Specific Acknowledgement of ERC StG “*PeV-Radio*”:
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Radio Detection of Cosmic Particles

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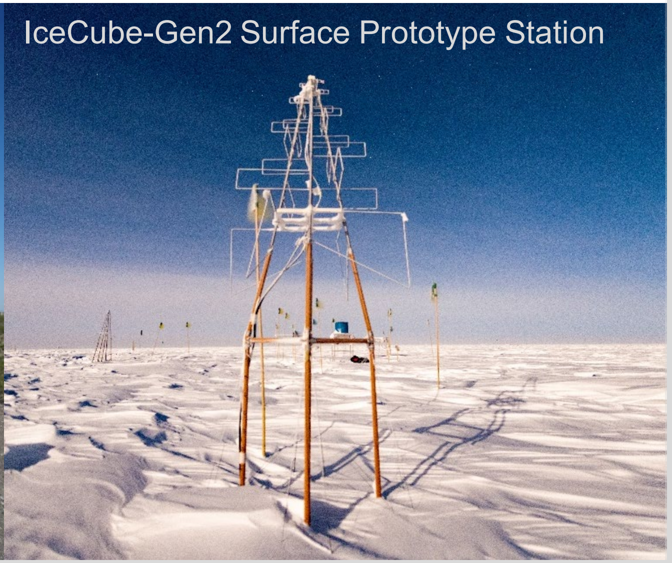
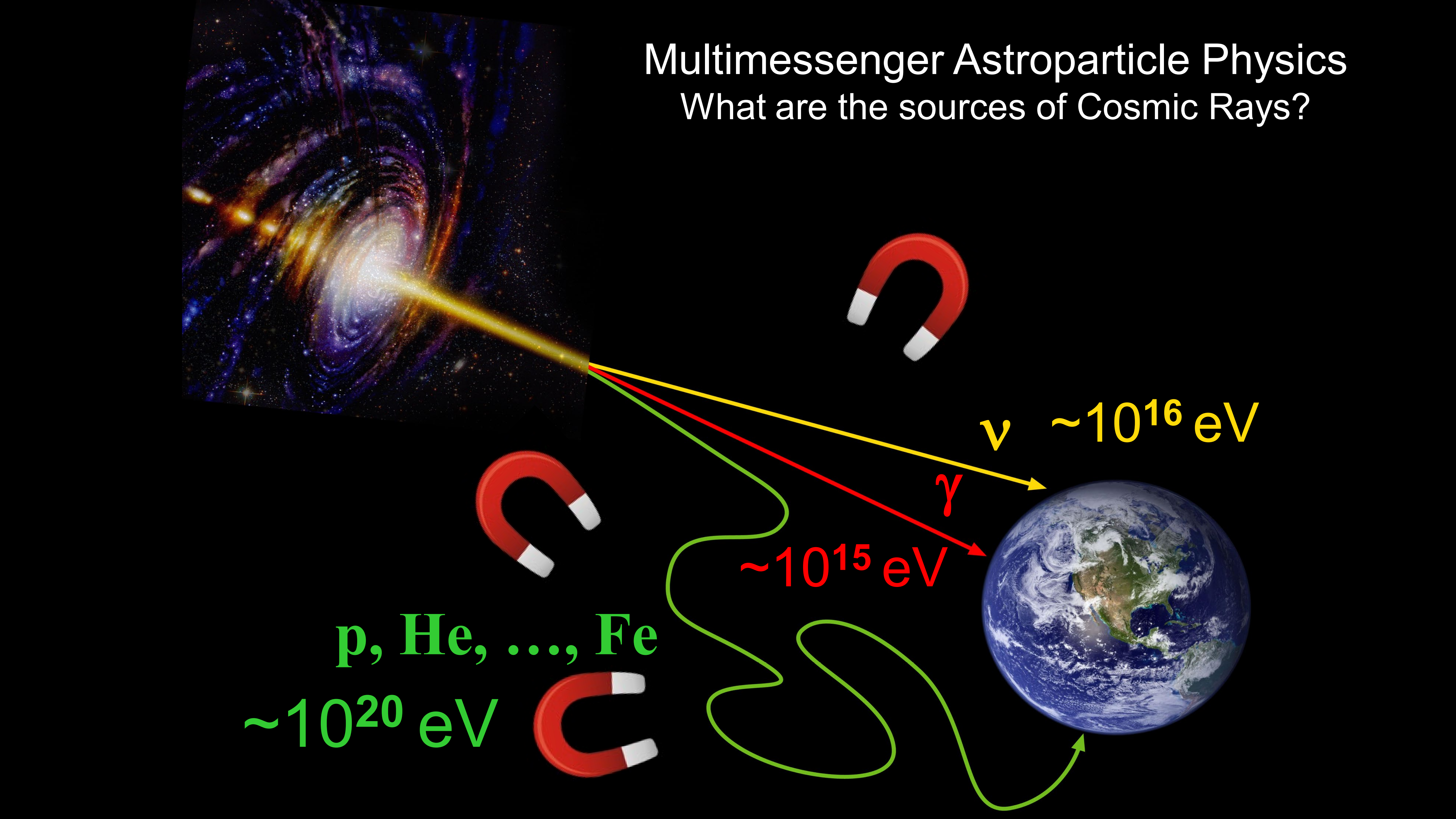
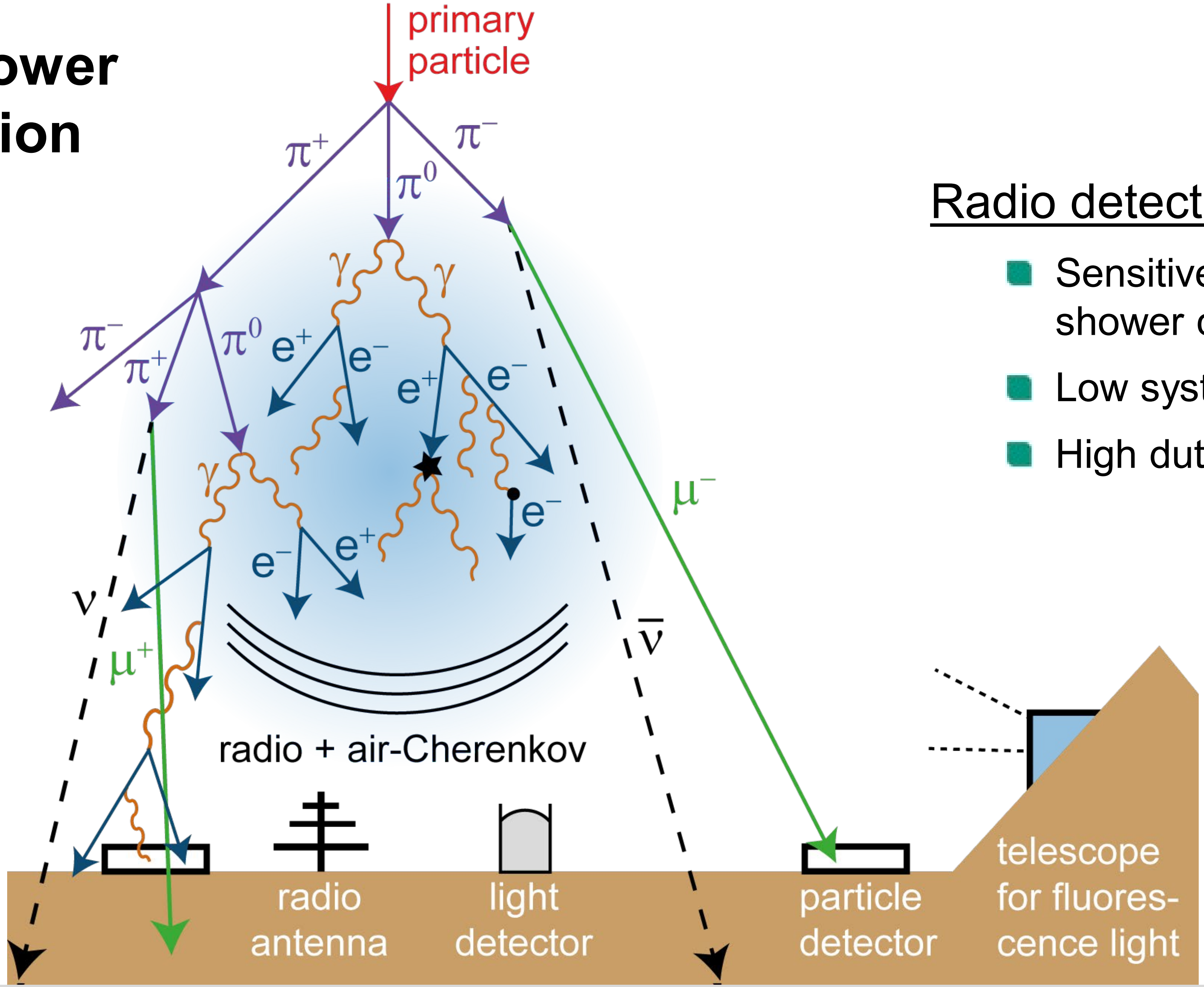



Multimessenger Astroparticle Physics
What are the sources of Cosmic Rays?
ν ~10^16 eV
γ
~10^15 eV
p, He, …, Fe
~10^20 eV

Air shower Detection



Radio detection of air showers:

- Sensitive to electromagnetic shower component
- Low systematic uncertainties
- High duty cycle

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arXiv: 1607.08781

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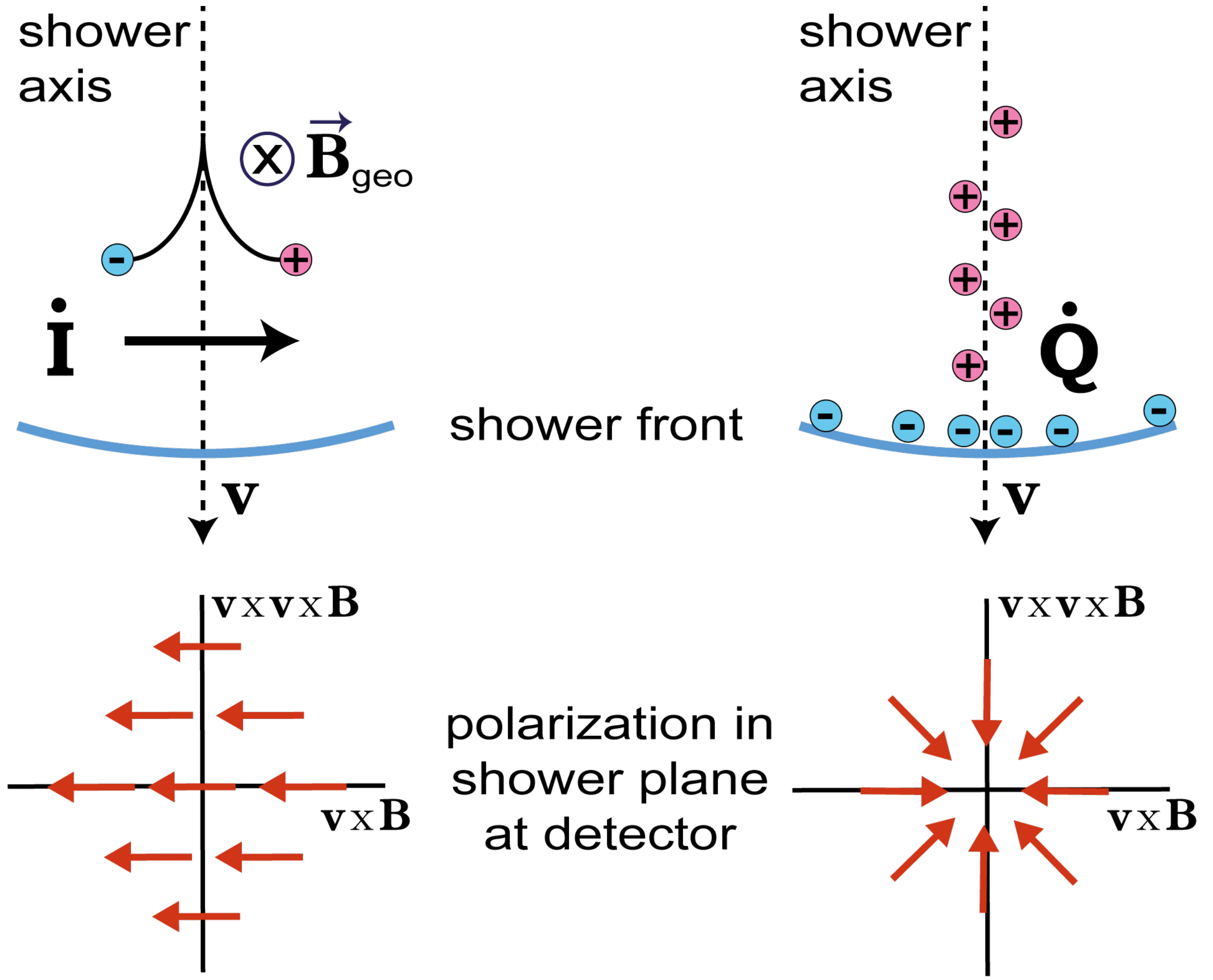
Radio: Emission Mechanisms

<u>Geomagnetic emission:</u>

Dominant mechanism in air showers.

Relevant for all primary particles.



Geomagnetic emission

Askaryan emission

<u>Askaryan emission:</u>

Dominant mechanism in dense media subdominant in air.

Most relevant for neutrino detection.

