V

RECENT RESULTS FROM ICECUBE

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UNIVERSITY OF ALBERTA

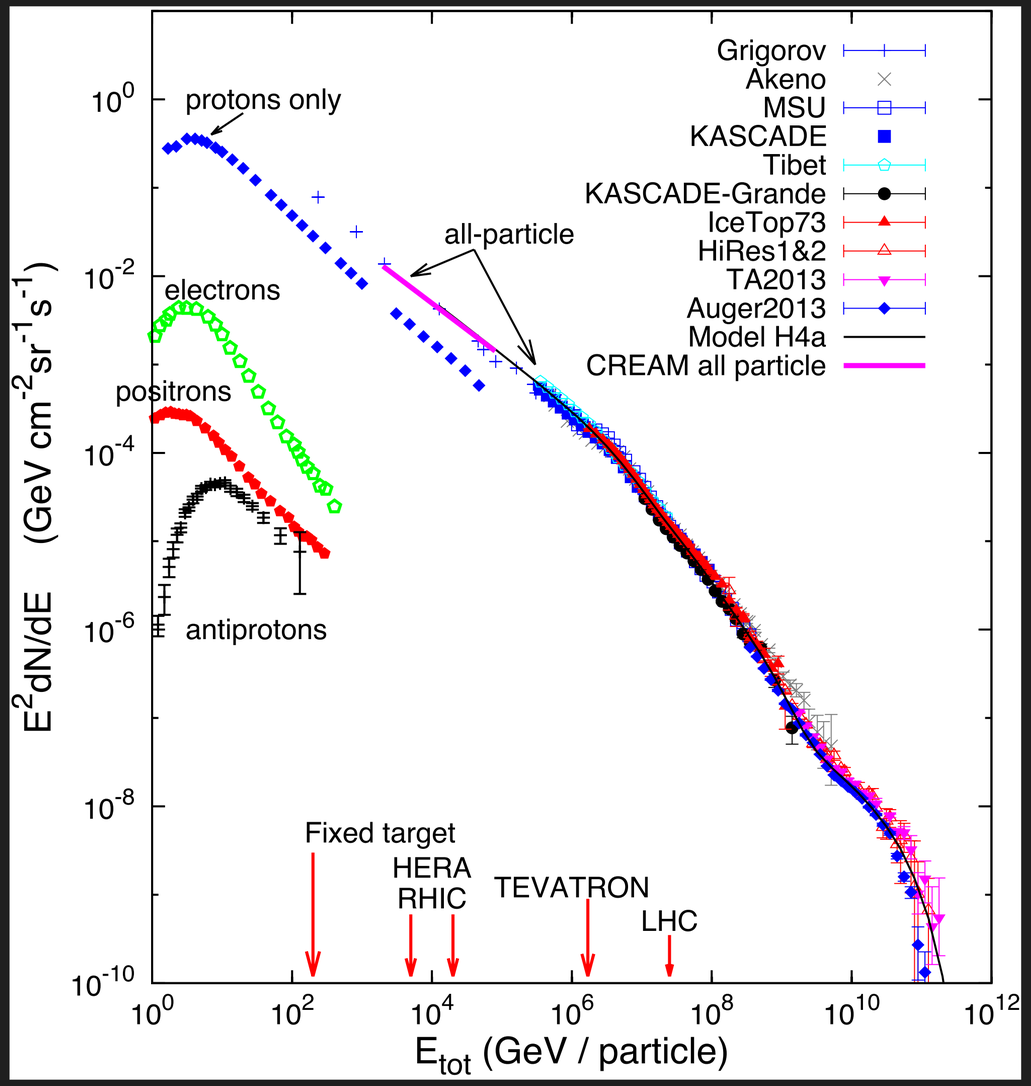
V

COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays

COSMIC RAYS

where (and how) are they accelerated?

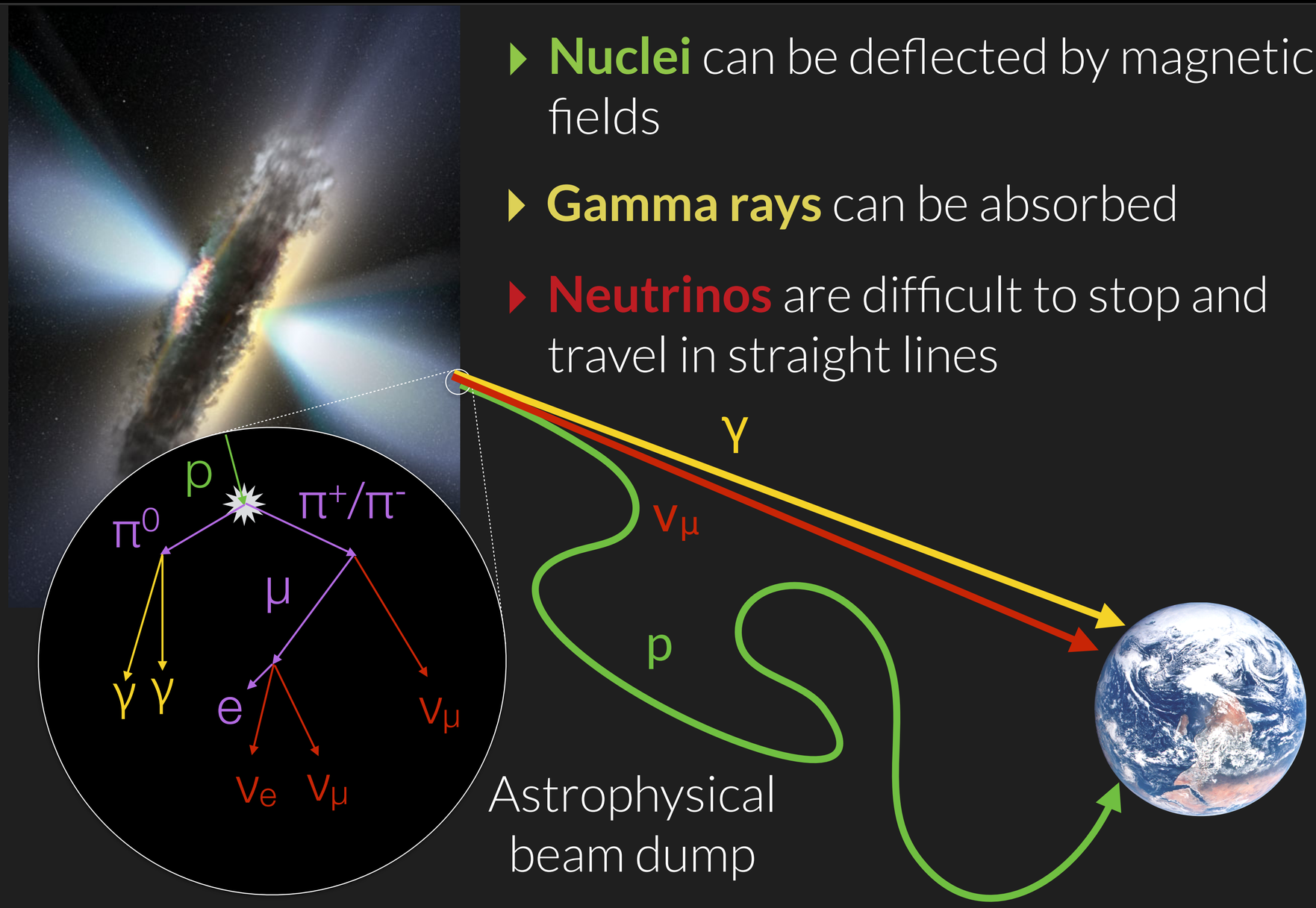


We know their energy spectrum over 11 orders of magnitude

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



NEUTRINOS ABOVE 1TEV

sketch of the different expected neutrino flux components

ATMOSPHERIC NEUTRINOS (π/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

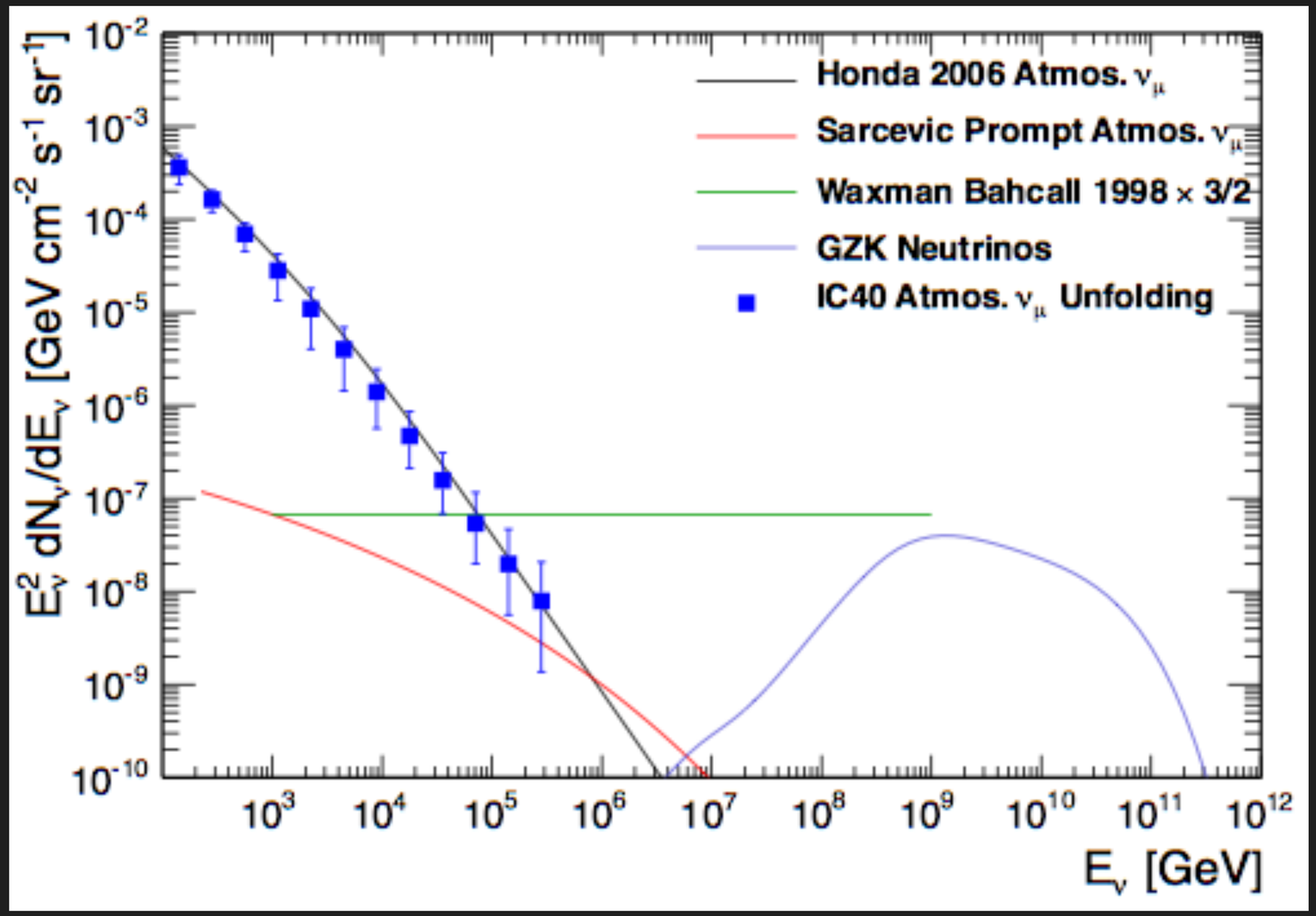
“prompt” ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

