IceCube

Neutrinos at the Bottom of the Earth

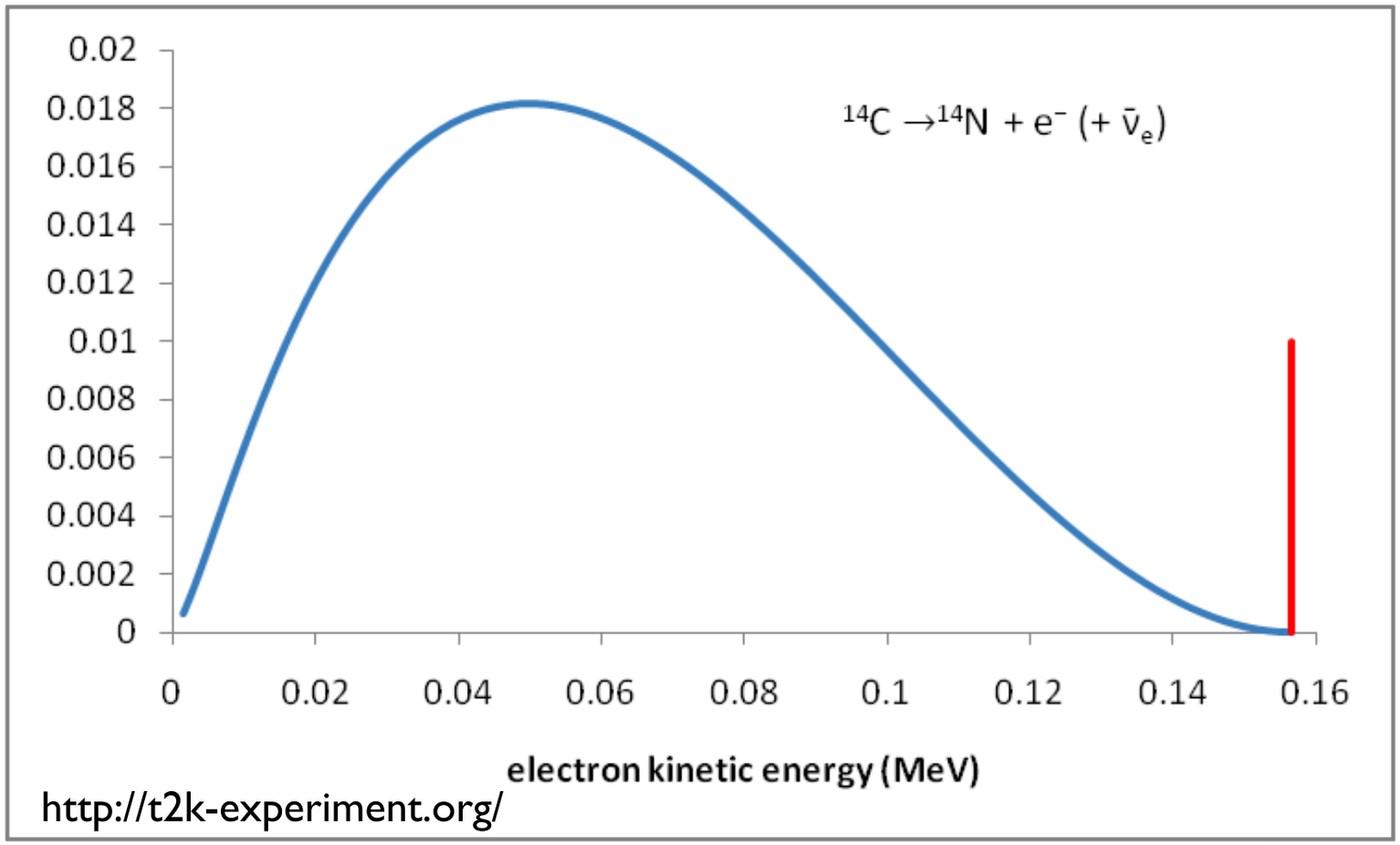
Erik Blaufuss
University of Maryland

Photo credit: J. Werthebach IceCube/NSF

A little about me

- Research scientist at the University of Maryland
- Active in neutrino and particle-astrophysics experiments my entire career
  - Super-Kamiokande - Japan
  - Milagro - New Mexico
  - **IceCube Neutrino Observatory - South Pole**
  - Deep Underground Neutrino Experiment

What is a neutrino?

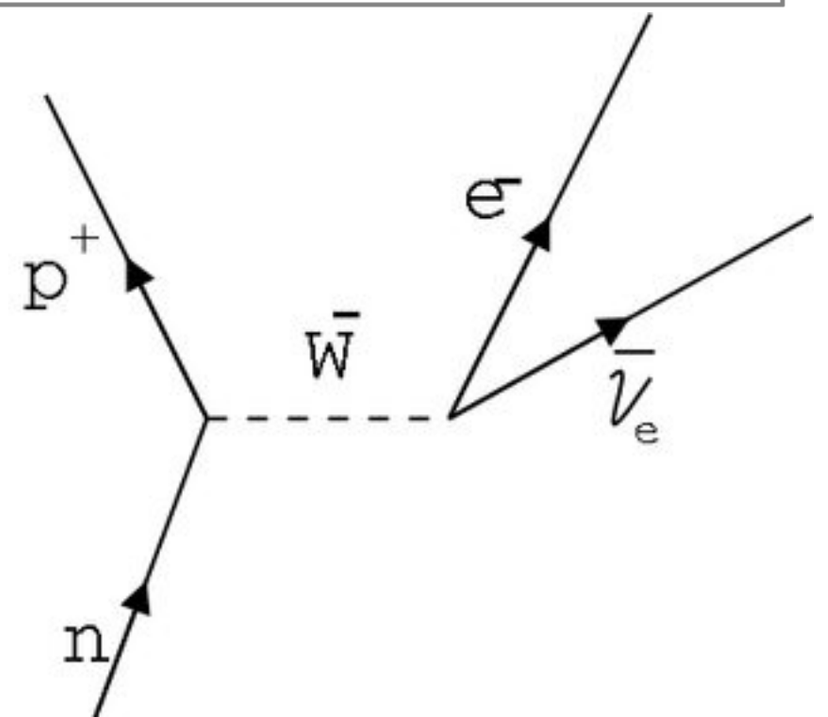


http://t2k-experiment.org/

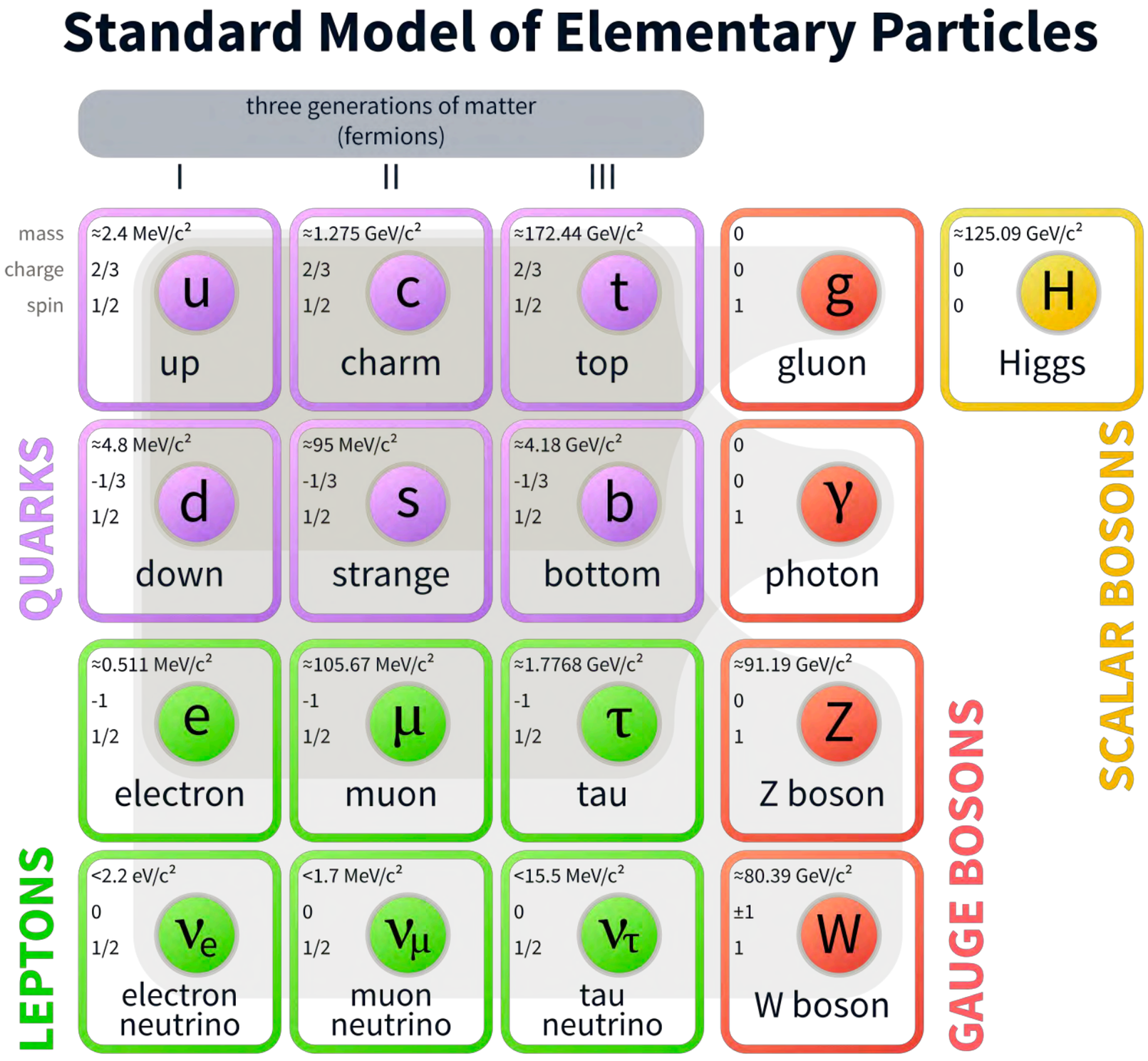
- Proposed by Wolfgang Pauli in 1930 to save energy conservation in beta-decay

- Name neutrino ("little neutral one") by Enrico Fermi

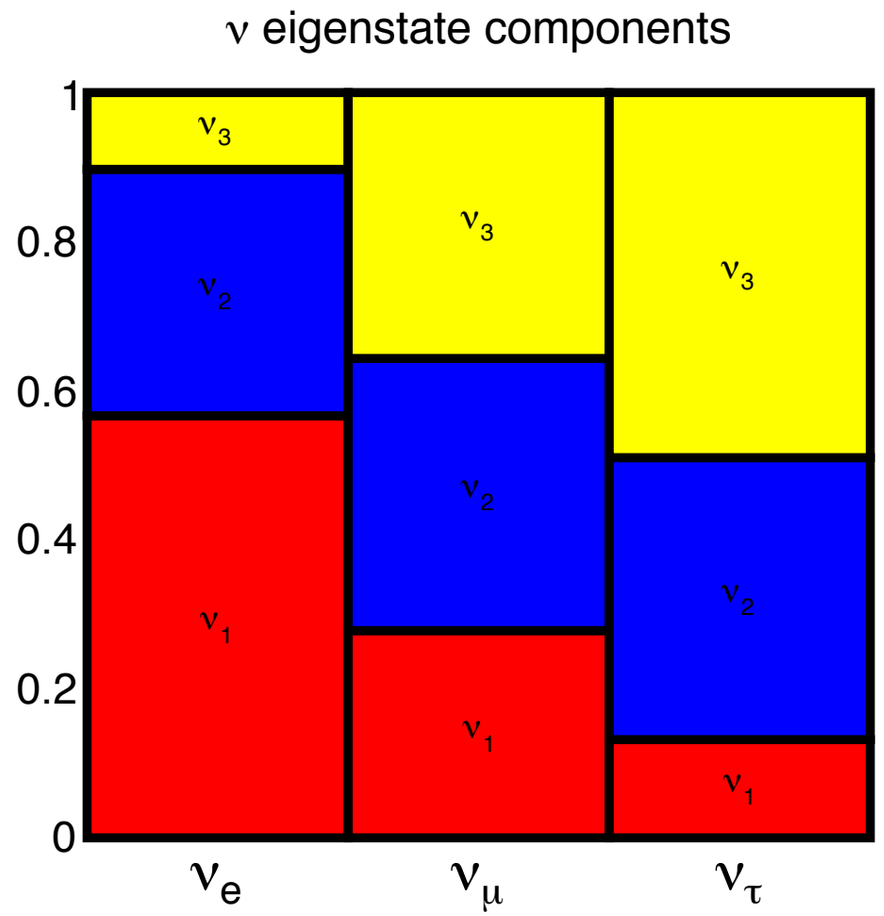
  - 1934 Theory of beta decay [3]



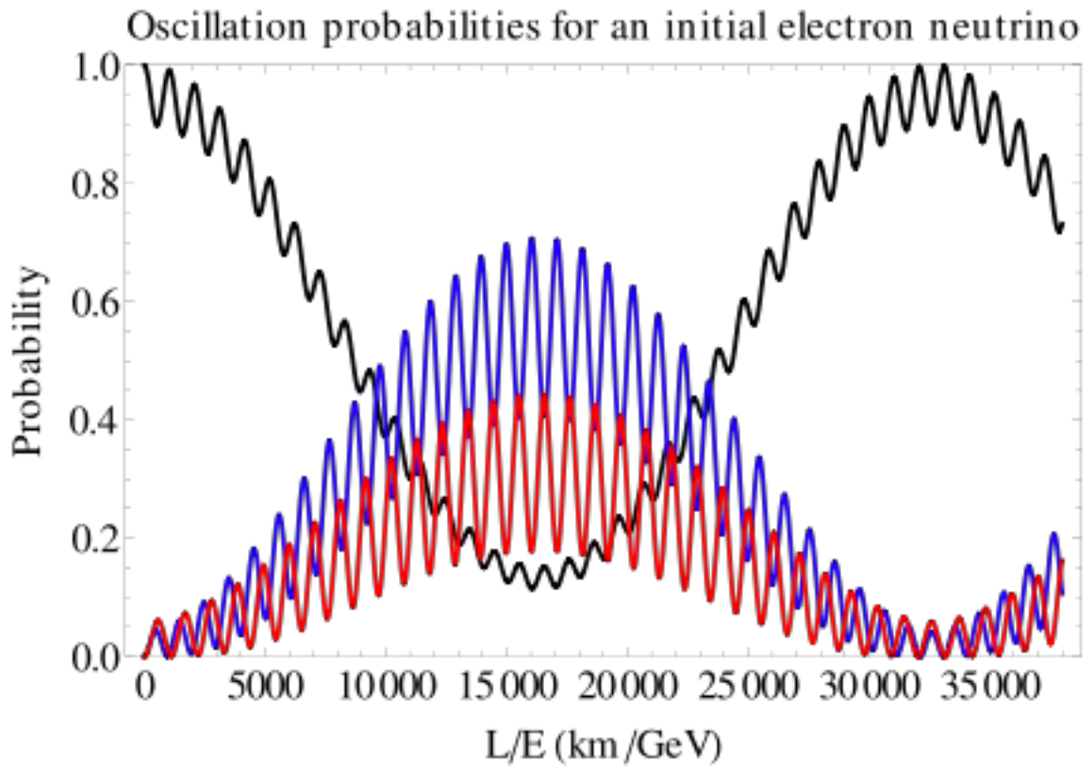
- Standard Model very successful in describing particle interactions
  - Neutrinos produced and interact via the Weak force
- But we know it is not the complete picture.
  - Neutrino masses and mixing
  - Matter-antimatter asymmetry



- Neutrinos have mass
- Quantum mechanics
- Flavor of neutrino changes as neutrino propagates from source



- Long baseline neutrino experiments
- Astrophysical neutrinos are fully oscillated



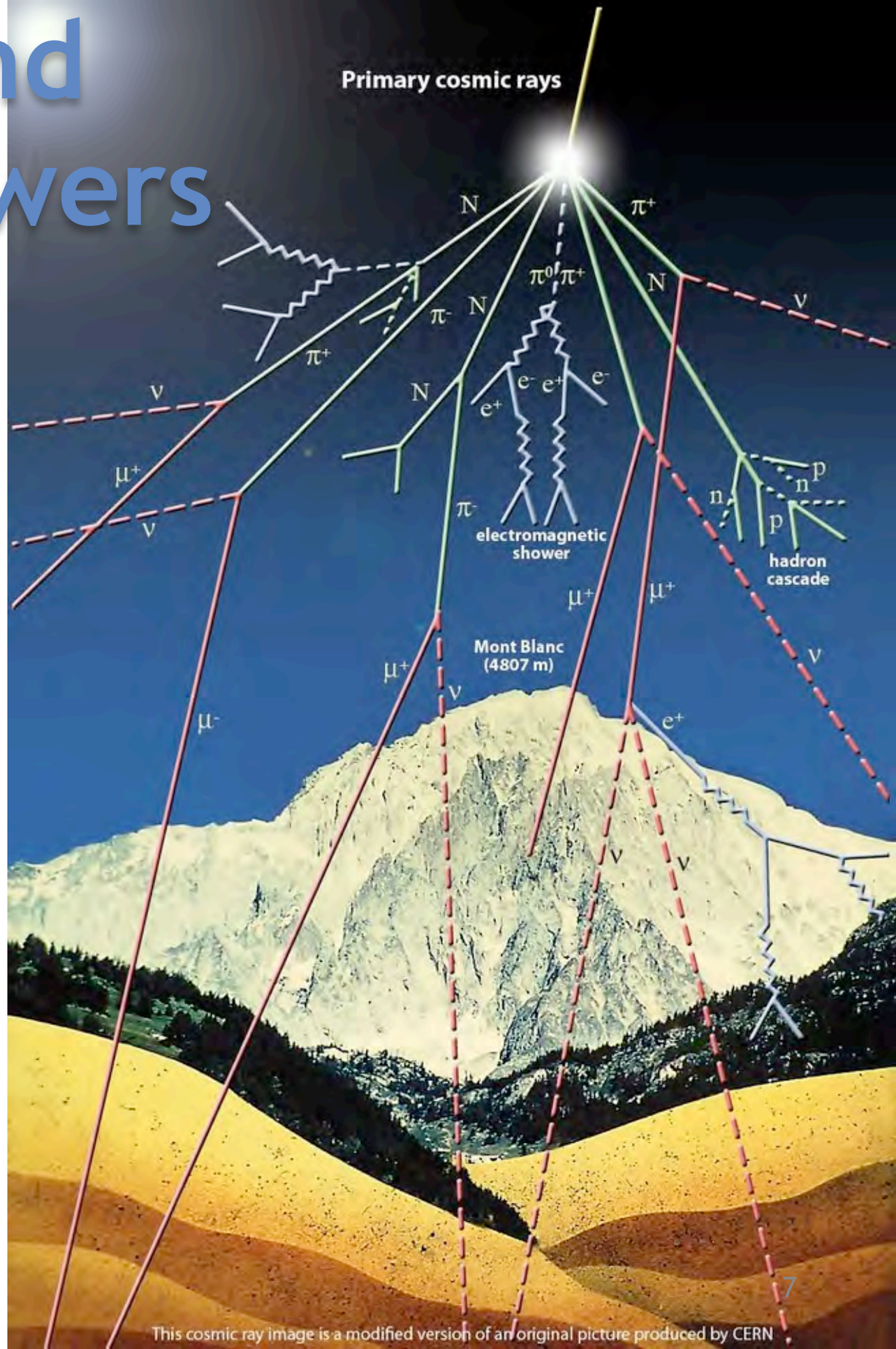
Victor Hess and Cosmic Rays

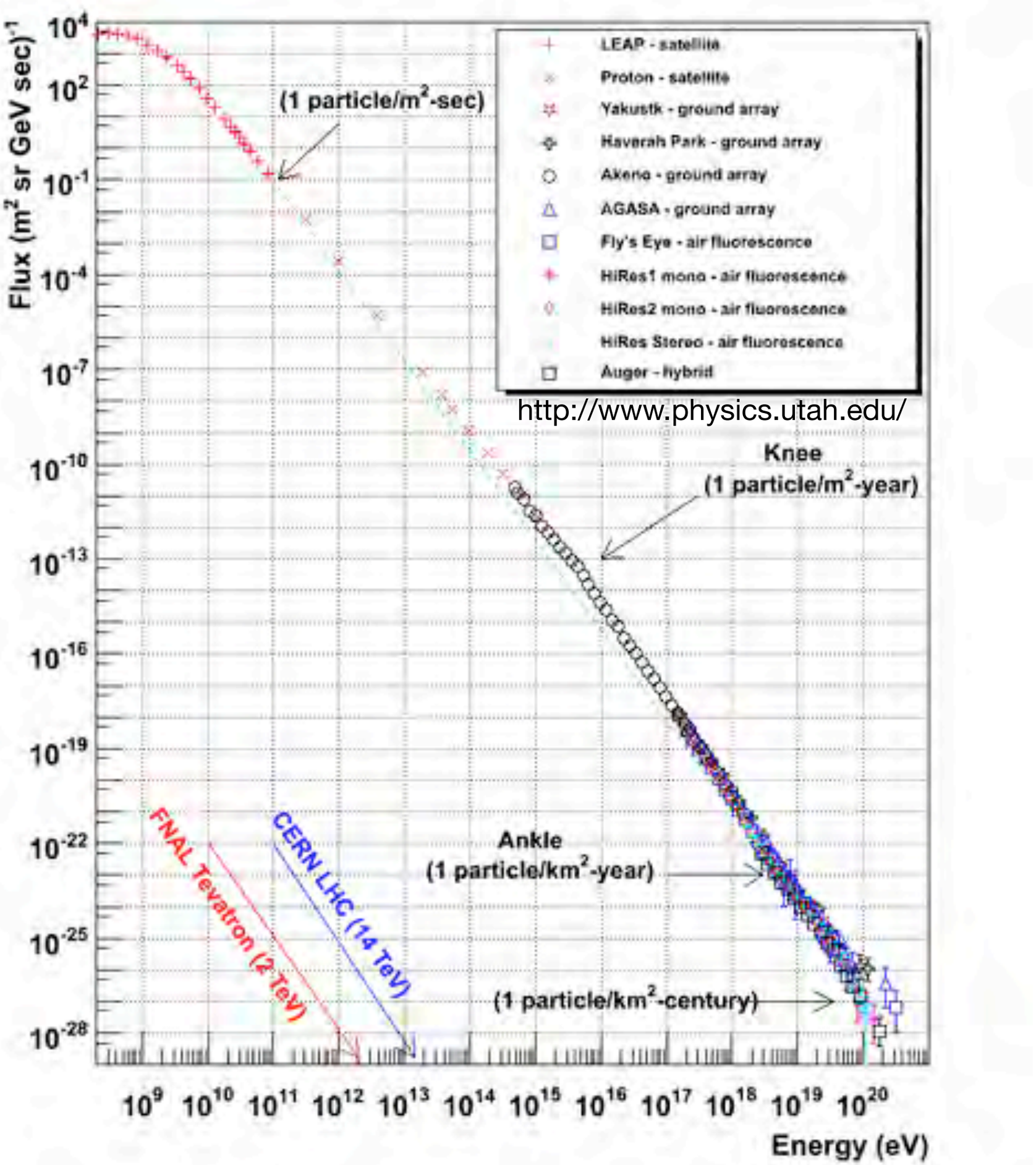
In the years 1911-1912, Austrian physicist Victor Hess made a series of balloon flights with an electroscope on board, expecting that radiation levels would decrease with altitude. The rate increased with altitude.

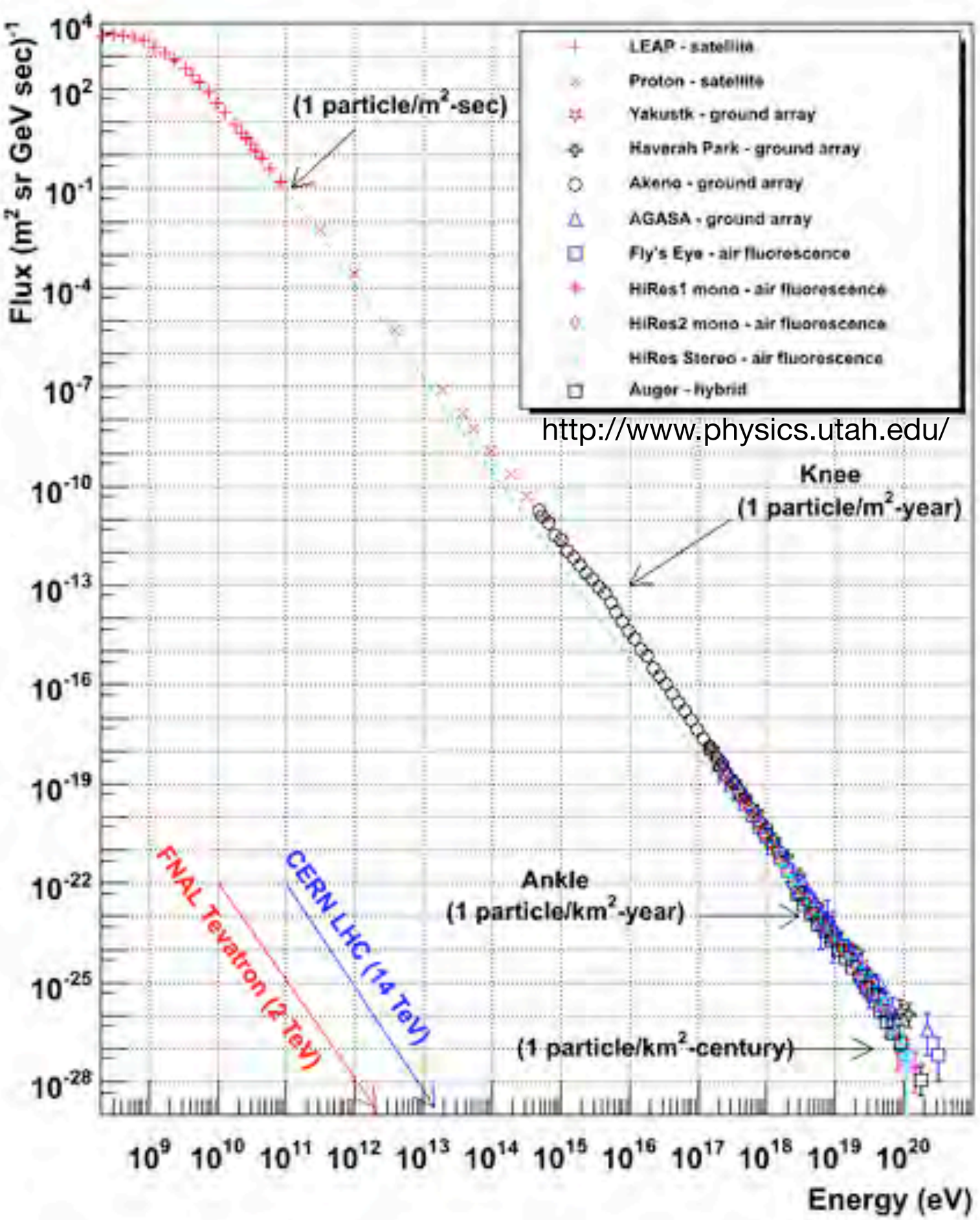
Source was not the Earth's radioactivity but particles from space.

Pierre Auger and extensive air showers

1938: Pierre Auger noticed that two particle detectors placed high in the Alps many meters apart registered hits at the same time. He had discovered extensive air showers with a parent particle energy of 10^{15} eV.



