Scintillation Detectors of AugerPrime

Event Reconstruction and Data Analysis of First Prototypes

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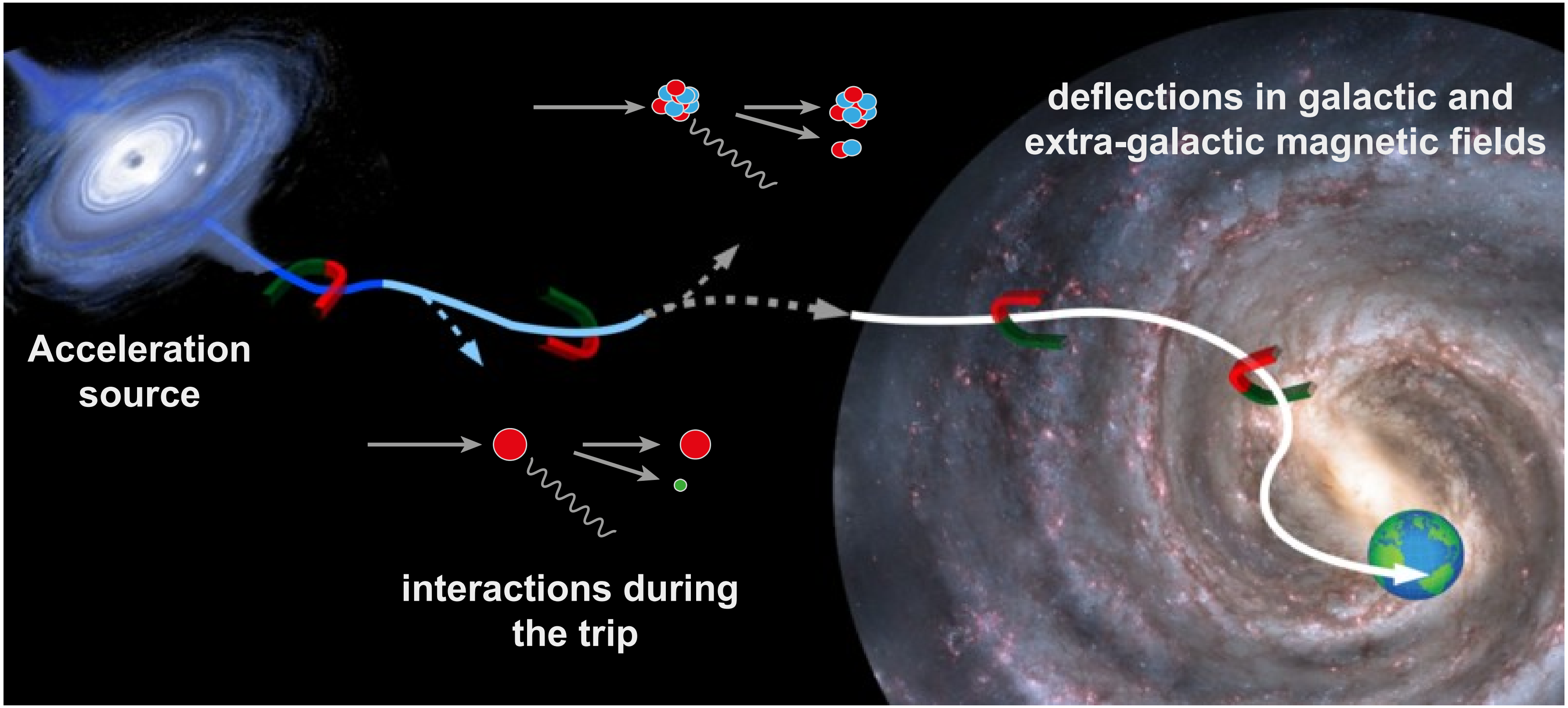
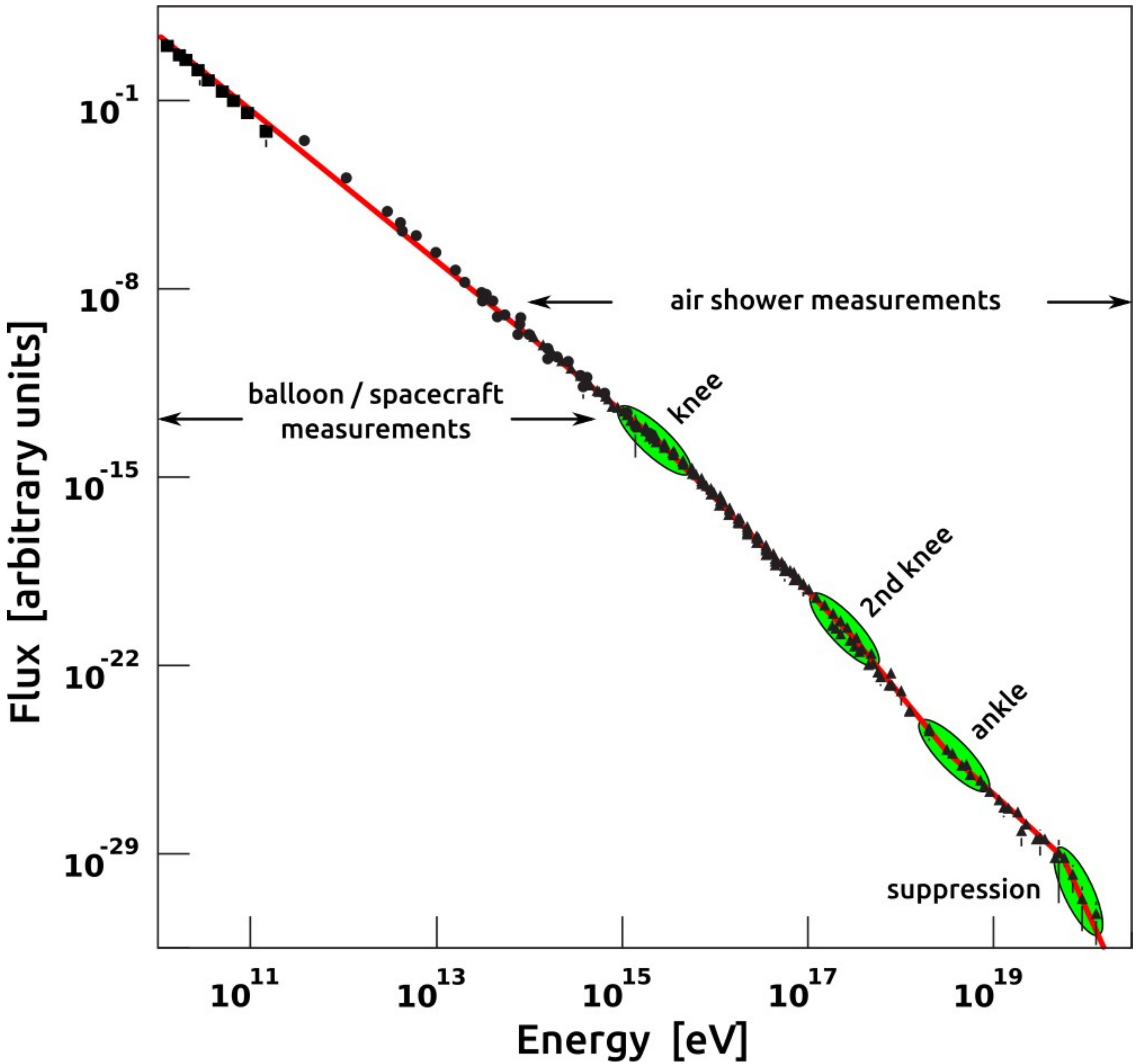
Ultra-high-energy cosmic rays



- What are the **sources**?
- How do they **propagate**?
- What is their **mass composition** on Earth?

Spectrum of cosmic rays



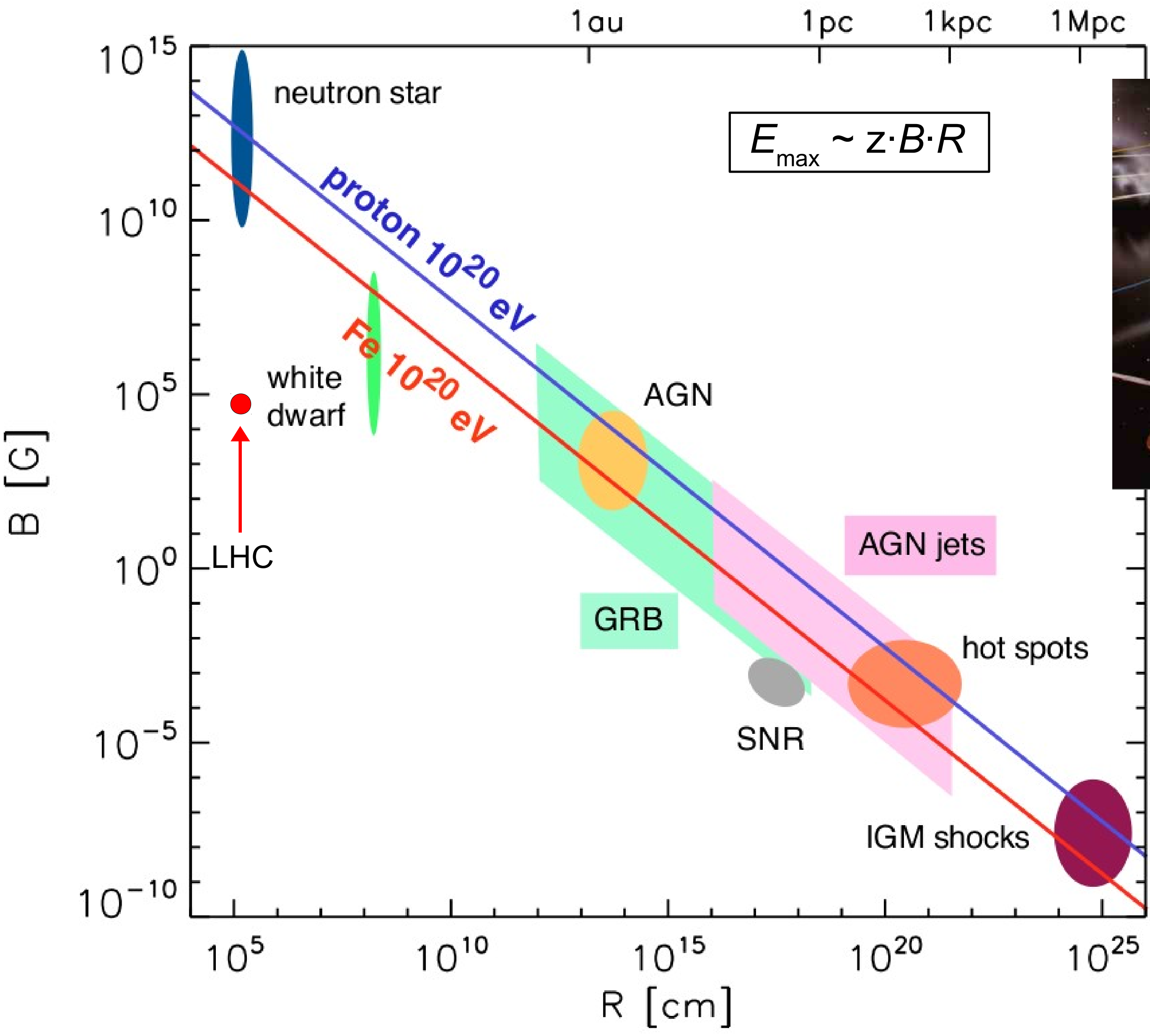
1 event / m² / second

1 event / m² / year

UHECR

1 event / km² / century

Sources of UHECRs ?



Accelerator with orbit of Mercury needed for 10^{20} eV protons!

