The Pierre Auger Observatory as a Test Environment

XIII International Conference on New Frontiers in Physics

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PIERRE AUGER OBSERVATORY

SCHOOL OF MINES 1874 COLORADO

The Pierre Auger Observatory

- **Cosmic ray observatory near Malargüe in the Mendoza province of Argentina**
- The location was chosen for:
  - Clear weather and dark nights
  - A flat open Pampa able to accommodate the Observatory's targeted aperture size
- The Observatory itself is 3000 km^2 and has accumulated roughly 100,000 km^2 sr yr of exposure
- The (upgraded) Observatory consists of:
  - The SD: 1600 water Cherenkov detectors (WCDs) + surface scintillator detectors (SSDs)
  - The FD: 27 fluorescence telescopes
  - The RD: 1600 radio antennas
  - The UMD: 30 m^2 of underground muon detectors (buried scintillator)

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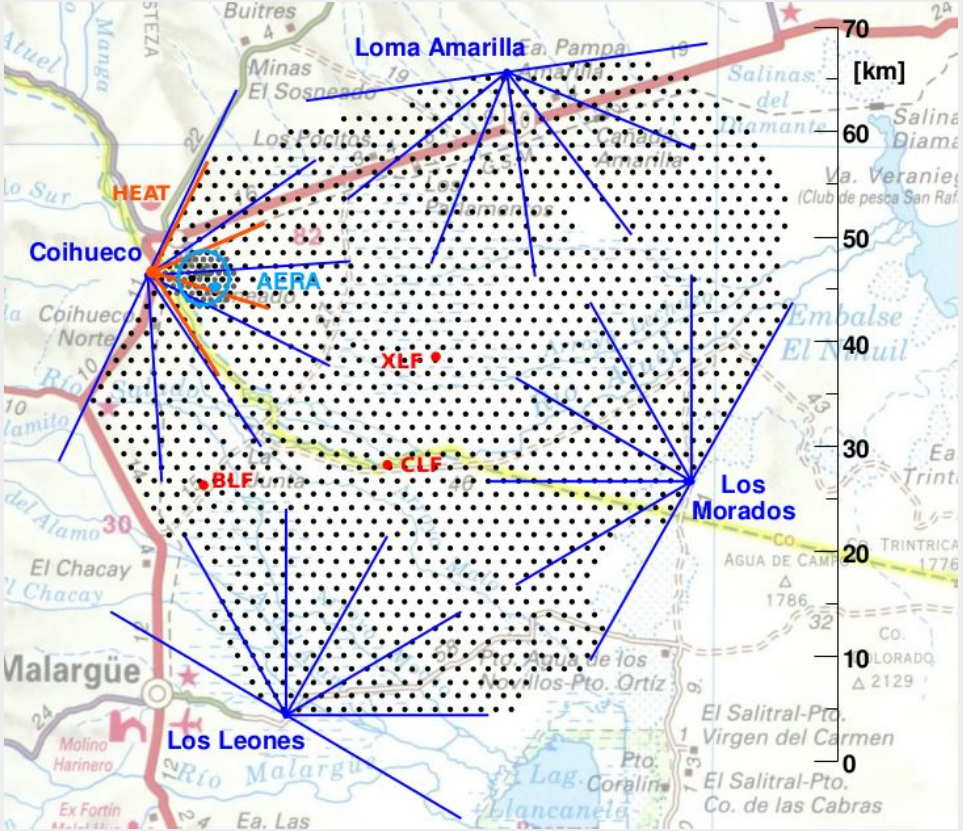

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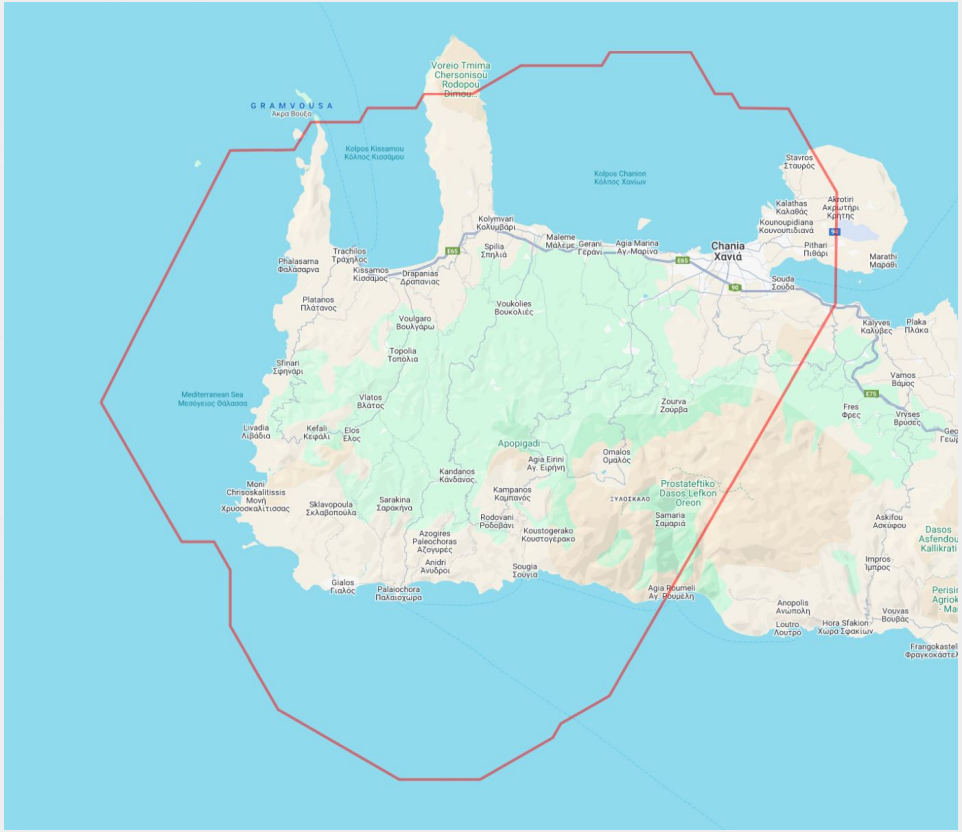

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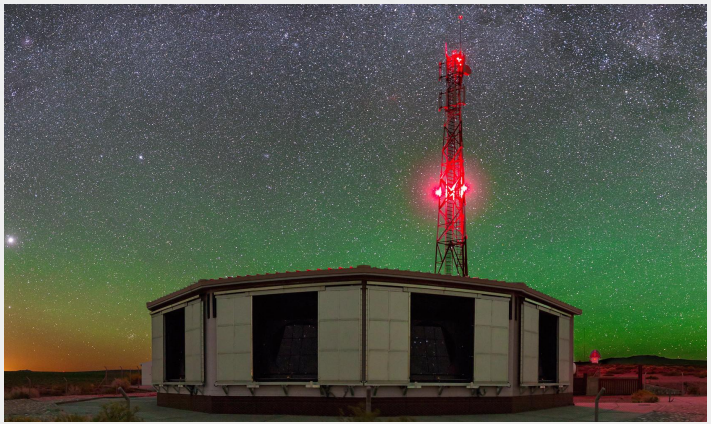


