RECENT RESULTS FROM ICECUBE

Claudio Kopper, University of Alberta

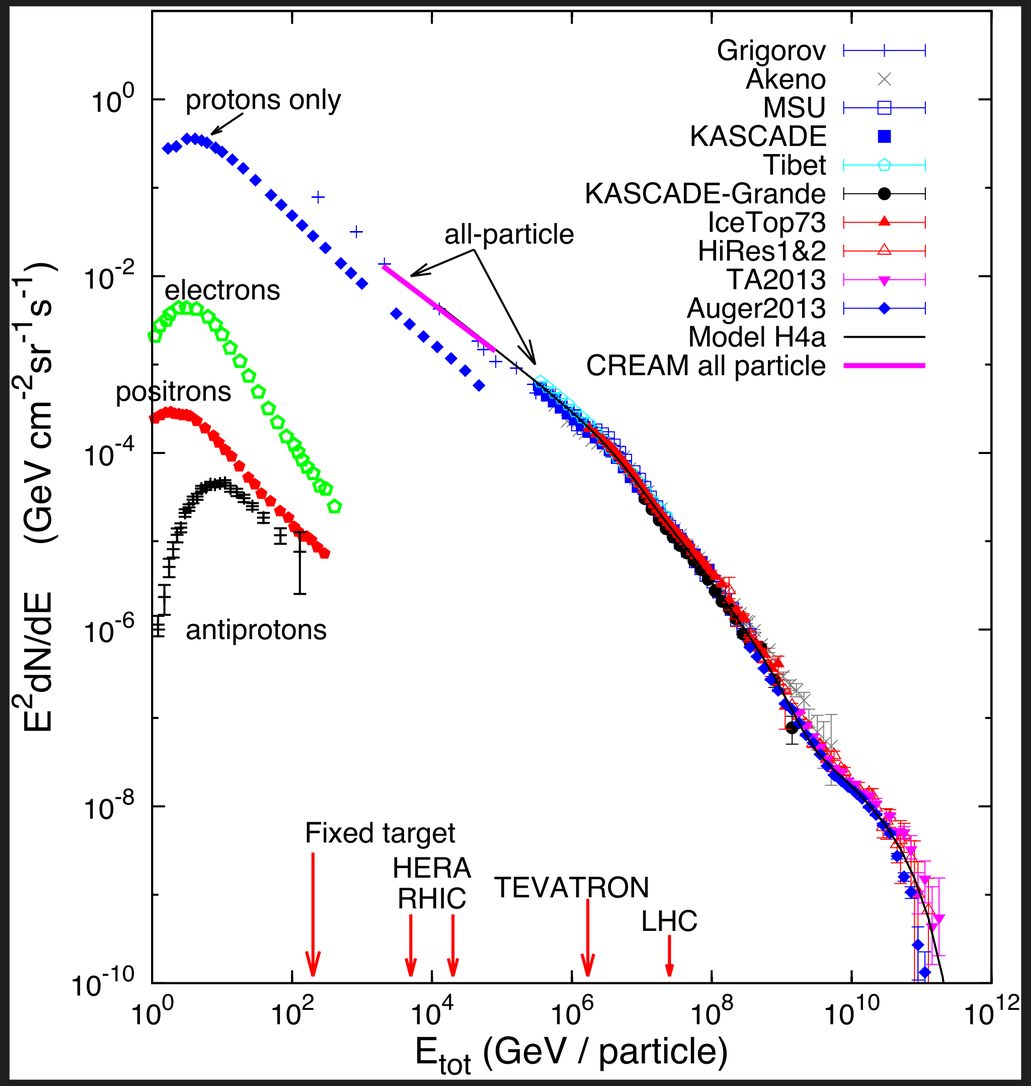
UNIVERSITY OF ALBERTA

COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays

COSMIC RAYS

where (and how) are they accelerated?



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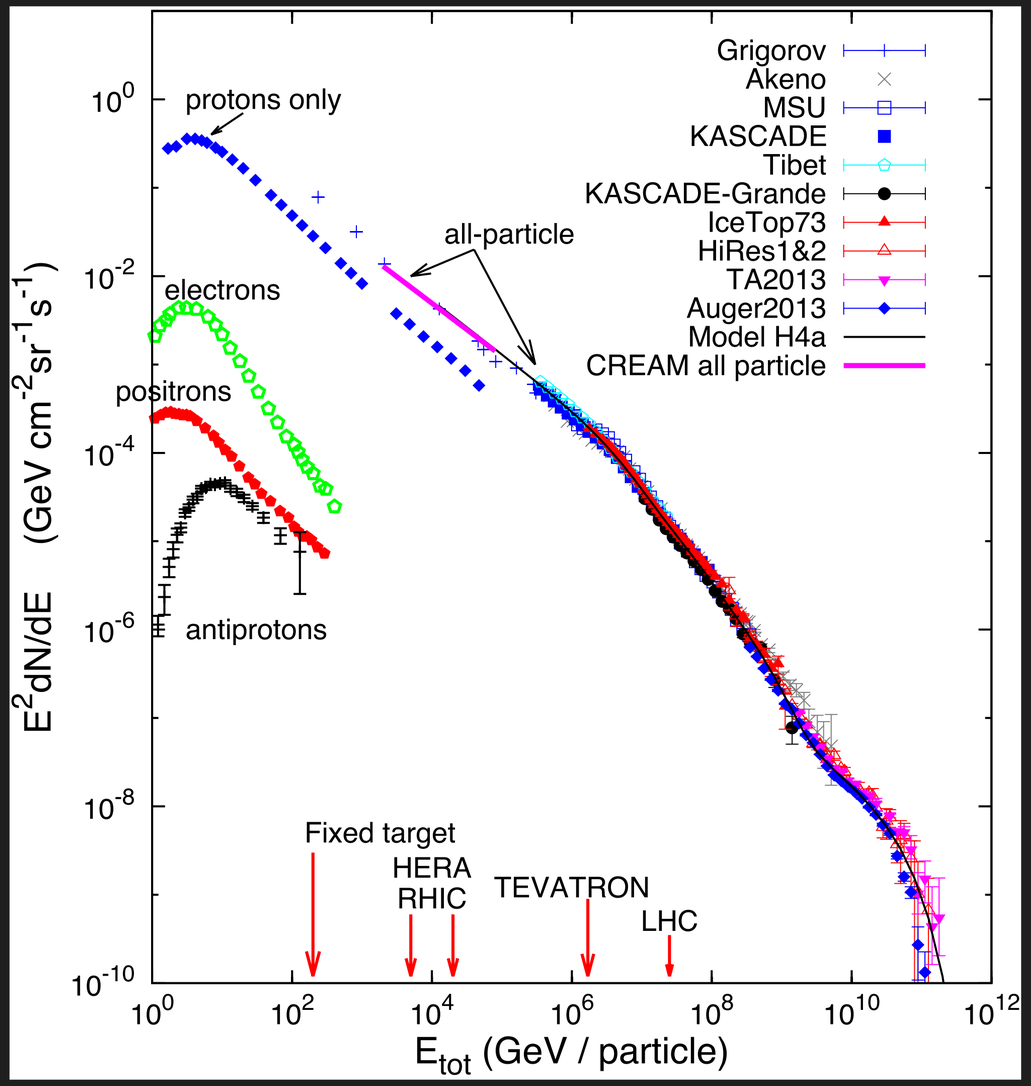
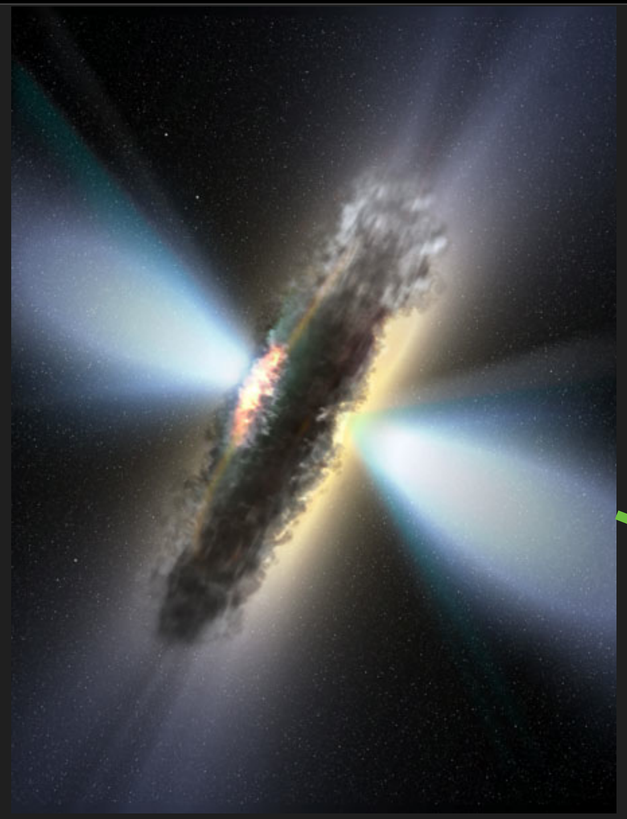


We know their energy spectrum over 11 orders of magnitude

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

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS



- **Nuclei** can be deflected by magnetic fields

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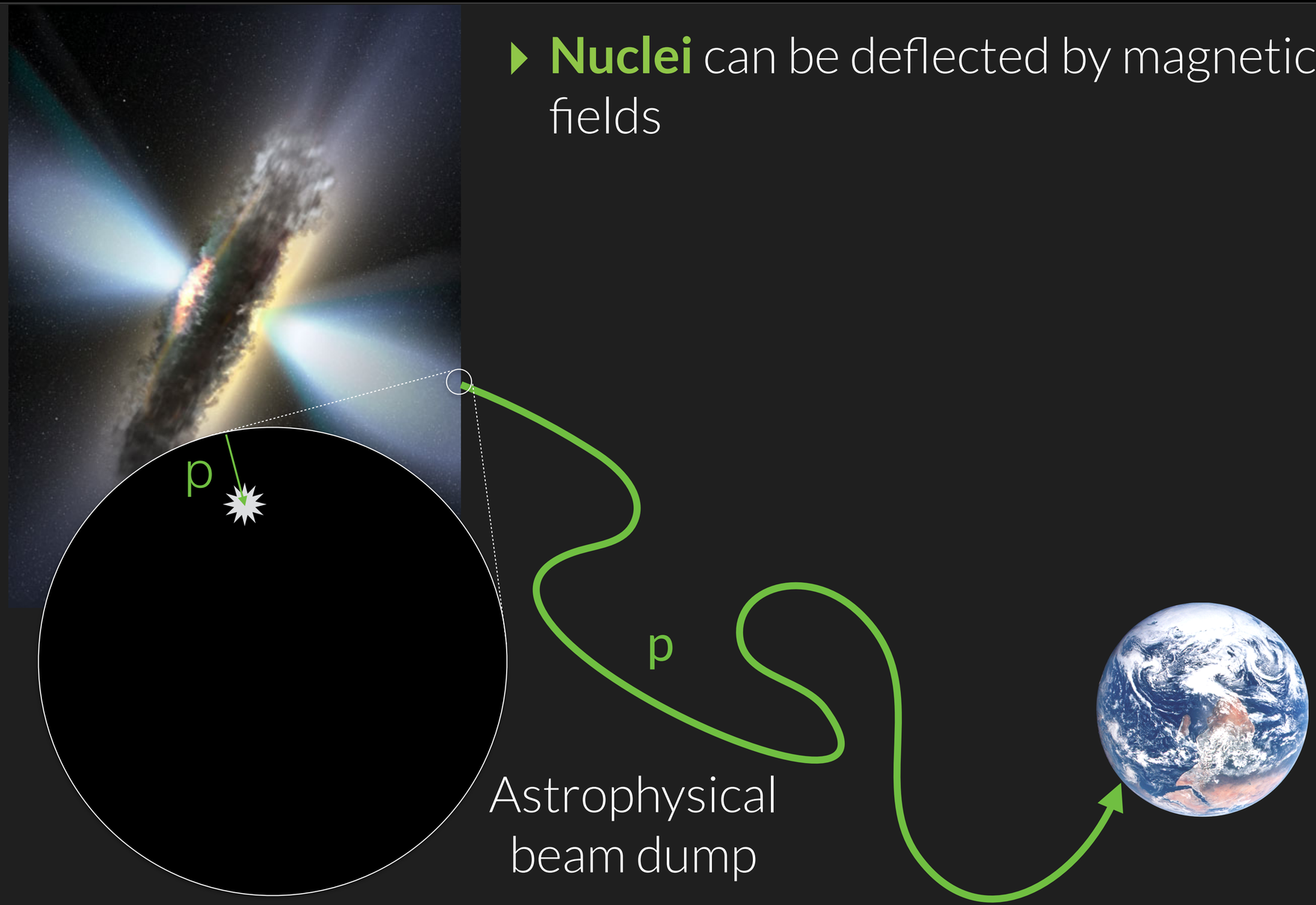

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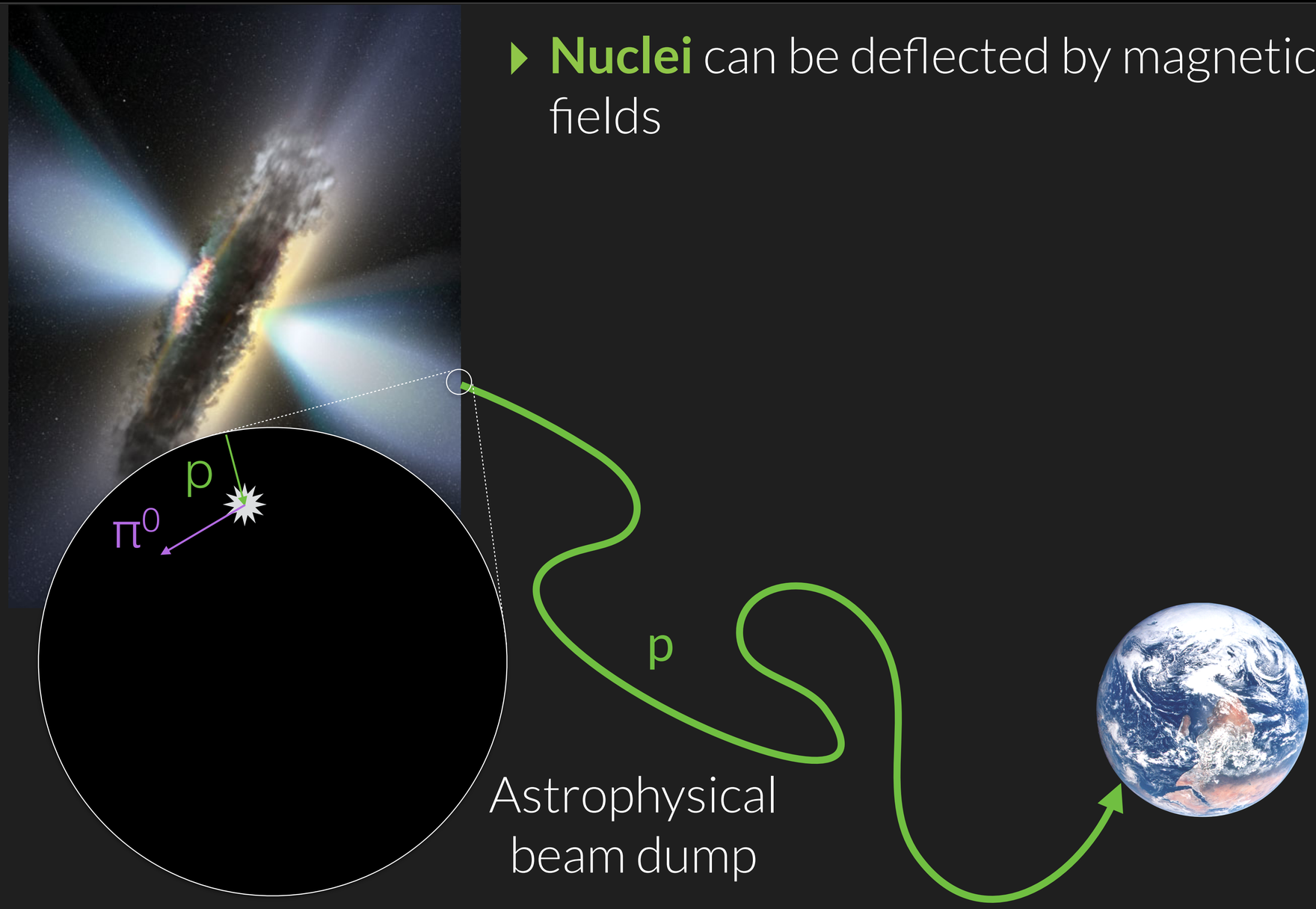

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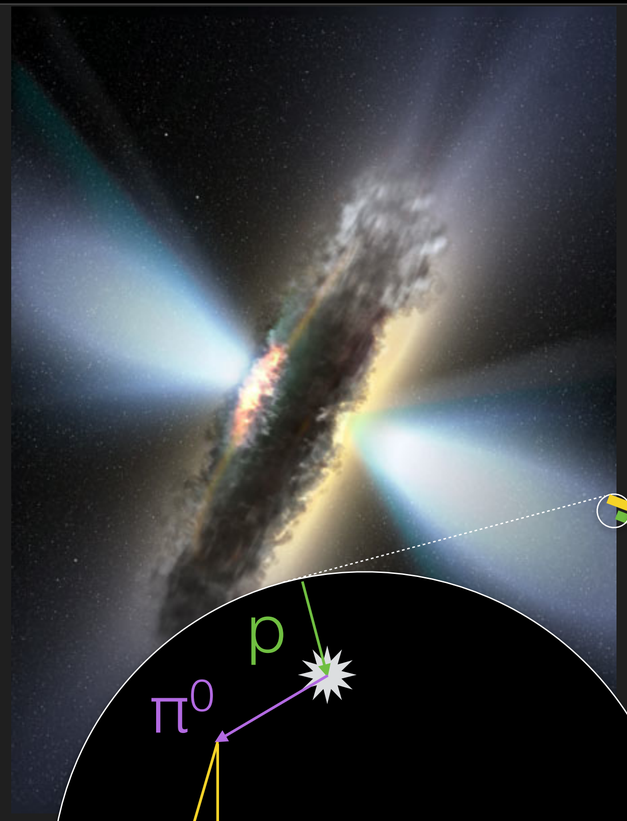
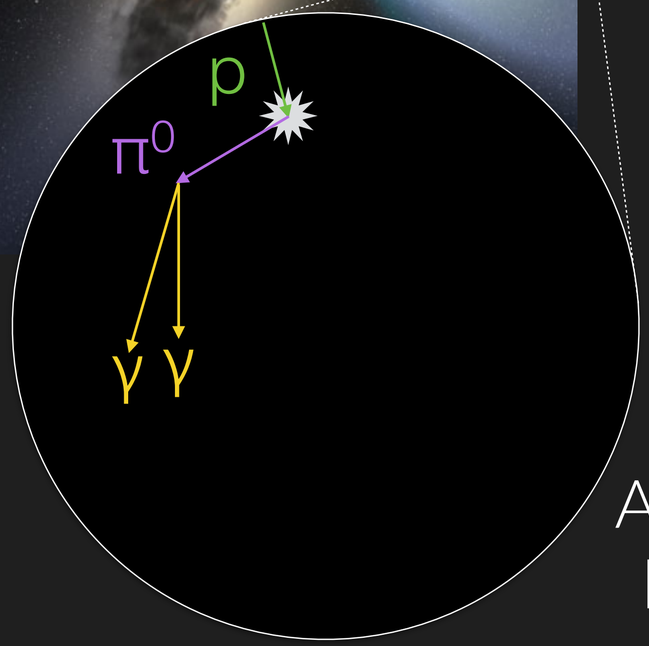
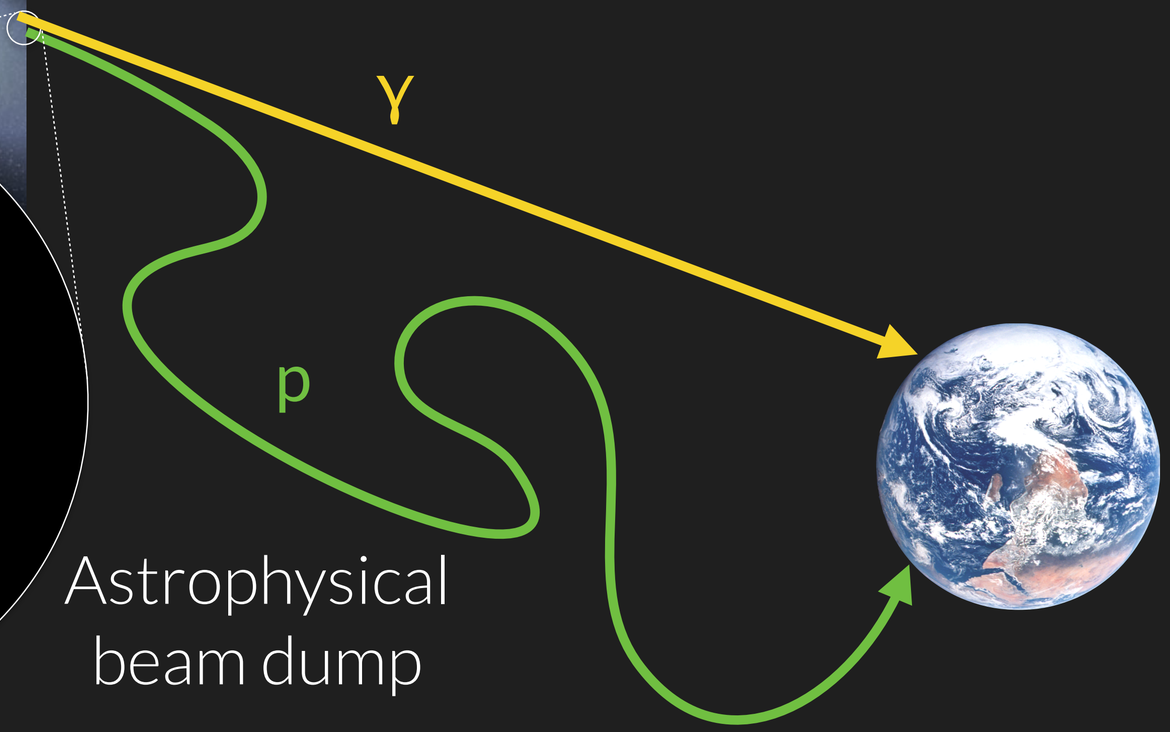


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed





Astrophysical beam dump

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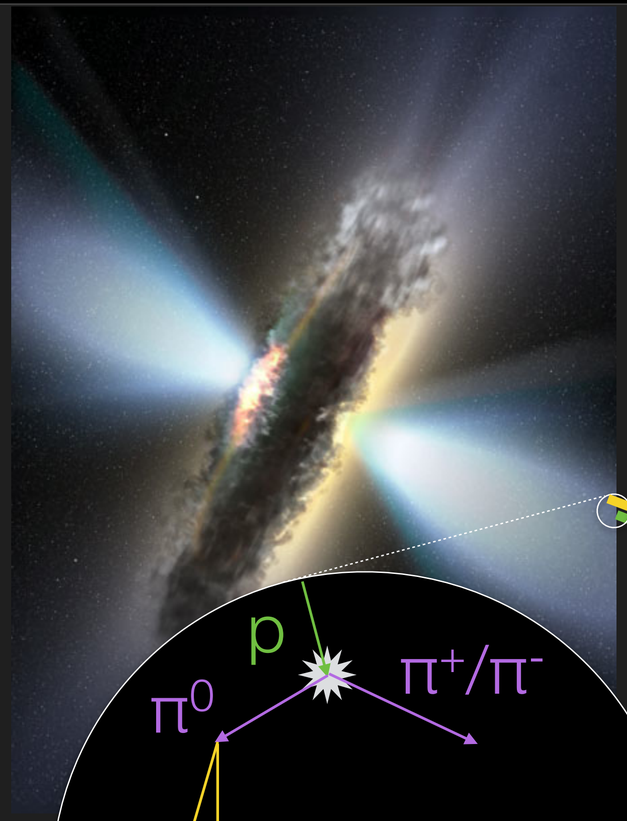

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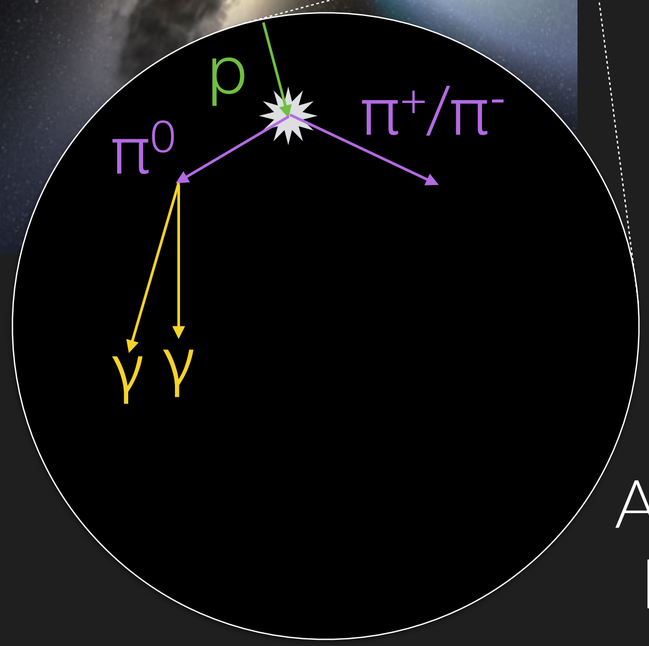

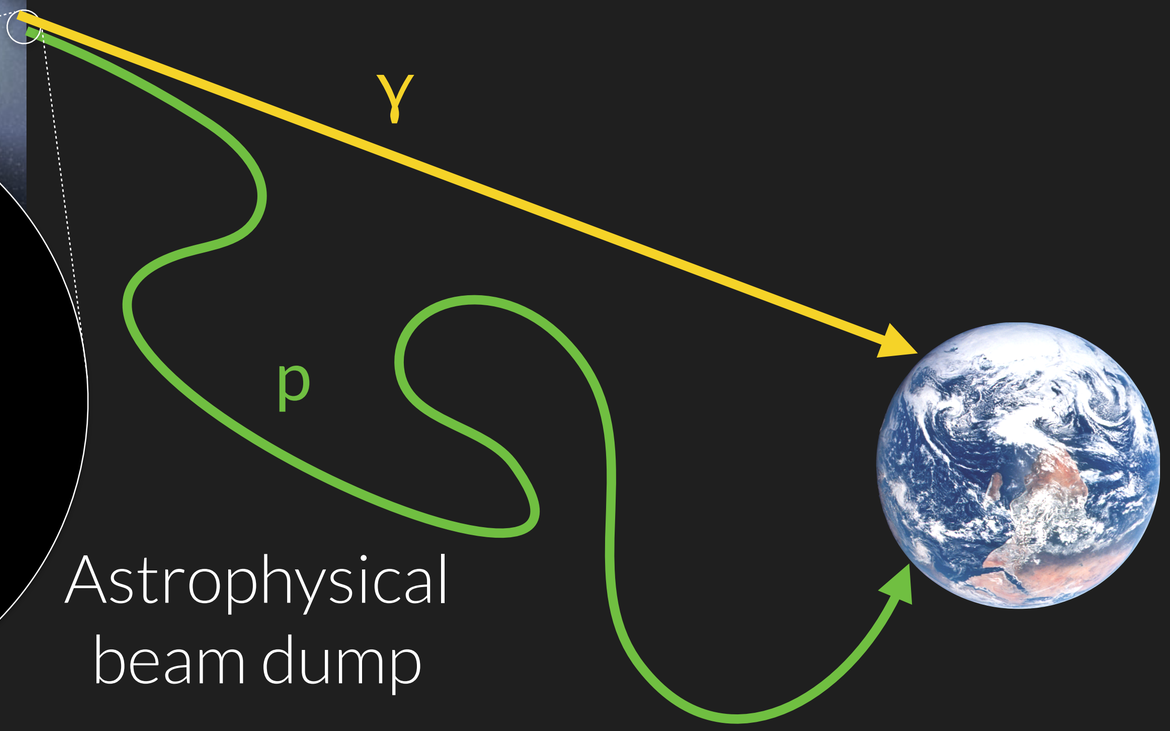

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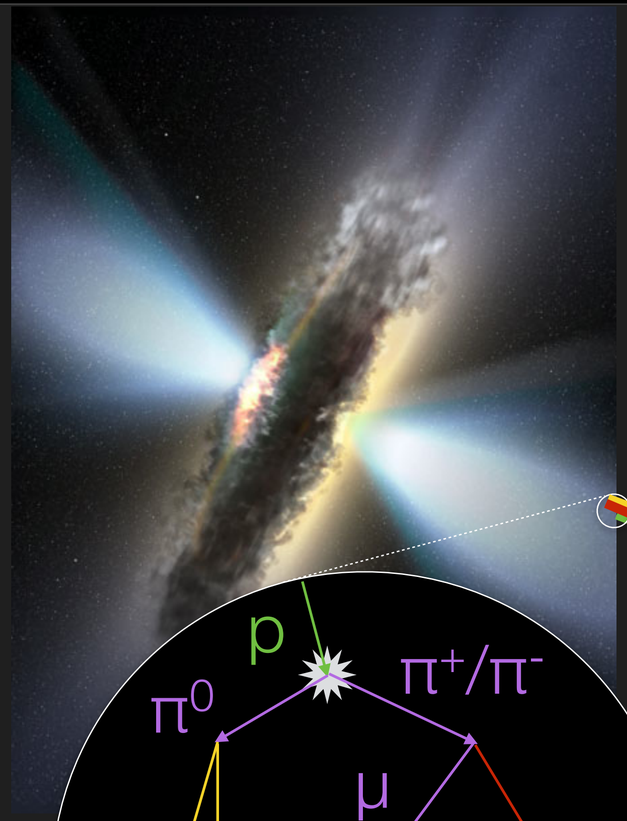
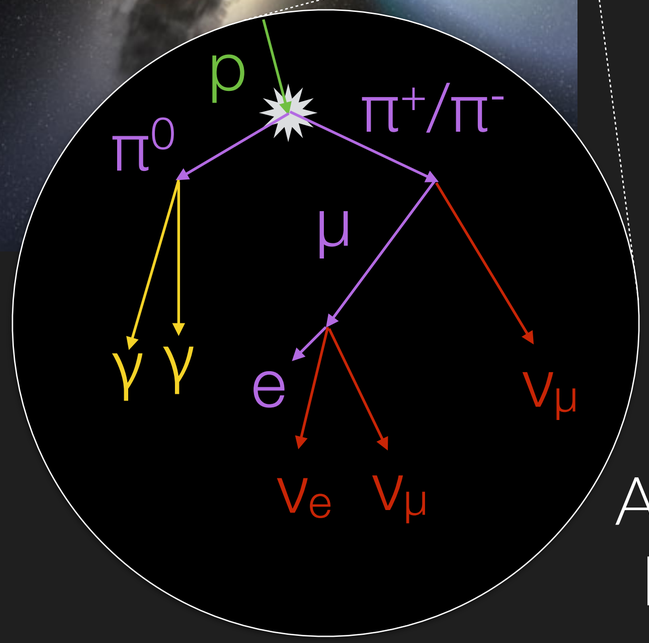
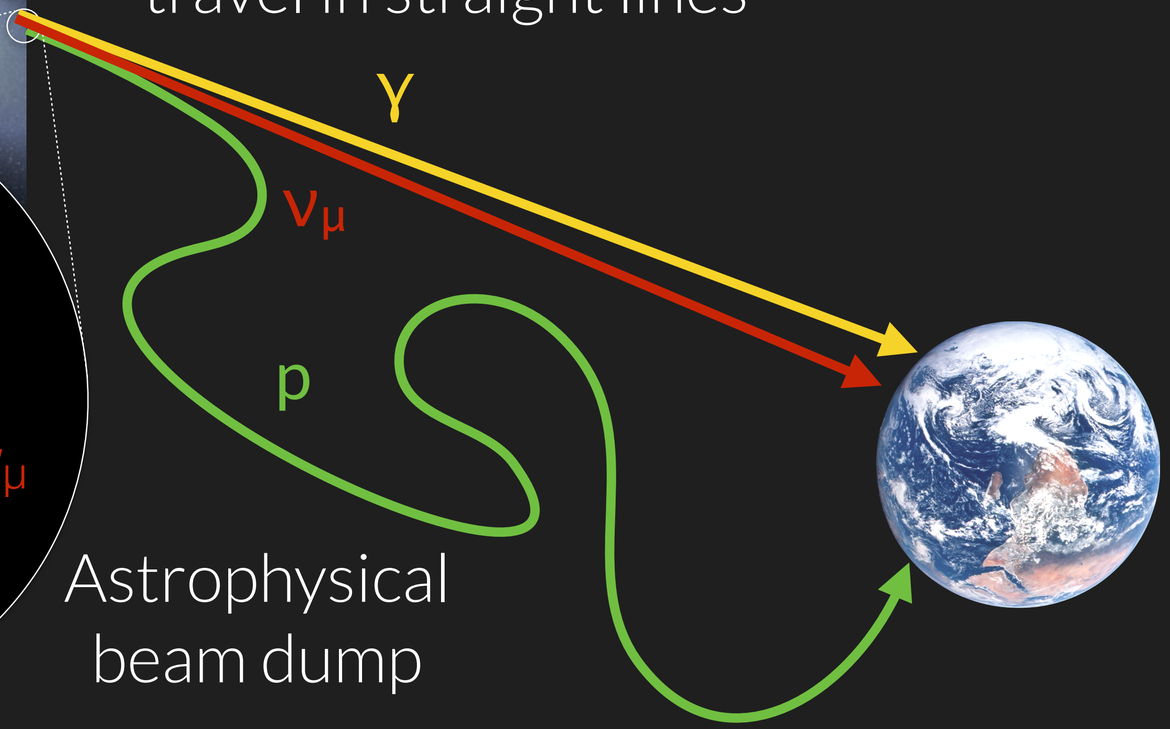


- **Nuclei** can be deflected by magnetic fields
- **Gamma rays** can be absorbed
- **Neutrinos** are difficult to stop and travel in straight lines

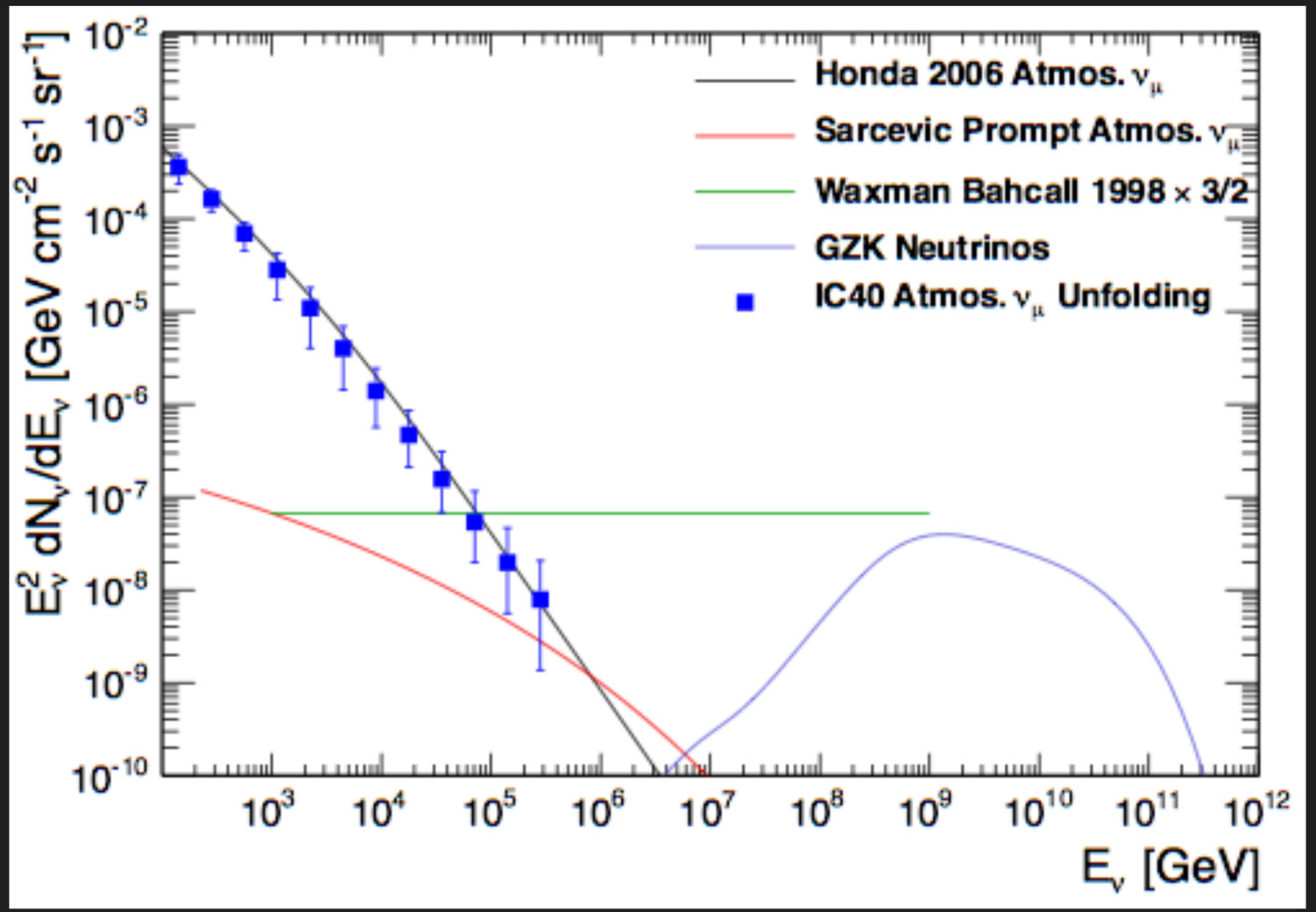




Astrophysical beam dump

NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components



NEUTRINOS ABOVE 1 TEV

sketch of the different expected neutrino flux components

ATMOSPHERIC NEUTRINOS (πτ/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

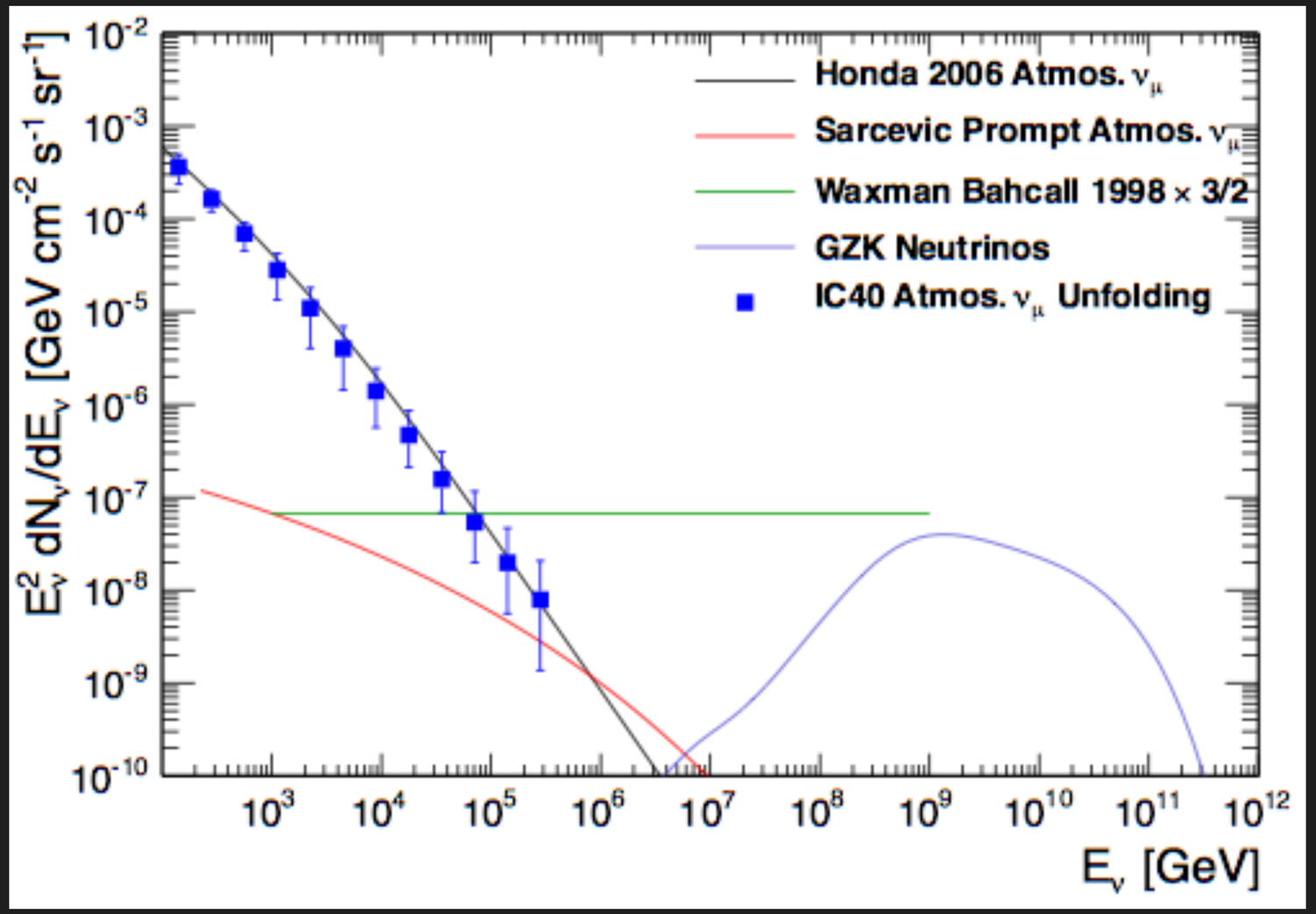
“prompt” ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

