

A photograph of the IceCube-Gen2 detector in Antarctica. The detector consists of a central building with a complex network of stairs and walkways, and two large cylindrical structures on either side. The scene is set against a dark night sky filled with stars and the Milky Way galaxy. A vibrant aurora borealis in shades of green and purple is visible in the upper half of the frame. The foreground is a flat, snow-covered landscape.

# IceCube-Gen2

*From Discovery to Astronomy*

IceCube Bootcamp  
June 2026

Albrecht Karle  
Univ. Wisconsin-Madison



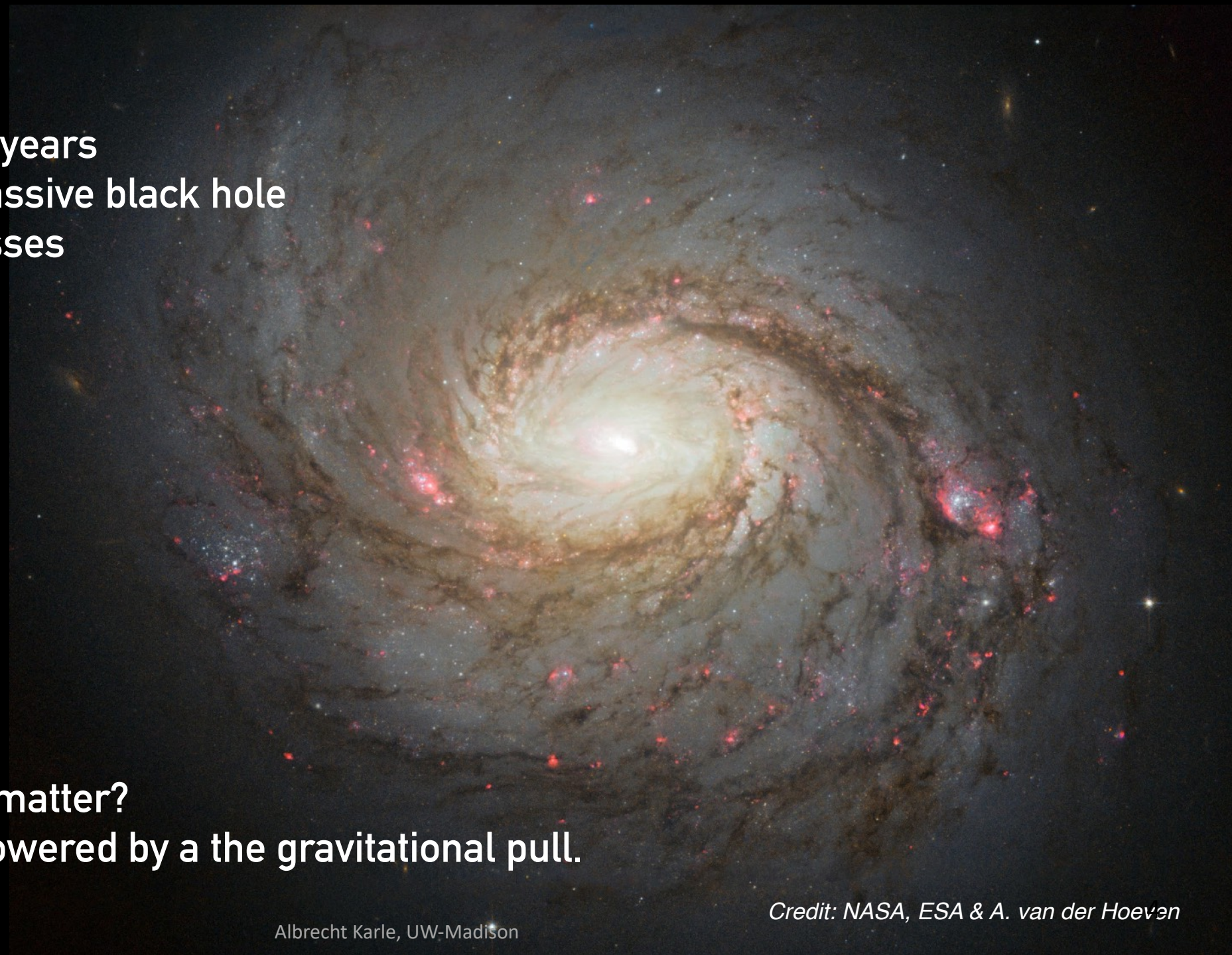
What is NGC 1068?

A Galaxy

Distance: 50 million light years

In the center: A super massive black hole

~20 million solar masses

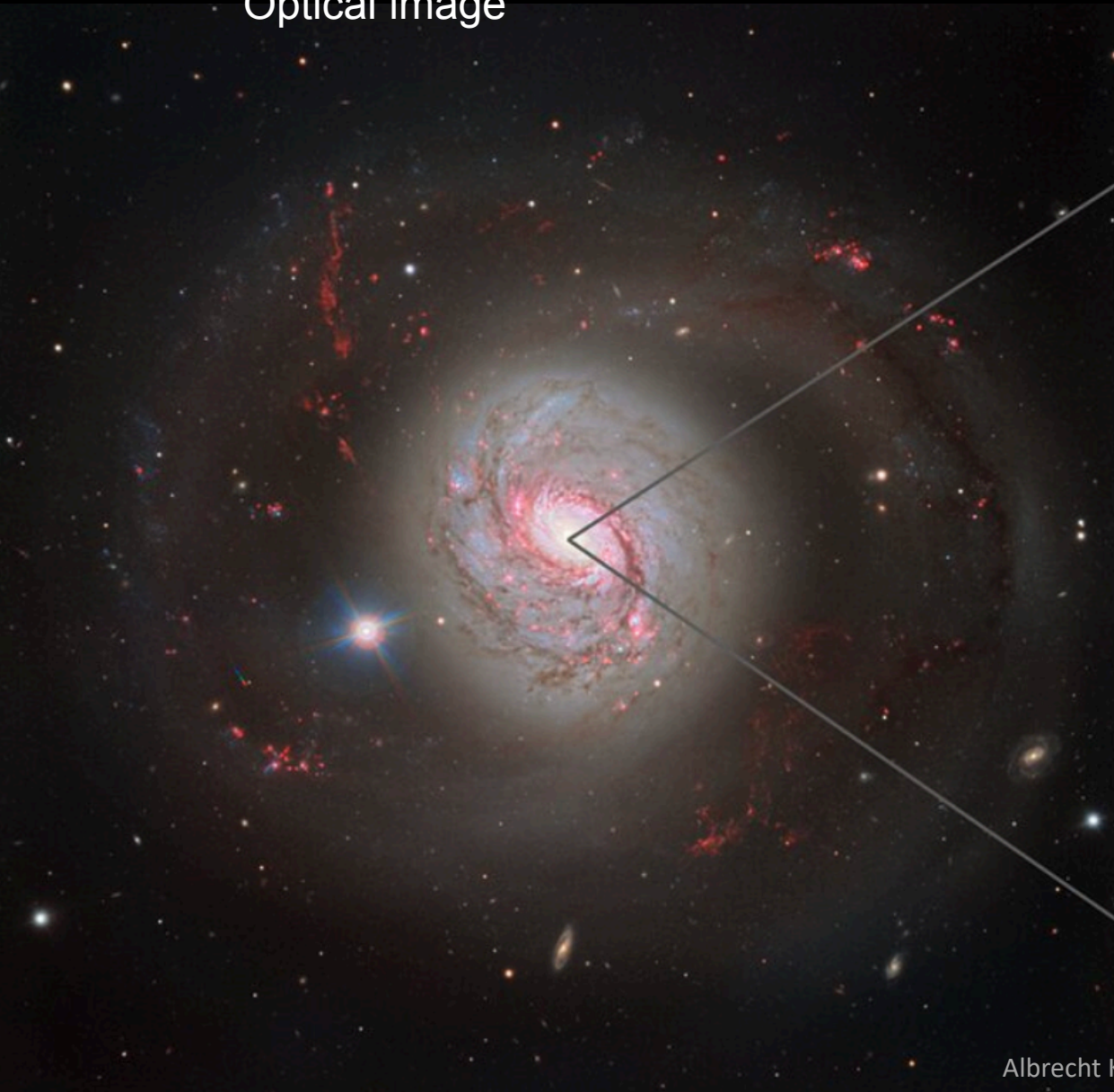


Why does the black hole matter?

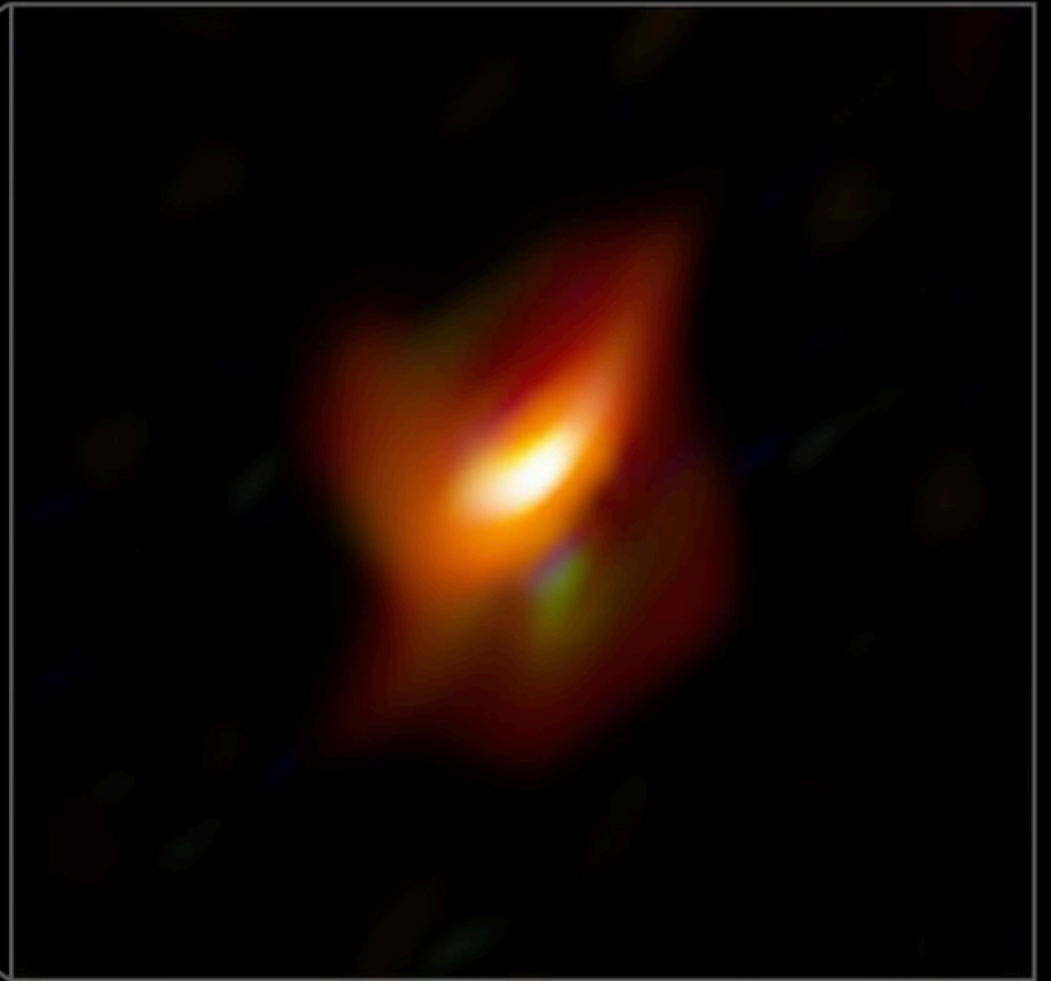
Particle acceleration is powered by a the gravitational pull.

# NGC 1068: The black hole region is obscured by dust.

Optical image



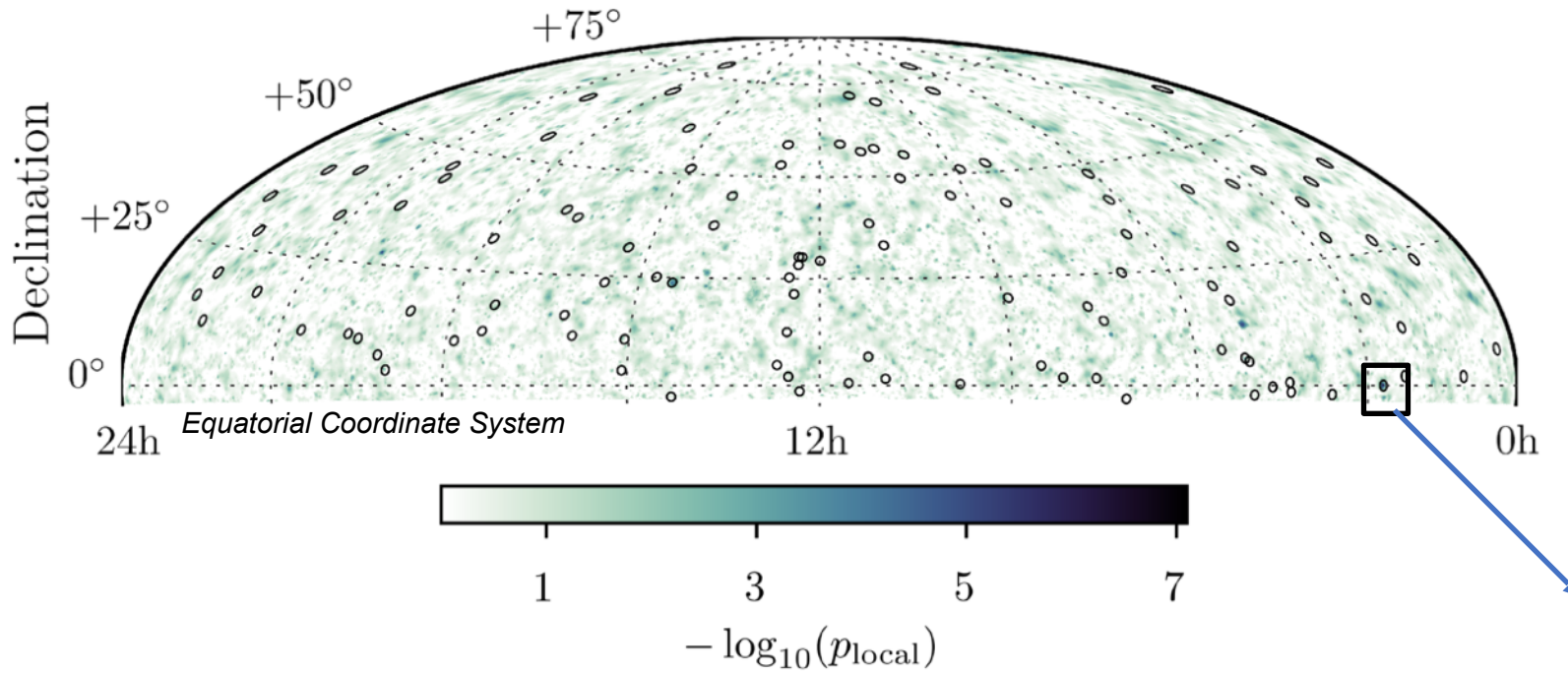
Infrared image confirms dust cloud surrounding black hole  
(Neutrinos don't care about dust.)



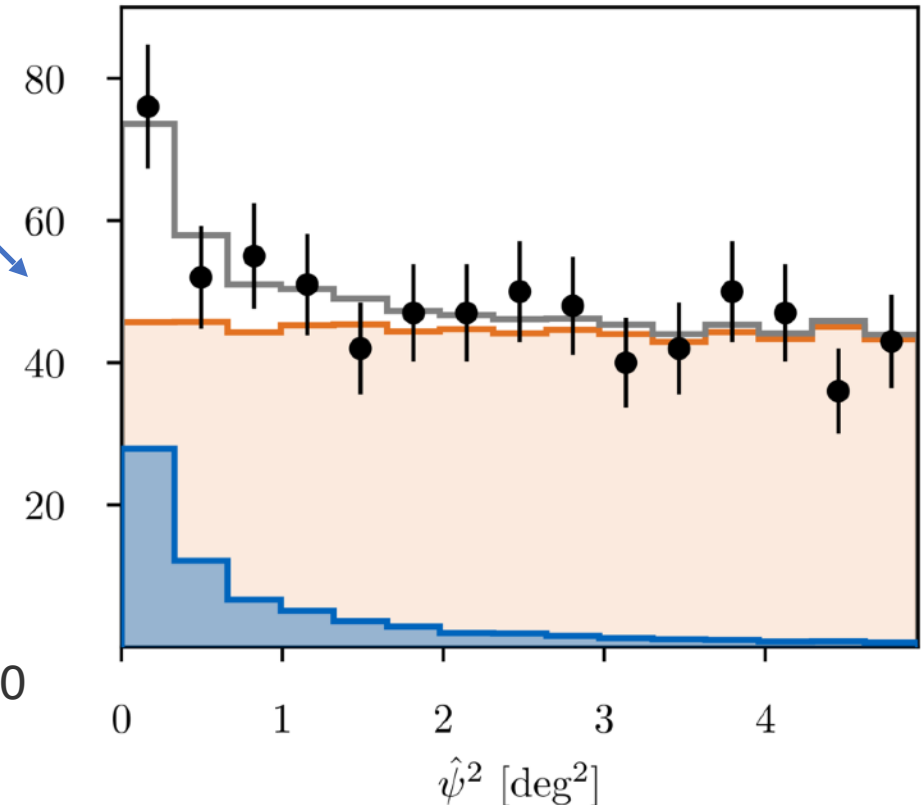
Rosas et al., [Nature](#), volume 602, pages, 403–407 (2022)

# Evidence for neutrino emission from the nearby galaxy M 77 (NGC 1068)

*Science* – Nov. 4, 2022



Signal (blue line)  
Background (orange line)  
Total (grey line)  
Data (black dots with error bars)



Lifetime: 9 years

At the NGC 1068 location:

**Astrophysical neutrino events = 79** <sup>+22</sup> <sub>-20</sub>

Spectral index =  $3.2 \pm 0.2$

... significance **4.2 $\sigma$**

p-value: 1:100,000



A statement that is attributed to Ernest Rutherford says:

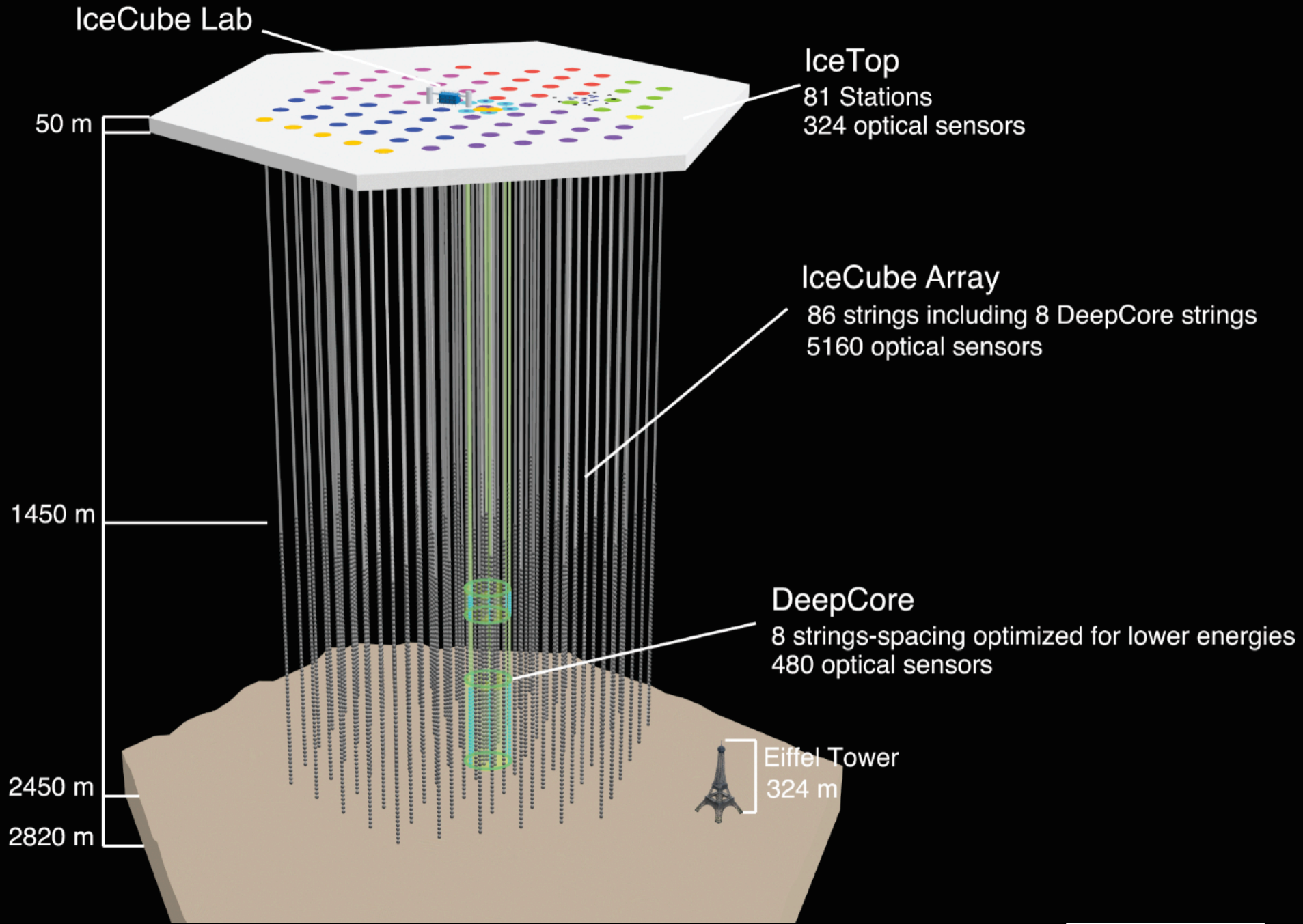
**“If your experiment needs a statistician,  
you need a better experiment.”**