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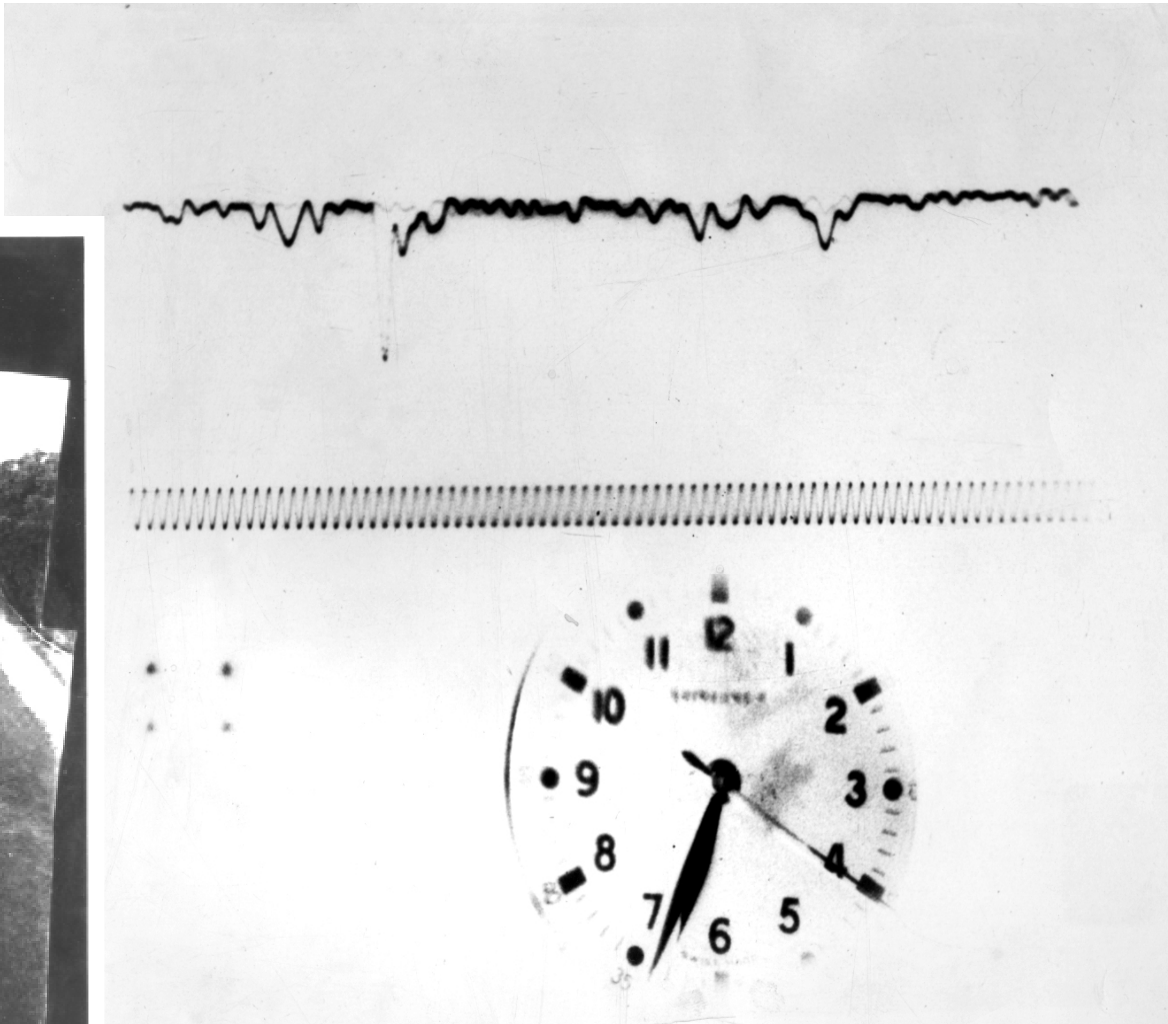
Experiments: First Detection

- Qualitative features discovered 60 years ago, but measurements lacking accuracy



Jelley et al Nature 1965,
R. A. Porter MSc Thesis 1967

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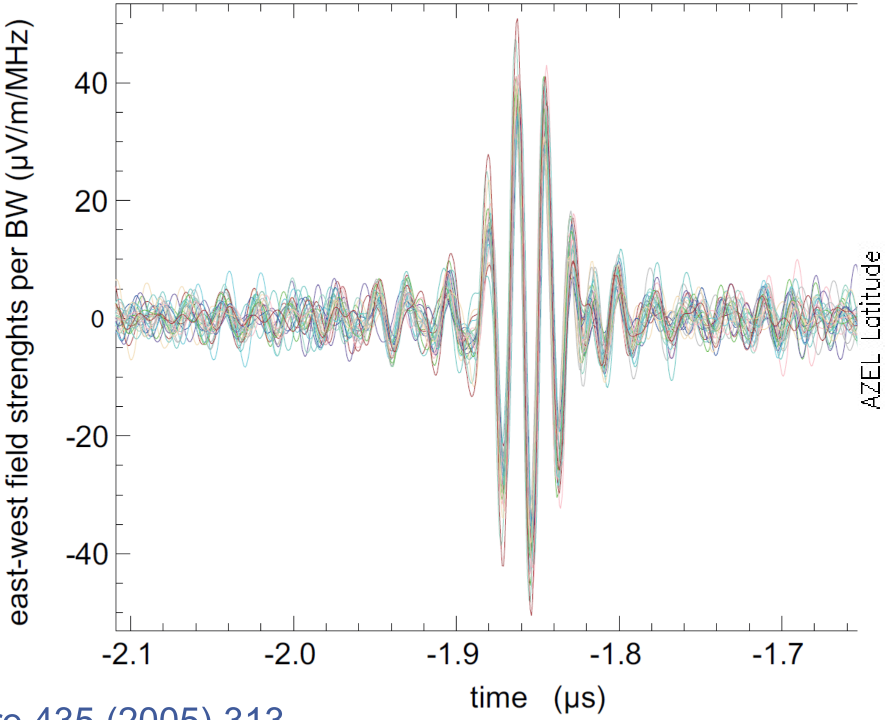
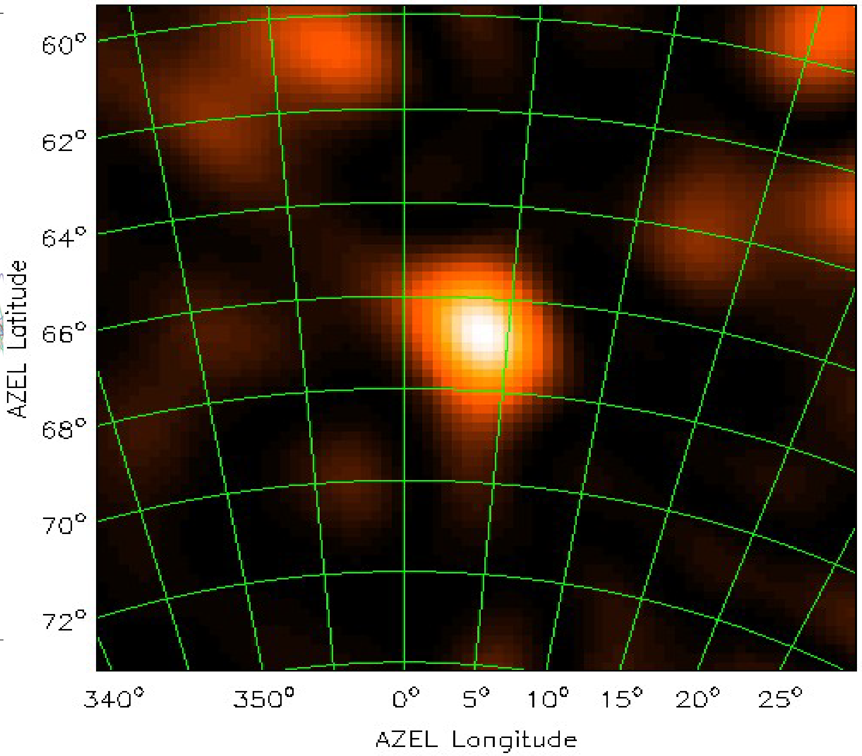
Digital Radio Interferometry of Air Showers at LOPES

- Operation: 2003 – 2013 as radio extension of KASCADE-Grande
- 30 antennas, 40 – 80 MHz, proof-of-principle for radio interferometry of cosmic-ray air showers: direction (< 0.5°), energy, shower maximum (X_{max})





LOPES Coll., EPJ C 81 (2021) 176 + Nature 435 (2005) 313

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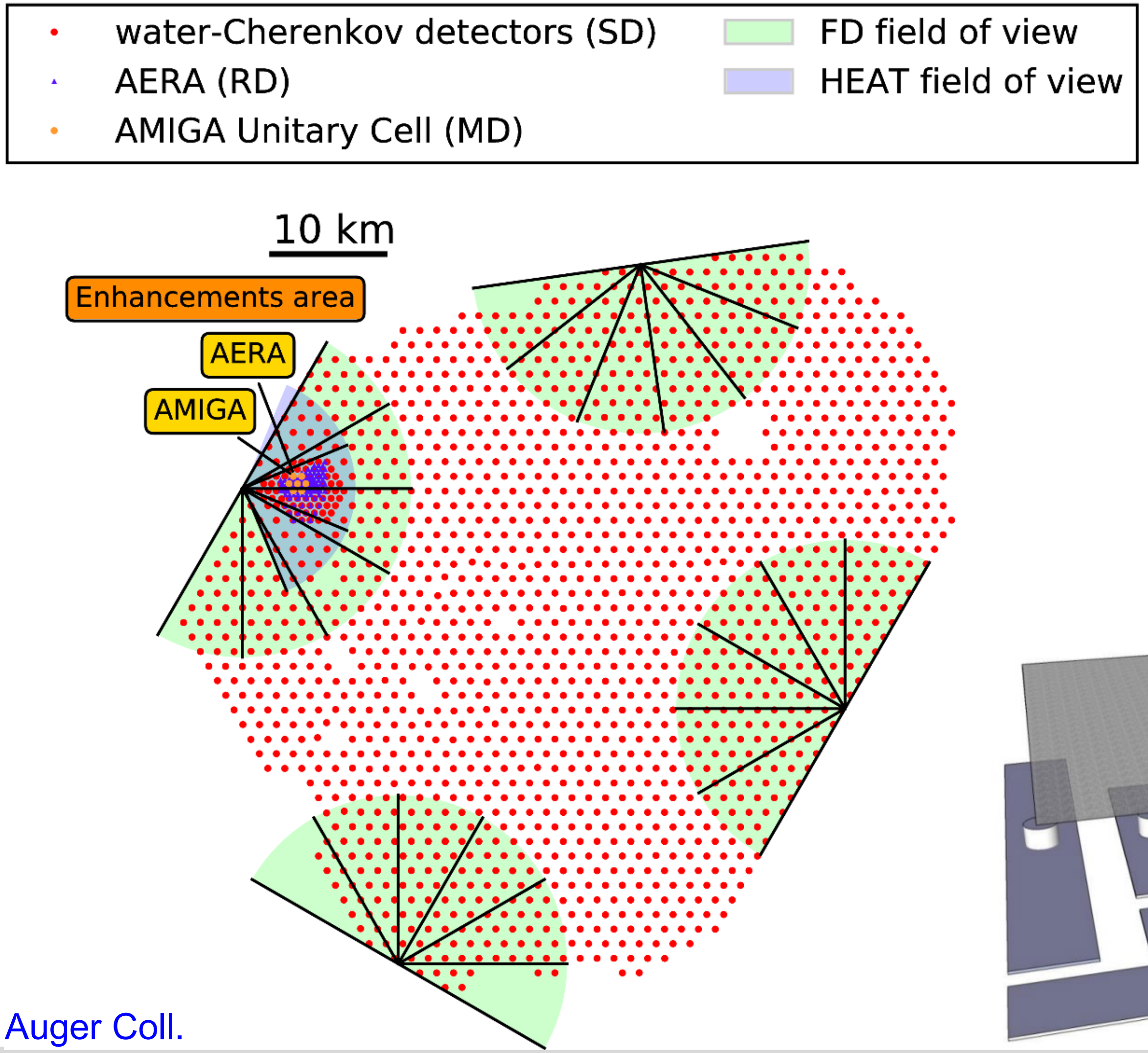
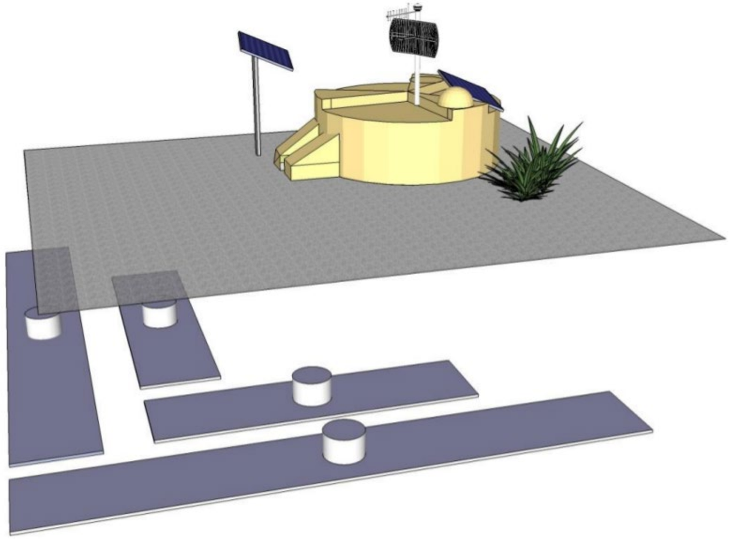
Auger Engineering Radio Array (AERA) at the Pierre Auger Observatory



- 153 autonomous radio stations on 17 km²
  - different antennas, electronics, triggers,…
- Coincident measurements with surface, underground and fluorescence detectors



