Ultrahigh Energy Cosmic Rays

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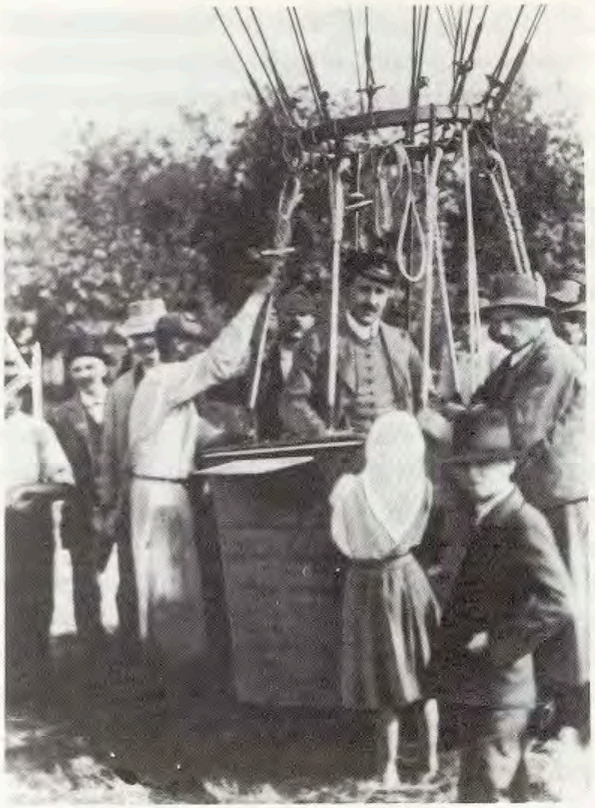
New York University

N3AS
July 20, 2023

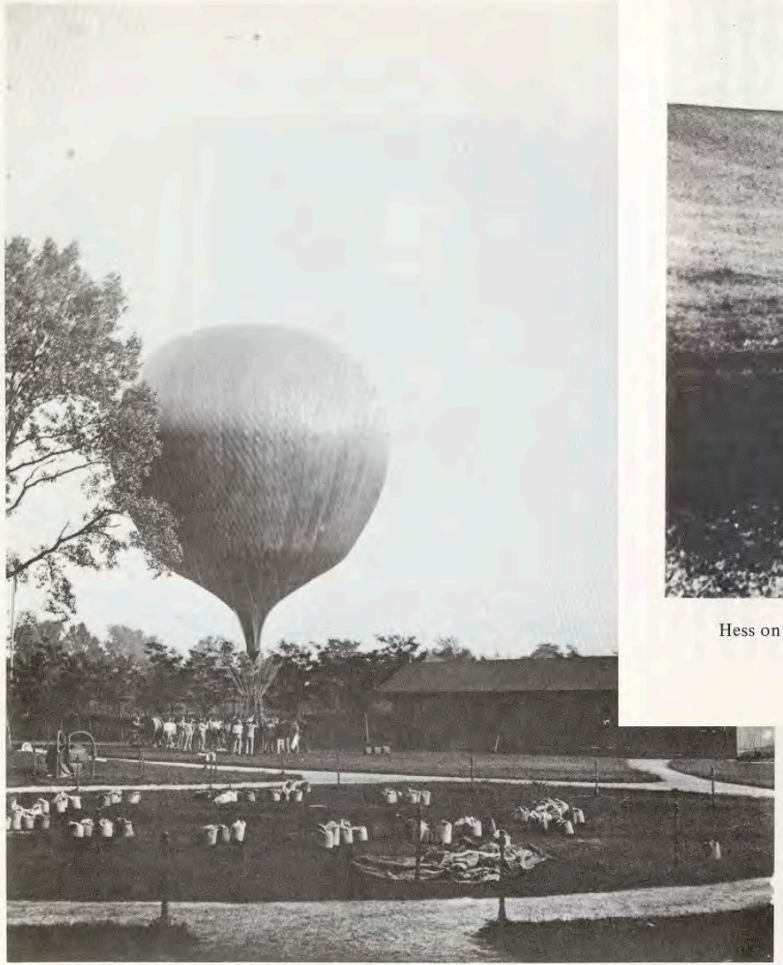
1911-1912
Victor Hess discovers cosmic rays

- Becquerel: Electroscope discharge rate measures ambient radiation.
- Residual radiation in absence of apparent source!
- Hess sets out in hot-air balloon to map fall off of radiation with altitude. Flies to 4880m
  - up to 1 km, flux drops with increasing altitude
  - above 1 km, flux *increases!*

Origin of highest energy cosmic rays still unknown!



Hess bei Ballonlandung (1912).

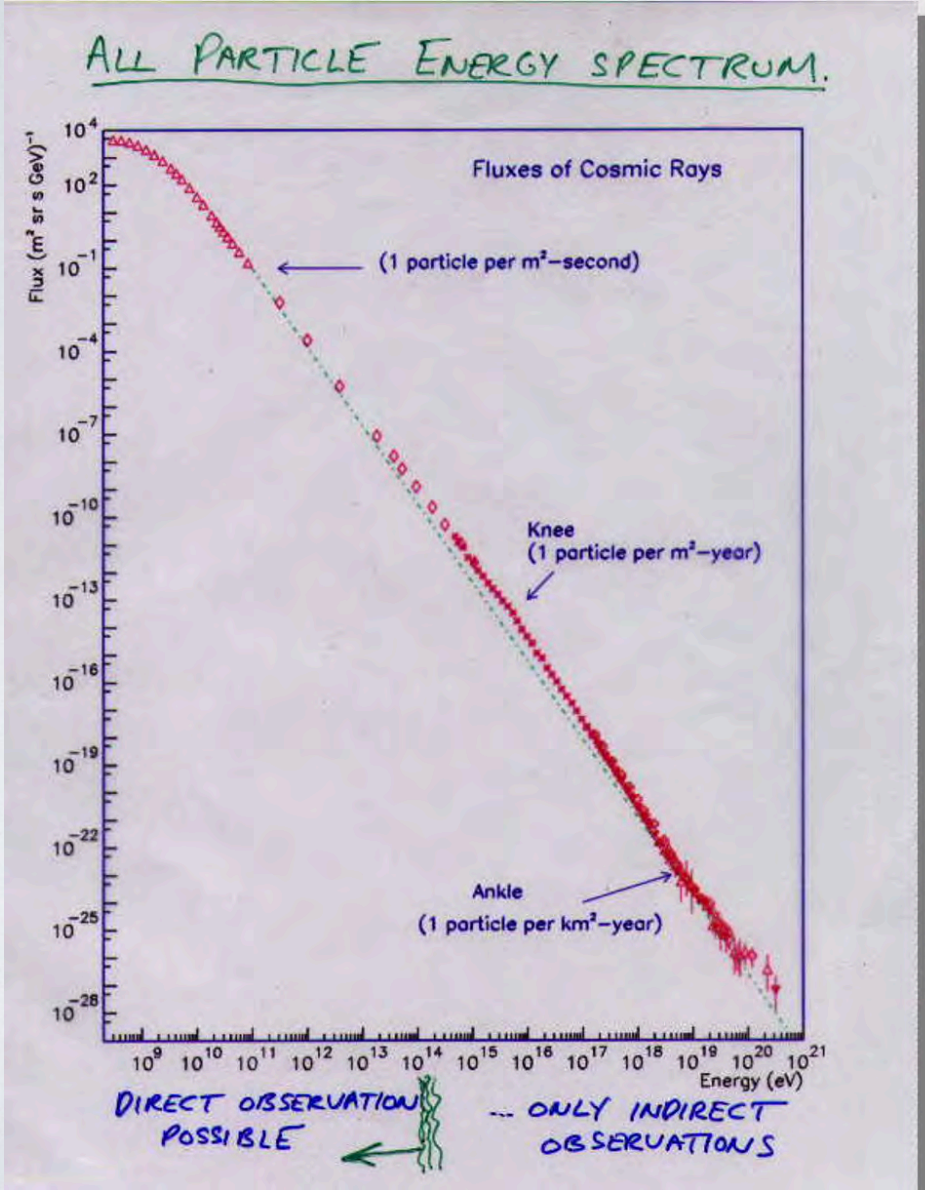


Aeronautisches Gelände im Wiener Prater, von dem aus V. F. Hess in den Jahren 1911/12 seine ersten Freiballon-Forschungsfahrten unternommen hatte. (Courtesy of Heeresgeschichtliche Museum, Vienna)

<Ed> Contributed by R. Steinmaurer. See p. 17.

