A New Dense Array of SKA Radio Antennas at the Pierre Auger Observatory

Benjamin Flaggs
(with results and efforts from many collaborators)

KIT Seminar – July 3, 2025

UNIVERSITY OF DELAWARE
BARTOL RESEARCH INSTITUTE

PIERRE AUGER OBSERVATORY

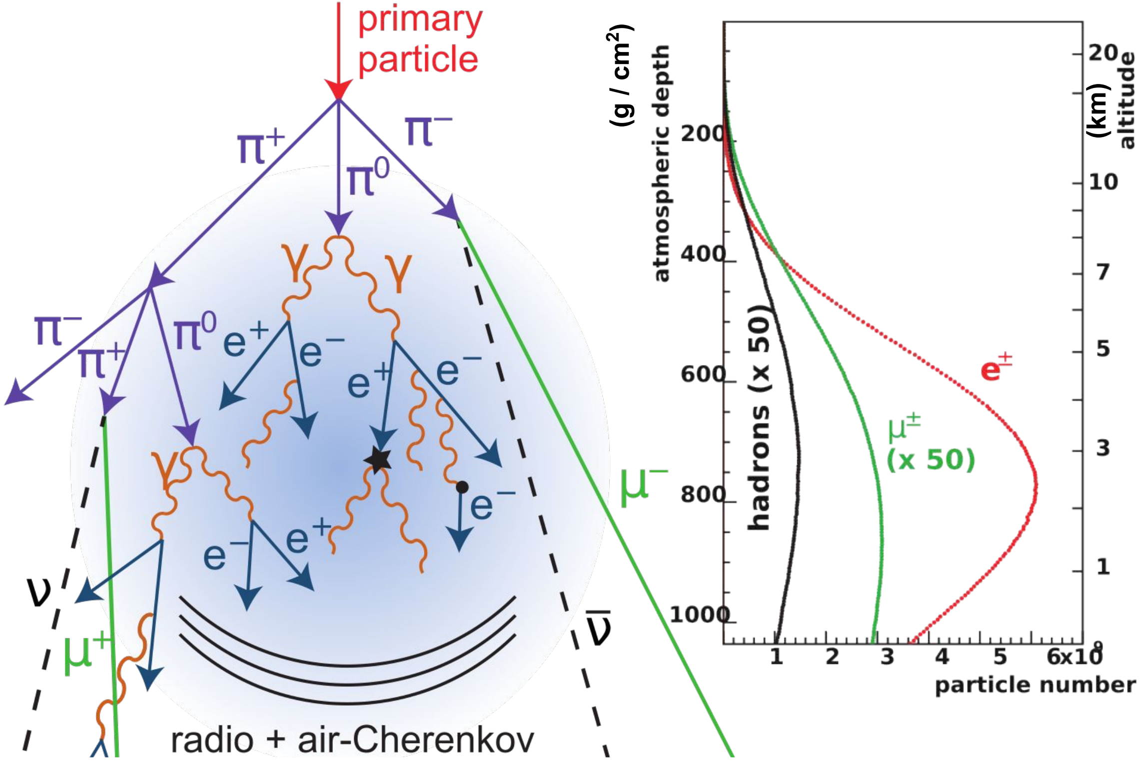
Cosmic-Ray Air Showers

Heitler-Matthews Model:

- ⅓ of CR energy ➡ π^0
- ⅔ of energy ➡ $\pi^\pm$

Hadronic component ($\pi^\pm$) feeds electromagnetic component ($e^{+/-}$, γ)

Shower development continues until the “depth of shower maximum” (X_{max})

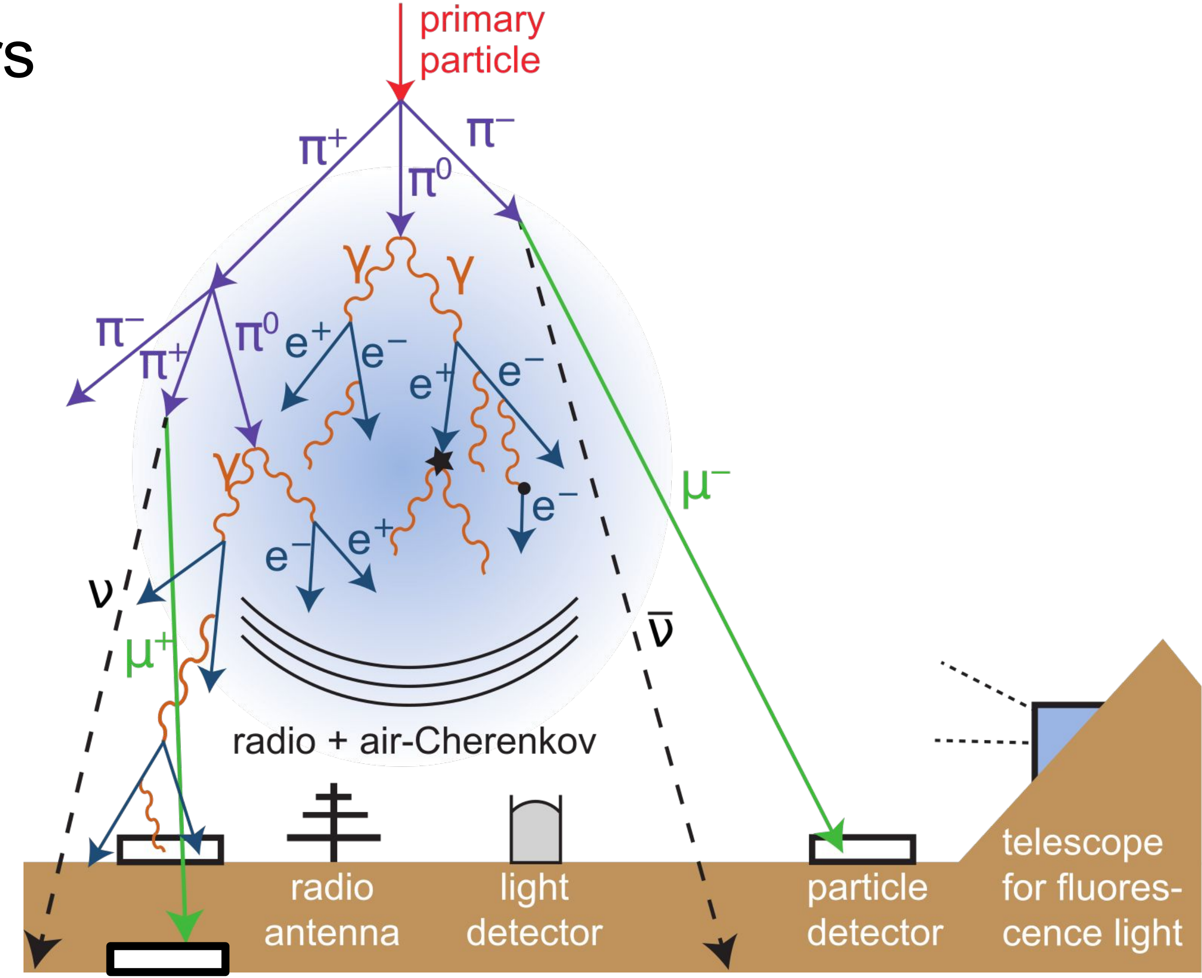


F.G. Schröder, Progress in Particle and Nuclear Physics 93 (2017) 1–68

Detection of Air Showers

Two main ways to detect air showers:

1. Particle detection
   a. Directly measure all shower particles at surface (water-Cherenkov detectors, scintillators)
   b. Measure penetrating muons (underground detectors)
2. Electromagnetic radiation
   a. Air-Cherenkov light
   b. Fluorescence light
   c. Radio emission



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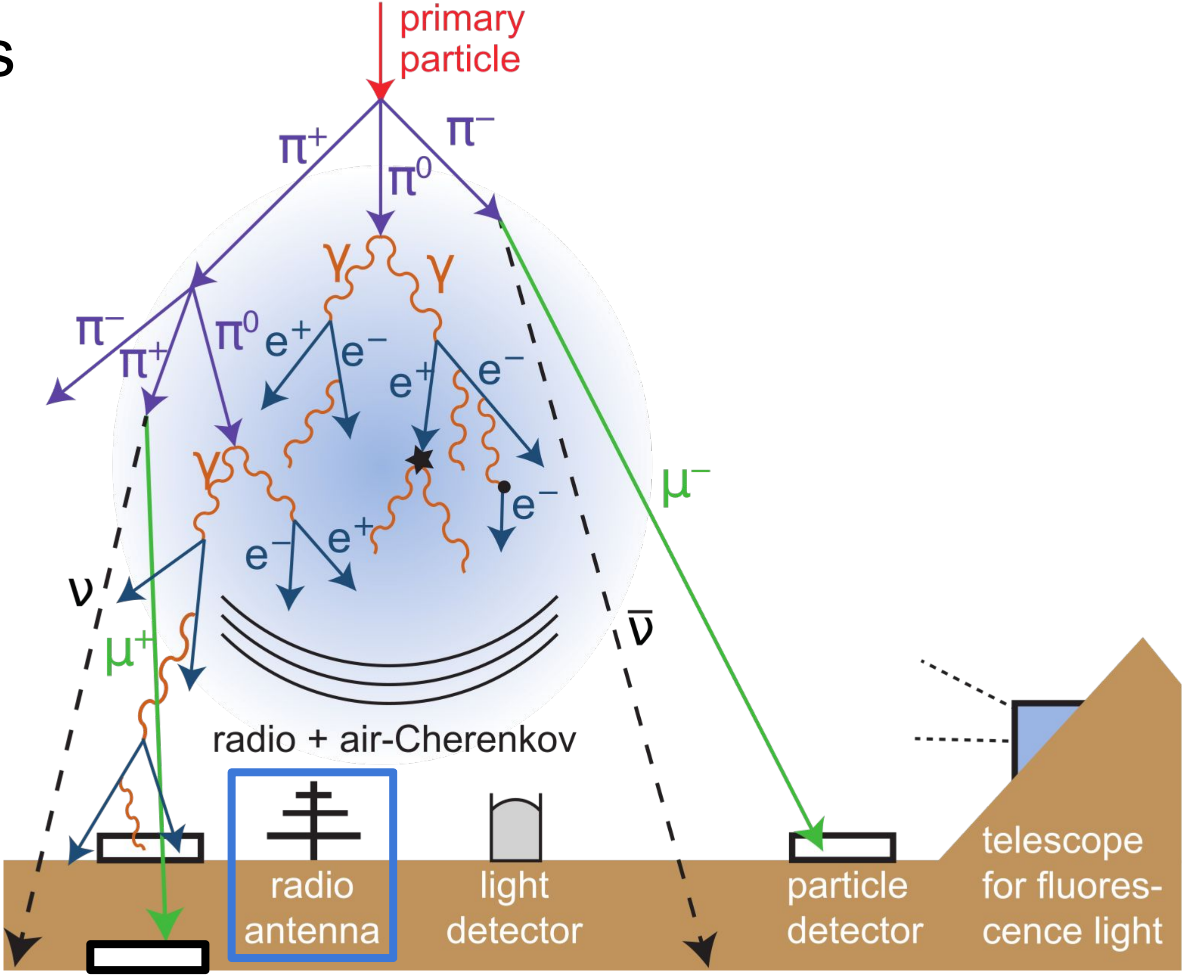


F.G. Schröder, Progress in Particle and Nuclear Physics 93 (2017) 1–68

Radio Emission from Air Showers

Time-varying charges generate EM emission

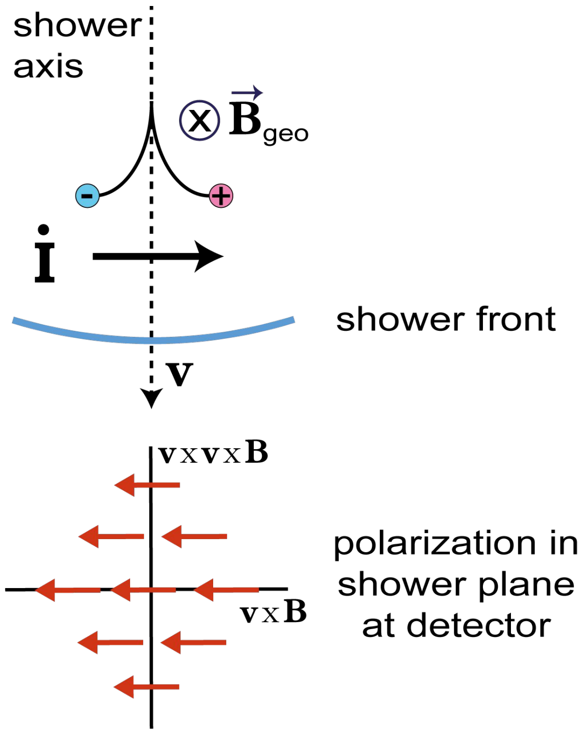
Radio Emission from Air Showers

Time-varying charges generate EM emission

Geomagnetic

Lorentz force deflection of e^+/e^-

$F = q\ (v \times B) = ma$



Geomagnetic emission

F.G. Schröder, Progress in Particle and Nuclear Physics 93 (2017) 1–68

Radio Emission from Air Showers

Time-varying charges generate EM emission

Geomagnetic

Lorentz force deflection of e^+/e^-

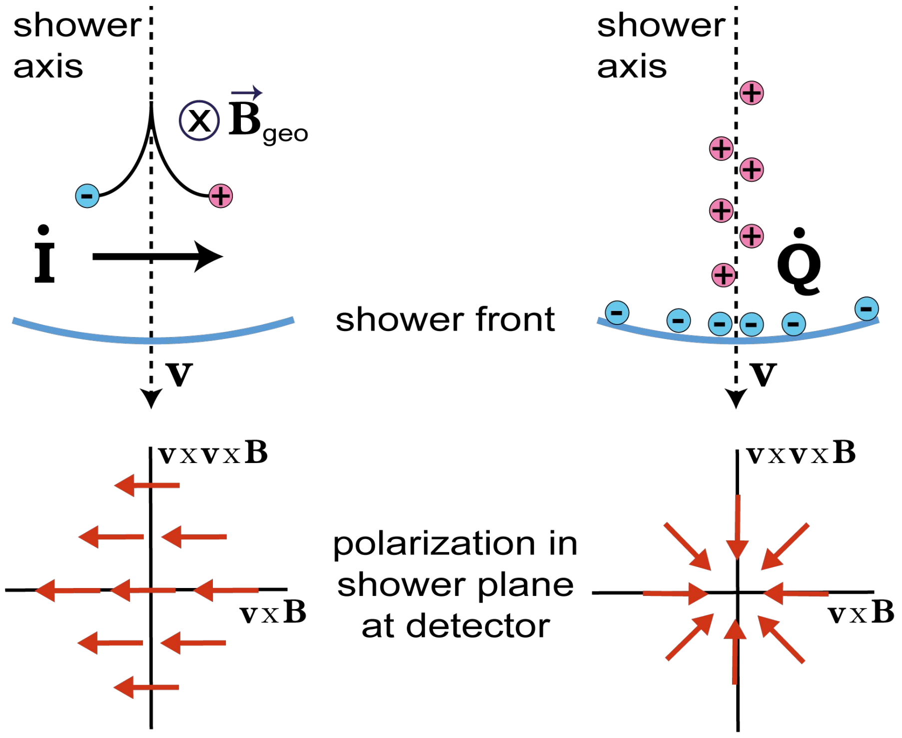
$F = q\ (v \times B) = ma$

Askaryan

Time-varying excess of e^- in shower front

e^+ annihilation with shell e^-

Ionization of air (excess e^-)



