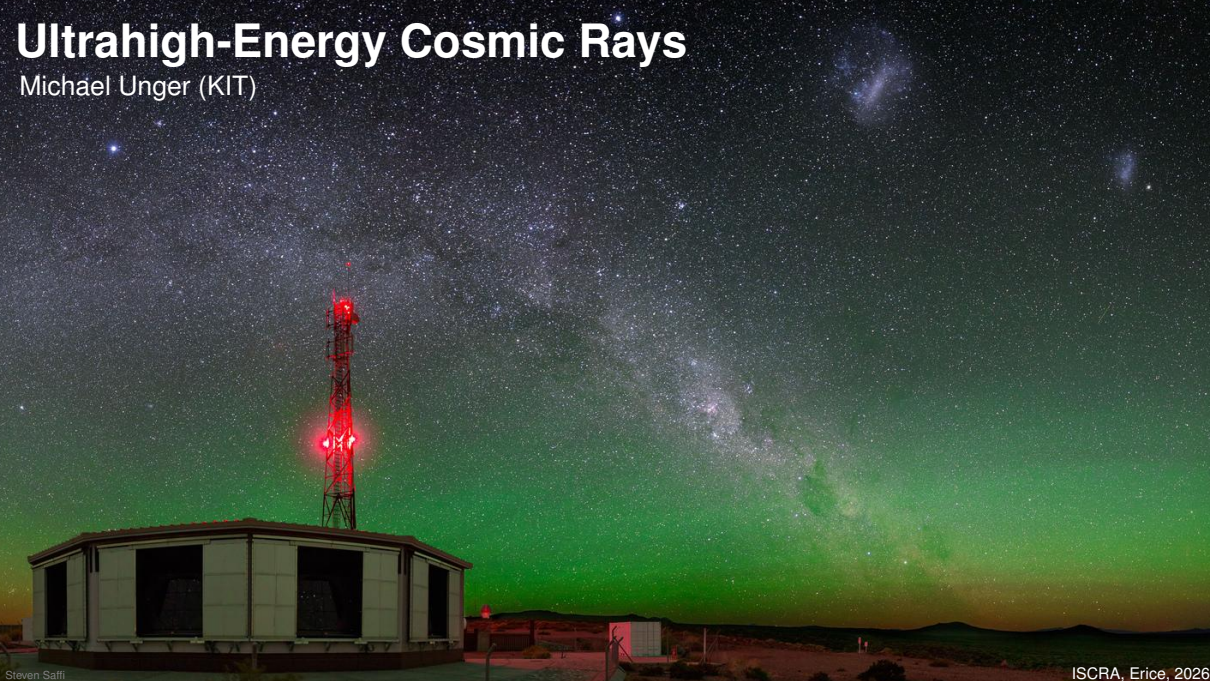


Ultrahigh-Energy Cosmic Rays

Michael Unger (KIT)



Recap: Air Showers

Nucleus-induced Shower

• number of muons: $N_\mu = A \cdot \left(\frac{E_0/A}{\varepsilon_\pi} \right)^\beta = \left(\frac{E_0}{\varepsilon_\pi} \right)^\beta A^{1-\beta}$ e.g. $M=50, \beta=0.9$
 $\rightarrow N_\mu(56)/N_\mu(1) = 56^{0.1} = 1.5$

• energy in γ, e^+, e^- : $E_{em} = E_0 - N_\mu \cdot \varepsilon_\pi$ e.g. $E_0 = 10^{20}$ eV, $M=50, A=1 \Rightarrow E_{em}/E_0 \approx 91\%$
 $A=56 \Rightarrow E_{em}/E_0 \approx 86\%$

• number of γ, e^+, e^- : $N_{em} = E_{em} / \varepsilon_{crit} = \frac{E_{em}}{E_0} \cdot N_{em}^0$

• Shower maximum from 1st interaction:

$$X_{max}^A = \lambda_p + X_0 \ln \left(\frac{E_0}{2 \cdot A \cdot M \cdot \varepsilon_c} \right)$$

$A \cdot \frac{1}{3} M \pi^0$ with $E = E_0/A/M \Rightarrow 2 \cdot A \cdot \frac{1}{3} M \gamma$ s with $E_\gamma = E_0/A/M/2$

$$\underline{X_{max}^A(E) = X_{max}^P(E/A)}$$

how to measure the CR mass + energy with air showers

measurement	primary CR	detector
N_e, N_μ	$\leftrightarrow E_0, A$	SD
X_{max}, E_{em}	$\leftrightarrow E_0, A$	FD/CD
E_{em}, N_μ	$\leftrightarrow E_0, A$	RD+SD
$N_e, N_\mu, X_{max}, E_{em}$	$\leftrightarrow E_0, A$	SD+FD

} "hybrid"

overconstrained $\Rightarrow$ check hadronic interaction models

(SD: surface detector (particles)
 FD: fluorescence detector
 CD: Cherenkov detector
 RD: radio detector)

Ultrahigh-Energy Cosmic Rays

- **Air Shower Physics**

(electromagnetic and hadronic showers, shower maximum, muons in air showers)

- **Detection Techniques**

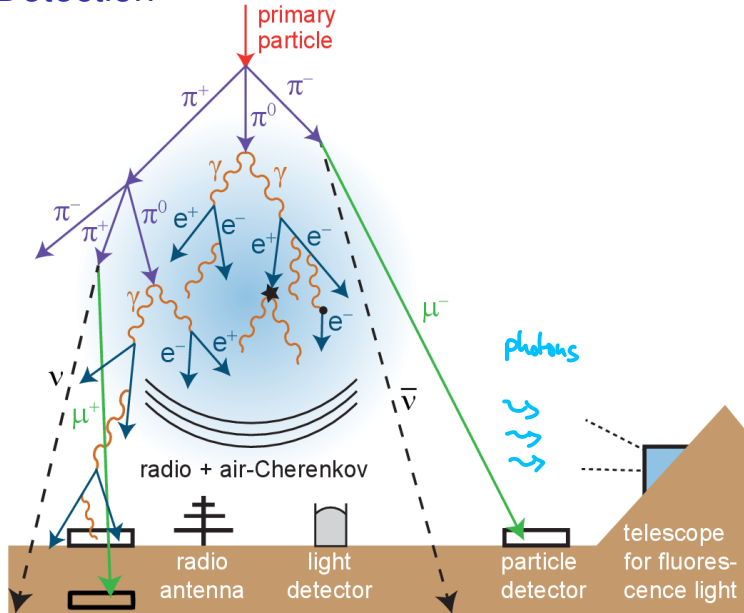
(particles, fluorescence- and Cherenkov-light, radio)

- **Key Observations (and their Interpretation)**

(anisotropies, mass, spectrum, Peters cycle, propagation, cosmic magnetic fields)



Air Shower Detection



Air Shower Detection

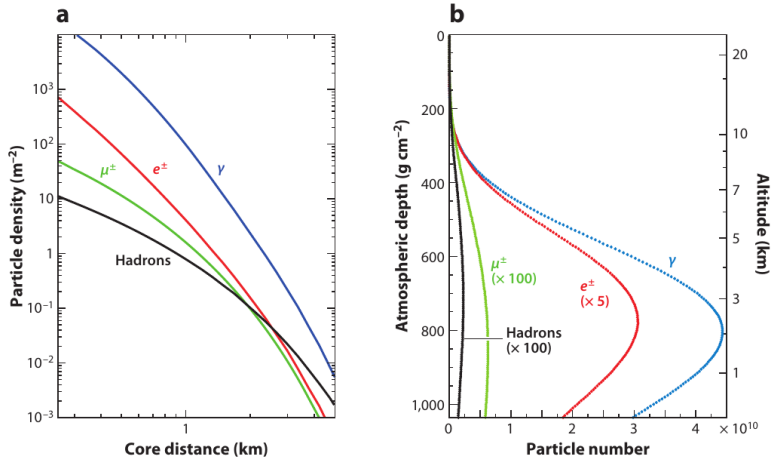
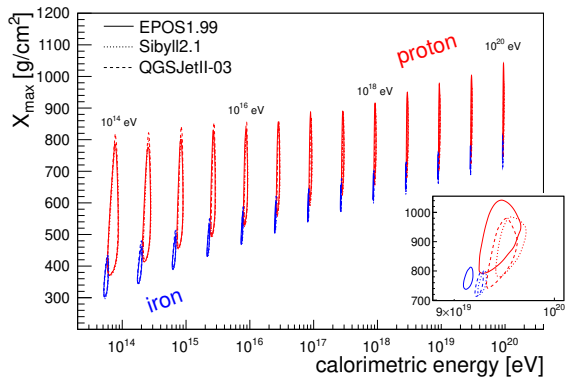
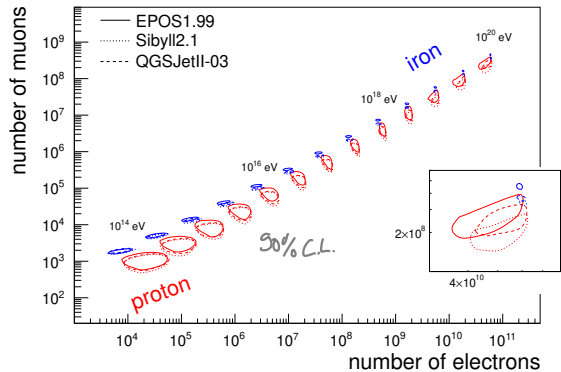
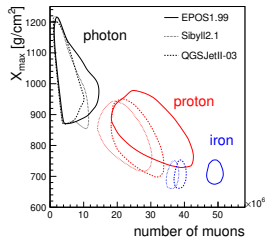
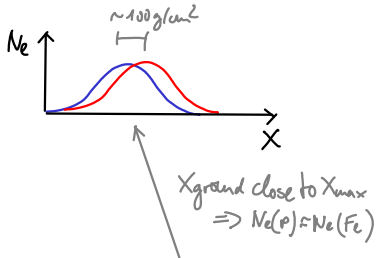


Figure 2

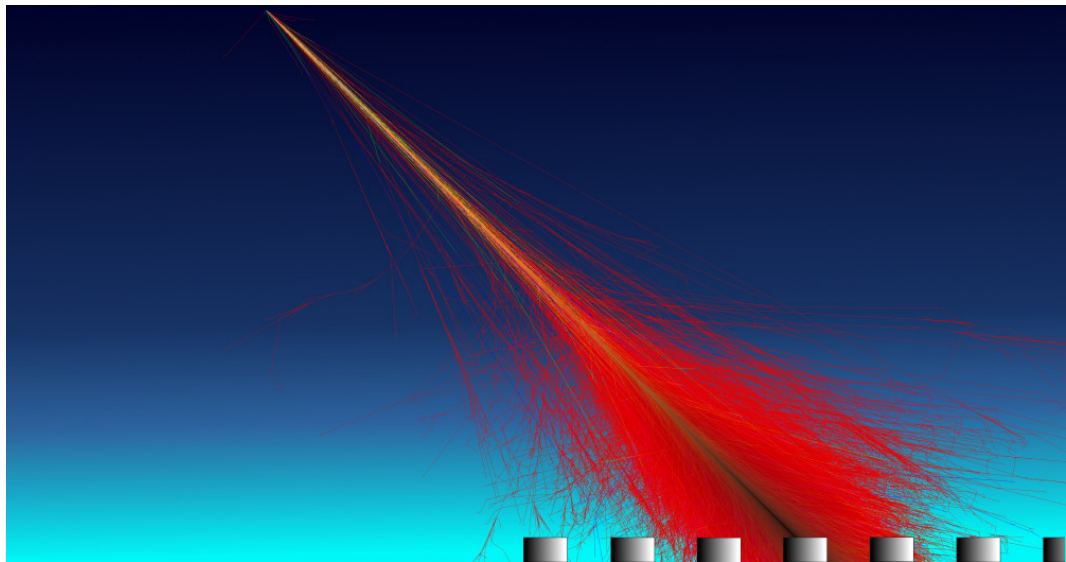
Average (a) lateral and (b) longitudinal shower profiles for vertical, proton-induced showers at 10^{19} eV. The lateral distribution of the particles at ground is calculated for 870 g cm^{-2} , the depth of the Pierre Auger Observatory. The energy thresholds of the simulation were 0.25 MeV for γ and $e^\pm$ and 0.1 GeV for muons and hadrons.

