# Workshop on Machine Learning for Analysis of High-Energy Cosmic Particles

Abstract Deadline extended to:

**30 Nov 2024**

27-31 January 2025
University of Delaware

Hybrid workshop: remote and in-person participants welcome.

Ask me for voucher code if registration fee would be an issue.

https://events.icecube.wisc.edu/event/243/


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# Science Potential and Technical Design of the
# **IceCube-Gen2 Surface Array**

**Frank G. Schröder** for the IceCube-Gen2 Collaboration

UD – University of Delaware
KIT – The Research University in the Helmholtz Association

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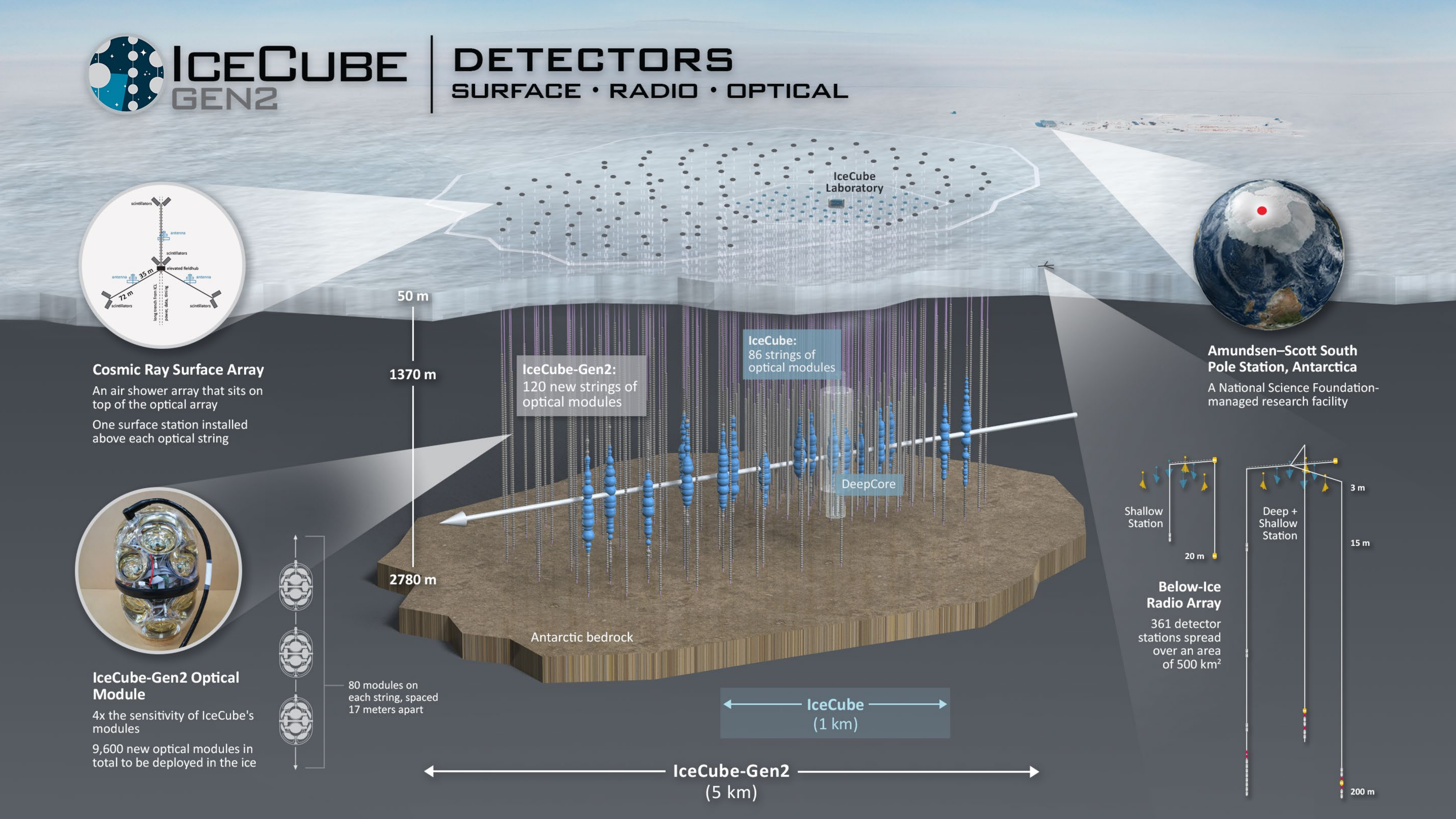
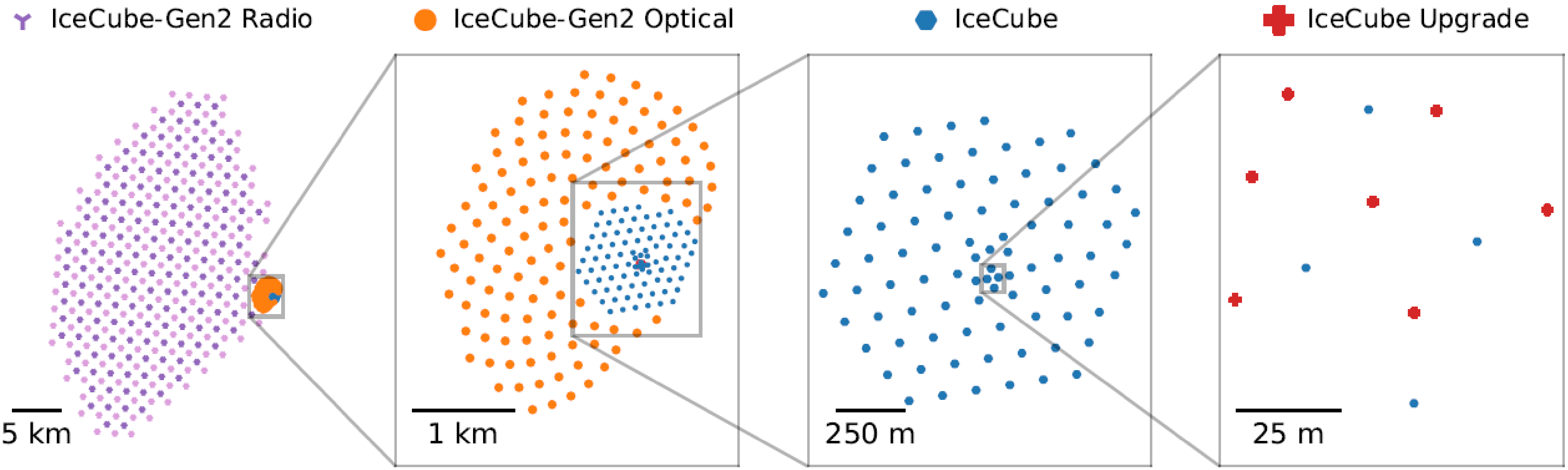

IceCube GEN2
DETECTORS
SURFACE • RADIO • OPTICAL
IceCube Laboratory
scintillators
antenna
elevated fieldhub
35 m
72 m
Cosmic Ray Surface Array
An air shower array that sits on top of the optical array
One surface station installed above each optical string
50 m
1370 m
2780 m
IceCube-Gen2: 120 new strings of optical modules
IceCube: 86 strings of optical modules
DeepCore
Antarctic bedrock
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
Shallow Station
Deep + Shallow Station
3 m
15 m
20 m
200 m
Below-Ice Radio Array
361 detector stations spread over an area of 500 km²
IceCube-Gen2 Optical Module
4x the sensitivity of IceCube's modules
9,600 new optical modules in total to be deployed in the ice
80 modules on each string, spaced 17 meters apart
IceCube (1 km)
IceCube-Gen2 (5 km)

# IceCube-Gen2: extending the IceCube Neutrino Observatory

- An order of magnitude larger *deep optical* and *surface* arrays
- Large *in-ice radio* array for ultra-high-energy neutrinos




IceCube-Gen2 Technical Design Report (TDR): https://icecube-gen2.wisc.edu/science/publications/tdr/



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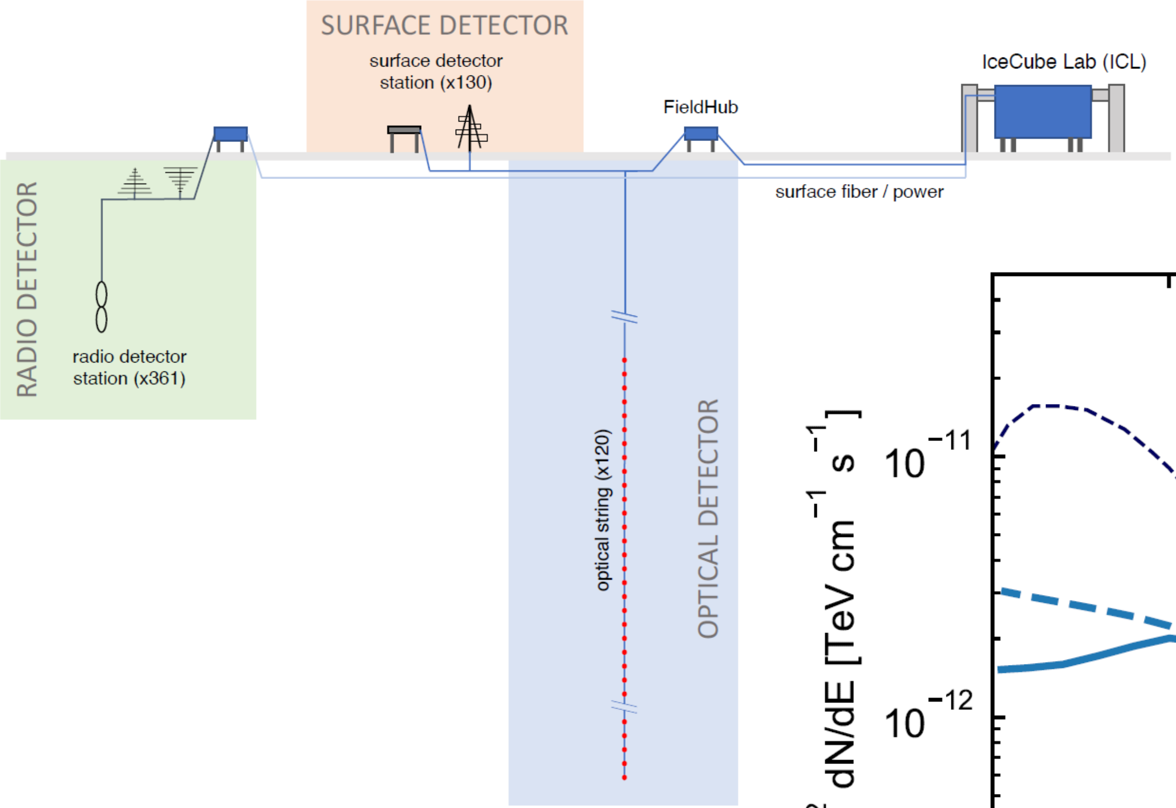
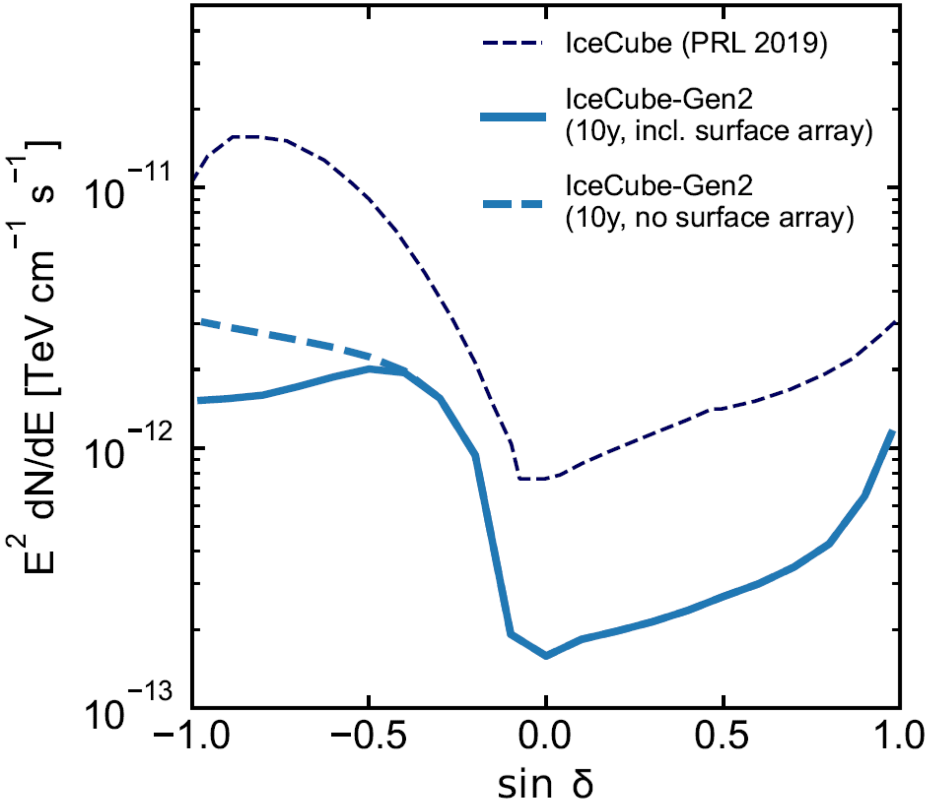
# IceCube-Gen2 Optical Array

- 10x of IceCube's volume
- 120 strings of Digital Optical Modules (DOMs)
- Improved DOM design