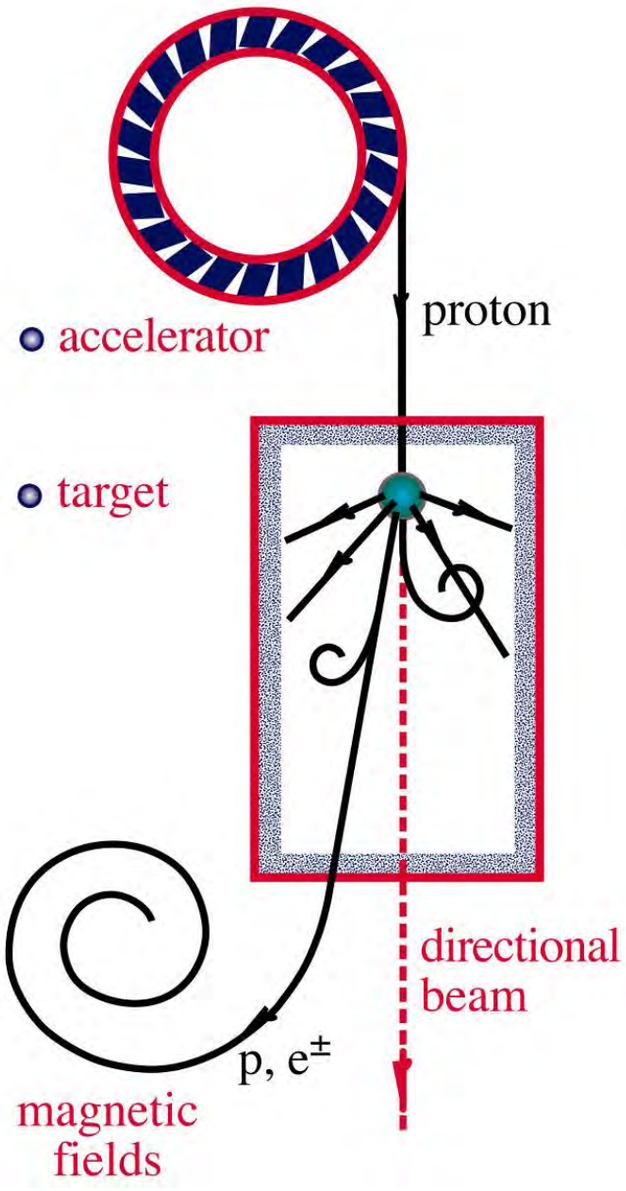

Flux (m² sr GeV sec)⁻¹
10⁴
10²
10⁻¹
10⁻⁴
10⁻⁷
10⁻¹⁰
10⁻¹³
10⁻¹⁶
10⁻¹⁹
10⁻²²
10⁻²⁵
10⁻²⁸
(1 particle/m²-sec)
LEAP - satellite
Proton - satellite
Yakustk - ground array
Haverah Park - ground array
Akeno - ground array
AGASA - ground array
Fly's Eye - air fluorescence
HiRes1 mono - air fluorescence
HiRes2 mono - air fluorescence
HiRes Stereo - air fluorescence
Auger - hybrid
http://www.physics.utah.edu/
Knee
(1 particle/m²-year)
Ankle
(1 particle/km²-year)
(1 particle/km²-century)
FNAL Tevatron (2 TeV)
CERN LHC (14 TeV)
10⁹ 10¹⁰ 10¹¹ 10¹² 10¹³ 10¹⁴ 10¹⁵ 10¹⁶ 10¹⁷ 10¹⁸ 10¹⁹ 10²⁰
Energy (eV)

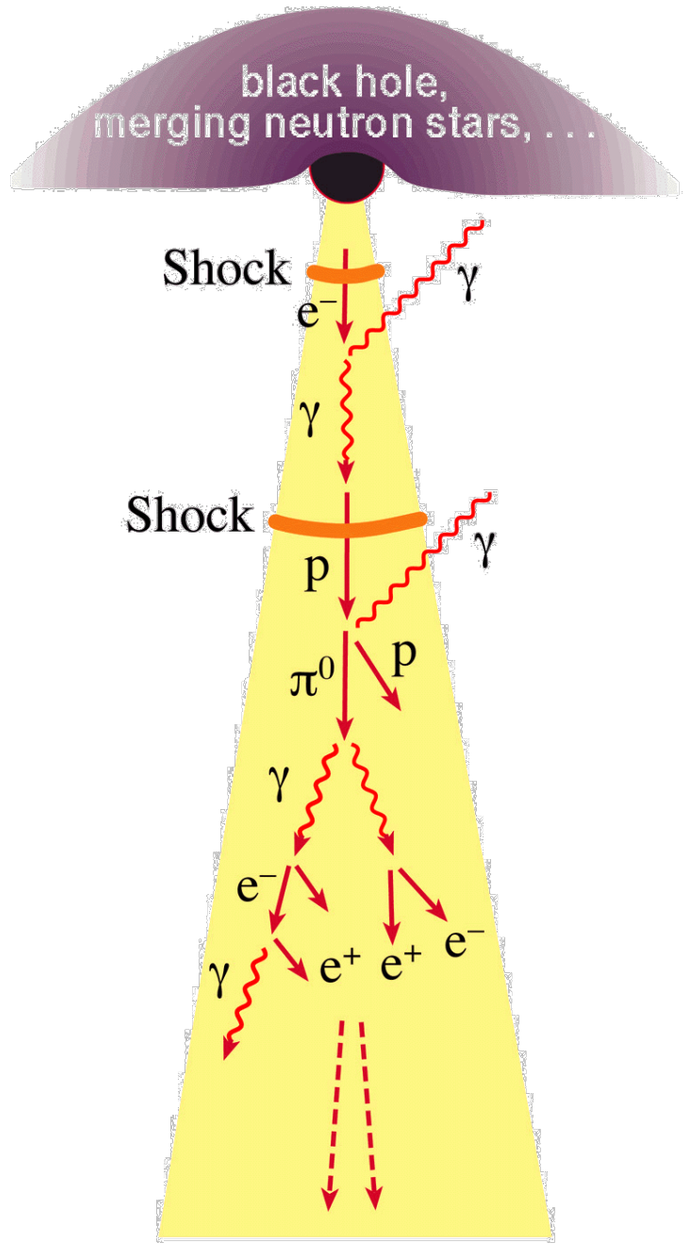


A 100 year old mystery:

- The source locations and acceleration mechanisms
- The composition (iron, vs. protons)
- Where the transition is from galactic to extra galactic

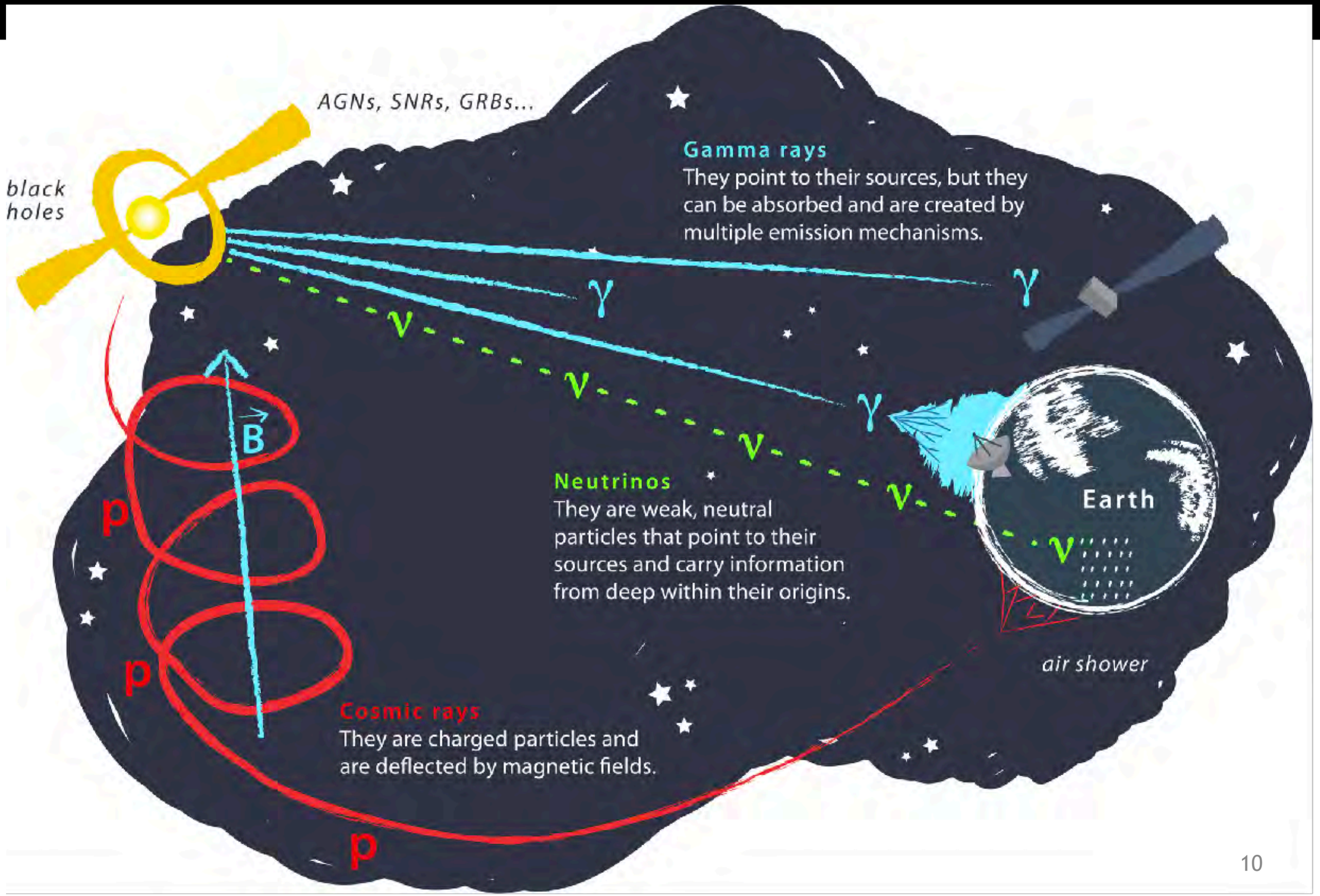
Why neutrinos?



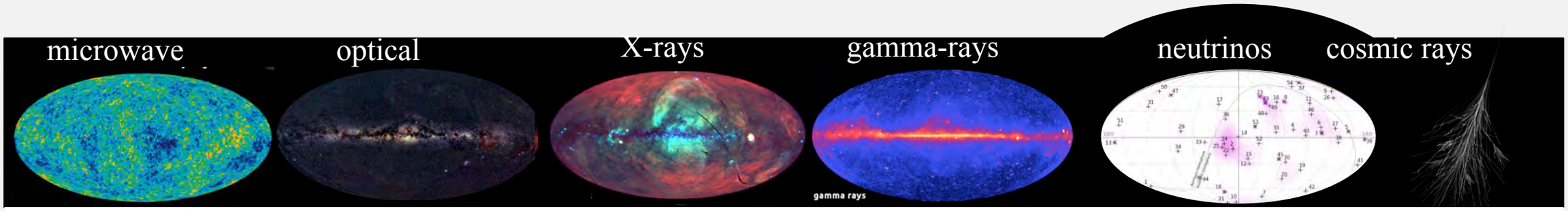


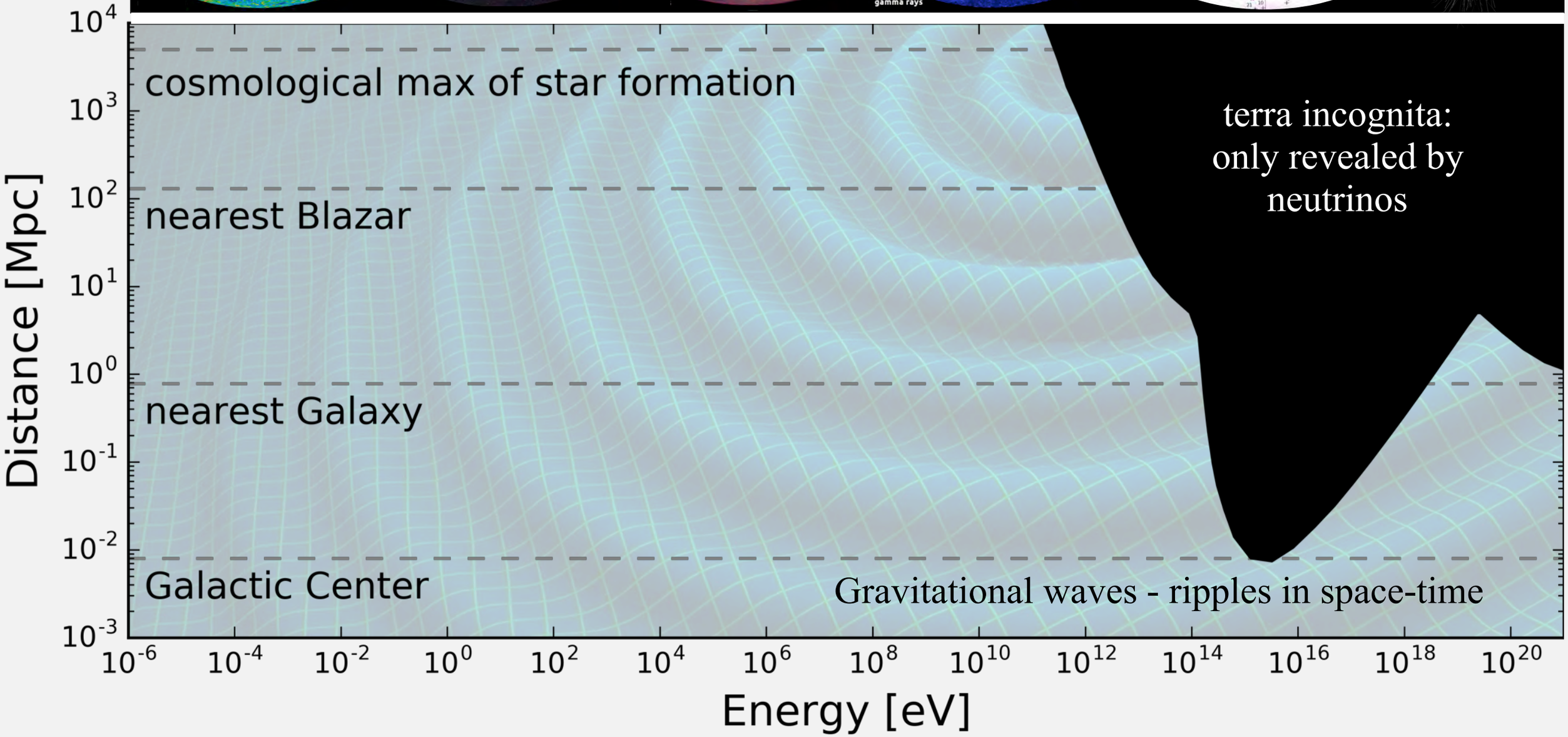
Accelerated electrons can produce gamma rays, but neutrinos are a unique signature and probe of Cosmic Ray (proton/ion) acceleration.

Why use neutrinos?



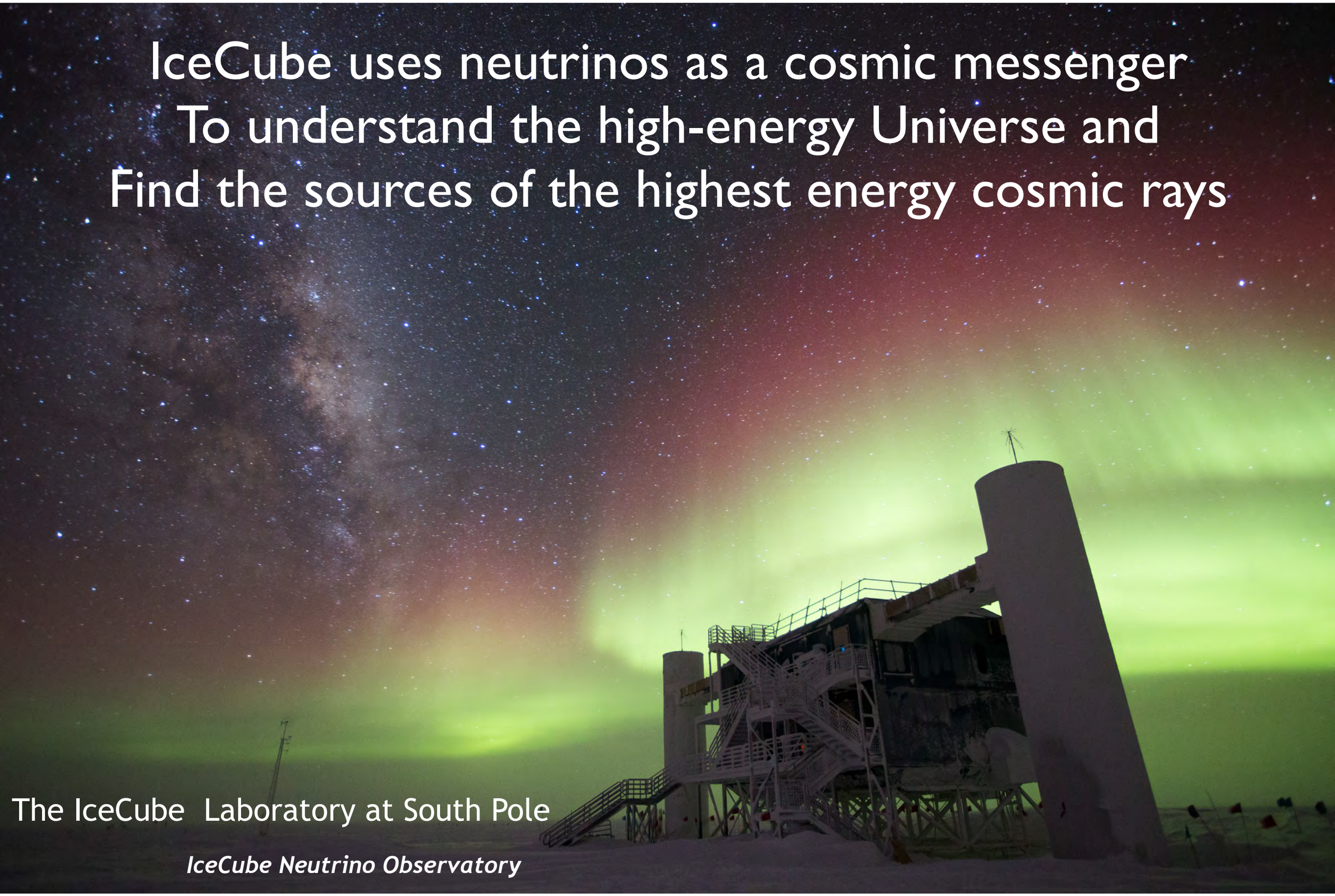
Multi-Messenger Astronomy





20% of the Universe is opaque to the EM spectrum

IceCube uses neutrinos as a cosmic messenger
To understand the high-energy Universe and
Find the sources of the highest energy cosmic rays



The IceCube Laboratory at South Pole

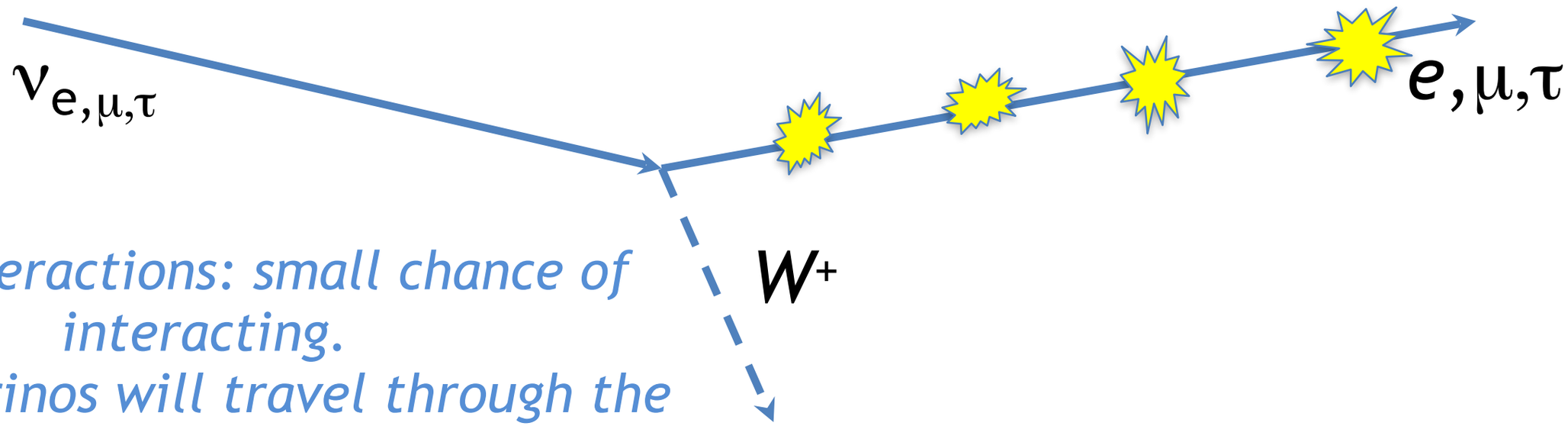
IceCube Neutrino Observatory

Neutrino Detection

Footprints of a ghost…

Incoming neutrino.

Charged, relativistic lepton emerges and creates unique patterns of light.



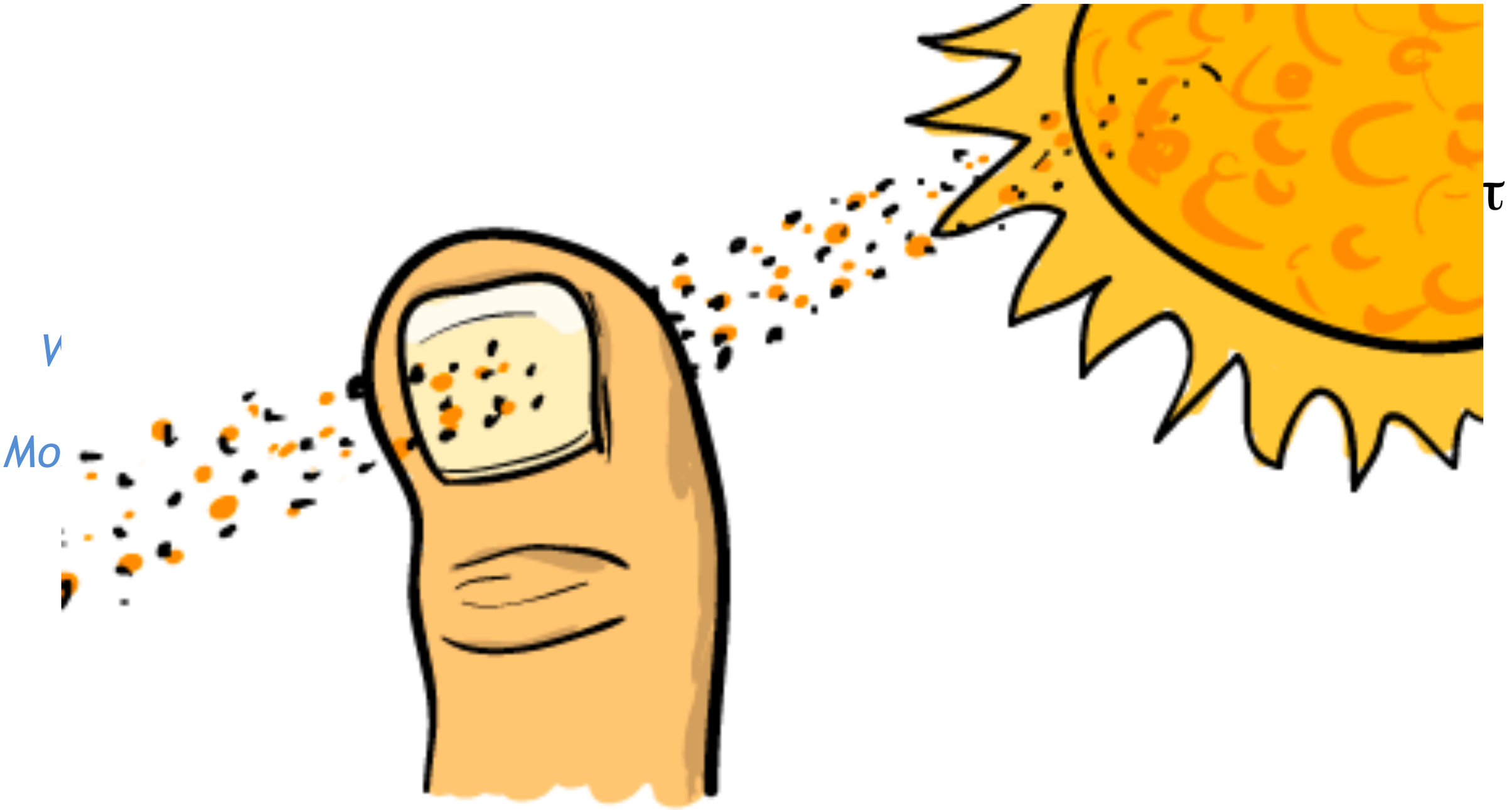
Weak interactions: small chance of interacting.
Most neutrinos will travel through the Earth unperturbed!

Recoiling nucleus creates a particle shower and detectable Cherenkov light.

time

Neutrino Detection

Footprints of a ghost...



FACT: about 65 million neutrinos pass through your thumbnail every second.

Learn Something New Every Day
LSNED.com

light.

time

Cherenkov radiation

- These relativistic leptons produce optical light in our detector

  - Cherenkov light emitted by charged particles moving faster than the speed of light in the medium….

    - Similar to a sonic boom but with light

- These particles leave distinct tracks in our detector

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- The our dete
  - C moving fa .
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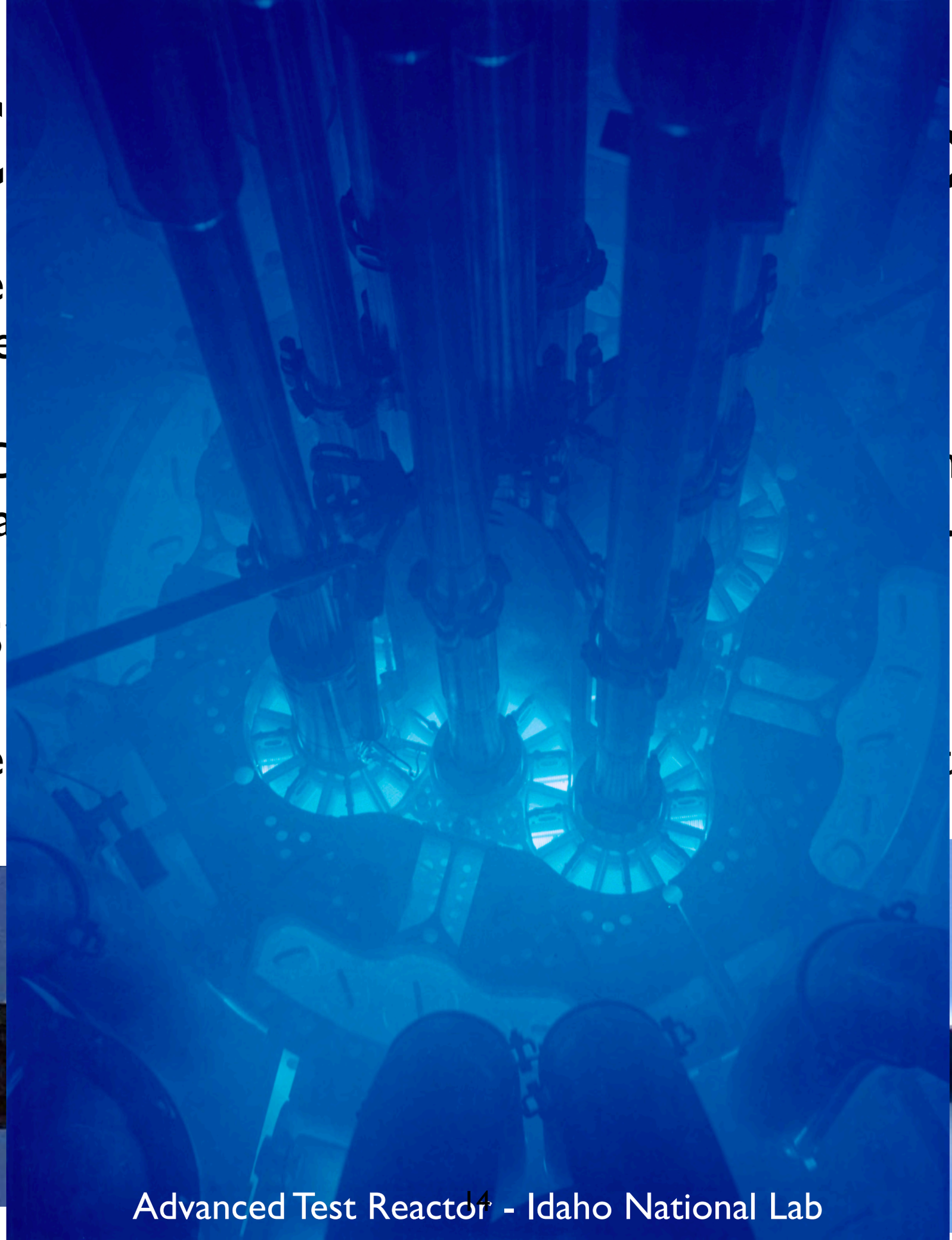
- The tor



Advanced Test Reactor - Idaho National Lab

Cable for power, communication and support

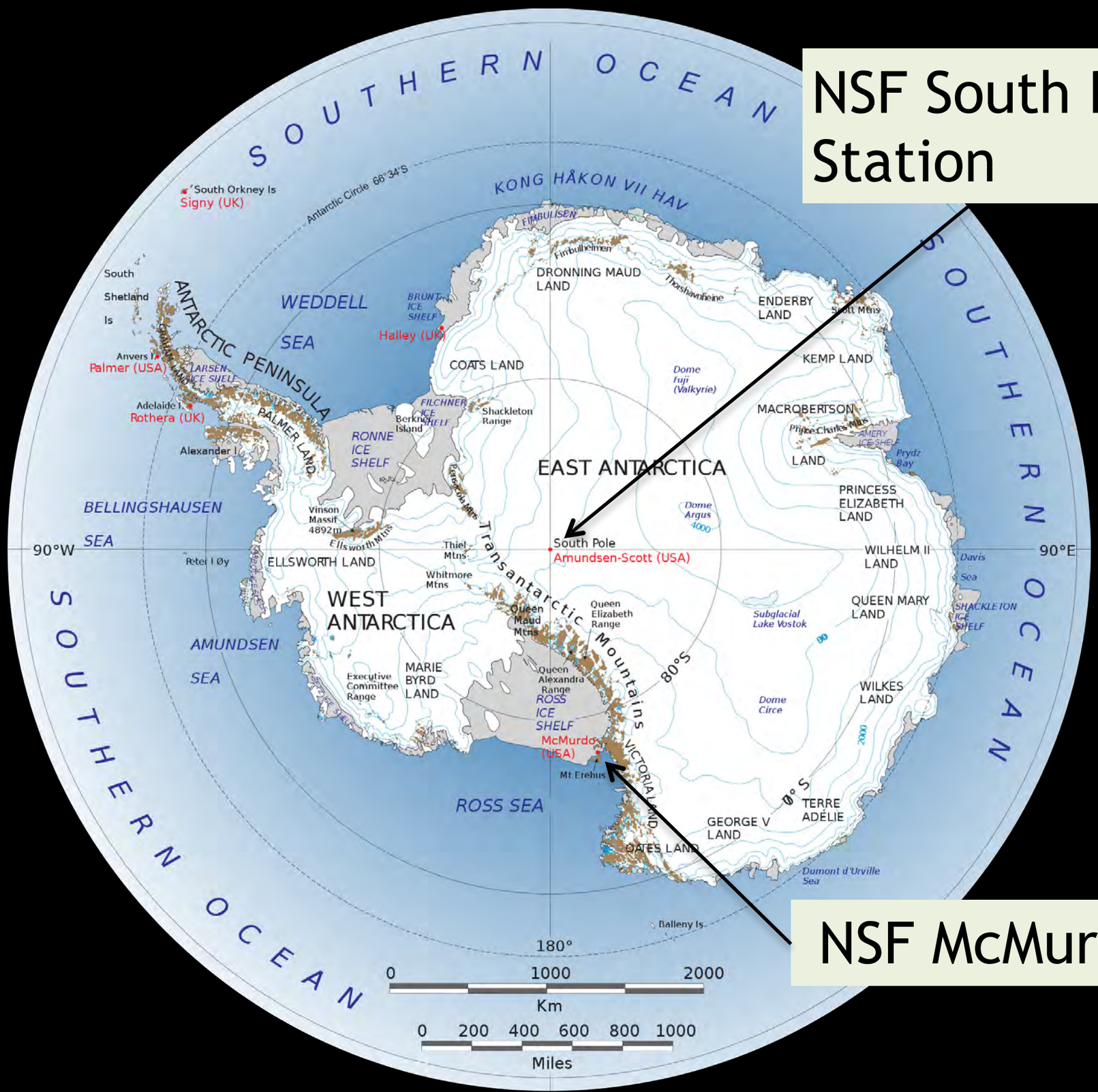
Digital optical modules (phototubes and data acquisition)

Clear ice serves as both a target medium and a Cherenkov radiator

μ

ν_μ

1 km³ of natural clear (ice) radiator!
→ The South Pole glacial icecap



NSF South Pole Station

NSF McMurdo Station

IceCube

South Pole Neutrino Observatory

IceCube Laboratory

Data is collected here and sent by satellite to the data warehouse at UW–Madison

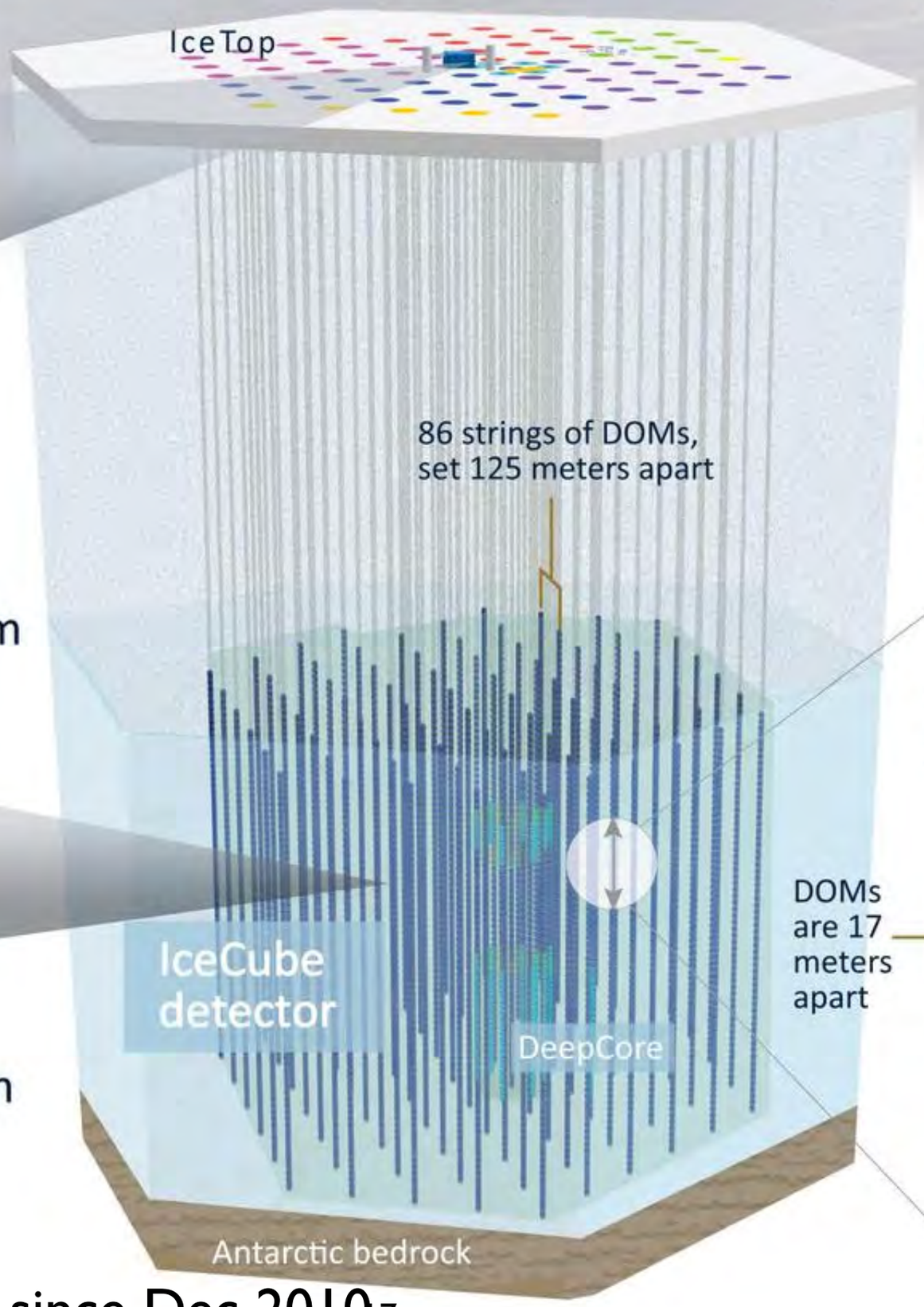
50 m

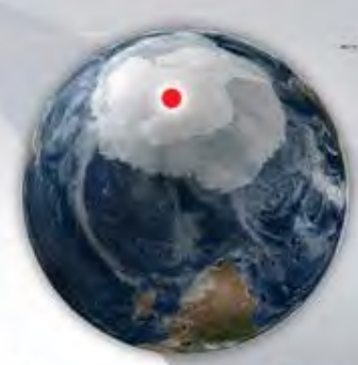
1450 m

Digital Optical Module (DOM)