PEPS@Auger

Content by Ioana Maris

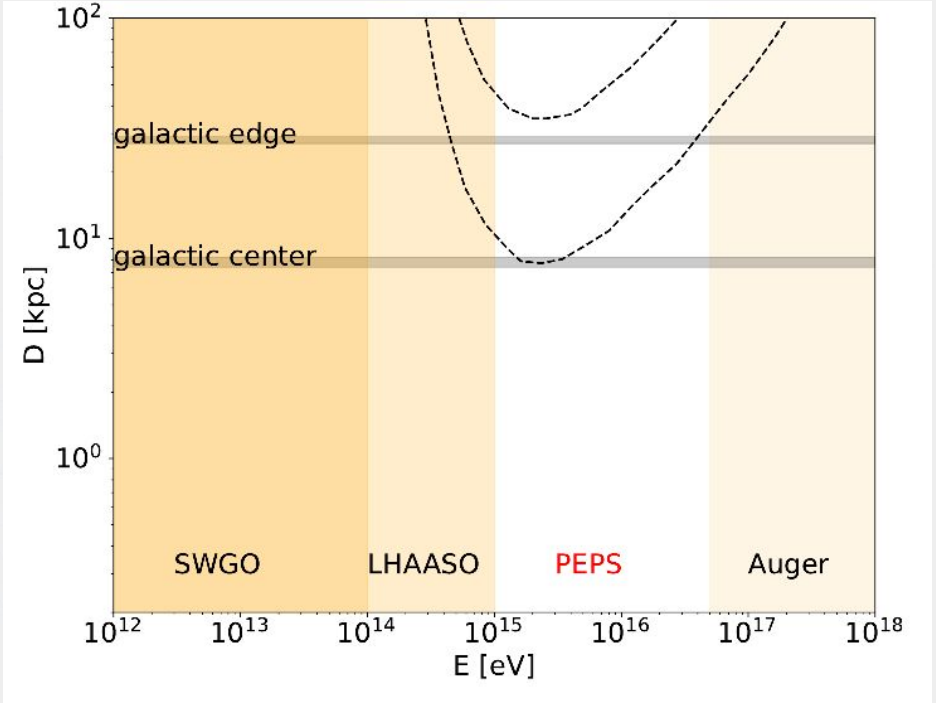
PEPS: Project for Extreme PeVatron Searches

Look for gamma rays in the $10^{15} - 10^{16.5}$ eV energy range

- Horizon limited to few tens of kpc:
  - Surely galactic sources
  - Local diffuse flux →Probe galactic halo
- Could probe fundamental physics: dark matter, axions

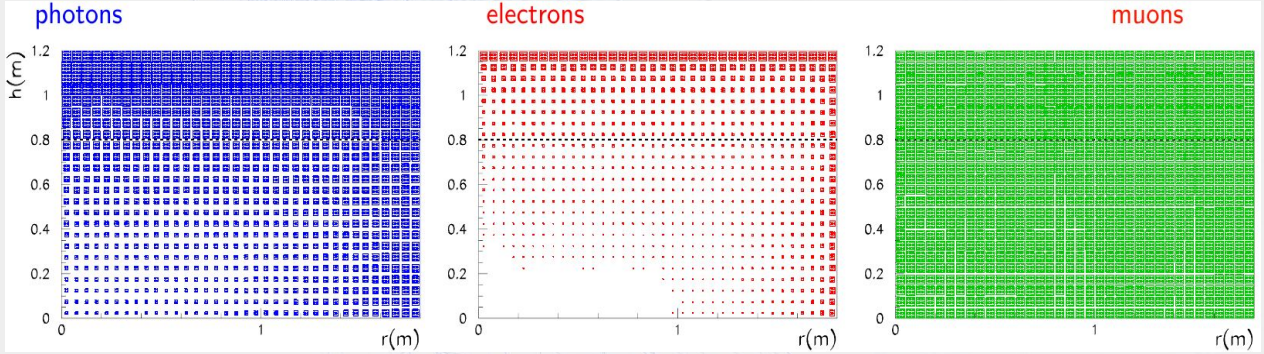
How large would an array need to be to compare to LHAASO?

- Standard surface detector assumptions: better than 1° angular resolution
- Extrapolate the fluxes from LHAASO sources in ideal case without any flux suppression
  - → 6 km^2
  - → 10 years of operation: possibility to measure/constrain tail of gamma sources above 3 PeV, diffuse flux at almost same order of magnitude



PEPS: Proton/photon separation?

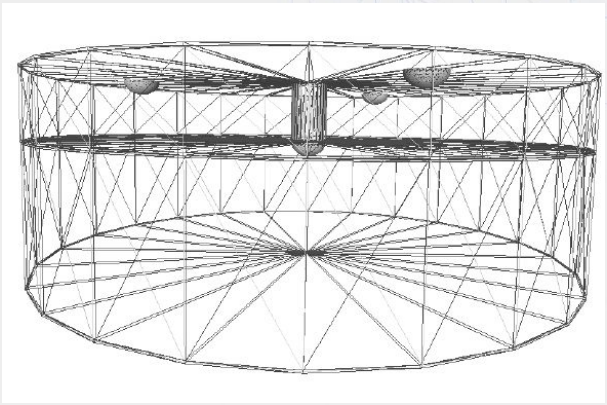
- Good proton/photon separation is needed
- Use segmented water Cherenkov Detector→Modify liner to have separate top and bottom “bladder”
- Top bladder still uses 3 PMTs, bottom bladder uses 1 PMT
- 5 prototypes deployed in 2014, 3 dismantled for other purposes, remaining 2 running stable for 10 years

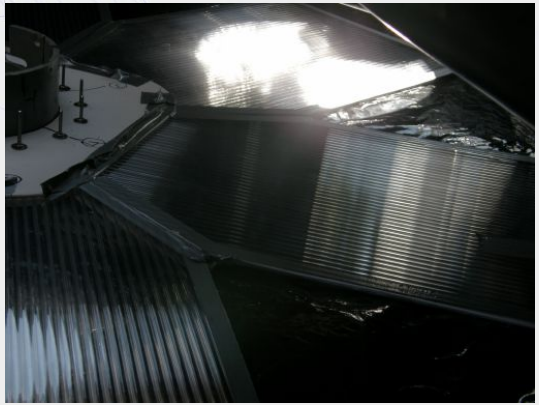


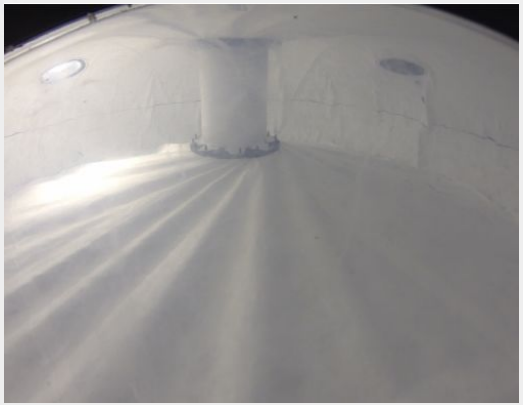
A water volume responds different to photons, $e^{\pm}$ and $\mu^{\pm}$

$$\begin{pmatrix} S_{top} \\ S_{Bottom} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{EM} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{EM} \\ S_{\mu} \end{pmatrix}$$

$$\begin{pmatrix} S_{EM} \\ S_{\mu} \end{pmatrix} \mathcal{M}^{-1} \begin{pmatrix} S_{top} \\ S_{Bottom} \end{pmatrix}$$



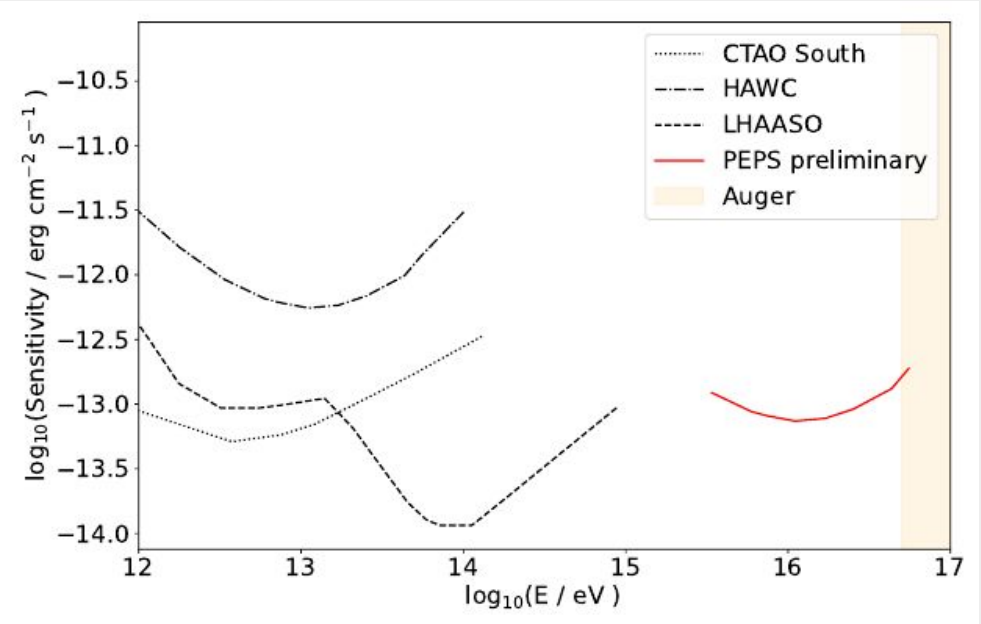




PEPS: Future Plans

Large array with segmented WCD, spacing of 145 m, at the Pierre Auger Observatory