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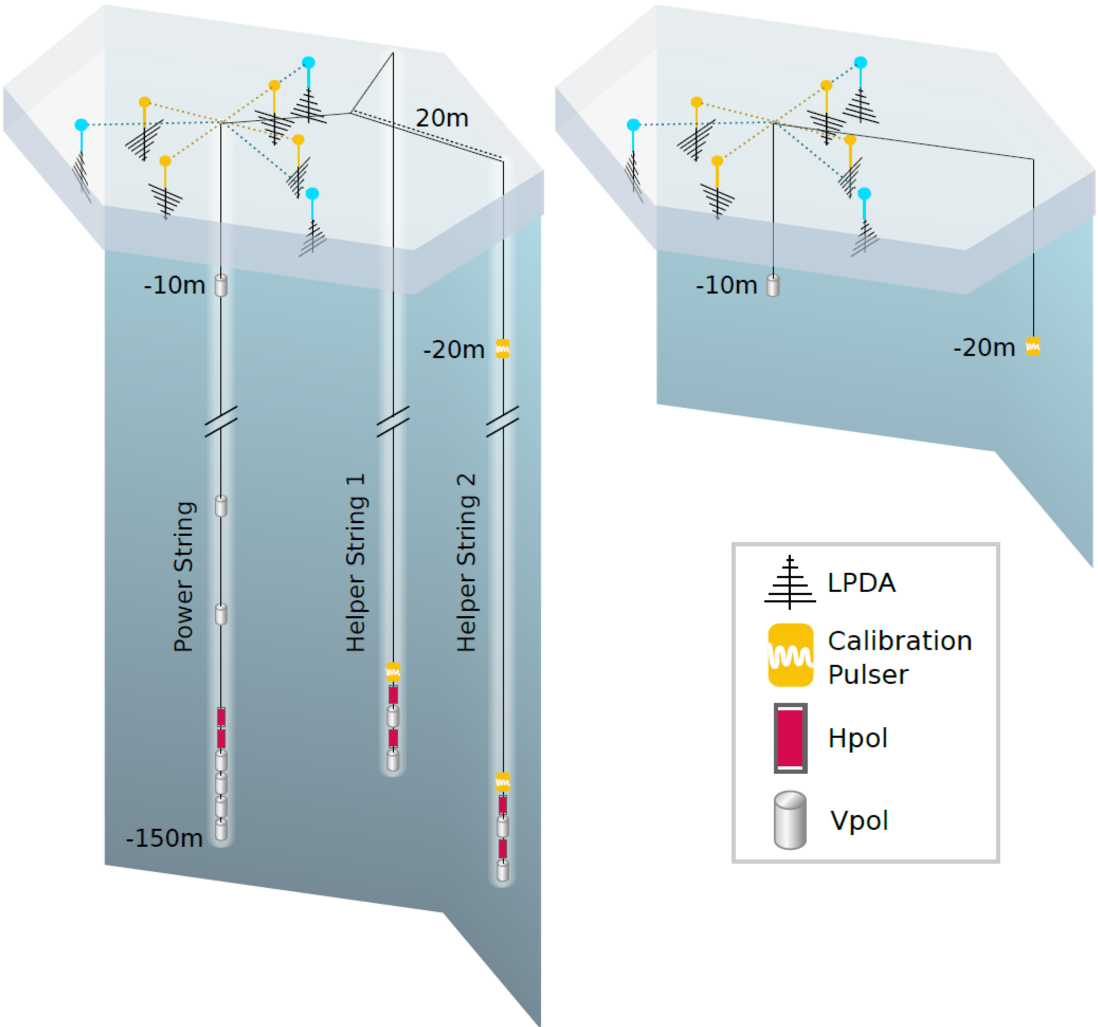
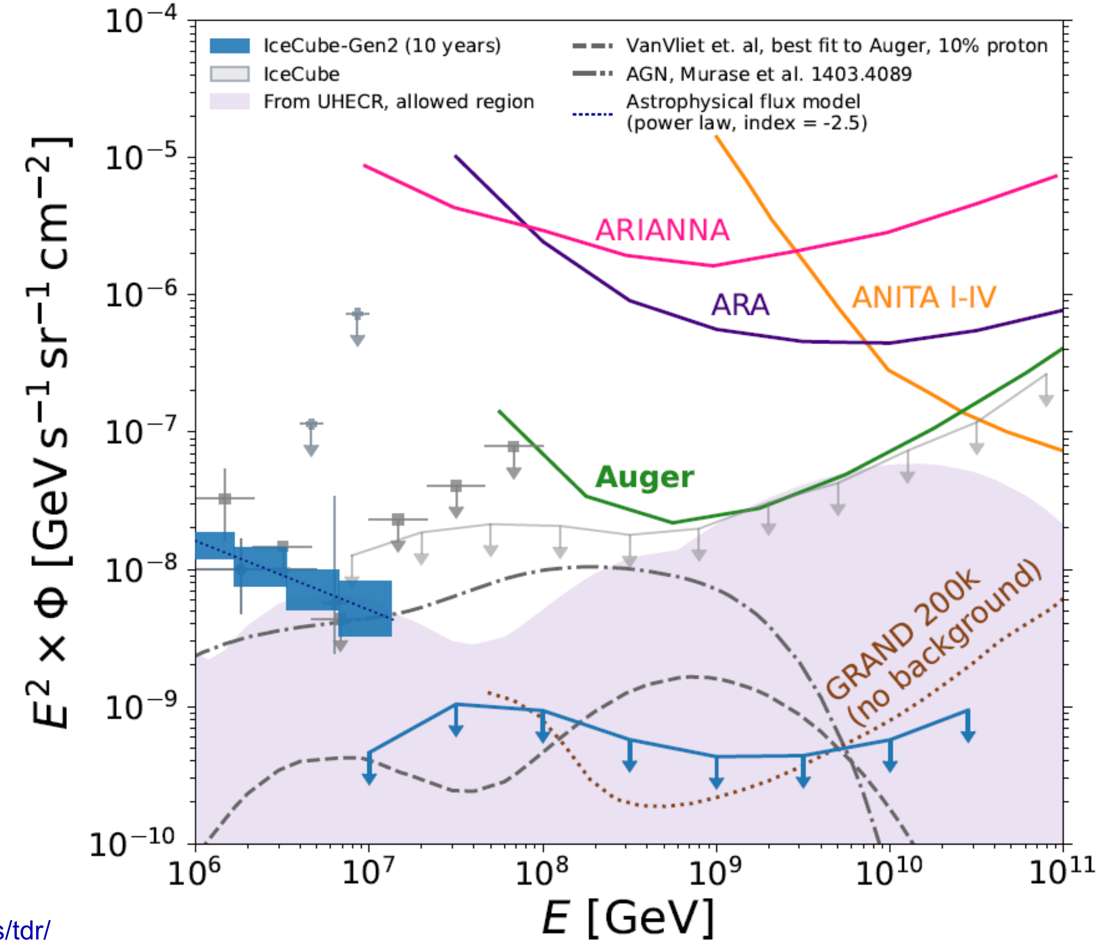
# IceCube-Gen2 Radio Array

- Shallow + deep antennas; tested at Radio Neutrino Observatory Greenland (RNO-G)

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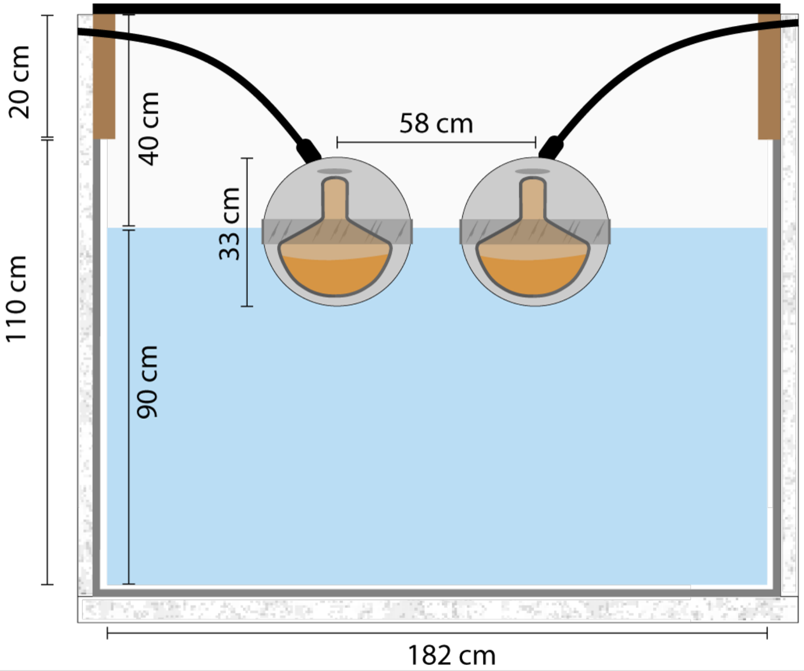
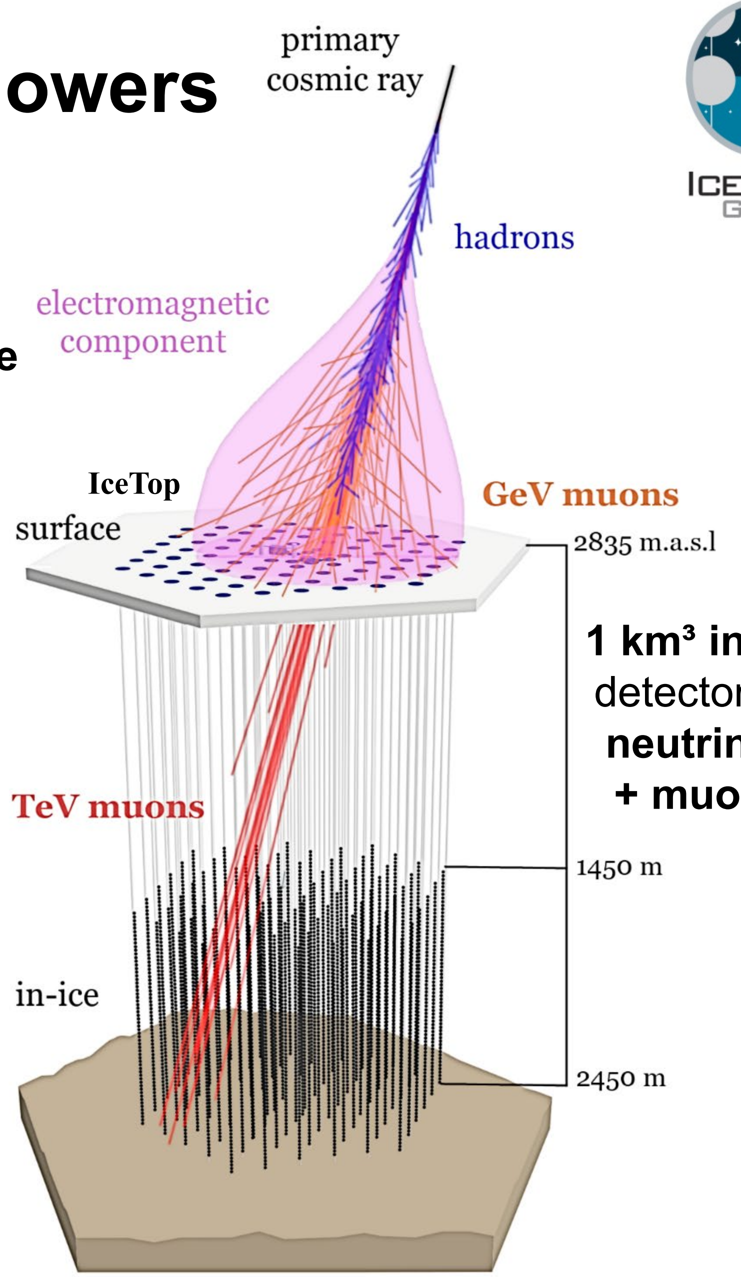
# IceCube as a Detector for Cosmic-Ray Air Showers

- IceTop = surface array of ice-Cherenkov detectors
  - Veto for neutrino detection with in-ice detector
  - Air-shower physics → atmospheric leptons
  - PeV cosmic rays and photons
- Threshold increase over time due to snow coverage




IceCube Coll., NIM A 700 (2013) 188

**1 km² surface** detector for **air showers**




**1 km³ in-ice** detector for **neutrinos + muons**

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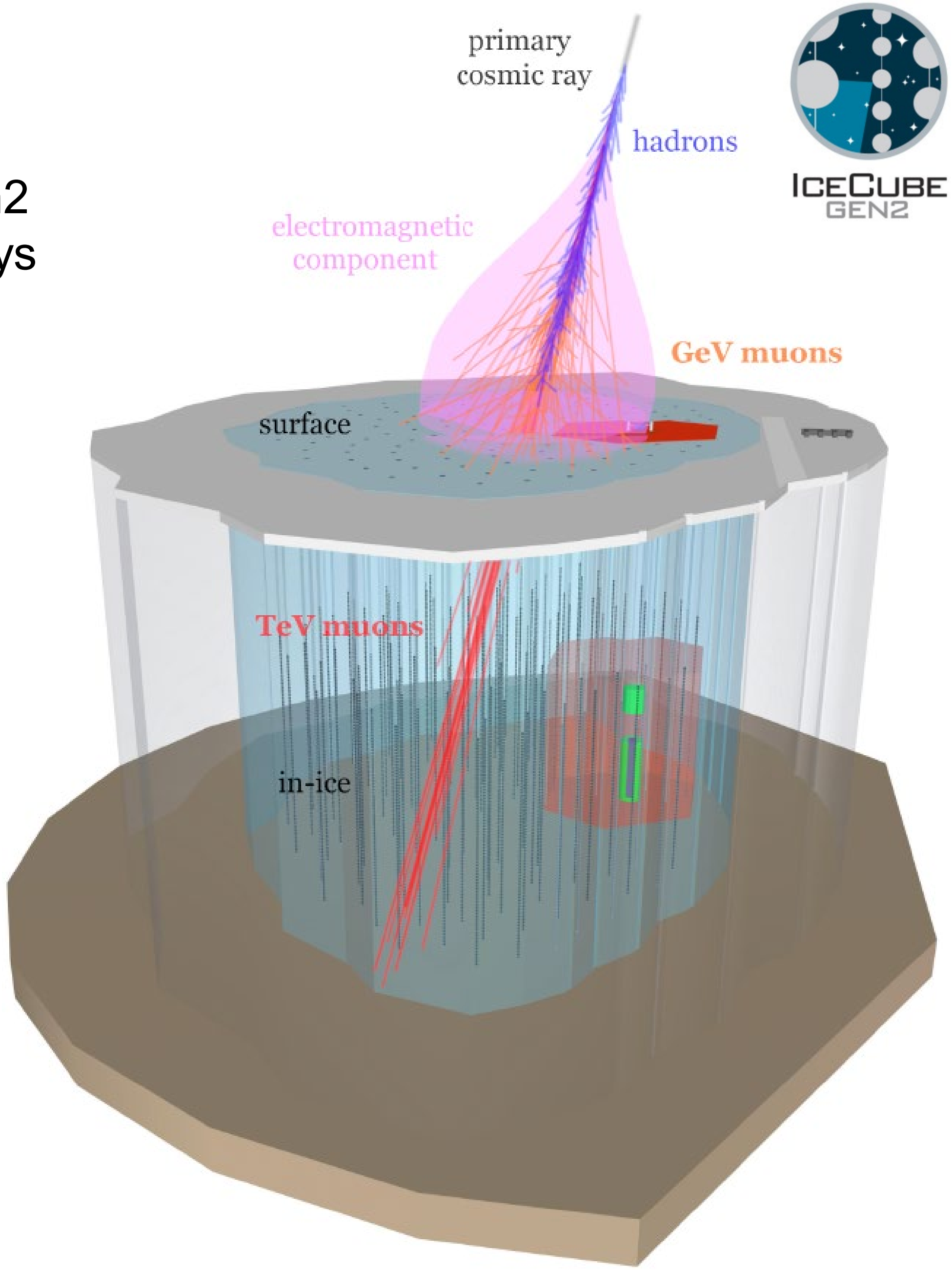
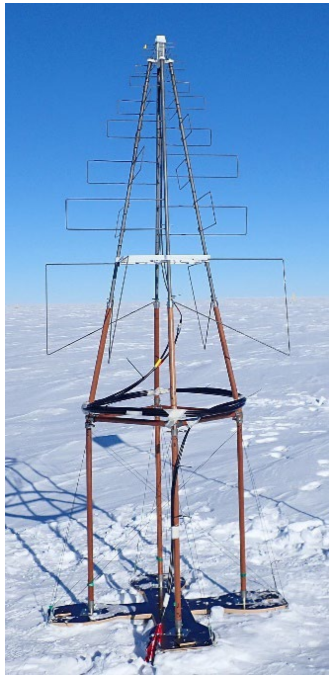
# IceCube-Gen2 and its Surface Array

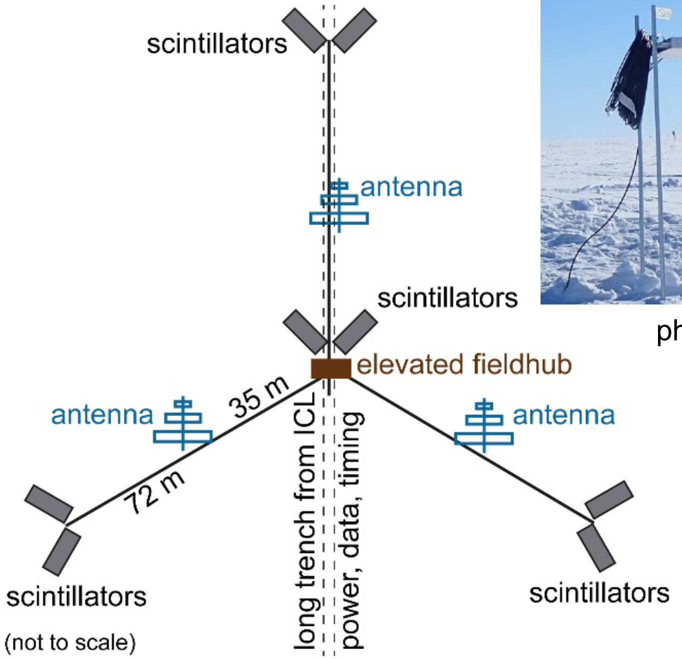
- Combination of deep and surface detector will make IceCube-Gen2 a unique laboratory for air-shower physics and Galactic cosmic rays
- 8x larger area, 30x larger aperture for in-ice coincidences




