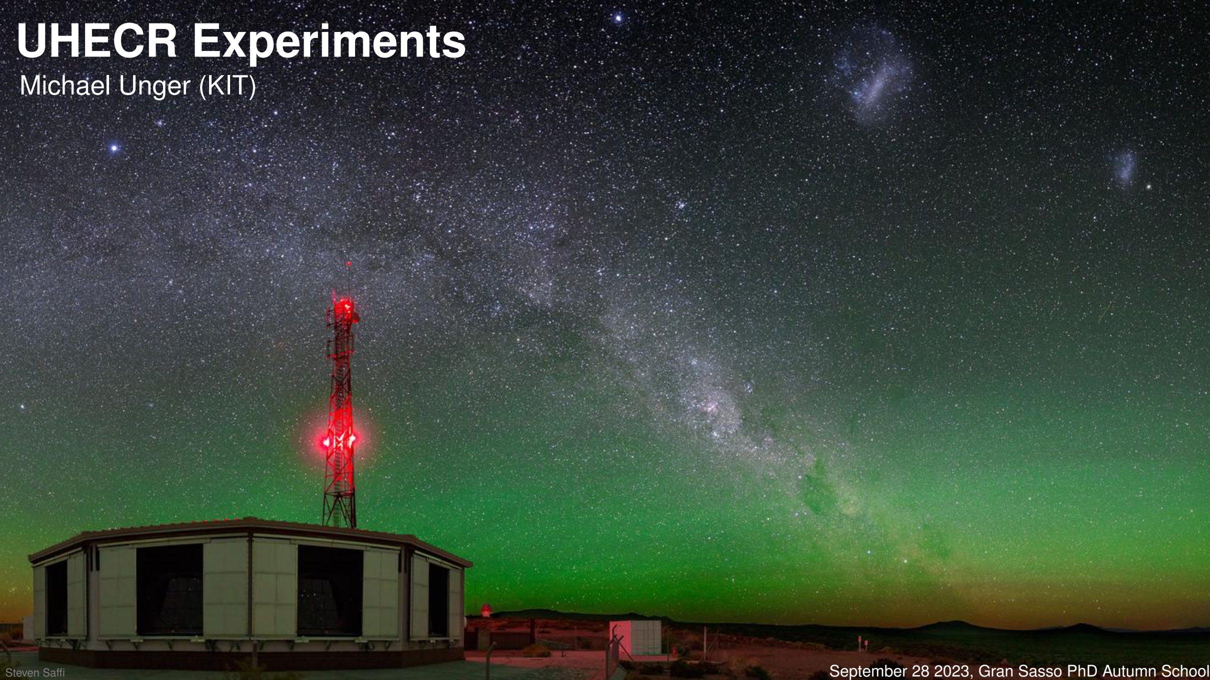
UHECR Experiments

Michael Unger (KIT)



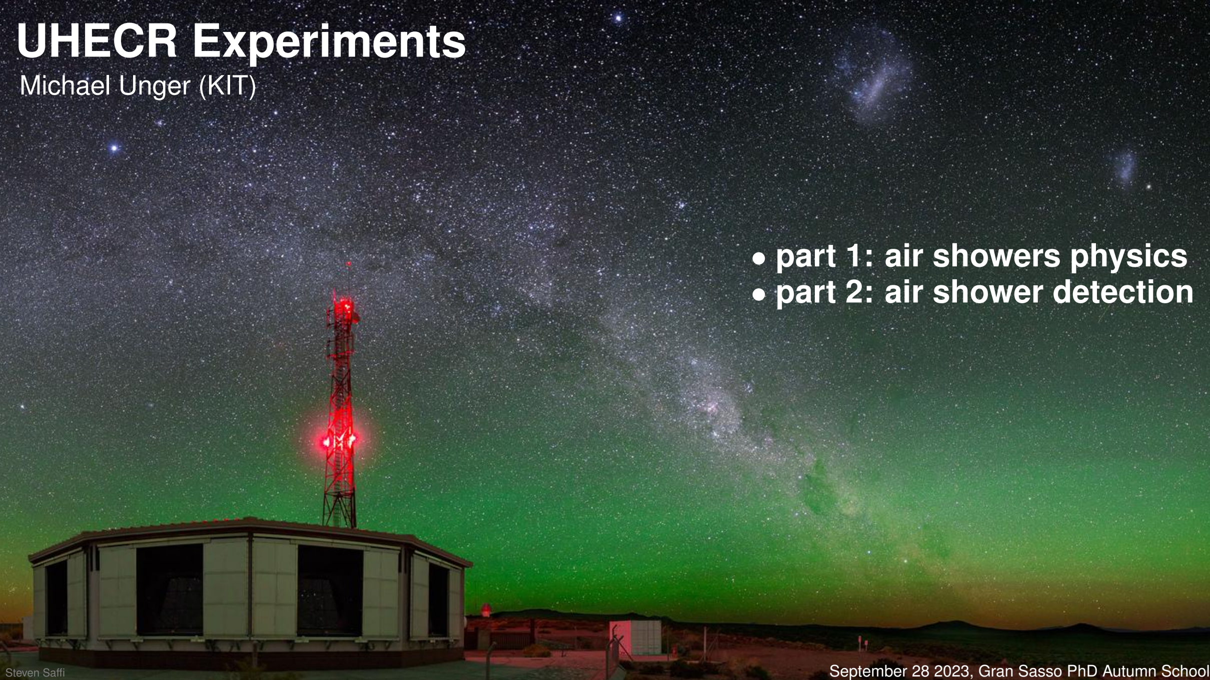
Steven Saffi

September 28 2023, Gran Sasso PhD Autumn School

UHECR Experiments

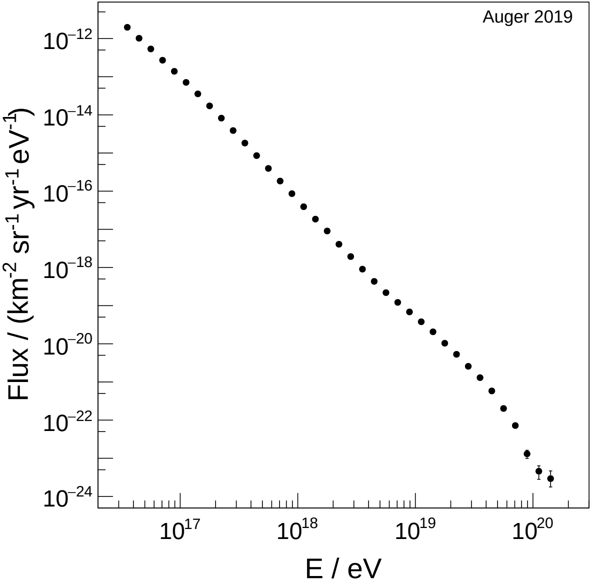
Michael Unger (KIT)

- part 1: air showers physics
- part 2: air shower detection



Steven Saffi

Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



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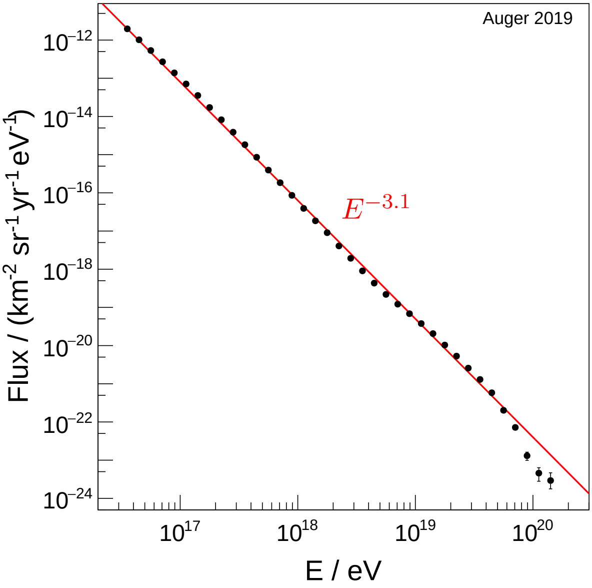

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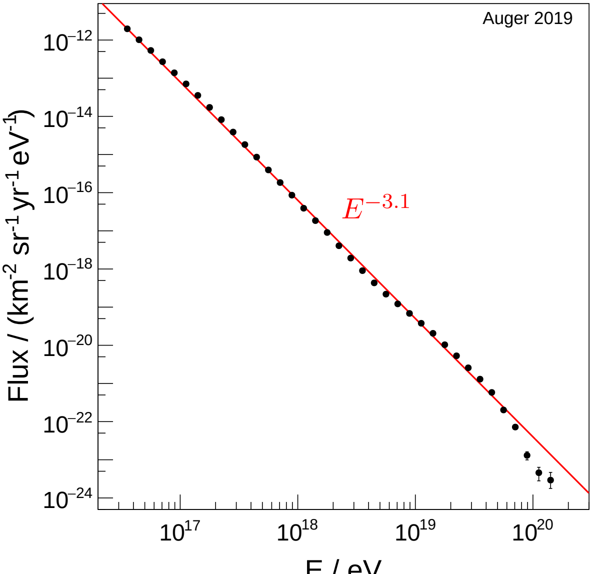
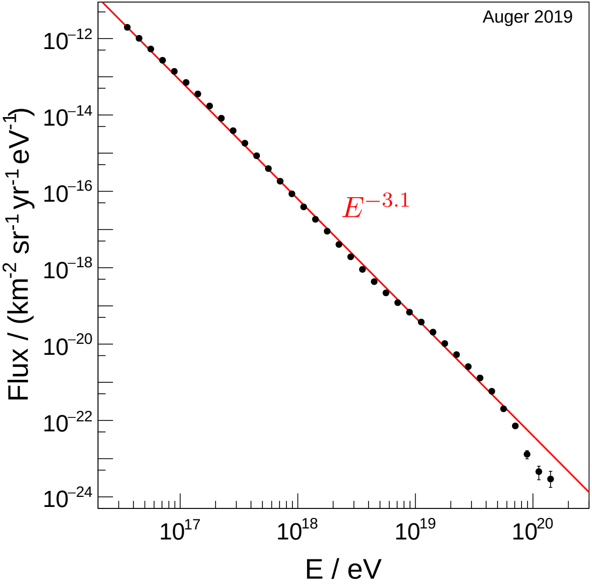


$E_{\text{beam}}^{\text{LHC}} = 7 \times 10^{12}$ eV

Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



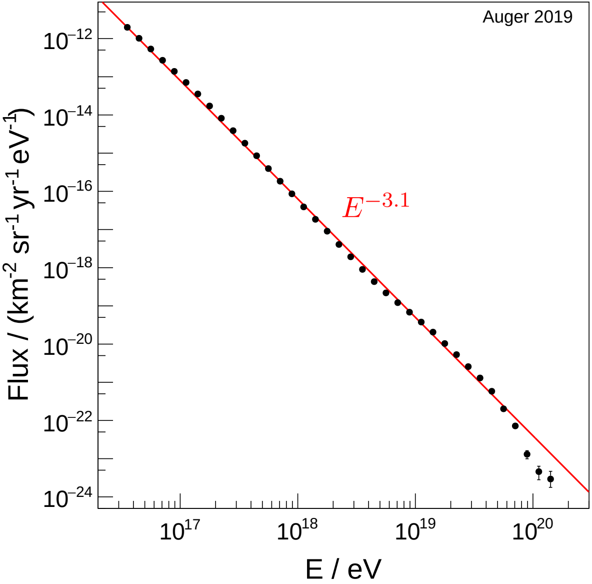
$\sim$20 J!

$E_{\mathrm{kin}} \sim 4$ TeV

$E_{\mathrm{beam}}^{\mathrm{LHC}} = 7 \times 10^{12}$ eV

Serena Williams' 2nd serve

Energy Spectrum of Ultrahigh-Energy Cosmic Rays (UHECRs)



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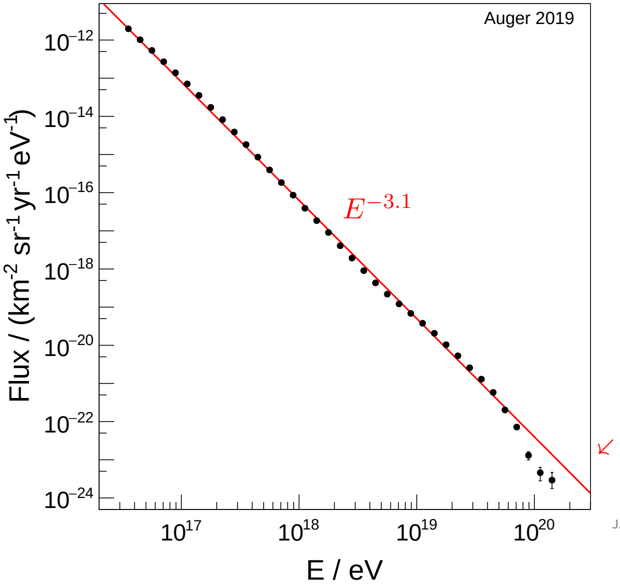
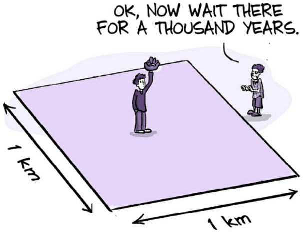
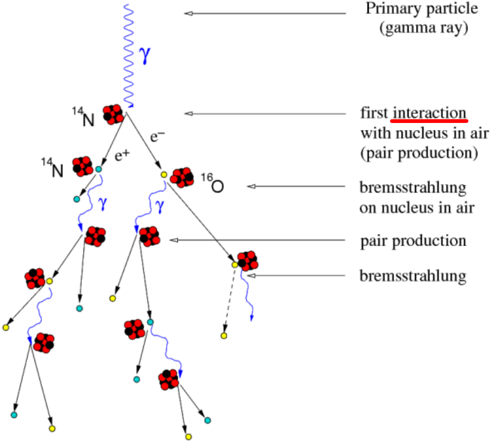