5,160 DOMs deployed in the ice

2450 m

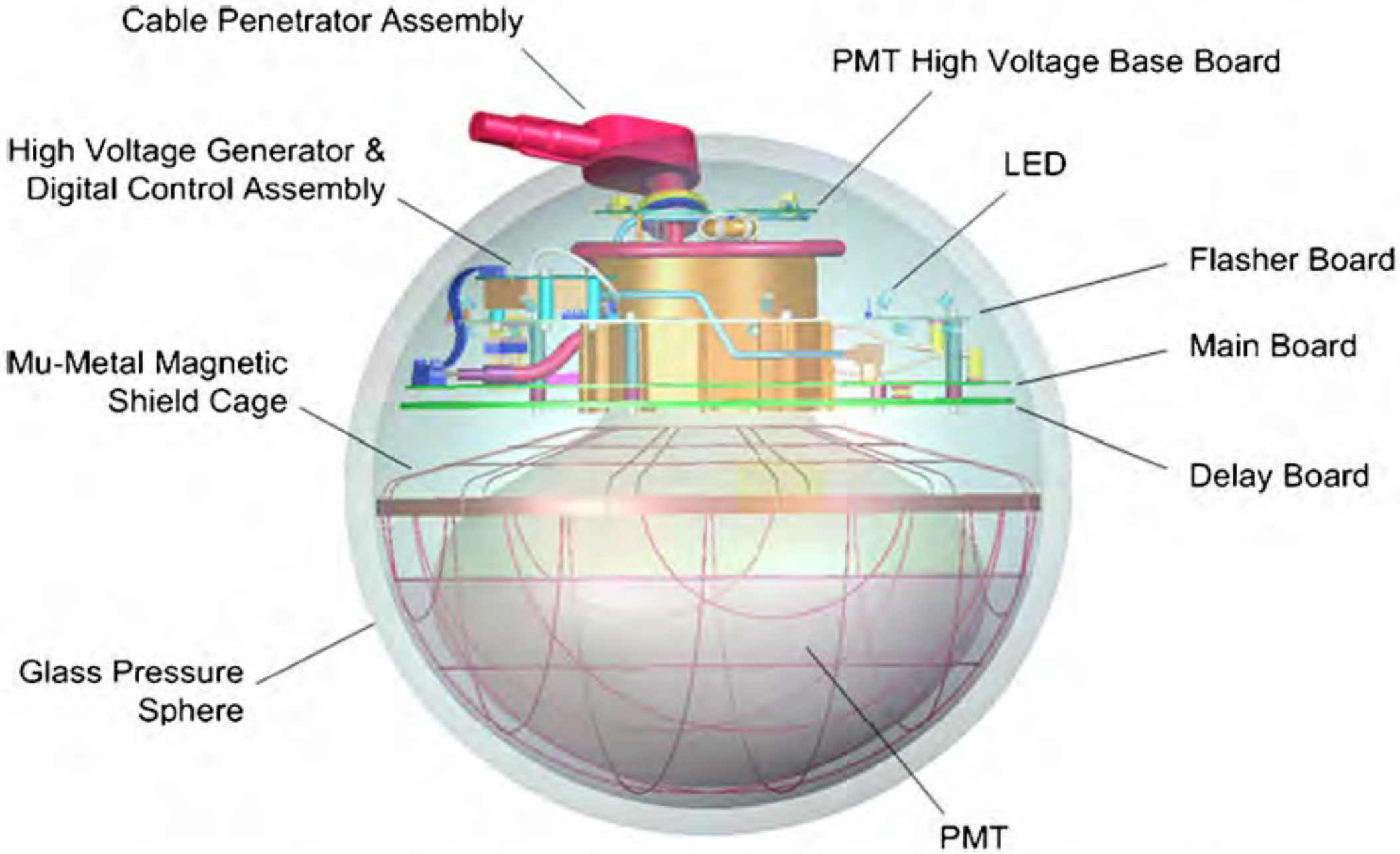




Amundsen–Scott South Pole Station, Antarctica

A National Science Foundation-managed research facility

Completed and taking data since Dec 2010



The IceCube Digital Optical Module (DOM)

~98% of DOMs still returning high quality data in 2019

Cable Penetr

High Voltage Genera
Digital Control Asse

Mu-Metal Magnetic
Shield Cage

Glass Pressure
Sphere

e Base Board

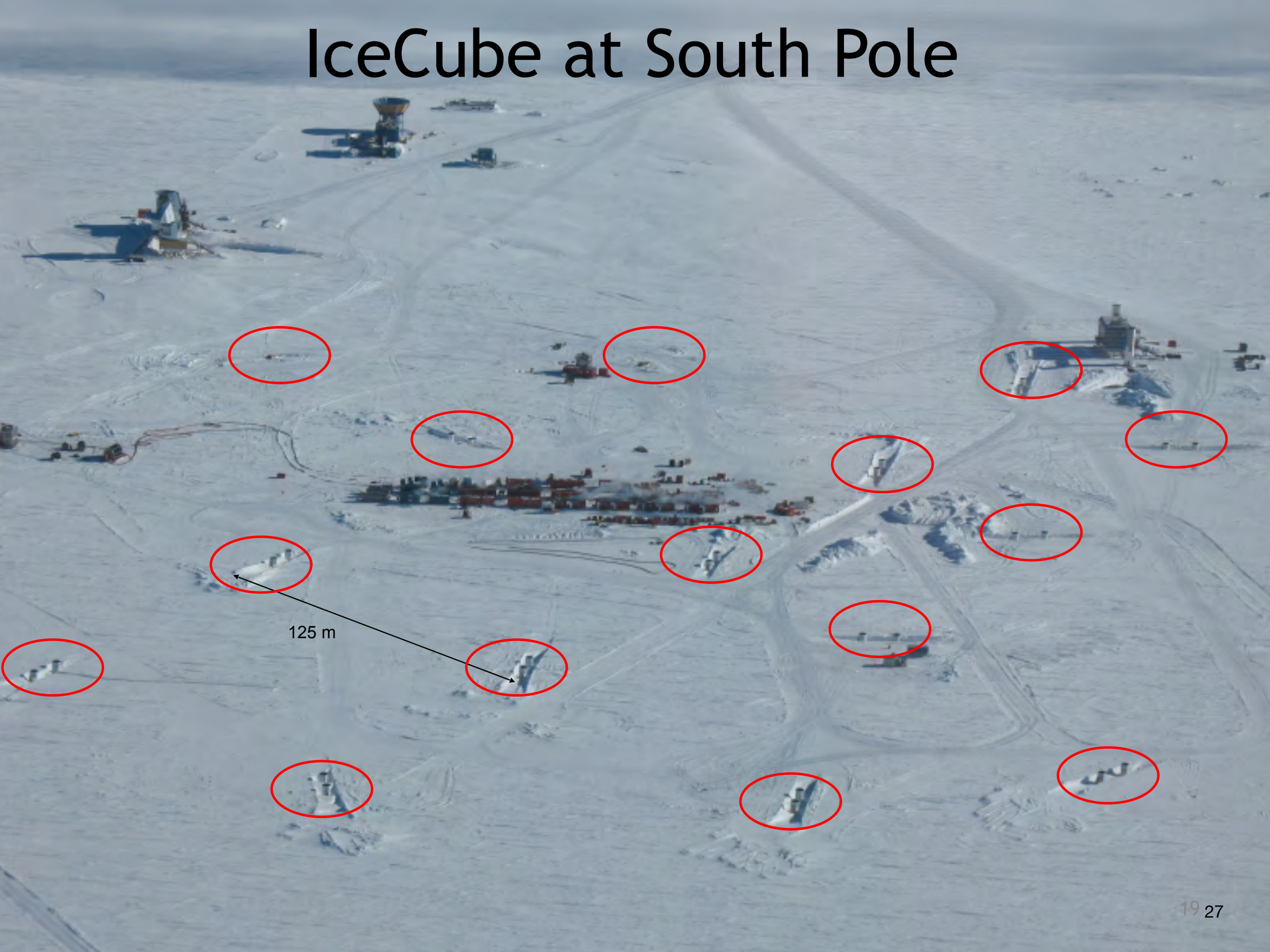
Flasher Board

Main Board

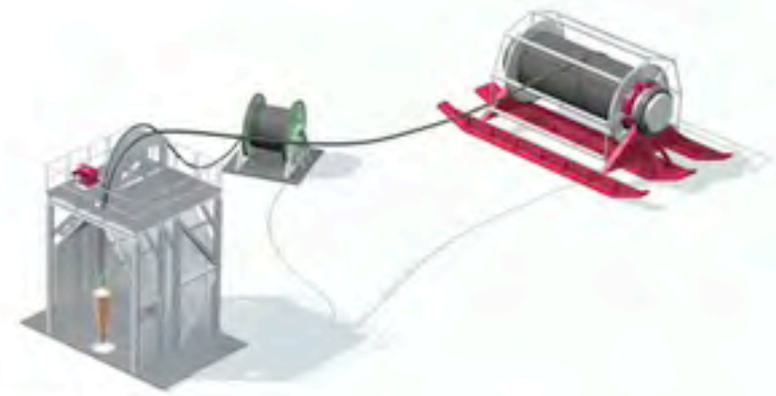
Delay Board

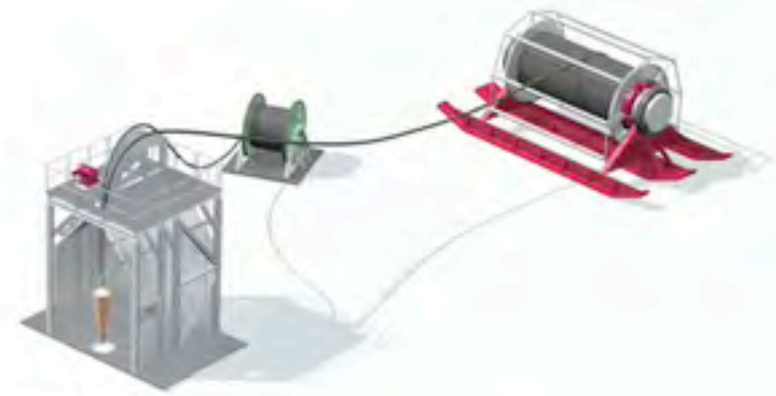
~98% of DOMs still retu
high quality data in 2(

IceCube at South Pole

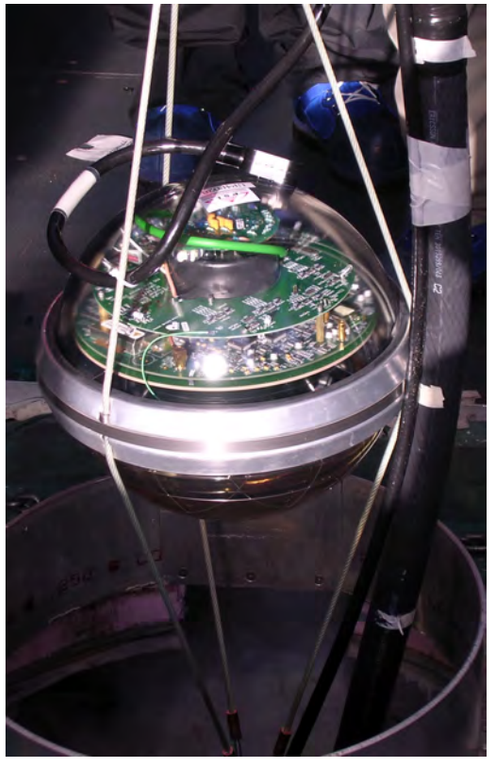


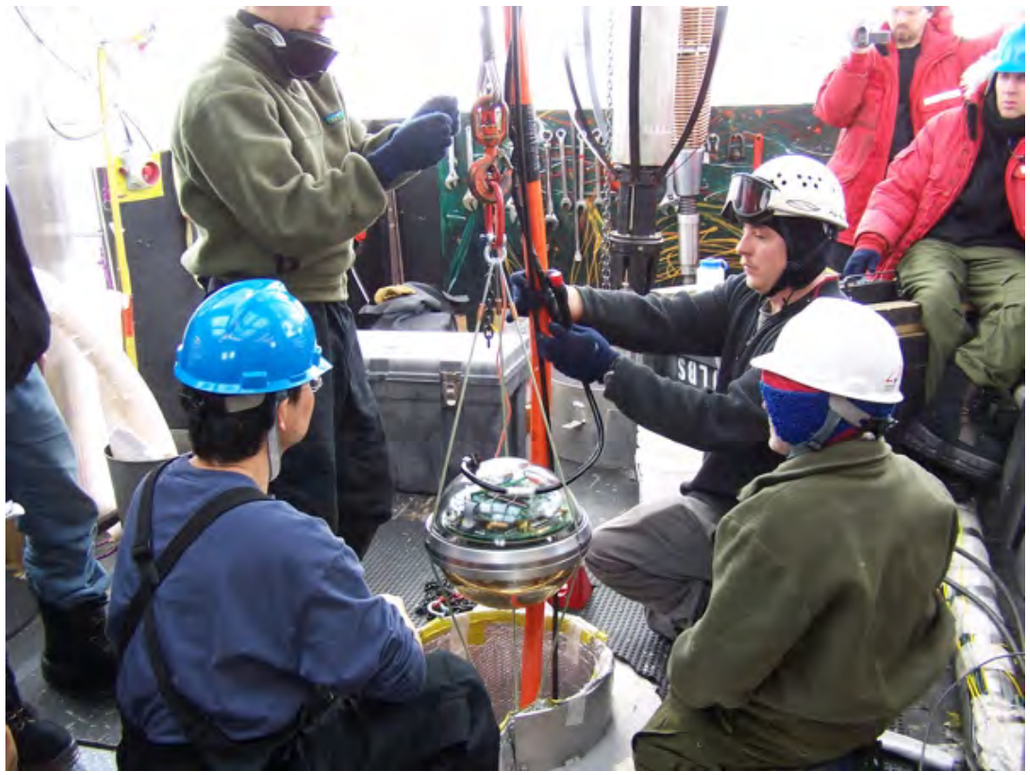
IceCube construction 20 Seasonal drill camp

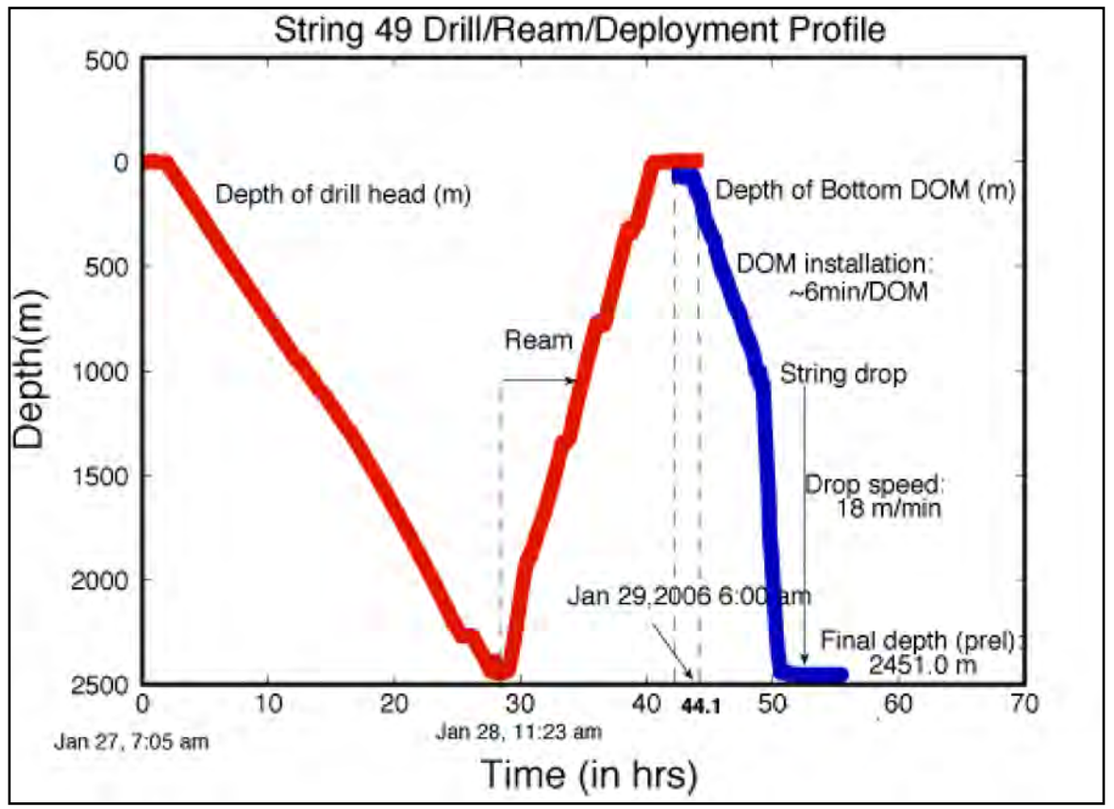




Drilling and deployment



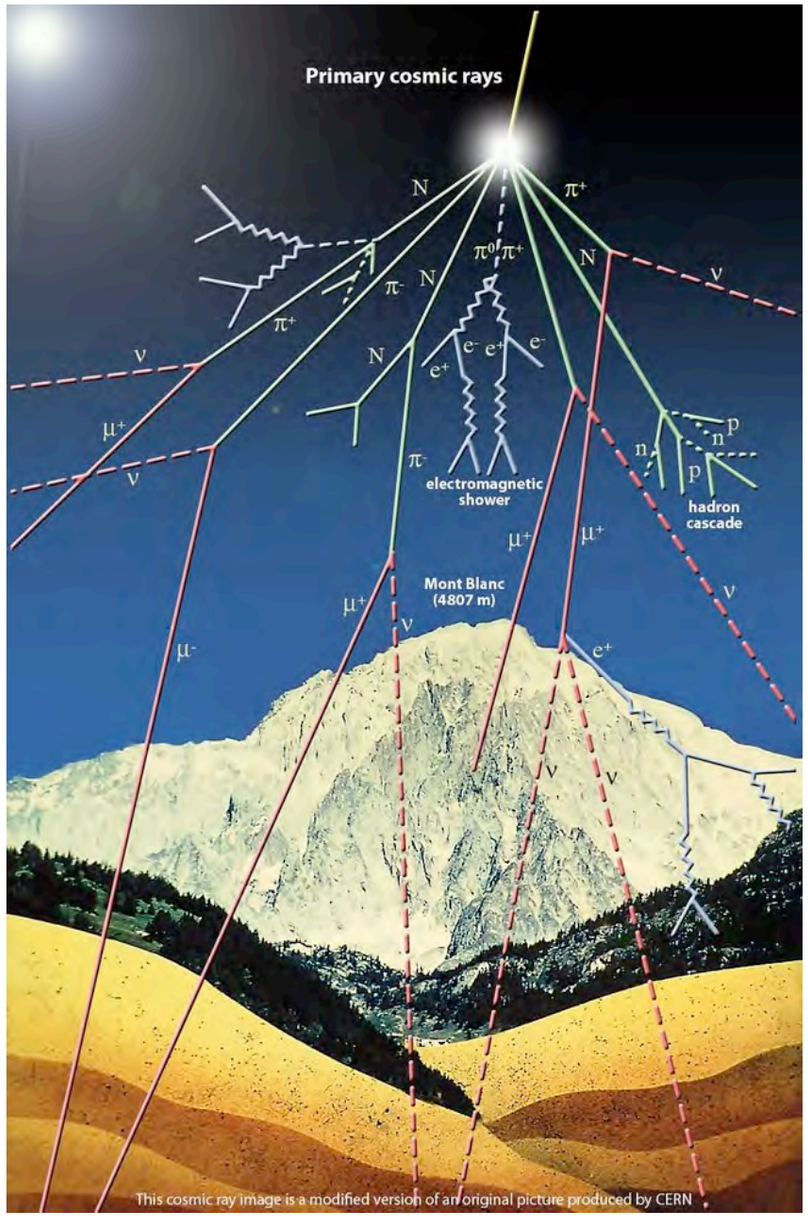




~3 days to drill and deploy a string of DOMs

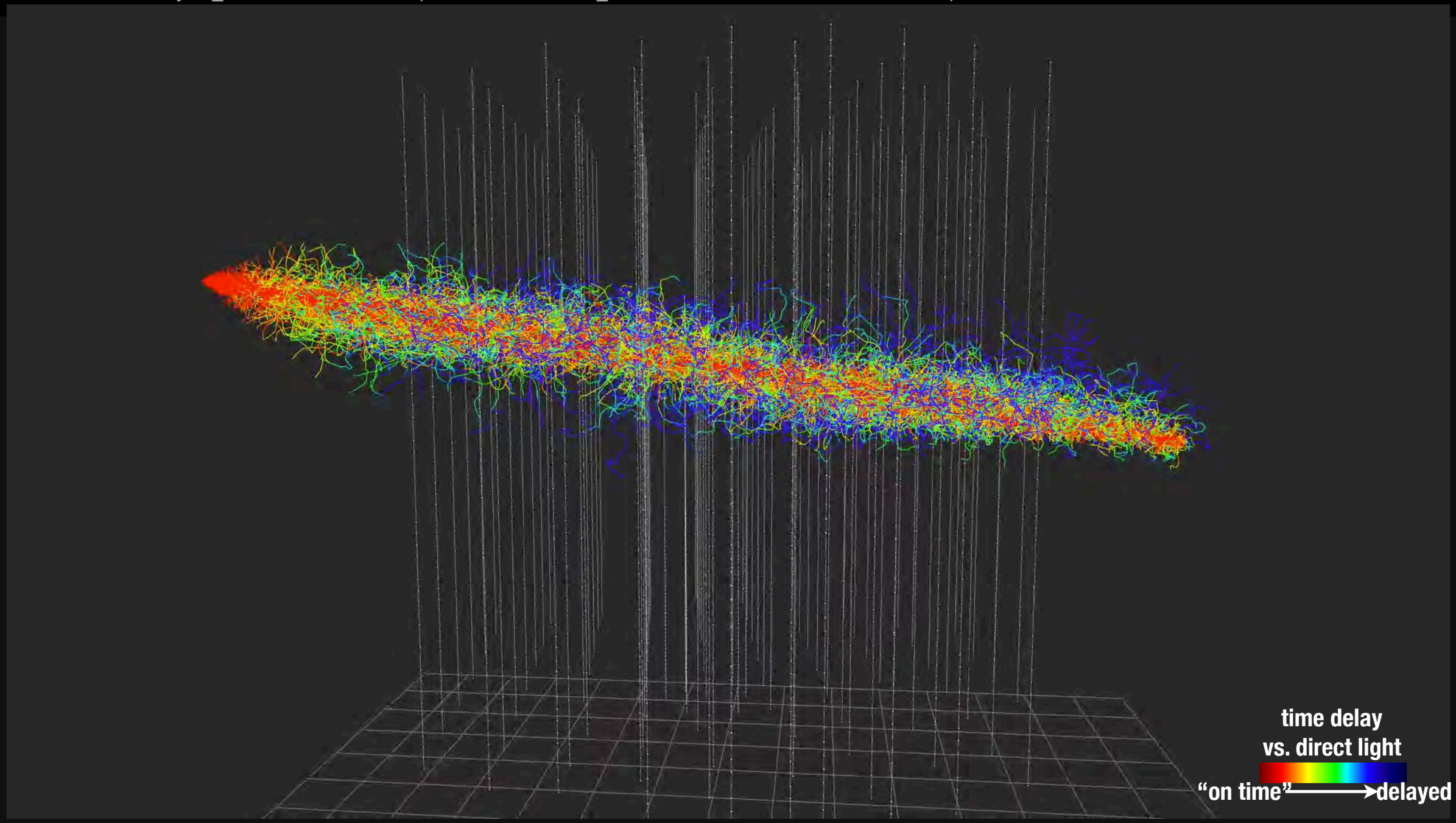
“One in a billion”

- IceCube is the largest physics experiment every built
- We have a large and multiple background signals
  - Collect ~2,800 events per second collected
    ~100 billion events (350 TB/yr)
    - Mostly down-going muons from air showers
  - “Background neutrinos” = ~100,000/year
    - Neutrinos from extensive air showers
  - “Signal neutrinos” = ~100s /year
    - Neutrinos from astrophysical sources
- Lots of effort required to find our signal neutrinos.
  - Astrophysical sources produce higher energy neutrinos
  - Astrophysical sources don’t arrive from random directions



The IceCube Neutrino Observatory

Neutrinos are detected by looking for Cherenkov radiation from secondary particles (muons, particle showers)



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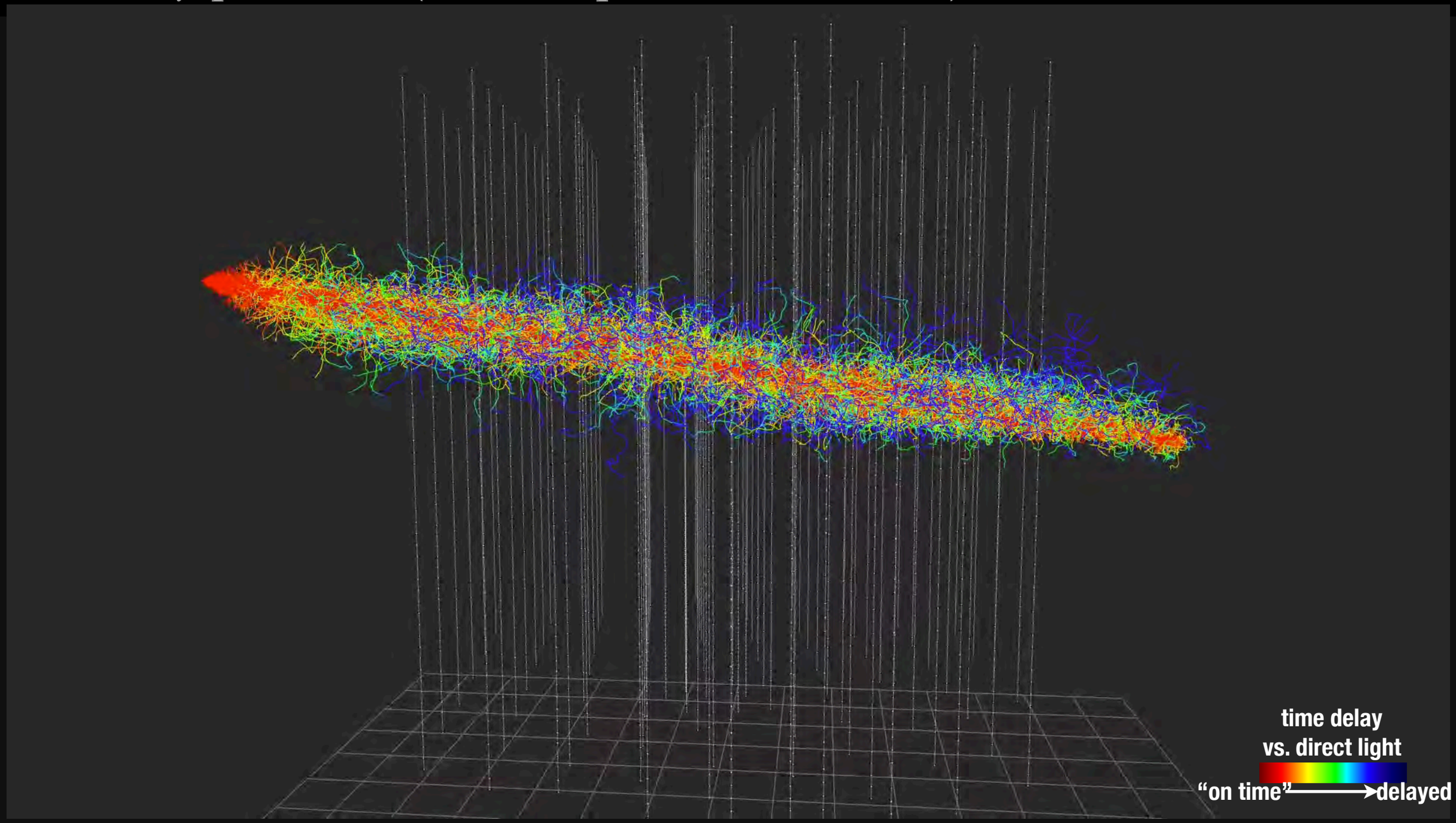
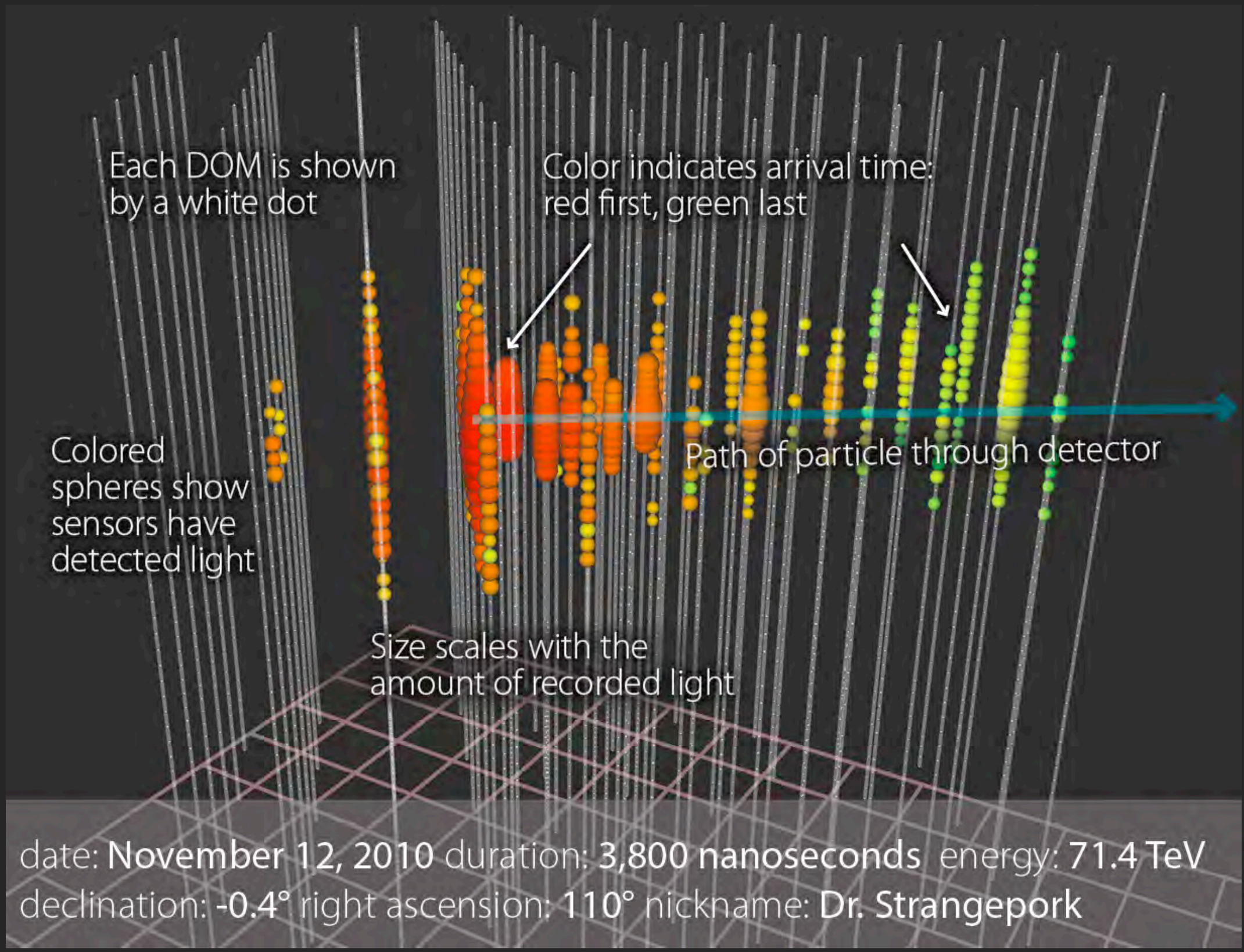


