# Outlook for future Ultra-high energy cosmic ray experiments

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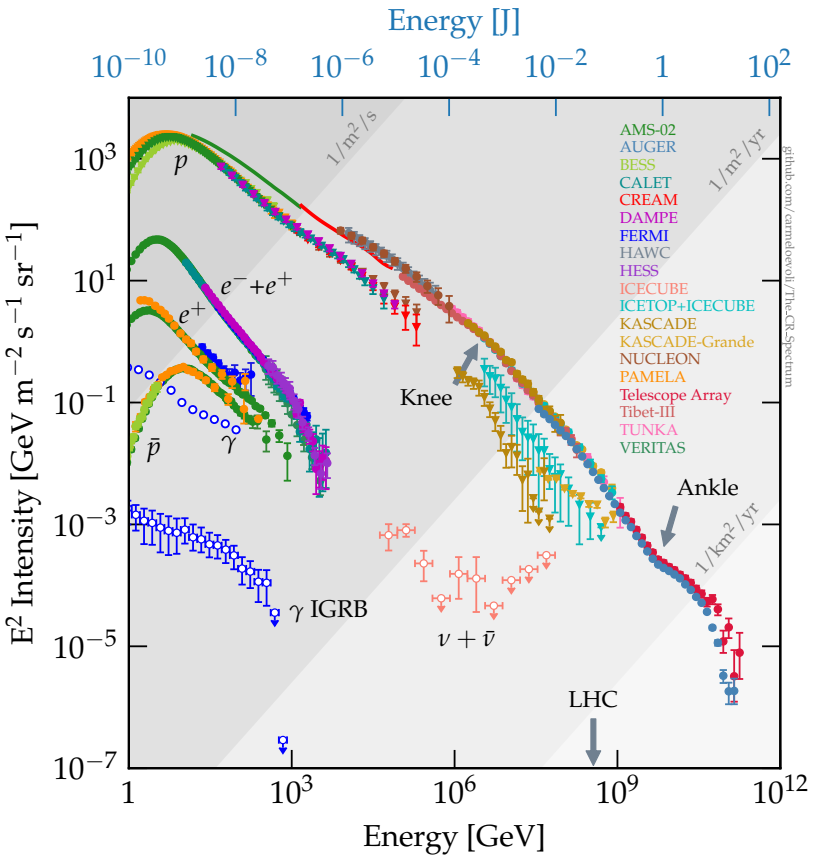
13th **C**osmic **R**ay **I**nternational **S**tudies &
**M**ulti-messenger **A**stro particle **C**onference

18th Jun 2024

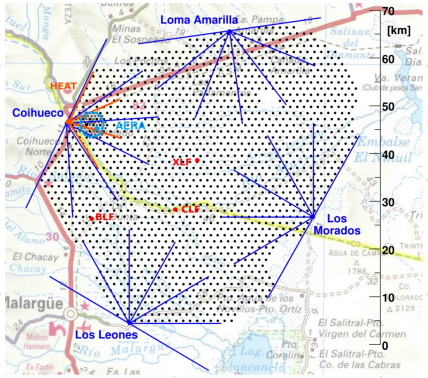
Osaka Metropolitan University

# Ultra-High Energy Cosmic Rays



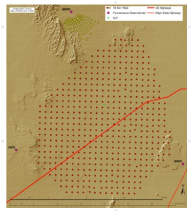

10.5281/zenodo.1468852

Pierre Auger Observatory (Auger)




https://auger.org

Telescope Array (TA)



Energy spectrum

$E > 10^{19.5}$ eV

Origin of cutoff

Acceleration max Rigidity?

Spectrum difference from anisotropy?

Mass composition

Heavier mass indication

Anisotropy

Auger anisotropies

TA hotspots

Interpretation relay on rigidity

# AugerPrime: Upgraded Surface Detector +

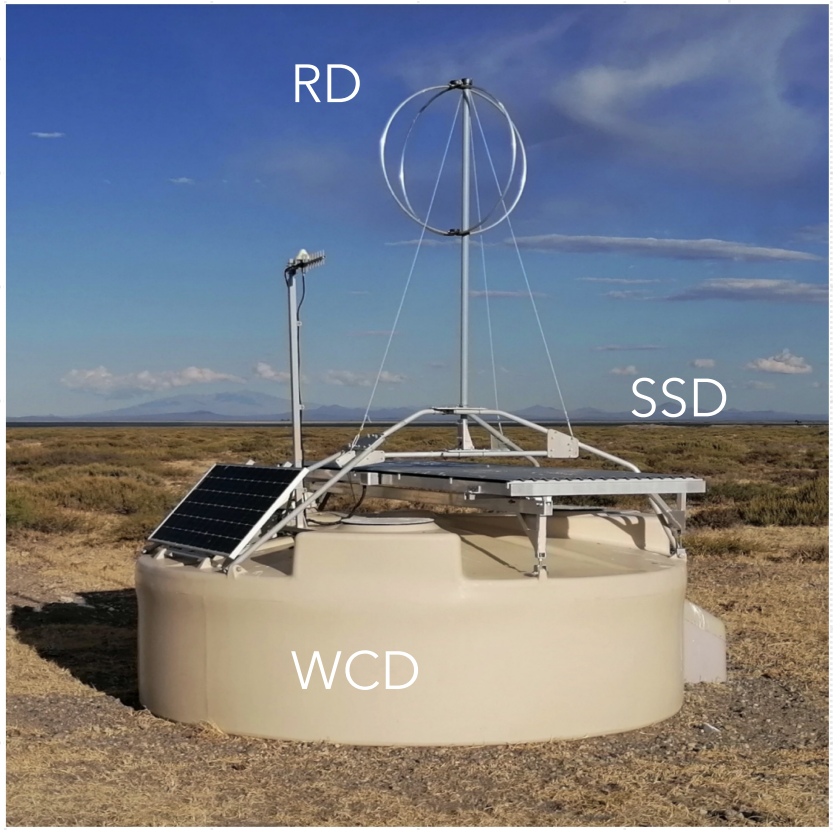
## Upgrade of the Pierre Auger Observatory

- Add information about hadronic interactions
- Evaluate the possible existence of a proton fraction
- Understand the origin of the flux suppression

## Upgrades on

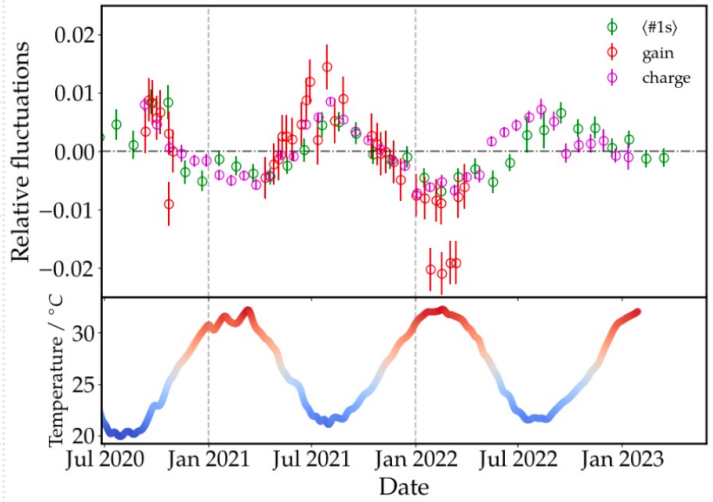
- Dynamic range extension with a new PMT in WCD
- Plastic scintillator (SSD): (3.8 x 1.9) $m^2$
- Radio Detector (RD)
- Underground Muon Detector (UMG)

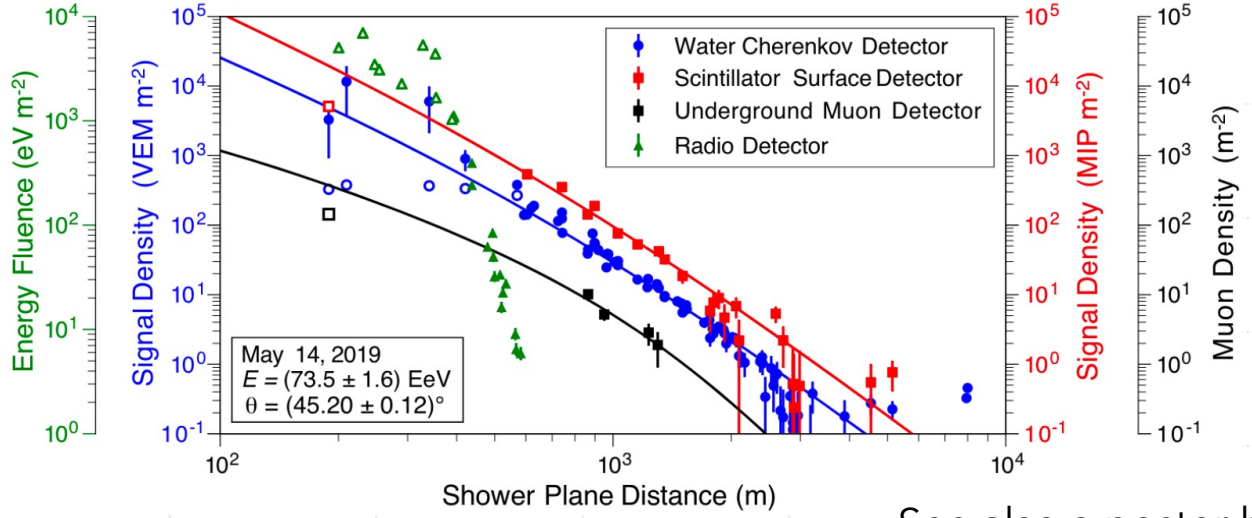
- WCD+SSD stations started operations since 2023.




