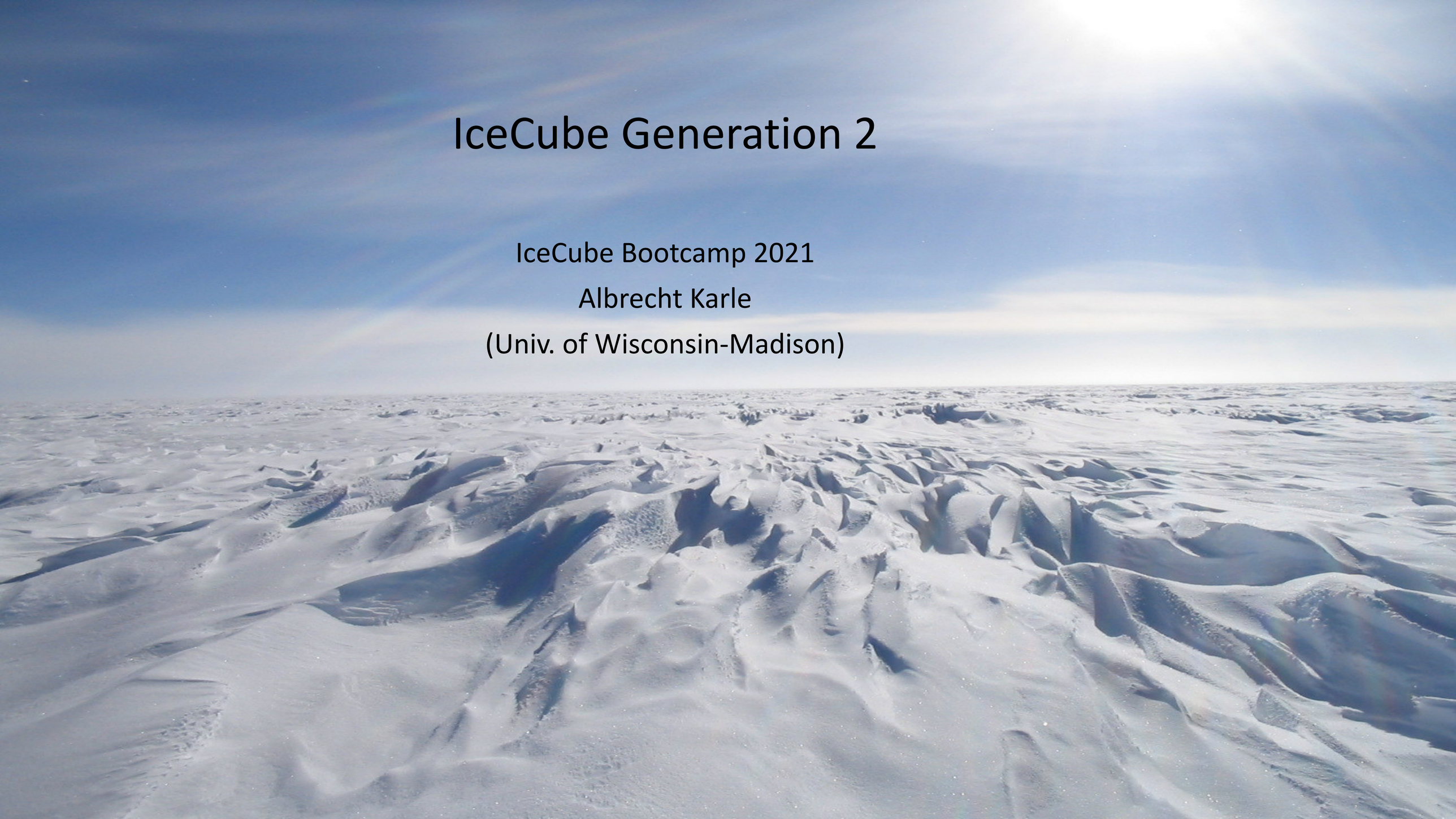


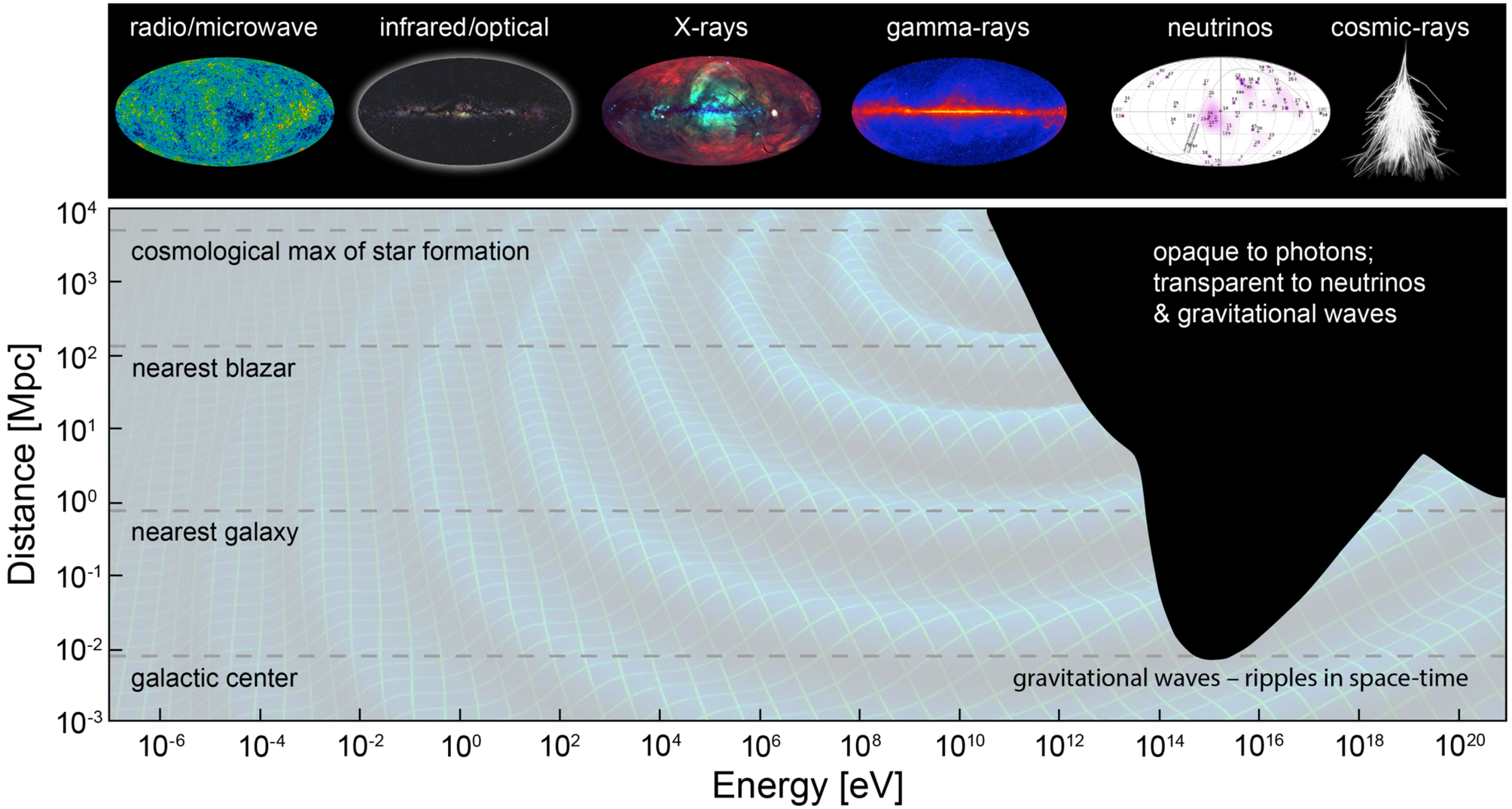
IceCube Generation 2

IceCube Bootcamp 2021

Albrecht Karle

(Univ. of Wisconsin-Madison)

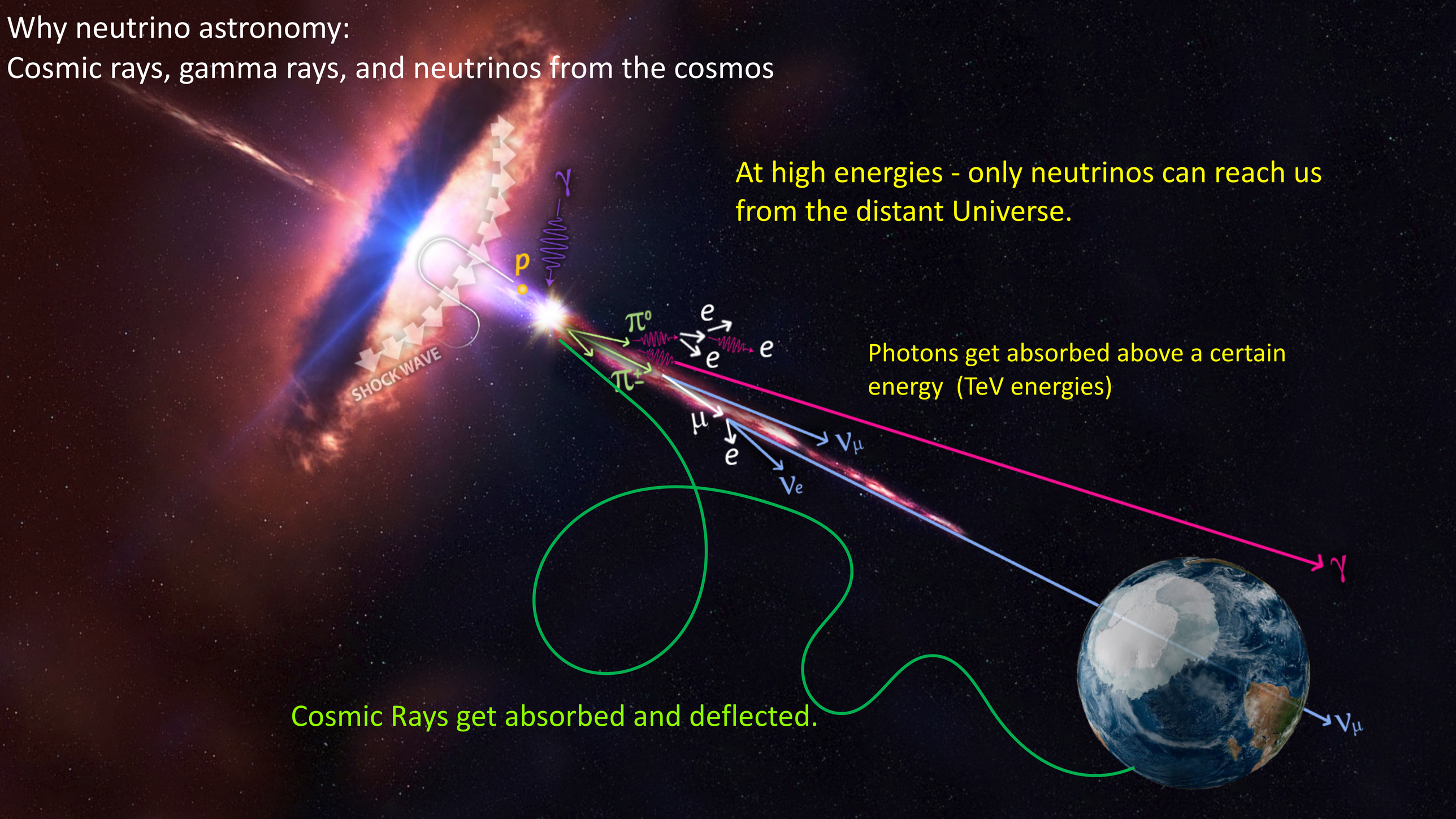
The energy frontier in astronomy



Universe opaque to photons for ¼ of the spectrum

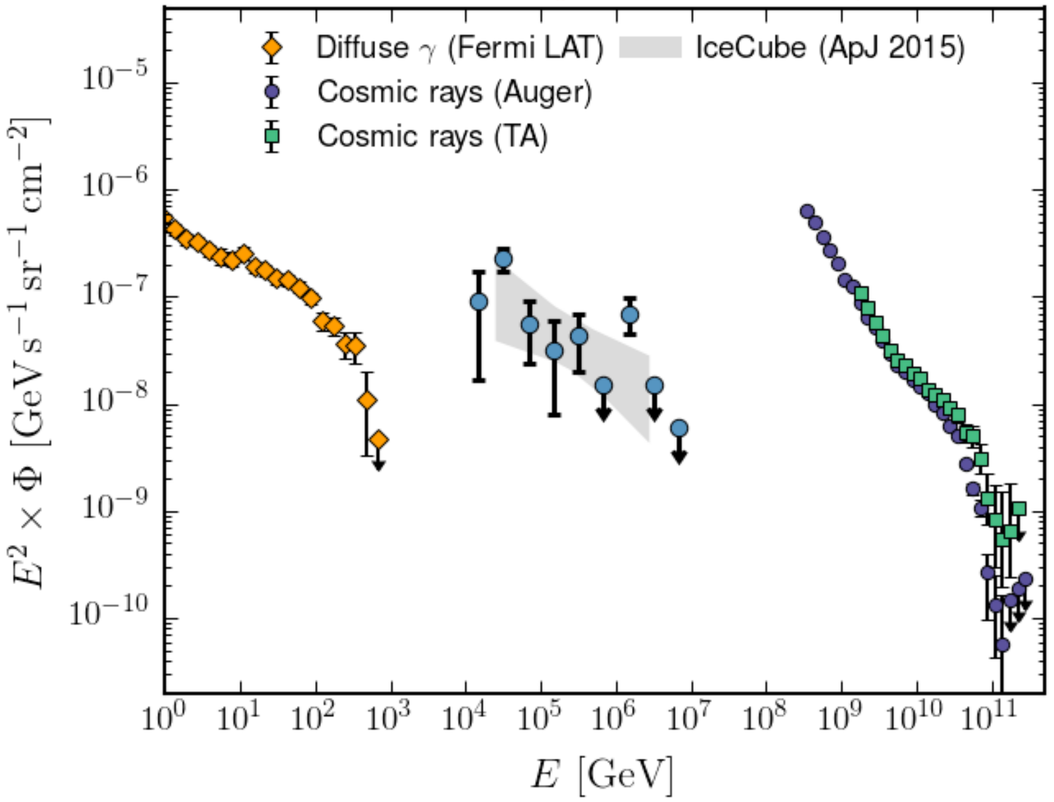
IceCube GEN2

Why neutrino astronomy:
Cosmic rays, gamma rays, and neutrinos from the cosmos

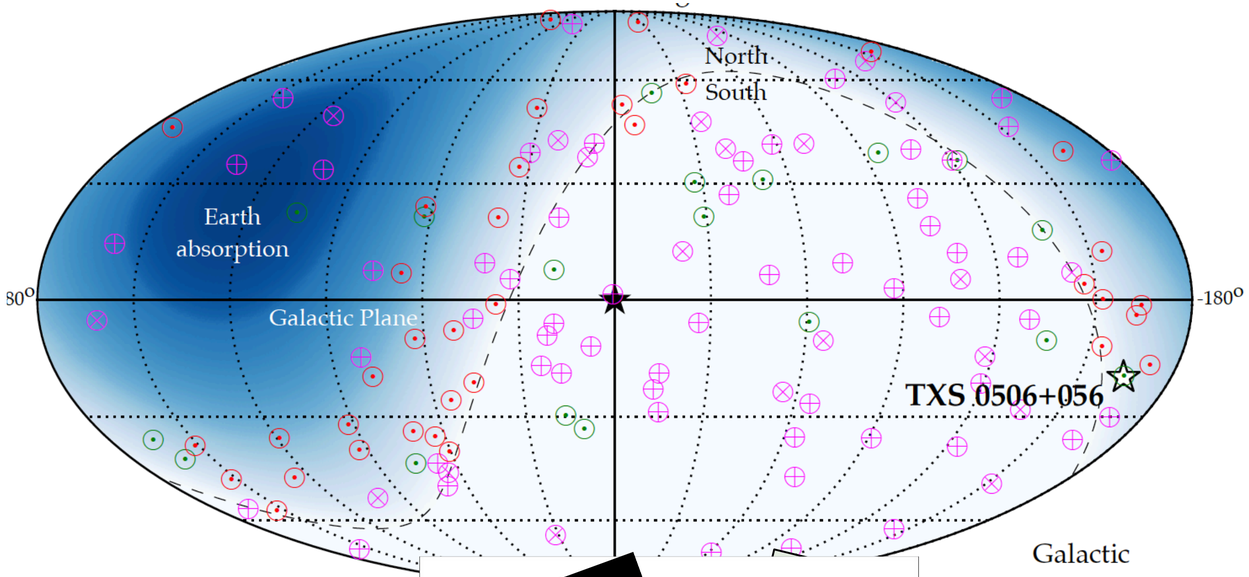


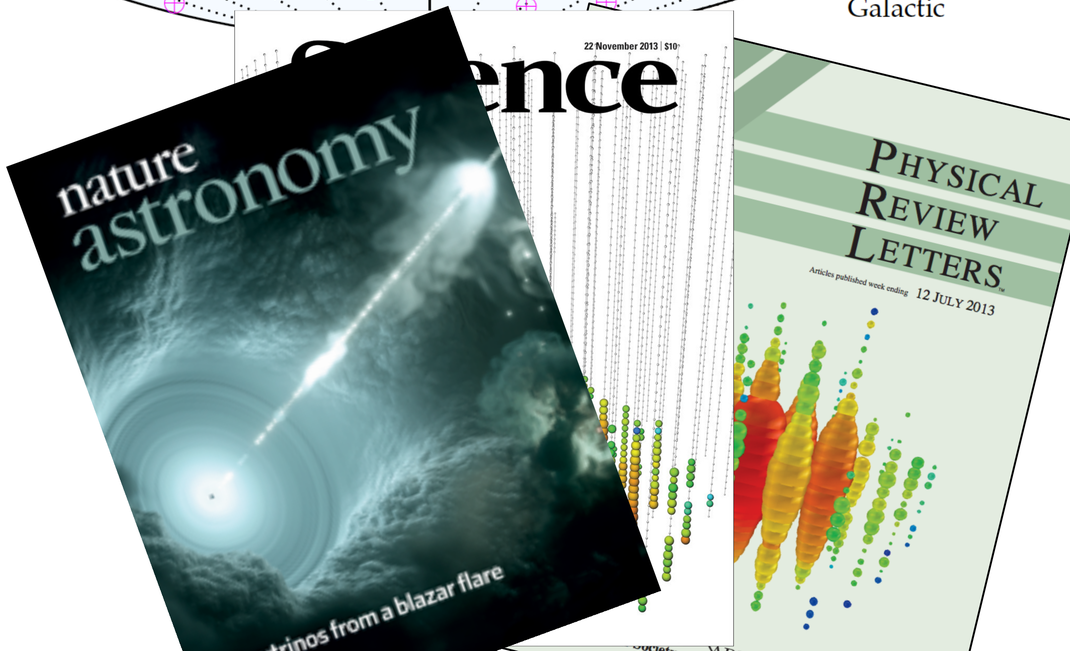
10 yrs of IceCube - a first view on the PeV Universe

