Recent Results from the IceCube Neutrino Observatory

Chad Finley
Oskar Klein Centre
Stockholm University

CEA Saclay

2015 January 19

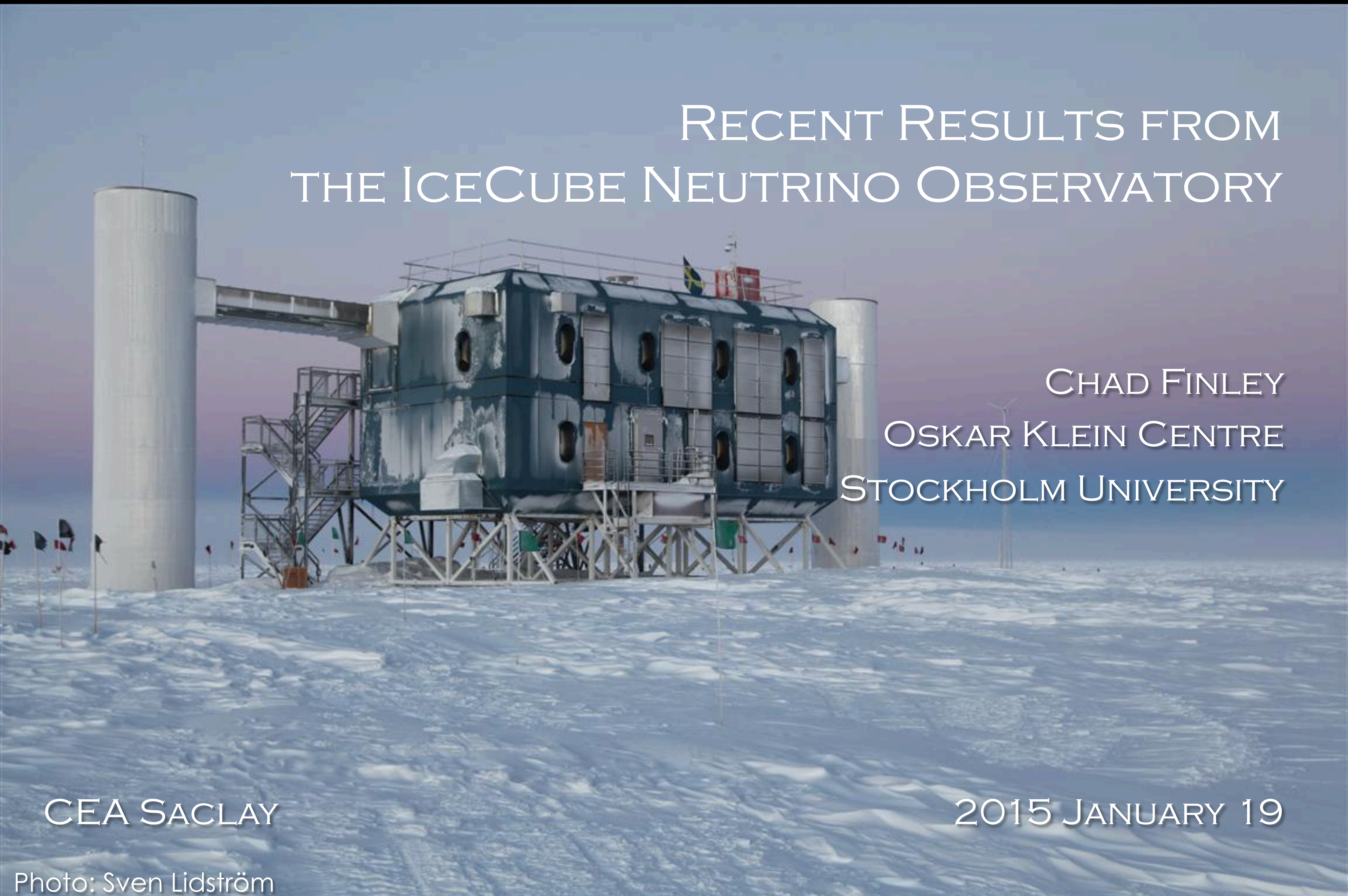
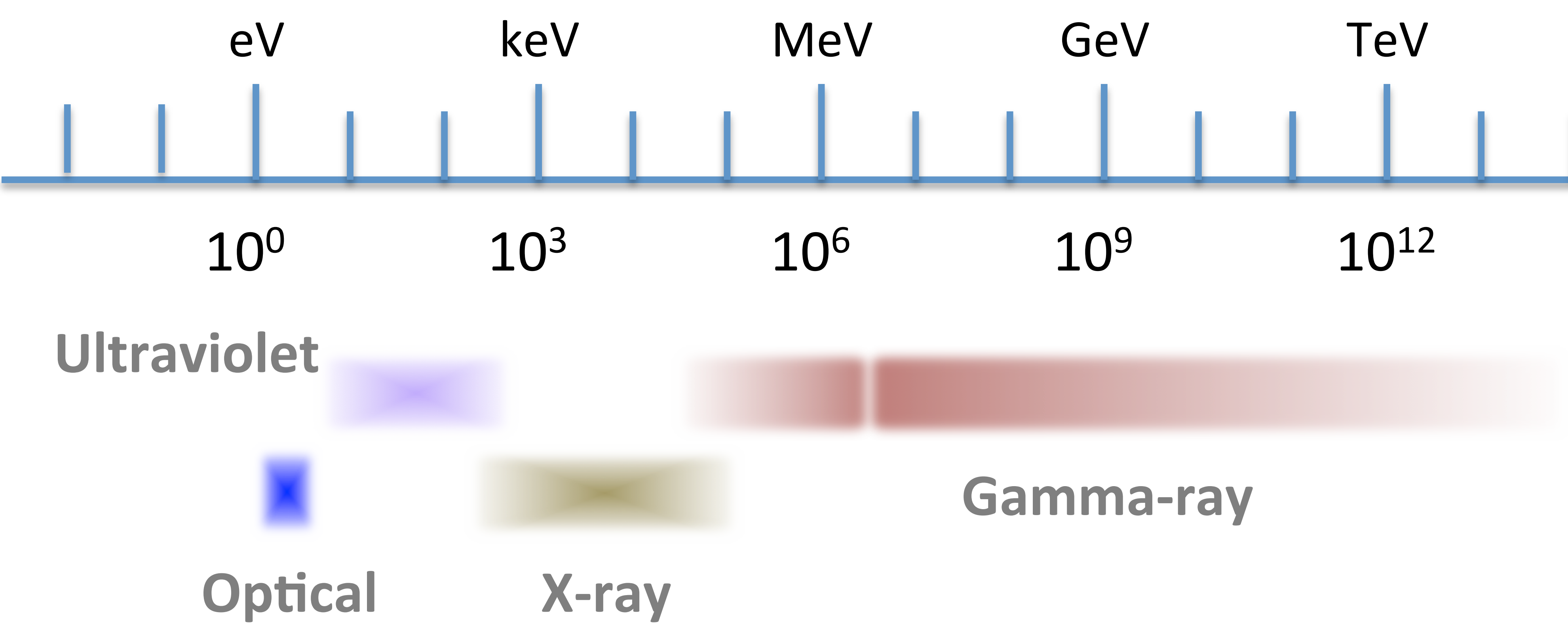


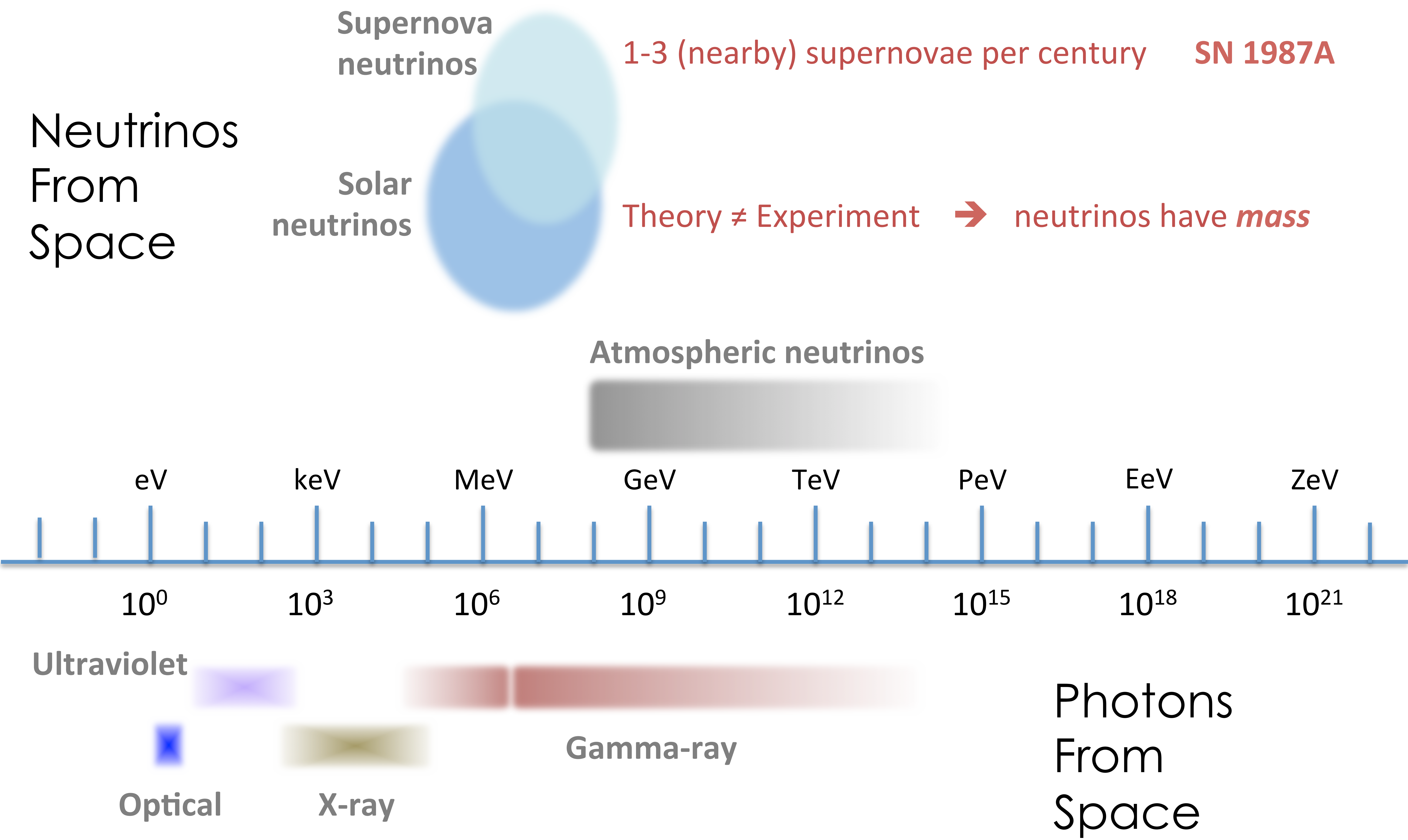
Photo: Sven Lidström

The Big Picture

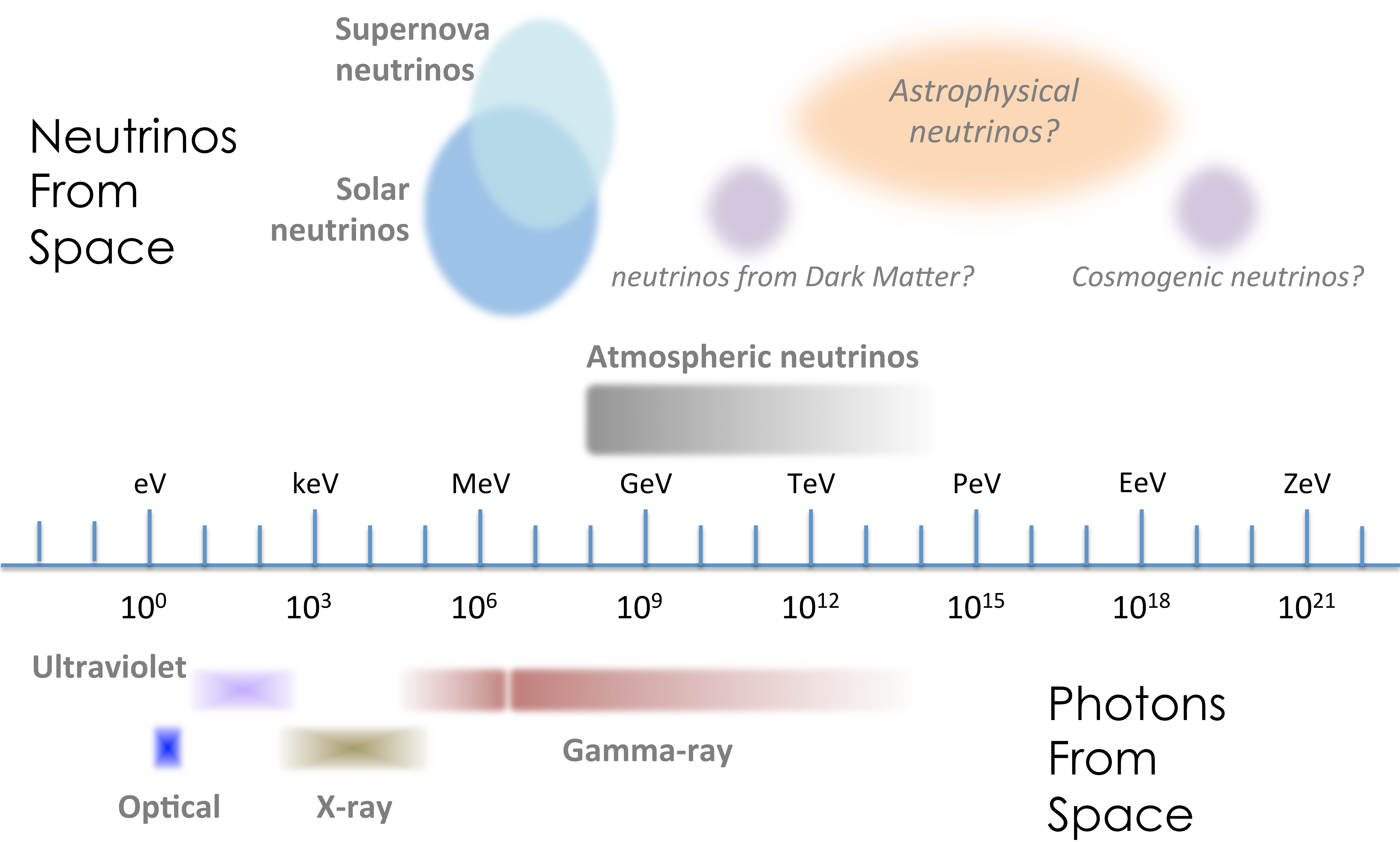


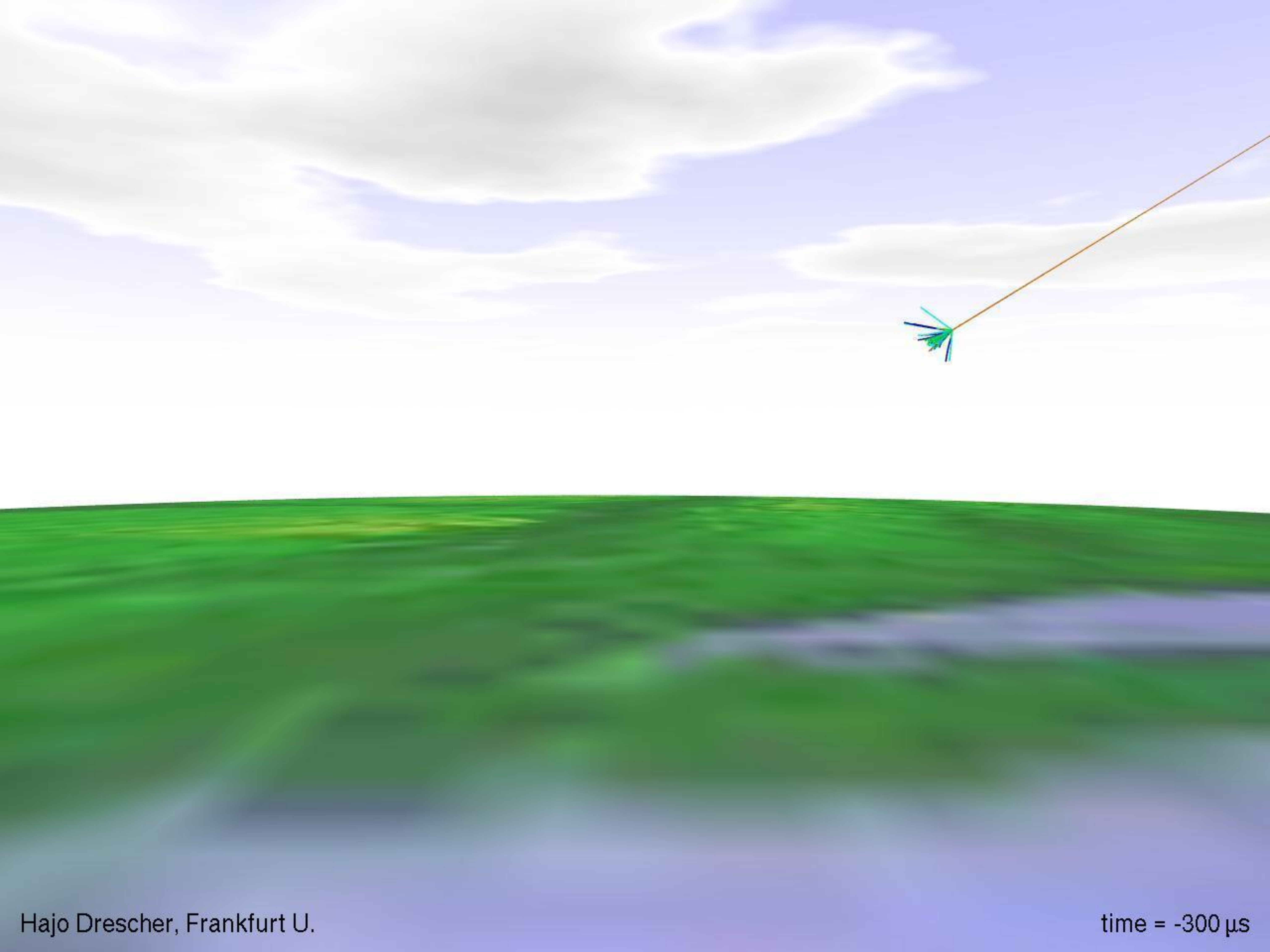
Photons
From
Space

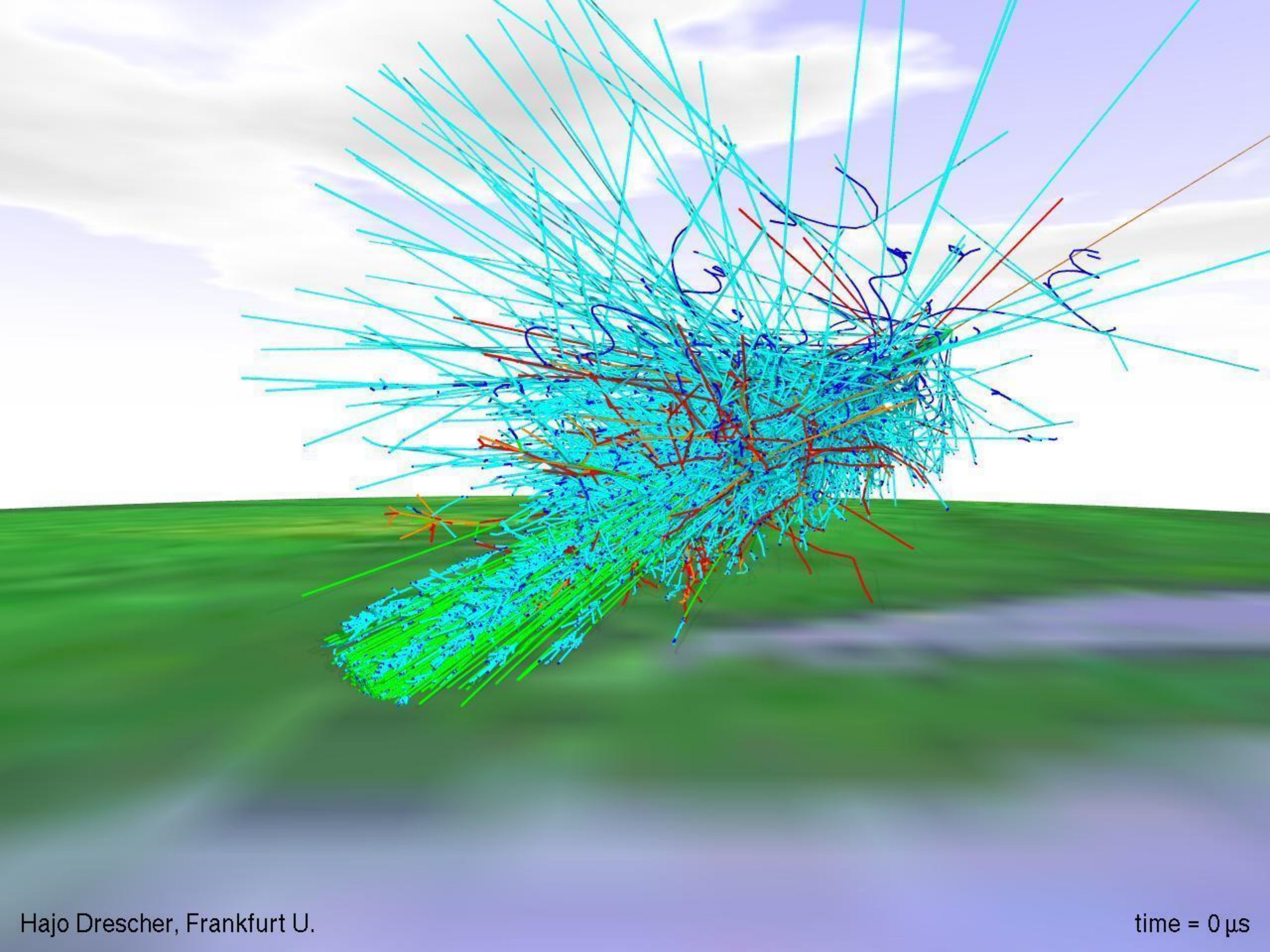
The Big Picture



The Big Picture




Hajo Drescher, Frankfurt U.
time = -300 µs


Hajo Drescher, Frankfurt U.
time = 0 μs

The Cosmic Ray Spectrum

Extraordinary particle accelerators **somewhere**,

but still **poorly identified** after a century

- Supernova remnants?
- Active galactic nuclei?
- Gamma ray bursts?

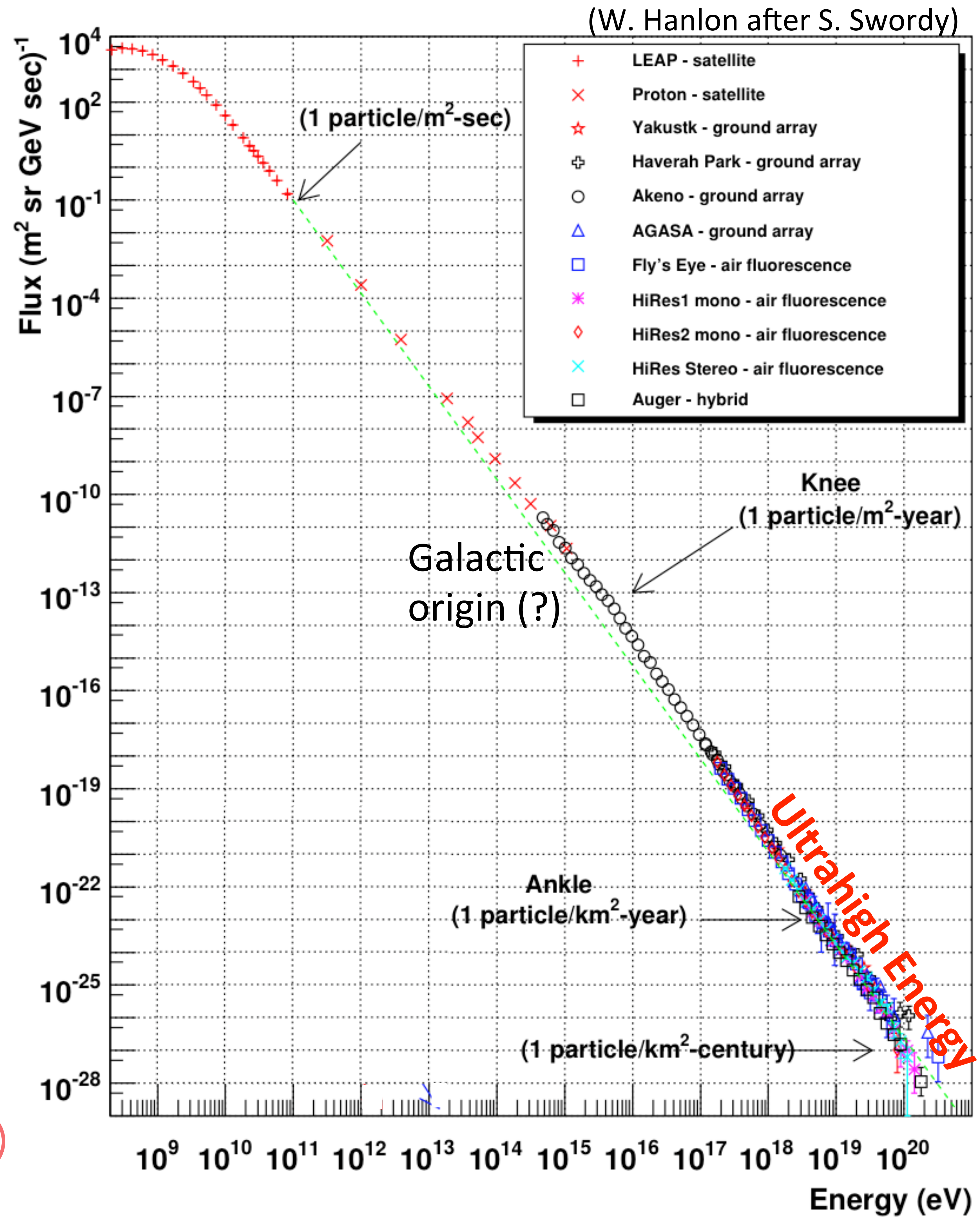
Cosmic ray interactions with matter and photons near source produce:

$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

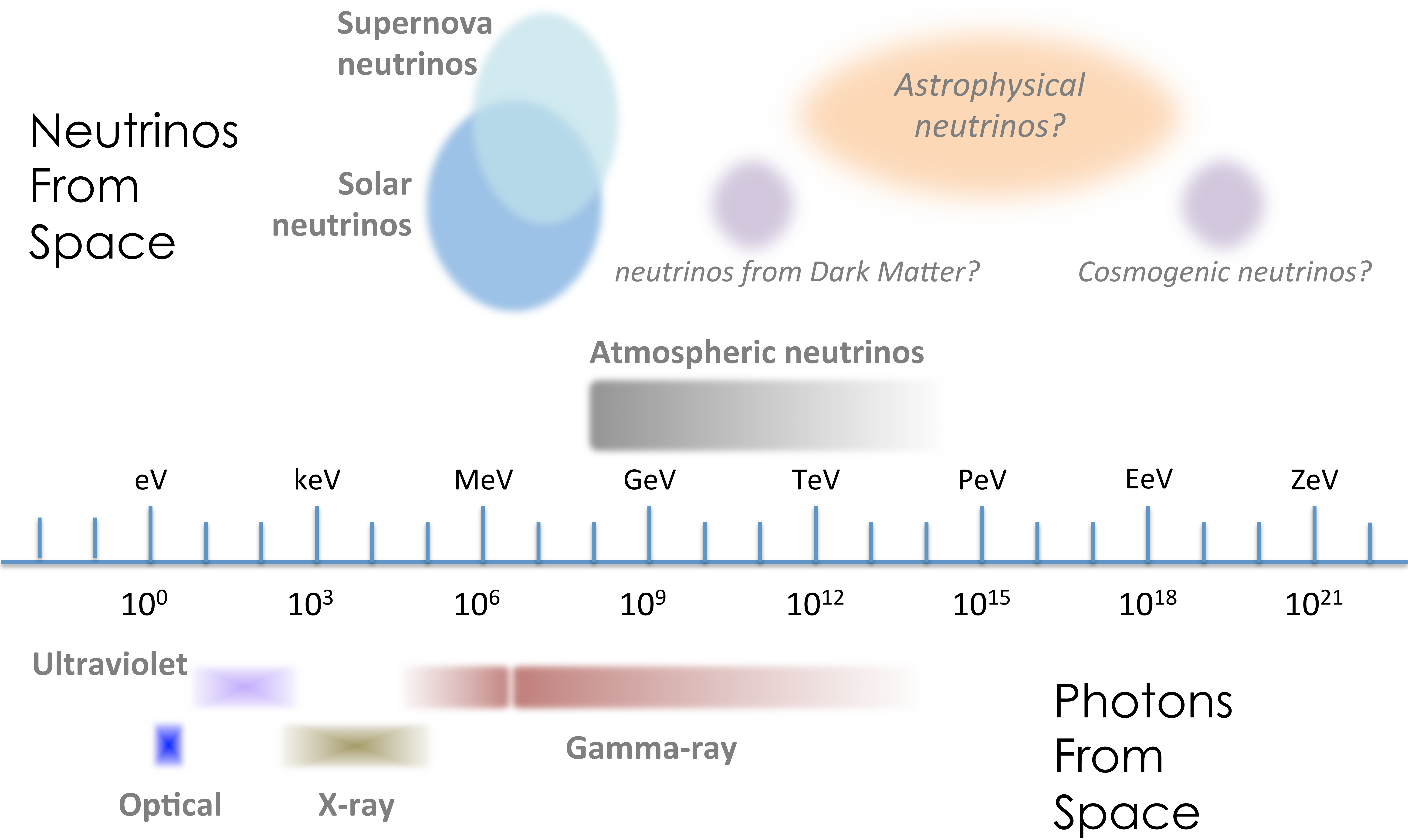
$$\pi^0 \rightarrow \gamma + \gamma$$

$$\pi^+ \rightarrow \mu^+ + \nu_\mu$$

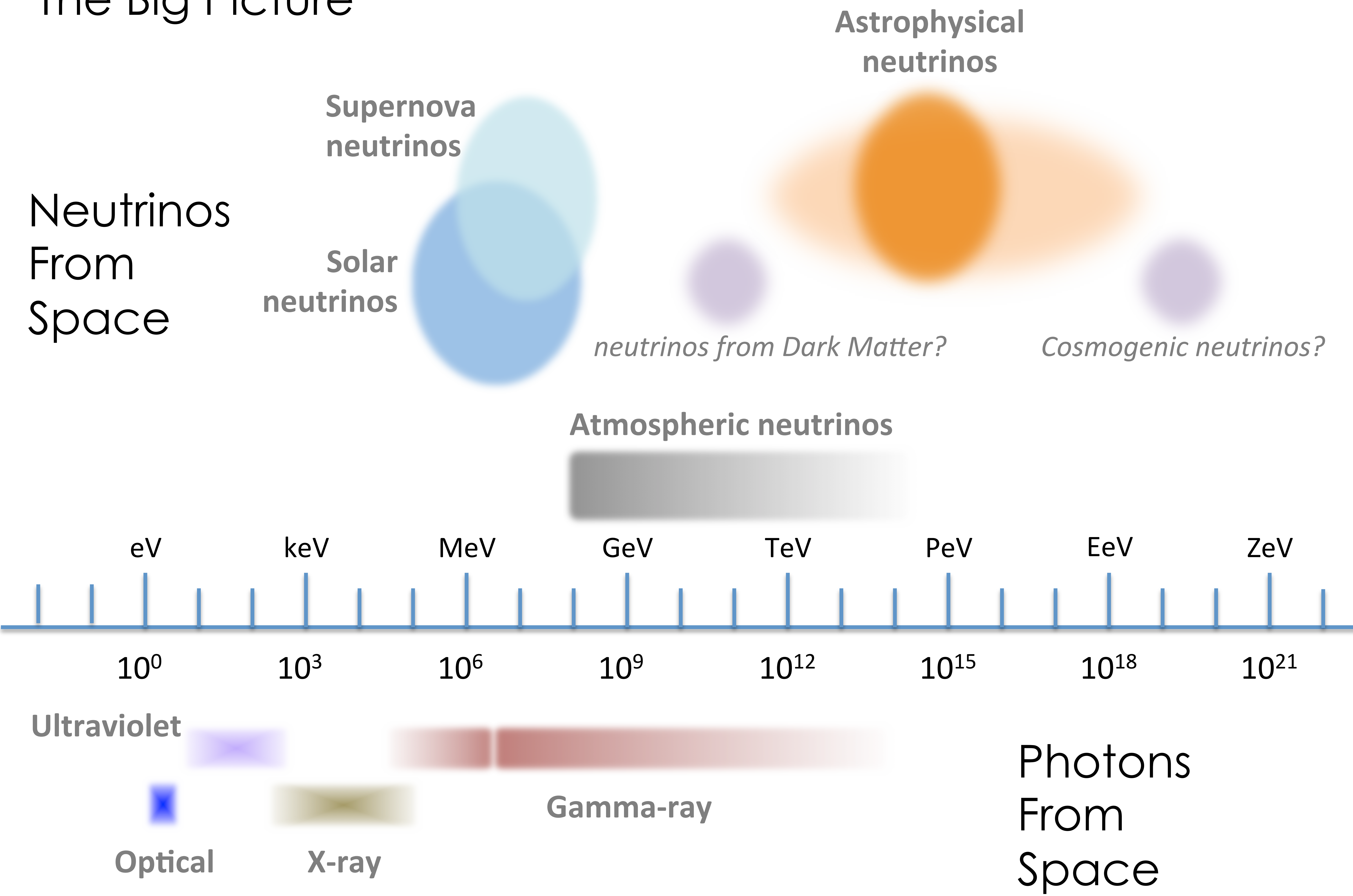
$$\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu$$



The Big Picture



The Big Picture



The IceCube Collaboration

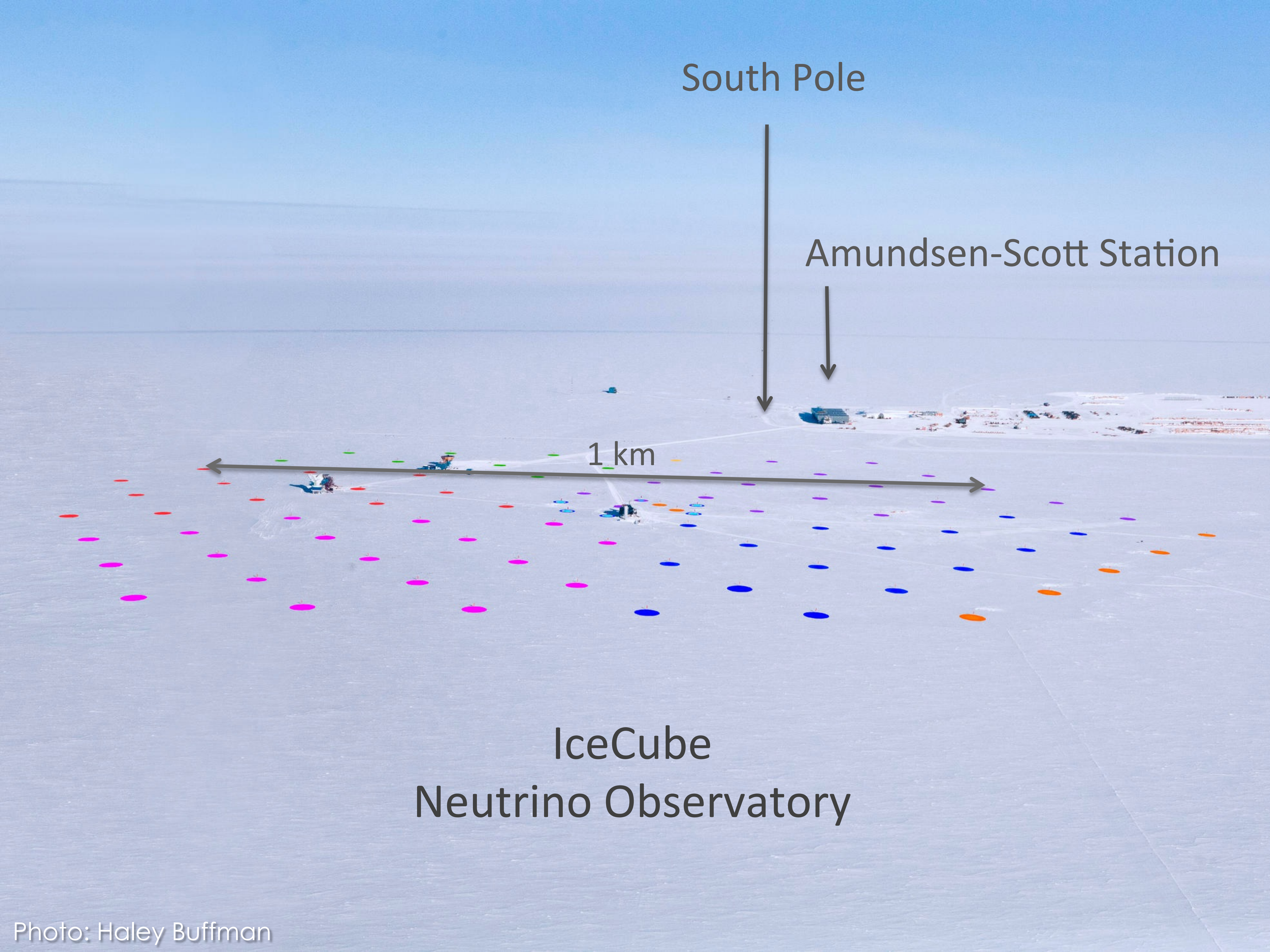
International Funding Agencies

Fonds de la Recherche Scientifique (FRS-FNRS)
Fonds Wetenschappelijk Onderzoek-Vlaanderen (FWO-Vlaanderen)
Federal Ministry of Education & Research (BMBF)
German Research Foundation (DFG)