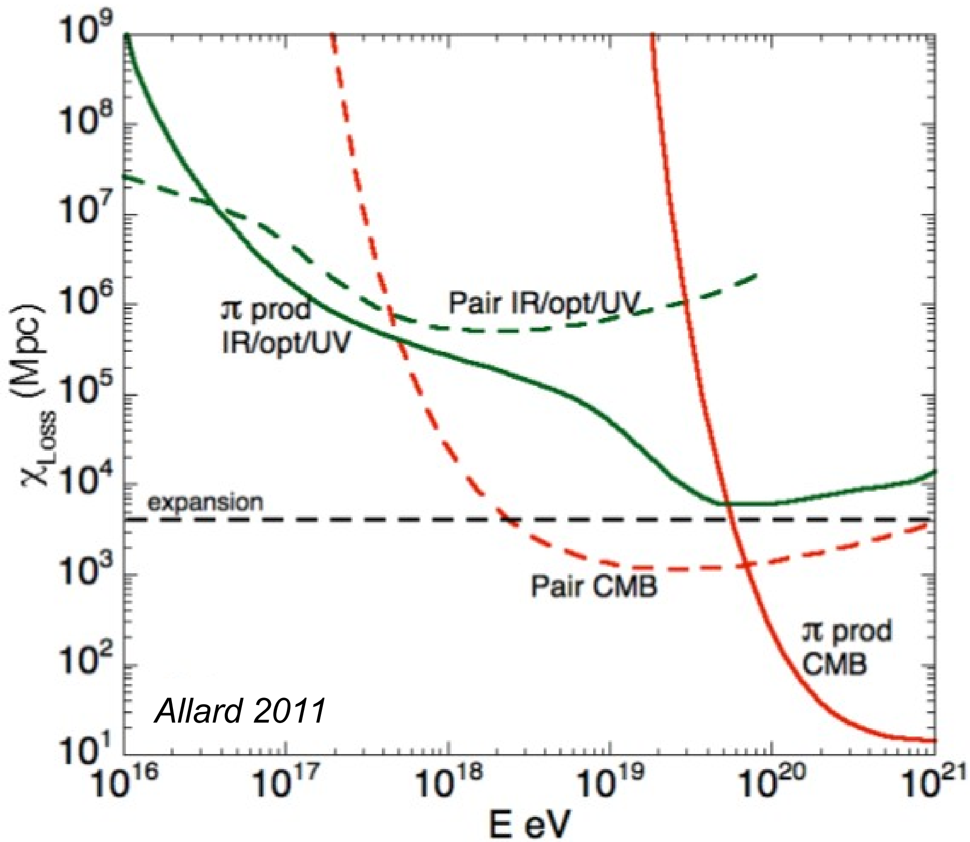
Propagation of cosmic rays

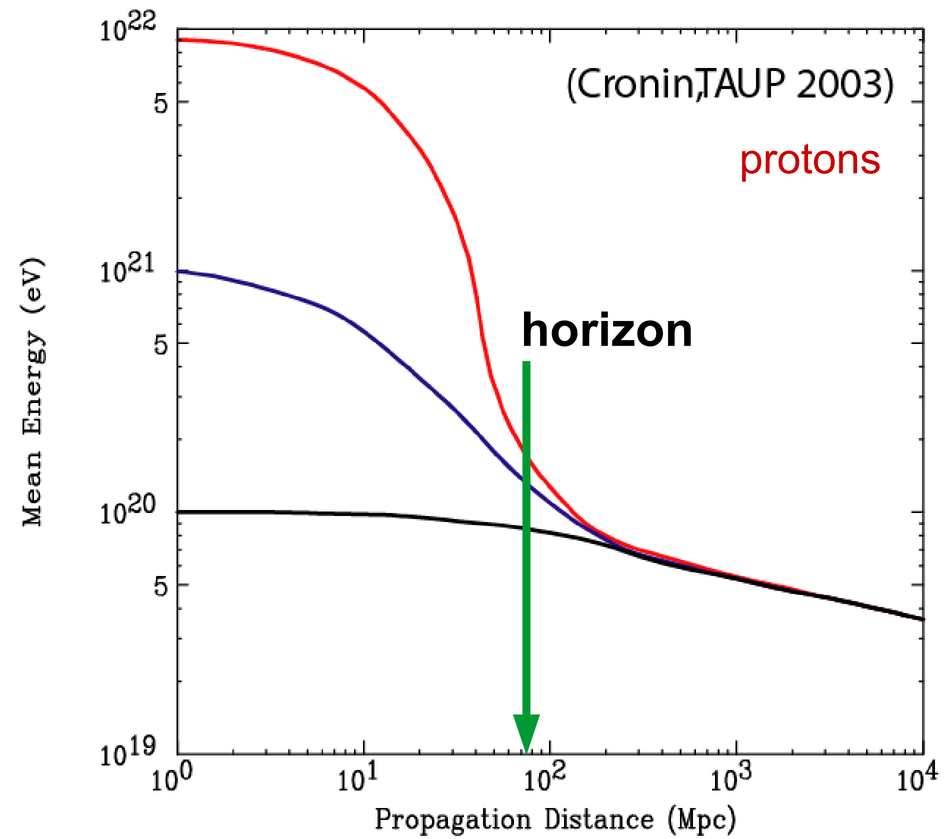
Energy loss through inelastic scattering on CMB

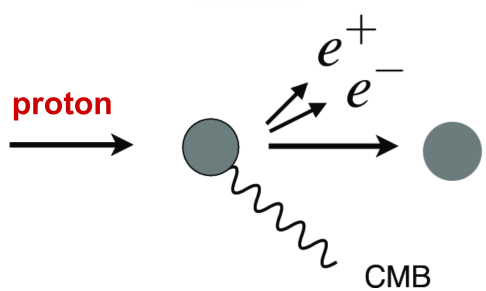
pair-production & photo-pion production via Δ resonance

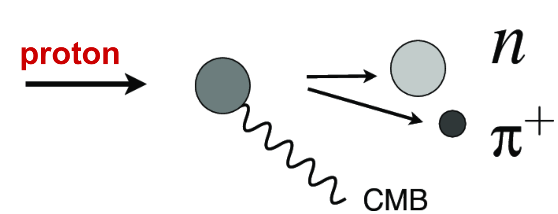
Greisen, PRL 16 (1966) 748.
Zatsepit, Kuz'min, JETP Lett. 4 (1966) 78.

→ **GZK effect**









Propagation of cosmic rays

Energy loss through inelastic scattering on CMB

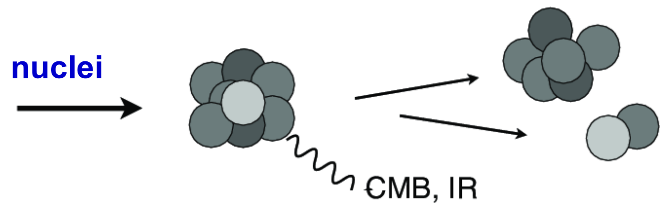
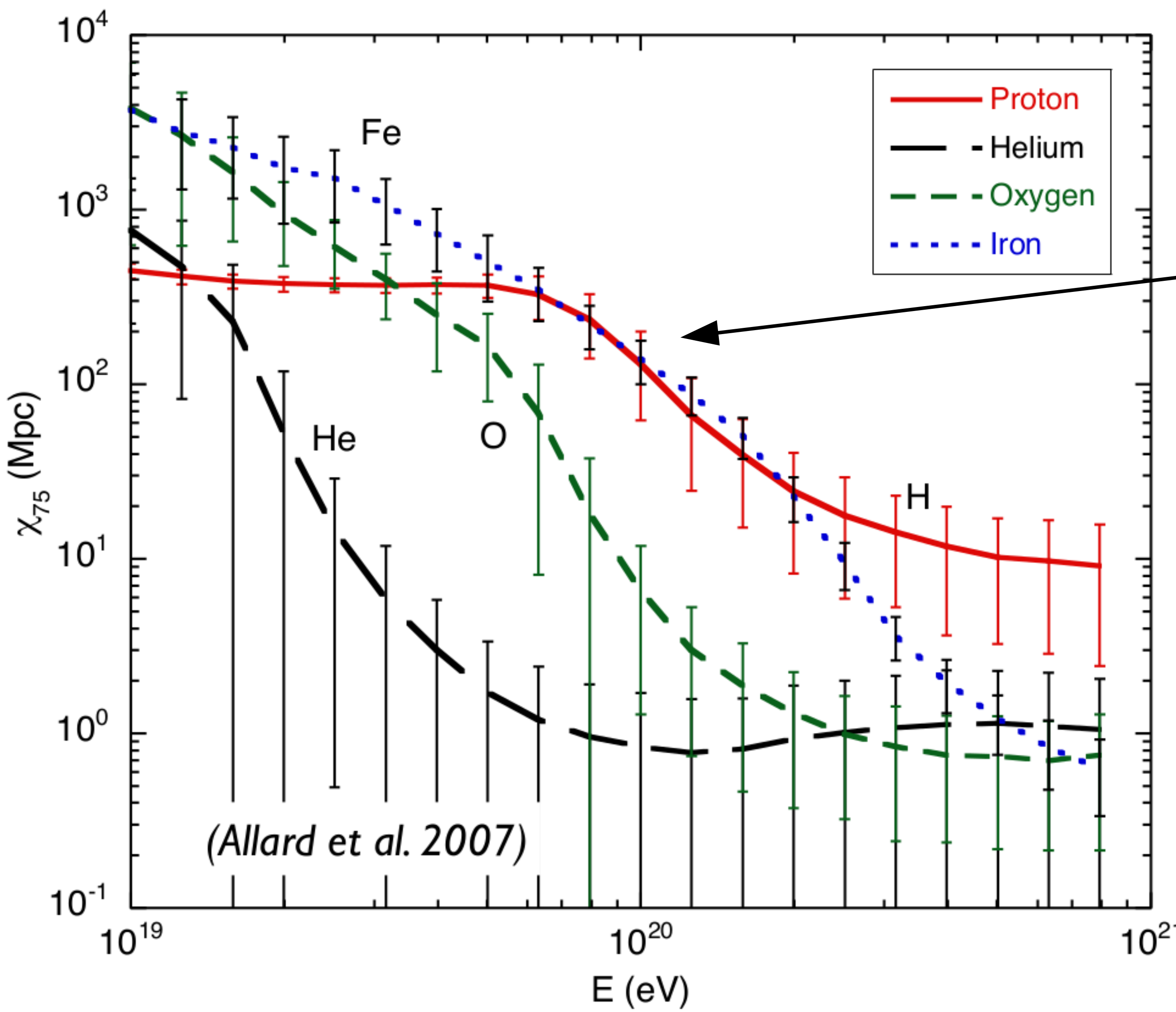


Photo-disintegration
(giant-dipole resonance)



Coincidence for **proton** and **iron**: similar suppression

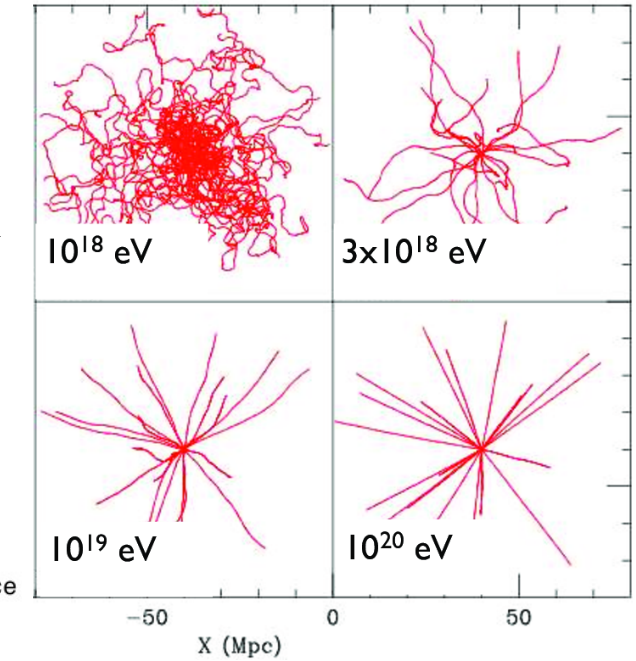
Magnetic deflection

- Deflection power scale with charge (*Z*)
- Astronomy at the highest energies?

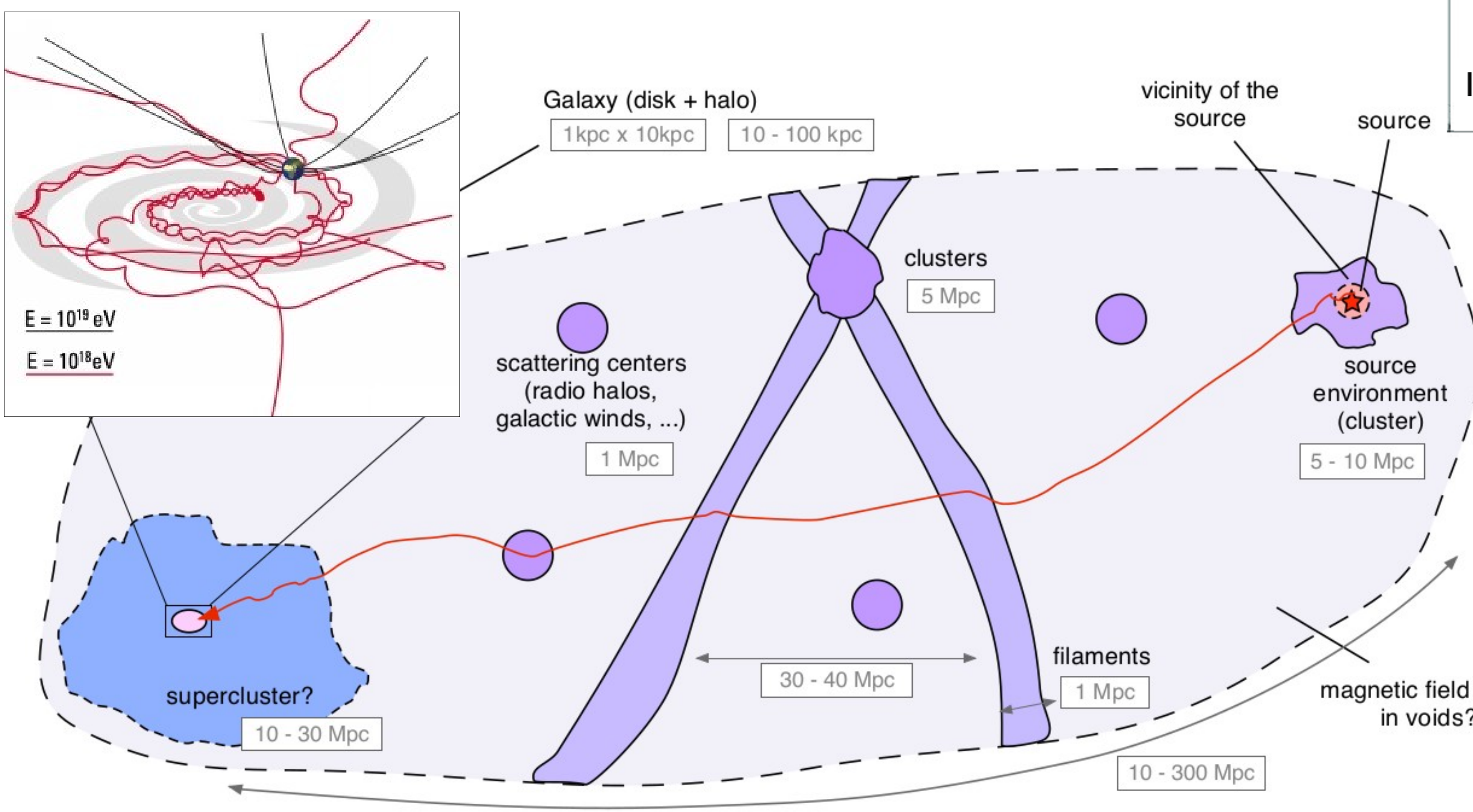
Galactic deflections

$$\delta \simeq 3^\circ \frac{B}{3\mu\mathrm{G}} \frac{L}{\mathrm{kpc}} \frac{6\times10^{19}\mathrm{eV}}{E/Z}$$

