Cosmic-Rays Physics with IceCube and IceCube-Gen2

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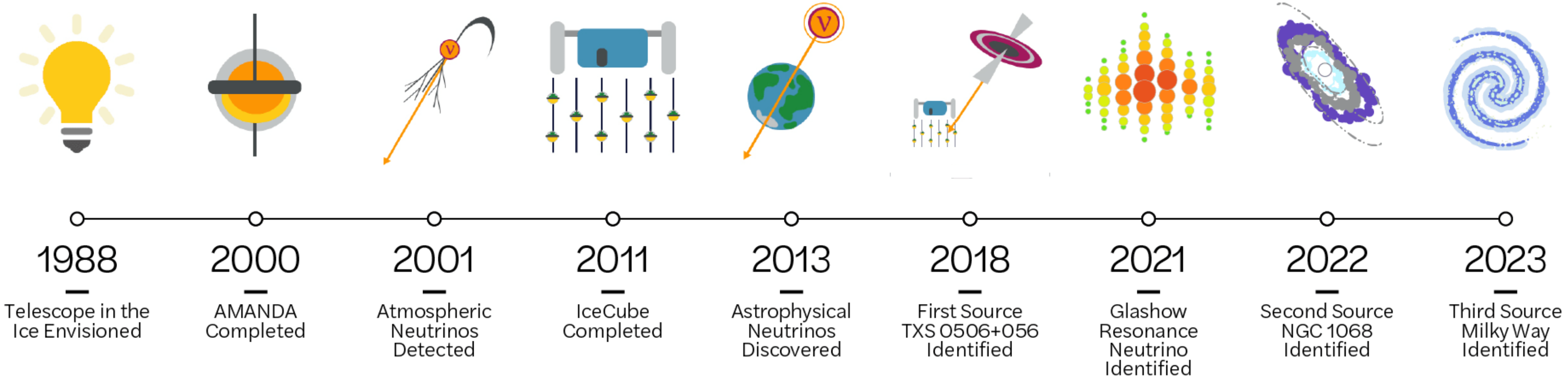
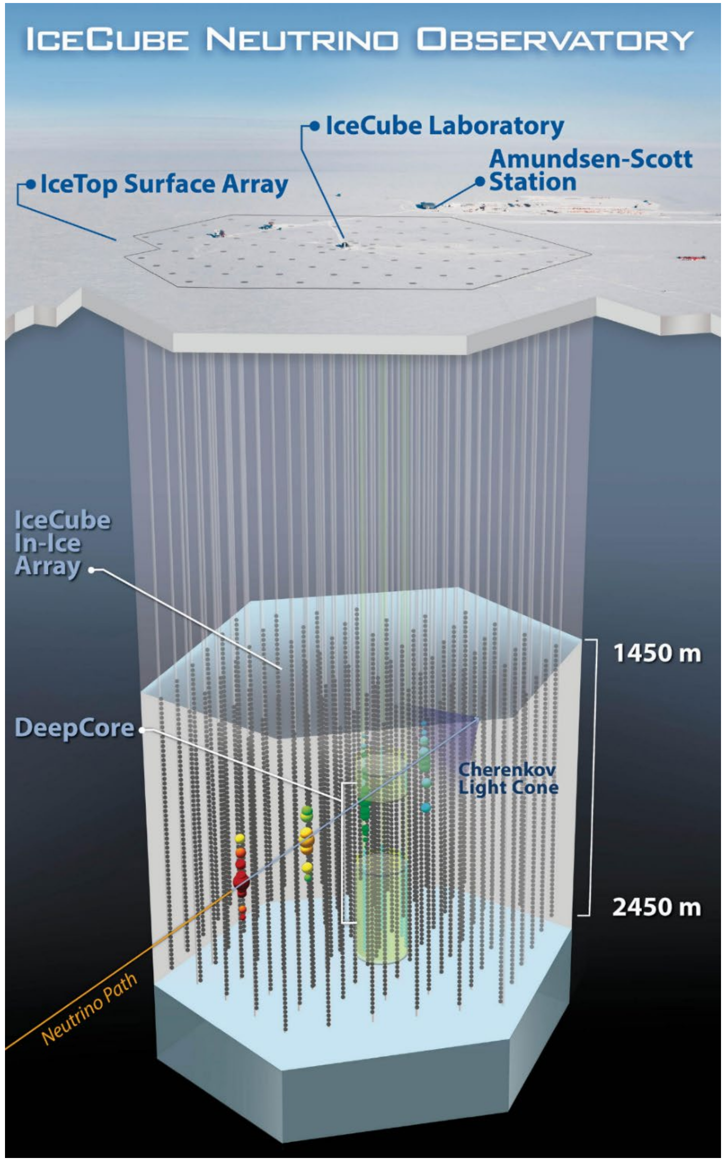
IceCube Neutrino Observatory at the South Pole

- 1 km³ optical detector deep in the ice
- Break-through discoveries in Neutrino Astronomy
- Key contribution to neutrino physics
- Unique cosmic-ray astro- and particle physics with air showers

String of digital optical modules (DOMs)





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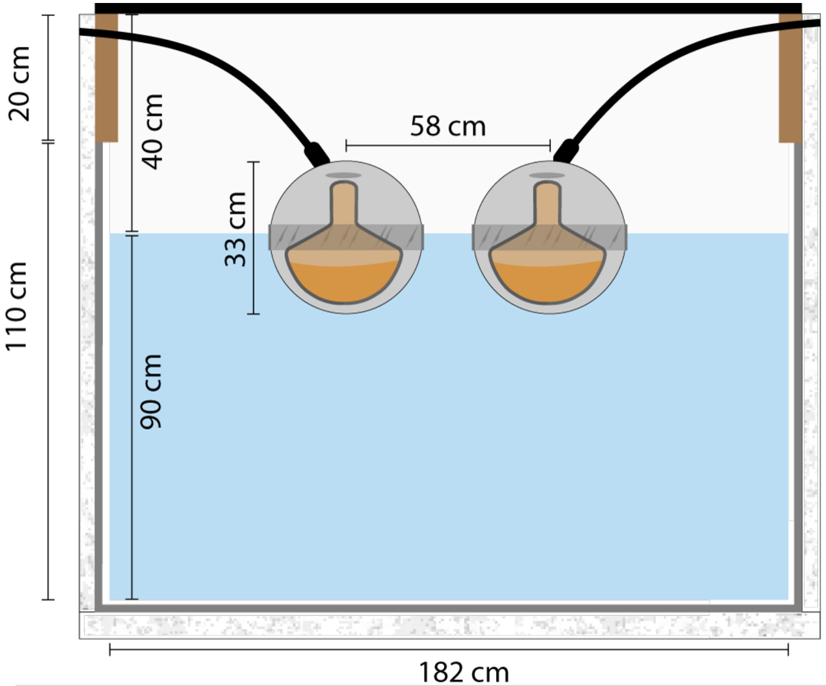
IceCube as a Detector for Cosmic-Ray Air Showers

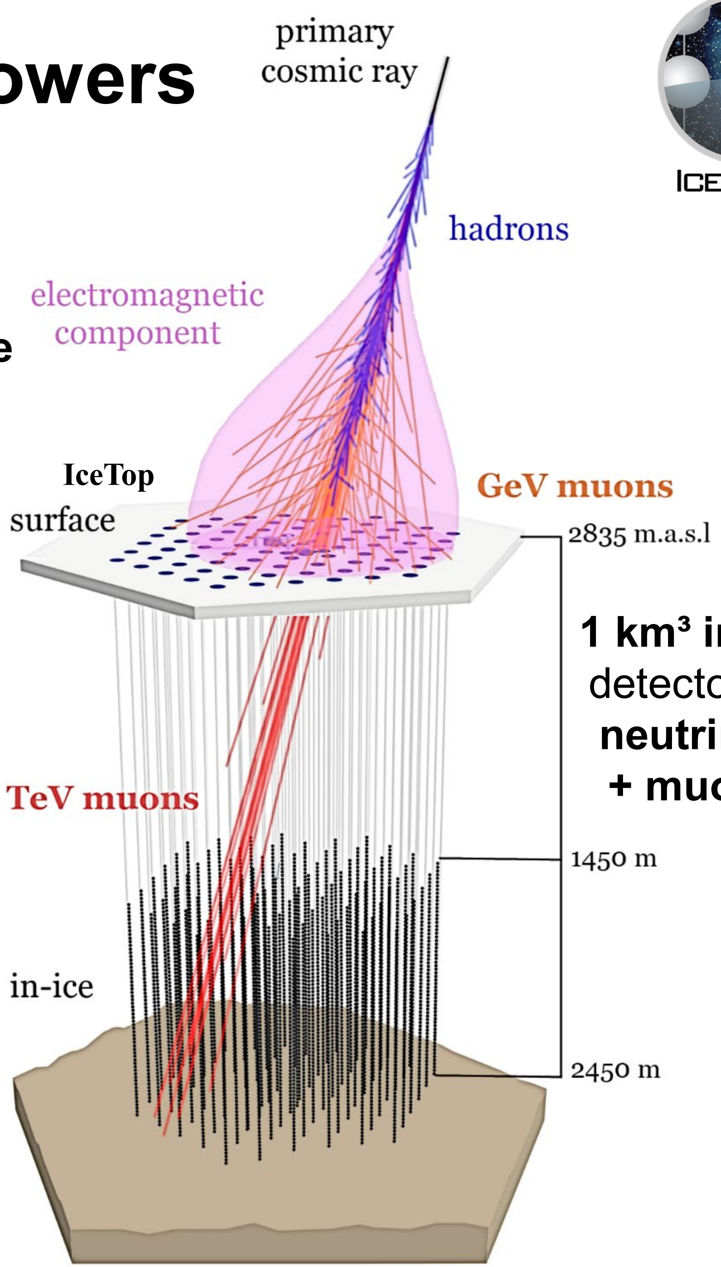
- IceTop = surface array of ice-Cherenkov detectors
  - Veto for neutrino detection with in-ice detector
  - Air-shower physics → atmospheric leptons
  - PeV cosmic rays and photons

1 km² surface detector for **air showers**

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



IceCube Coll., NIM A 700 (2013) 188



PoS(ICRC2021)357

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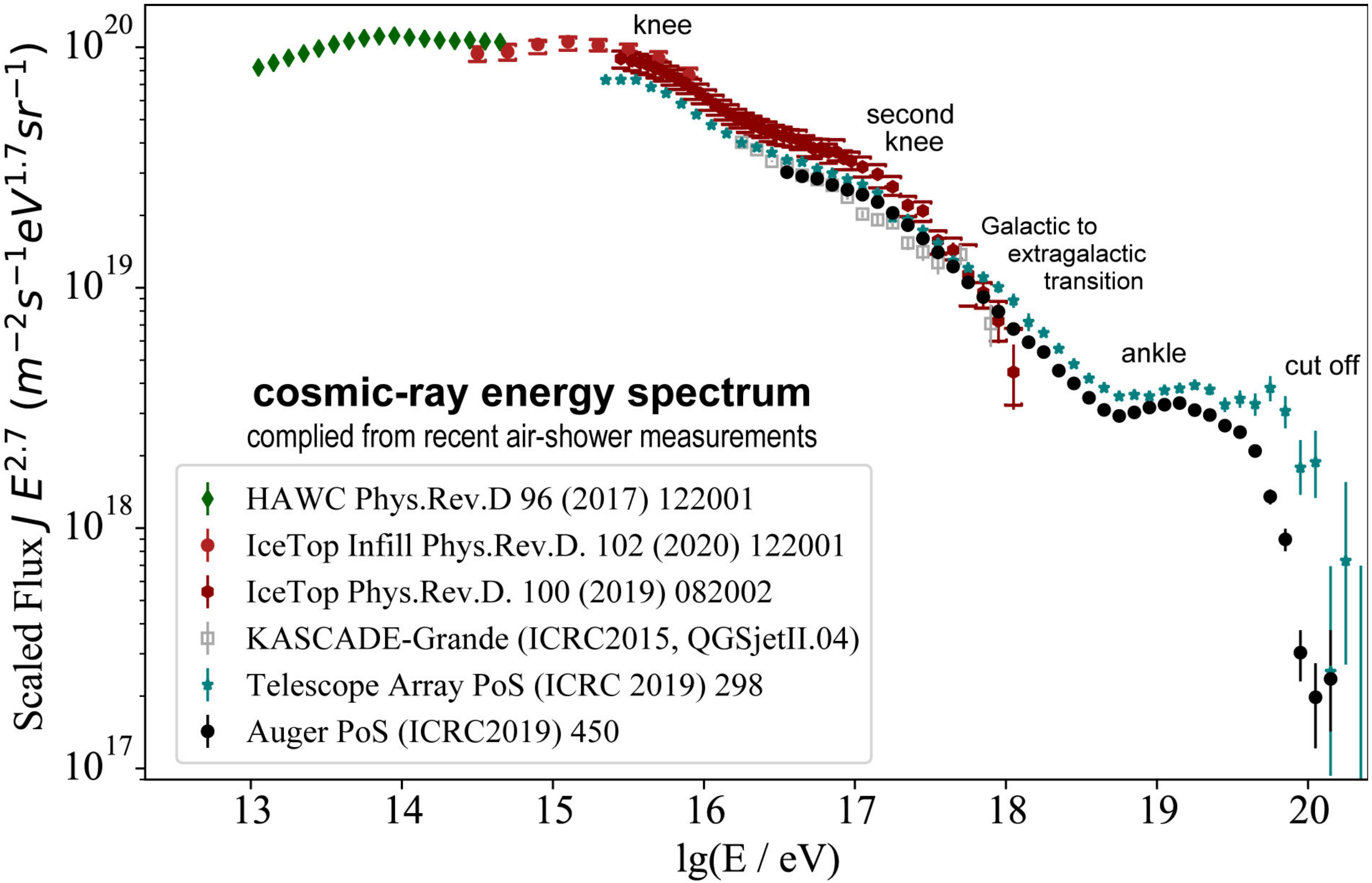
Bird's view of IceCube at the South Pole (color code: year of deployment)

Energy reach until Galactic-to-extragalactic Transition



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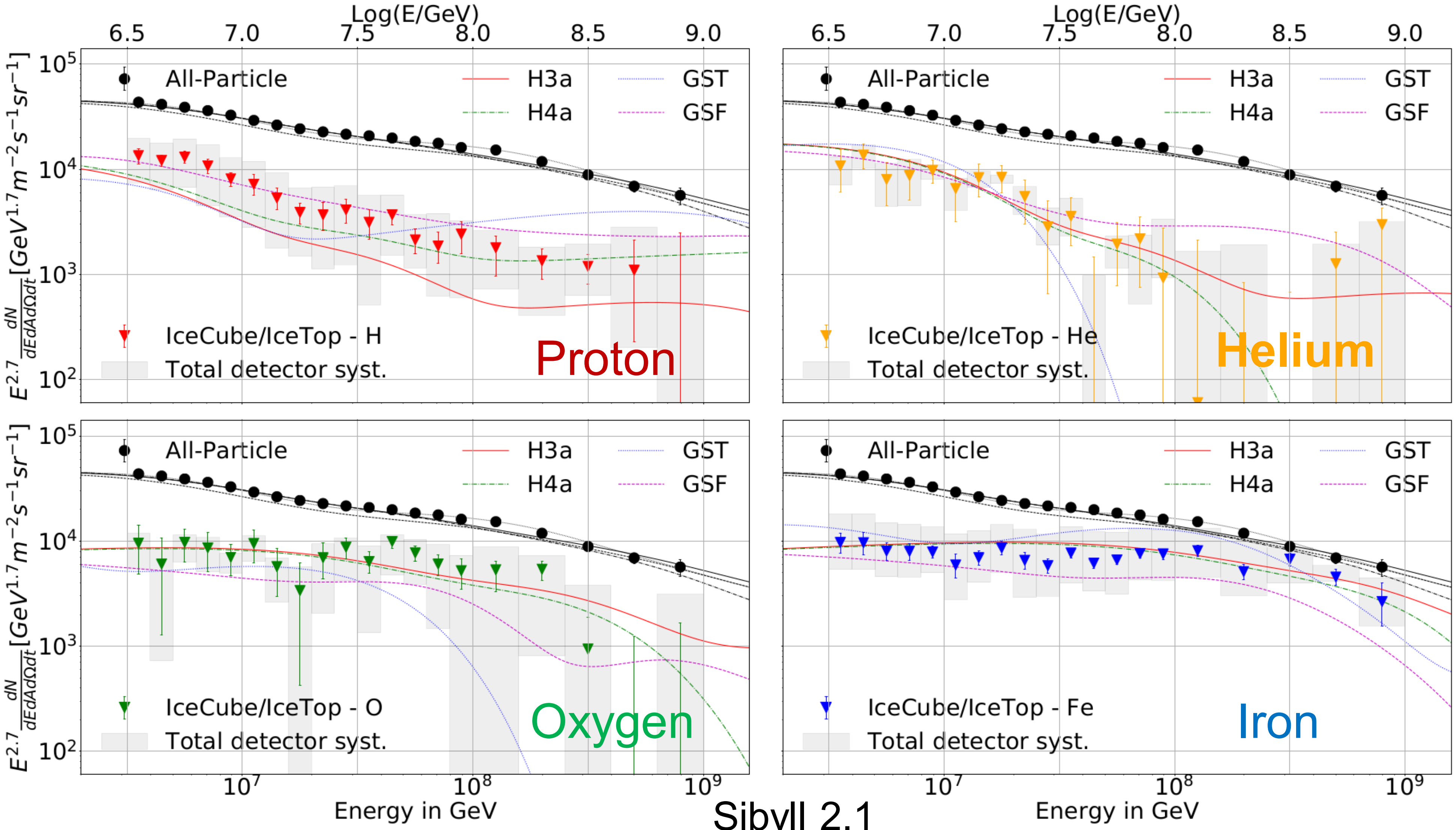
IceCube Cosmic-Ray Mass Composition



Sibyll 2.1

Neural network analysis:

energy mostly from IceTop signal at 125m, dominated by electromagnetic particles at surface

mass mostly from in-ice signal, dominated by high-energy muons above 500 GeV

PRD100(2019)082002

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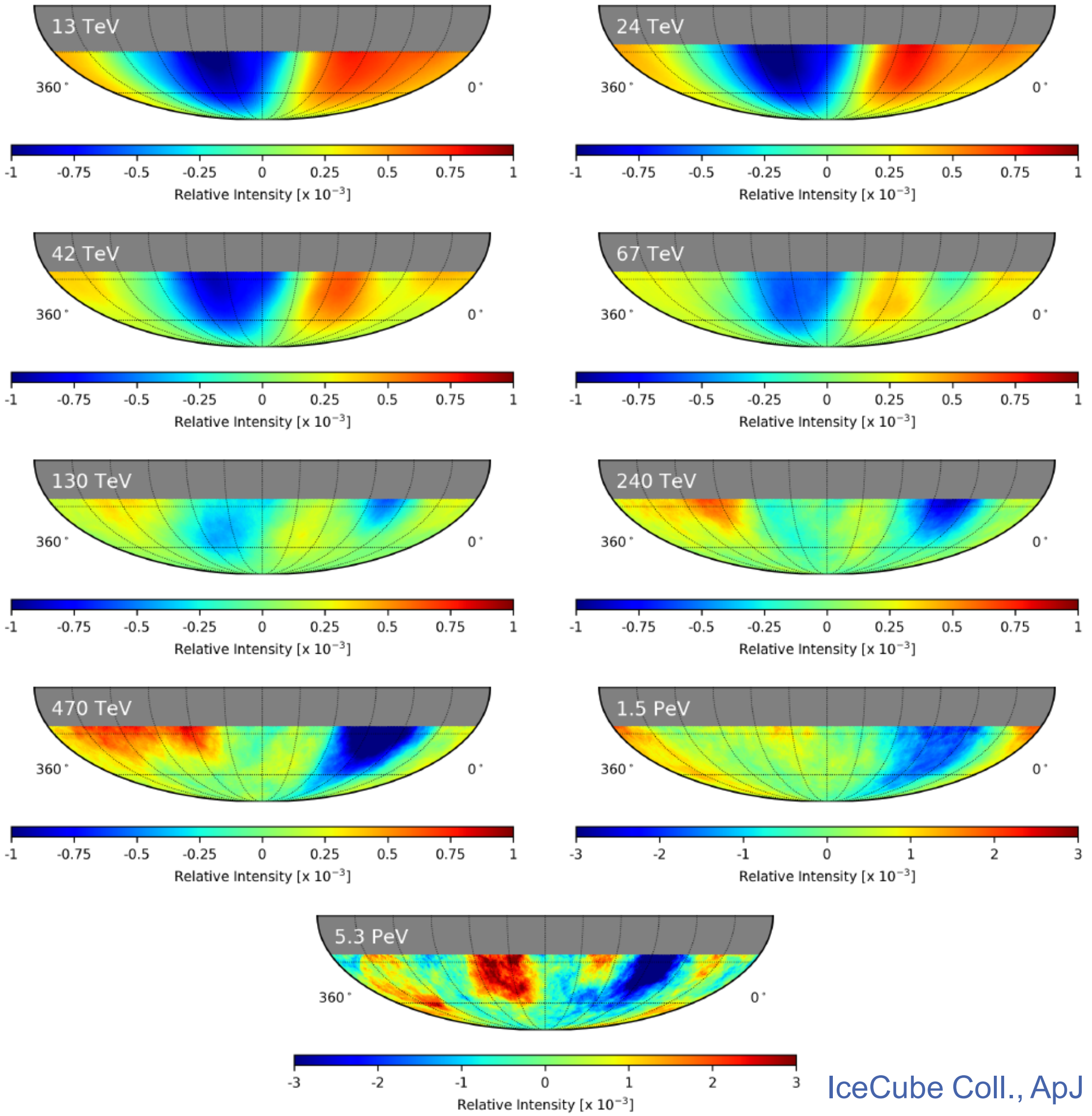
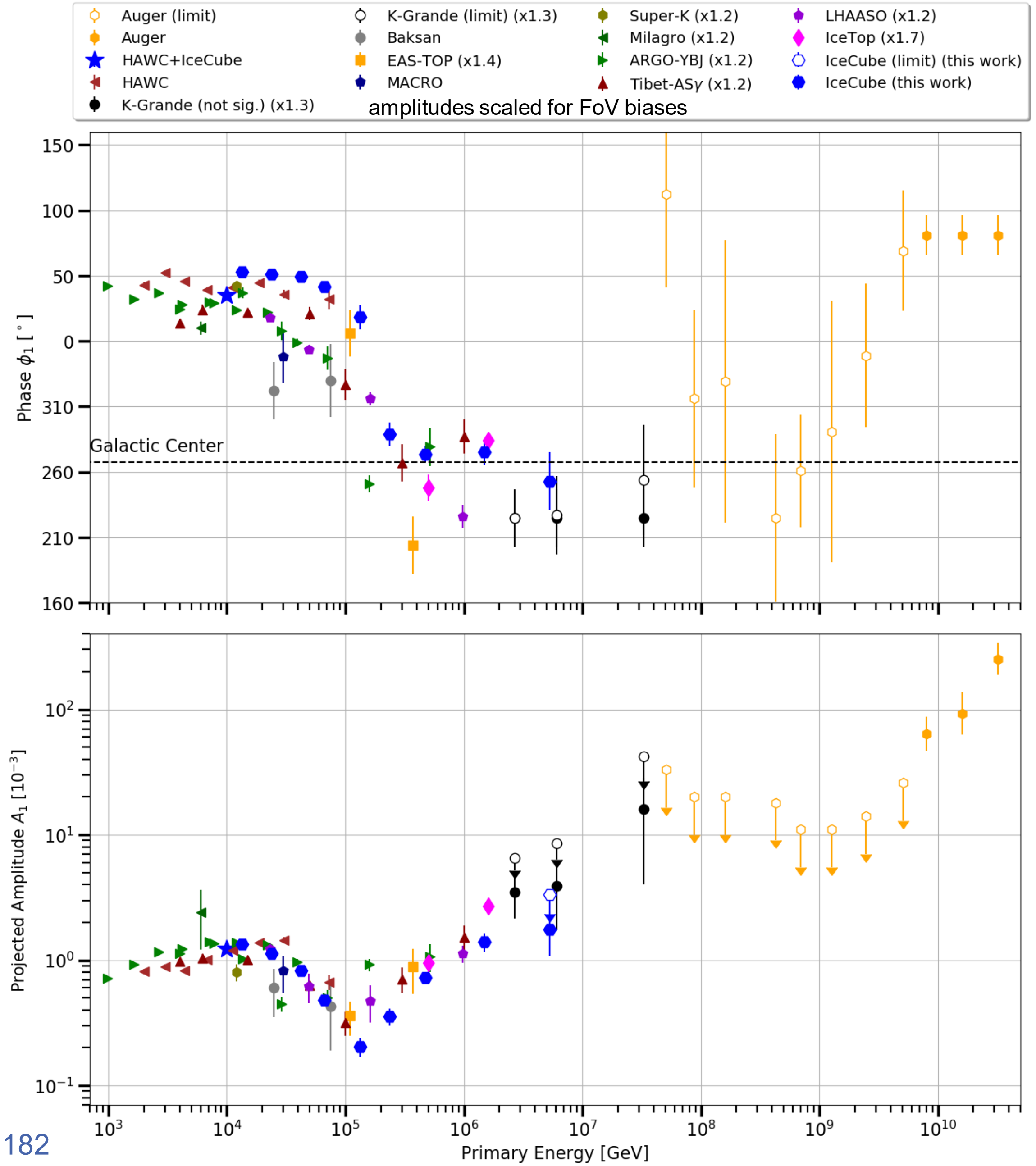
Cosmic-Ray Anisotropy





