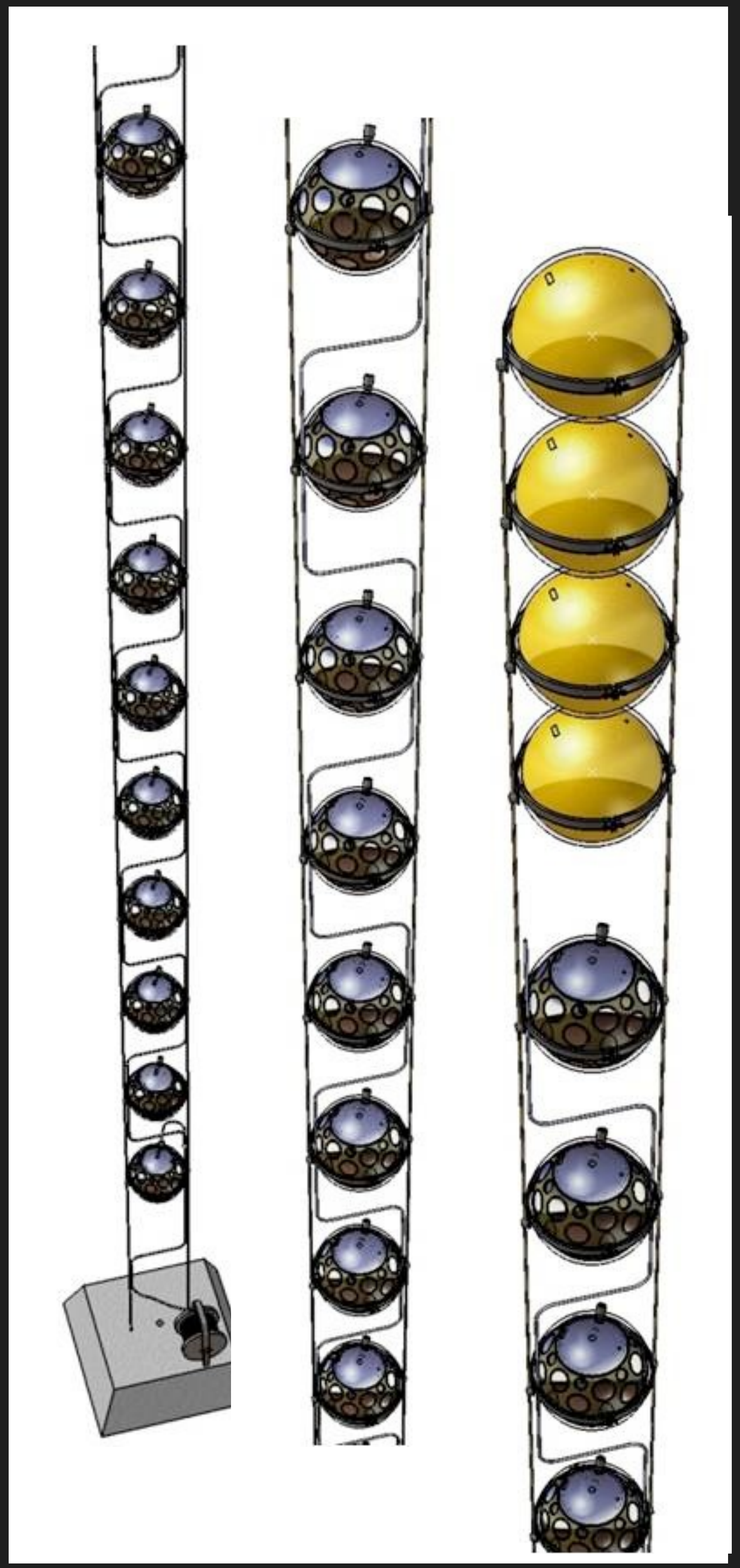
Extending the sensitivity to higher energies, new hemispheres

THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction



KM3NeT "building block"



string with OMs

Multi-PMT digital optical module ("DOM")

THE KM3NET NEUTRINO TELESCOPE

Multi-site installation in the Mediterranean Sea (France, Italy), instrumented in "building blocks", started construction