**<u>Surface Array of approx. 150 stations</u>**:

4 pairs of scintillators + 3 antennas






photos: prototype station at South Pole

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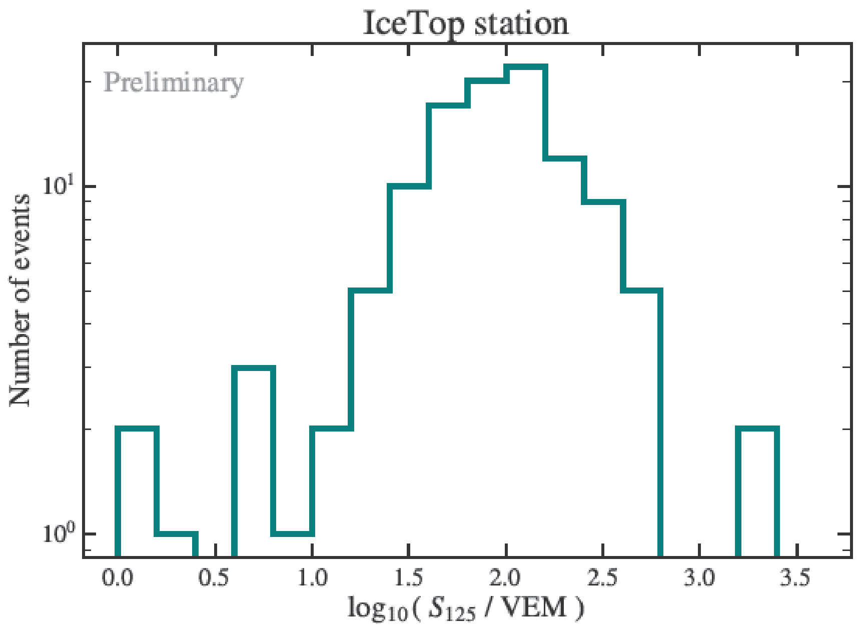
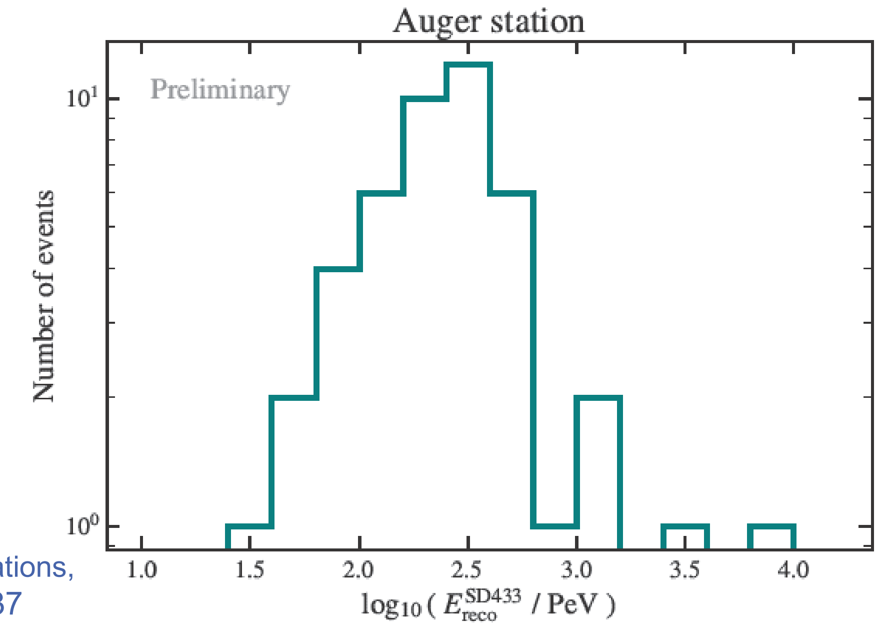
# Prototype Stations of the IceCube-Gen2 Surface Array

- Prototype stations of 3 antennas and 8 scintillators at IceCube, Telescope Array, Pierre Auger Observatory
- Right: radio observation of air-showers with these stations upon a trigger by the scintillation panels

Photos of Auger Station




IceCube-Gen2 and Pierre Auger Collaborations, PoS(ARENA2024)037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# Overview on Science Case of IceCube-Gen2 Surface Array

Rich science case makes use of unique combination of surface + deep detector

Surface radio antennas critical for accuracy needed for some science goals

| Science Goals | Scientific Measurements and Observables |
|---|---|
| **Veto** | 1) Veto for down-going events and check of real-time alters<br>2) Test potential of radio veto for very inclined showers |
| Physics using surface *and* in-ice detector | **1) Hadronic interactions** including prompt muons<br>**2) Mass composition** and other cosmic-ray physics using the in-ice detector |
| Other cosmic-ray physics | **1) Anisotropy**, mass composition, energy spectrum, etc. with the surface detector |
| Multi-Messenger: Photons | **1) PeV photon search** has discovery potential for Galactic sources. |
| Calibration of in-ice detectors | 1) Energy scale for air showers, including cross-calibration of in-ice radio antennas<br>2) Calibration of in-ice detectors by air-shower signals and muons |



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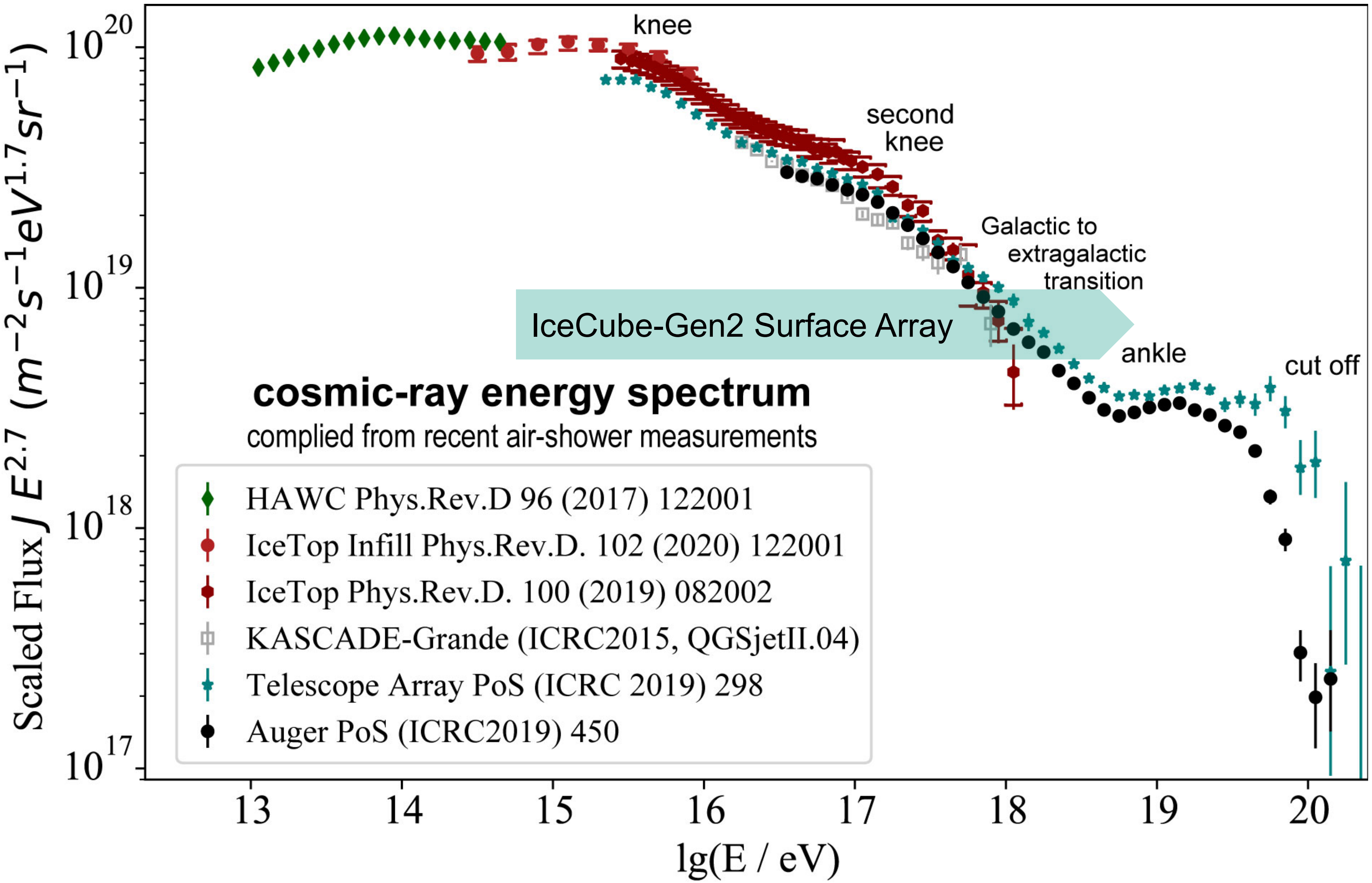
# Energy reach until Ankle: Galactic-to-extragalactic Transition







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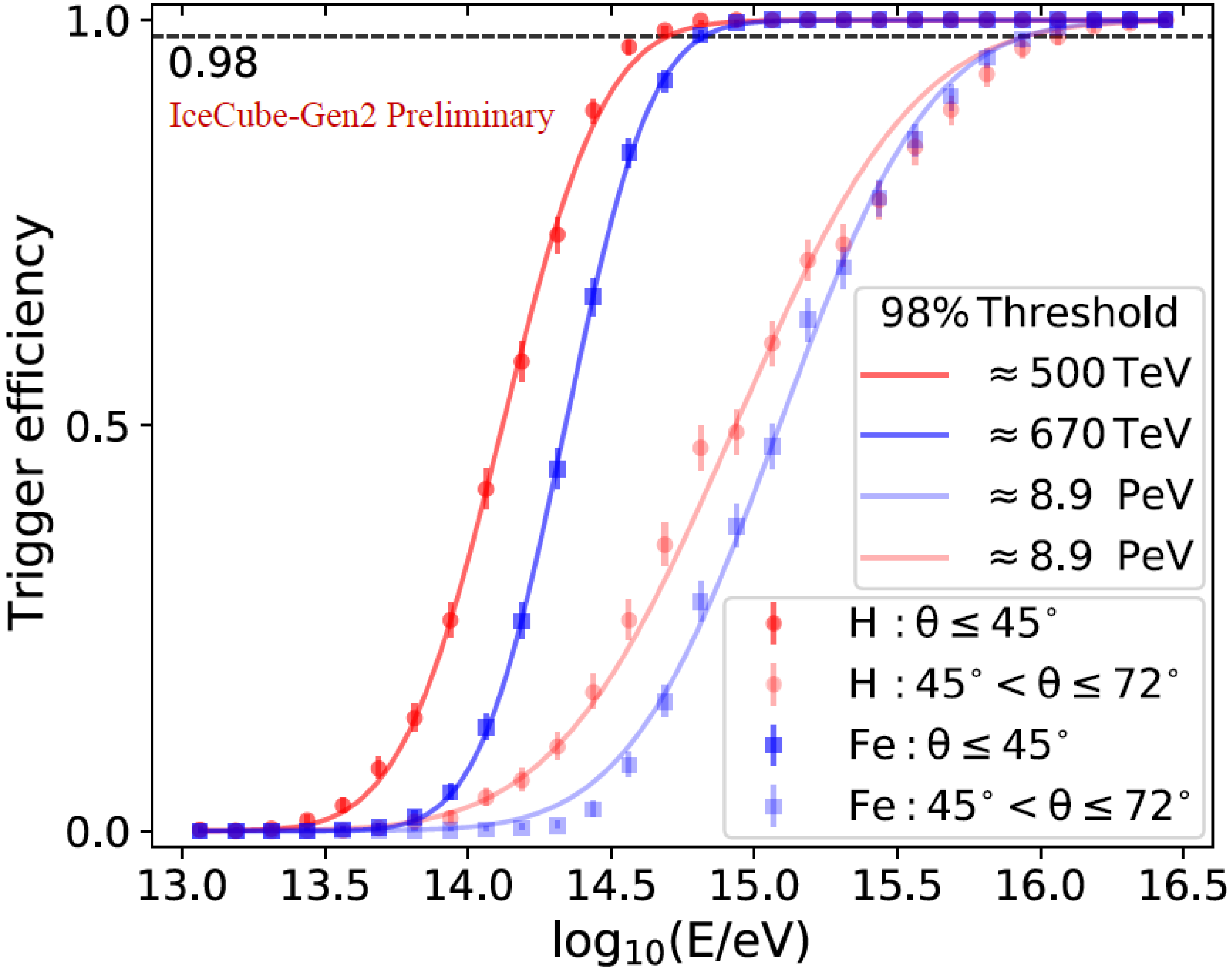
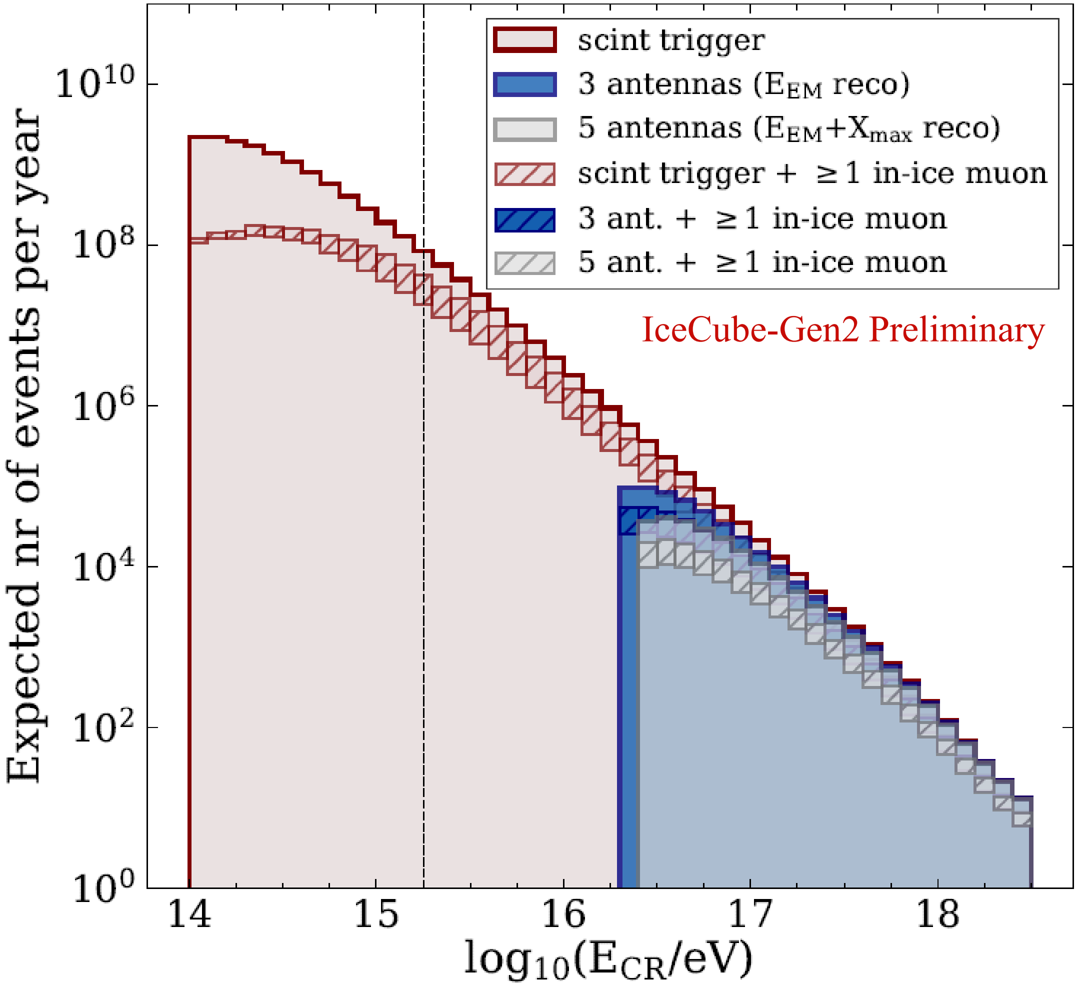
# Low Detection Threshold provided by Scintillators