Deutsches Elektronen-Synchrotron (DESY)
Inoue Foundation for Science, Japan
Knut and Alice Wallenberg Foundation
Swedish Polar Research Secretariat
The Swedish Research Council (VR)

University of Wisconsin Alumni Research Foundation (WARF)
US National Science Foundation (NSF)


South Pole
Amundsen-Scott Station
Photo: Haley Buffman


South Pole
Amundsen-Scott Station
1 km
IceCube
Neutrino Observatory
Photo: Haley Buffman

IceCube Neutrino Observatory

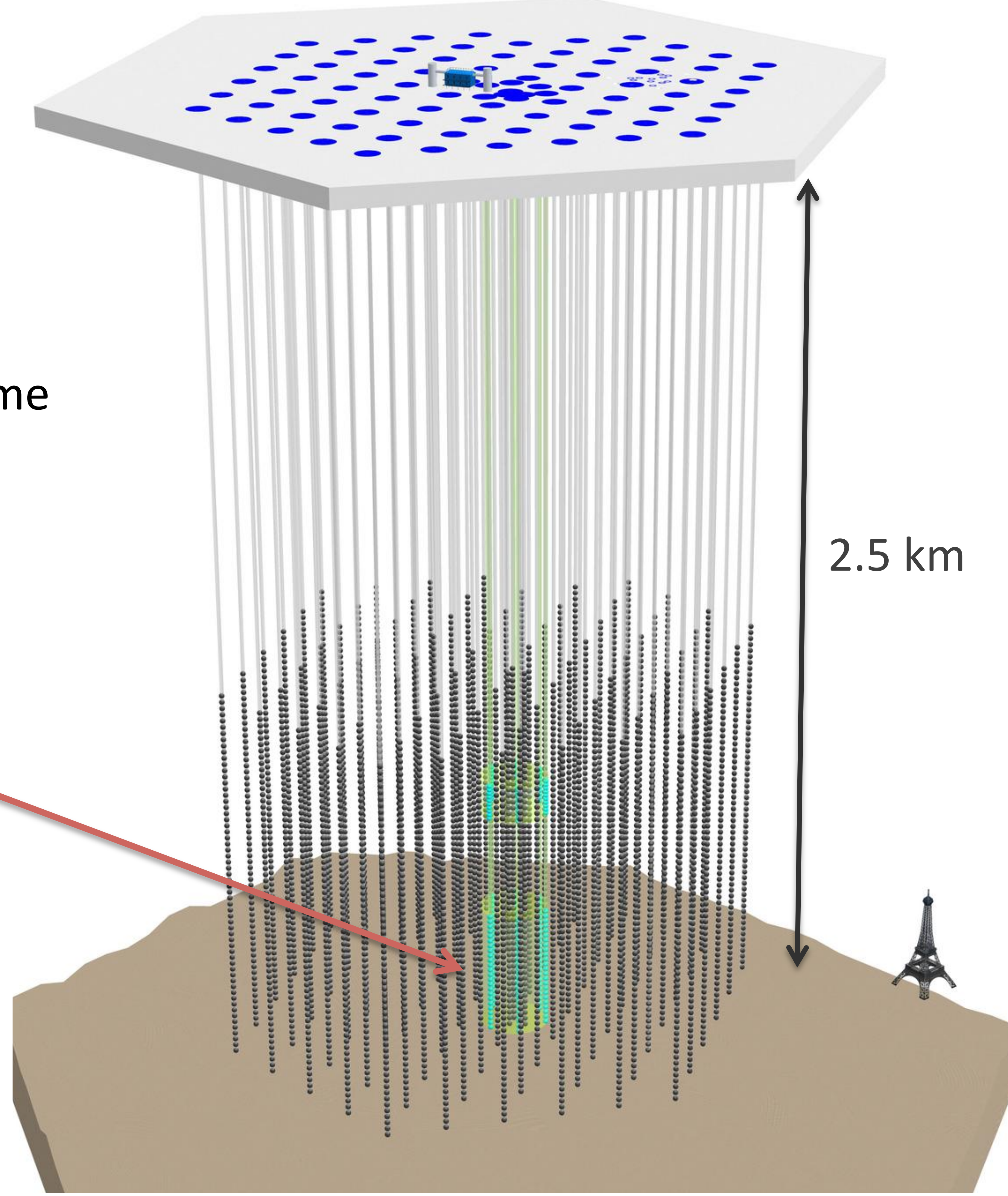
86 strings

60 Optical Modules per string

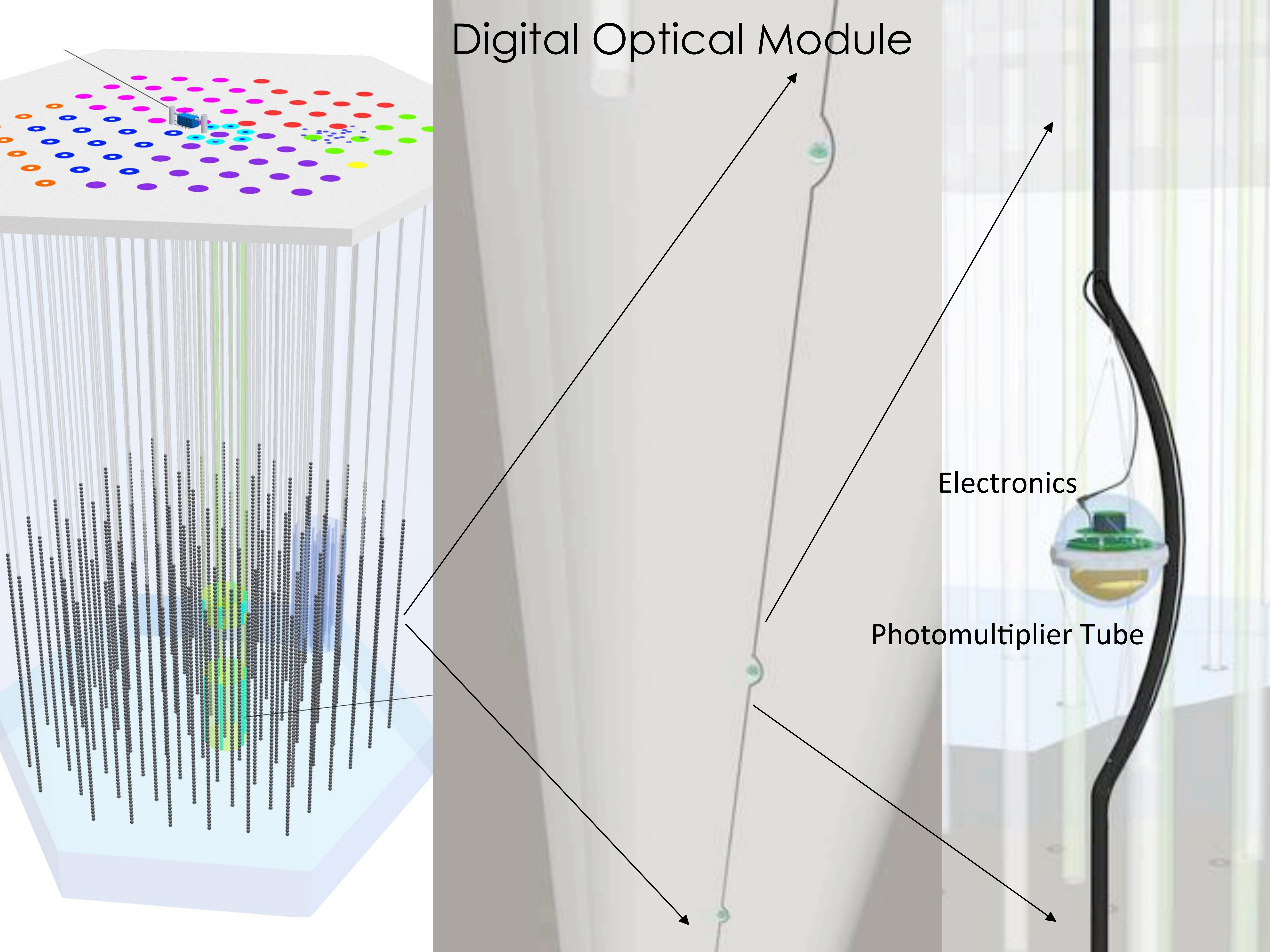
5 160 total modules in Ice

1 km^3 = Gigaton instrumented volume

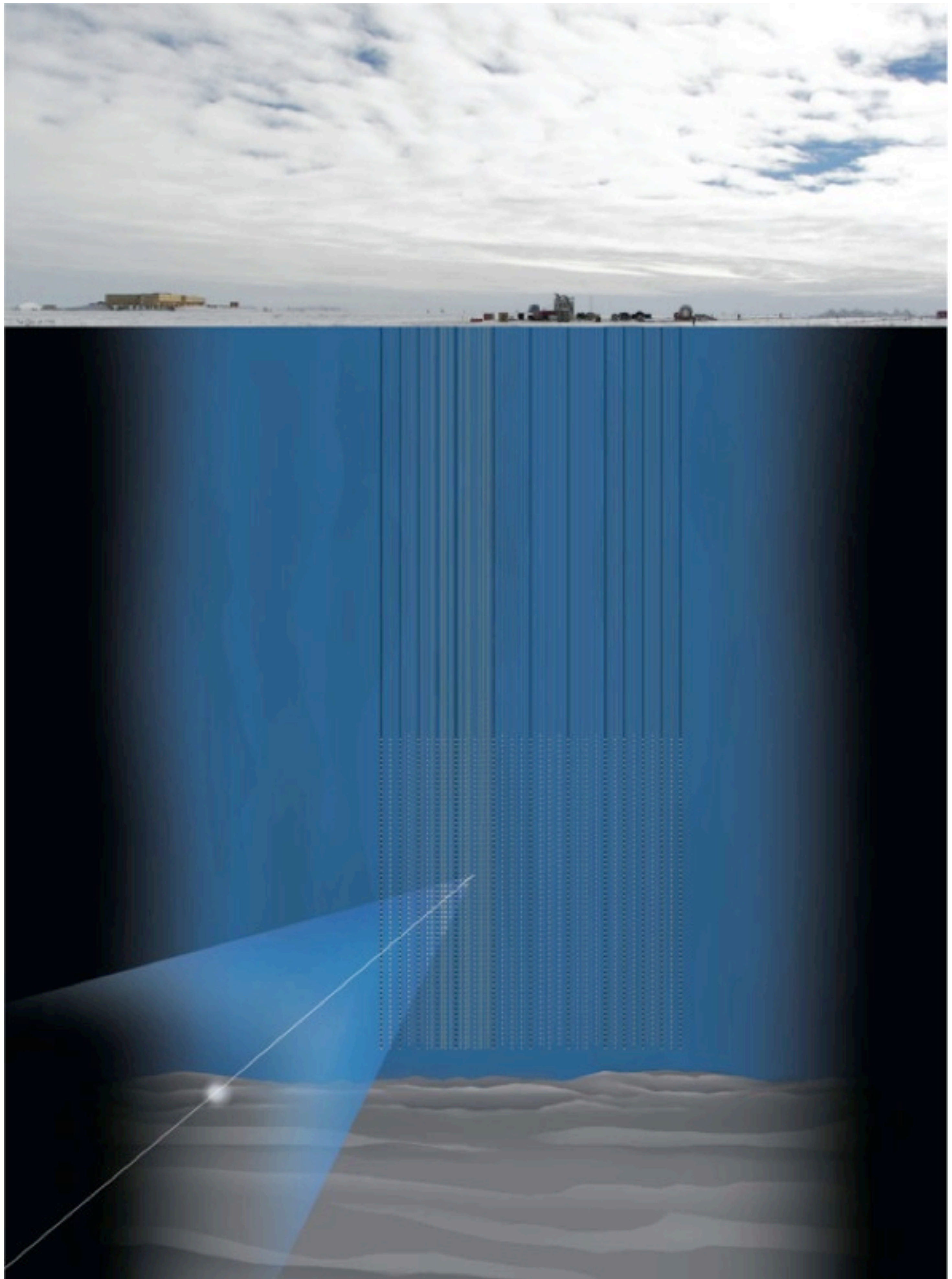
Began full operations May 2011

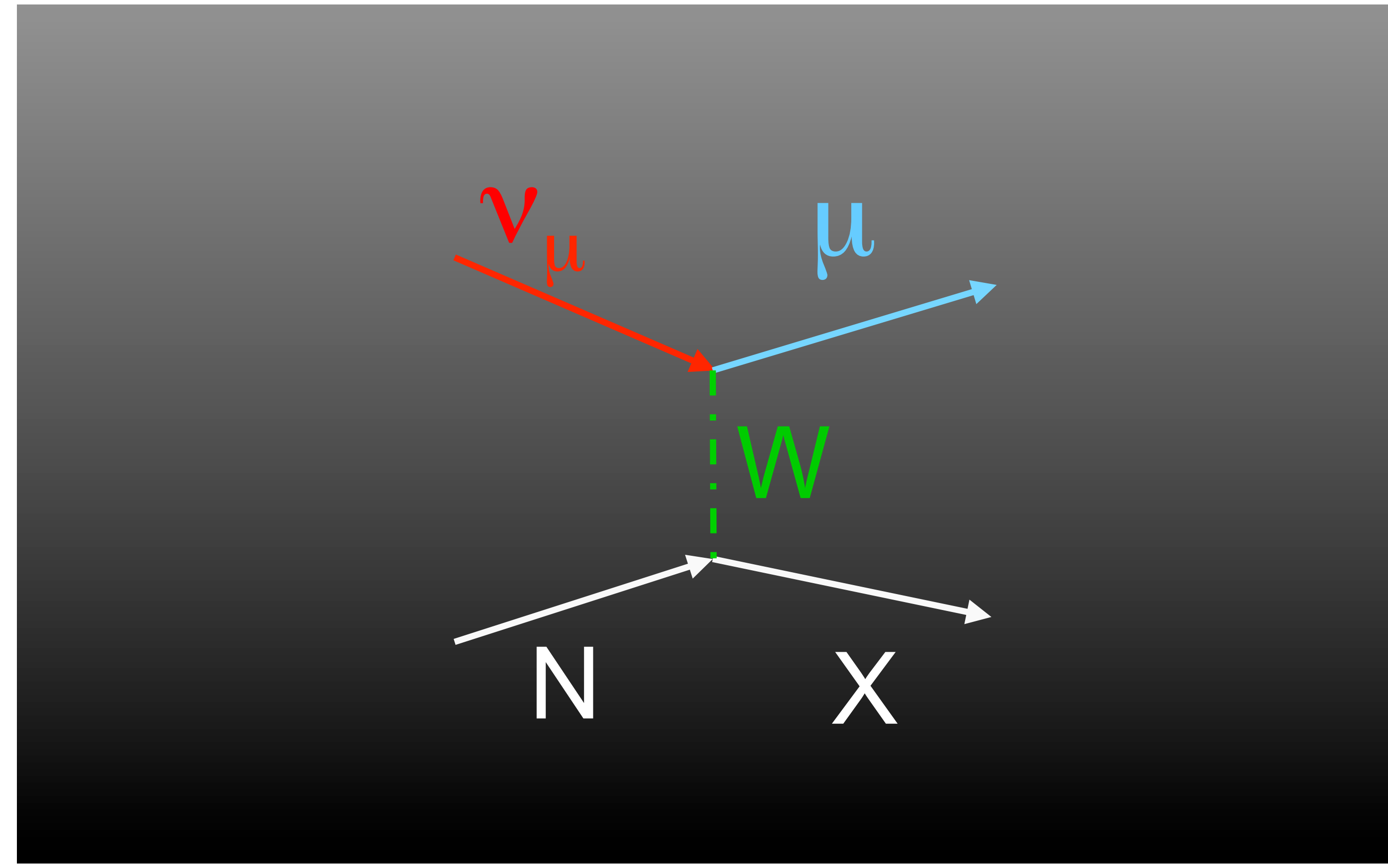


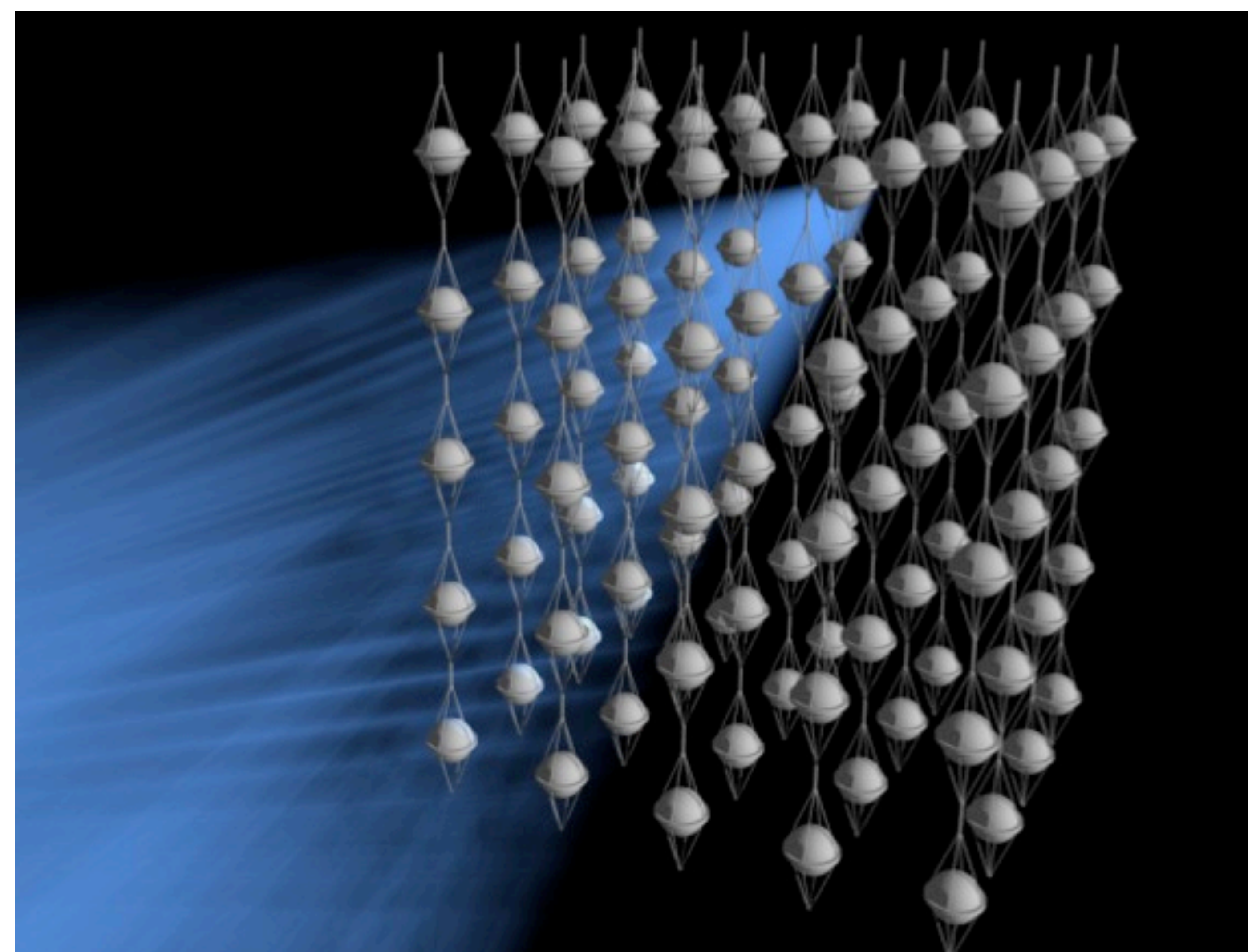
Digital Optical Module



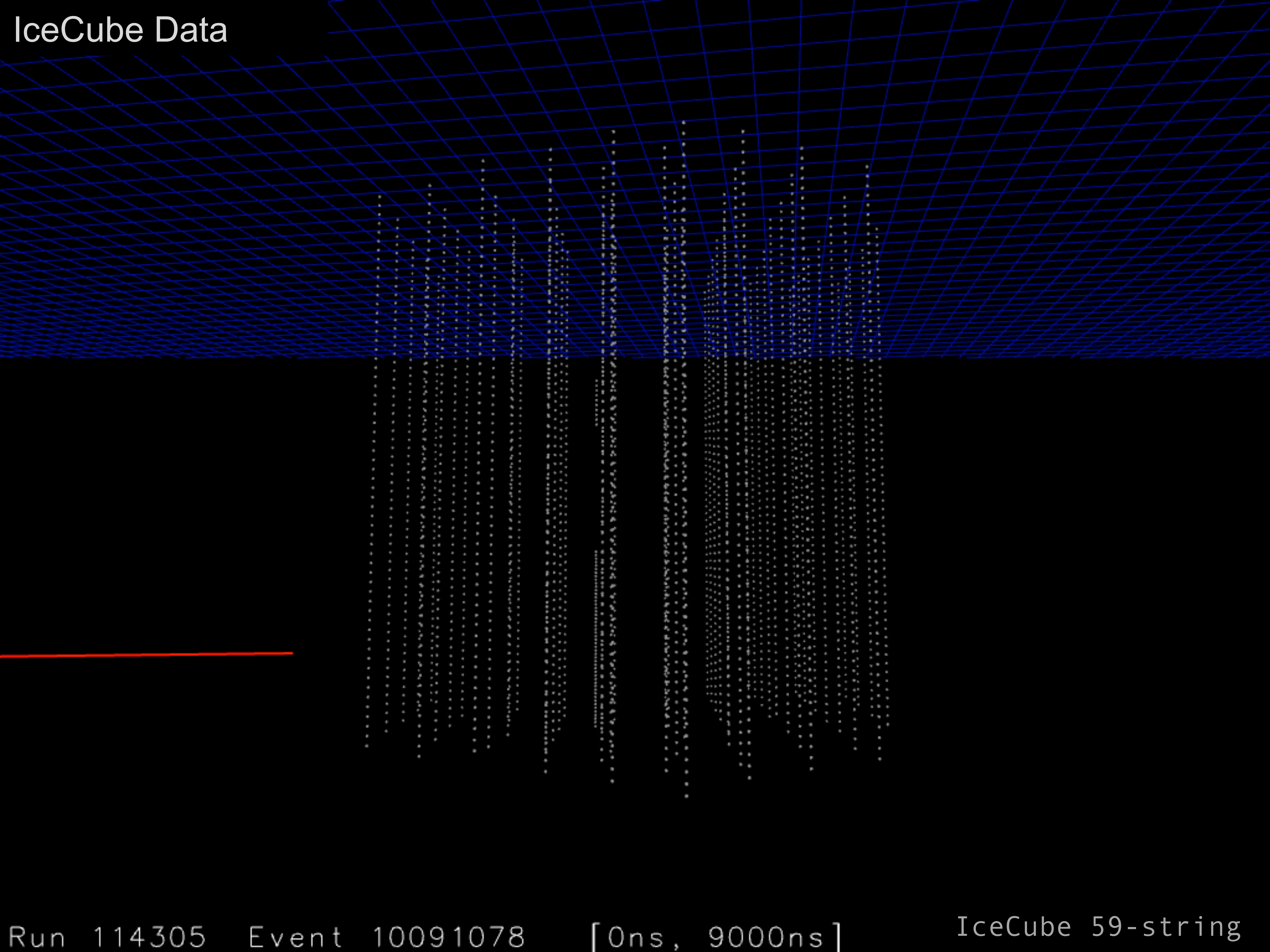
High Energy Neutrino Detection Principles







IceCube Data



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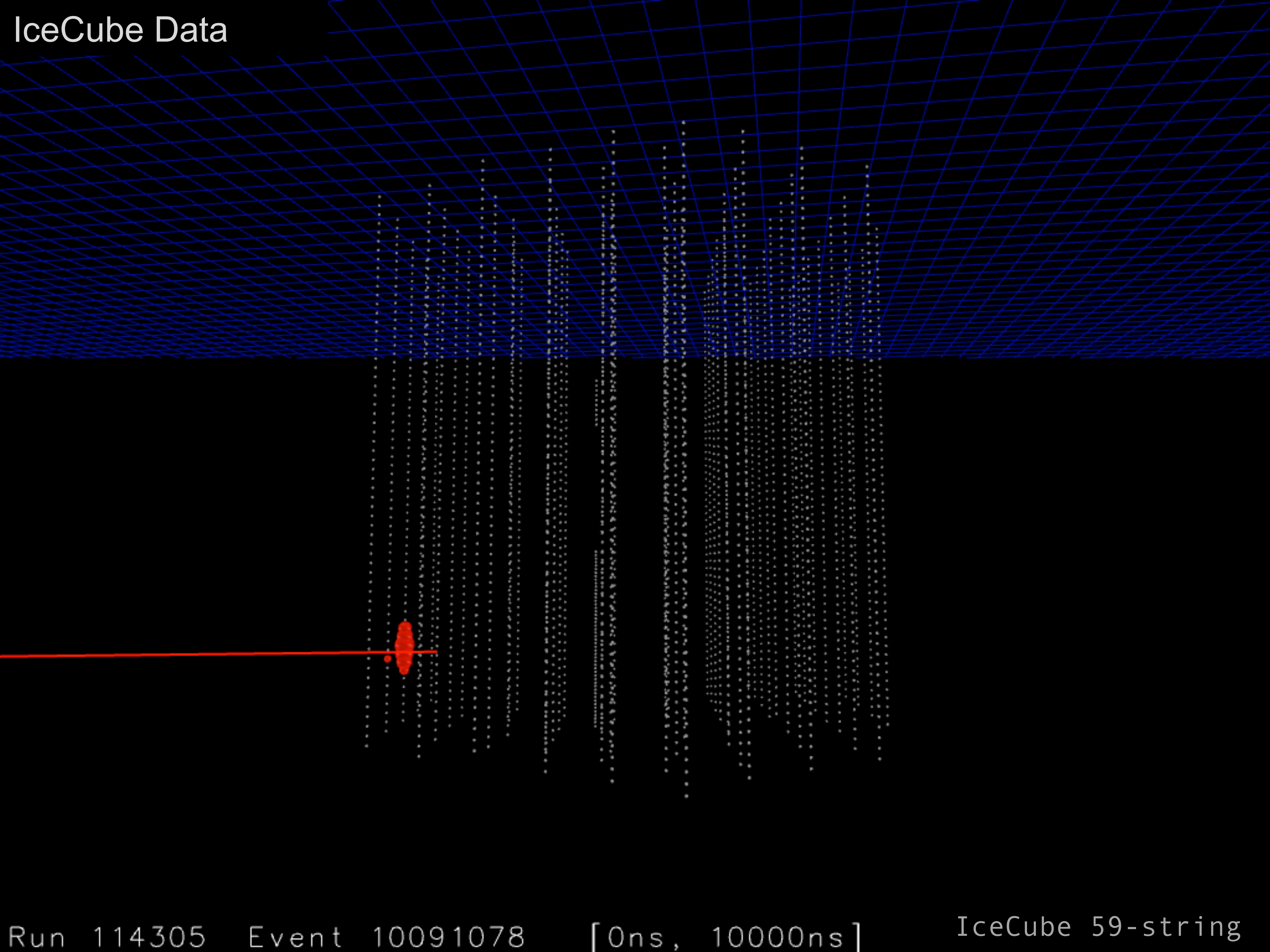
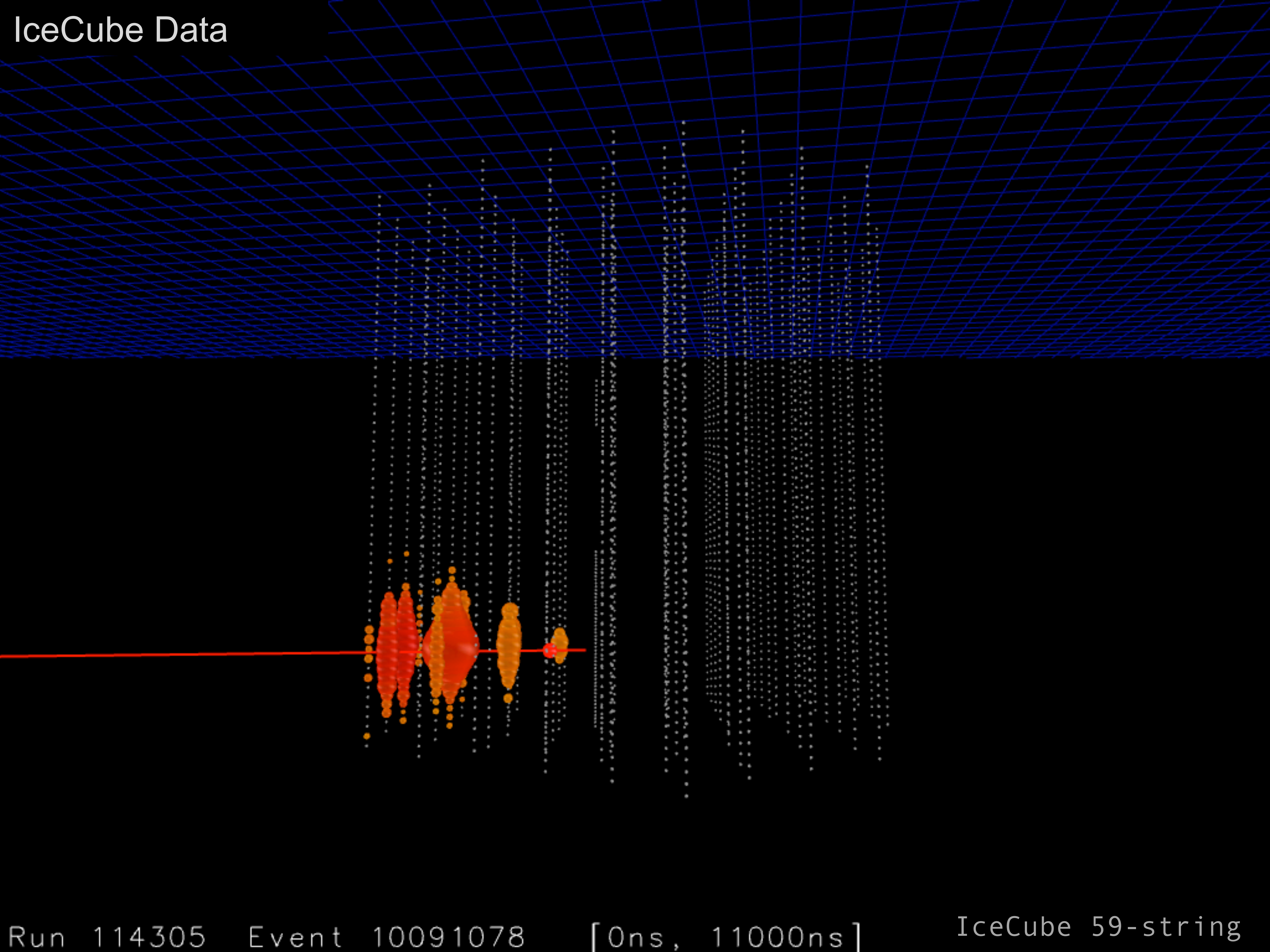
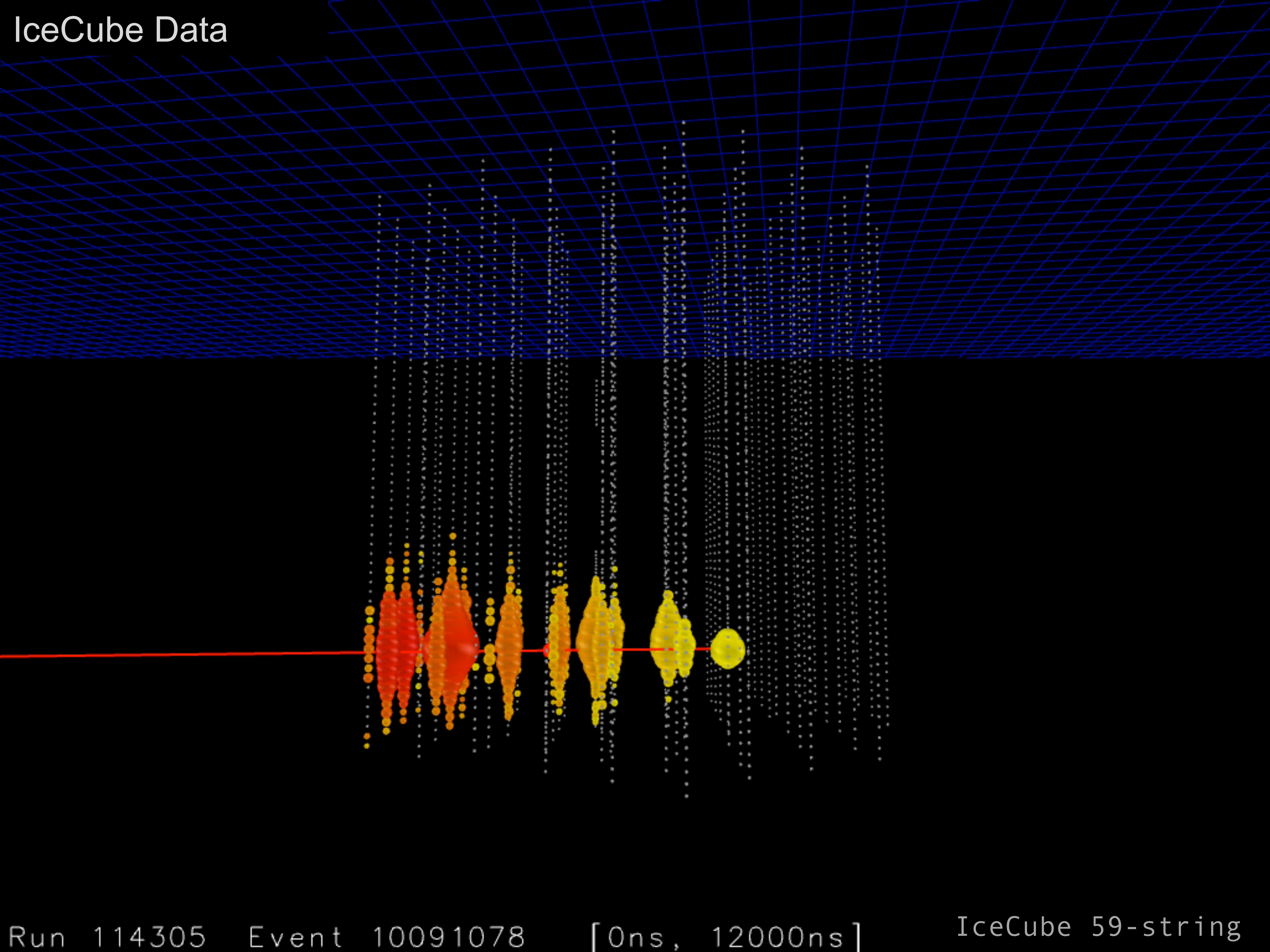
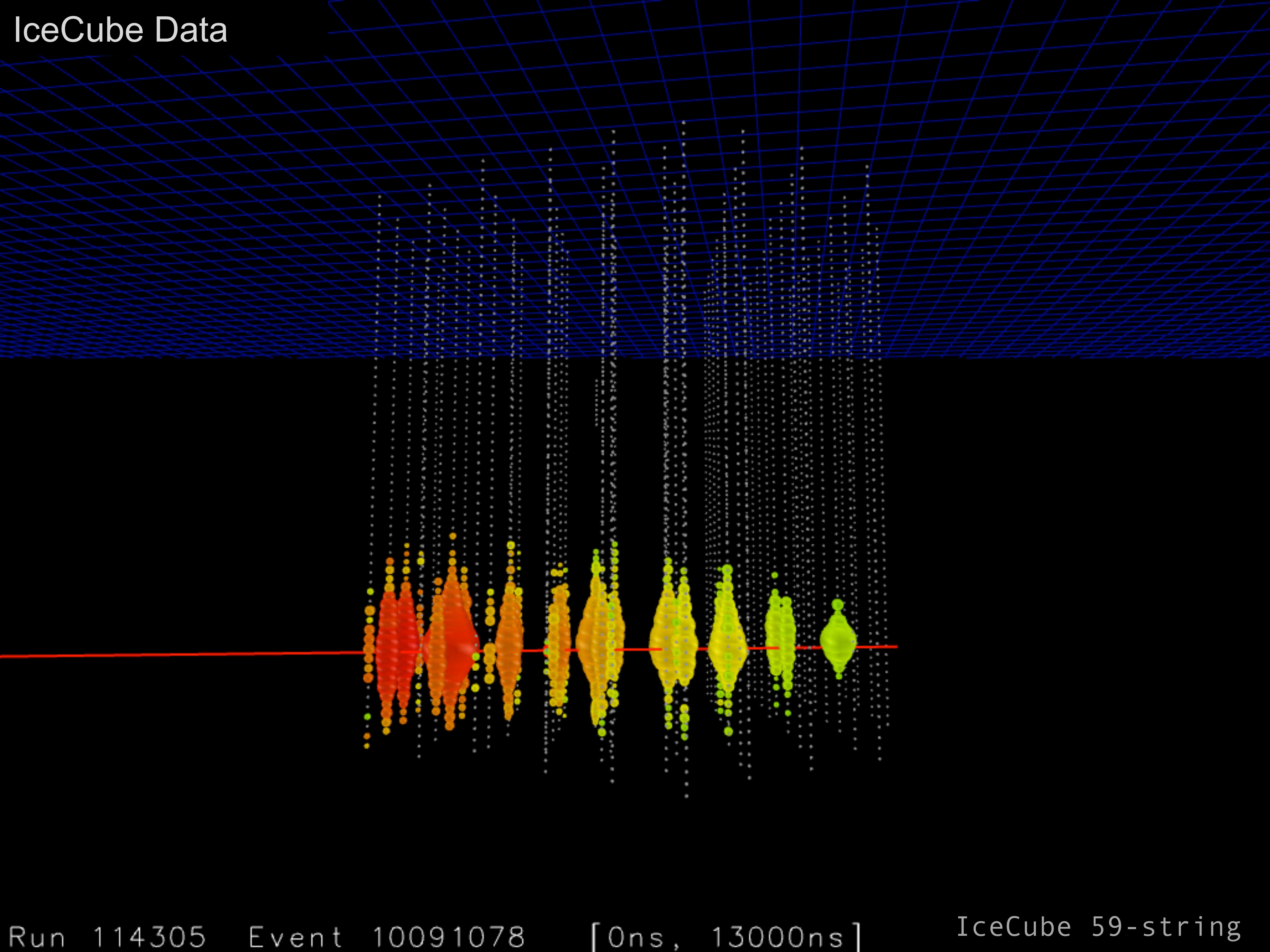
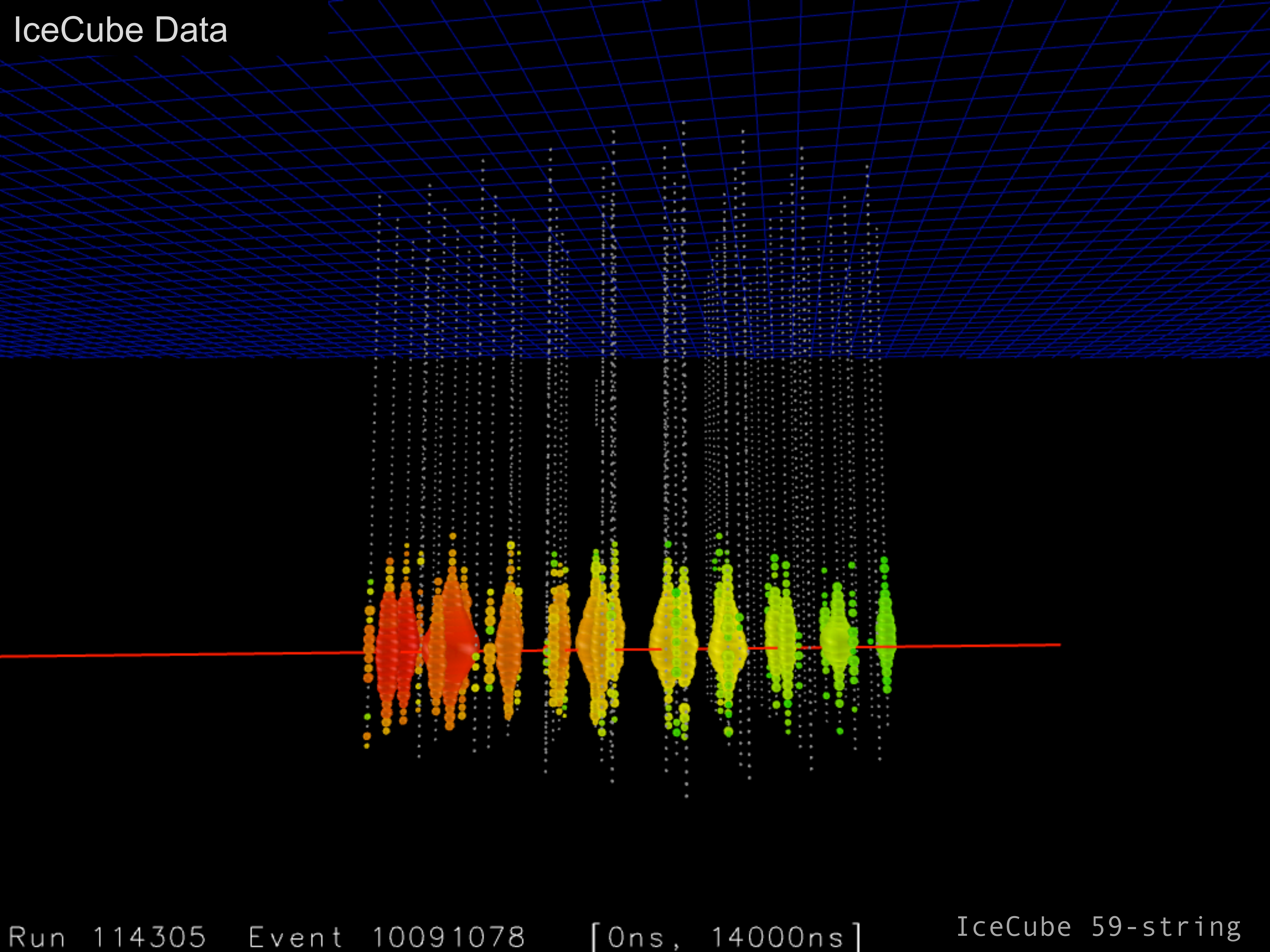
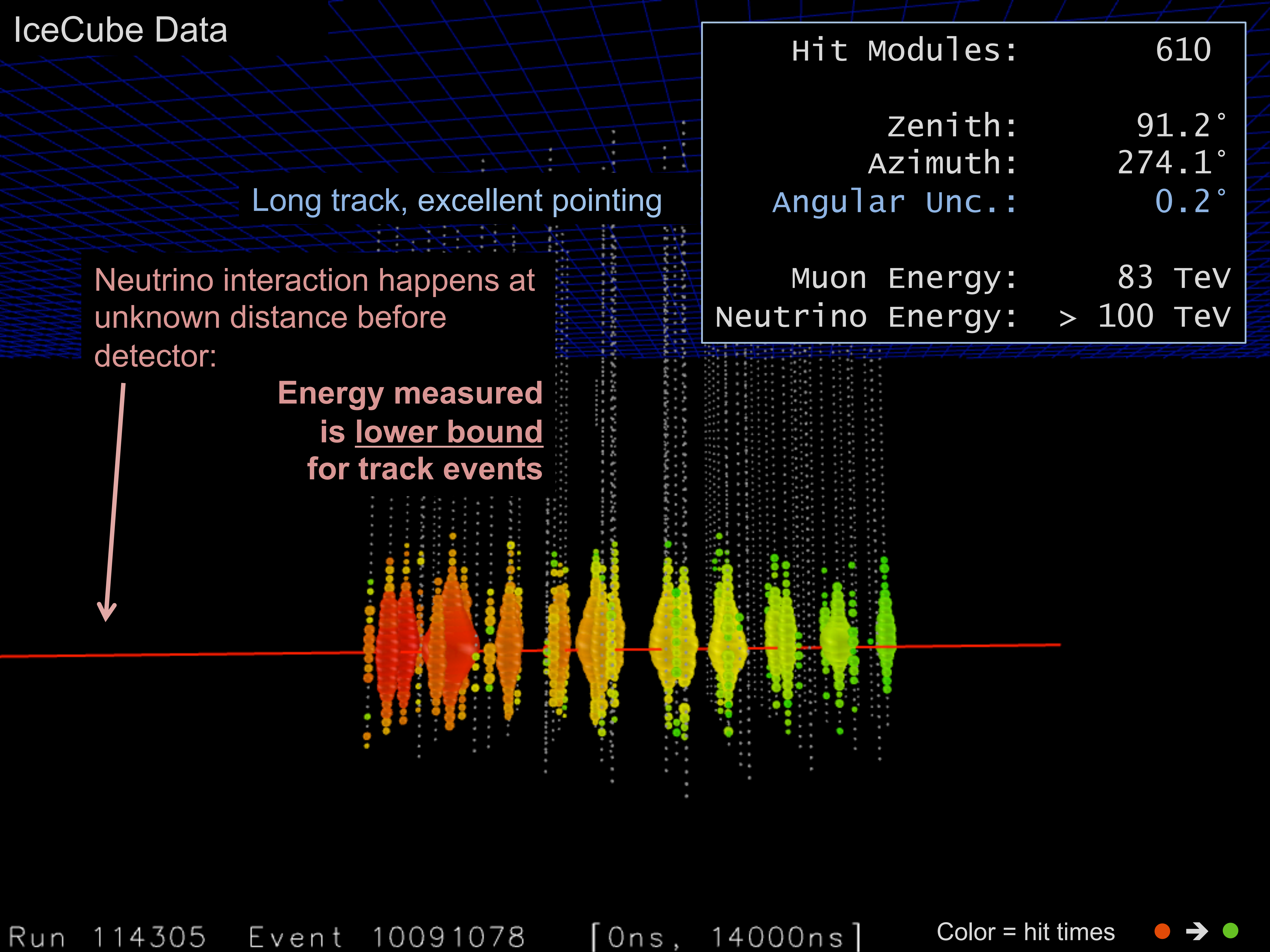