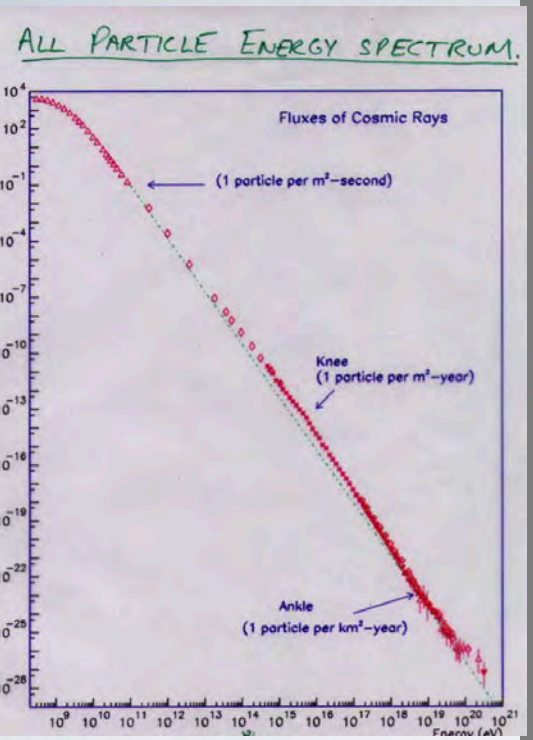
Hess on gondola in 1912 probably in test flight. The date and place is not clear at present.

<Ed> Contributed by R. Steinmaurer. See p. 17.



Cosmic Rays

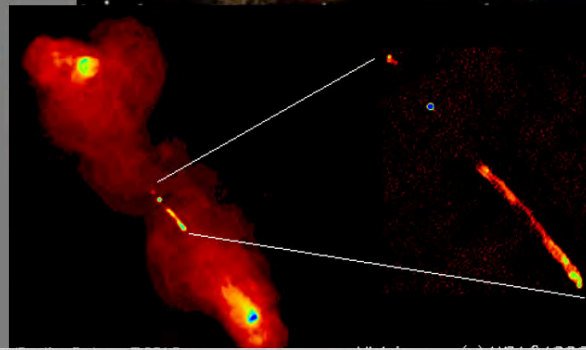
- 32 decades of flux
- 12 decades of energy
- Highest energy particles ever observed:
  - 10^8 times higher energy than LHC beams
  - E_{CM} of collision with air nucleus is ~ 100 times higher than at the LHC.



- Low energy CR's: from sun

- Medium energy: Milky Way
  - accelerated in supernovae remnants (Fermi mechanism)
  - Confined by Galactic magnetic field
    Larmour radius = 1 $E_{18}/(Z\ B_{\mu G})$ kpc

- High energy: Extragalactic
  - What are they? (protons, nuclei,…)
  - What are their sources?
  - How are they accelerated?



UHECR Trivia

- 200 EeV = 2 10^{20} eV: Kinetic Energy of golf ball, in an single particle.
- Speed = 0.99999999999999999999 c
- Relativistic time dilation $\gamma \sim 10^{11}$ => neutron lives ~ million years, instead of 15 minutes if at rest.
- Bending by magnetic fields decreases with energy => potential for UHECR astronomy.
- Very rare: ~ 1 per square kilometer, *per century*

What we know about UHECRs:

- No single (apparent) dominant source (or source class ???)
- Complex composition (nuclei from p to Fe)
- Highest energy Galactic CRs overlap in energy the lowest energy (extragalactic) UHECRs

✦ Acceleration, propagation and interactions near source, all shape the spectrum

- Multi-messenger approach will be essential

What we WANT TO know:

- Are sources <u>weak and abundant</u> or <u>strong and rare</u>?
- What are the principal source types?
  - Sources may not all be visible today (e.g., transients)
- What are the sources' spectra and composition?
  - Are UHECR sources (approximately) standardized?
- Better knowledge of magnetic fields

Many topics to discuss…

- Observational methods and data
- Complexities of interpreting measurements
  - Air showers depend on UHE particle physics
  - Arrival direction ≠ source direction due to magnetic deflections
- Key results from UHECR observations, so far
- Multimessenger approach: also use neutrinos & gamma rays
- Acceleration mechanisms & possible sources

UHECR Hybrid Observatories

V.Versi, UHECR22

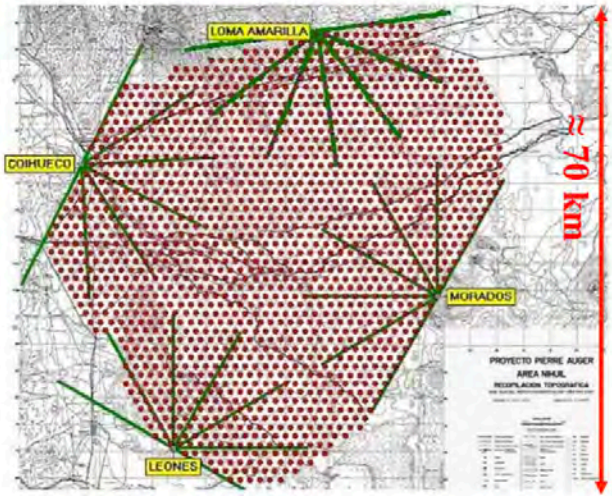
PIERRE AUGER OBSERVATORY

Malargüe Mendoza (Argentina)
35^0 S latitude

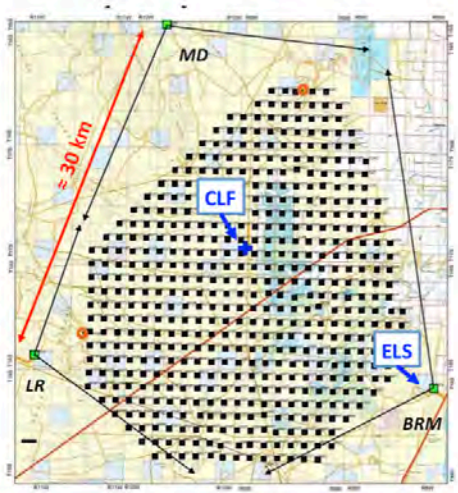
3000 km^2

1660 WCDs
1500 m spacing
triangular grid

4 FD sites



TELESCOPE ARRAY



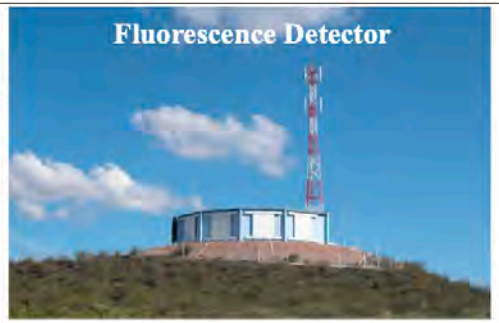
Millard County
Utah (USA)
39^0 N latitude

700 km^2

507 scintillators
1200 m spacing
square grid

3 FD sites

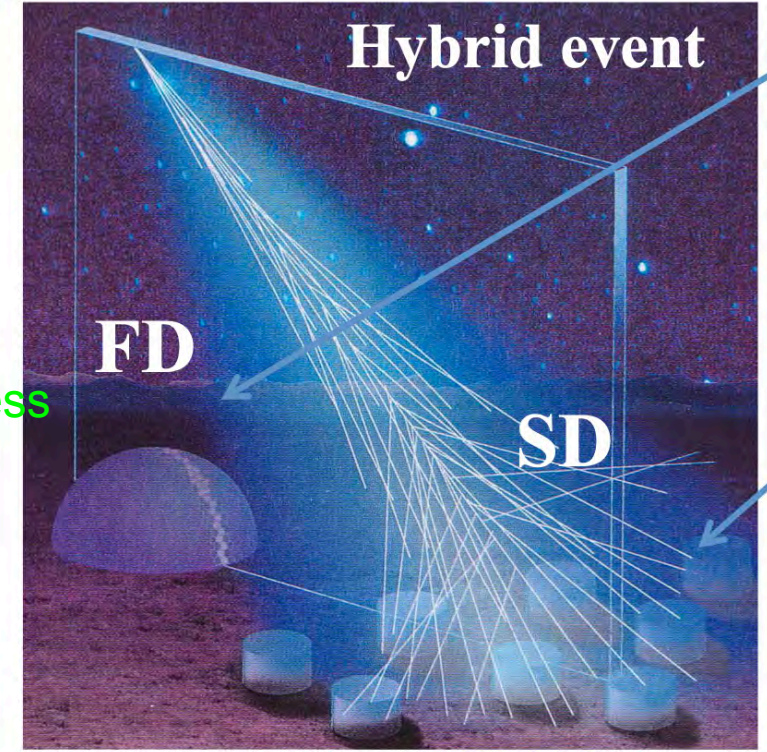
WCD = water Cherenkov detector; FD = fluorescence detector



