NEUTRINO ASTRONOMY

Claudio Kopper, University of Alberta

ICRC 2015

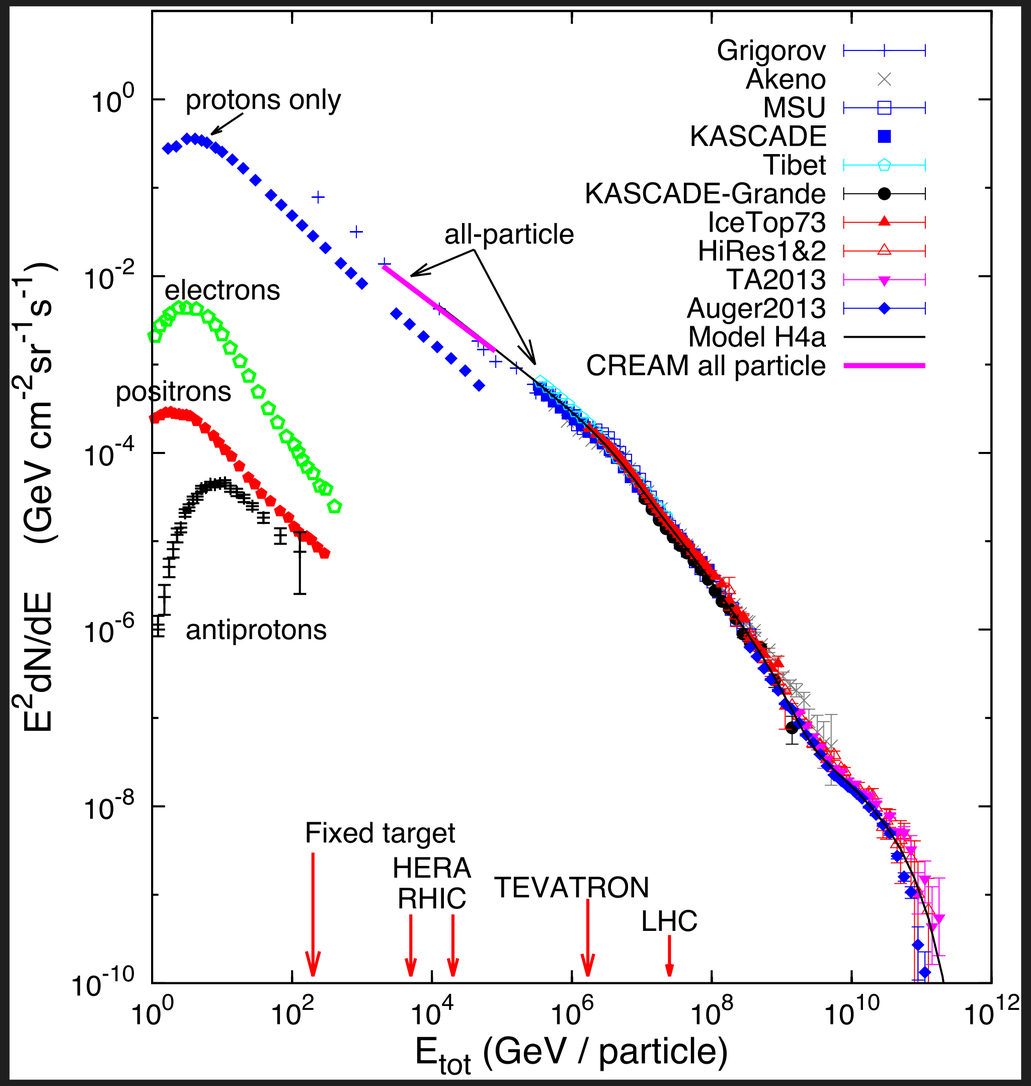
UNIVERSITY OF ALBERTA

COSMIC RAYS AND NEUTRINOS

Search for the sources of Cosmic Rays

COSMIC RAYS

where



COSMIC RAYS

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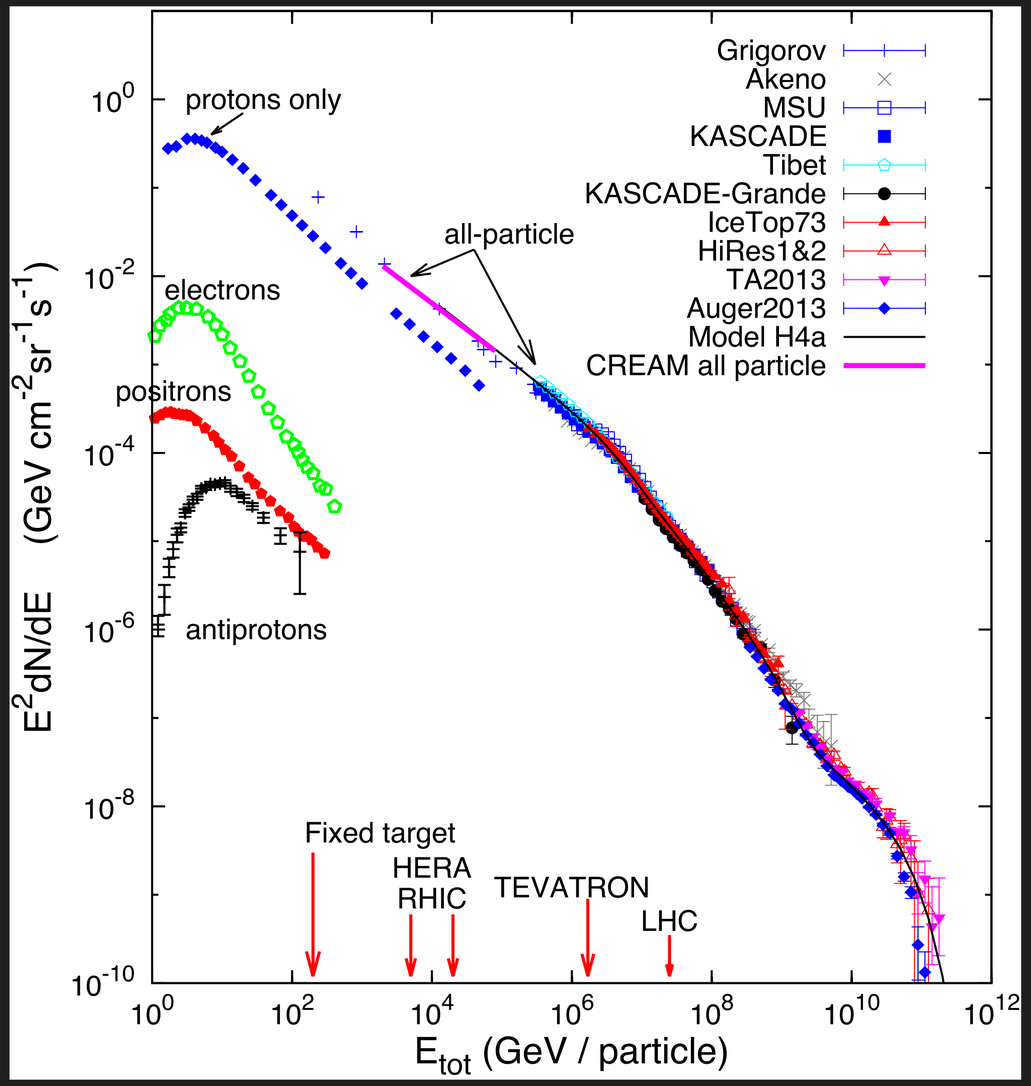
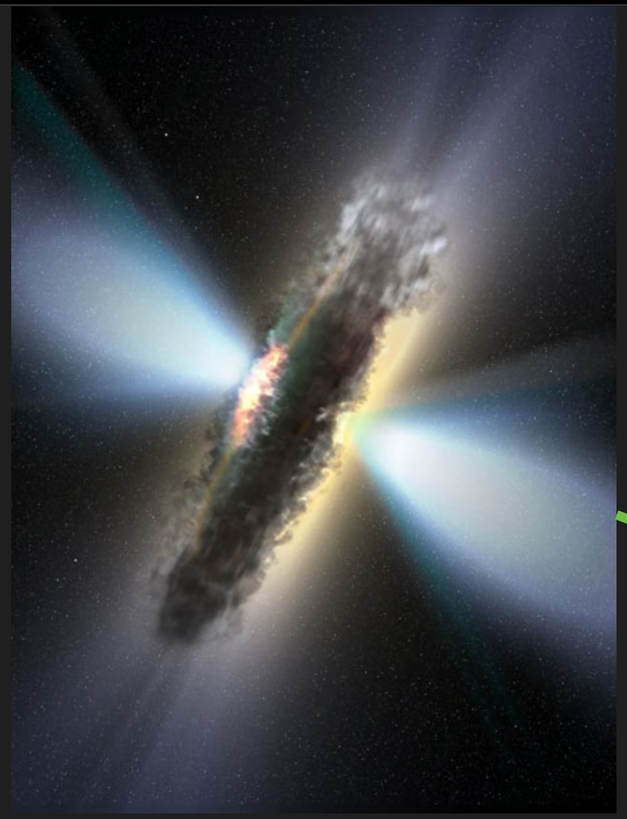


We know their energy spectrum over 11 orders of magnitude

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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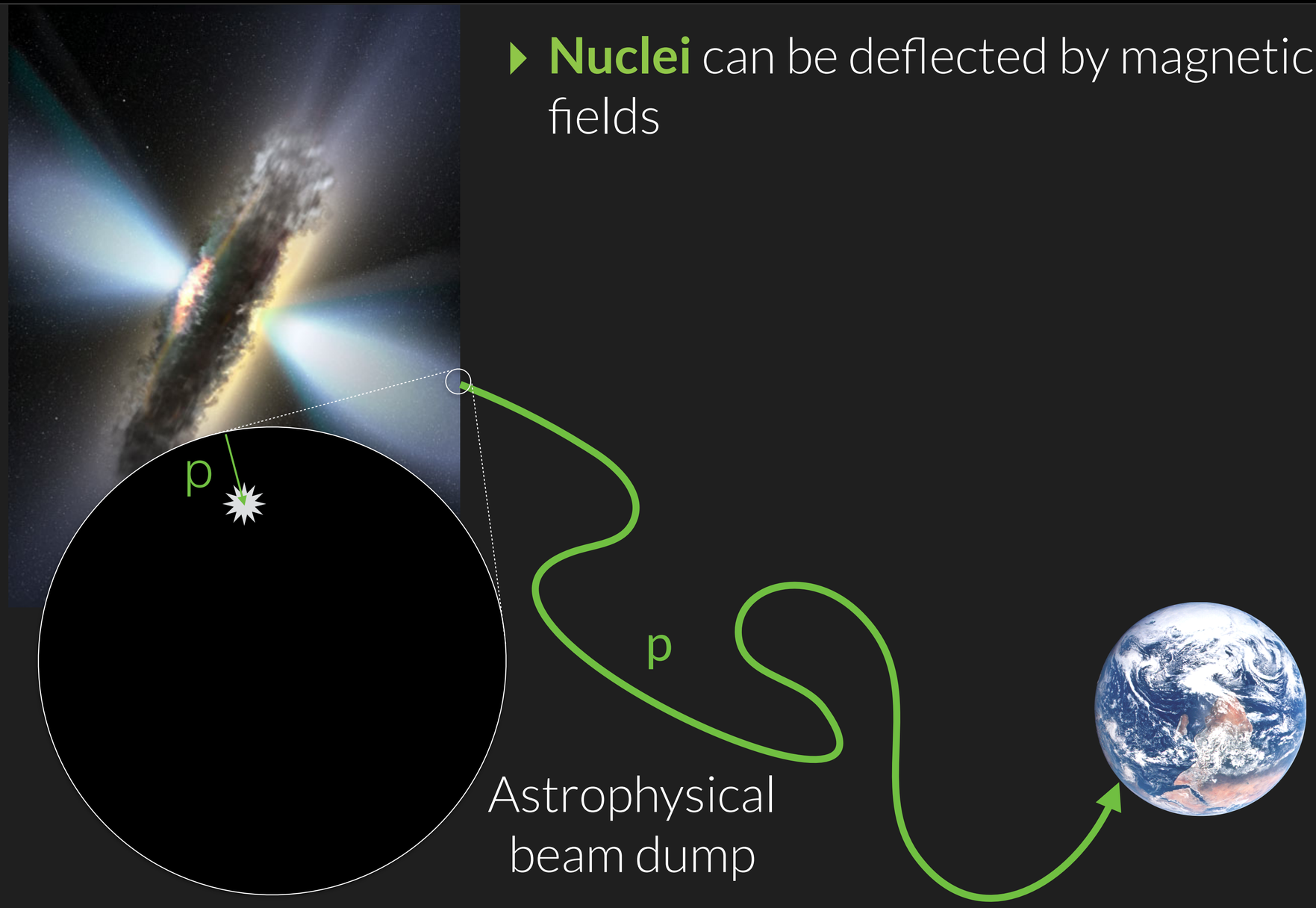

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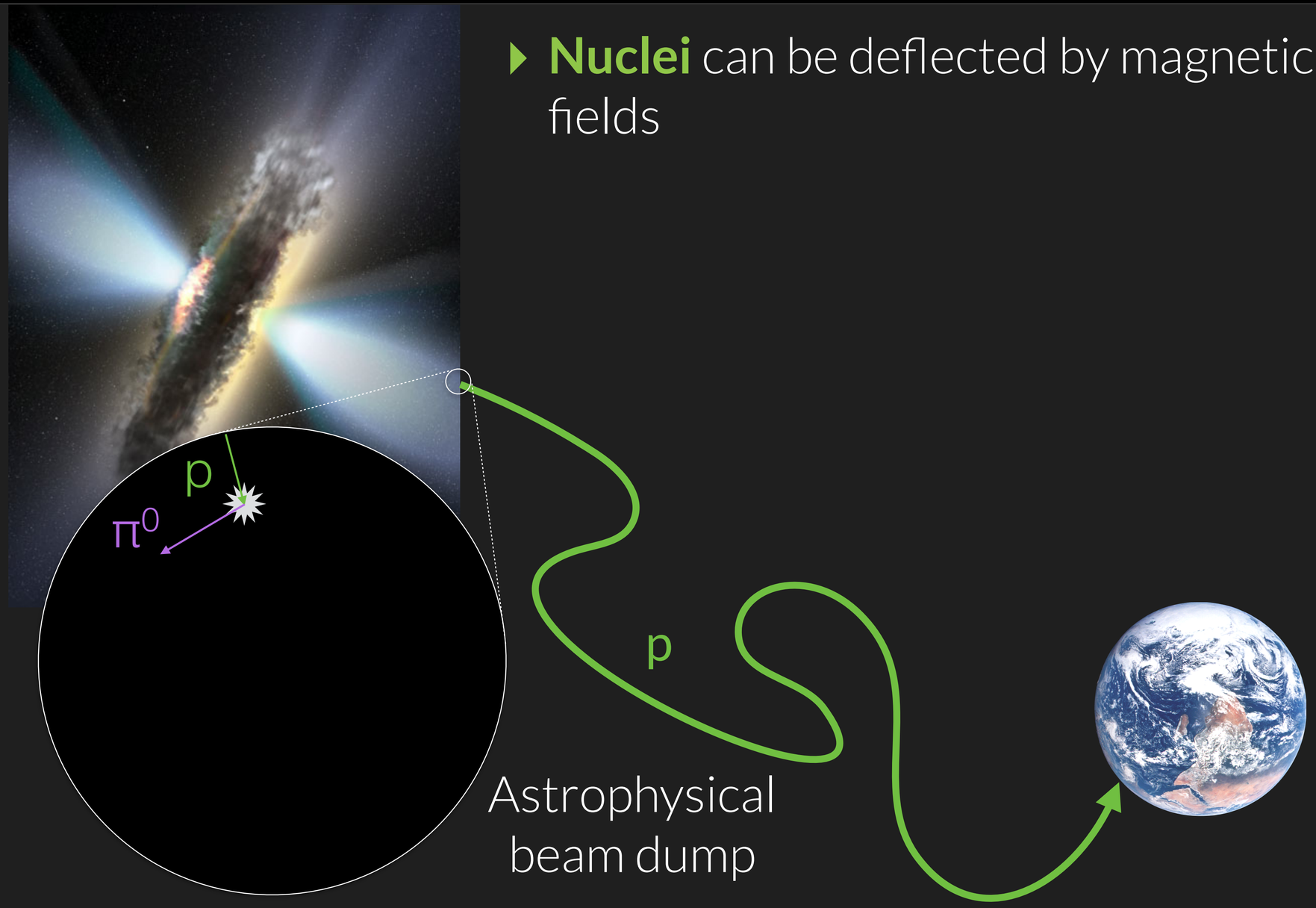

MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS

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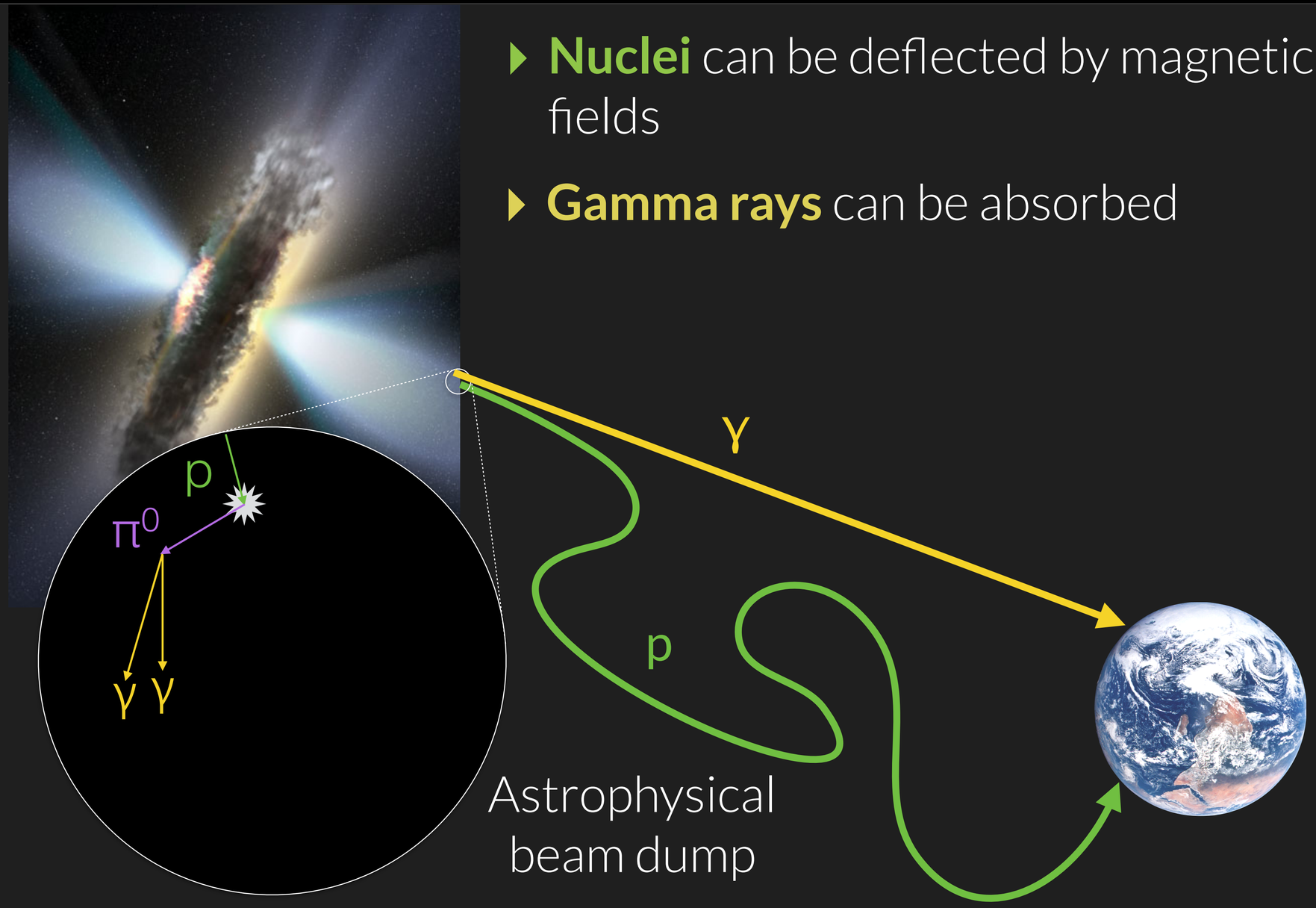

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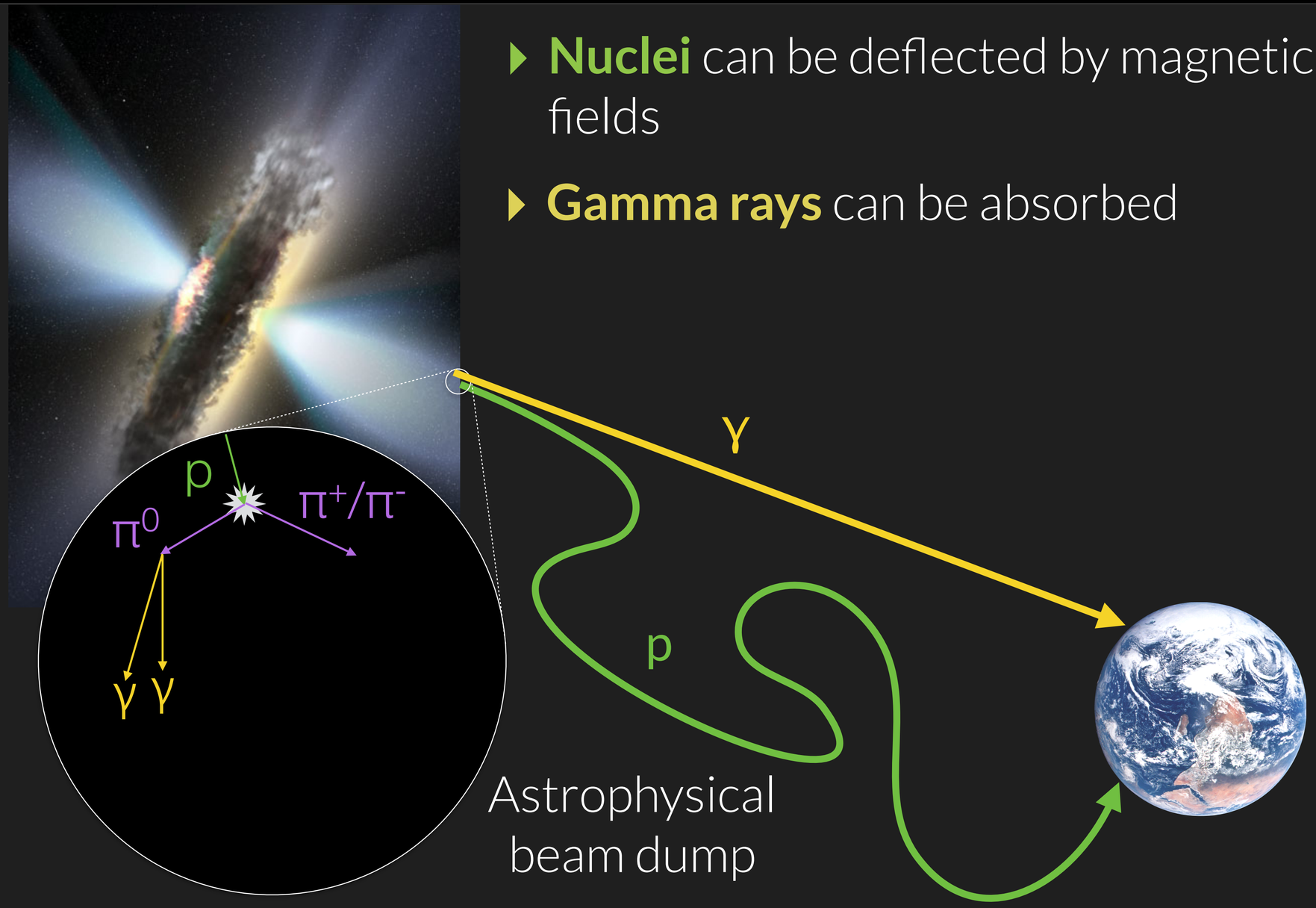
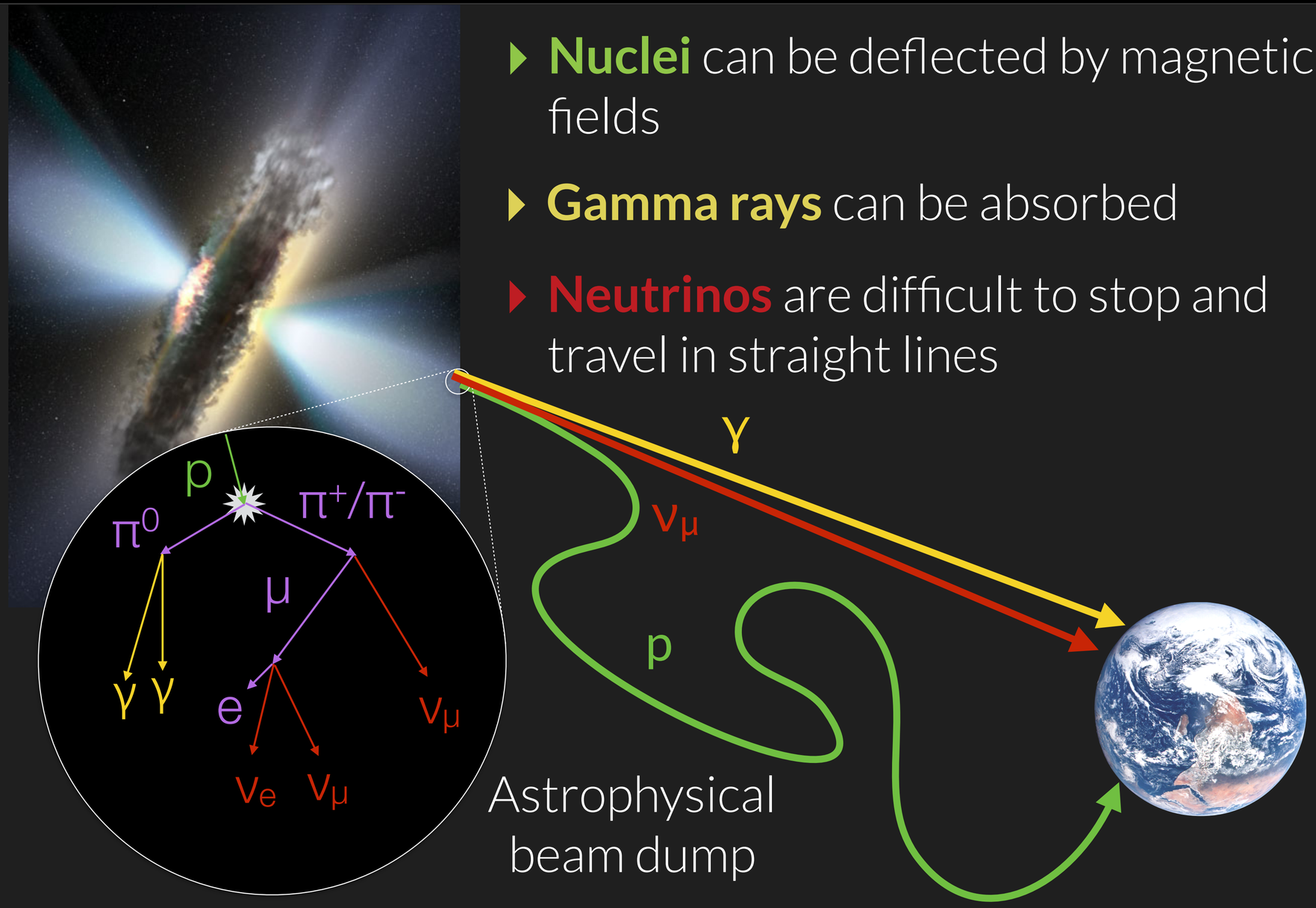


MULTI-MESSENGER ASTROPHYSICS WITH NEUTRINOS

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



TEV NEUTRINOS

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

(can also be from leptonic processes...)

$$\mathrm{p} + \gamma \rightarrow \pi^0 + \mathrm{p}$$

or p, ...

$$\hookrightarrow \gamma + \gamma + \mathrm{p}$$

TeV gamma rays

$$\rightarrow \pi^+ + \mathrm{n}$$

Cosmic rays?

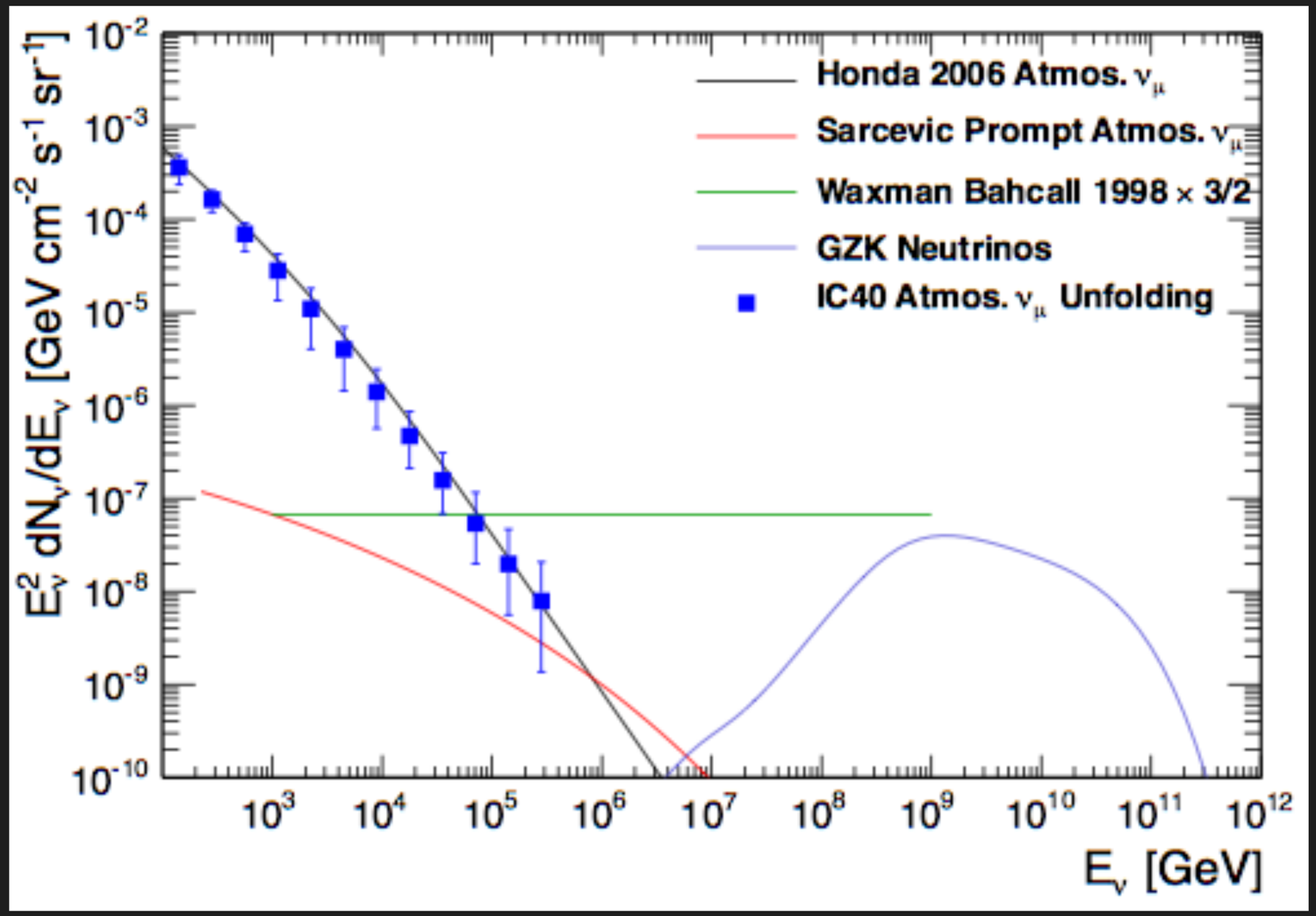
$$\hookrightarrow \mu^+ + \nu_\mu + \mathrm{n}$$

$$\hookrightarrow \mathrm{e}^+ + \nu_{\bar{\mu}} + \nu_\mathrm{e} + \nu_\mu + \mathrm{n}$$

TeV neutrinos

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 (π/K)

dominant < 100 TeV

ATMOSPHERIC NEUTRINOS (CHARM)

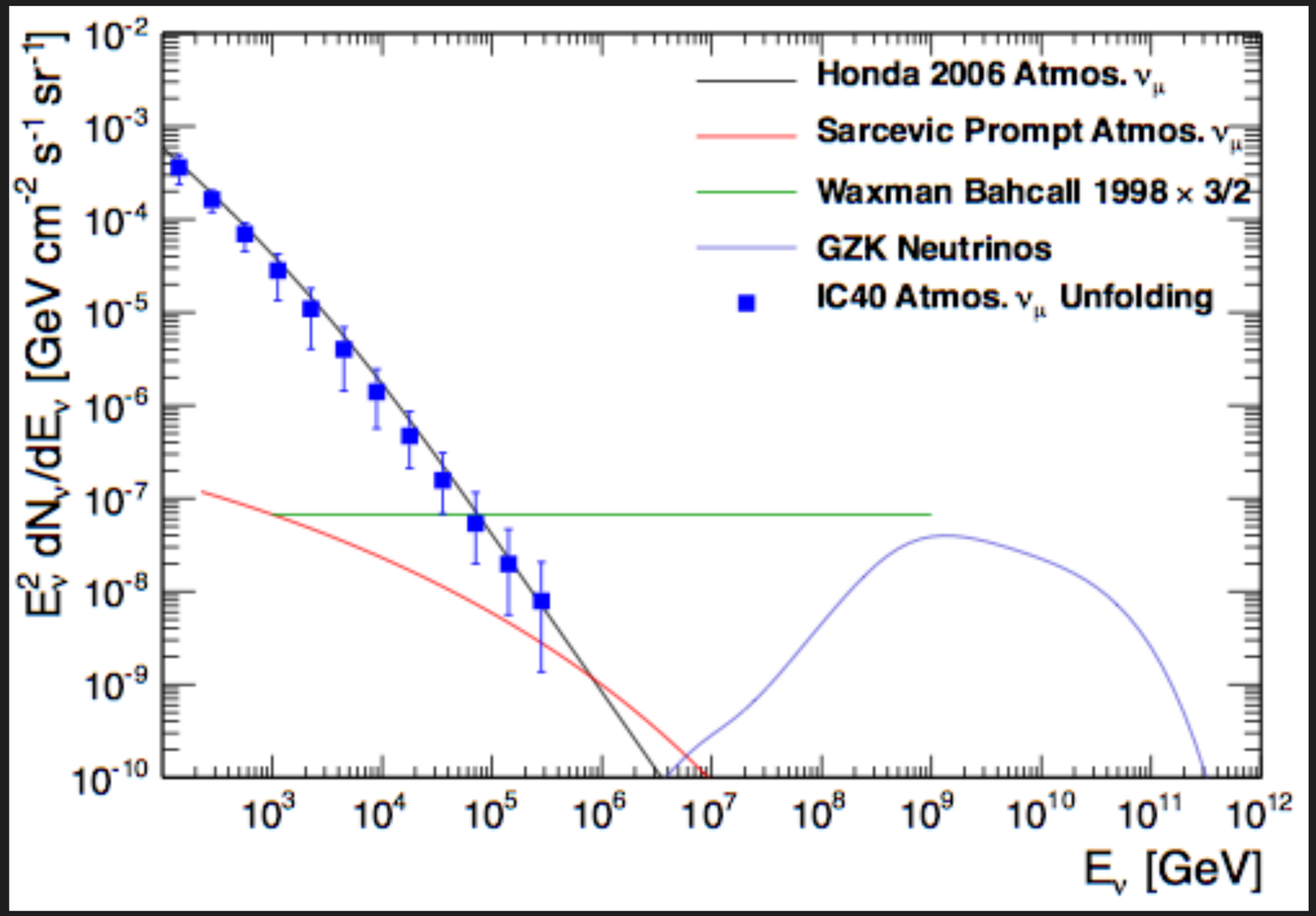
“prompt” ~ 100 TeV

ASTROPHYSICAL NEUTRINOS

maybe dominant > 100 TeV

COSMOGENIC NEUTRINOS

$>10^6$ TeV



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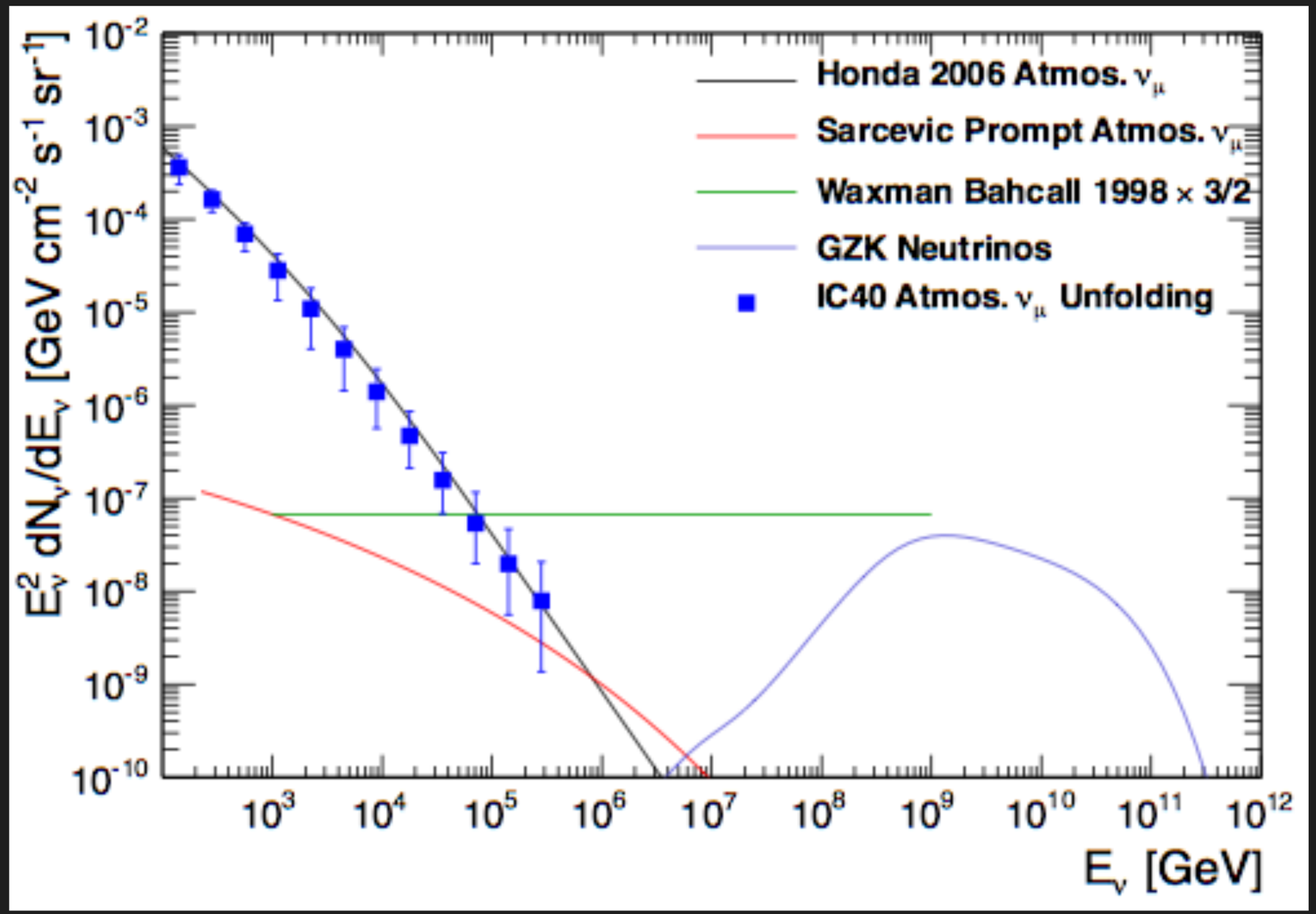
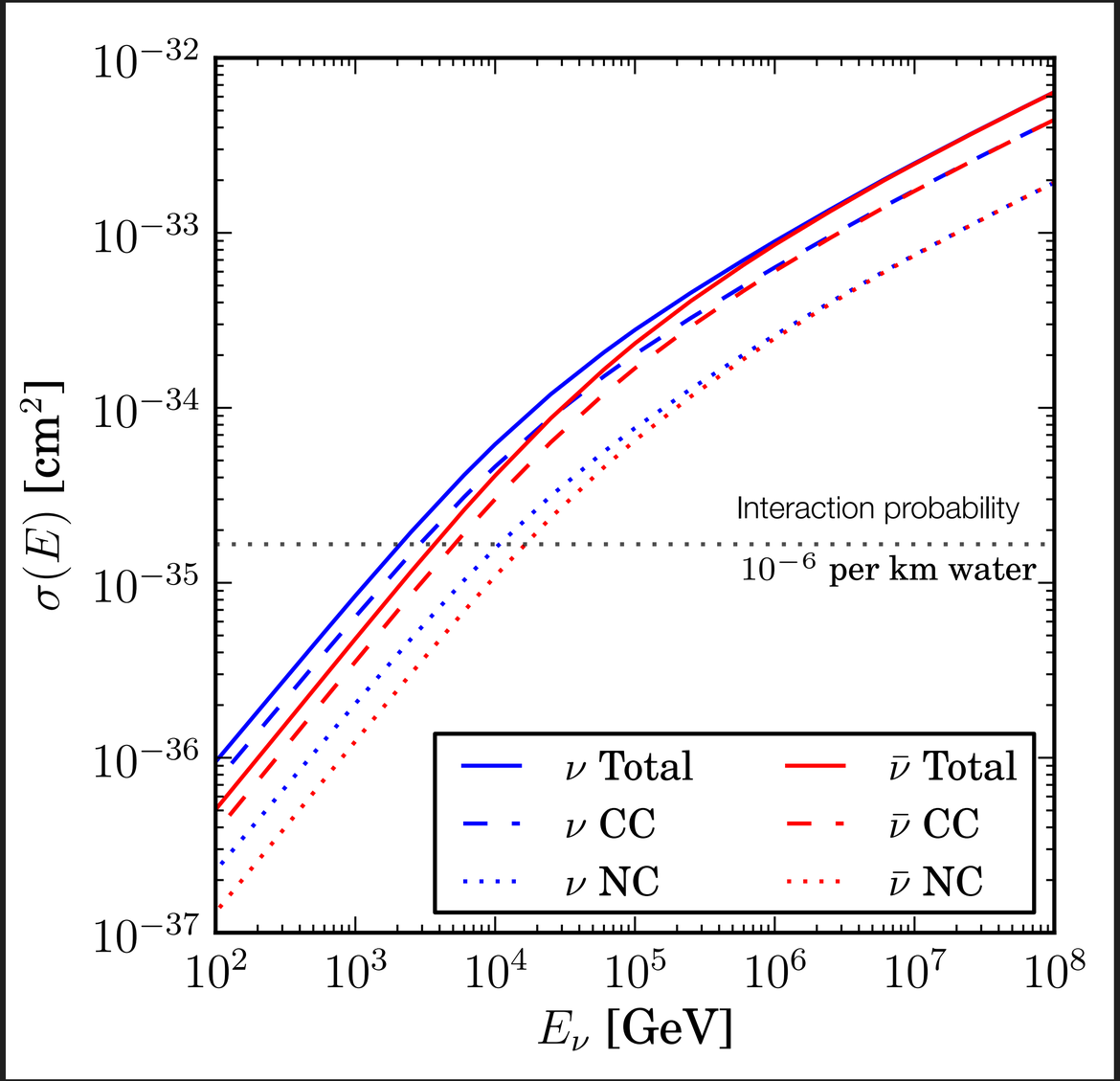
Paolo Desiati - "Recent Observations of Atmospheric Neutrinos with the IceCube Observatory" - August 5, 17:00 **(highlight)**



DETECTING TEV NEUTRINOS

Interaction cross-sections are very small



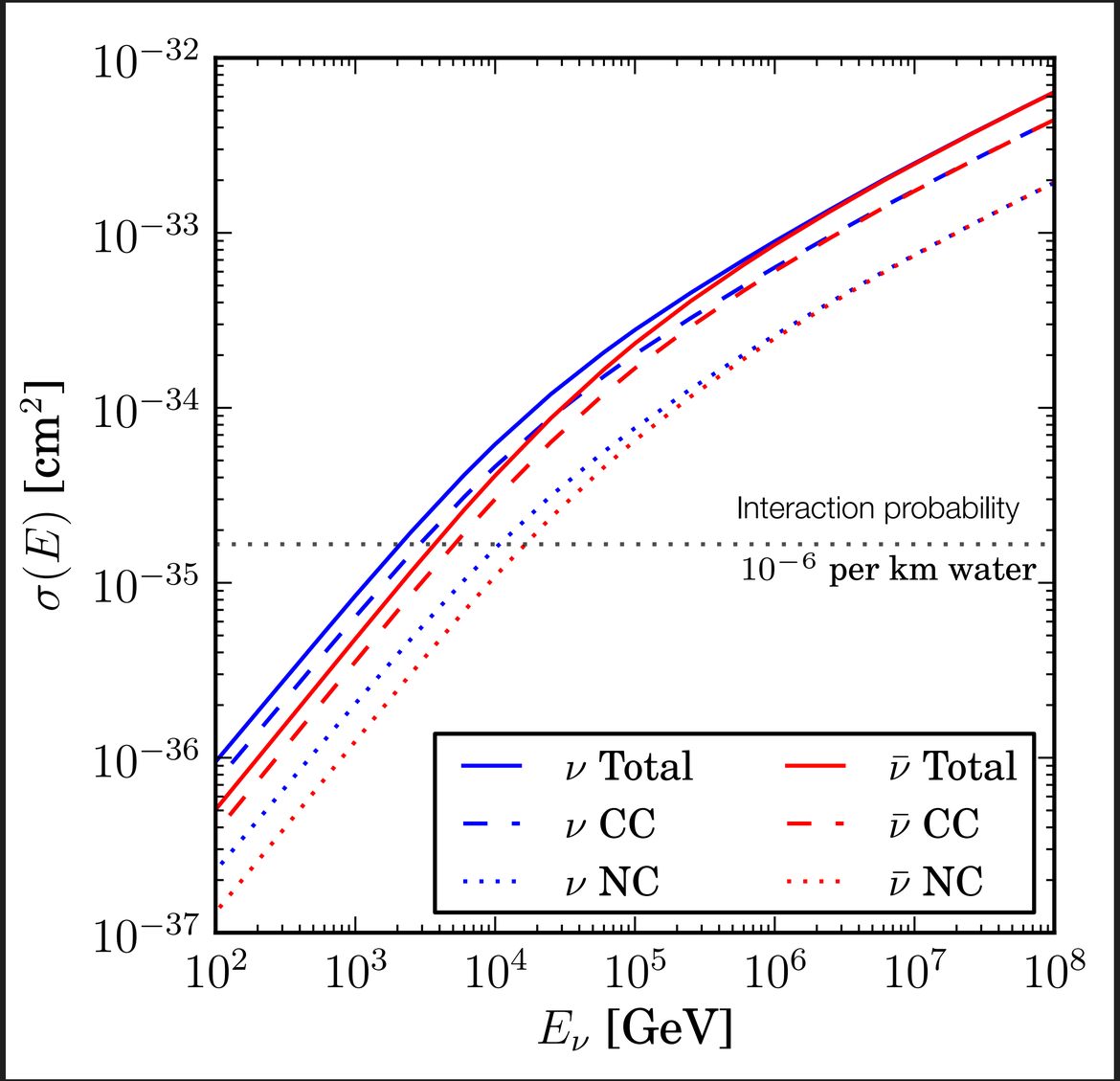
DETECTING TEV NEUTRINOS

Interaction cross-sections are very small

Benchmark astrophysical flux: O(10^5) per km^2 per year above 100 TeV

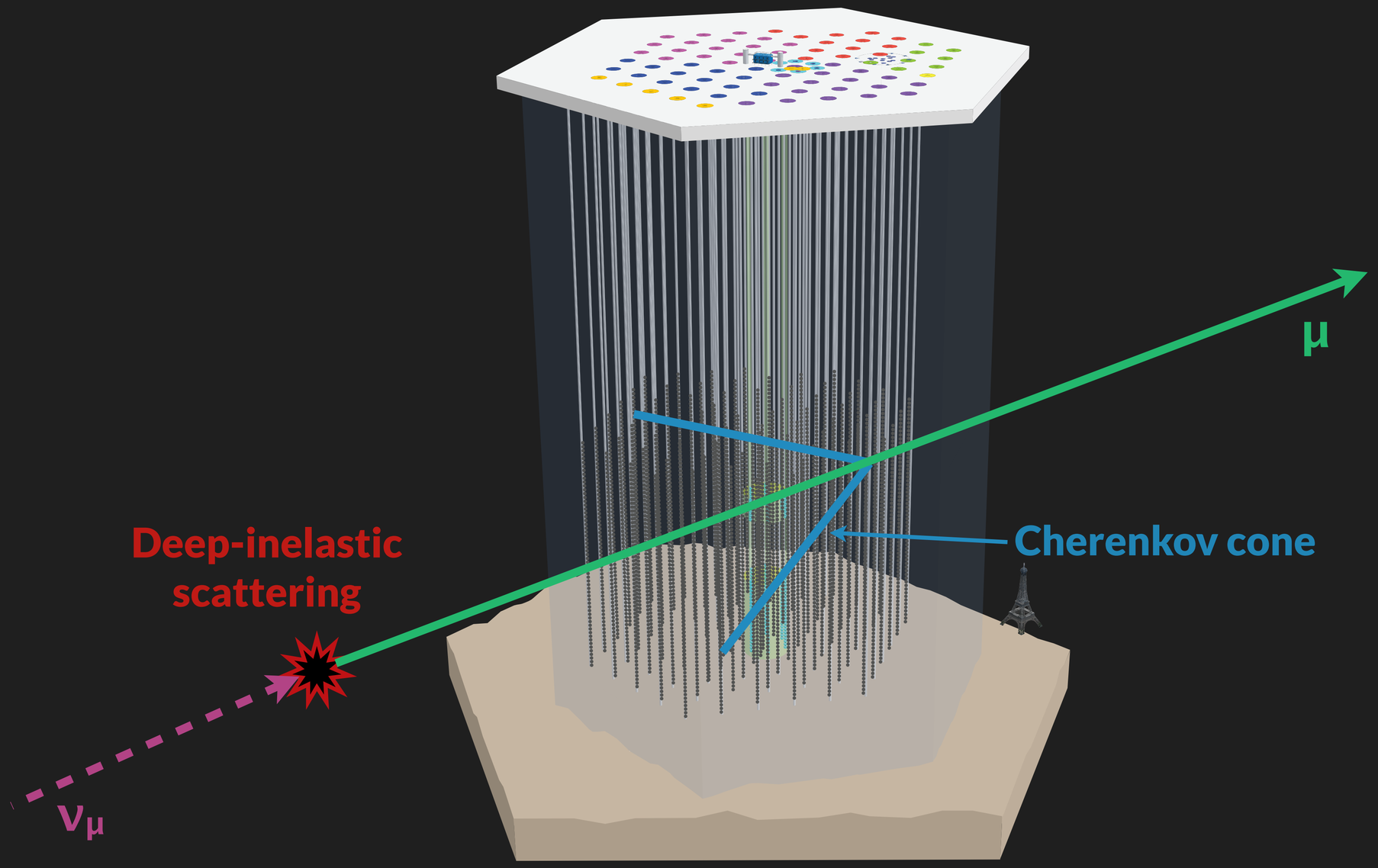
Need **km^3-scale** detectors!

