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IceCube-Gen2 Surface Array

ICECUBE GEN2

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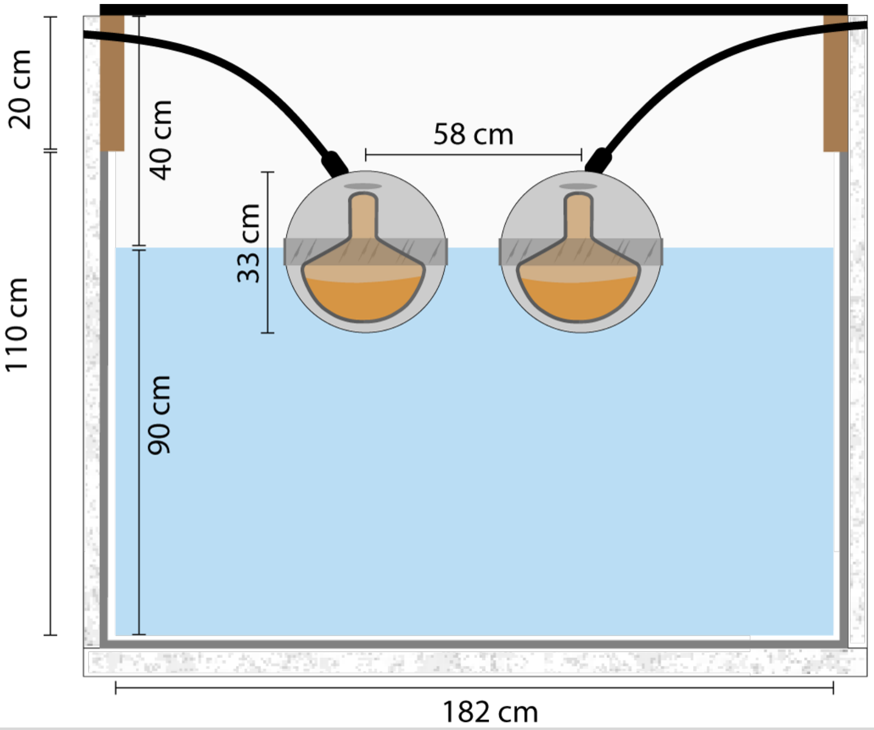
Frank G. Schröder for the IceCube-Gen2 Collaboration

Bartol Research Institute, Department of Physics and Astronomy, University of Delaware, Newark, DE, USA,
and Karlsruhe Institute of Technology (KIT), Institute for Nuclear Physics , Karlsruhe, Germany

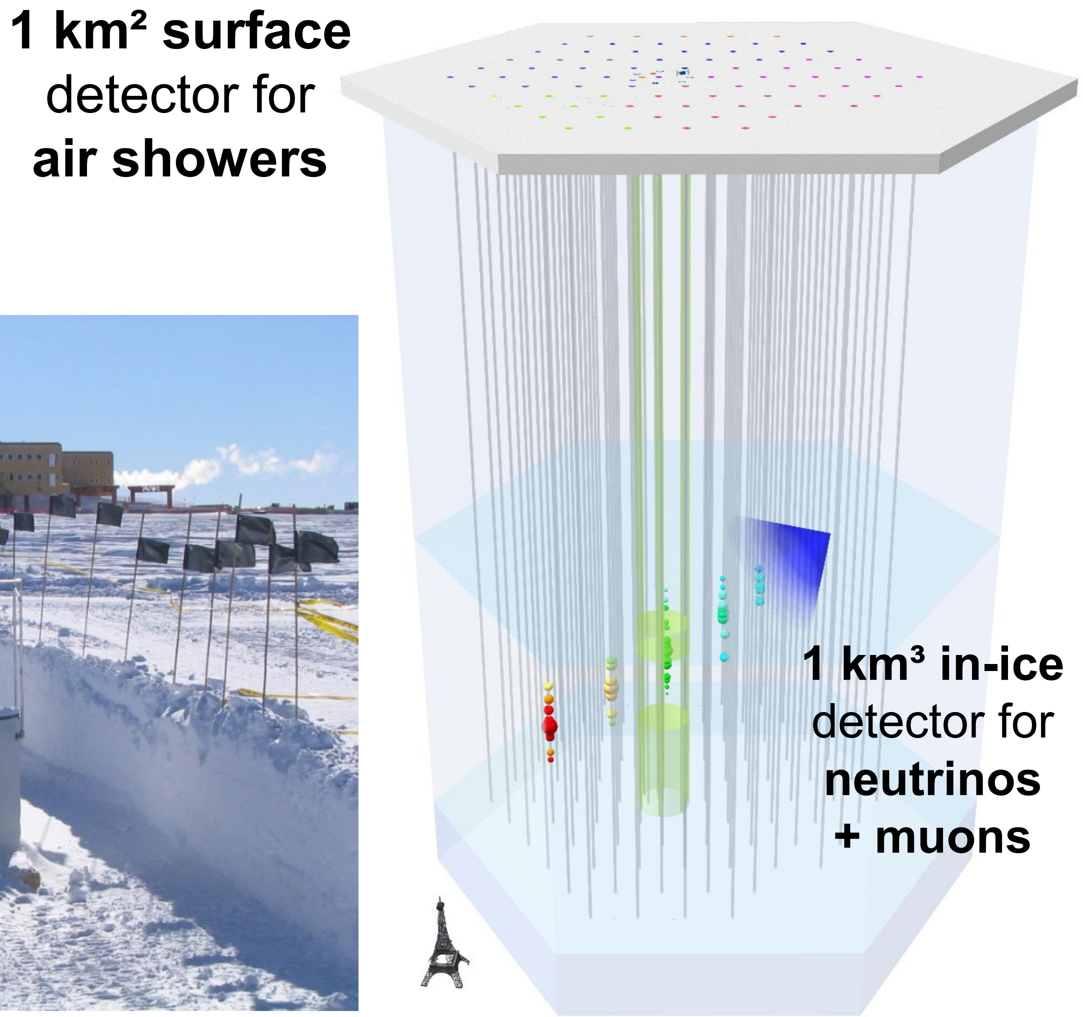
IceCube Neutrino Observatory today: surface + in-ice detector

- IceTop = surface array of ice-Cherenkov detectors
  - cosmic-ray physics + veto
- Deep optical array for neutrino detection
  - most in-ice signals are cosmic-ray muons



IceCube Coll., NIM A 700 (2013) 188

IceCube at the South Pole



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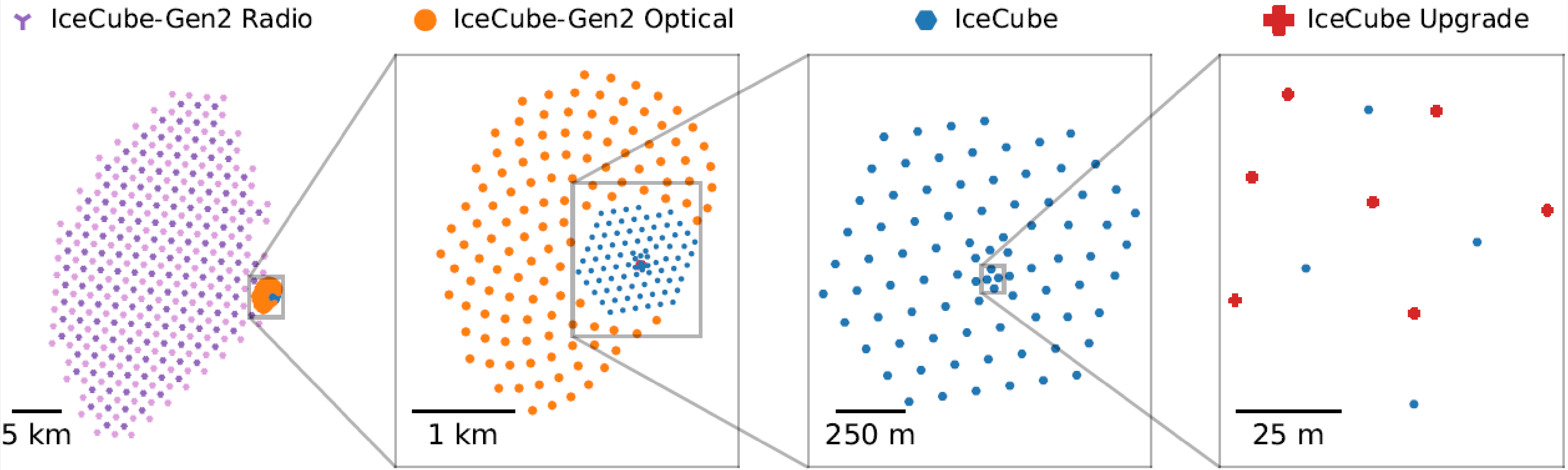
IceCube-Gen2: extending the IceCube Neutrino Observatory

- an order of magnitude larger *deep optical* and *surface* arrays
- sparse *in-ice radio* array for detection of Askaryan emission from ultra-high-energy neutrinos



https://icecube-gen2.wisc.edu/science/publications/tdr/

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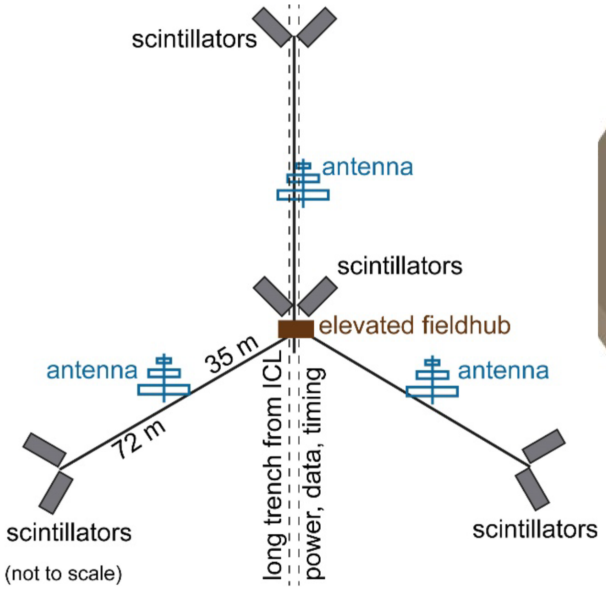
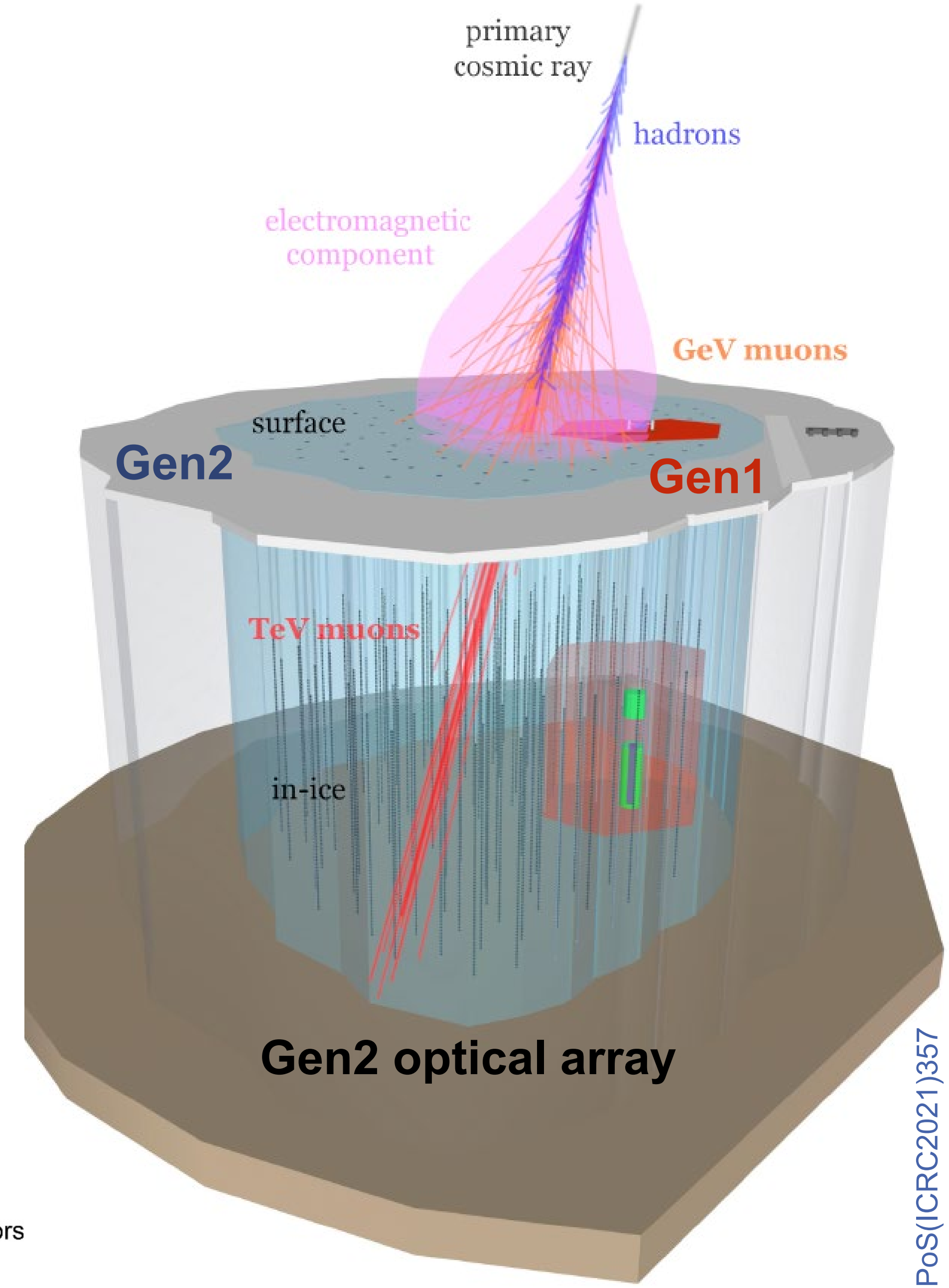
IceCube-Gen2 Surface Array