**—> IceCube-Gen2**

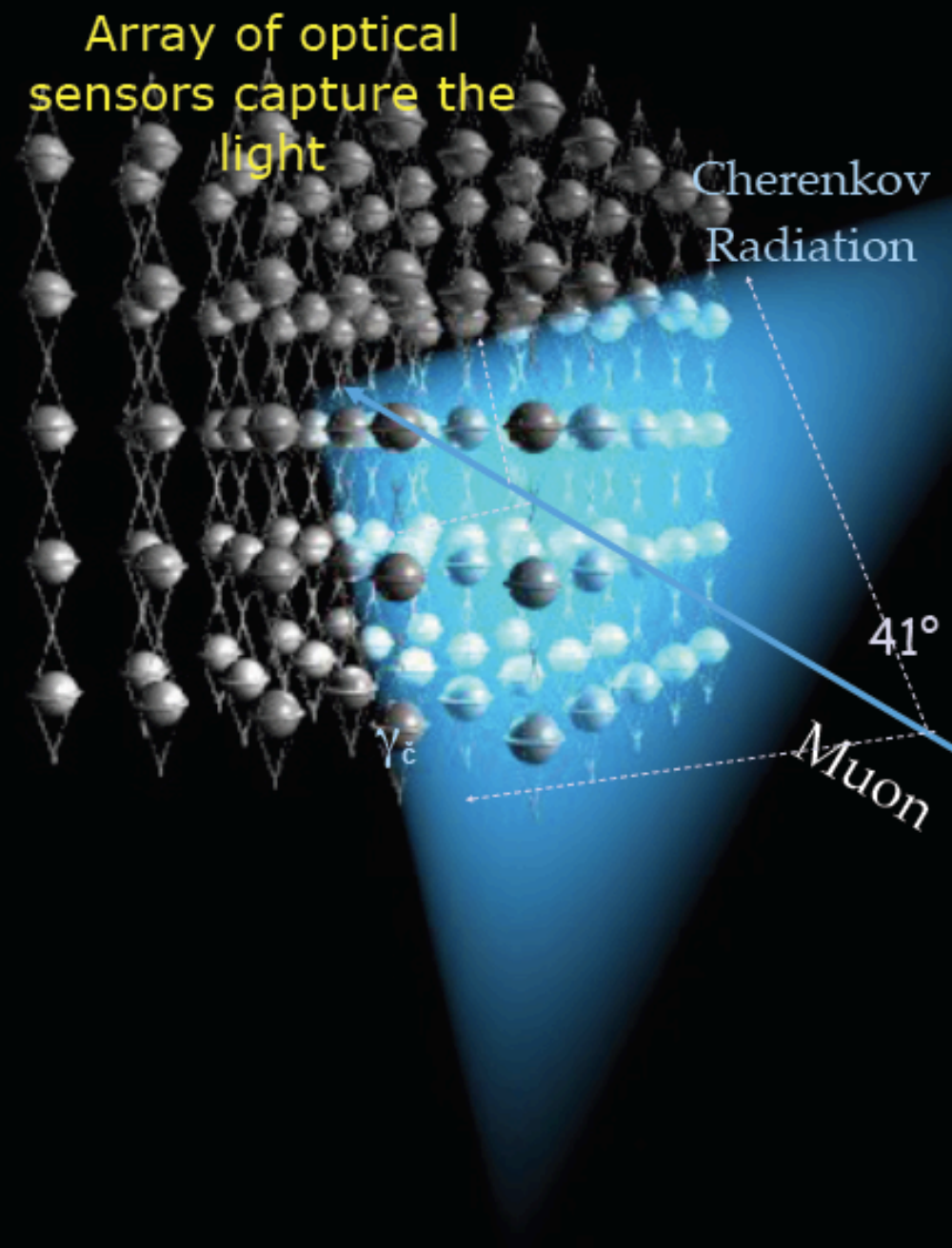
Spoiler alert:  
They are neutrinos, you will still need  
statistics.

# The IceCube Neutrino Observatory

Instrumented volume:  
 $\sim 1 \text{ km}^3$

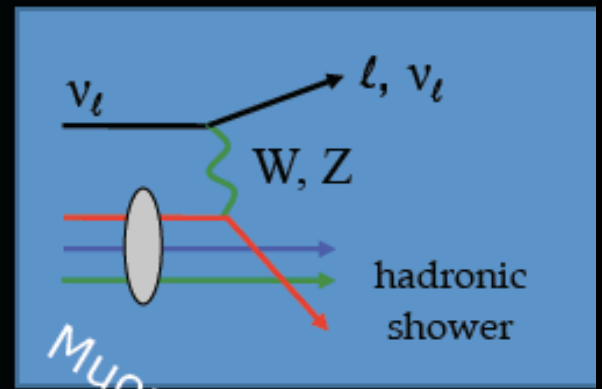


Array of optical sensors capture the light



Neutrinos interact in or near the detector  
Depending on the interaction a lepton (CC) or a shower (NC) is produced

- (km) muons from  $\nu_\mu$
- (10m) cascades from  $\nu_e, \nu_\tau, \text{NC}$

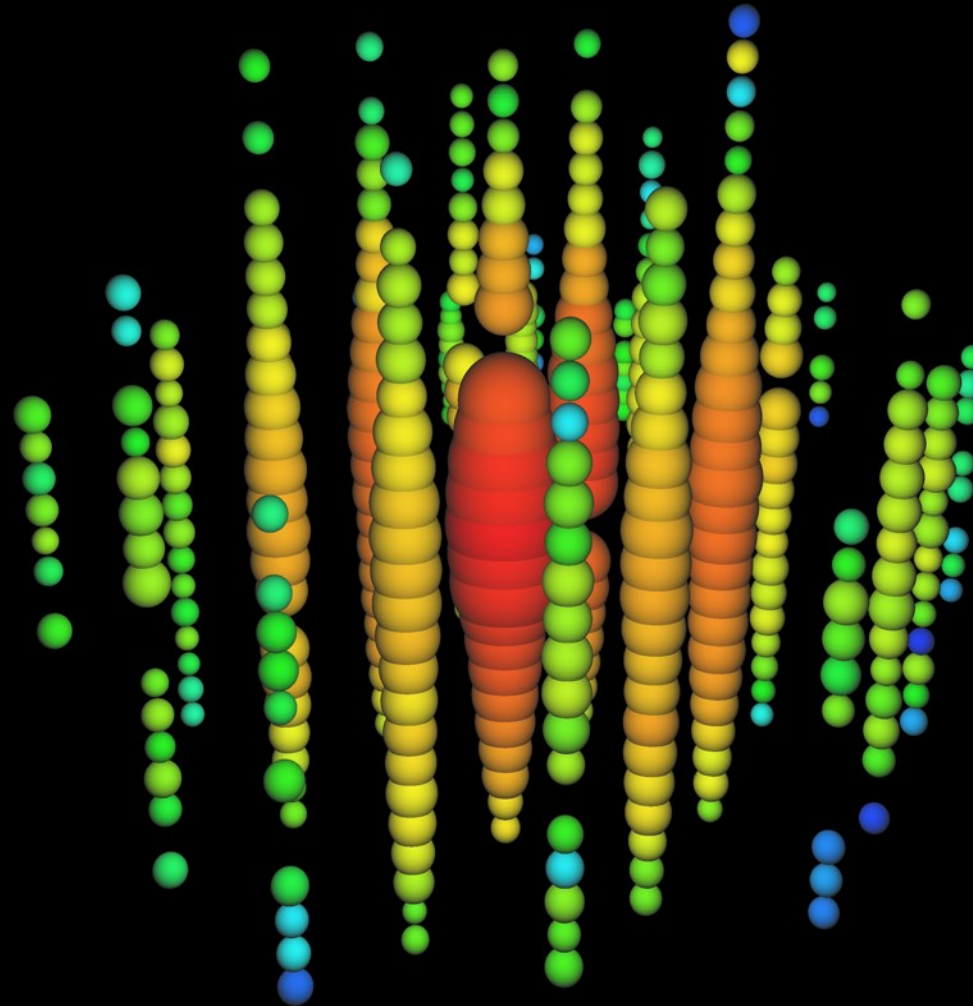


interaction  
Muon Neutrino

Bert: Energy 1 PeV

How well could we reconstruct this event with fewer strings?

Analyzed event using only subsets of 20 IceCube strings spaced at 250m.



**Result:**

Vertex reconstruction: ~ 12m

Angular resolution: ~30°

(Estimate today to do better, like 15°)

**Energy resolution: 10%**

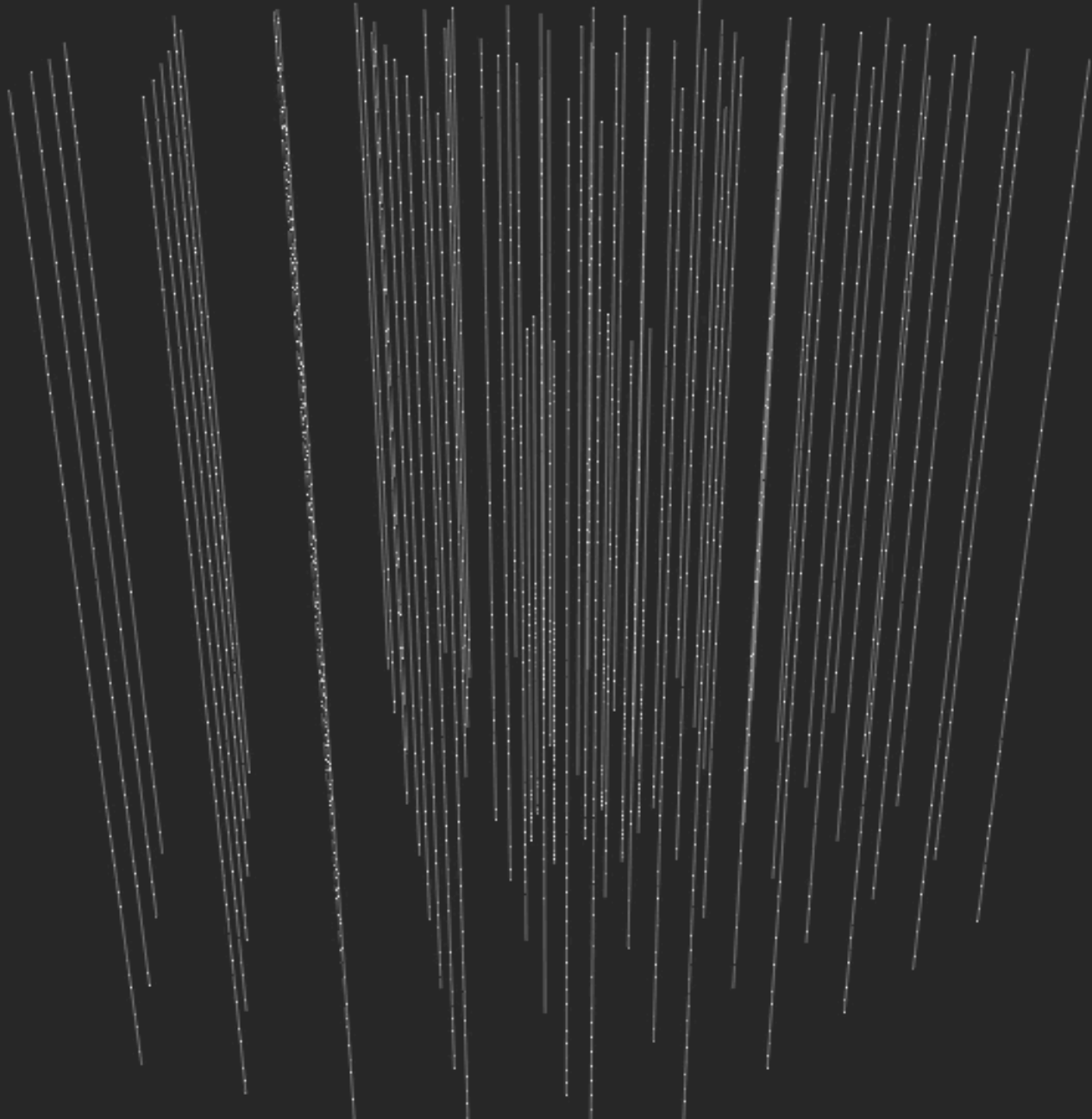
Same result for Ernie, the other PeV event.

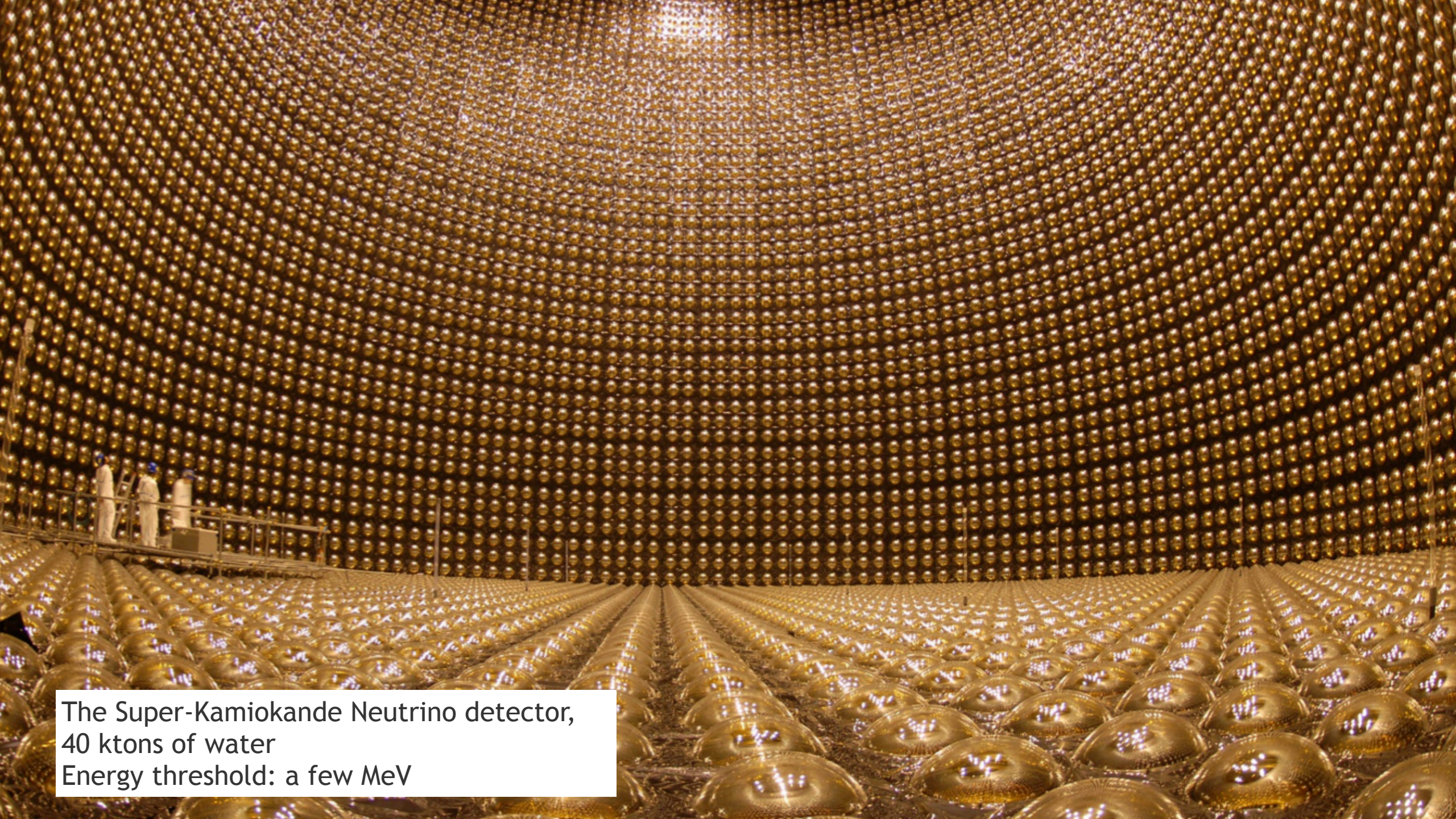
→ Don't need 100,000 photoelectrons to measure energy to 10%.

Dr. Strangepork

Deposited energy: 71 TeV

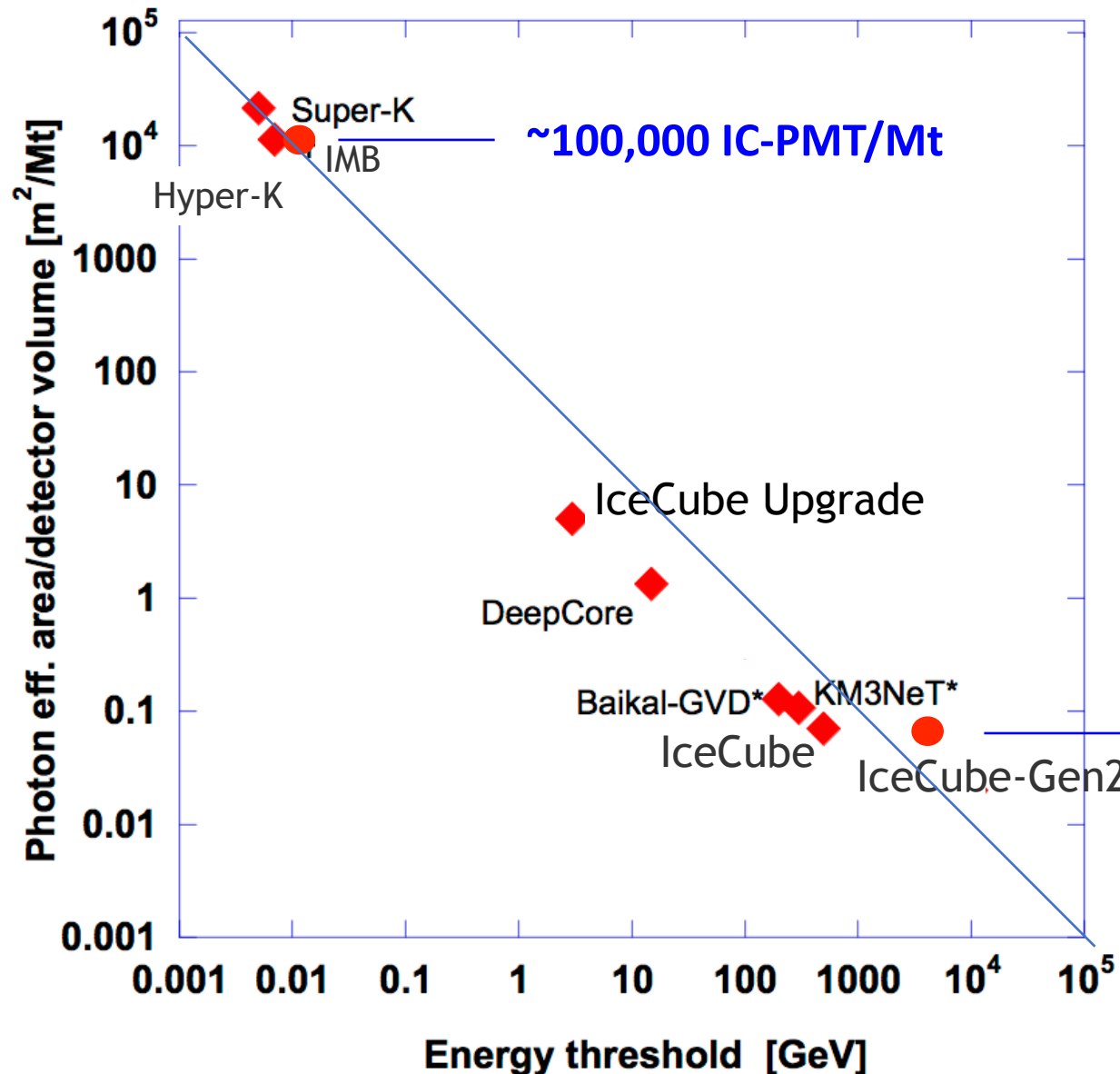
$7.1 \times 10^{13}$  eV





The Super-Kamiokande Neutrino detector,  
40 ktons of water  
Energy threshold: a few MeV

# Water Cherenkov detectors: PMT coverage vs energy threshold



No. of Cherenkov photons proportional to integrated energy loss of all charged particles.