- Preliminary studies are encouraging, it will be hard but not impossible to see photons!
- Including the Auger underground muon detectors in the separation power might allow improvement of sensitivities at lower energies as well as more advanced techniques like DNNs
- Number of detectors: 55/km^2
- Possible synergies within our collaboration: IceCube scintillators, Cherenkov telescopes
- If the proof of concept successful, expected strong synergies also with Auger, SWGO, CTAO, IceCube



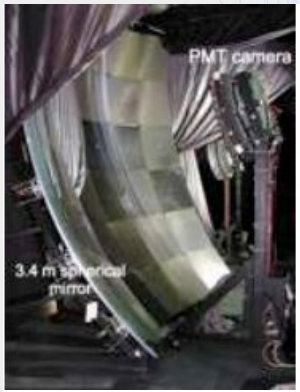
FAST@Auger

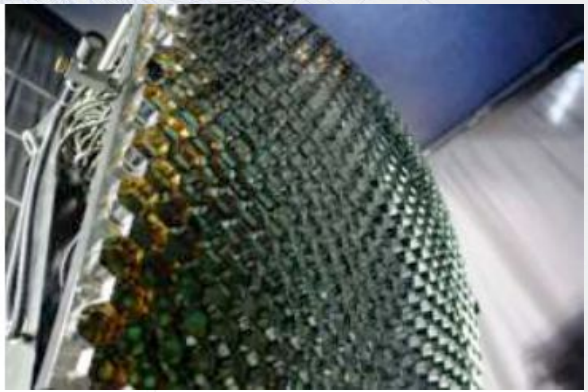
Content by Toshihiro Fuji

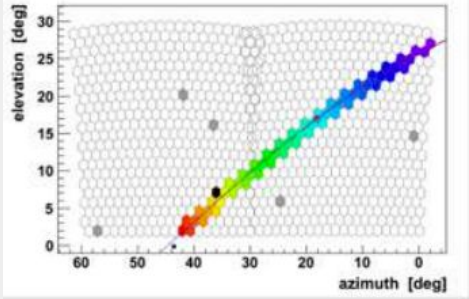
FAST: Fluorescence detector Array of Single-pixel Telescopes

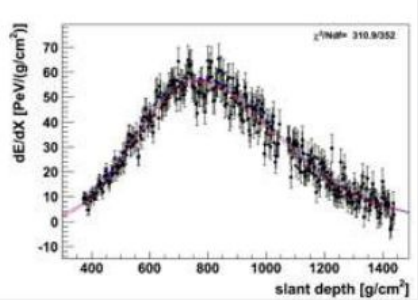
- Target: >$10^{19.5}$ eV, ultrahigh-energy cosmic rays, neutrinos and gamma rays
- Huge target volume → Fluorescence detector array

Fine pixelated camera→Too expensive to cover large area

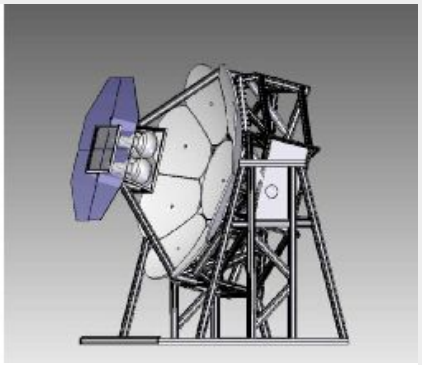


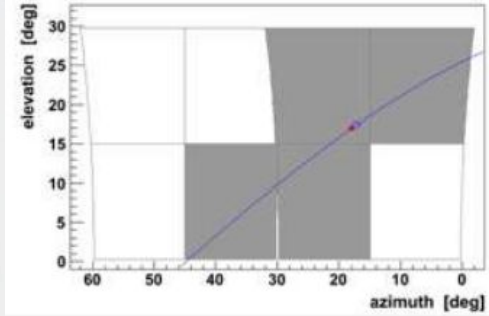


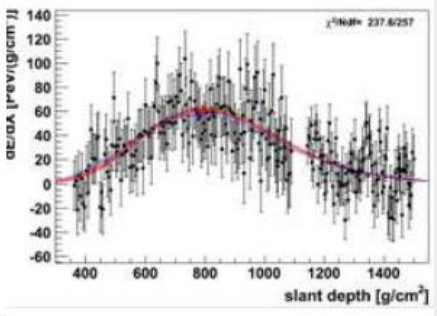




Smaller optics/fewer pixels → Low cost → Cover large area



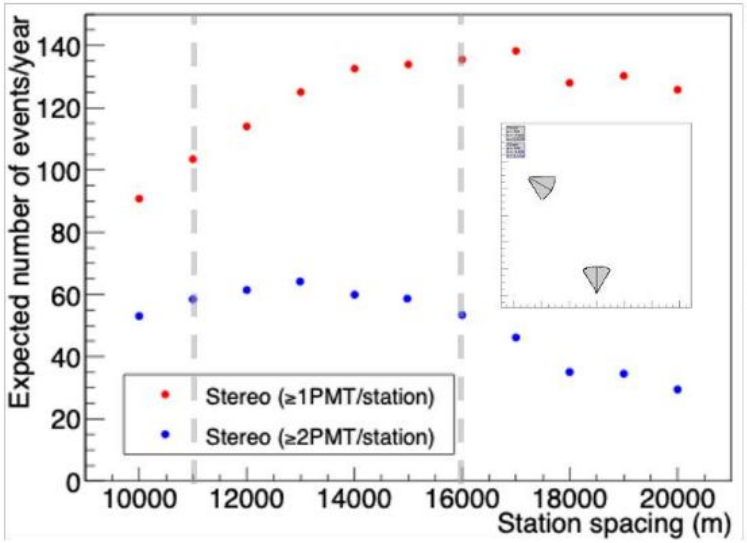


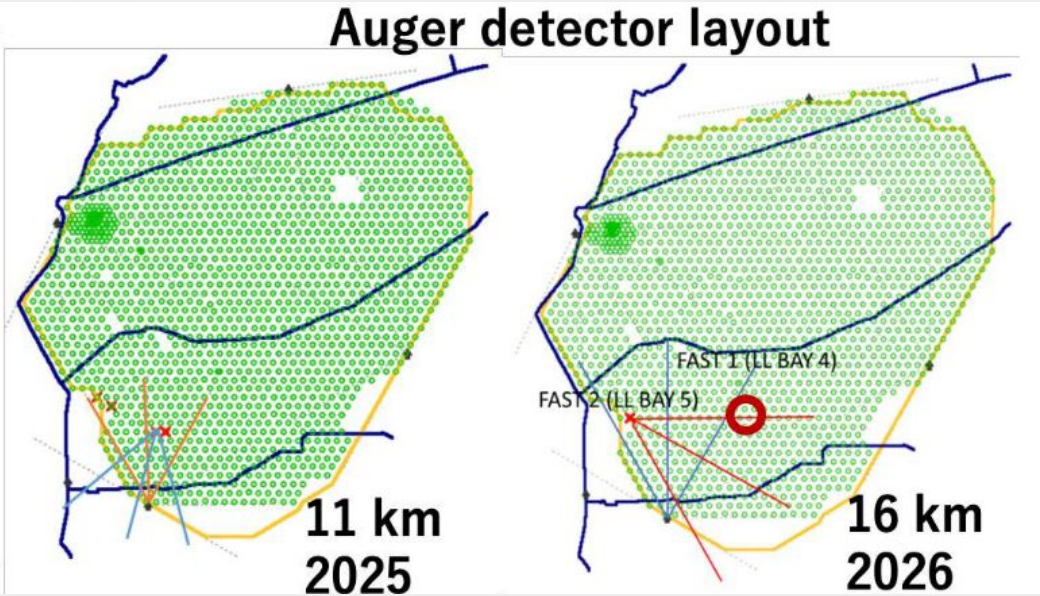


FAST: Future Plans

- A lot of analysis done on FAST@TA setup →to be applied to FAST@Auger data
- Optimization of FAST design:
  - 9 segment mirror → 4 segment mirror,
  - 1/4 size container, modified PMT design + new electronics
- Test Array setup:
  - Start with ~11 km spacing (validate stereo observation with high quality events)
  - Move to ~16 km to increase statistics