- 0.5 PeV for vertical protons, 9 PeV for inclined showers → trigger for radio

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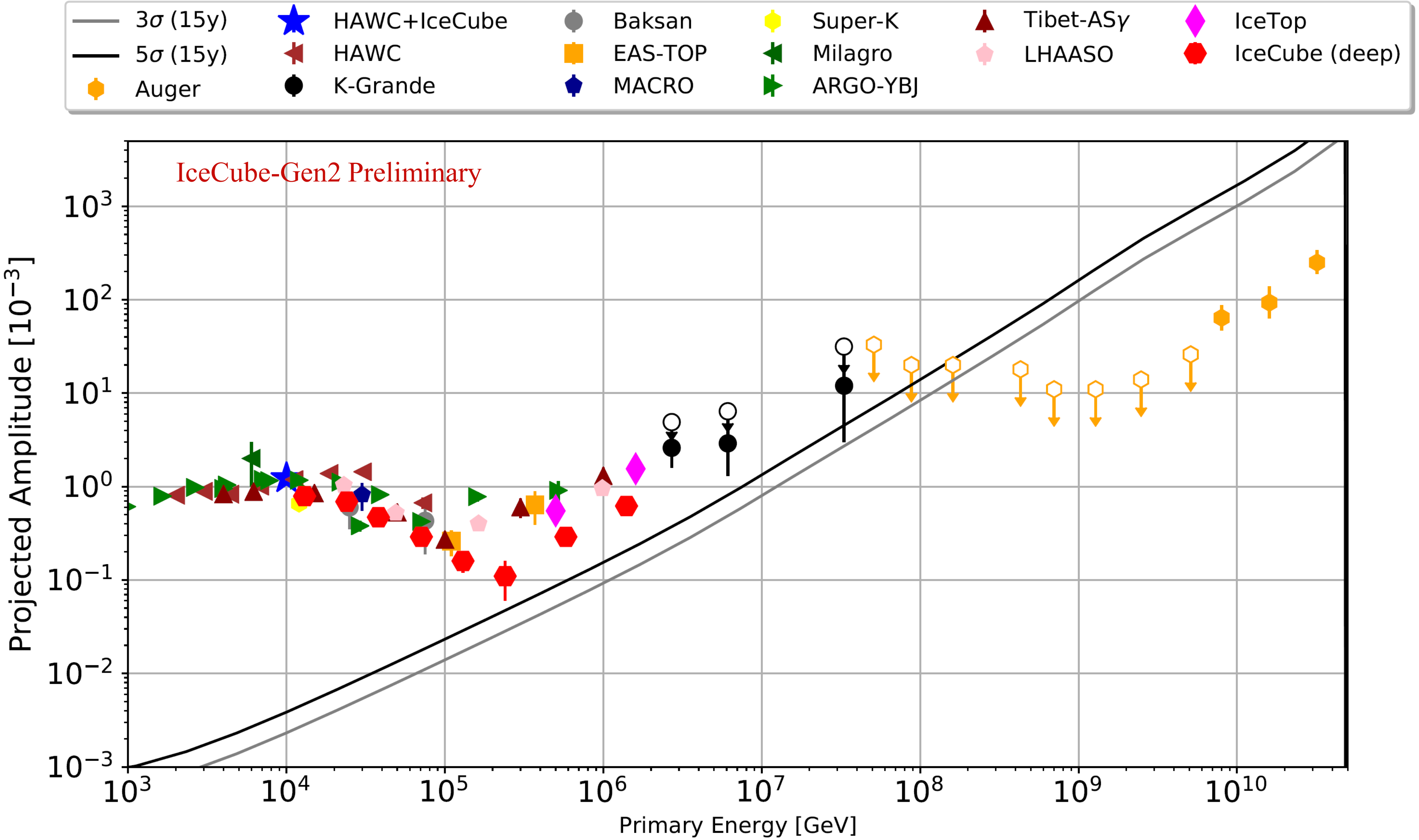
# IceCube-Gen2 Sensitivity to Cosmic-Ray Dipole Anisotropy



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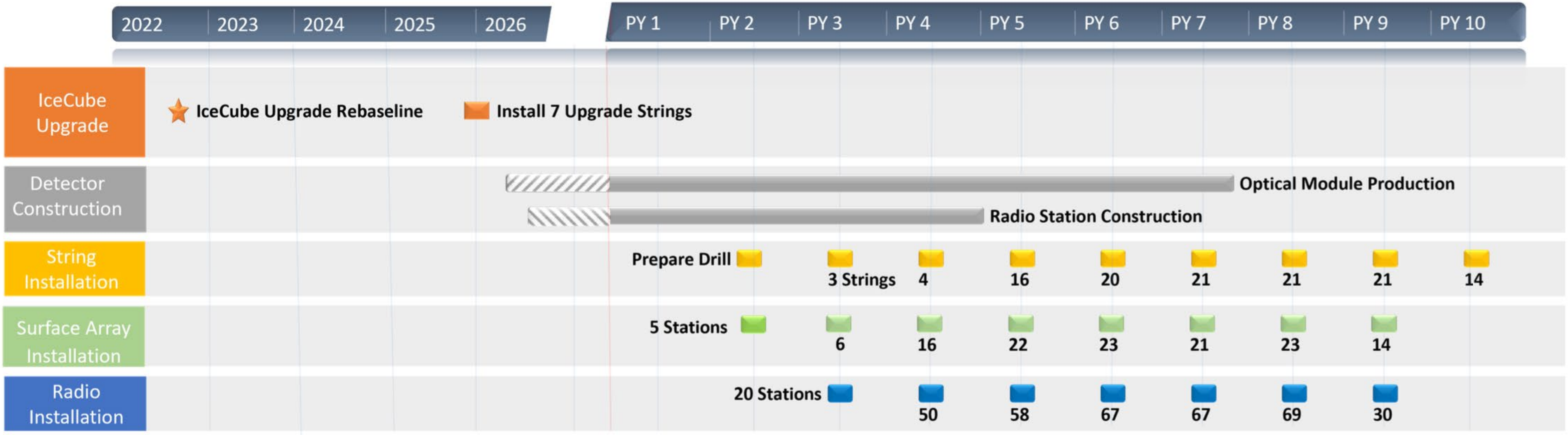
# IceCube-Gen2 Timeline

- Installation of Radio Array, Optical Array, and Surface Array during next decade
  - the IceCube Upgrade (7 additional strings in the center) will inform about IceCube-Gen2
- IceCube-Gen2 recommended by P5 panel in the U.S., but needs to wait for reinforcement of infrastructure at the South Pole planned for the next few years

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# Conclusion

## IceCube-Gen2 Surface Array

- Cover footprint of Gen2 optical array by an array of elevated scintillators and radio antennas
- Threshold of 0.5 PeV constantly provided by scintillation panels → veto and hadronic interactions
- Radio antennas increase accuracy in energy range of galactic-to-extragalactic transition

→ IceCube-Gen2 will also be a unique cosmic-ray laboratory with its surface and in-ice detectors


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# Additional Slides


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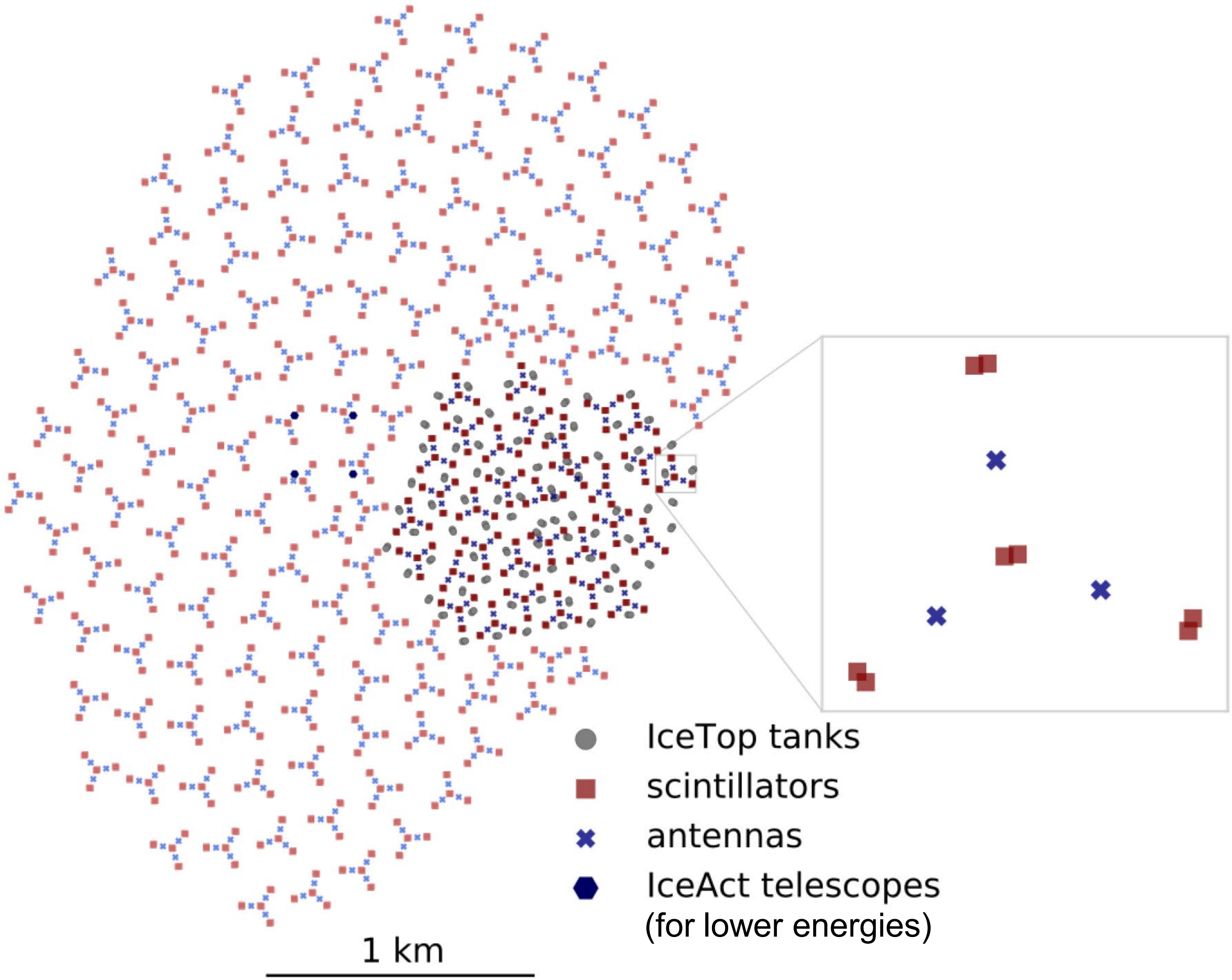
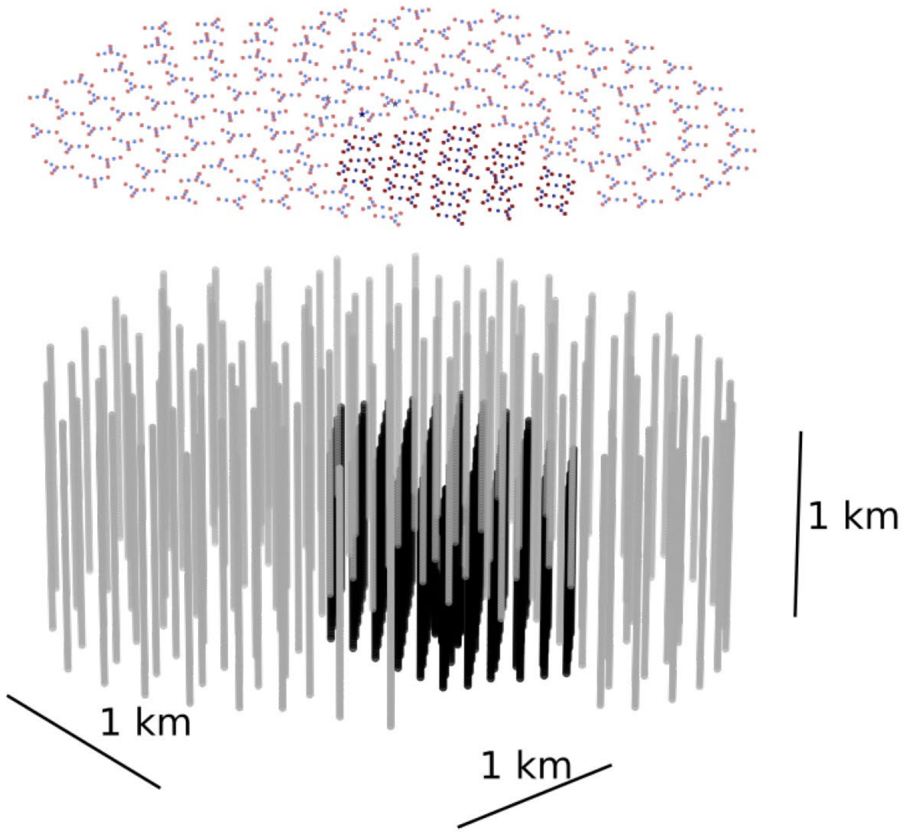
# IceCube-Gen2 Surface Array above the Optical Array





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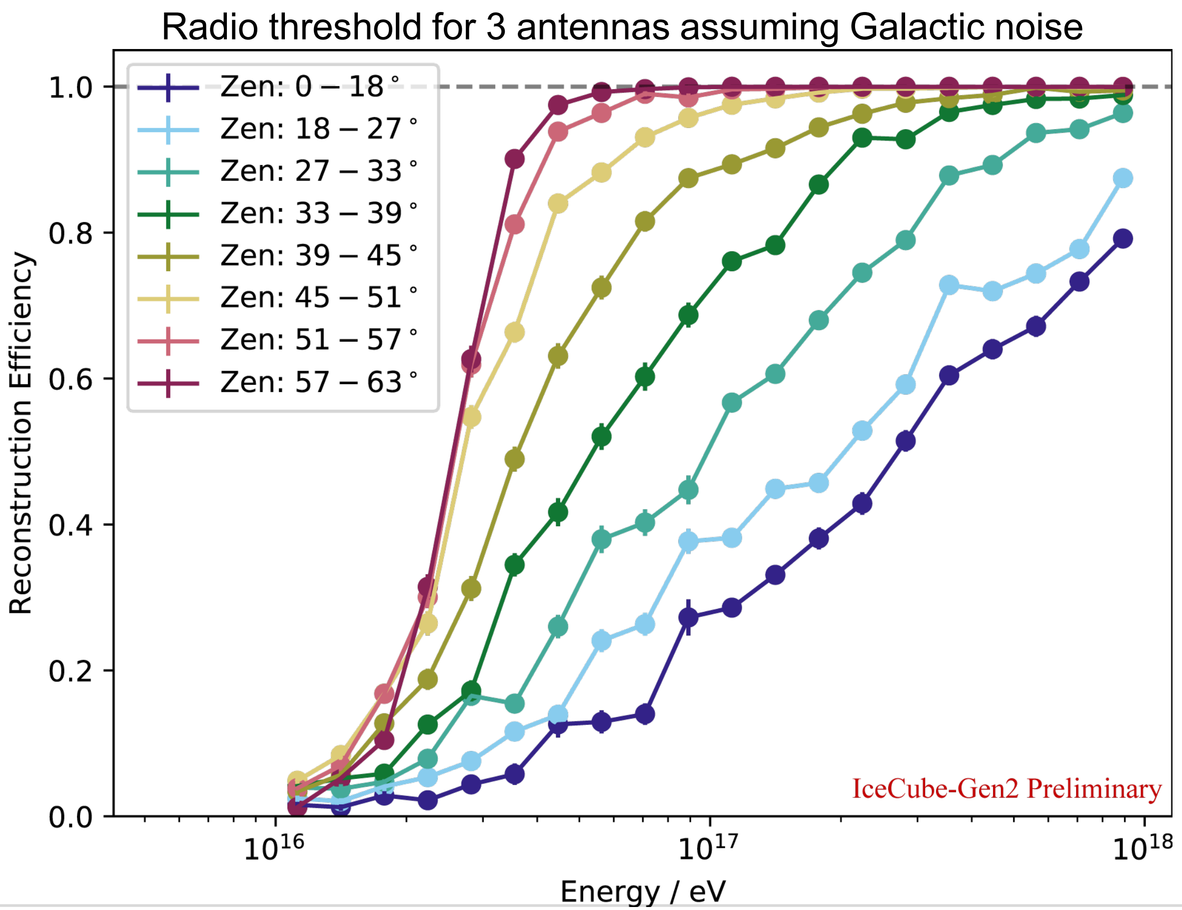
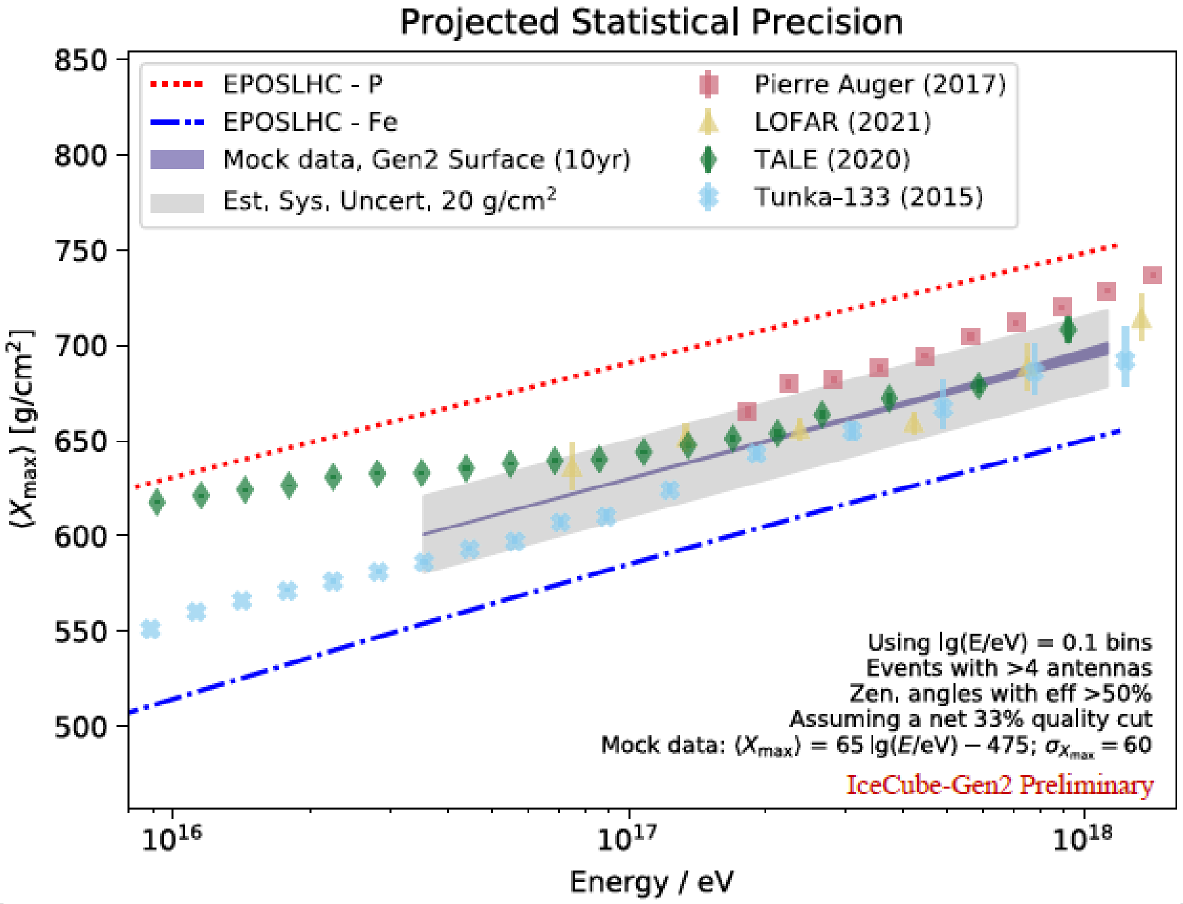
# Result: Radio antennas will increase accuracy above $10^{16.5}$ eV