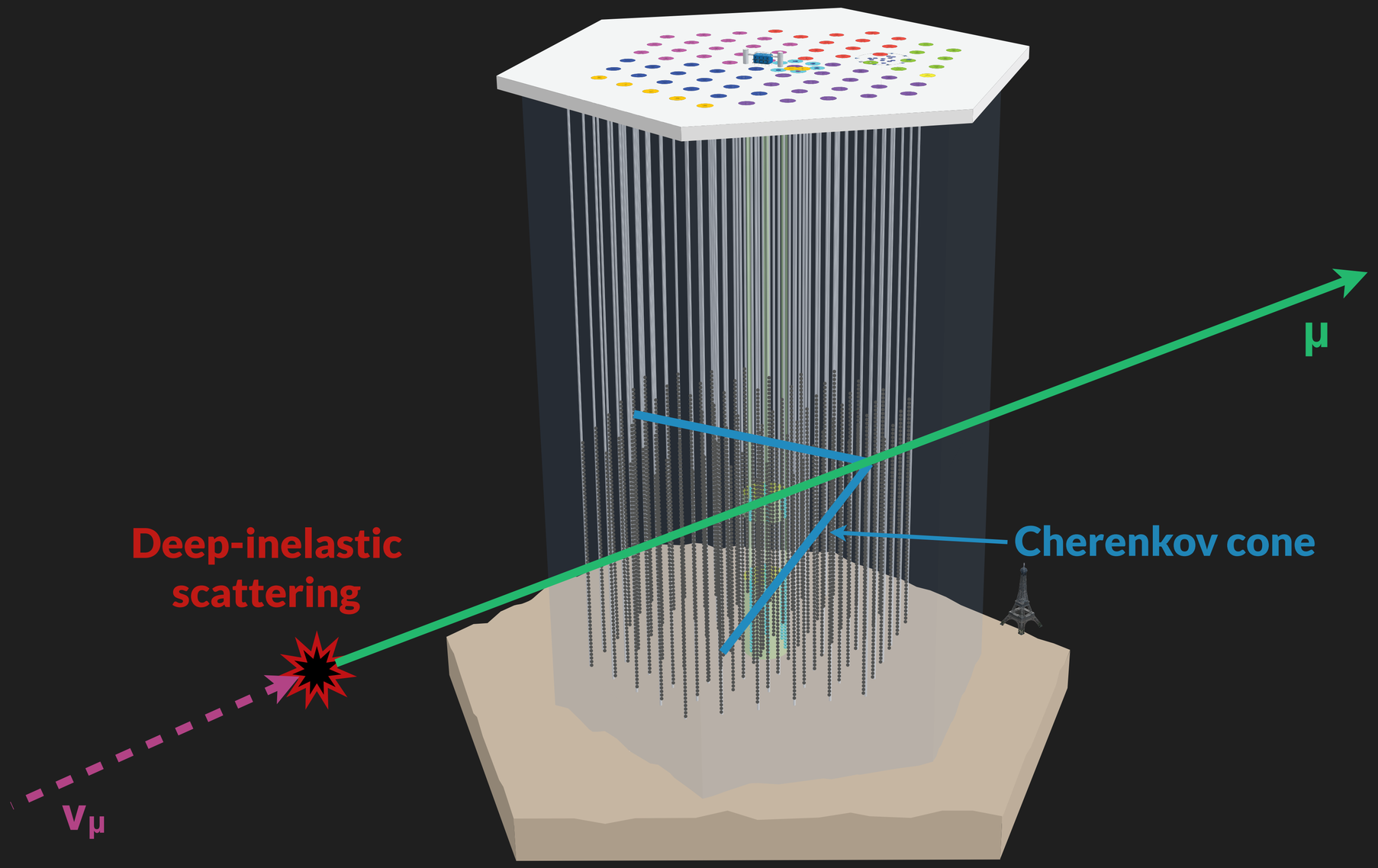
COSMOGENIC NEUTRINOS

$>10^6$ TeV



DETECTING NEUTRINOS

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



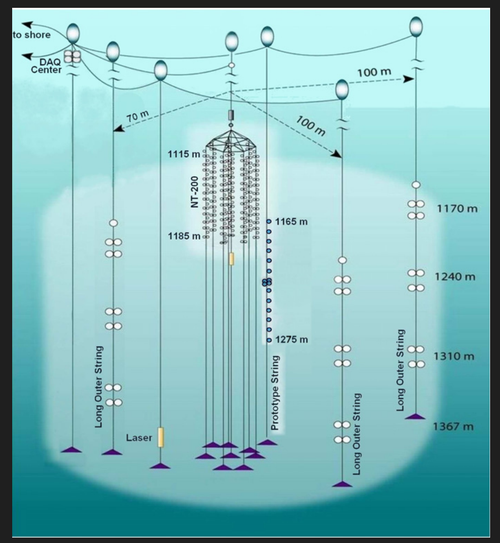
NEUTRINO TELESCOPE SITES

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

THE WORLD'S NEUTRINO TELESCOPES

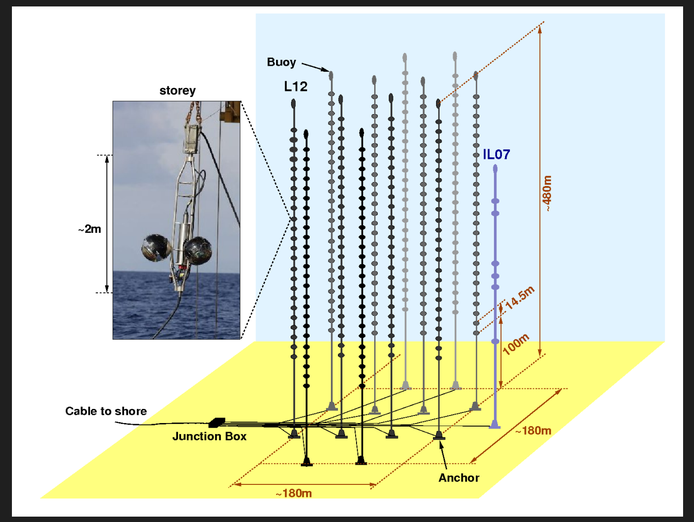
lakes, sea, glaciers

NT-200+



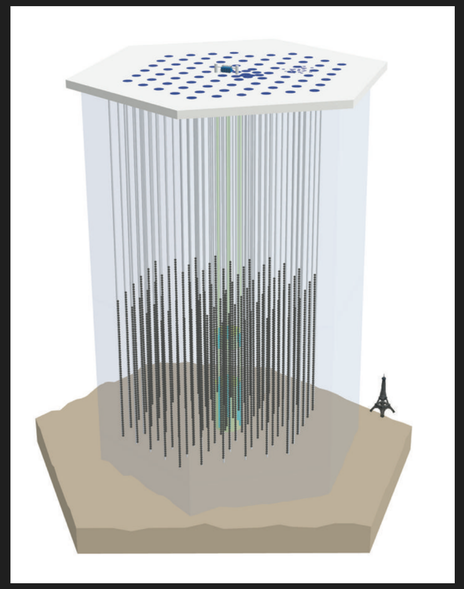
Lake Baikal
1/2000 km^3
228 PMTs

Antares



Mediterranean Sea
1/100 km^3
885 PMTs

IceCube

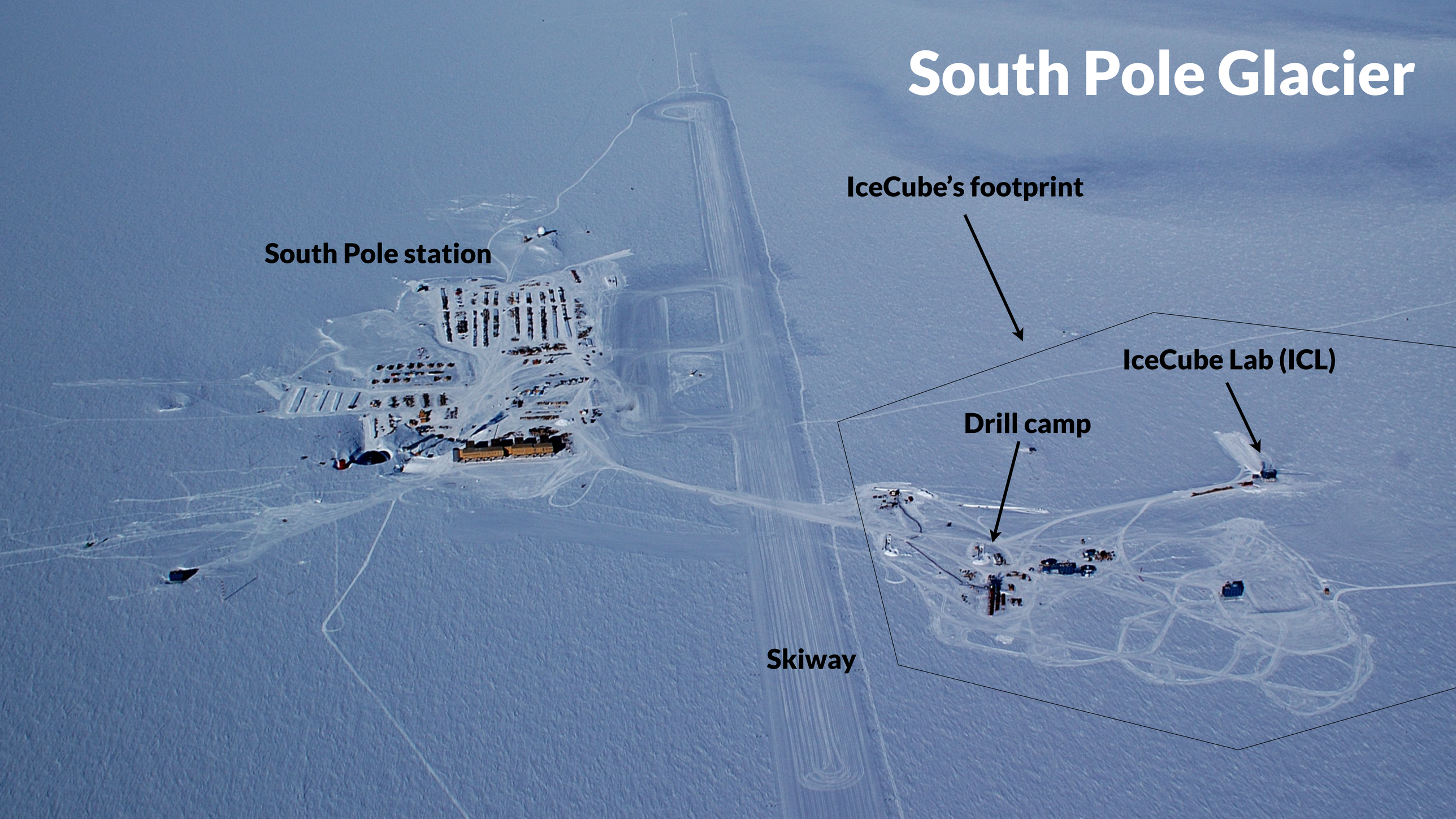


South Pole glacier
1 km^3
5160 PMTs

Larger, sparser ⟶ higher energies


Mediterranean Sea

South Pole Glacier



THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

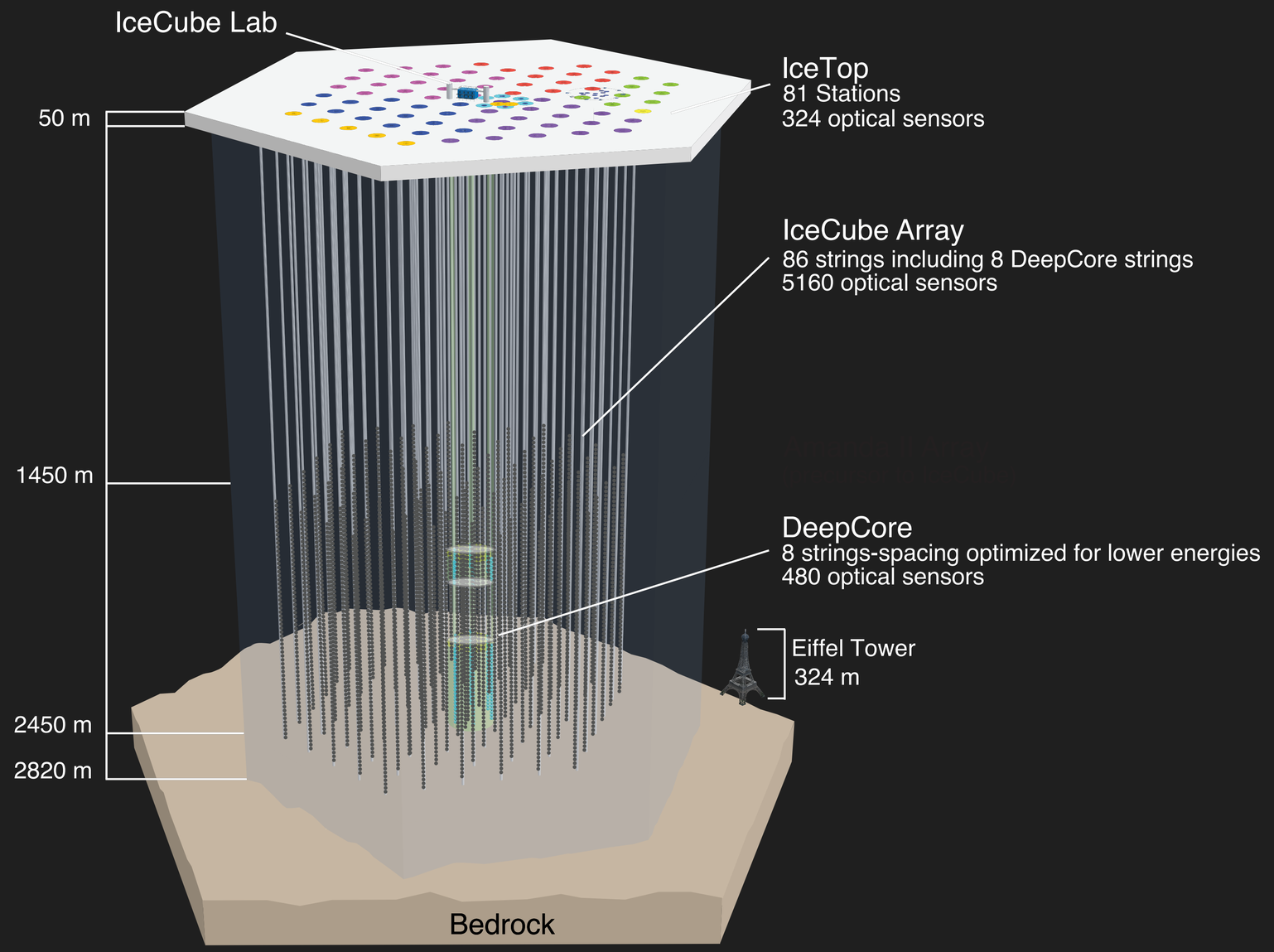
1km^3 volume

86 strings

17m vertical spacing

125m string spacing

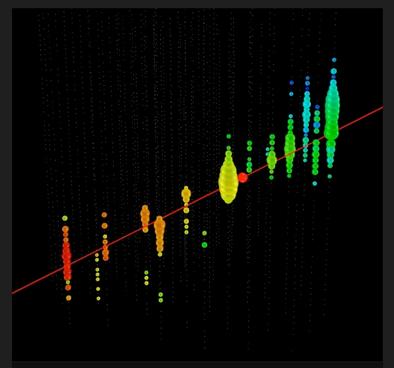
Completed **2010**



NEUTRINO EVENT SIGNATURES

Signatures of signal events

CC Muon Neutrino

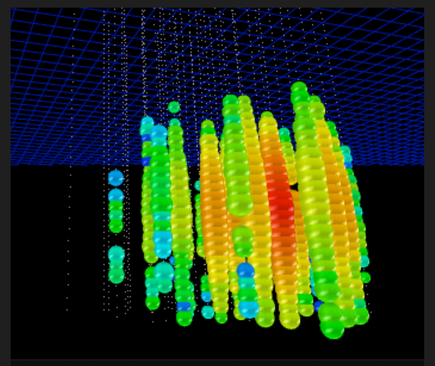


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution at high energies

Neutral Current / Electron Neutrino



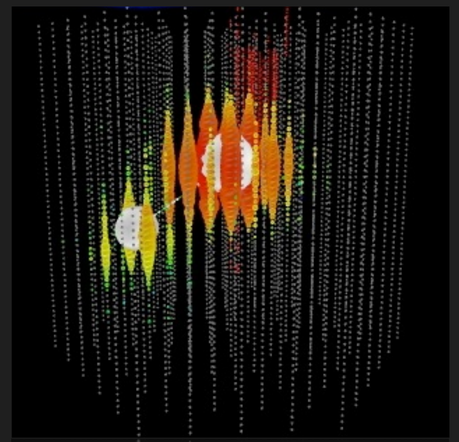
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

$$\nu_\mathrm{x} + N \rightarrow \nu_\mathrm{x} + X$$

cascade (data)

≈ ±15% deposited energy resolution
≈ 10° angular resolution (in IceCube)
(at energies ? 100TeV)

CC Tau Neutrino



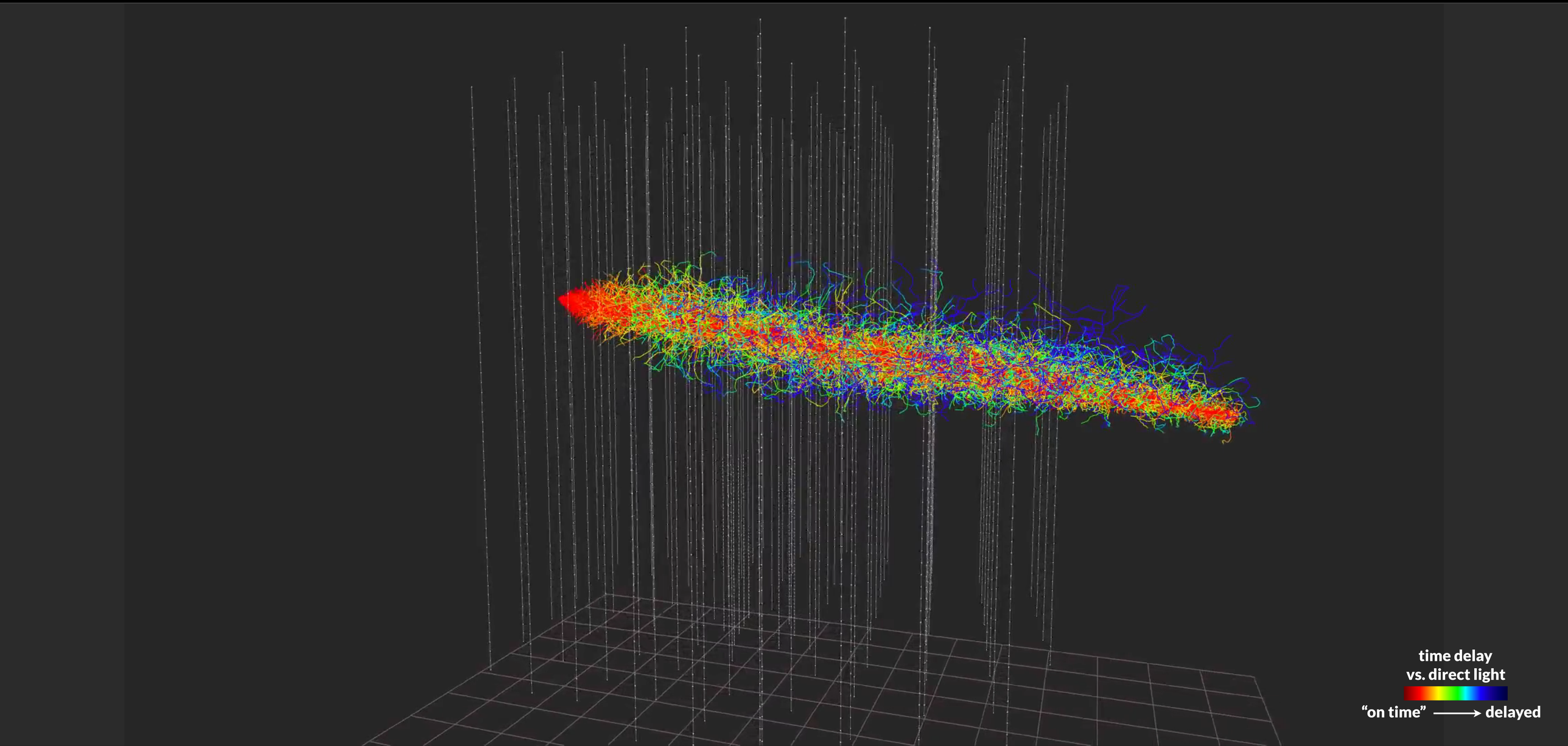
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" (?10PeV) and other signatures (simulation)

(not observed yet: τ decay length is 50 m/PeV)

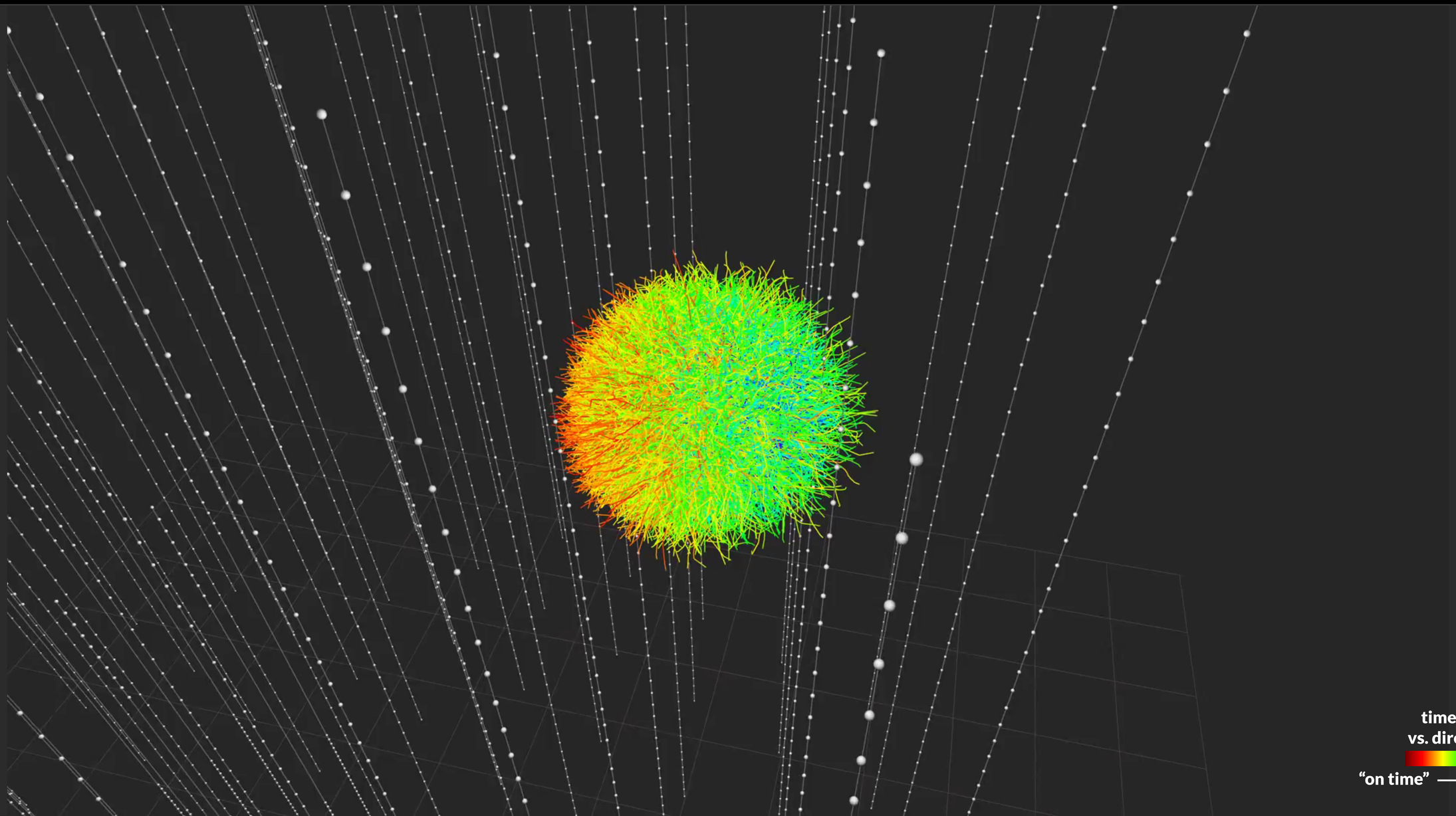
DETECTION PRINCIPLE (MUON IN ICE)

Neutrinos are detected by looking for Cherenkov radiation from secondary particles

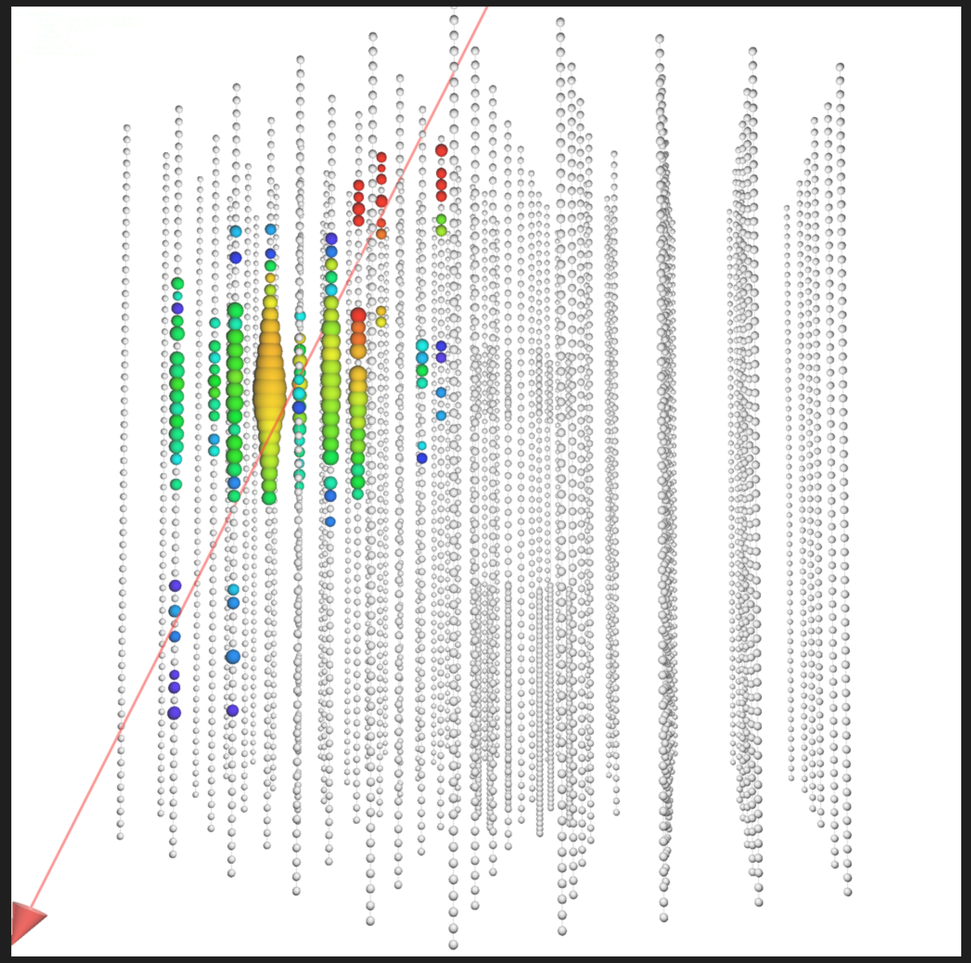


DETECTION PRINCIPLE (CASCADE IN ICE)

