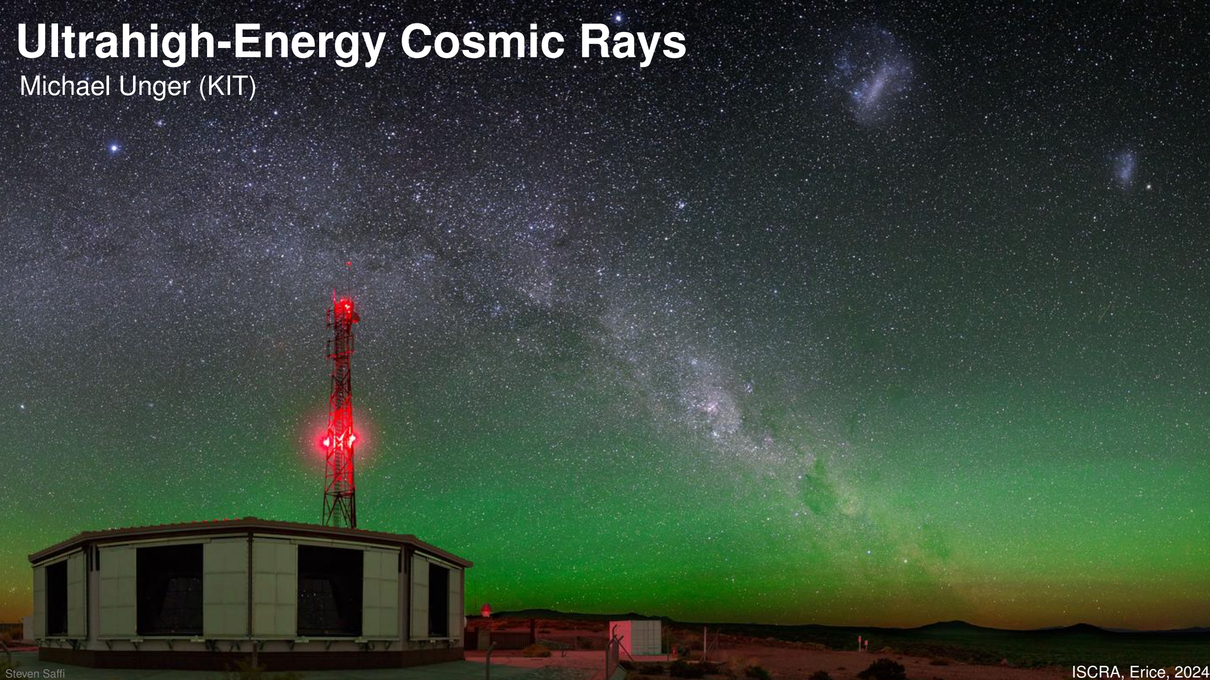
Ultrahigh-Energy Cosmic Rays

Michael Unger (KIT)

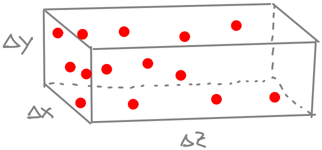


Steven Saffi

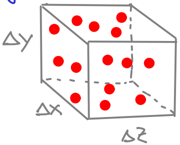
ISCRA, Erice, 2024

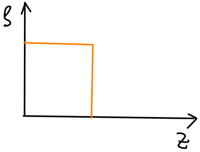
Column Depth X (cont.)

non-uniform density

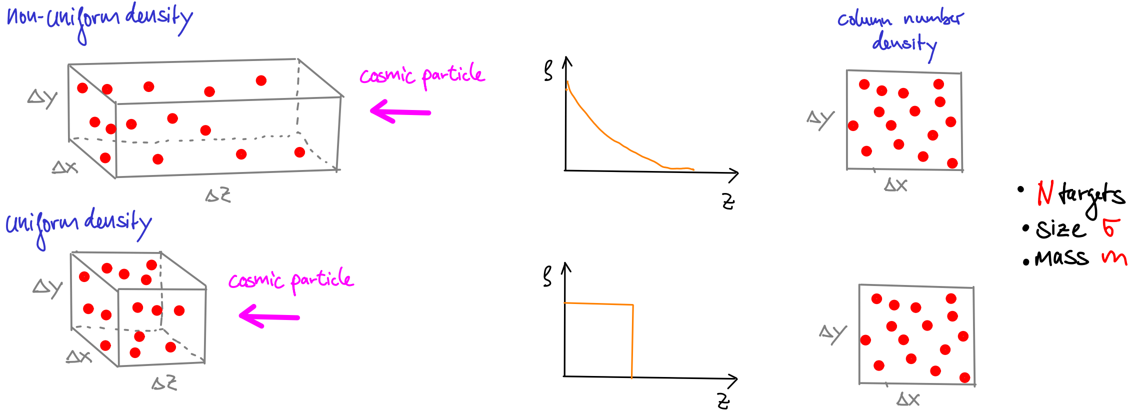


uniform density





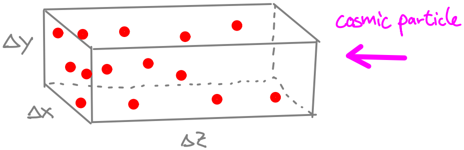
Column Depth X (cont.)

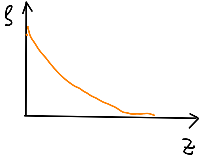


$$P(\text{interaction}) = \frac{S_{\text{target}}}{S_{\text{tot}}} = \frac{N \cdot \sigma}{\Delta x \, \Delta y}$$

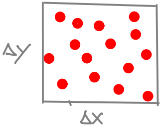
Column Depth X (cont.)

non-uniform density



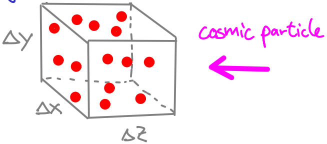


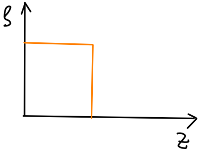
column number density

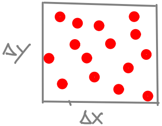


- N targets
- size σ
- mass m

uniform density







$$P(\text{interaction}) = \frac{\sigma_{target}}{\sigma_{tot}} = \frac{N \cdot \sigma}{\Delta x \, \Delta y}$$

→ column depth $X = \int \rho(z)\, dz$: mass per area $X = \frac{N \cdot m}{\Delta x \Delta y \Delta z} \Delta z$

→ interaction length $\lambda = \frac{m}{\sigma}$

$$\Rightarrow P(\text{int}) = 1 - e^{-X/\lambda} \approx \frac{X}{\lambda} = \frac{N \cdot \sigma}{\Delta x \, \Delta y}$$

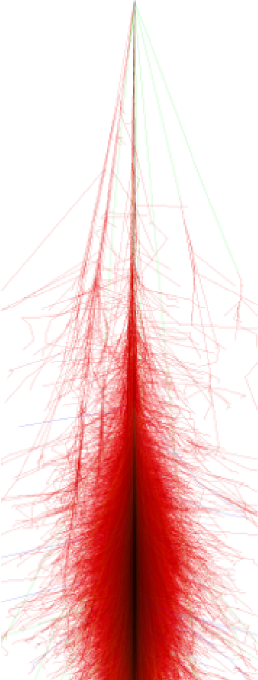
Recap Air Showers

- particle beam: primary cosmic rays from space
- target: atmosphere, avalance of elemetary particles
- avalance of secondary particles
- traversed matter density: slant depth X, units [g/cm^2]

  sea level: $\sim$ 1000 g/cm^2 at vertical incidence
  $\sim$ 2000 g/cm^2 at 60°
  $\sim$ 35000 g/cm^2 at 90°

- electromagnetic component: photons, electrons, positrons
  - splitting length: radiation length $X_0 \sim 37$ g/cm^2
  - critical energy: $\varepsilon_{\text{em}} \sim 87$ MeV (brems./rad. = ion.)
- hadronic component: baryons and mesons
  - splitting length: interaction length $\lambda_p \sim 80$ g/cm^2
  - critical energy: $\varepsilon_{\text{had}} \sim 10$ GeV ($\lambda_{\text{int}} = \lambda_{\text{dec}}$)
  - shower maximum $X_{\text{max}} = \lambda_p + X_0 \ln\left(E_0/(2\,A\,M\,\varepsilon_{\text{em}}\right)$
  - number of muons ($X \geq X_{\text{max}}$) $N_\mu = (E_0/\varepsilon_{\text{had}})^\beta A^{1-\beta}$
  - number of em particles (at X_{max}) $N_{\text{em}} = \left(E_0 - N_\mu \varepsilon_{\text{had}}\right)/\varepsilon_{\text{em}}$

(primary energy E_0, pion multiplicity M, mass number A, $\beta = \ln 2/3M/\ln M \approx 0.9$)



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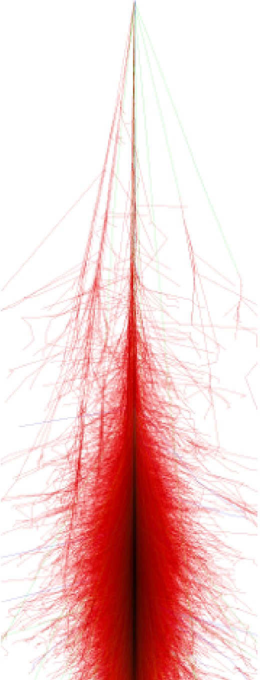