31 x 3" PMTs
Hamamatsu, ETL, HZC

Light collection ring
20–40% gain in PC for free

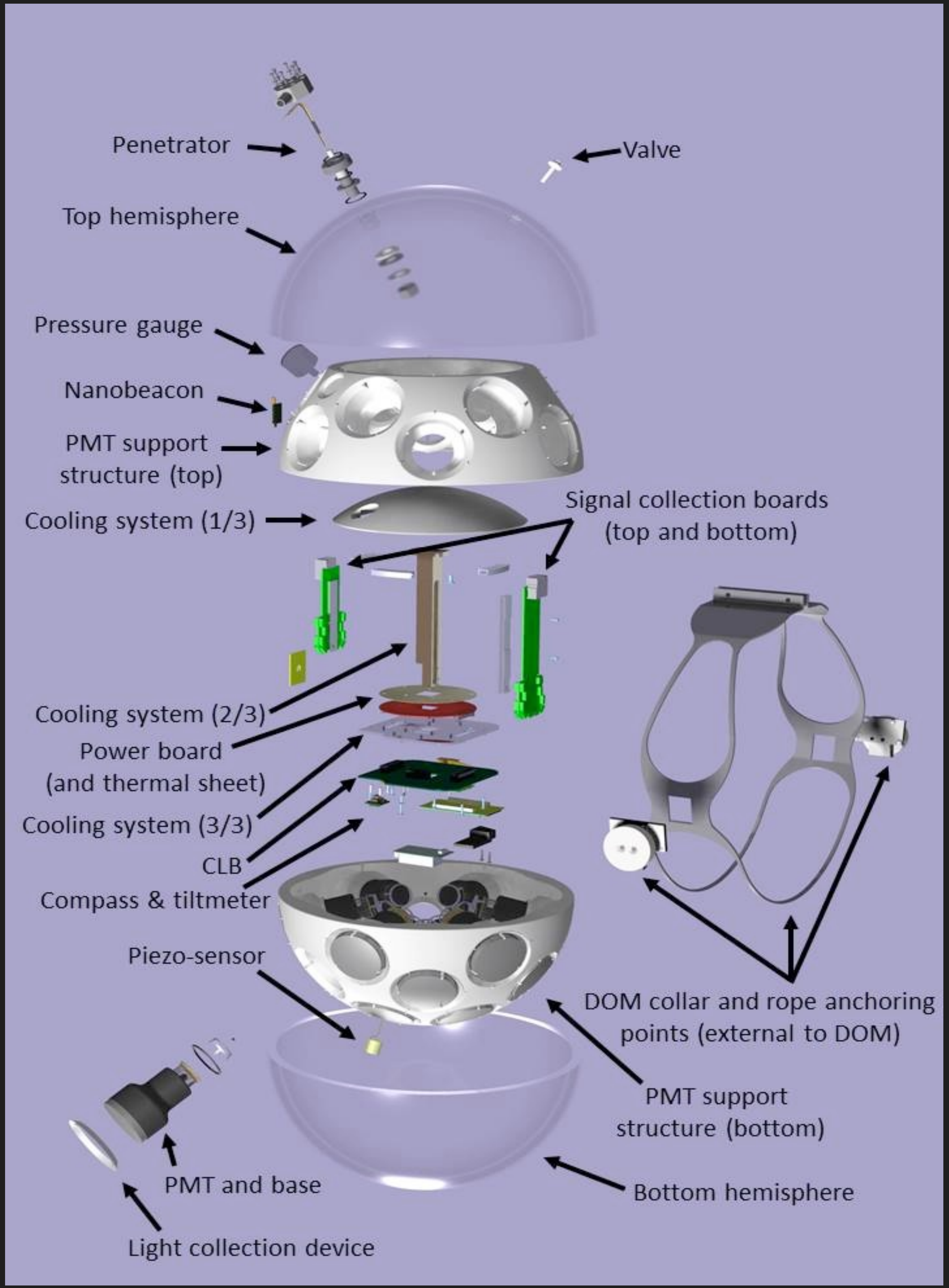
Low power
< 10 W / DOM

FPGA readout
sub-ns time stamping
time over threshold

Calibration
LED & acoustic piezo

Optical fibre data transmission
DWDM with 80 wavelengths
Gb/s readout

multiPMT optical module



KM3NET: ARCA AND ORCA

two different building blocks

ARCA: "Astrophysical Research with Cosmic in the Abyss"