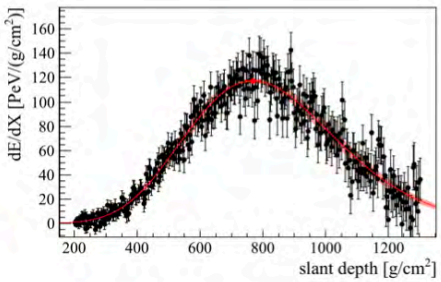
The hybrid detection technique

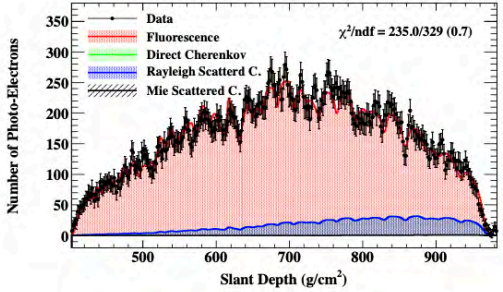
15% duty cycle

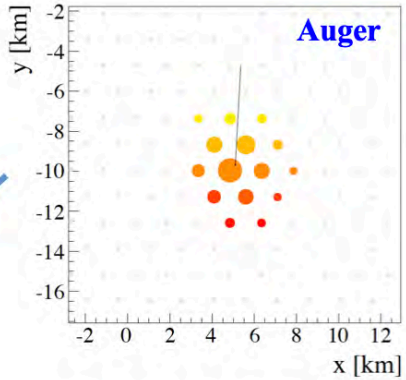
moonless nights

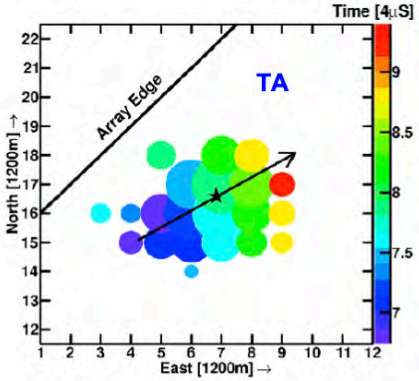


100% duty cycle







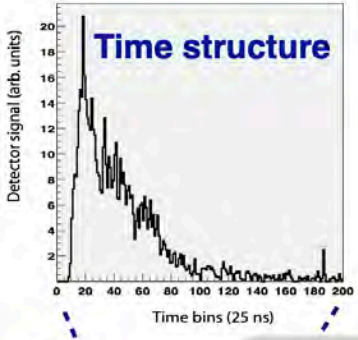


UHECR spectrum

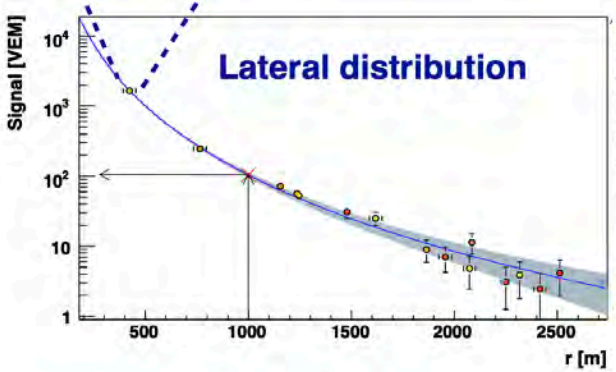
- **high efficiency of SD**
- **calorimetric energy scale from FD**

V.Versi, UHECR22

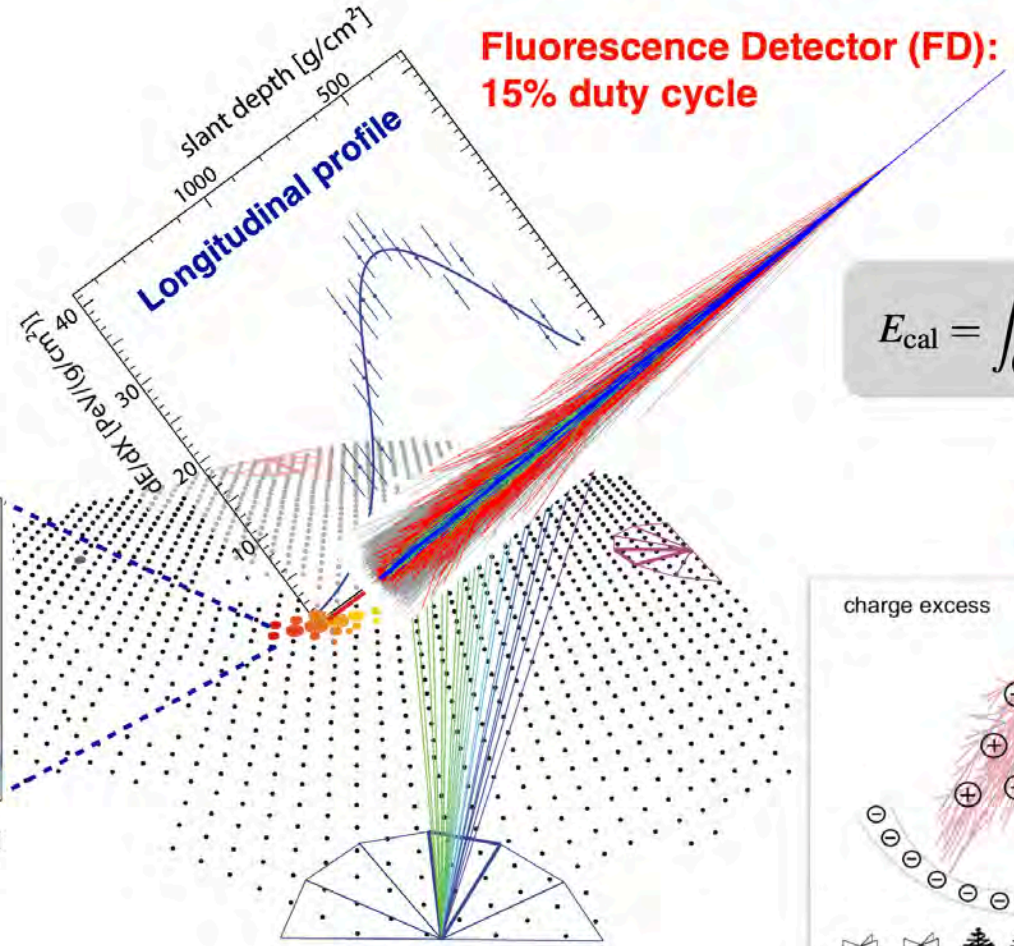
Air shower observables (hybrid observation)



$$E_{\mathrm{rec}} = f(S_{1000}, \theta)$$



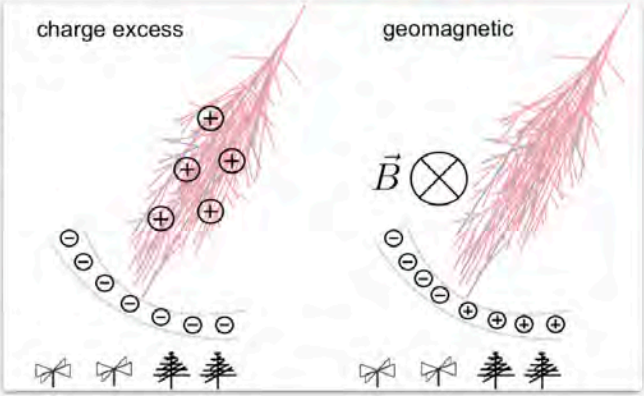
Surface Detector (SD)
100% duty cycle



Fluorescence Detector (FD):
15% duty cycle

$$E_{\mathrm{cal}} = \int_0^{\infty} \left(\frac{\mathrm{d}E}{\mathrm{d}X}\right)_{\mathrm{obs}} \mathrm{d}X$$

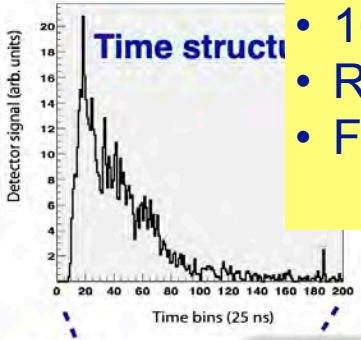
Radio Detector (RD):
100% duty cycle



Air shower observables (hybrid observation)

Key components of UHECR observatory:

- 1600 (ea) Water Cherenkov & Scintillator Detectors, 1.5 km spacing (100%)
- Radio (100%, best for large zenith angle)
- Fluorescence Detector ➜ Longitudinal profile (15%)



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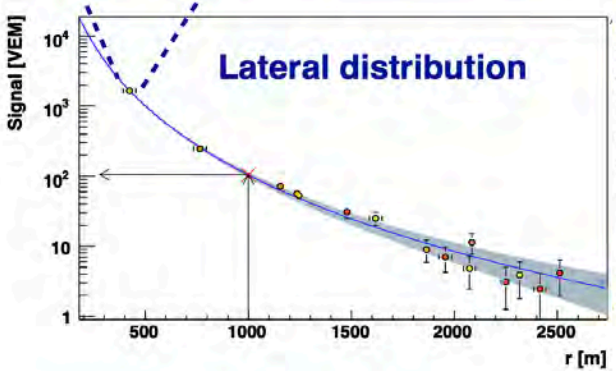
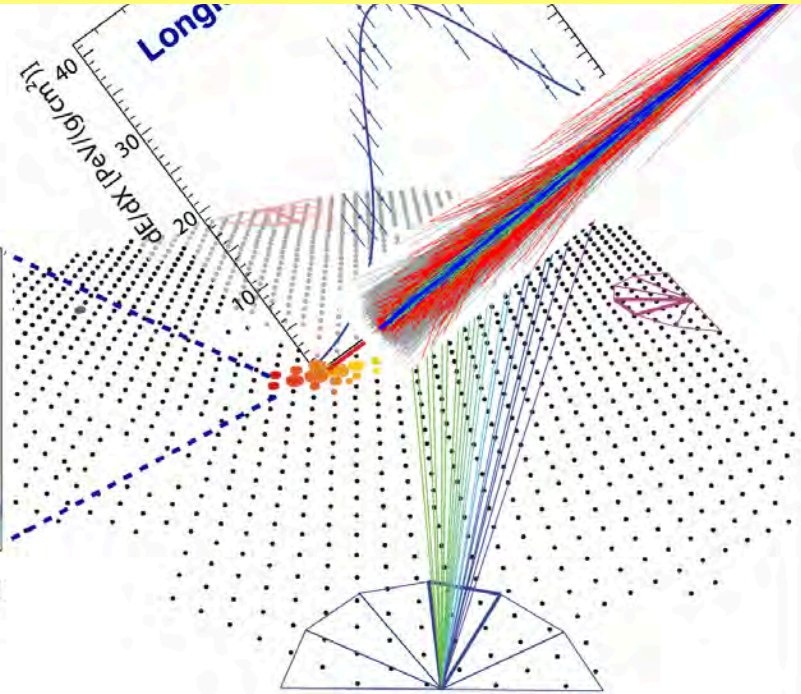