Multimessenger spectroscopy



First sky map of cosmic neutrinos





Some highlights:

2013: Discovery of cosmic PeV neutrino flux

2018: Evidence for Blazars as neutrino sources

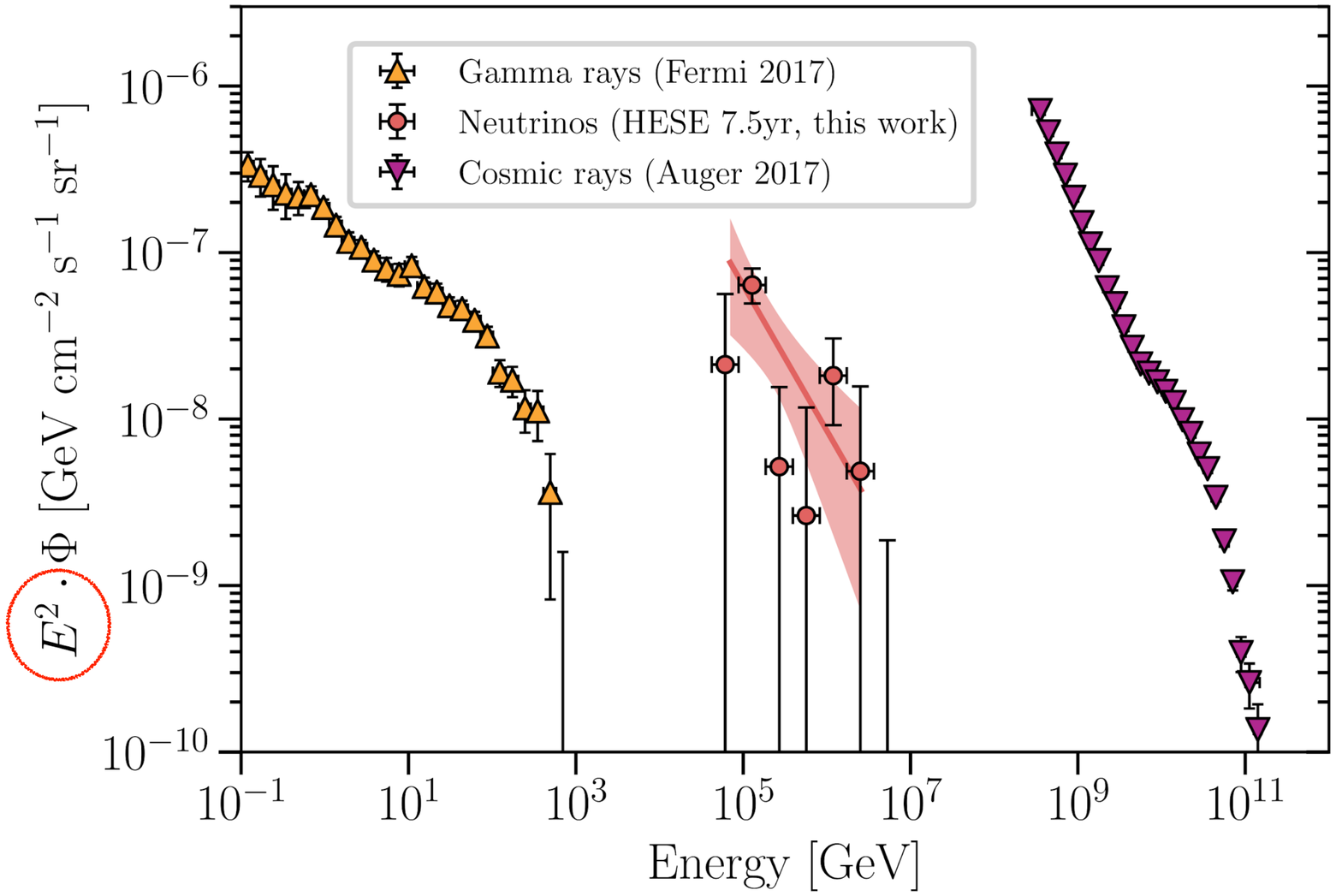
2019: Observation of first tau neutrino

IceCube GEN2

Gamma Rays — Neutrinos — Cosmic Rays

Multimessenger astrophysics: diffuse flux, point sources, transients, real time

Equal amount of power in very different energy regimes of different particles.



TA

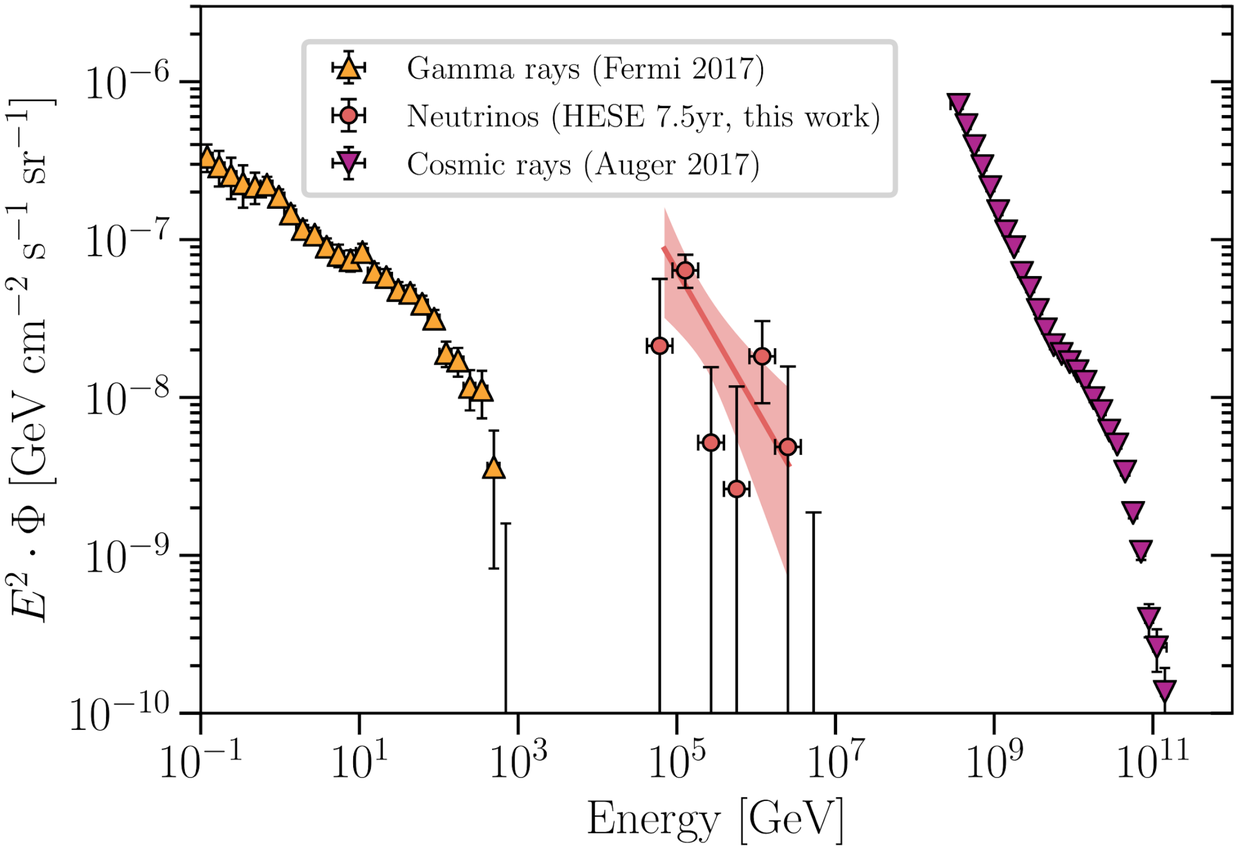
Gamma Rays — Neutrinos — Cosmic Rays

Multimessenger astrophysics: diffuse flux, point sources, transients, real time

Equal amount of power in very different energy regimes of different particles.

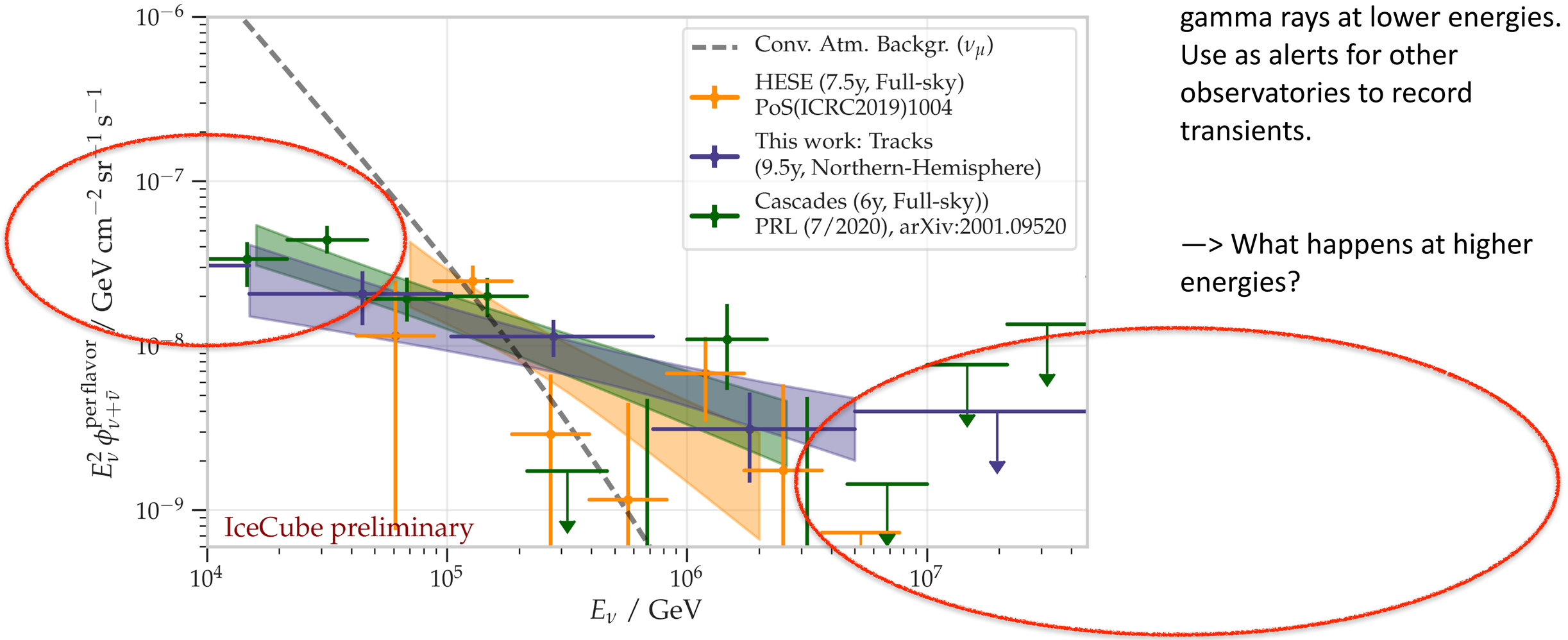
$$p + \gamma \rightarrow \pi^0 + p$$
$$\hookrightarrow \gamma + \gamma + p$$

$$\rightarrow \pi^+ + n$$
$$\hookrightarrow \mu^+ + \nu_\mu + n$$
$$\hookrightarrow e^+ + \nu_{\bar{\mu}} + \nu_e + \nu_\mu + n$$



Multi-Messenger astrophysics

IceCube has discovered and measured
a cosmic neutrino flux from 100 TeV to 10 PeV.



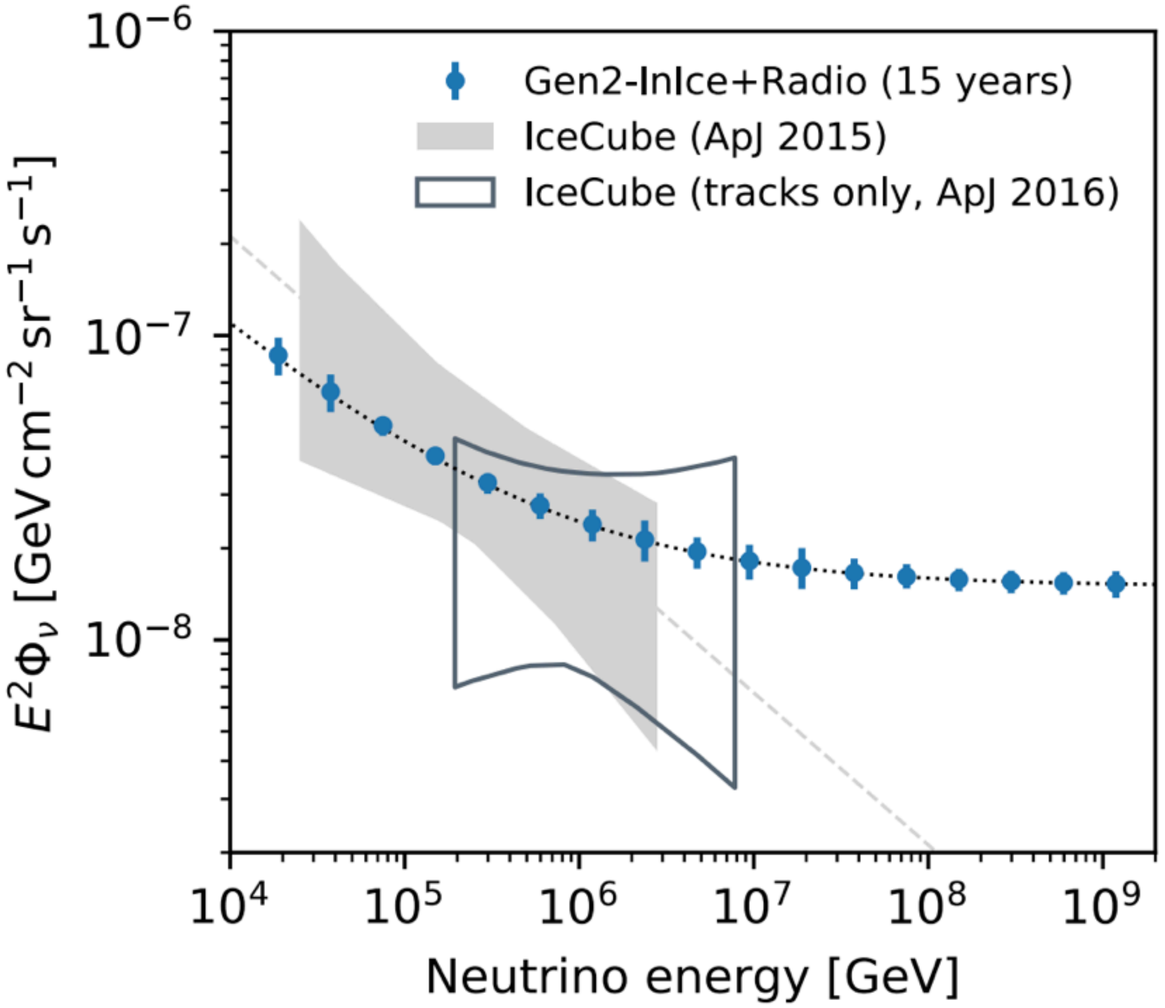
Extension to lower energies:
—> Strong correlation to gamma rays at lower energies.
Use as alerts for other observatories to record transients.

—> What happens at higher energies?