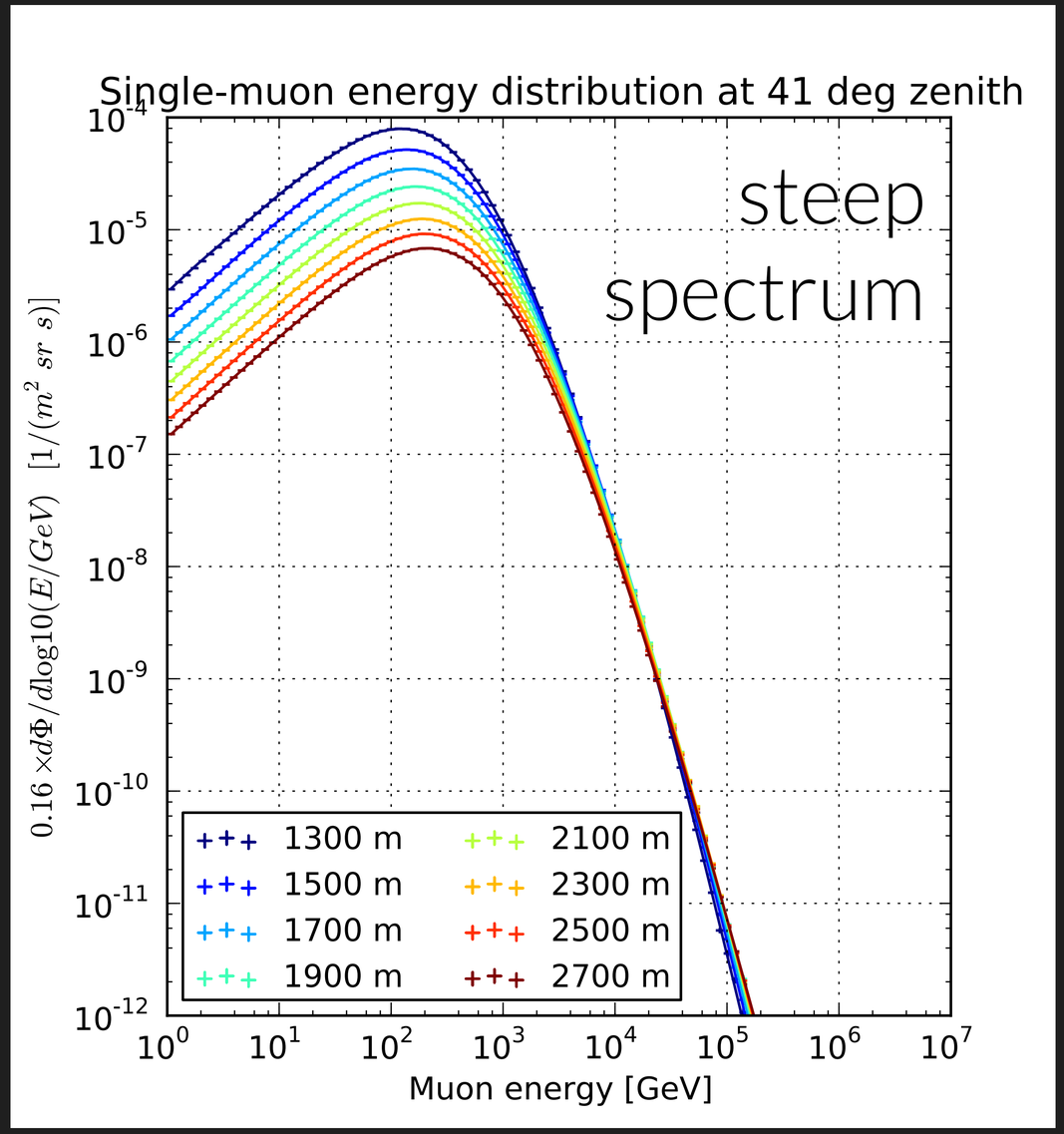
Neutrinos are detected by looking for Cherenkov radiation from secondary particles



BACKGROUND: PENETRATING MUONS



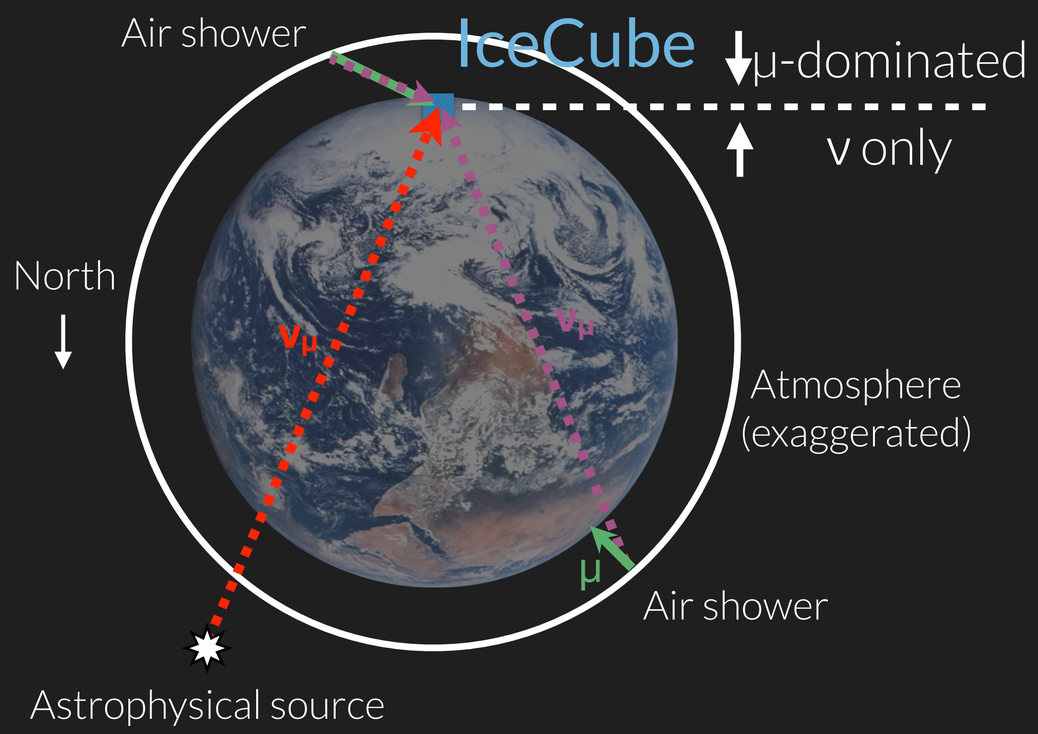
100 TeV single muon



ISOLATING NEUTRINO EVENTS

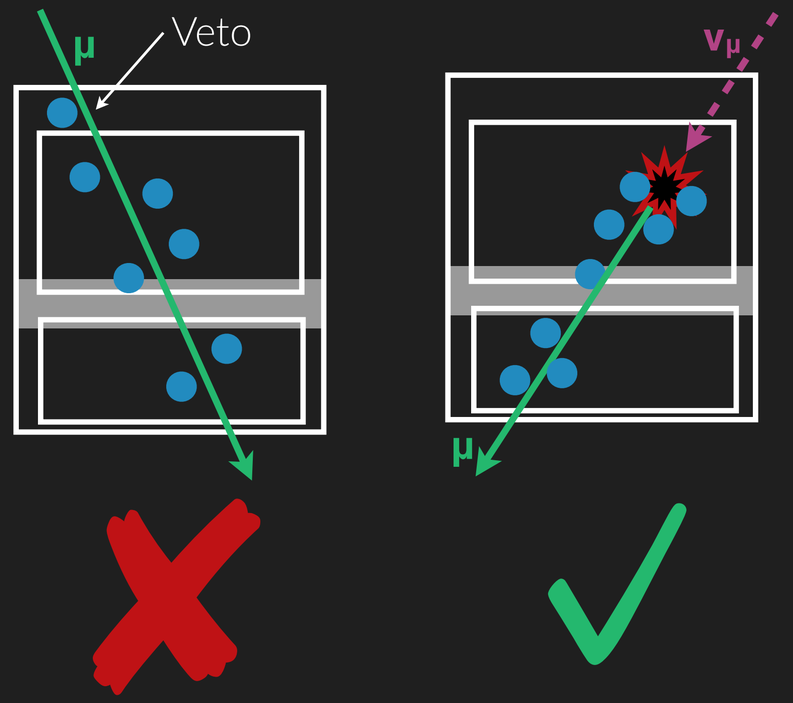
two strategies

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) /ApJ 805 L5 (2015))
- Ultra-high energy "GZK" neutrinos from proton interactions on the CMB

Low energy:

- Neutrino oscillations + more with PINGU/ORCA upgrades

Others:

- Dark Matter / WIMPs
- …

V

THE (VERY) HIGH-ENERGY TAIL

Update of the high-energy astrophysical flux discovery analysis

"HISTORY"

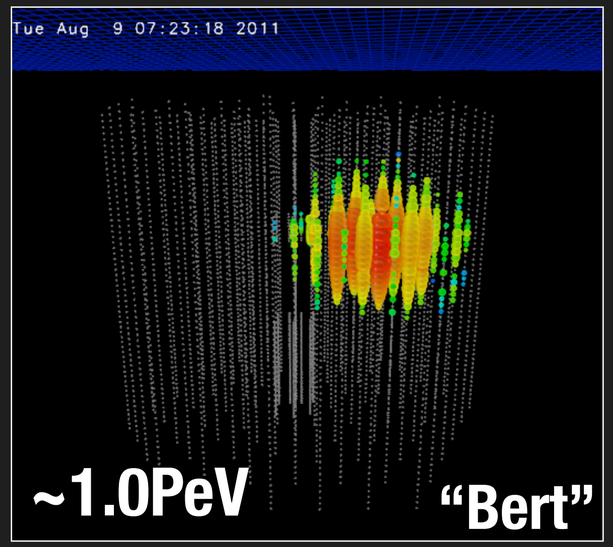
Appearance of ~1 PeV cascades as an at-threshold background

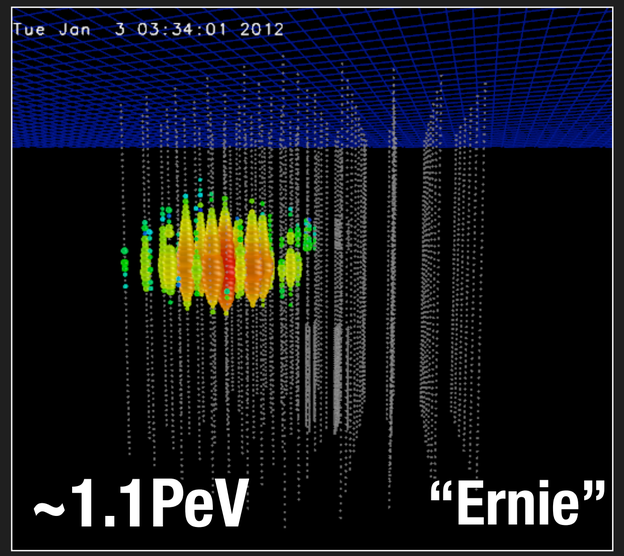
Two very interesting events in IceCube (between May 2010 and May 2012)

2.8σ excess over expected background in GZK analysis (PRL 111, 021103 (2013))

There should be more

GZK analysis is only sensitive to very specific event topologies at these energies





"STARTING EVENT" ANALYSIS

Specifically designed to find contained events.

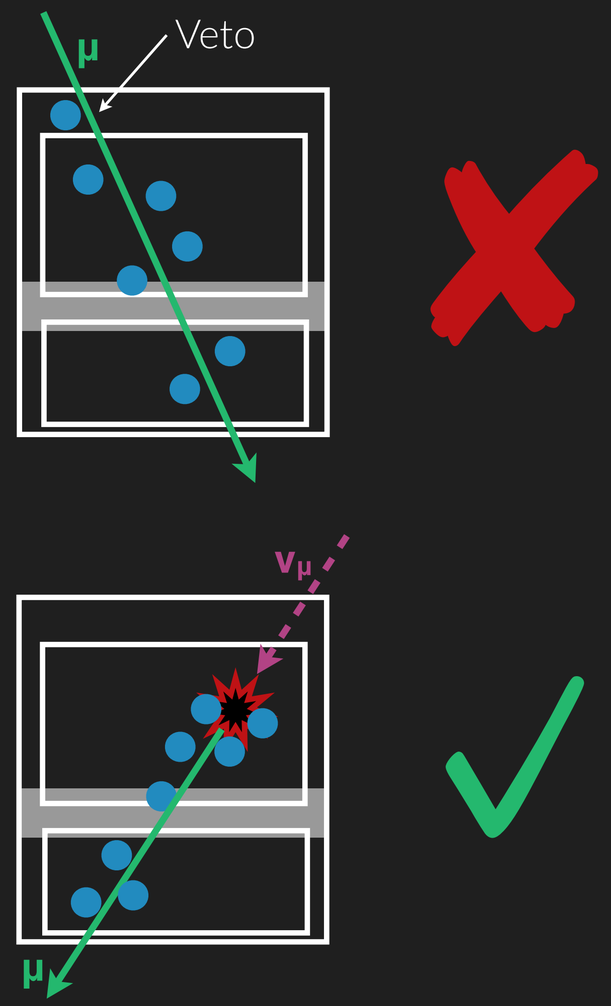
Explicit contained search at high energies (cut: Qtot>6000 p.e.)

400 Mton effective fiducial mass

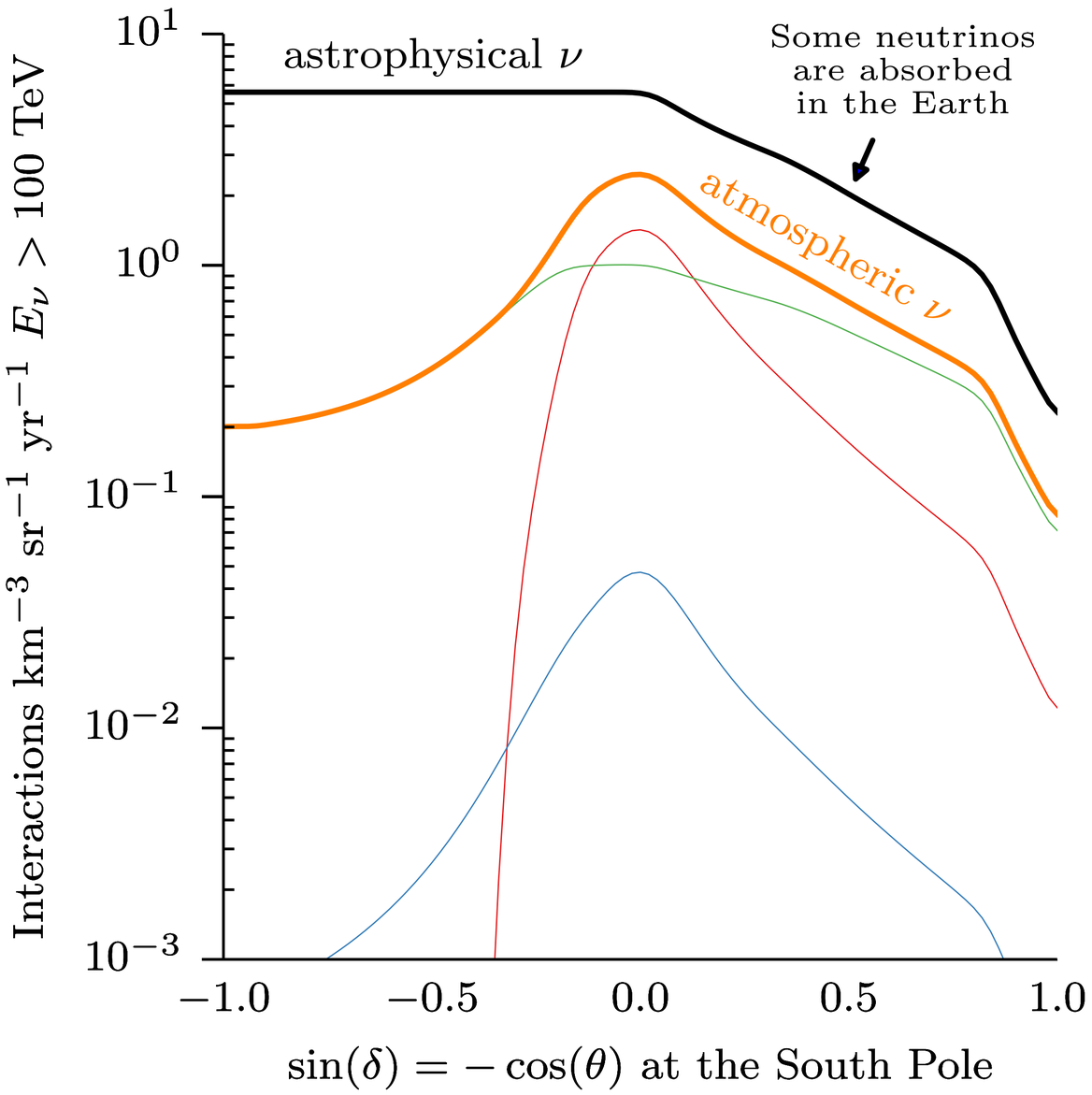
Use atmospheric muon veto

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

WHAT DID ICECUBE FIND? (4 YEARS)

54 events!

53(+1) events observed!