- Assuming a precise $X_{max}$ reconstruction with 5+ antennas, highest accuracy for mass composition is provided from $10^{16.5}$ eV to above $10^{18}$ eV → most energetic Galactic Cosmic Rays
- Combination with muon measurements will maximize accuracy for this important energy range







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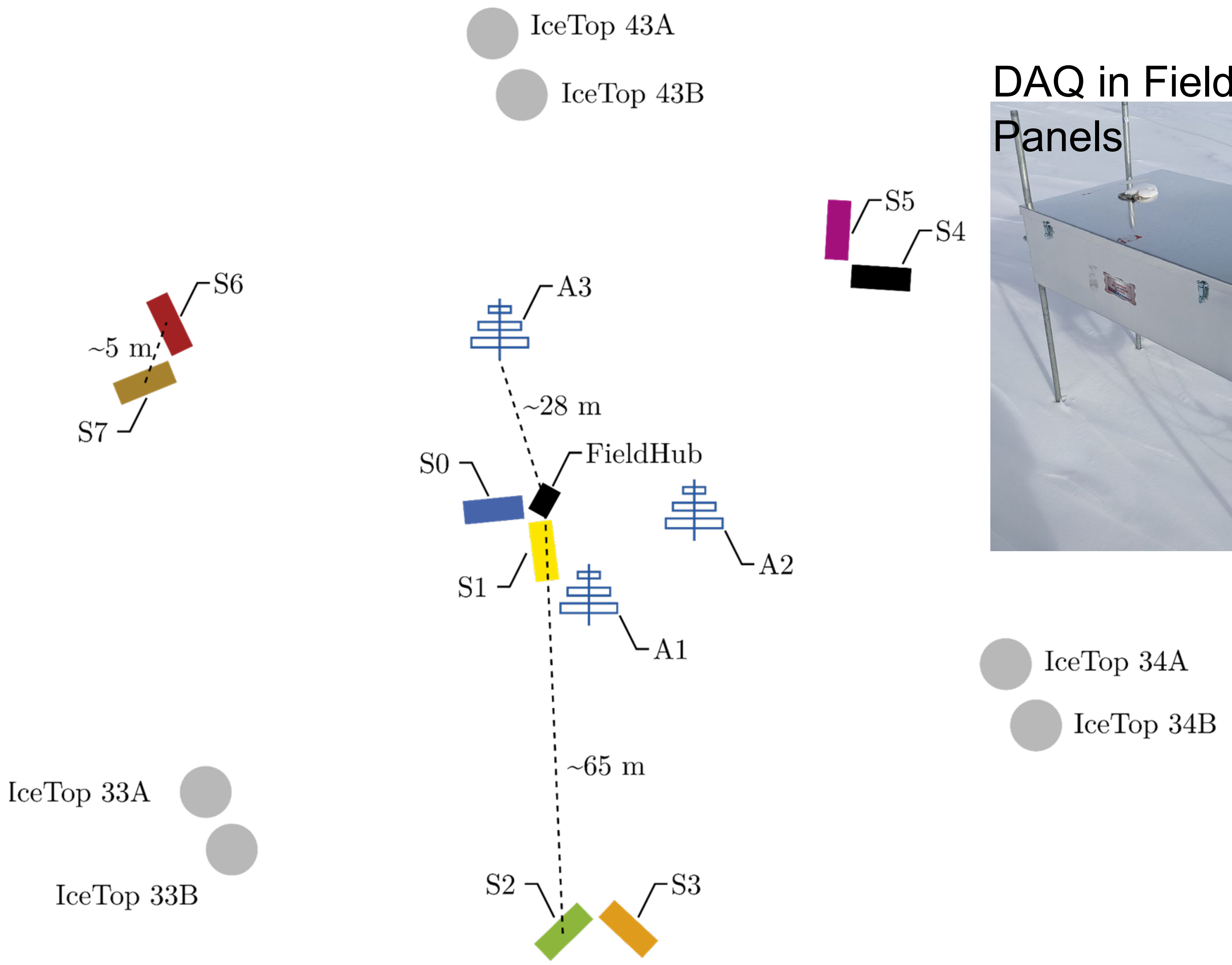
# New Surface Detectors for IceTop and IceCube-Gen2





- Prototype Station of 8 scintillators and 3 antennas deployed in 2020
  - several hardware and software configurations
- Radio readout triggered by scintillators
- Merging with IceTop events offline

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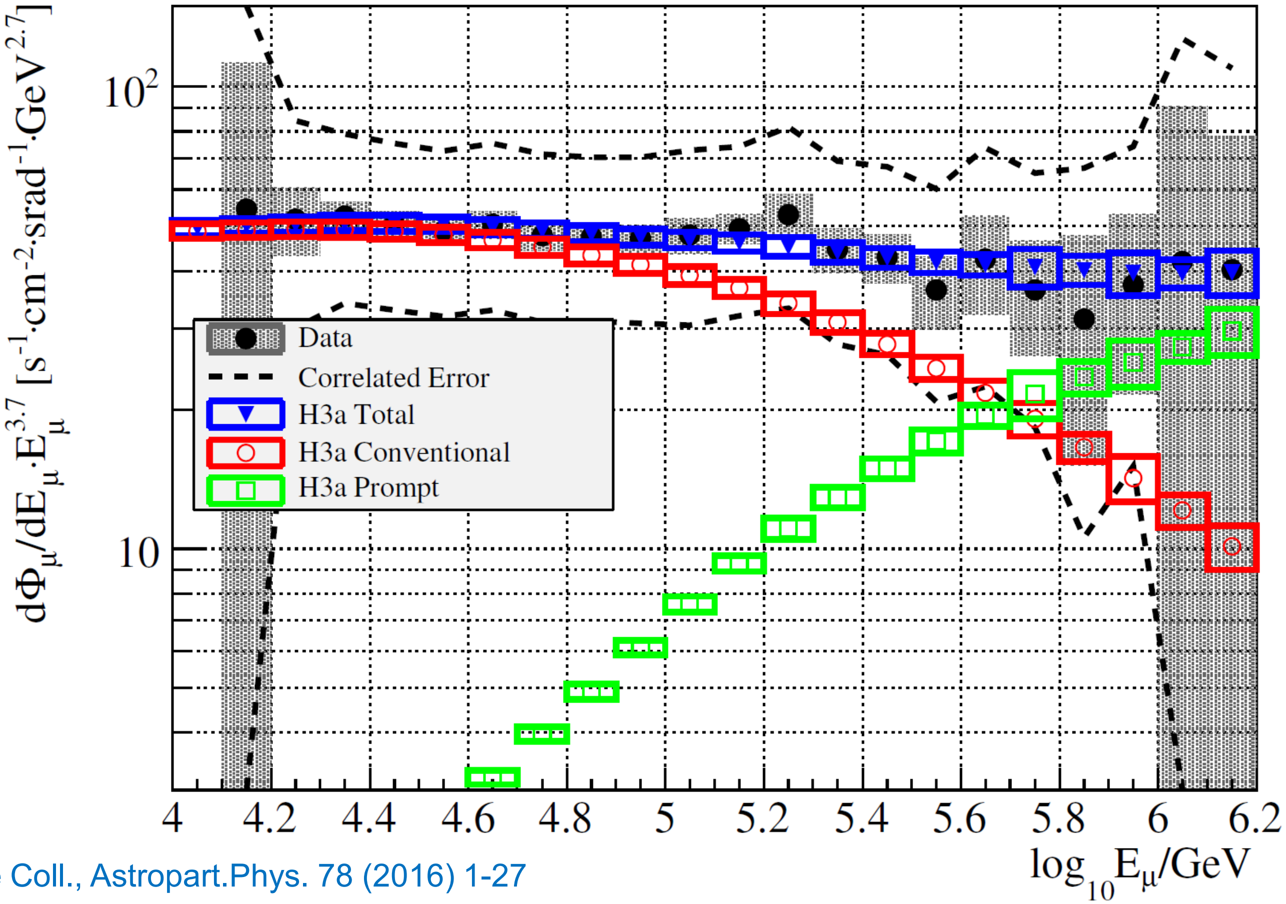
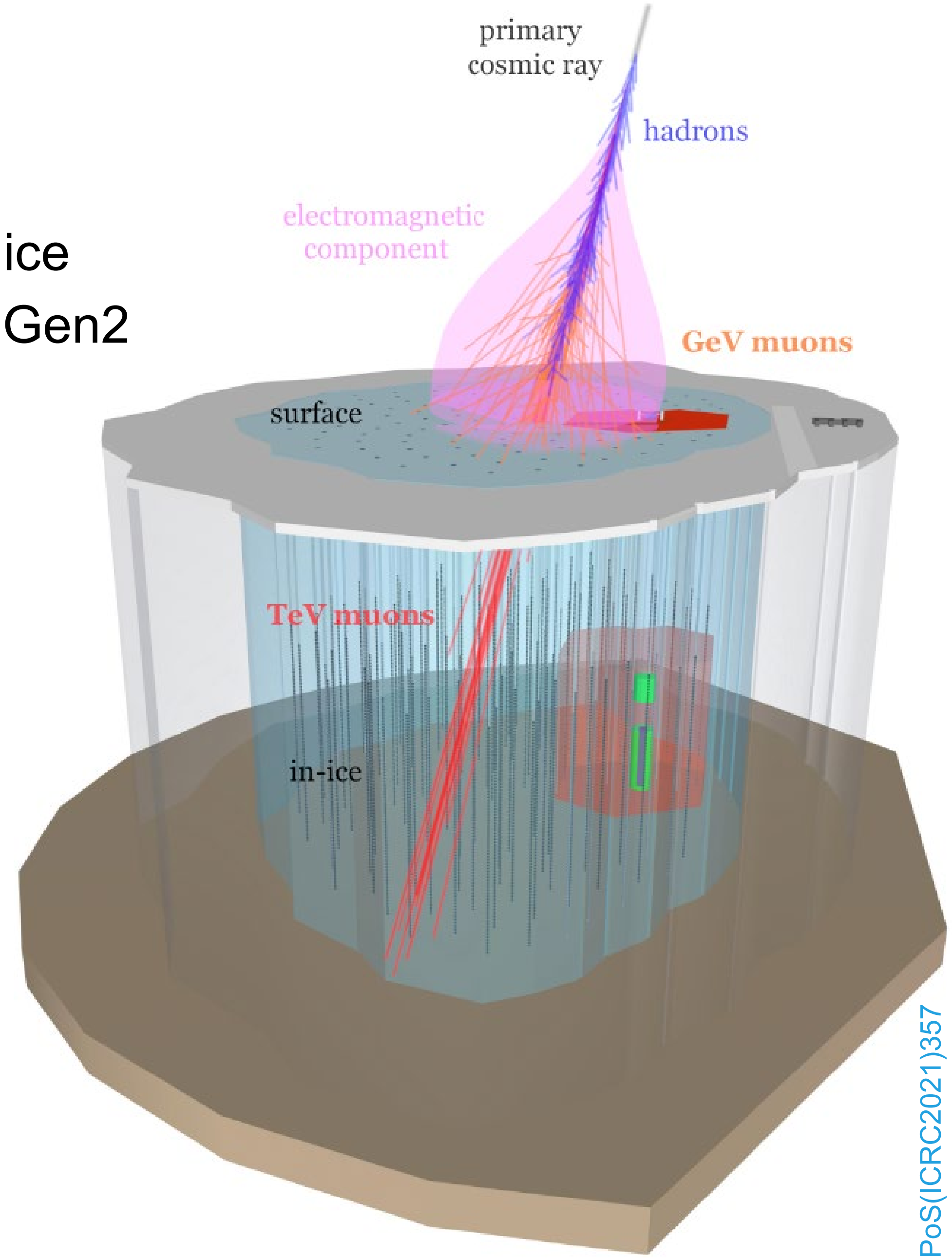
# Muon Spectrum and PeV Prompt Muons

- scrutinize hadronic interaction models by *muon spectrum:* GeV muons at surface detectors + TeV-PeV muons in the ice
- possible with Gen1, but huge aperture increase (> 30×) in Gen2