IceCube: 5000 IC PMTs/Gtons

Gen2: 10,000 Gen2 DOMs/8 Mtons

Define:

Photon effective area =

Number of PMT

x Cathode area

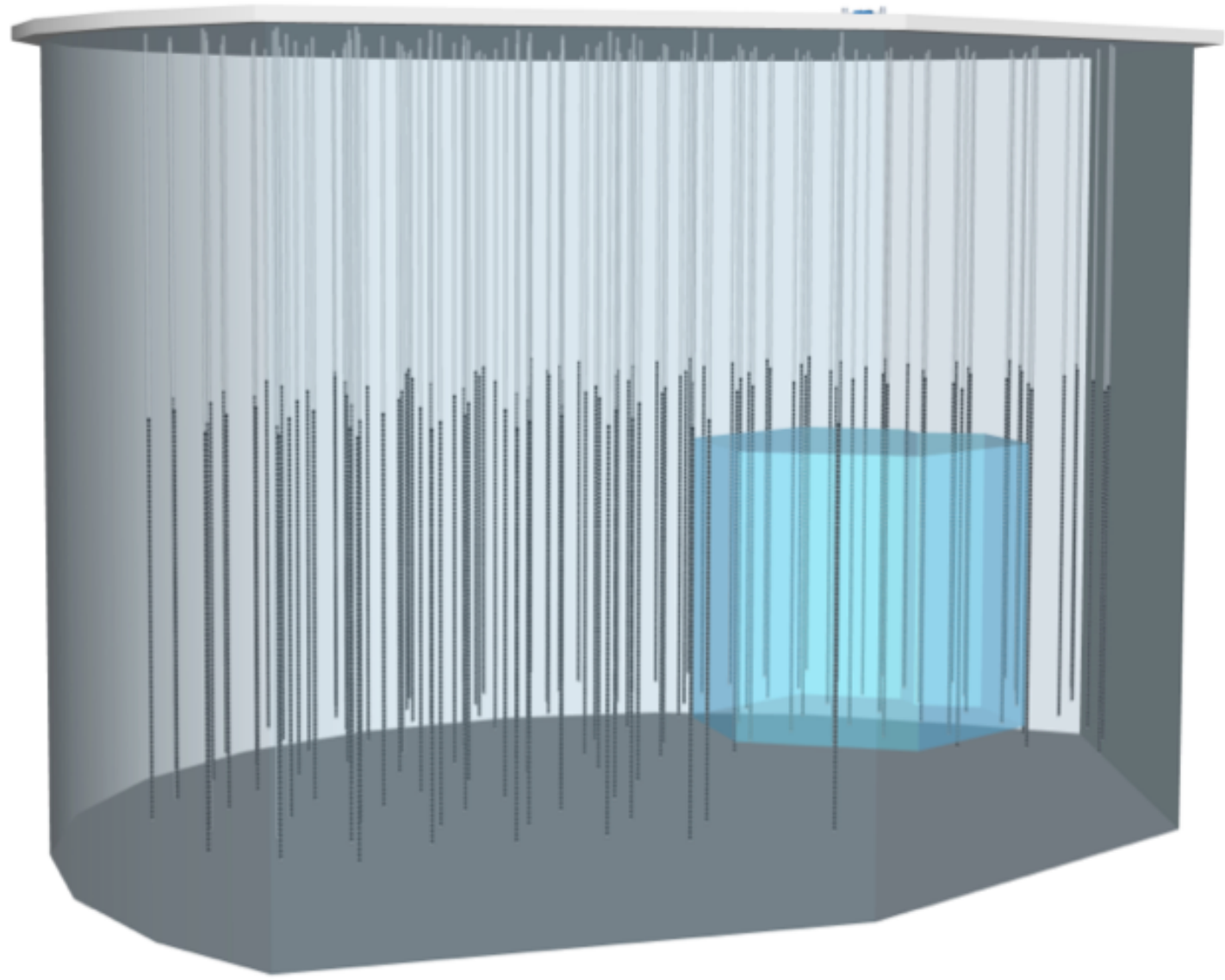
x Quantum efficiency

= equivalent area of 100% photon detection.

(collection efficiency not included here.)

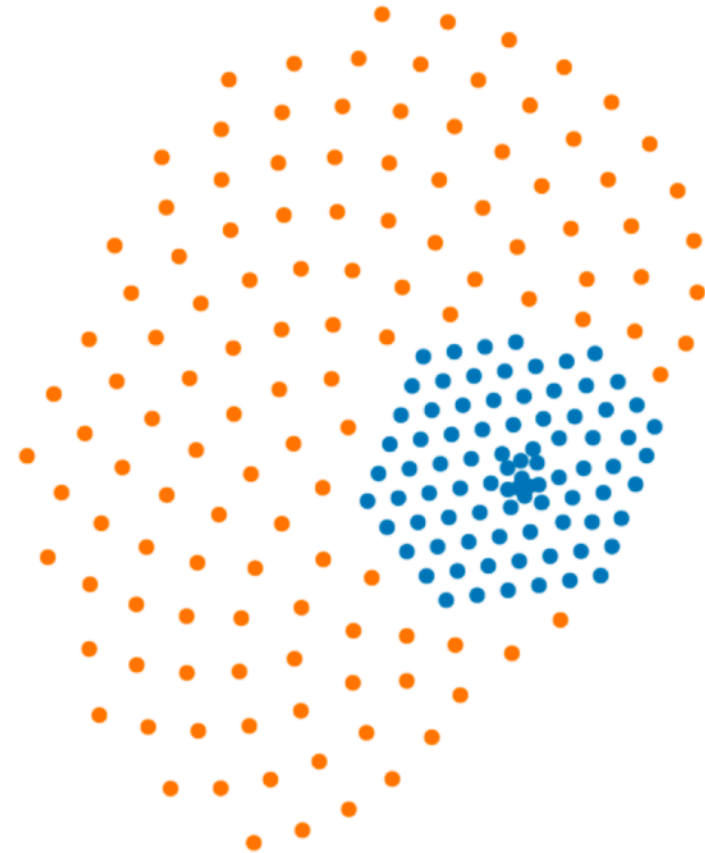
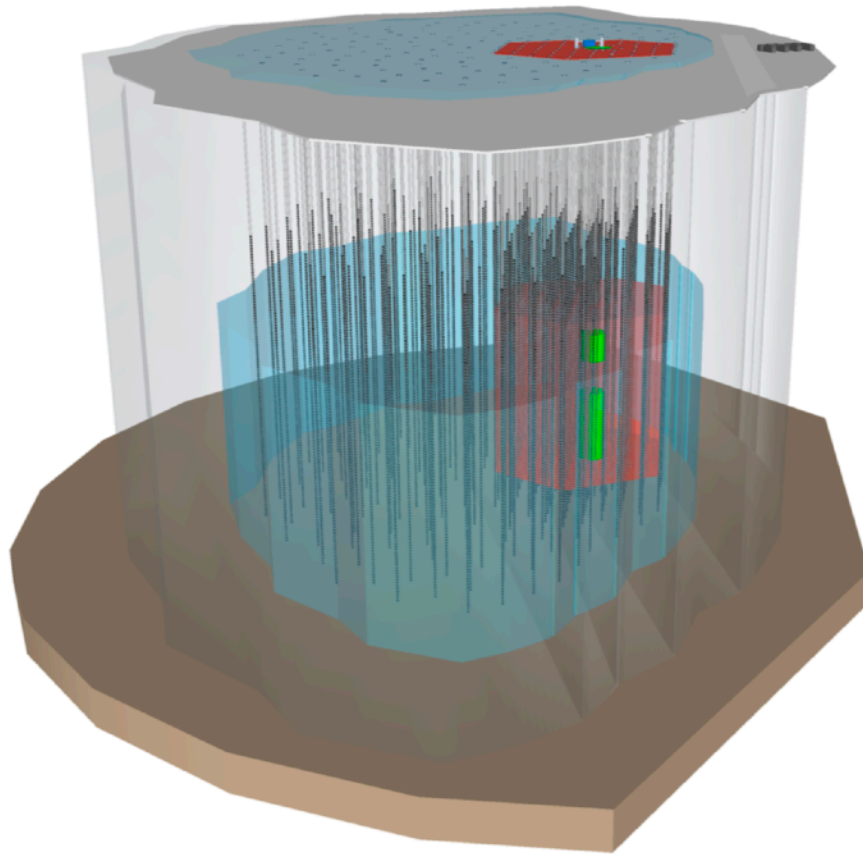
Photon effective area prop.  $\sim 1/\text{Energy threshold}$ .

Detector arrangements and optical properties of water and ice are different, yet the PMT density scales well with energy threshold.



# IceCube-Gen2

*A Vision for the Future of Neutrino Astronomy in Antarctica (arXiv:1412.5106)*



Artist's conception  
120 strings at 240 m spacing



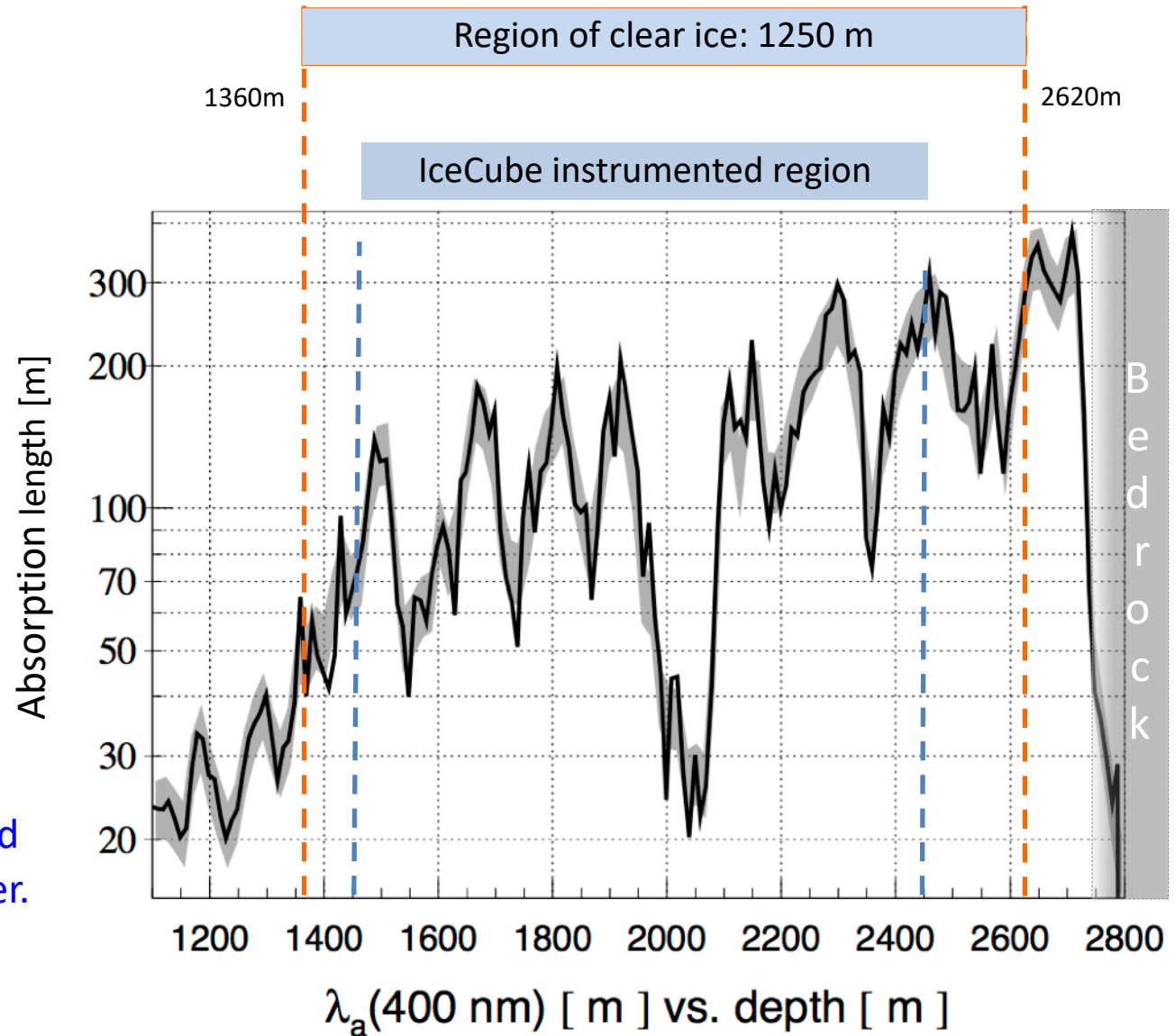
**The next-generation IceCube: from discovery to astronomy**

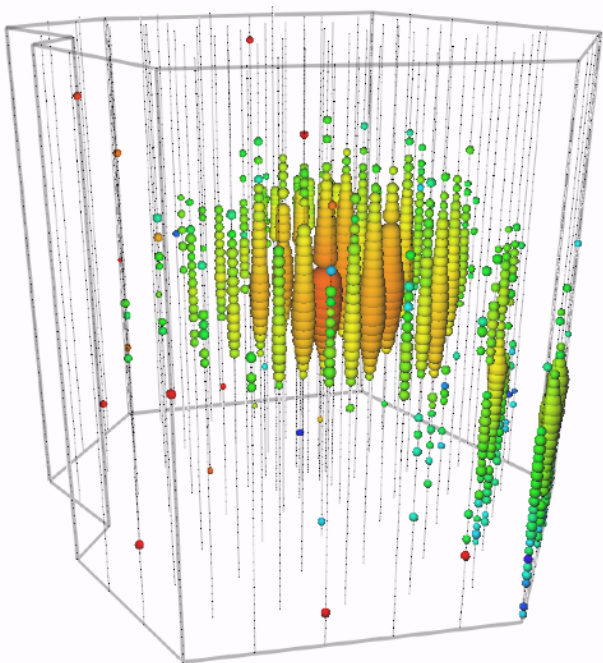


# Extending the region of ice to instrument with DOMs

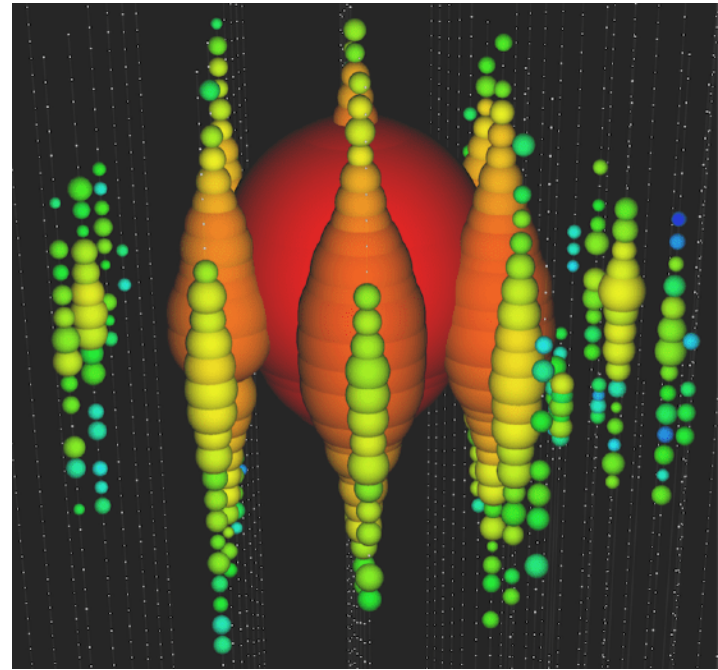
- Bedrock estimated depth 2750m – 2850m
- 150 m to 200 m of very clear and usable ice below IceCube (need safety distance from bedrock)
- 100 m of good ice above

→ Can make instrumented region 250 to 300m longer.

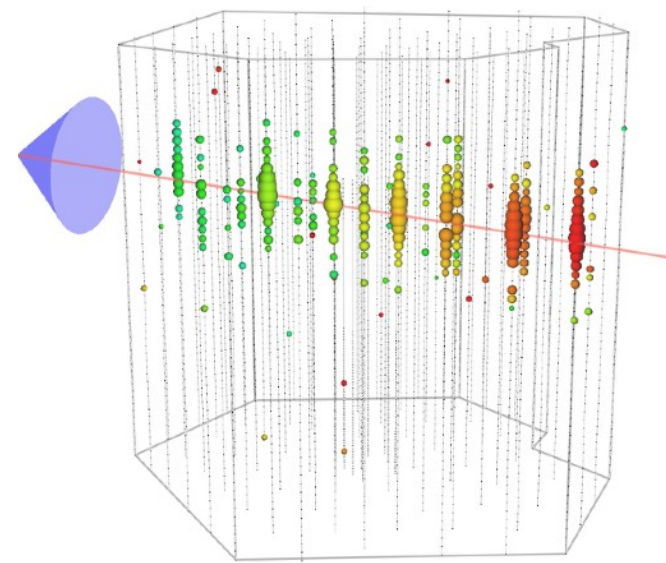




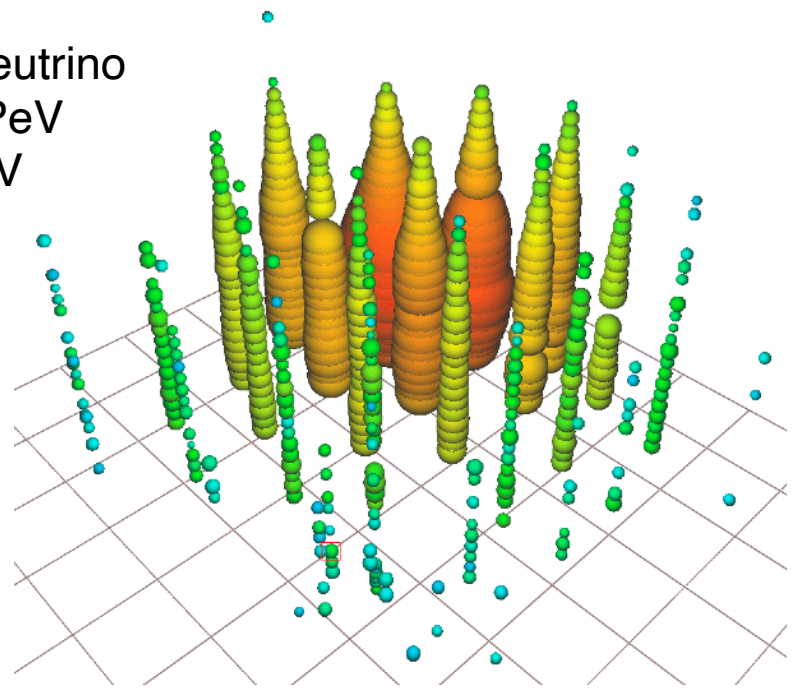
Event 190331A  
 highest energy muon neutrino  
 est. energy:  $11.6 \pm 2.6$  PeV  
 deposited energy: 5 PeV



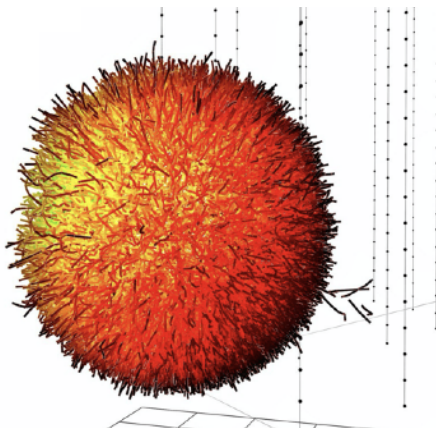
The "Big Bird"  
 contained neutrino  
 cascade interaction  
 est. energy: 2 PeV  
 December 4, 2012



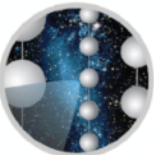
Event 240327A  
 gold alert  
 est. energy: 200 TeV  
 signalness: 54%



"Hydrangea"  
 cascade interaction  
 outside of Icecube  
 Glashow resonance event  
 $6.05 \pm 0.72$  PeV  
 December 8, 2016



