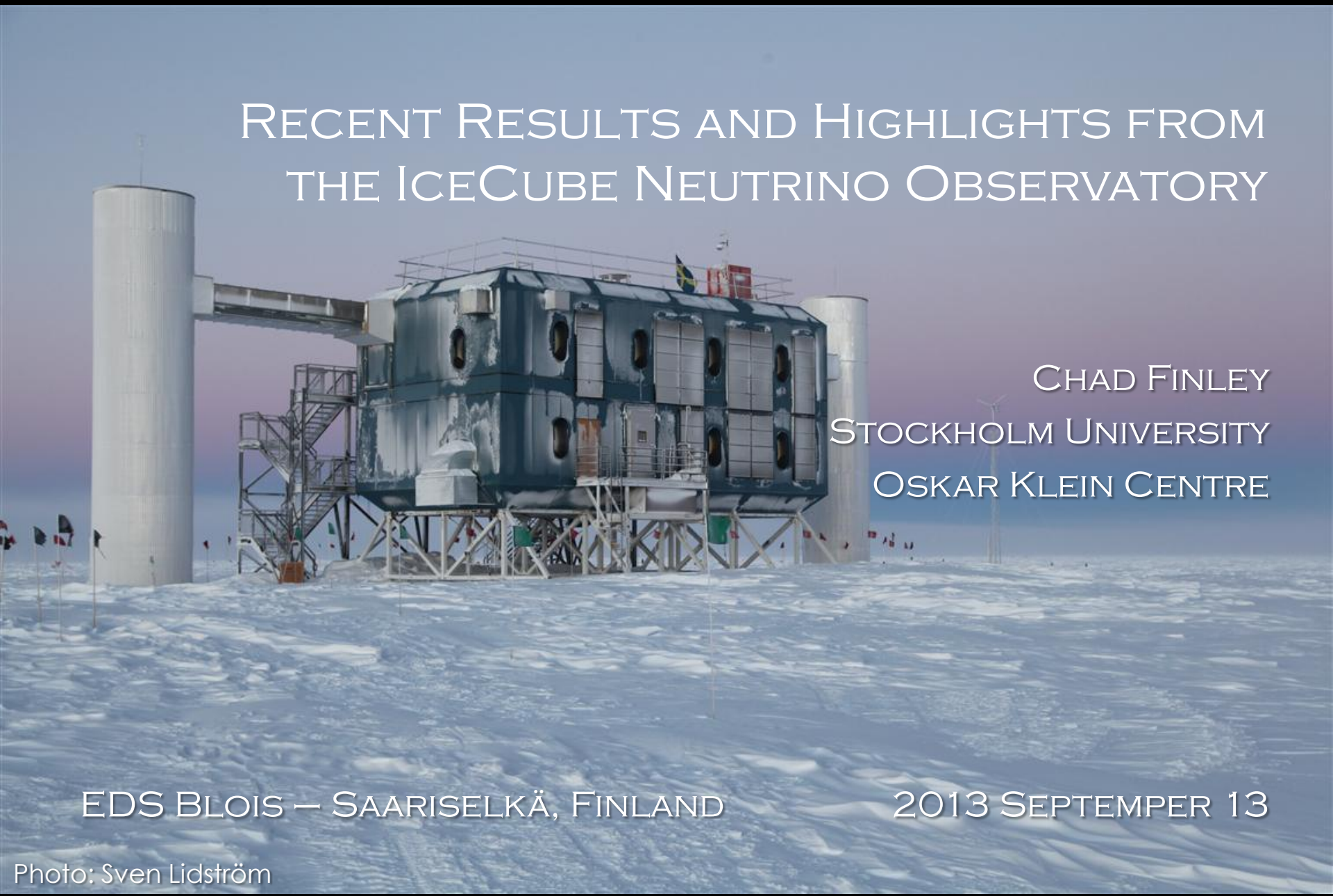
# Recent Results and Highlights from the IceCube Neutrino Observatory



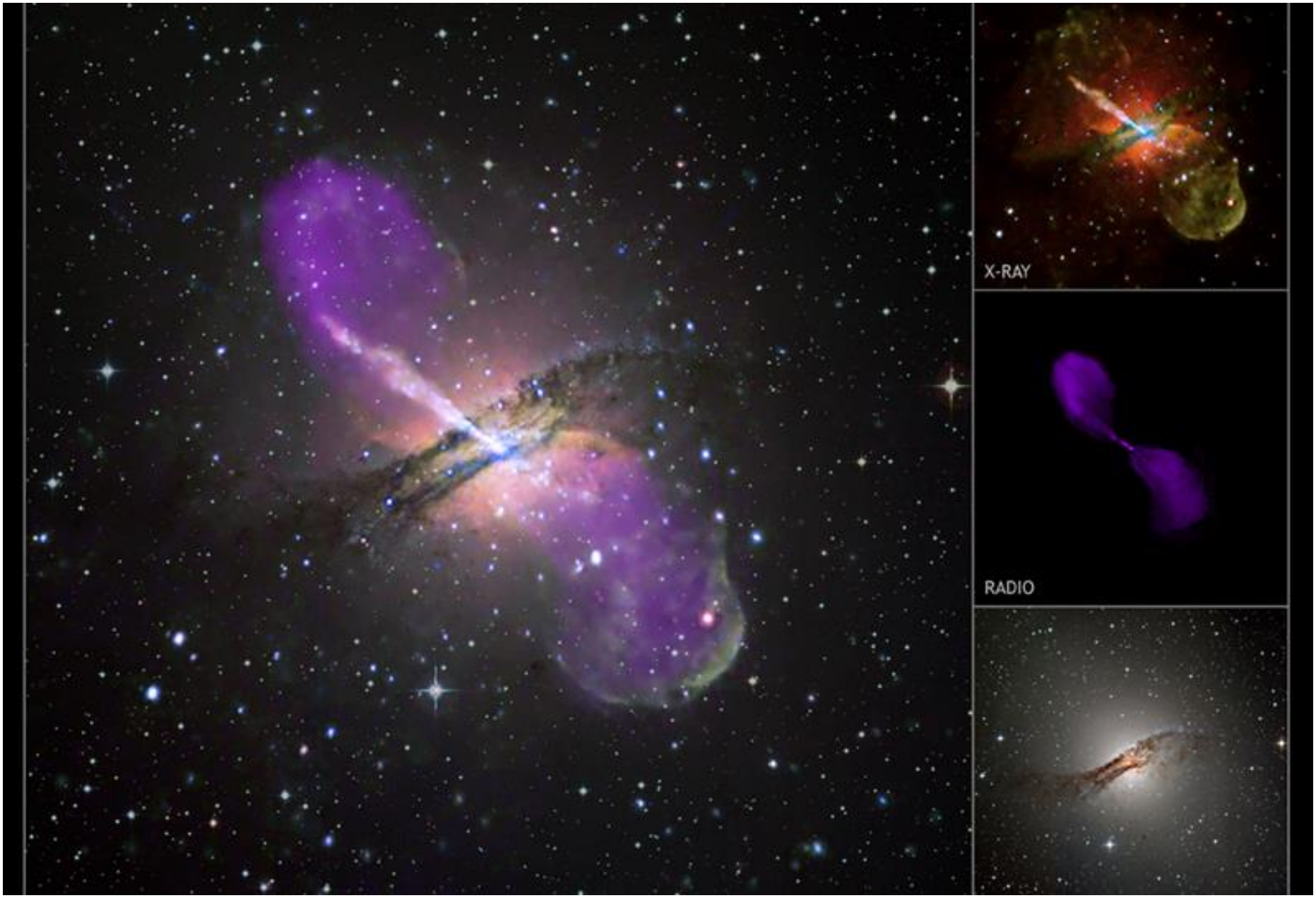
Chad Finley
Stockholm University
Oskar Klein Centre

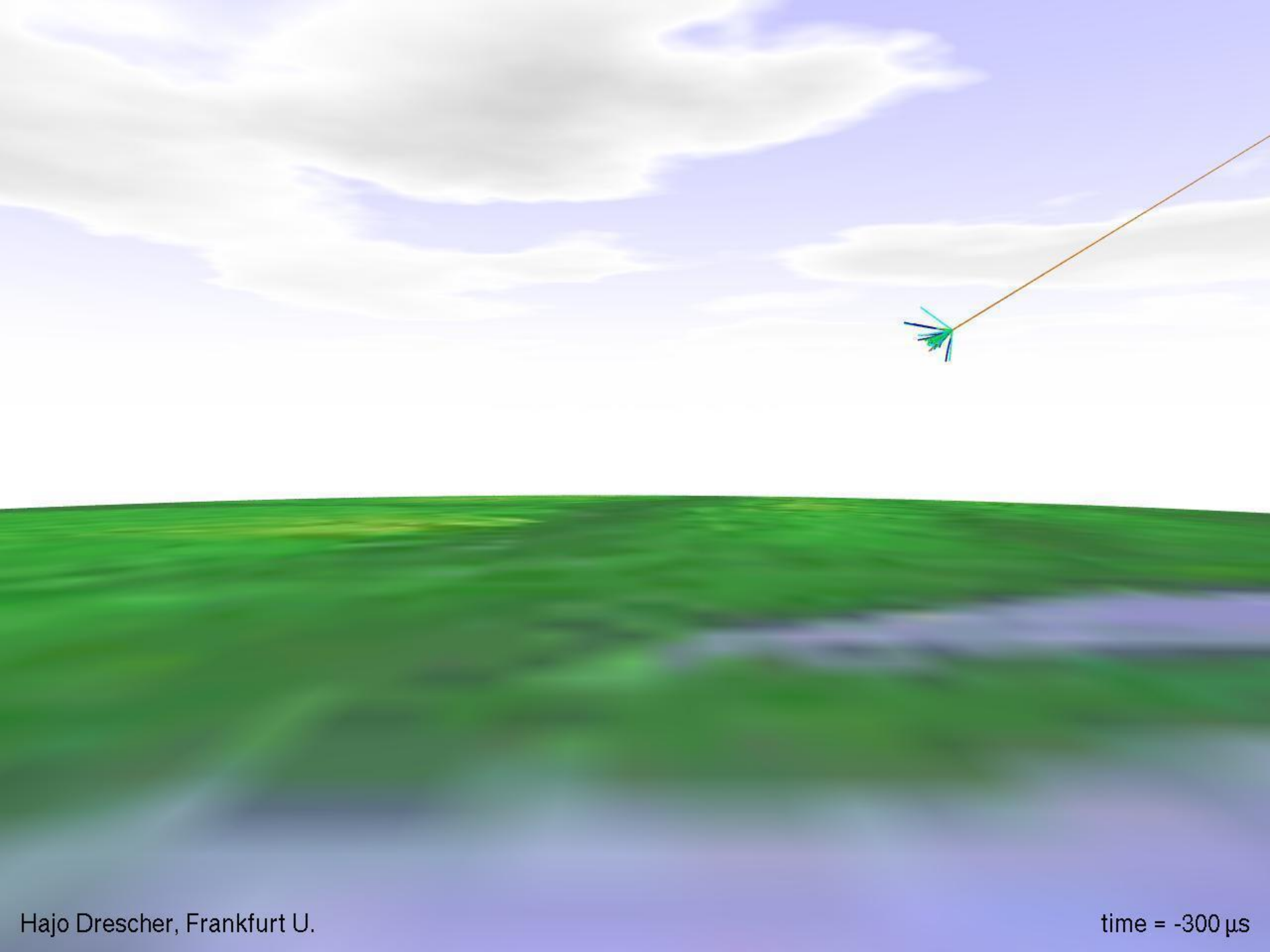
EDS Blois – Saariselkä, Finland

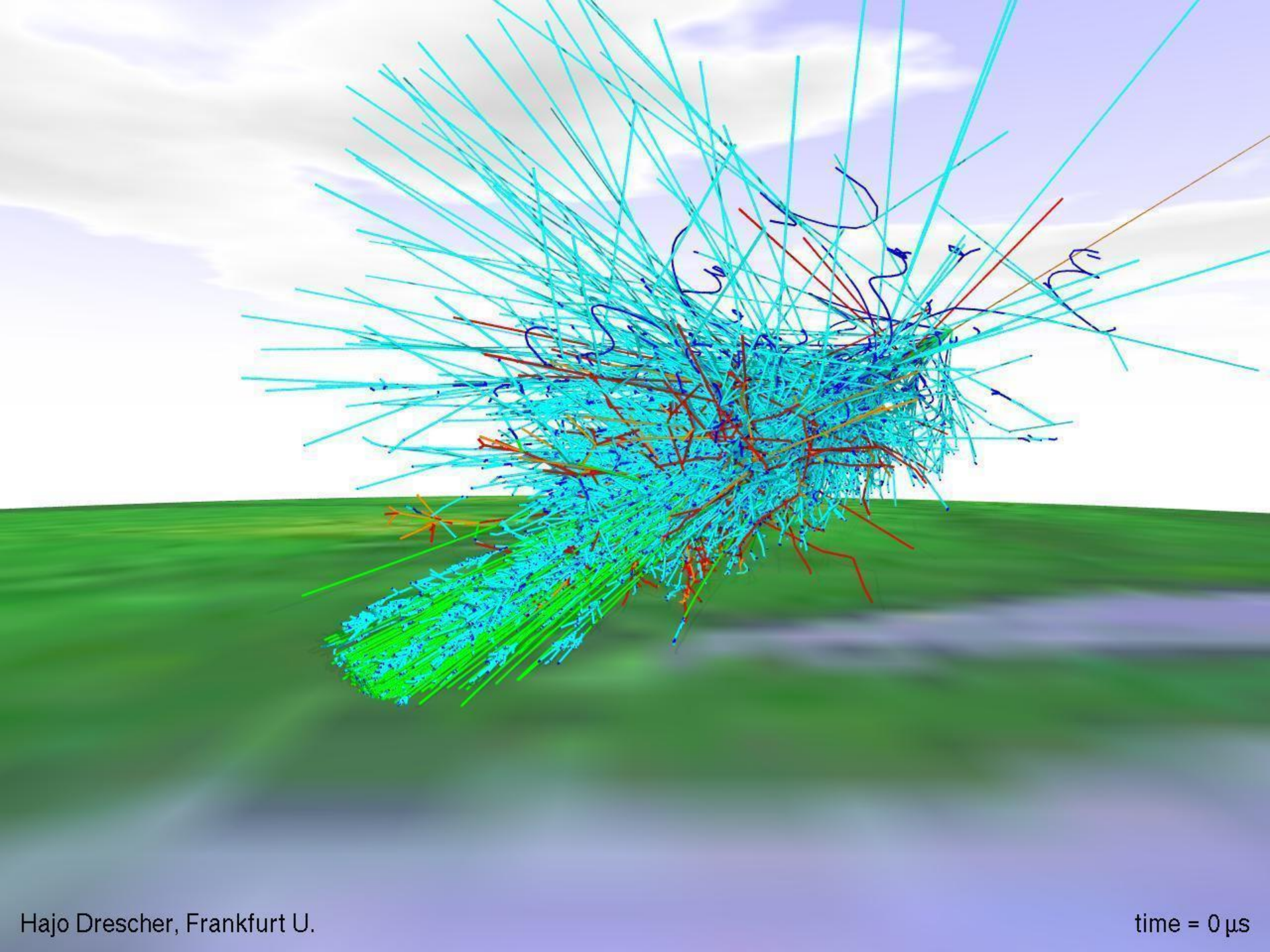
2013 Septemper 13

Photo: Sven Lidström

# Goal: Neutrino Astronomy




Hajo Drescher, Frankfurt U.
time = -300 µs

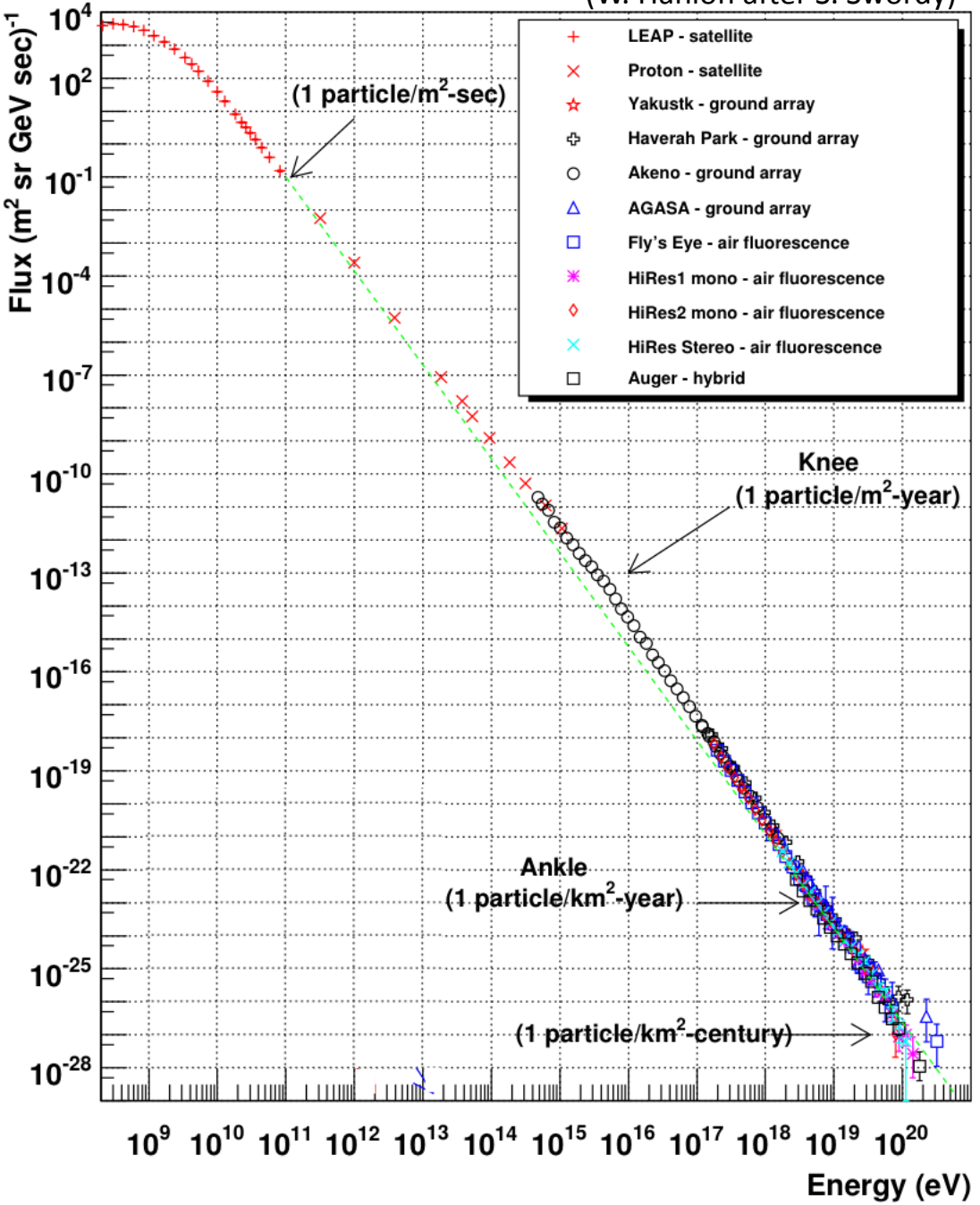

Hajo Drescher, Frankfurt U.
time = 0 µs

# The Cosmic Ray Spectrum

Extraordinary particle accelerators **somewhere**, but still **poorly identified** after a century