Extra-galactic deflections

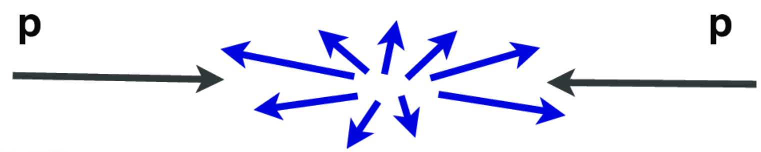


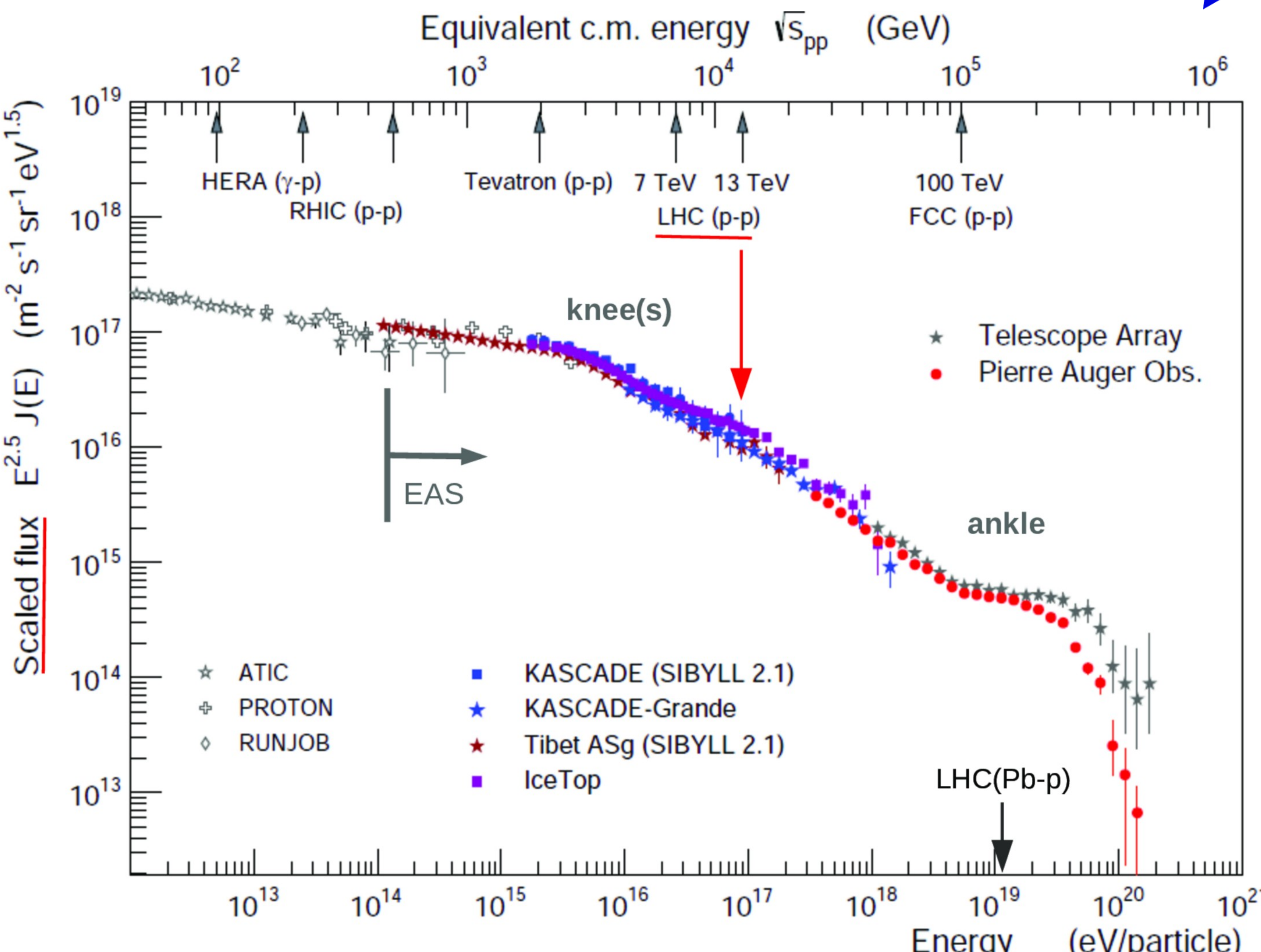
UHECR (protons in particular) should point to the source



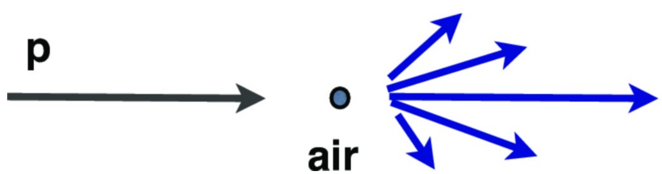
Kotera & Olinto, ARAA 2011

Energy spectrum



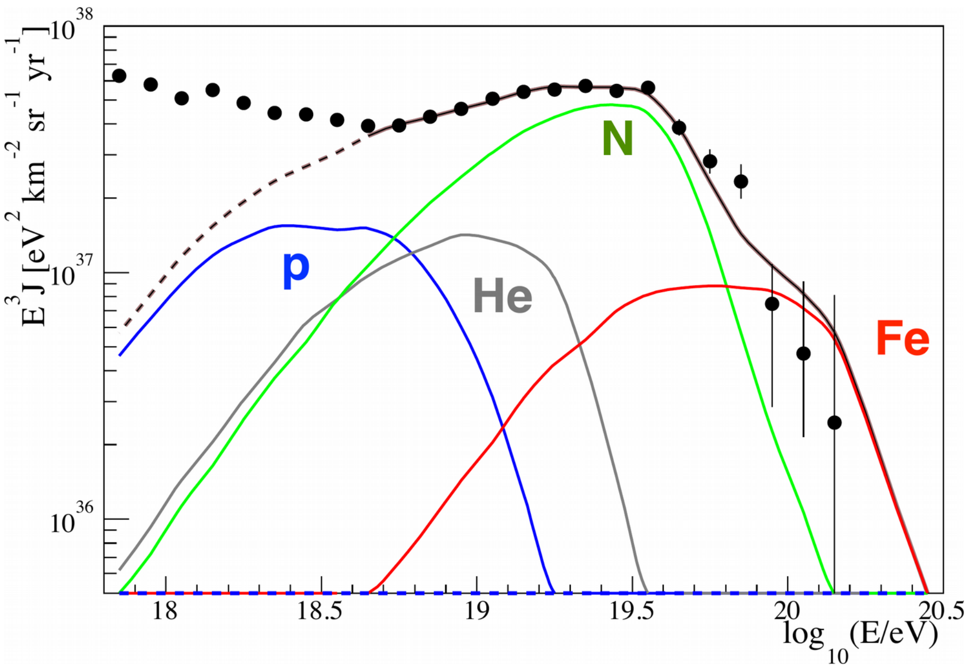


$$\frac{1 \text{ event}}{\text{km}^2 \text{ century}}$$



Possible composition scenarios

Reason for the flux suppression at highest energies?



Rigidity dependent scenario

(tired sources, maximum acceleration scales with charge)

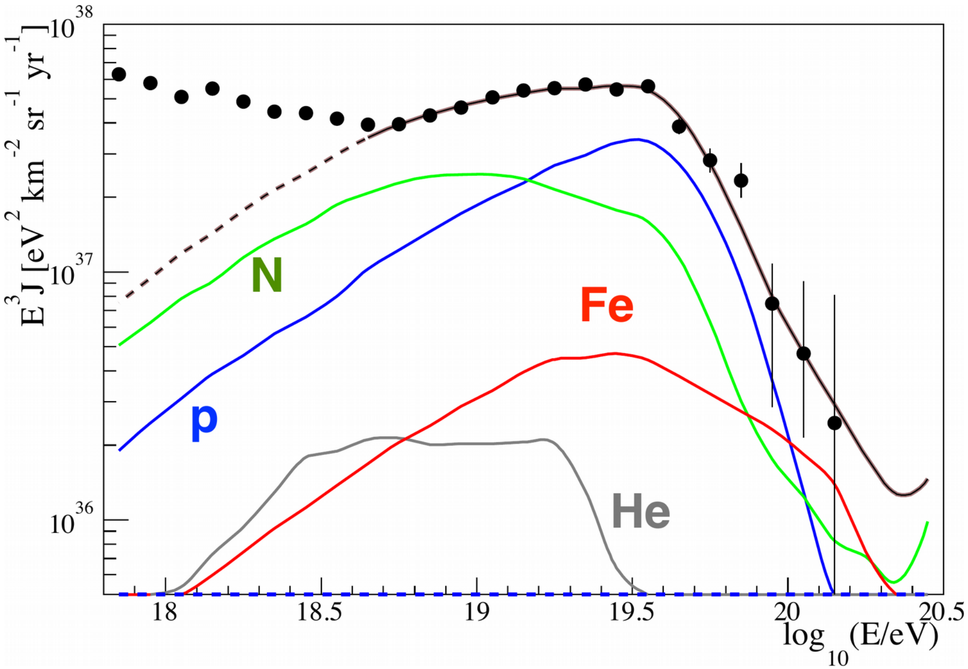
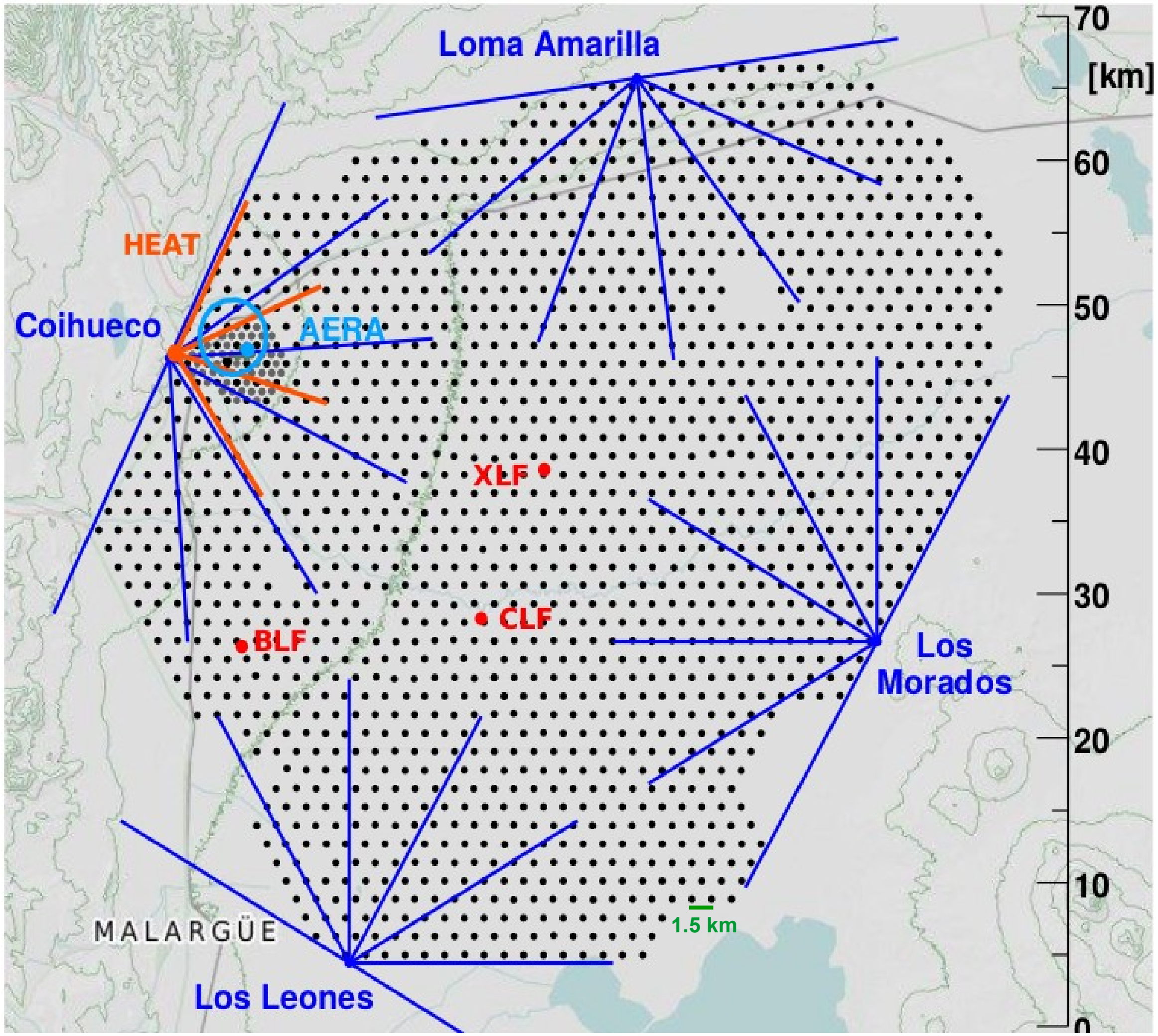