Surface Detector (SD)
100% duty cycle



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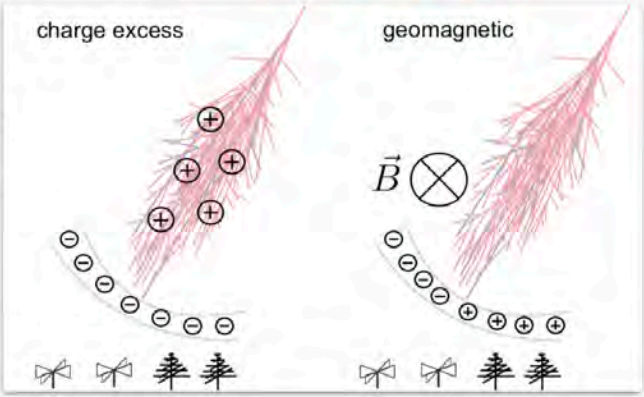
Radio Detector (RD):
100% duty cycle



R. Engel, CRMME22

UHECRs: Facts to remember

- Mixed composition, evolves with energy
- Upper limit on energy mainly from accelerator(s) — not GZK
- Sources apparently abundant rather than few & powerful

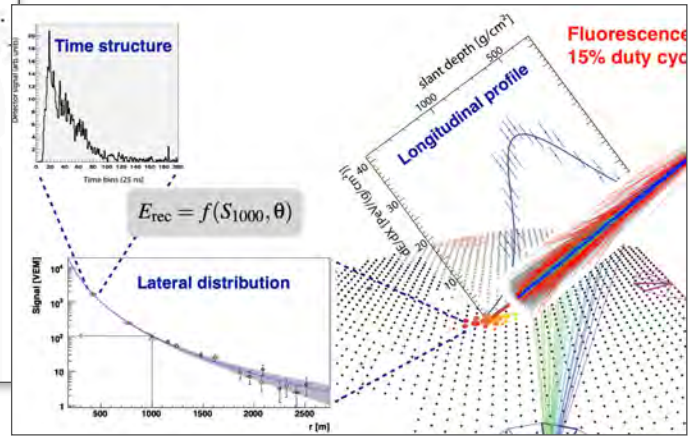
Air shower development & X_{max}

e.g. 50 EeV = 5×10^{19} eV = $5\ 10^{10}$ GeV ; $A \sim 20 \rightarrow E/A \sim 25\times10^{8}$ GeV

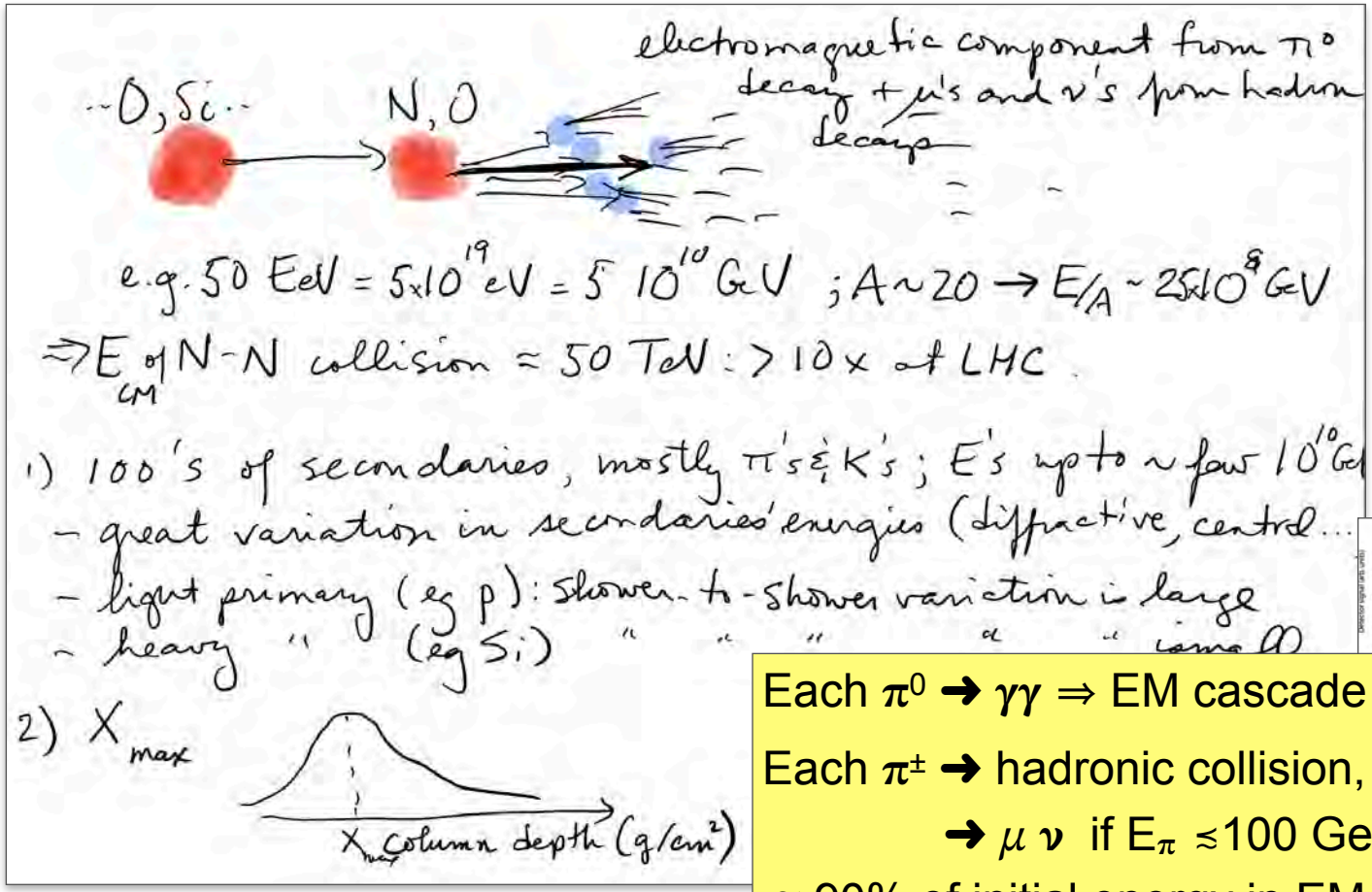
$\Rightarrow E_{CM}$ of N-N collision ≈ 50 TeV : > 10x at LHC

1) 100's of secondaries, mostly π's & K's ; E's up to ~ few 10^{10} GeV
- great variation in secondaries' energies (diffractive, central...
- light primary (eg p): shower-to-shower variation is large
- heavy " (eg Si) " " " " " small

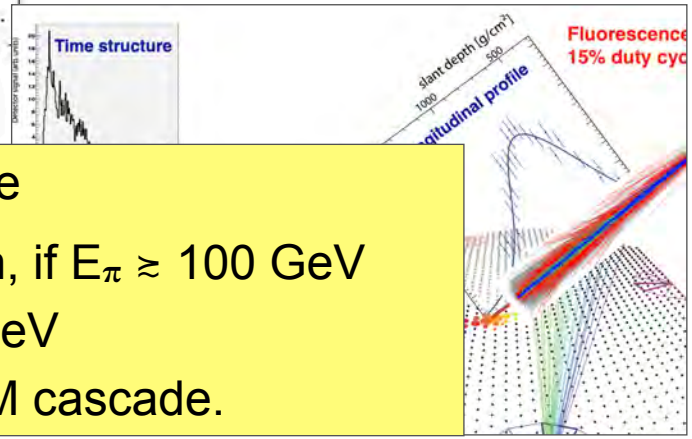
2) X_{max}



Air shower development & X_{max}



- Integrated long. profile ➜ E_{tot}
- X_{max}:
  - deep: light
  - shallow: light *or* heavy
  - variation "σ(X_{max})"
    - large: light or mixed composition
    - narrow:
      - small range of A; heavy



Each π^0 ➜ $\gamma\gamma$ ⇒ EM cascade

Each $\pi^\pm$ ➜ hadronic collision, if $E_\pi \gtrsim 100$ GeV

➜ $\mu\,\nu$ if $E_\pi \lesssim 100$ GeV

≈ 90% of initial energy in EM cascade.