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

(W. Hanlon after S. Swordy)



# The Cosmic Ray Spectrum

Biggest challenge: **UHECR**
Ultrahigh energy cosmic rays:
- acceleration up to **$10^8$ TeV**

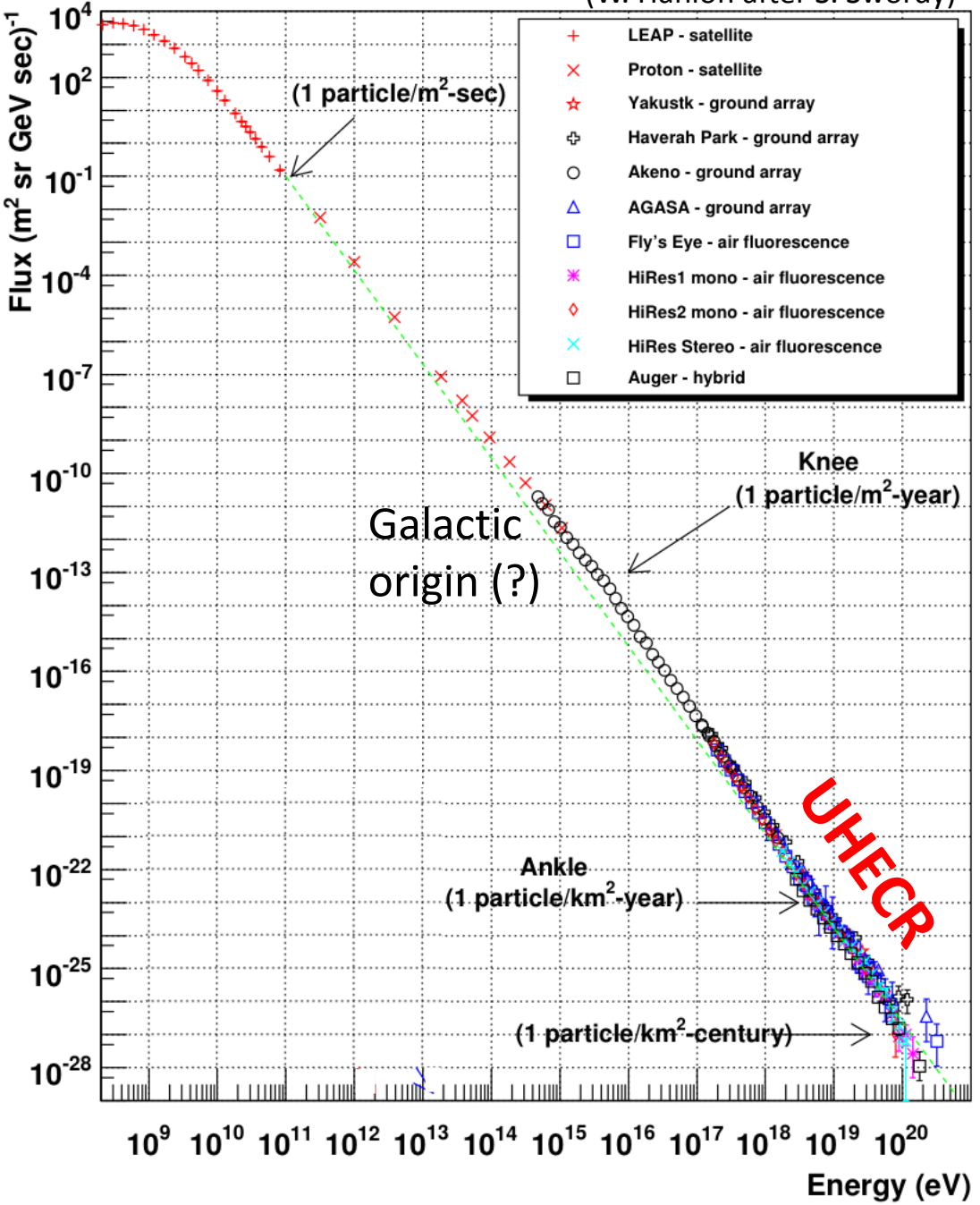
Unlike lower energies, cannot be contained by Galactic Magnetic Field

Extragalactic origin most likely

Cosmic ray interactions with matter and photons near source produce:

pions ➔ decay to
**gammas** and **neutrinos**

(W. Hanlon after S. Swordy)

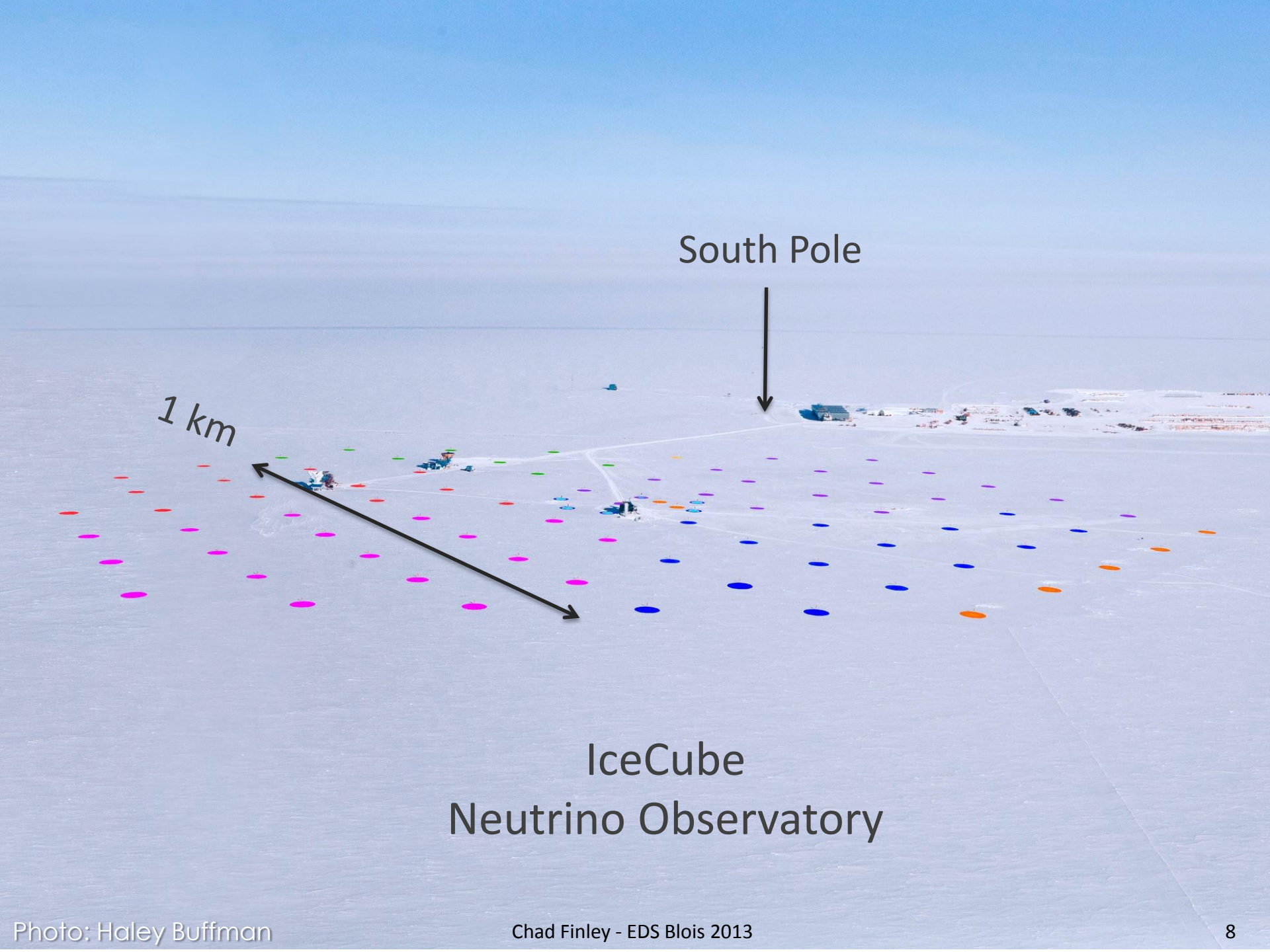


# The IceCube Collaboration



## 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)




# IceCube
# Neutrino Observatory

Photo: Haley Buffman

# IceCube Neutrino Observatory

**86 strings**

**60 Optical Modules** per string

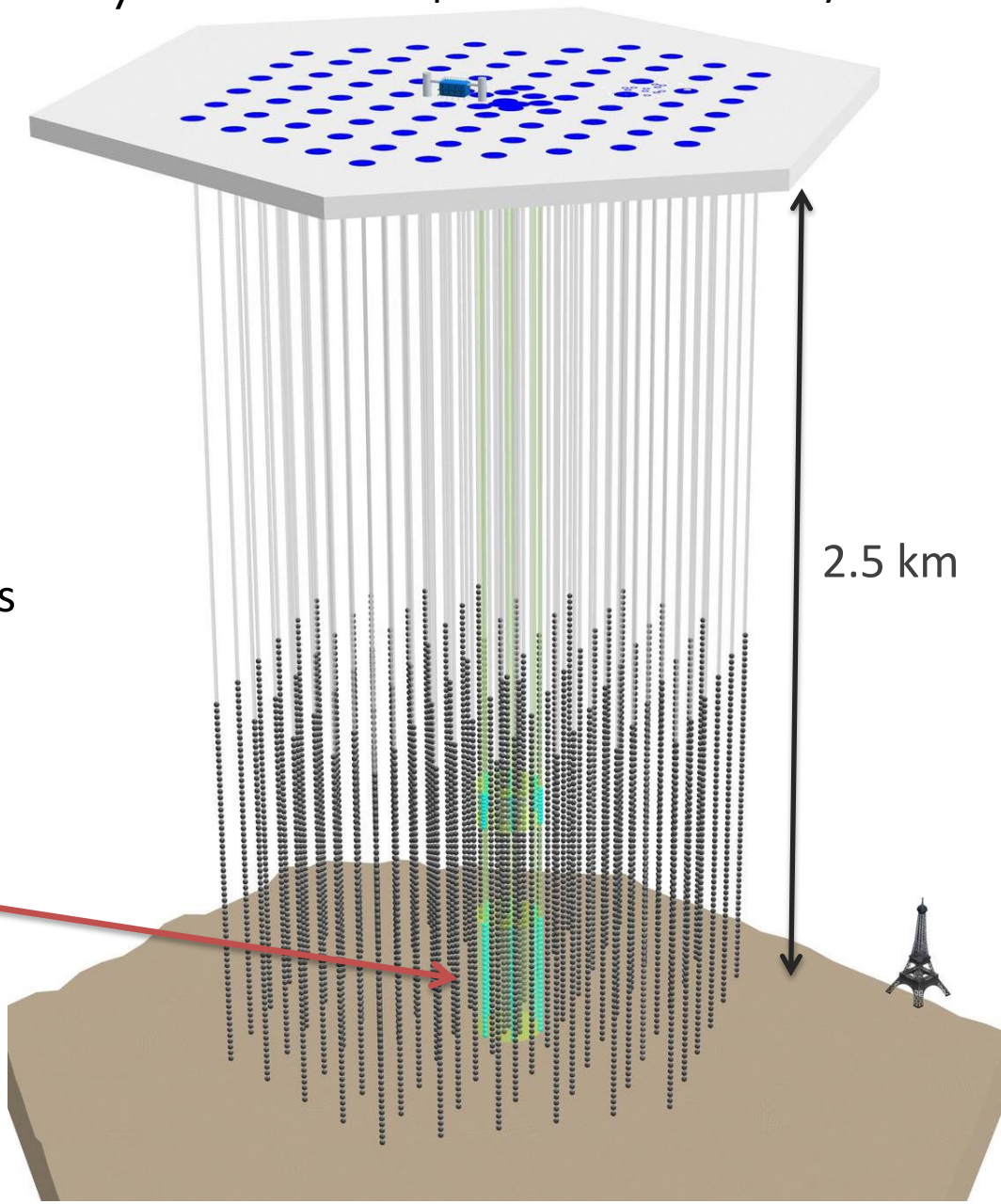
**5 160 total** modules in Ice

**1 km$^3$ = Gton instrumented volume**

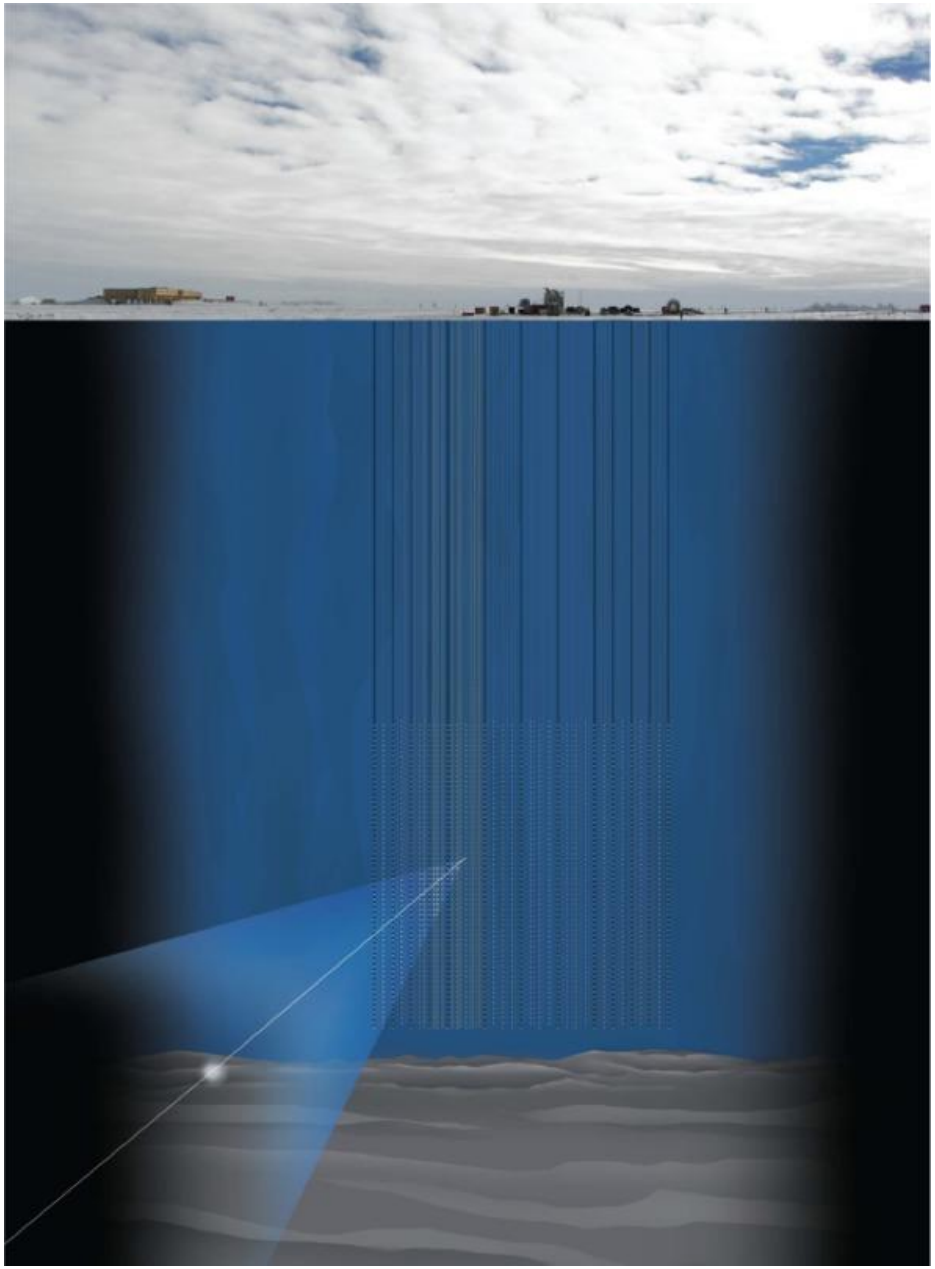
Completed and began full operations
May 2011