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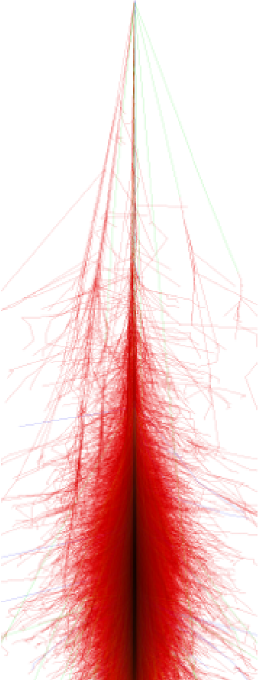
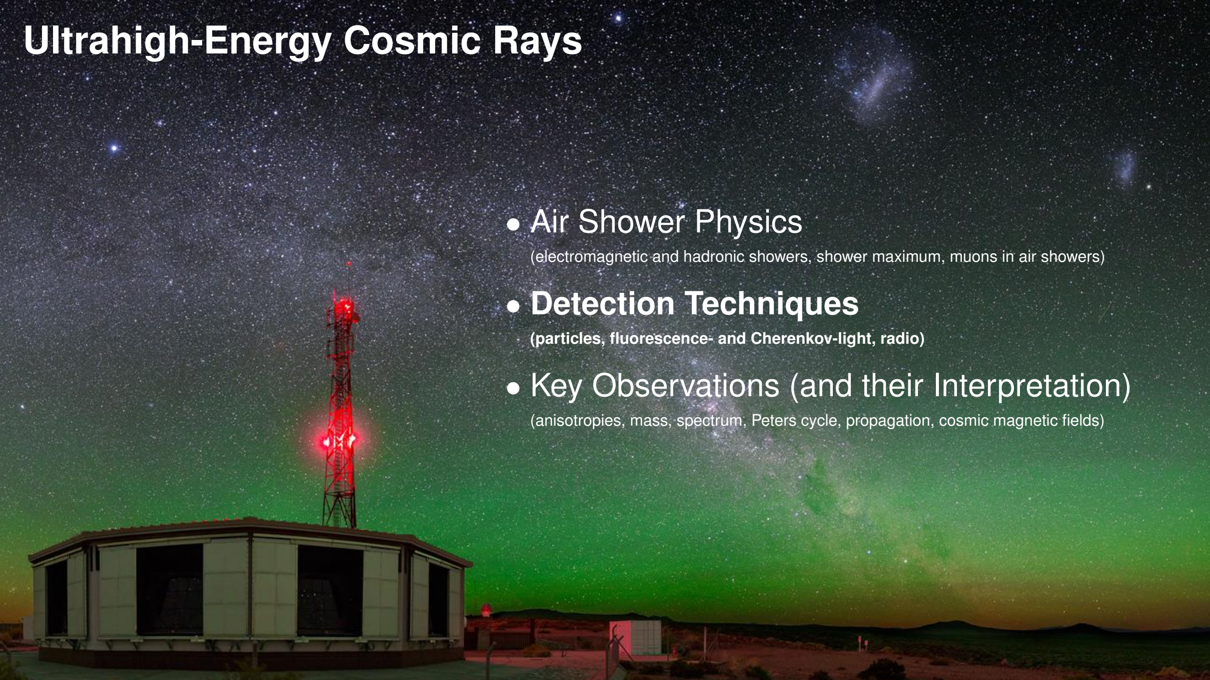


Recap Air Showers

the bare minimum air shower knowledge:

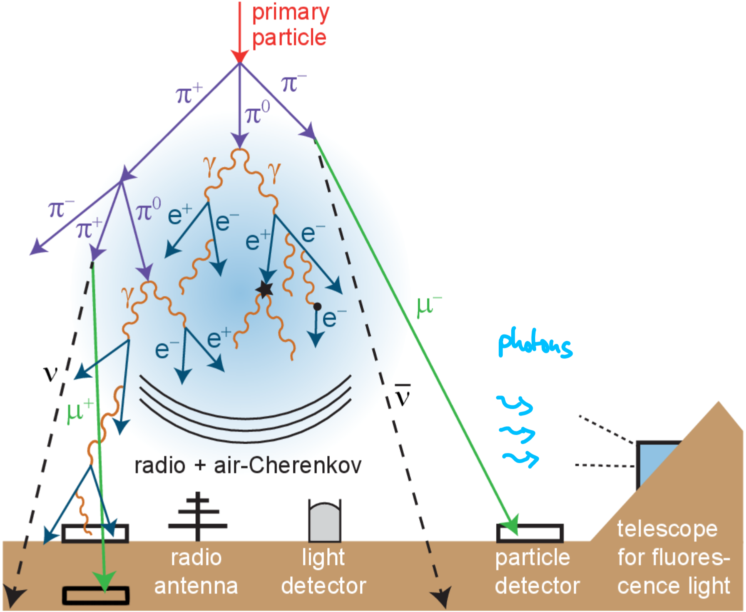
- shower maximum $X_{\text{max}} \propto \ln(E_0/A)$
  - X_{max} increases logarithmically with energy
  - proton showers penetrate deeper than iron showers ($\Delta X_{\text{max}} \sim 100$ g/cm^2)
- number of muons $N_\mu \propto E_0^{0.9}\, A^{0.1}$
  - proton showers have less muons than iron showers ($\Delta N_\mu / N_\mu \approx 30\%$)
- details depend on properties hadronic interactions at UHE (multiplicity, elasticitiy, cross sections, ...)

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



F. Schröder, 2017

Air Shower Detection

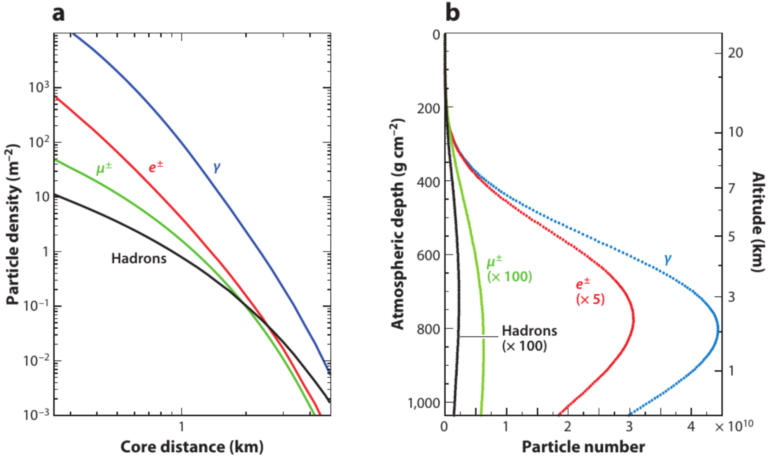
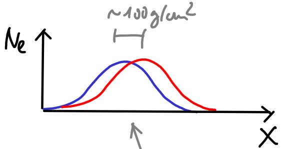


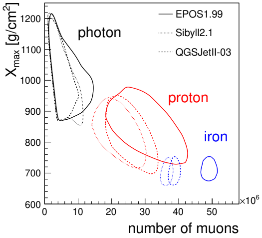
Figure 2

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.

Engel, Heck, Pierog Ann.Rev.Nucl.Part.Sci. 61 (2011) 467

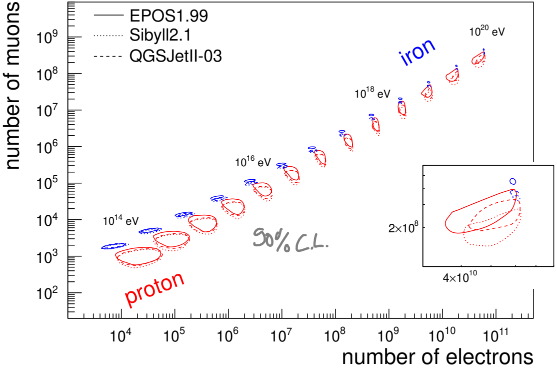
E and A

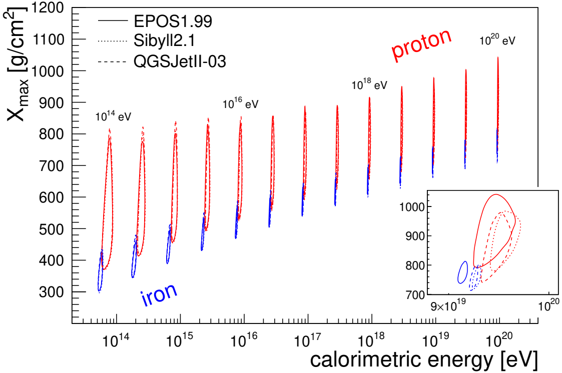




$\theta = 0°$, $X = 800 g/cm^2$

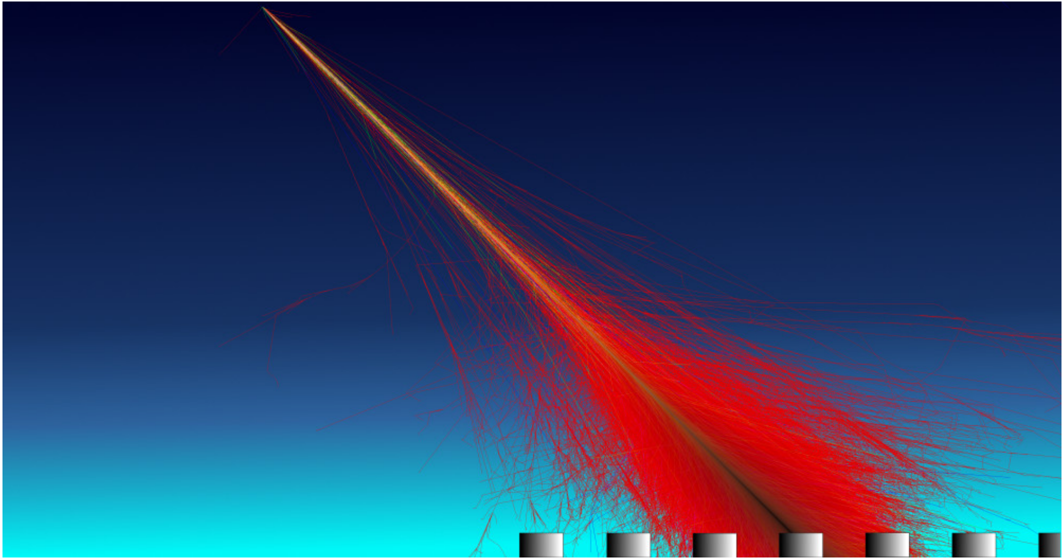
X_{ground} close to X_{max}
$\Rightarrow N_e(p) \approx N_e(Fe)$





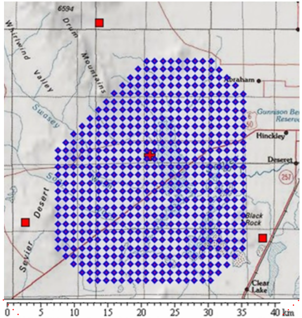
Kampert&Unger APP 2012

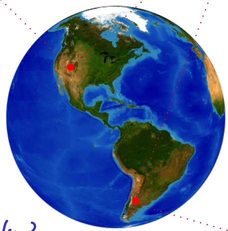
Particle Detectors



Telescope Array "TA"