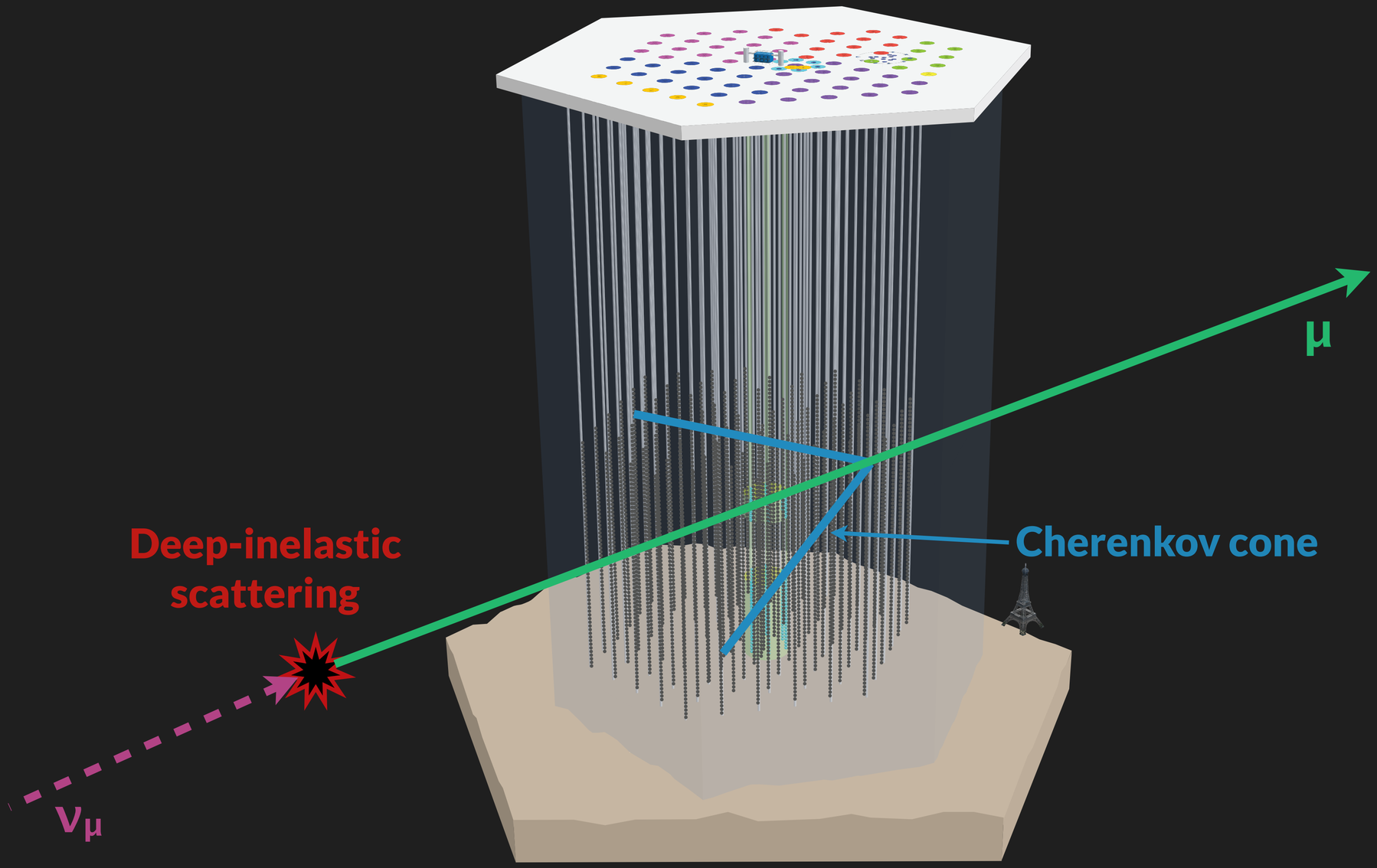
COSMOGENIC NEUTRINOS

>10^6 TeV



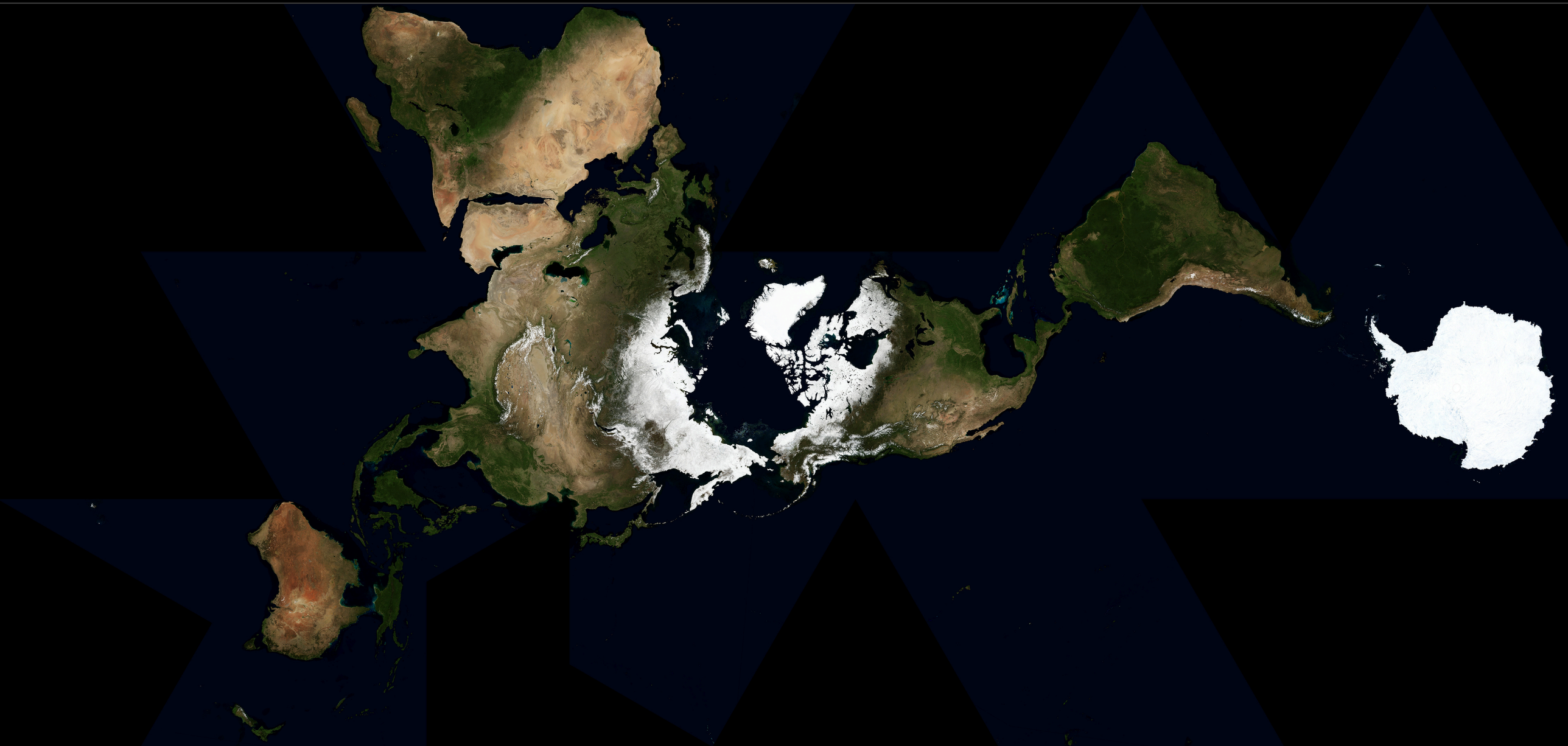
DETECTING NEUTRINOS

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)



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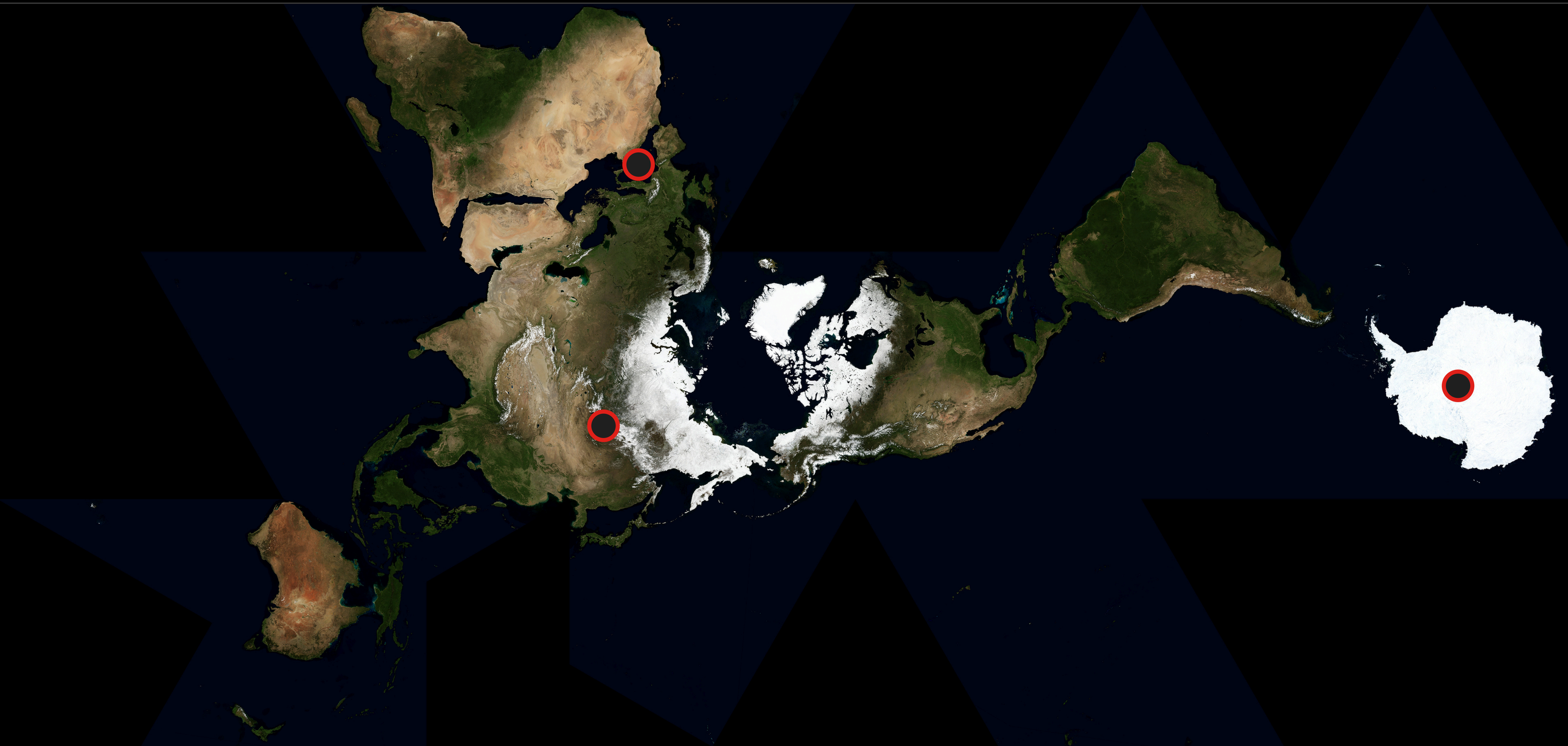

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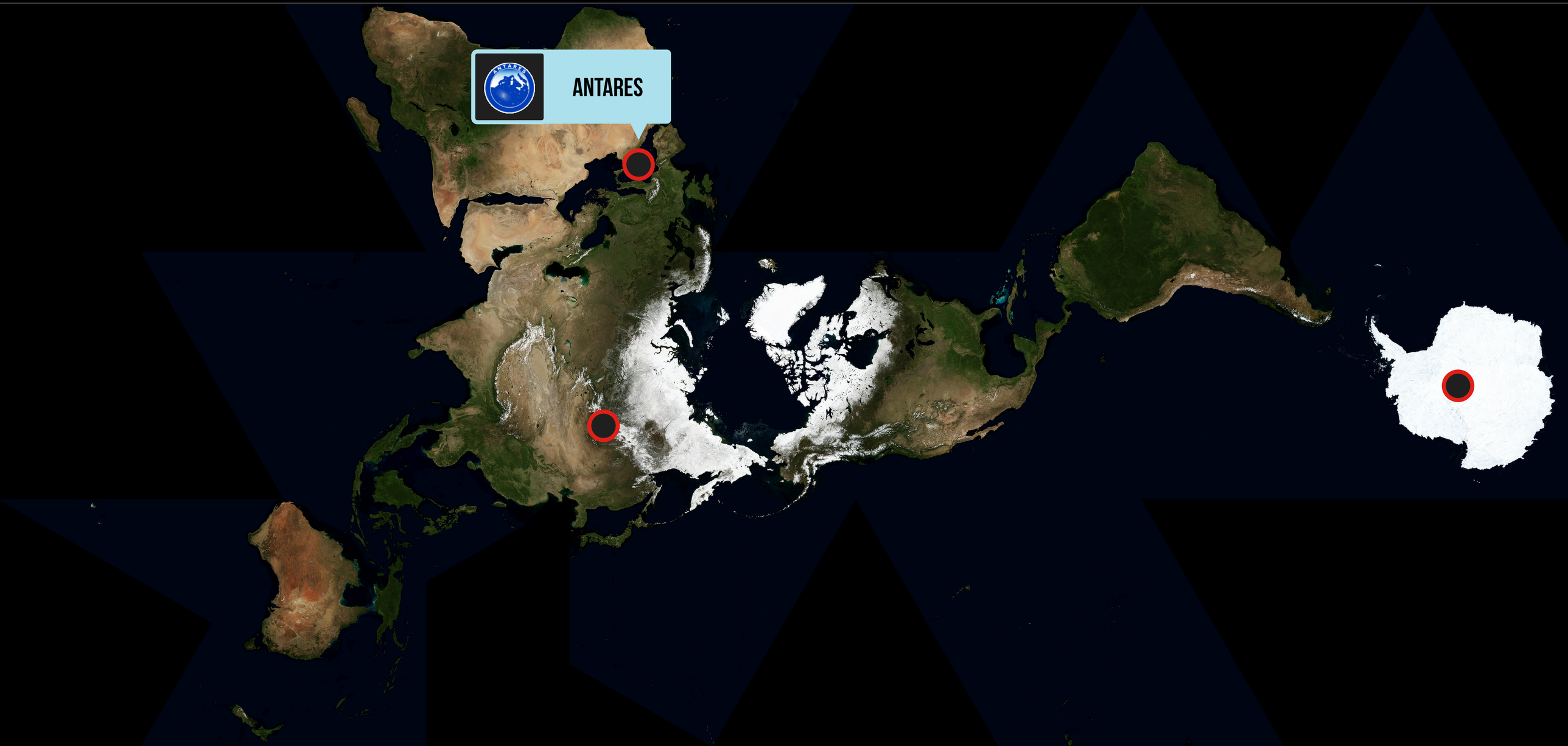

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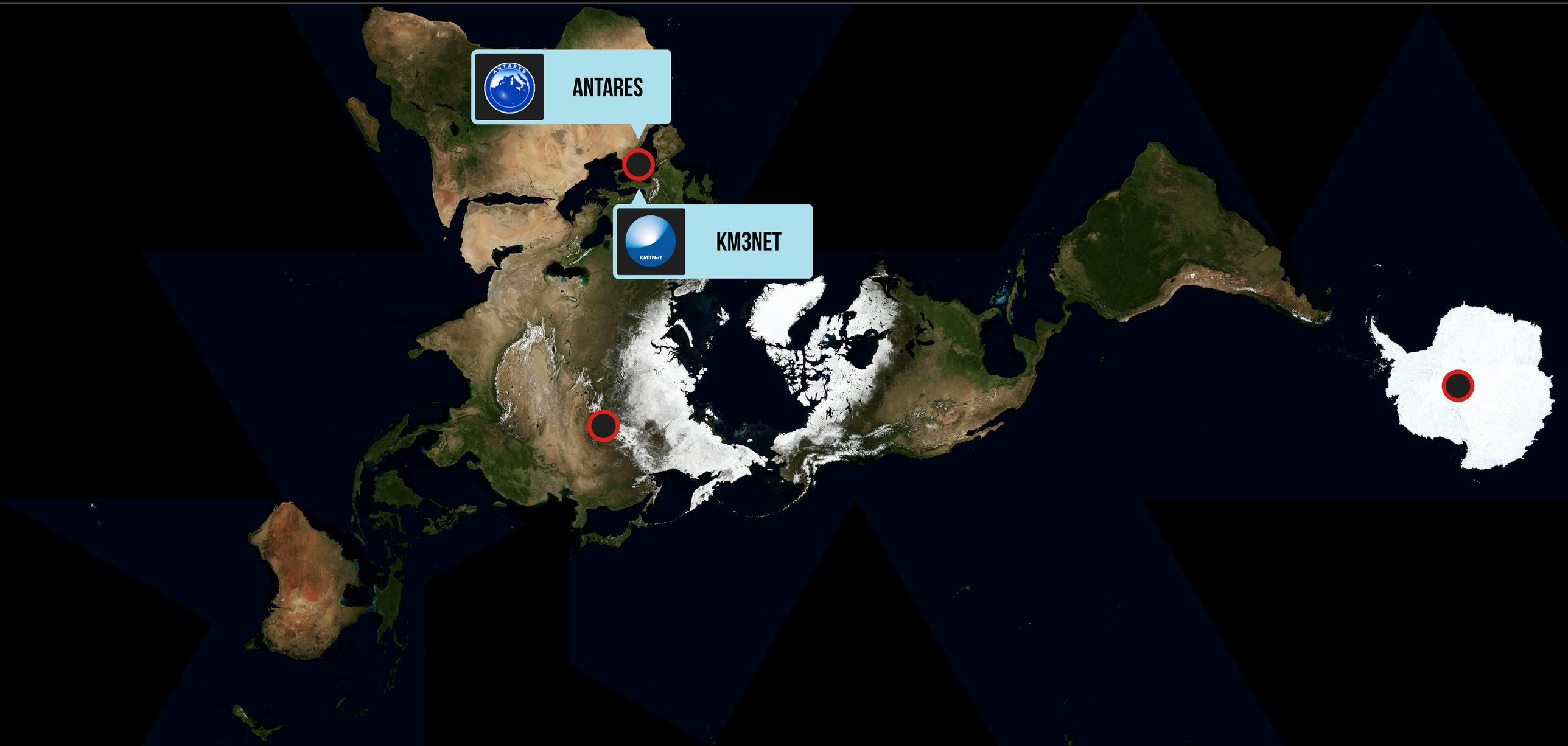

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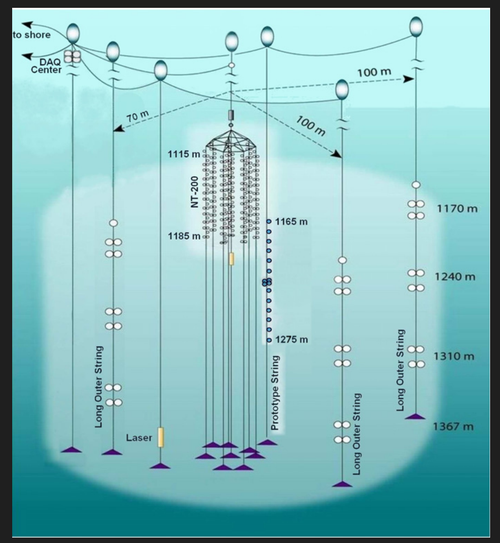
THE WORLD'S NEUTRINO TELESCOPES

lakes, sea, glaciers

NT-200+

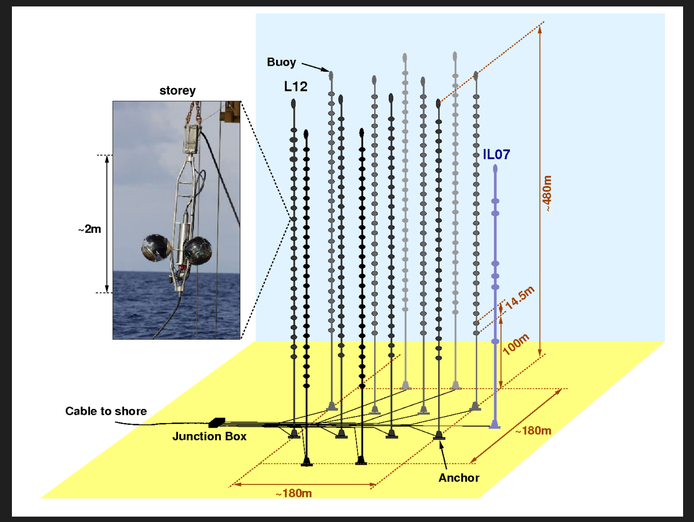


Lake Baikal

1/2000 km^3

228 PMTs

Antares

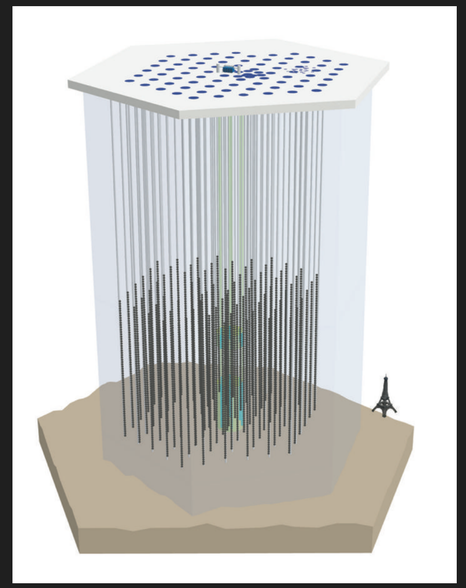


Mediterranean Sea

1/100 km^3

885 PMTs

IceCube



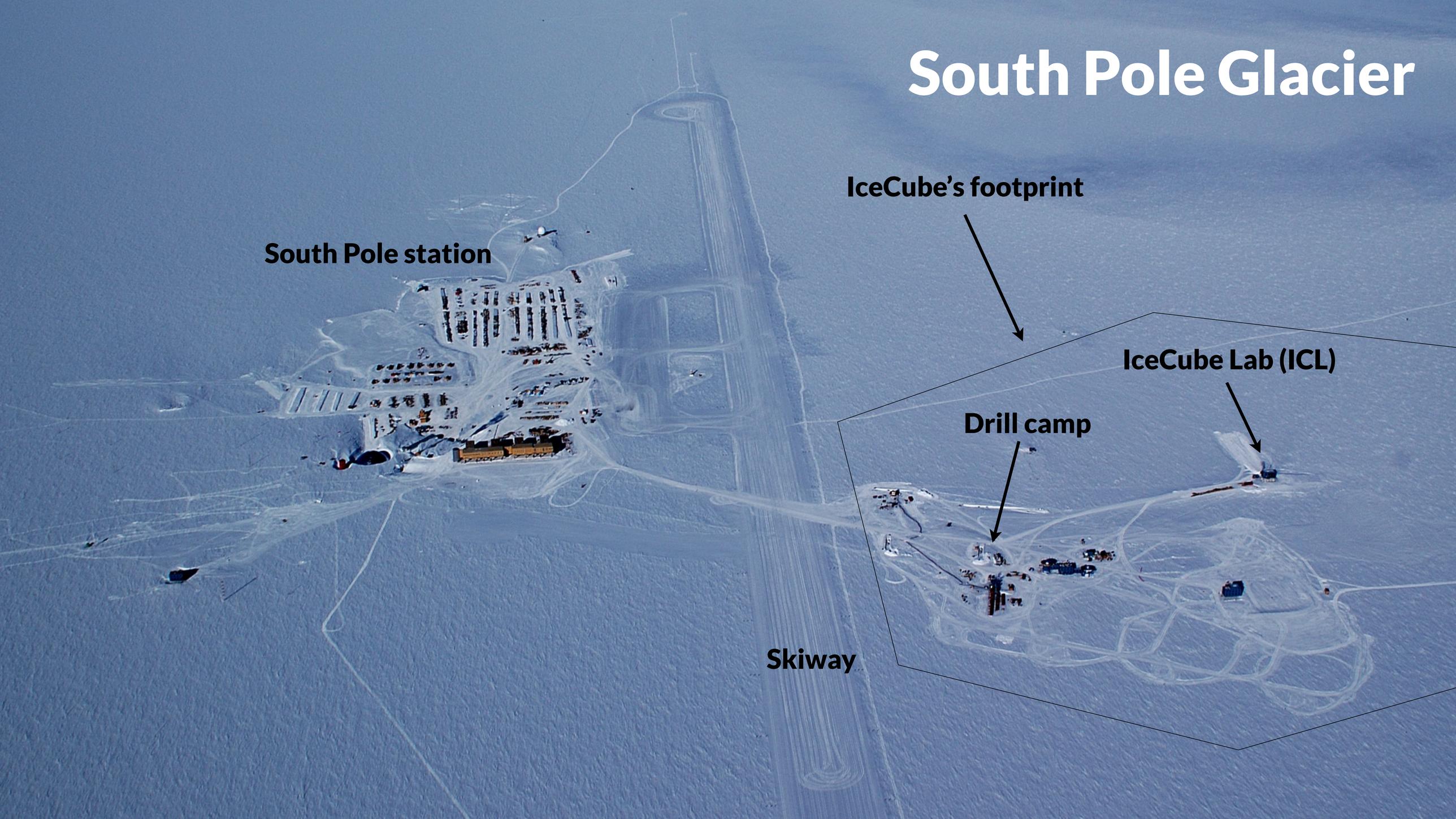
South Pole glacier

1 km^3

5160 PMTs

Larger, sparser → higher energies


Mediterranean Sea


South Pole Glacier
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

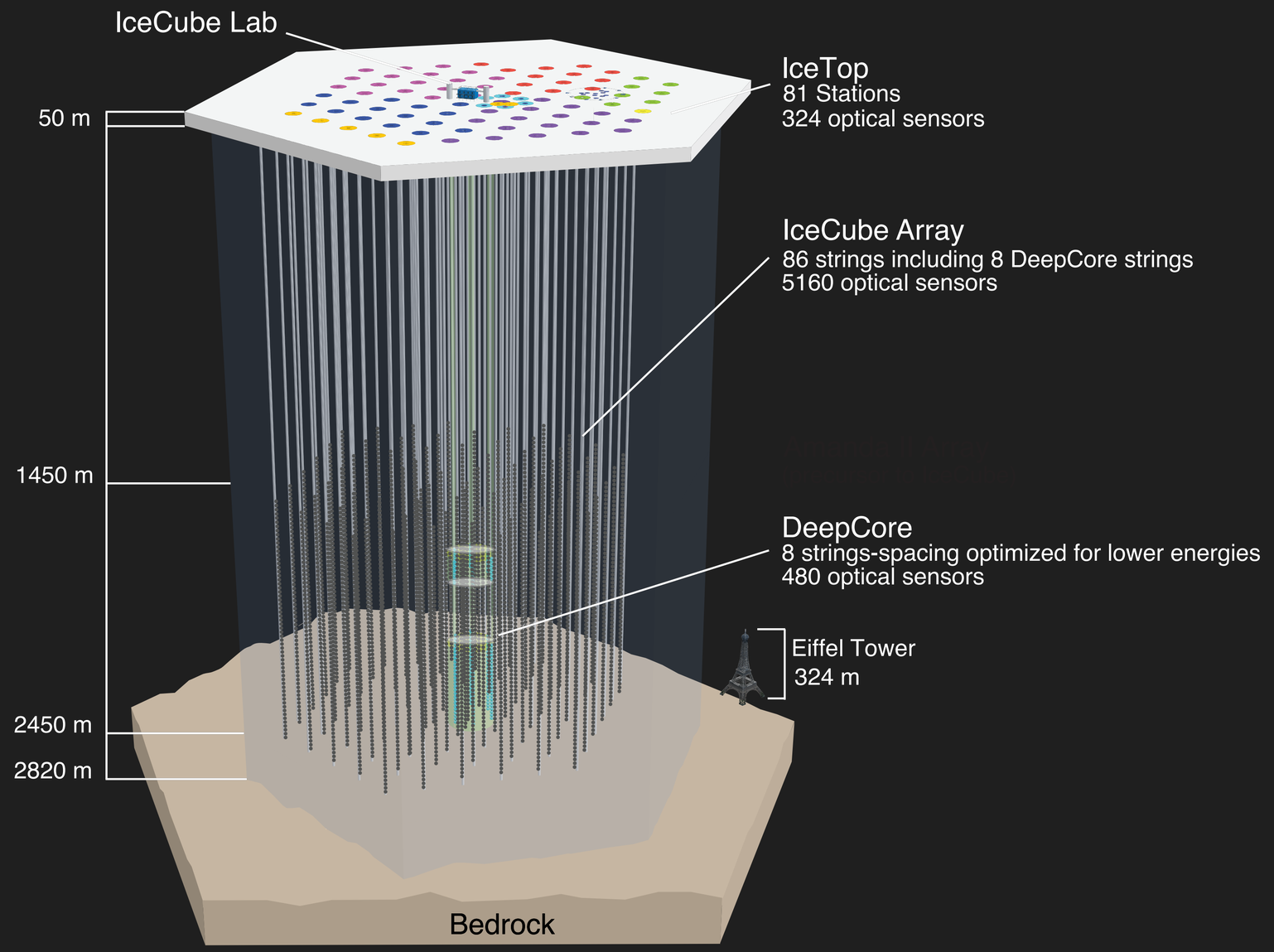
1 km^3 volume

86 strings

17 m vertical spacing

125 m string spacing

Completed **2010**

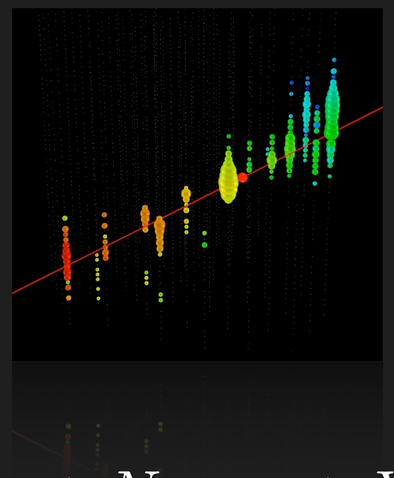


NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

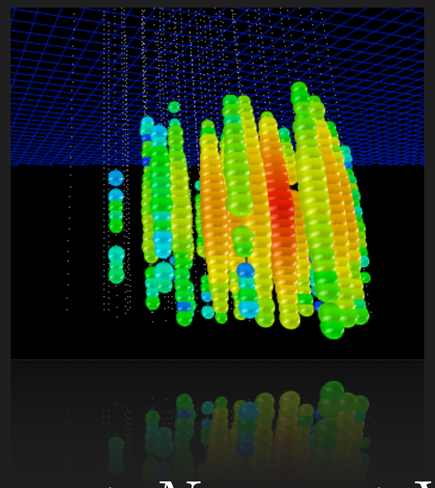


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current / Electron Neutrino



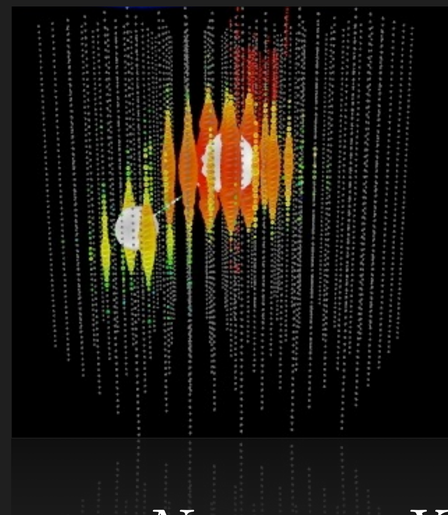
$$\nu_e + N \rightarrow e + X$$

$$\nu_x + N \rightarrow \nu_x + X$$

cascade (data)

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

CC Tau Neutrino



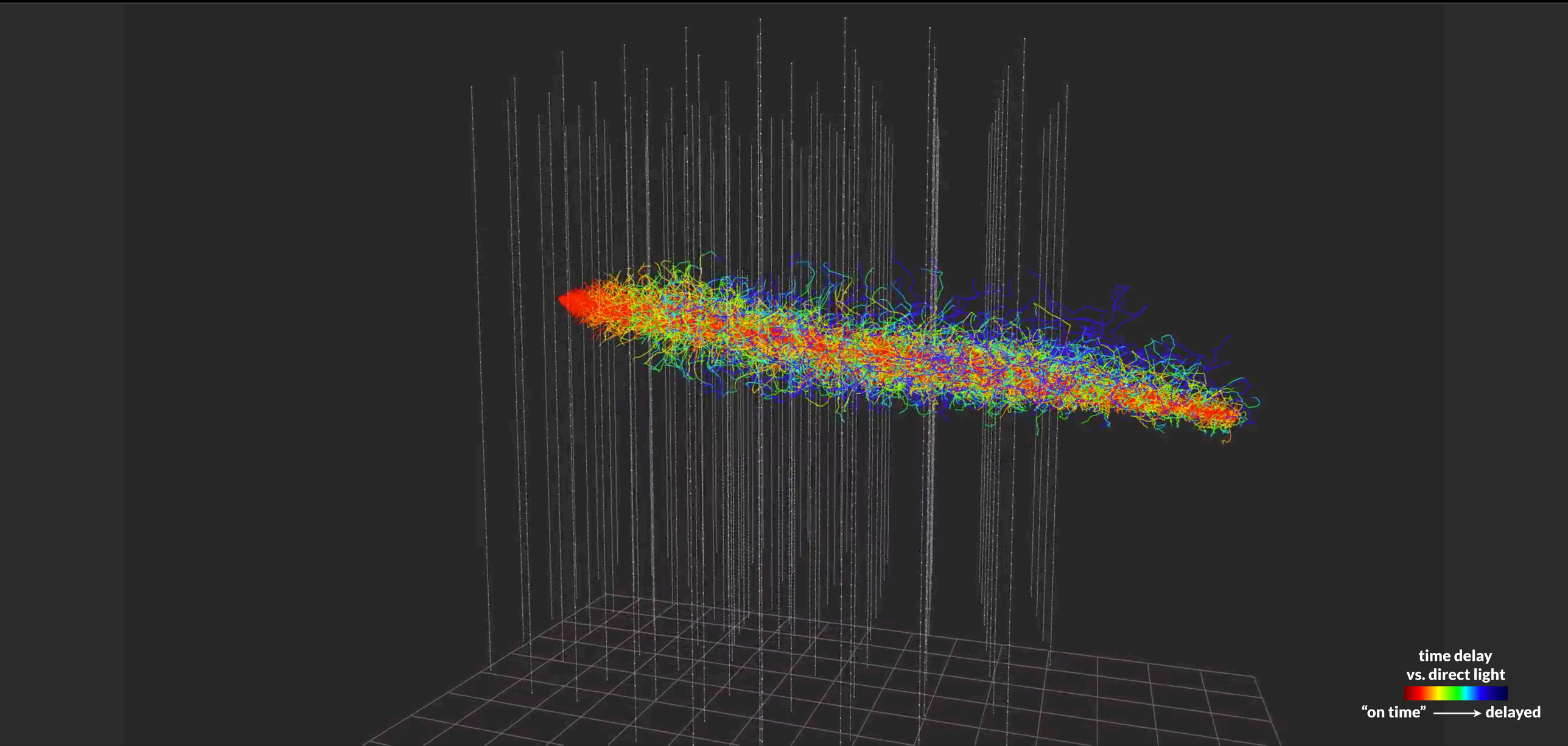
$$\nu_\tau + N \rightarrow \tau + X$$

“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



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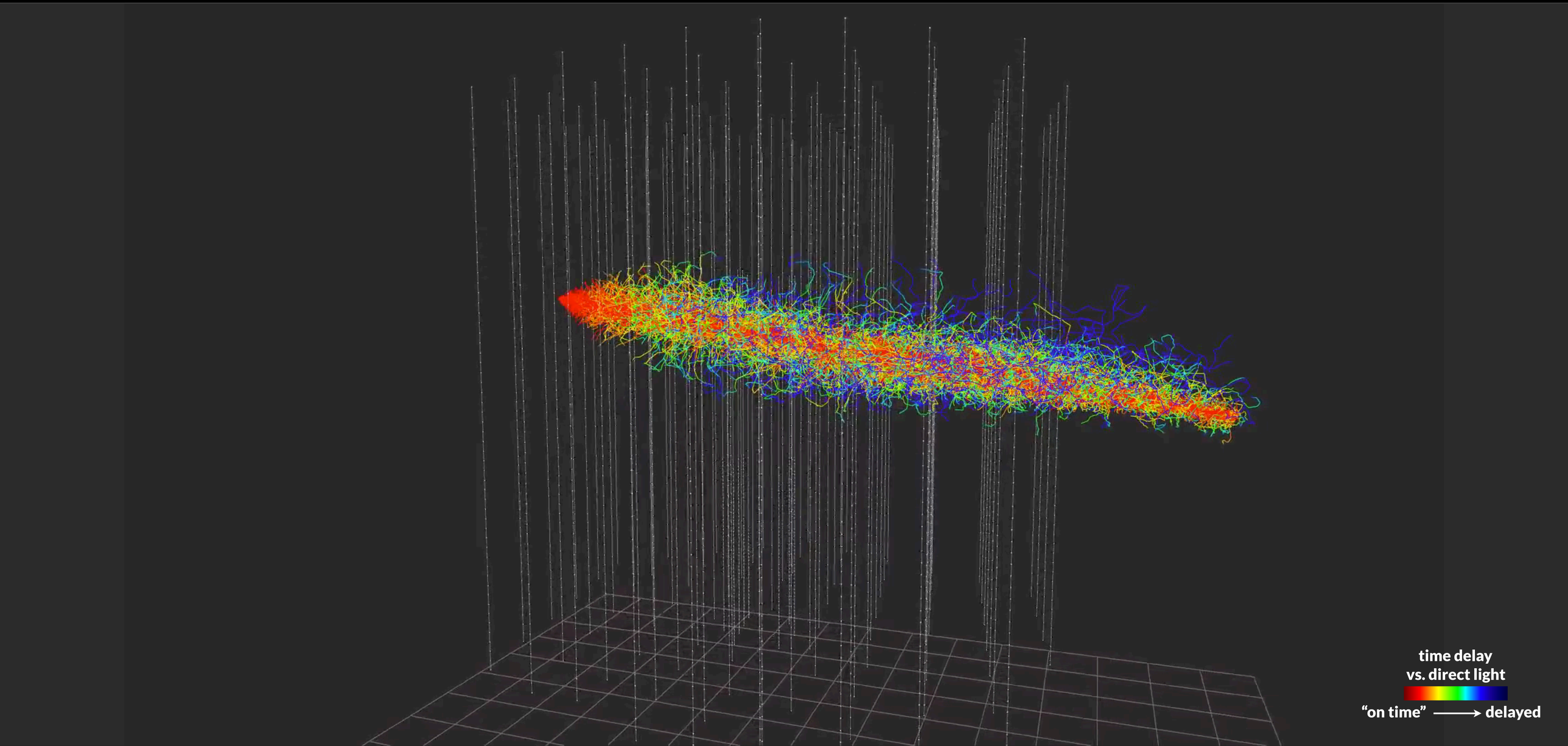

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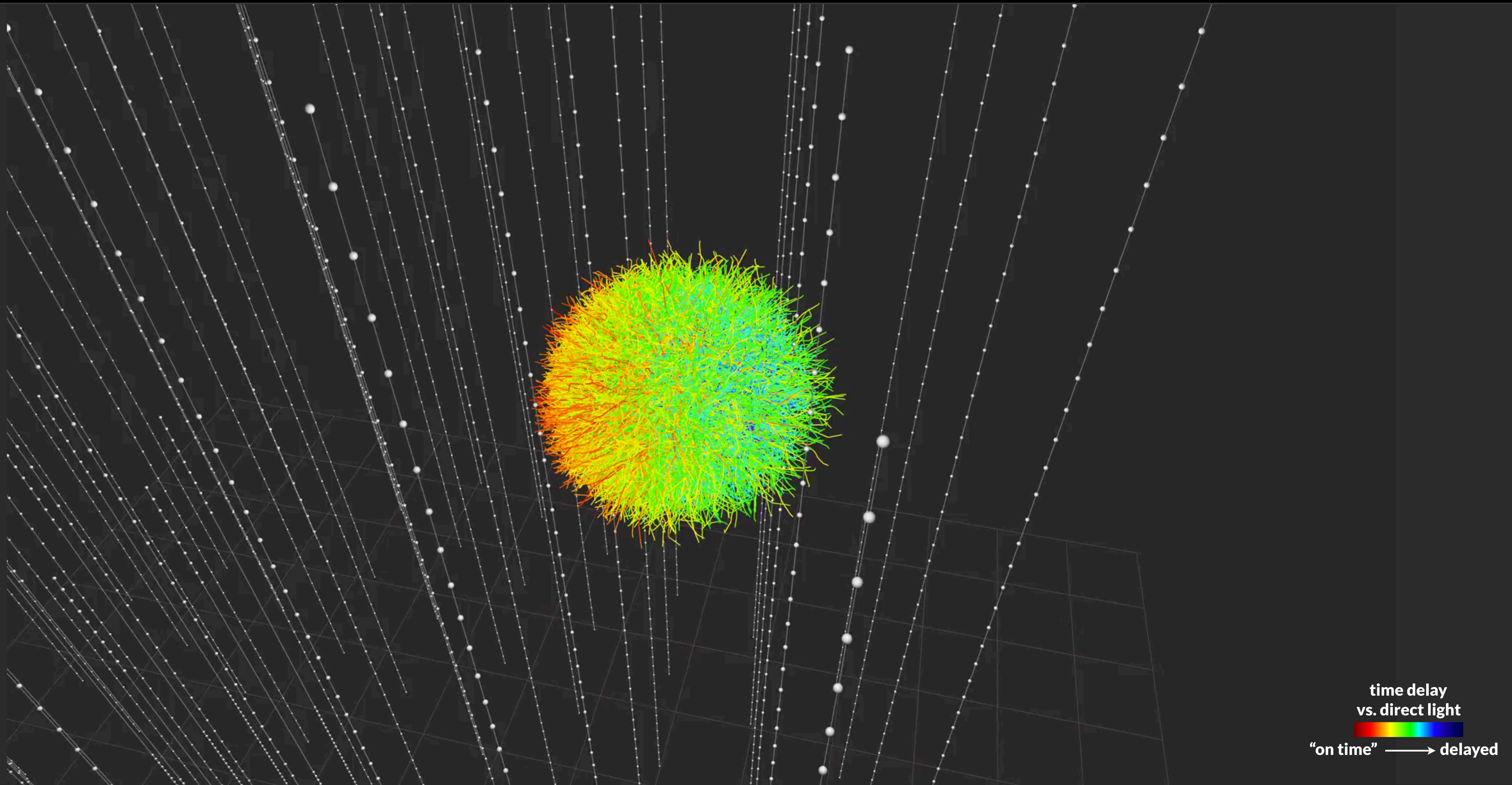