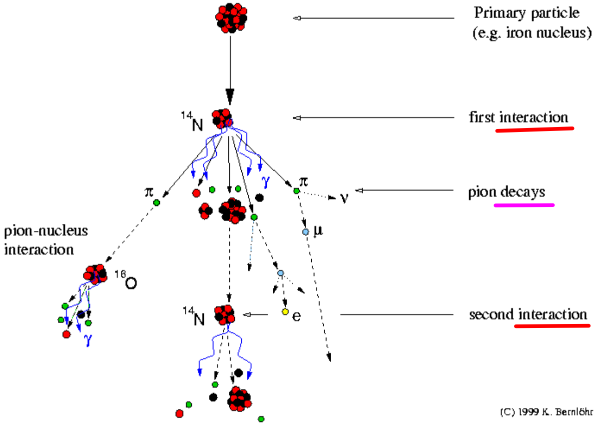


J. Cham&D. Whiteson “We have no idea”, Penguin, 2018

$E_{\text{beam}}^{\text{LHC}} = 7\times10^{12}$ eV

Particle Cascade in the Atmosphere / Air Shower





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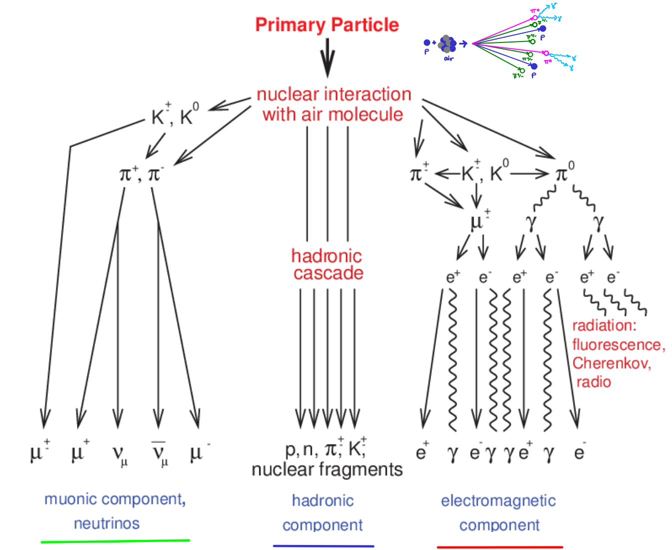
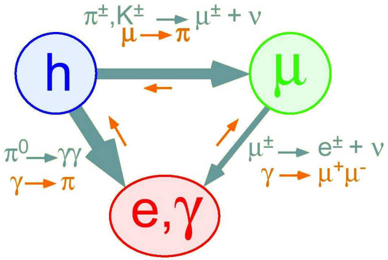
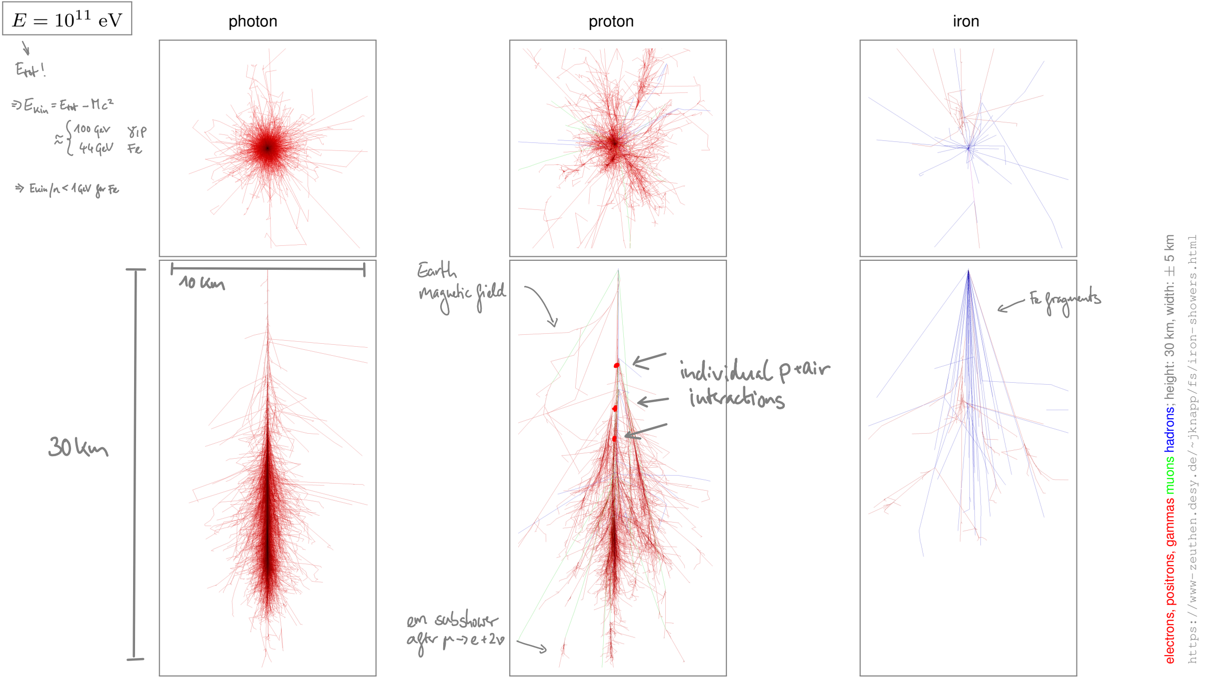




⇒ complicated coupled particle transport through atmosphere

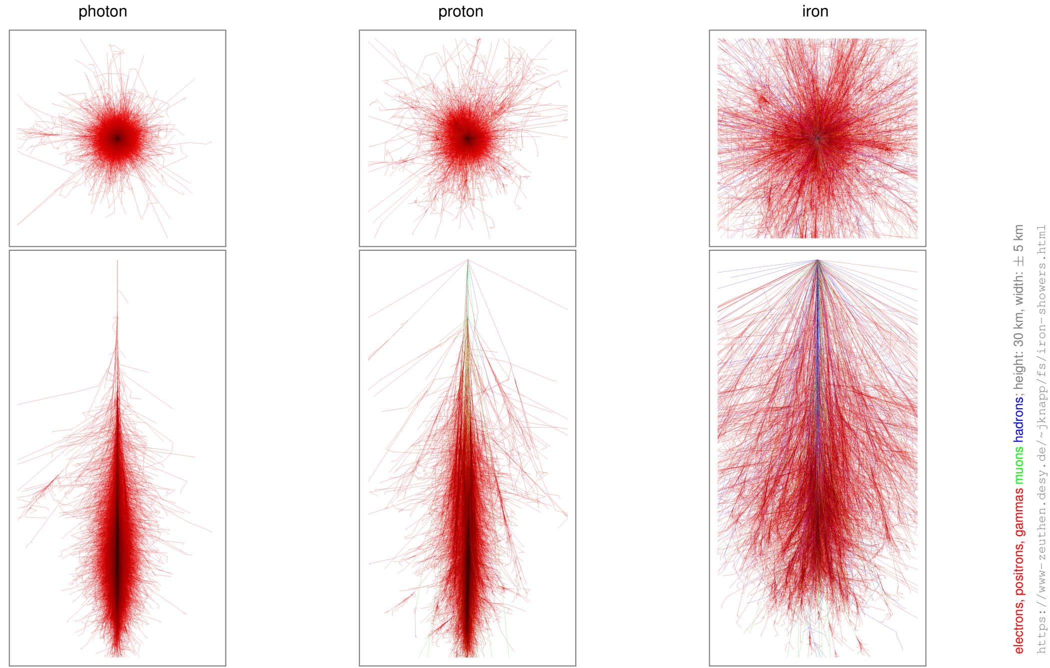
⇒ numerical solutions or Monte Carlo

e.g. CORSIKA (dev. at IAP!)



$E = 10^{11}$ eV
photon
proton
iron
E_{tot}!
$\Rightarrow E_{kin} = E_{tot} - Mc^2$
$\approx$ 100 GeV γ, p
44 GeV Fe
$\Rightarrow E_{kin}/n < 1$ GeV for Fe
10 km
30 km
Earth magnetic field
individual p+air interactions
em subshower after $\mu \to e + 2\nu$
Fe fragments
electrons, positrons, gammas muons hadrons; height: 30 km, width: ± 5 km
https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

$E = 10^{12}$ eV


photon
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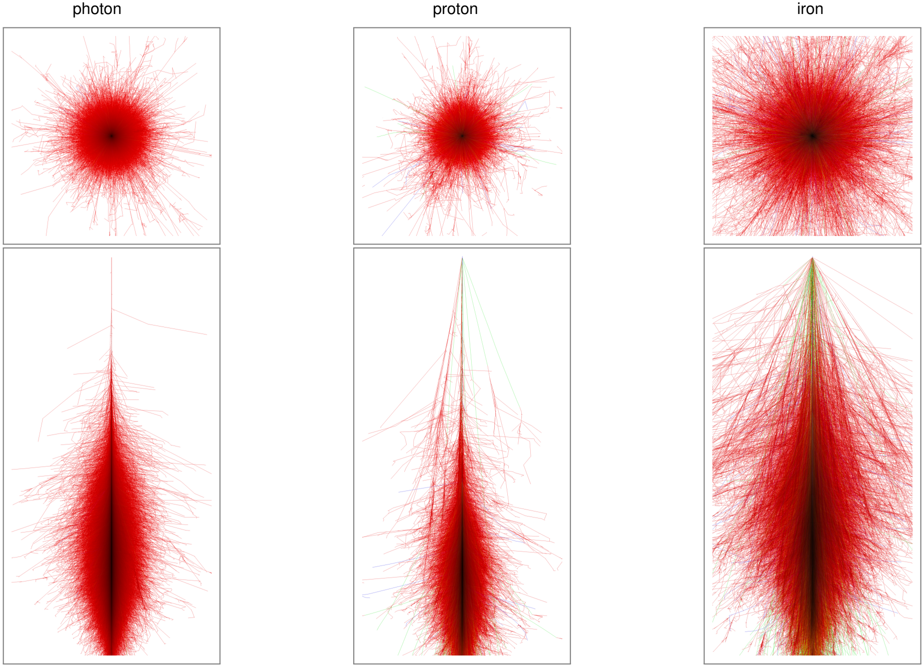

electrons, positrons, gammas muons hadrons; height: 30 km, width: ± 5 km

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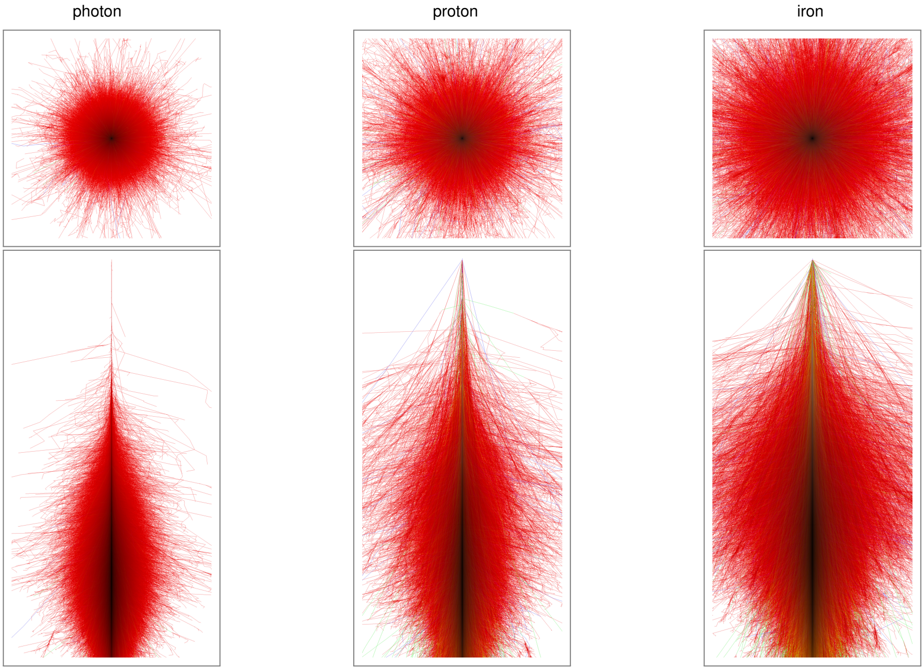
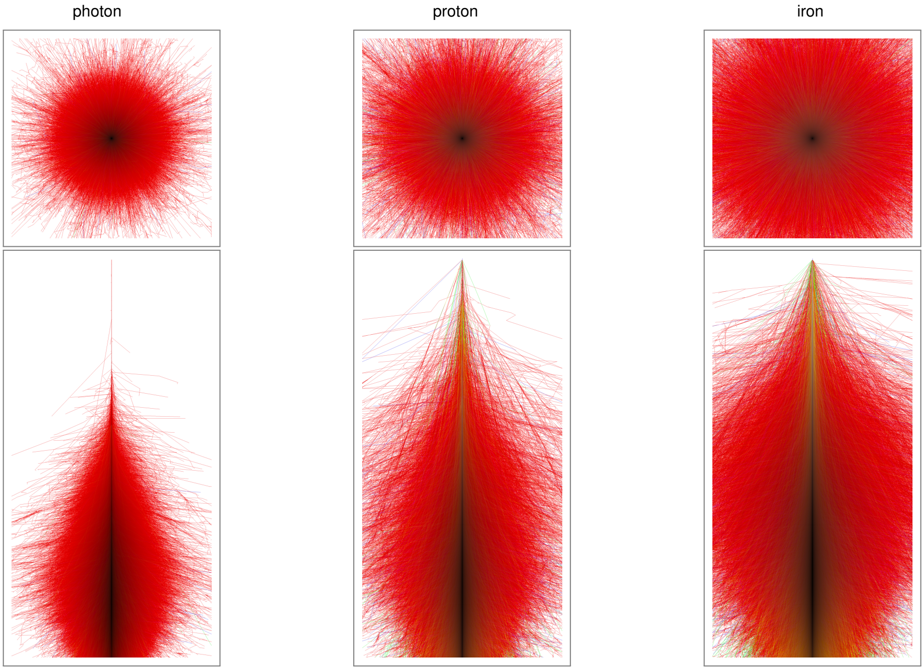
$E = 10^{14}$ eV



electrons, positrons, gammas muons hadrons; height: 30 km, width: ± 5 km

https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

$E = 10^{15}$ eV



electrons, positrons, gammas muons hadrons; height: 30 km, width: $\pm$ 5 km

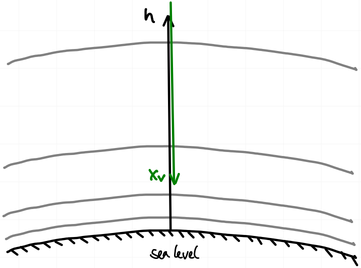
https://www-zeuthen.desy.de/~jknapp/fs/iron-showers.html

Atmosphere

- height above sea level h
- air density $\rho(h)$
- vertical depth X_v

$$X_v = \int_h^\infty \rho(h')\,dh'$$

$[X_v] = g/cm^2 \Rightarrow$ "grammage"