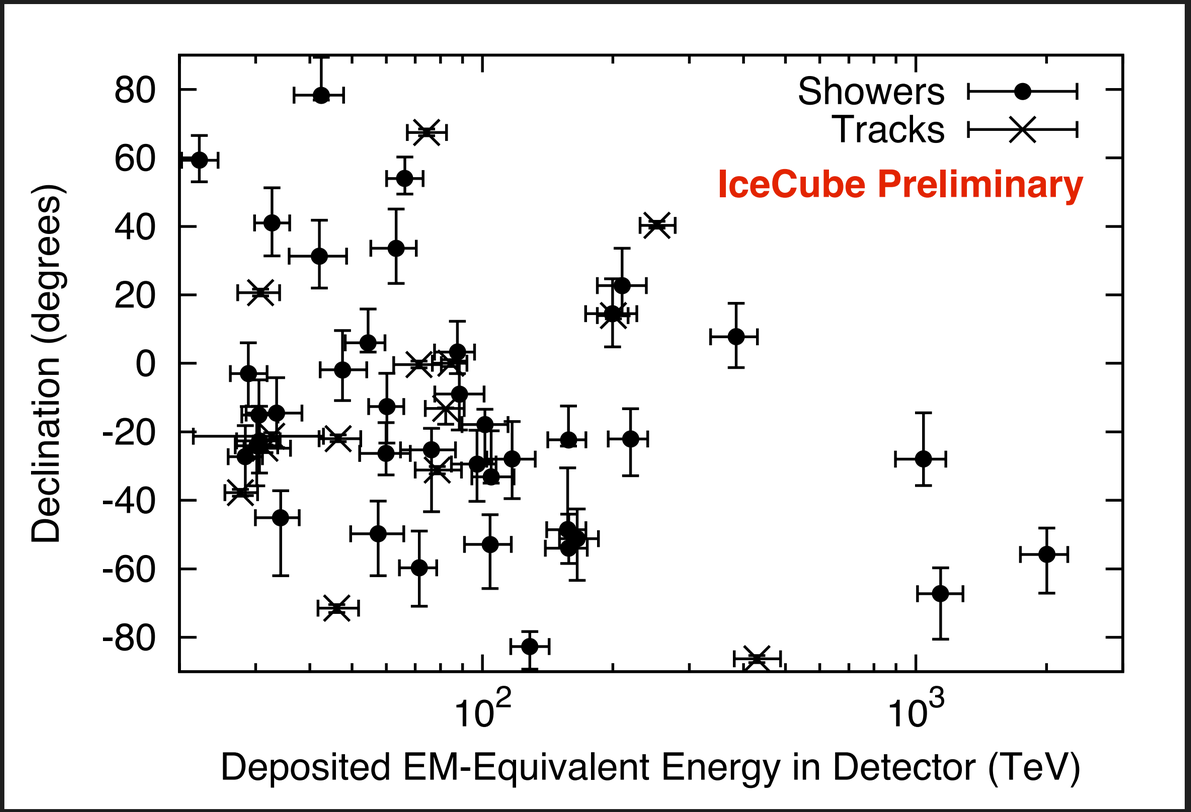
Estimated background:

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

12.6±5.1 atm. muons

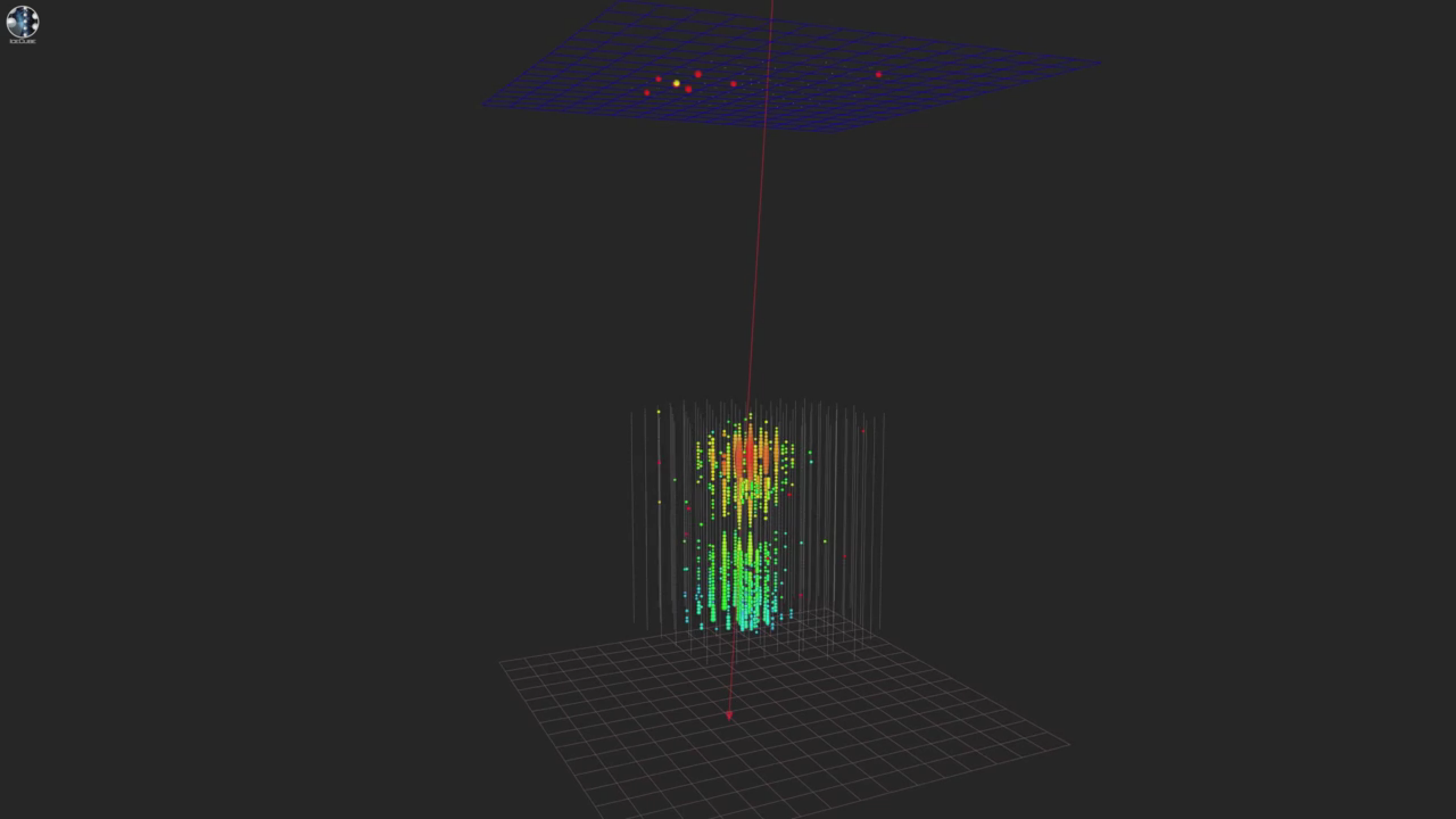
One of them is an obvious (but expected) background

coincident muons from two CR air showers



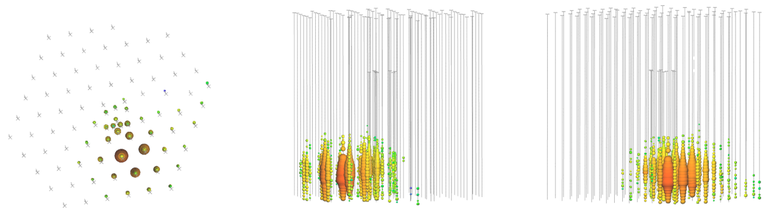
full likelihood fit of all components: 6.5σ for 53(+1) events

presented at ICRC2015 / PoS(ICRC2015)1081

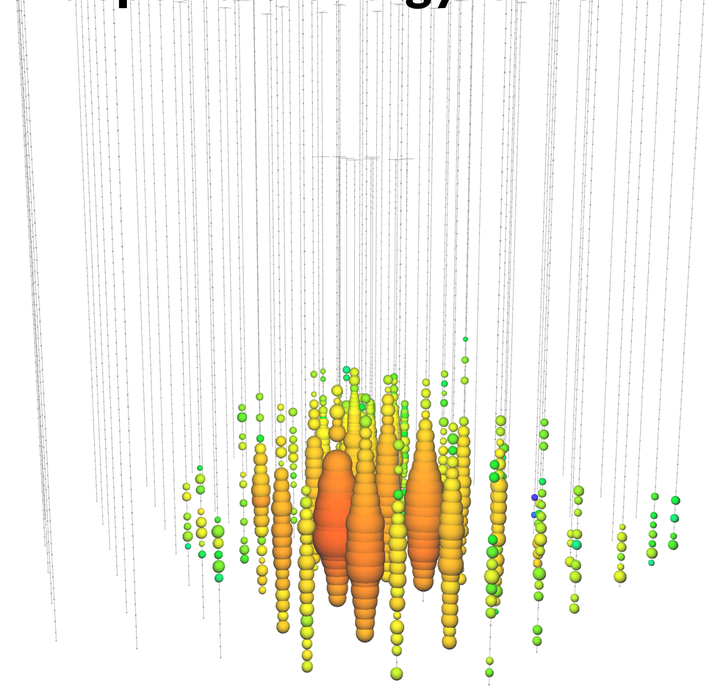


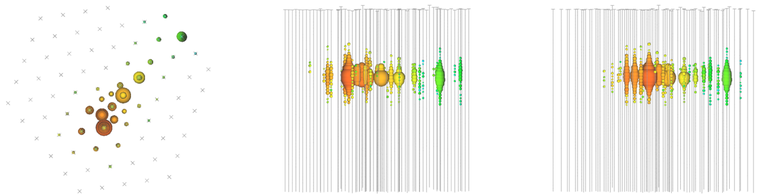
WHAT DID ICECUBE FIND?

some examples

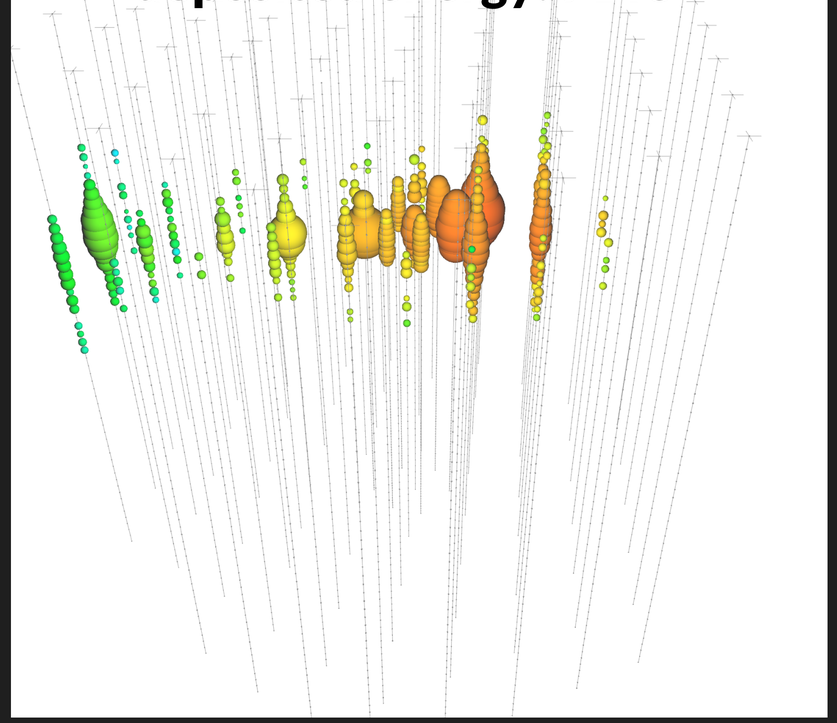


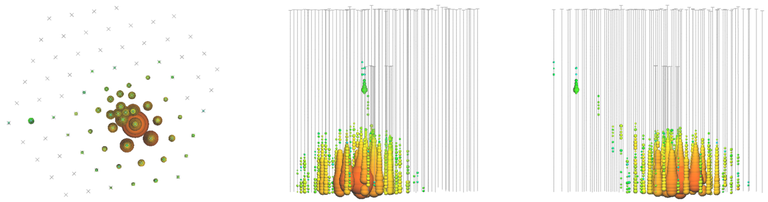
declination: -13.2°
deposited energy: 82TeV



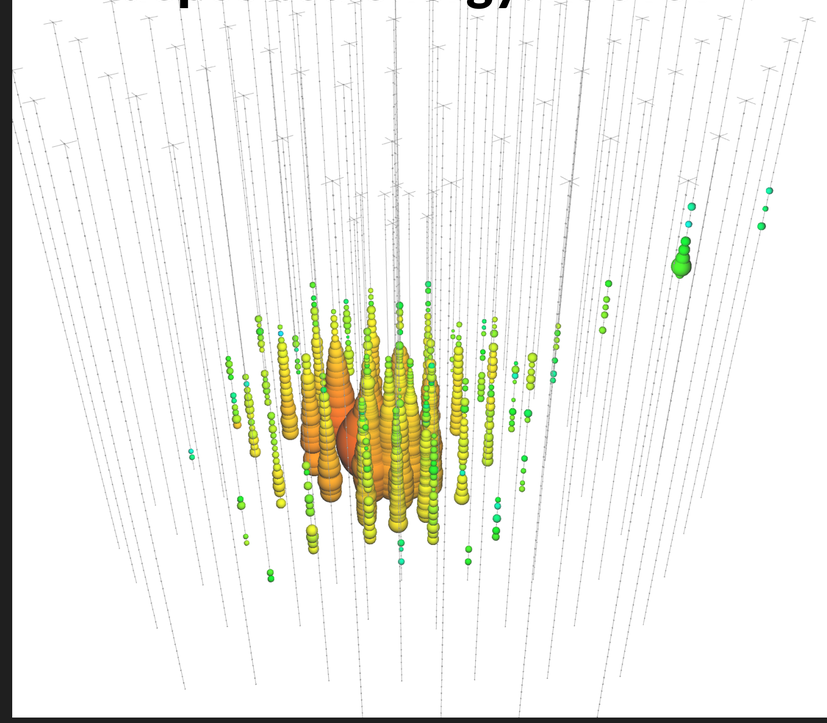


declination: -0.4°
deposited energy: 71TeV





declination: 40.3°
deposited energy: 253TeV



ENERGY SPECTRUM (4 YEARS)

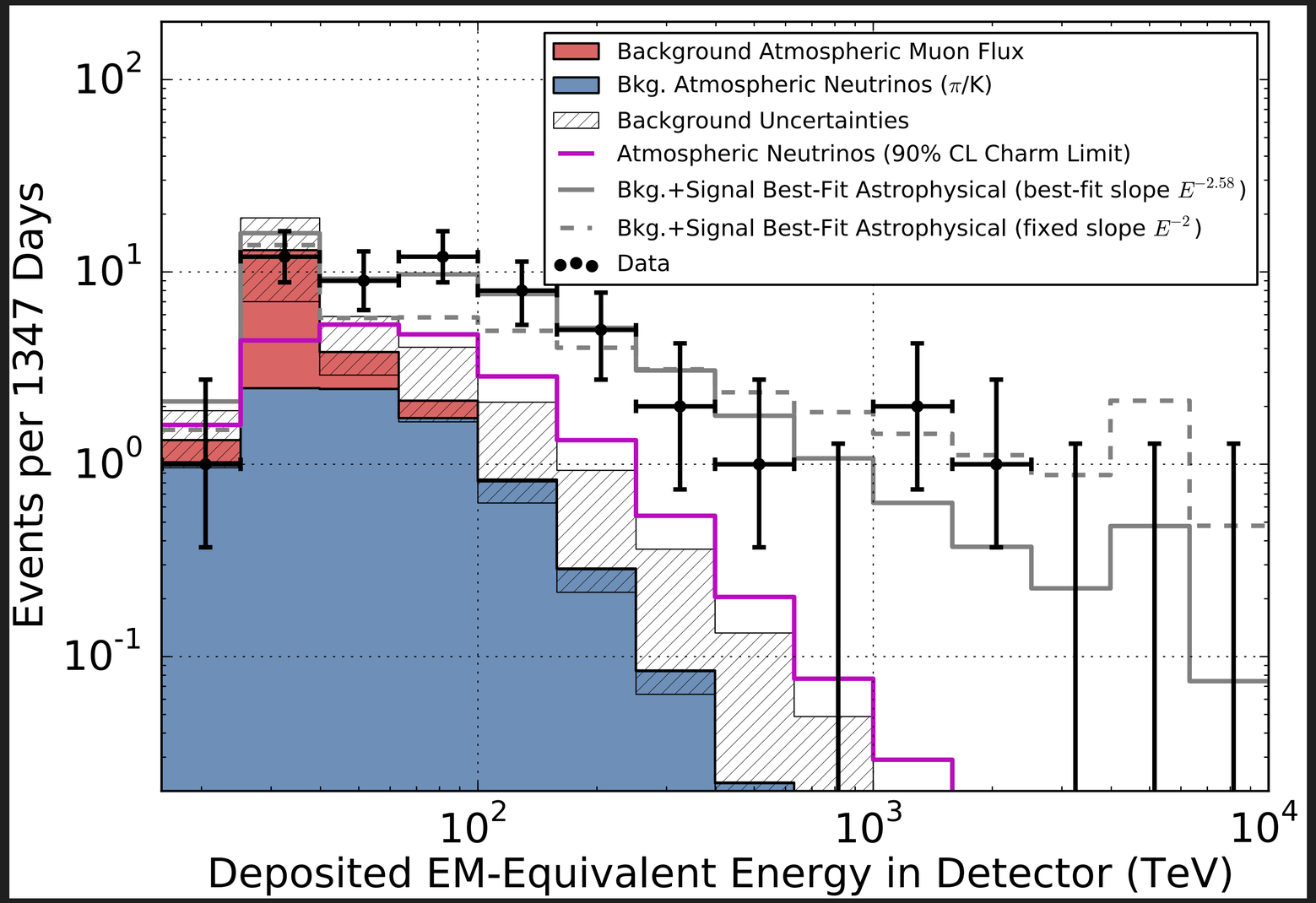
energy deposited in the detector (lower limit on neutrino energy)

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):