IceCube Coll., Astropart.Phys. 78 (2016) 1-27

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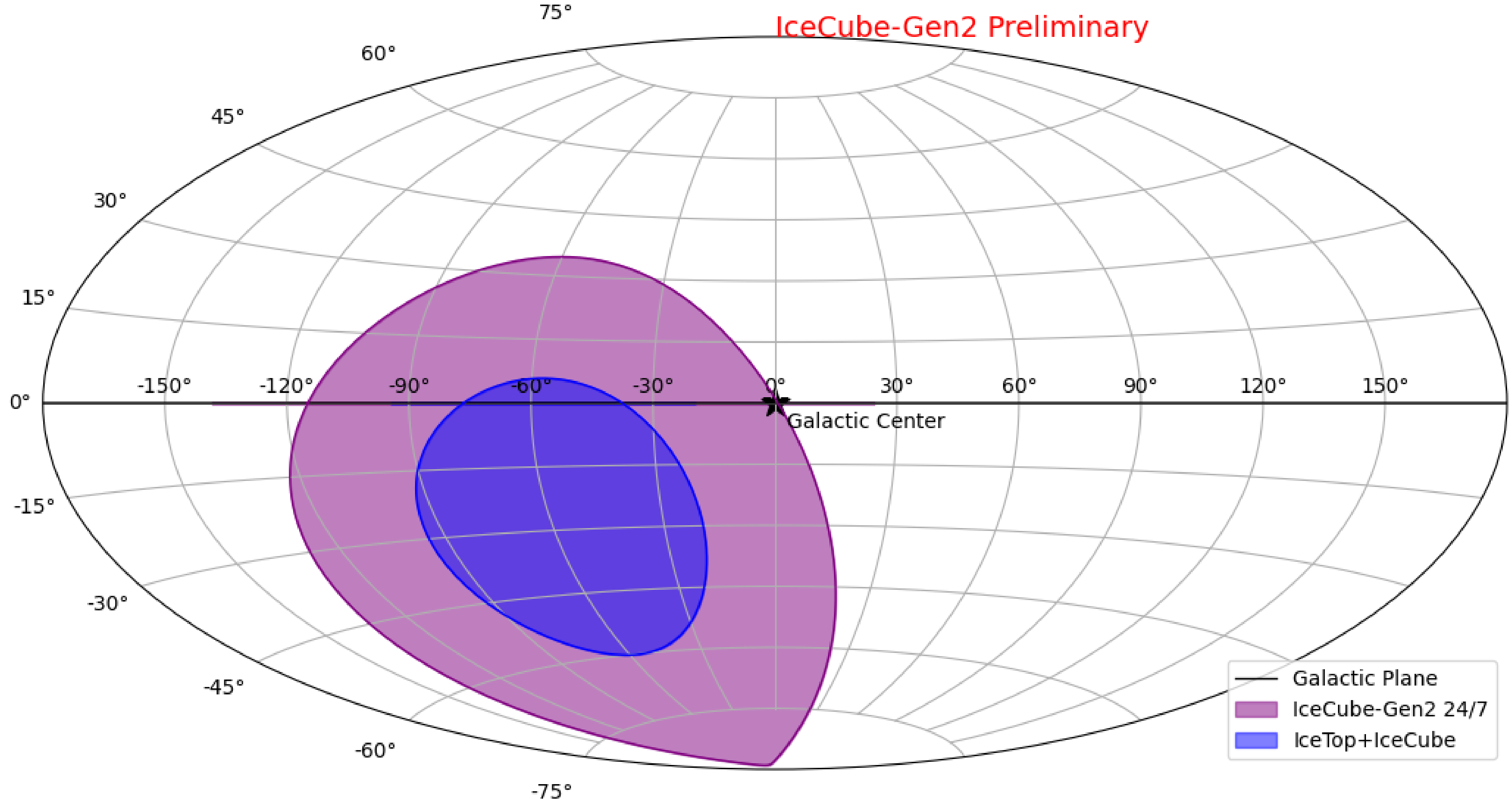
# IceCube-Gen2 Field-of-View for PeV Photons





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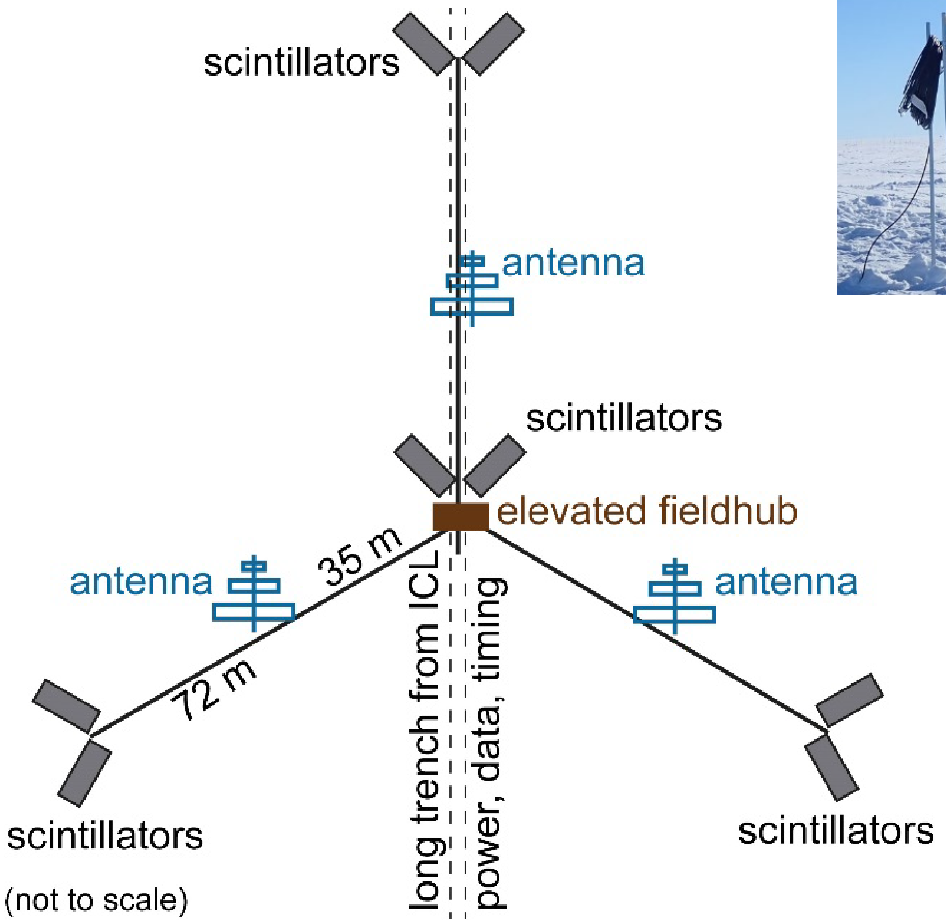
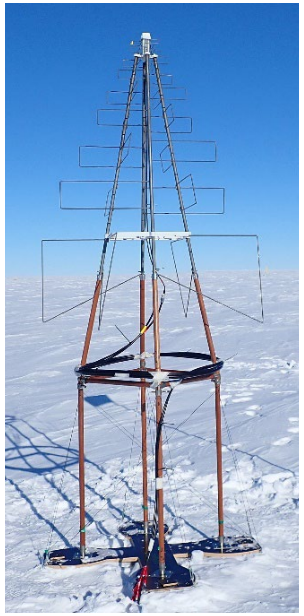
# Baseline Design Follows Planned Enhancement of IceTop

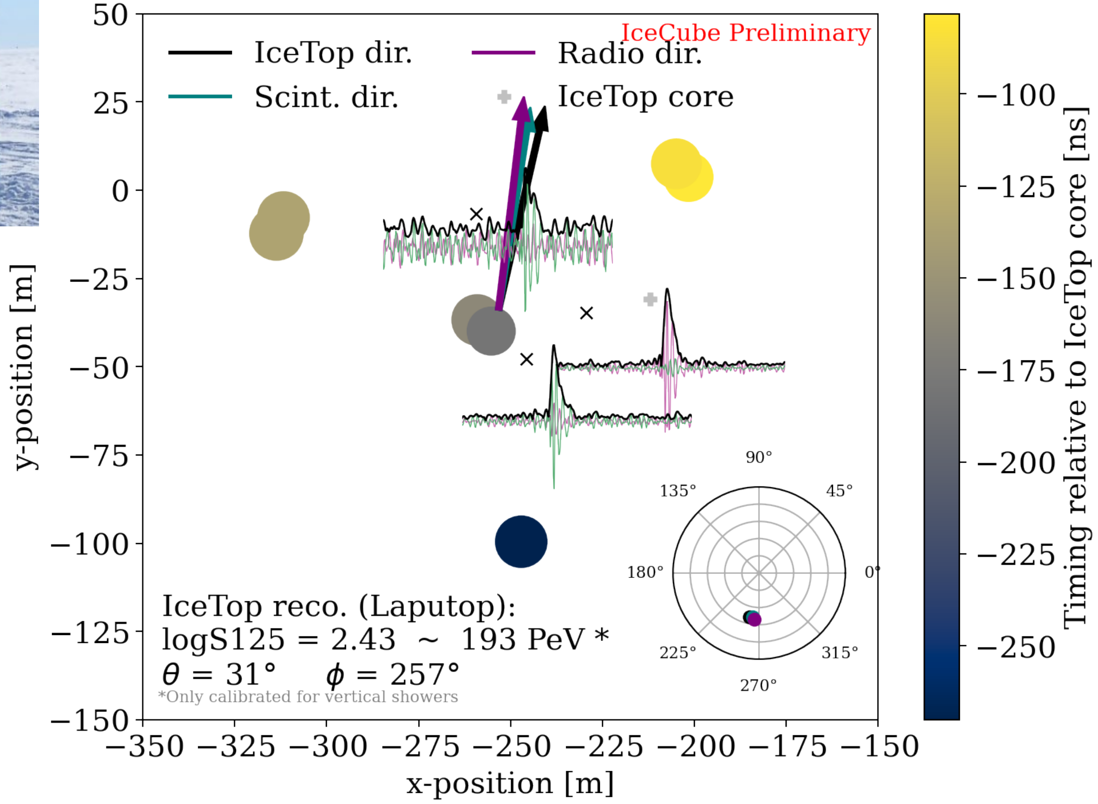
## Station Design:

4 pairs of scintillators + 3 antennas



Complete prototype station since 2020:
scintillator + radio + IceTop coincidences




Example event detected in coincidence with IceTop



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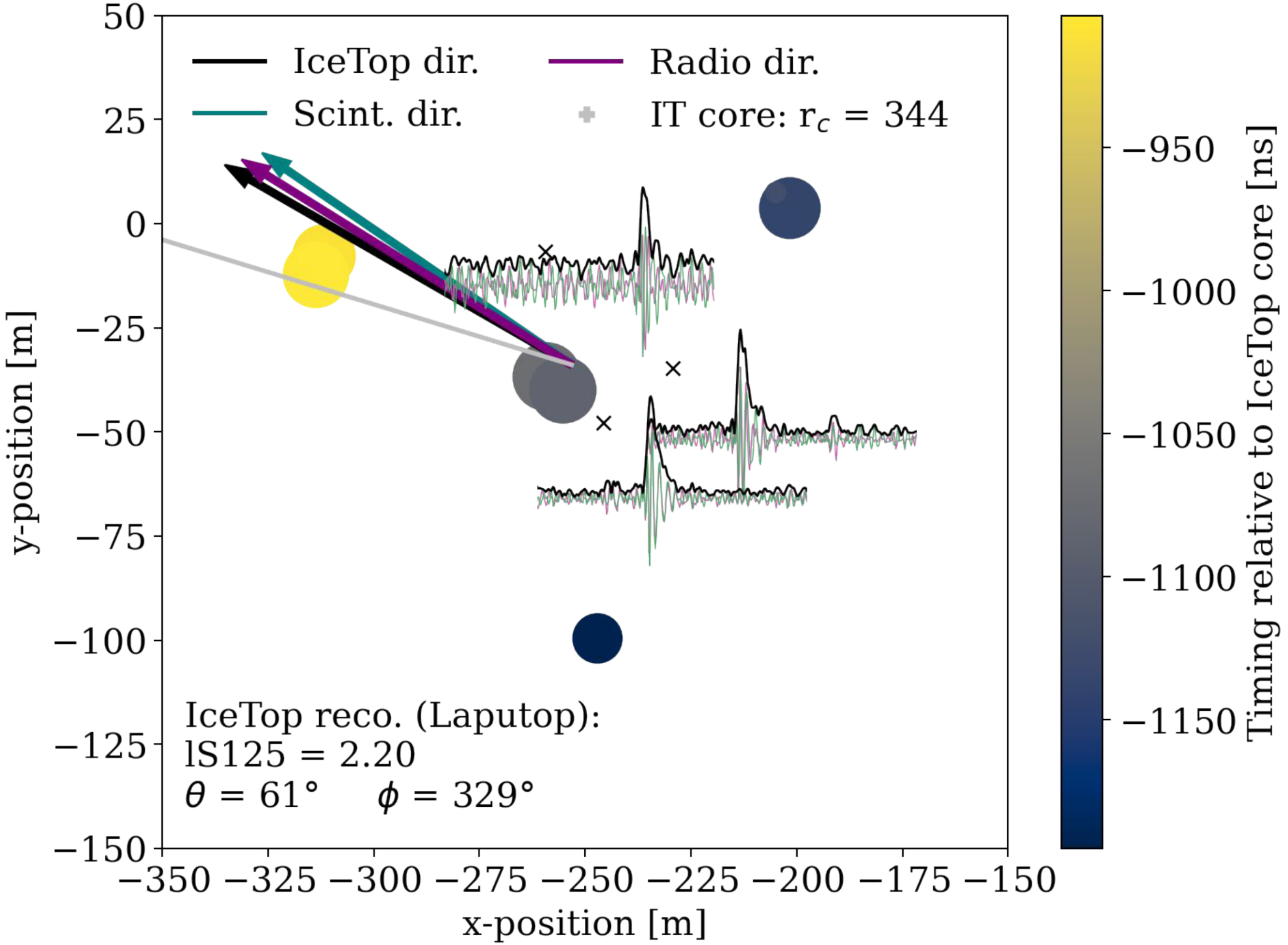
# Example Event of Prototype Station at IceTop

- Complete prototype station of 8 scintillators and 3 antennas running since 2020
- A few clear radio event per day with a reconstructed direction consistent with IceTop and with scintillators
- Goals of the prototype are
  - general feasibility (done)
  - threshold at the South Pole
  - properties of radio signal at 70-350 MHz (higher than Auger)
  - energy measurement with radio