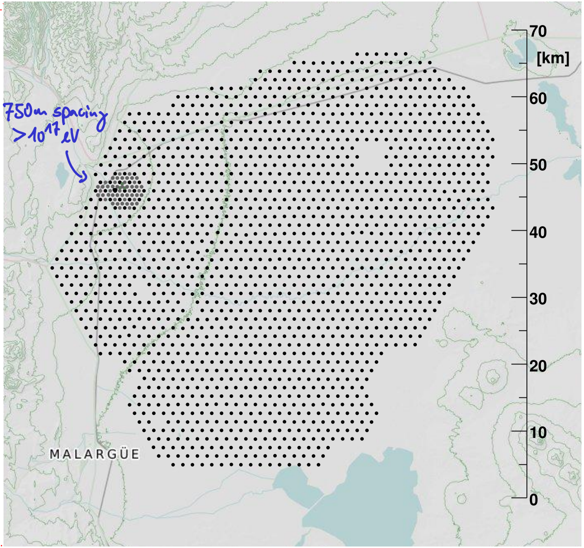
500 SCNTs
1.2 km spacing
A = 700 km²





Pierre Auger Observatory

1600 WCDs
1.5 km spacing $> 10^{18}$ eV
A = 3000 km²



750m spacing
$> 10^{17}$ eV

both at $X_{ground} \approx 850$ g/cm²

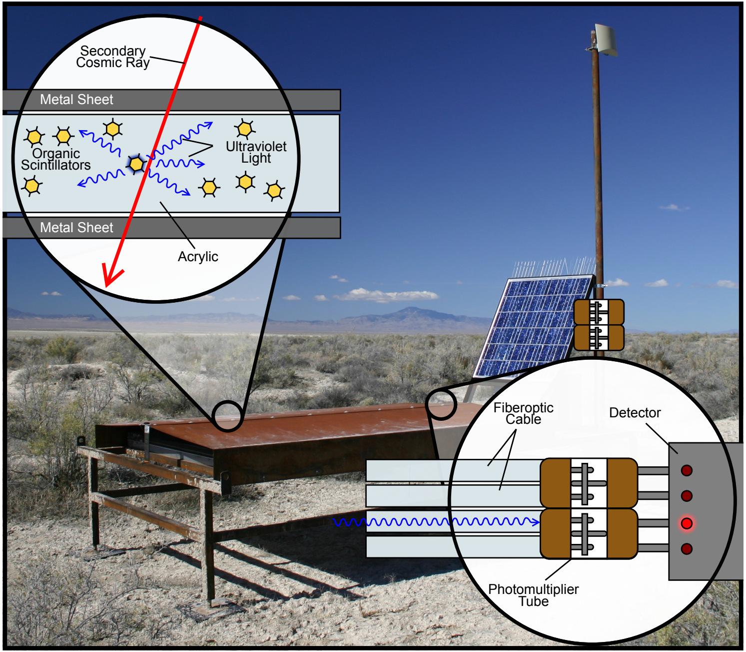
Telescope Array: scintillator as particle detector

Signal

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

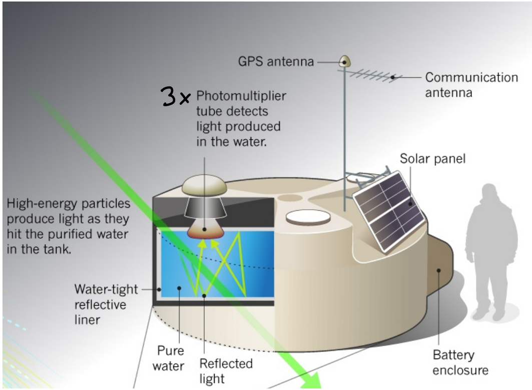
$(+\gamma \to e^+e^-$ conversion)

area ~ $\cos\theta$



Pierre Auger Observatory: Water Cherenkov detectors (WCD)

12 t ultrapure water



Cherenkov threshold: ~ 0.8 MeV e^+e^-

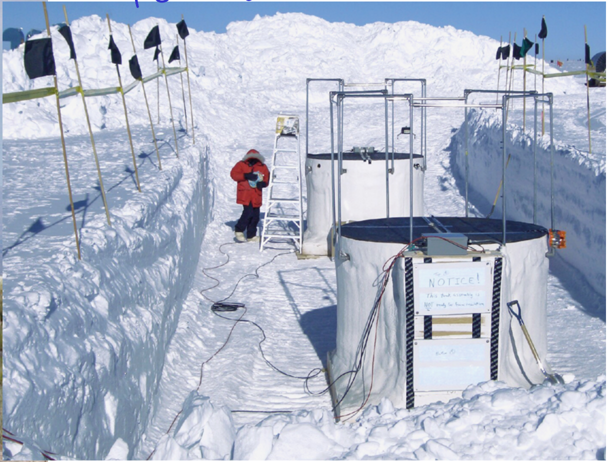
~ 160 GeV $\mu^+\mu^-$

Signal $\frac{dN_c}{dl} \sim l$ → more signal for muons that traverse full det.

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

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

IceTop @ IceCube

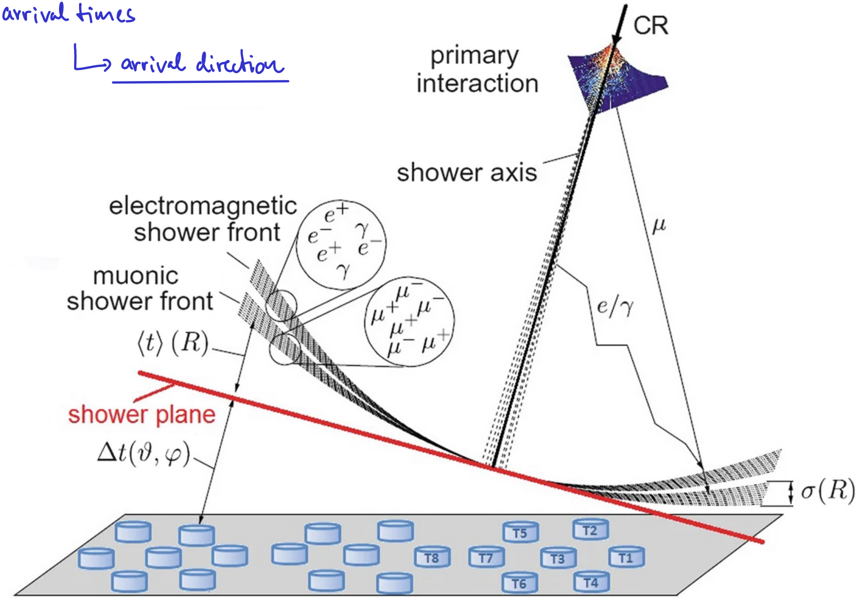


"Ice-Cherenkov" detectors

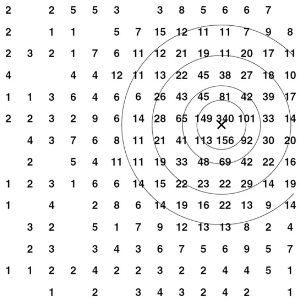

WCDs

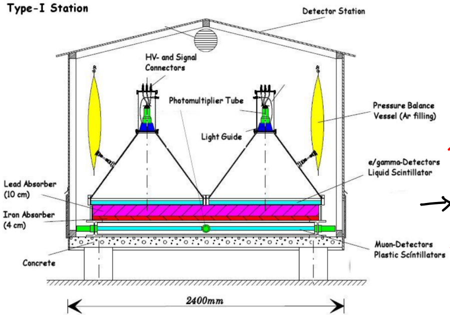
Shower Front / arrival times

↳ arrival direction



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

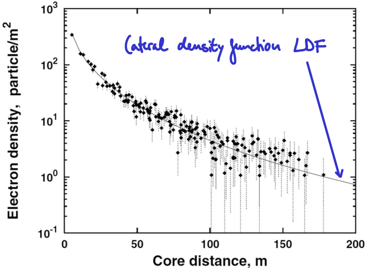




→ $N_{ch} = N_{e^+e^-} + N_\mu$

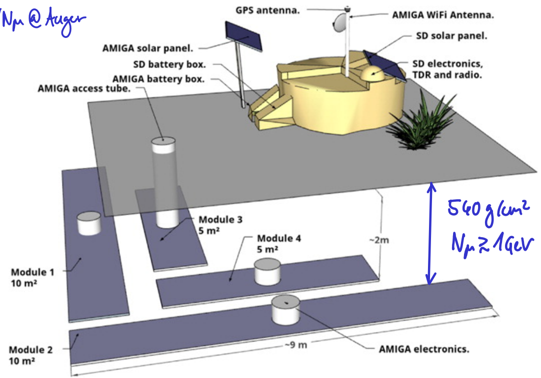
→ 20 attenuation lengths shielding

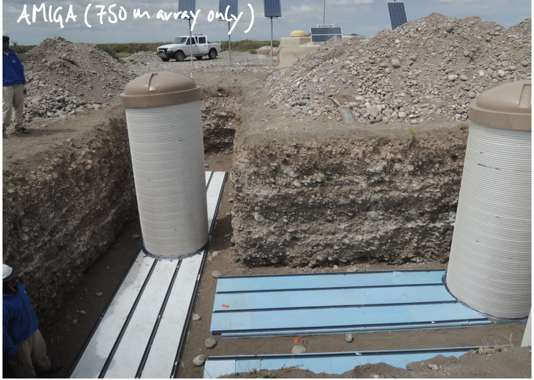
→ N_μ $E_\mu > 250$ MeV

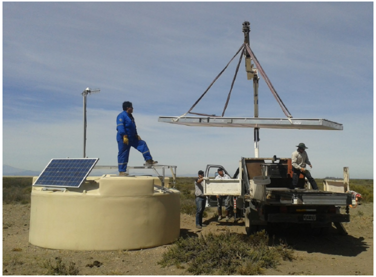


T.Stanev, "High Energy Cosmic Rays" (2010)

N_e/N_μ @ Auger







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

schematically:

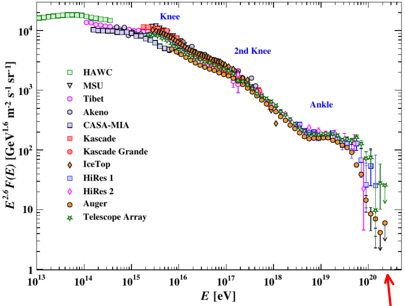
$$S_{SCNT} \sim N_\mu + N_e$$

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

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

$\Rightarrow N_e$ and N_μ

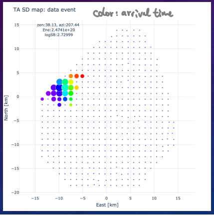
highest energy event measured with an PD

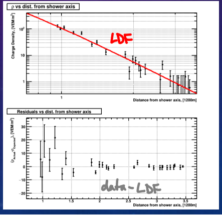


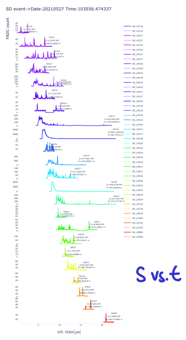
PDG 2022

NEW HIGHEST EVENT DETECTED BY TA

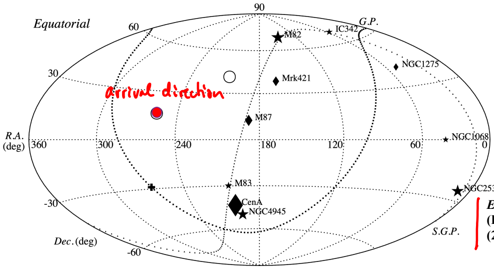
- 2021/05/27 10:35:56.47, No FD observation
  - E = **243.6 ± 10.7 EeV**, θ = 38.6°, φ = 206.8° - **Preliminary**
    - (E = 242.8 EeV with the atmospheric energy correction) - **Preliminary**







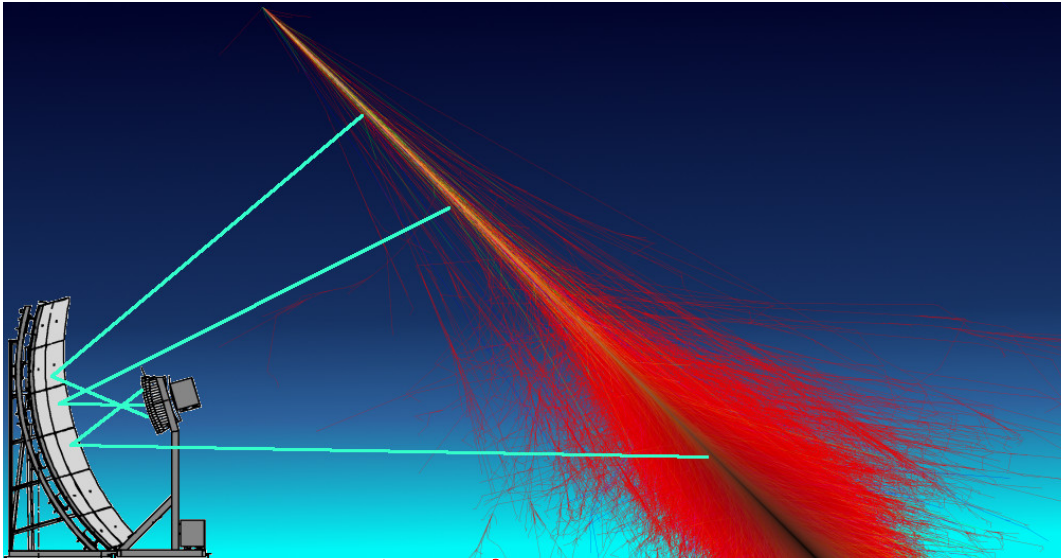
DIRECTION IN THE SKY-MAP



E = 243.6 EeV
(RA, Dec) = (255.85, 16.08)

J. Matthews, TA Coll. 2022

Fluorescence Telescopes



$r_{max} \approx 45$ km at 10^{20} eV

Air Fluorescence

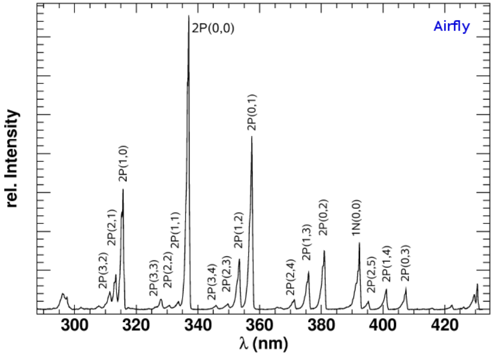
- N_2 excitation by charged particles
- isotropic emission !!
- fluorescence yield $Y \sim f(\rho, T, H) \cdot \frac{dE}{dx}$

  density ρ, temperature T, humidity H

  $\frac{dE}{dx}$: energy deposit in atmosphere
- rule of thumb: ≈ 3-4 photons/m/particle

  ≙ 30 W light bulb
- precise measurement in lab

emission in UV (~10 ns)



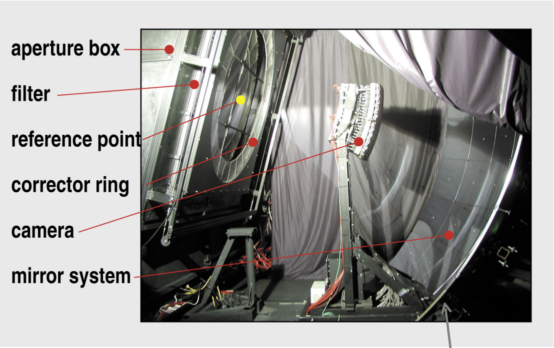
shower visible up to 30 km @ 10^{19} eV ⇒ 3000 km²

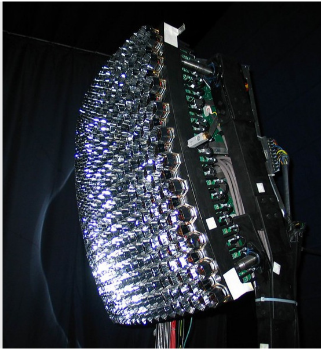
45 km @ 10^{20} eV ⇒ 6000 km²

but: duty cycle ≲ 15% (moon, sun, clouds, thunderstorms...)

"Schmidt optics"

camera





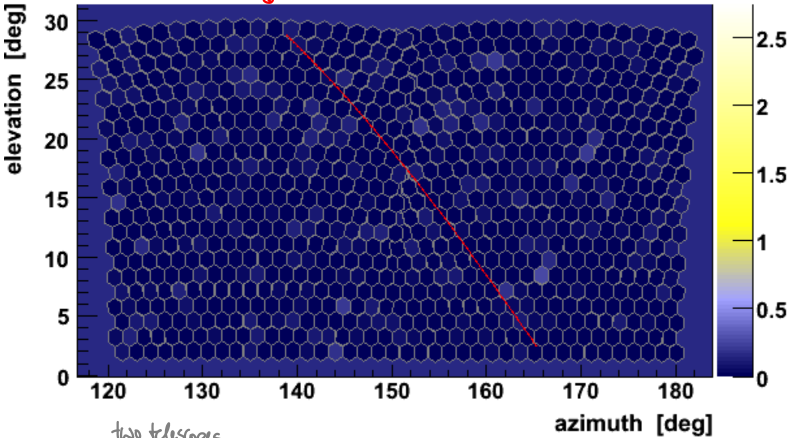
6 telescopes per building

4 buildings at edge of array (looking inward)

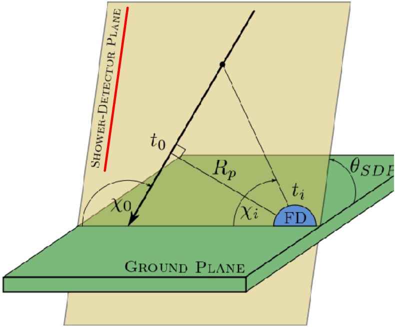
spherical mirror

440 hexagonal PMTs

shower detector plane

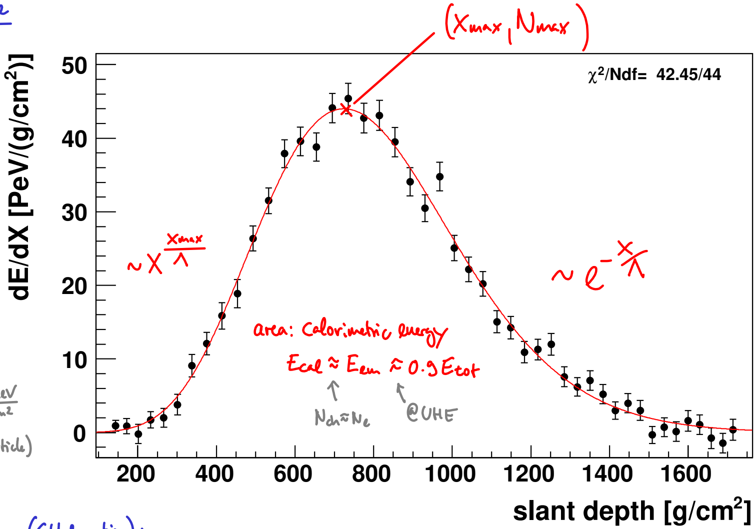


two telescopes



⇒ see separate file for animation

Longitudinal profile



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

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

(average energy deposit per particle)

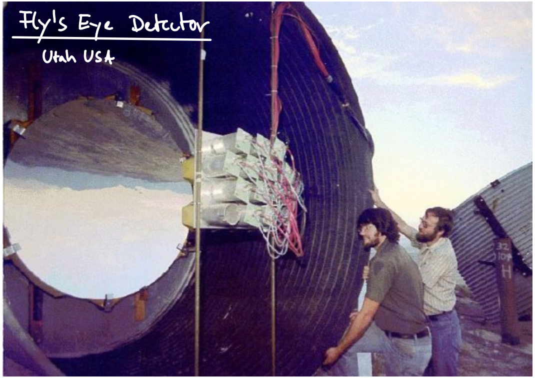
Nucl.Instrum.Meth.A 798 (2015) 172

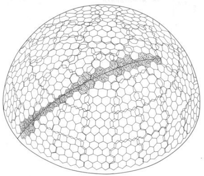
Gaisser-Hillas function (GH function):