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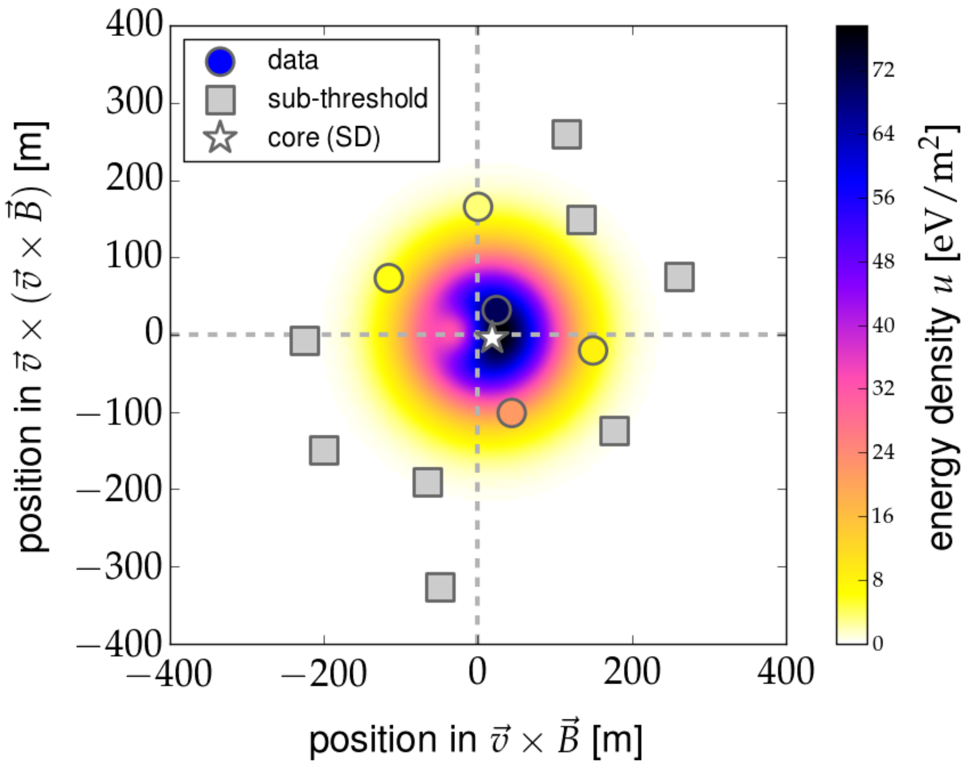
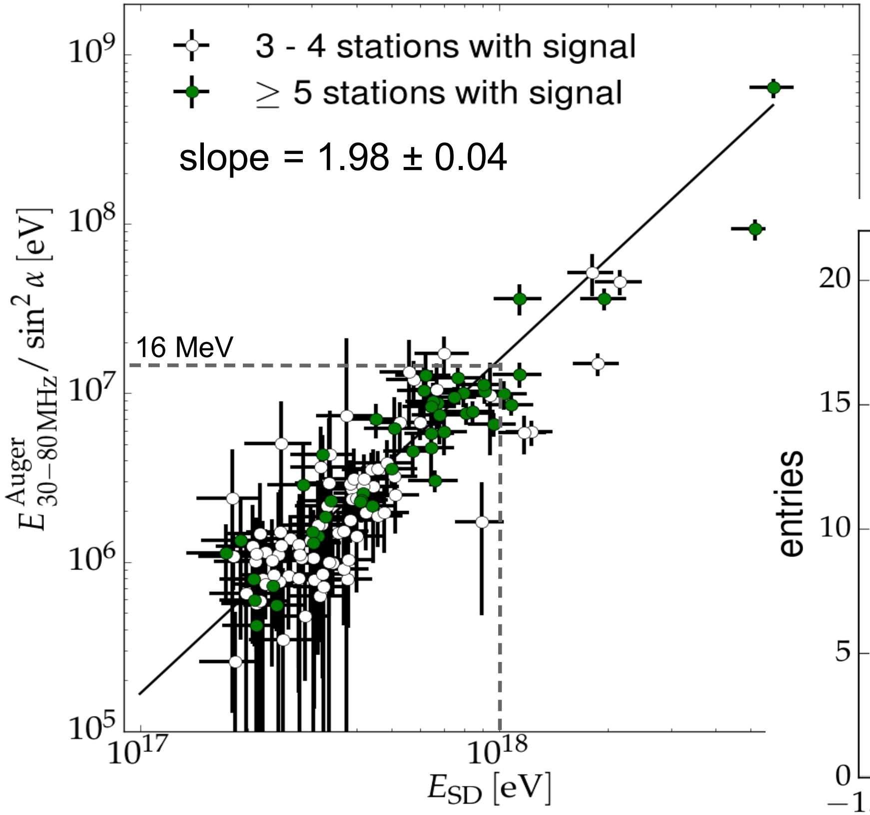
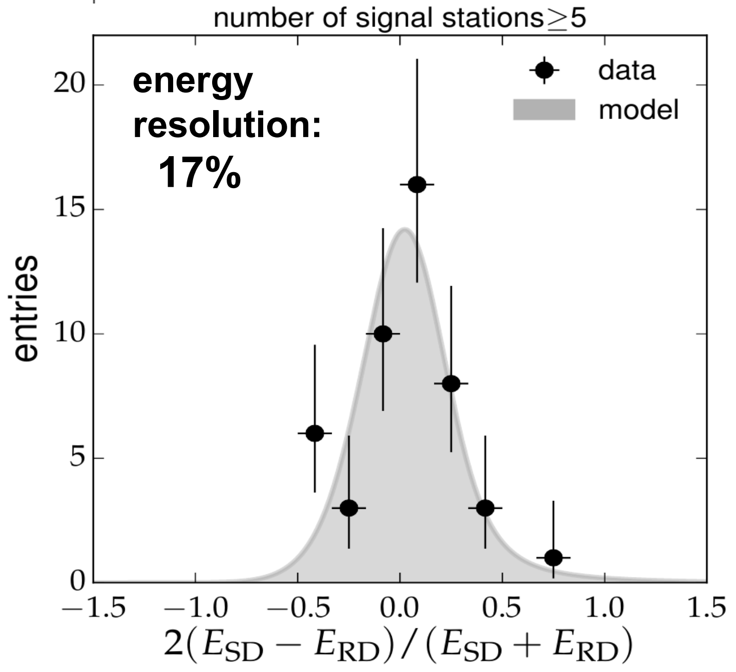
Radio Measurement of Cosmic-Ray Energy

- Total energy in radio signal scales quadratically with electro-mag. shower energy
- Precision and accuracy competes with optical techniques, with radio available 24/7





16 MeV radiation energy for a 1 EeV cosmic ray



Pierre Auger Coll., PRL 116 (2016) 241101

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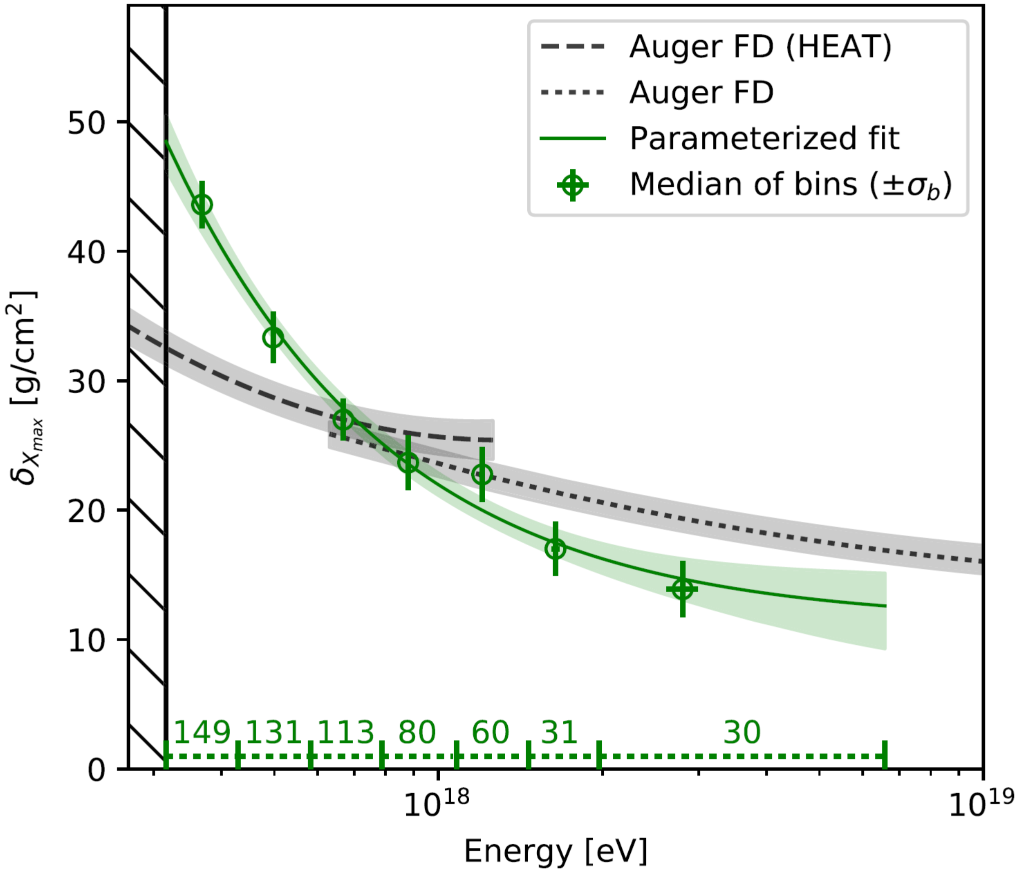
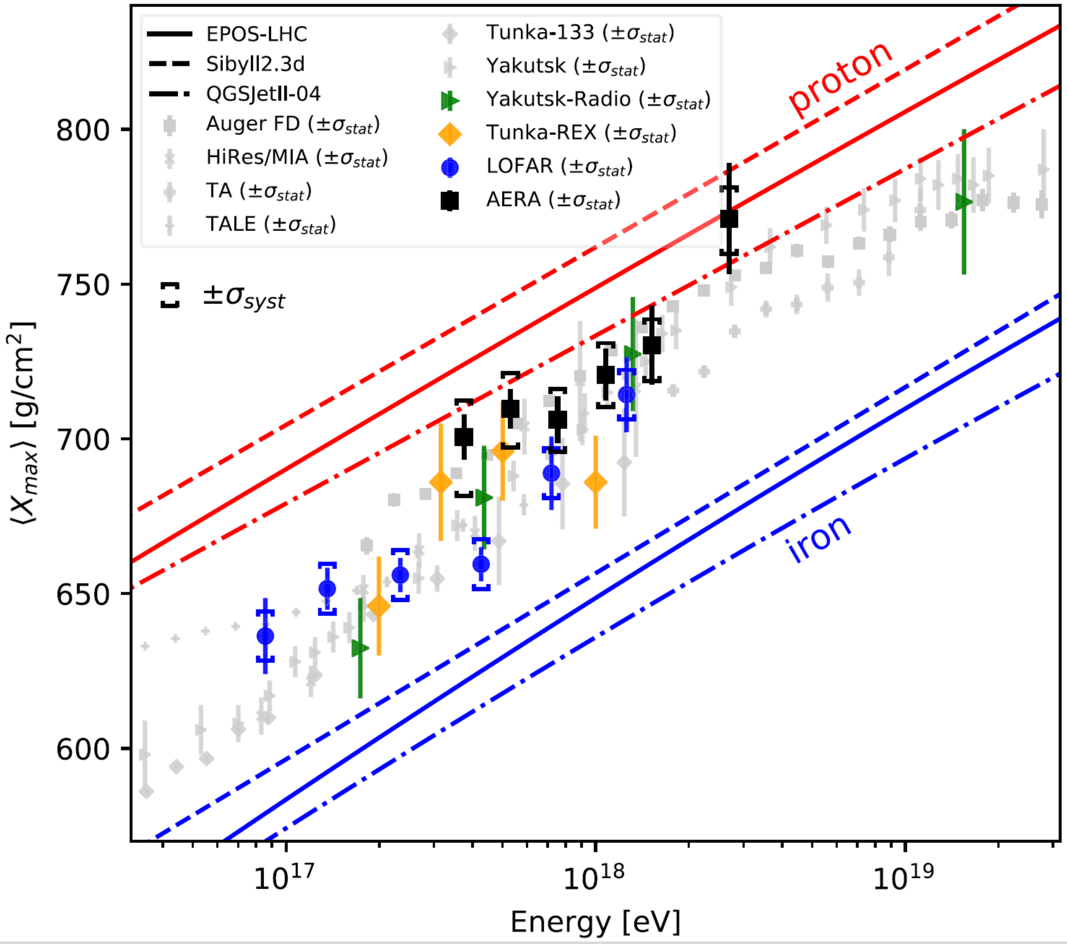
Mass Sensitivity of Radio Emission (through X_{max})

- Depth of shower maximum (X_{max}) by matching templates of simulated radio amplitude
- Accuracy competes with optical techniques, with radio available 24/7





Pierre Auger Coll., PRL 132 (2024) 021001

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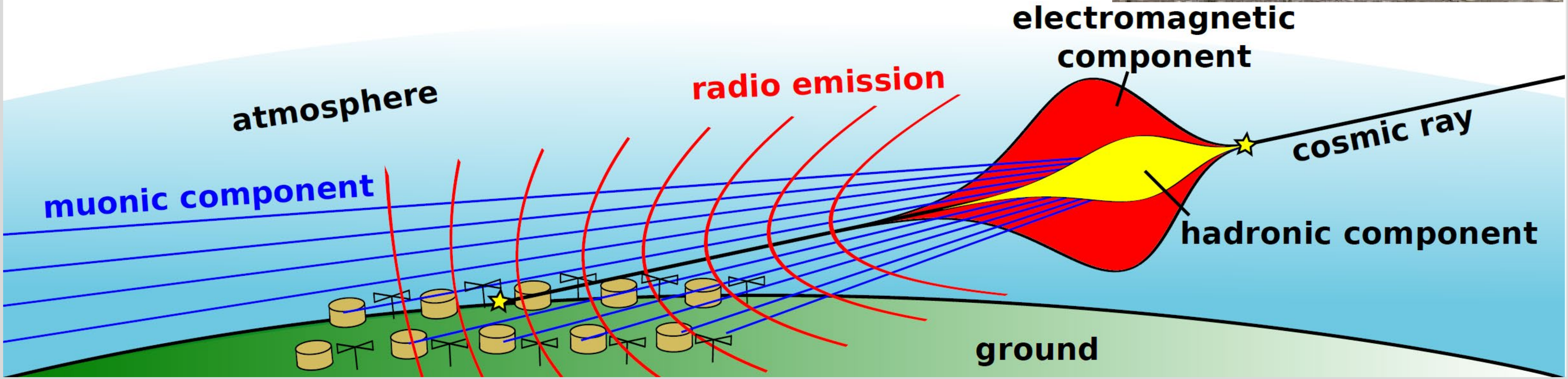
AugerPrime: Upgrade of the Pierre Auger Observatory

- Improved quality of surface detector:
  - scintillators + radio antennas
  - electronics upgrade
  - radio+muons enables per-event mass discrimination



