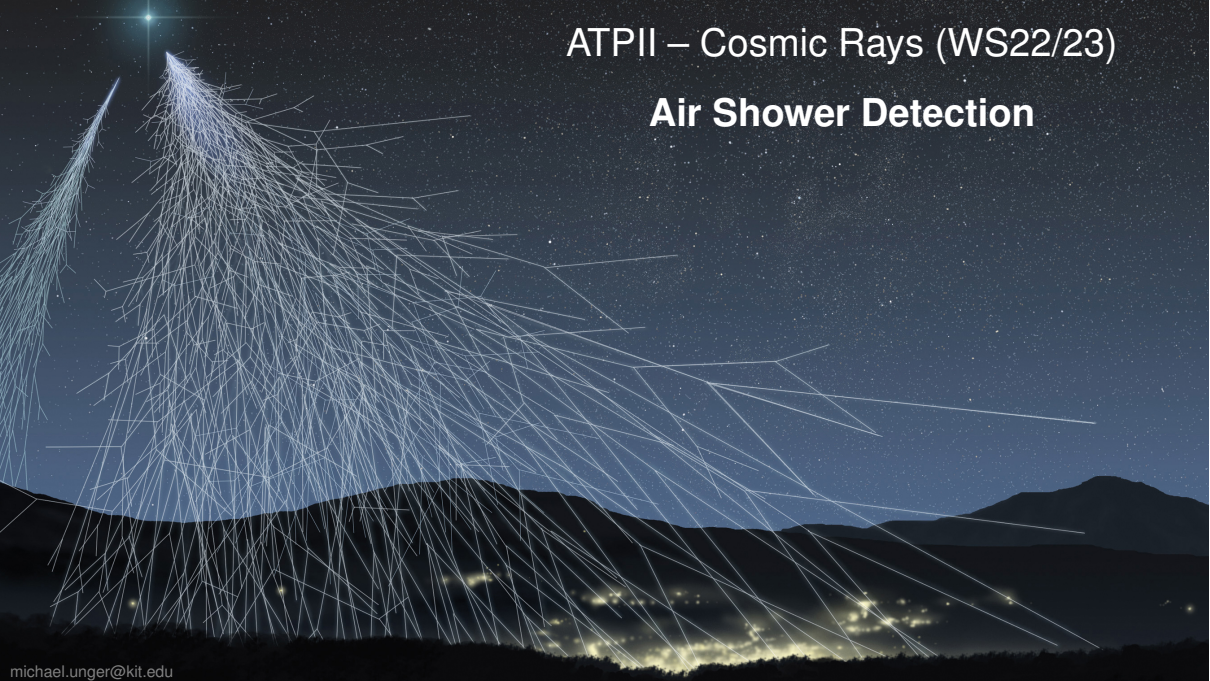
ATPII – Cosmic Rays (WS22/23)

Air Shower Detection



michael.unger@kit.edu

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, $M=50$, $A=1 \Rightarrow E_{em}/E_0 \approx 31\%$

  $A=56 \Rightarrow E_{em}/E_0 \approx 86\%$

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

- shower maximum from 1st interaction:

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

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

$$X^A_{max}(E) = X^p_{max}(E/A)$$

how to measure the CR mass + energy with air showers

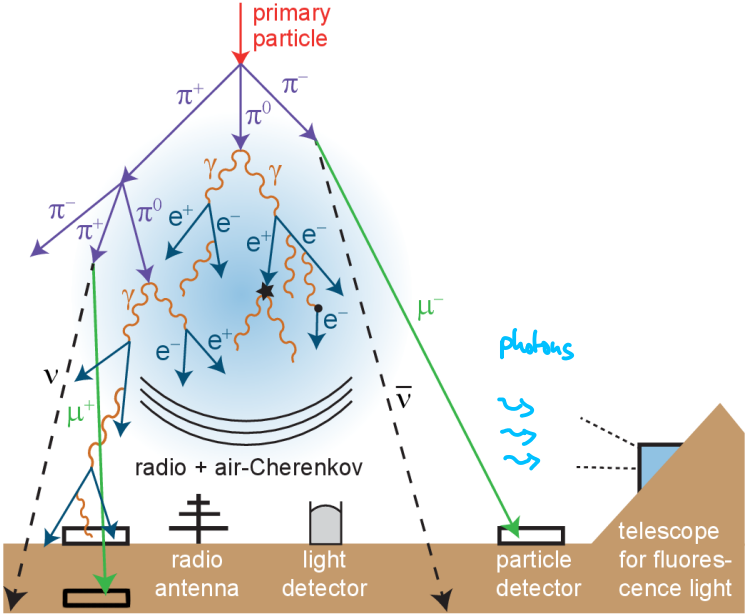
measurement		primary CR	detector
N_e, N_μ	$\leftrightarrow$	E_0, A	SD
X_{max}, E_{em}	$\leftrightarrow$	E_0, A	FD/CD
E_{em}, N_μ	$\leftrightarrow$	E_0, A	RD+SD
$N_e, N_\mu, X_{max}, E_{em}$	$\leftrightarrow$	E_0, A	SD+FD

"hybrid"

overconstrained $\Rightarrow$ check hadronic interaction models

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

Air Shower Detection



F. Schröder, 2017

Air Shower Detection

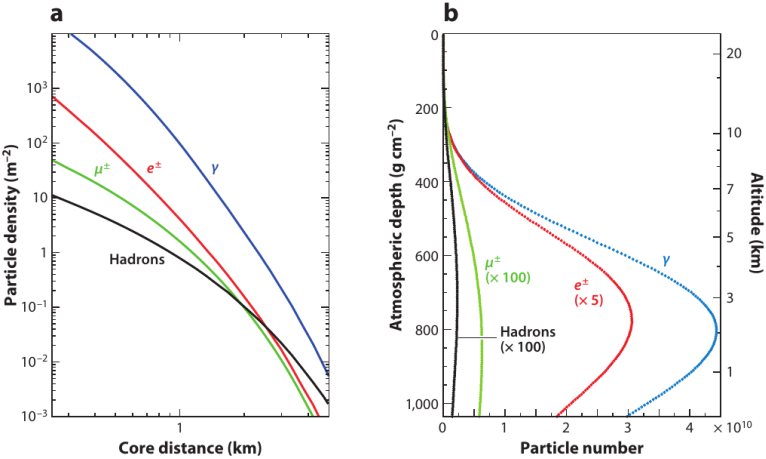
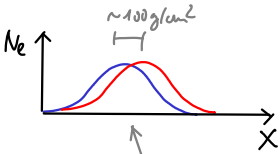


Figure 2

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.