Photo-disintegration scenario

The Pierre Auger Observatory

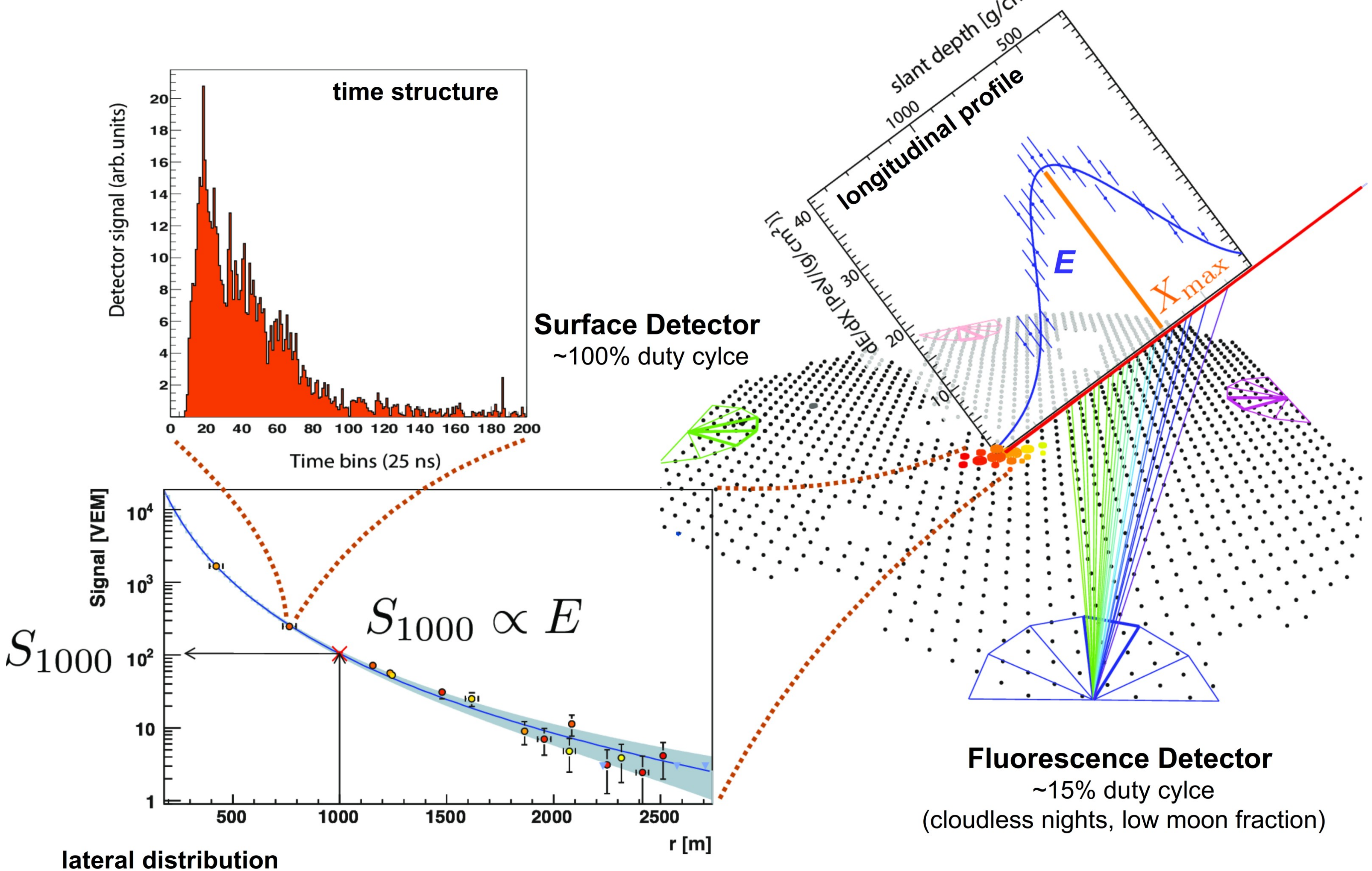


Fluorescence detector (FD)
27 telescopes, 15% duty cycle

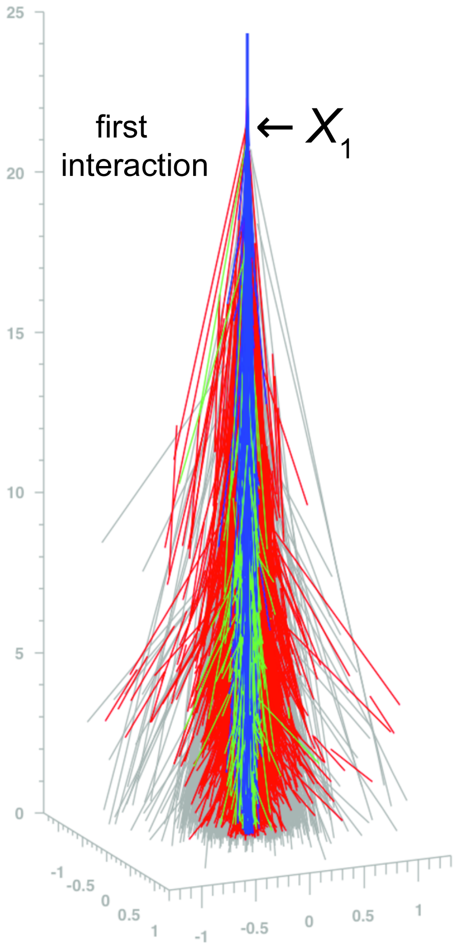
Surface Detector (SD)
1660 water-Cherenkov detectors
100% duty cycle

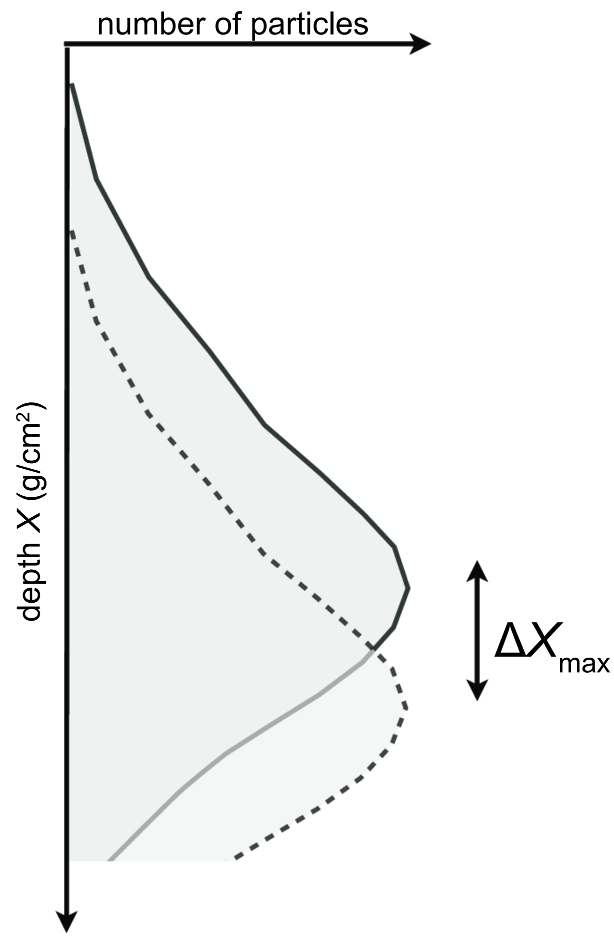
Location: Malargüe, Mendoza (Argentina)
Area: 3000 km^2
Height: 1450 m (860 g/cm^2)
Energy Threshold: $10^{17.5}$ eV