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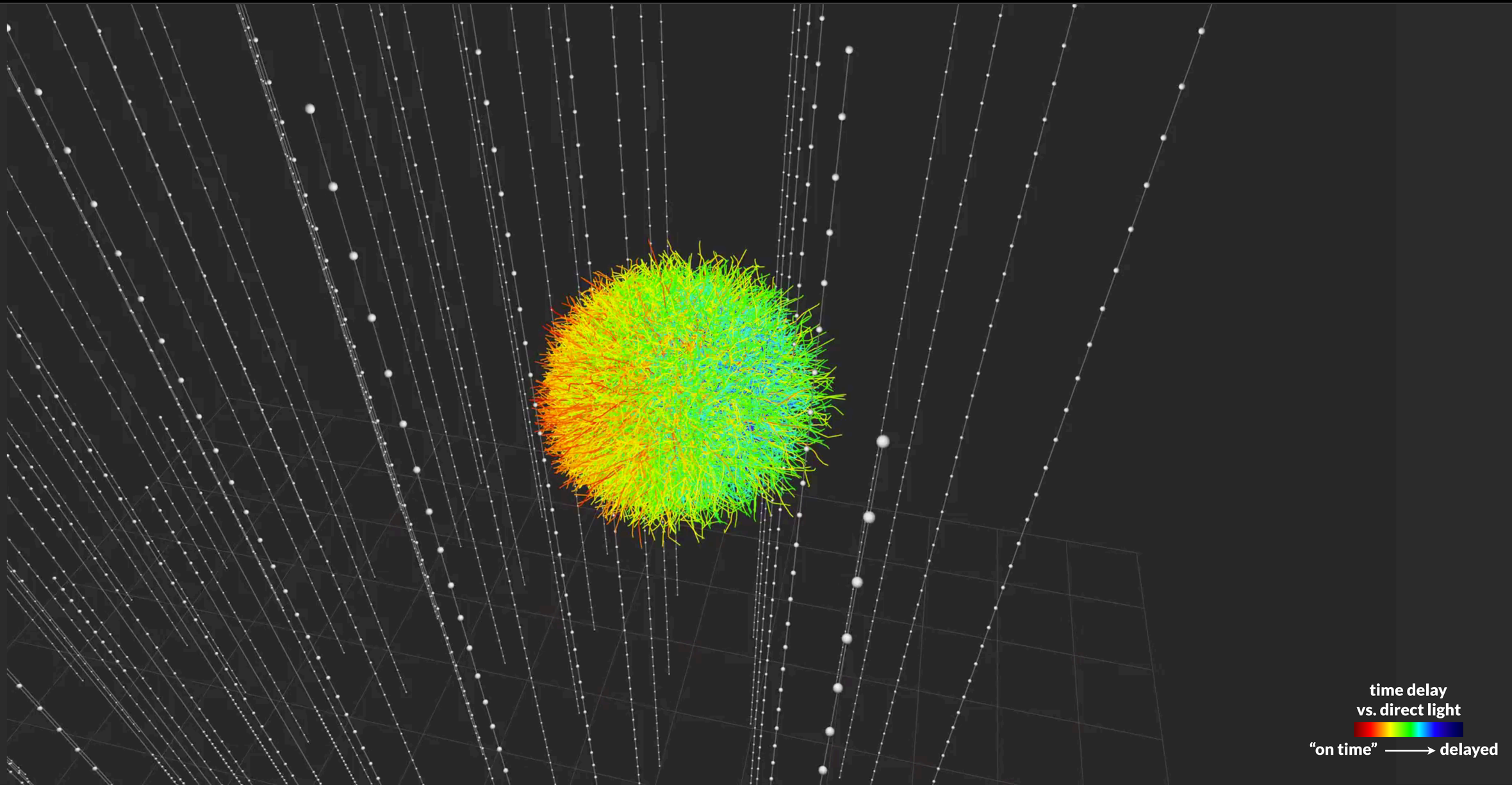
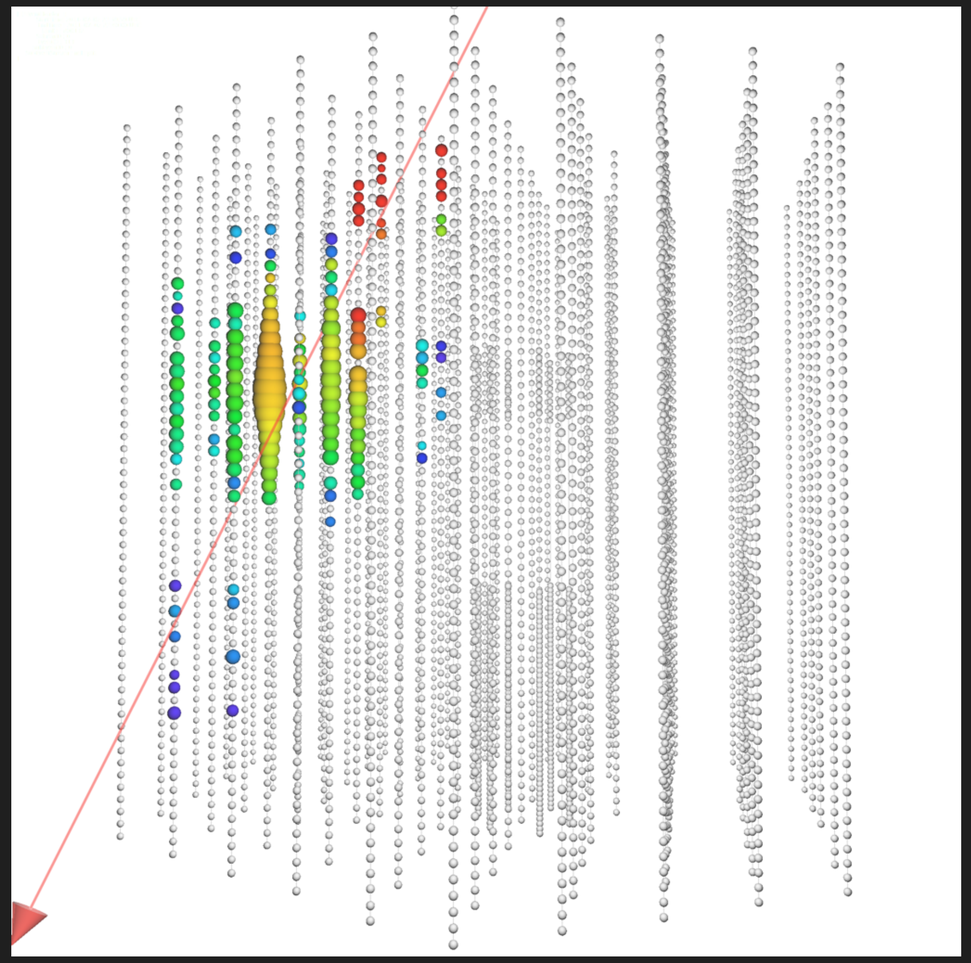
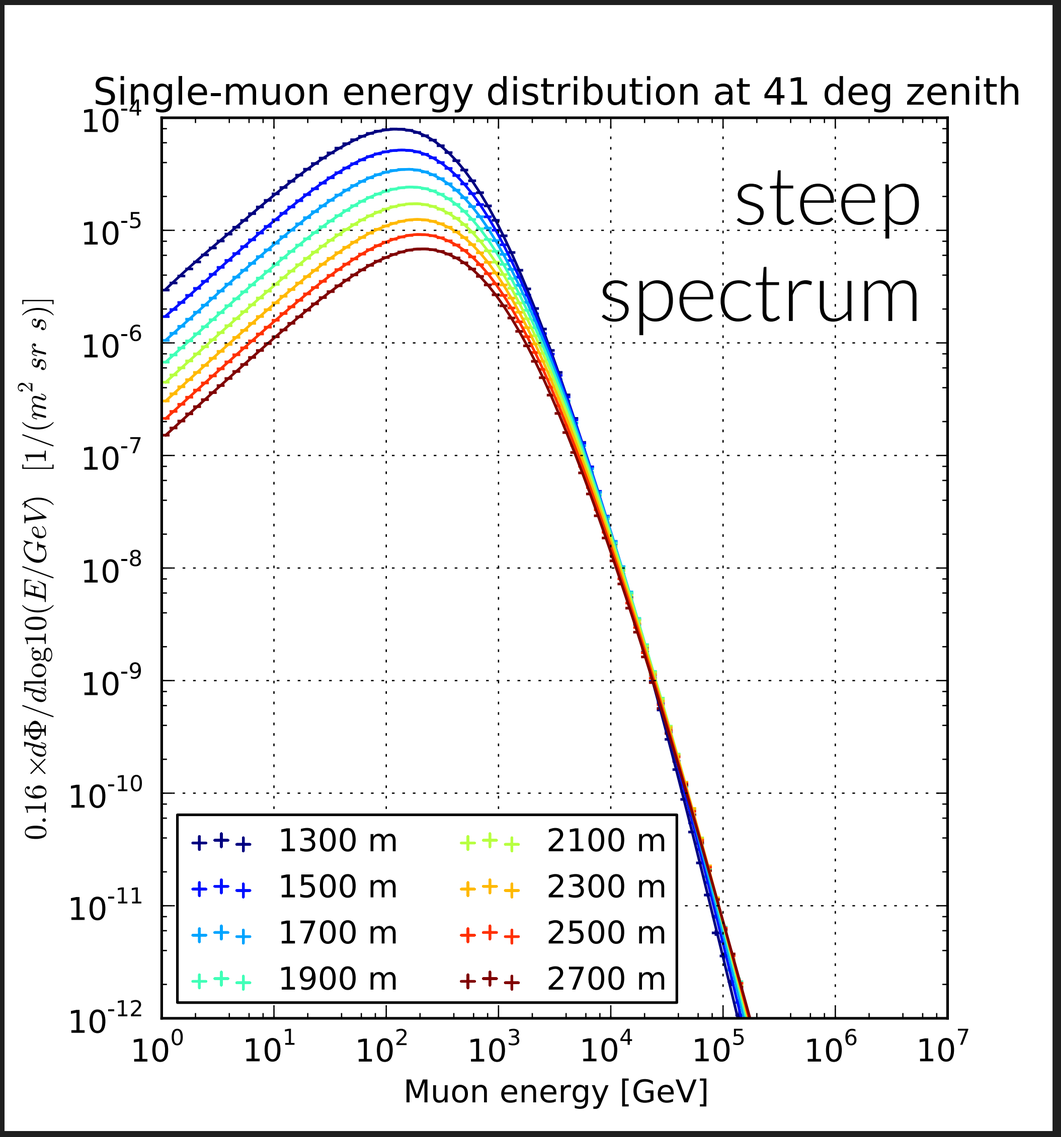


BACKGROUND: PENETRATING MUONS



100 TeV single muon



ISOLATING NEUTRINO EVENTS

two strategies

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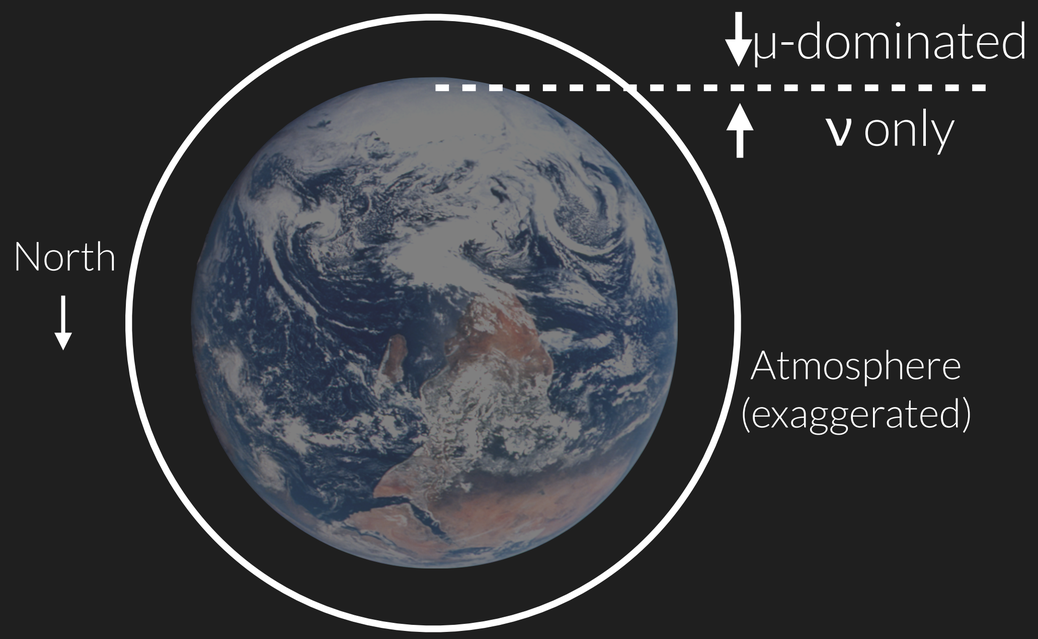
two strategies

Up-going tracks



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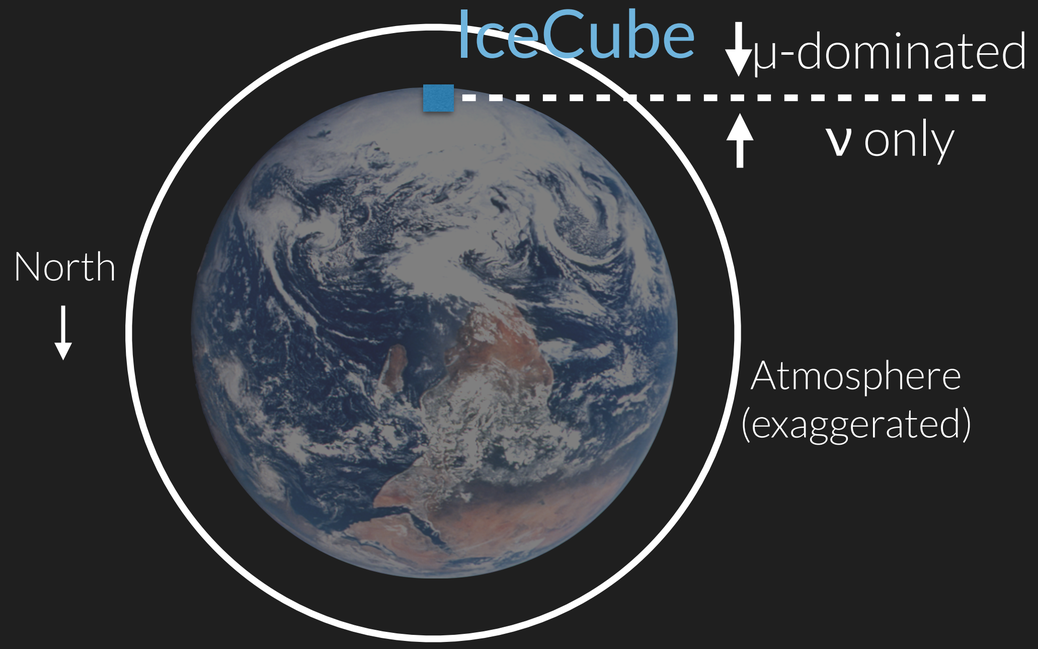

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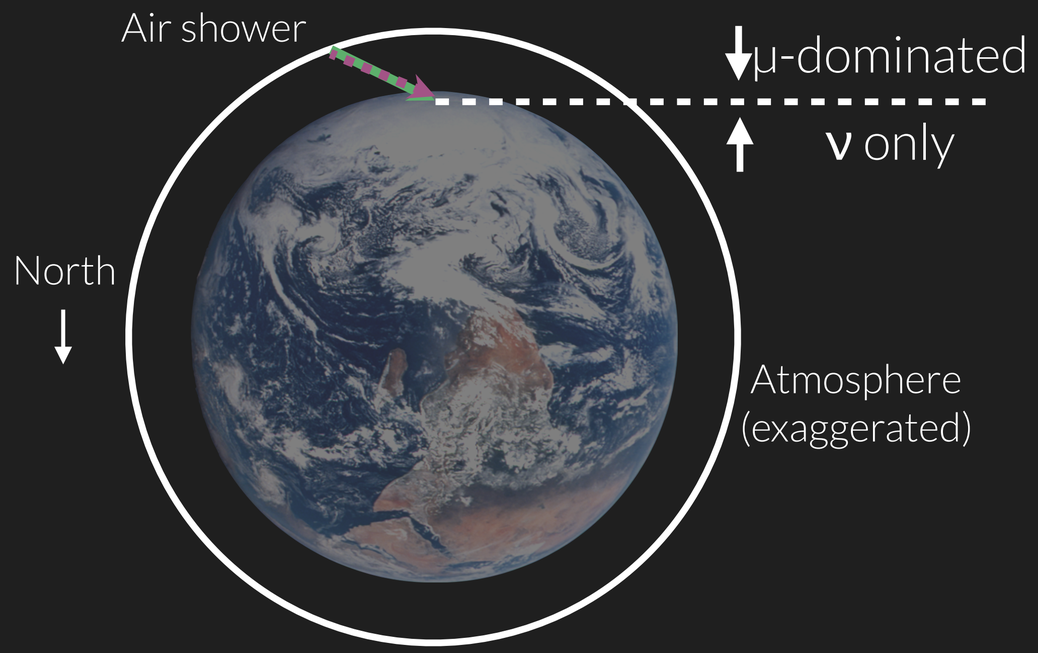

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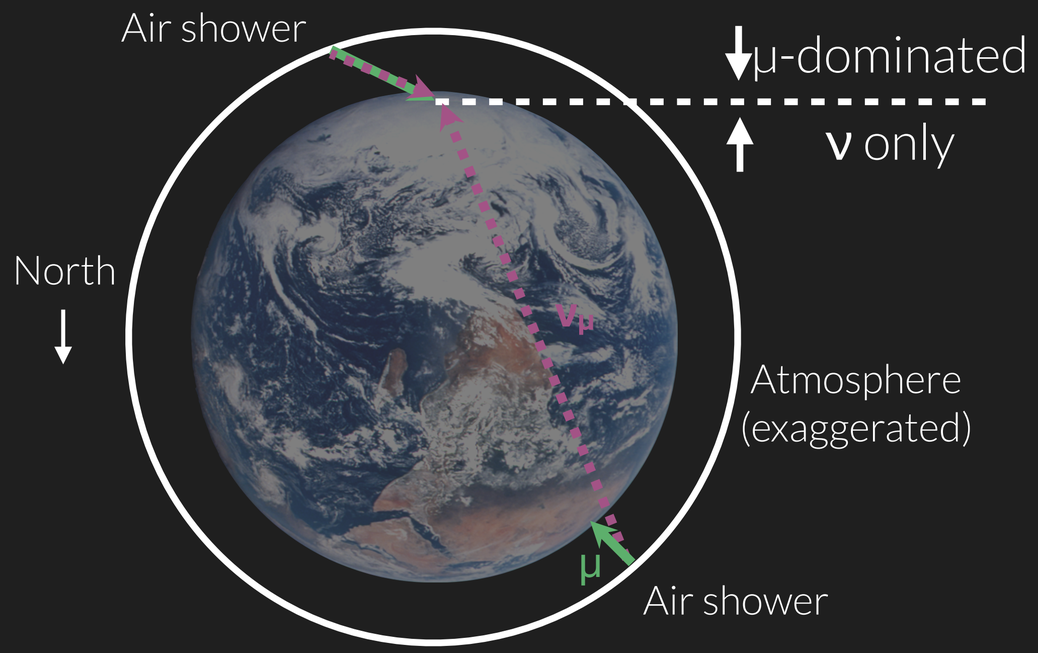

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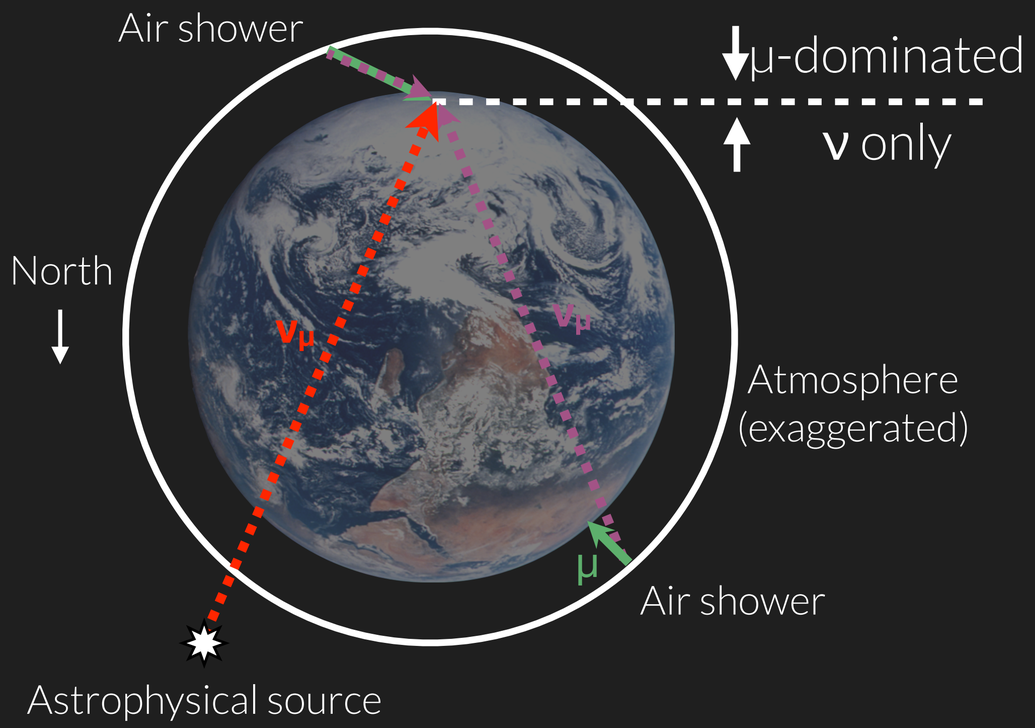

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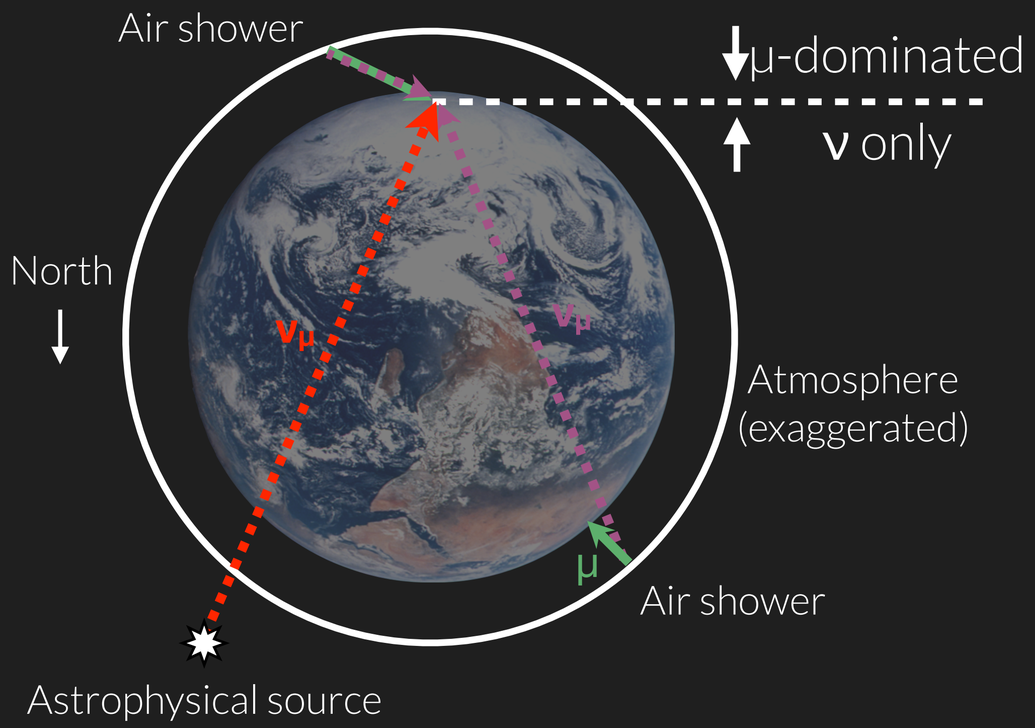


Earth stops penetrating muons

Effective volume larger than detector

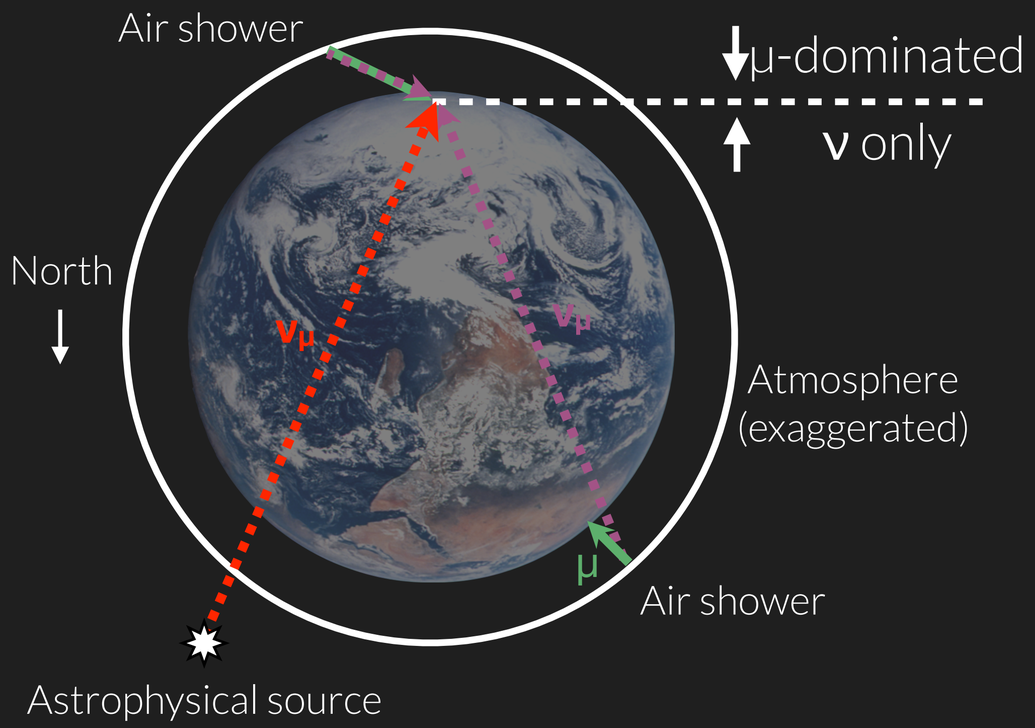
Sensitive to ν_μ only

Sensitive to “half” the sky

ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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Active veto

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two strategies

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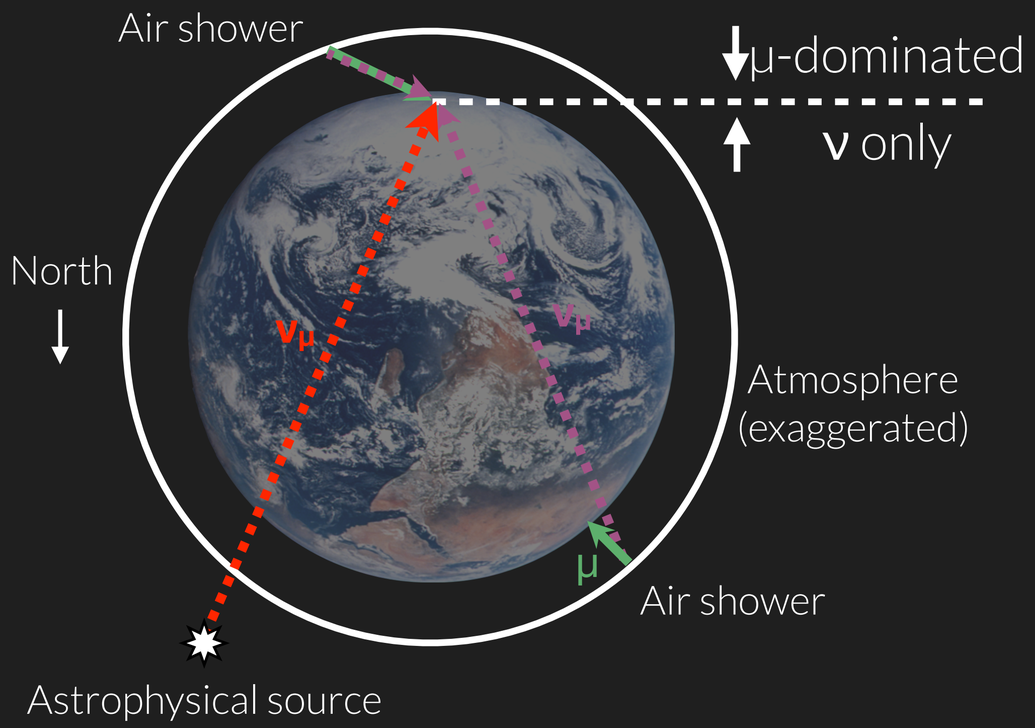

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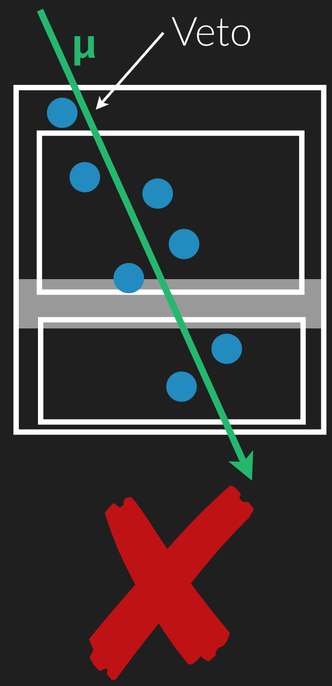

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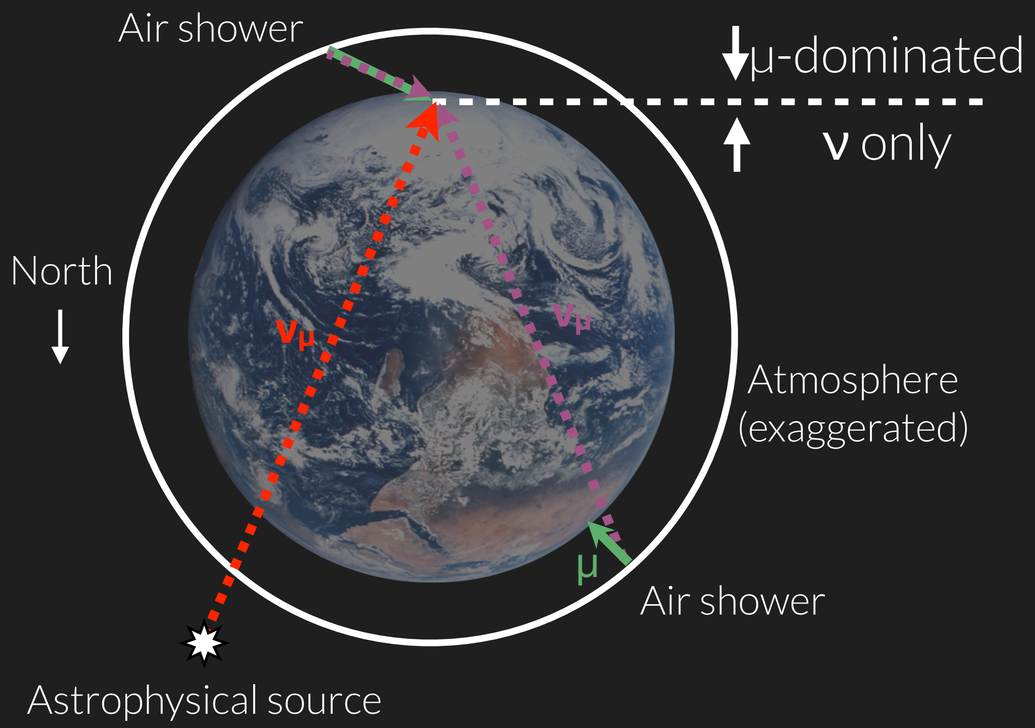

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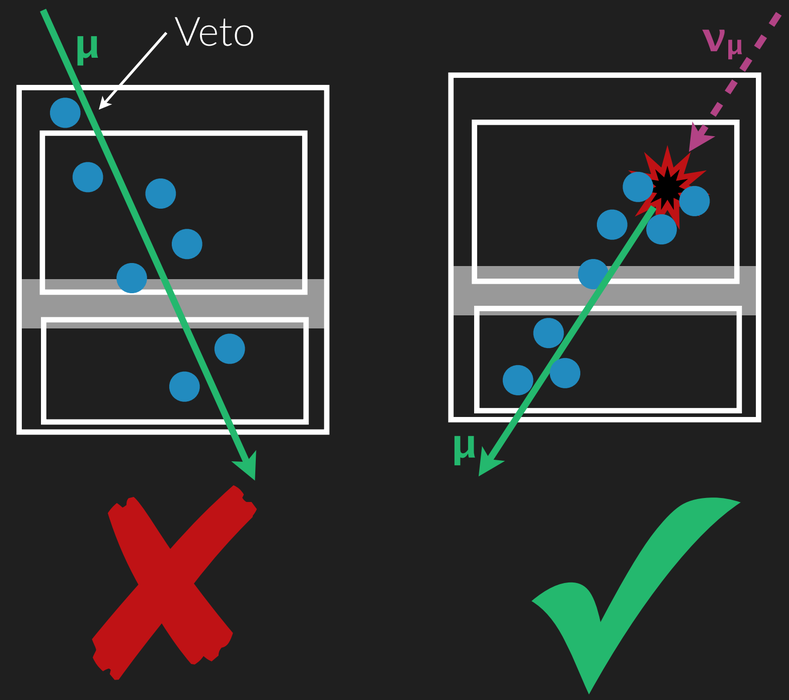

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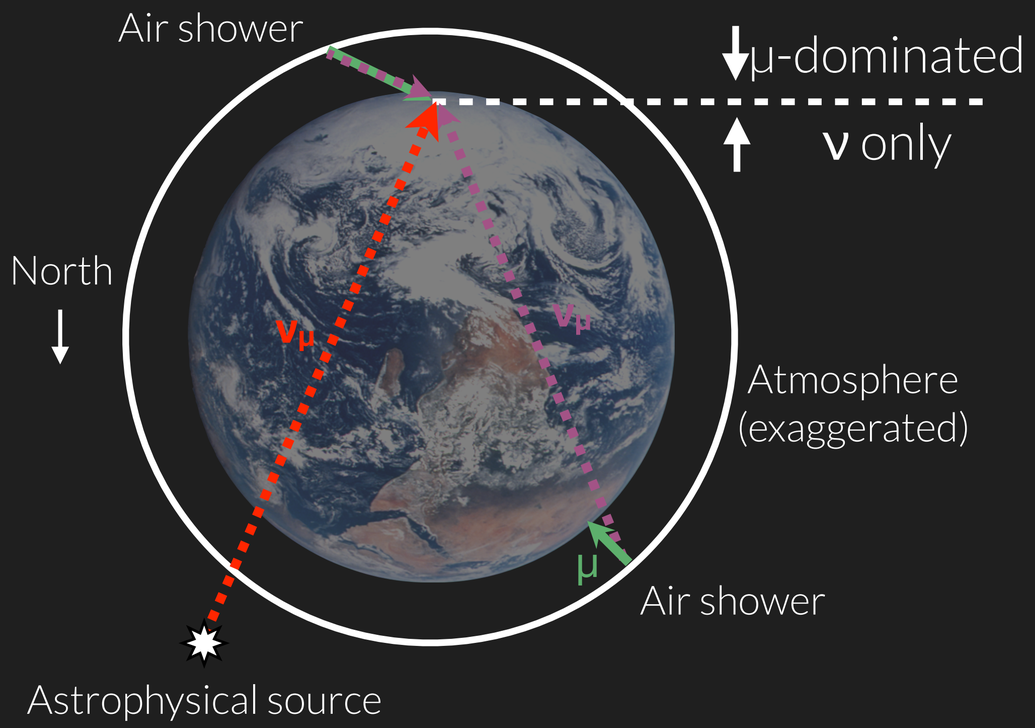

Earth stops penetrating muons
Effective volume larger than detector
Sensitive to ν_μ only
Sensitive to "half" the sky

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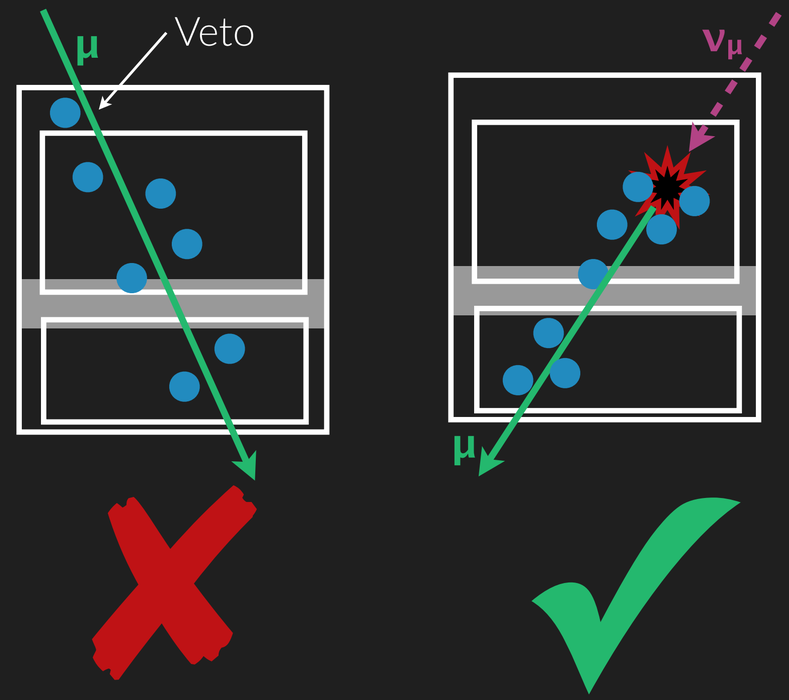


Veto detects penetrating muons
Effective volume smaller than detector
Sensitive to all flavors
Sensitive to the entire sky

CALIBRATION

Various calibration devices/methods to control detector systematics (example: IceCube)

LED flashers on each DOM

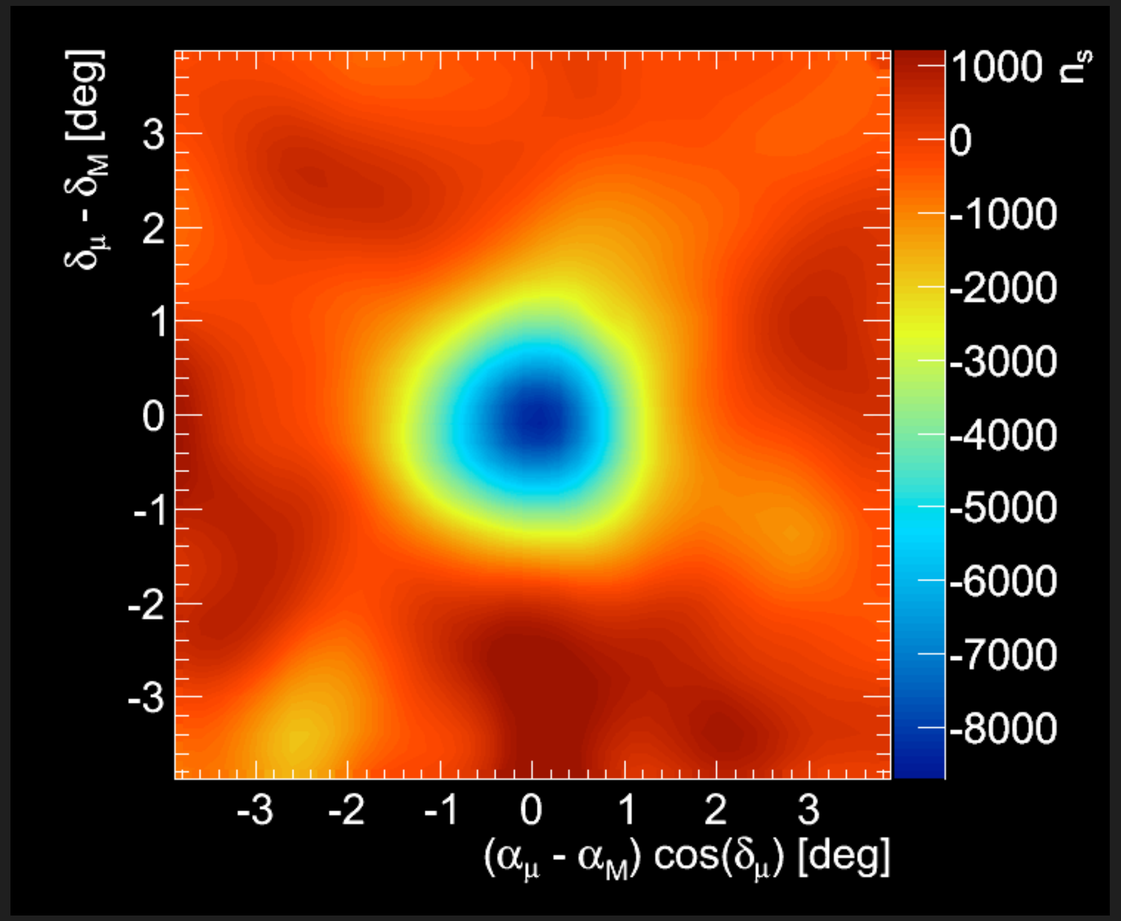
In-ice calibration **laser**

Cosmic ray **energy spectrum**

Moon shadow

Atmospheric neutrino energy spectrum

Minimum-ionizing muons



Moon Shadow in Cosmic Rays
Muons in IceCube (59 strings)

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
- …

THE (VERY) HIGH-ENERGY TAIL

Update of the high-energy astrophysical flux discovery analysis

“HISTORY”

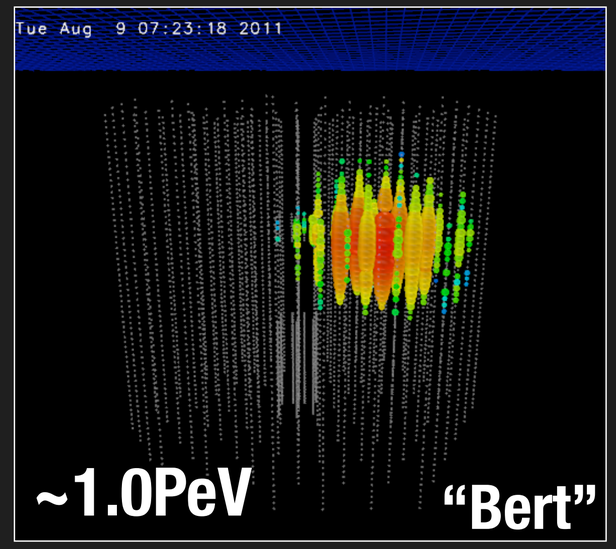
Appearance of ~1 PeV cascades as an at-threshold background

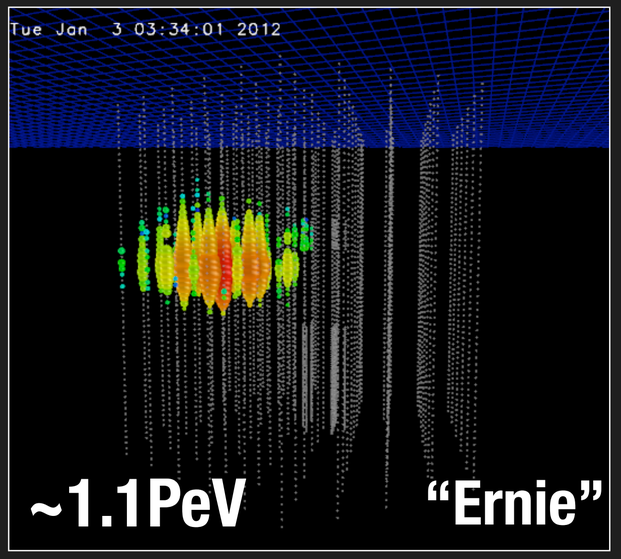
Two very interesting events in IceCube (between May 2010 and May 2012)

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.

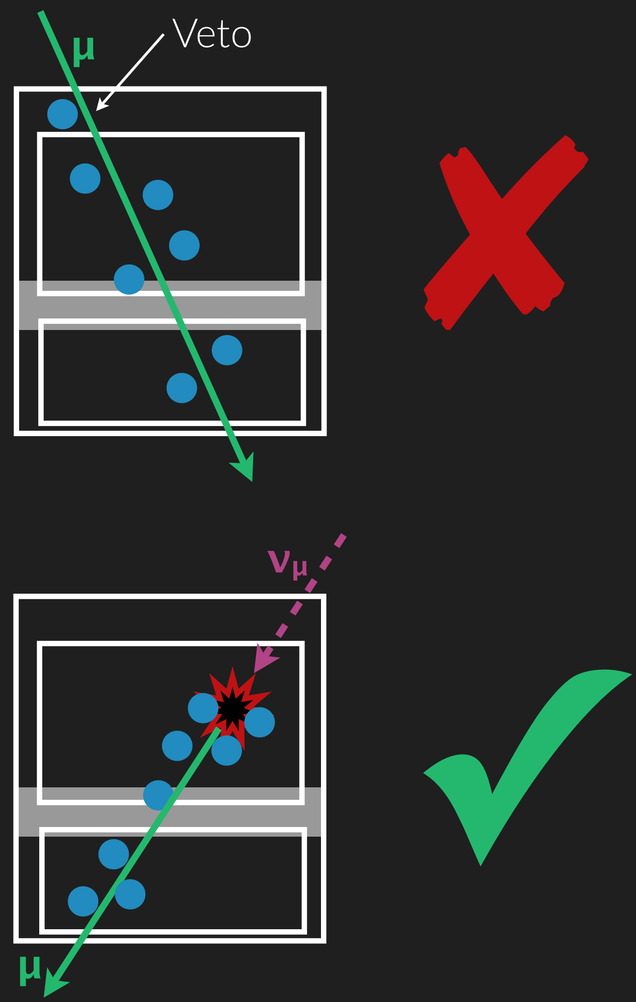
Explicit contained search at high energies (cut: Qtot>6000 p.e.)