Air shower development & X_{max}

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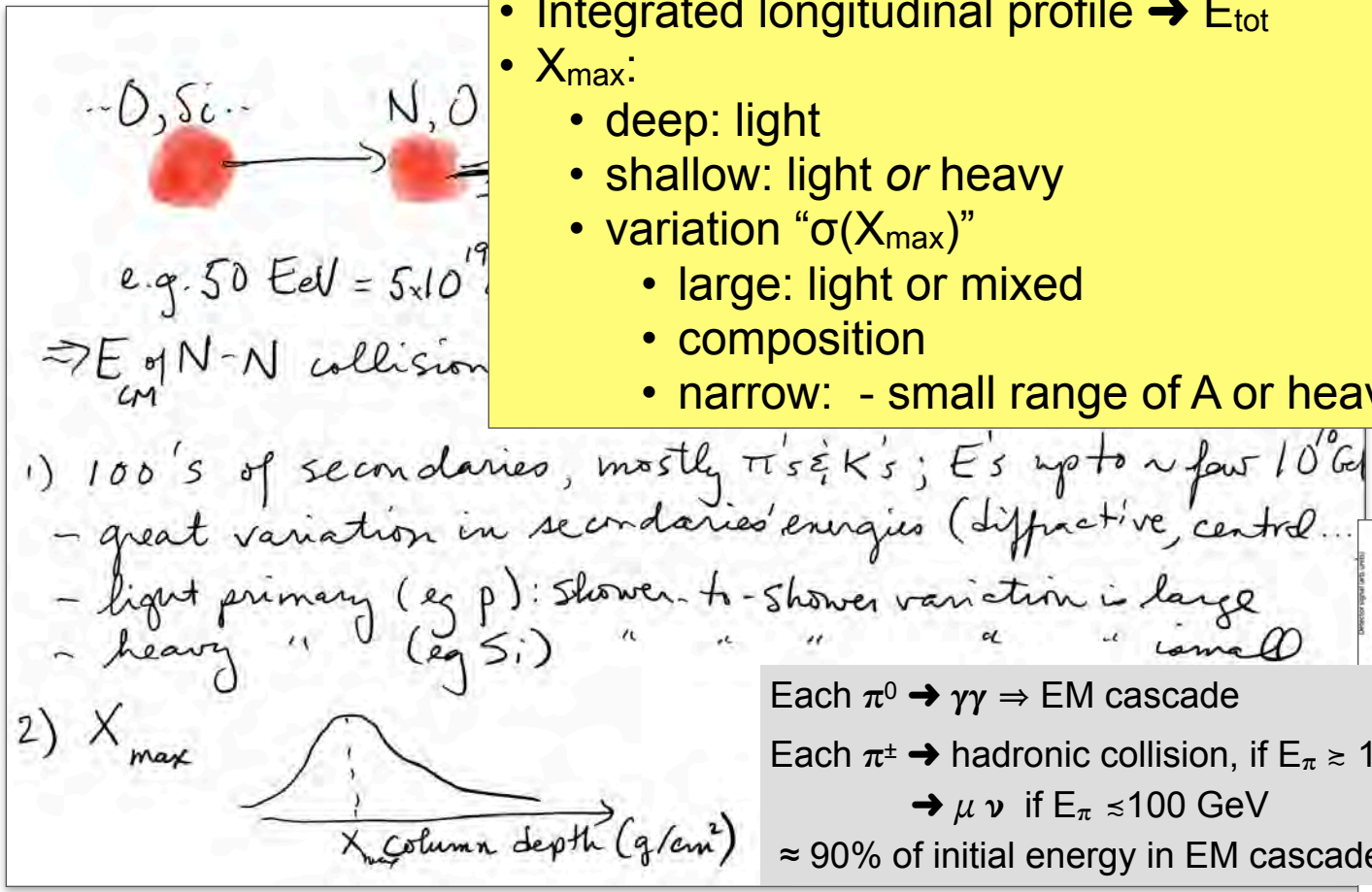

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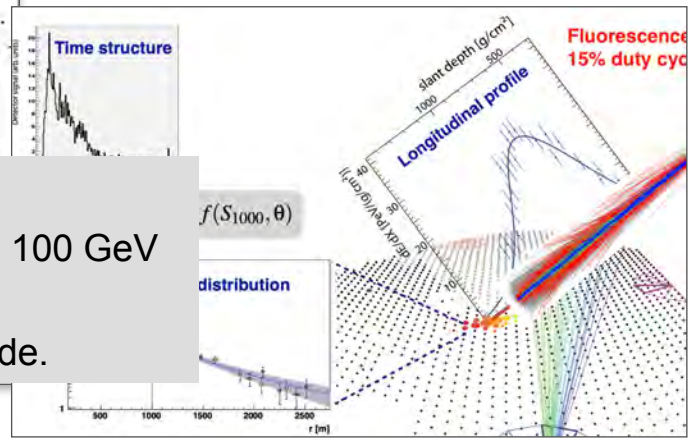


Energy Spectrum

- ✦ Upper limit on energy comes mainly from accelerator(s)
  - ✦ Peak rigidity R (≡ E/Z) ≈ 5 EV (70 EeV Si, 35 EeV N)
- <u>Distinct features emerging in spectrum</u>
- <u>Auger and TA agree within uncertainties</u> (Auger has ~5x statistics and direct energy calibration; less reliance on modeling)
- Highest energy Galactic CRs overlap the lowest energy extragalactic UHECRs

The energy scale depends on Air Fluorescence Yield

AUGER

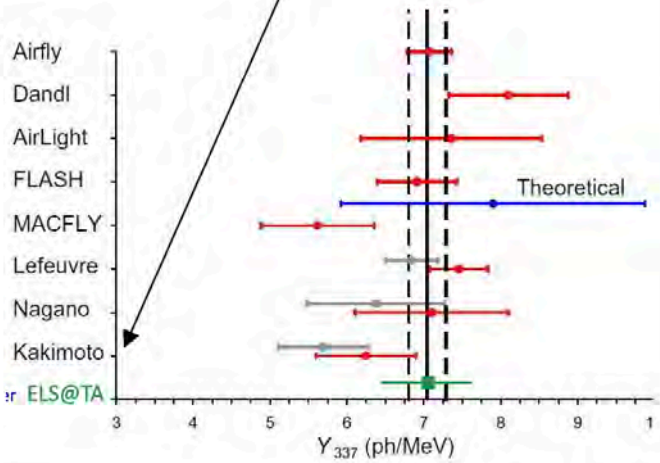
Proc. 34 ICRC 2013 (Rio de Janeiro, Brazil)
[arXiv:1307.5059]

Absolute fluorescence yield	3.4%
Fluores. spectrum and quenching param.	1.1%
Sub total (Fluorescence Yield)	**3.6%**
Aerosol optical depth	3% ÷ 6%
Aerosol phase function	1%
Wavelength dependence of aerosol scattering	0.5%
Atmospheric density profile	1%
Sub total (Atmosphere)	**3.4% ÷ 6.2%**
Absolute FD calibration	9%
Nightly relative calibration	2%
Optical efficiency	3.5%
Sub total (FD calibration)	**9.9%**
Folding with point spread function	5%
Multiple scattering model	1%
Simulation bias	2%
Constraints in the Gaisser-Hillas fit	3.5% ÷ 1%
Sub total (FD profile rec.)	**6.5% ÷ 5.6%**
Invisible energy	**3% ÷ 1.5%**
Statistical error of the SD calib. fit	**0.7% ÷ 1.8%**
Stability of the energy scale	**5%**
TOTAL	**14%**

TA

Proc. 32nd ICRC 2011 (Beijing, China), 12, 67 (2011)
Astropart.Phys. 61 (2015) 93-101

Item	Error (%)	Contributions
Detector sensitivity	10	PMT (8%), mirror (4%), aging (3%), filter (1%)
Atmospheric collection	11	aerosol (10%), Rayleigh (5%)
Fluorescence yield	11	model (10%), humidity (4%), atmosphere (3%)
Reconstruction	10	model (9%) missing energy (5%)
Sum in quadrature	21	



Auger uses Airfly
Astrop. Phys. 42. 90 (2013)
Astrop. Phys. 28, 41 (2007)