Geomagnetic emission

Askaryan emission

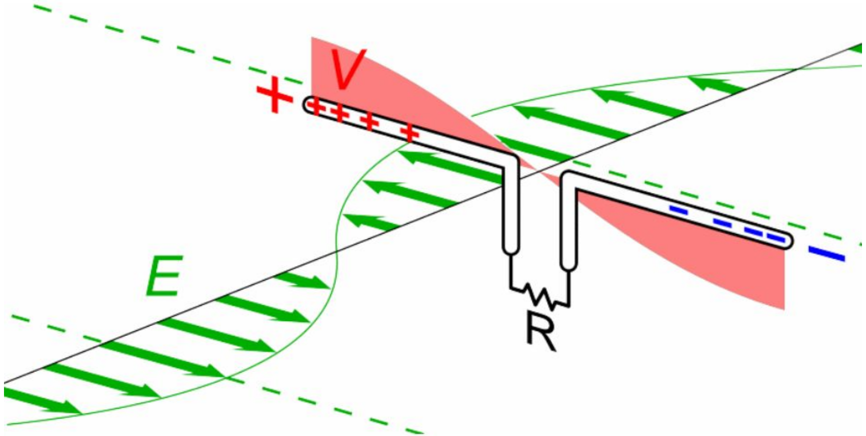
F.G. Schröder, Progress in Particle and Nuclear Physics 93 (2017) 1–68

Radio Emission to Antenna Signal

Oscillating E field from radio waves exerts force on free electrons at antenna surface

Induces oscillating voltage on antenna arm

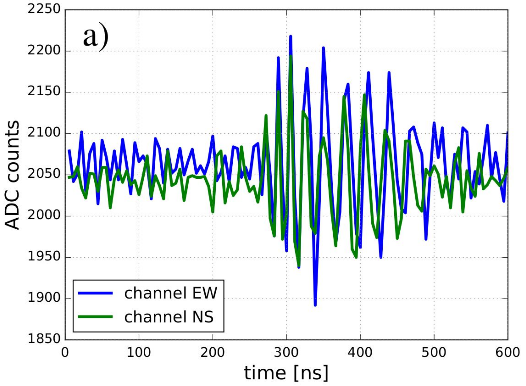
Signal on order of microvolts to millivolts, must be amplified (makes self triggering radio difficult)



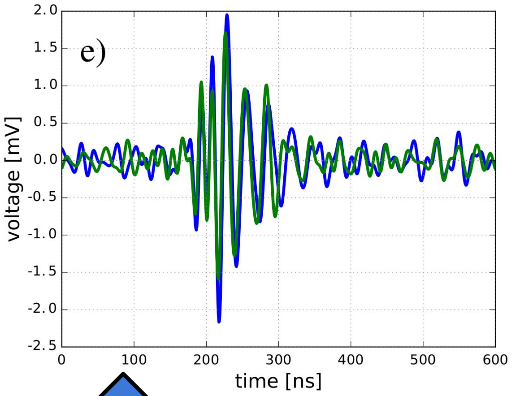
B. Pont, Auger Early Career Masterclass 2024.

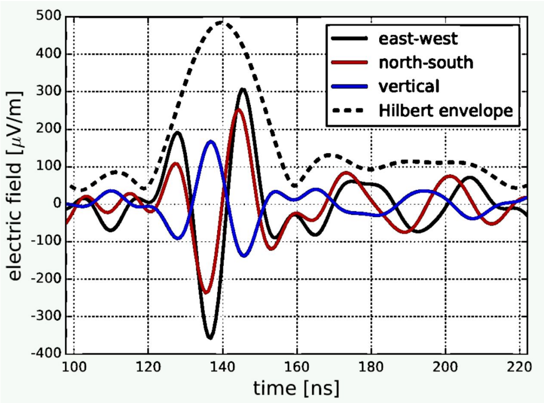
Raw Signal Towards an Energy Fluence

1. Raw signal amplified by low noise amplifier (LNA)



2. Digitizer converts signal to voltage





3. Unfold the antenna response → transforms voltage to E field

C. Glaser, PhD Thesis.

The Radio Footprint

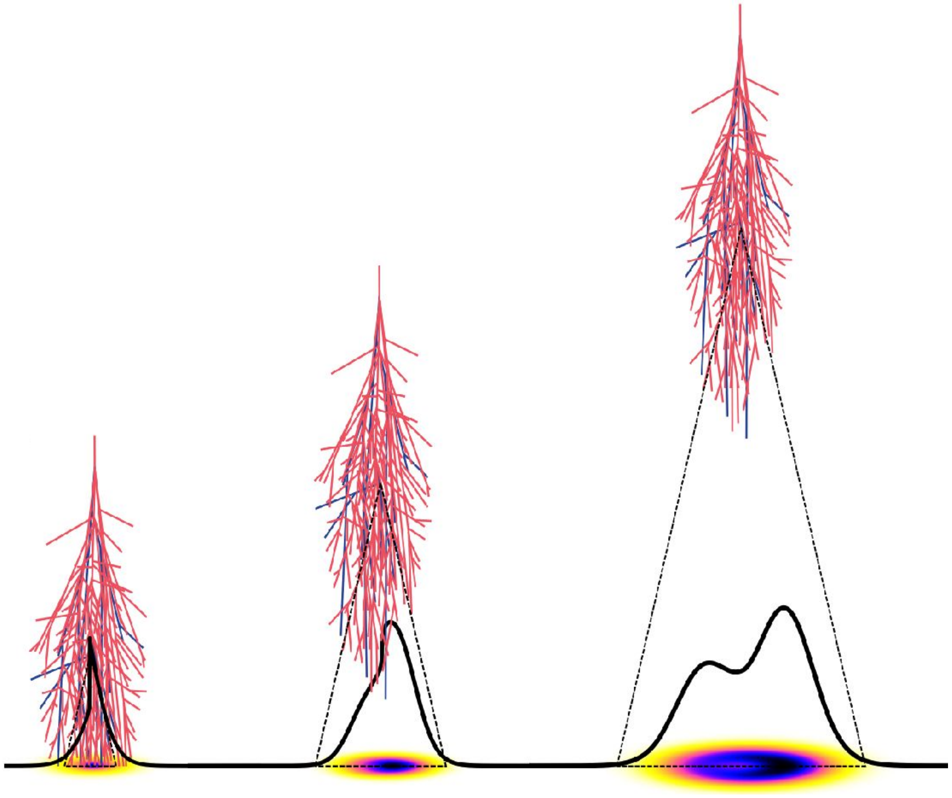
Energy fluence (radio) footprint from LDF fit

- Direction
- Primary mass
- Energy

Shower Maximum closer to ground means smaller footprint and steeper LDF

Spatial integral of fluence footprint yields total radiation energy

$$E_{rad} \propto E_{CR}^2$$

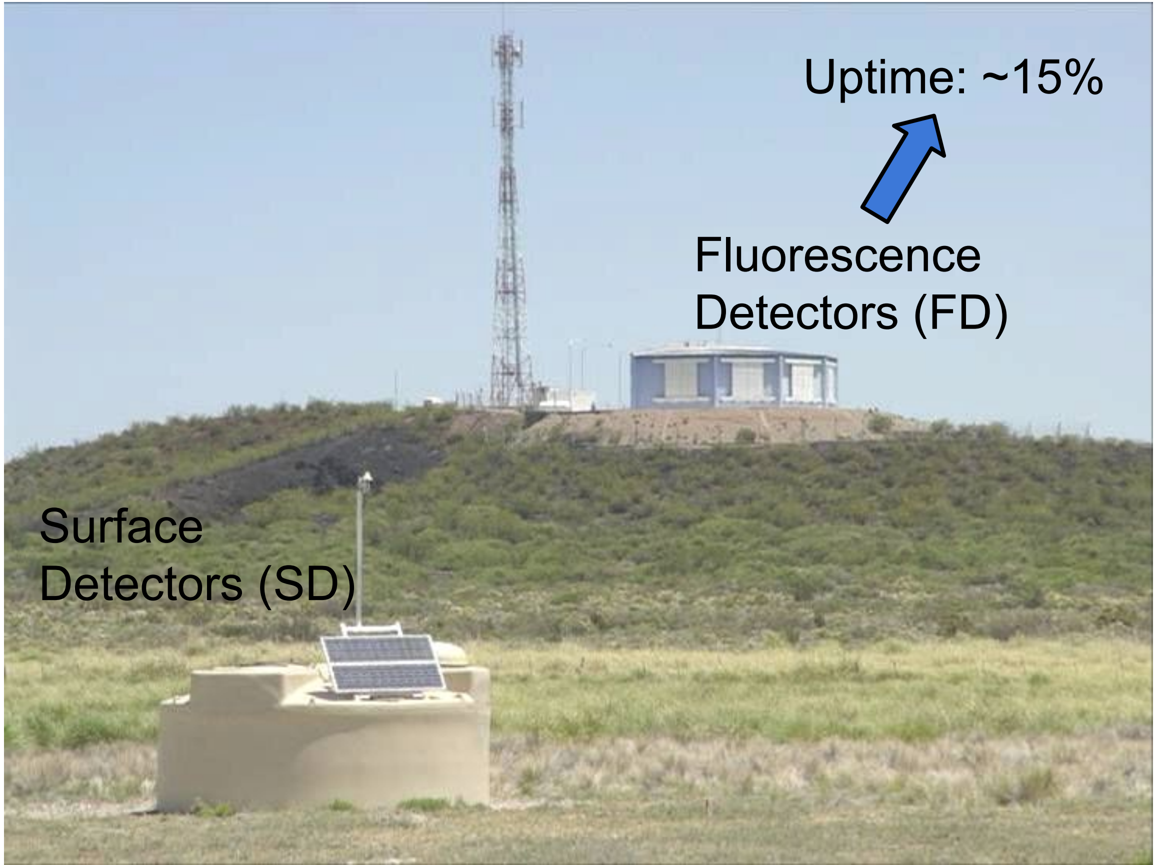


C. Glaser et al. Astroparticle Physics 104 (2019) 64–77

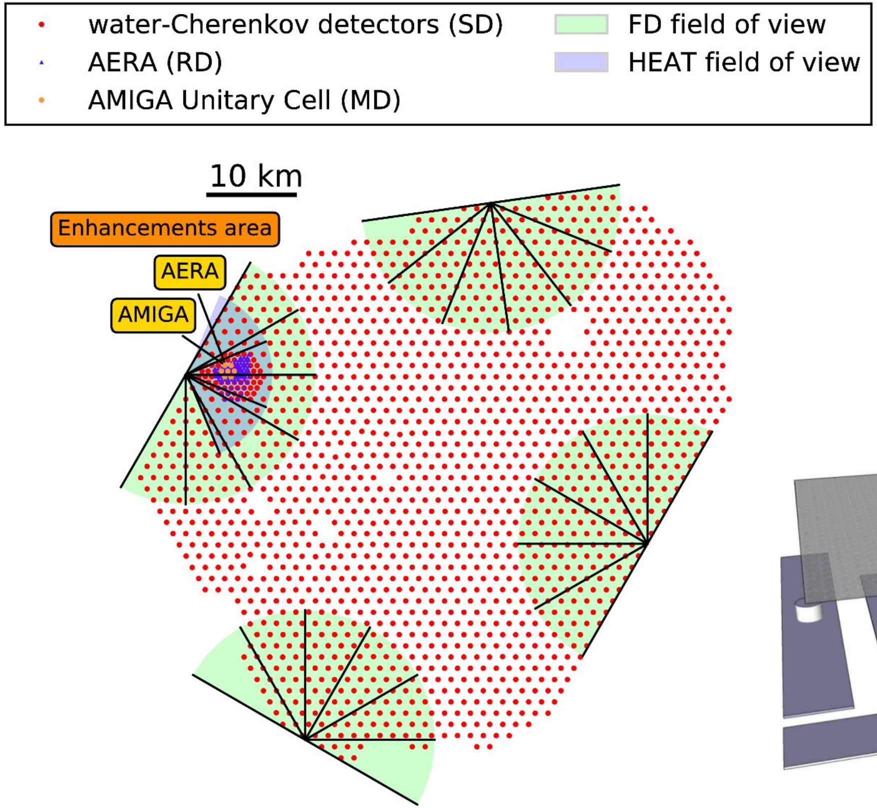
Pierre Auger Observatory

World's largest cosmic-ray observatory, 3000 km^2 in size

Hybrid observations of air showers!



Enhancements to the Pierre Auger Observatory

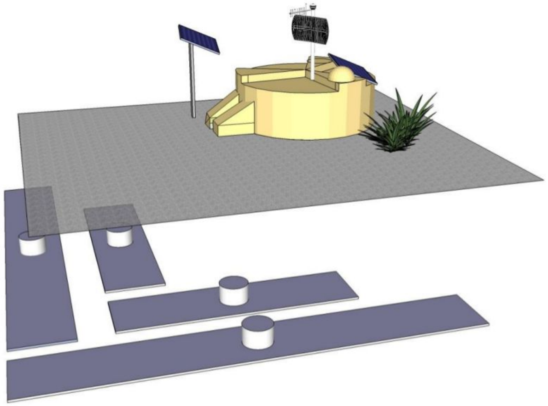


Auger Muons and Infill for the Ground Array (AMIGA)

- Denser detector spacing → lowers energy threshold (~ 10^{17} eV)
- Underground muon detectors

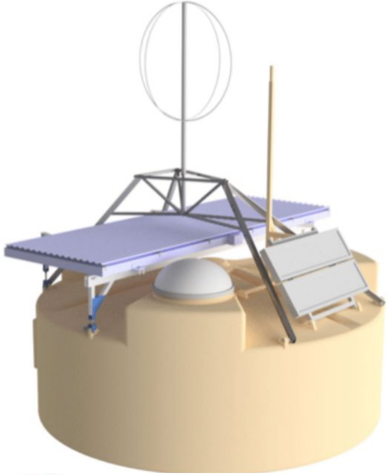
Auger Engineering Radio Array (AERA)

- 153 radio stations over 17 km^2



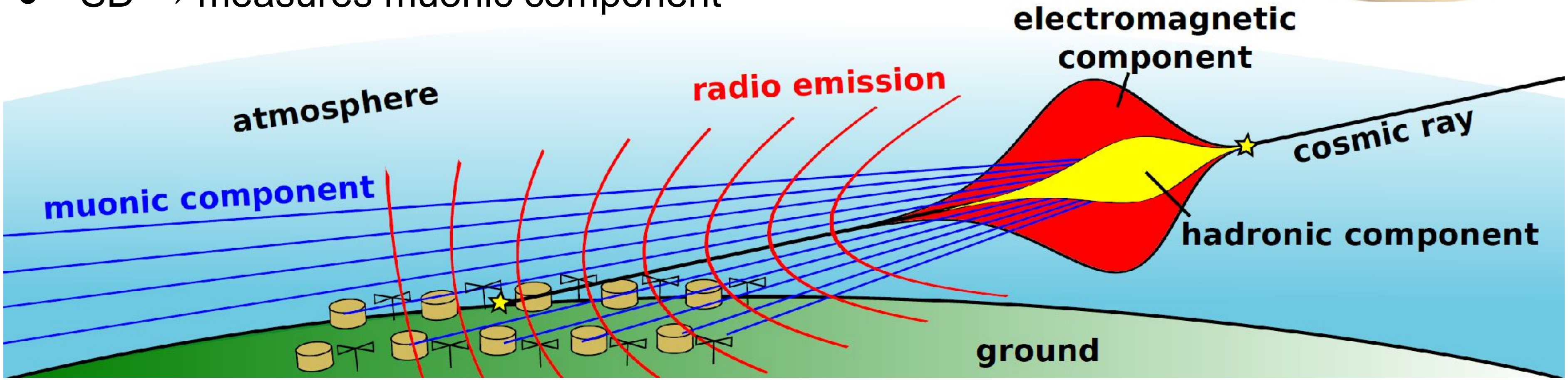
AugerPrime: Upgrade of the Pierre Auger Observatory