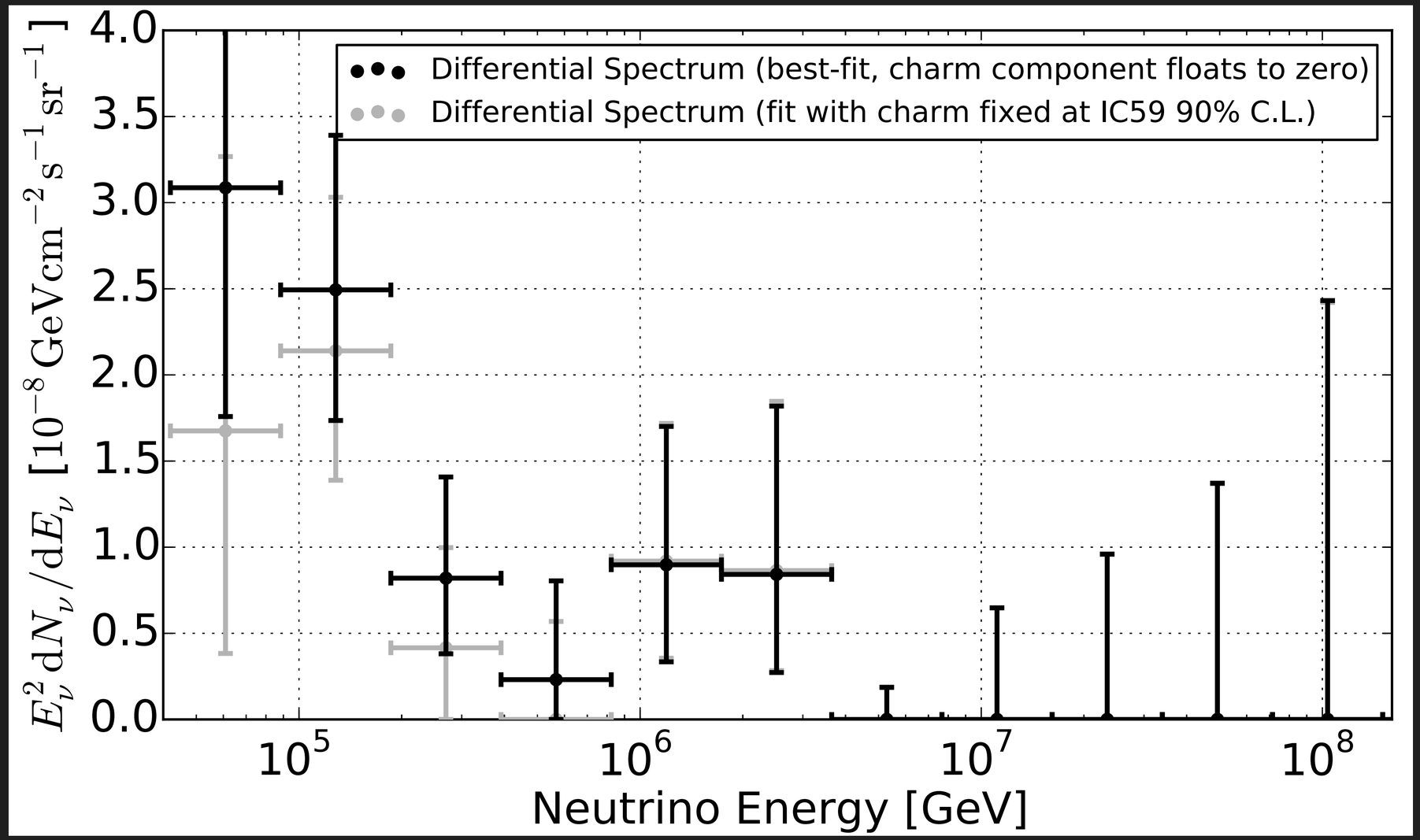
$0.84 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

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



UNFOLDING TO NEUTRINO ENERGY

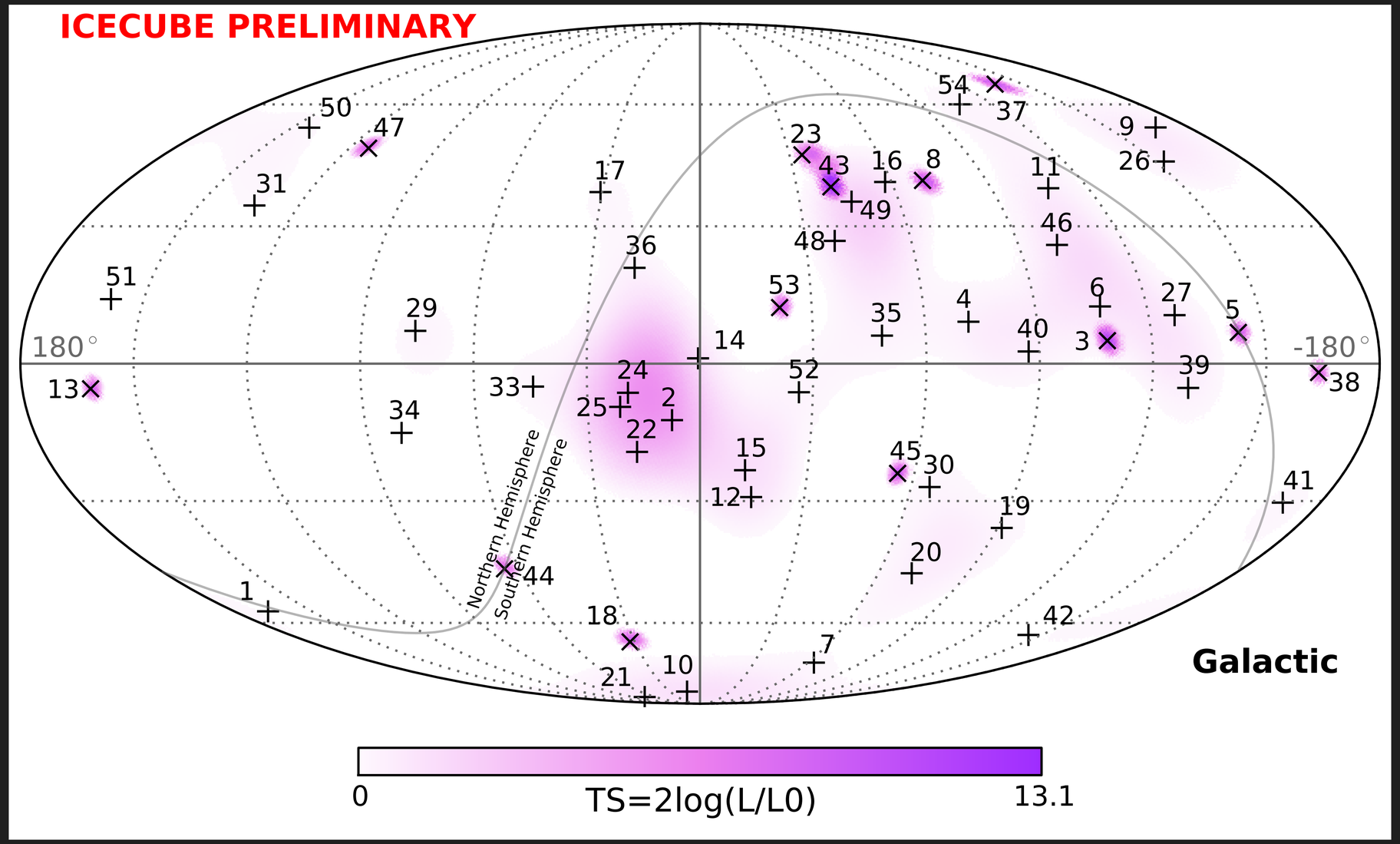
updated from PRL plot version with priors for backgrounds - 4 years



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

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

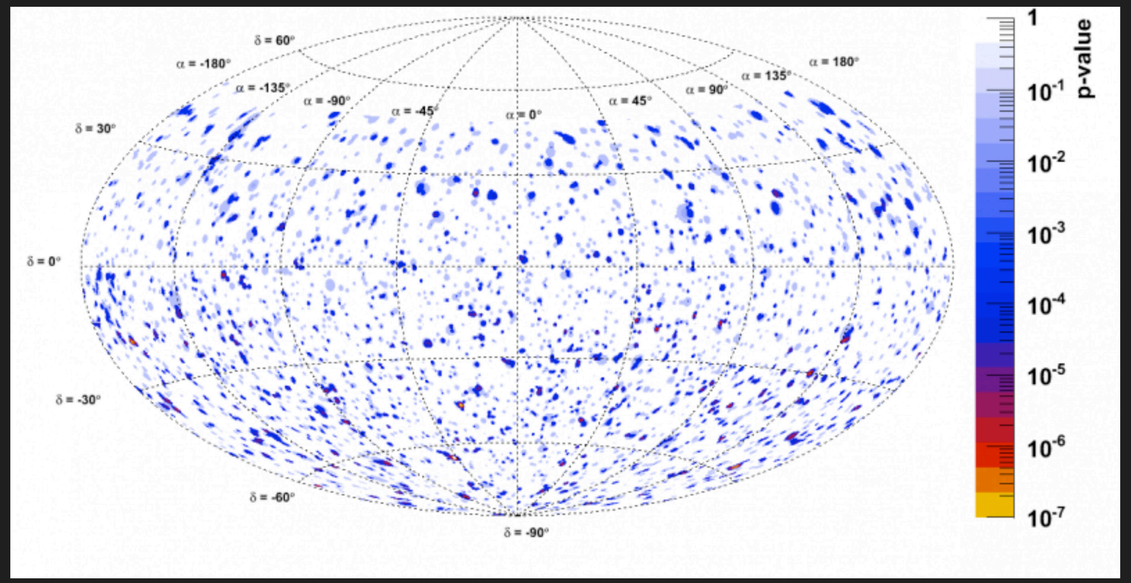
Significance: **44%** (not significant)

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

WHERE ARE THE SOURCES?

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

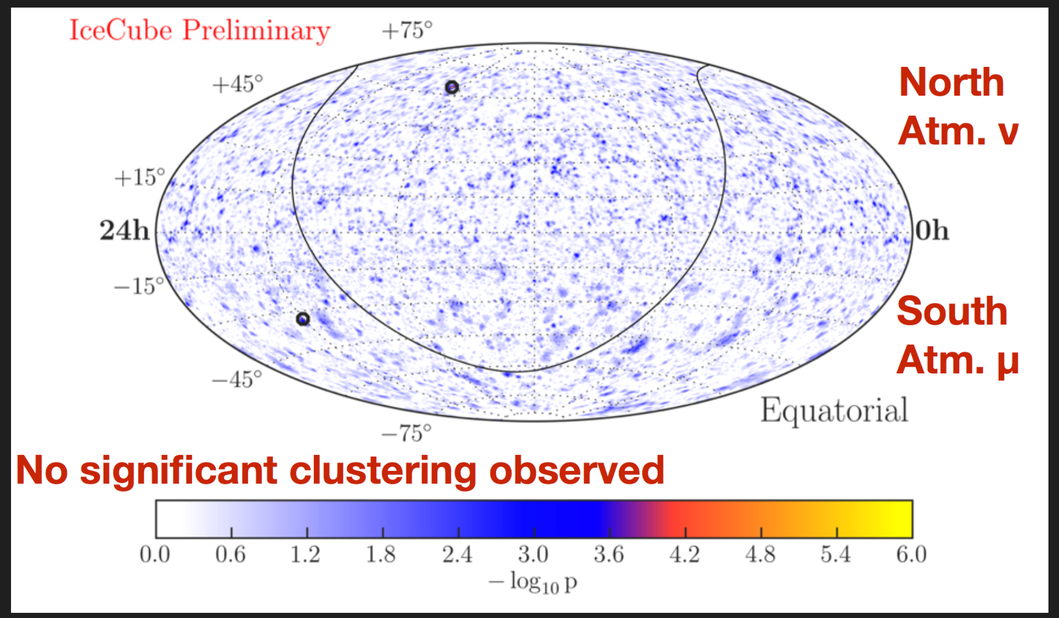
ApJ Lett, 786, L5 (2014)



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

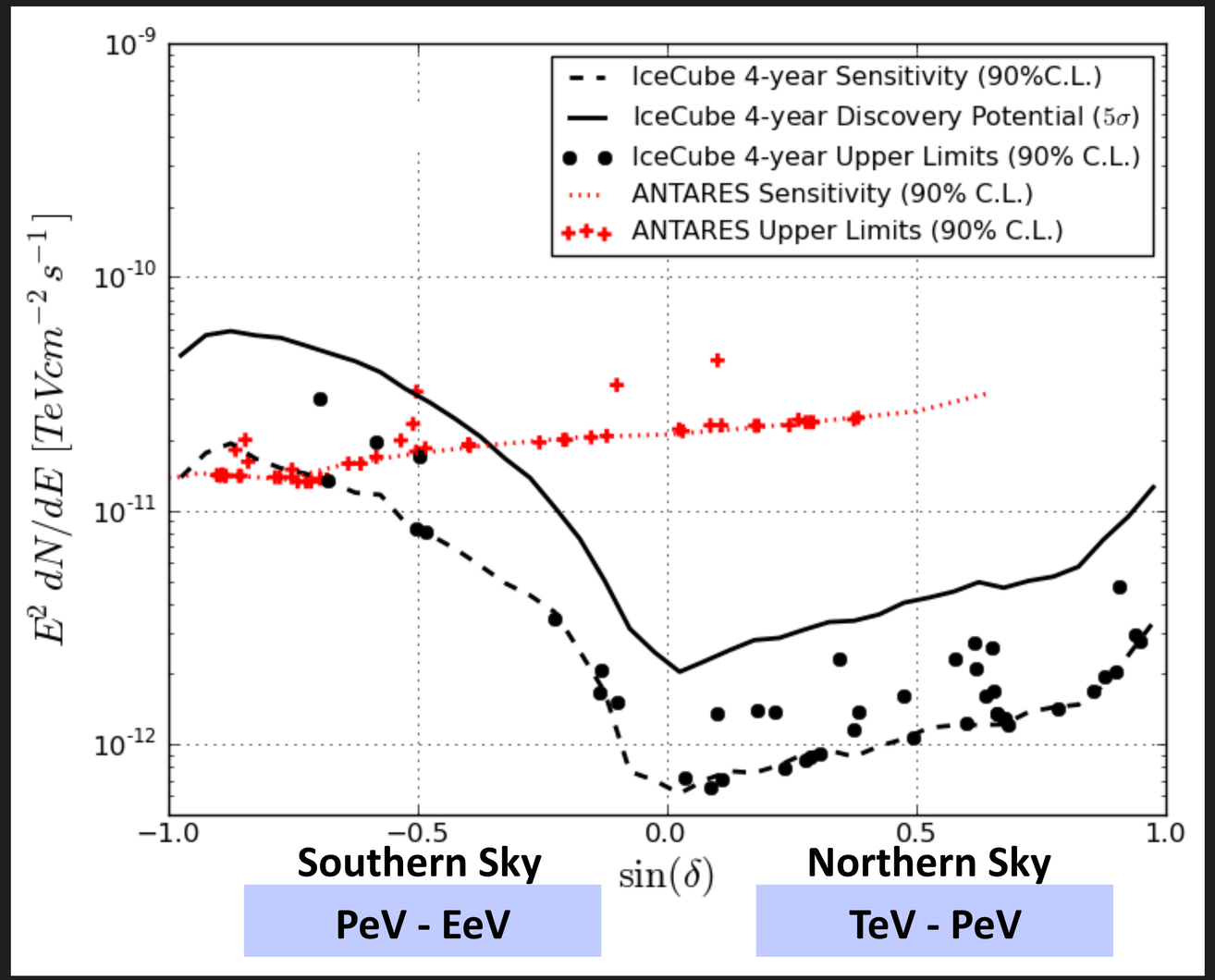


CONSTRAINTS ON POINT SOURCES

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

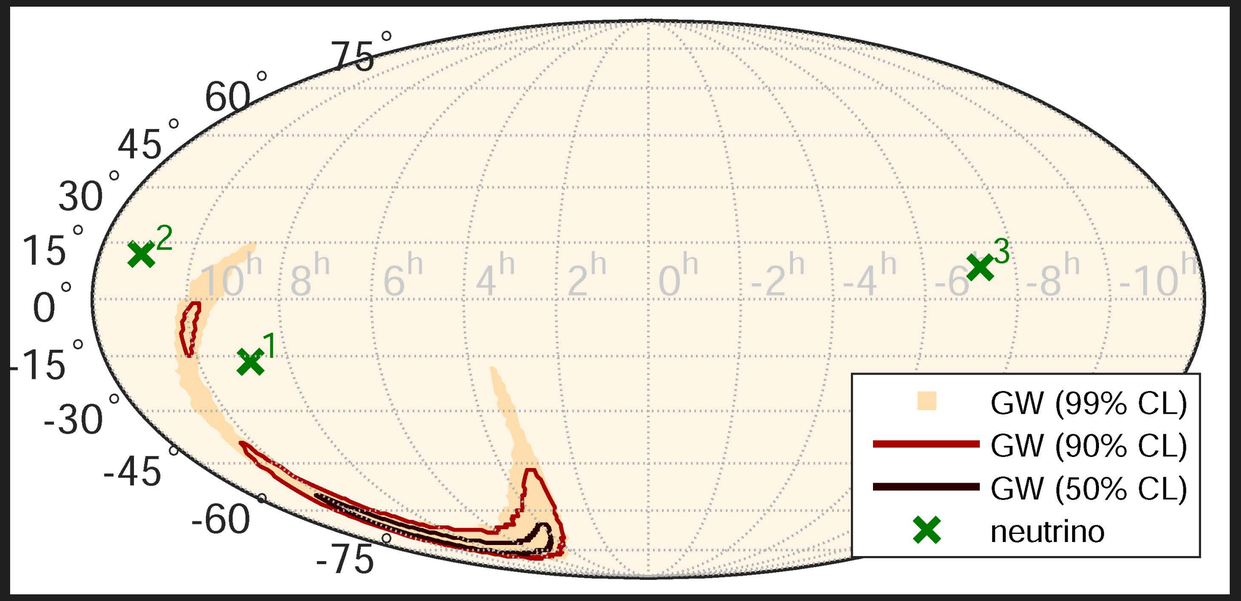


GRAVITATIONAL WAVES AND NEUTRINOS

LIGO just discovered gravitational waves! Did we see any neutrinos from their source? (Search in ANTARES and IceCube)

Search within a time window of +/-500s of GW150914 - 3 neutrino candidates in IceCube, none of them compatible in direction (and rather low in energy).

Consistent with background.



joint IceCube/ANTARES/LIGO publication currently at:

https://dcc.ligo.org/LIGO-P1500271/public

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

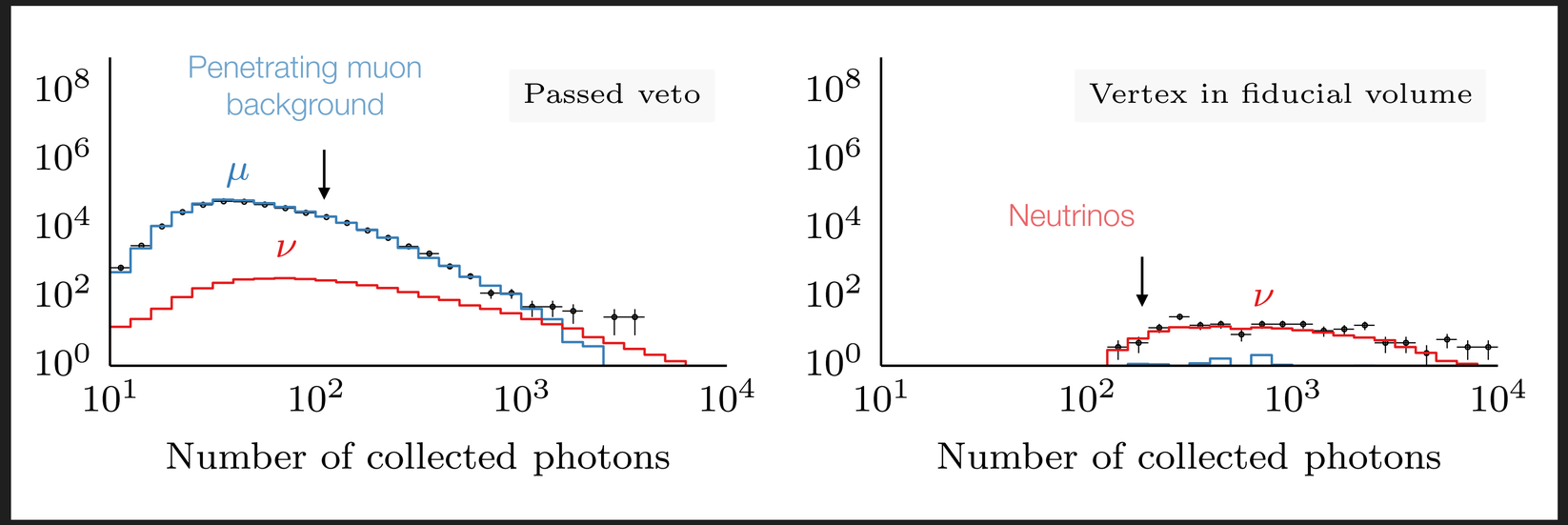
What happens to the astrophysical flux below 60 TeV?