Study astrophysical neutrino fluxes at **E > 100 GeV**

2 "blocks" at the **Italian** site (~10% being constructed right now!)

ORCA: "Oscillations Research with Cosmics in the Abyss"

Resolve the neutrino mass hierarchy (**1 GeV < E < 100 GeV**)

1 "block" at the **French** site (~5% being constructed right now!)

KM3NET CONSTRUCTION

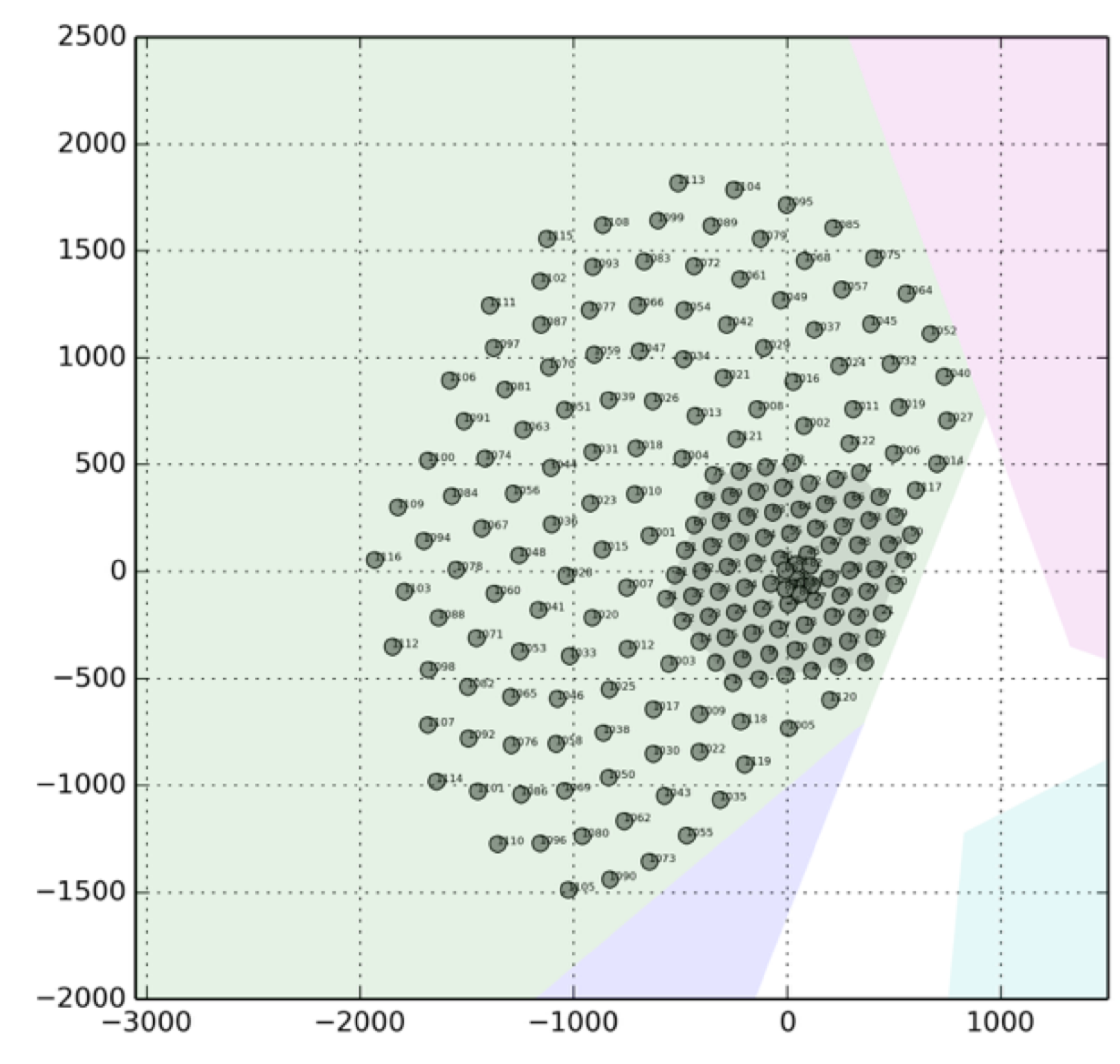
first string has been deployed!