# IceCube-Gen2 Optical Sensor Evolution



ICECUBE



IceCube DOM

10" PMT & dia. 33 cm

>98% still in operation



ICECUBE  
UPGRADE

**DEgg**  
Elongated vessel



Image Credit: N. Shimizu/CEHAP

**mDOM**  
PMT segmentation  
with  $4\pi$  angular  
coverage



Image Credit: S. Niedworok/DESY



ICECUBE  
GEN2

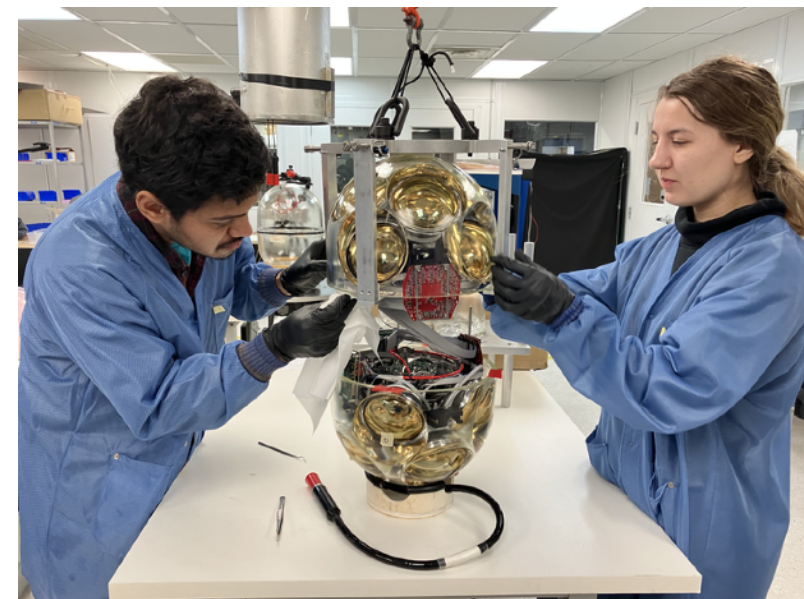
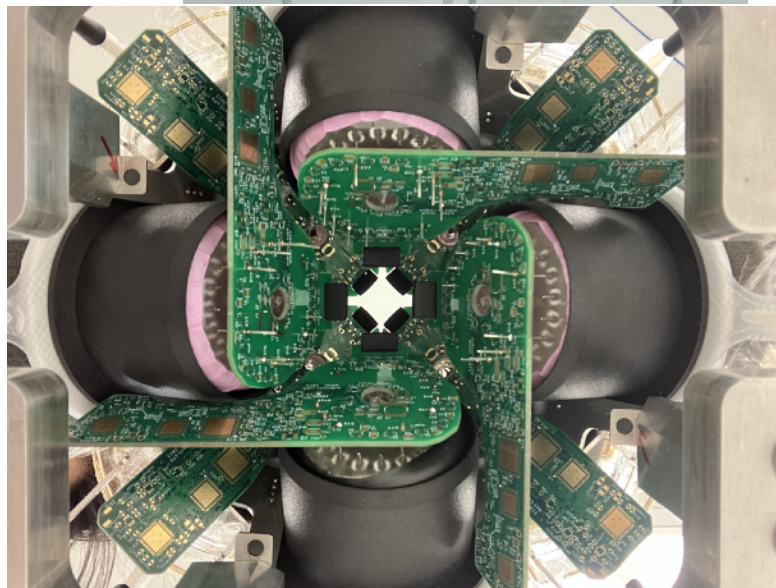
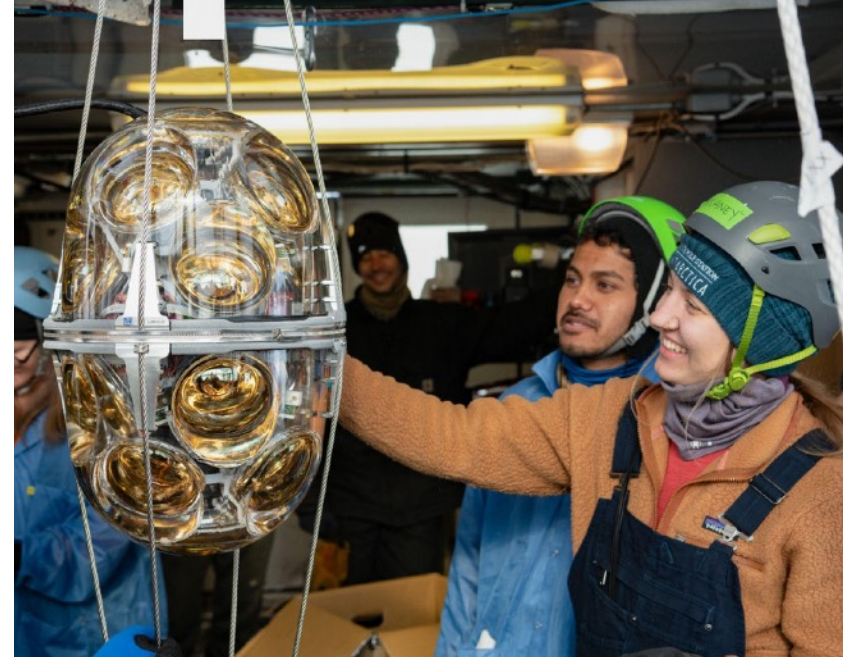
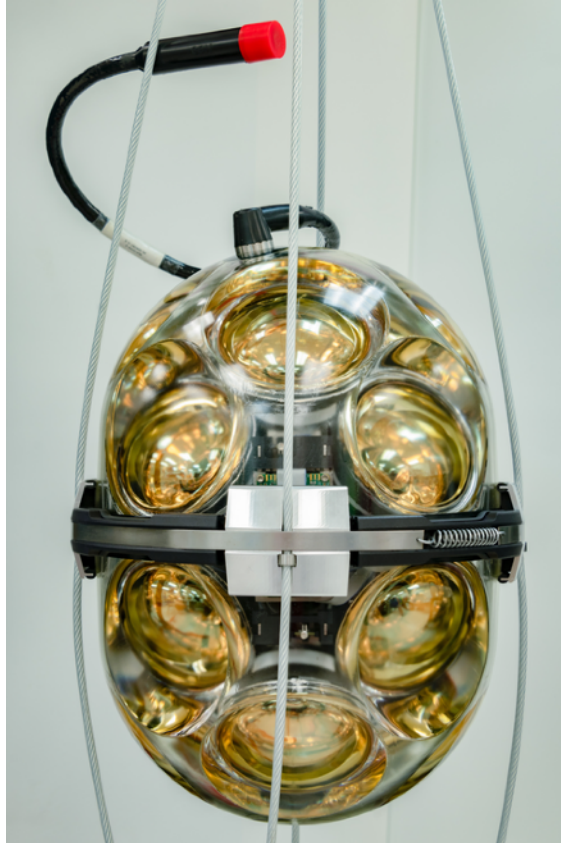


Image Credit: Y. Makino/WIPAC

**Gen2-DOM**  
PMT segmentation with  $4\pi$  angular  
coverage in an elongated vessel

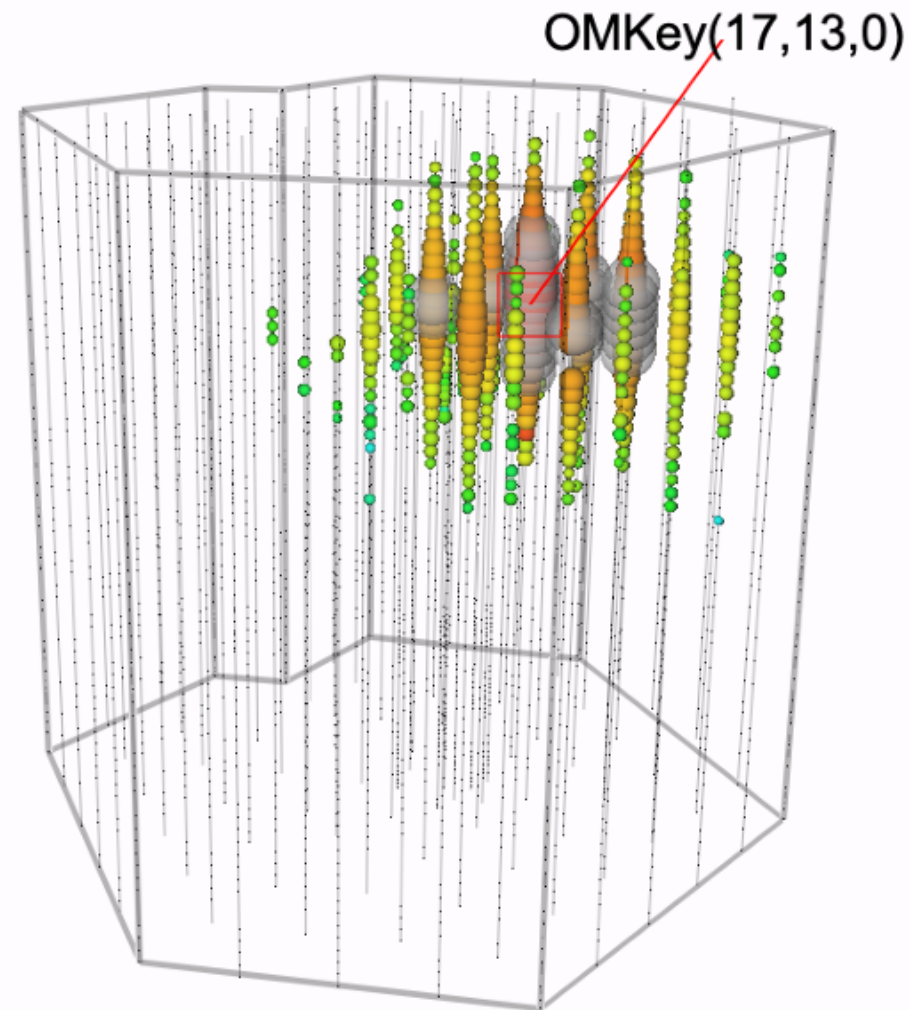
# Gen2-DOM Development

- New self-contained DAQ
  - wuBases → able to readout waveforms directly from new bases
  - Two channels (anode and dynode) for high gain and low gain readout
- Newly designed integration components → “Gel pads”
- Prototypes deployed in the Upgrade!



# PMT Dynamic Range

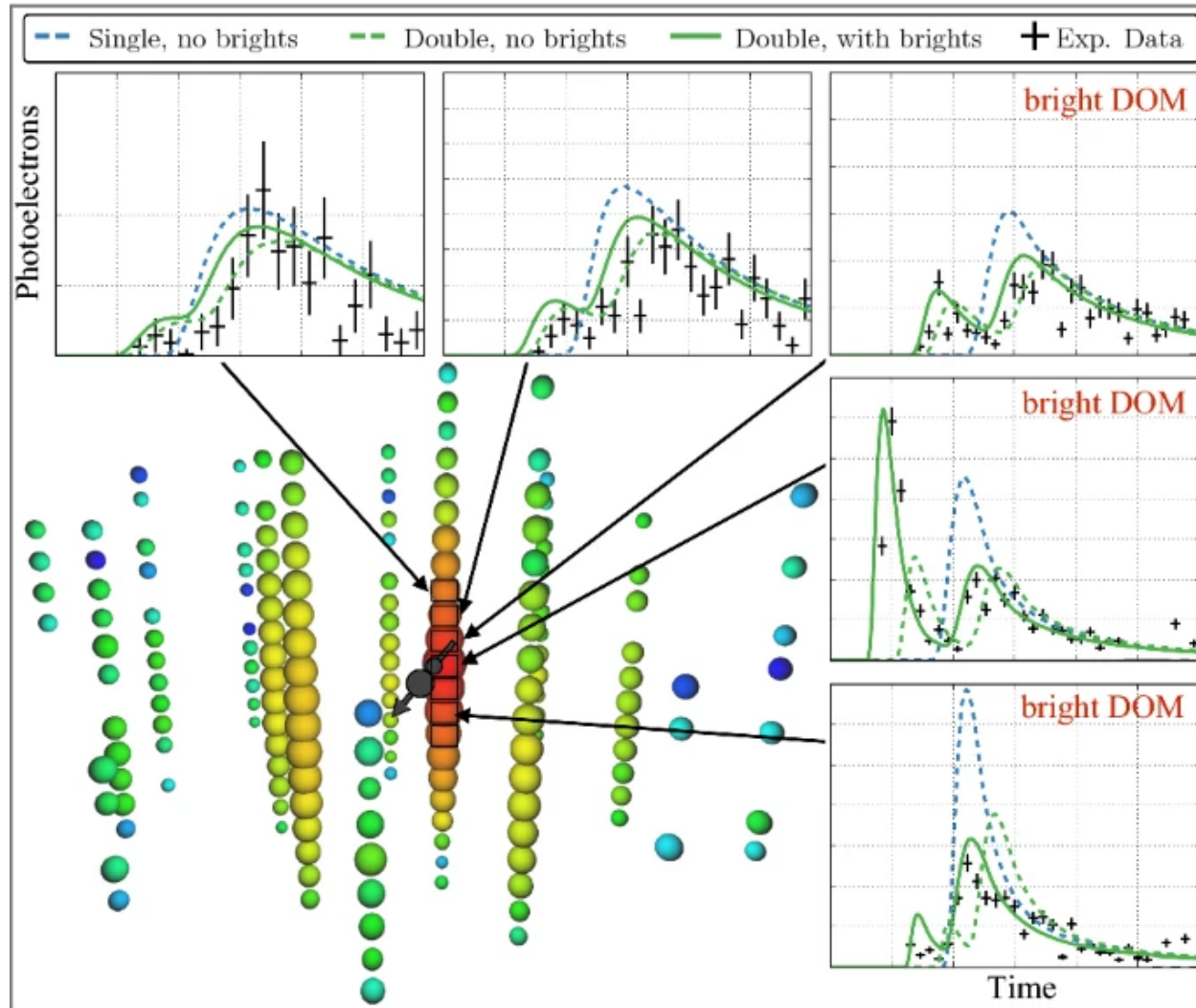
- Increased dynamic range prevents saturation of PMTs near high energy events
- Saturated DOMs in Gen1 are excluded from event reconstruction
  - DOMs closest to event provide crucial information
- Science requirement for linear dynamic range: 2 PeV energy at 30m from sensor



*Event display shows a 2 PeV shower in IceCube. The gray bubbles represent saturated DOMs and are excluded from event reconstruction. OMKey(17,13,0) is a saturated DOM that is ~30m from the vertex of the event.*

# PMT Timing Resolution

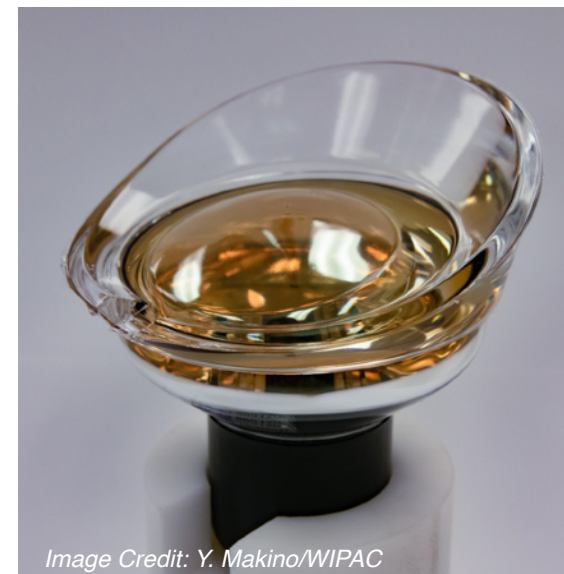
- Timing resolution vital in identifying particle and reconstructing direction
  - Especially important in double cascade structure of tau neutrino interaction
- Only minor effect on muon track reconstruction due to sparser string spacing
  - Many photons have undergone in ice scattering before arriving at sensor



*Event display shows a double-cascade event. Photoelectron pulse waveforms show double pulse structure.*  
[Abbasi et al 2022 Eur. Phys. J. C 82, 1031](#)

# Gel Pad Design

- PMTs are optically coupled to pressure vessel using silicone based gel
  - Gel has similar refractive index as glass
  - Conical shape increases collection efficiency via total internal reflection
- Two step coupling procedure:
  - Cast hollow gel pad before PMT integration to PMT glass surface
  - During integration, precast hollow pads adhered to pressure vessel and backfilled with optical gel
- Casting process enables production of highly smooth surfaces that act as light concentrators



*Left: Hollow gel pad coupled to PMT photocathode*

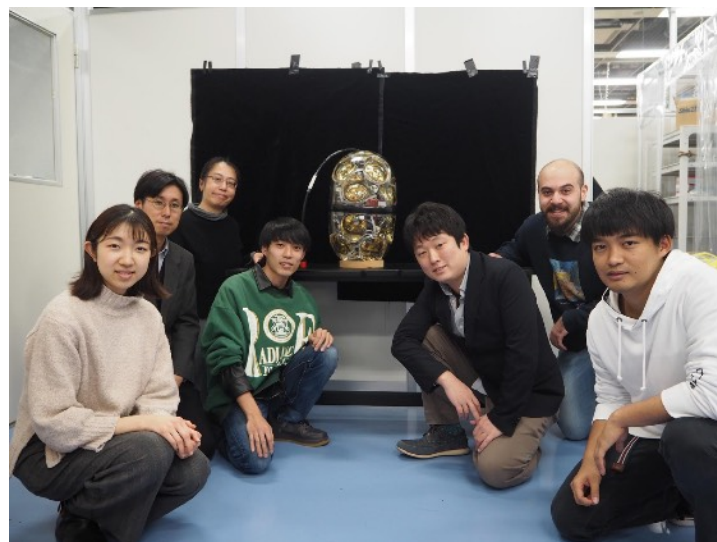
*Below: Time lapse of backfilling hollow pads with optical gel*

*Image Credit: Y. Makino/WIPAC*



# Gen2-DOM Expected Performance

- 4x the sensitivity of current IceCube DOMs
- All prototype modules have been constructed and passed final acceptance testing
- Prototype modules deployed in the Upgrade!
- Process to merge designs underway!

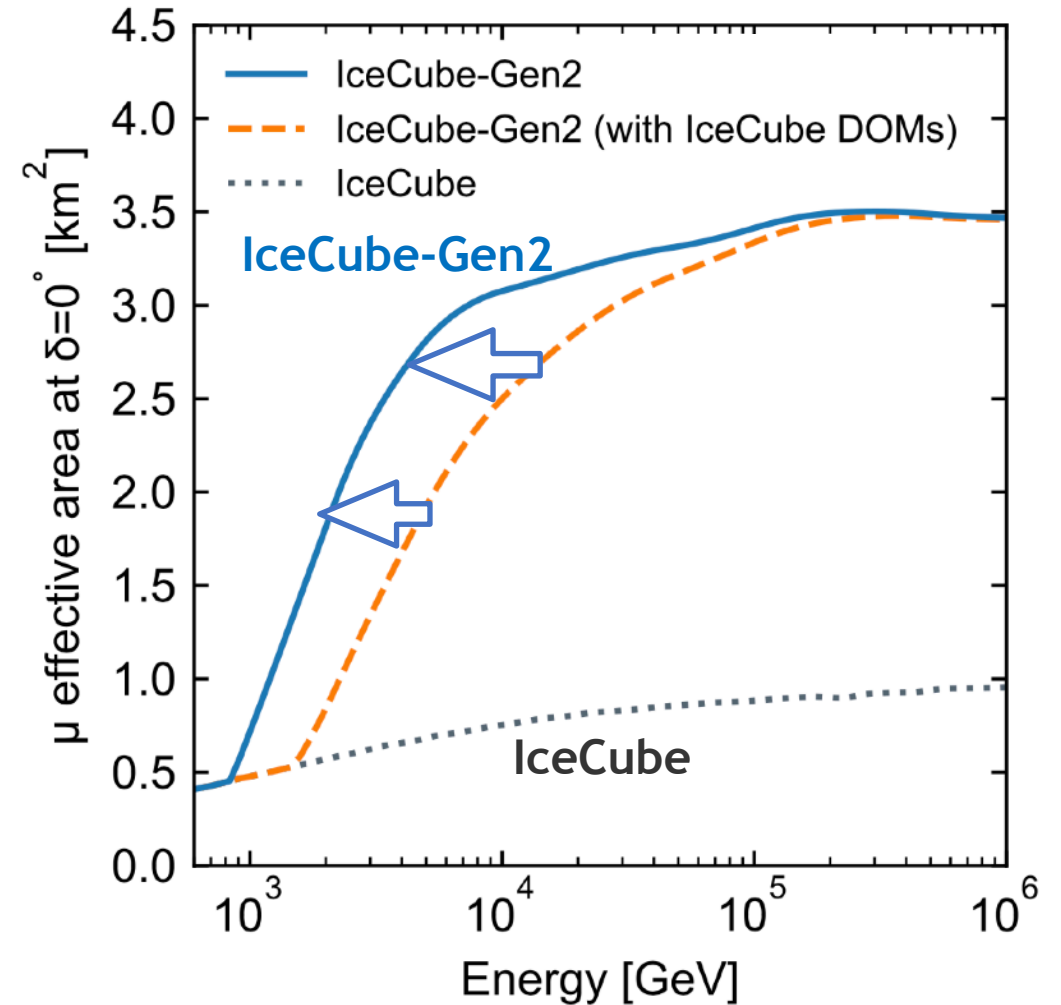
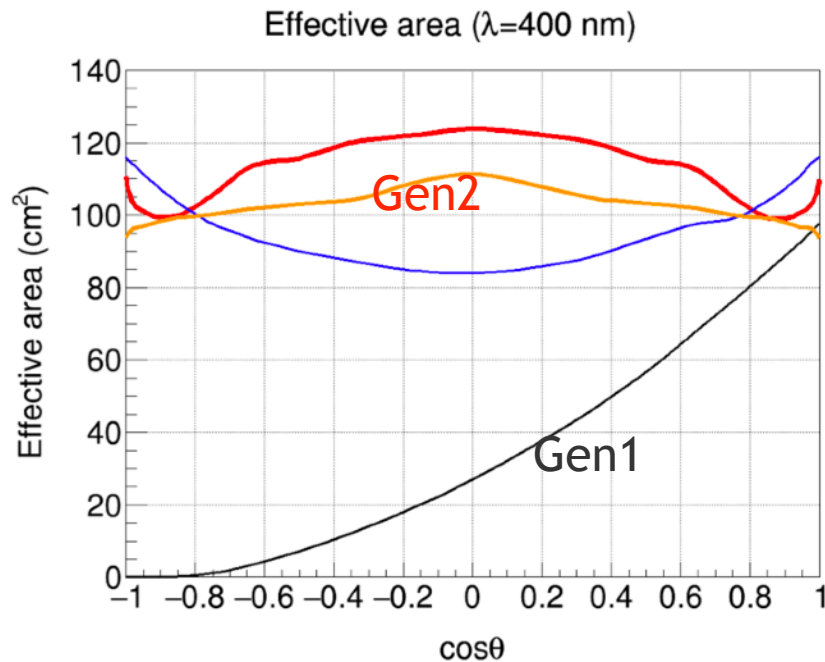


# Higher Sensor sensitivity $\rightarrow$ Larger Muon Effective Area

Factor 4 more photons detected

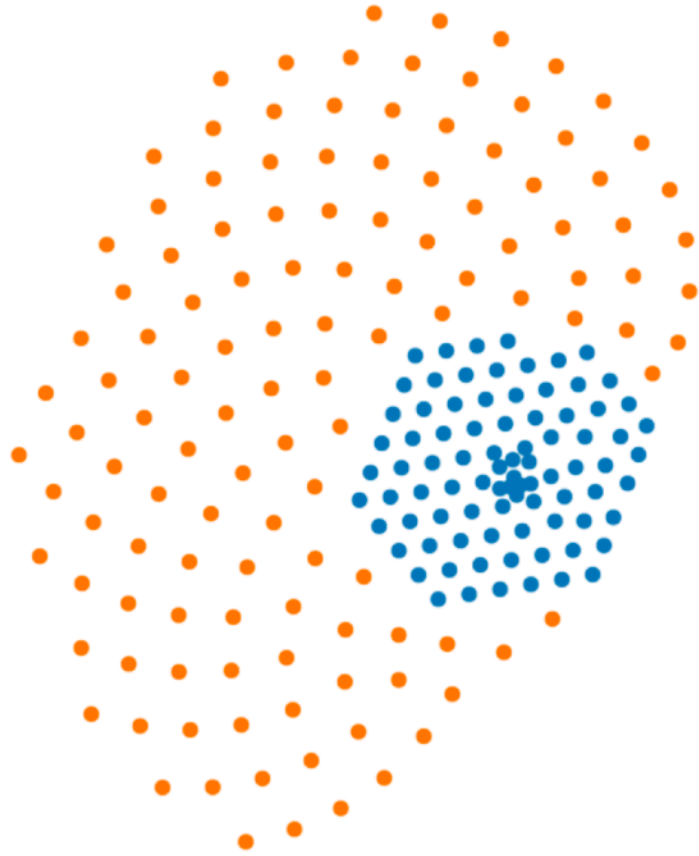
$\rightarrow$

- Lower energy threshold
- Angular resolution:  $0.1 - 0.3^\circ$



This plot was made using only a factor of 3 increased photodetection potential (photon effective area)

# IceCube-Gen2



Ideally, uniform spacing of sensors.