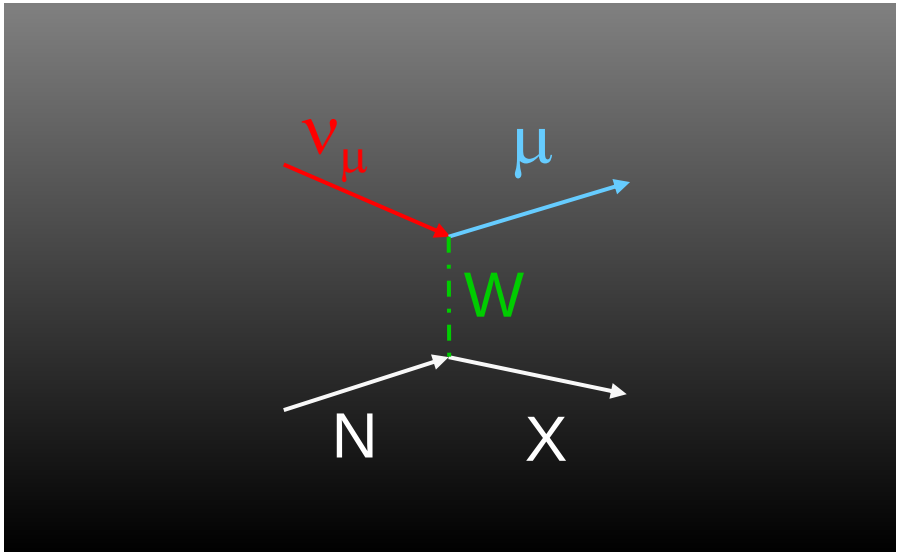
**DeepCore**

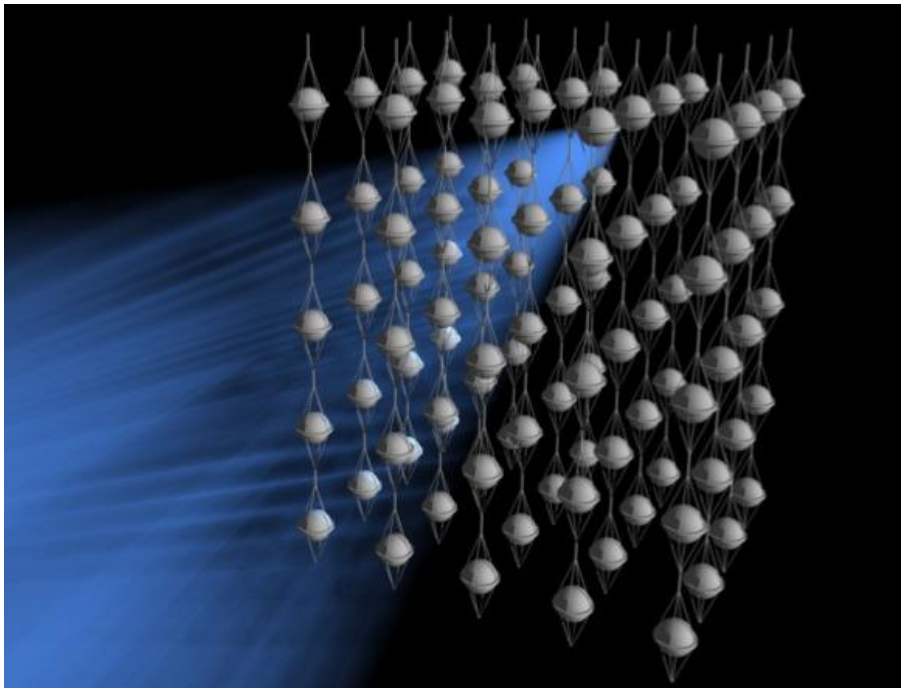
Low-energy Infill Array



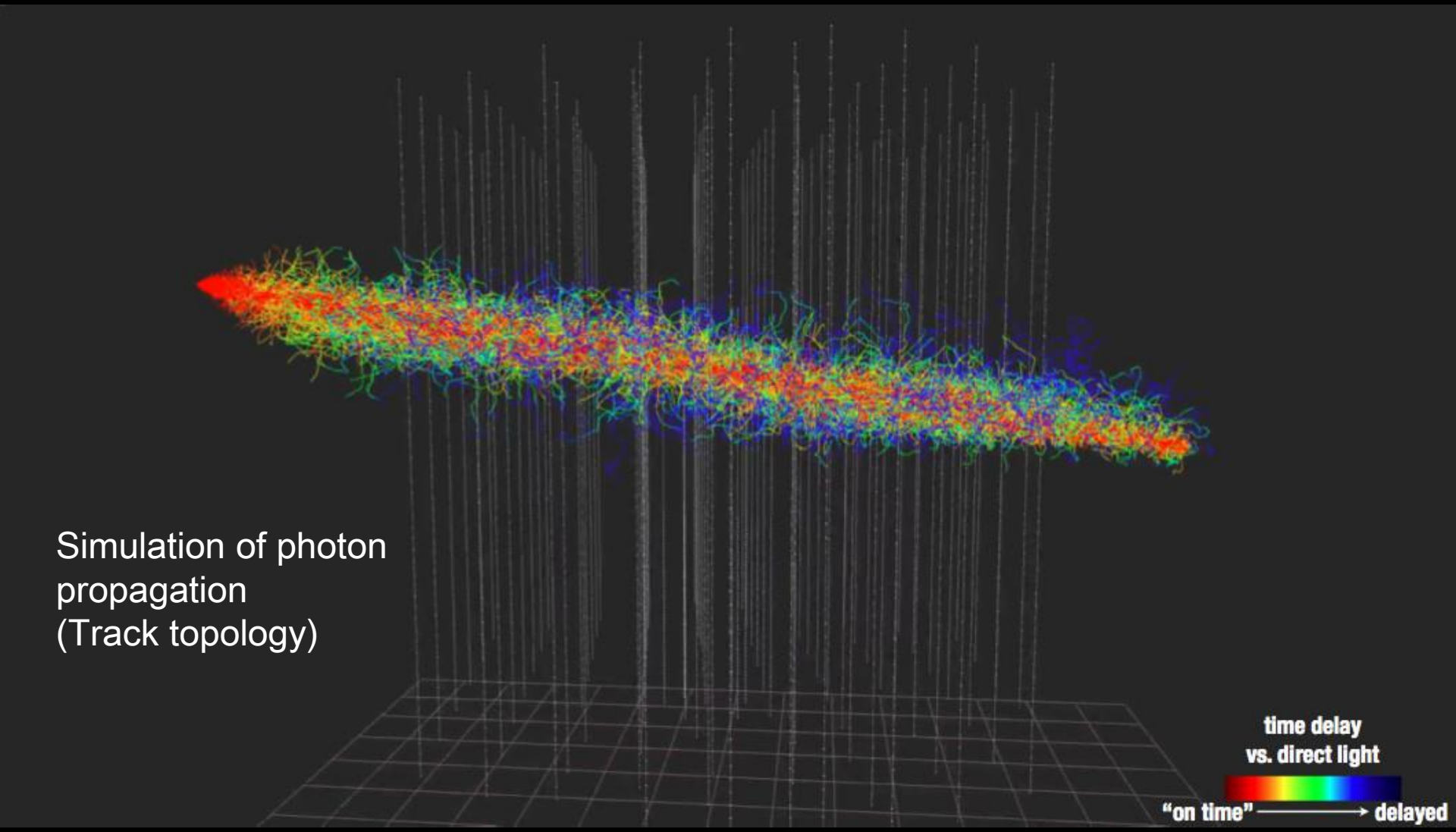
# High Energy Neutrino Detection Principles





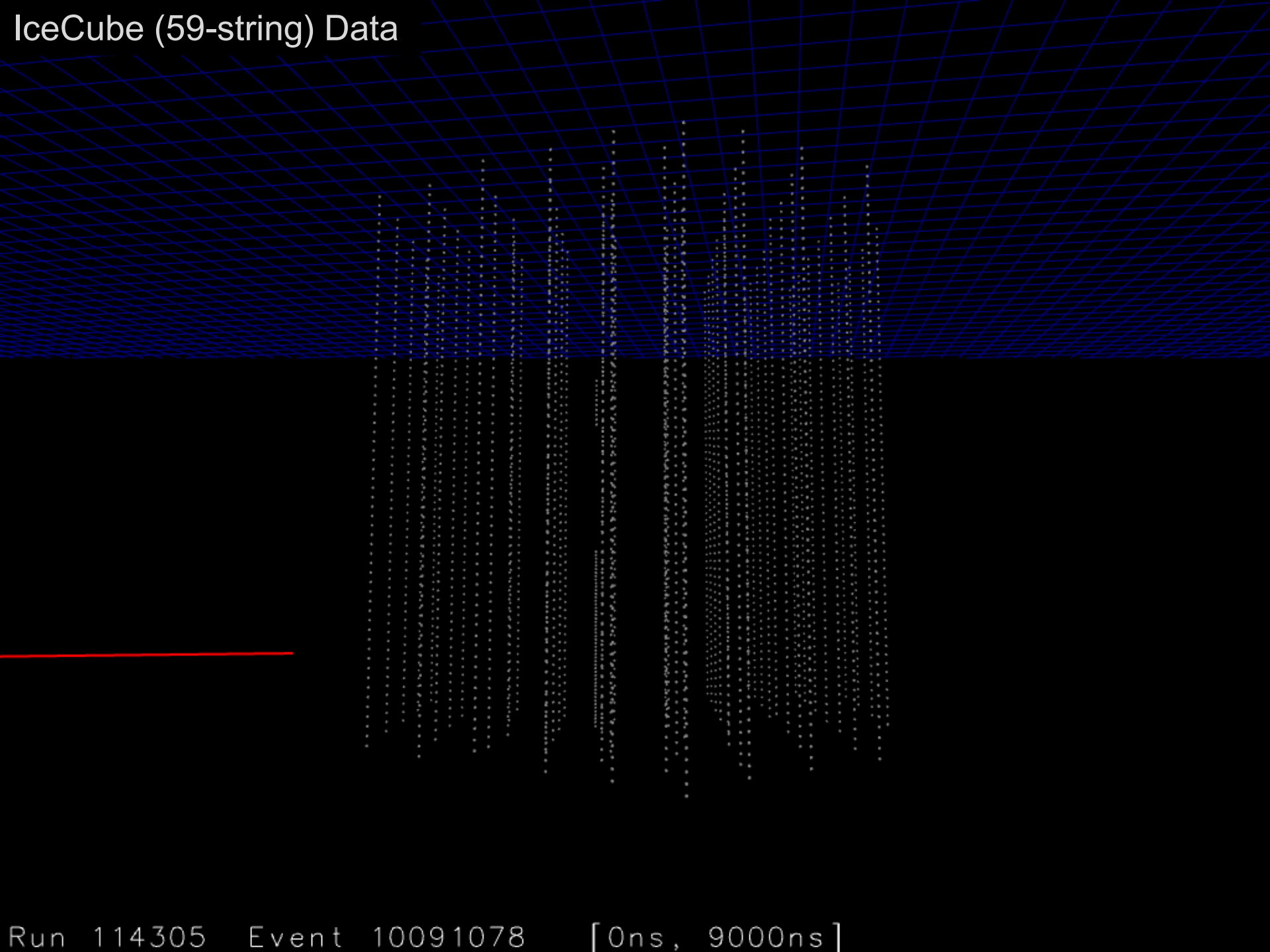
**Charged-current muon neutrino** interaction – create muon, can travel kilometers

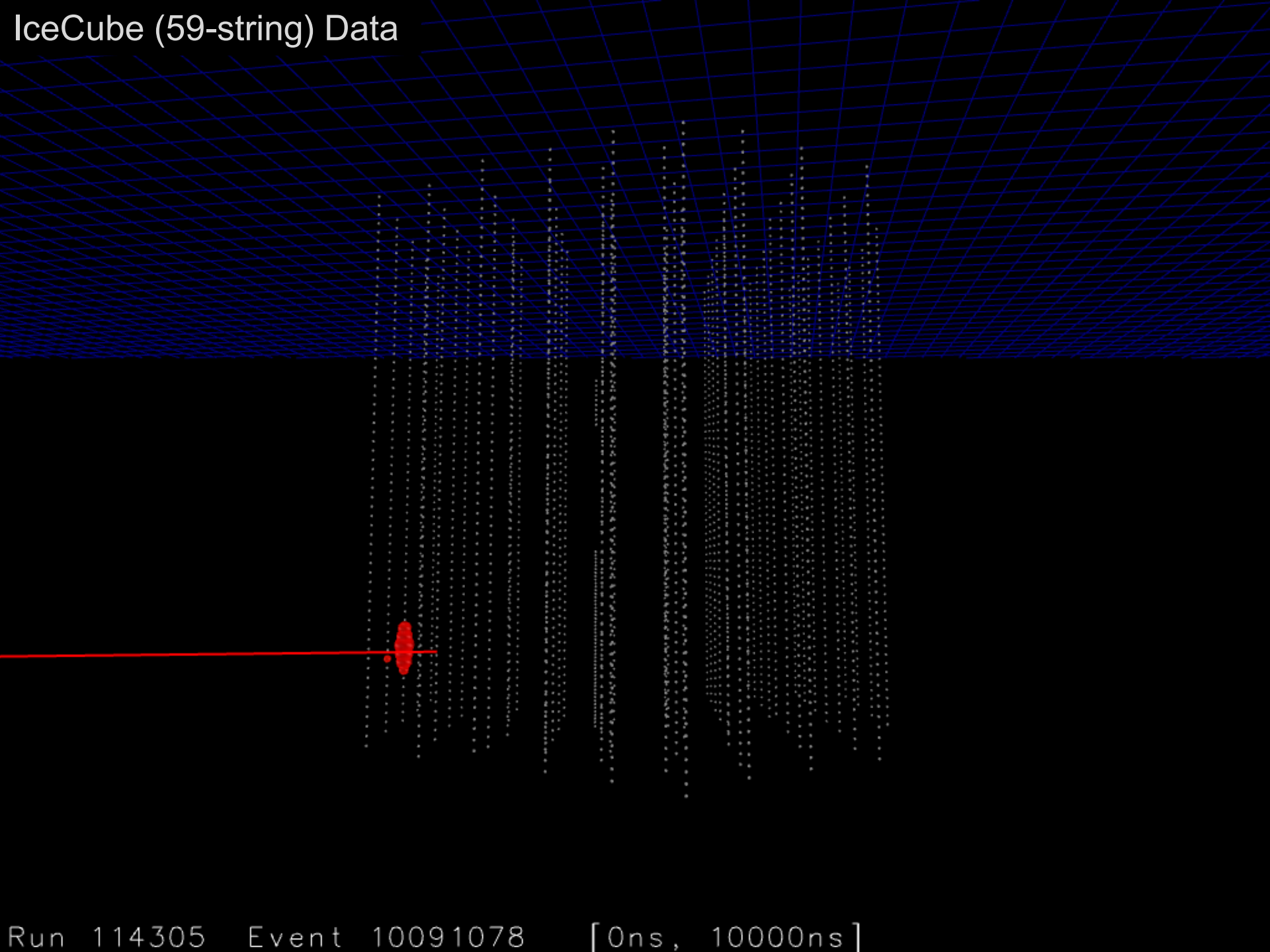


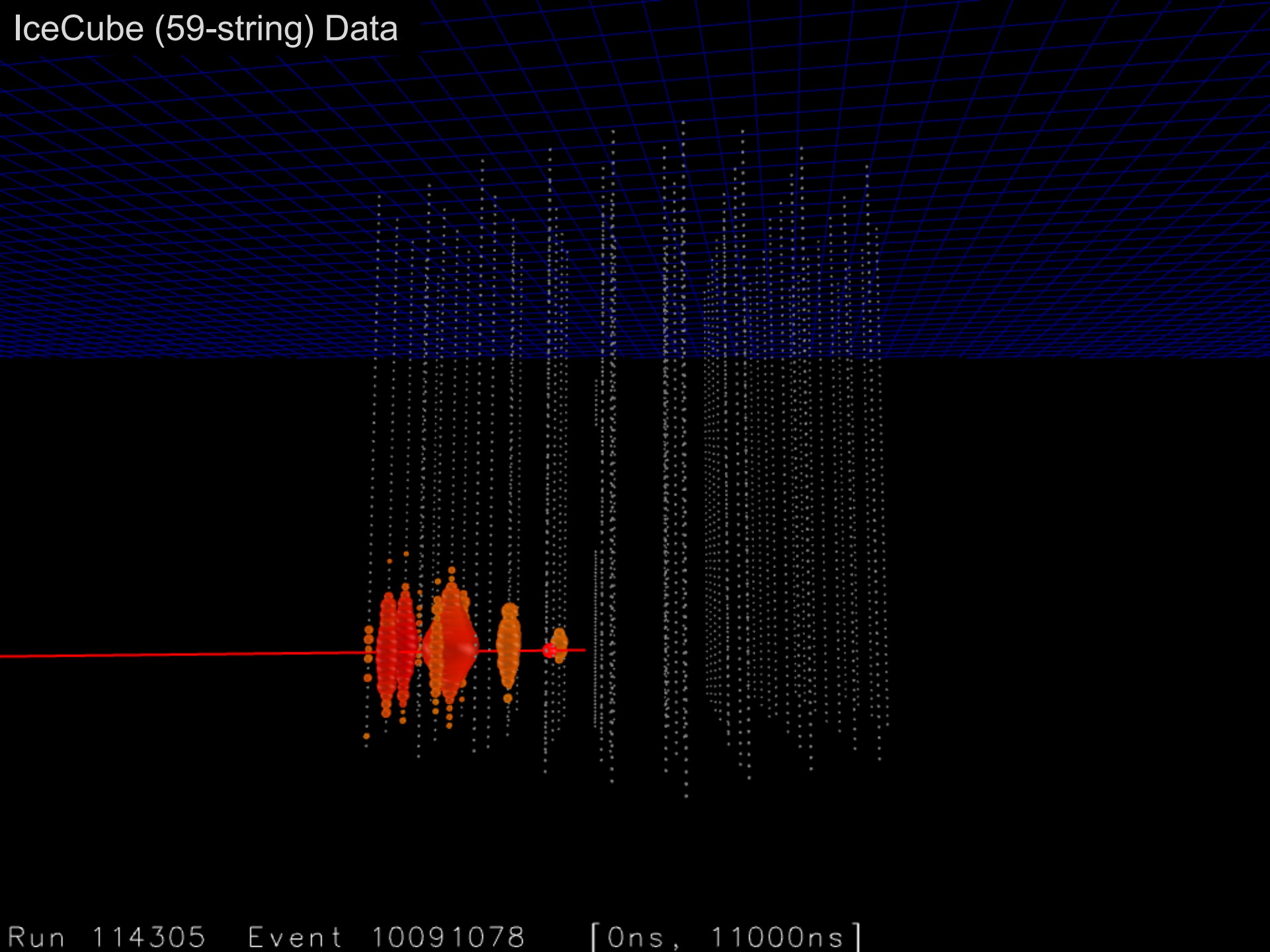

Simulation of photon propagation
(Track topology)