Based on Salamida, 2023

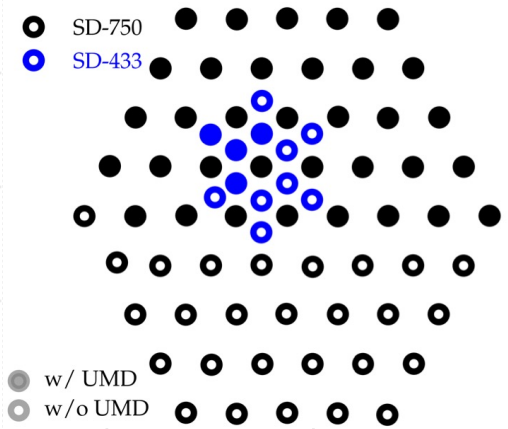
# Auger Prime status

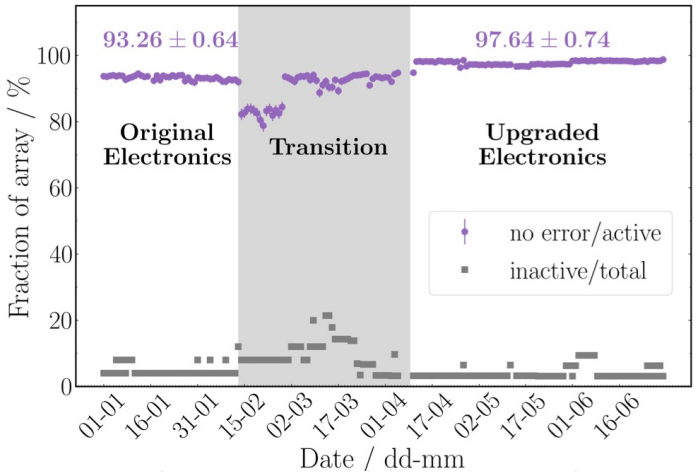



Salamida, 2023

See also a poster by Mohit Saharan



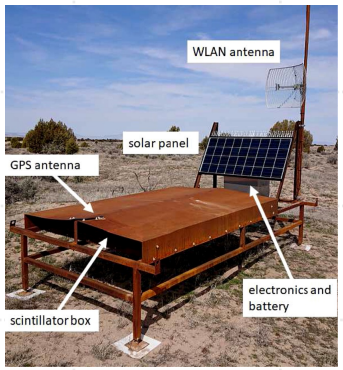

de Jesús 2023

Hybrid event provides detailed information from EAS

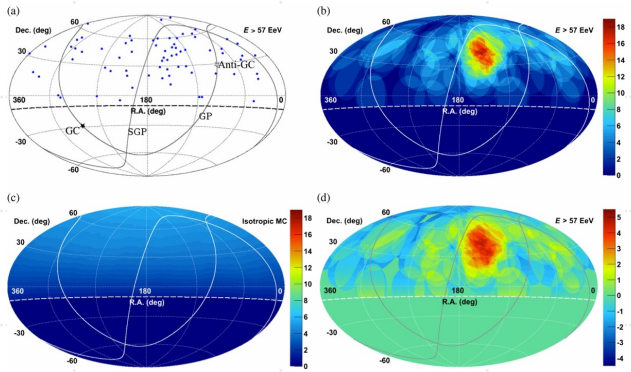
Deployment of UMD and RD will be completed soon!

# TAx4

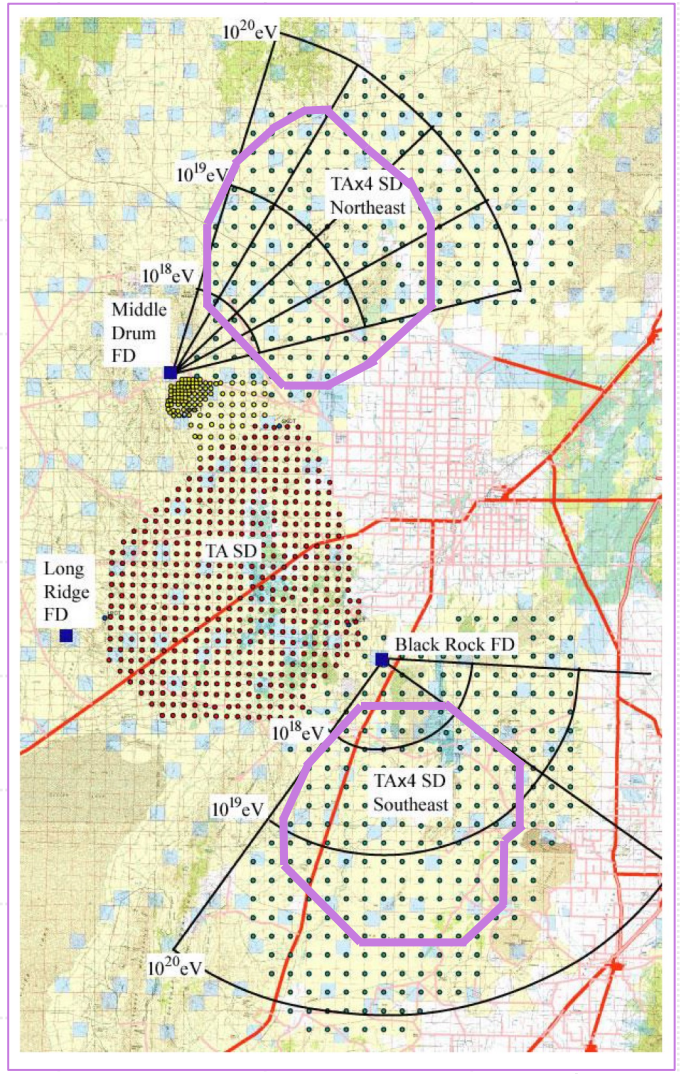
- Area extension of the Telescope Array experiment
  - 700 km$^2$ to 2800 km$^2$
  - Tring to validate the existence of the hot spot
- TAx4 Scintillation detector
  - Improved dynamic range
  - (1.5 x 2) m$^2$
  - 257 of 500 deployed ~ +1000 km$^2$



TA coll., 2021

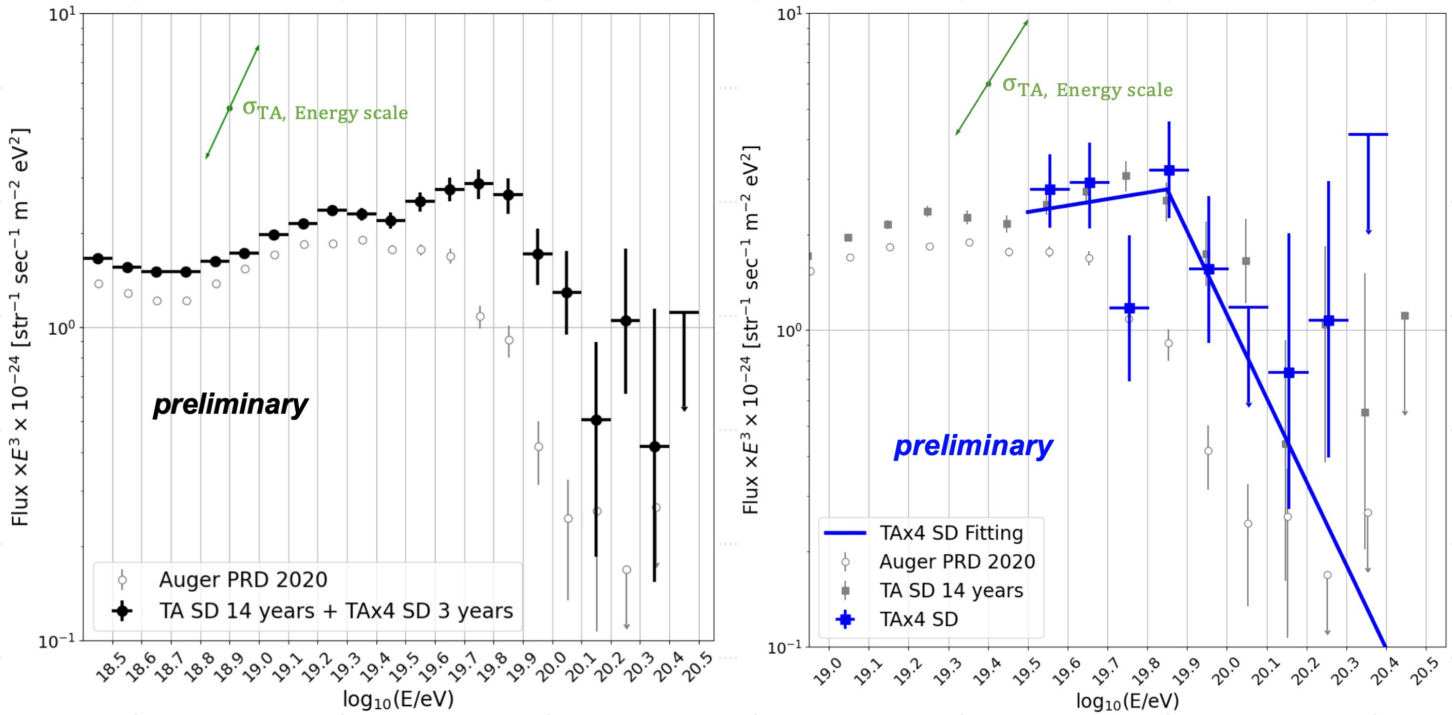


Abbasi et al., 2014



1.2 km -> 2.08 km spacing

# TAx4 Preliminary Spectra




Fujisue, 2023

Further systematic studies would be performed by Auger-TA with Auger-SSD, TAx4-SD