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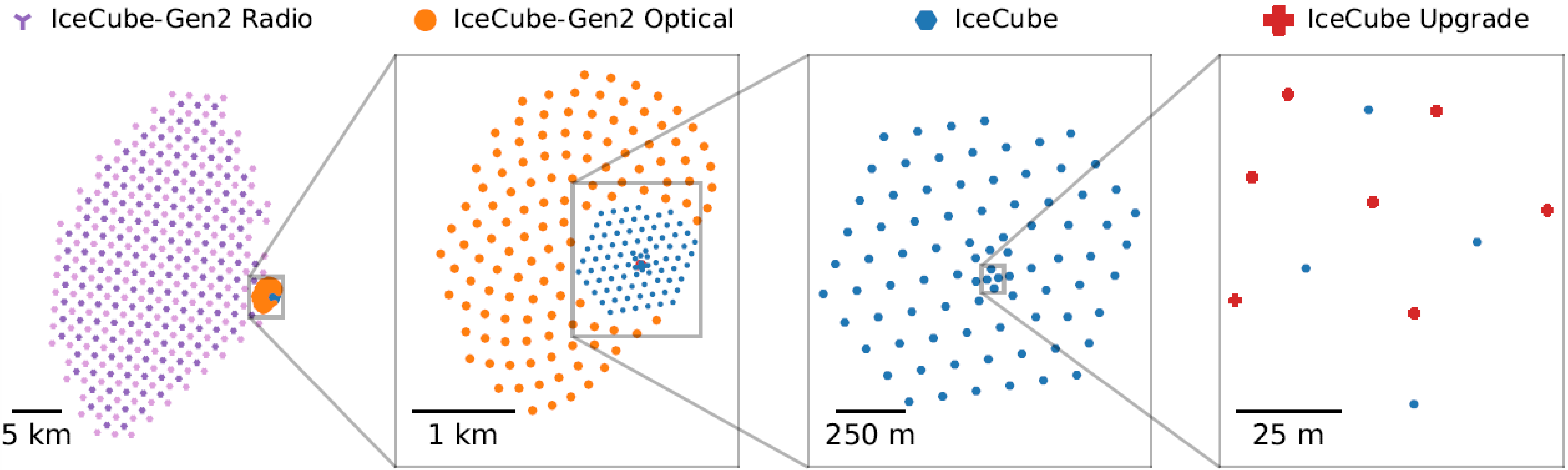
IceCube-Gen2: extending the IceCube Neutrino Observatory

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



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

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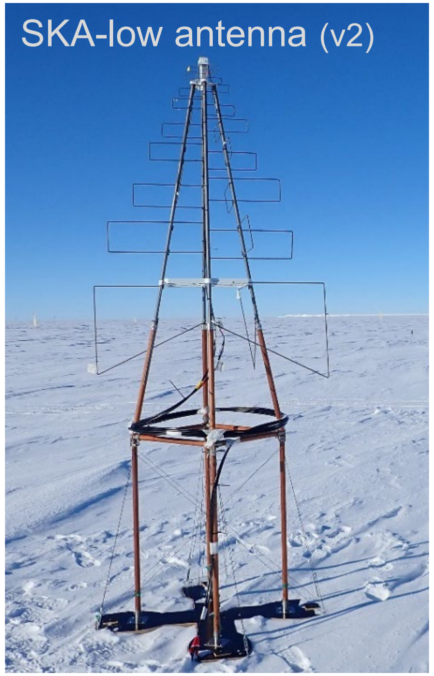
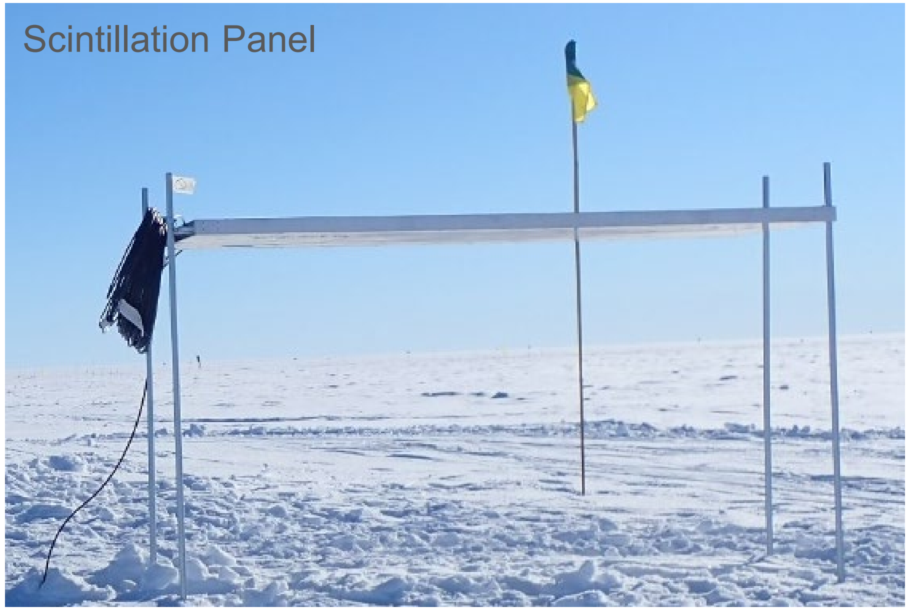
IceCube-Gen2 Surface Array

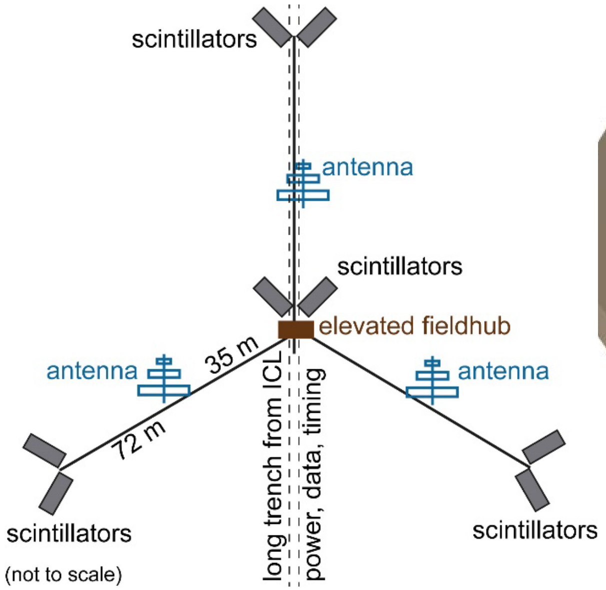
Design based on success of prototype station operation at the South Pole

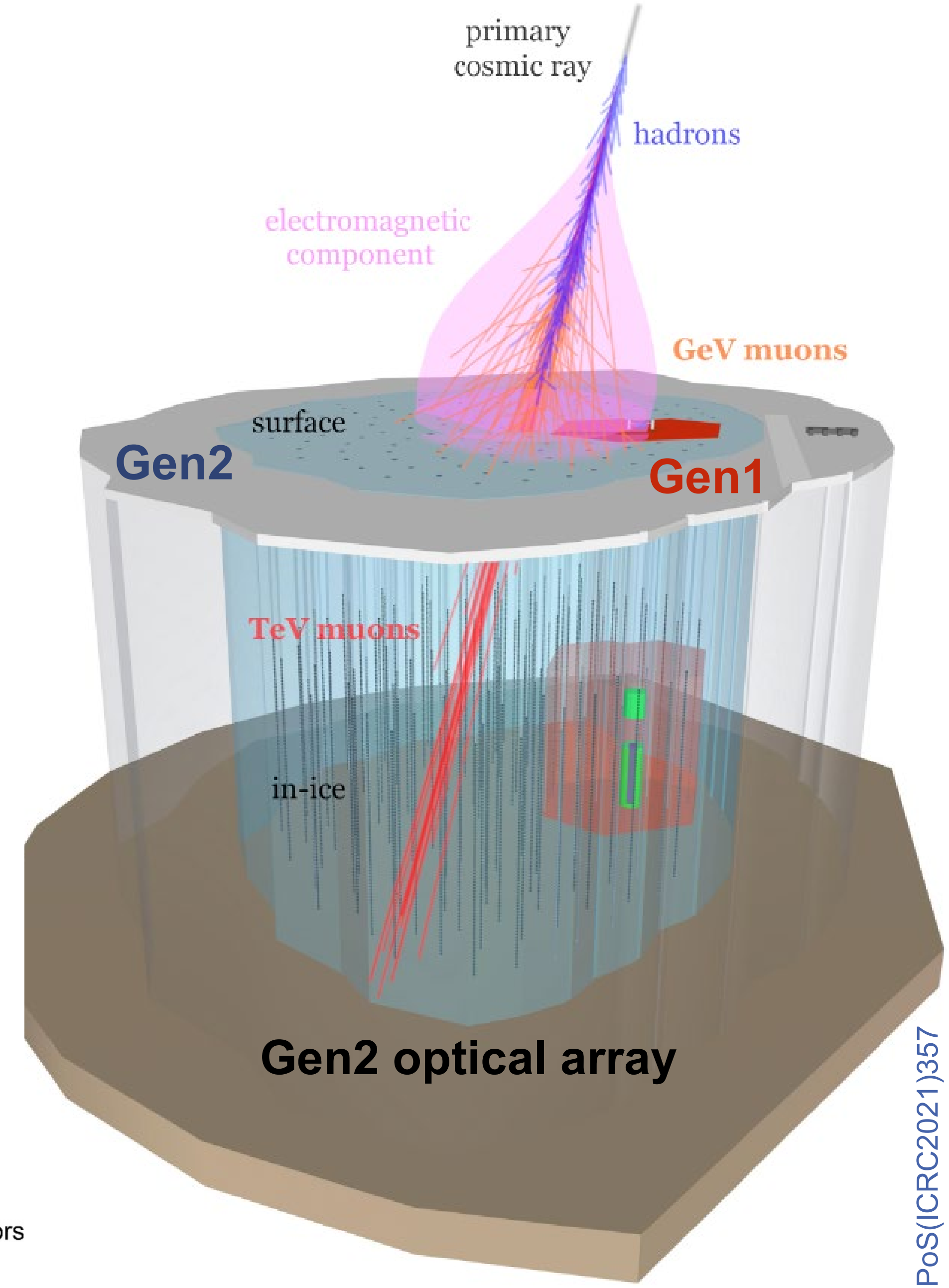
Science Case:

- veto for downgoing events
- PeV-EeV cosmic rays + PeV photons
- particle physics, e.g., prompt muons









PoS(ICRC2021)357

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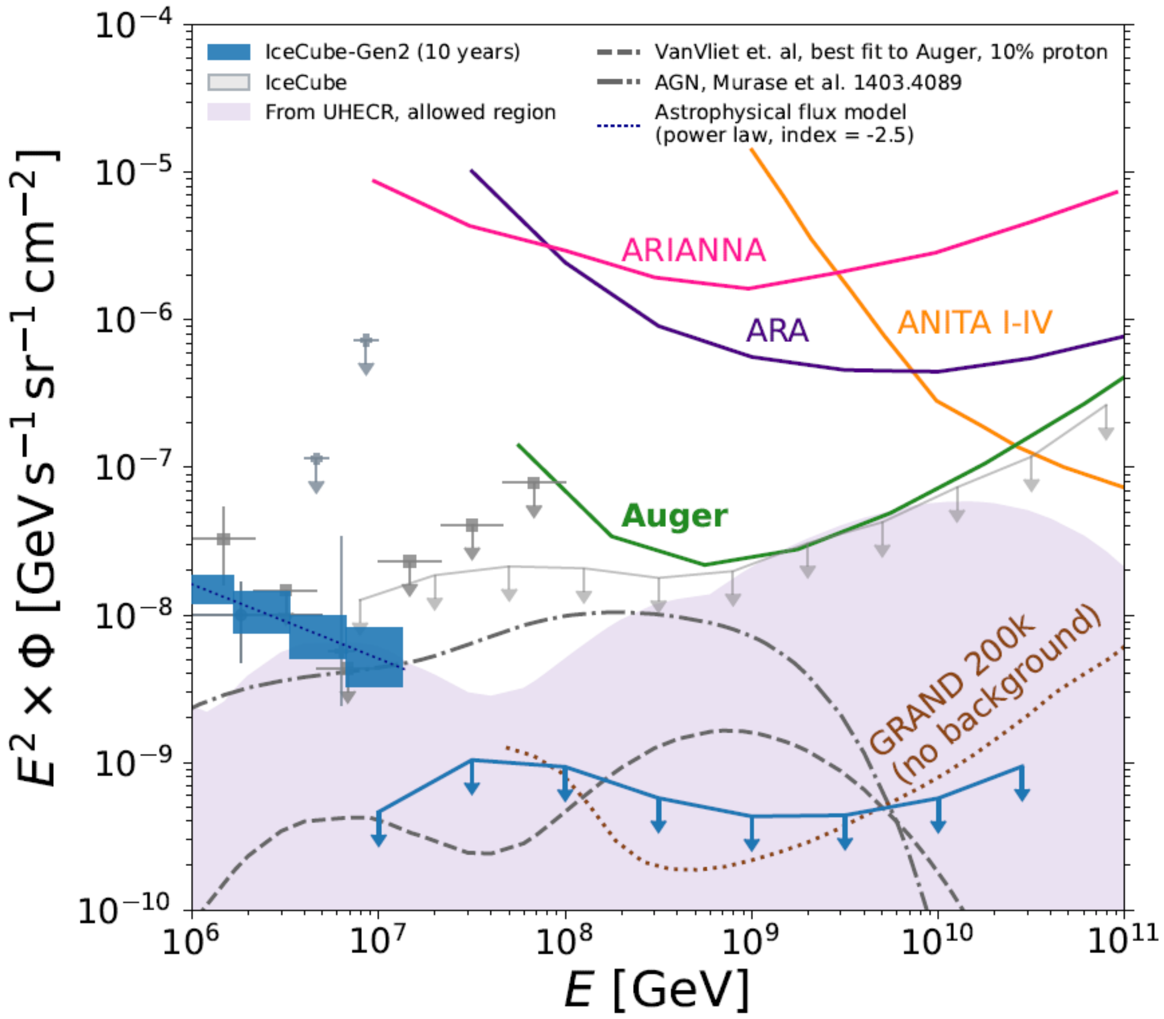
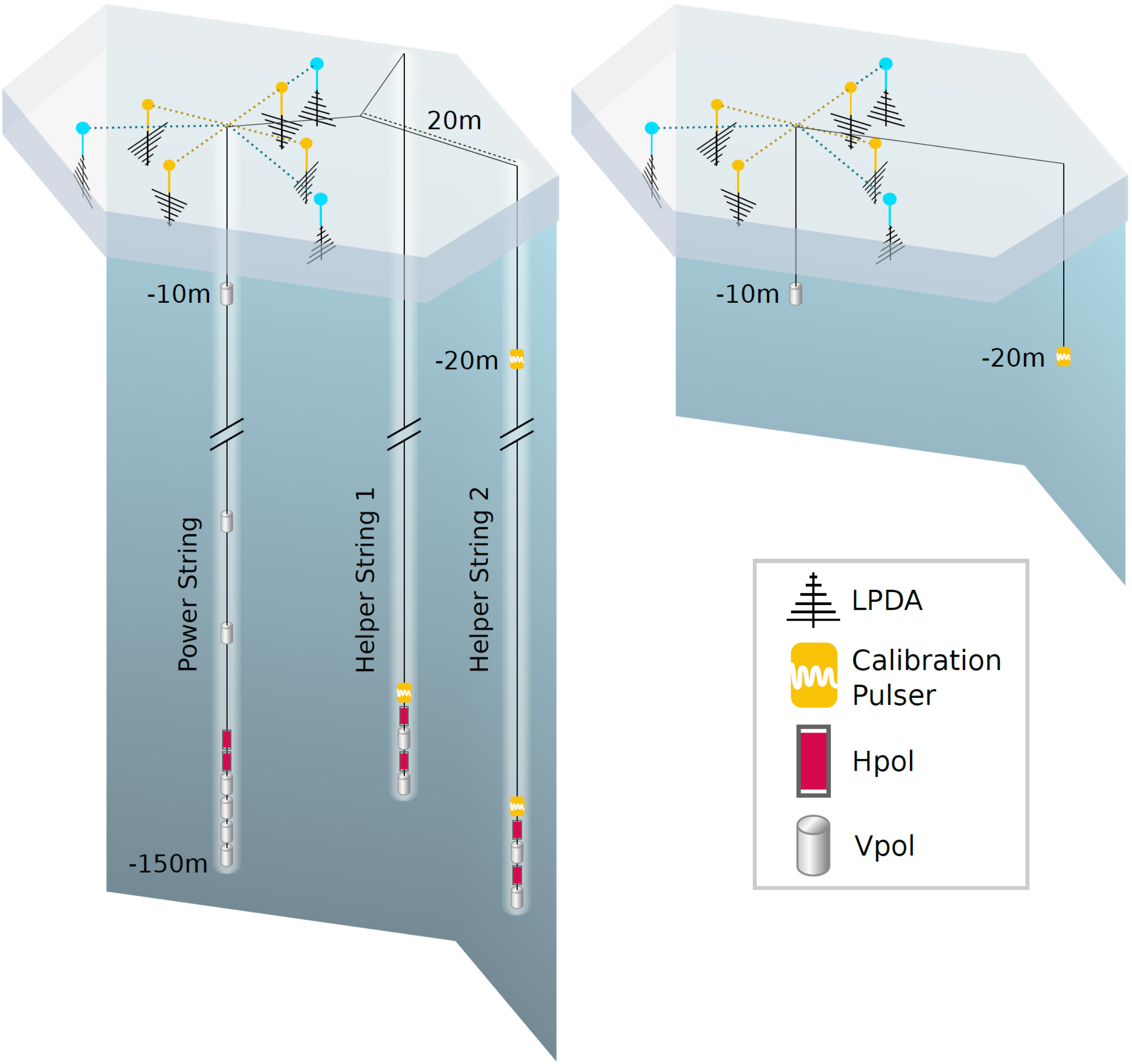
IceCube-Gen2 Radio Array for UHE Neutrinos