IceCube Data
Run 114305 Event 10091078 [0ns, 11000ns]
IceCube 59-string


IceCube Data
Run 114305 Event 10091078 [0ns, 12000ns]
IceCube 59-string


IceCube Data
Run 114305 Event 10091078 [0ns, 13000ns]
IceCube 59-string


IceCube Data
Run 114305 Event 10091078 [0ns, 14000ns]
IceCube 59-string

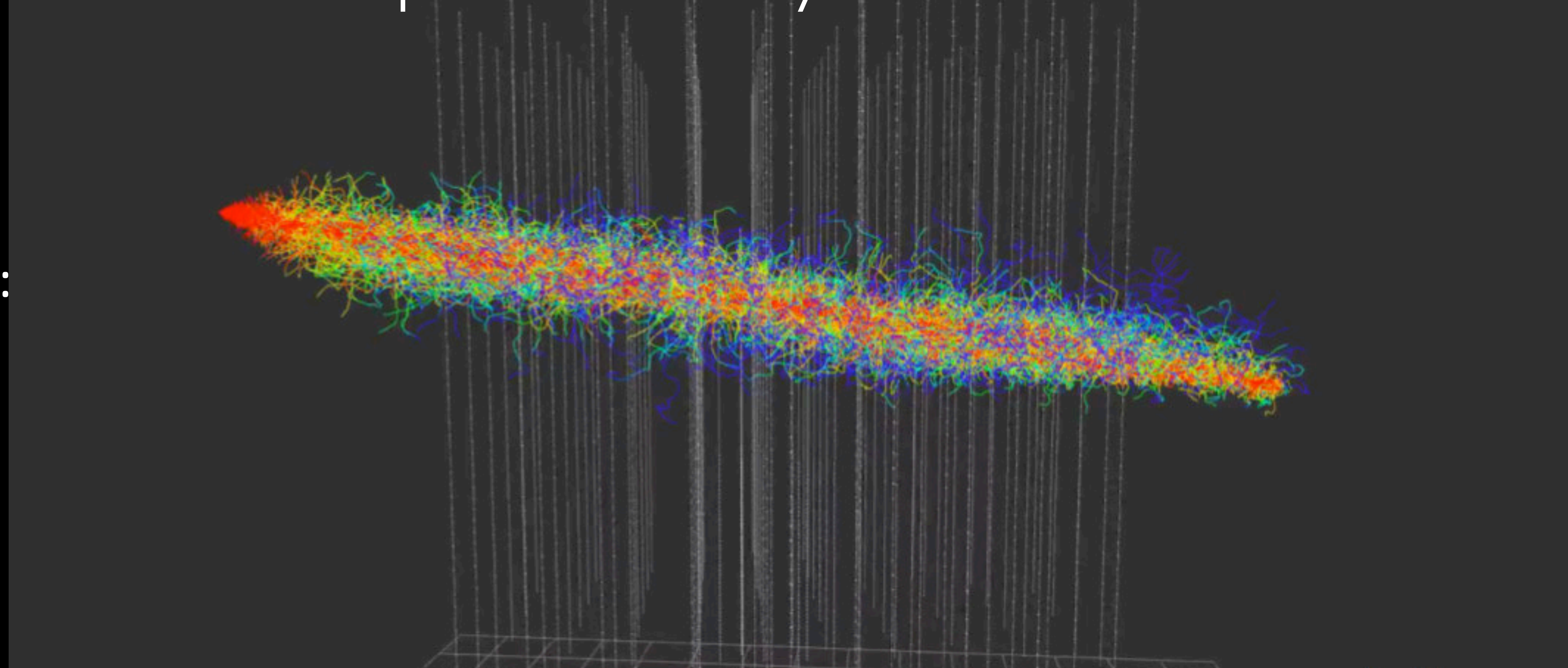

IceCube Data
Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV
Long track, excellent pointing
Neutrino interaction happens at unknown distance before detector:
Energy measured is lower bound for track events
Run 114305 Event 10091078 [0ns, 14000ns]
Color = hit times

LiPhotons produced by Neutrino Interactions

Track topology

Energy measured: lower bound

Good pointing:
0.2° - 1°



Photons produced by Neutrino Interactions

Track topology

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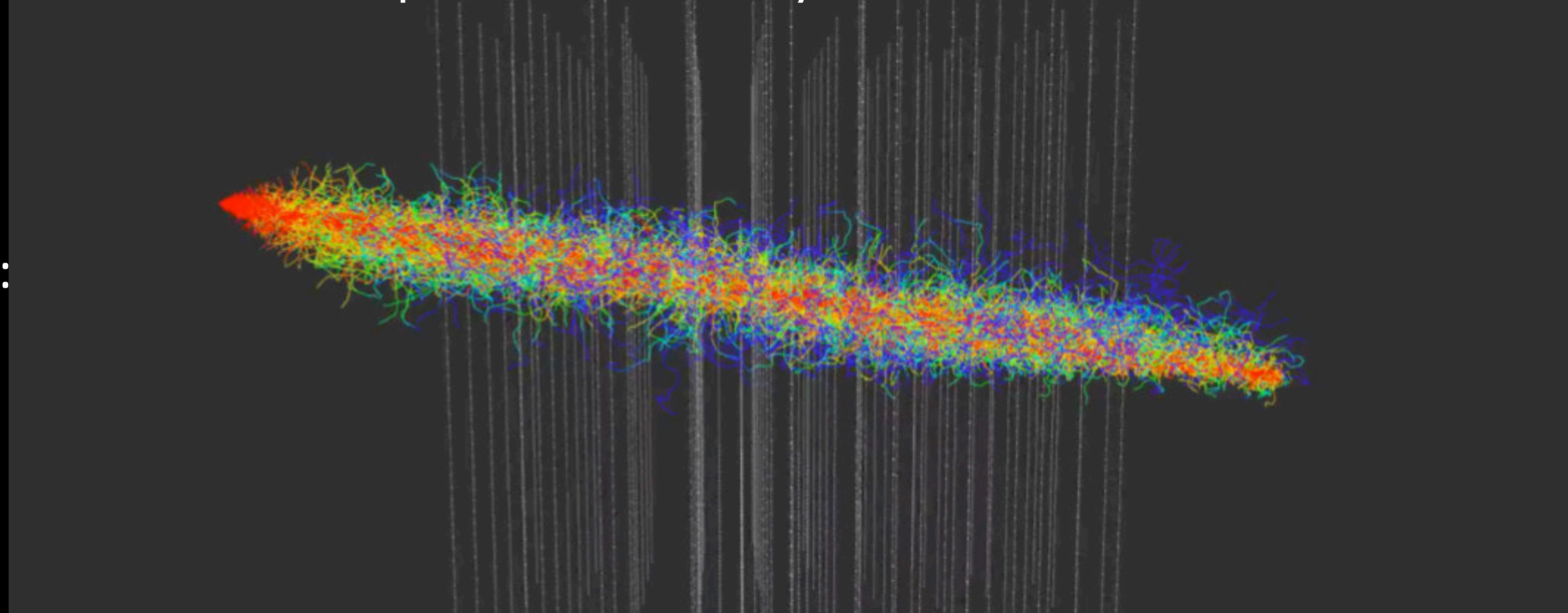
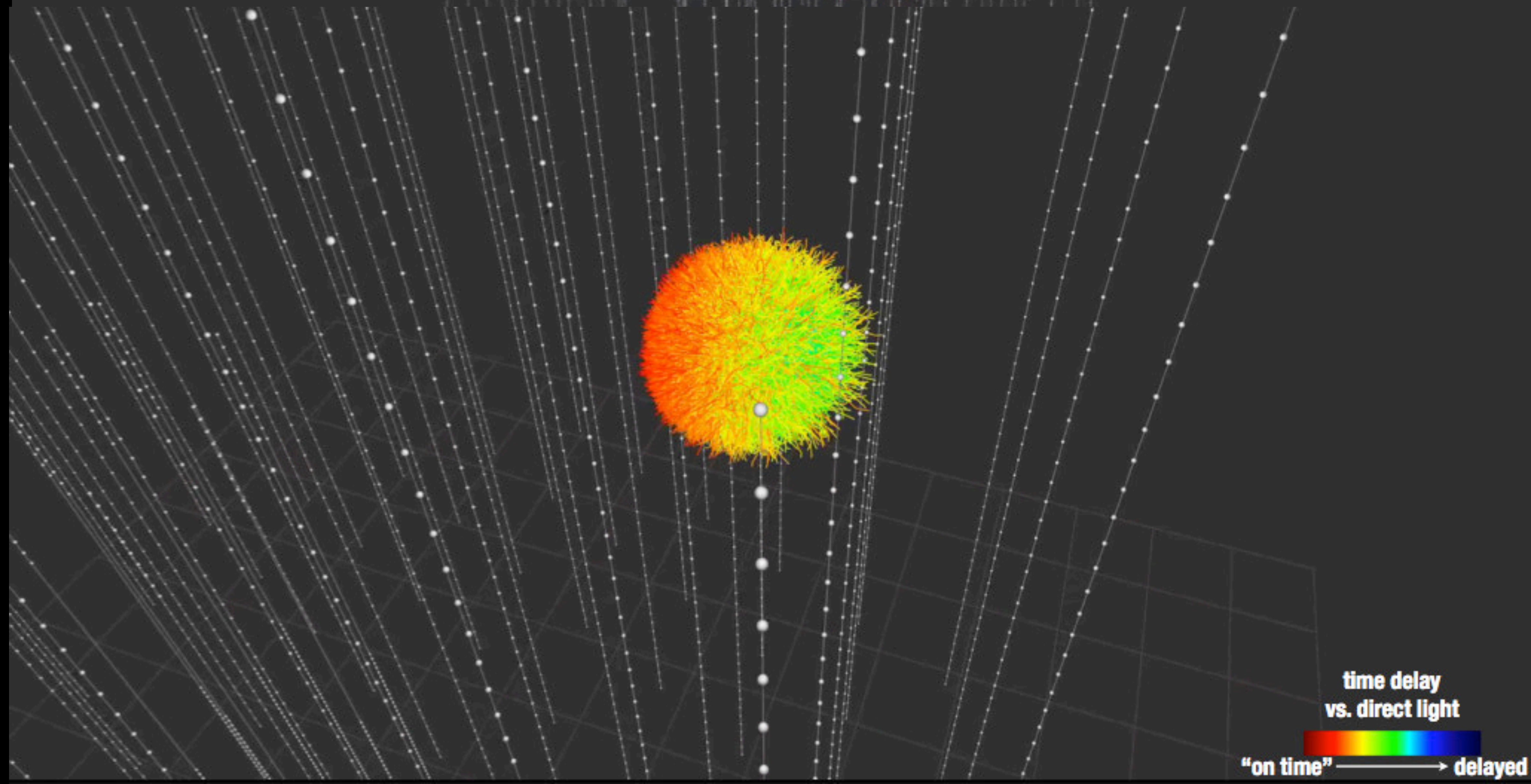


Cascade topology

Good energy resolution, 15%

Some pointing, 10° - 15°



Photons produced by Neutrino Interactions

Track
topology

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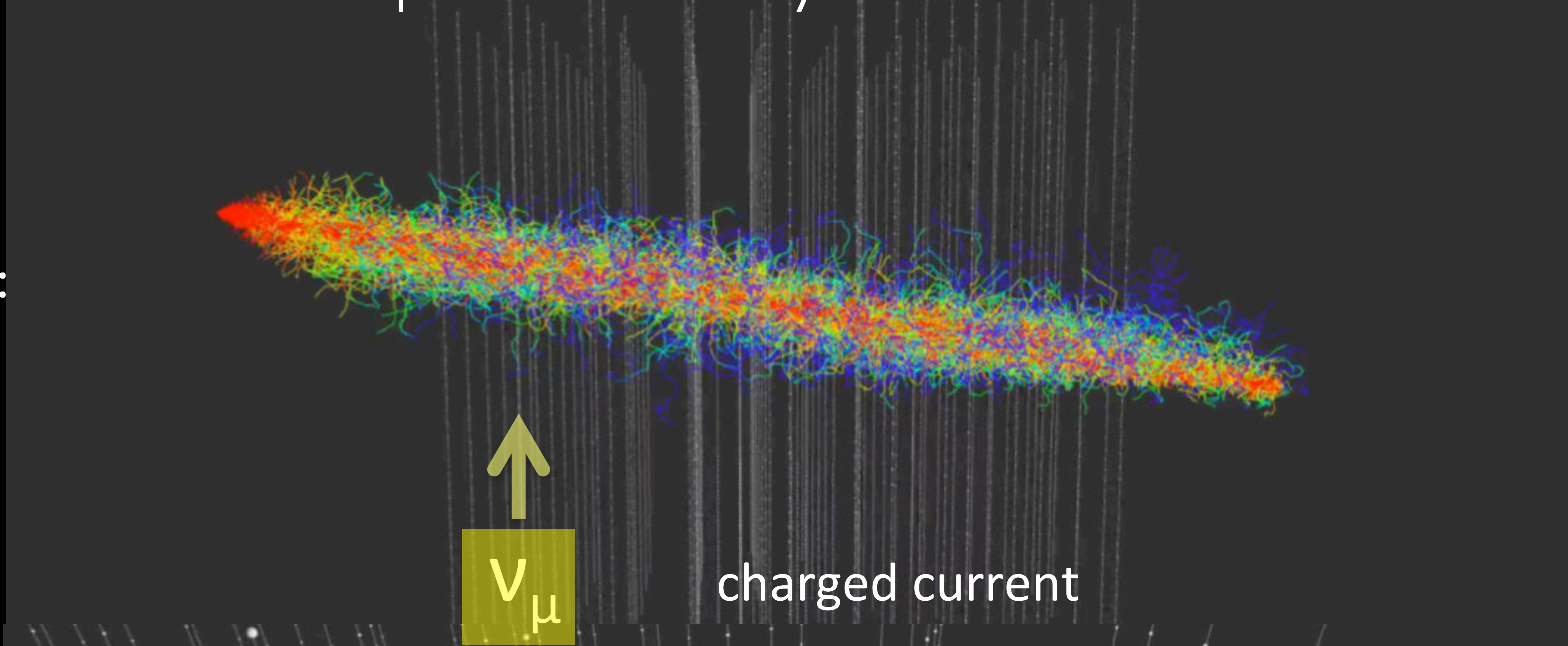

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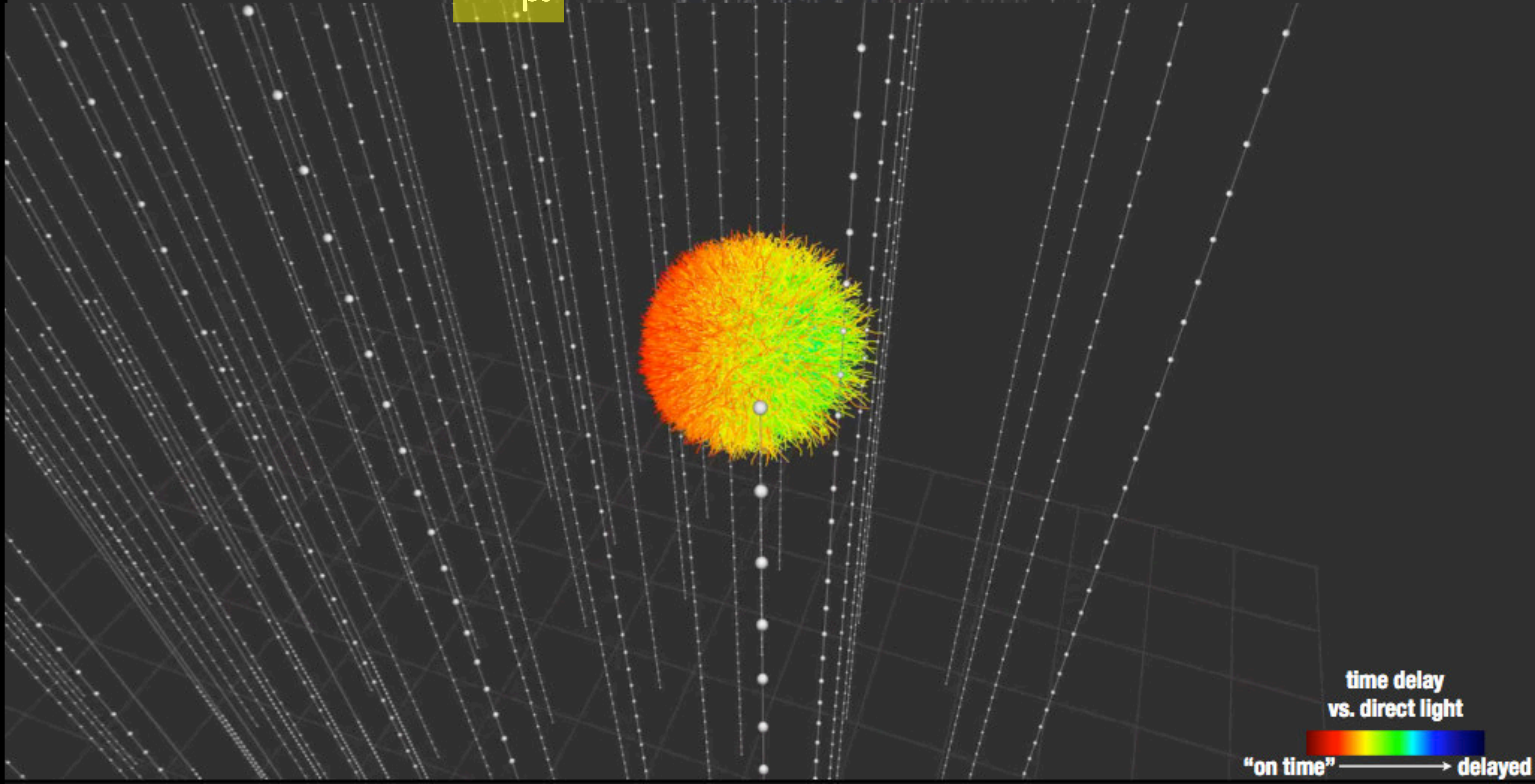

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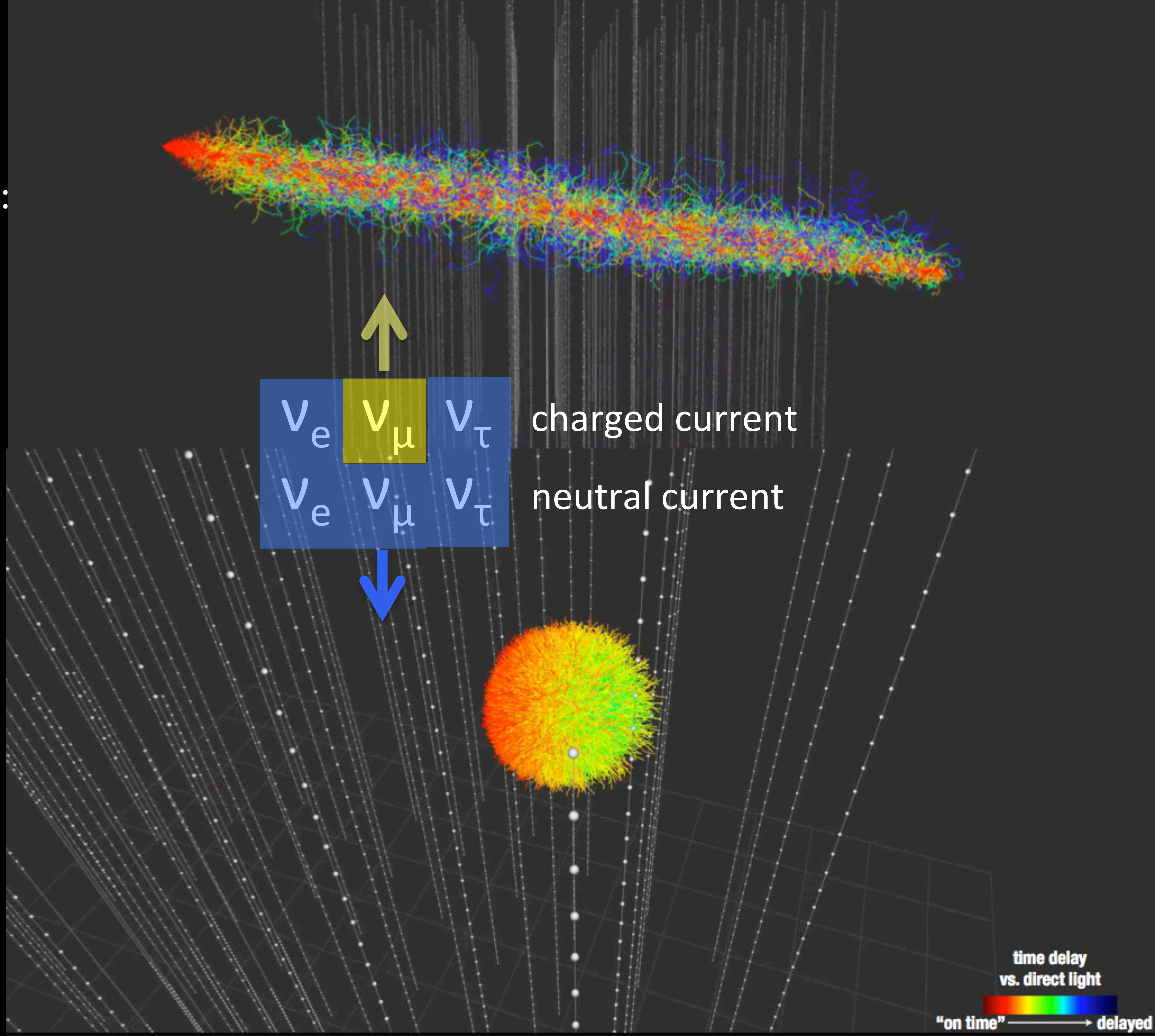

IceCube records per year (order of magnitude):

~ 100 000 000 000 triggered events – mostly muons from cosmic rays above ice

~ 100 000 neutrino events – mostly from cosmic ray air showers

~ 100 astrophysical neutrinos – that we estimate so far…

Wide-ranging analysis topics across different data sets…

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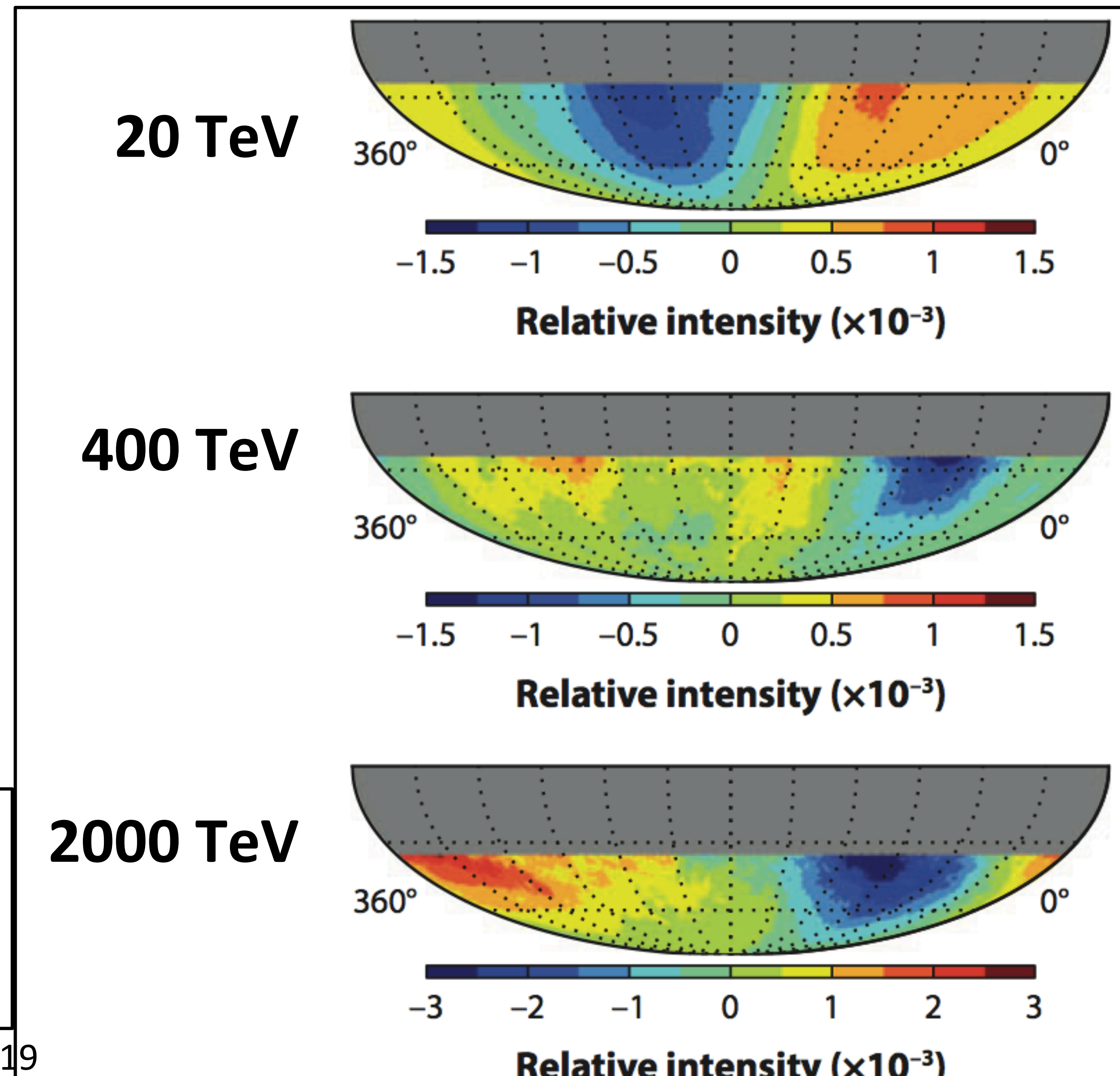
Cosmic Ray Anisotropy

Measured with
- IceCube events (20 TeV, 400 TeV)
- IceTop events (2000 TeV)

Large scale structure changes dramatically with energy

Gaisser & Halzen, Annu. Rev. Nucl. Part. Sci. 2014. 64:4.1–4.23
ApJL 718:L194 (2010);
ApJ 746:33 (2012); ApJ 765:55 (2013)



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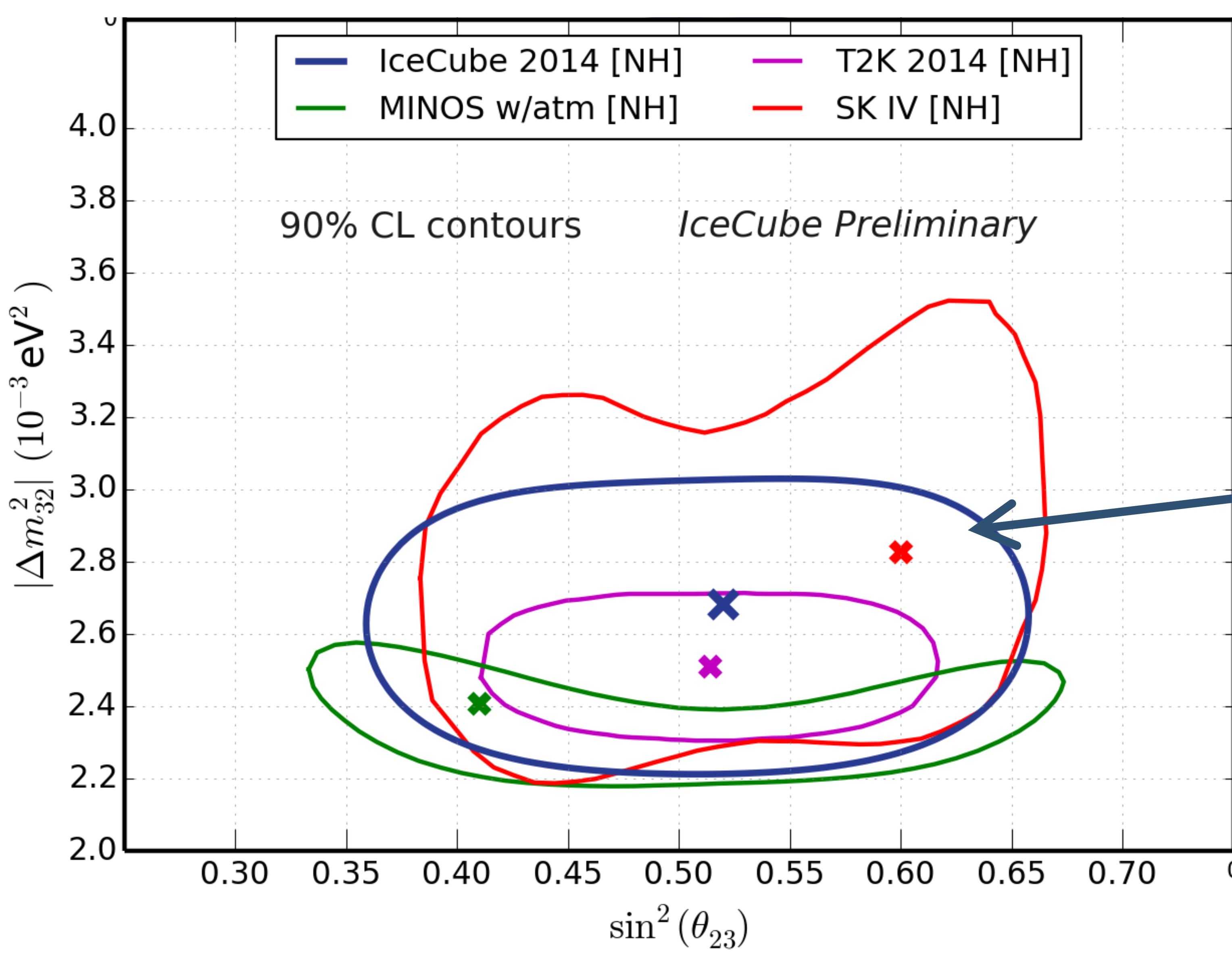