IceCube Events

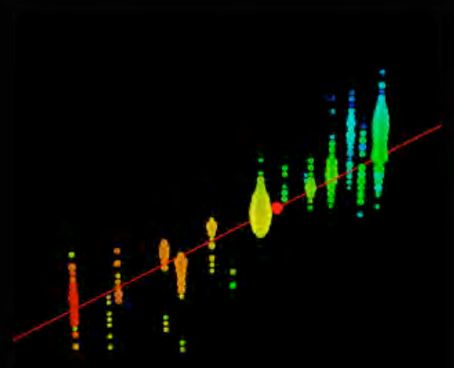


Neutrino Event Signatures

Signatures of signal events

time

CC Muon Neutrino

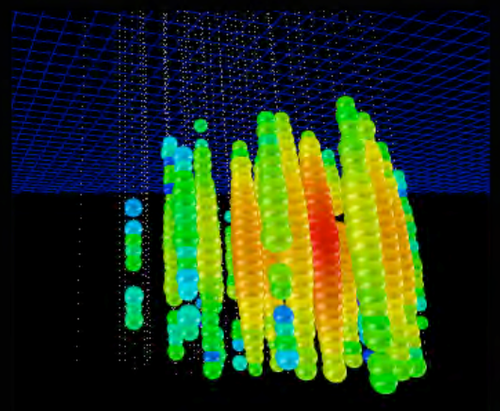


$$\nu_\mu + N \rightarrow \mu + X$$

track (data)

factor of ≈ 2 energy resolution
< 1° angular resolution

Neutral Current /Electron Neutrino



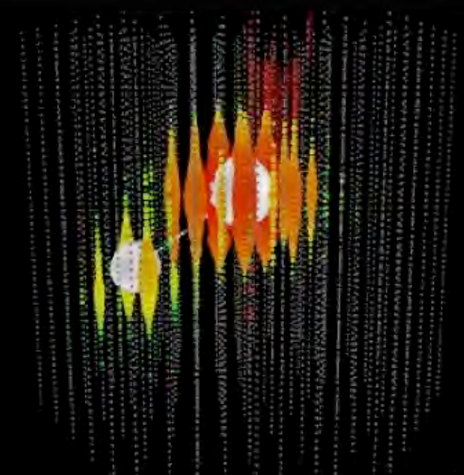
$$\nu_e + N \rightarrow e + X$$

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

cascade (data)

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

CC Tau Neutrino



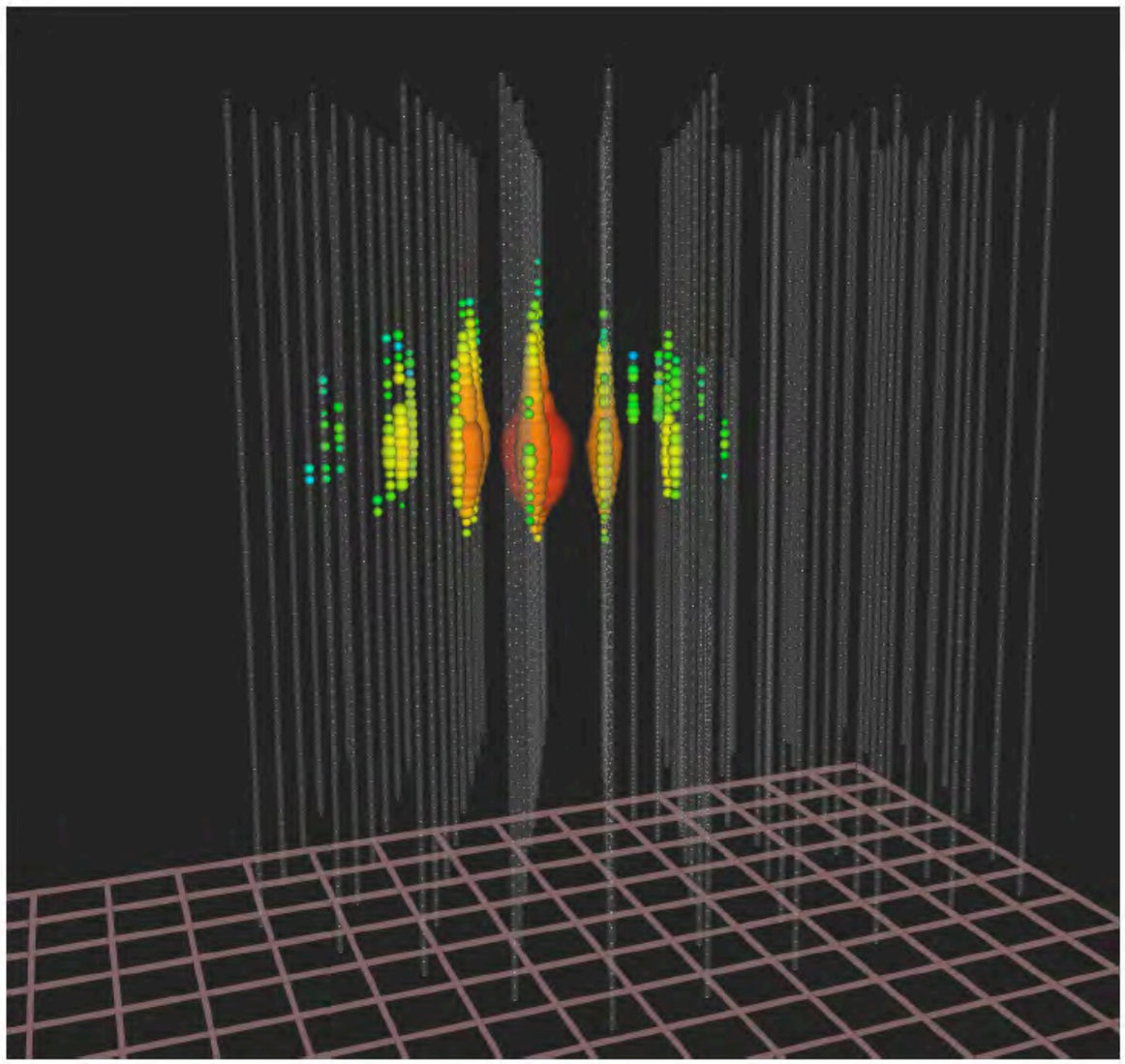
$$\nu_\tau + N \rightarrow \tau + X$$

"double-bang" and other signatures
(simulation)

(not observed yet)

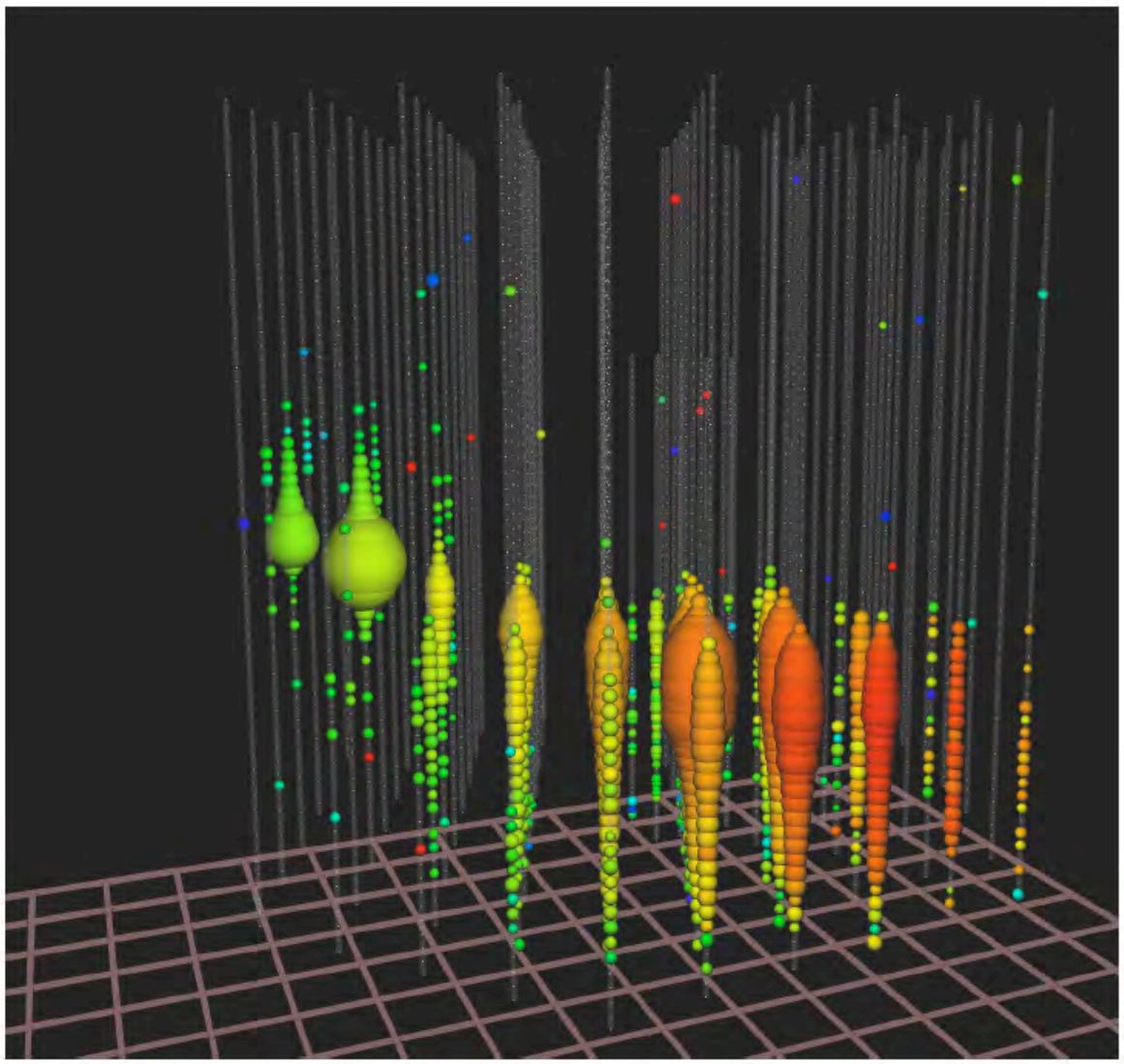
IceCube Preliminary

Isolated neutrinos interacting *inside* the detector



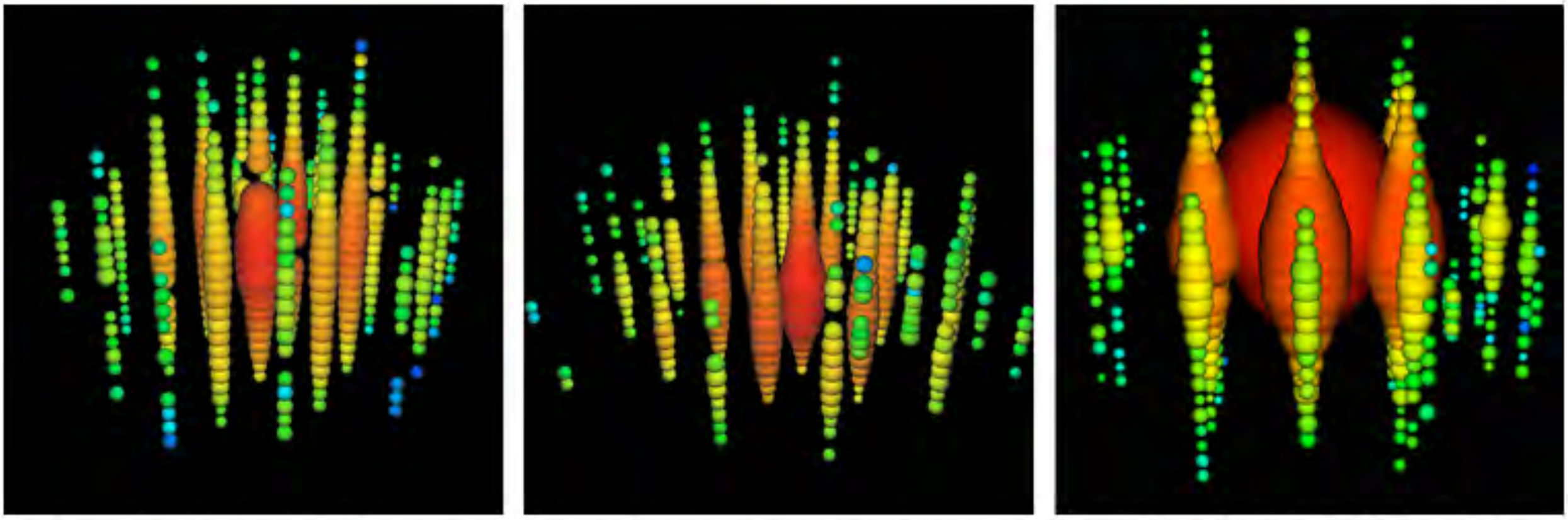
total energy measurement
all flavors, all sky

Up-going muon-neutrino tracks



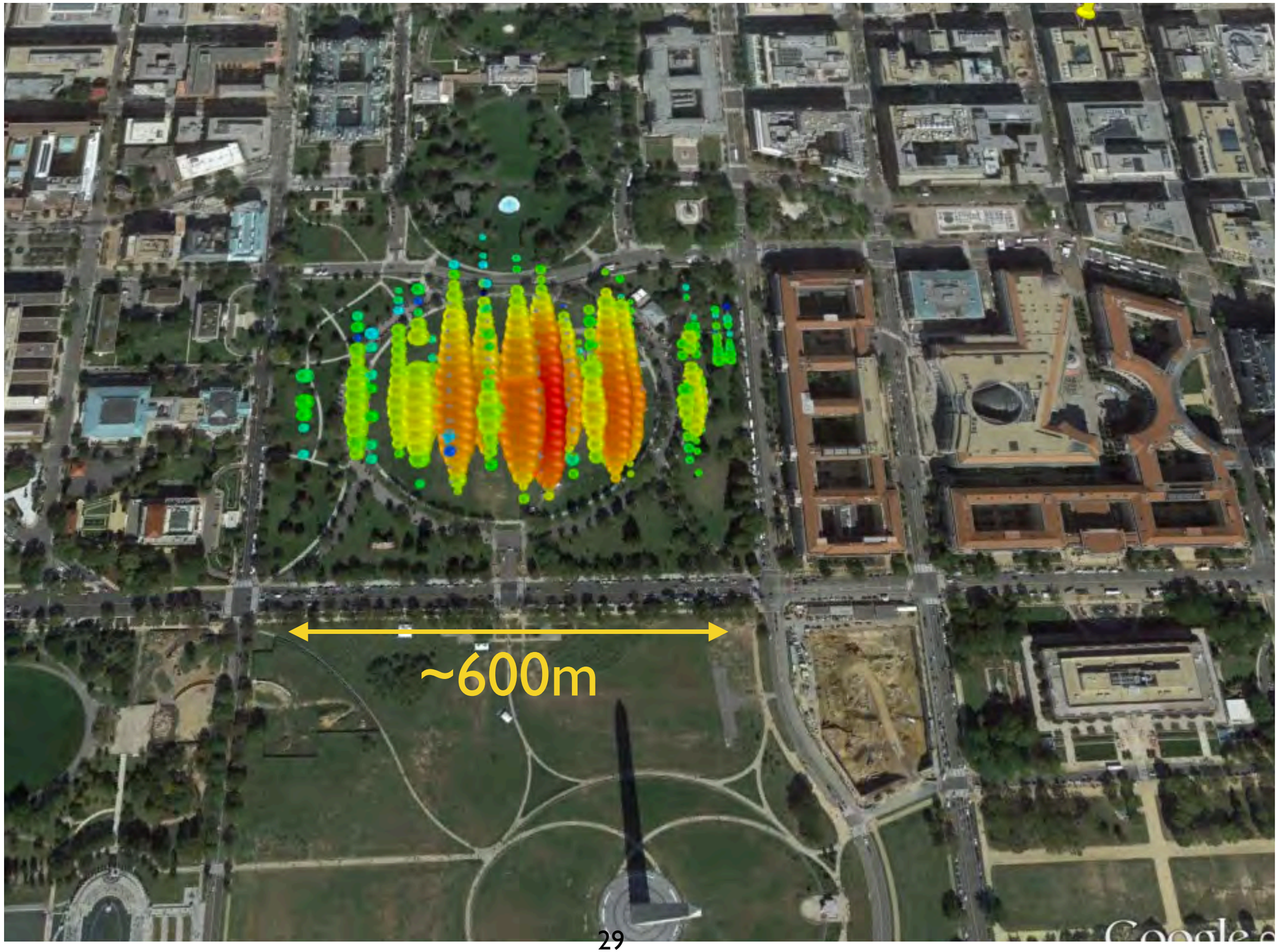
astronomy: angular resolution superior (<0.5^{o})

Isolated starting events

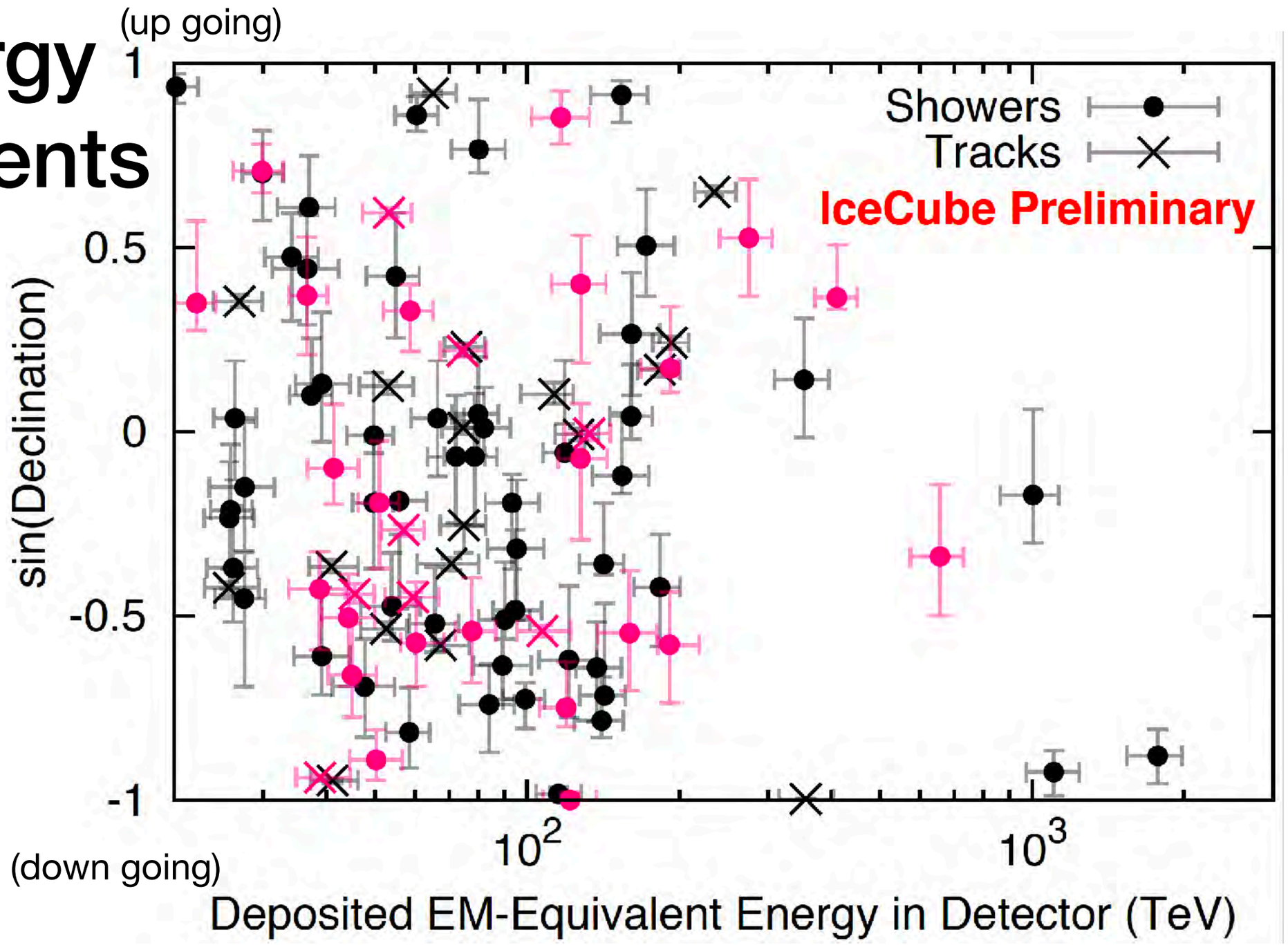


IceCube has detected the highest energy neutrinos ever recorded, with energies reaching above 2 PeV. From left to right, Bert, Ernie and Big Bird, with energies of 1.0, 1.1 and 2.2 PeV.

The PeV Scale



High-Energy Starting Events



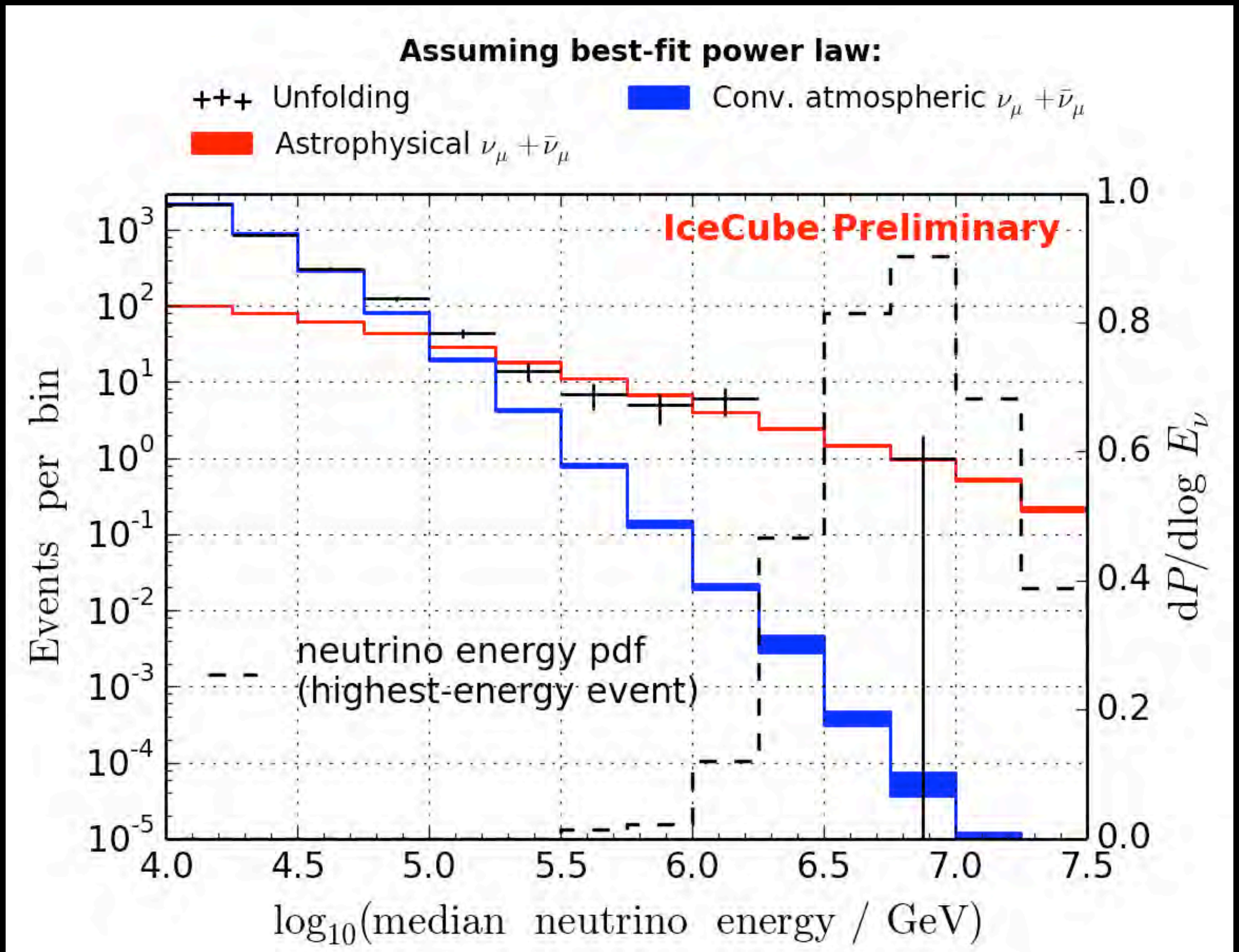
- 7.5 years of exposure
- Updated calibrations and modeled ice properties
  - Small changes to RA, Dec, energy
- 103 events, with 60 events >60 TeV
  Changes to RA, Dec, energy

Phys. Rev. Lett. **113**, (2014) 101101

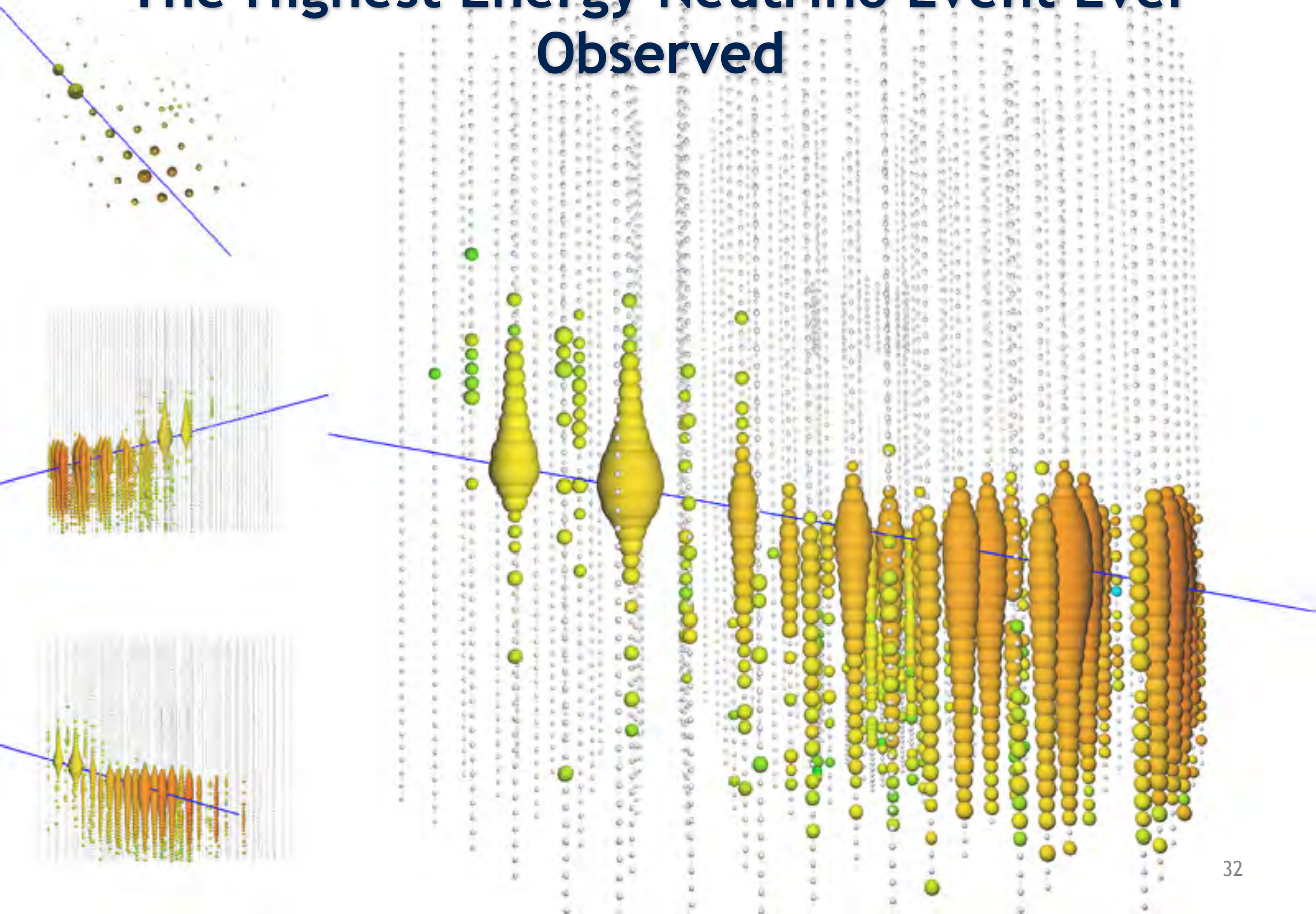
Updated: Neutrino 2018

Up-going neutrino tracks

~ 550 cosmic neutrinos in a background of ~340,000 atmospheric neutrinos



The Highest Energy Neutrino Event Ever Observed



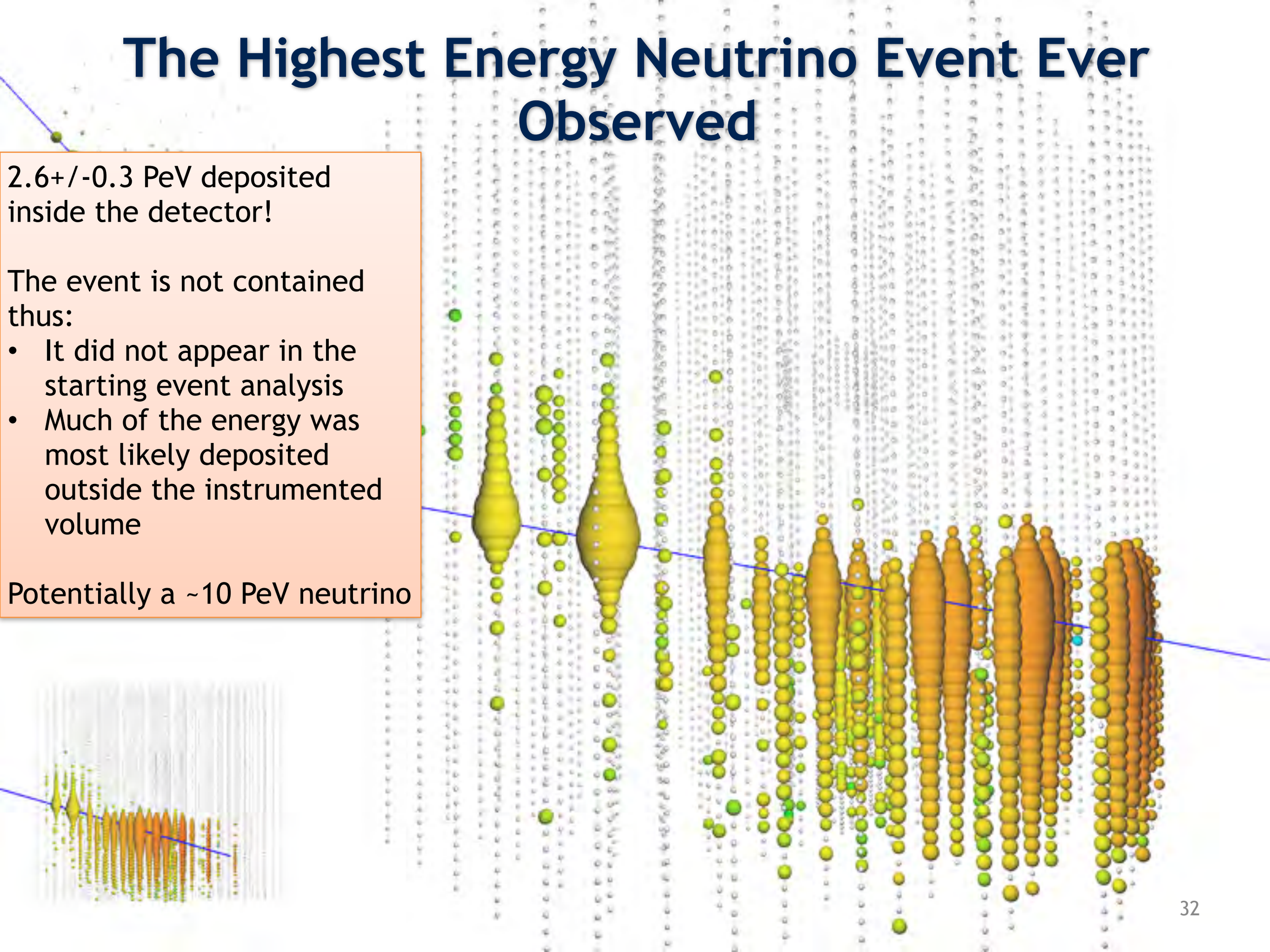
The Highest Energy Neutrino Event Ever Observed

2.6+/-0.3 PeV deposited inside the detector!