400 Mton effective fiducial mass

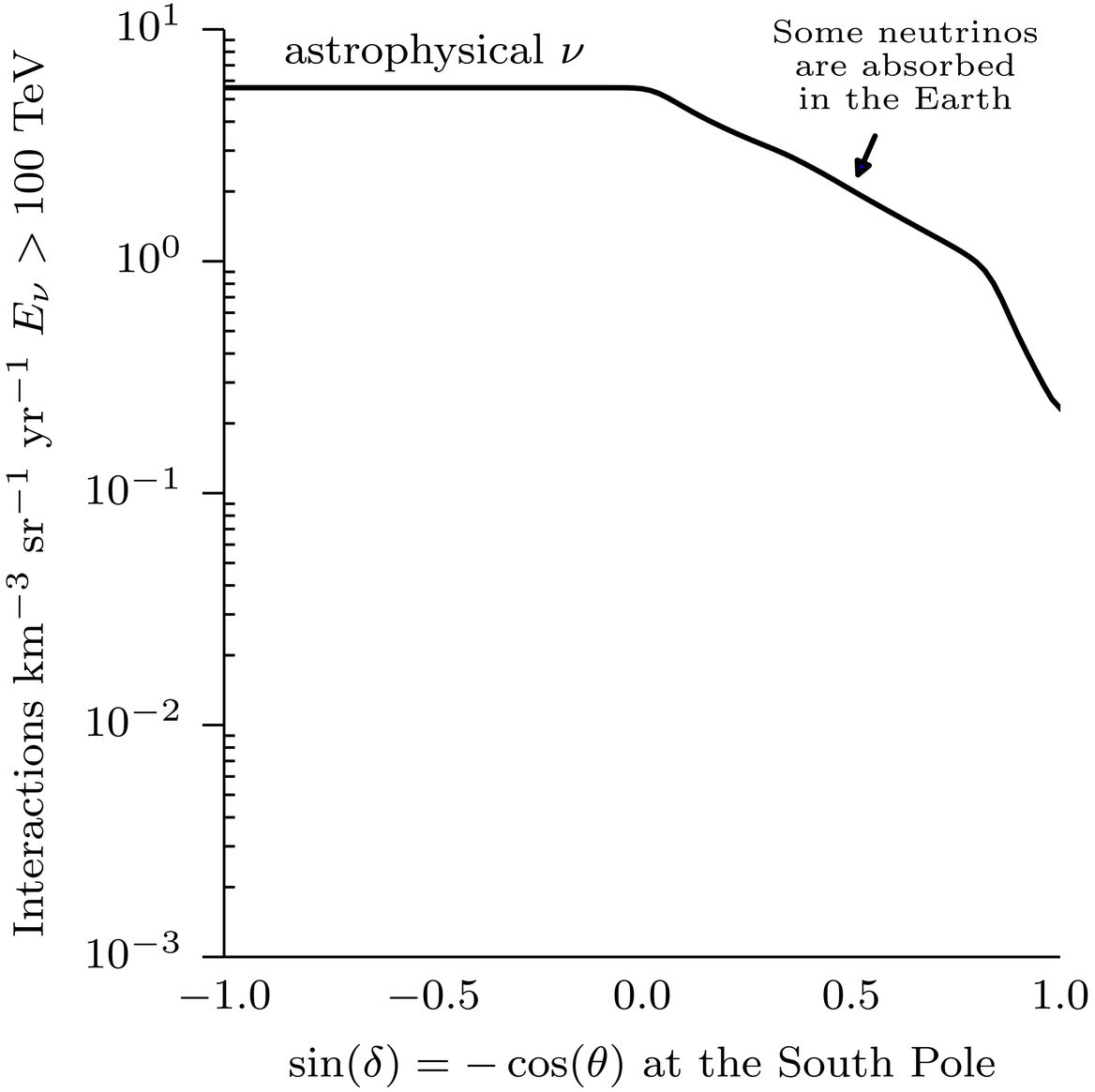
Use atmospheric muon veto

Sensitive to all flavors in region above 60TeV deposited energy

Estimate background from data

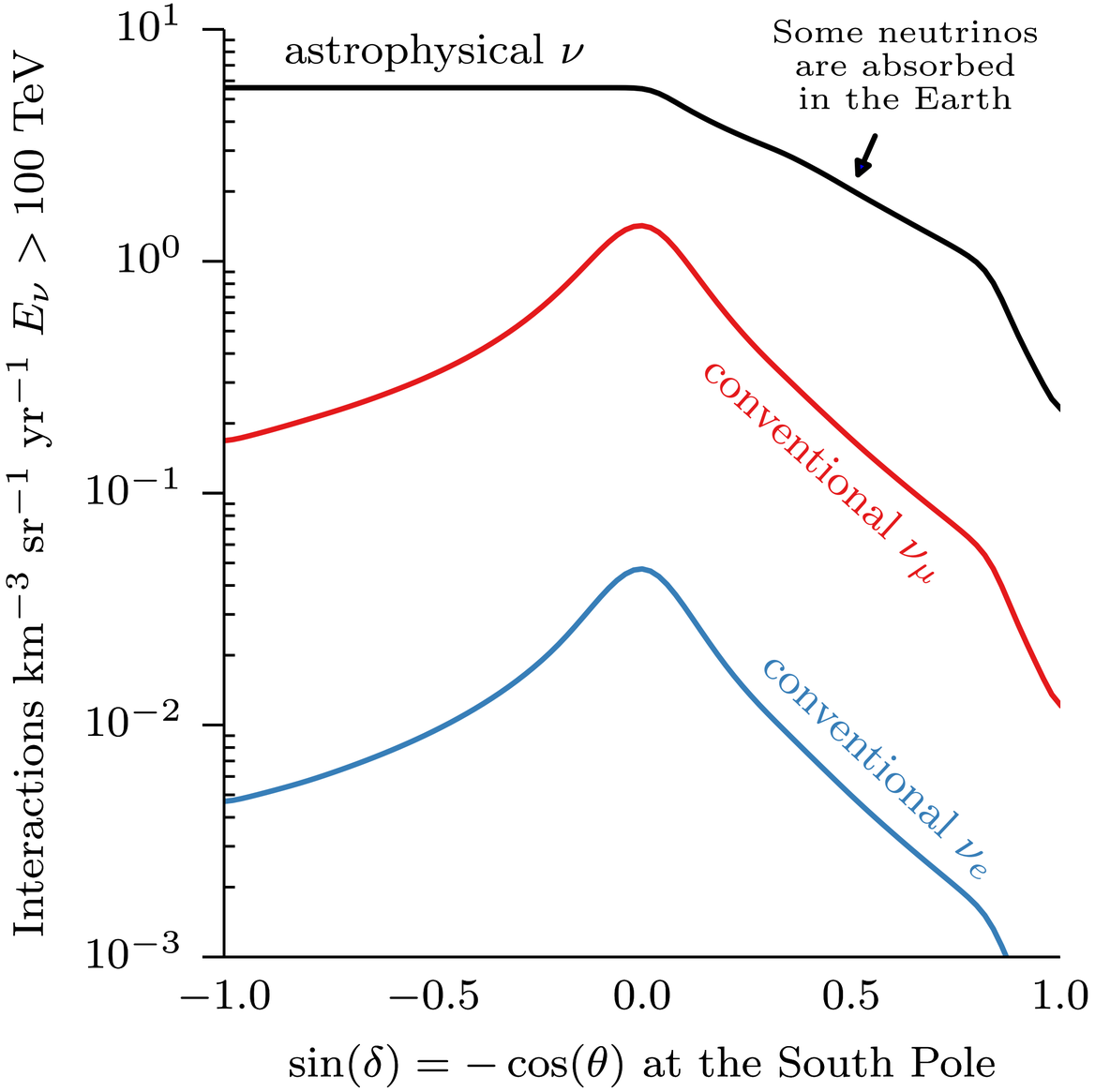


Atmospheric neutrino self-veto



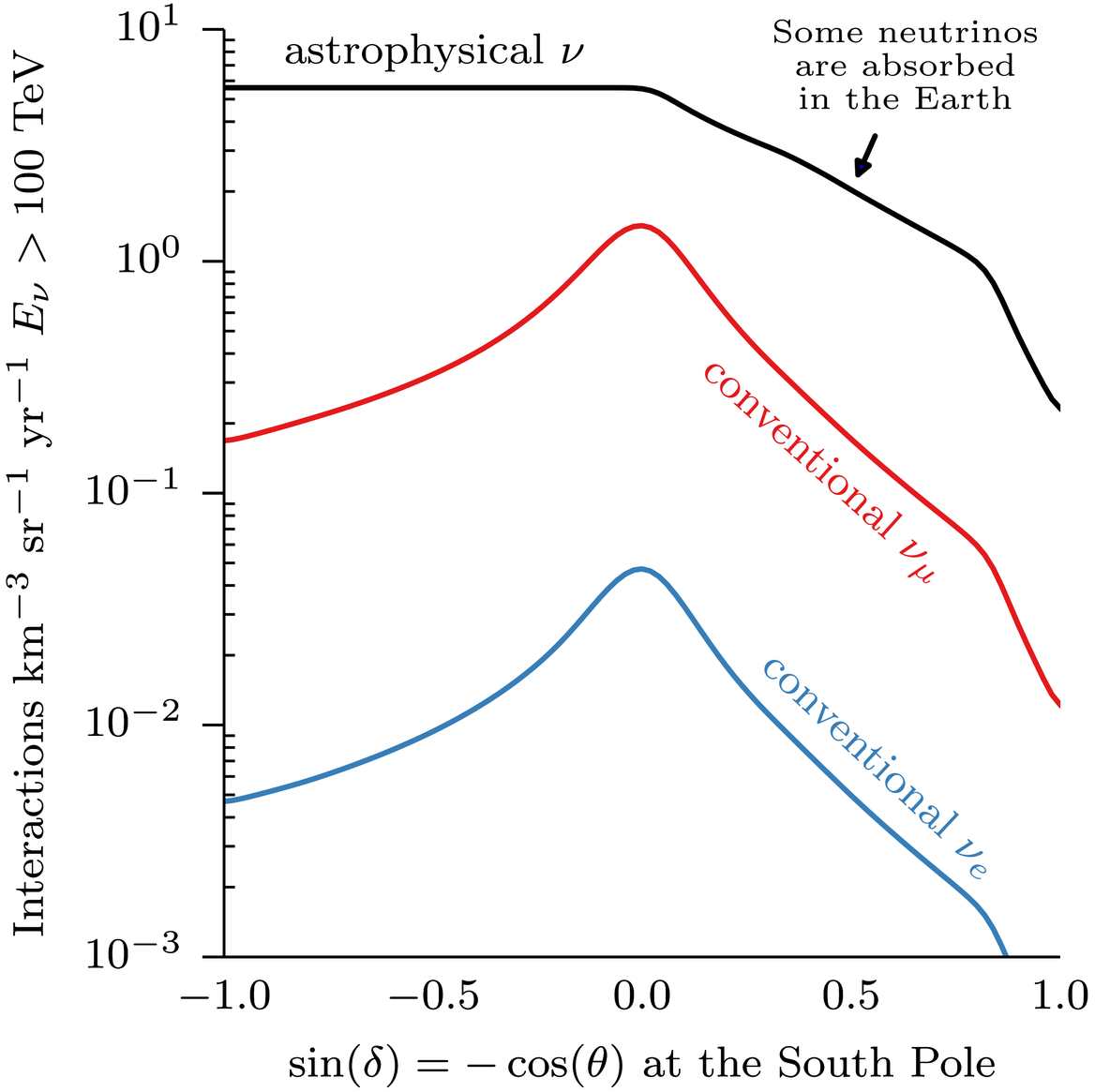
slide courtesy of J. van Santen

Atmospheric neutrino self-veto

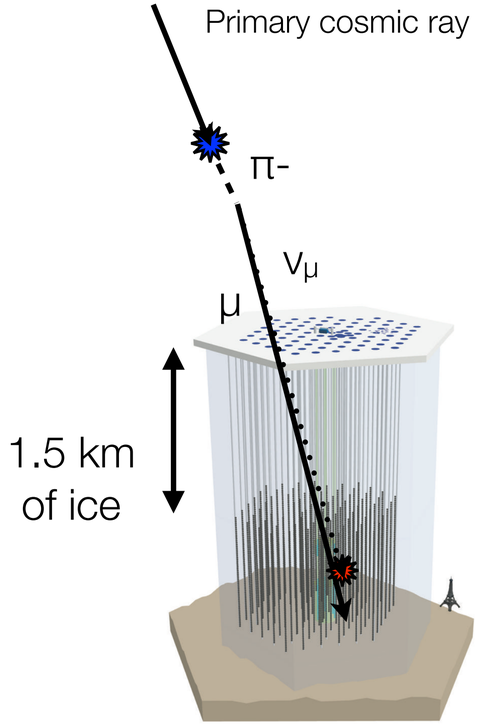


slide courtesy of J. van Santen

Atmospheric neutrino self-veto



An active muon veto removes down-going atmospheric neutrinos.

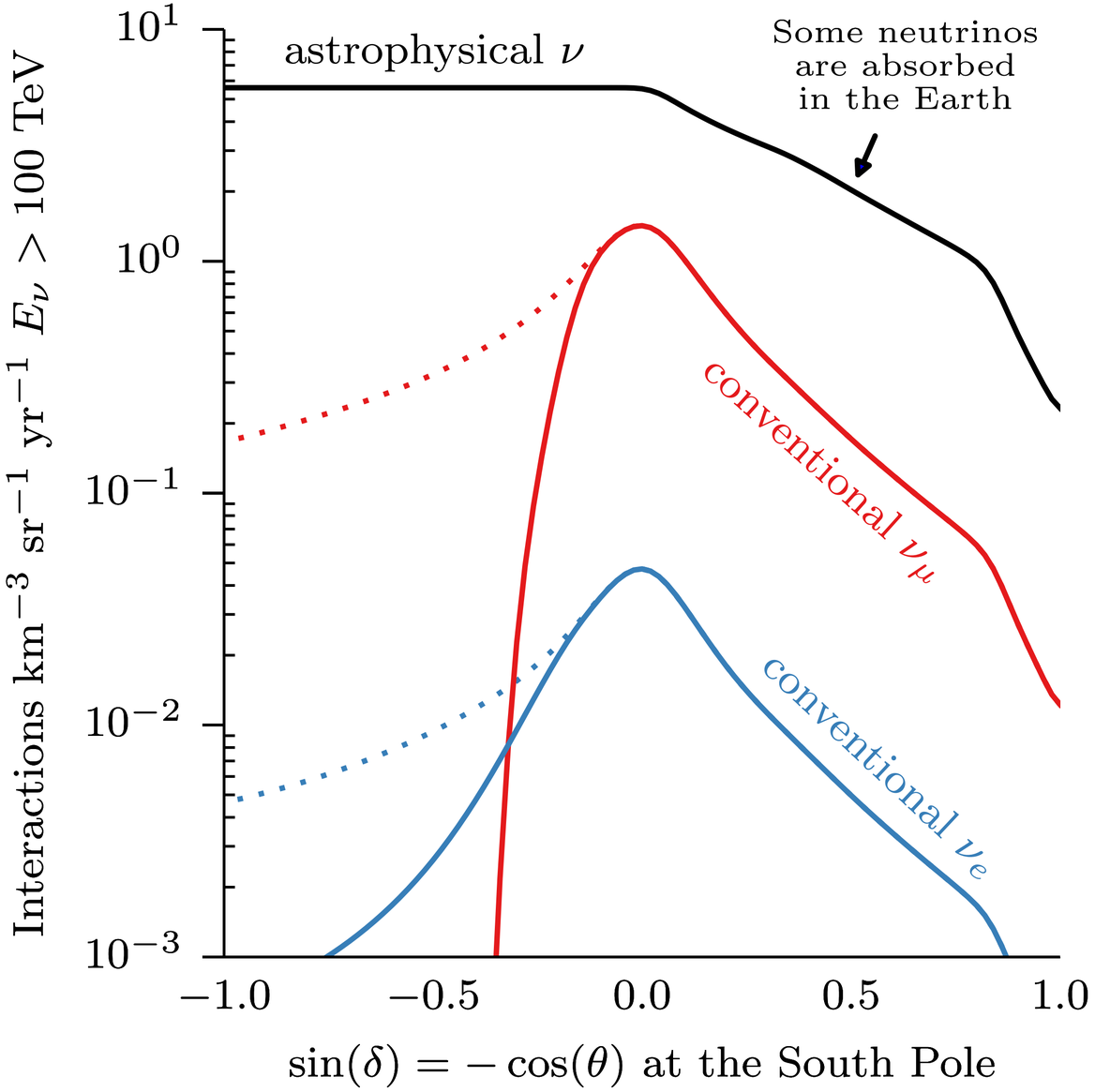


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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

slide courtesy of J. van Santen

Atmospheric neutrino self-veto



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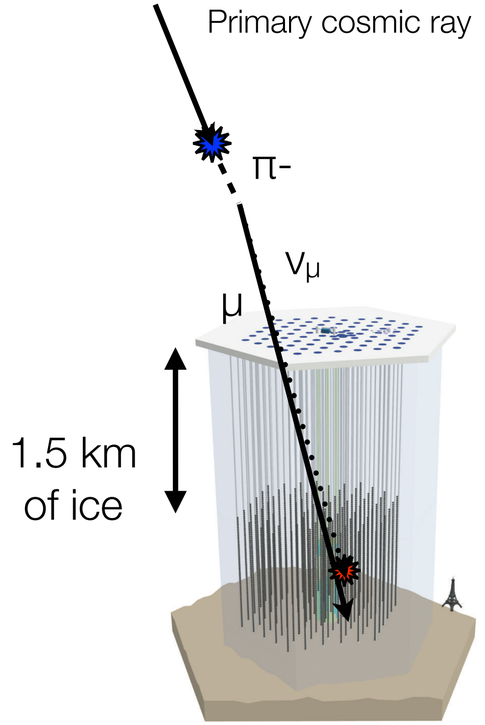

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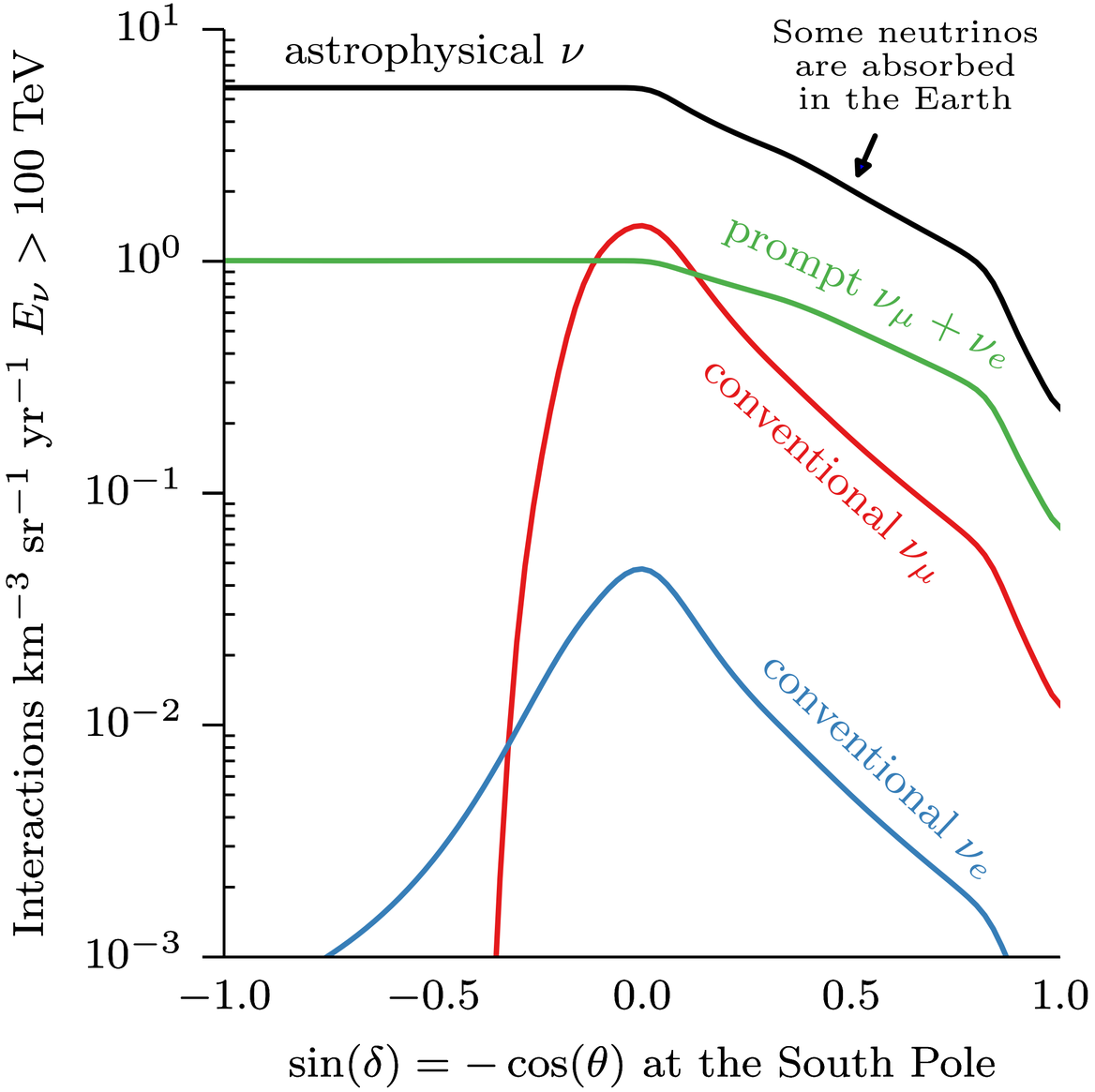
Atmospheric neutrino self-veto



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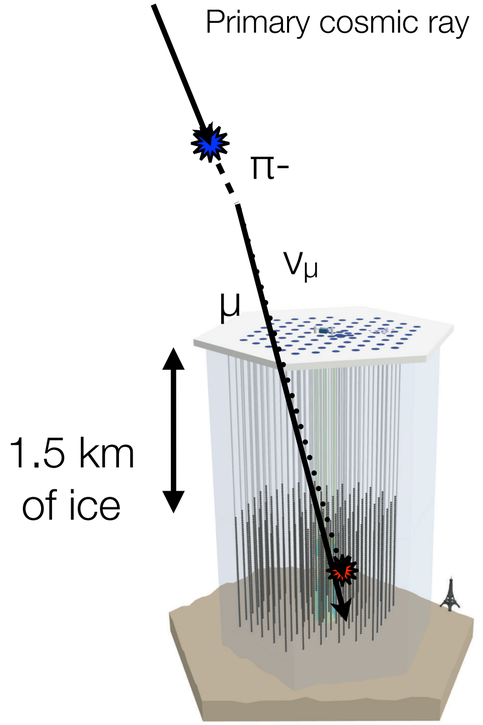

Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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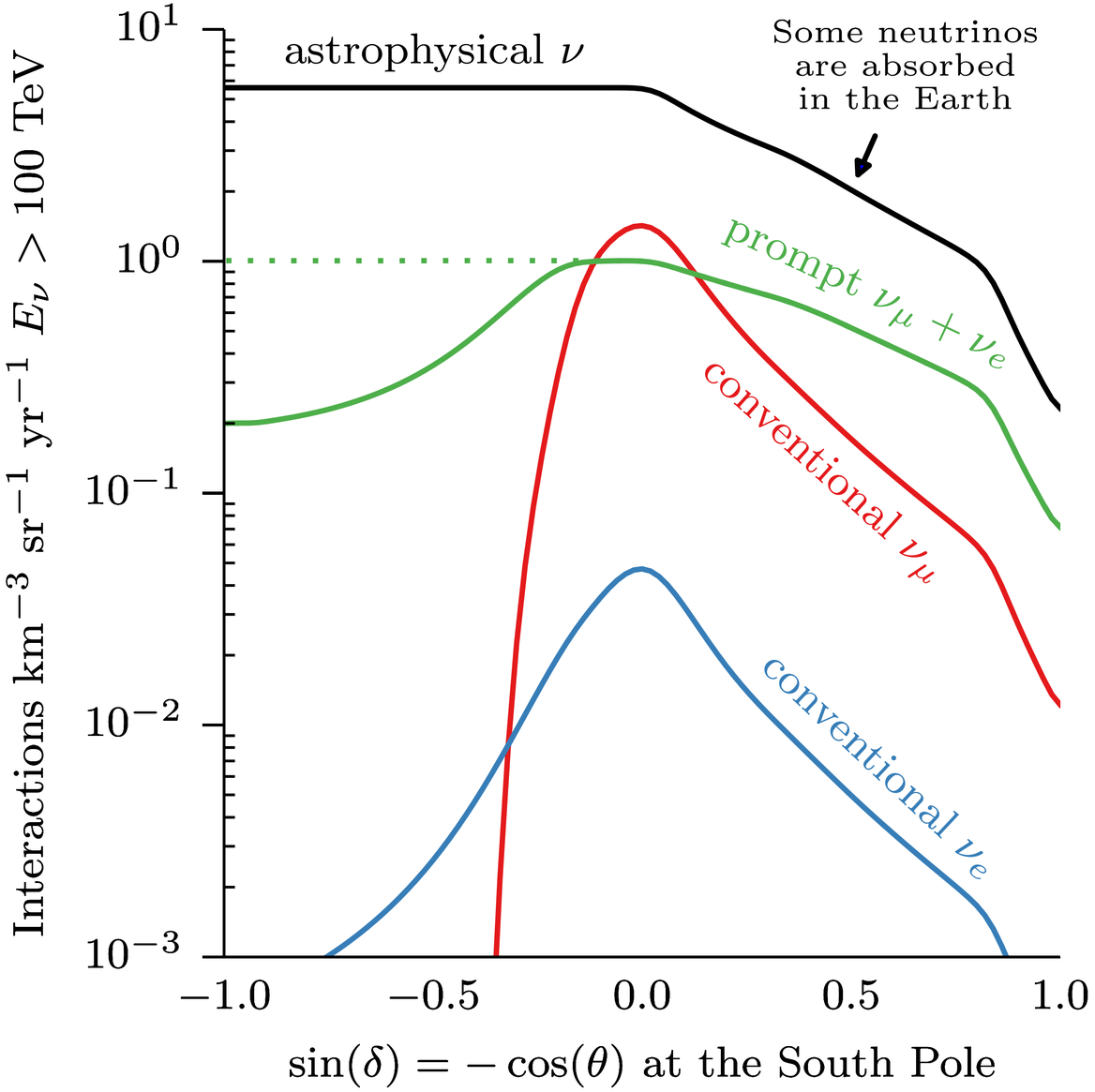
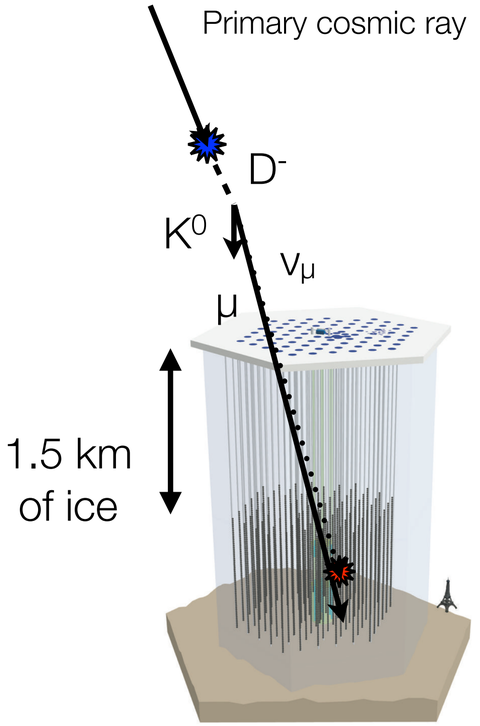
slide courtesy of J. van Santen

Atmospheric neutrino self-veto



Prompt atmospheric neutrinos are vetoed, too.

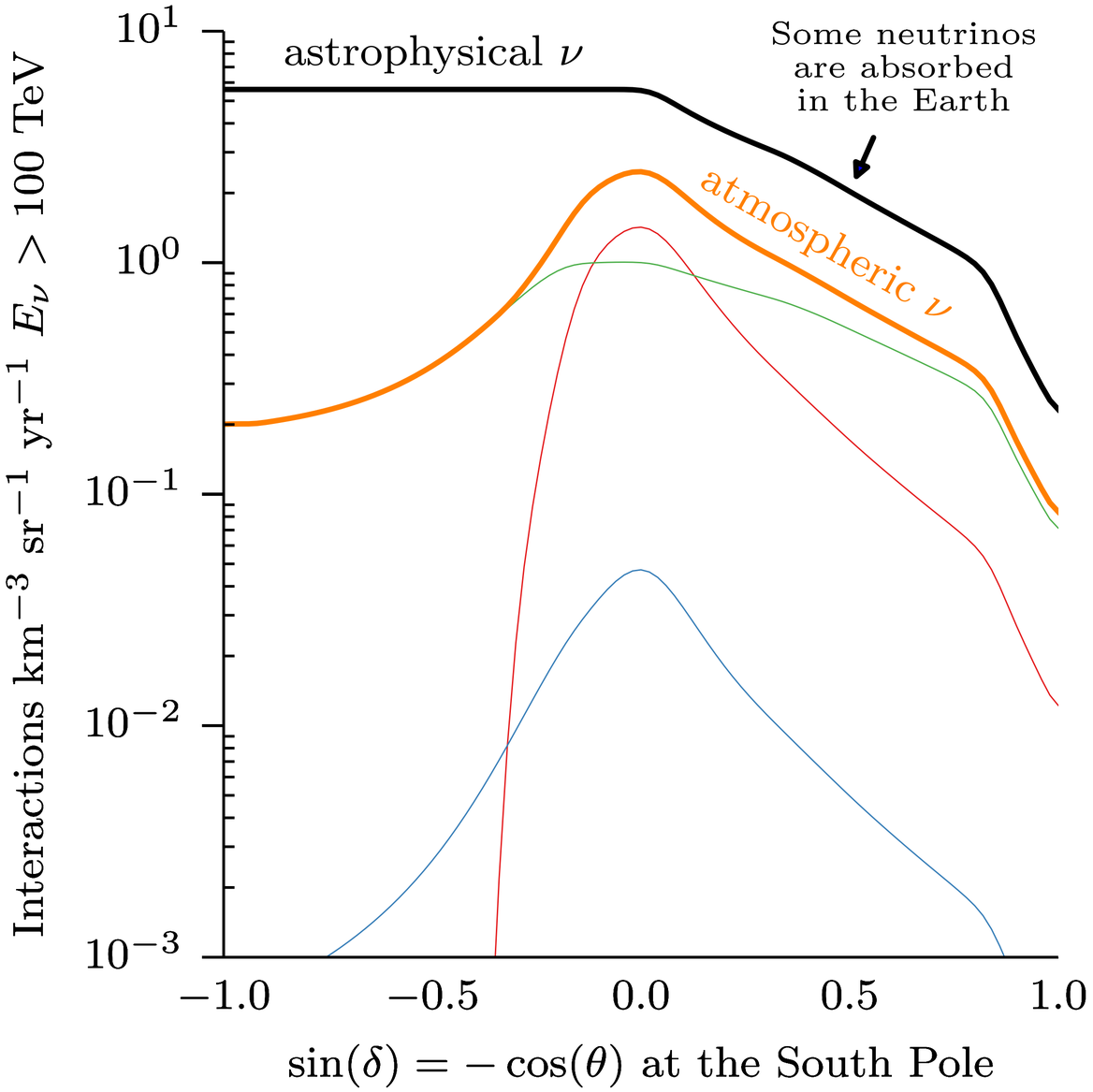


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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

slide courtesy of J. van Santen

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!

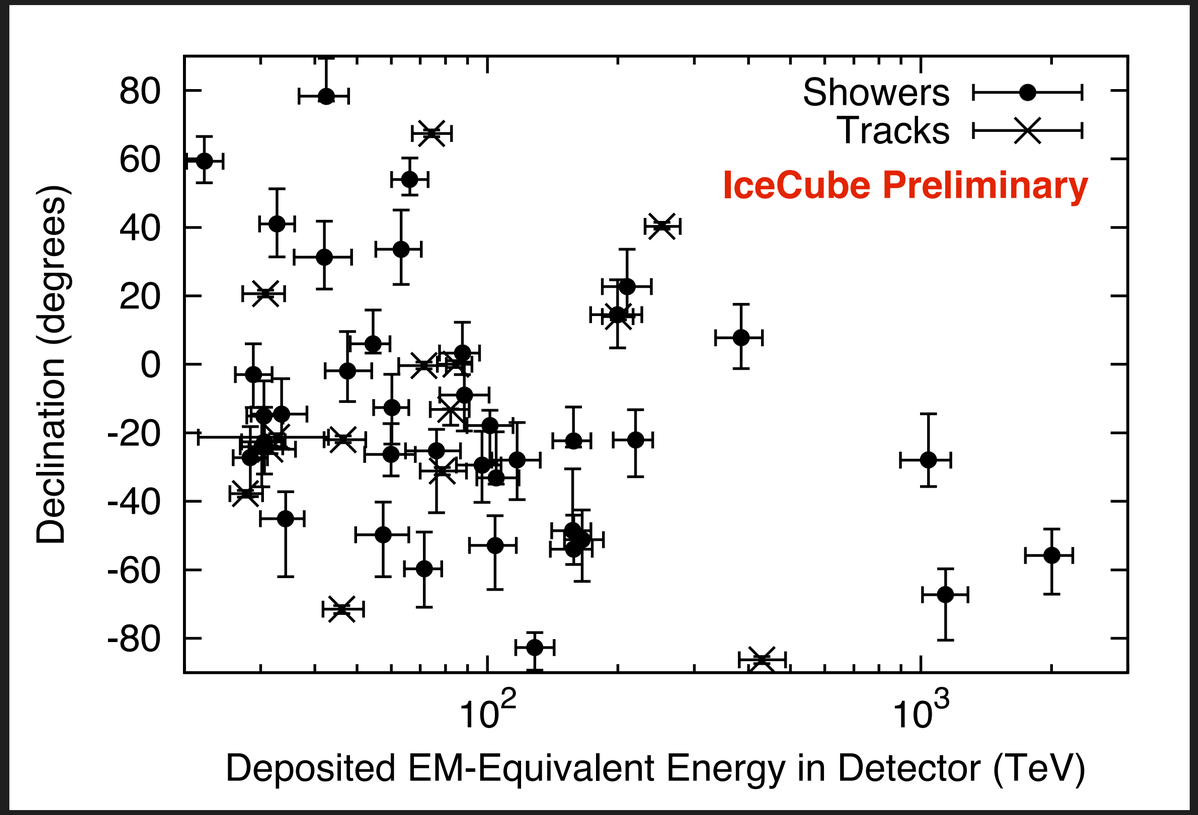
Estimated background:

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

12.6±5.1 atm. muons

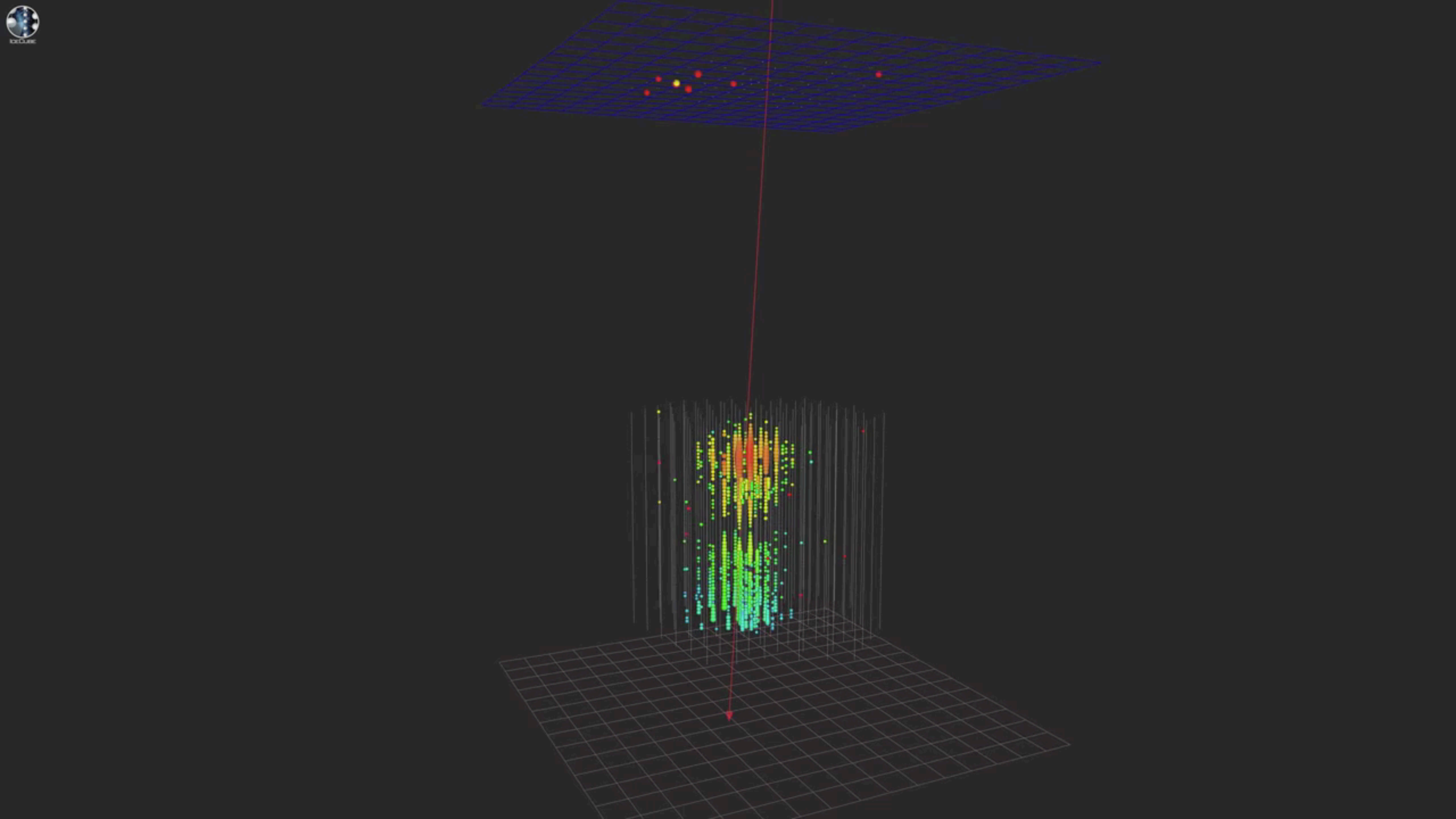
One of them is an obvious (but expected) background

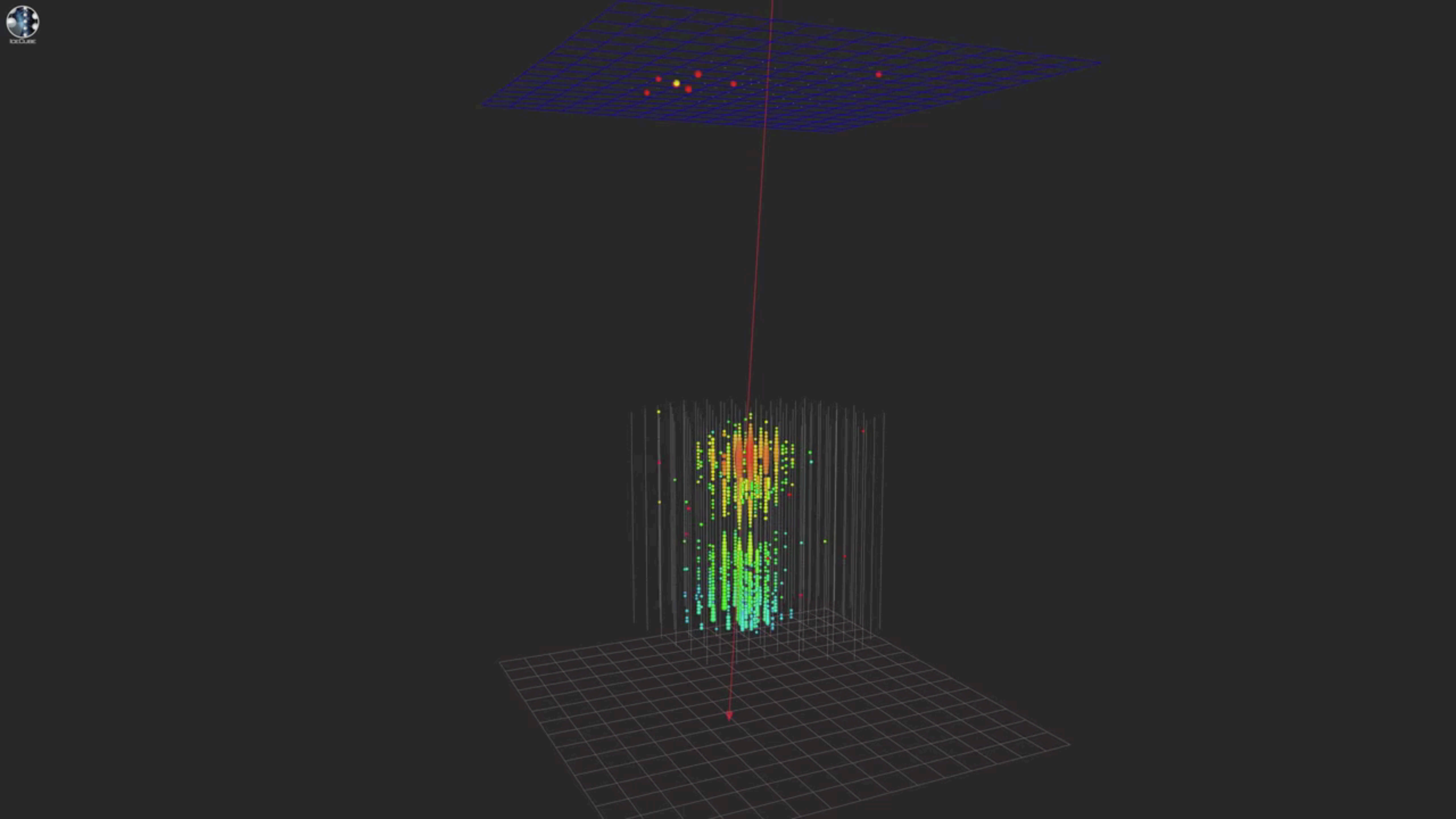
coincident muons from two CR air showers



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

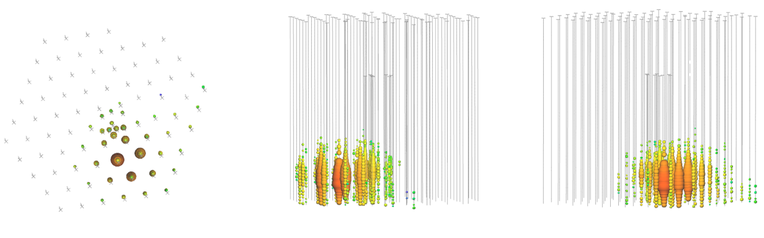
presented at ICRC2015 / PoS(ICRC2015)1081