Large volumes, use natural water or ice



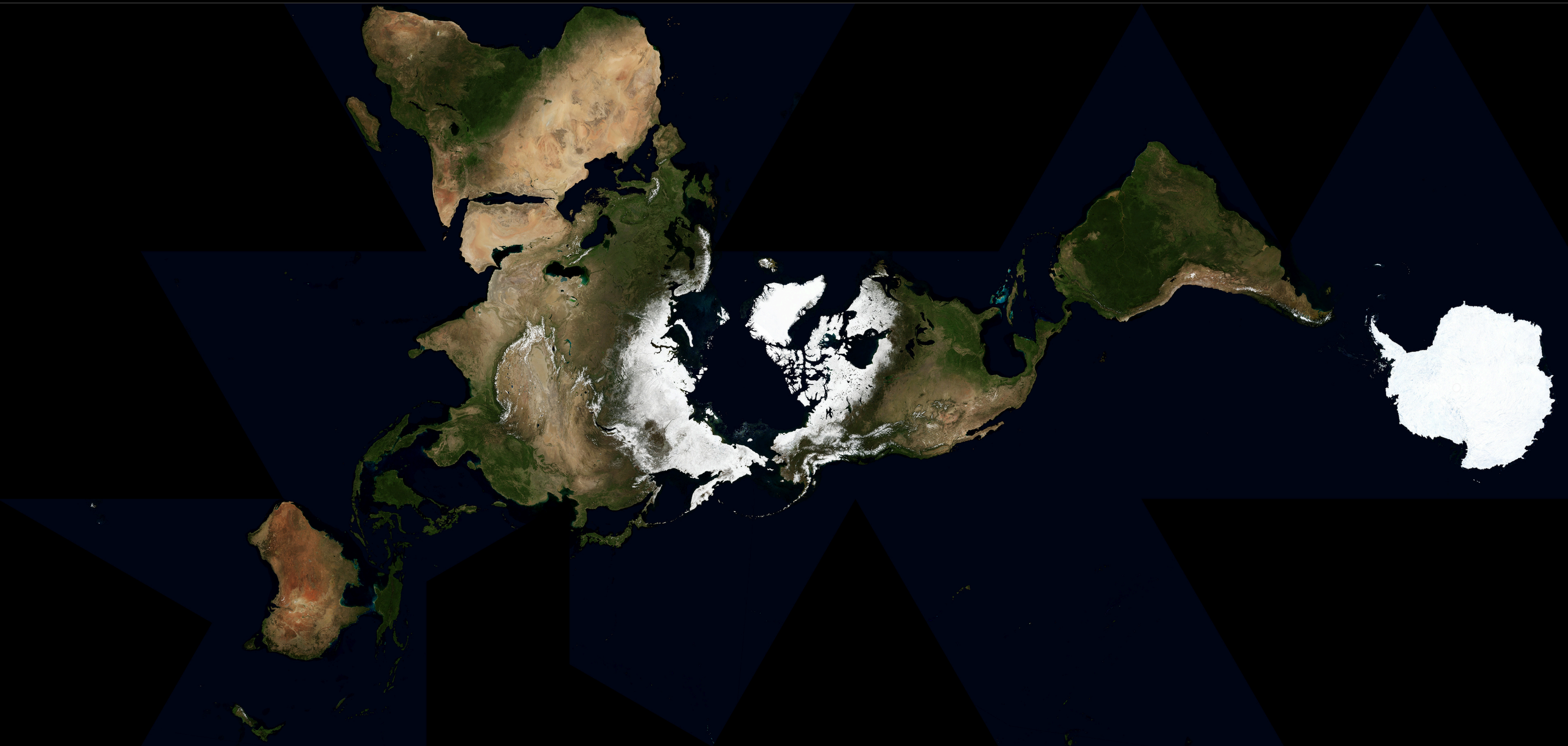
DETECTING NEUTRINOS

Neutrinos are detected by looking for



NEUTRINO TELESCOPE SITES

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



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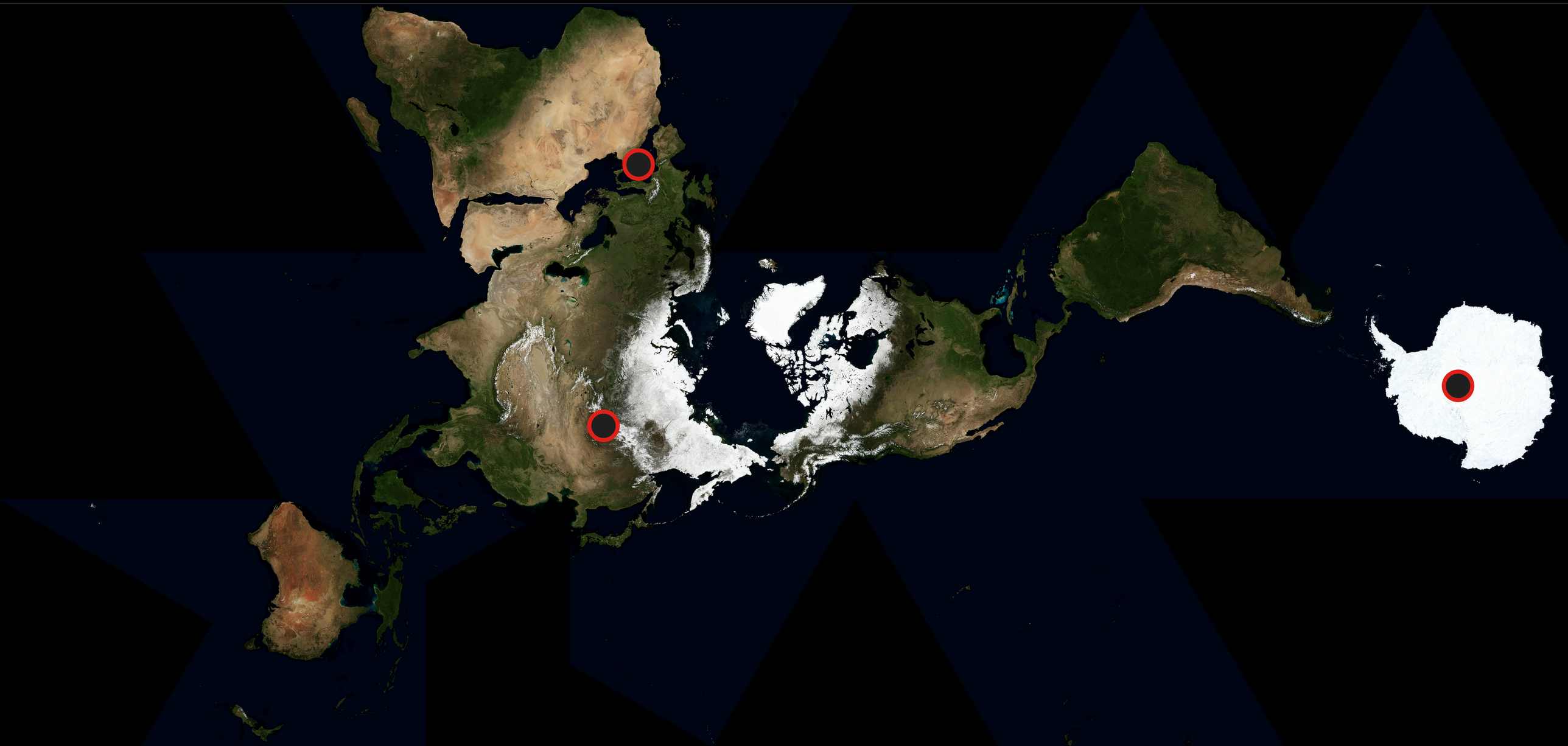

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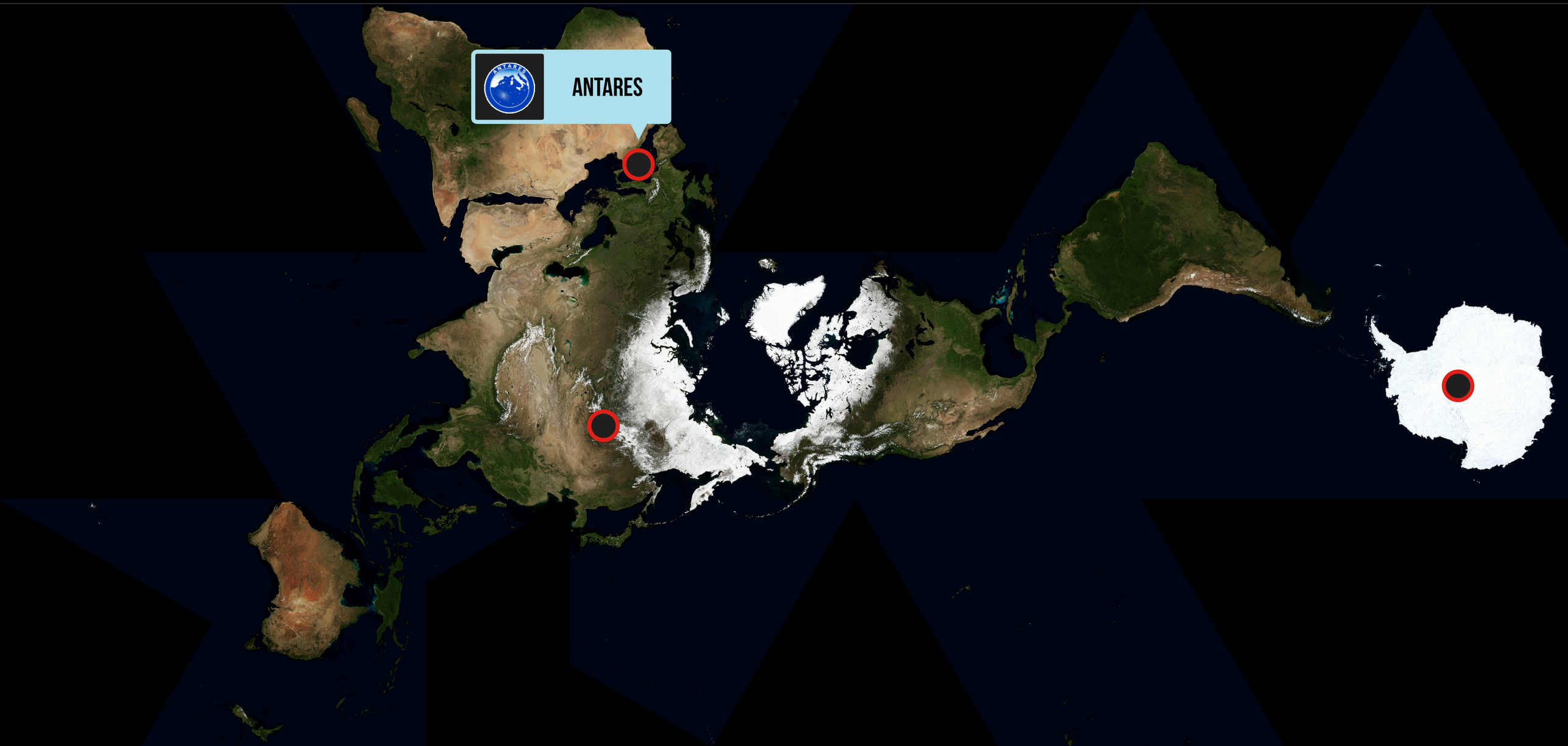

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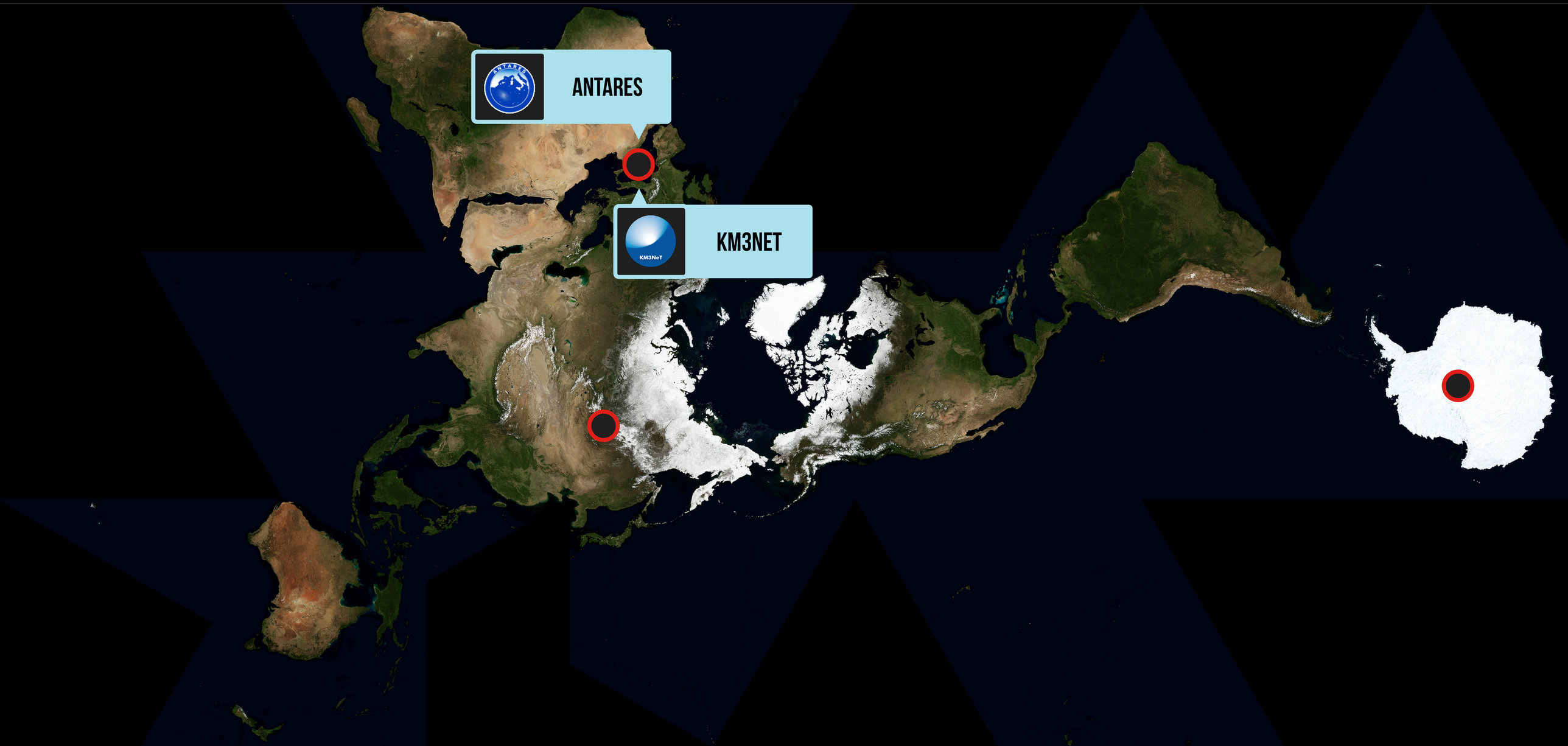

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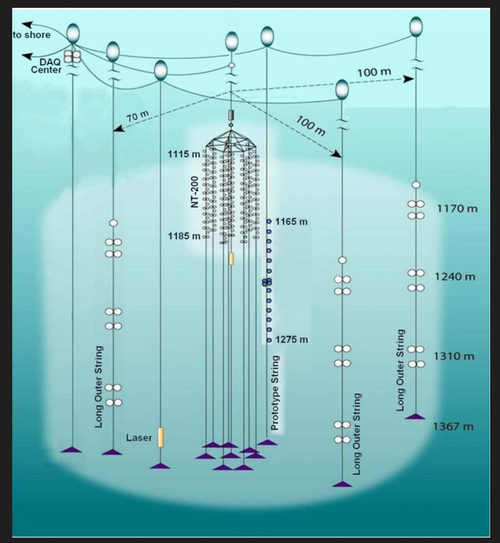
THE WORLD'S NEUTRINO TELESCOPES

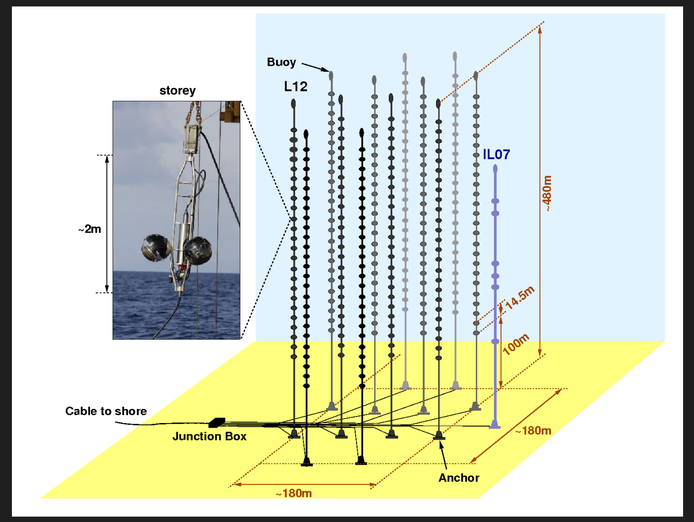
lakes, sea, glaciers

NT-200+



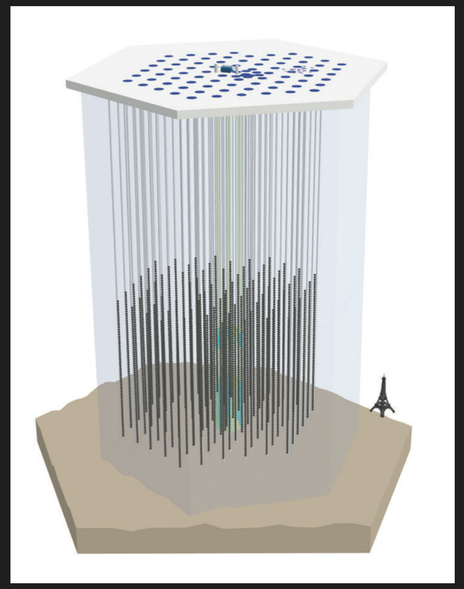
Lake Baikal
1/2000 km^3
228 PMTs

Antares



Mediterranean Sea
1/100 km^3
885 PMTs

IceCube



South Pole glacier
1 km^3
5160 PMTs

Larger, sparser → higher energies

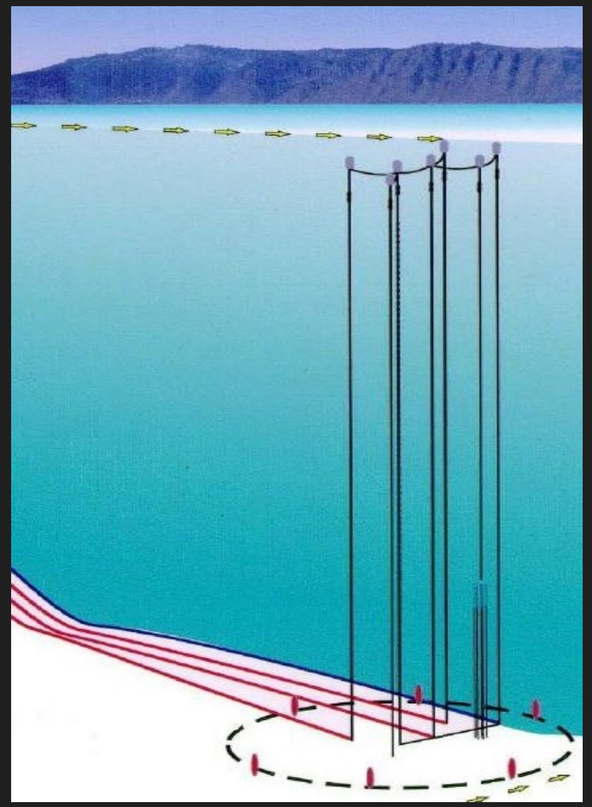

Lake Baikal

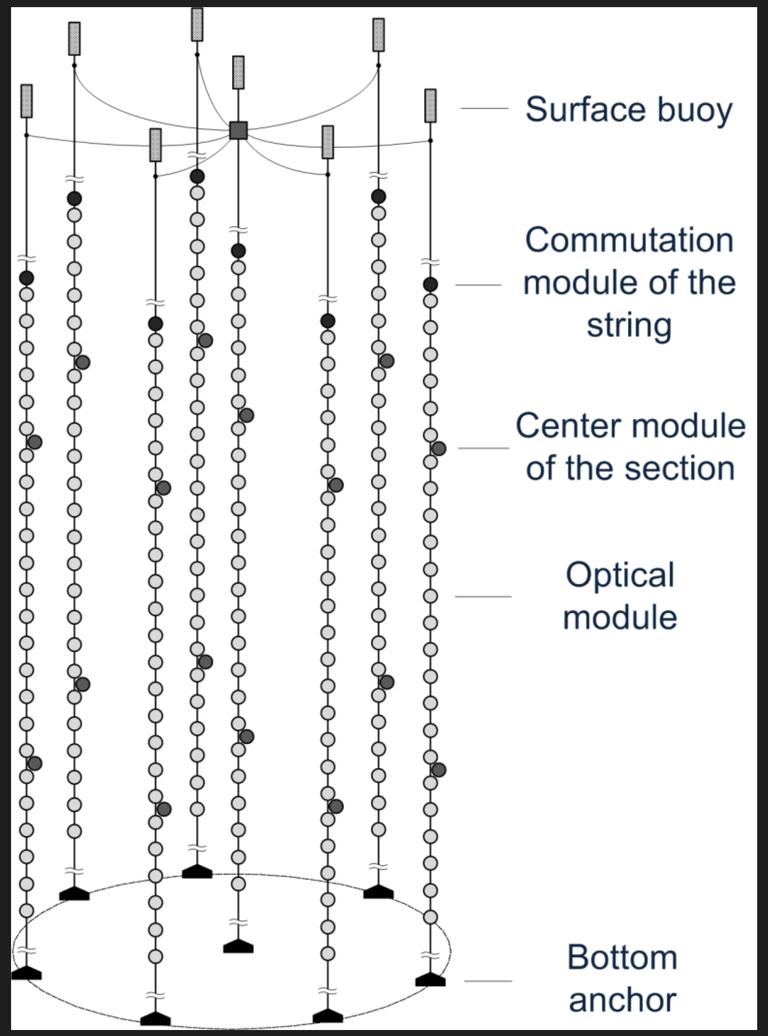
BAIKAL / BAIKAL-GVD

Neutrino telescope deployed in Lake Baikal

First cluster of the gigaton detector deployed in April 2015

Plan: 8-12 such arrays





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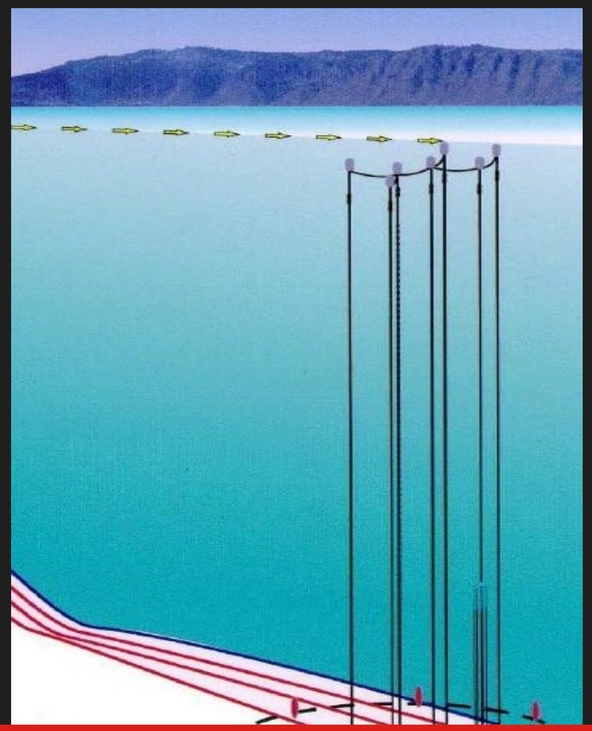
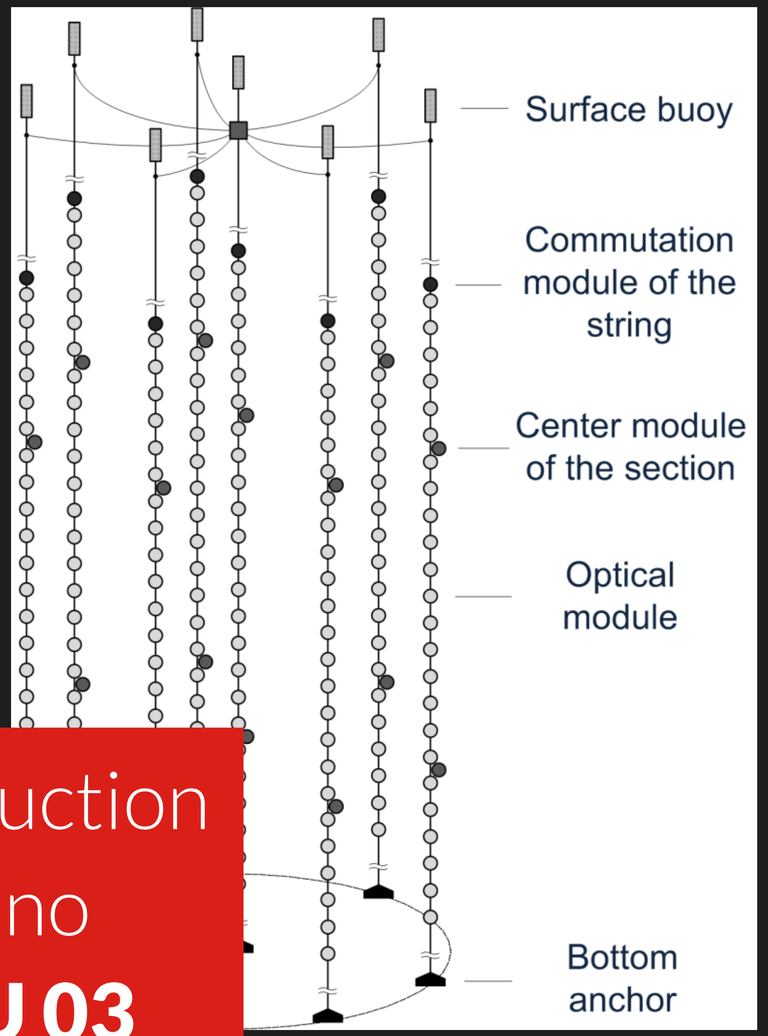


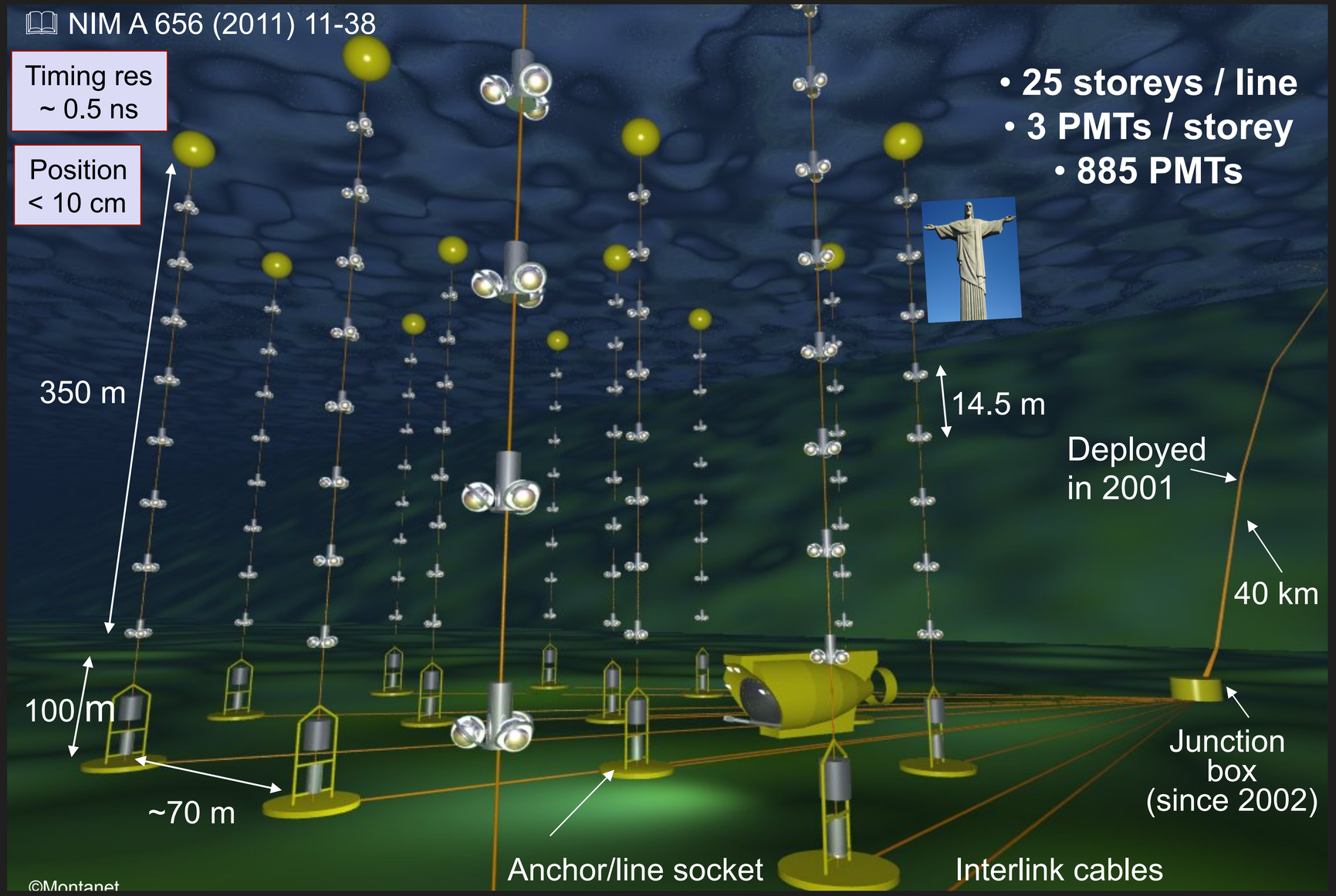


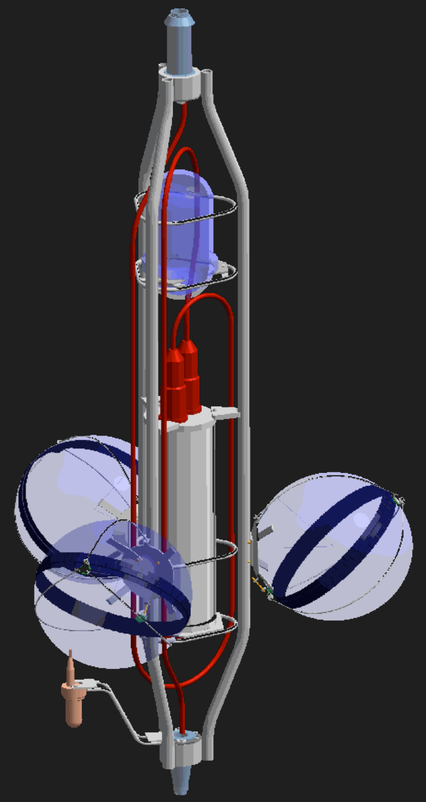
Bair Shaybovov - "The first construction phase of the Baikal-GVD neutrino telescope" - August 1, 14:15 - **NU 03**


Mediterranean Sea

THE ANTARES NEUTRINO TELESCOPE

In the





“storey” with 3 OMs

THE ANTARES NEUTRINO TELESCOPE

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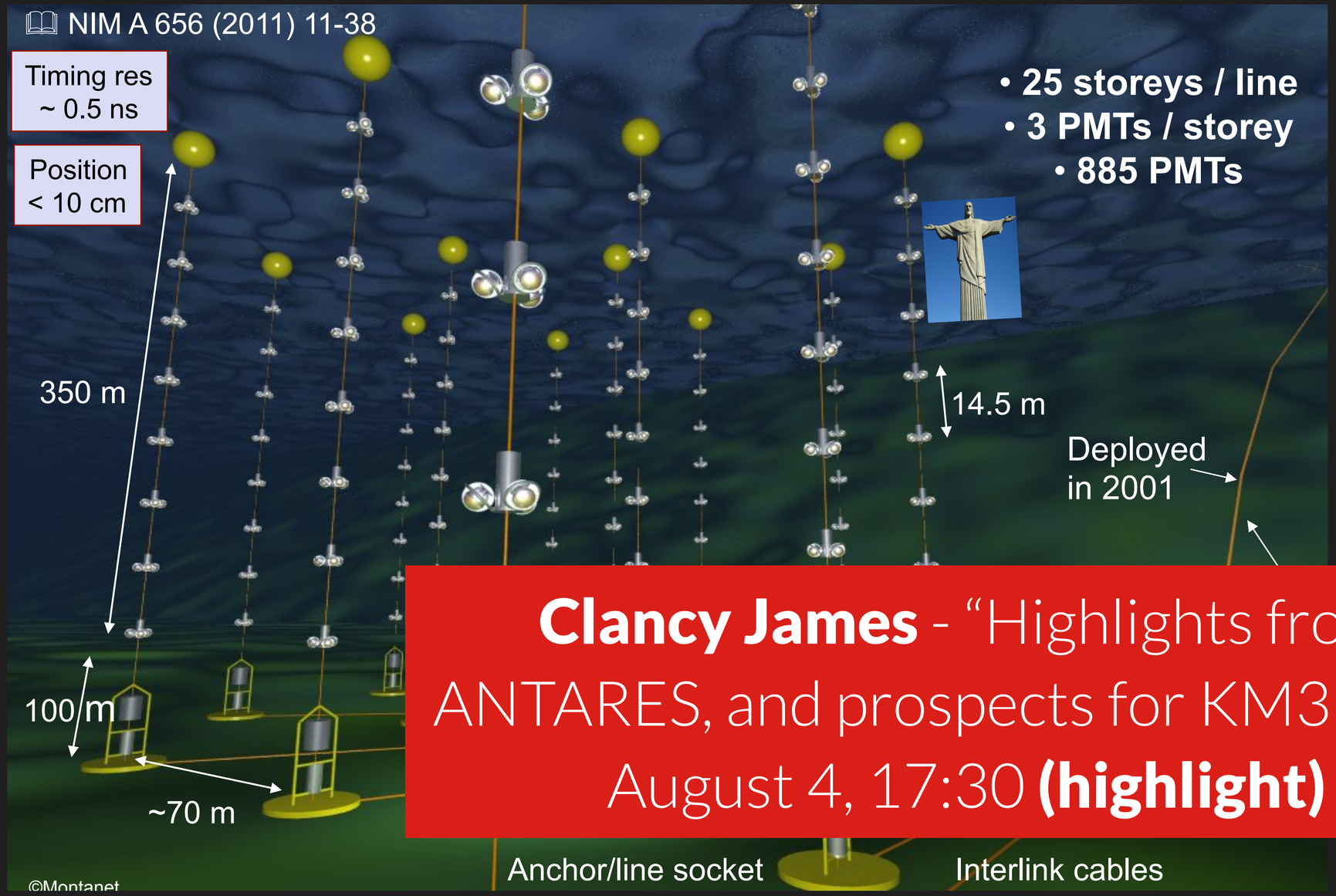
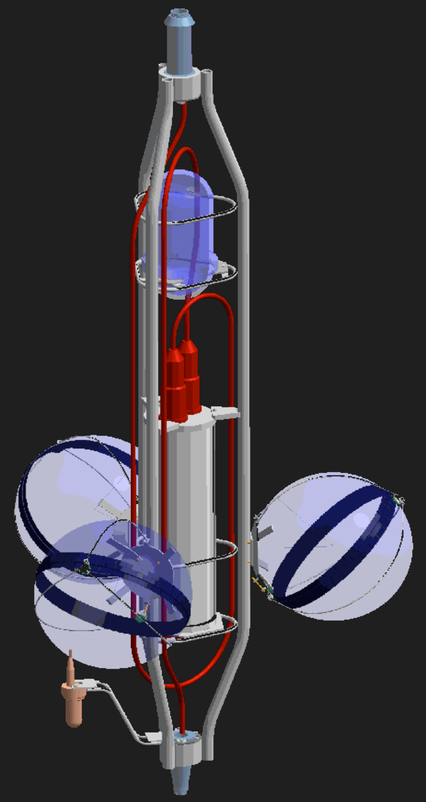
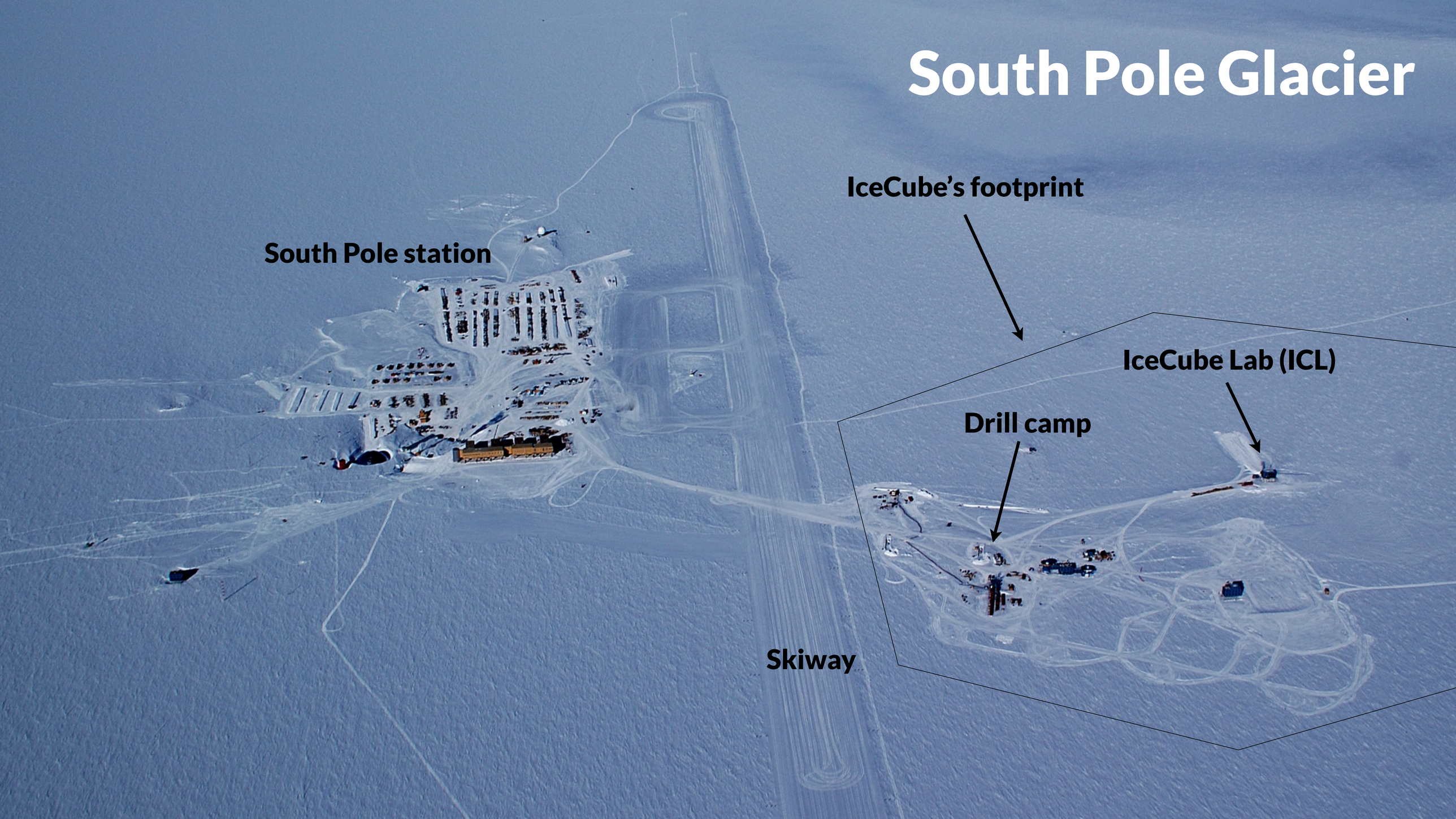


Clancy James - "Highlights from ANTARES, and prospects for KM3NeT" - August 4, 17:30 **(highlight)**



"storey" with 3 OMs

South Pole Glacier



THE ICECUBE NEUTRINO OBSERVATORY

Deployed in the deep glacial ice at the South Pole

5160 PMTs

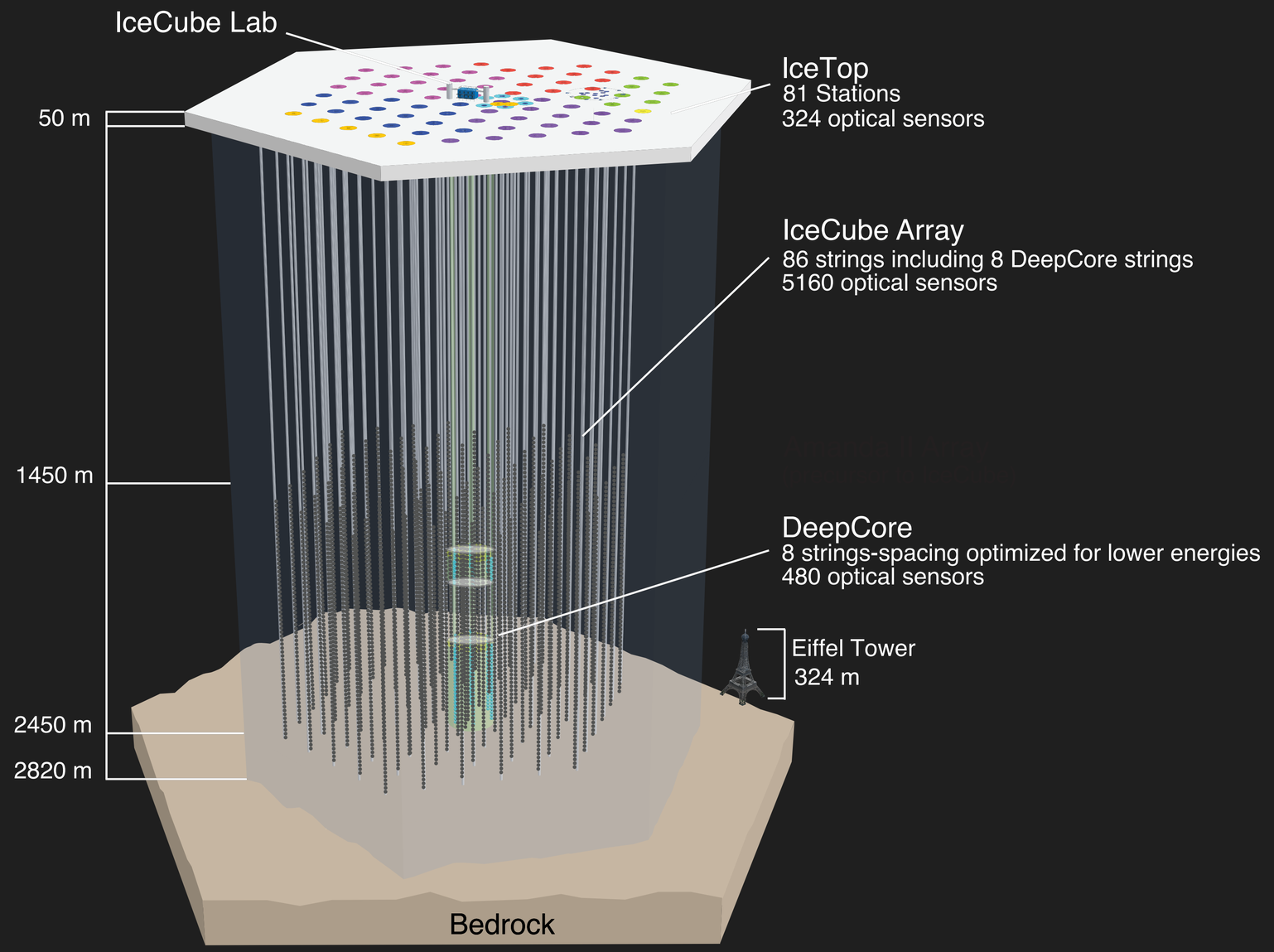
1 km^3 volume

86 strings

17 m vertical spacing

125 m string spacing

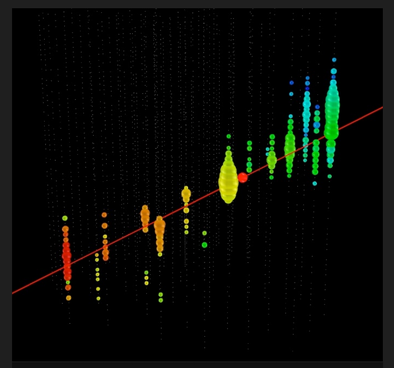
Completed **2010**



NEUTRINO EVENT SIGNATURES

Signatures of signal events

CC Muon Neutrino

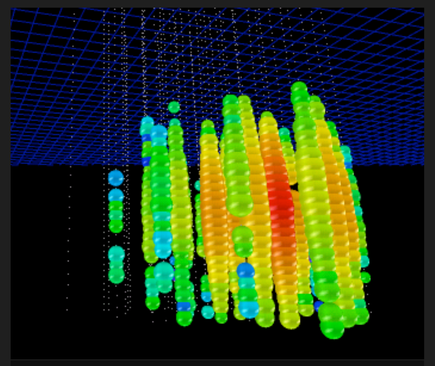


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current / Electron Neutrino



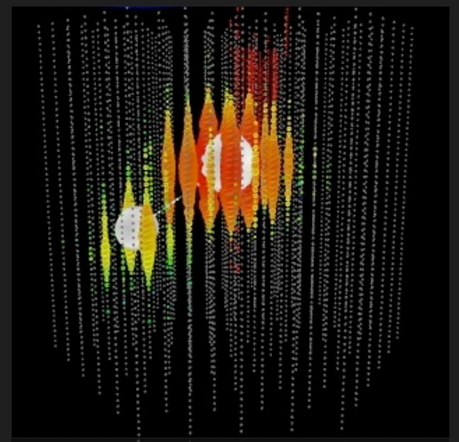
$$\nu_\mathrm{e} + N \rightarrow \mathrm{e} + X$$