IceCube Coll., ApJ 981 (2025) 182

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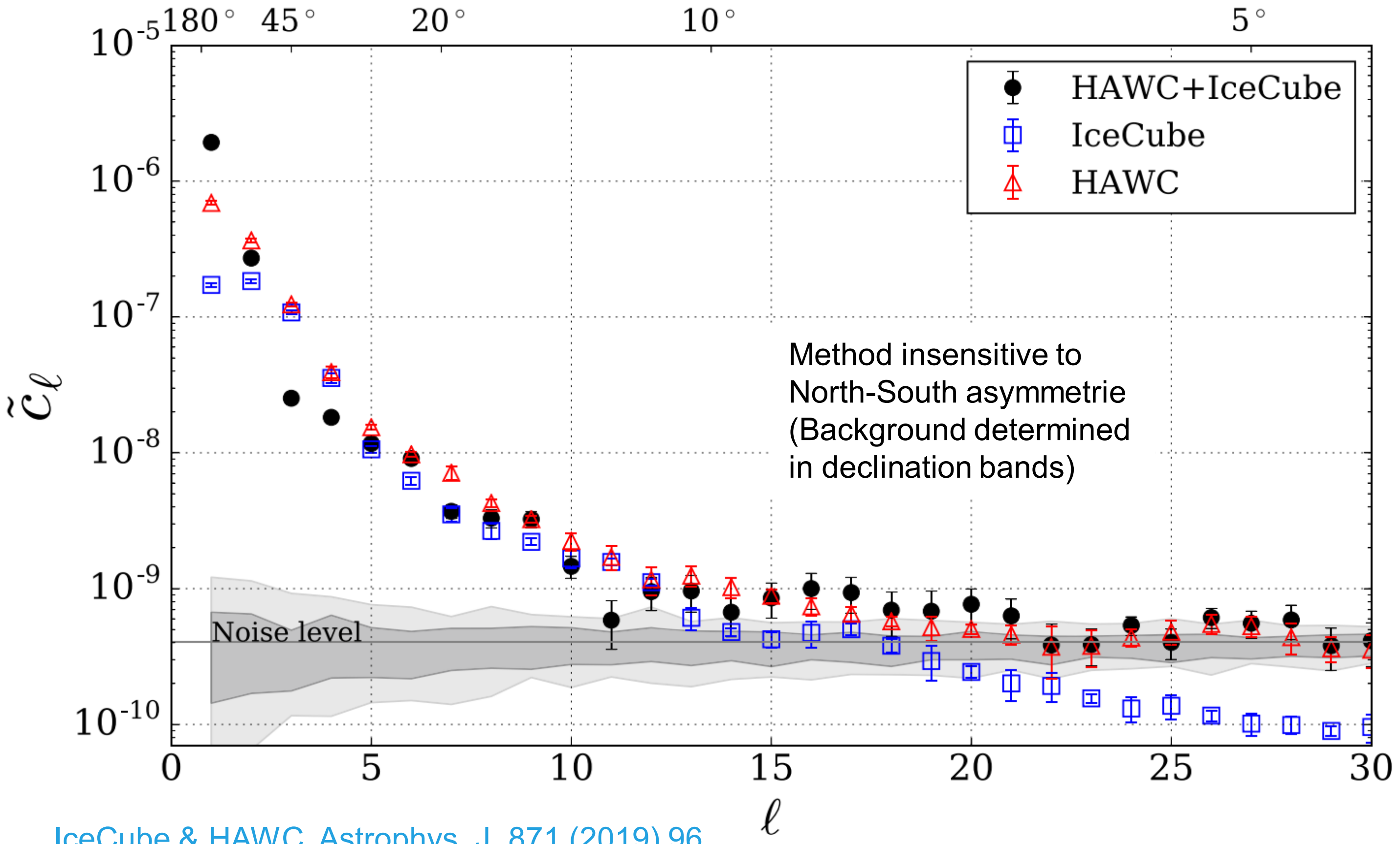
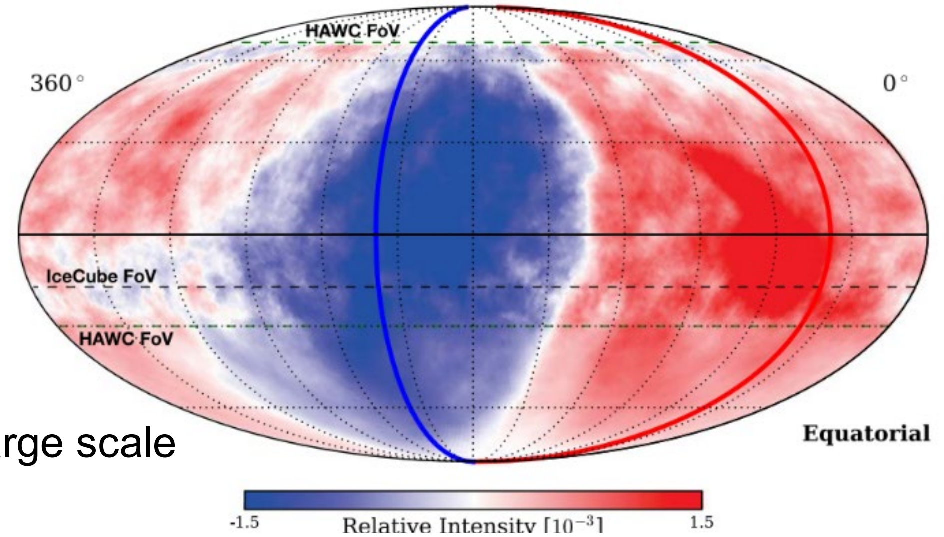
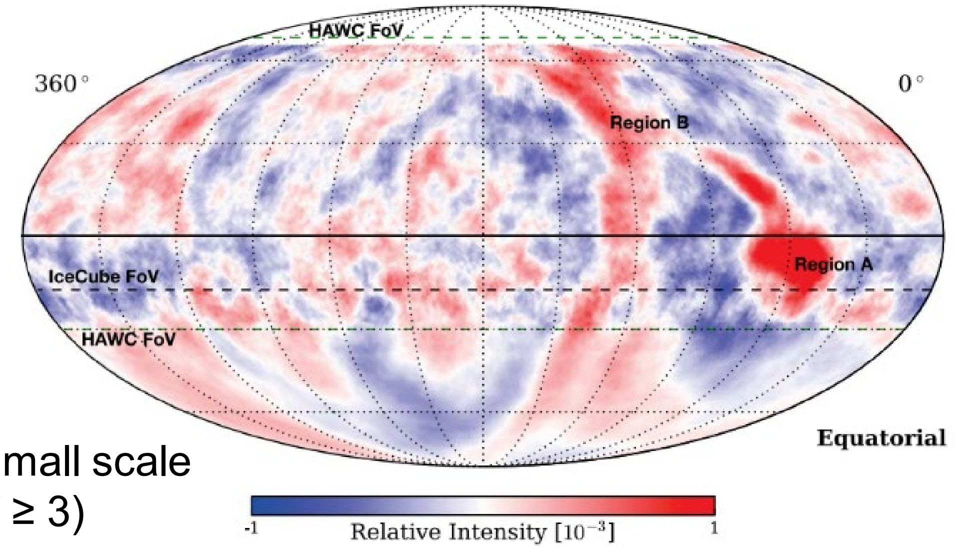
Combination with HAWC for all sky sensitivity at 10 TeV

- Many multipole moments measurable in combined IceCube+HAWC anisotropy sky.
- Combinations with other air-shower arrays planned





Large scale



Small scale ($l \geq 3$)

IceCube & HAWC, Astrophys. J. 871 (2019) 96

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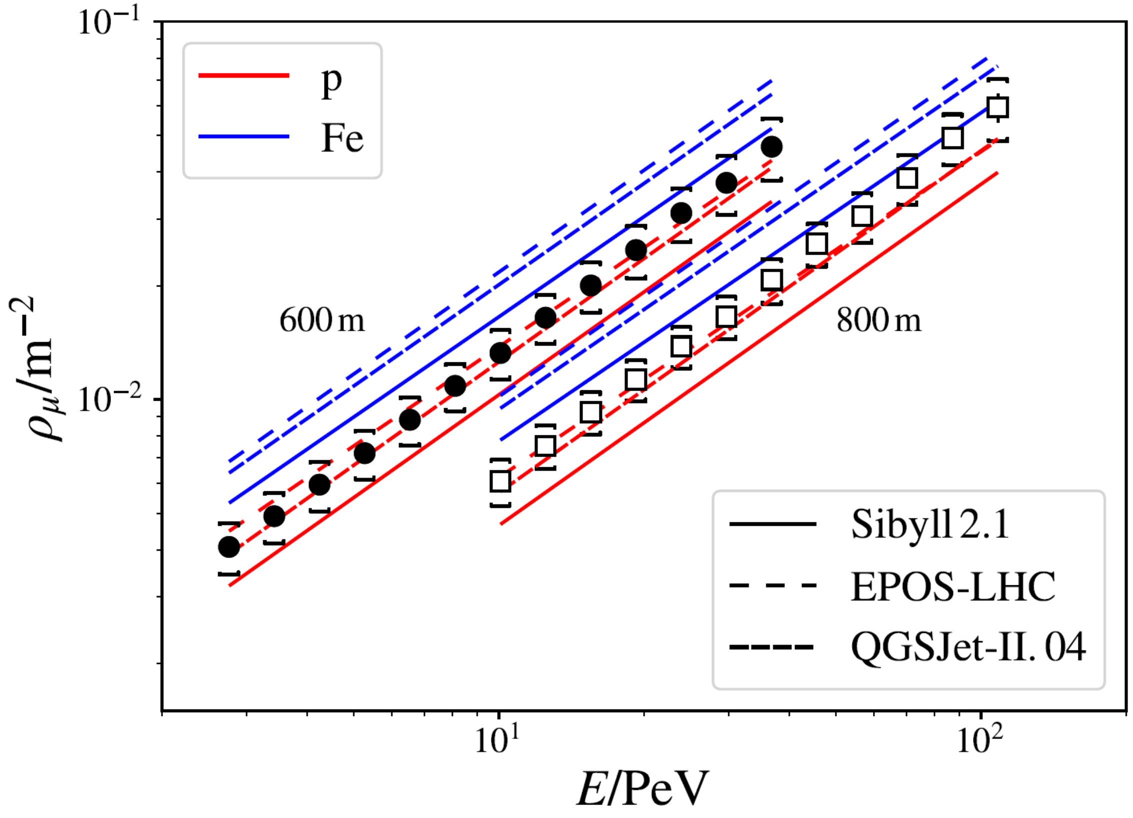
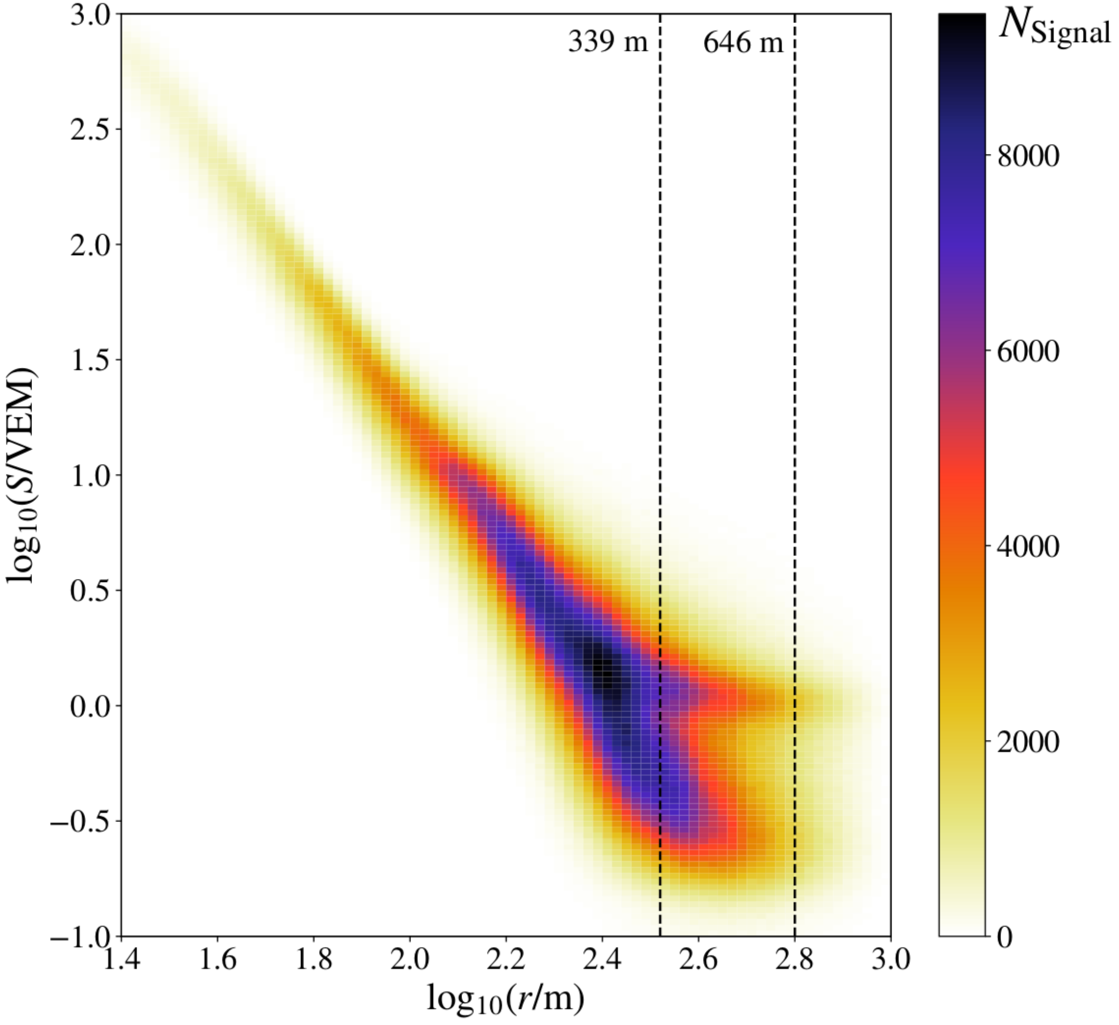
GeV Muon Density at 600m and 800m distance

- At larger distances, higher signals around 1 vertical equivalent muons, are almost exclusively from single muons crossing an IceTop tank
- Statistical evaluation of muon density possible





PRD 106 (2022) 032010

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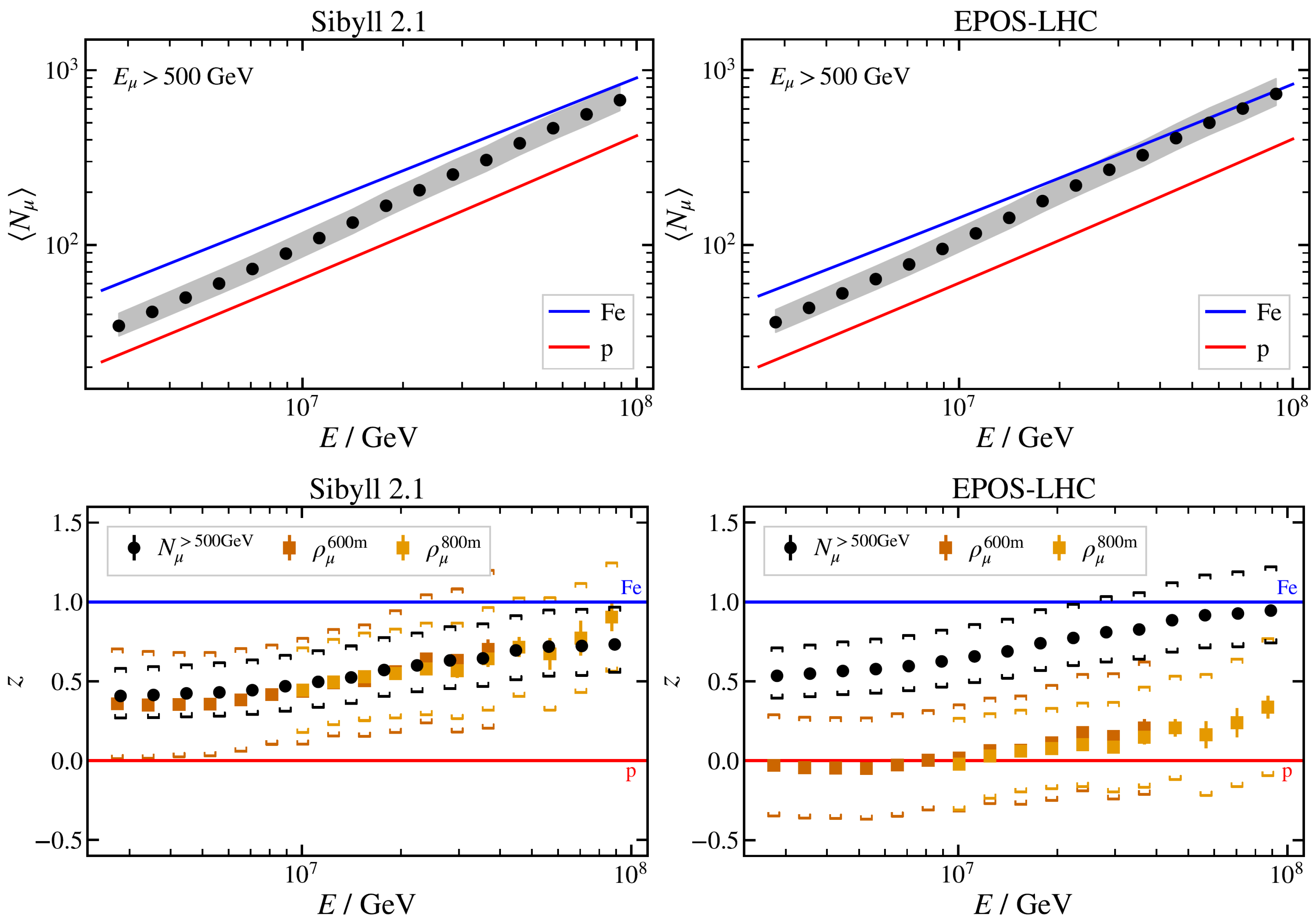
Testing hadronic interaction models with muons at IceCube

- Surface measurement
  - air-shower energy
  - GeV muons
- Deep detector
  - TeV muons

- Sibyll 2.1 only tested model that is compatible, but inconsistent in electromagnetic shower component (not shown)

- Tests of new interaction models planned



IceCube Coll., Phys. Rev. D 112 (2025) 082004

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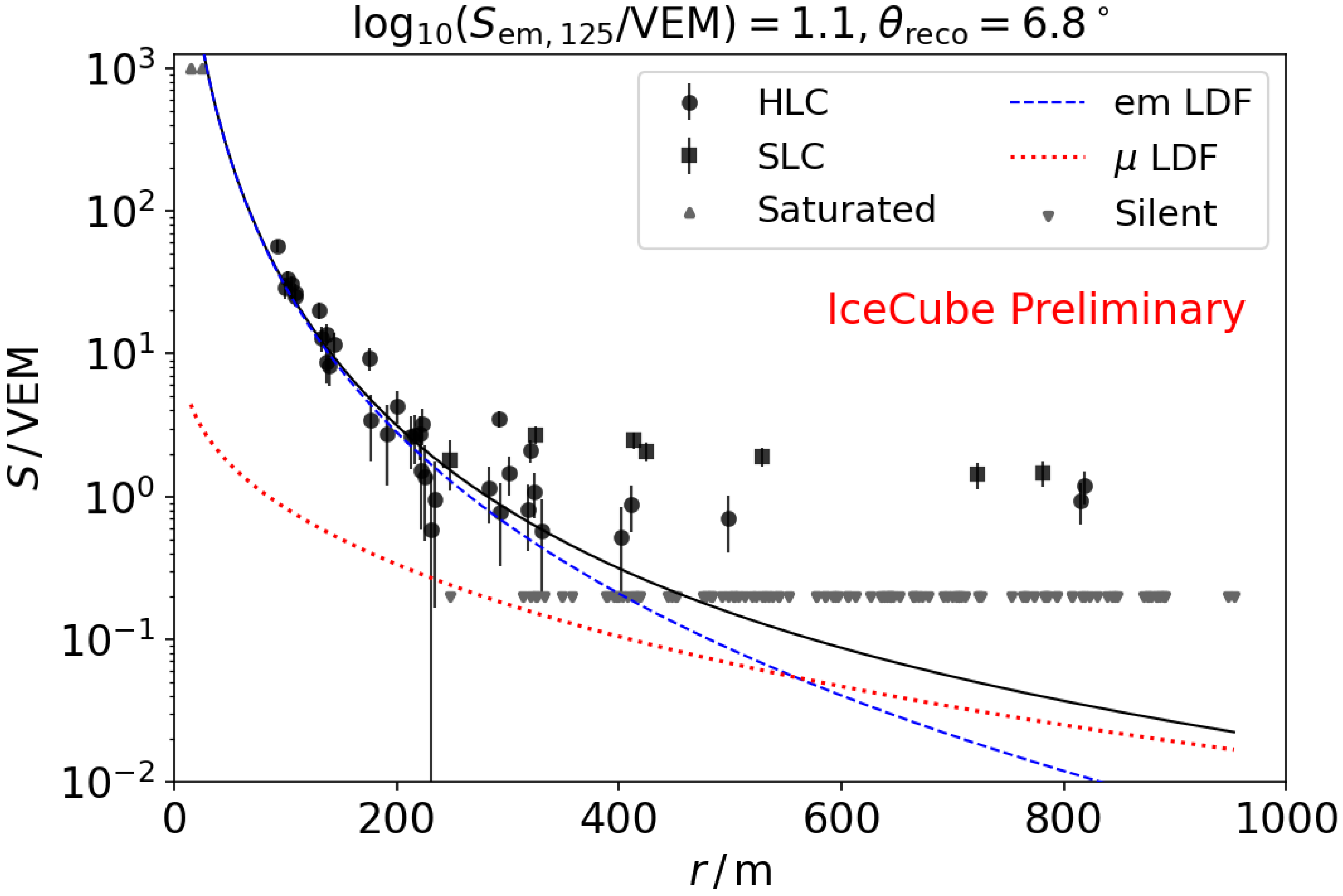
New Method: Two-Component LDF

New software reconstruction framework *RockBottom* will enable new analyses:

- Fitting muonic and electromagnetic LDF to each event
- Taking into account signal-tank hits instead of only pairs of tanks
- Events uncontained in IceTop but with axis through in-ice detector



IceCube Coll., PoS (ICRC2025) 437

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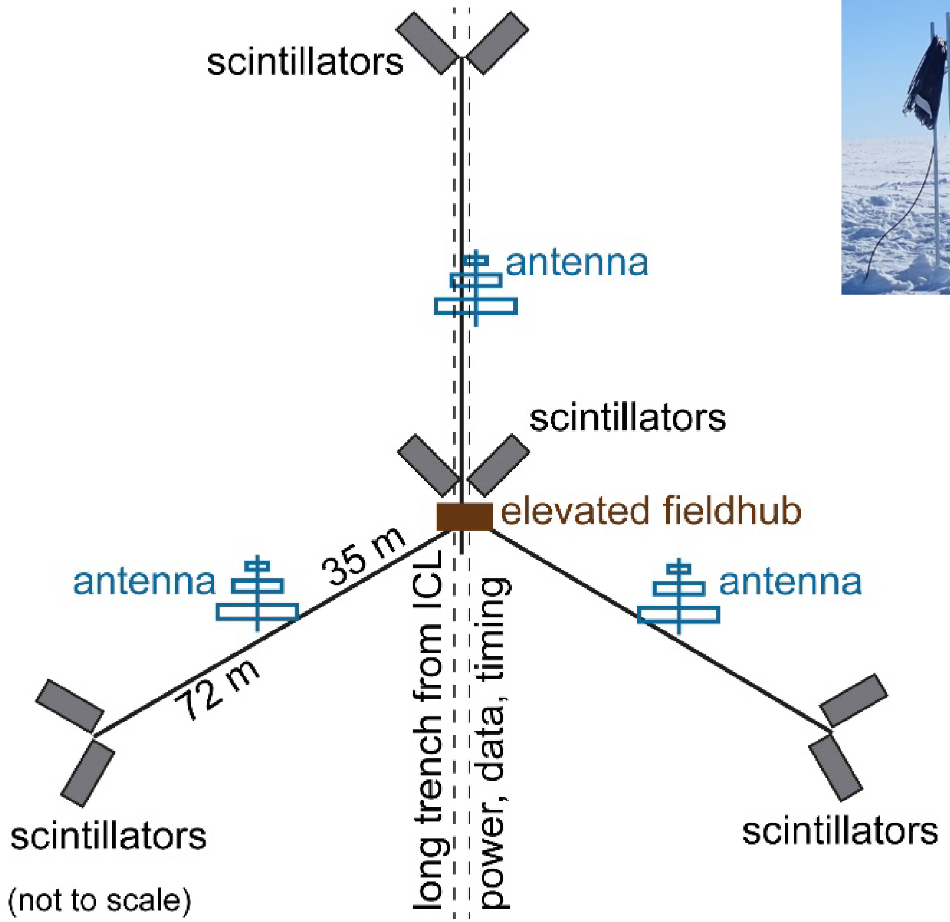
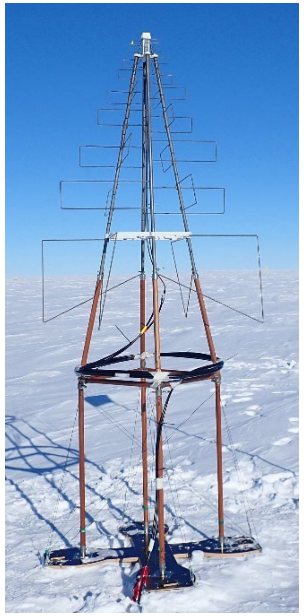
Planned Enhancement of IceTop with Scintillators and Antennas

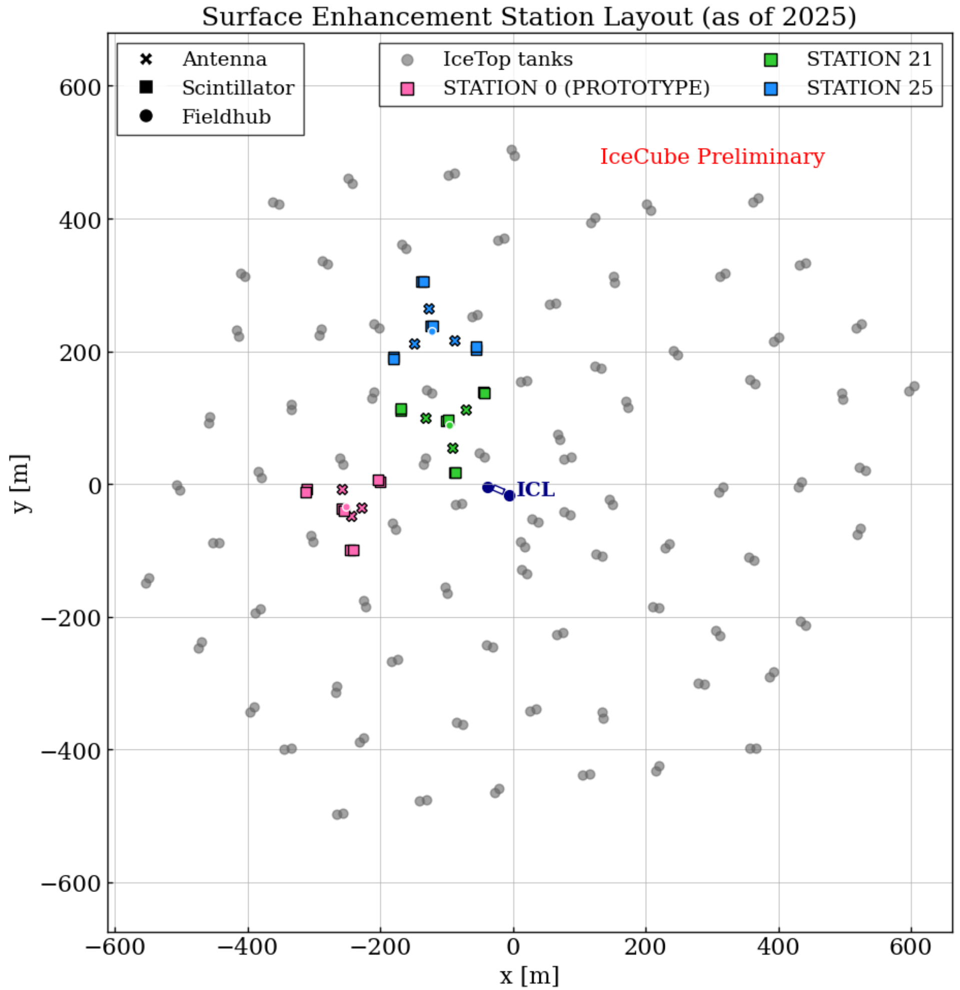
Station Design:

4 pairs of scintillators + 3 antennas





Complete prototype station since 2020, two further stations installed in 2025:



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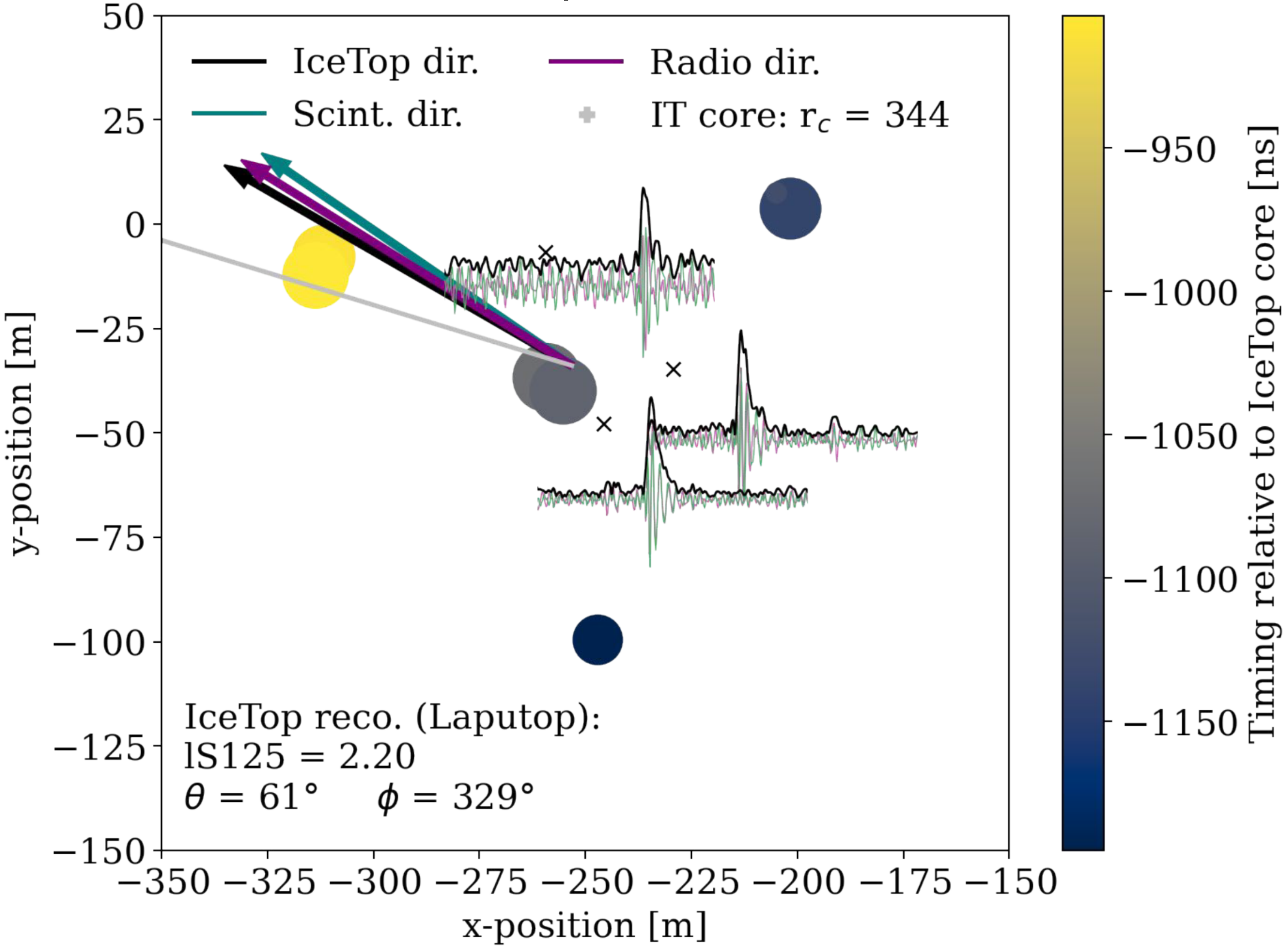
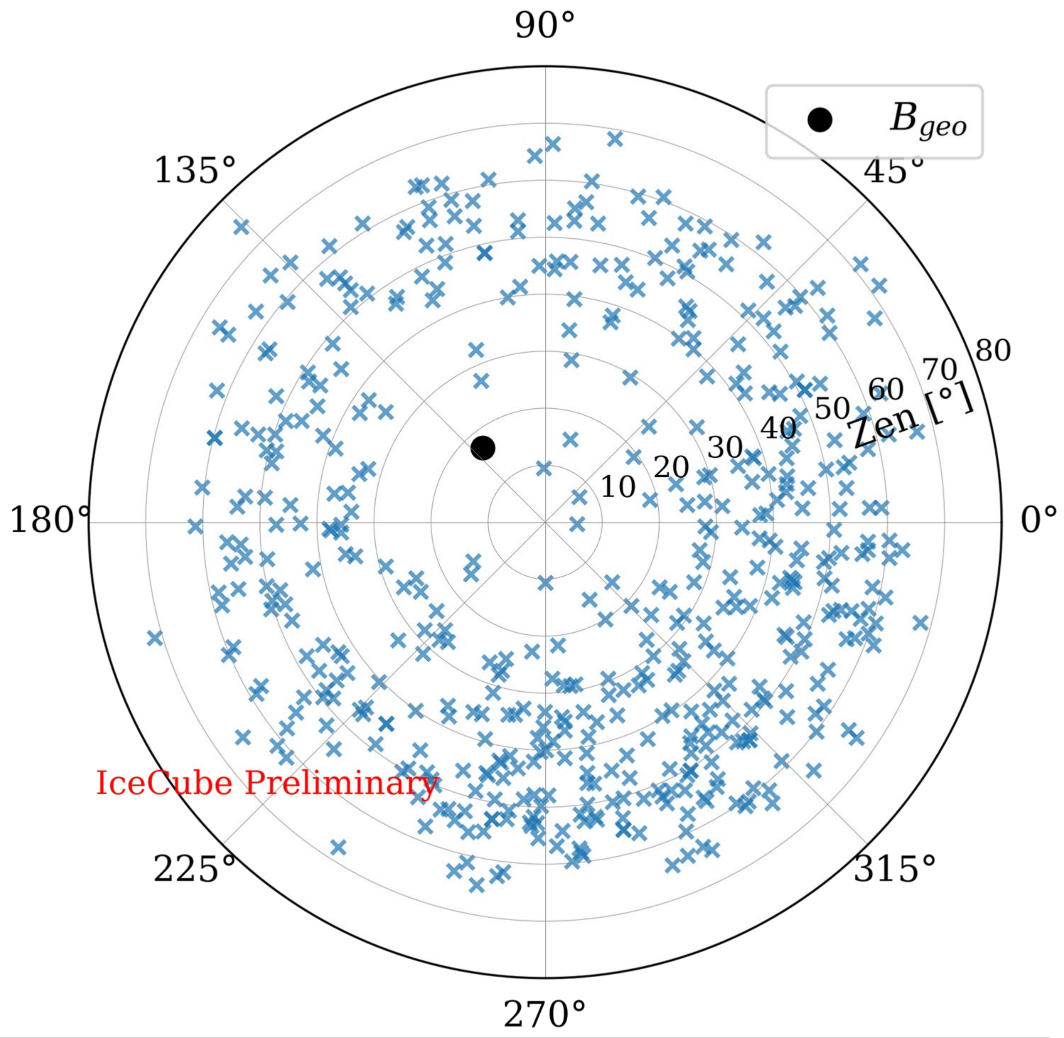
Prototype Station Operating Successfully

Example Event



Sky Map of Radio Events



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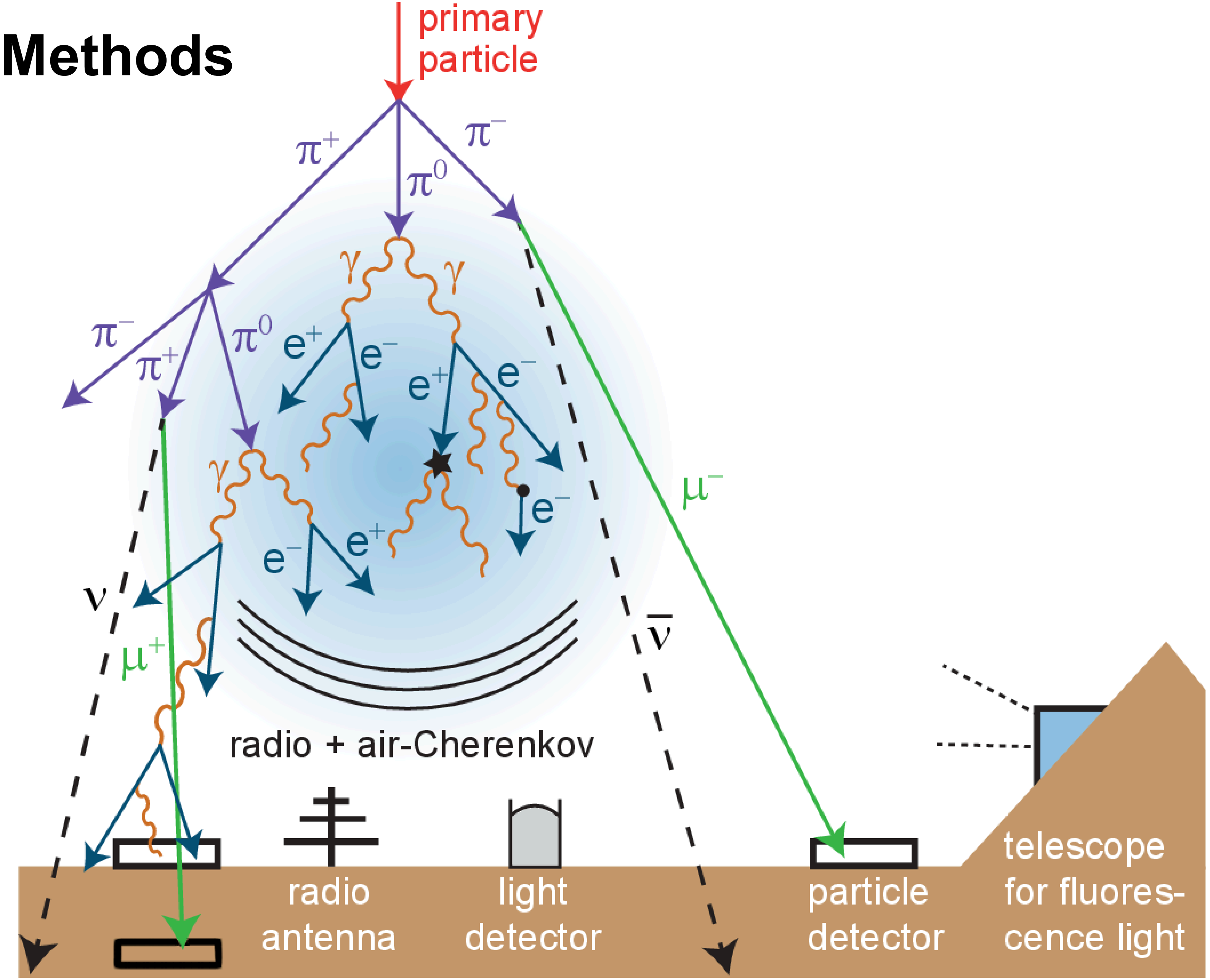
Air Shower Detection Methods

Two main detection categories:

1. Electromagnetic radiation emitted during the shower development:
   - Air-Cherenkov light
   - Fluorescence light
   - Radio emission
2. Particle on/under ground:
   - All-particle detectors, which depending on distance and design may be dominated by electrons/positrons, photons or muons
   - Muon detectors, usually with a shield absorbing electromagnetic particles



Prog. Part. Nucl. Phys. 93 (2017) 1

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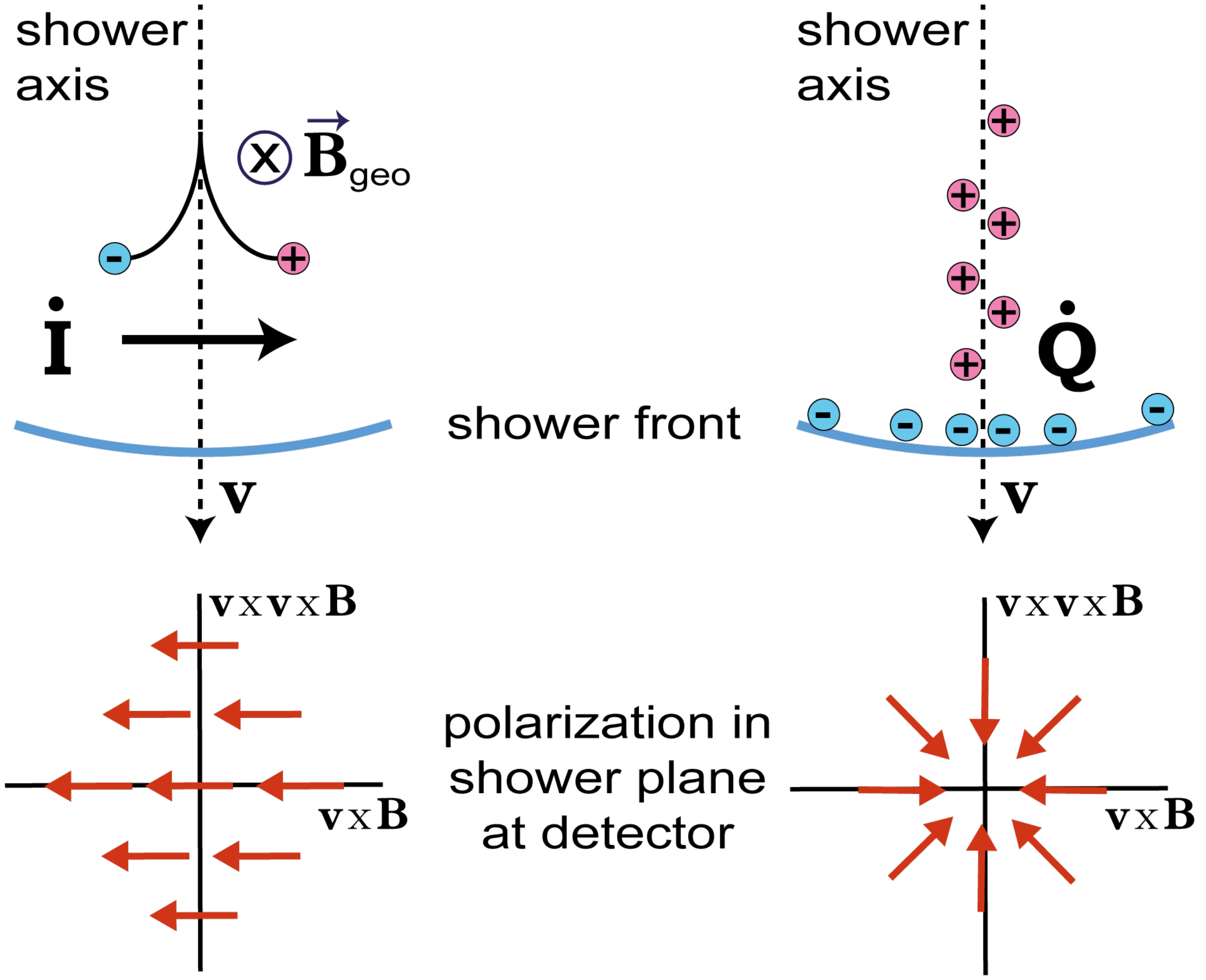
Radio: Emission Mechanisms



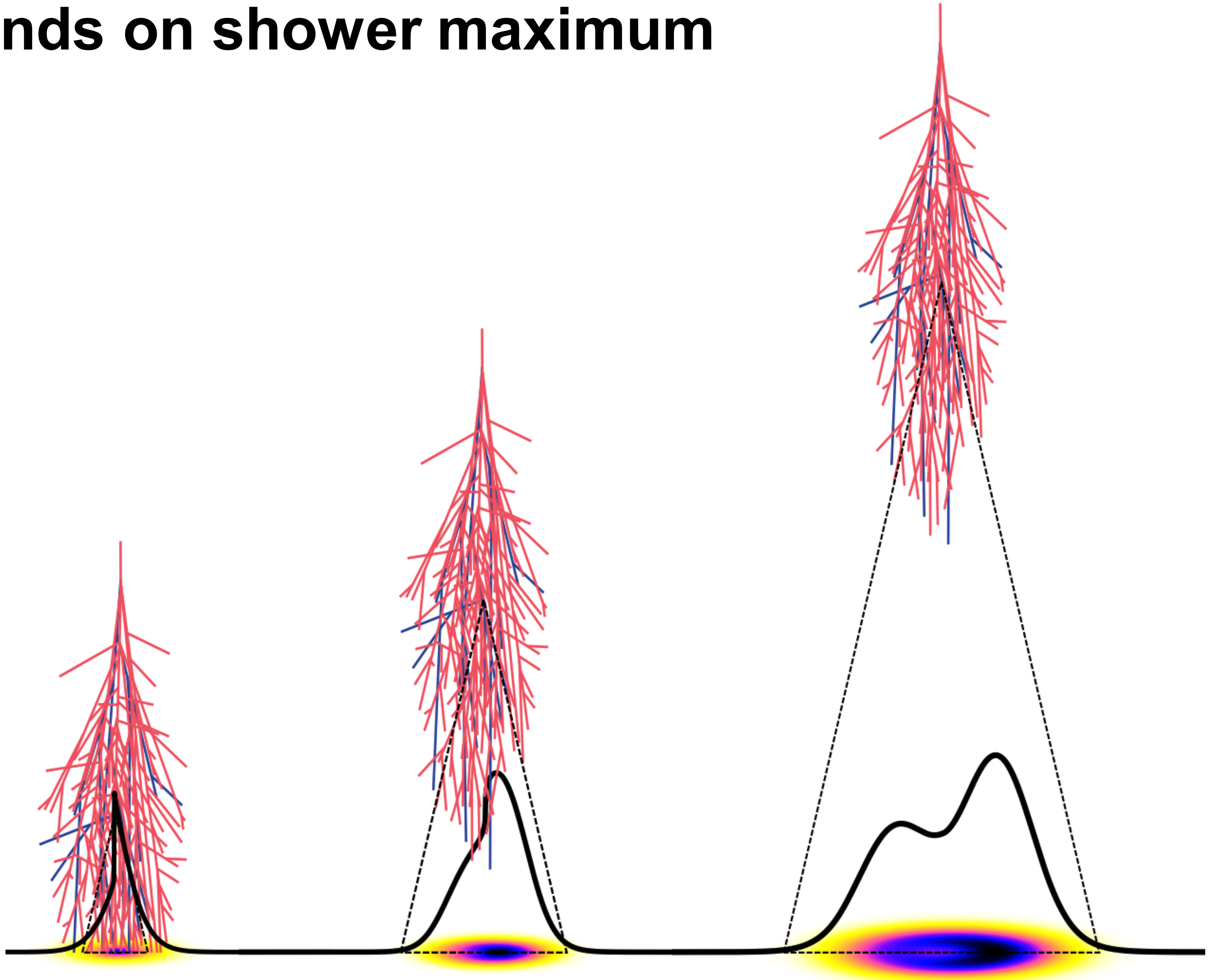
Geomagnetic emission

Askaryan emission

Prog. Part. Nucl. Phys. 93 (2017) 1-68
arXiv: 1607.08781

Shape of Footprint depends on shower maximum

- The closer the shower maximum to ground, the smaller the footprint and the steeper the lateral distribution.
- Asymmetry due to interference of geomagnetic and Askaryan emission
- For distant shower maximum, Cherenkov ring is visible at ~ 1°

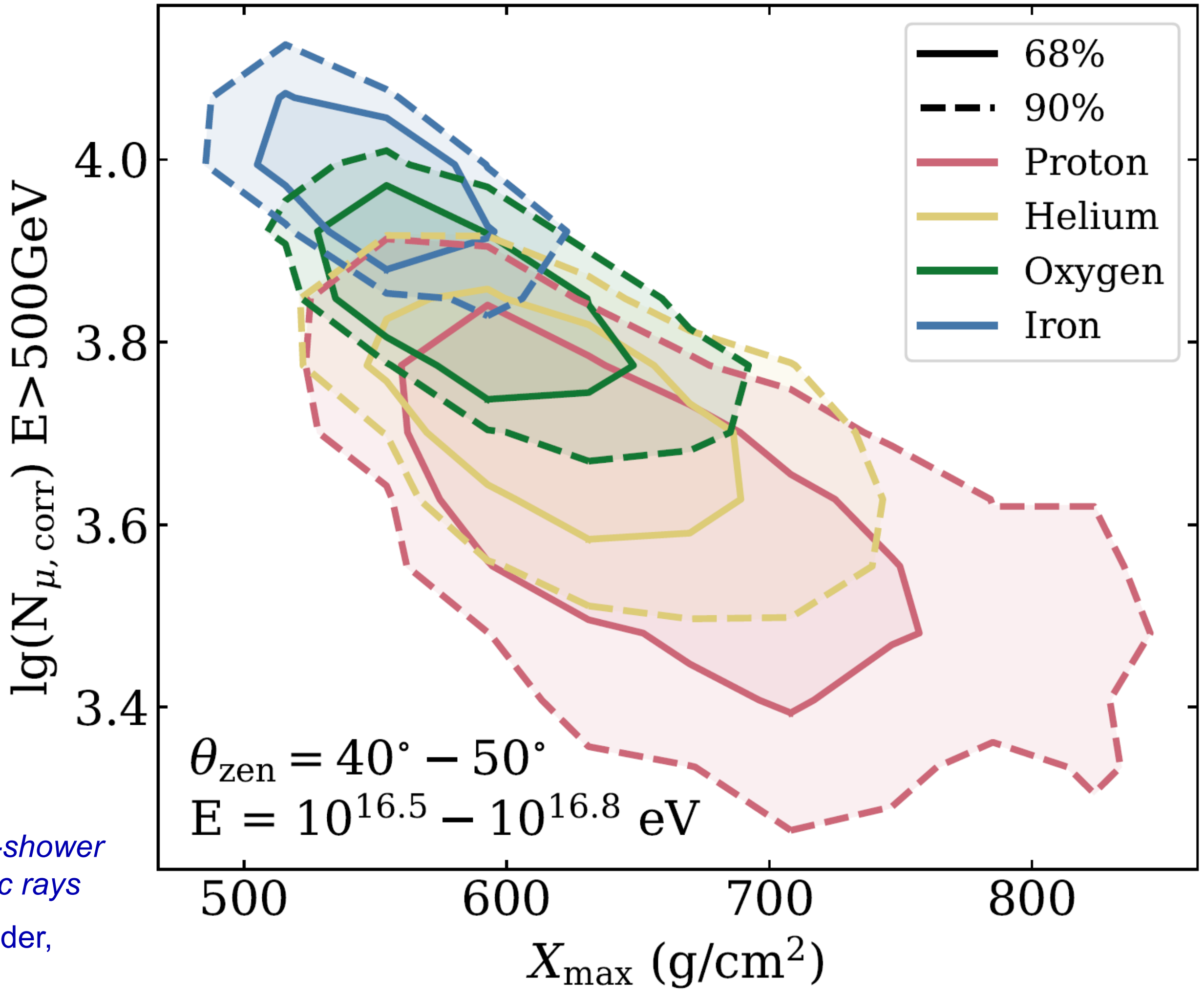


Pierre Auger Coll., PRD 109 (2024) 022002

Mass discrimination by X_{max} and Muon number

- Most mass sensitive shower parameters
  - depth of shower maximum X_{max}
  - muon number, if shower energy is known
  - → complementary mass sensitivity
- Radio measurement provides
  - depth of shower maximum X_{max}
  - calorimetric energy measurement

CORSIKA simulations of air showers



Studying the mass sensitivity of air-shower observables using simulated cosmic rays

Ben Flaggs, A. Coleman, F. Schroeder, Phys. Rev. D 109 (2024) 042002

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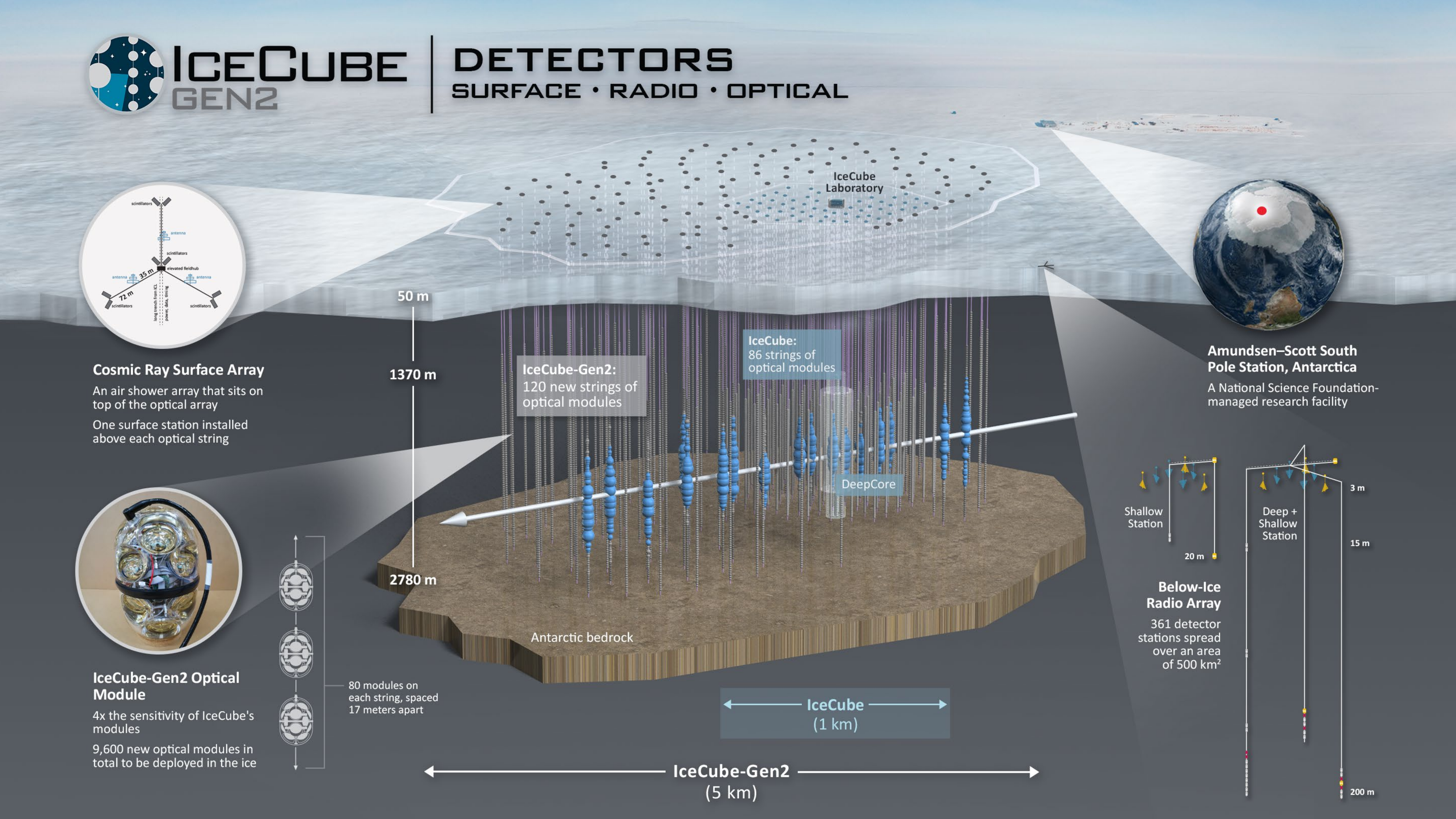
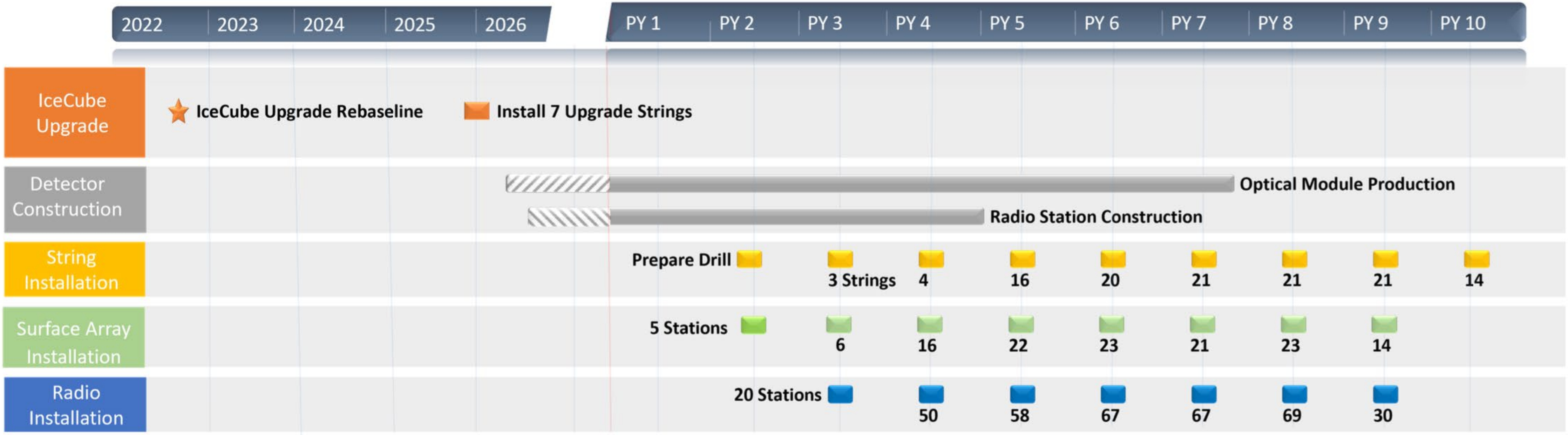