E and A

$$\theta = 0^\circ, X = 800 \text{ g/cm}^2$$

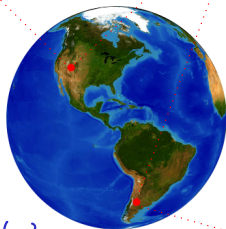
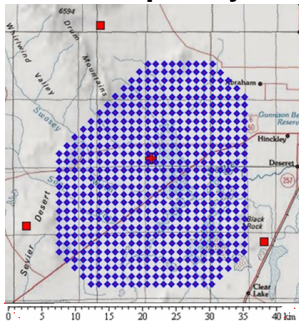


Particle Detectors



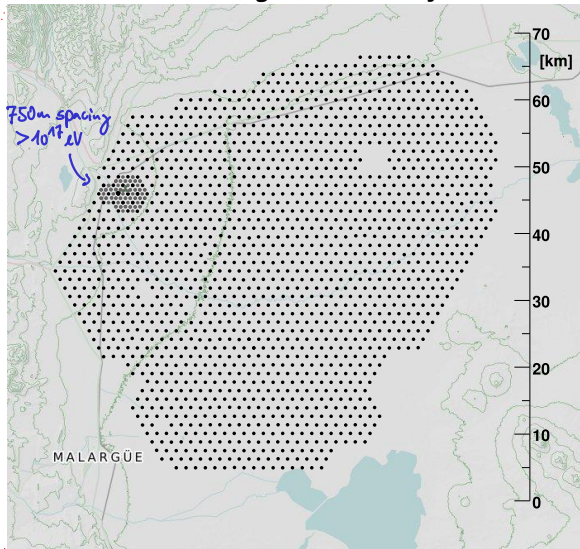
Telescope Array "TA"

500 SCWTs
1.2 km spacing
 $A = 700 \text{ km}^2$



Pierre Auger Observatory

1600 WCDs
1.5 km spacing $> 10^{18} \text{ eV}$
 $A = 3000 \text{ km}^2$



both at $X_{\text{ground}} \approx 850 \text{ g/cm}^2$

Telescope Array: scintillator as particle detector

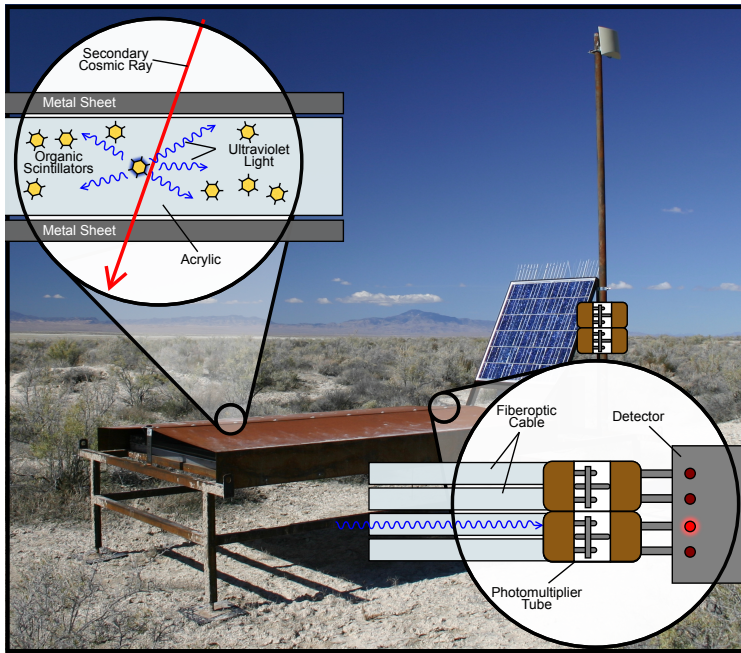


Signal

$$S \sim N_{ch} = N_{\mu} + N_e$$

($\gamma \rightarrow e^+e^-$ conversion)

$$\text{Area} \sim \cos \theta$$

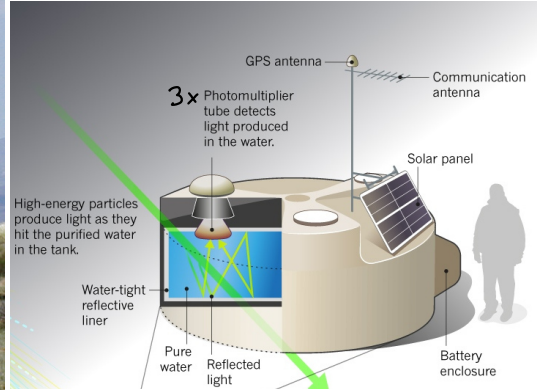


Pierre Auger Observatory: Water Cherenkov detectors (WCD)



area $\sim$ const (volume detector, $h \sim r$)

12t ultrapure water

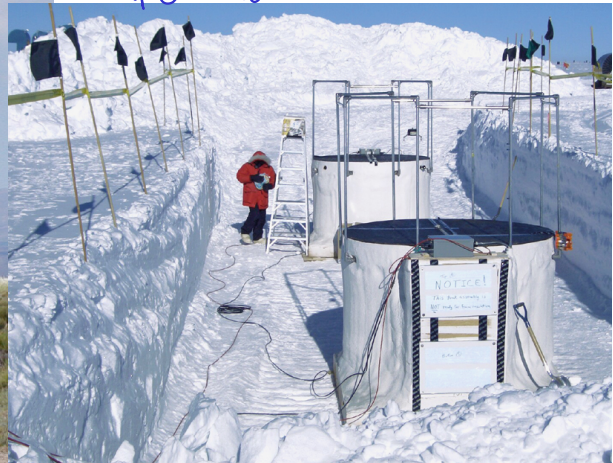


Cherenkov threshold: $\sim 0.8 \text{ MeV } e^-$
 $\sim 160 \text{ GeV } \mu^-$

Signal $\frac{dN_c}{dE} \sim E \rightarrow$ more signal for muons that traverse full det.

$$S = a \cdot N_\mu + b \cdot N_{e/\gamma}$$

IceTop @ IceCube



"Ice-Cherenkov" detectors

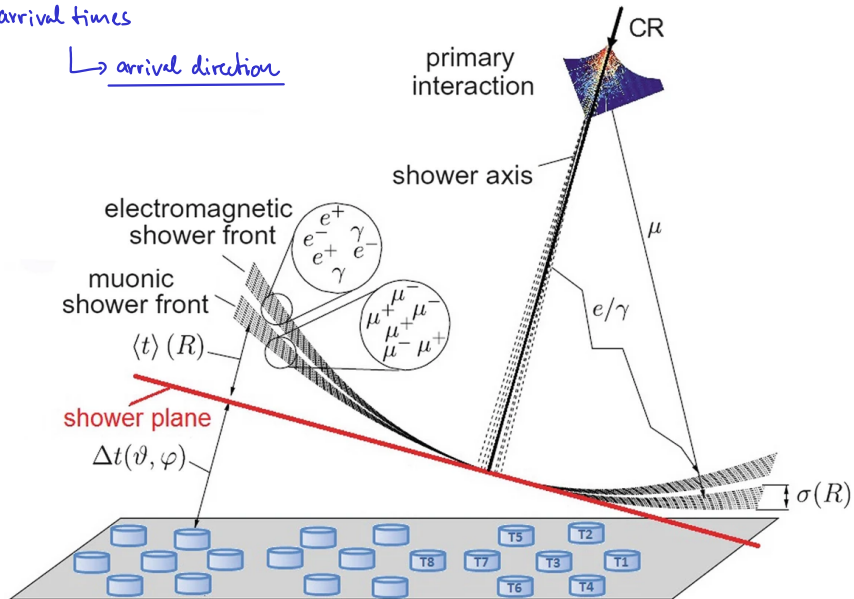




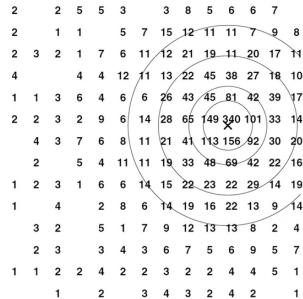
WCDs

Shower Front / arrival times

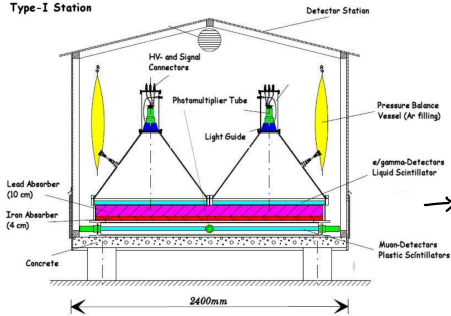
↳ arrival direction



N_e/N_μ : e.g. KASCADE @ Campus North (1996-2015)



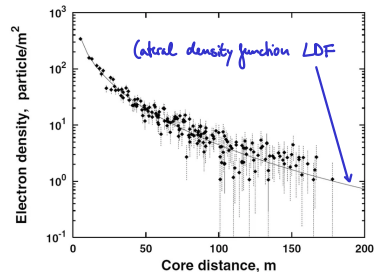
Type-I Station



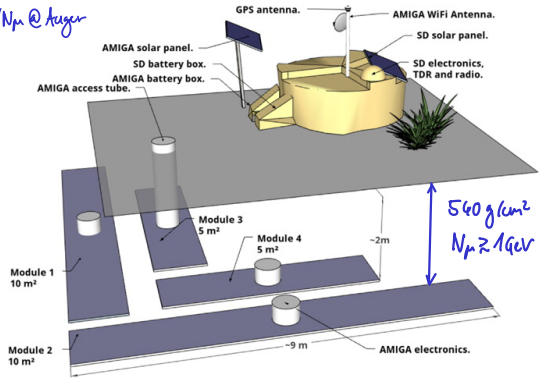
$$N_{ch} = N_{e\gamma} + N_\mu$$

→ 20 attenuation lengths shielding

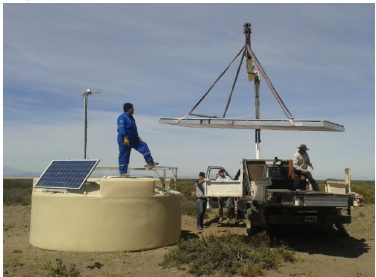
$$\rightarrow N_\mu \quad E_\mu > 250 \text{ MeV}$$



N_e/N_μ @ Auger



AMIGA (750 m array only)



"AugerPrime" → additional scintillator on each station (since 2022)

schematically:

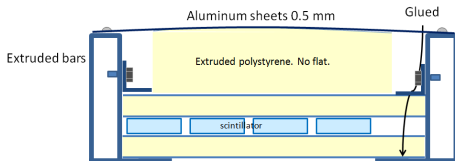
$$S_{SWR} \sim N_\mu + N_e$$

$$S_{WCO} \sim a N_\mu + b N_e$$

$$\begin{pmatrix} S_{SWR} \\ S_{WCO} \end{pmatrix} \sim \begin{pmatrix} 1 & 1 \\ a & b \end{pmatrix} \begin{pmatrix} N_\mu \\ N_e \end{pmatrix}$$

⇒ N_e and N_μ

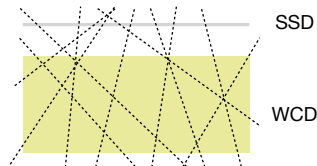
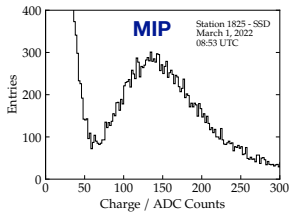
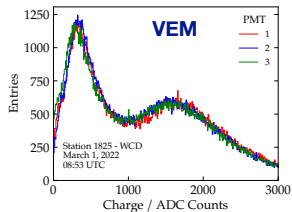
Scintillator detectors of the Auger Observatory



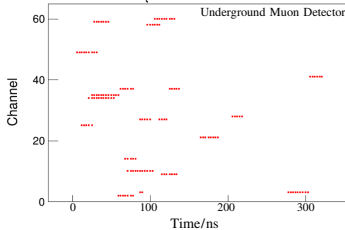
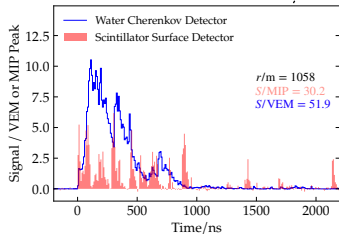
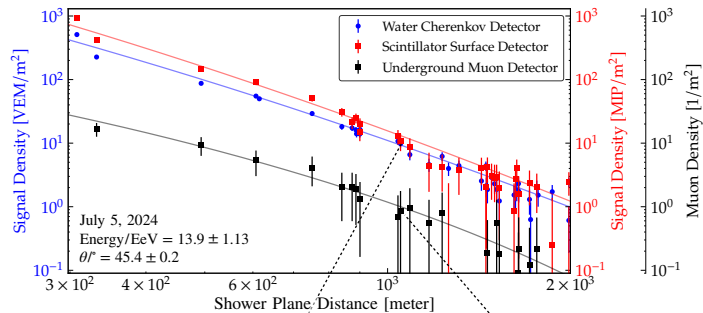
Plastic scintillator 1cm thick