Extensive Air Shower observables



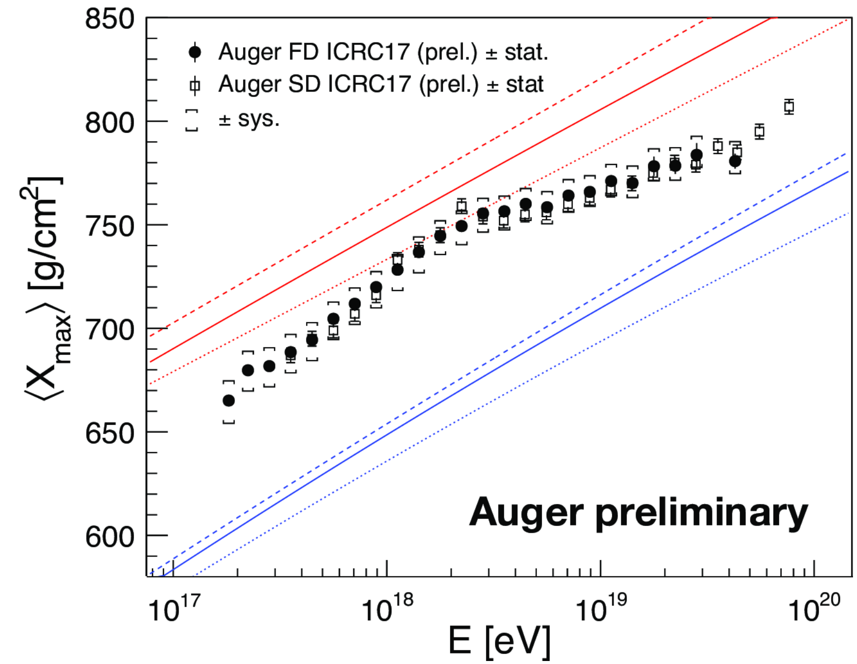
Shower profile

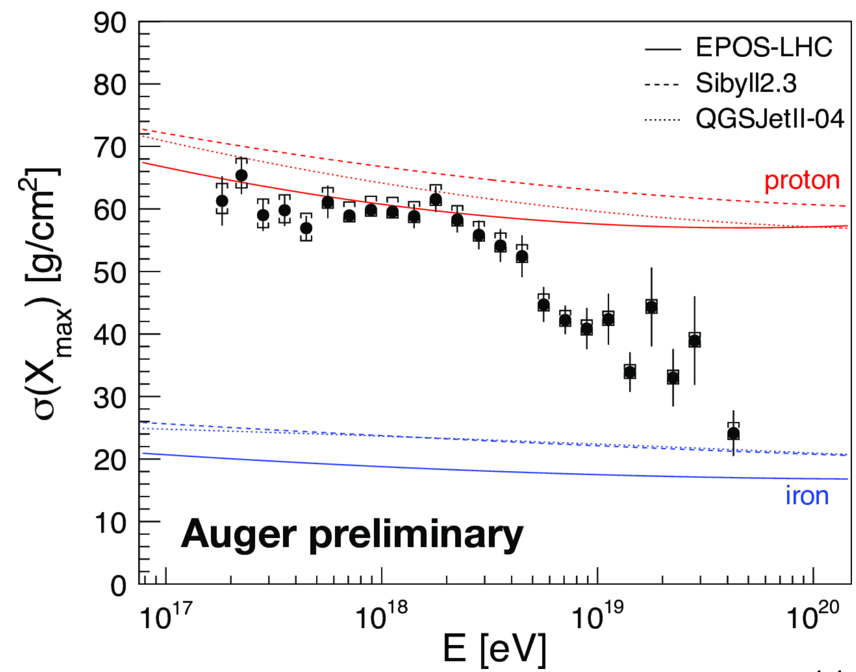




break in elongation rate above the ankle

$\langle X_{max} \rangle \sim \ln\langle A \rangle + D \ln(E/E_0)$





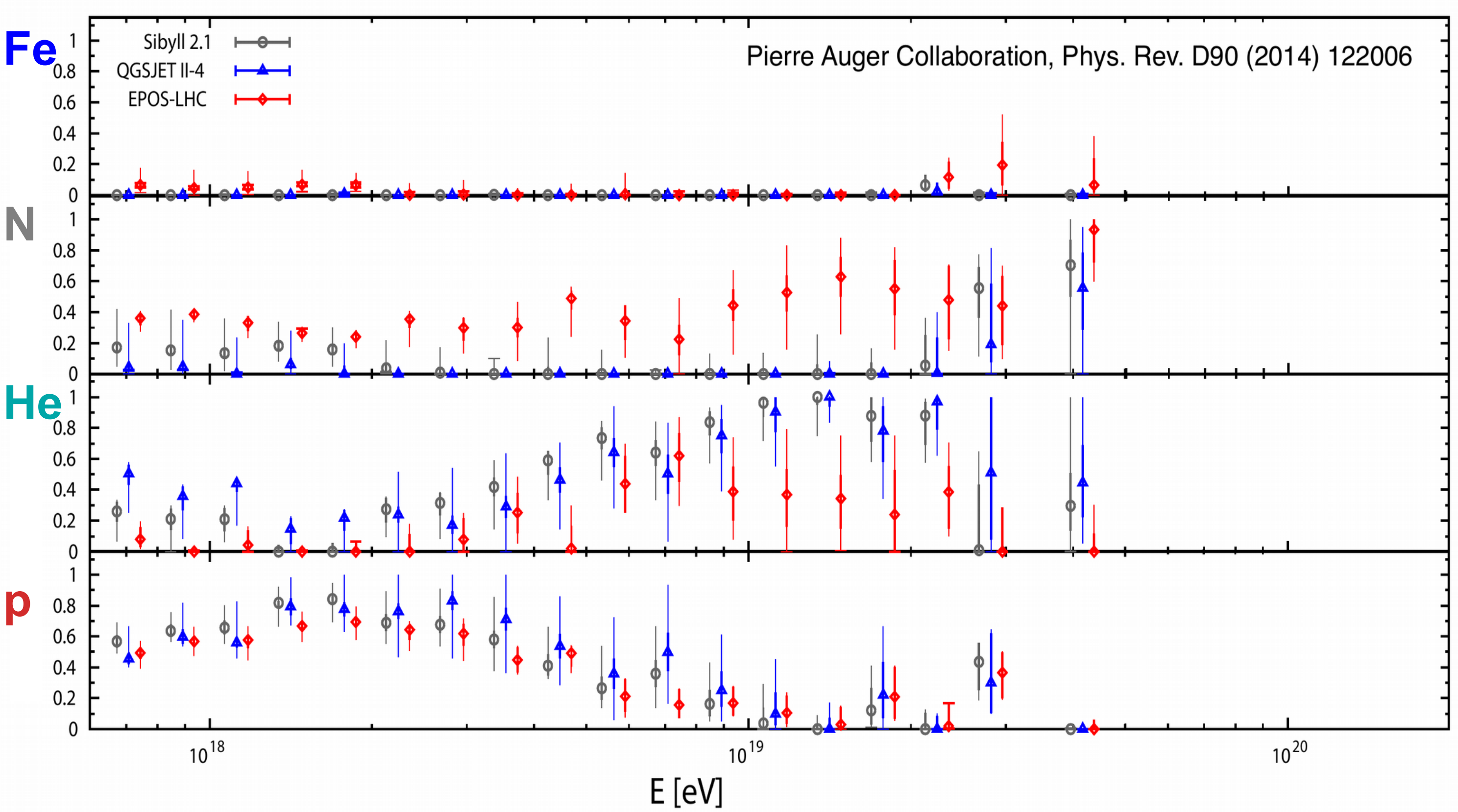
showers get elongated with *E*

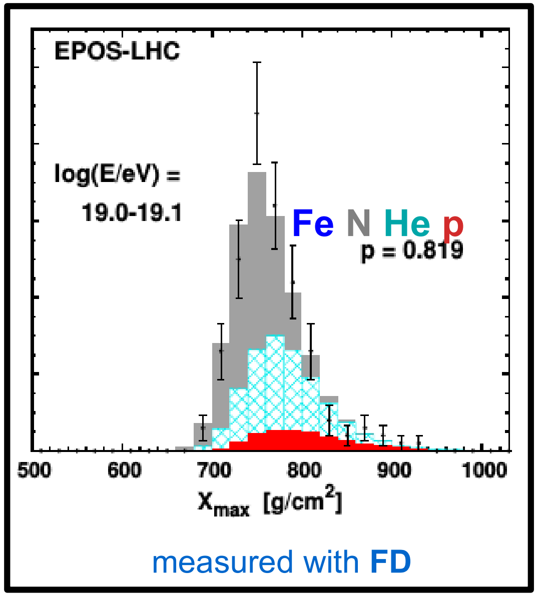
proton:

deeper than iron and has larger shower-to-shower fluctuations

Composition Fits to X_{max}

Monte-Carlo distributions fitted to data

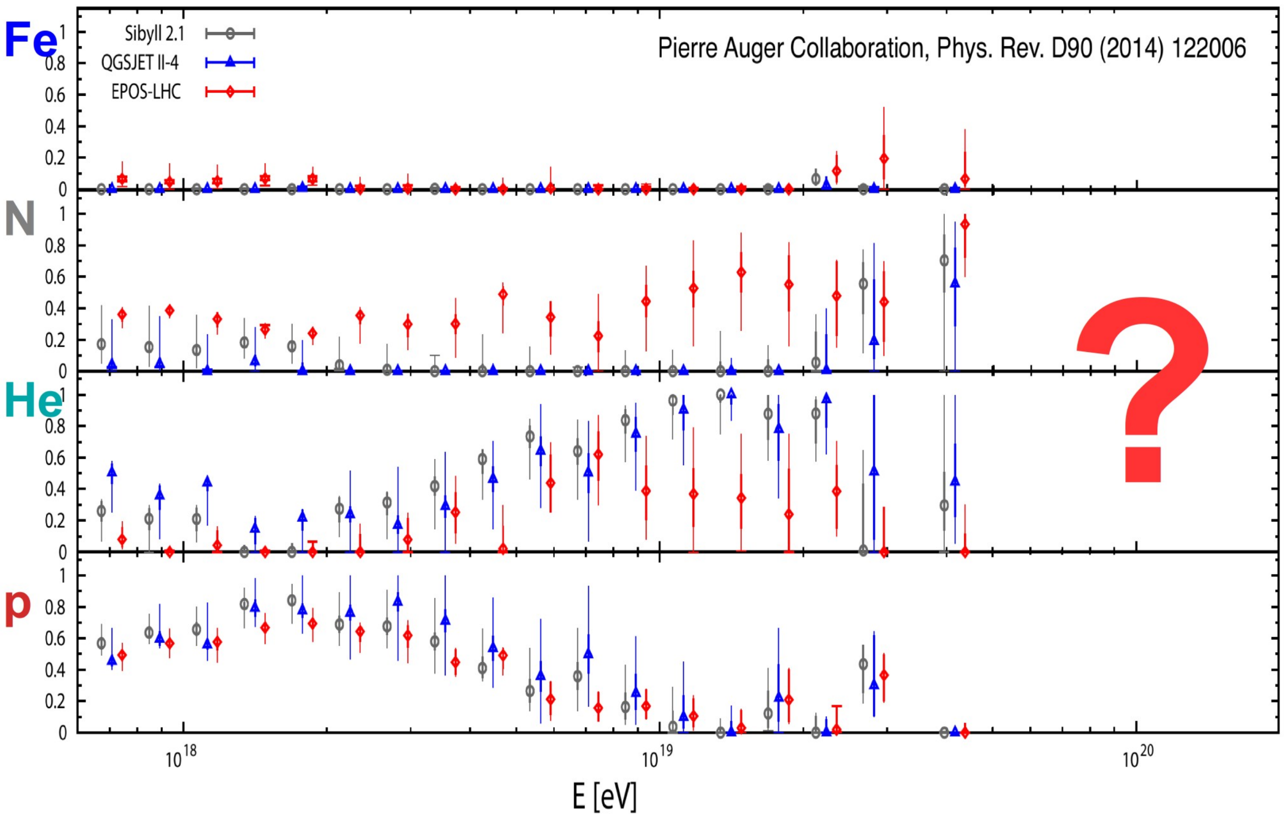


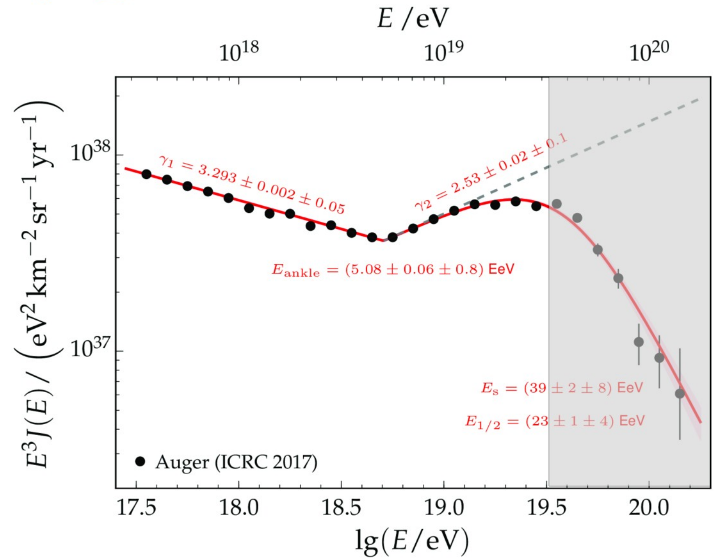


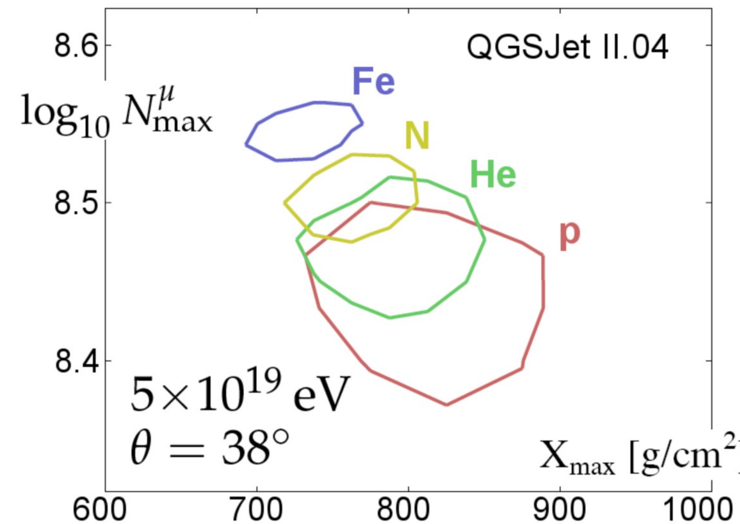
Energy evolution of composition

Transition energy ~10^{18} eV

Motivations for the Upgrade





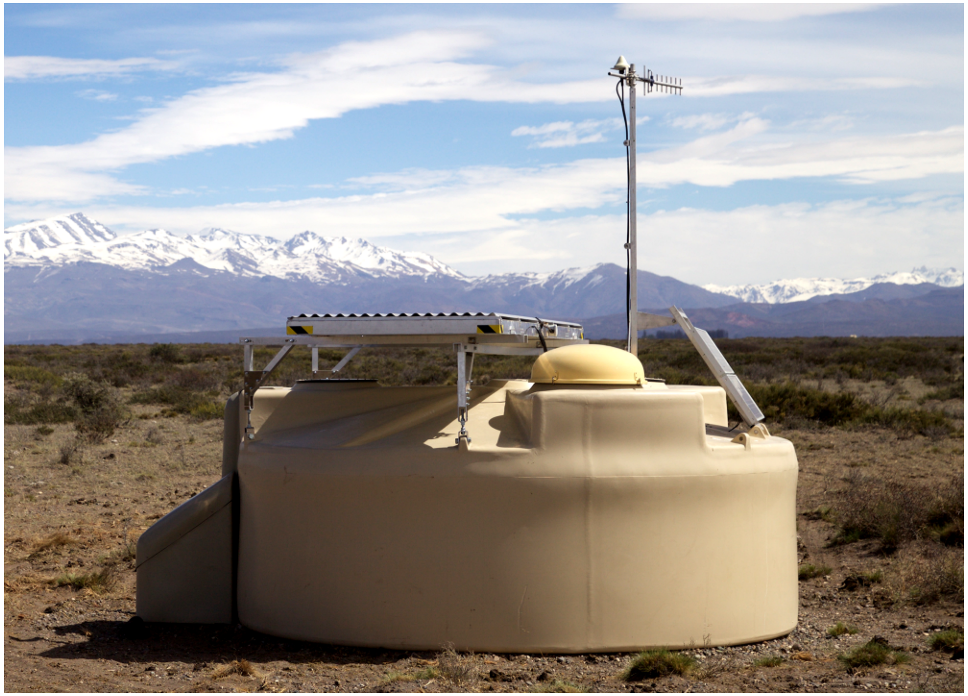


- mass composition at $E > 10^{19}$ eV
- proton fraction at highest energies
- hadronic interaction models

⇨ **increase composition sensitivity with Surface Detector (100% duty cycle)!**

AugerPrime Upgrade

Scintillator Surface Detector (SSD) on top of each of the existing Water-Cherenkov Detectors