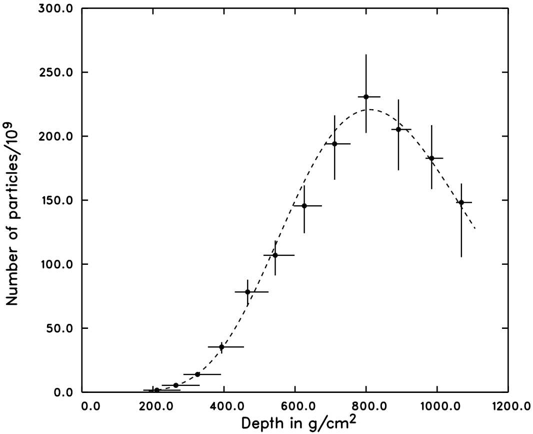
$$N_{fluo} \sim \frac{dE}{dX} \sim N_e(X) = N_{max} \left(\frac{X - X_1}{X_{max} - X_1} \right)^{(X_{max} - X_1)/\Lambda} e^{-\frac{X - X_{max}}{\Lambda}}$$

$(X_1 \approx 0\ g/cm^2,\ \Lambda \approx 60\ g/cm^2)$

highest energy fluorescence detector event







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

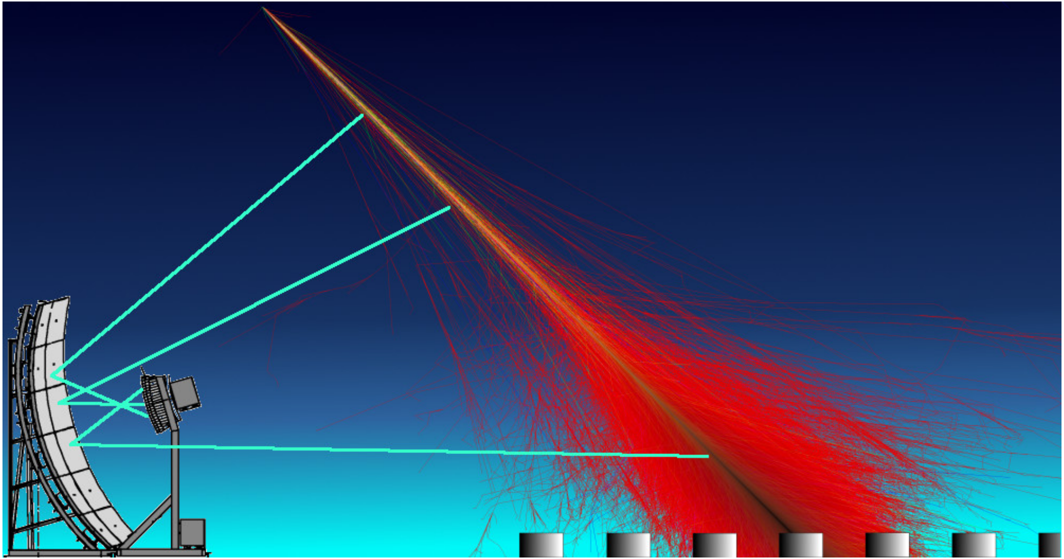
see also T.Fitoussi et al, JCAP 01 (2020) 042

RA = 85.2°, DEC = 48°

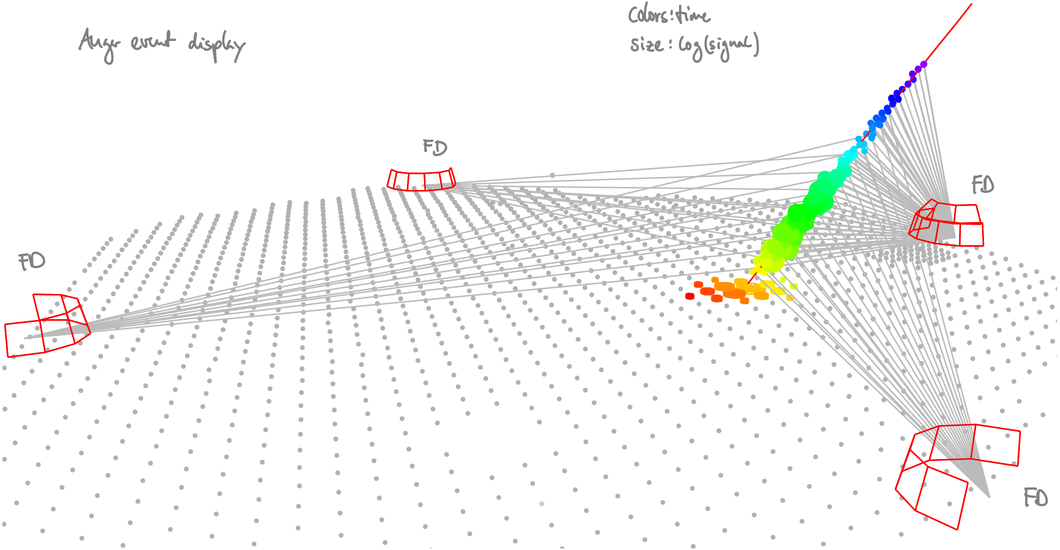
$E = (320 \pm 90) \cdot 10^{20}\,eV$ (51 Joule!)

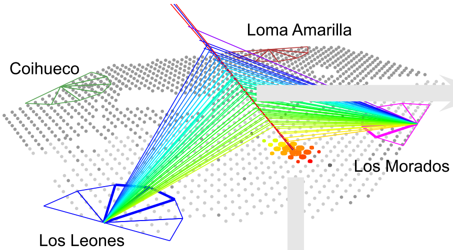
$X_{max} = (815 \pm 60)\,g/cm^2$ (compatible with p/Fe/γ)

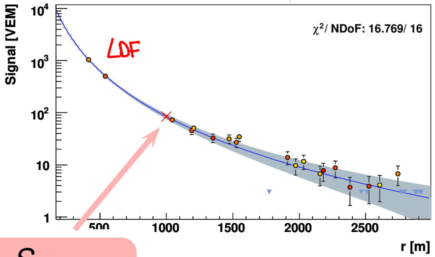
“Hybrid Detection” (e.g. fluorescence and particles)



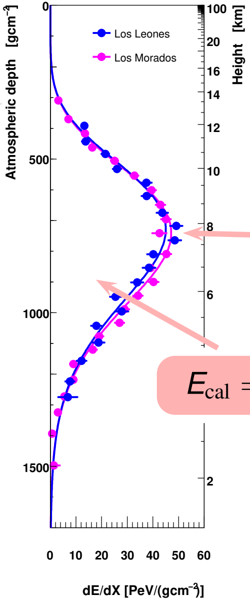
“Hybrid Detection” (e.g. fluorescence and particles)