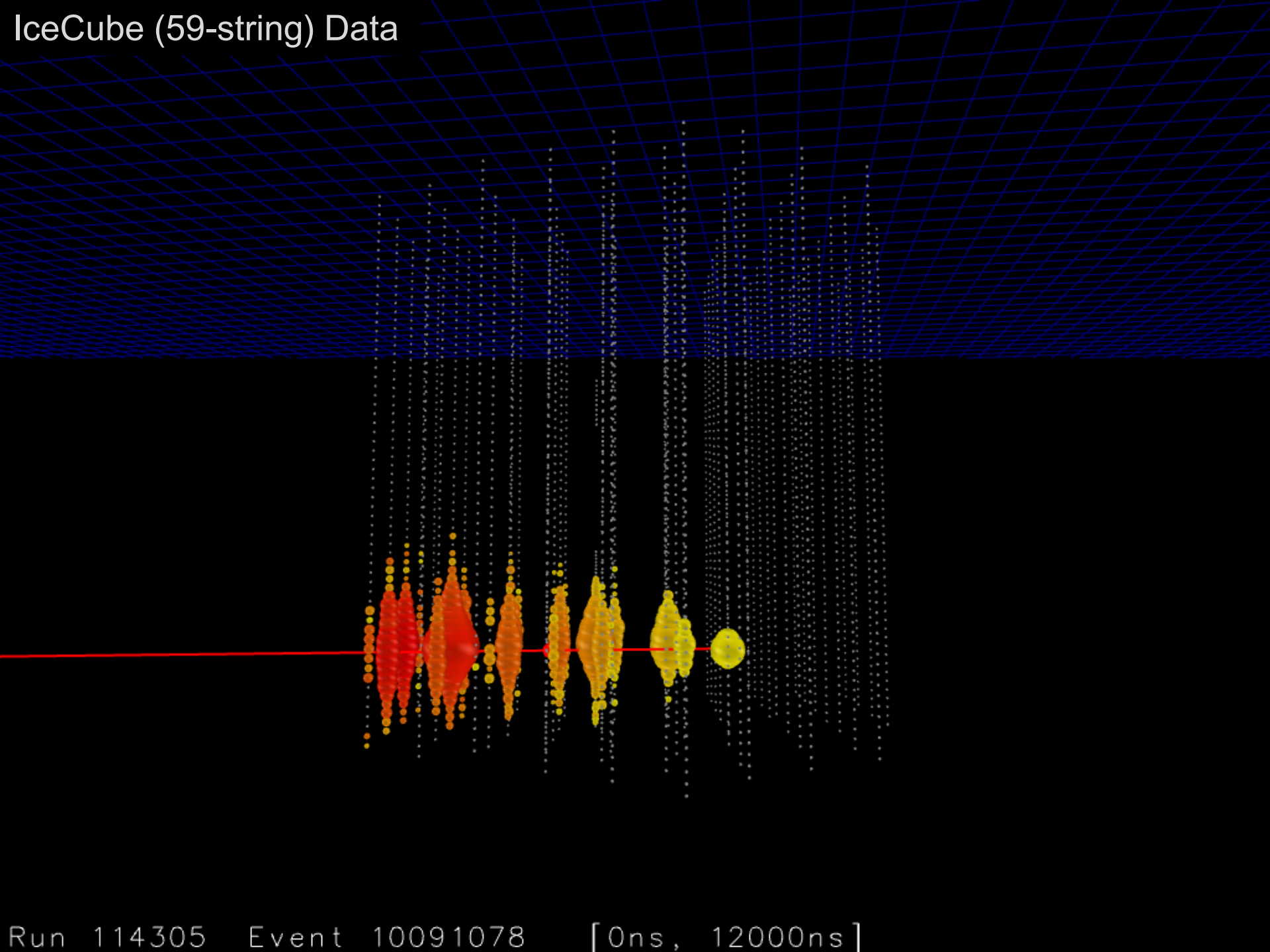
**Angular reconstruction:** can be as good as 0.2°

**Energy reconstruction:** only lower bound – most energy deposited outside the detector


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


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


IceCube (59-string) Data
Run 114305 Event 10091078 [0ns, 11000ns]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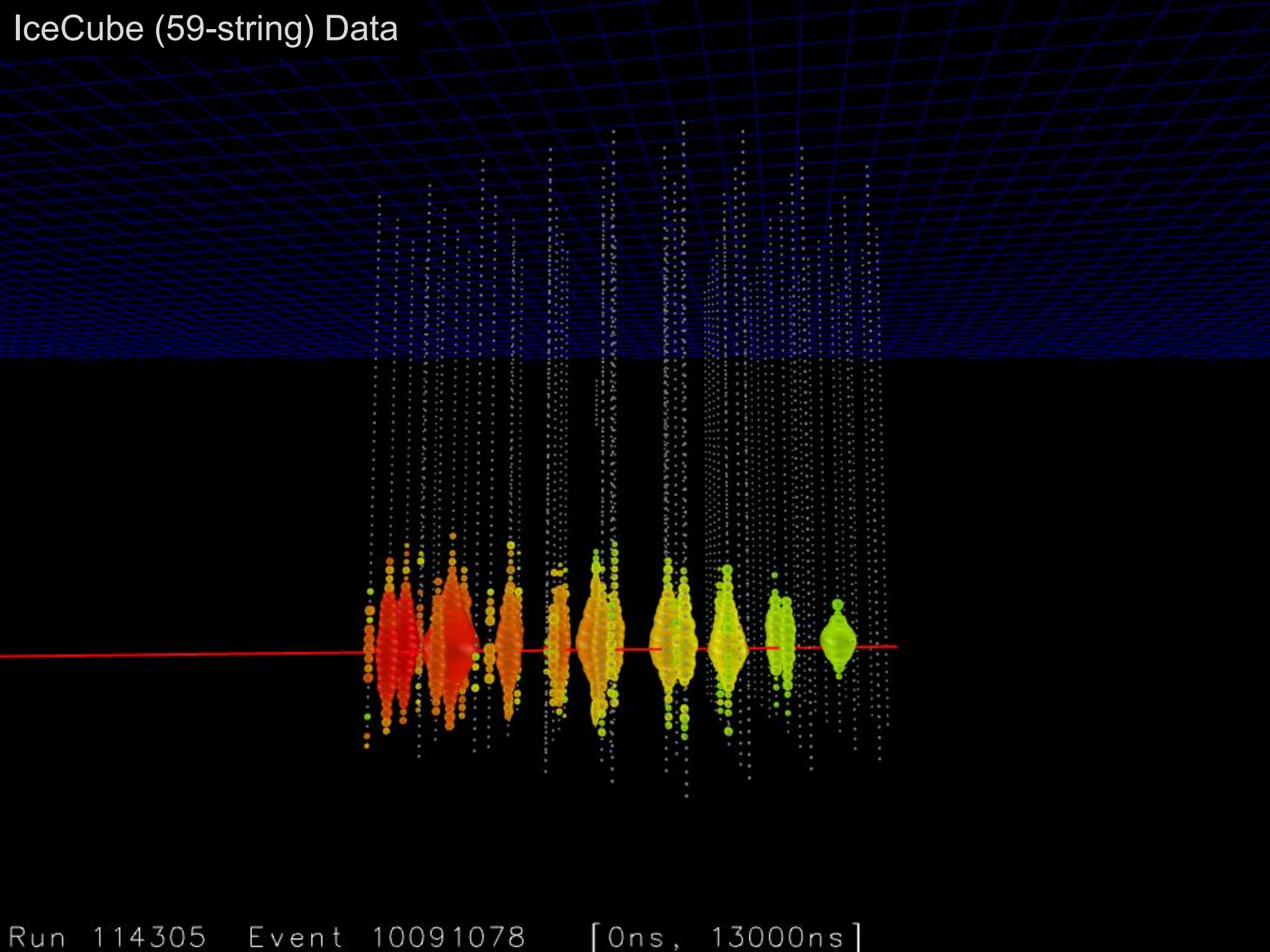
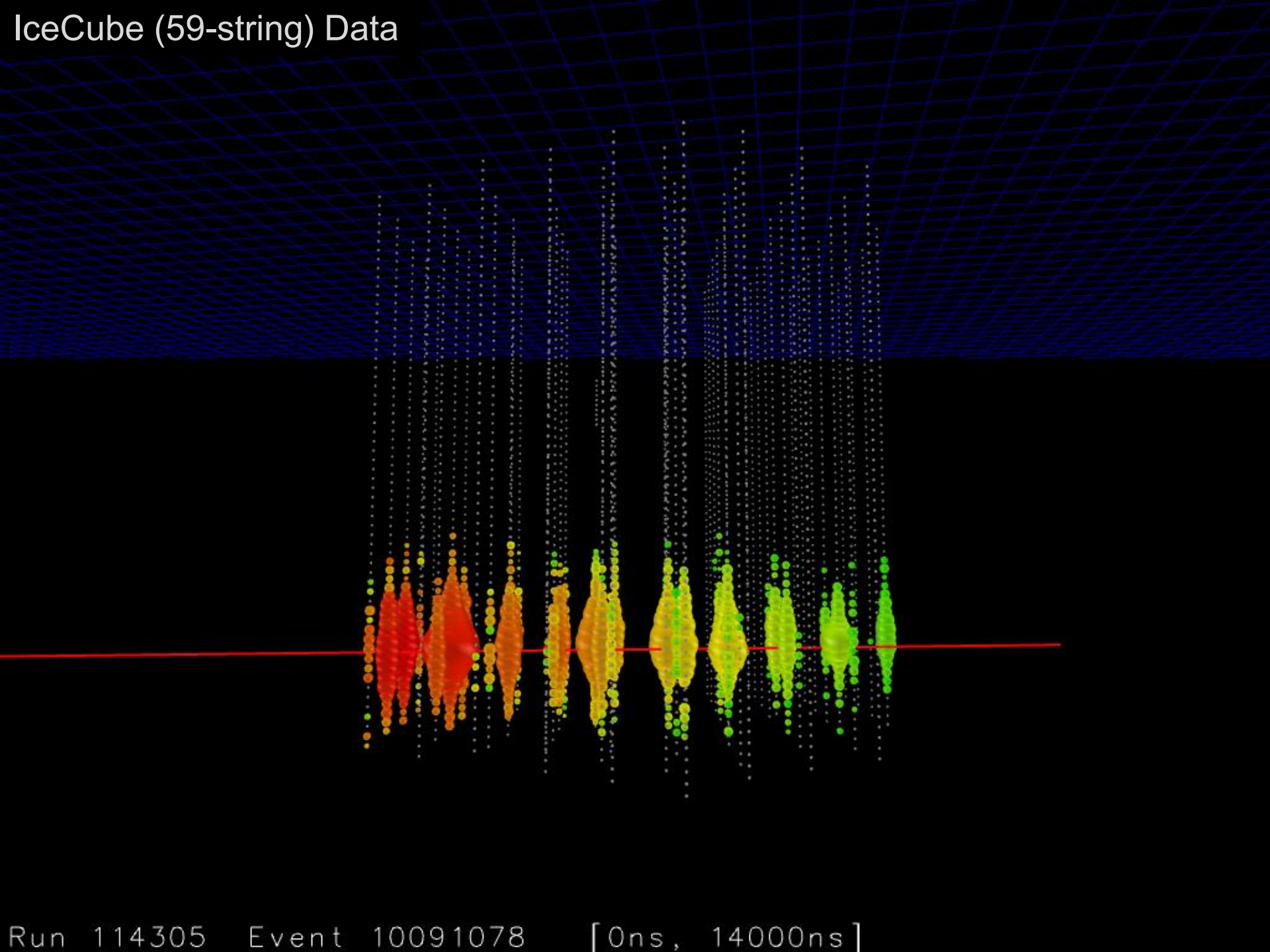
Run 114305 Event 10091078 [0ns, 12000ns]


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

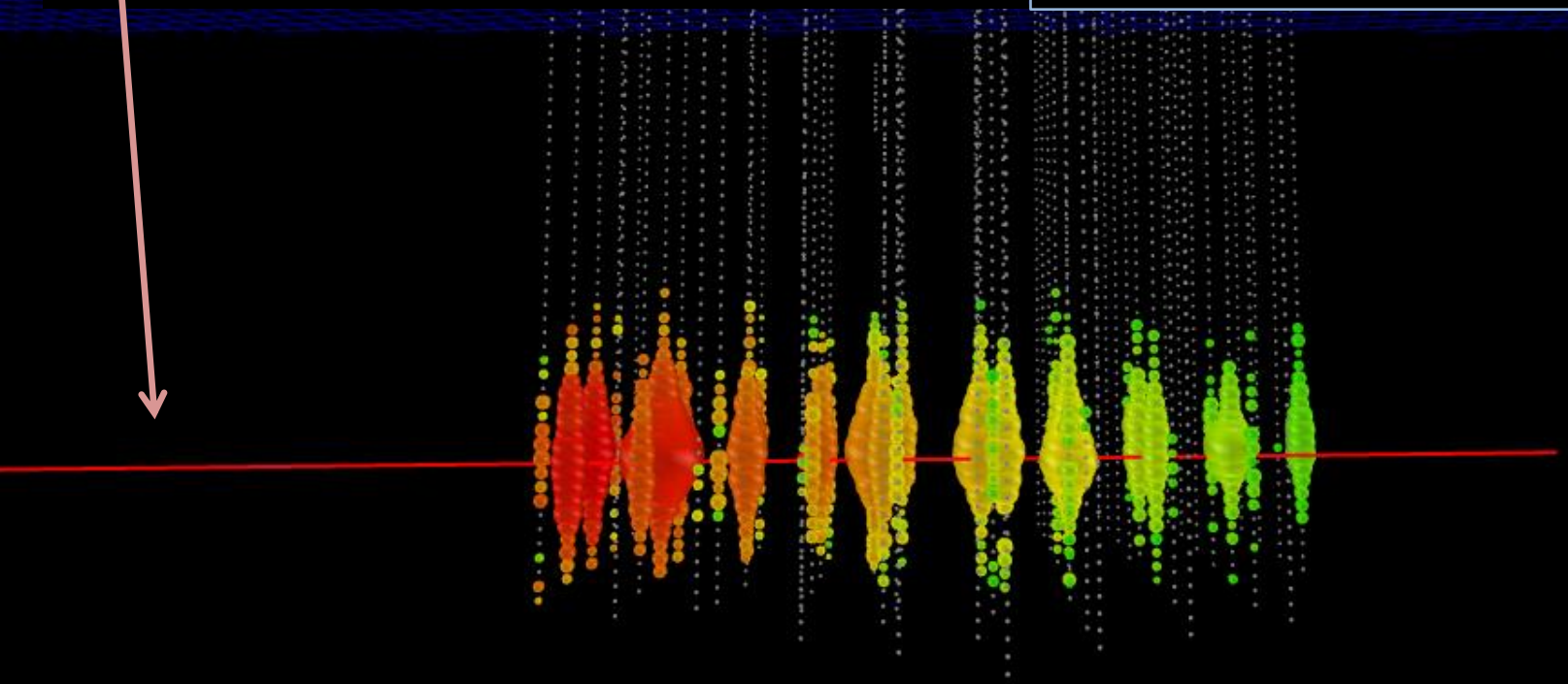

IceCube (59-string) Data
Run 114305 Event 10091078 [0ns, 14000ns]