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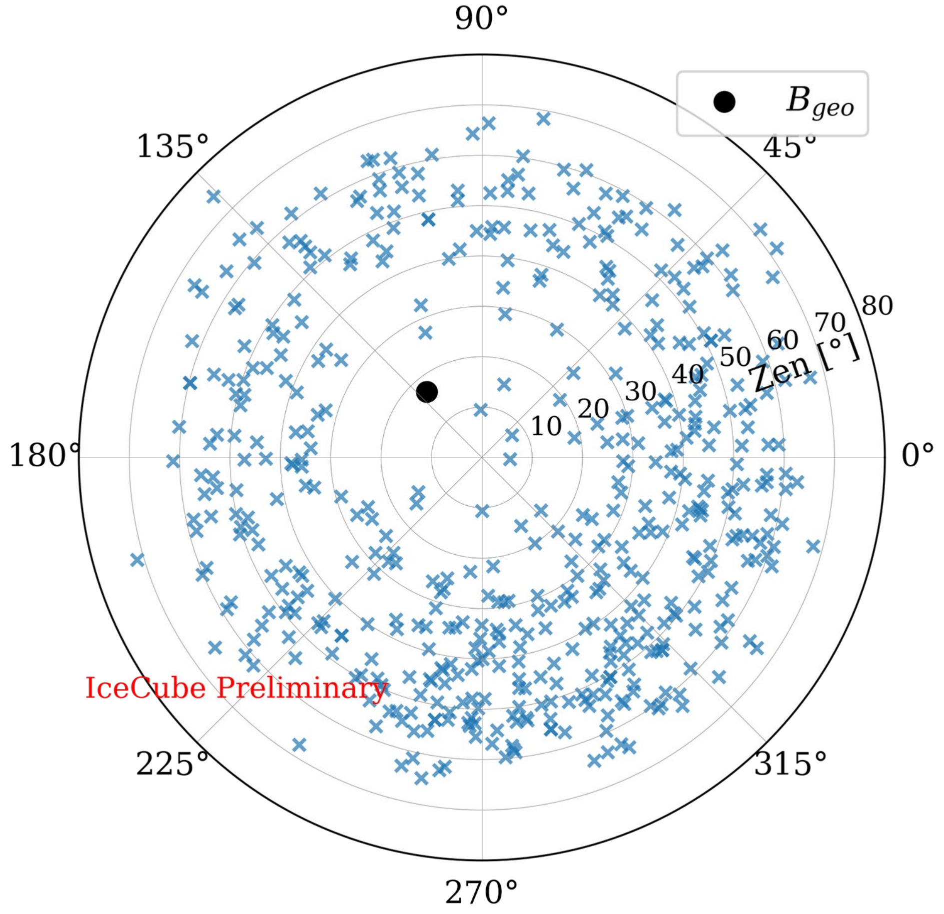
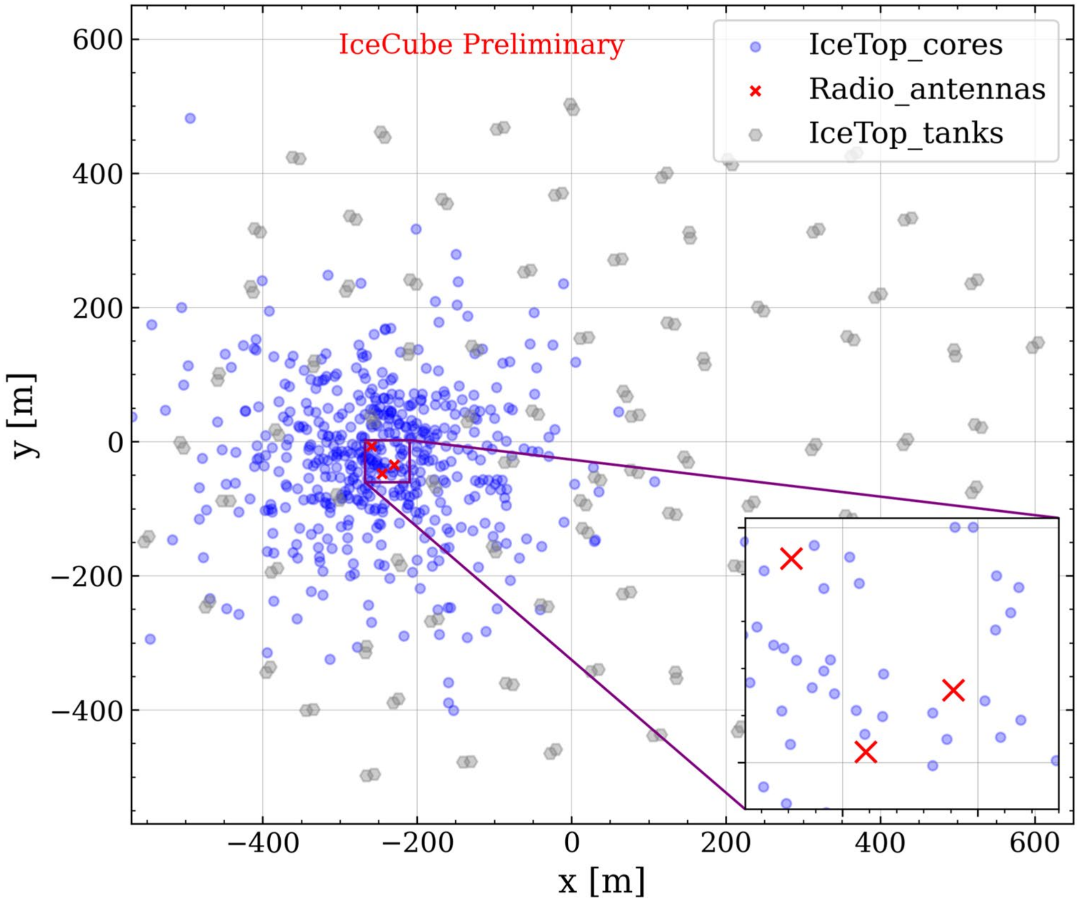
# Arrival Directions and Core Position

- Distribution of IceTop arrival directions and core positions of denoised radio events
  - as expected, large geomagnetic angles and small distances to the antennas more prominent



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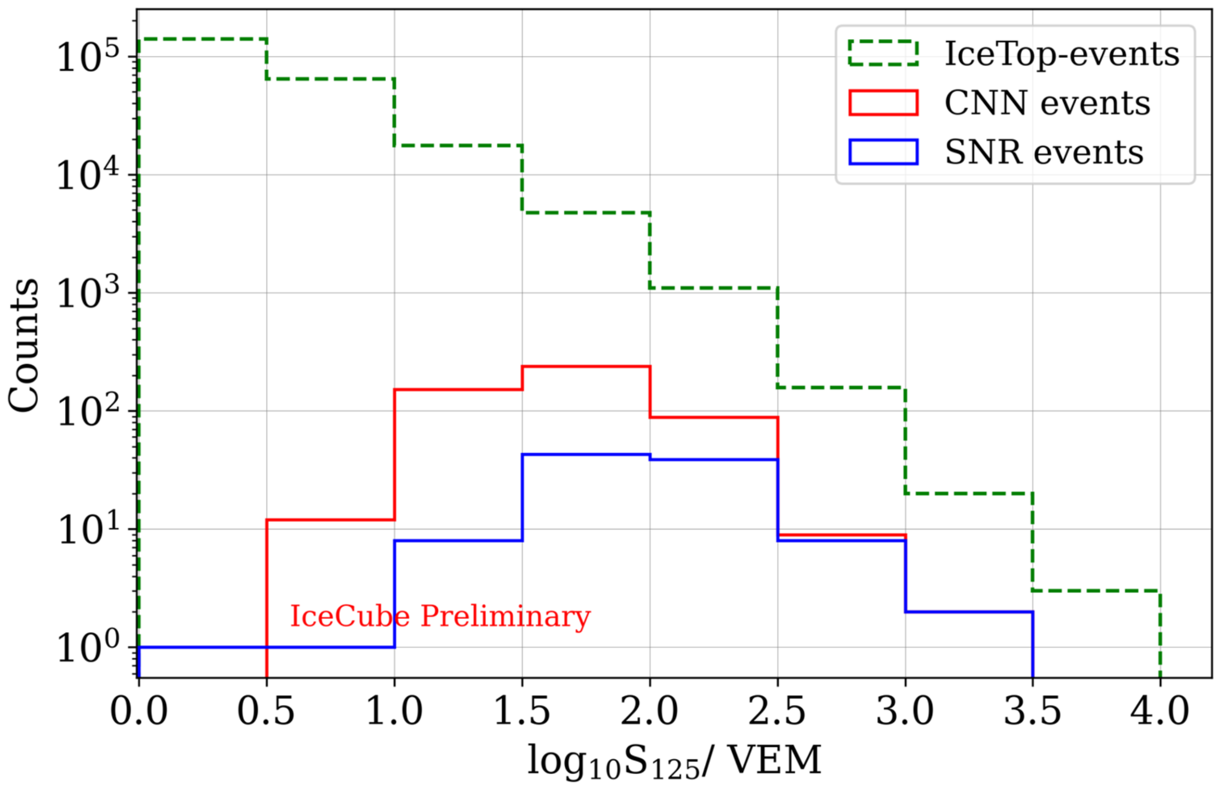
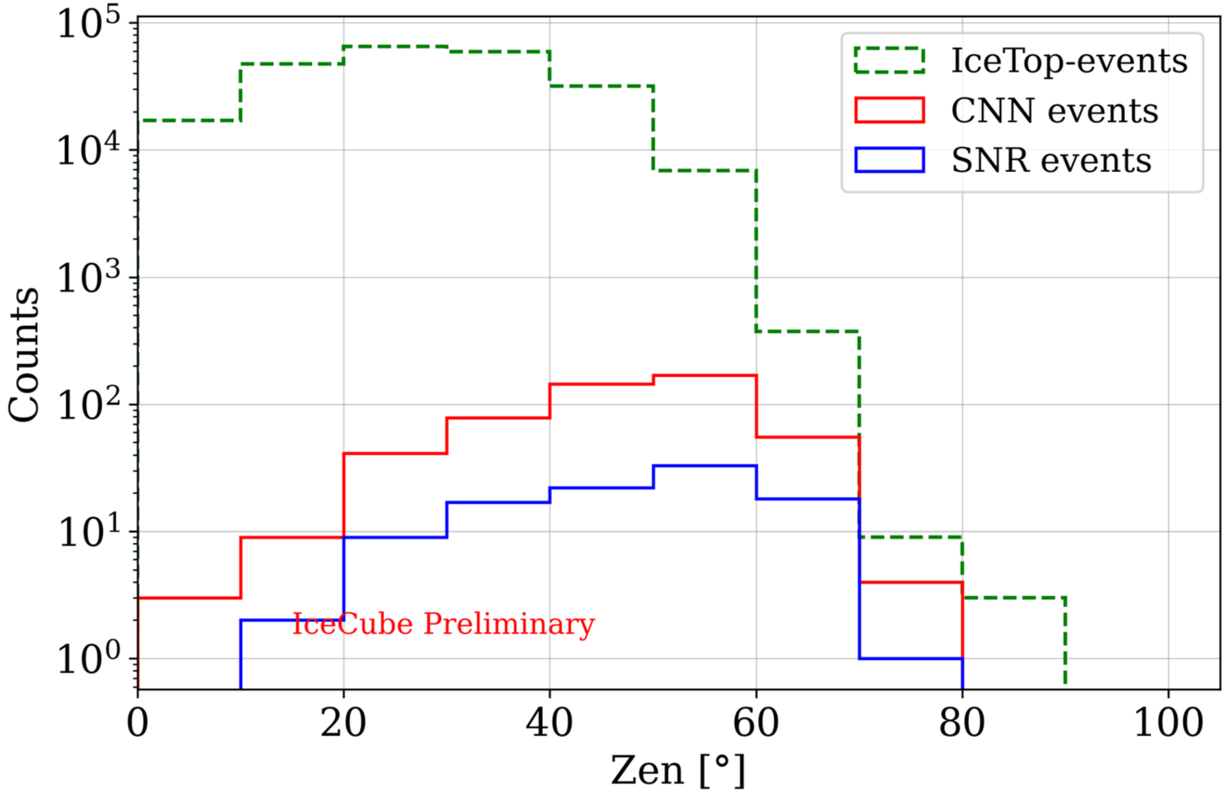
# Energy and Zenith Distribution

- Distribution of IceTop S125 energy estimator and zenith angle of radio events
  - CNN lowers threshold of radio detection and adds events at lower energy and at all zenith angles
  - S125 not yet calibrated for complete zenith range, roughly 1 VEM ~ 1 PeV for near-vertical events



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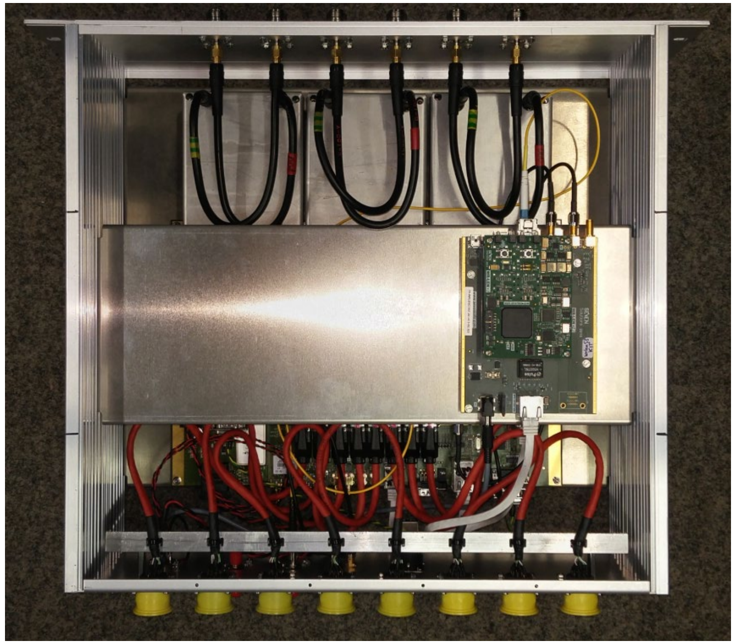
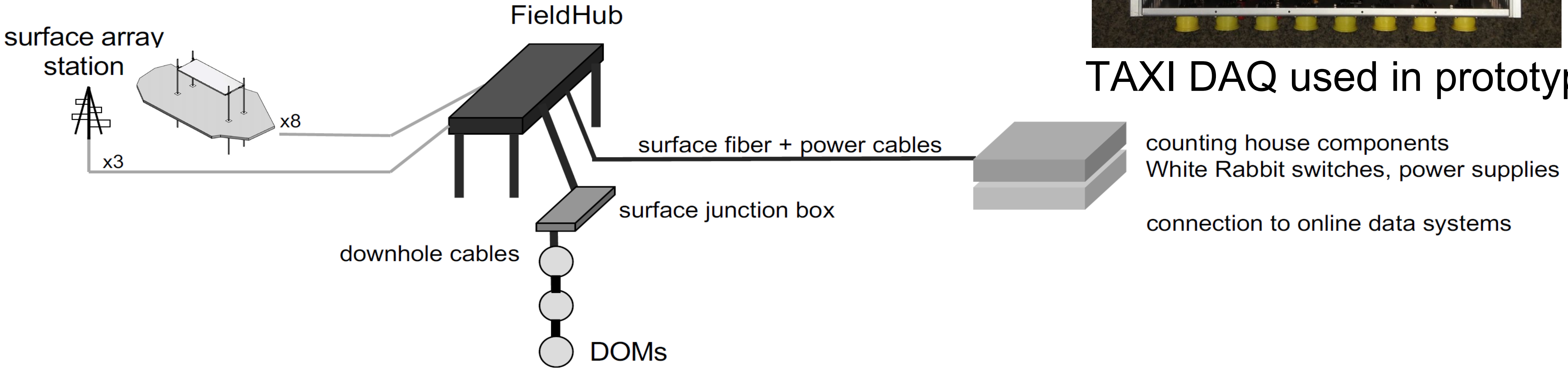
# Radio Antennas added for Accuracy at higher energies

## Joint DAQ for Surface Array Stations

- Sharing fieldhub with optical string for power, WhiteRabbit timing and communication
- Surface DAQ digitizes radio signals upon trigger received from the scintillators of that station
- Deep buffer and array-wide trigger on wish list



TAXI DAQ used in prototype s







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# IceCube-Gen2 Optical Array