Baseline design of Gen2 Surface Array:
one station per optical string (120)

- 4 pairs of scintillators enabling low threshold for veto
- 3 radio antennas increasing accuracy at high energies





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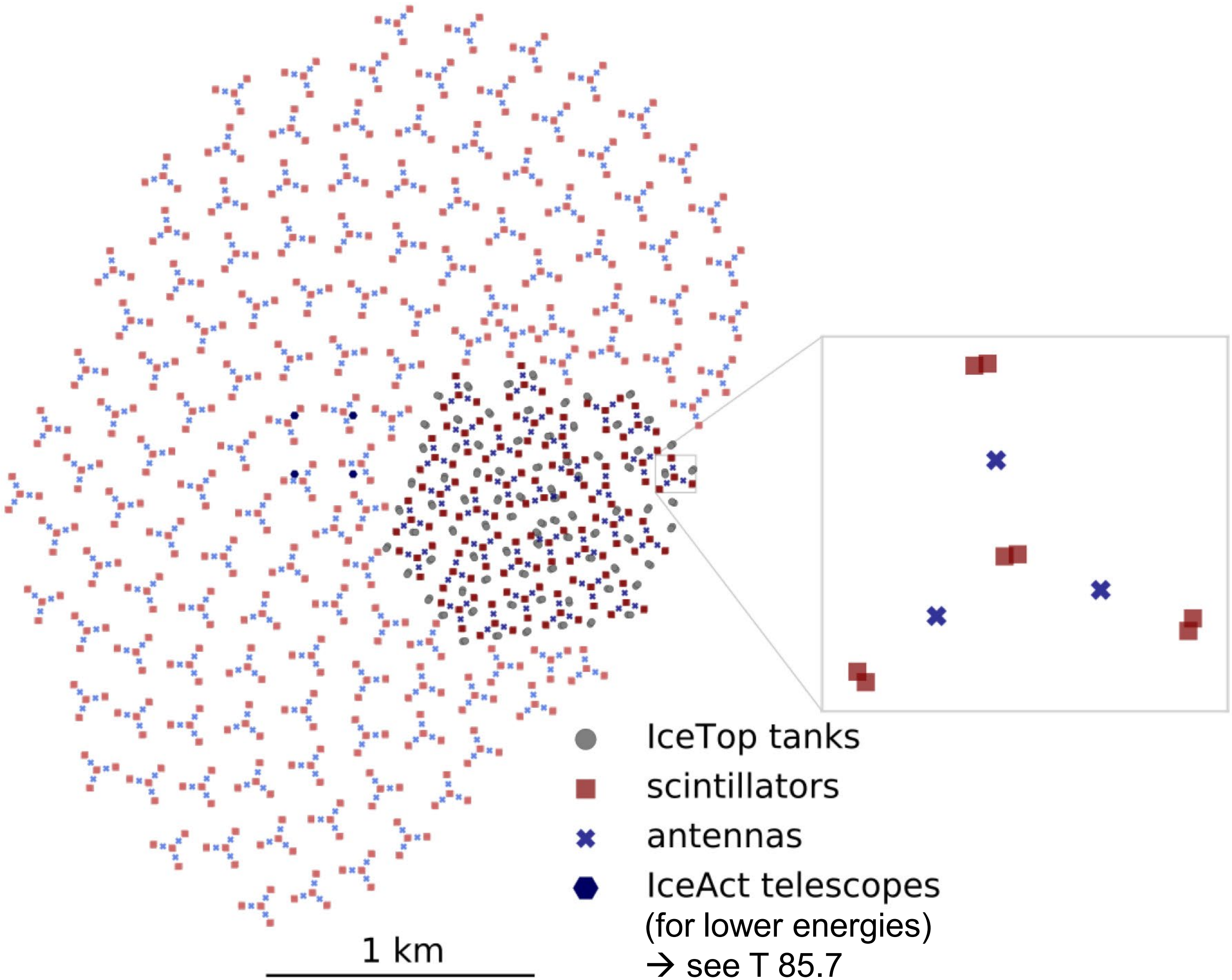
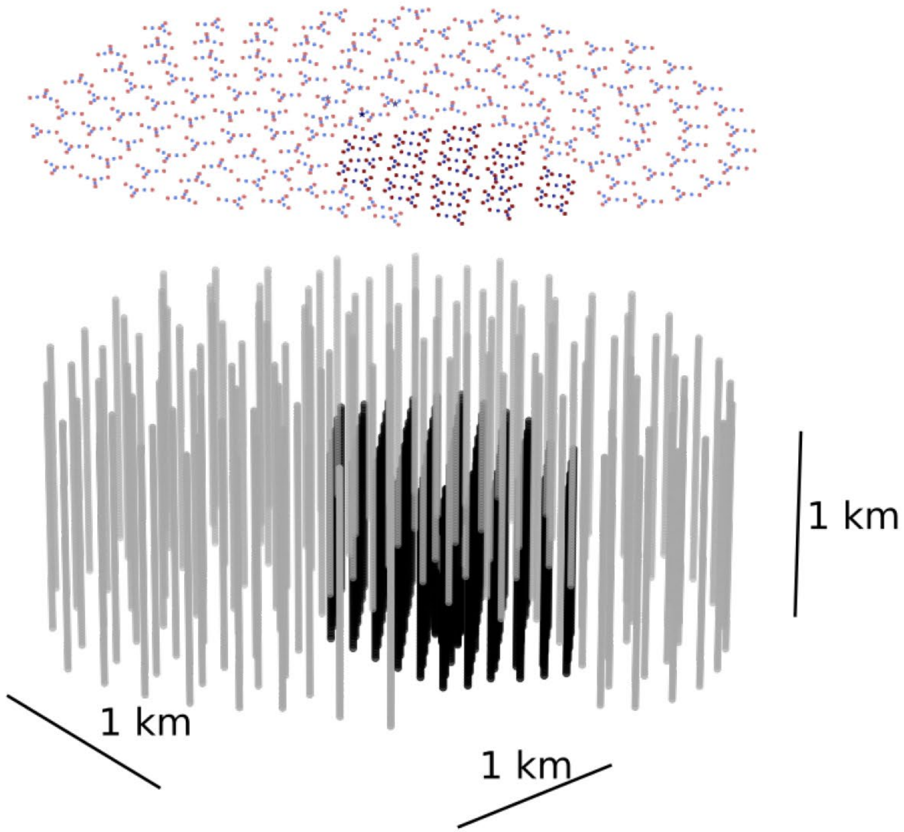
IceCube-Gen2 Surface Array above the Optical Array



→ see T 85.7



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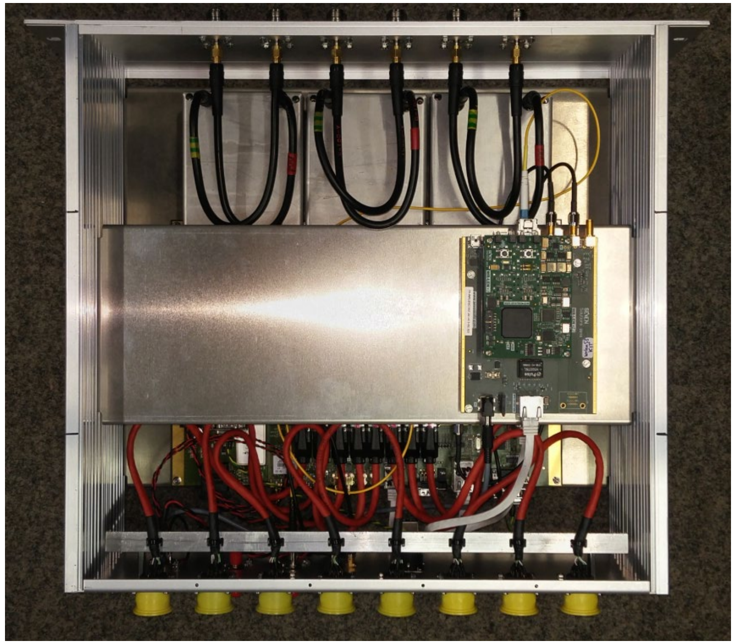
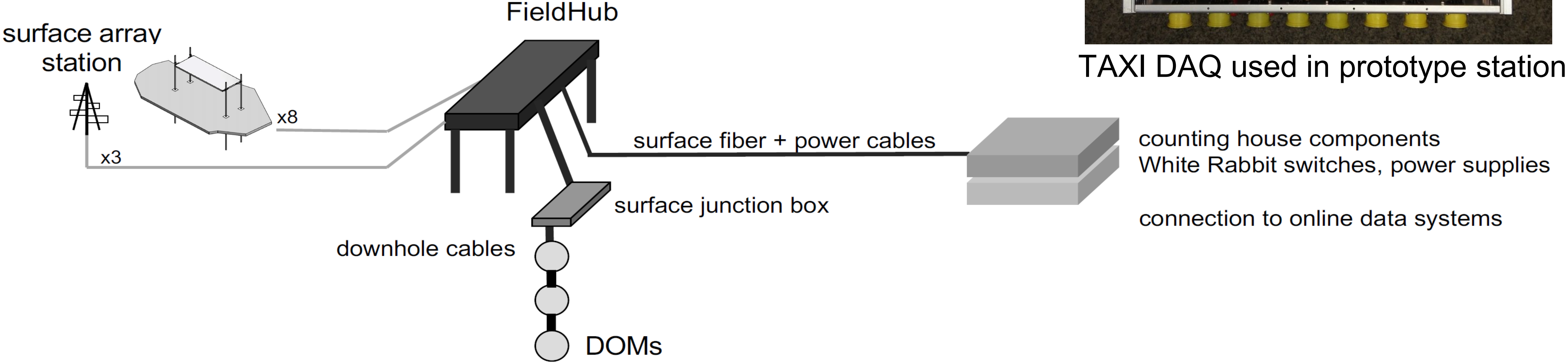
DAQ baseline design

DAQ for Surface Array Stations in each FieldHub

- 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
- New DAQ with deep buffer and array trigger under development



TAXI DAQ used in prototype station



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Overview on Science Case of IceCube-Gen2 Surface Array