# IceCube (59-string) 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

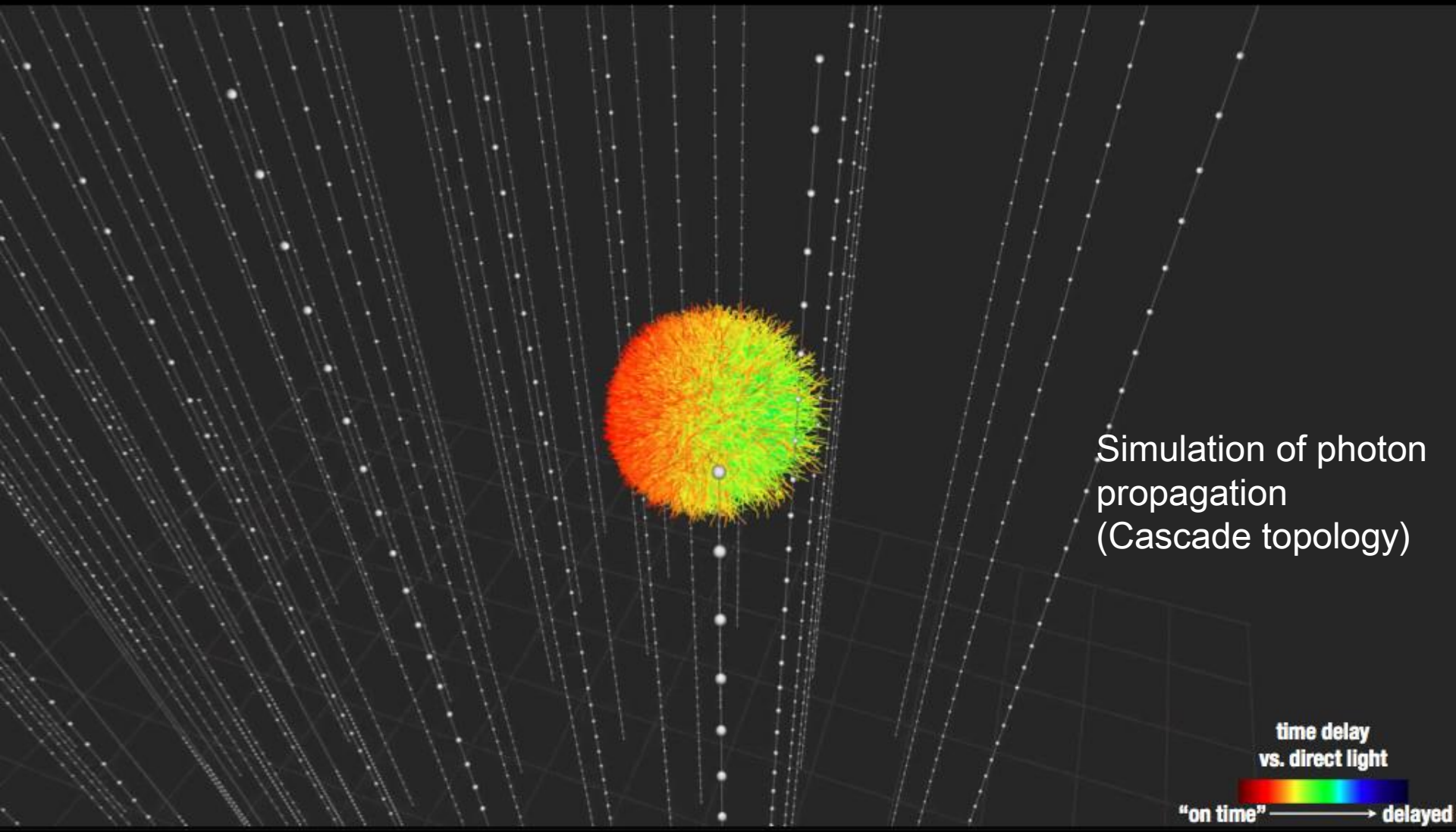
Neutrino interaction before detector:
energy measured is lower bound



Run 114305 Event 10091078 [0ns, 14000ns]

Color = hit times

**Charged-current electron, tau neutrino** interaction – electron, tau travels short distance
**Neutral-current (any flavor)** interaction – hadron shower and outgoing neutrino




Energy reconstruction ~ 10% for deposited energy (less than neutrino energy if NC)
Angular reconstruction -- Difficult, ~ 15° limited by scattering and absorption unc. in ice

# IceCube Recent Highlights

2010 Dec: Construction completed

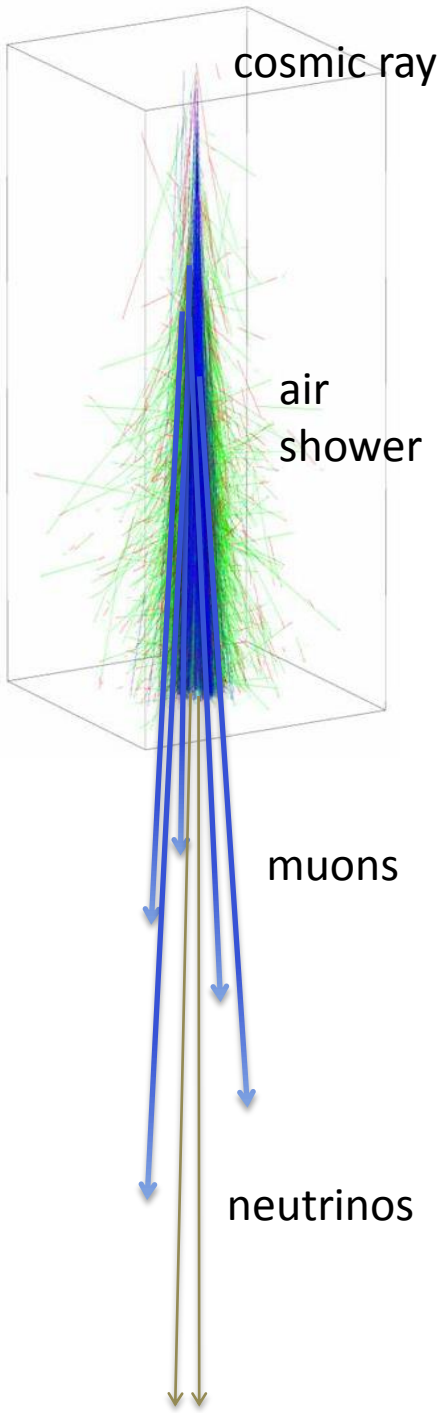
2011 May: IceCube begins full operations

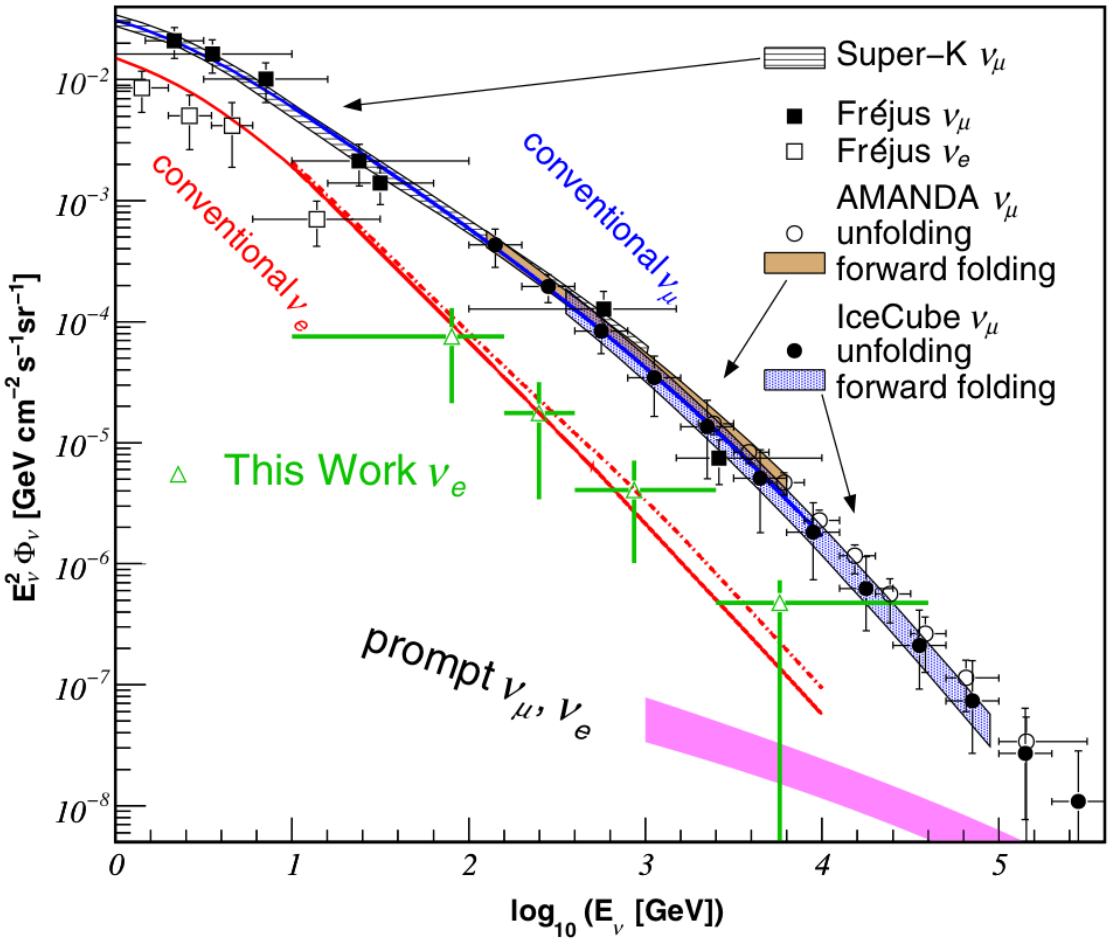
Recent Highlights:

- **Dark Matter (Solar WIMP search)** PRL **110**, 131302 (2013)
  - Best spin-dependent limits above 35 GeV for most models
- **Neutrino Oscillations** PRL **111**, 081801 (2013)
  - Pathway toward PINGU and Neutrino Mass Hierarchy
- **Atmospheric Electron Neutrinos** PRL **110**, 151105 (2013)
  - First measurements of atm. $\nu_e$ above 100 GeV
- **PeV Neutrinos** PRL **111**, 021103 (2013)
  - Highest energy neutrinos yet observed
- **High Energy Neutrino Excess**
  - Evidence of beyond-Earth origin

# Measurement of Atmospheric $\nu_e$ Flux

PRL **110,** 151105 (2013)

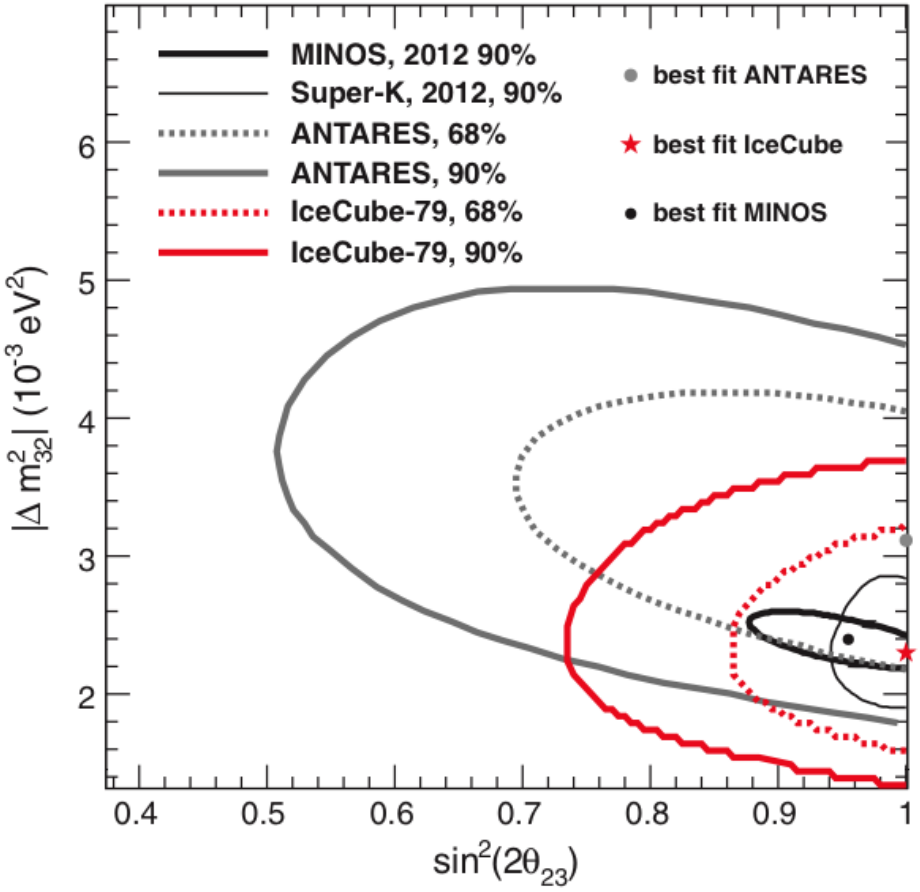


# Measurement of Atmospheric Neutrino Oscillations

PRL **111,** 081801 (2013)

"Disappearance of low-energy upward-going muon neutrinos was observed, and the non-oscillation hypothesis is rejected with more than 5σ significance."



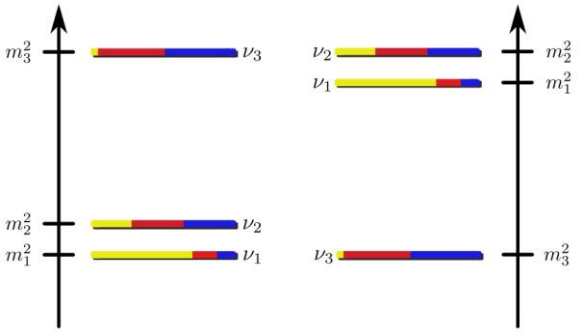

**Paving the way for PINGU – Measure Neutrino Mass Hierarchy**

# Precision In-Ice Next Generation Upgrade: PINGU

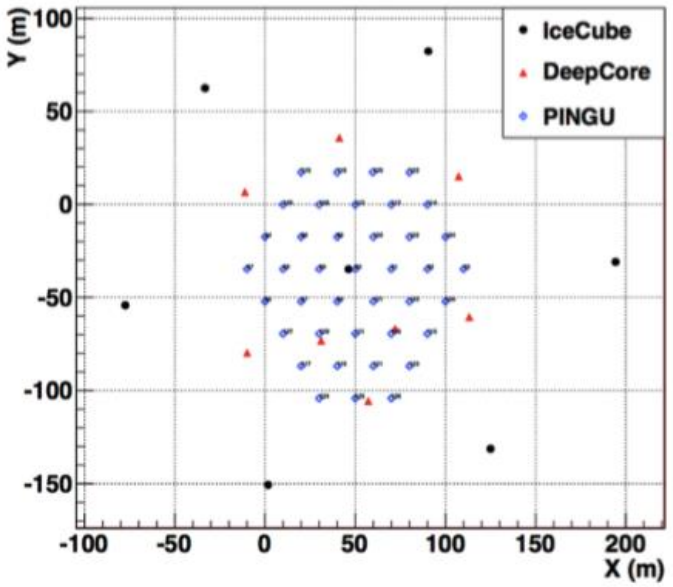
Neutrino Mass Hierarchy Measurement is primary goal

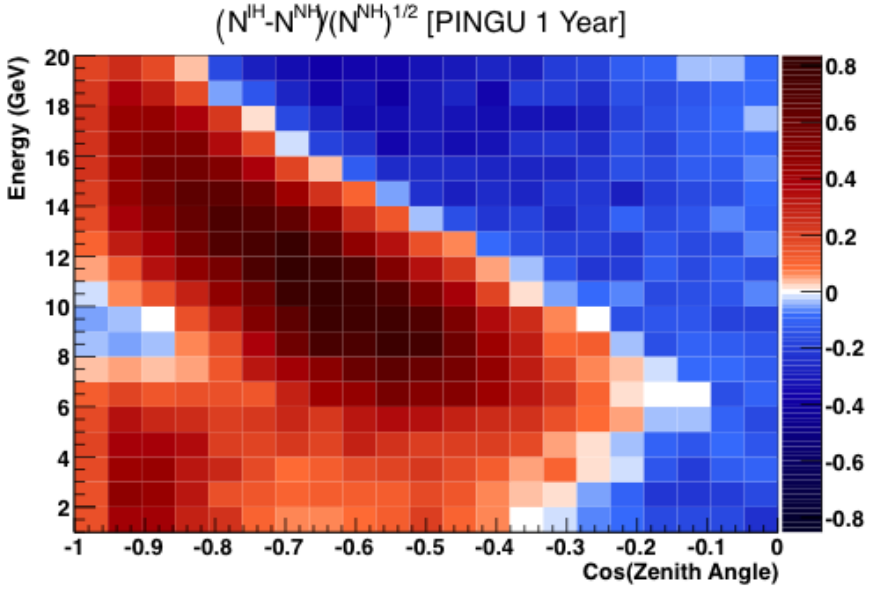
Step toward completing Standard Model and toward possible hints beyond SM