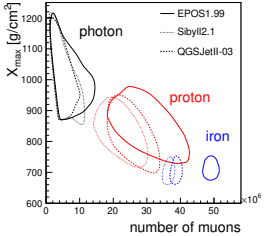
Engel, Heck, Pierog Ann.Rev.Nucl.Part.Sci. 61 (2011) 467

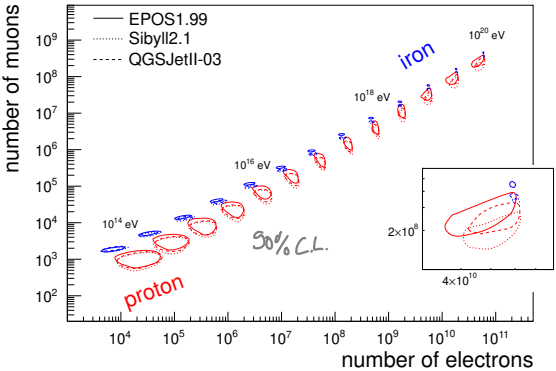
E and A

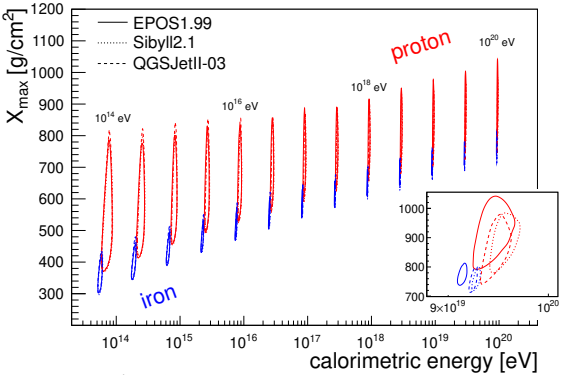


$\theta = 0°$, $X = 800\,g/cm^2$

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

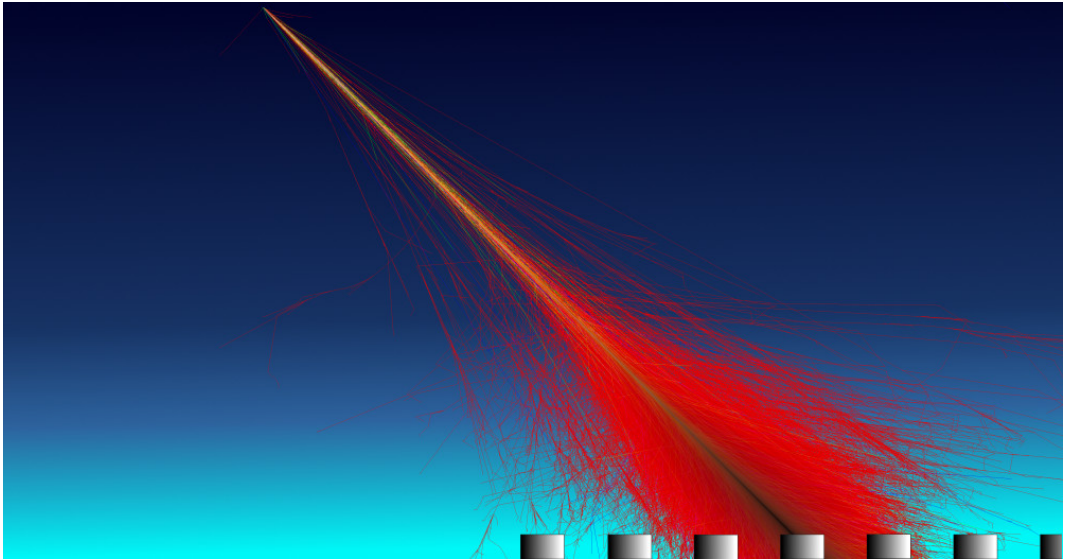






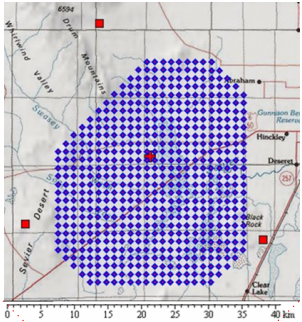
"E_{em}" in lecture 10

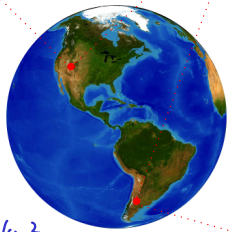
Particle Detectors



Telescope Array "TA"

500 SCNTs
1.2 km spacing
$A = 700\ km^2$

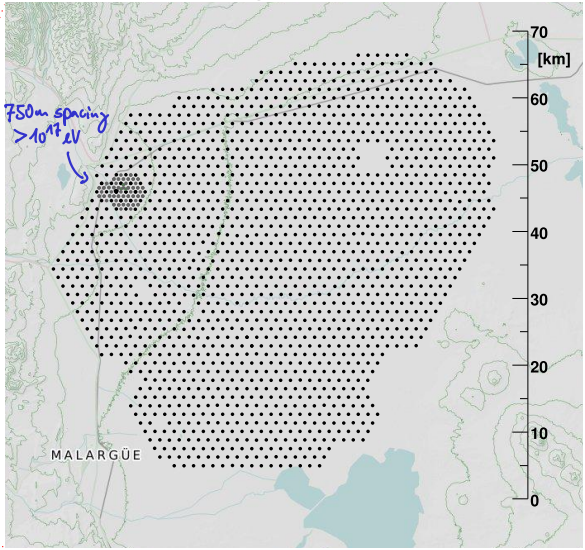




1600 WCDs
1.5 km spacing $> 10^{18}$ eV
$A = 3000\ km^2$

Pierre Auger Observatory

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



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

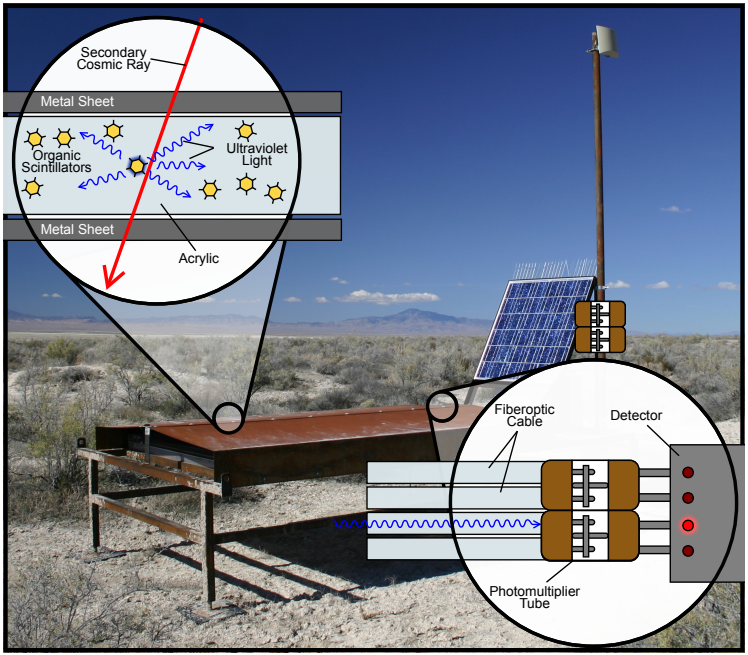

Telescope Array: scintillator as particle detector

Signal

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

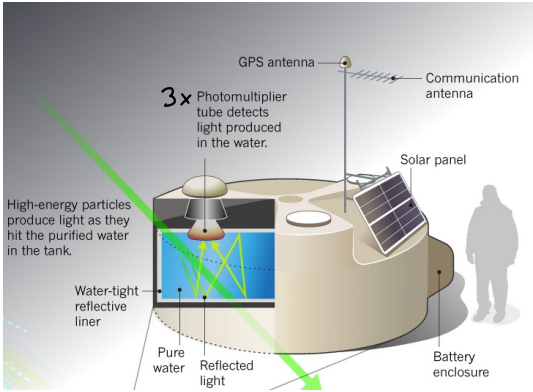
($+\gamma \to e^+e^-$ conversion)

area ~ $\cos\theta$



Pierre Auger Observatory: Water Cherenkov detectors (WCD)