Water-Cherenkov detector
triggers scintillator readout

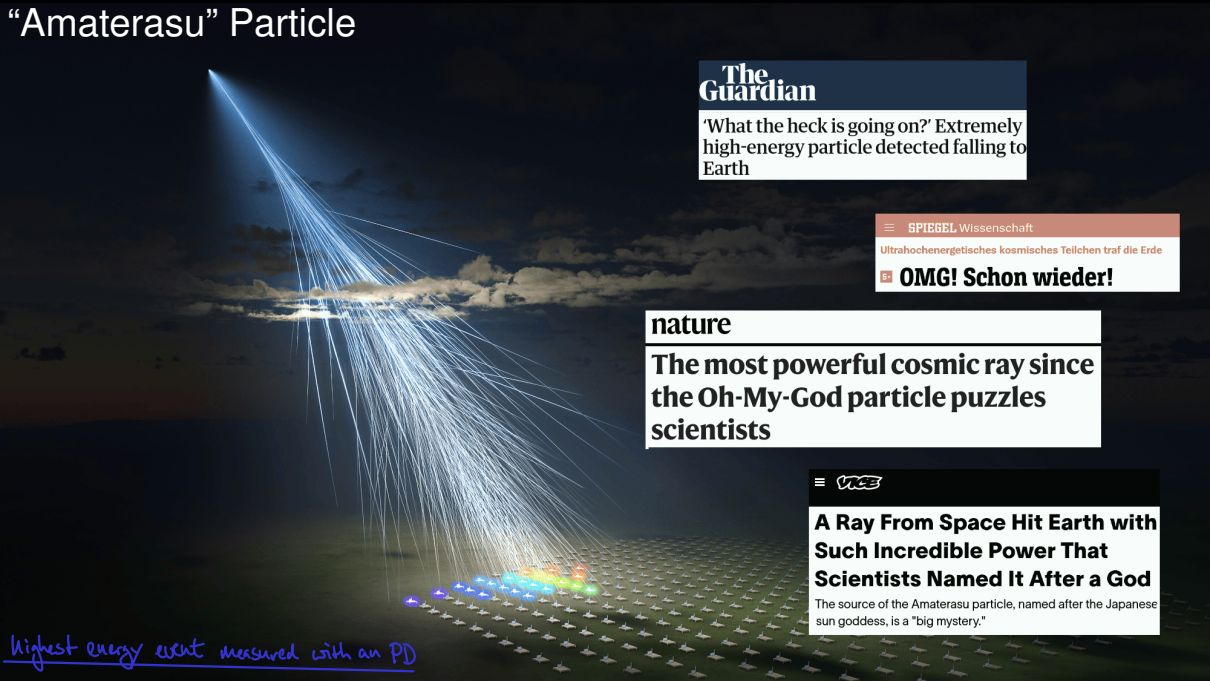
*MIP calibration:
work in progress*



Comparison of water-Cherenkov and scintillation signals



“Amaterasu” Particle



**The
Guardian**

'What the heck is going on?' Extremely high-energy particle detected falling to Earth

SPiEGEL Wissenschaft

Ultrahochenergetisches kosmisches Teilchen traf die Erde

5+ **OMG! Schon wieder!**

nature

The most powerful cosmic ray since the Oh-My-God particle puzzles scientists

VICE

A Ray From Space Hit Earth with Such Incredible Power That Scientists Named It After a God

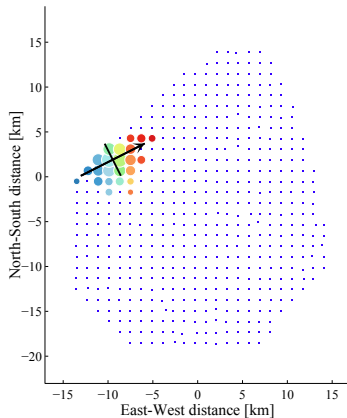
The source of the Amaterasu particle, named after the Japanese sun goddess, is a "big mystery."

highest energy event measured with an PD

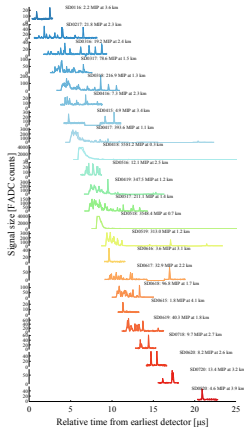
An extremely energetic cosmic ray observed by a surface detector array

TELESCOPE ARRAY COLLABORATION^{††}, R. U. ABBASI, M. G. ALLEN, R. ARIMURA, J. W. BELZ, D. R. BERGMAN, S. A. BLAKE, B. K. SHIN, I. J. BUCKLAND, [...], AND Z. ZUNDEL

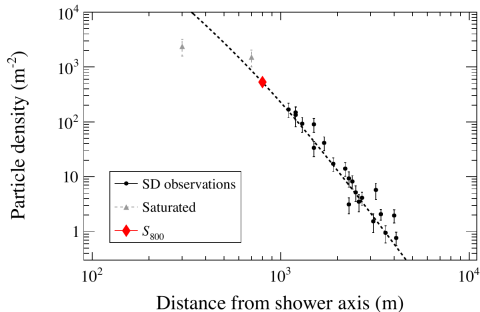
(A) Surface detector array of TA



(B) Date: 27 May 2021 Time: 10:35:56.474337 UTC



- $E = \left(2.44 \pm 0.29 \text{ (stat.)} {}^{+0.51}_{-0.76} \text{ (syst.)} \right) \times 10^{20} \text{ eV}$
- if Fe: $E_{\text{nom}} = (2.12 \pm 0.25) \times 10^{20} \text{ eV}$
- Fe at $-1\sigma_{\text{syst.}}$: $E_{\text{low}} = (1.64 \pm 0.19) \times 10^{20} \text{ eV}$



Extension of Telescope Array – TAx4

Aim

- Quadruple TA
- Four-times-faster highest-energy cosmic-ray collection

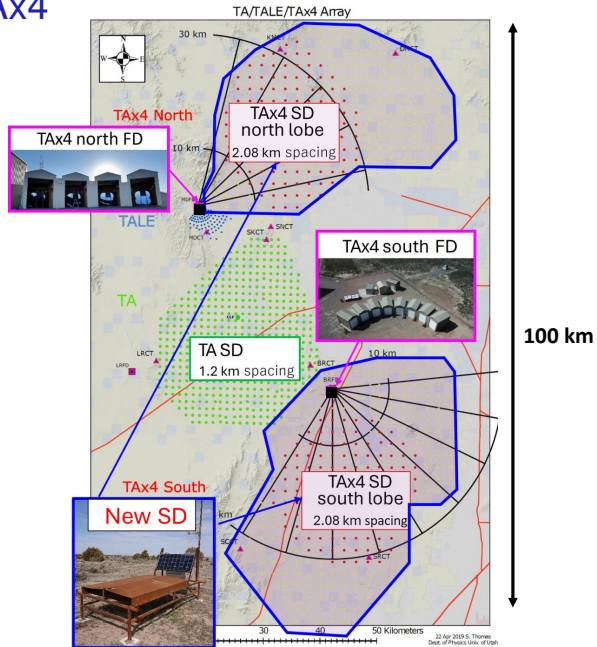
TAx4 SD

Goal

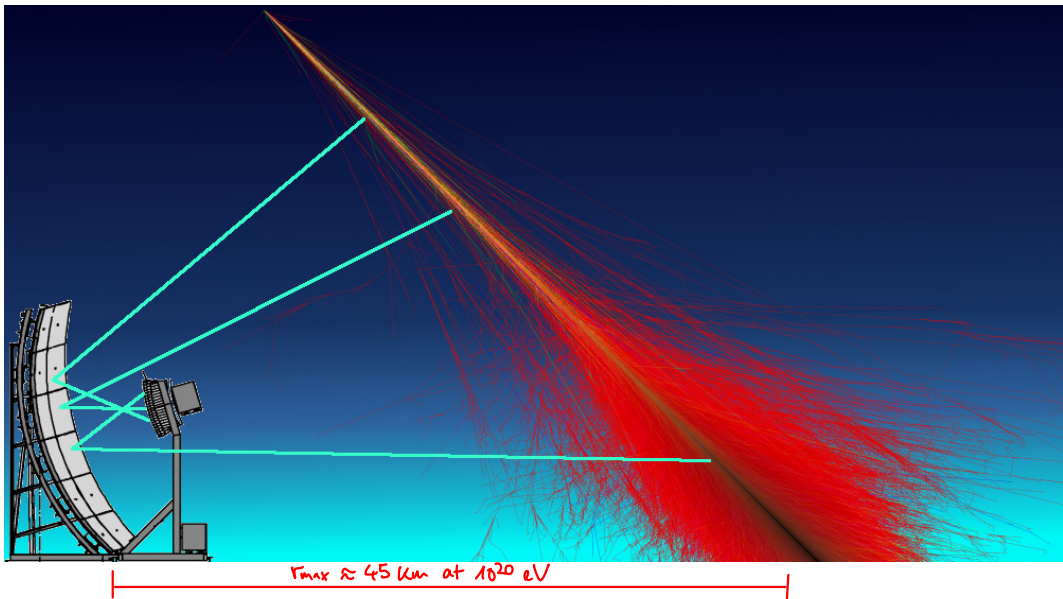
- Deploy 500 SDs with 2.08 km spacing
- Expand the array to $\sim 3,000 \text{ km}^2$ (TA SD + new SD)

Current Status

- 257 SDs deployed in 2019 (current size: TAx2.5)



Fluorescence Telescopes



Air Fluorescence

- N_2 excitation by charged particles

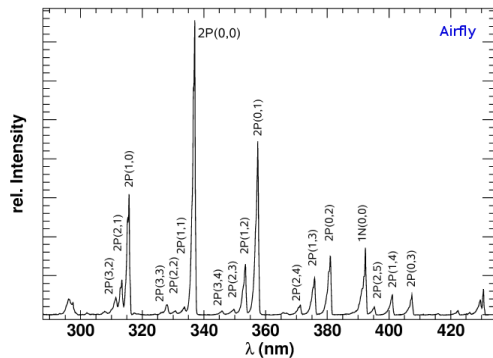
- isotropic emission !!

- fluorescence yield $Y \sim f(S, T, H) \cdot \frac{dE}{dx}$
density S
temperature T
humidity H
energy deposit
in atmosphere

- rule of thumb: $\approx 3-4$ photons/m/particle
 $\approx 30W$ light bulb

- precise measurement in lab

emission in UV ($\sim 10ns$)



show visible up to $30km @ 10^{10} eV \Rightarrow 3000 km^2$

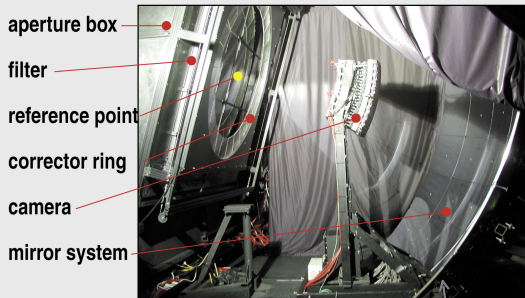
$45 km @ 10^{20} eV \Rightarrow 6000 km^2$

but: duty cycle $\lesssim 15\%$ (moon, sun, clouds, thunderstorms...)

"Schmidt optics"

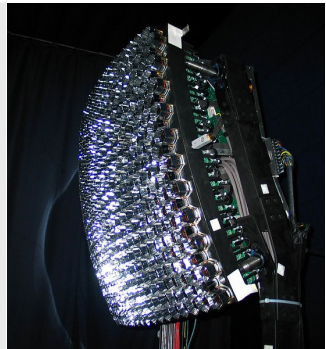


6 telescopes per building
4 buildings at edge of array (looking inward)