40 string in-fill array
Sensitivity down to ~ 3 GeV



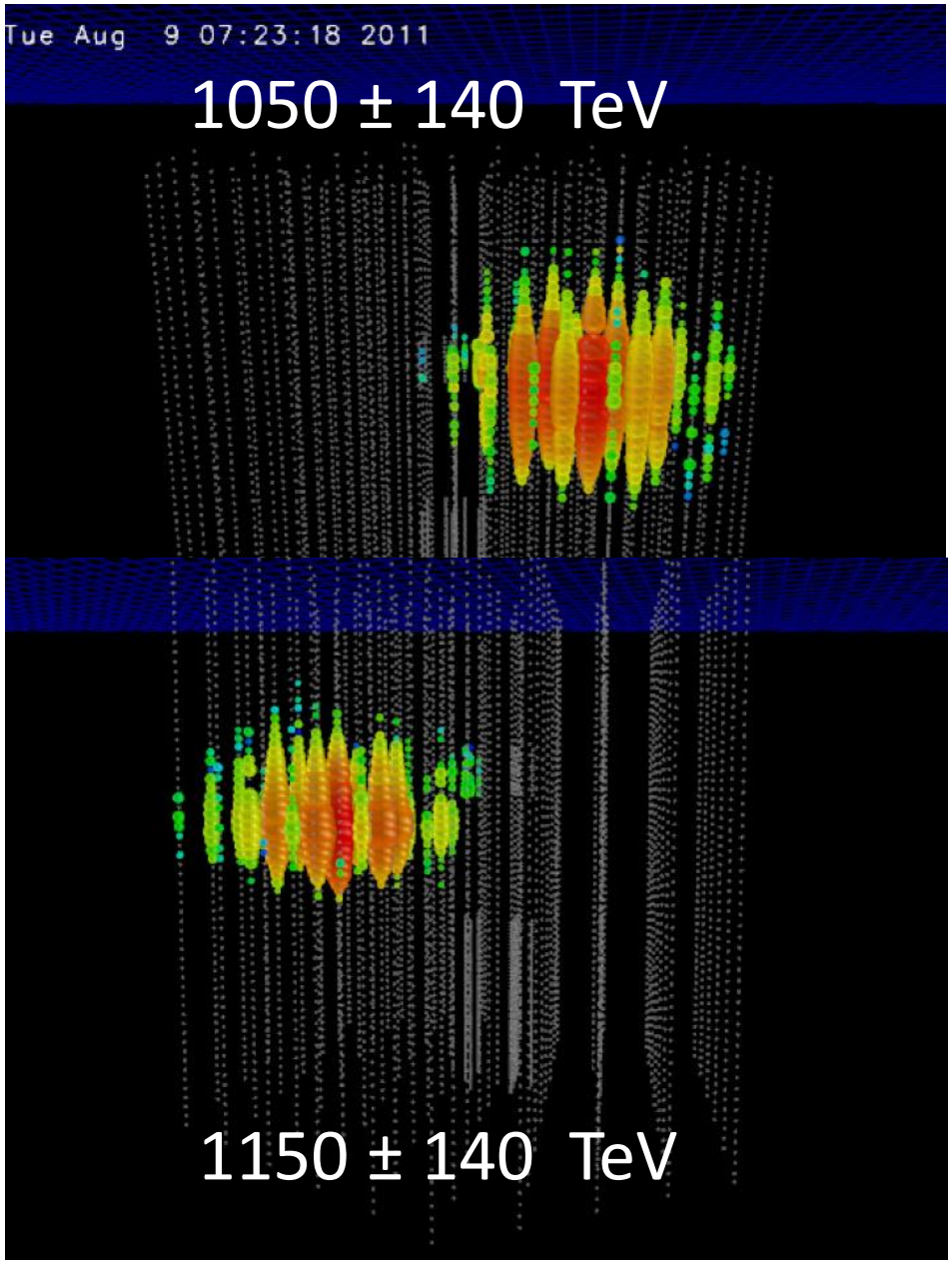

Hierarchy signature is a distinctive structure in energy-angle plane

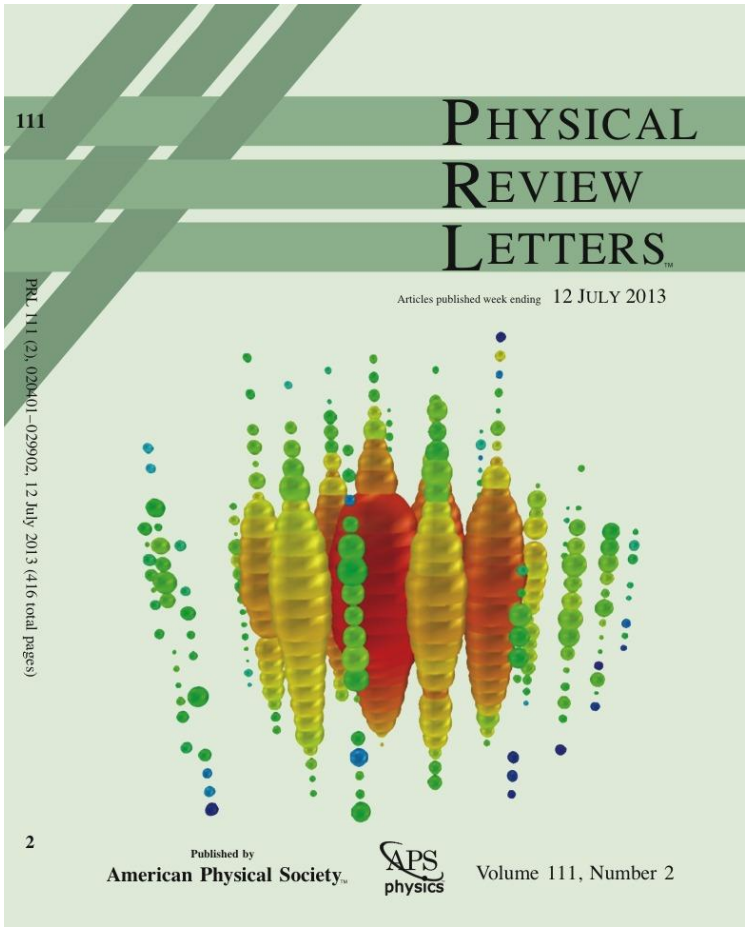


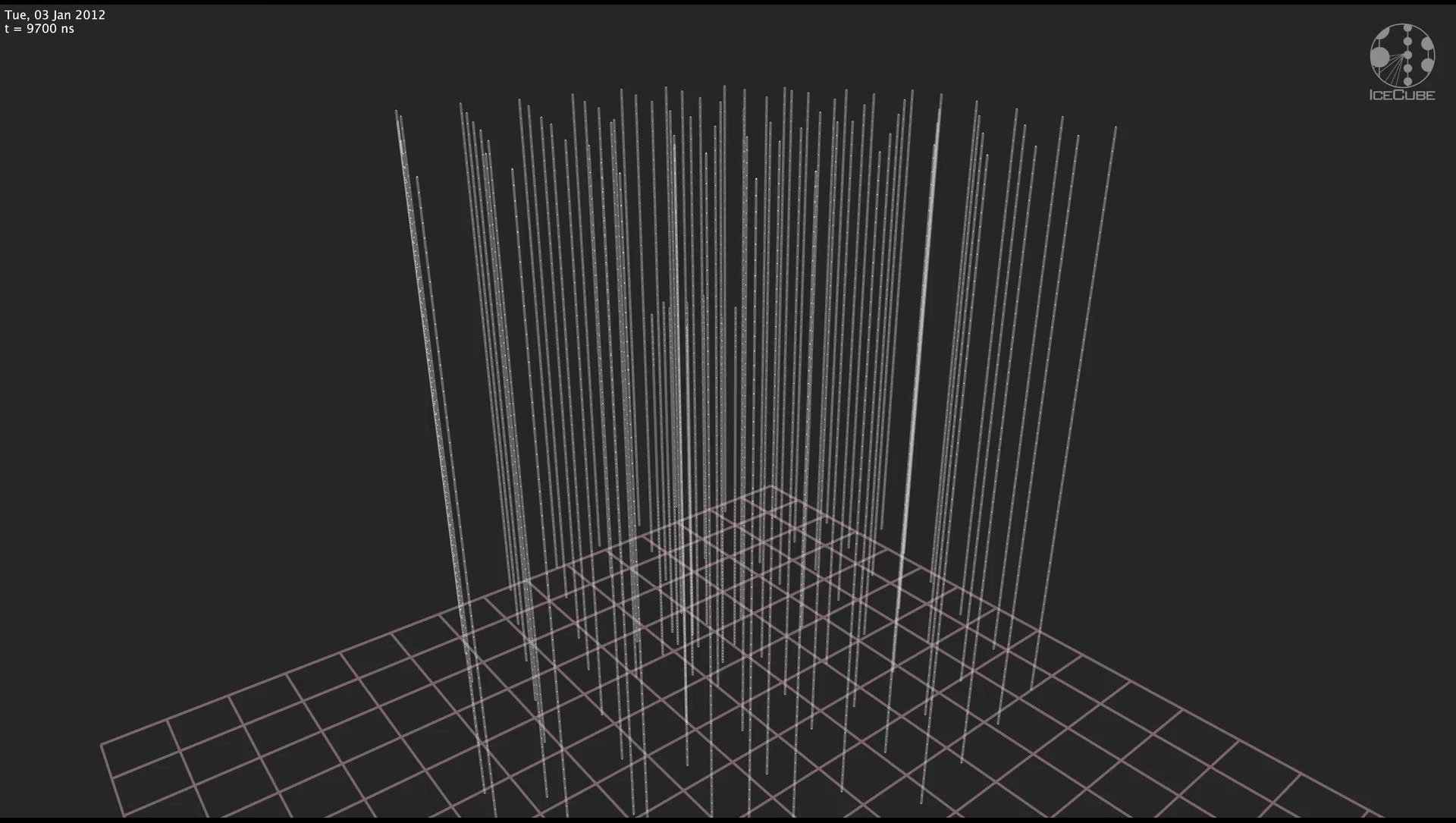




Includes: estimated energy and angular resolution

# First Observation of PeV-Energy Neutrinos




Tue, 03 Jan 2012
t = 9700 ns
IceCube

# First Observation of PeV-Energy Neutrinos

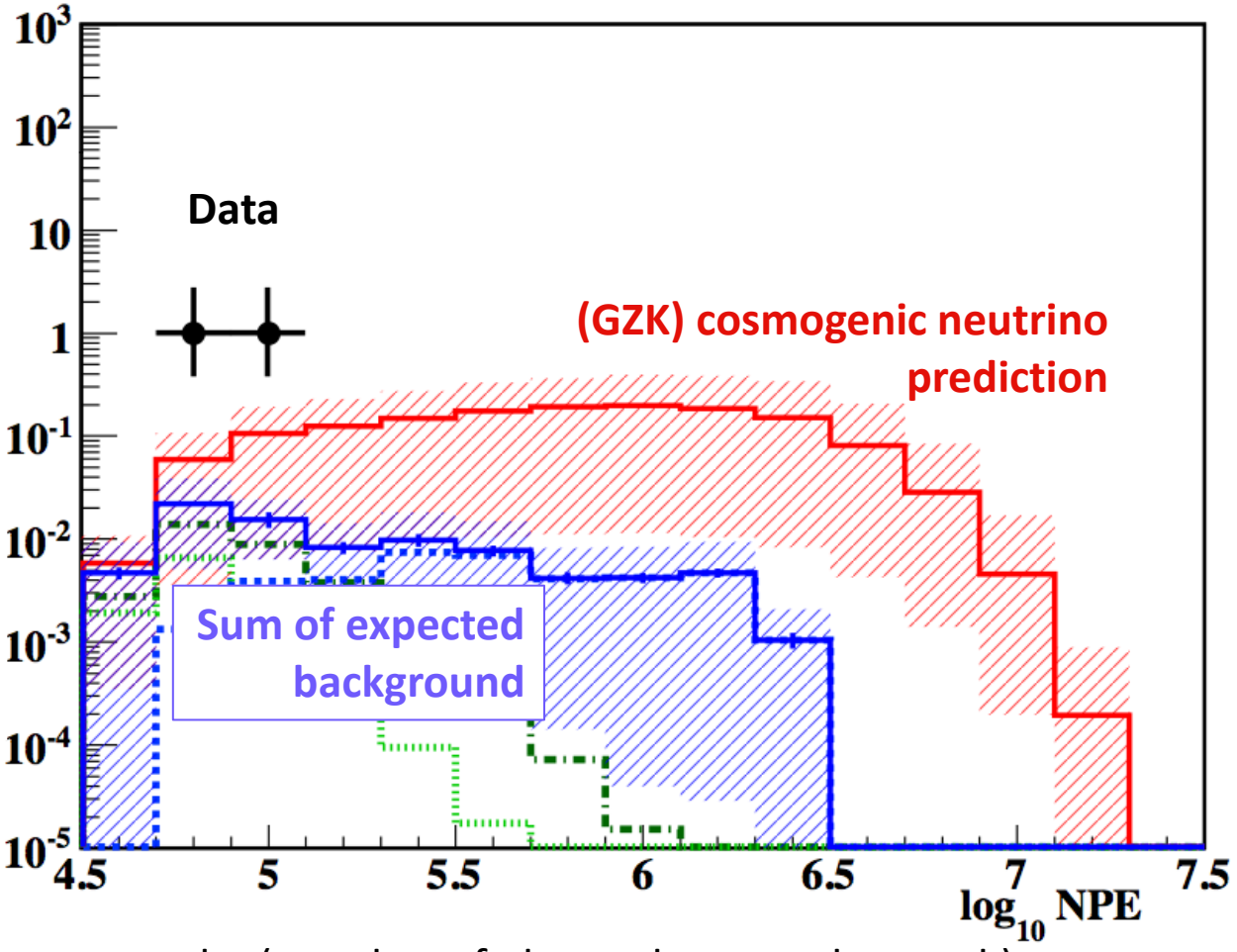
PRL **111,** 021103 (2013)

Combined analysis of **79-string data (1 year)** and **first** analysis of full-detector **86-string data (1 year)**

PeV events were found in a search targeting much higher energy neutrinos (related to GZK cutoff)

Expected background: **0.08 ± 0.05 events**

**2.8σ excess**




log( number of photo-electrons detected )

# Interesting Fact about PeV energies…

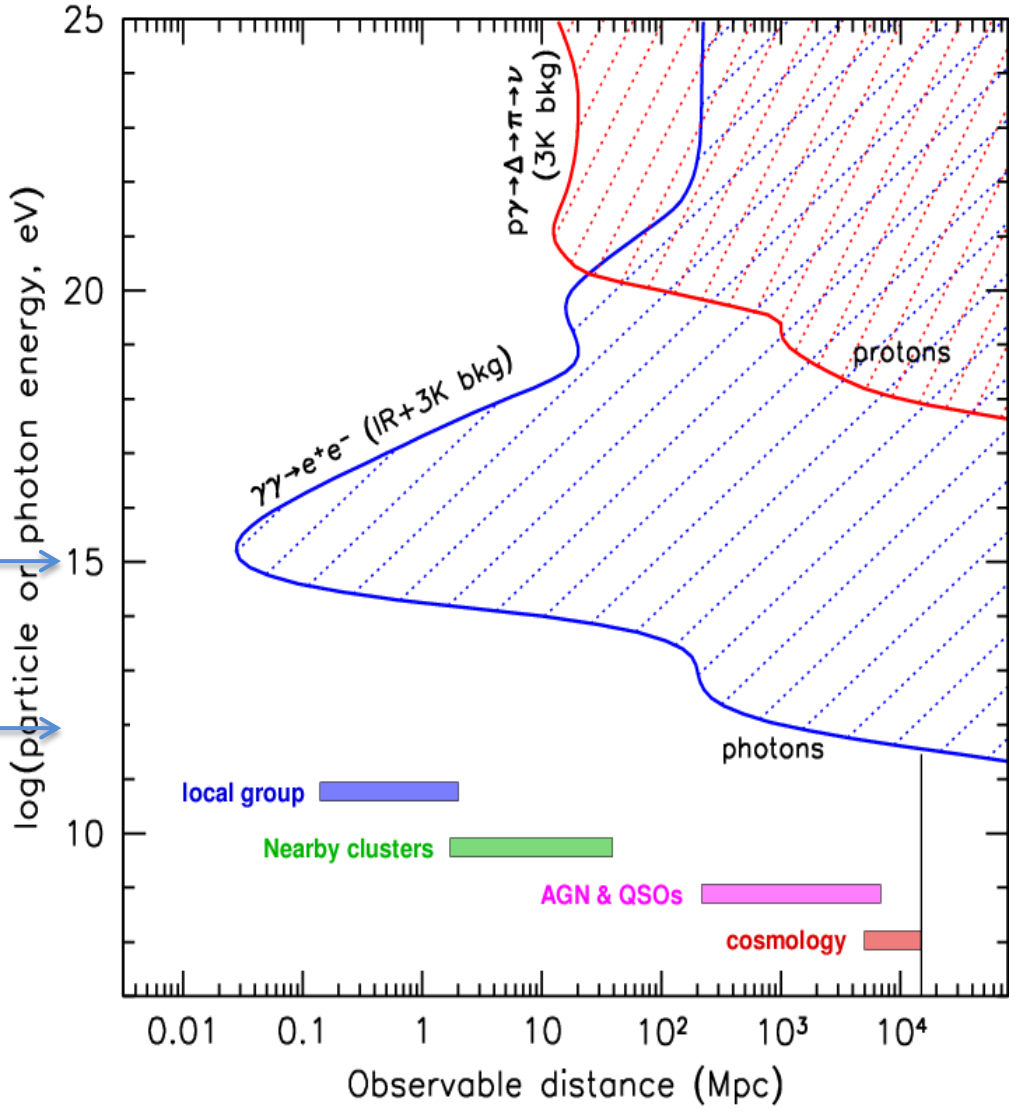
At PeV energies, universe is **opaque for photons**, due to pair-production off background radiation fields (Cosmic Microwave Background, Infrared Background)