- Builds on current RNO-G experience





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Radio Detection in Mutli-Messenger Observatories

- Radio one of the main techniques for future UHECR and UHE neutrino observatories
  - will also contribute to particles physics and photon search above 10 PeV

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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Conclusion

- Understanding highest energy cosmic-ray sources requires
  - Detection techniques for EeV neutral particles: photons + neutrinos
  - Higher accuracy for cosmic rays: mass sensitivity anisotropy measurements

  → Radio technique important for both applications

- Radio technique has matured for energies E > 10 PeV
  - Competitive accuracy for cosmic-ray direction, energy, and mass (X_{max}) demonstrated
  - Further R&D in progress for stand-alone radio arrays, e.g., for neutrino

  → Several current and future experiments with radio for multi-messenger astrophysics

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Additional Slides

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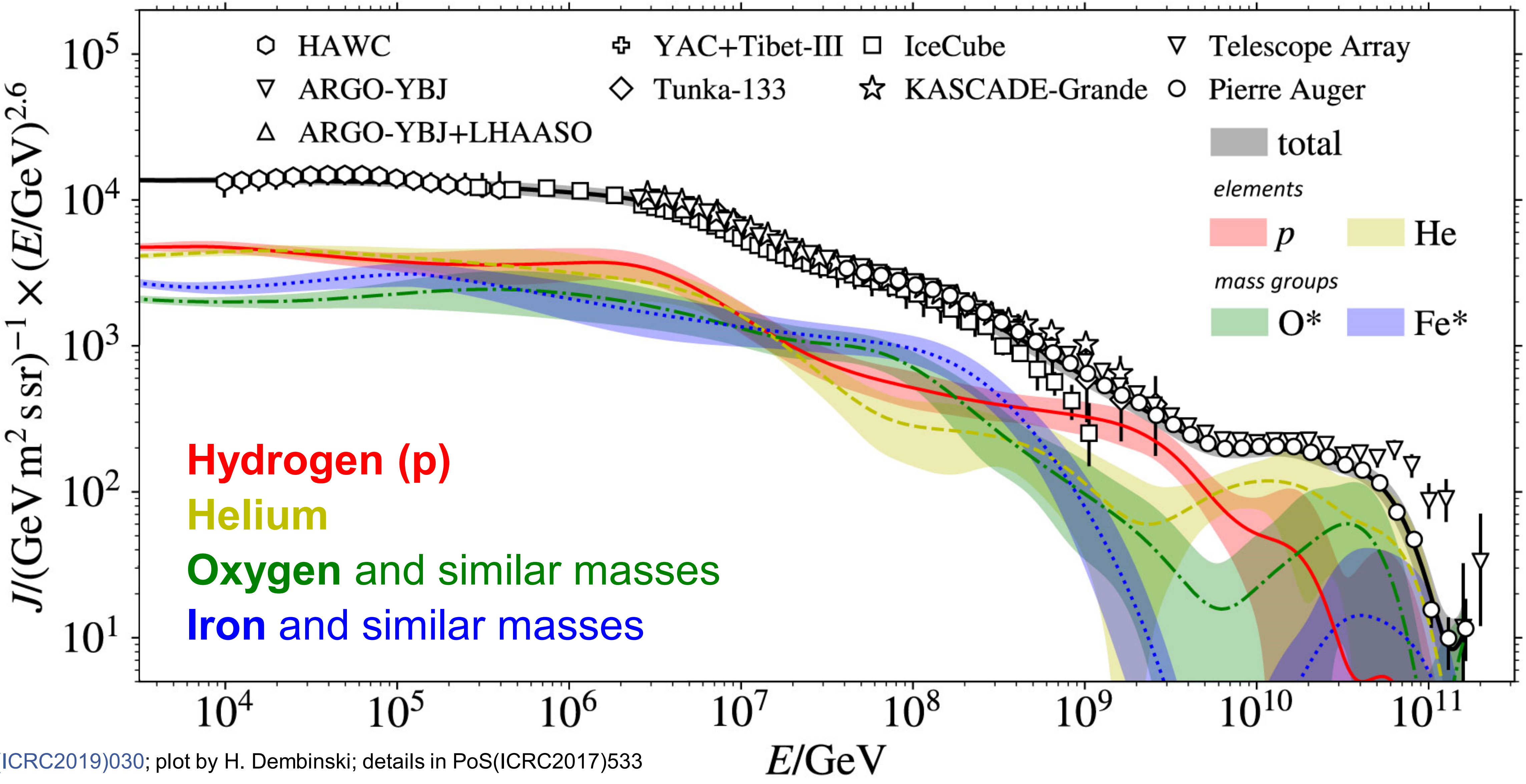
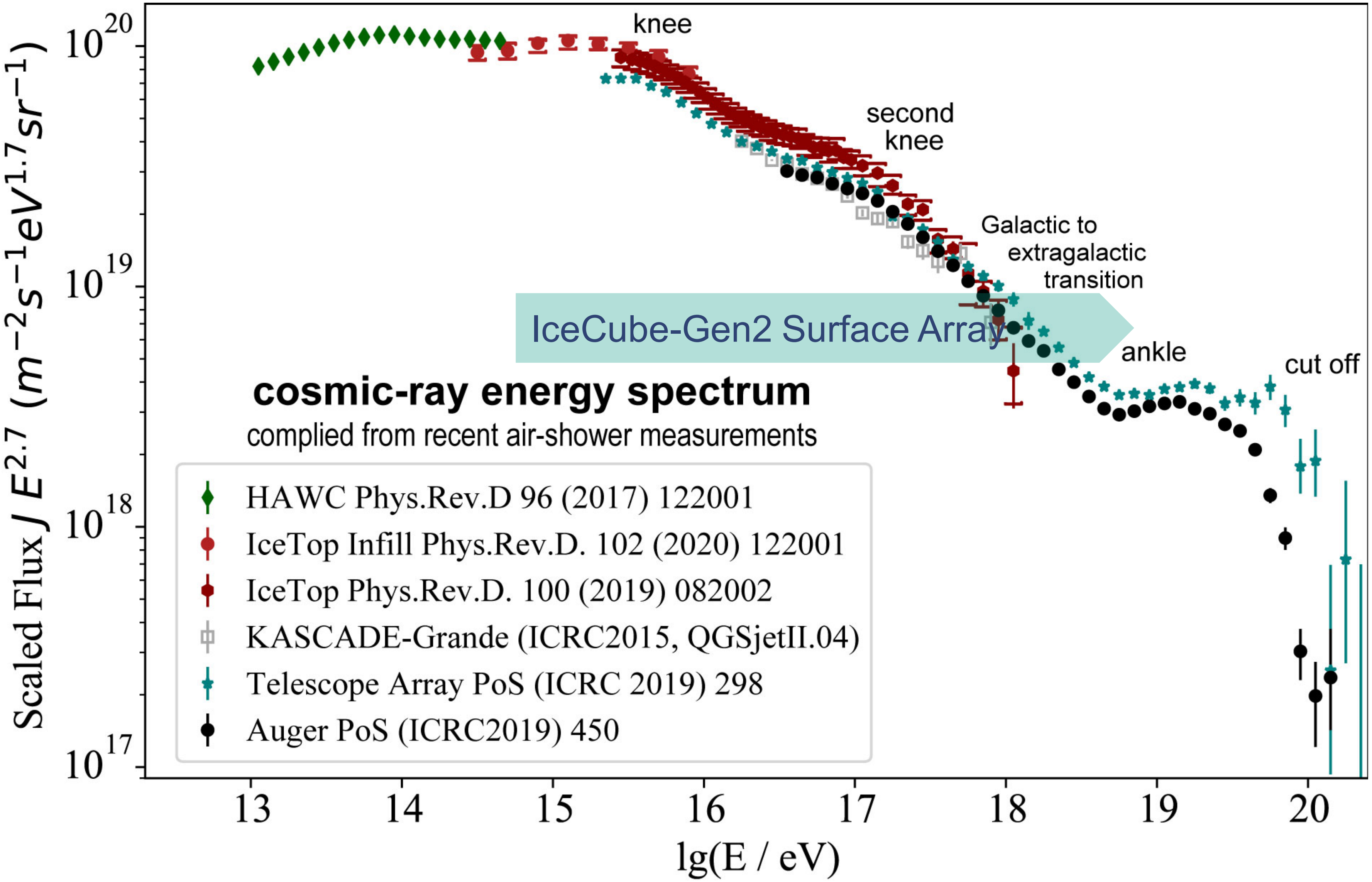
Cosmic-Ray Energy Spectrum and Mass Composition



PoS(ICRC2019)030; plot by H. Dembinski; details in PoS(ICRC2017)533

Energy reach until Ankle: Galactic-to-extragalactic Transition



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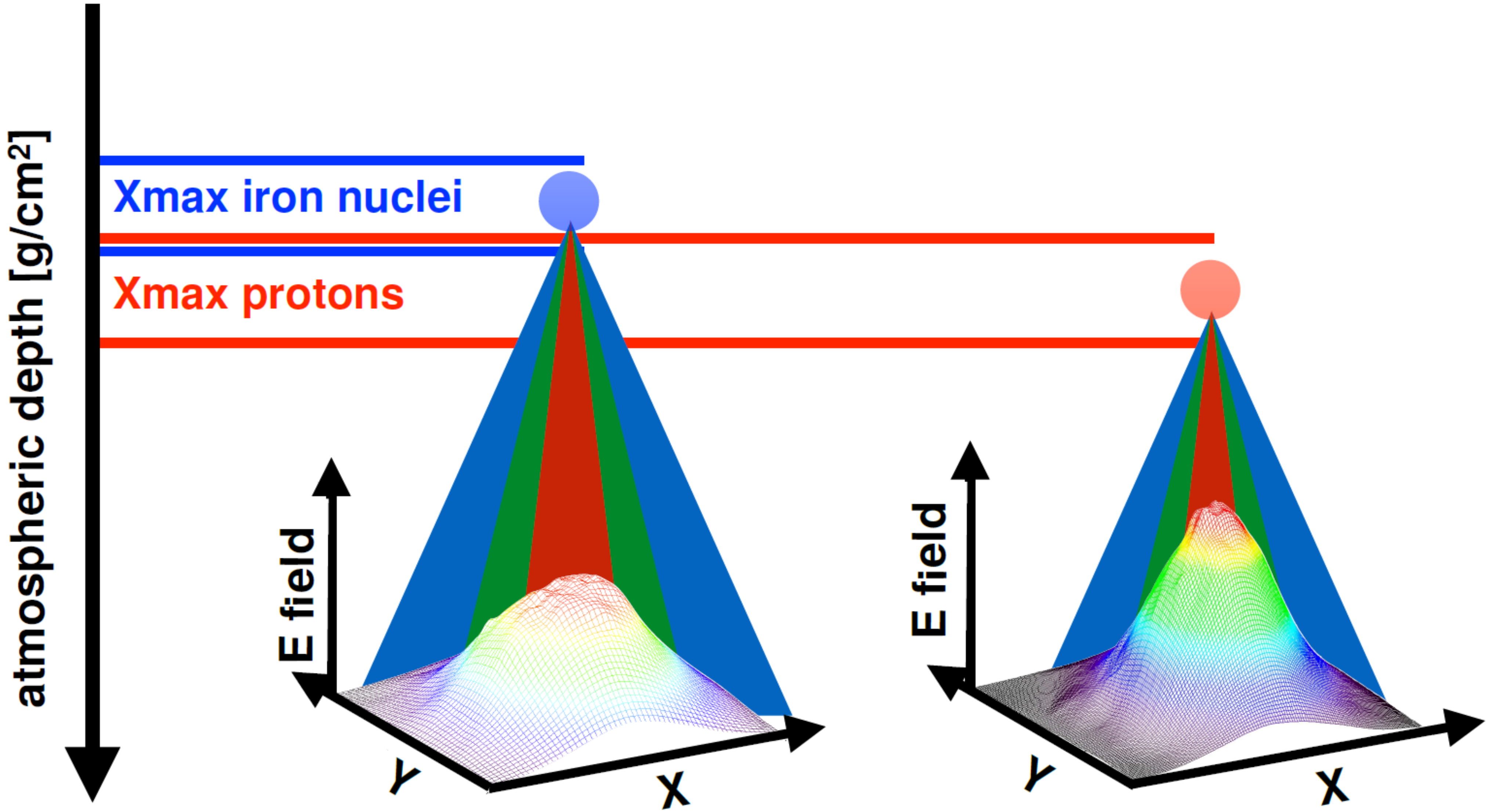
Radio emission beamed in forward cone