ICECUBE
GEN2
DETECTORS
SURFACE • RADIO • OPTICAL
IceCube Laboratory
scintillators
antenna
scintillators
elevated fieldhub
35 m
antenna
antenna
72 m
scintillators
long trench from ICL
power, data, timing
scintillators
Cosmic Ray Surface Array
An air shower array that sits on top of the optical array
One 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
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)
Amundsen–Scott South Pole Station, Antarctica
A National Science Foundation-managed research facility
Shallow Station
20 m
Deep + Shallow Station
3 m
15 m
200 m
Below-Ice Radio Array
361 detector stations spread over an area of 500 km²

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., and on German FIS roadmap
  - Technical Design Report ready, NSF proposal pending for process through final design



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

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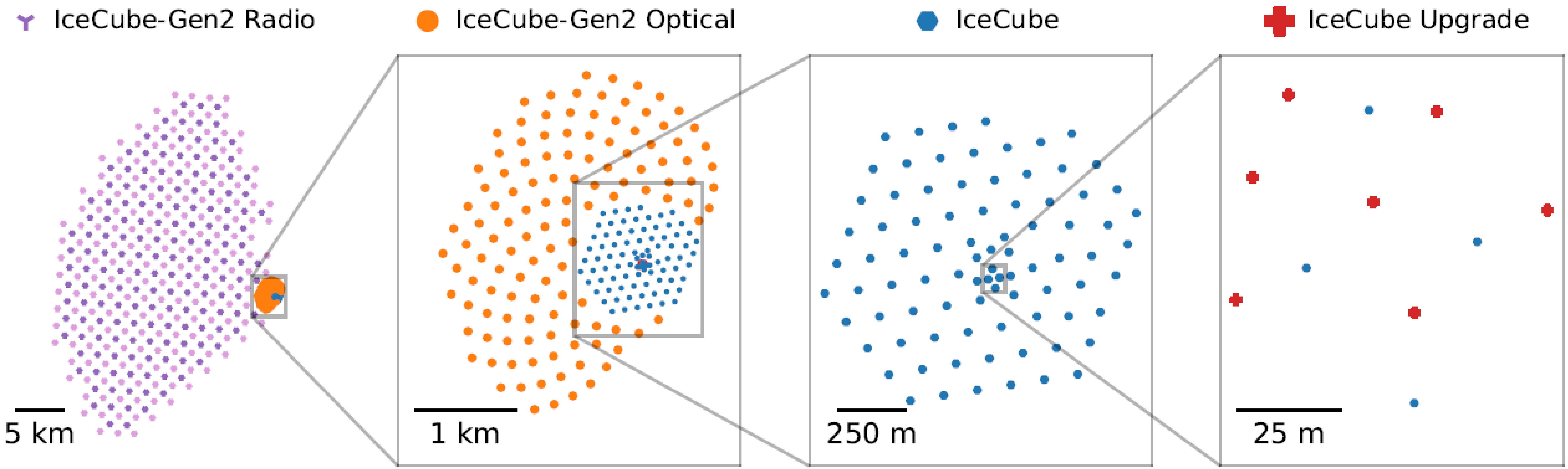
IceCube-Gen2: extending the IceCube Neutrino Observatory

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



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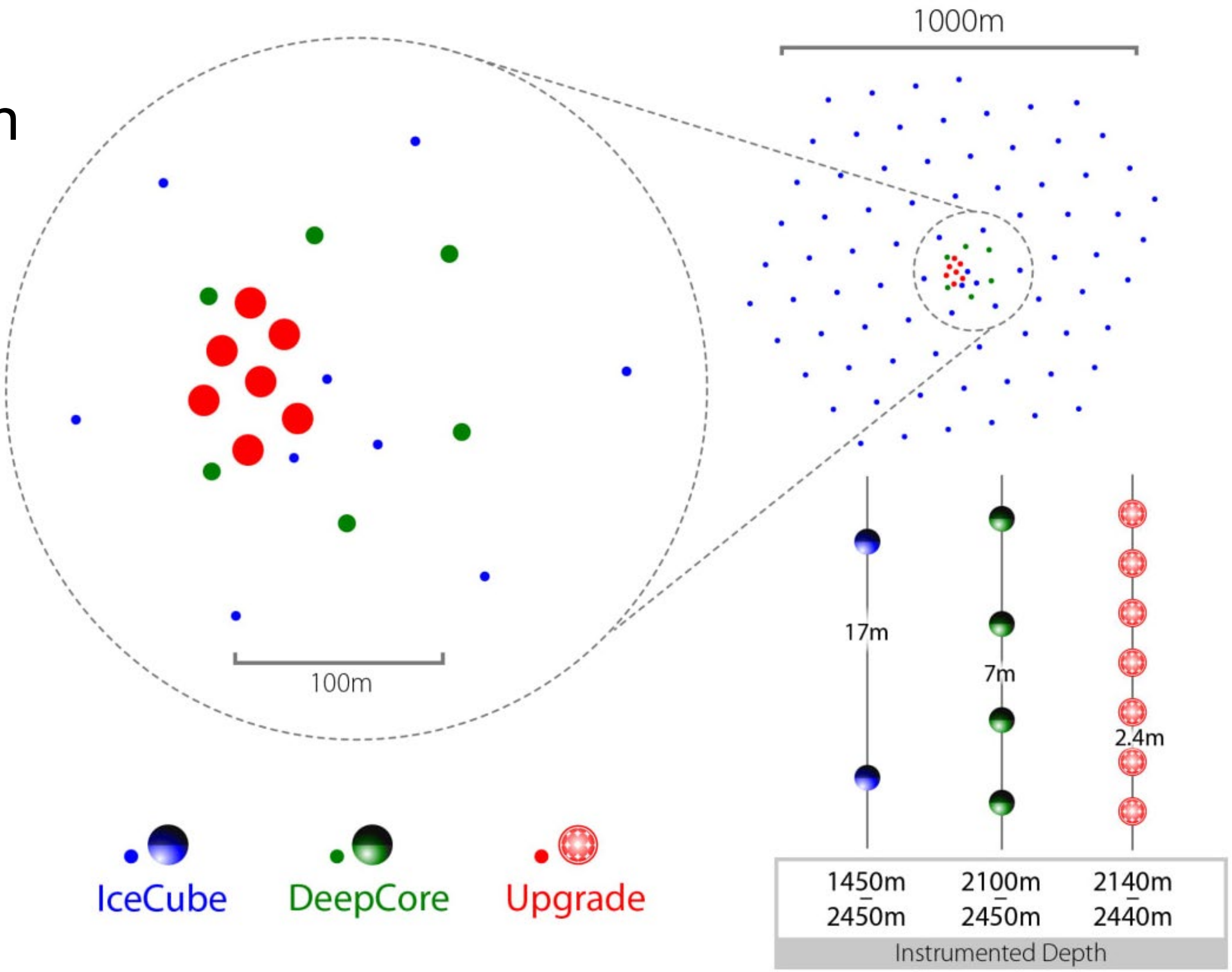
IceCube Upgrade

- Deployment in polar season 2025/26
- Denser and improved instrumentation
  - neutrino physics at lower energies
  - improved modelling of ice properties

mDOM

D-Egg



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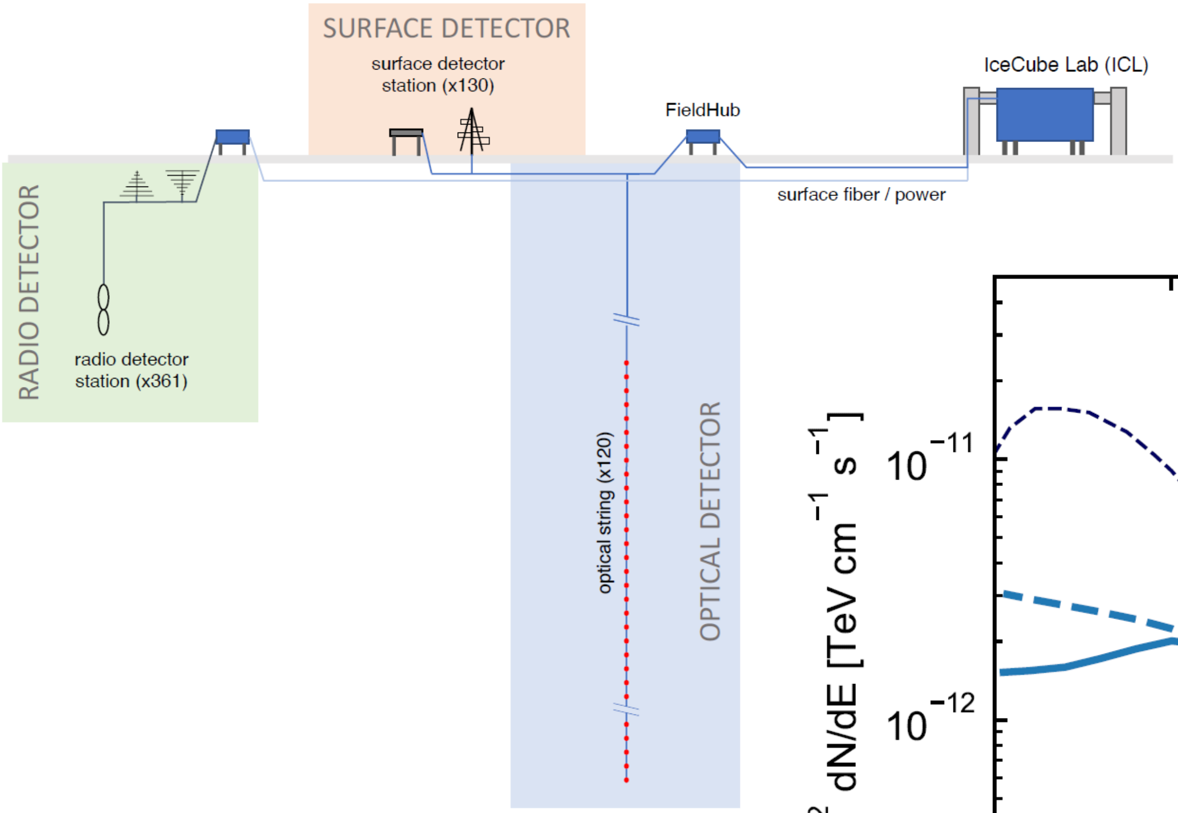
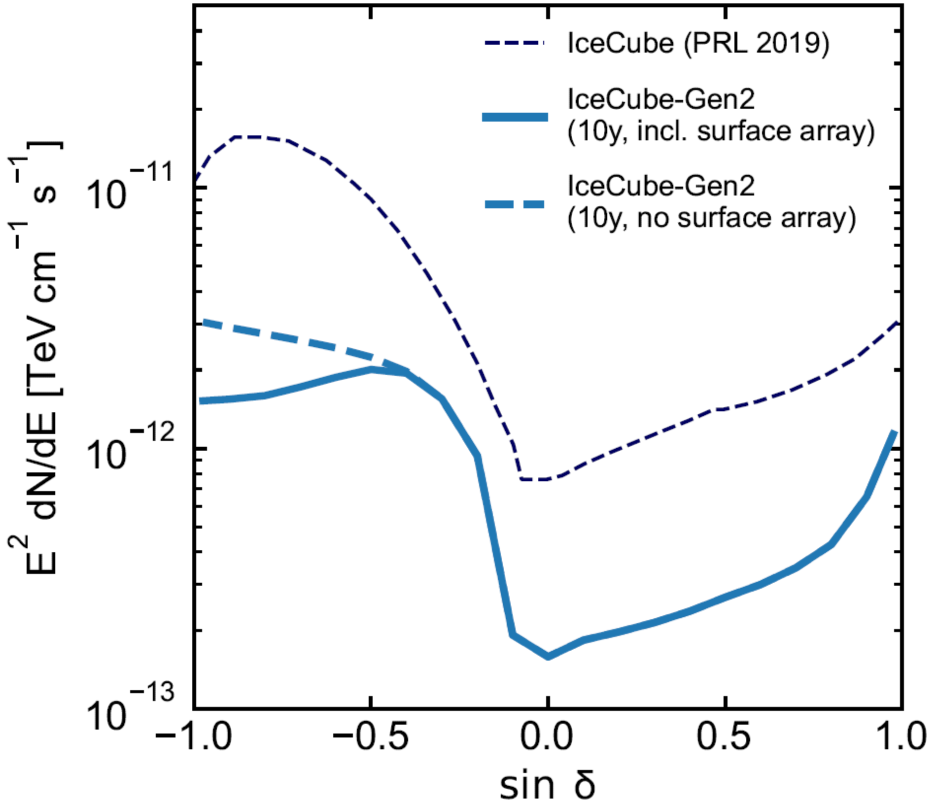
IceCube-Gen2 Optical Array

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

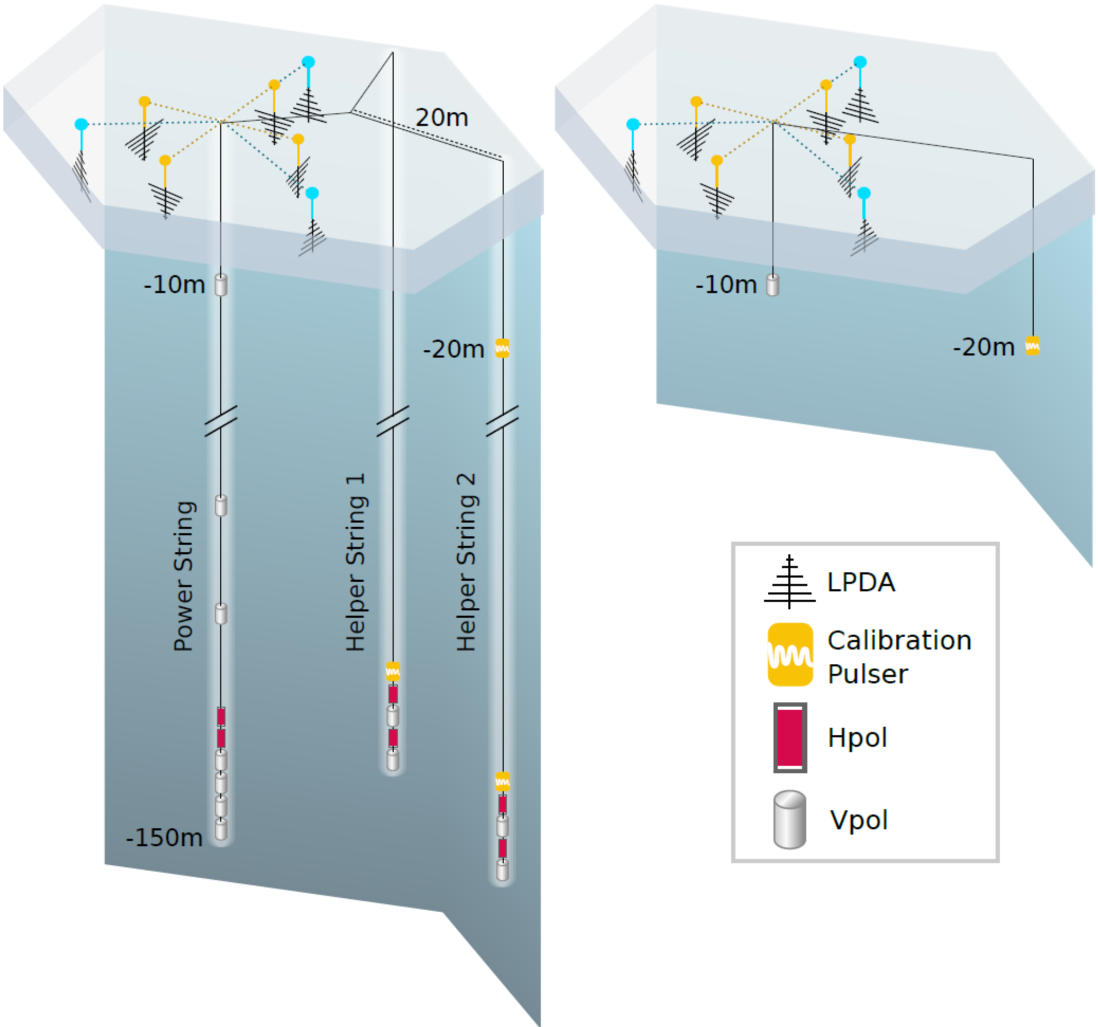


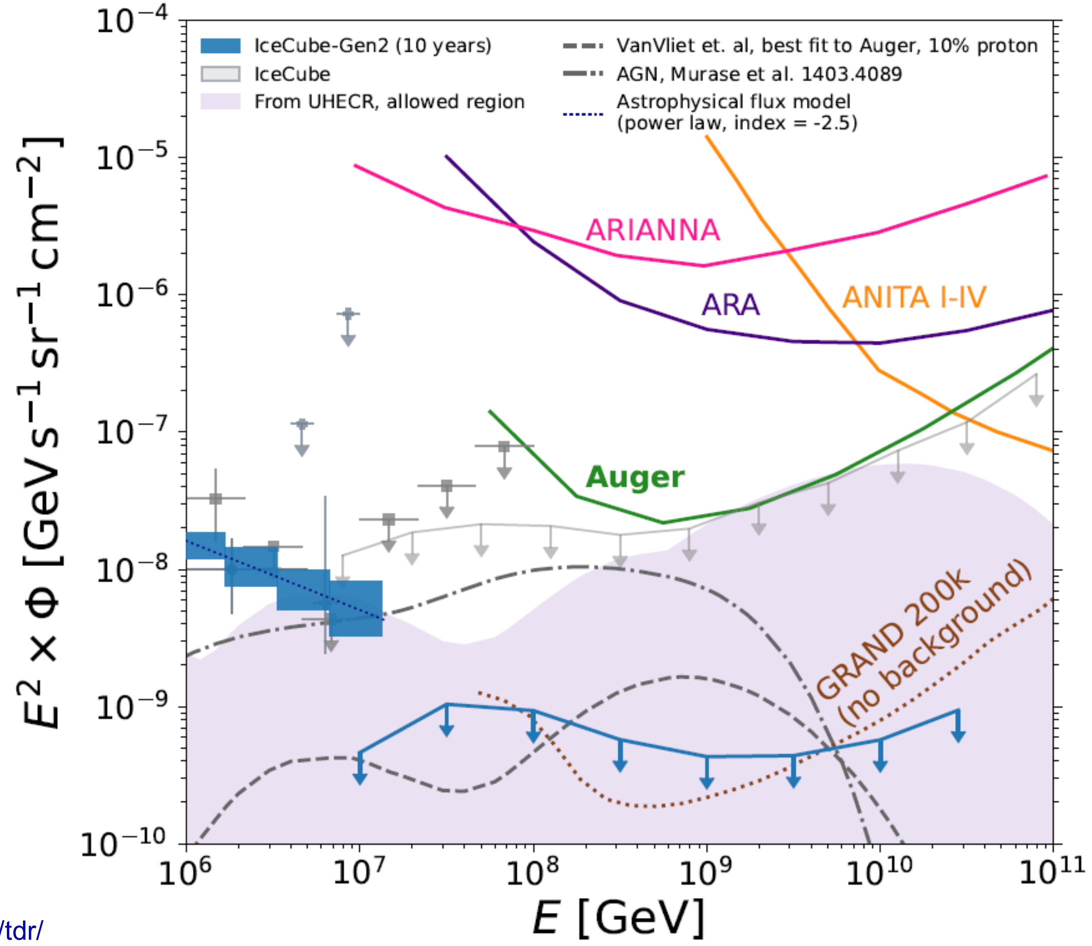


IceCube-Gen2 Technical Design Report (TDR): https://icecube-gen2.wisc.edu/science/publications/tdr/

IceCube-Gen2 Radio Array

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





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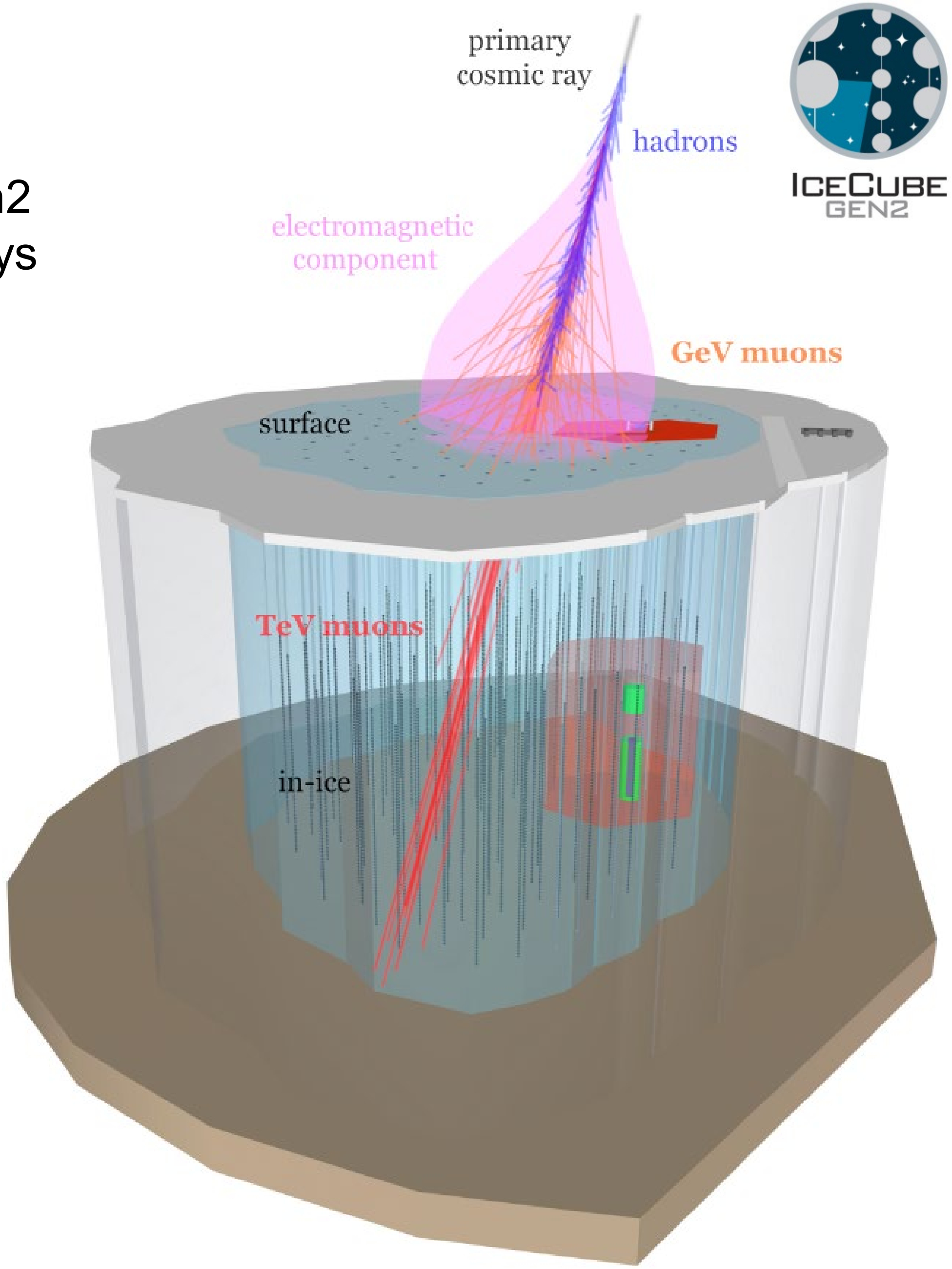
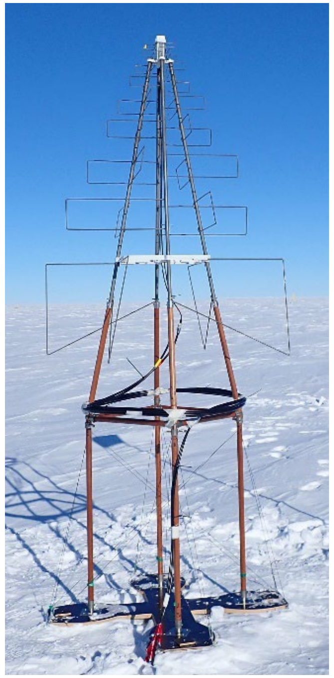
IceCube-Gen2 and its Surface Array

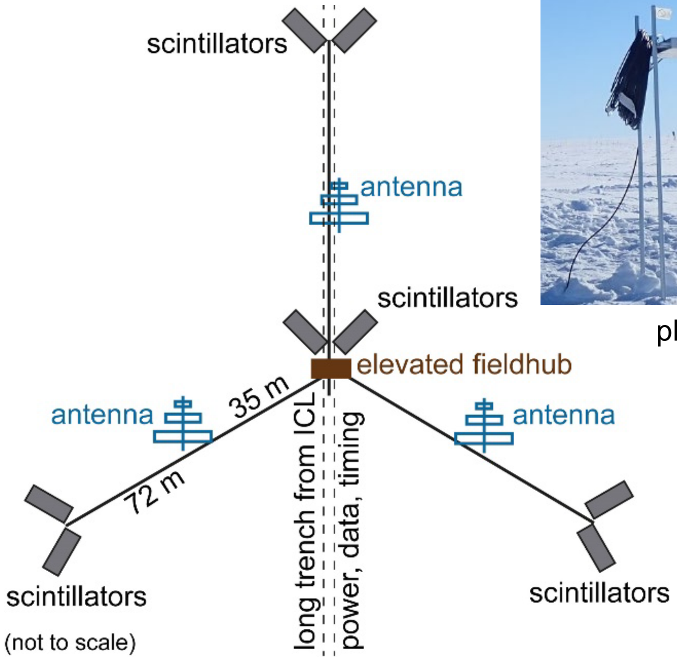
- Combination of deep and surface detector will make IceCube-Gen2 a unique laboratory for air-shower physics and Galactic cosmic rays
- 8x larger area, 30x larger aperture for in-ice coincidences