Requirements for IceCube-Gen2

Collect 10 times more neutrinos per year than the current IceCube array in the energy range 100 TeV to 10 PeV

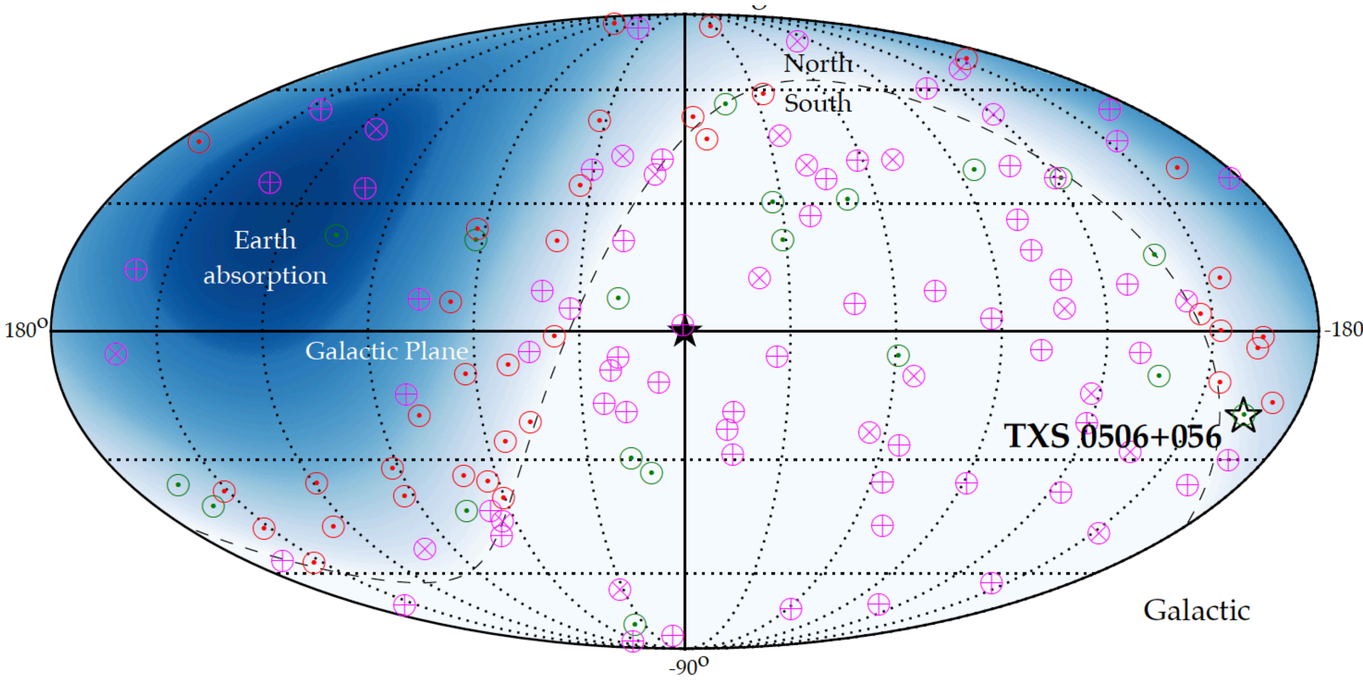
Projected spectral measurement uncertainties



IceCube GEN2

Scientific objectives: building on 10 yrs of IceCube

1. **Resolving the high-energy sky from TeV to EeV energies**



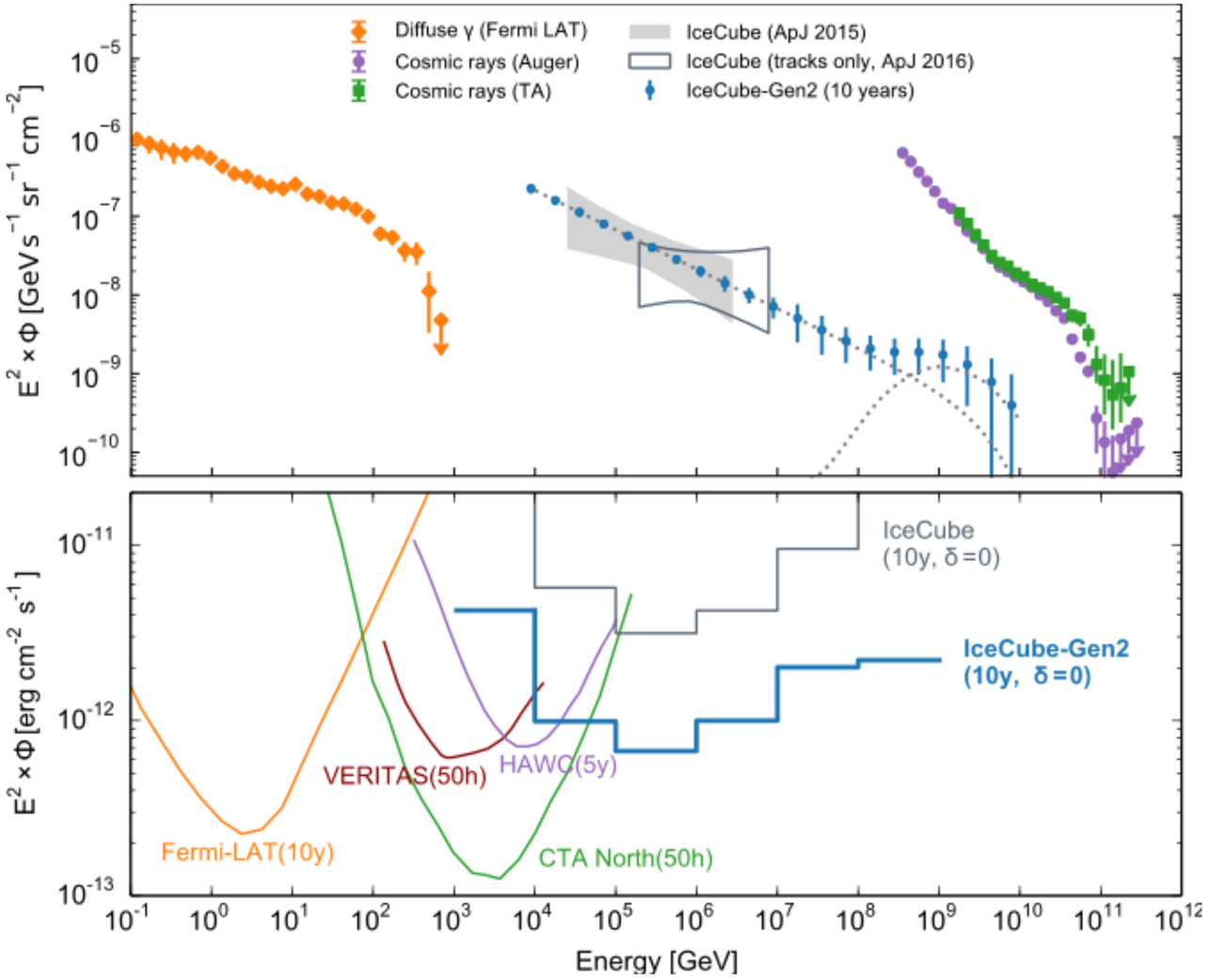
—> Need good angular resolution and high statistics to resolve sources!

IceCube GEN2

Scientific objectives: building on 10 yrs of IceCube

2. Understanding cosmic particle acceleration through multimessenger observation

—> Need good angular resolution and high statistics to resolve sources!
Real time observations.



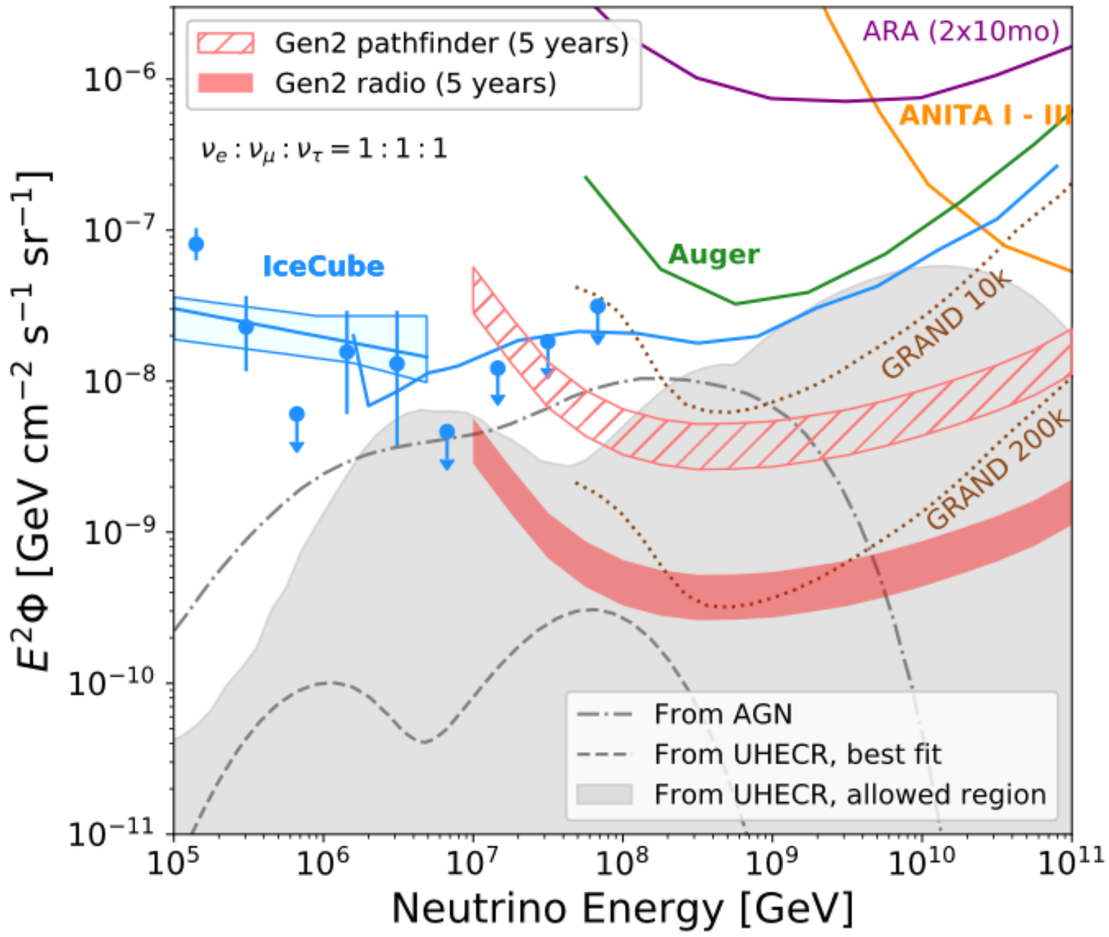
IceCube GEN2

Completing the multi-wavelength view of the Universe

Scientific objectives: building on 10 yrs of IceCube

3. Revealing the sources and propagation of the highest energy particles in the universe

—> Need high sensitivity
at highest energies: energies above 30 PeV,
a factor 50 better than IceCube.



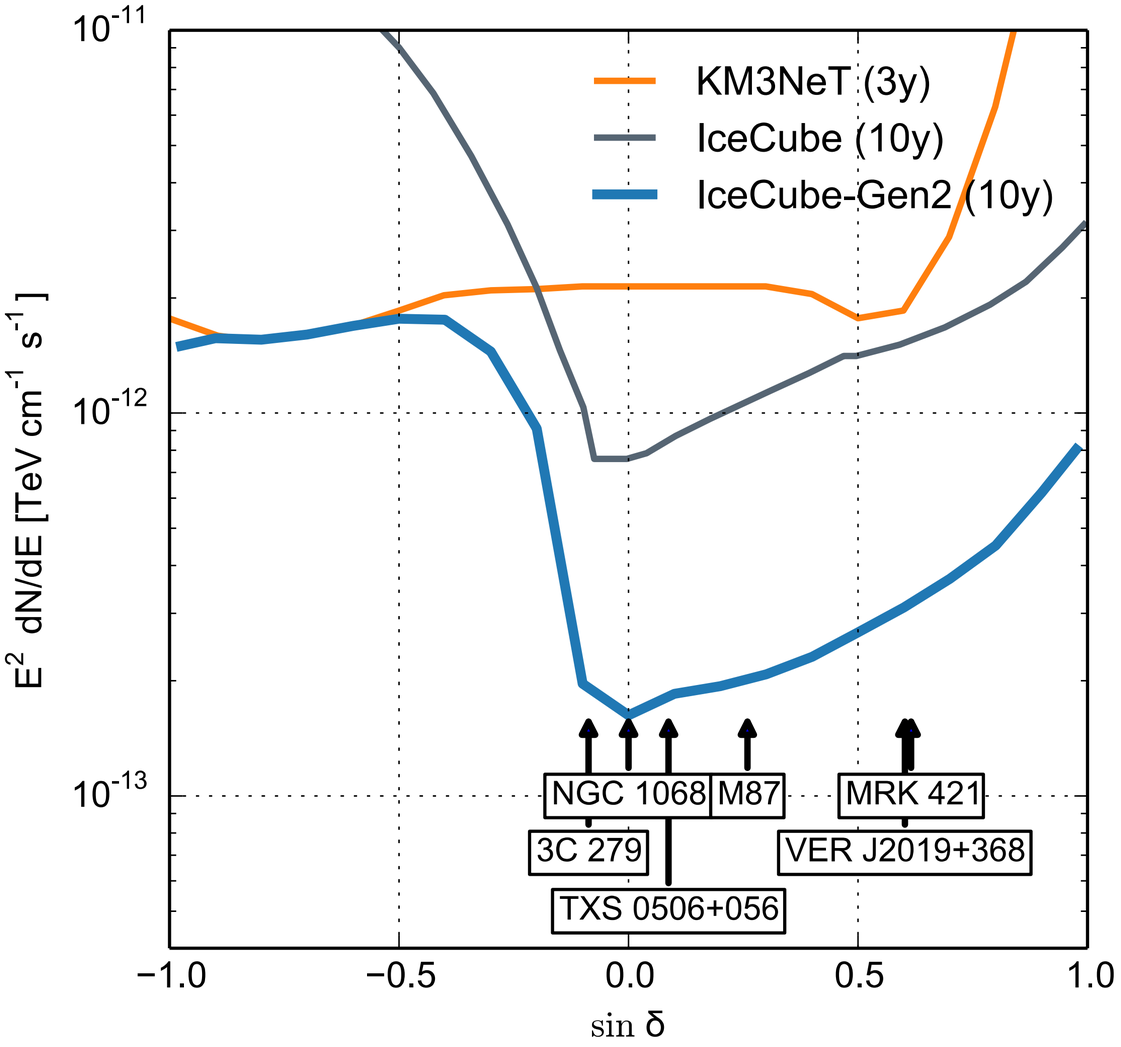
Probing source populations and composition of highest energy cosmic rays

IceCube GEN2

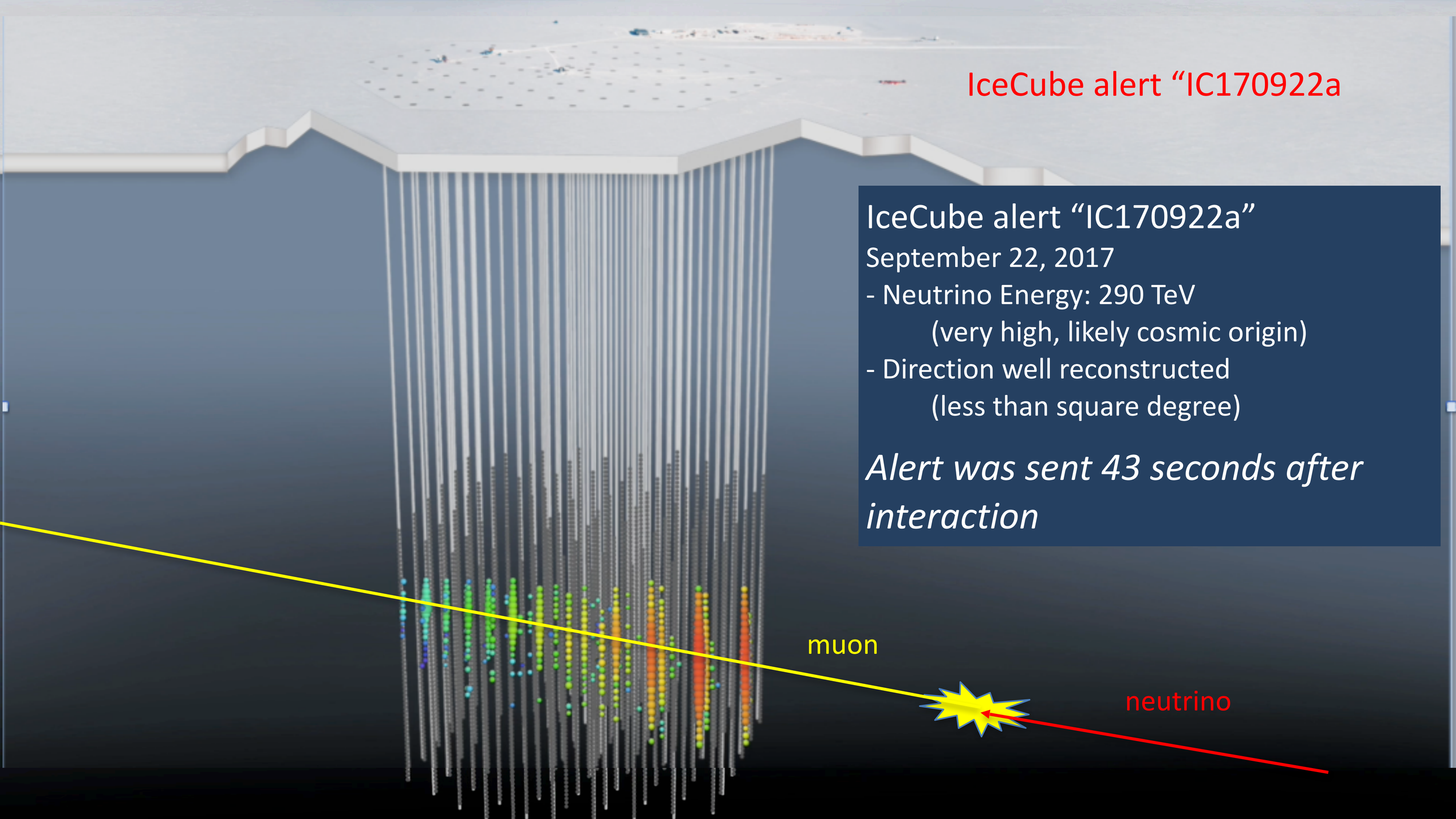
Requirements for IceCube-Gen2

1. Increase the neutrino point source sensitivity at least 5 times over the current IceCube array

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



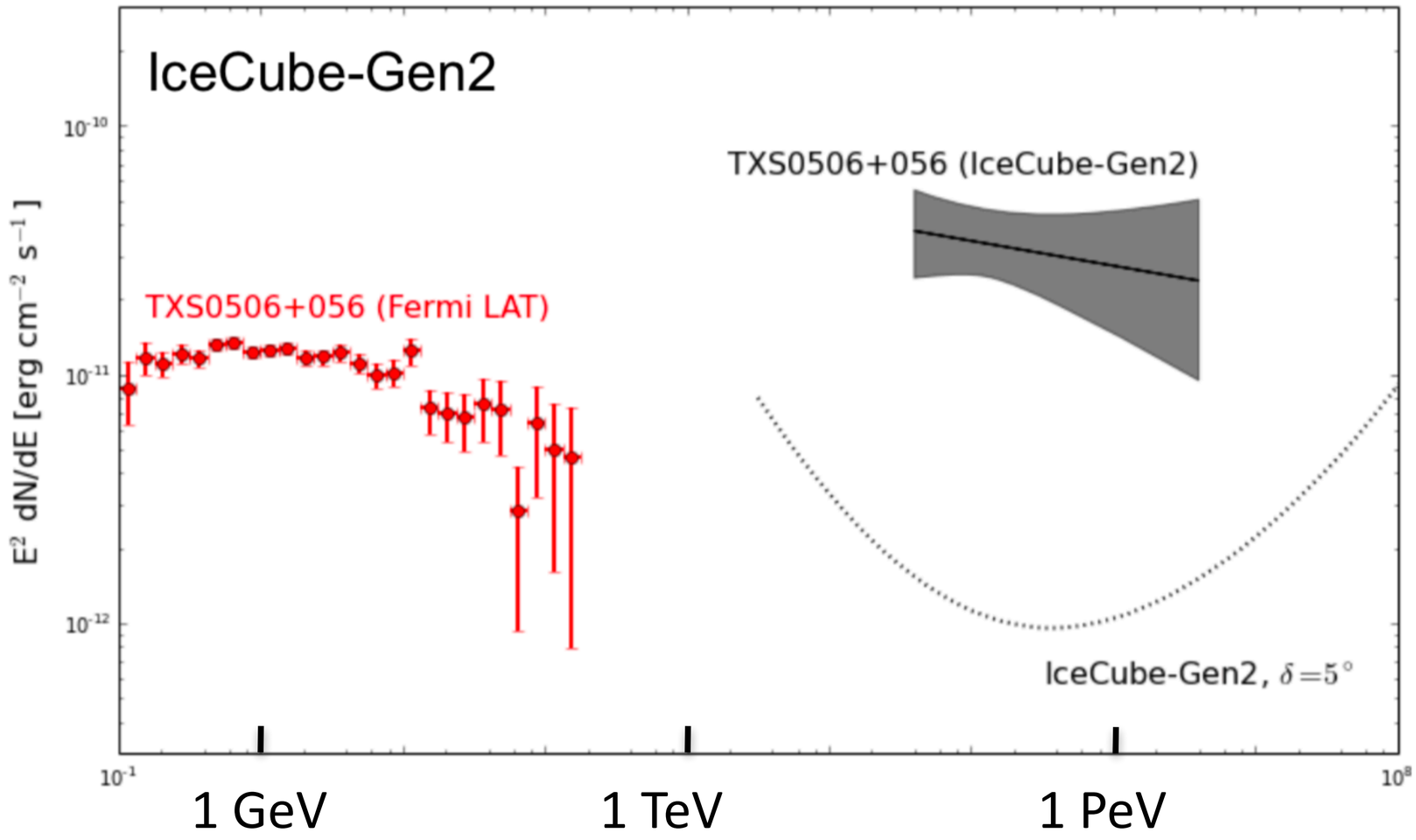
IceCube GEN2


IceCube alert “IC170922a
IceCube alert “IC170922a”
September 22, 2017
- Neutrino Energy: 290 TeV
(very high, likely cosmic origin)
- Direction well reconstructed
(less than square degree)
Alert was sent 43 seconds after interaction
muon
neutrino