PRD 91, 022001

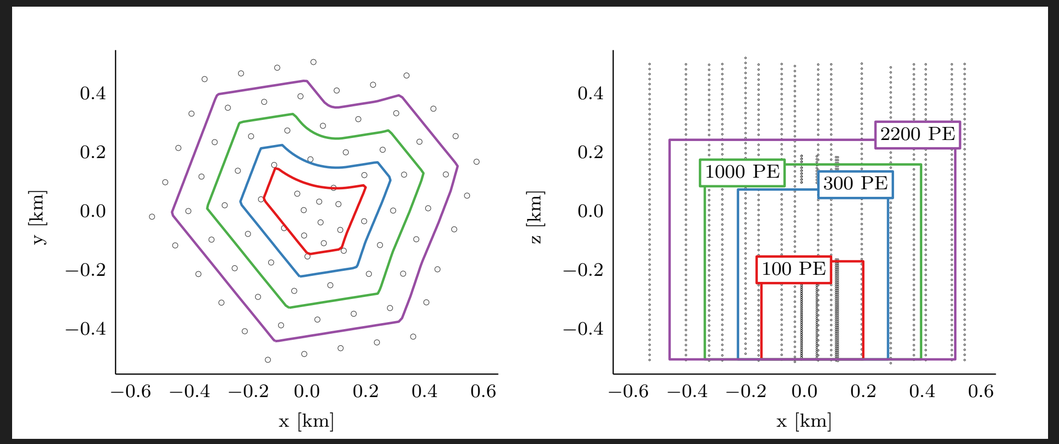
Outer-layer veto → **Energy-dependent veto**

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?

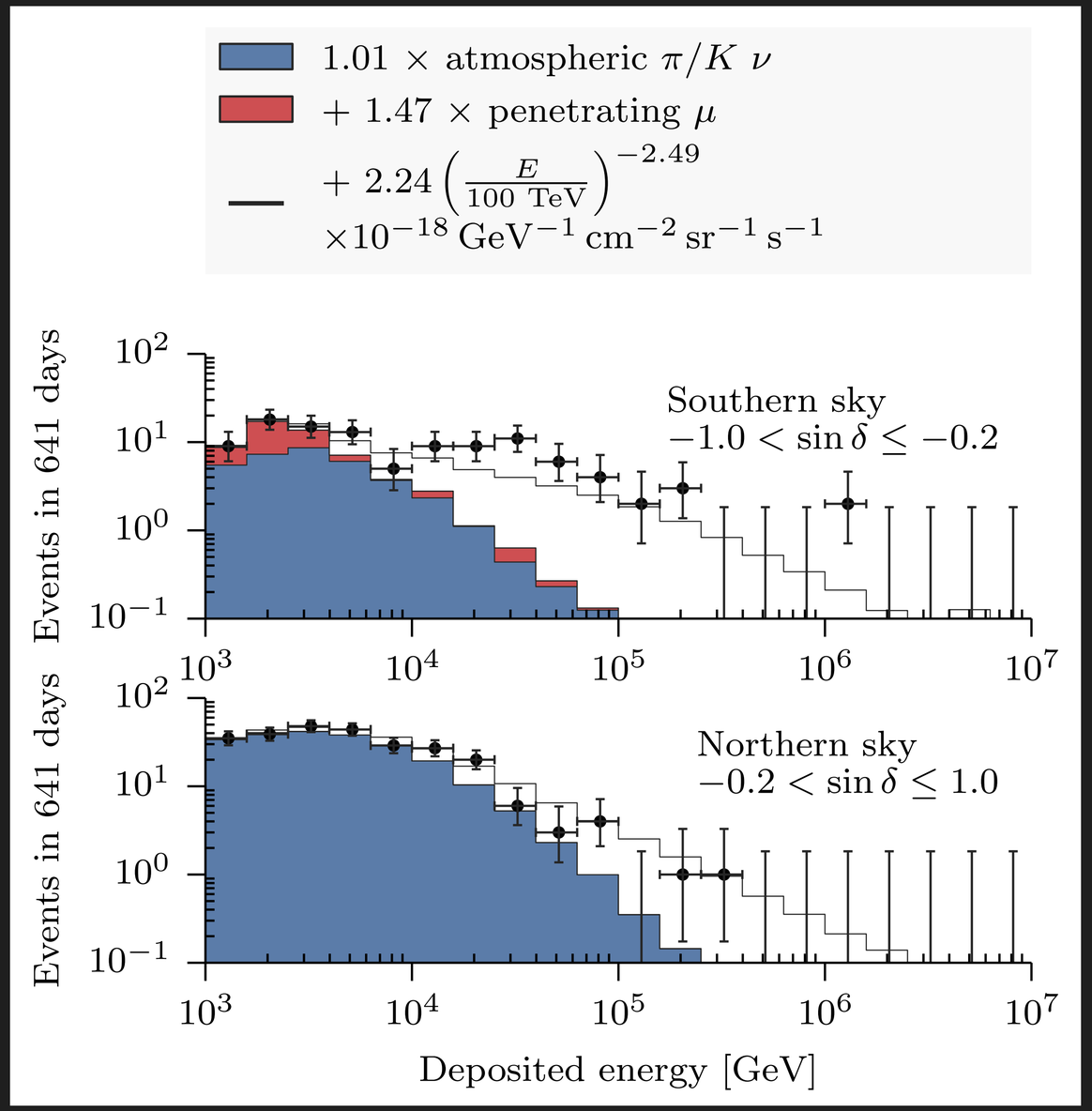
106 events > 10 TeV, 9 events > 100 TeV (7 of those in high-energy starting event sample)

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

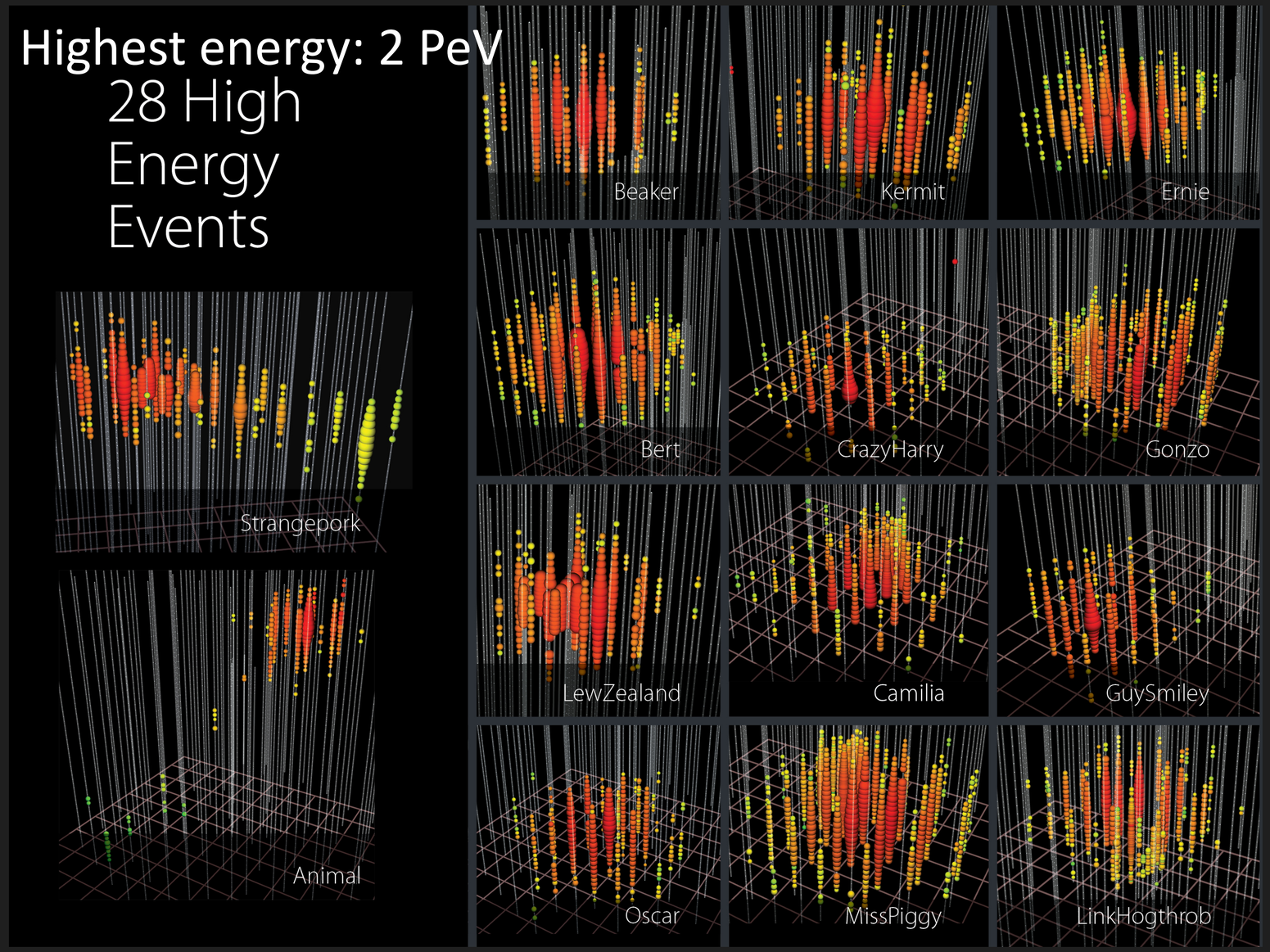


OTHER CHANNELS

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

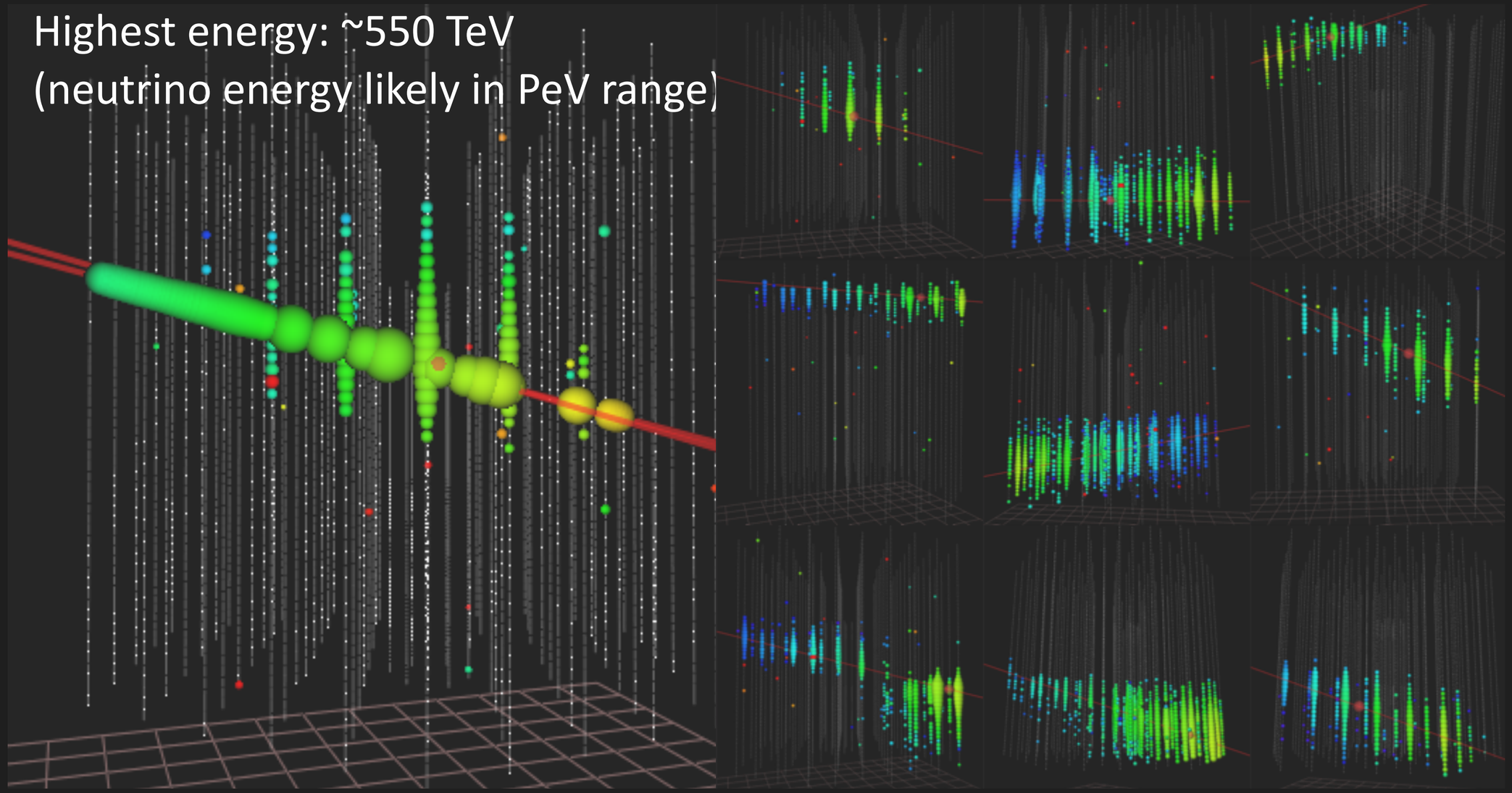


High-Energy Starting Event Search (“HESE”)

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

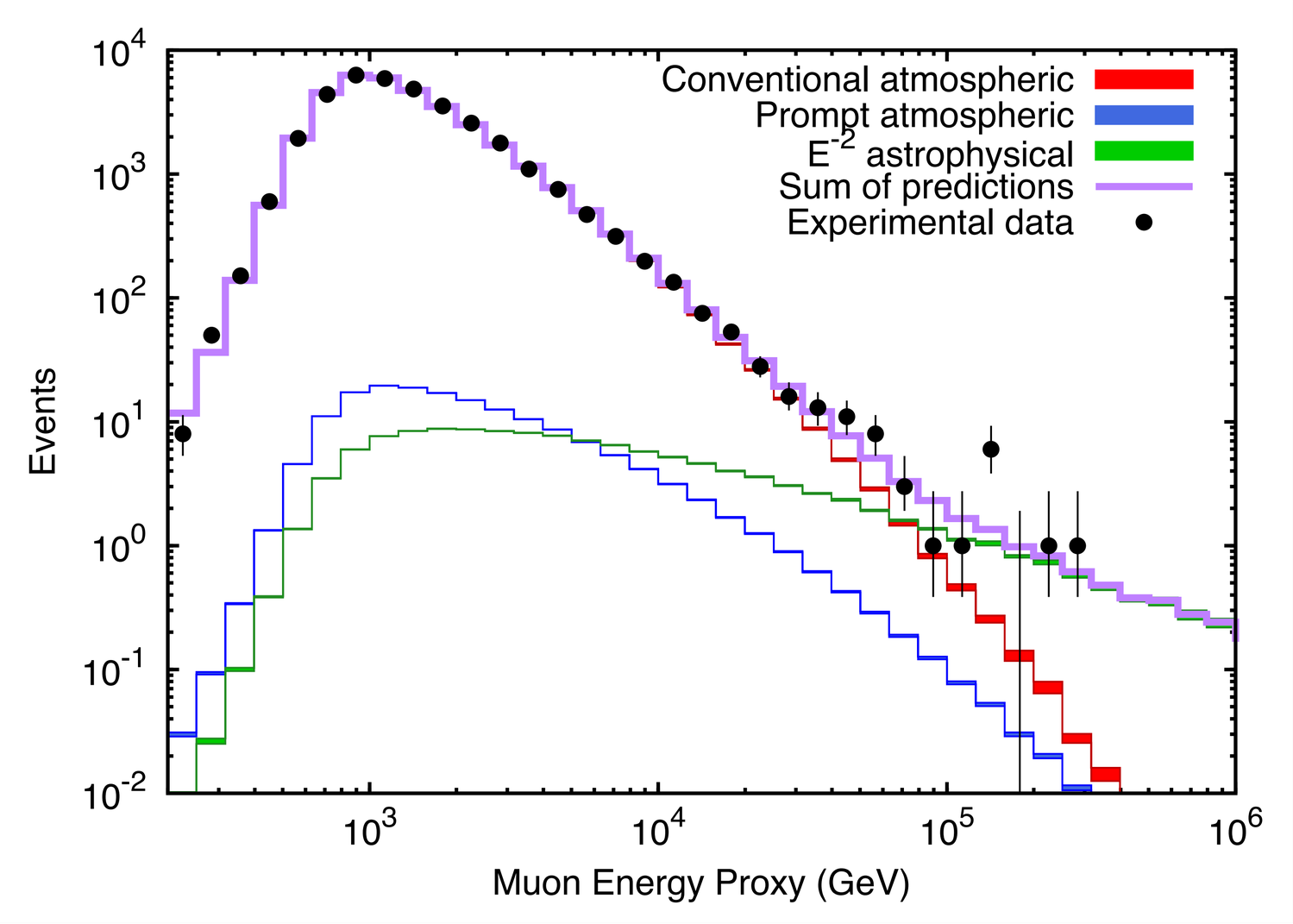
Two years of data

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

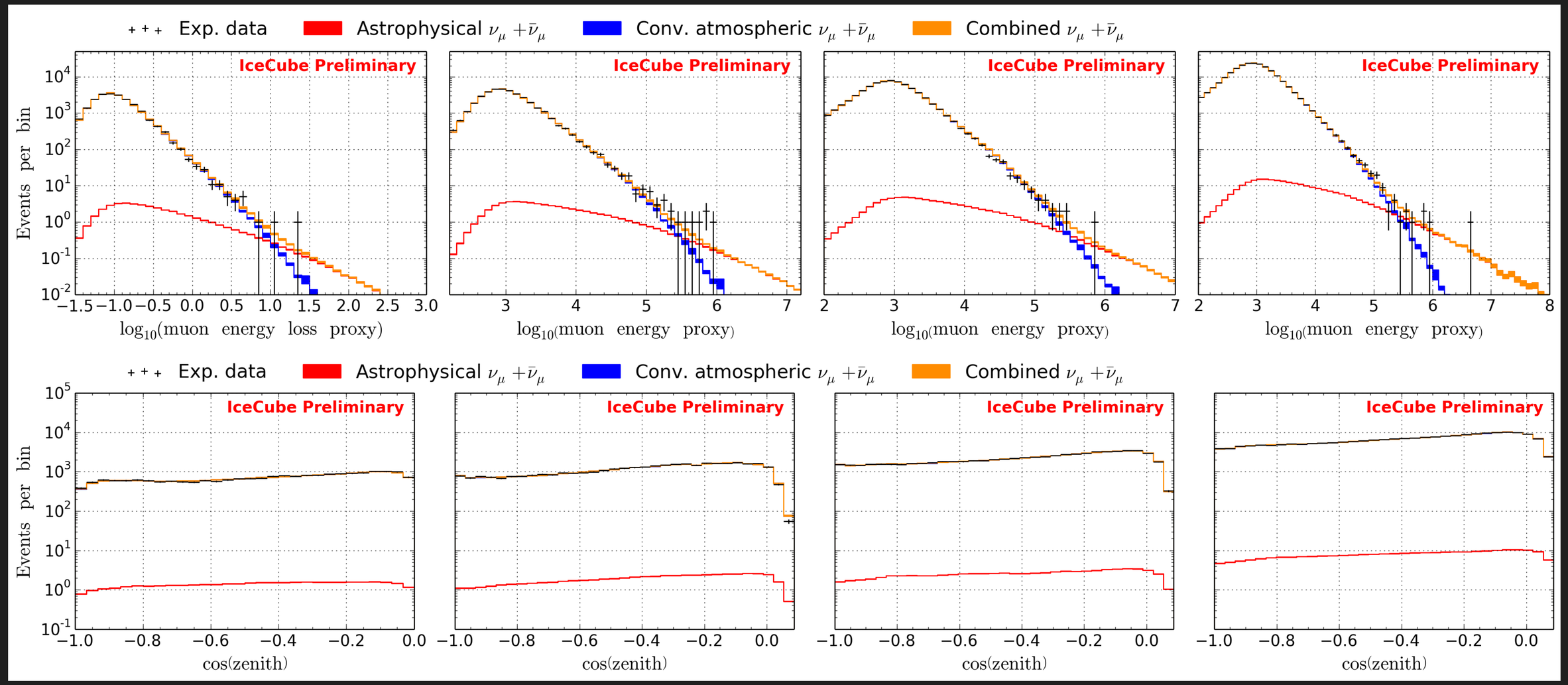
PRL 115, 081102 (2015)



