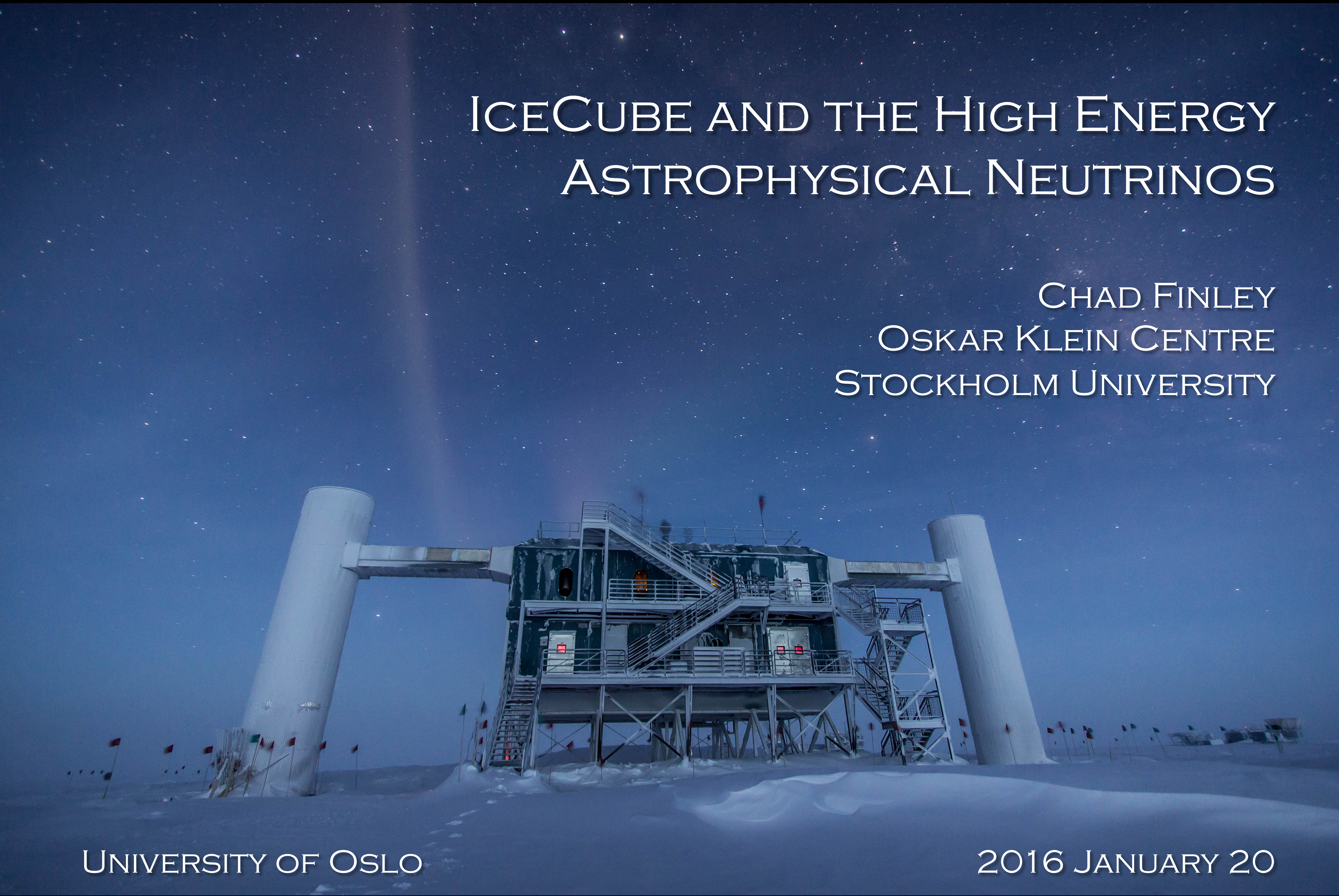
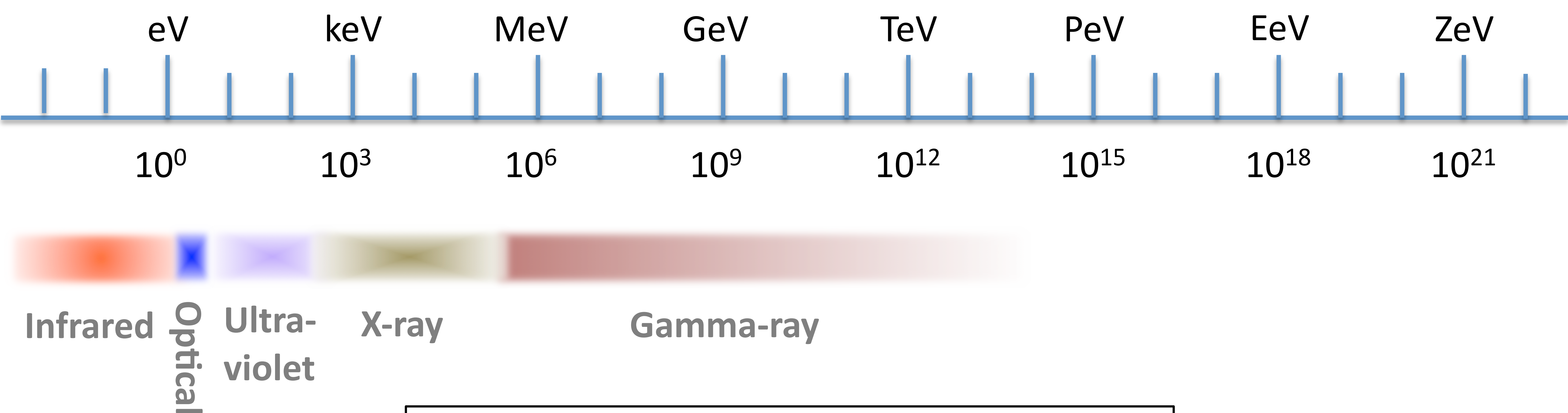


IceCube and the High Energy Astrophysical Neutrinos

Chad Finley
Oskar Klein Centre
Stockholm University

University of Oslo

2016 January 20



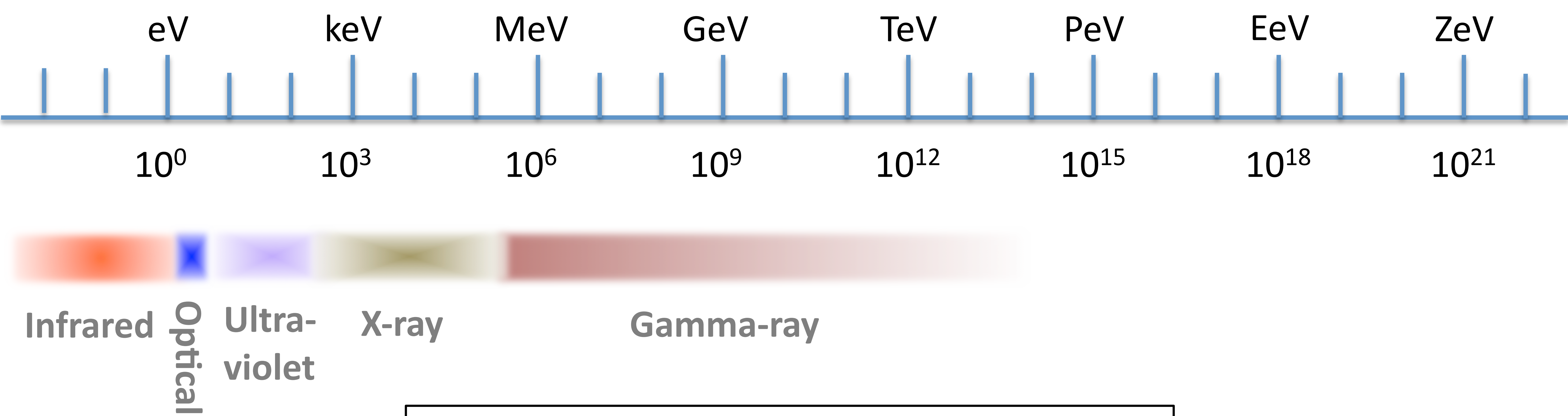
Photons From Space

Neutrinos From Space

Supernova neutrinos — observed in 1987, exploding star in nearby galaxy, expect 1-3 per century

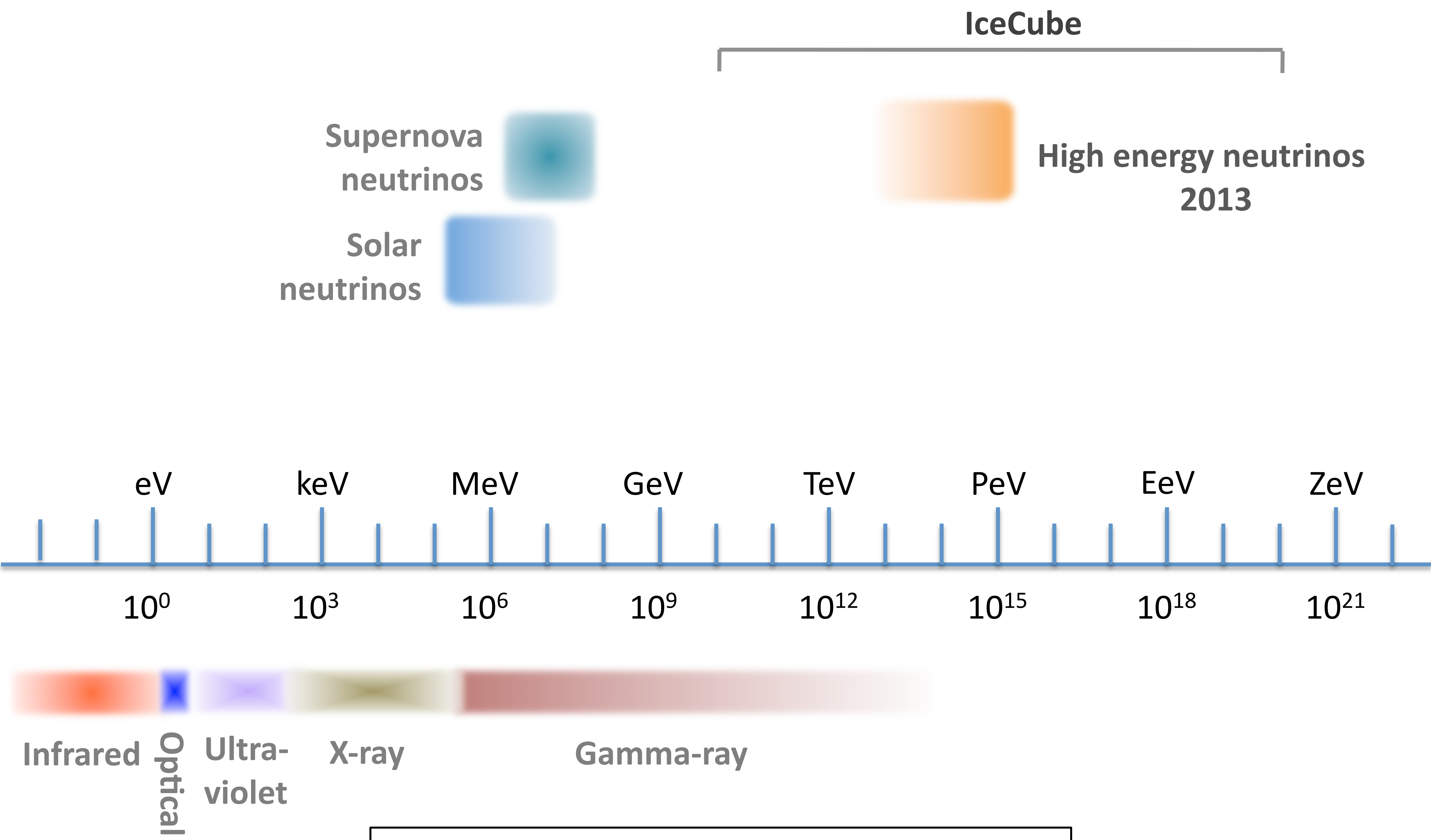
Solar neutrinos — theory ≠ experiment …

oscillations: neutrinos have mass



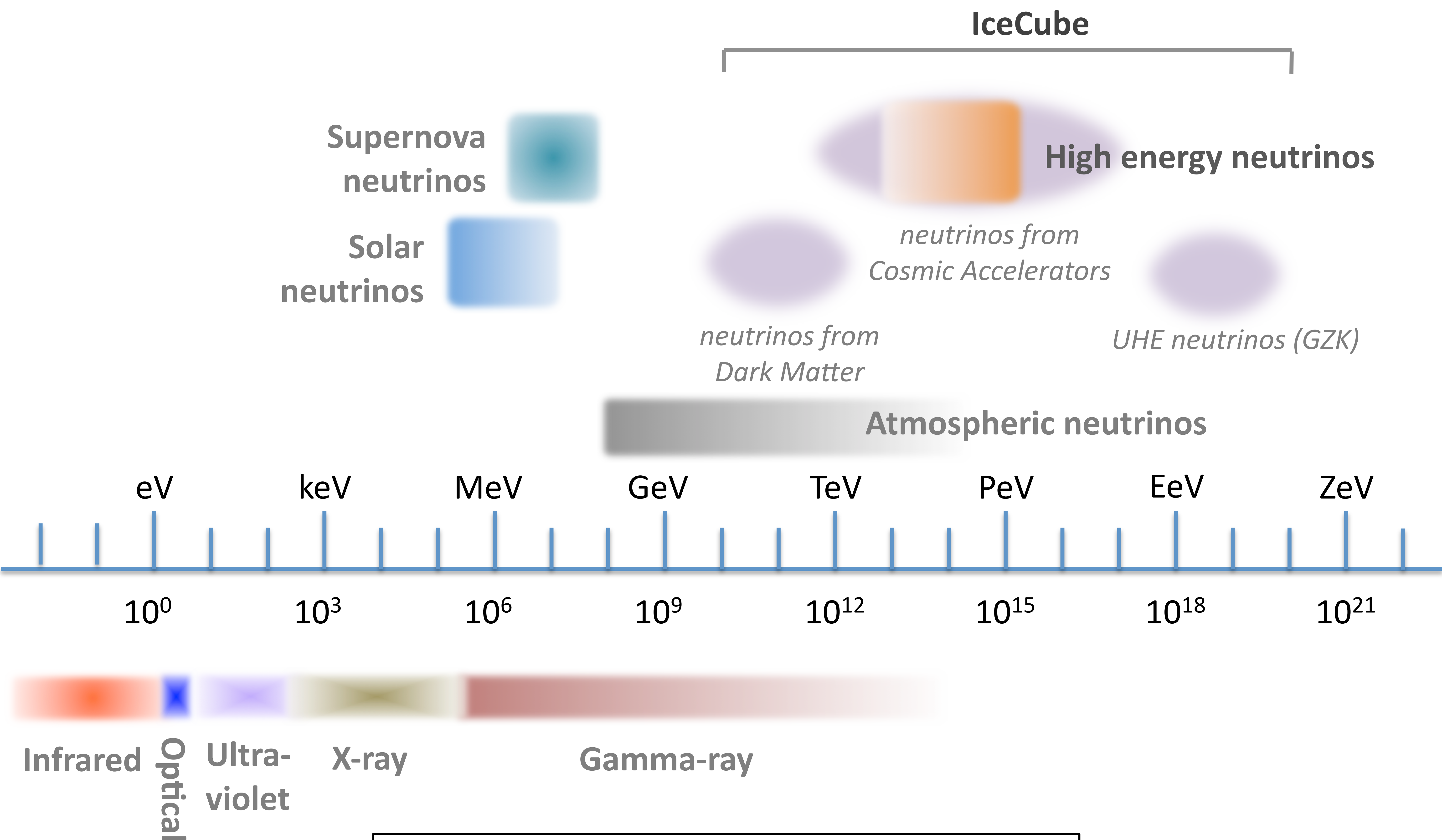
Photons From Space

Neutrinos From Space

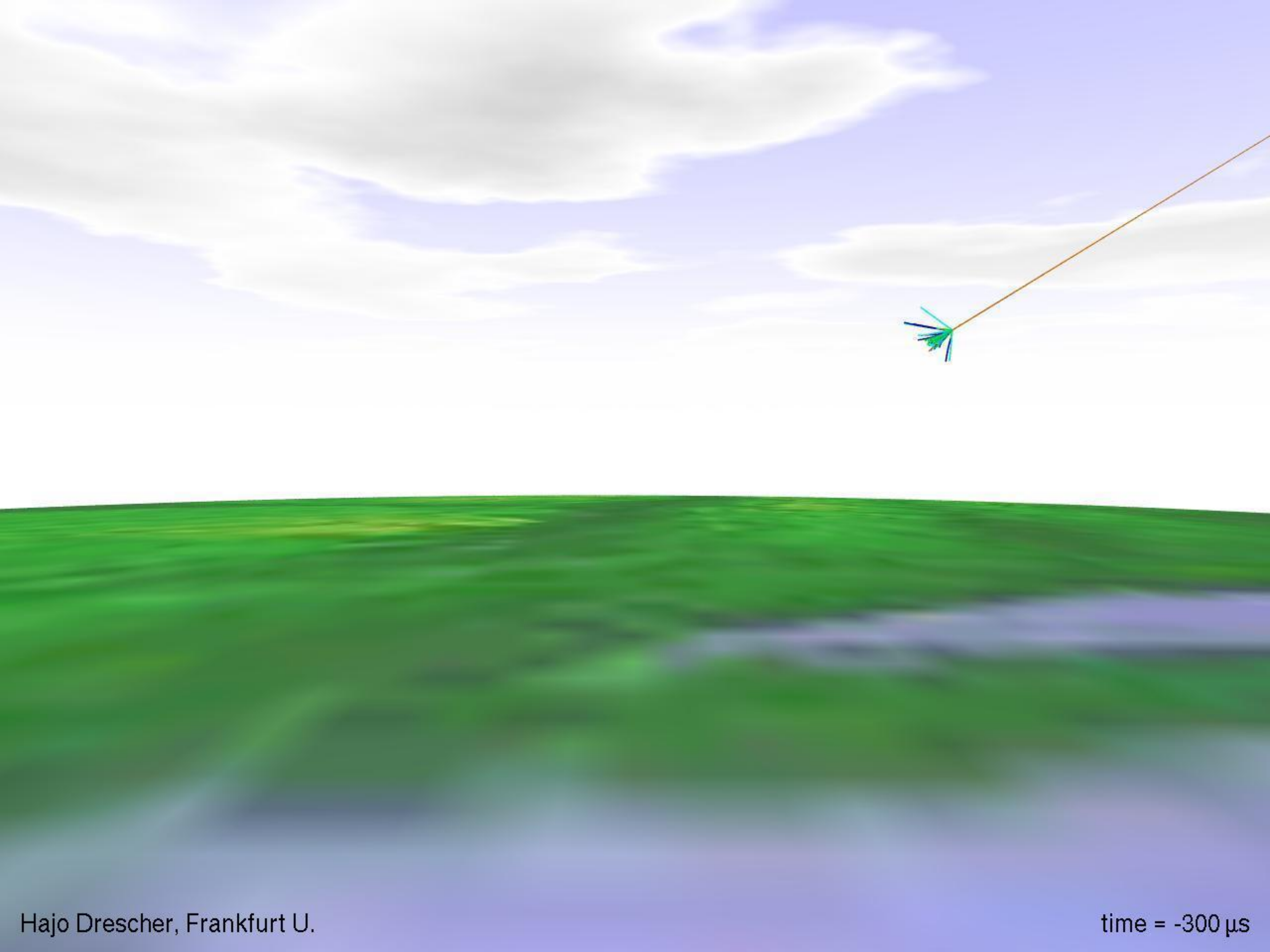


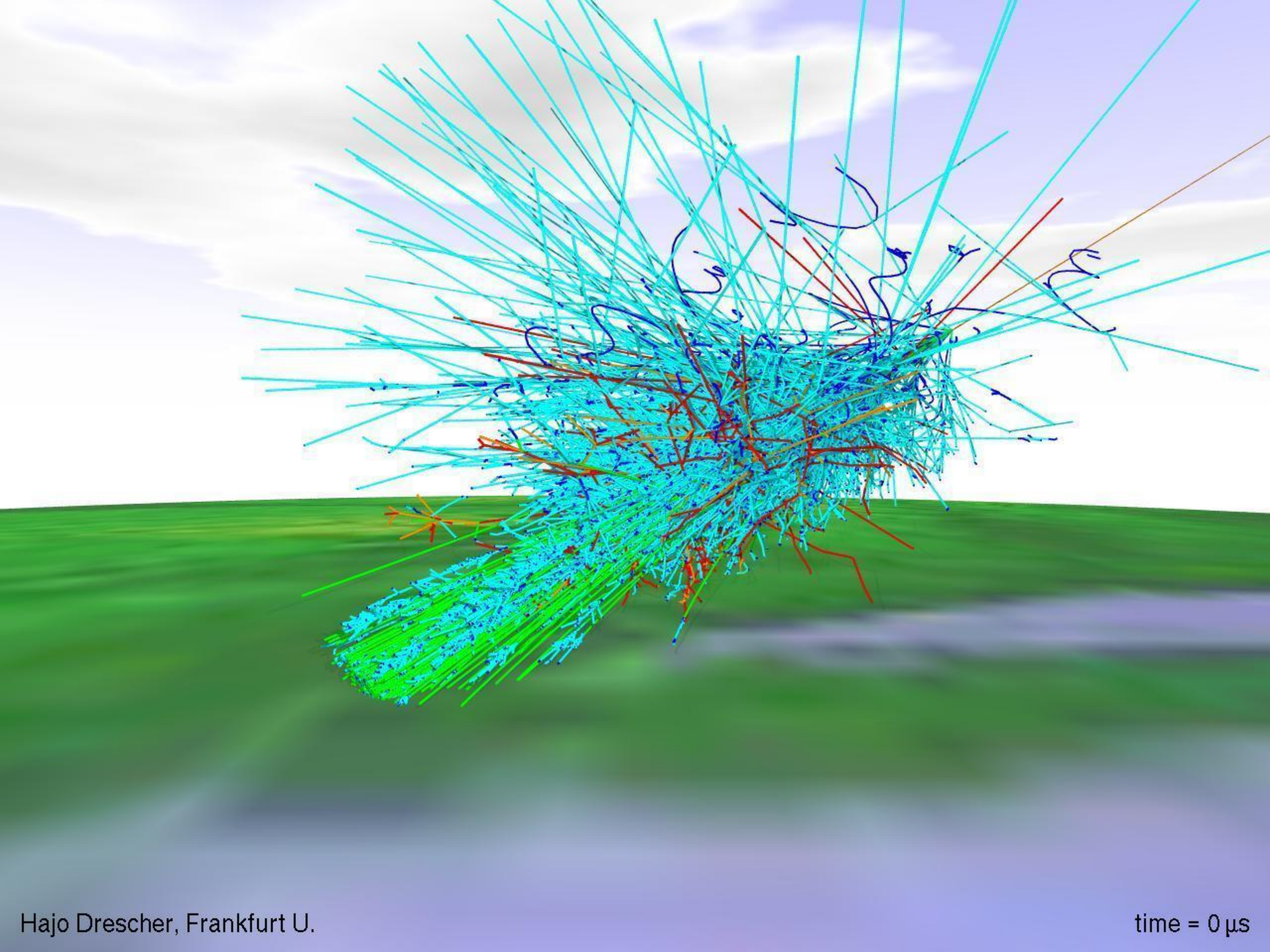
Photons From Space

Neutrinos From Space



Photons From Space


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:

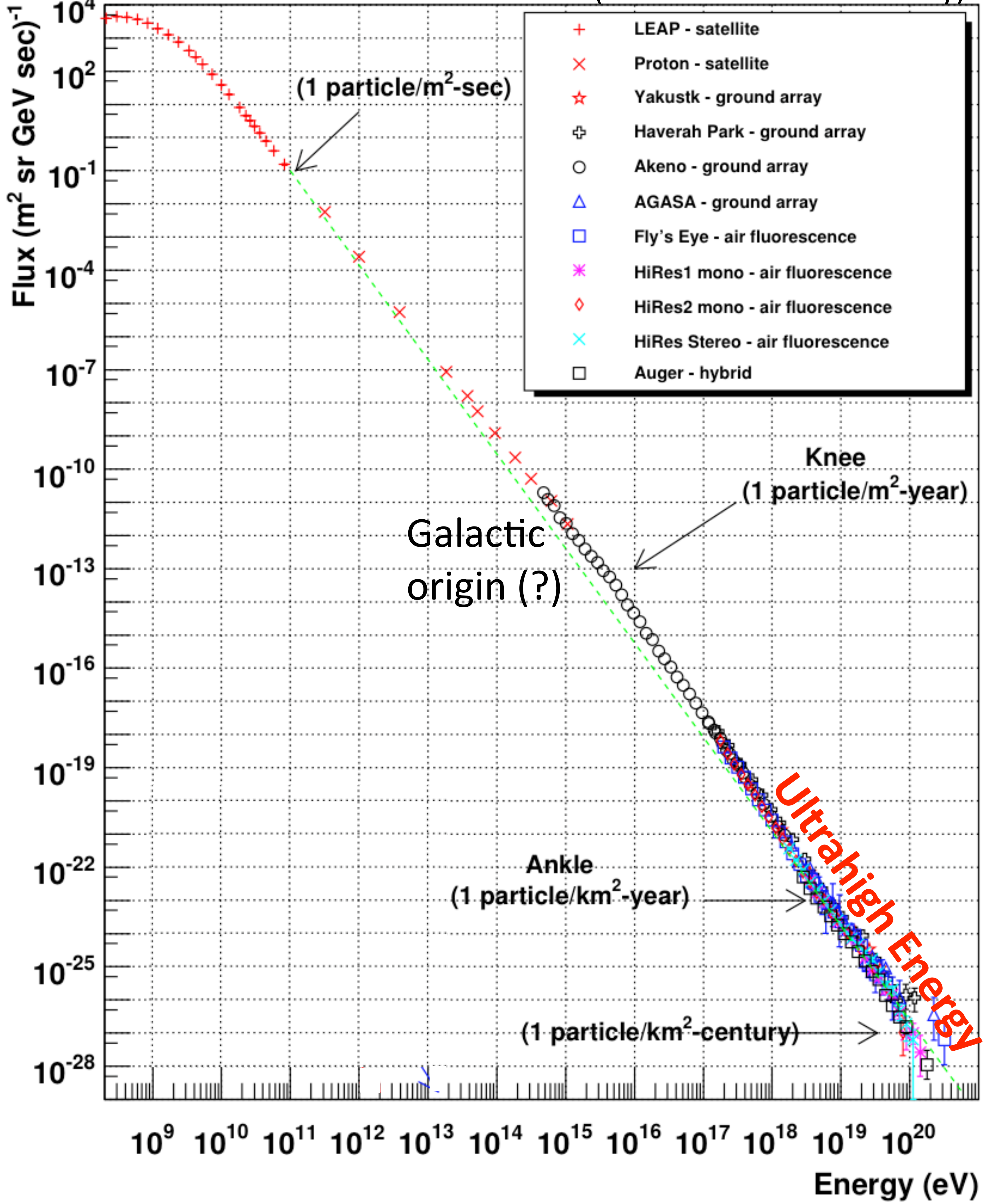
$$p + N \rightarrow X + \{\pi^+, \pi^-, \pi^0\}$$