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

cascade (data)

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

CC Tau Neutrino



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

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

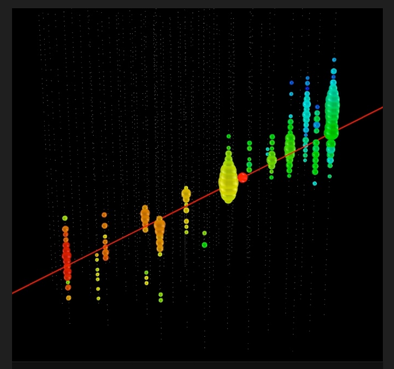
(not observed yet: τ decay length is 50 m/PeV)

NEUTRINO EVENT SIGNATURES

Signatures of signal events

time

CC Muon Neutrino

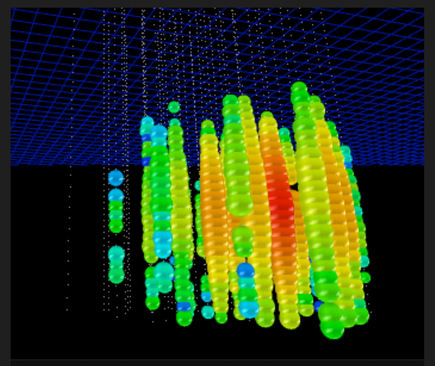


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

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

Neutral Current / Electron Neutrino



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CC Tau Neutrino

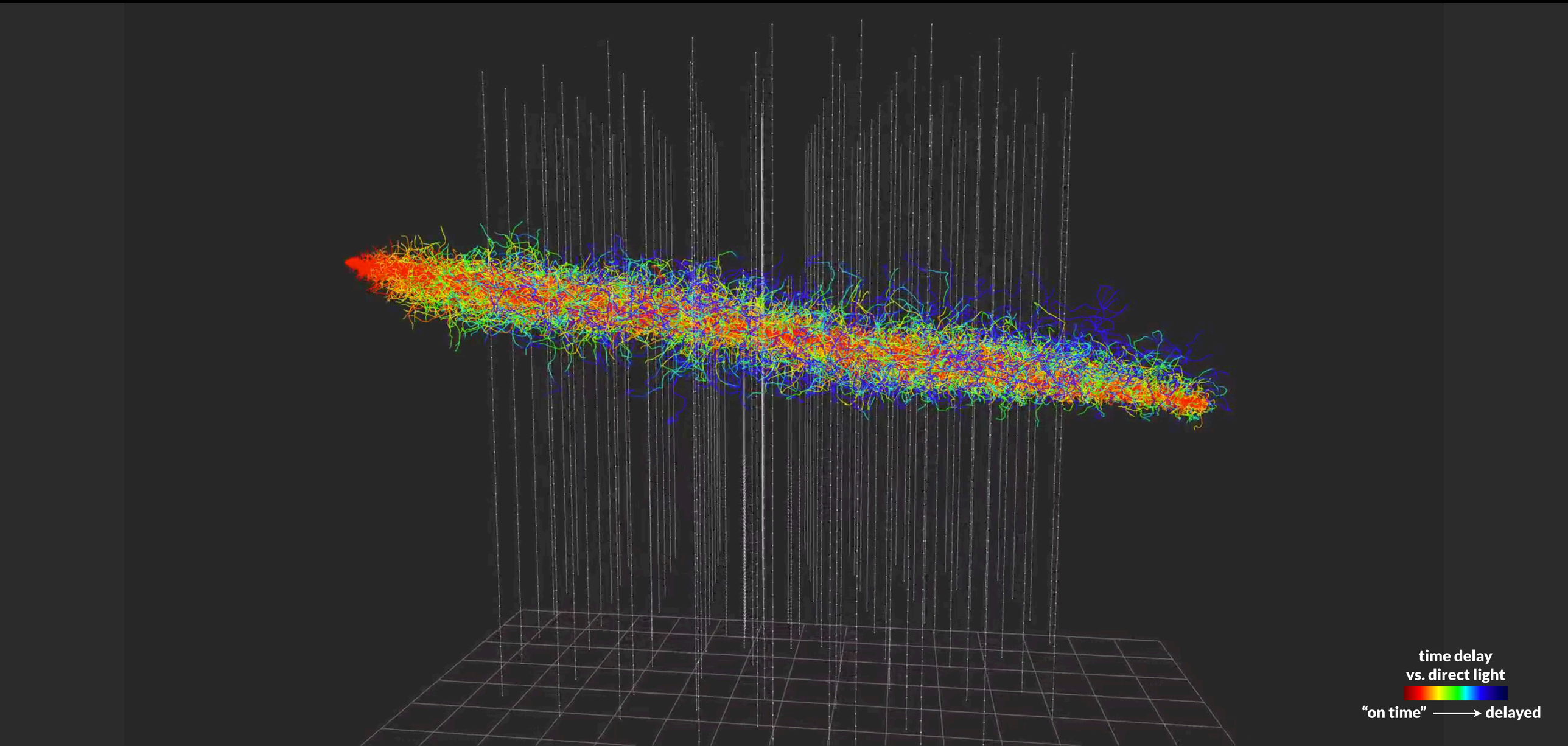
Dawn Williams - "A Search for Astrophysical Tau Neutrinos in Three Years of IceCube Data" -August 3, 15:15 - **NU 04**

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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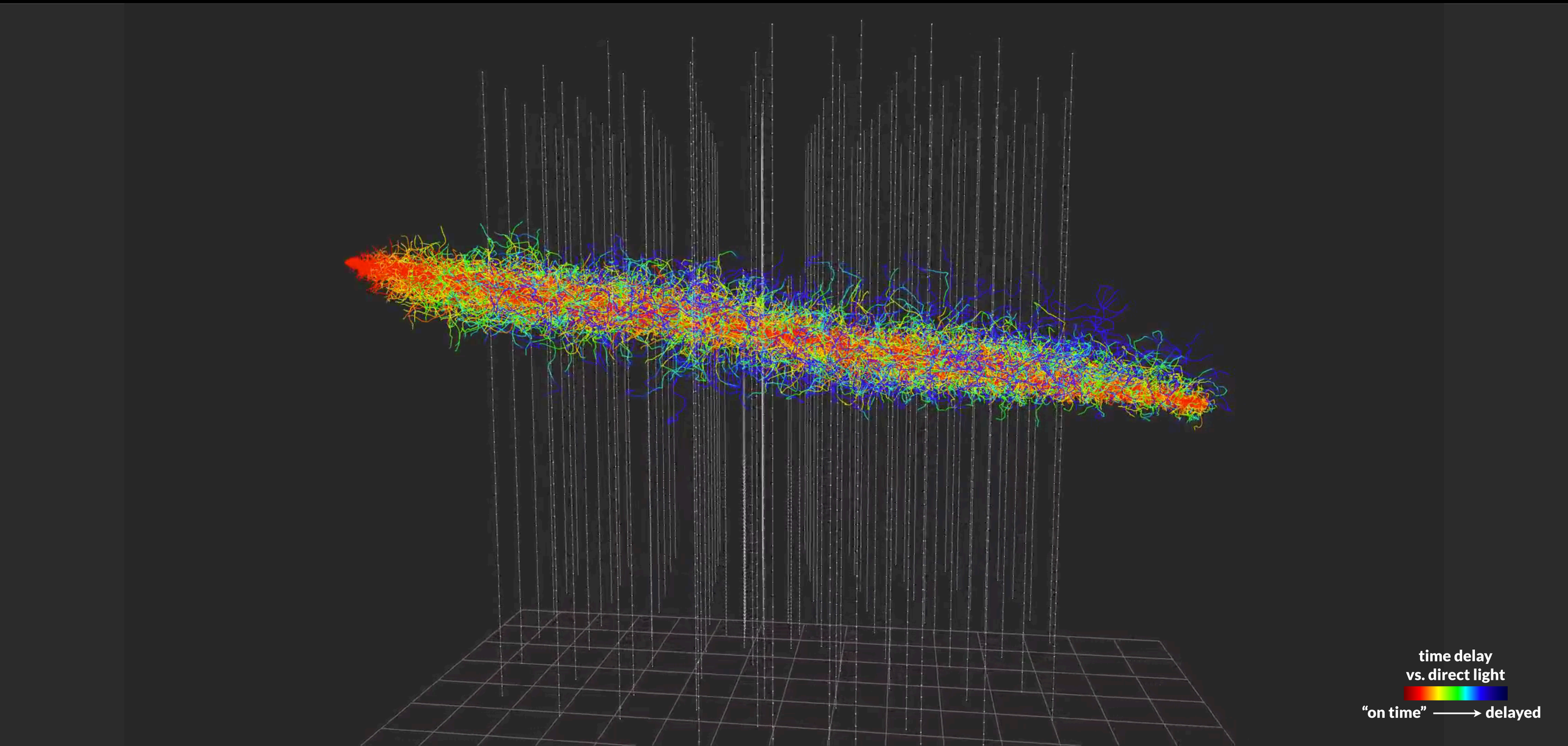

DETECTION PRINCIPLE (CASCADE IN ICE)

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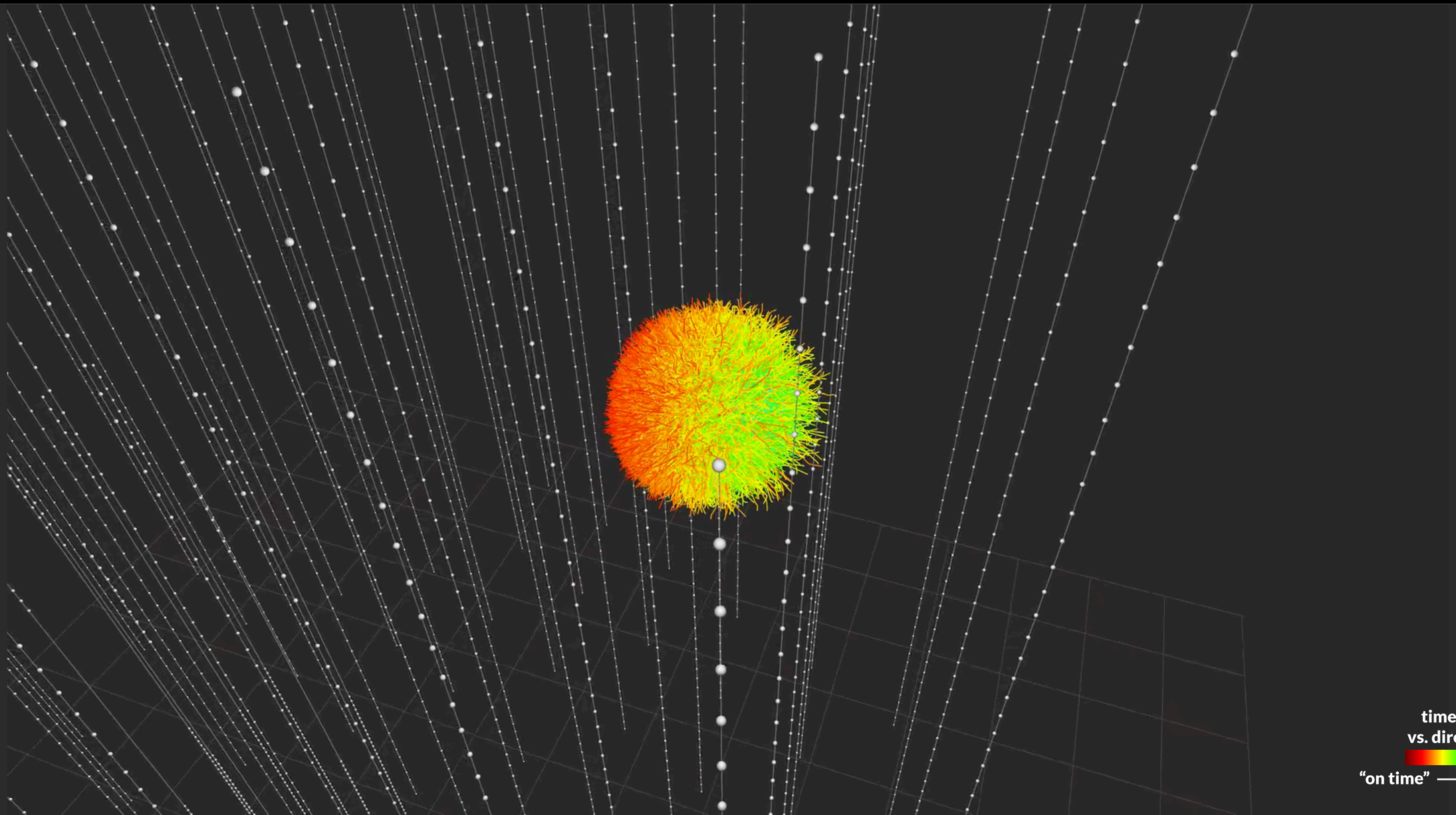

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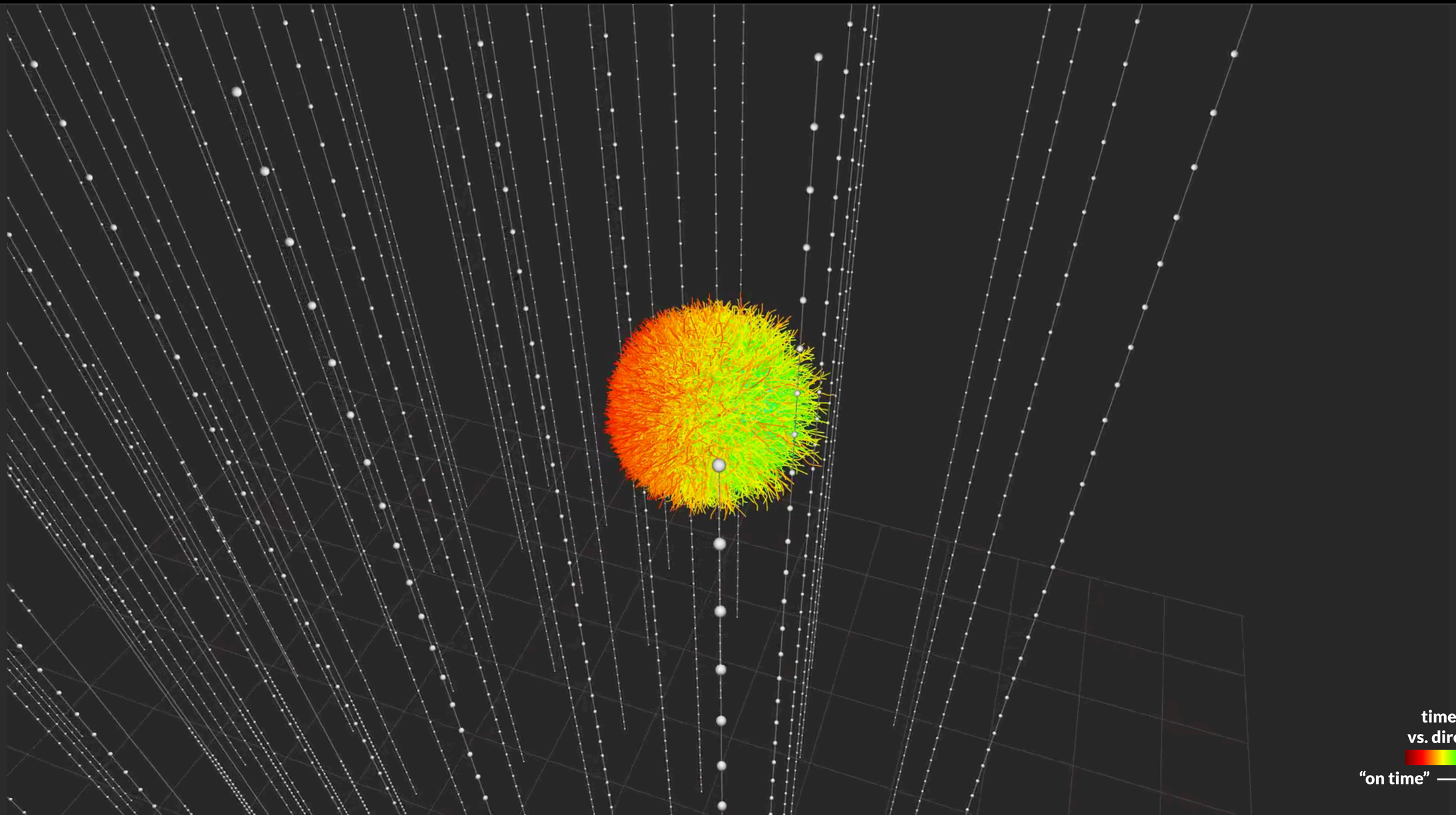
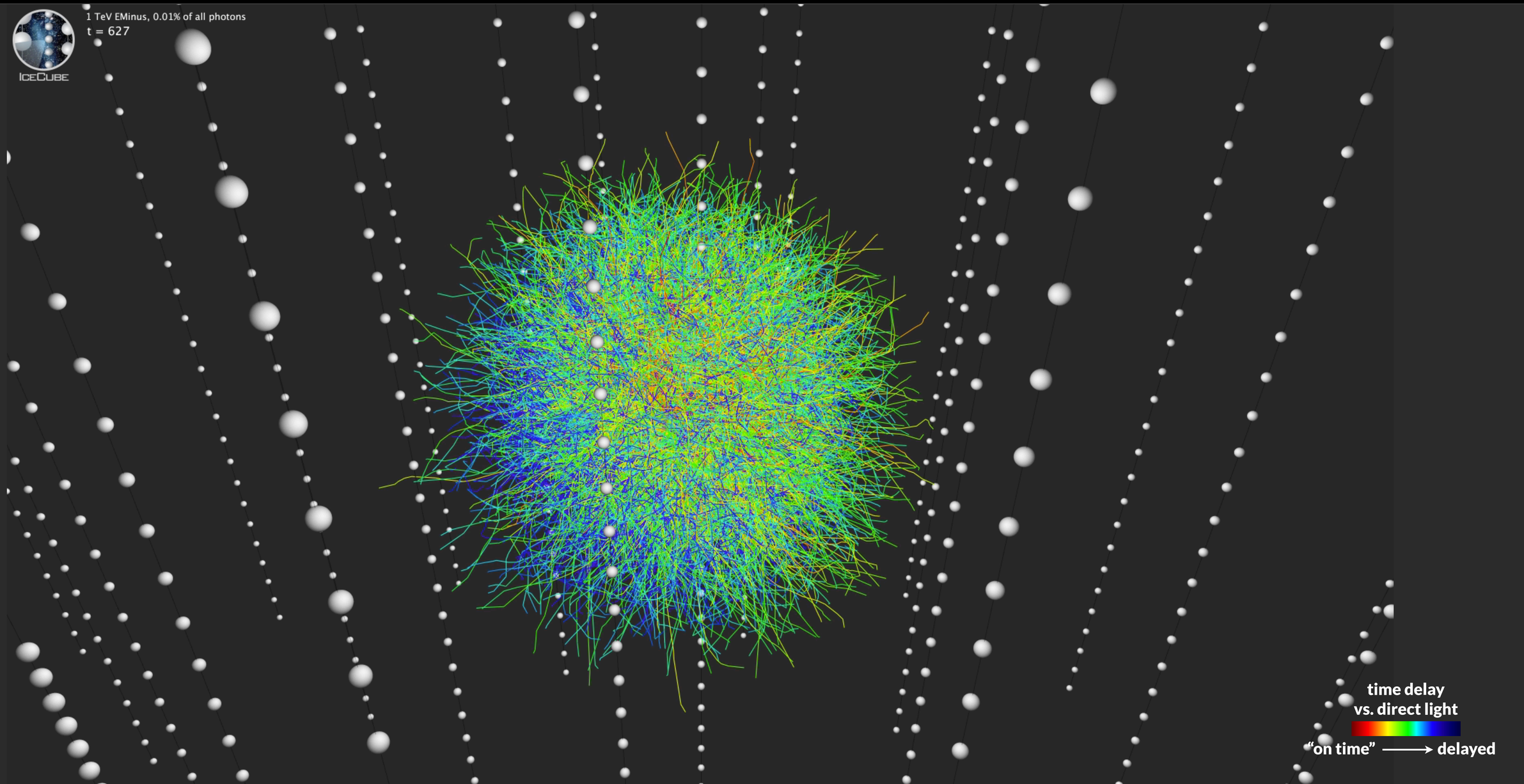


DETECTION PRINCIPLE (CASCADE IN ICE)

Another Shower



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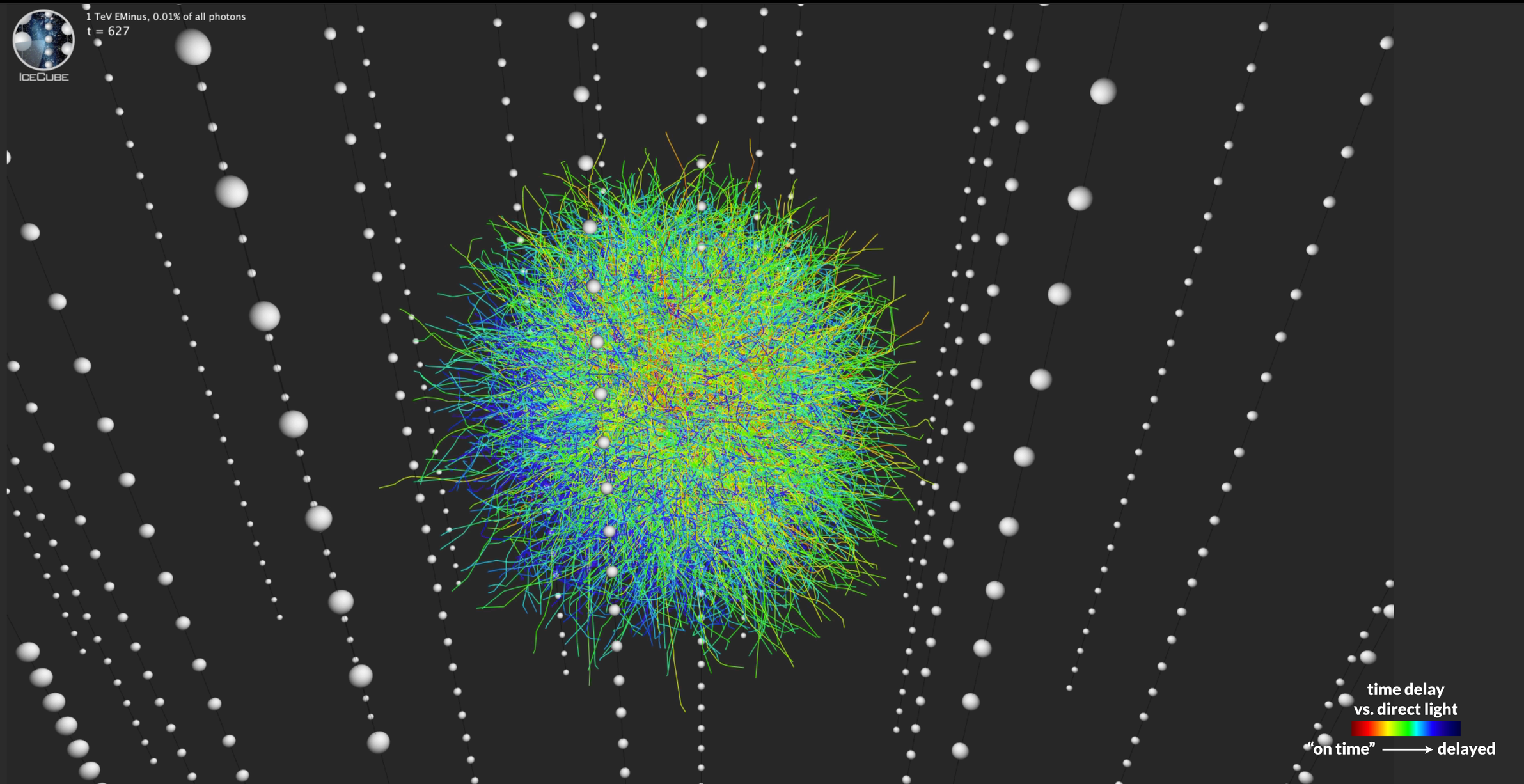
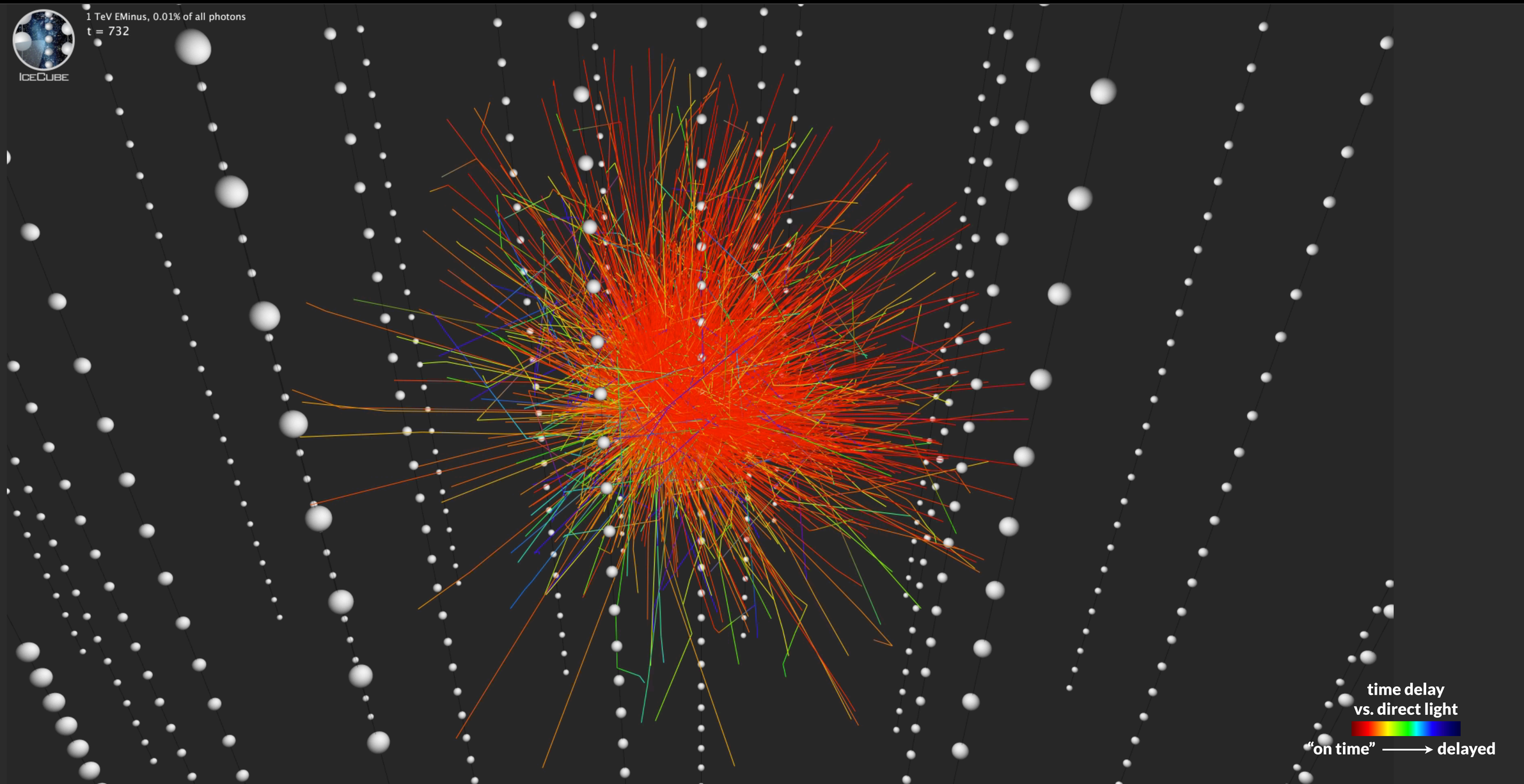


DETECTION PRINCIPLE (CASCADE IN WATER)

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



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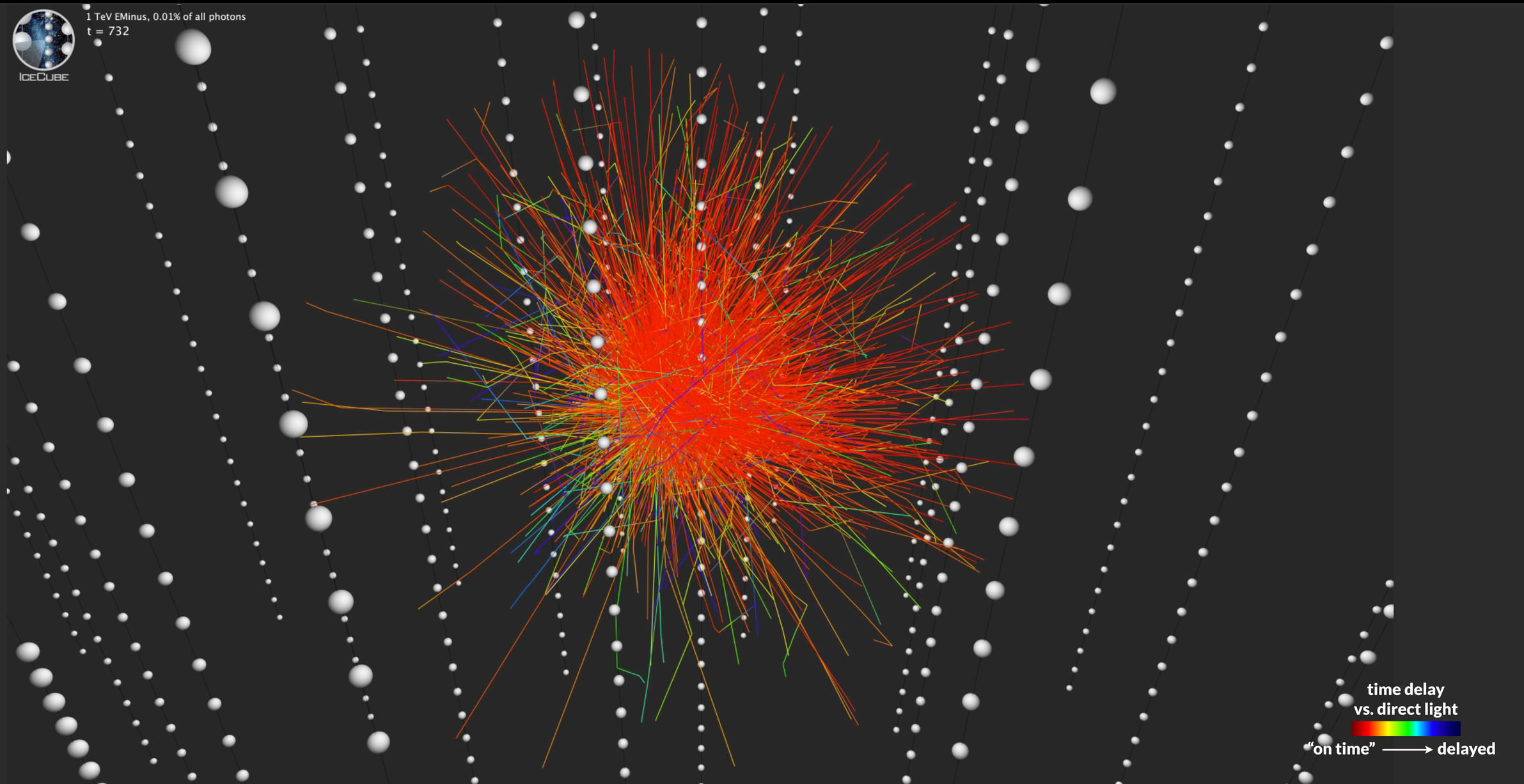


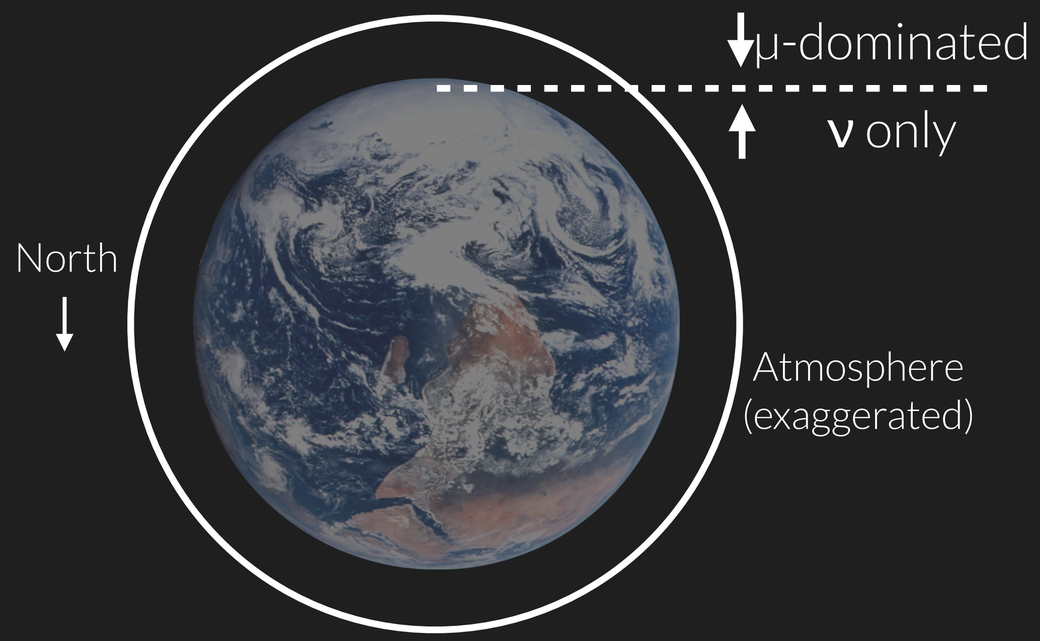
ISOLATING NEUTRINO EVENTS

two strategies

ISOLATING NEUTRINO EVENTS

two strategies

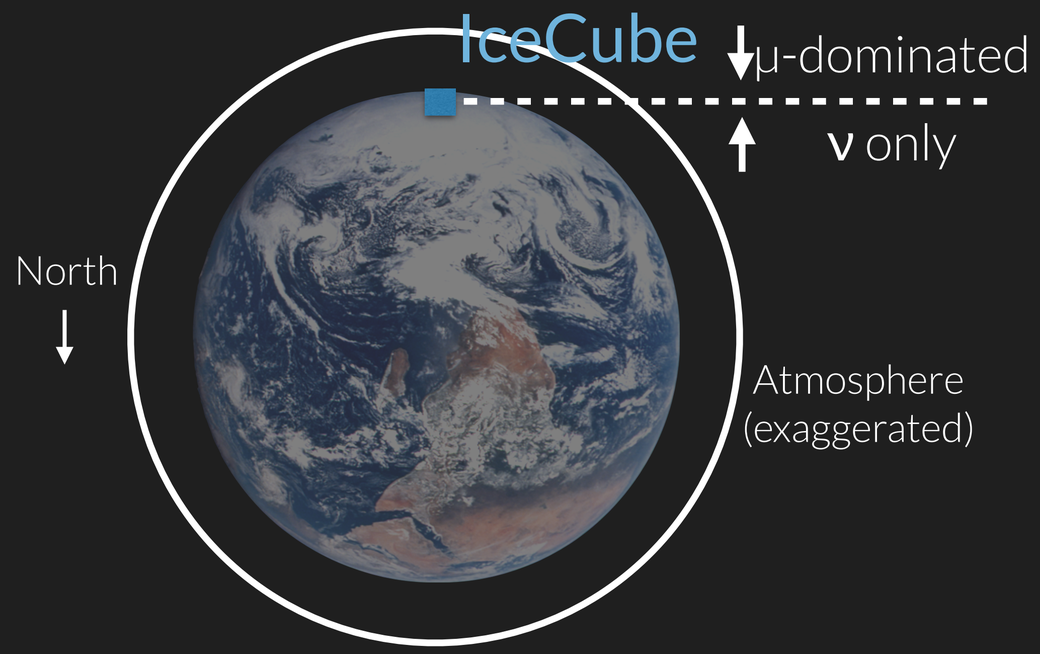
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

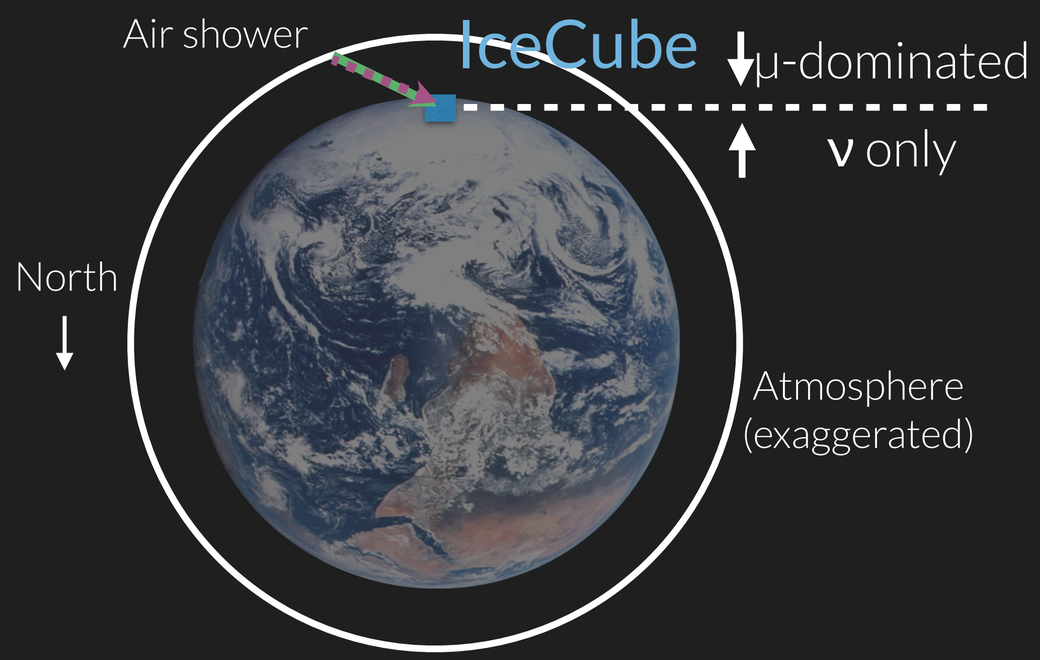
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

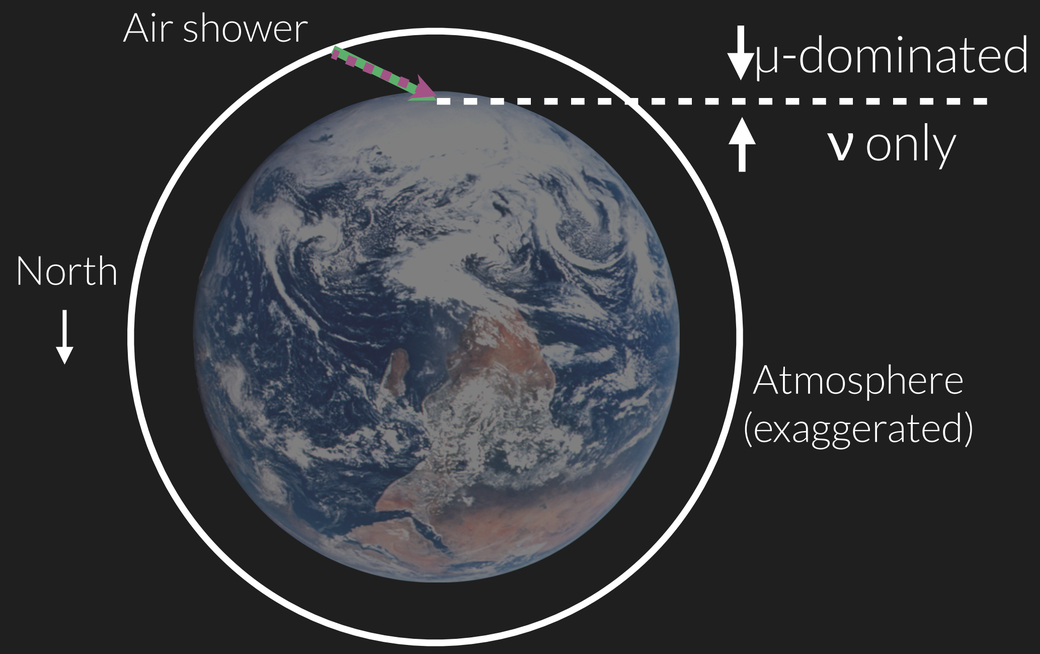
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

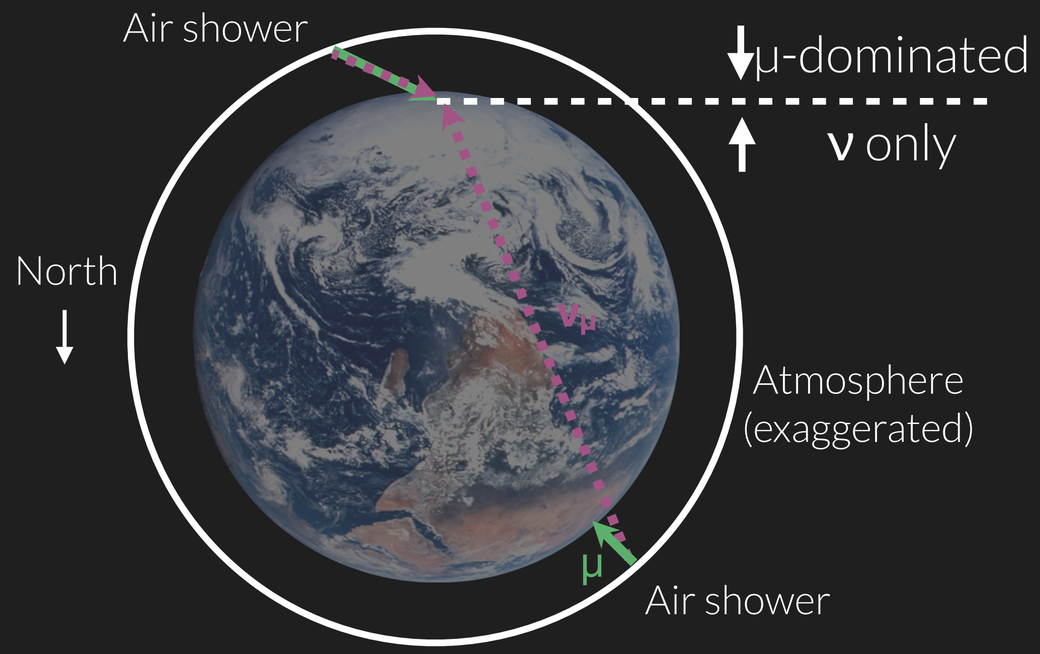
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

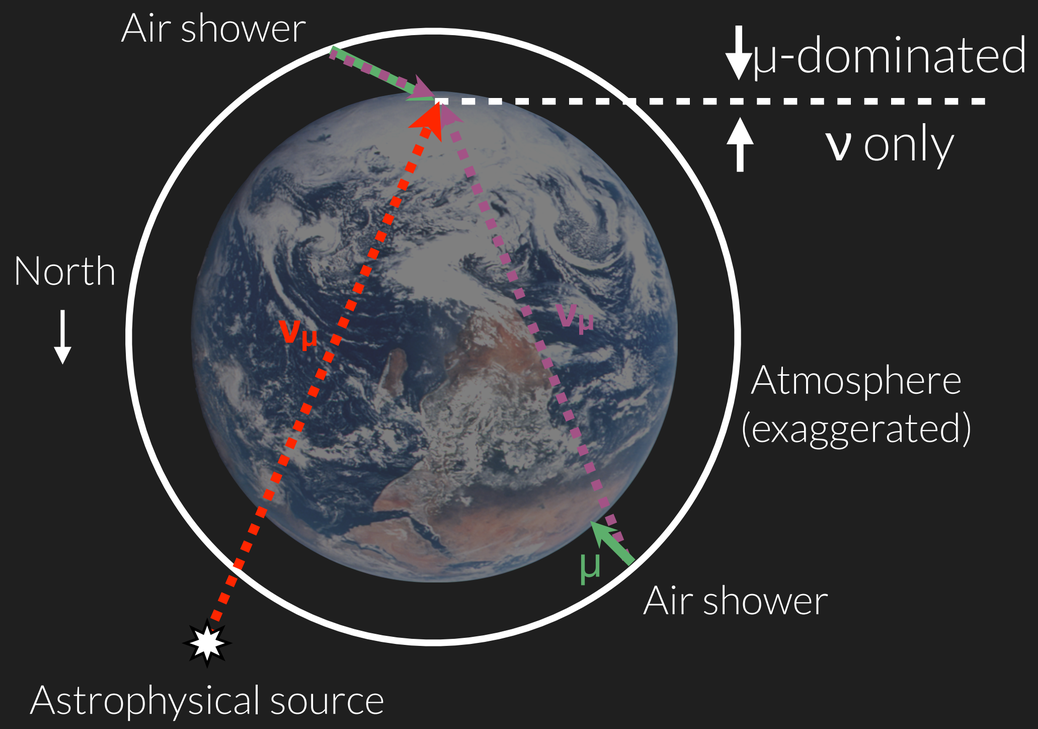
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