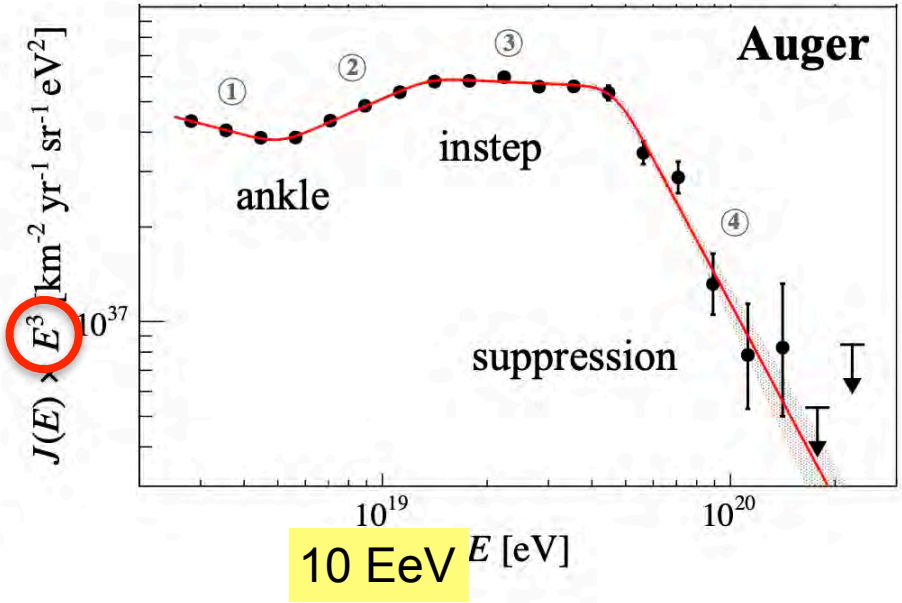
figure from M. Fukushima, GCOS workshop 2022

TA uses Kakimoto et al. NIM-A 372, 527 (1996) +FLASH spectrum

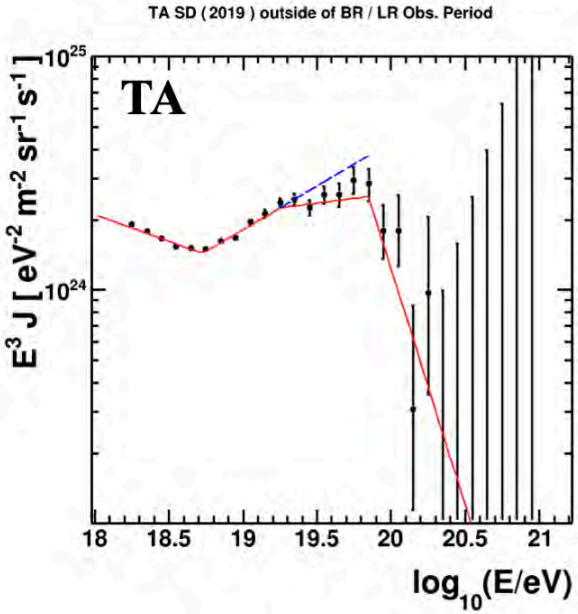
TA 21% Auger 14% both almost energy independent

Spectrum measured

at the two observatories



10 EeV



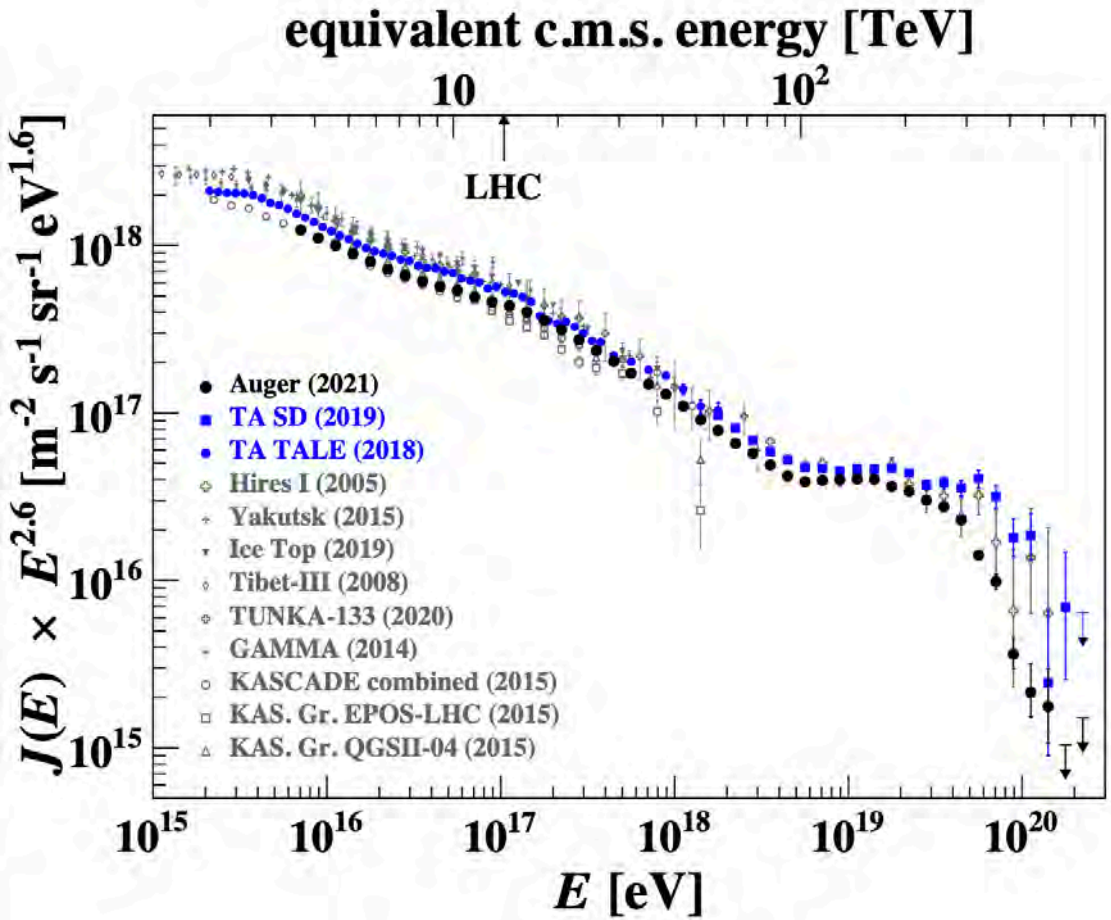
Auger, Phys. Rev. D 102 (2020) 062005
TA, PoS (ICRC2019) 298
see also WG report PoS (ICRC2021) 337

Parameter	Auger	TA
γ_1	3.29 ± 0.02	3.23 ± 0.01
γ_2	2.51 ± 0.03	2.63 ± 0.02
γ_3	3.05 ± 0.05	2.92 ± 0.06
γ_4	5.1 ± 0.3	5.0 ± 0.4
$E_{\rm ankle}$/EeV	5.0 ± 0.1	5.4 ± 0.1
$E_{\rm instep}$/EeV	13 ± 1	18 ± 1
$E_{\rm cut}$/EeV	46 ± 3	71 ± 3

- **same characterization of the spectral features**
- **agreement at the ankle and some tension at highest energies**
- **common declination band to disentangle astrophysical from experimental effects: $-15^o < \delta < 24.8^o$**

V. Versi, UHECR22

The joint Auger TA working group on energy spectrum



Understand the difference among the measurements at the UHEs:

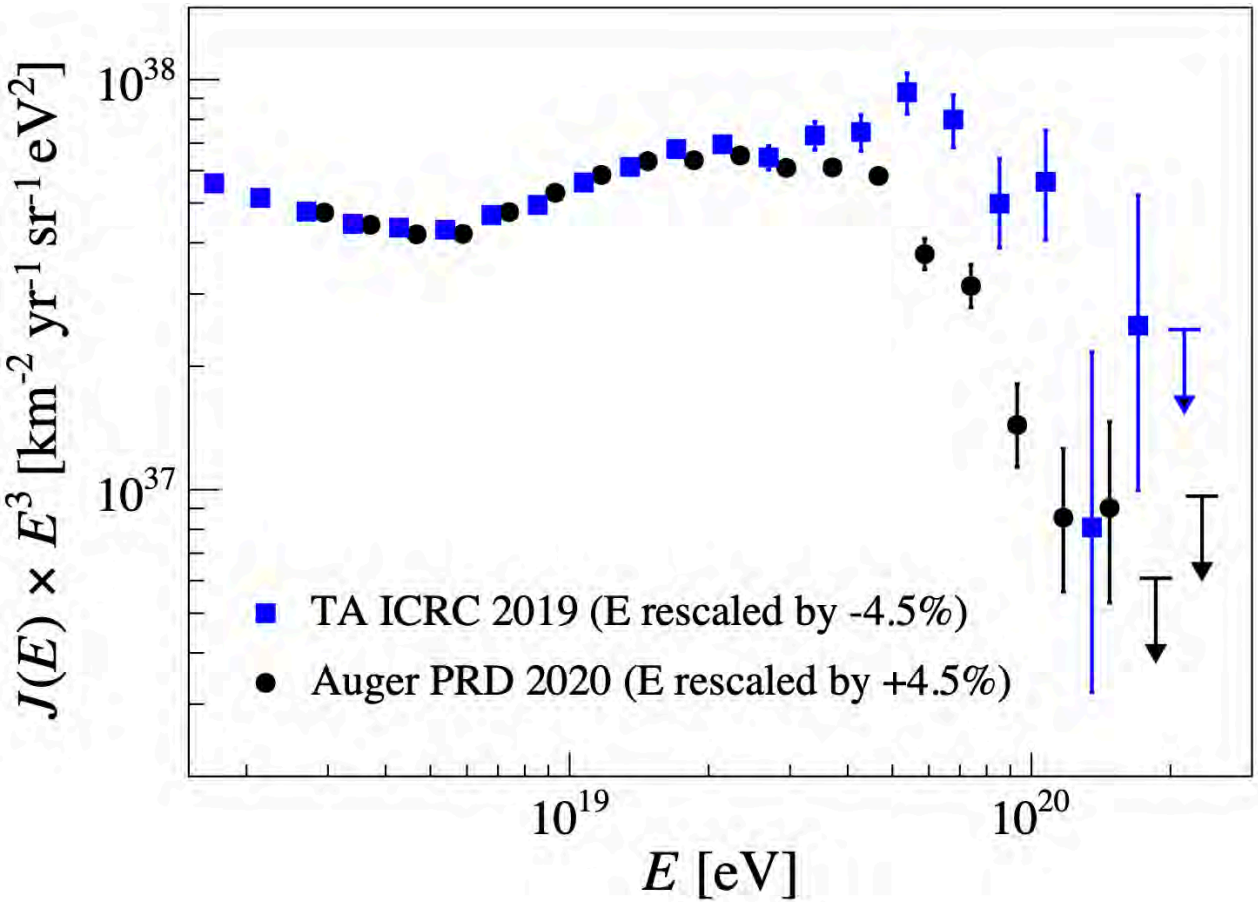
- **information on astrophysical phenomena**
- **correct combination of the data to achieve the full sky coverage**