# 2030s & beyond, requirements?

| Experiment | Feature | Cosmic Ray Science* | Timeline |
|---|---|---|---|
| Pierre Auger Observatory | Hybrid array: fluorescence, surface $e/\mu$ + 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 $X_{\max}$ + $e/\mu$ 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 |

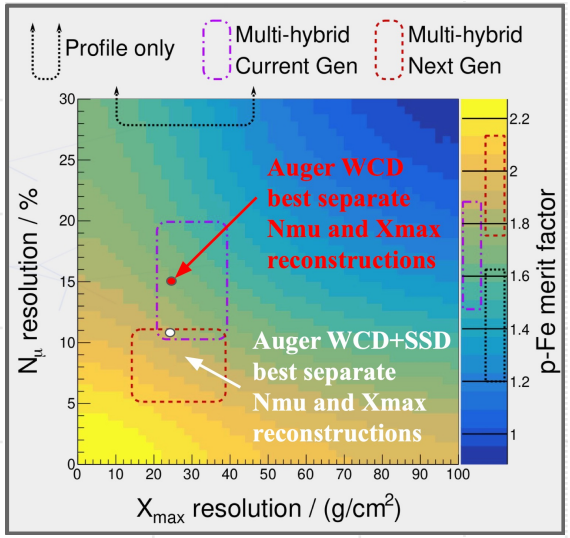
2025 2030 2035 2040

*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.

Coleman et al., 2023

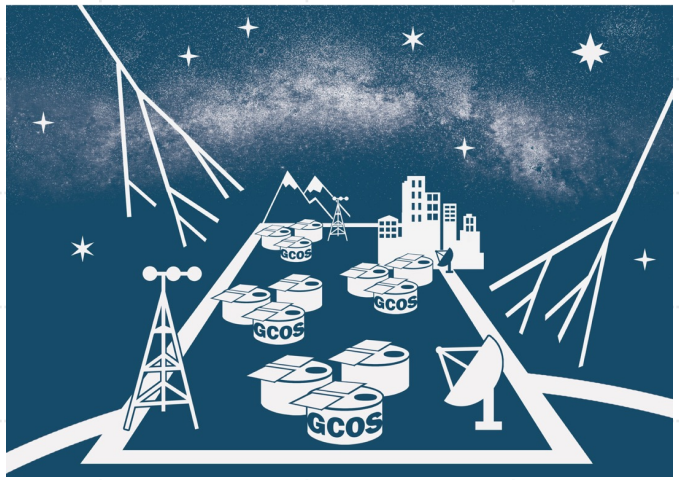
AugerPrime and TAx4 contributions are etablish to fix the strategy of the future UHECR experiments.
(Hadronic interaction model, muon puzzle, proton fraction)

Larger exposure is required.
Mass sensitivity is important: $X_{\max}$ and $N_{\mu}$

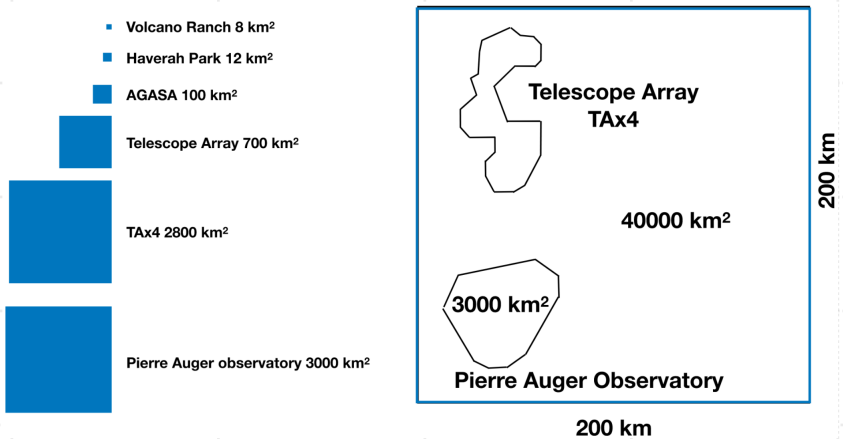



from a slide by Mayotte in 2nd GCOS workshop

# Global Cosmic Ray Observatory




http://particle.astro.ru.nl/gcos/




Proposed in 2021, still in design phase

Aim: Accurate UHECR measurement

- UHE Multi-messenger astrophysics
- Astrophysical transients
- Dark matter
- Particle physics
- Fundamental physics
- Geophysics & Atmospheric science

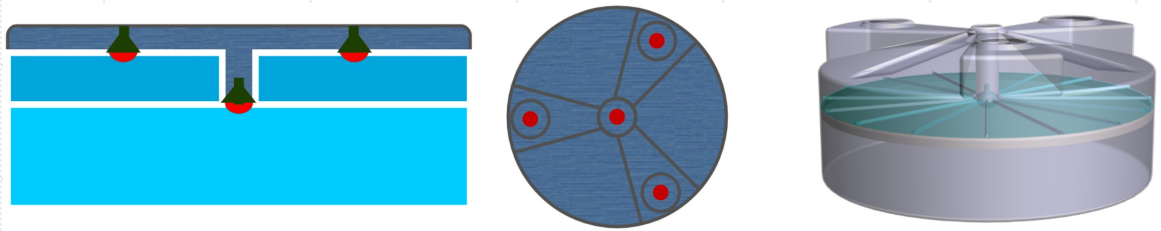
Whole sky exposure with 40,000 ~ 80,000 km$^2$

To be sensitive in rigidity.
$X_{max}$ resolution < 20 g/cm$^2$ is preferable.
(10 – 15)% energy resolution.

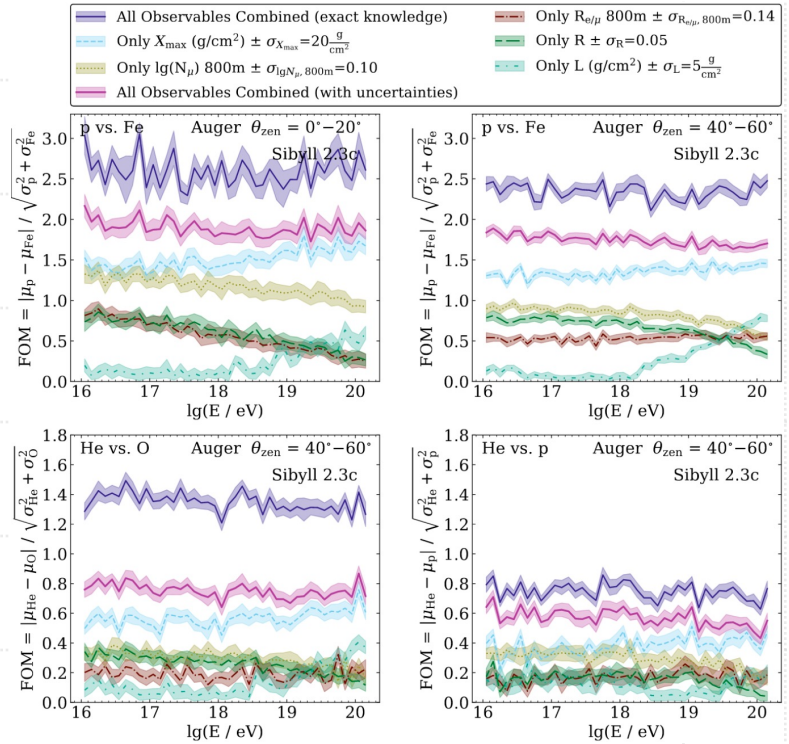
Several measurement technique will be combined.

# GCOS-Surface Detector

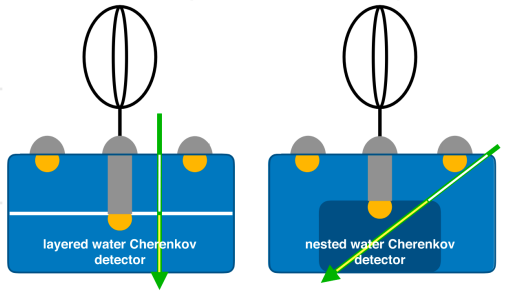
- Water Cherenkov Detector or Scintillator.
  - Need 10,000+ detectors, need costly effective
- e/mu discrimination is required ($N_{mu}$)
  - WCD+SSD (as AugerPrime)
  - Double layer? (Letessier-Selvon et al, 2014)
- < 0.5 deg angular resolution with ~2 km spacing
- $X_{max}$ sensitivity with Machine Learning, hopefully.