Drilling holes is much effort, therefore: strings.

Spacing:

Strings: 125 m  $\rightarrow$  240m

Sensors: 17 m  $\rightarrow$  17m, but factor 4 more sensitive.

How can that work?

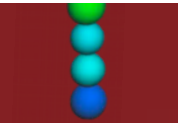
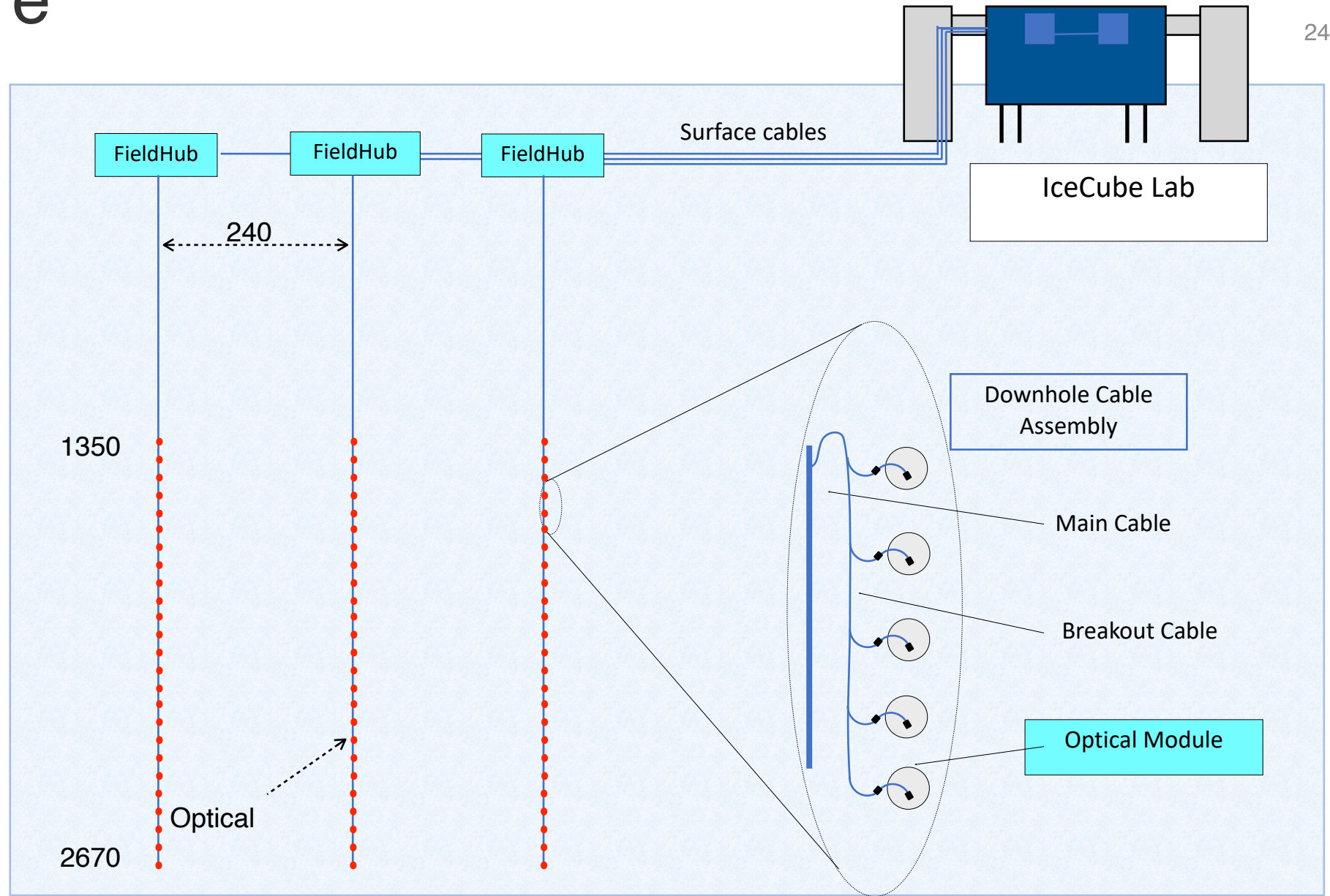


# Architecture

- Power and communications architecture: simplified requirements for cable hardware.

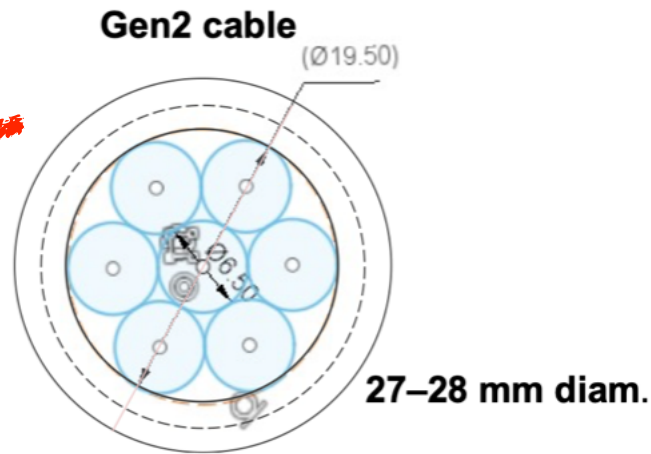
### Concept:

1. send trigger messages to surface (low rate)
2. store all signals on module for long time (1 week)
3. Request only signals that are associated with "events".
4. Save a factor 10 of

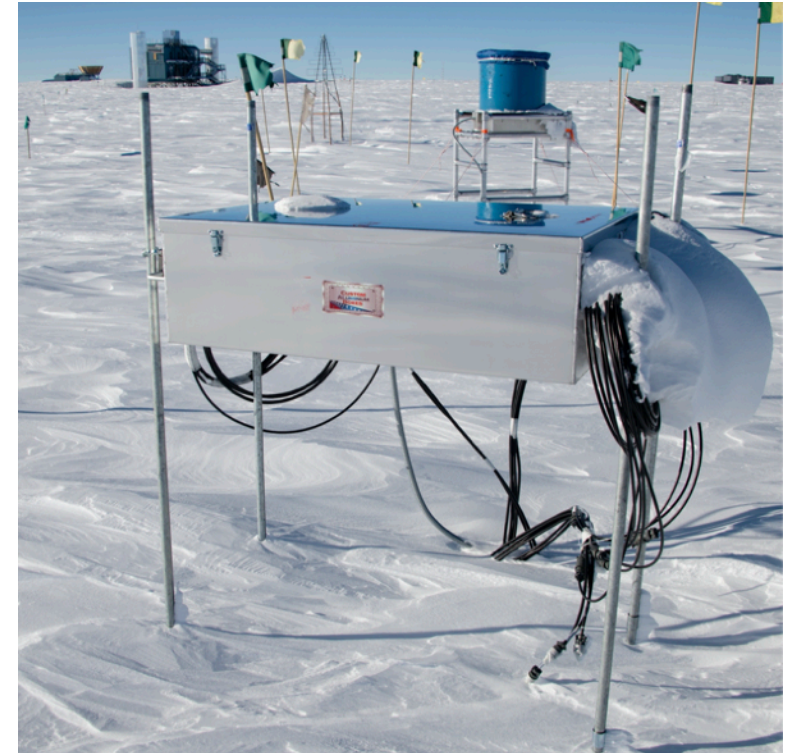


# Data acquisition and cables

Upgrade cable.



Gen2 Fieldhub



IceCube: 2 DOMs/wire pair

Upgrade: 3 DOMs / wire pair

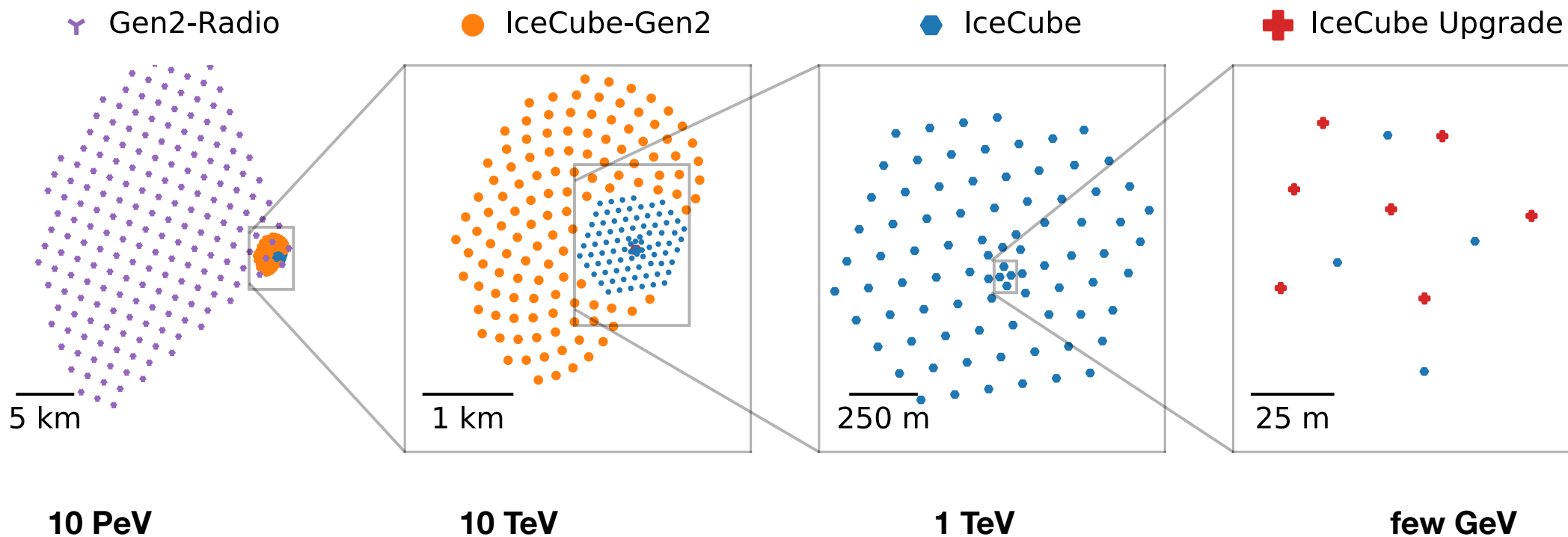
IceCube-Gen2: 6 Gen2-DOMs/wire pair (=18 x photo detection/wire pair)

This is possible due to a change in DAQ/trigger architecture:

Gen2 will not send all noise hits to the top.

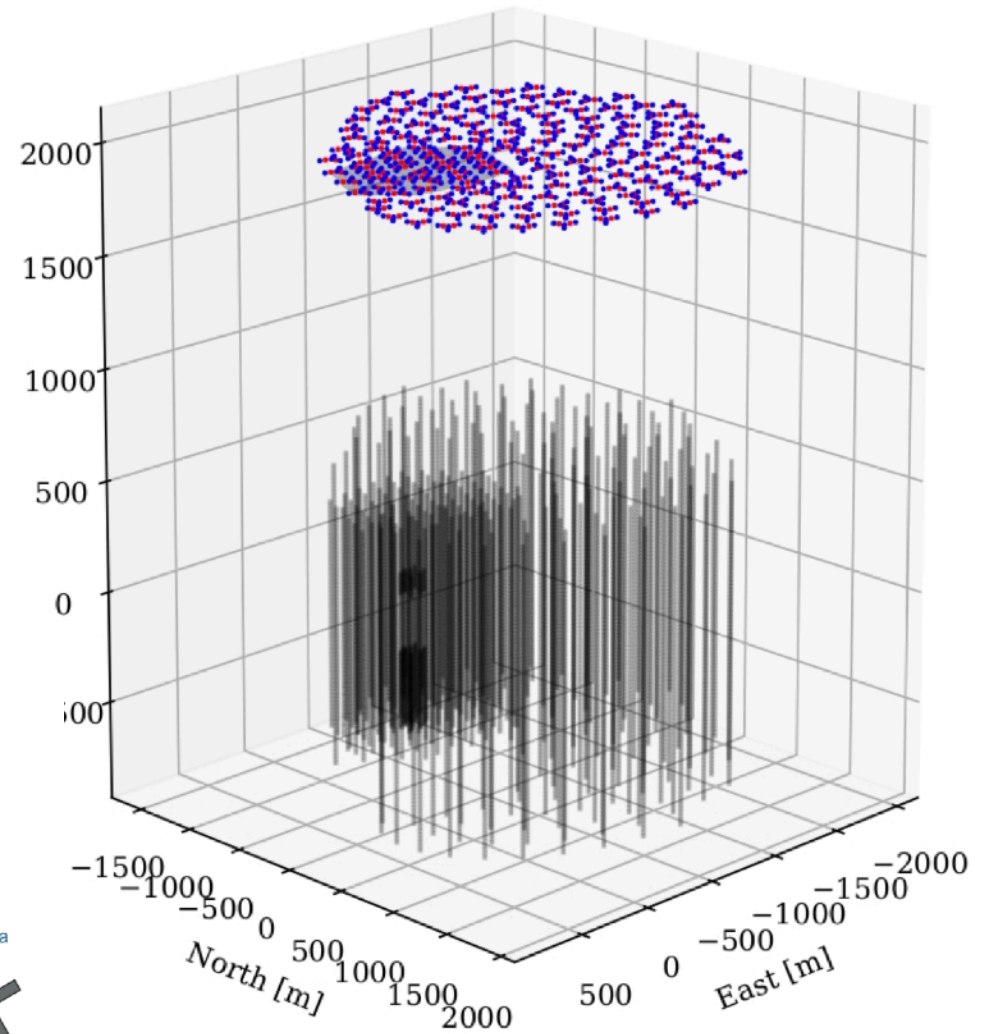
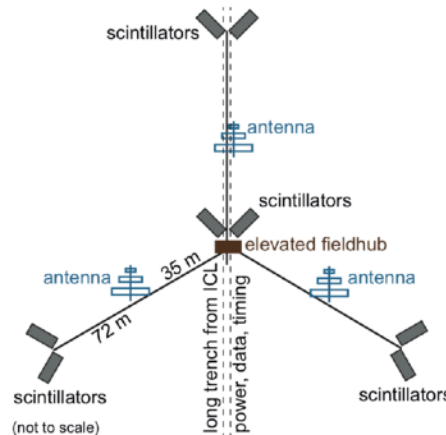
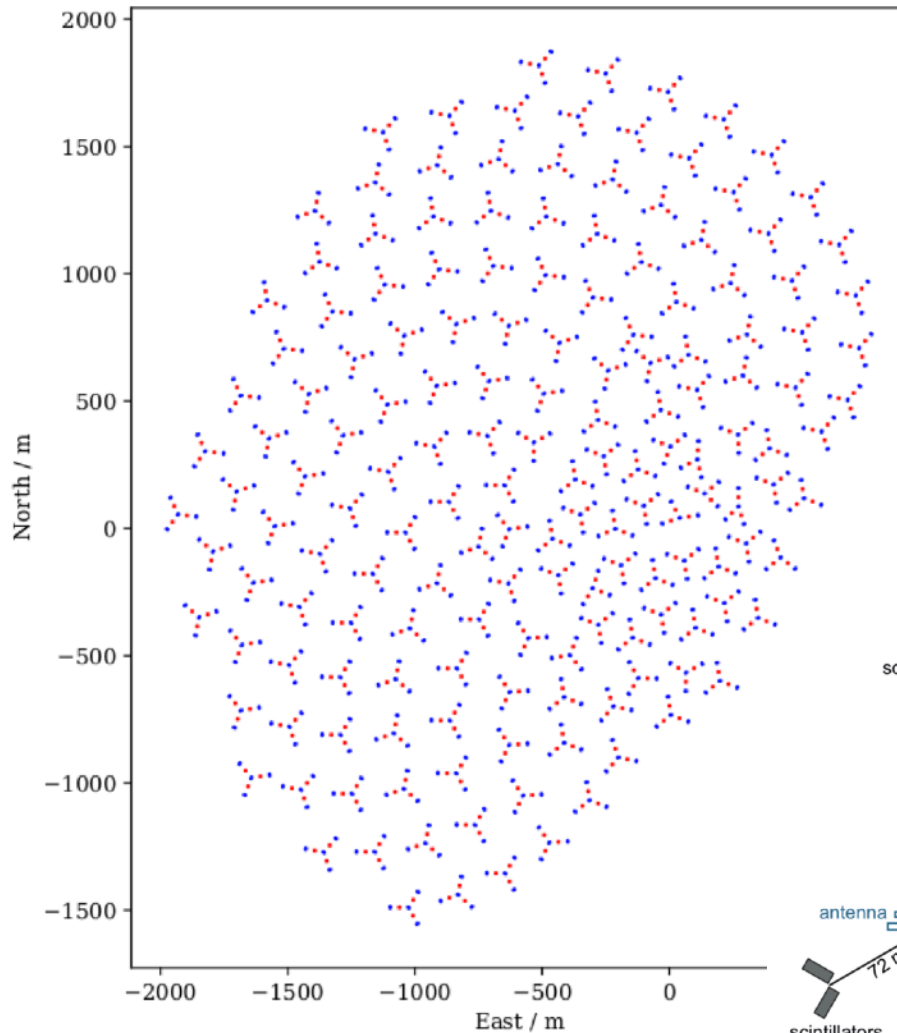
# IceCube-Gen2 — scope

IceCube and Gen2 on different scales reflecting different energies



# Surface detector Gen2

- Hybrid station (8 scintillators + 3 antennas) above each string → 122\* stations
- Optimised for orientation, gap stations

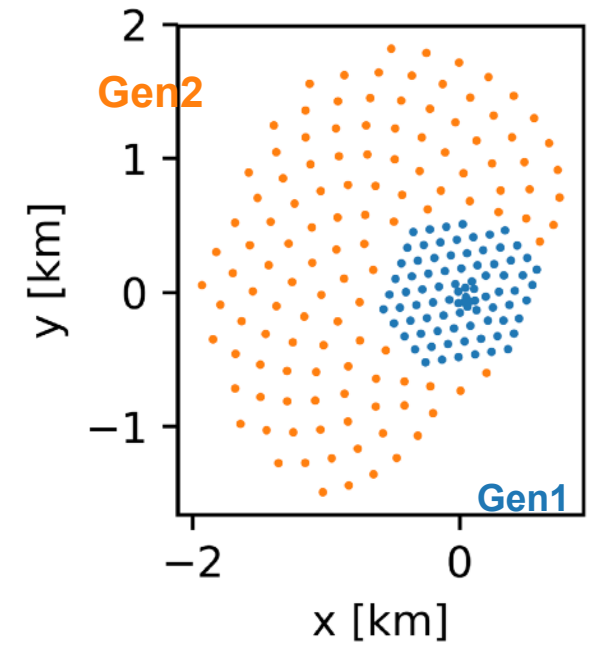
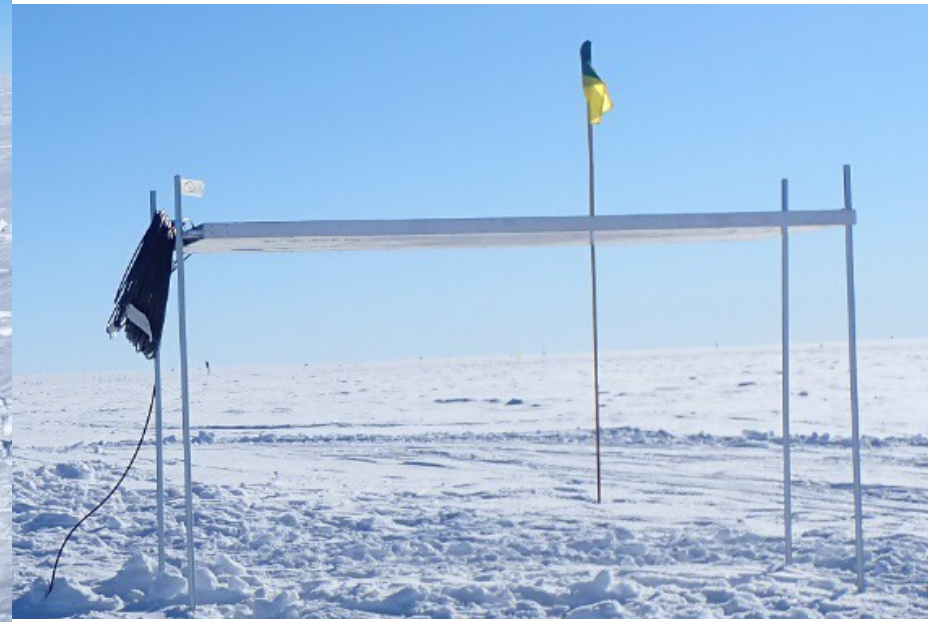
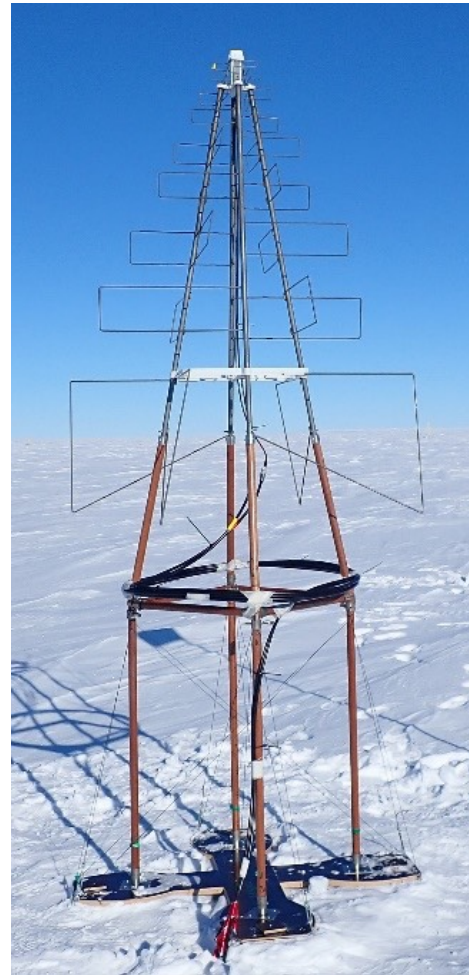
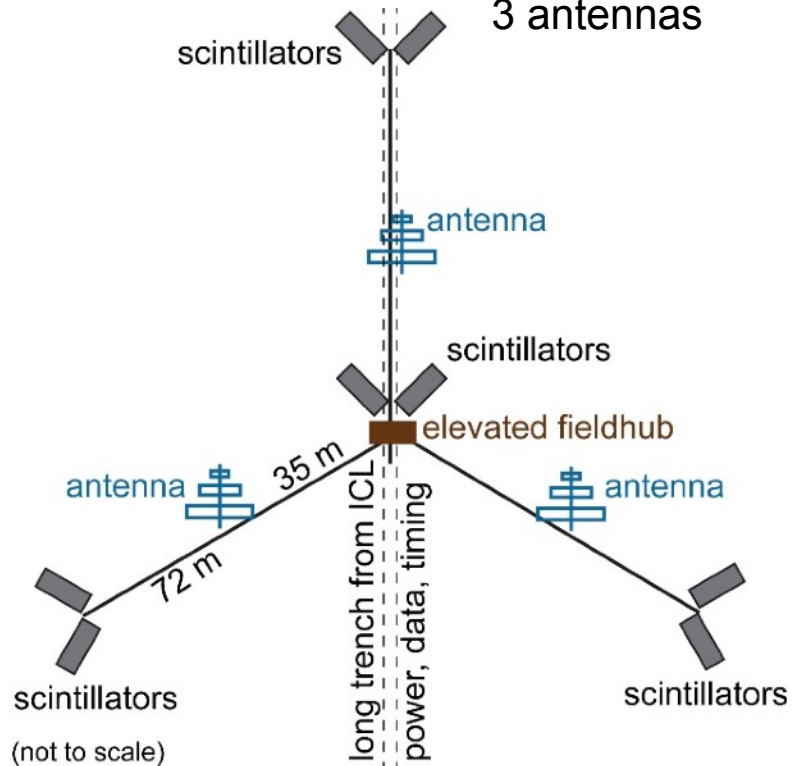