- isothermal atmosphere:

$$\rho(h) = \rho_0\, e^{-h/h_0}$$
$$X_v = X_0\, e^{-h/h_0}$$

- $X_0 \approx 1030\ g/cm^2$ at sea level

- scale height $h_0 \approx 8.4$ km at sea level, ≈ 6.4 km high altitudes above $h \approx 10$ km

lateral spread due to Coulomb scattering — see lecture 2

h — X_v — $\rho(h)$

altitude (km)	vertical depth (g/cm^2)	local density (10^{-3} g/cm^3)	Molière unit (m)	Cherenkov threshold (MeV)	Cherenkov angle (°)
40	3	3.8×10^{-3}	2.4×10^4	386	0.076
30	11.8	1.8×10^{-2}	5.1×10^3	176	0.17
20	55.8	8.8×10^{-2}	1.0×10^3	80	0.36
15	123	0.19	478	54	0.54
10	269	0.42	223	37	0.79
5	550	0.74	126	28	1.05
3	715	0.91	102	25	1.17
1.5	862	1.06	88	23	1.26
0.5	974	1.17	79	22	1.33
0	1032	1.23	76	21	1.36

Atmosphere

- slant depth:

$$X = \int_{\ell}^{\infty} \rho(h(\ell'))\, d\ell'$$

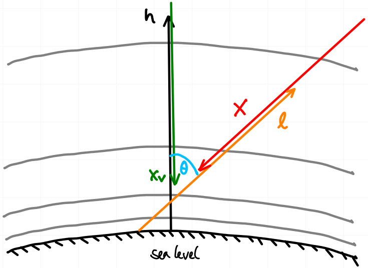
- zenith angle θ $\quad h/\ell = \cos\theta$

- flat atmosphere approximation for $\theta \lesssim 65°$

$$X = X_v / \cos\theta$$

- horizontal thickness of curved atmosphere:

$$X(\theta = 90°) \approx 3.5 \cdot 10^4\ g/cm^2$$



zenith angle degree	planar distance km	planar slant depth g/cm²	spherical distance km	spherical slant depth g/cm²
0	112.8	1036.1	112.8	1036.1
30	130.3	1196.4	129.9	1196.0
45	159.6	1465.3	158.2	1463.7
60	225.7	2072.2	220.1	2065.3
70	329.9	3029.4	310.7	3003.9
80	649.8	5966.7	529.0	5765.9
85	1294.6	11887.9	770.9	10572.1
89	6465.0	59367.2	1098.3	25920.4
90	∞	∞	1204.4	36481.8

Table 1: Distances and slant depths in planar and spherical geometry, calculated with the Linsley parametrization of the U.S. standard atmosphere.

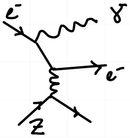
D. Heck FZKA-6954 2004

Electromagnetic Interactions

interactions with nuclei of material (Z)

energy loss

$$\left\langle -\frac{dE}{dx} \right\rangle_{brems,pair} = \frac{E}{X_0} \quad \leftrightarrow \quad E(x) = E_0 e^{-x/X_0}$$



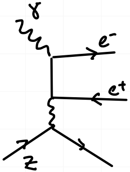
bremsstrahlung

radiation length:

$$X_0 \sim \Big(\underbrace{\frac{Z^2}{A}\rho}_{\text{material}}\Big)^{-1}$$

⇒ electron radiation length in air:

$$X_0^{air} = 36.6\ g/cm^2$$



pair production

critical energy:

$$\left\langle -\frac{dE}{dx} \right\rangle_{brems} \sim E$$

$$\left\langle -\frac{dE}{dx} \right\rangle_{ion} \sim const$$

E_{crit} when $\left\langle -\frac{dE}{dx} \right\rangle_{brems} = \left\langle -\frac{dE}{dx} \right\rangle_{ion}$

⇒ critical energy in air:

$$E_{crit}^{air} = 84\ MeV$$

Hadronic Interactions

- charge radius (e+p scattering):

$$r_p = 0.88 \cdot 10^{-15}\ m$$

$\rightarrow \sigma_{pp} \approx (2 r_p)^2 \pi \approx 100\ mb$

(b: "barn", $1b = 10^{-28}\ m^2$)

- inelastic cross section: $\sigma_{inel} = \sigma_{tot} - \sigma_{ela}$

  ≙ particle production — total — elastic

$\sigma_{inel} \approx 35\ mb$

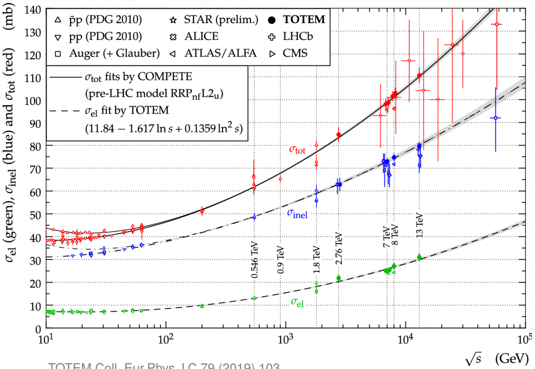
($10\ GeV < E_{lab} < 1\ TeV$)

- particle production: $p + p \rightarrow p + p + m \cdot \pi^{+/-} + n \cdot \pi^0$

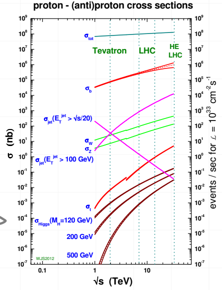
(and $K^{+/-}$, Λ, K^0, n, Higgs ...)

but...

- pion multiplicity: $m \approx 2 \cdot n$



TOTEM Coll. Eur.Phys.J.C 79 (2019) 103



Hadronic Interactions

- interaction length: $j + air \to X$

$$\lambda_j = \ell_j \rho = \frac{\rho}{n_A \sigma_j^{air}} = \frac{\langle A \rangle m_p}{\sigma_j^{air}}$$

(mass density: ρ; $[\lambda] = g/cm^2$; $[\ell] = cm$; n_A: number density; σ_j^{air}: cross section)

- typical values: @ 10 TeV

$\lambda_N \approx 80\ g/cm^2$ p+air/n+air

$\lambda_\pi \approx 100\ g/cm^2$ π+air

- average air mass: $\langle A \rangle = 14.6$ (78.09% N, 20.95% O, 0.93% Ar)
- nucleon + nucleus interactions:

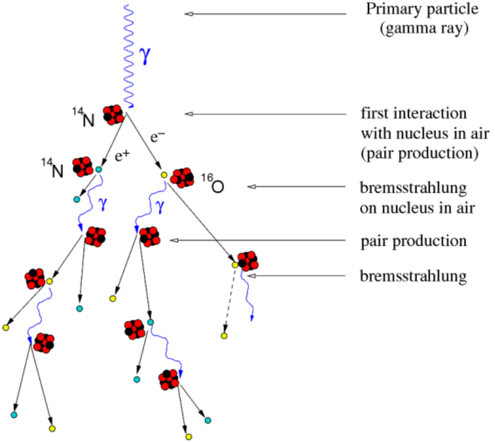
$$\sigma(p+A) \sim A^{2/3}$$ ← geometrical size of nucleus with A spherically packed nucleons

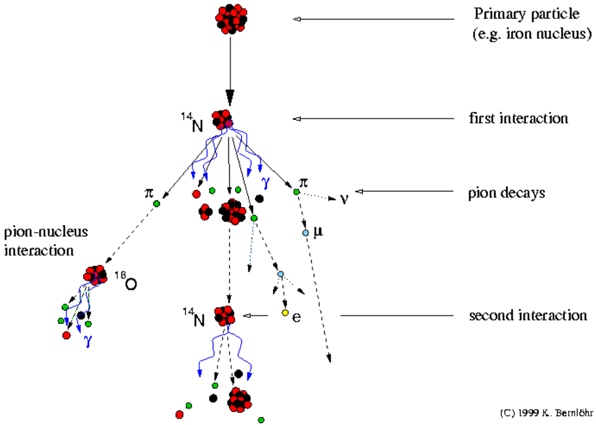
- nucleus + nucleus interactions:

$$\sigma(A_1 + A_2) \approx \pi R_0^2 \left(A_1^{1/3} + A_2^{1/3} - \delta\right)^2$$ ($\delta = 1.12$, $R_0 = 1.47$ fm)

- Glauber model of n+A scattering (see CRPP A6 and Glauber + Matthiae Nucl. Phys. B 21 (1970) 135)

Particle Cascade in the Atmosphere / Air Shower

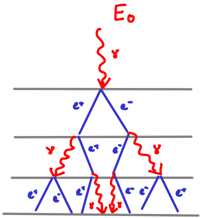




Photon-induced Shower

Heitler model

γ, e^-, e^+ shower



	N_n	E_n
$n=0$	1	E_0
$n=1$	2	$E_0/2$
$n=2$	4	$E_0/4$
$n=3$	8	$E_0/8$
⋮	⋮	⋮

Carlson + Oppenheimer 1937, Heitler 1954

Photon-induced Shower

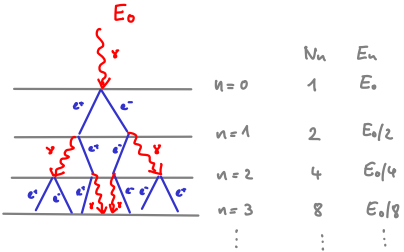
- radiation length X_0 in air: 37 g/cm²

$$\left\langle -\frac{dE}{dx}\right\rangle_{brems,pair} = \frac{E}{X_0} \leftrightarrow E(x) = E_0 e^{-x/X_0}$$

- splitting length $d = \ln 2 \cdot X_0$ $E(d) = E_0/2$
  - $E_{i+1} \to E_i/2$
  - $N_{i+1} \to 2 \cdot N_i$

Heitler model

γ, e^-, e^+ shower



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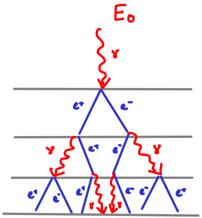
- splitting length $d = \ln 2 \cdot X_0$ $\quad E(d) = E_0/2$
  - $E_{i+1} \to E_i/2$
  - $N_{i+1} \to 2 \cdot N_i$
- after n splitting lengths:
  - $X_n = n \ln 2\, X_0$
  - $N_n = 2^n = e^{x/X_0}$
  - $E_n = E_0/N_n$

Heitler model

γ, e^-, e^+ shower



	N_n	E_n
n = 0	1	E_0
n = 1	2	$E_0/2$
n = 2	4	$E_0/4$
n = 3	8	$E_0/8$
⋮	⋮	⋮

Carlson + Oppenheimer 1937, Heitler 1954

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  - $N_{i+1} \rightarrow 2 \cdot N_i$
- after n splitting lengths:
  - $X_n = n \ln 2\, X_0$
  - $N_n = 2^n = e^{X/X_0}$
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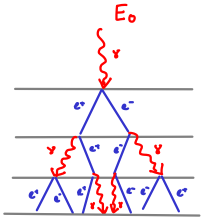
Heitler model

γ, e^-, e^+ shower



	N_n	E_n
$n=0$	1	E_0
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$n=2$	4	$E_0/4$
$n=3$	8	$E_0/8$
⋮	⋮	⋮

Carlson + Oppenheimer 1937, Heitler 1954

critical energy:
$$\frac{dE_{rad}}{dx}(\varepsilon_{crit}) = \frac{dE_{ion}}{dx}(\varepsilon_{crit})$$
in air: 84 MeV

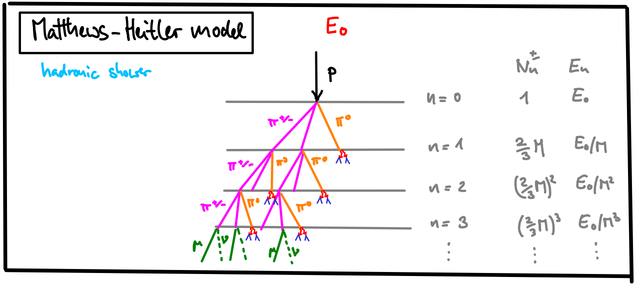
- shower development stops when $E_n \leq \varepsilon_{crit}$
  - $N_{max} = E_0/\varepsilon_{crit} \quad = 10^{11}$
  - $n_{max} = \ln(E_0/\varepsilon_{crit})/\ln 2 \quad = 37$
  - $X_{max} = X_0 \ln(E_0/\varepsilon_{crit}) \quad = 940\ g/cm^2$

} $E_0 = 10^{19}$

Proton-induced Shower

$M = M_- + M_+ + M_0$, $M_- \approx M_+$

- production of M pions, $p + air \to M_- \cdot \pi^- + M_+ \cdot \pi^+ + M_0 \cdot \pi^0 + \ldots$
  (M: multiplicity)



J. Matthews APP 2005

Proton-induced Shower

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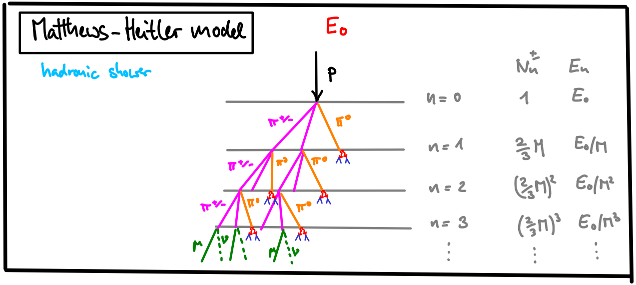
- production of M pions, $p + air \to M_- \cdot \pi^- + M_+ \cdot \pi^+ + M_0 \cdot \pi^0 + \ldots$
  (M: multiplicity)
- interaction length λ_{int}
  - $E_{i+1} \to E_i / M$, $E_n = E_0 / M^n$
- $\pi^{+/-} + air \to \frac{2}{3} M \cdot \pi^{\pm} + \frac{1}{3} M \pi^0$

re-interaction → hadronic shower

decay: $\pi^0 \to \gamma\gamma$ → electromagnetic shower



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re-interaction → hadronic shower

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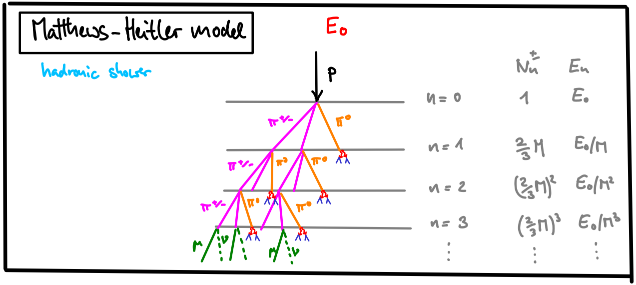

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- hadronic cascade stops when $\lambda_{int} = \lambda_{dec}$ $\quad \pi^+ \to \mu^+ \nu_\mu$
  ($\lambda_{dec} = \beta\gamma c\tau$) $\quad \pi^- \to \mu^- \bar{\nu}_\mu$