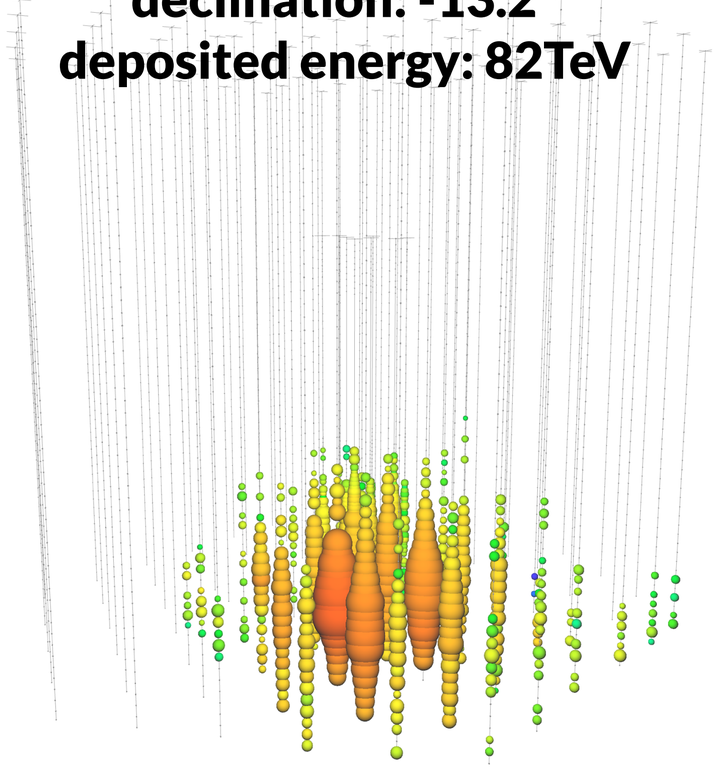


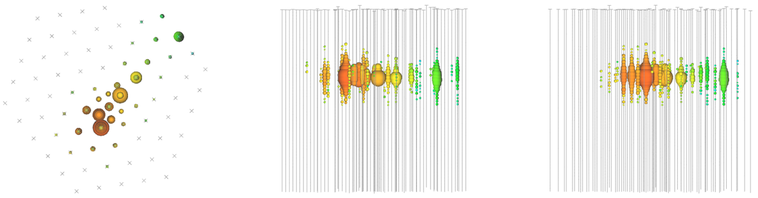
WHAT DID ICECUBE FIND?

some examples

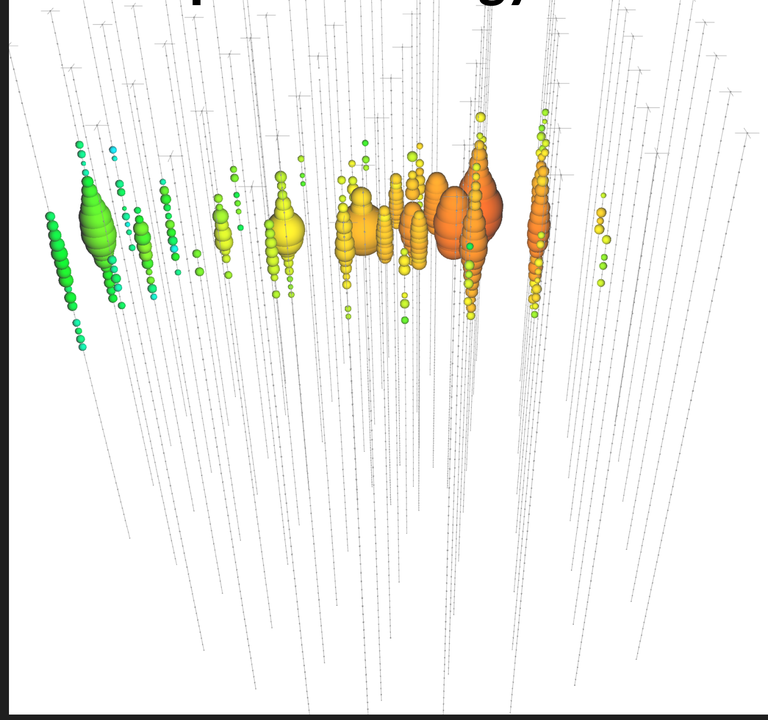


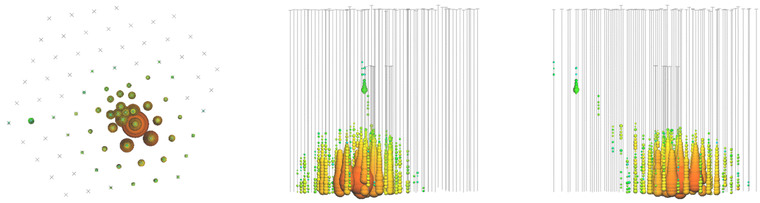
declination: -13.2°
deposited energy: 82TeV



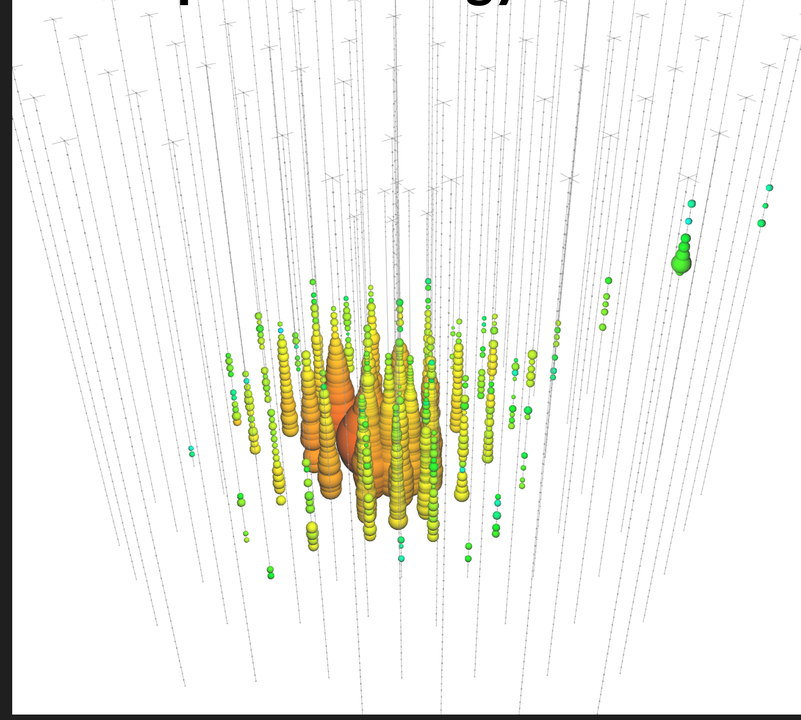


declination: -0.4°
deposited energy: 71TeV





declination: 40.3°
deposited energy: 253TeV



ENERGY SPECTRUM (4 YEARS)

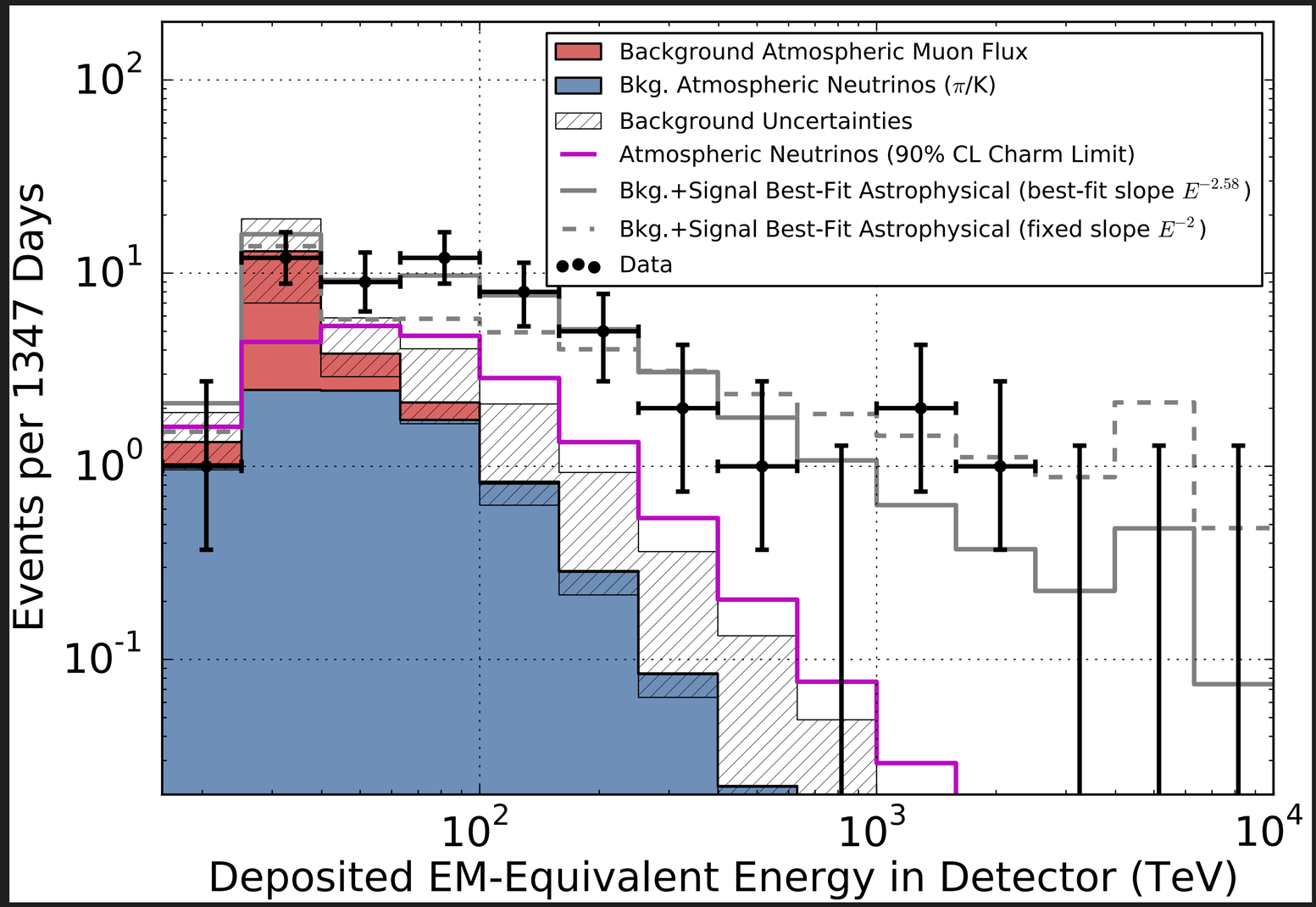
energy deposited in the detector (lower limit on neutrino energy)

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):

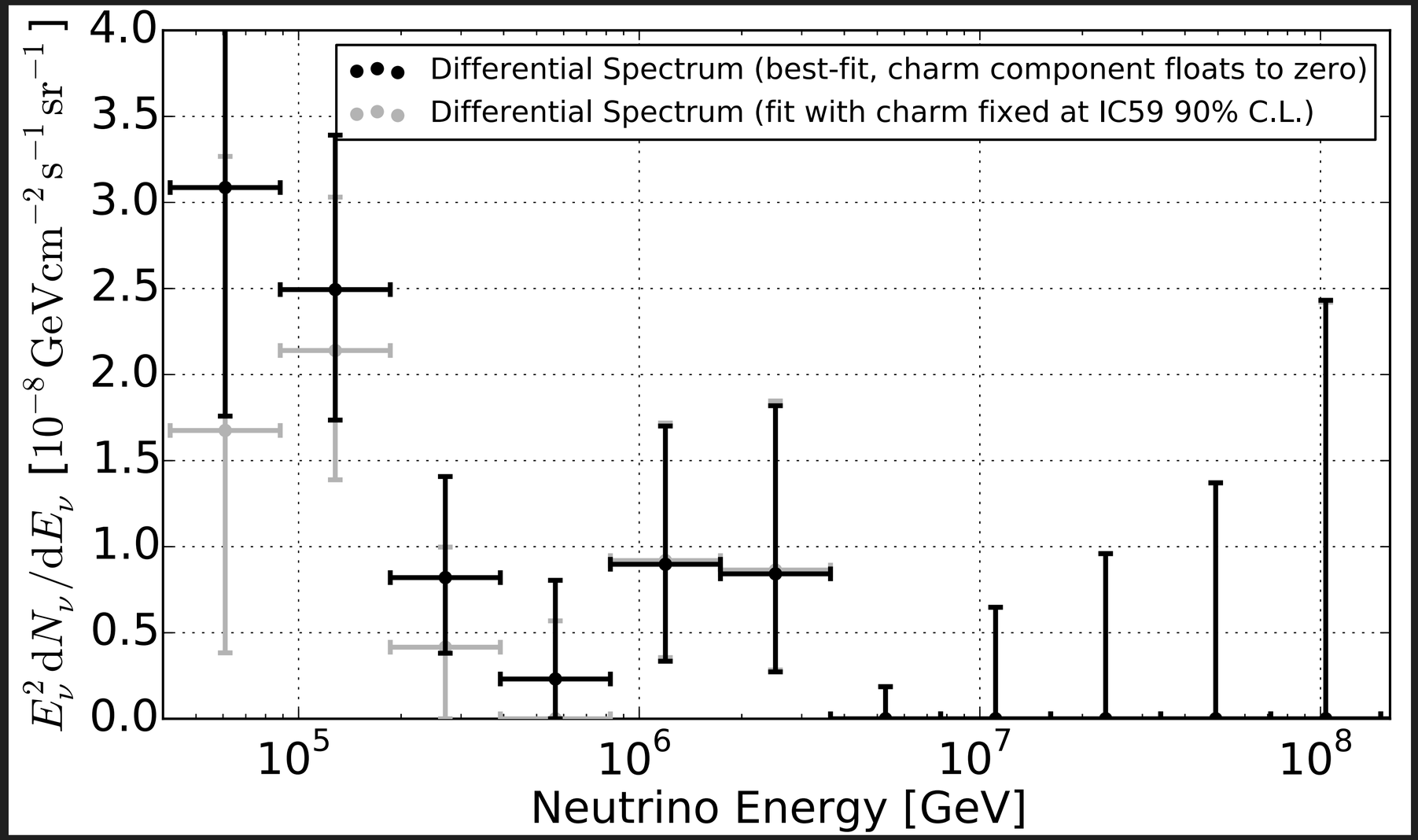
$0.84 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV cm^{-2} s^{-1} sr^{-1}

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



UNFOLDING TO NEUTRINO ENERGY

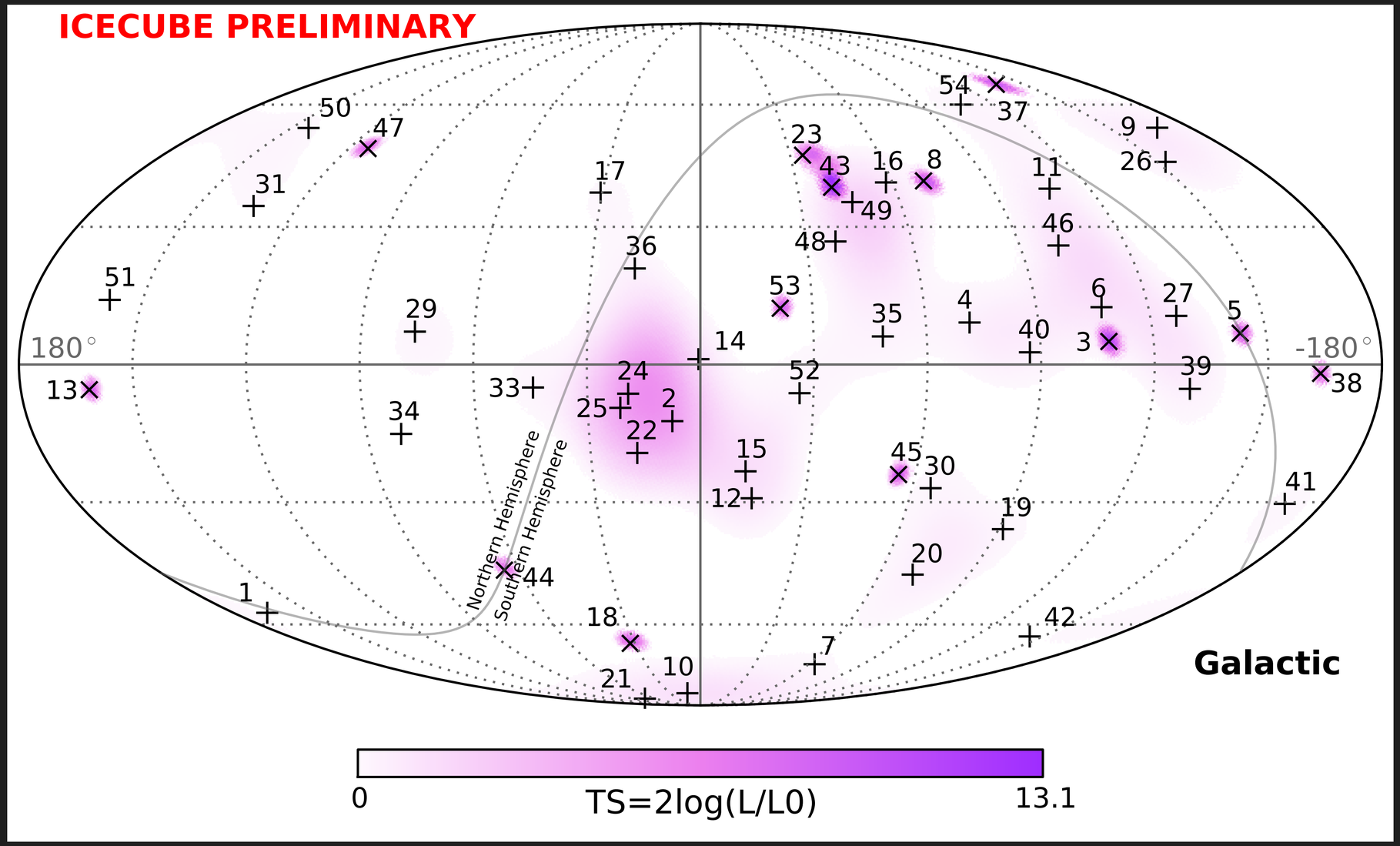
updated from PRL plot version with priors for backgrounds - 4 years



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)

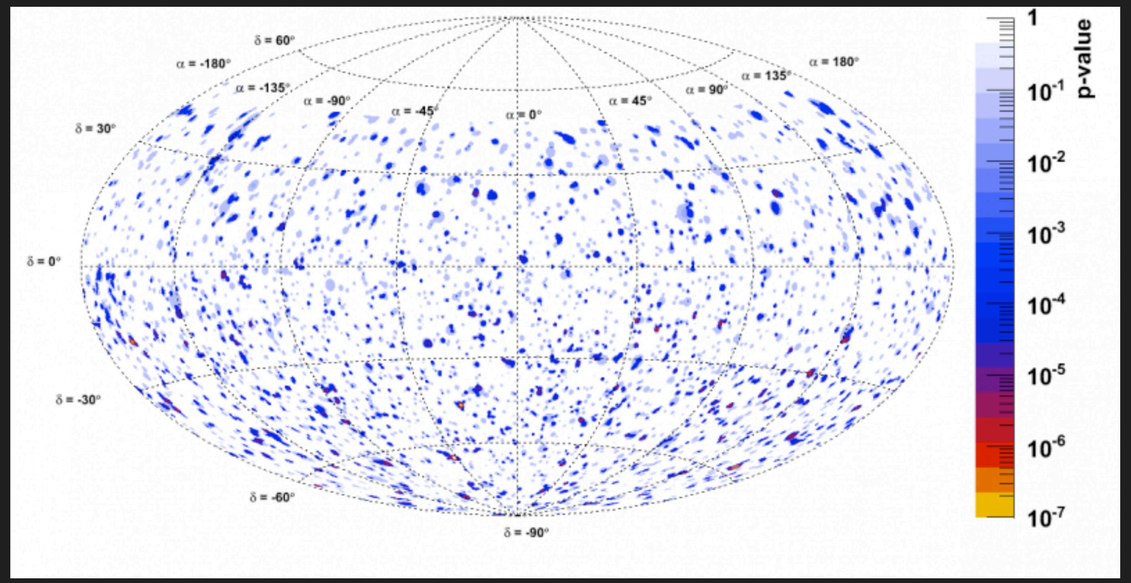
Most significant excess close to (but not at!) the Galactic Center

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.

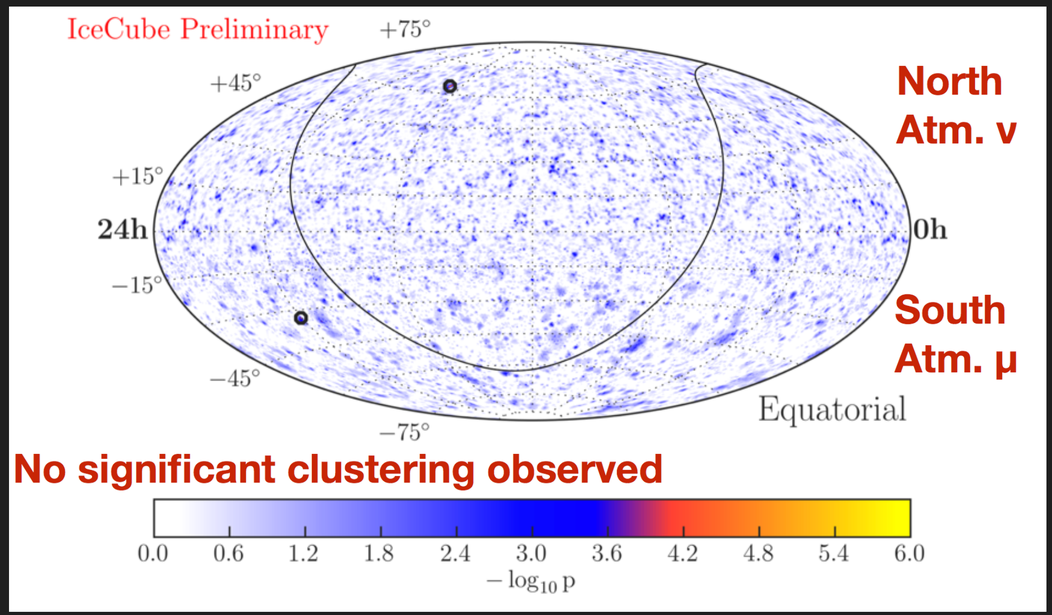


ApJ Lett, 786, L5 (2014)

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

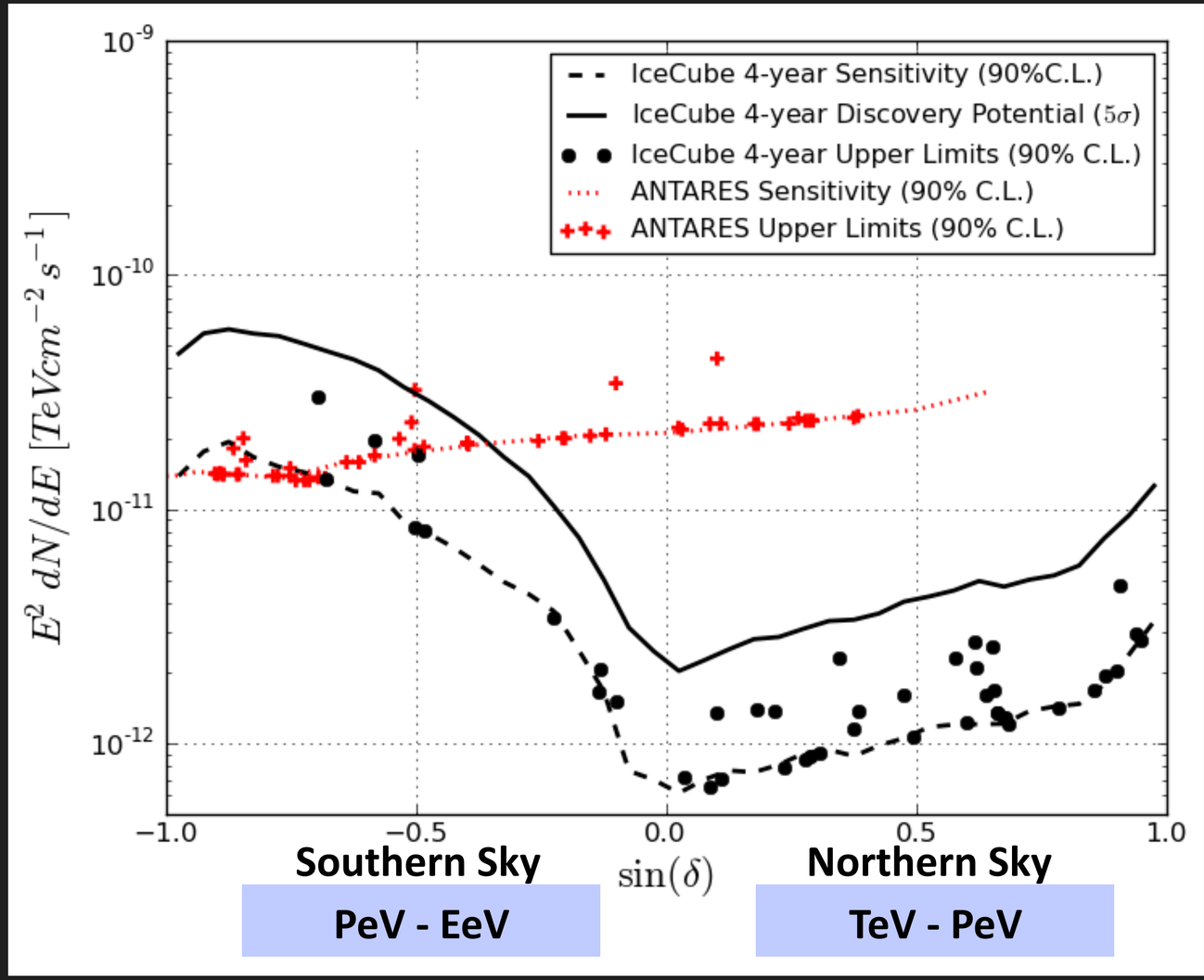


CONSTRAINTS ON POINT SOURCES

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

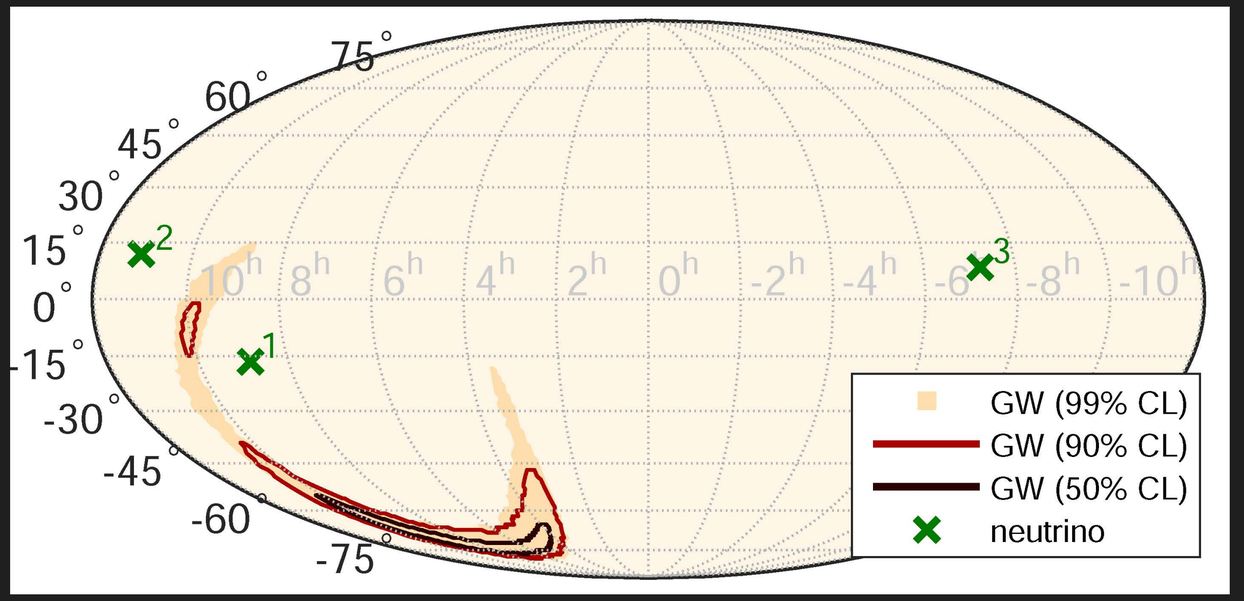


GRAVITATIONAL WAVES AND NEUTRINOS

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

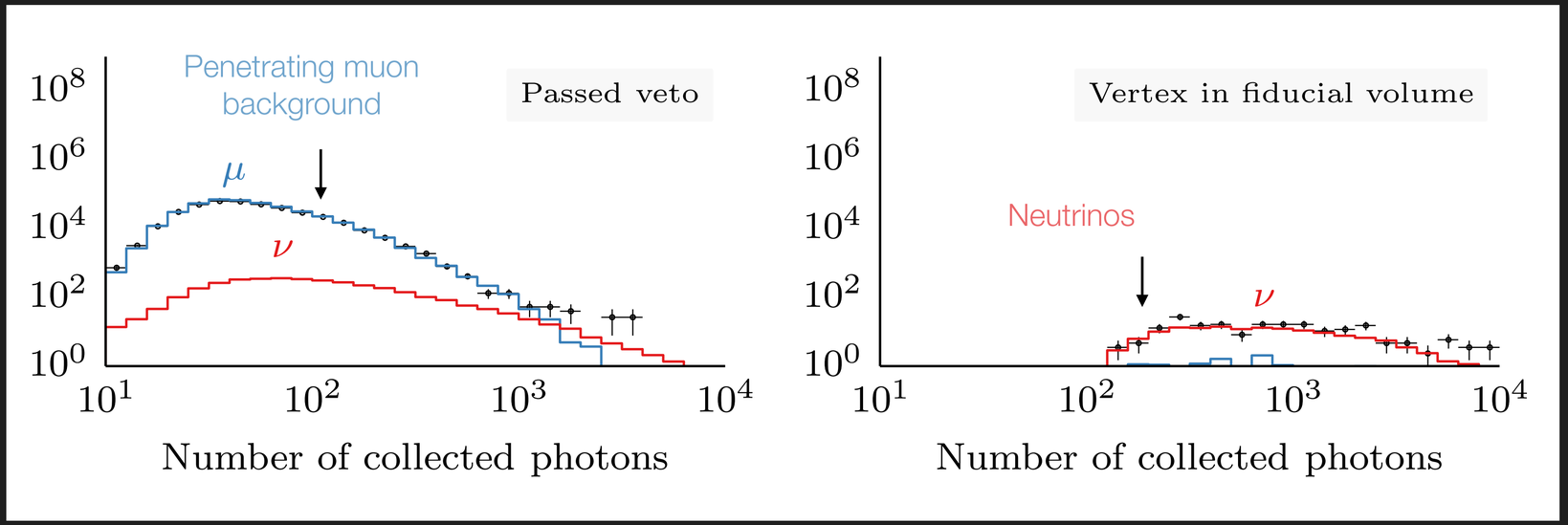
What happens to the astrophysical flux below 60 TeV?

PRD 91, 022001

Outer-layer veto → Energy-dependent veto

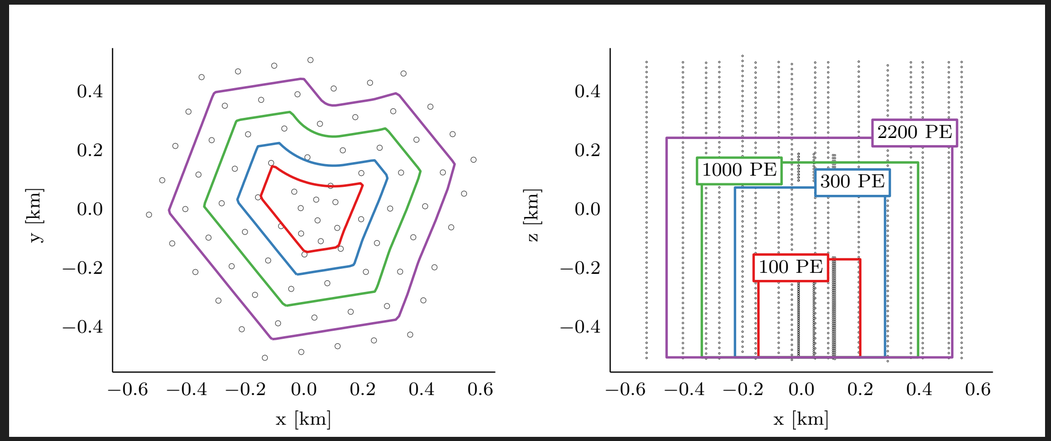
Neutrino-dominated for E_{dep} > 60 TeV

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?

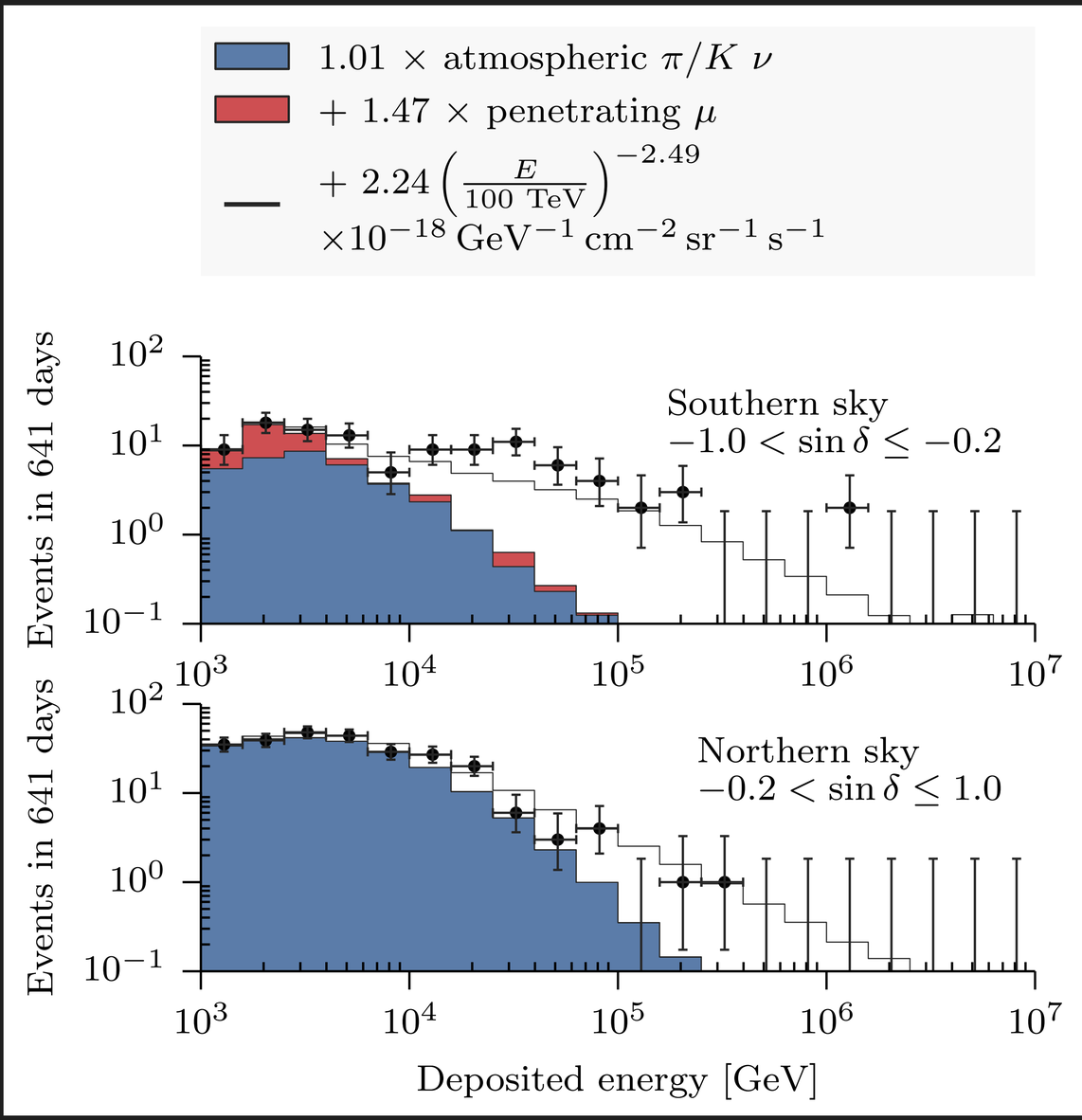
106 events > 10 TeV, 9 events > 100 TeV (7 of those in high-energy starting event sample)

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

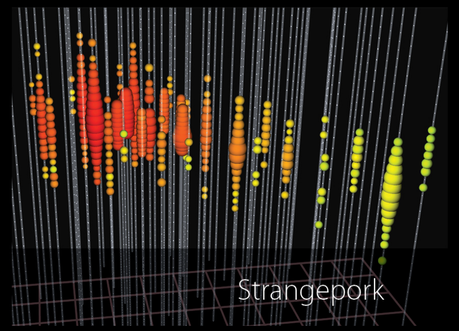
Most of the “starting” sample consists of showers, with a high acceptance in the southern sky

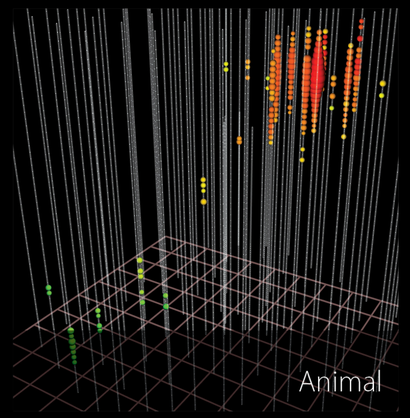
Deposited (i.e. measured) energies closely related to neutrino energies

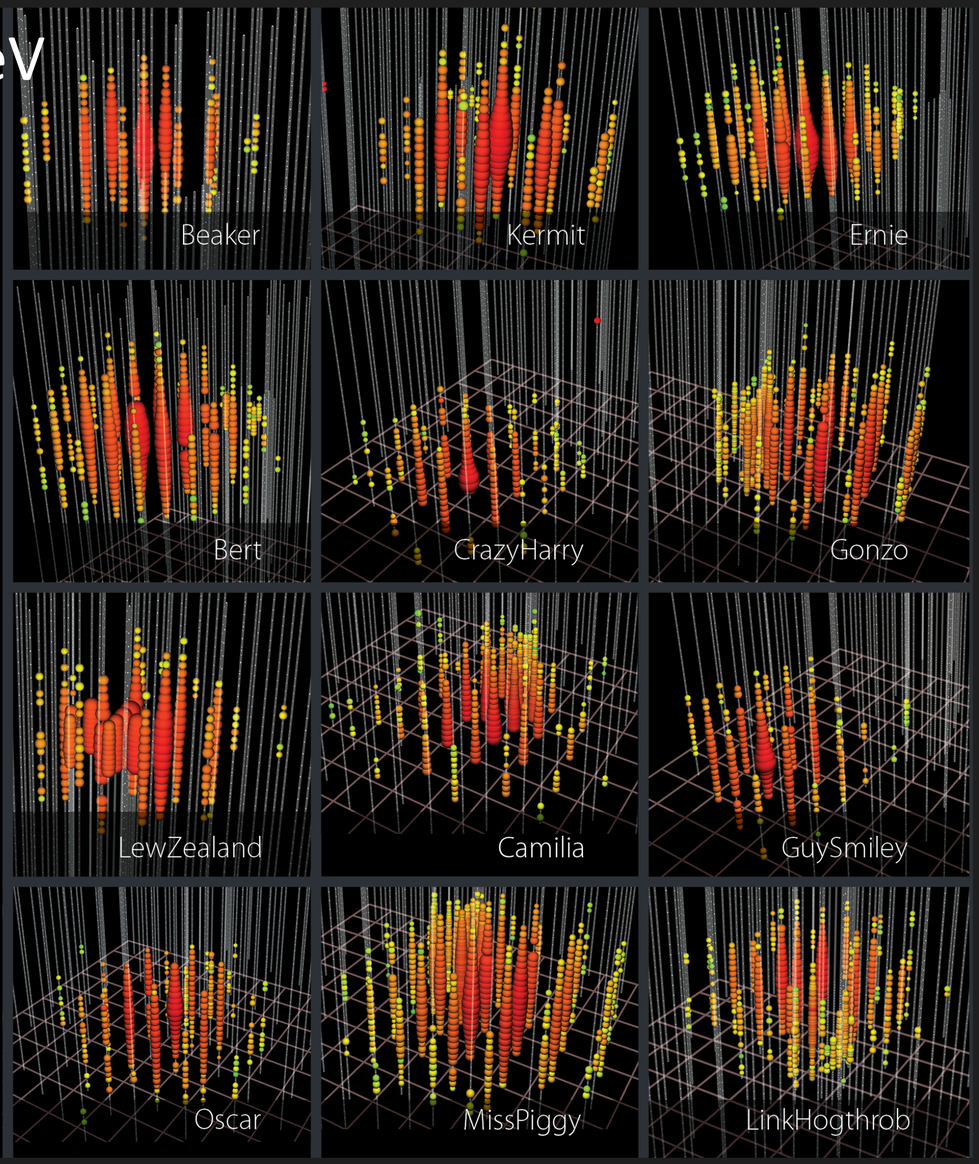
Great for discovering a signal

Highest energy: 2 PeV

28 High Energy Events







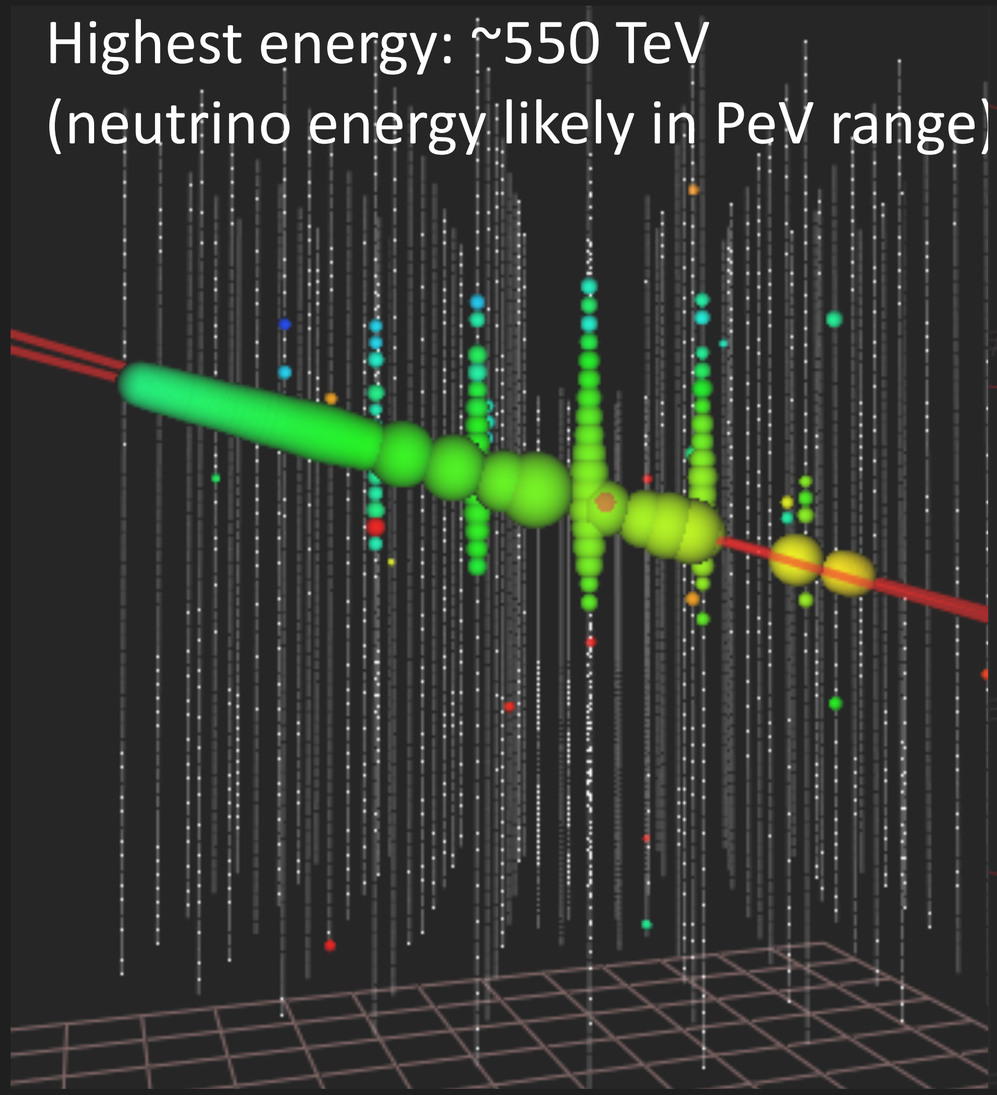
High-Energy Starting Event Search (“HESE”)