12 t ultrapure water



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

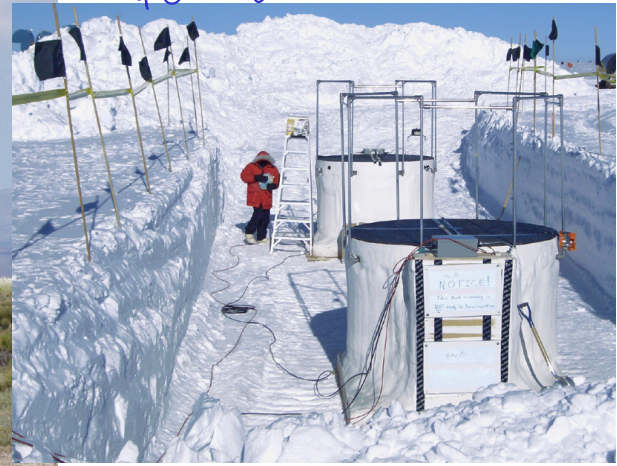
~ 160 GeV $\mu^+\mu^-$

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

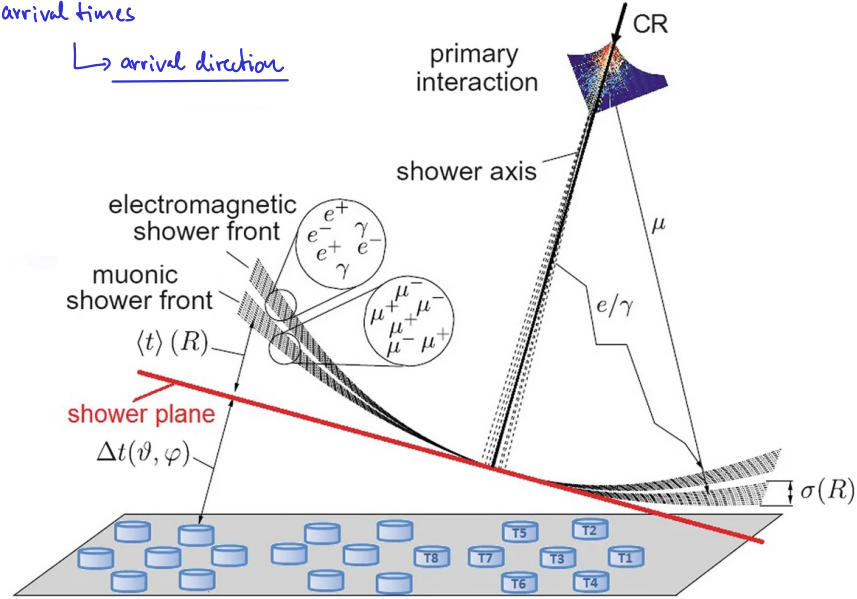


"Ice-Cherenkov" detectors

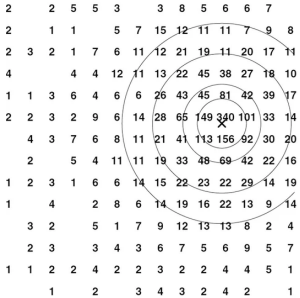

WCDs

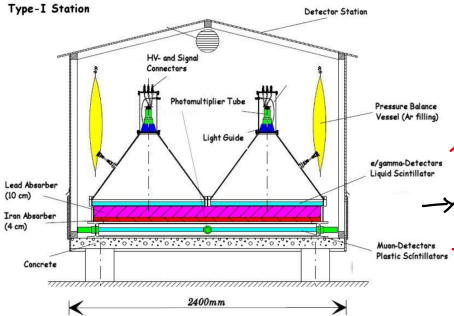
Shower Front / arrival times

↳ arrival direction



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

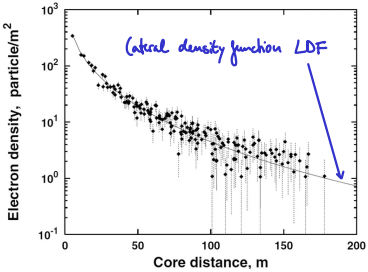




$N_{ch} = N_{e^+e^-} + N_\mu$

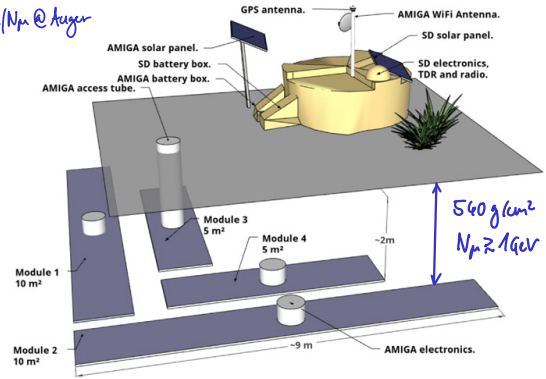
→ 20 attenuation lengths shielding

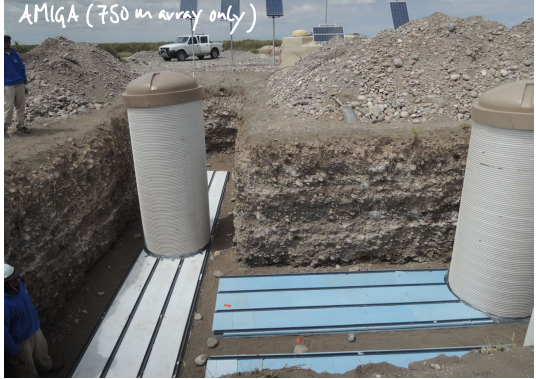
→ N_μ $E_\mu > 250$ MeV

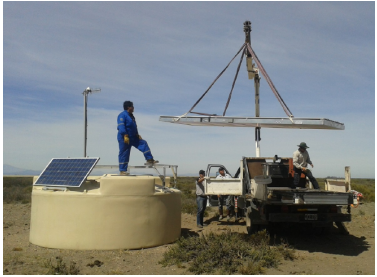


T.Stanev, "High Energy Cosmic Rays" (2010)

N_e/N_μ @ Auger







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

schematically:

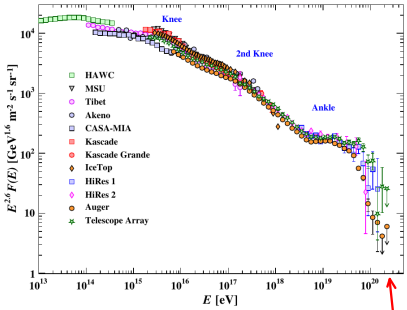
$$S_{SWT} \sim N_\mu + N_e$$

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

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

⇒ N_e and N_μ

highest energy event measured with an PD

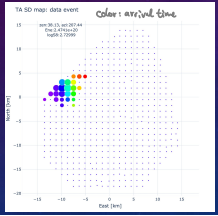


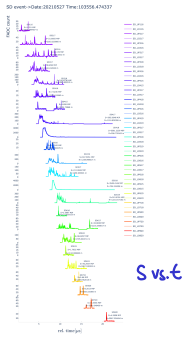
PDG 2022

!!!