FAST@Auger
w/ external trigger
Work: Jakub Kmec, Petr Hamal



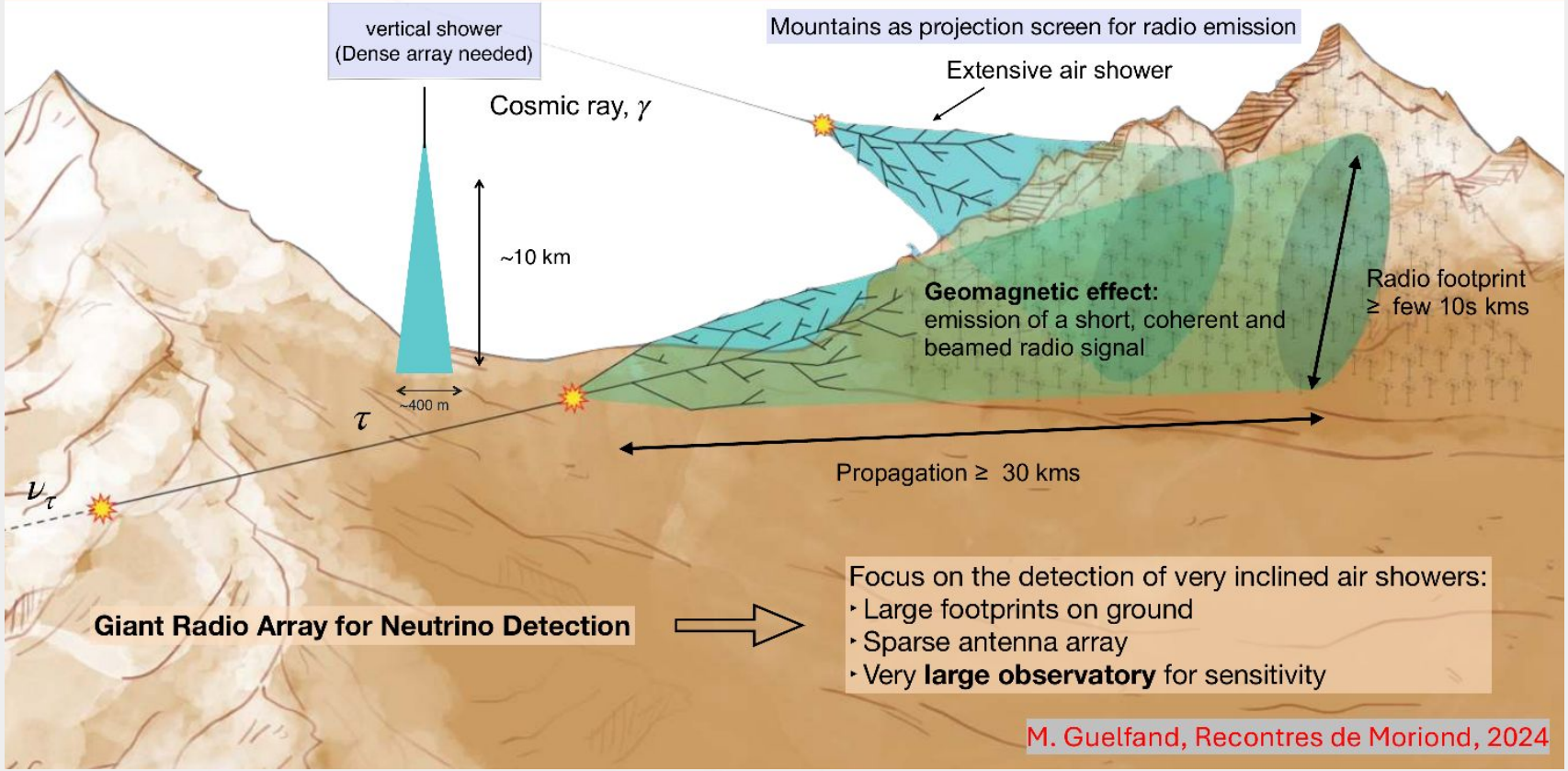


GRAND@Auger

Content by Charles Timmermans

GRAND: Giant Radio Array for Neutrino Detection

- 200,000 antennas total at 20 sites



GRAND Prototypes

Goal: detection of very inclined cosmic rays with autonomous trigger on radio signals

- The Horizon Antenna
  - 3 Butterfly arms at 3.5m + LNAs
  - Wifi antenna connected to bullet
  - Solar panel + Battery
  - DAQ box with electronics
  - 30-200 MHz analog filtering

- GRAND@Auger
  - One of three prototype arrays
  - 10 antennas
  - Deployed in AERA in over ~1 year (03/2023-03/2024)