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

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

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

(W. Hanlon after S. Swordy)



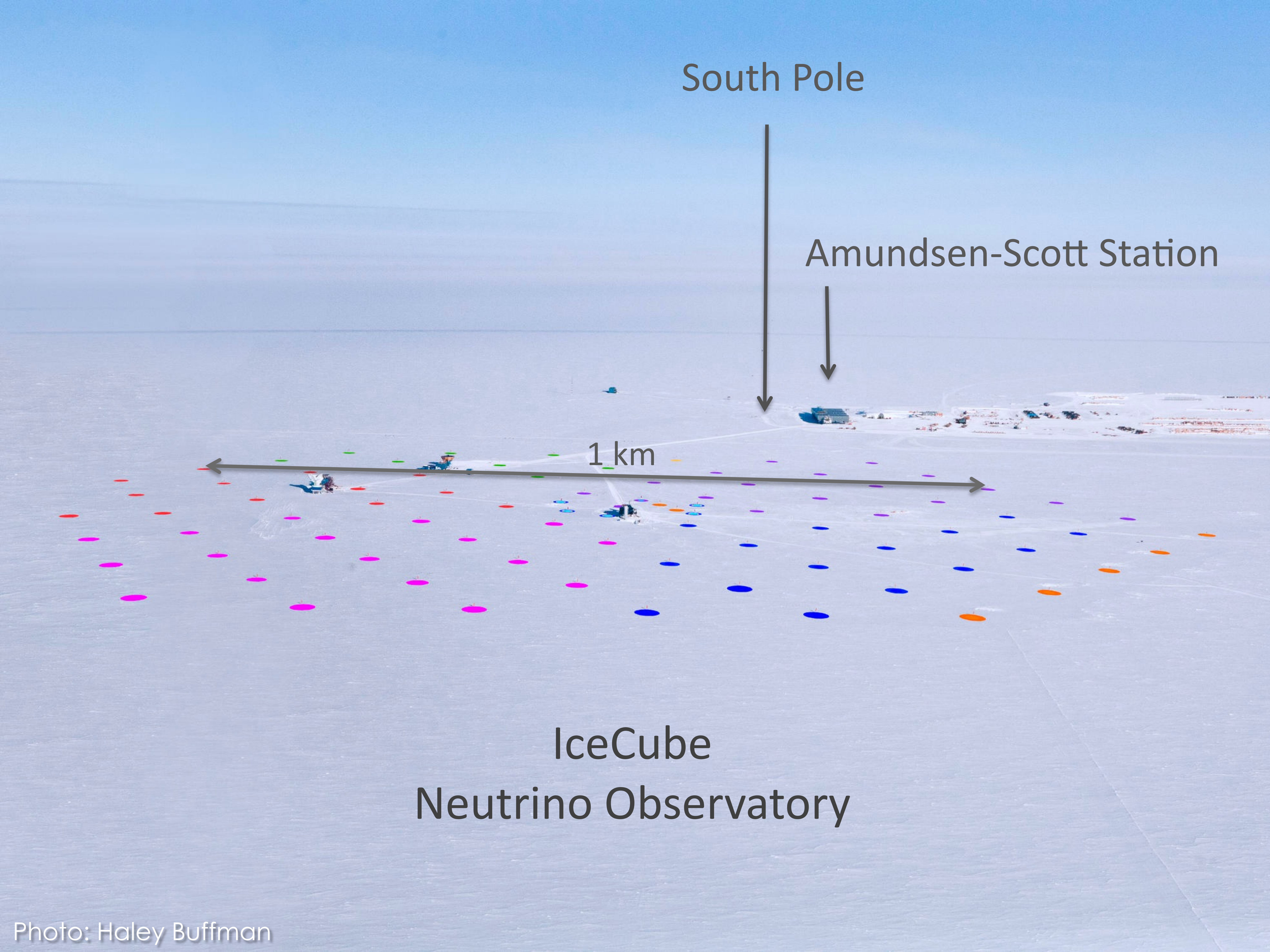
IceCube Collaboration

The Collaboration: 12 countries — 44 institutes — 300 scientists
(Main financial support from: USA, Germany, Sweden, Belgium)

Current Spokesperson (2013-2017): Olga Botner (Uppsala)

Largest neutrino telescope in the world
15x more sensitive than next largest (ANTARES in Mediterranean)


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

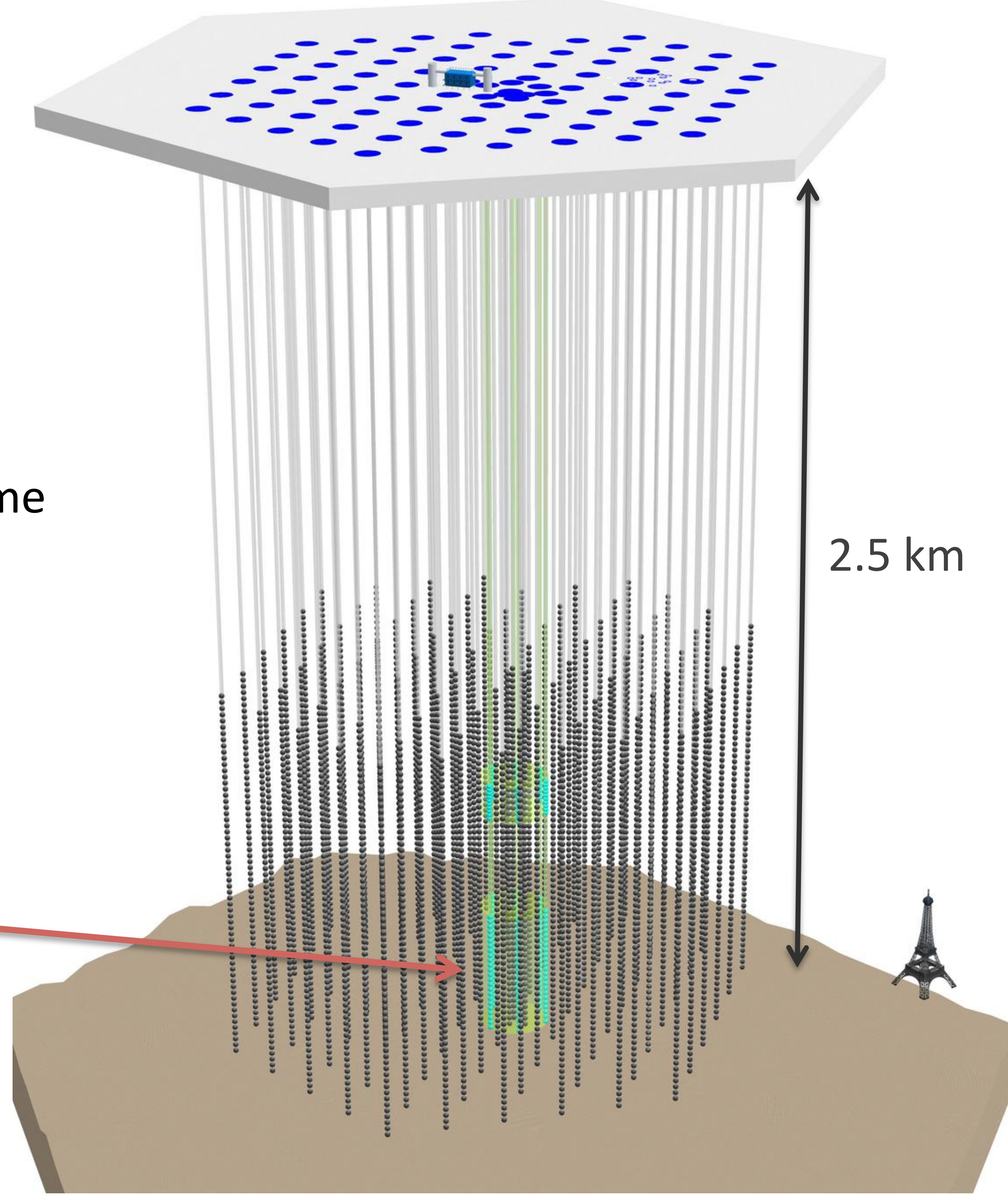
1 km^3 = Gigaton instrumented volume

Began full operations May 2011

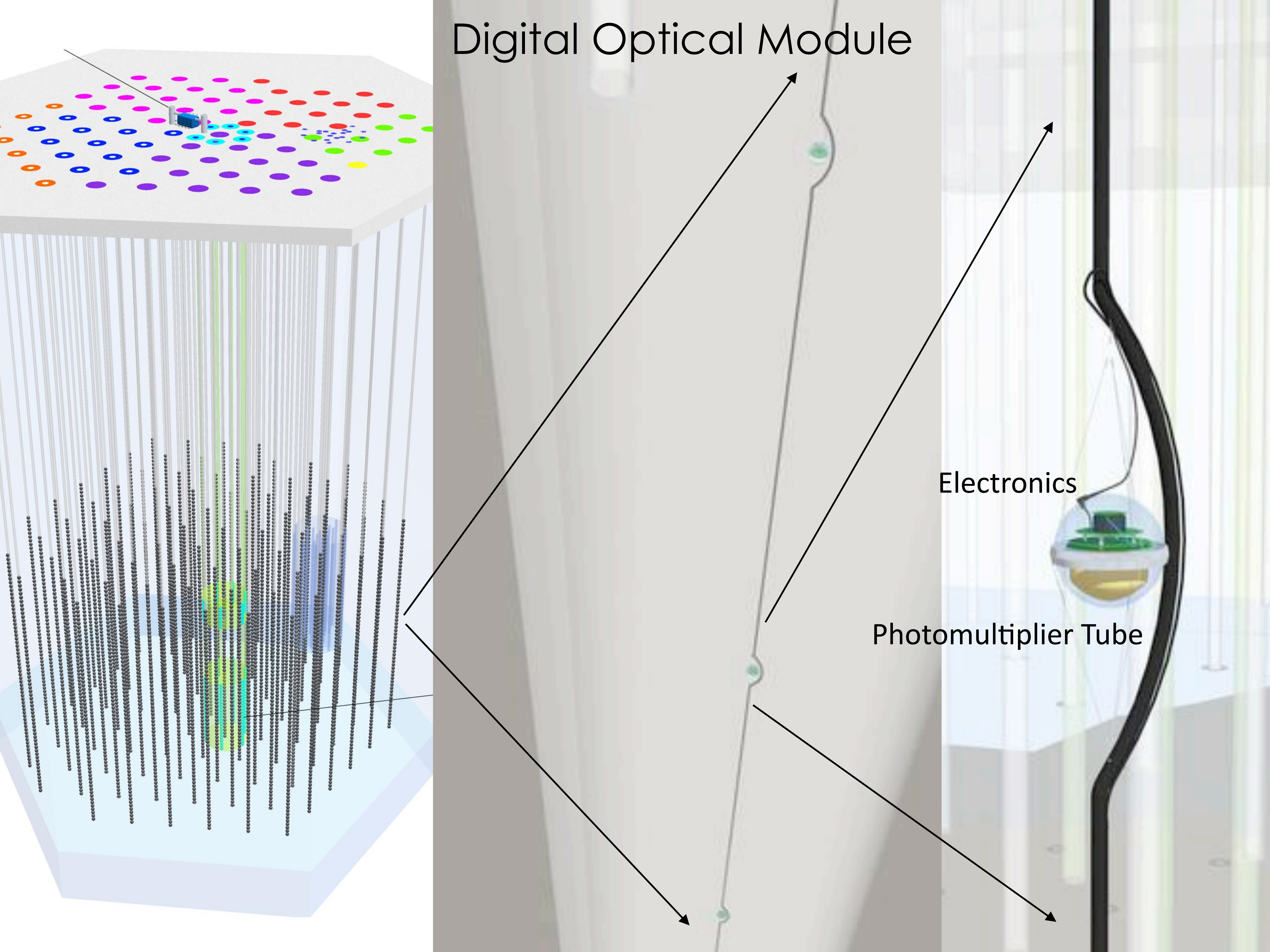
DeepCore
Low-energy Extension

Dark Matter,
Neutrino Oscillations

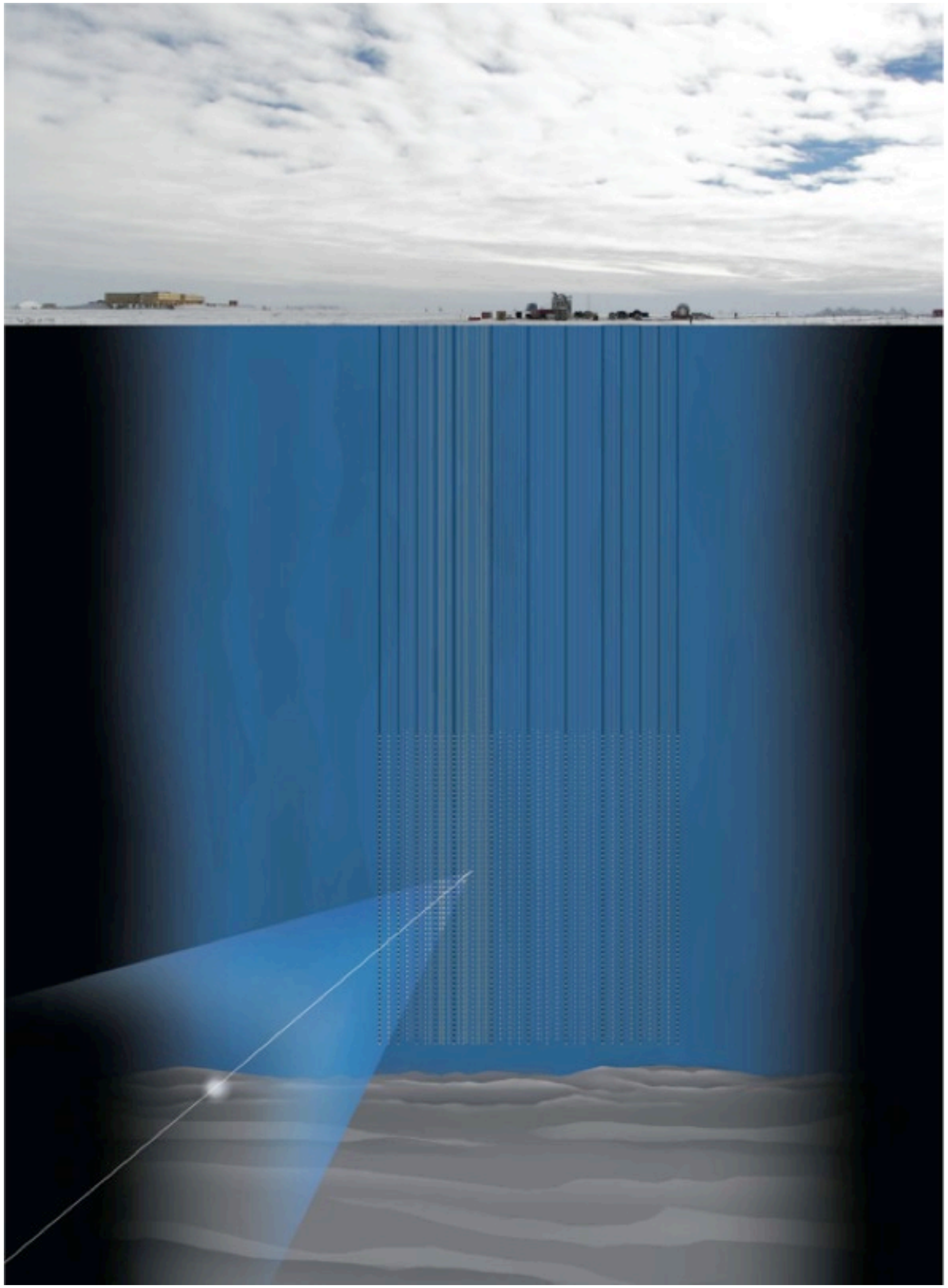
IceTop: 1 km^2 surface array

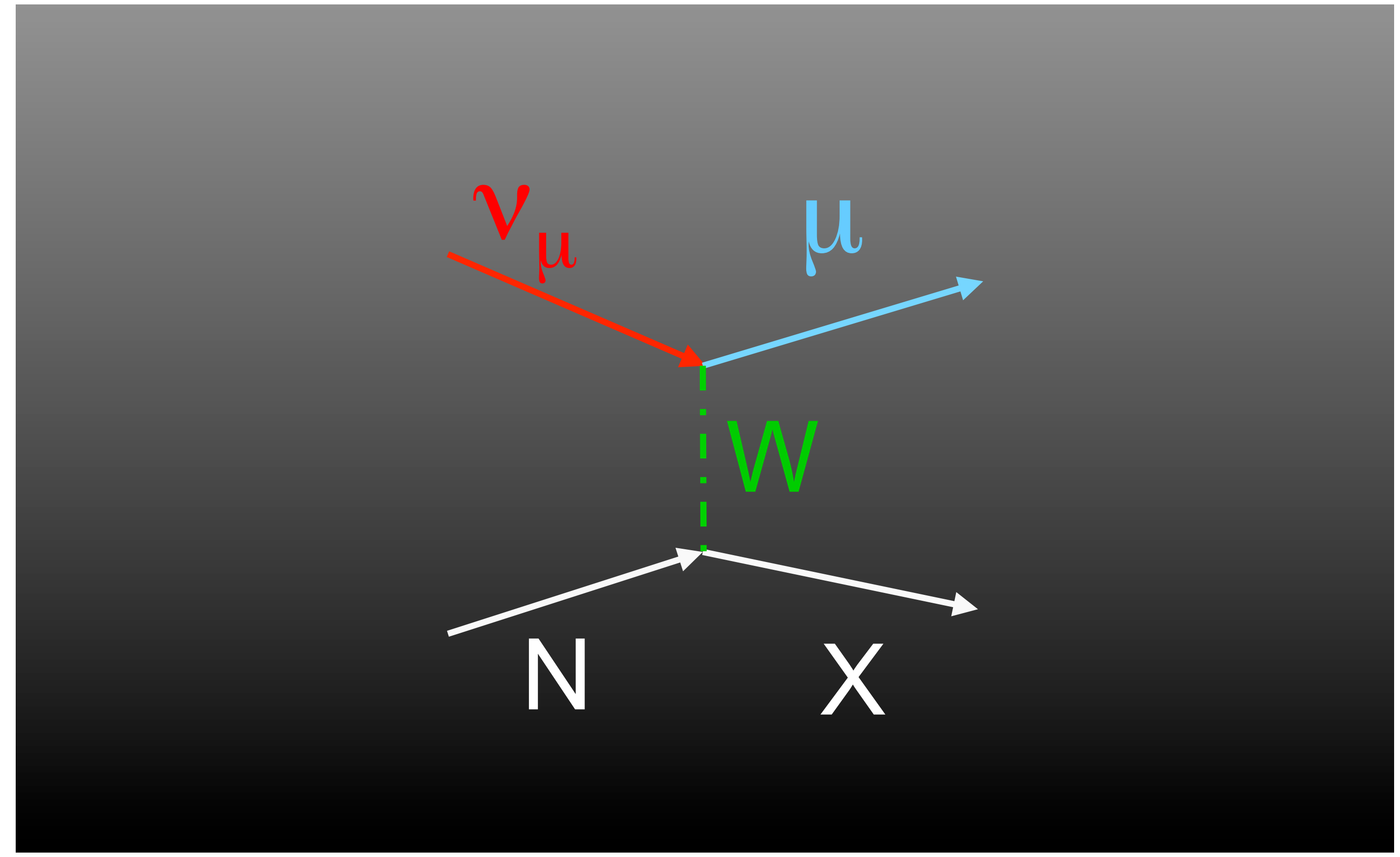


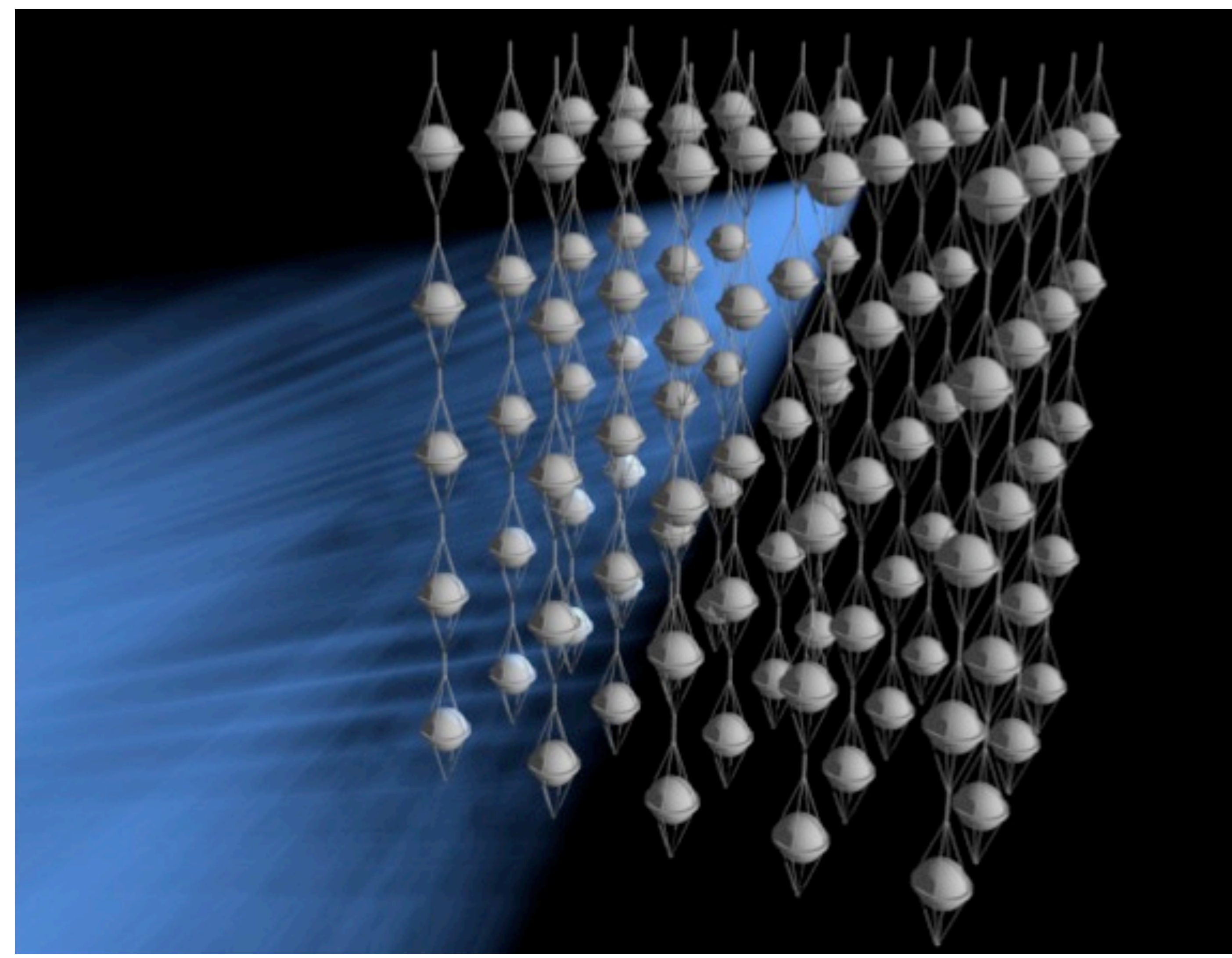
Digital Optical Module

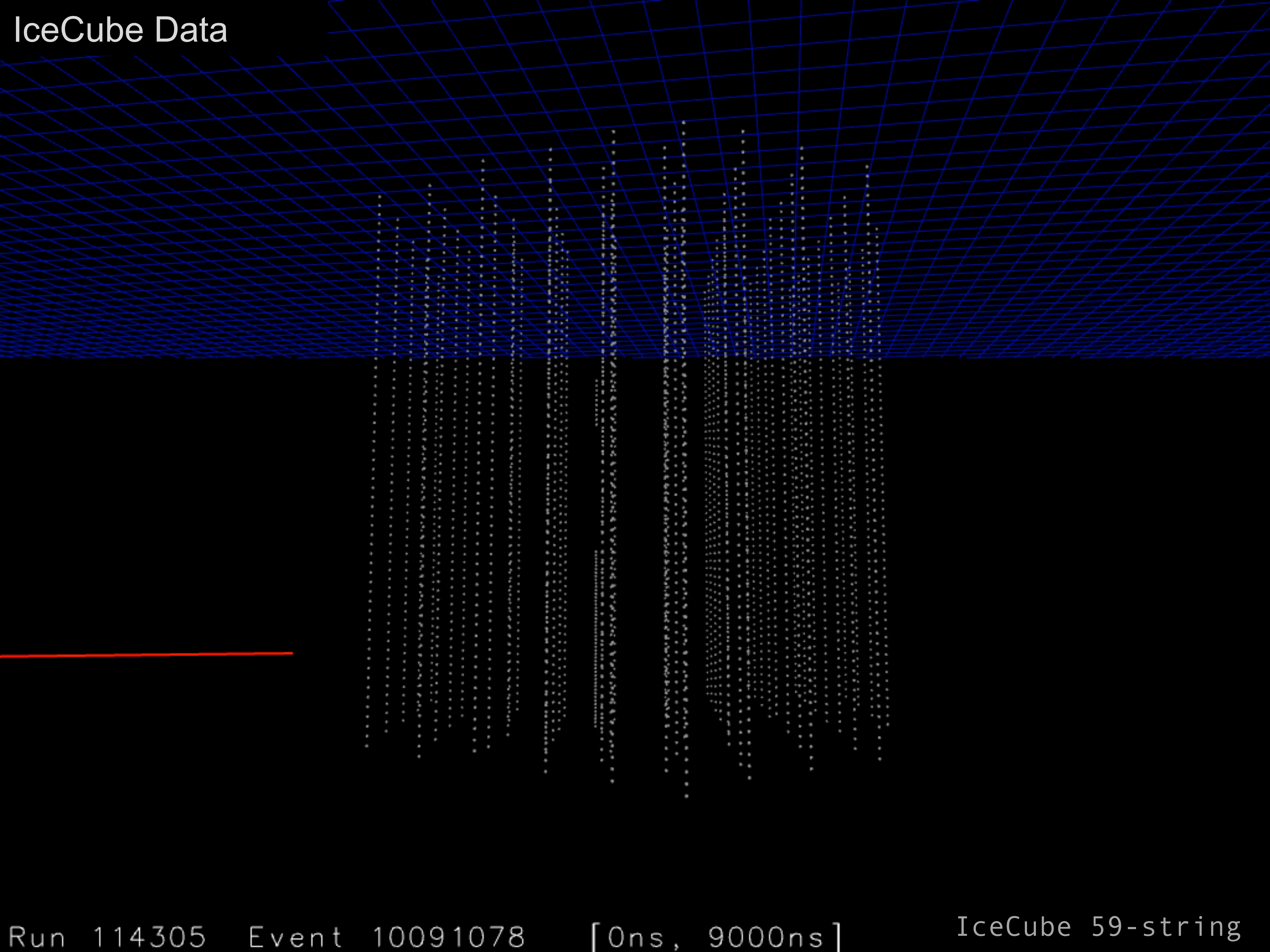


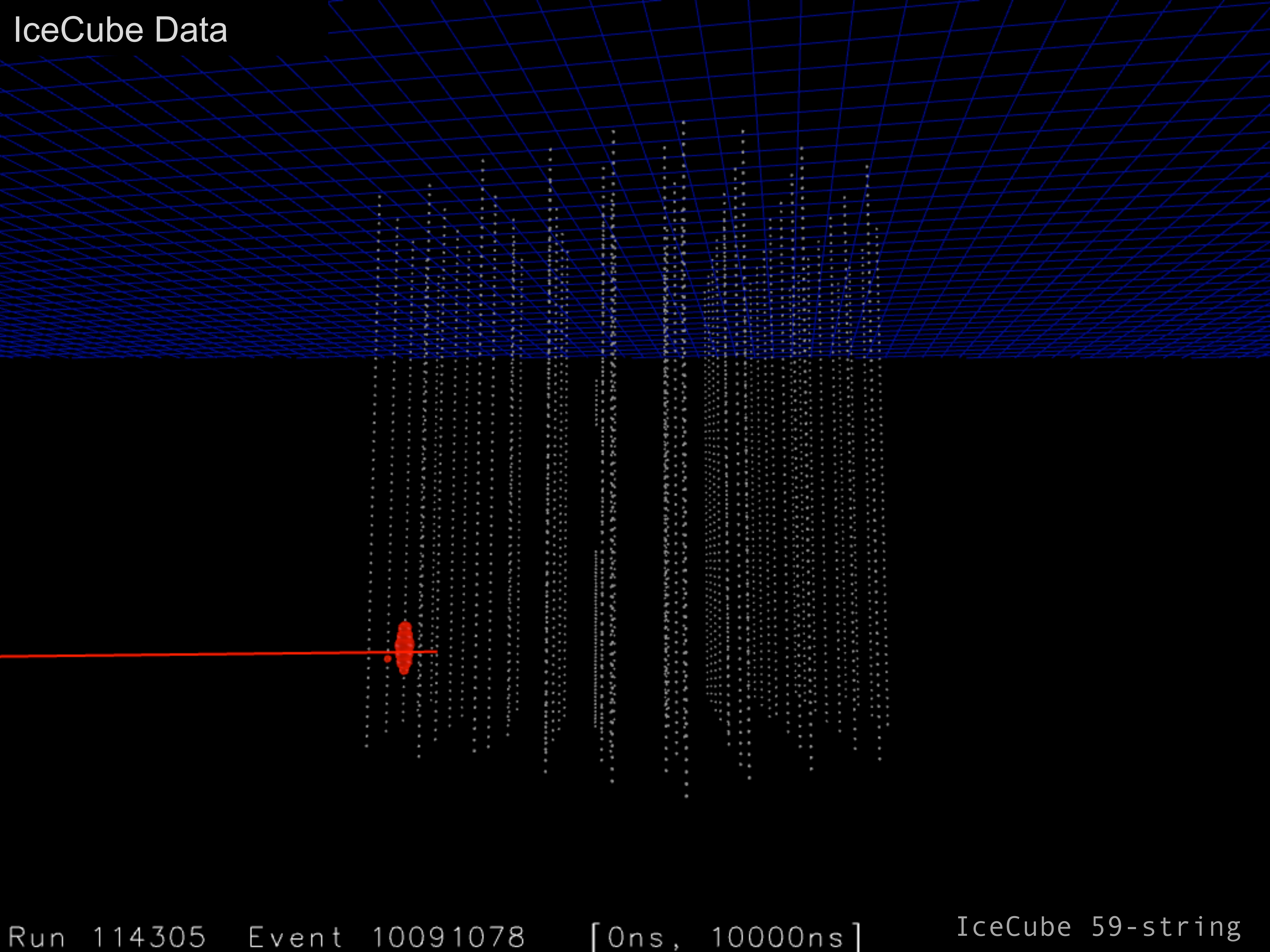
High Energy Neutrino Detection Principles