Rich science case that makes use of unique combination of surface + in-ice 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 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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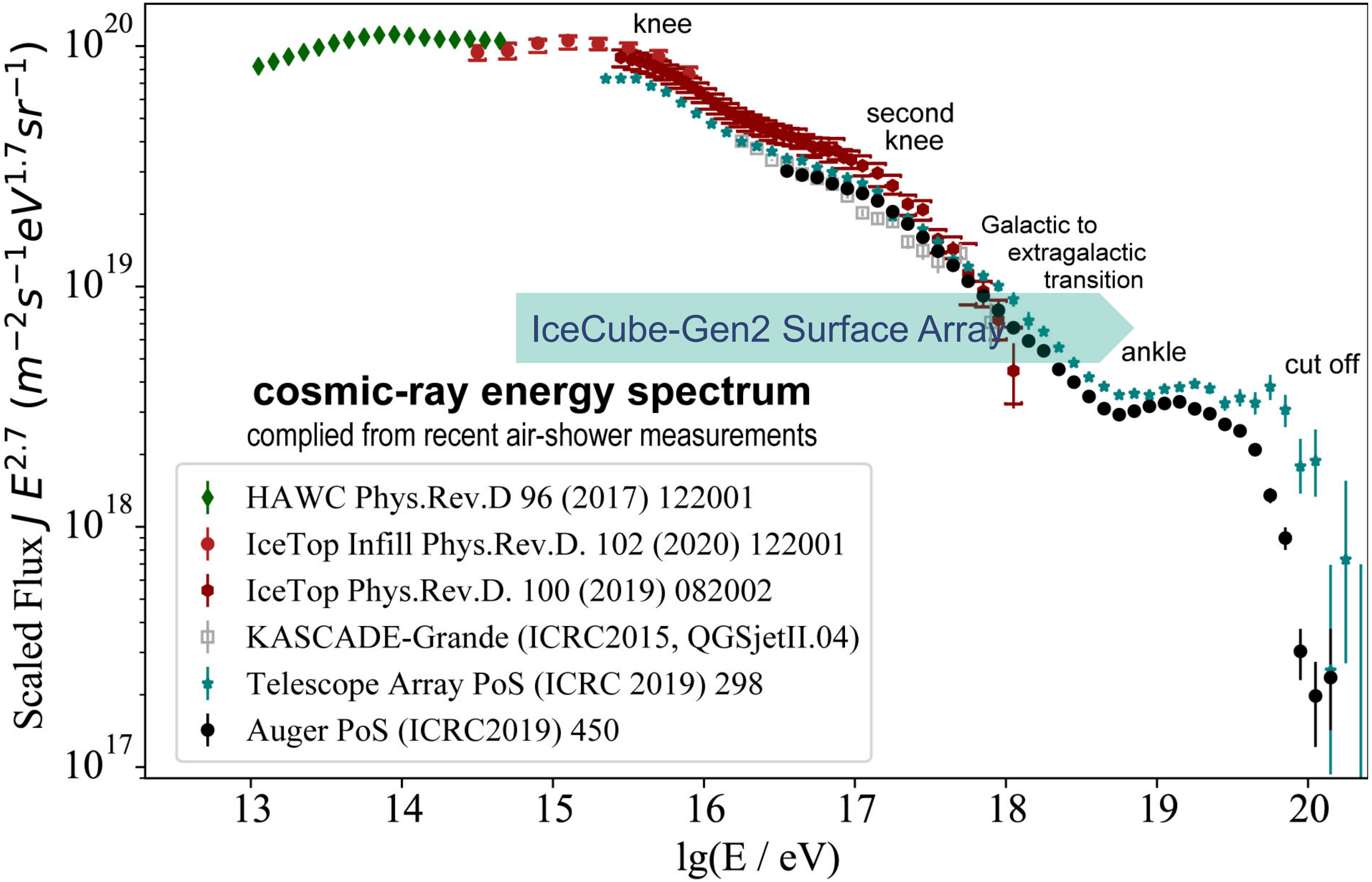
Energy reach until Ankle: Galactic-to-extragalactic Transition



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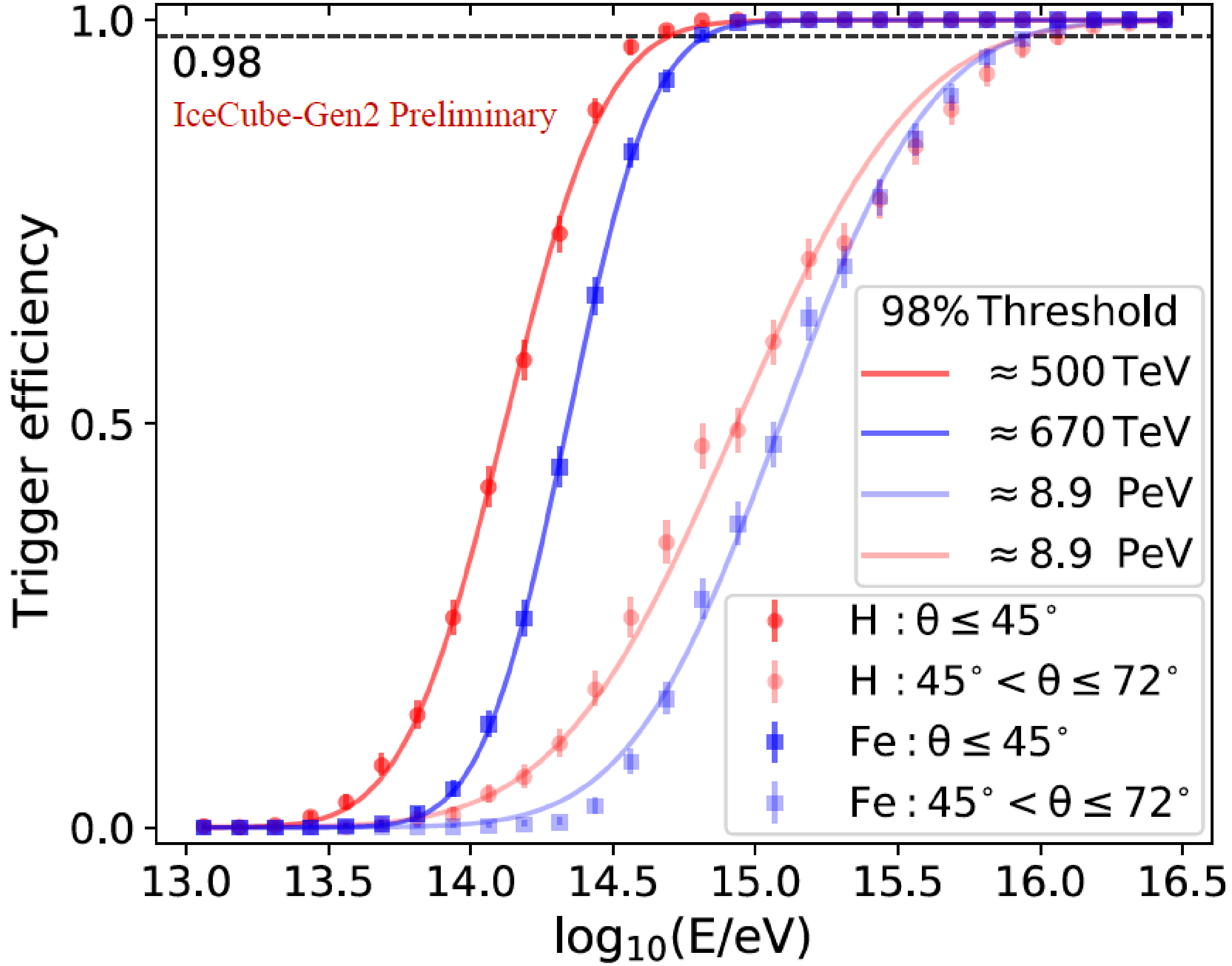
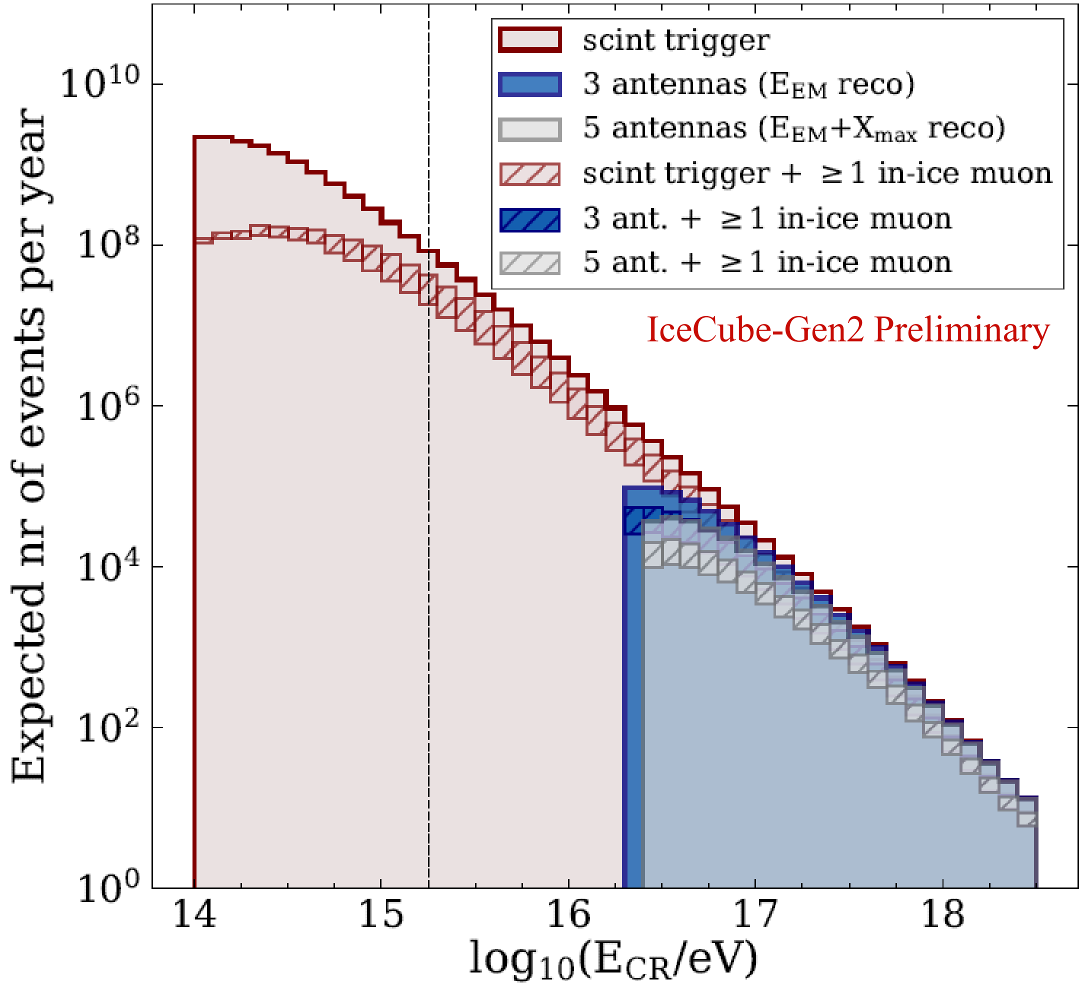
Low Detection Threshold provided by Scintillators