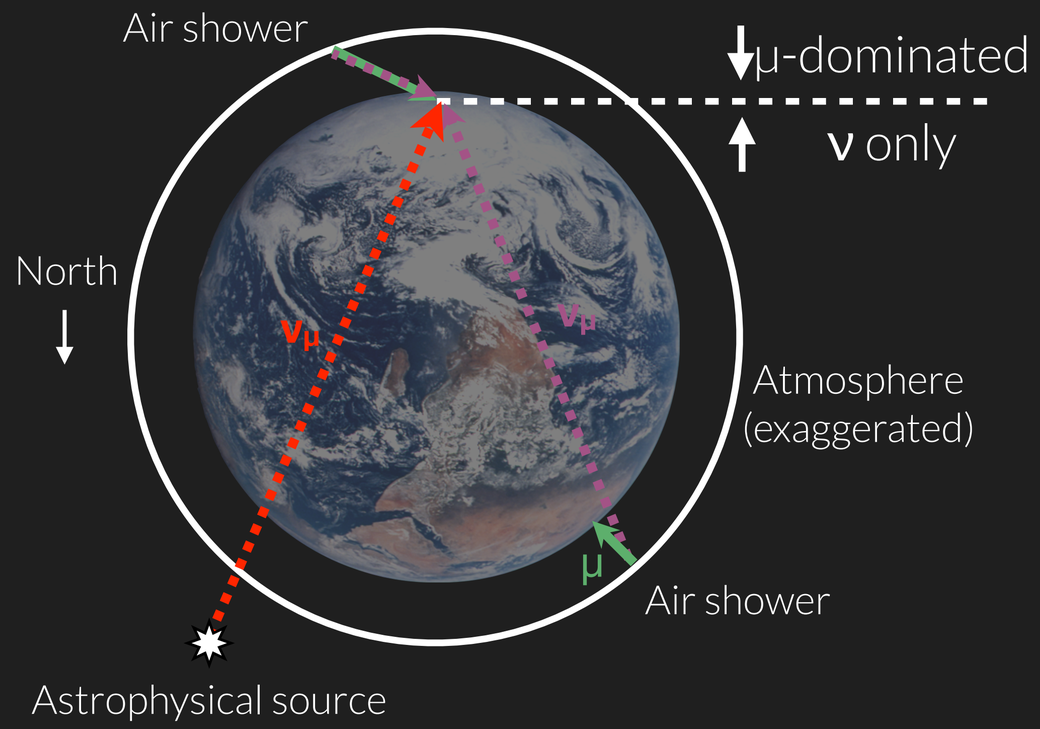
Up-going tracks



ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



Earth stops penetrating muons

Effective volume larger than detector

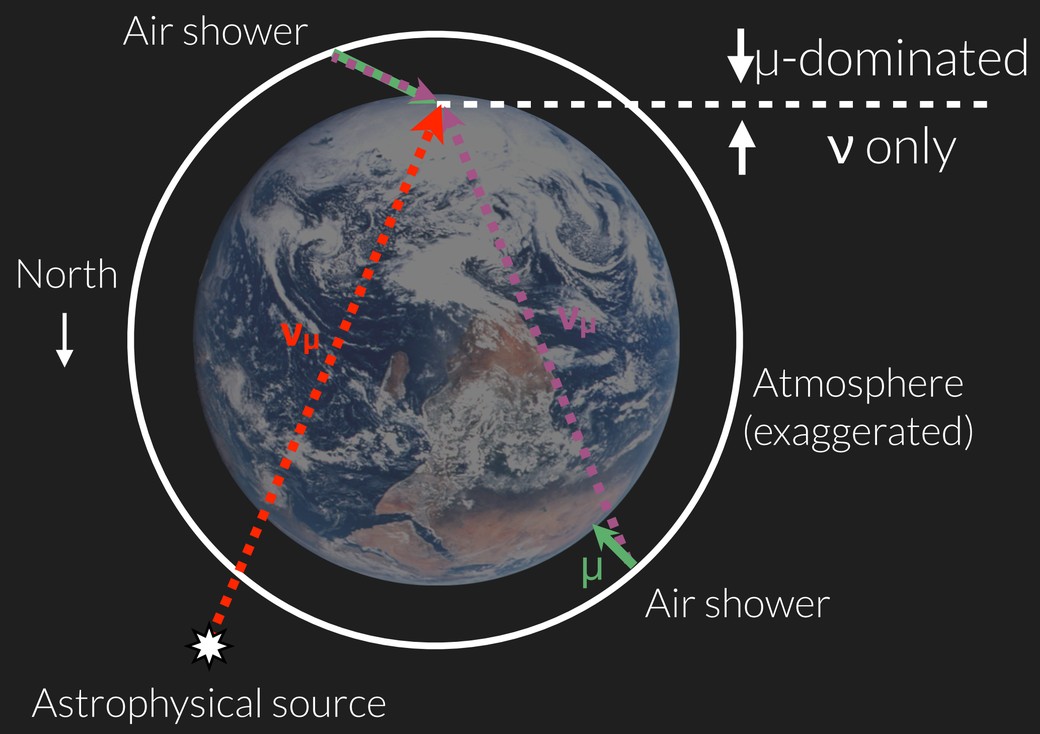
Sensitive to ν_μ only

Sensitive to “half” the sky

ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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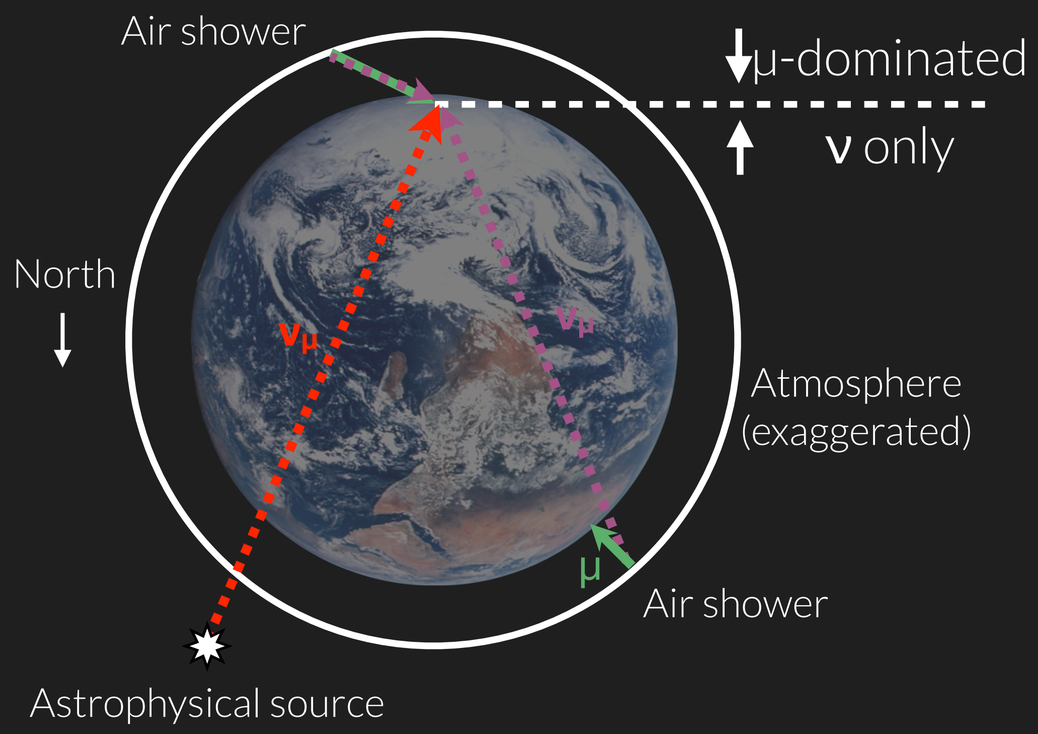
Active veto

ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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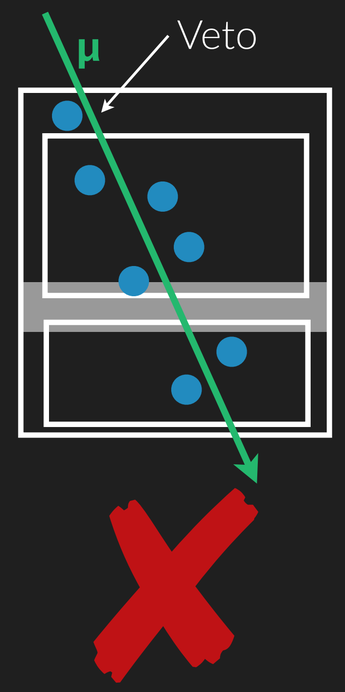
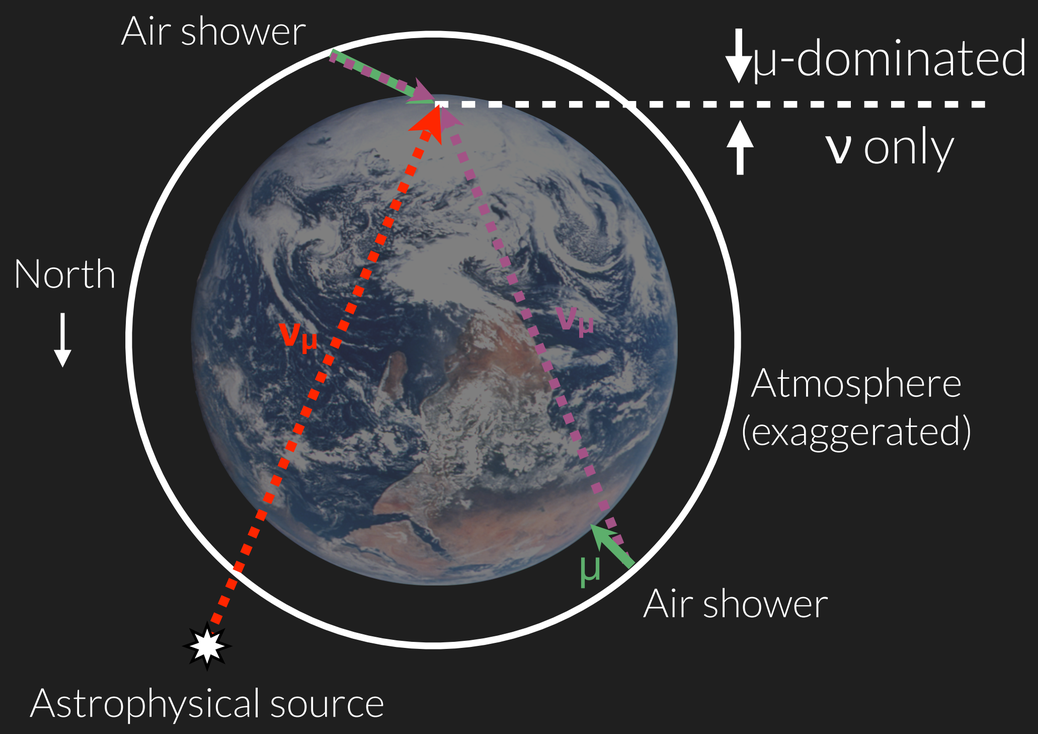


ISOLATING NEUTRINO EVENTS

two strategies

Up-going tracks



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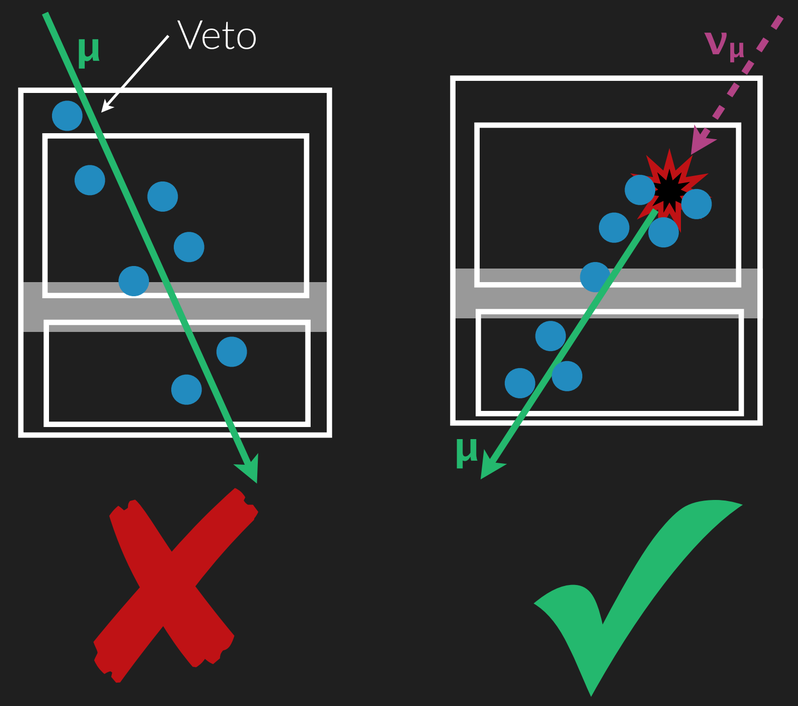
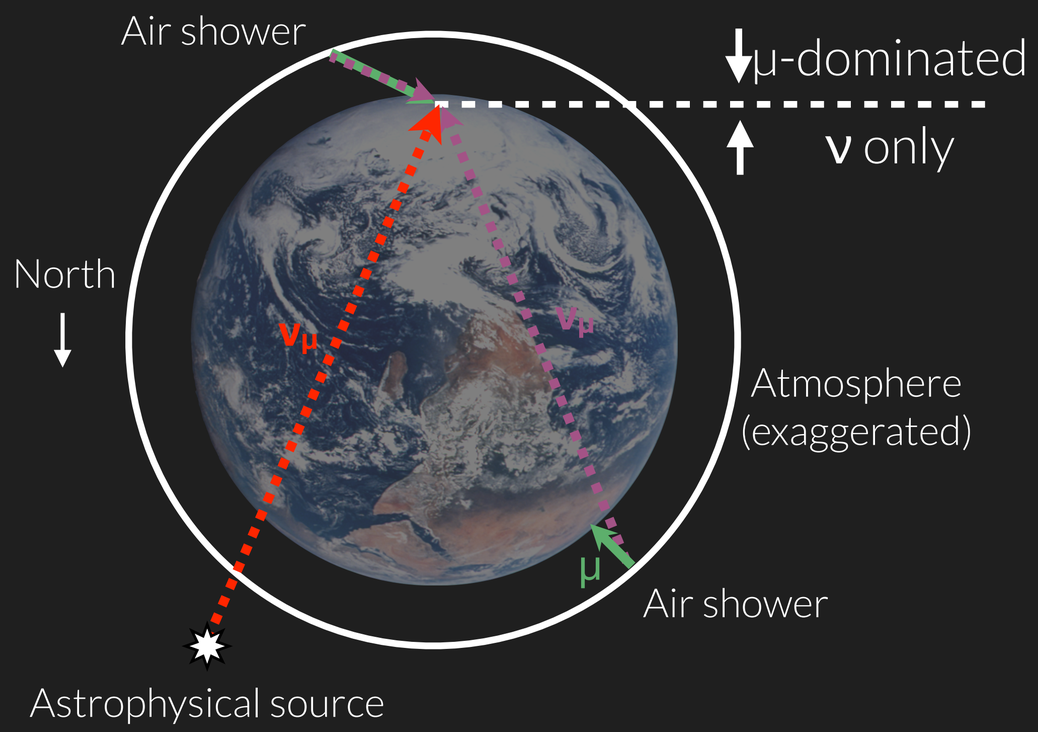
Active veto



ISOLATING NEUTRINO EVENTS

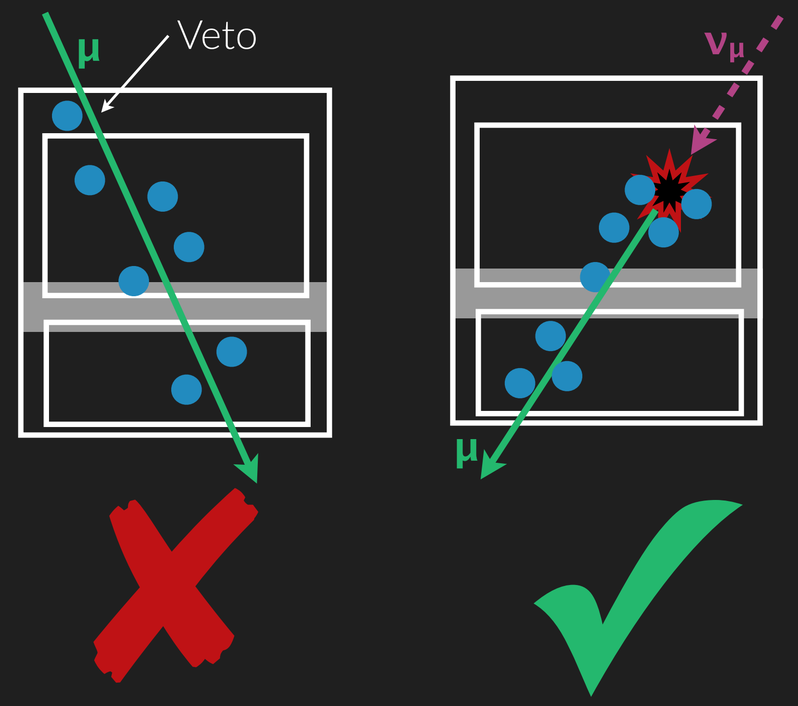
two strategies

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

CALIBRATION

Various calibration devices/methods to control detector systematics

LED flashers on each DOM

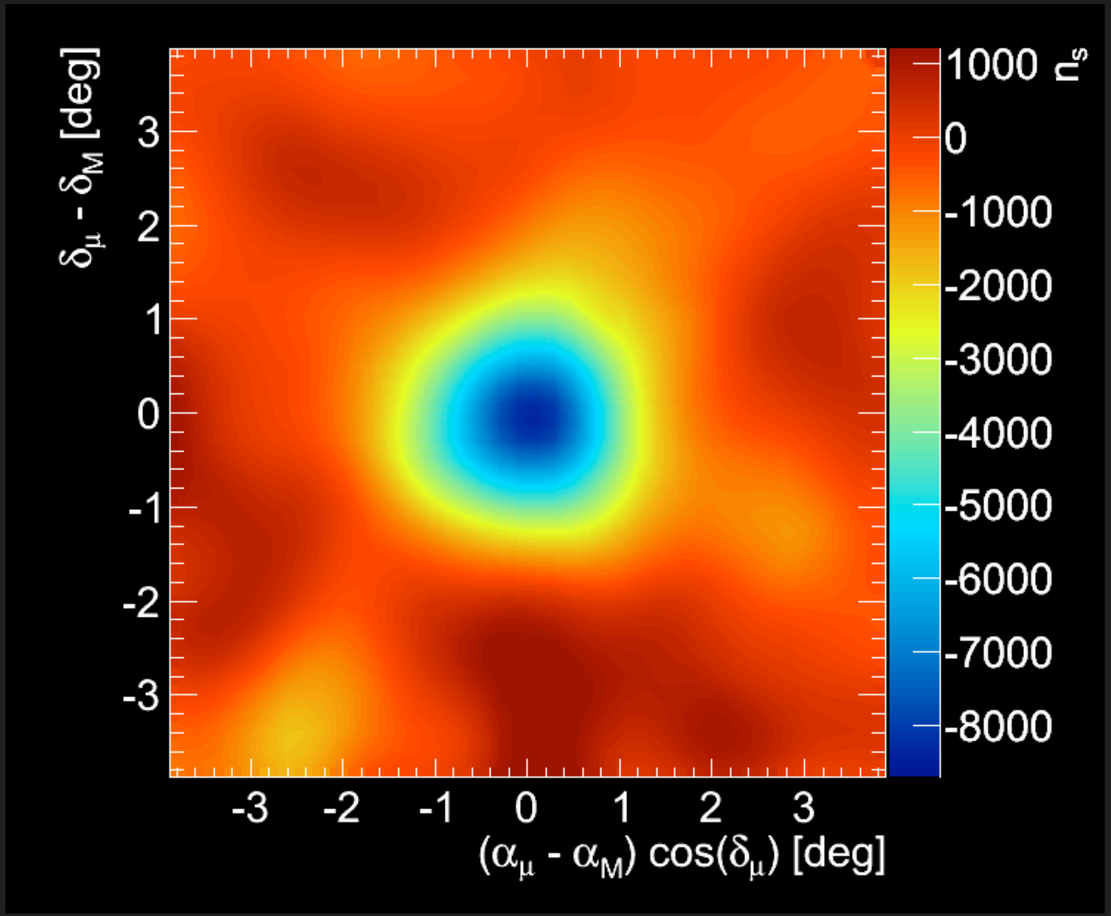
In-ice calibration **laser**

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))
- 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	Background
Dominated by showers (~80% per volume) from oscillations	Track-like events from Cosmic Ray muons and atmospheric ν_μ
High energy (benchmark spectrum is typically E^{-2})	Soft spectrum ($E^{-3.7}$ - $E^{-2.7}$)
Mostly in the Southern Sky due to absorption of high-energy neutrinos in the Earth	Muons in the Southern Sky, neutrinos from the North

"STARTING EVENT" ANALYSIS

Specifically designed to find contained events.

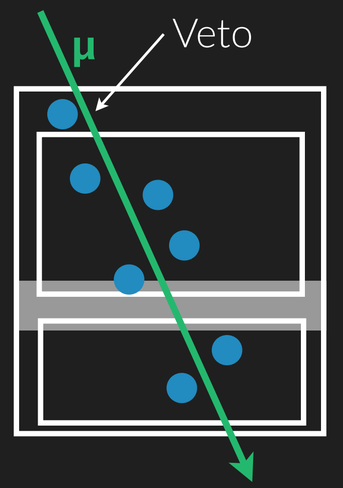
Explicit contained search at high energies (cut: Qtot>6000 p.e.)

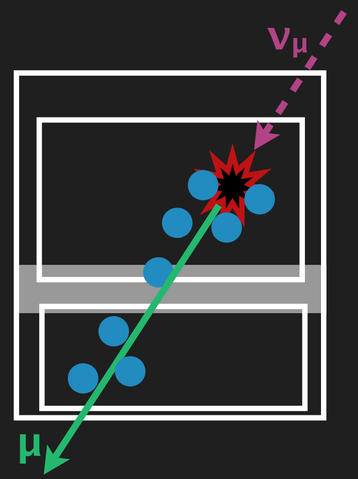
400 Mton effective fiducial mass

Use atmospheric muon veto

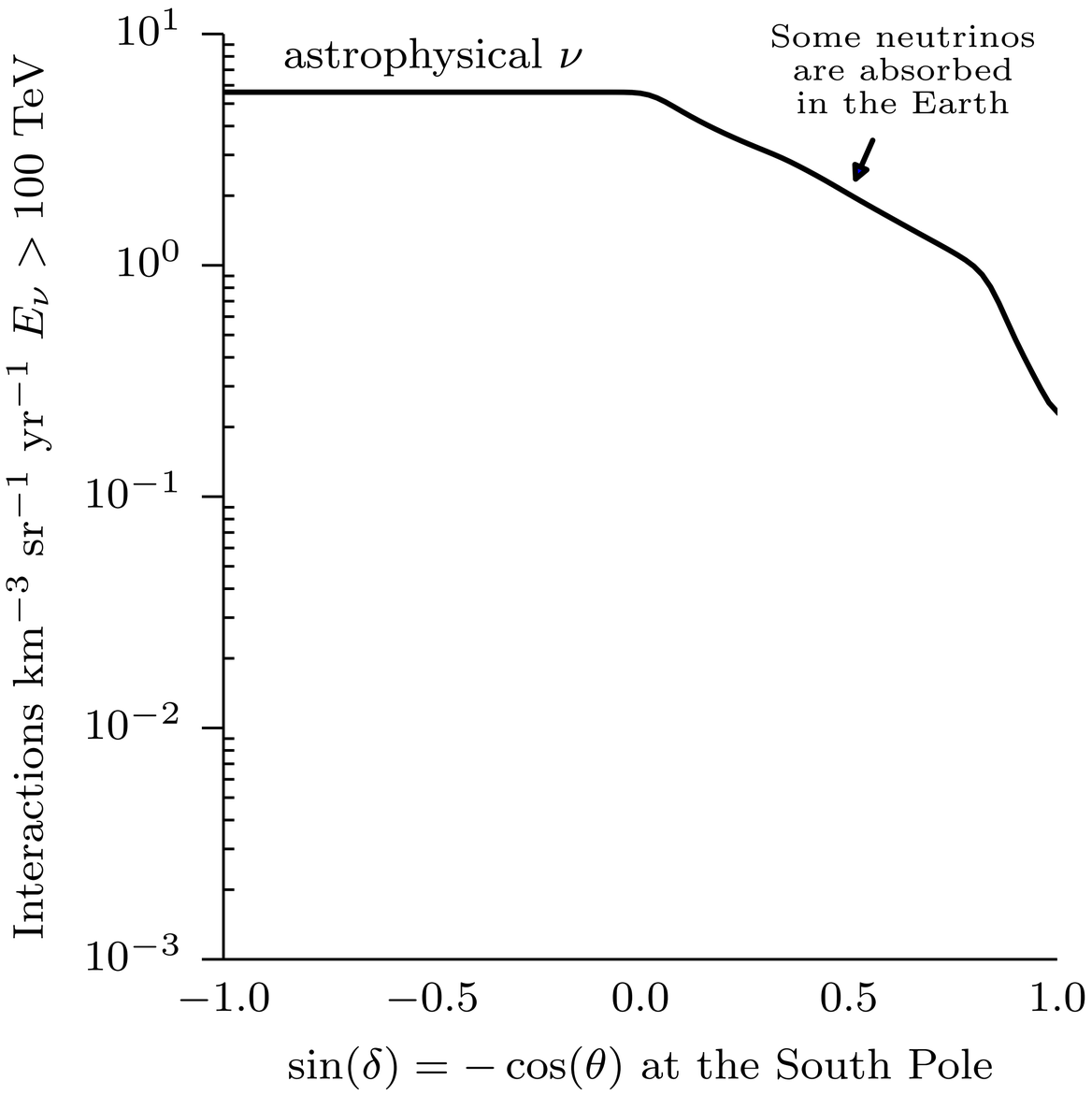
Sensitive to all flavors in region above 60TeV deposited energy

Estimate background from data



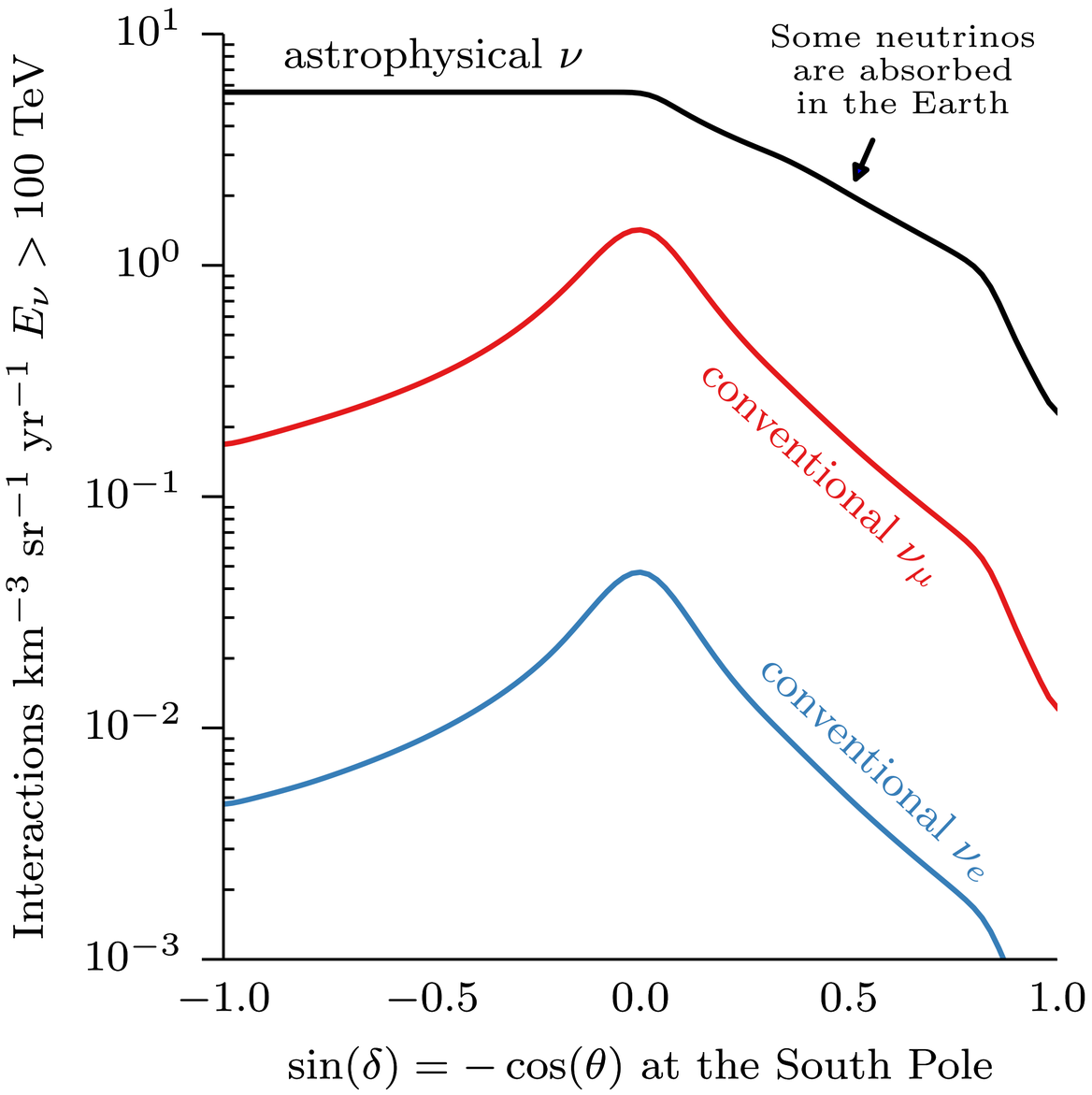


Atmospheric neutrino self-veto



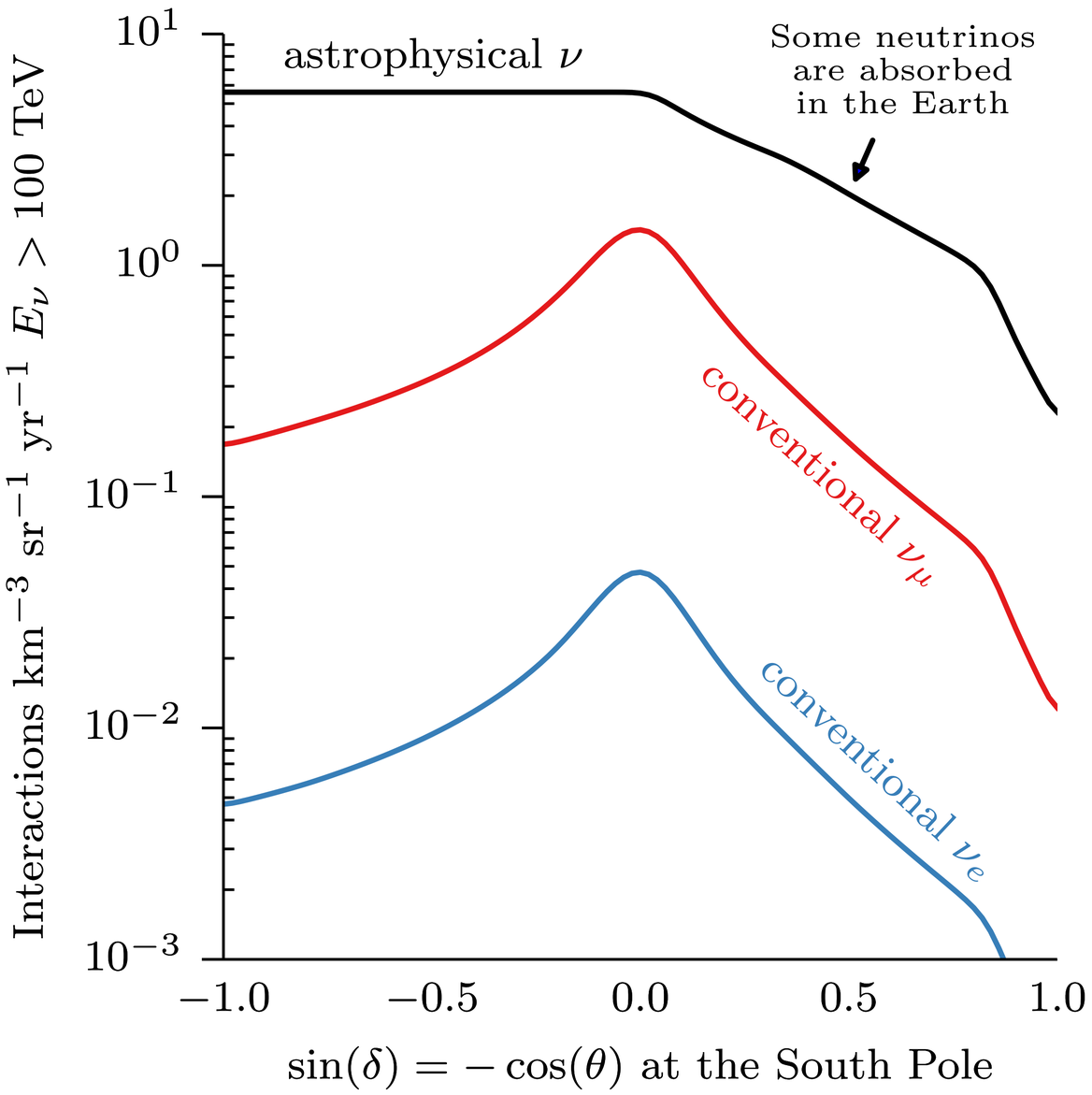
slide courtesy of J. van Santen

Atmospheric neutrino self-veto

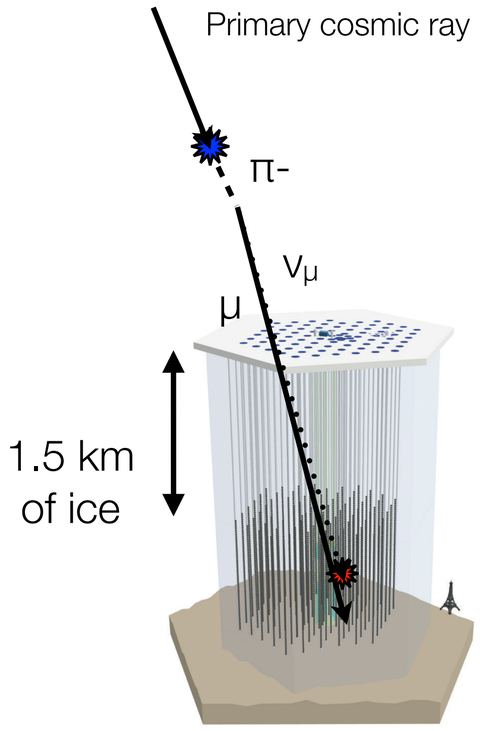


slide courtesy of J. van Santen

Atmospheric neutrino self-veto



An active muon veto removes down-going atmospheric neutrinos.

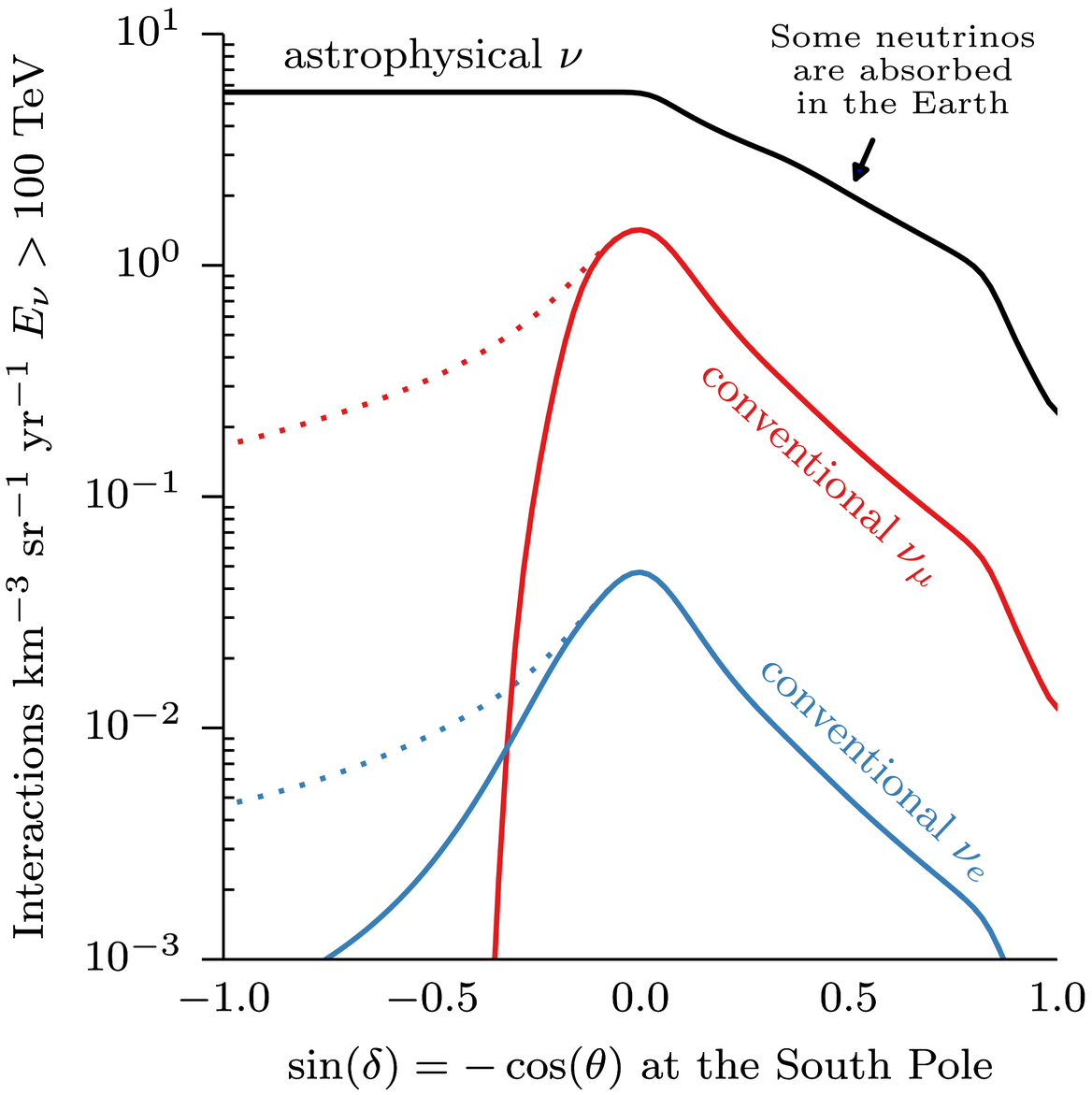


Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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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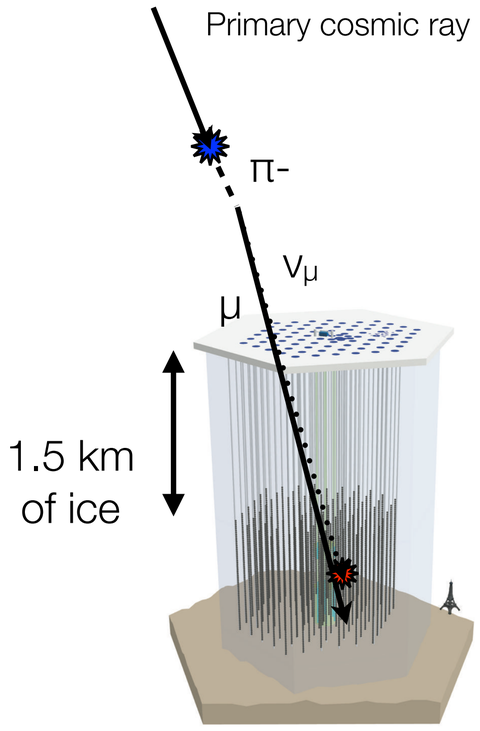

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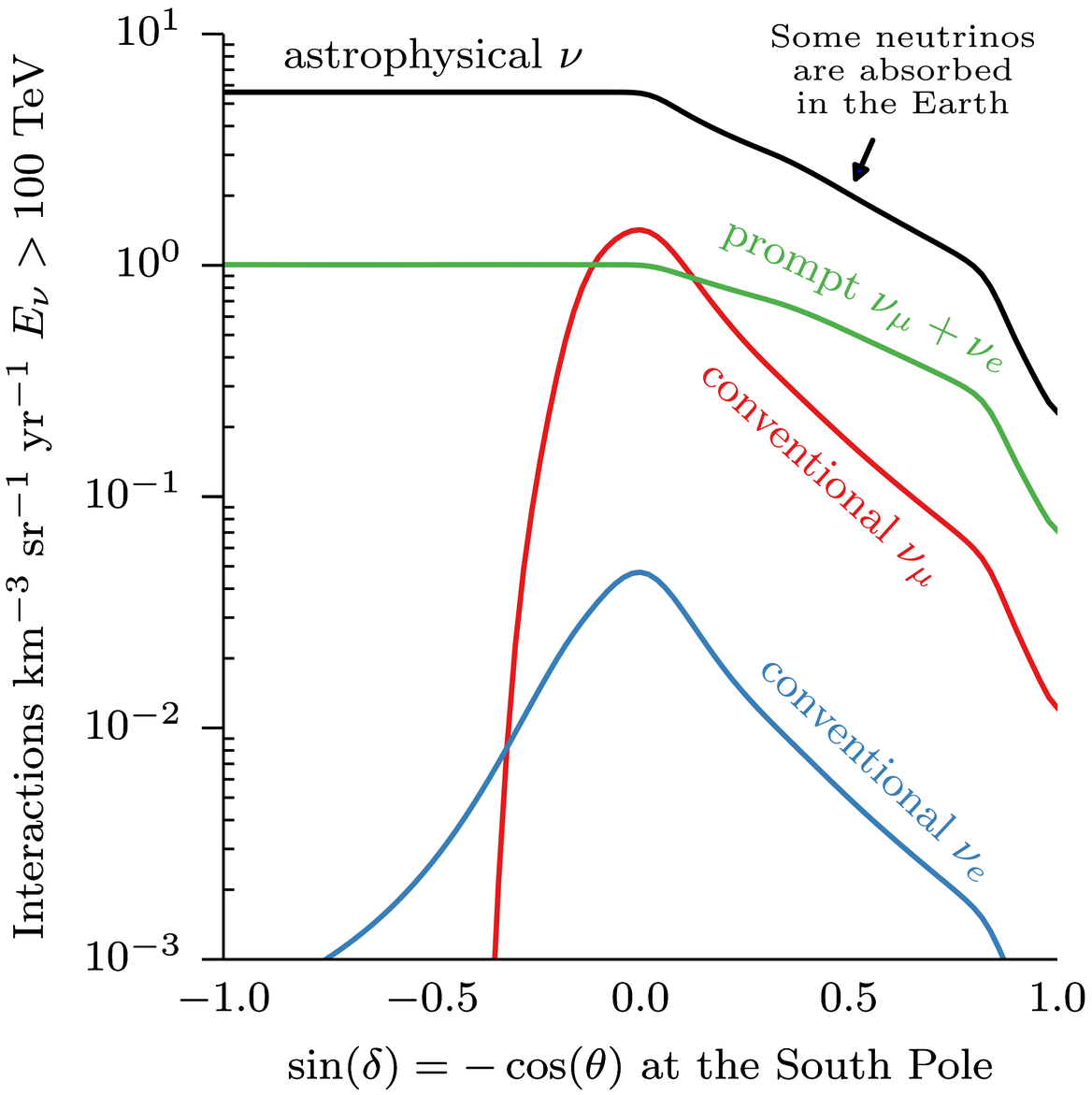

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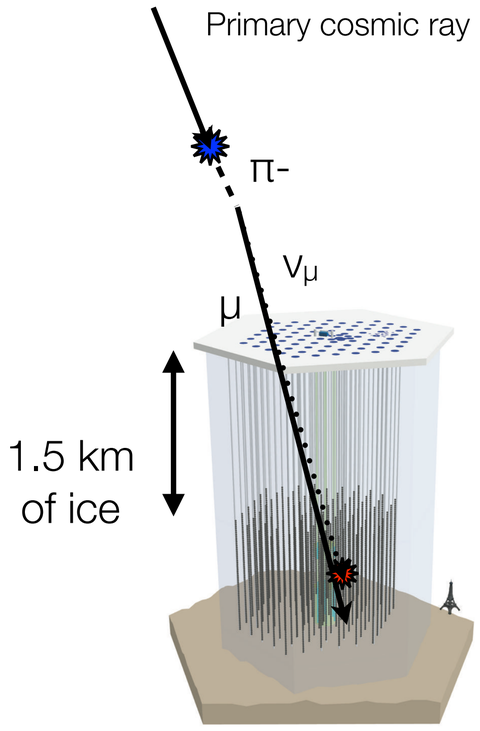

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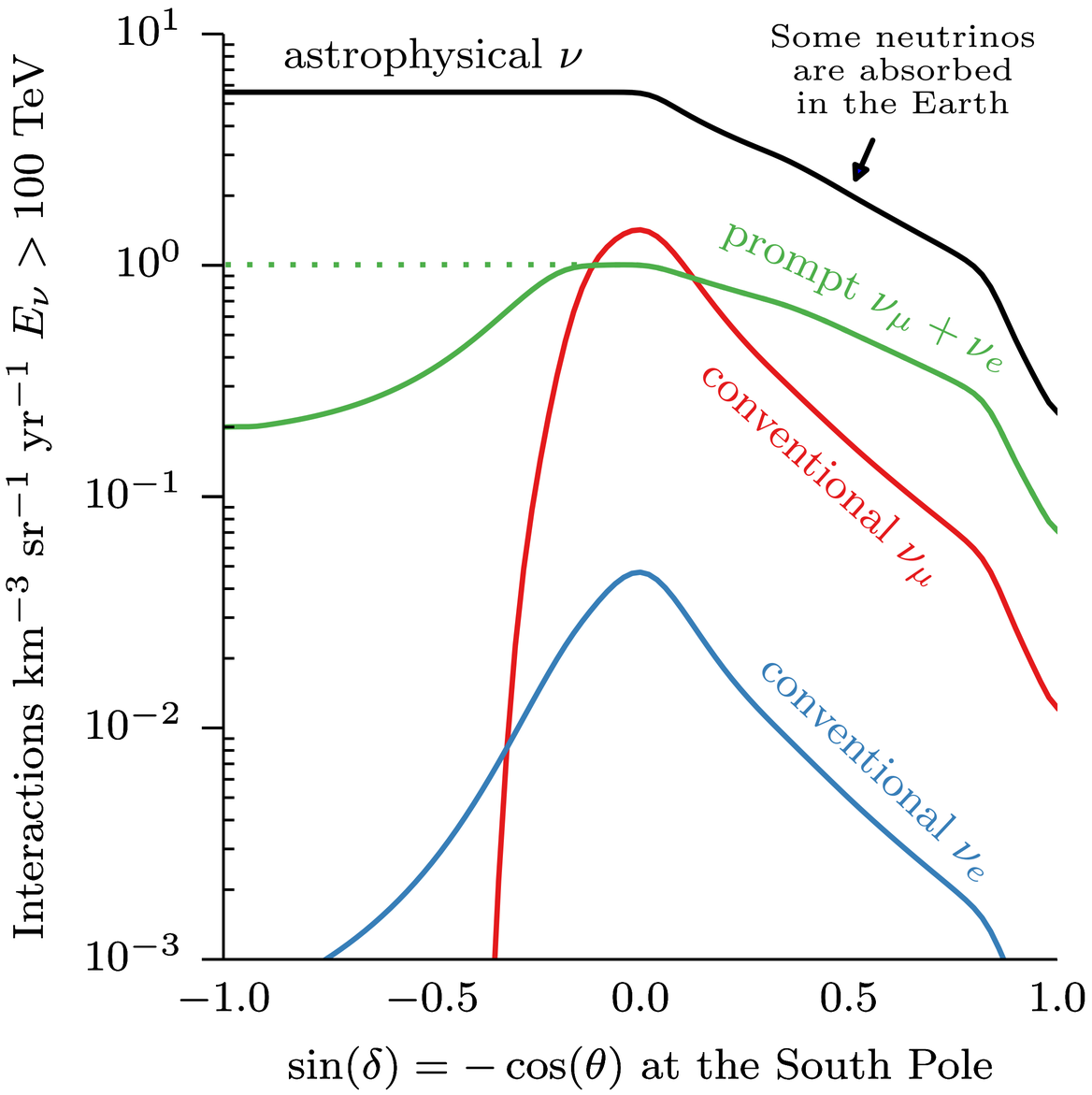
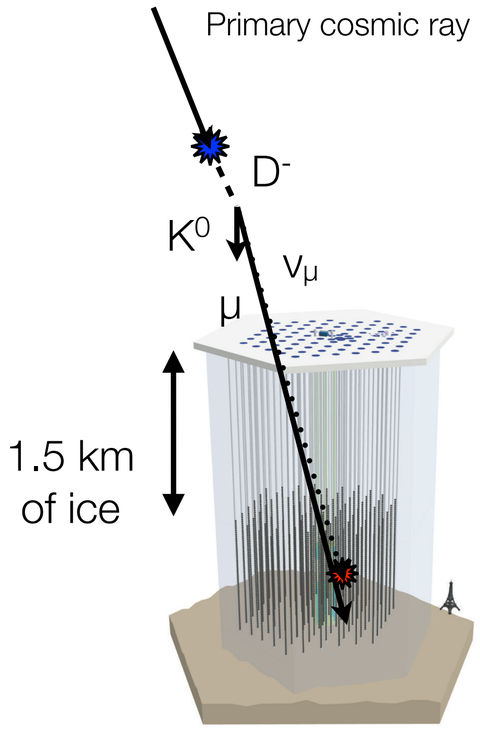


Prompt atmospheric neutrinos are vetoed, too.