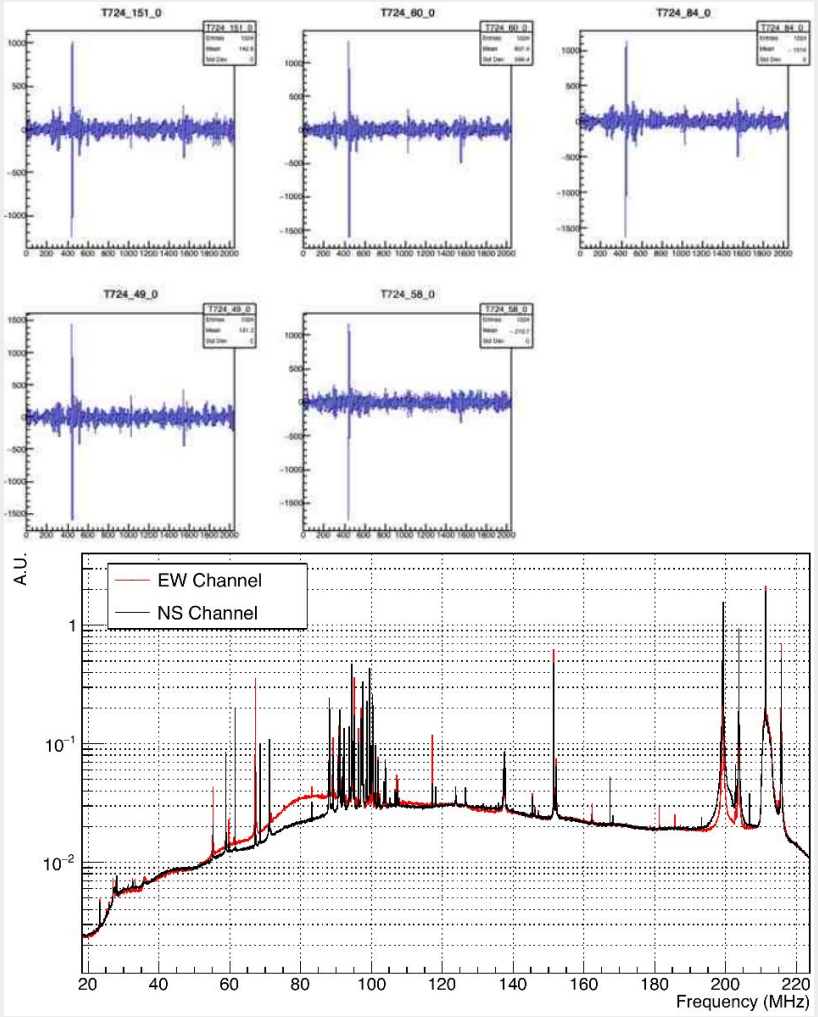
  → Cross-calibration with AERA

GRAND Prototypes

- Triggered events with multiple stations have been measured

→ Seem to point to known noise sources

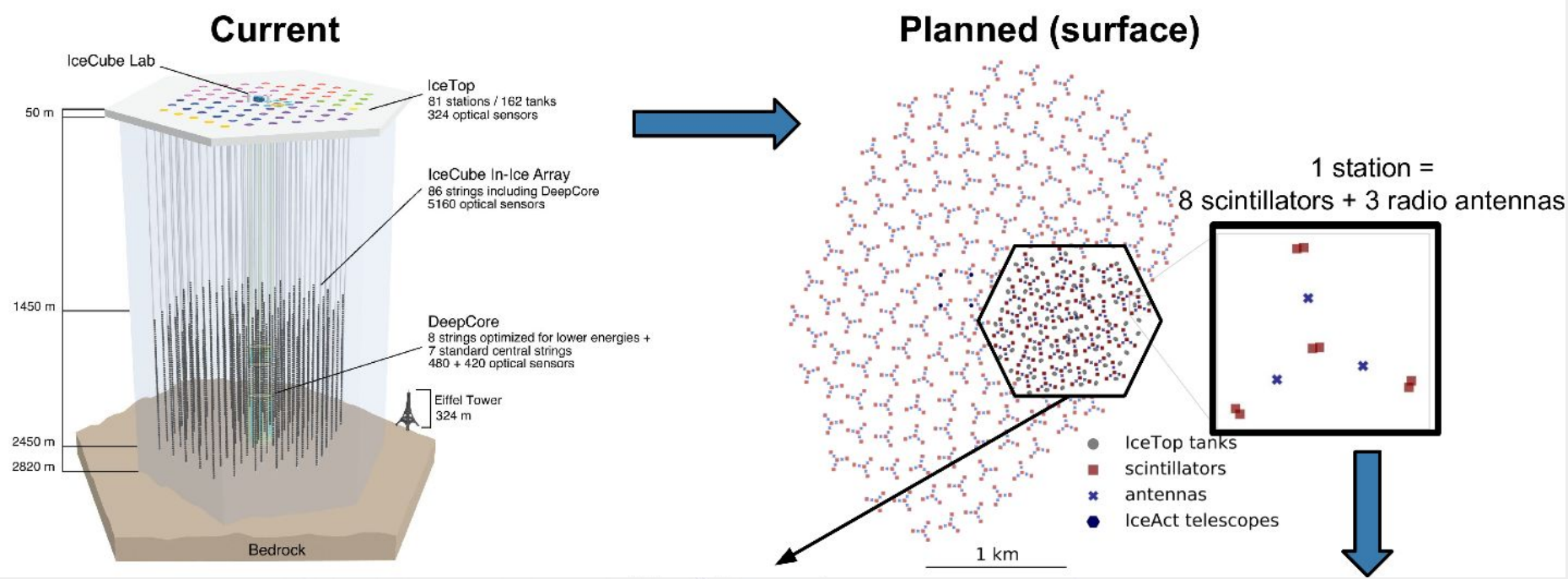
- Next Steps
  - Main goal is to find coincidence events with Auger
    - Need to reduce the threshold!
    - Reduce noise contribution from battery charge controllers by adding filters
    - Use digital filters to reduce the noise contribution from radio and TV
  - A writeup of GRAND@Auger is in preparation



IceCube@Auger

Content by Benjamin Flaggs, Stef Verpoest

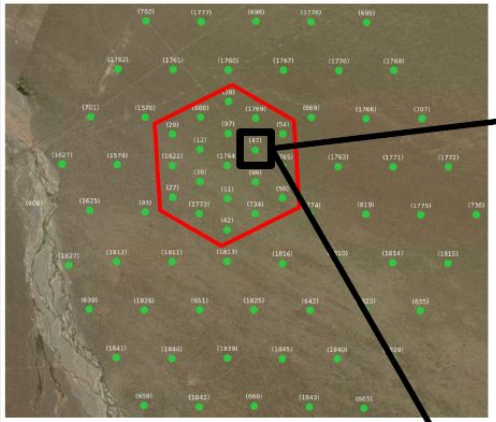
IceCube: Testing Gen2 Surface Array at Auger

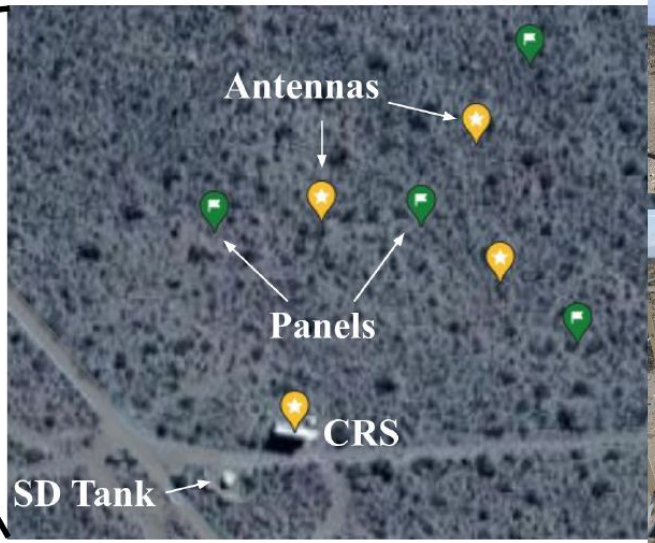


Size of current IceCube surface array

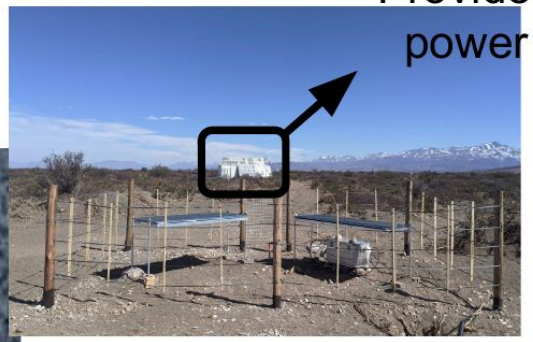
Full prototype station deployed within SD-433

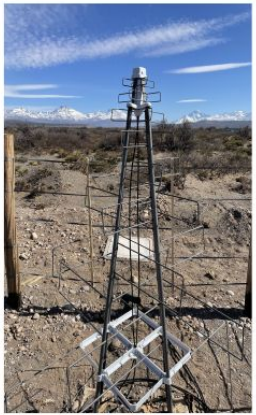
IceCube: Testing Gen2 Surface Array at Auger





Provides power





Deployed Aug. 2022

Stable data taking since Nov. 2022

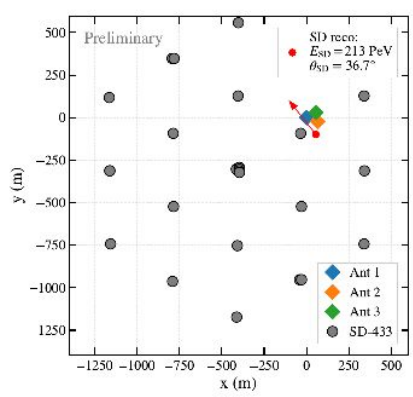
→Coincident event search based on IceCube radio reconstruction

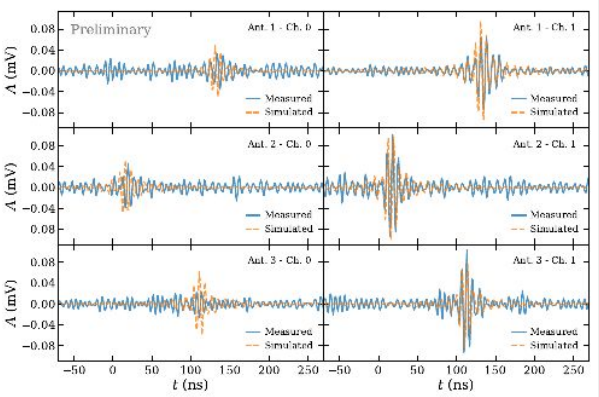
IceCube: Testing Gen2 Surface Array at Auger