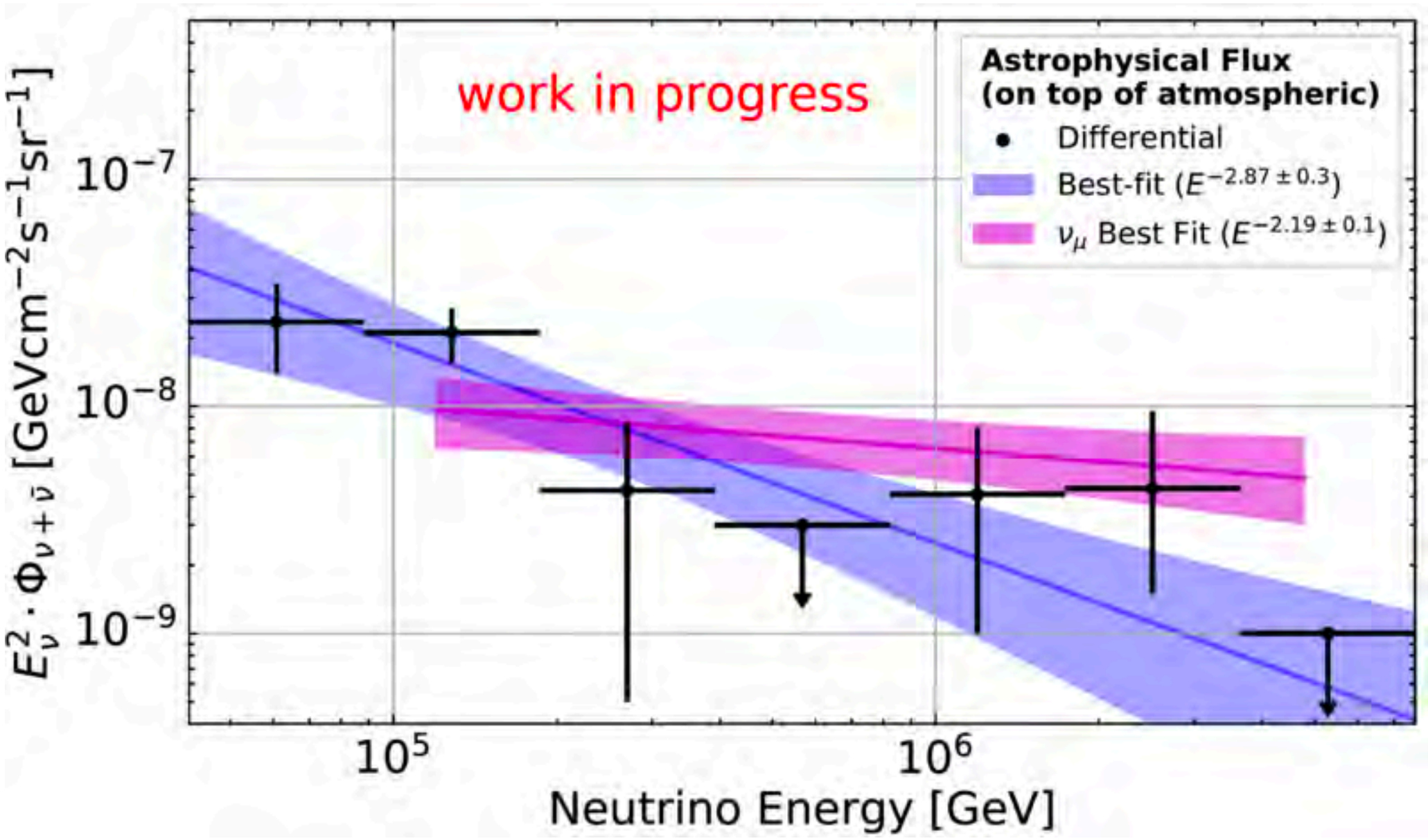
The event is not contained thus:

- It did not appear in the starting event analysis
- Much of the energy was most likely deposited outside the instrumented volume

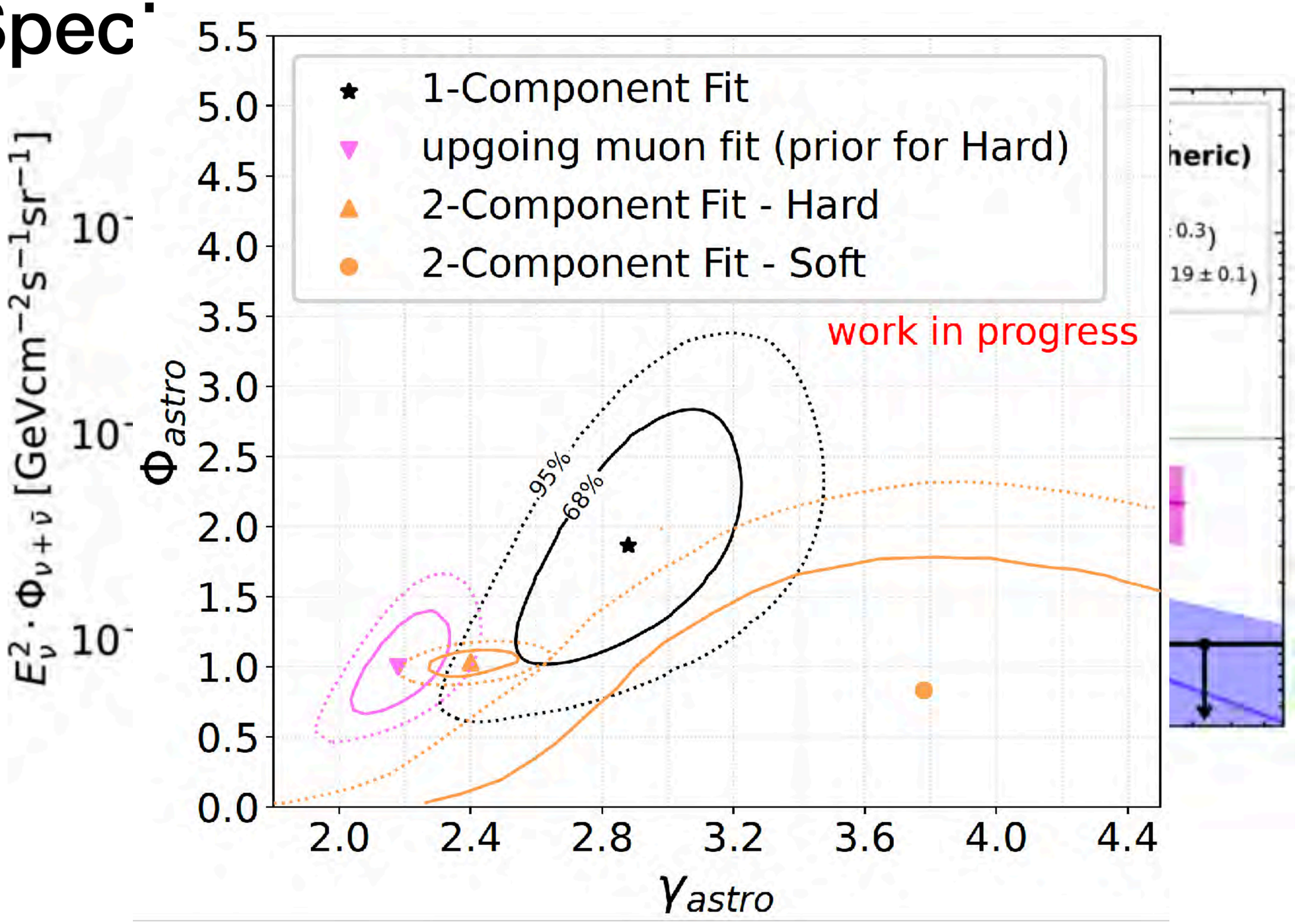
Potentially a ~10 PeV neutrino



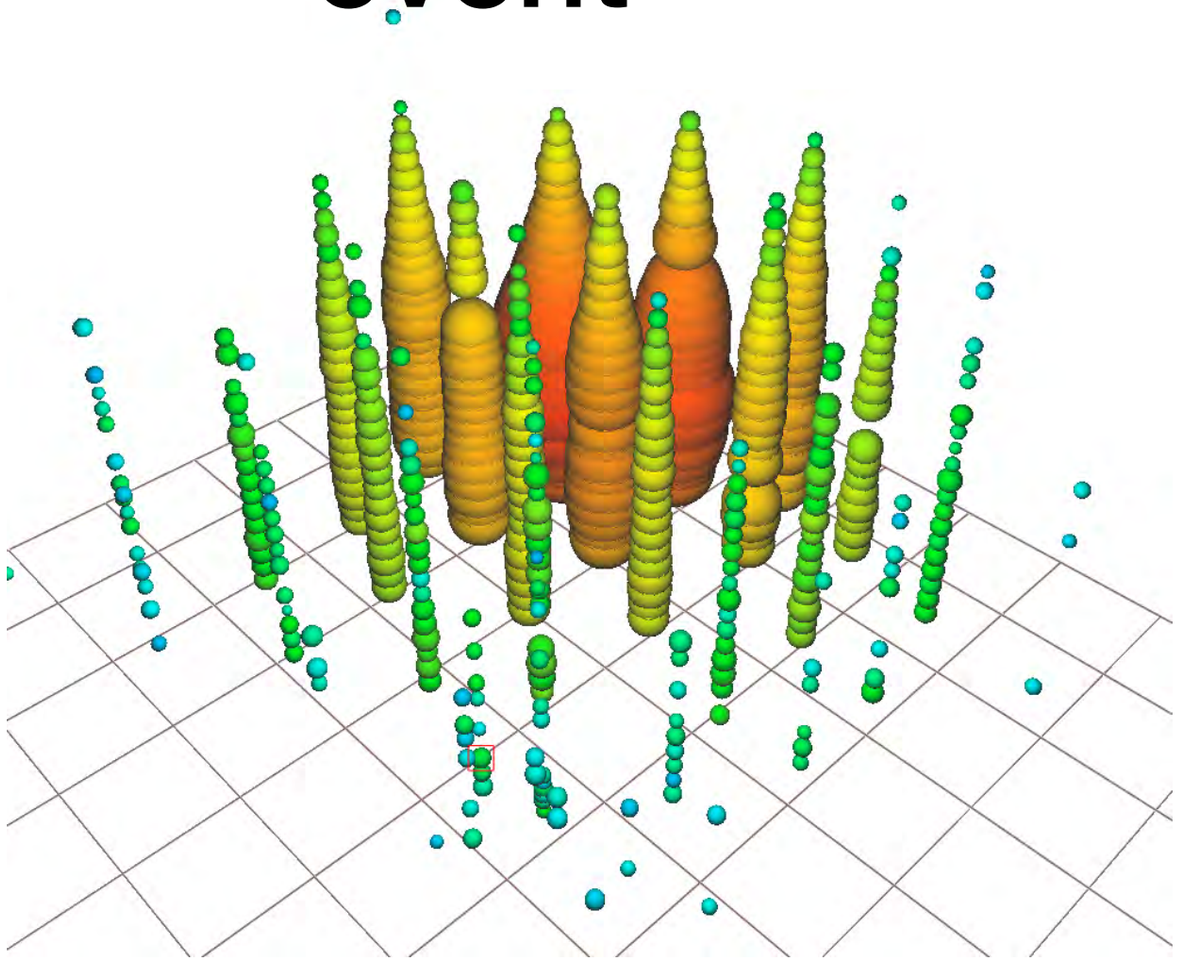
High-Energy Starting Events Spectrum



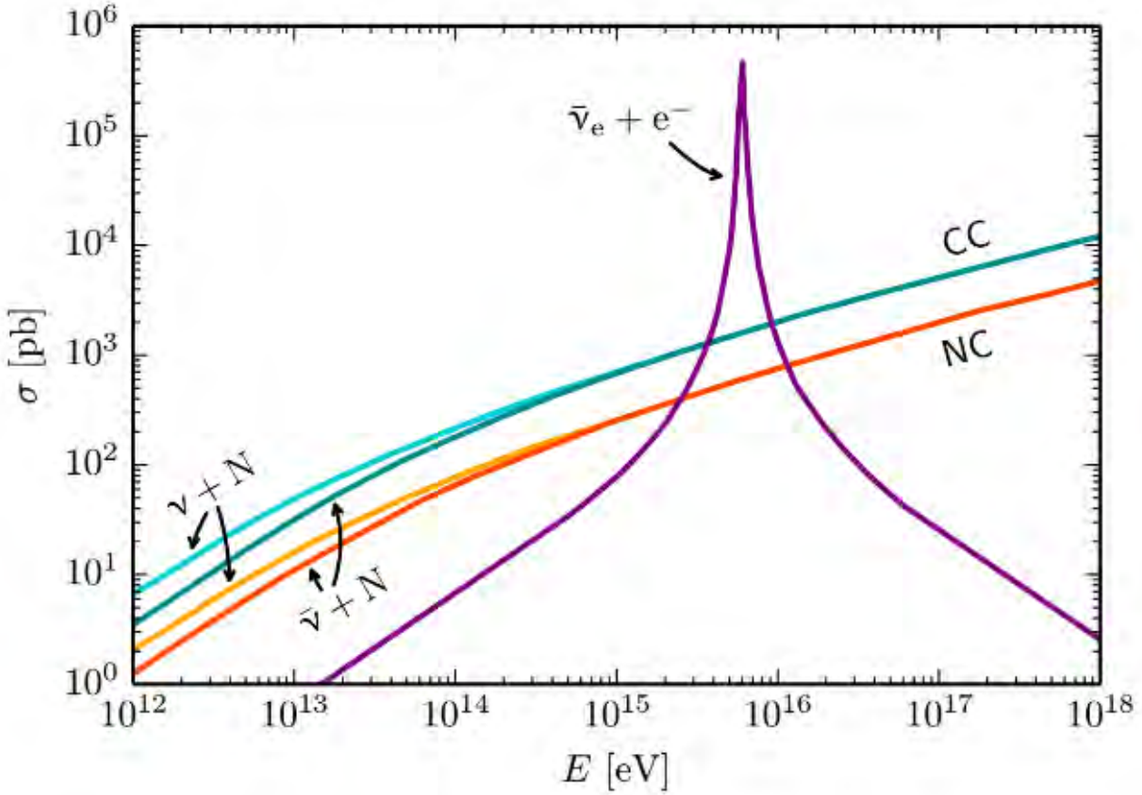
High-Energy Starting Events Spec



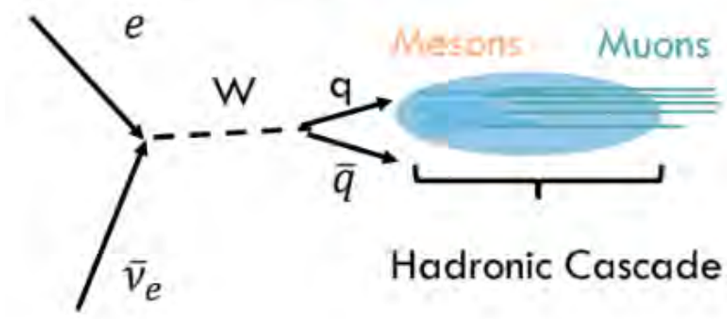
5.9 PeV shower event



Event identified in a partially-contained PeV search (PEPE)
Deposited energy: 5.9±0.18 PeV (stat only)
ICRC 2017 arXiv:1710.01191



Glashow Resonance



Resonance: E_ν = 6.3 PeV
Typical visible energy is 93%

Potential hadronic nature of this event is being investigated

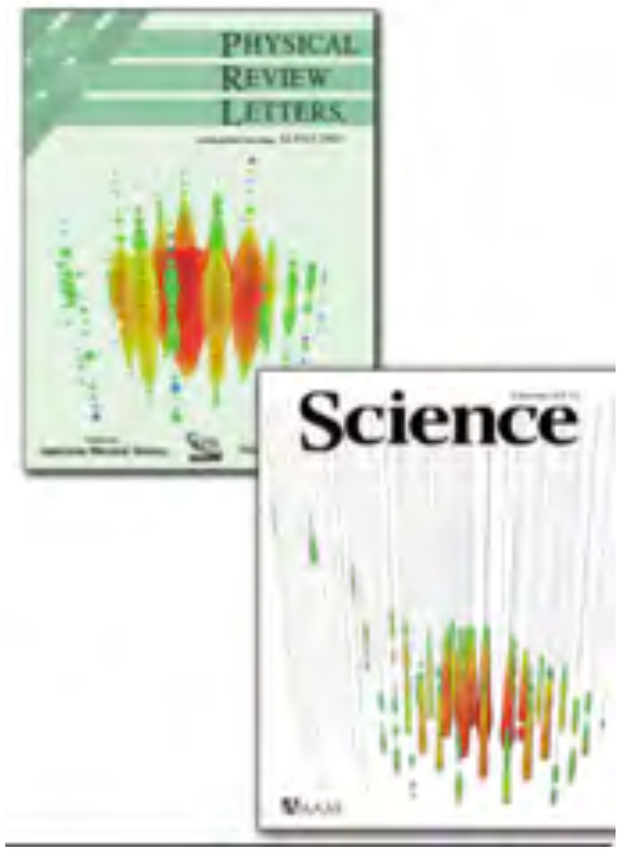
Work in progress

First Light for Astrophysical neutrinos

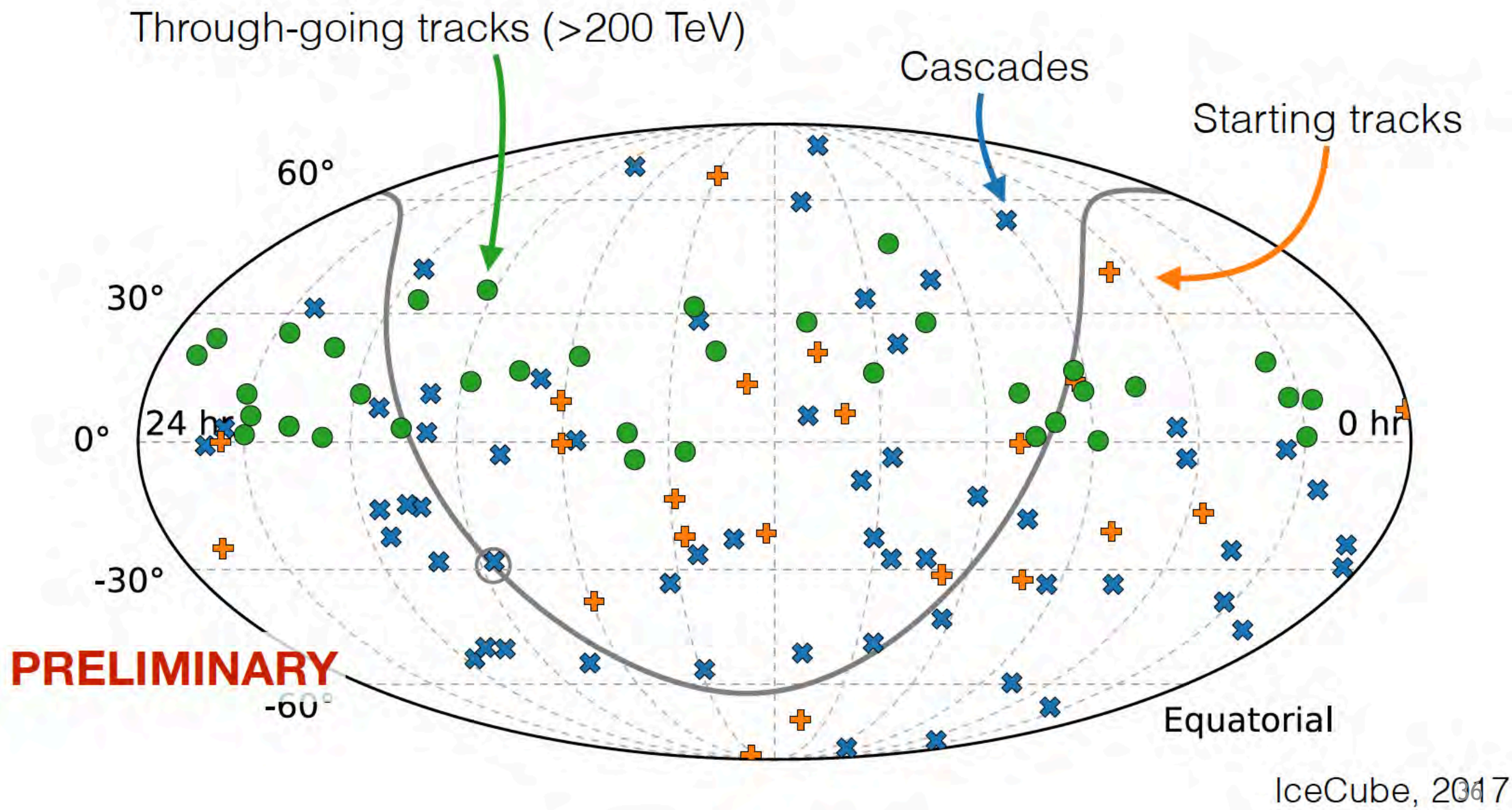
- Strong evidence we are seeing astrophysical neutrinos

- Many questions remain
  - What are their sources?
  - Are they generated in cosmic ray accelerators? Other exotic phenomena?

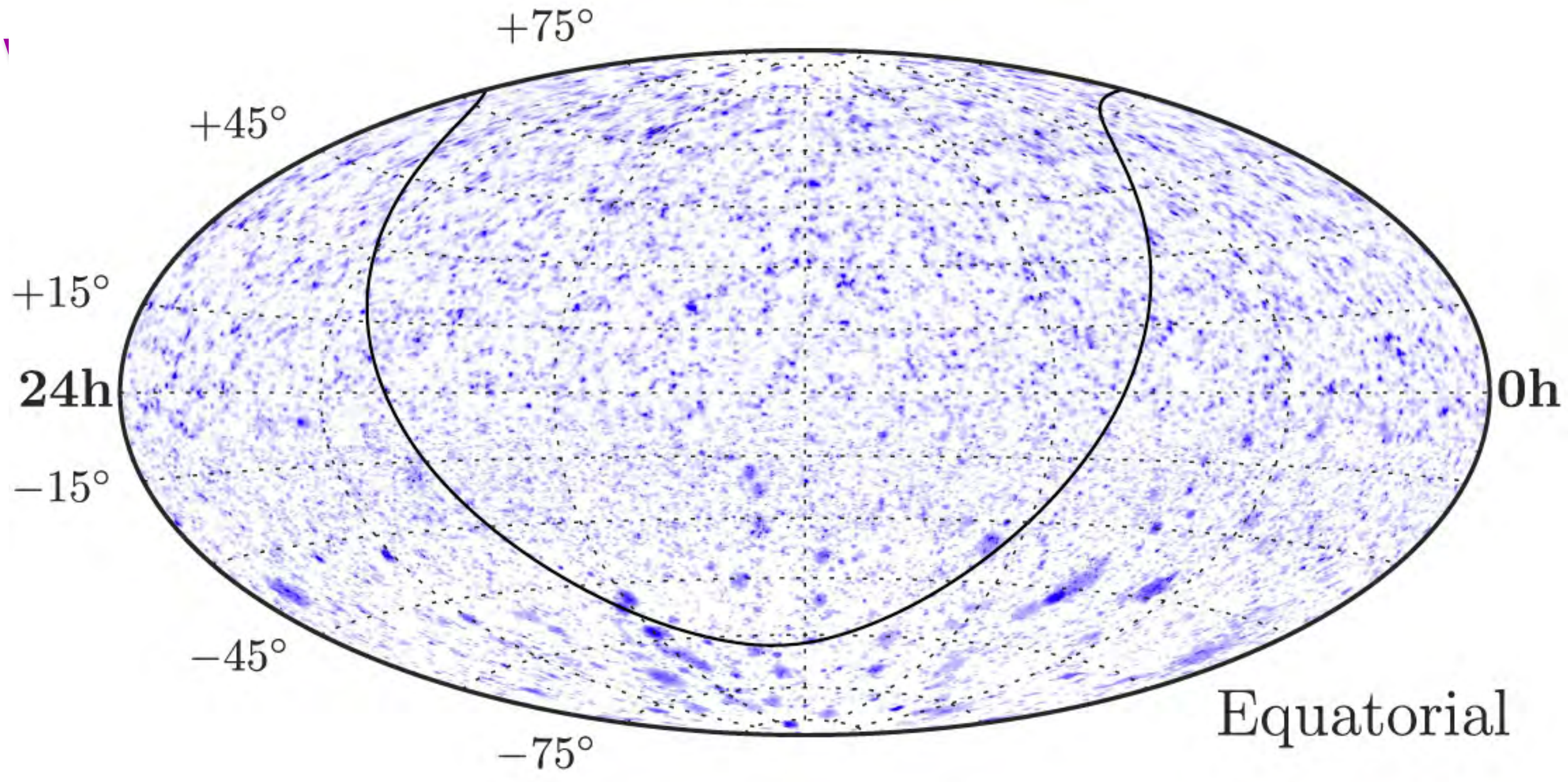
- Data is less clear here…



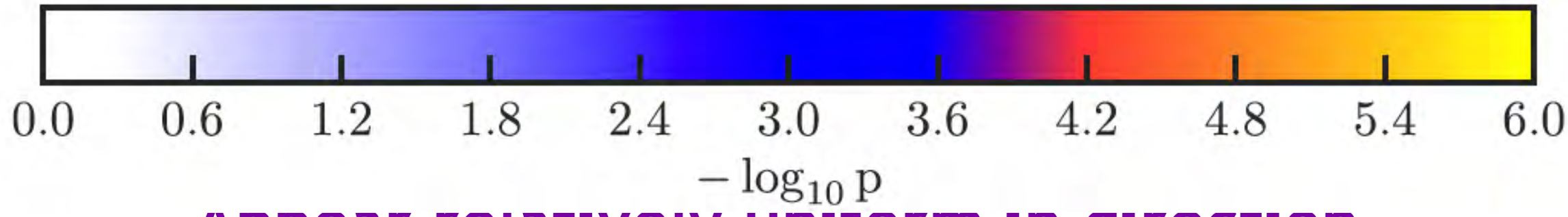
Where do they come from?



Appear relatively uniform in direction.



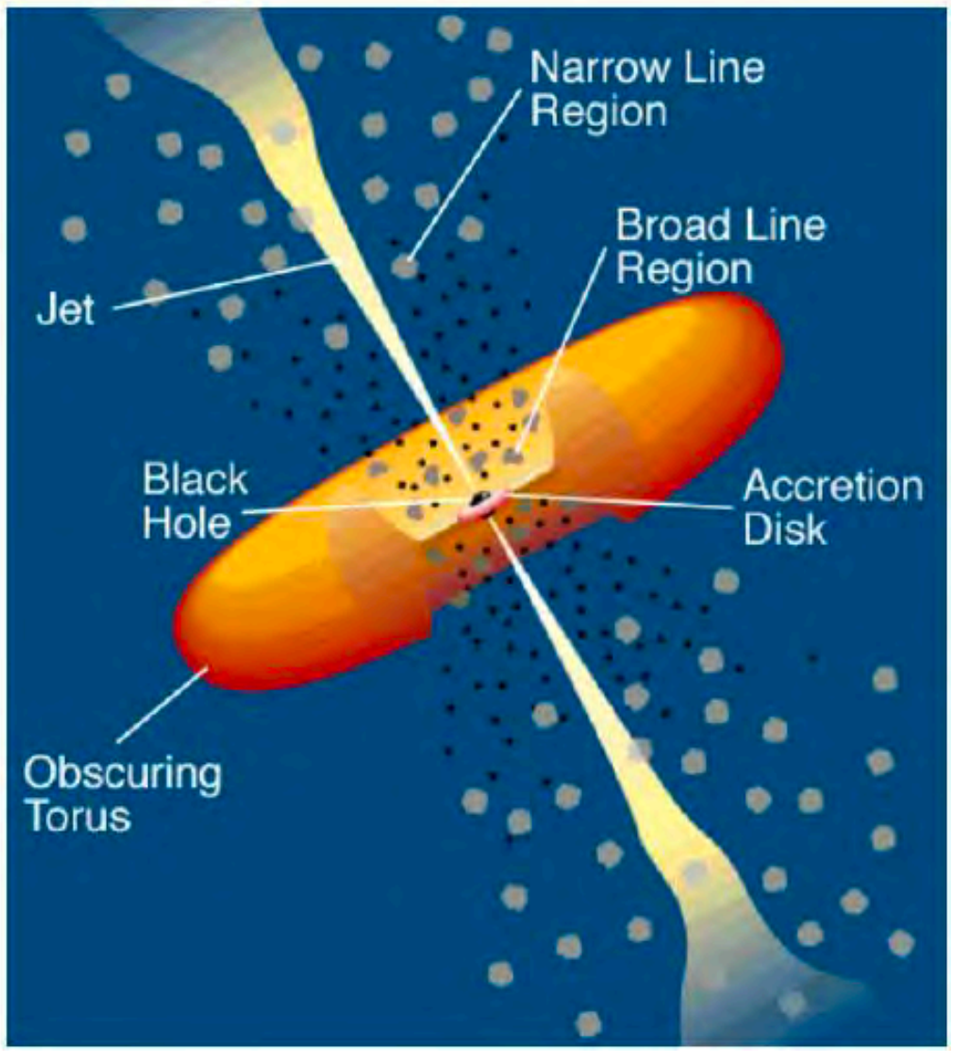
7 yr point source search



Appear relatively uniform in direction.