Measurement of Neutrino Oscillation parameters (IceCube-DeepCore)

1-year analysis: PRL **111**, 081801 (2013)

3-year analysis: preliminary (arXiv:1410.7227)

Pathway to future **PINGU** low-energy extension detector for precision measurements and determination of **Neutrino Mass Hierarchy**

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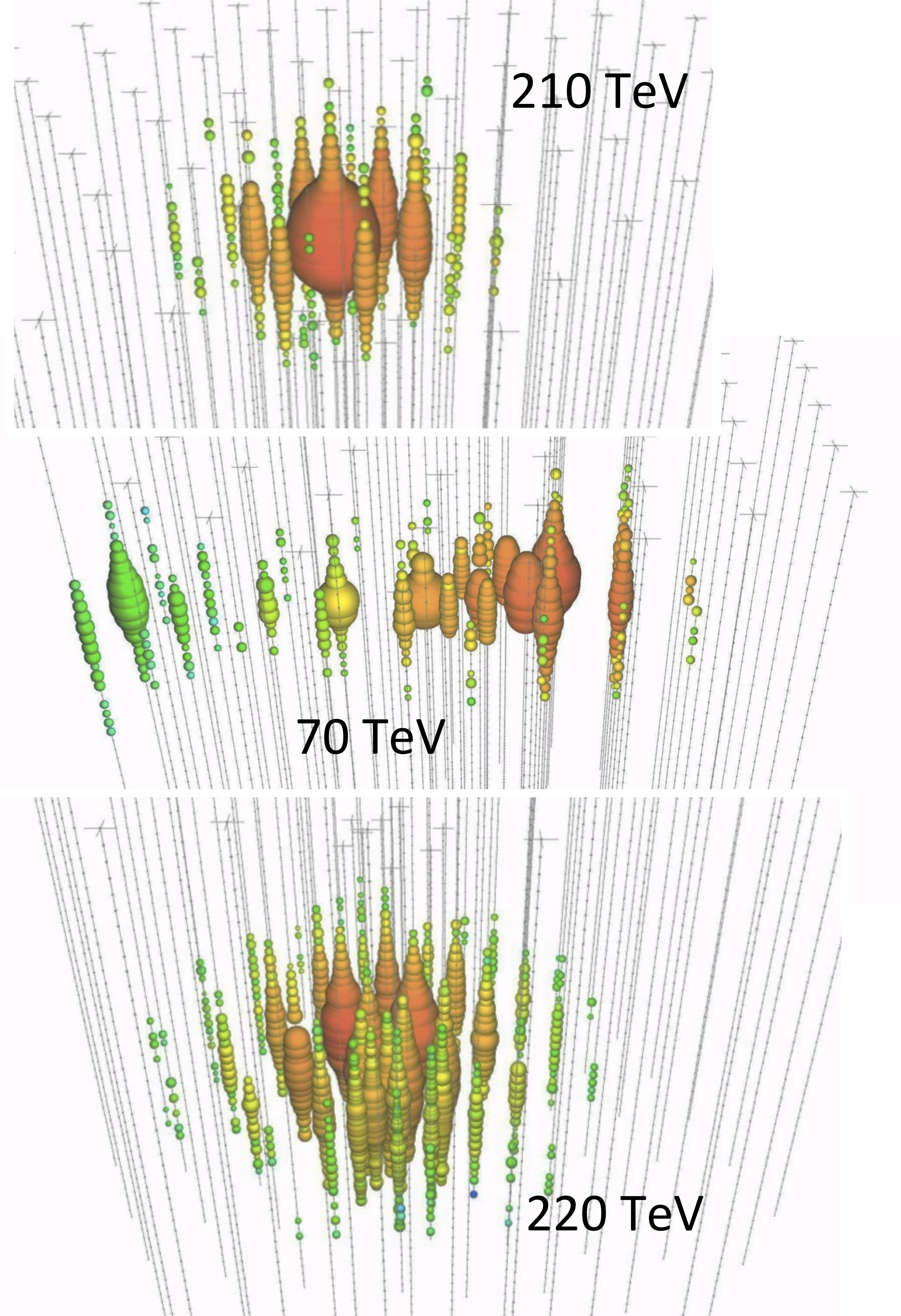
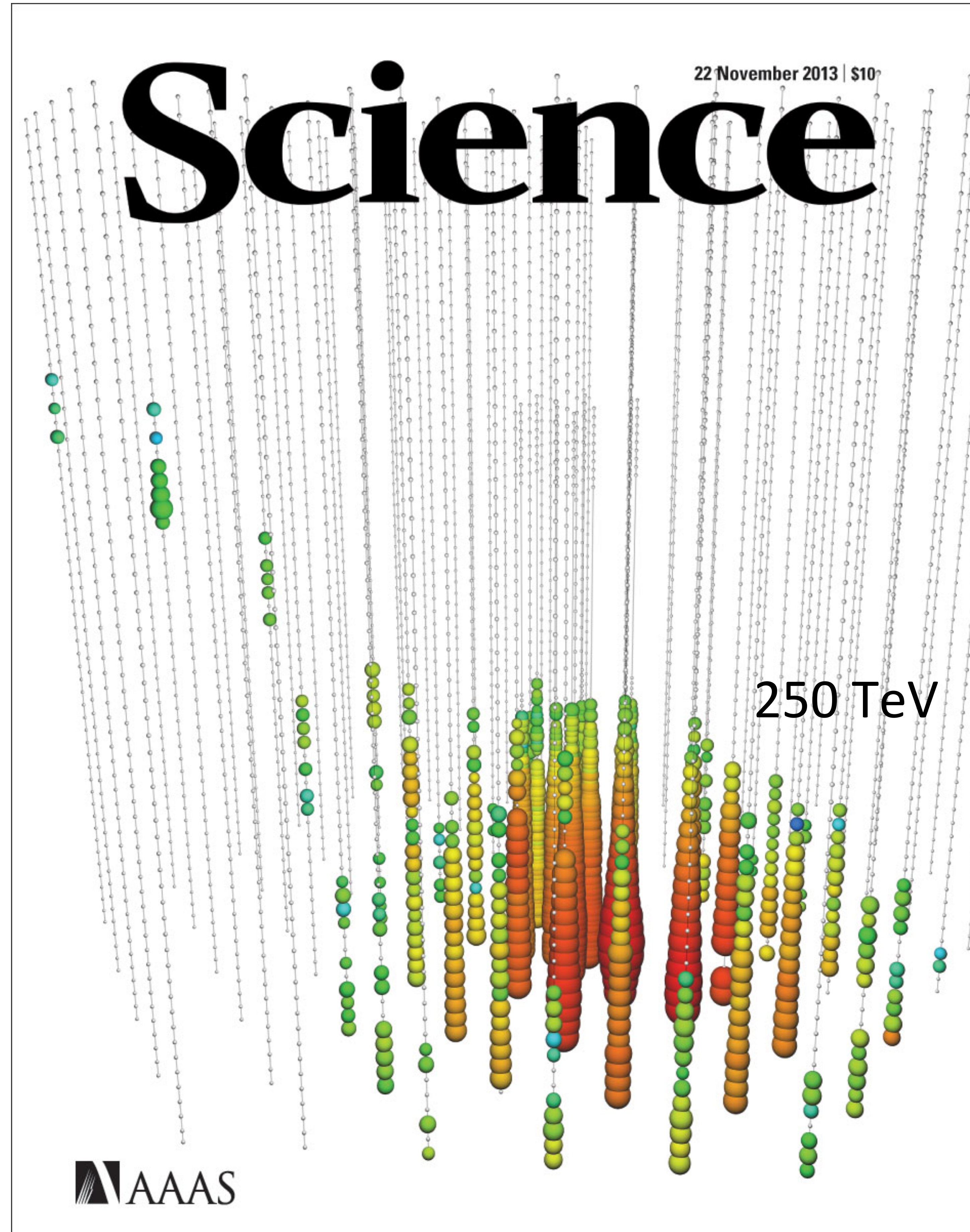
Extracting information about the ~ 10^2 astrophysical neutrinos requires many different analysis strategies and event selections.

Here I will focus on:

- **High-Energy Starting Event Analysis (3-year)**
- **Muon Neutrino Diffuse Analysis (2-year)**
- **Point Source Analysis (4-year)**

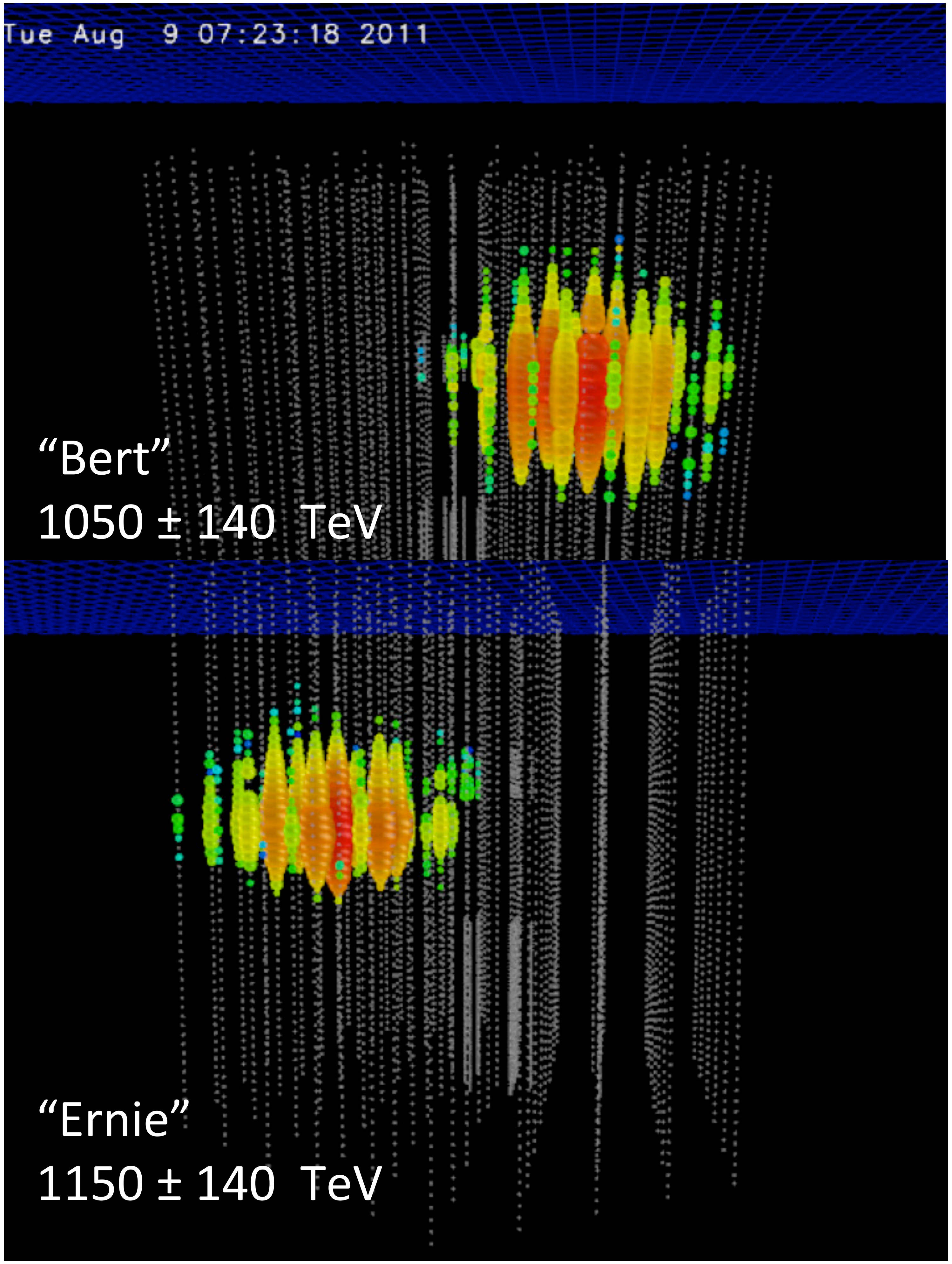
High Energy Starting Event Analysis





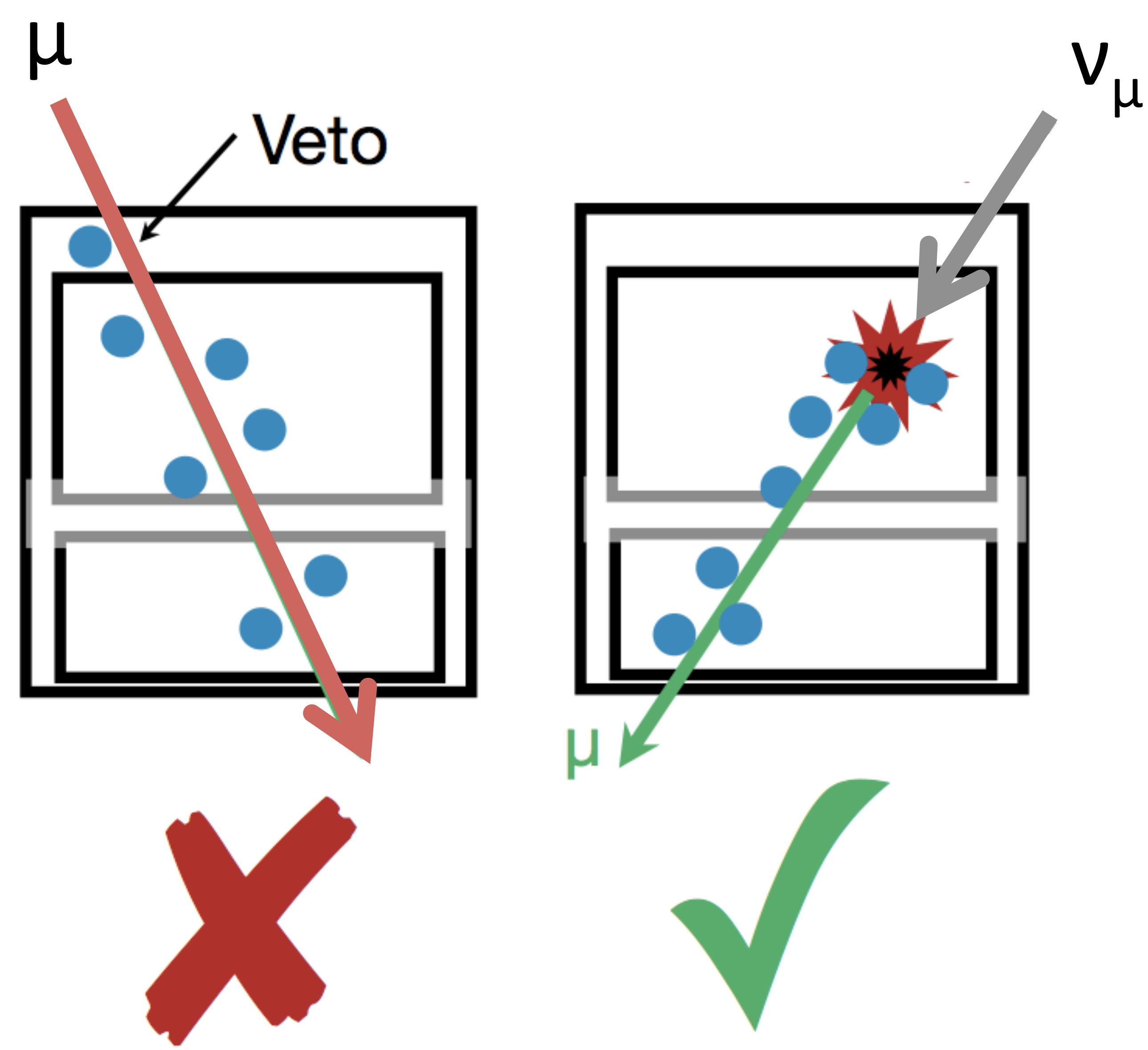
2-year analysis: Science **342**, 1242856 (2013)

High Energy Starting Event Analysis



Require that event:

- Does not start in veto region
- Has at least 6000 photoelectrons

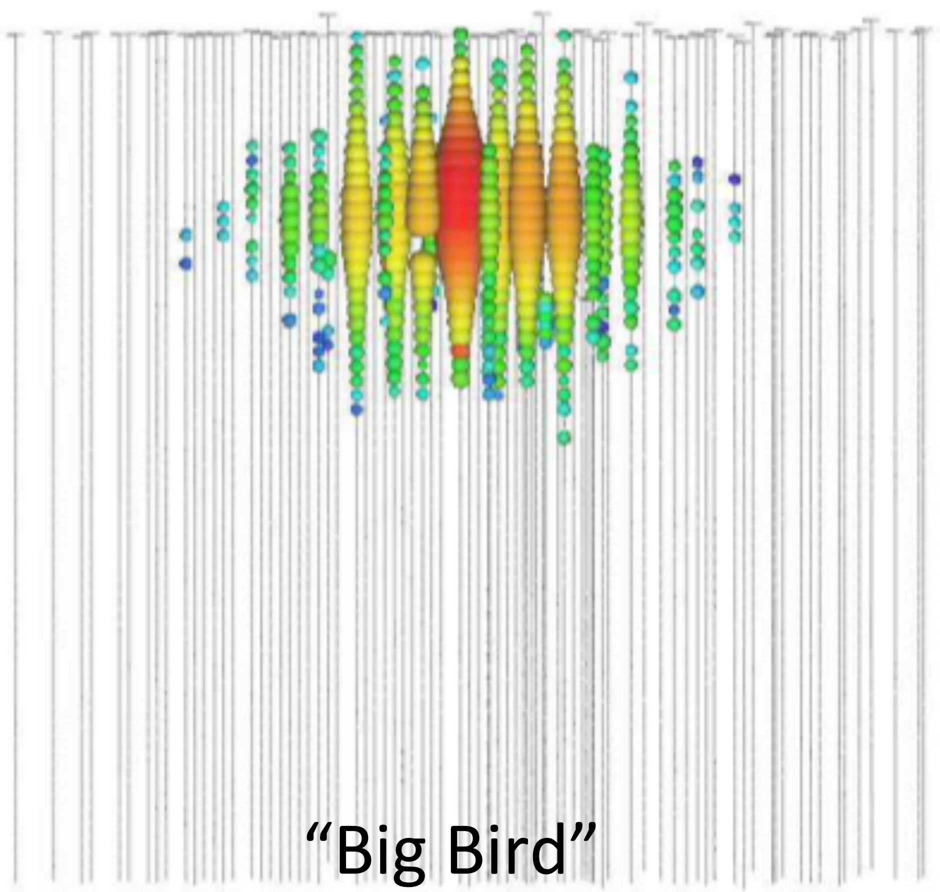


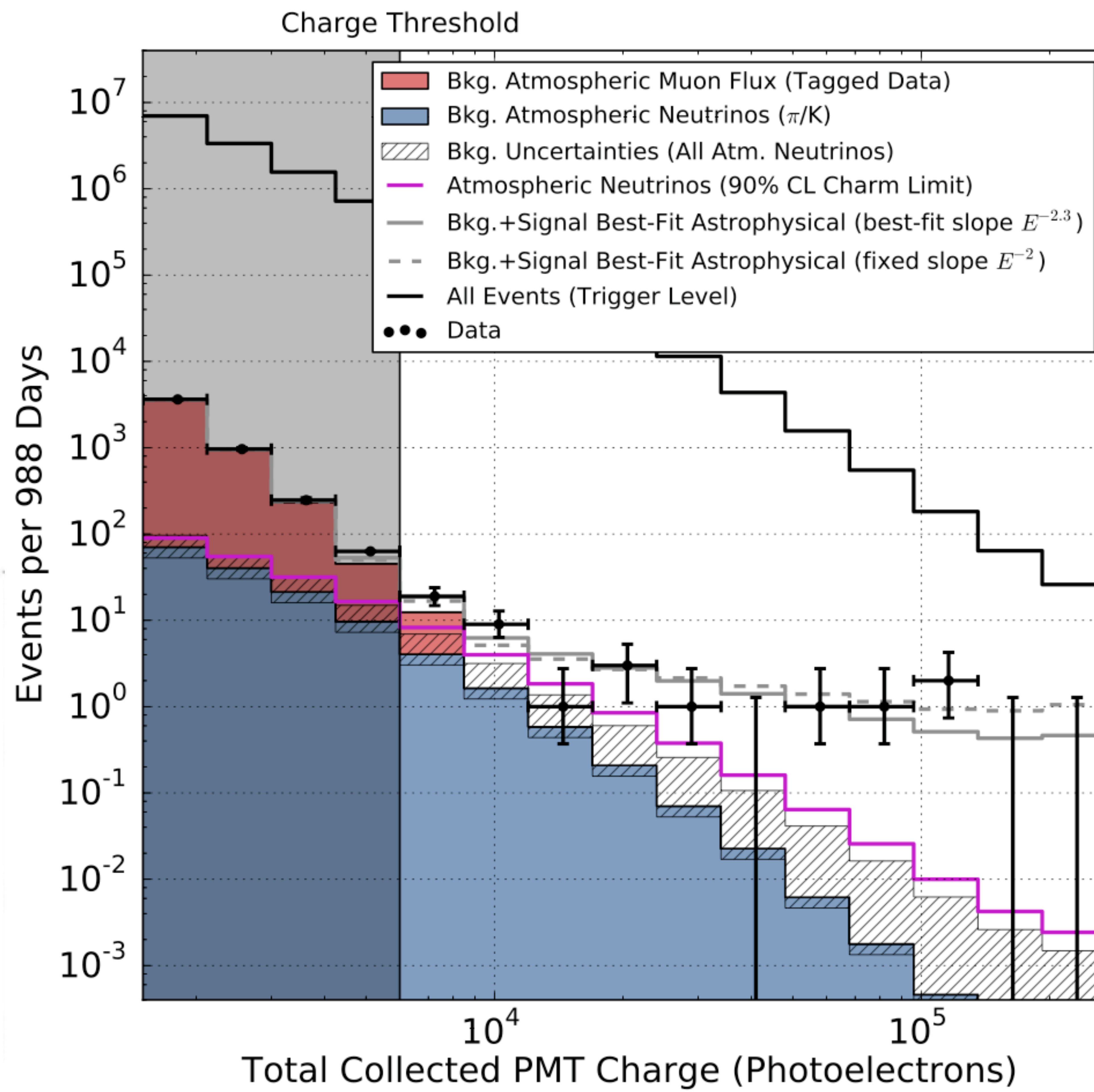
High Energy Starting Event Analysis

3-Year Analysis
PRL **113**, 101101 (2014)

36 events in 3 years

New highest-energy event:
2-PeV neutrino





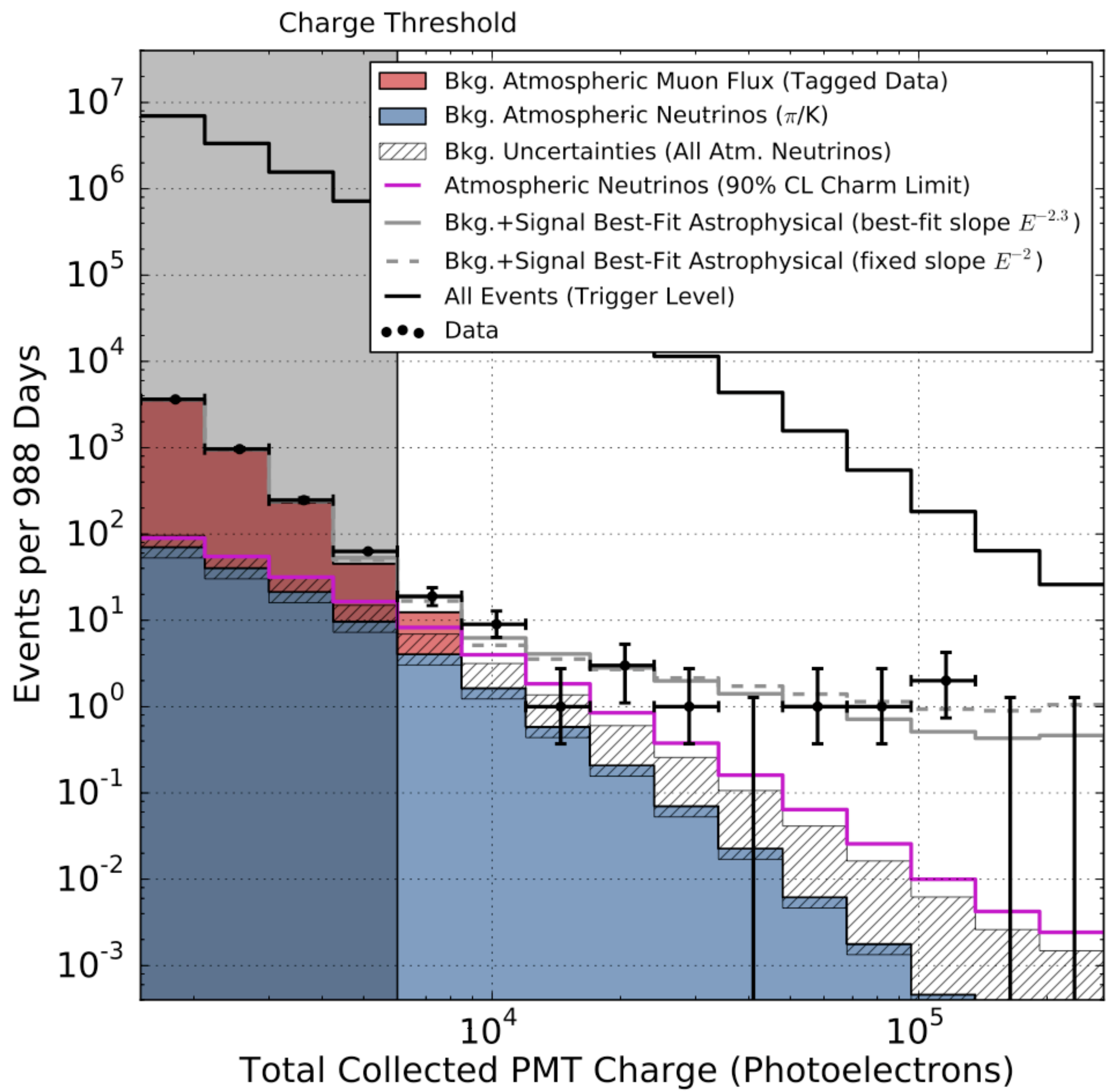
High Energy Starting Event Analysis

Significance of astrophysical flux: **5.7 σ**

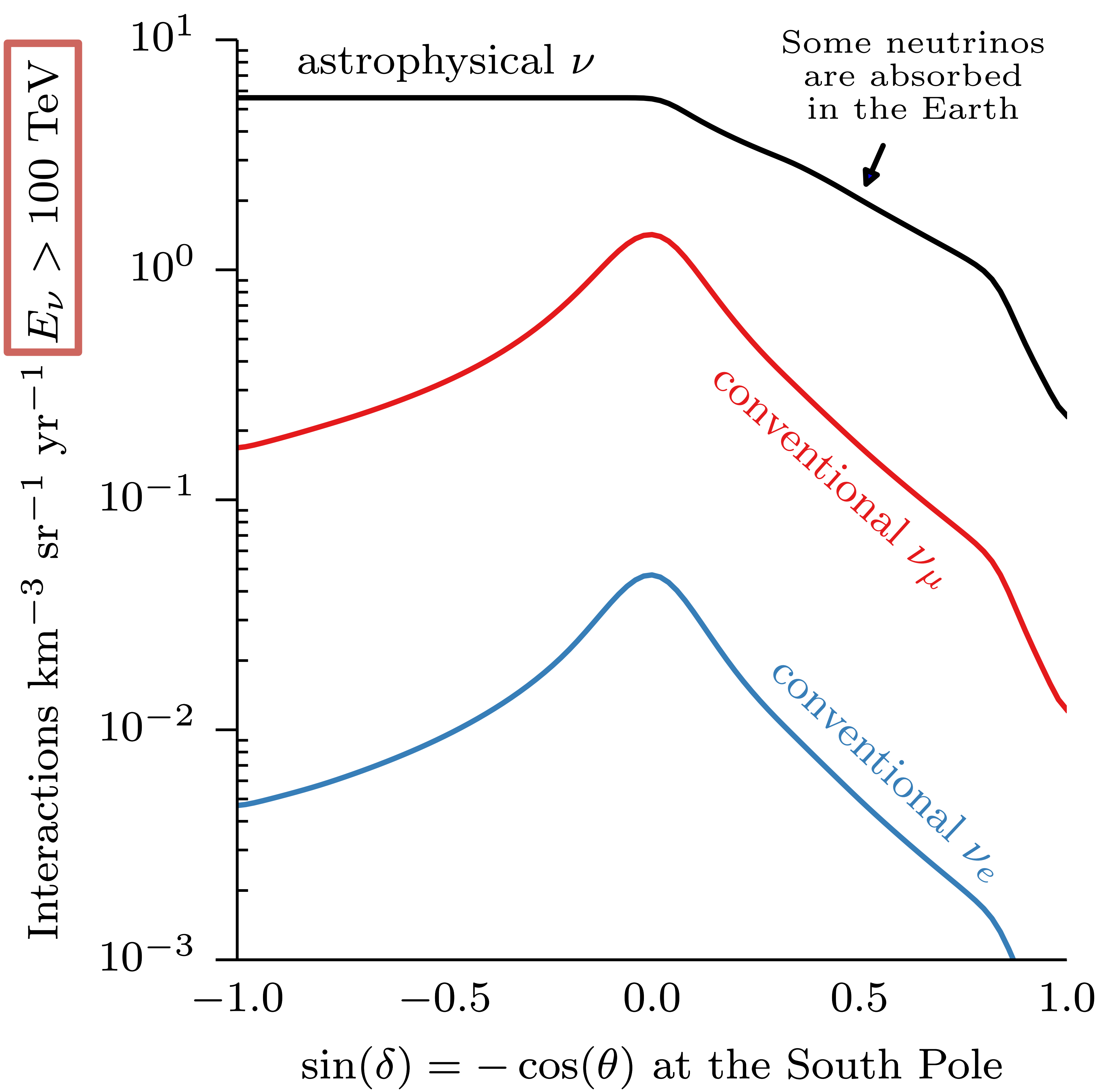
Of the 36 events,
~ half are expected to be bkg (atm. muons and atm. neutrinos)

Astrophysical fit (and its significance) depends on **number, direction, and energy**

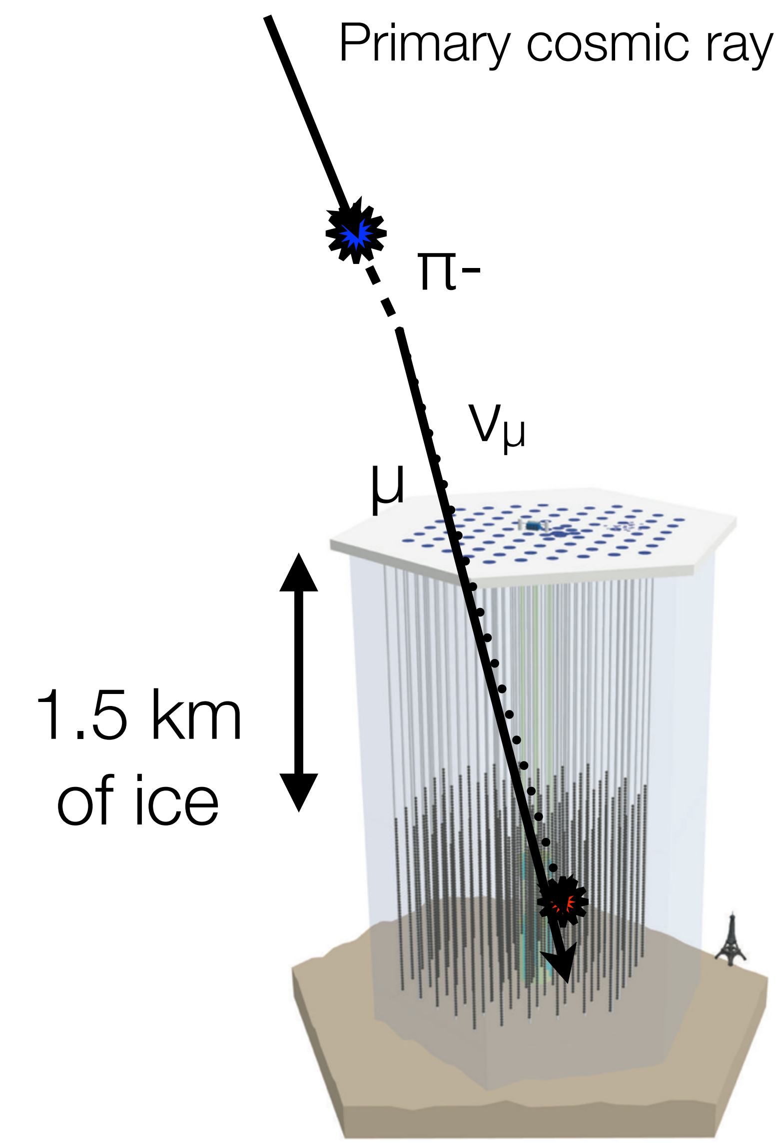
Shape (energy and zenith distribution) of signal and background is different…



Atmospheric neutrino self-veto



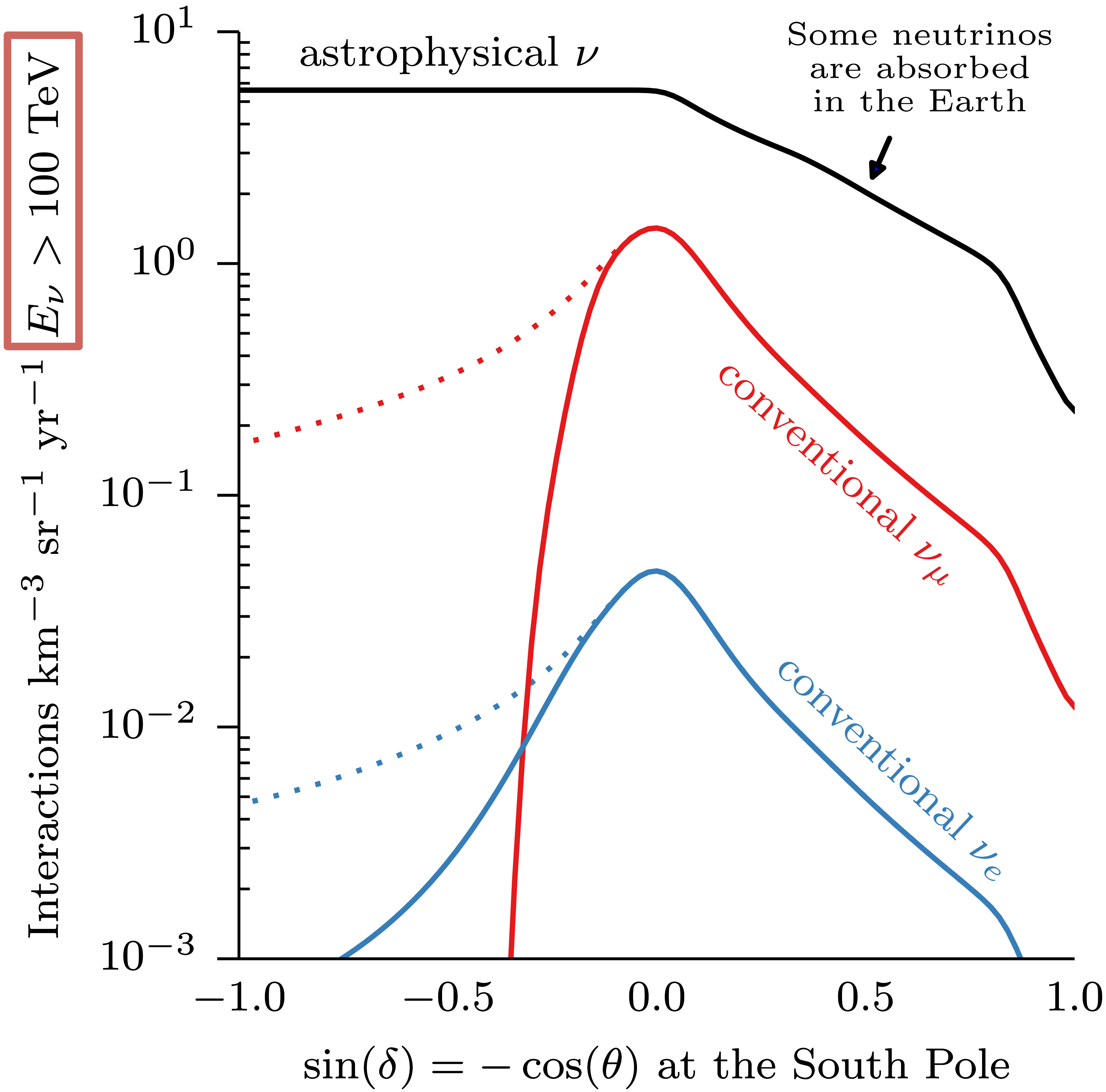
An active muon veto removes down-going atmospheric neutrinos.