  → critical energy $\epsilon_\pi \approx 10\,GeV = E_n \to n_{crit} = \ln(E_0/\epsilon_\pi)/\ln M$
- $N_n = \left(\frac{2}{3}M\right)^n$

Proton-induced Shower

$M = M_- + M_+ + M_0\,,\; M_- \approx M_+$

- production of M pions, $p + air \to M_- \cdot \pi^- + M_+ \cdot \pi^+ + M_0 \cdot \pi^0 + \ldots$
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- interaction length λ_{int}
  - $E_{i+1} \to E_i / M\,,\quad E_n = E_0 / M^n$
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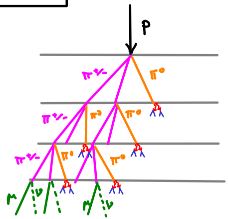
  re-interaction → hadronic shower
  decay → $\pi^0 \to \gamma\gamma$ → electromagnetic shower

Matthews-Heitler model



n	$N_n^{\pm}$	E_n
$n = 0$	1	E_0
$n = 1$	$\frac{2}{3} M$	E_0/M
$n = 2$	$(\frac{2}{3} M)^2$	E_0/M^2
$n = 3$	$(\frac{2}{3} M)^3$	E_0/M^3
⋮	⋮	⋮

J. Matthews APP 2005

$$N_\mu = N_{n_{crit}} = \left(E / \varepsilon_\pi \right)^\beta$$

- hadronic cascade stops when $\lambda_{int} = \lambda_{dec}$ $\quad \pi^+ \to \mu^+ \nu_\mu$
  ($\lambda_{dec} = \varsigma \gamma c \tau$) $\quad \pi^- \to \mu^- \bar{\nu}_\mu$
  → critical energy $\varepsilon_\pi \approx 10\,\mathrm{GeV} = E_n \to n_{crit} = \ln(E_0/\varepsilon_\pi) / \ln M$
- $N_n = \left(\frac{2}{3} M \right)^n$

with $\beta = \frac{\ln \frac{2}{3} M}{\ln M} = 1 - \frac{\ln 3/2}{\ln M} = 1 - \frac{\lg 3/2}{\lg M} \approx 1 - \frac{0.18}{\lg M}$

≈ 0.9 for $M = 50$

e.g. $N_\mu \approx 10^8$ for $E_0 = 10^{19}\,\mathrm{eV}$ and $M = 50$

Proton-induced Shower

estimate of shower maximum:

- photons produced in π^0 decays after first interaction:

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

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- $2\cdot\frac{1}{3}M$ electromagnetic showers starting at $\langle x_1\rangle = \lambda_p$

  $$\langle X^p_{max}\rangle = \lambda_p + X^\gamma_{max}\left(E = \frac{E_0}{2M}\right)$$

$$\Rightarrow \boxed{\langle X^p_{max}\rangle = \lambda_p + X_0 \ln\left(\frac{E_0}{2\cdot M\cdot \varepsilon_c}\right)}$$

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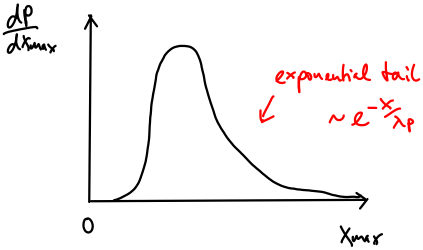
$\Rightarrow$ X_{max} distribution

$$\underbrace{}_{}\frac{dp}{dX_{max}} = \underbrace{\frac{dp}{dX_1}}_{\text{1st interaction}}^{\text{exp}} \otimes \underbrace{\frac{dp}{d\Delta X}}_{\text{shower development}}^{\approx\text{gauss}} \qquad \Delta X = X_{max} - X_1$$

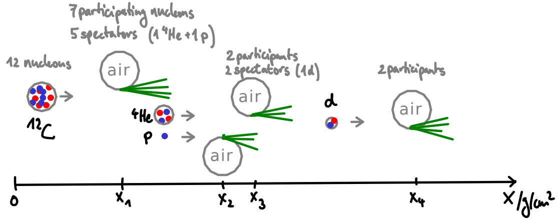


$\Rightarrow$ measurement of $\sigma_{p\text{-}air}$ @ $\sqrt{s} \approx 100$ TeV $\gg \sqrt{s}_{LHC}$

Nucleus-induced Shower

superposition model $(E,A) + \text{air} \rightarrow X \;\hat{=}\; A\cdot(E/A,1) + \text{air} \rightarrow X$

but e.g.:



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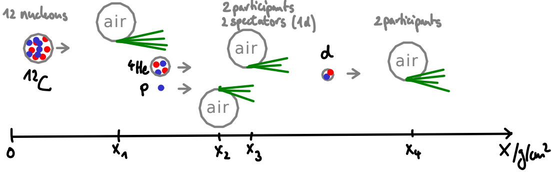
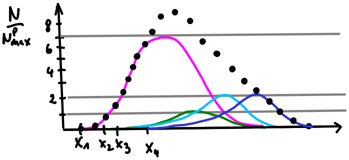


$\to p(X_{i+1} - X_i) \sim e^{-\frac{X_{i+1}-X_i}{\lambda_{A\kappa}}}$

→ superposition of 12 N+air showers from 4 A_κ+air interactions: 7N@X_1, 1N@X_2, 2N@X_3, 2N@X_4



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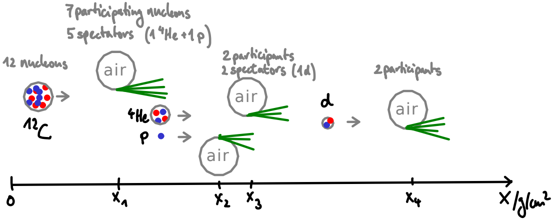

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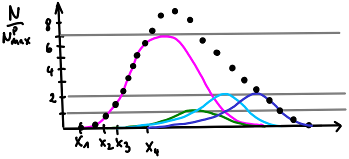


Superposition theorem J. Engel et al. PRD 1992

if average number of participating nucleons in projectile A+air interactions

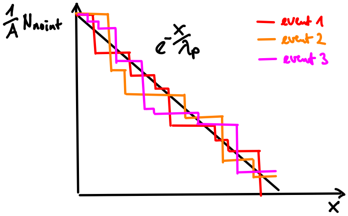
$$\langle n_A \rangle = A\,\frac{\lambda_A}{\lambda_p} \qquad \langle n_A \rangle = \sum n\,P(n)$$

then probability of depth of interaction of nucleons

$$\boxed{\frac{dp_A}{dX} = \frac{1}{\lambda_p}\, e^{-X/\lambda_p}}$$

irrespective of fragmentation of spectator nucleus

number of nucleons that have not yet interacted $\frac{1}{A} N_{noint} = 1 - \int_0^X \frac{dp_A}{dX'}\,dX'$
$= \exp(-X/\lambda_p)$



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. $M=56$, $\beta=0.9$

  $\rightarrow$ $N_\mu(56)/N_\mu(1) = 56^{0.1} = 1.5$

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

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

$$X_{max}^A(E) = X_{max}^p(E/A)$$

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$$X_{max}^A(E) = X_{max}^p(E/A)$$

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" (RD+SD, SD+FD)

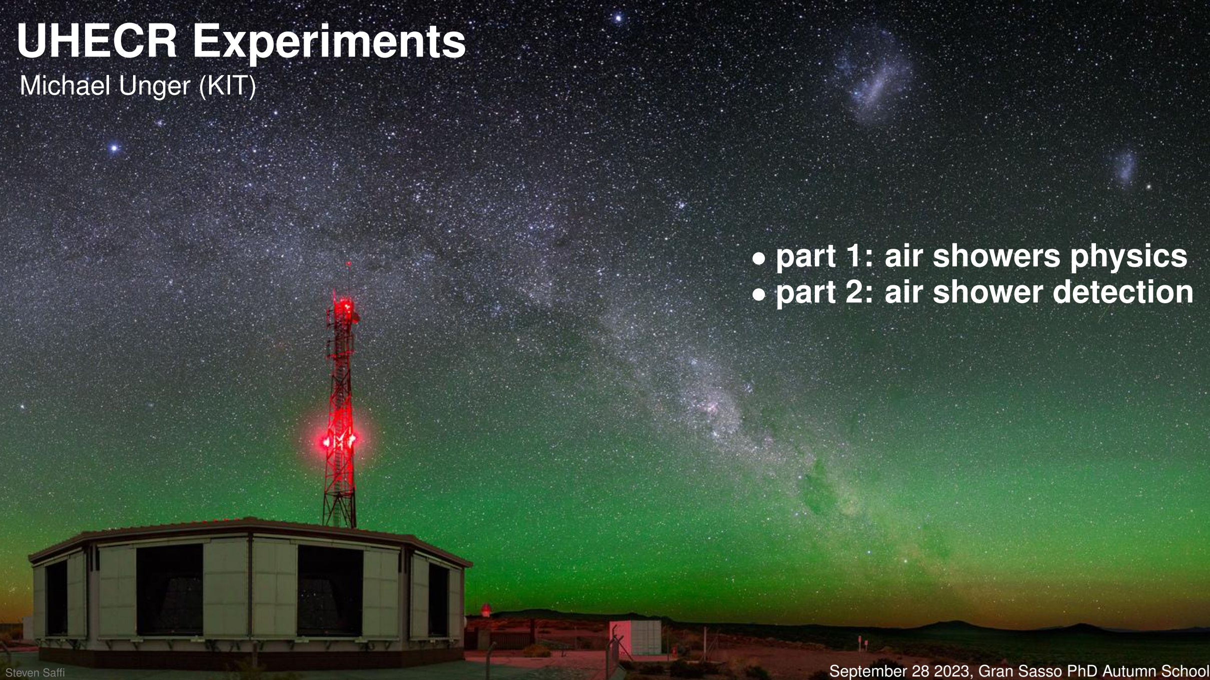
overconstrained ⇒ check hadronic interaction models

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

UHECR Experiments

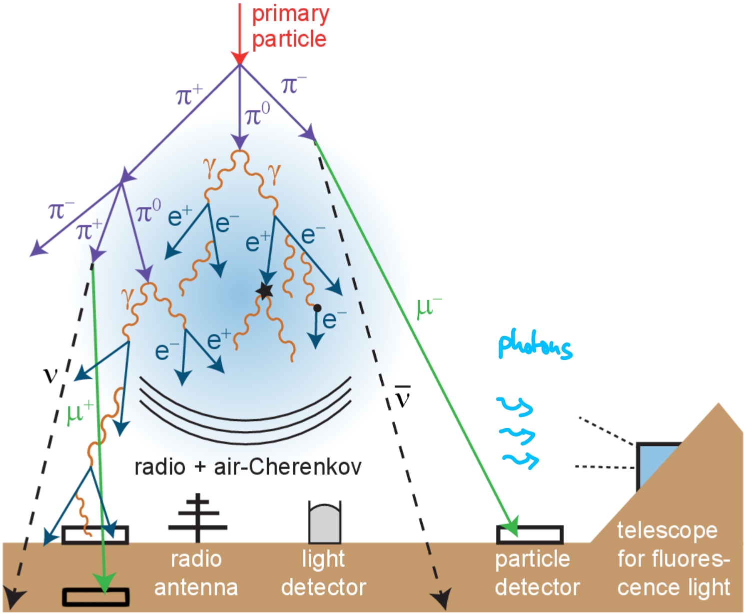
Michael Unger (KIT)

- part 1: air showers physics
- part 2: air shower detection



Steven Saffi

Air Shower Detection



F. Schröder, 2017

Air Shower Detection

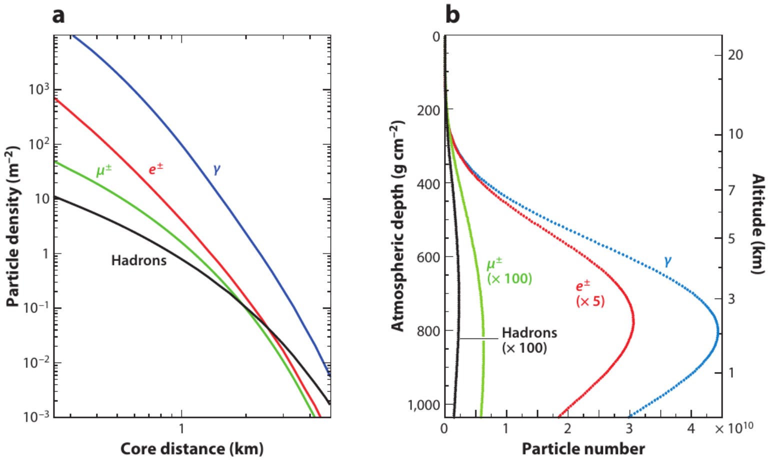
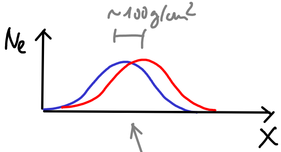


Figure 2

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.