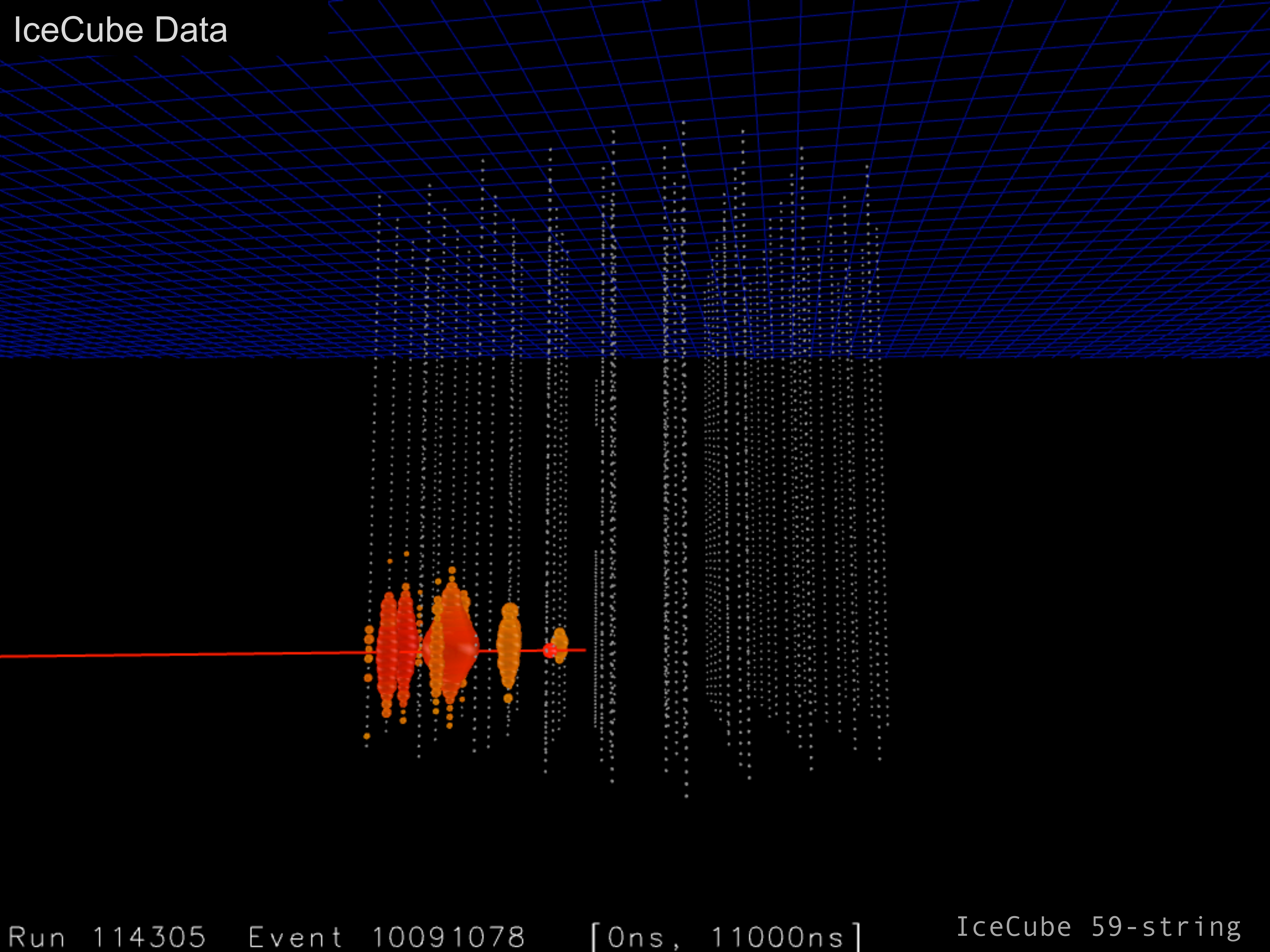


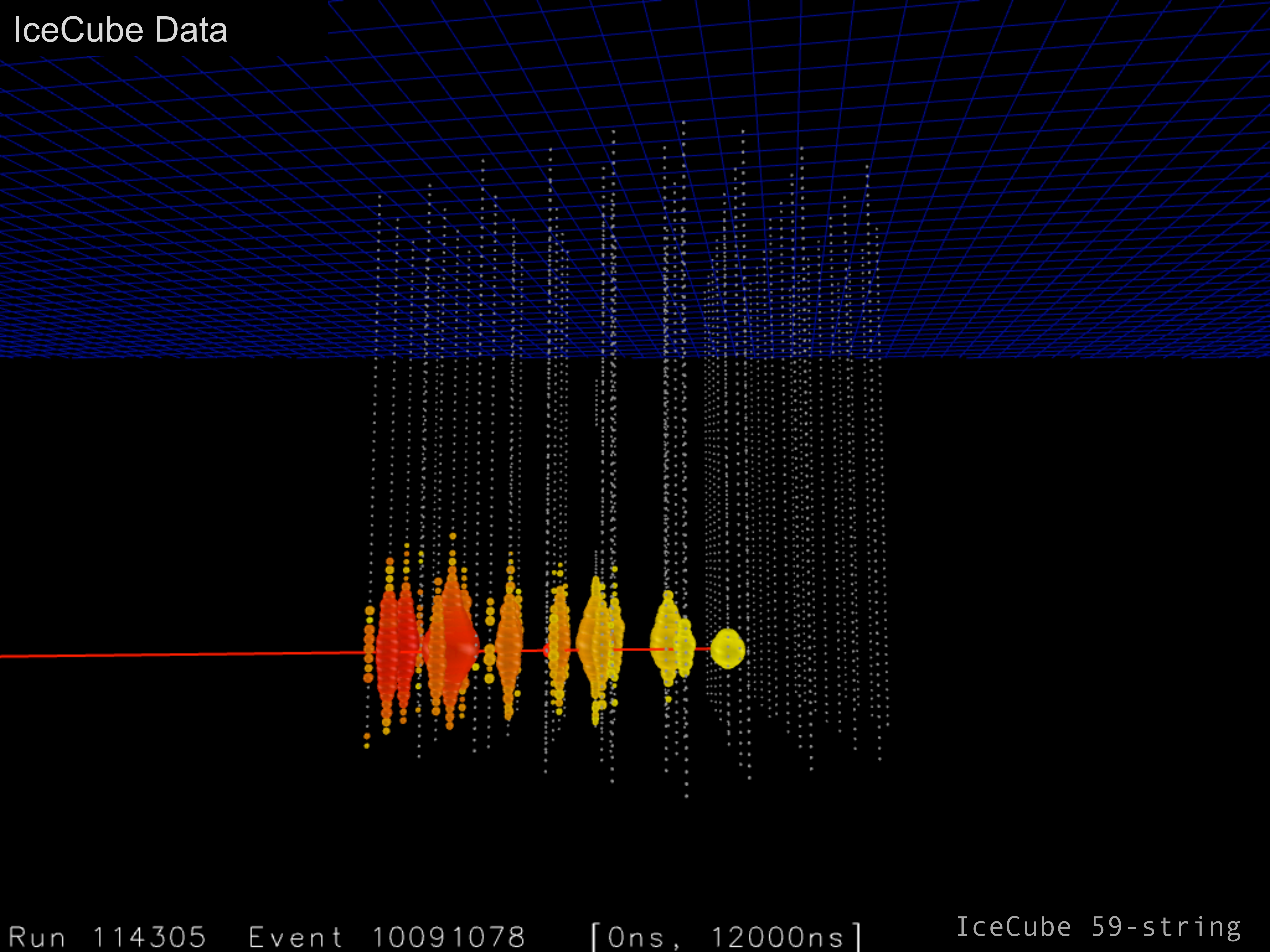


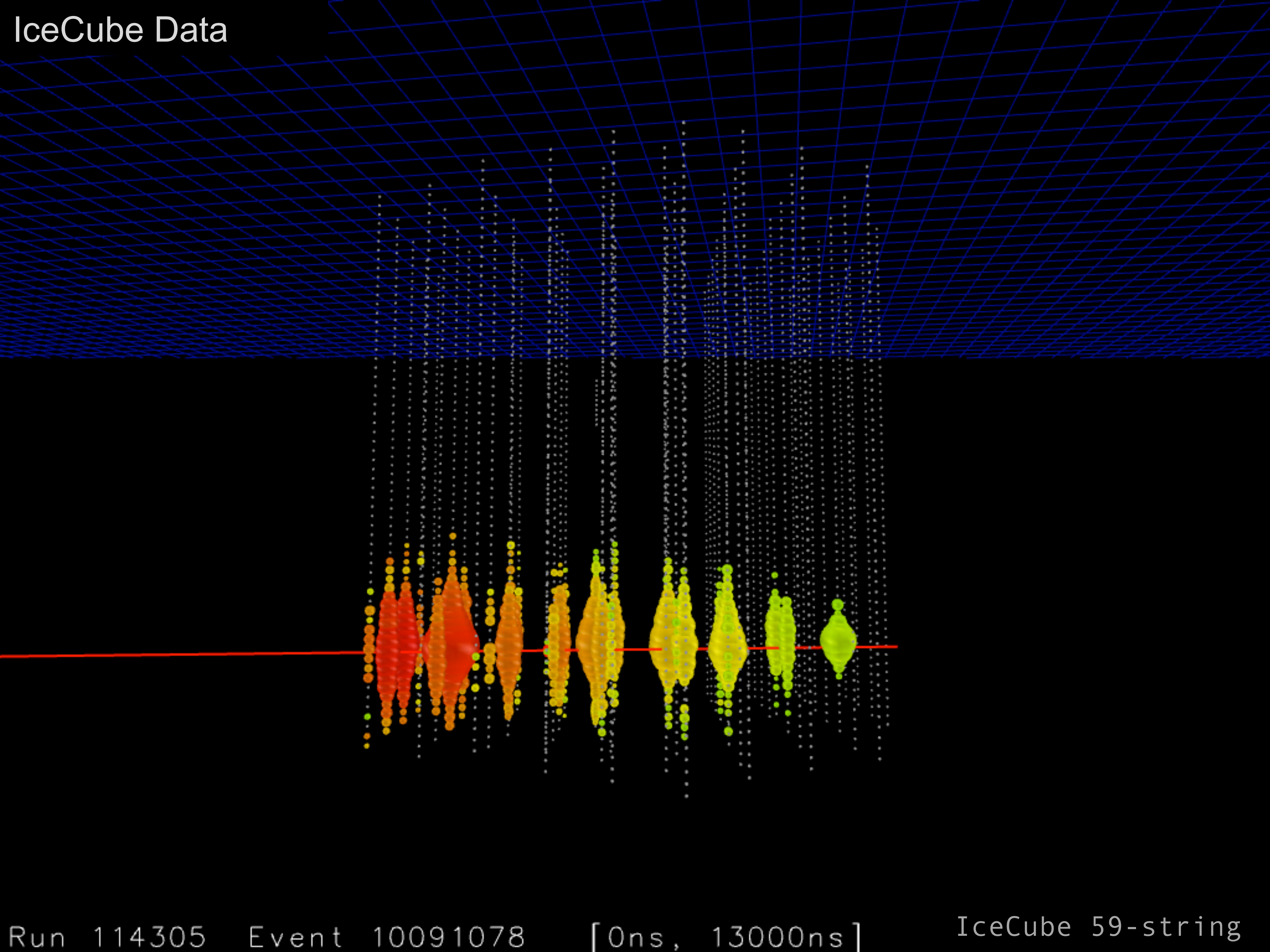


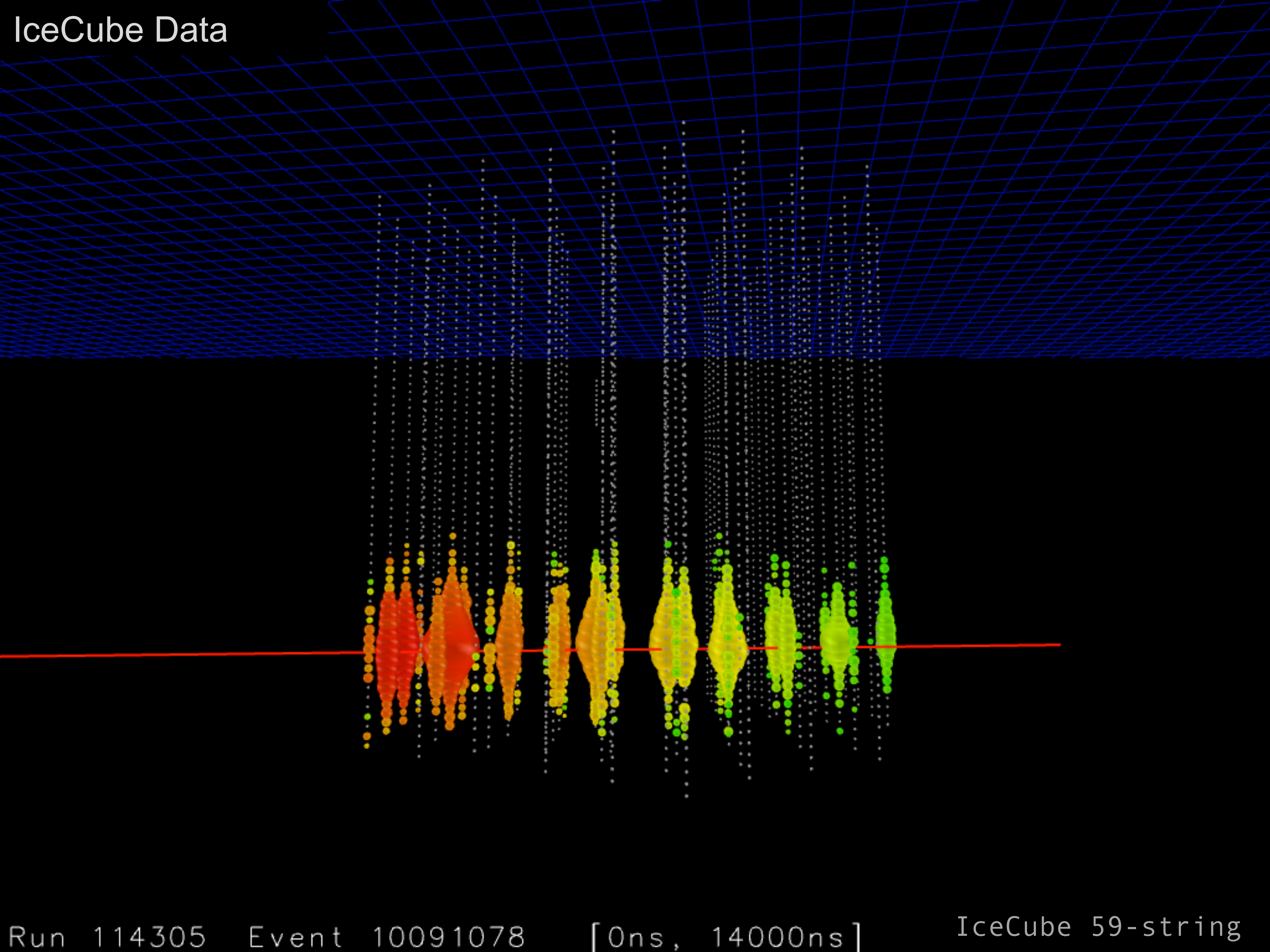

IceCube Data
Run 114305 Event 10091078 [0ns, 9000ns]
IceCube 59-string

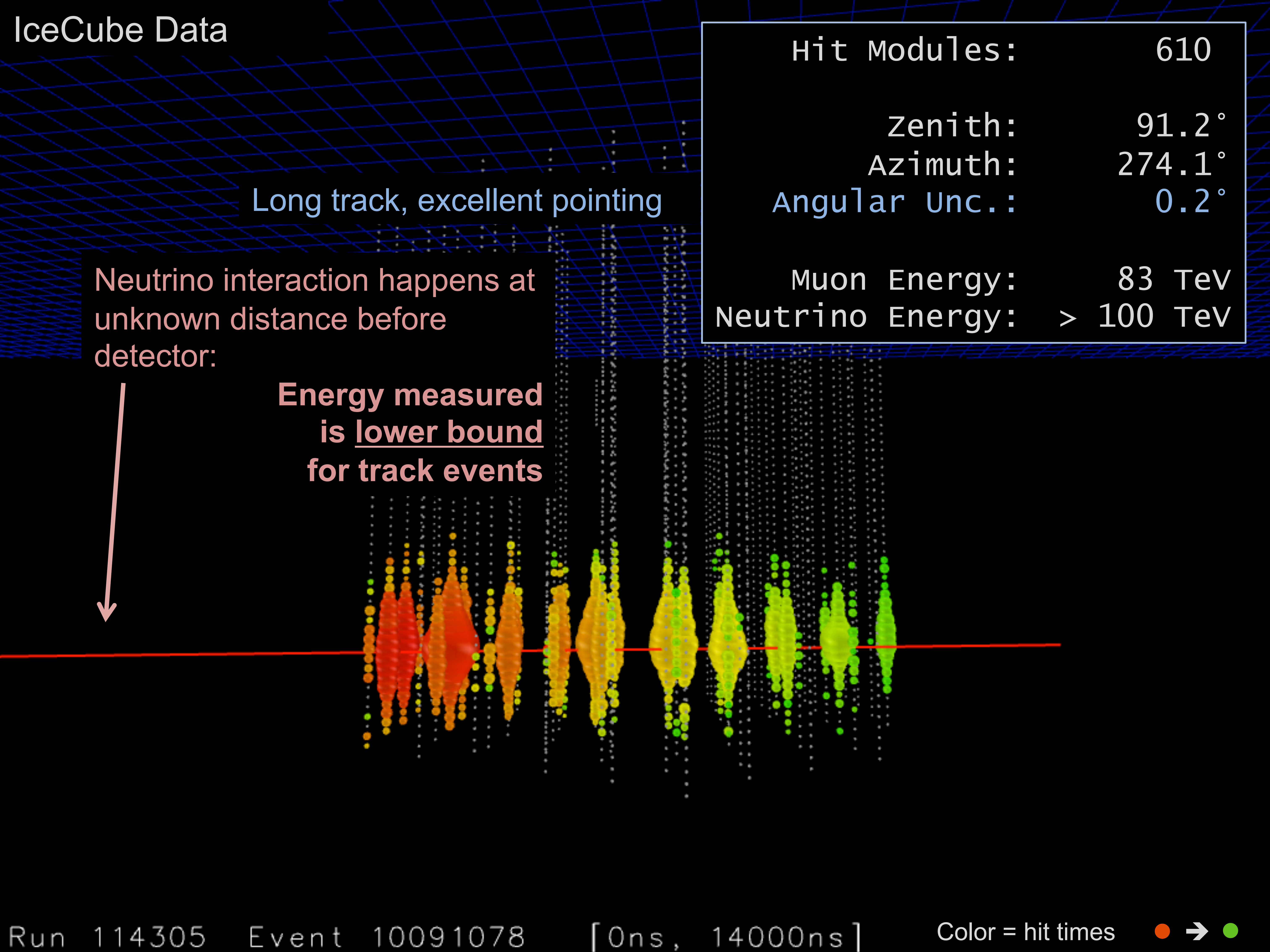

IceCube Data
Run 114305 Event 10091078 [0ns, 10000ns]
IceCube 59-string


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



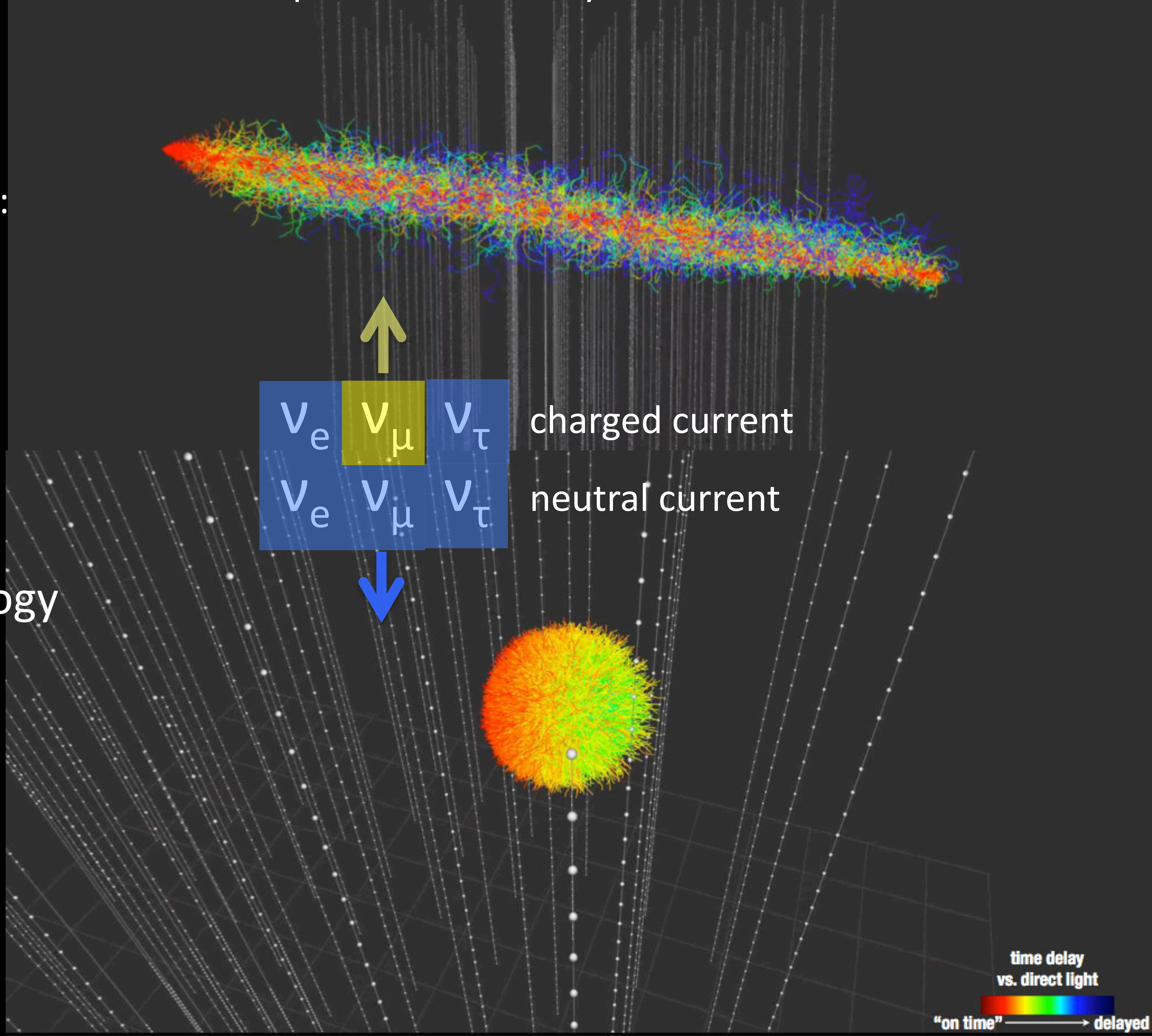
IceCube Data
Long track, excellent pointing
Hit Modules: 610
Zenith: 91.2°
Azimuth: 274.1°
Angular Unc.: 0.2°
Muon Energy: 83 TeV
Neutrino Energy: > 100 TeV
Neutrino interaction happens at unknown distance before detector:
Energy measured is lower bound for track events
Run 114305 Event 10091078 [0ns,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