Letessier-Selvon et al., 2014




Coleman et al., 2023

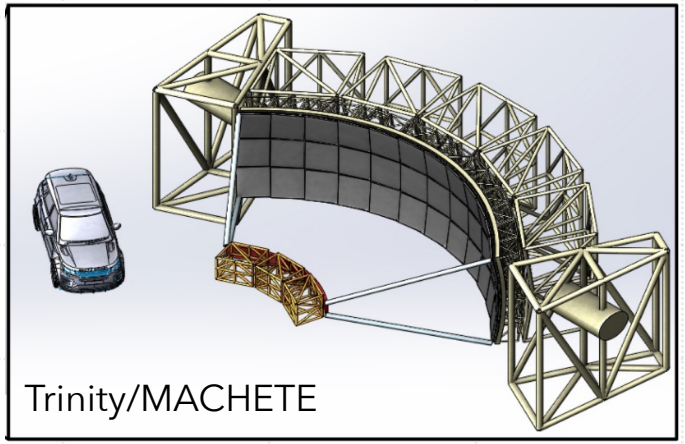


# GCOS-FD/RD

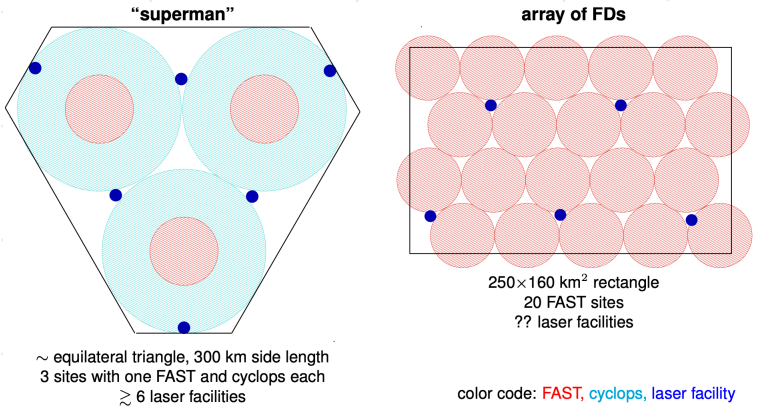
- Fluorescence Detector
  - Pros:
    - Direct $X_{max}$ measurement
  - Note:
    - Fluorescence yield
    - Aerosol monitoring
- Radio Detector
  - Pros: Long-term stability
    100% duty cycle
  - Note:
    - Galactic sky background

| | $\sqrt{A/\Omega_{pix}}$/(m/deg) | $R_{max}$/km at $10^{20}$ eV | stations for GCOS | cost/station/M$ | total cost/M$ |
|---|---|---|---|---|---|
| Cyclops | 13 | 60 | 3.5 | 2 | 7 |
| Auger | 1.2 | 45 | 6.3 | 2.4 | 15 |
| FAST/CRAFFT | 0.07 | 25 | 20.4 | 0.4 | 8 |

From slide by Unger in 3rd GCOS WS



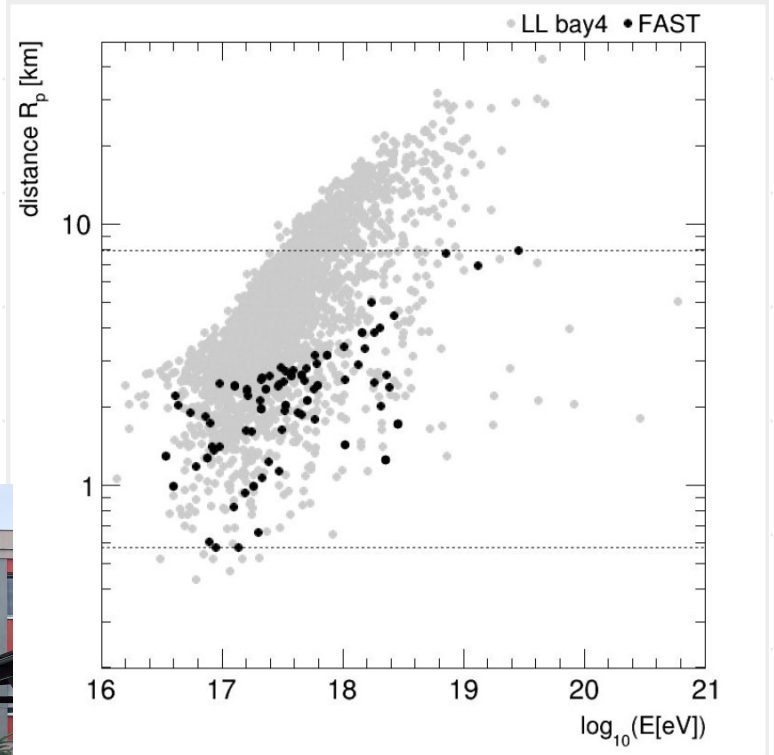


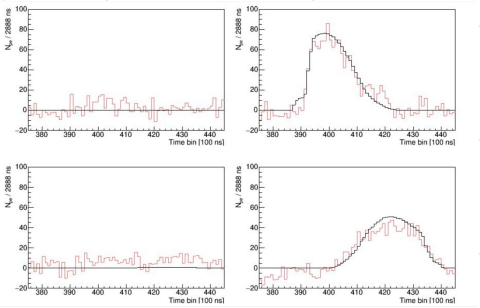



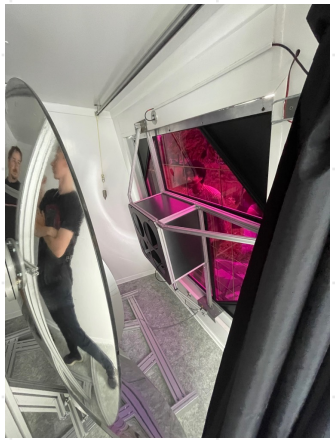

From slide by Unger in 3rd GCOS WS

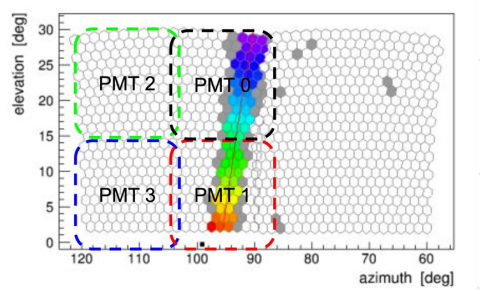
# Fluorescence Array of Single-pixel Telescopes





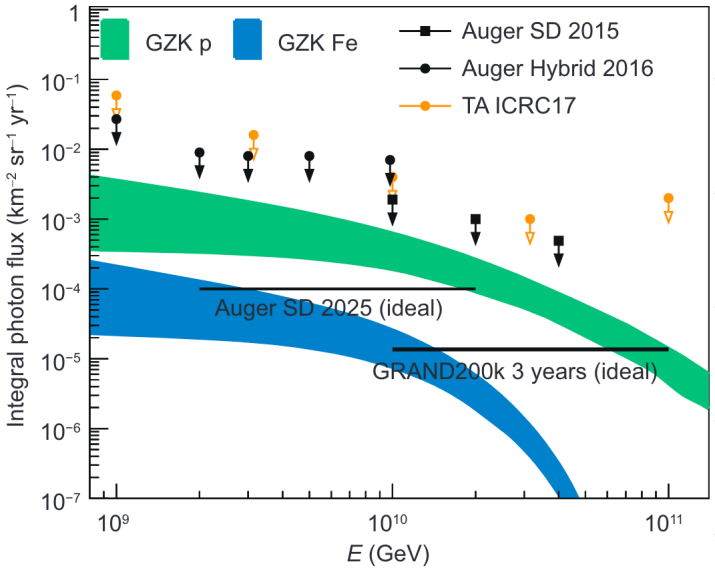





FAST prototype
since 2016
@ Auger & TA site

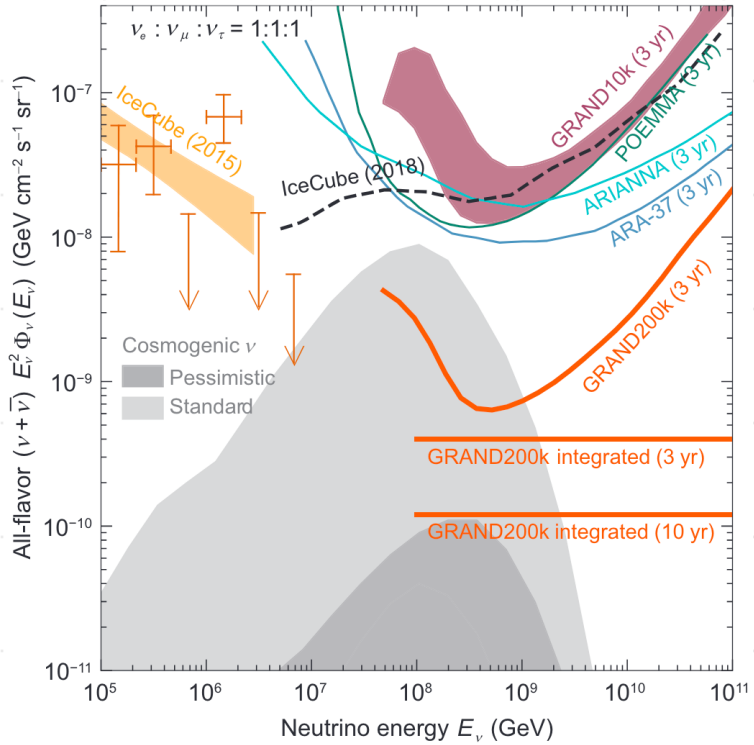
# Giant Radio Array for Neutrino Detection

- Earth-skimming Neutrino & Cosmic Rays by observing radio.
- ~100% duty-cycle observation with 200,000 km$^2$