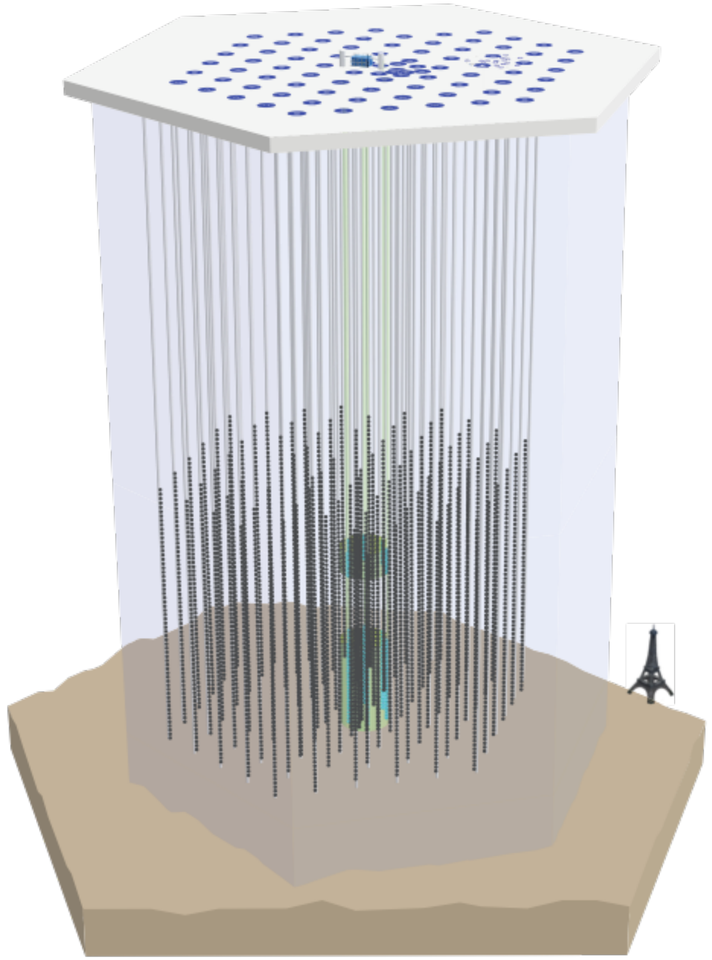
Sensitivity to point sources

Example: TXS0506+056-like source observed with Gen2

- **Order of magnitude increase of # TXS0506+056-like flares observable with Gen2**



The IceCube Neutrino Observatory



IceTop (surface array): 81 stations

IceCube: 86 strings

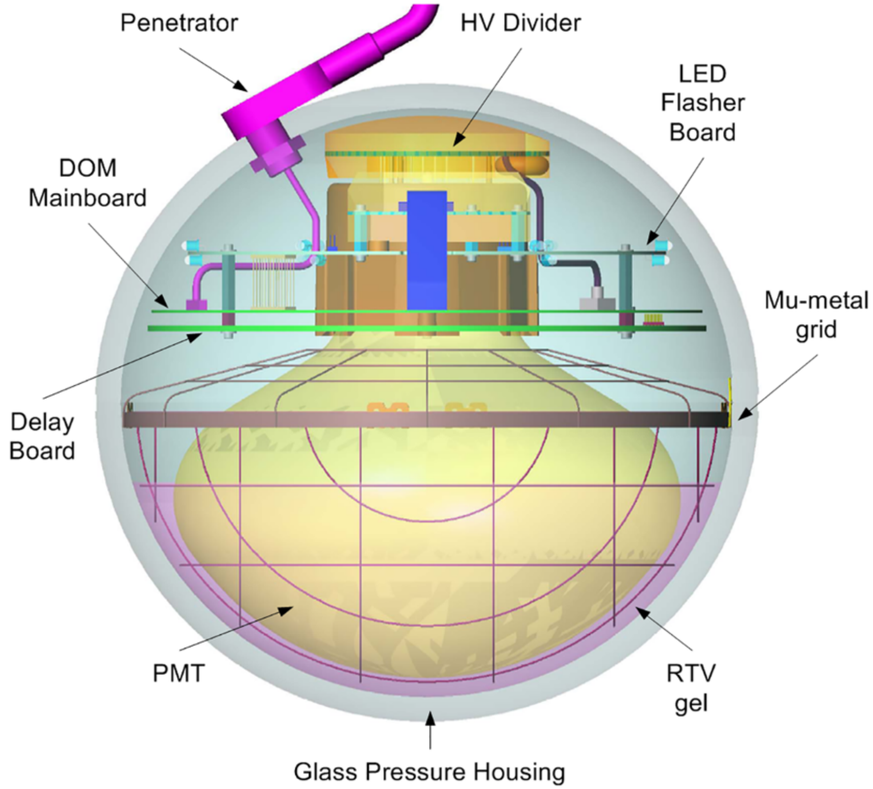
5160 optical sensors over 1 km^3 volume

17 m vertical spacing

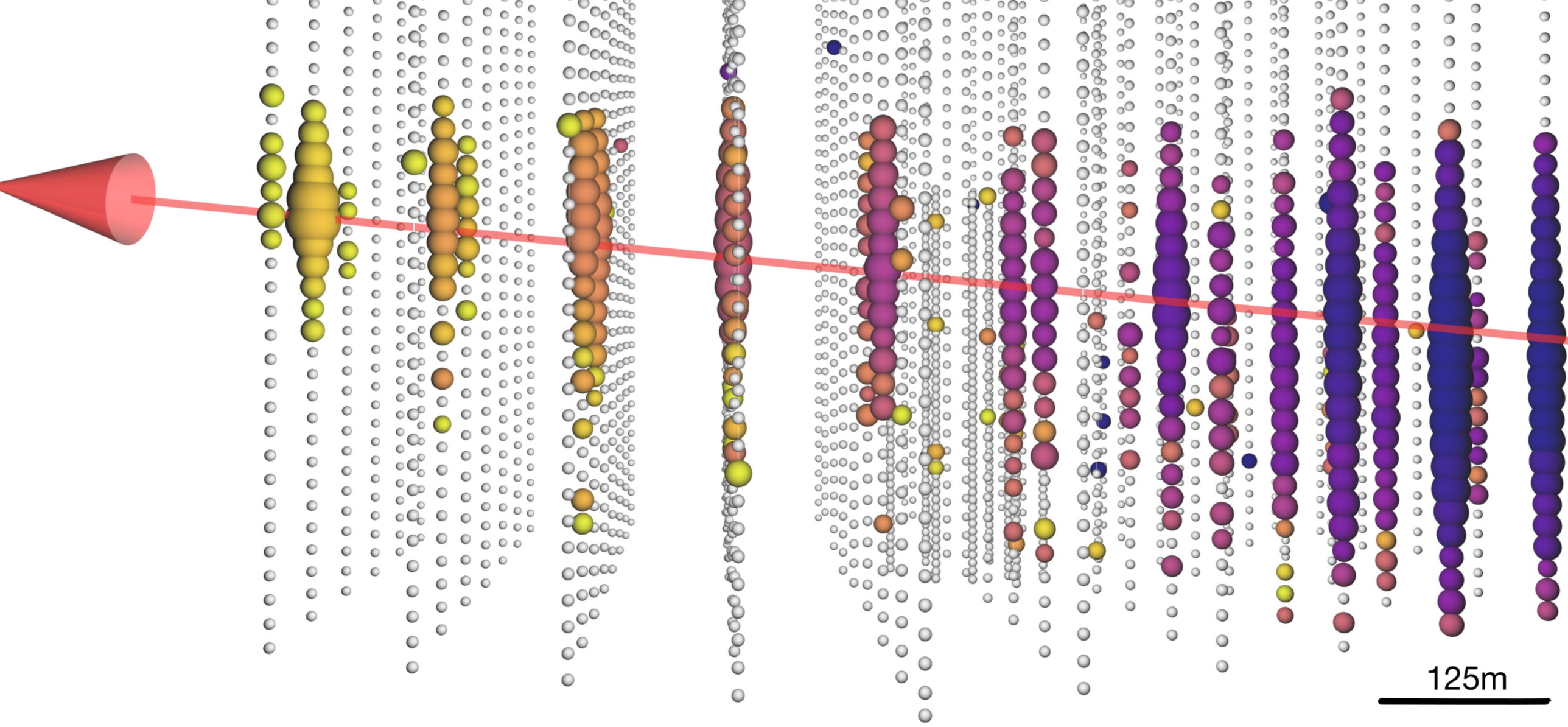
125 m horizontal spacing

Highly stable operation.

Since 2016: livetime > 99.5%



DeepCore (low energy threshold)



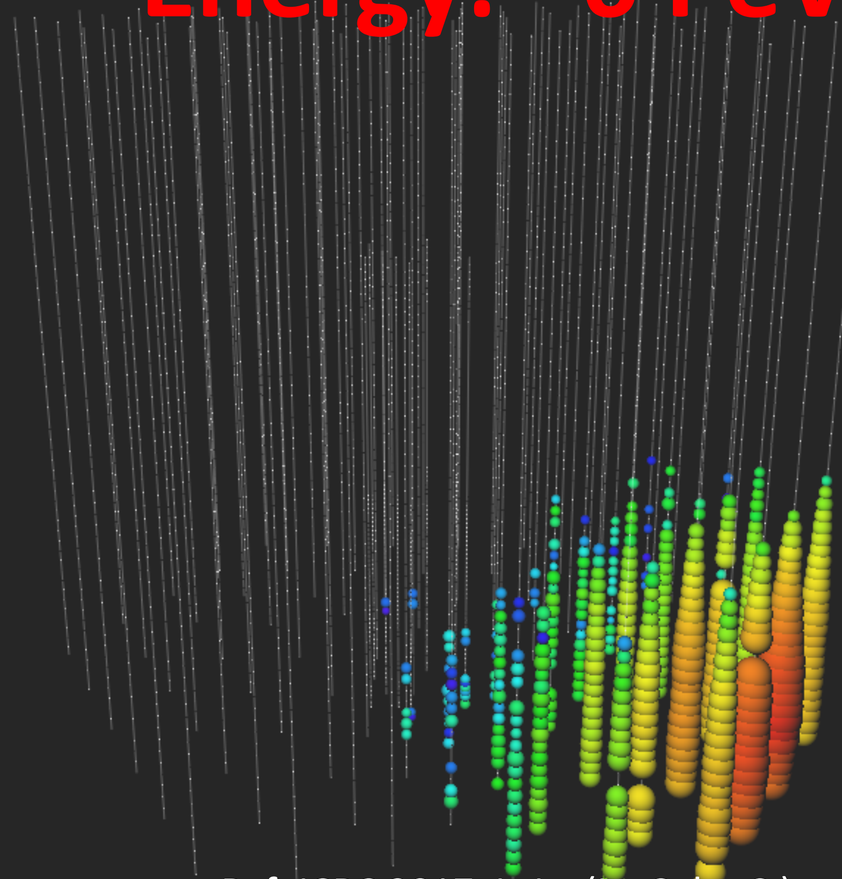
Slightly upgoing with an estimated neutrino energy of 300TeV

A neutrino event near Glashow resonance?

Interesting event found in expanded search.

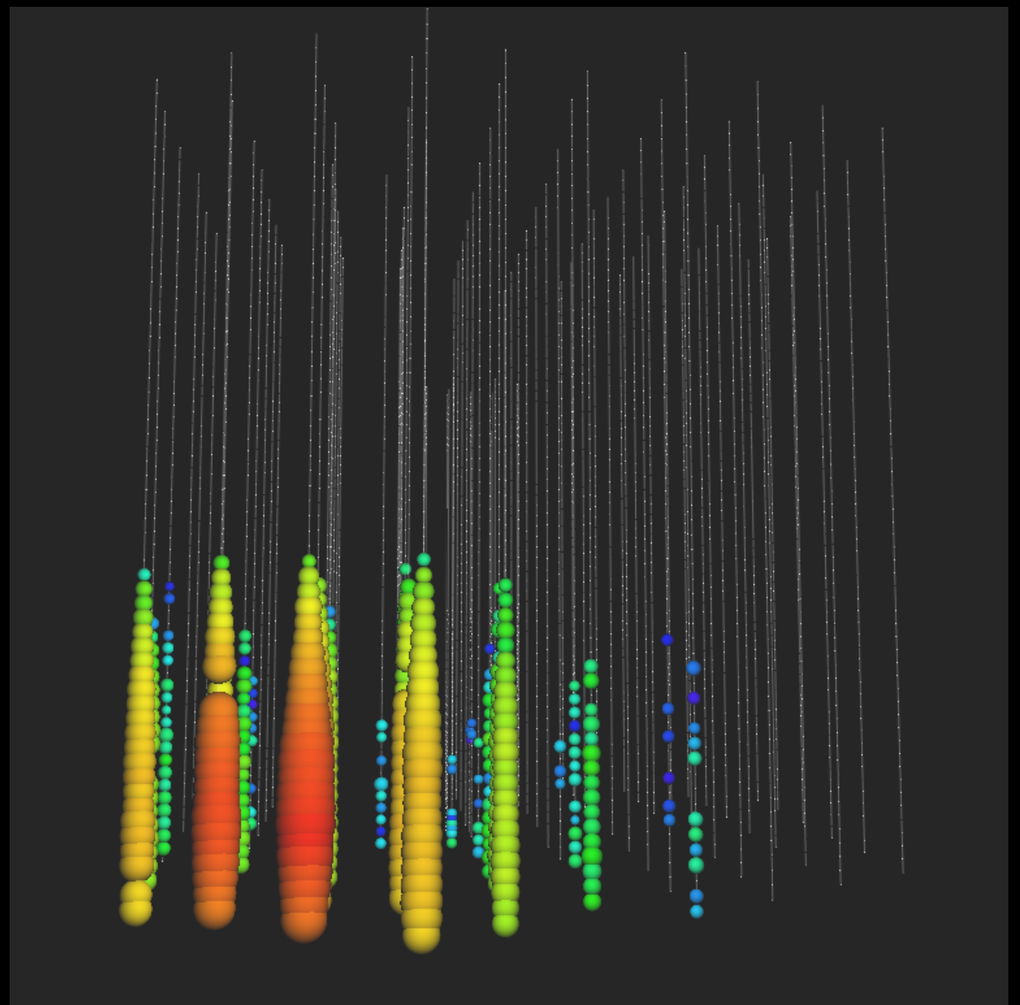
Charge: 200,000 photoelectrons

Energy: ~6 PeV



Ref: ICRC 2017, L. Lu (IceCube C.)