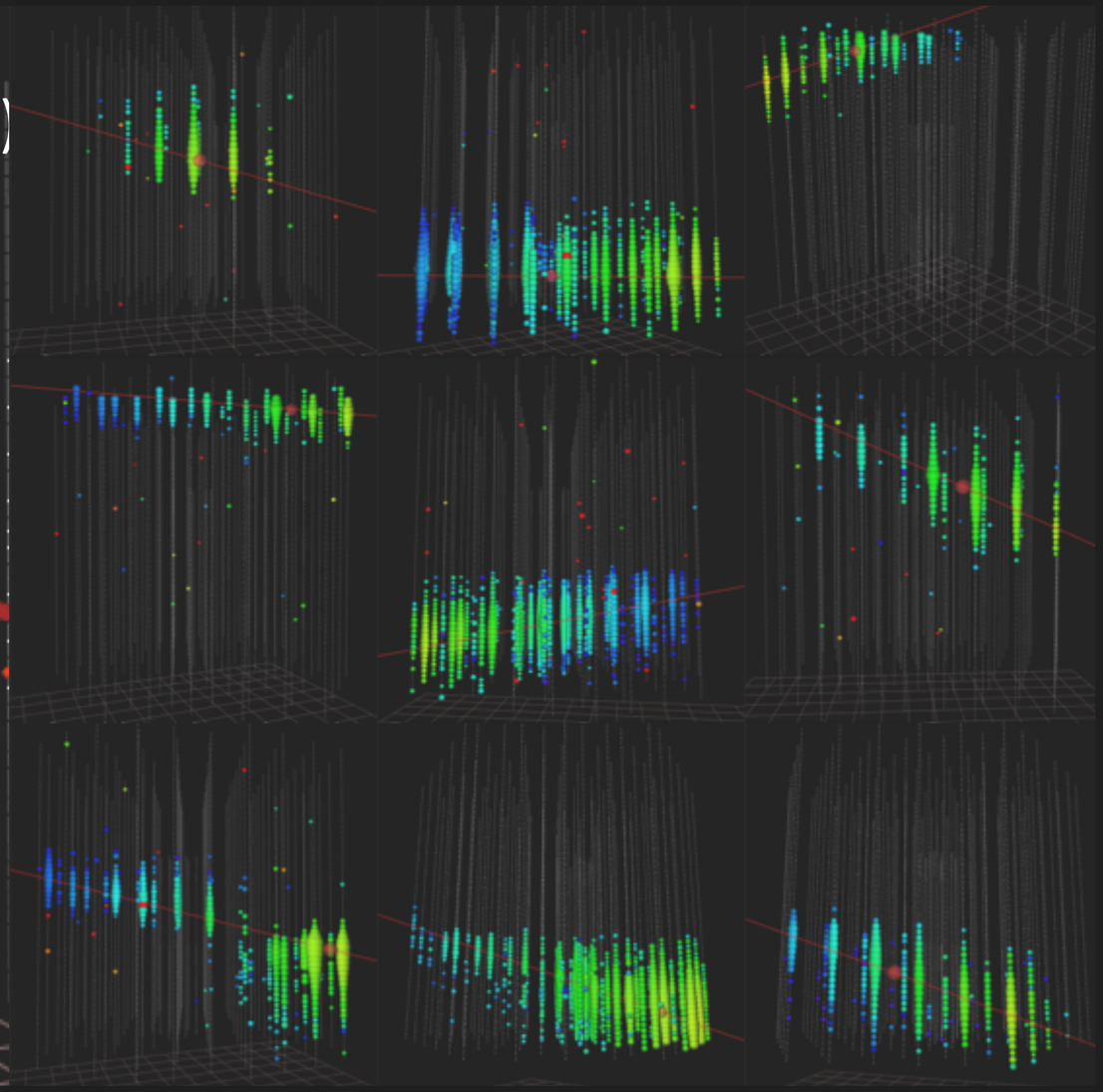
OTHER CHANNELS

Two years of data

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

Highest energy: ~550 TeV
(neutrino energy likely in PeV range)





Throughgoing Muons

PRL 115, 081102 (2015)

UPGOING MUONS - SPECTRAL COMPONENTS

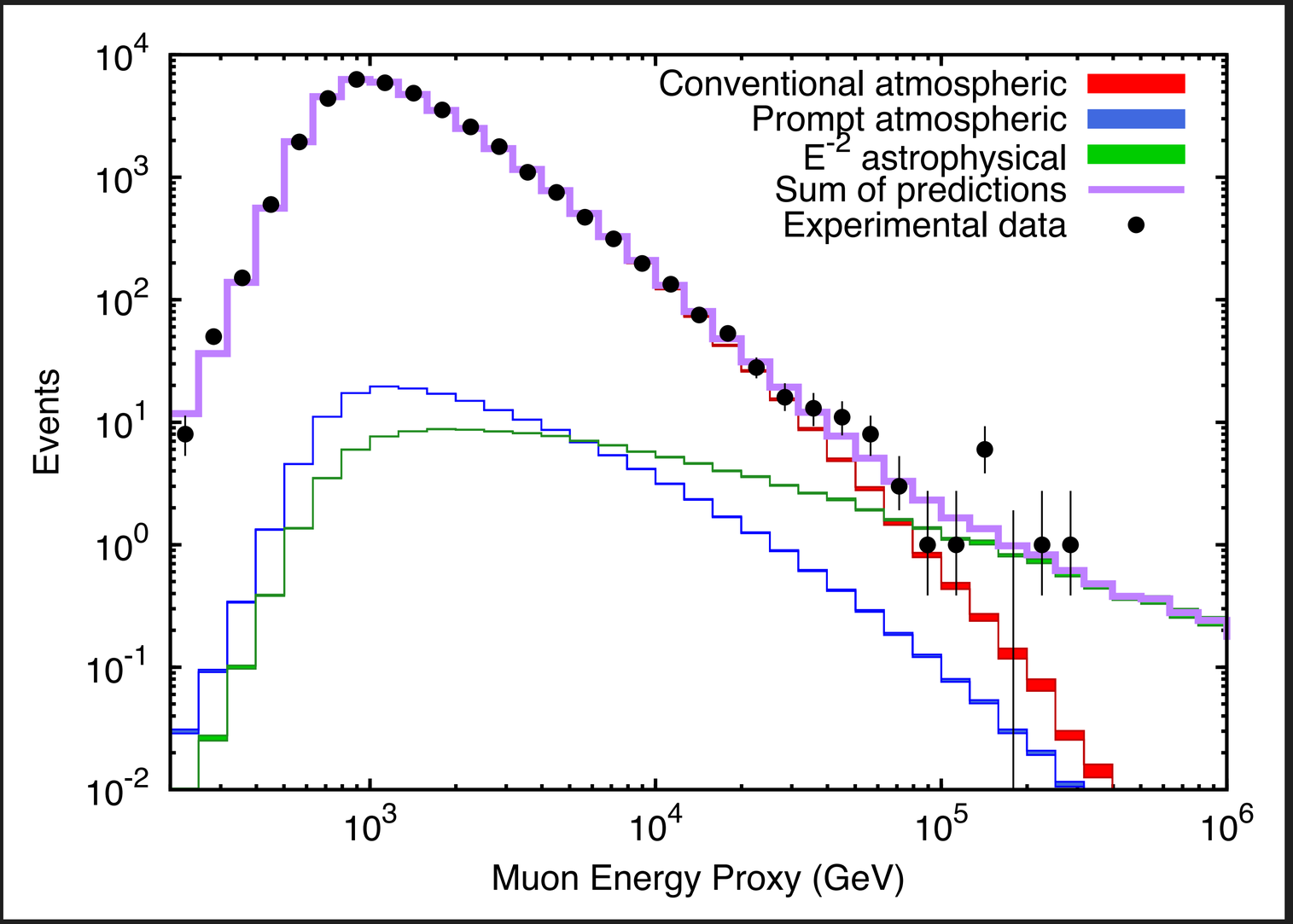
Two years of data

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}

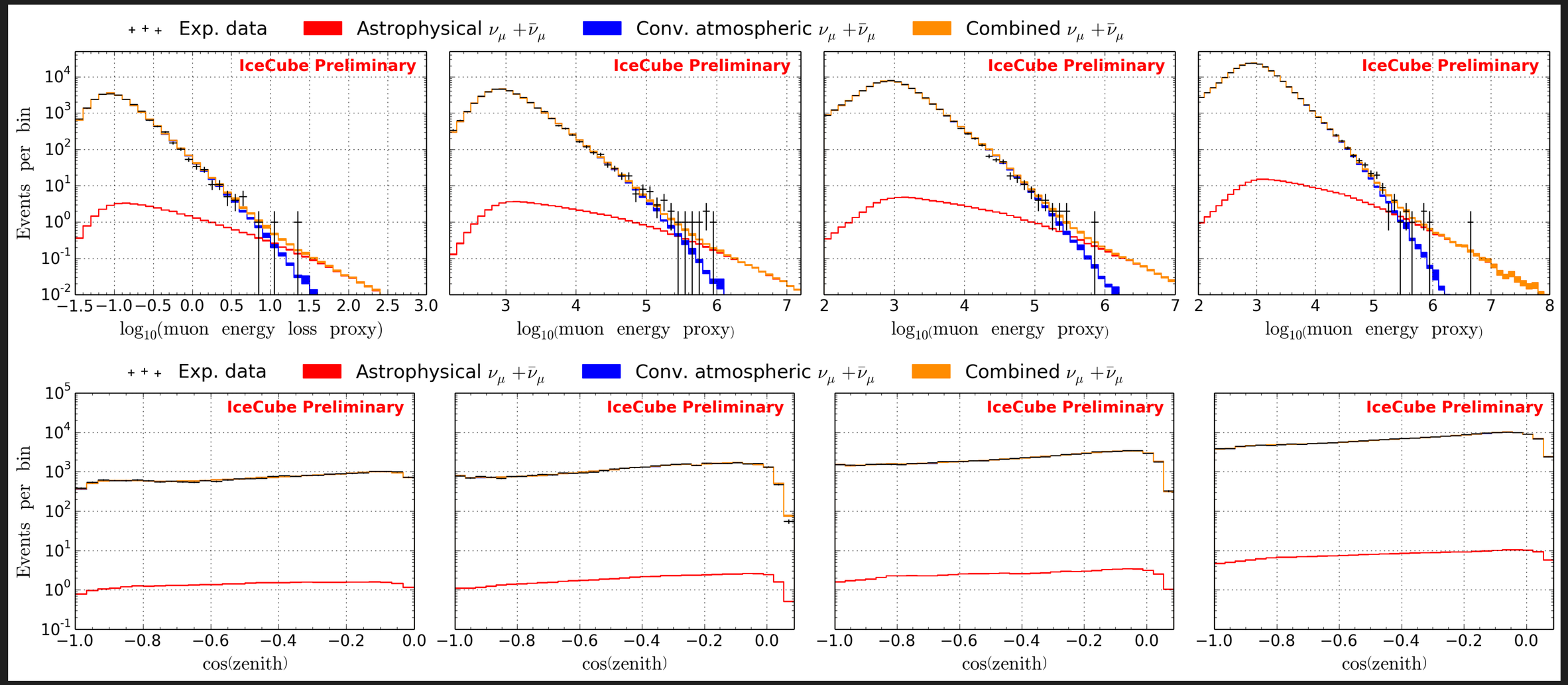
PRL 115, 081102 (2015)



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

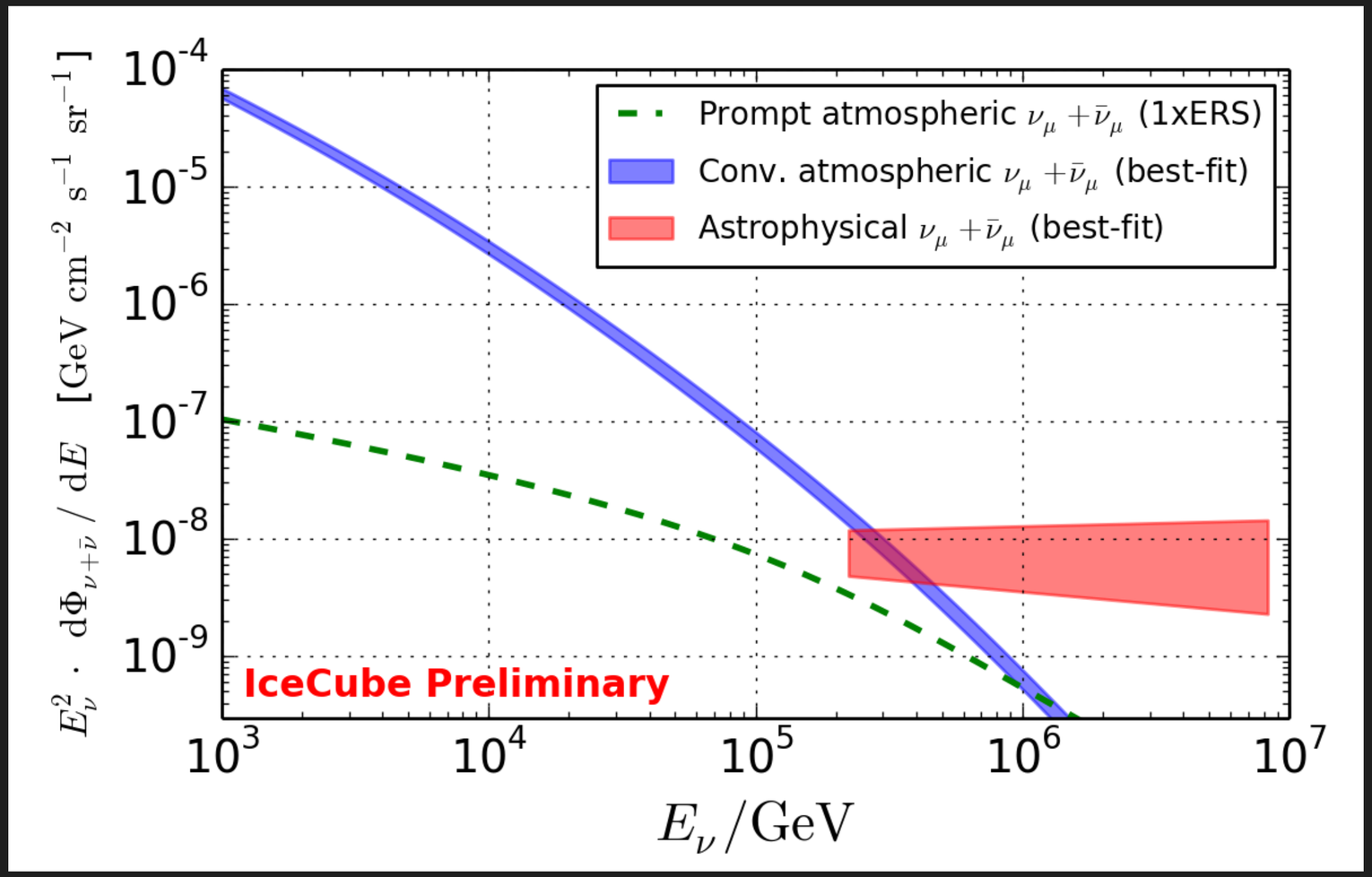


UPGOING MUONS - SPECTRAL COMPONENTS

Six years of data

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

prompt fits to 0, upper limit details under study

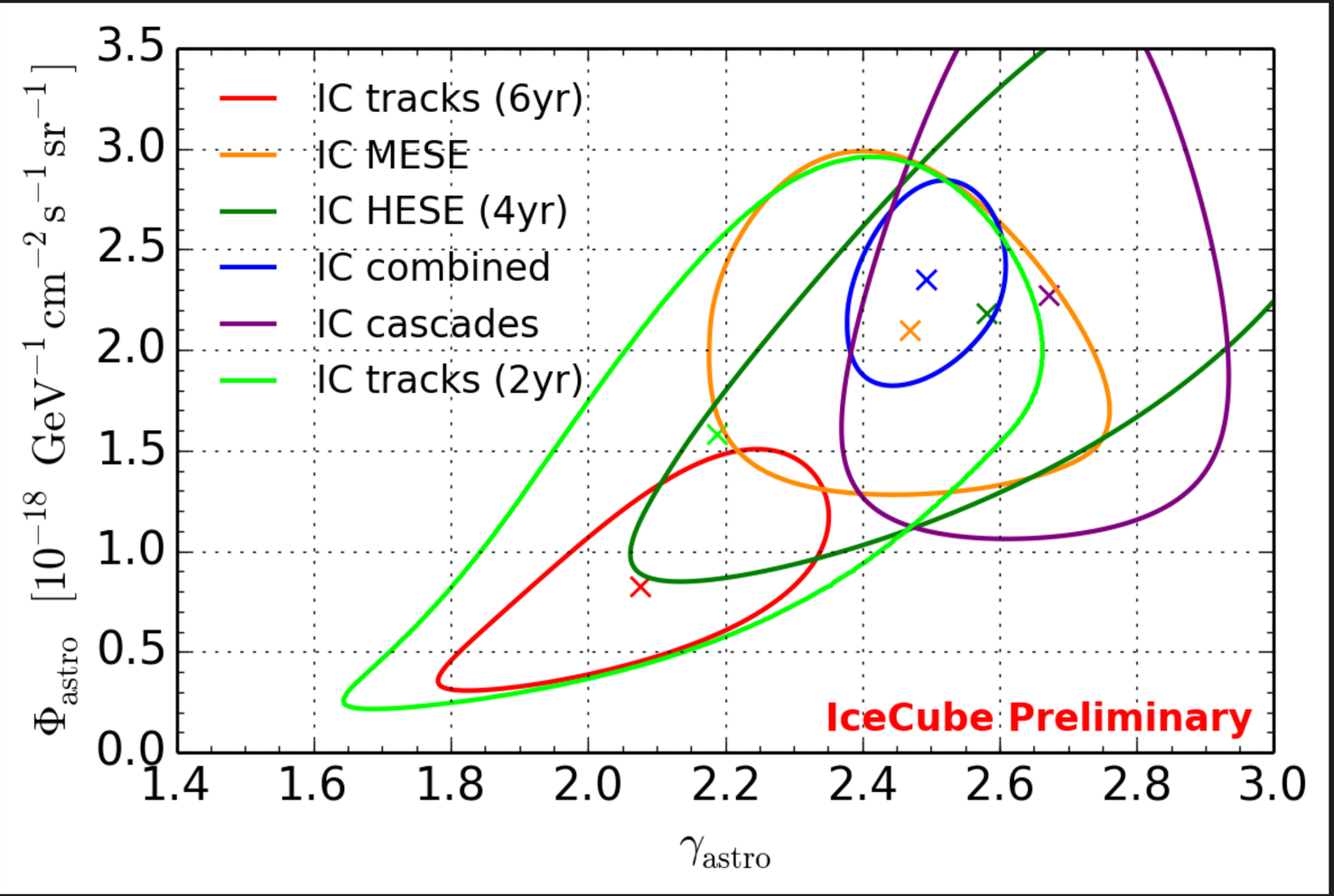


SUMMARY OF VARIOUS ICECUBE DIFFUSE RESULTS

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)

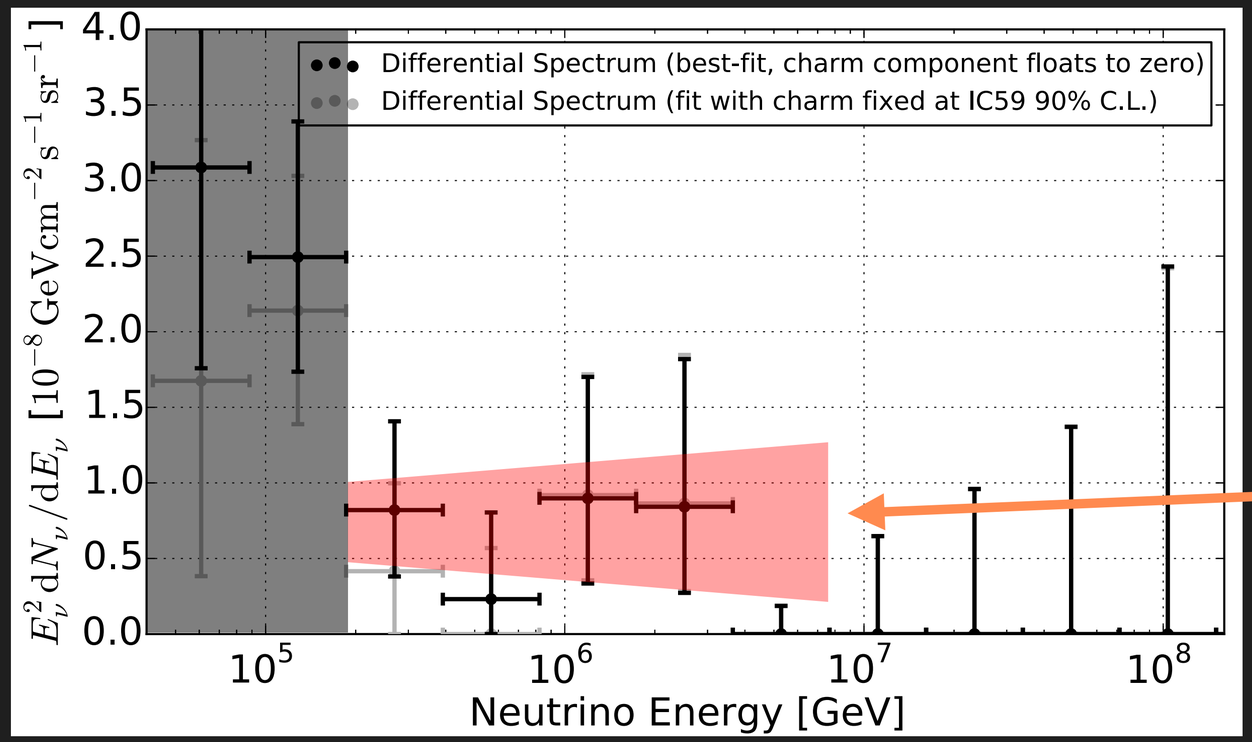
PoS(ICRC2015)1109
(cascades)

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

COMPARISON WITH STARTING EVENT RESULTS

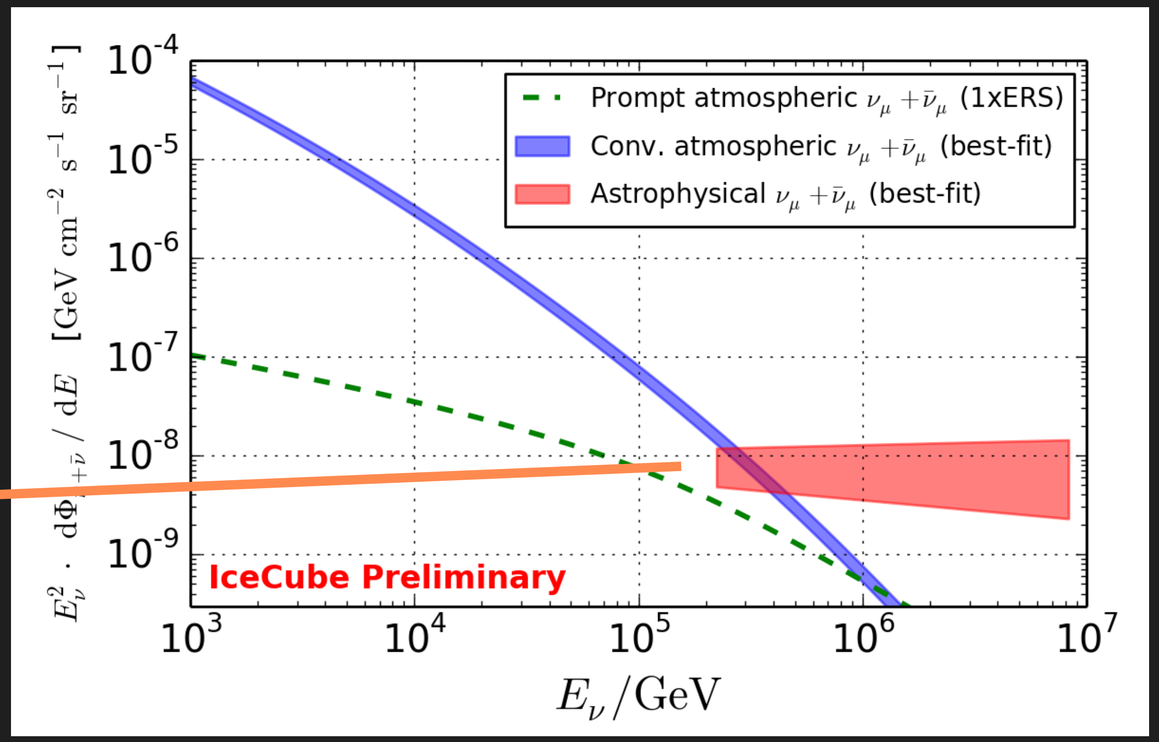
we start to see that simple power laws for the whole sky are probably not enough...

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

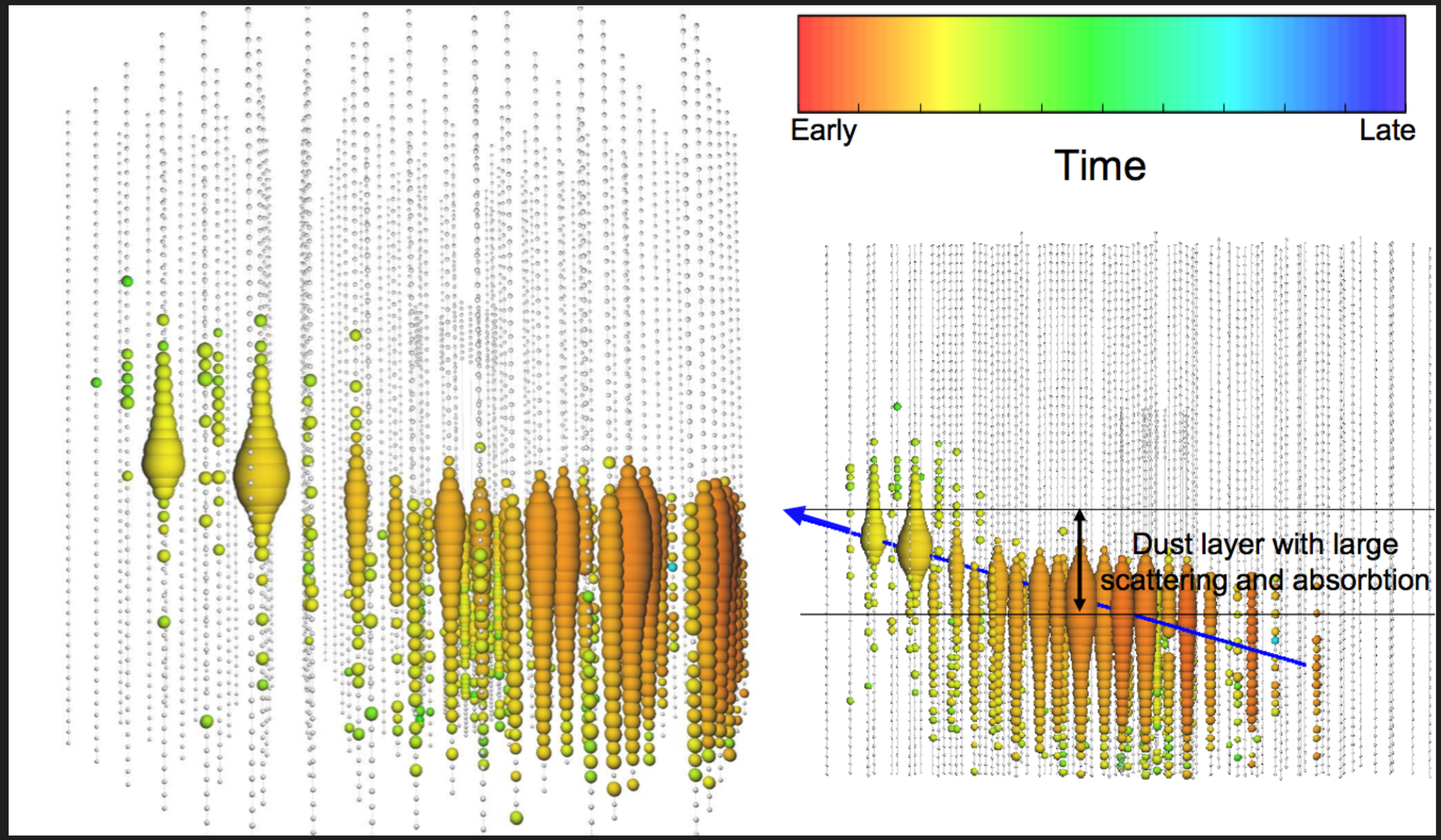
an interesting event in the six-year sample!

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

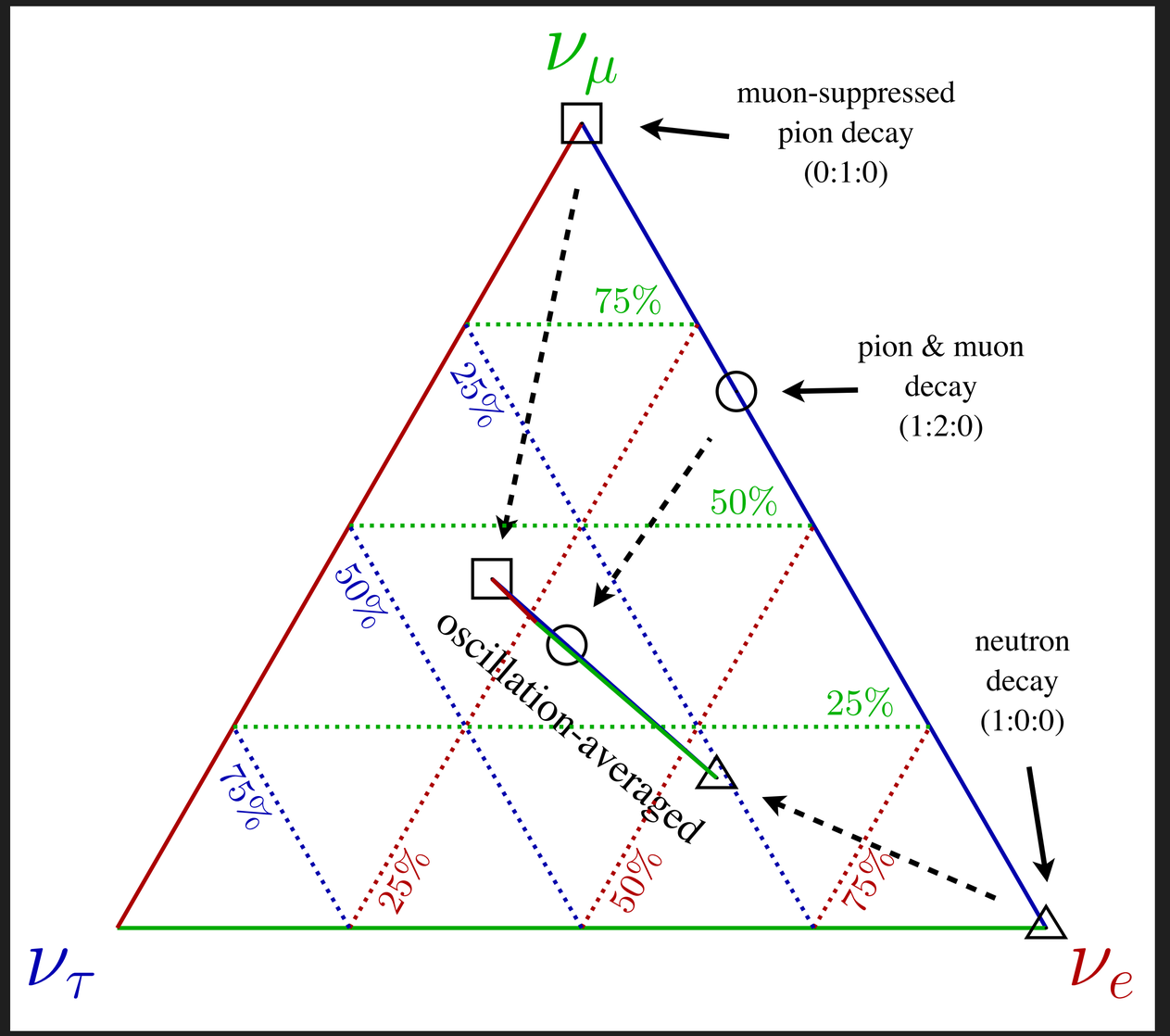


FLAVOR COMPOSITION

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

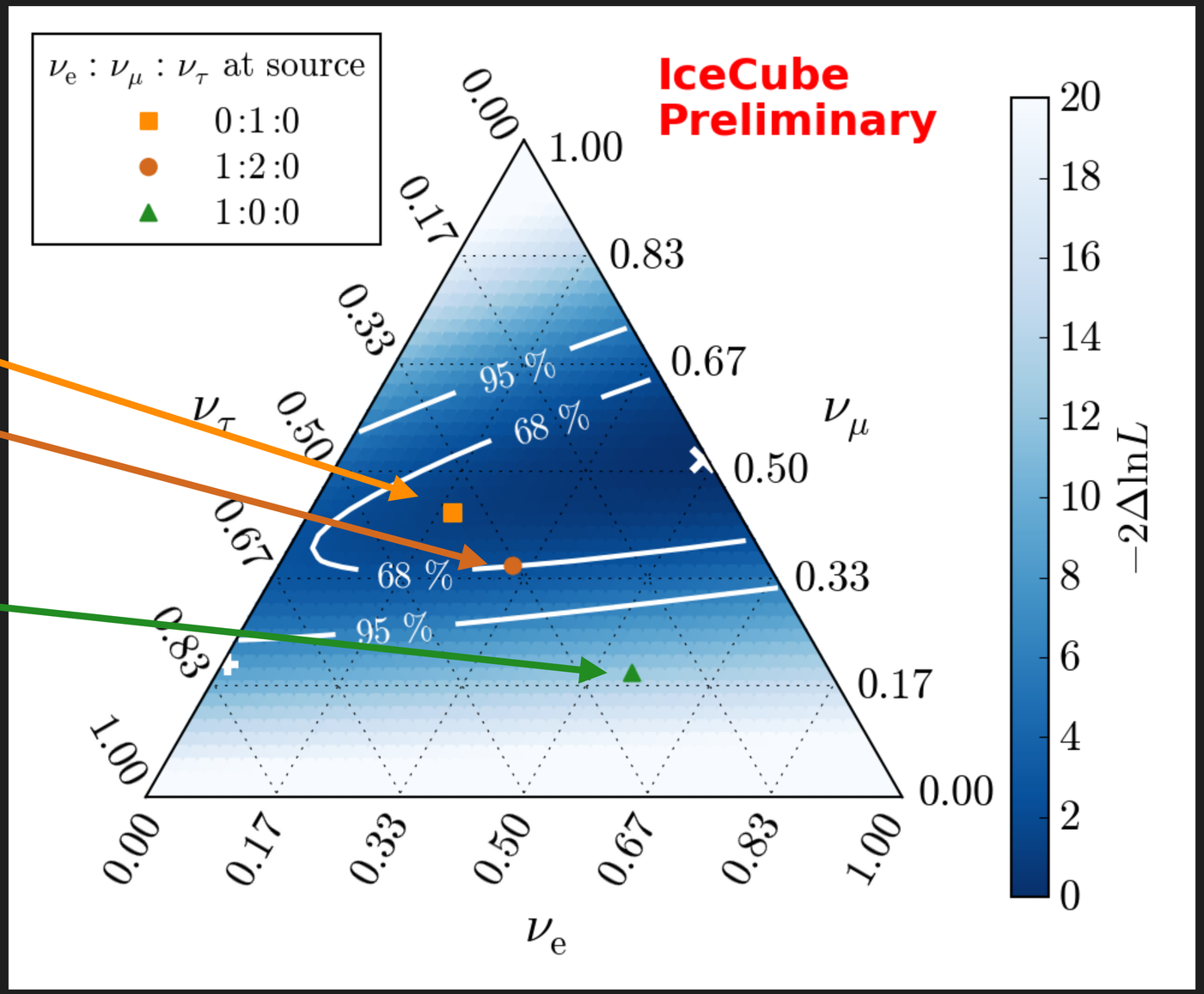
muon-damped (0:1:0)

pion decay (1:2:0)

→ compatible

neutron decay (1:0:0)

→ excluded at 3.7σ

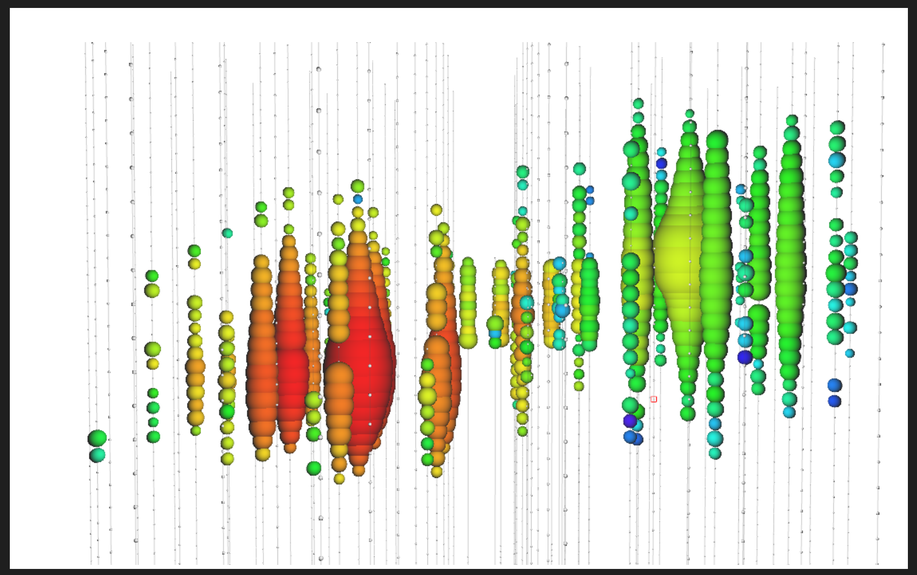


ApJ 809, 98 (2015)/ PoS(ICRC2015)1066

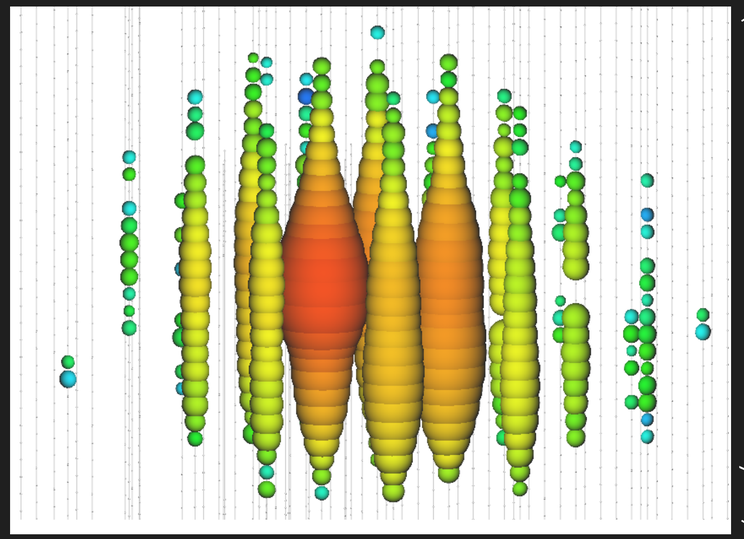
TAU NEUTRINOS

should see the first taus soon

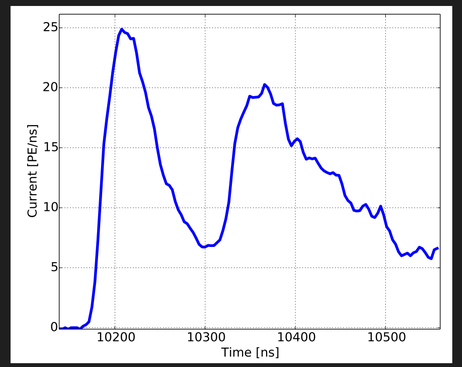
should be able to identify a “double-bang” signature above ~PeV - not observed yet!

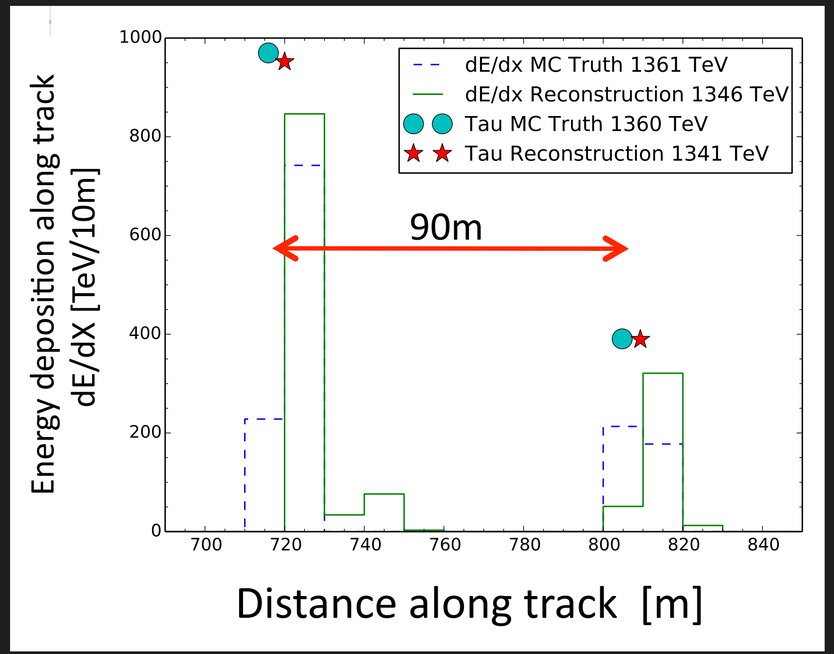


event with longer decay length



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





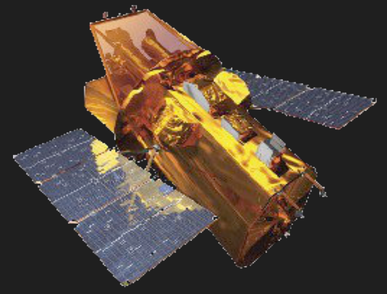
at lower energies identification is more challenging - IceCube just set new limits!

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/…

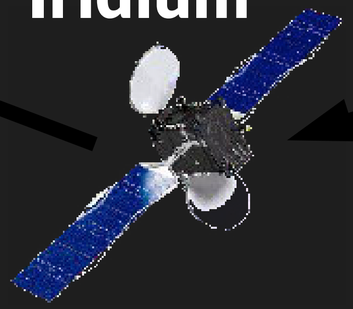
ν

IceCube

working on extending this effort significantly!