Photons produced by Neutrino Interactions

Track topology

Energy measured: lower bound

Good pointing: 0.2° - 1°



Cascade topology

Good energy resolution, 15%

Some pointing, 10° - 15°

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…

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

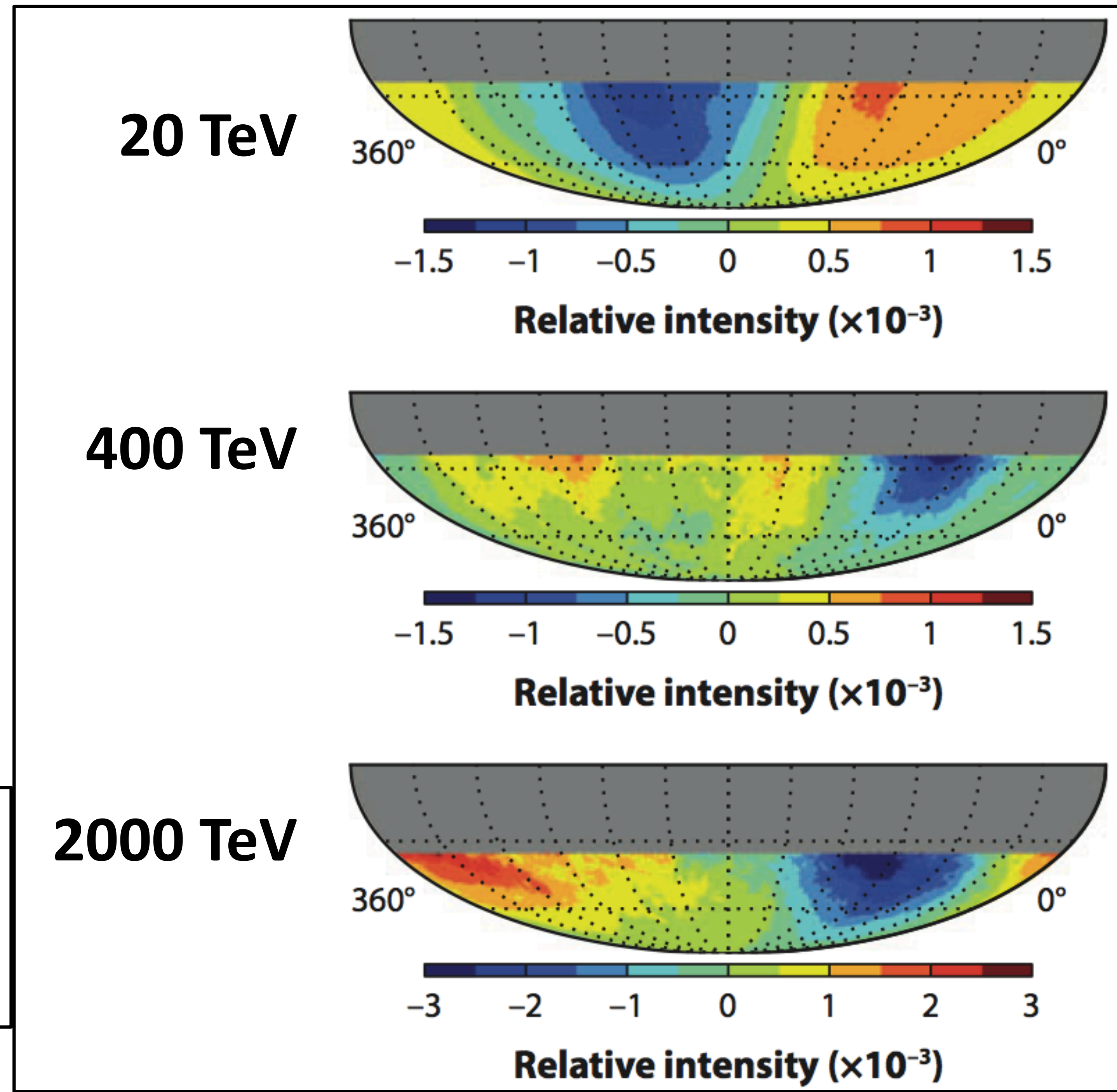
~ 100 astrophysical neutrinos – that we estimate so far…

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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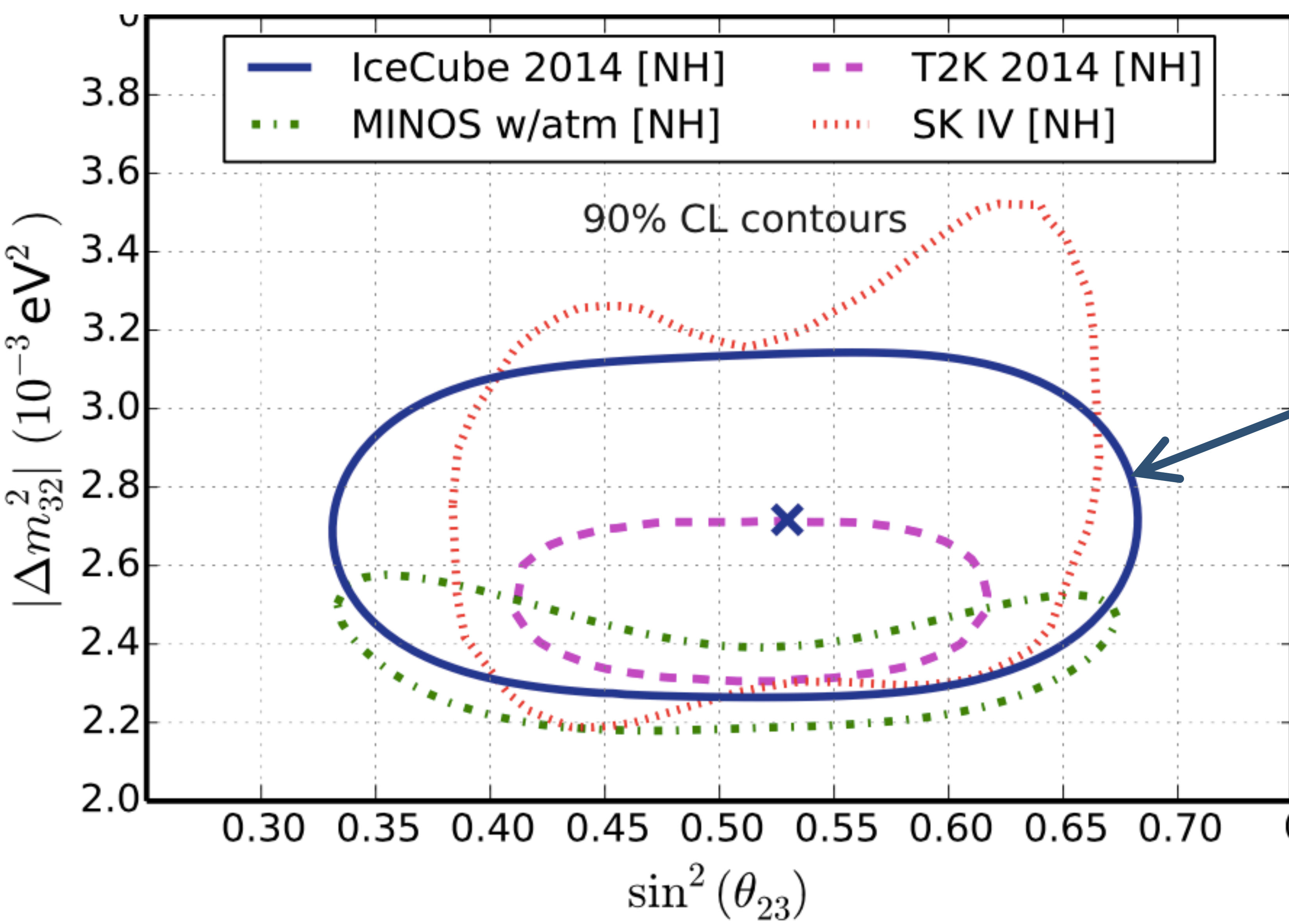


Measurement of Neutrino Oscillation parameters (IceCube-DeepCore)

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

3-year analysis
Phys. Rev. D 91, 072004 (2015)

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

Indirect Dark Matter Searches

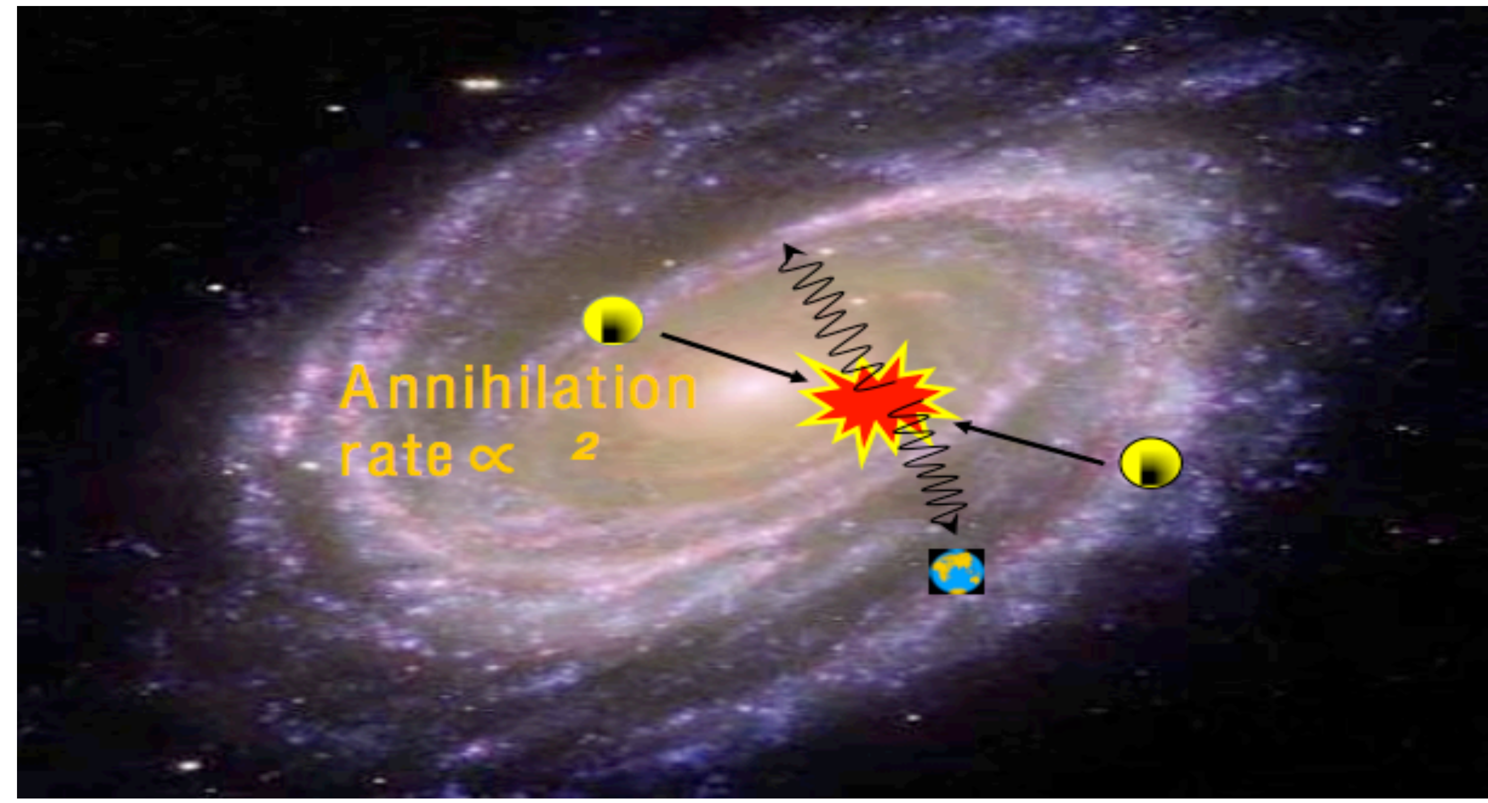
$$\chi + \chi \rightarrow W + W \rightarrow \nu + \nu$$

Neutrinos are typical end products of dark matter annihilation

Galactic Halo Searches:

Annihilation occurs in densest region of dark matter halo in galactic center

Search sensitive to **annihilation cross section**

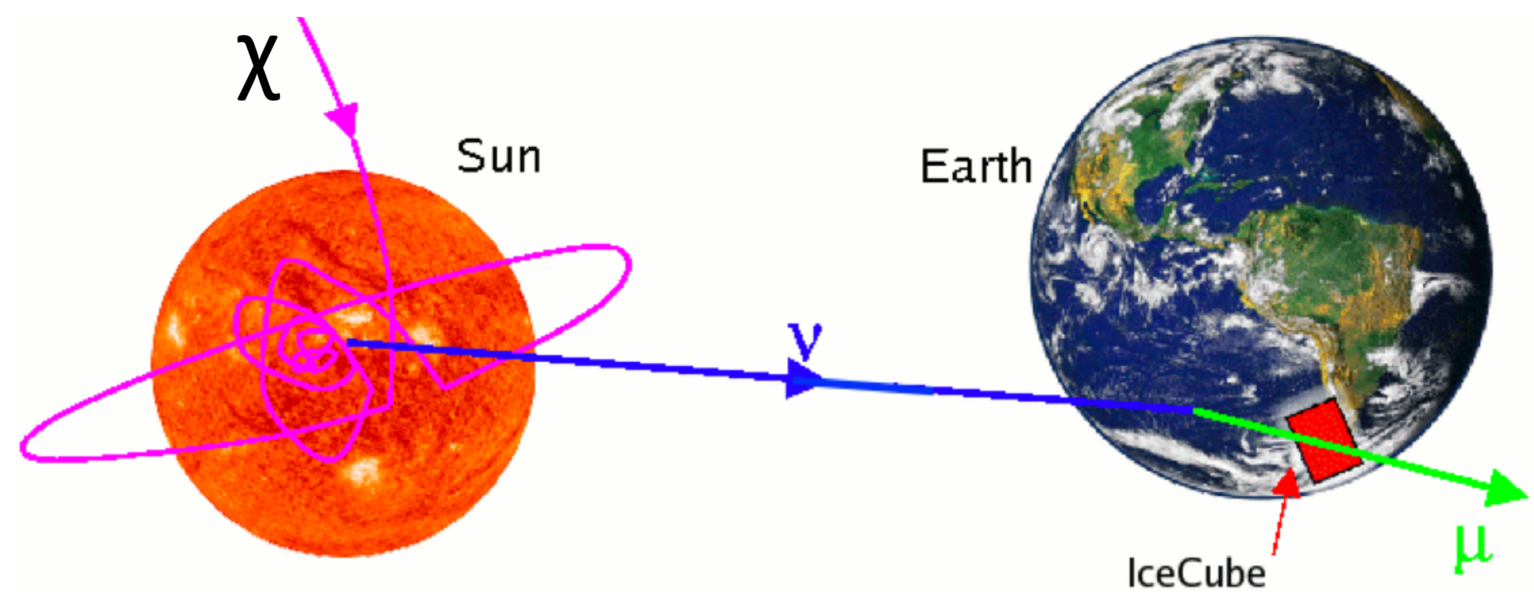


Solar Searches:

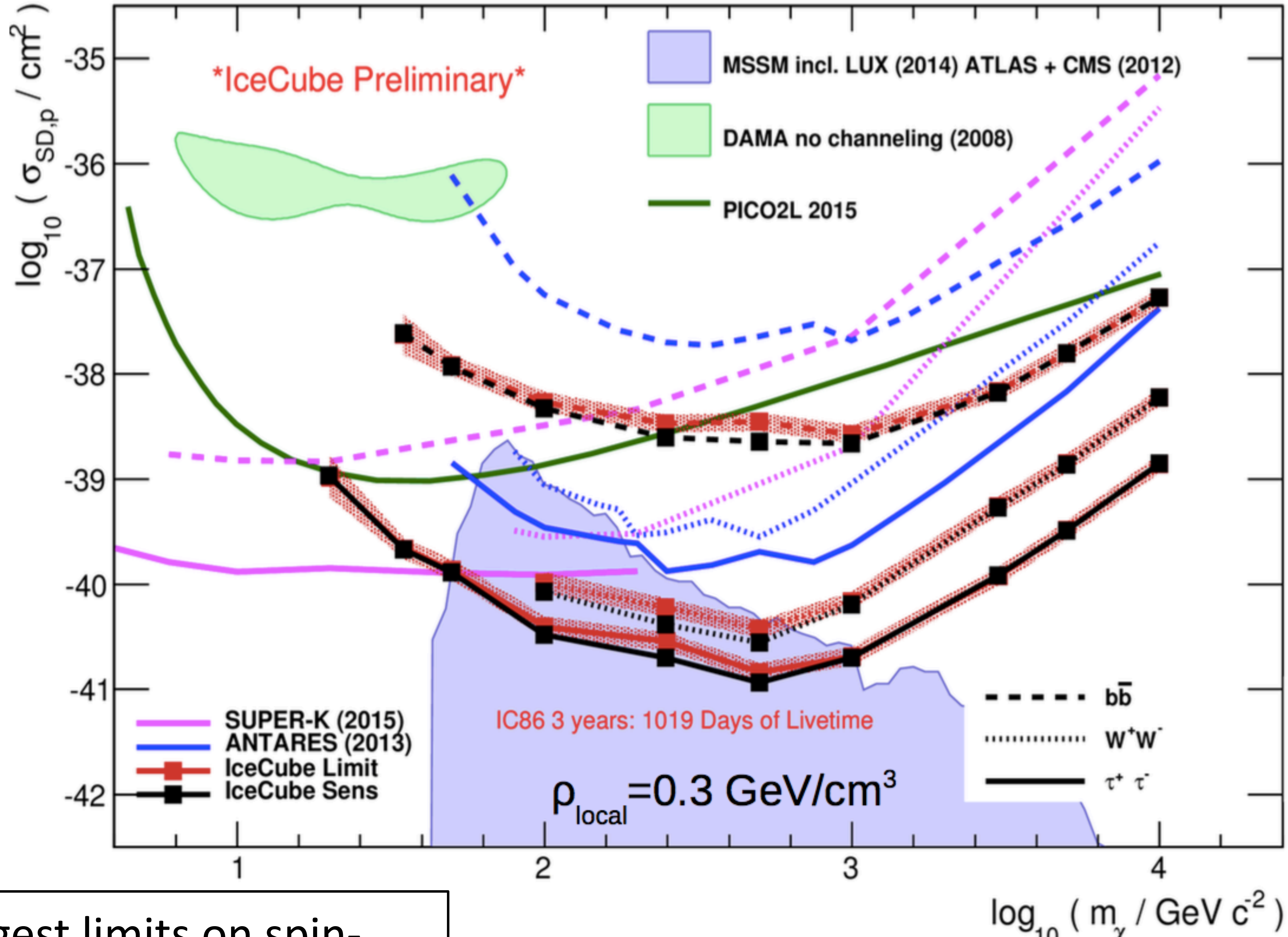
Dark matter particles scatter and get trapped in sun.

As trapped density grows, annihilation rate reaches equilibrium with capture rate.

Search sensitive to **scattering cross section**

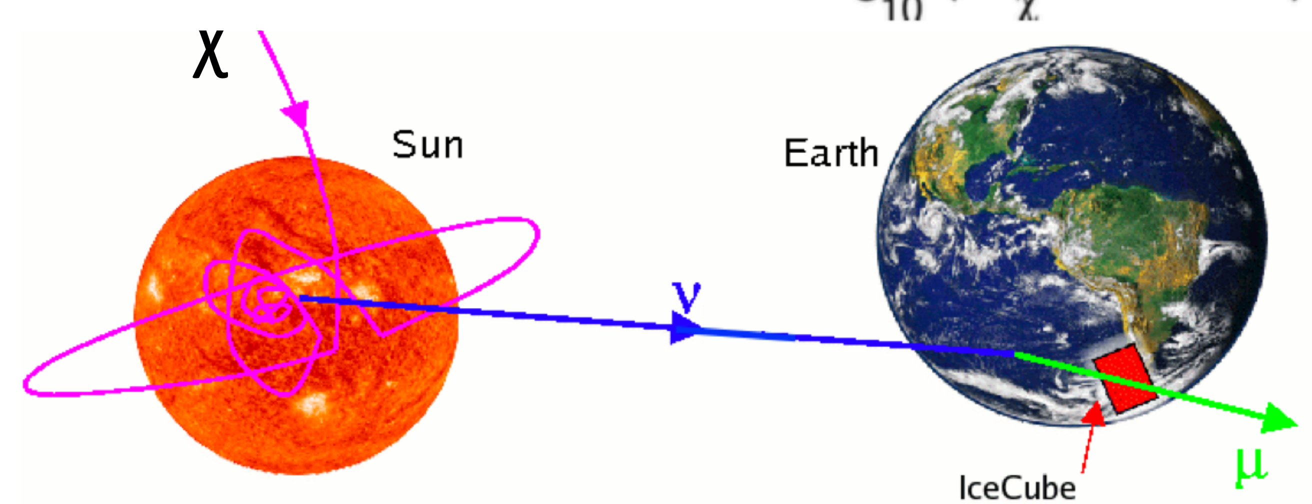


Indirect Dark Matter Searches

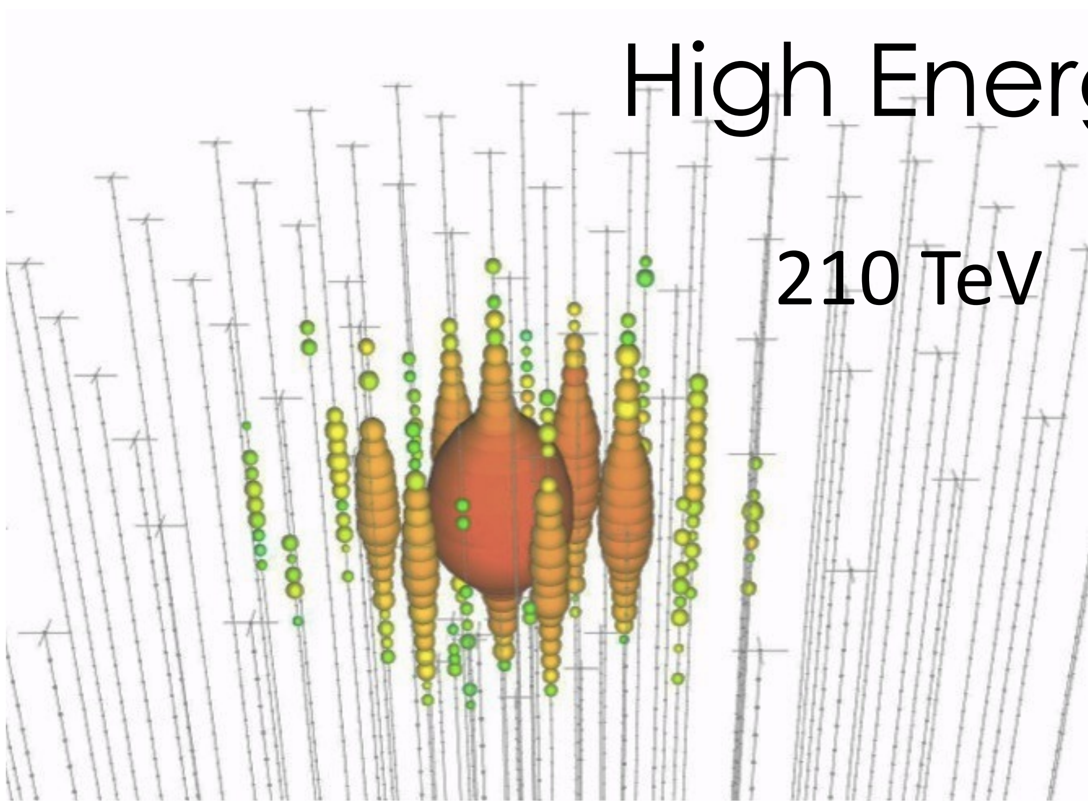


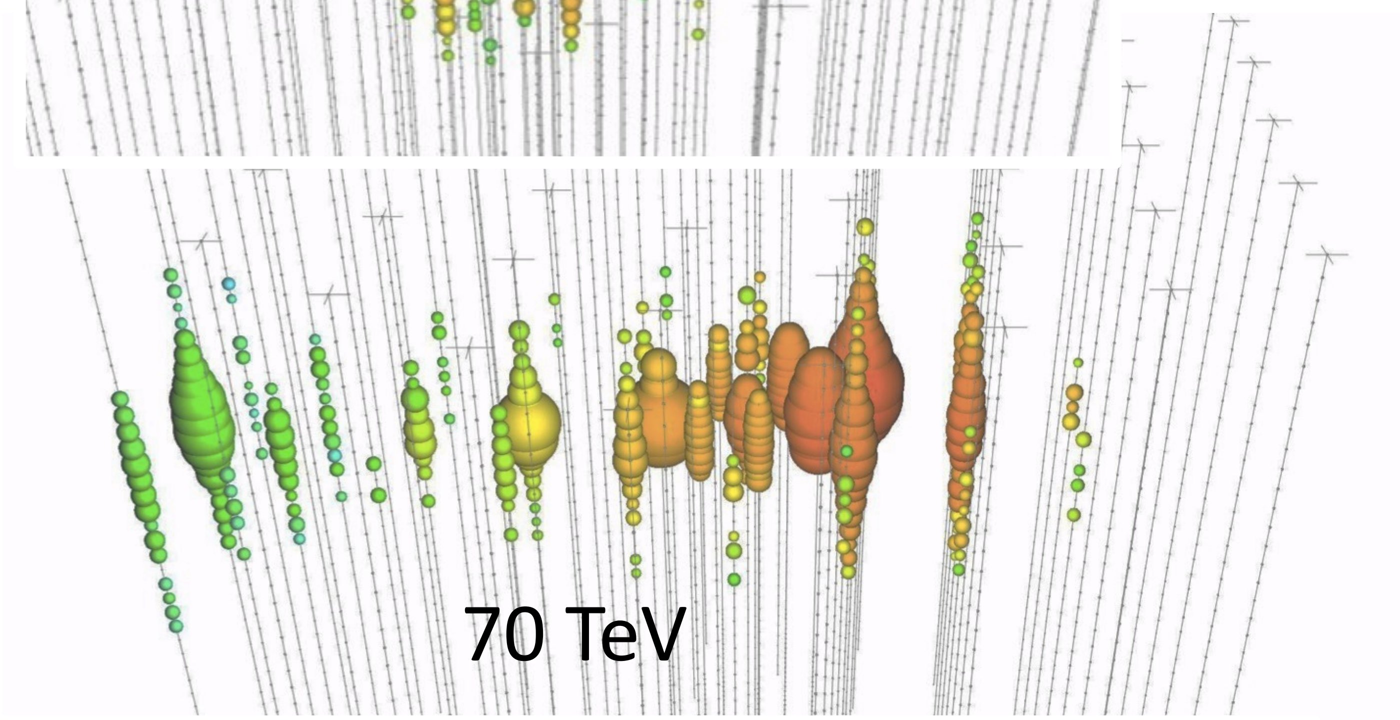
Analysis of 3-year IceCube-DeepCore data:

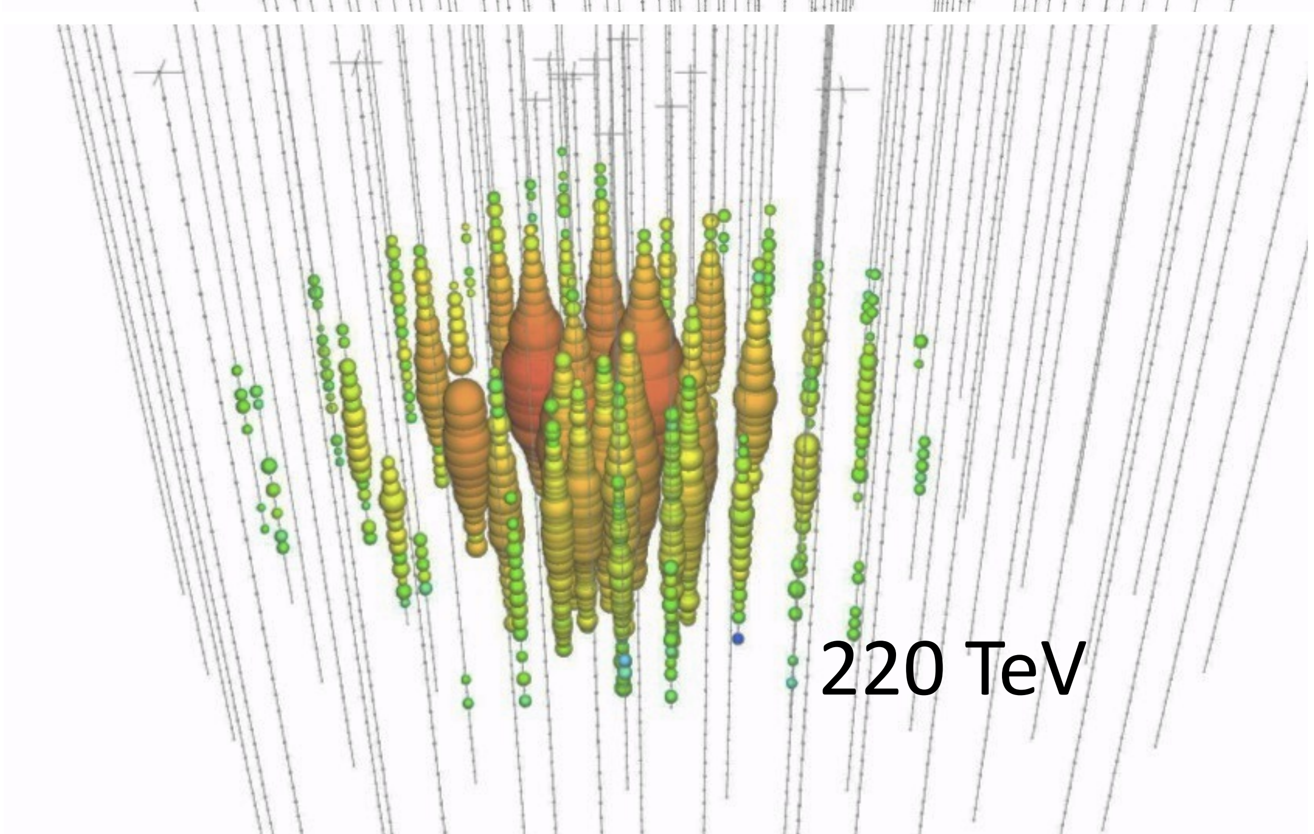
IceCube sets strongest limits on spin-dependent WIMP-nucleon scattering cross-section for WIMP masses greater 40 GeV

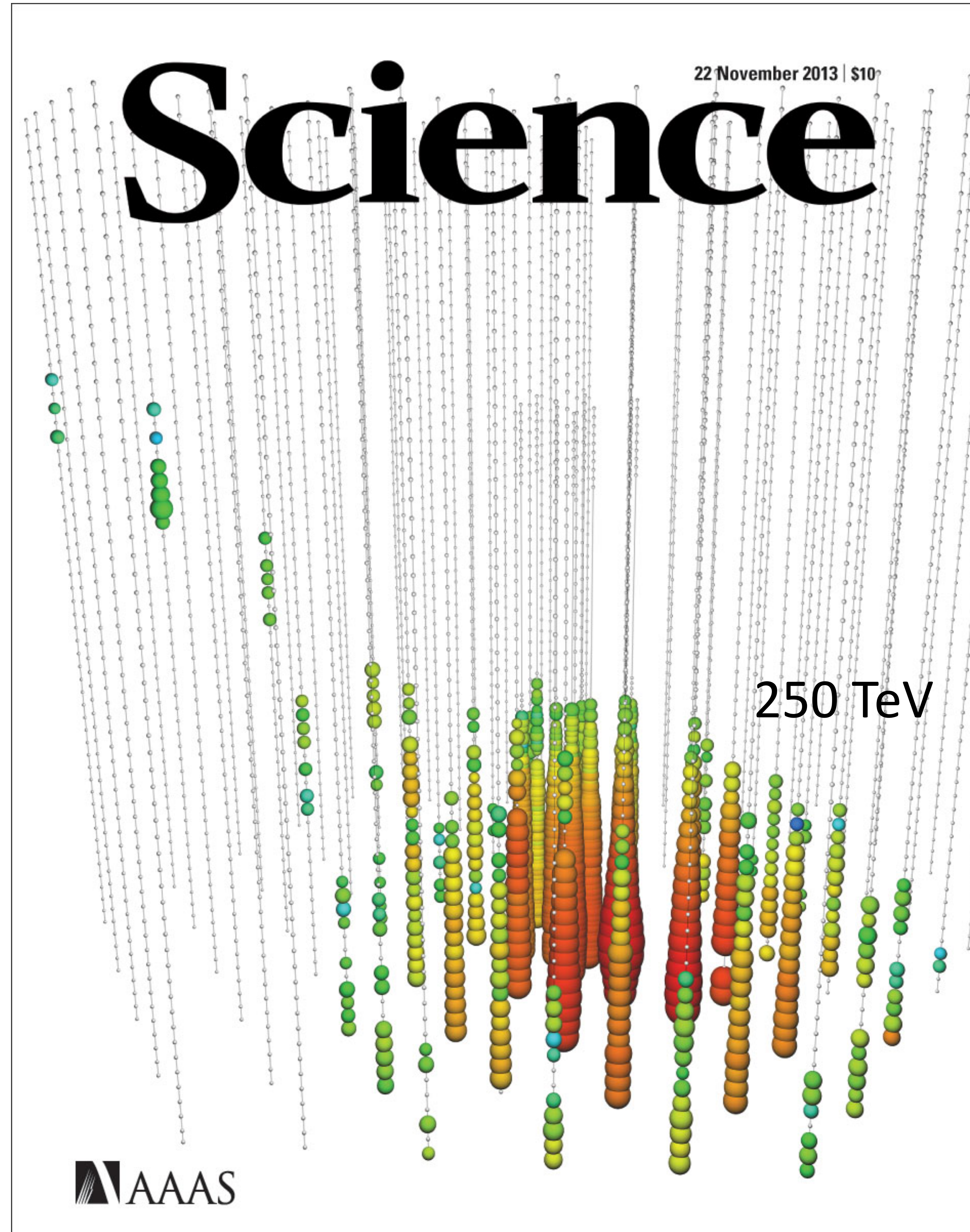


High Energy Starting Event Analysis



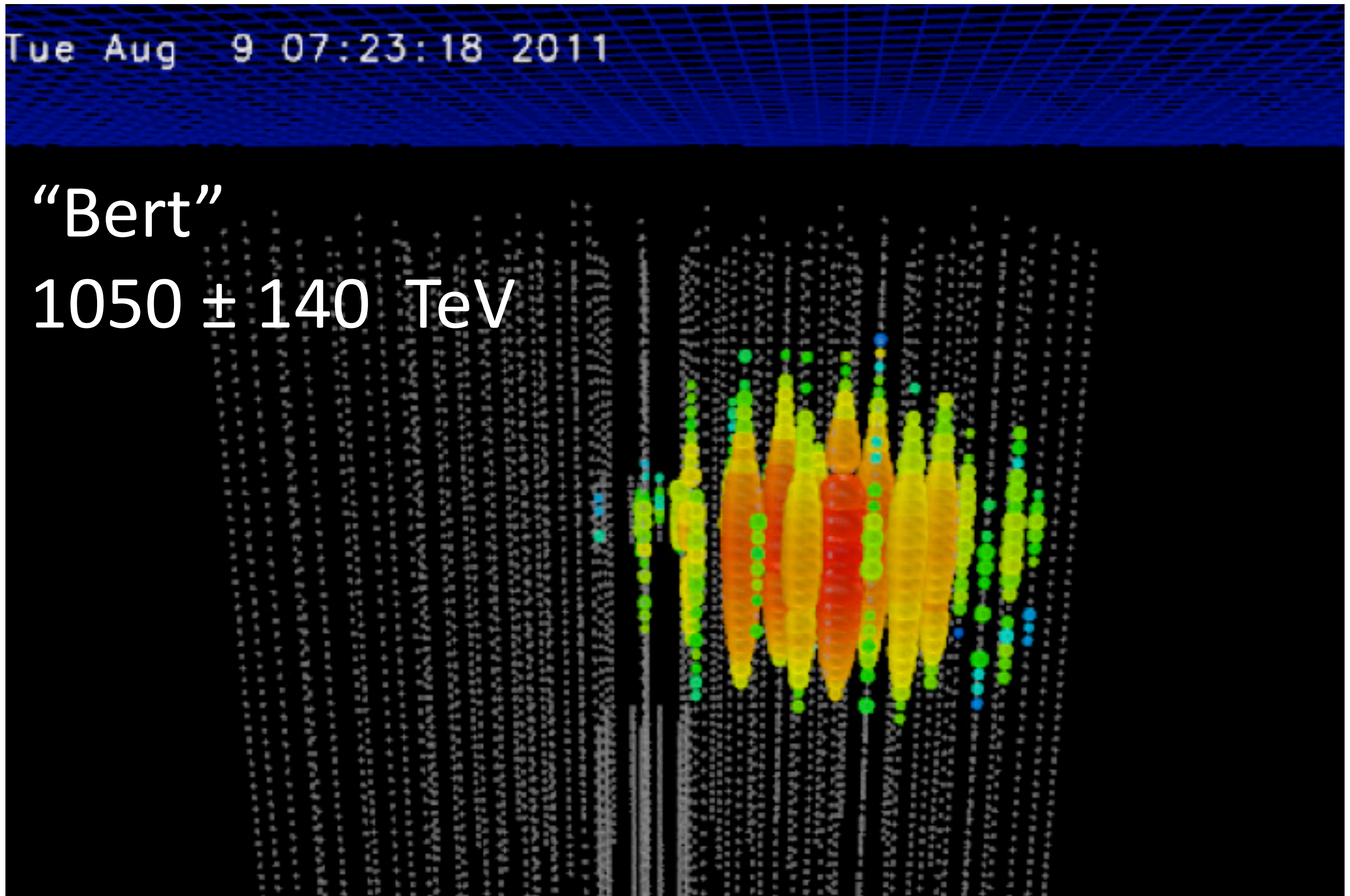


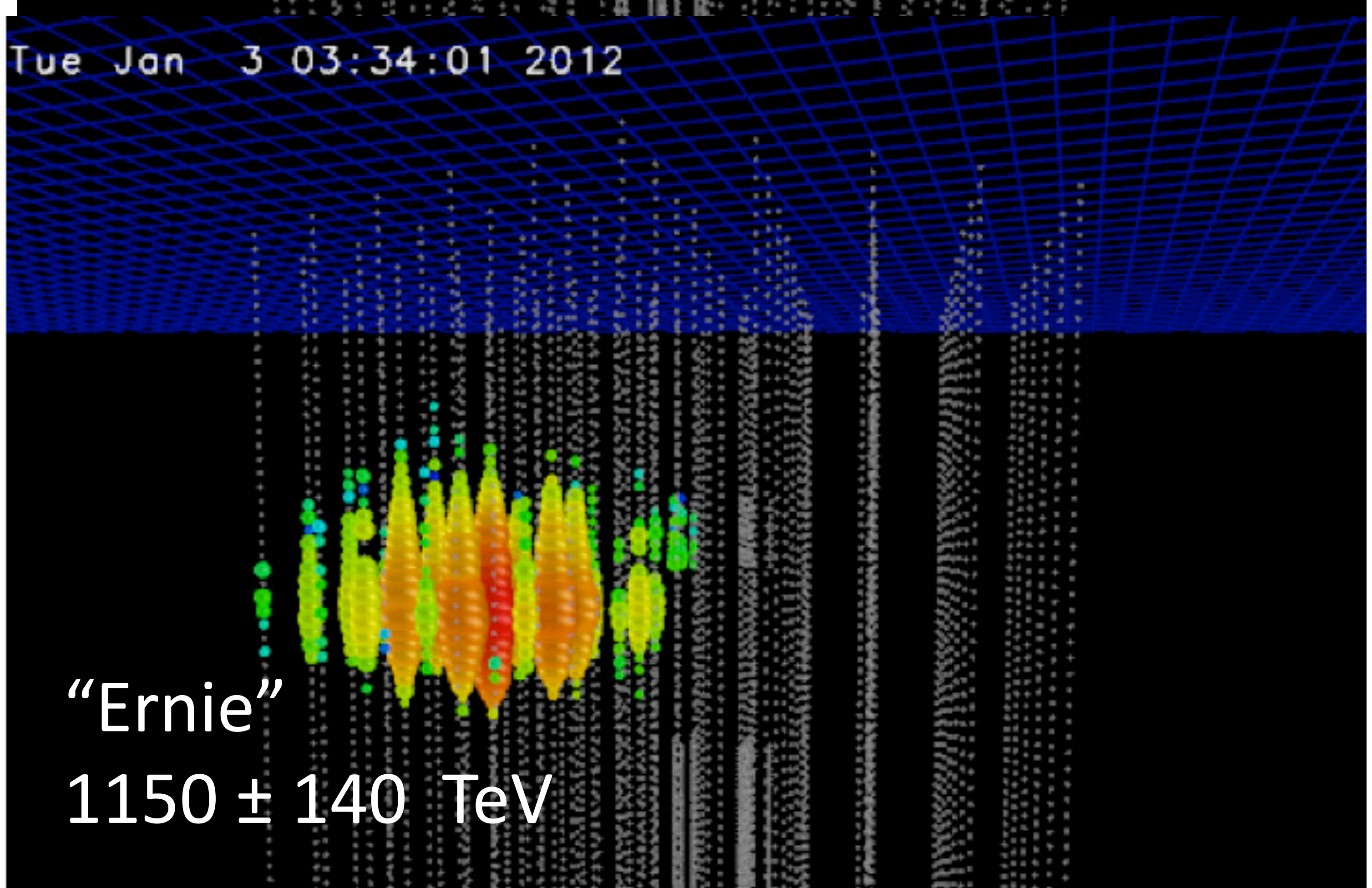




2-year analysis: Science **342**, 1242856 (2013)

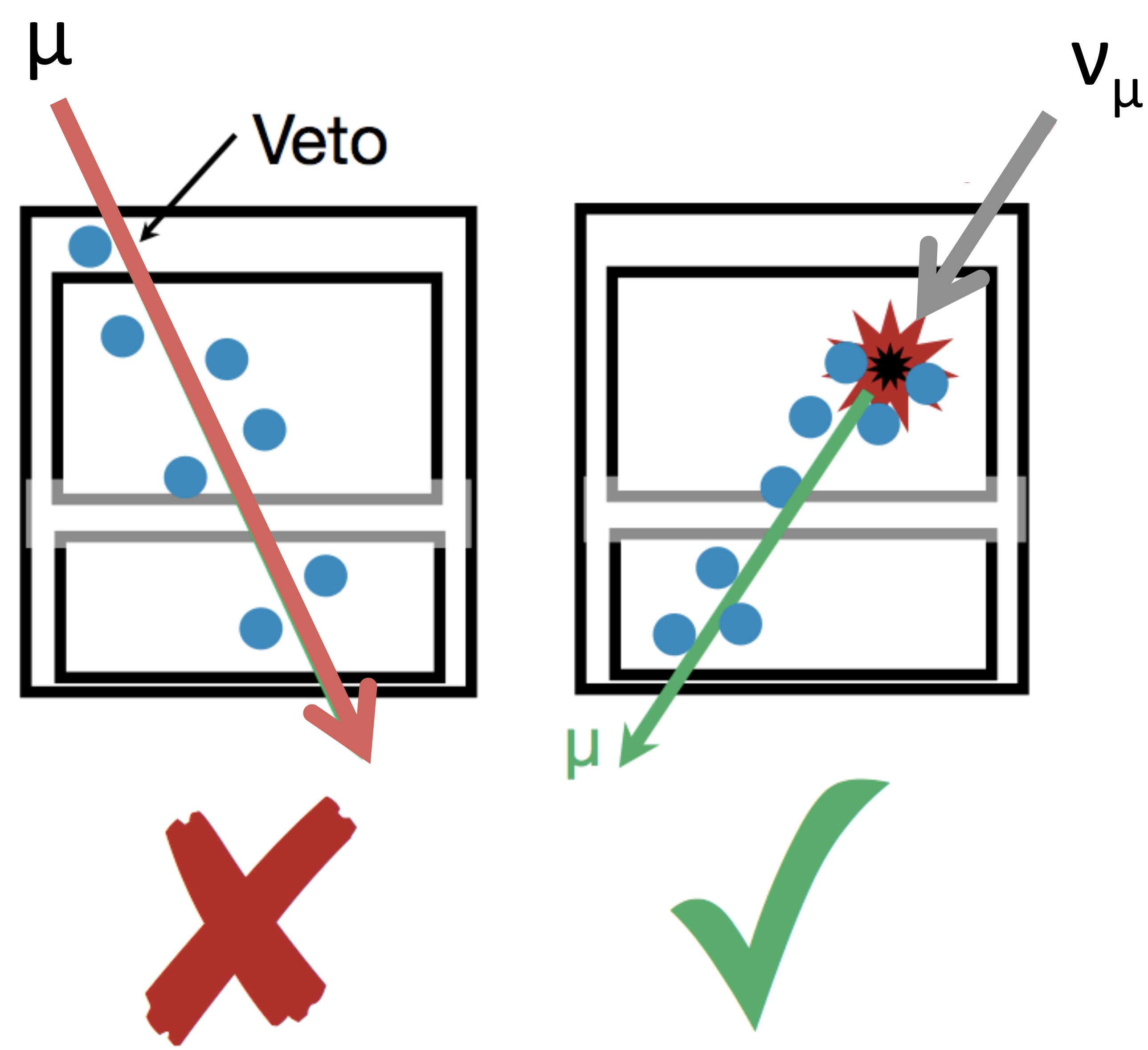
High Energy Starting Event Analysis





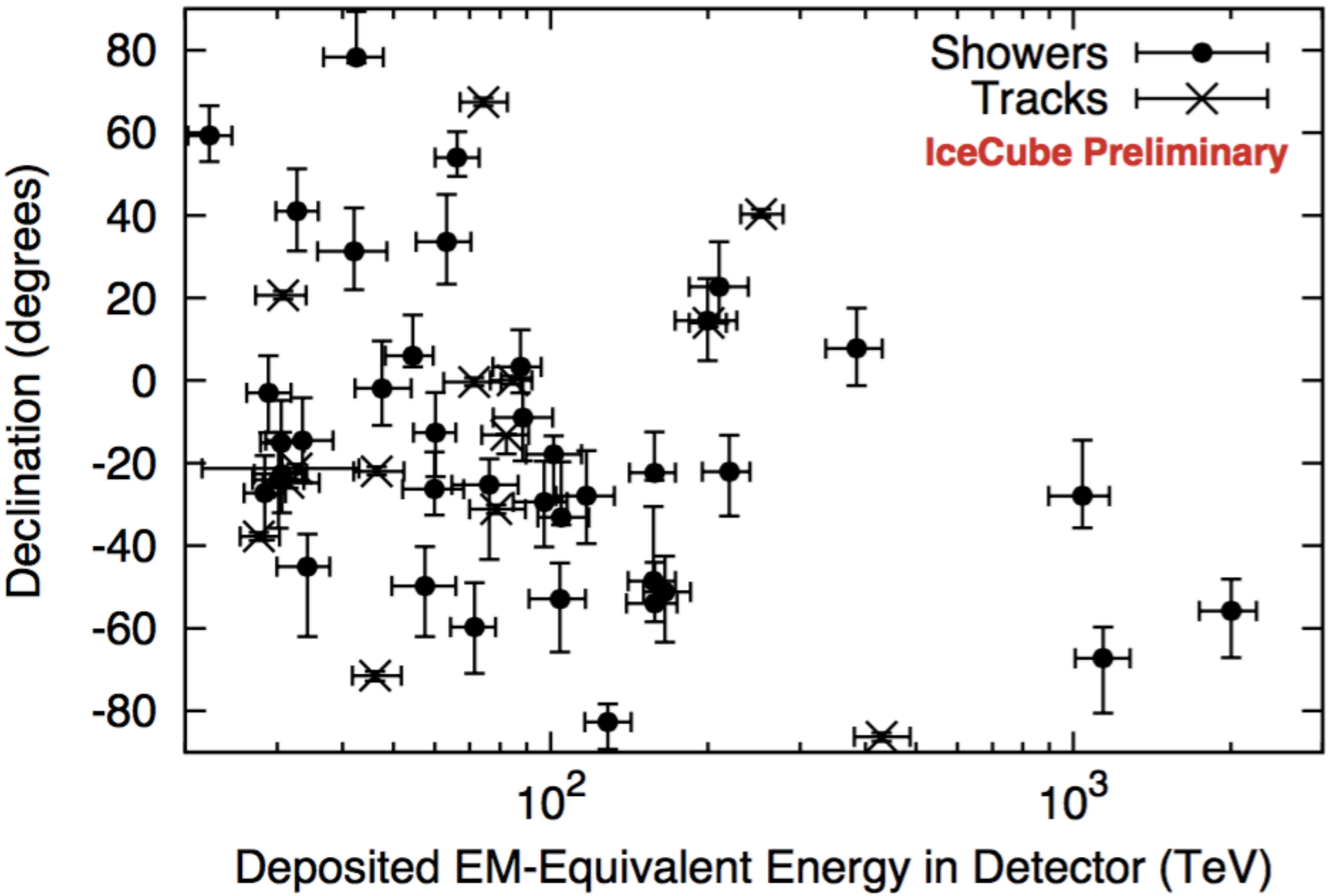
Require that event:

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

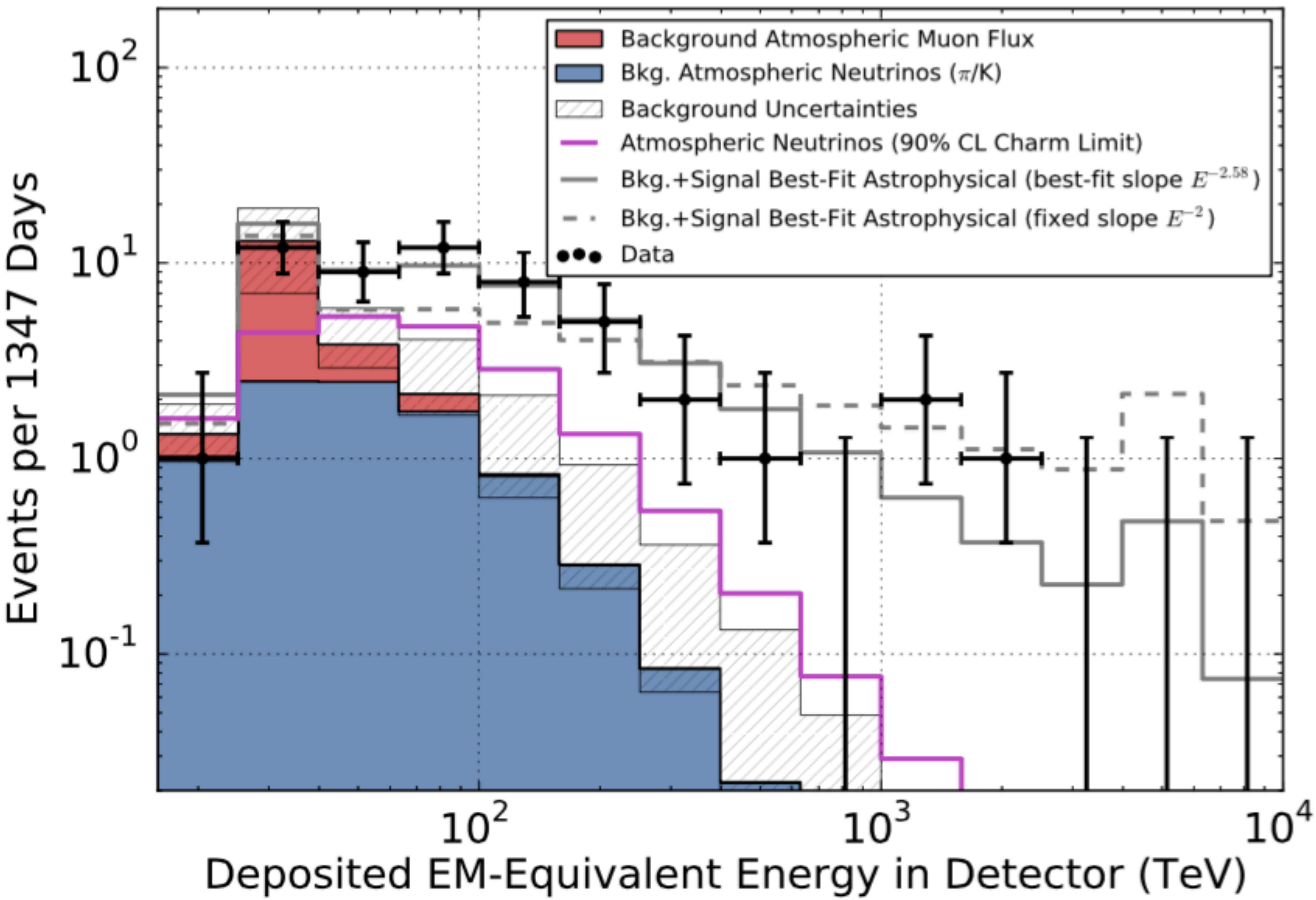


4-Year High Energy Starting Events – Energy Distribution

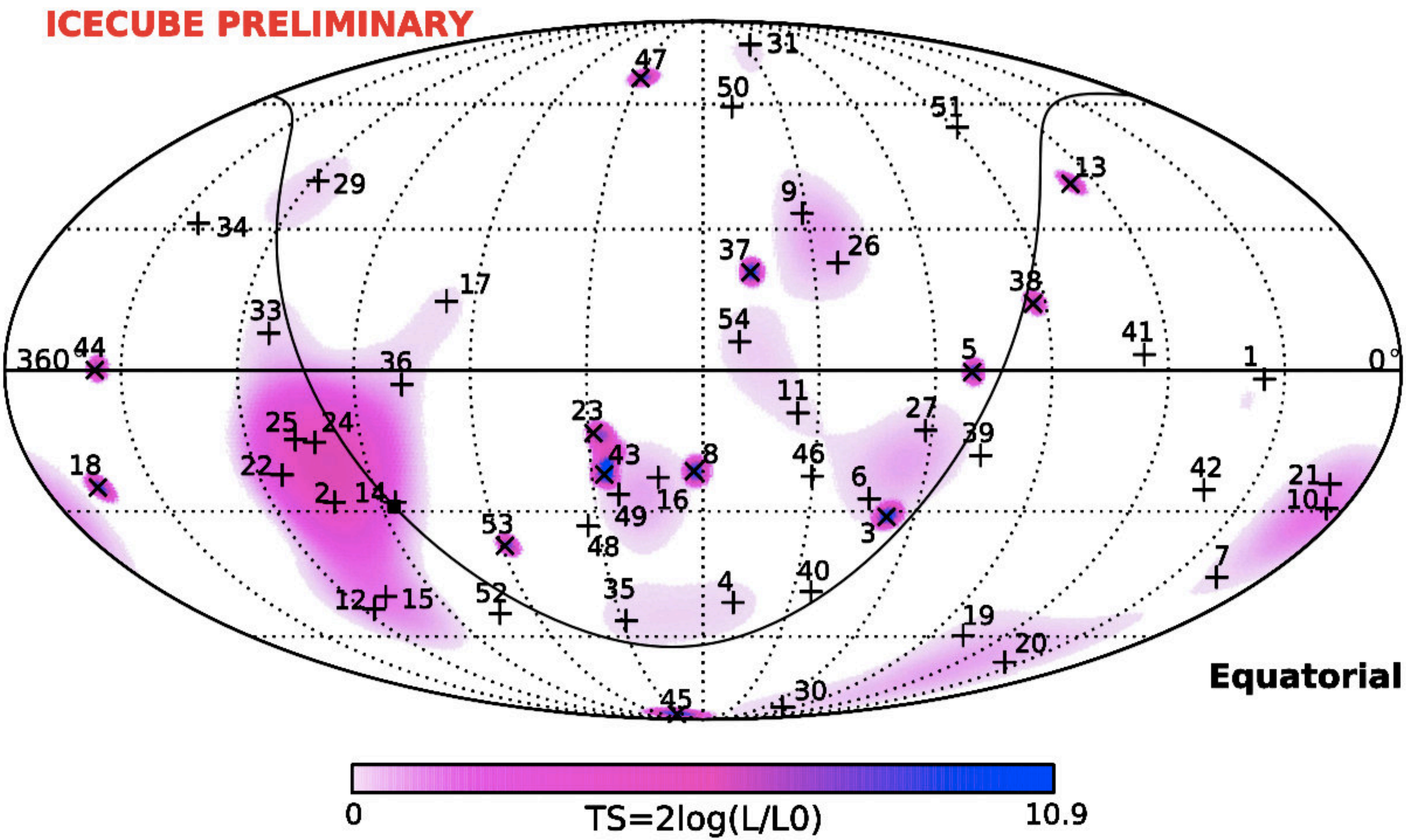
53 High-energy starting-events now observed in 4 years