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





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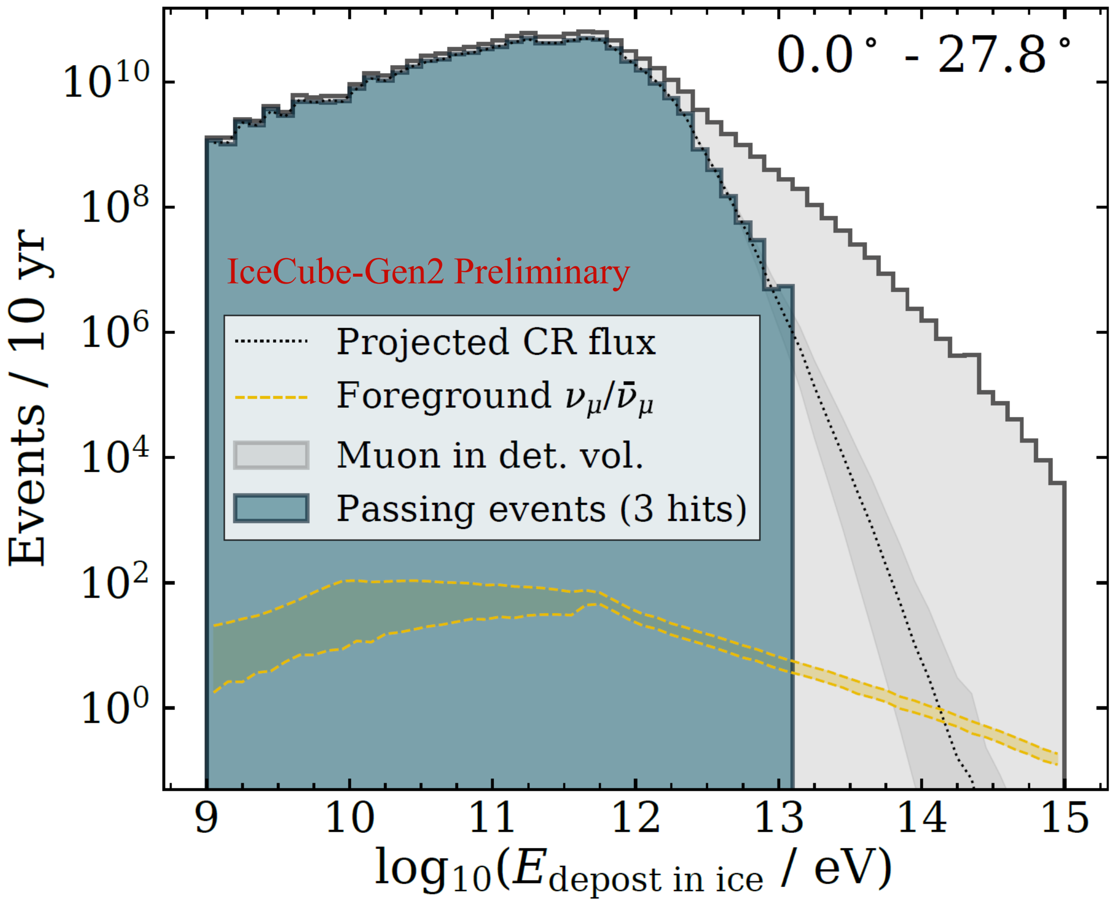
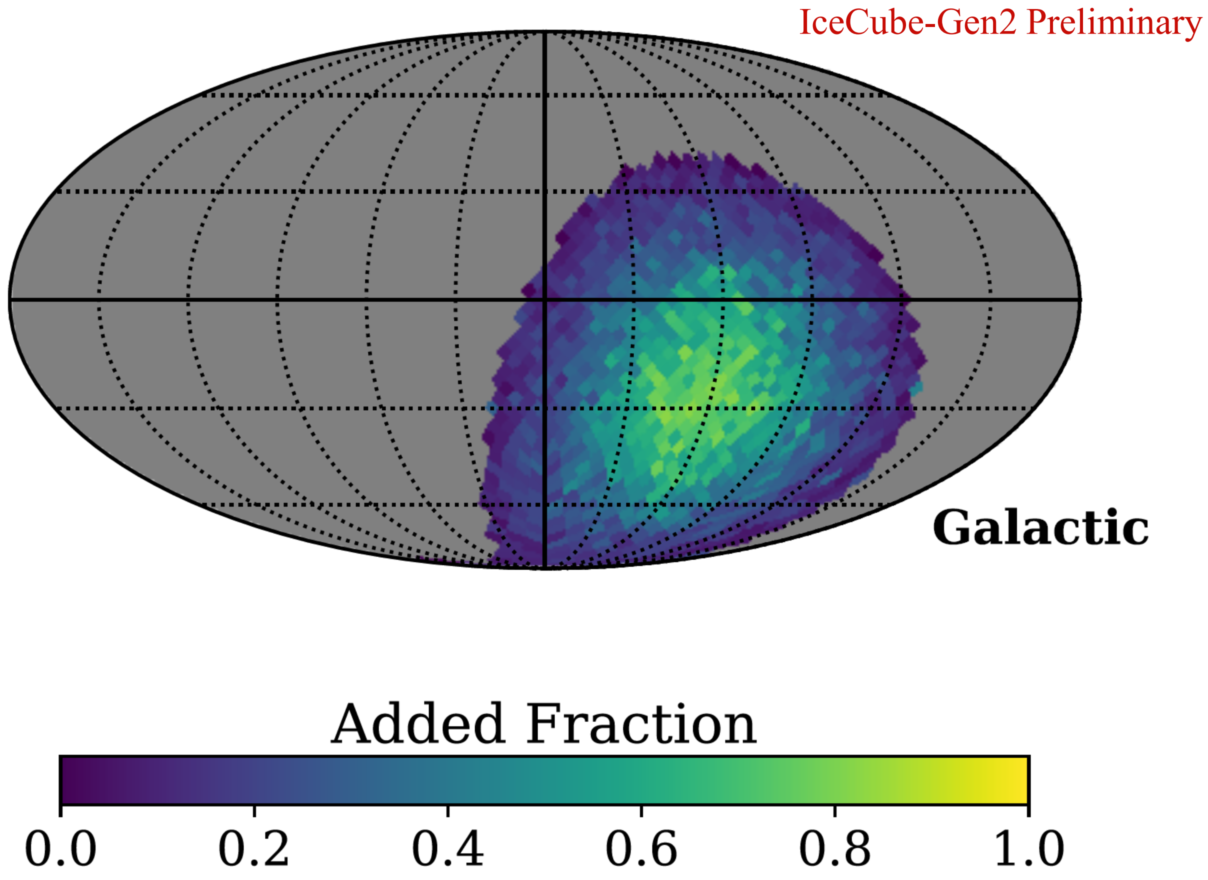
Veto Performance of Gen2 Surface Array

- 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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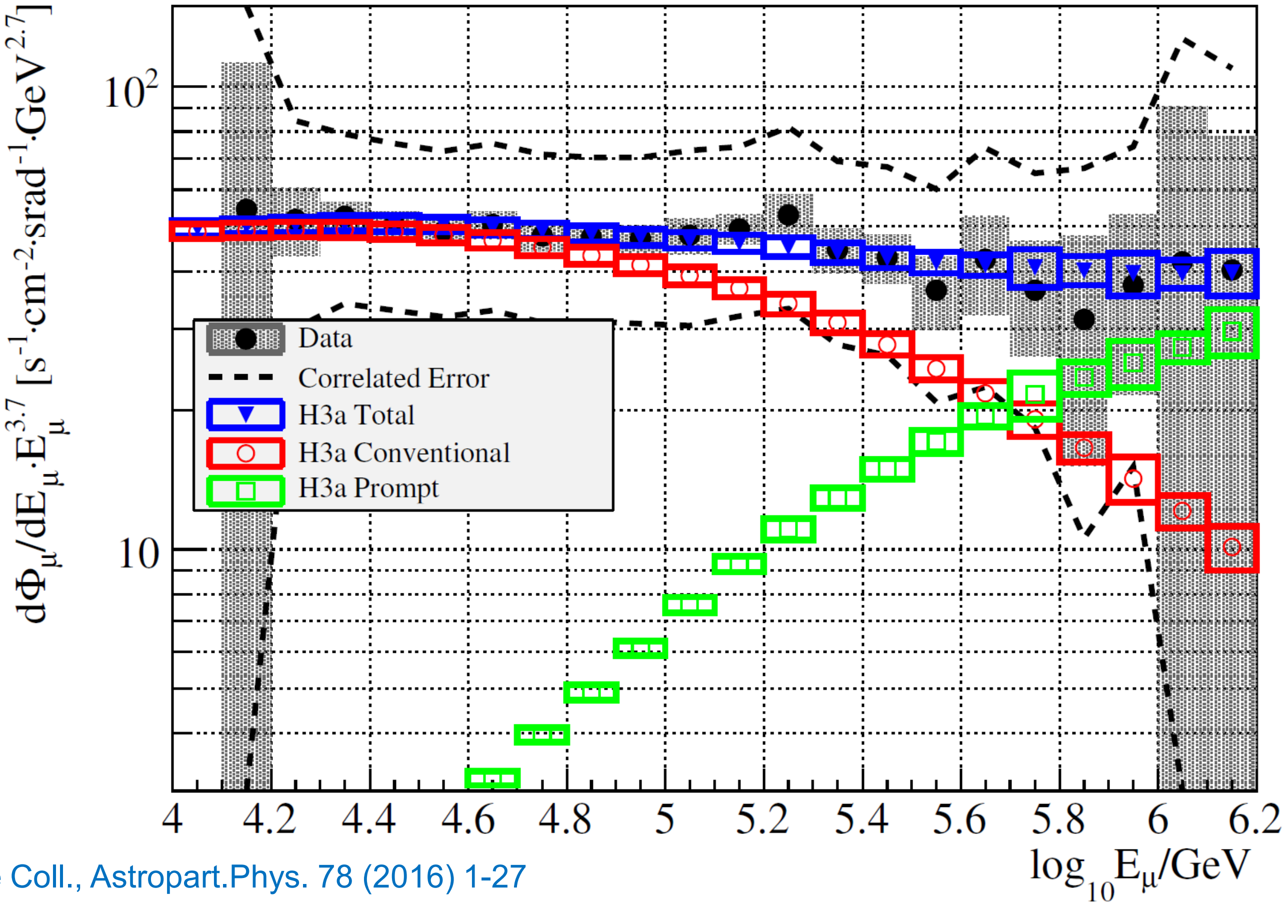
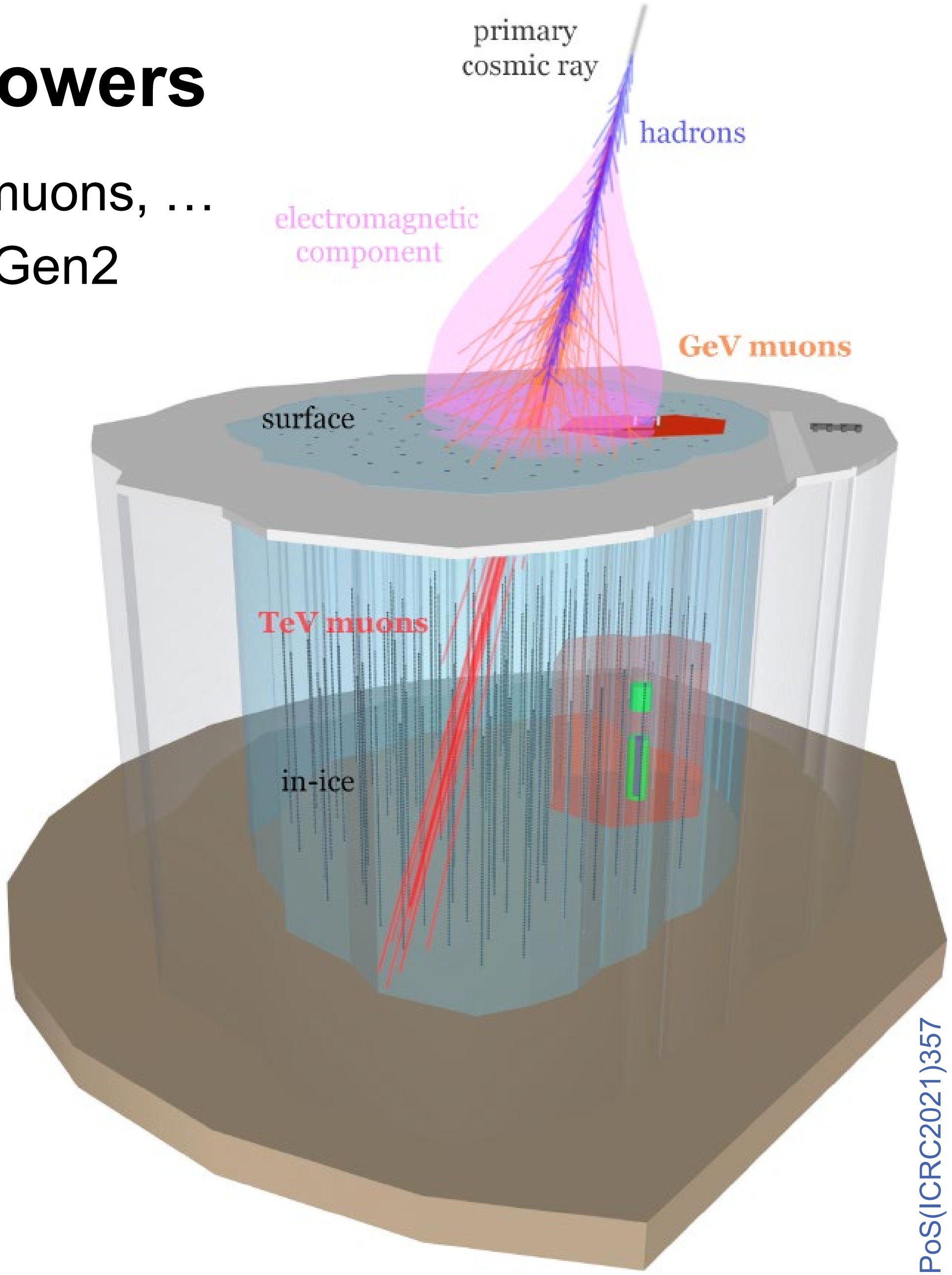
A unique lab for particle physics in air showers