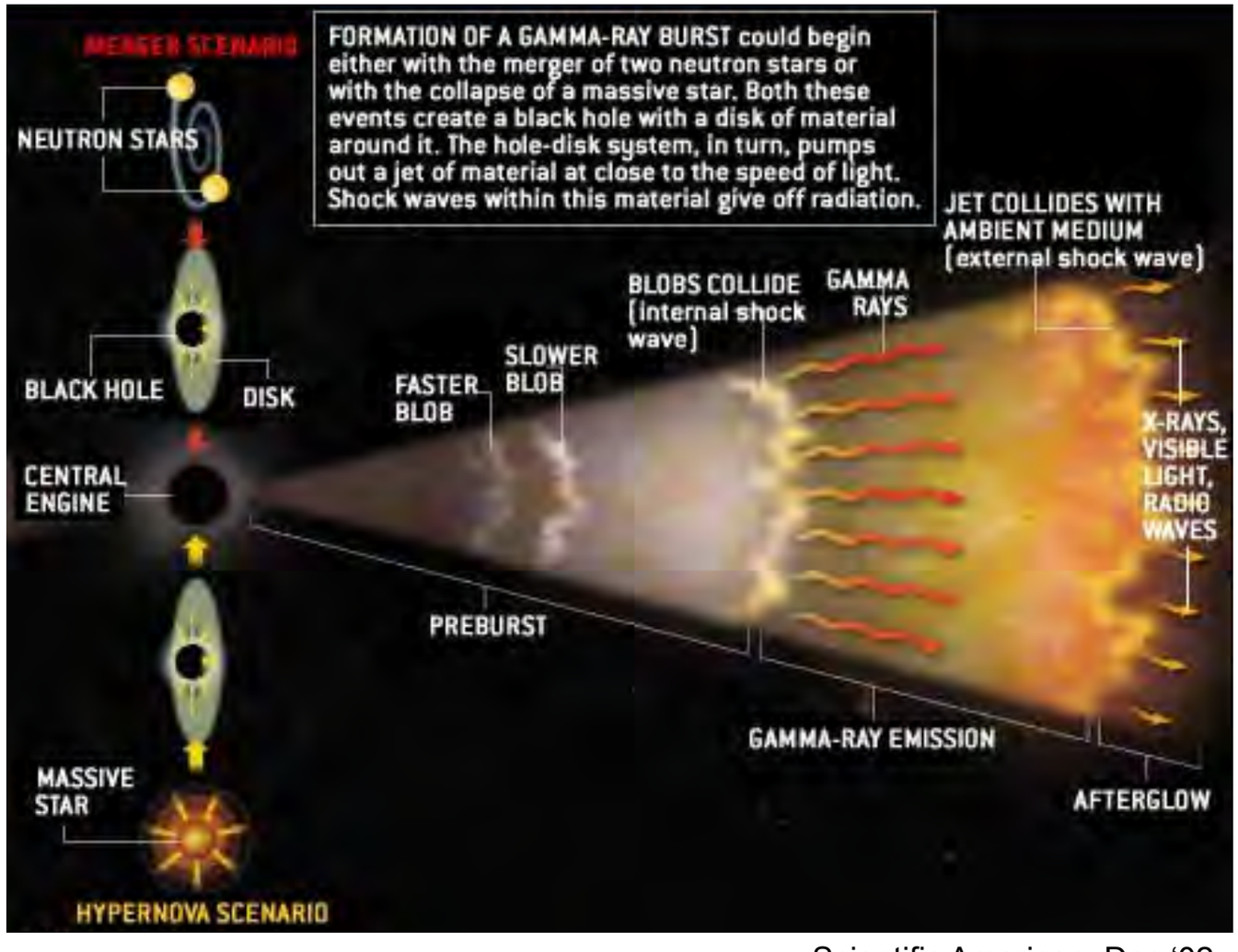
Other potential sources?

Active Galactic Nuclei?



Urry and Padovani (1995)

Gamma ray bursts?



Scientific American, Dec '02

Known catalogs of these objects can not explain the observed flux levels.

Mysteries still remain

- No clear point(s) in the sky seen as a source
  - All appear *Isotropic*
- How is this possible?
  - Many sources, maybe transient phenomena?
- How to resolve this?
  - Work more closely with other astronomical observatories
    - Trigger followup observations
  - Build large neutrino telescopes.

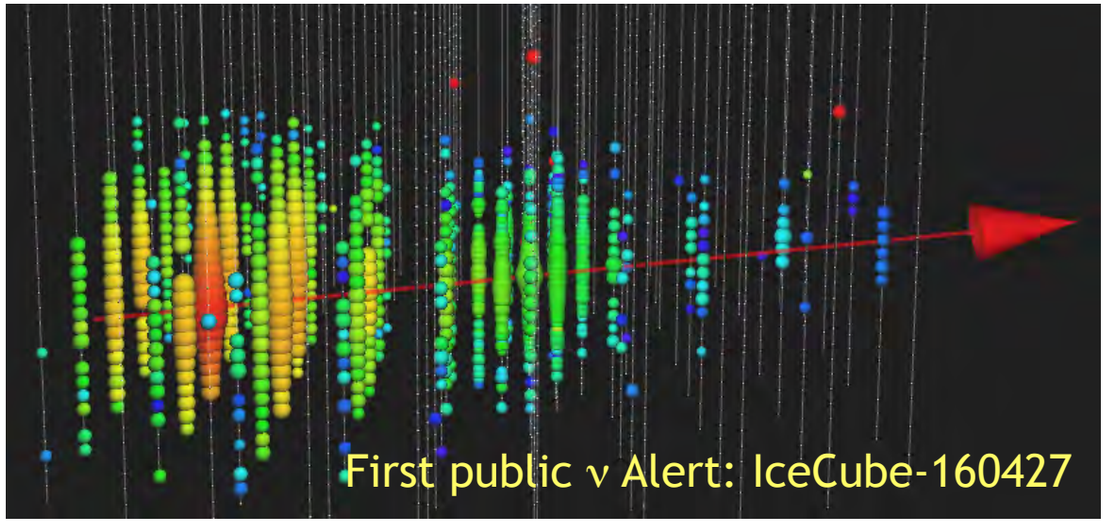
Source Searches Multi-messenger alerts

Realtime alerts from IceCube

Issued immediately upon the detection of an astrophysical neutrino candidate

- Select well reconstructed track-like events
- Since April 2016
- ~8 alerts per year
- Latency from detection to alert typically less than 1 minute
- Rapid northern hemisphere follow-up program after each alert

Alerts usually receive wide followup across the electromagnetic spectrum



Extensive real-time and offline follow up:
PTF, ZTF, HAWC, VERITAS, MAGIC, HESS,
Fermi LAT, Fermi GBM, Swift, …

Alert followup from IceCube

IceCube has broad followup program in place to respond to community alerts

- Followup ATel/GCNs, focusing on high-energy transient sources
- Realtime searches for neutrinos from GW candidates
- Rapid public notification in the event of detection
-

Multi-messenger alerts: TXS 0506+056

On September 22, 2017, IceCube issued a neutrino alert:

- A muon neutrino track event created by a ~290 TeV neutrino (IceCube-170922A)
- Found to be spatially coincident with a known blazar (TXS 0506+056) that was in a flaring state
- Blazar was also detected by the MAGIC air-Cherenkov telescope in the days after the alert, with γ-rays up to 400 GeV.
- This launched a very active multi-messenger follow-up campaign that included observations from radio to γ-rays.

TITLE: GCN CIRCULAR
NUMBER: 21916
SUBJECT: IceCube-170922A - IceCube observation of a high-energy neutrino candidate event
DATE: 17/09/23 01:09:2
FROM: Erik Blaufuss at

Claudio Kopper (Universit
Maryland) report on beha
icecube.wisc.edu/).

On 22 Sep, 2017 IceCube
high probability of being
the Extremely High Ener
was in a normal operatin
interaction vertex that is
the detector volume, and

Fermi-LAT detection of increased gamma-ray activity of TXS 0506+056, located inside the IceCube-170922A error region.

ATel #10791; *Yasuyuki T. Tanaka (Hiroshima University), Sara Buson (NASA/GSFC), Daniel Kocevski (NASA/MSFC) on behalf of the Fermi-LAT collaboration*
on 28 Sep 2017; 10:10 UT
Credential Certification: David J. Thompson (David.J.Thompson@nasa.gov)

Subjects: Gamma Ray, Neutrinos, AGN

Referred to by ATel #: 10792, 10794, 10799, 10801, 10817, 10830, 10831, 10833, 10838, 10840, 10844, 10845, 10861, 10890, 10942, 11419, 11430, 11489

Tweet Recommend 3

We searched for Fermi
neutrino event error r
10787) with all-sky surv
ray Space Telescope. W
and also included in the
located inside the IceCu
at energies abo
(https://fermi.gsfc.nasa.
Indeed, the LAT 0.1--3
cm-2 s-1 (errors are sta
nearly the same power-l
of this source. We also
unknown. According to
175, 97). Radio observ
http://www.astro.caltech
http://www.physics.purd

Because Fermi operates
region will continue.
(ytanaka@astro.hiroshir
the energy band from
collaboration between
Italy, Japan and Sweden

First-time detection of VHE gamma rays by MAGIC from a direction consistent with the recent EHE neutrino event IceCube-170922A

ATel #10817; *Razmik Mirzoyan for the MAGIC Collaboration*
on 4 Oct 2017; 17:17 UT
Credential Certification: Razmik Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de)

Subjects: Optical, Gamma Ray, >GeV, TeV, VHE, UHE, Neutrinos, AGN, Blazar

Referred to by ATel #: 10830, 10833, 10838, 10840, 10844, 10845, 10942

Tweet Recommend 448

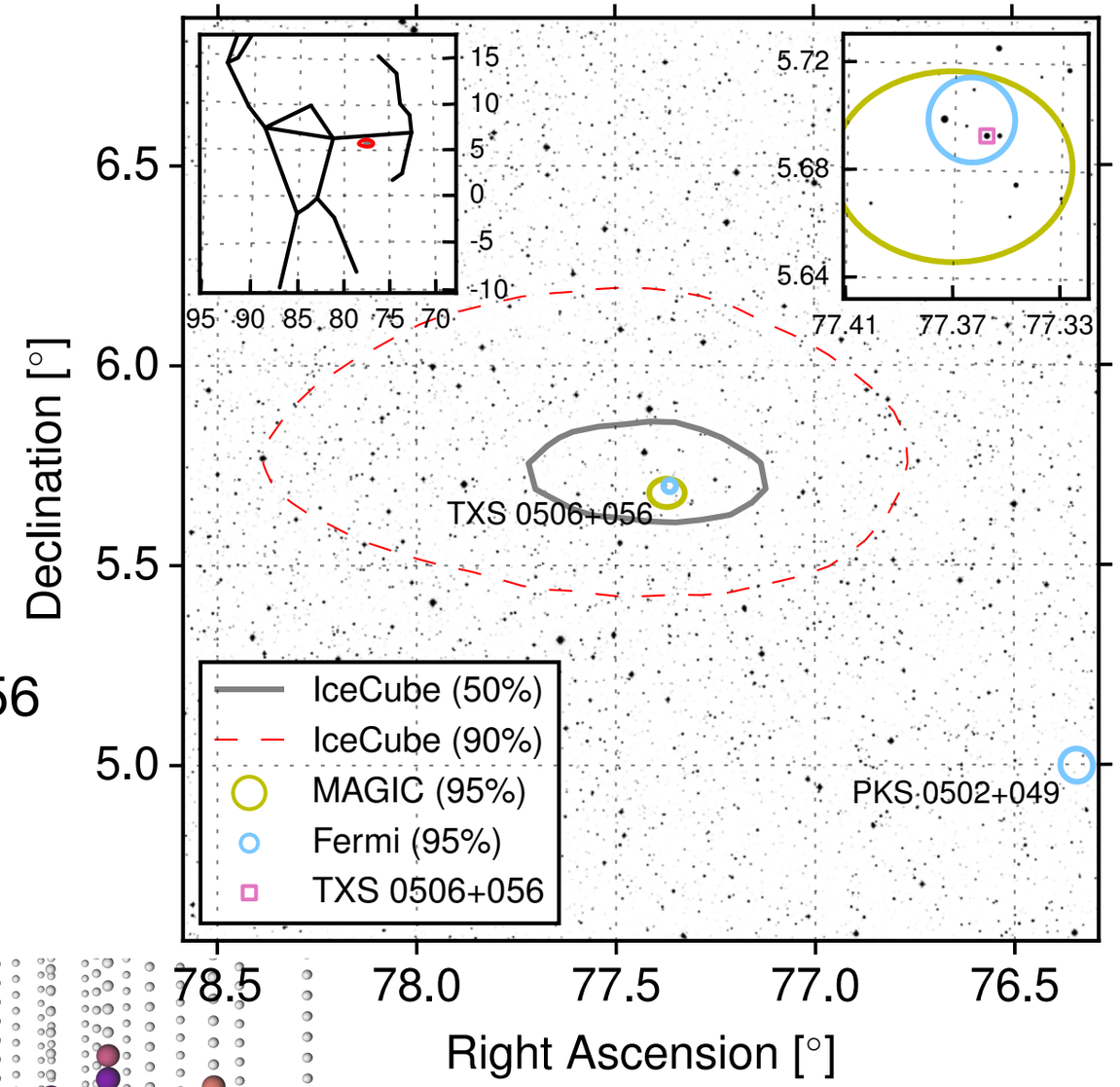
After the IceCube neutrino event EHE 170922A detected on 22/09/2017 (GCN circular #21916), Fermi-LAT measured enhanced gamma-ray emission from the blazar TXS 0506+056 (05 09 25.96370, +05 41 35.3279 (J2000), [Lani et al., Astron. J., 139, 1695-1712 (2010)]), located 6 arcmin from the EHE 170922A estimated direction (ATel #10791). MAGIC observed this source under good weather conditions and a 5 sigma detection above 100 GeV was achieved after 12 h of observations from September 28th till October 3rd. This is the first time that VHE gamma rays are measured from a direction consistent with a detected neutrino event. Several follow up observations from other observatories have been reported in ATels: #10773, #10787, #10791, #10792, #10794, #10799, #10801, GCN: #21941, #21930, #21924, #21923, #21917, #21916. The MAGIC contact persons for these observations are R. Mirzoyan (Razmik.Mirzoyan@mpp.mpg.de) E. Bernardini (elisa.bernardini@desy.de), K.Satalecka (konstancja.satalecka@desy.de). MAGIC is a system of two 17m-diameter Imaging Atmospheric Cherenkov Telescopes located at the Observatory Roque de los Muchachos on the Canary island La Palma, Spain, and designed to perform gamma-ray astronomy in the energy range from 50 GeV to greater than 50 TeV.

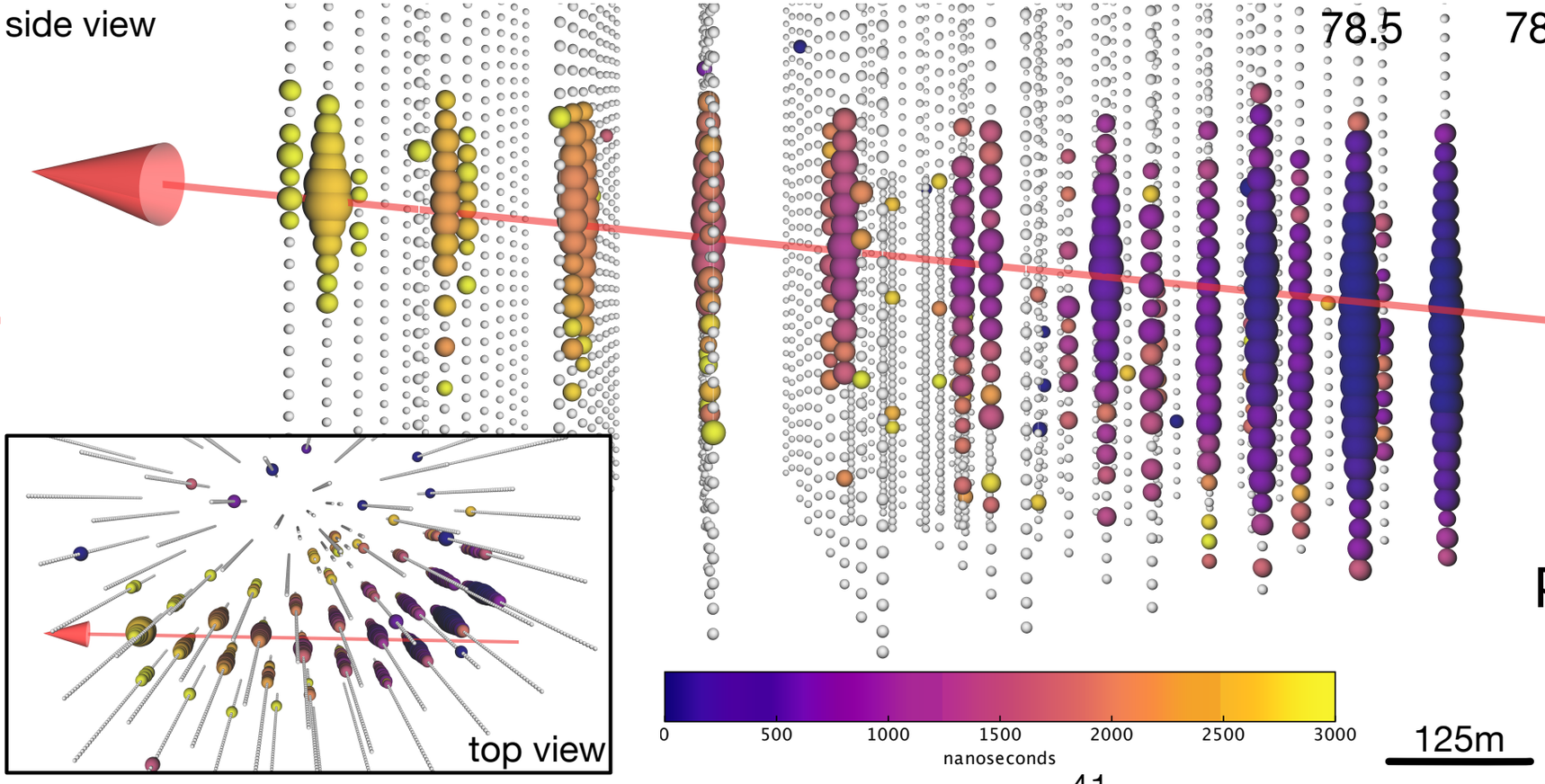
Recently published in Science:
IceCube Coll. et al., Science 361 (2018)

Multi-messenger alerts: TXS 0506+056

Neutrino direction was well reconstructed

- Uncertainty of less than 1 sq. deg at 90% CL
- Positionally consistent with blazar TXS 0506+056
- ~290 TeV estimated neutrino energy

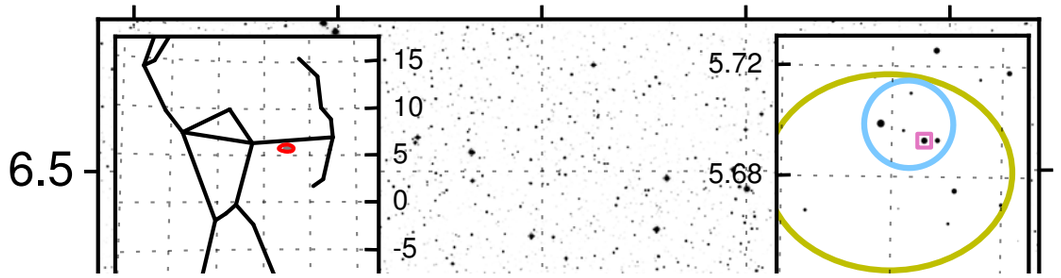


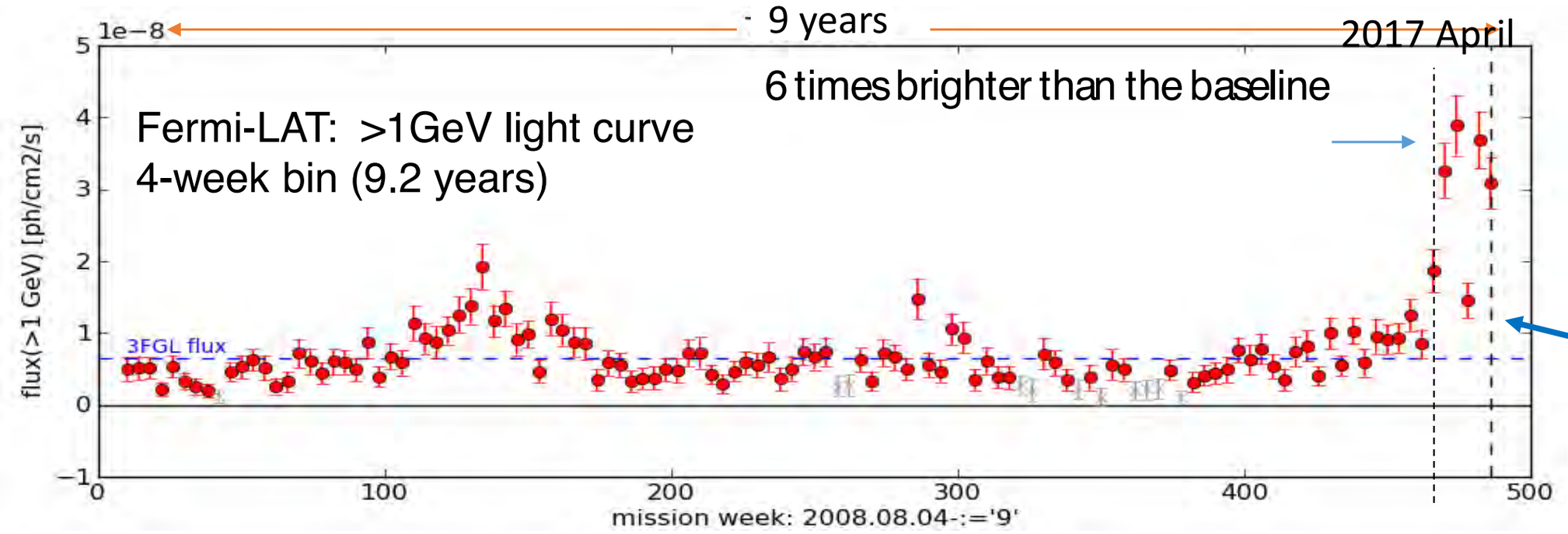


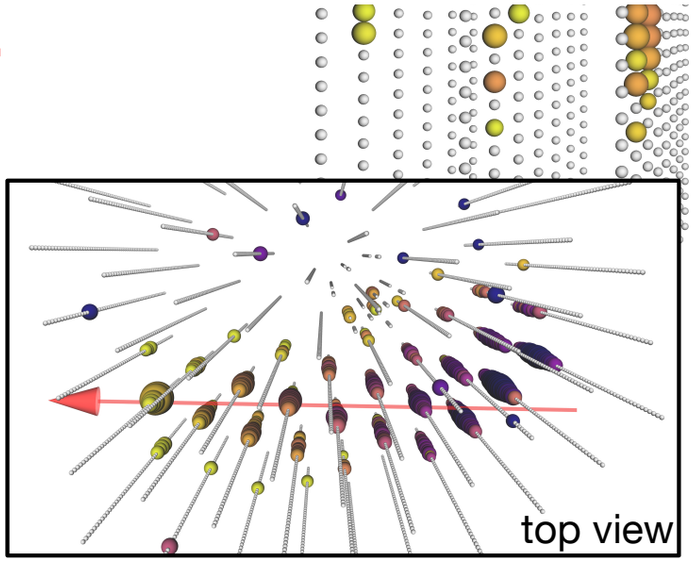
More than 2000 known Blazars from Fermi catalogs

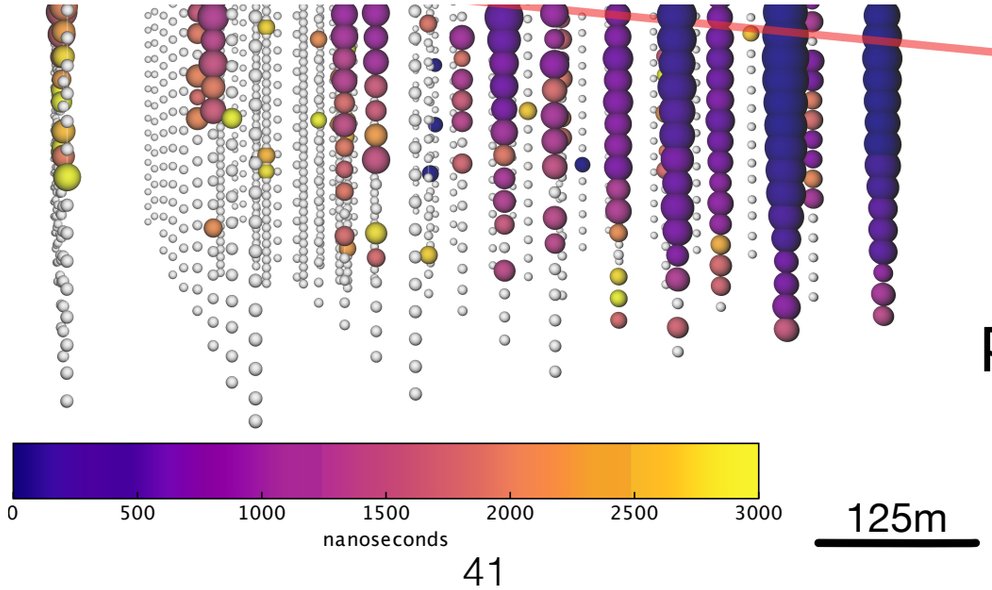
Just be chance? Unlikely probability of chance overlap is < 0.2%

Multi-messenger alerts: TXS 0506+056





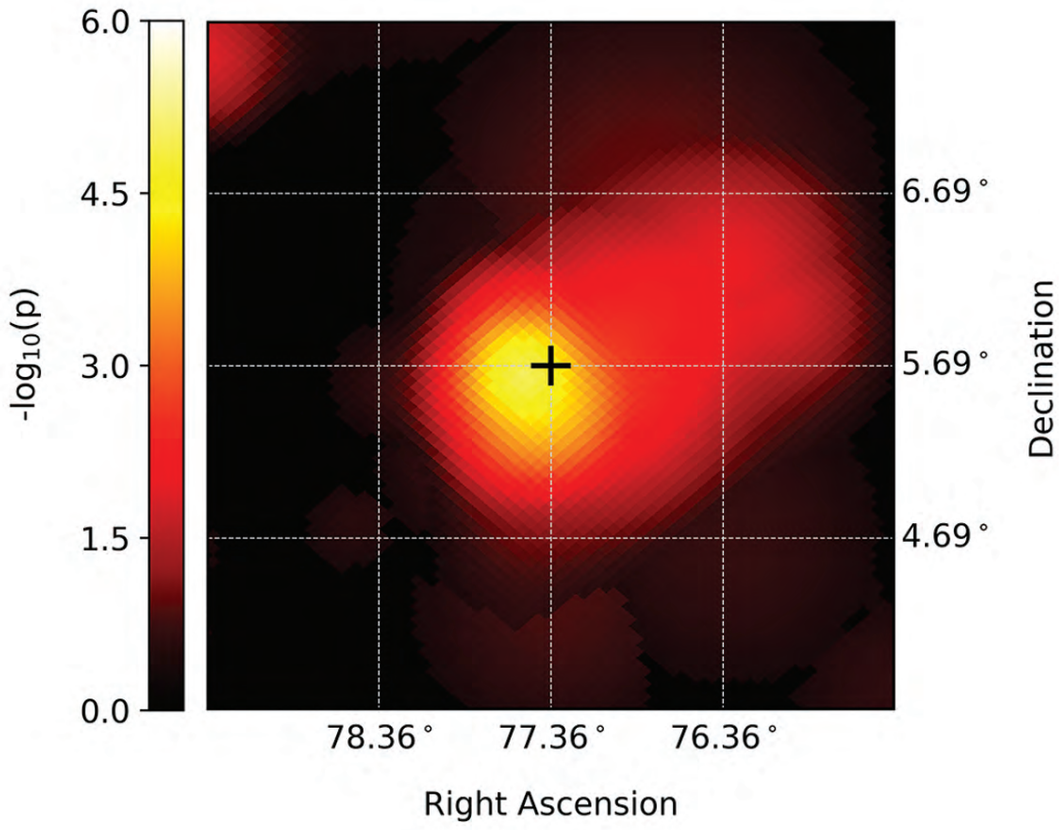




More than 2000 known Blazars from Fermi catalogs

Just be chance? Unlikely probability of chance overlap is < 0.2%

IceCube point source search: TXS 0506+056



Based on the neutrino alert - flaring blazar correlation, IceCube performed a search for evidence of a neutrino flux from TXS 0506+056 in archival point source data samples

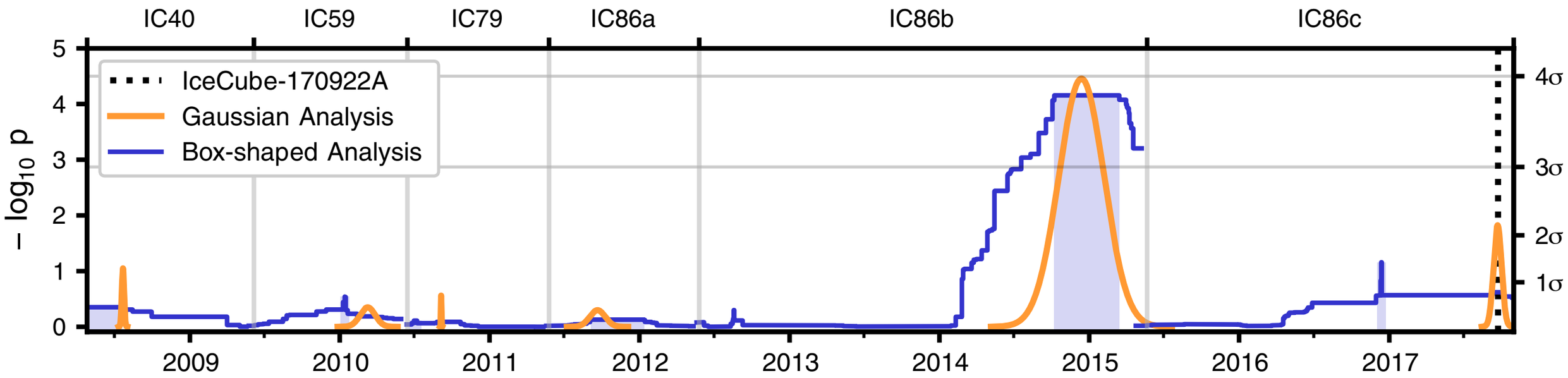
- Is it a constant neutrino source?
- Does is exhibit time dependent emission?
- Apply standard unbinned likelihood analysis

Evidence of time-dependent emissions is observed:

- September 2014 - March 2015
  - Independent of, and prior to neutrino alert
- 3.5σ excess over expected background
  - Background only rejected at < 0.05%
  - 13 ± 5 events over background

Recently published in Science:
IceCube Coll. Science 361 (2018) 147

IceCube point source search: TXS 0506+056



Multi-messenger source: TXS 0506+056

Two analyses provide evidence that TXS 0506+056 is the first of the long-sought sources of astrophysical neutrinos.