- Adding scintillators + radio antennas to each surface detector
- Upgraded electronics



Inclined shower mass composition ($\theta > 65°$)

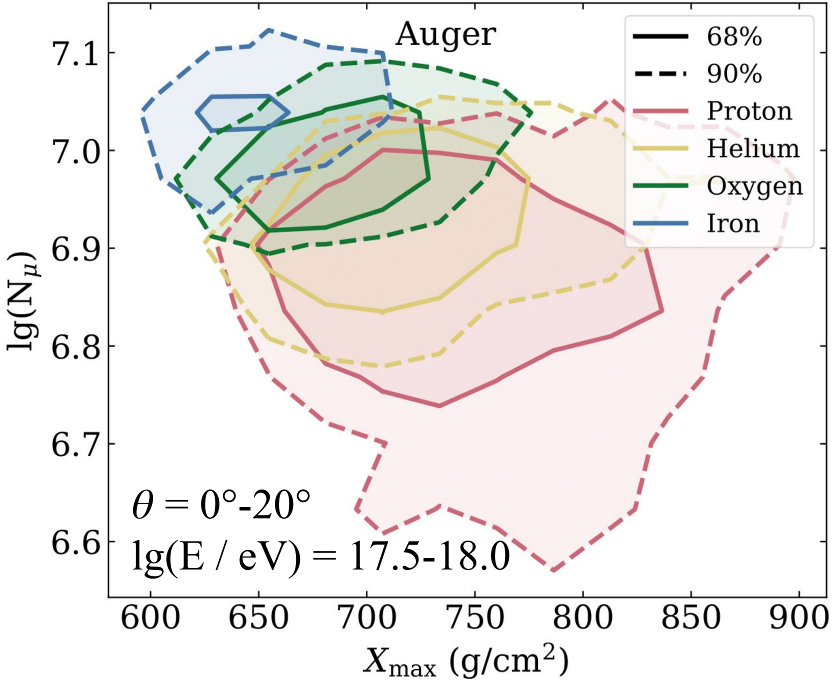
- Radio → probes EM component
- SD → measures muonic component

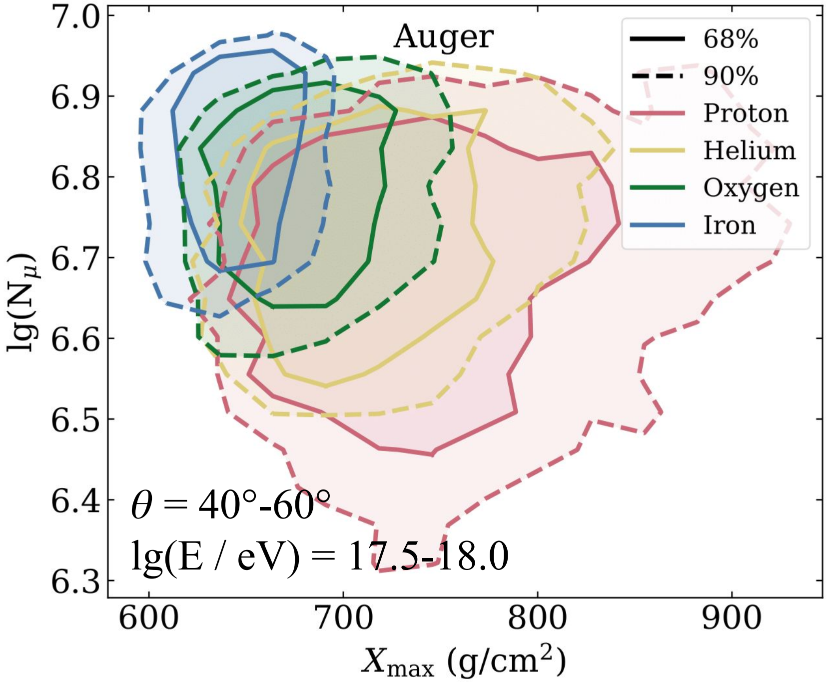


Separately Probing EM and Muonic Components

Best prospects for mass separation

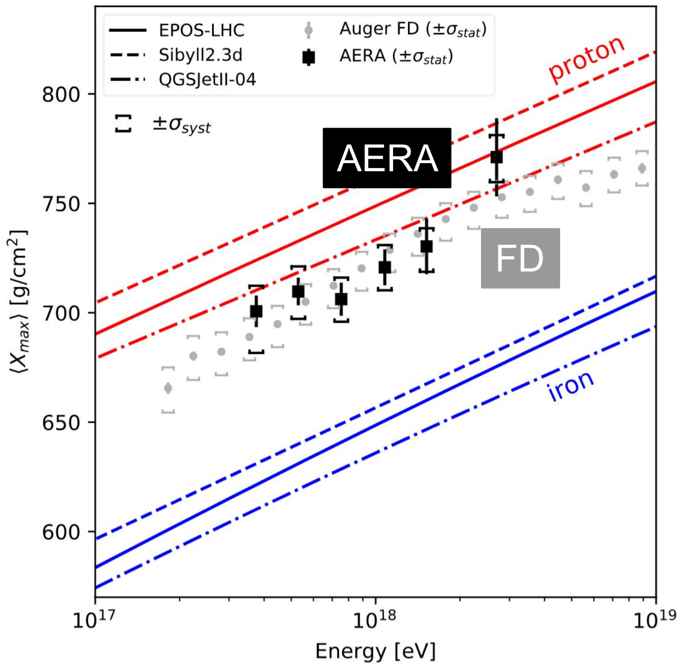
Holds across all zenith angles, better for vertical showers





B. Flaggs et. al, Phys. Rev. D 109, 042002 (2024)

AERA Results – Xmax



Pierre Auger Collaboration, Phys. Rev. D 109, 022002 (2024)

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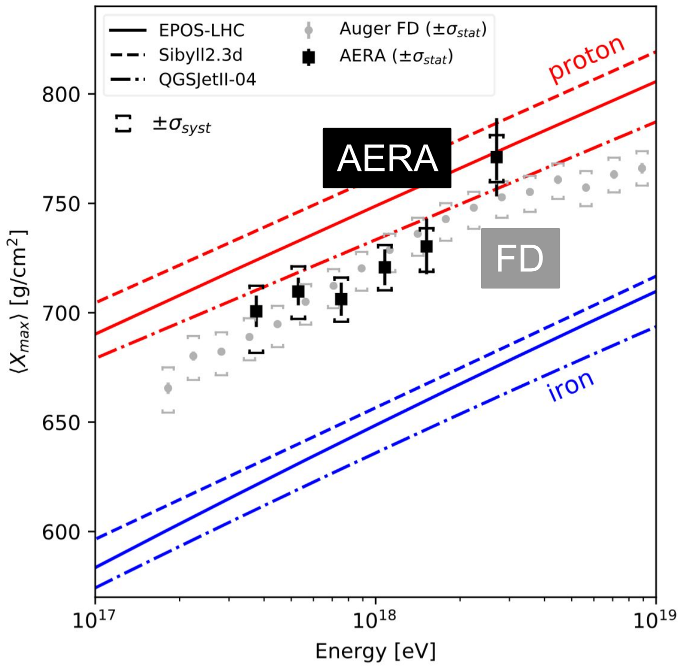

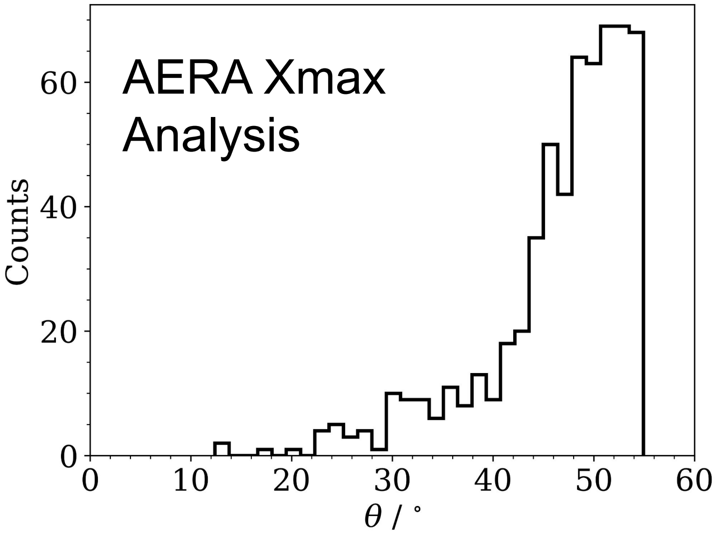

Pierre Auger Collaboration, Phys. Rev. D 109, 022002 (2024)

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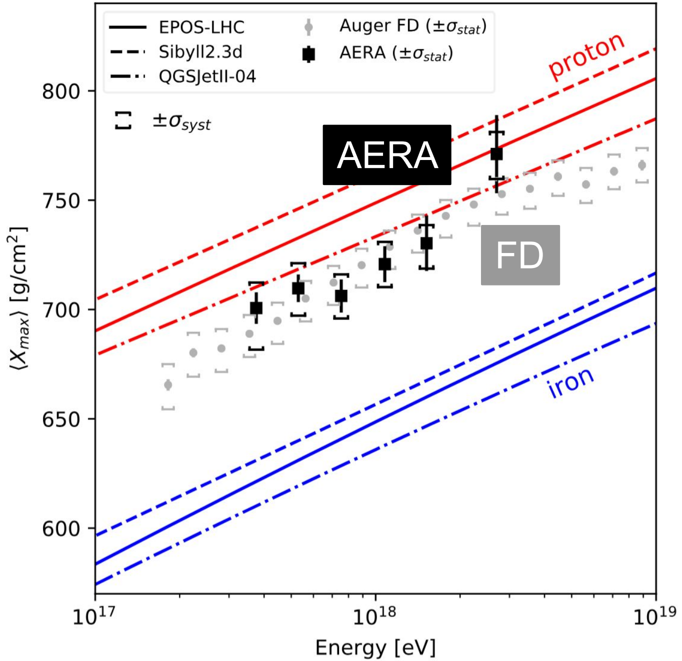
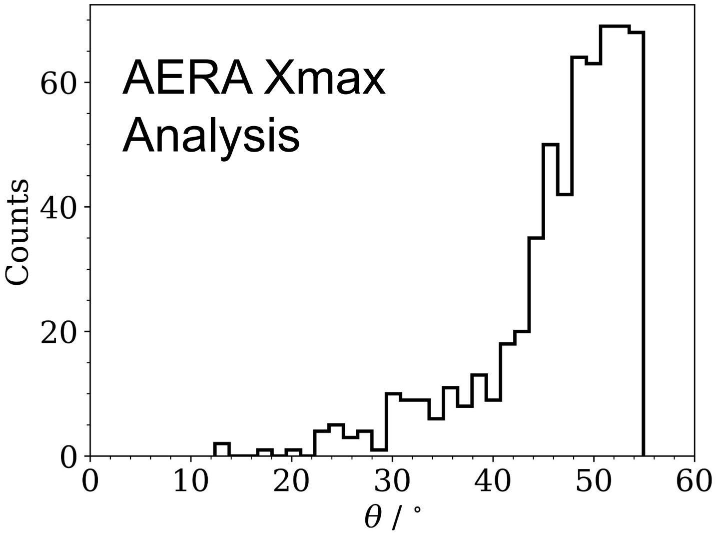
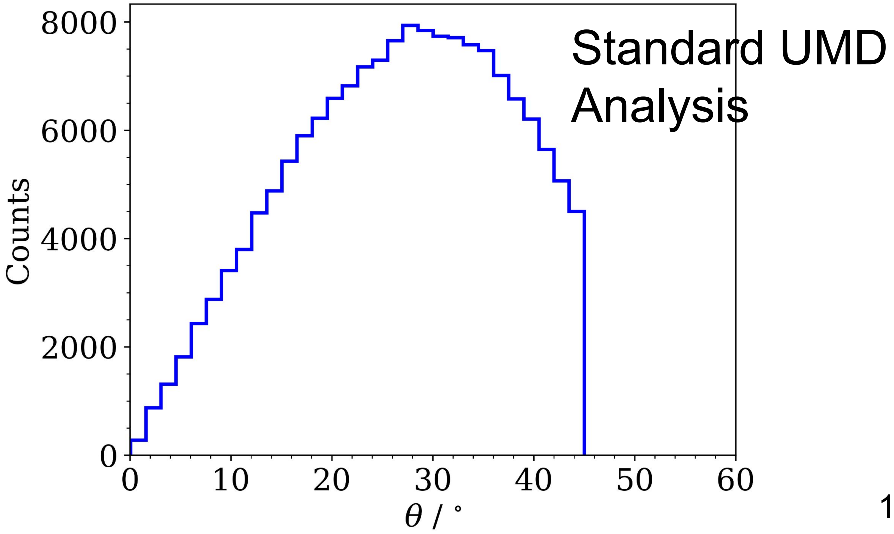


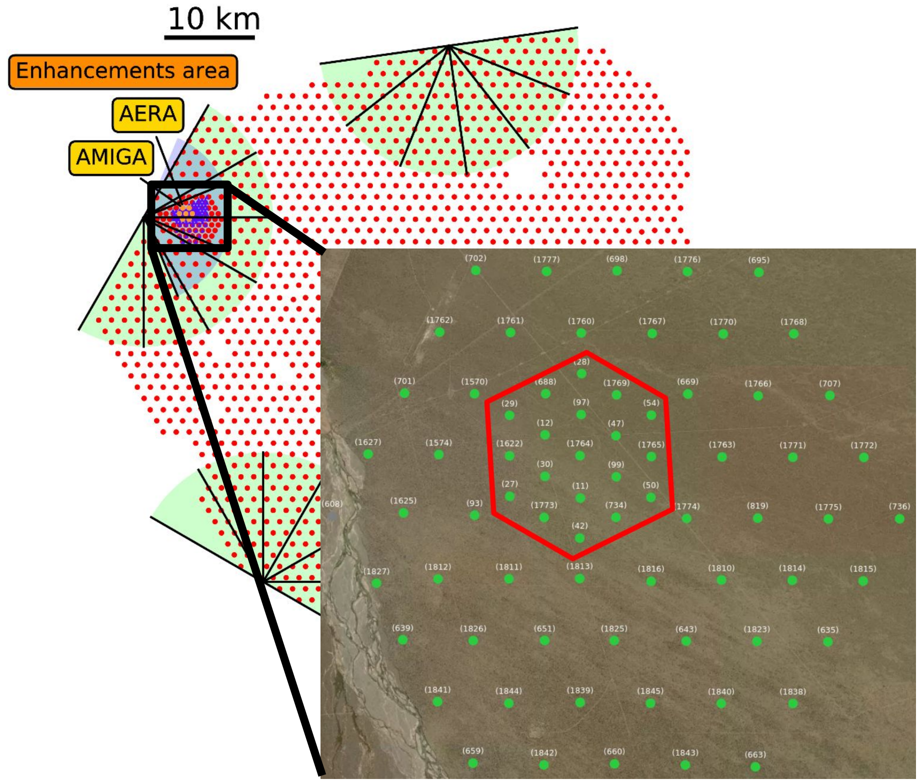




Pierre Auger Collaboration, Phys. Rev. D 109, 022002 (2024)