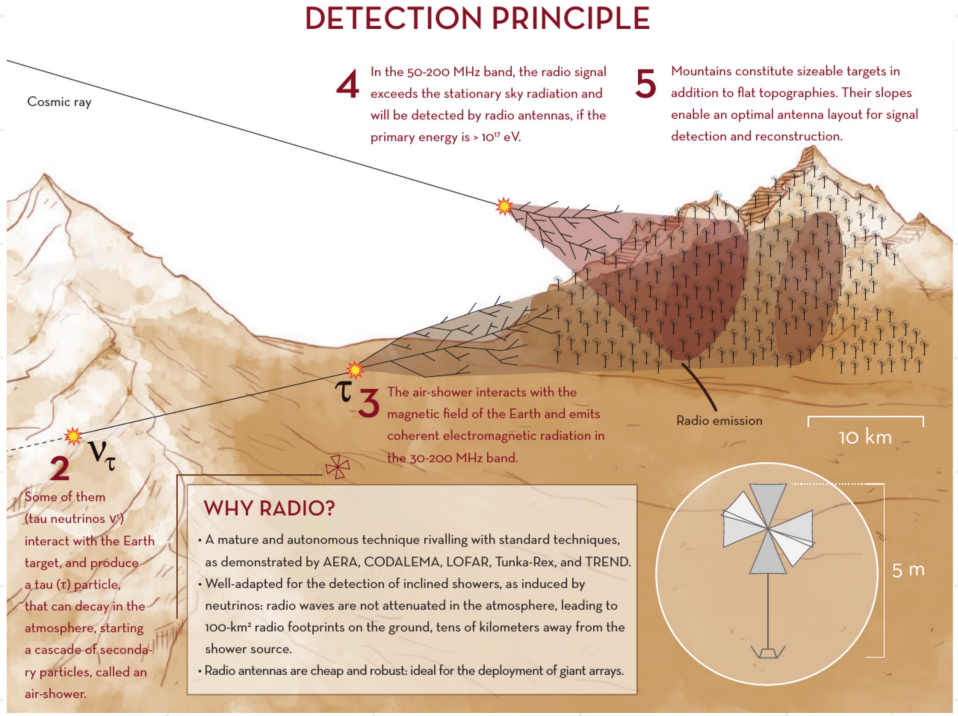



de Mello Neto, 2023

$X_{max}$ resolution ~ 20 g/cm$^2$
x 20 event rate than Auger




Alvalez-Muniz, 2020




https://grand.cnrs.fr/overview/

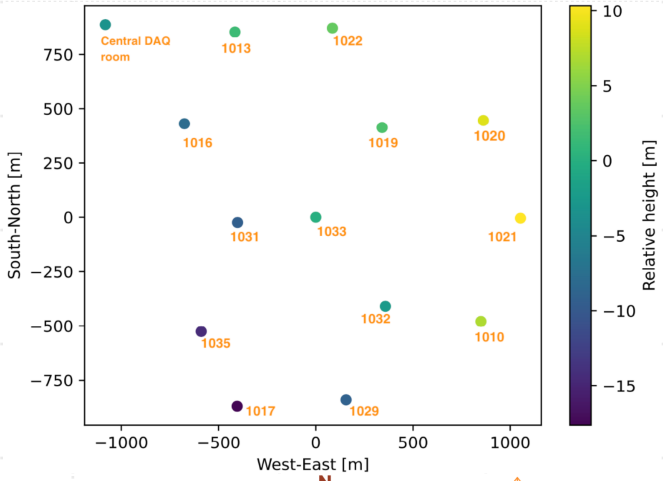
# GRAND prototypes

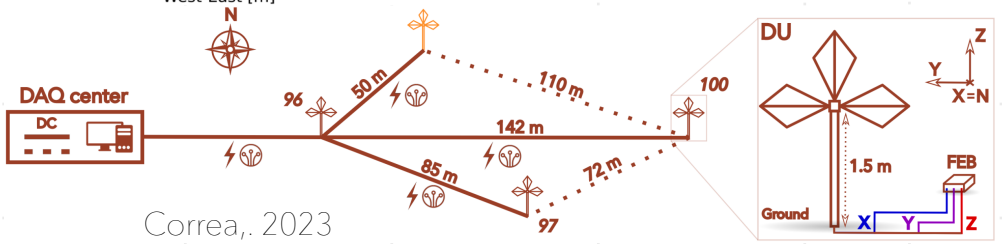
- GrandProto13@Gobi desert
  - 13 Detection Unit (DU) have been installed in Feb. 2023
  - ~~70~~ 80 DU will be deployed.