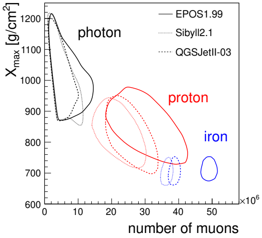
Engel, Heck, Pierog Ann.Rev.Nucl.Part.Sci. 61 (2011) 467

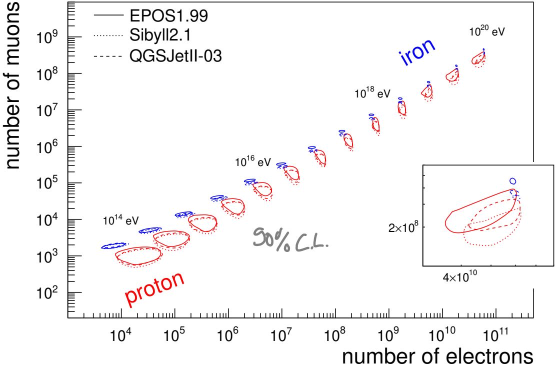
E and A

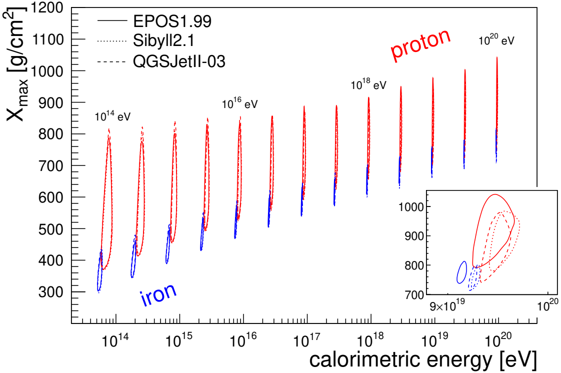


$\theta = 0°$, $X = 800\,g/cm^2$

Xground close to Xmax
⇒ Ne(p) ≈ Ne(Fe)

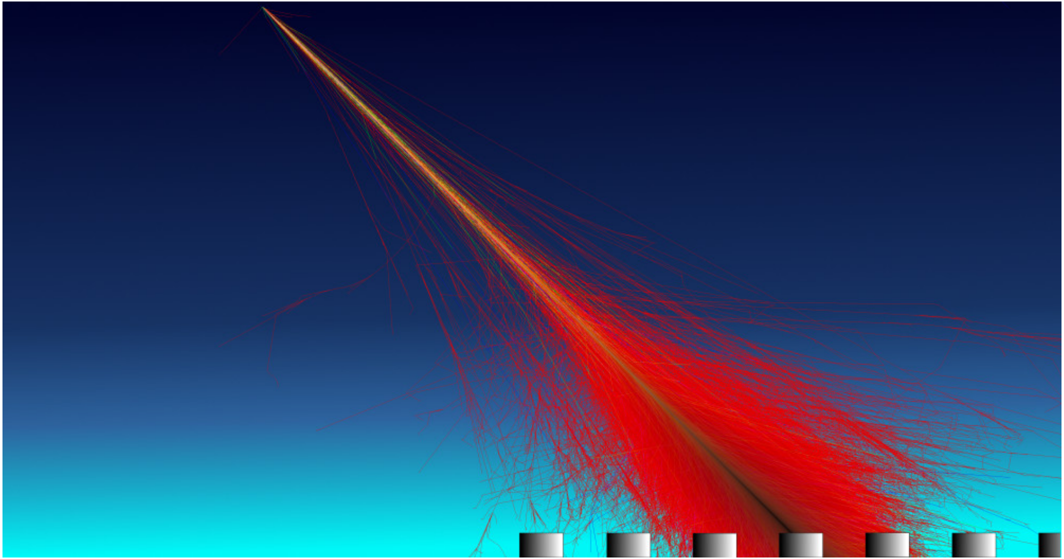






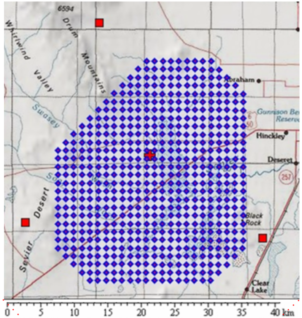
Kampert&Unger APP 2012

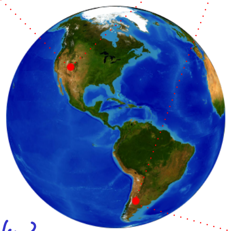
Particle Detectors



500 SCNTs
1.2 km spacing
A= 700 km²

Telescope Array "TA"

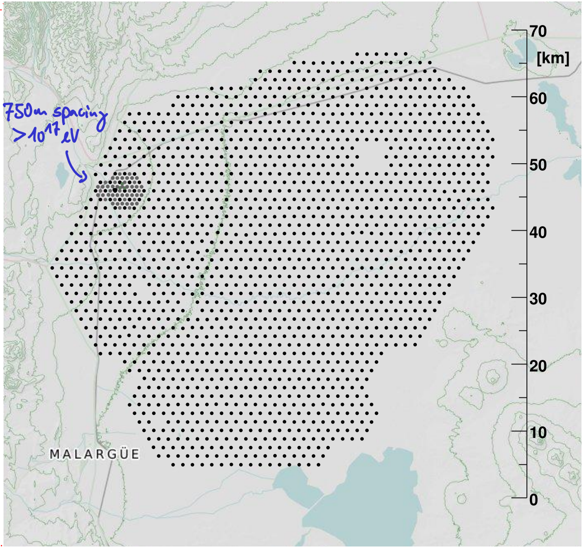




1600 WCDs
1.5 km spacing $> 10^{18}$ eV
A=3000 km²

Pierre Auger Observatory

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



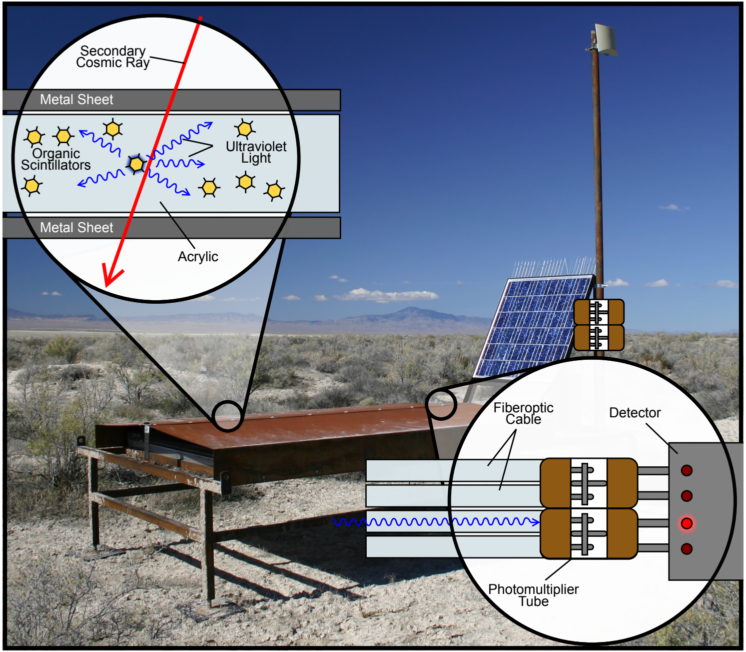
both at $X_{ground} \approx 850$ g/cm²

Telescope Array: scintillator as particle detector

Signal

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

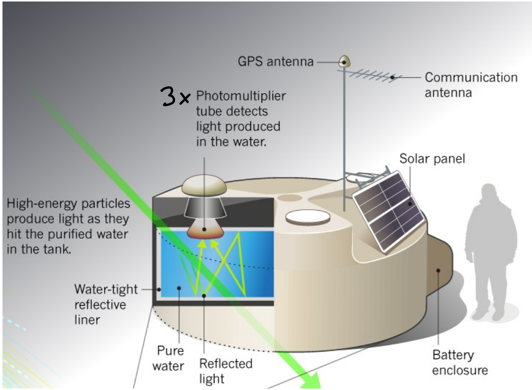
$(+\gamma \to e^+e^-$ conversion$)$



area $\sim \cos\theta$

Pierre Auger Observatory: Water Cherenkov detectors (WCD)

12t ultrapure water



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

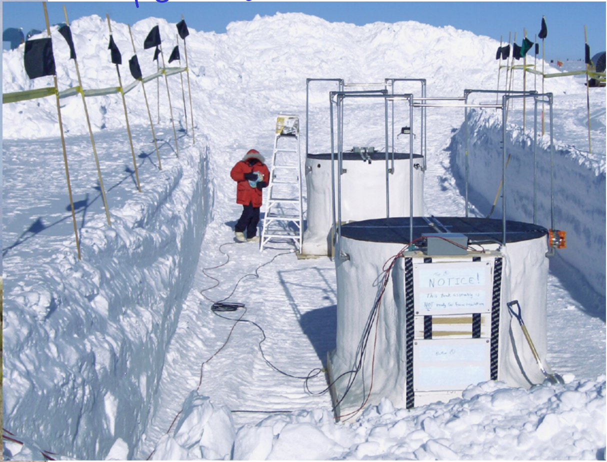
~ 160 GeV $\mu^+\mu^-$

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 ~ r)

IceTop @ IceCube

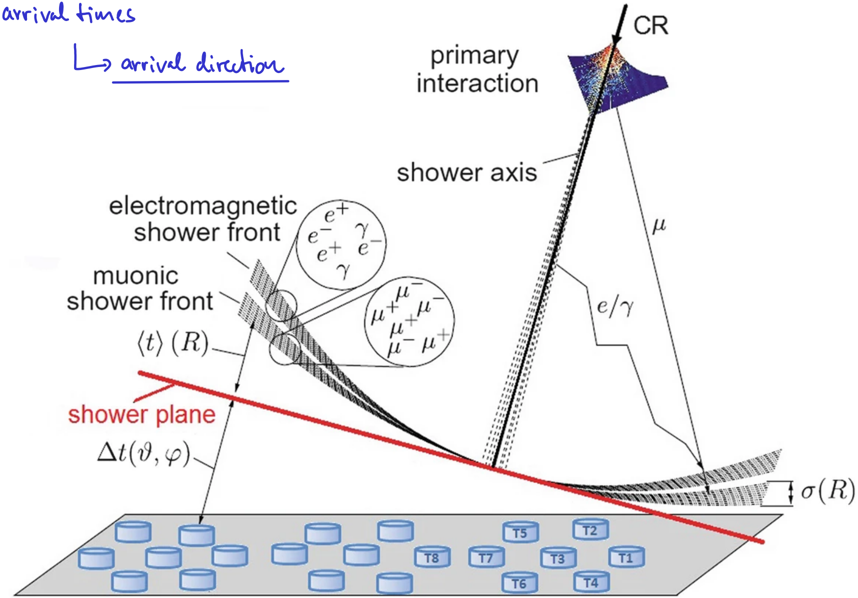


"Ice-Cherenkov" detectors

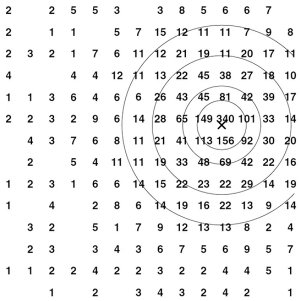

WCDs

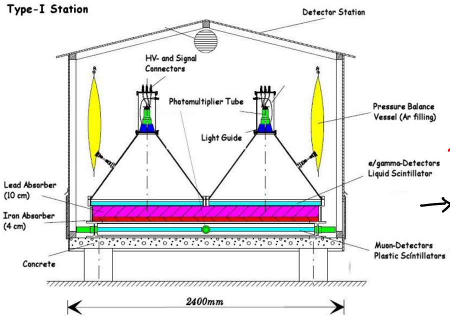
Shower Front / arrival times

↳ arrival direction



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

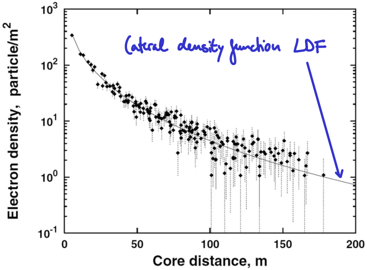




$\nearrow$ $N_{ch} = N_{e^+e^-} + N_\mu$

$\rightarrow$ 20 attenuation lengths shielding

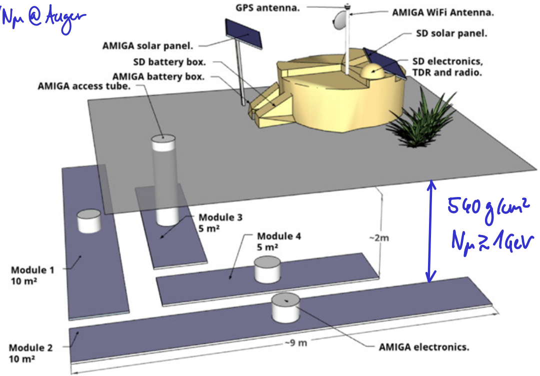
$\rightarrow$ N_μ $E_\mu > 250$ MeV

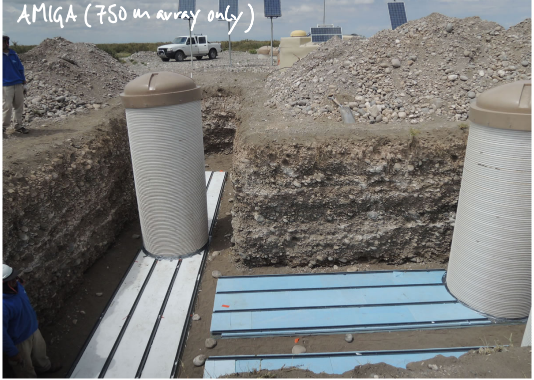


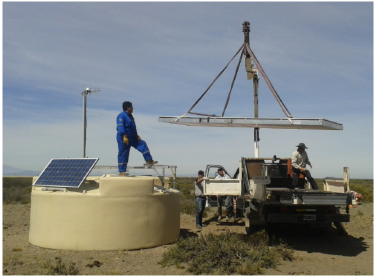
lateral density function LDF

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

N_e/N_μ @ Auger







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

schematically:

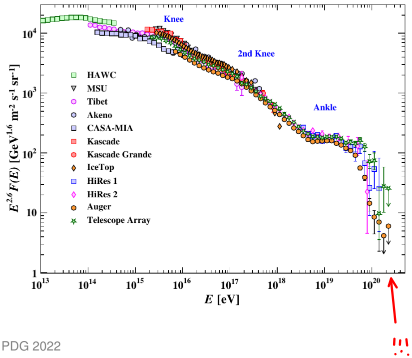
$$S_{scnt} \sim N_\mu + N_e$$

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

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

$\Rightarrow N_e$ and N_μ

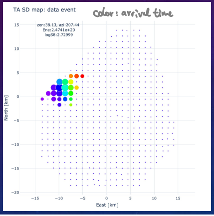
highest energy event measured with an PD

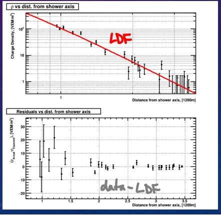


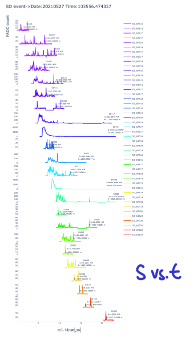
PDG 2022

NEW HIGHEST EVENT DETECTED BY TA

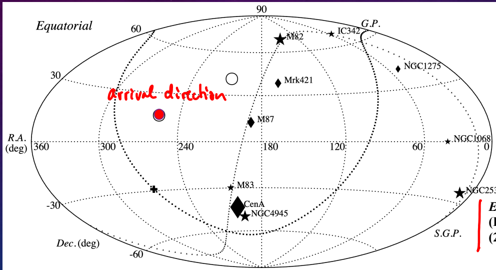
- 2021/05/27 10:35:56.47, No FD observation
  - $E = 243.6 \pm 10.7$ EeV, $\theta = 38.6°$, $\varphi = 206.8°$ - Preliminary
    - ($E = 242.8$ EeV with the atmospheric energy correction) - Preliminary