First observation of this interaction



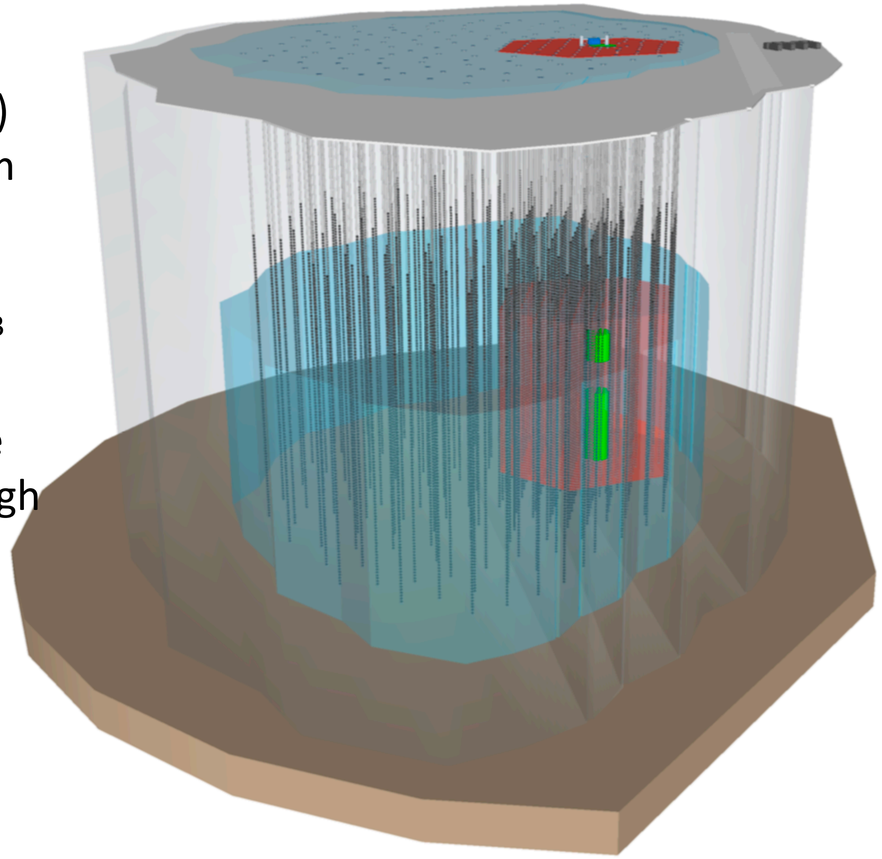
IceCube-Gen2

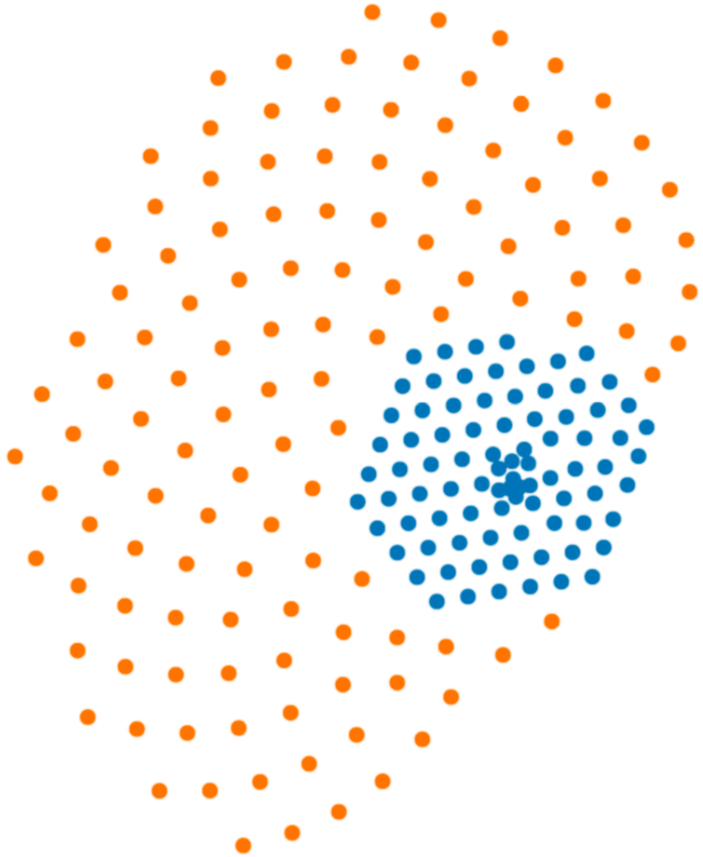
A Vision for the Future of Neutrino Astronomy in Antarctica (arXiv:1412.5106)

Surface Area: ~6.5km^2 (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km^3

Order of magnitude increase of contained event rate at high energies.



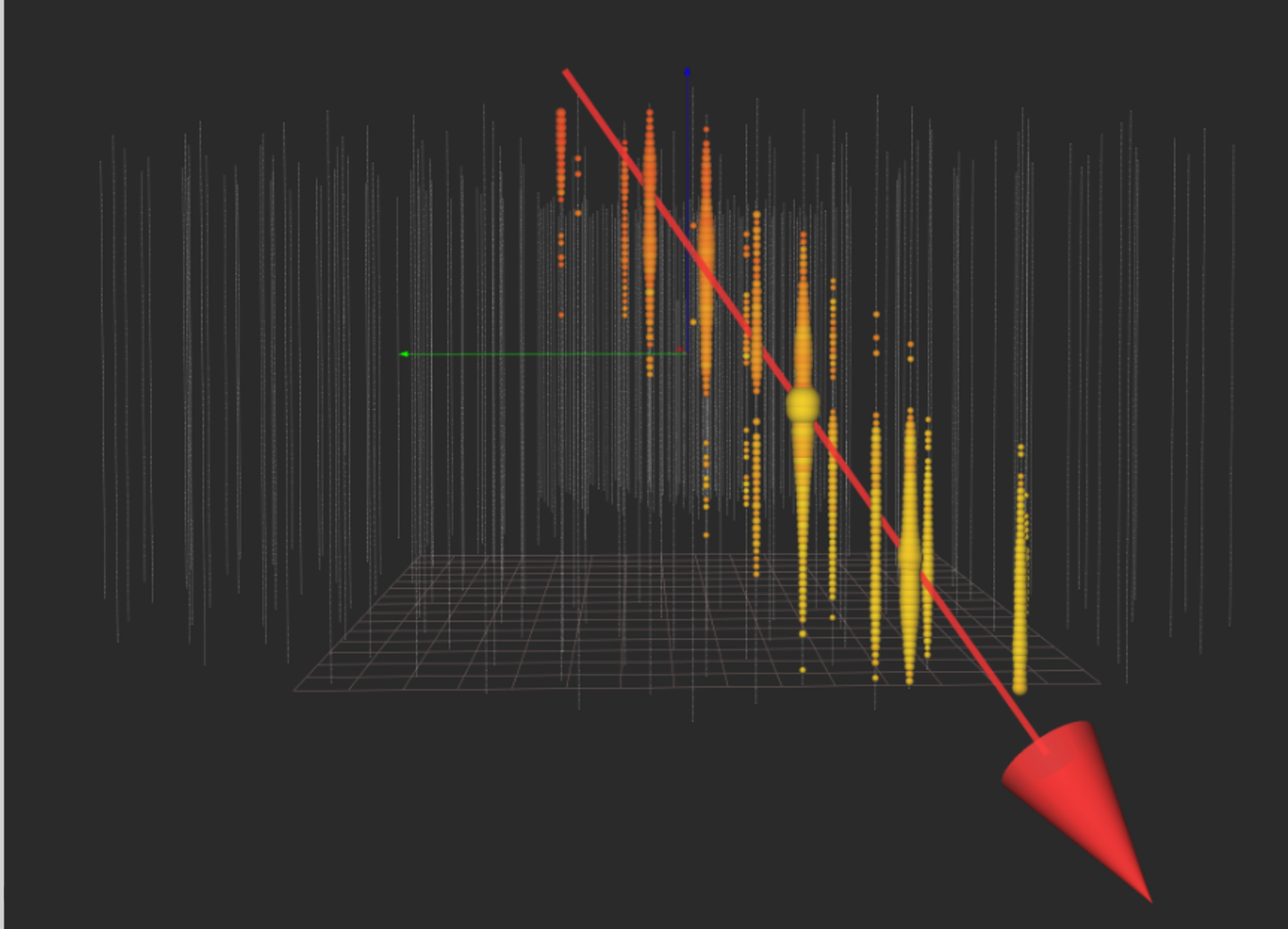


Artist's conception
120 strings at 240 m spacing

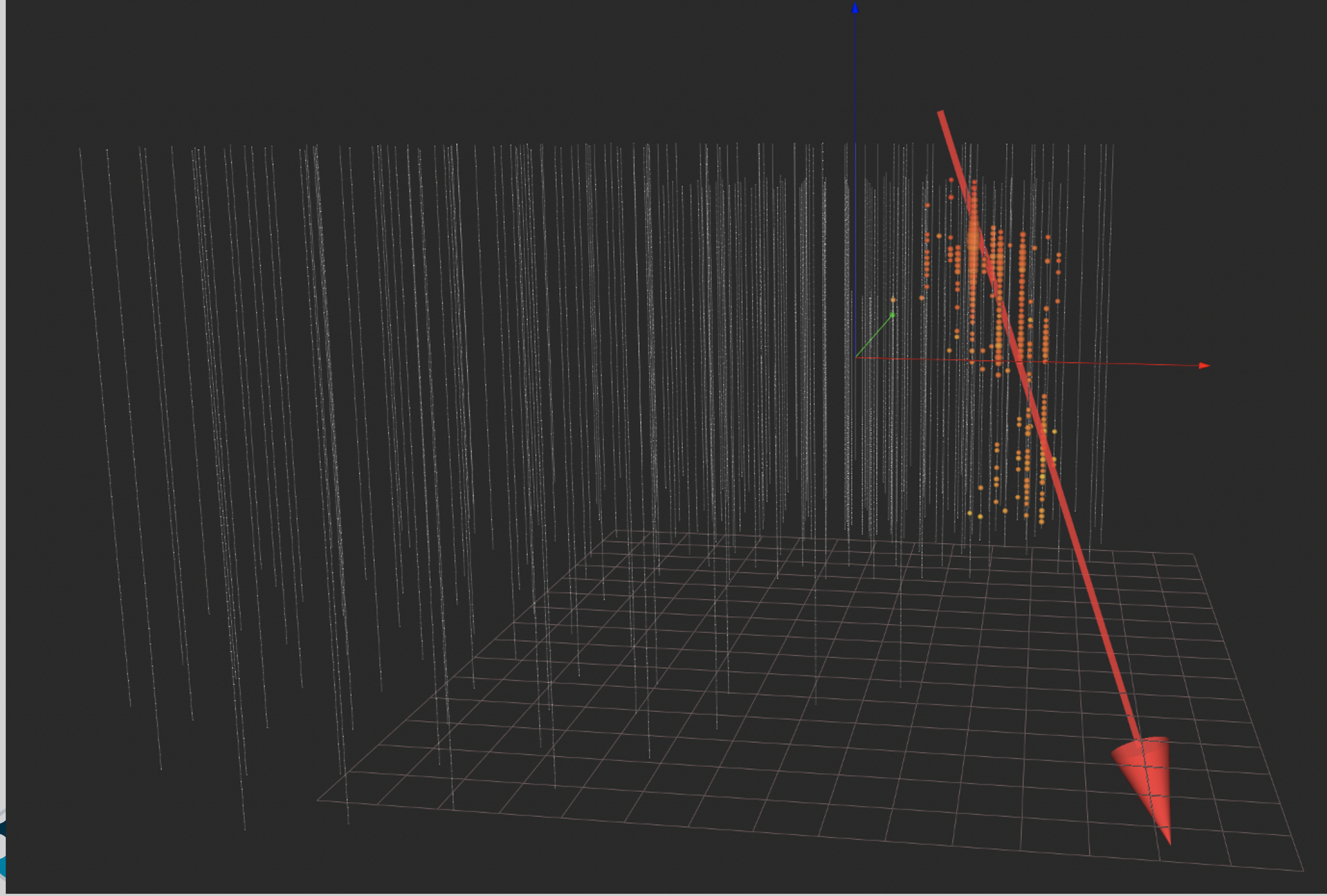
IceCube GEN2

The next-generation IceCube: from discovery to astronomy

10 PeV



96 TeV



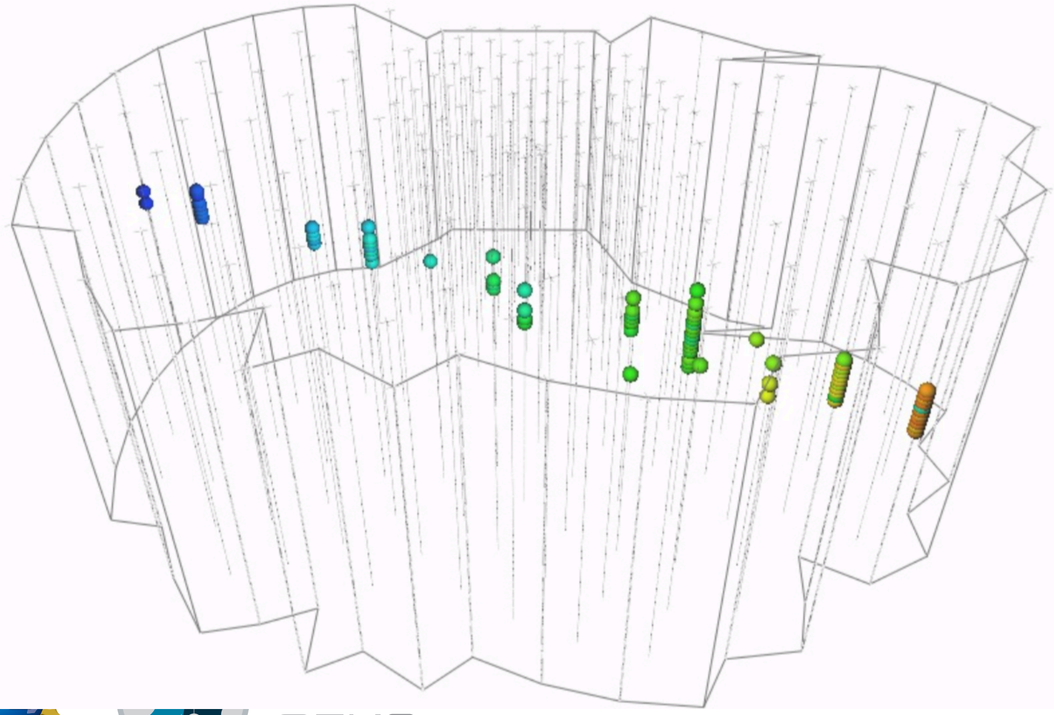
Gen2-Optical Performance

Event Topologies

Like IceCube (and many other telescopes!) two primary detection channels

Tracks

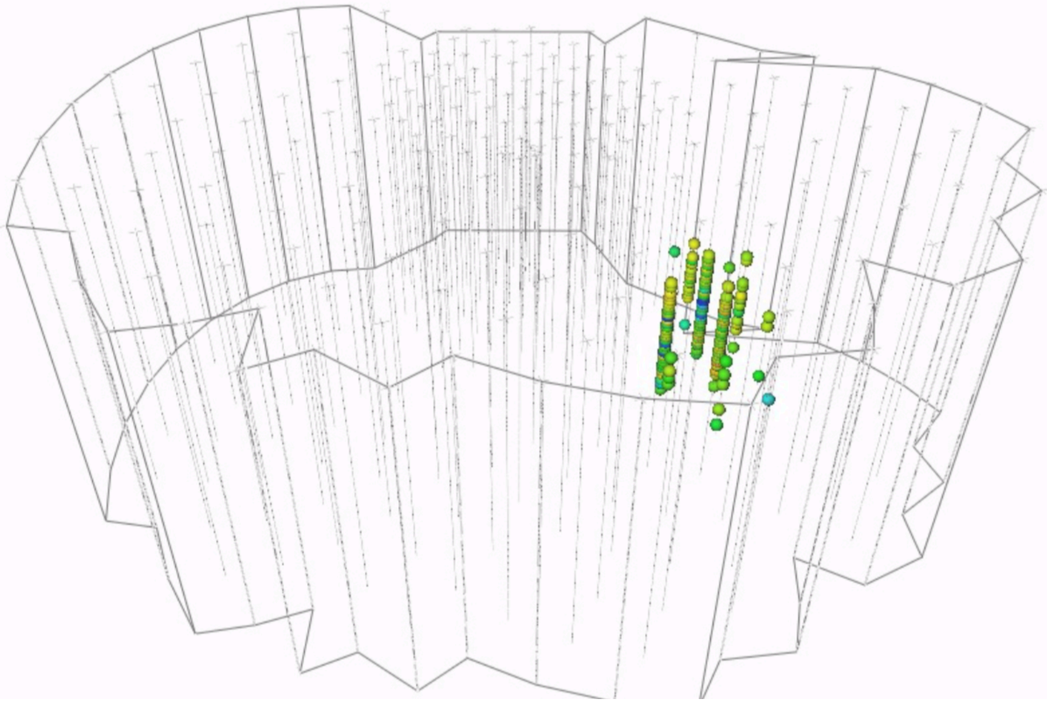
Mostly $\nu_\mu/\bar{\nu}_\mu$ charged current