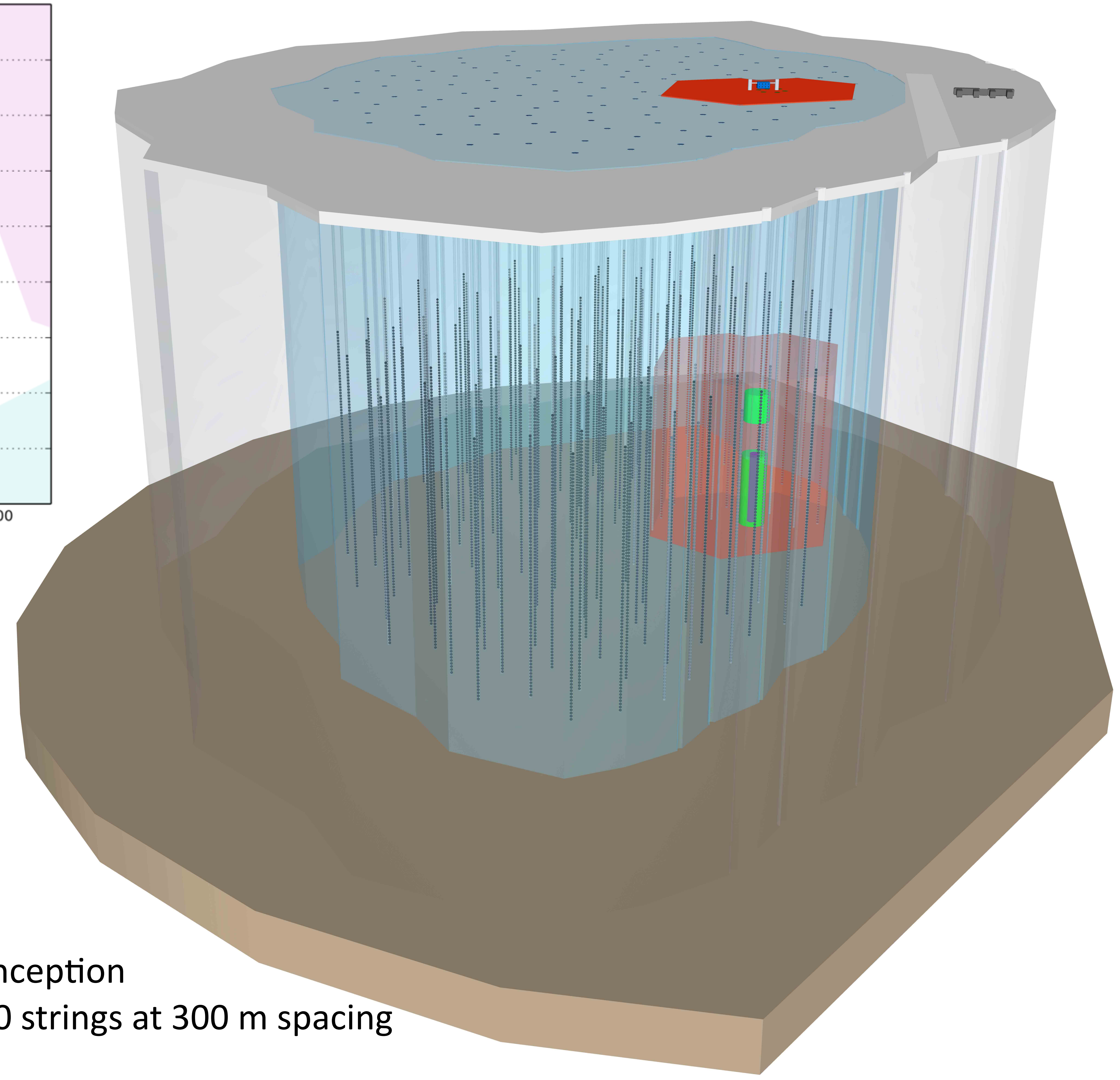
ICECUBE-GEN2: HIGH-ENERGY

IceCube has provided an amazing sample of events, but is still limited by the small number of events