Main objective

Reconstruct mass of primary cosmic ray with 100% duty cycle

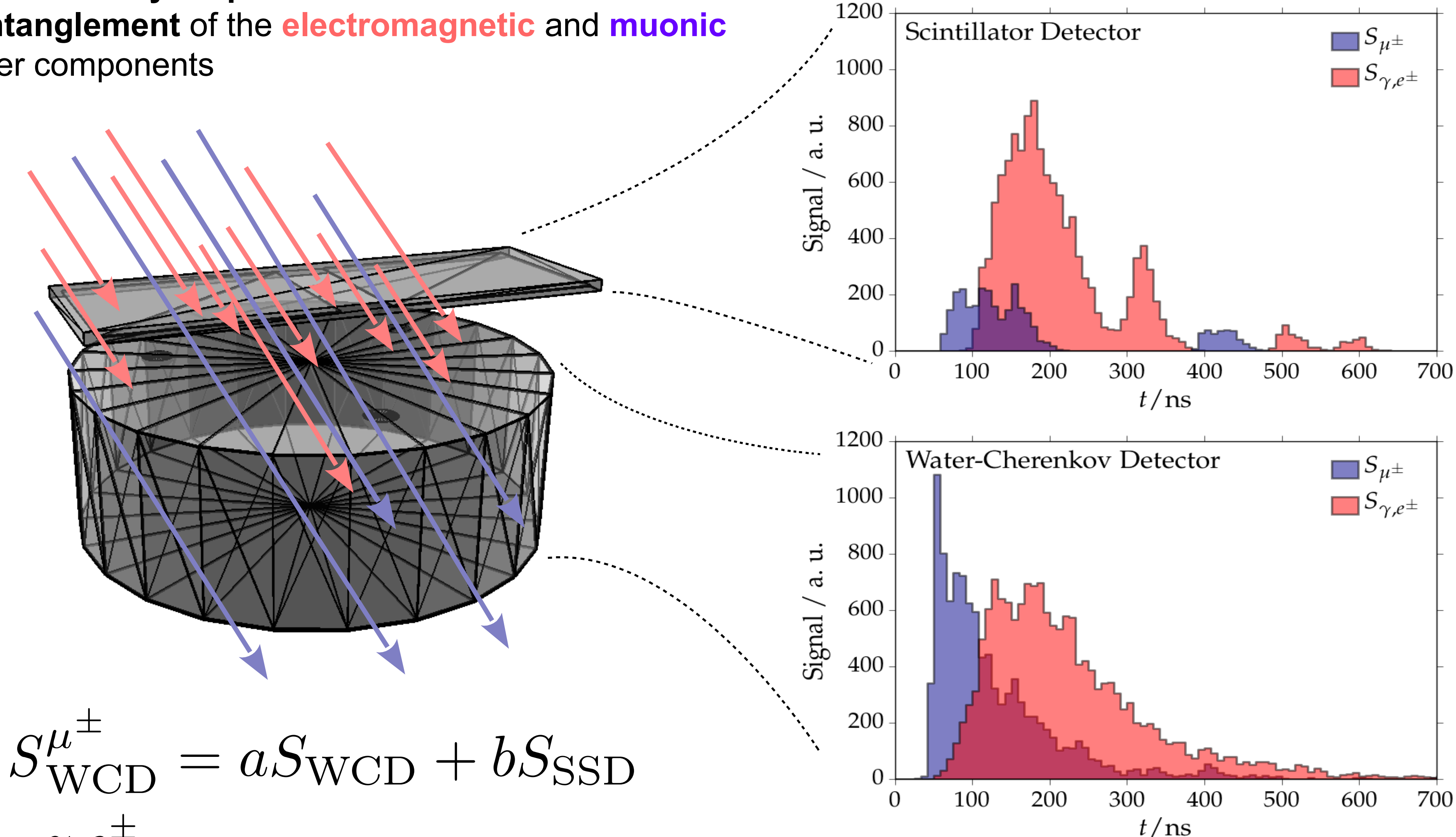
(AugerPrime design report 1604.03637)

Further upgrades:

- **Electronics Upgrade & Dynamic Range:**
  - Higher sampling frequency (120 Mhz) and enhanced amplitude resolution (2 more bits)
  - Additional small PMT to WCD → increase dynamic range
- Increase of FD duty cycle (up to 30%)
- Underground Muon Detector (UMD)
- Radio upgrade

Different response to shower particles

Complementary response of two detectors **allows for disentanglement** of the electromagnetic and muonic shower components

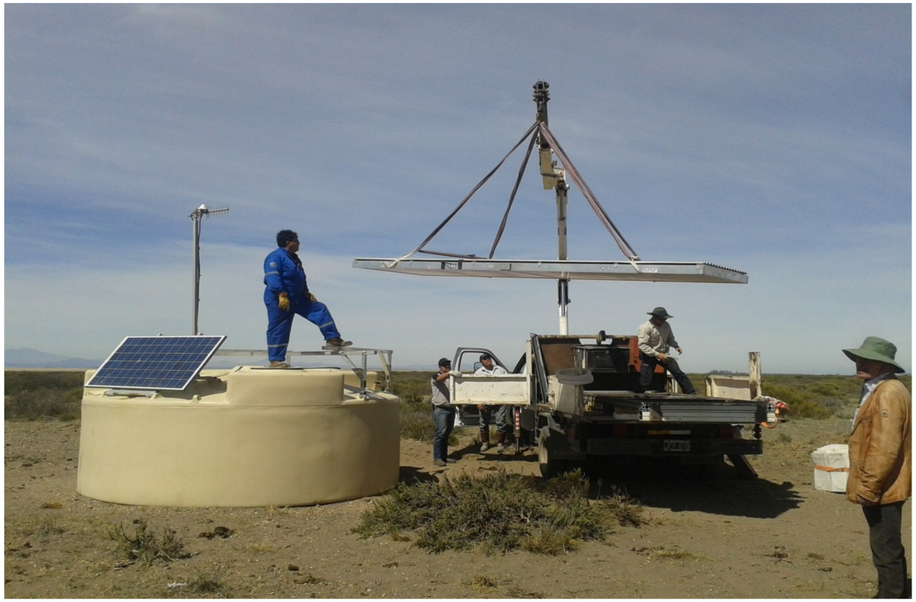


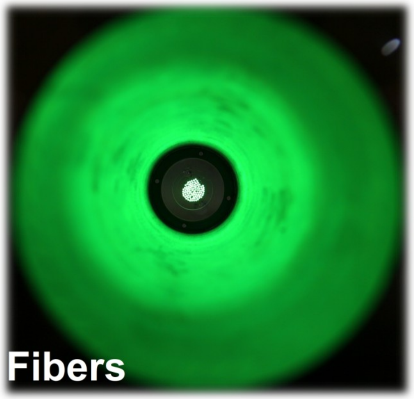
$$S_{\mathrm{WCD}}^{\mu^\pm} = aS_{\mathrm{WCD}} + bS_{\mathrm{SSD}}$$

$$S_{\mathrm{WCD}}^{\gamma,e^\pm} = cS_{\mathrm{WCD}} + dS_{\mathrm{SSD}}$$

Scintillator Surface Detector (SSD)

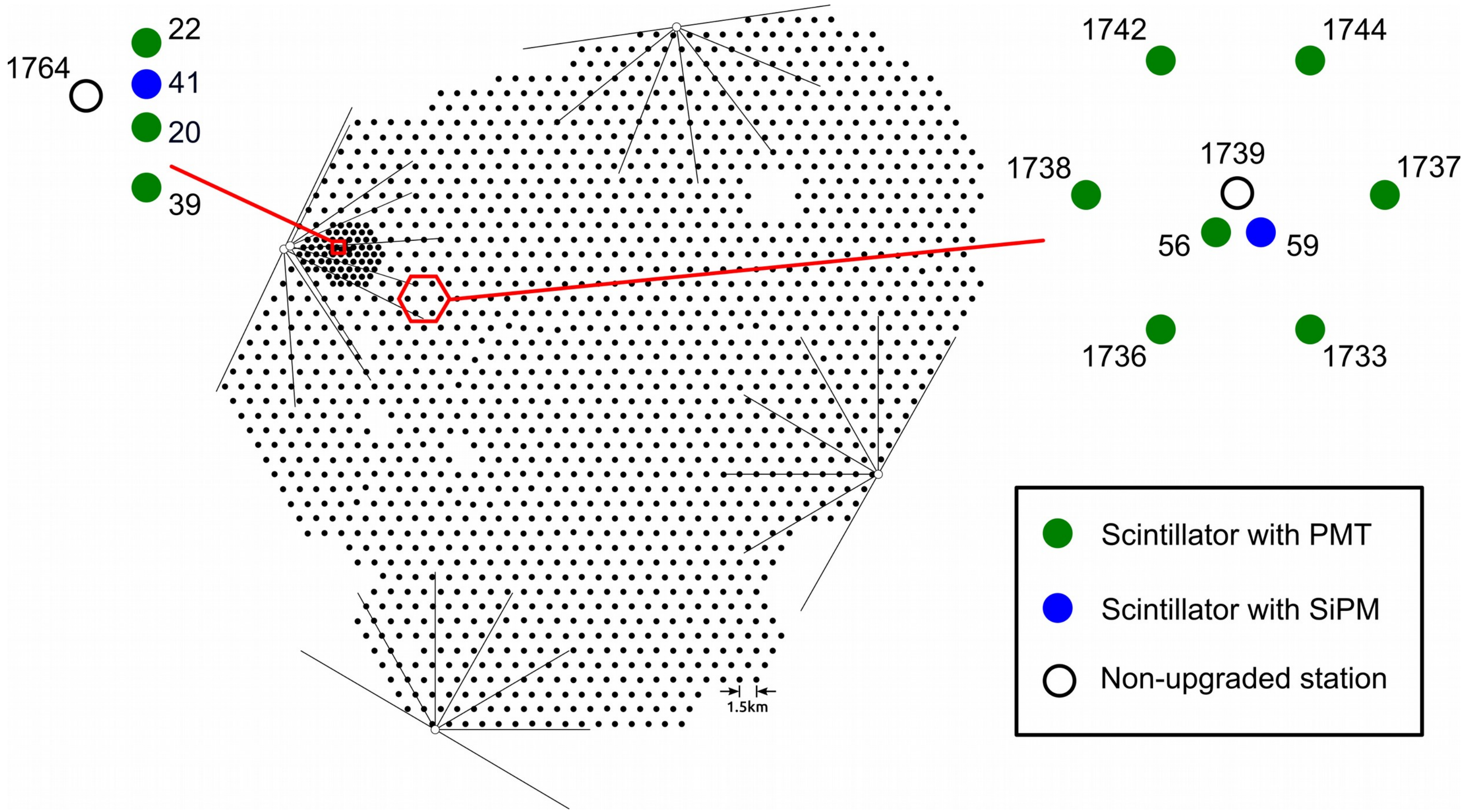
- **3.8 m² scintillator detector on top of each WCD**
- **48 scintillator bars** coupled with **WLS fibers** guiding scintillation photons to a **PMT**
- **Aluminum housing**





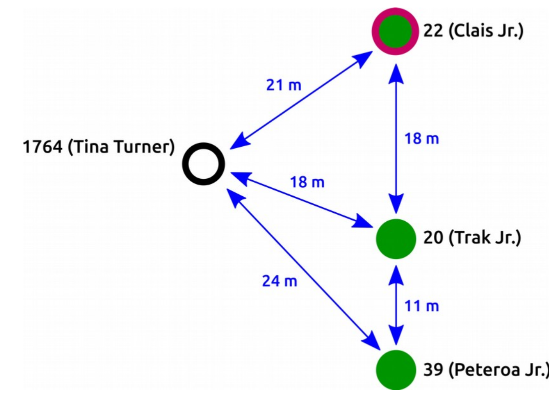
Engineering Array

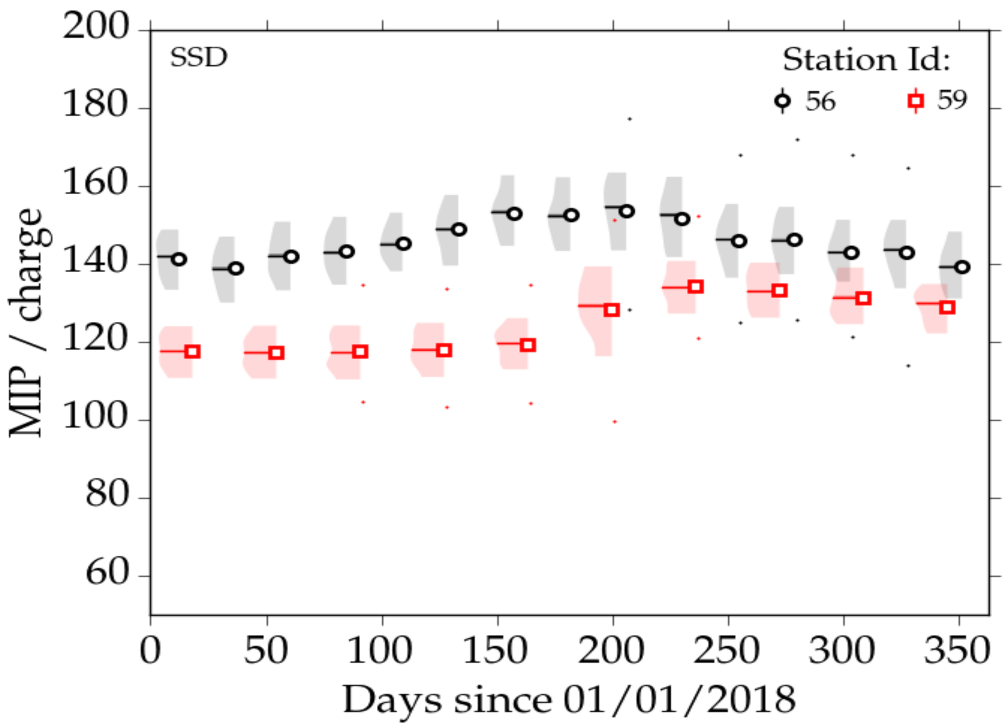
- **12 upgraded stations** (new electronics & SSD) deployed in the **Engineering Array (EA)**
- **Data** acquisition started **October 2016**
- **Currently deployed @ EA:**
  4 stations in the SD-750 m array
  8 stations in the SD-1500 m array