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**





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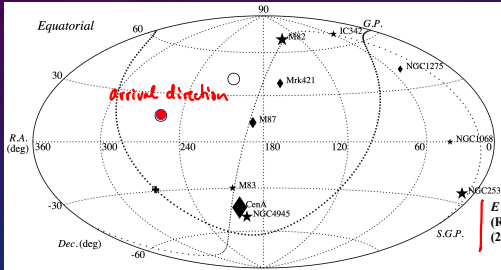
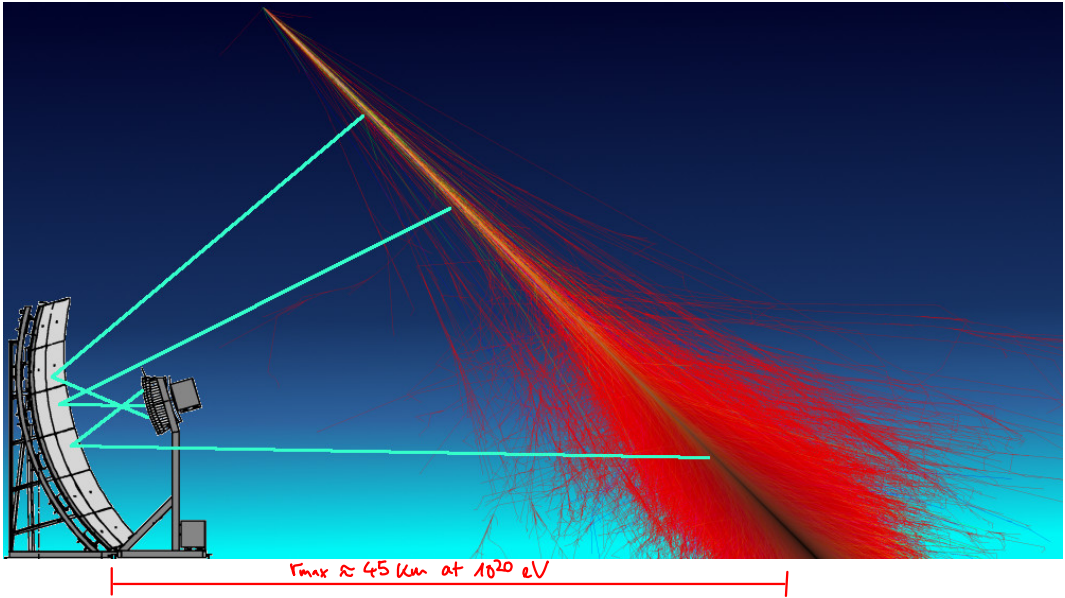
DIRECTION IN THE SKY-MAP



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

J. Matthews, TA Coll. 2022

Fluorescence Telescopes



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

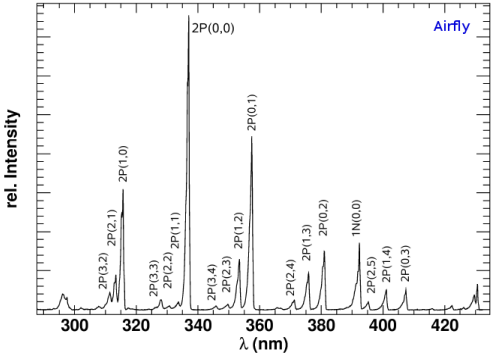
  energy deposit in atmosphere

- rule of thumb: $\approx$ 3-4 photons/m/particle

  $\hat{=}$ 30 W light bulb

- precise measurement in lab

emission in UV (~10 ns)

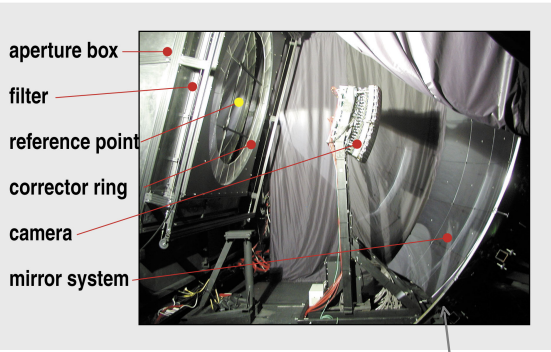


shower visible up to 30 km @ 10^{19} eV $\Rightarrow$ 3000 km^2

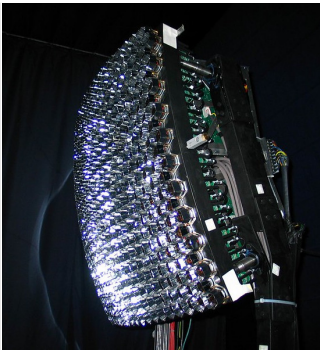
45 km @ 10^{20} eV $\Rightarrow$ 6000 km^2

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

"Schmidt optics"



camera



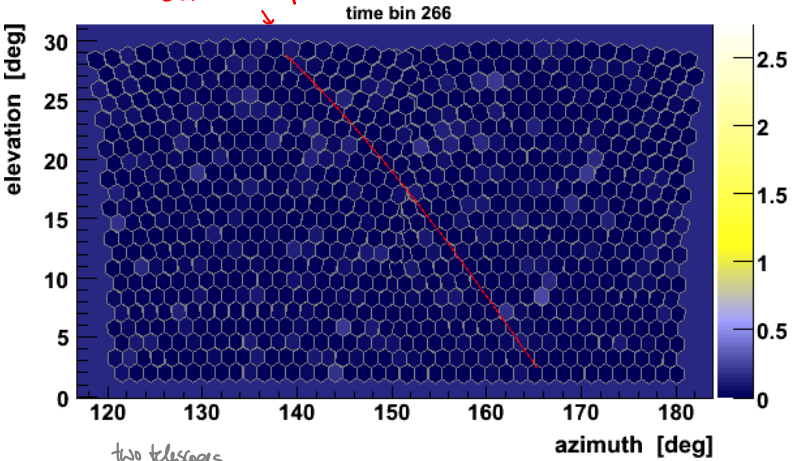
6 telescopes per building

4 buildings at edge of array (looking inward)