Cascades

$\nu_e/\bar{\nu}_e$, $\nu_\tau/\bar{\nu}_\tau$ charged current

All flavors neutral current

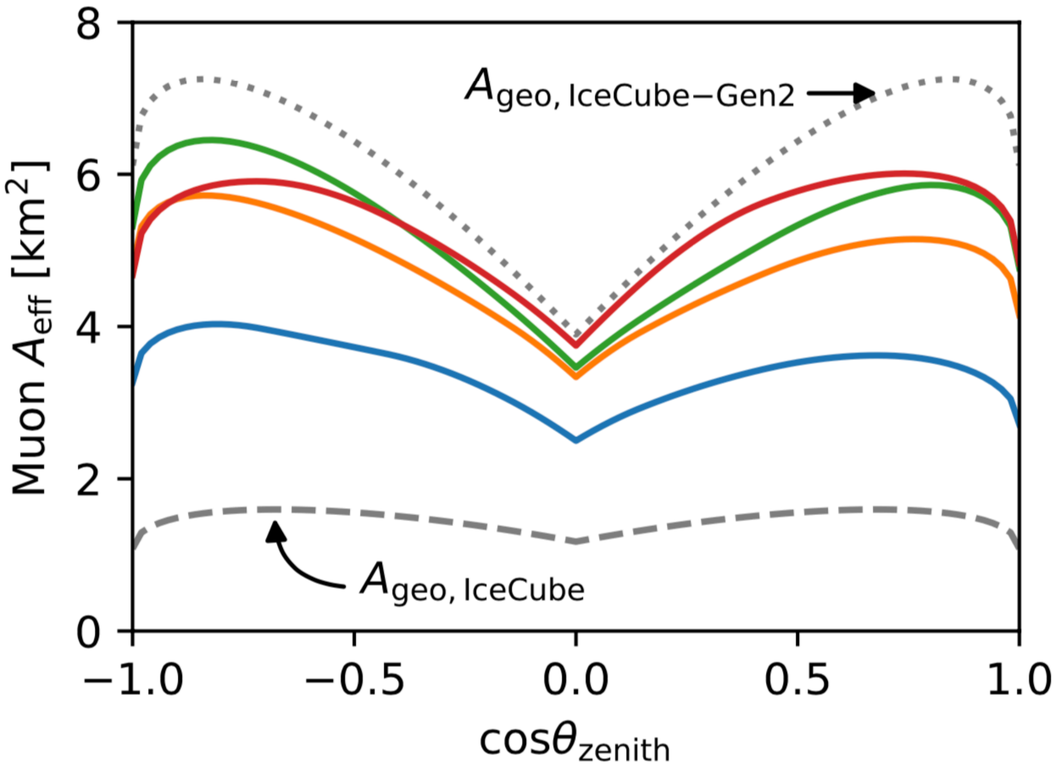


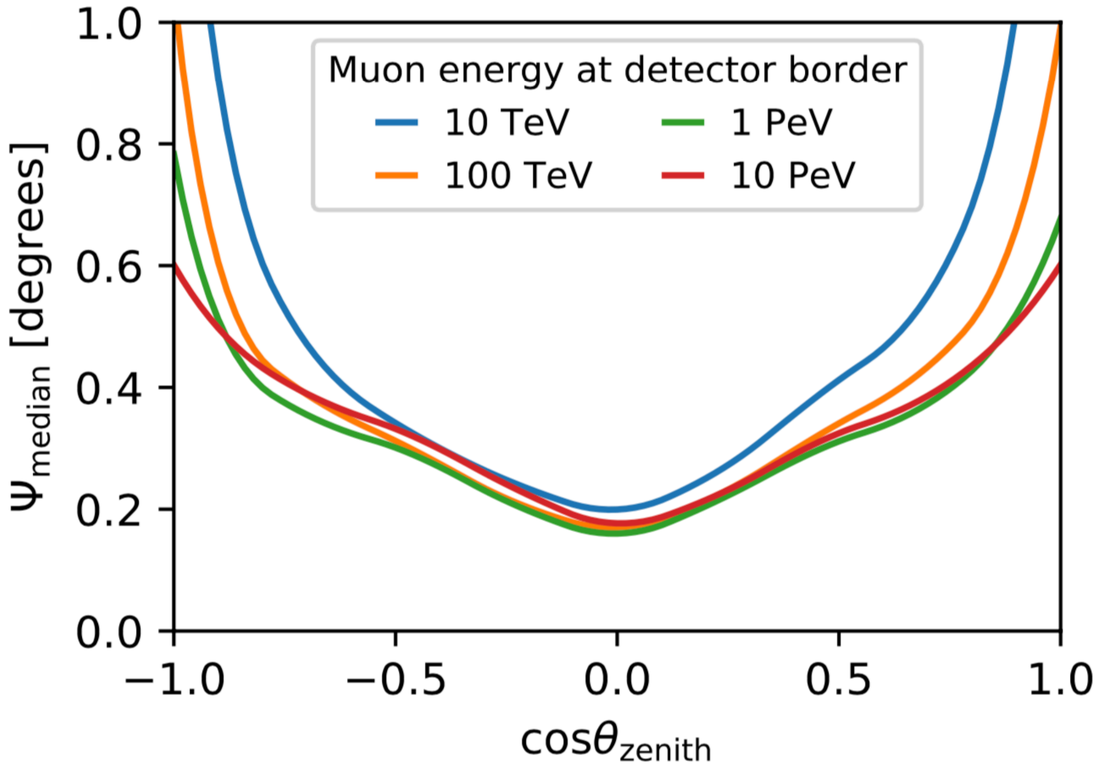
GEN2

Gen2-Optical Performance

Through-going tracks

5x the effective area of IceCube
2x improvement in angular resolution

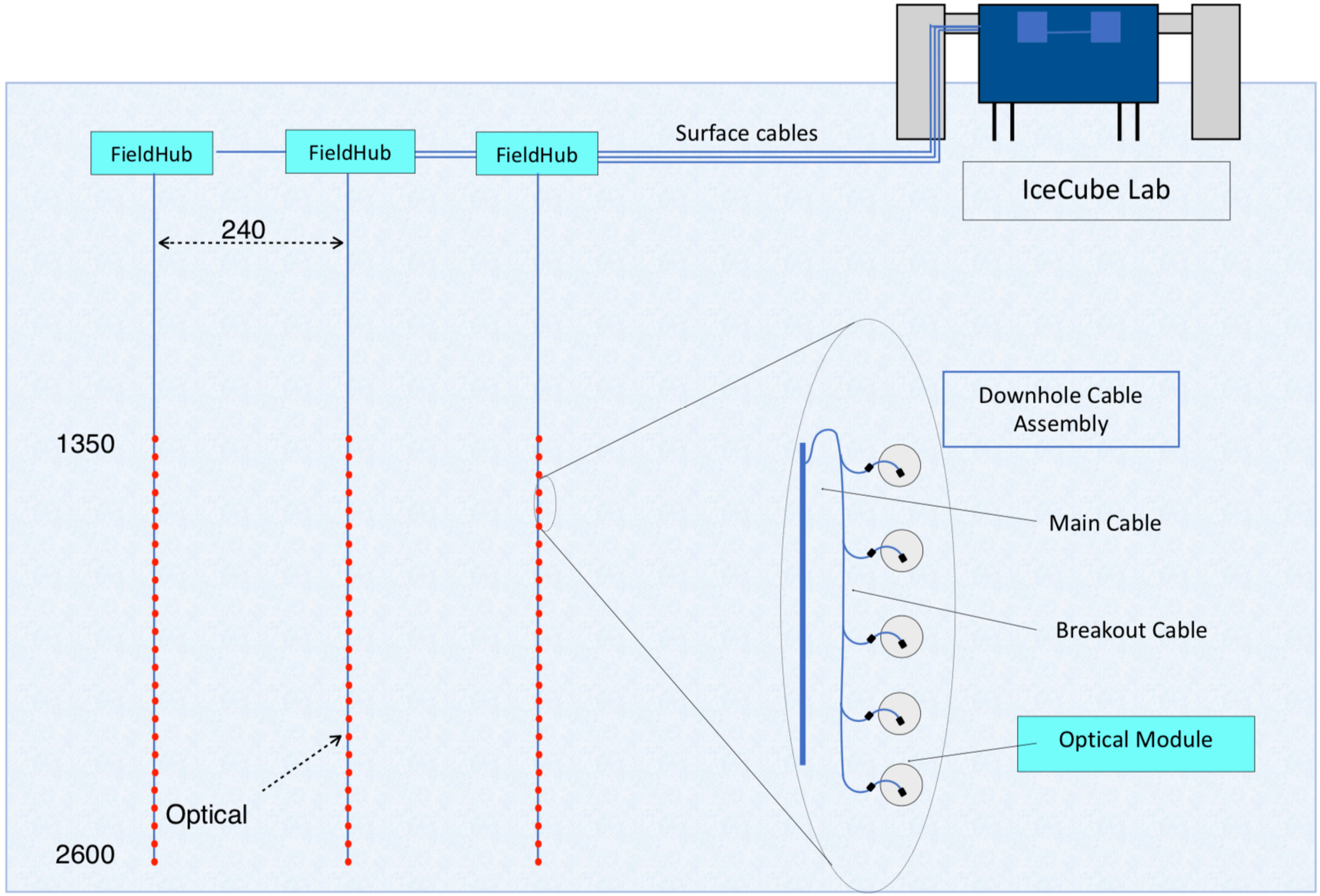




IceCube GEN2

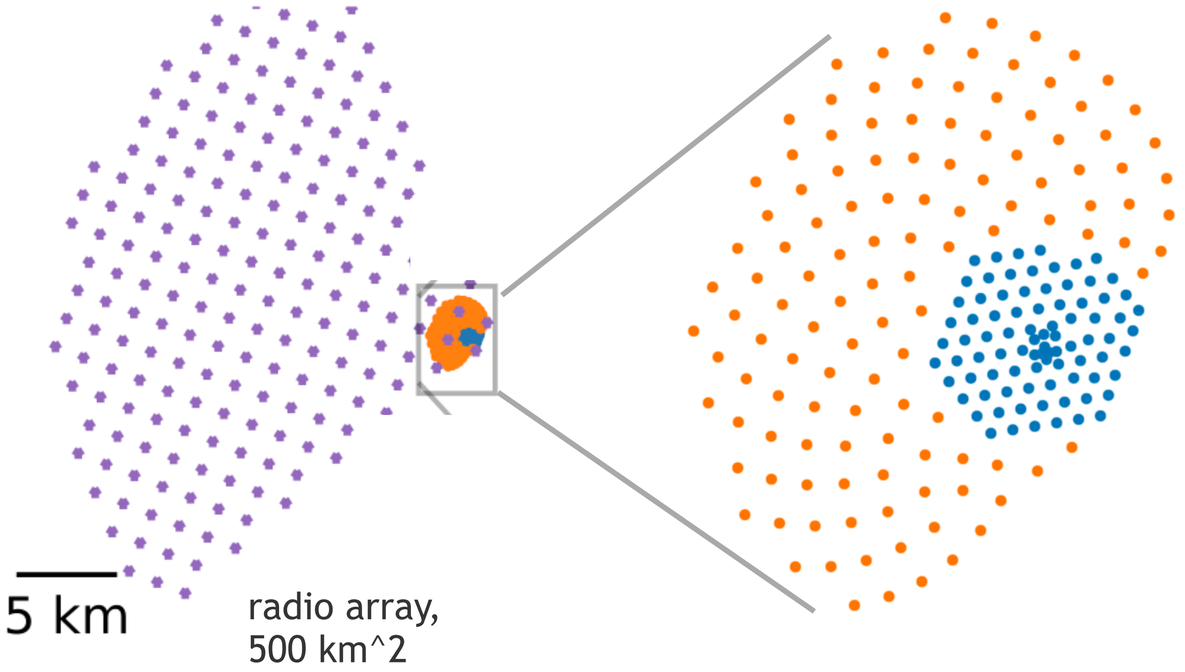
Power and communications architecture

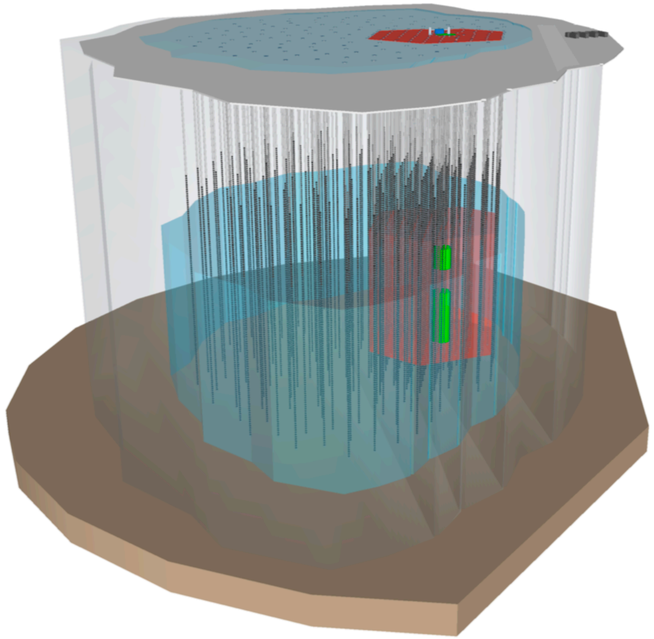
- Reference design
  - New design requires only 1/3 of copper cables to the strings.
  - ~6 modules per wire pair.



IceCube-Gen2: Scope

Optical Array of 120 strings with 100 sensors each
Surface array: for cosmic rays and veto
Radio Array: 500 km^2 for neutrino detection above 10 PeV





Surface Area: ~6.5km² (0.9)
Instrumented depth: 1.26 km (1.0)

Instrumented Volume: 8 km³

References:
Submission to Decadal Survey on Astronomy and Astrophysics 2020

White paper: IceCube-Gen2: The Window to the Extreme Universe.
(accepted in J. Physics G, arxiv.org/abs/2008.04323)

NSF

IceCube GEN2

Optical sensors

IceCube
DOM

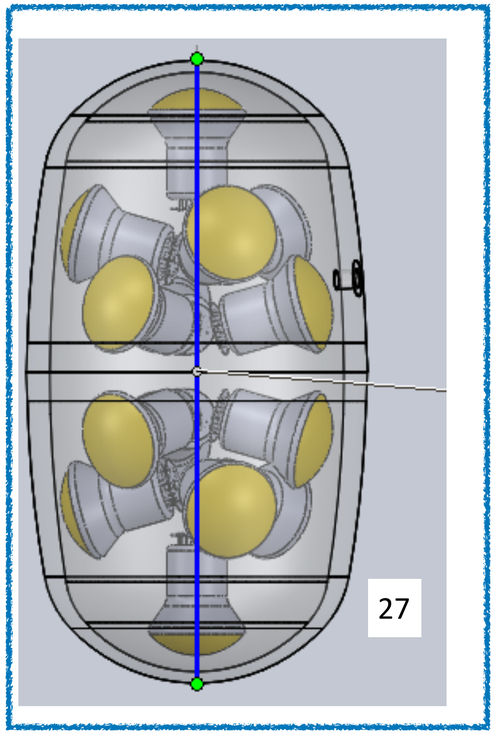
Diameter 33 cm
10 inch PMT

IceCube Upgrade (under construction) primary sensors

Directional information
24 x 3 inch PMT
Diameter 36 cm

2 x 8 inch PMT
Smaller diameter 30 cm

Gen2 sensor design studies: MDOM with smaller diameter, Development briefly discussed.



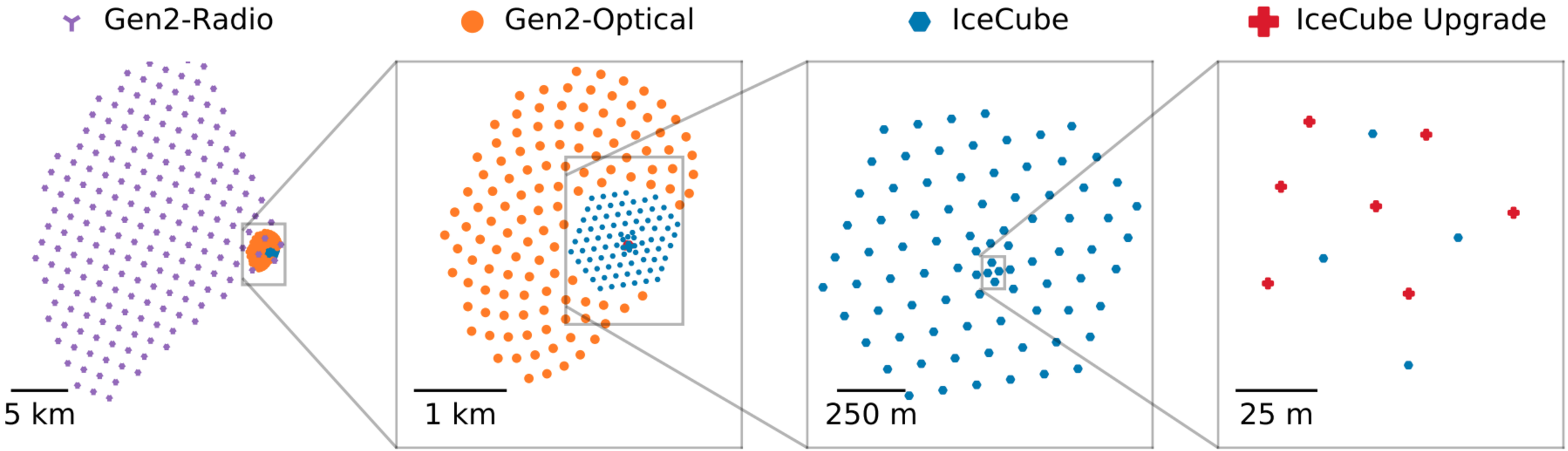
12 x 4 inch PMT
Smaller diameter 30 cm

IceCube GEN2

From Upgrade to Gen2:

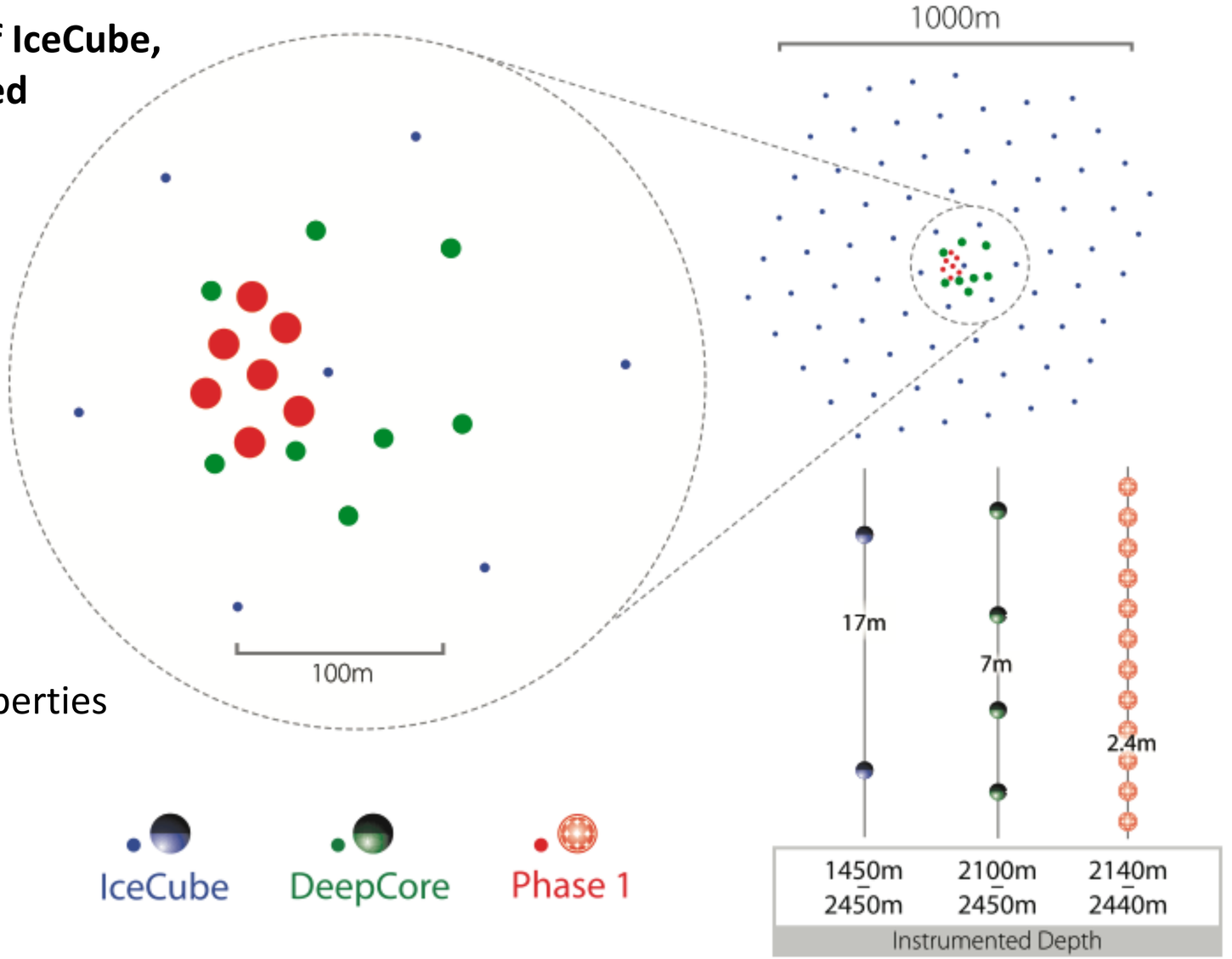
- Key elements of design approach:
  - Use of new 4” diam. PMTs to reduce the number needed
  - Limit the diameter to ~12” (for ref.: IceCube 13”, mDOM 14”, DEgg 12”)
  - PMT base with integrated digitizer and HV generation.