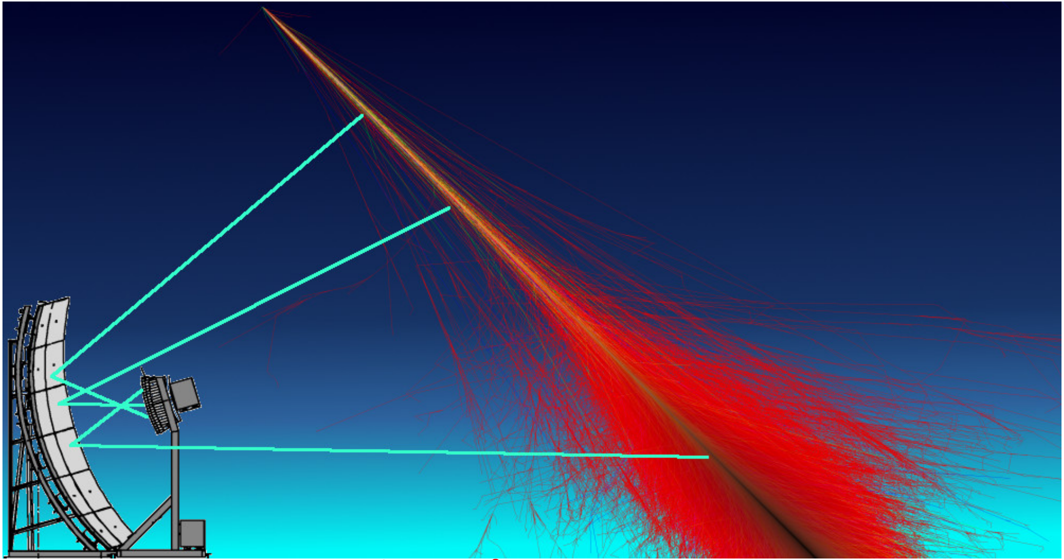
DIRECTION IN THE SKY-MAP



$E = 243.6$ 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

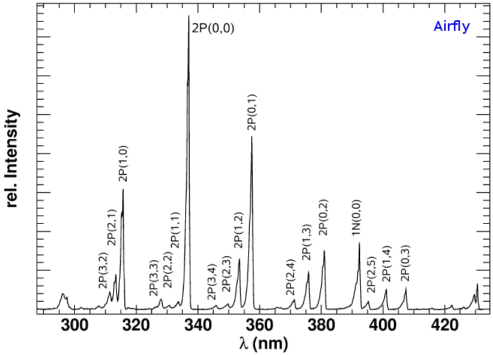
- N_2 excitation by charged particles
- isotropic emission !!
- fluorescence yield $Y \sim f(\varrho, T, H) \cdot \frac{dE}{dx}$

  density ϱ, temperature T, humidity H

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

  ≙ 30W light bulb
- precise measurement in lab

emission in UV (~10 ns)



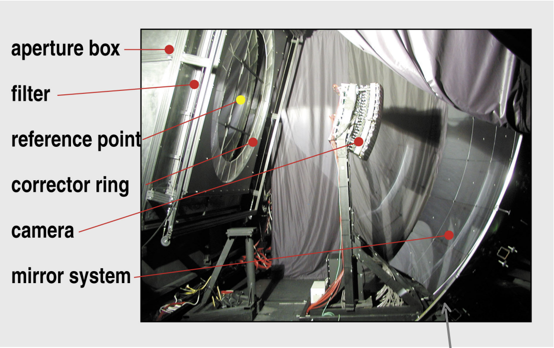
shower visible up to 30 km @ 10^{19} eV ⇒ 3000 km²

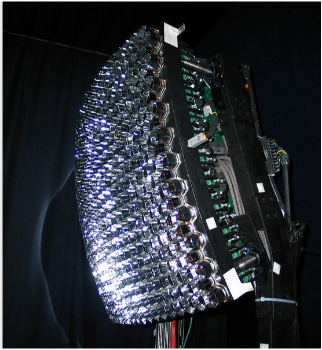
45 km @ 10^{20} eV ⇒ 6000 km²

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

"Schmidt optics"

camera





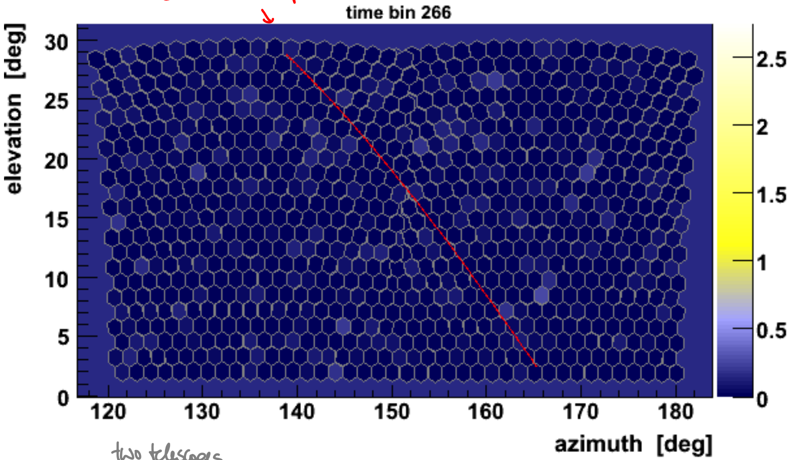
6 telescopes per building

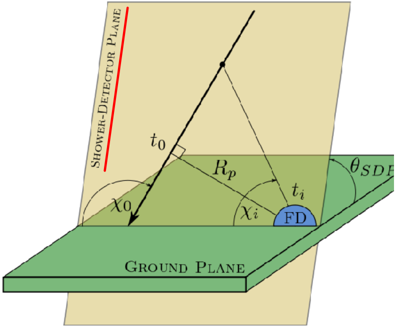
4 buildings at edge of array (looking inward)

spherical mirror

440 hexagonal PMTs

shower detector plane ↘

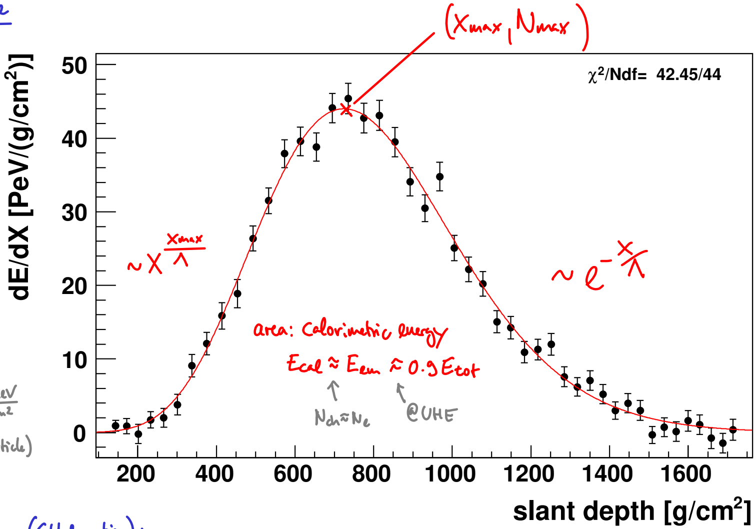




two telescopes

⇒ 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)

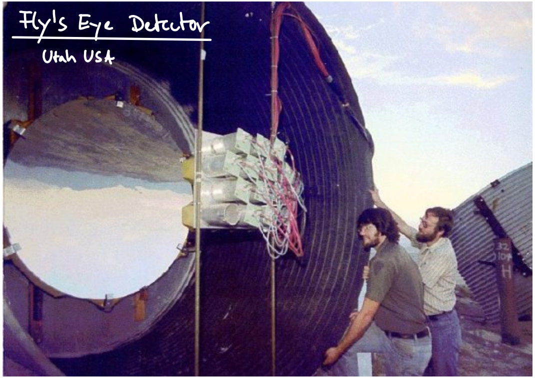
Nucl.Instrum.Meth.A 798 (2015) 172

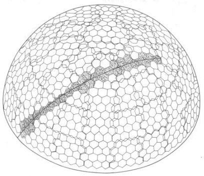
Gaisser-Hillas function (GH function):

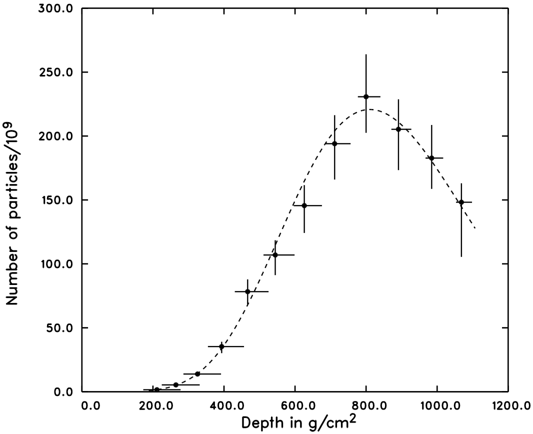
$$N_{fluo} \sim \frac{dE}{dX} \sim N_e(X) = N_{max}\left(\frac{X-X_1}{X_{max}-X_1}\right)^{(X_{max}-X_1)/\Lambda} e^{-\frac{X-X_{max}}{\Lambda}}$$

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

highest energy fluorescence detector event







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

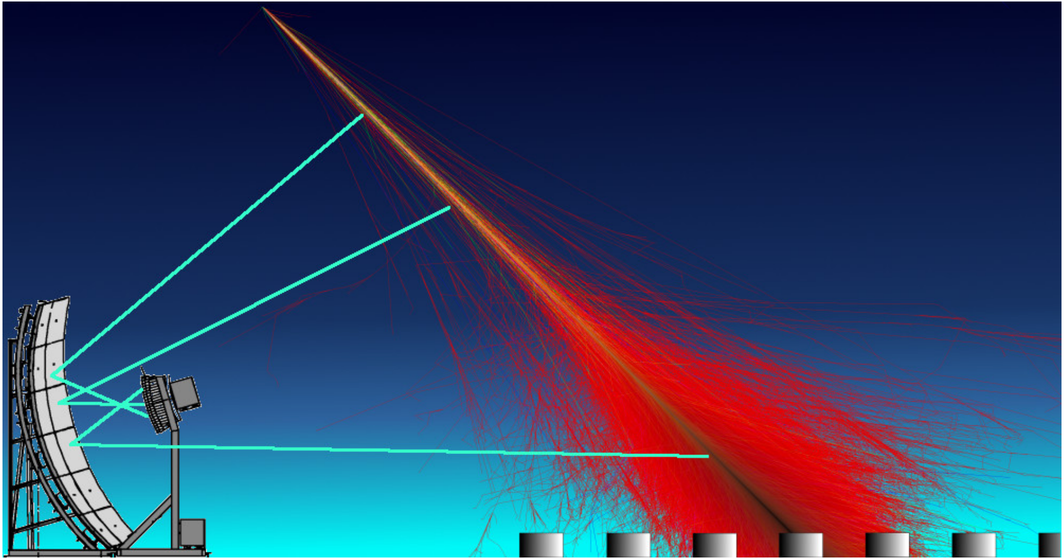
see also T.Fitoussi et al, JCAP 01 (2020) 042

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

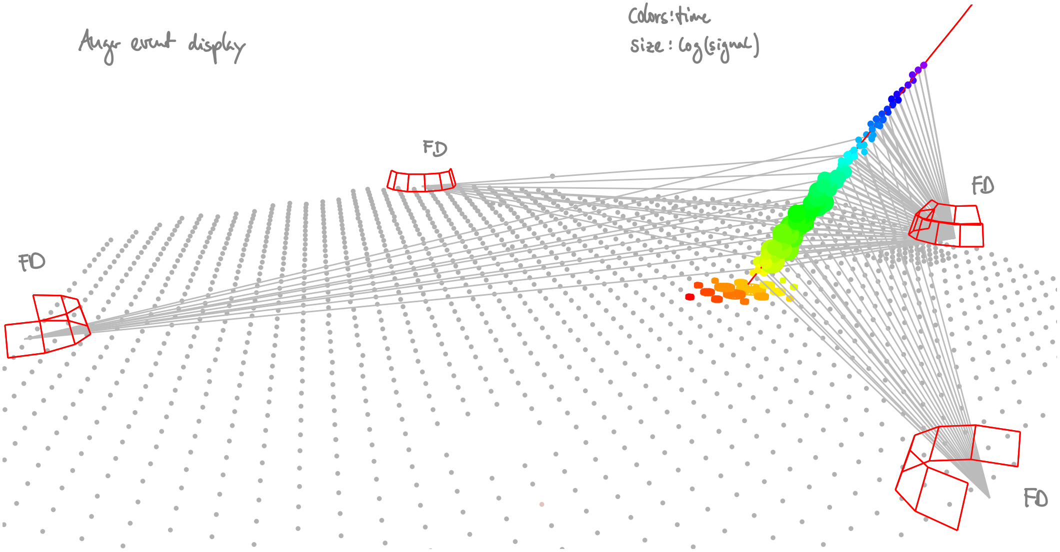
$E = (320 \pm 90) \cdot 10^{20}\, eV$ (51 Joule!)