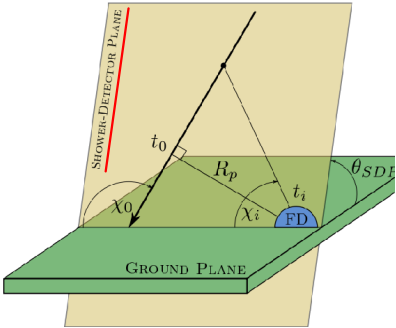
spherical mirror

440 hexagonal PMTs

shower detector plane

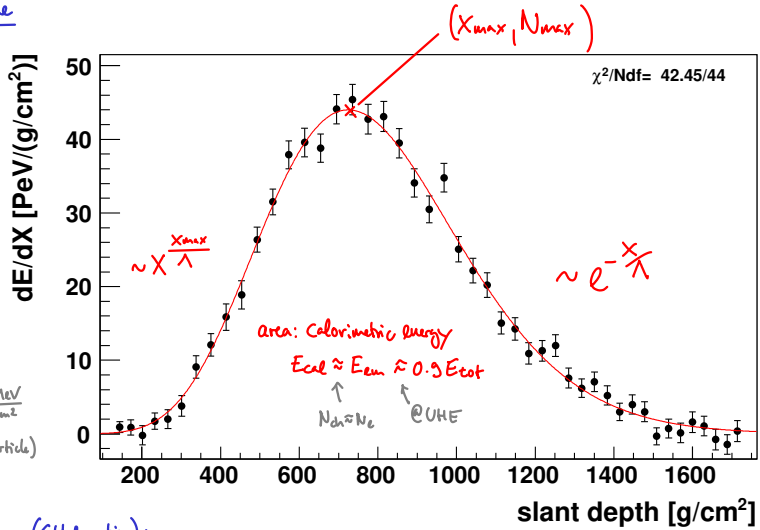


two telescopes



⇒ see separate file for animation

Longitudinal profile



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

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

(average energy deposit per particle)

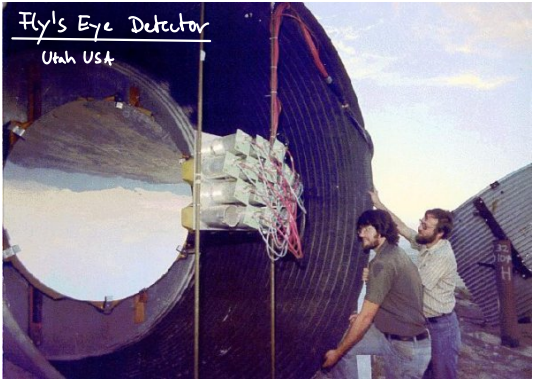
Gaisser-Hillas function (GH function):

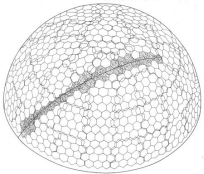
Nucl.Instrum.Meth.A 798 (2015) 172

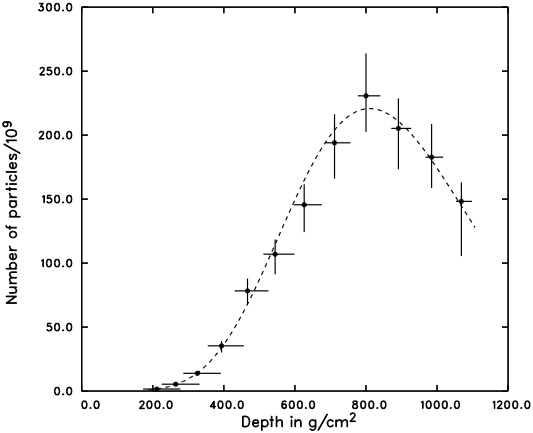
$$N_{gem} \sim \frac{dE}{dx} \sim N_e(X) = N_{max} \left(\frac{X - X_1}{X_{max} - X_1} \right)^{(X_{max} - X_1)/\Lambda} e^{-\frac{X - X_{max}}{\Lambda}}$$

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

highest energy fluorescence detector event







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

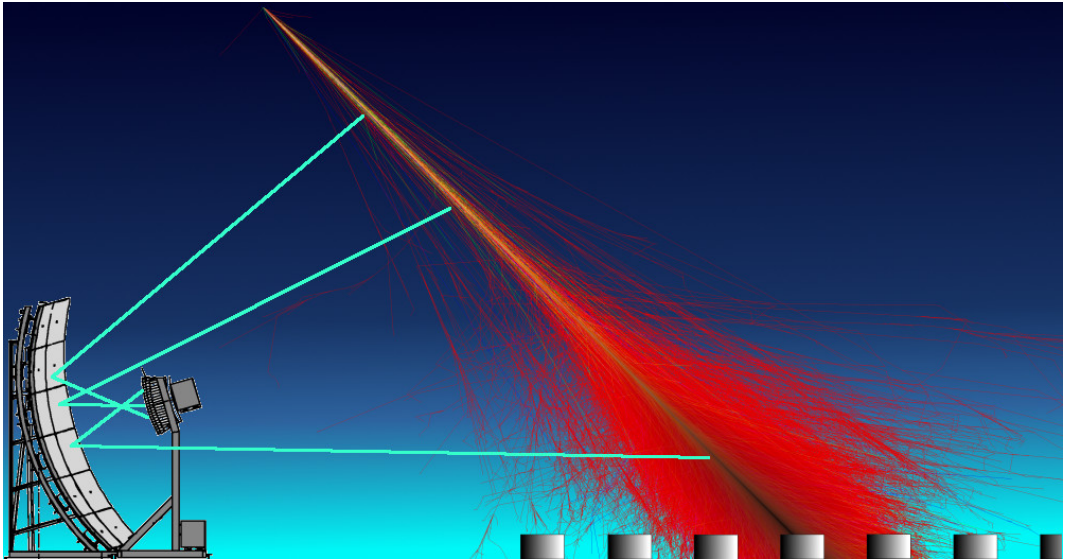
see also T.Fitoussi et al, JCAP 01 (2020) 042

$RA = 85.2°$, $DEC = 48°$

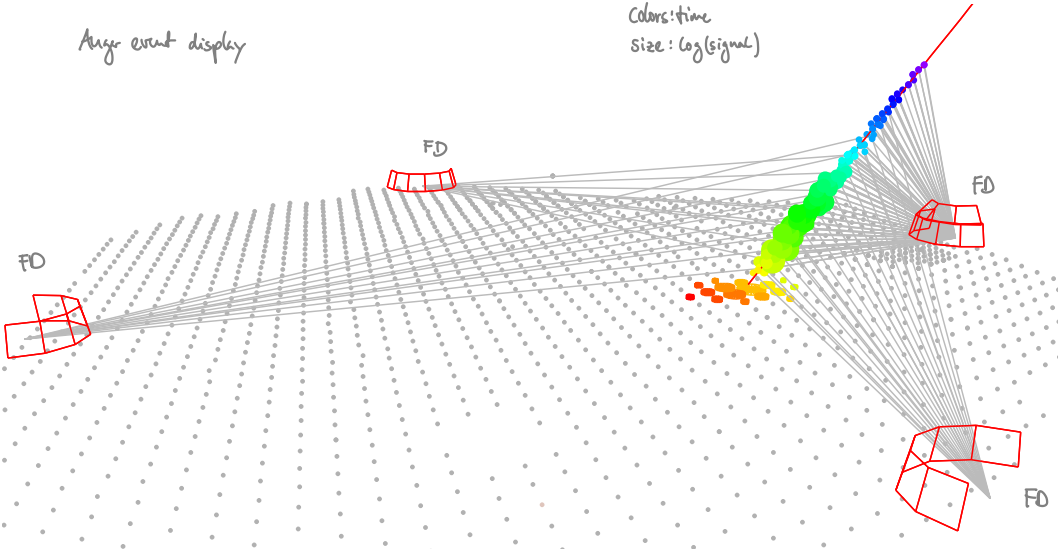
$E = (320 \pm 90) \cdot 10^{20}\,eV$ (51 Joule!)