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

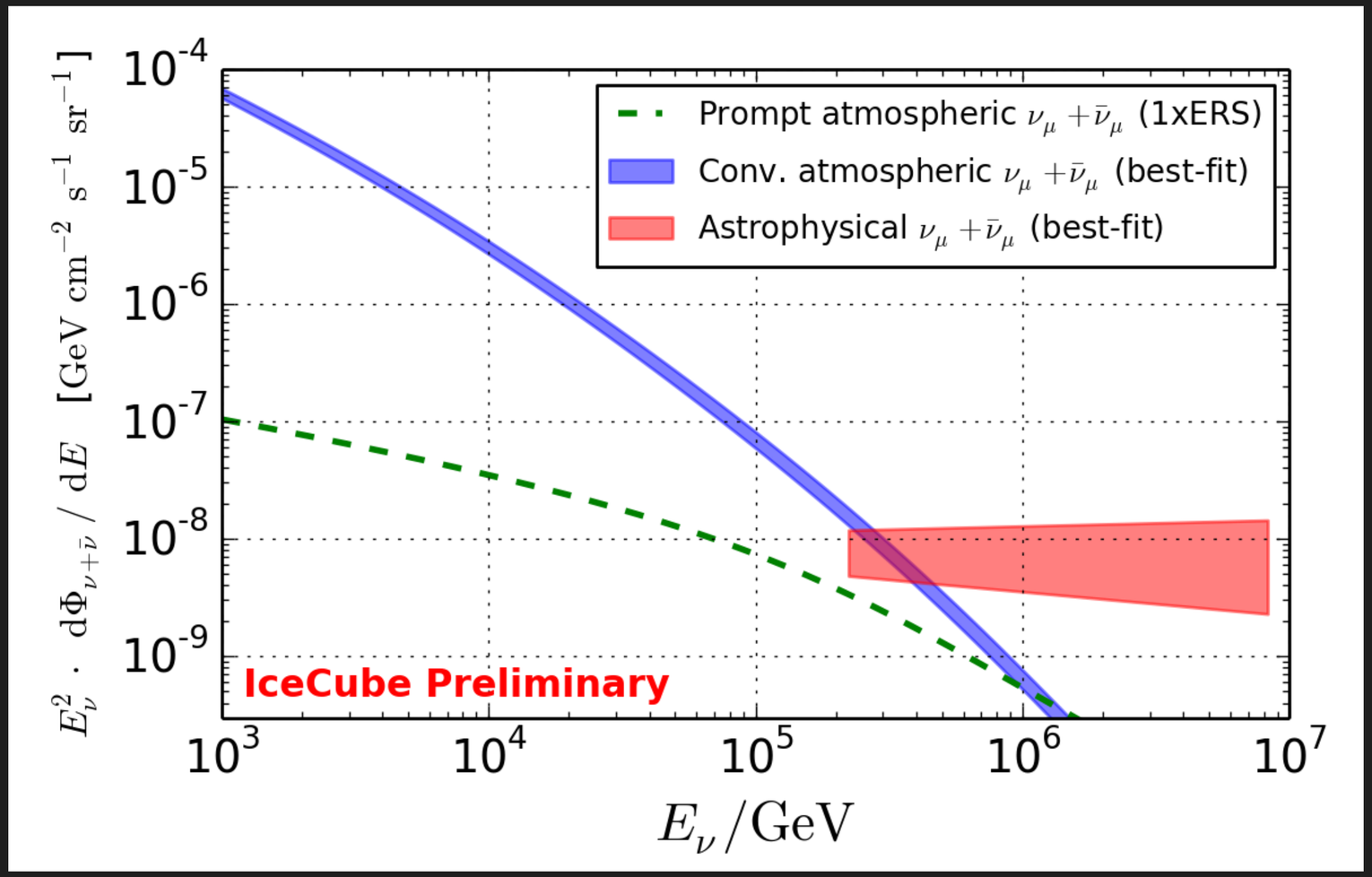


UPGOING MUONS - SPECTRAL COMPONENTS

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

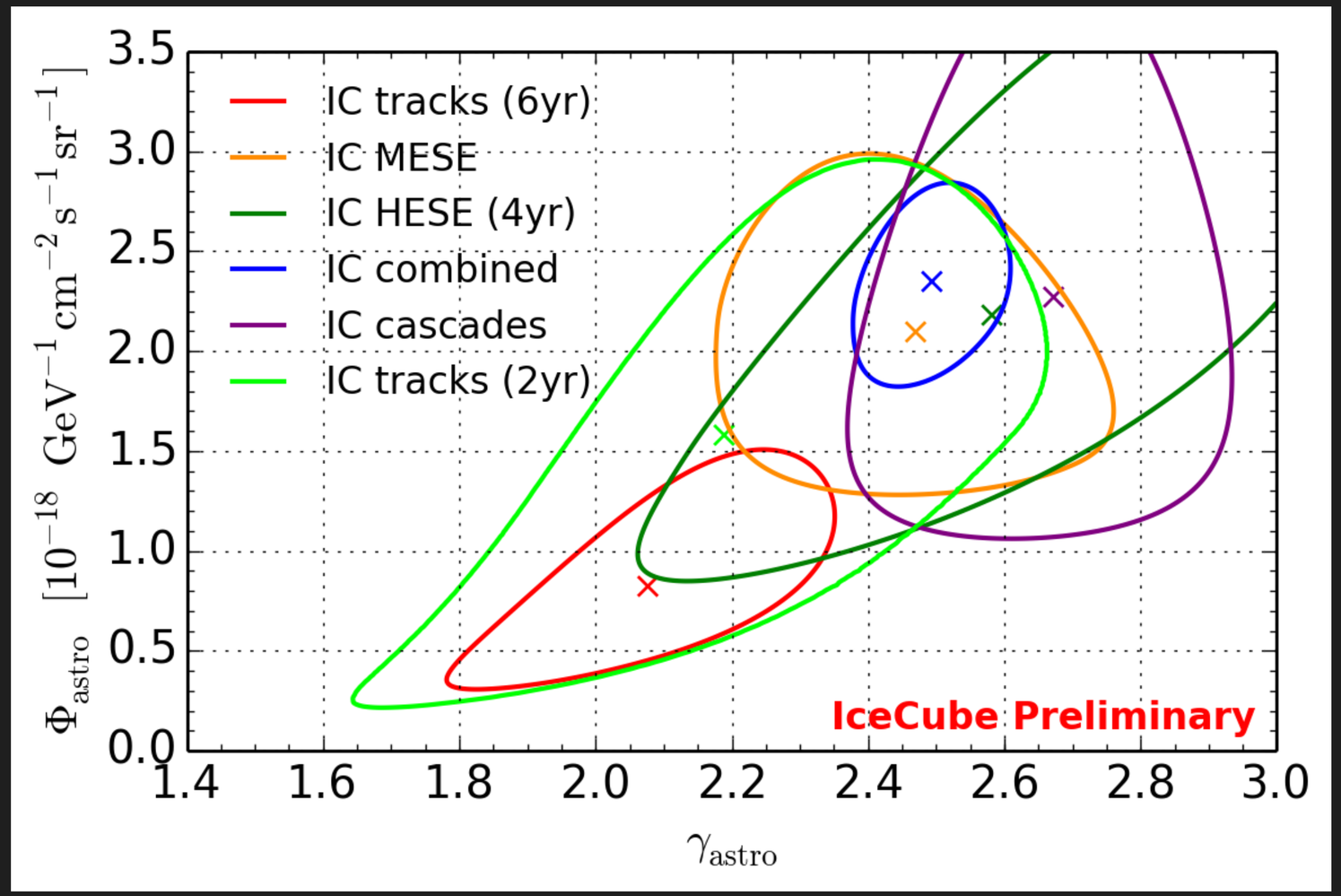


SUMMARY OF VARIOUS ICECUBE DIFFUSE RESULTS

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)

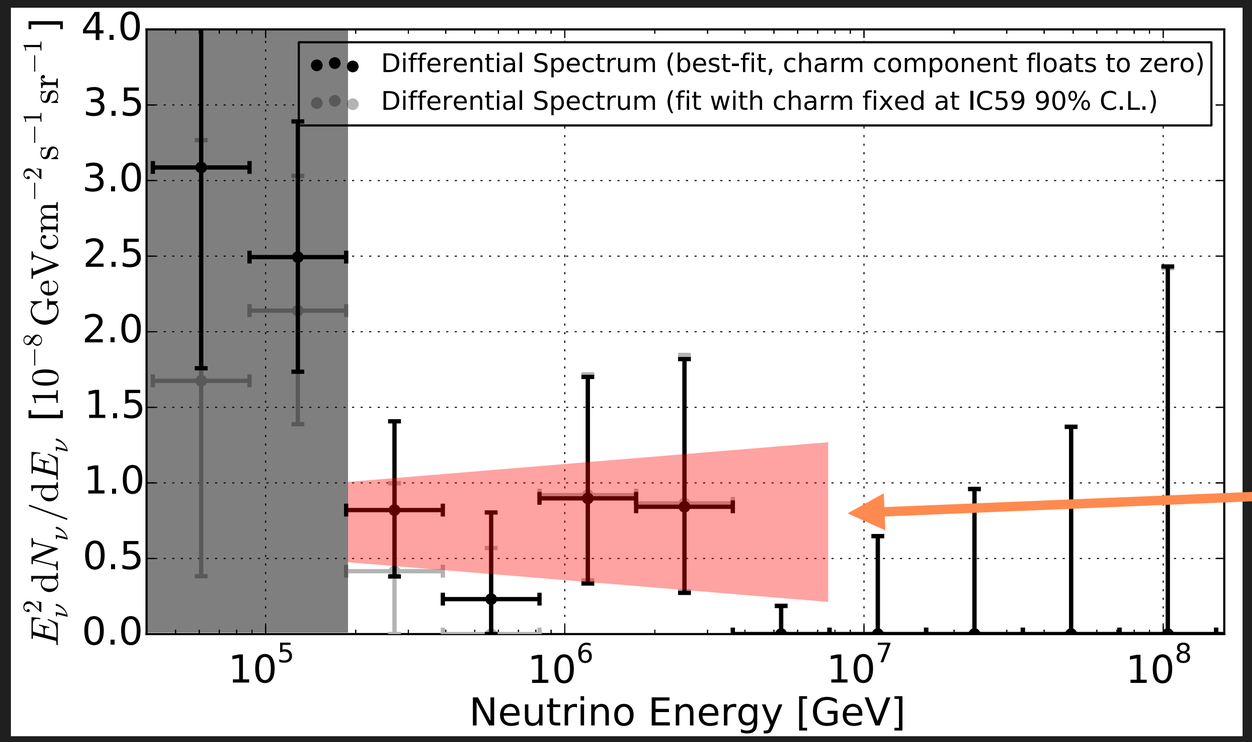
PoS(ICRC2015)1109
(cascades)

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

COMPARISON WITH STARTING EVENT RESULTS

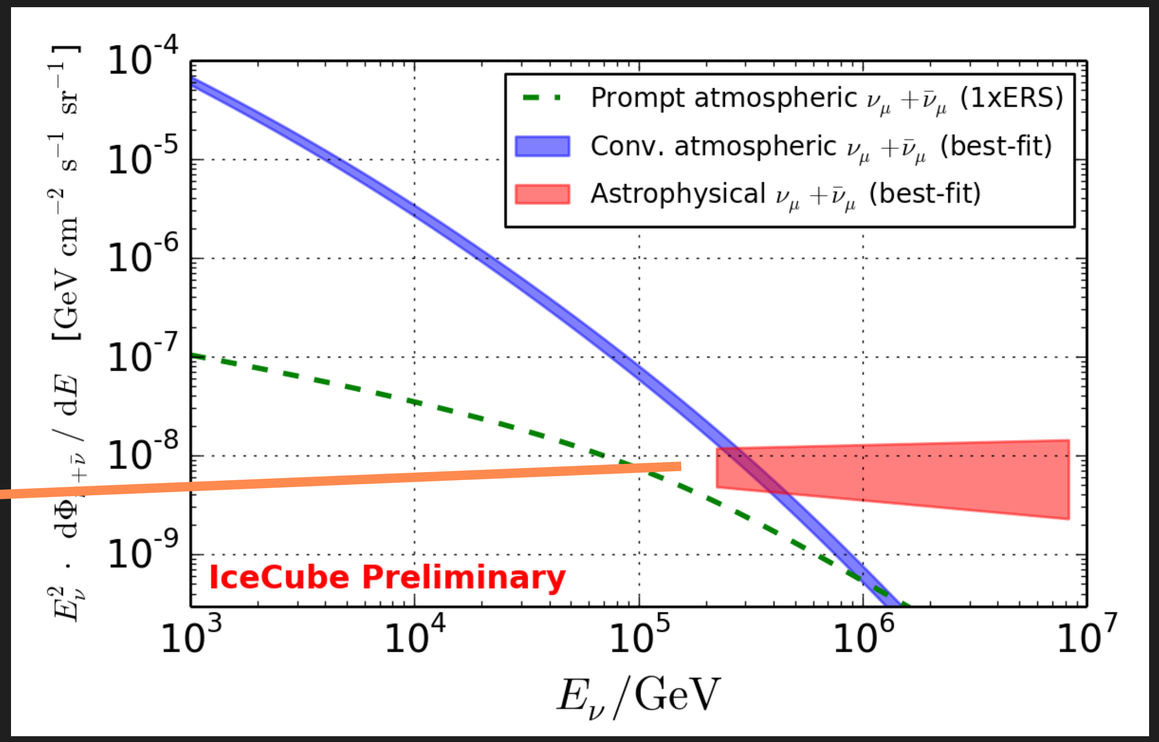
we start to see that simple power laws for the whole sky are probably not enough...

starting events (unfolding)
(dominated by showers)



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

6 year up-going ν_μ analysis



threshold of about 200 TeV
compatible at higher energies

UPGOING MUONS

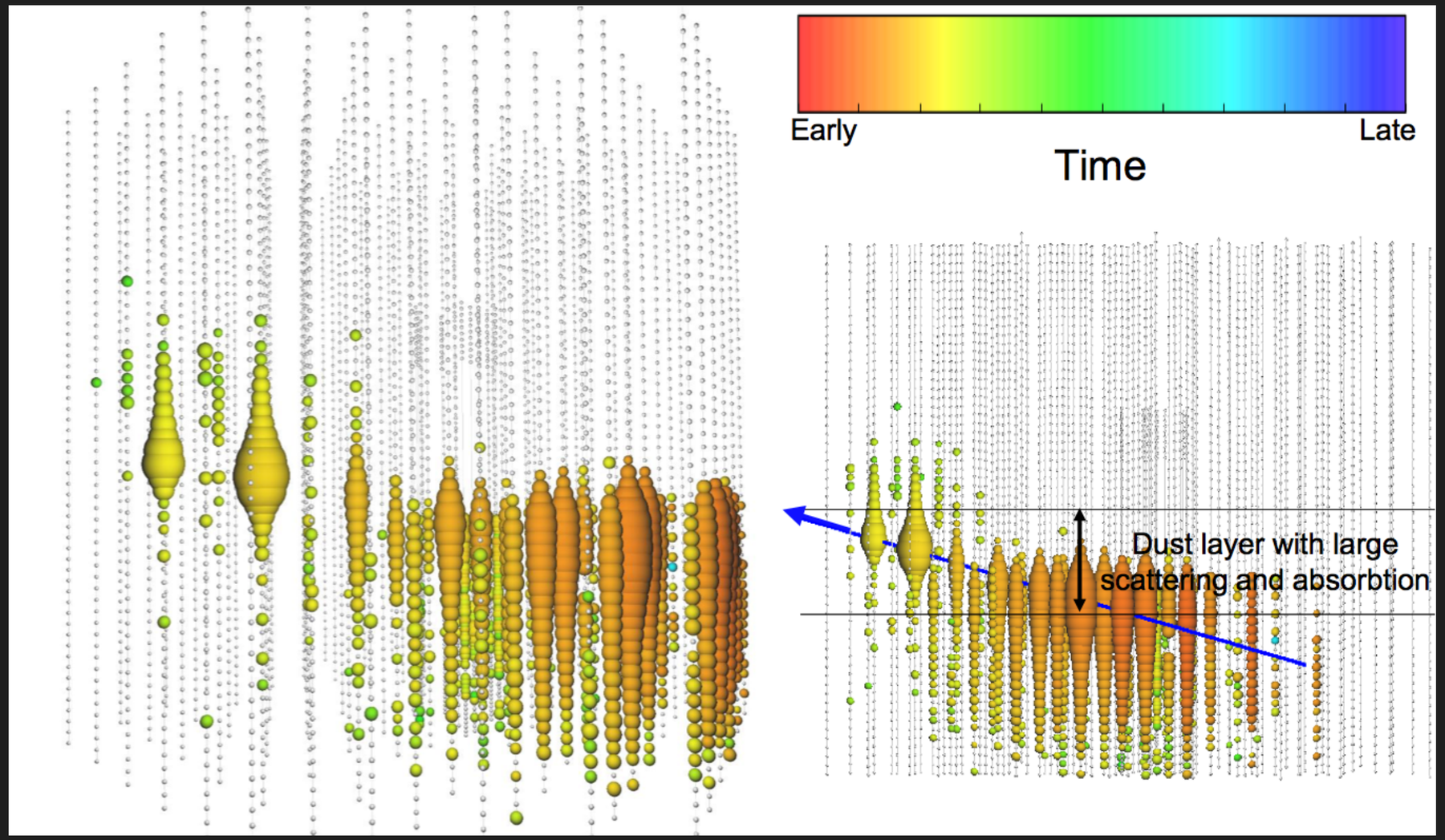
an interesting event in the six-year sample!