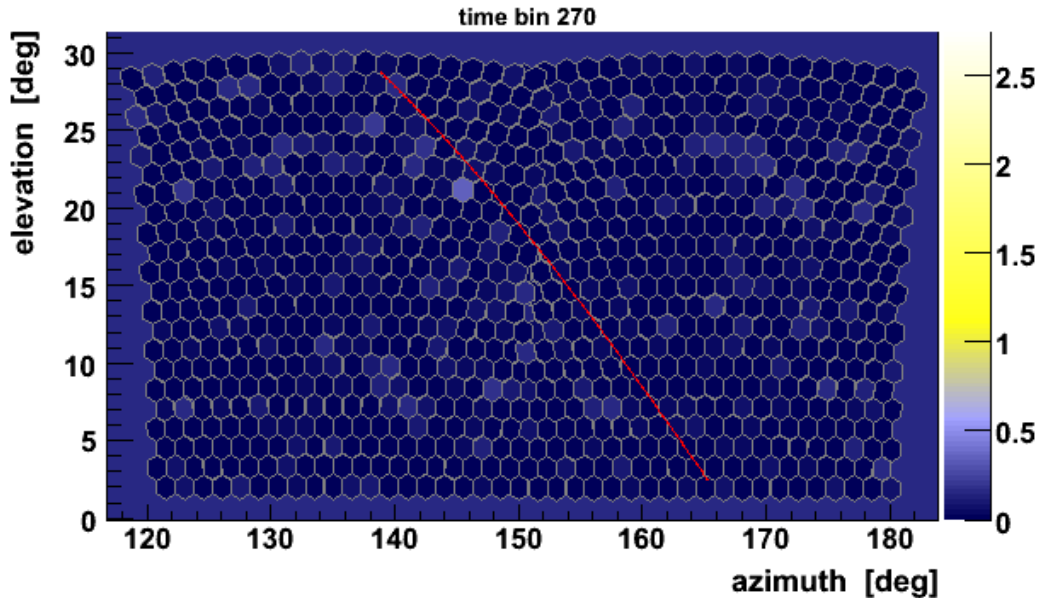
spherical mirror

camera

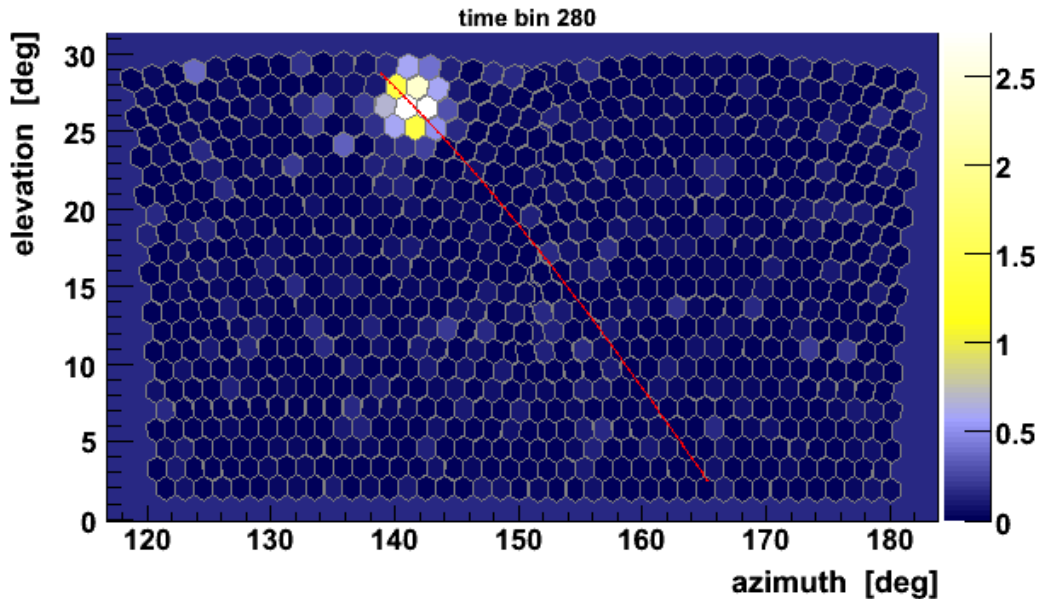


440 hexagonal PTTs

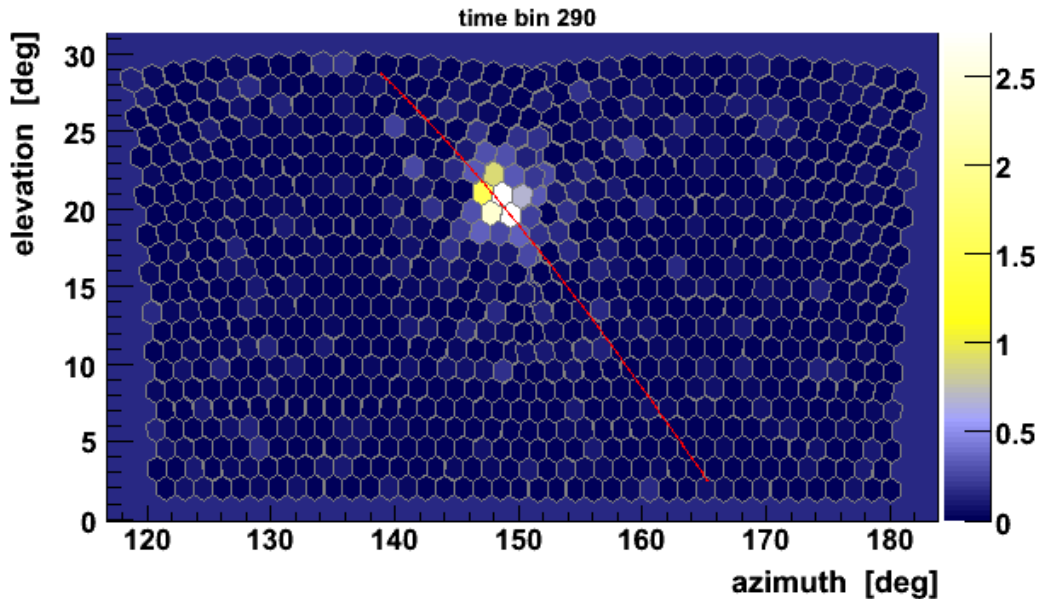
Air Shower Detected by Auger FD



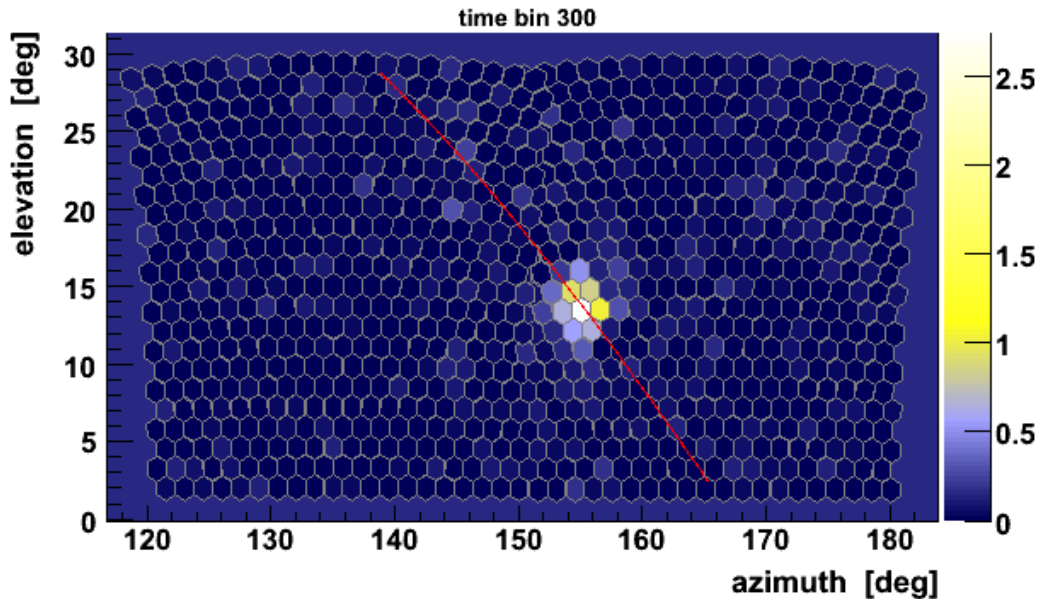
Air Shower Detected by Auger FD



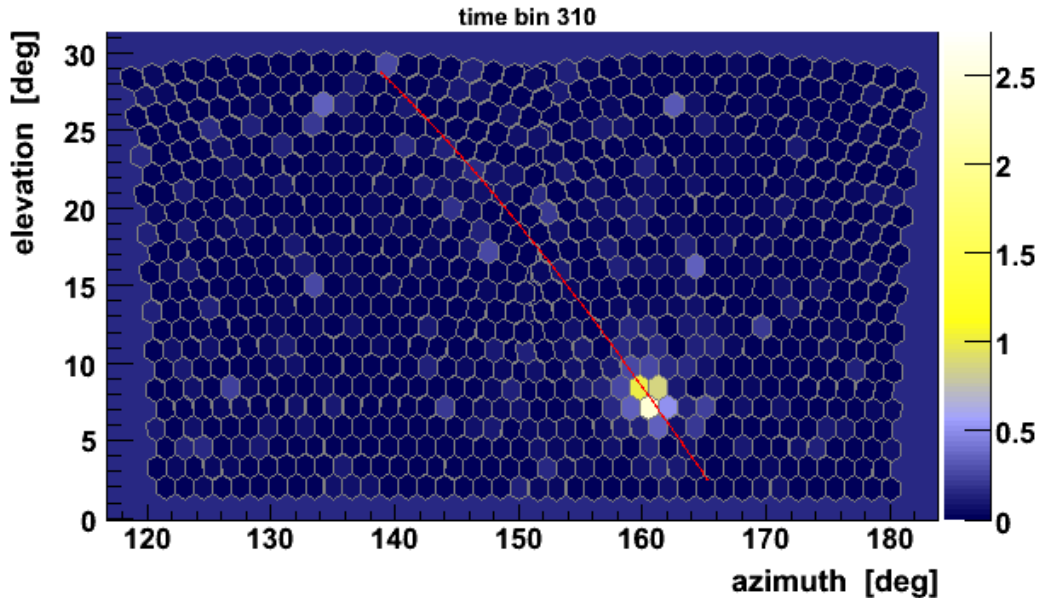
Air Shower Detected by Auger FD



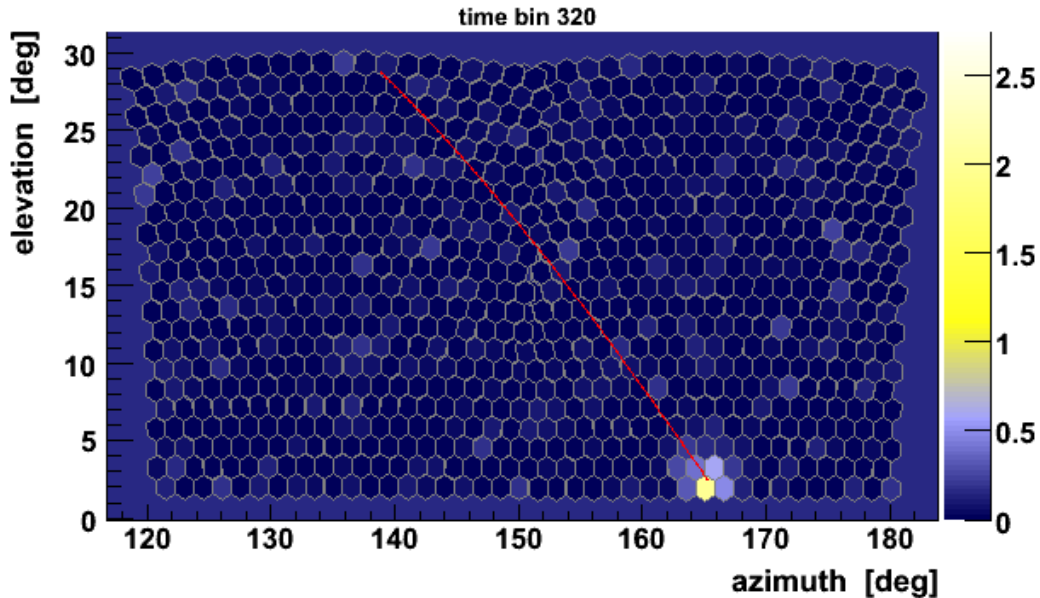
Air Shower Detected by Auger FD



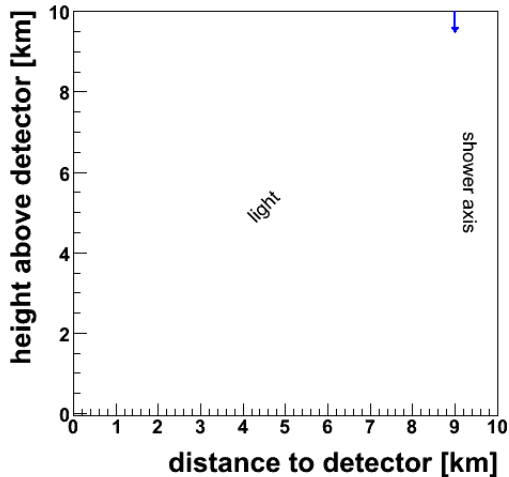
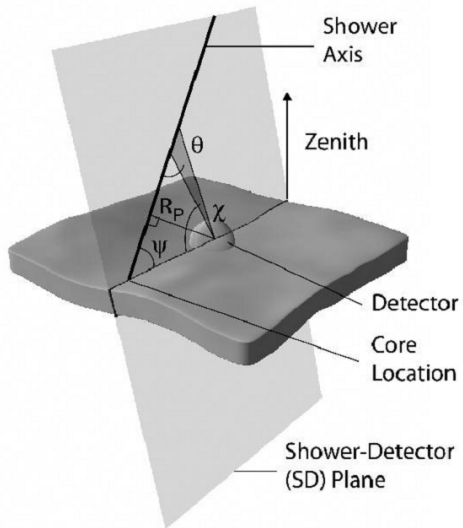
Air Shower Detected by Auger FD



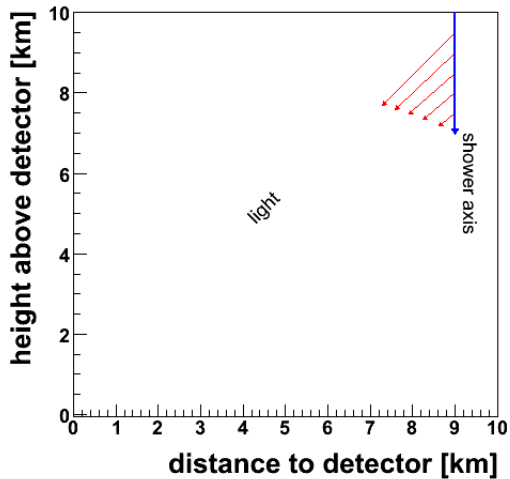
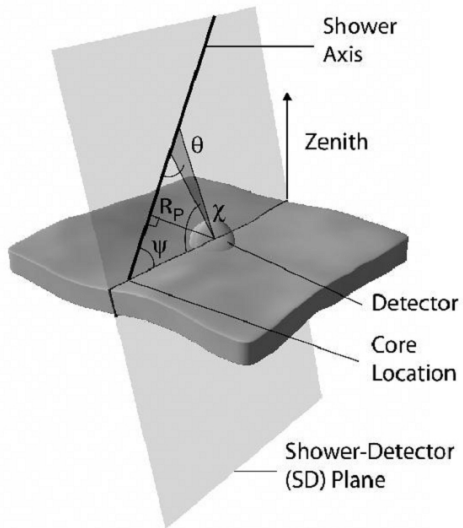
Air Shower Detected by Auger FD