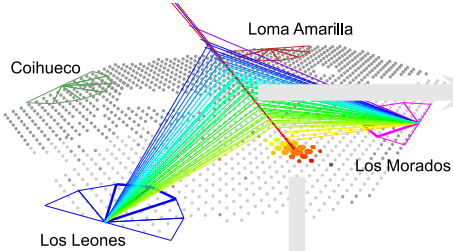
$X_{max} = (815 \pm 60)\,g/cm^2$ (compatible with p/Fe/γ)

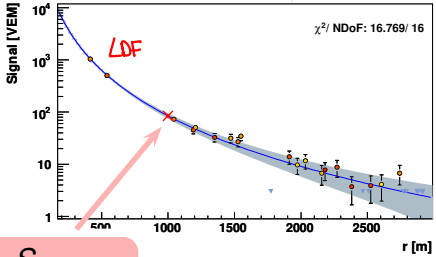
“Hybrid Detection” (e.g. fluorescence and particles)



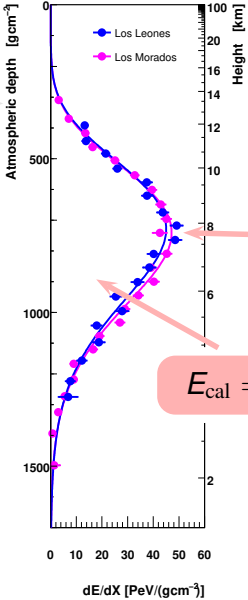
“Hybrid Detection” (e.g. fluorescence and particles)





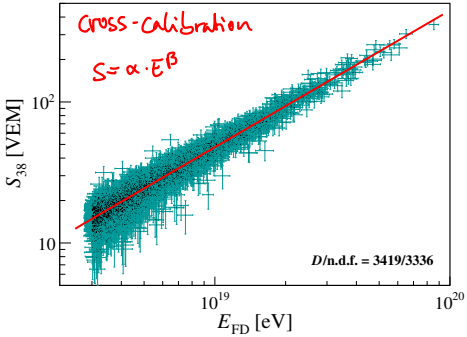


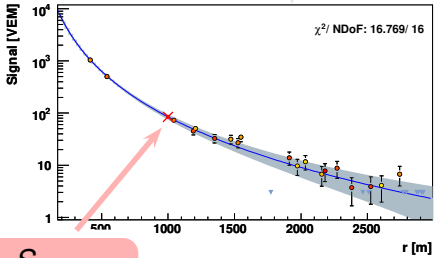
S_{1000}



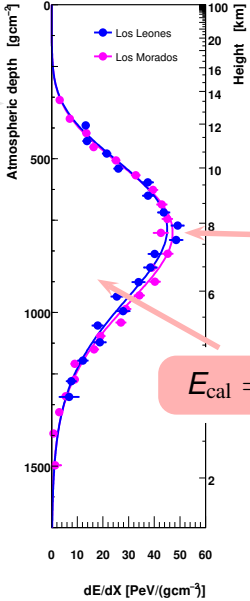
X_{max}

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





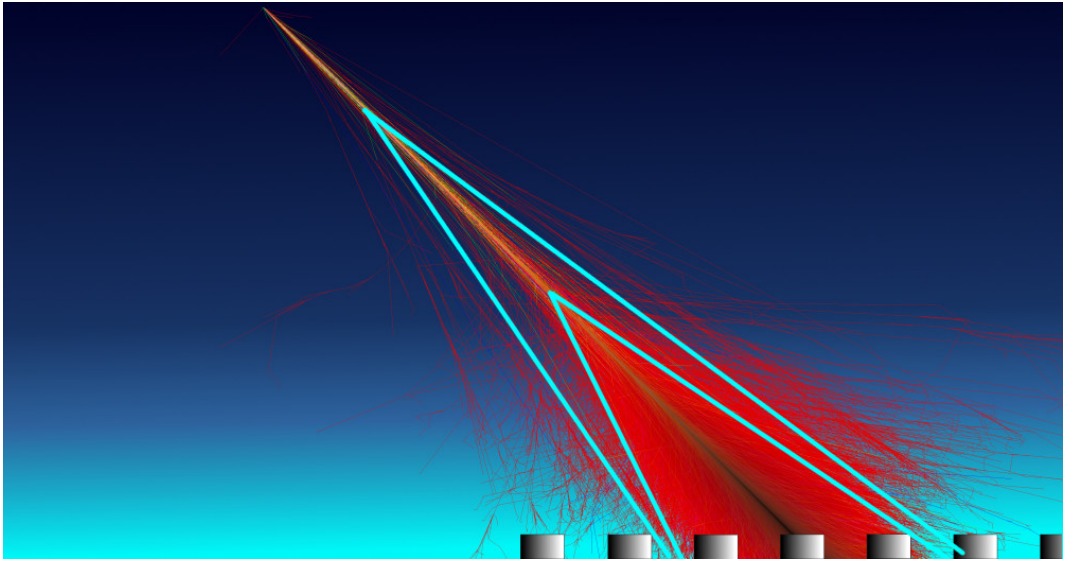
S_{1000}



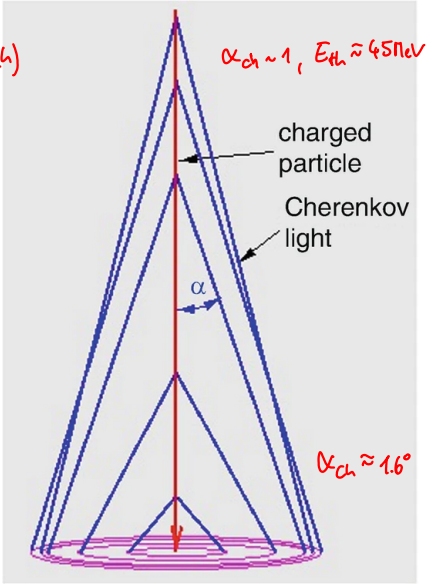
X_{max}

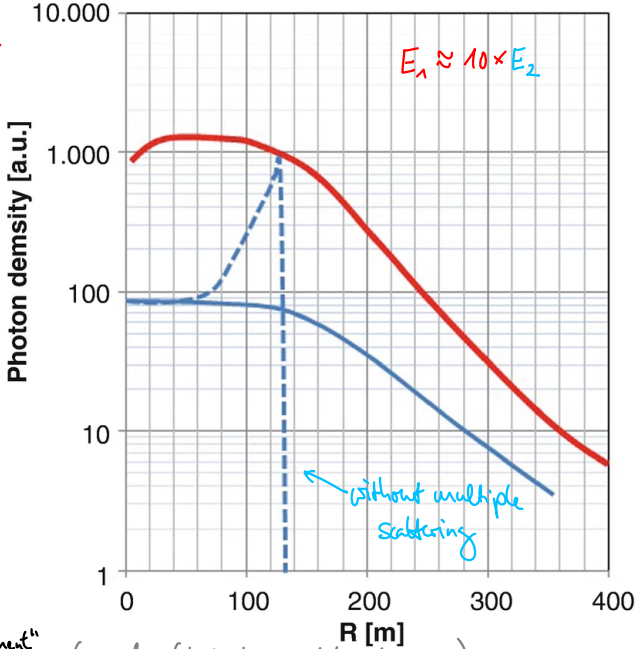
$$E_{cal} = \int \frac{dE}{dX}\, dX$$

Non-Imaging* Cherenkov Detectors



* see summer semester for Cherenkov telescopes



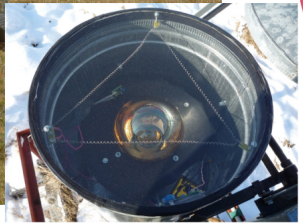


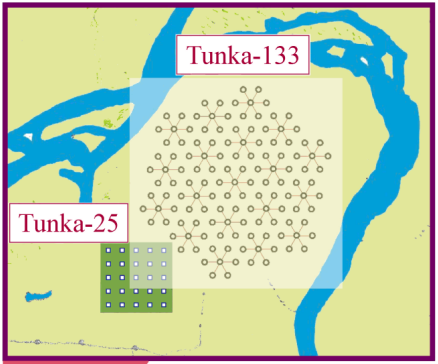
$N_\gamma \sim N_e \sim E_{em}$

"Calorimetric measurement"