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

4 pairs of scintillators + 3 antennas

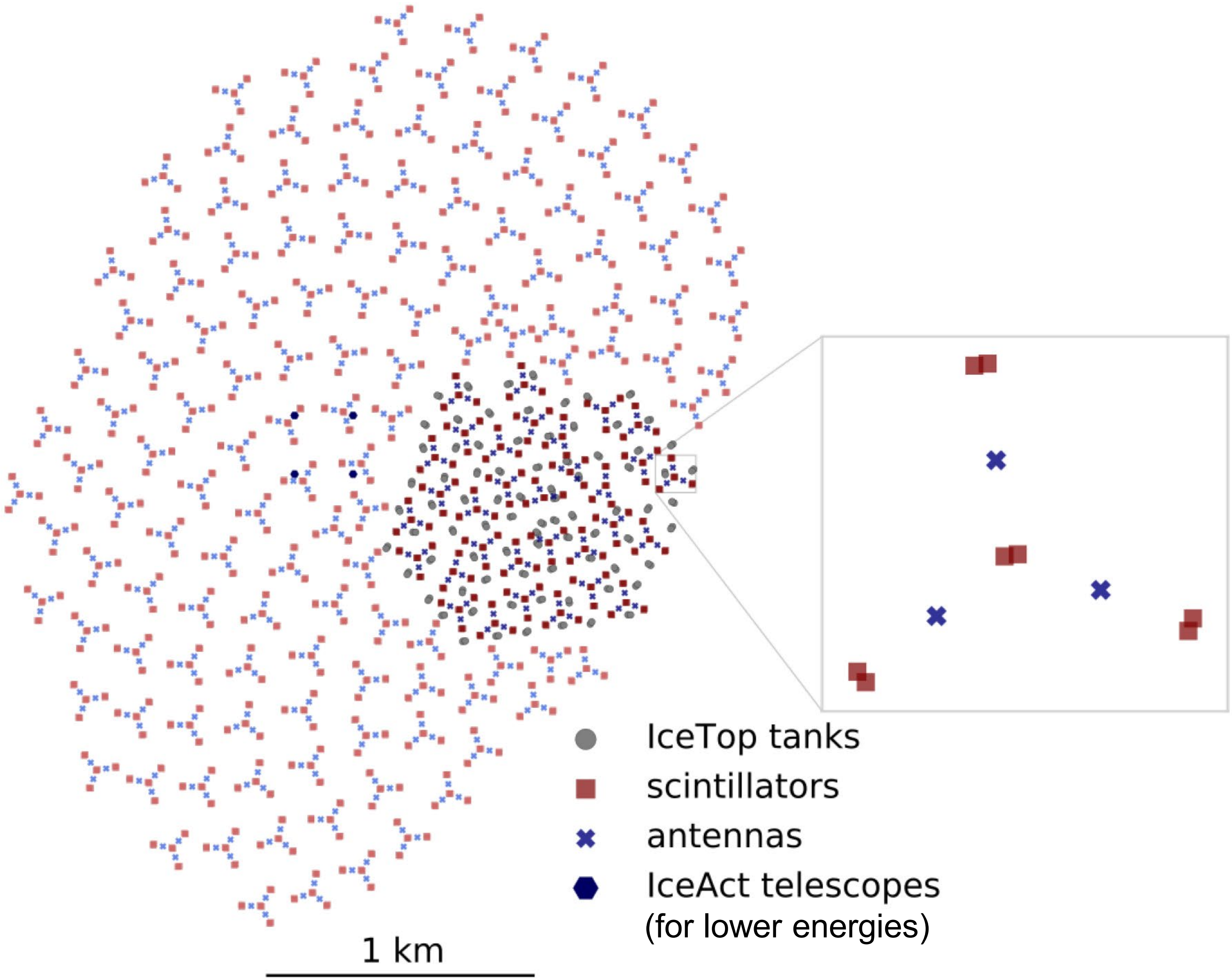


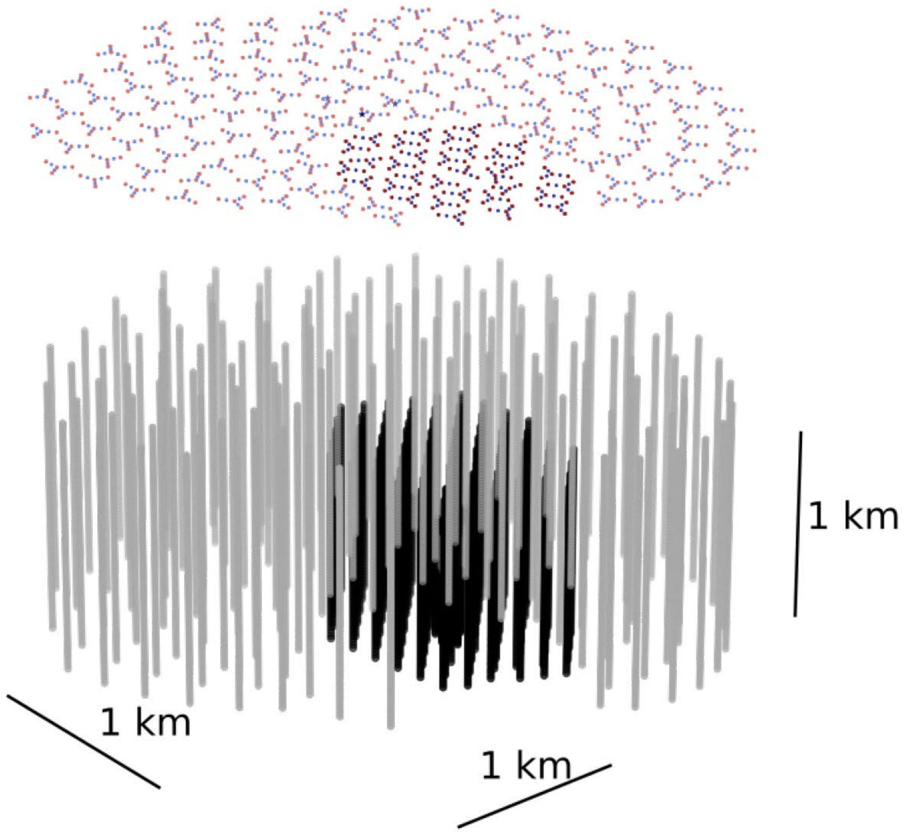


photos: prototype station at South Pole

see also:
PoS(ICRC2025)394
PoS(ICRC2025)427

IceCube-Gen2 Surface Array above the Optical Array





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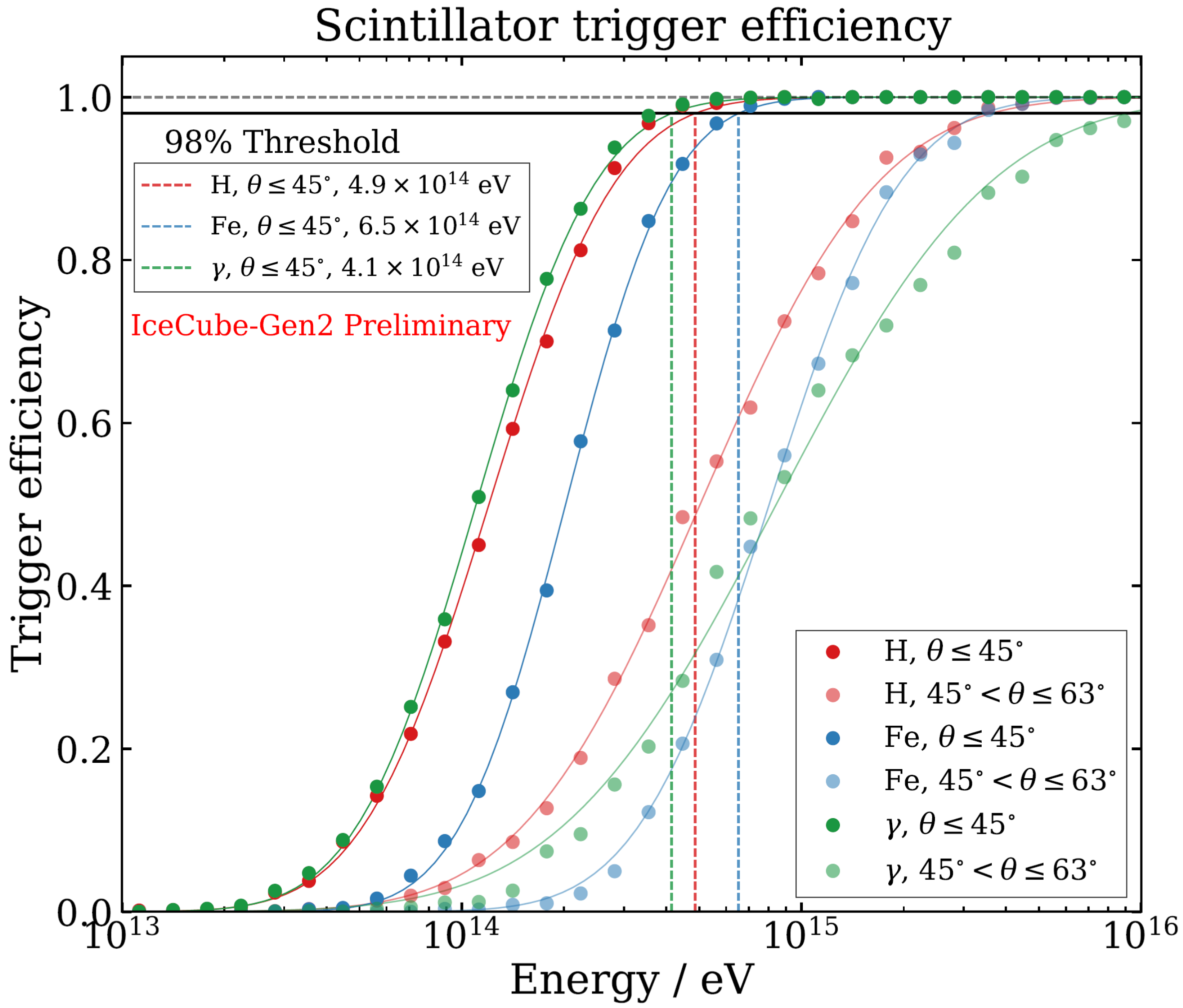
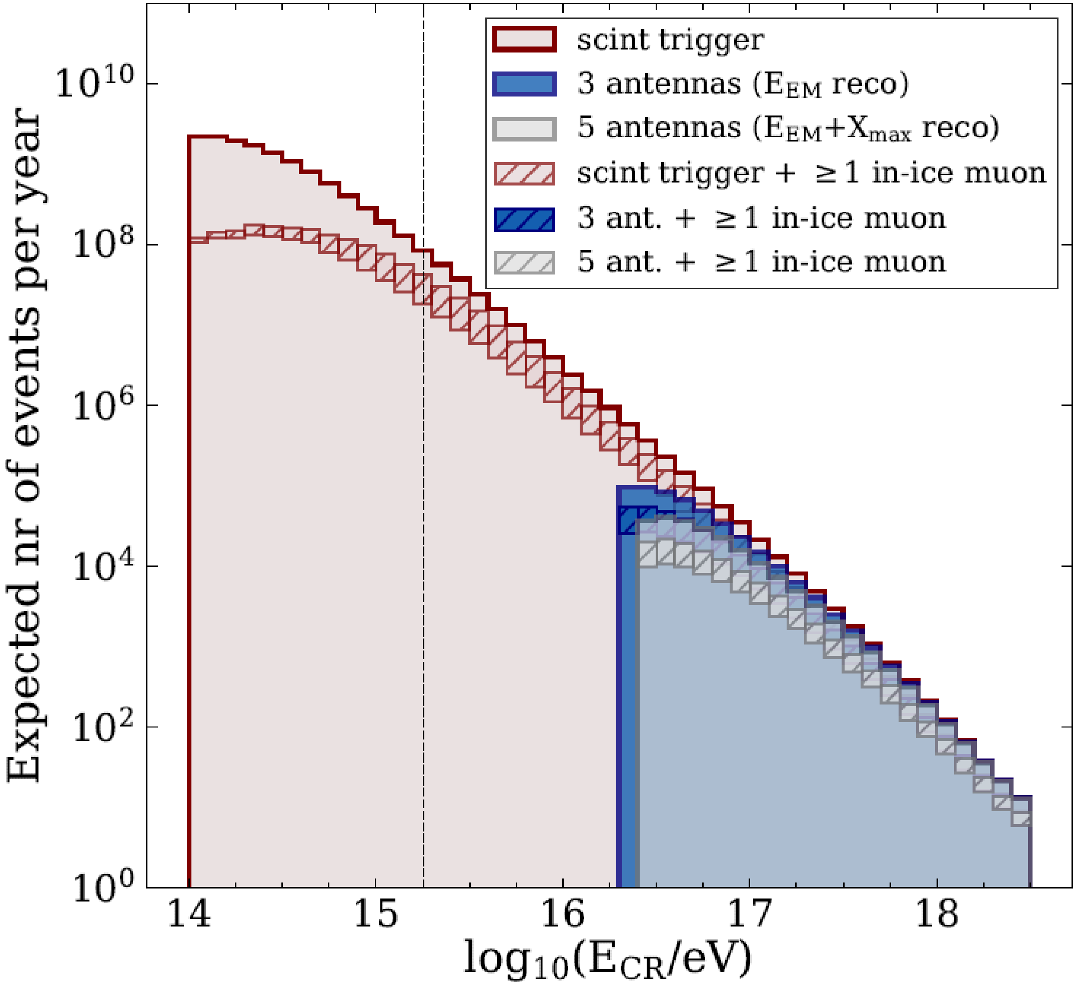
Low Detection Threshold provided by Scintillators

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





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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 alerts 2) Test potential of radio veto for very inclined showers
Physics using surface *and* in-ice detector	**1) Hadronic interactions** including prompt muons **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 2) Calibration of in-ice detectors by air-shower signals and muons

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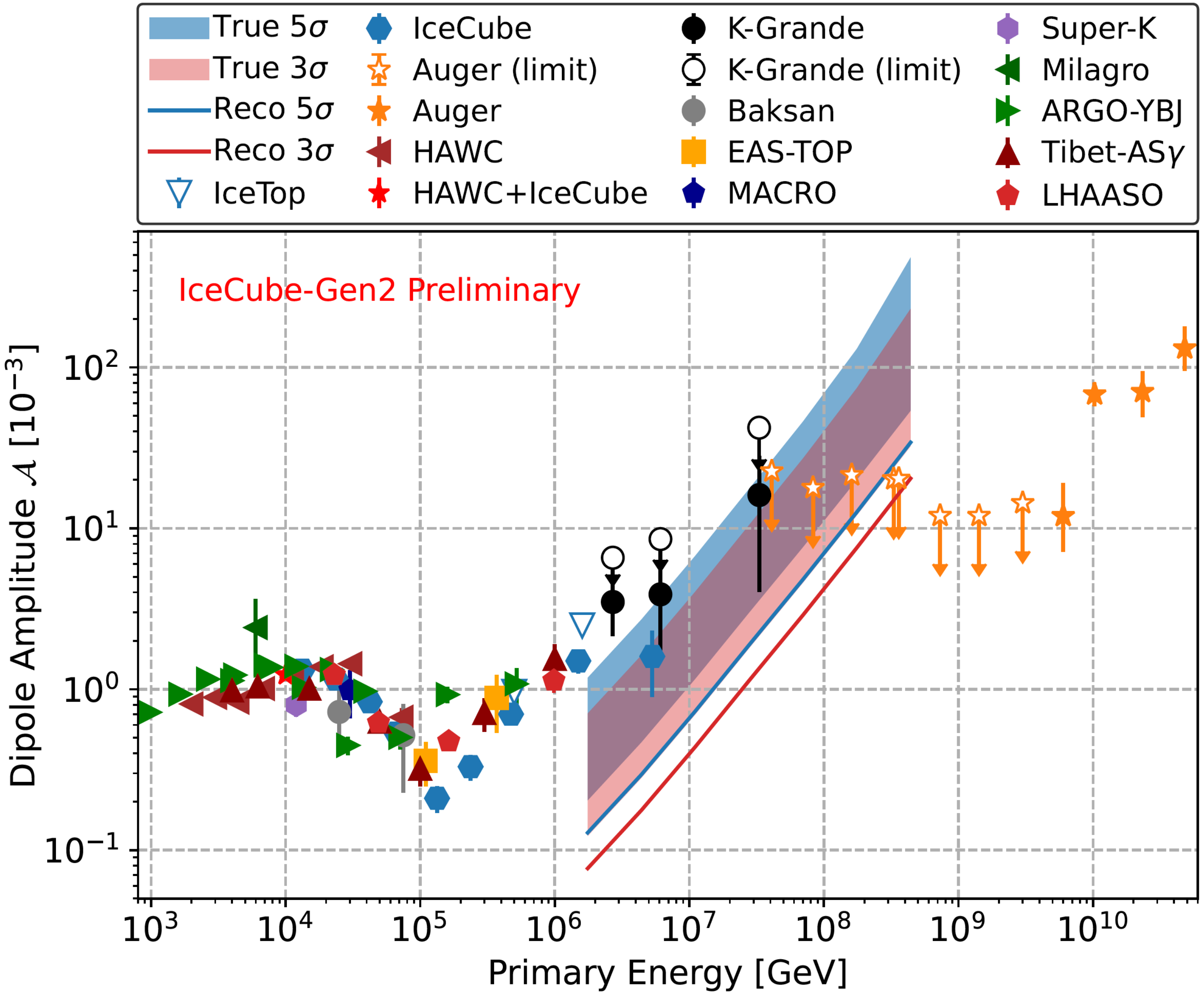
IceCube-Gen2 Sensitivity to Cosmic-Ray Dipole Anisotropy



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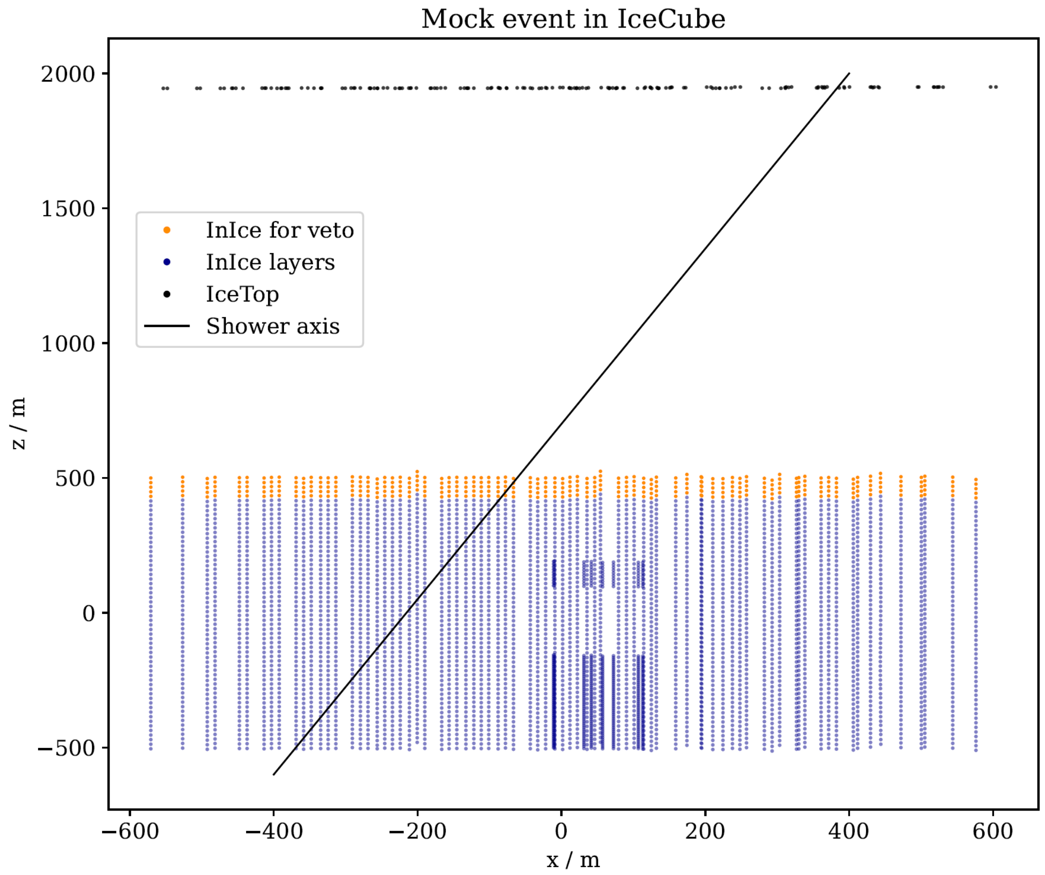
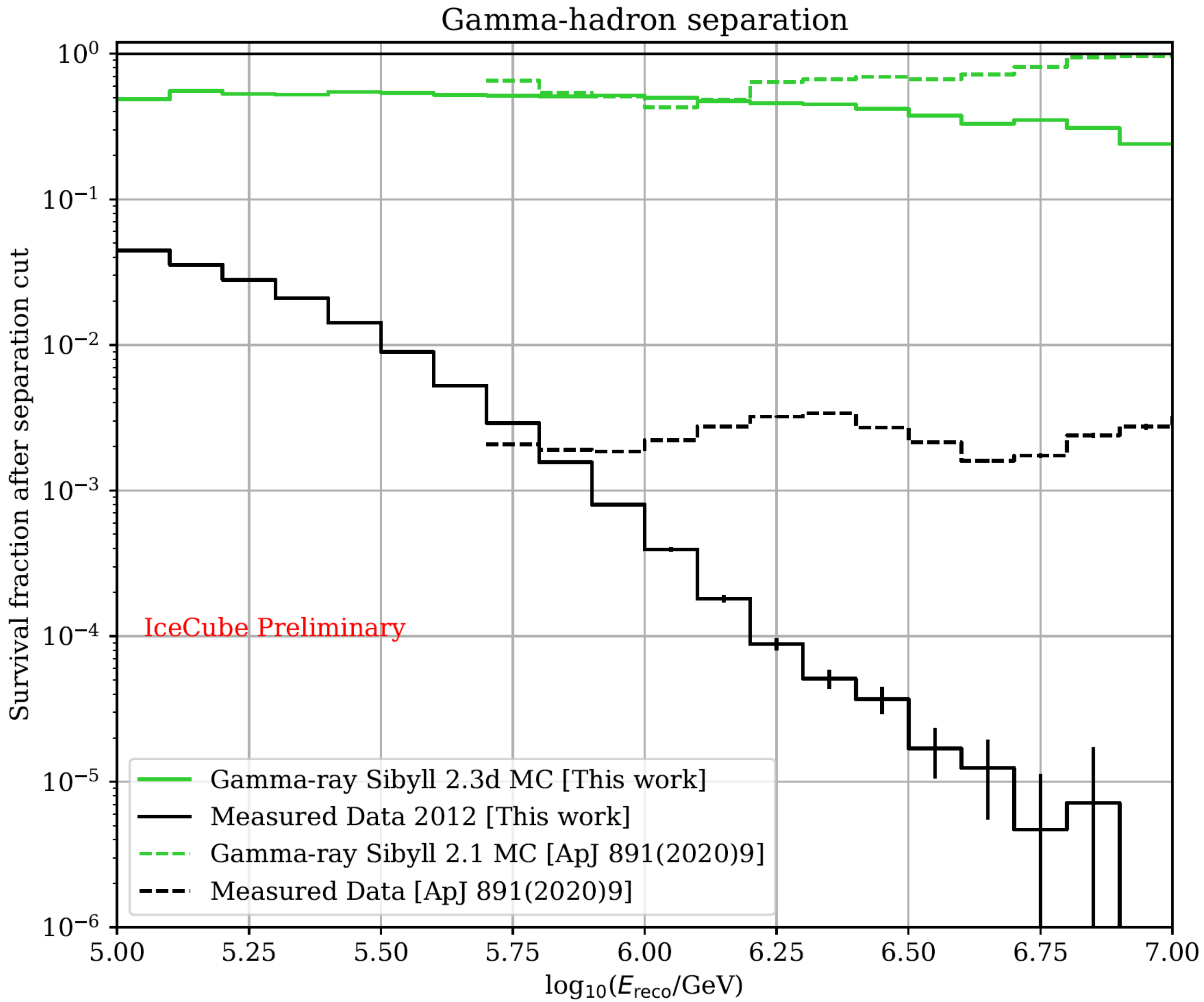
Gamma-Hadron Separation with IceCube

- In contrast to hadronic air showers, most PeV gamma-ray showers do not contain high-energy muons





F. Schroeder and F. Bontempo for the IceCube Collaboration, PoS (ICRC2025) 837

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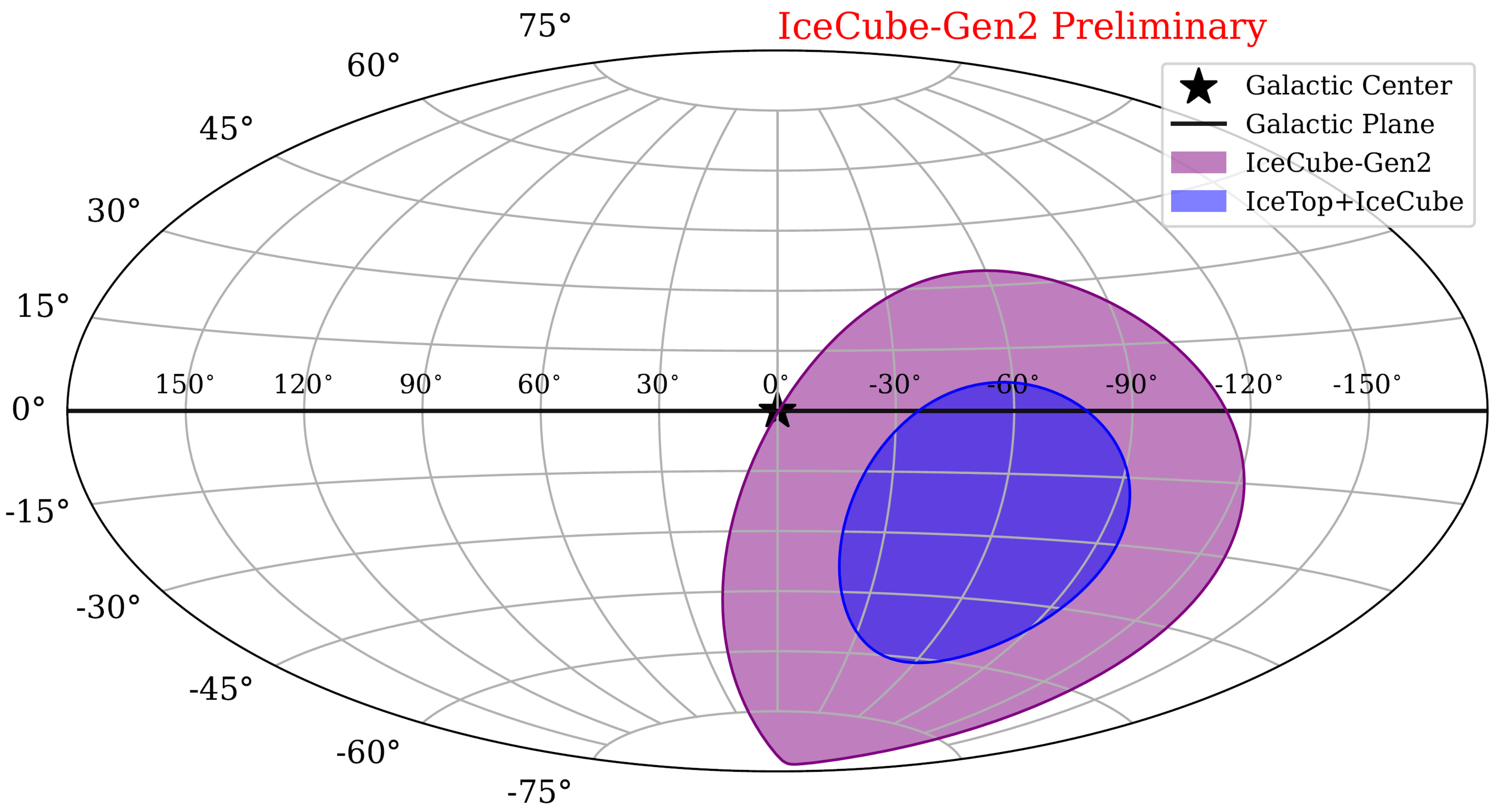
Field-of-view (FOV) for PeV gamma rays