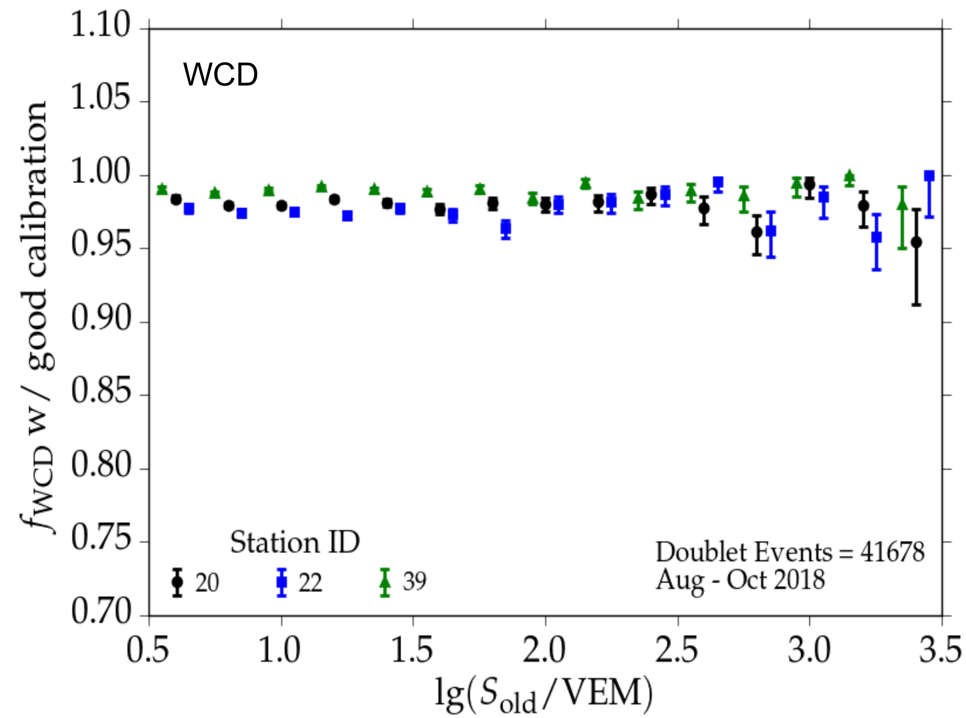


Performance of EA detectors

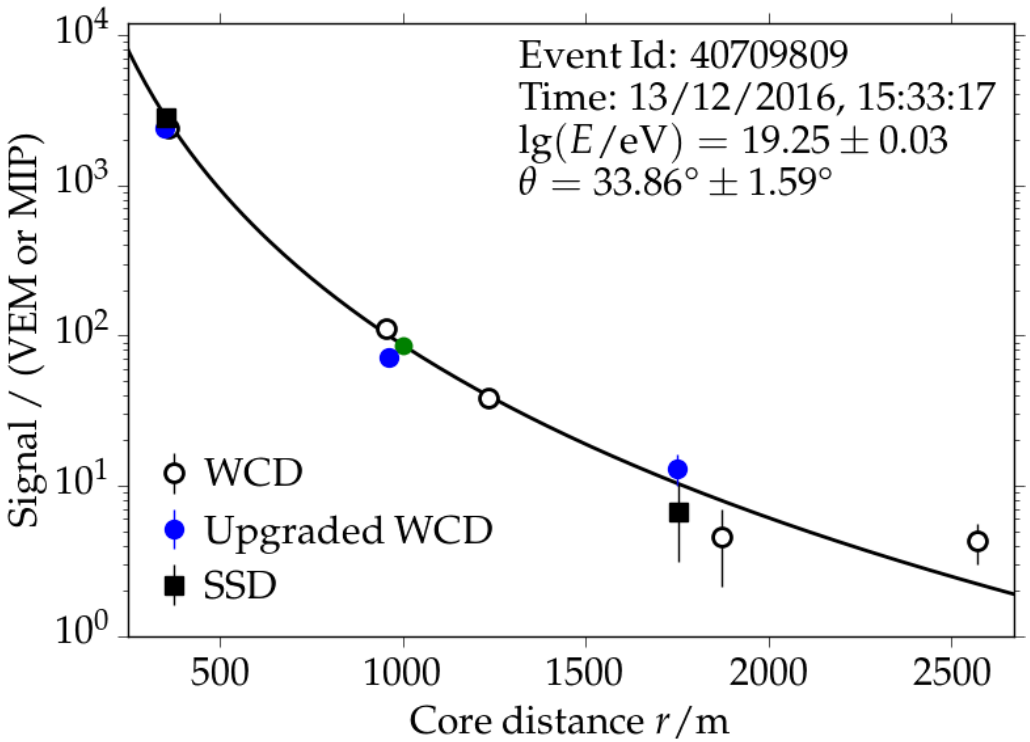
- Observed **MIP modulation** could be related to seasonal variation
- Computed fraction of **well-calibrated** WCD of about **~98%**
  - this fraction gets reduced for SSDs ~85%
- In general: **good performance** of the **upgraded** detectors

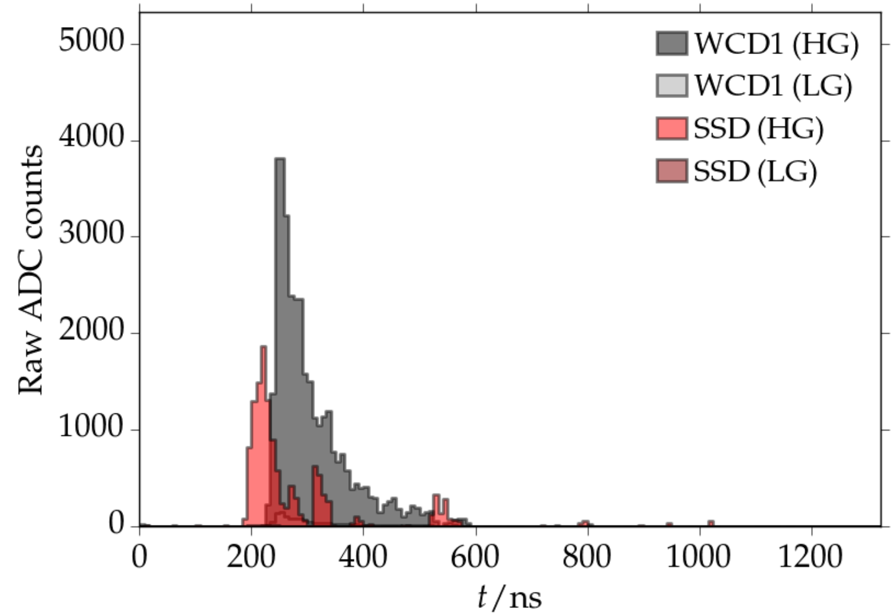






Reconstruction w/ Upgraded Detectors





Lateral Distribution Function (LDF)

$$S(r) = S_{1000} \left(\frac{r}{1000}\right)^{\beta} \left(\frac{r+700}{1700}\right)^{\gamma}$$

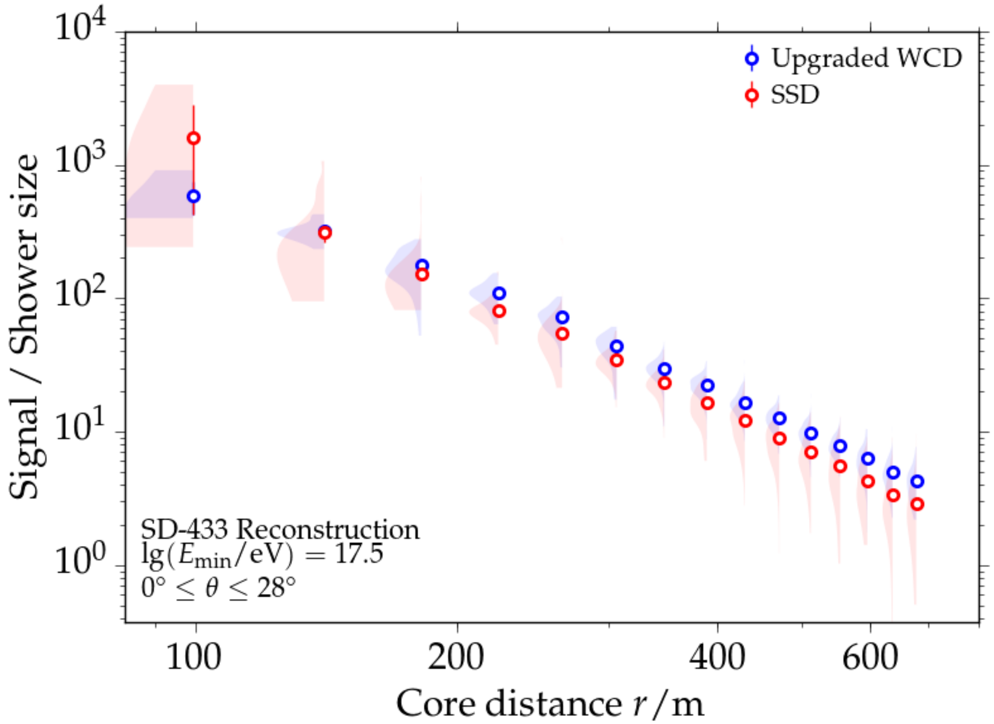
$$E_{\mathrm{rec}} = f\left(S_{1000}, \theta\right)$$

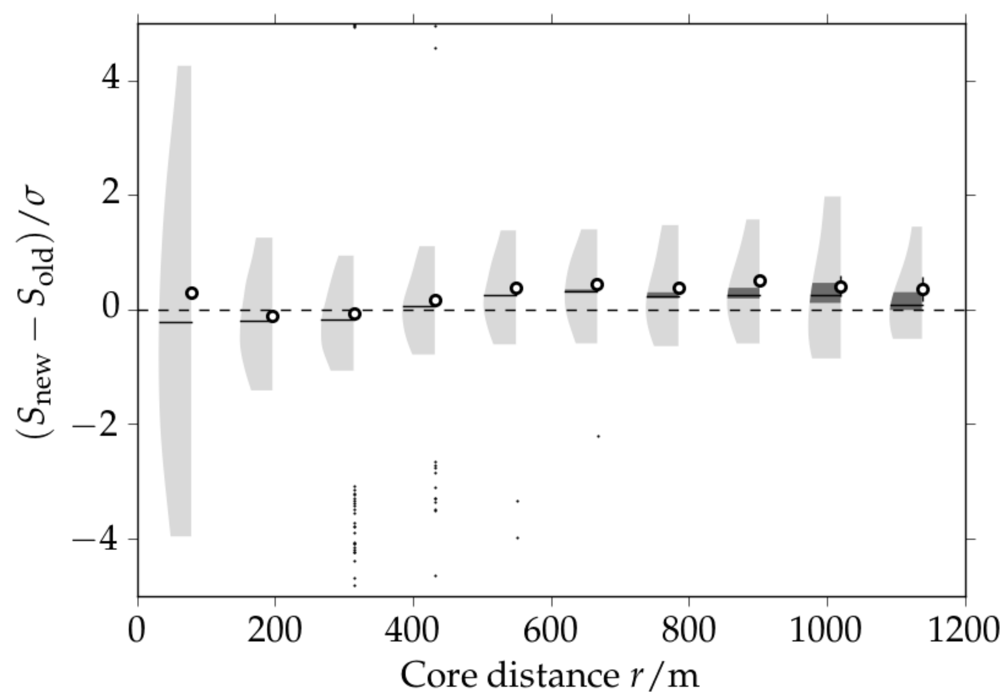
Reconstruction with
Upgraded Detectors implemented in