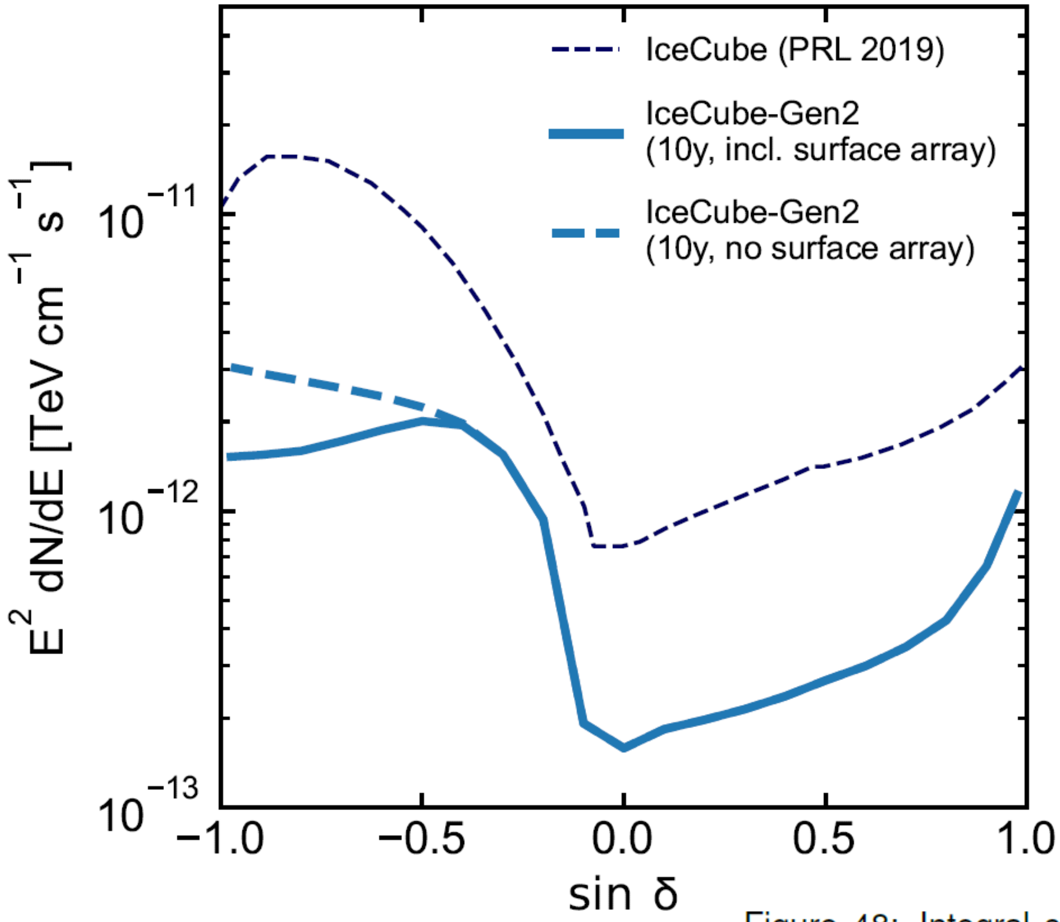
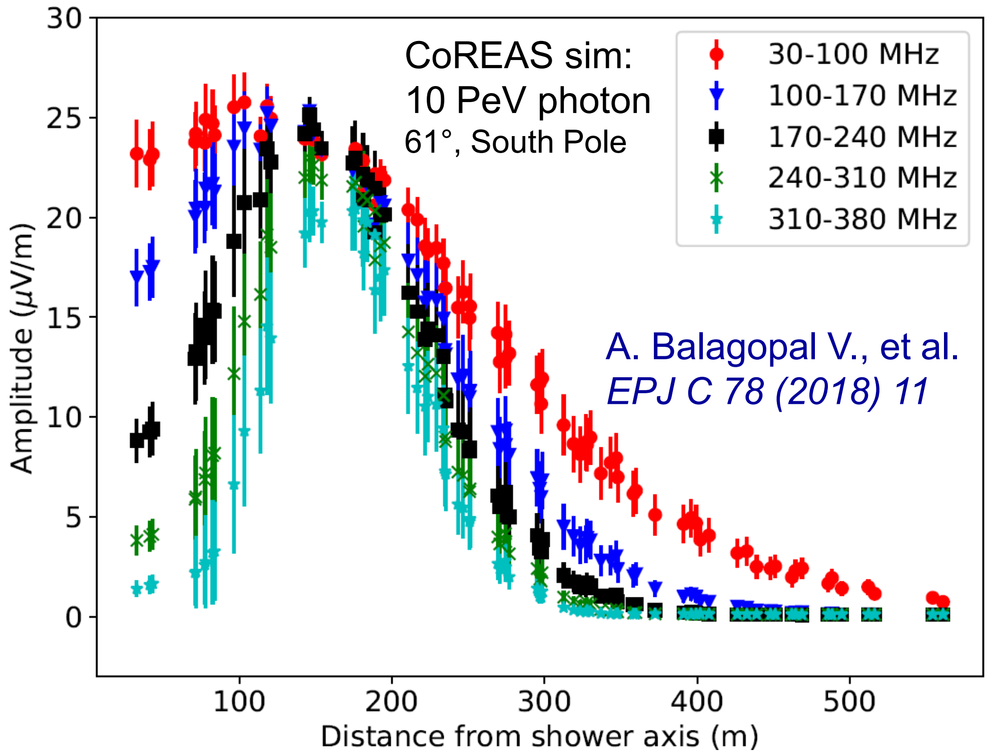
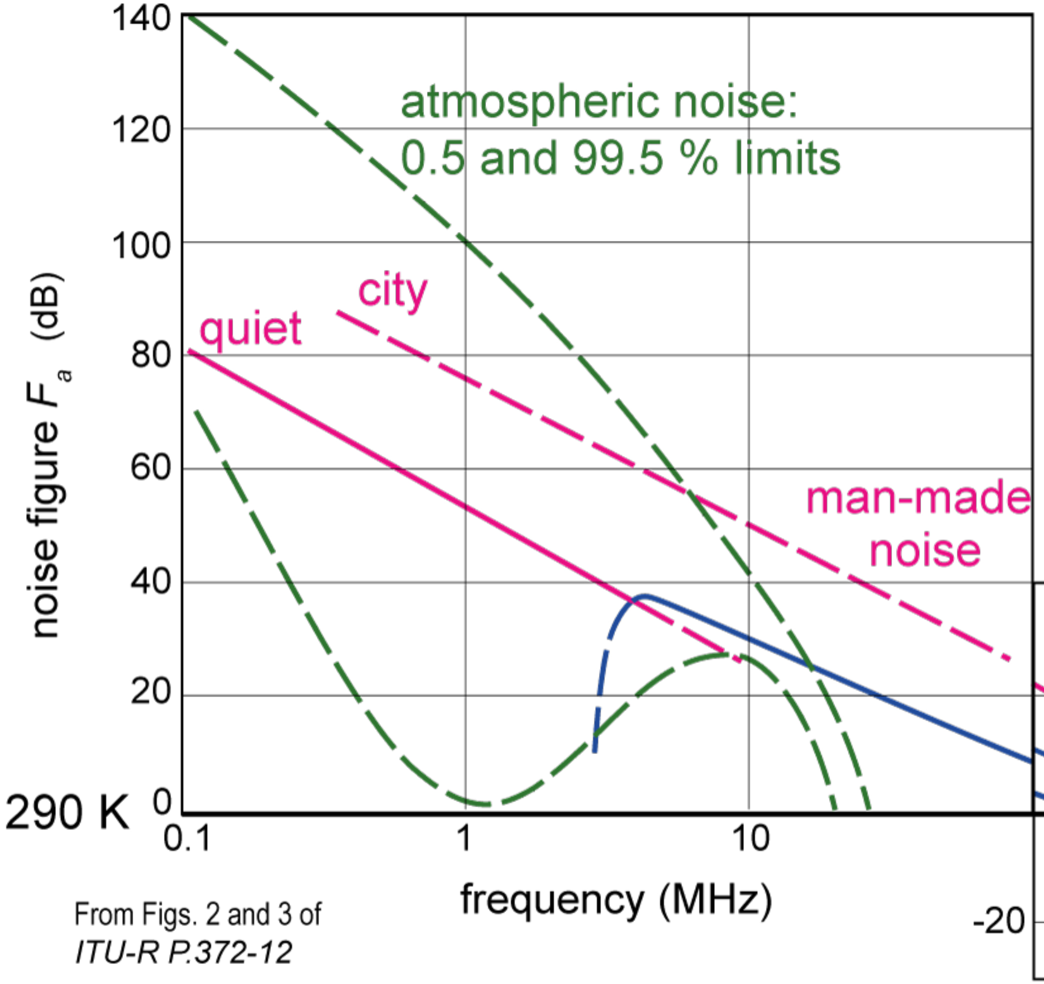
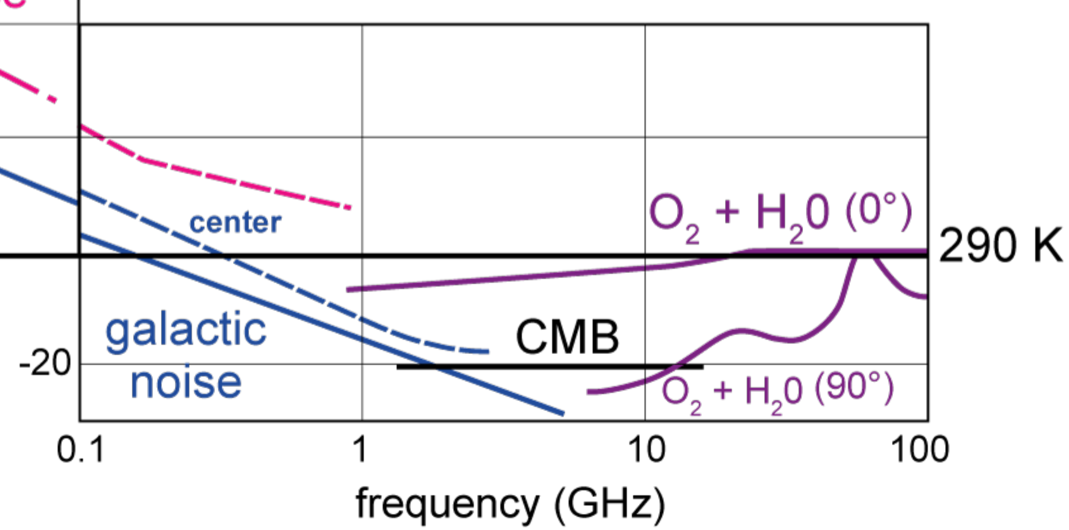



Figure 48: Integral sensitivity for the discovery ($5\sigma$ discovery potential) of a point source featuring a power-law spectrum with an index of -2, after 10 years of observations. The sensitivity of the optical array is presented as a function of declination, in combination with and without the surface array. The IceCube sensitivity (including the IceTop surface array) from [577] calculated for the analysis of a ten-year dataset is indicated for comparison. The neutrino flux is shown as the per-flavor sum of neutrino plus anti-neutrino flux, assuming an equal flux in all flavors.

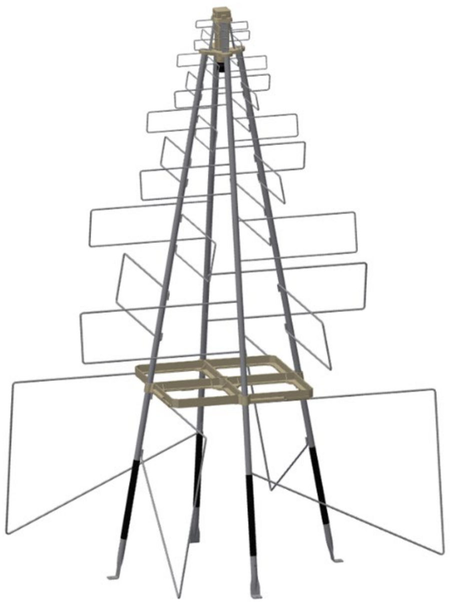
# Better signal-to-noise ratio expected at high frequencies




From Figs. 2 and 3 of
*ITU-R P.372-12*



**SKALA v2: 70-350 MHz**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# Antenna of Choice: SKALA

- High gain of 40dB with smooth sky coverage
- Noise figure of LNA above 100 MHz is about 0.5 dB with thermal noise < 40K, which is below the galactic noise.
- Used at Pole: SKALA v2 (prototype version for SKA-low)

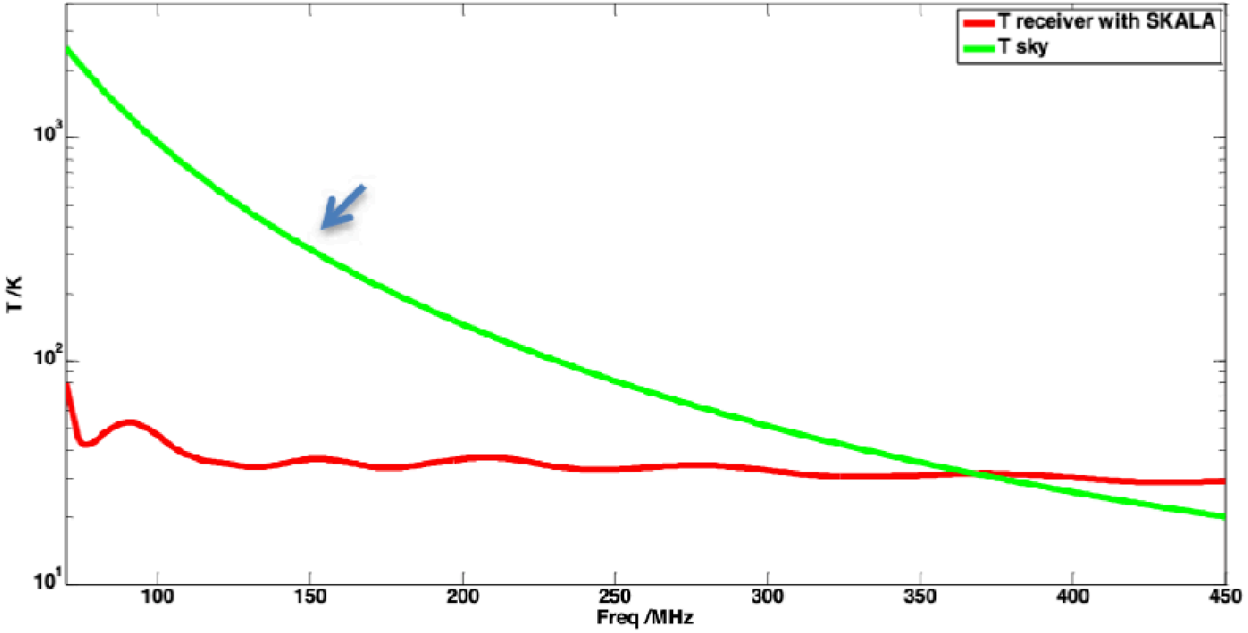
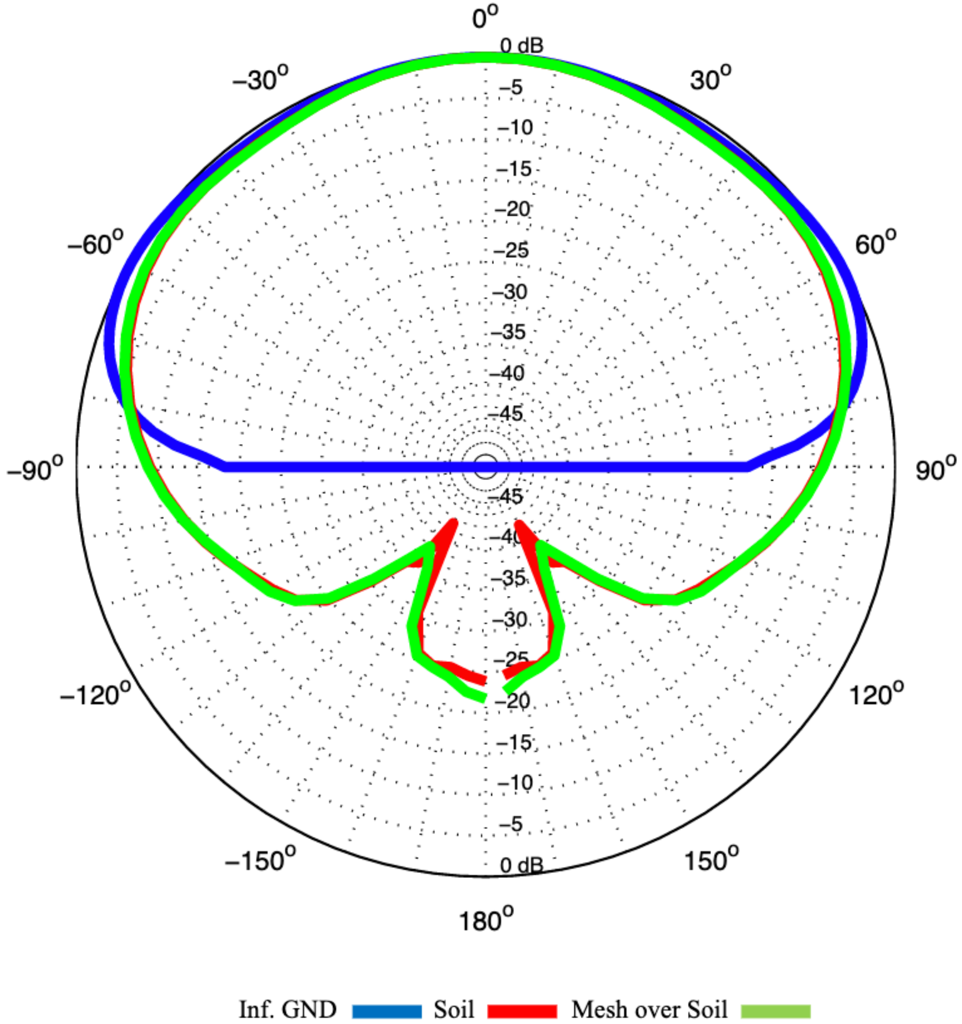



Fig. 9. Receiver noise temperature versus sky noise.

H-plane cut - 150 MHz




E. de Lera Acedo, N. Drought, B. Wakley and A. Faulkner, "Evolution of SKALA (SKALA-2), the log-periodic array antenna for the SKA-low instrument," *2015 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2015, pp. 839-843, doi: 10.1109/ICEAA.2015.7297231.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