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

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

Atmospheric neutrino self-veto



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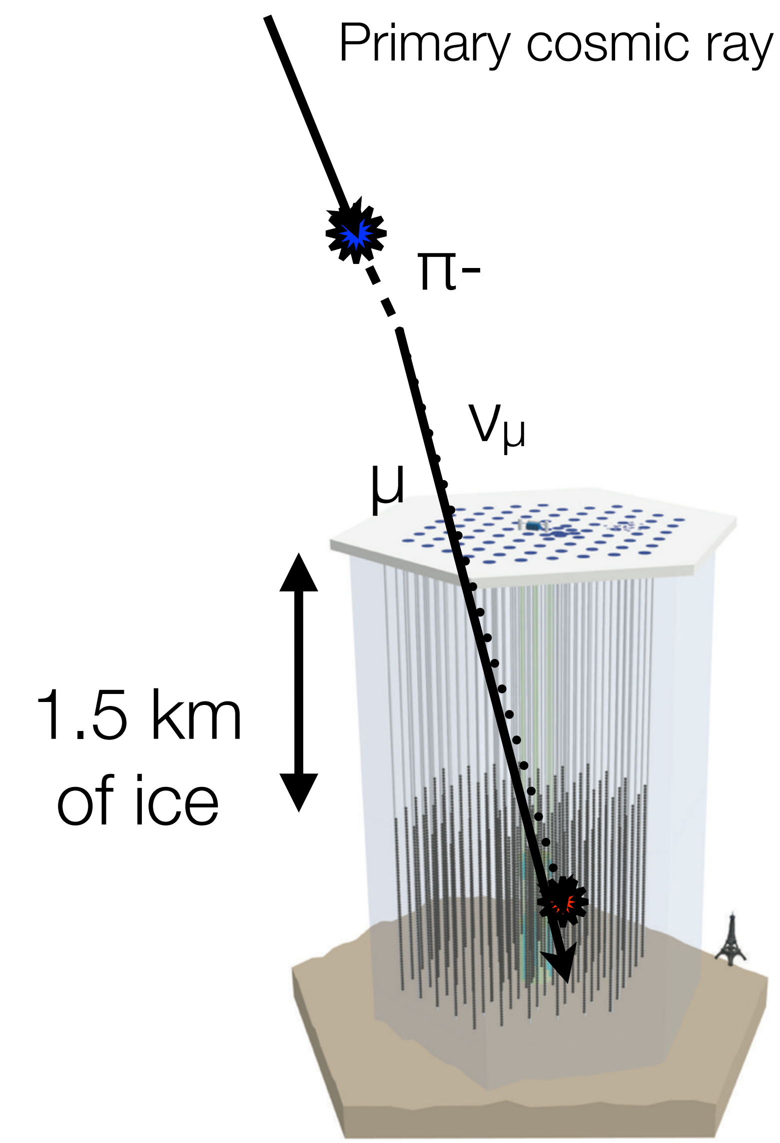

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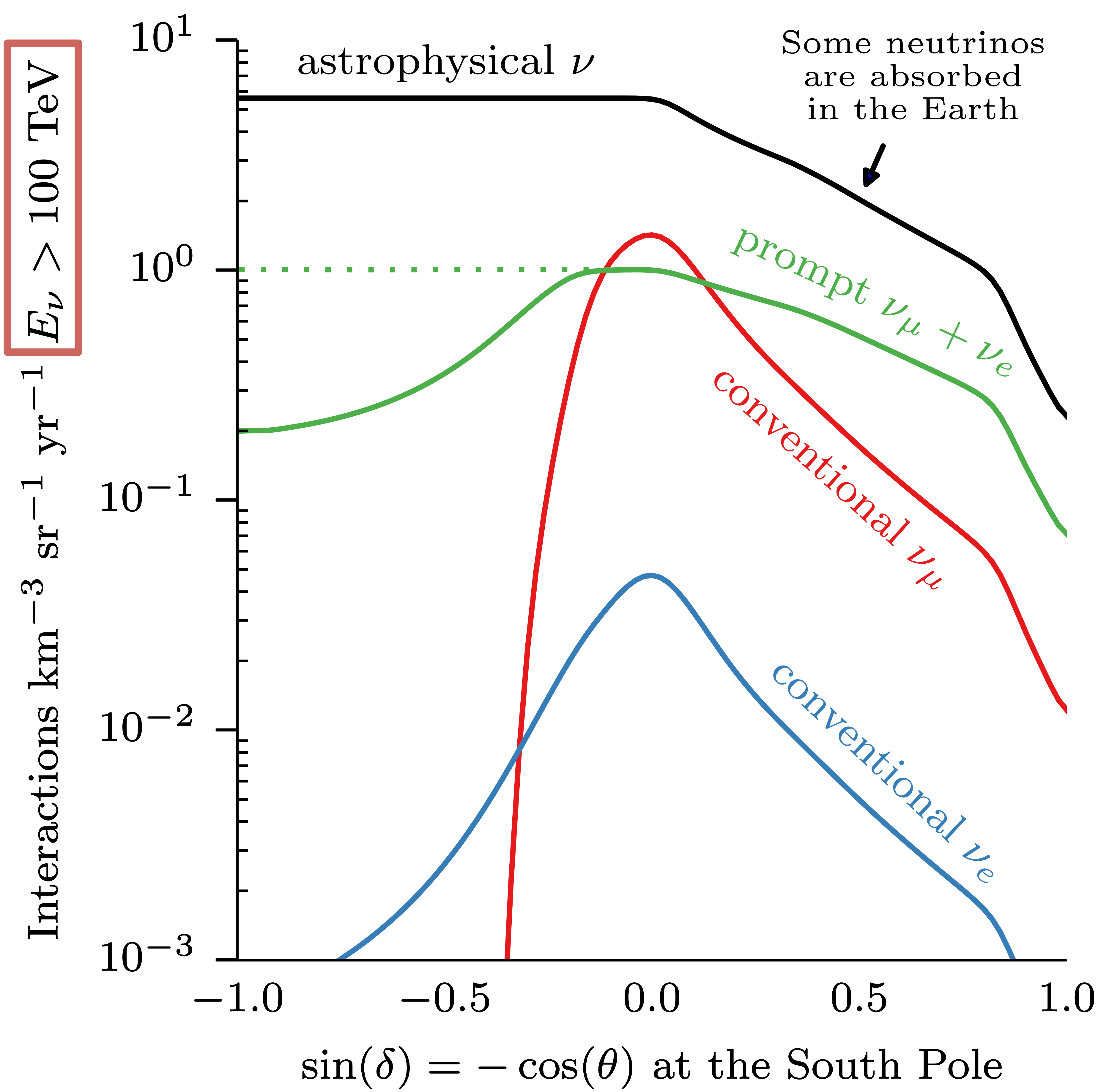
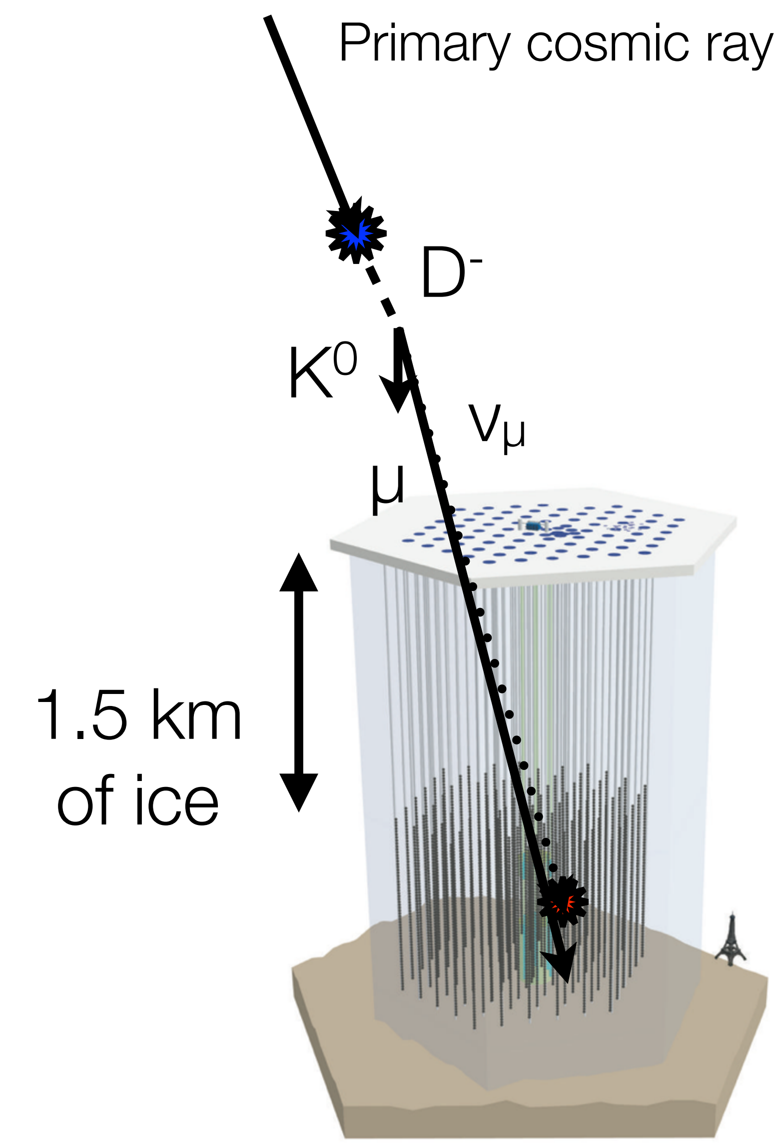


Prompt atmospheric neutrinos are vetoed, too.



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

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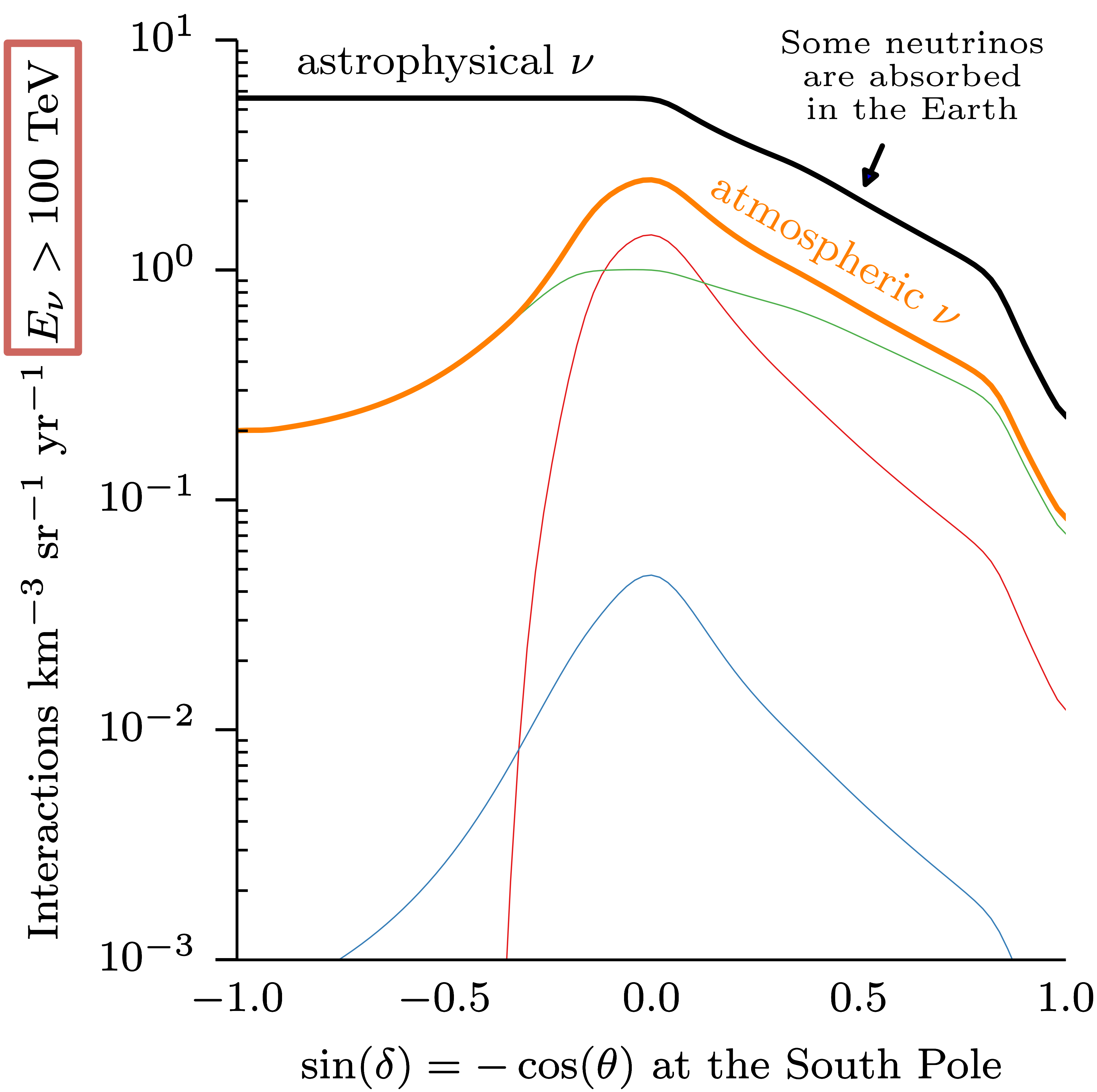


The zenith distributions of high-energy astrophysical and atmospheric neutrinos are fundamentally different.

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

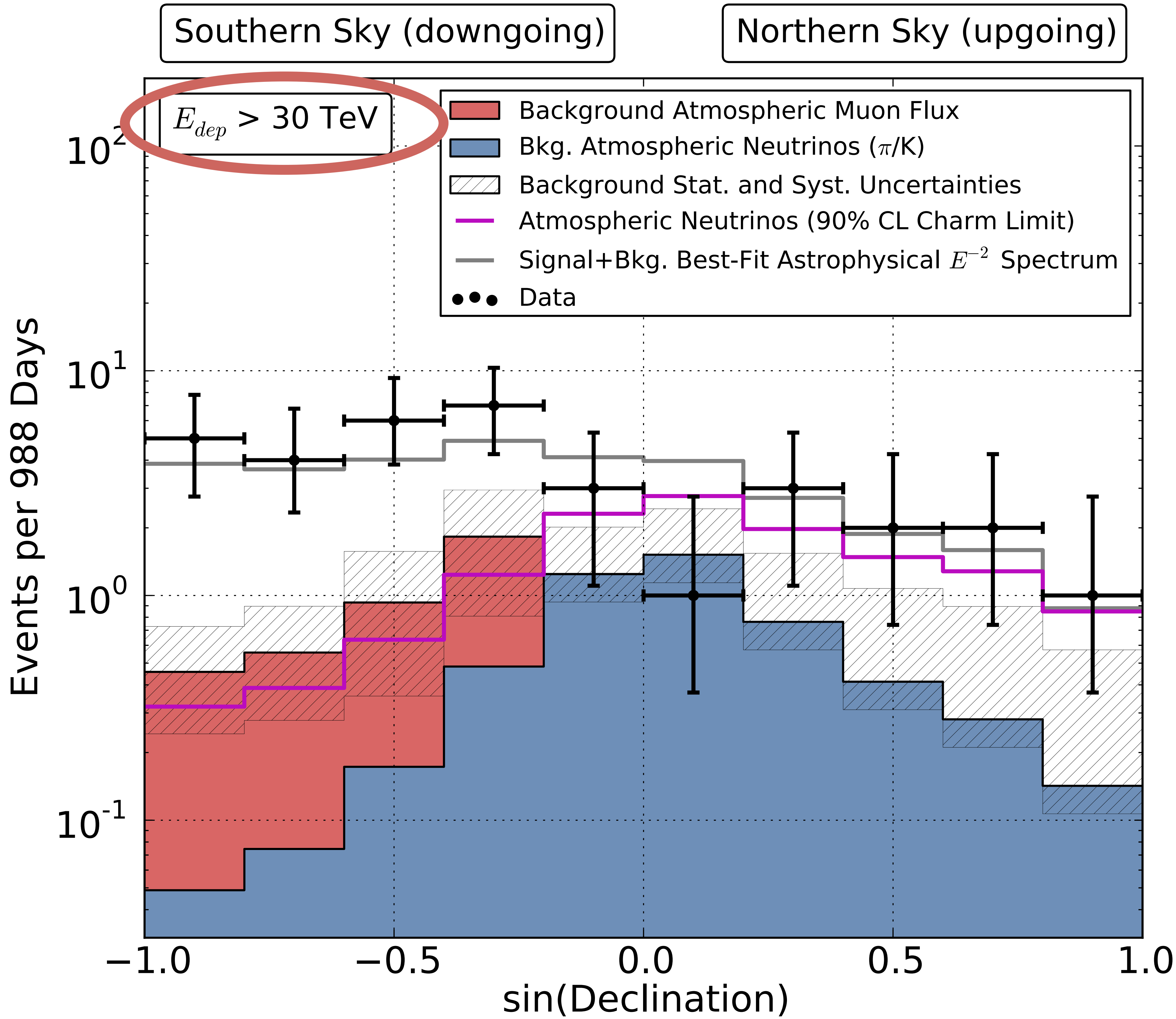
Gaisser, Jero, Karle, van Santen, Phys. Rev. D, 90:023009 (2014)

3-Year

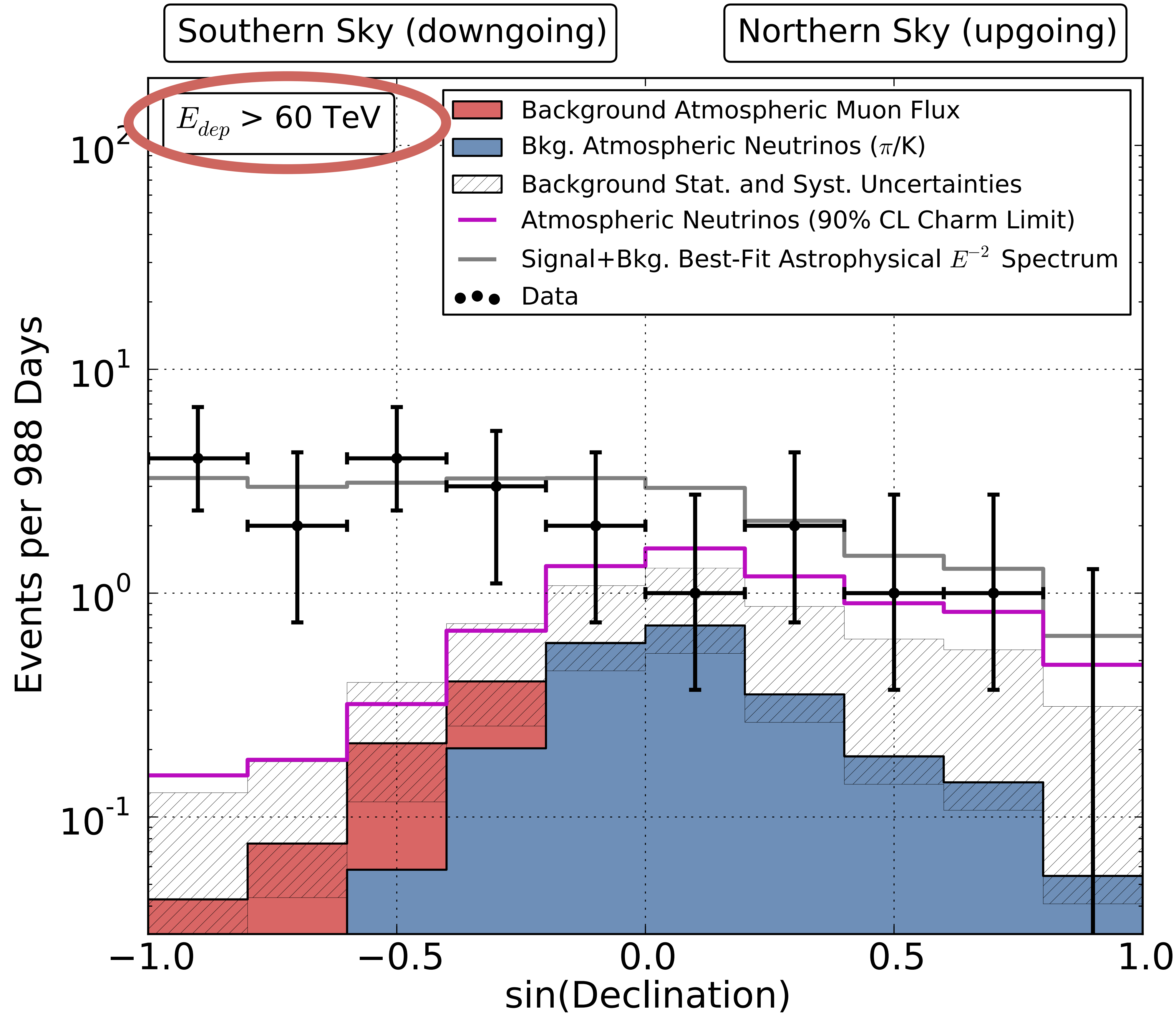
High Energy

Starting Event

Analysis



3-Year
High Energy
Starting Event
Analysis



3-Year

High Energy

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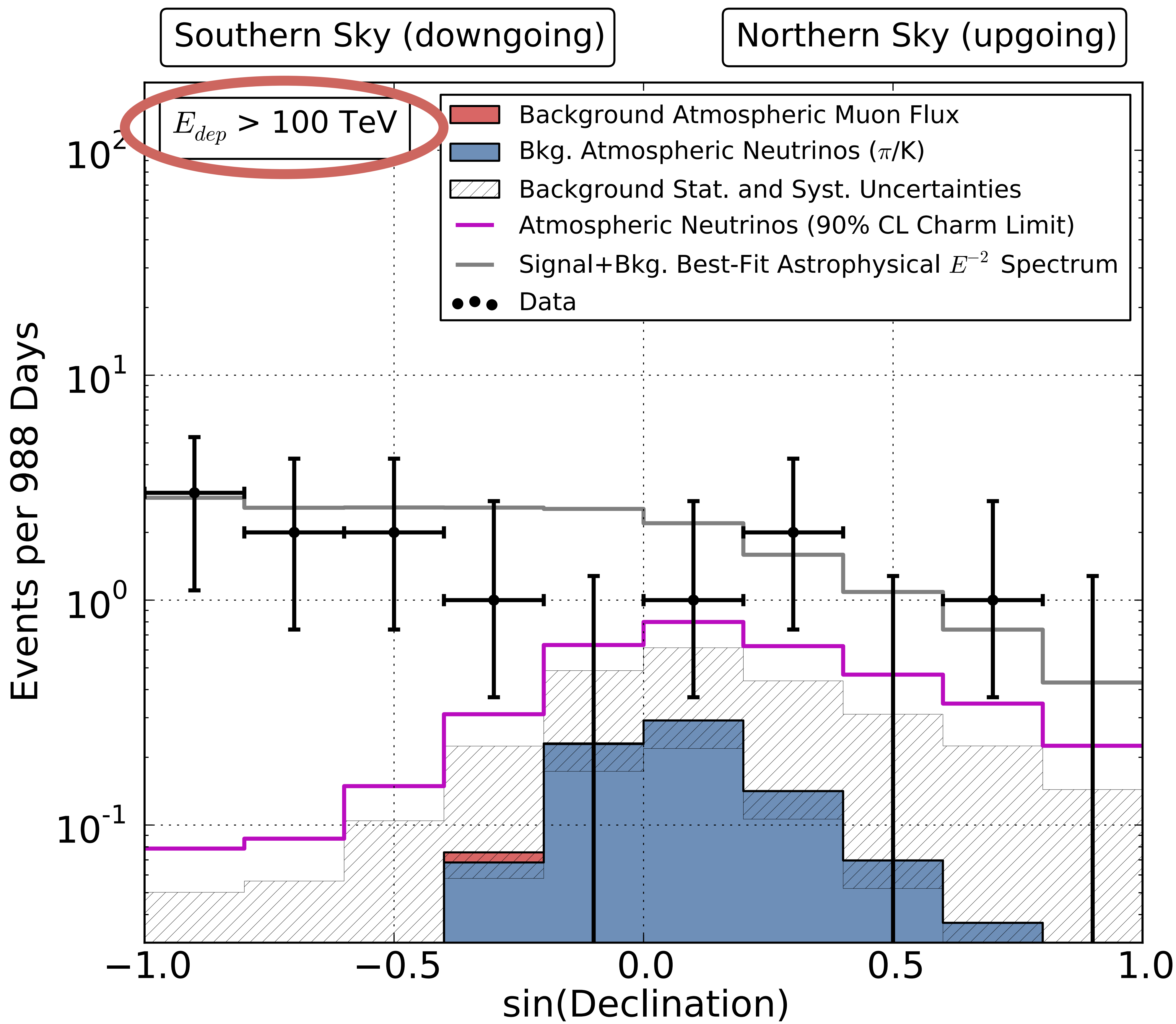

3-Year
High Energy
Starting Event
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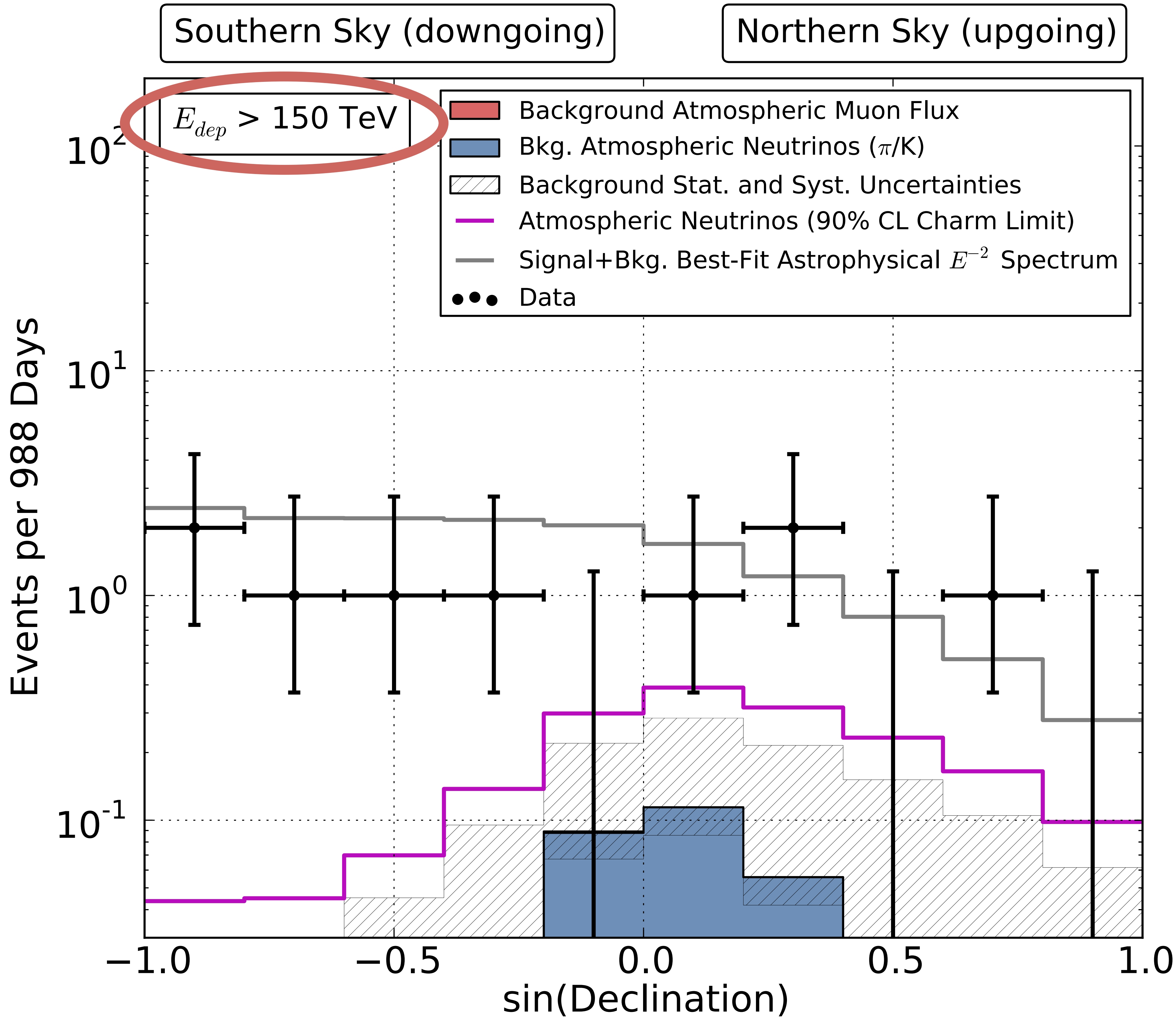
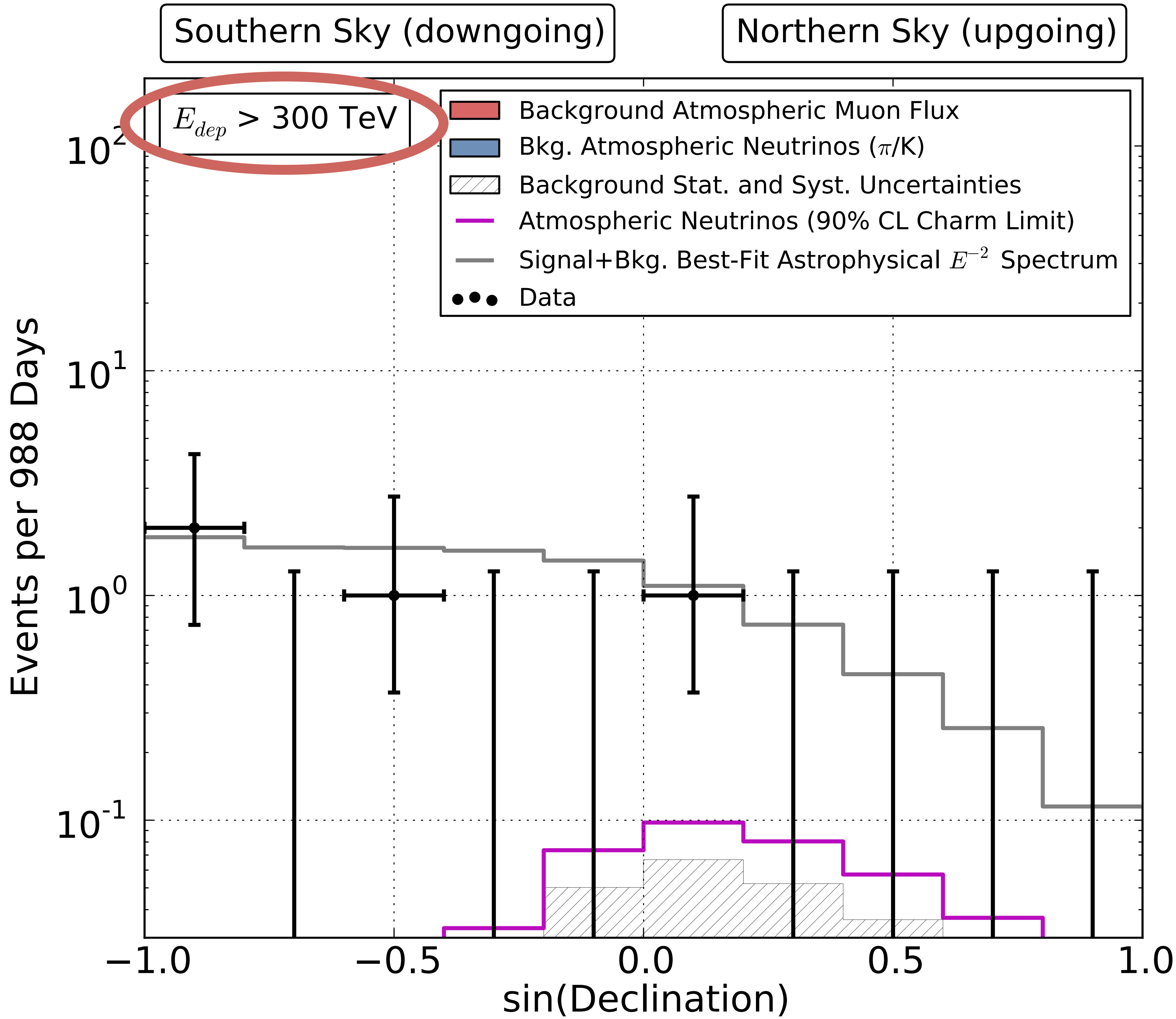


3-Year

High Energy

Starting Event

Analysis



High Energy Starting Event Analysis

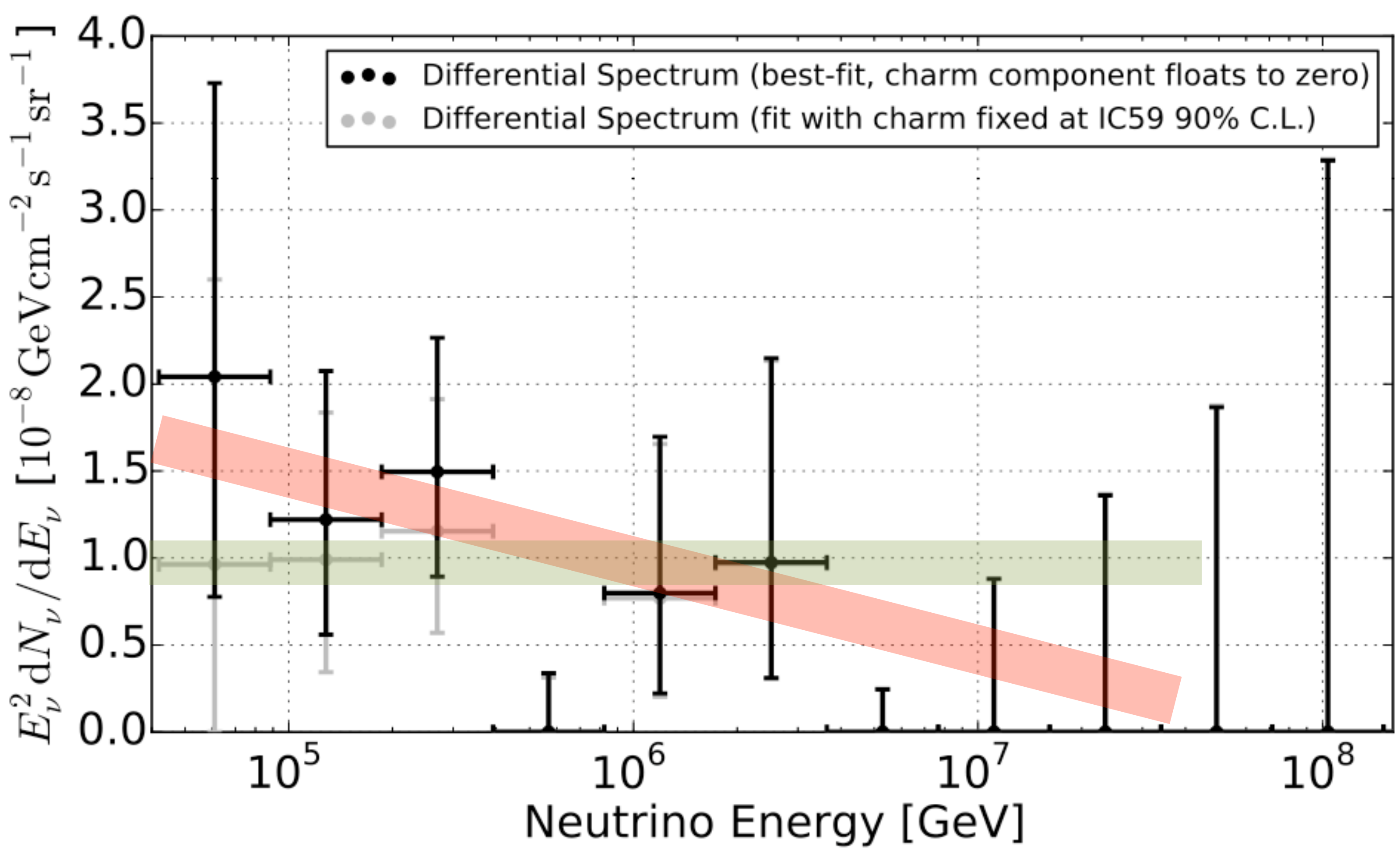
Assuming unbroken E^{-2} spectrum, best-fit astrophysical normalization is:

$$E^2\phi(E) \;=\; 0.95 \pm 0.3 \times 10^{-8}\,\mathrm{GeV\,cm^{-2}\,s^{-1}\,sr^{-1}}$$

Lack of events above 2 PeV (3.1 expected in this analysis; more in the EHE analysis, PRL 111, 021103 (2013)) suggests unbroken E^{-2} disfavored

Best power-law fit yields a spectral index of -2.3 (and fits 0 charm component):

$$E^2\phi(E) = 1.5 \times 10^{-8}(E/100\mathrm{TeV})^{-0.3}\mathrm{GeVcm^{-2}s^{-1}sr^{-1}}$$