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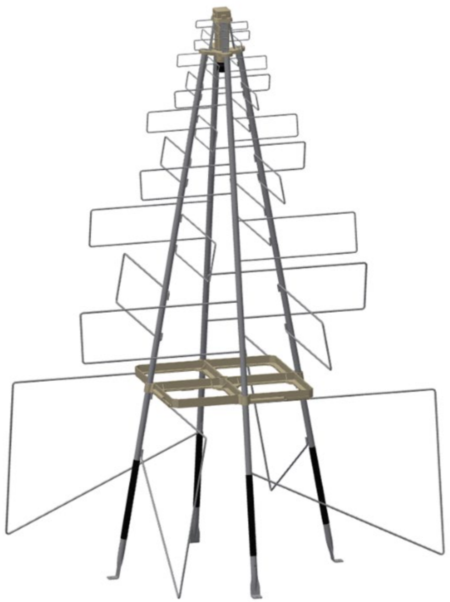
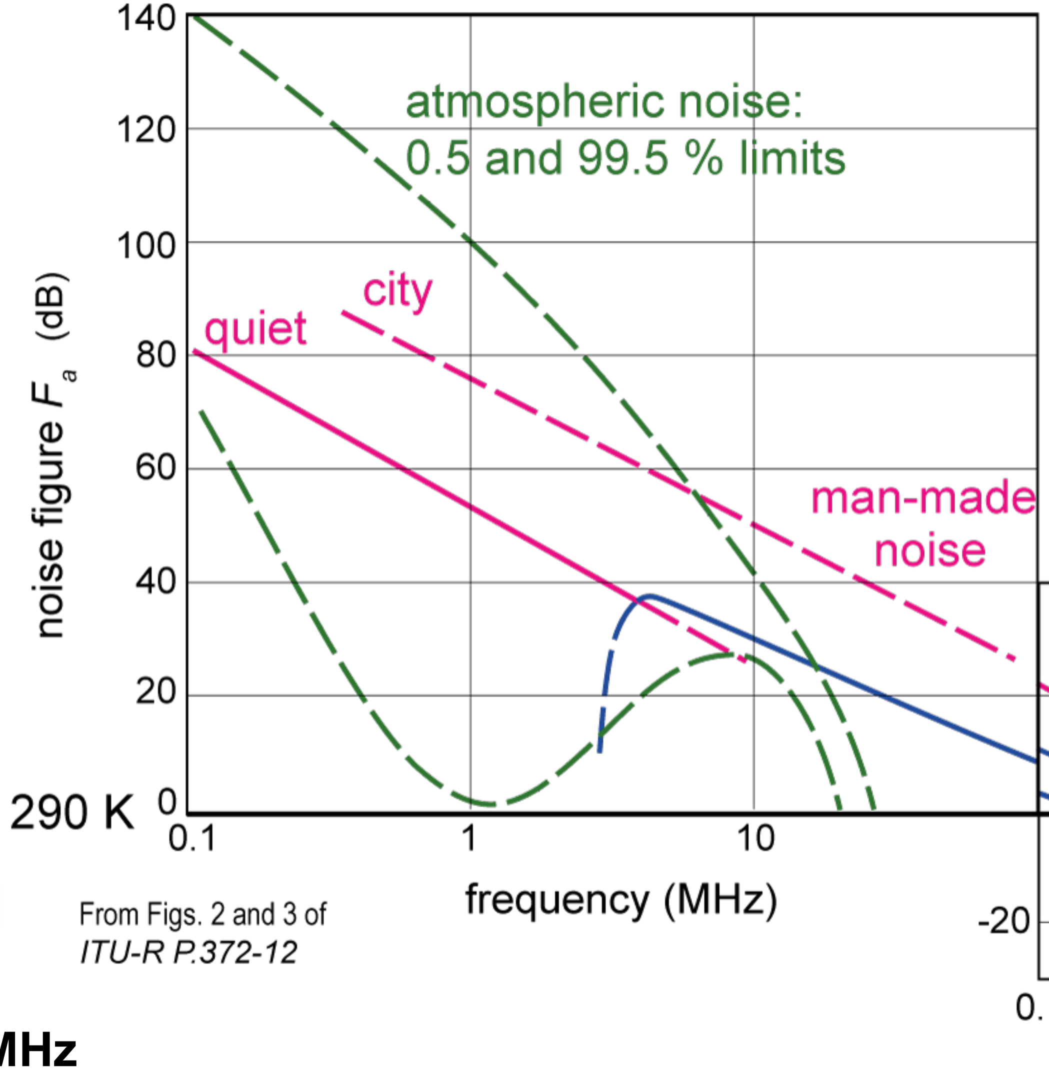
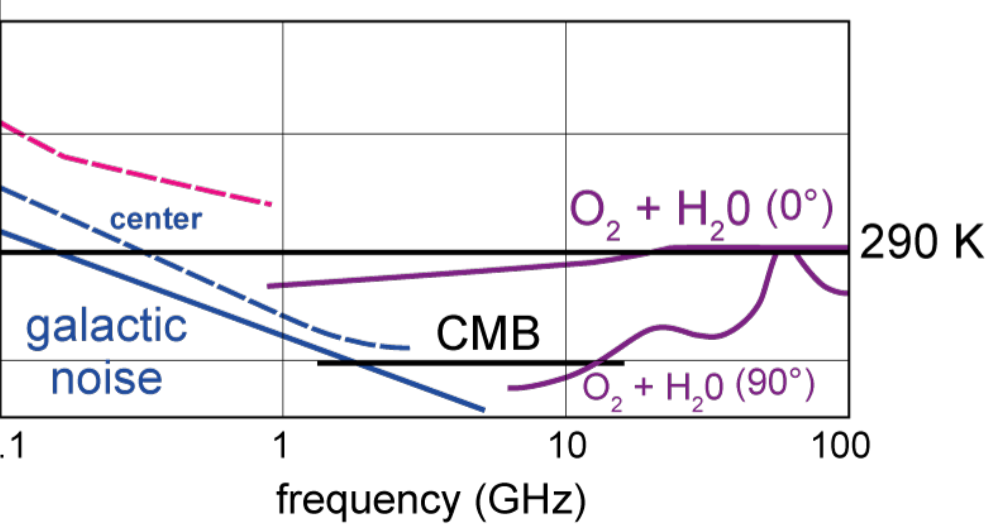
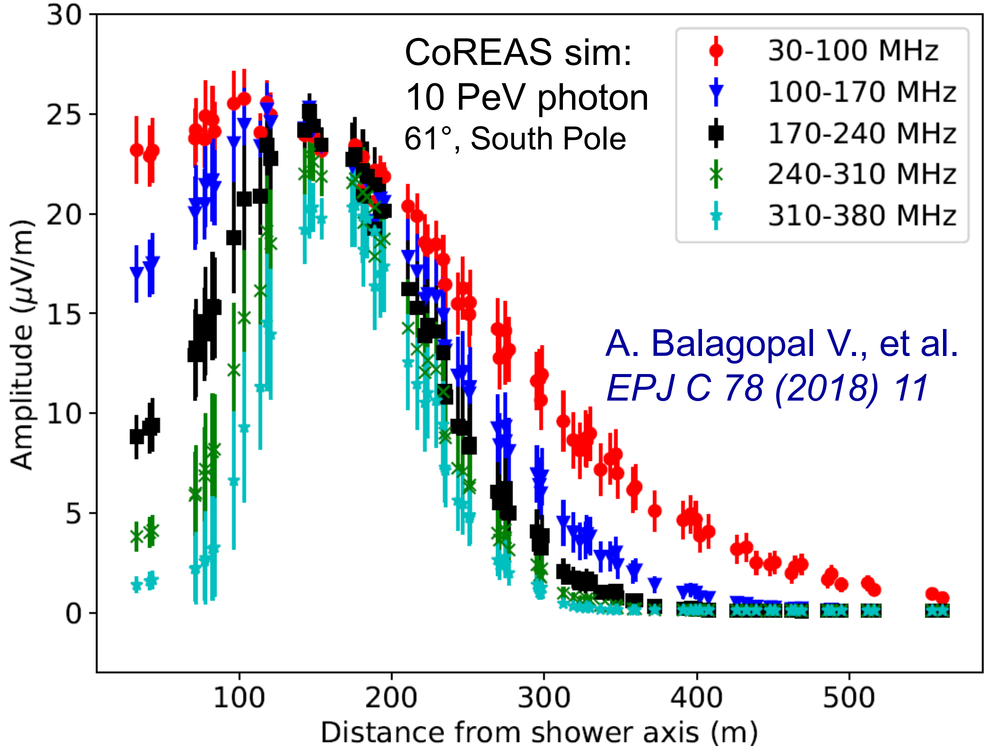
Better signal-to-noise ratio expected at high frequencies



SKALA v2: 70-350 MHz

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



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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)

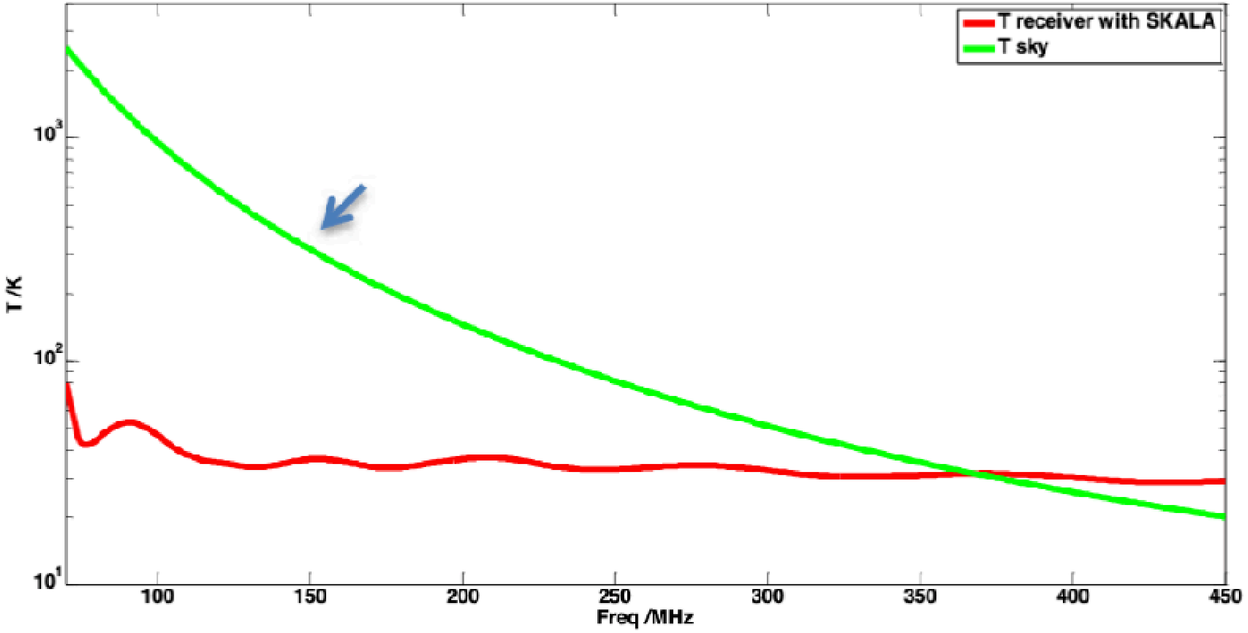
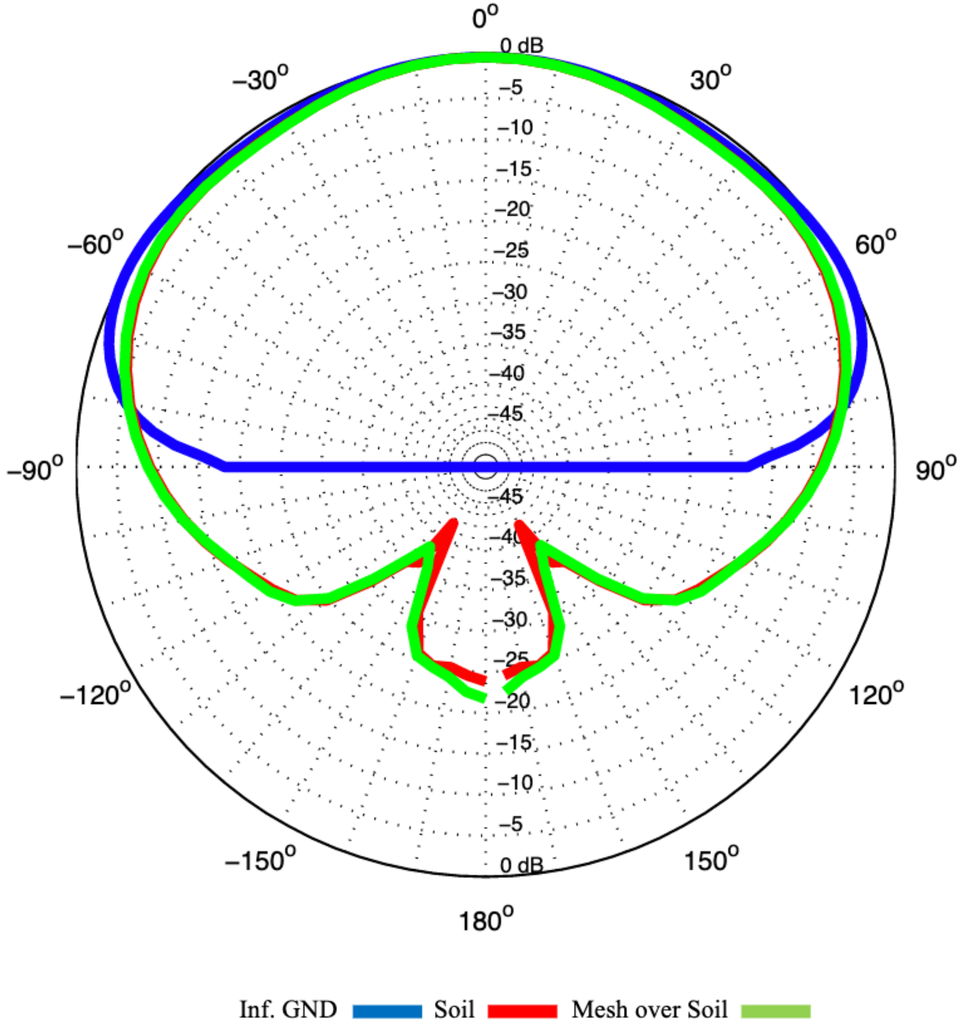