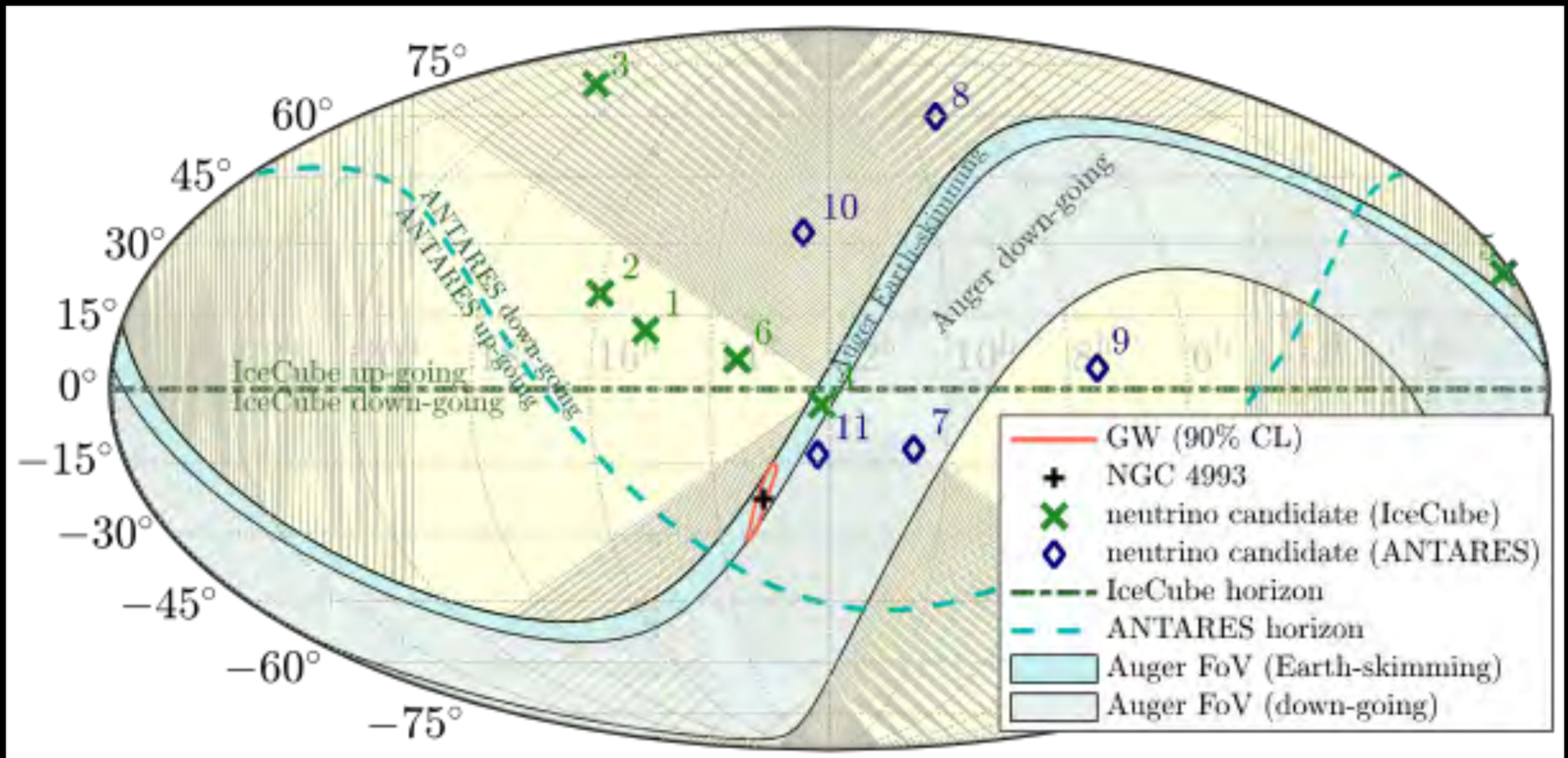
When both results are considered together, this provides evidence that blazars, especially TXS 0506+056, is a site of high-energy cosmic ray acceleration, and blazars are a potential source of a sizable fraction of the IceCube diffuse neutrino flux.

Many question still remain:

- Why TXS 0506+056?
  - A distant (4 Bly) and very luminous blazar
  - Why not closer blazars?
- What other objects are out there like TXS 0506+056?
  - Ongoing investigations with partners to resolve
  - Continued alerts
- What about the highest energy cosmic rays?
  - O(10 PeV) cosmic rays explain neutrinos and a gamma-rays

Multi-messenger Astronomy!

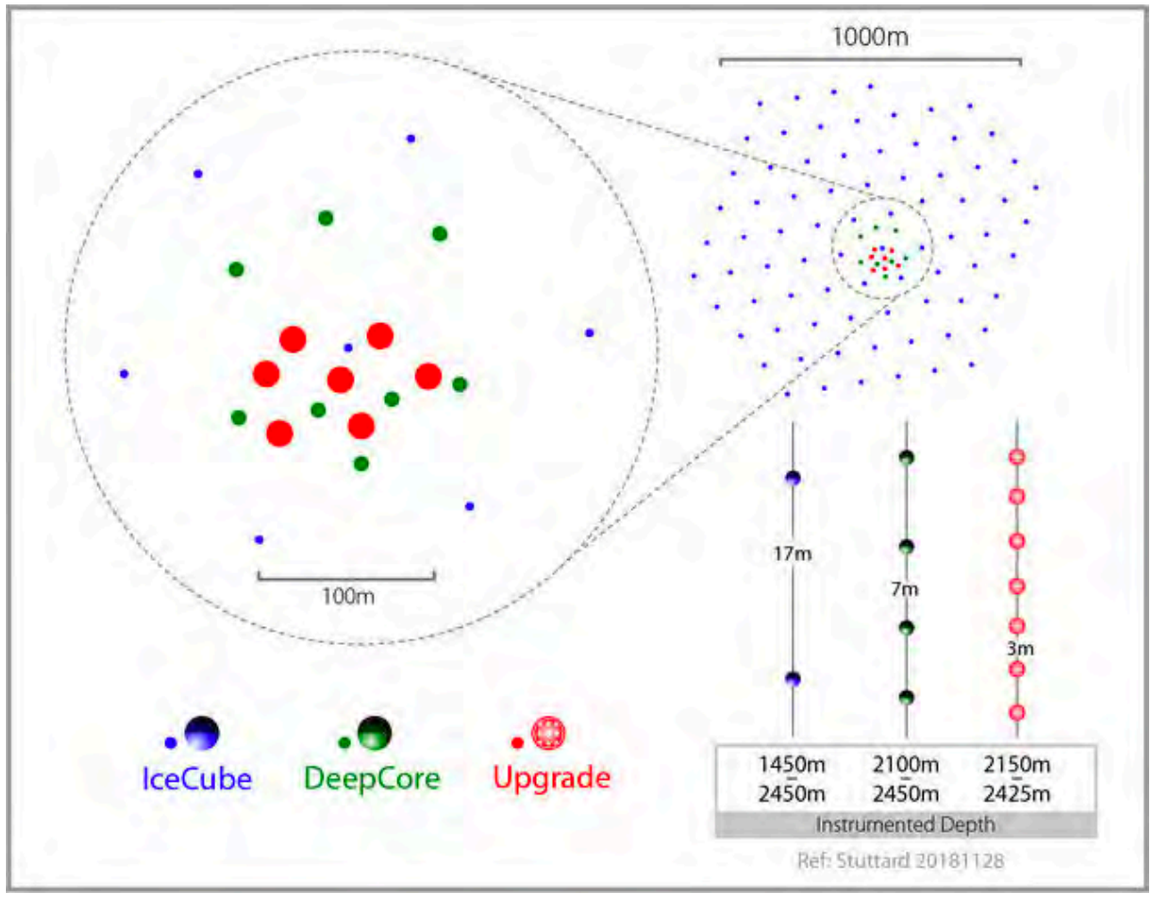
Gravity waves, Gamma-rays, Neutrinos



- On August 17, 2017 Adv LIGO and Adv Virgo observed GW170817 from a binary NS inspiral (Abbot et al 2017)
- Fermi-GB and INTEGRAL detected a short GRB consistent with the location
- Optical follow ups localized the merger in the galaxy NGC4993
- Afterglow was detected in X-rays and radio consistent with a short GRB
- Within ±500 s no significant neutrino from IceCube, ANTARES and Auger nor in subsequent 14 days
- This non-detection is consistent with our expectations from a typical GRB observed off-axis, or with a low-luminosity GRB.

Future prospects

IceCube Upgrade

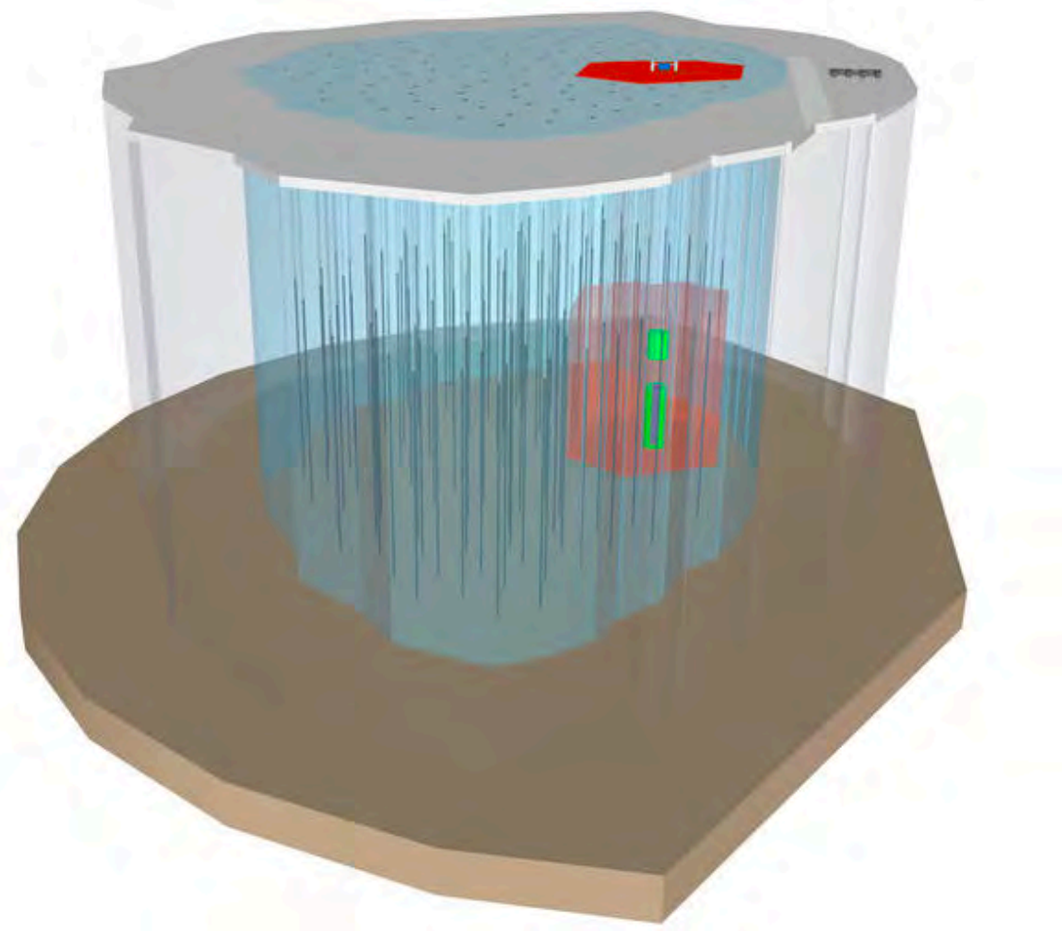


Near Term

- Add 7 strings with > 800 advanced DOMs
- Advanced calibration devices
- Improved measurement of neutrino oscillations
- Improved angular resolution for neutrino astronomy

NSF funding secured, 2022-23 deployment

IceCube Gen2

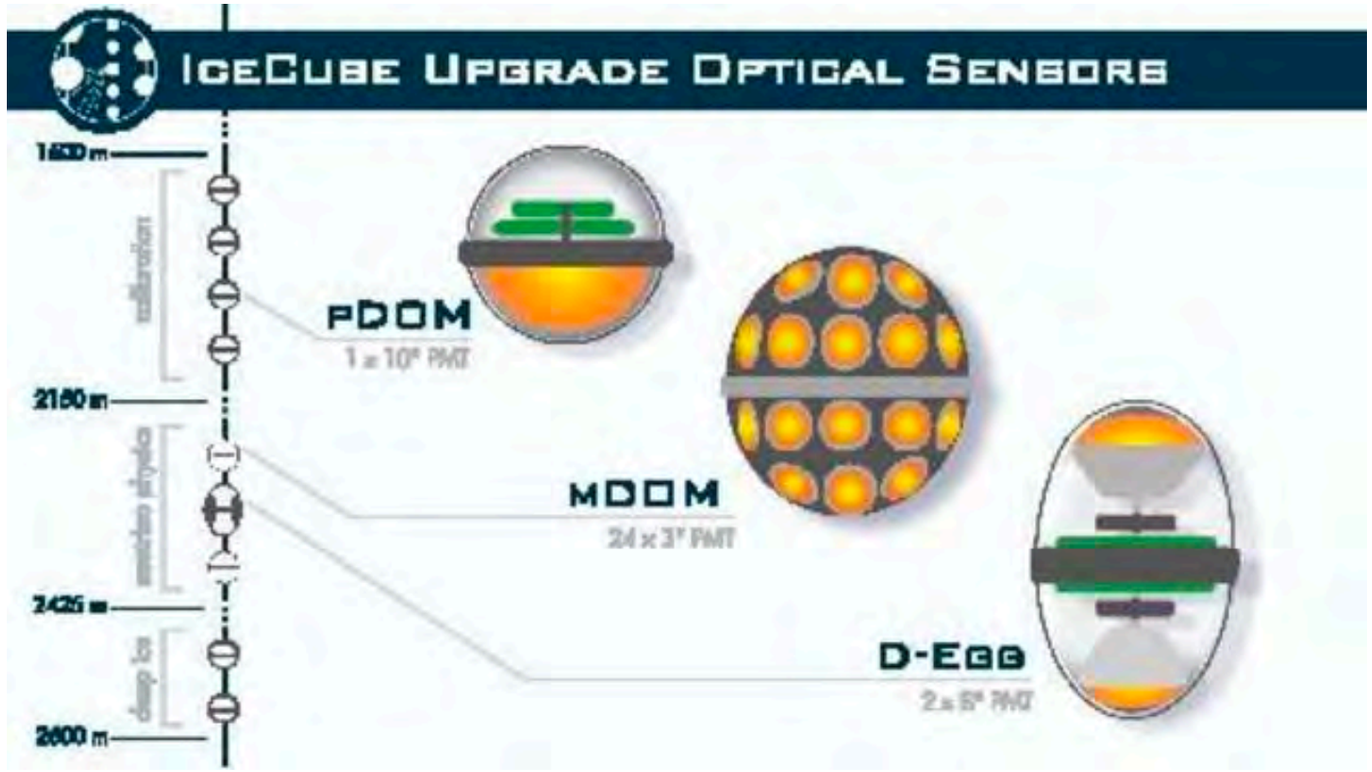


Long Term

- ~8-10 larger volume than IceCube
- Larger samples of astrophysical neutrinos
- Radio neutrino detection and air shower detection/veto all under consideration

New instrumentation

- Several new optical sensors planned for Upgrade
  - pDOM - refurbished DOMs
  - mDOM - 24 x 3” PMTs
  - DEgg - 2 x 8” PMTs

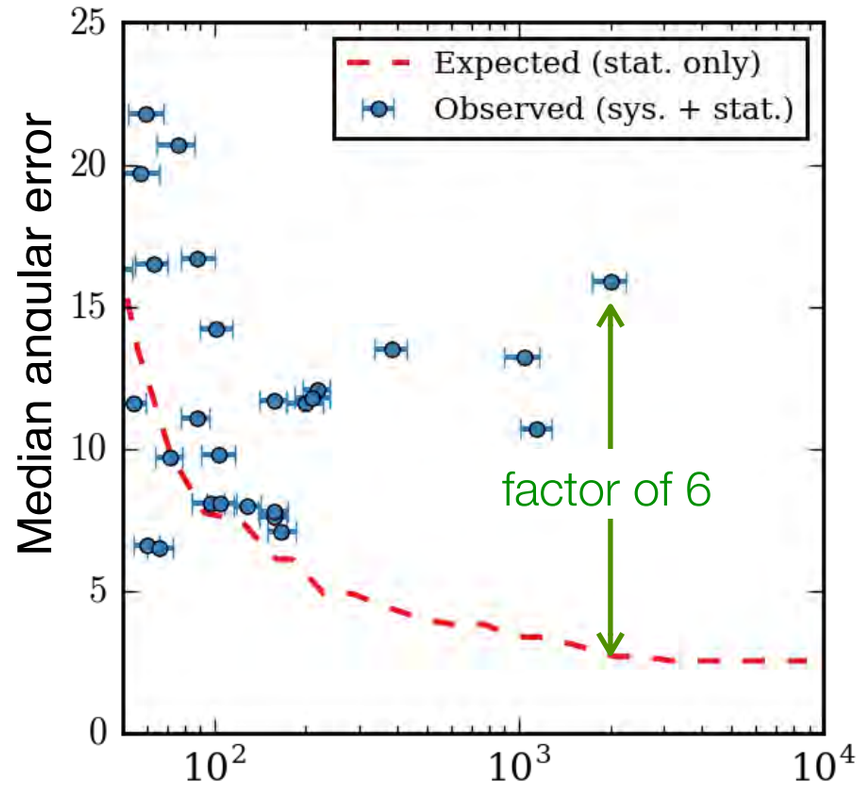


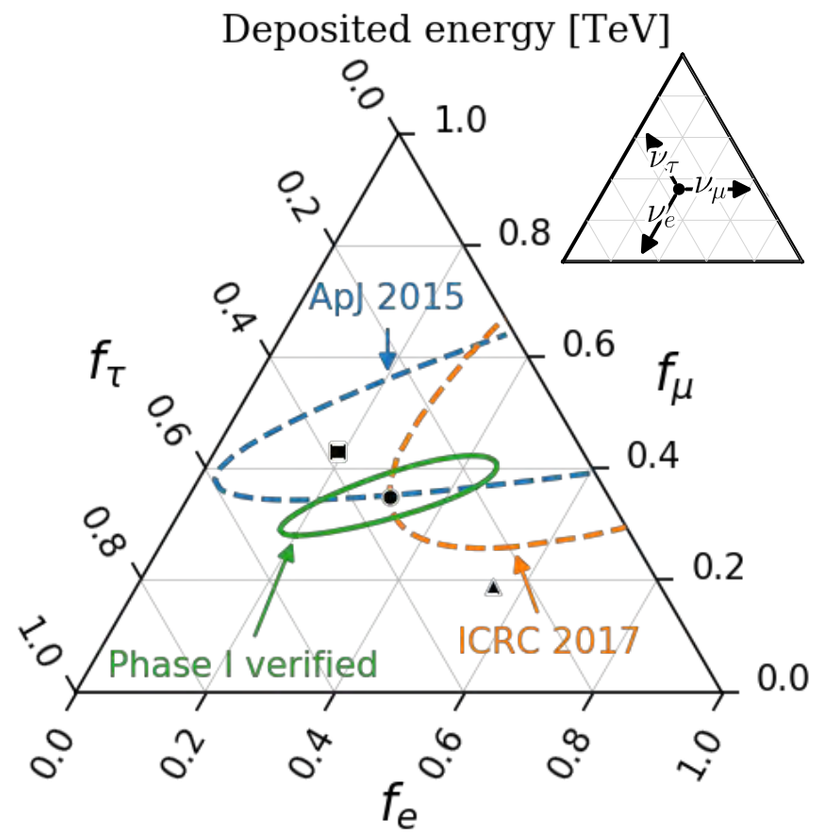
- New electronic designs
- New Calibration devices
  - Built-in Flashers
  - Dedicated light sources

Upgrade Physics Goals

- Improved understanding of glacial optical properties
  - Far from statistical limits on angular resolution at high energies
    - O(0.1) deg for tracks and O(3) deg for showers
  - Cleaner identification of Tau events
- Ice is stable: Able to reprocess decade of neutrinos with better understanding

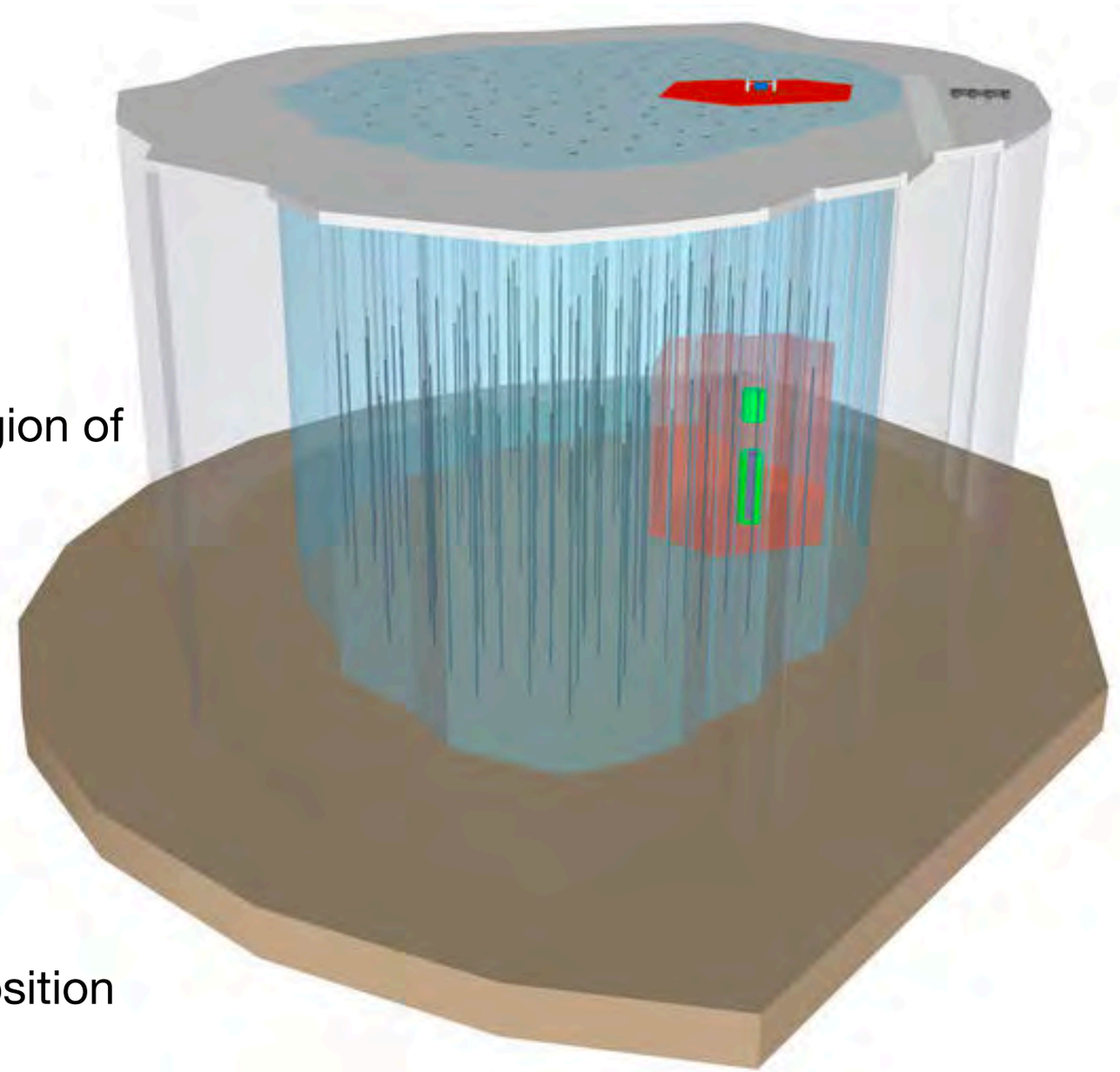
Neutrino Astronomy



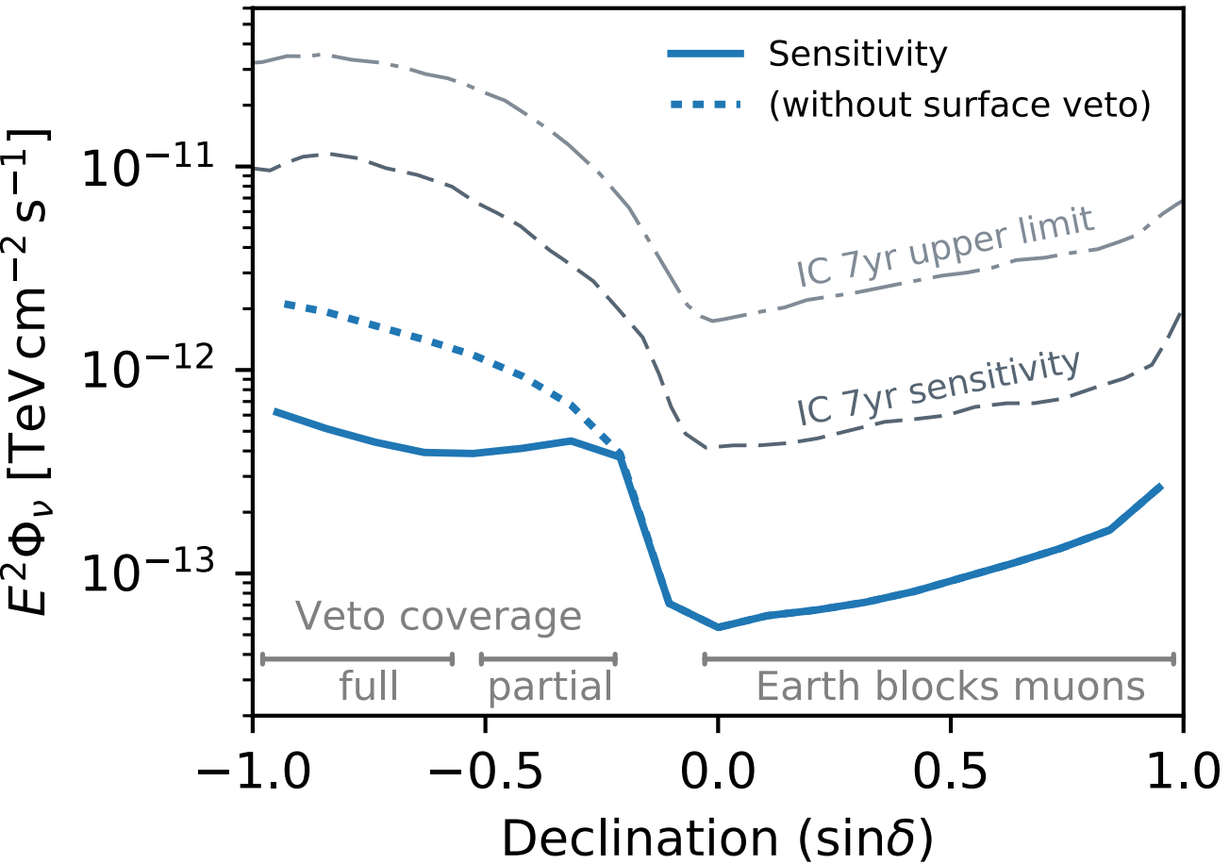


IceCube Gen2

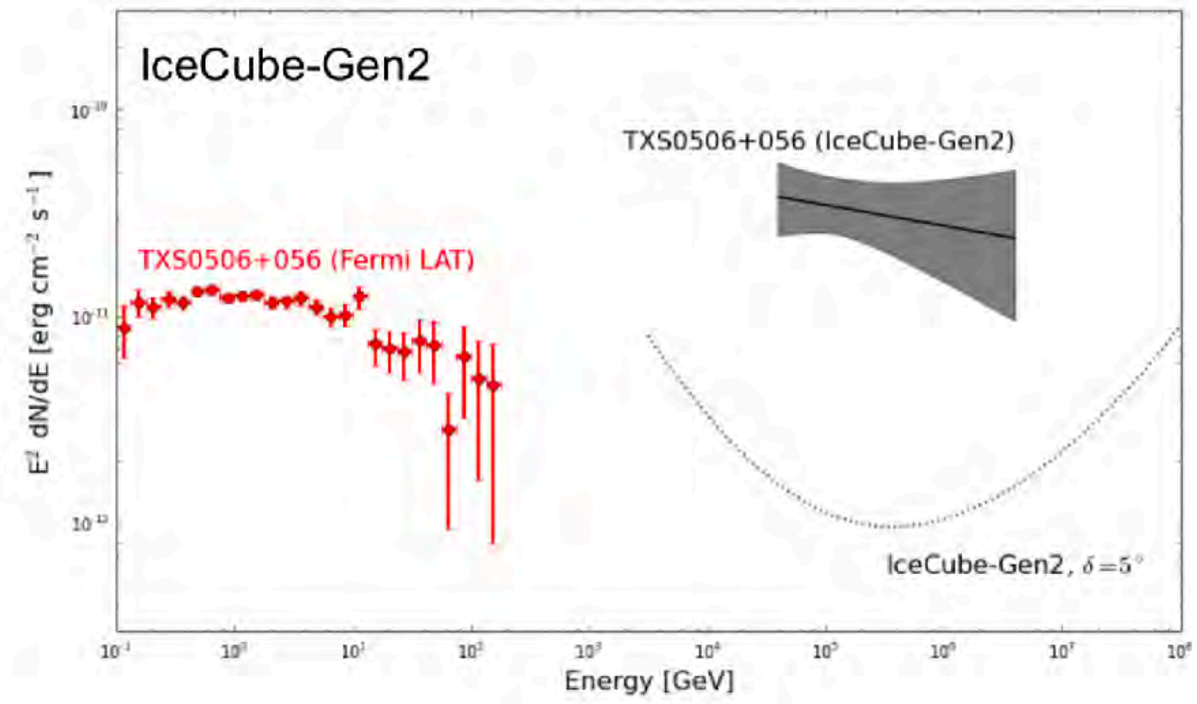
- Looking forward, to get larger and better samples of astrophysical neutrinos, a larger detector is needed
- Envision a wide-band neutrino observatory
  - 8-10 x larger optical Cherenkov detector
    - Neutrino astronomy and multi-messenger astrophysics
  - Additional strings in densely instrumented region of DeepCore
    - Probe neutrino mass hierarchy
  - Askaryan radio detector array
    - Probe neutrinos beyond EeV energies
  - Surface particle detector
    - Detailed cosmic ray spectrum and composition measurements and veto capabilities