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

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slide courtesy of J. van Santen

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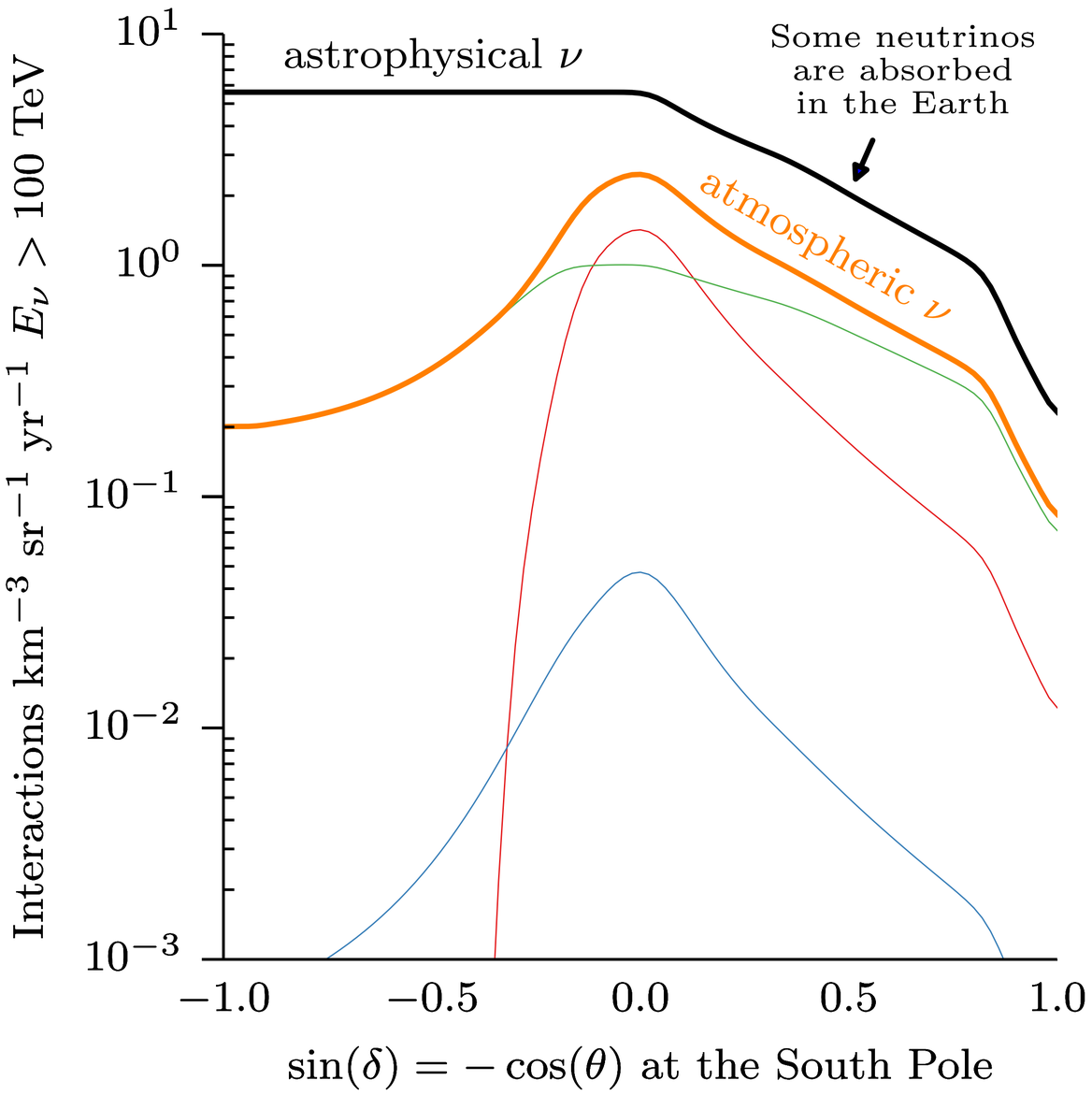


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

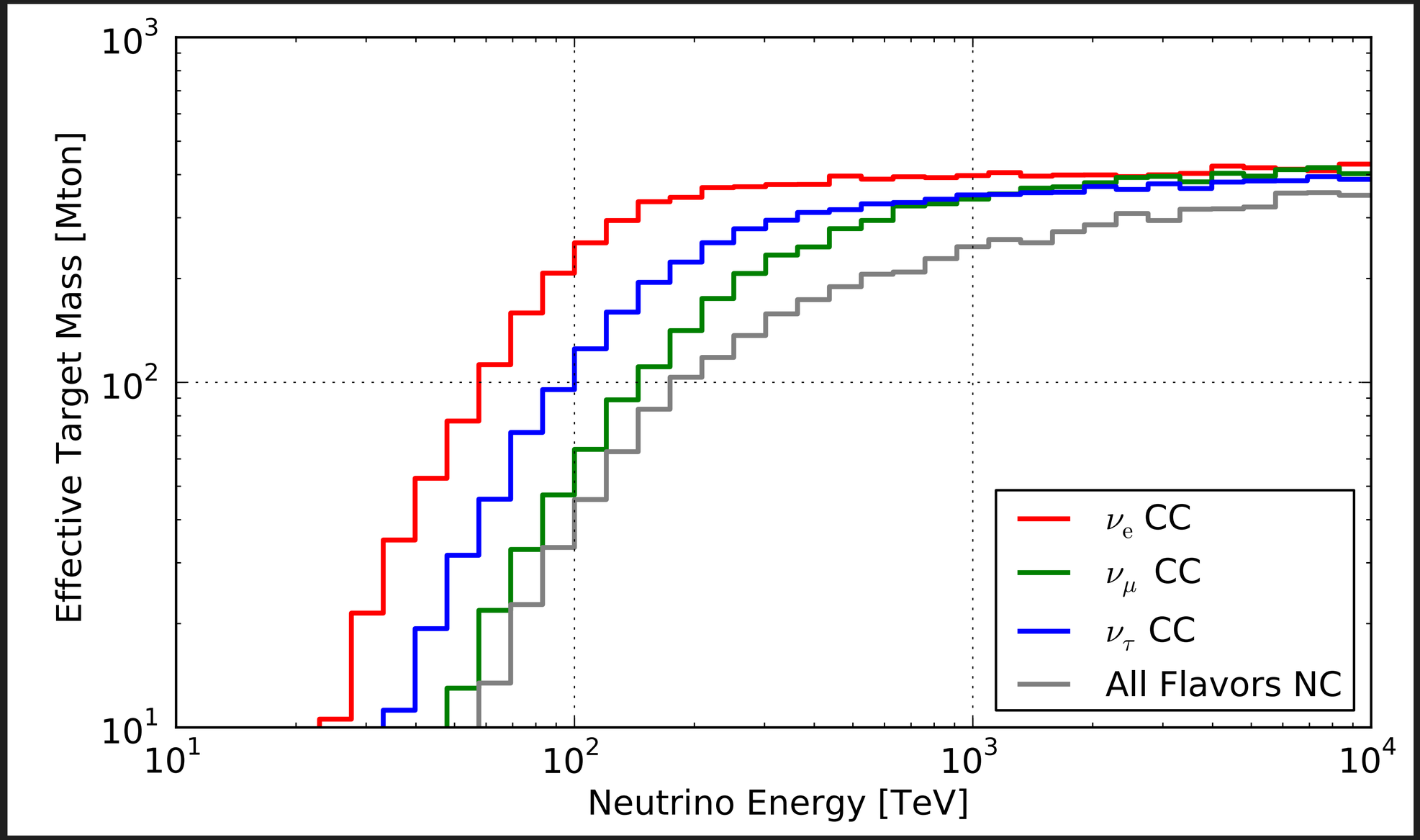
Schönert, Resconi, Schulz, Phys. Rev. D, 79:043009 (2009)

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!

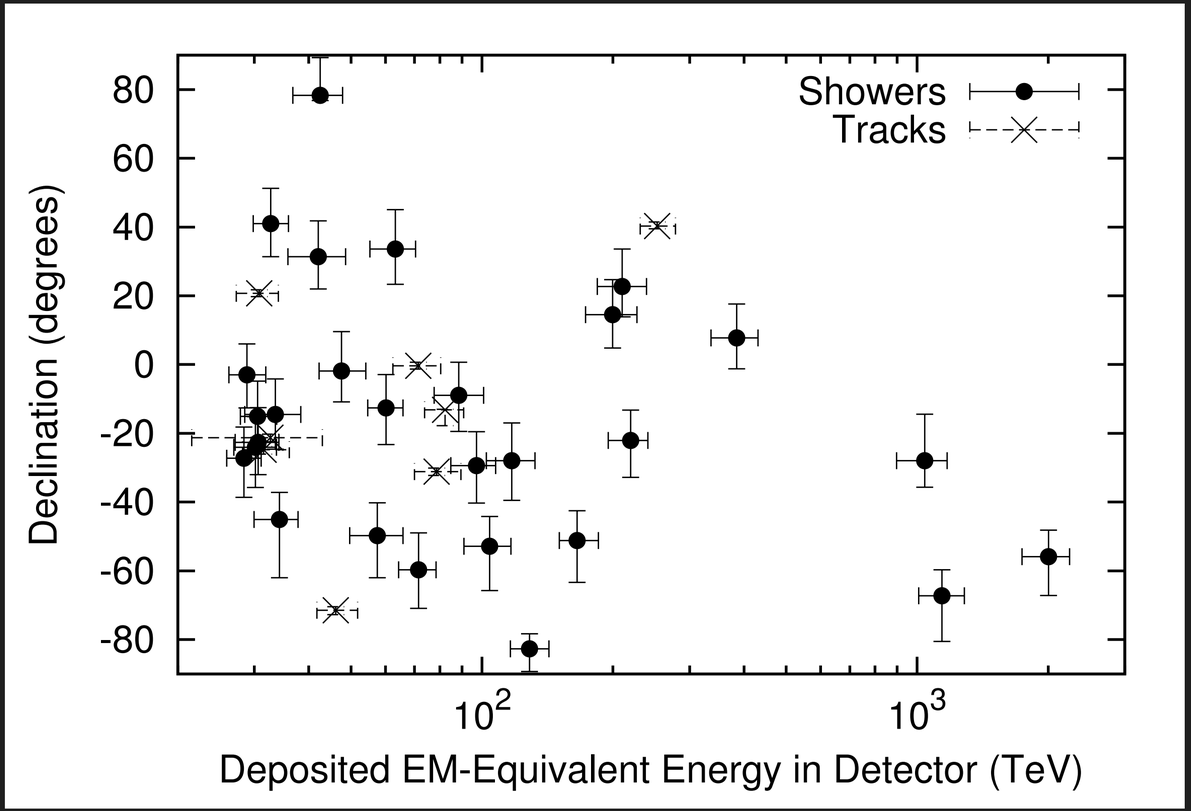
Estimated background:

$6.6^{+5.9}_{-1.6}$ 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!

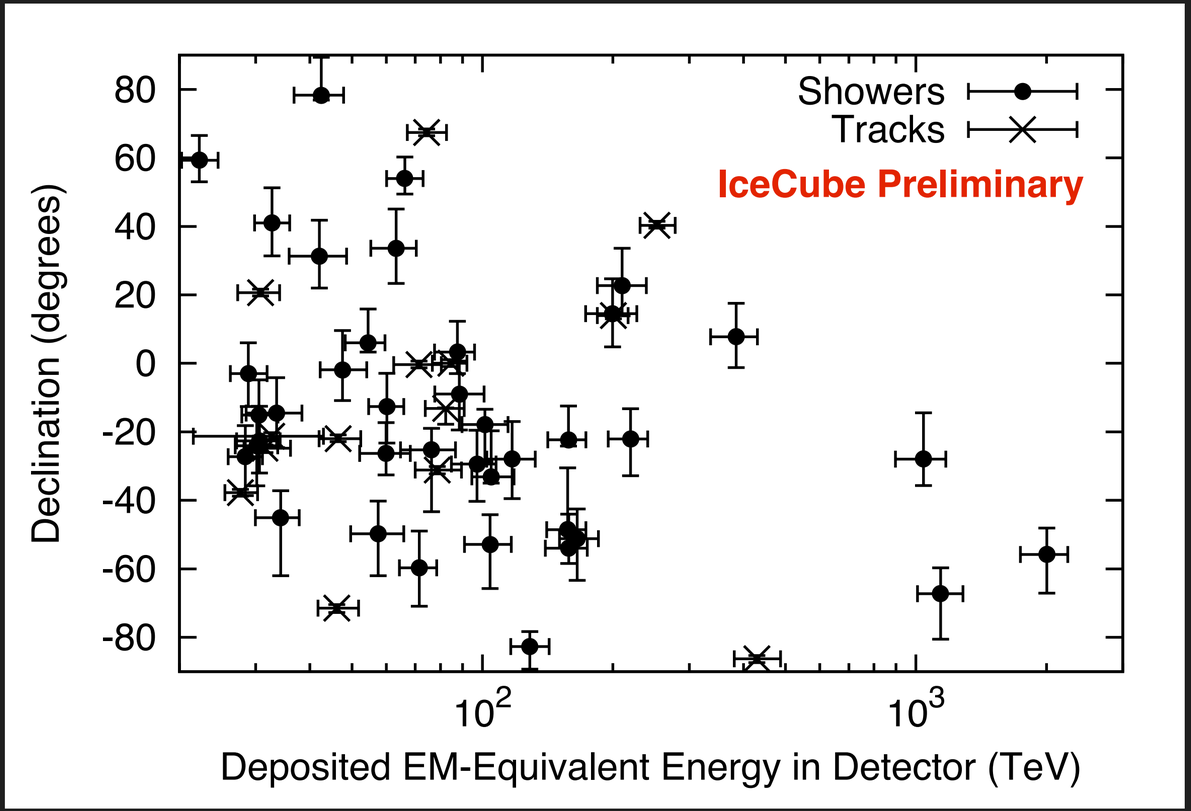
Estimated background:

$9.0^{+8.0}_{-2.2}$ 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

WHAT DID ICECUBE FIND? (4 YEARS)

54 events!

53(+1) events observed!

Estimated background:

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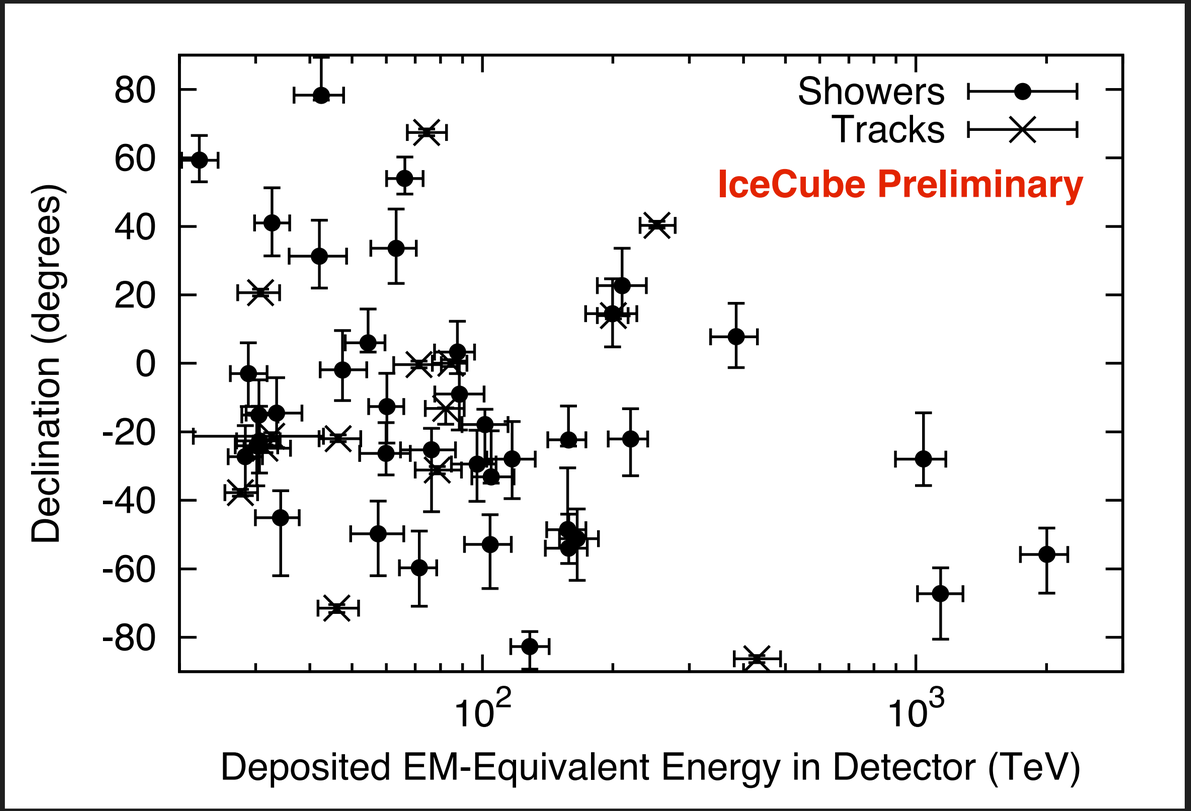

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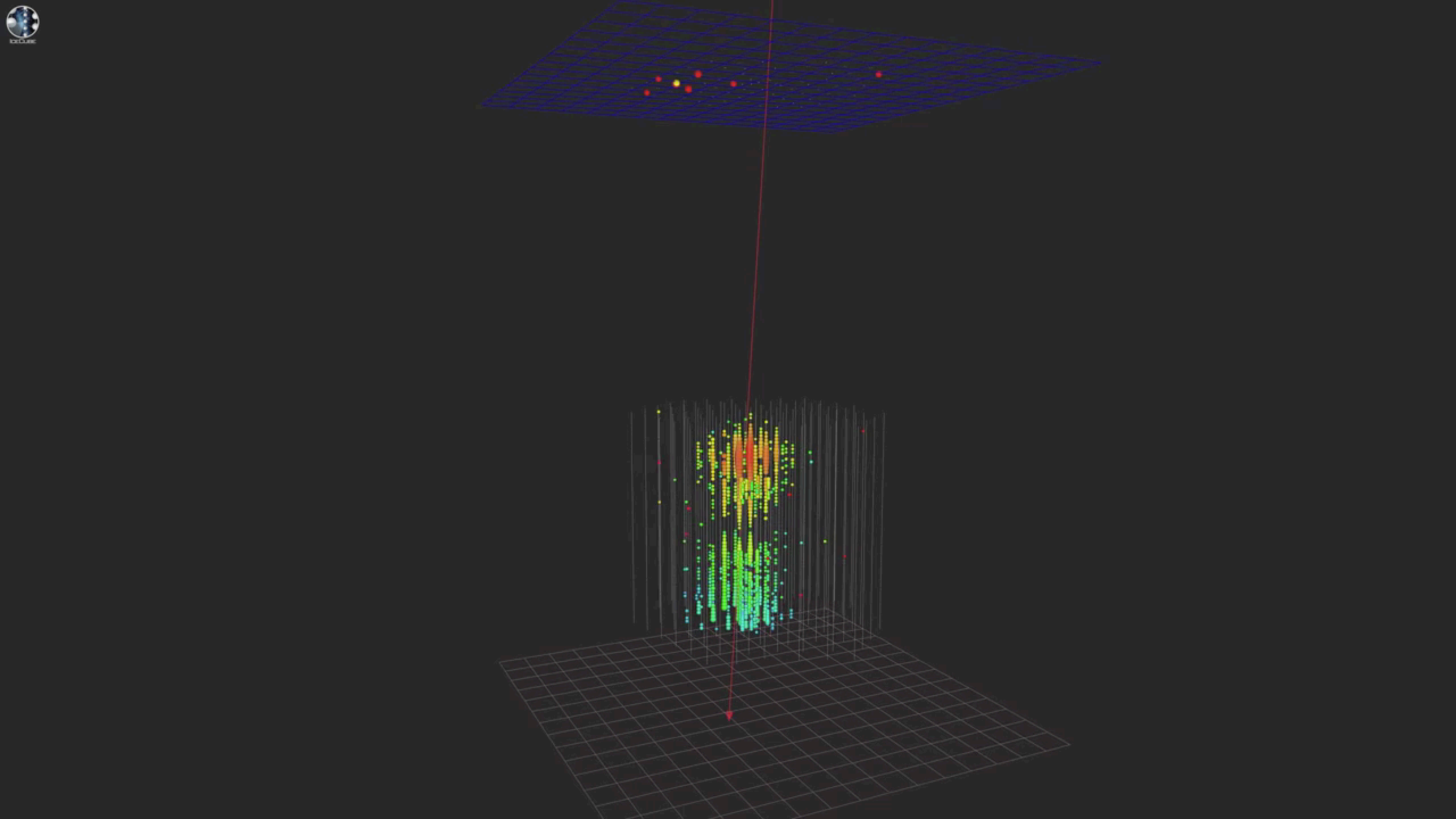
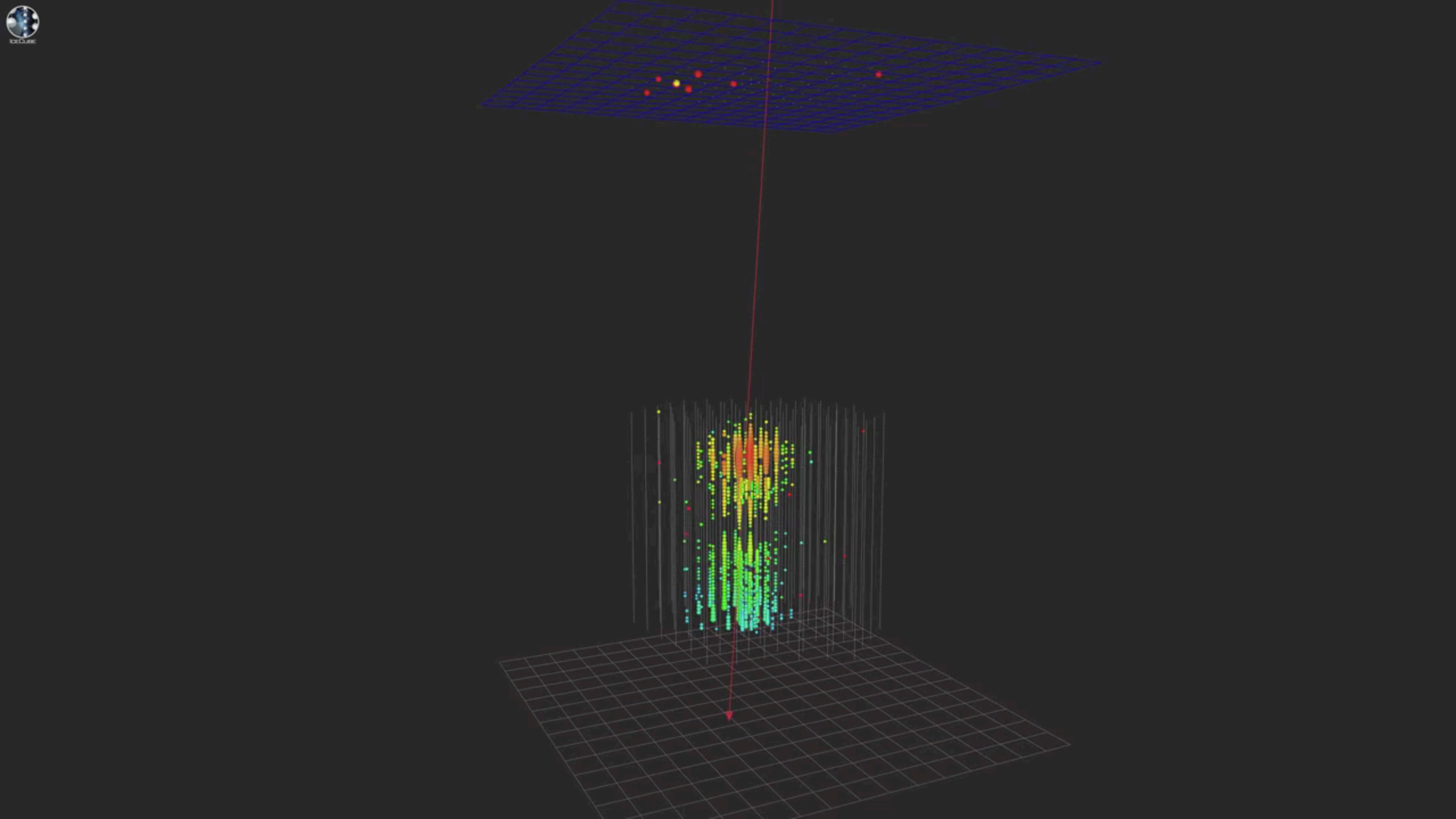
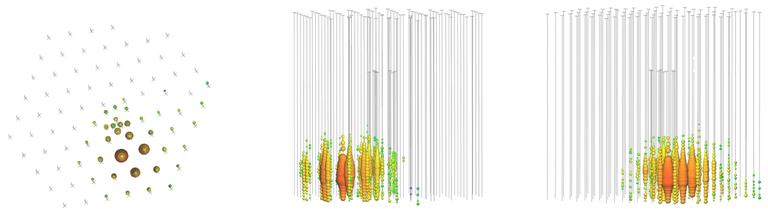
Poster 278 (Poster 3 DM and NU)



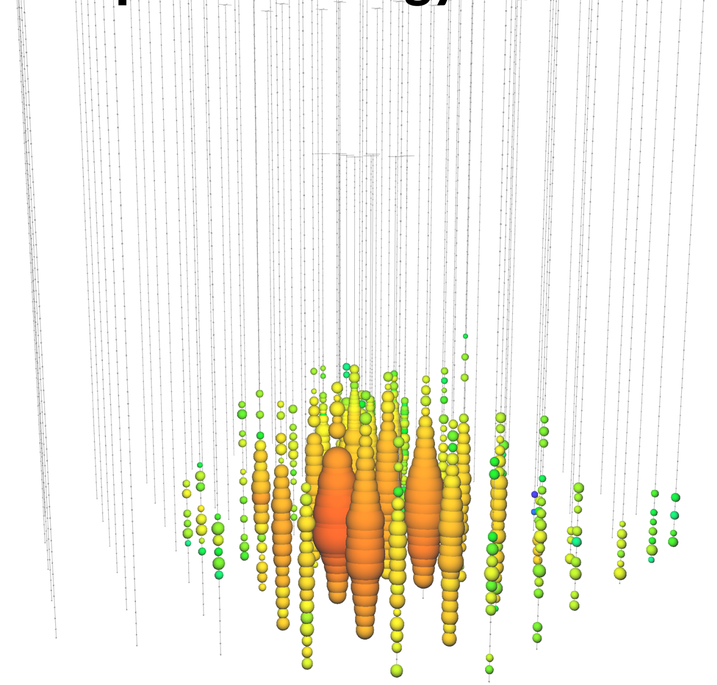


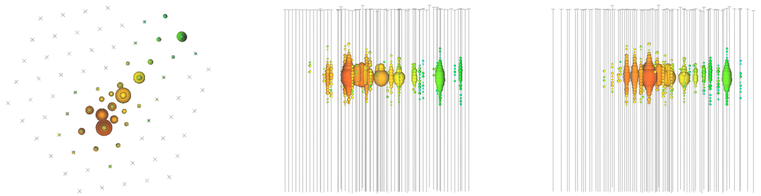
WHAT DID ICECUBE FIND?

some examples

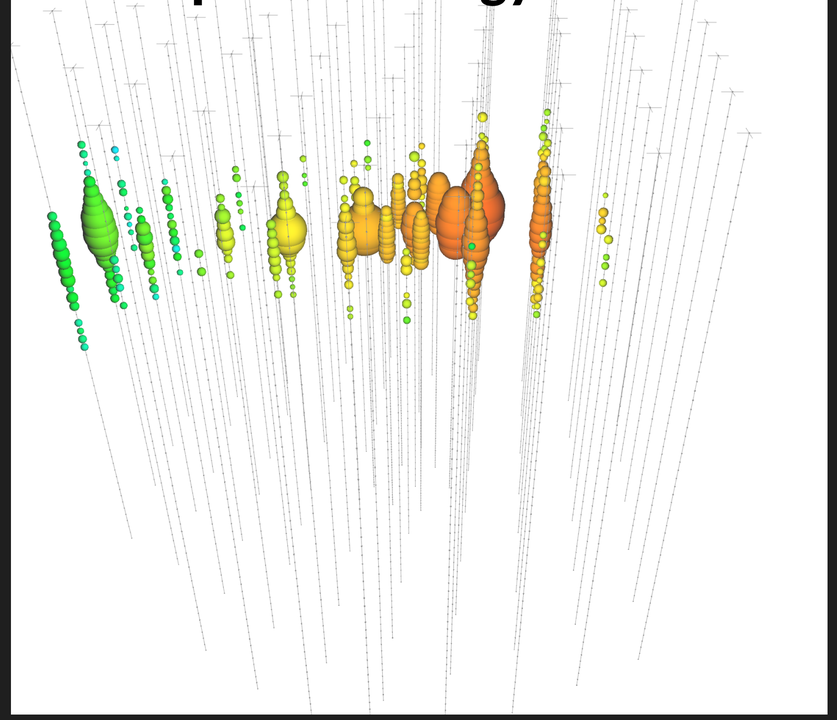


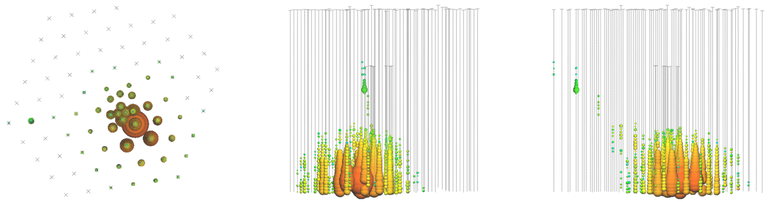
declination: -13.2°
deposited energy: 82TeV



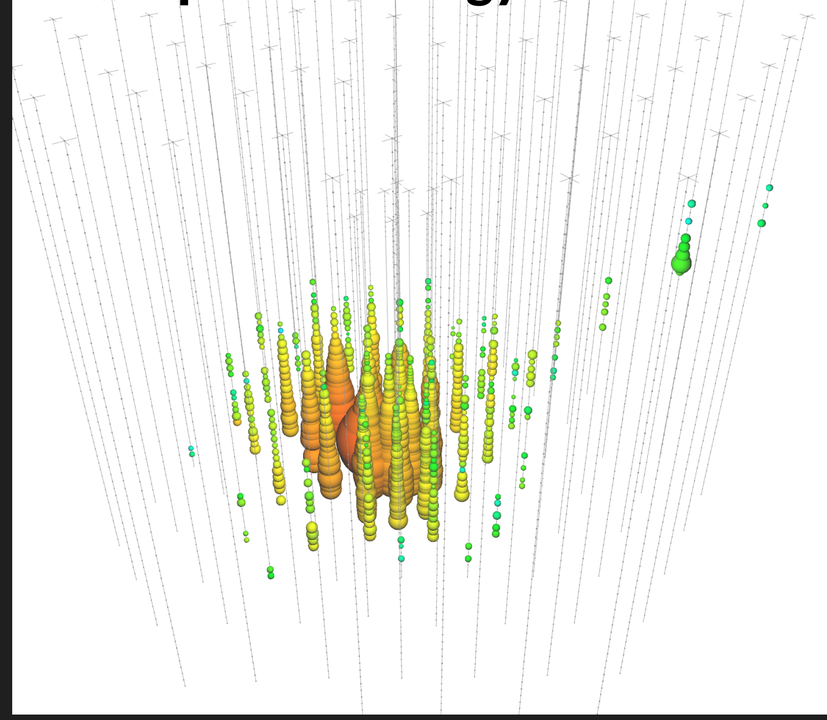


declination: -0.4°
deposited energy: 71TeV





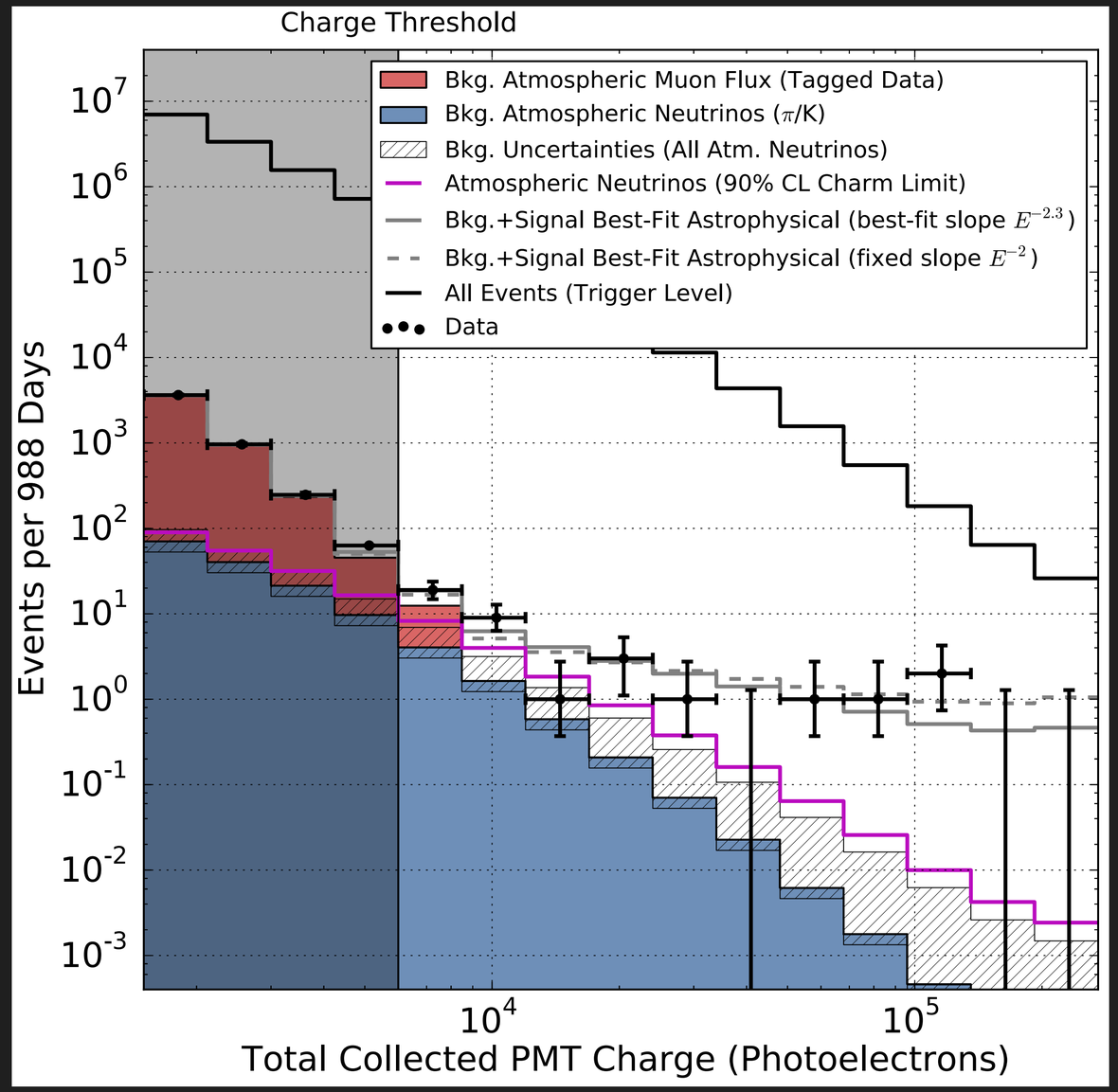
declination: 40.3°
deposited energy: 253TeV



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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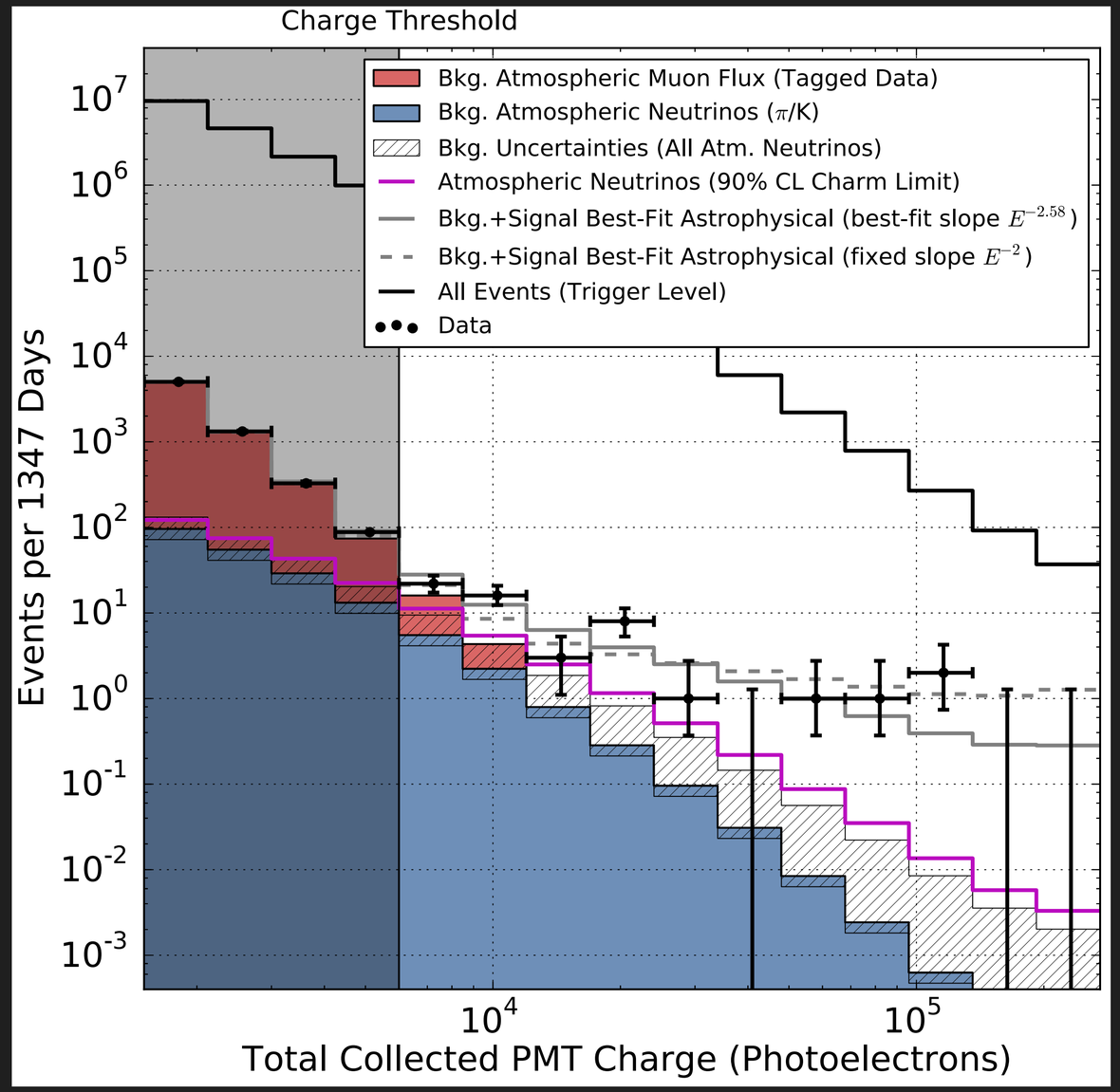


ENERGY SPECTRUM (3 YEARS)

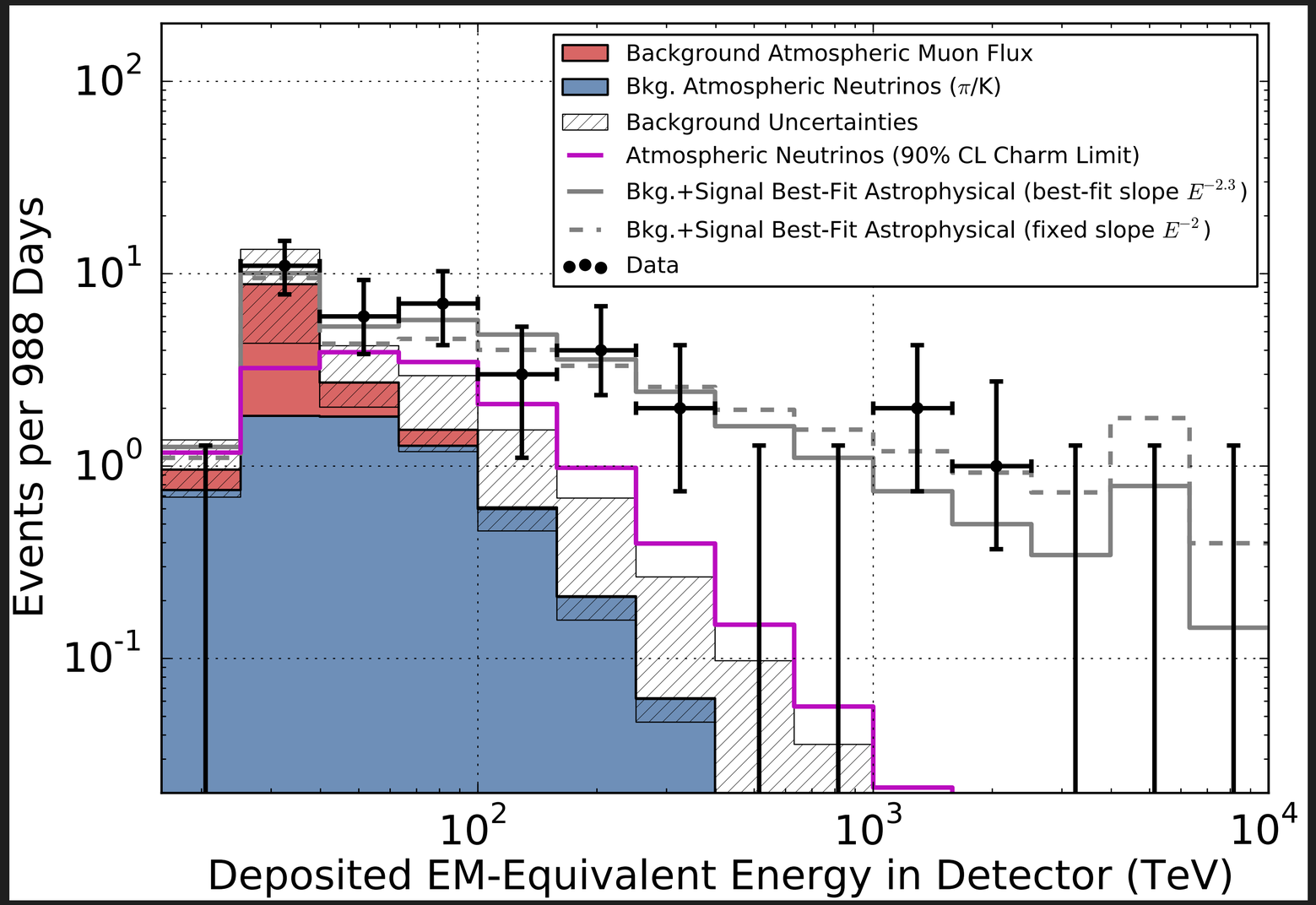
energy deposited in the detector (lower limit on neutrino energy)

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)

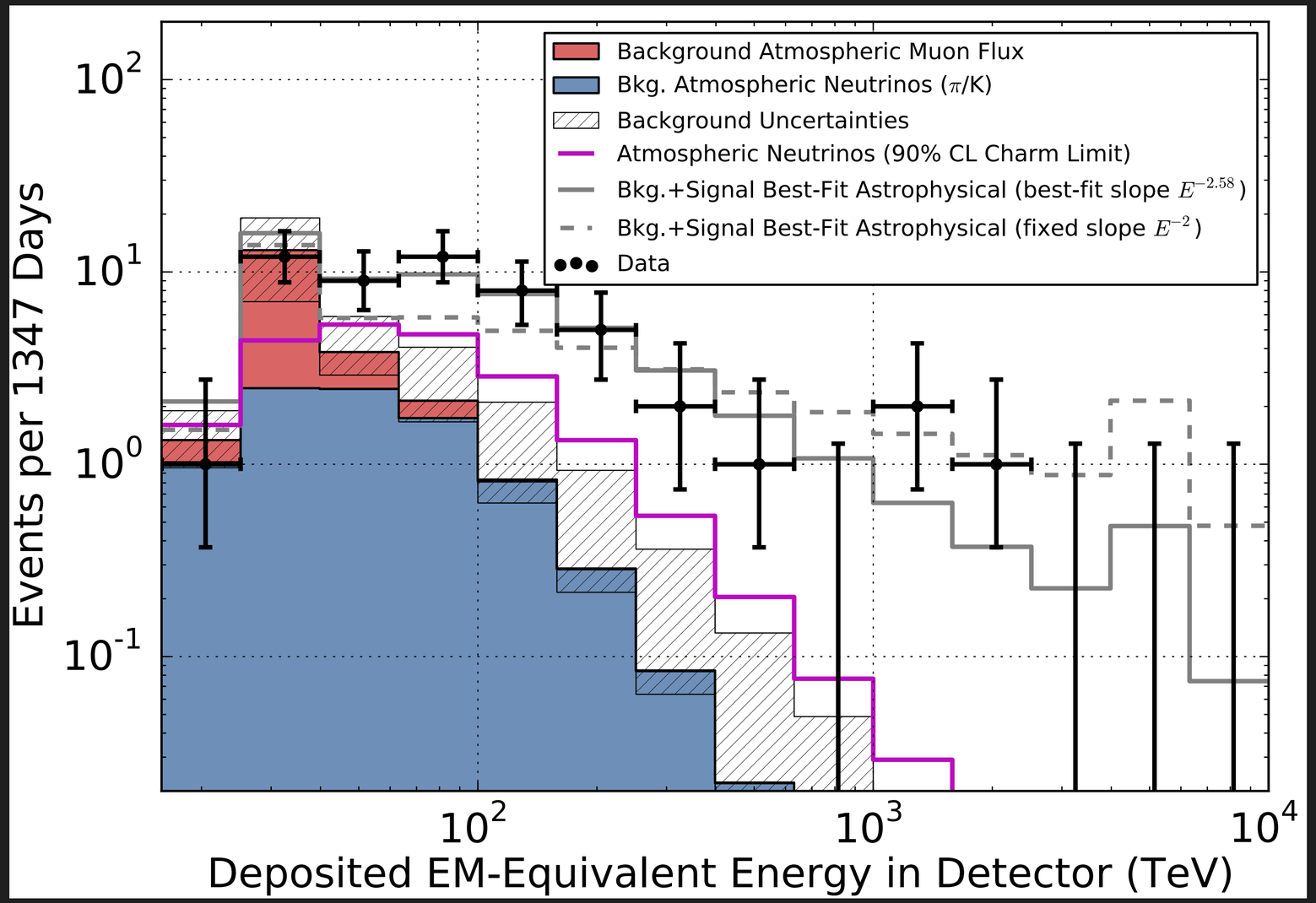
energy deposited in the detector (lower limit on neutrino energy)

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):

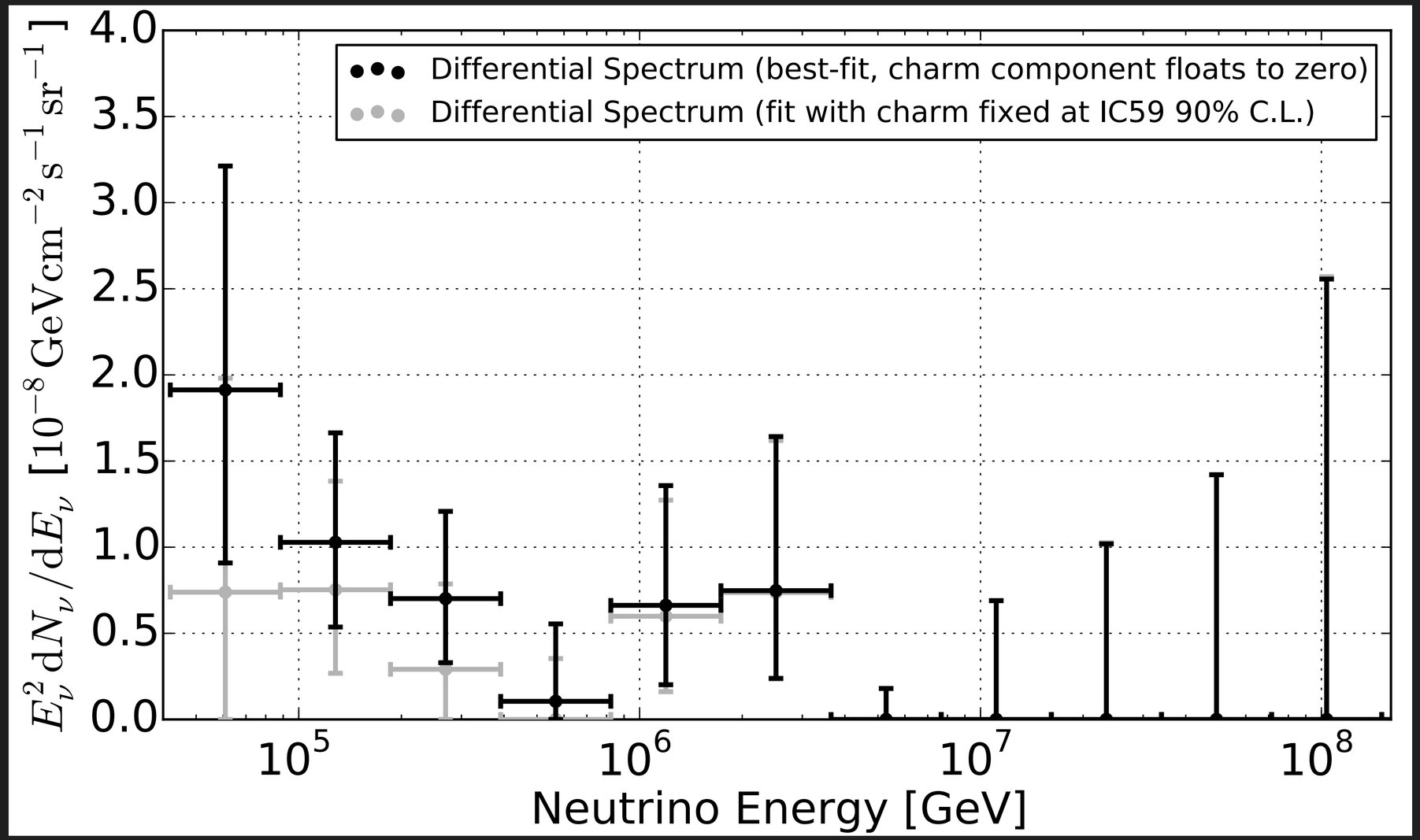
$0.84 \pm 0.3\ 10^{-8}\ E^{-2}$ GeV $cm^{-2}\ s^{-1}\ sr^{-1}$