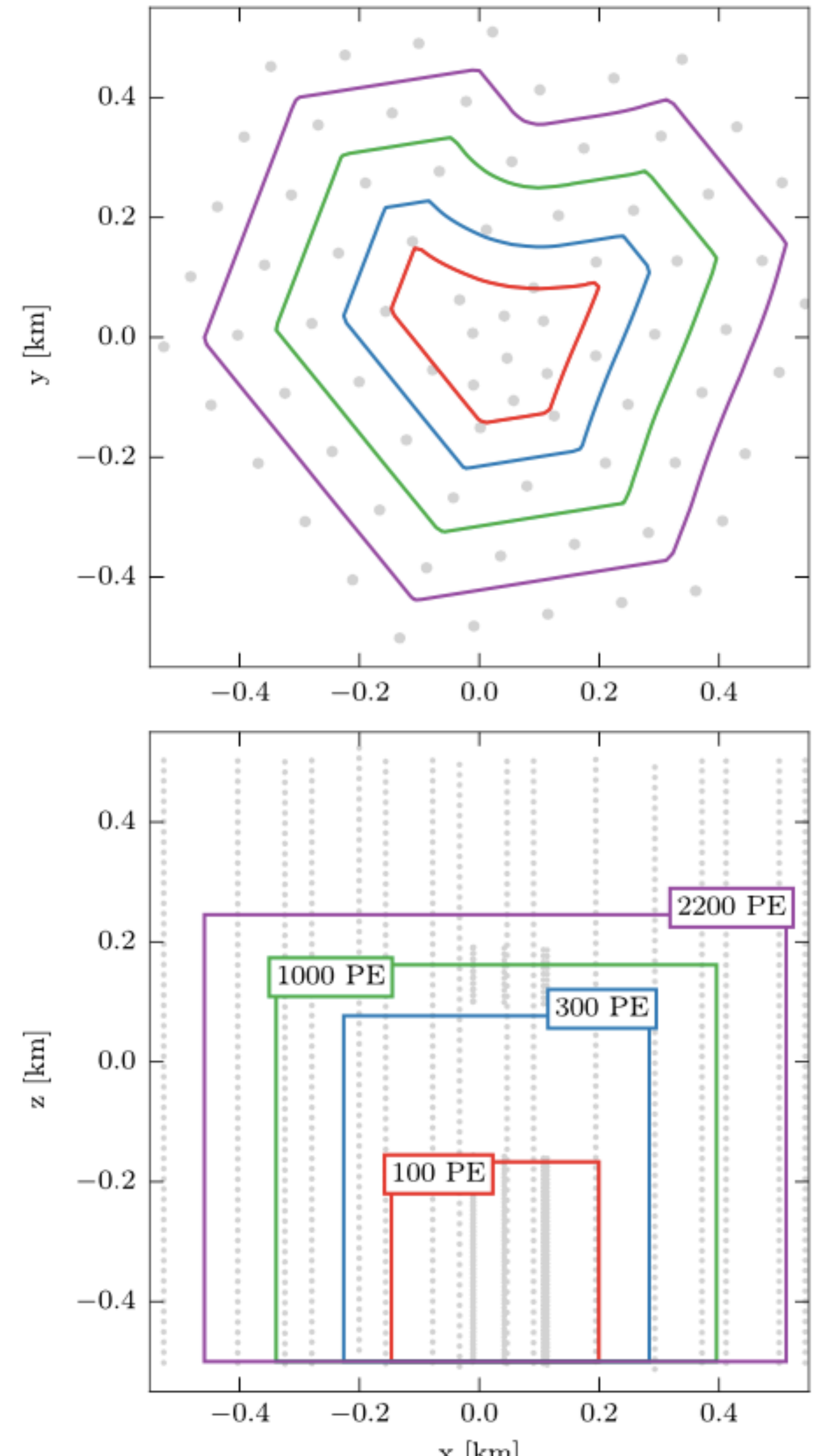
More sophisticated analysis published this fall: PRD 91:022001 (2014)

Nested layers of vetoes

Series of lower energy thresholds

388 events selected in 2 years of data

87 ± 14 astrophysical neutrinos

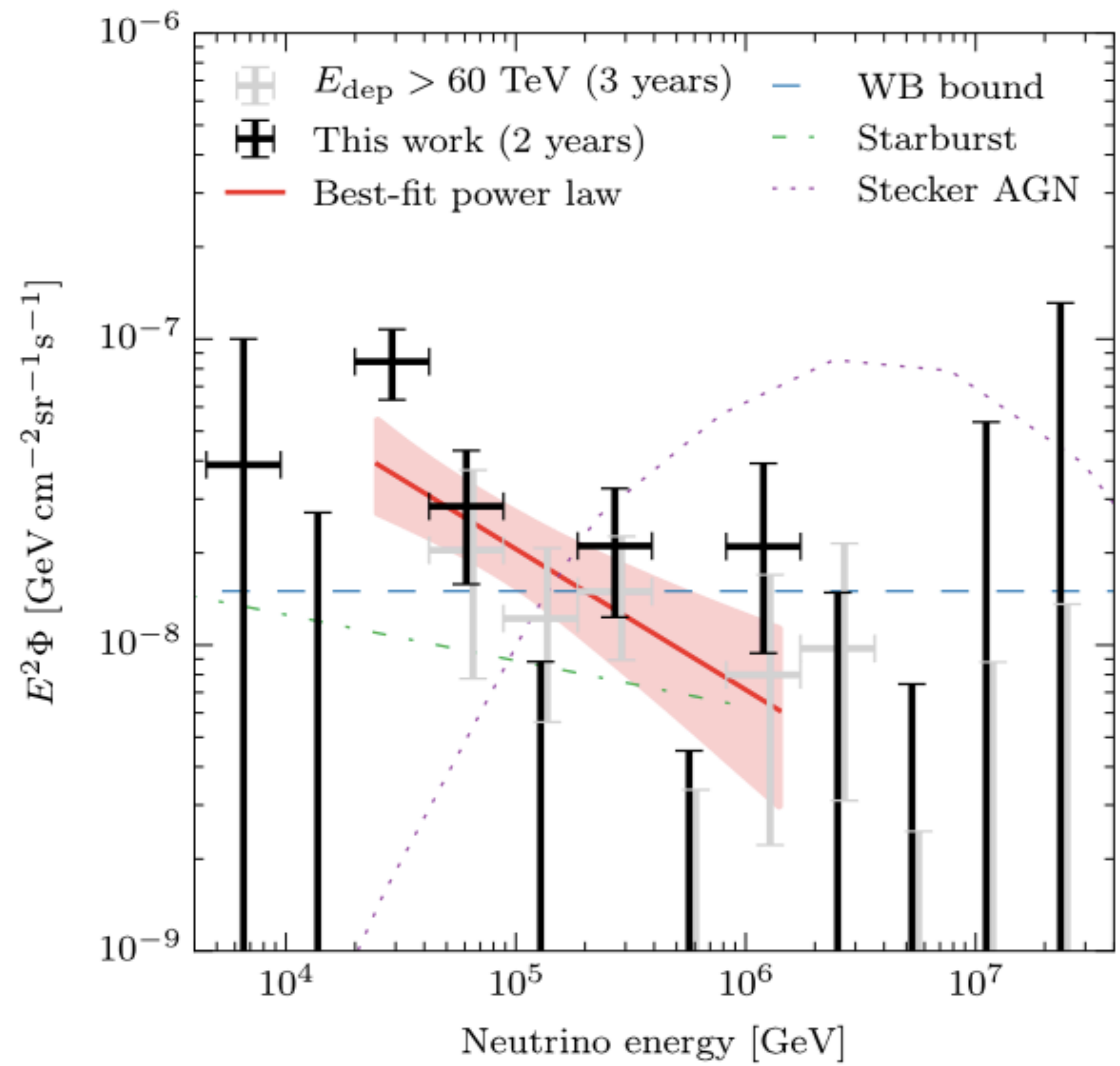


Prompt component of background atmospheric neutrinos still not observed, but limits now:

$$\Phi_{prompt} < 1.52 \times \text{ERS Model}$$

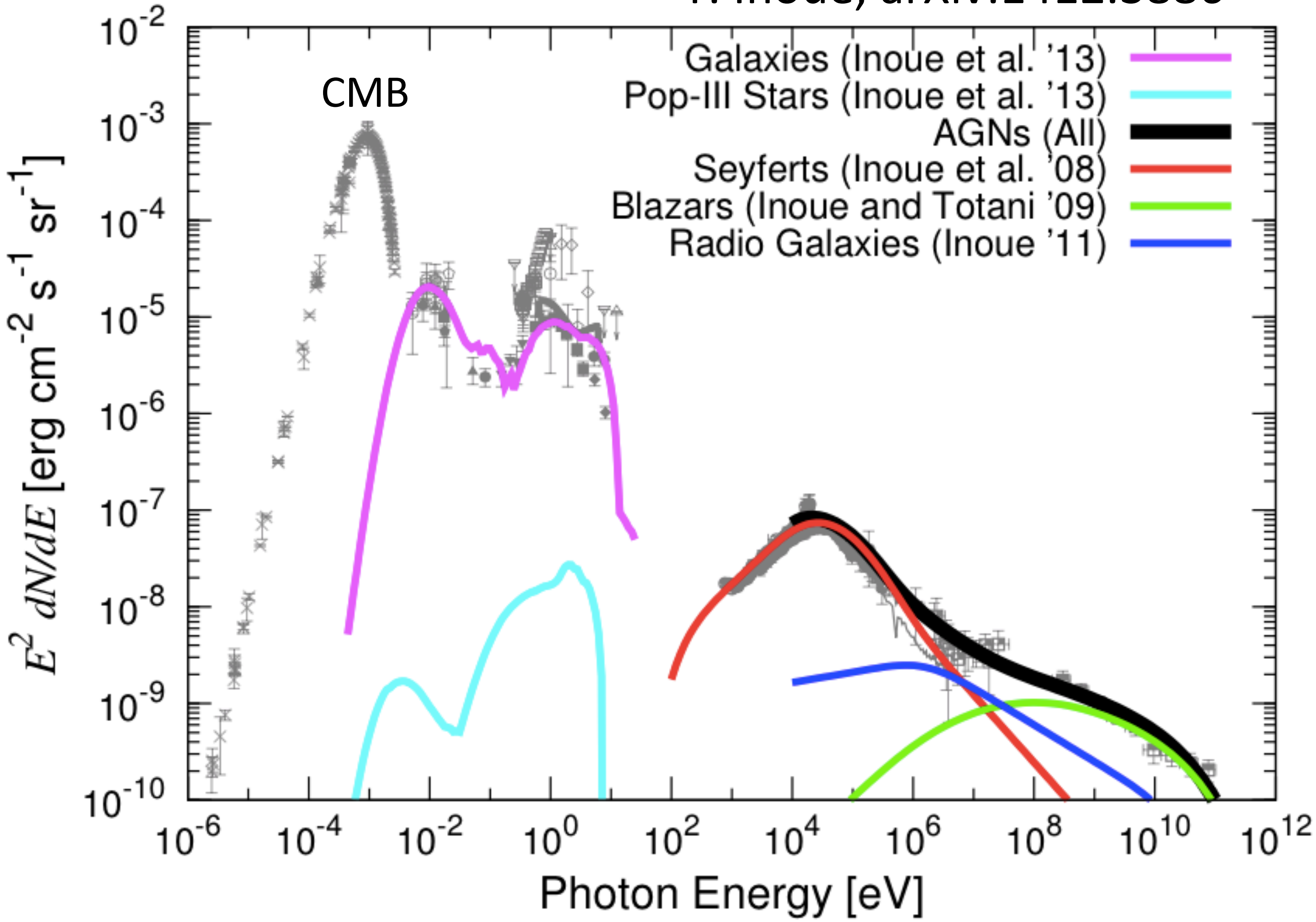
Best-fit astrophysical spectral index $E^{-\gamma}$

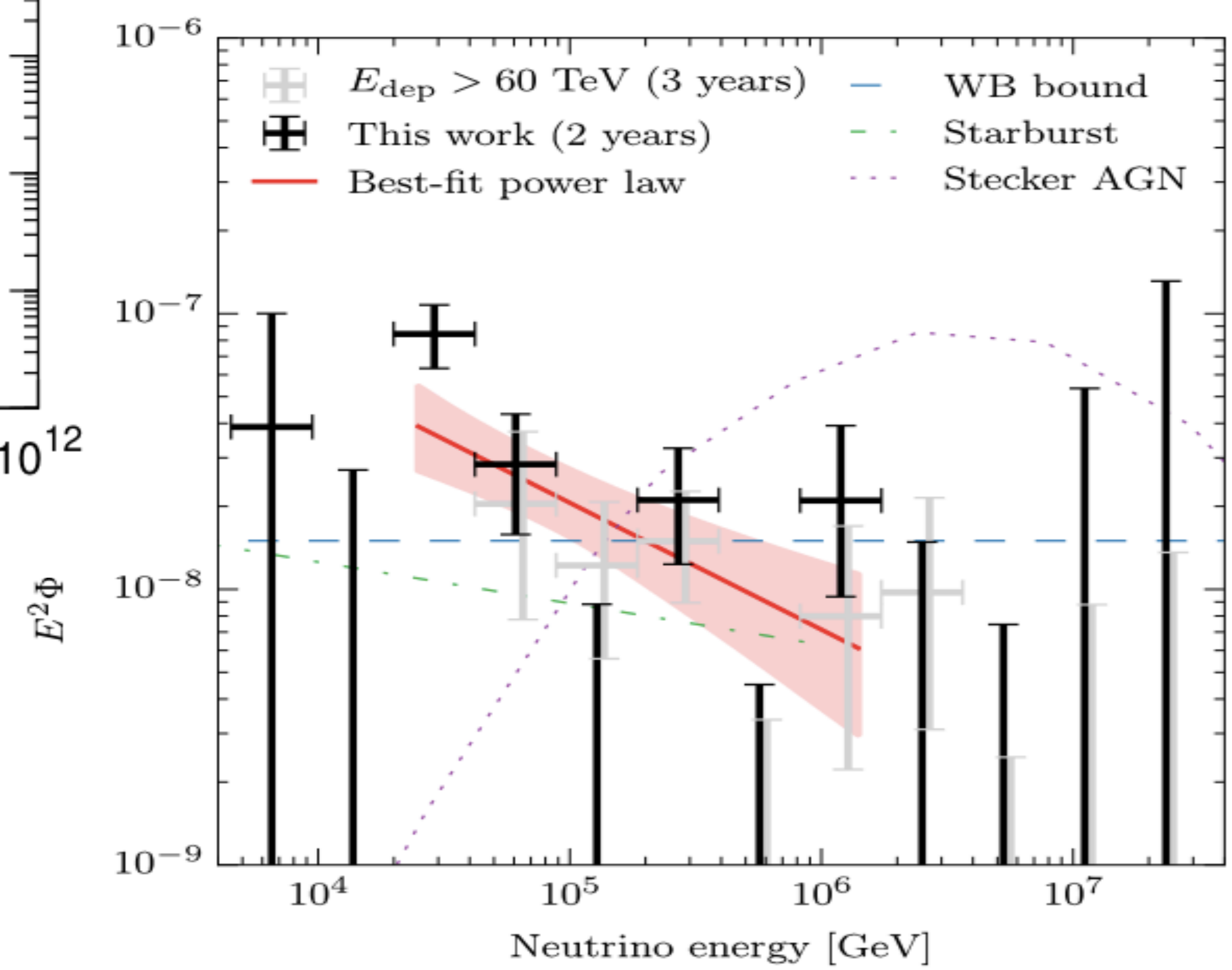
$$\gamma = 2.46 \pm 0.12$$



Diffuse Cosmic Background Radiation

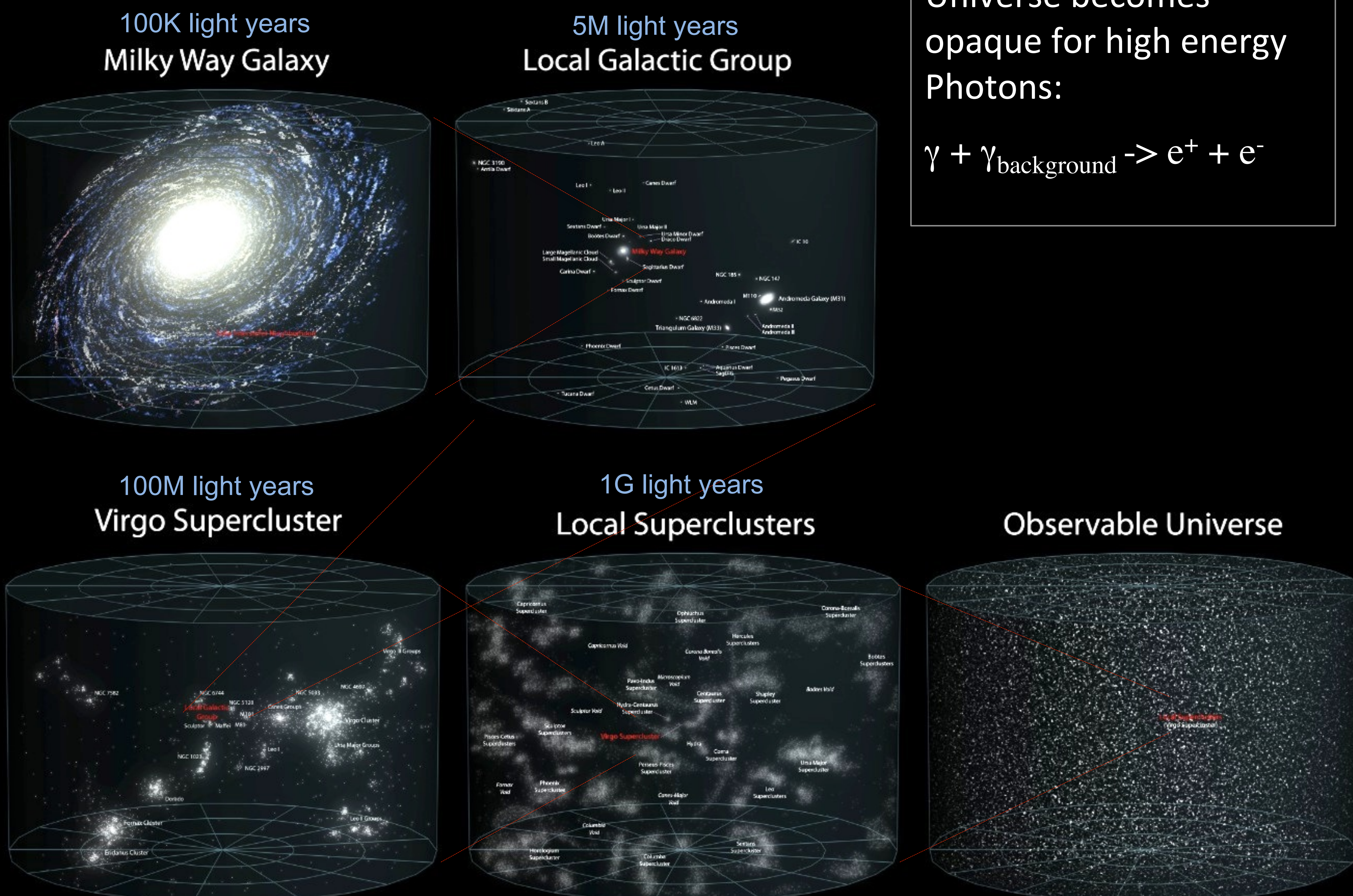
Y. Inoue, arXiv:1412.3886





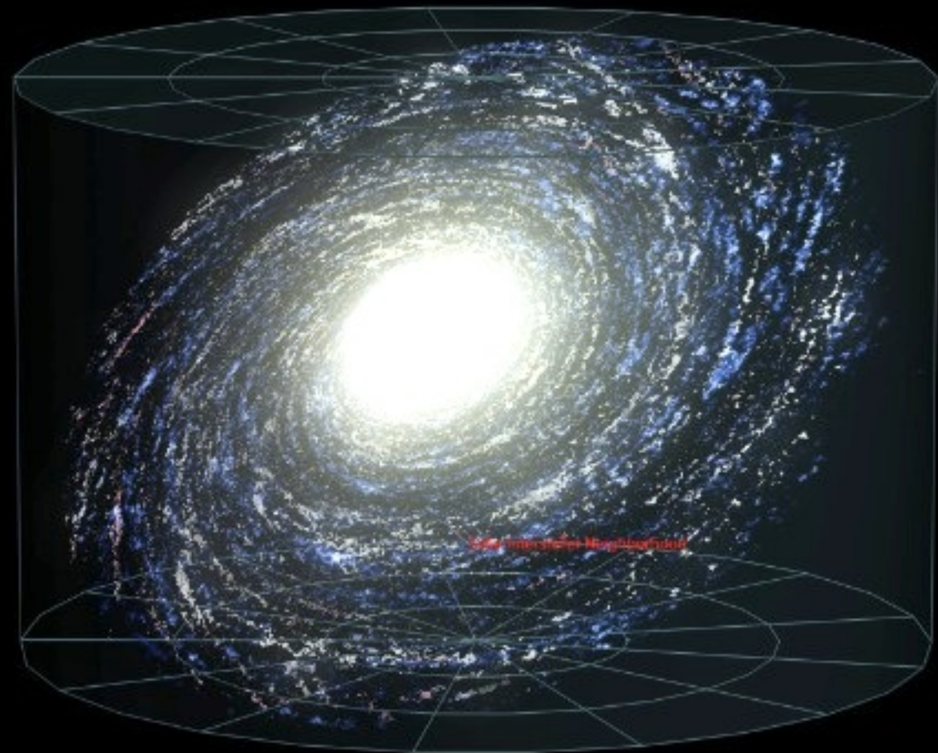
Universe becomes opaque for high energy Photons:

$$\gamma + \gamma_{background} \rightarrow e^{+} + e^{-}$$



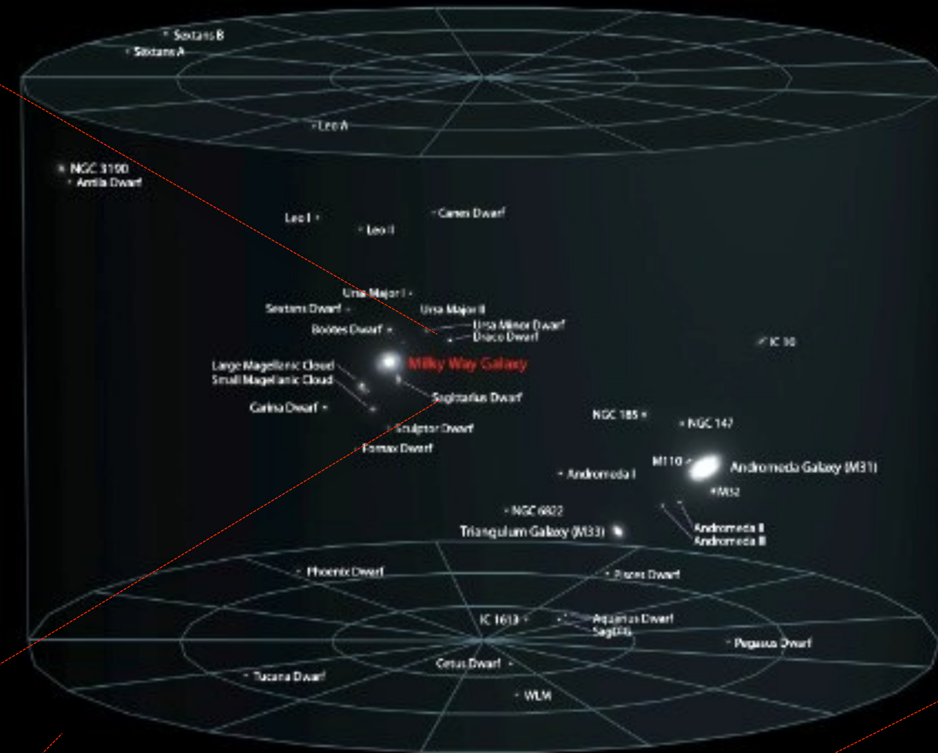
100K light years

Milky Way Galaxy



5M light years

Local Galactic Group



Universe becomes opaque for high energy Photons:

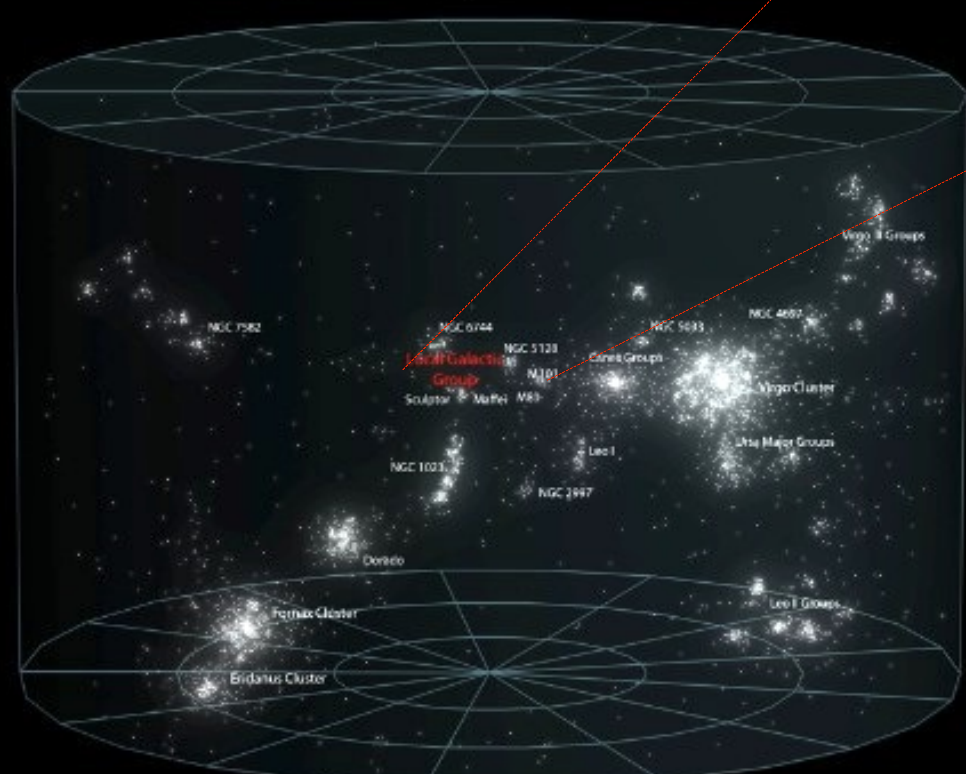
$\gamma + \gamma_{background} \rightarrow e^+ + e^-$

Mean free path at:

- 10 TeV

100M light years

Virgo Supercluster



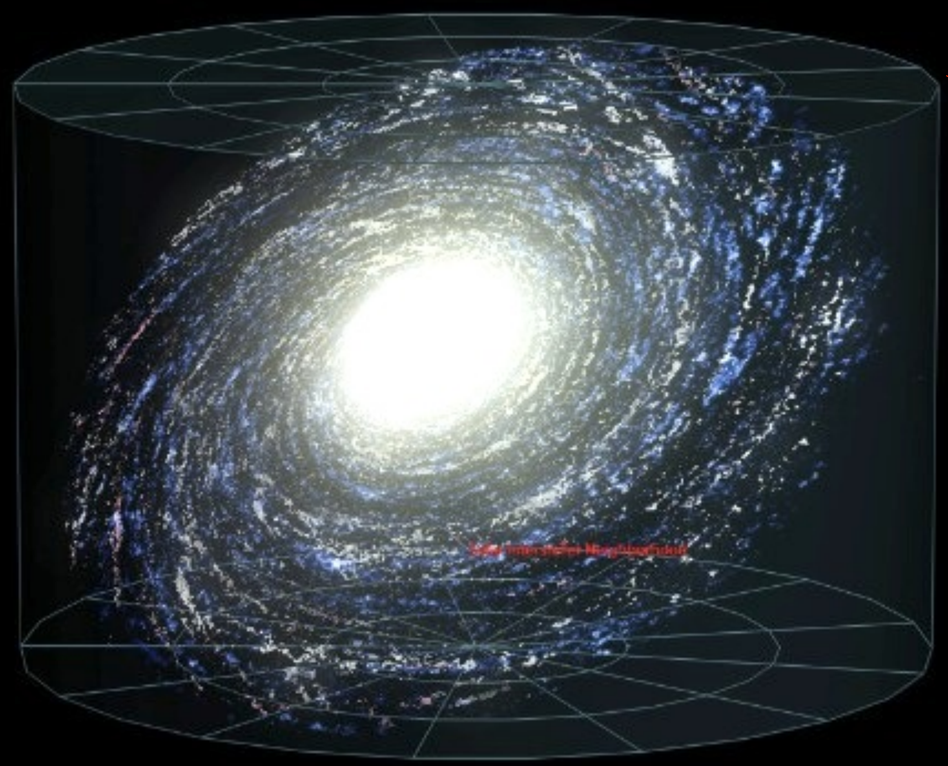
1G light years

Local Superclusters

Observable Universe

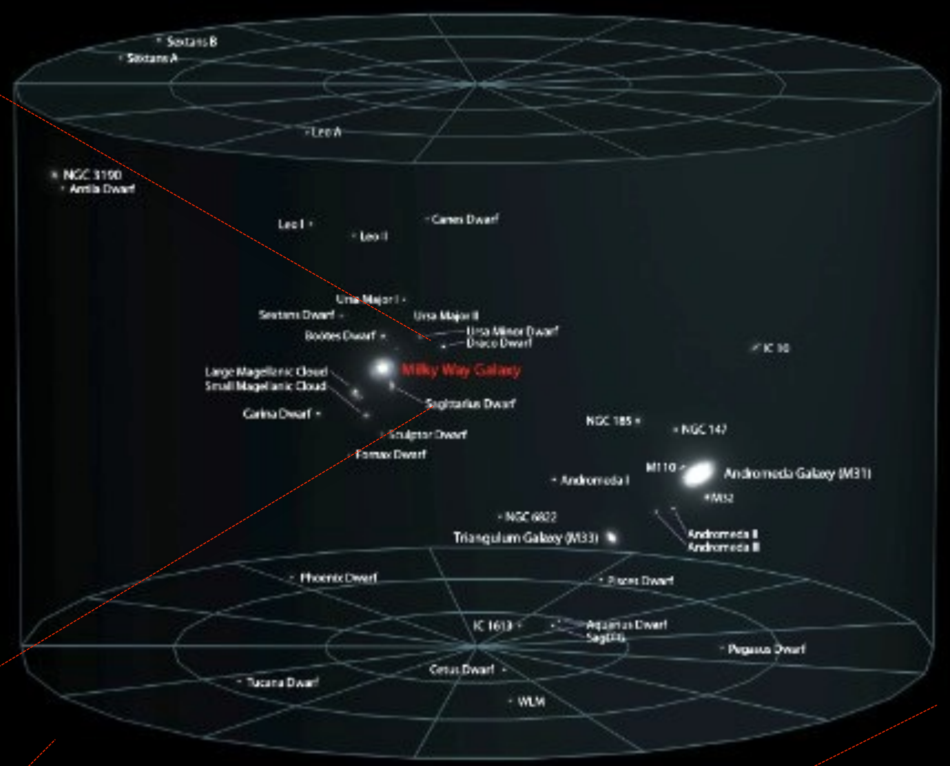
100K light years

Milky Way Galaxy



5M light years

Local Galactic Group



Universe becomes opaque for high energy Photons:

$\gamma + \gamma_{background} \rightarrow e^+ + e^-$

Mean free path at:

- 10 TeV
- 100 TeV

100M light years

Virgo Supercluster

1G light years

Local Superclusters

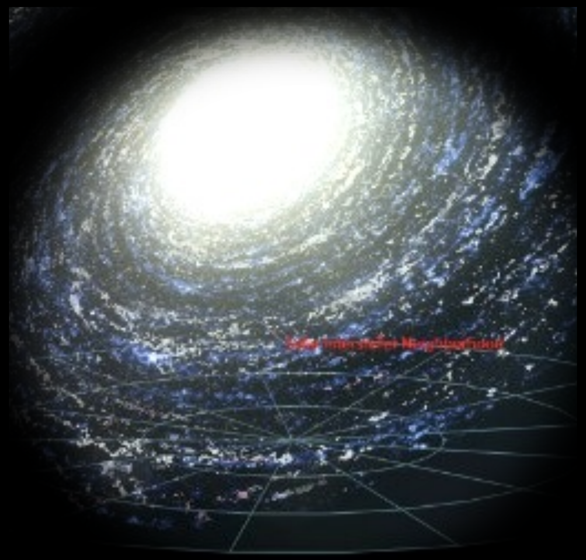
Observable Universe

100K light years

Milky Way Galaxy

5M light years

Local Galactic Group



100M light years

Virgo Supercluster

1G light years

Local Superclusters

Observable Universe

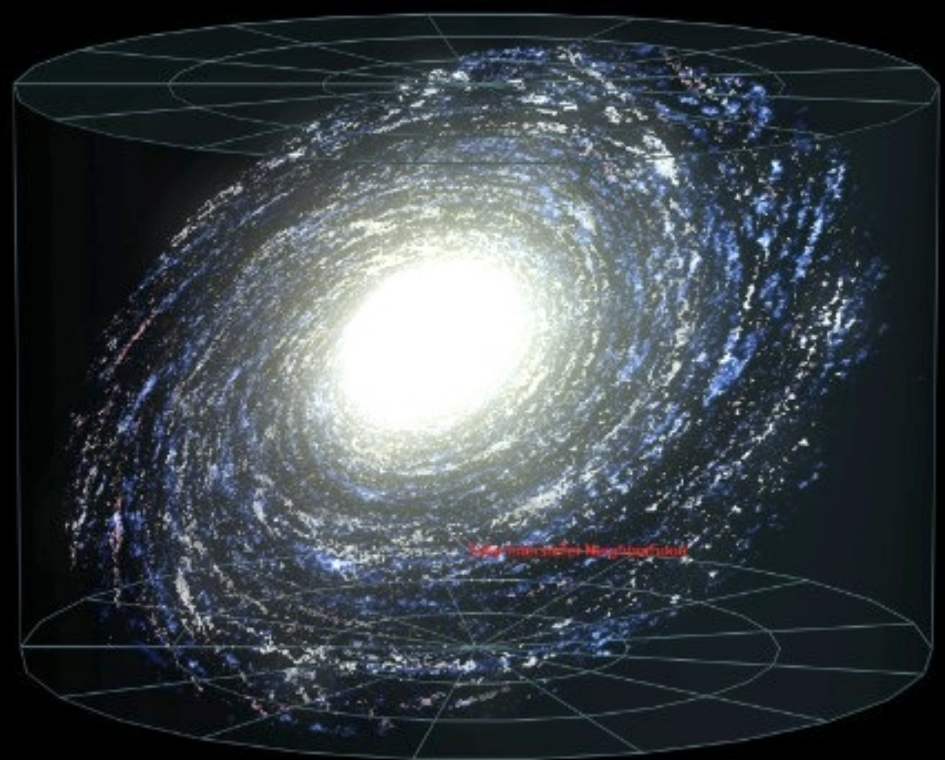
Universe becomes opaque for high energy Photons:

$\gamma + \gamma_{background} \to e^{+} + e^{-}$

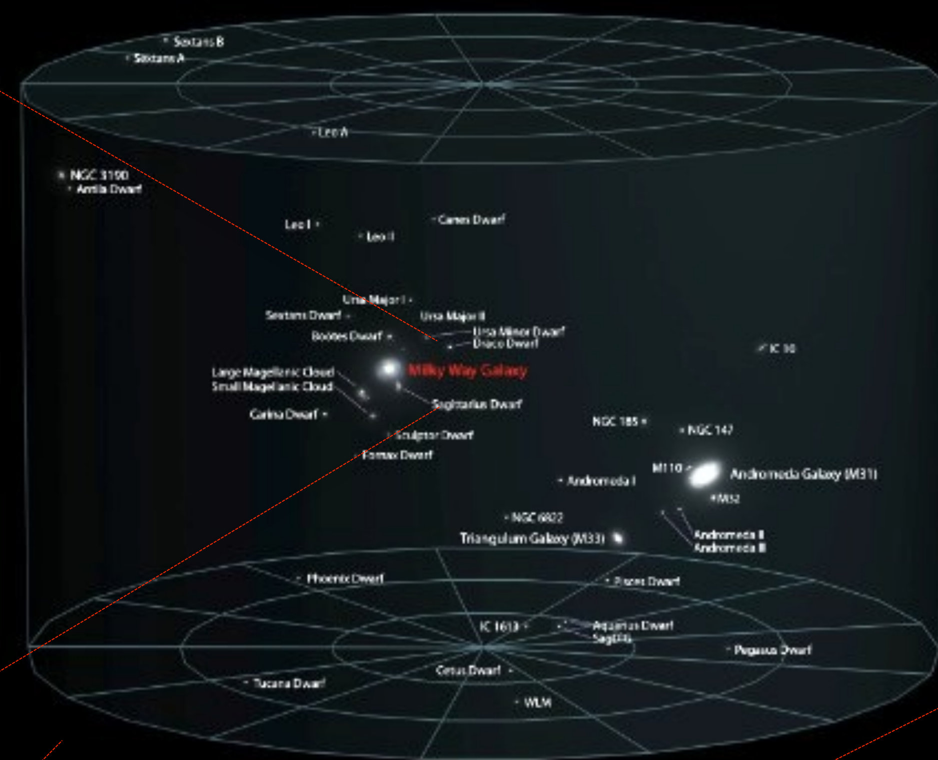
Mean free path at:

- 10 TeV
- 100 TeV
- 1 PeV

100K light years
Milky Way Galaxy

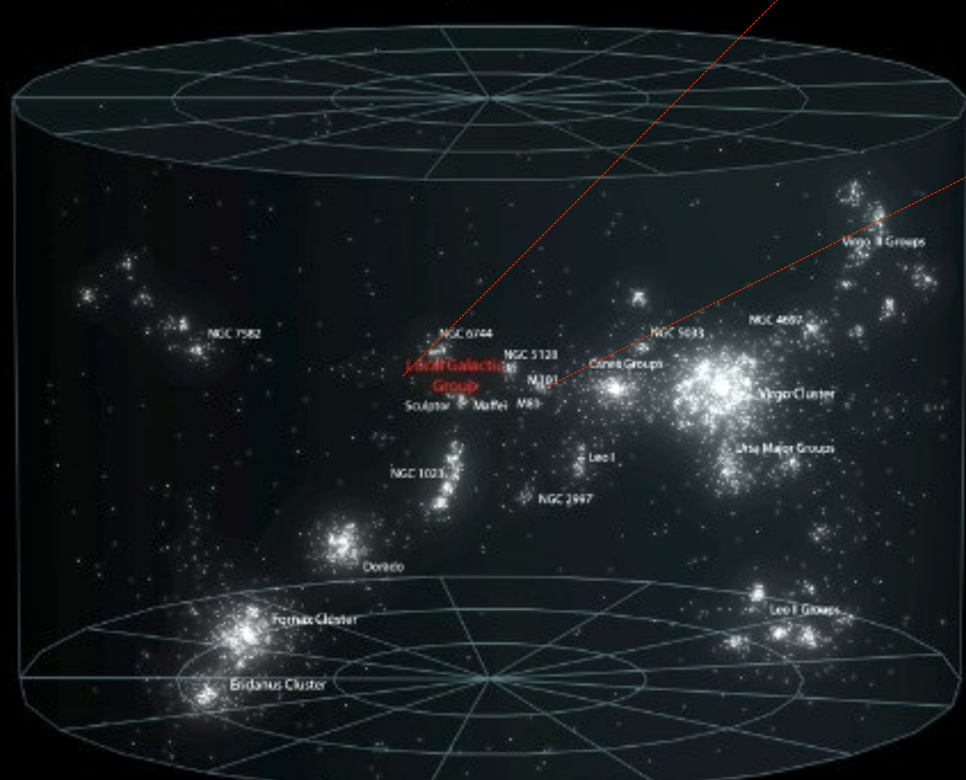


5M light years
Local Galactic Group

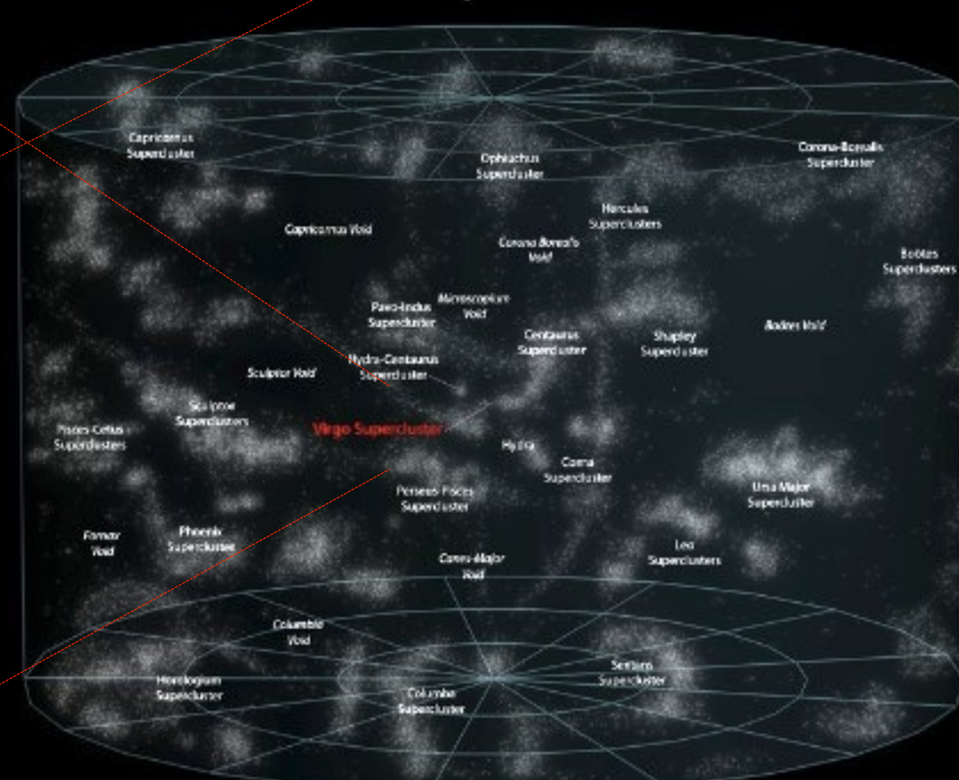


Universe is transparent to neutrinos at all energies

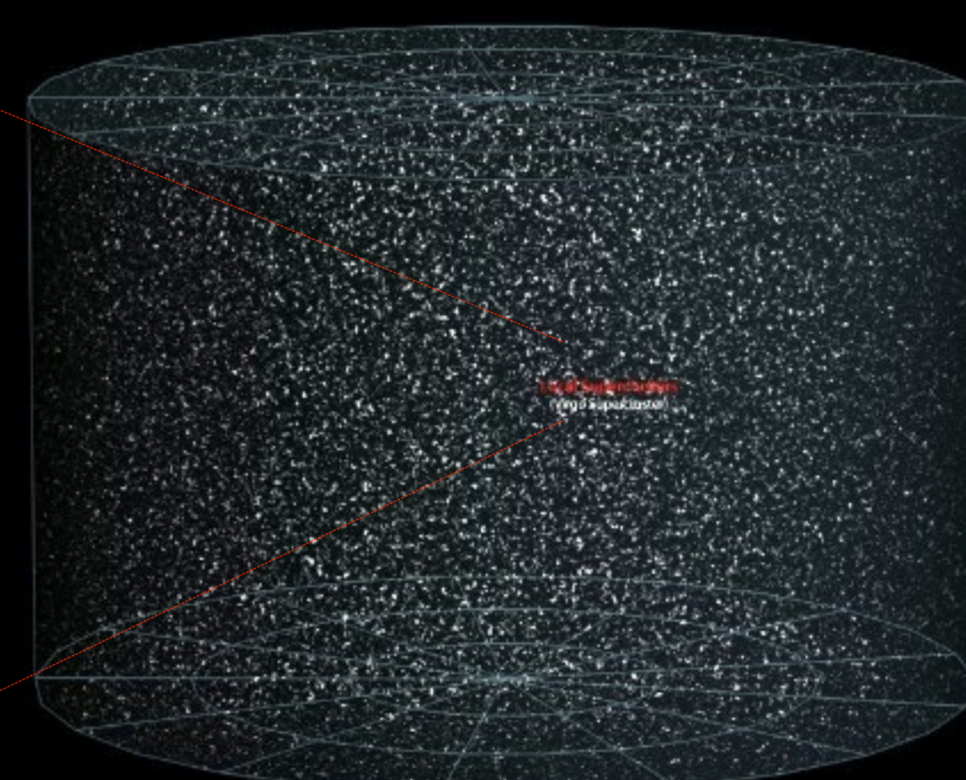
100M light years
Virgo Supercluster



1G light years
Local Superclusters

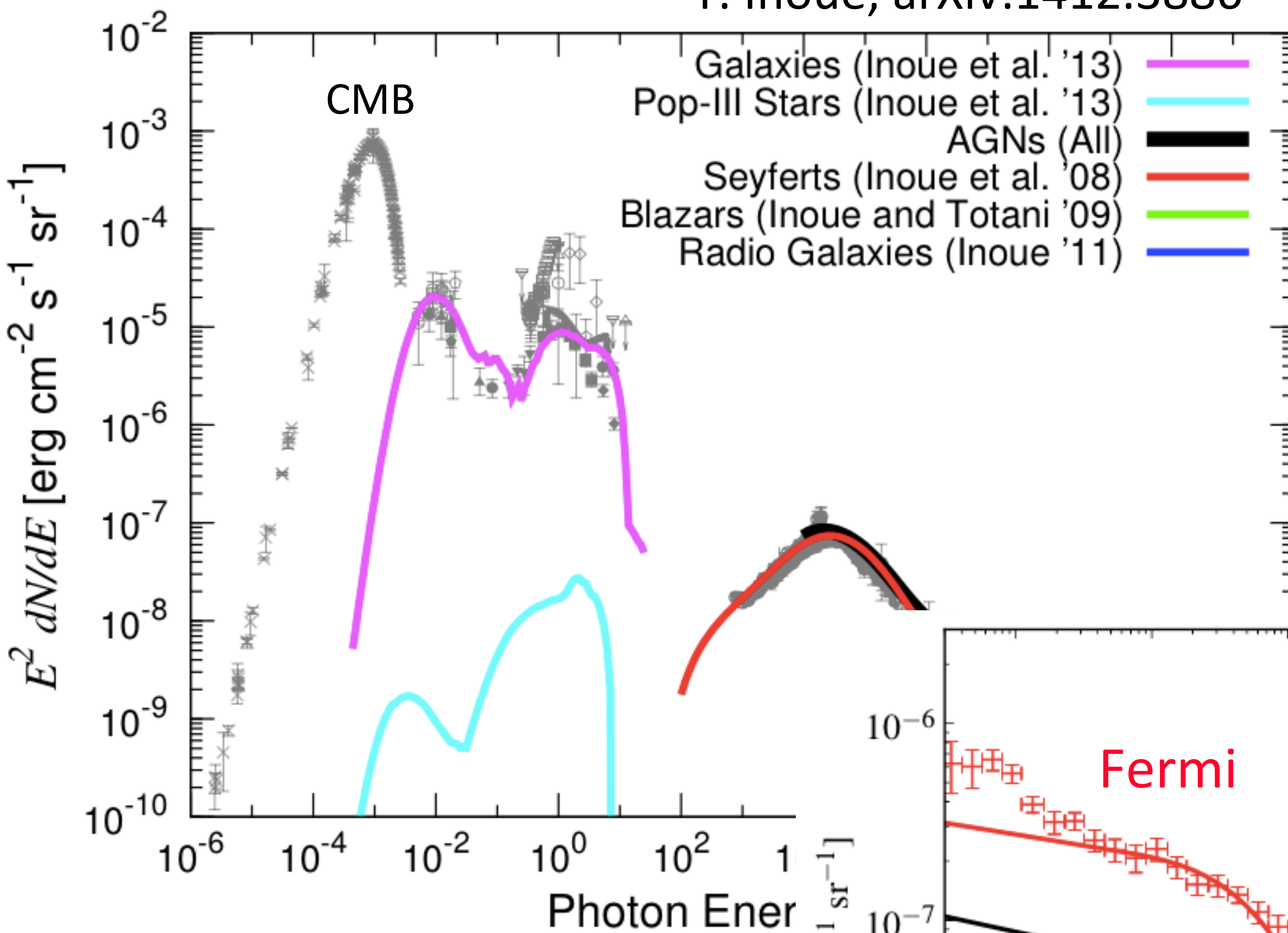


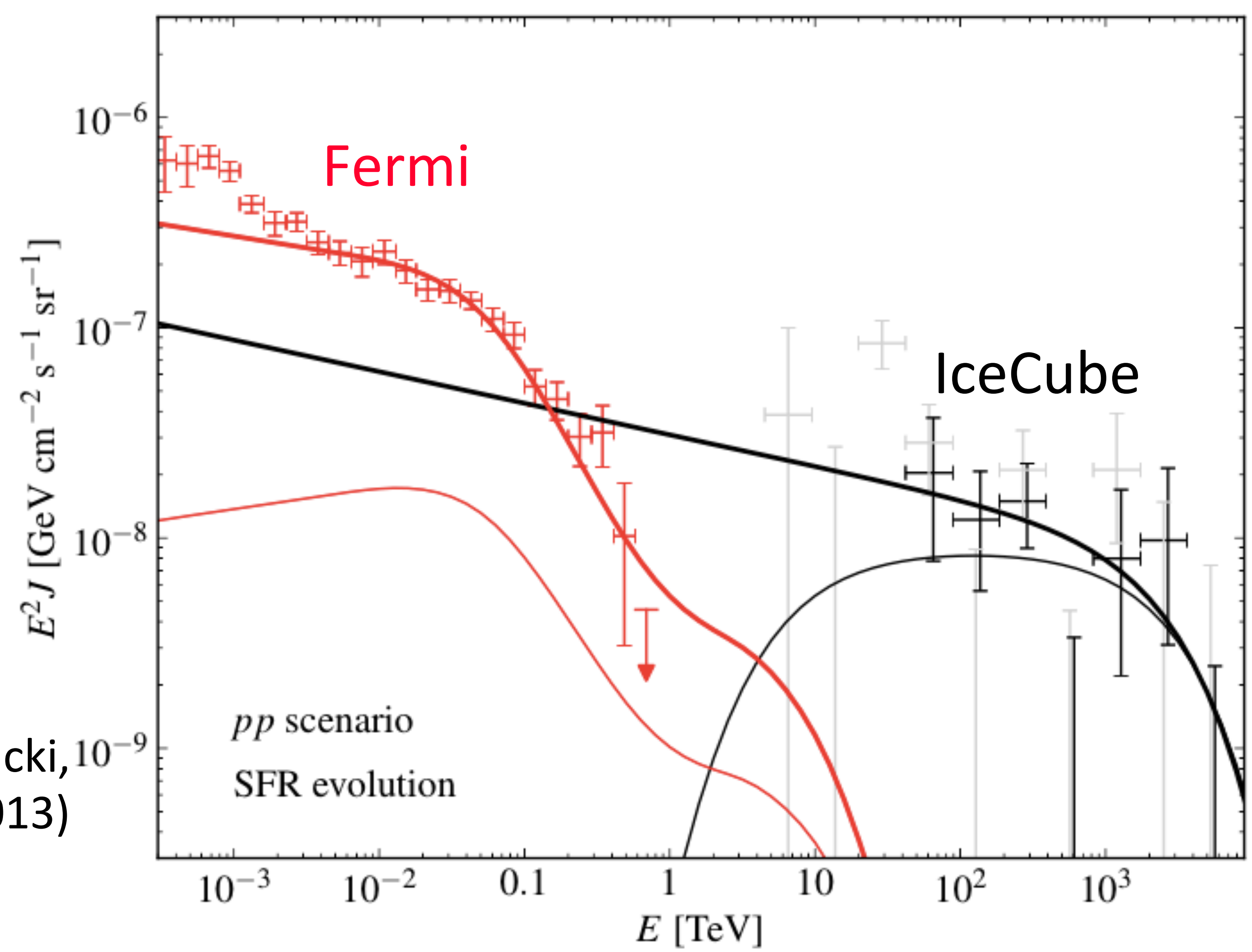
Observable Universe



Diffuse Cosmic Background Radiation

Y. Inoue, arXiv:1412.3886





pp interactions can produce IceCube PeV neutrino flux

corresponding PeV gamma flux cascades down, fits Fermi flux

arXiv:1412.5106, after Murase, Ahlers, Lacki, Phys.Rev. D88, 121301 (2013)

Muon Neutrino Diffuse Analysis

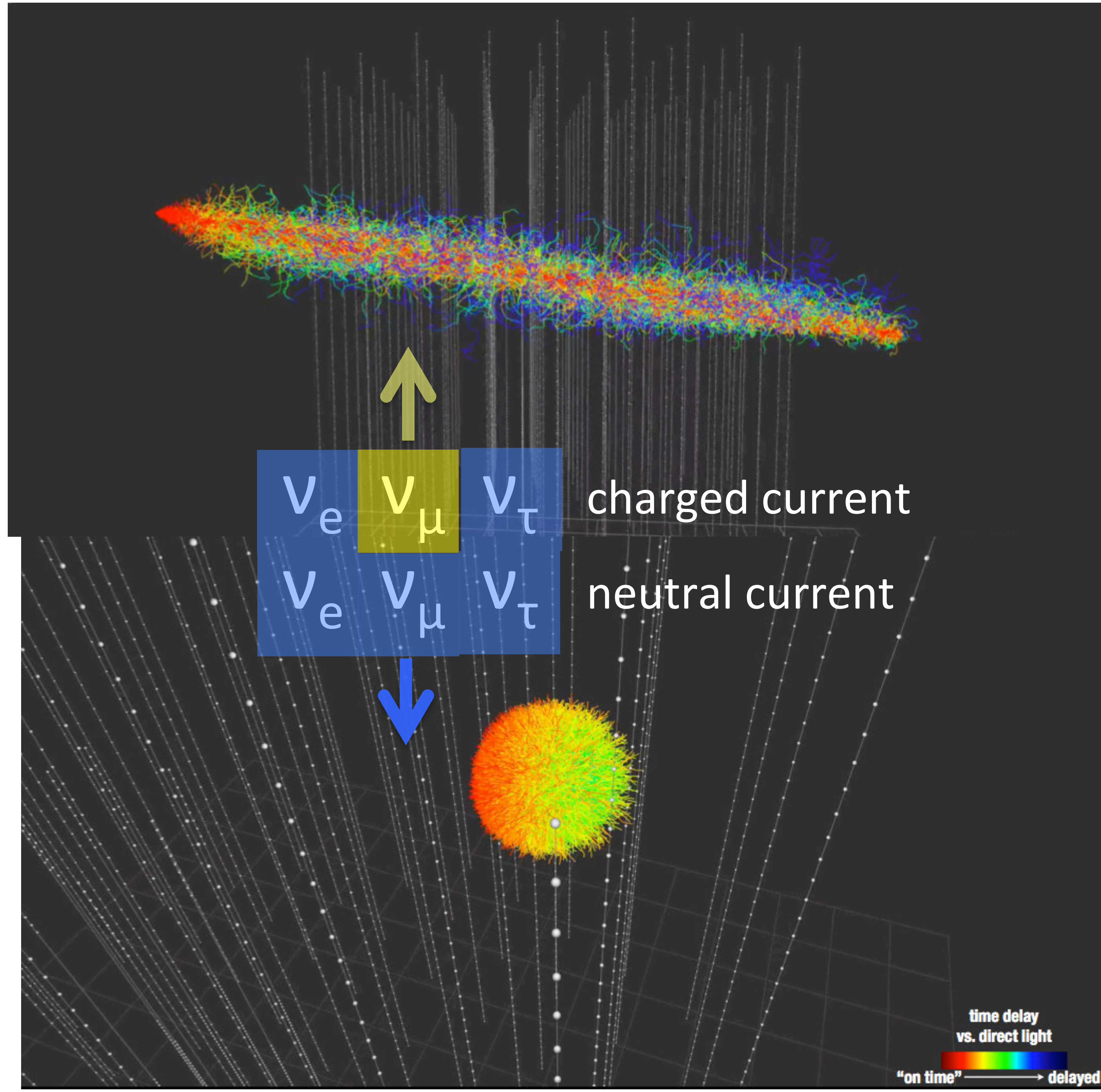
Allow events to enter from **outside** detector, use Earth as filter against muons from cosmic rays

Track events from muon neutrinos

Good pointing: ~ 0.5°

$\log_{10}$ muon energy resolution ~ 0.3
(at energies ~ 100 TeV)

Complementary analysis to Starting Event analysis



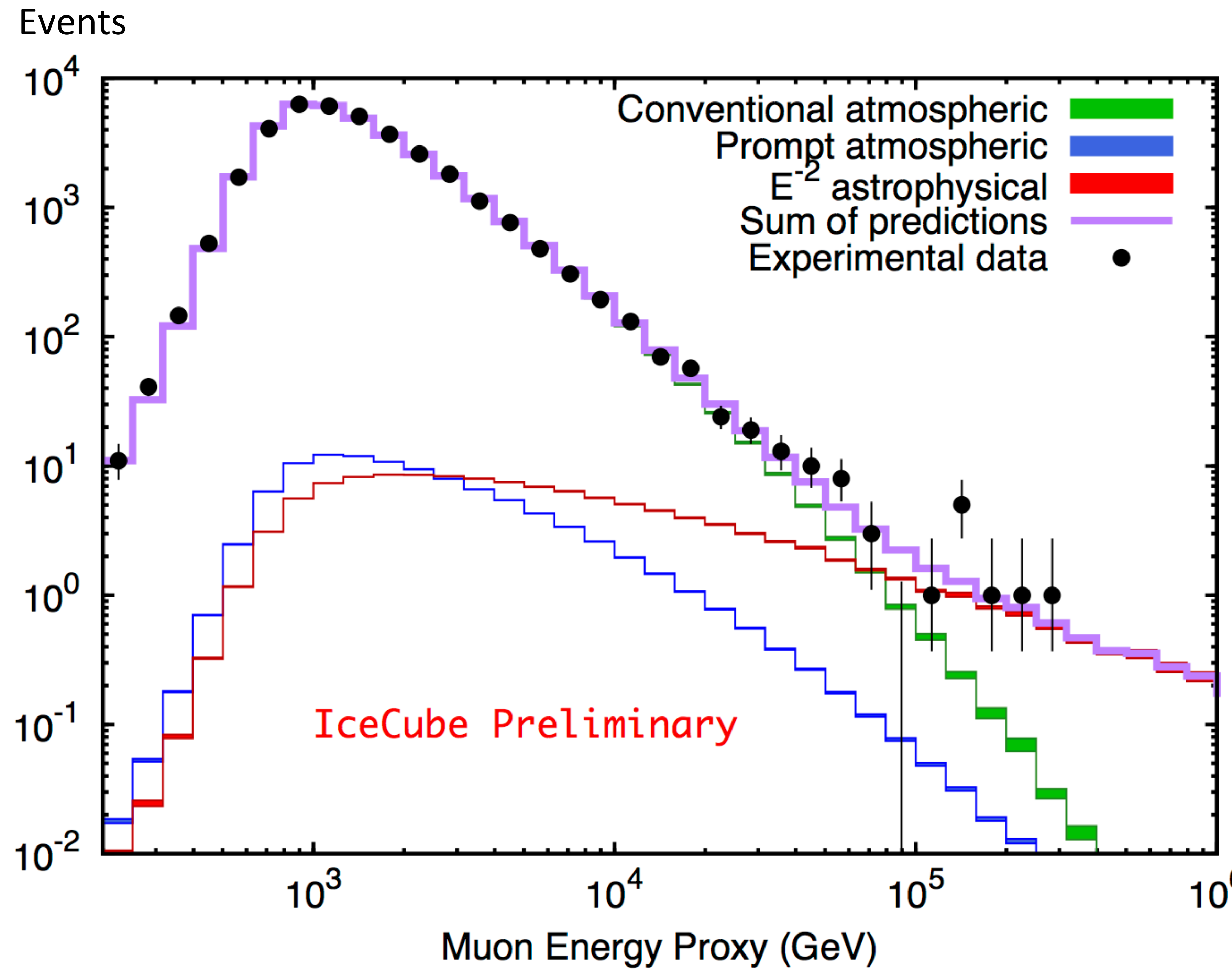
Muon Neutrino Diffuse Analysis

35 000 events in 2-year analysis

Estimated 99.9% pure muon neutrino sample

3.9σ evidence of astrophysical flux

(nearly) **independent** of starting event analyses



Energy estimate for the muon track.
Only lower-bound on neutrino energy
(interacted before reaching detector)

Muon Neutrino Diffuse Analysis

Still only upper limits on prompt background.

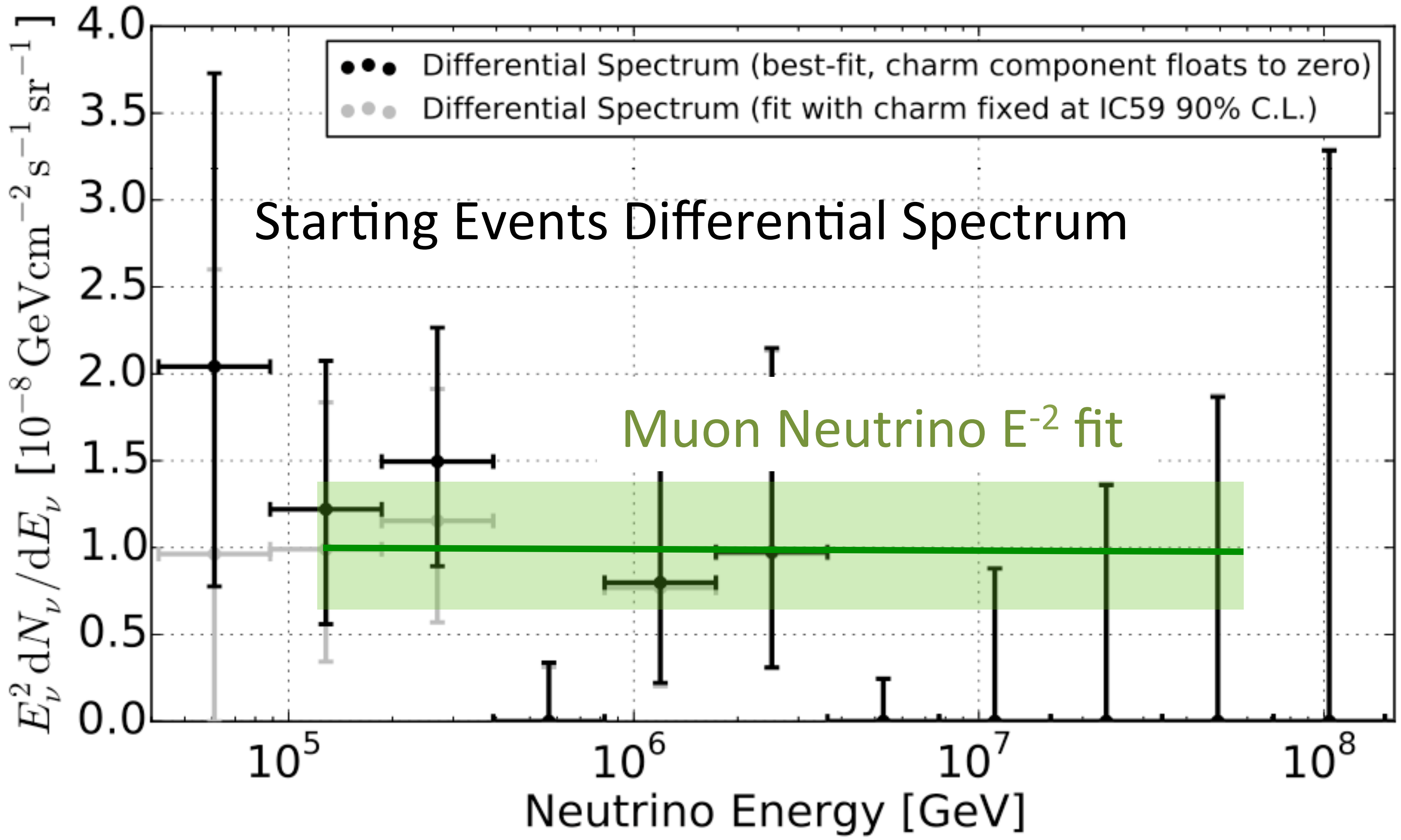
Best fit for E^{-2} astrophysical spectrum is:

$0.96 \pm 0.35 \times 10^{-8}$ GeV^{-1} cm^{-2} s^{-1} sr^{-1}

Strengthens evidence that:

flux is all-sky

flavor ratio is 1:1:1



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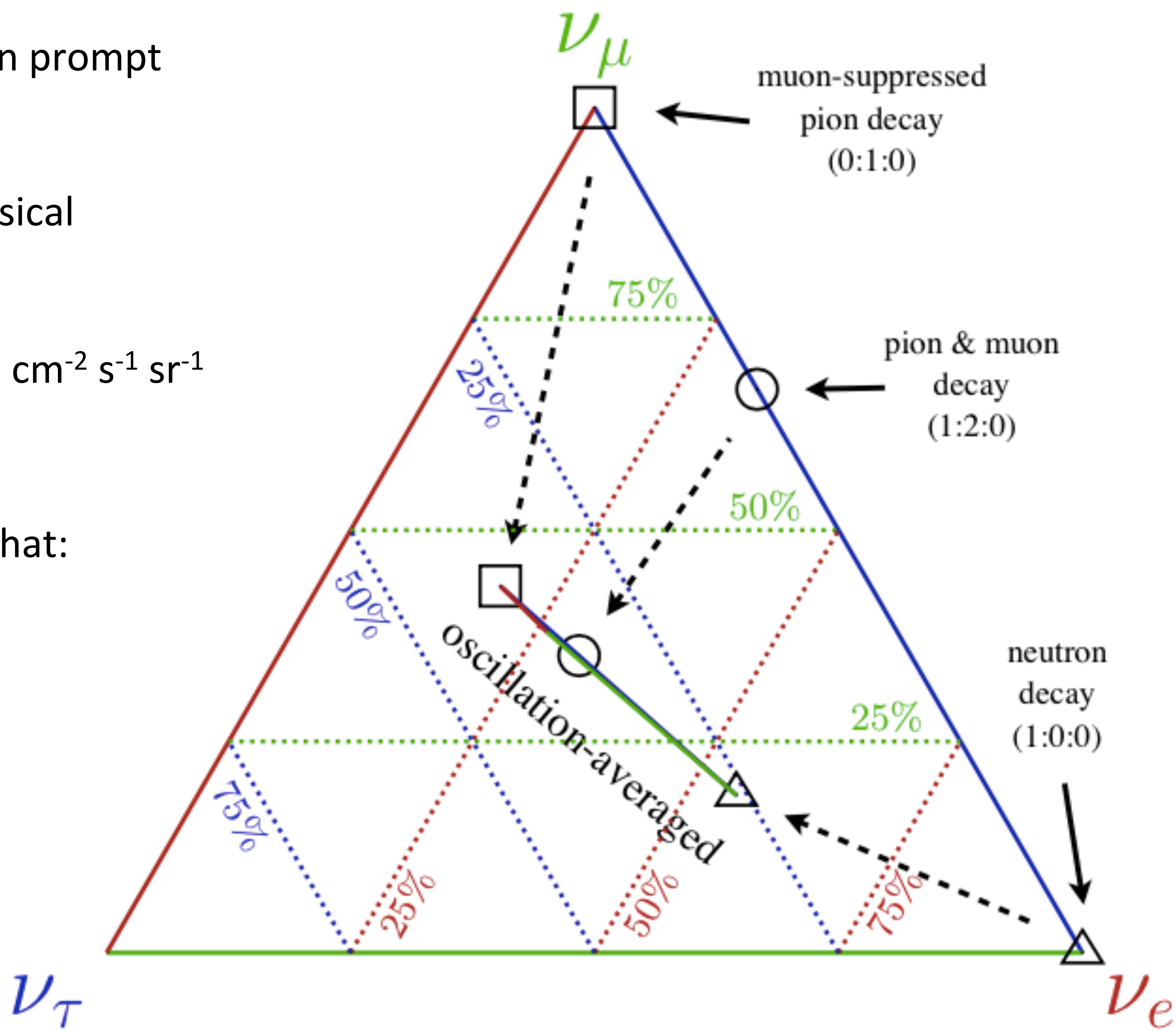
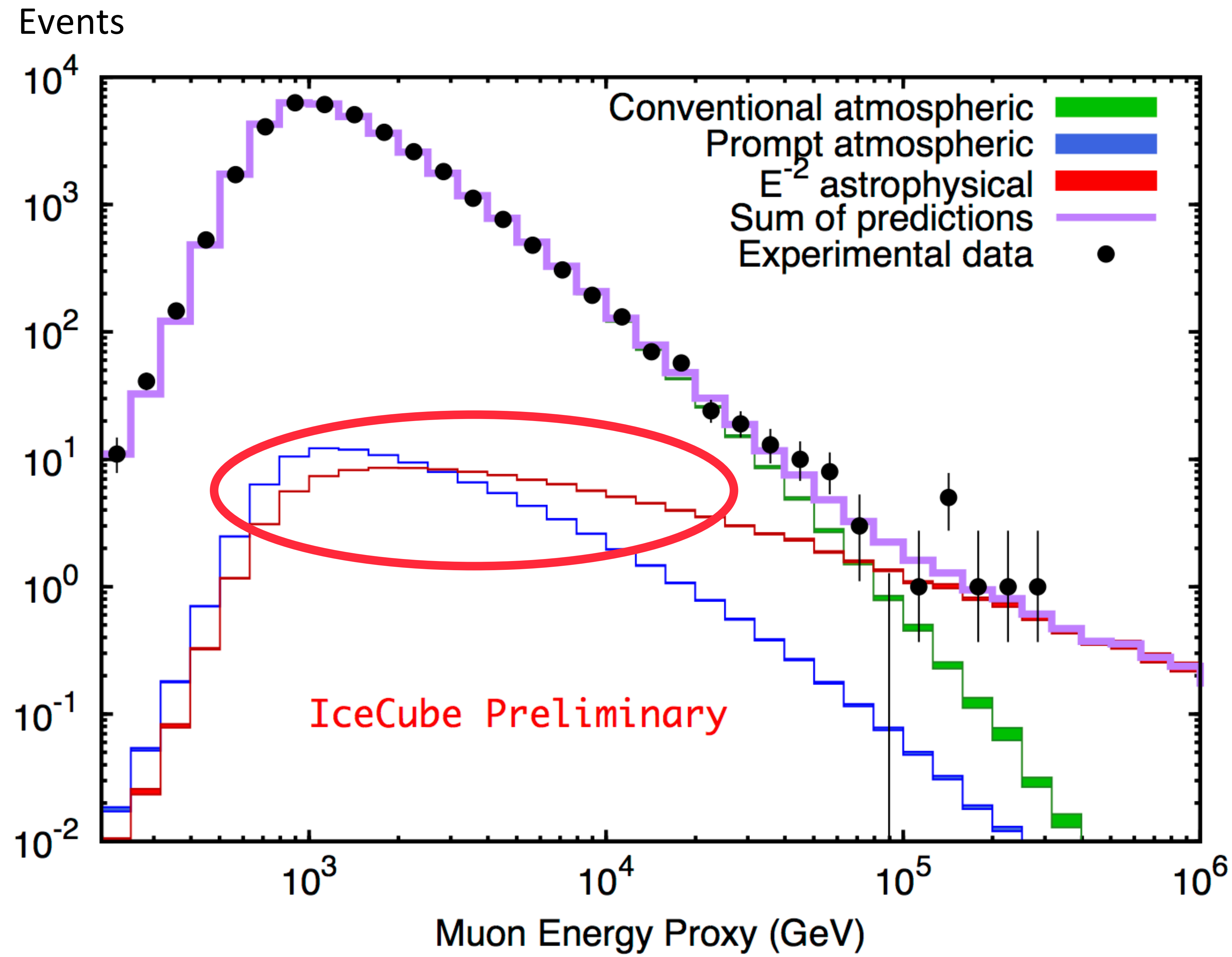


Muon Neutrino Diffuse Analysis

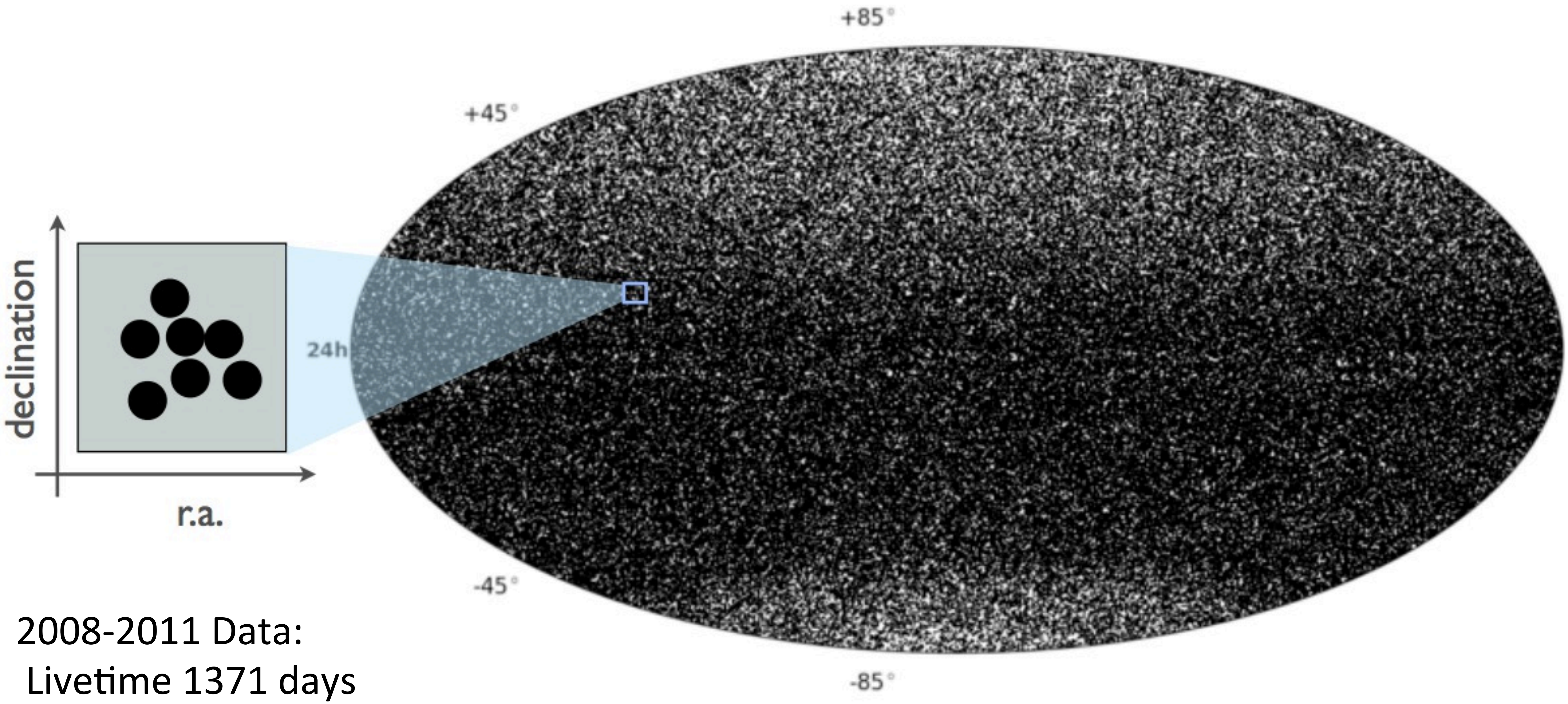
E^{-2} flux implies there are ~ 100 astrophysical muon neutrino events in sample at lower energies…

or much more, if spectrum is softer than E^{-2}

These events are nearly hidden in diffuse analysis, but can stand out in point source analysis