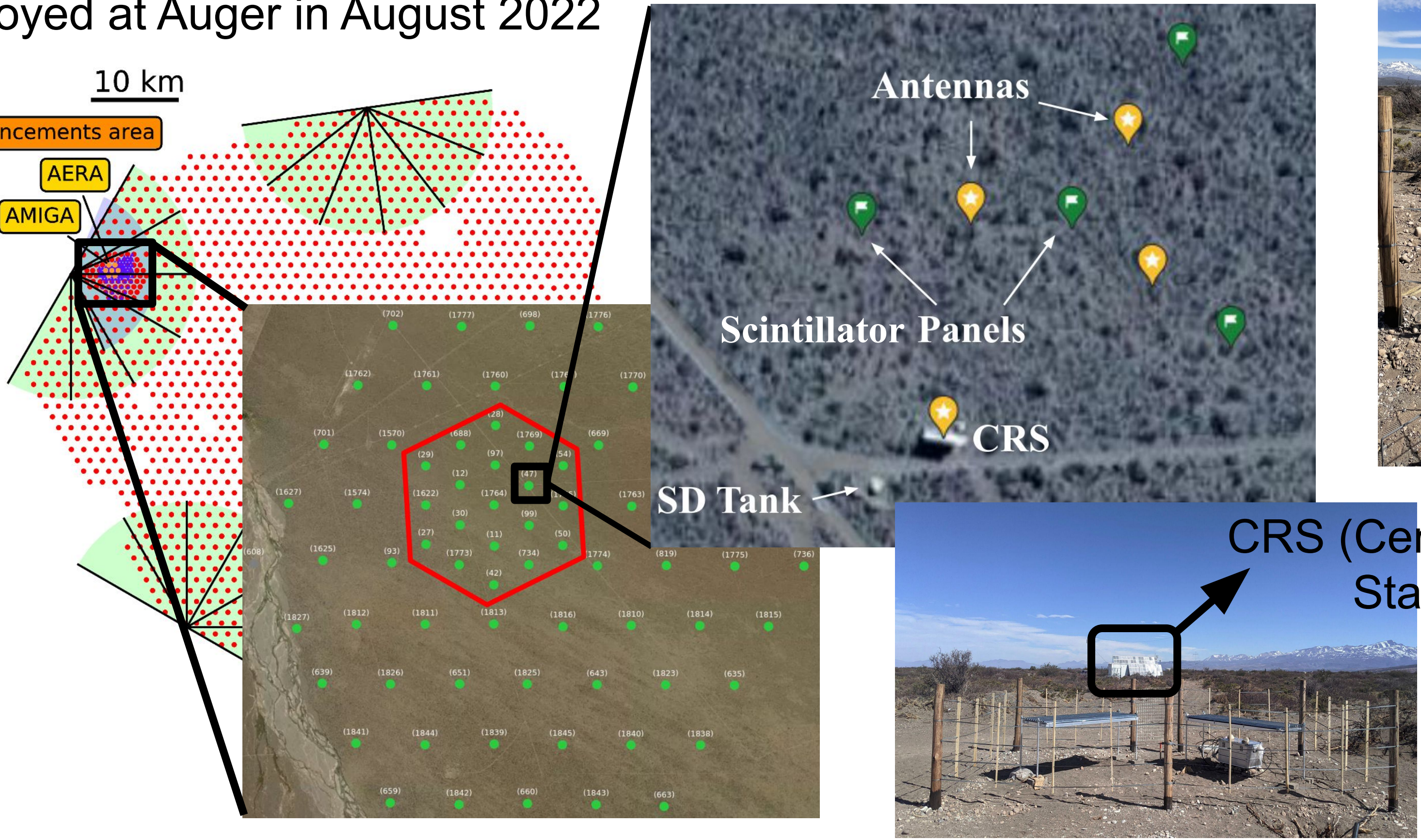
Plans for Further Radio Antennas

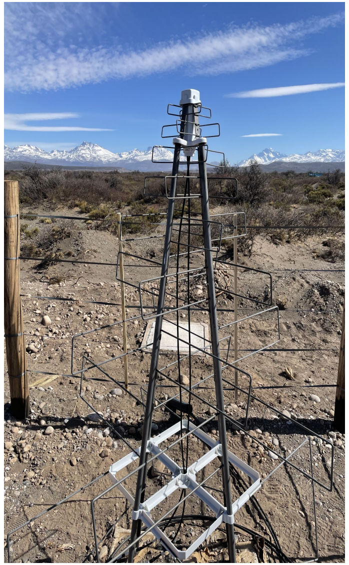
Synergize with existing detectors to maximize science potential



Existing SKALA Antennas @ Auger for IceCube-Gen2

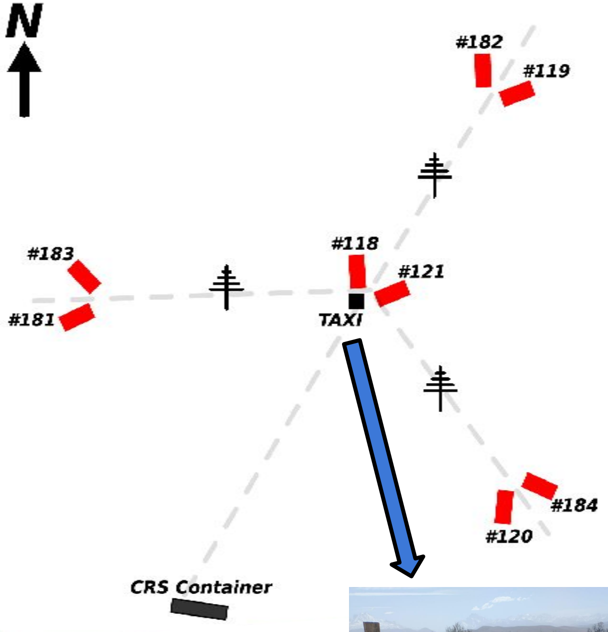
Prototype station of IceCube-Gen2 Surface Array deployed at Auger in August 2022





Prototype IceCube-Gen2 Station

Power from CRS
Communication and timing via fiber from CRS



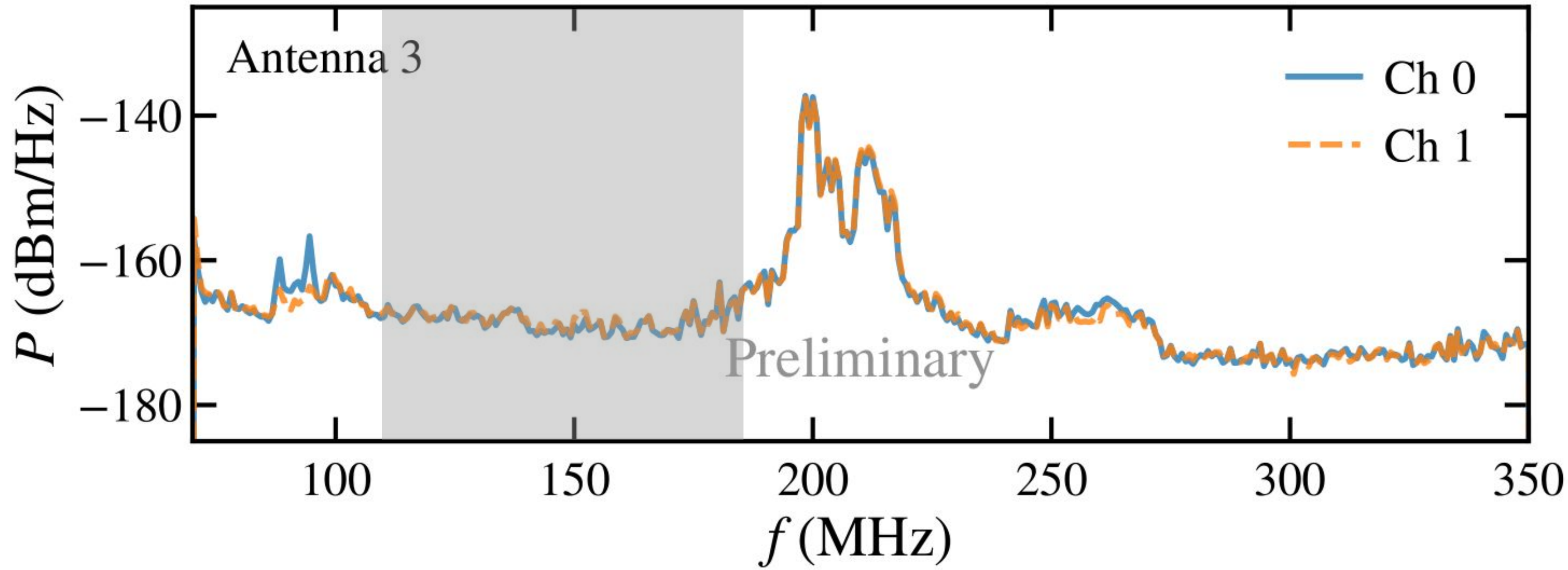
Radio antennas triggered by scintillator panels

Drone photo by Tim Huege

Air-Shower Search

Search for air showers in band not dominated by noise sources

Use 110-185 MHz → lessens contribution from anthropogenic noise + high signal-to-noise ratio



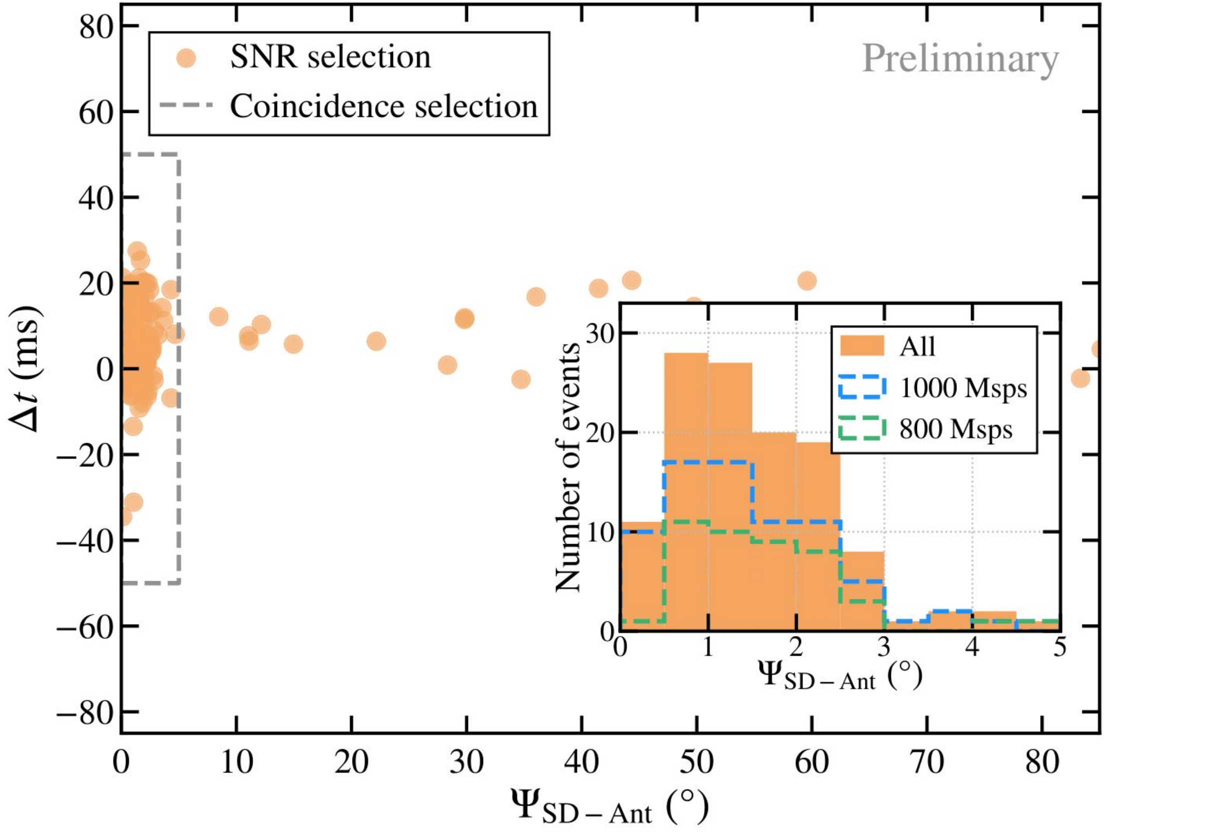
IceCube-Gen2 and Pierre Auger Collaborations, PoS(ARENA2024)037

Coincident Air Showers with Auger

Match scintillator triggered events to Auger SD reconstructed events by timestamp

Search in time window of +/- 50 ms

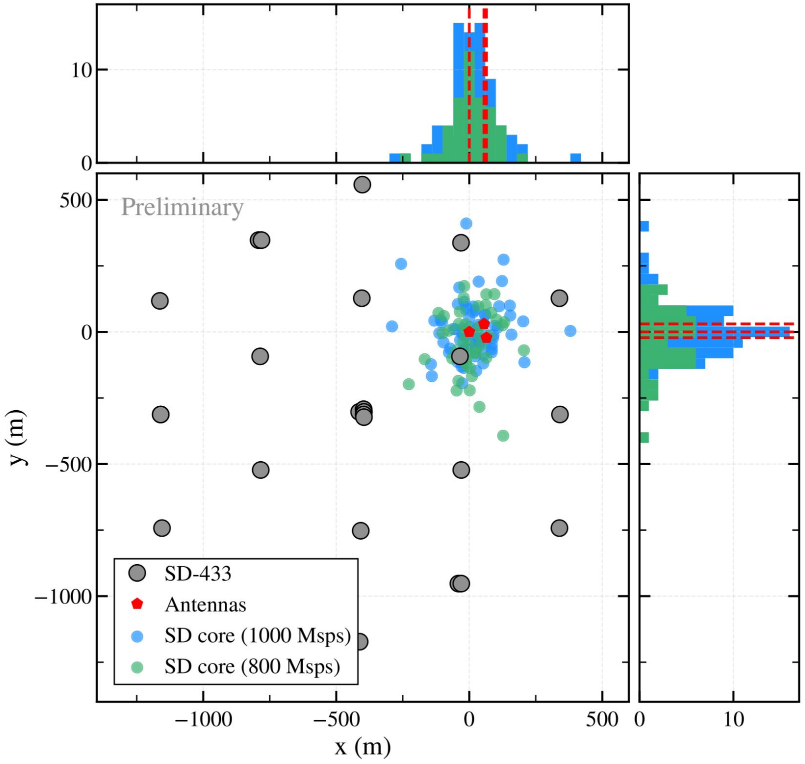
- Timing offset between WhiteRabbit and Auger SD
- Working on fix with Andreas Weindl to achieve o(ns) precision

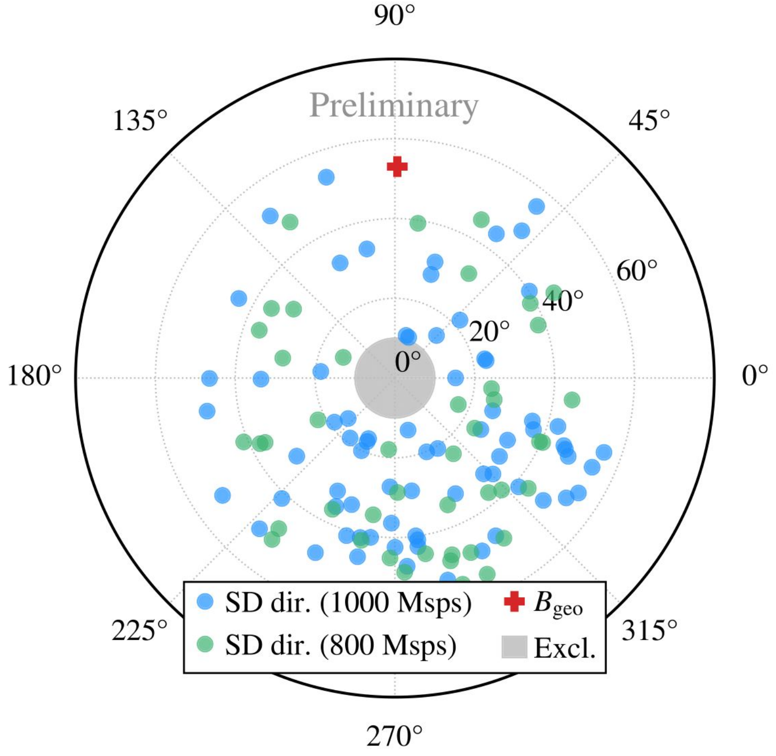


IceCube-Gen2 and Pierre Auger Collaborations, ICRC2025 upcoming

Coincident Air Showers with Auger

Events passing time window and directional reconstruction cuts, ~ 0.5 events / day