# Gen2 Surface Array

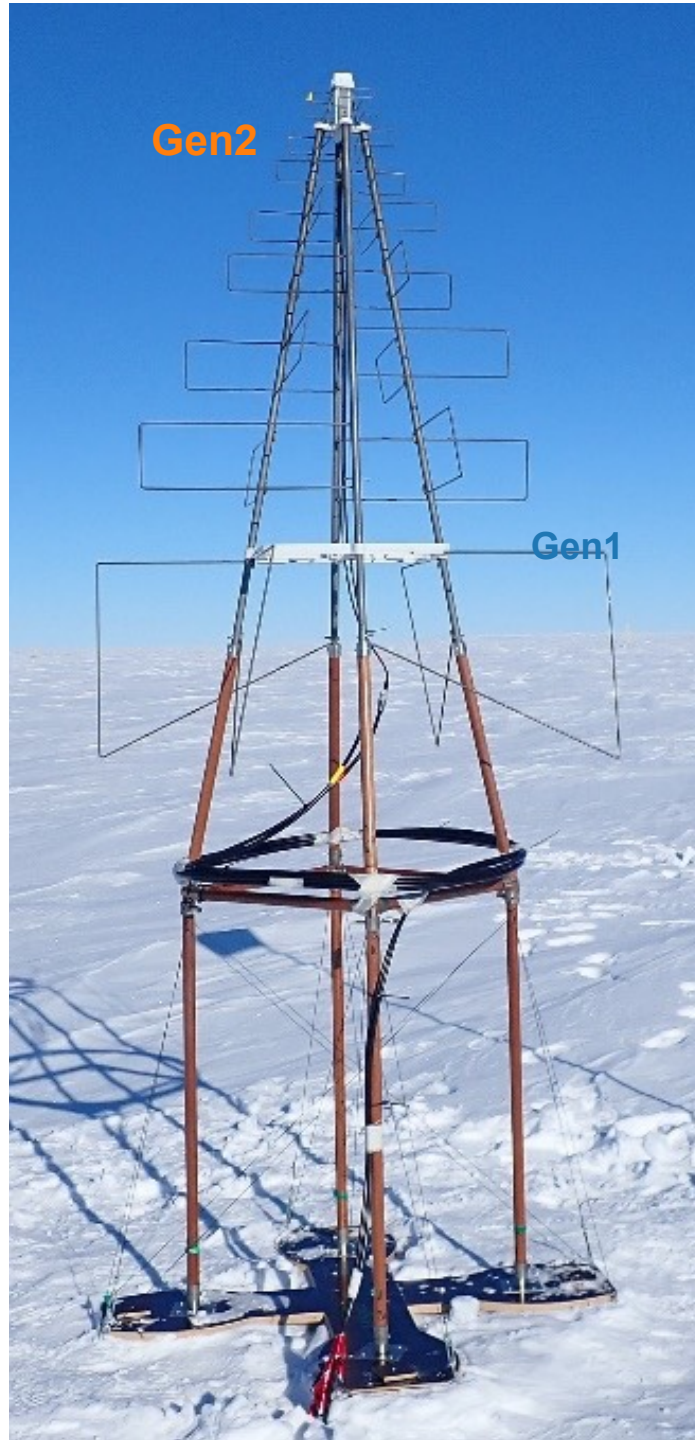
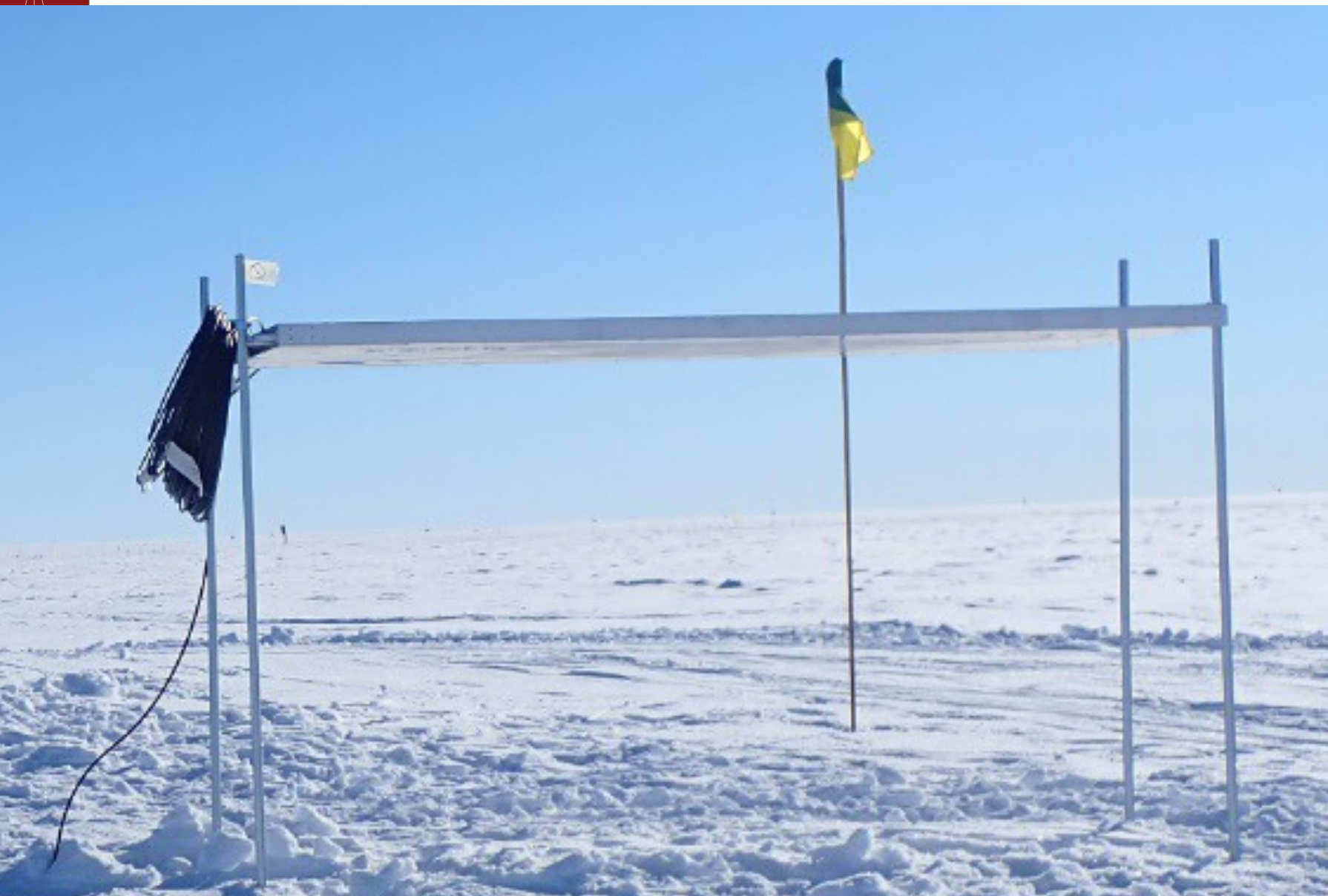
Baseline design extends the planned IceTop enhancement to footprint of the IceCube-Gen2 optical array

## Station Design:

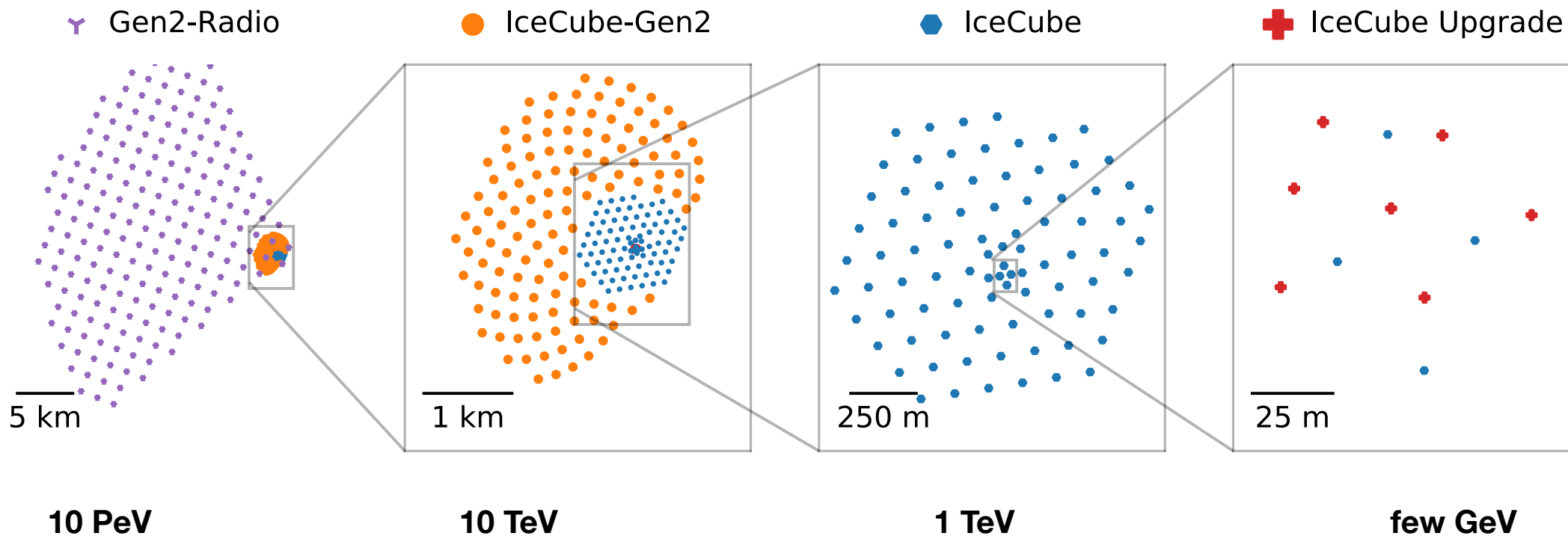
4 pairs of scintillators  
3 antennas



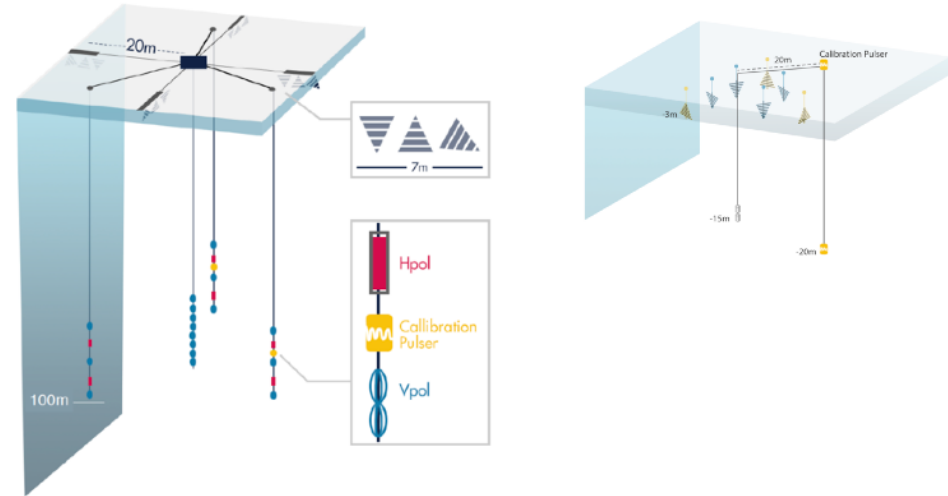
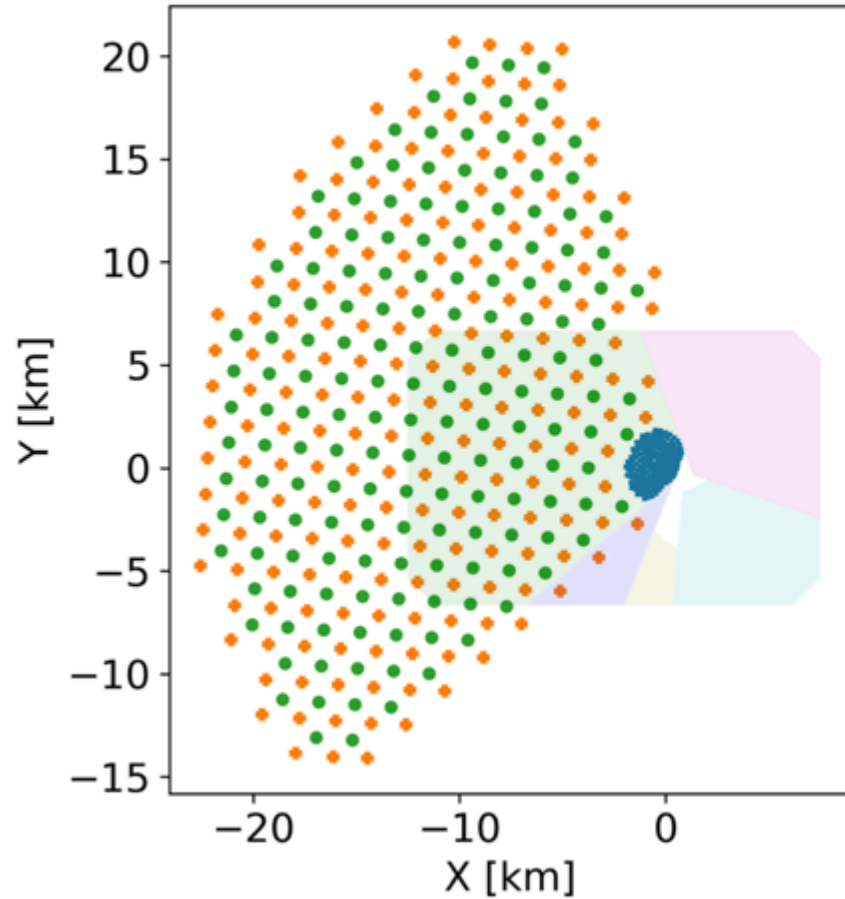
# Gen2 Surface Array



# IceCube-Gen2 — scope



# The Gen2 radio array - options considered



Area:  $500 \text{ km}^2$

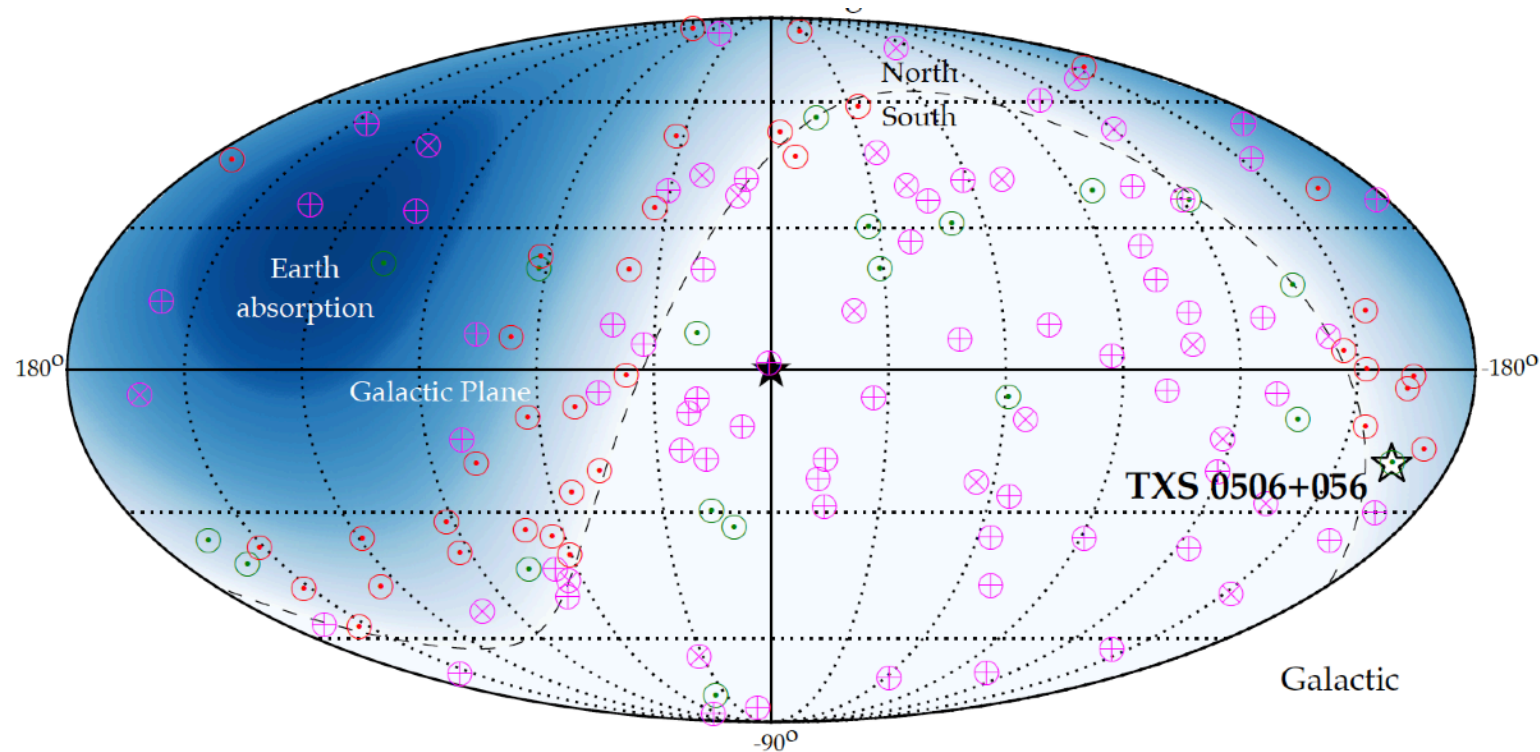
300 stations

$1000 \text{ km}^3$  of ice volume

How will IceCube-Gen2 science compare to IceCube?