- scrutinize hadronic interaction models, study prompt PeV muons, …
- possible with Gen1, but huge aperture increase (> 30×) in Gen2



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



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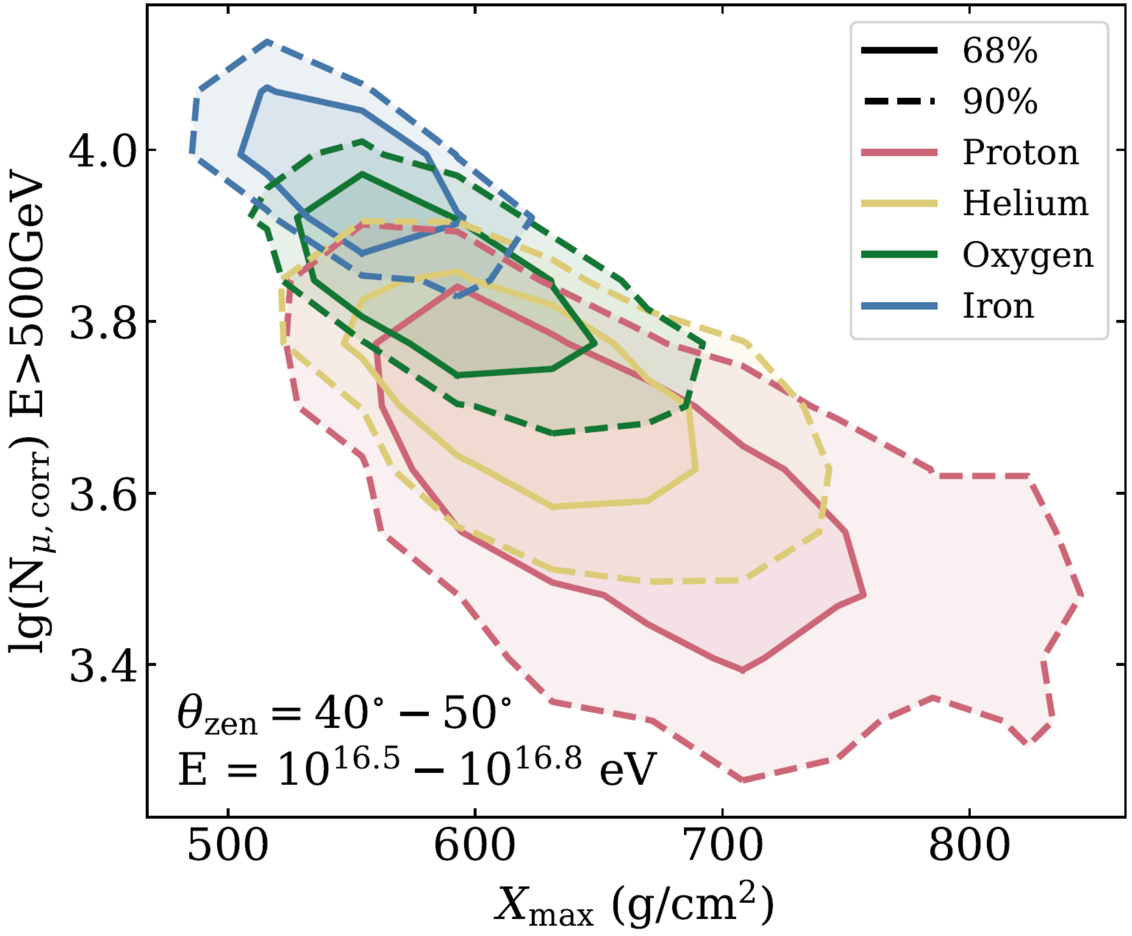
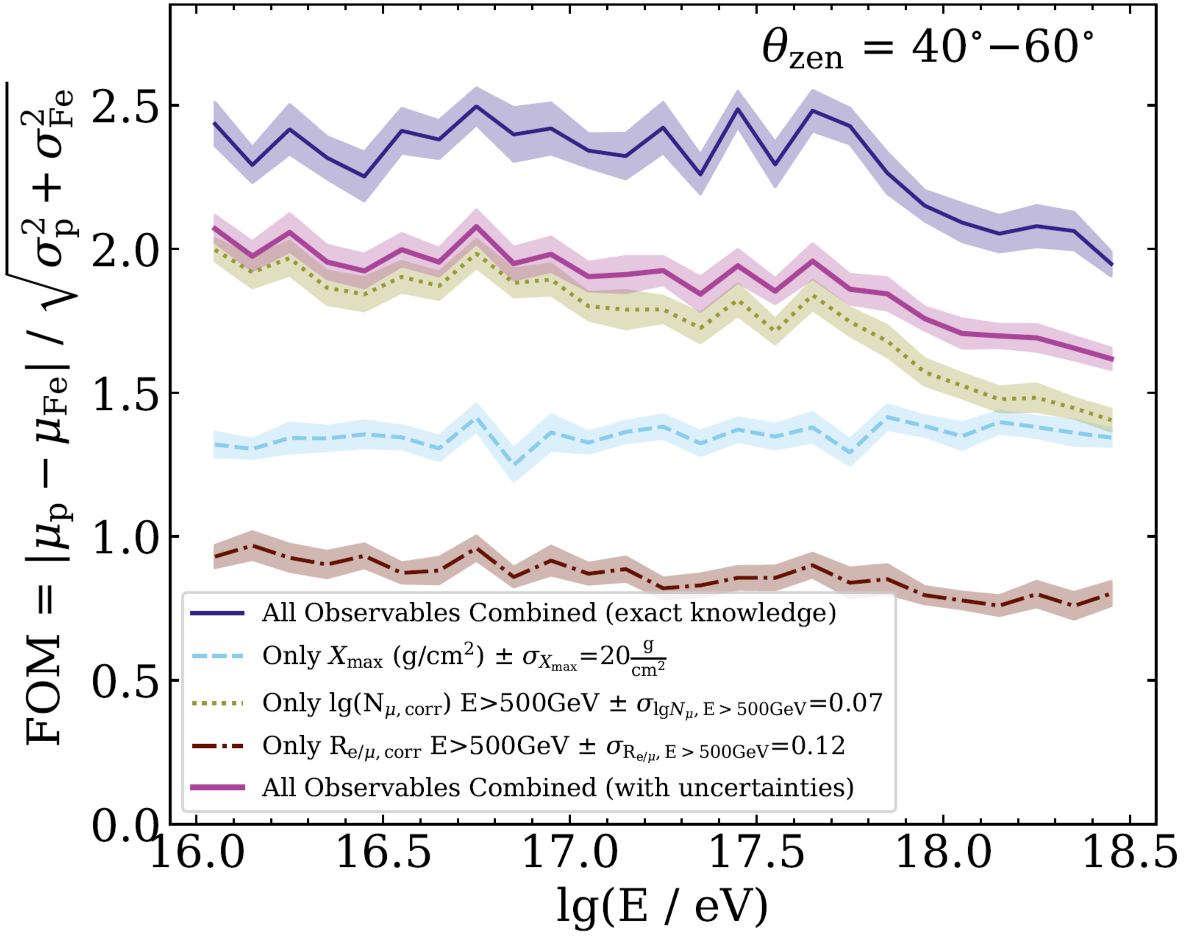
Event-by-Event Mass Sensitivity of Gen2 Surface + Optical Arrays

- In-ice muons have highest separation power, if separate energy measurement
- X_{max} gains importance at highest energies and has smaller systematics





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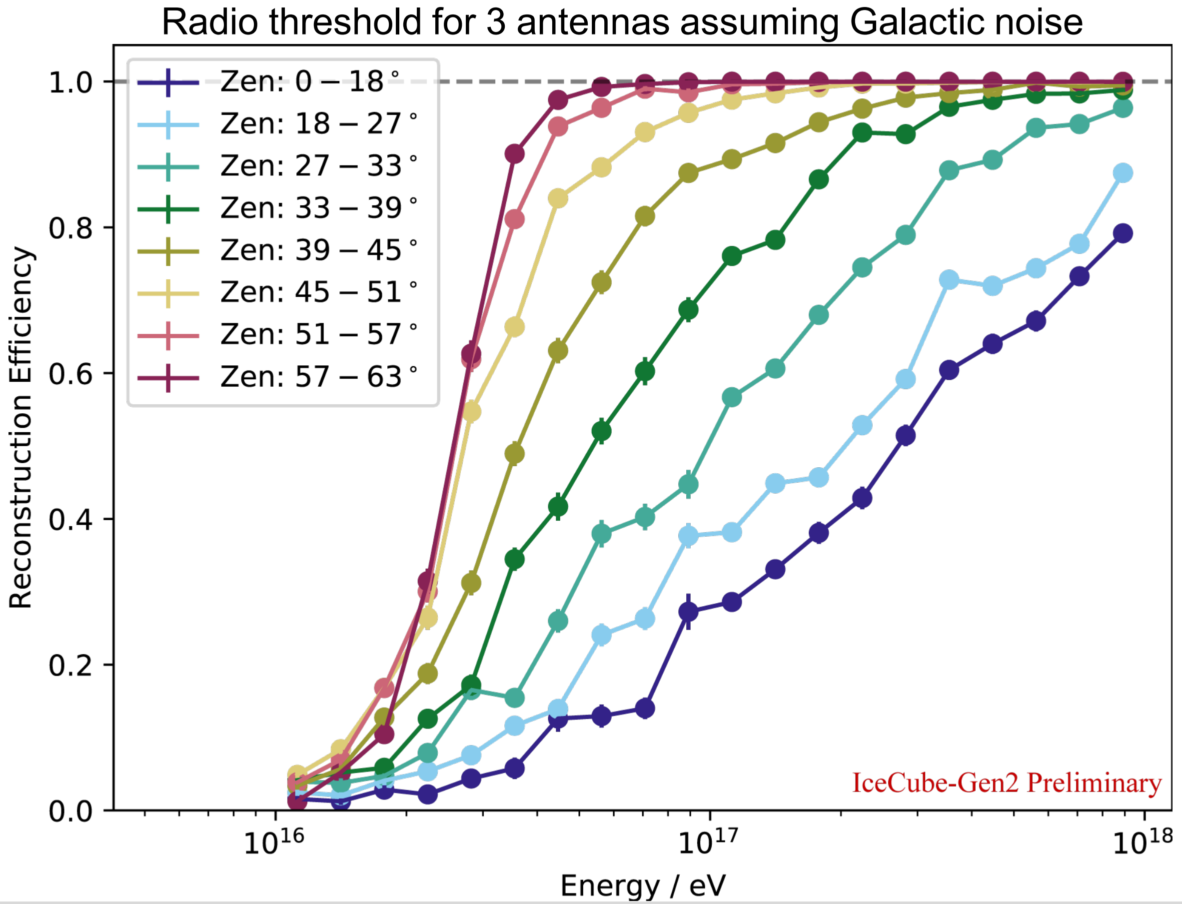
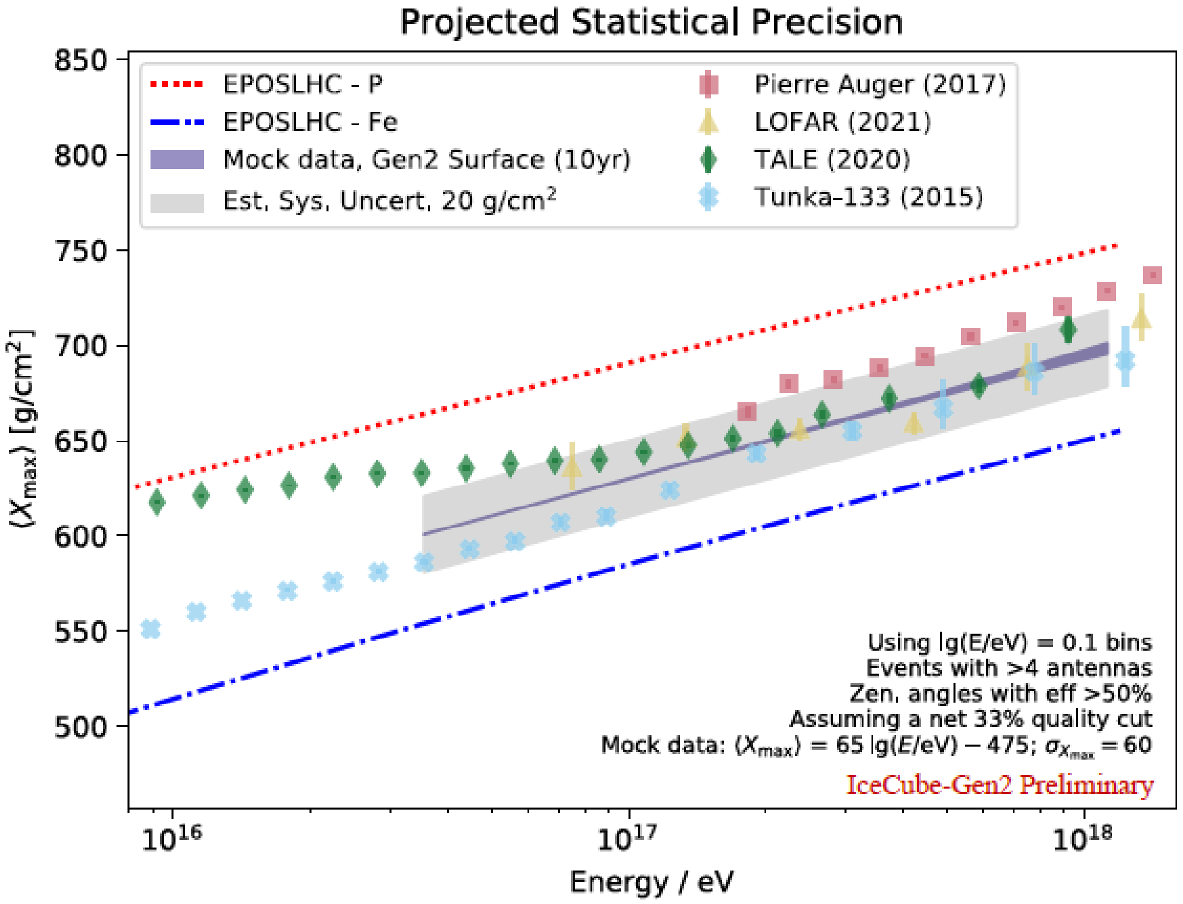
Result: Radio antennas will increase accuracy above $10^{16.5}$ eV