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



UNFOLDING TO NEUTRINO ENERGY

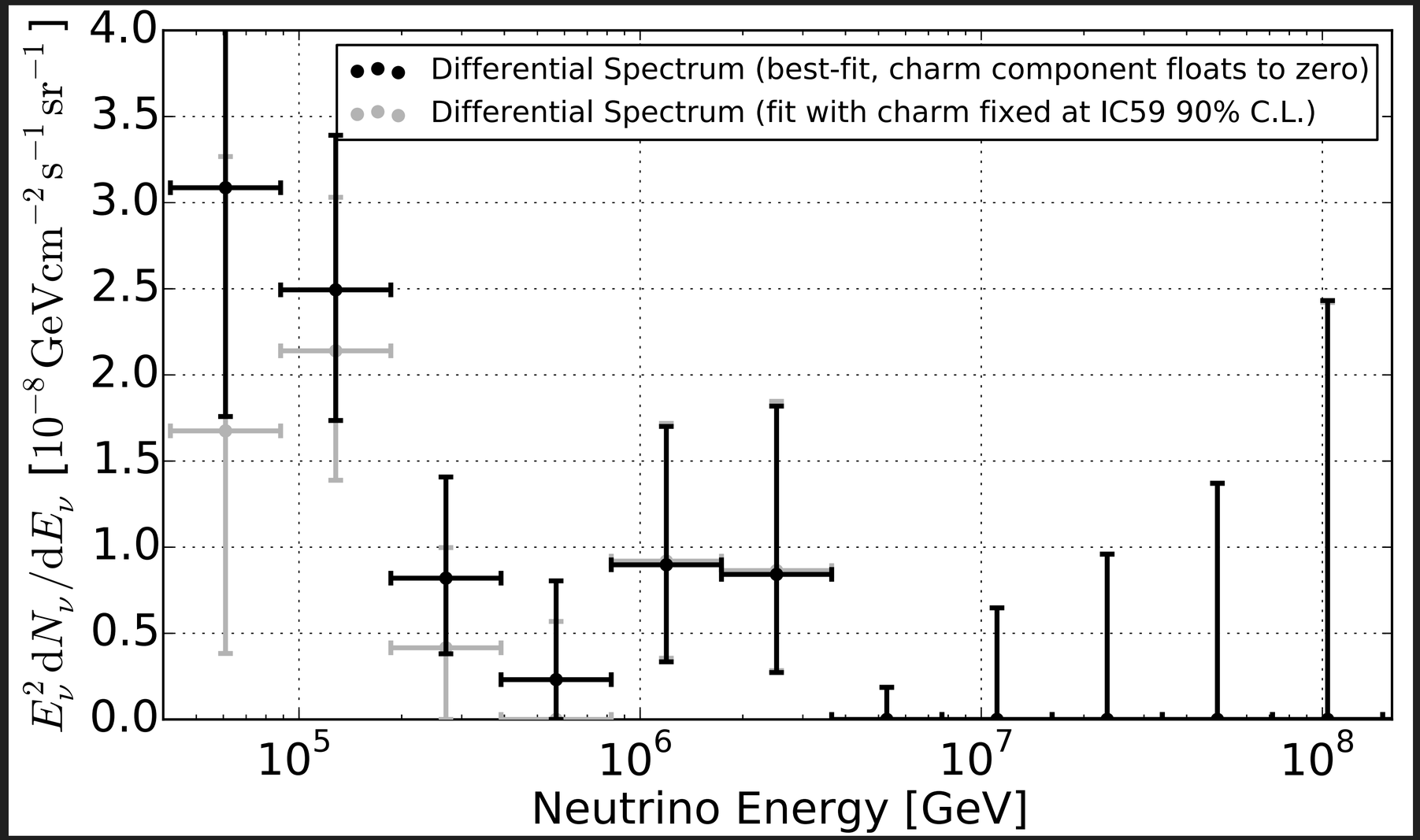
updated from PRL



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

UNFOLDING TO NEUTRINO ENERGY

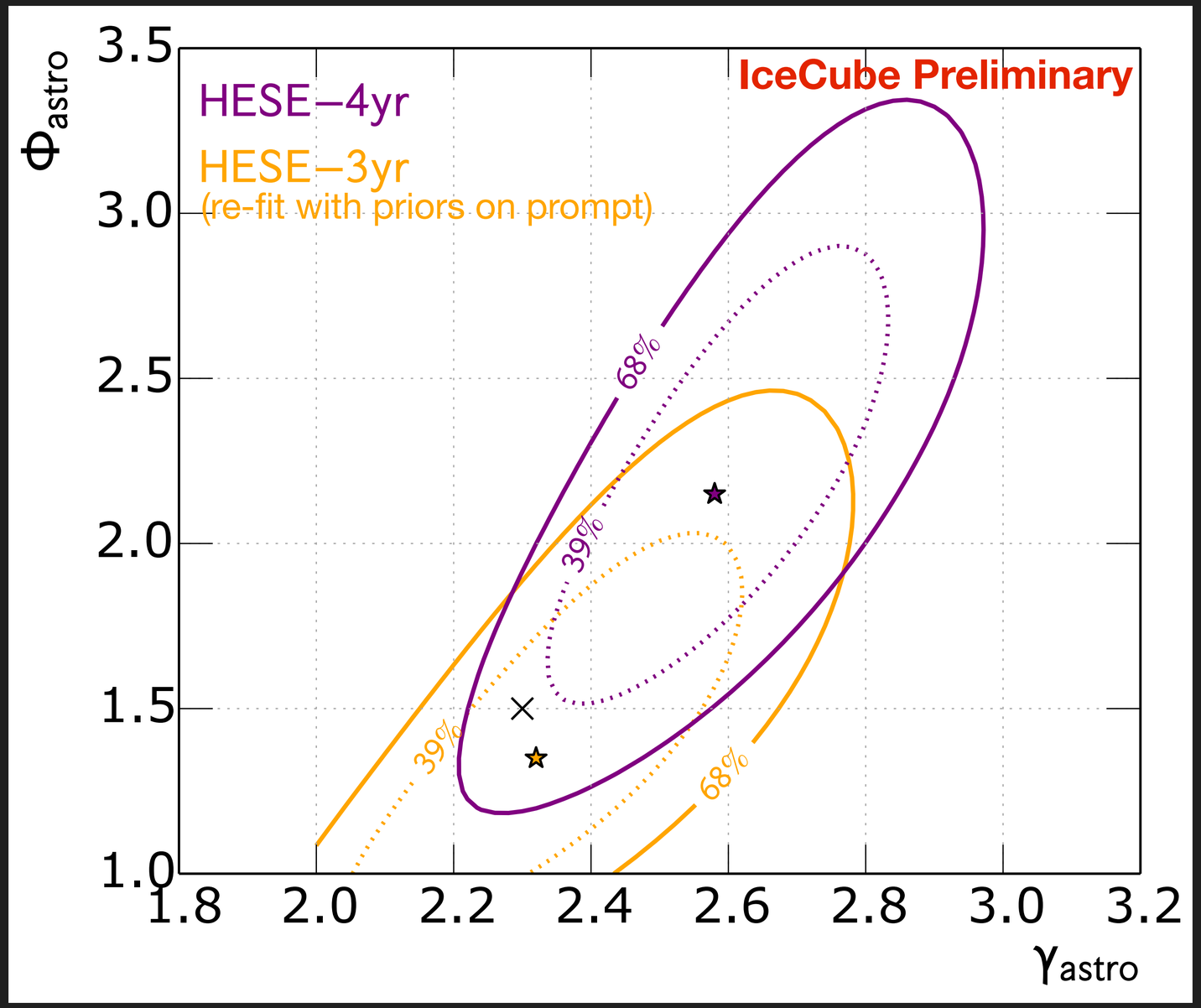
updated from PRL plot version with priors for backgrounds - 4



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

SPECTRAL FIT

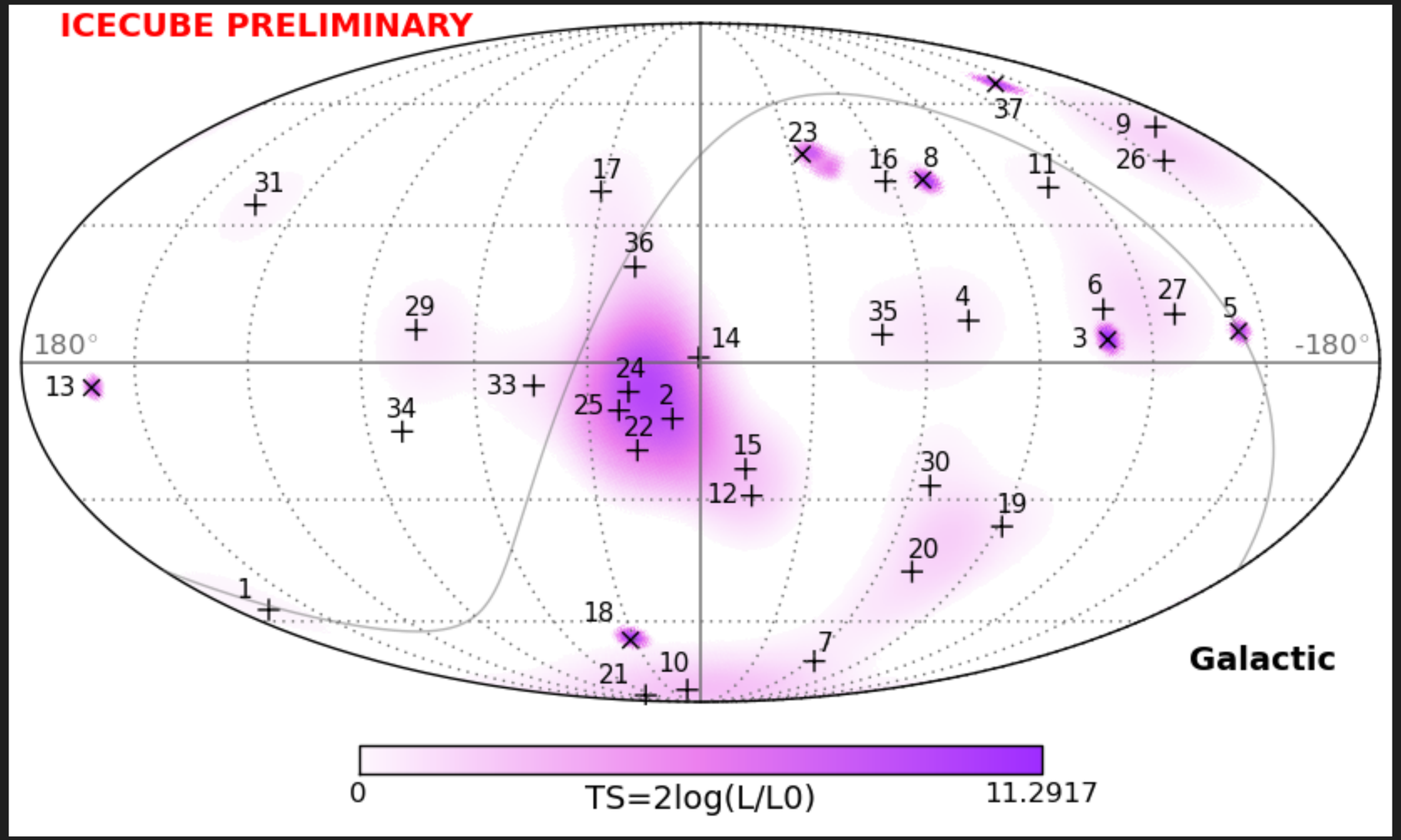
Normalization vs. spectral index contour plot



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

SKYMAP / CLUSTERING

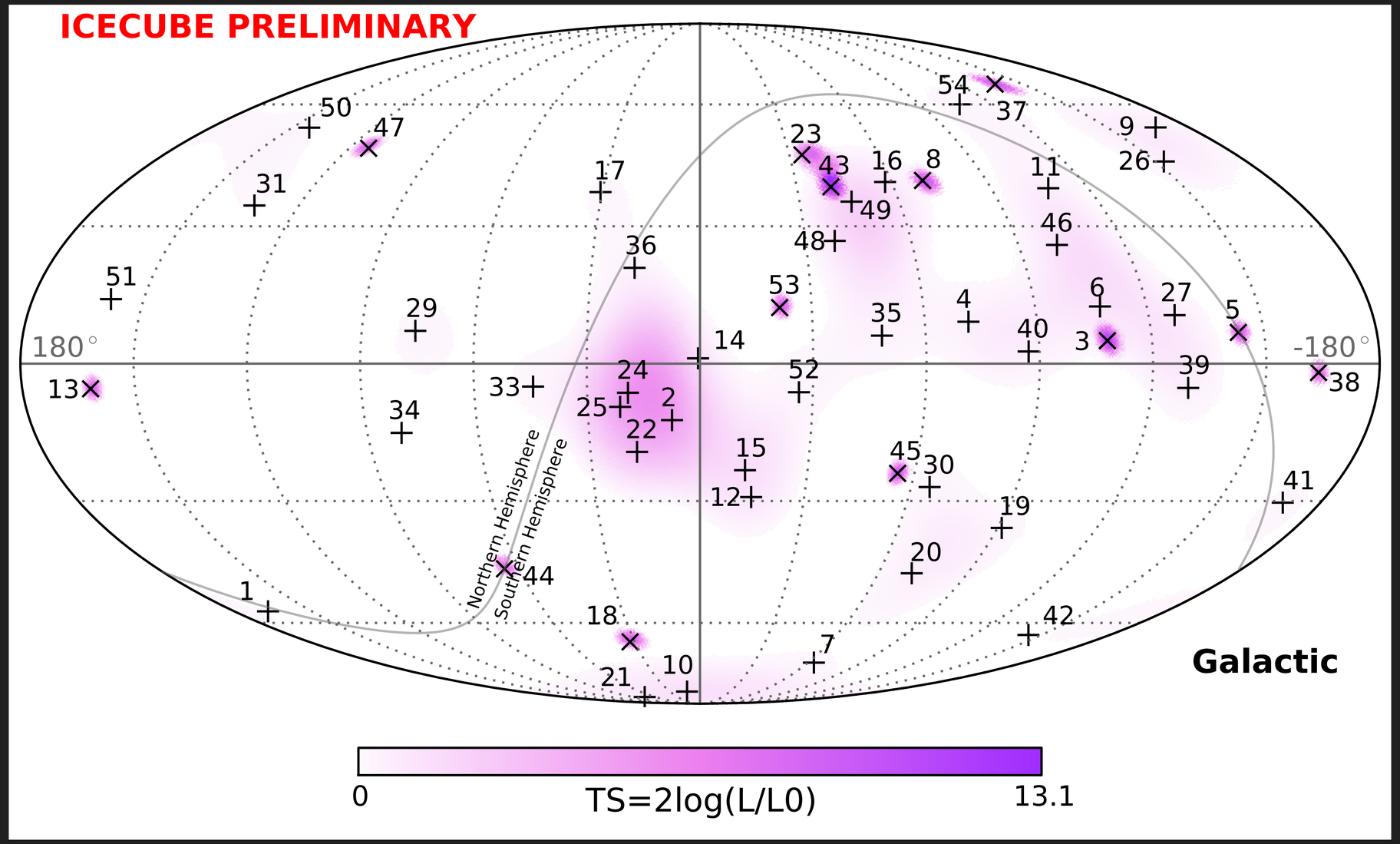
No significant clustering observed (three years)



(all p-values are post-trial)

SKYMAP / CLUSTERING

No significant clustering observed (three years)



(all p-values are post-trial)

SKYMAP / CLUSTERING

No significant clustering observed (three years)

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

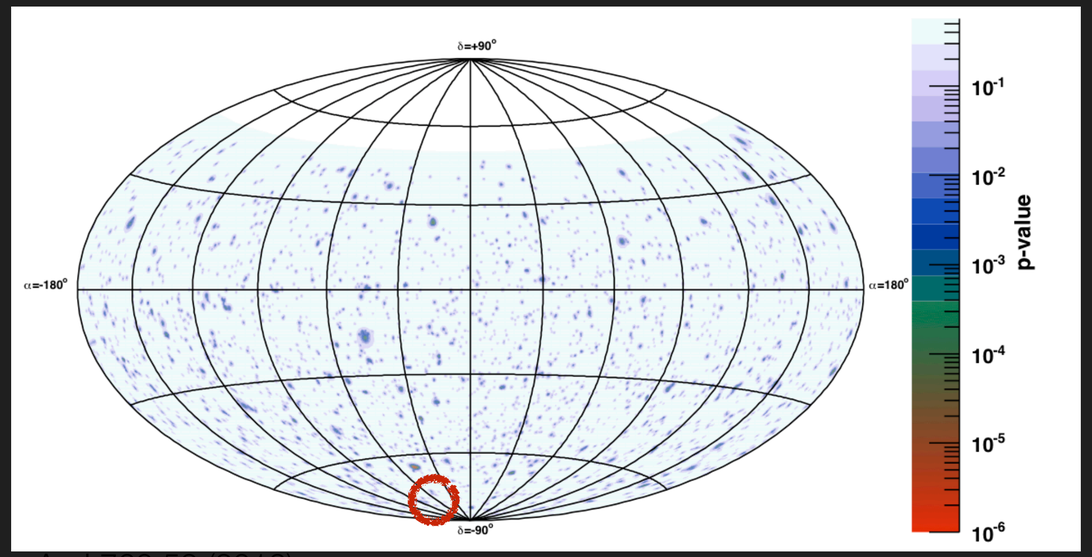
WHAT CAN ANTARES SAY?

Analysis of the galactic center “excess” (only limit)

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

WHERE ARE THE SOURCES?

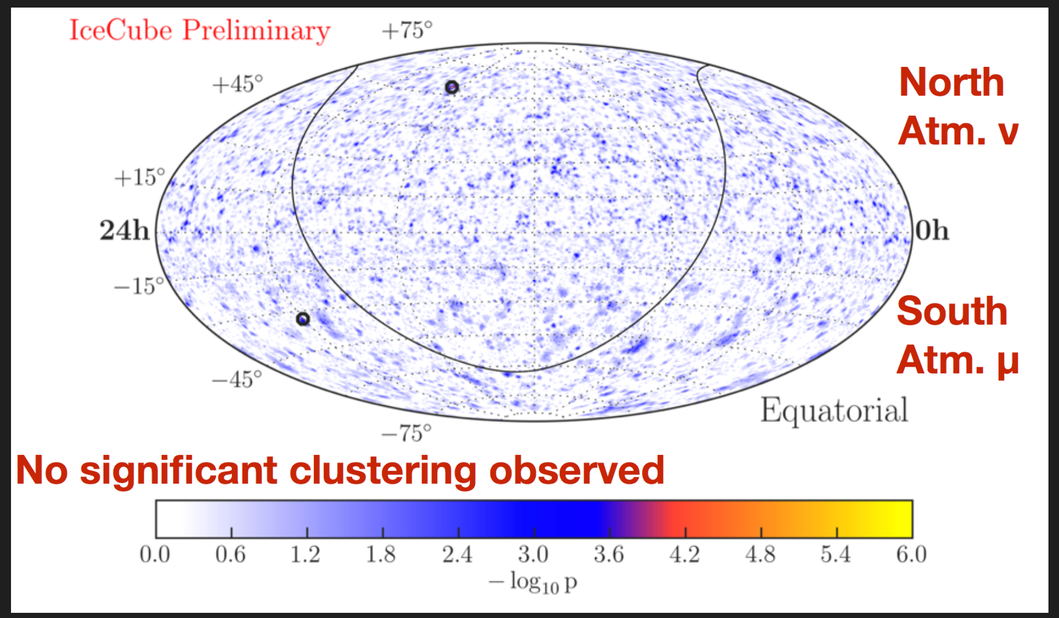
There is still no evidence for point sources of high-energy neutrinos.



ApJ 760:53 (2012)

ANTARES 4-year up-going muon point source search: **2.6%** chance probability

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



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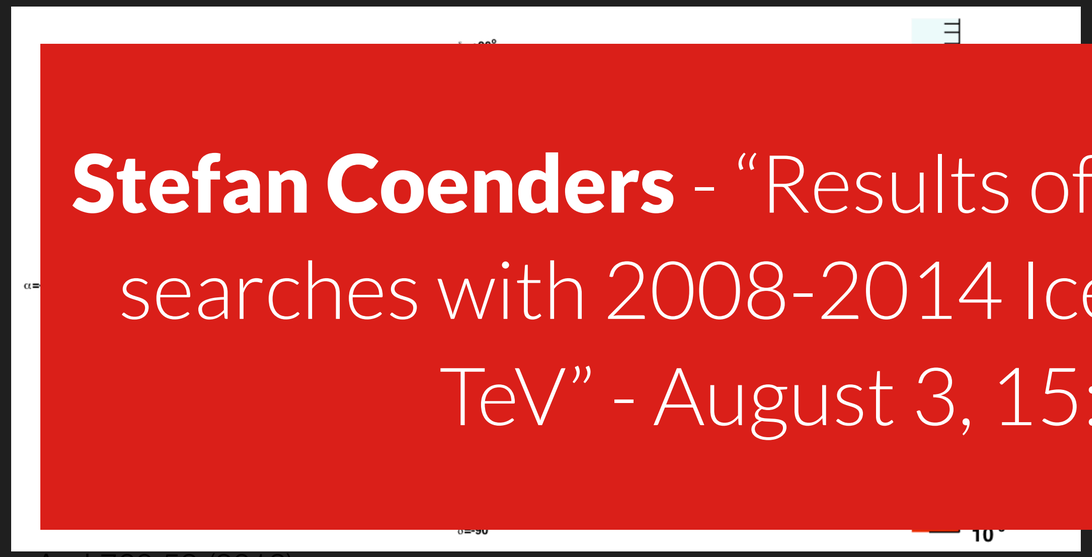

ApJ 760:53 (2012)

Stefan Coenders - "Results of neutrino point source searches with 2008-2014 IceCube data above 10 TeV" - August 3, 15:00 - **NU 04**

n point
bability

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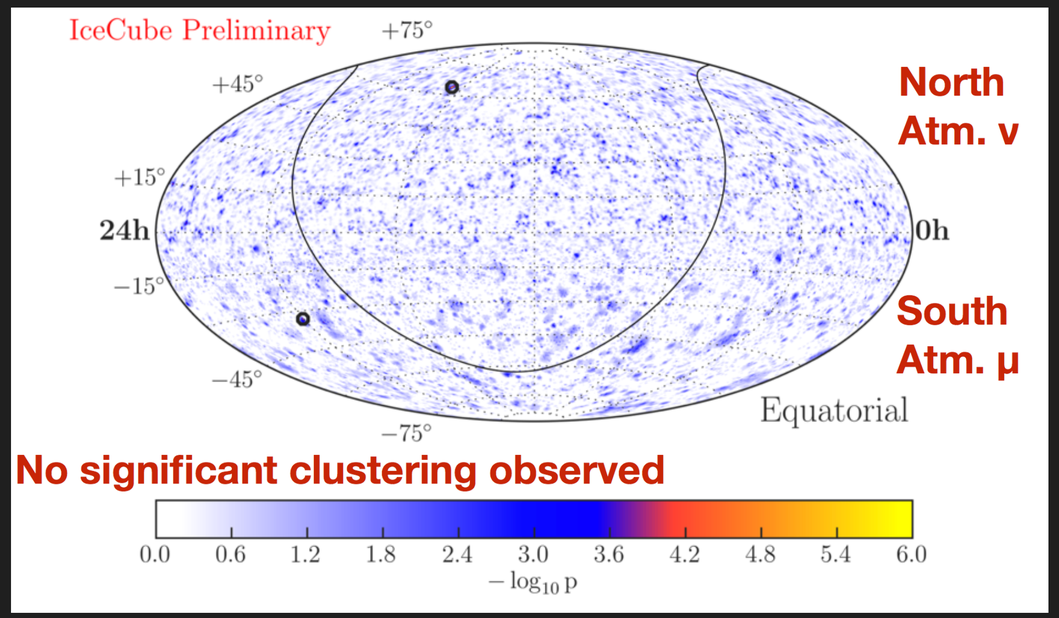
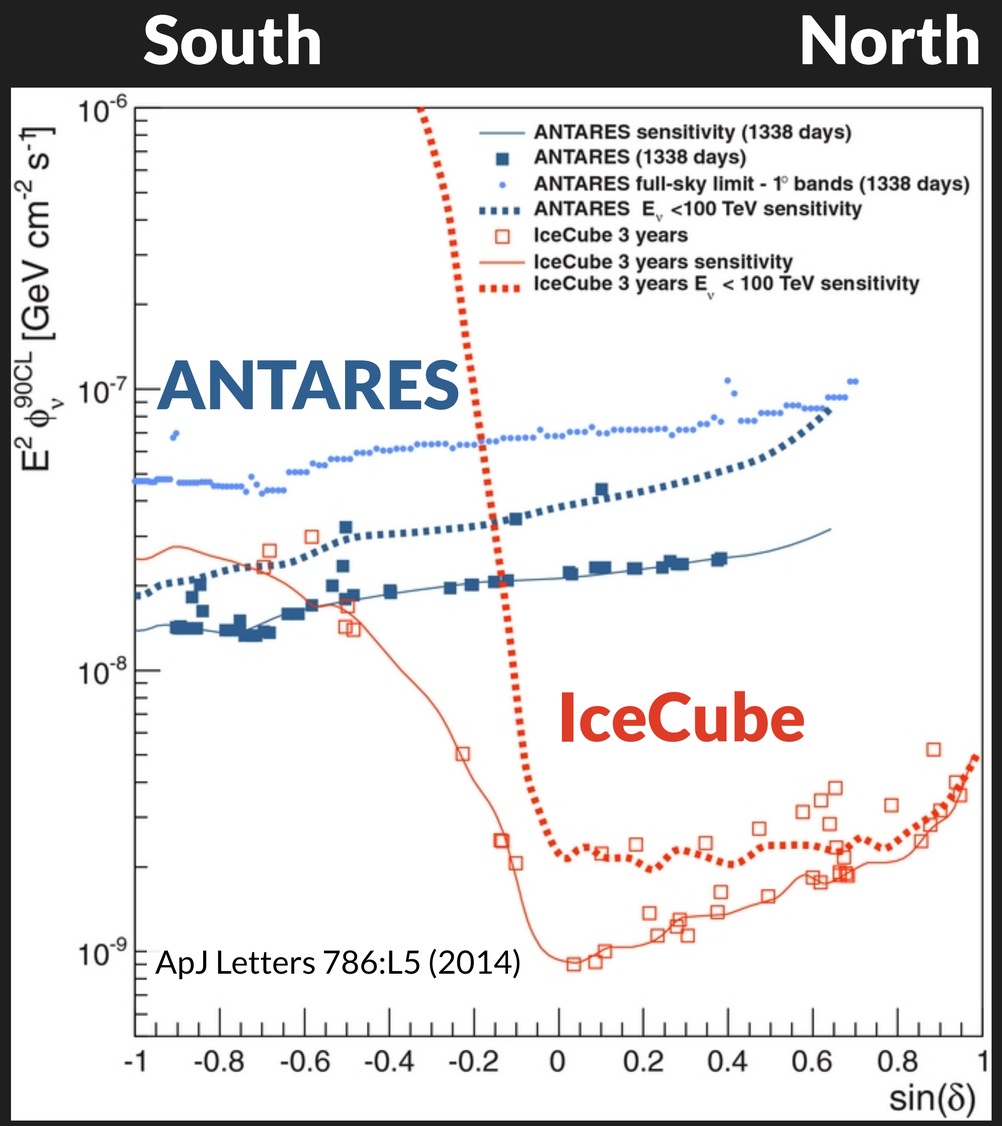


CONSTRAINTS ON POINT SOURCES

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



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IceCub
→ mor
north

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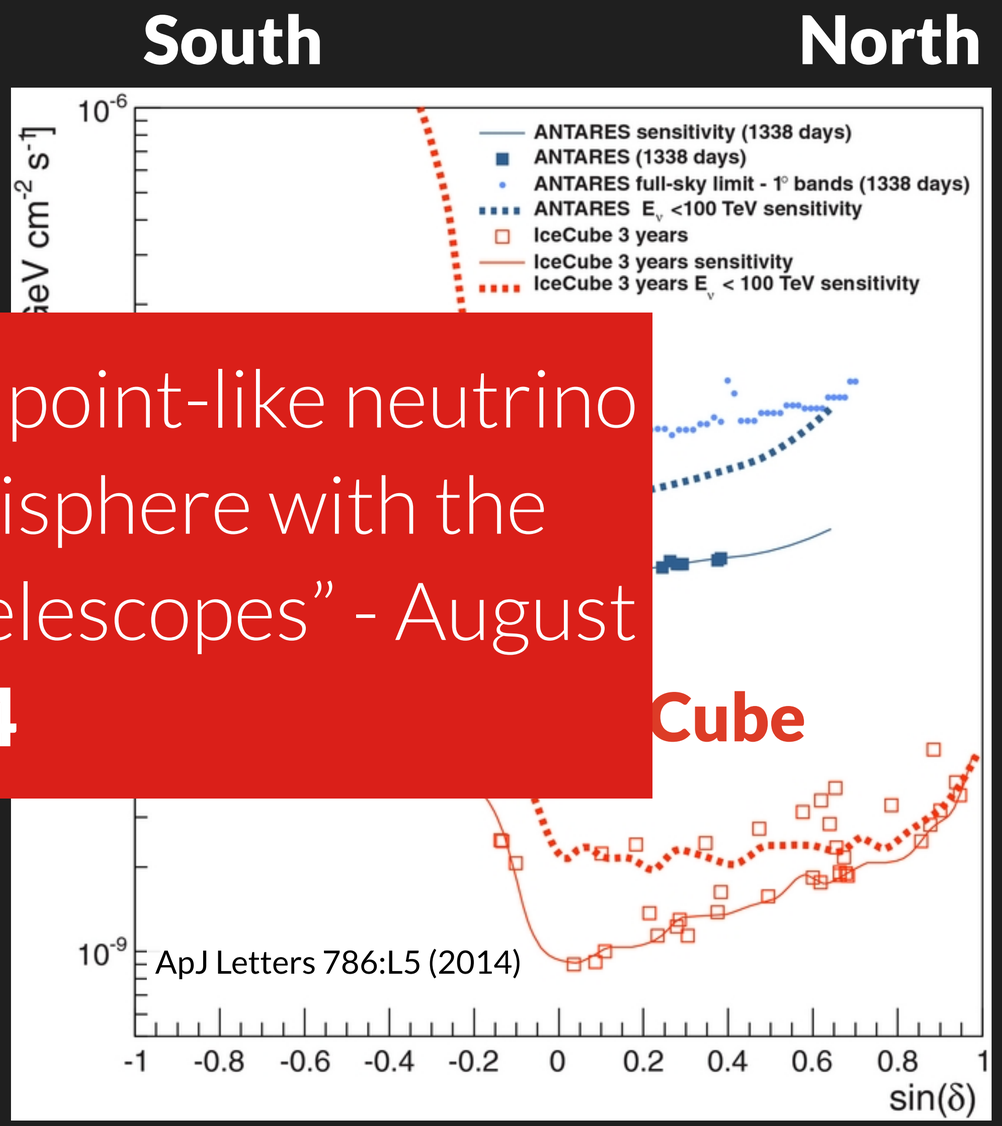
Javier Barrios Martí - "Search for point-like neutrino sources over the Southern Hemisphere with the ANTARES and IceCube neutrino telescopes" - August 3, 14:00 - **NU 04**



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

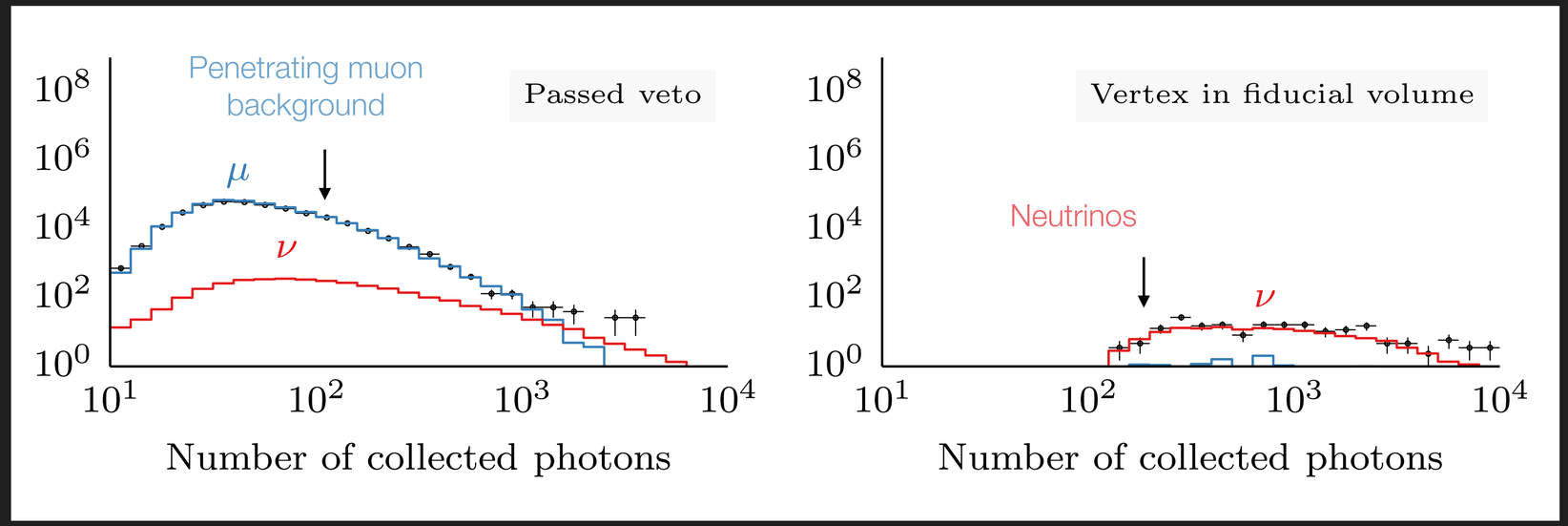
What happens to the astrophysical flux below 60 TeV?

PRD 91, 022001

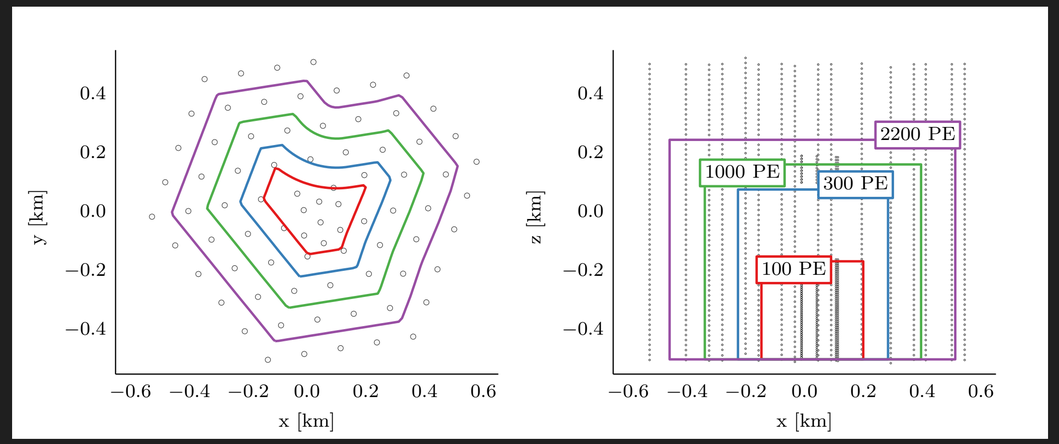
Outer-layer veto → **Energy-dependent veto**

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?

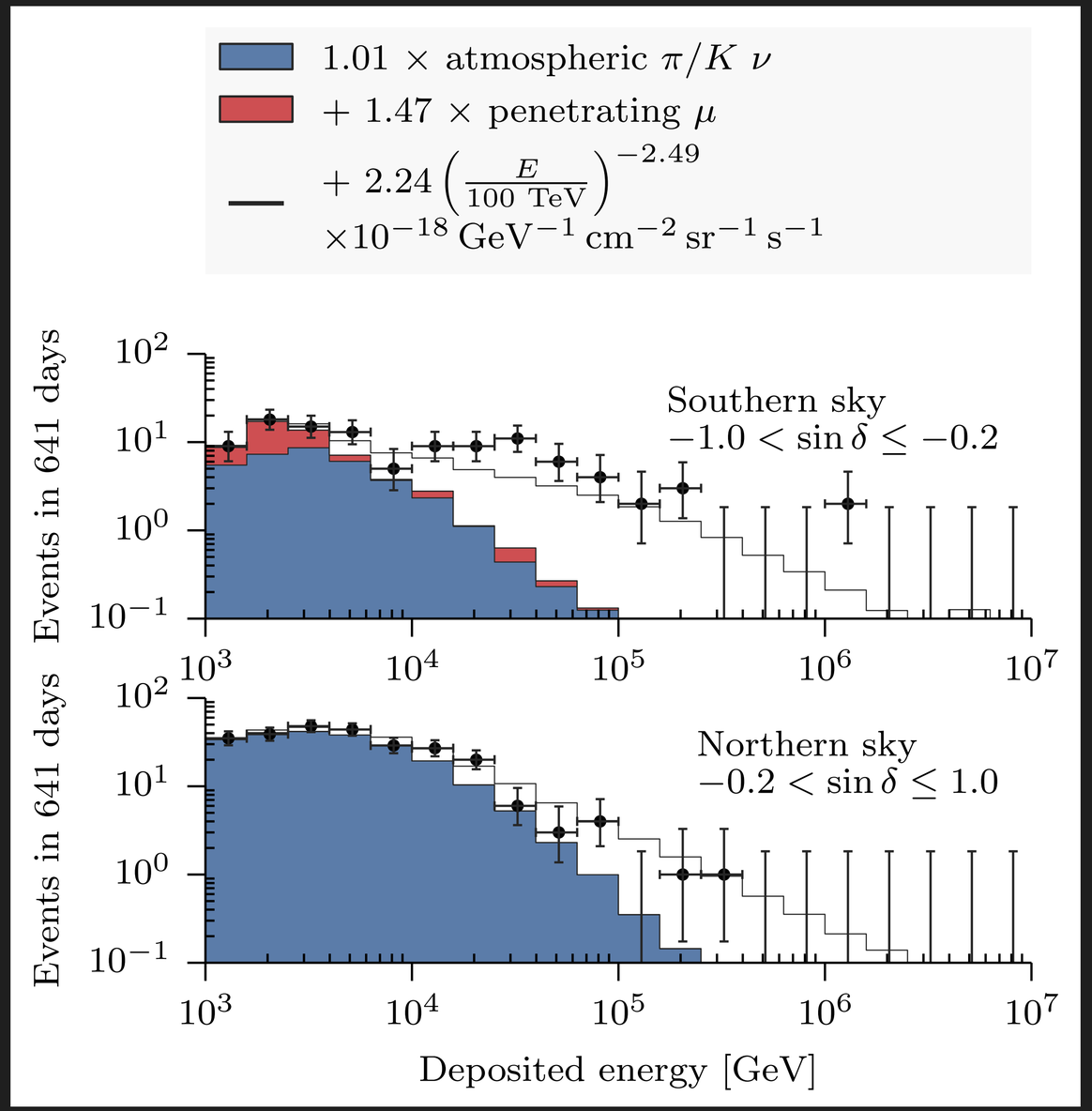
106 > 10 TeV, 9 > 100 TeV (7 of those already in high-energy starting event sample)

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

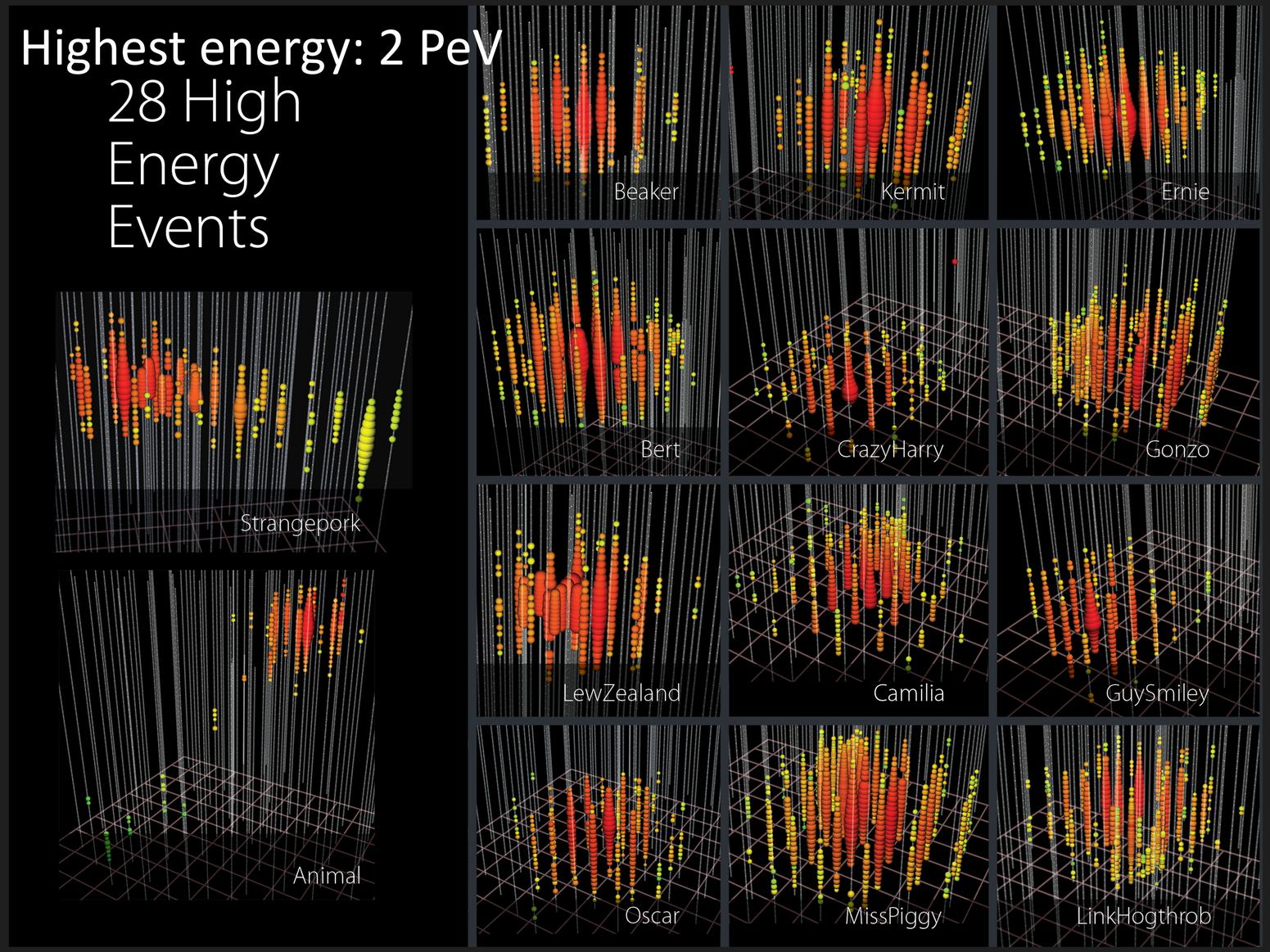


OTHER CHANNELS

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

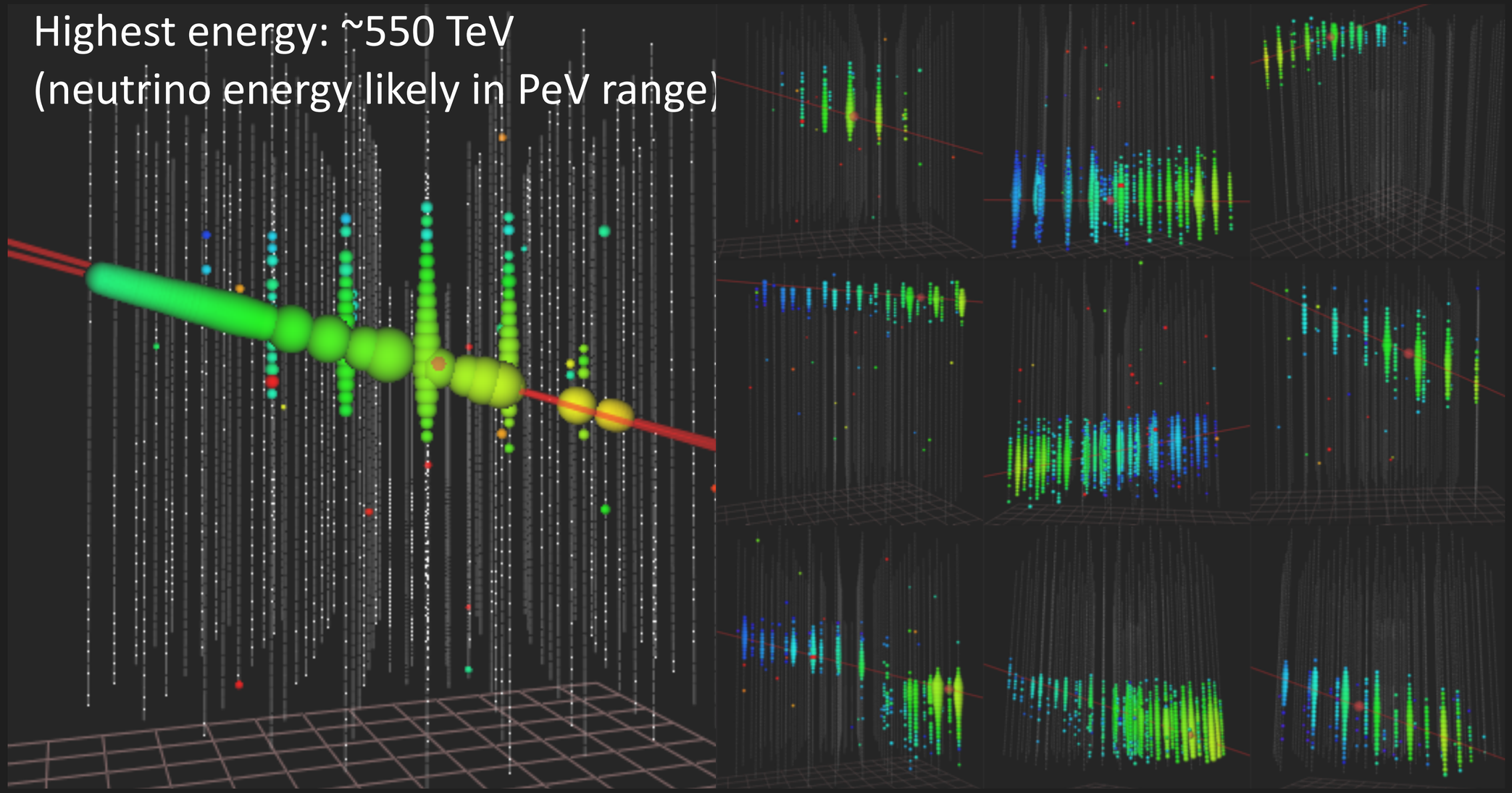


High-Energy Starting Event Search (“HESE”)