see F. Urban at this conference

UHECR 2010	Nagoya, Japan
UHECR 2012	Cern, Geneva
UHECR 2014	Springdale (Utah), USA
UHECR 2016	Kyoto, Japan
ICRC 2017	Busan, Korea
UHECR 2018	Paris, France
ICRC 2019	Madison, USA
ICRC 2021	Berlin, Germany

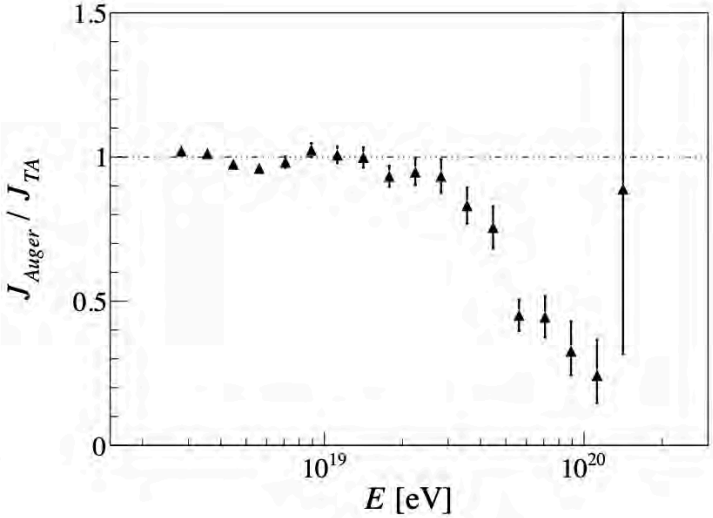
V. Versi, UHECR22

Measurements in the full sky



good agreement up to ≈ 10^{19} eV after an overall 9% rescaling of the energies

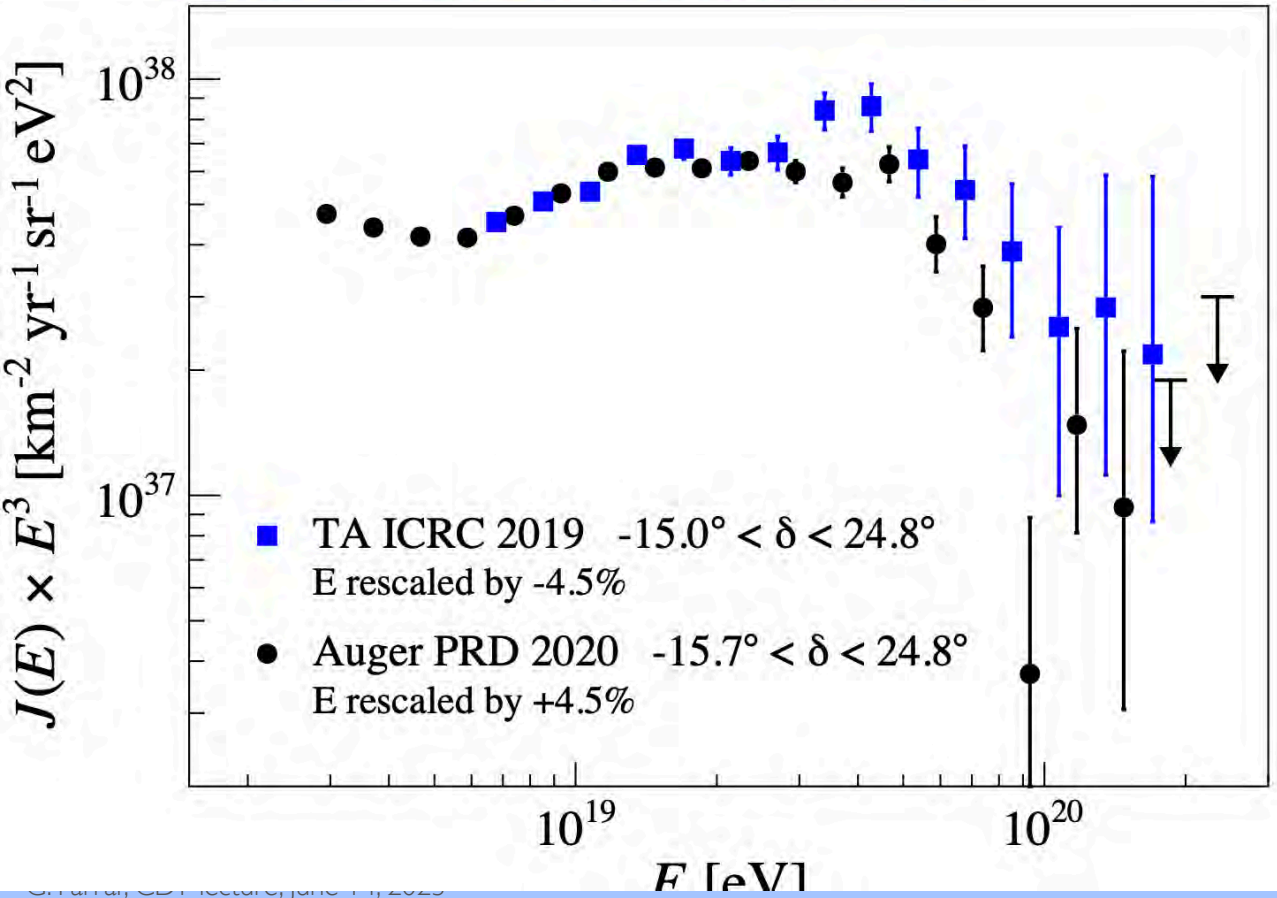
significant discrepancy at the highest energies



V.Versi, UHECR22

Measurements in the common declination band

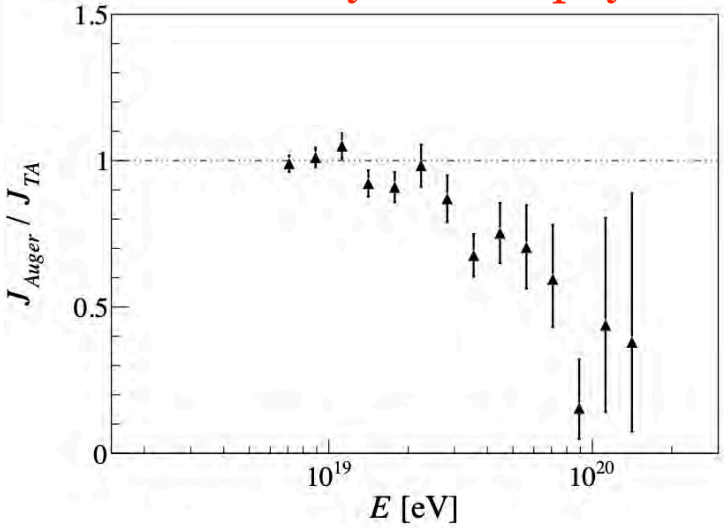
note: TA full trigger efficiency $E>10^{18.8}$ eV



Low energy discrepancy resolved by common fluorescence yield & invisible energy

discrepancy at the highest energies persists in the common declination band

➜ spectrum discrepancy ≳30EeV; cannot mostly be astrophysical



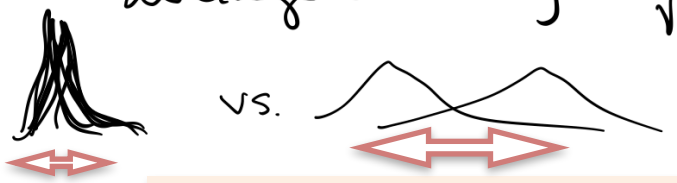
Composition

- <u>Composition becomes heavier with energy</u>
- <u>TA & Auger observations agree</u>
- Interpreting data to infer actual composition requires UHE air shower modeling

COMPARE Fe & p shower development

Fe vs p:

- $\sigma_{Fe\text{-}air} \sim (56)^{2/3} \times \sigma_{p\text{-}Air}$ $\Rightarrow$ shower starts sooner
- E_{Fe} is shared among 56 nucleons $\Rightarrow$ fluctuations averaged out by $\sim \frac{1}{\sqrt{56}}$



"GZK" energy loss:

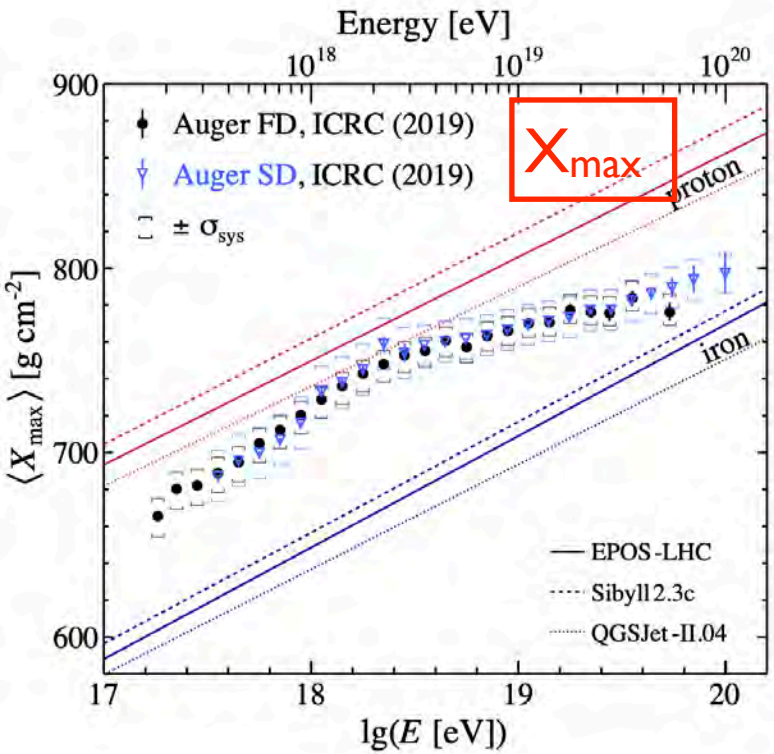
① $p + \gamma_{CMB} \Longleftrightarrow \gamma p \to \Delta^+ \to \pi p$ at ~ 1.2 GeV cm

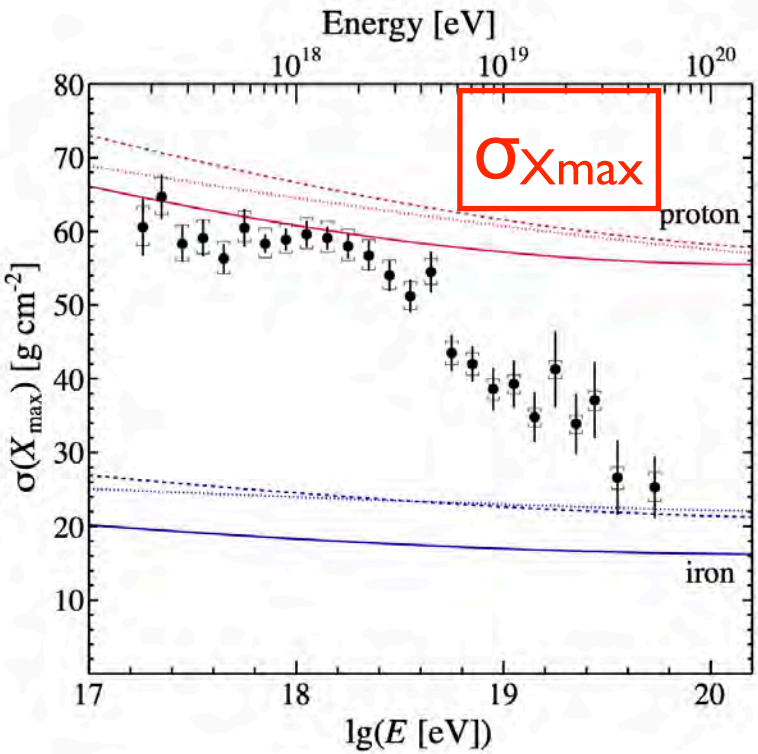
← less energy

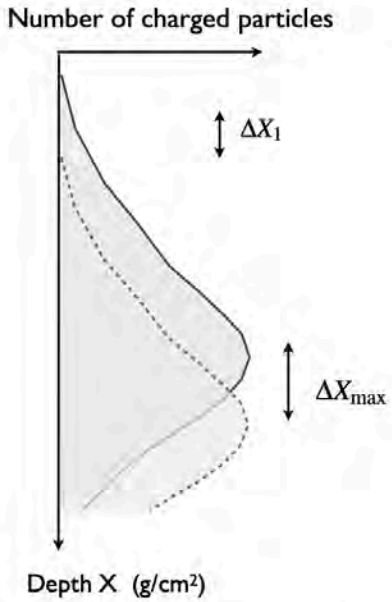
② $A + \gamma_{CMB} \Longleftrightarrow \gamma + A \to (A-1) + p$, $A-2+d$, etc.

final nucleus has less energy

Mass composition results (i)







$$\frac{dP}{dX_1} = \frac{1}{\lambda_{int}} e^{-X_1/\lambda_{int}}$$

$$\sigma_{X_1,p} \sim 45 - 55\,\mathrm{g/cm^2}$$
$$\sigma_{X_1,Fe} \sim 10\,\mathrm{g/cm^2}$$

$(E \sim 10^{18}\,\mathrm{eV})$

Important: LHC-tuned interaction models used for interpretation

(Phys. Rev. D90 (2014), 122005 & 122005, updated ICRC 2019) *(Phys. Rev. D96 (2017), 122003)*

TA measurement of composition is consistent with Auger's

Testing the Compatibility of the Depth of the Shower Maximum Measurements performed at Telescope Array and the Pierre Auger Observatory

Auger-TA Mass Composition Working Group Report

D.R. Bergman, J. Bellido, V. de Souza, R. Engel, Z. Gerber, J.H. Kim, E. Mayotte, O. Tkachenko, M. Unger, A. Yushkov for the TA and Auger collaborations

Conclusion

We have constructed a representation of Auger X_{max} measurements as would have been seen in the TA detector using the Sibyll 2.3d high-energy interaction model.

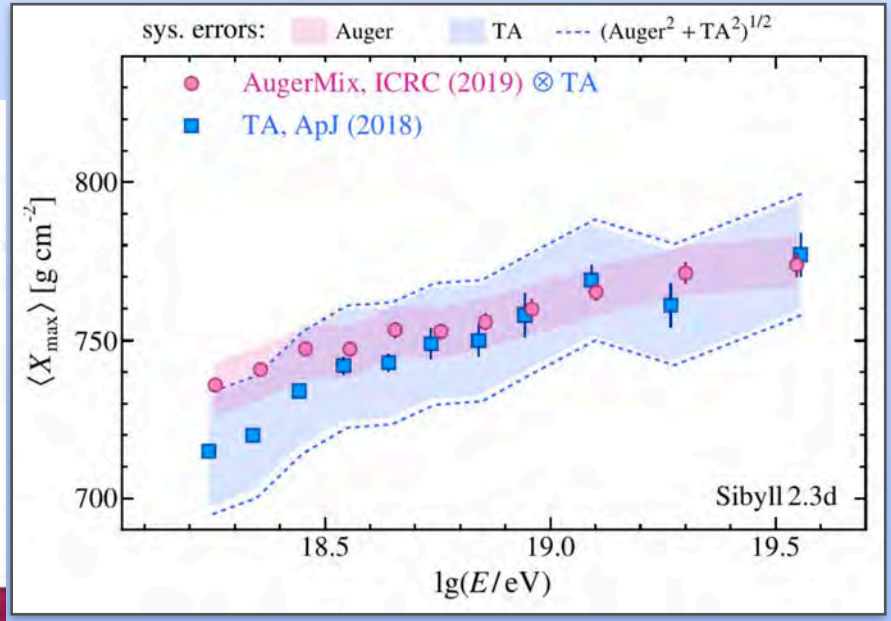
This representation agrees with TA $<X_{max}>$ measurements well, but there is disagreement at some energies in $\sigma(X_{max})$. This disagreement is plausibly due to the handling of X_{max} resolution due to varying aerosols at TA

A robust difference between the Auger and TA X_{max} measurements **has not been found**

A journal publication from the Mass Composition Working Group is forthcoming

Earlier differences due to:

- TA reliance on simulations
- low statistics
- sensitivity to shower modeling



UHECR air shower modeling

- Leading models: Sibyll23.d and EPOS-LHC [also QGSJET]
- Tuned to LHC-data
- Discrepancies describing UHE air showers (10x greater CM energy; not p-p: UHECR + air nucleus, then pi's,etc + air)
  - ~30% more muons observed than models predict
  - predicted $\langle X_{max} \rangle \sim 1\sigma$ too deep
  - muon production depth,…

➜ Composition may be somewhat heavier than current models