4-Year High Energy Starting Events – Energy Distribution



4-Year High Energy Starting Events Skymap



Muon-Neutrino Analysis – Energy Distribution

Upgoing or Horizontal track =
Earth-filtered

Estimated 99.9% pure muon-neutrino sample

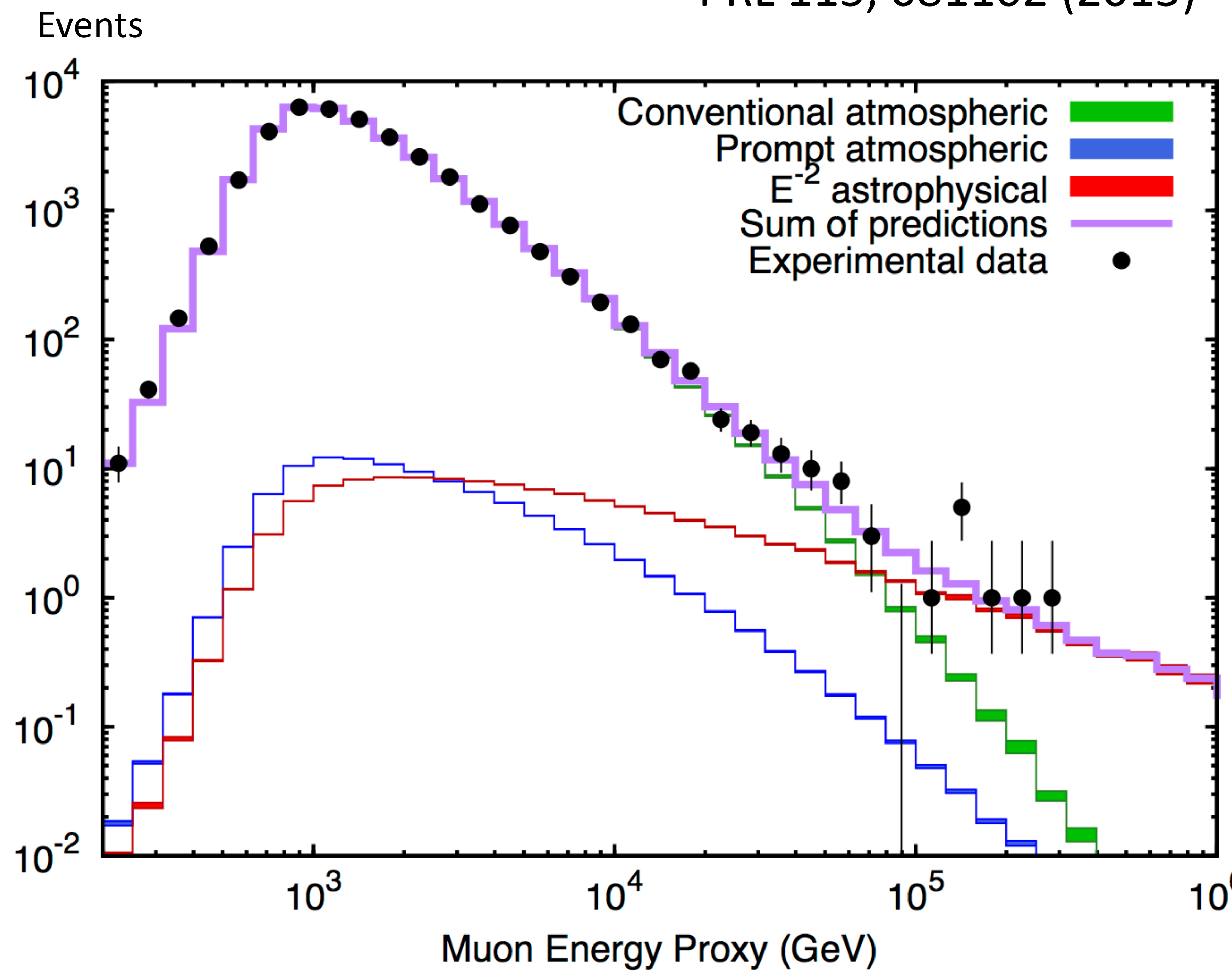
35 000 events in 2-year analysis

3.7σ evidence of astrophysical flux

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

- thru-going tracks vs. starting events (mainly showers)
- up-going events vs. (mainly) down-going

PRL 115, 081102 (2015)



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

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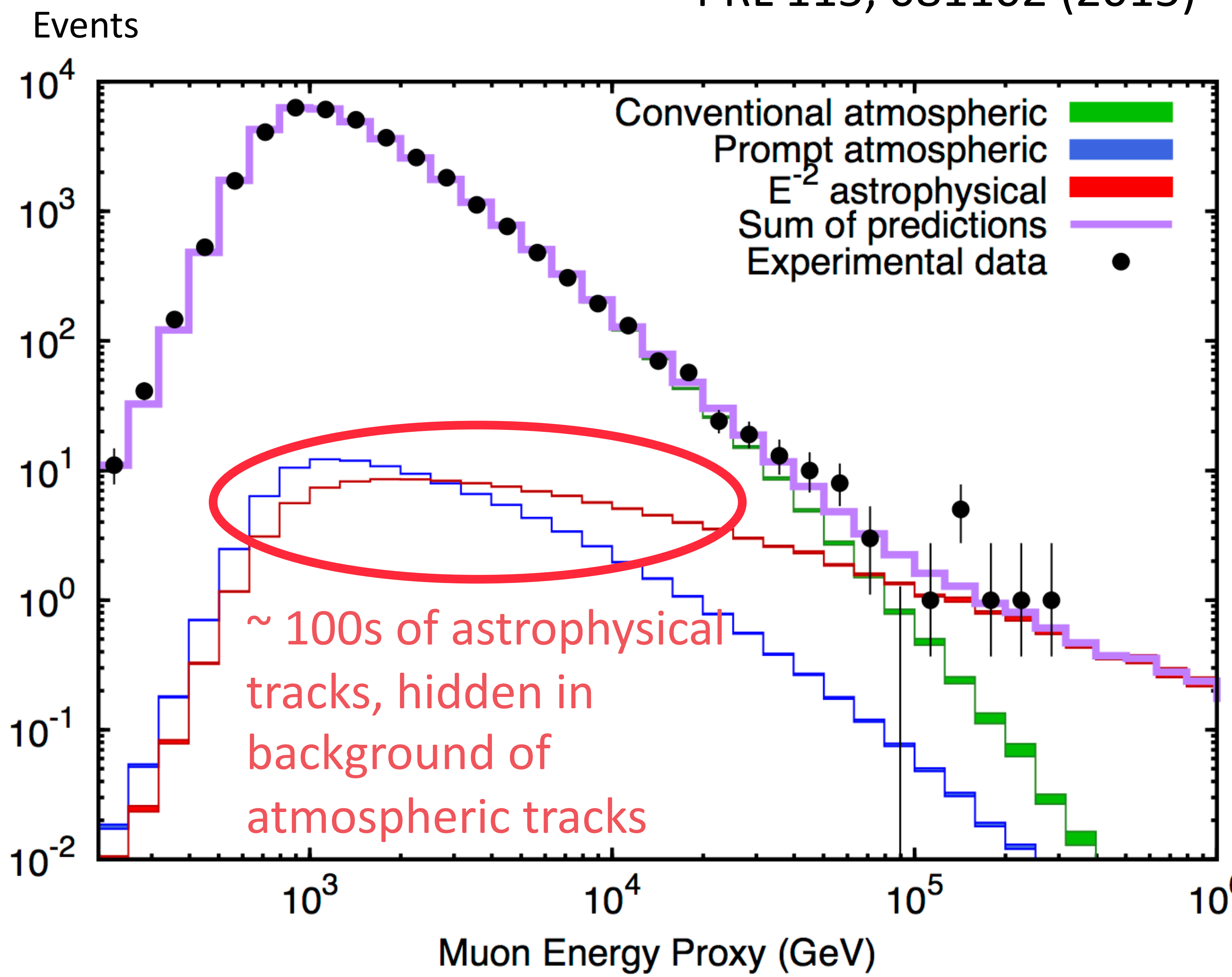
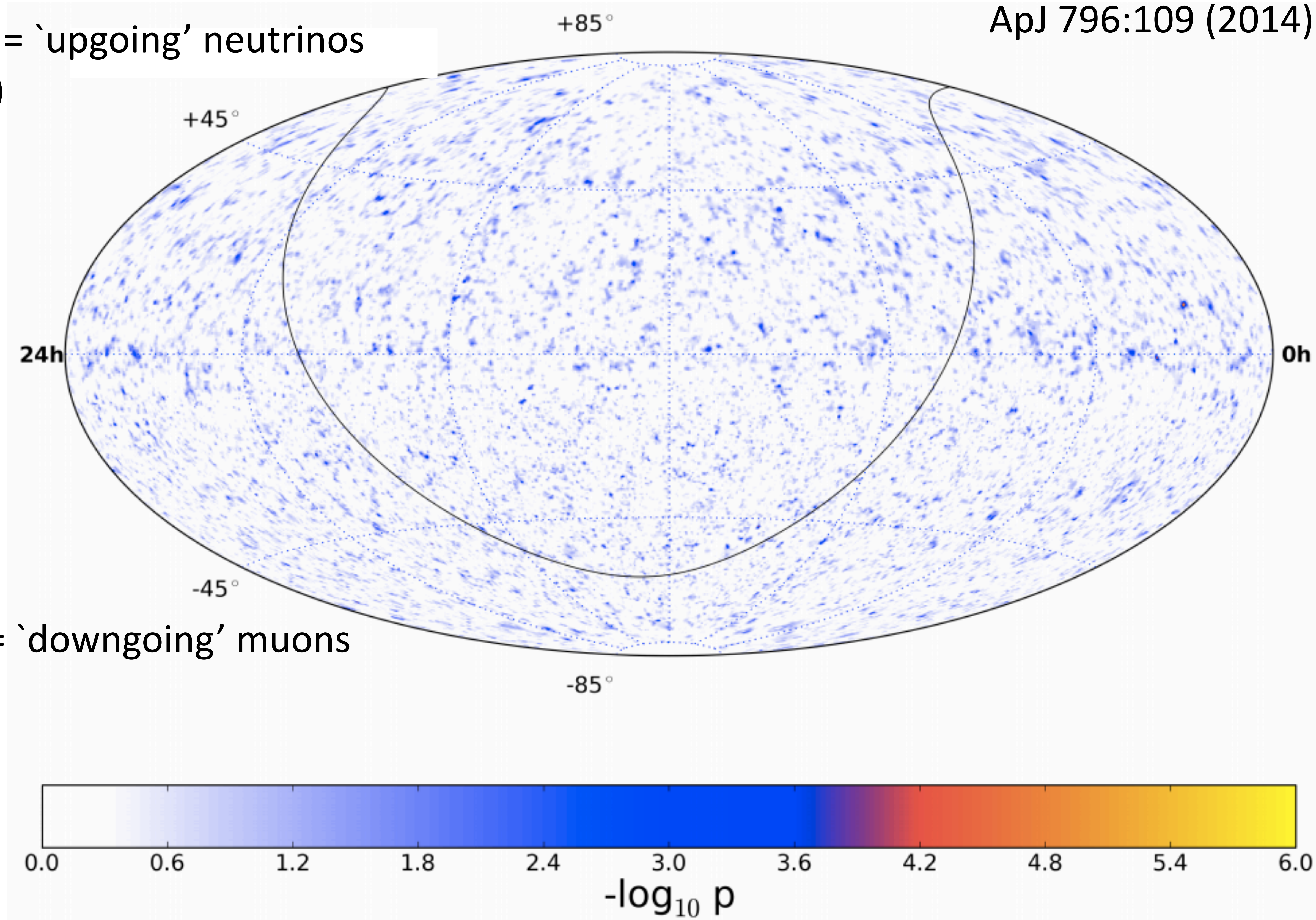


Energy estimate for the muon track…
Only lower-bound on neutrino energy
(interacted before reaching detector)

4-year Maximum Likelihood Point-Source Analysis

Northern sky = `upgoing' neutrinos
(178K events)

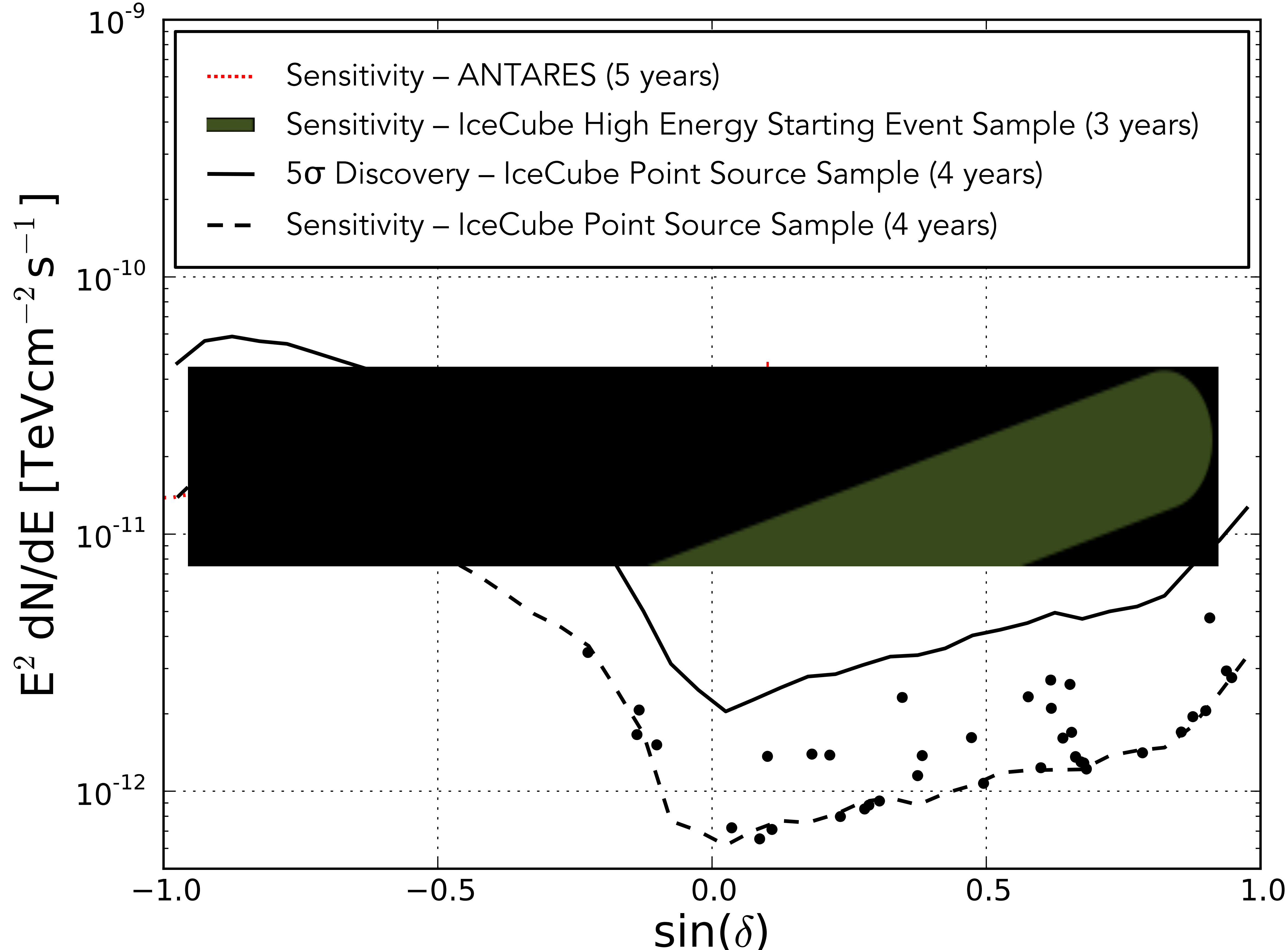


Southern sky = `downgoing' muons
(216k events)

Events are predominantly atmospheric background from cosmic rays.

Despite est. ~ 100s of astro neutrinos, No significant point-like excess seen.

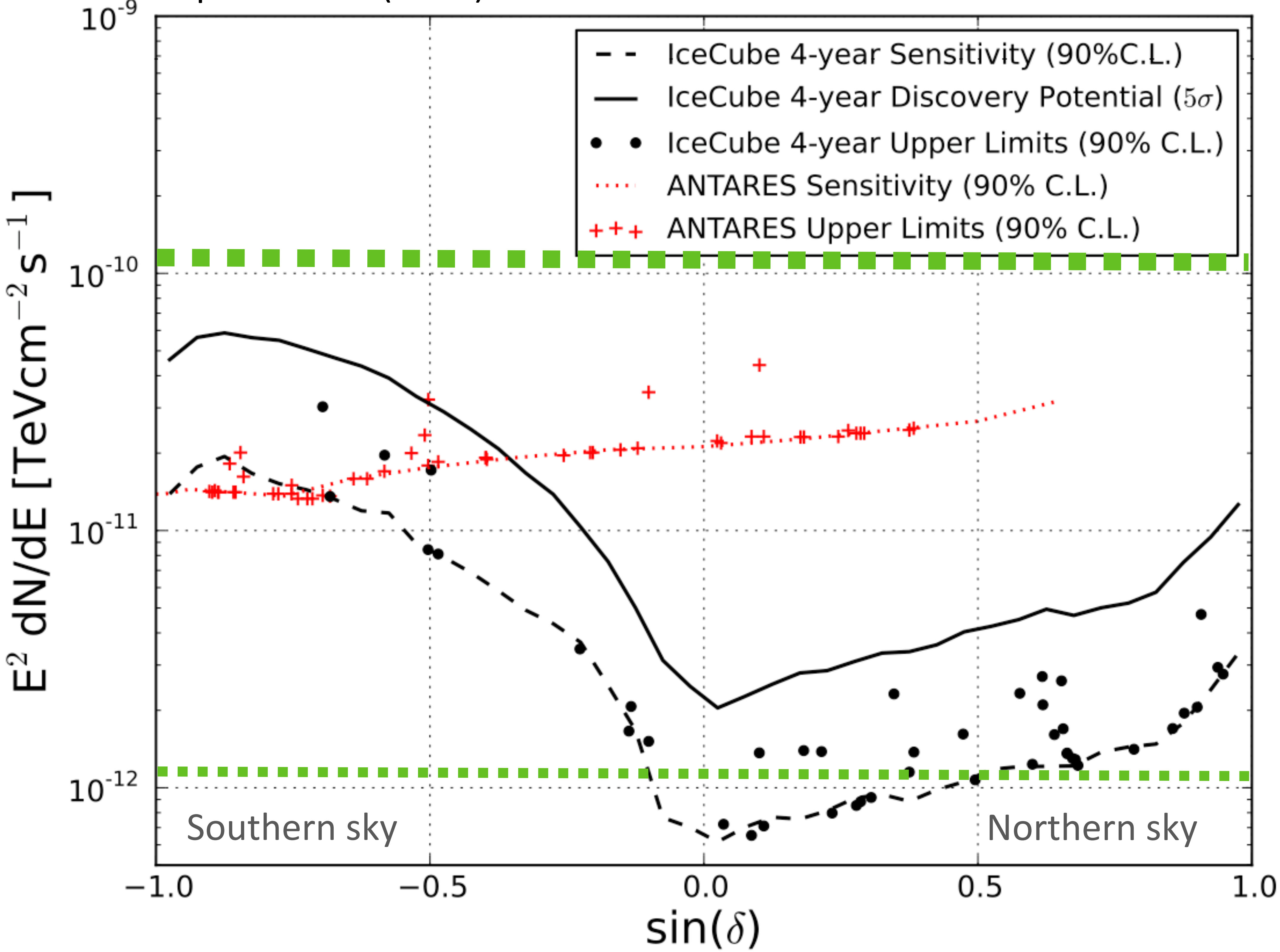
Sensitivity to Point Sources



Southern sky Northern sky

Sensitivity to Point Sources

ApJ 796:109 (2014)



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

one point in the sky

100 points in the sky

Population studies with Stacking Searches:

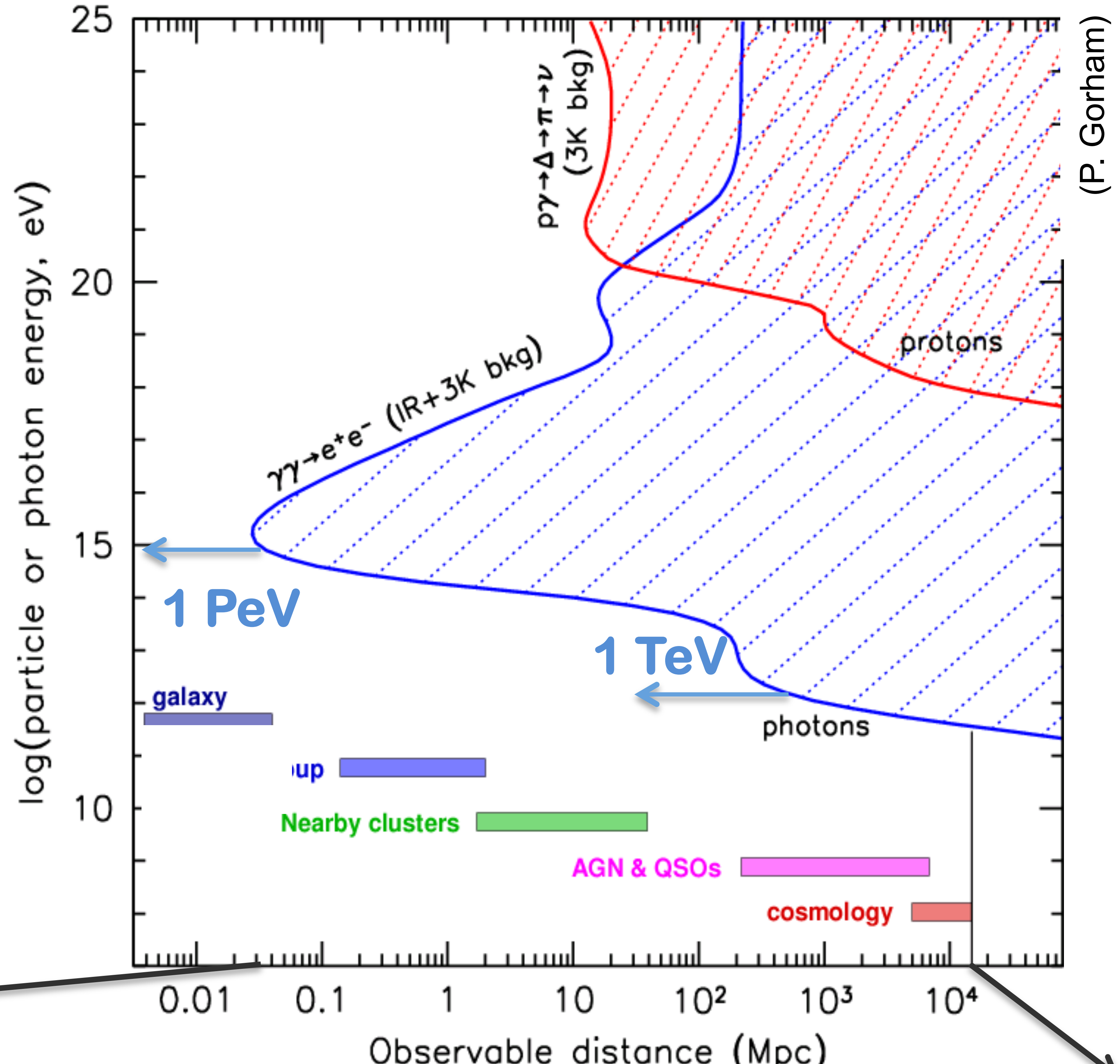
1000 points in the sky

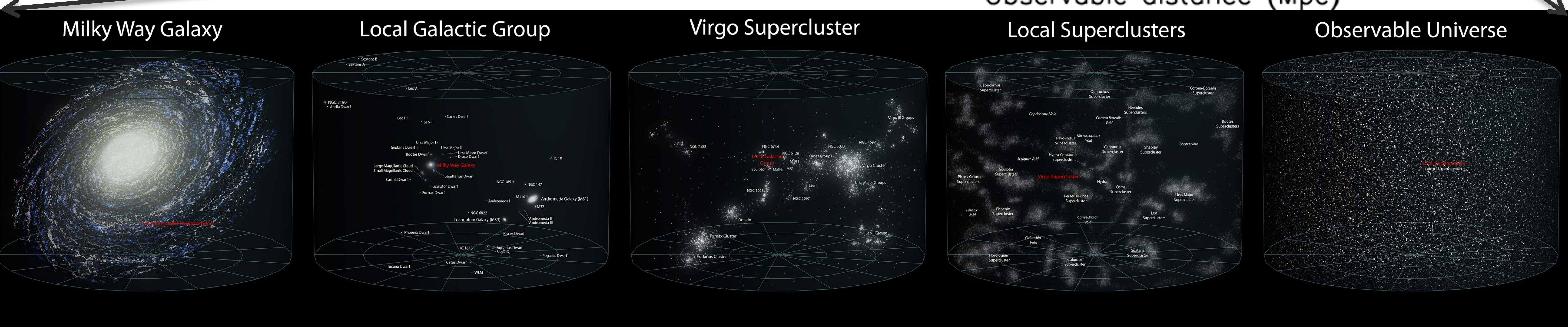
PeV Photons

Mean free path of gamma-rays shrinks as energy increases:

At PeV energies, universe is **opaque for photons**, due to pair-production off background radiation fields (Cosmic Microwave Background, Infrared Background)

$$\gamma + \gamma_{IR,CMB,radio} \rightarrow e^{+} + e^{-}$$





Point-Source Population Study: Blazars

Stacked Neutrino Point Source Search

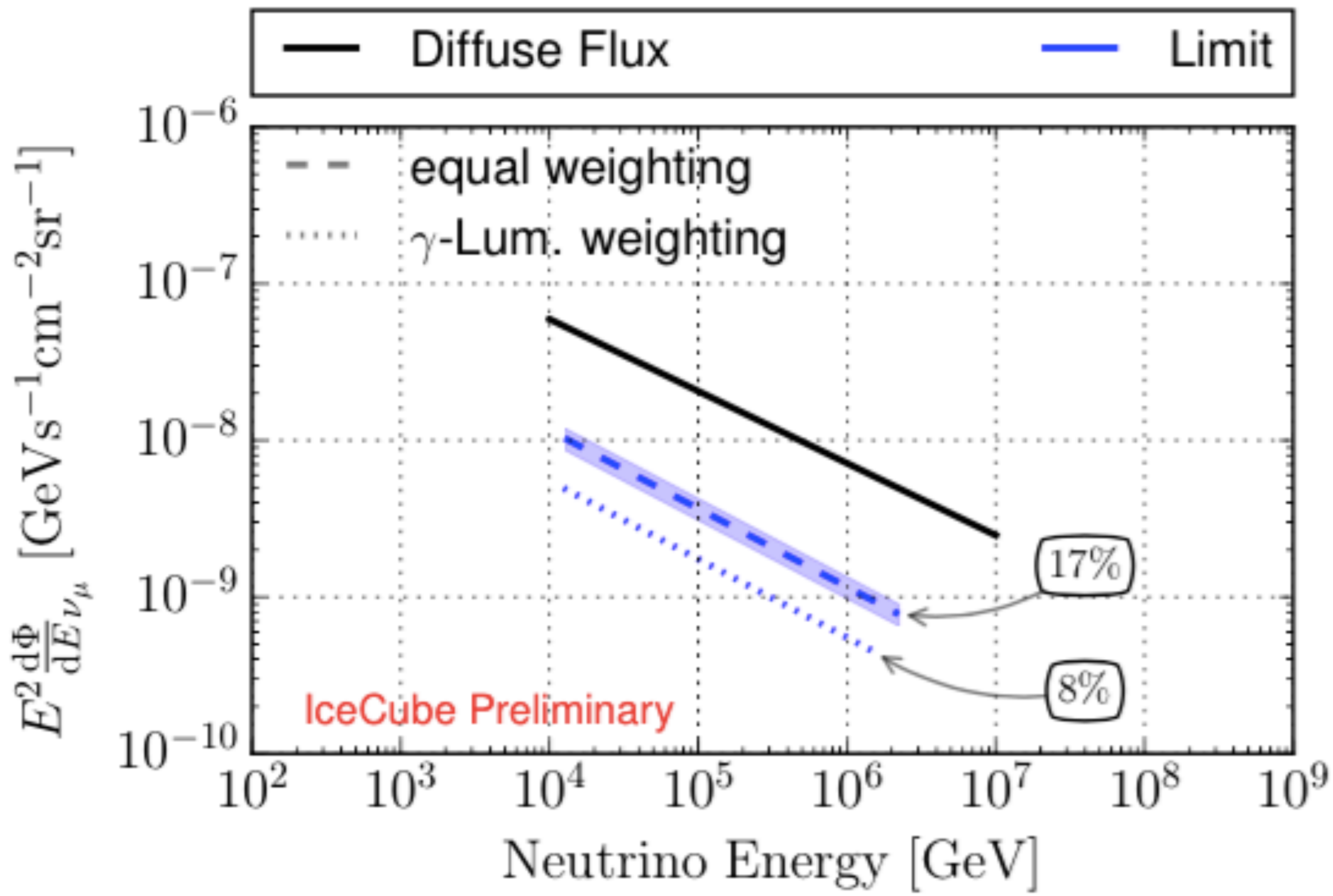
using Fermi LAT catalog of 862 Blazars (active galactic nuclei whose jets point directly at us)

No significant excess seen

Total flux upper limit is below measured diffuse neutrino flux

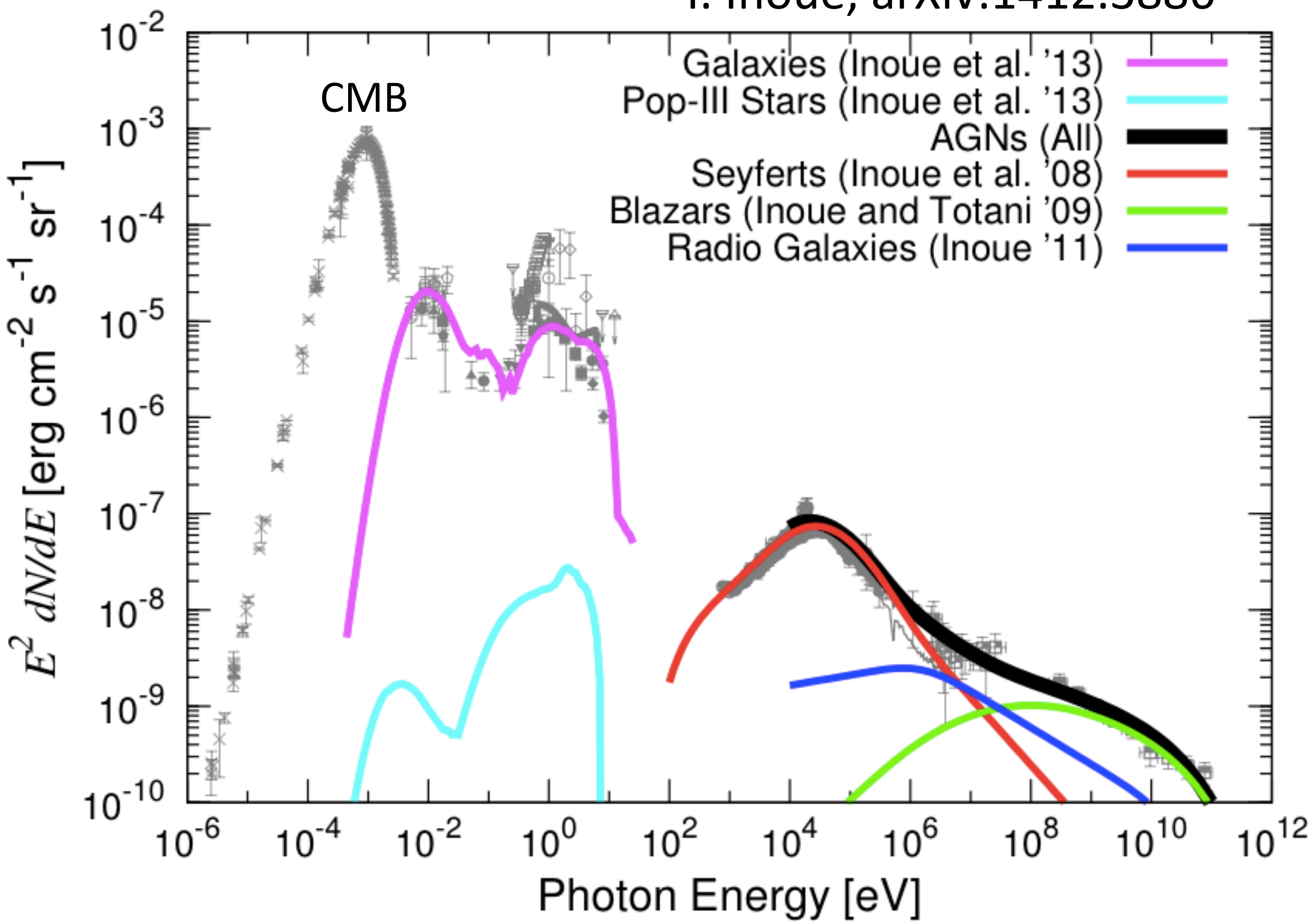
Gamma-ray Bursts already excluded, < 1% of diffuse astrophysical neutrino flux

Glüsenkamp, RICAP 2014 Proceedings



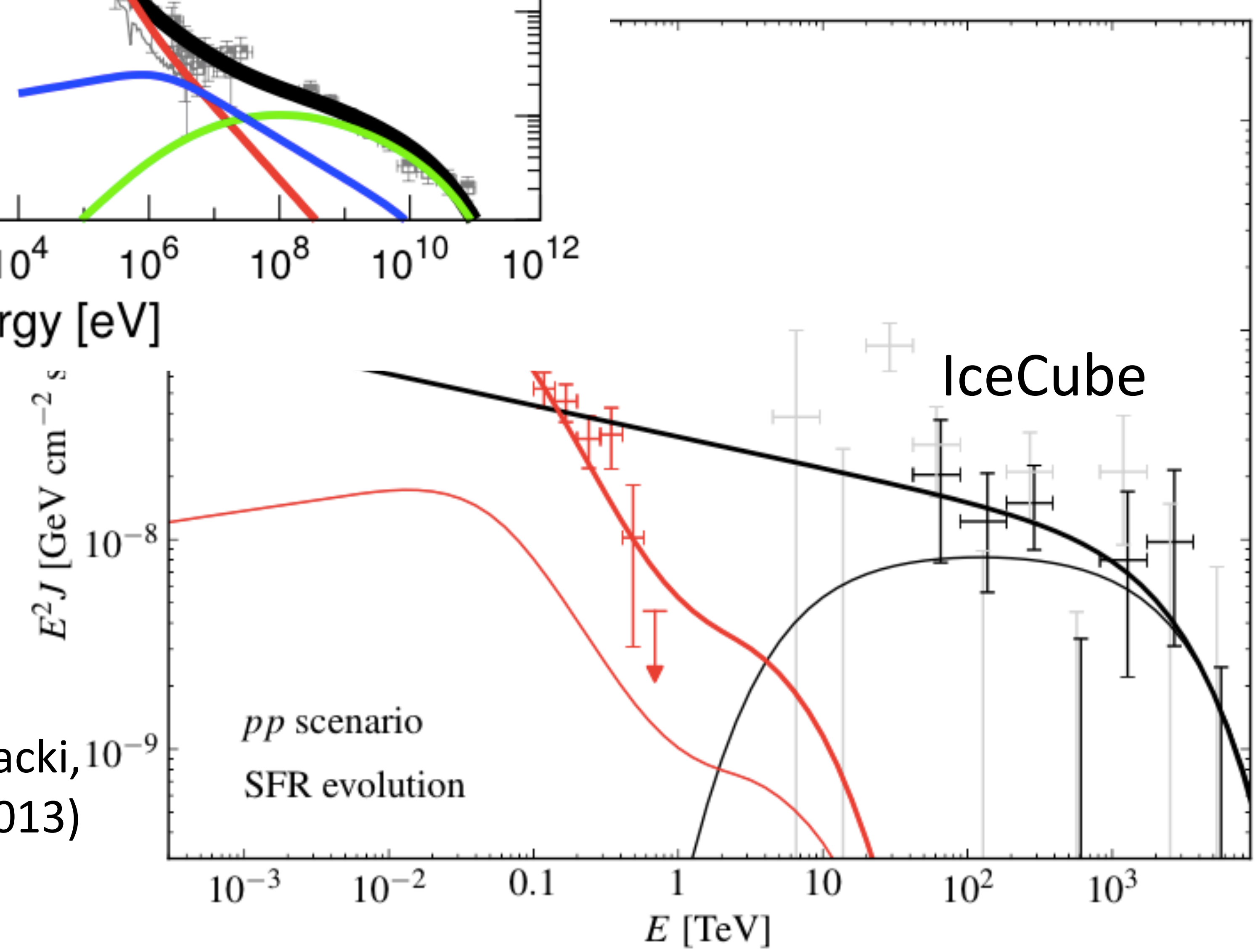
Diffuse Cosmic Background Radiation

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)

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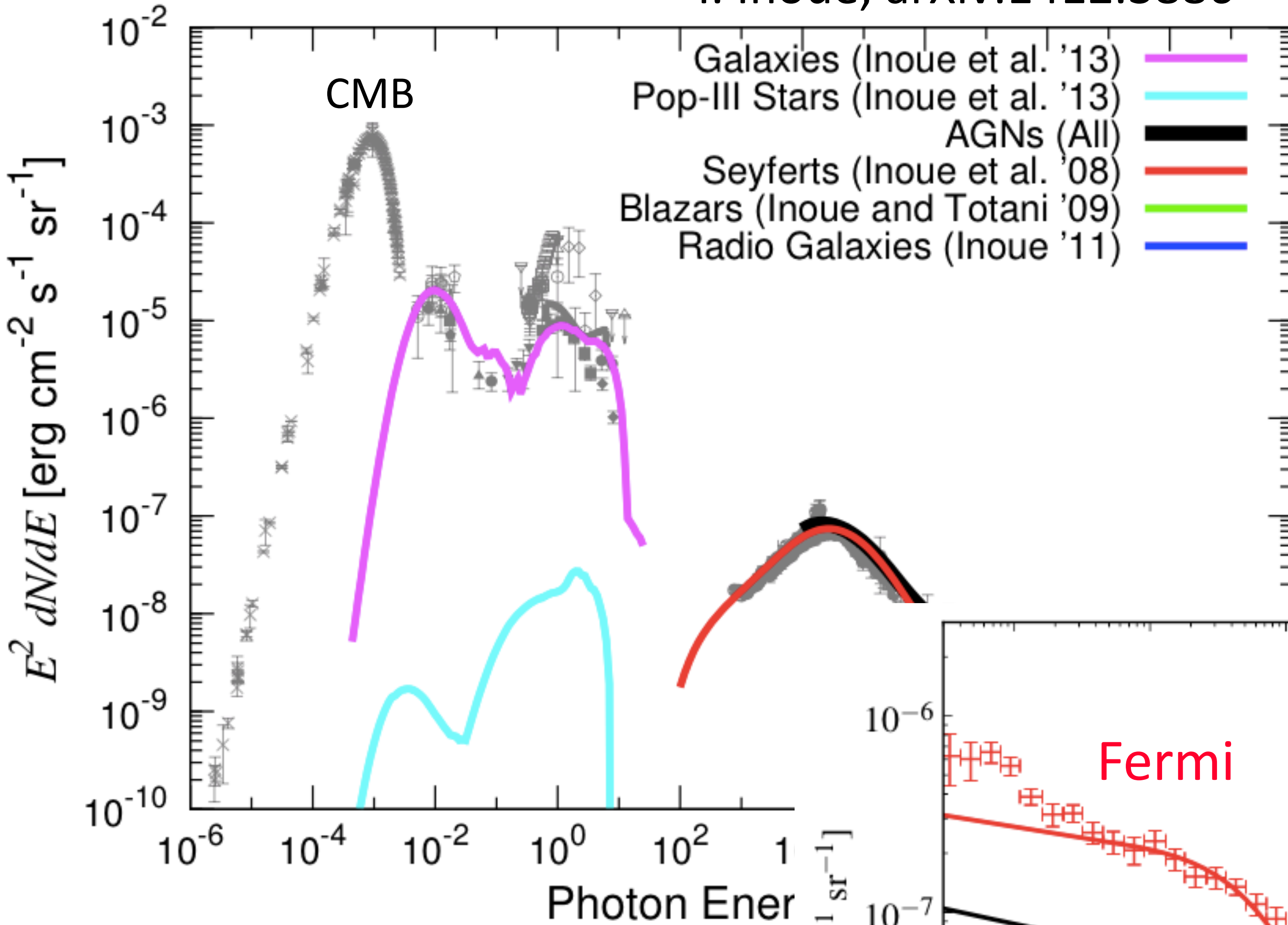

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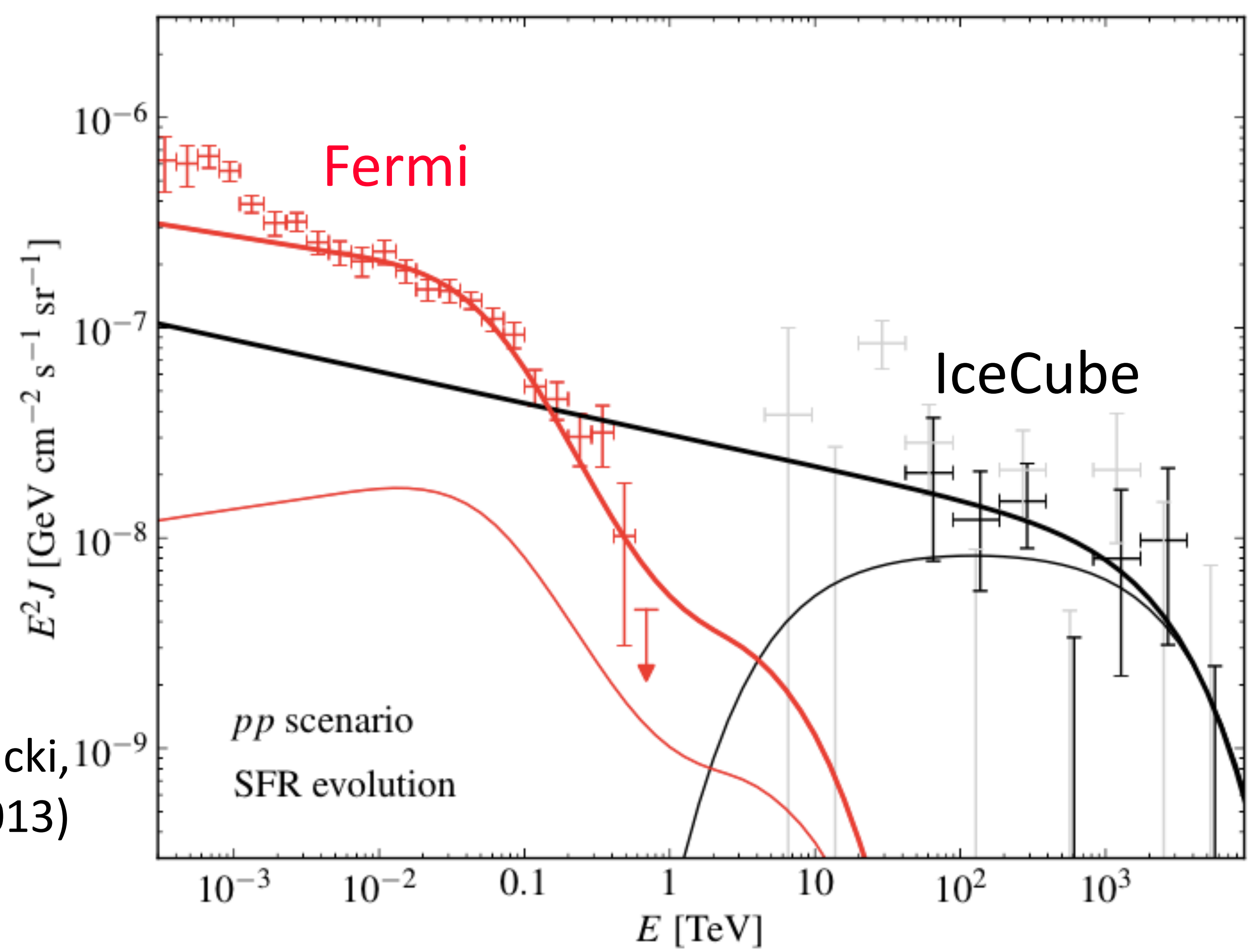


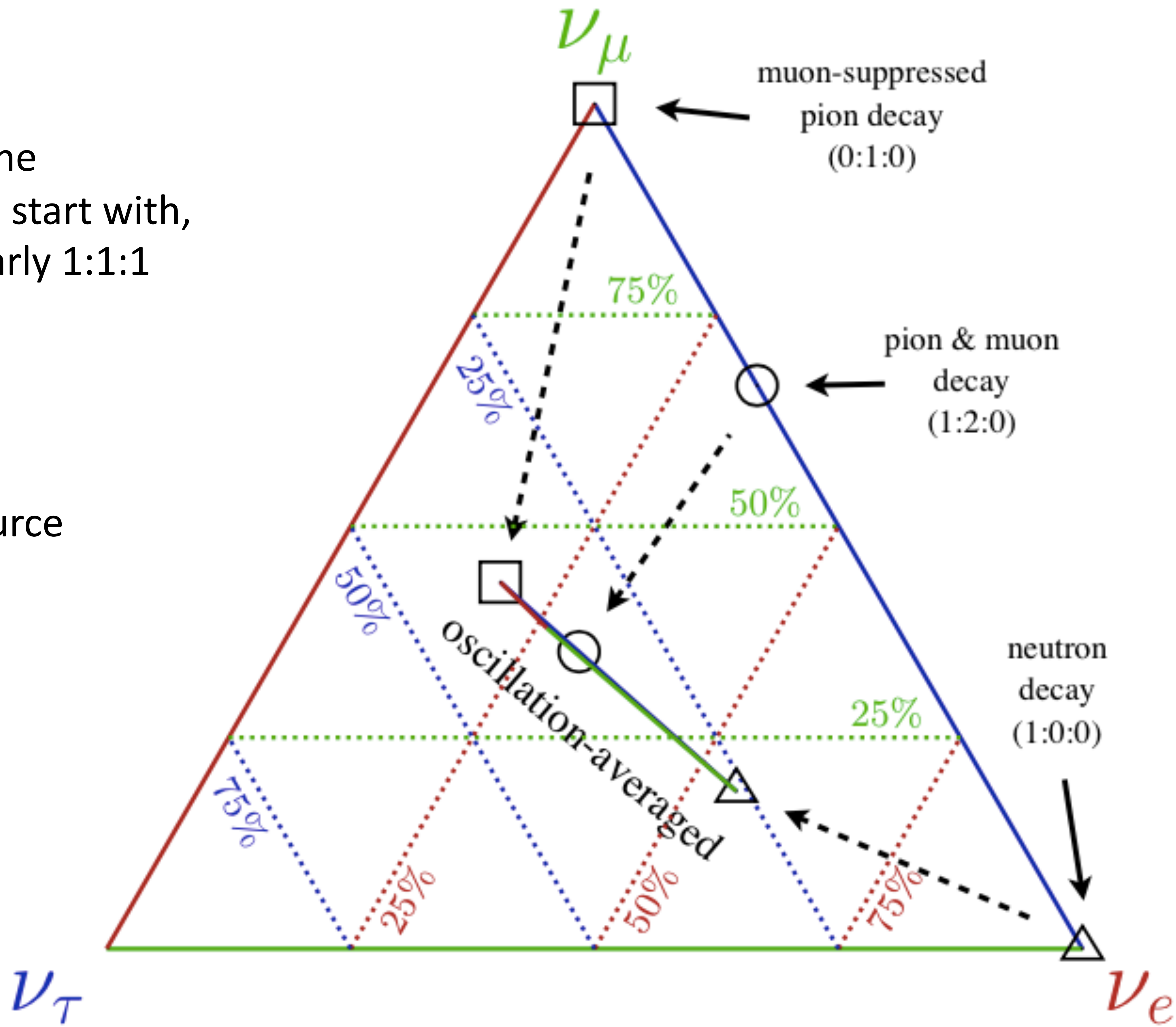
arXiv:1412.5106, after Murase, Ahlers, Lacki, Phys.Rev. D88, 121301 (2013)

Astrophysical Neutrino Flavor Ratio

Neutrino Oscillations:

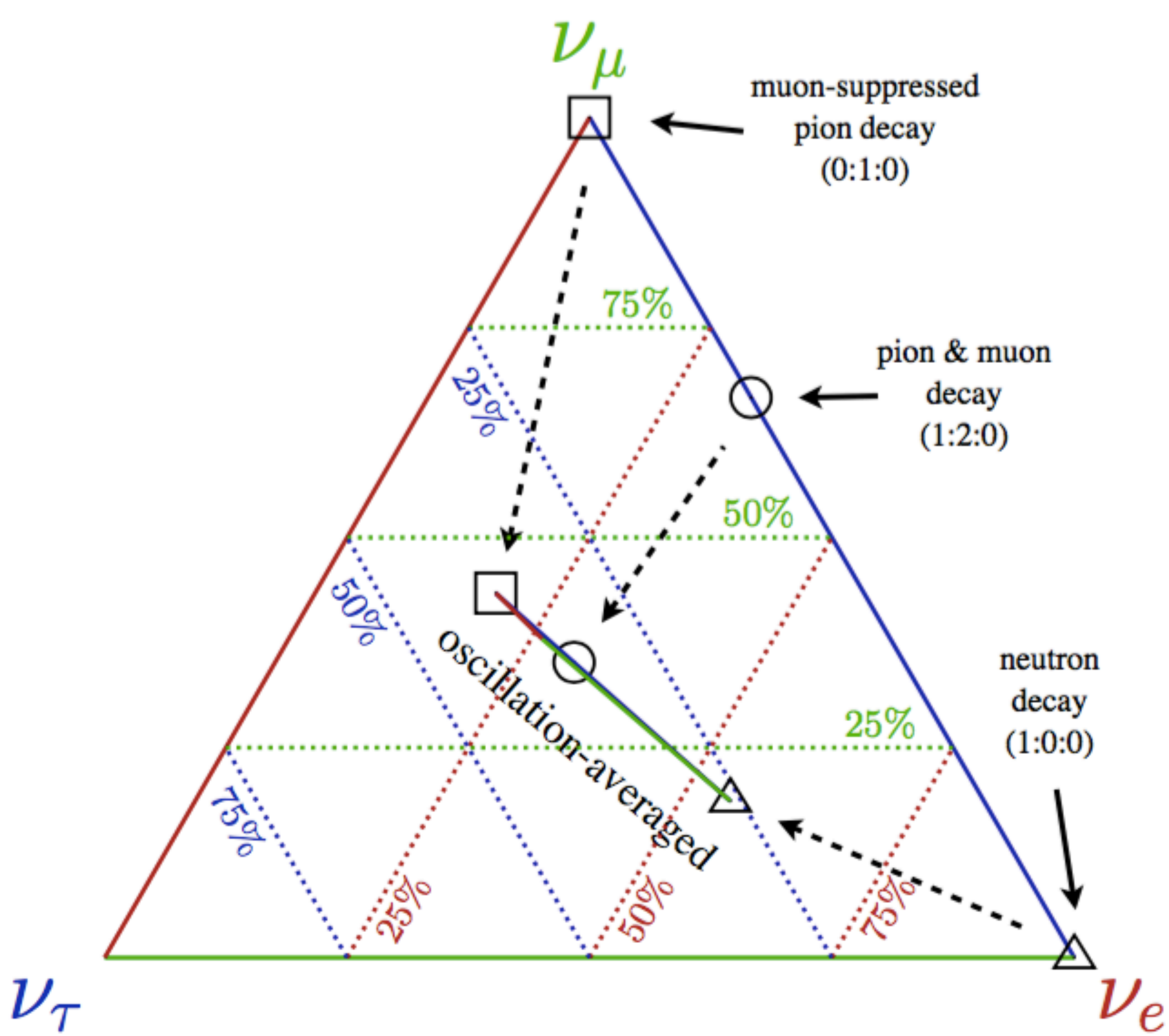
Whatever flavor ratio the astrophysical neutrinos start with, arrive at Earth with nearly 1:1:1 flavor ratio