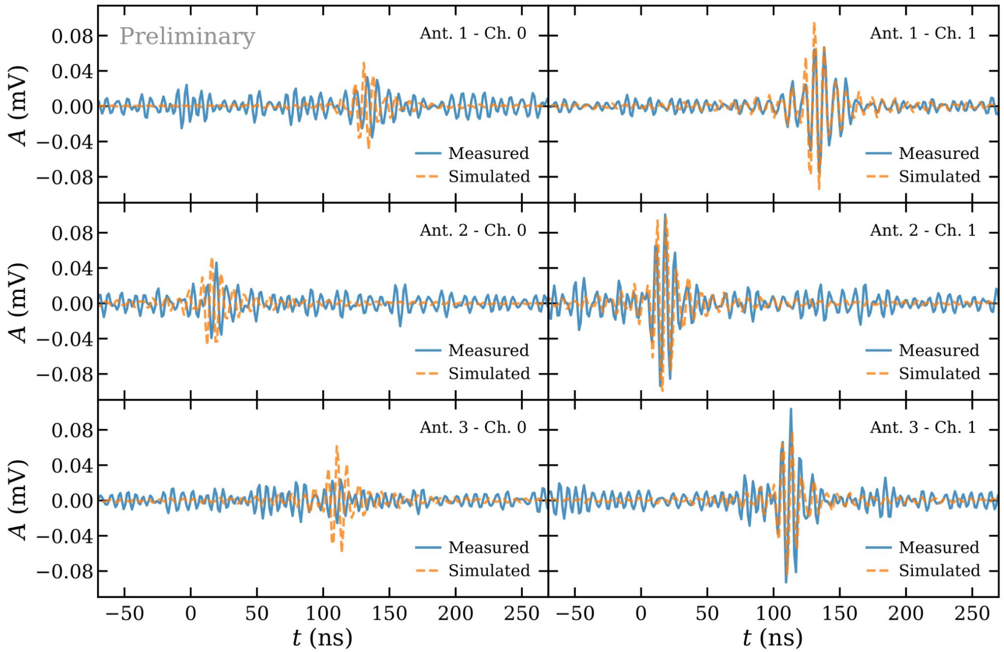


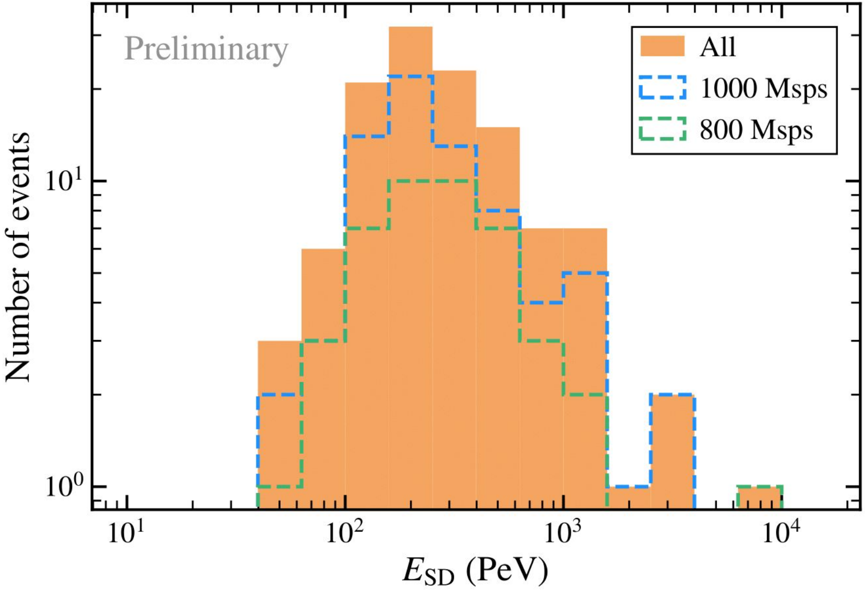
IceCube-Gen2 and Pierre Auger Collaborations, PoS(ARENA2024)037, ICRC2025 upcoming

Coincident Air Showers with Auger

Simulate radio emission w/ CoREAS as consistency check

Cosmic rays measured from o(10 PeV) with only three antennas

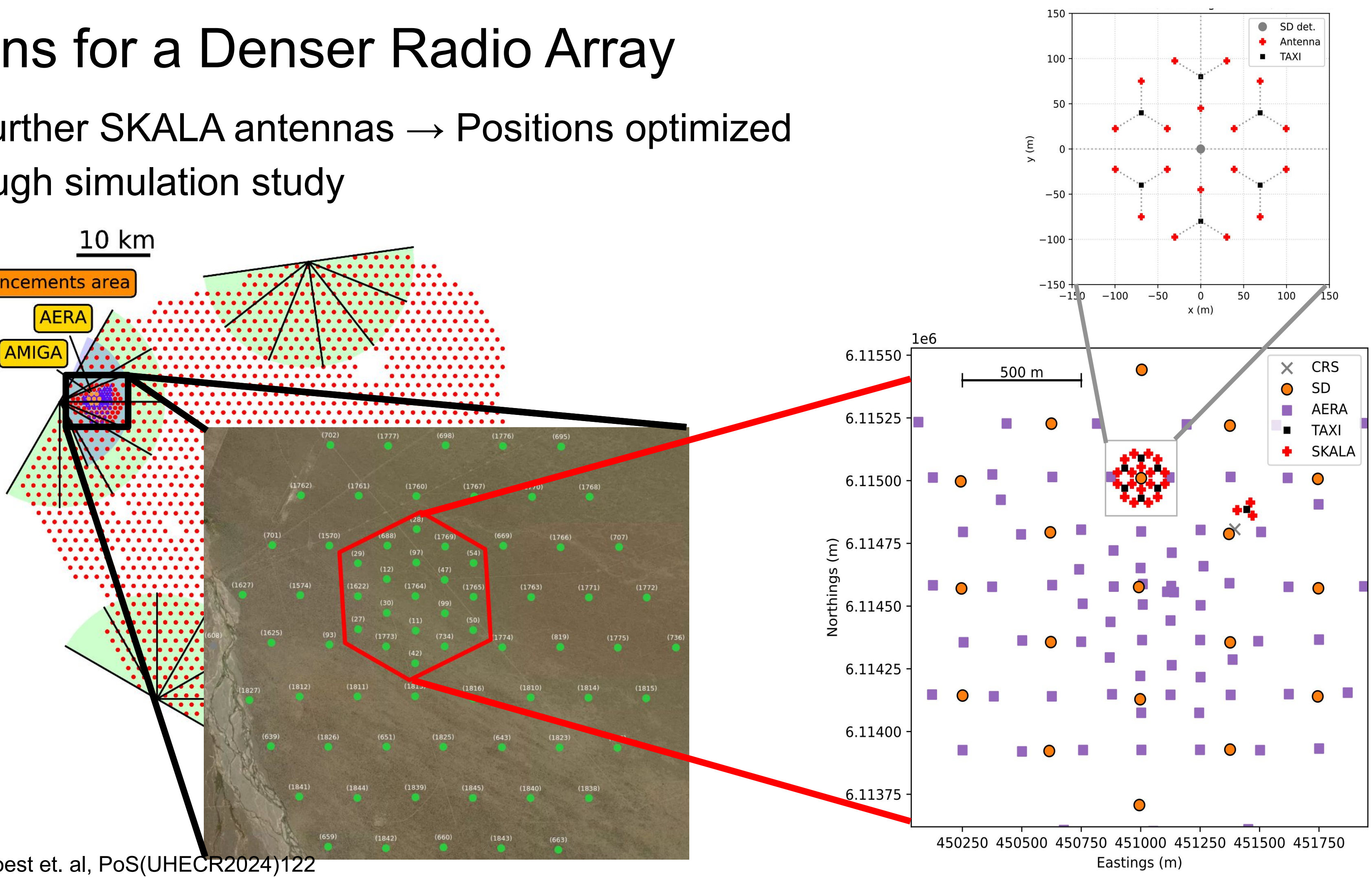




IceCube-Gen2 and Pierre Auger Collaborations, PoS(ARENA2024)037, ICRC2025 upcoming

Plans for a Denser Radio Array

18 further SKALA antennas → Positions optimized through simulation study

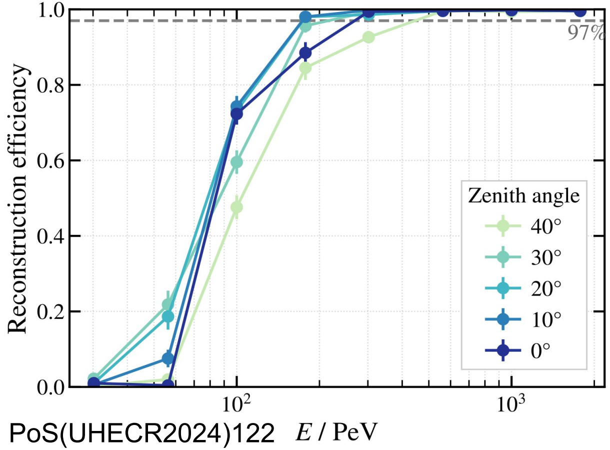


S. Verpoest et. al, PoS(UHECR2024)122

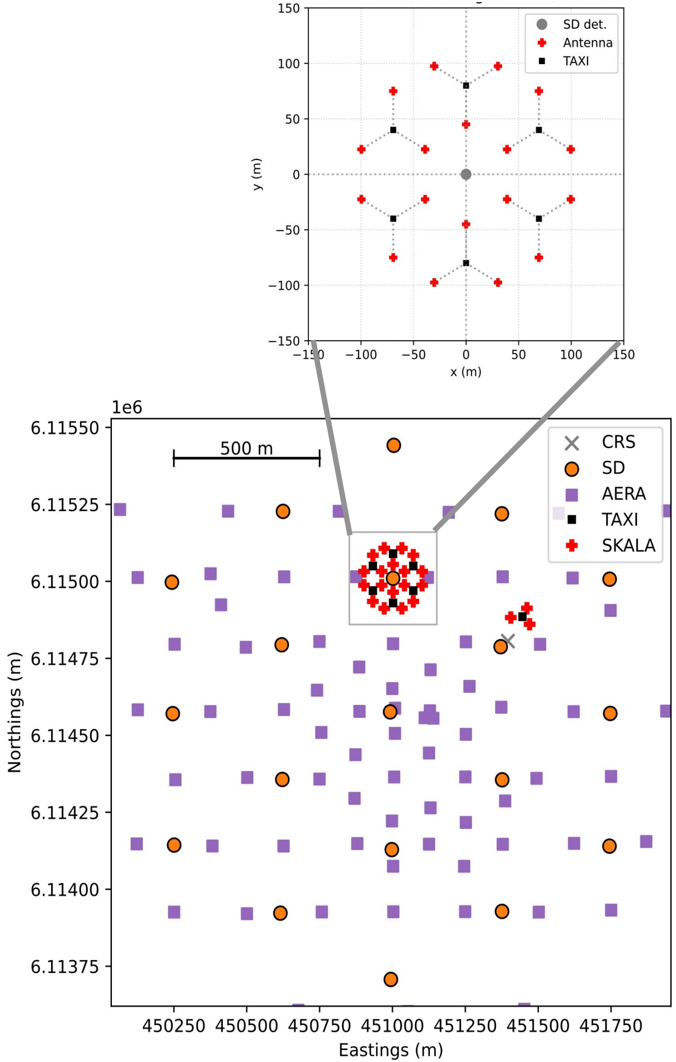
Science Potential

- Adds full efficiency for vertical shower ($\theta < 30°$) reconstructions above ~$10^{17.5}$ eV
- SKALA → 70-350 MHz, AERA → 30-80 MHz
- Coincident measurements with underground muon detectors → shower physics
- Optional: Interferometry and cross-calibration

simulated radio detection efficiency



S. Verpoest et. al, PoS(UHECR2024)122



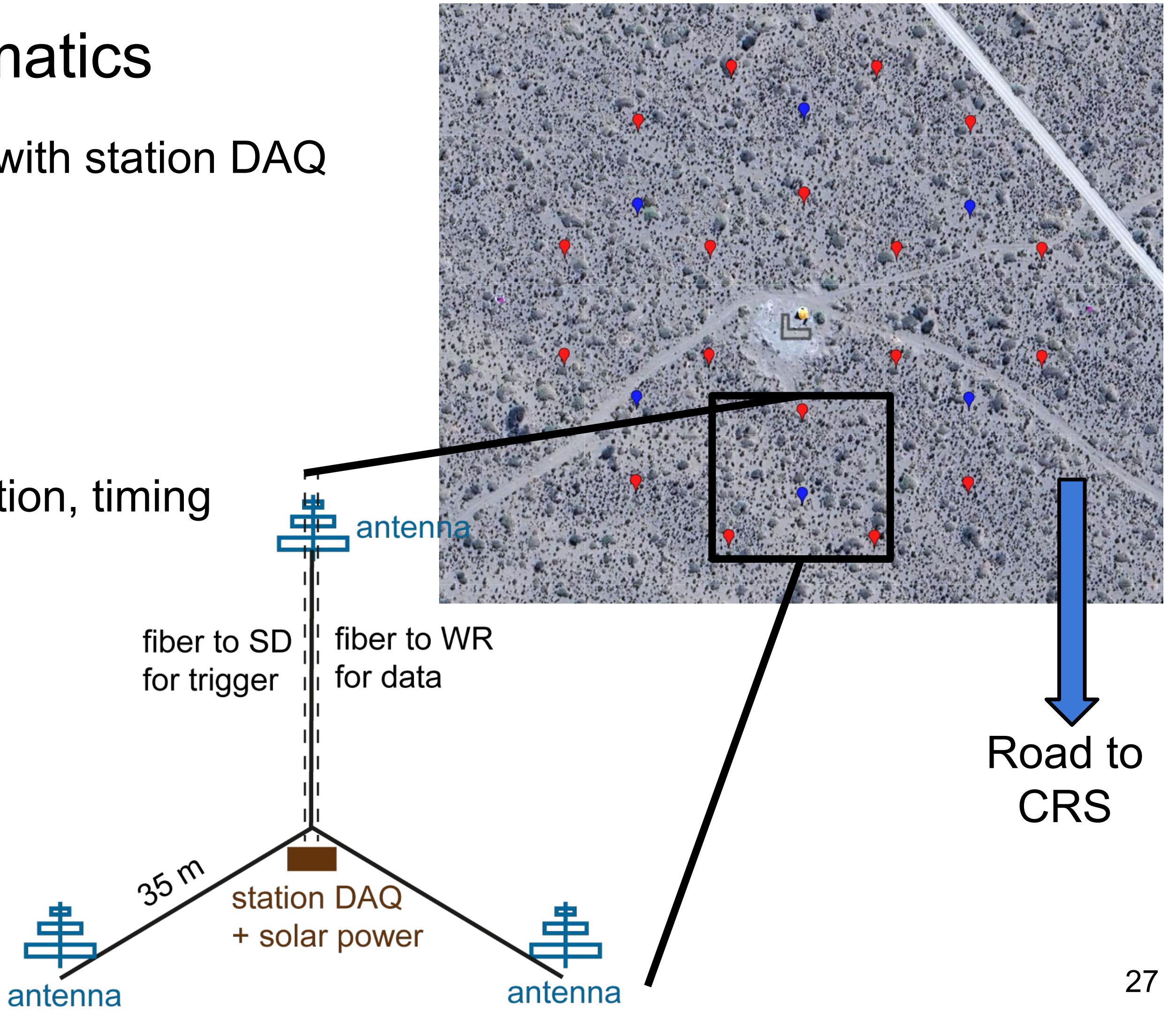
Array + Station Schematics

6 stations of 3 antennas each with station DAQ (TAXI)