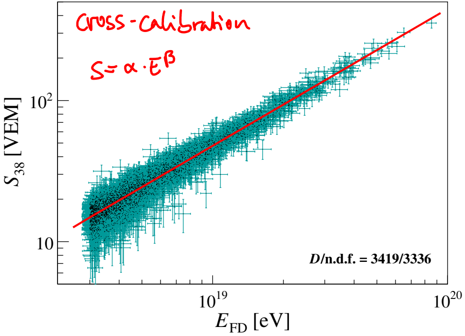


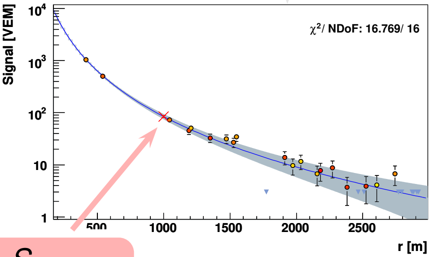
S_{1000}



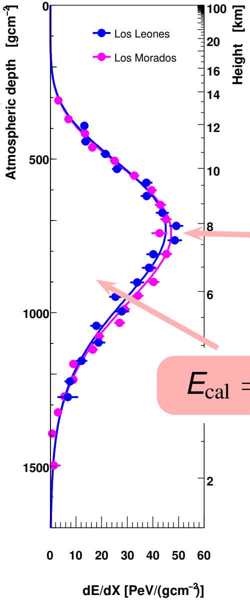
$X_{\max}$

$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$





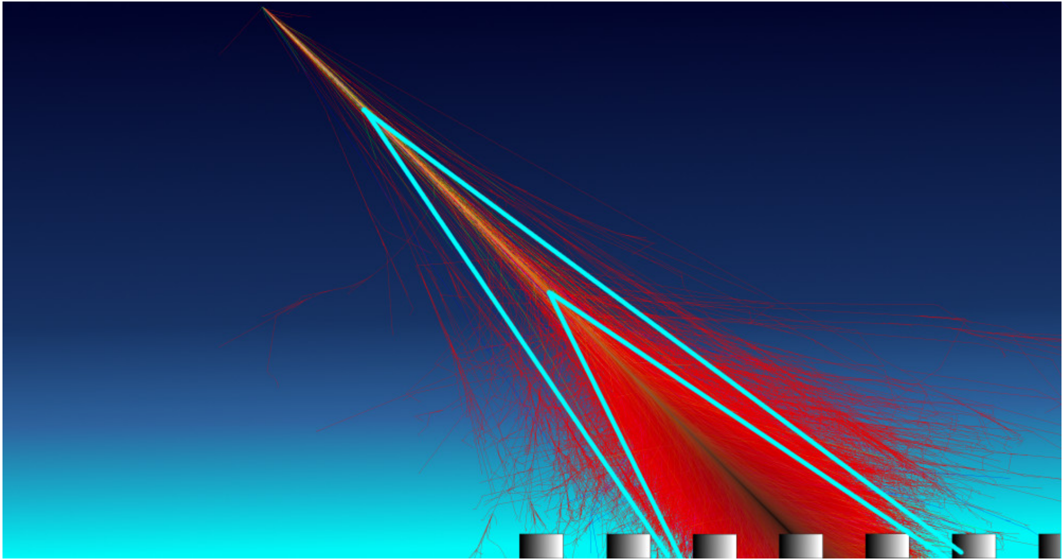
S_{1000}

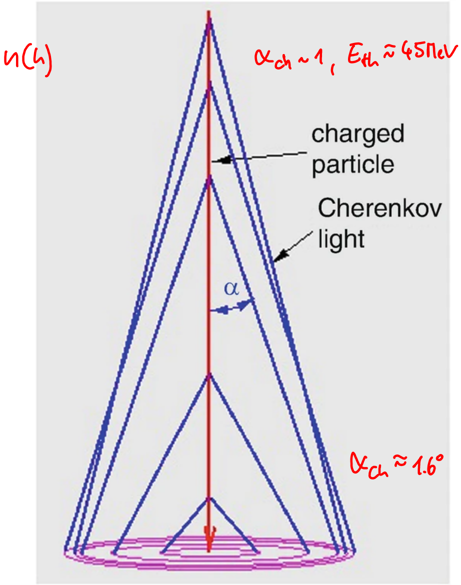


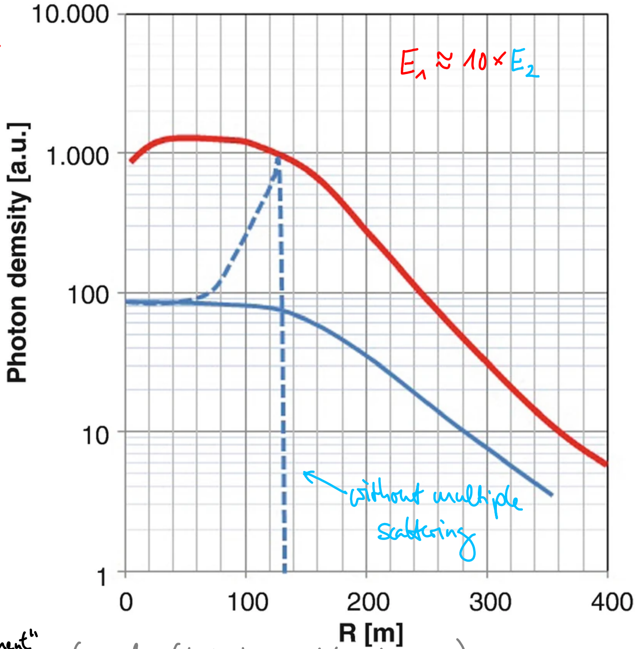
$X_{\max}$

$$E_{\mathrm{cal}} = \int \frac{\mathrm{d}E}{\mathrm{d}X}\,\mathrm{d}X$$

Non-Imaging Cherenkov Detectors





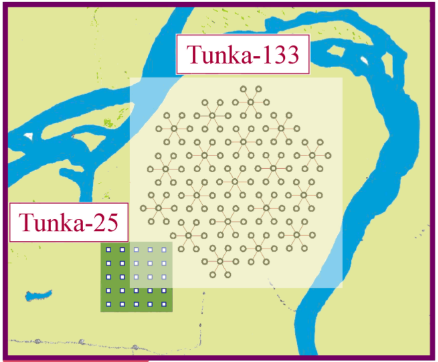


$N_\gamma \sim N_e \sim E_{em}$

"calorimetric measurement"

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

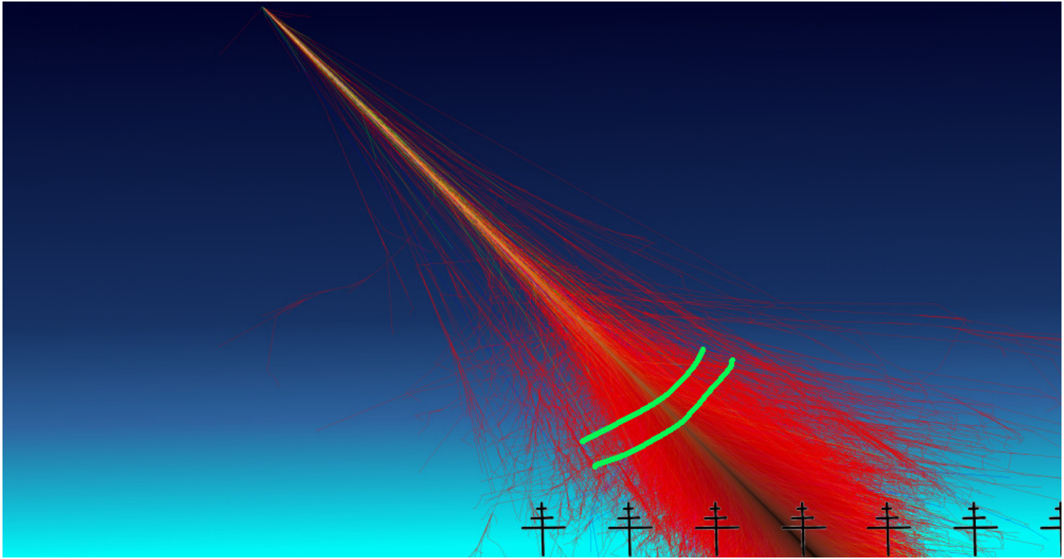
TUNKA array



85m spacing

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

Radio Detectors

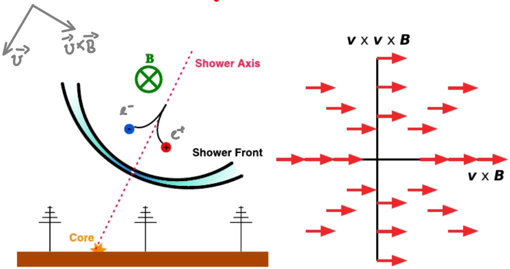


$\lambda >$ shower front thickness

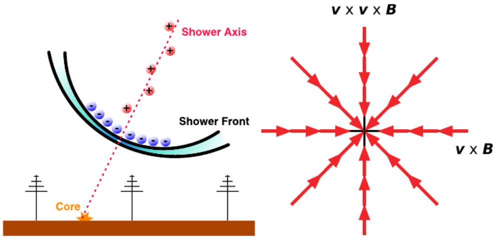
$\Rightarrow f \lesssim 100\,\mathrm{MHz}$

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

shower ≈ point charge ⇒ radial $\vec{E}$ from $\dot{Q}$



polarization



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

geomagnetic effect > charge excess / Askaryan effect

in air!

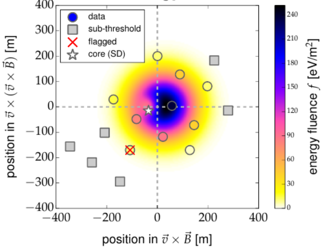
(Askaryan dominates in solids)

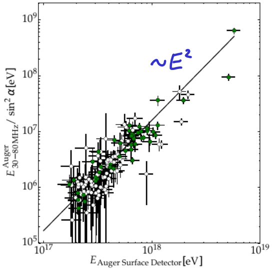
≈ 10% in air

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

Auger Coll., PRL 116 (2016) 241101

AERA event





2 pol

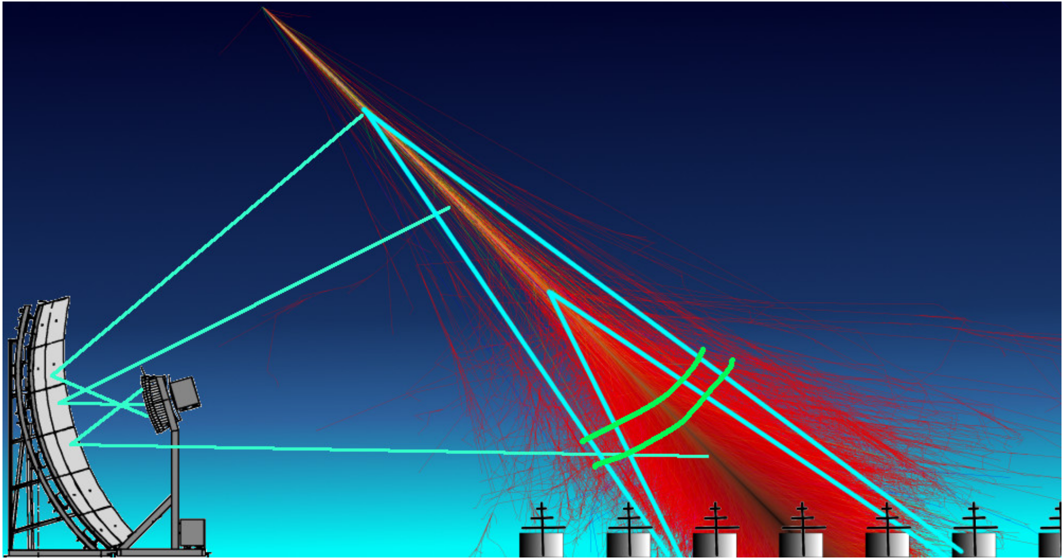
LOPES @ KASCADE

SALLA @ Tunka

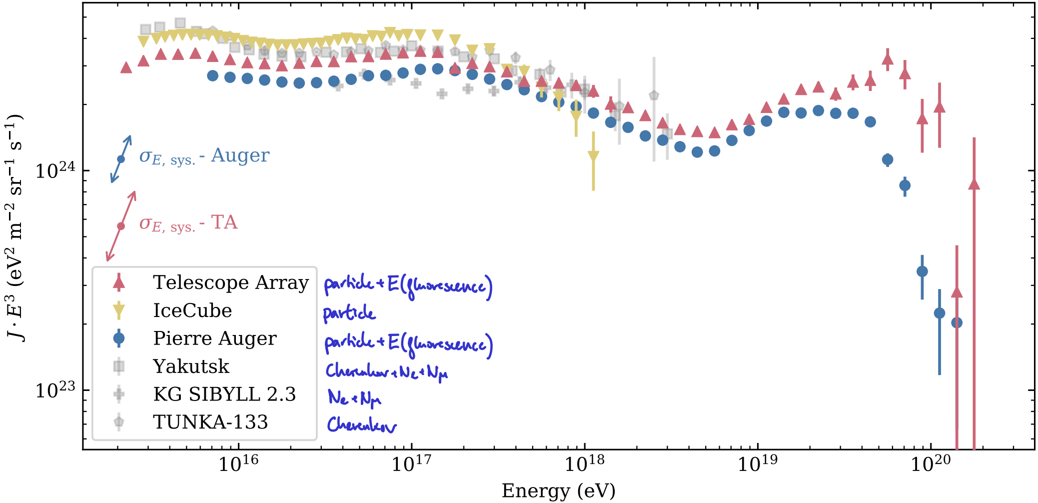
LPDA @ Auger

SALLA @ Auger

Some Results (E and A)