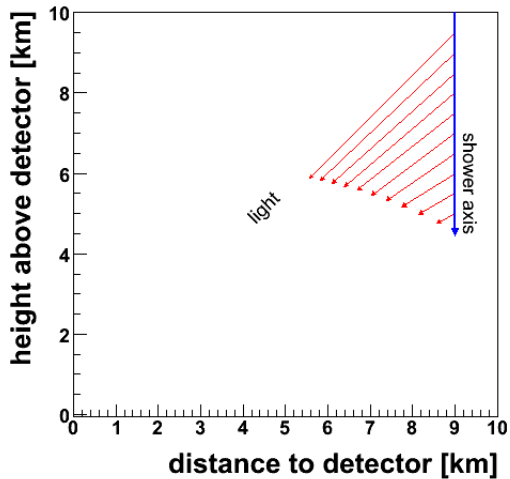
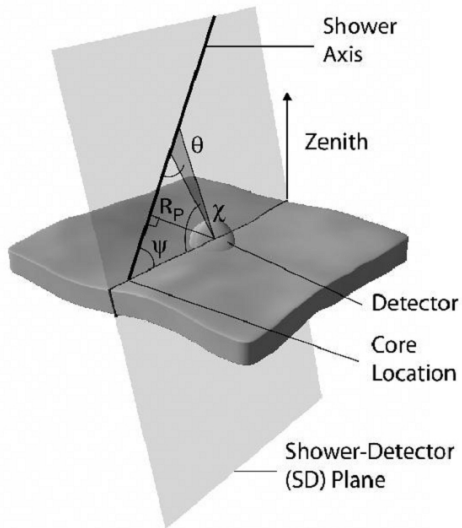
Time of Photon Arrival at Camera



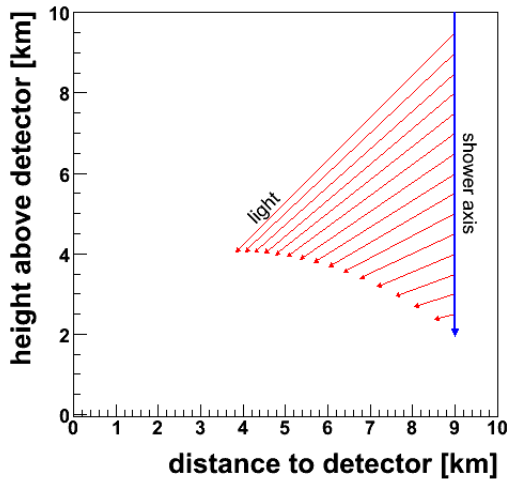
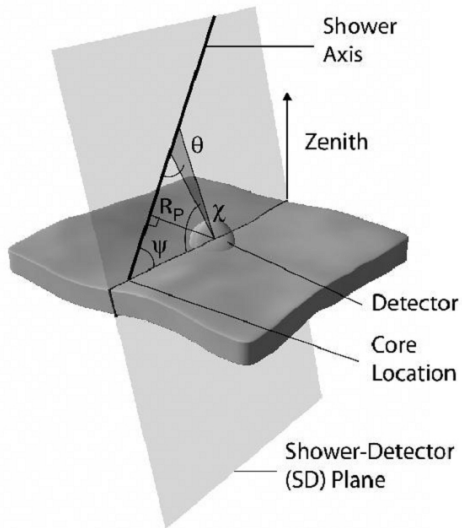
Time of Photon Arrival at Camera



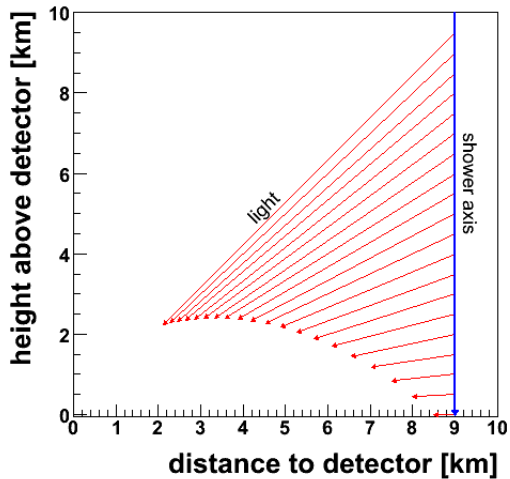
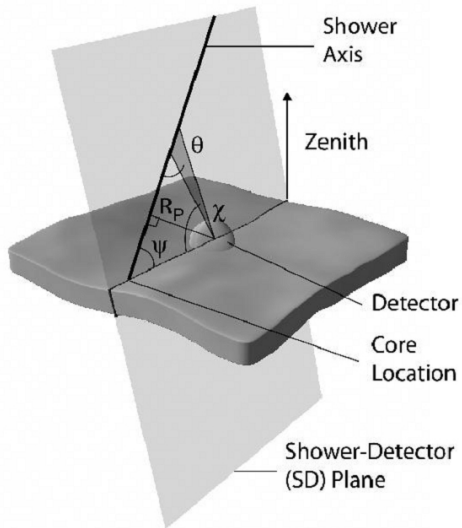
Time of Photon Arrival at Camera



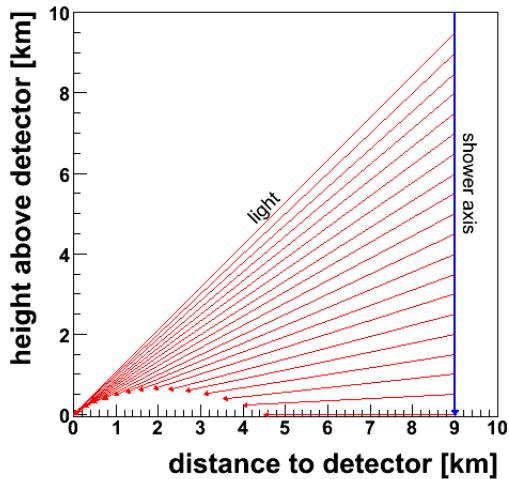
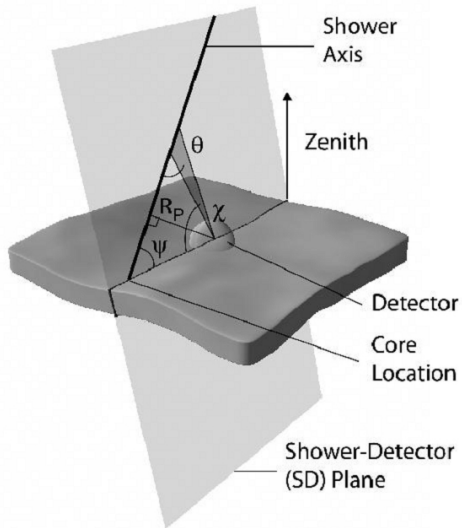
Time of Photon Arrival at Camera



Time of Photon Arrival at Camera



Time of Photon Arrival at Camera



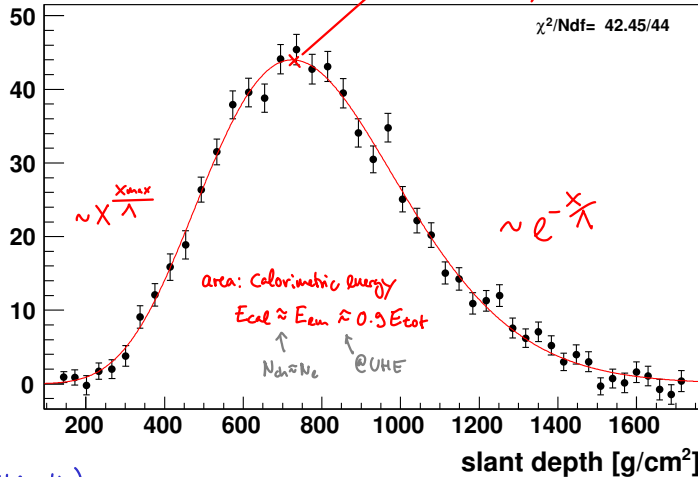
time at FD:

$$t = t_0 + (R_p/c) \tan \left(\frac{\chi_0 - \chi}{2} \right)$$

$$(\chi_0 = \pi - \psi)$$

Longitudinal profile

dE/dX [PeV/(g/cm²)]



$$\frac{dE}{dx}(x) = \langle \alpha(x) \rangle N_e(x)$$

$$\langle \alpha(x) \rangle \approx \text{const} = \frac{2.4 \text{ MeV}}{\text{g/cm}^2}$$

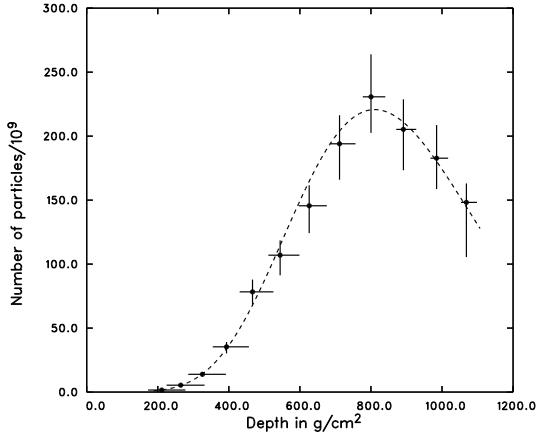
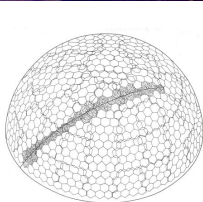
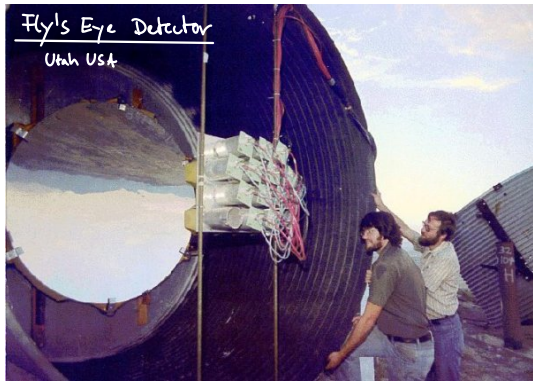
(average energy deposit per particle)

Gaisser-Hillas function (GH function):

$$N_{fluo} \sim \frac{dE}{dx} \sim N_e(x) = N_{max} \left(\frac{x-x_1}{x_{max}-x_1} \right)^{(x_{max}-x_1)/\lambda} e^{-\frac{x-x_{max}}{\lambda}}$$

$$(x_1 \approx 0 \text{ g/cm}^2, \lambda \approx 60 \text{ g/cm}^2)$$

highest energy fluorescence detector event



Fly's Eye Coll., ApJ 441 (1995) 144

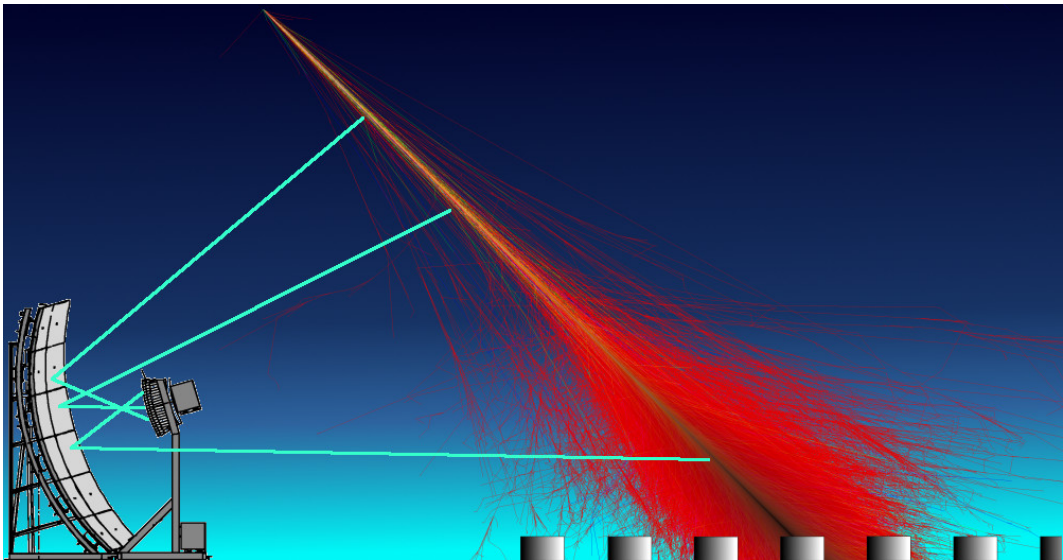
see also T.Fitoussi et al, JCAP 01 (2020) 042

$$RA = 85.2^\circ, DEC = 48^\circ$$

$$E = (320 \pm 90) \cdot 10^{20} \text{ eV} \quad (51 \text{ Joule!})$$

$$X_{\text{max}} = (815 \pm 60) \text{ g/cm}^2 \quad (\text{compatible with } p/\text{Fe}/8)$$

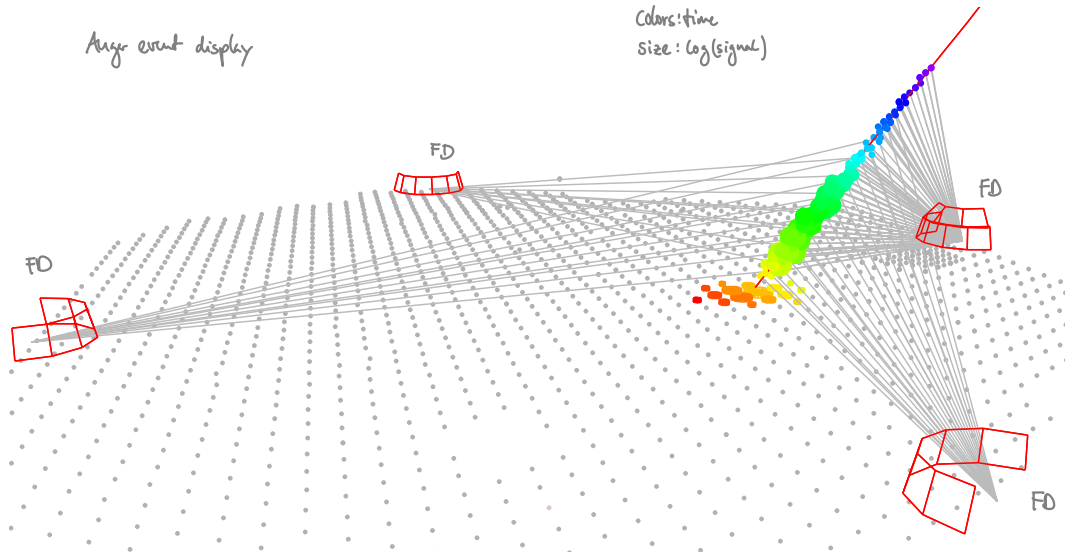
“Hybrid Detection” (e.g. fluorescence and particles)