Fig. 9. Receiver noise temperature versus sky noise.

H-plane cut - 150 MHz

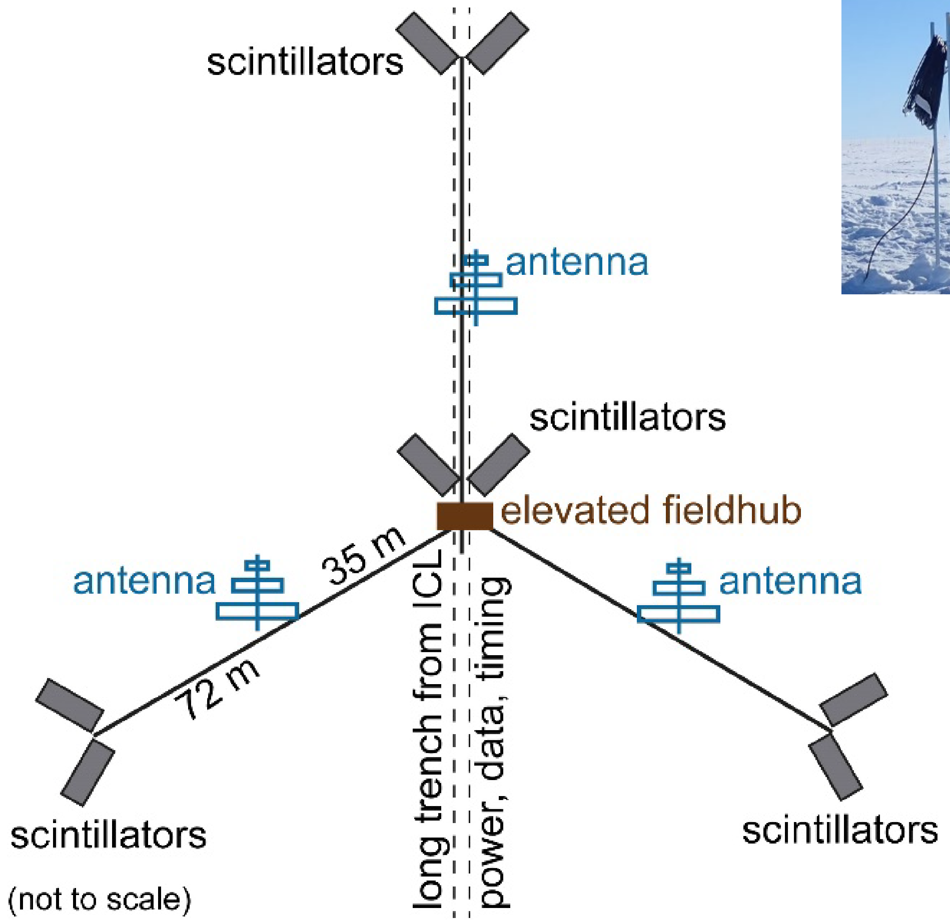


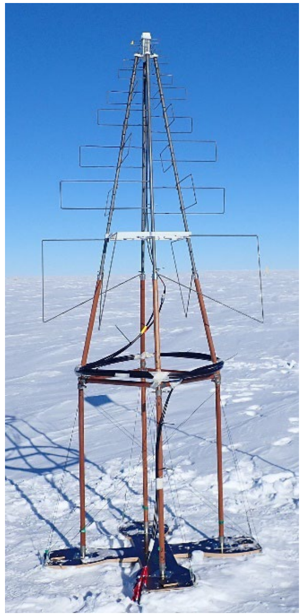
E. de Lera Acedo, N. Drought, B. Wakley and A. Faulkner, "Evolution of SKALA (SKALA-2), the log-periodic array antenna for the SKA-low instrument," *2015 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, 2015, pp. 839-843, doi: 10.1109/ICEAA.2015.7297231.

Baseline Design Follows Planned Enhancement of IceTop

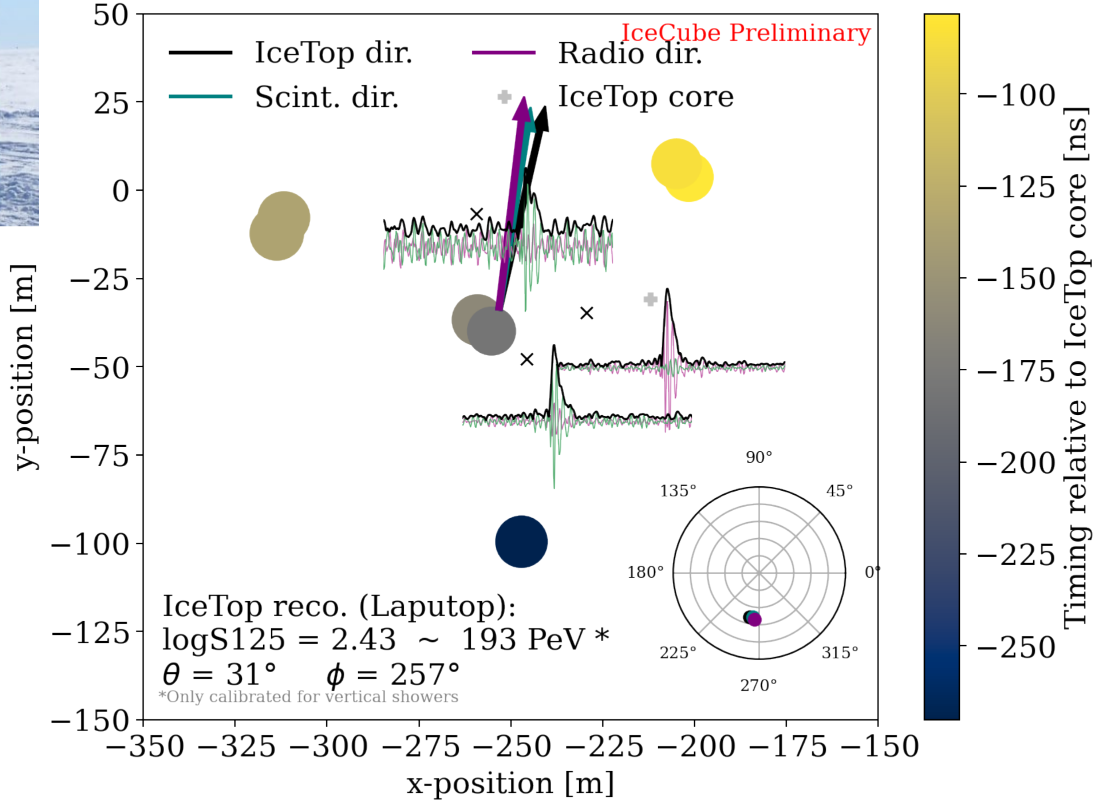
Station Design:

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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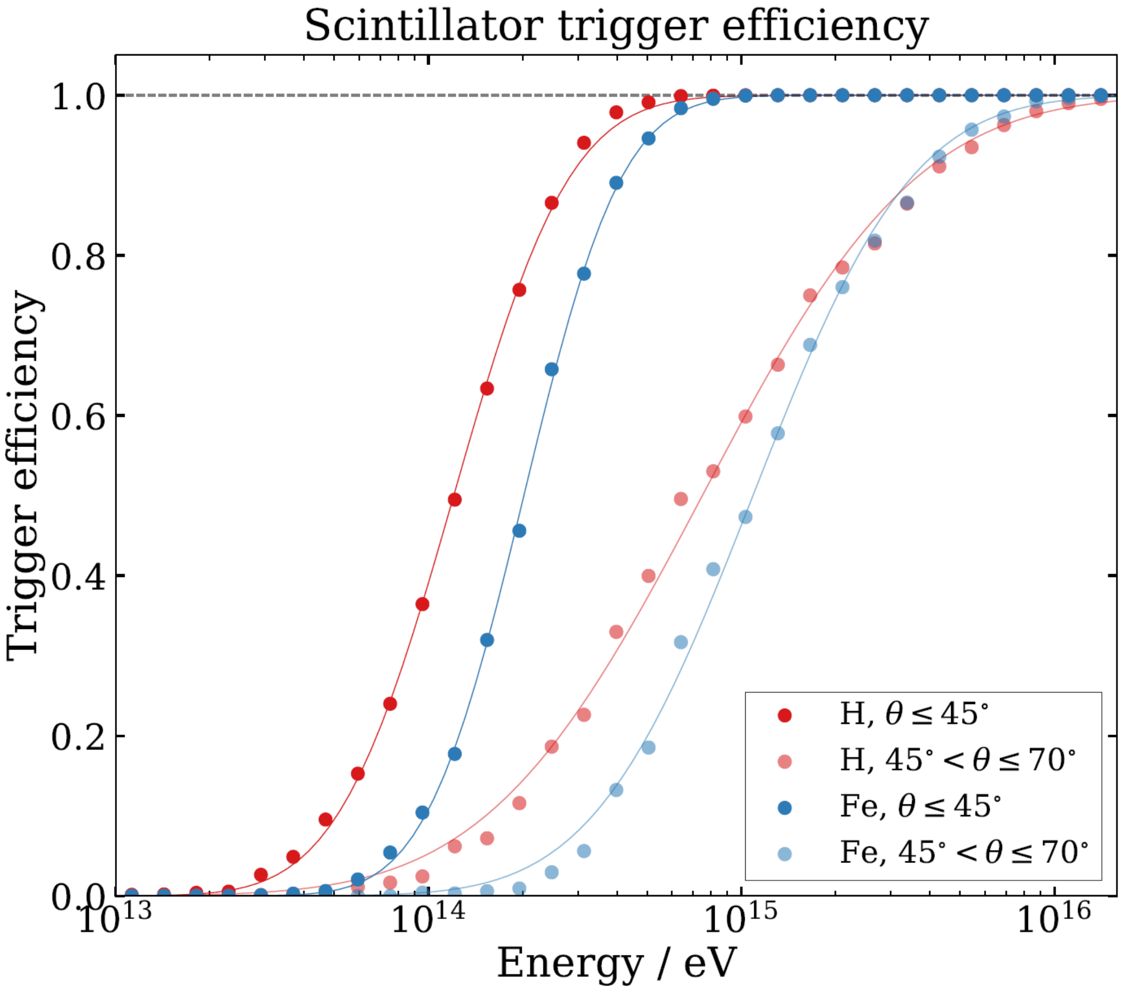
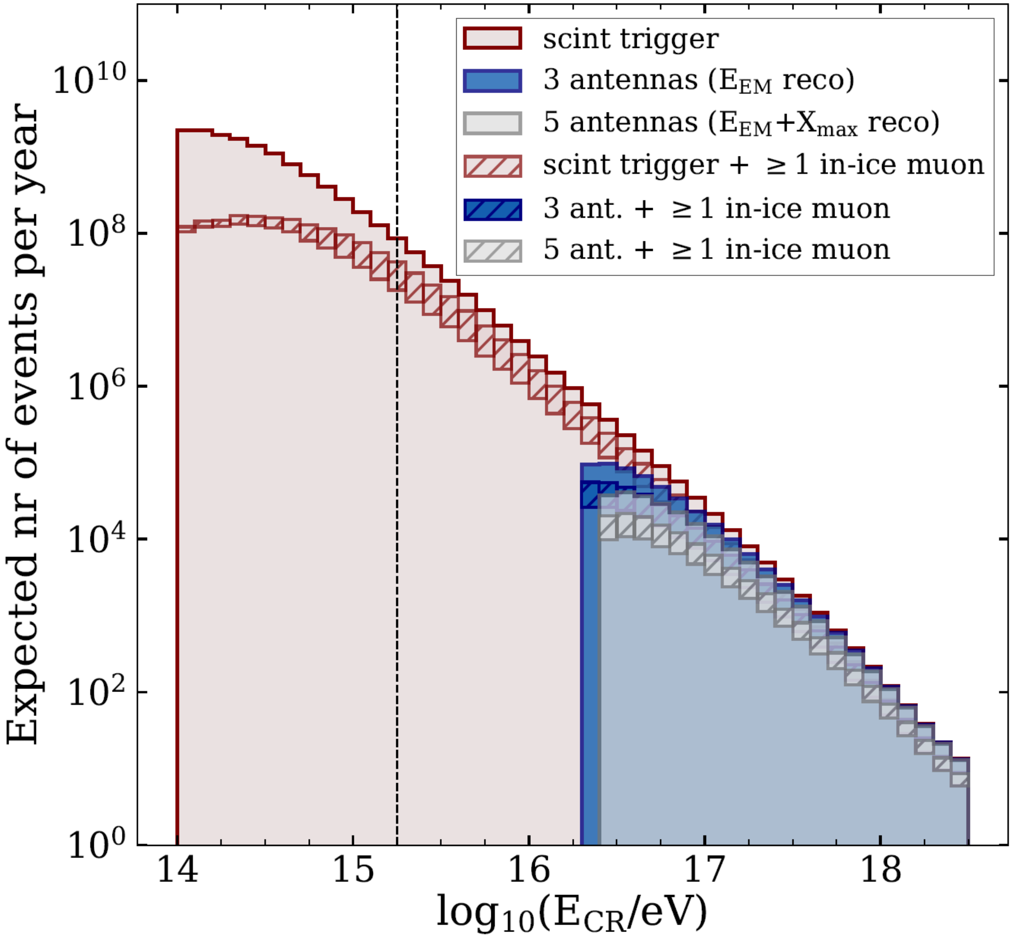
Low Detection Threshold provided by Scintillators