Upgrades at the South Pole



IceCube Upgrade (a step towards Gen2)

7 strings in center of IceCube, densely instrumented

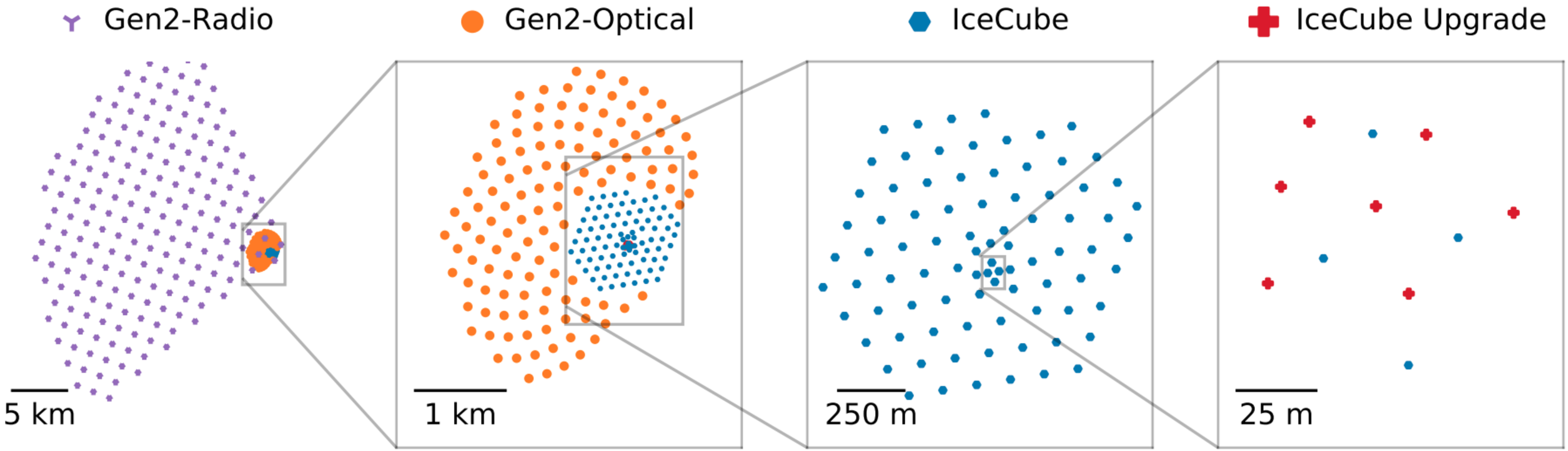


Science goals:

- ν_μ disappearance
- ν_τ appearance
- Precise calibration of IceCube optical properties and DOM response

A big step towards IceCube-Gen2

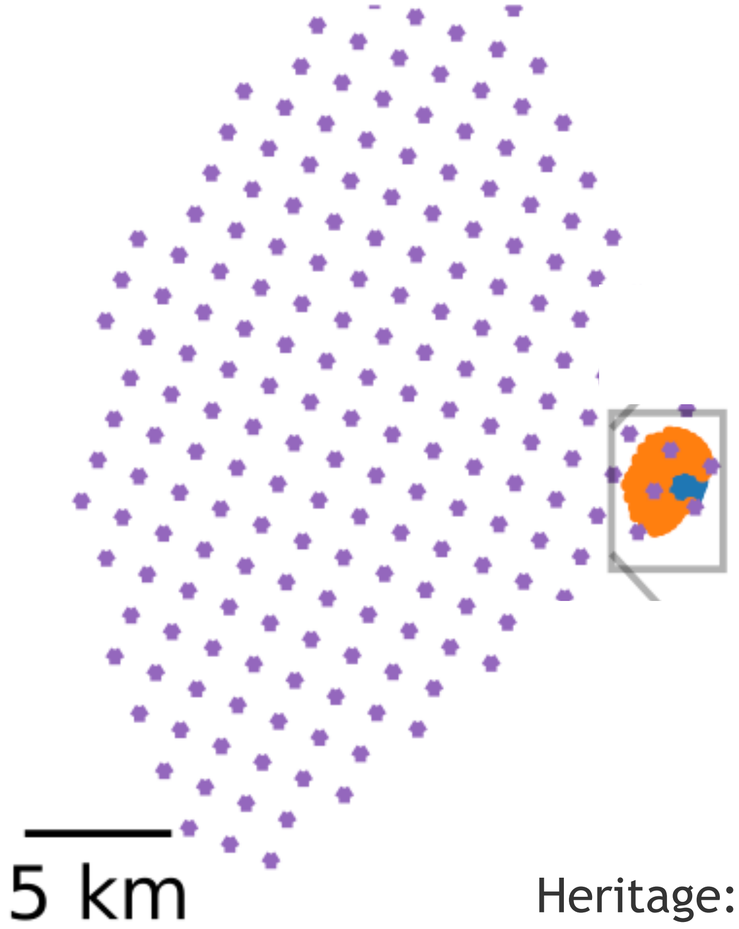
Upgrades at the South Pole

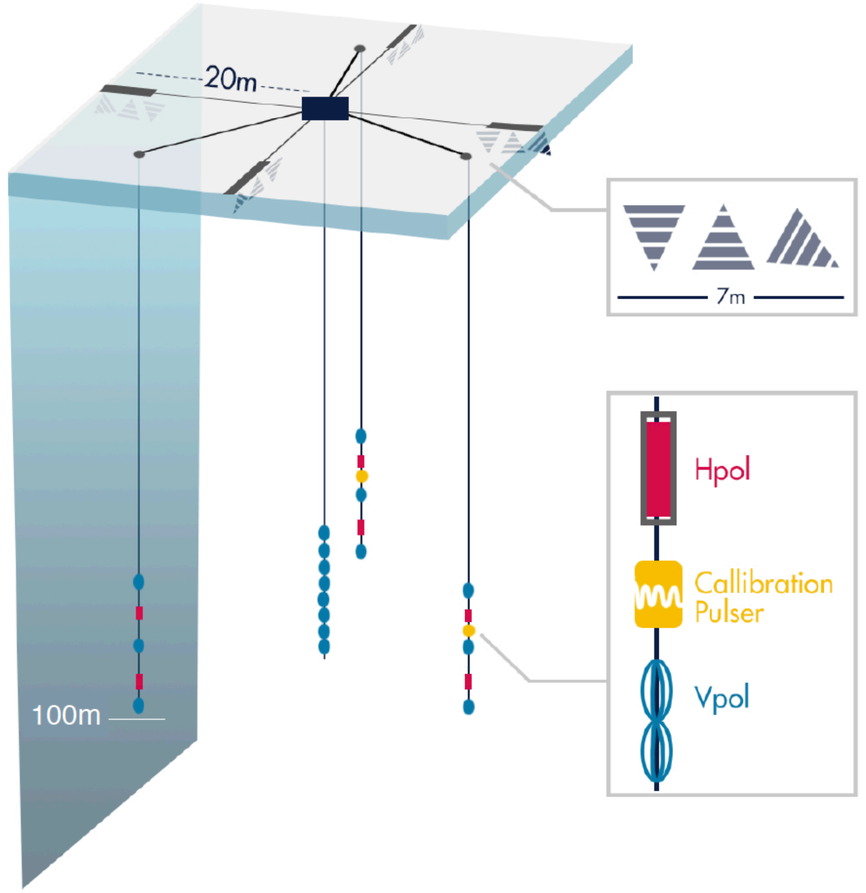


The Gen2 radio array

200 stations
~500 km^2

- A daunting scale! Impact on Gen2 deployment.
- Highly efficient deployment will be critical.





Heritage:
RICE, ARA, ARIANNA

RNO-G (Greenland) first deployment summer 2020

IceCube GEN2

10^7 to 10^{11} GeV: Radio ice Cherenkov detection

Detection principle: Coherent radio emission from e.m. cascade

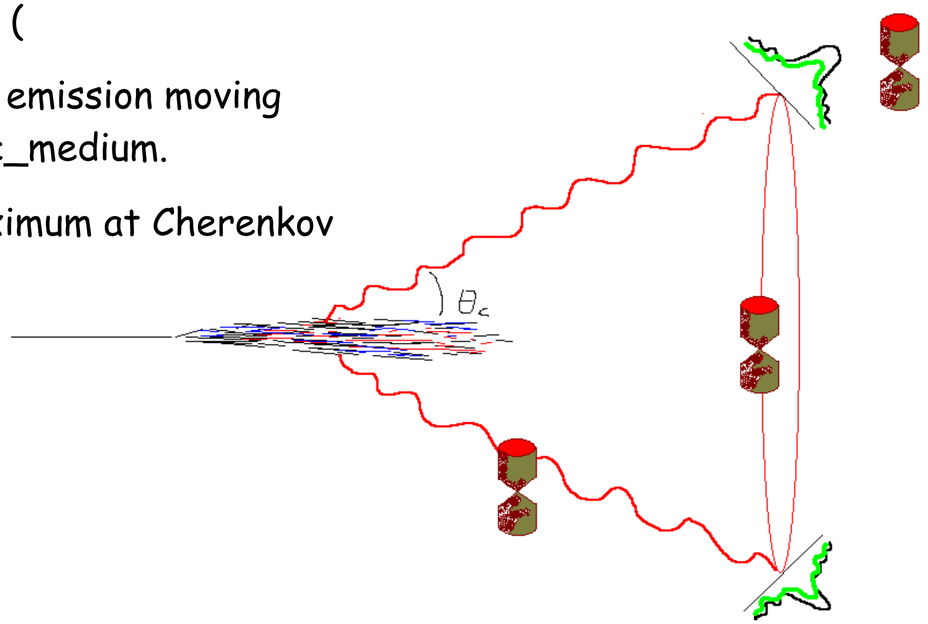
Gurgen Askaryan, 1962
proposes radio detection of showers

Principle:

Charge asymmetry in particle shower development produces a net charge of cm extension. (

→coherent radio emission moving charge when c > c_medium.

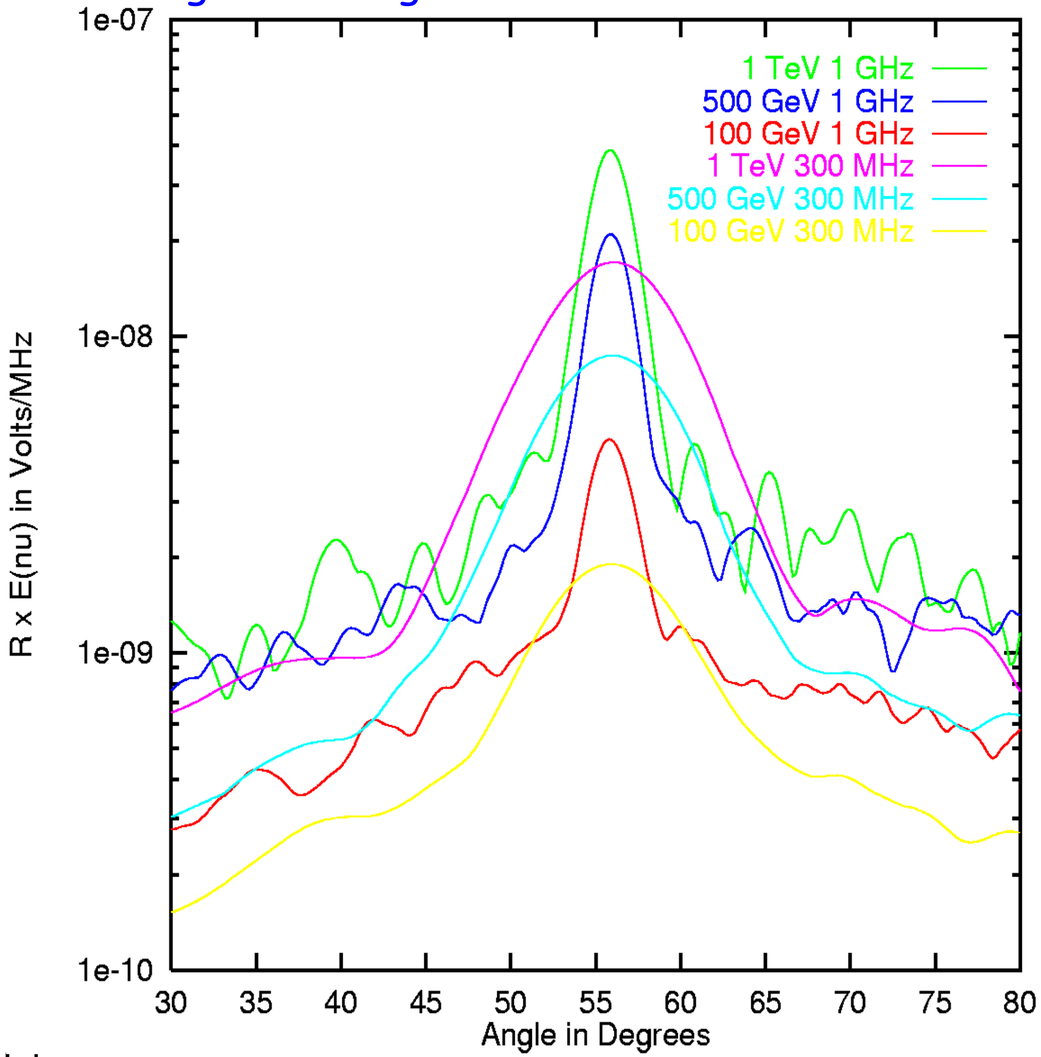
→Radio cone maximum at Cherenkov angle



SLAC 25 GeV electrons on a block of ice make radio pulses in good agreement of theory with data:
D. Saltzberg *et al.,* PRL **86**, 2802 (2001)

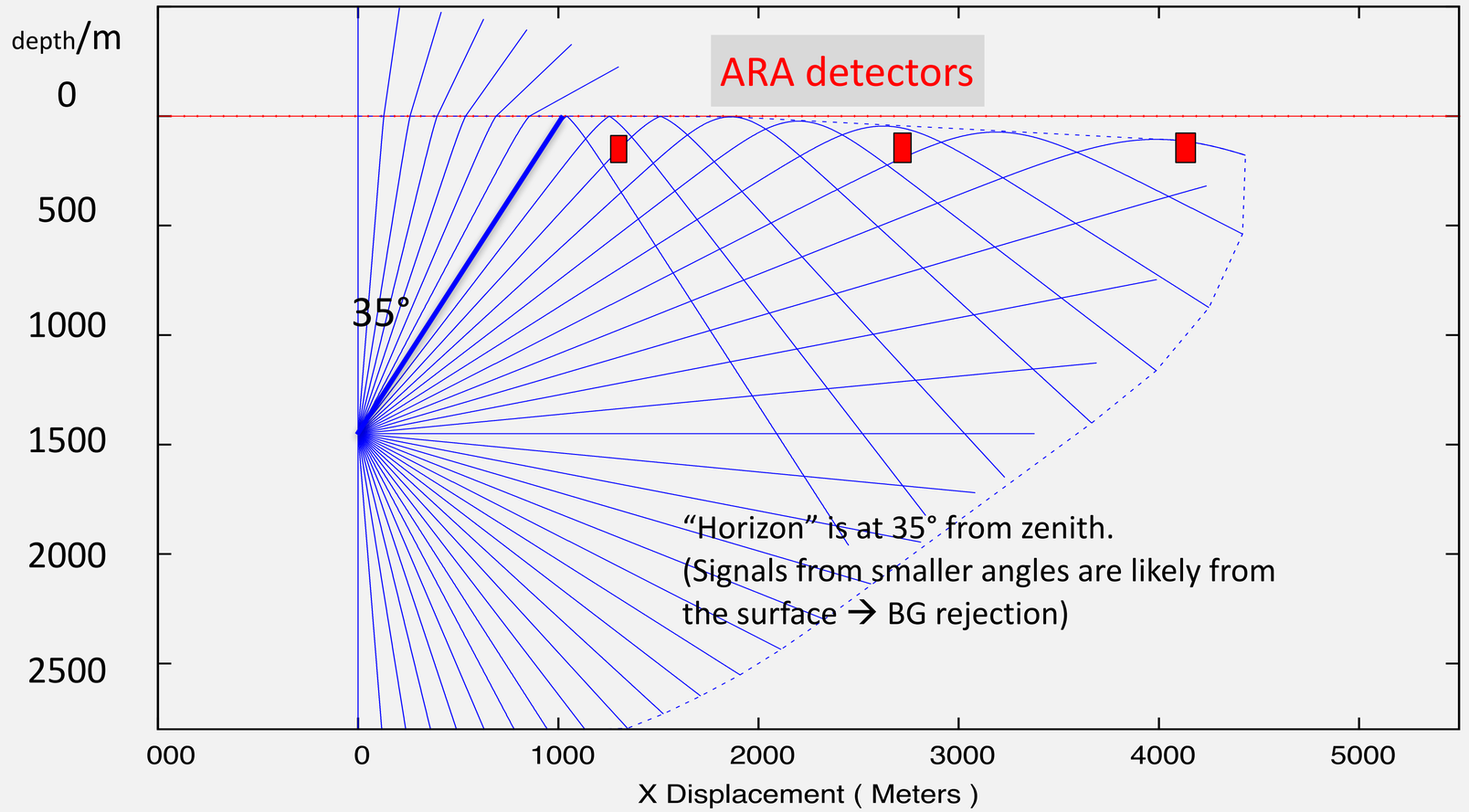
Add coherently!