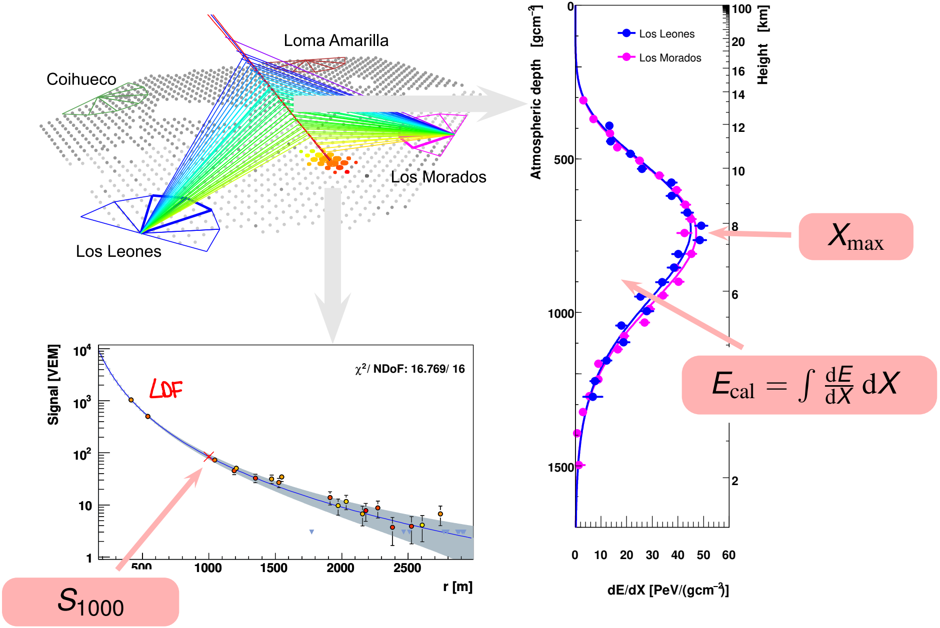
$X_{max} = (815 \pm 60)\, g/cm^2$ (compatible with p/Fe/γ)

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

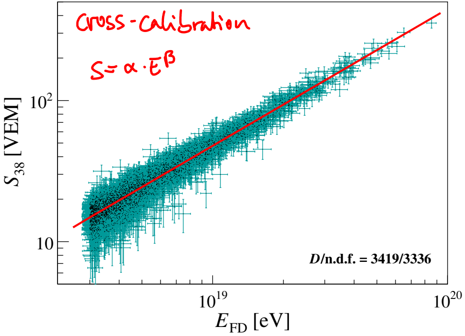


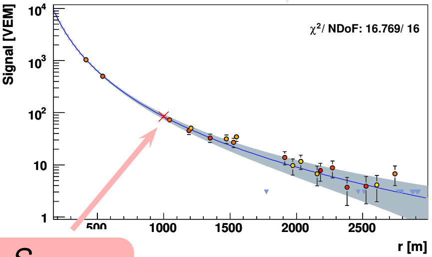
"Hybrid Detection" (e.g. fluorescence and particles)



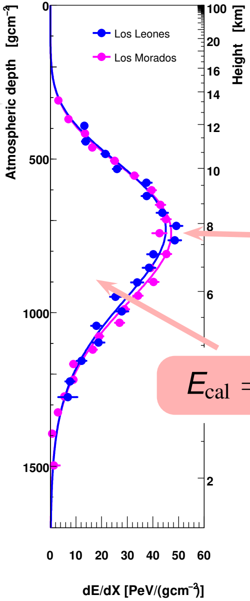


Loma Amarilla
Coihueco
Los Morados
Los Leones
Signal [VEM]
r [m]
χ^2/ NDoF: 16.769/ 16
LDF
S_{1000}
Atmospheric depth [gcm^{-2}]
Height [km]
Los Leones
Los Morados
dE/dX [PeV/(gcm^{-2})]
$X_{\rm max}$
$E_{\rm cal} = \int \frac{dE}{dX}\, dX$





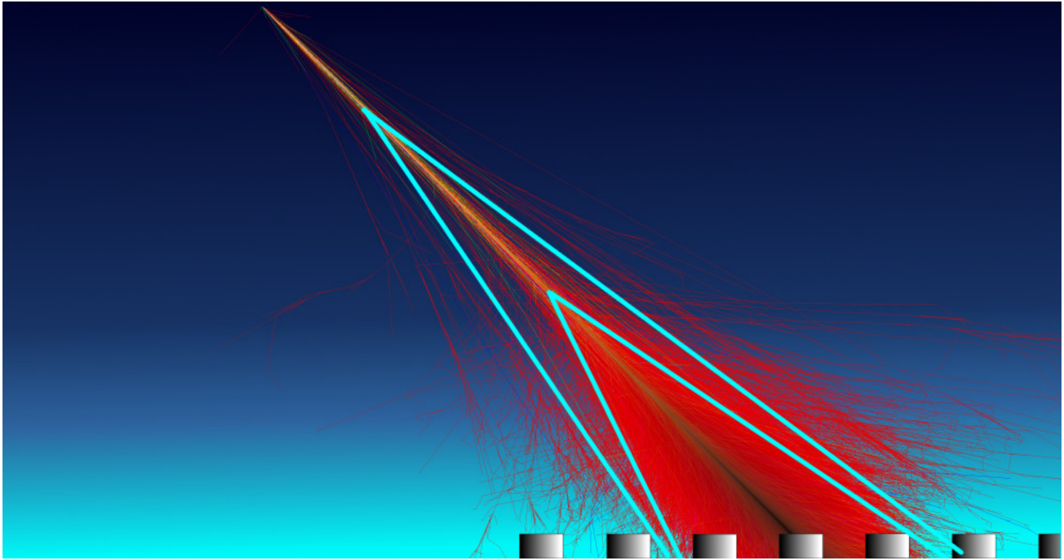
S_{1000}

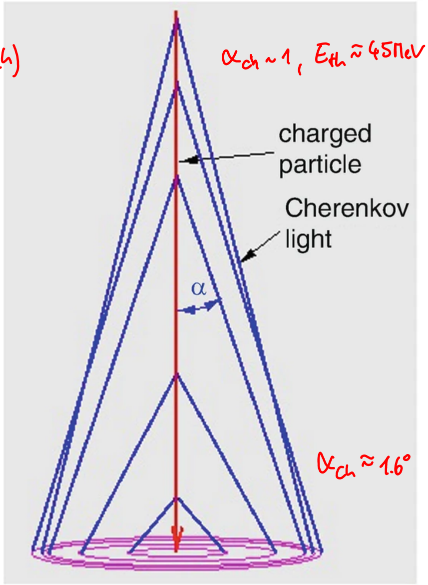


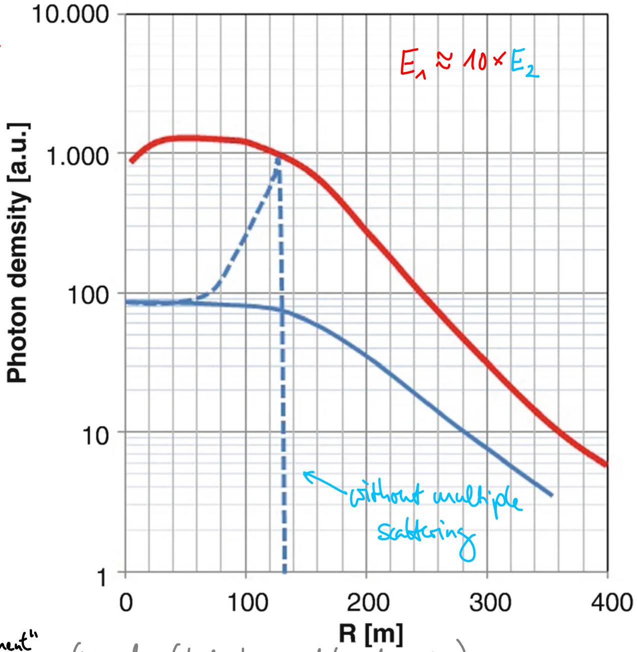
$X_{\rm max}$

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

Non-Imaging Cherenkov Detectors





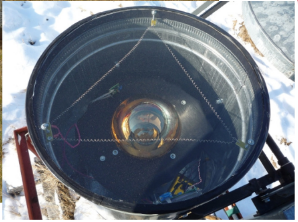


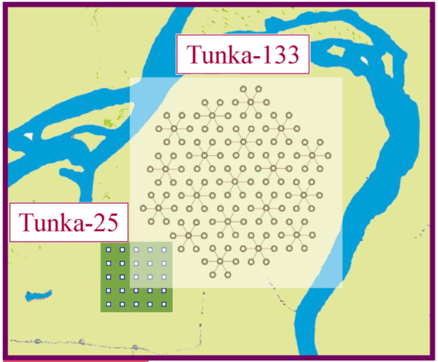
$N_\gamma \sim N_e \sim E_{em}$

"calorimetric measurement"

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

TUNKA array

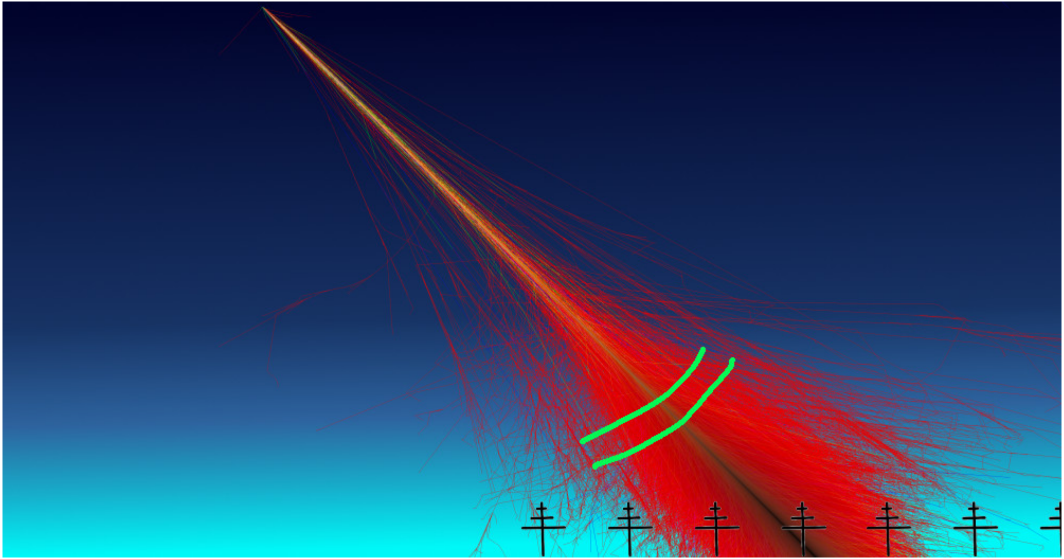




85m spacing

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

Radio Detectors



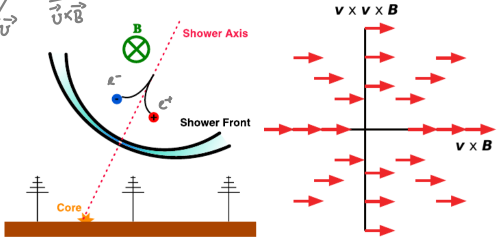
$\lambda >$ shower front thickness

$\Rightarrow f \lesssim 100$ MHz

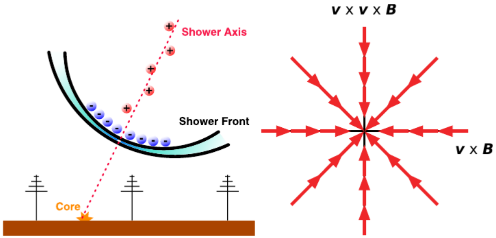
$\vec{E} \perp \vec{B}$ from $\dot{I}$

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

$\vec{v}$ $\vec{v} \times \vec{B}$



polarization



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

geomagnetic effect > charge excess / Askaryan effect

in air !

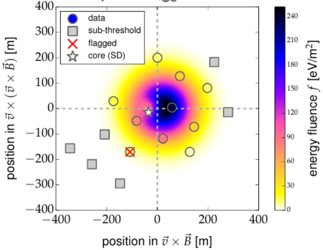
(Askaryan dominates in solids)

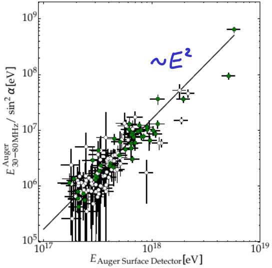
$\approx 10\%$ in air

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

Auger Coll., PRL 116 (2016) 241101

AERA event





2 pol

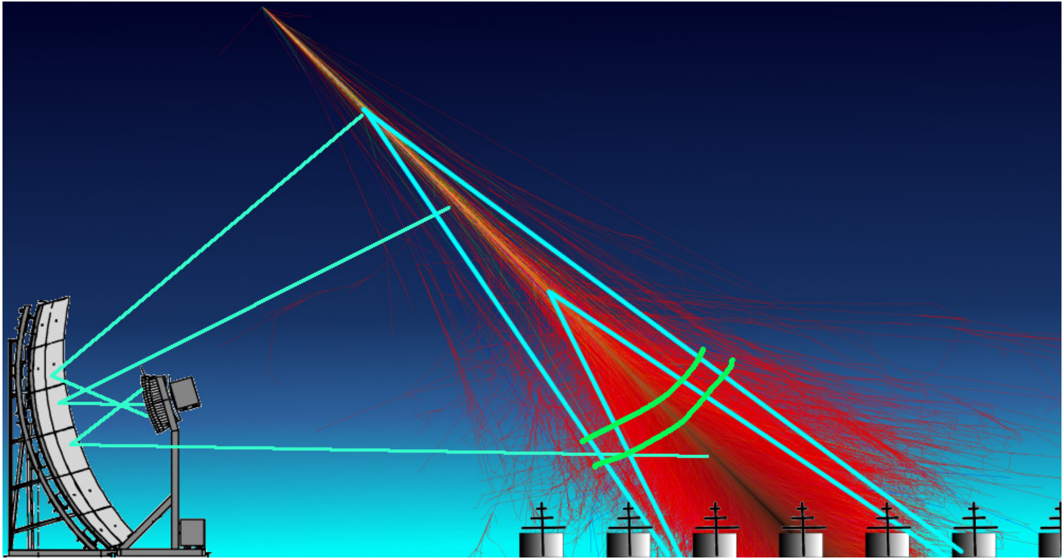
LOPES @ KASCADE

SALLA @ Tunka

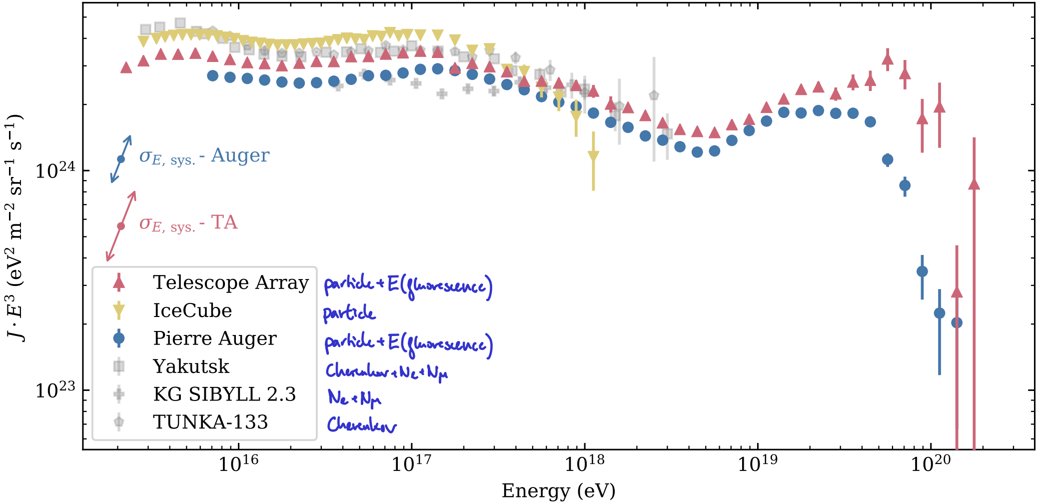
LPDA @ Auger

SALLA @ Auger

Some Results (E and A)