- few 10’s of astrophysical neutrinos per year

The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume (~10km^3)





Artist conception
Here: 120 strings at 300 m spacing

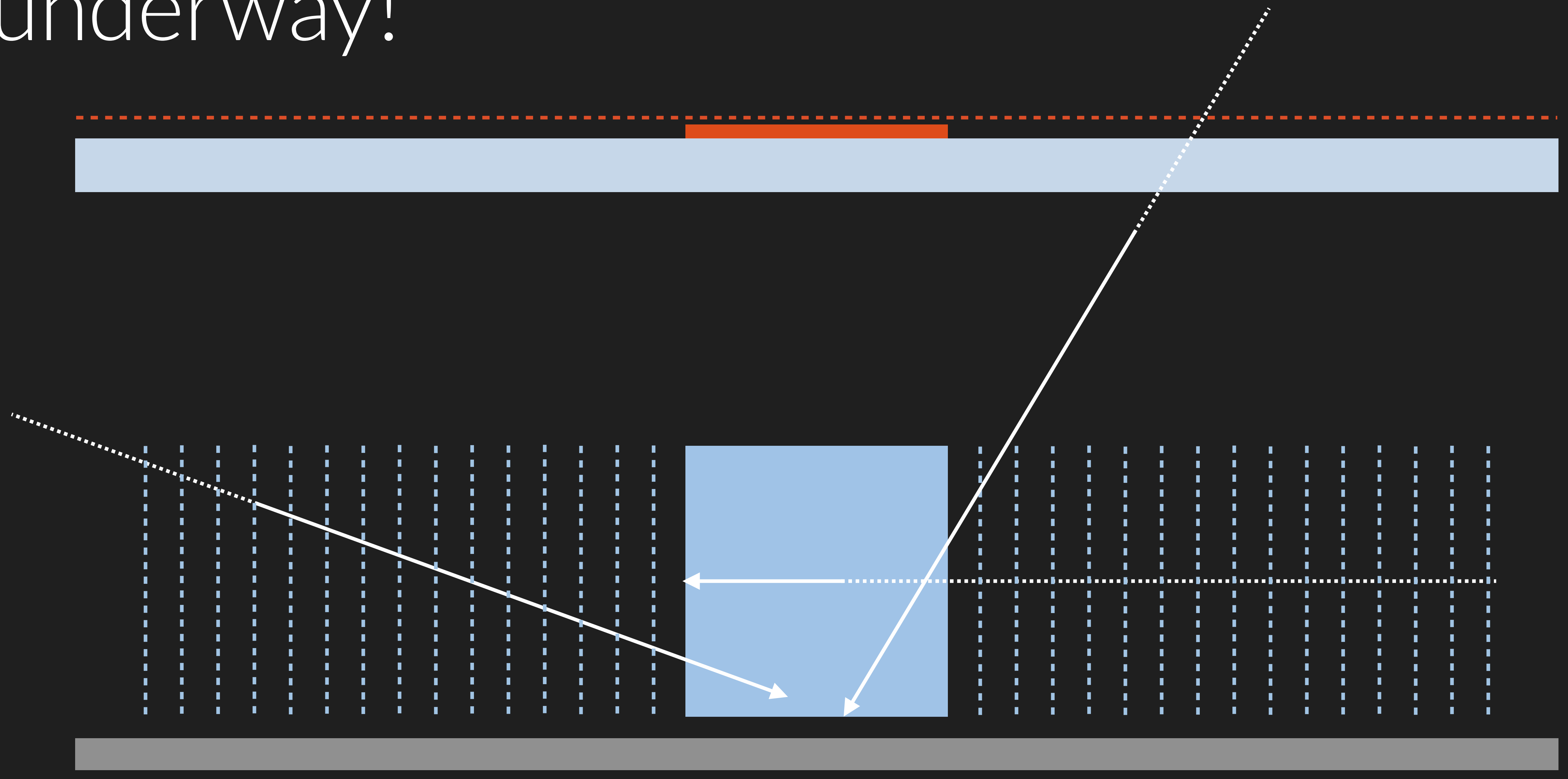
ICECUBE-GEN2: SURFACE VETO

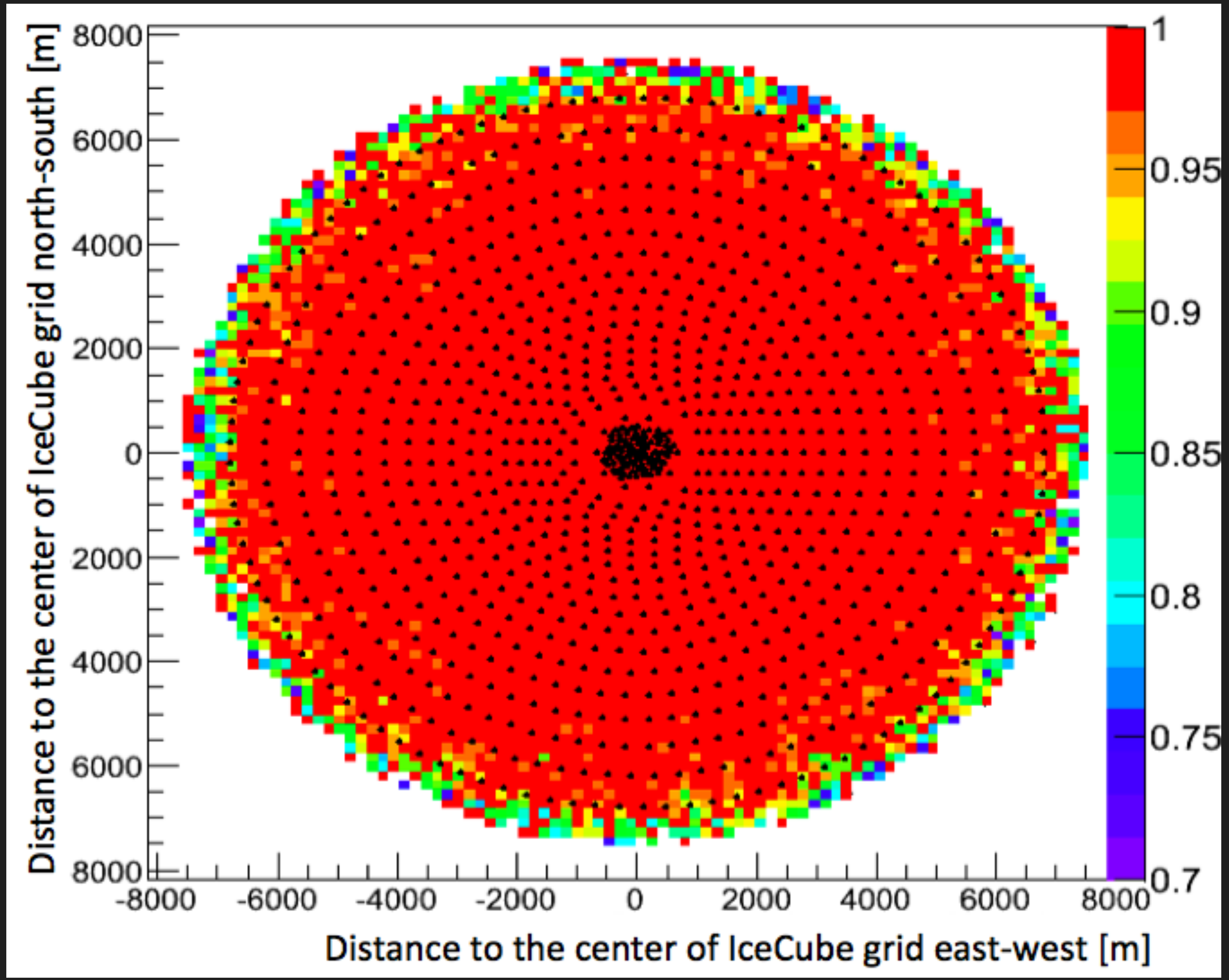
R&D for a surface array

similar to the current "IceTop" surface array (or alternative technology) - CR physics and veto neutrinos from CR air showers at the ice surface

increase volume for starting tracks

R&D is underway!





ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos

cover energies down to a **few GeV**

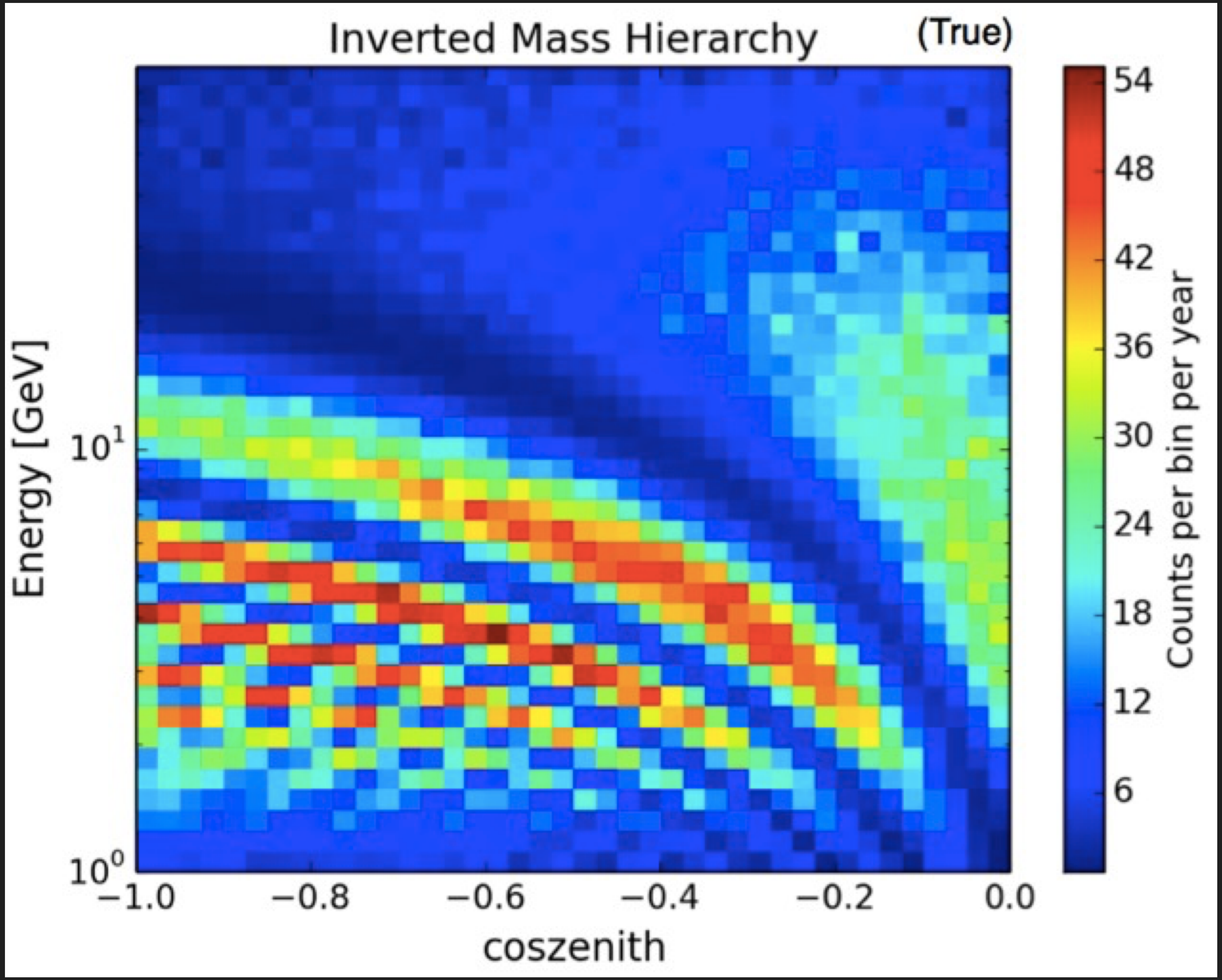
add **40** strings to IceCube/DeepCore

22m string spacing

2m DOM spacing

use the difference in MSW effect for **ν** and anti-**ν**

combine with difference in **ν** and anti-**ν** cross-section



ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos

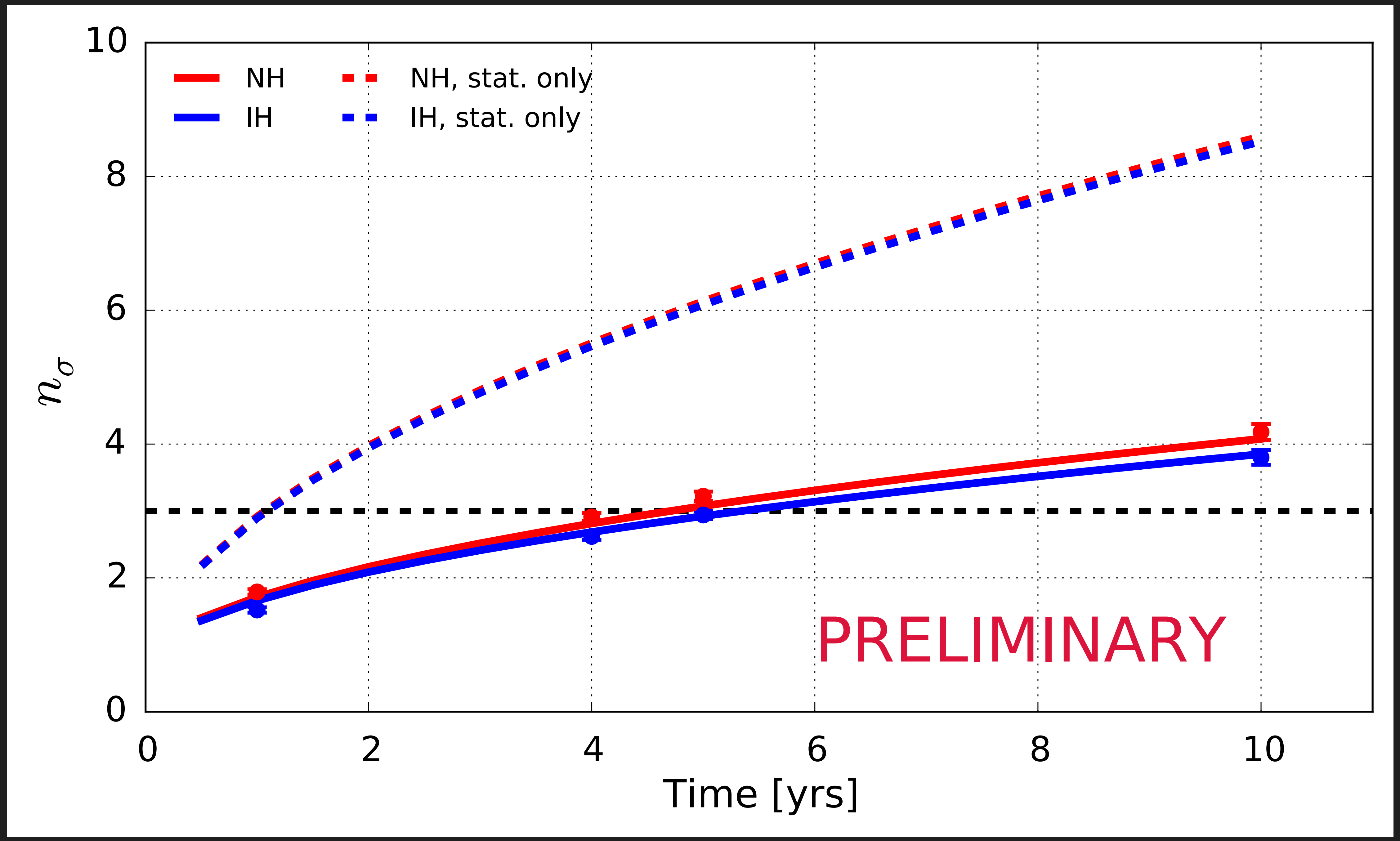
PINGU AND ORCA

measuring the mass hierarchy using atmospheric neutrinos

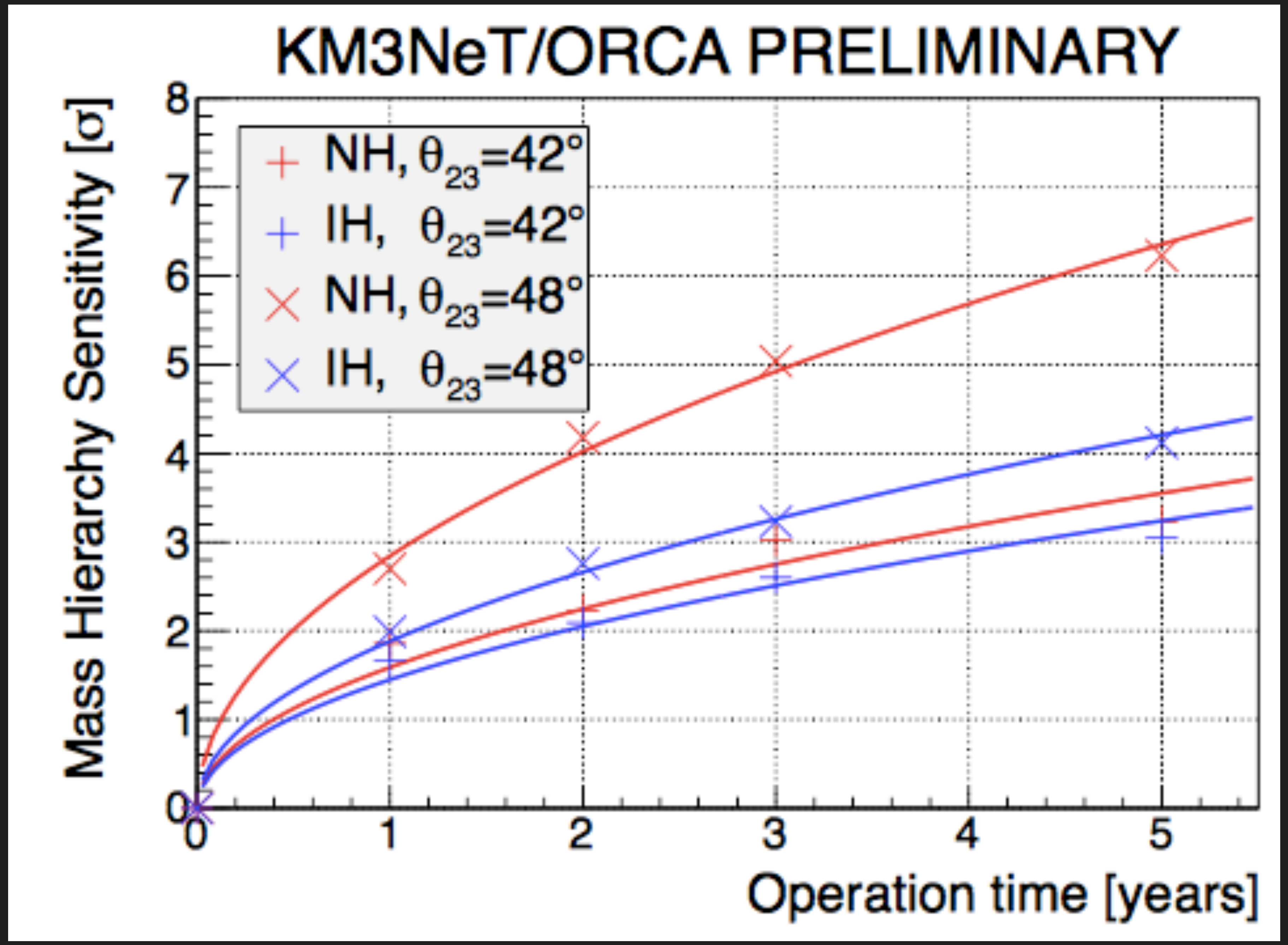
very similar concepts, ORCA in water, PINGU in ice

both claim to be able to measure the mass ordering at 3sigma after ~3-4 years of operation