cone narrows for higher frequencies
- analogous to single slit diffraction

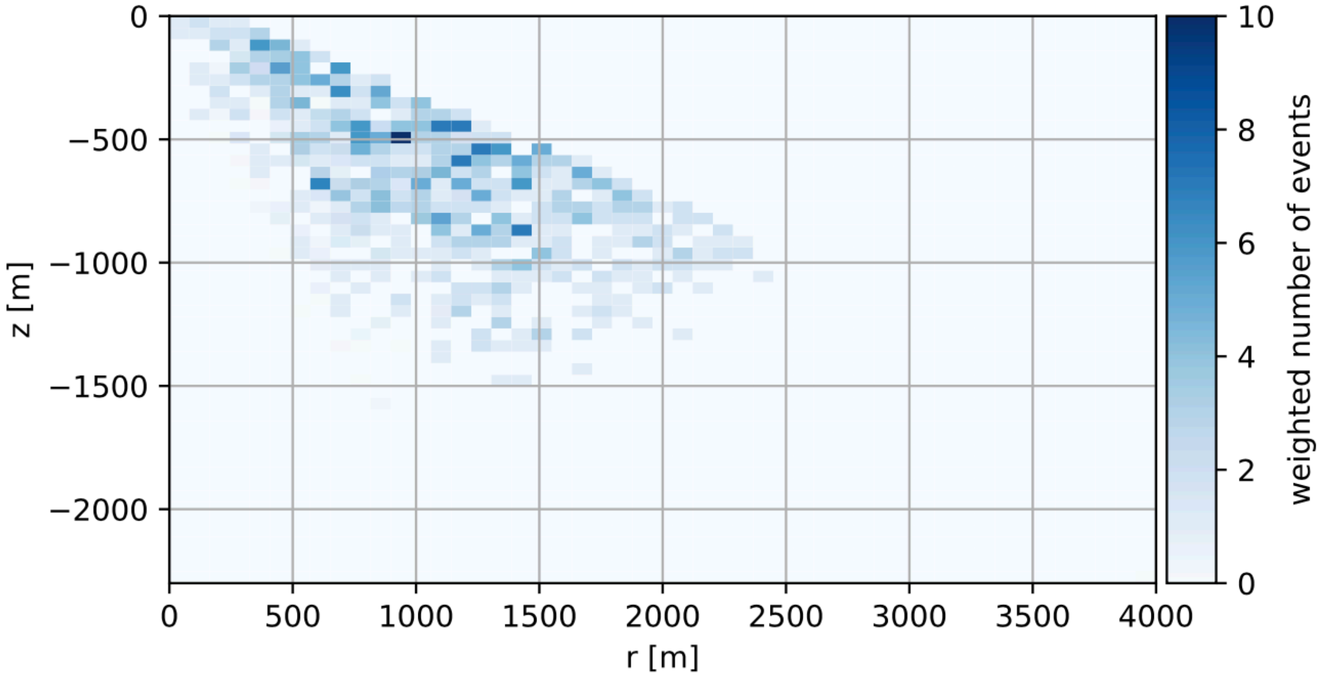


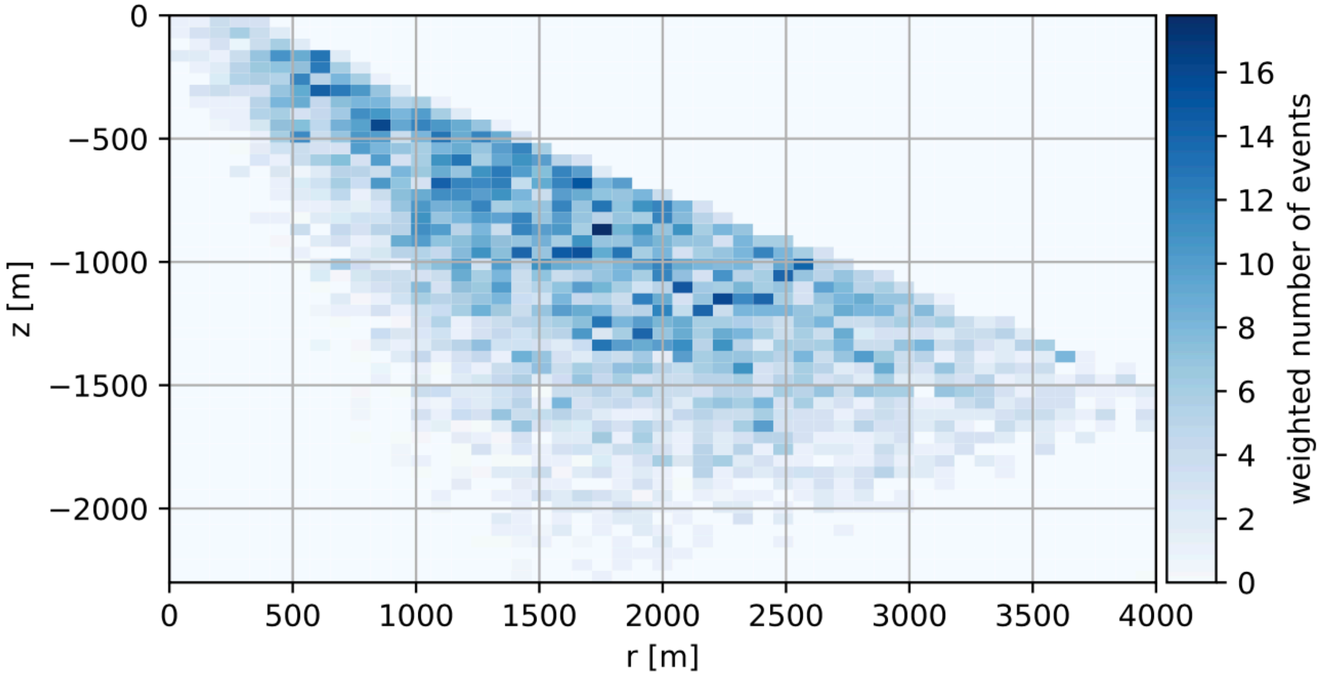
see eg.: J. Alvarez-Muniz et al., Astrop. Phys. 35 (2012) 287-299 and references therein

Calibration pulser deployed with IceCube at 1500m
observed with ARA detectors in more than 3 km distance



How a radio detector can view a large volume of ice: vertex distributions at 100 TeV and 1000 TeV



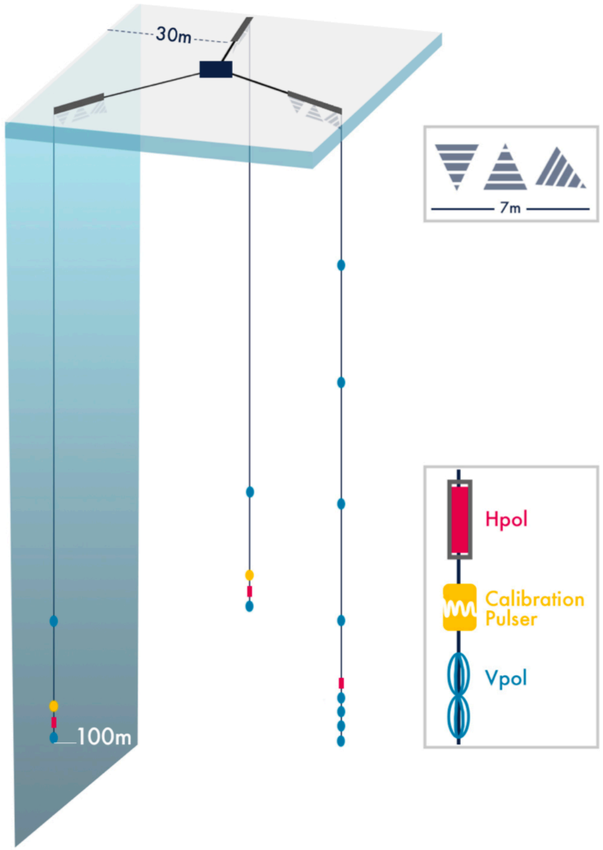


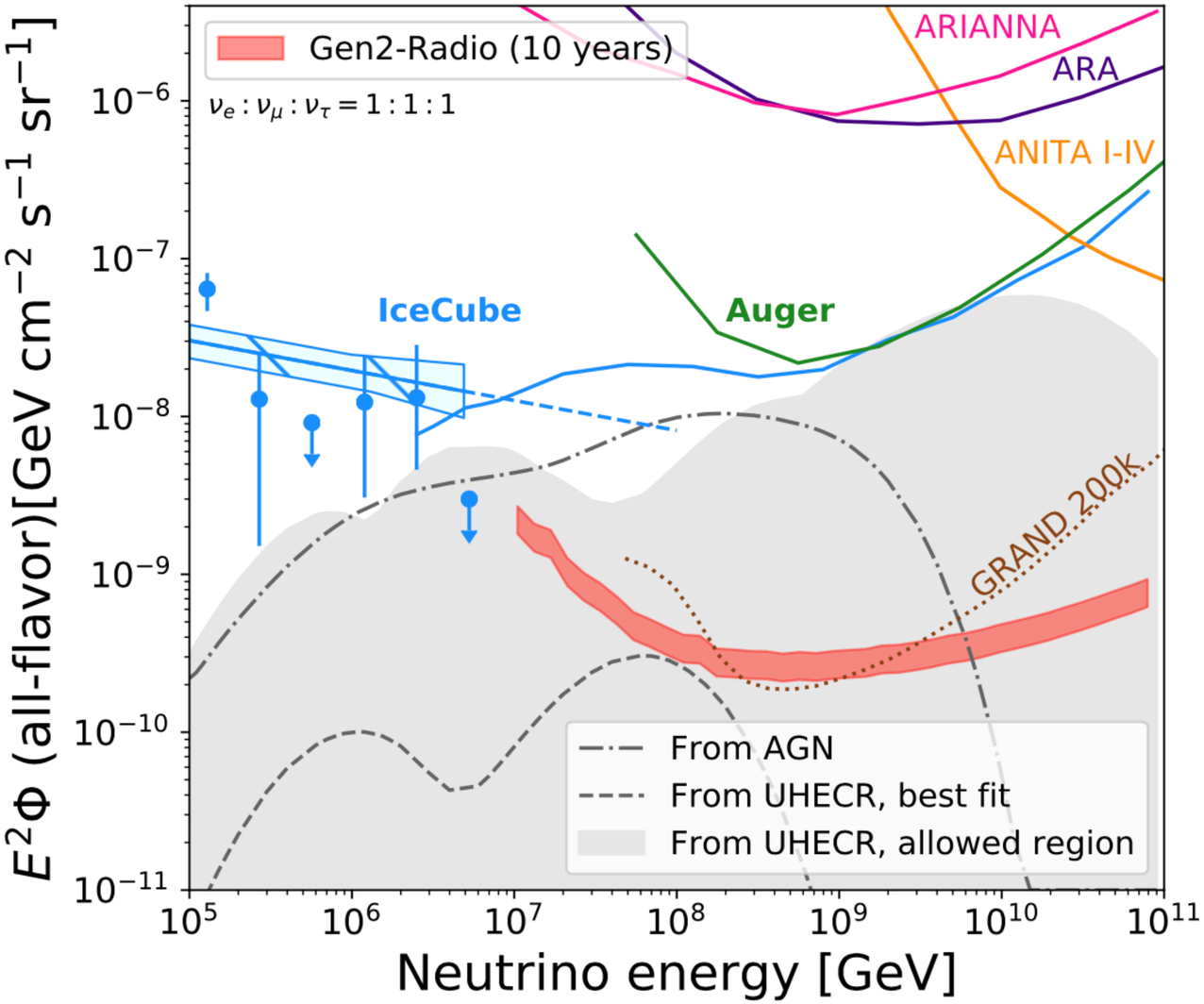
NSF

IceCube GEN2

The Gen2 radio array

Design under review.
Task Force assigned to advance and detail the conceptual design.





IceCube-Gen2 - Challenges: Radio array deployment

Drilling

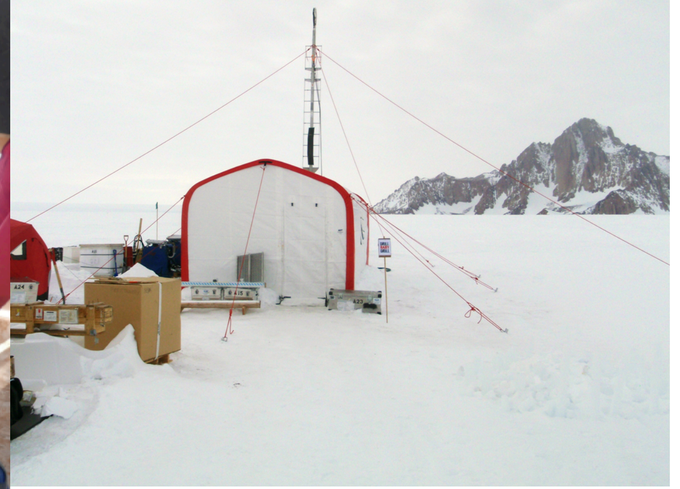
1. Drilling 600 holes for radio while a challenge, is conceptually straightforward.
2. Scalable solutions exist. ASIG drill is current reference. Requires to people to operate. can be turned on and off.
3. For production, a conceptually similar but more automated design of the British Antarctic Survey may be employed..

Population: 2 - 3 people/hole/day

Deployment

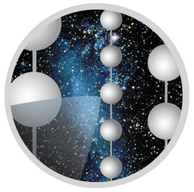
1. Deployment takes most of the labor. about 2/3 of the population will be needed for deployment.
2. Long distances require special safety considerations.
3. Good equipment for transportation: Field shelters, Arctic trucks.

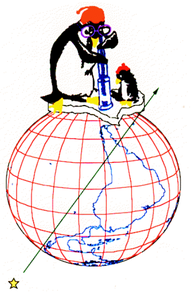
ASIG drill
https://icedrill.org/equipment/agile-sub-ice-geological-drill.shtml

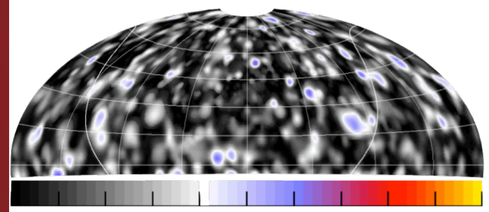


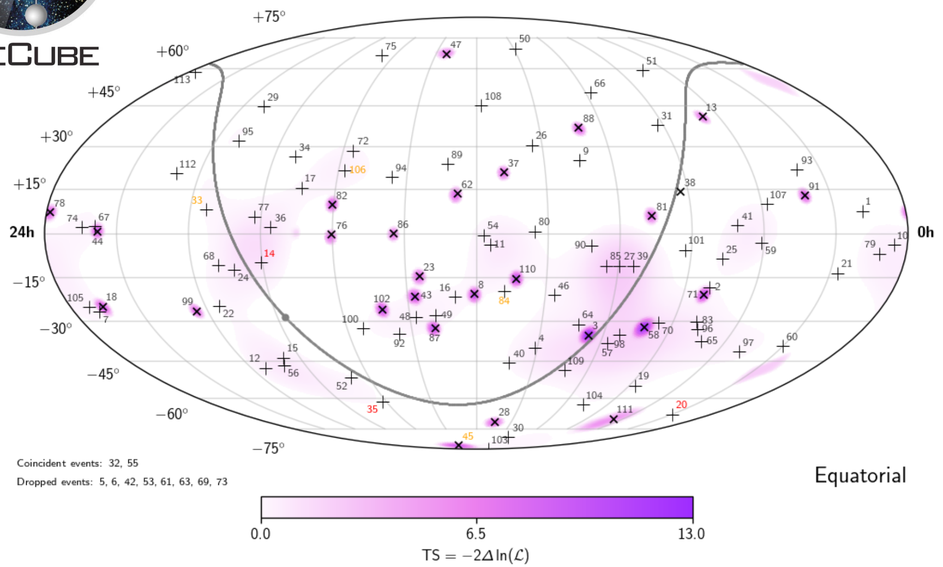
IceCube-Gen2: *From Discovery to Astronomy*

…building the future of a new field









Gen2 Phase 1 (Upgrade) drill camp; January 29, 2020

$E < 300\,\text{TeV}$ | $300\,\text{TeV} < E < 1\,\text{PeV}$ | $1\,\text{PeV} < E$

1st atmospheric neutrinos in ice

Discovery of astrophysical neutrino flux

First source identified

2002 AMANDA

2004 IceCube

2013

2018

2020

2023 Gen2 Phase 1 (Upgrade)

2026

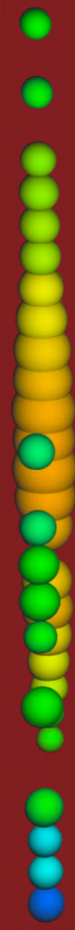
2032 IceCube-Gen2

First full Gen2 deployment season

Gen2 full detector completion

NSF

IceCube GEN2



IceCube
GEN2