OTHER CHANNELS

Two years of data

IceCube has now seen a similar flux in the muon channel - at **3.7σ**



accepted by PRL, arXiv:1507.04005

UPGOING MUONS - SPECTRAL COMPONENTS

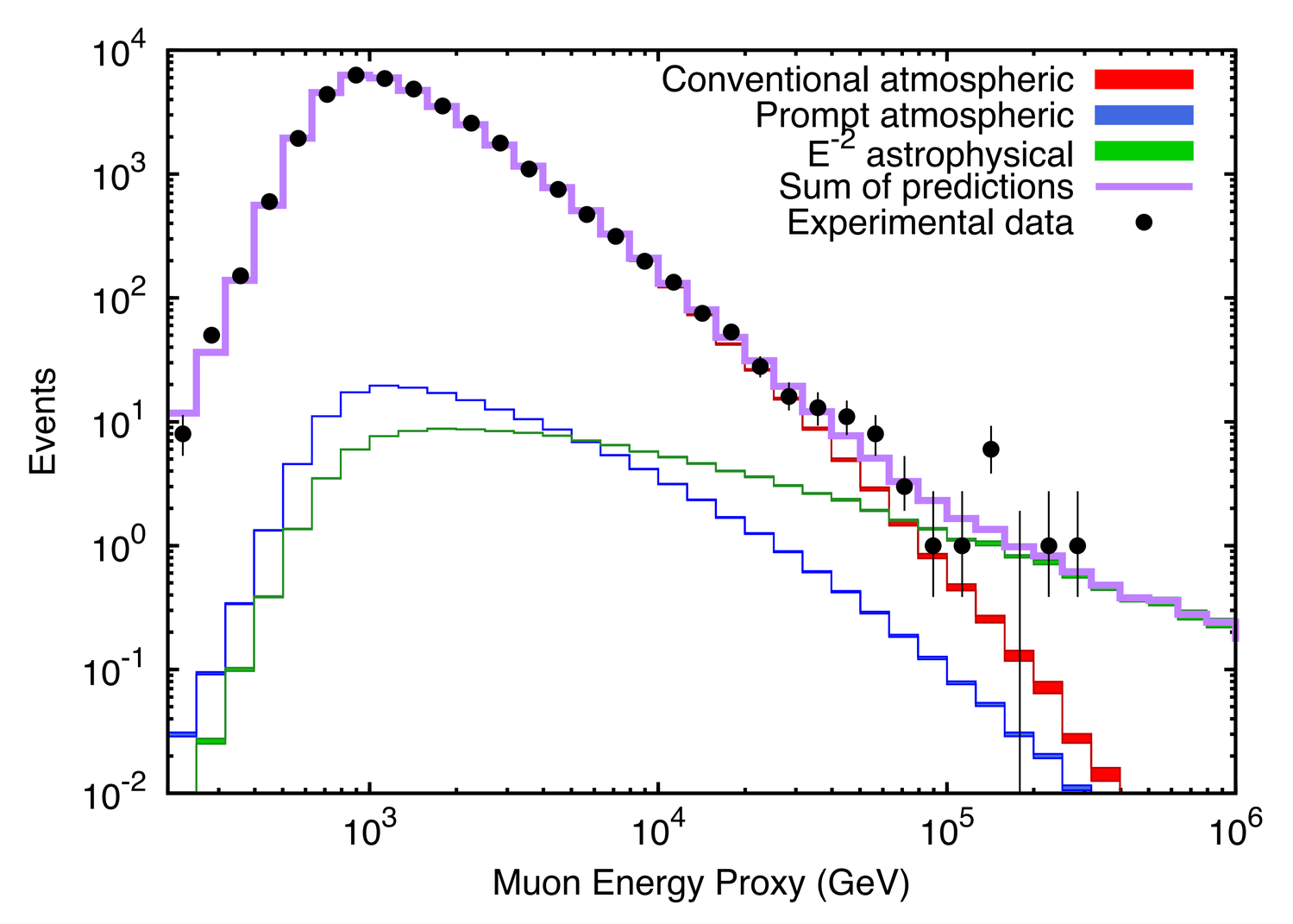
Two years of data

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 $cm^{-2}\ s^{-1}\ sr^{-1}$

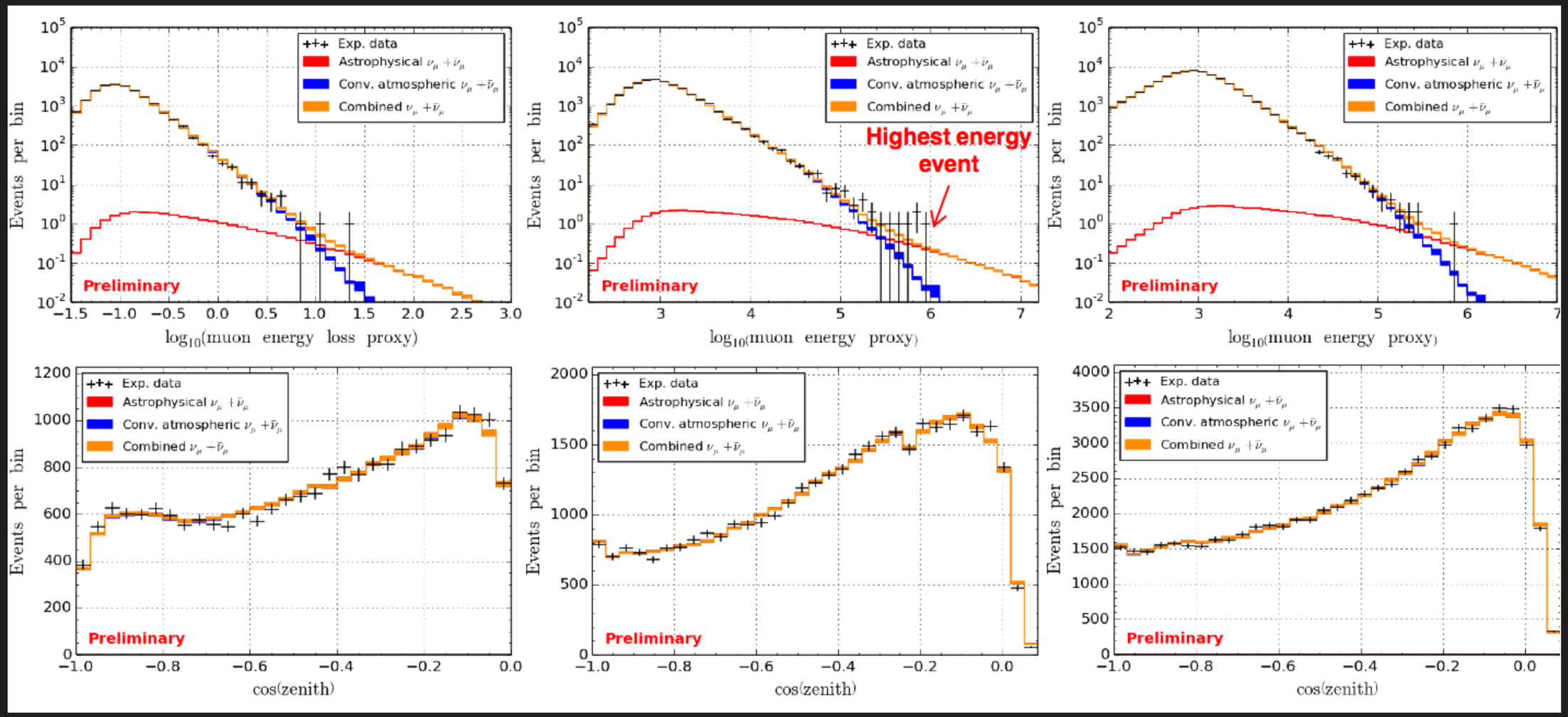
accepted by PRL, arXiv:1507.04005



UPGOING MUONS - SPECTRAL COMPONENTS

Three years of data

New @ ICRC - now looking at up to 6 years of muon data (work in progress) - re-analyzed 3 years (presented here) and working on details of the 6 year result



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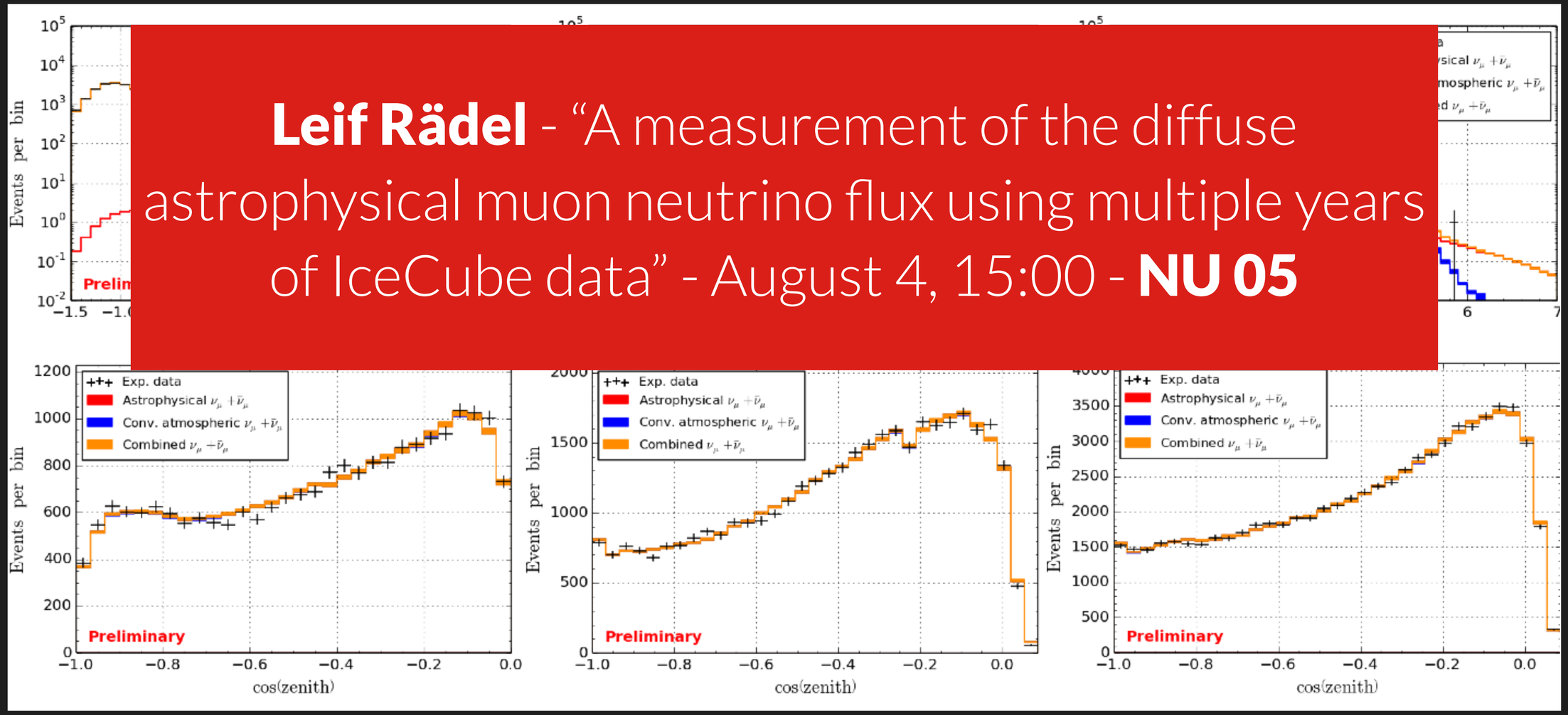
Leif Rädel - "A measurement of the diffuse astrophysical muon neutrino flux using multiple years of IceCube data" - August 4, 15:00 - **NU 05**



UPGOING MUONS

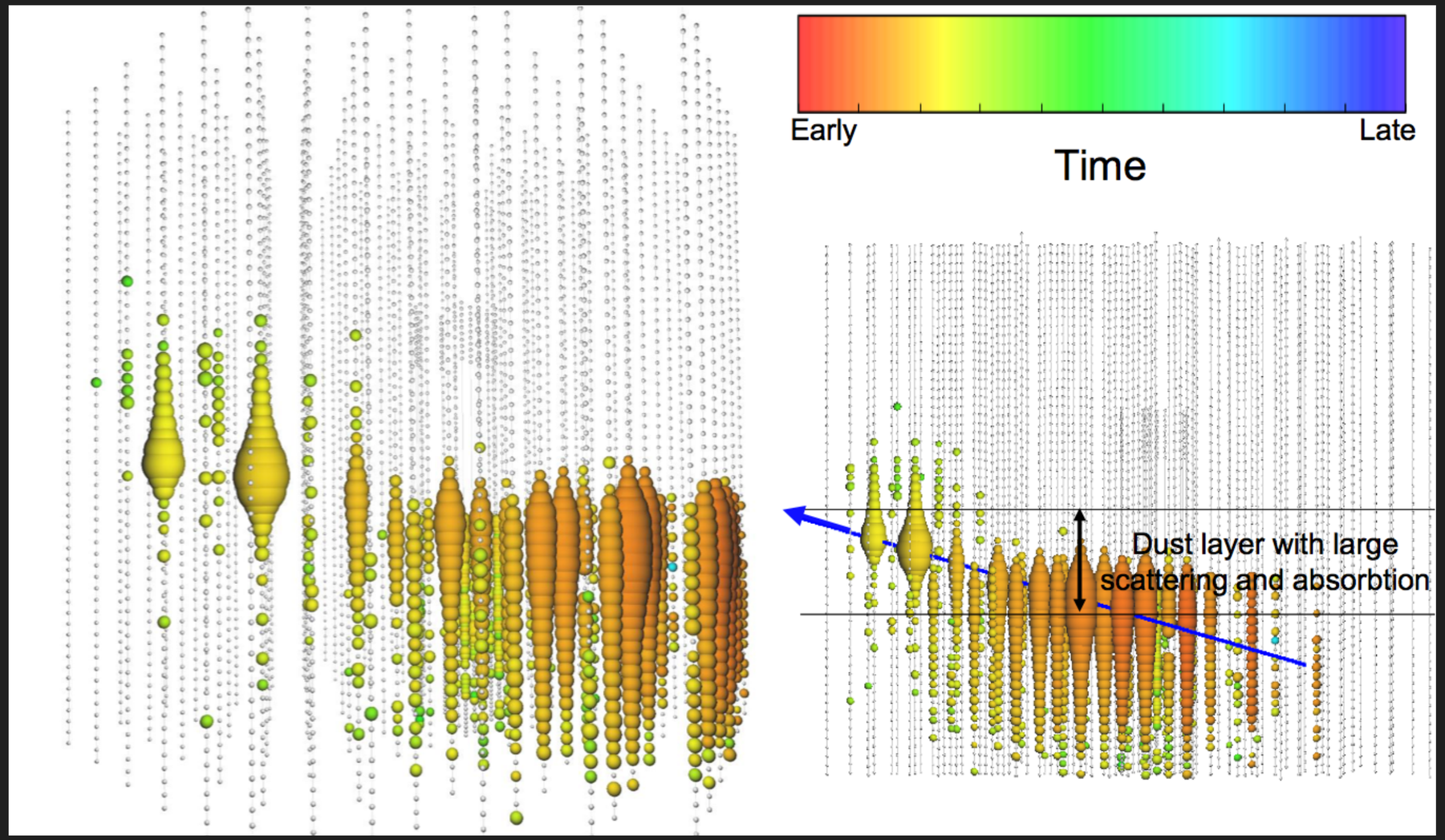
an interesting event in the six-year sample!

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



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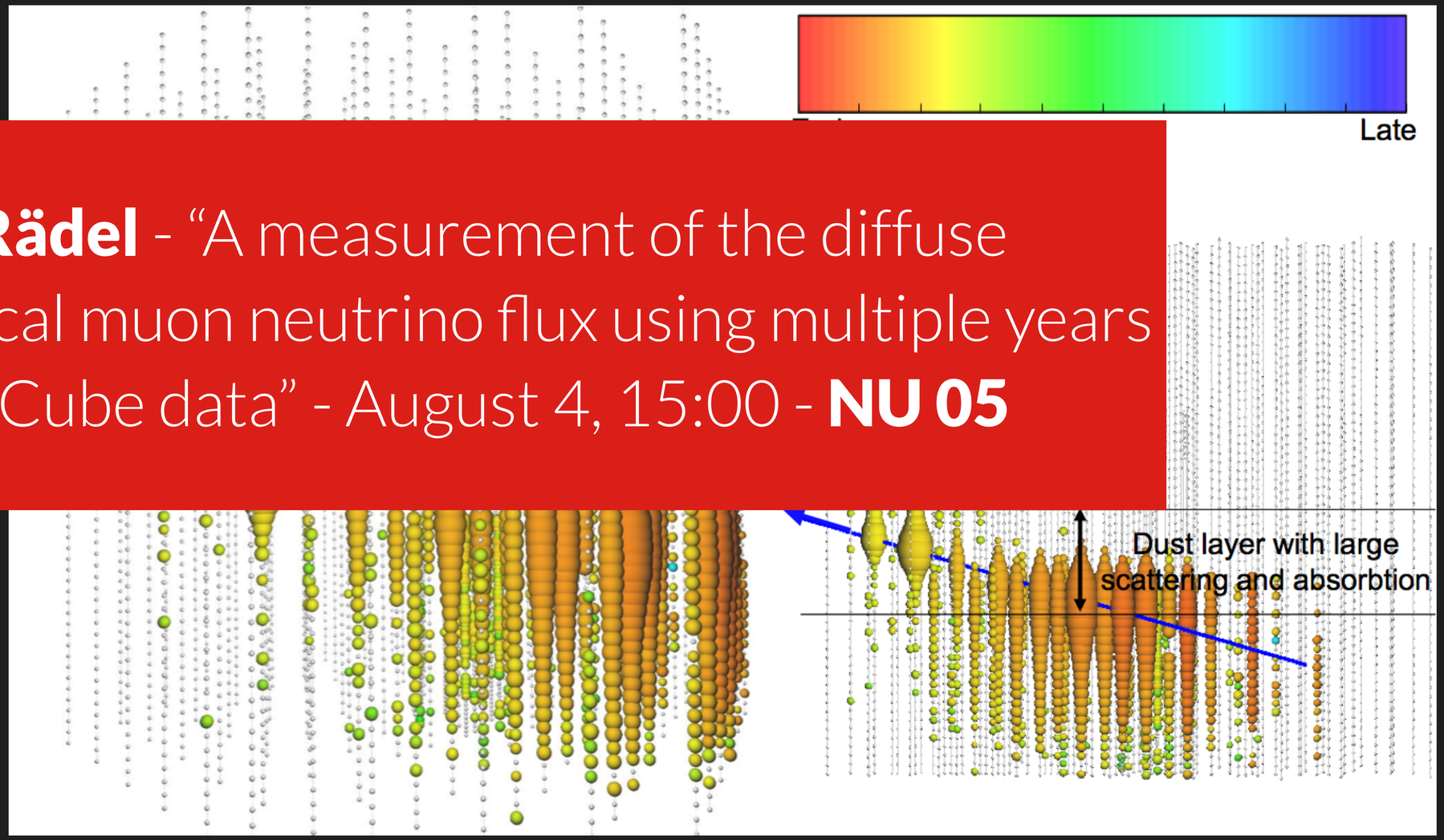

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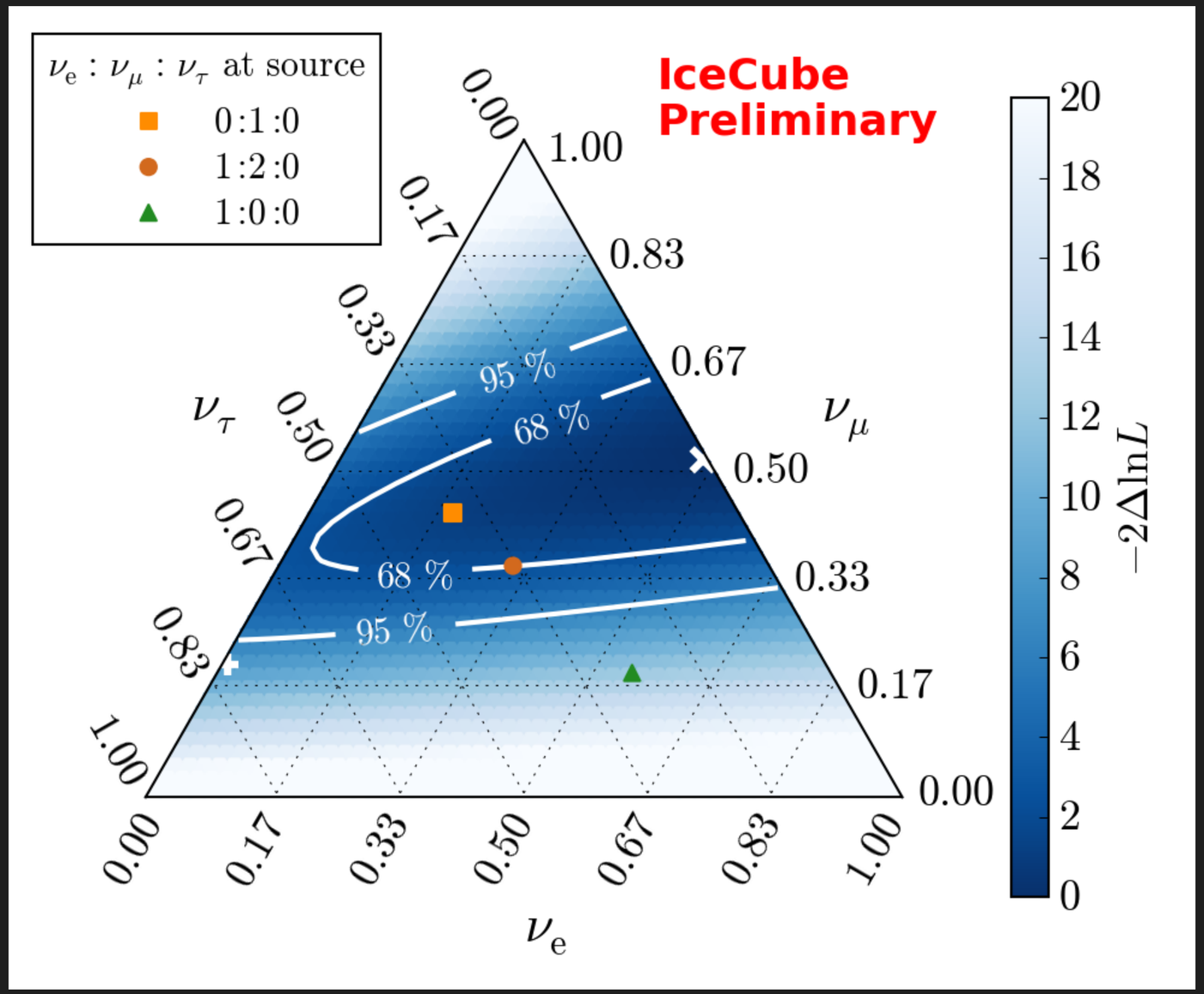
GLOBAL FIT OF ICECUBE ANALYSES

interesting results such as flavour ratio

fit for flavour ratio, spectral shape and cutoff



accepted by ApJ, arXiv:1507.03991

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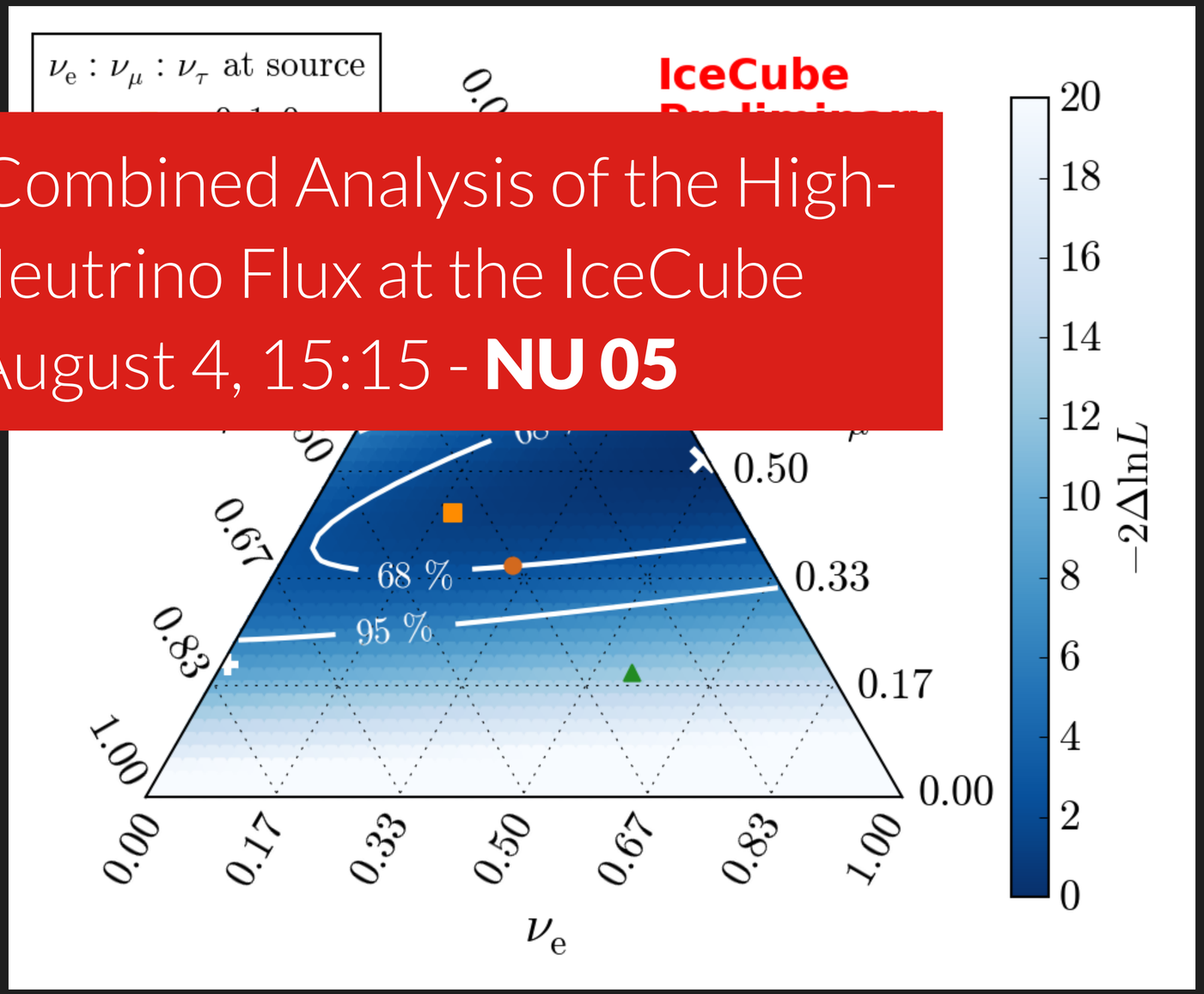
Lars Mohrmann - "Combined Analysis of the High-Energy Cosmic Neutrino Flux at the IceCube Detector" - August 4, 15:15 - **NU 05**



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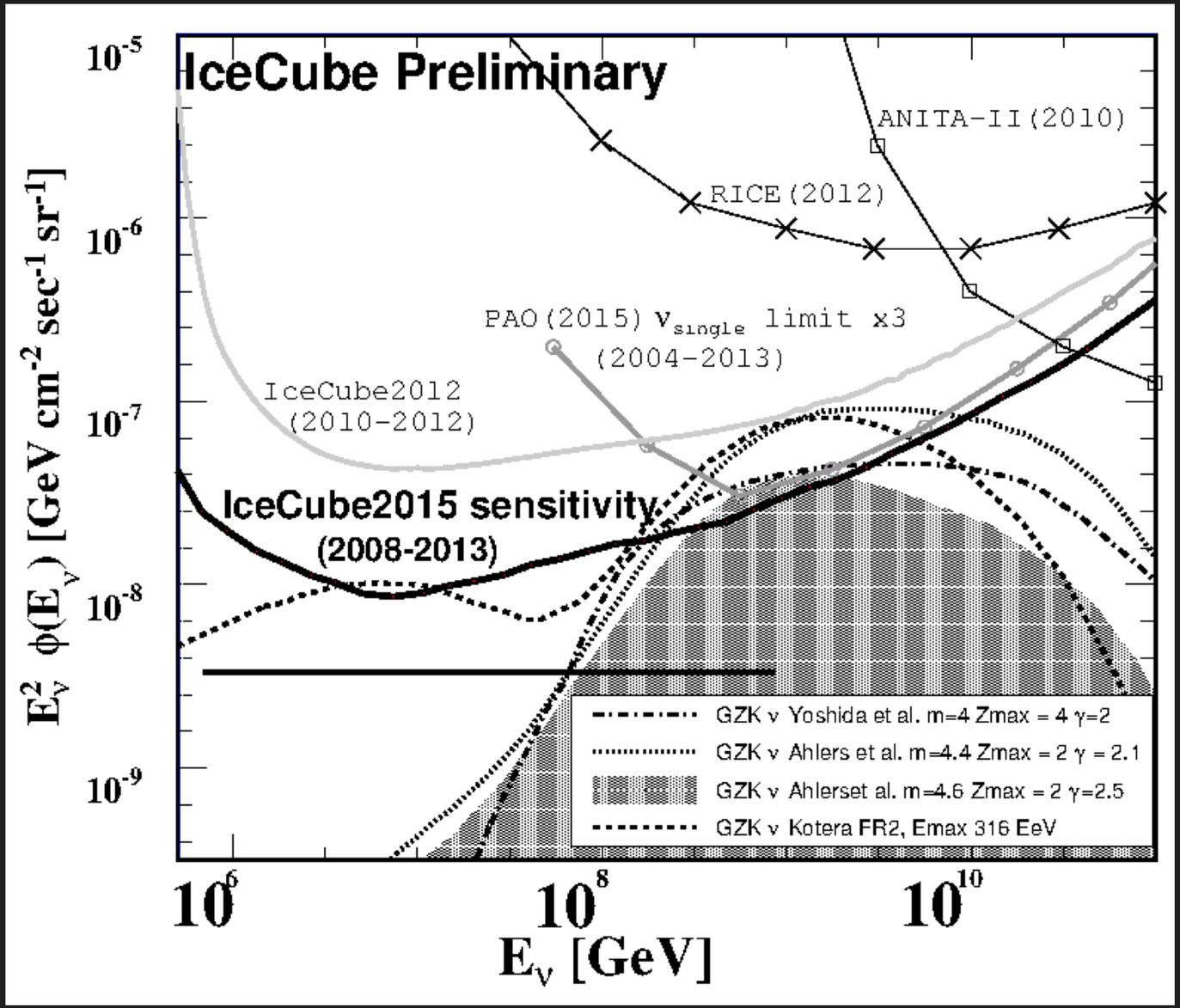
COSMOGENIC (GZK) NEUTRINOS

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

Just updated to 6 years of data



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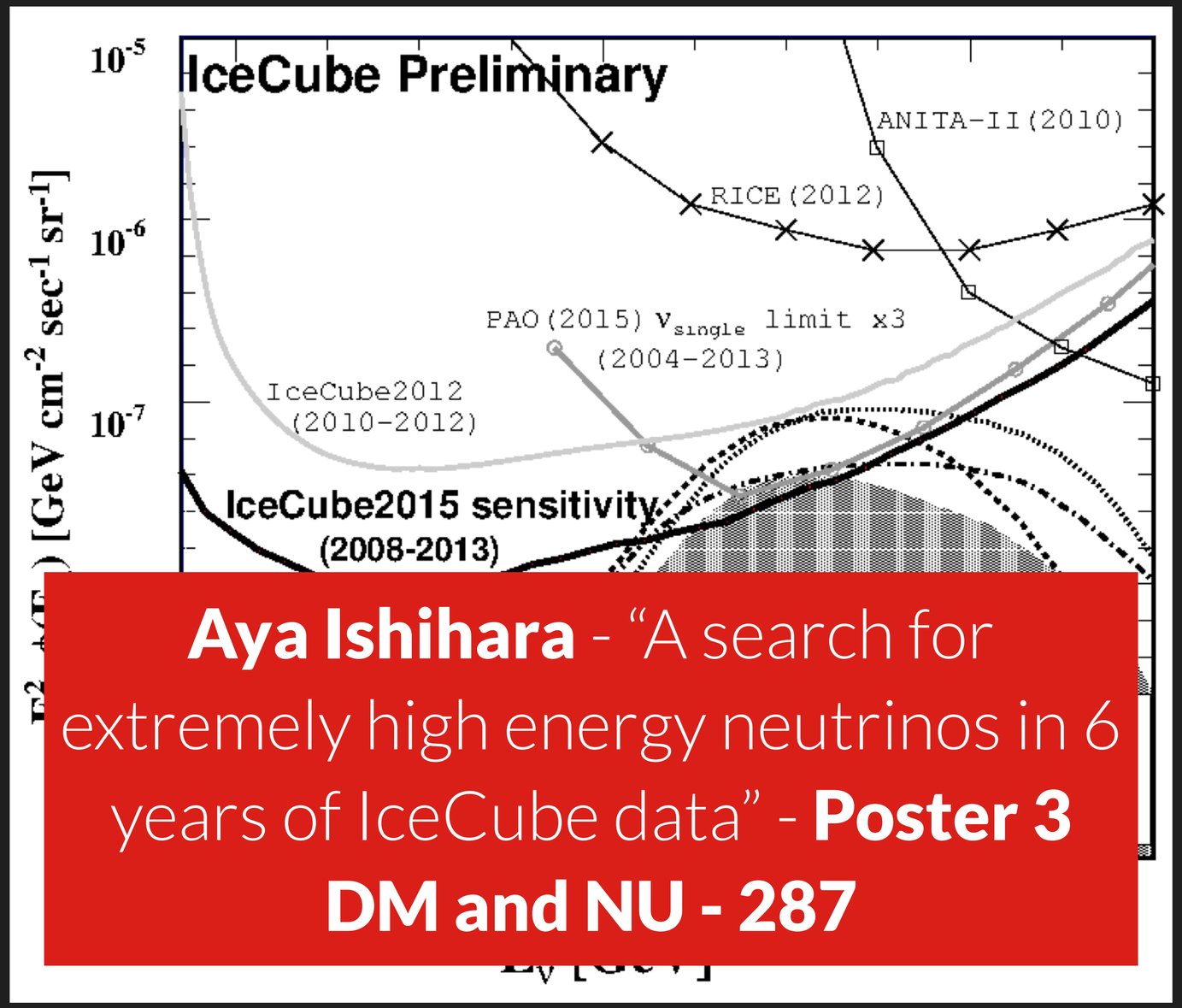


Aya Ishihara - "A search for extremely high energy neutrinos in 6 years of IceCube data" - **Poster 3**

DM and NU - 287

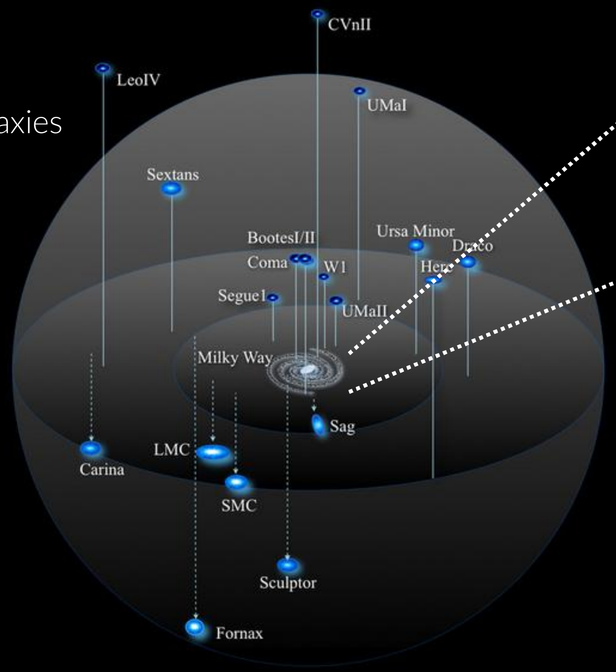
DARK MATTER

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

INDIRECT DARK MATTER SEARCHES

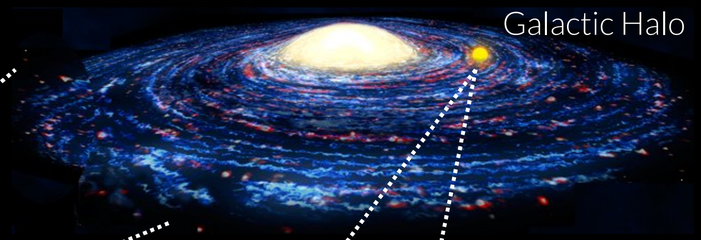
Look at objects where dark matter might have accumulated gravitationally over the evolution of the Universe

Clusters of Galaxies



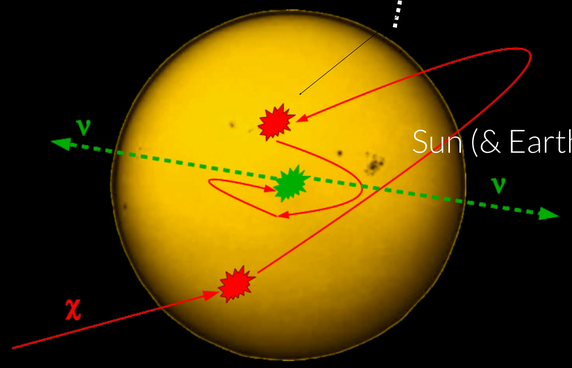
Dwarf spheroidal galaxies

Galactic Center



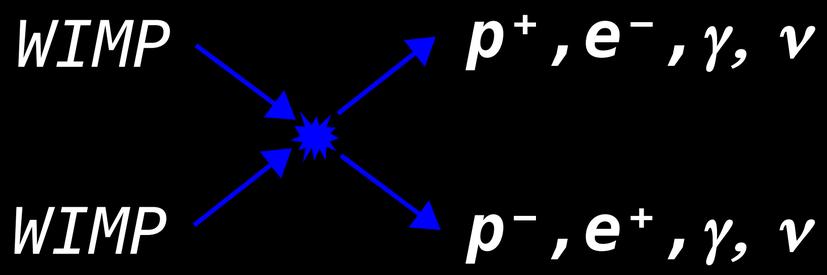
Galactic Halo

accumulate due to WIMP-proton elastic scattering



Sun (& Earth)

MSSM - neutralino



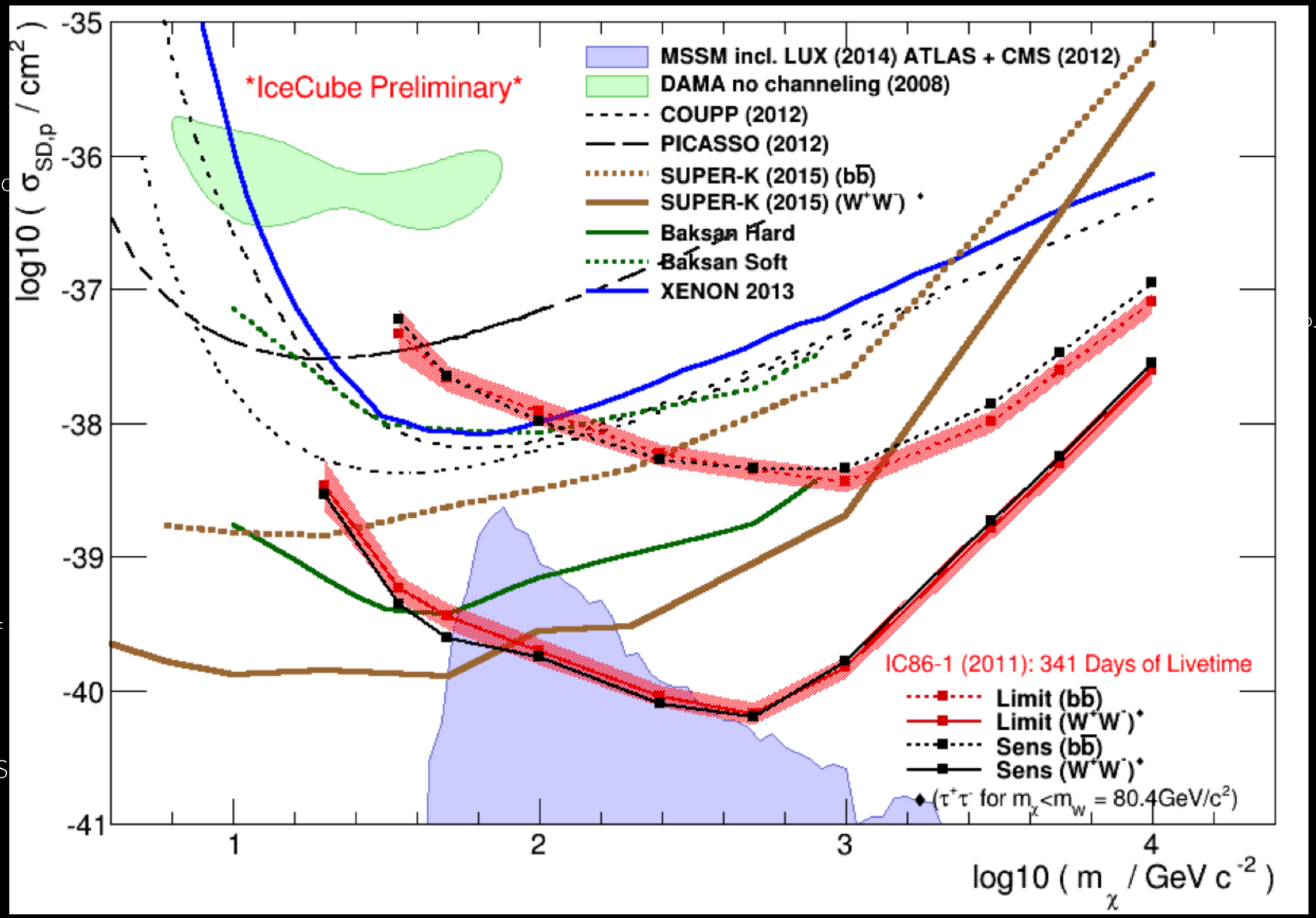
INDIRECT DARK MATTER SEARCHES

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

Clusters c

Dwarf

MS

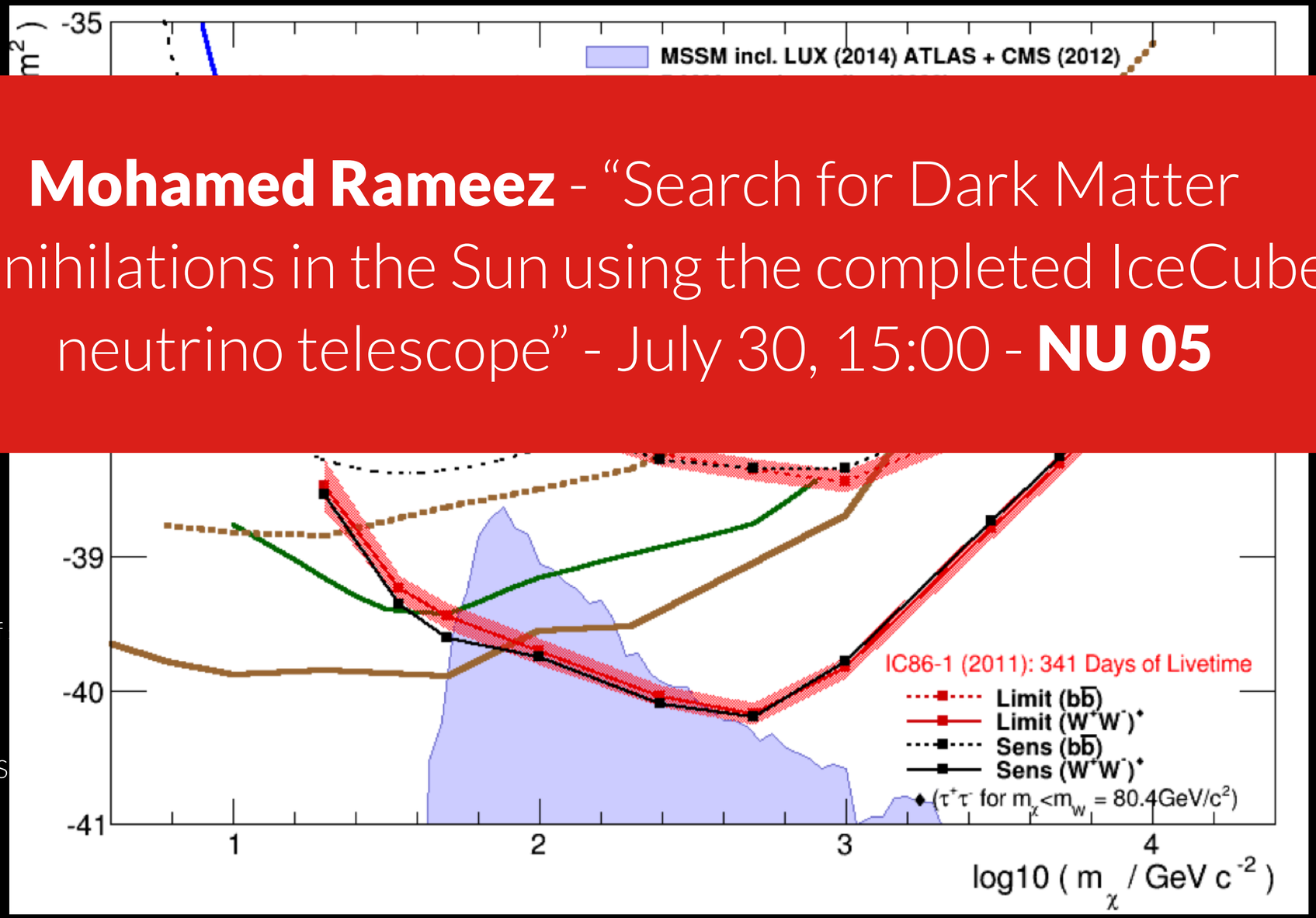


-proton

INDIRECT DARK MATTER SEARCHES

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

Mohamed Rameez - "Search for Dark Matter annihilations in the Sun using the completed IceCube neutrino telescope" - July 30, 15:00 - **NU 05**



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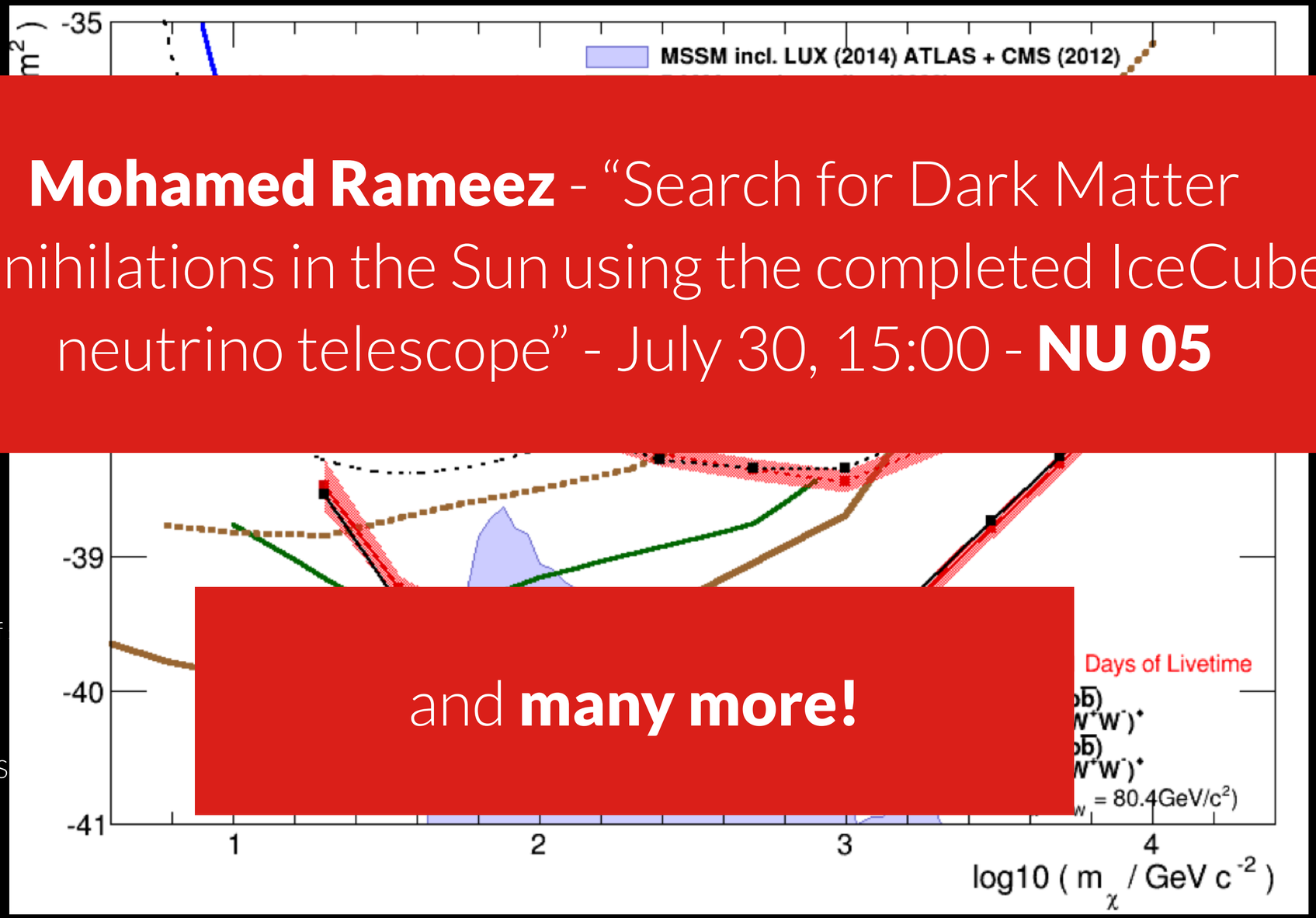