- GRAND@Nancay
  - 4 DU deployed
  - Development of autonomous radio triggers

- GRAND@Auger
  - 10 DU deployed

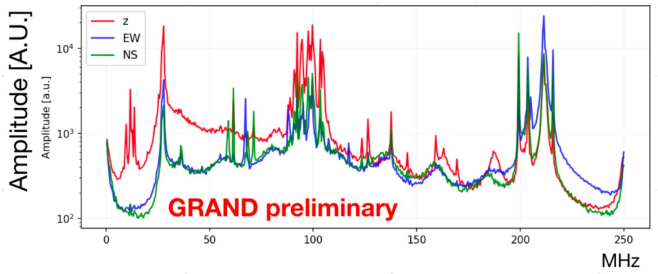
Ma, 2023

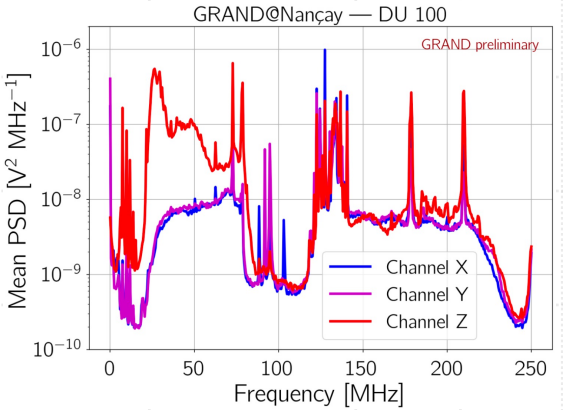



Correa,. 2023

de Mello Neto,. 2023



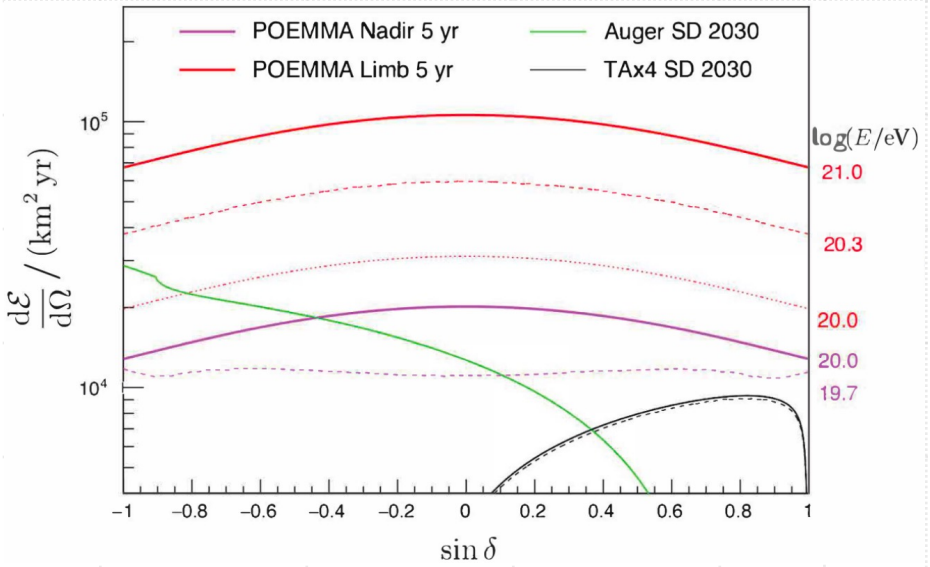



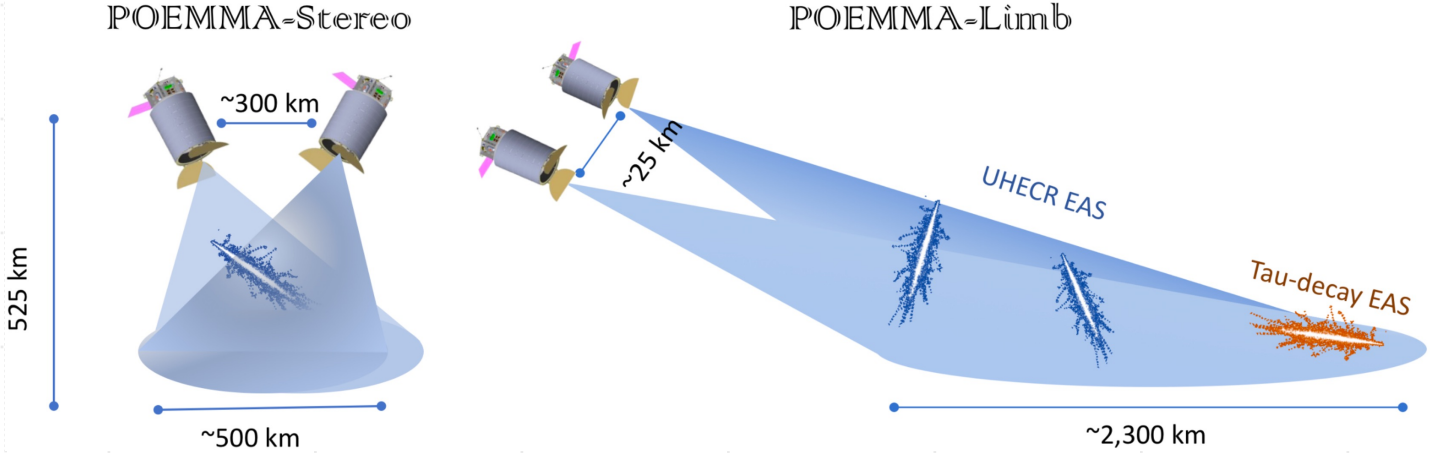

Correa,. 2023

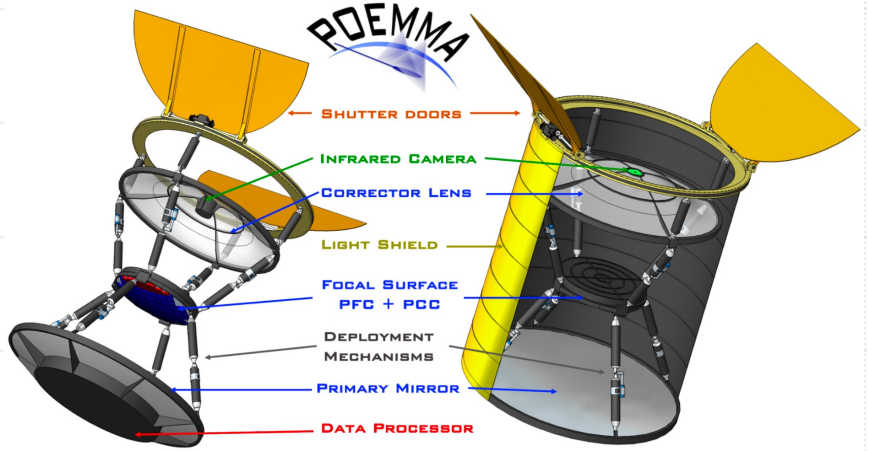
# EUSO/POEMMA

- Joint Experiment Mission for Extreme Universe Space Observatory
  - EUSO-TA
  - Mini-EUSO
  - EUSO-SPB
- Probe Of Extreme Multi-Messenger Astrophysics: $X_{max}$ res ~ 40 g/cm$^2$

Olinto, 2023

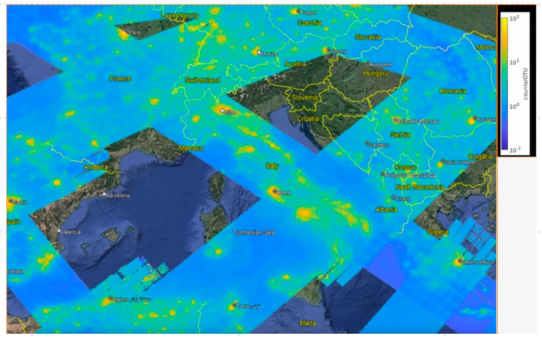


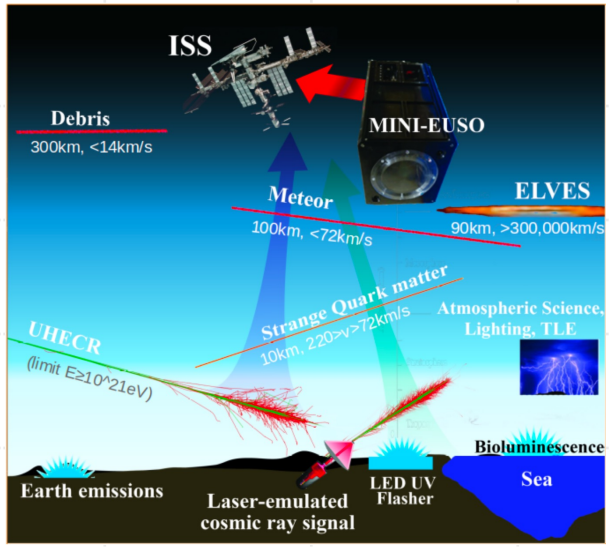
# EUSO/POEMMA pathfinders

- Mini-EUSO:
  - Observing since 2019 on the International Space Station

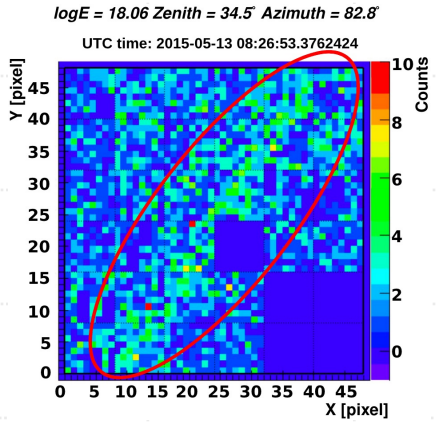


PoS(ICRC2023)353

Marcelli, 2023




- EUSO-TA: ground-based UV telescope
  - Installation since 2013, working sine 2015
  - Upgraded to EUSO-TA2 in 2022
  - Succeeded to record 9 showers in 120 h




Plebaniak, 2023

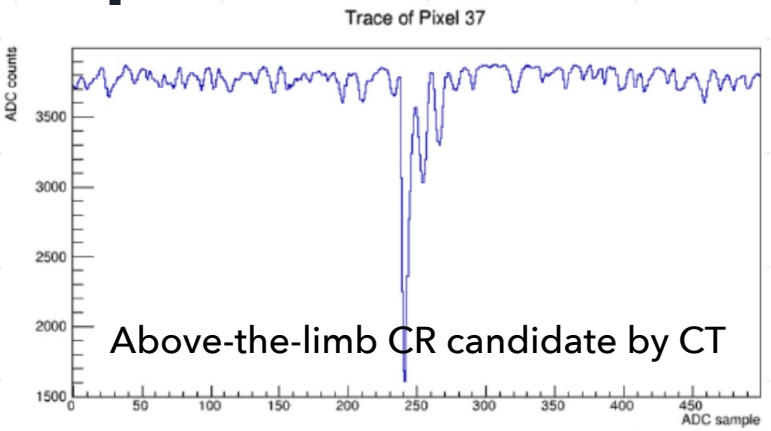
# EUSO/POEMMA pathfinders

## EUSO-SPB: CR > 1EeV, Nu > 1PeV

- EUSO-Balloon
- EUSO-SPB1
- EUSO-SPB2
- POEMMA-Balloon with Radio will be launched in 2026.

See also a poster by Julia Burton & talk by Tobias Heibges

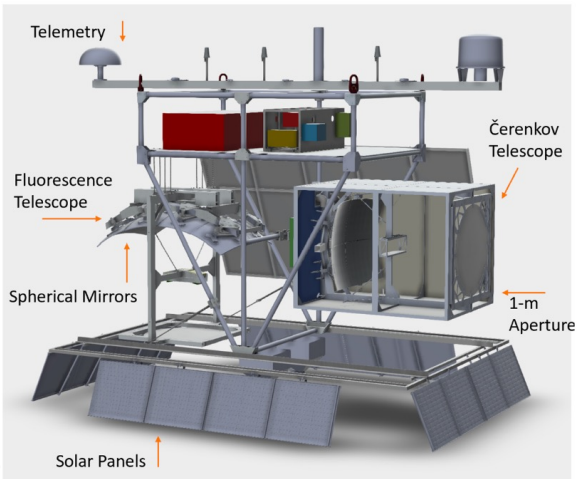
- Testing Fluorescence Telescope and Cherenkov Telescope