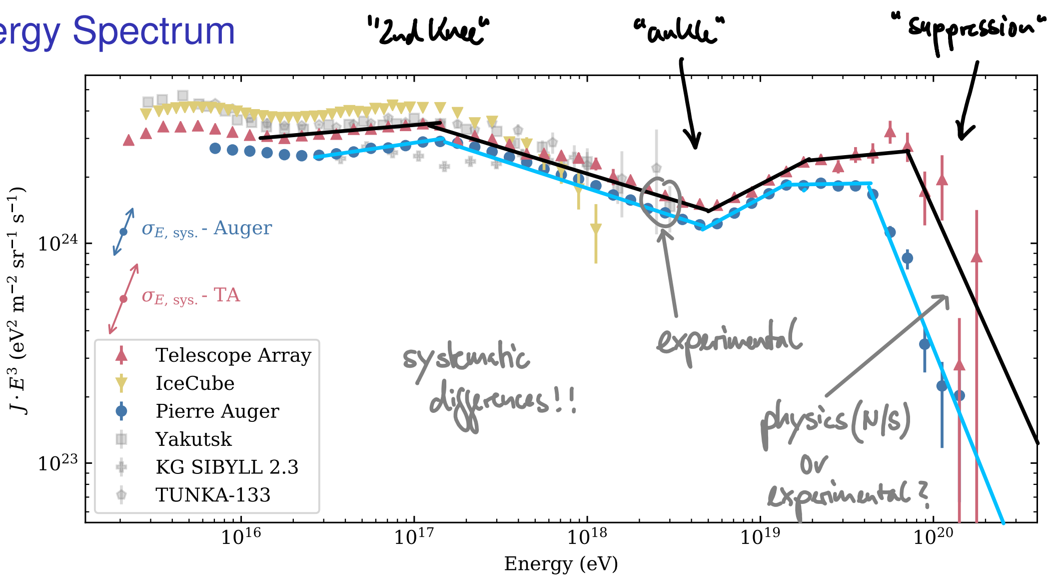


Energy Spectrum



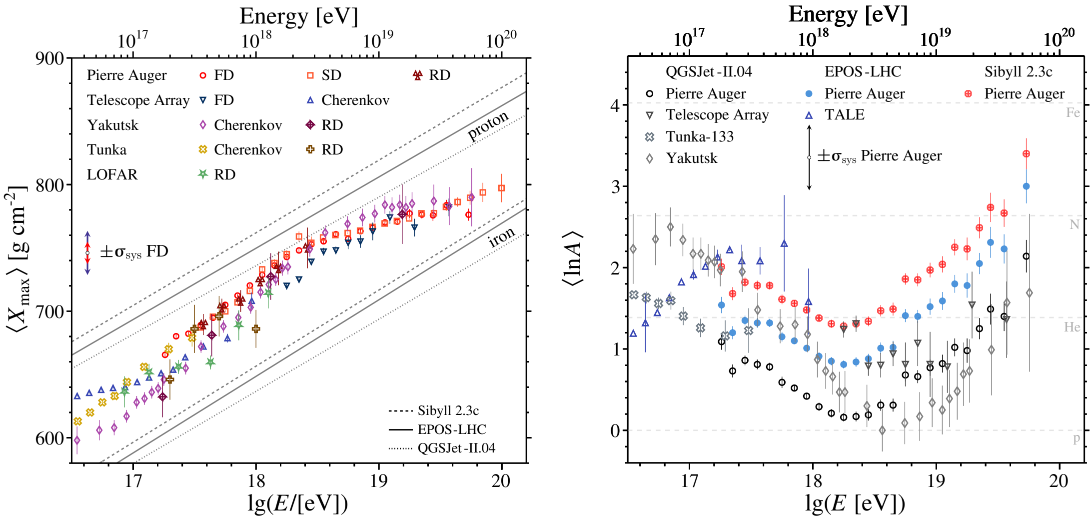
arXiv:2205.0584

Energy Spectrum



arXiv:2205.0584

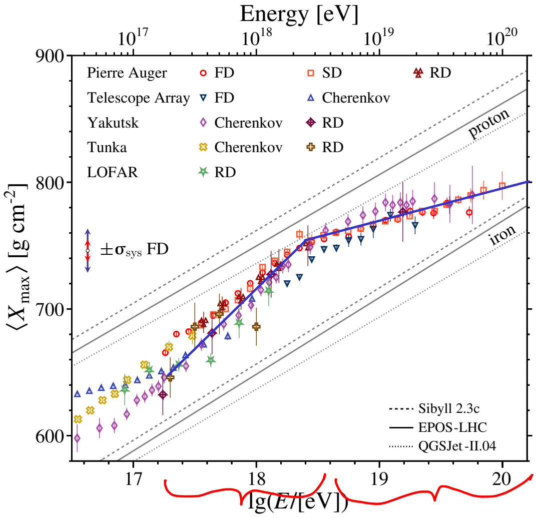
Mass Composition

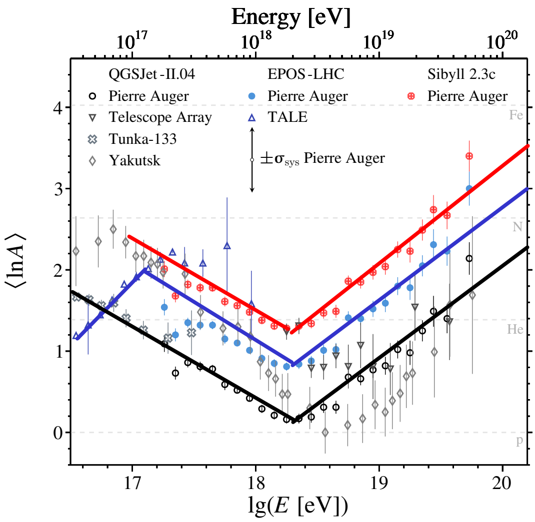


arXiv:2205.0584

Mass Composition

hadronic interactions!





arXiv:2205.0584

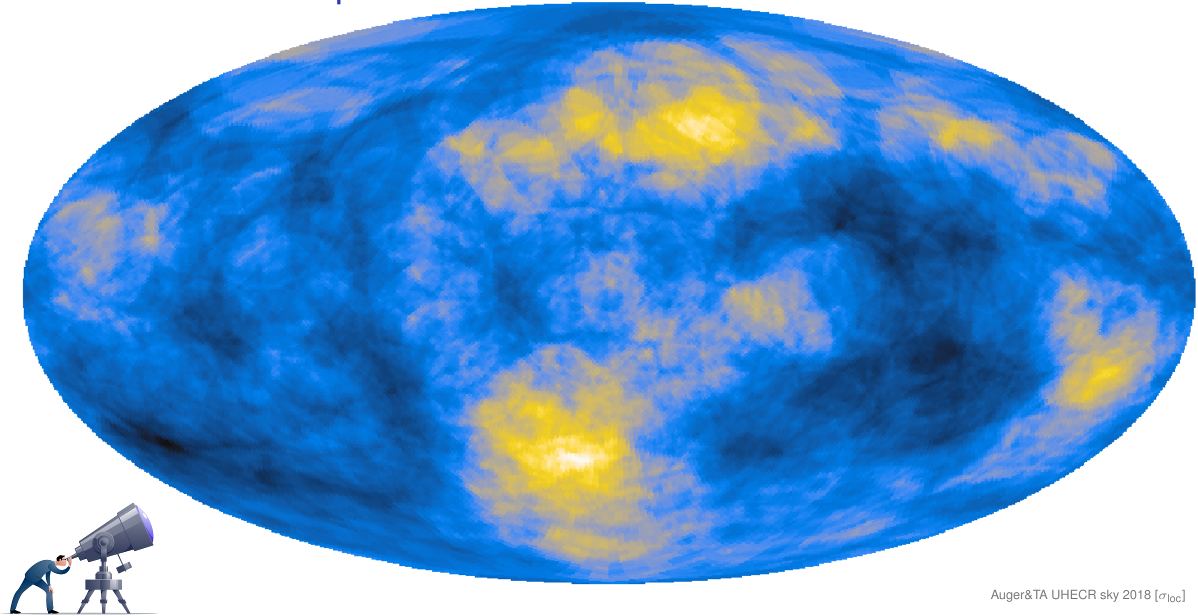
elongation rate $D_{10} > D_{10}^{had}$ $D_{10} < D_{10}^{had}$

$D_{10} = \frac{d\langle X_{max}\rangle}{d\lg E}$ 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_μ)	high	low
fluorescence	E_{em}/X_{max}	$\approx 1/2000\ \mathrm{km}^2$	$\leq 15\%$	high	low	high
radio	E_{em}/X_{max}	1 (E_{em}) … $\gtrsim 100/\mathrm{km}^2$ (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}]

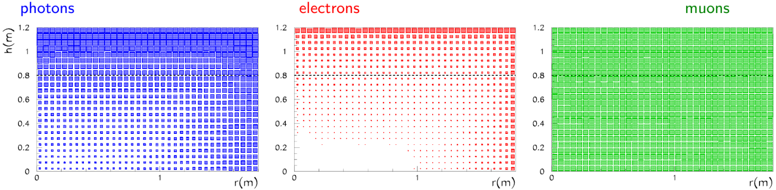
UHECR Detection at Ground?

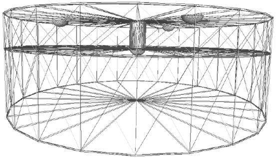
e.g. Global Cosmic-Ray Observatory (GCOS): 2 $\times$ (Auger $\times$ 10) (North and South)

60000 km^2, 2-2.5 km detector spacing, 15-22k stations, threshold 30 EeV

The idea: optical separation of a Water Cherenkov Tank

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





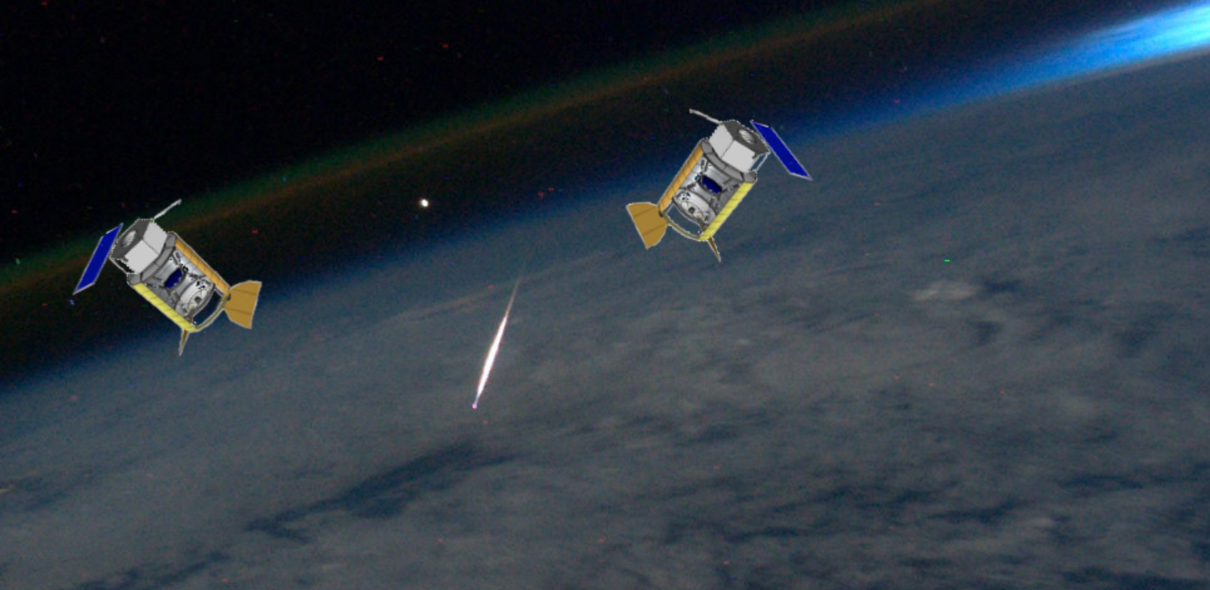
$$\begin{pmatrix} S_{\text{top}} \\ S_{\text{bot}} \end{pmatrix} = \mathcal{M} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix} = \begin{pmatrix} a & b \\ 1-a & 1-b \end{pmatrix} \begin{pmatrix} S_{\text{EM}} \\ S_{\mu} \end{pmatrix}$$

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

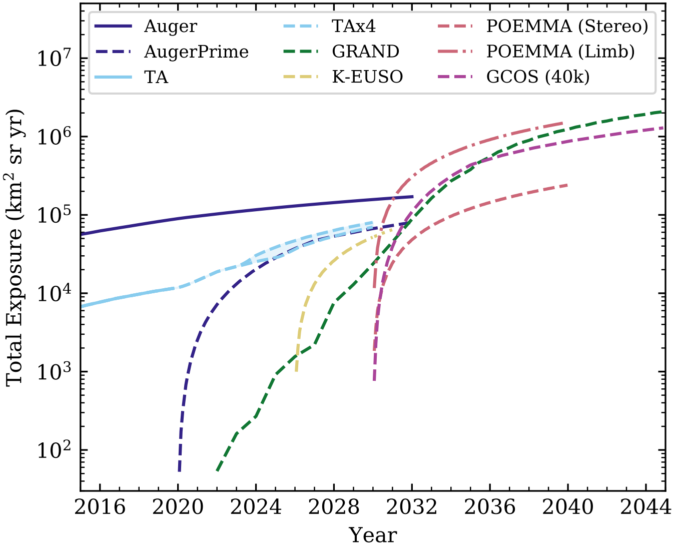
A. Letessier-Selvon, P. Billoir, M. Blanco, I. C. Mariş, M. Settimo

UHECR Detection From Space?

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

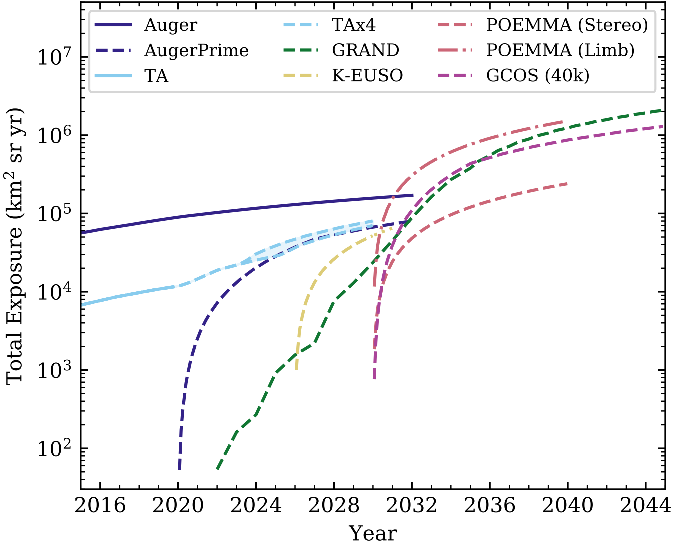


Future UHECR Experiments



arXiv:2205.05845

Future UHECR Experiments



Thanks!

arXiv:2205.05845