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

**1 PeV** →

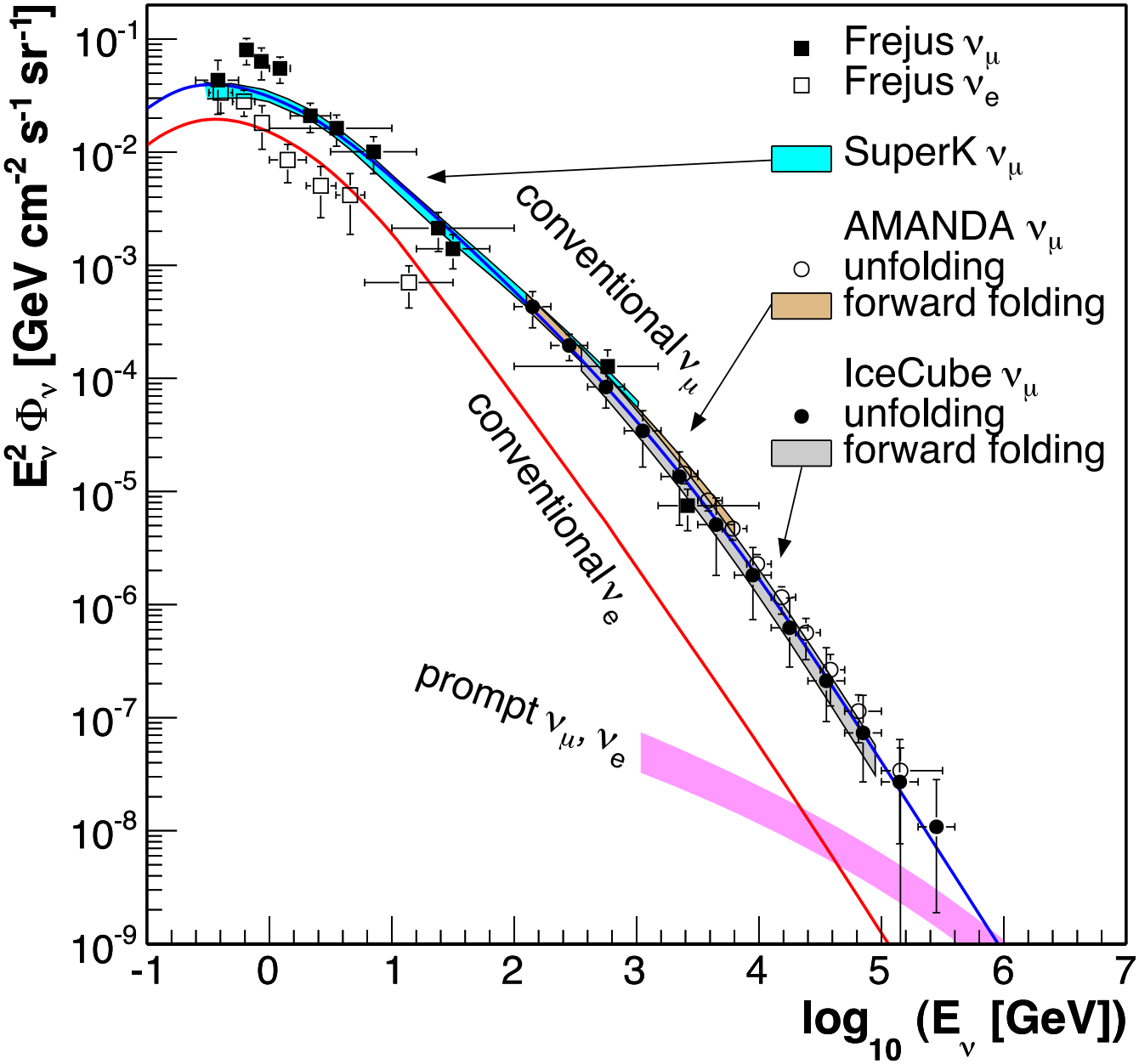
**1 TeV** →

Photon propagation distances (P. Gorham)

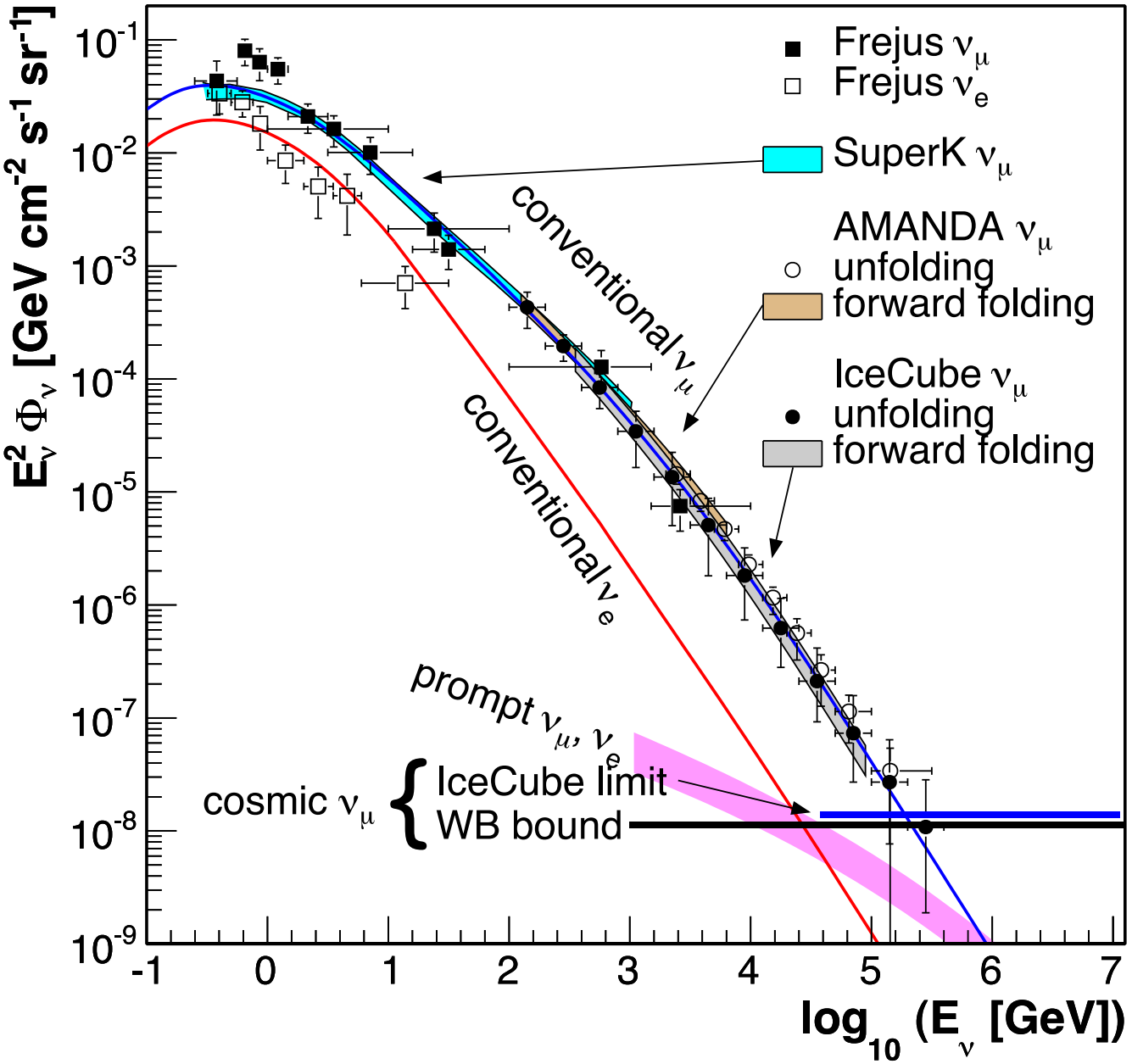



Neutrinos are unique probe above 100 TeV

# Atmospheric Neutrino Spectrum



# Atmospheric Neutrino Spectrum



# High Energy Starting Event Analysis

Follow-up based on PeV events.

**In a nutshell:**

1. **Lower** energy threshold, from ~ PeV to ~40 TeV

   (Still very bright events… require > 6000 photo-electrons)

2. Use outer-most layer of IceCube as a **veto**

   Removes atmospheric background (muon & neutrino) **from above**
   (Earth filters muon background **from below**)

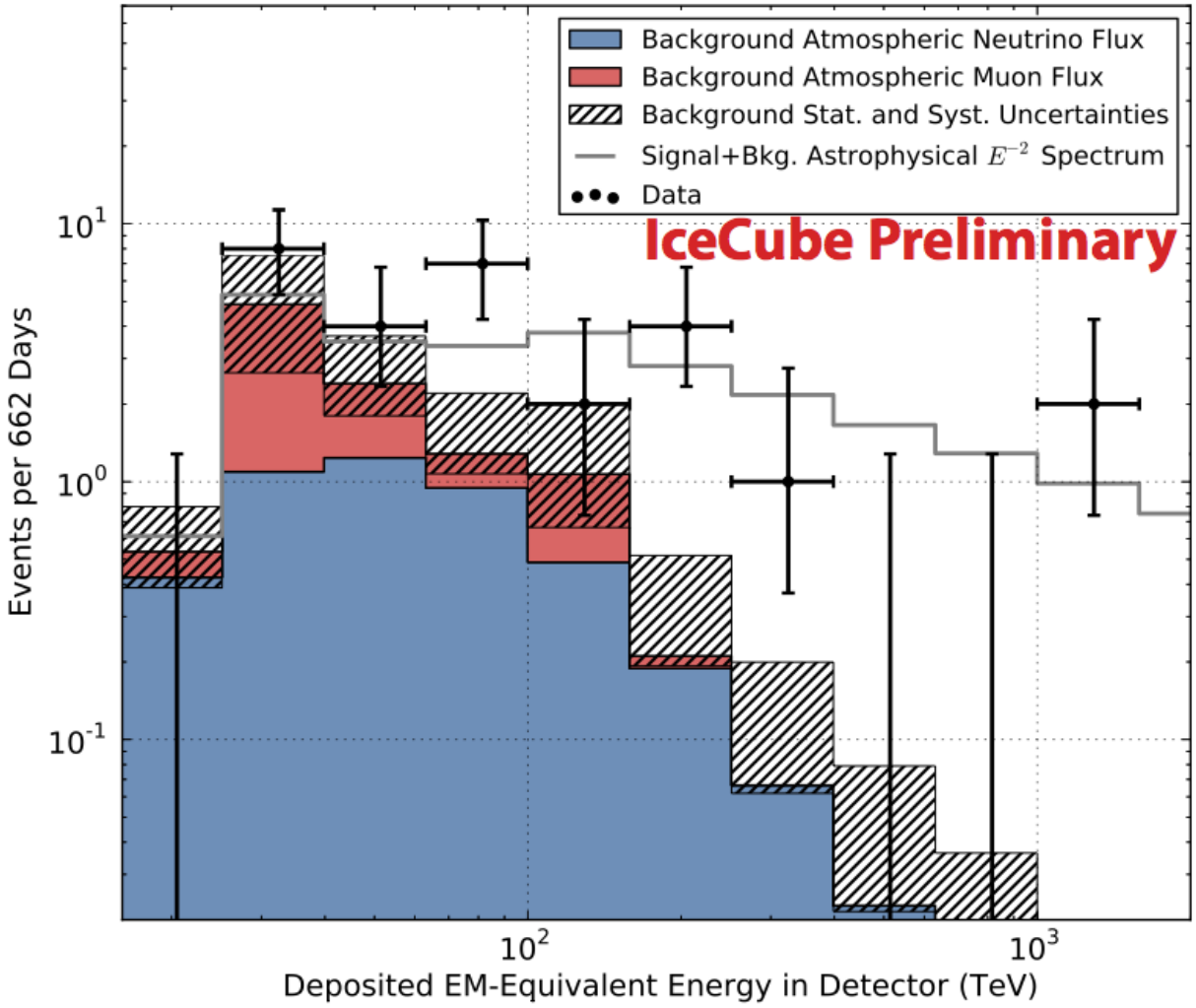
   (NB: track-events will be somewhat suppressed when using veto)