- 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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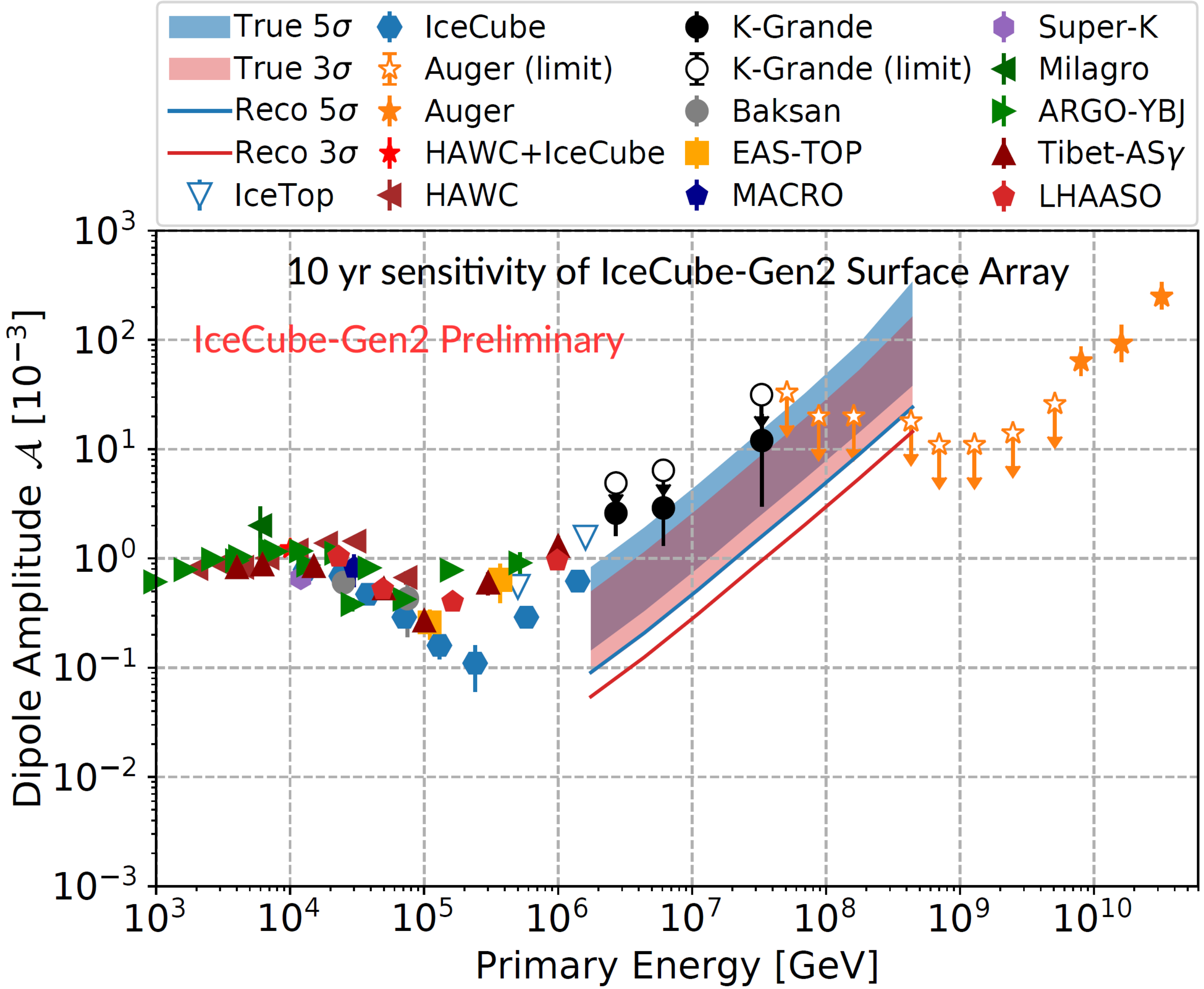
Extended Energy Range of Gen2: Sensitivity to Dipole Anisotropy



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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 for neutrino astronomy
- High accuracy for cosmic-ray air showers provided at high energies by radio antennas

→ 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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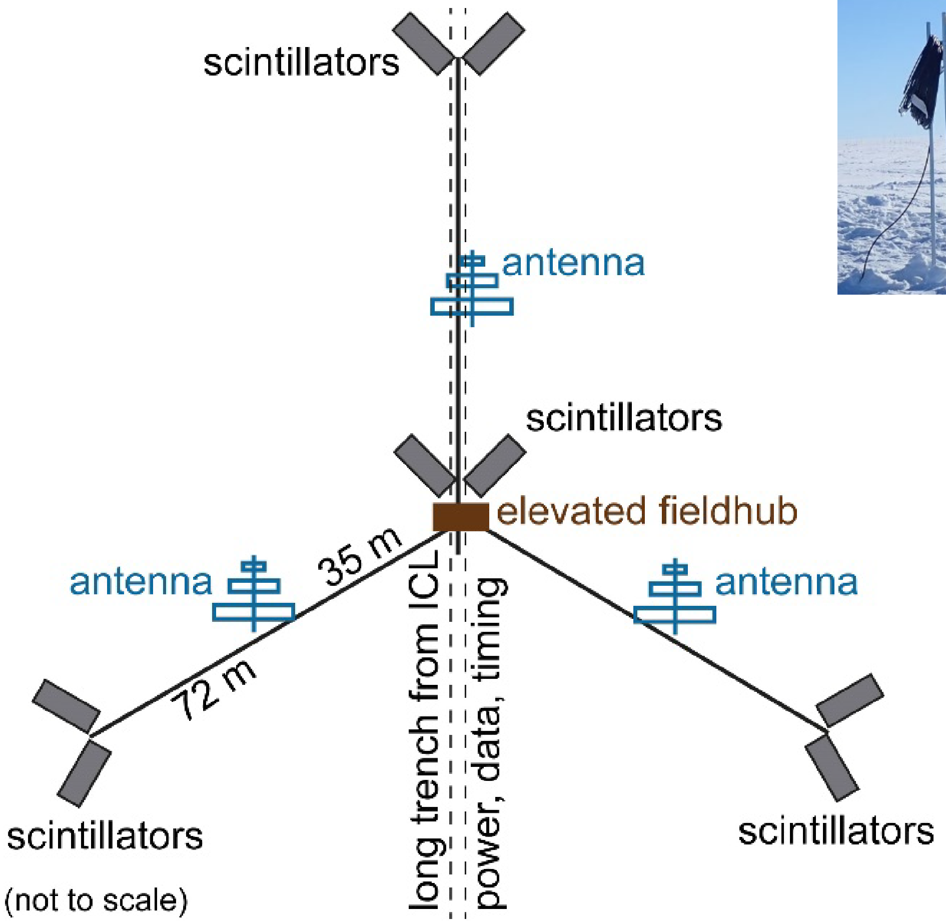
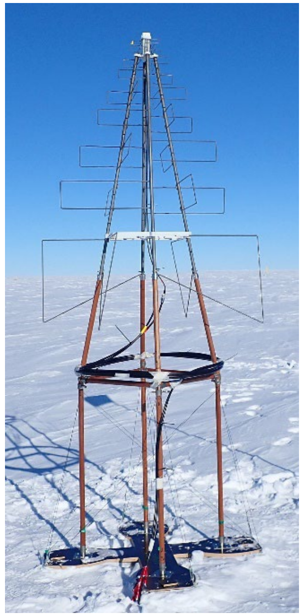
Baseline Design Follows Planned Enhancement of IceTop