Mohamed Rameez - "Search for Dark Matter annihilations in the Sun using the completed IceCube neutrino telescope" - July 30, 15:00 - **NU 05**

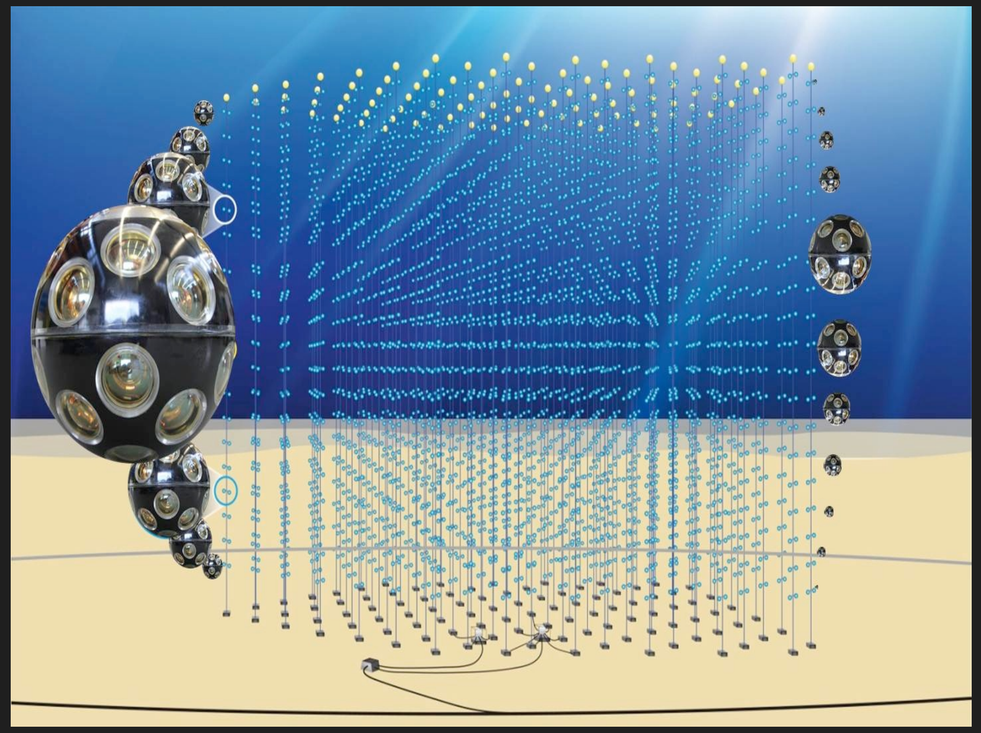
and **many more!**

THE FUTURE

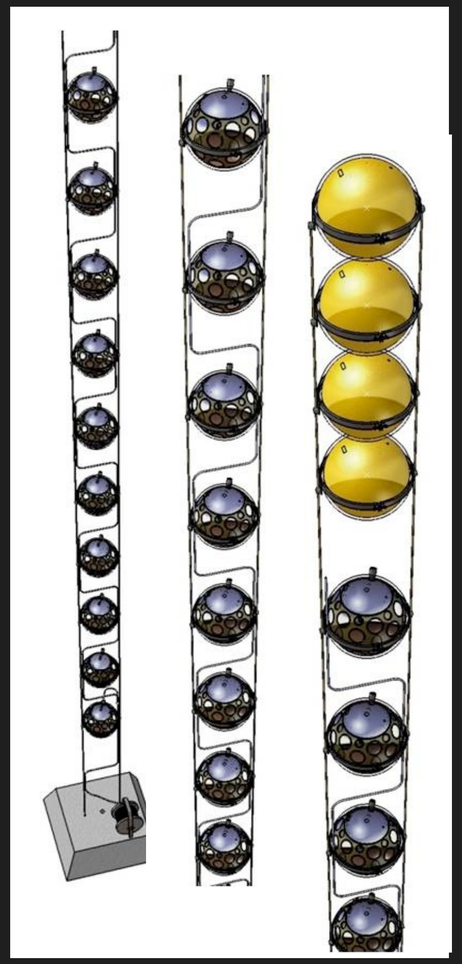
Extending the sensitivity to higher energies, new hemispheres

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

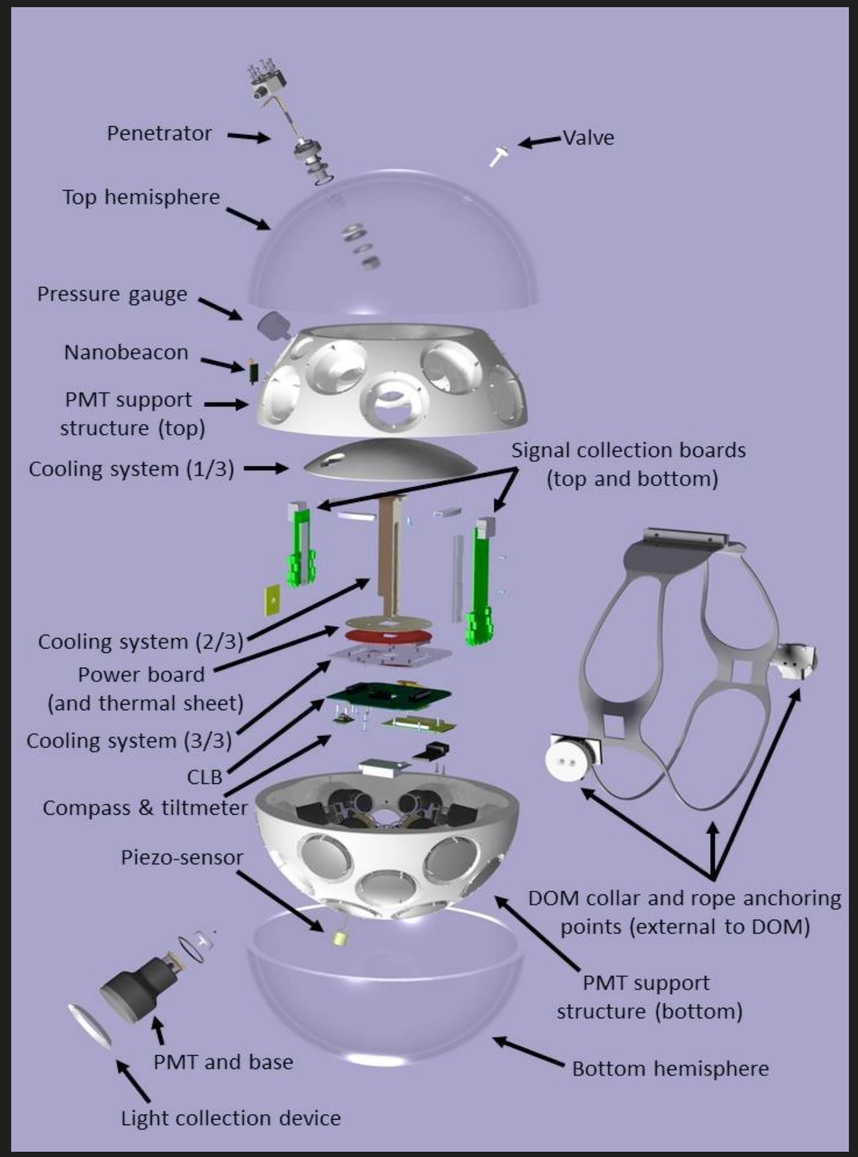
Low power
< 10 W / DOM

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: ARCA AND ORCA

two different building blocks

Clancy James - "Highlights from ANTARES, and prospects for KM3NeT" - August 4, 17:30 **(highlight)**

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Study astro[illegible]

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Clancy James - "Highlights from ANTARES, and prospects for KM3NeT" - August 4, 17:30 **(highlight)**

Paolo Piatelli - "All-flavour high-energy neutrino astronomy with KM3NeT/ARCA" - July 31, 14:18 - **NU 02**

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Paolo Piatelli - "All-flavour high-energy neutrino astronomy with KM3NeT/ARCA" - July 31, 14:18 - **NU 02**

Jürgen Brunner- "KM3NeT - ORCA: Measuring neutrino oscillations and the mass hierarchy in the Mediterranean" - July 31, 14:36 - **NU 02**

KM3NET CONSTRUCTION

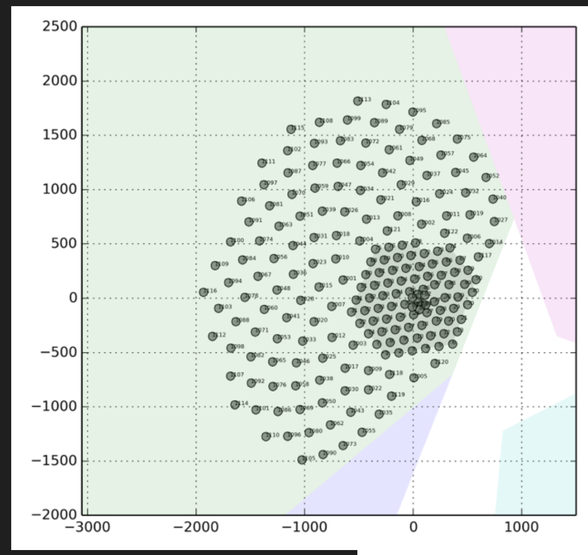
strings are ready to deploy!

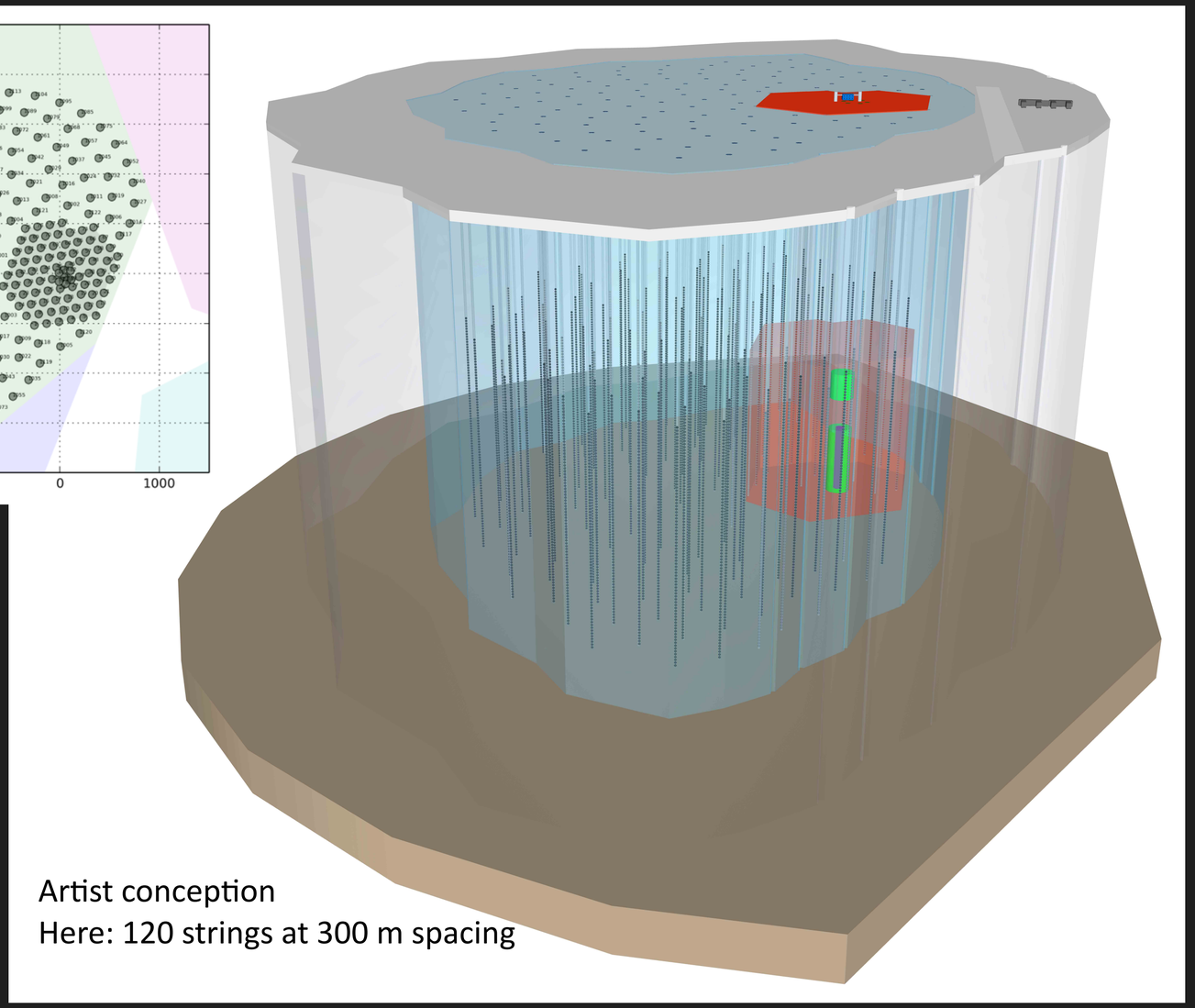
ICECUBE-GEN2: HIGH-ENERGY

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

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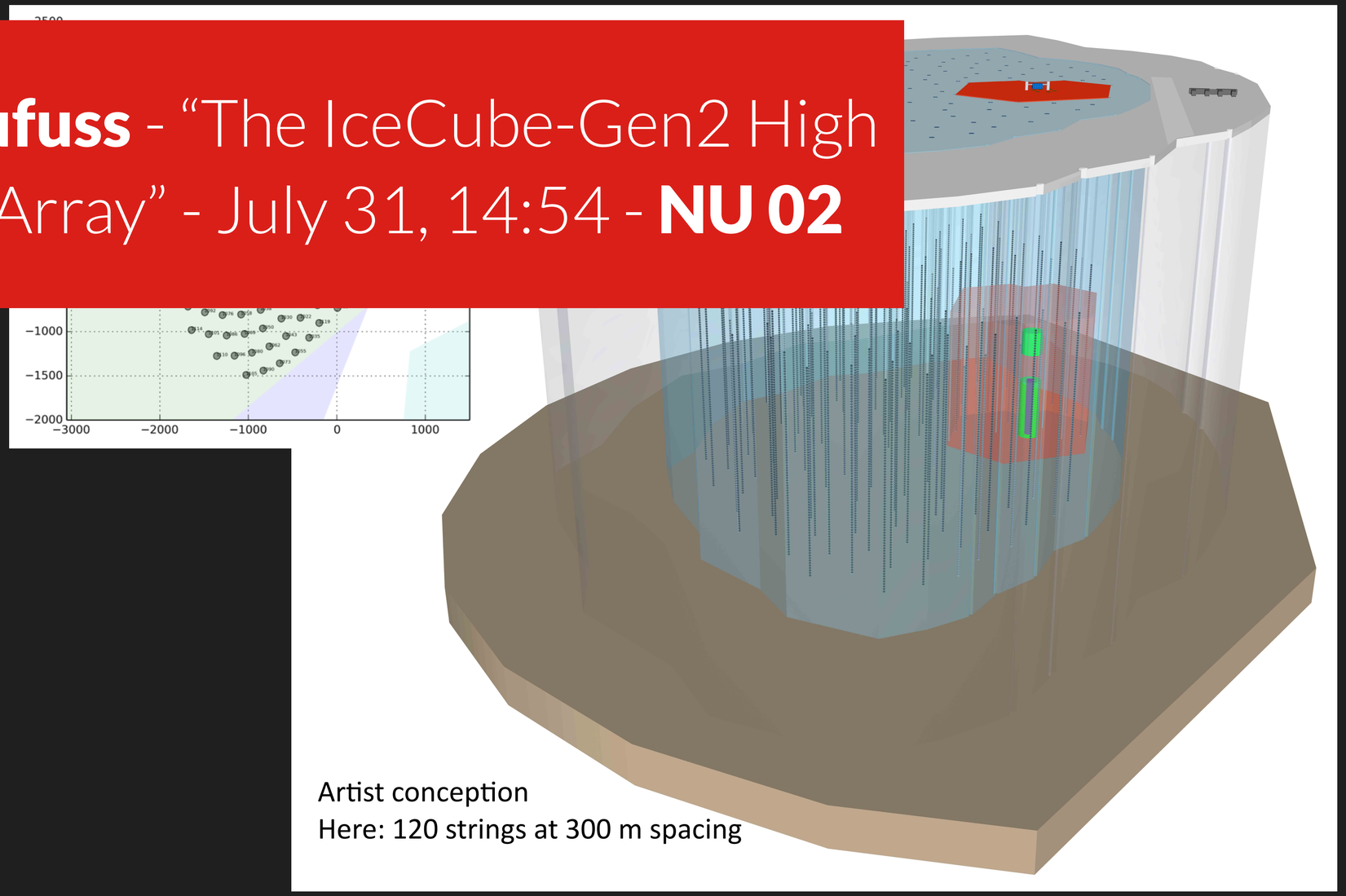
The IceCube-Gen2 High-Energy Array will instrument a significantly larger volume (~10km^3)

Erik Blaufuss - "The IceCube-Gen2 High Energy Array" - July 31, 14:54 - **NU 02**



Artist conception
Here: 120 strings at 300 m spacing

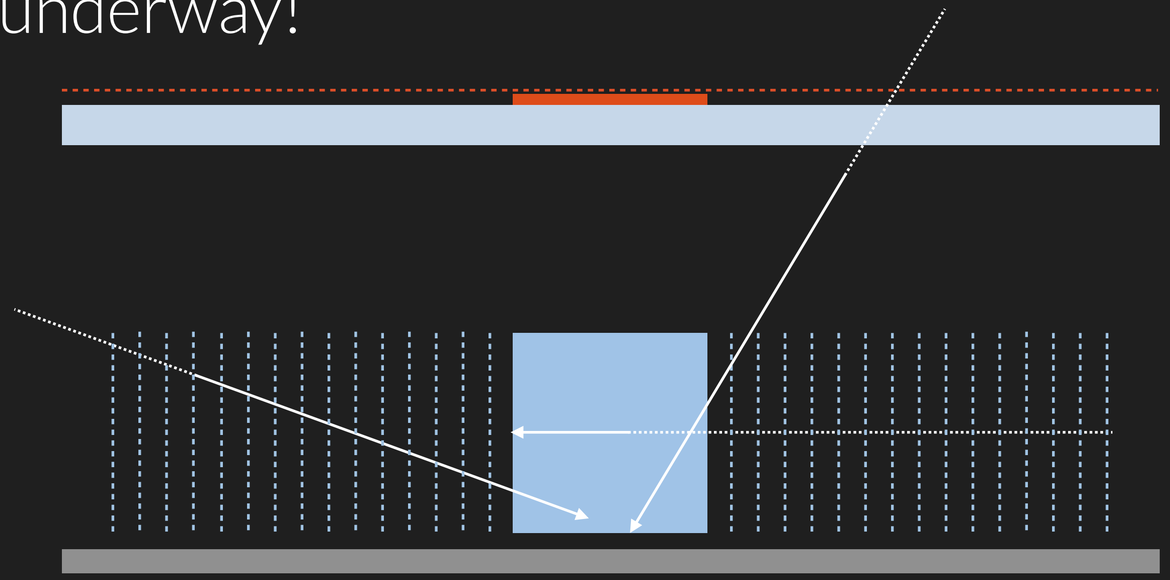
ICECUBE-GEN2: SURFACE VETO

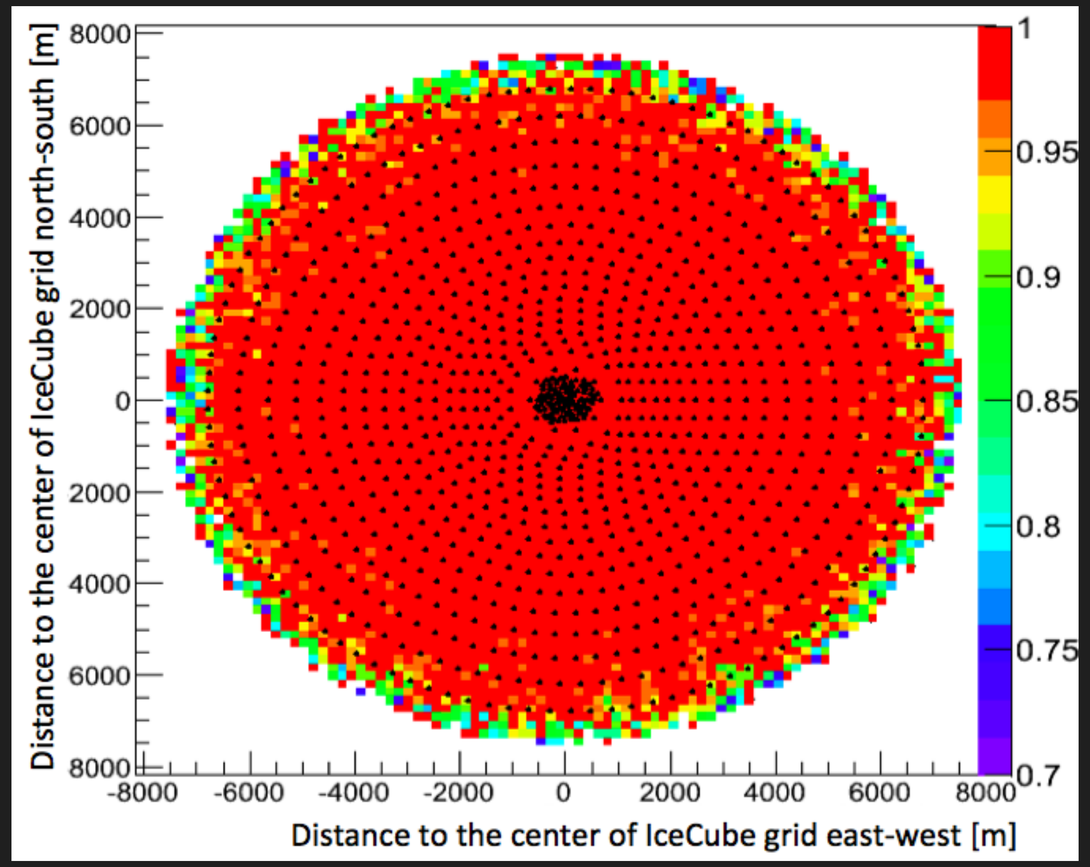
R&D for a surface array

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: SURFACE VETO

R&D for a surface array

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alternative tech
neutrinos from
surface

David Seckel - "Cosmic Ray Science Potential for an Extended Surface array at the IceCube Observatory" - August 5, 11:30 - **CR 19**

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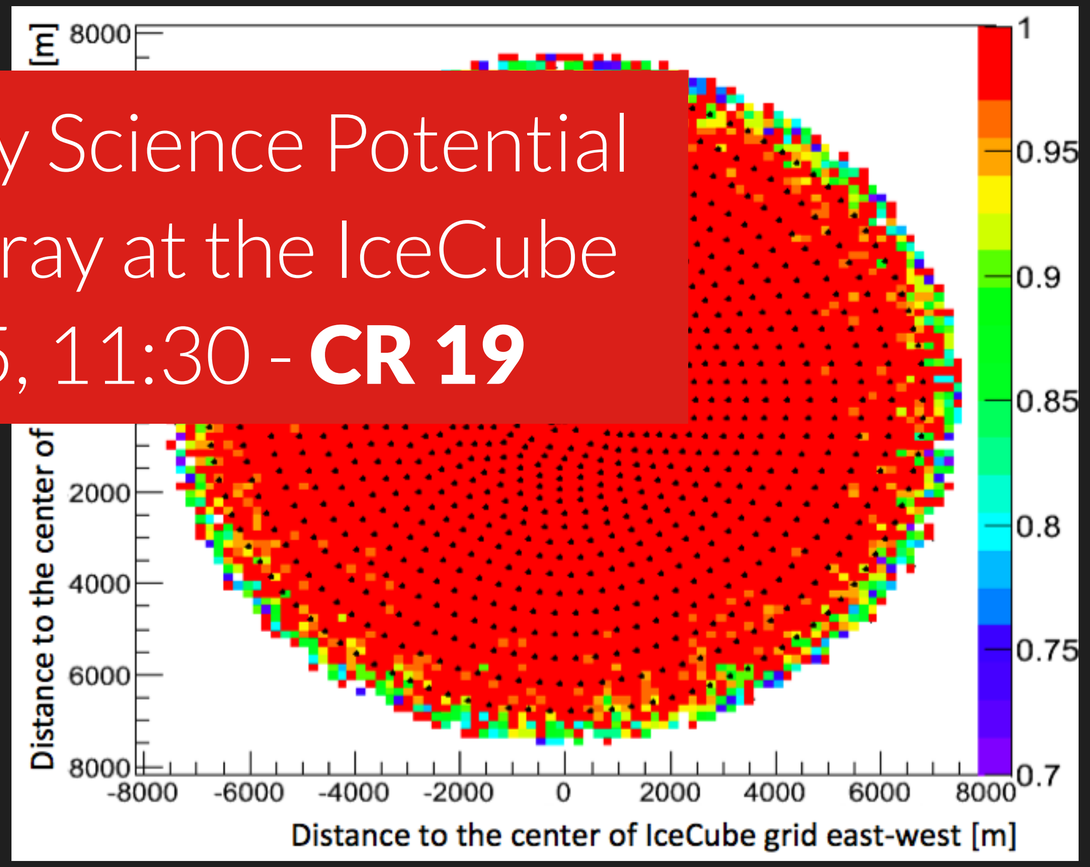
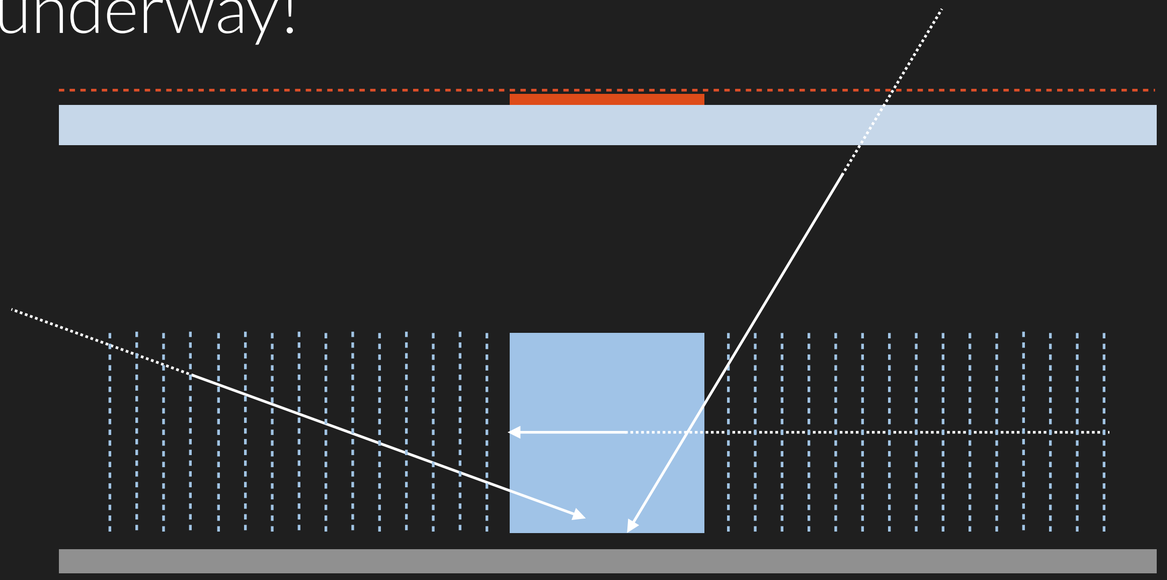




ICECUBE-GEN2: SURFACE VETO

R&D for a surface array

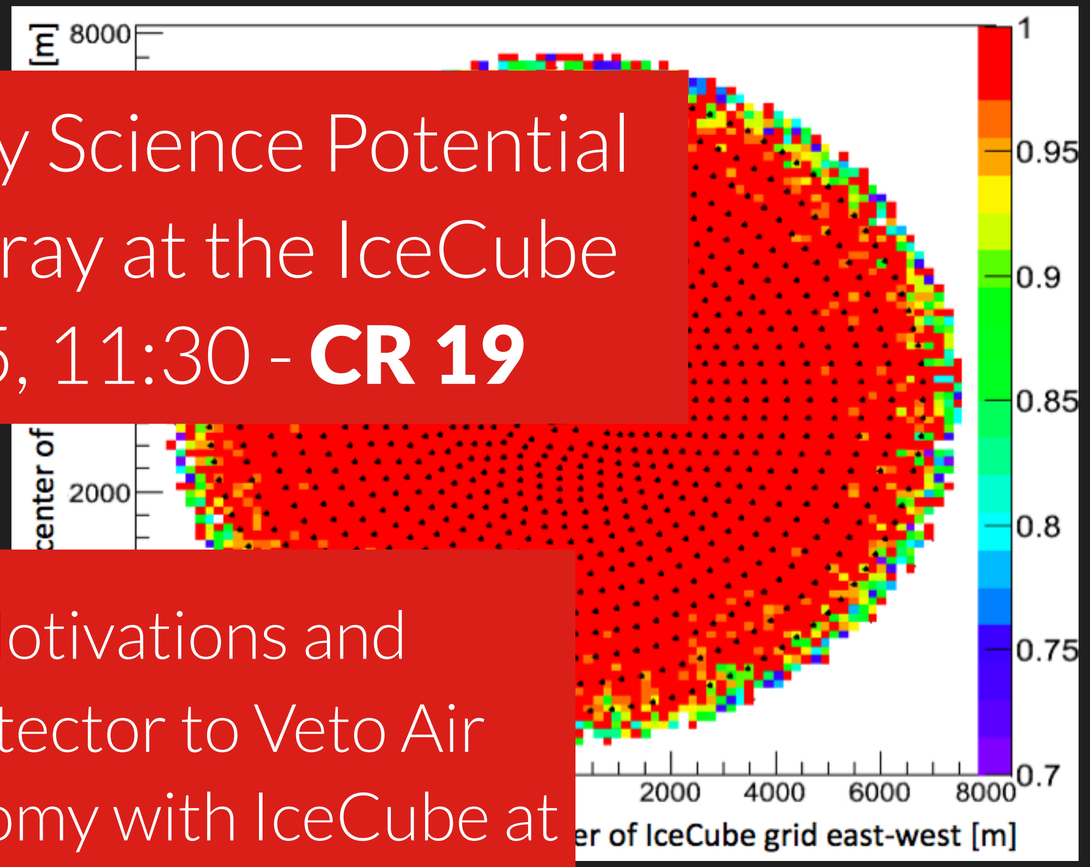
similar to the current "IceTop" surface array (or alternative tech
neutrinos from
surface

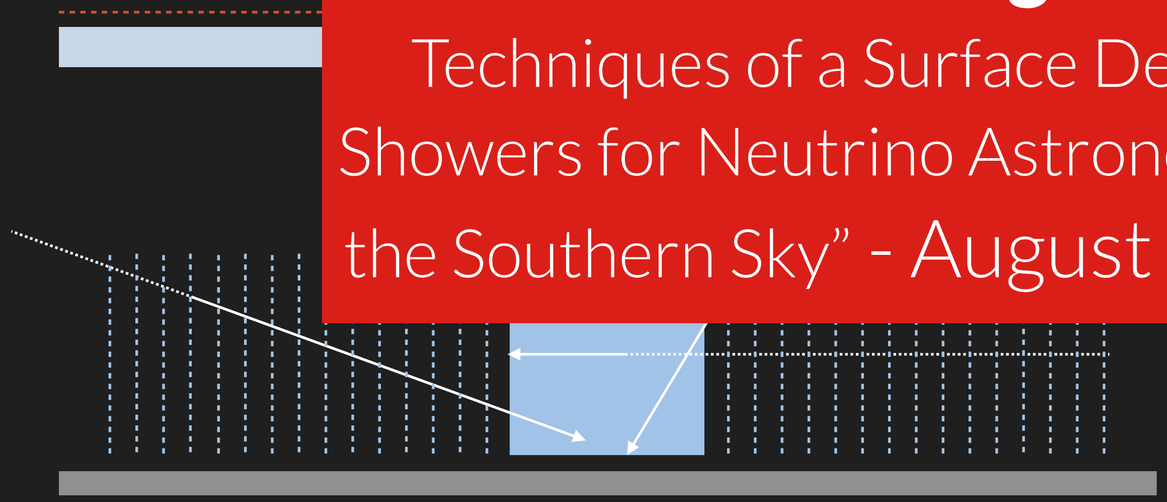
David Seckel - "Cosmic Ray Science Potential for an Extended Surface array at the IceCube Observatory" - August 5, 11:30 - **CR 19**

increase volume for starting tracks

R&D is underway!

Jan Auffenberg - "Motivations and Techniques of a Surface Detector to Veto Air Showers for Neutrino Astronomy with IceCube at the Southern Sky" - August 1, 14:00 - **NU 03**





ICECUBE-GEN2: PINGU

measuring the mass hierarchy using atmospheric neutrinos

cover energies down to a couple of GeV

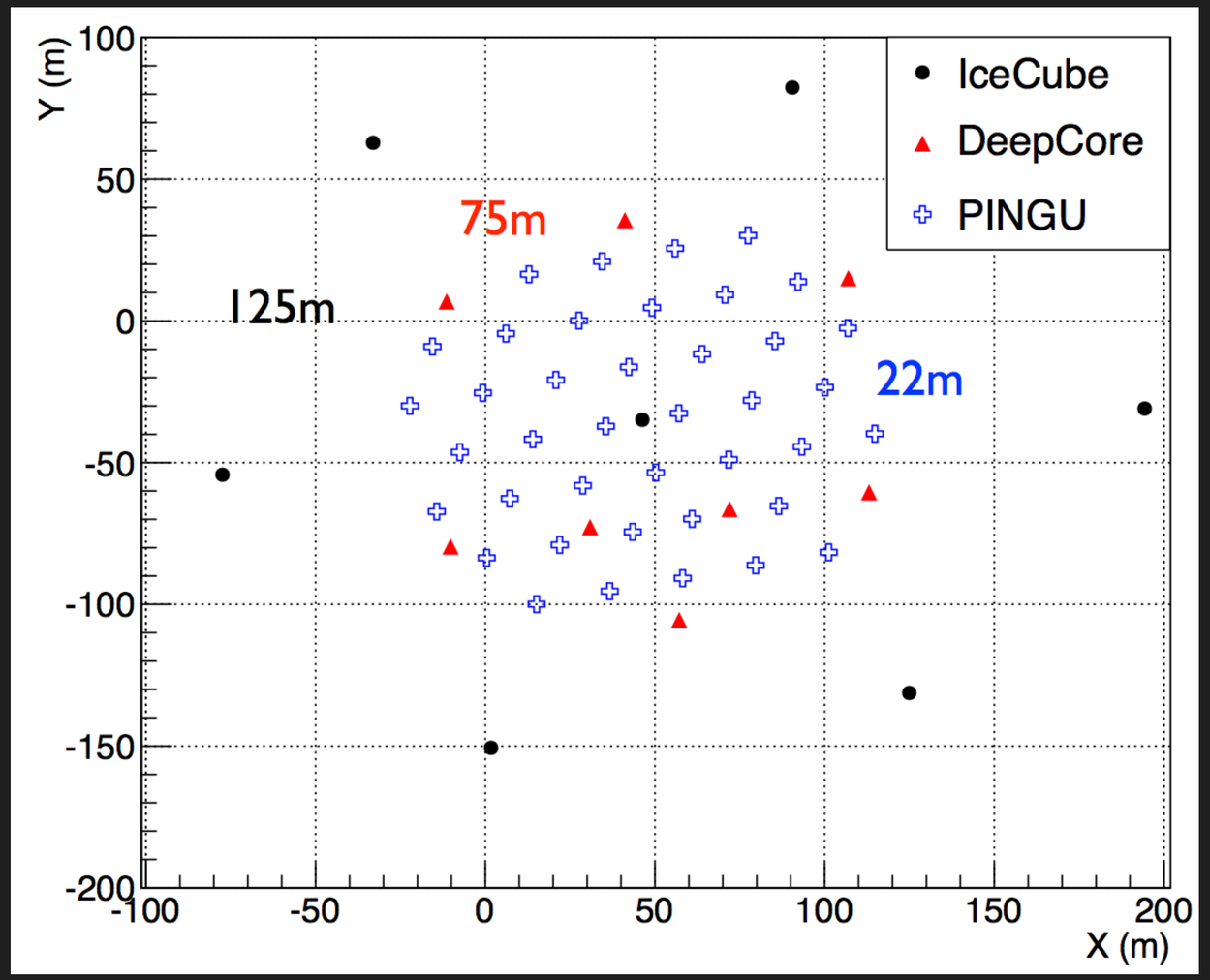
add **40** strings to IceCube/DeepCore

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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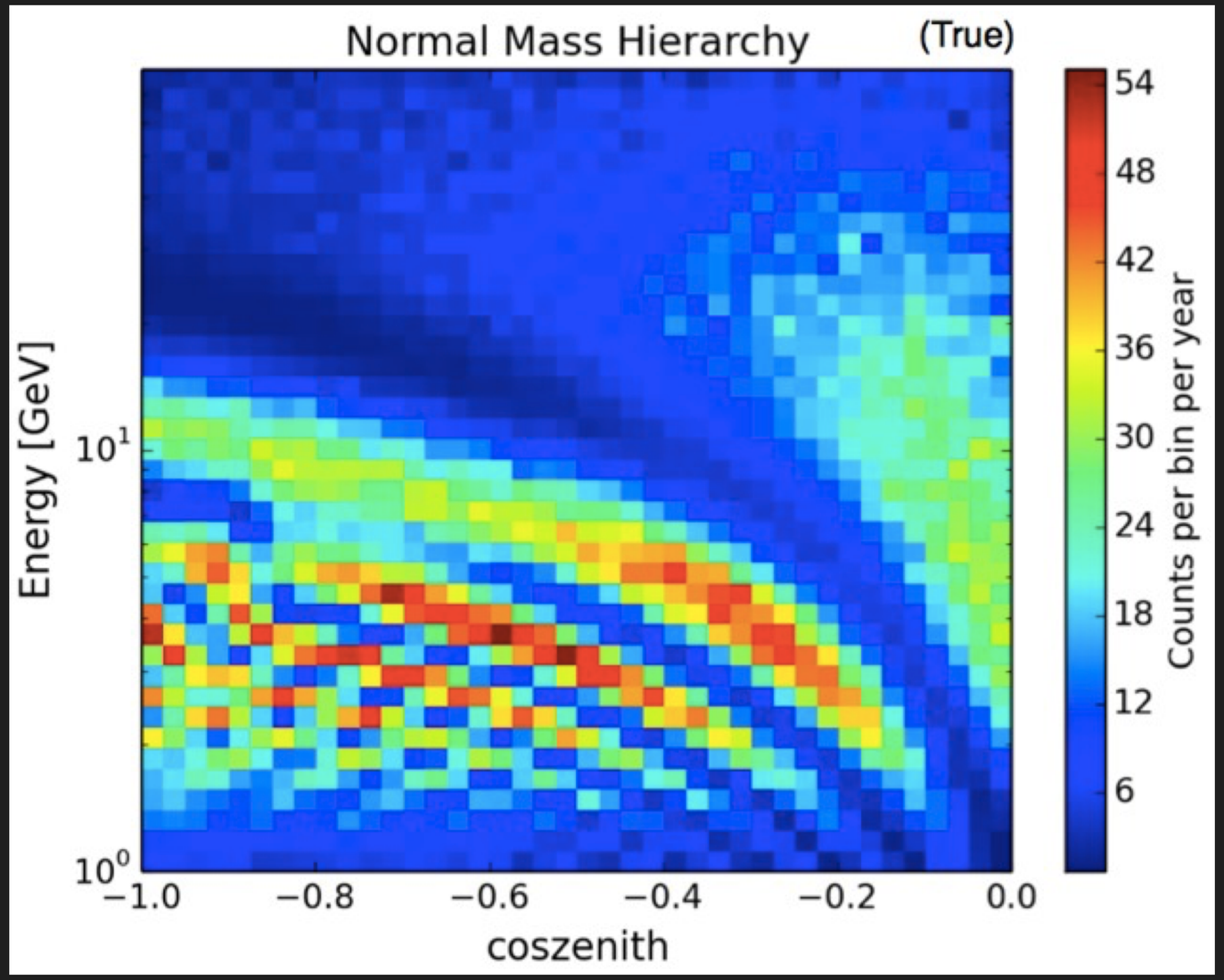

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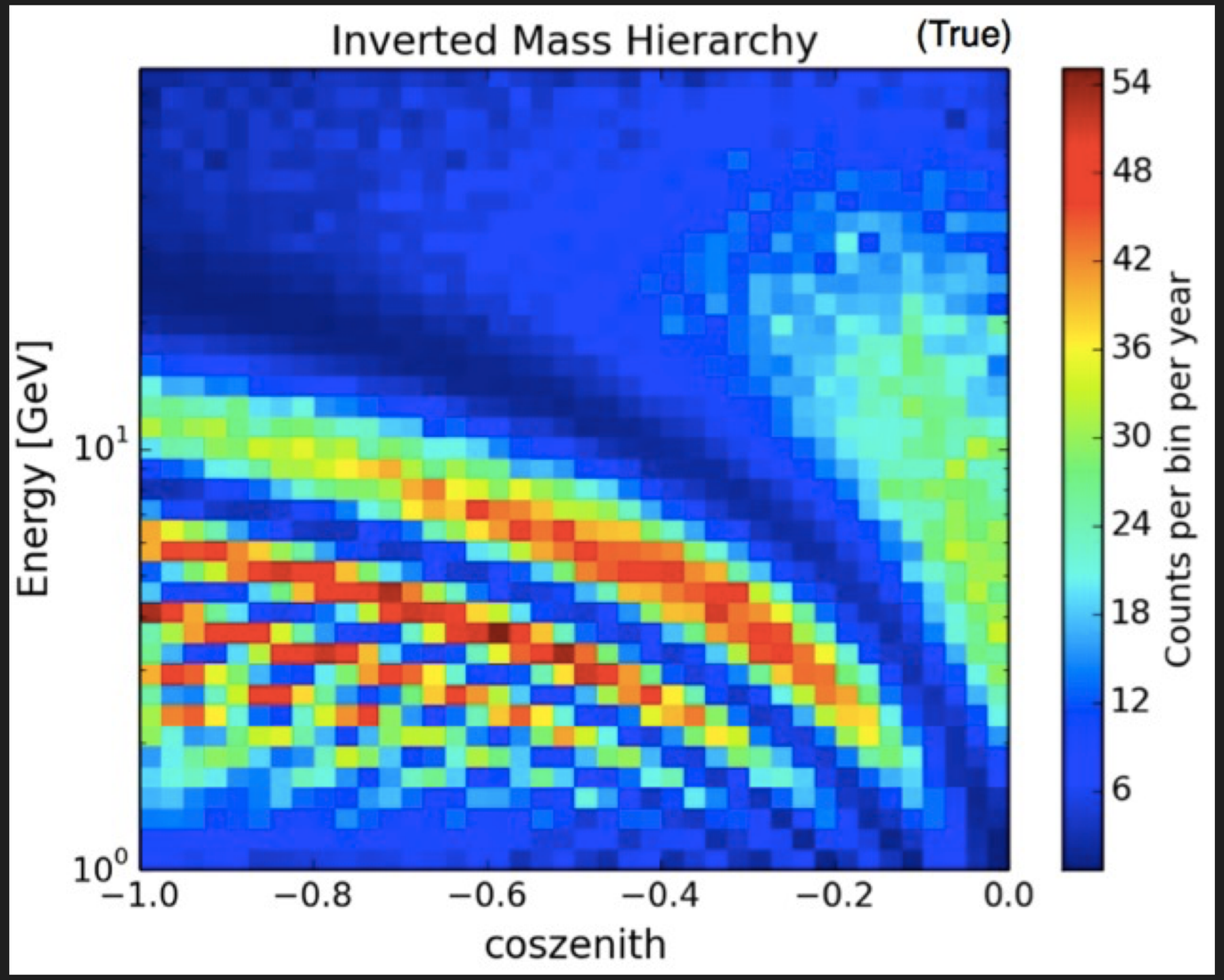

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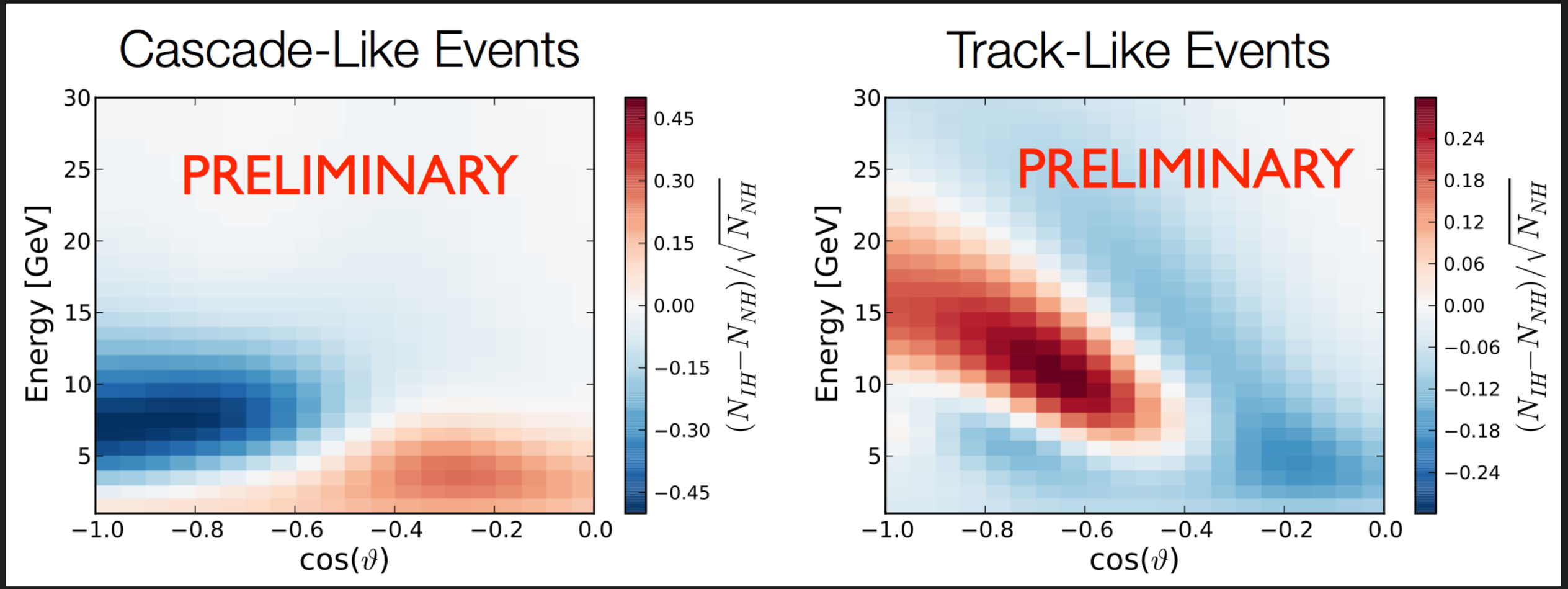
measuring the mass hierarchy using atmospheric neutrinos



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 years of operation

MORE HIGH-ENERGY NEUTRINOS AT ICRC

Point Sources, Neutrino Astronomy

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Point Sources, Neutrino Astronomy

Stefan Coenders - "Results of neutrino point source searches with 2008-2014 IceCube data above 10 TeV" - Aug 3, 15:00 - **NU 04**

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Point Sources, Neutrino Astronomy

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Hans Niederhausen - "High energy astrophysical neutrino flux characteristics for neutrino-induced cascades using IC79 and IC86-string IceCube configurations" - Aug 4, 14:15 - **NU 05**

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MORE HIGH-ENERGY NEUTRINOS AT ICRC

Follow-up and multi-messenger observations

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Geraldine Golup - "Correlation between the UHECRs measured by the Pierre Auger Observatory and Telescope Array and neutrino candidate events from IceCube" - Aug 3, 15:45 - **NU 04**

MORE HIGH-ENERGY NEUTRINOS AT ICRC

MORE HIGH-ENERGY NEUTRINOS AT ICRC

everyone I forgot or did not have the time to mention!

THANK YOU!