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

TUNKA array

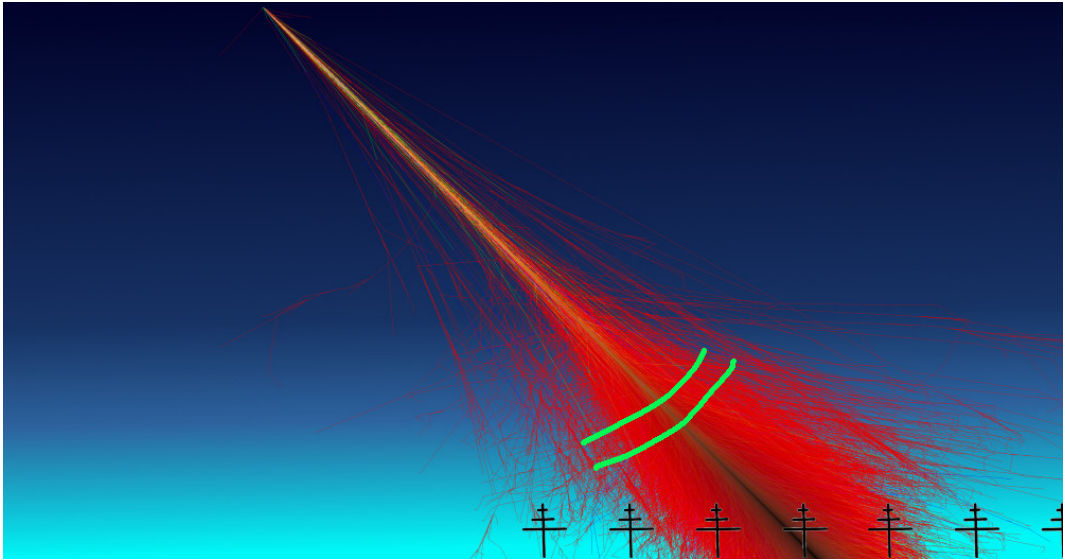




85m spacing

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

Radio Detectors

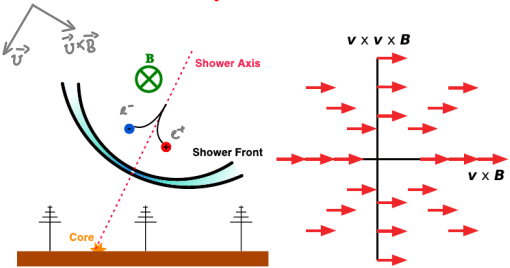


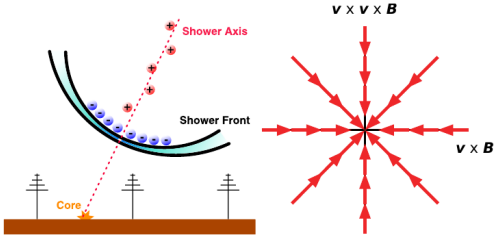
$\lambda >$ shower front thickness

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

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

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





polarization

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

geomagnetic effect $>$ charge excess / Askaryan effect

in air!

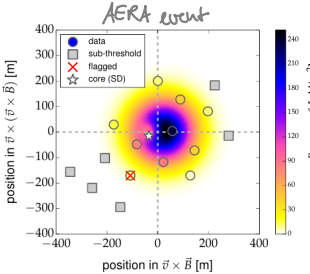
(Askaryan dominates in solids)