"The North"

Iridium



Veritas/
H.E.S.S./
MAGIC/…

PoS(ICRC2015)1069

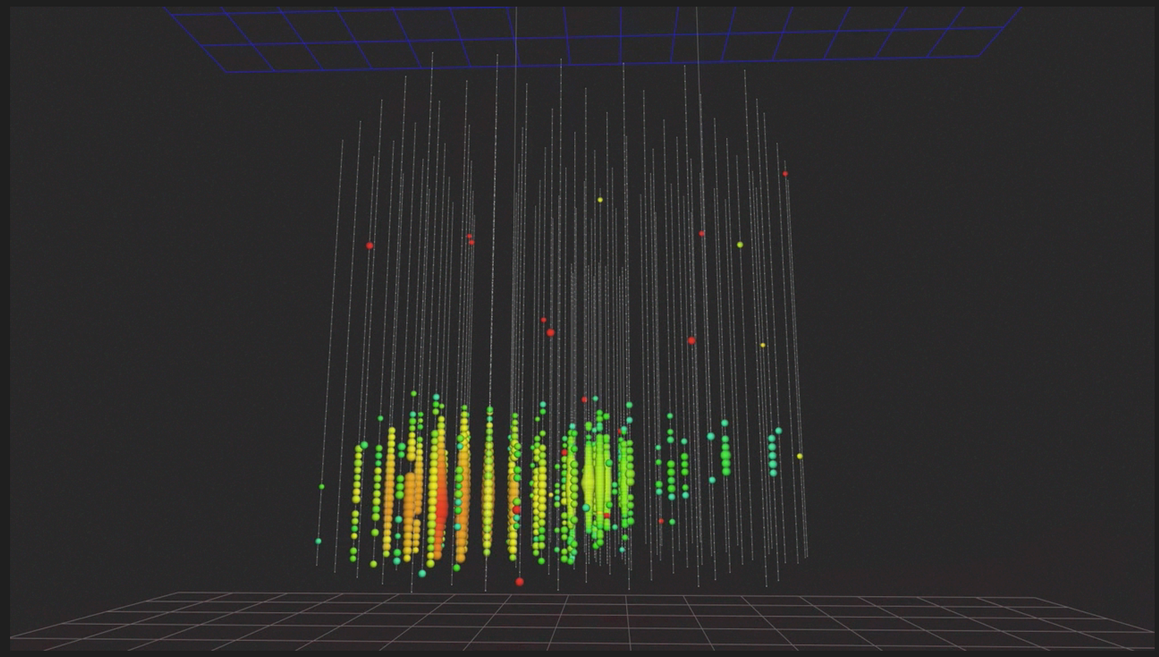
HIGH-ENERGY EVENTS NOW PUBLIC ALERTS!

We send our high-energy events in real-time as public GCN alerts now!


```
TITLE:            GCN/AMON NOTICE
NOTICE_DATE:      Wed 27 Apr 16 23:24:24 UT
NOTICE_TYPE:      AMON ICECUBE HESE
RUN_NUM:          127853
EVENT_NUM:        67093193
SRC_RA:           240.5683d {+16h 02m 16s} (J2000),
                  240.7644d {+16h 03m 03s} (current),
                  239.9678d {+15h 59m 52s} (1950)
SRC_DEC:           +9.3417d {+09d 20' 30"} (J2000),
                   +9.2972d {+09d 17' 50"} (current),
                   +9.4798d {+09d 28' 47"} (1950)
SRC_ERROR:        35.99 [arcmin radius, stat+sys, 90% containment]
SRC_ERROR50:      0.00 [arcmin radius, stat+sys, 50% containment]
DISCOVERY_DATE:   17505 TJD;   118 DOY;   16/04/27 (yy/mm/dd)
DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
SUN_POSTN:         35.75d {+02h 23m 00s}  +14.21d {+14d 12' 45"}
```

GCN notice for starting track sent Apr 27

We send **rough reconstructions first** and then **update them.**



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DISCOVERY_TIME:   21152 SOD {05:52:32.00} UT
REVISION:         2
N_EVENTS:         1 [number of neutrinos]
STREAM:           1
DELTA_T:          0.0000 [sec]
SIGMA_T:          0.0000 [sec]
FALSE_POS:        0.0000e+00 [s^-1 sr^-1]
PVALUE:           0.0000e+00 [dn]
CHARGE:           18883.62 [pe]
SIGNAL_TRACKNESS: 0.92 [dn]
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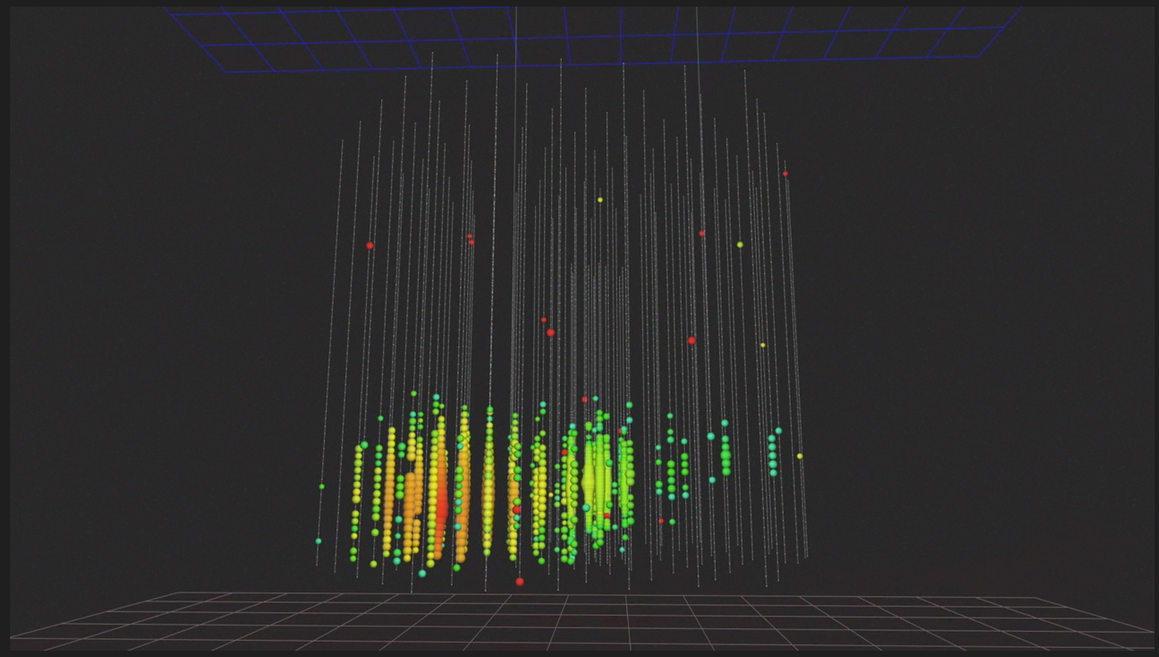
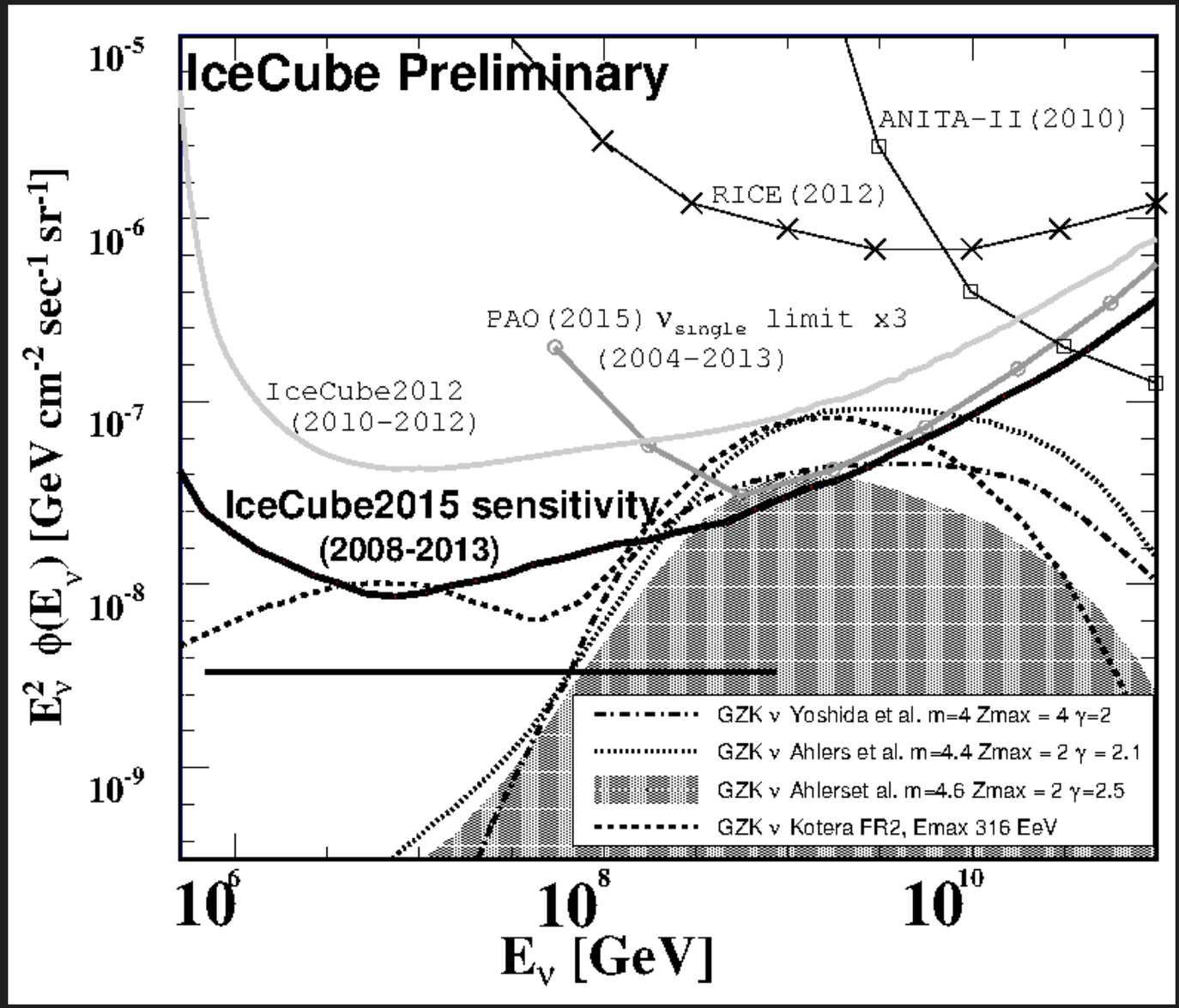


COSMOGENIC (GZK) NEUTRINOS

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

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!

BACKUP

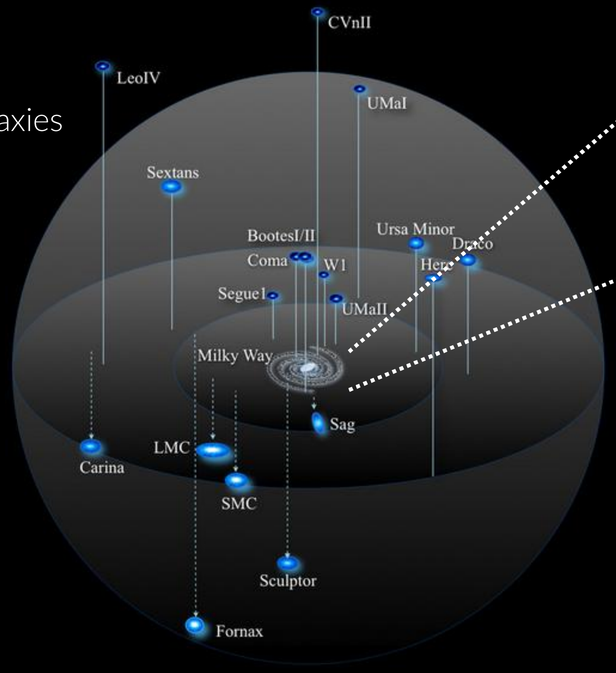
DARK MATTER

(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

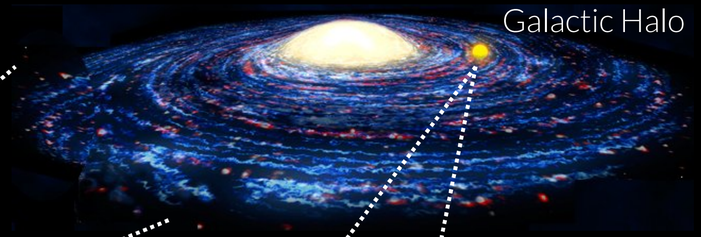
Clusters of Galaxies



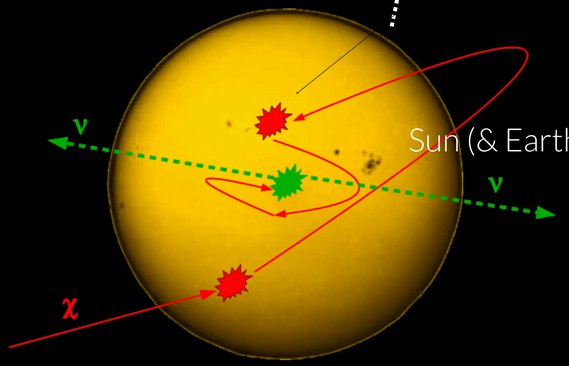
Dwarf spheroidal galaxies

Galactic Center

Galactic Halo

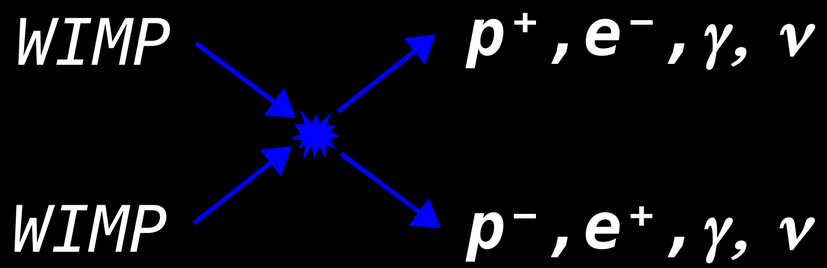


accumulate due to WIMP-proton elastic scattering



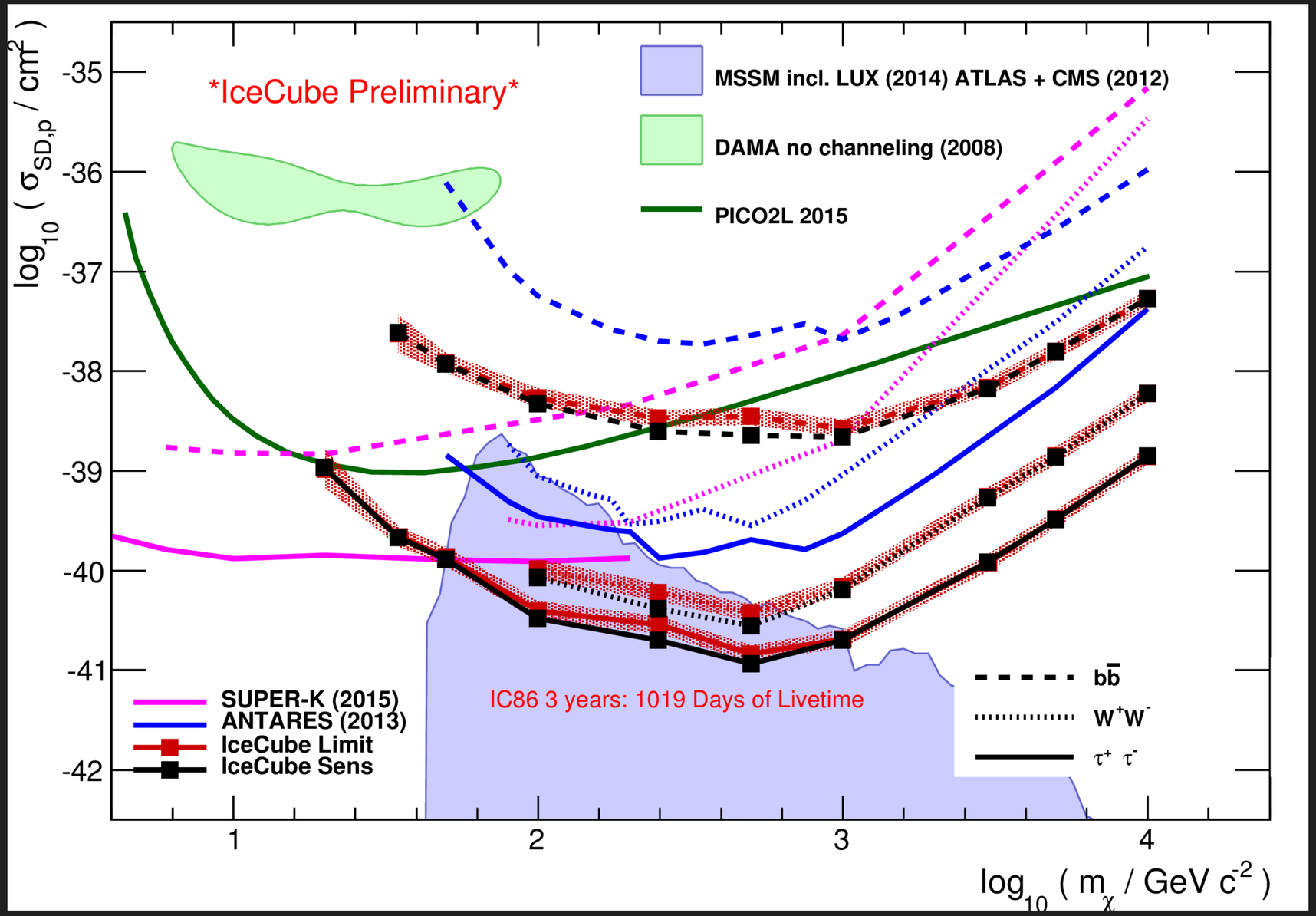
Sun (& Earth)

MSSM - neutralino



SOLAR WIMP RESULTS - ICECUBE 3 YEARS

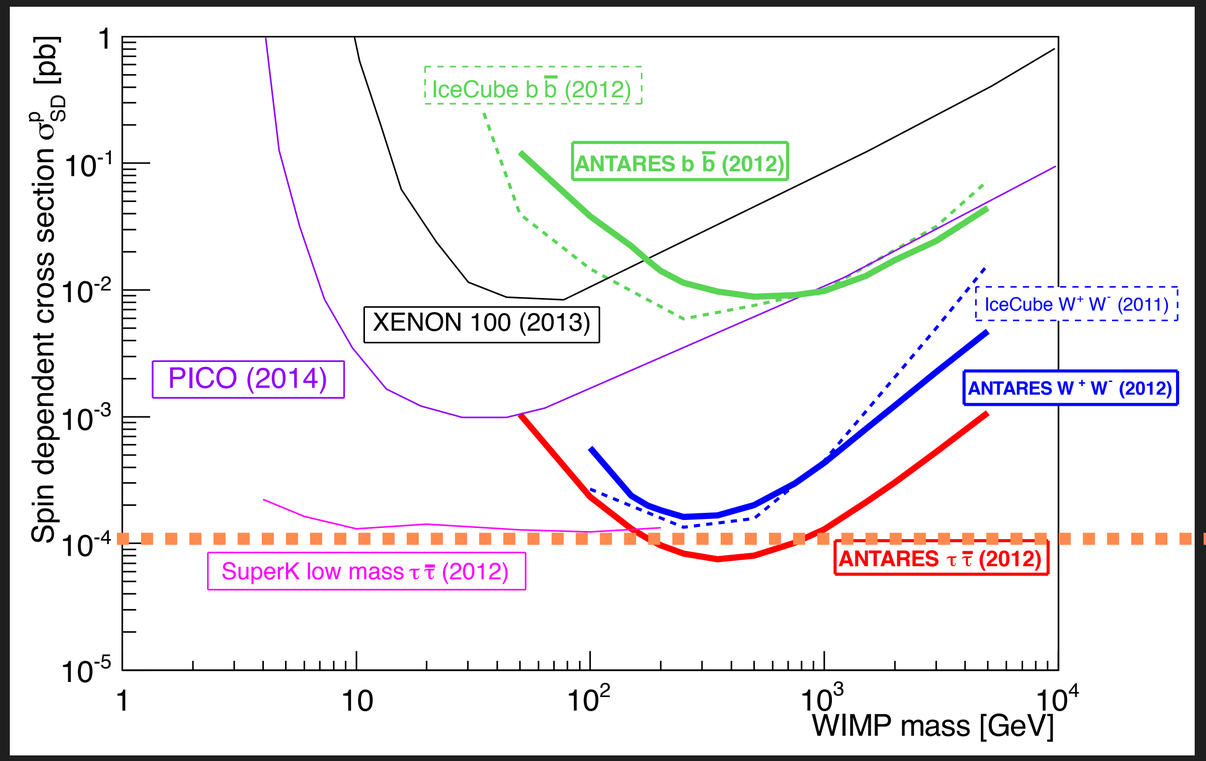
example of one channel where IceCube sets competitive limits



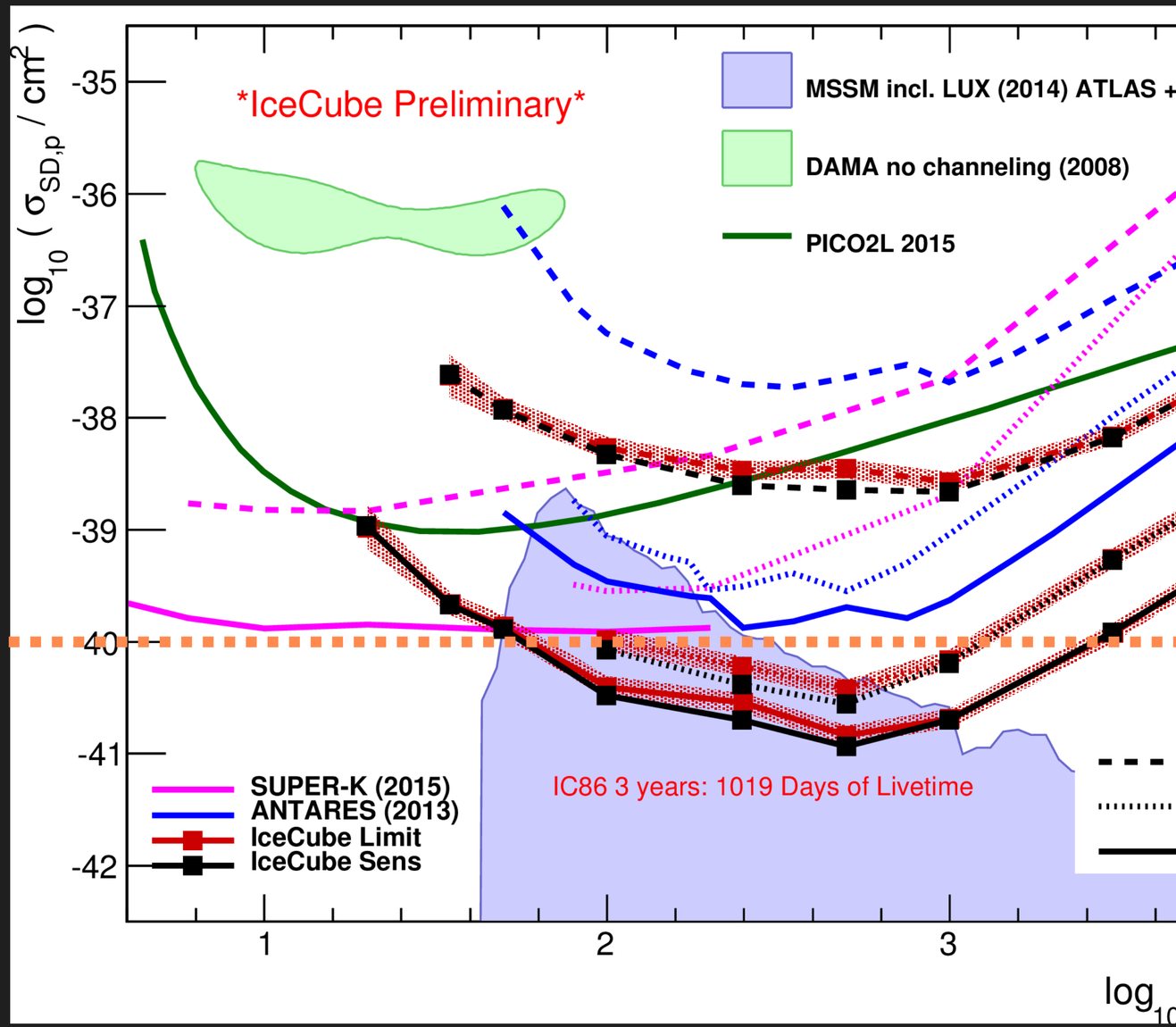
SOLAR WIMP RESULTS - ANTARES

compared to similar limits from ANTARES

ANTARES



PoS(ICRC2015)024



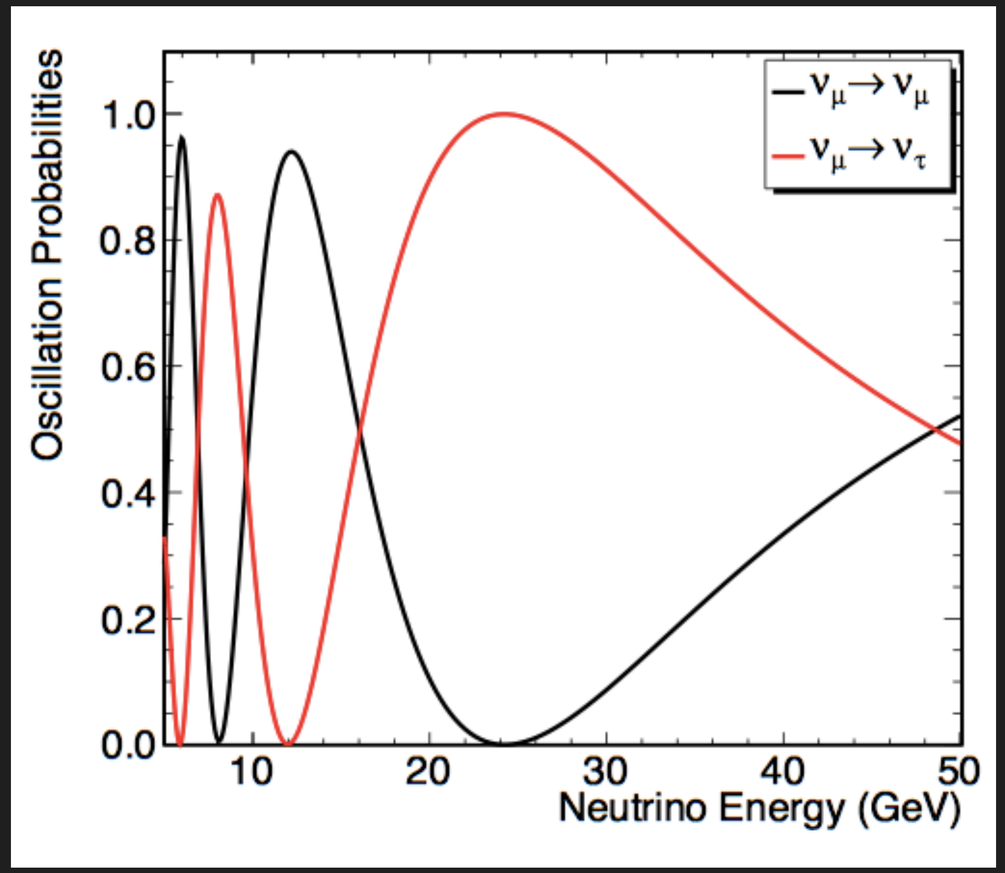
NEUTRINO OSCILLATIONS

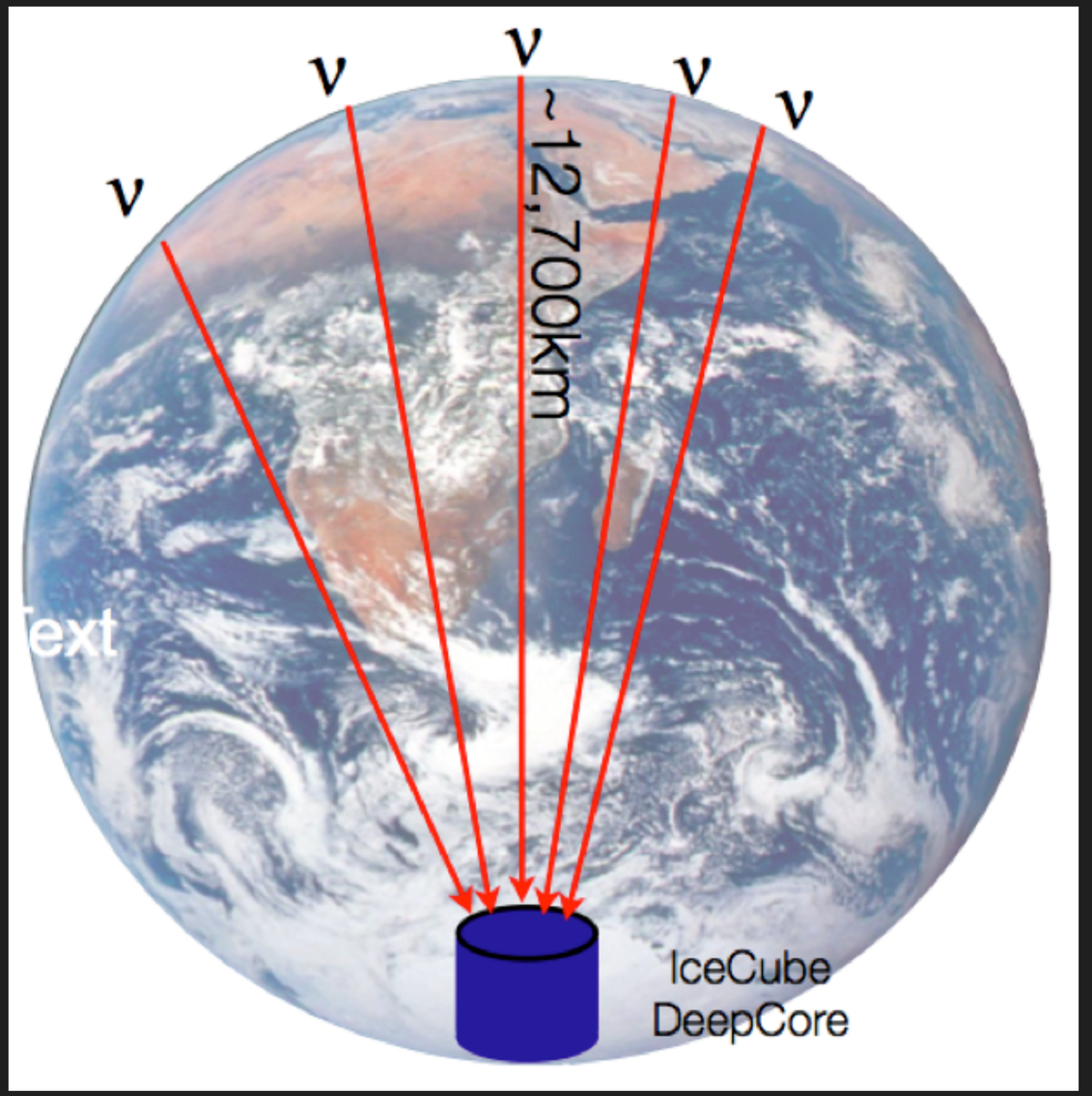
Using the atmospheric neutrino
“background” to study neutrino physics

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





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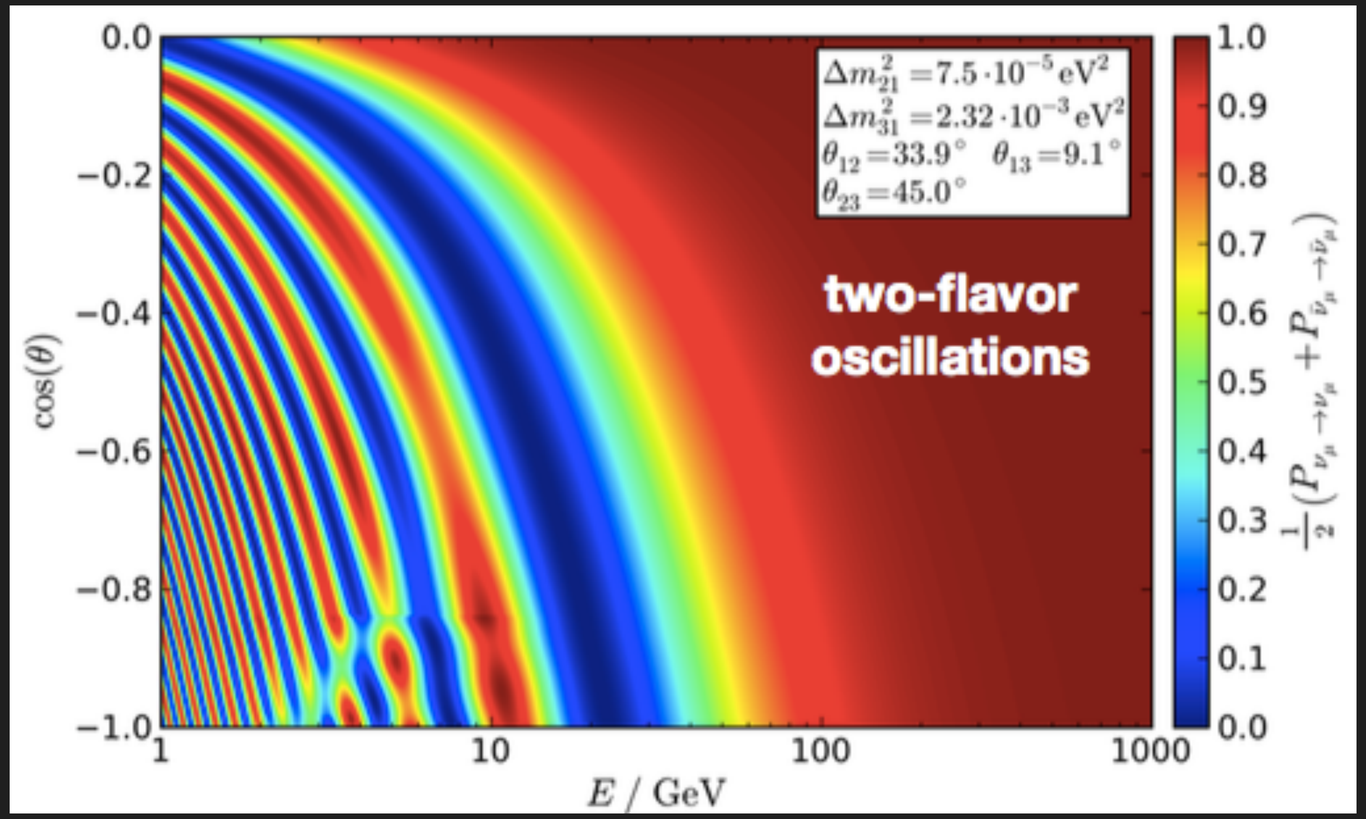
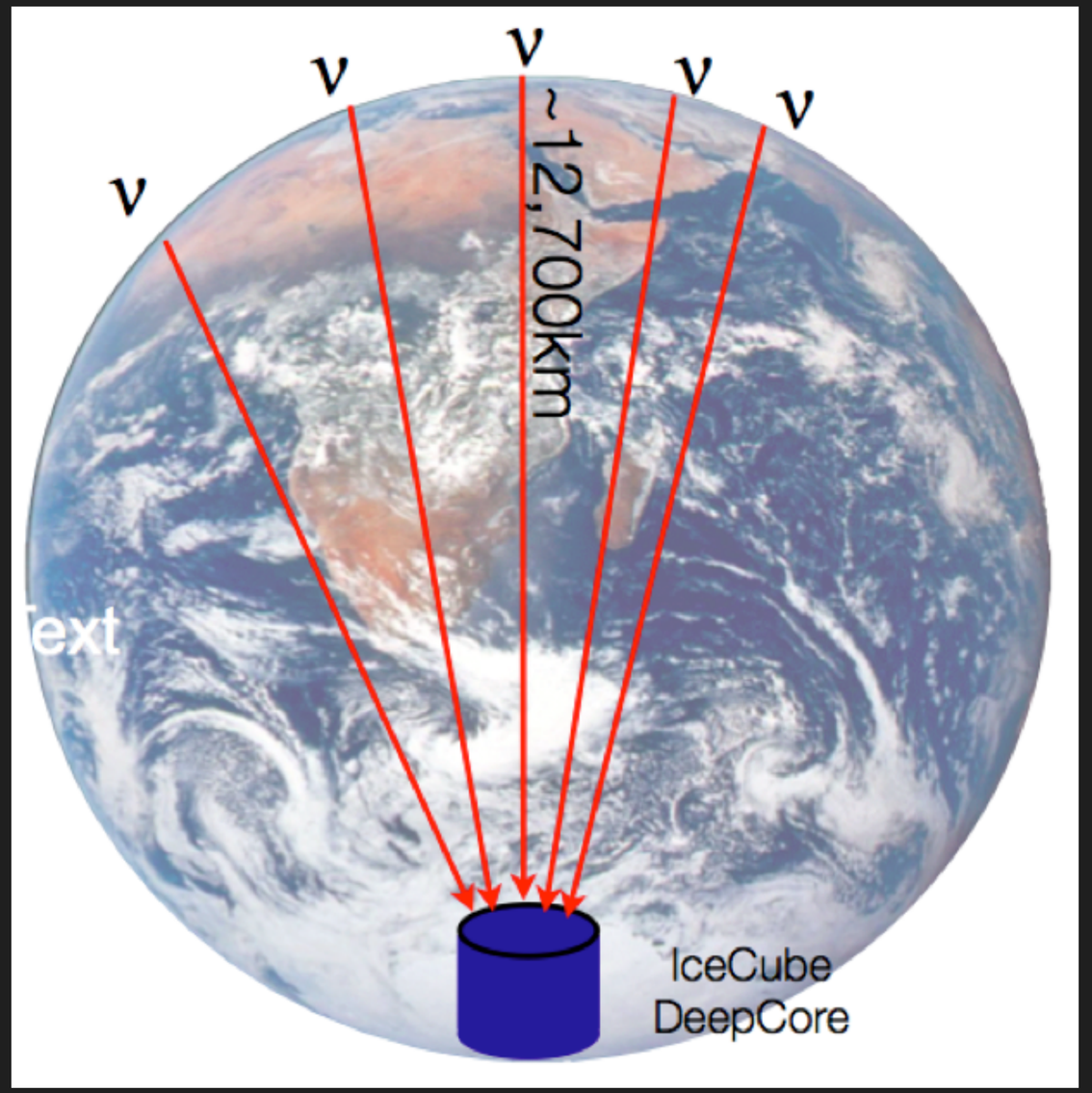
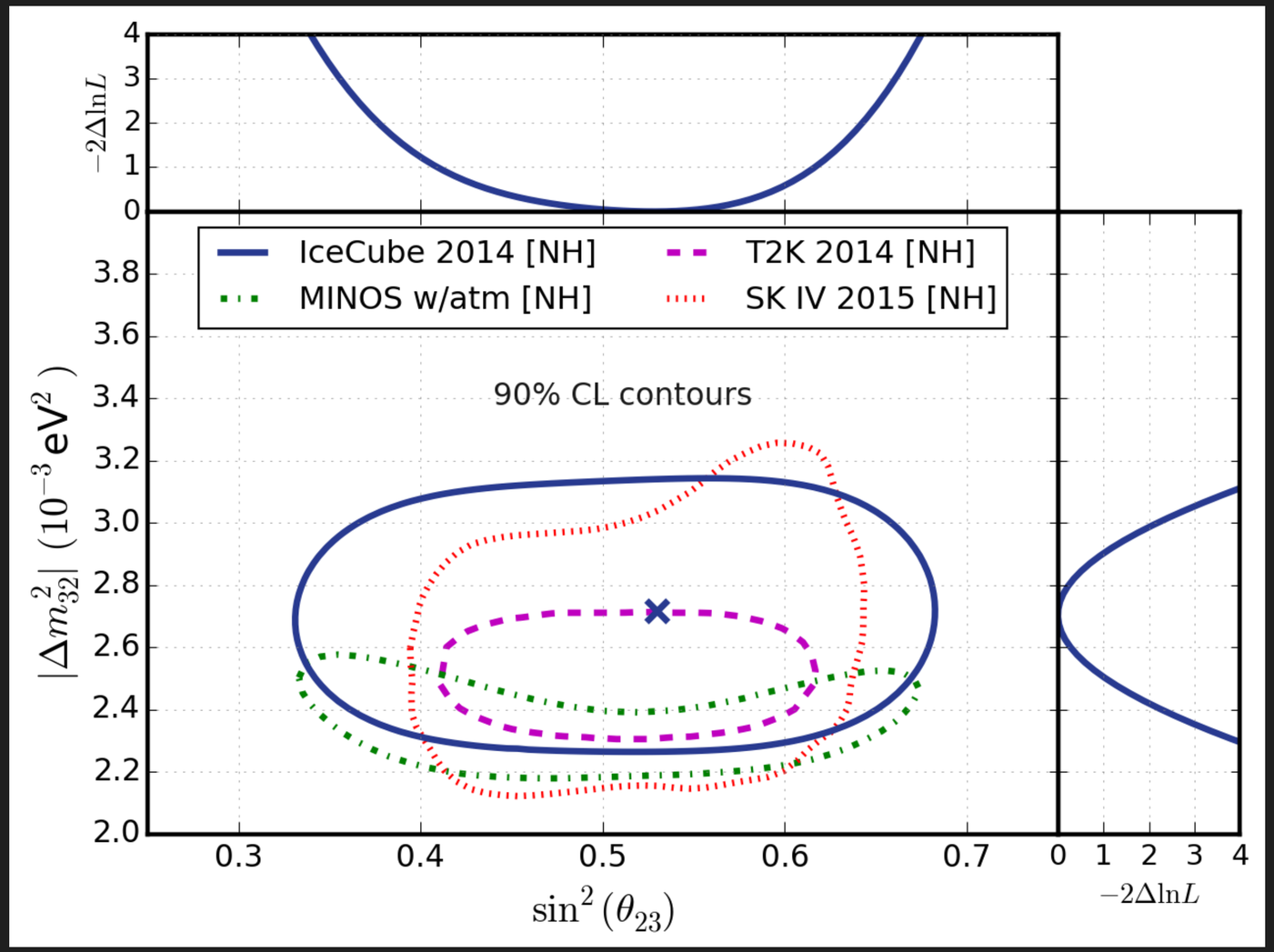
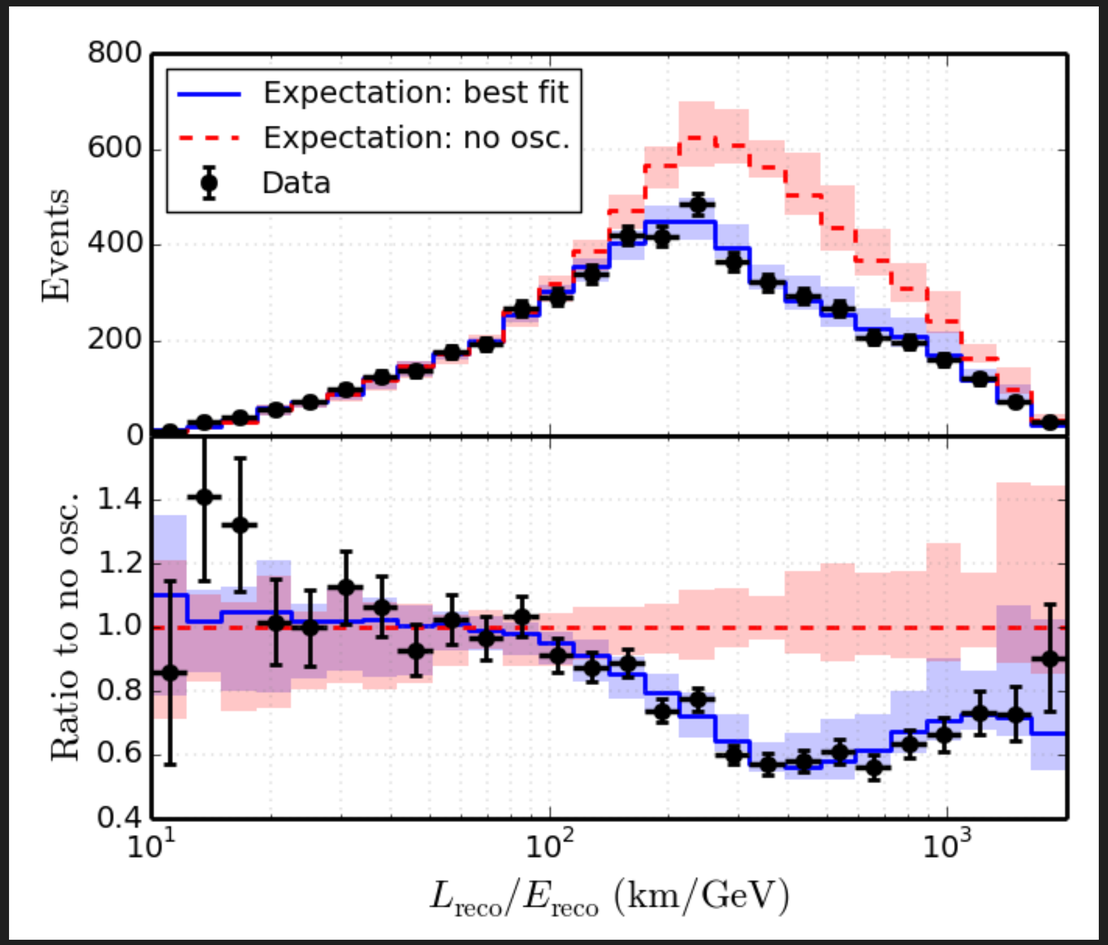