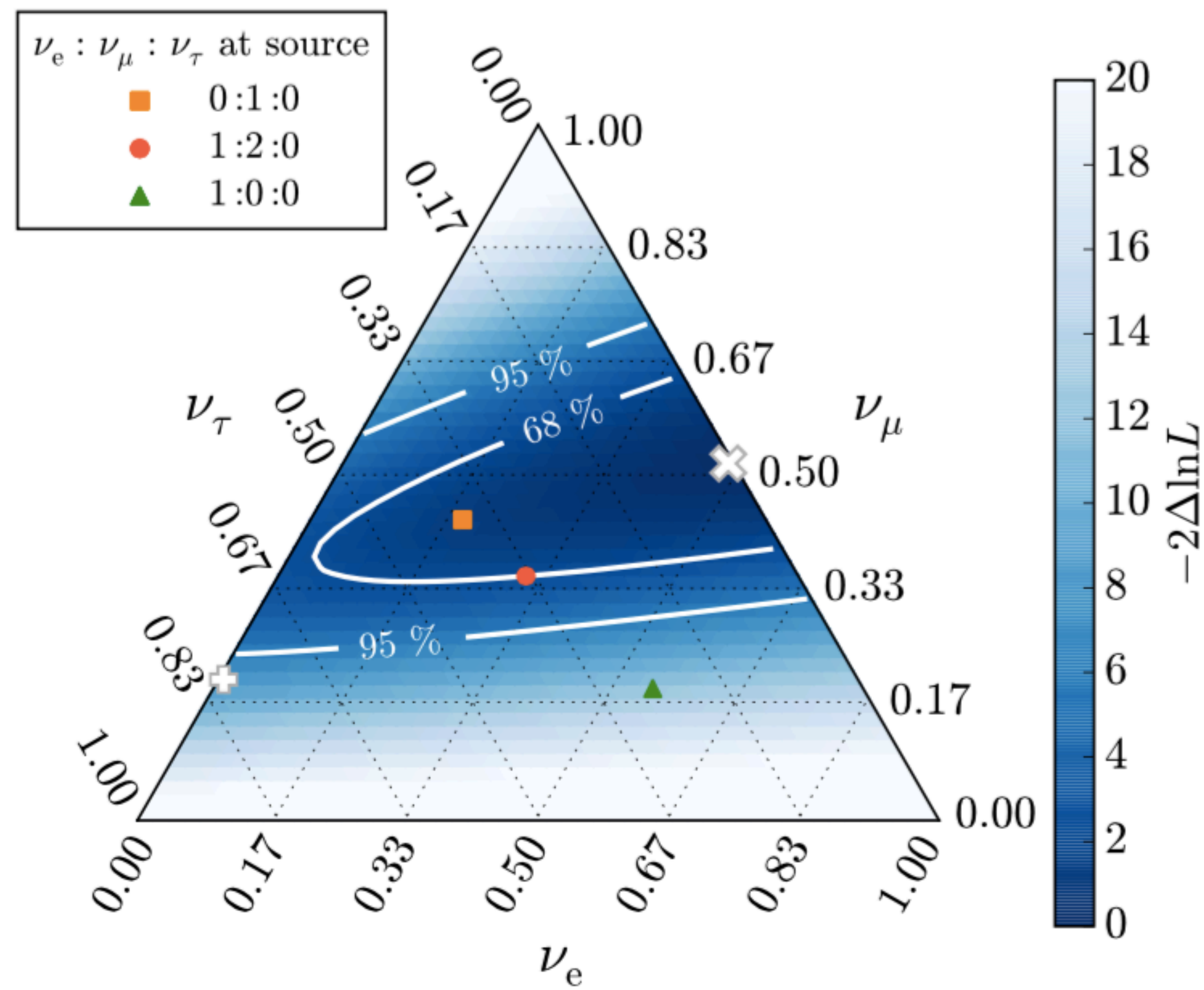
But not exactly 1:1:1…
depends on ratio at source



Astrophysical Neutrino Flavor Ratio at Earth

Measurement of flavor ratio for astrophysical neutrinos based on fit with both shower and track analyses





PRL 114, 171102 (2015) & ApJ 809, 98 (2015)

Where we stand:

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

Universe is bright at PeV energies in neutrinos!

What are the sources? Conventional, Extreme, or Exotic?

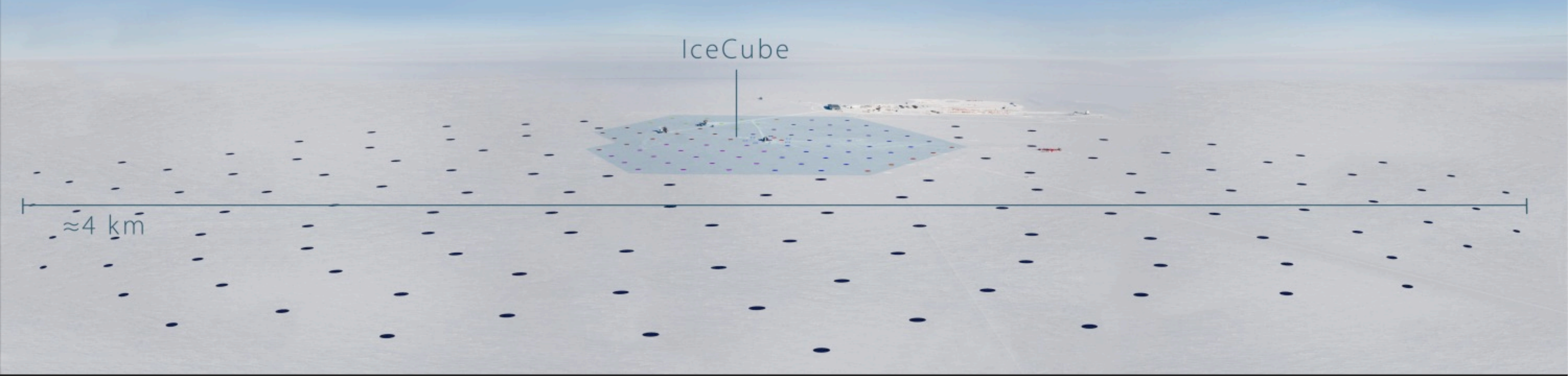
Is the spectrum and unbroken power-law? Or are there features?

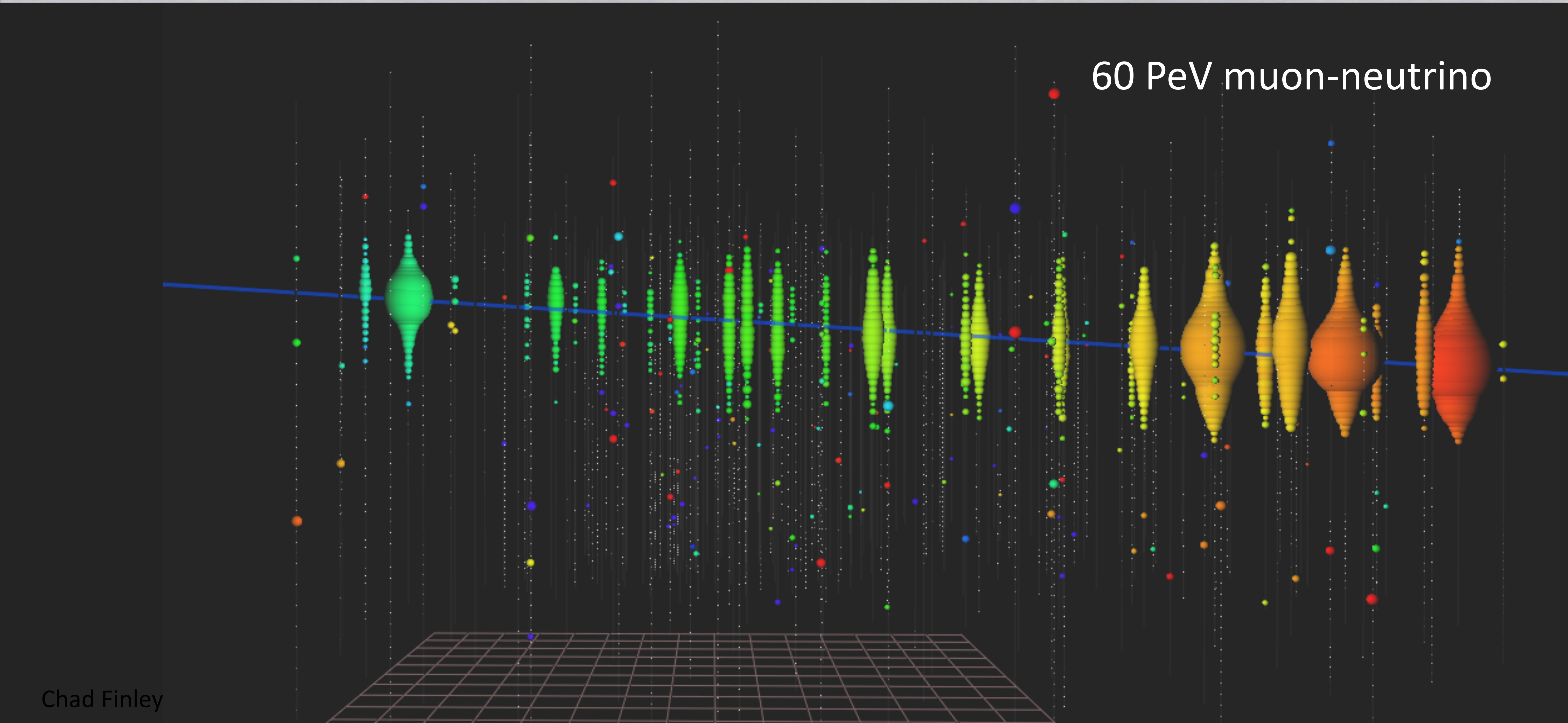
What is the flavor ratio? How well can we identify the flavor ratio at source?

Is it isotropic? Or can we identify a (sub-dominant?) galactic component?

Are the high energy neutrinos emitted from transient bursts? Or steady sources?

Simulated Event in High-Energy Array



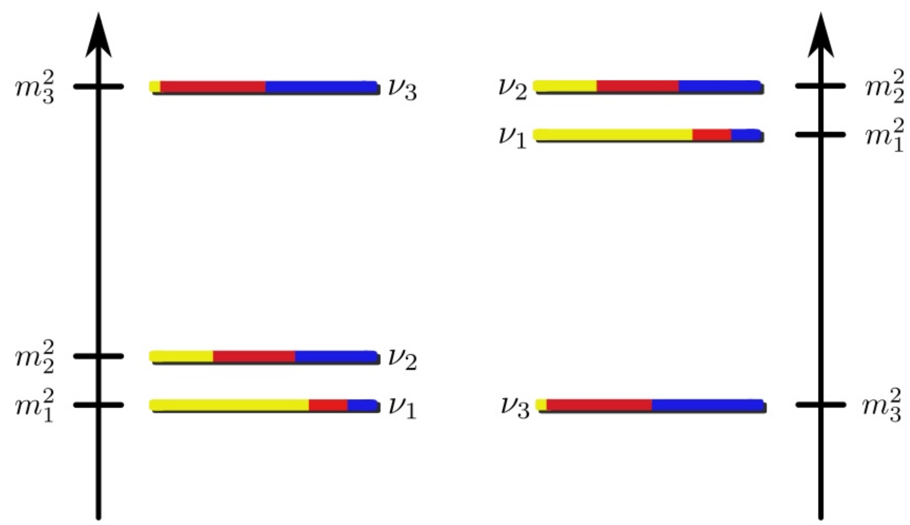


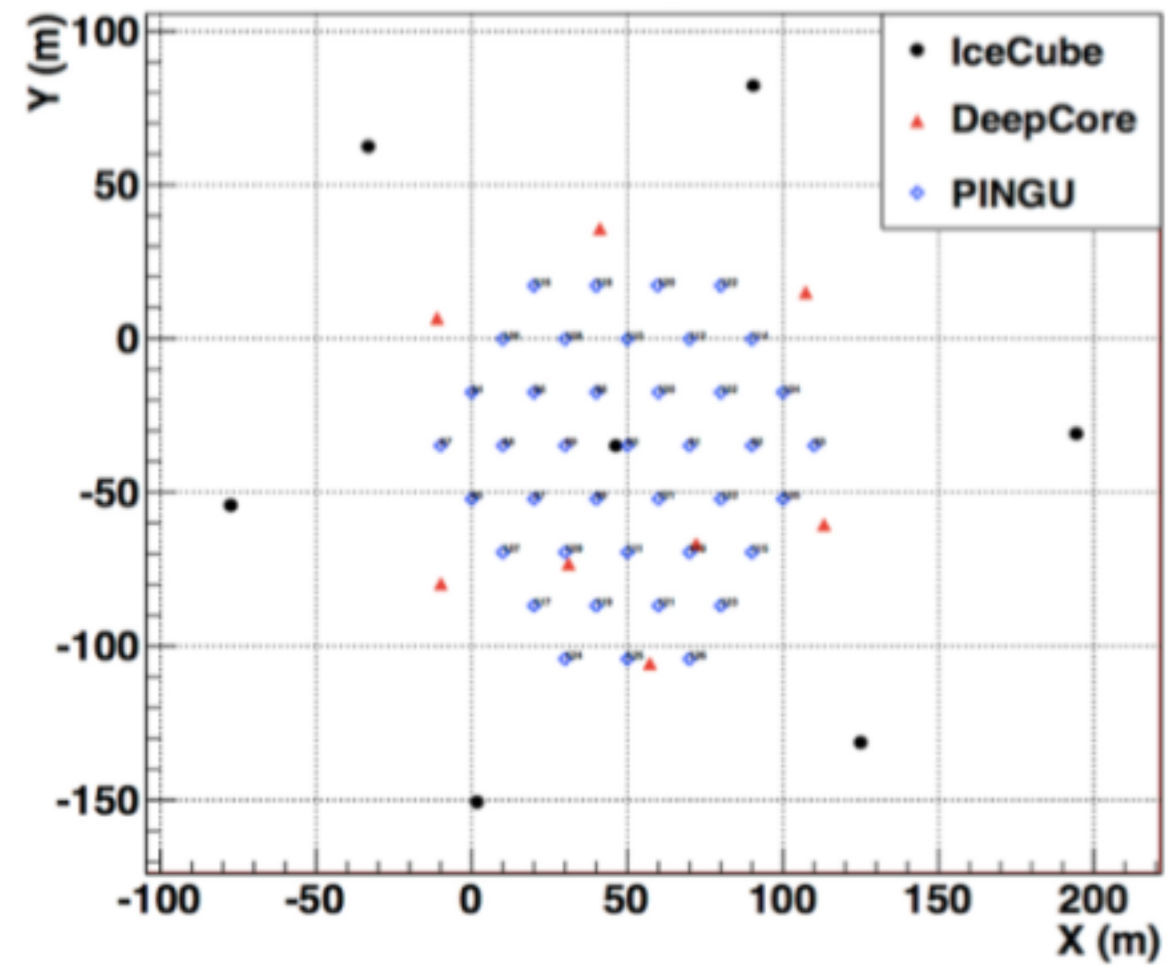
PINGU – Low Energy Array

PINGU is DeepCore infill array

- 20 m string spacing, 3-5 m DOM spacing
- 40 strings, 96 DOMs per string

Major goal: determine Neutrino Mass Ordering





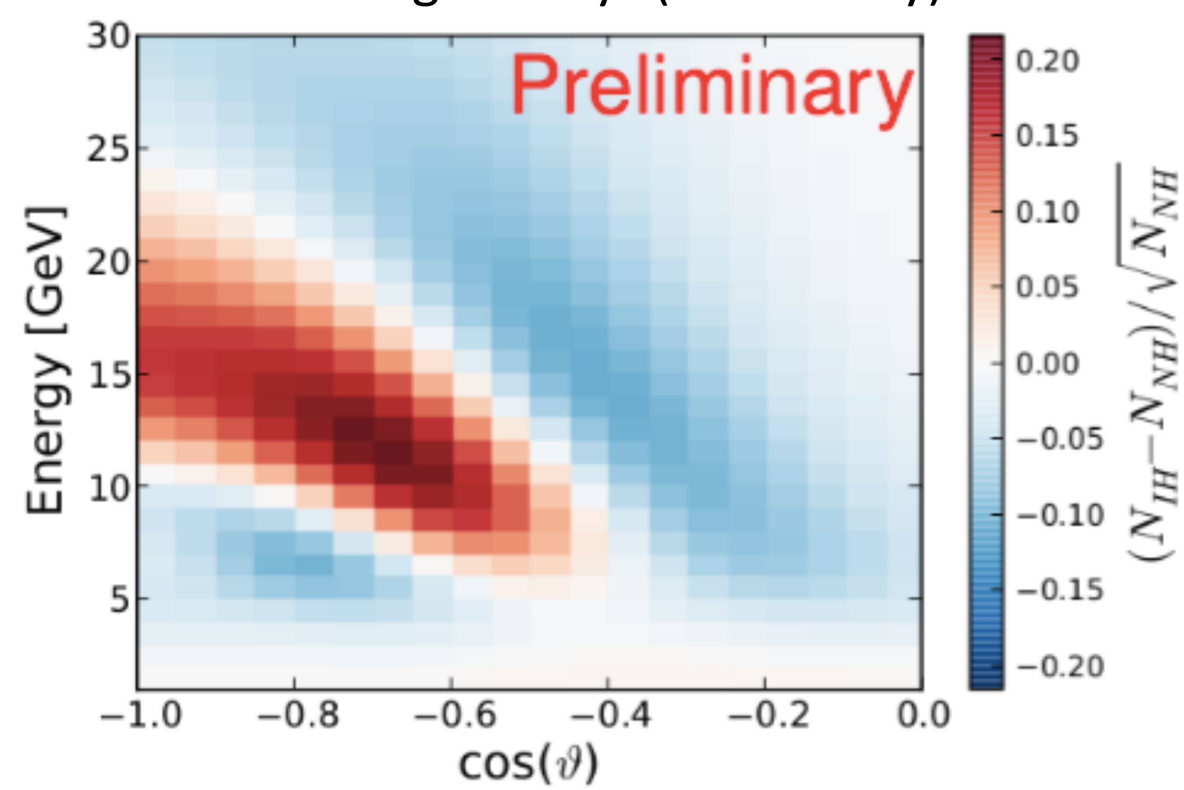
Atmospheric neutrinos in 3-15 GeV range – Oscillation pattern affected differently depending on NMO

3 sigma determination of NMO with 3-4 yrs data

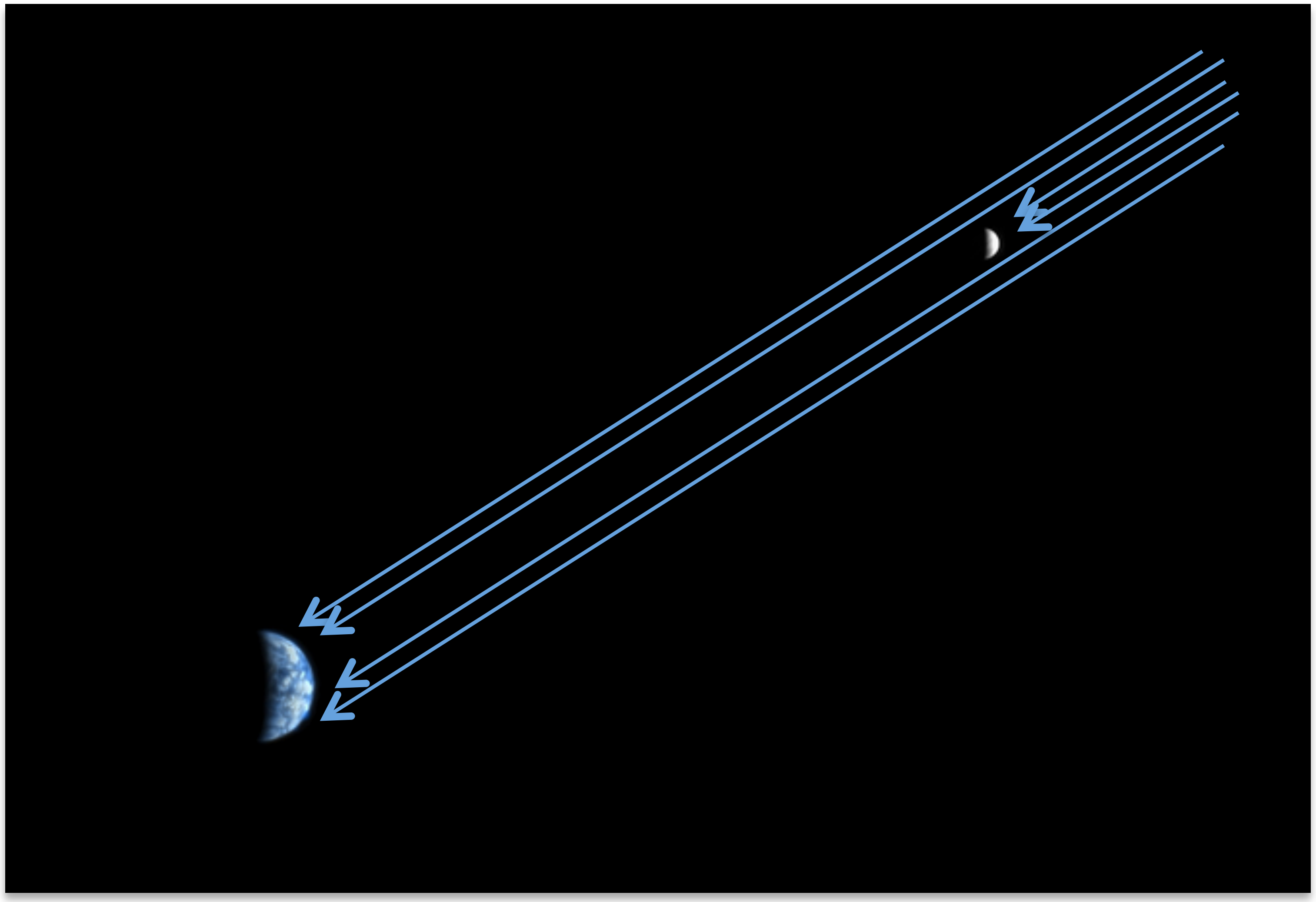
Competitive osc. parameter measurements obtained with DeepCore demonstrate capability

PRD 91, 072004 (2015), PRL 111, 081801 (2013)

bin-wise sig. for 1 yr (tracks only)



Cosmic Ray Moon Shadow



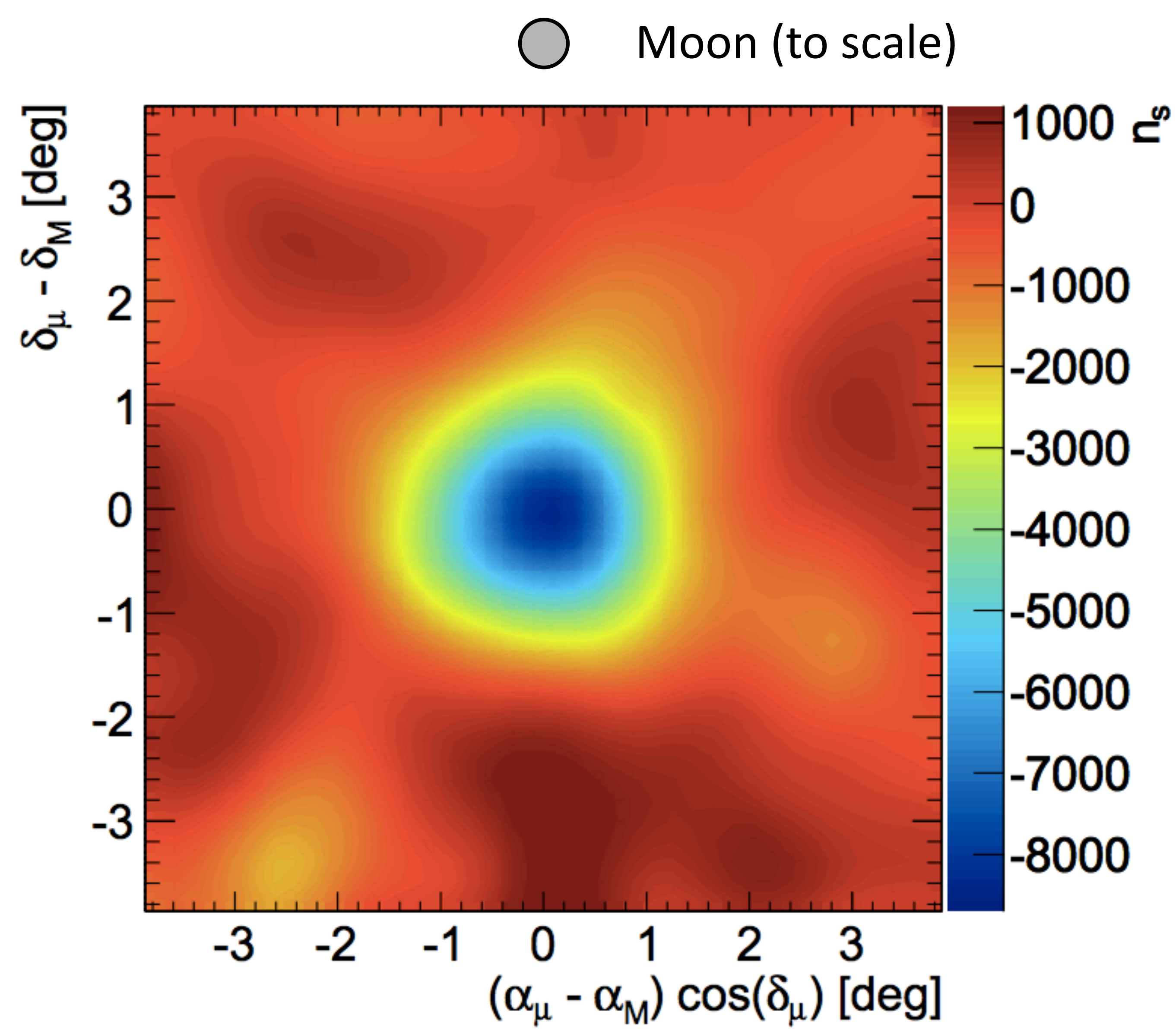
Cosmic rays are blocked by the moon (radius 0.25°)

Causes small point-like deficit of cosmic ray showers detected by IceCube

There are no neutrino sources bright enough to calibrate pointing with!

But, cosmic ray moon shadow “negative” source is used to verify:

- absolute pointing is correct
- ~1° typical point spread function (size of deficit and shape agree with sim.)



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