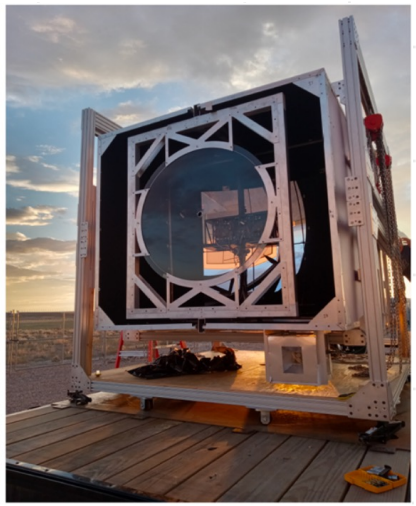



Cummings, 2023

Eser, 2023

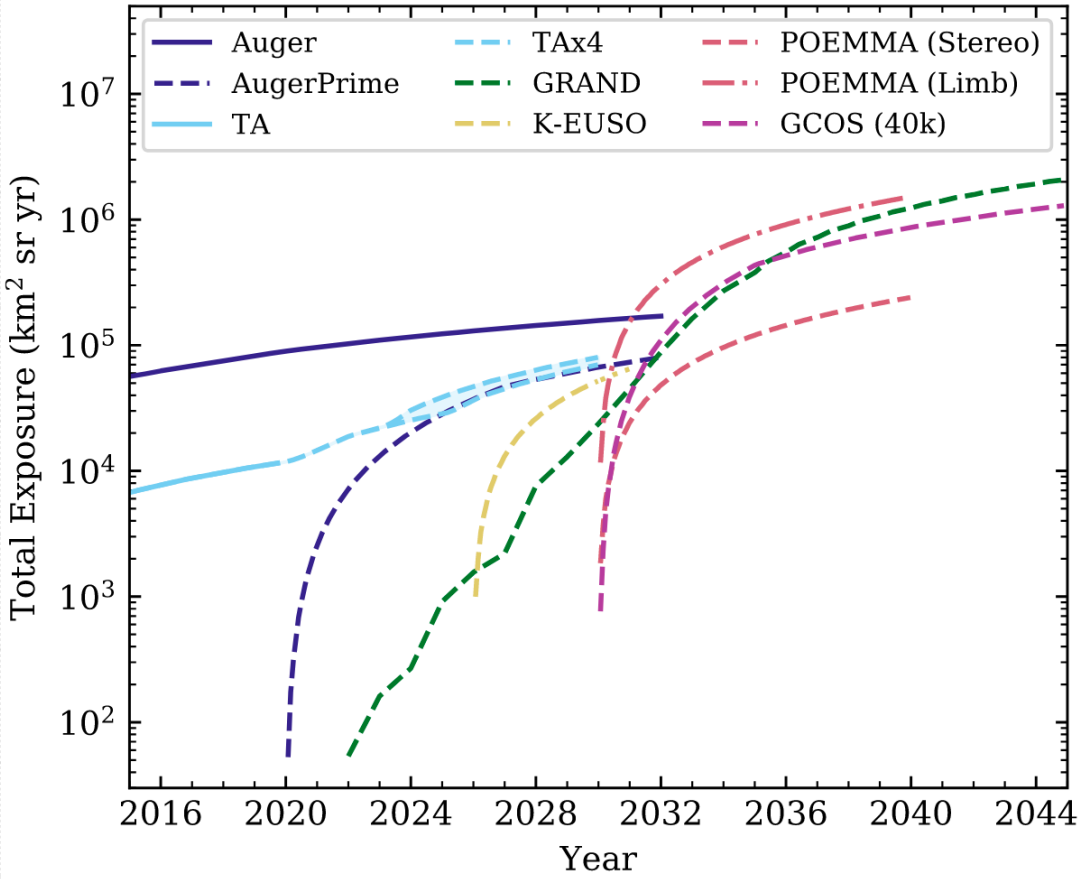
Kungel, 2023

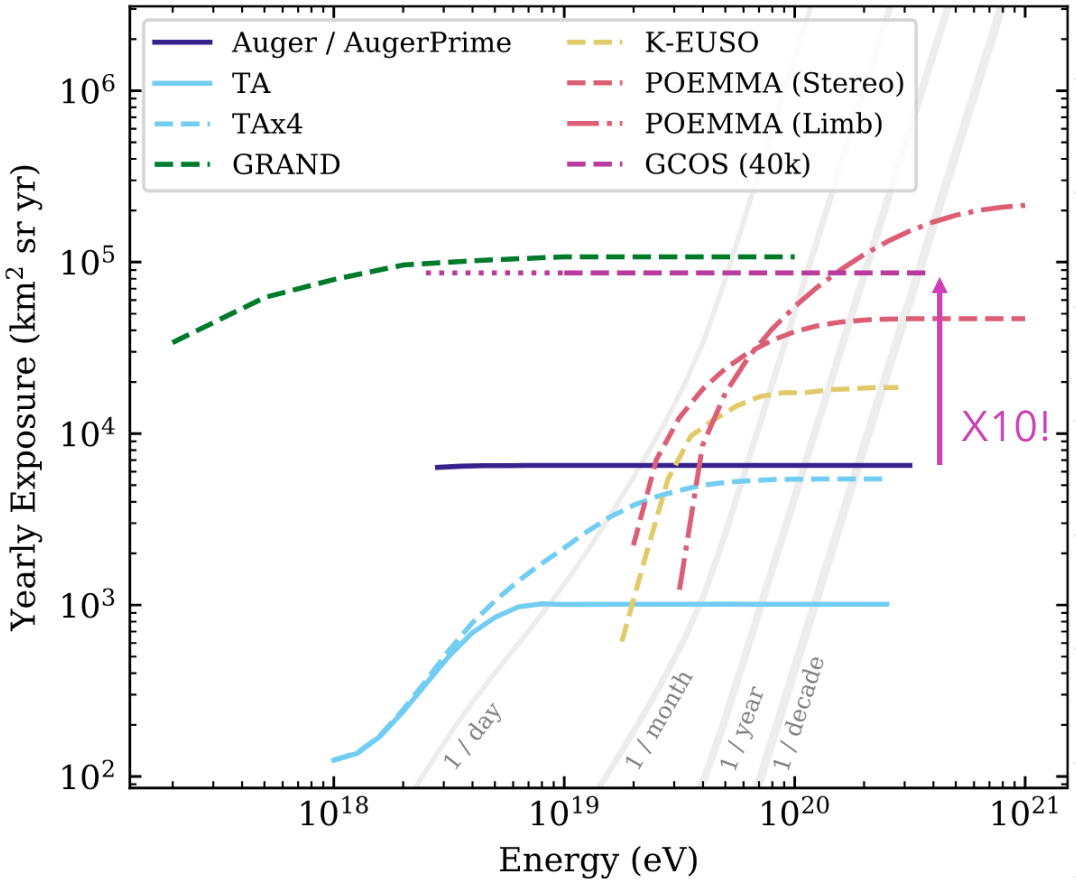


# Future exposures

Coleman et al., 2023



# Summary

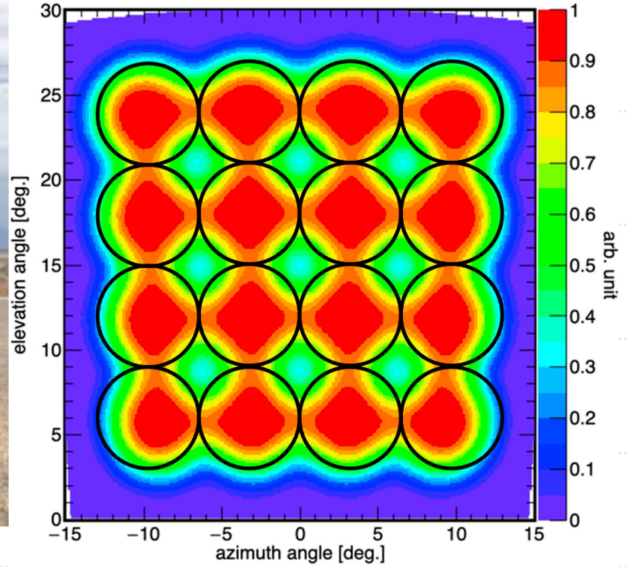
- UHECR study have been progressed in last two decades, but we have still not concluded yet.
- AugerPrime and TAx4 will contribute for ~ 5-10 years to examine some issues such as Muon puzzle problem, Hadronic Interaction Models, Anisotropies. This will be quite important to establish the strategies in 2030s and beyond. We need studying as much as we can for the future projects under the collaboration between Auger & TA+
- Future projects with unprecedented detection area (GRAND, GCOS, EUSO/POEMMA) were proposed. Prototyping and validation using pathfinders are on going.

Thank you!

# Backup

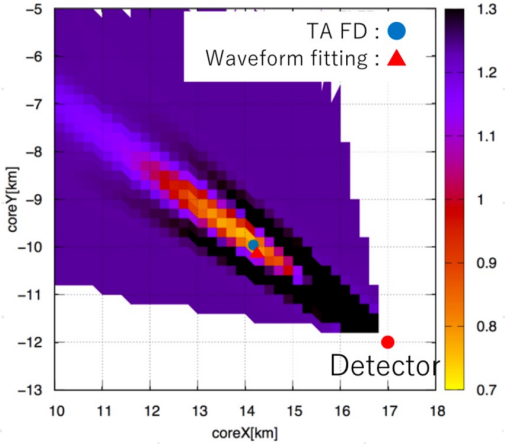
# Cosmic Ray Air Fluorescence Fresnel lens Telescope