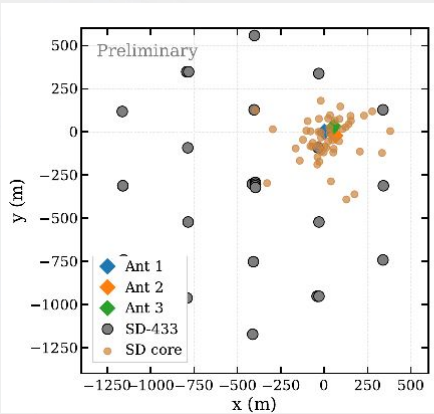
- For each radio event candidate
  - SD events in a window of ±0.5 s are selected
  - Rate of events in the SD dataset is only of the order 10 mHz
  - Directions reconstructed with radio signals and SD detector are then compared

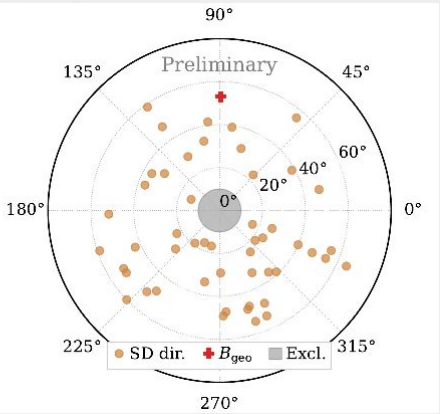
  → If the difference is smaller than 5° events are considered to be caused by same air shower
  - For validation: Use SD reconstruction (shower core, shower axis, energy) to simulate radio signal and compare

  → 50 coincident events detected so far
- Future Plan: Increase size of array



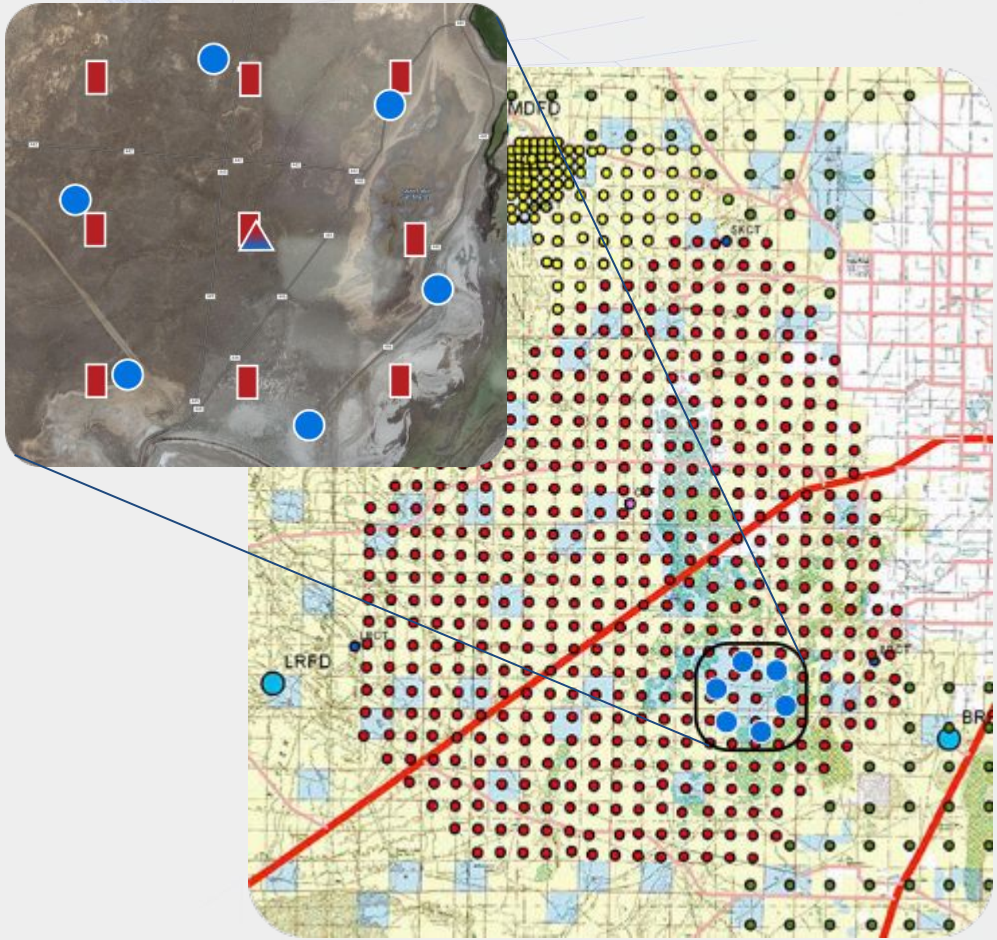






Auger@TA

Overview



Cross-calibration of Auger and TA with an Auger-like SD Array consisting of 8 stations:

- Deployment in south-east corner of TA array
  - 7 Auger@TA (1 PMT) stations (full hexagon)
  - 1 AugerSouth (3 PMT) station (in center)

  → Feature: Auger@TA / Auger South / TA triplet
- Fully independent trigger and measurements
- Comms station housing all equipment to talk to outer hexagon + local CDAS computer etc.

Status overview

- Found correct procedure to bring stations online
- Can now make PMT bases from scratch
  - Bottleneck with procuring HV supplies
  - HV supplies difficult to recover from broken bases

  → Have now figured out a way
- Comms is working very well
- In September/October: Shake-down array and deploy remaining SSDs

Site	Station deployed	Components commissioned	Electronics deployed	SSD deployed	Station up & running
Sam (C-A@TA)	✓	✓	✓	✓	✗
Merry (C-AS)	✓	✓	✓	✓	✓
Pippin (C-TA)	✓	✓	✗	–	✗
Aragorn(1)	✓	(✓)	✓	✗	✗
Arwen (2)	✓	✓	✓	✗	✗
Gimli (3)	✓	✓	✓	✗	✓
Legolas (4)	✓	✗	✓	✗	✗
Bilbo (5)	✓	✓	✓	✗	✓
Galadriel (6)	✓	✓	✓	✗	✗
Frodo (Comms)	✓	✓	✓	–	✗

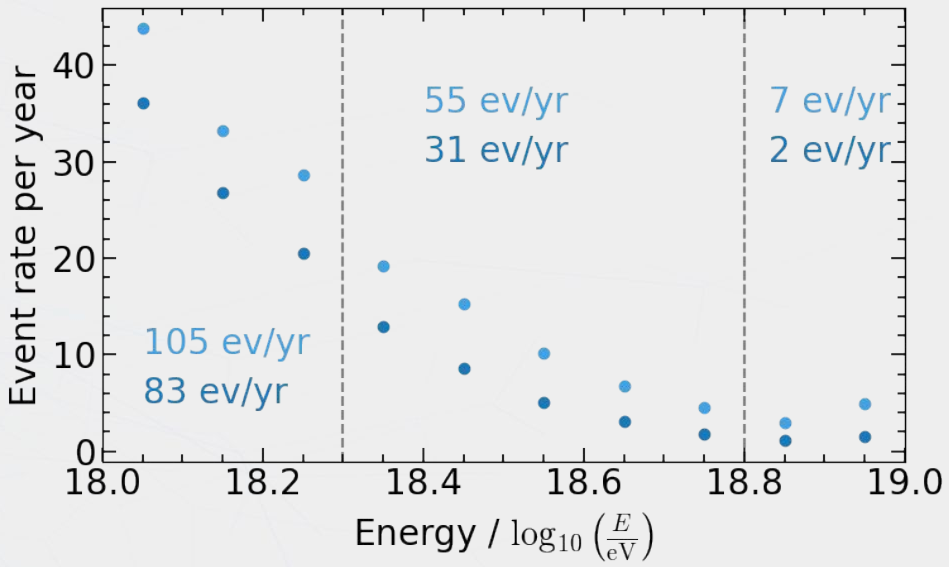
Single Hexagon Projected Event Rate & Flux Measurement

- Calculate expected event rate of Single Hexagon array for each energy bin for
  - Full 5 x 5 km simulated area (with “TA” core rec.)
  - Events inside 1.125km circle (A@TA only HQ)