Searches with Gen2



After 15 years of Gen2…



Order of magnitude increase in observing neutrino flares like TXS0506+056

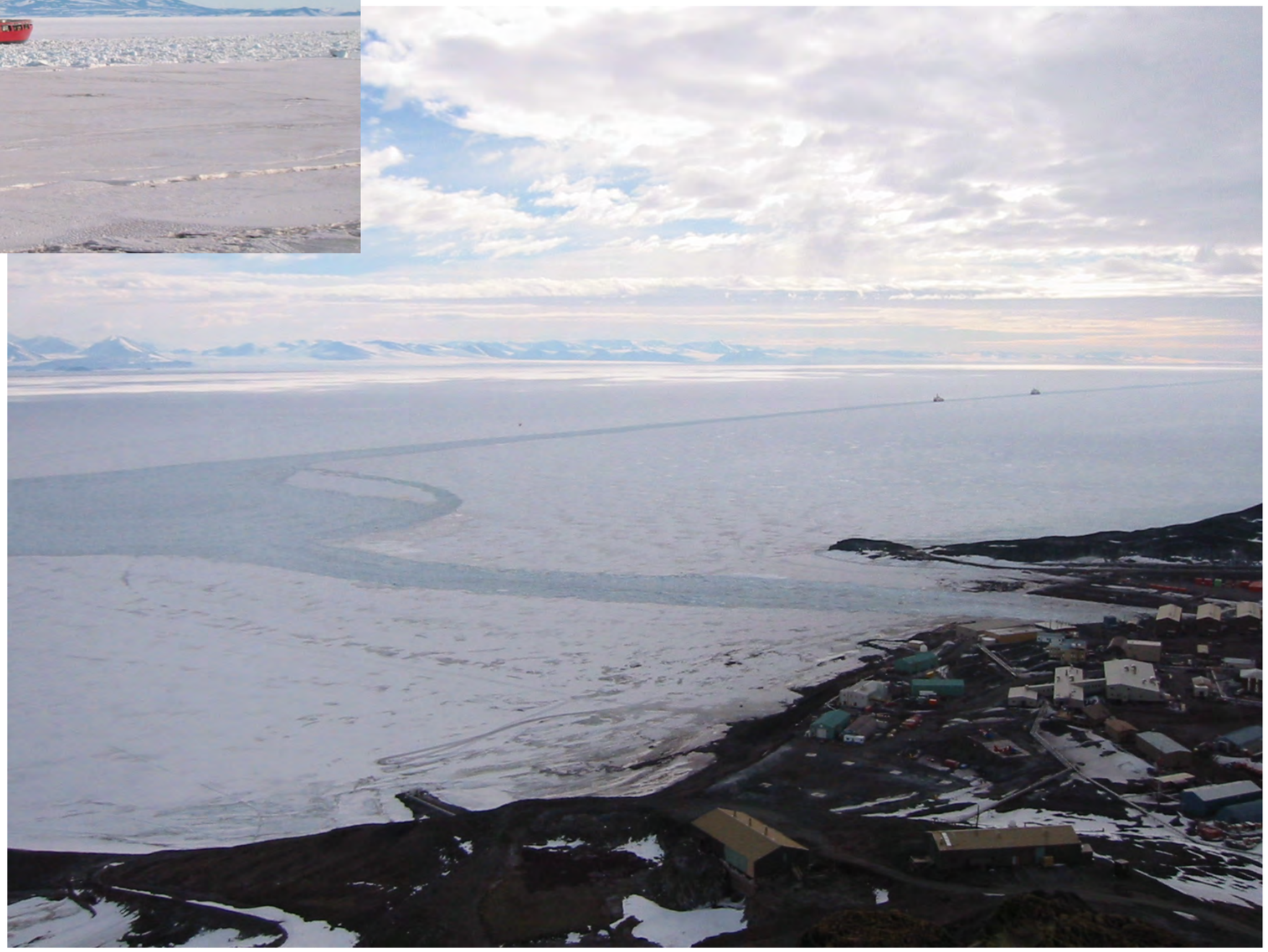
PoS (ICRC 2017) 991

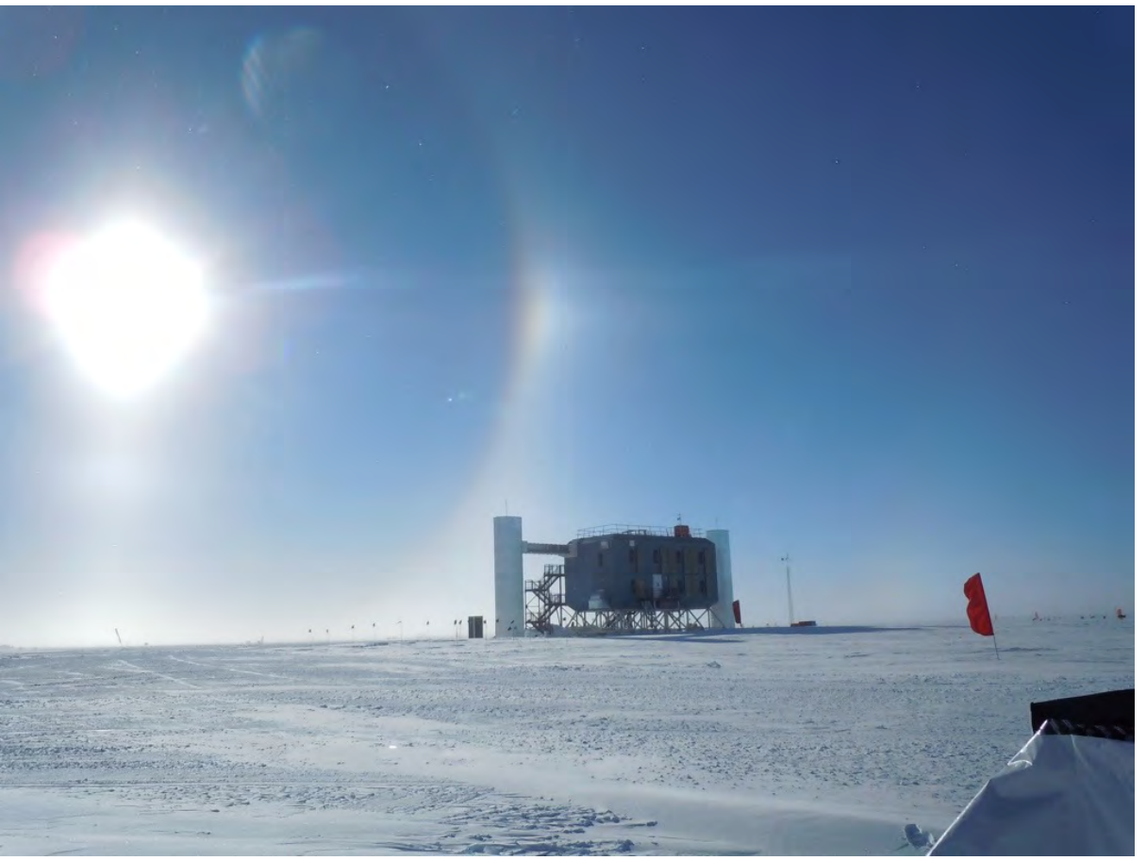
Life in Antarctica

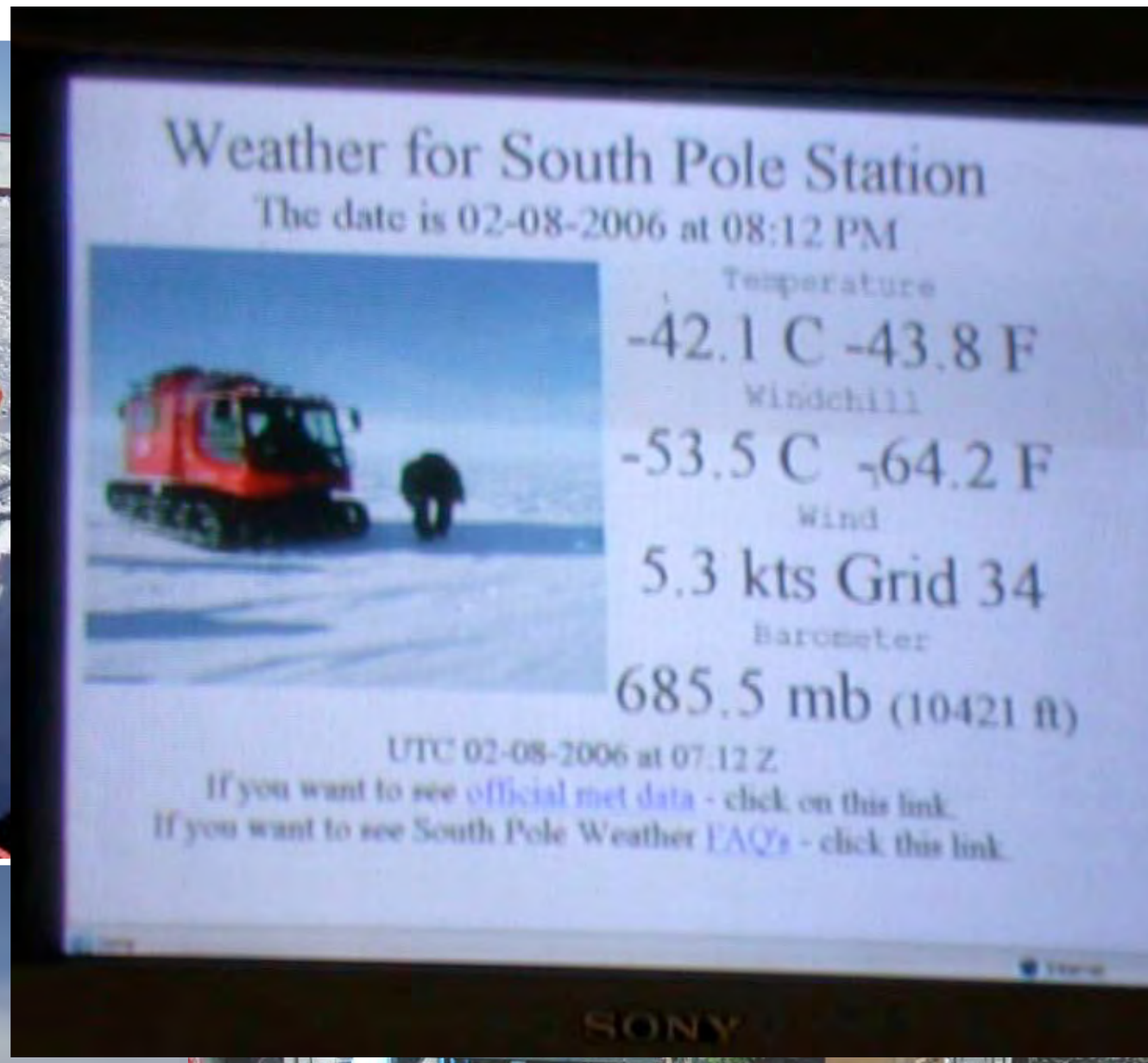

CARHARTT
JACKET
RED
NO SMOKIN
MENS CHANGING
LAPTOP
CHECKS


U.S. AIR FORCE
0196


U. S. COAST GUARD






Weather for South Pole Station
The date is 02-08-2006 at 08:12 PM
Temperature
-42.1 C -43.8 F
Windchill
-53.5 C -64.2 F
Wind
5.3 kts Grid 34
Barometer
685.5 mb (10421 ft)
UTC 02-08-2006 at 07:12 Z
If you want to see official met data - click on this link.
If you want to see South Pole Weather FAQs - click this link.
SONY

Weather for South Pole Station

Today is Saturday, July 4th 12:32am

Temperature

-78.3 °C -108.9 °F

Windchill

-108.8 °C -163.9 °F

Wind

16.6 kts Grid 143

Barometer

671.3 mb (3,340 m/10,958 ft)

Thank you!

IceCube at the South Pole

South Pole Station

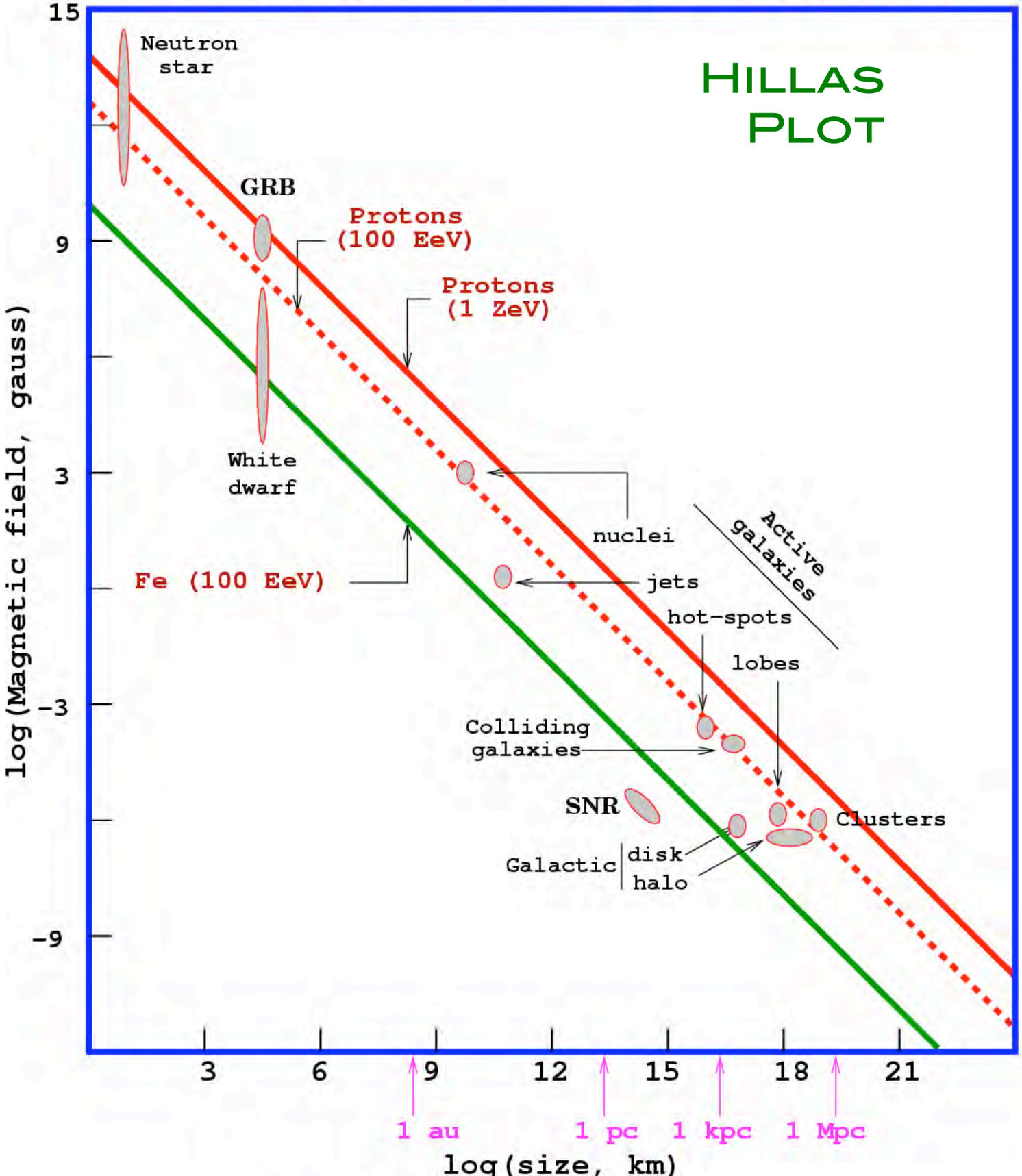
IceCube

Skiway

Geographic South Pole

Dark sector

Candidate accelerators



Requirements:

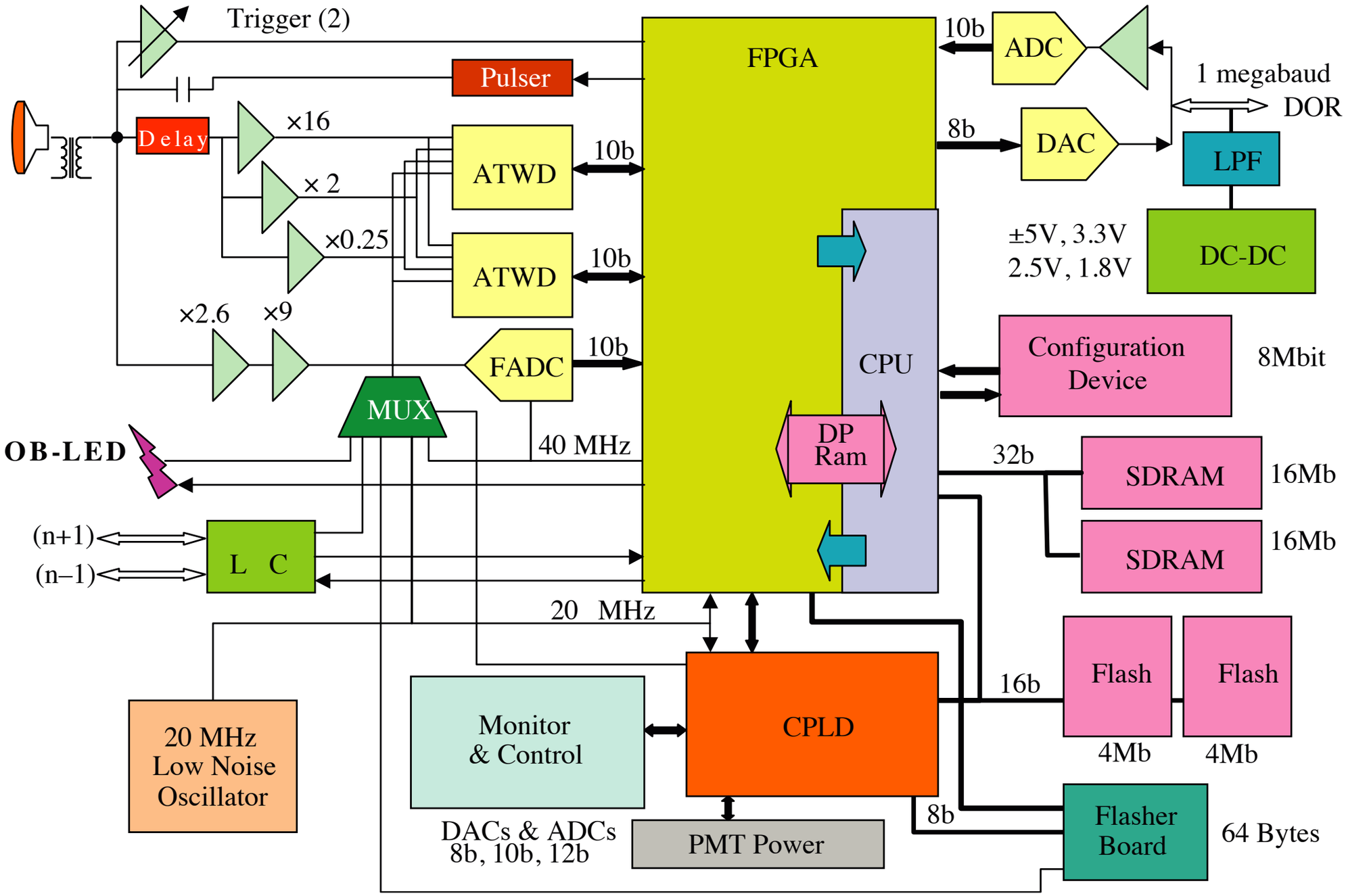
$$R_{gyro}\,(=\frac{E}{\mathrm{v}qB}) \le R$$

$$E \le \mathrm{v}\,qBR$$

Large magnetic field

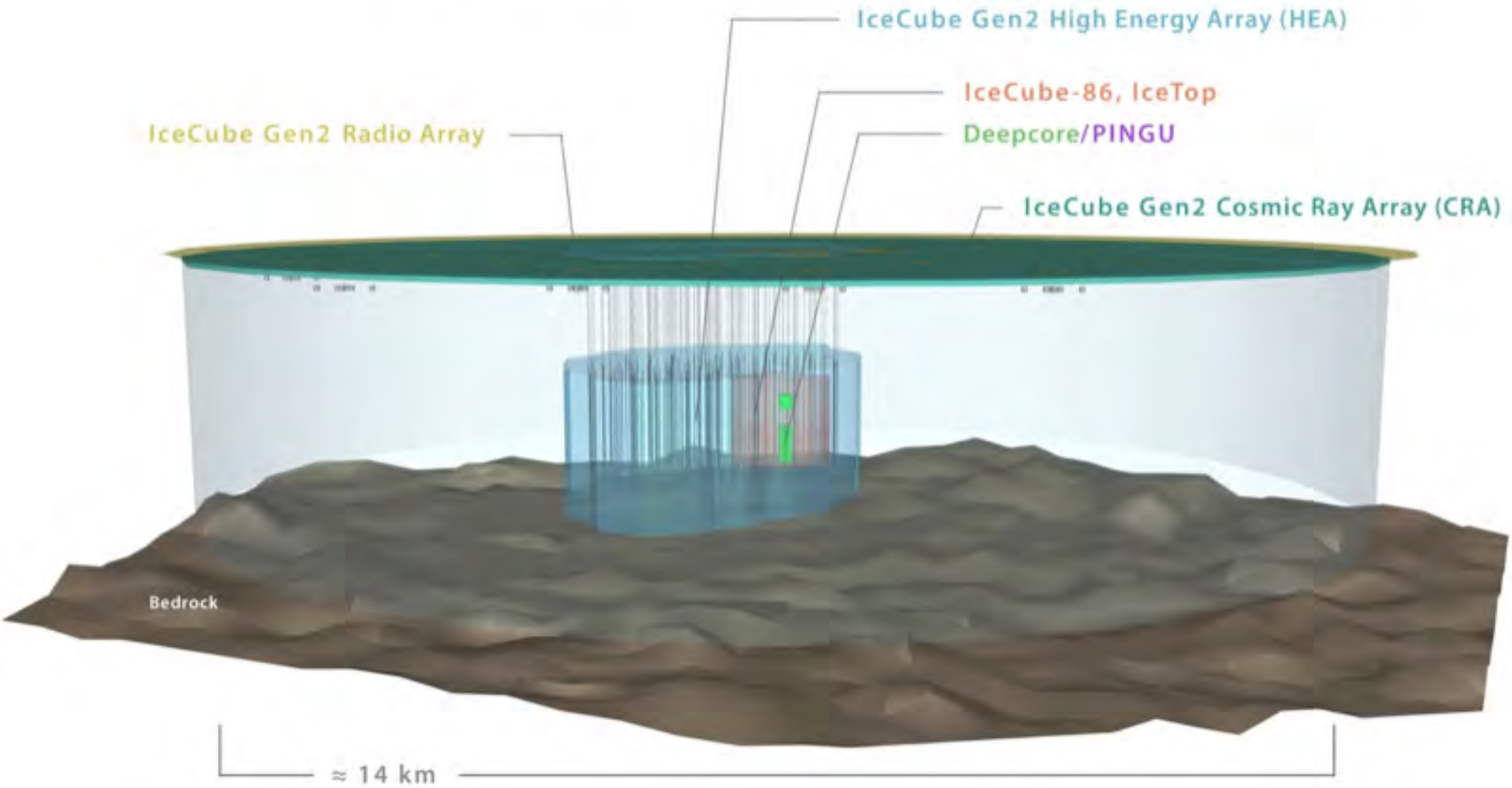
Large radius

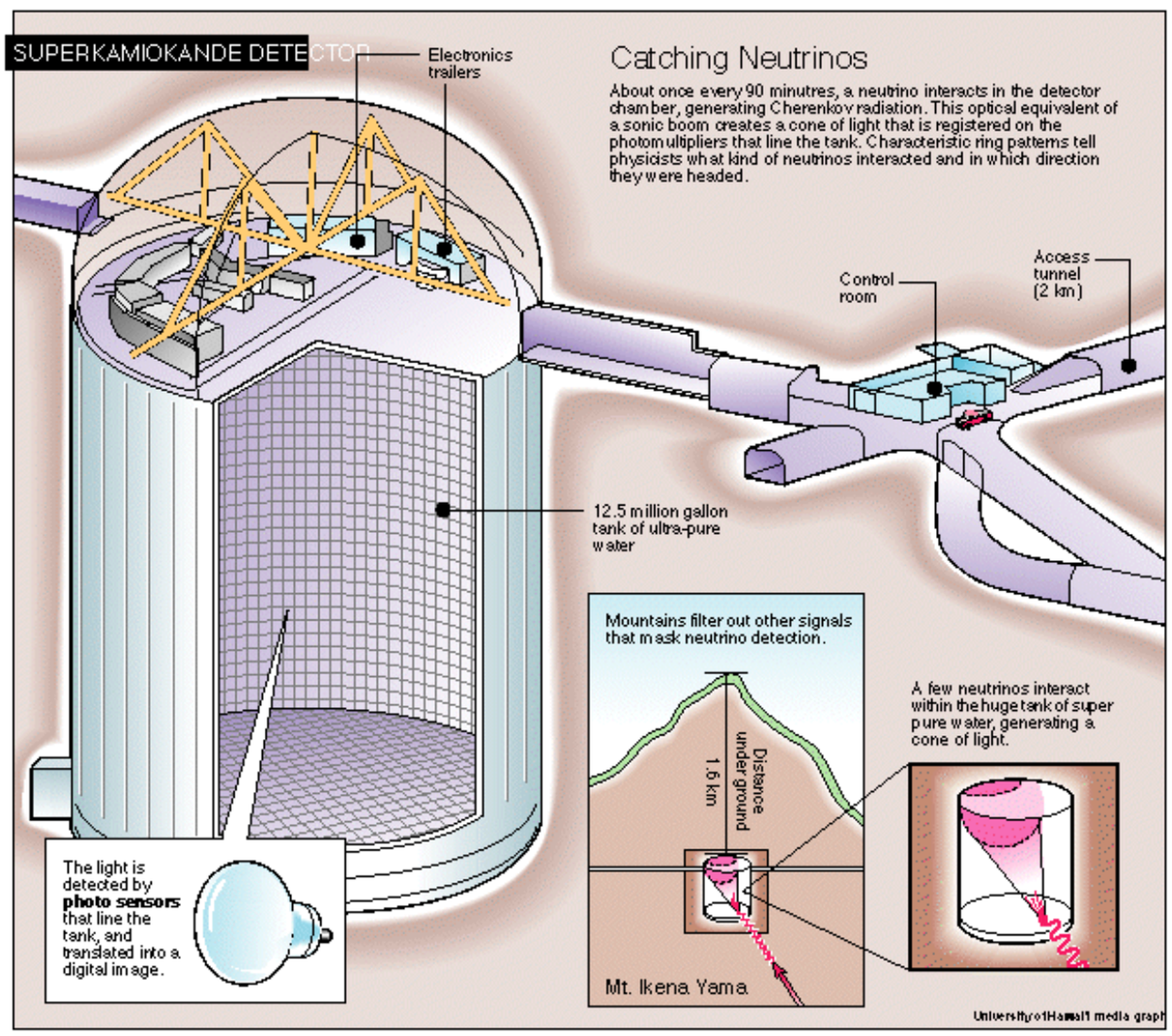
The "Real" DOM

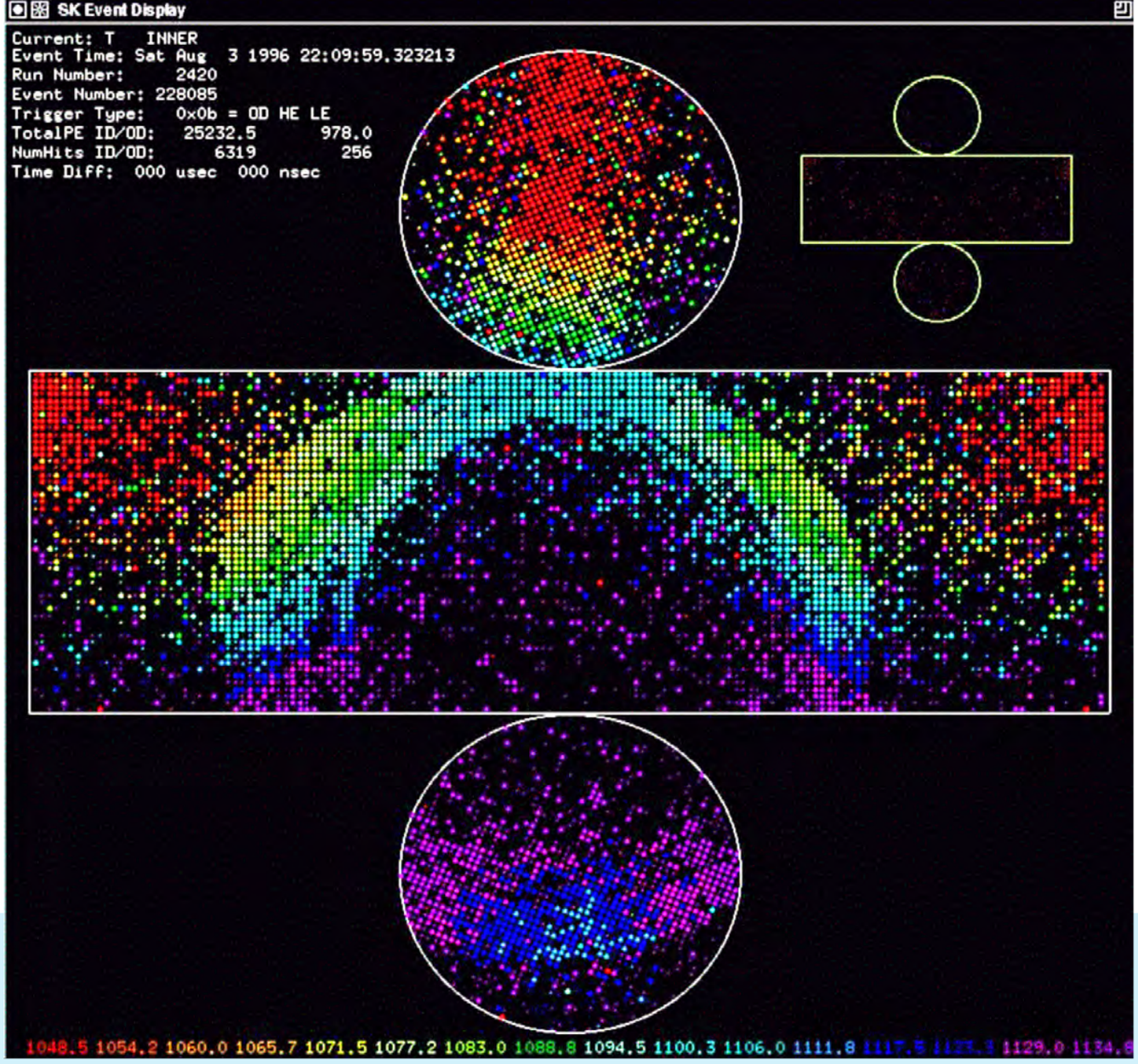


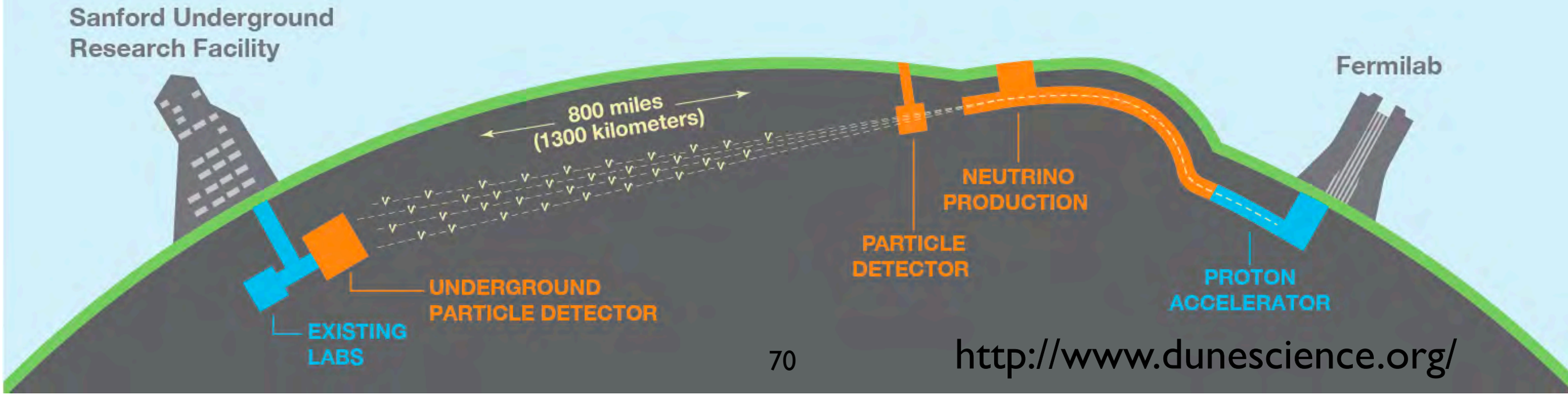
A complicated digitizer, calibration system and control computer on a large network

The IceCube Gen2 Facility









http://www.dunescience.org/

Drilling and deployment