Solar power for each station

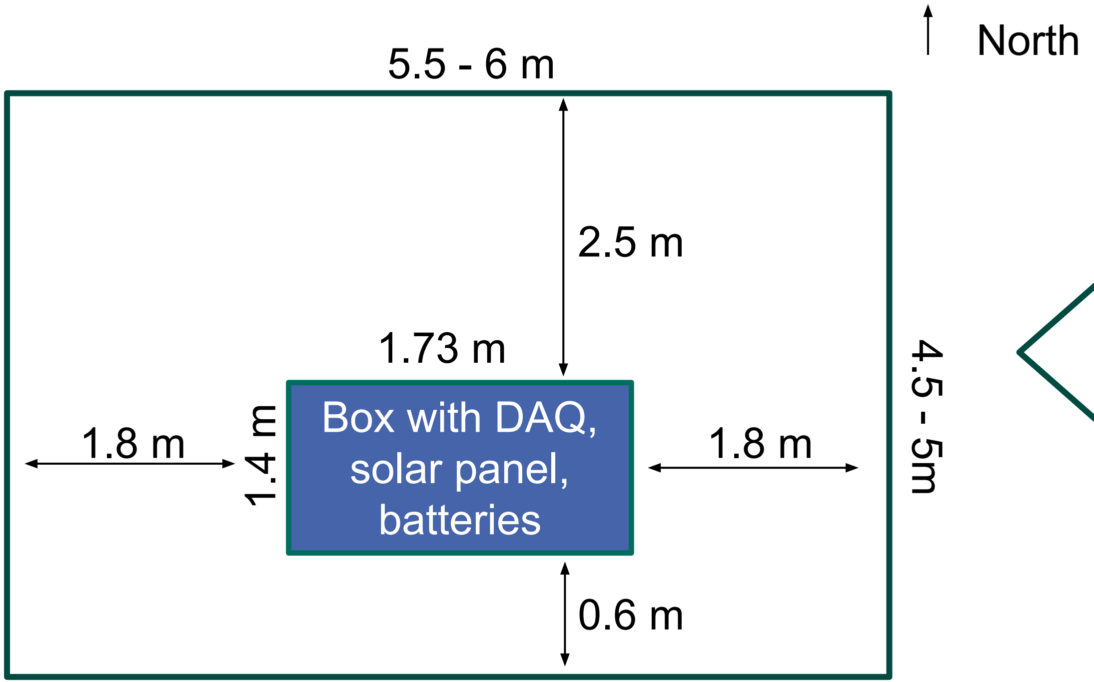
2 fibers per station:

- Data transfer, communication, timing
- Trigger from Auger SD



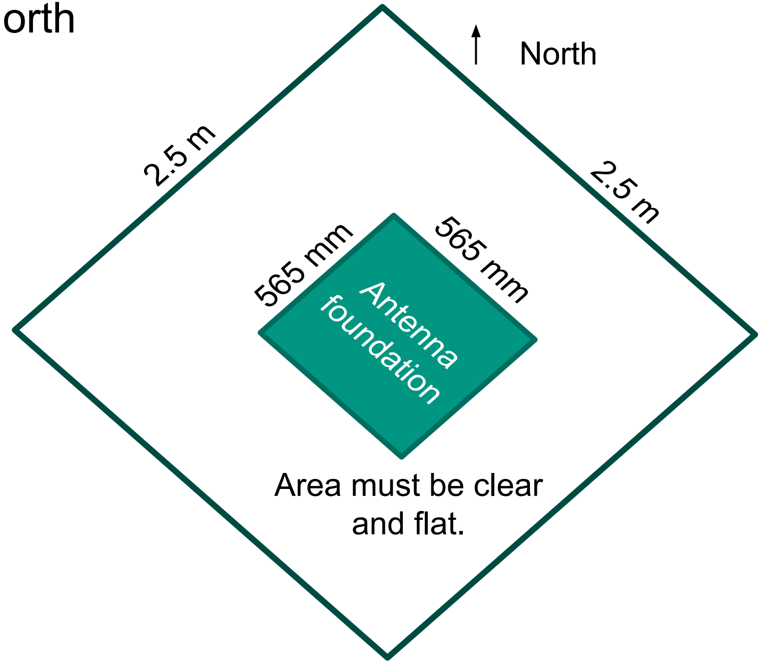
Site Schematics

Station Centers



Area must be clear and flat.

Antennas



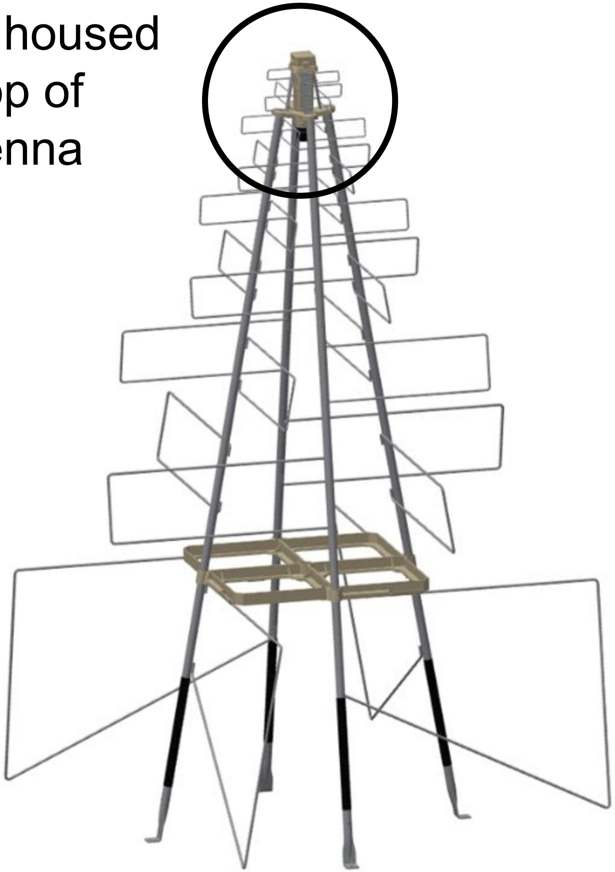
sketches not to scale

Site Inspection – Antennas

Access tubes to route coaxial cables to LNAs

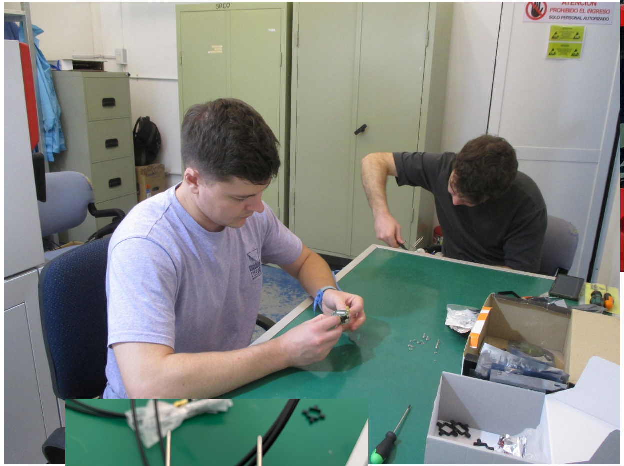
Fencing to keep animals out

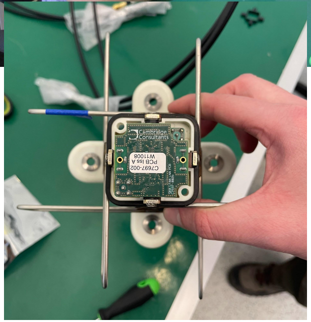
2 LNAs housed at top of antenna



Deployment – Antennas

Antenna heads + LNAs assembled at observatory to minimize risk of ESD in field

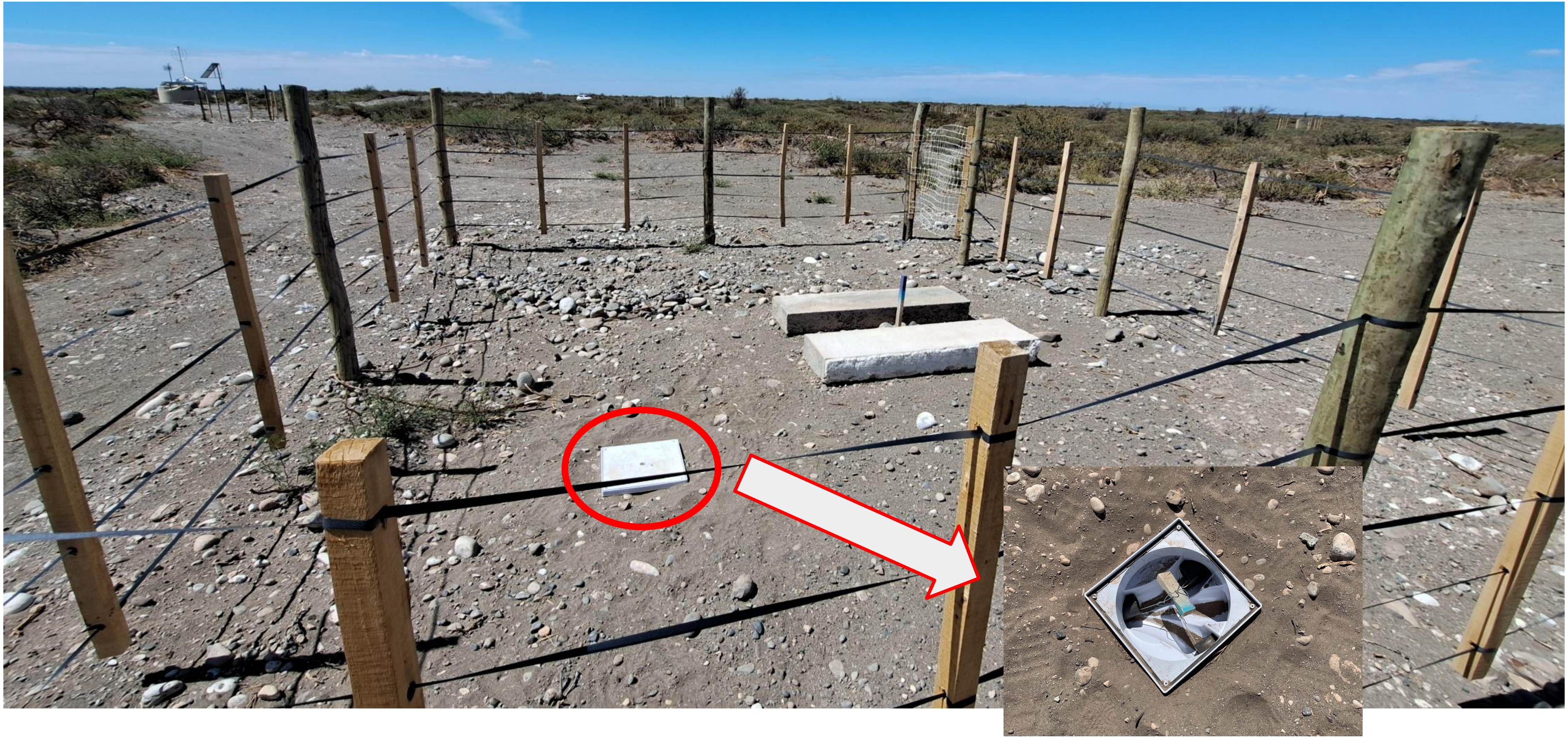




Antennas assembled at CRS and transported by truck to sites

Antenna legs fixed to concrete foundations

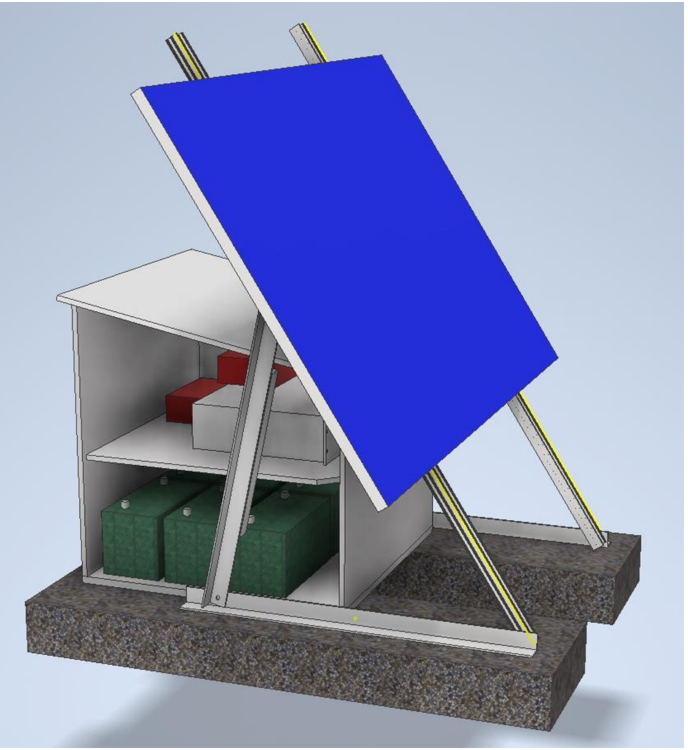
Site Inspection – Station Centers



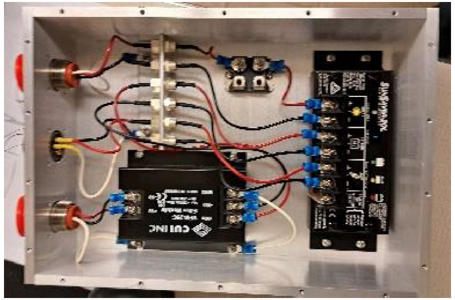
Concrete slabs for mounting station center

Access port for cables/fibers

Schematic – Station Centers



Charge Controller
with RFI shielding



TAXI
DAQ

Solar Panel
(24V, 440Wp,
bifacial)