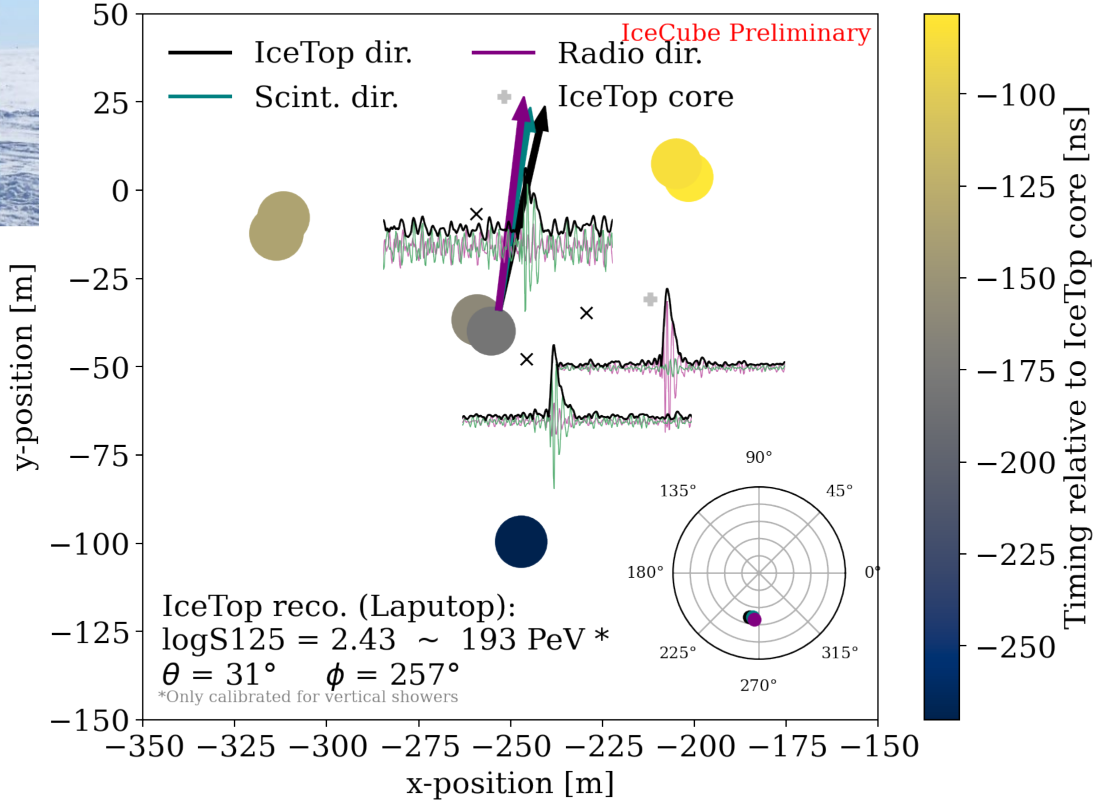
Station Design:

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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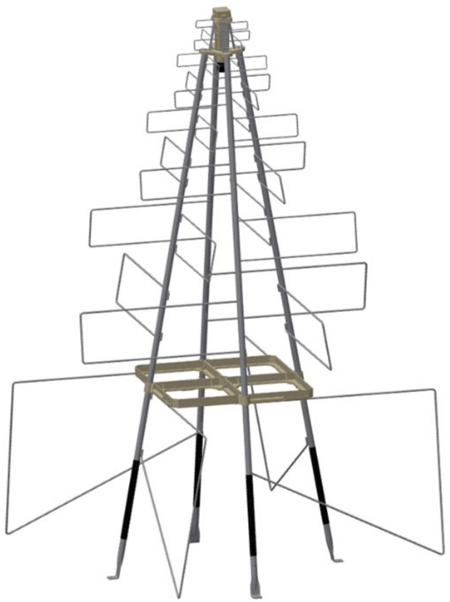
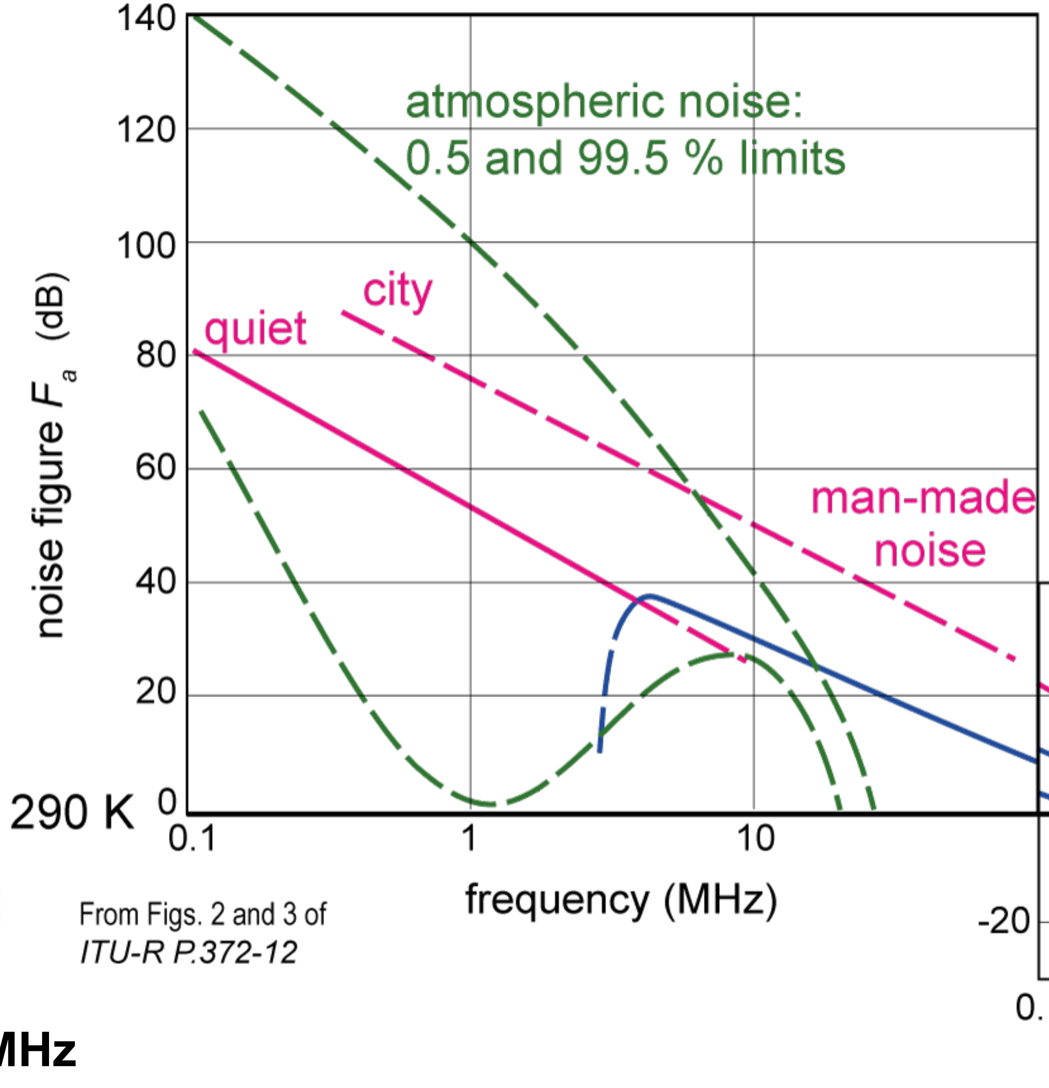
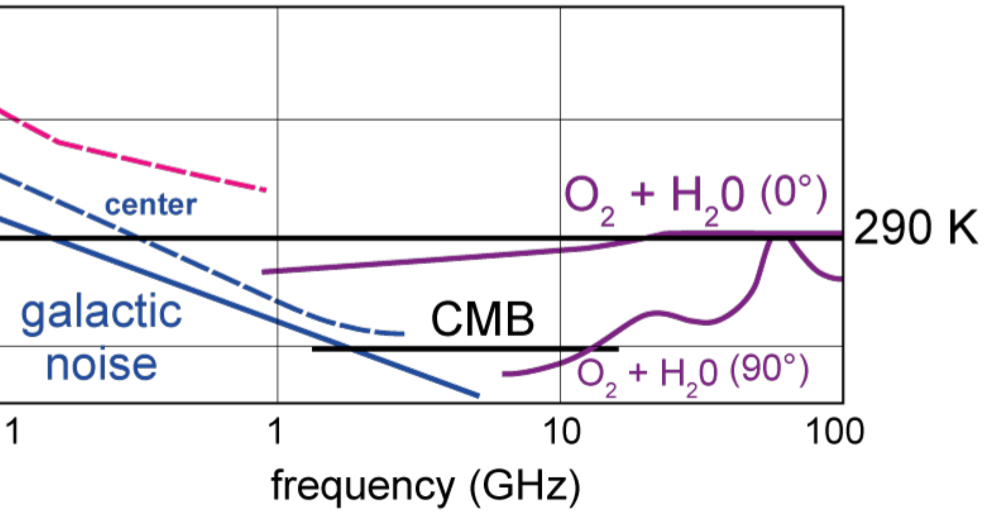
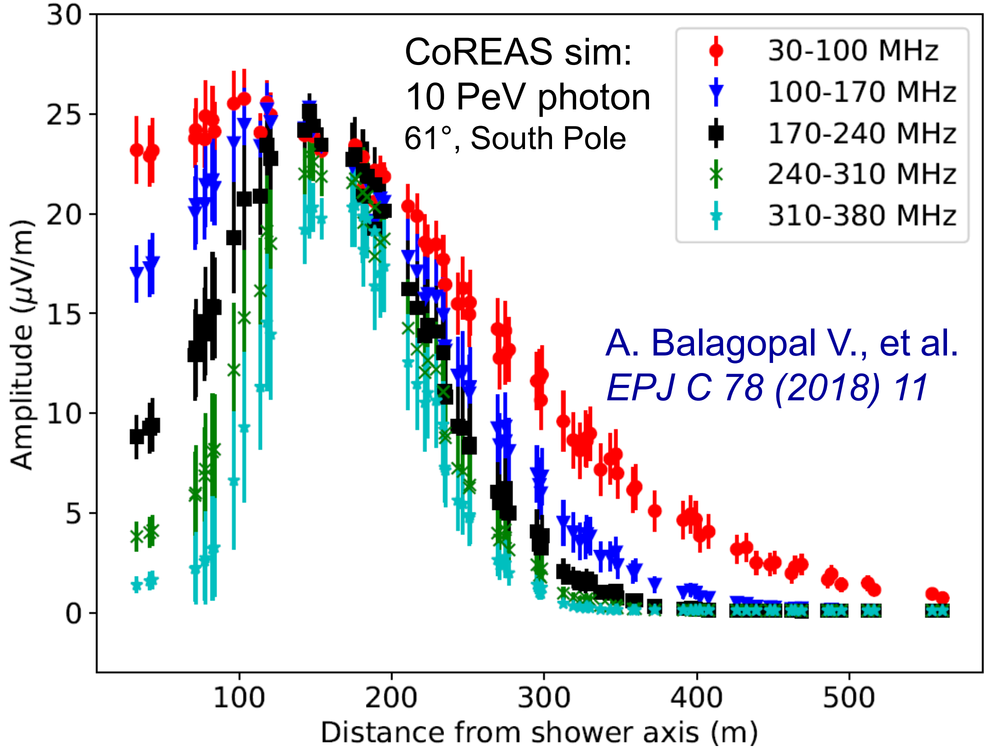
Better signal-to-noise ratio expected at high frequencies







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



SKALA v2: 70-350 MHz

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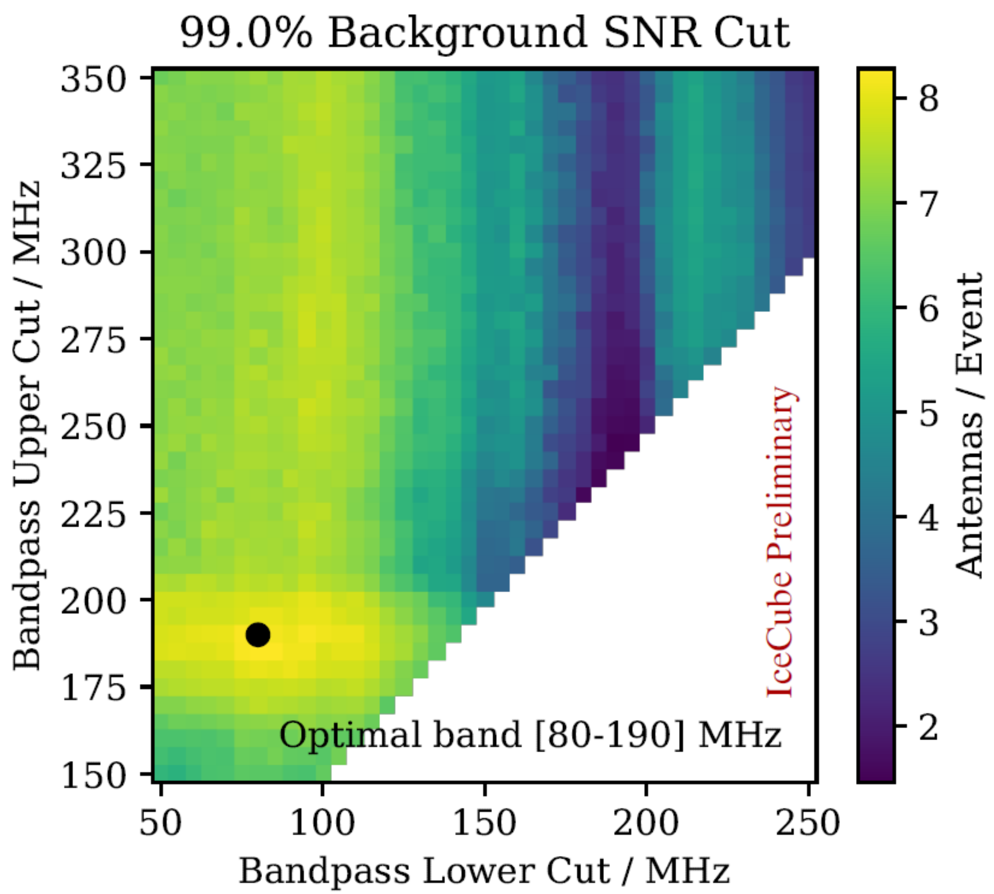
Best Frequency band