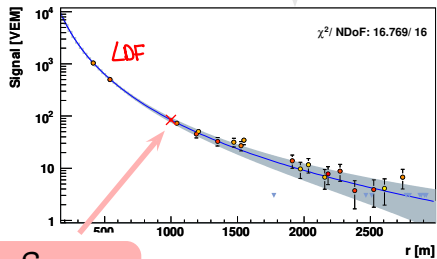
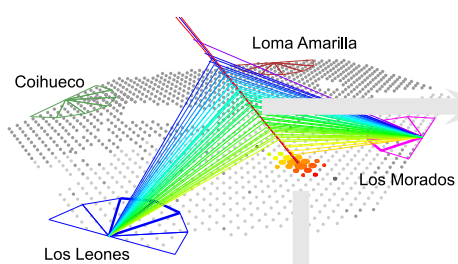


“Hybrid Detection” (e.g. fluorescence and particles)

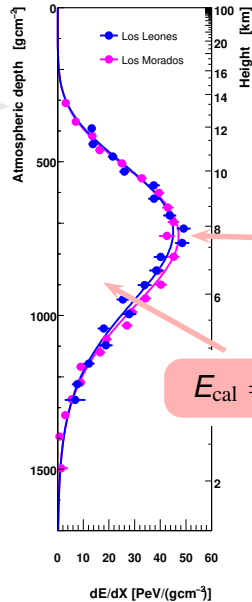
Angular event display

Colors: time
Size: $\log(\text{signal})$



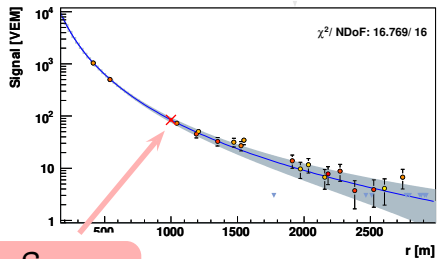
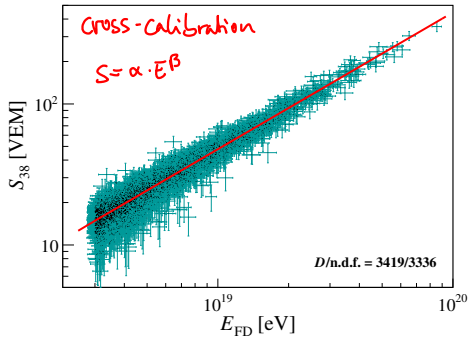


S_{1000}

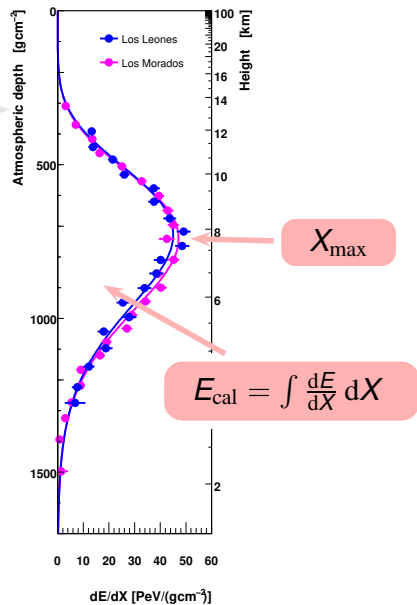


X_{max}

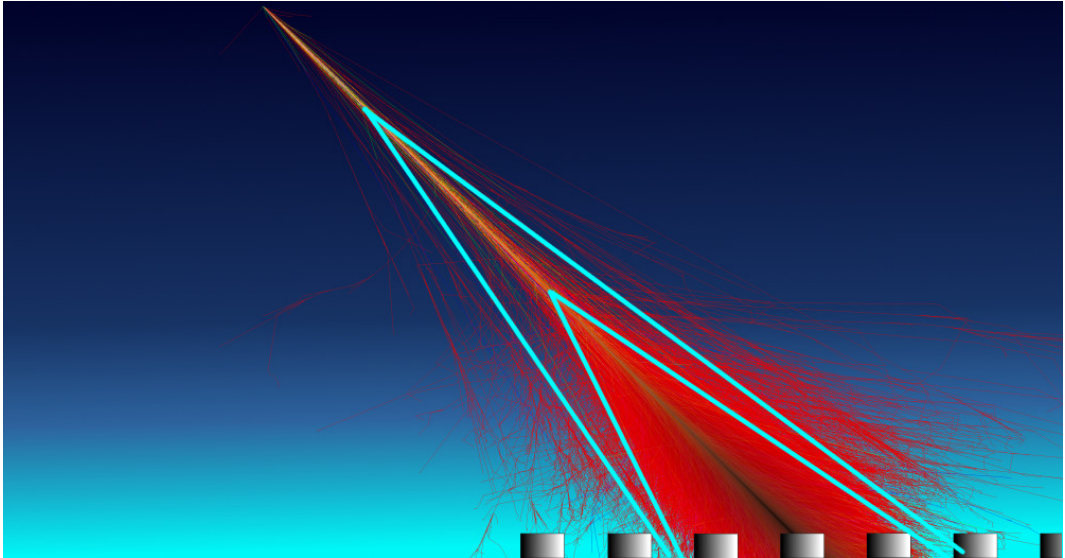
$$E_{\text{cal}} = \int \frac{dE}{dX} dX$$

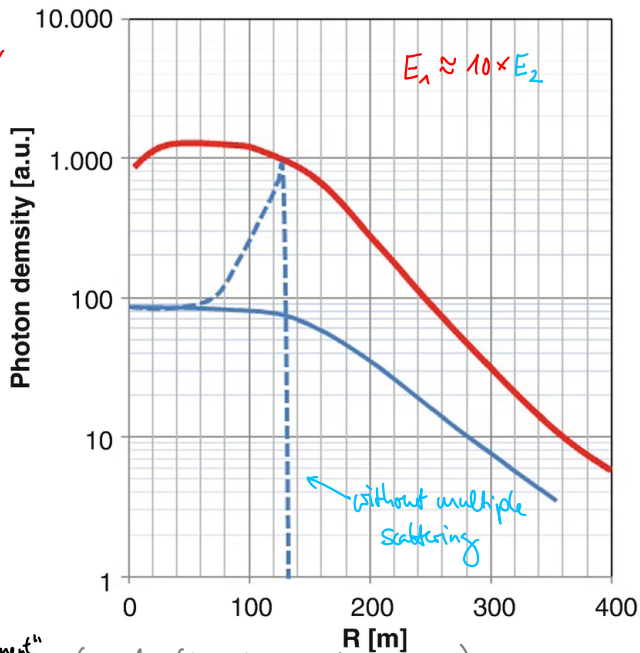
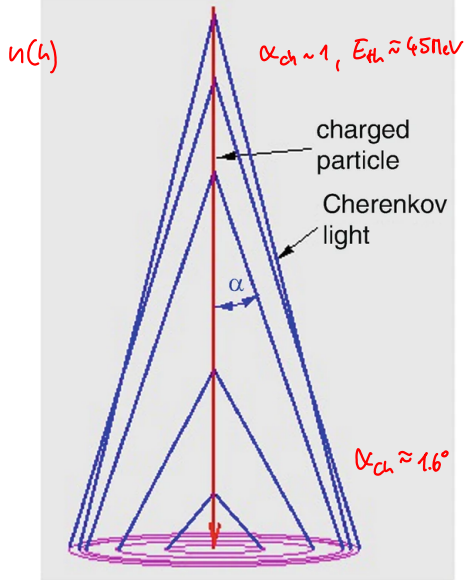


S_{1000}



Non-Imaging Cherenkov Detectors



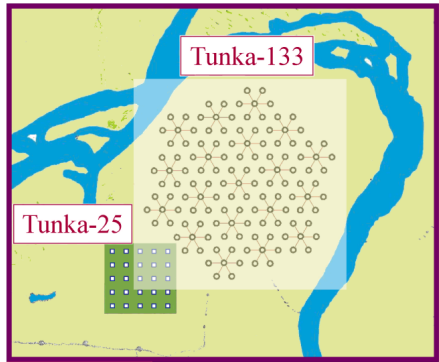
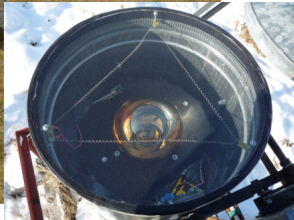


$$N_g \sim N_e \sim E_{em}$$

"Calorimetric measurement"

(X_{max} from lateral shape and time dispersion)

TUNKA army



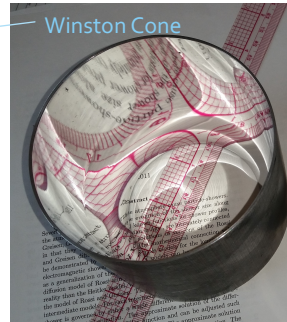
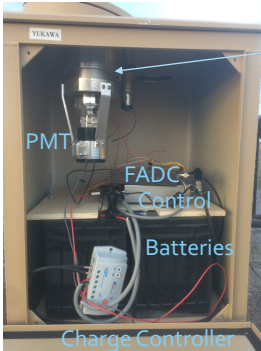
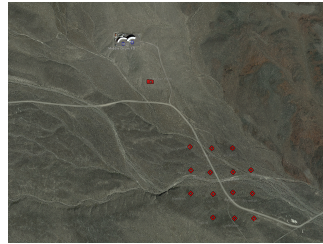
85m
spacing

51° 48' 35" N
103° 04' 02" E
675 m a.s.l.

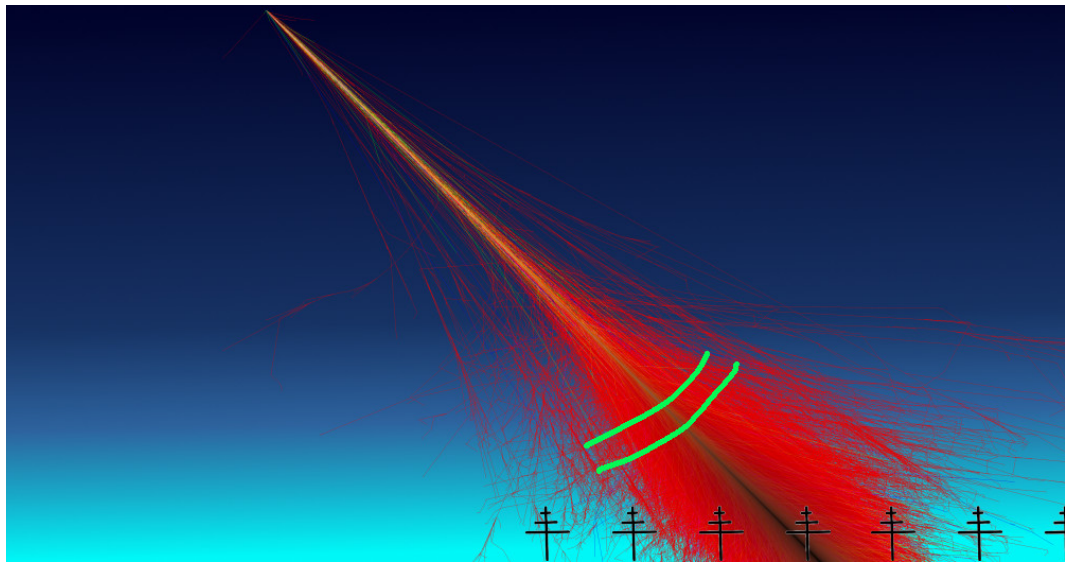


NICHE Array at TA

14 stations on 100 m grid
(1-100 PeV)



Radio Detectors

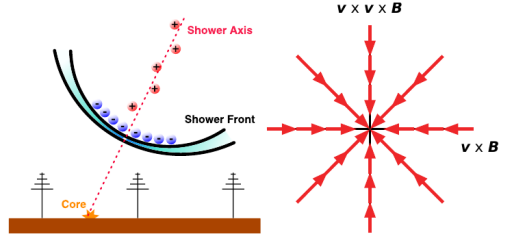
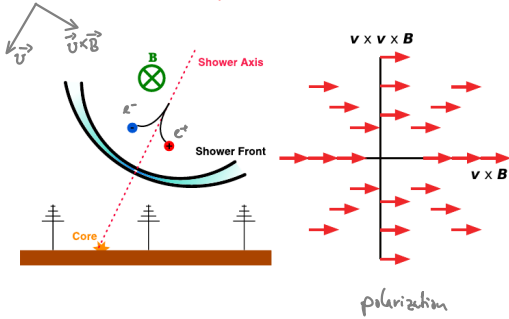


$\lambda > \text{shower front thickness}$

$\Rightarrow f \lesssim 100 \text{ THz}$

shower $\approx$ point charge $\Rightarrow$ radial $\vec{E}$ from Q

$\vec{E} \perp \vec{B}$ from $\vec{I}$



T. Huege, Phys.Rept. 620 (2016) 1

geomagnetic effect

$>$

in air!