up-going
(i.e. not a CR muon)

deposited energy:
2.6±0.3 PeV
(lower limit on neutrino energy)

date: June 11, 2014

direction:
11.48° dec / 110.34° RA

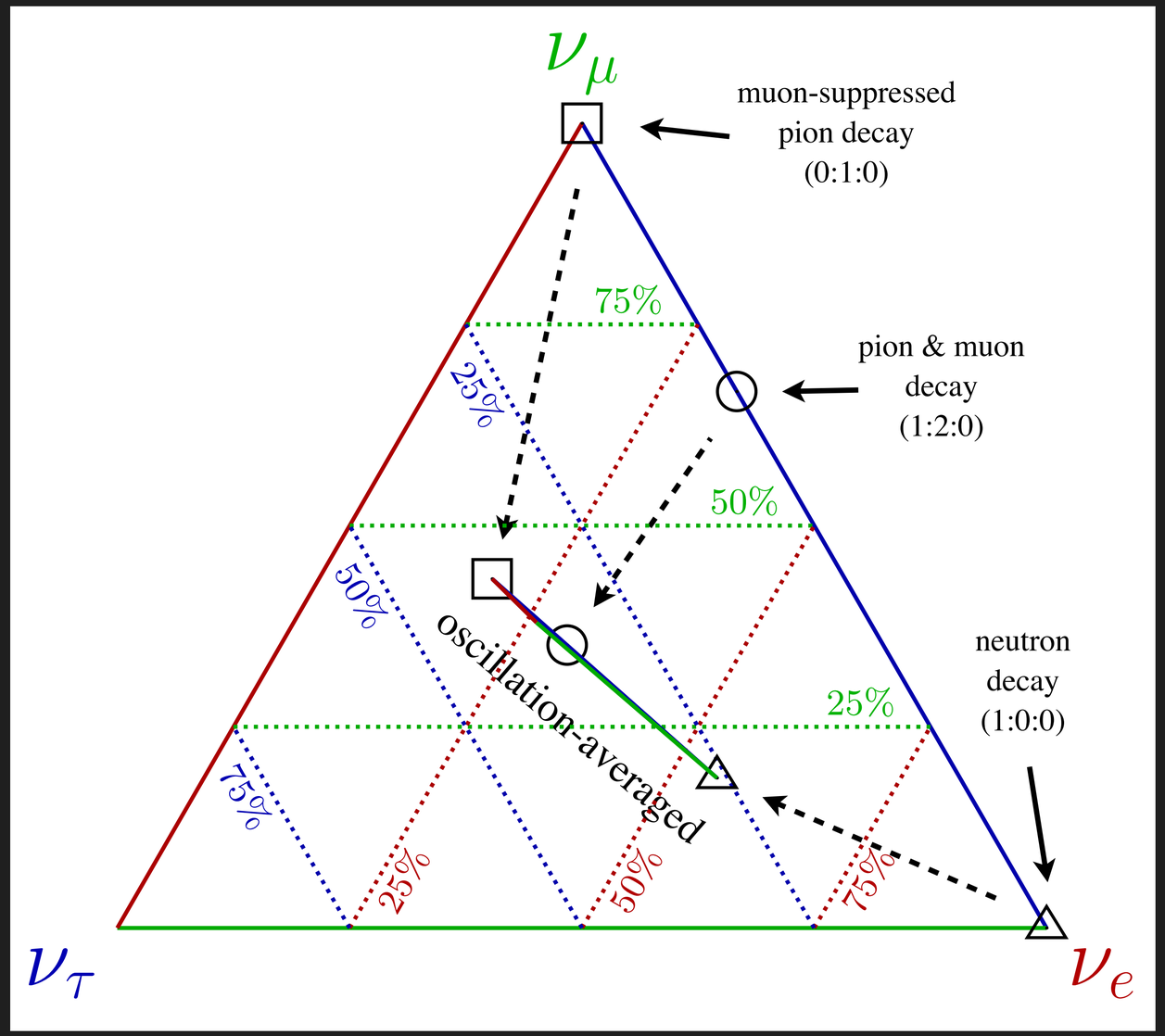


FLAVOR COMPOSITION

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

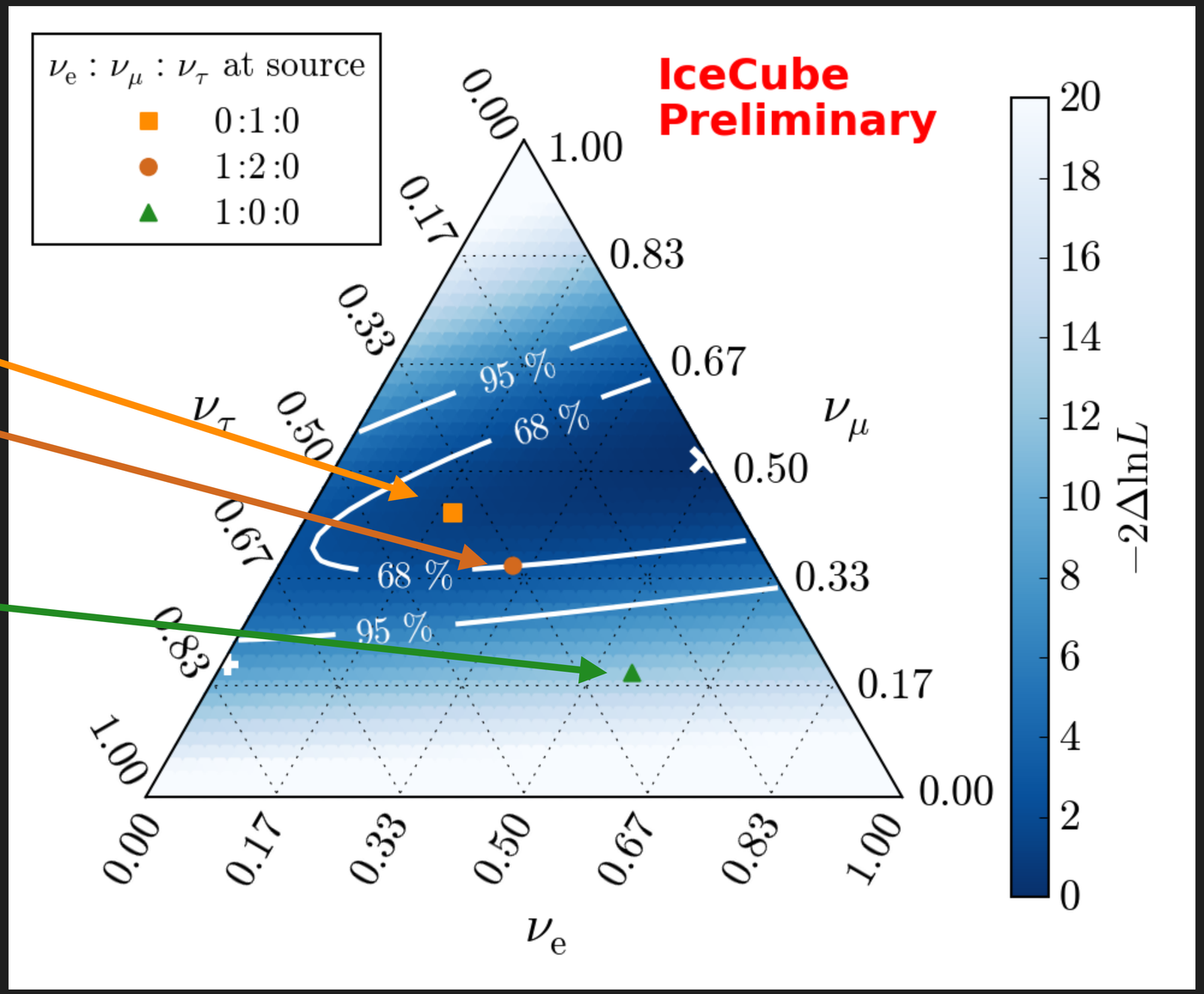
muon-damped (0:1:0)

pion decay (1:2:0)

→ compatible

neutron decay (1:0:0)

→ excluded at 3.7σ

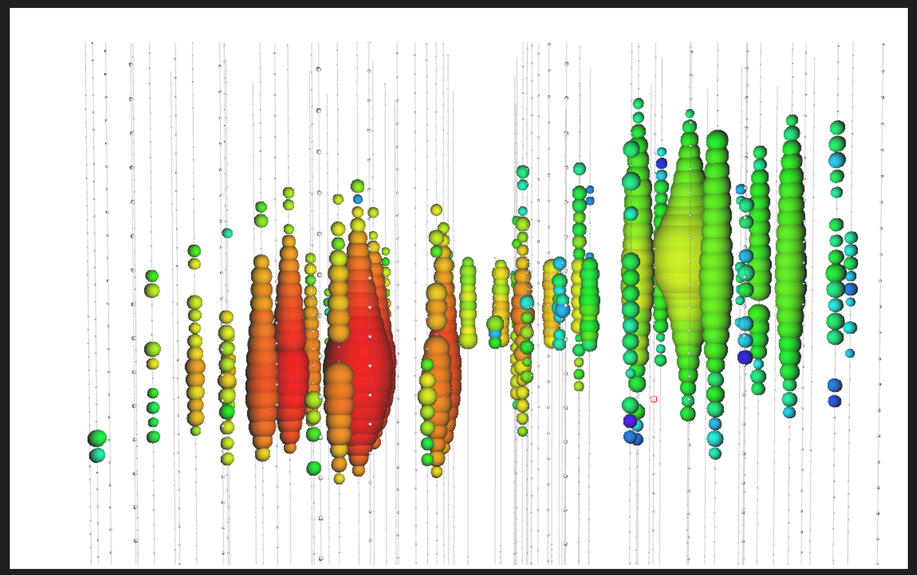


ApJ 809, 98 (2015)/ PoS(ICRC2015)1066

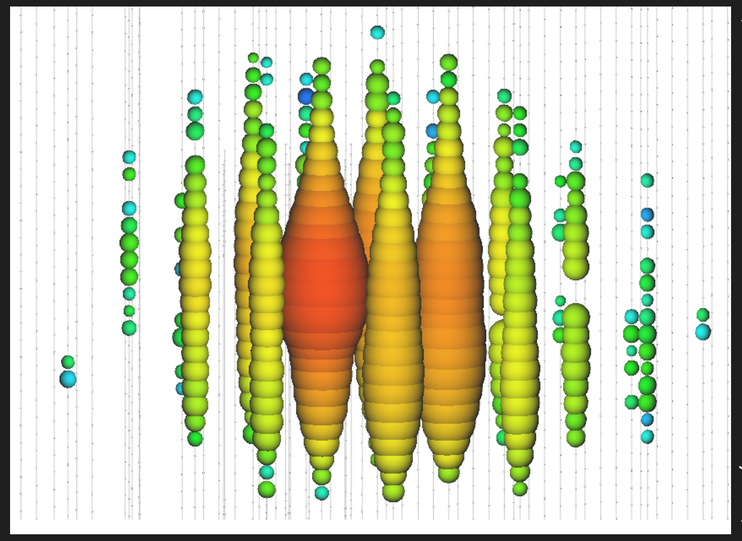
TAU NEUTRINOS

should see the first taus soon

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

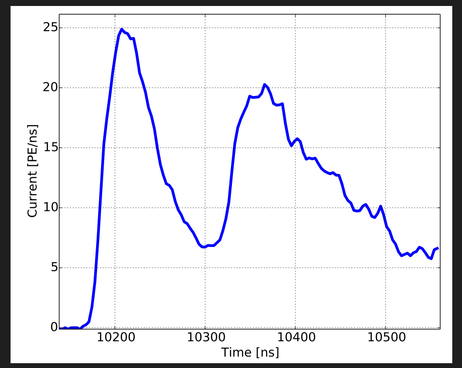


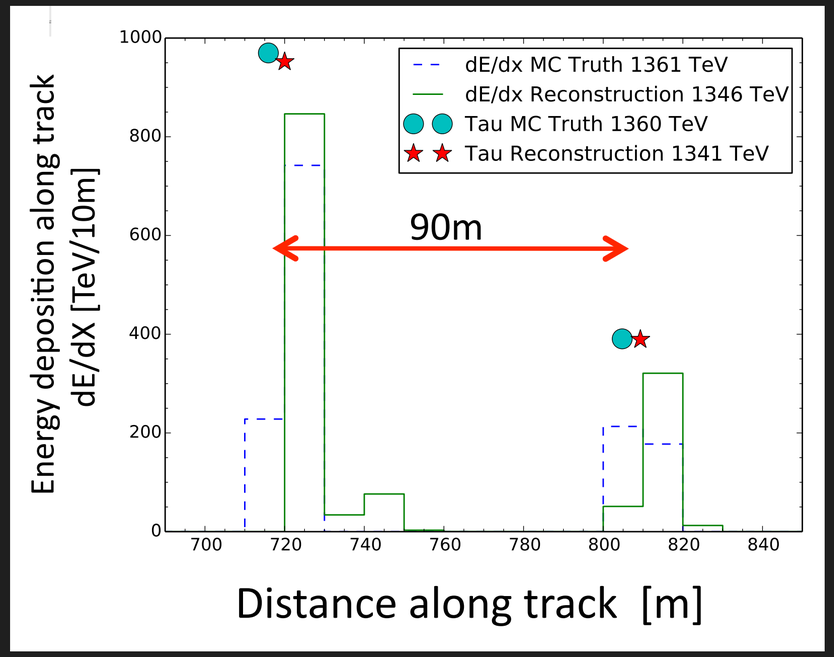
event with longer decay length



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

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





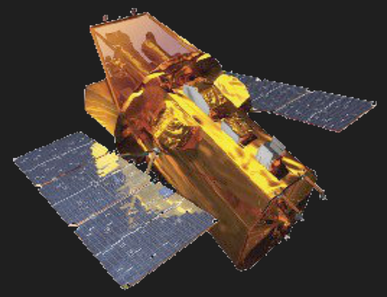
lower energy tau study

PRD 93, 022001 (2016)

ALERTS/FOLLOW-UPS

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

PTF (optical)



Swift (X-Ray)

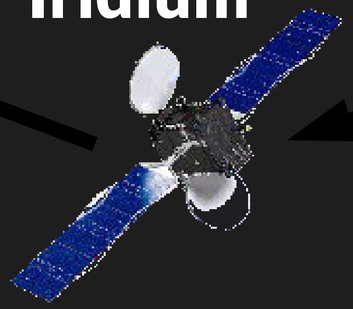
SN/GRB/...

ν

IceCube

"The North"

Iridium



Veritas/
H.E.S.S./
MAGIC/...

working on extending this effort significantly!

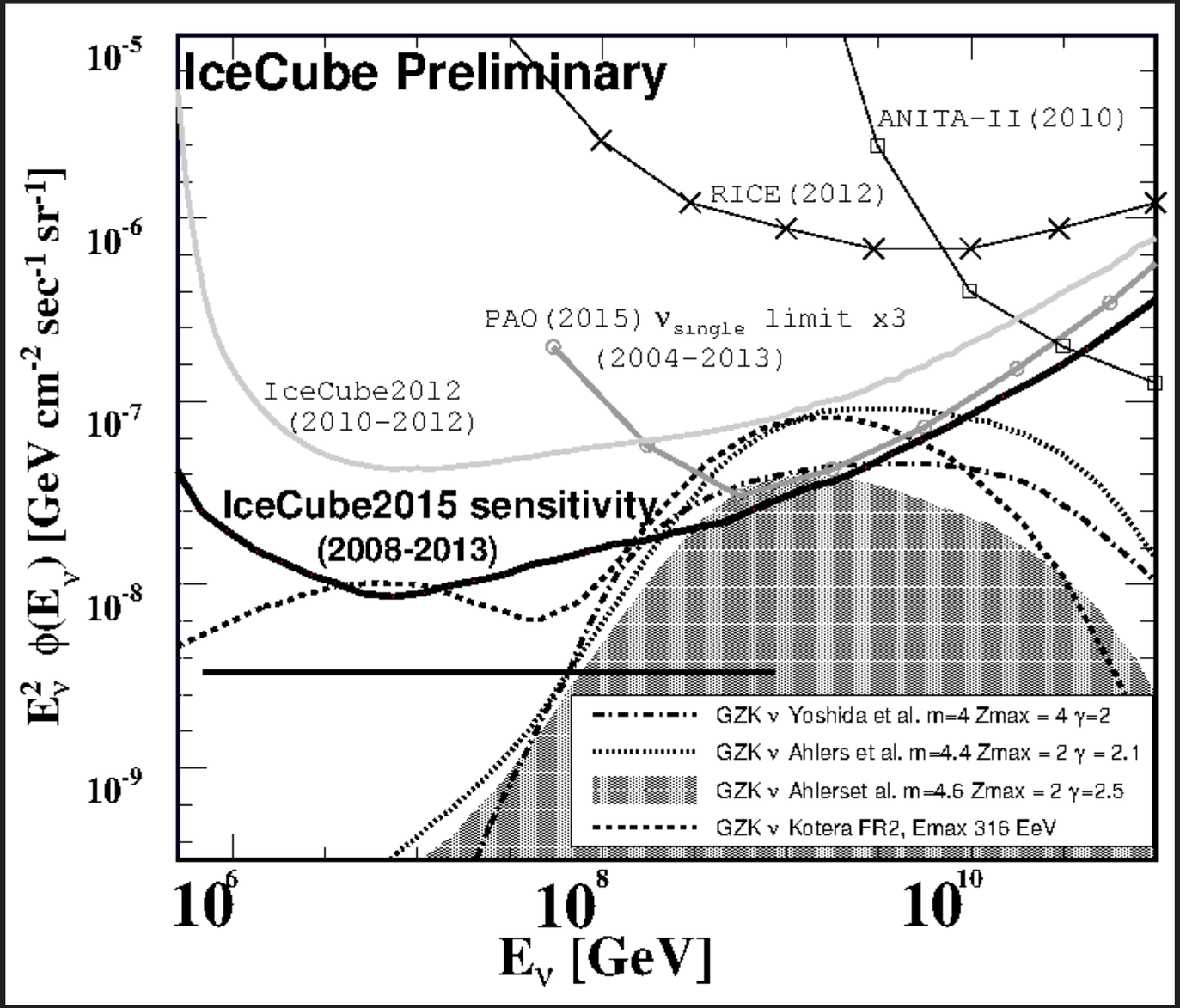
PoS(ICRC2015)1069

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

THANK YOU!