3-YEAR MUON DISAPPEARANCE STUDY

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





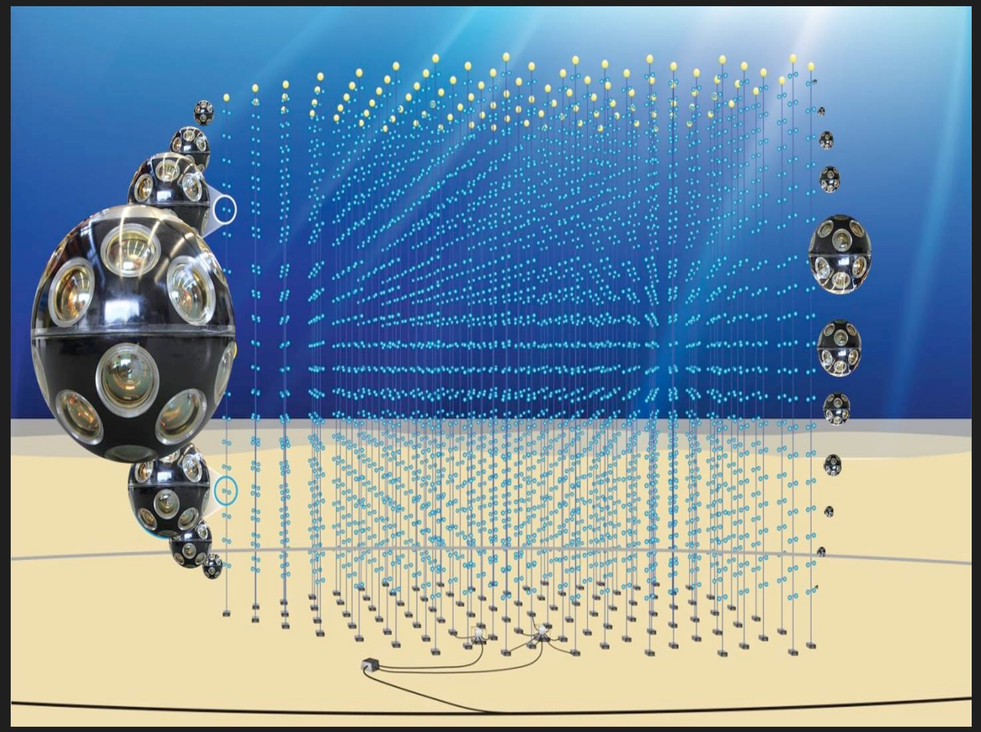
PRD 91, 072004 (2015)

THE FUTURE

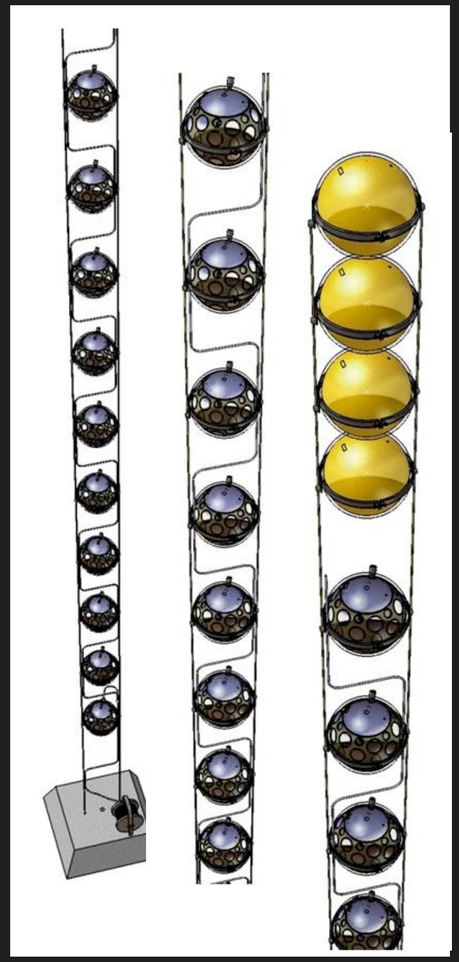
Extending the sensitivity to higher energies, new hemispheres

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

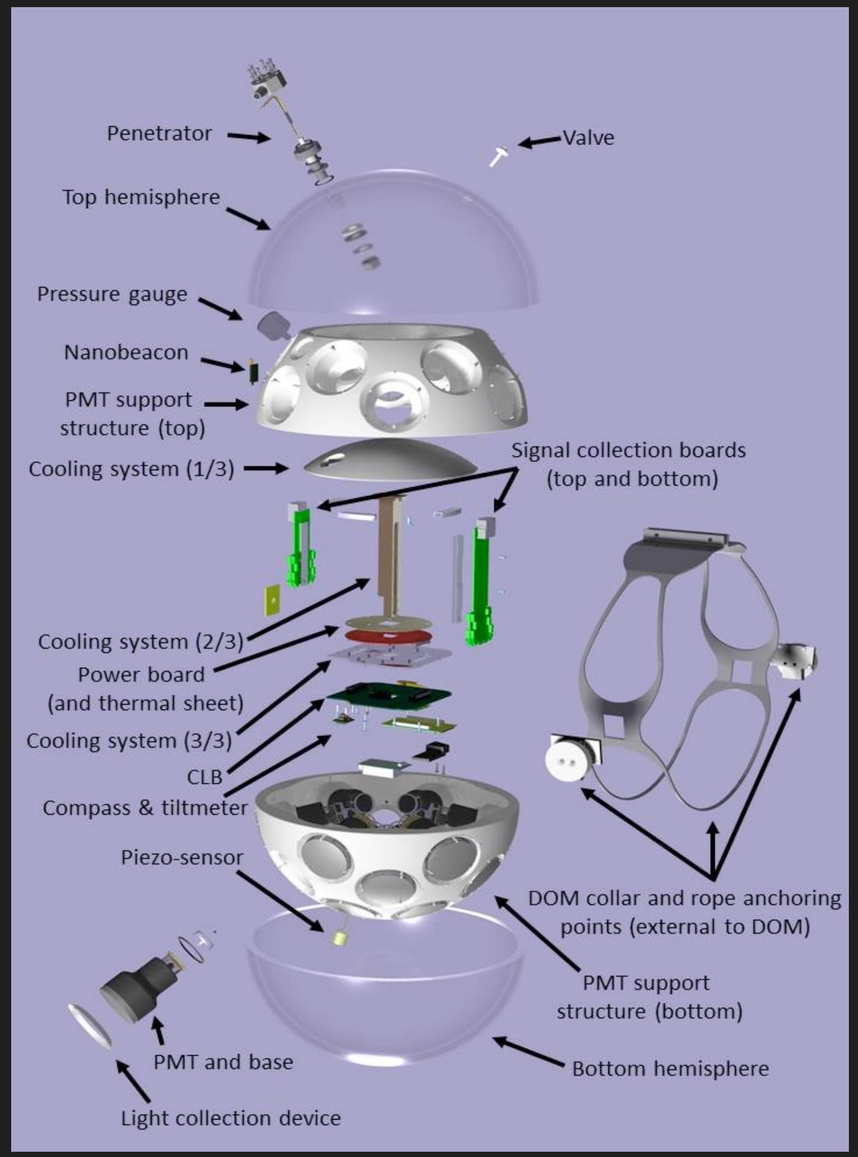
Low power
< 10 W / DOM

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

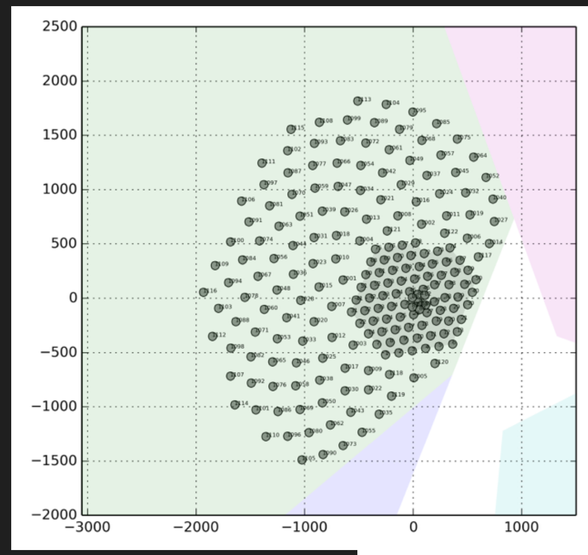
first string has been deployed!

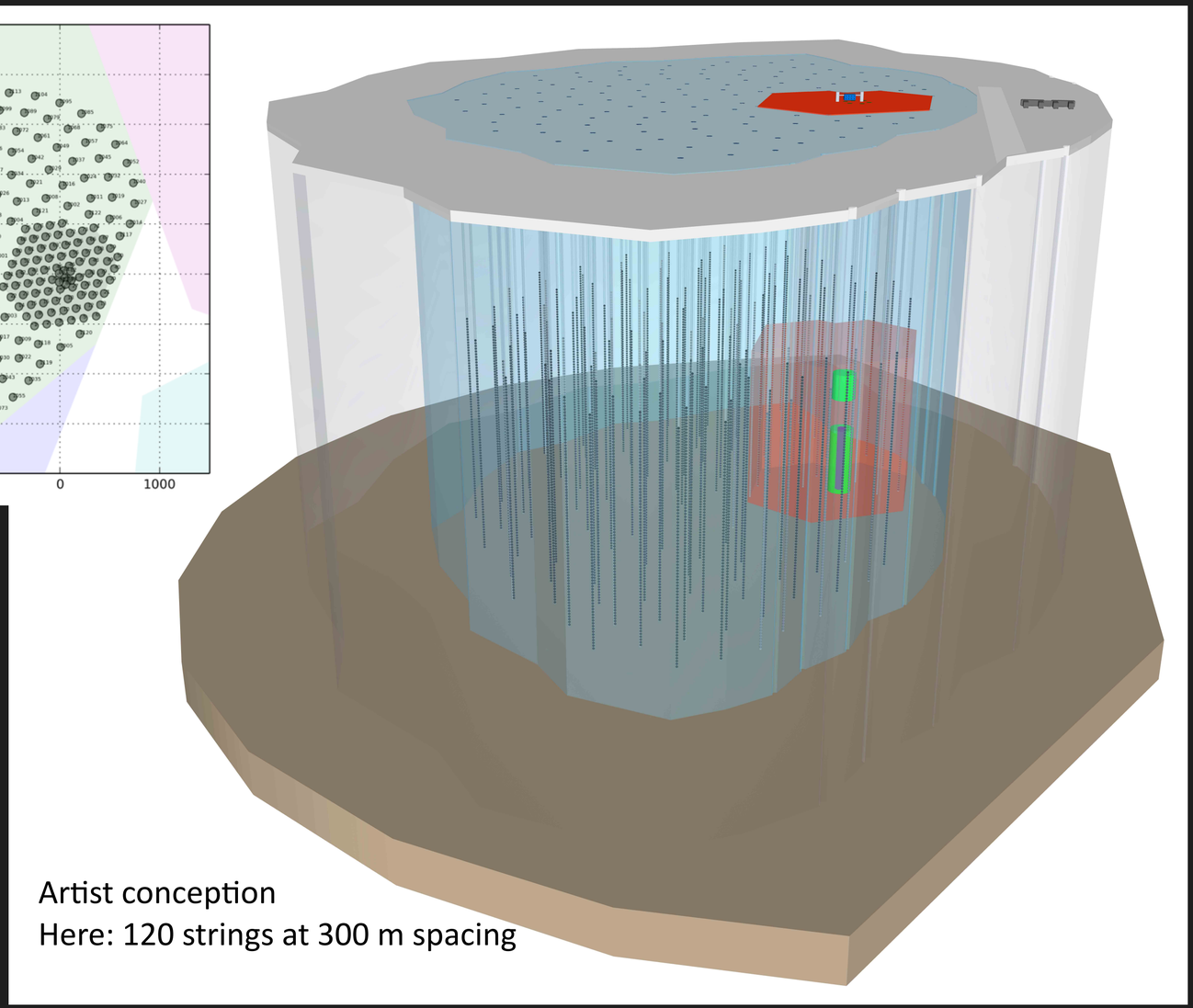
ICECUBE-GEN2: HIGH-ENERGY

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

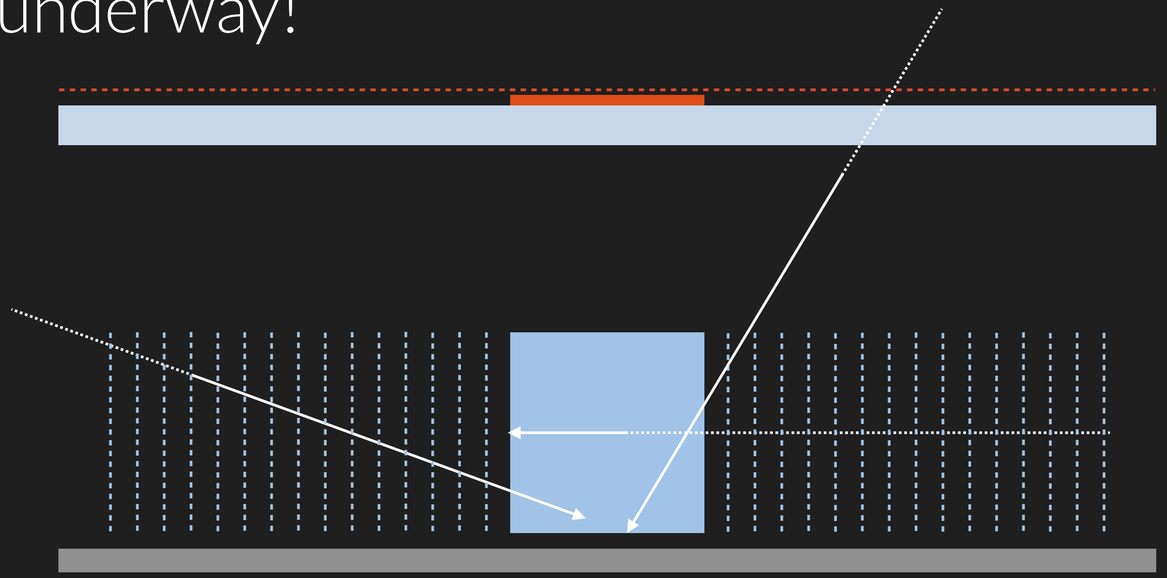
ICECUBE-GEN2: SURFACE VETO

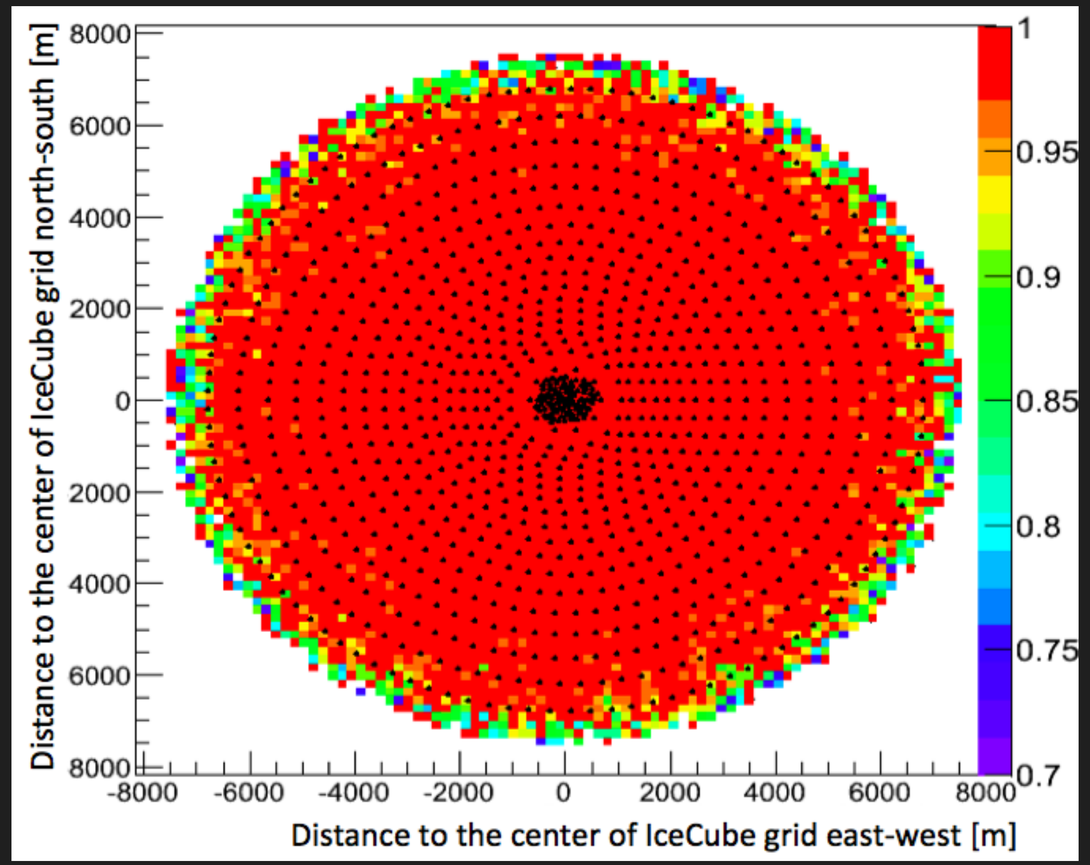
R&D for a surface array

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**

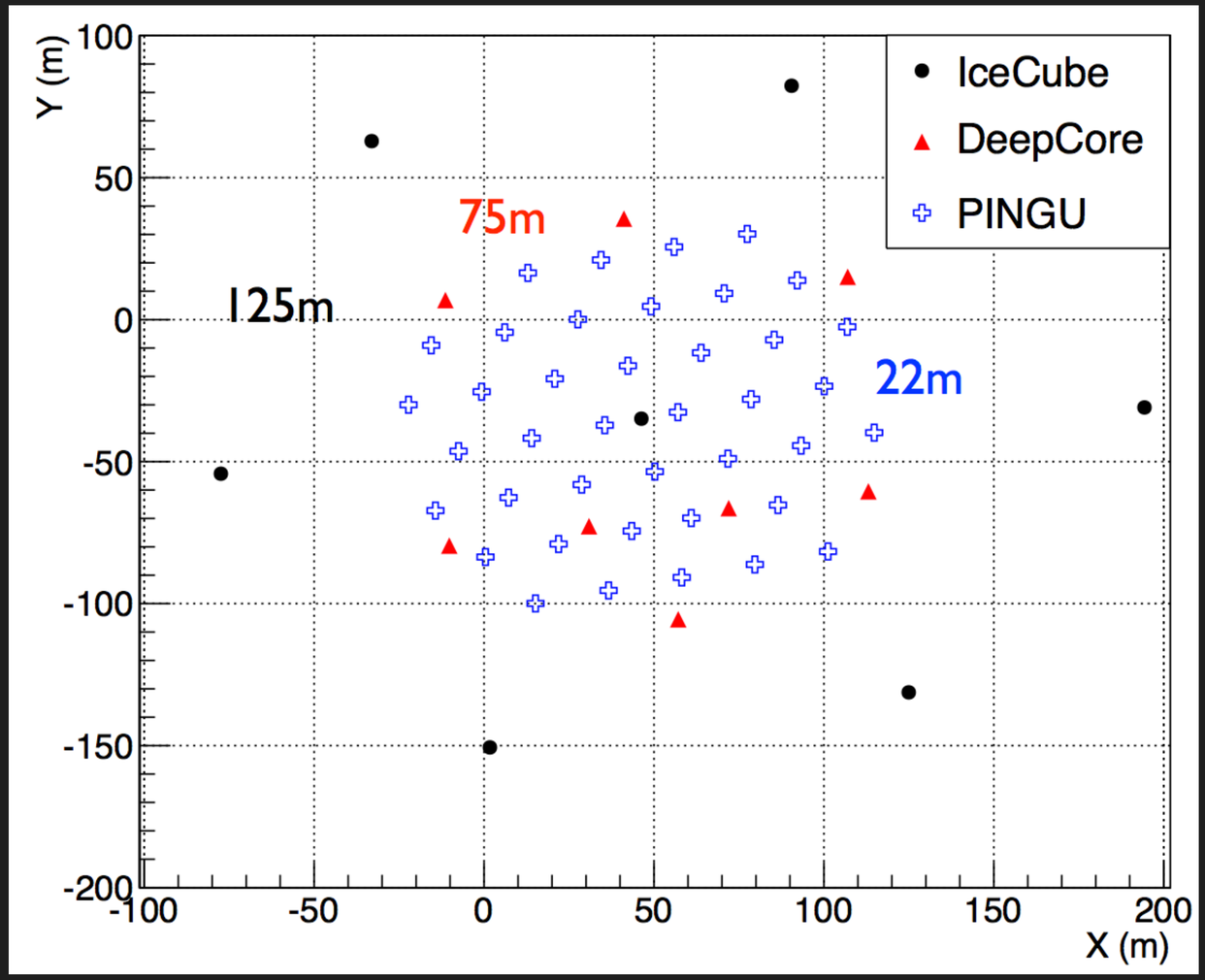
add **40** strings to IceCube/DeepCore

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



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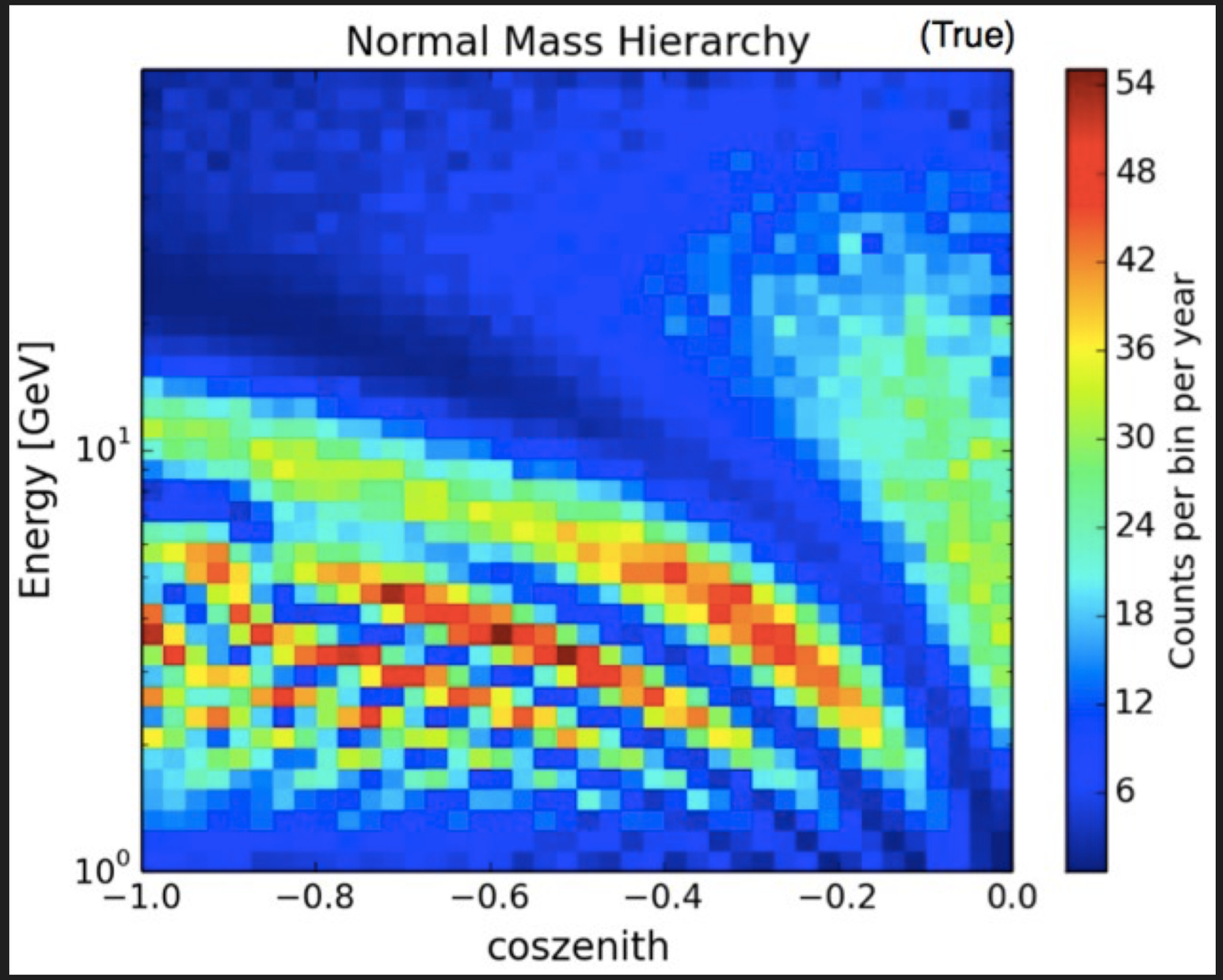

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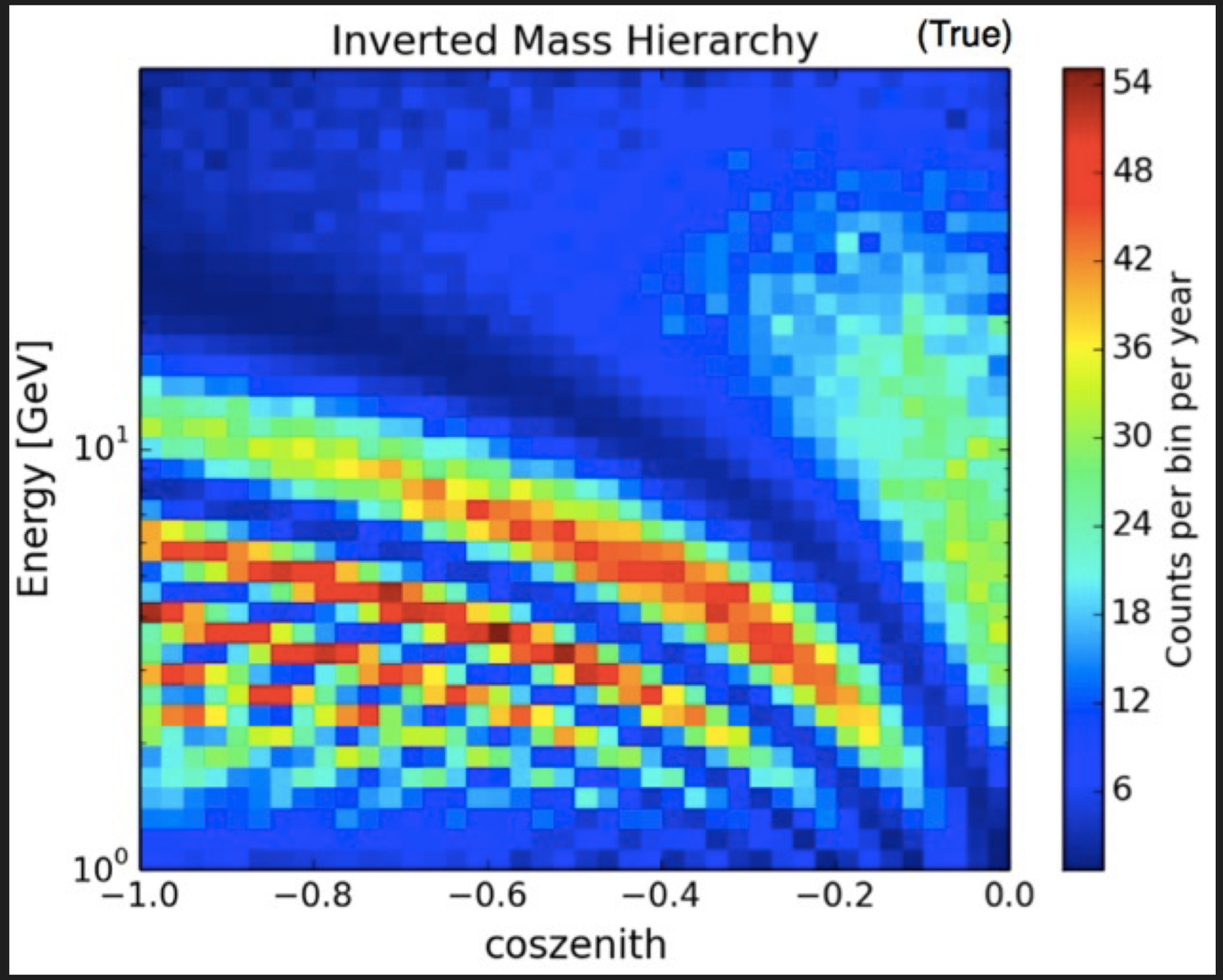
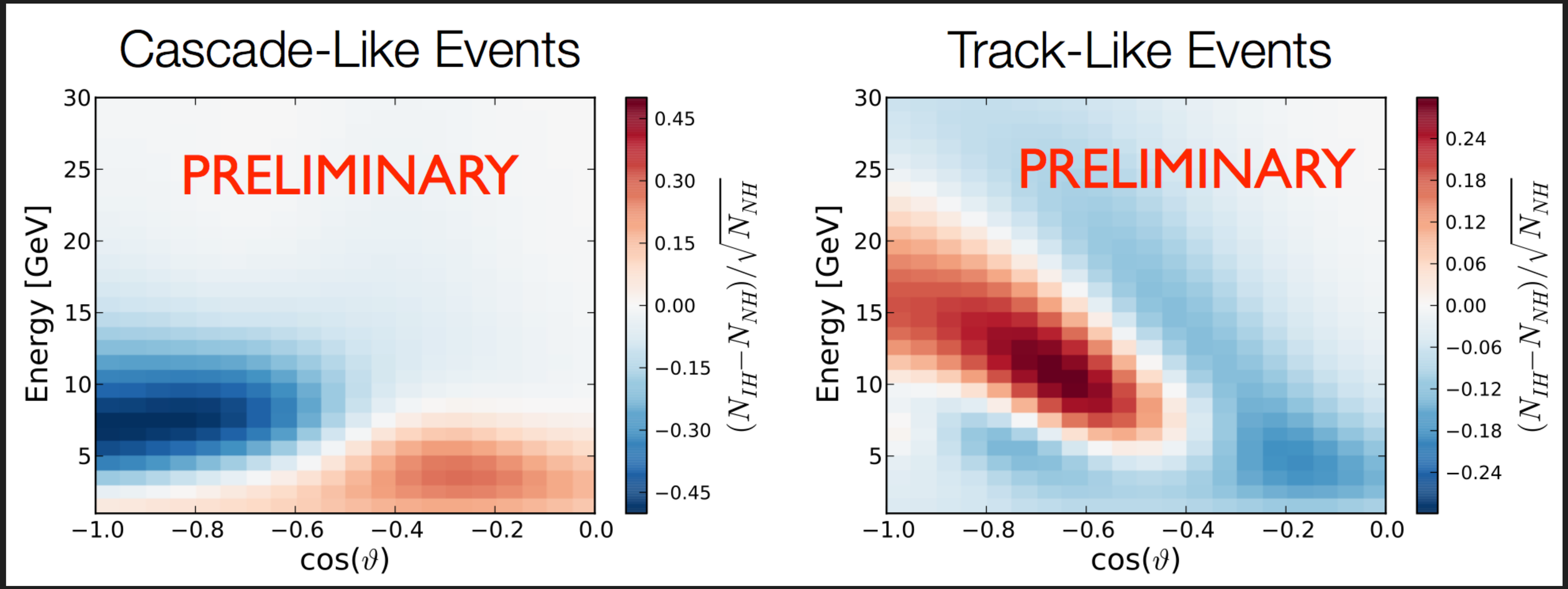


ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos



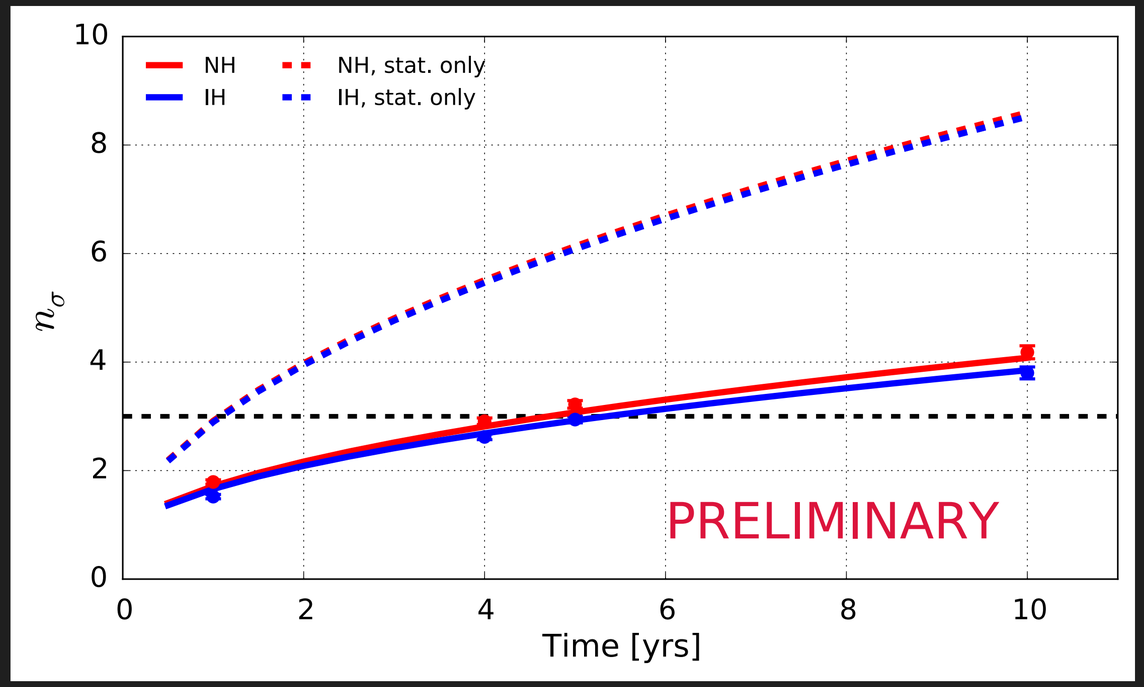
PINGU AND ORCA

measuring the mass hierarchy using atmospheric neutrinos

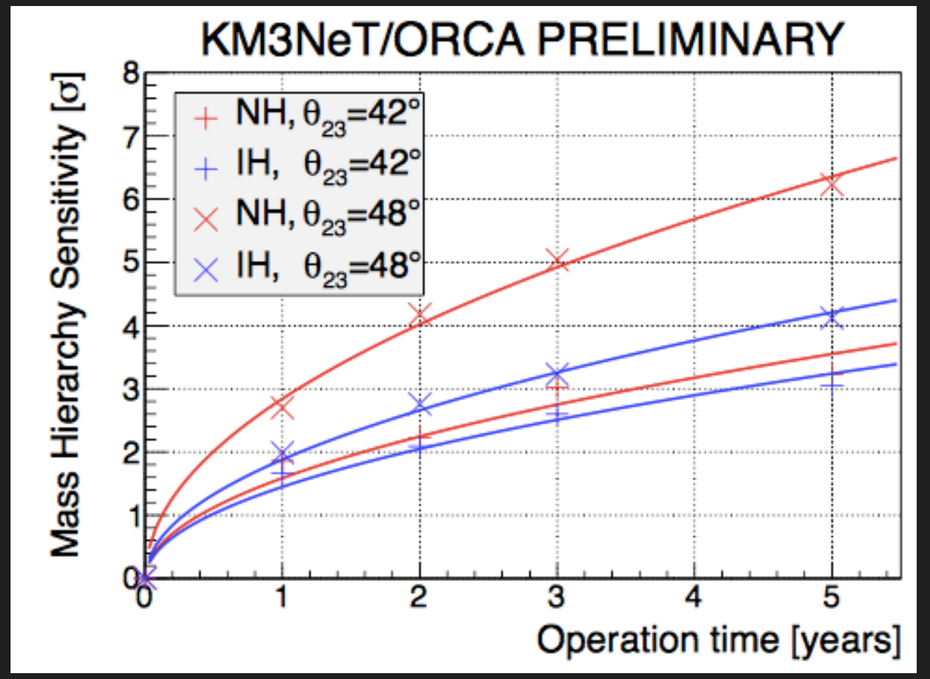
very similar concepts, ORCA in water, PINGU in ice

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

PINGU

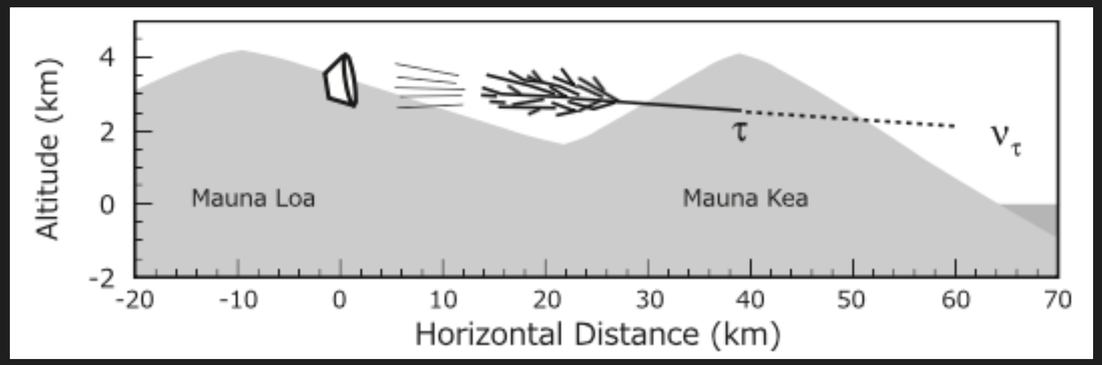


ORCA



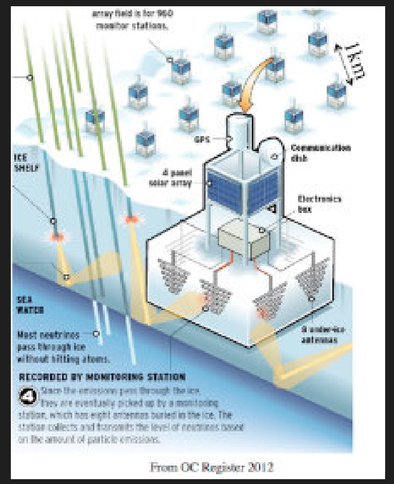
MORE DETECTORS / METHODS

non-water detectors and radio detectors

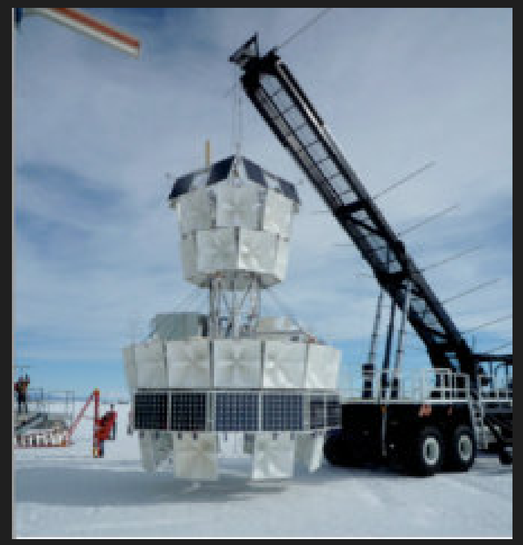


earth skimming tau Cherenkov shower detection (arXiv:1202.5656) - can be deployed on land!

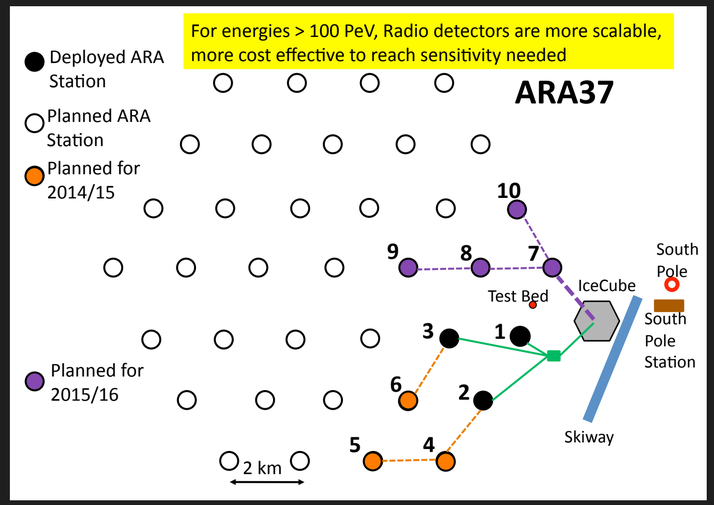
radio detectors for energy range above ~10 PeV (Askaryan effect)



ARIANNA



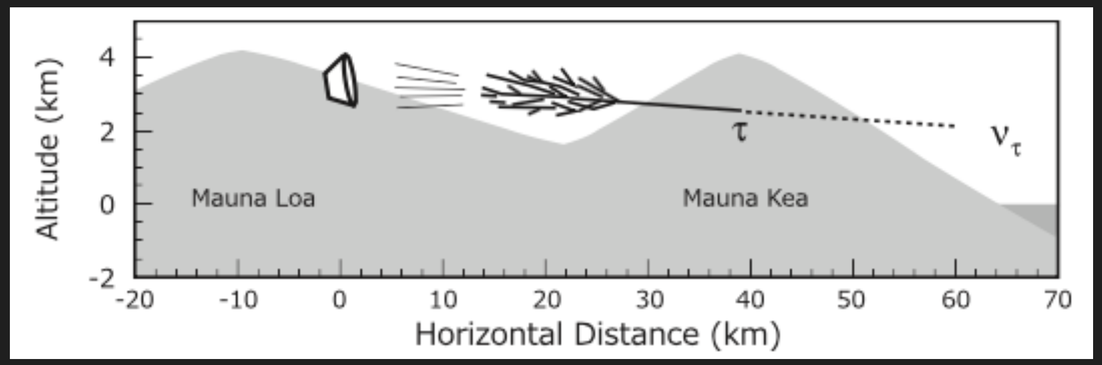
ANITA



ARA

MORE DETECTORS / METHODS

non-water detectors and radio detectors



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radio detectors for energy range