  → ~120 high quality events/yr using Auger@TA only

  → ~170 high quality events/yr using TA core rec
- Using $\frac{\sqrt{\sigma_{TA}^2+\sigma_{Auger}^2+\sigma_{SH-FA}^2}}{\sqrt{N}} + \sigma_{signal} \approx 8.11\,\%$ as resolution on Auger@TA flux measurement

  → ~1σ-level flux comparison possible with one year of data



Area	Events per year
5x5 km	167
R ≤ 1.125 km	117

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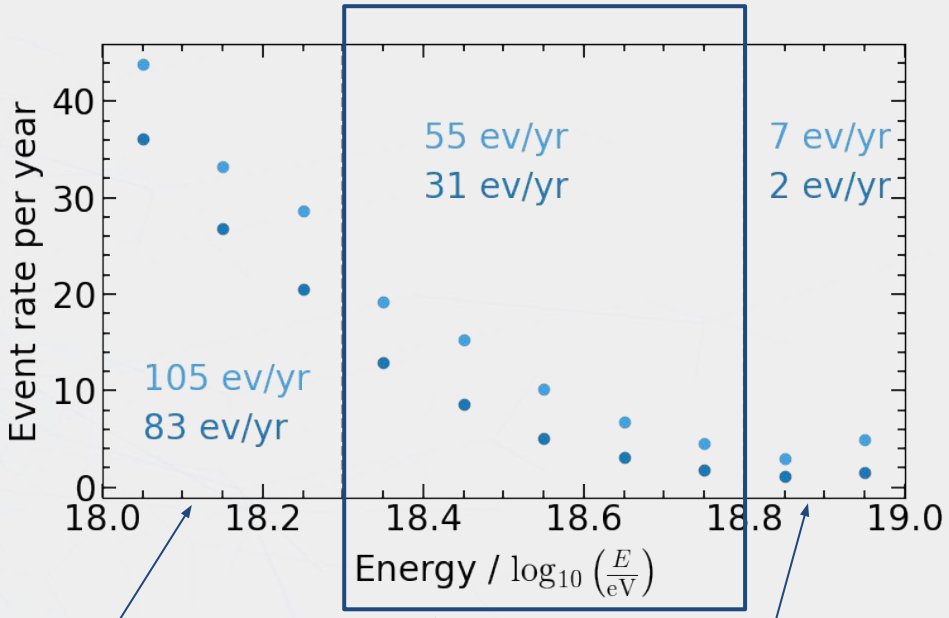


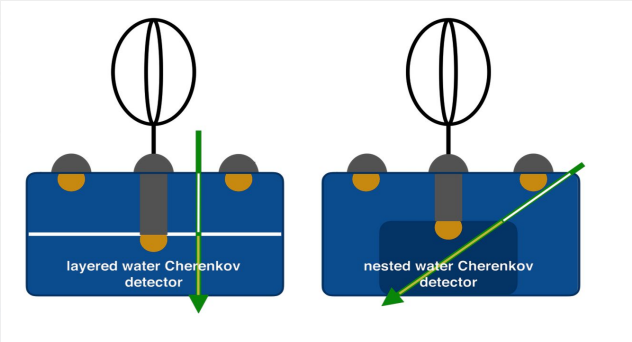
low *E* station by station cross-calibration

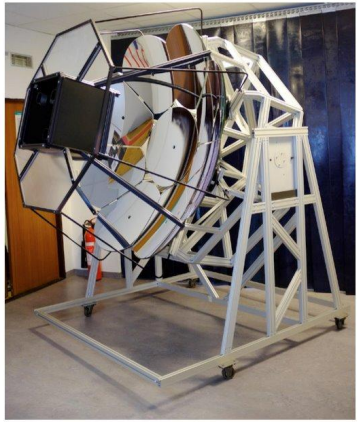
direct comparison of Northern flux with Auger-like and TA arrays

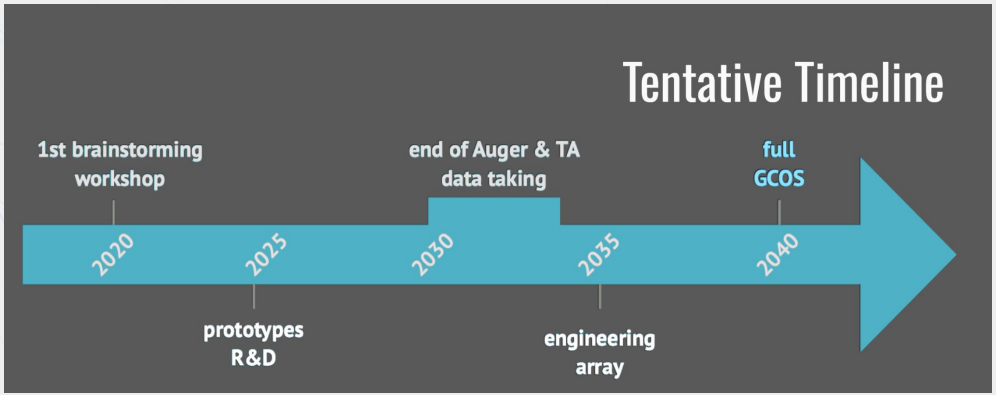
investigation of energy-dependent station response differences

Summary and Outlook

- Pierre Auger Observatory strongly collaborating with other experiments
- More are always welcome!
- Extend all current collaborations further
- Global Comic Ray ObServatory prototyping:
  → 40,000km (13x the size of Auger)

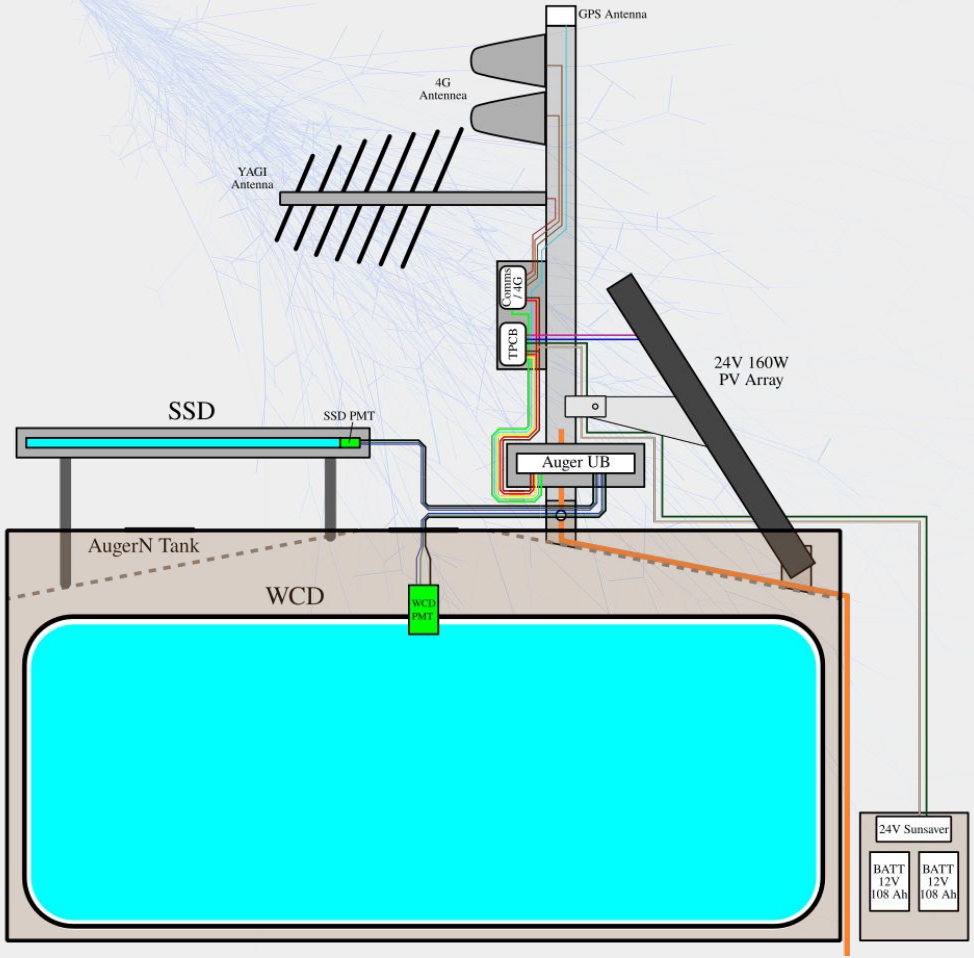






Backup Slides

The Auger@TA Station



Design and implementation

- Retrofit of AugerNorth hardware with standard Auger components
  - Prototype AugerN tank shell
  - Single central WCD PMT with Auger base
  - Auger UB and TPCB
- Thanks to efforts of KIT/BUW an SSD being mounted on every station
  - SSDs assembled by KIT from spare material
  - 8 new SSD supports by KIT
  - PMTs + Bases from BUW
  - SSD to UB cables from Malargüe
- Upgraded solar power system 24V/160W/216Ah
- Internet connectivity via 4G cell network/modem
- Local comms via YAGI 2-way communication
- Independent trigger and DAQ at central station