- Surface-deep coincident events approximately down to the elevation of the Galactic Center



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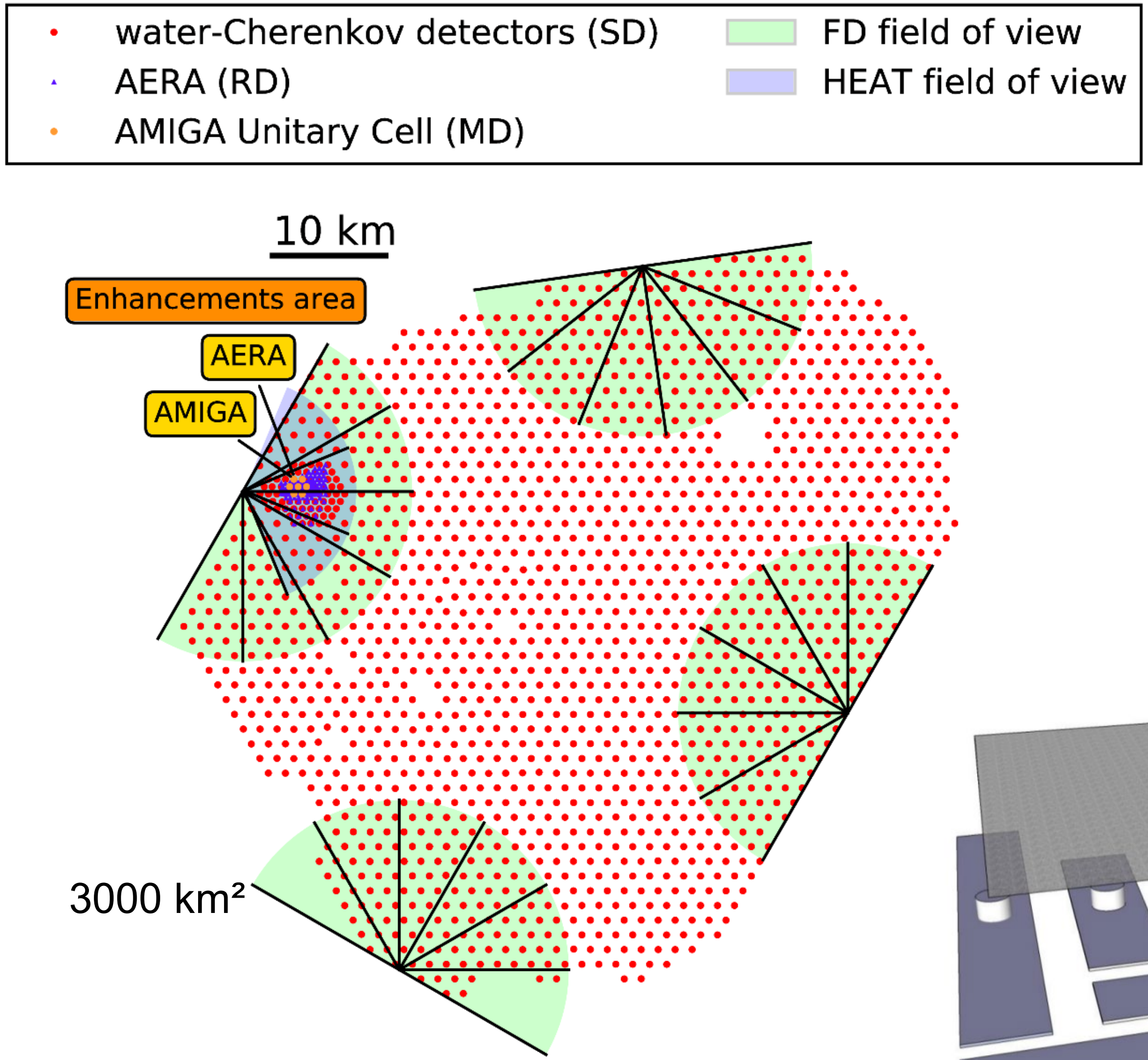
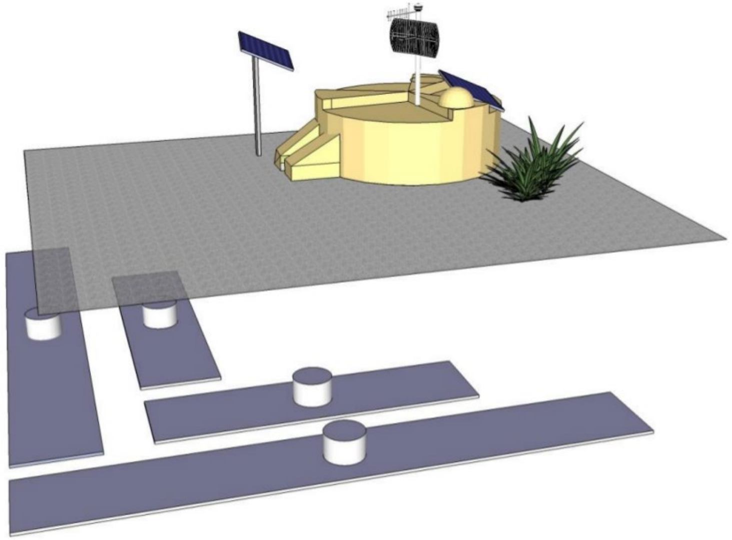
Pierre Auger Observatory and its Upgrade and Enhancements

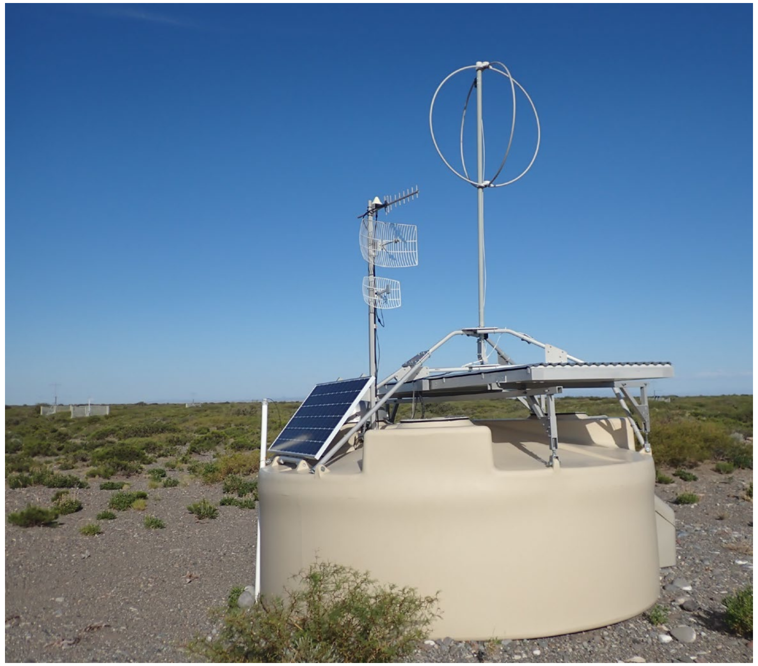


Auger Coll.

- AugerPrime Upgrade completed 2024
- Enhancements AMIGA and AERA
  - Auger Muon and Infill for the Ground Array (AMIGA)
  - Auger Engineering Radio Array (AERA)

→ IceCube prototype station deployed in 2022





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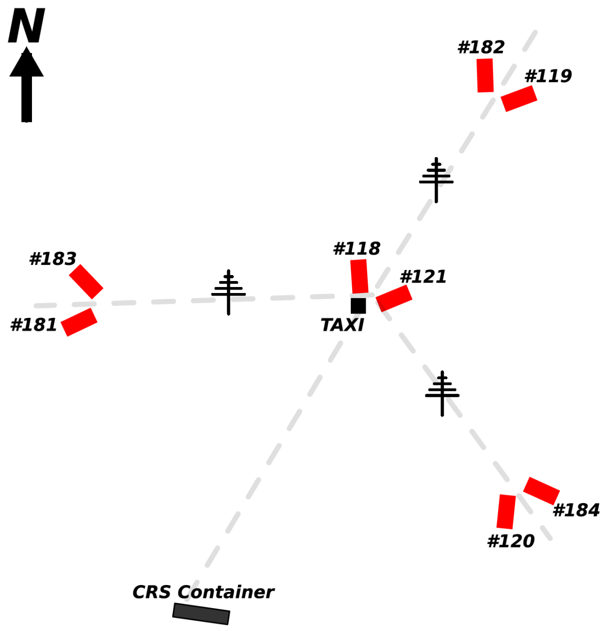
Top View of IceCube station at Auger SD433



drone photo by Tim Huege

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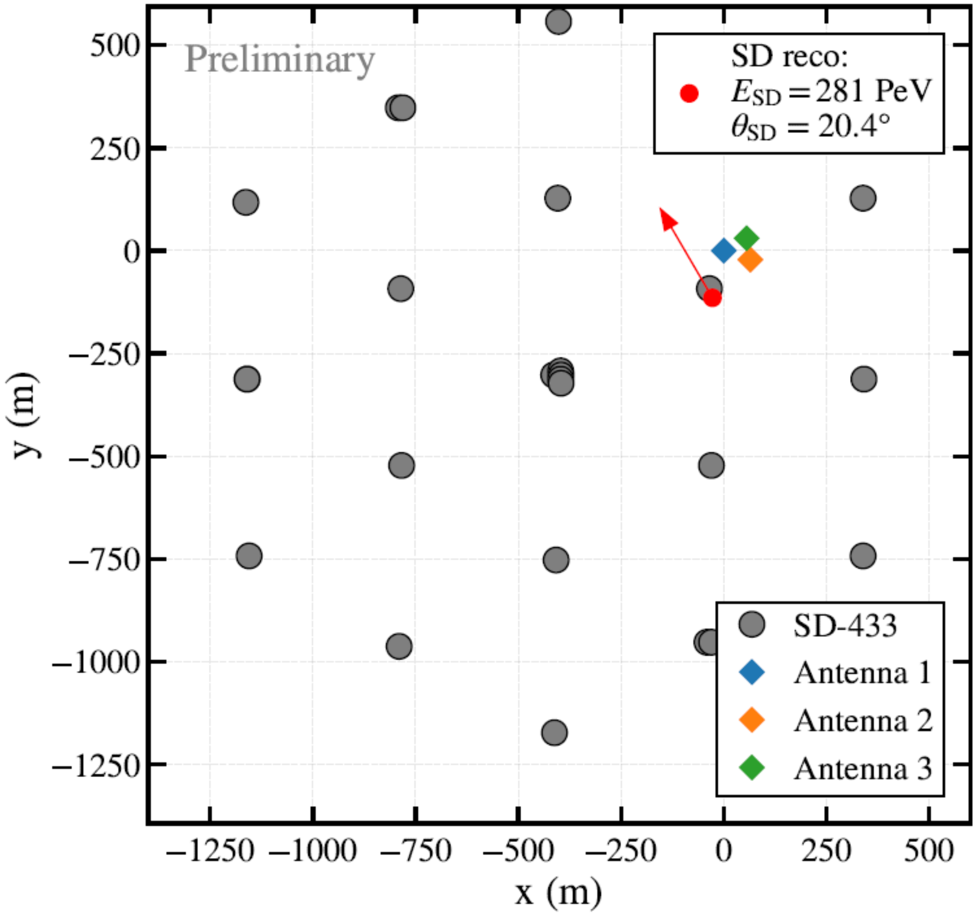
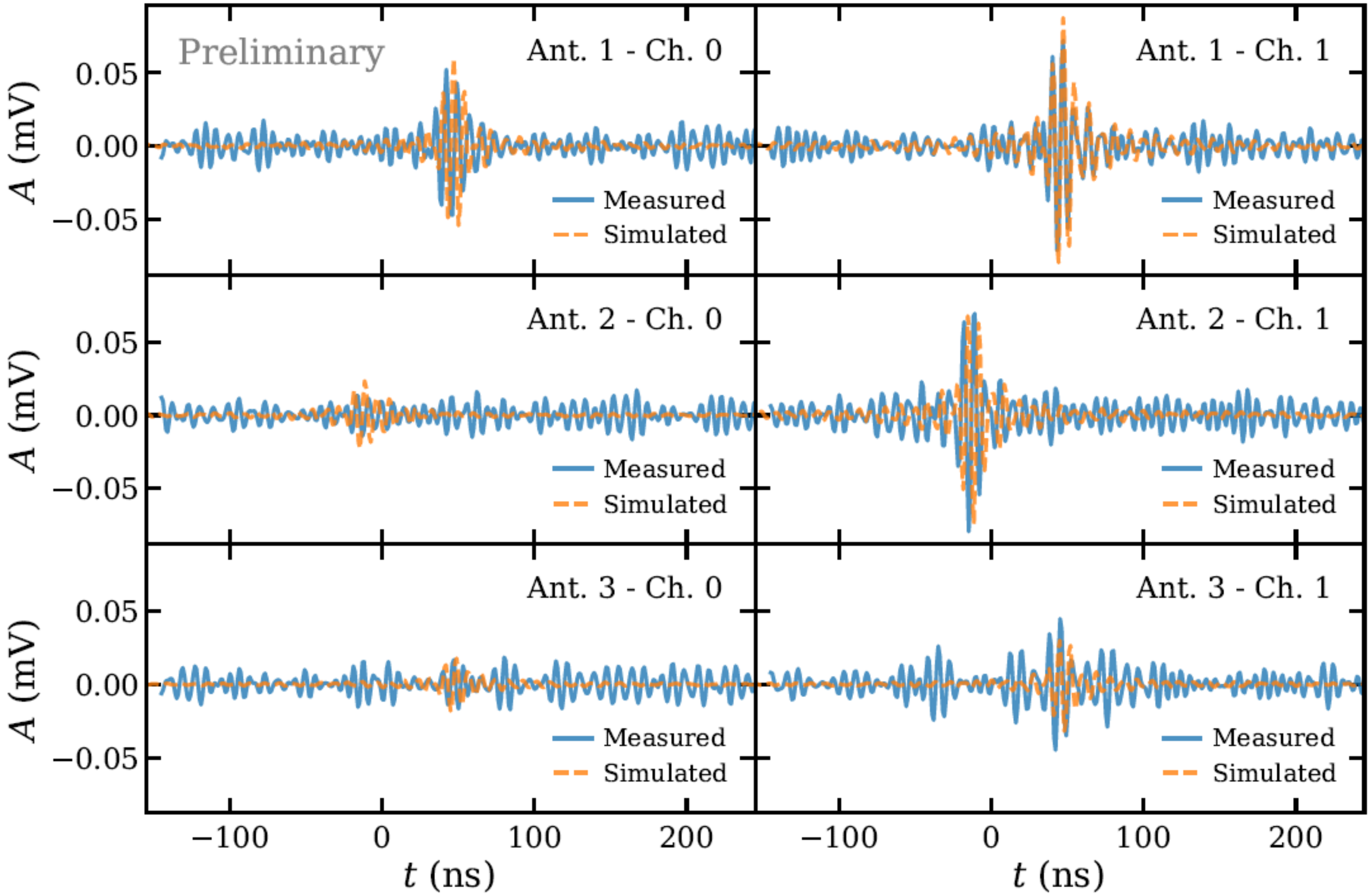
Air-Shower event measured with IceCube Station at Auger

- 3 antennas with two channels each, triggered by 8 scintillation panels





Stef Verpoest, Carmen Merx, Ben Flaggs for the Pierre Auger and IceCube Collaborations, PoS (ICRC2025) 428

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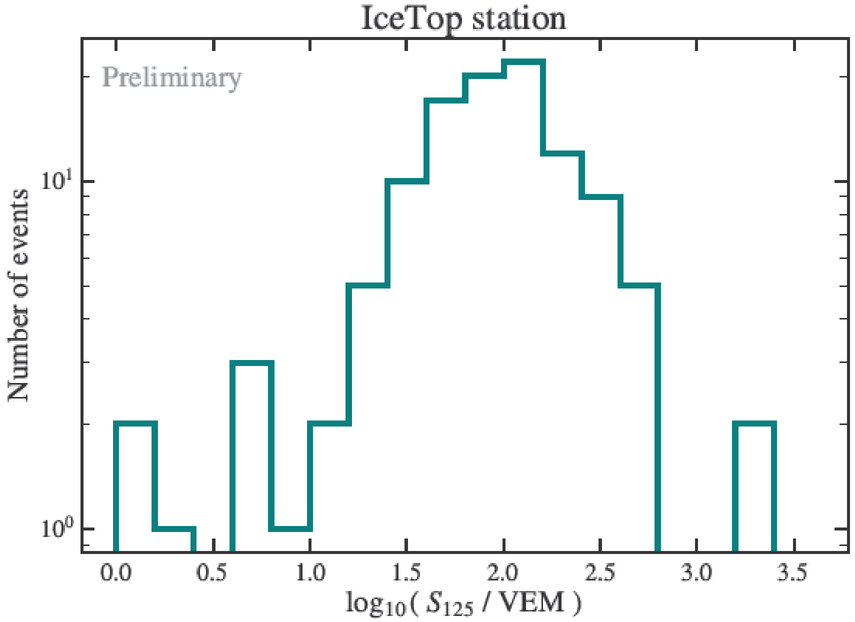
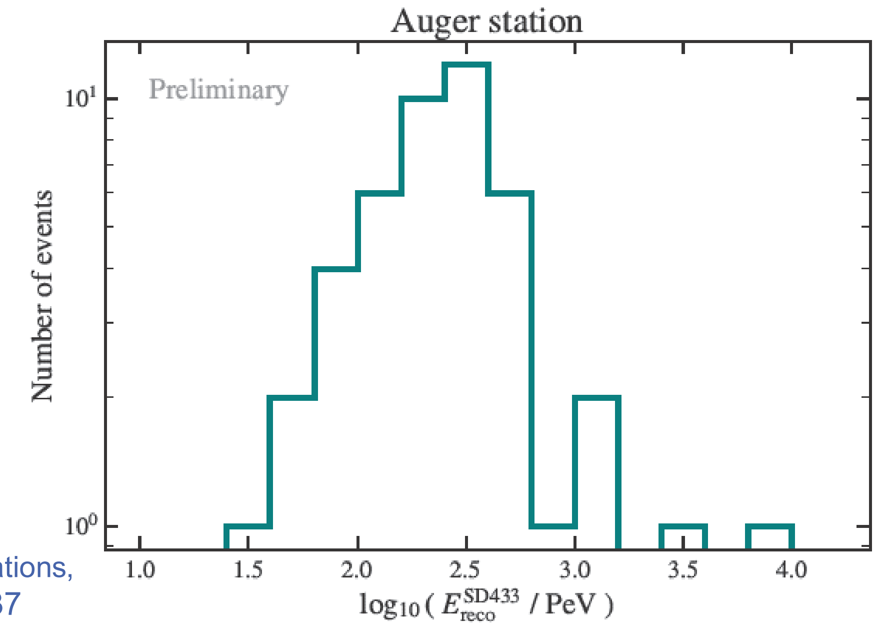
Comparing Prototype Stations

- Prototype stations of 3 antennas and 8 scintillators each at IceCube and the Pierre Auger Observatory
- Energy distribution of measured events roughly consistent with expectations
- Detailed analysis for cross-calibration is planned



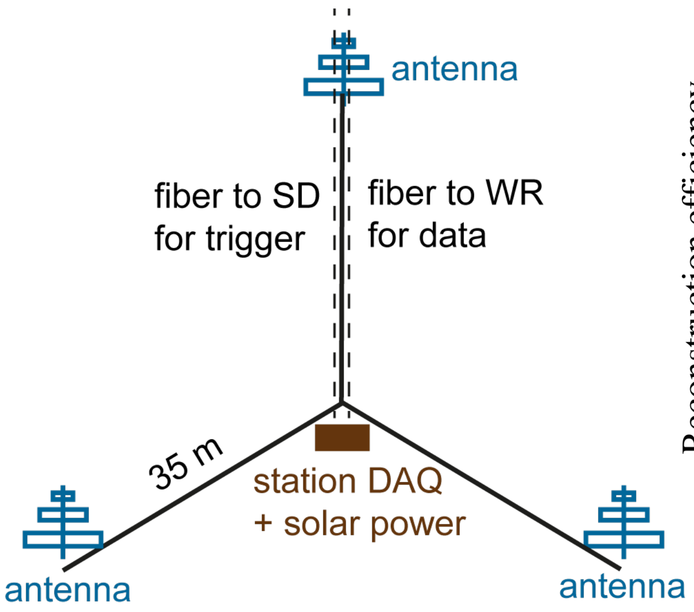
Photos of Auger Station

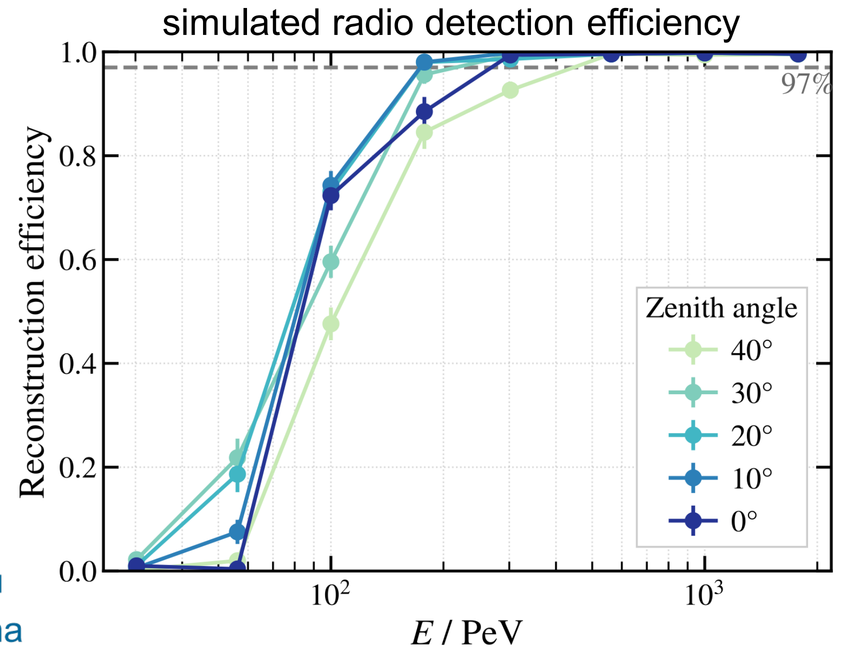


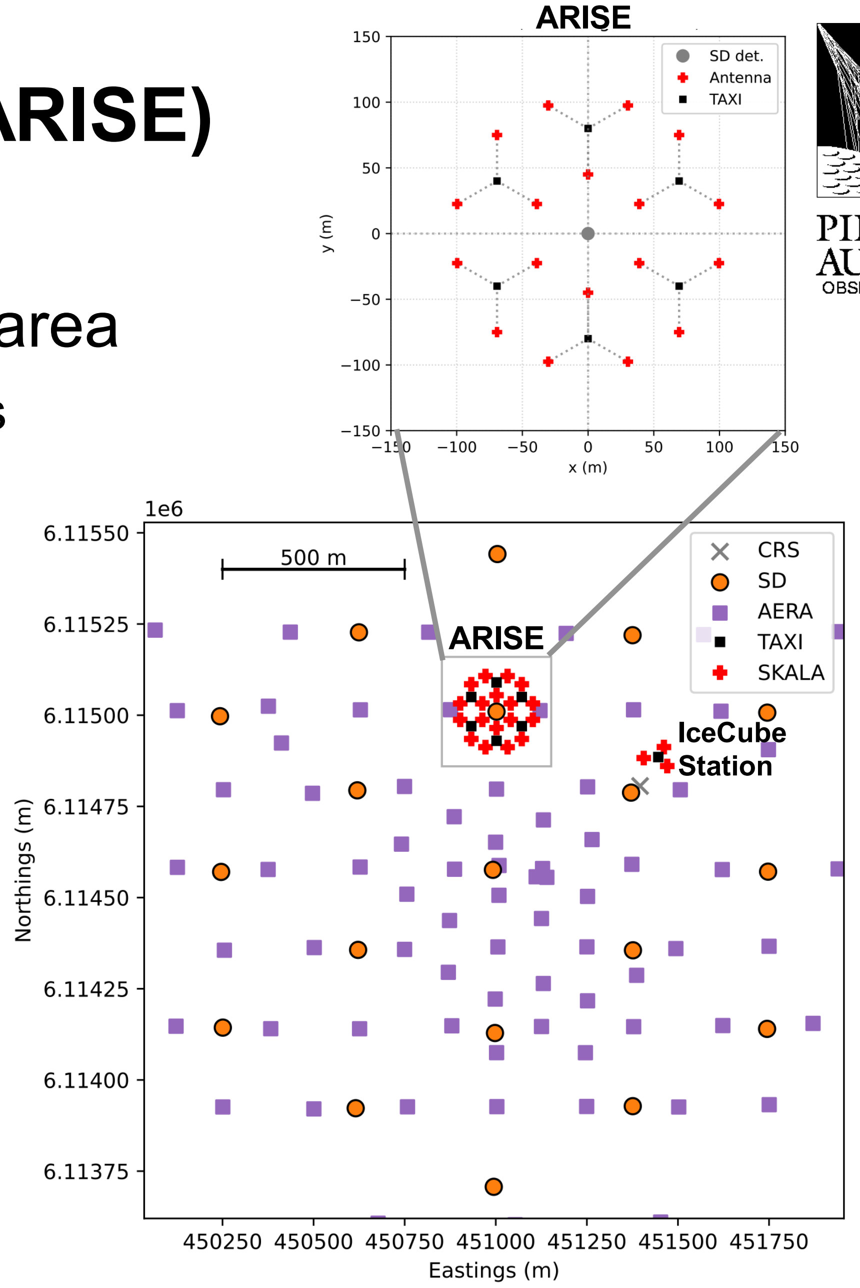
IceCube-Gen2 and Pierre Auger Collaborations, PoS(ARENA2024)037

Auger Radio Infill SKALA Enhancement (ARISE)

- 18 more SKALAs deployed at Auger in 2025
- Exploit high air-shower accuracy in enhancement area
  - denser surface detectors + underground muon detectors
  - ARISE adds fully efficient radio detection
- Shower physics + cross-calibration with IceCube







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Installing SKALA v2 Antennas

Antennas are assembled at the Central Radio Station (CRS) and then transported by truck to the 18 fenced deployment sites surrounding SD tank Lety Jr. at around 500m distance from the CRS.

Antennas are attached to concrete foundations providing stability in windy conditions.

Two coaxial cables, one for each polarization channel, are connected to Low Noise Amplifiers (LNAs) in the antennas.