3. Look both **up** and **down**

   PeV neutrinos **absorbed** in Earth; seen only horizontally or from above

# High Energy Starting Event Analysis: Results

**Deposited Energy in Detector**



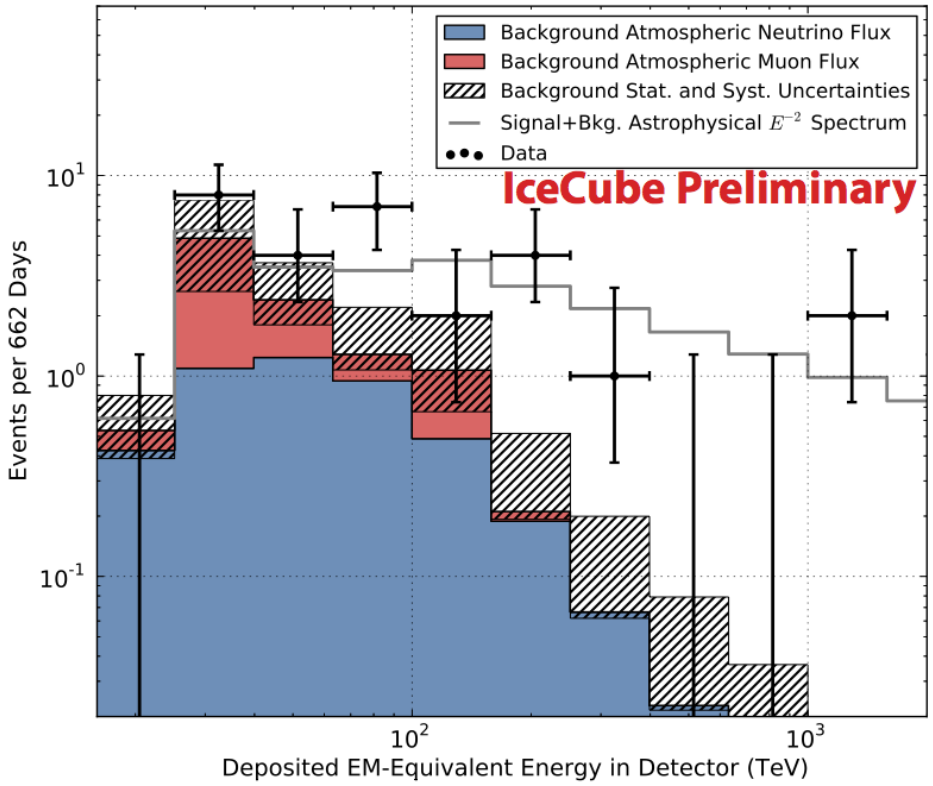

26 new events

Expected background:
10.6 ± 4 atm. events

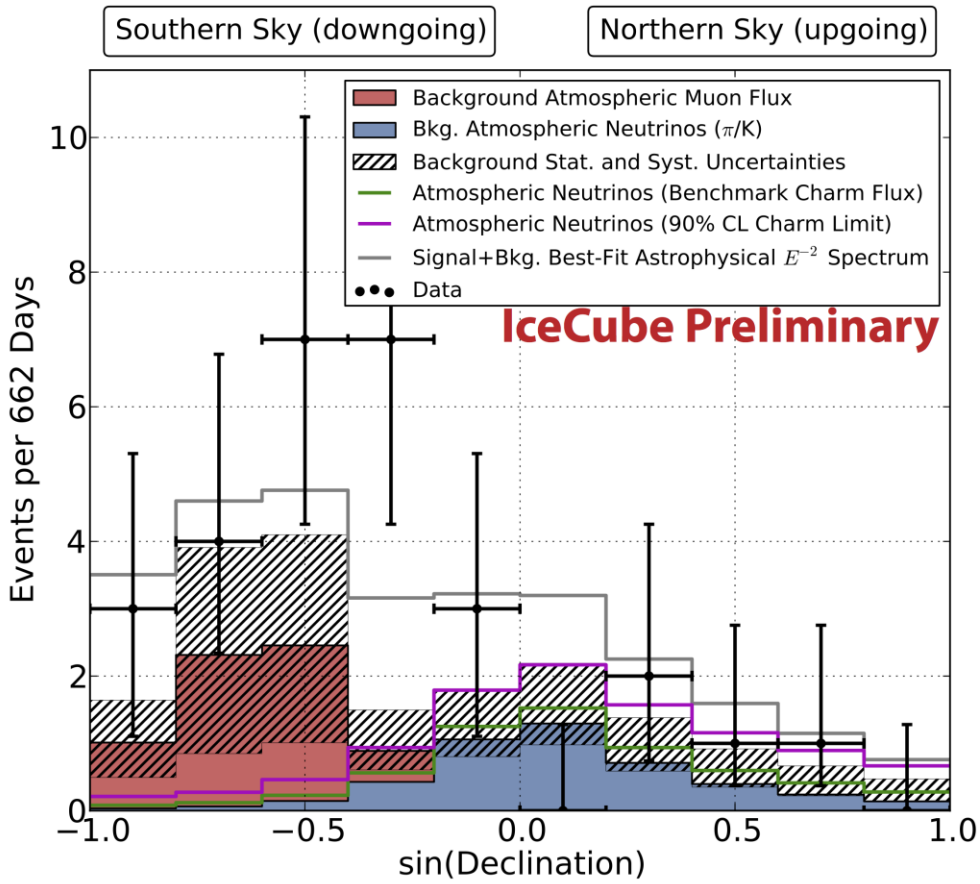
**~ 4σ combining both analyses**

# High Energy Starting Event Analysis: Results

**Deposited Energy in Detector**

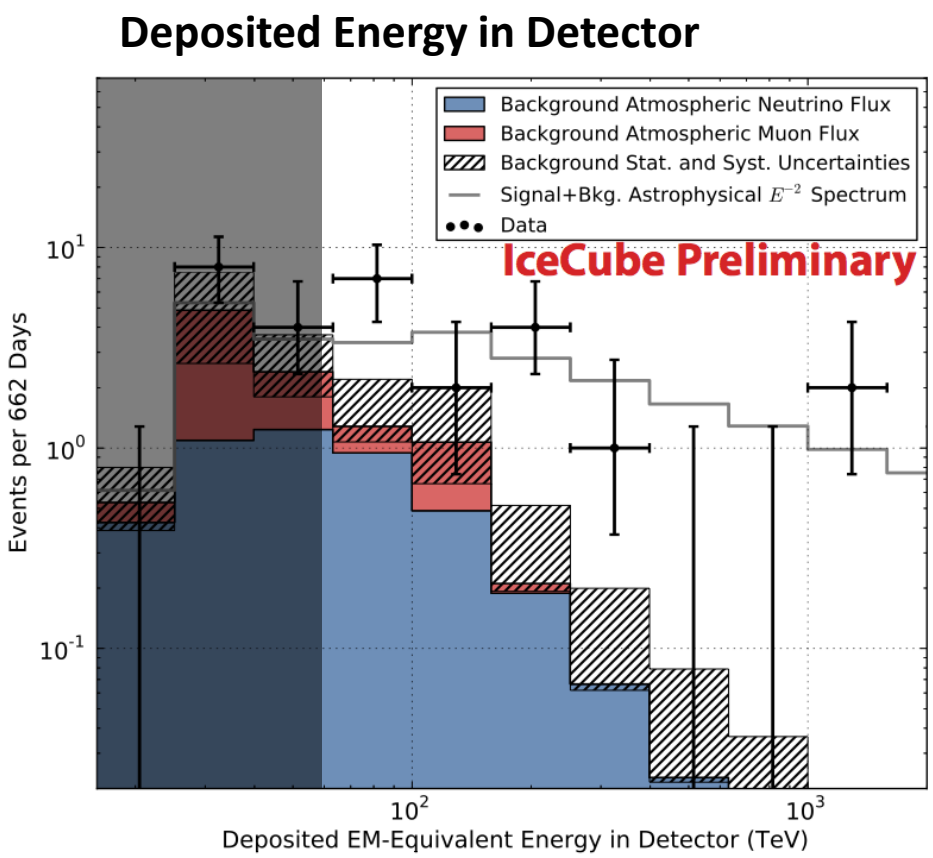


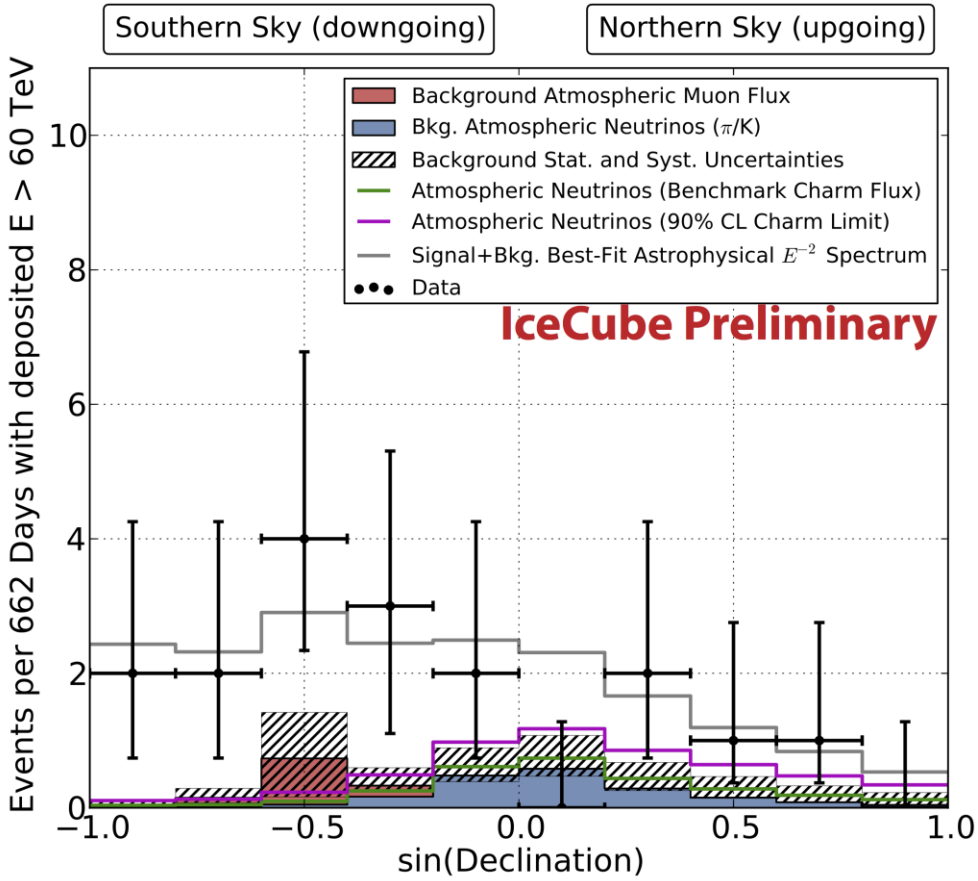

**Distribution in Sky**



# High Energy Starting Event Analysis: Results

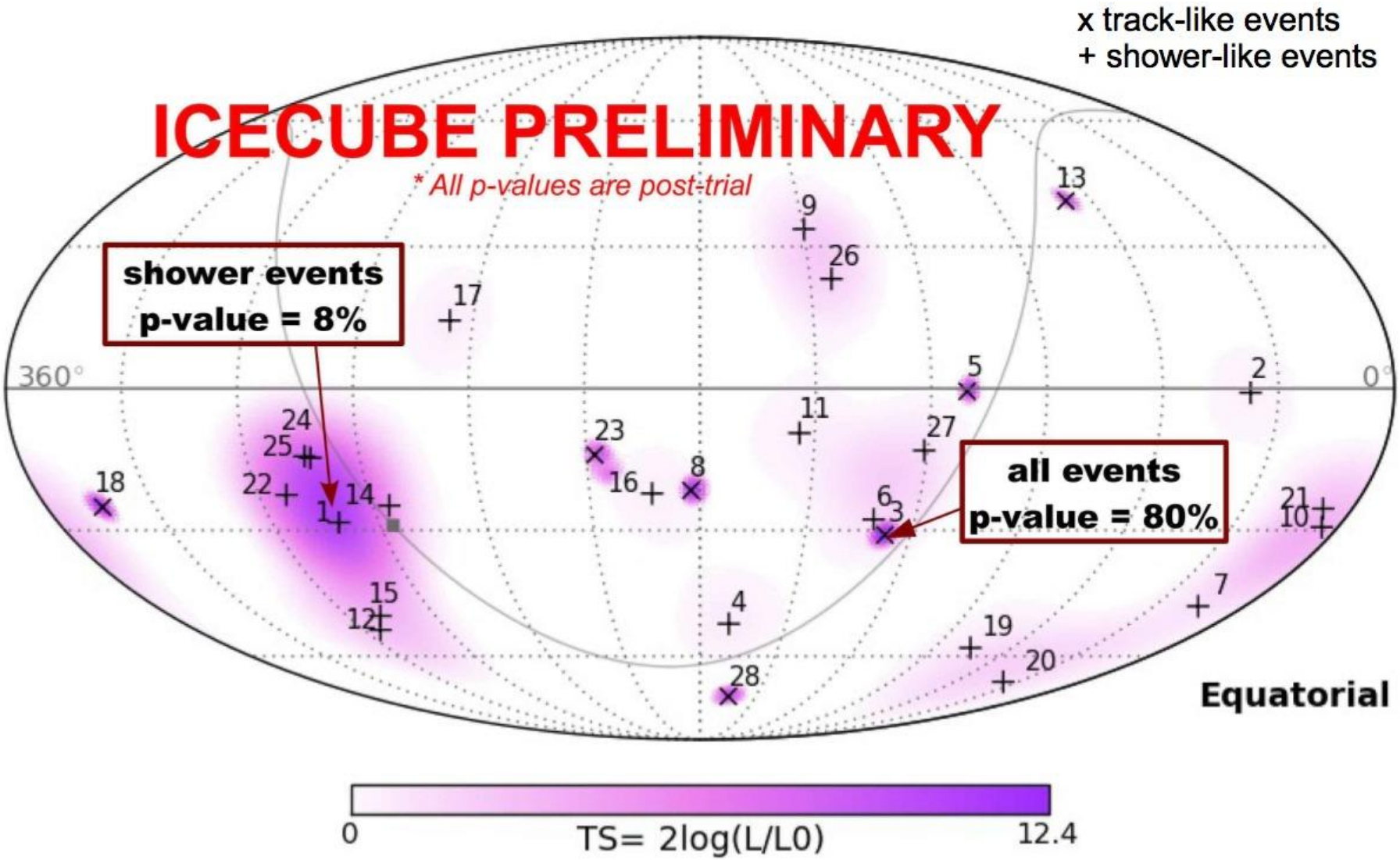
For the high energy range ( > 60 TeV deposited energy),
Most astrophysical events expected from above (South)



# High Energy Starting Event Analysis: Results

## Point Source Search (likelihood analysis)



Multiple mile-stones achieved this past year:
Dark-matter searches, Neutrino oscillations, Atmospheric electron neutrinos

First analyses of data from completed detector:
Exceed predicted terrestrial backgrounds at > 4σ

Data are consistent with first glimpse of astrophysical flux (but not yet proven)

## Questions

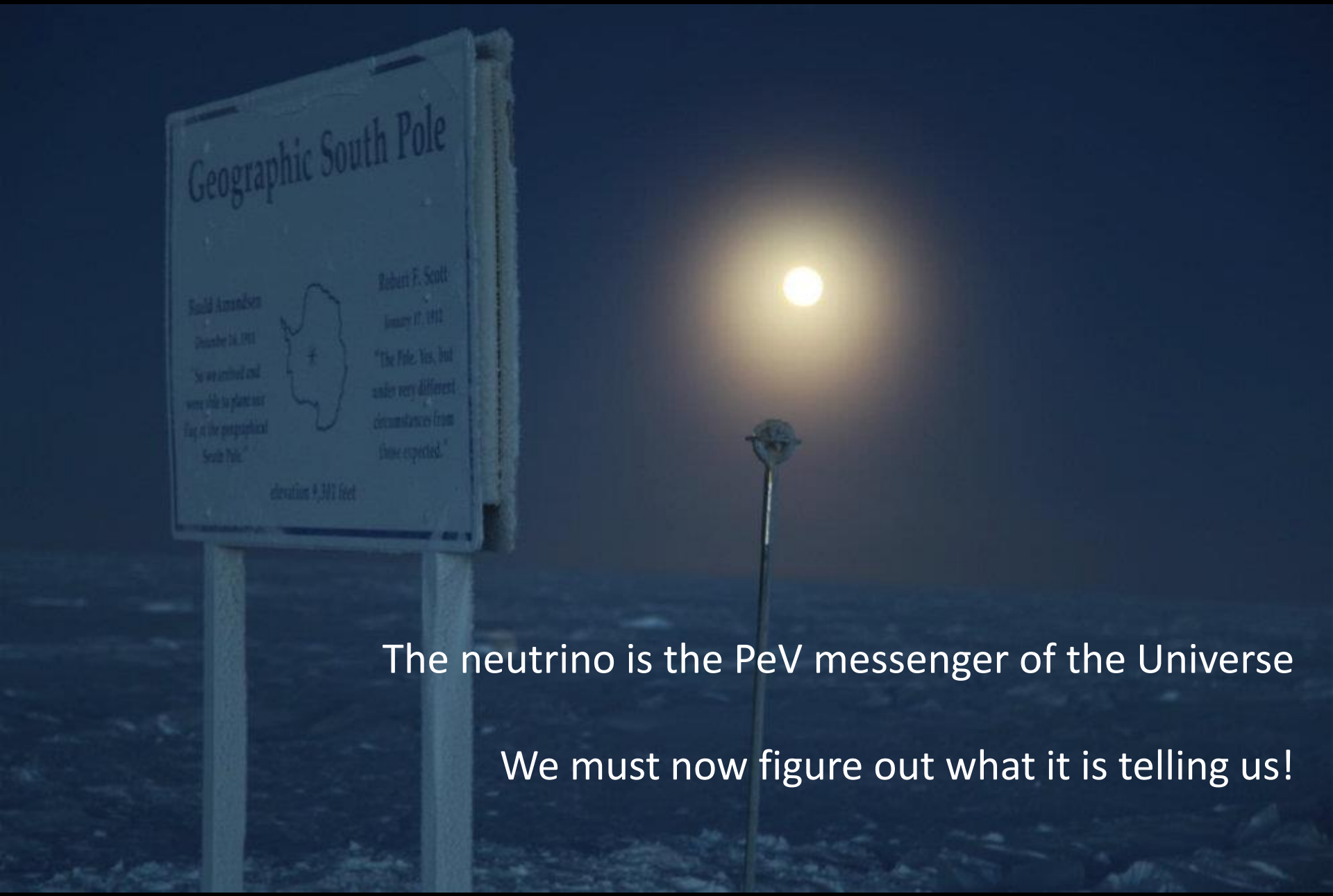
High Energy Excess:

- Is it extra-terrestrial? What is energy spectrum?
- Diffuse, or evidence for one or more sources?

- Improved event reconstruction may be critical
- Results impact plans for future detectors, in ice and in the sea



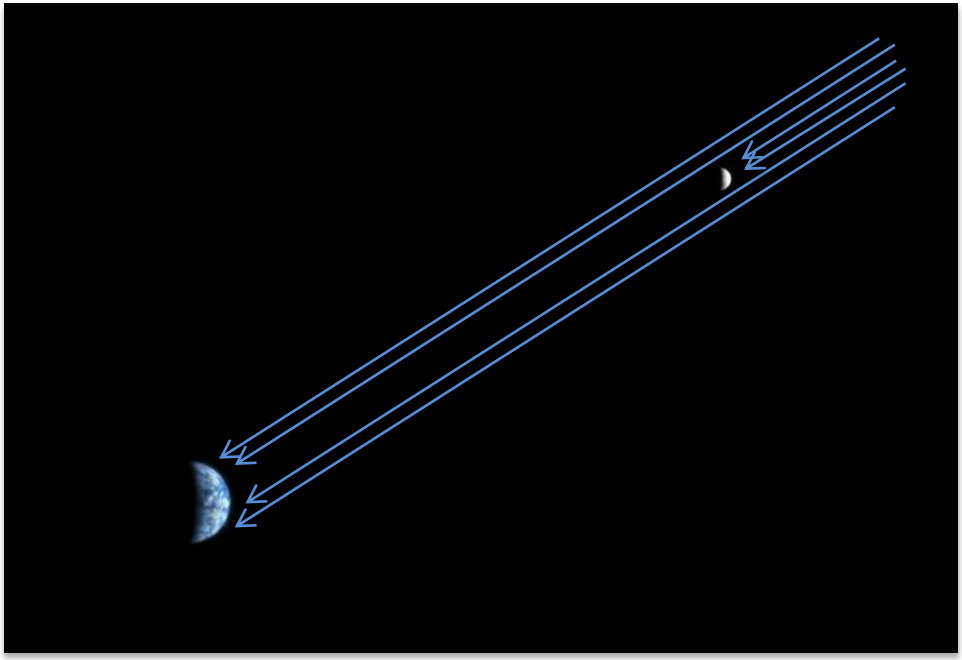
Photo: Sven Lidström




The neutrino is the PeV messenger of the Universe

We must now figure out what it is telling us!

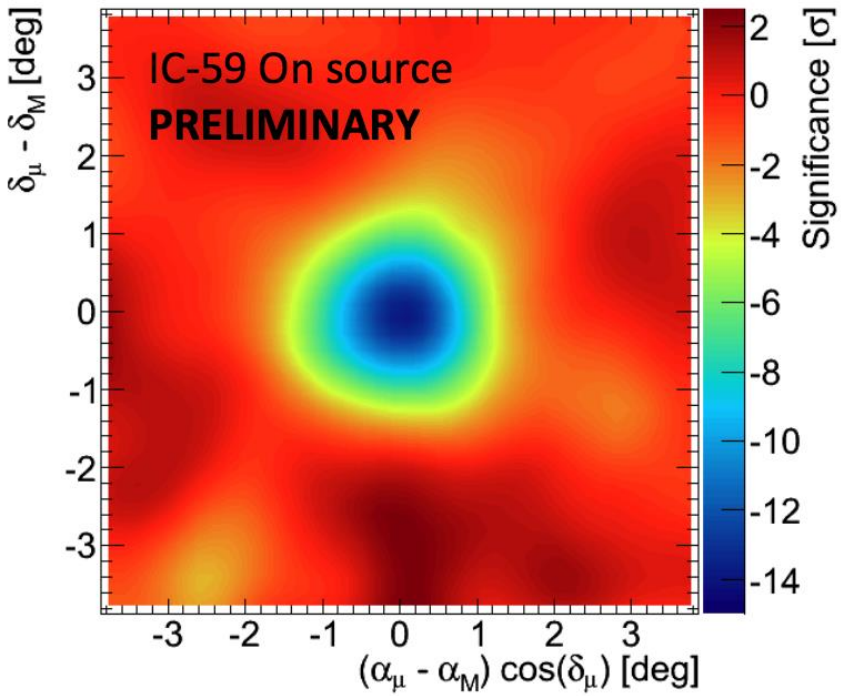
# Cosmic Ray Moon Shadow



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

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

Moon (to scale)




Spoiler alert: 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.)

Starting vertices of events well distributed throughout detector volume