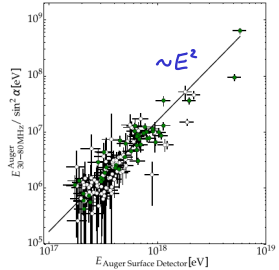
$\approx 10\%$ in air

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

Auger Coll., PRL 116 (2016) 241101

AERA event





2 pC

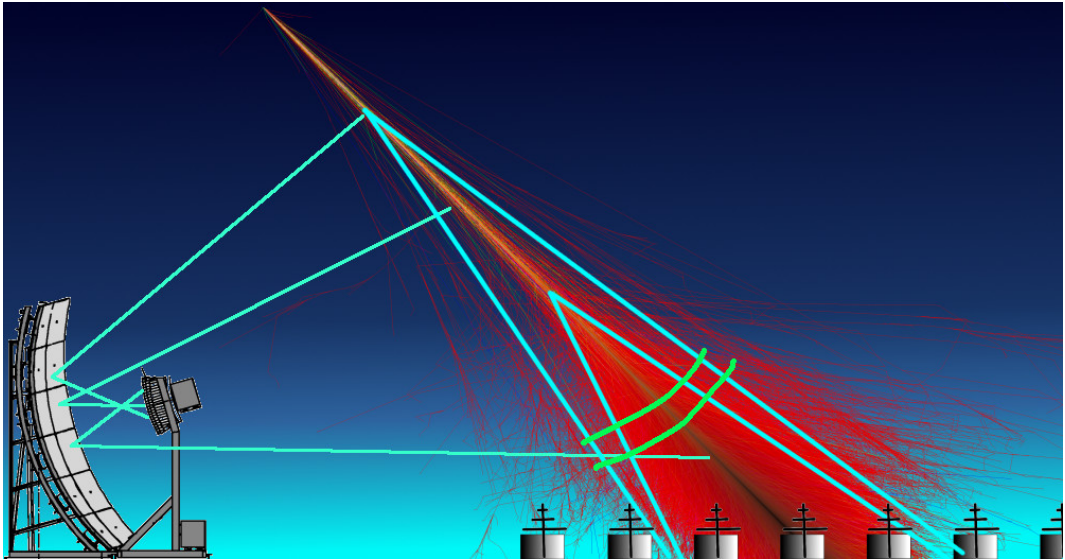
LOFES@KASCADE

SALLA @ Tunka

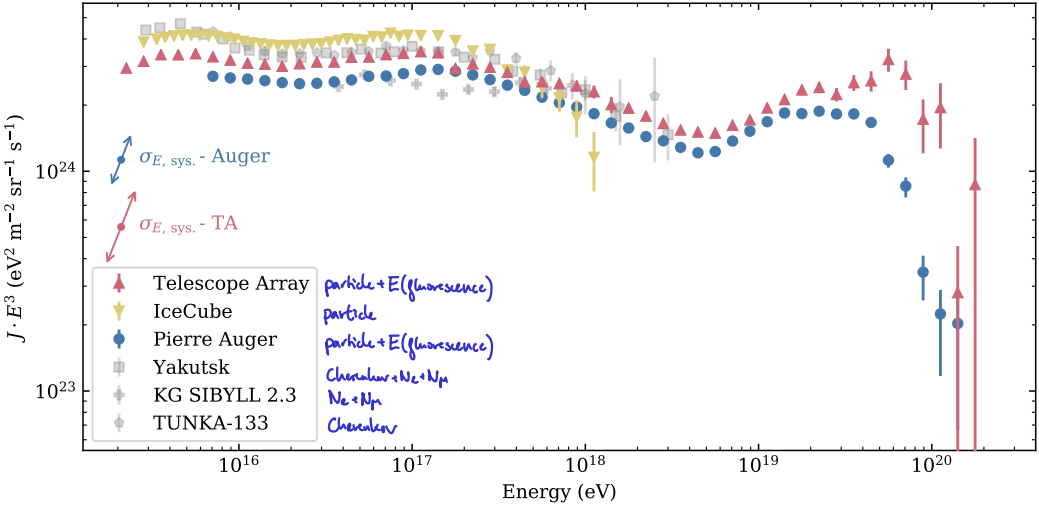
LPDA @ Auger

SALLA @ Auger

Some Results (E and A)

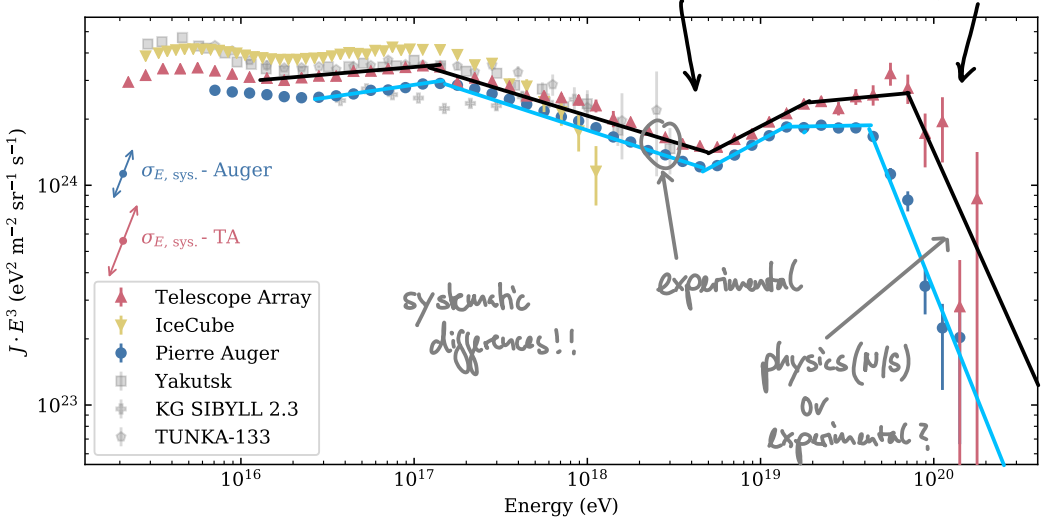


Energy Spectrum



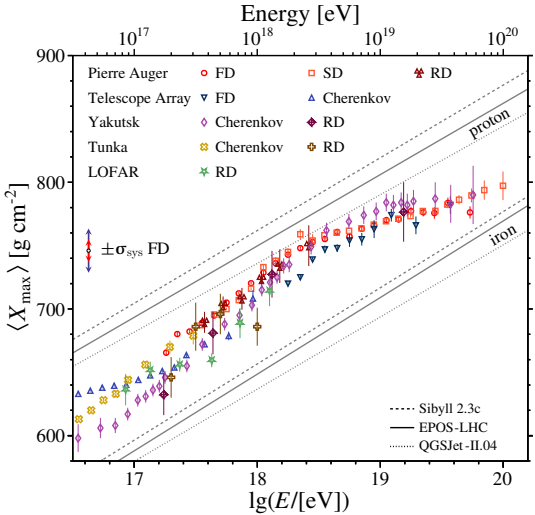
arXiv:2205.0584

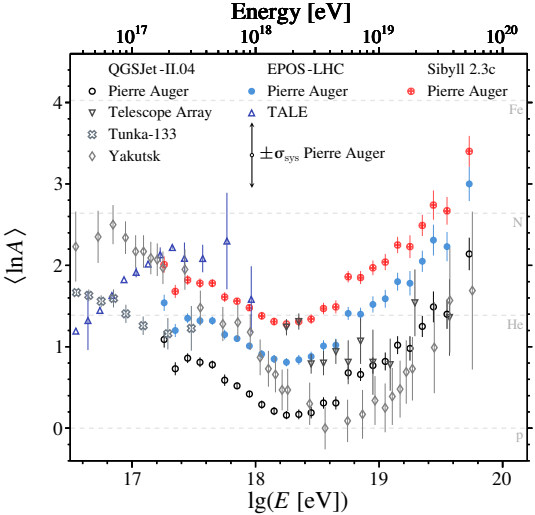
Energy Spectrum



arXiv:2205.0584

Mass Composition

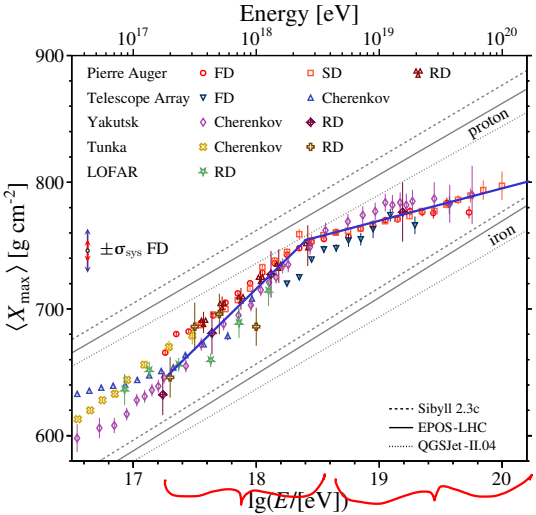


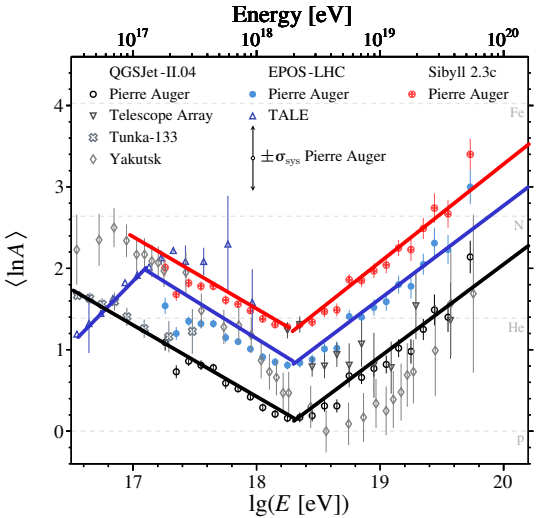


arXiv:2205.0584

Mass Composition

hadronic interactions!





arXiv:2205.0584

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

Detector Score Card (UHE)

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