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Installation of Antennas and Station Centers

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Conclusion

IceCube and IceCube-Gen2 are also unique laboratories for cosmic rays

- Surface array on top of optical array: IceTop + 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

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Additional Slides

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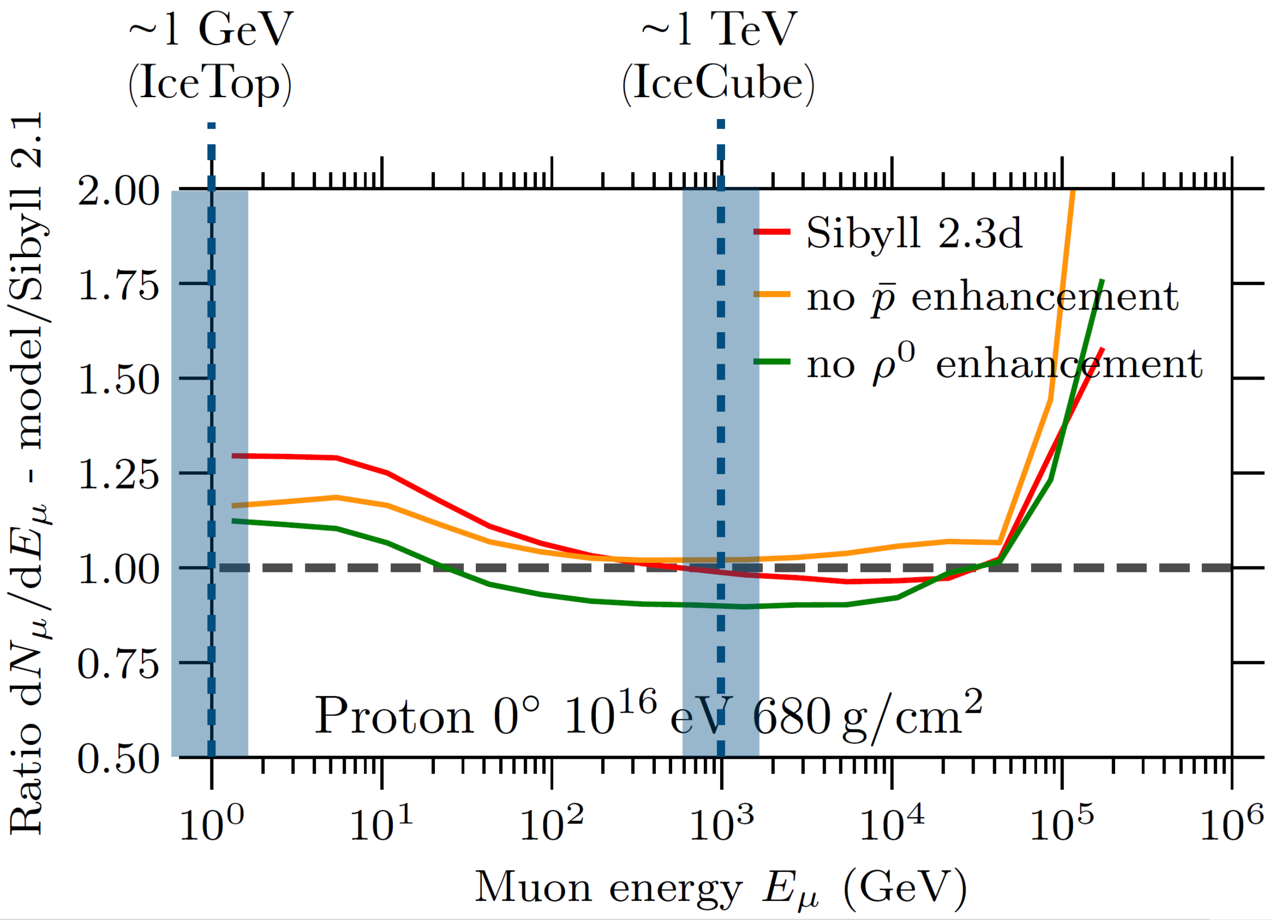
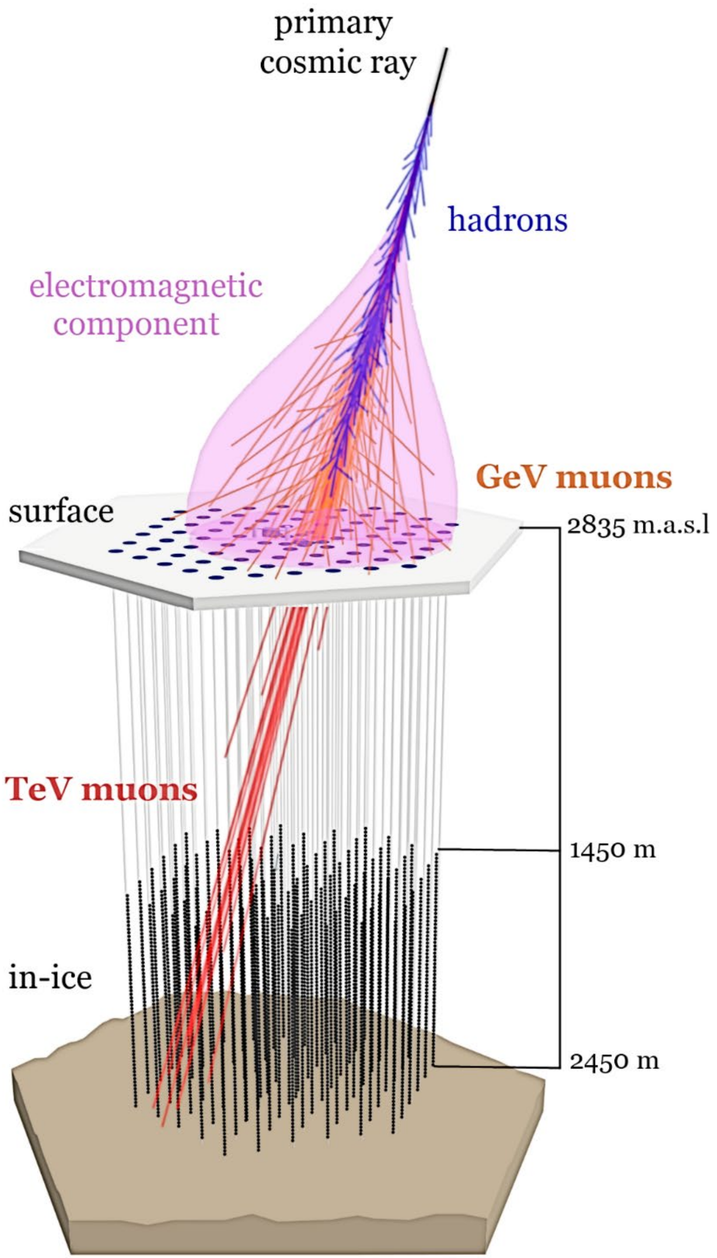
In-Ice Coincidences: Muon Spectrum

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



F. Riehn et al, PRD 102 (2020) 063002



D. Soldin et al. (IceCube Coll.) PoS 369 (ICRC2021) 357

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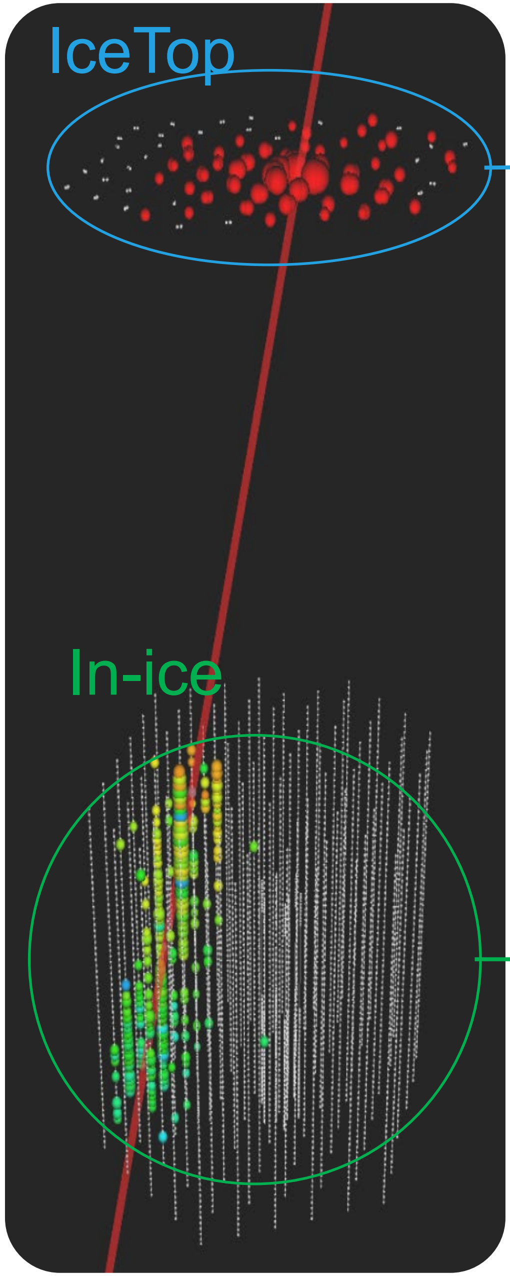


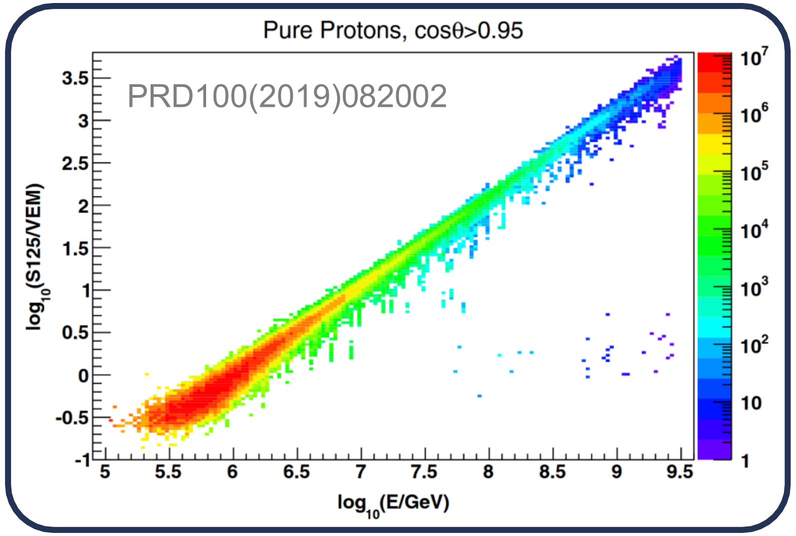
Energy Reconstruction and Mass Composition

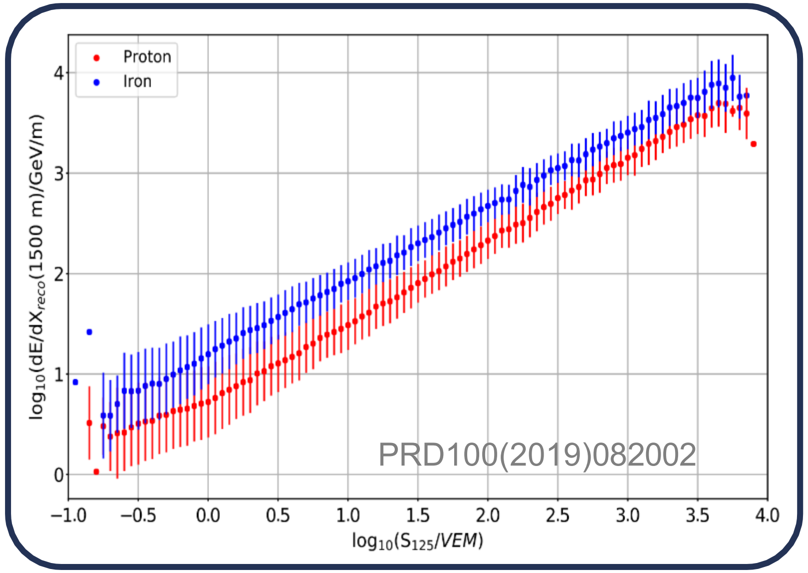
Electromagnetic component of air shower at surface:

- IceTop energy proxy S_{125} signal at 125 m distance
- Nearly composition independent
- Linear and low fluctuations because of high altitude

High-energy muons (>300 GeV):

- Mean muon number has a strong composition sensitivity
- Energy loss (d*E*/d*X*) at fixed slant depth (*X*=1500m) in the





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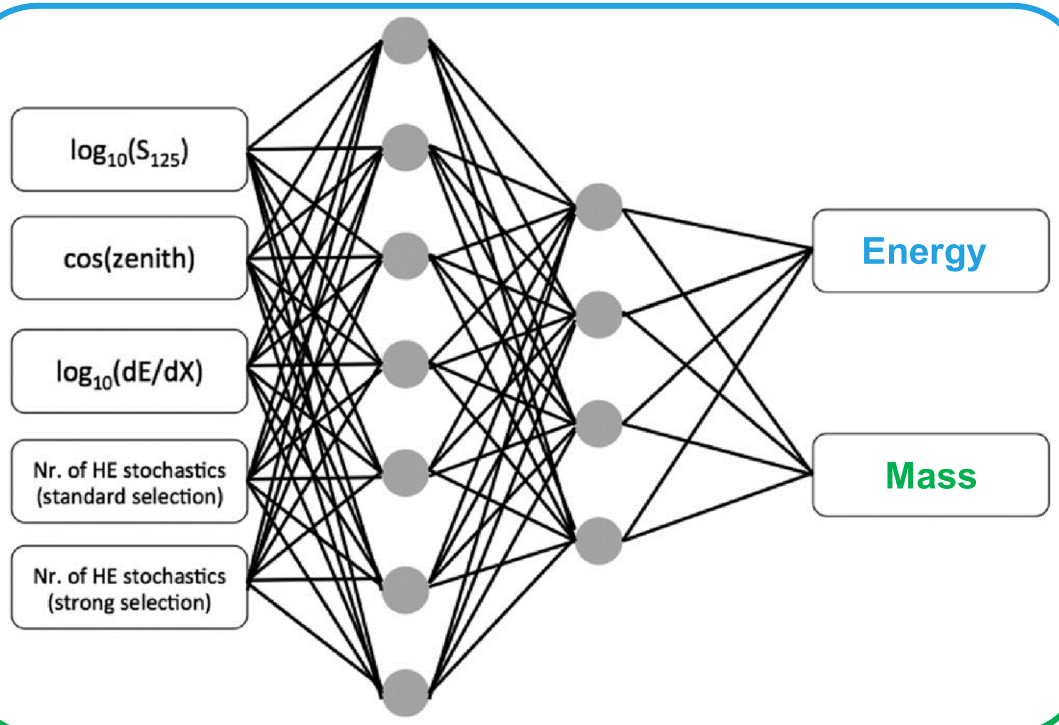
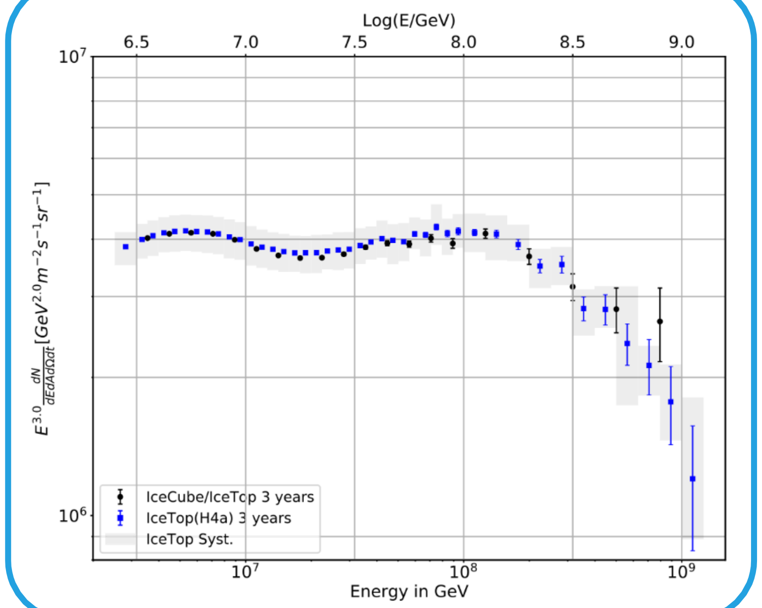
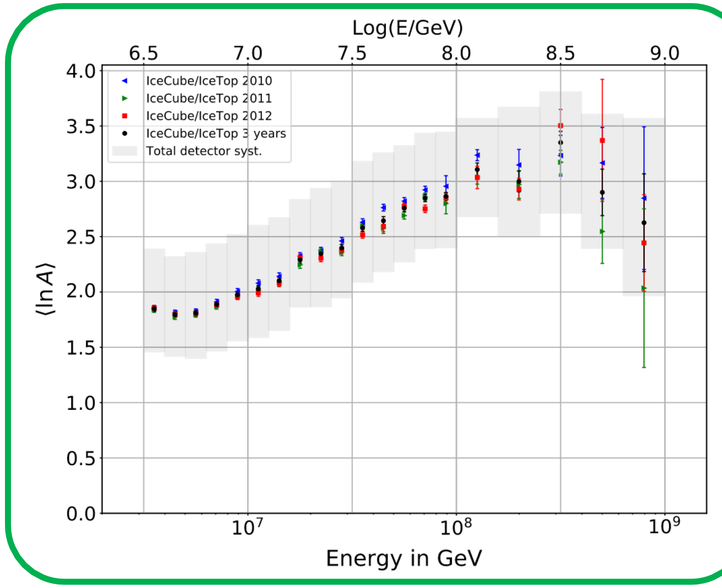
Energy Spectrum and Mass Composition

- Neural network trained with CORSIKA simulations used to predict energy and mass of each primary particle
- Mass composition derived for statistical sample, as there are large systematic uncertainties for mass estimation
- Results consistent with other air-shower arrays







PRD100(2019)082002

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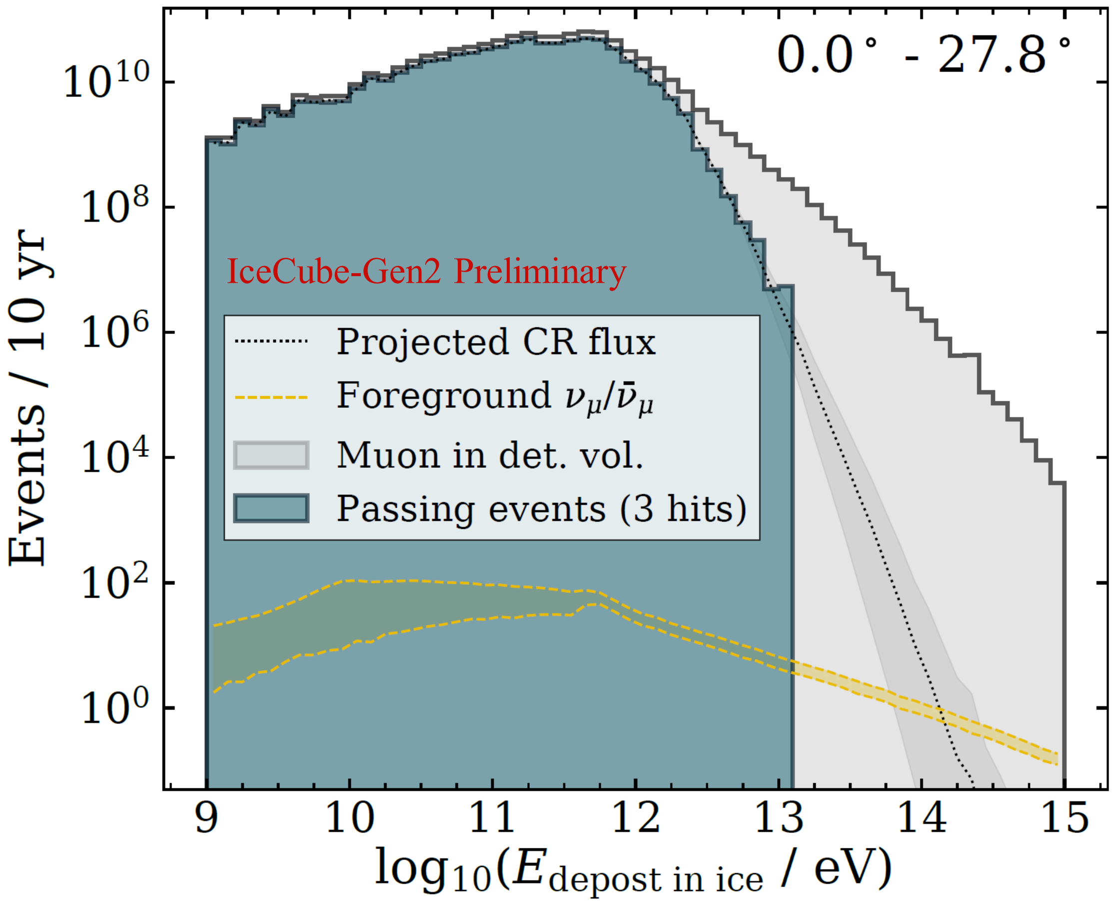
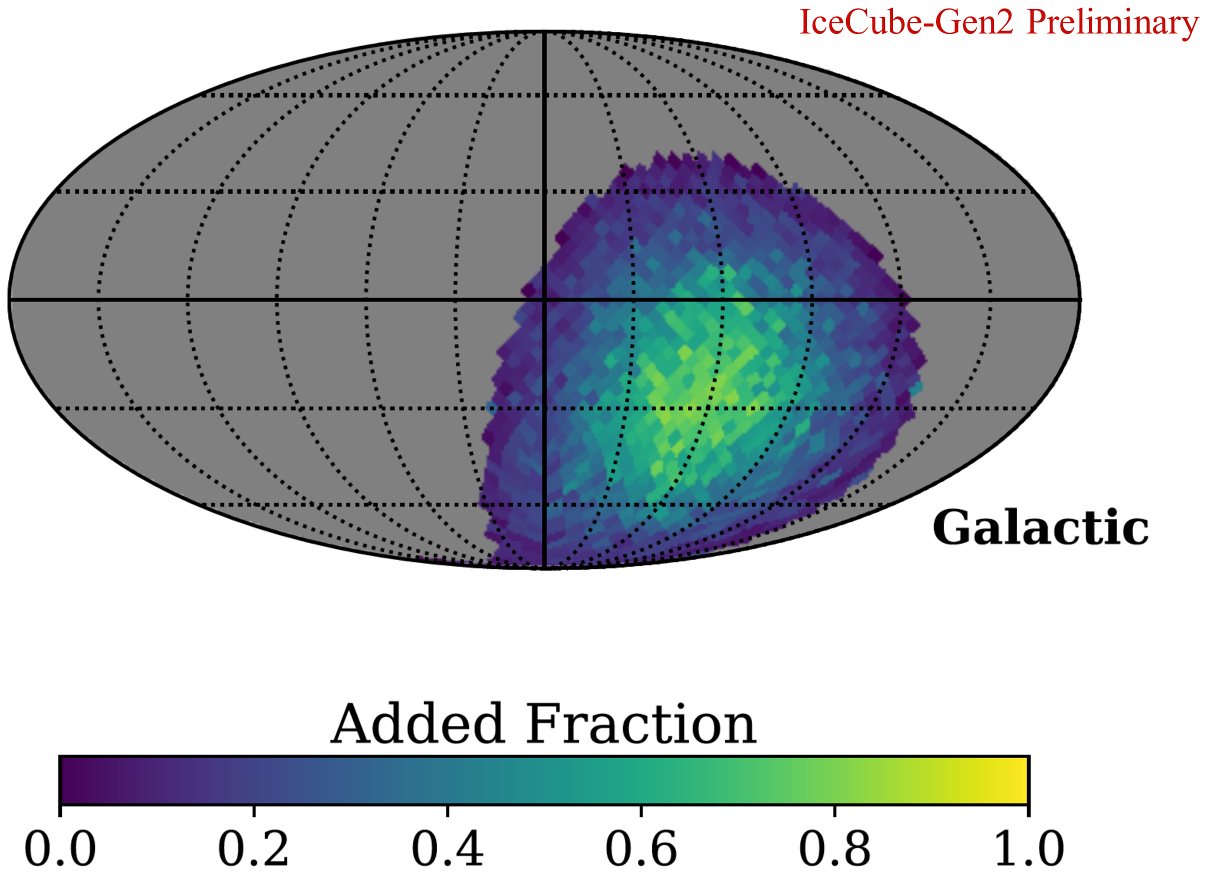
Veto Performance of Gen2 Surface Array

- Veto adds 8 to 17 of energy $\mathcal{O}$(PeV) downgoing neutrinos per decade
- Increases sensitivity by +80% for sky region where IceCube is least sensitive





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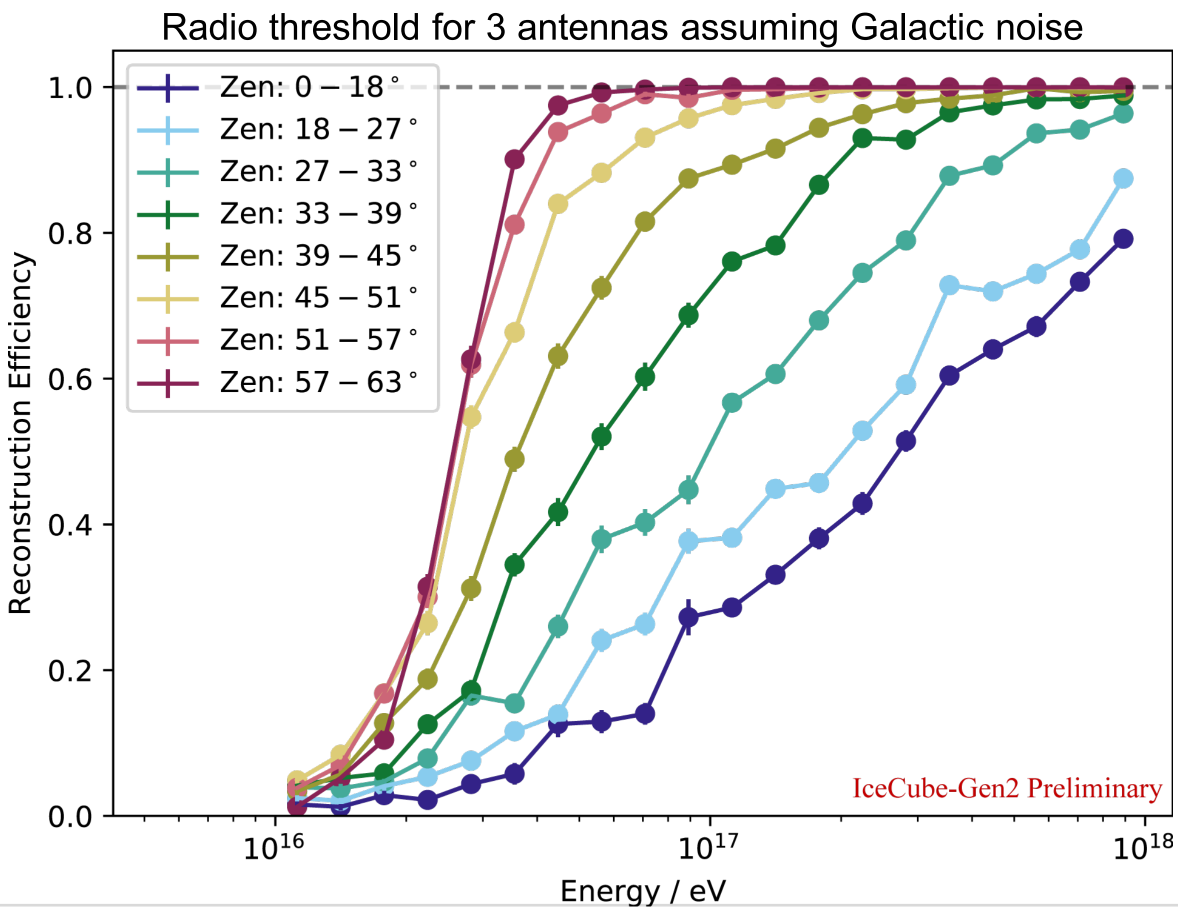
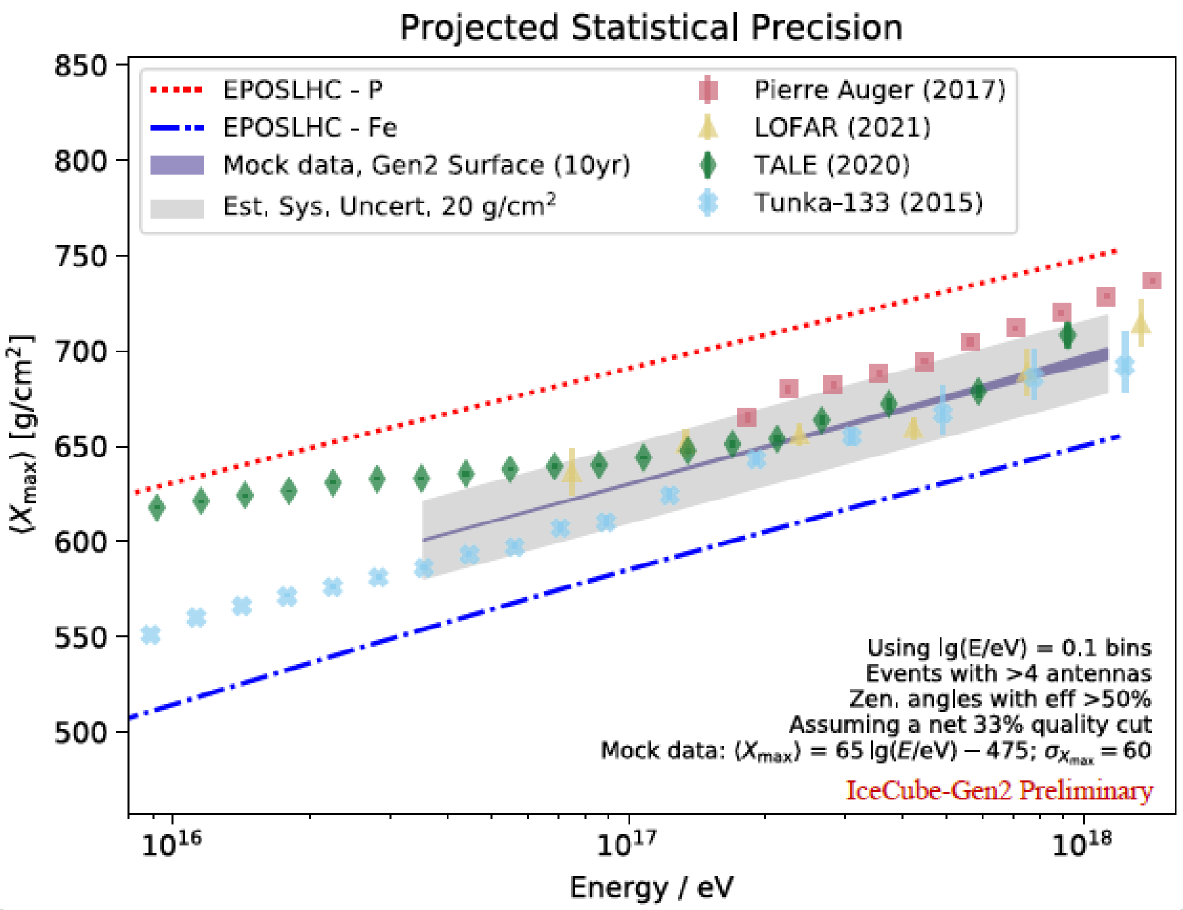
Result: Radio antennas will increase accuracy above $10^{16.5}$ eV