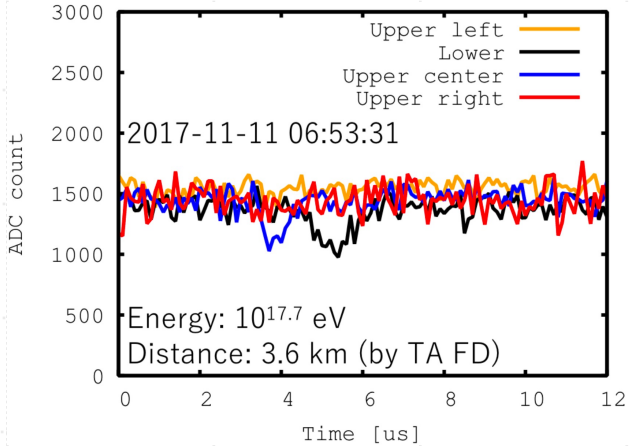

Tametda, 2023

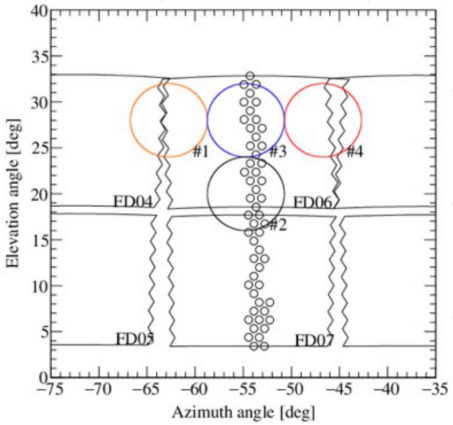



CRAFFT prototypes since 2017@ TA site

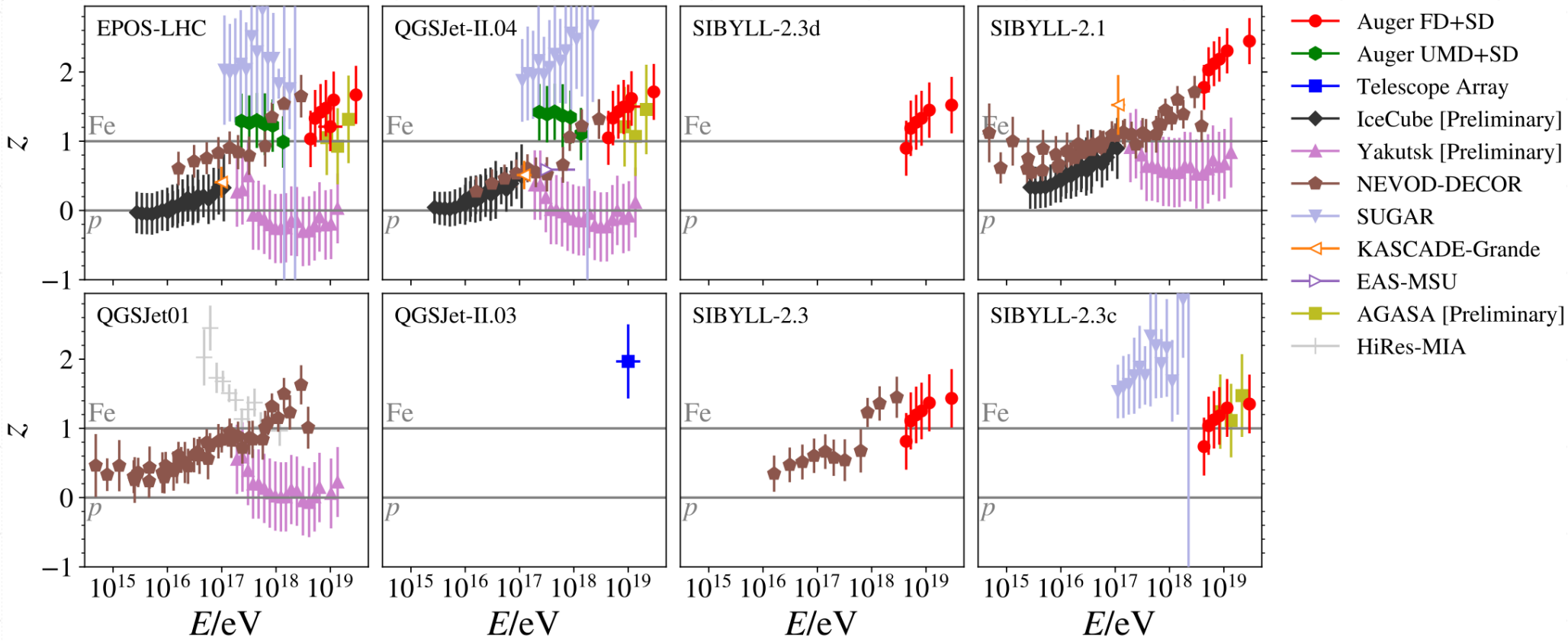
Delta core ~ 200 m



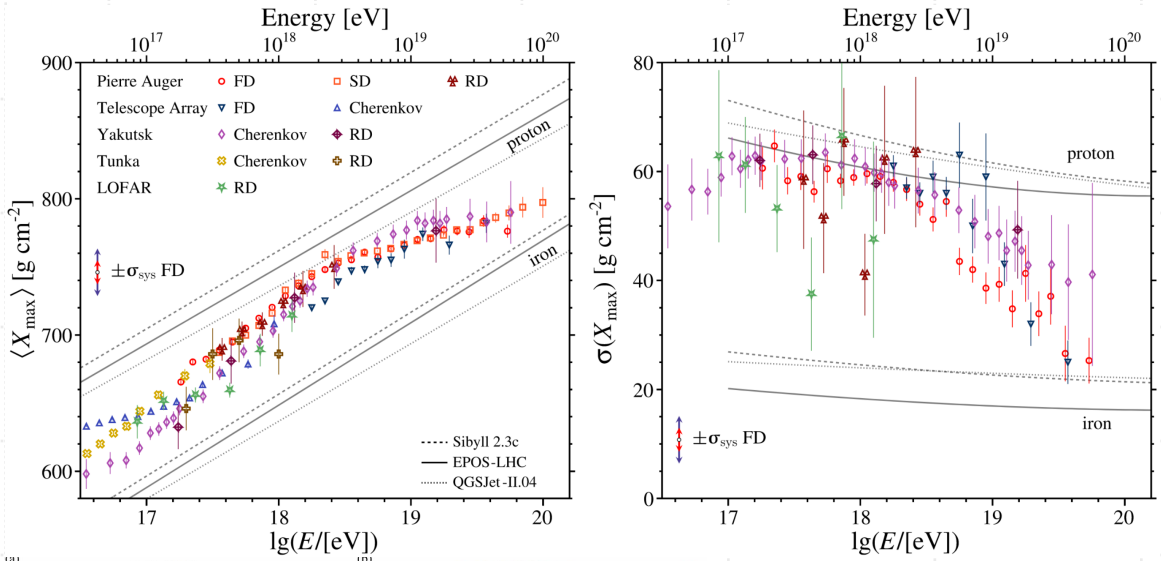



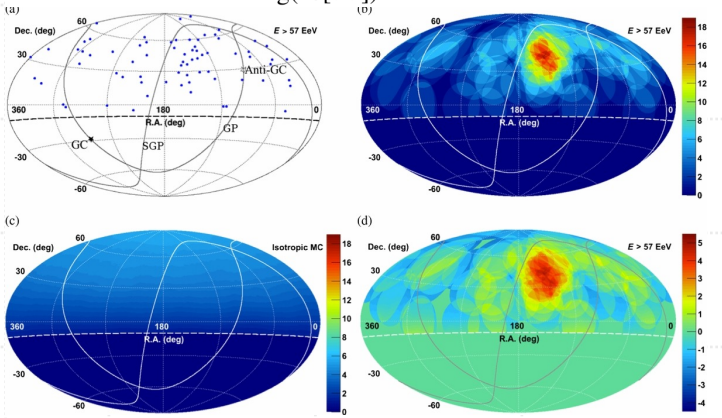
# Muon puzzle


EPOS-LHC
QGSJet-II.04
SIBYLL-2.3d
SIBYLL-2.1
QGSJet01
QGSJet-II.03
SIBYLL-2.3
SIBYLL-2.3c
Fe
p
Z
E/eV
Auger FD+SD
Auger UMD+SD
Telescope Array
IceCube [Preliminary]
Yakutsk [Preliminary]
NEVOD-DECOR
SUGAR
KASCADE-Grande
EAS-MSU
AGASA [Preliminary]
HiRes-MIA

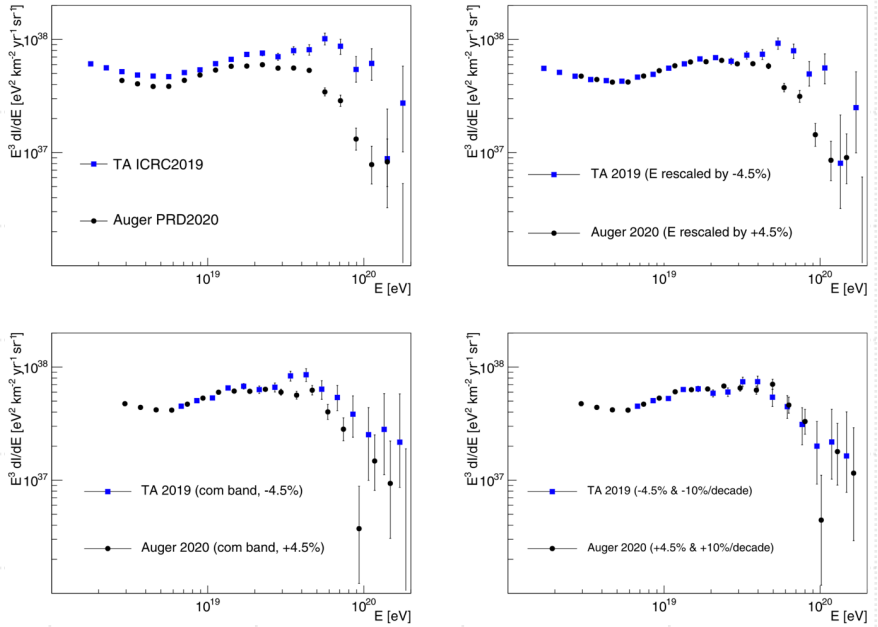
# Auger and TA remarkable results



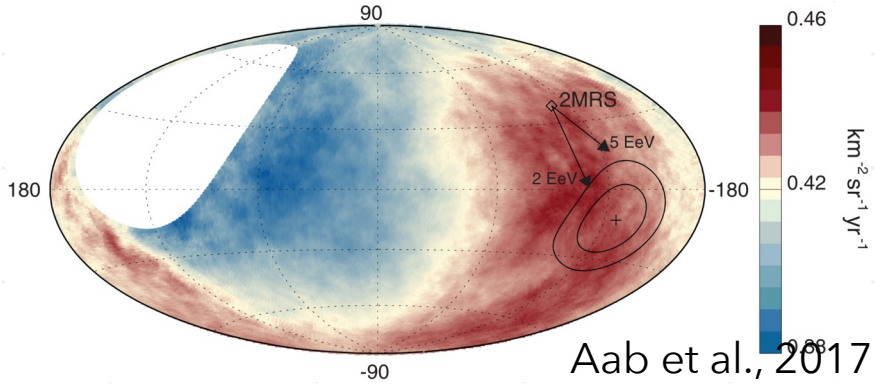

Coleman et al., 2023




Abbasi et al., 2014




Coleman et al., 2023




Aab et al., 2017