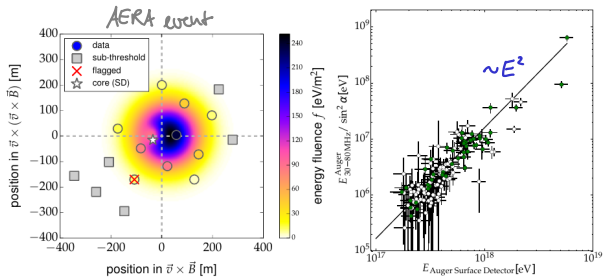
(Askaryan dominates in solids)

charge excess / Askaryan effect

$\approx 10\%$ in air

$$\vec{E} \sim N_e \Rightarrow \text{radiated power} \sim N_e^2 \sim E^2$$

Auger Coll., PRL 116 (2016) 241101



2p1c



LOPES@KASCADE



SALLA@Tunka

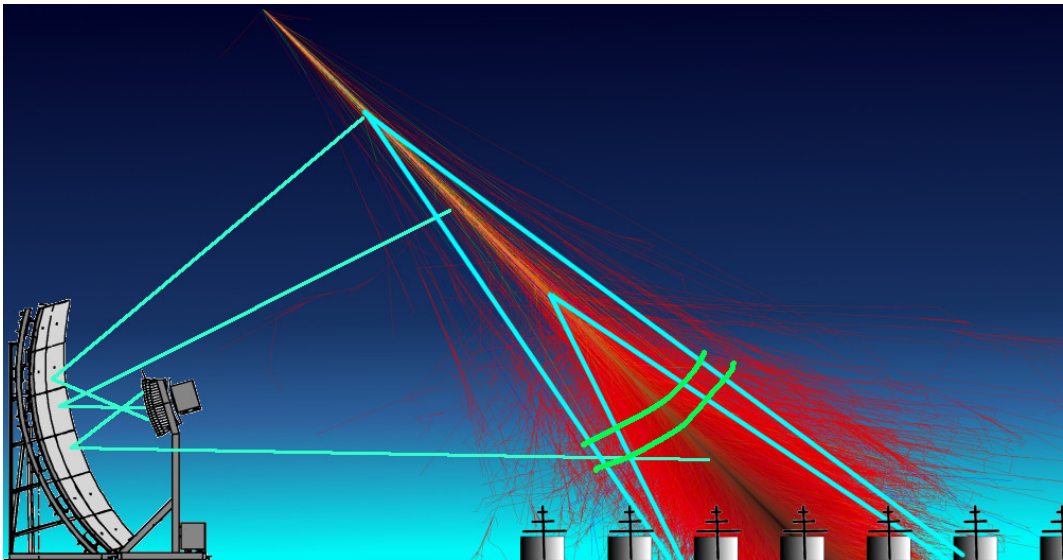


LPDA@Auger

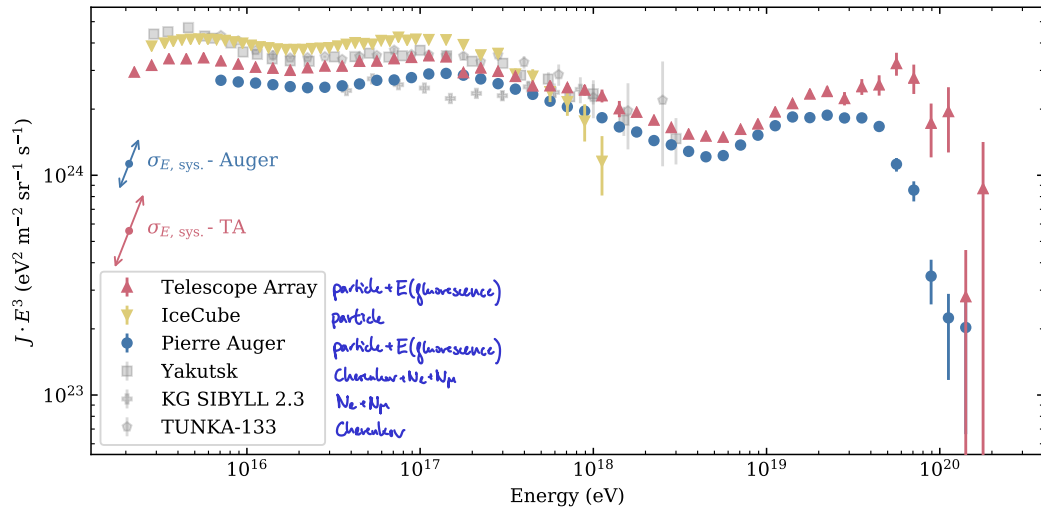


SALLA@Auger

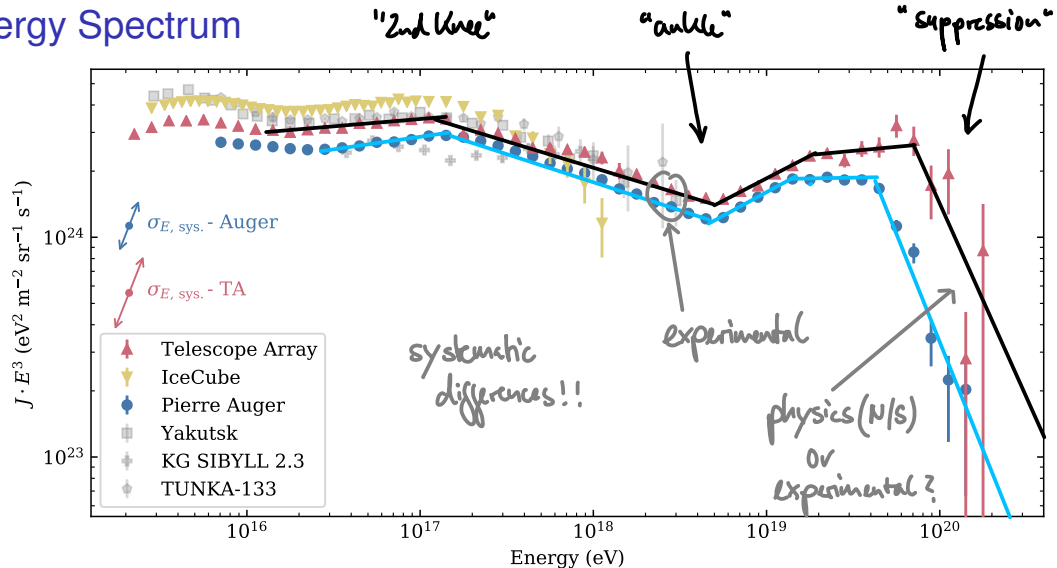
Some Results (E and A)



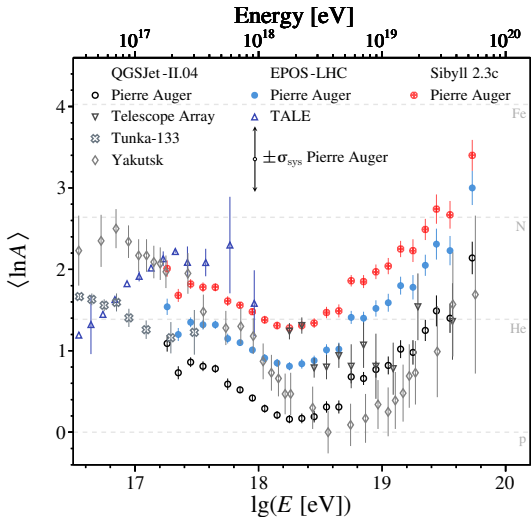
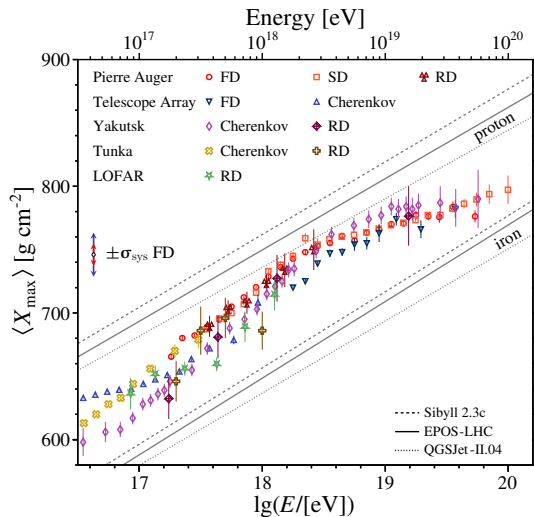
Energy Spectrum



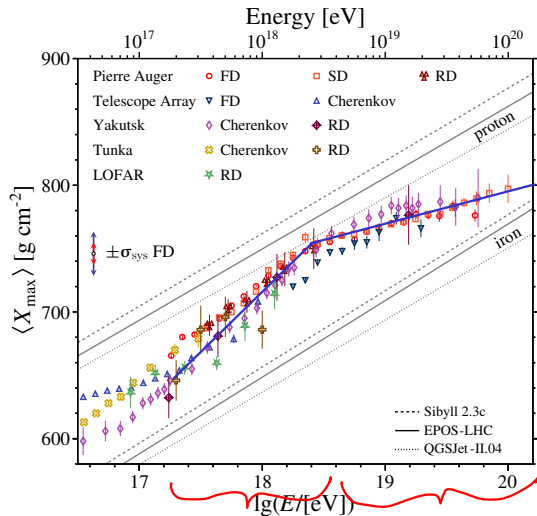
Energy Spectrum



Mass Composition



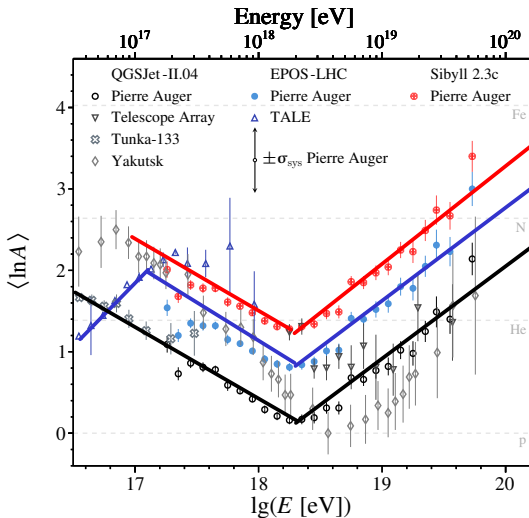
Mass Composition



elongation rate

$D_{10} > D_{10}^{\text{had}}$

$D_{10} < D_{10}^{\text{had}}$



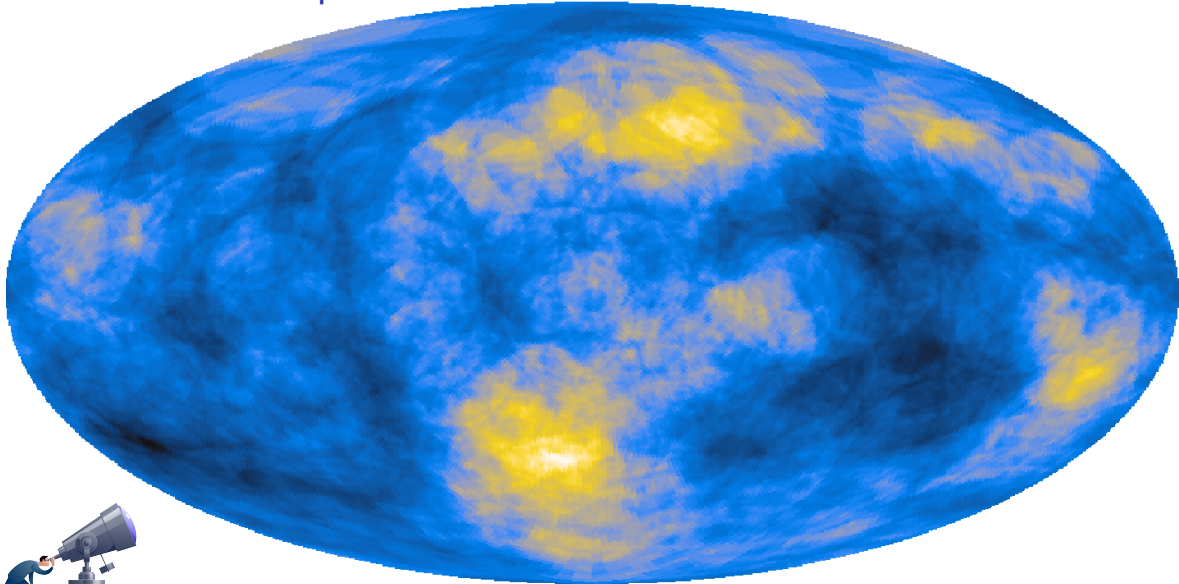
$D_{10} = \frac{d\langle X_{\max} \rangle}{d \lg E}$

change of average shower maximum per log of energy

Detector Score Card (UHE)

	EAS variable	detector density	duty cycle	cost/unit	model dependence	maintenance/calibration
particle	N_E/N_μ	$\approx 1/\text{km}^2$	$\approx 100\%$	low... medium $N_E \sim N_\mu$	high	low
fluorescence	E_{em}/X_{max}	$\approx 1/2000 \text{ km}^2$	$\leq 15\%$	high	low	high
radio	E_{em}/X_{max}	$1 \dots \gtrsim 100/\text{km}^2$ E_{em} X_{max}	$\approx 100\%$	low... medium electronics!	low	low
Cherenkov	E_{em}/X_{max}	$\gtrsim 100/\text{km}^2$	$\leq 15\%$	low... medium	low	medium... high

Future UHECR Experiments



Auger&TA UHECR sky 2018 [σ_{loc}]



UHECR Detection at Ground?