Prototype station



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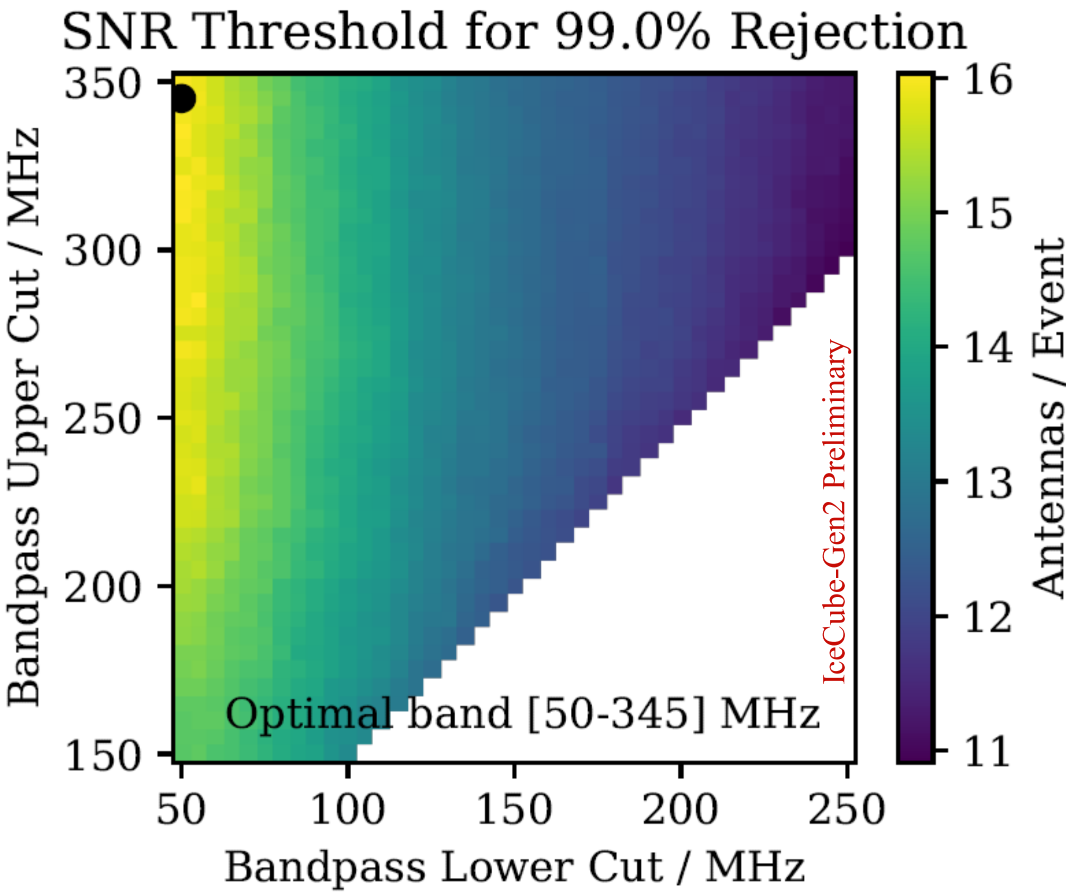
At SNR of 41

IceCube-Gen2, Galactic noise only



At SNR of 20

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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)

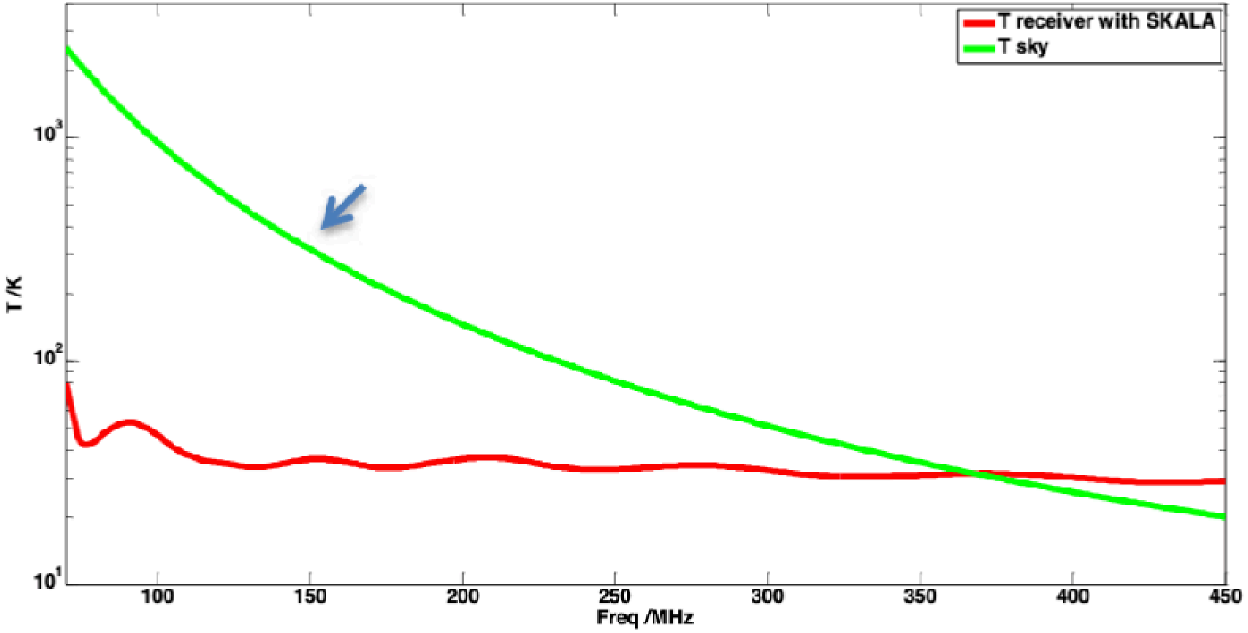
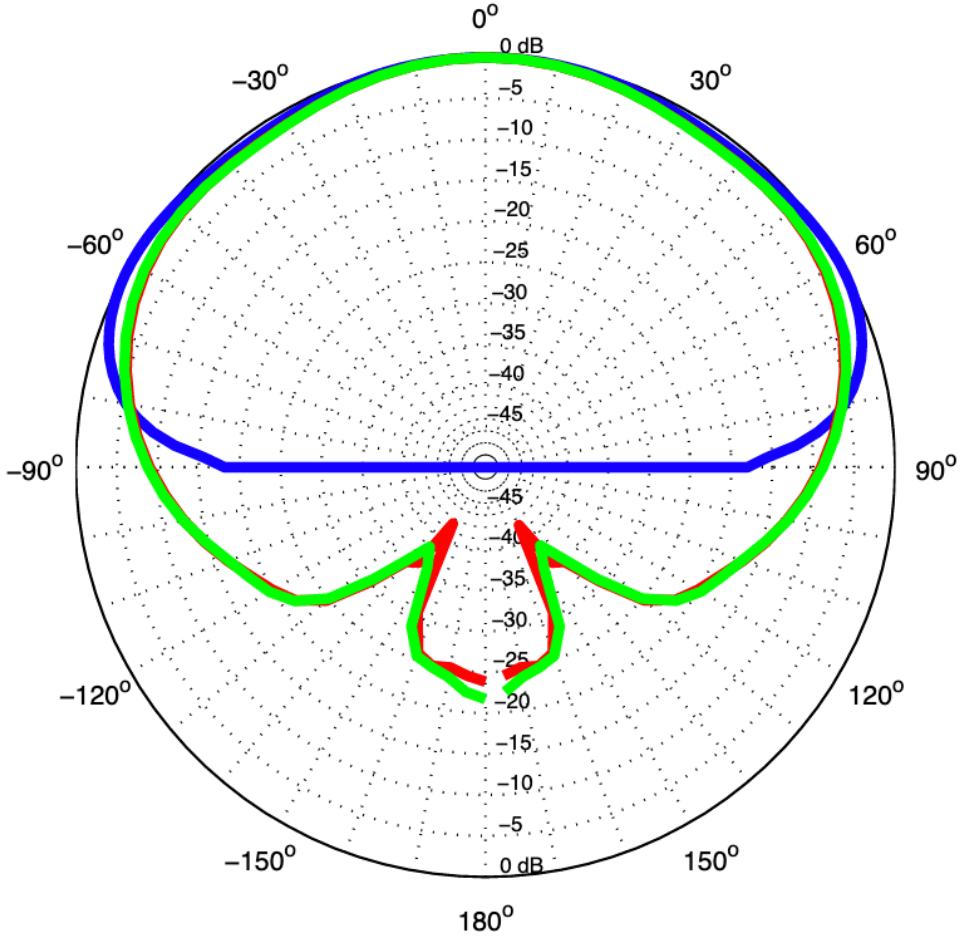


Fig. 9. Receiver noise temperature versus sky noise.

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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IceCube-Gen2 – a neutrino and also a cosmic-ray experiment

- IceCube-Gen2 will be primarily a next-generation observatory for neutrino astrophysics
- It will also be a unique lab for cosmic rays in the PeV to EeV range thanks to the combination of a surface array with the deep optical array in the ice.

Ultra-high-energy Cosmic Ray Instrumentation Roadmap from Snowmass UHECR whitepaper:

Experiment	Feature	Cosmic Ray Science*	Timeline
Pierre Auger Observatory	Hybrid array: fluorescence, surface e/μ + radio, 3000 km^2	Hadronic interactions, search for BSM, UHECR source populations, $\sigma_{\text{p-Air}}$	AugerPrime upgrade
Telescope Array (TA)	Hybrid array: fluorescence, surface scintillators, up to 3000 km^2	UHECR source populations proton-air cross section ($\sigma_{\text{p-Air}}$)	TAx4 upgrade
IceCube / IceCube-Gen2	Hybrid array: surface + deep, up to 6 km^2	Hadronic interactions, prompt decays, Galactic to extragalactic transition	Upgrade + surface enhancement; IceCube-Gen2 deployment; IceCube-Gen2 operation
GRAND	Radio array for inclined events, up to 200,000 km^2	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	GRANDProto 300; GRAND 10k; GRAND 200k multiple sites, step by step
POEMMA	Space fluorescence and Cherenkov detector	UHECR sources via huge exposure, search for ZeV particles, $\sigma_{\text{p-Air}}$	JEM-EUSO program; POEMMA
GCOS	Hybrid array with $X_{\max}$ + e/μ over 40,000 km^2	UHECR sources via event-by-event rigidity, forward particle physics, search for BSM, $\sigma_{\text{p-Air}}$	GCOS R&D + first site; GCOS further sites
			2025 2030 2035 2040

*All experiments contribute to multi-messenger astrophysics also by searches for UHE neutrinos and photons; several experiments (IceCube, GRAND, POEMMA) have astrophysical neutrinos as primary science case.

Ultra-High-Energy Cosmic Rays: The Intersection of the Cosmic and Energy Frontiers (white paper prepared for Snowmass CF7),

A. Coleman, J. Eser, E. Mayotte, F. Sarazin, F. G. Schröder, D. Soldin, T. M. Venters, Astroparticle Physics 149 (2023) 102819, arxiv:2205.05845

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