# Scientific objectives: building on 10 yrs of IceCube 33

Resolving the high-energy sky from TeV to EeV energies

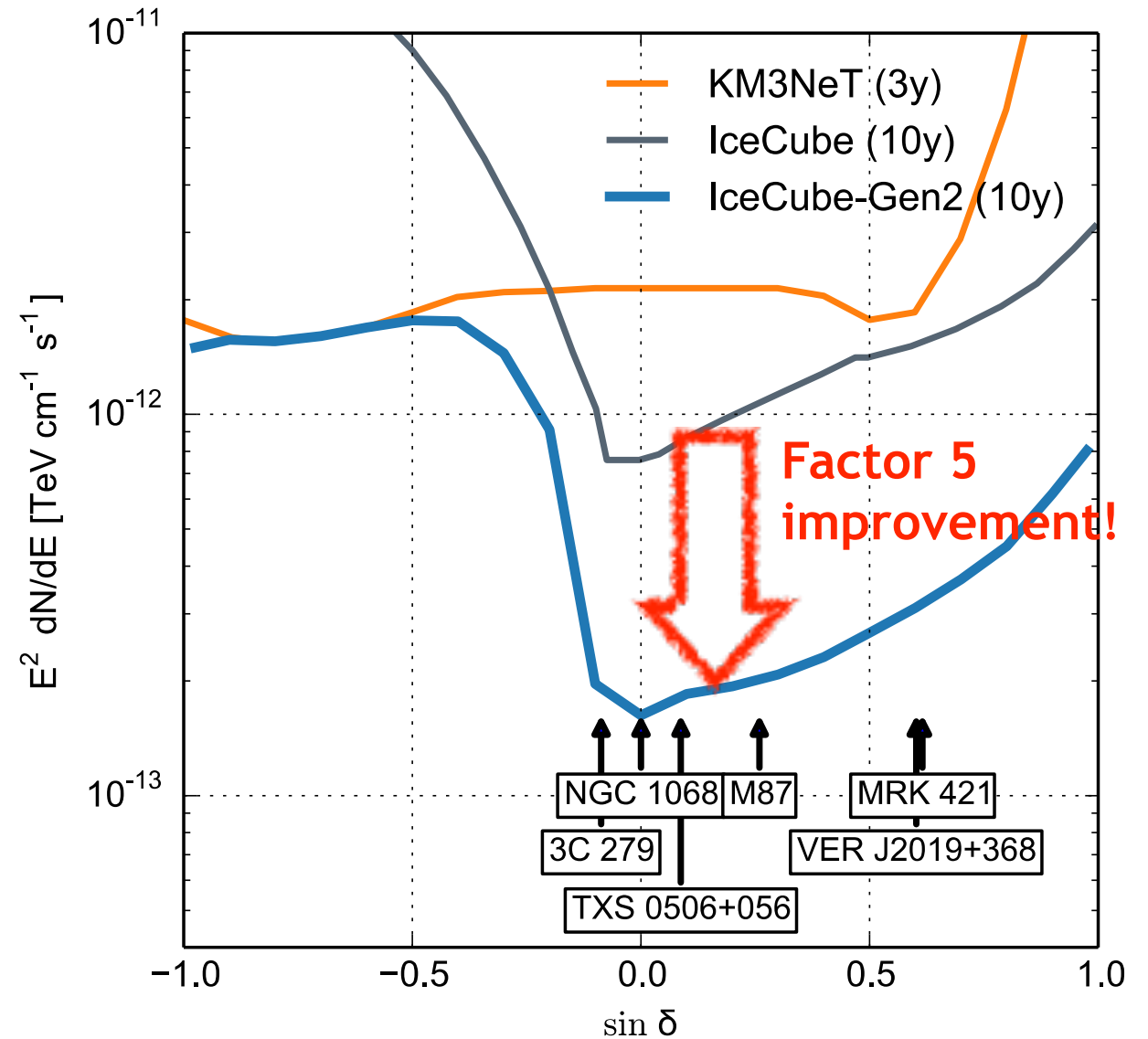


What are the sources of IceCube's high energy neutrinos?

# Understanding cosmic particle acceleration through multimessenger observation

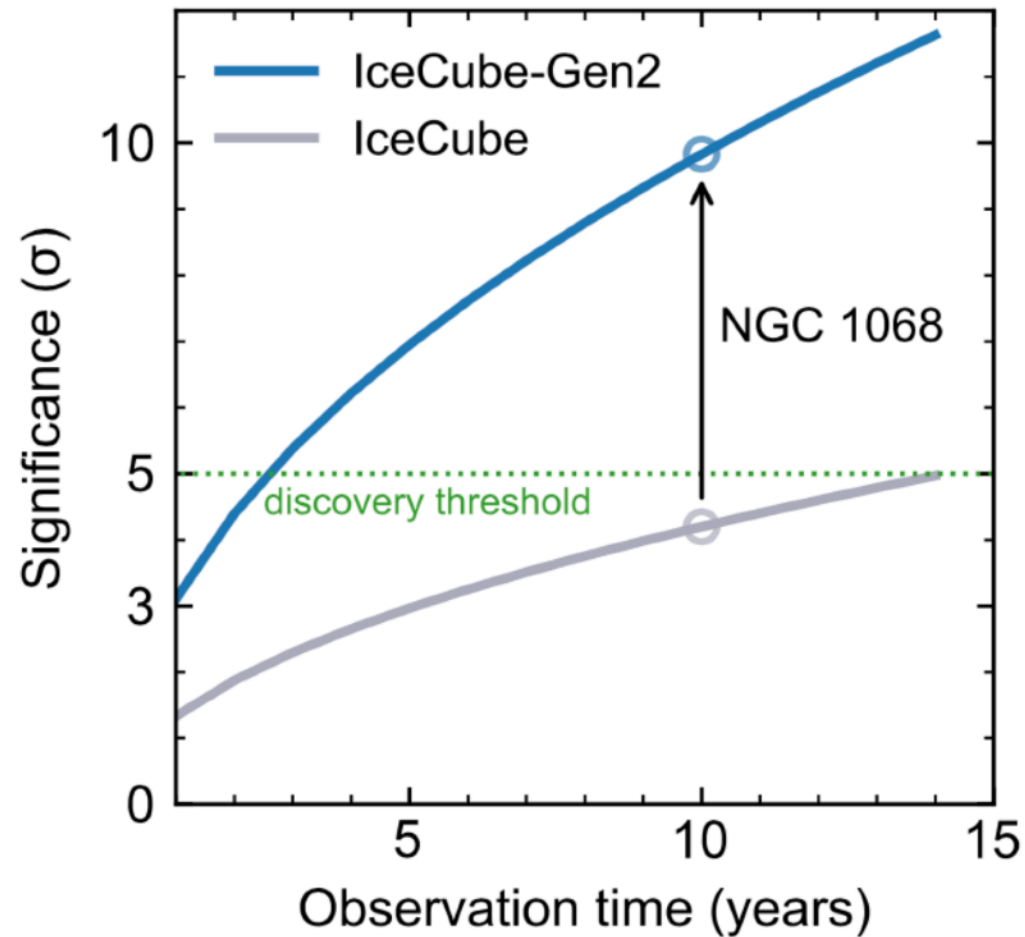
## Pointsources sensitivity

Sensitivity to all realistic source populations (steady and transient) explaining the diffuse flux



# How would NGC 1068 look in IceCube-Gen2?

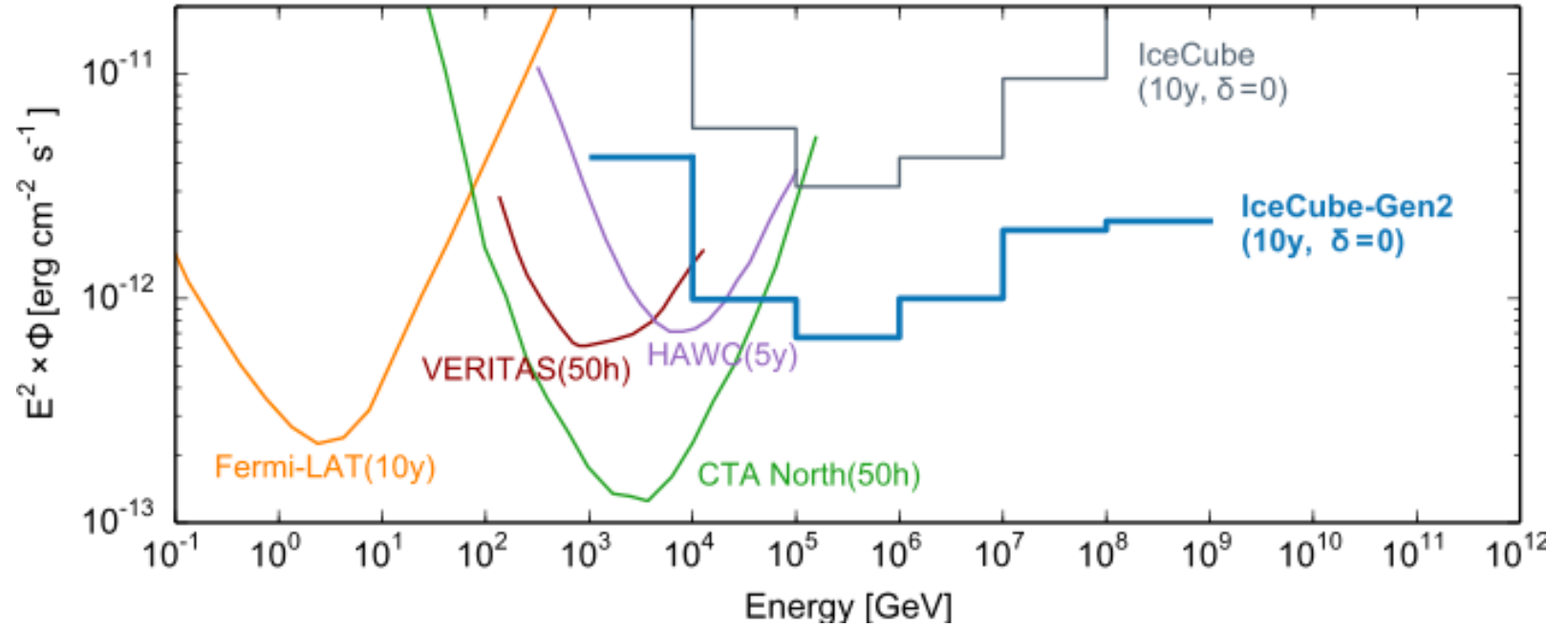
*5 sigma in < 2 years  
10 sigma in 10 years.*



# Understanding cosmic particle acceleration through multimessenger observation

Pointsources sensitivity

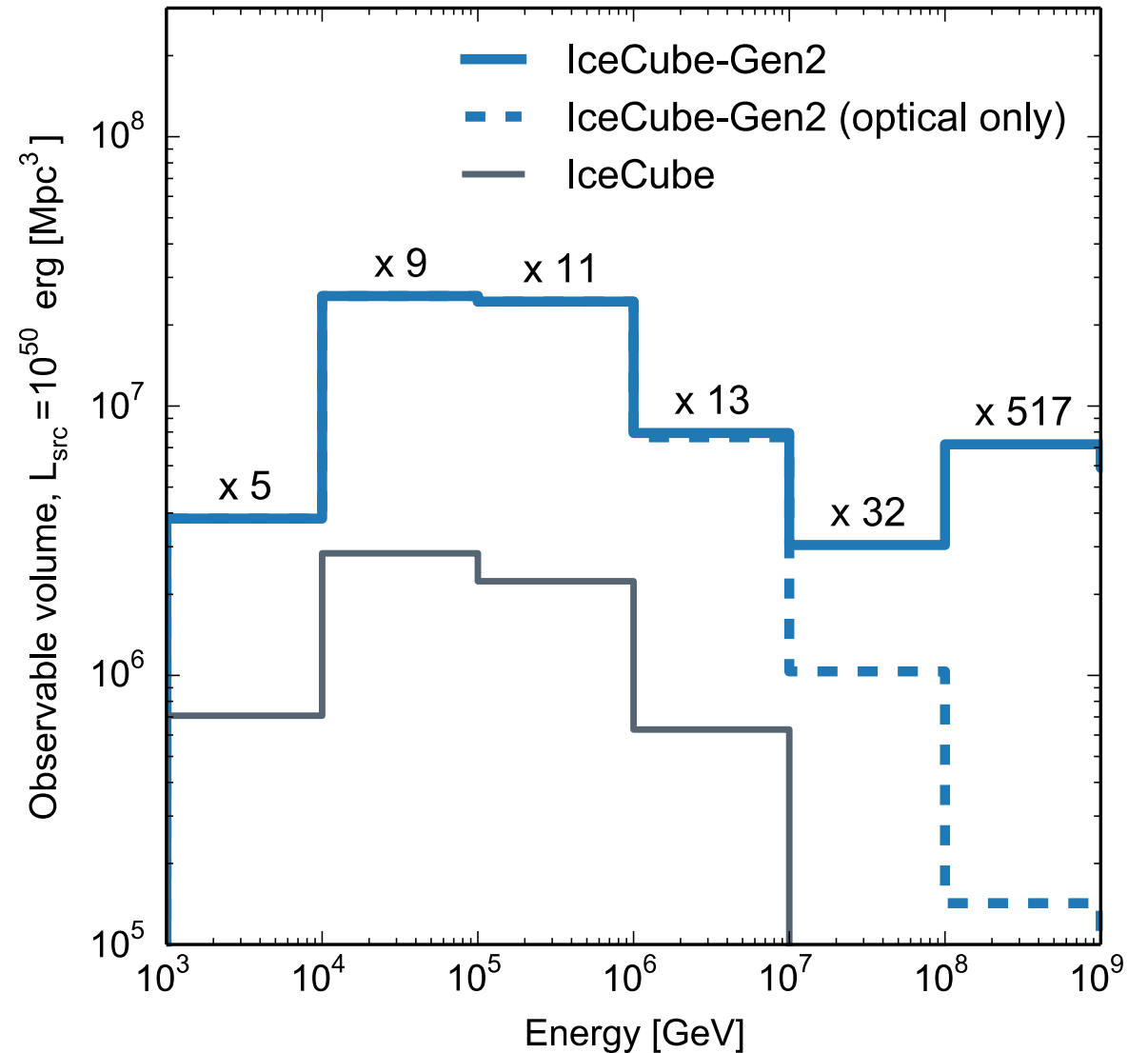
Completing the multi-wavelength view of the Universe



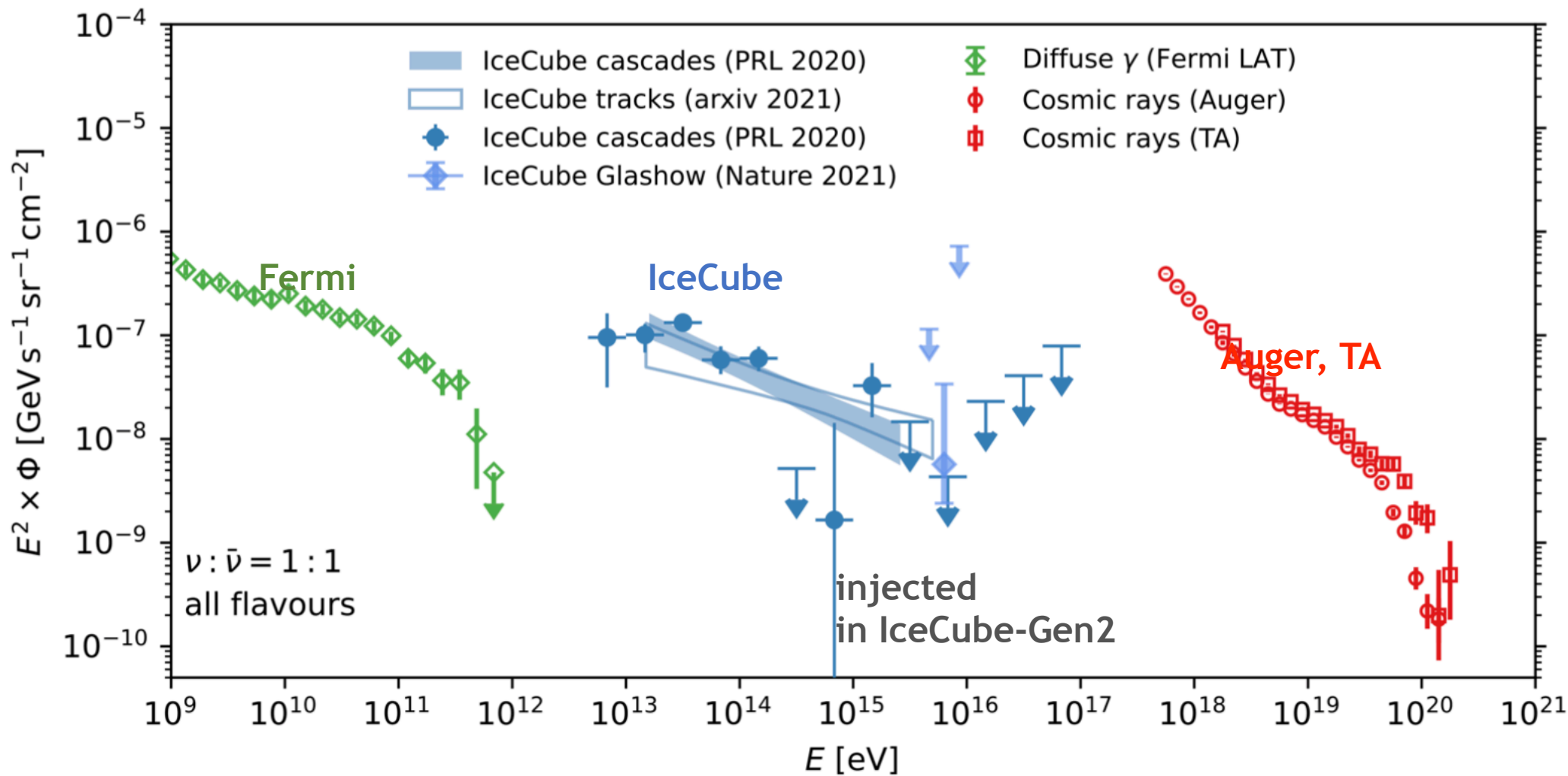
# Observable volume with IceCube-Gen2

Expand energy range to beyond  $10^{18}$  eV with sensitivity improved by two orders of magnitude

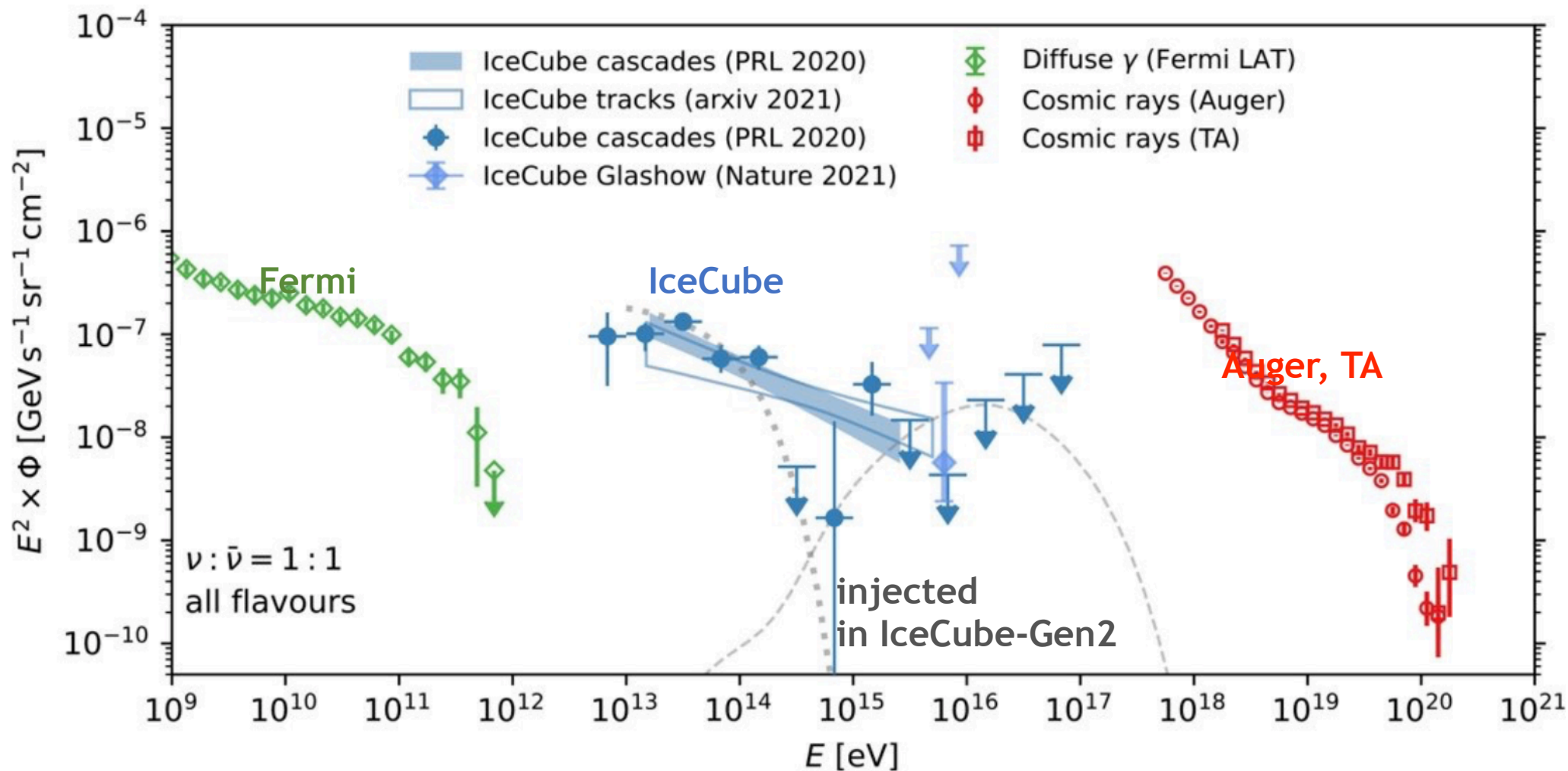
Uniform sensitivity over a large energy range, over more than 6 orders of magnitude.