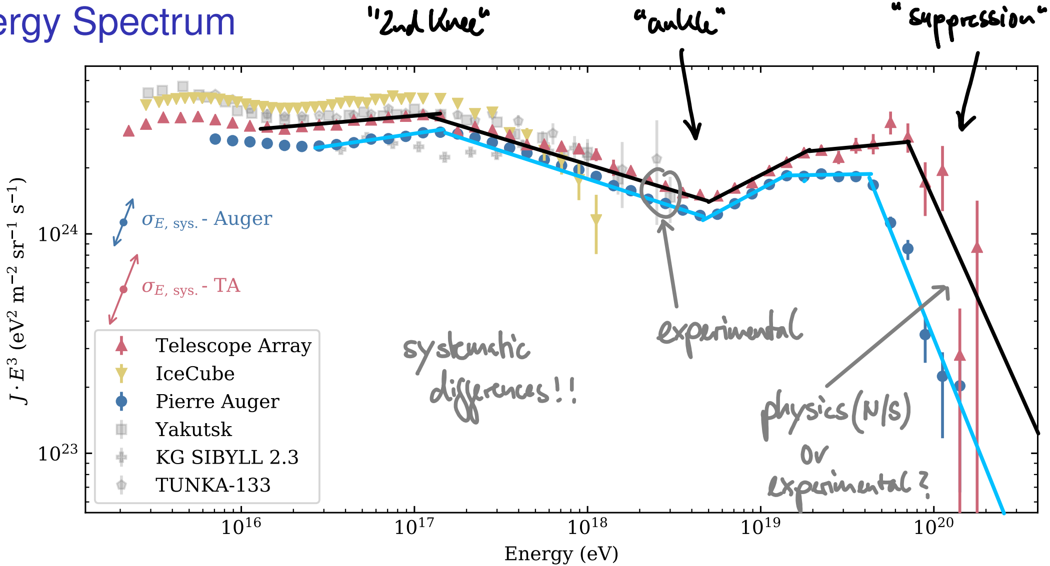


Energy Spectrum



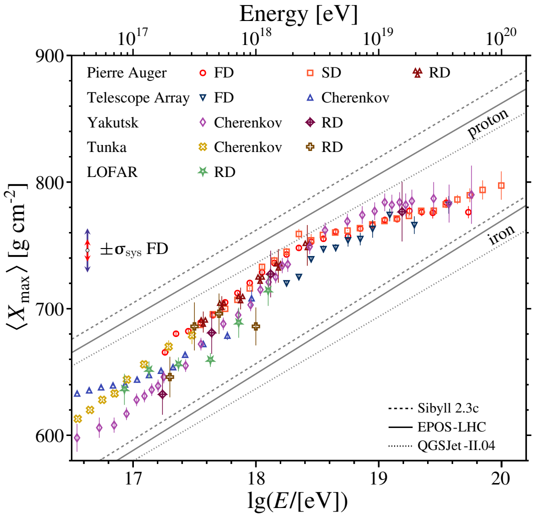
arXiv:2205.0584

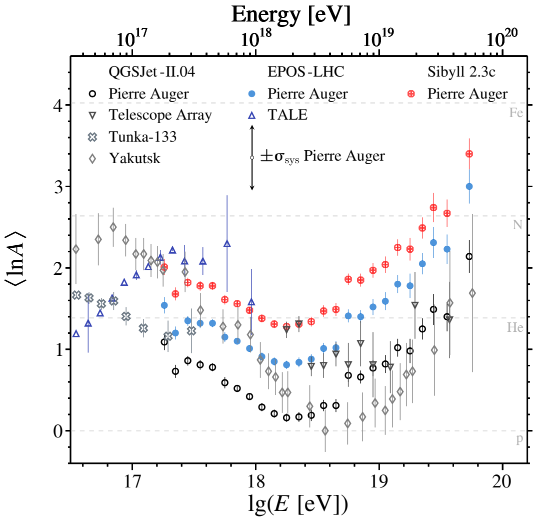
Energy Spectrum



arXiv:2205.0584

Mass Composition

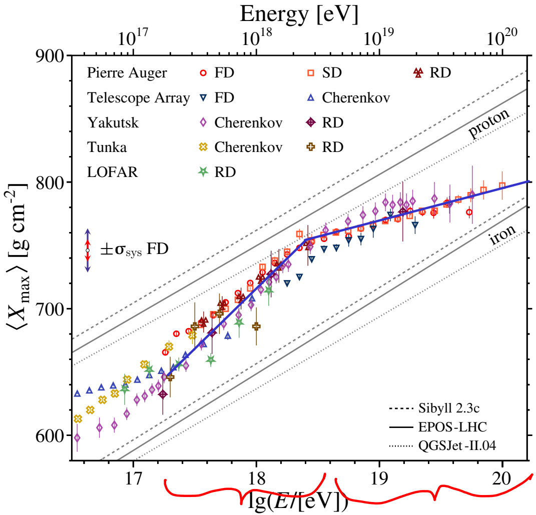


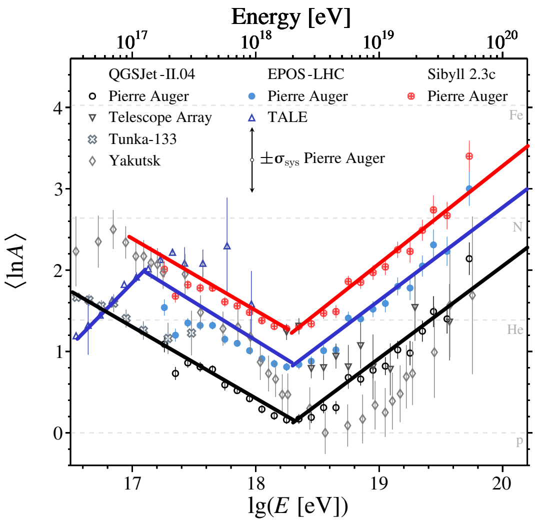


arXiv:2205.0584

Mass Composition

hadronic interactions!





arXiv:2205.0584

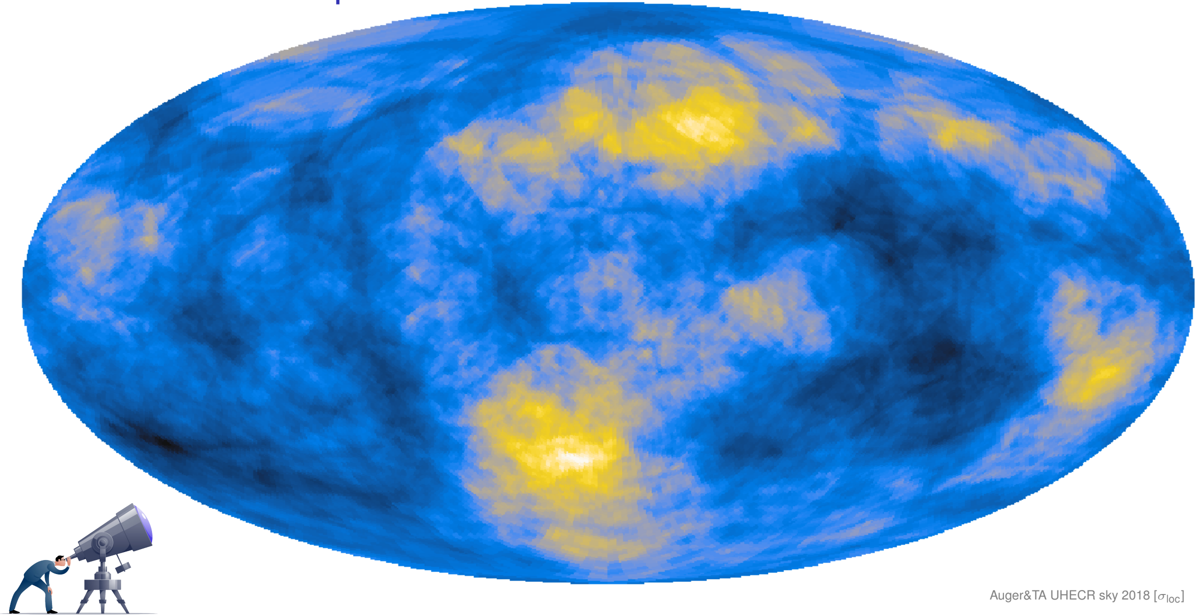
elongation rate $D_{10} > D_{10}^{had}$ $D_{10} < D_{10}^{had}$

$D_{10} = \frac{d\langle X_{max}\rangle}{d\lg E}$ 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	$\approx 1/\mathrm{km}^2$	$\approx 100\%$	low ... medium $N_e - N_\mu$	high	low
fluorescence	E_{em}/X_{max}	$\approx 1/2000\ \mathrm{km}^2$	$\leq 15\%$	high	low	high
radio	E_{em}/X_{max}	1 ... $\gtrsim 100/\mathrm{km}^2$ E_{em} X_{max}	$\approx 100\%$	low ... medium electronics!	low	low
Cherenkov	E_{em}/X_{max}	$\gtrsim 100/\mathrm{km}^2$	$\leq 15\%$	low ... medium	low	medium ... high

Future UHECR Experiments



Auger&TA UHECR sky 2018 [σ_{loc}]

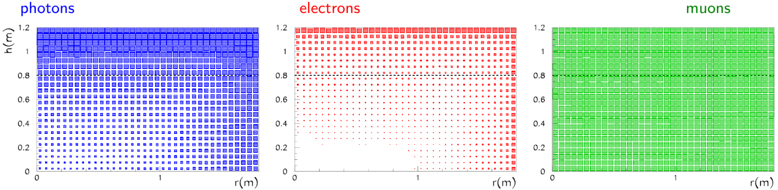
UHECR Detection at Ground?