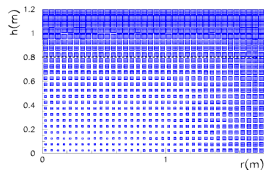
e.g. Global Cosmic-Ray Observatory (GCOS): $2 \times (\text{Auger} \times 10)$ (North and South)

$2 \times 30000 \text{ km}^2$, 2.2 km detector spacing, 2×9000 stations, threshold 30 EeV

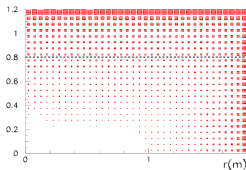
The idea: optical separation of a Water Cherenkov Tank

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

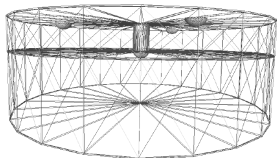
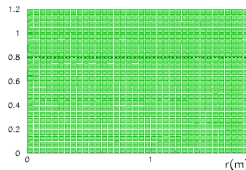
photons



electrons



muons



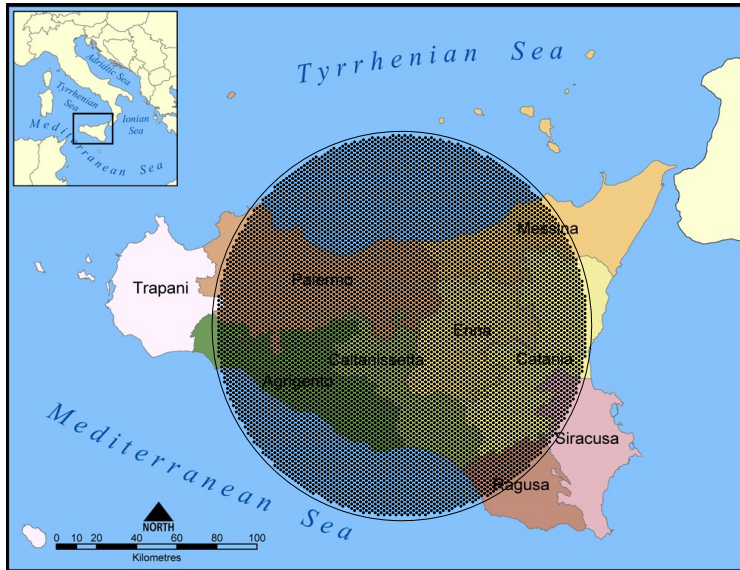
$$\begin{pmatrix} S_{\text{top}} \\ S_{\text{bot}} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix}$$

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

A. Letessier-Selvon, P. Billoir, M. Blanco, I. C. Mariş, M. Settimo

UHECR Detection at Ground?

One GCOS site (30k km²) vs. Sicily (25k km²)



see "Ideas and Requirements for the Global Cosmic-Ray Observatory (GCOS)" arXiv:2502.05657

UHECR Detection From Space?

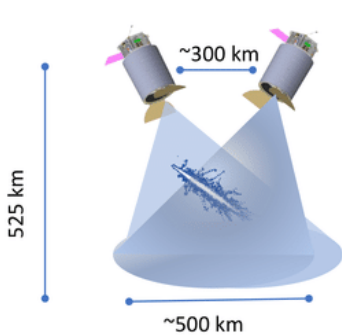
e.g. POEMMA (JCAP 06 (2021) 007)



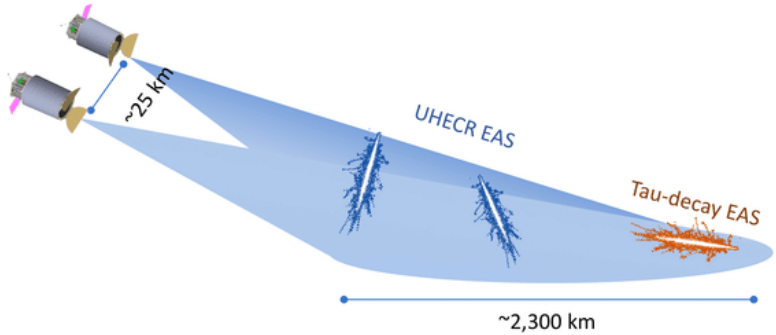
UHECR Detection From Space?

e.g. POEMMA (JCAP 06 (2021) 007)

POEMMA-Stereo



POEMMA-Limb

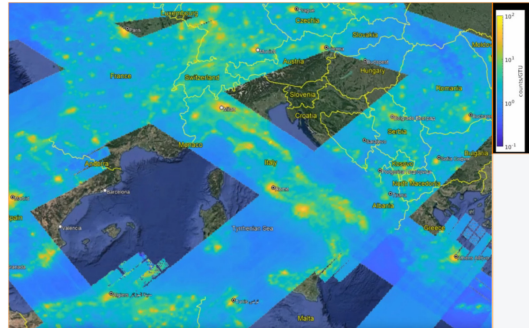
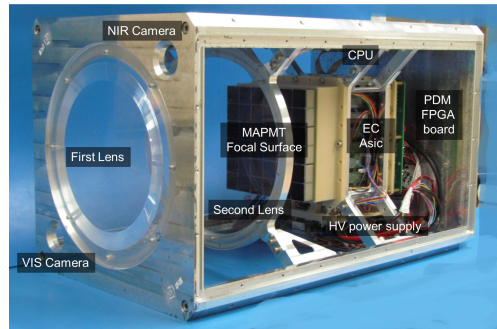


UHECR Detection From Space?

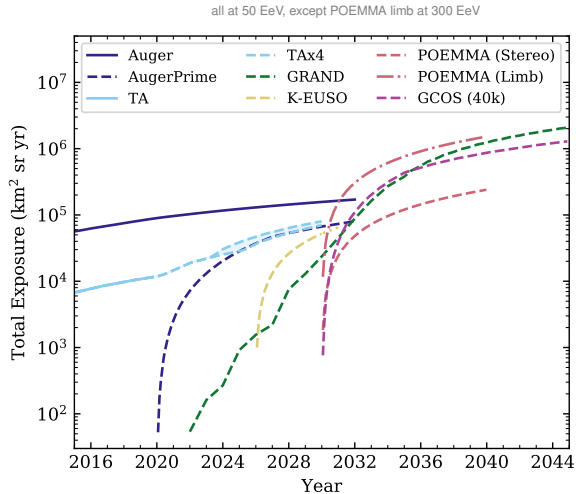
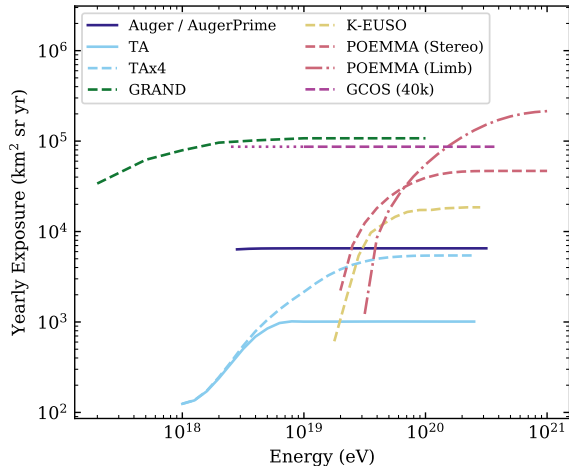
Pathfinder Mini-EUSO on the ISS



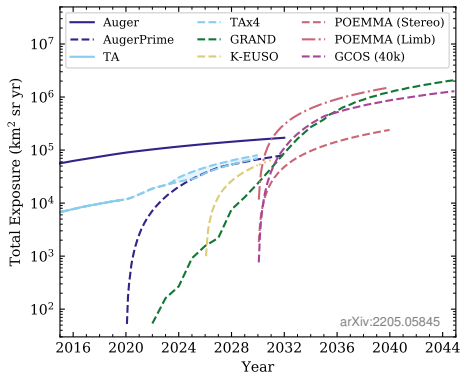
→ possible duty cycle: 18%
(13% taking into account clouds)



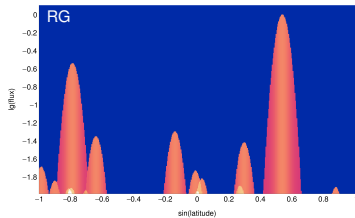
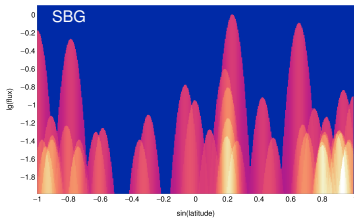
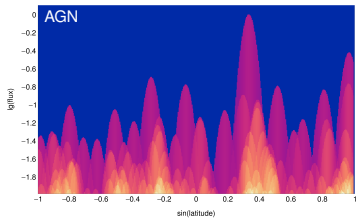
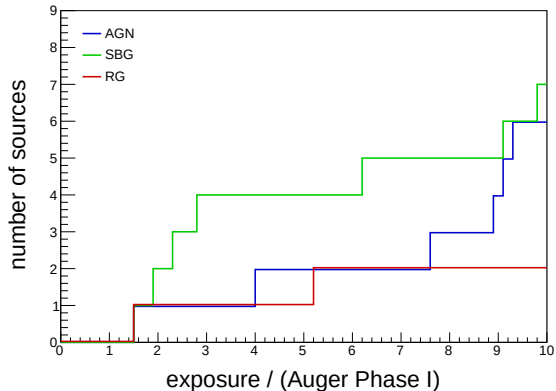
Future UHECR Experiments



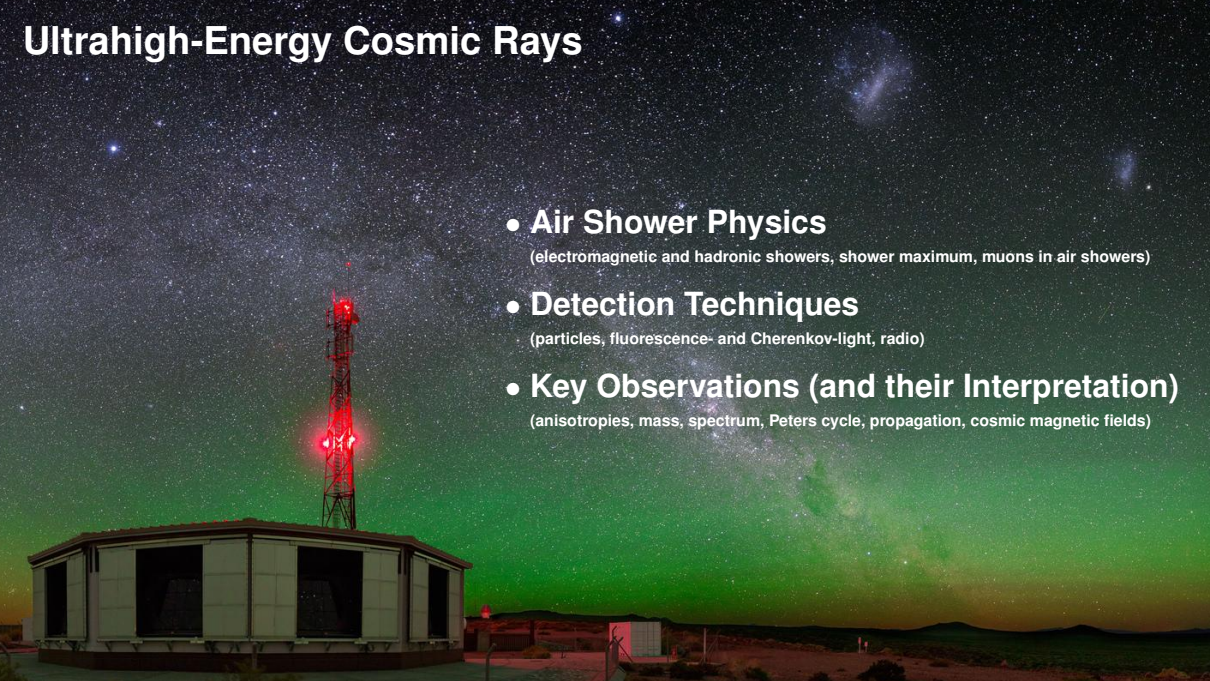
Future UHECR Experiments



AGN: active galactic nuclei, SBG: starburst galaxies, RG: radio galaxies



Ultra-high-Energy Cosmic Rays

A night sky with a green aurora borealis and a radio telescope structure. The sky is dark with many stars and a prominent green aurora borealis. In the foreground, there is a white, octagonal building with a red radio telescope structure on top. The structure has several red lights and a red antenna. The background shows a dark landscape with some distant lights.

- **Air Shower Physics**

(electromagnetic and hadronic showers, shower maximum, muons in air showers)

- **Detection Techniques**

(particles, fluorescence- and Cherenkov-light, radio)

- **Key Observations (and their Interpretation)**

(anisotropies, mass, spectrum, Peters cycle, propagation, cosmic magnetic fields)