# Understanding cosmic particle acceleration through multimessenger observation

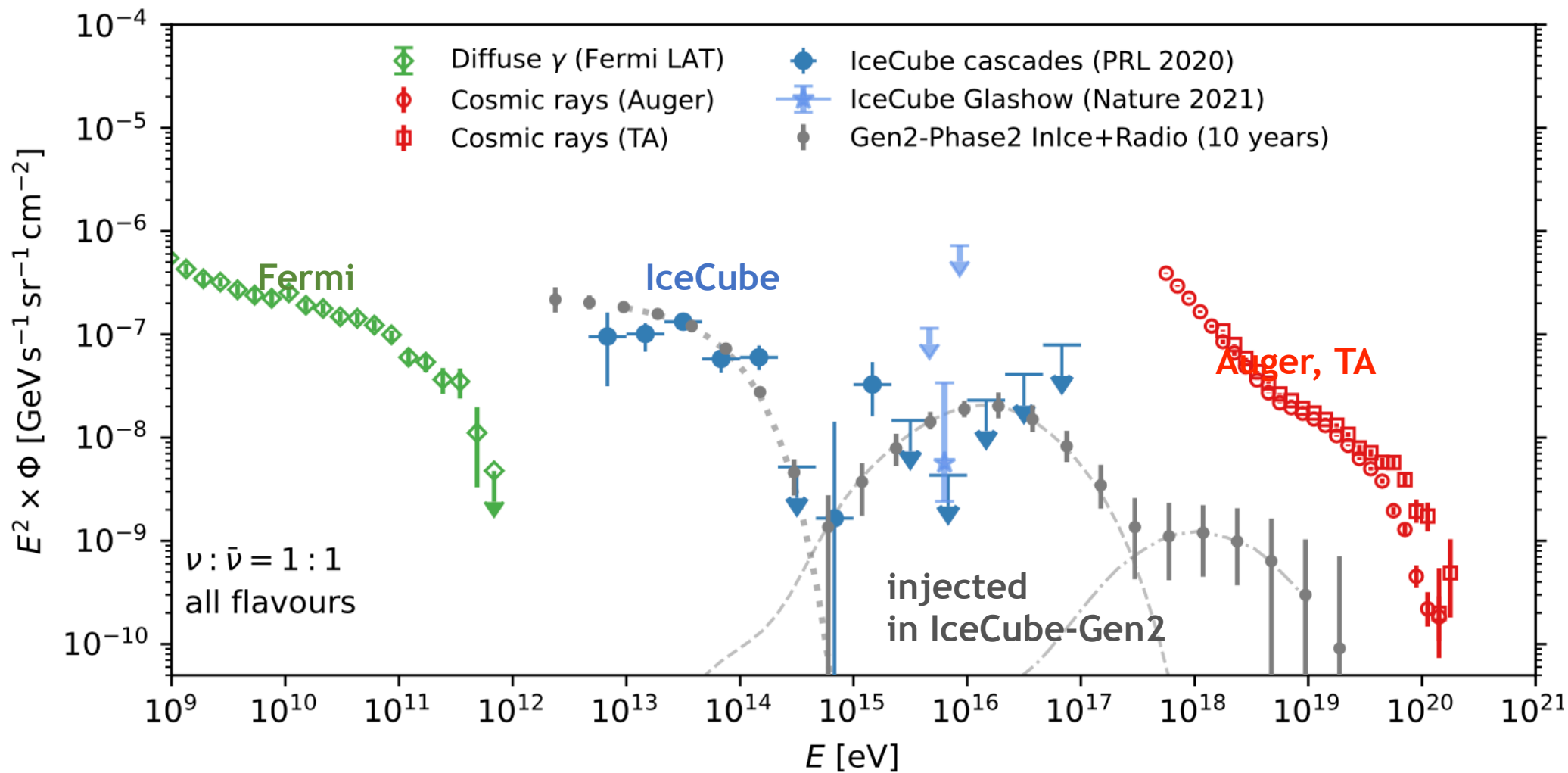


# Understanding cosmic particle acceleration through multimessenger observation



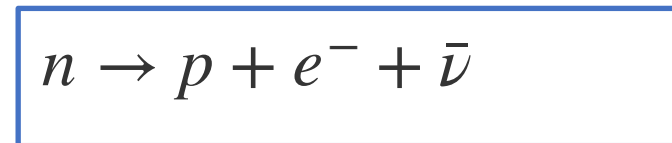
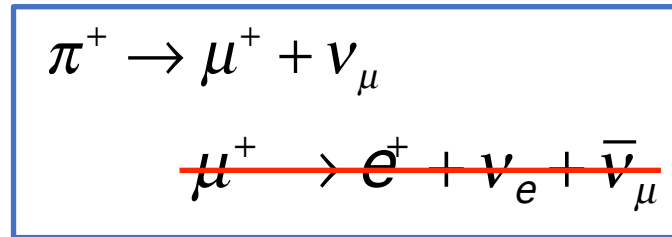
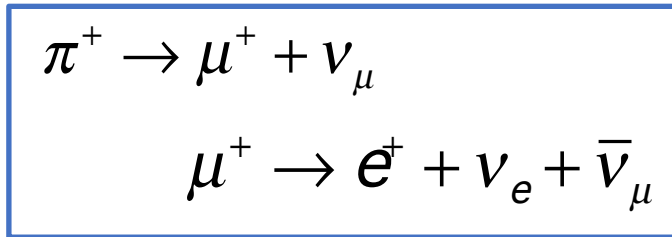
A common origin with UHECR?

# Understanding cosmic particle acceleration through multimessenger observation



# Neutrino production mechanisms with cosmic rays: Accelerate protons and have them interact.

Result: Pions and other stuff

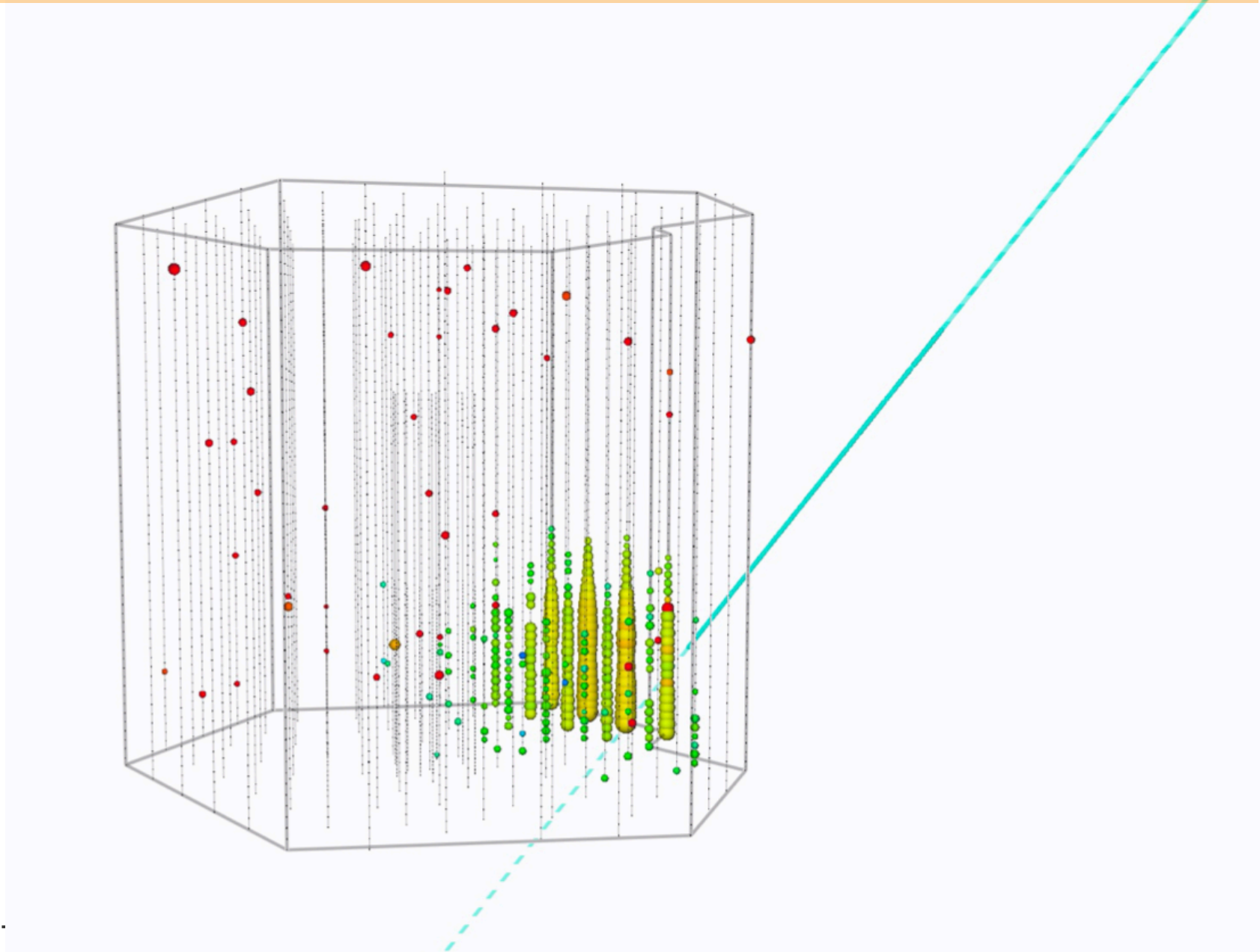


- $\pi$  decay:  $(1 : 2 : 0)_{\text{Source}}$
- $\mu$ -damped:  $(0 : 1 : 0)_{\text{Source}}$
- ▲  $n$  decay:  $(1 : 0 : 0)_{\text{Source}}$

We will be able to infer the flavor composition at the source.



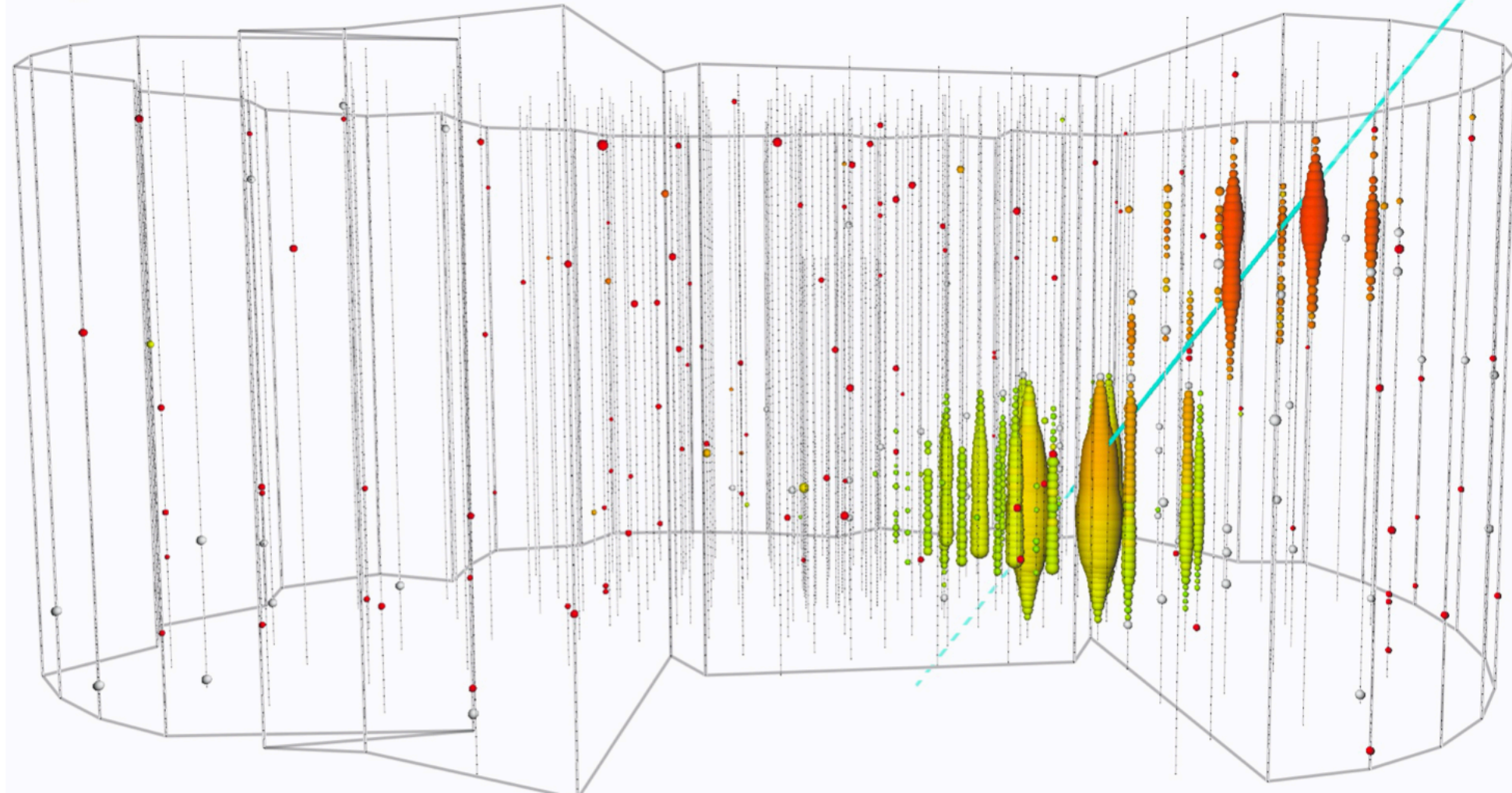
# 1 simulated event in IceCube - what is it?



Currently: have ~2 events at the 100'

# The same event in IceCube-Gen2

Size - Contained Volume matters.



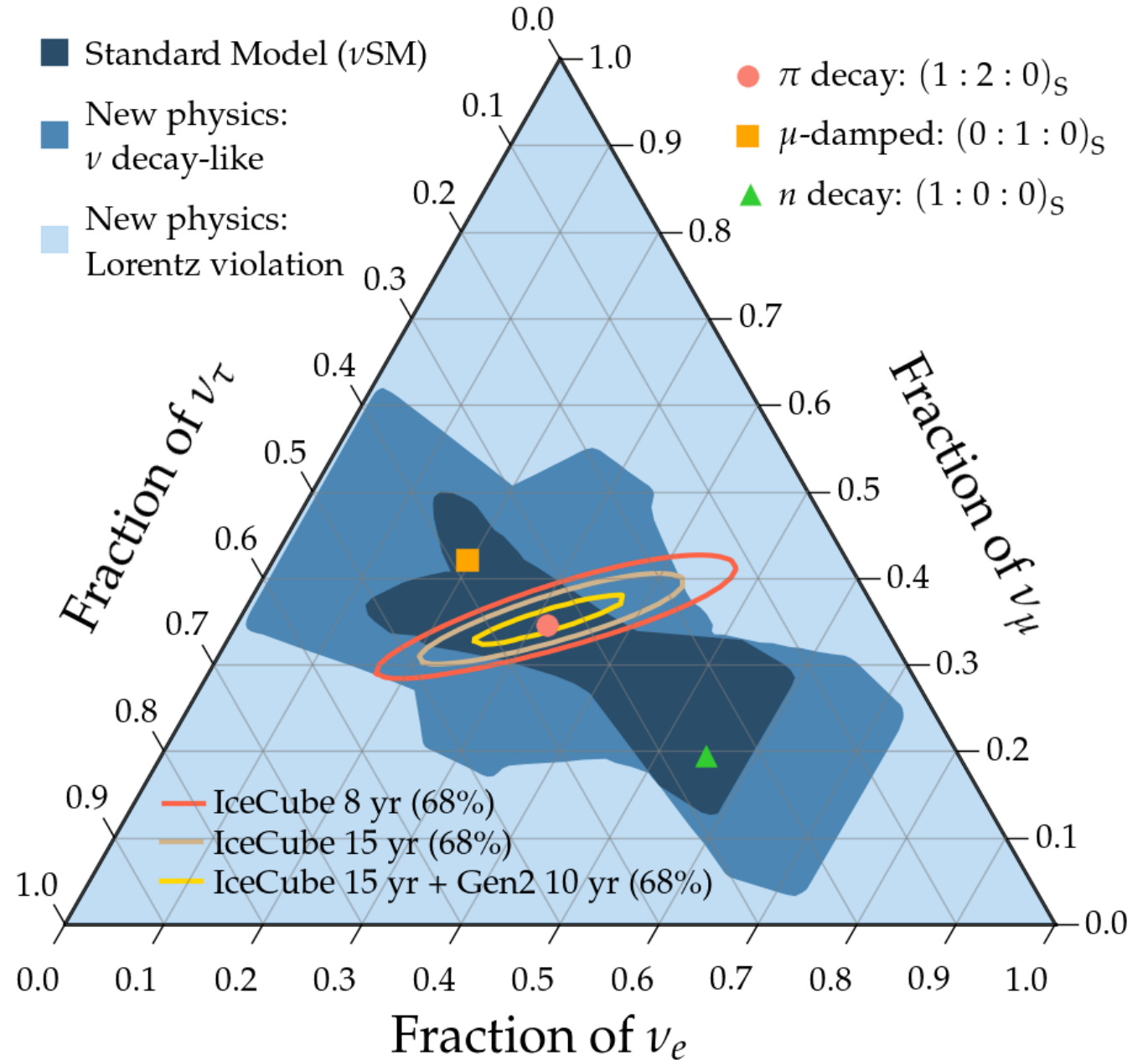
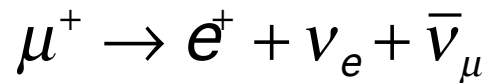
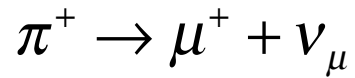
Currently: have ~2 events at the 100 TeV energy scale

credit.: Lu Lu, IceCube

# Probing fundamental physics with high-energy neutrinos

Probing neutrino oscillations over cosmic baselines

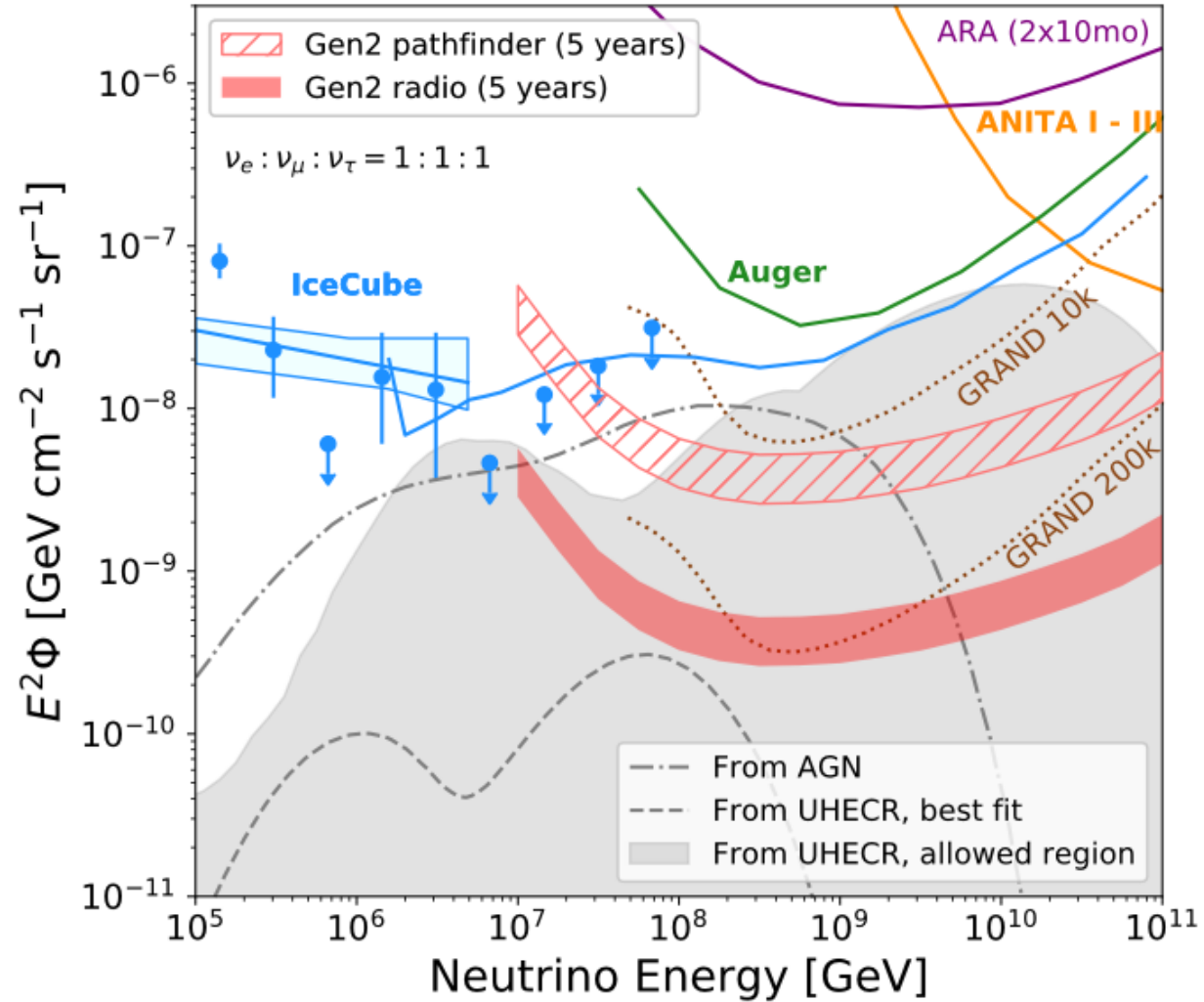
We can infer the neutrino composition at their cosmic origin.

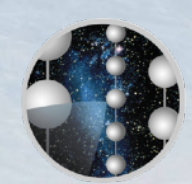


# Revealing the sources and propagation of the highest energy particles in the universe

The radio array will have unprecedented sensitivity at energies above 1E17 eV.

Abby's talk on radio detection.





Hose reel

Mobile drill/deployment towers

EHWD heating plant: stationary  
—> Gen2: mobile

# Current Status:

Received very good recommendations by National reviews (Astro2020 and Snowmass/P5)

A lot of momentum internationally.

IceCube Upgrade, 6 (5) strings successfully deployed 2025/26.

Good basis to get started in earnest within 3 or 4 years.

# THE

The  
High-energy  
IceCube of the  
Next  
Generation



—> IceCube-Gen2

**THE**

The

High-energy

IceCube of the

Next

Generation



—> IceCube-Gen2