- 0.5 PeV for vertical protons, 10 PeV for inclined showers → trigger for antennas





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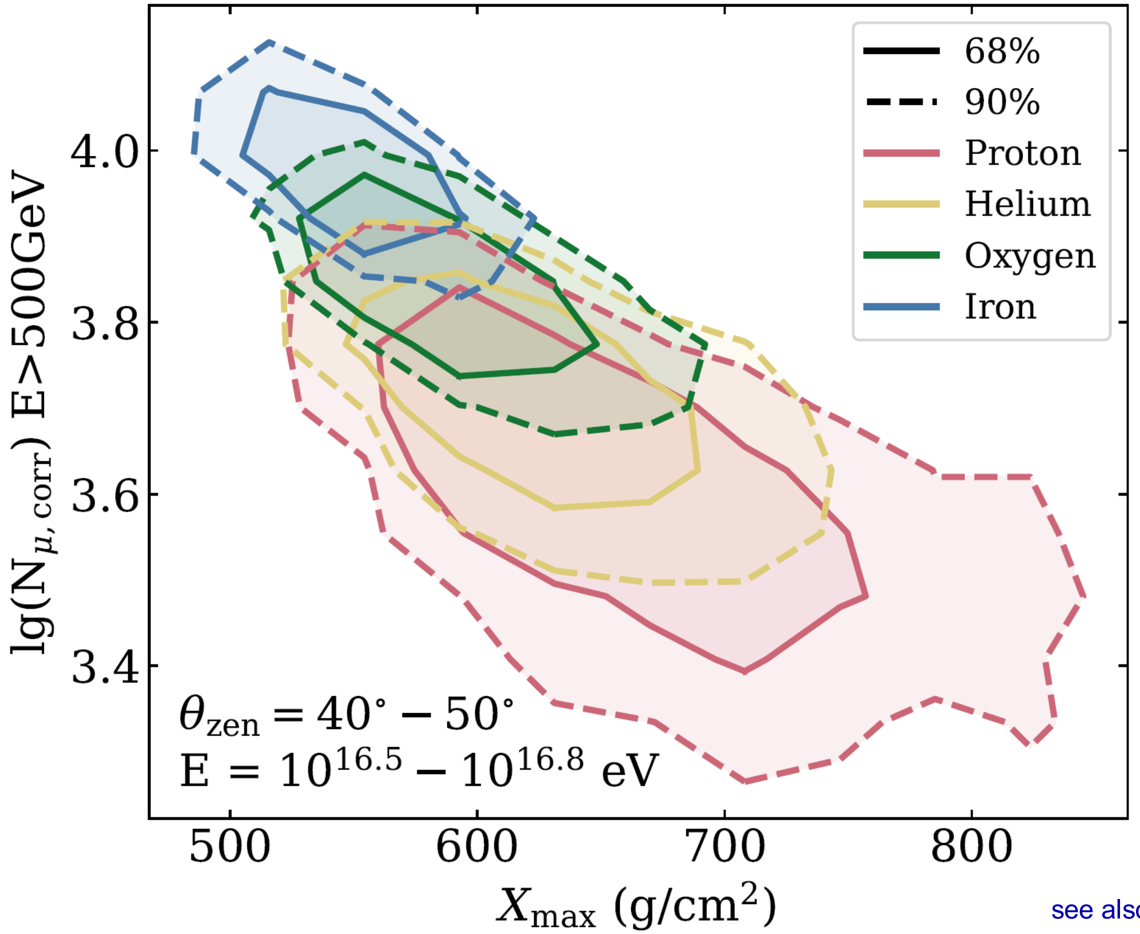
Event-by-Event Mass Sensitivity of Gen2 Surface + Optical Arrays

- In-ice muons have highest separation power, provided a separate energy measurement
- X_{max} gains importance at highest energies and has smaller systematic uncertainties



see also B. Flaggs, A. Coleman, F. Scrhoeder, PRD 109 (2024) 042002

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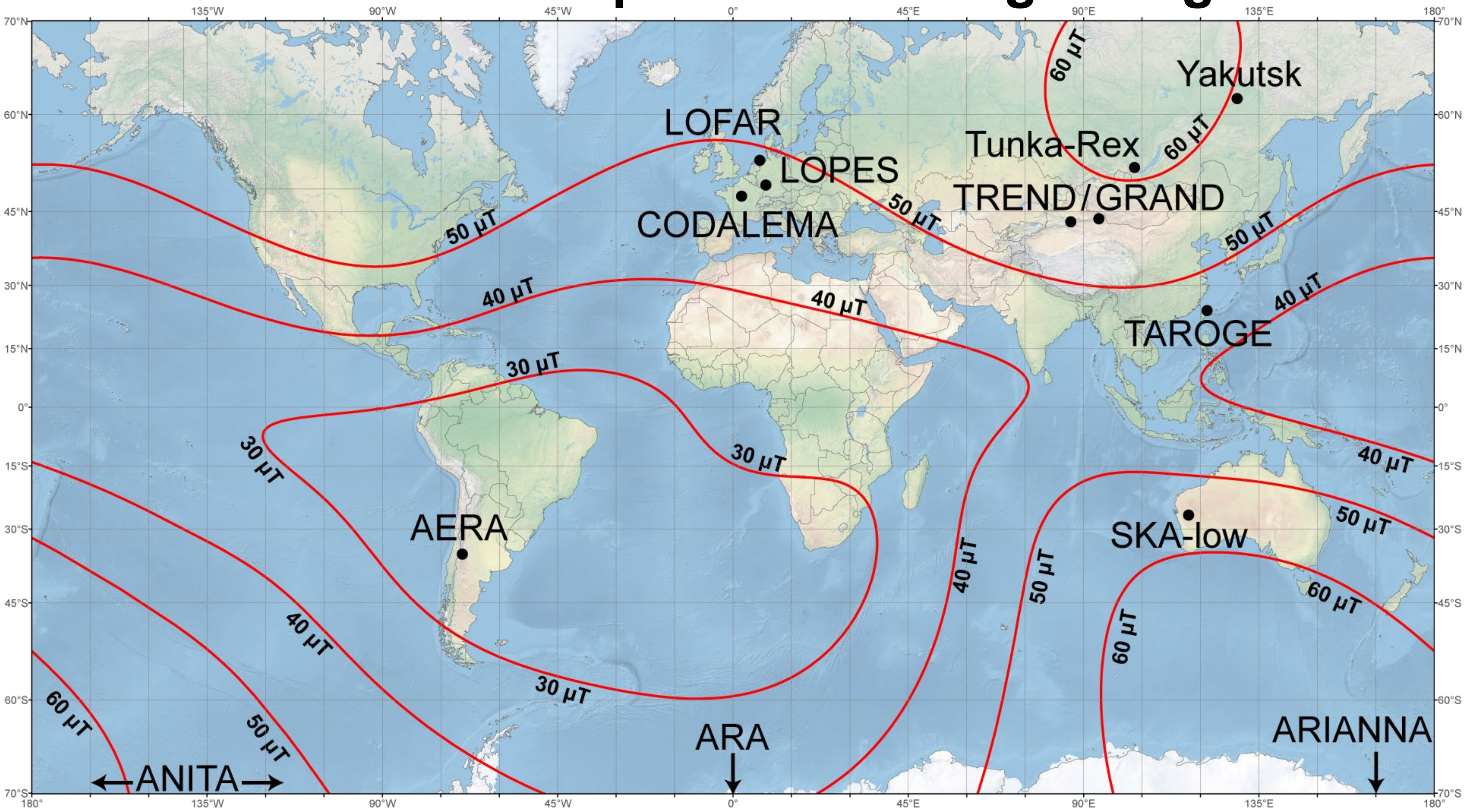
Location of selected experiments and geomagnetic field



Underlying map (Mercator projection):
Main Geomagnetic Field Total Intensity with contour intervals of 10 µT according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIRES http://ngdc.noaa.gov/geomag/WMM

Map reviewed by NGA and BGS Published December 2014

Overlayed: **Location of radio experiments for cosmic-ray air showers** added on underlying map by Frank G. Schröder Karlsruhe Institute of Technology (KIT), Germany

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

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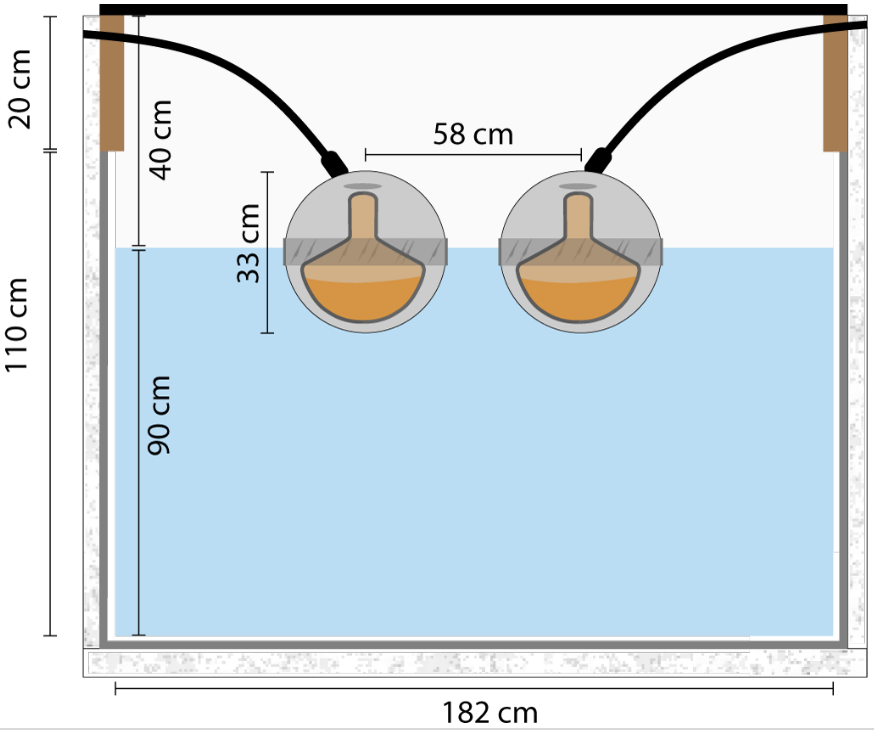
IceCube Neutrino Observatory today: surface + in-ice detector

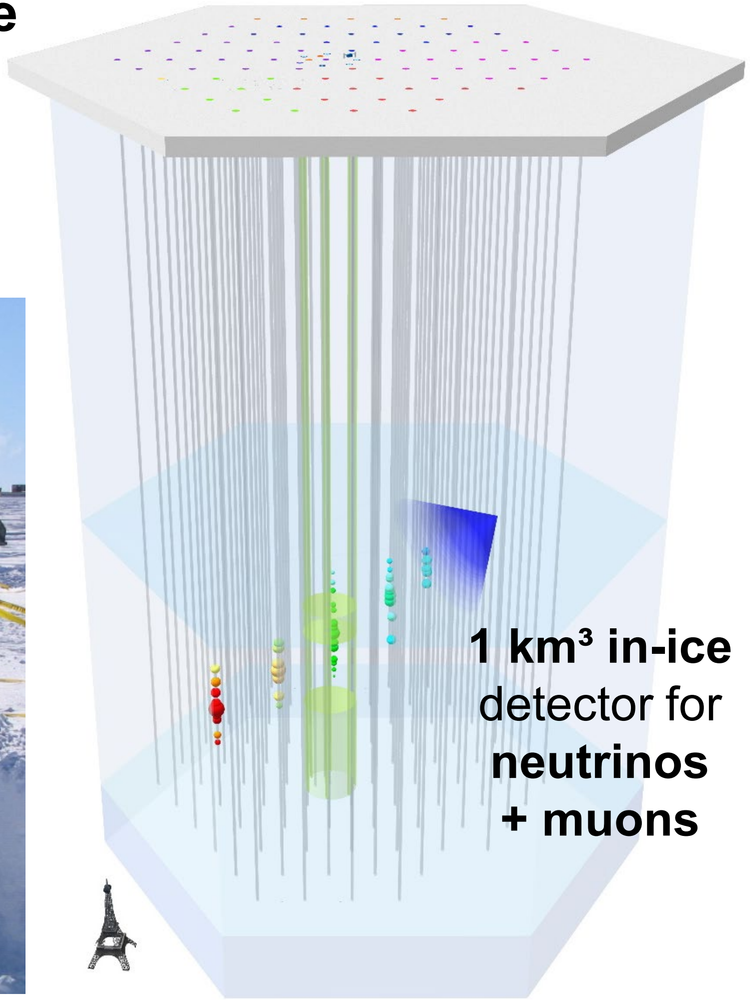
- IceTop = surface array of ice-Cherenkov detectors
  - cosmic-ray physics + veto
- Deep optical array for neutrino detection
  - most in-ice signals are cosmic-ray muons



IceCube Coll., NIM A 700 (2013) 188

IceCube at the South Pole

1 km² surface detector for **air showers**



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

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