- 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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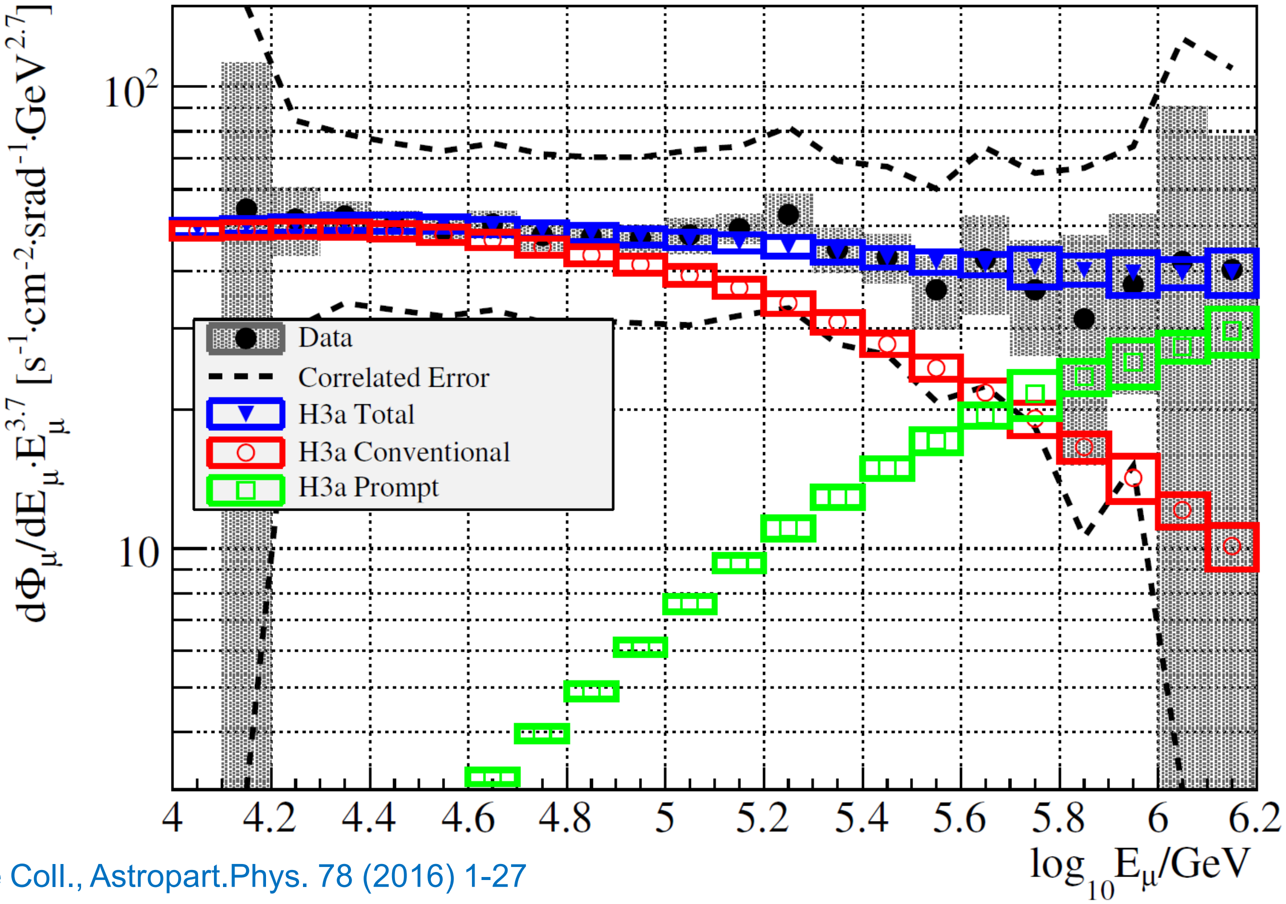
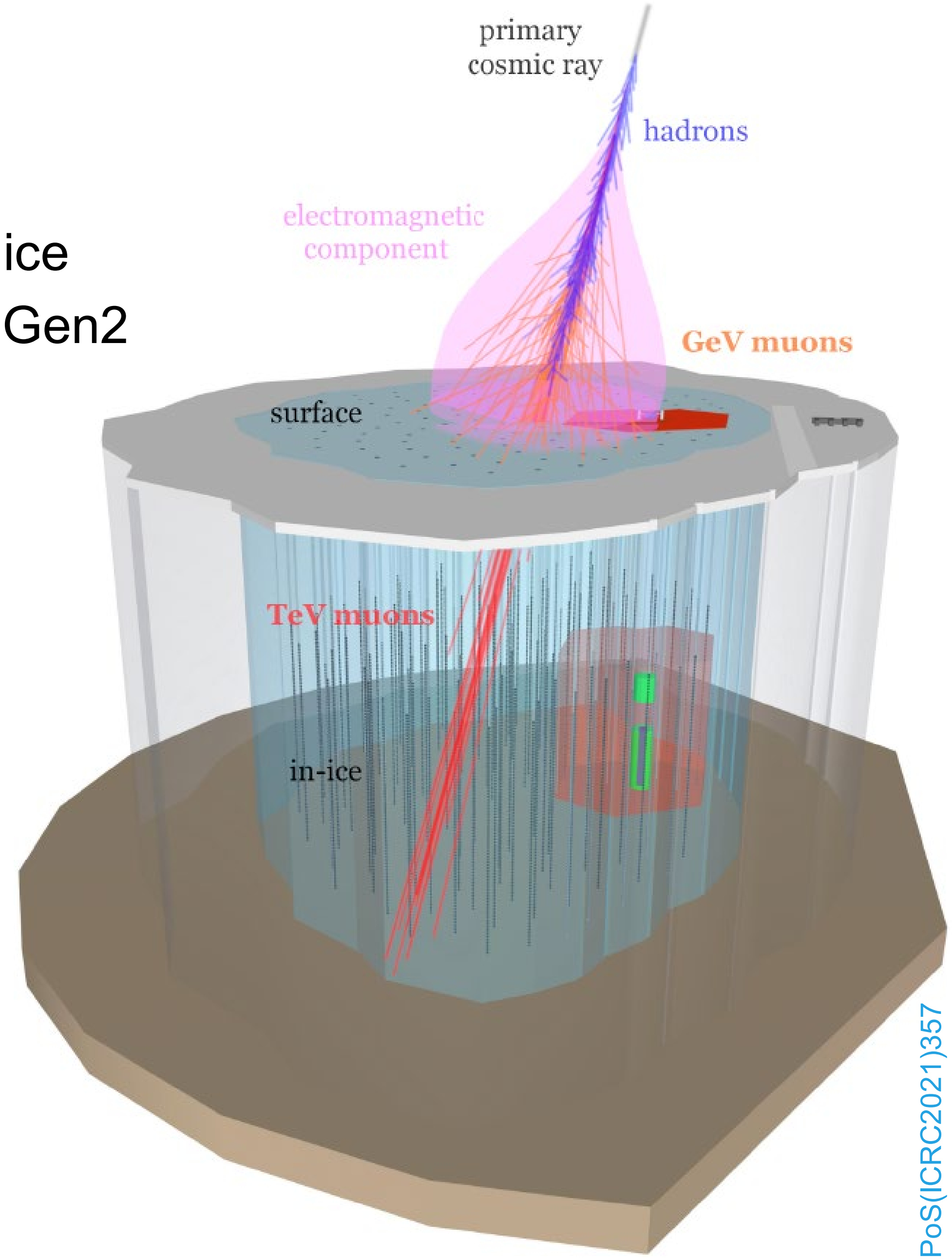
Muon Spectrum and PeV Prompt Muons

- 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



PoS(ICRC2021)357

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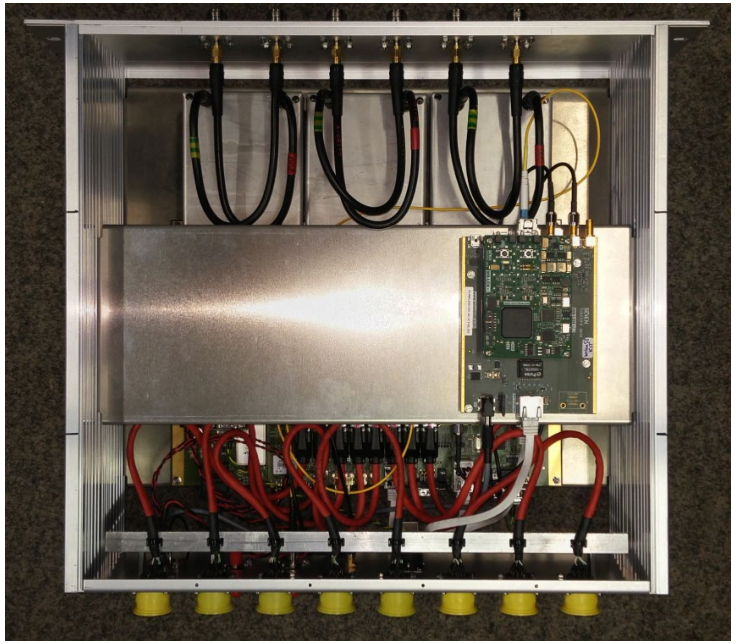
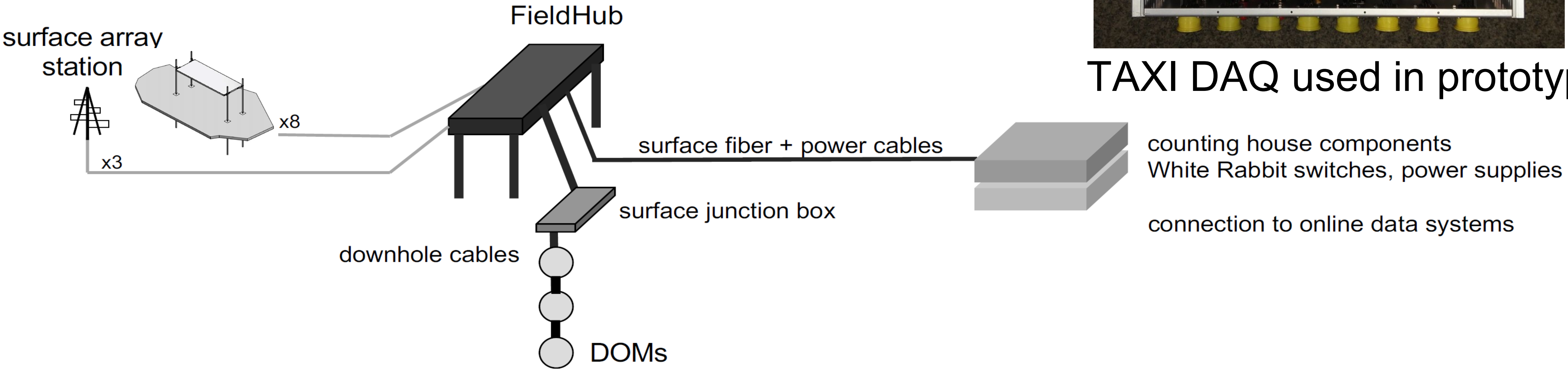
Radio Antennas added for Accuracy at higher energies

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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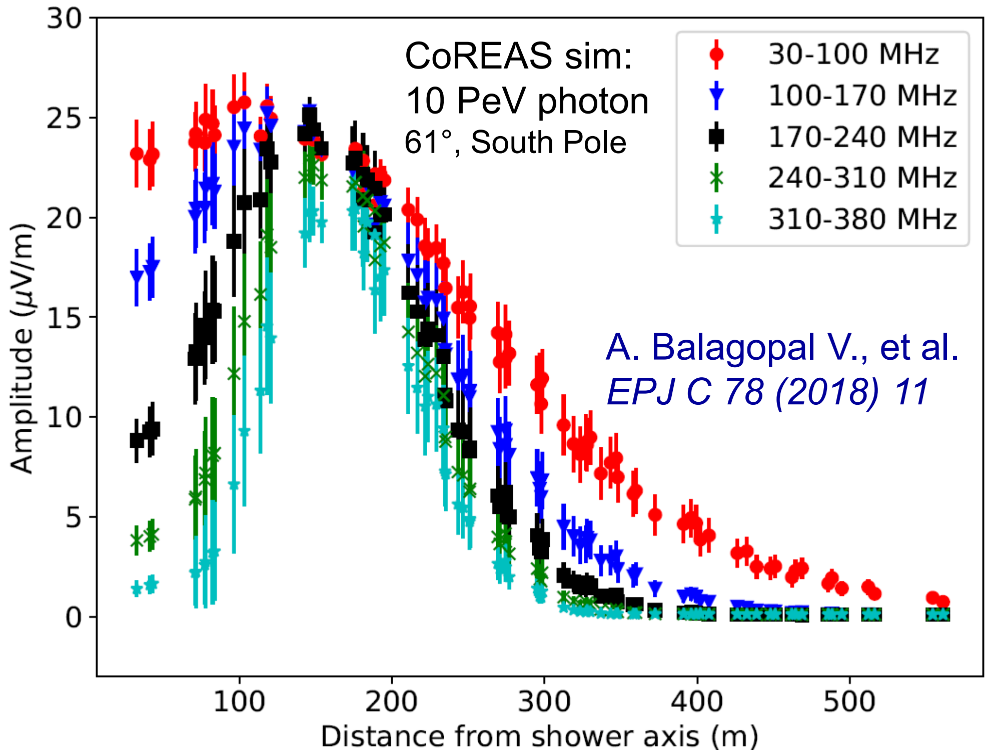
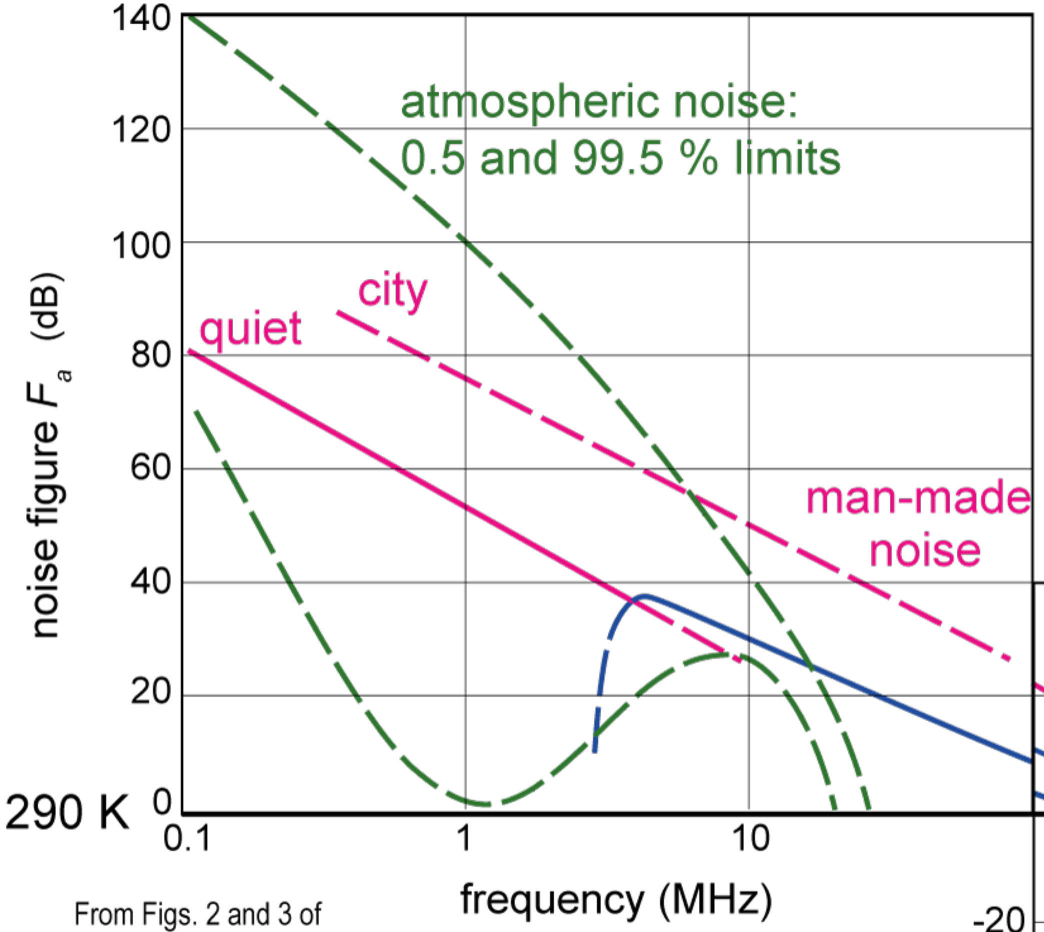
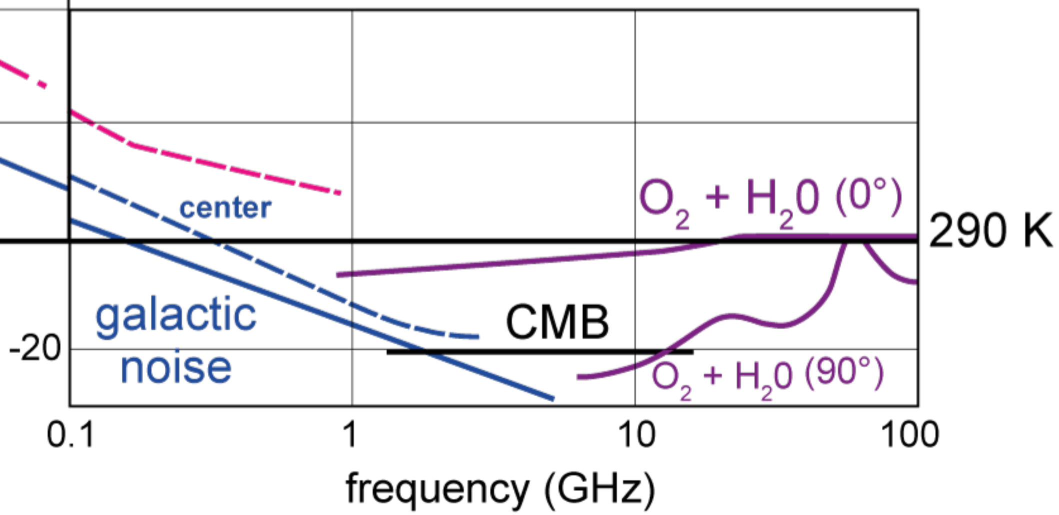
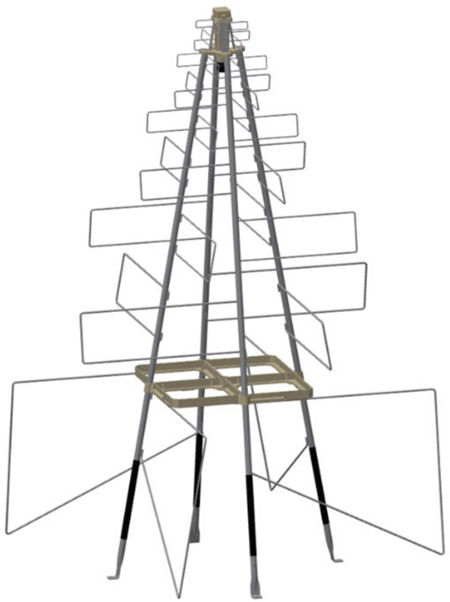
Better signal-to-noise ratio expected at high frequencies







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)

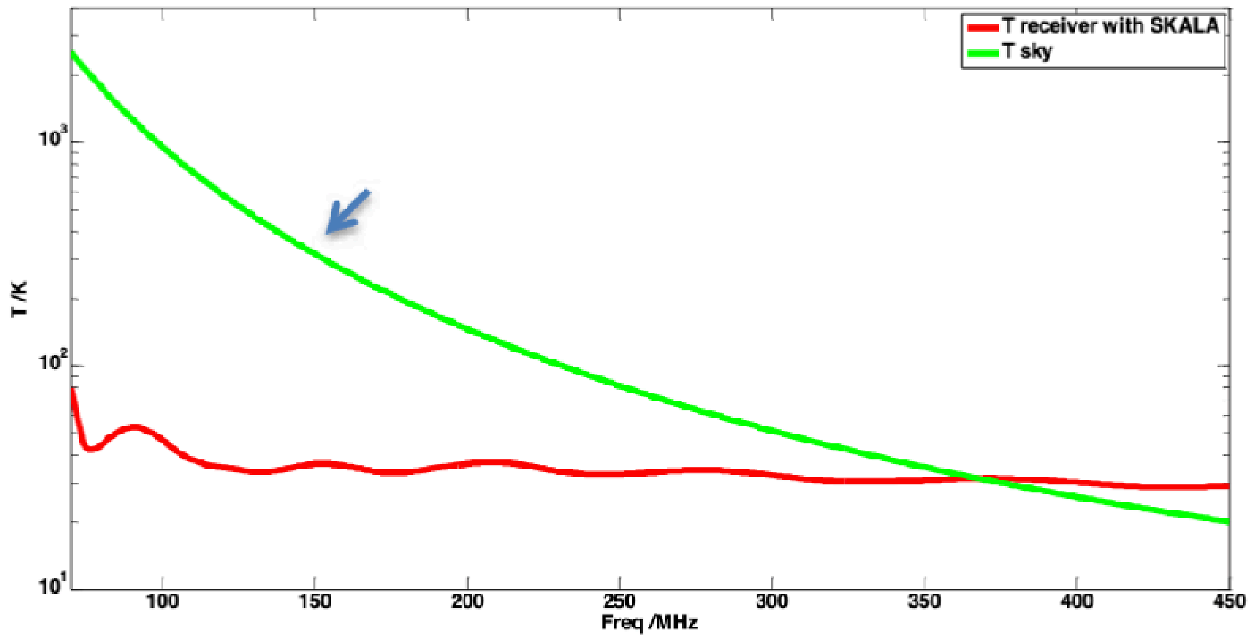
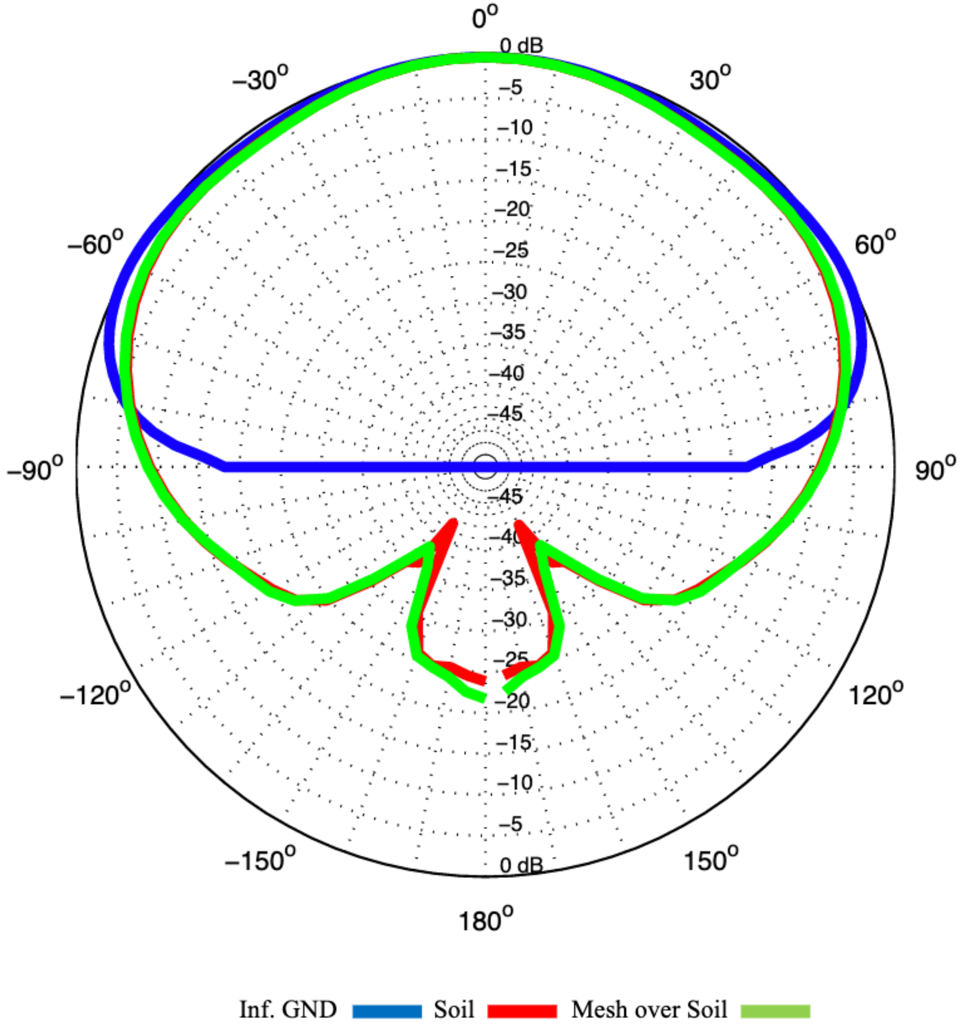


Fig. 9. Receiver noise temperature versus sky noise.

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.

H-plane cut - 150 MHz



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