Wooden box with
aluminum roof and
solar panel stands

6 AGM Batteries
(12V, 120 Ah)

Deployment – Station Centers

Drill into concrete to secure boxes

Local staff drive truck to location, unload, then assist

Batteries in 3 parallel, 2 series to provide at least 24V, 1A to DAQ

Trenching from Access Ports

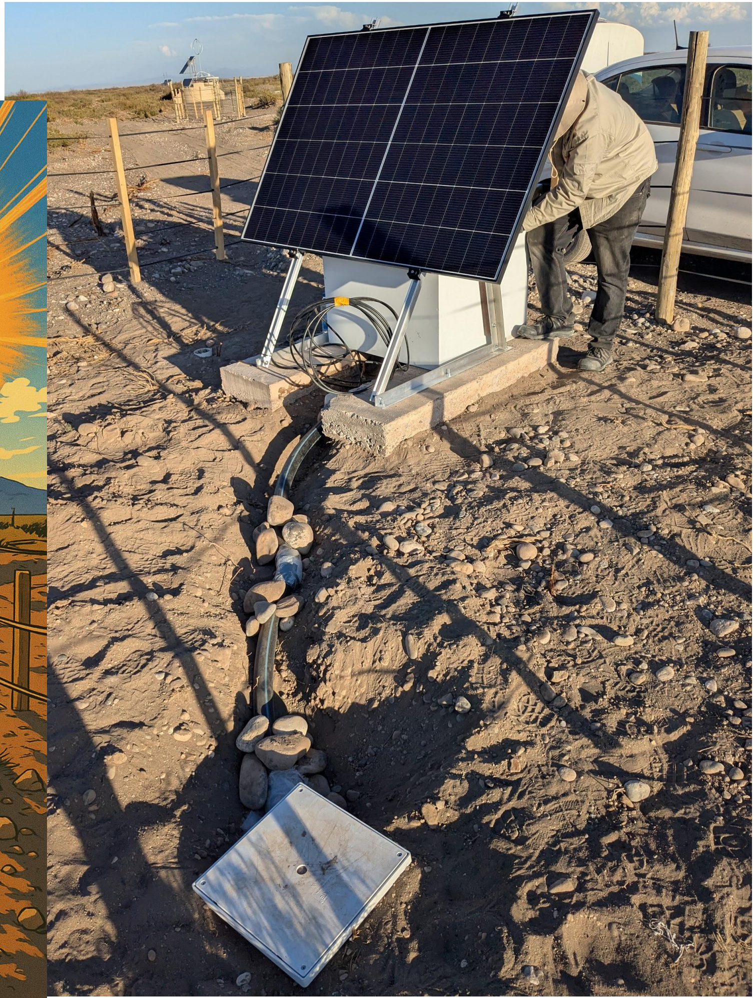
Very rocky area of the Auger array

Feed cables/fibers through tubing

Cover openings where possible

Bury when finished

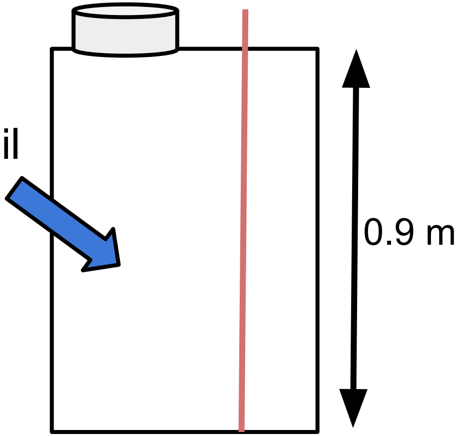
Trenching from Access Ports



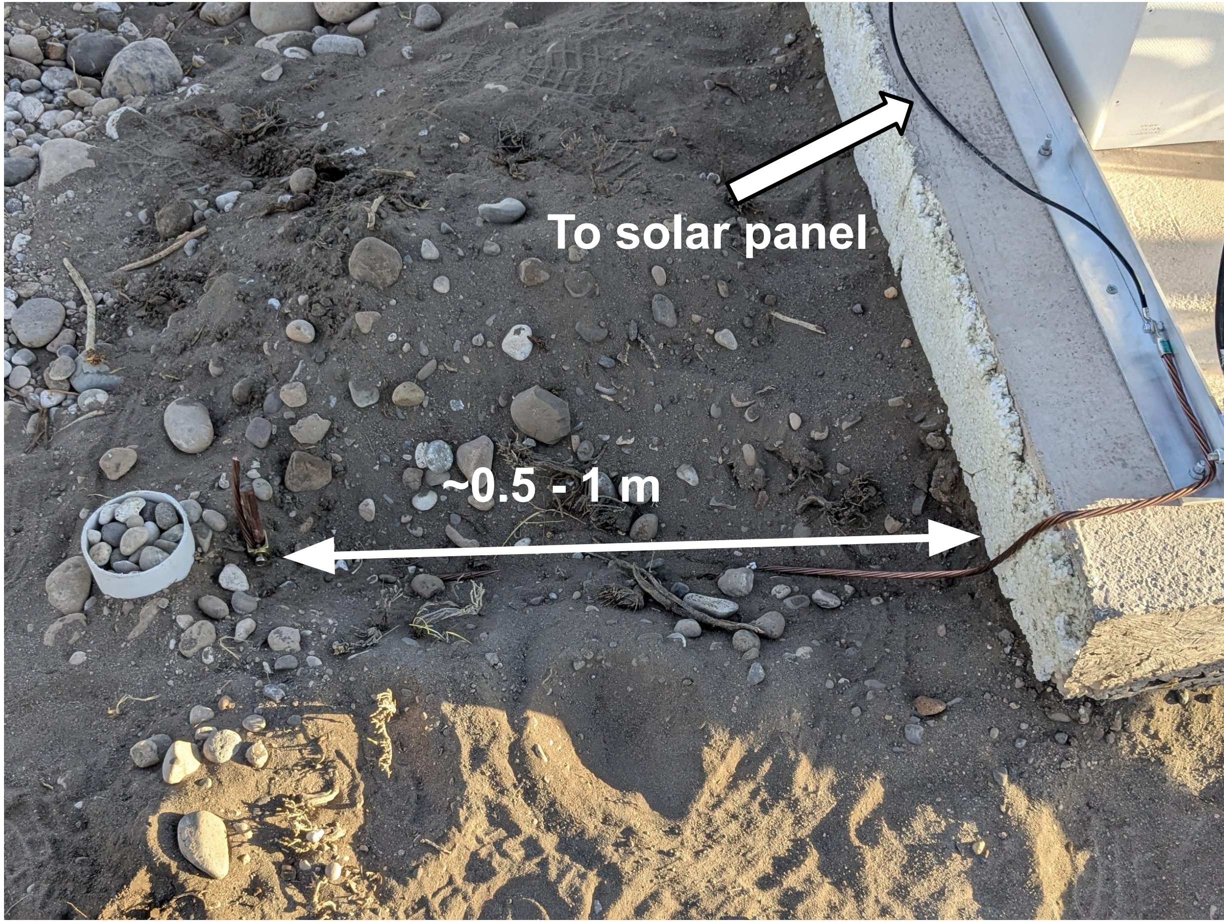
Grounding

Dry and rocky area → low conductivity in soil

Fill with salt + soil mixture



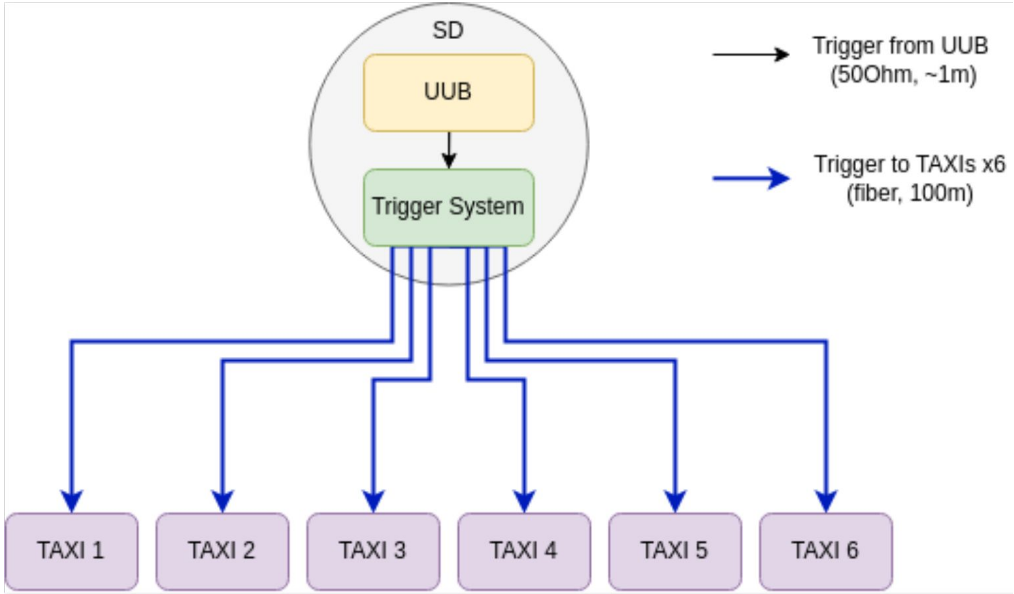
Salt will retain moisture in soil, increases conductivity

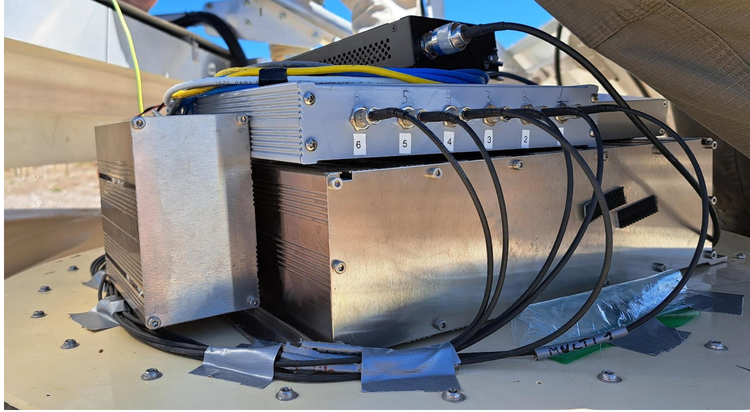


Fibers – Trigger

Optical trigger from surface detector tank Lety Jr

- o(100 Hz) local trigger rate (T1 level trigger)
- reduced to <0.01 Hz when later comparing to T3 triggers

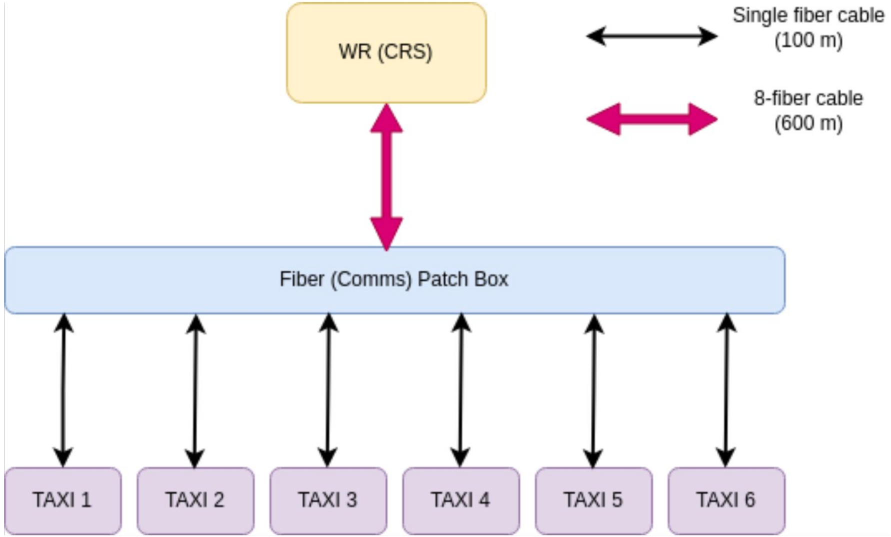


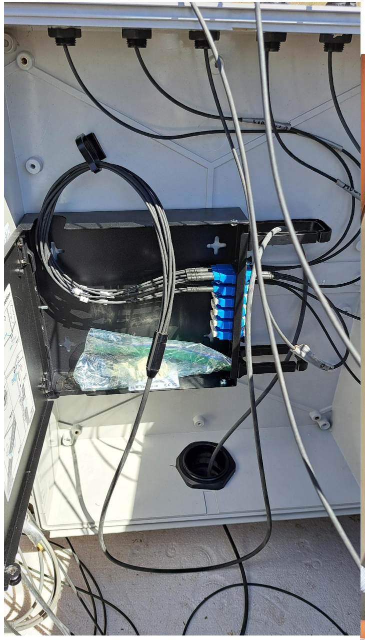


Small box in SD electronics dome connects to UUB trigger out

Notch made and fibers put in tube for protection

Fibers – Communication

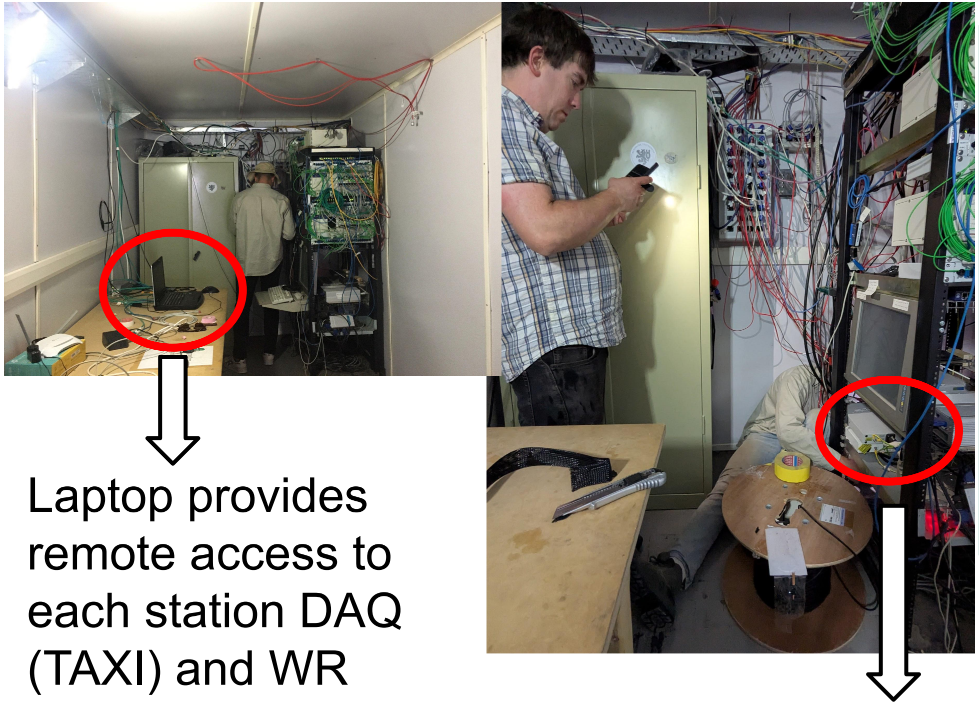




Fiber distribution box for connection to WhiteRabbit in CRS

Provides communication, data transfer, and timing

Main DAQ Control in CRS

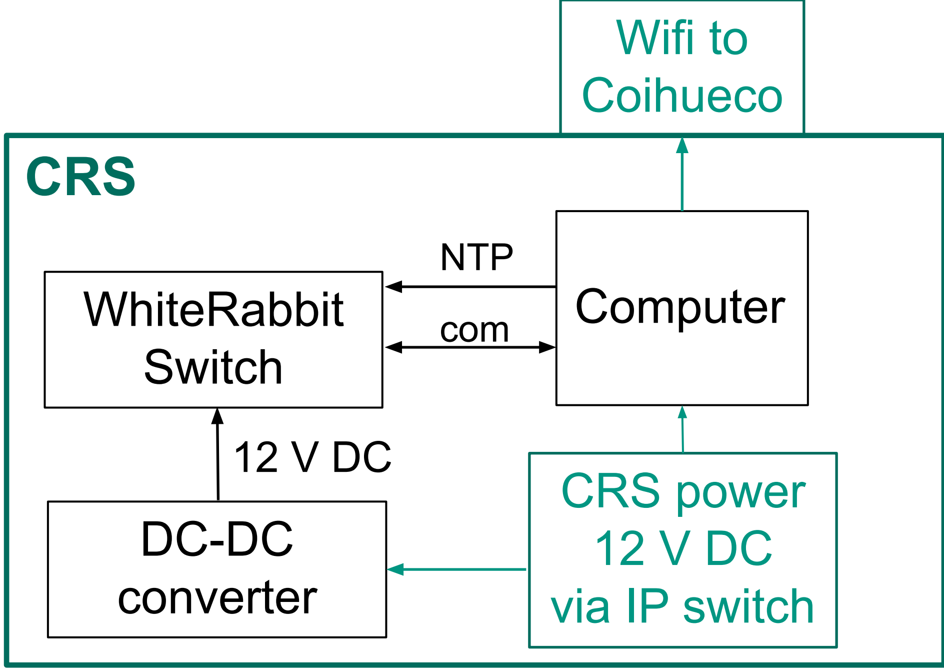


Laptop provides remote access to each station DAQ (TAXI) and WR

Data storage on 8TB SSD

All communication fibers connected to WhiteRabbit via 8 cable fiber

WR to provide ns precision (in progress via GPS)