Simulation Status & Quality Cuts

simulation work by Adriel Bartz Mocellin

Simulation status

- Auger@TA detector simulation with Offline in place
- Napoli/praha CORSIKA showers in range
  $E_{MC} \in 18.0 - 19.0 \log_{10}(E/eV)$
- Throw in 5 x 5 km square around central hexagon for Single Hexagon (SH) and Full Auger (FA) array
- Same random seeds/shower for each generated event for each detector configuration

→ Allows 1:1 comparison

Using TA to regain events

- Events outside of SH under-reconstruct energy
- Events on SH border over-reconstruct energy

→ Can cut on circle inside hexagon (R ≤ 1.125 km) at cost of losing a lot of events

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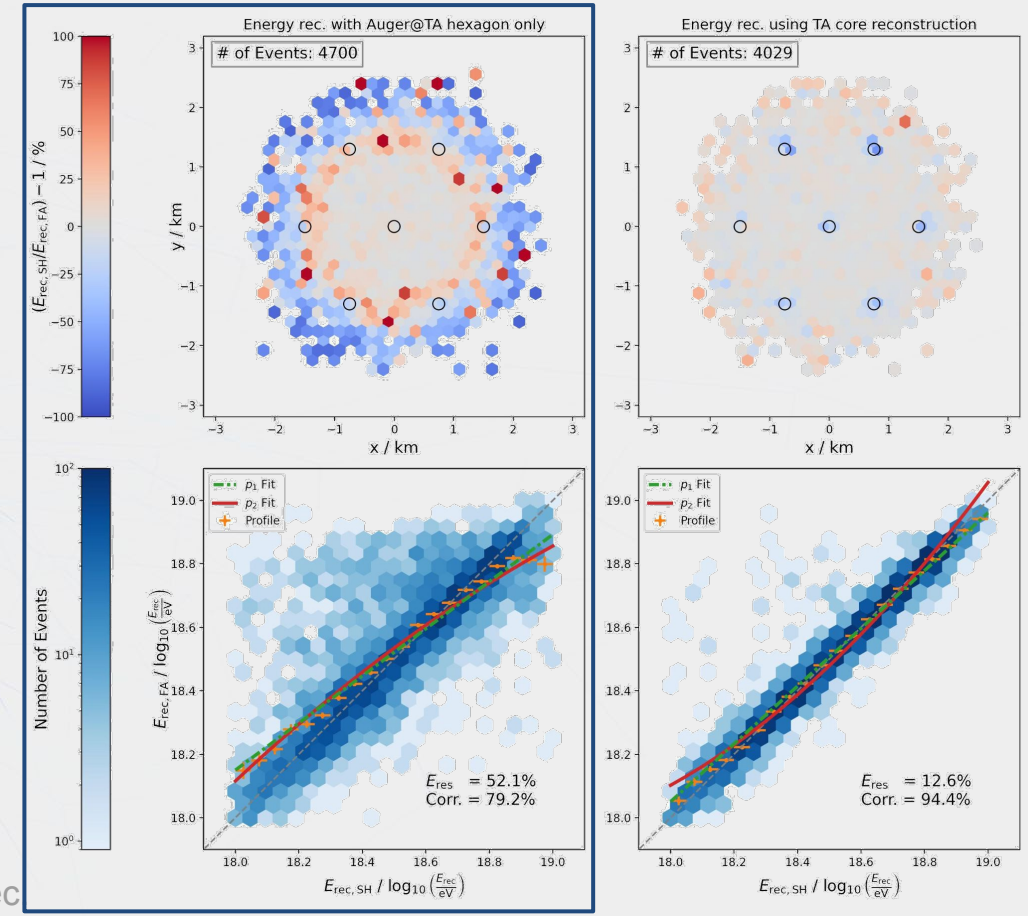

Simulation Status & Quality Cuts

simulation work by Adriel Bartz Mocellin

Simulation status

- Auger@TA detector simulation with Offline in place
- Napoli/praha CORSIKA showers in range

$$E_{MC} \in 18.0 - 19.0 \log_{10}(E/eV)$$

- Throw in 5 x 5 km square around central hexagon for Single Hexagon (SH) and Full Auger (FA) array
- Same random seeds/shower for each generated event for each detector configuration

→ Allows 1:1 comparison

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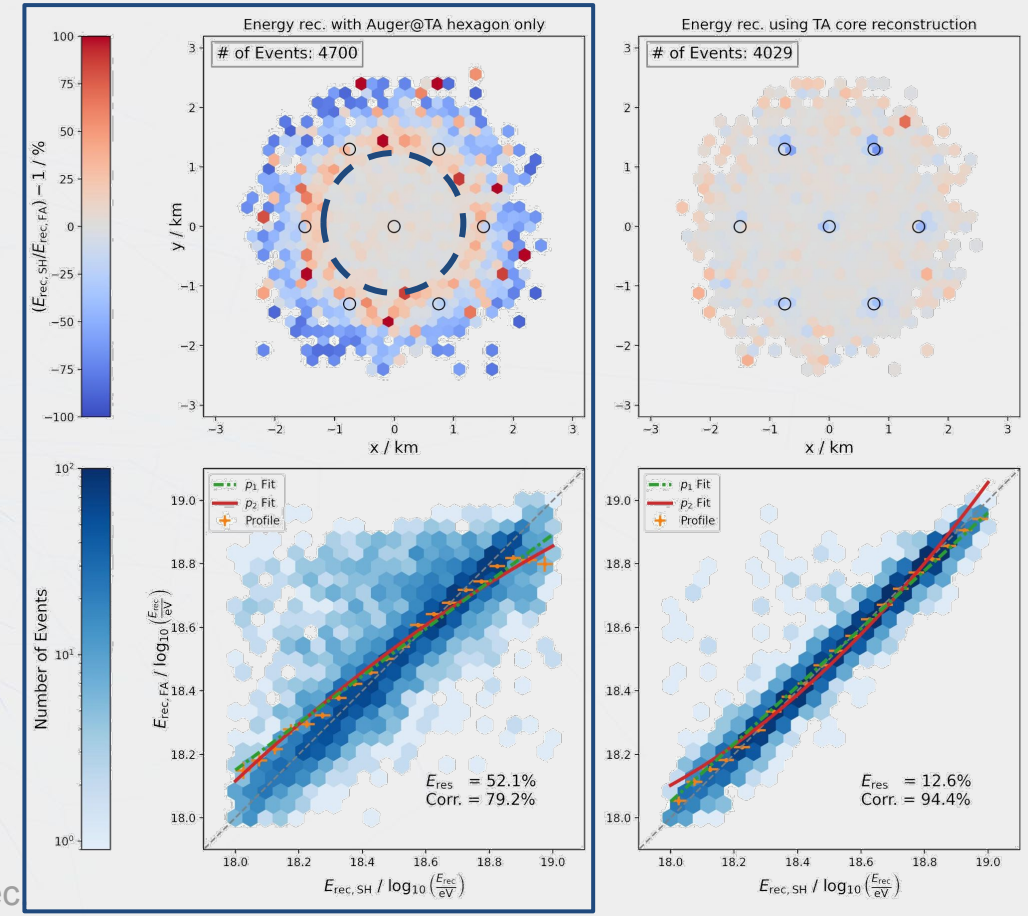

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