PINGU

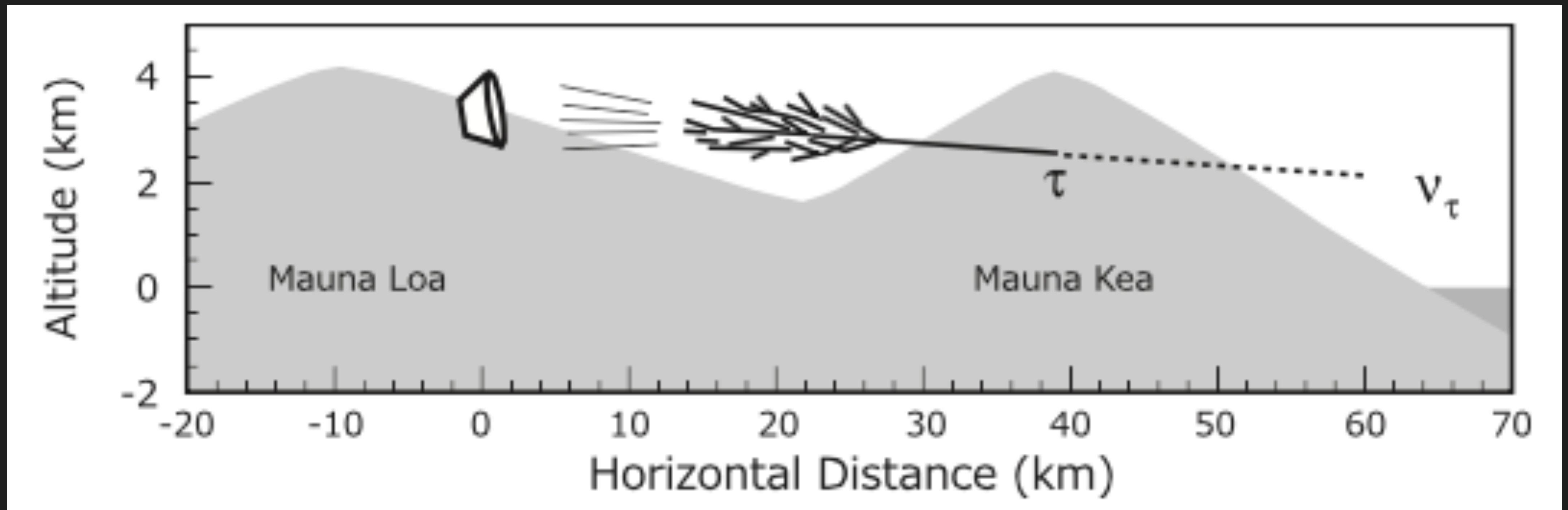


ORCA



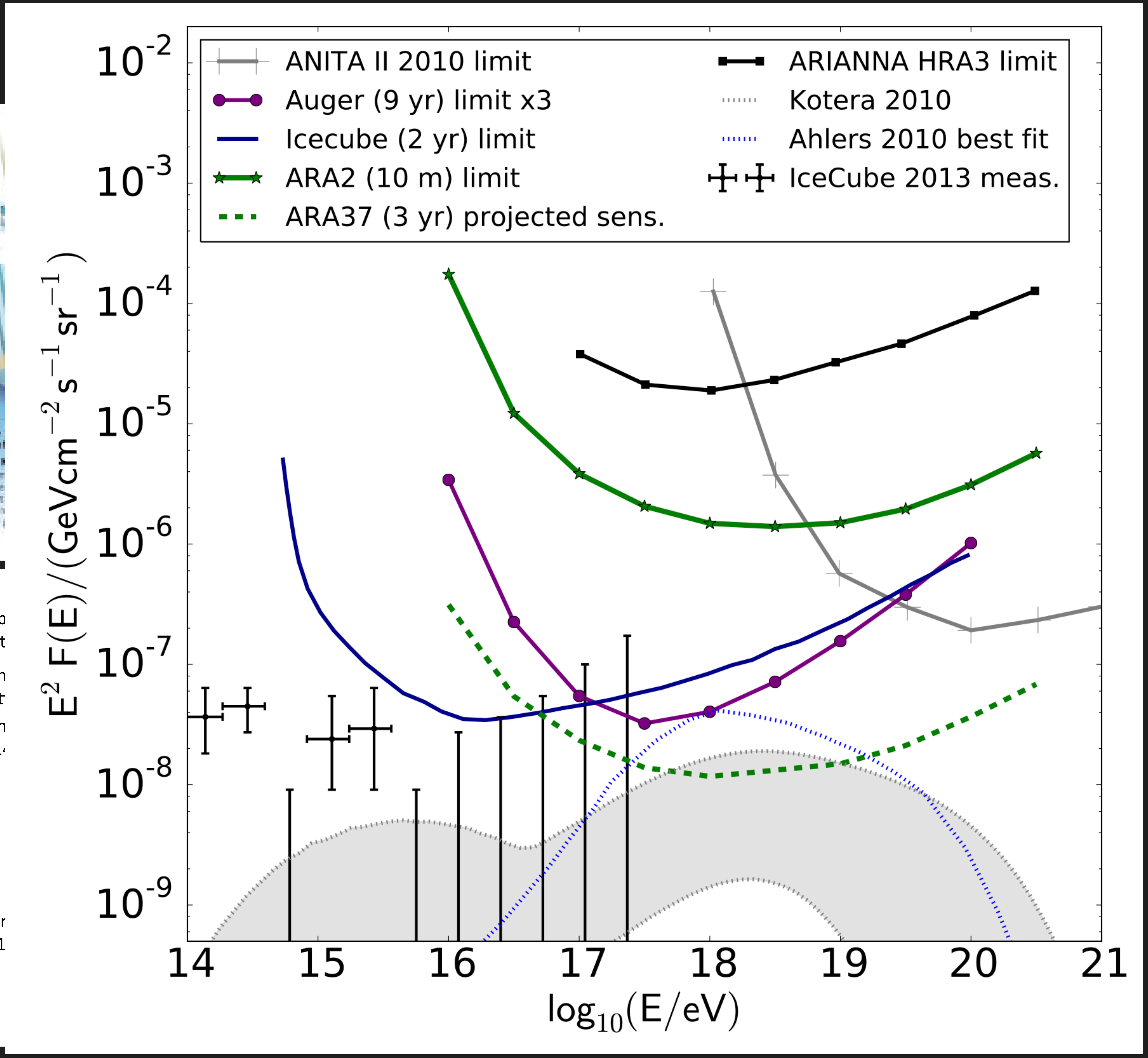
MORE DETECTORS / METHODS

non-water detectors and radio detectors



earth skimming tau Cherenkov shower detection (arXiv:1202.5656) - can be deployed on land!

radio detectors for energy range



ν

CONCLUSIONS
and summary

I could only cover a very small subset of topics…

We are studying the detailed properties of the flux of astrophysical neutrinos and are looking for its sources

In addition we are using atmospheric neutrinos to study neutrino physics (oscillations!)

Had to omit many other results (CR composition, searches for neutrinos from GRBs, …)

More data is being taken and analyses are ongoing

We are looking at future projects!

THANK YOU!