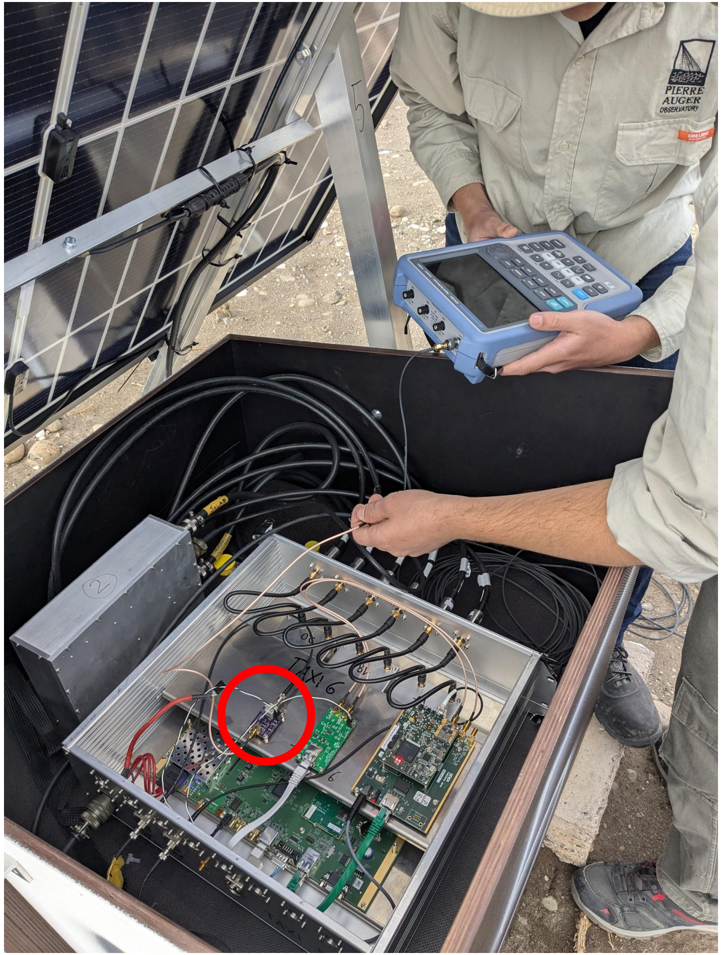


Fiber Testing for Signal Confirmation

Measure pulses output by SD trigger out (fed to 6 trigger Tx boards)

Measure signal as seen by 6 trigger Rx boards at station DAQs

Some signals attenuated too much at Tx, Sasha Novikov + Andres Travaini working on fix



Dust Accumulation in Station Centers

Large dust accumulation in 3 of 6 station centers after one week

Seal DAQs with electrical tape to prevent dust reaching electronics

dGPS Measurements + Merging to Offline

Differential GPS measurements taken for all station and antenna locations

Also for orientation of antenna arms to check alignment

Carmen Merx currently working to implement antenna locations and SKALA antenna models to offline

Matching Events via Timestamps

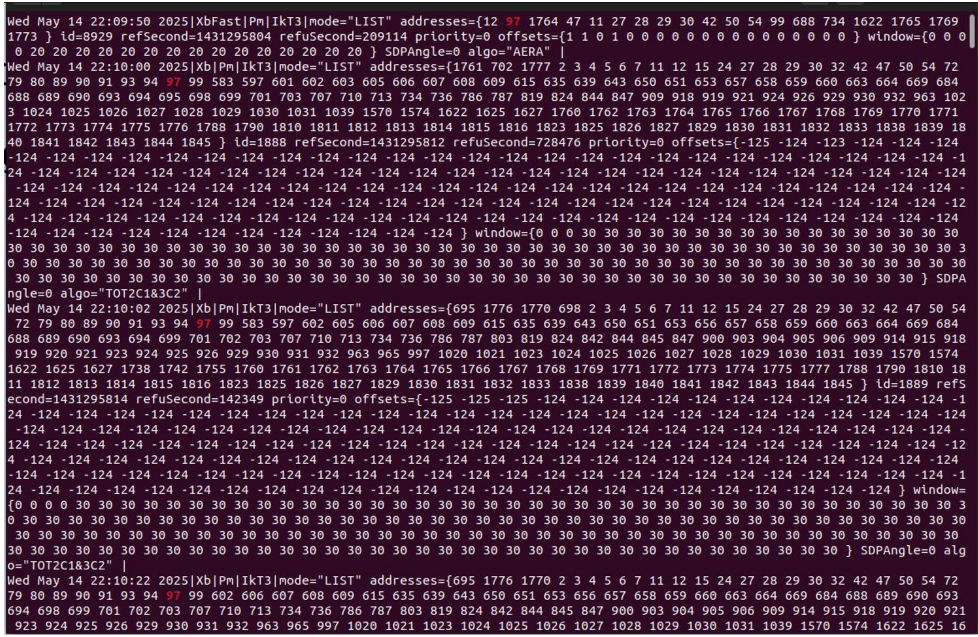
100 Hz trigger rate for 18 antennas

- ~2 TB of data per day
- Would fill 8 TB SSD quickly…

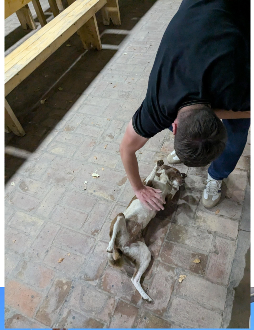
Matching timestamps of T1 trigger with Lety Jr. T3 requests reduces to o(0.01 Hz)

Stef Verpoest working to extract matched times from radio binaries

Full data taking to start once extraction is working



Deployment + Fun



Summary

Array of 18 SKALA antennas (70-350 MHz) deployed in the densest part of the Auger array

- Goals: Full efficiency of vertical showers, coincident measurements with underground muon detectors
- Potential for cross-calibration of radio energy scales between AERA and SKALA

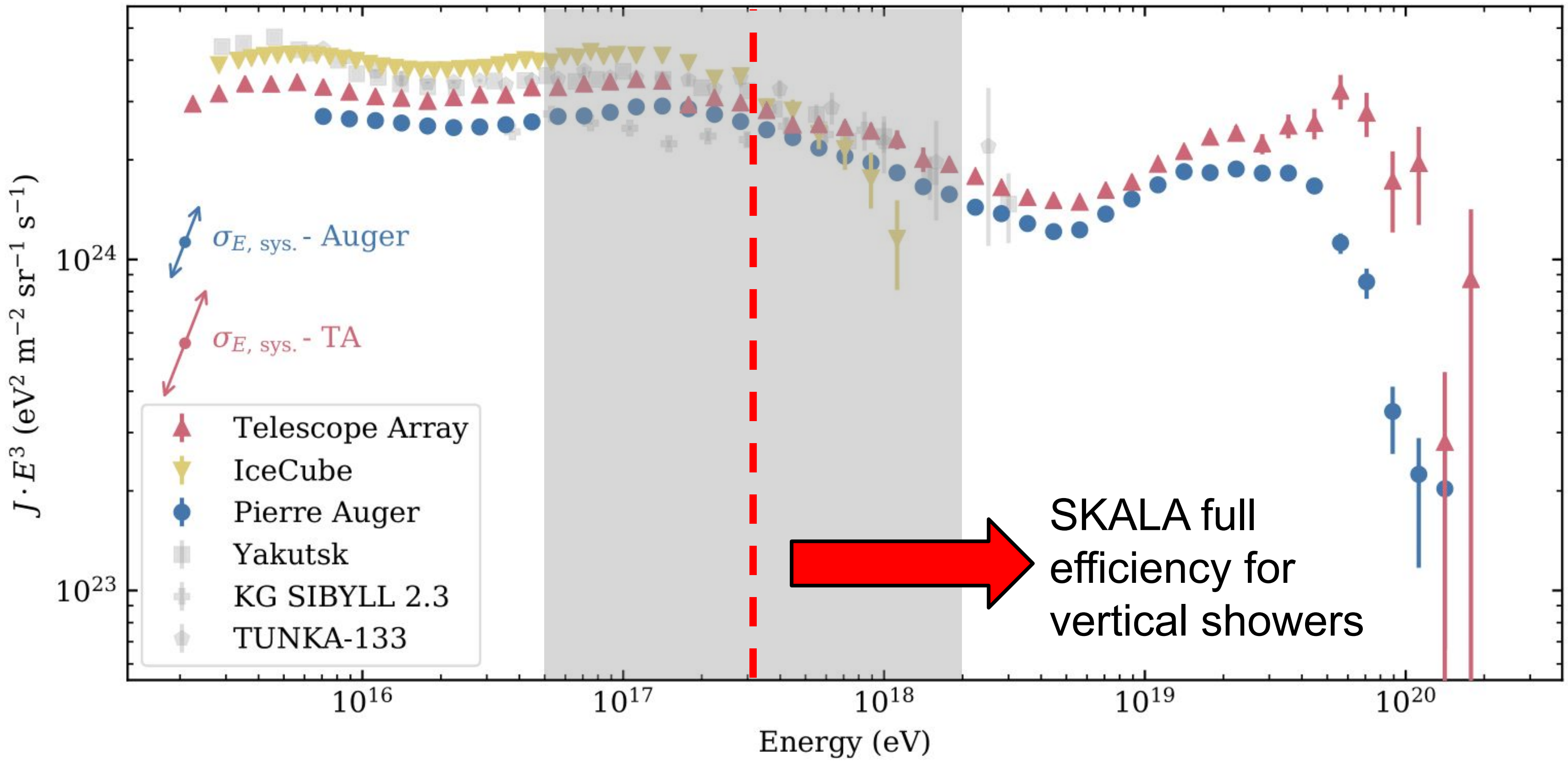
Array fully deployed in March 2025

- Partial data taking since April 2025
- Similar analysis pipeline to IceCube prototype station @ Auger → physics results to follow soon!

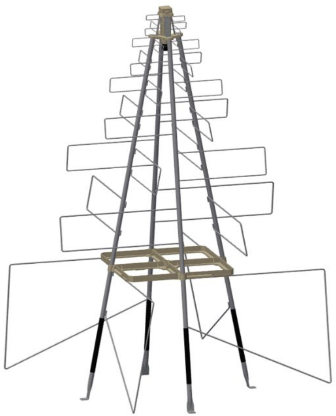
A big thank you to all involved in the station, here at KIT, at UD, and all the local staff at Auger

Backup

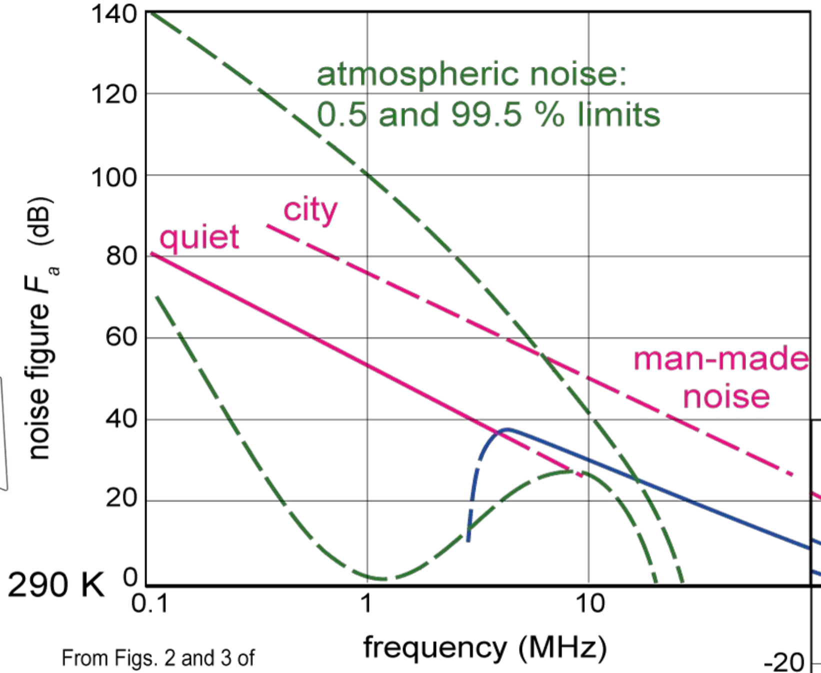
Energy Range for Auger/IceCube Cross-Calibration

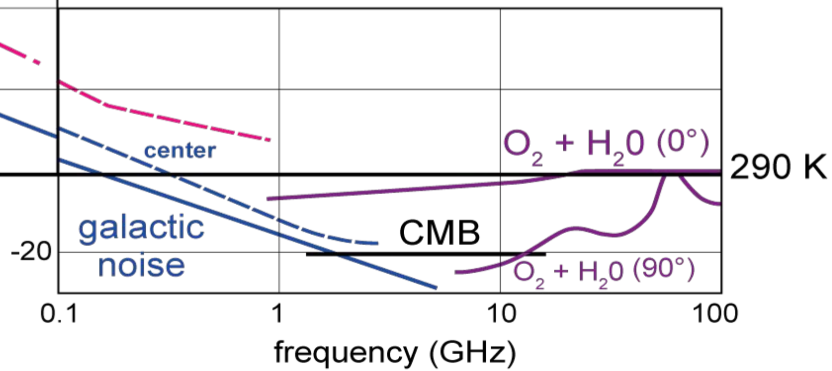


Radio signal-to-noise ratio best at high frequencies (> 100 MHz)

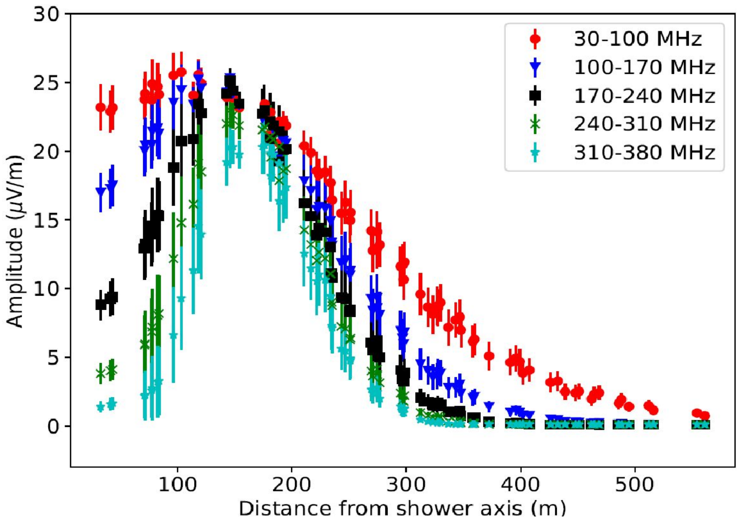


SKALA v2:
70-350 MHz





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



Slide from Frank Schröder

Measuring Energy Fluence at Antenna

The Poynting vector gives the energy flux of an EM field

$$\vec{S} = \vec{E} \times \vec{H} = \frac{1}{\eta}|\vec{E}|^2 \cdot \hat{n}$$

(assuming plane waves in isotropic medium, such as lower atmosphere 🙂)

Integrating Poynting vector over radio trace (time) yields energy fluence observed by antenna

Must subtract omnipresent noise background

$$f = \int_{t_0}^{t_1} \varepsilon_0 c|\vec{E}(t)|^2\, dt - \frac{t_1 - t_0}{t_{b1} - t_{b0}} \int_{t_{b0}}^{t_{b1}} \varepsilon_0 c|\vec{E}(t)|^2\, dt$$

Labeling of Station Centers

Labeled with spray paint for easy visibility from road

Andres Travaini from local staff to label baseplates of antennas