Point Source Analysis



2008-2011 Data:
Livetime 1371 days

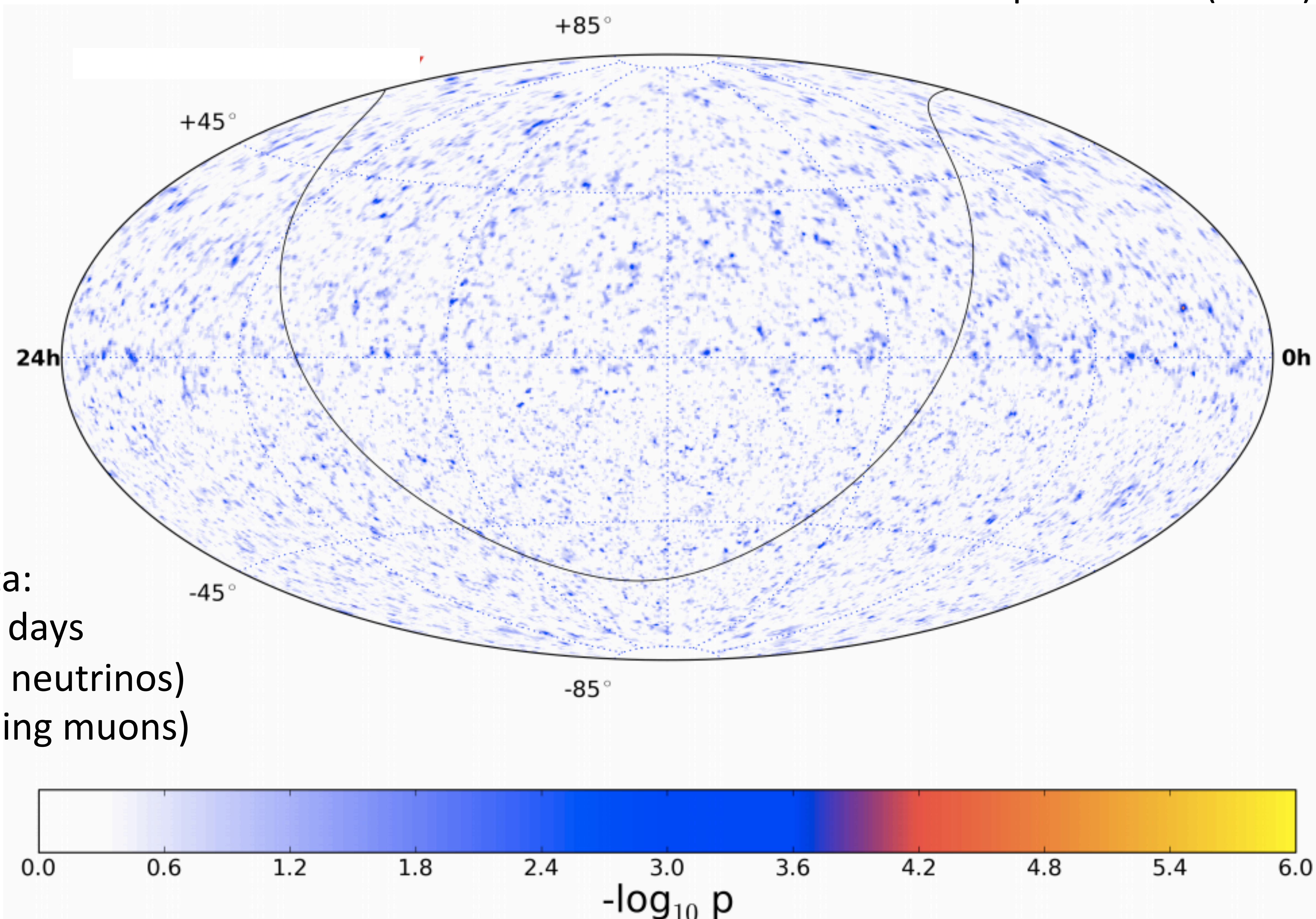
178 000 upgoing neutrinos

216 000 downgoing CR muons

Perform a search looking for significant clustering of events above random background expectation (unbinned maximum likelihood analysis)

Point Source Analysis

ApJ 796:109 (2014)

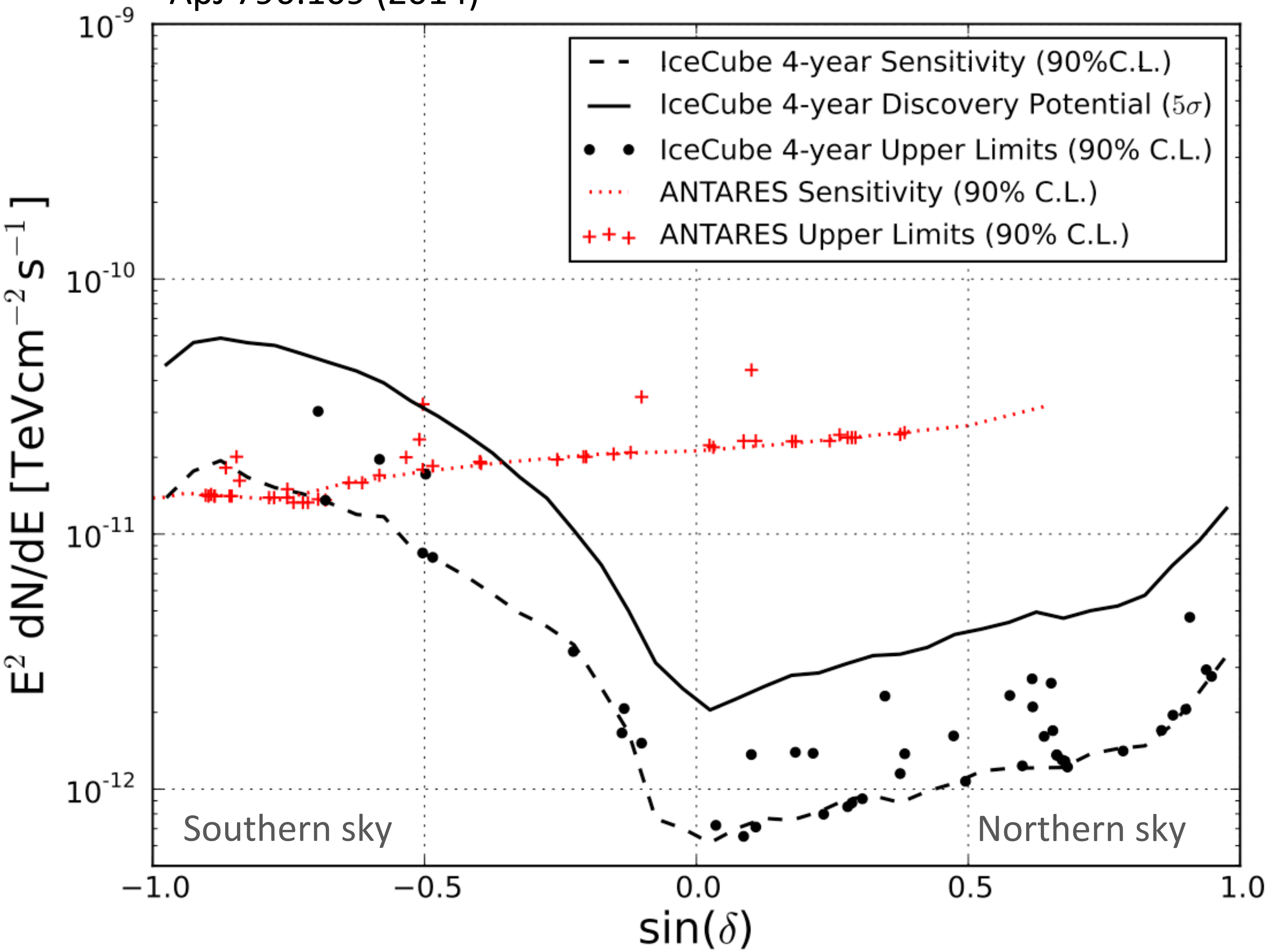


2008-2011 Data:
- Livetime 1371 days
- 178k (upgoing neutrinos)
- 216k (downgoing muons)

No significant excess seen

Point Source Analysis

ApJ 796:109 (2014)



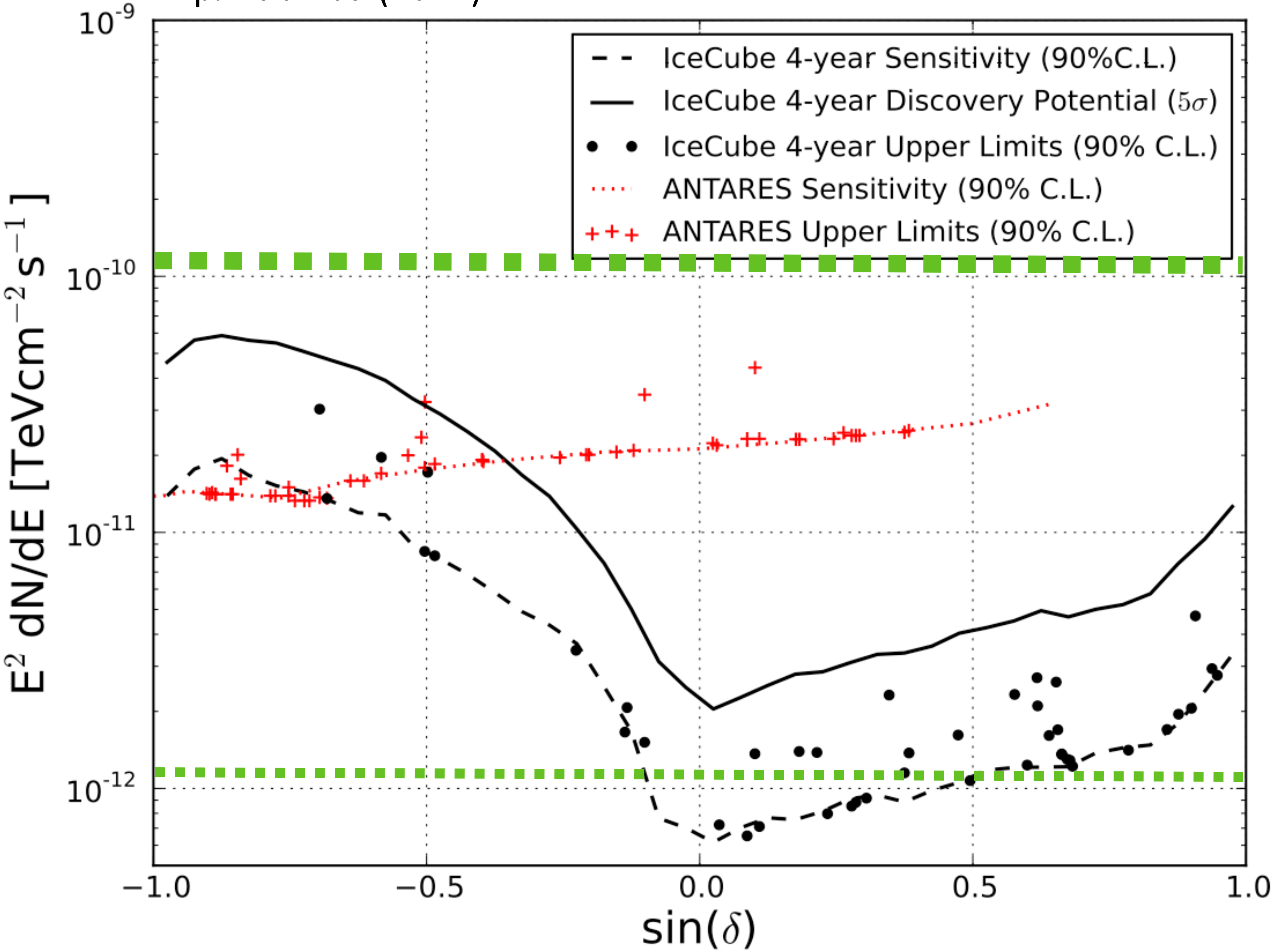
Northern Sky sensitive for TeV – PeV

Southern Sky sensitive mainly > PeV

ANTARES sensitive to TeV – PEV in both skies

Point Source Analysis

ApJ 796:109 (2014)



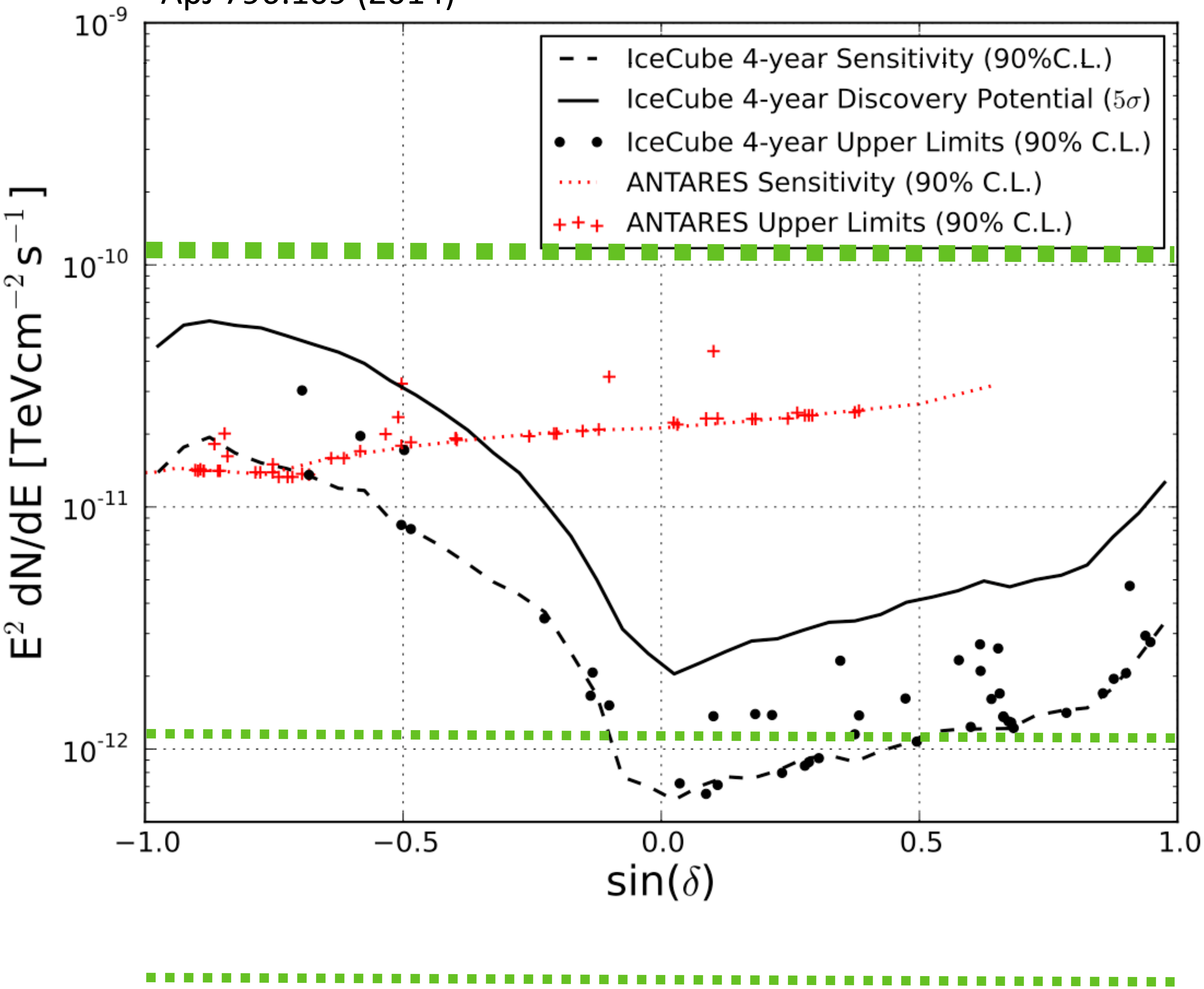
Point-source equivalent flux if the diffuse flux came from:

one point in the sky

100 points in the sky

Point Source Analysis

ApJ 796:109 (2014)



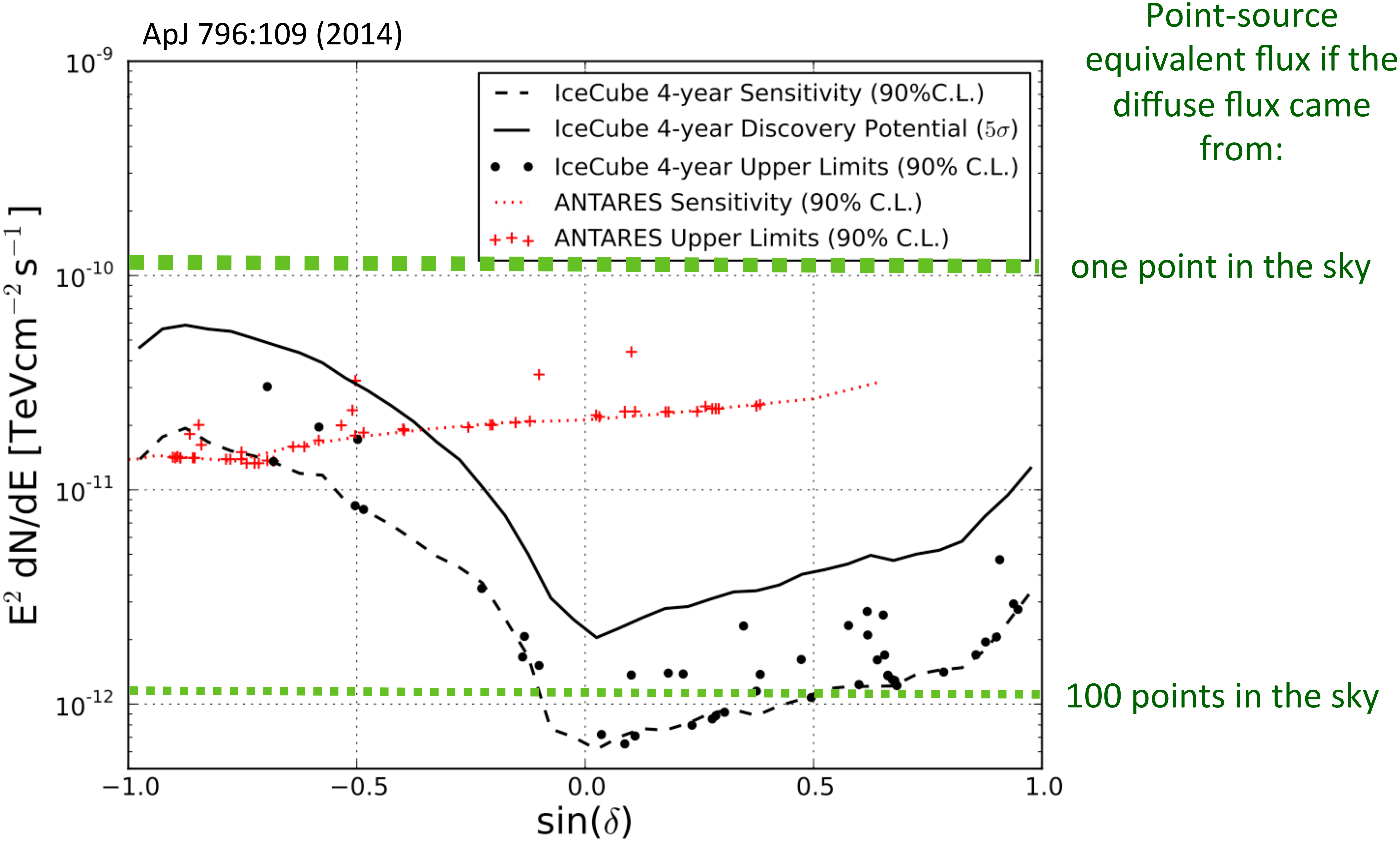
Point-source equivalent flux if the diffuse flux came from:

one point in the sky

100 points in the sky

1000 points in the sky

Point Source Analysis



Point-source equivalent flux if the diffuse flux came from:

Population studies with Stacking Searches:

1000 points in the sky

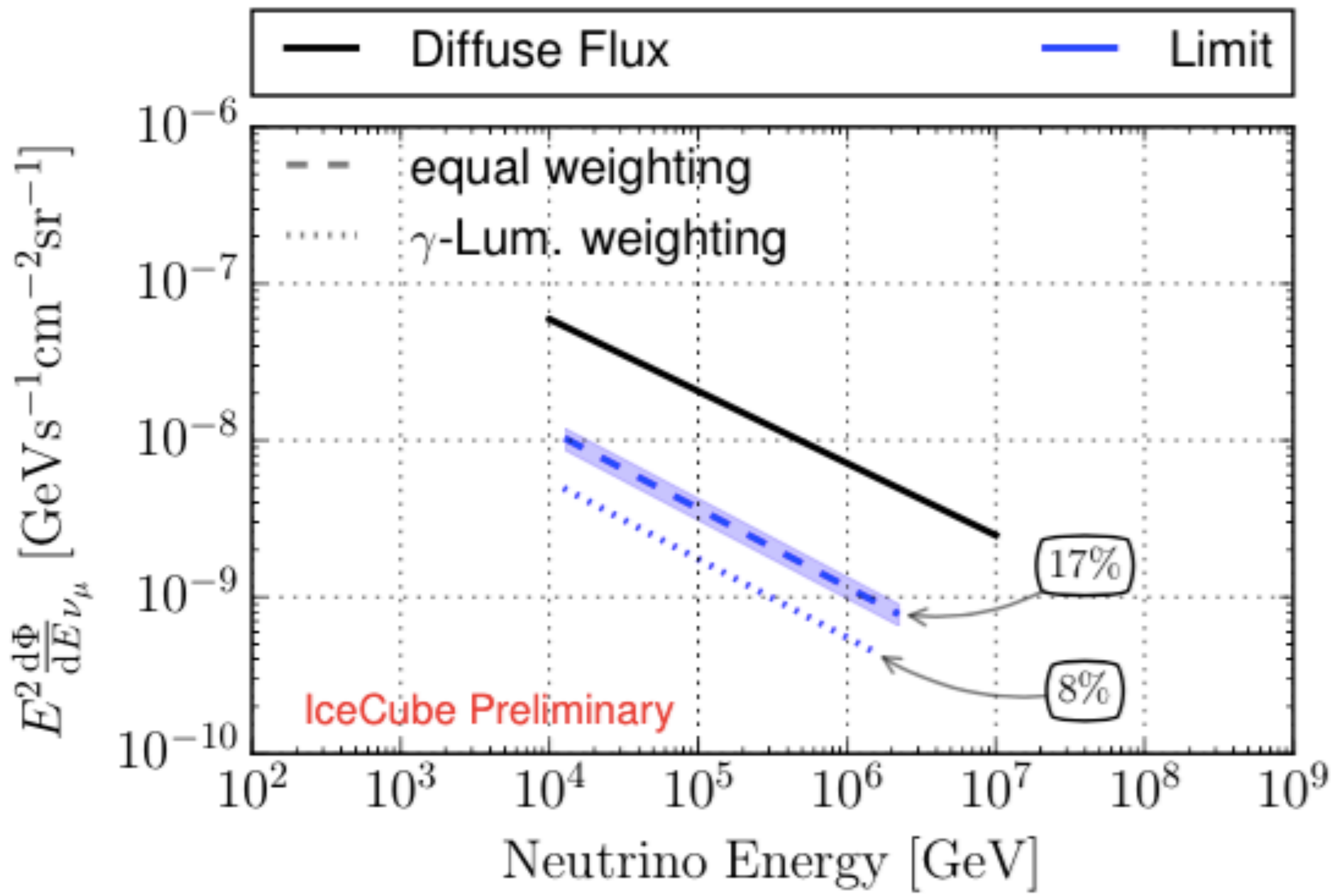
Stacked Neutrino Point Source Search

using Fermi LAT catalog of 862 Blazars

No significant excess seen

Total flux upper limit is well below measured diffuse neutrino flux

Glüsenkamp, RICAP 2014 Proceedings



Summary

Detection of astrophysical neutrino flux in TeV - PeV range

- Complementary analyses: all-flavor cascades and tracks (mainly southern sky) and muon-neutrino tracks (northern sky) agree on flux measurement.
- Consistent so far with simplest assumptions of:
  - diffuse, all-sky flux
  - 1:1:1 flavor ratio
- Spectrum can be reasonably fit with power law between $E^{-2.2}$ and $E^{-2.6}$

Summary

Immediate Challenges

Diffuse:

Better measurement of spectrum: unbroken power-law, or features?

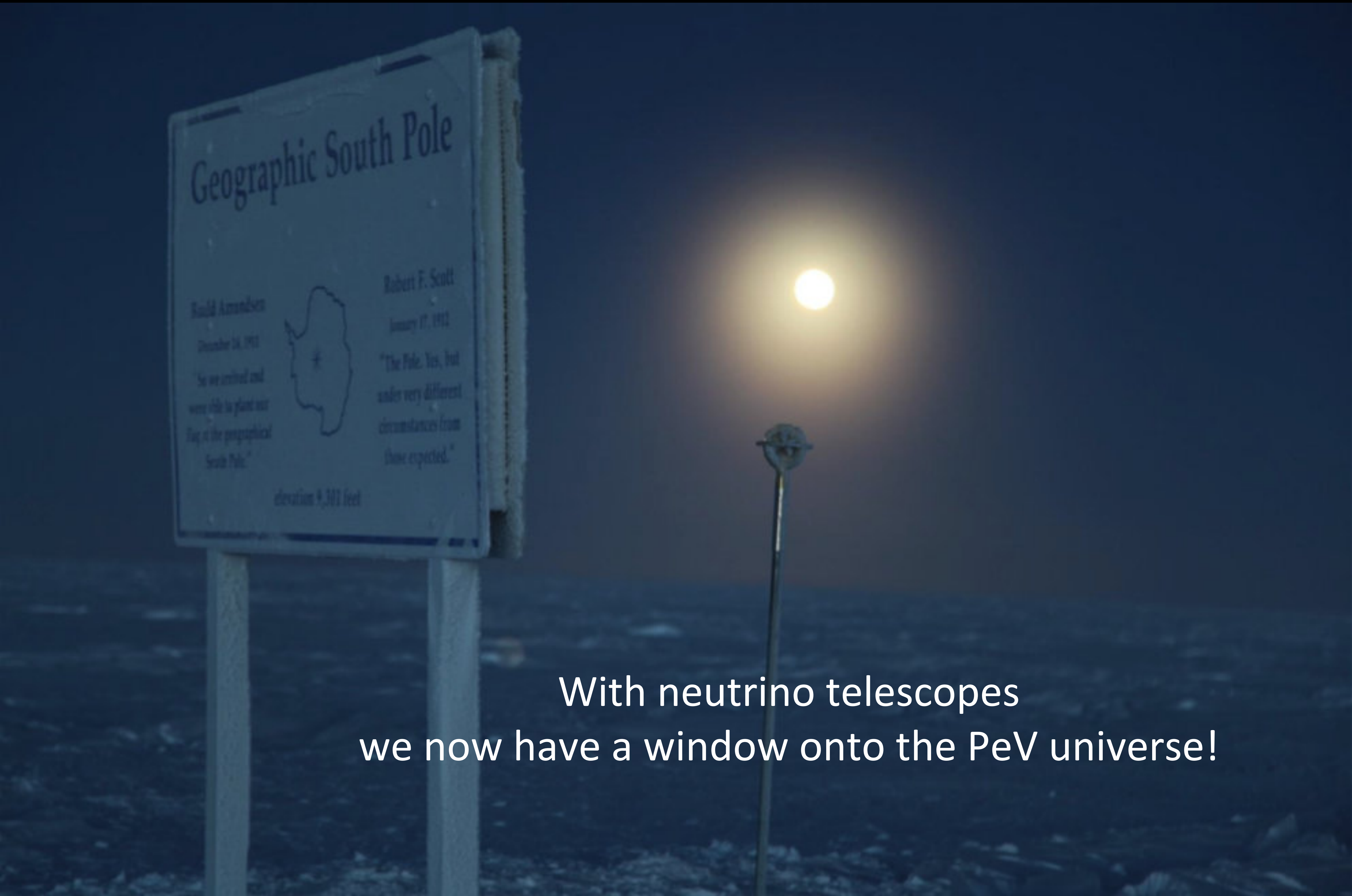
Single all-sky component?   Or mixture of extra-galactic and galactic component?

Equal Flavor ratio?

Point source:

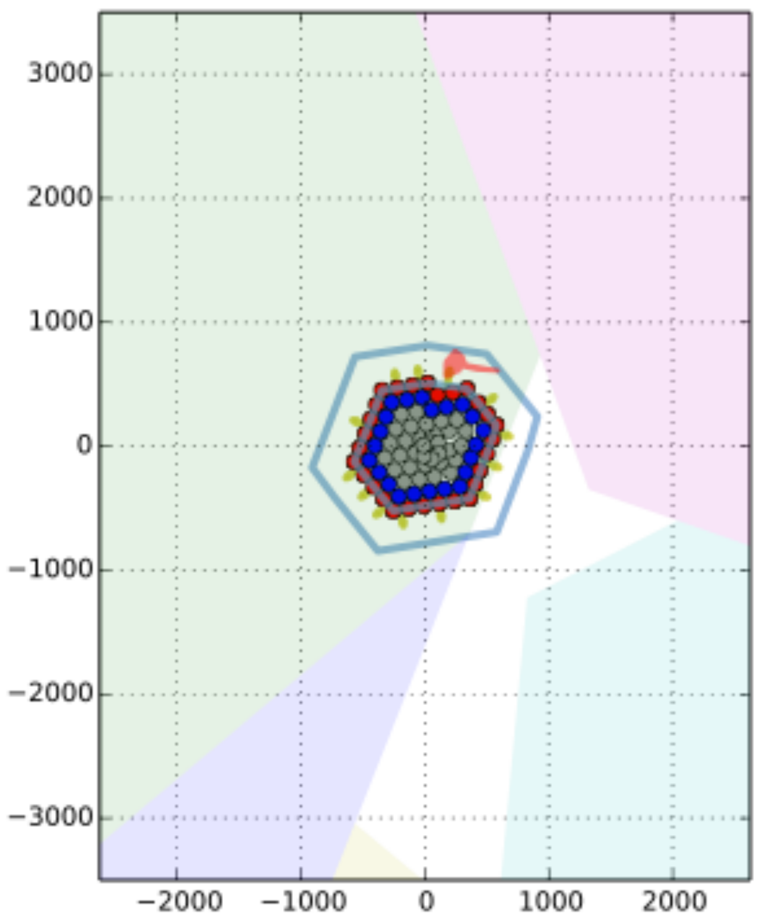
Galactic sources should be coming within reach (maybe unrelated to diffuse flux)

Extragalactic sources individually fainter, but may be detected or constrained by stacking searches, or timing searches (e.g. GRBs)

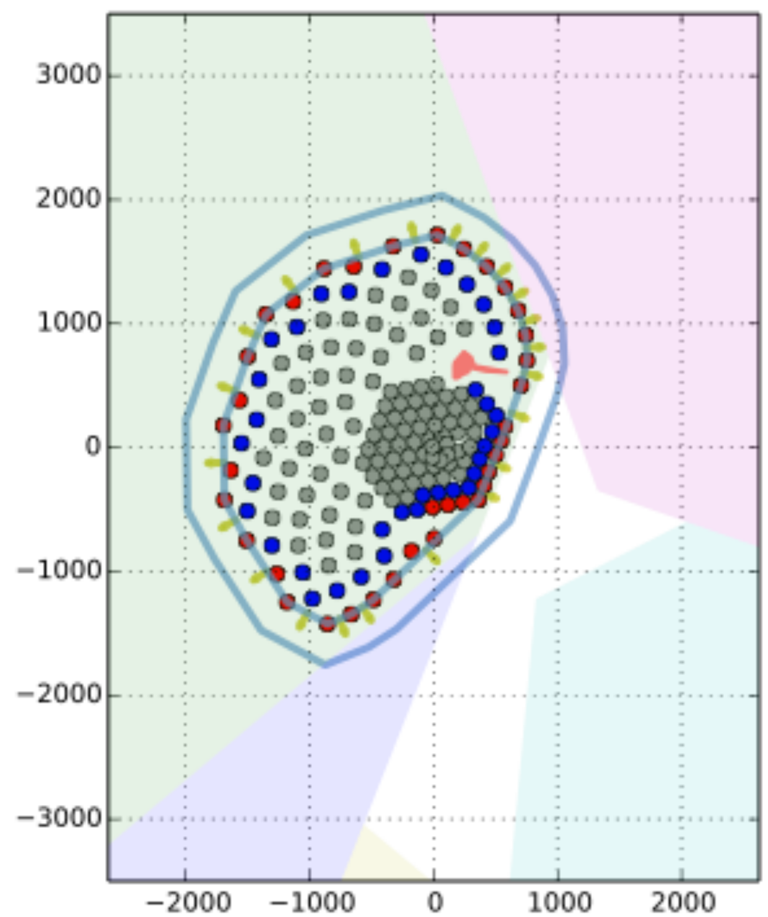


With neutrino telescopes
we now have a window onto the PeV universe!

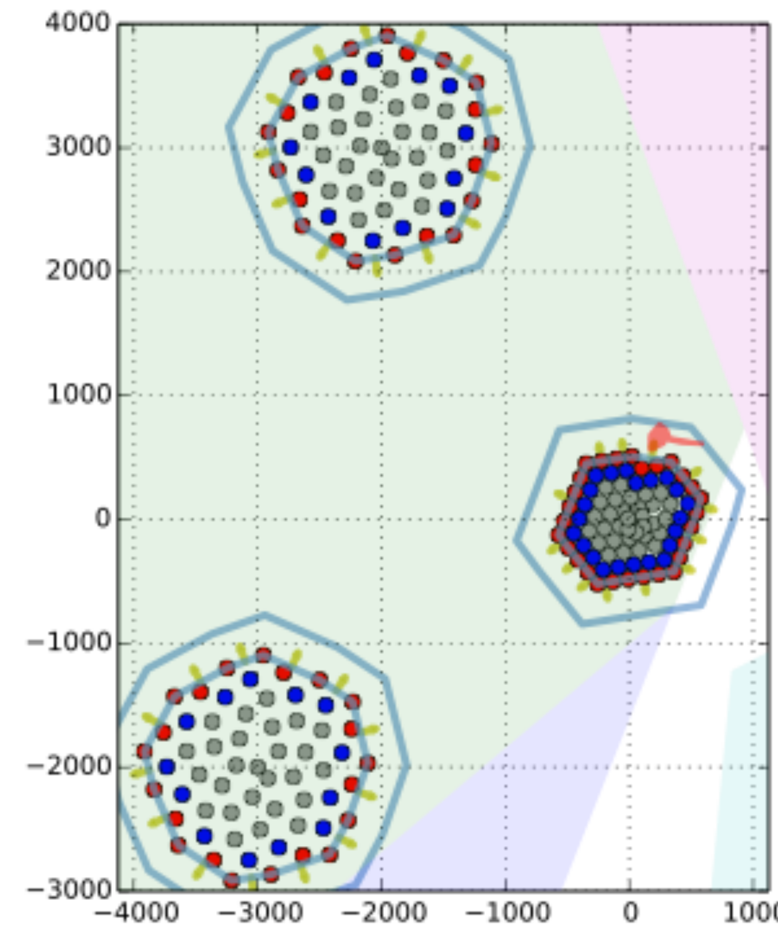
strings: IC86 spacing: ~125m

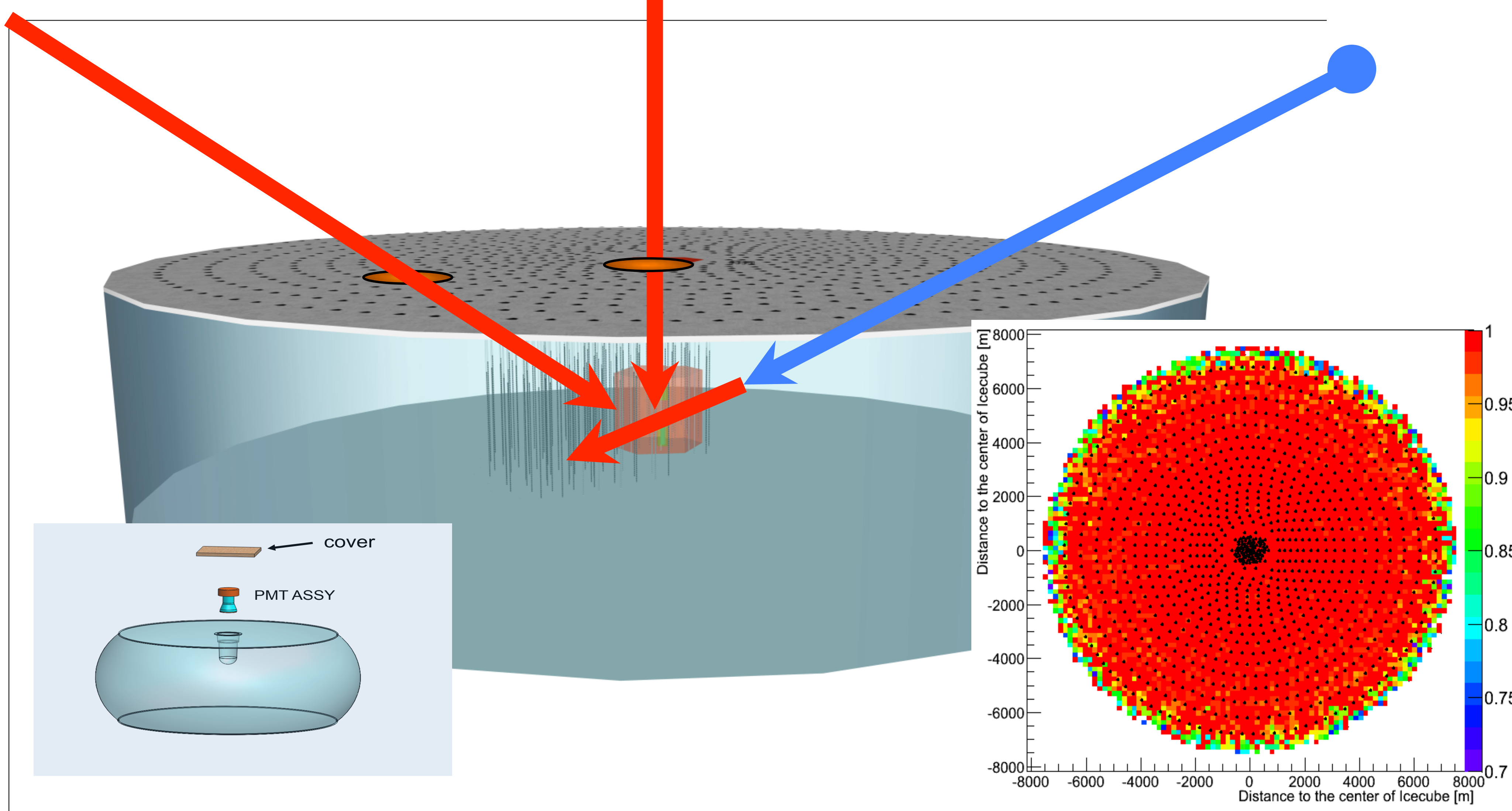


strings: IC86+96 spacing: ~240m



strings: IC86+2x60 spacing: ~240m





High Energy Extension

InIce Strings
+
Surface Veto