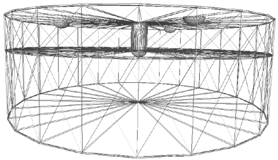
e.g. Global Cosmic-Ray Observatory (GCOS): $2 \times$ (Auger $\times$ 10) (North and South)

2×30000 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 $\mu^{\pm}$





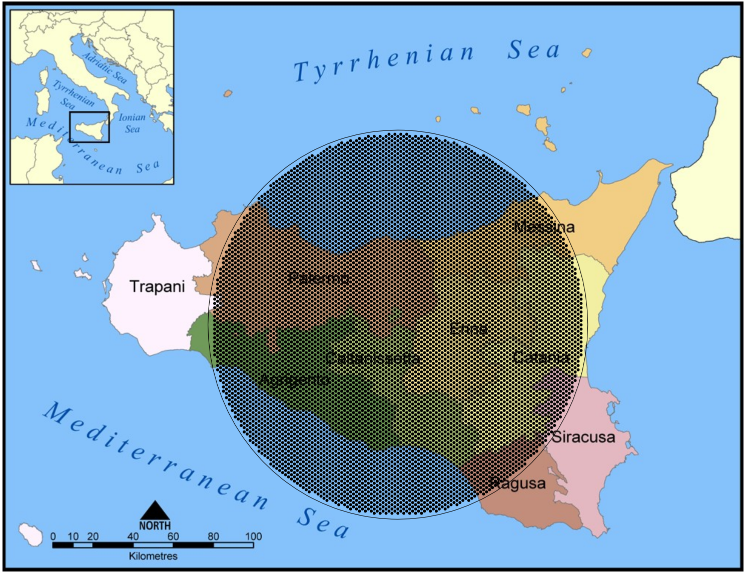
$$\begin{pmatrix} S_{\text{top}} \\ S_{\text{bot}} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix}$$

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

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

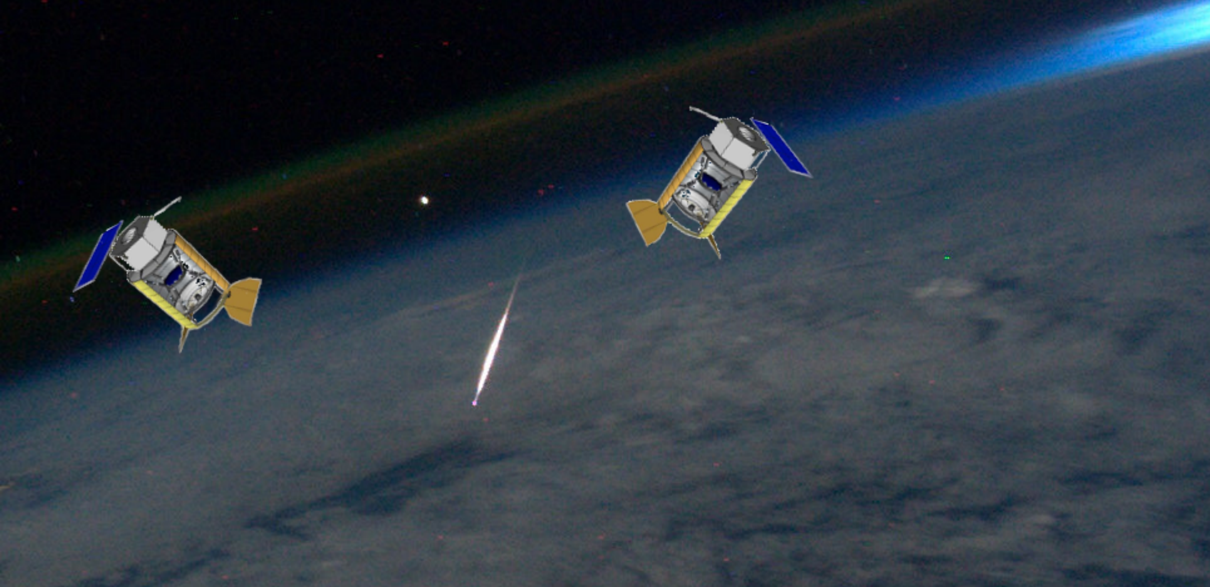
UHECR Detection at Ground?

One GCOS site (30k km^2) vs. Sicily (25k km^2)



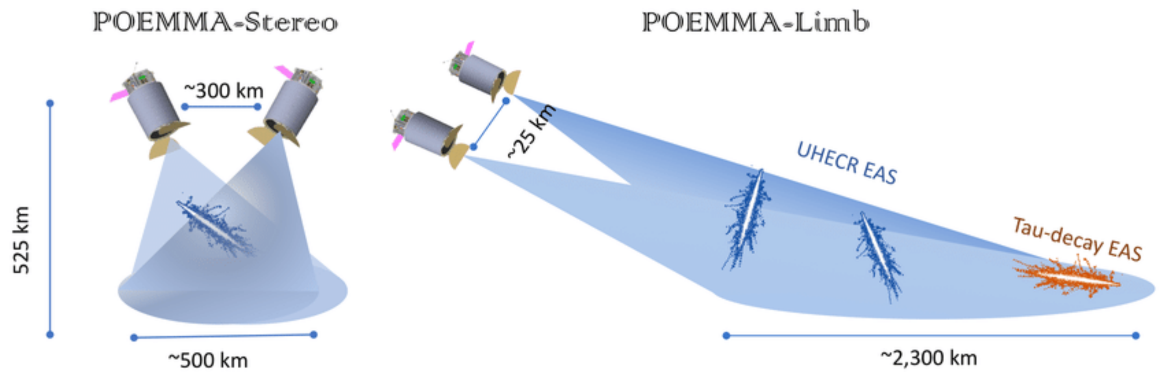
UHECR Detection From Space?

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



UHECR Detection From Space?

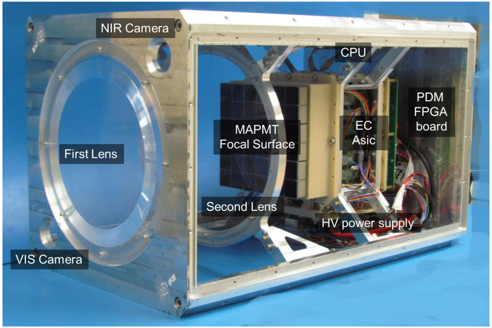
e.g. POEMMA (JCAP 06 (2021) 007)

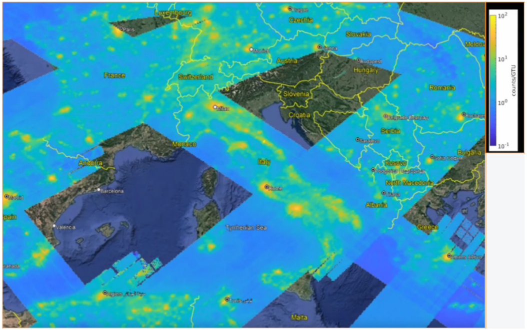


UHECR Detection From Space?

Pathfinder Mini-EUSO on the ISS

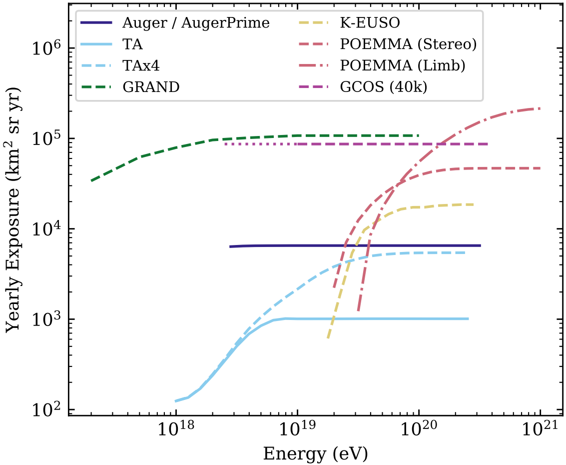
→ possible duty cycle: 18%
(13% taking into account clouds)

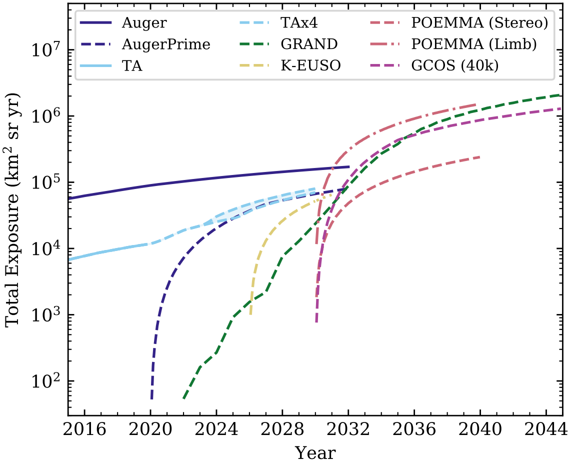




Future UHECR Experiments

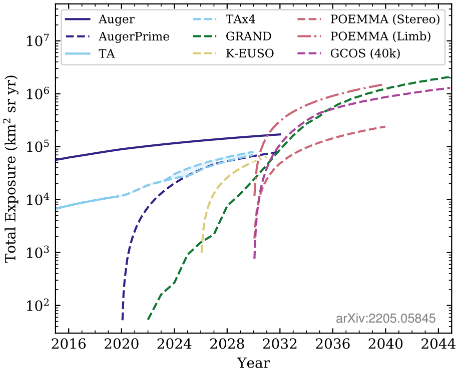
all at 50 EeV, except POEMMA limb at 300 EeV



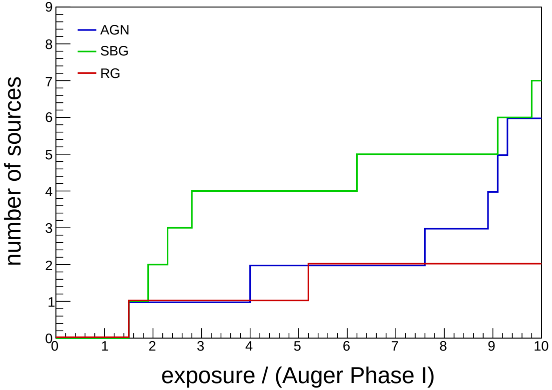


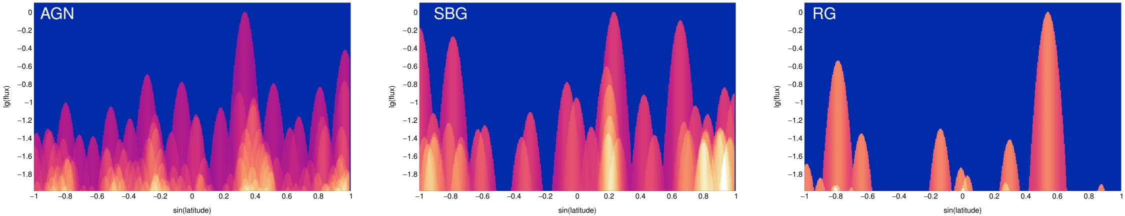
arXiv:2205.05845

Future UHECR Experiments



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





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)