simulation & reconstruction framework
of the Pierre Auger Collaboration

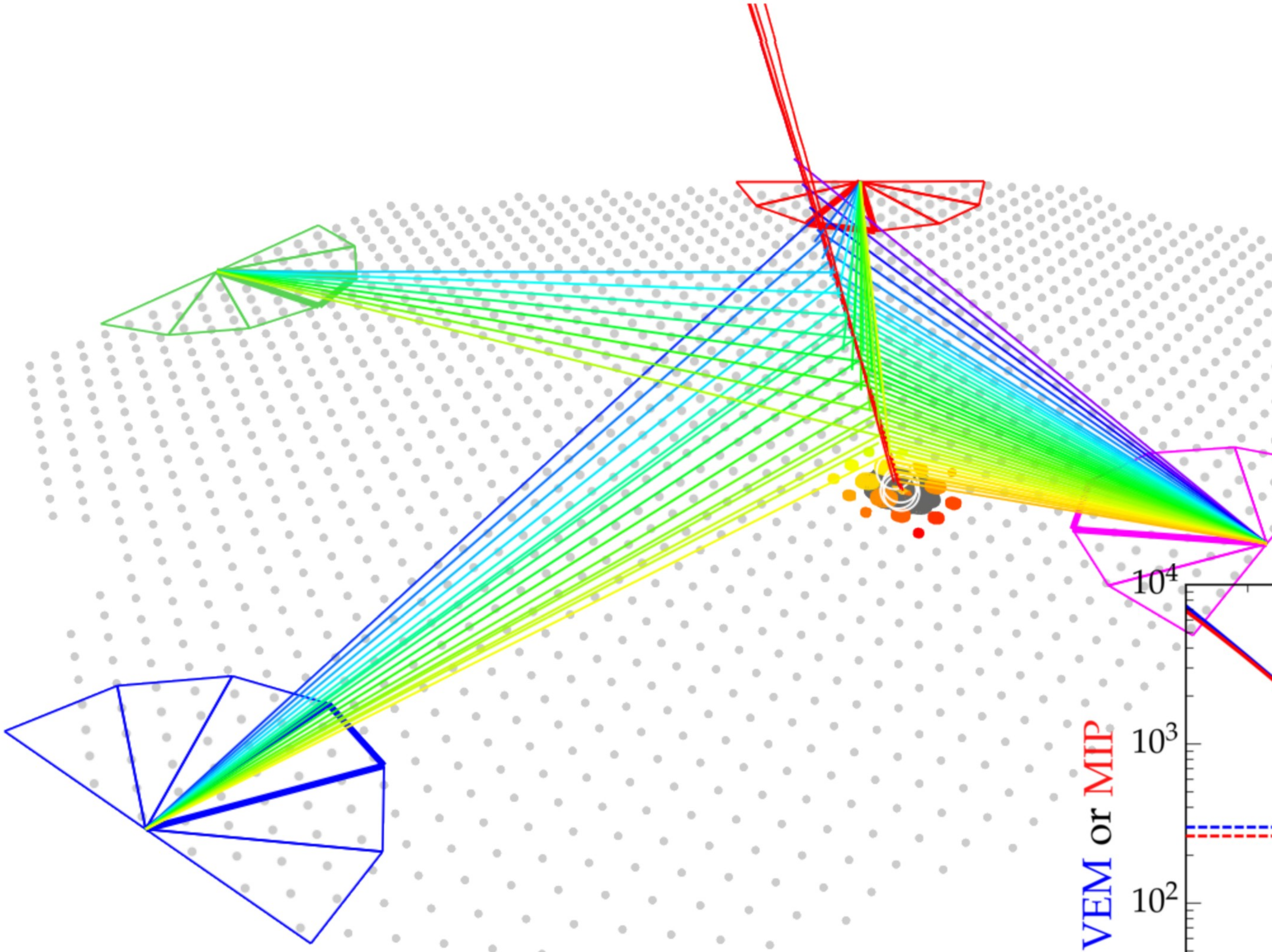
Analysis from first prototypes

- **Global LDF**: each reconstructed **signal** is **normalized** by reconstructed **energy**
  - Slightly steeper LDF measured with SSD is visible
  - Quality cuts needed to improve analysis
- **Good agreement** between signals from **old** and **upgraded electronics**



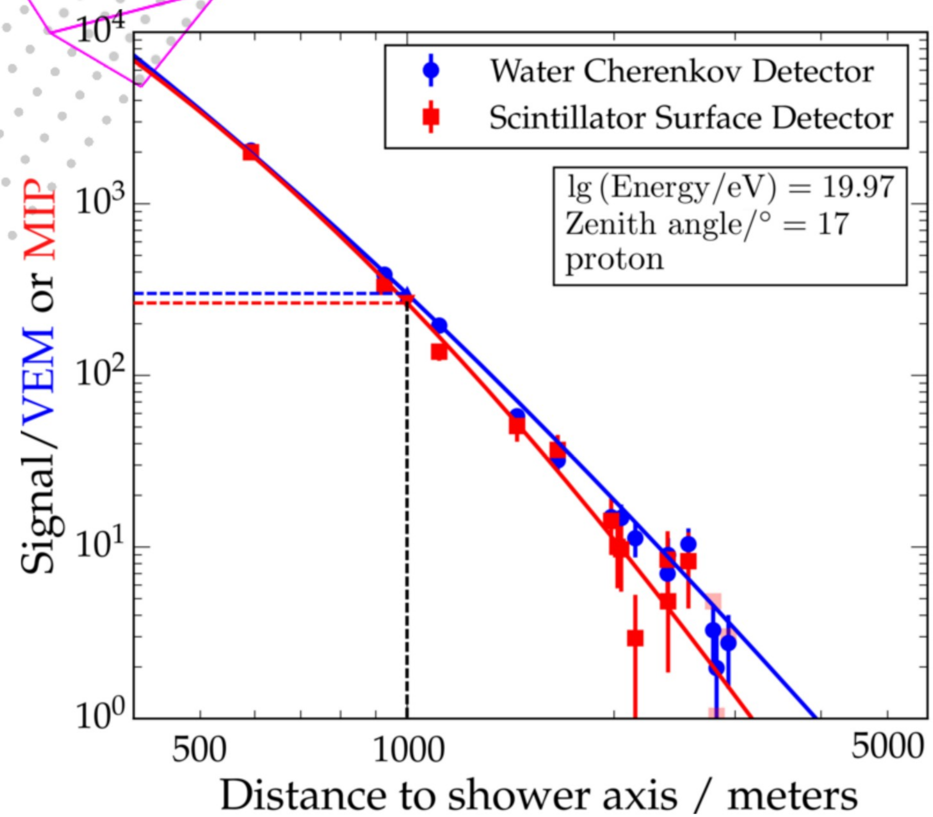


Towards event reconstruction with the SSD



Simulations to study **scintillator** and **water-Cherenkov detector responses** to air shower particles

Parameterizations needed for SSD: **signal variance** and **LDF**



$$S(r) = S(r_{\rm opt}) \left(\frac{r}{r_{\rm opt}}\right)^{\beta} \left(\frac{r + r_s}{r_{\rm opt} + r_s}\right)^{\gamma}$$

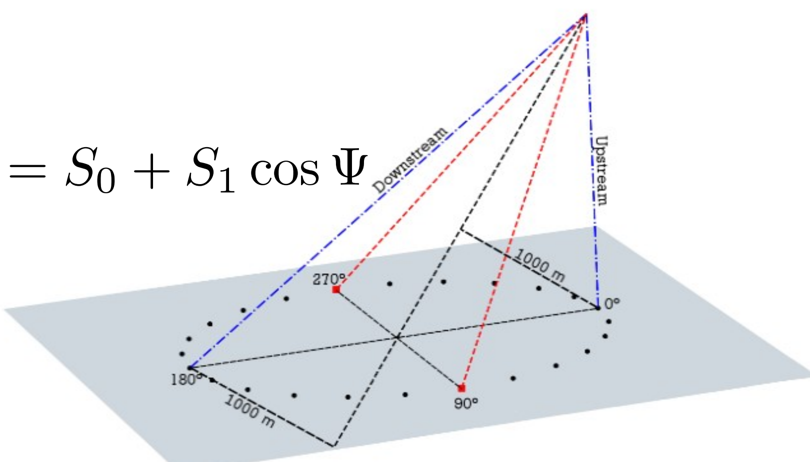
Signal variance for the SSD

Making use of simulations to parametrize the variance of SSD signals

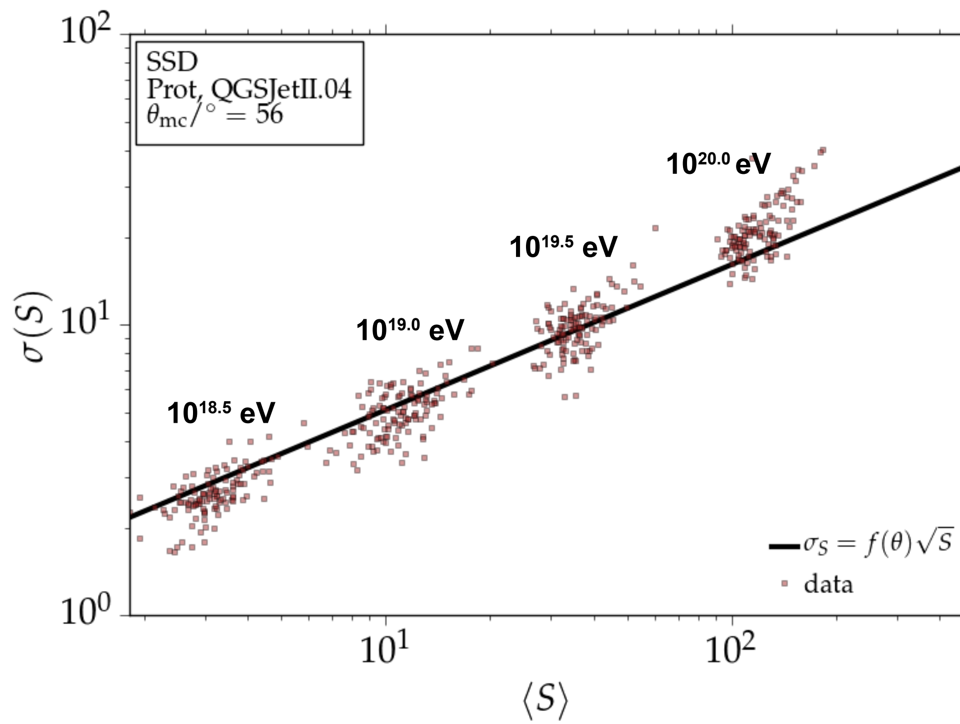
Set of simulated showers

Primaries	Proton, Iron
Had. Int. Models	EPOS-LHC, QGSJetII.04
log(*E* / eV)	18.0, 18.5 19.0, 19.5, 20.0
θ / °	0, 22, 12, 32, 38, 48, 56
φ / °	Uniformly Distributed

$$\mathrm{S}(\Psi) = S_0 + S_1 \cos\Psi$$



$$\sigma(S,\theta) = f(\theta) \times \sqrt{S}$$



Next

Parameterization of the slope parameters β and γ of the Lateral Distribution Function

Summary

UHECRs

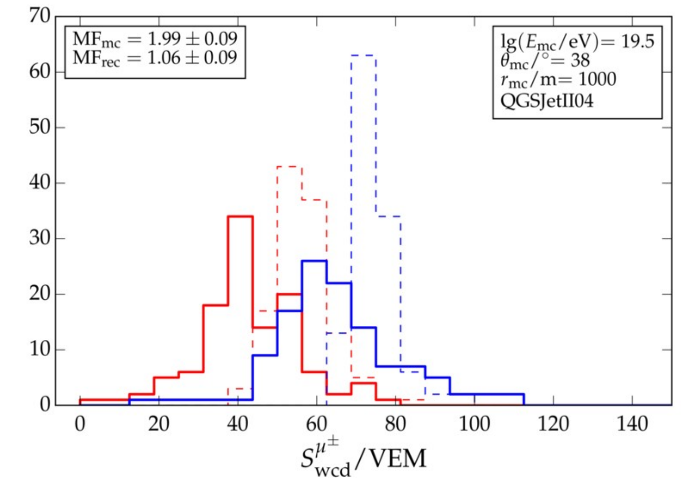
- **Open questions** regarding **sources**, **acceleration** mechanisms and **propagation**
- **We need mass!**

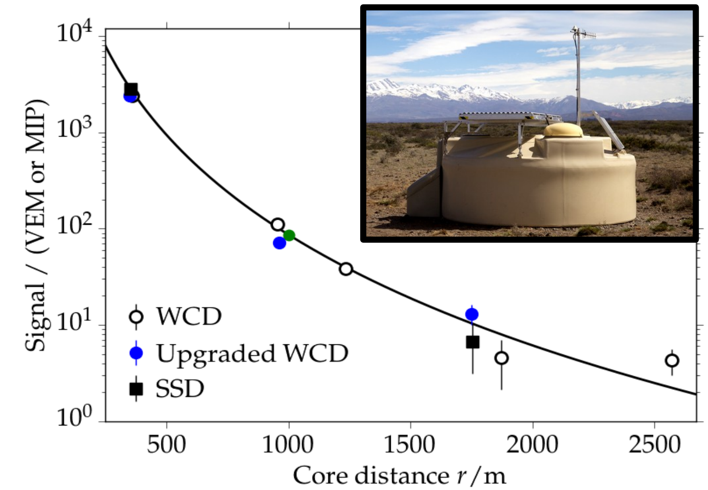
AugerPrime

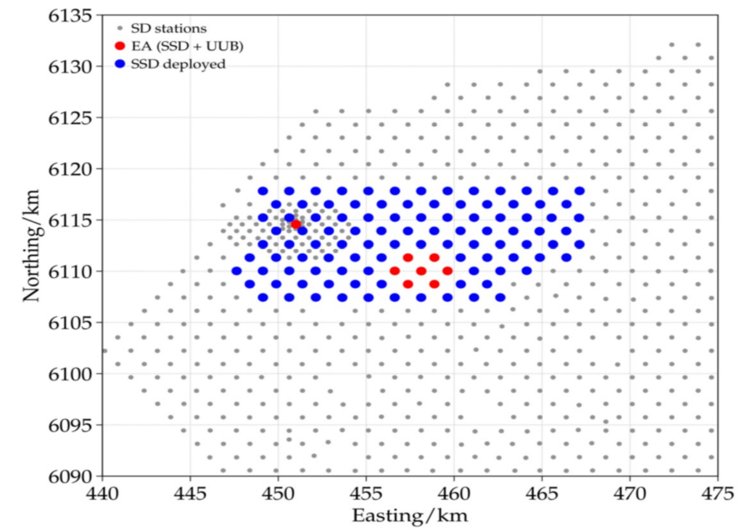
- **Scintillator detectors** with complementary response to EAS particles
- **Analysis** from **first prototypes** look **promising**

Future work

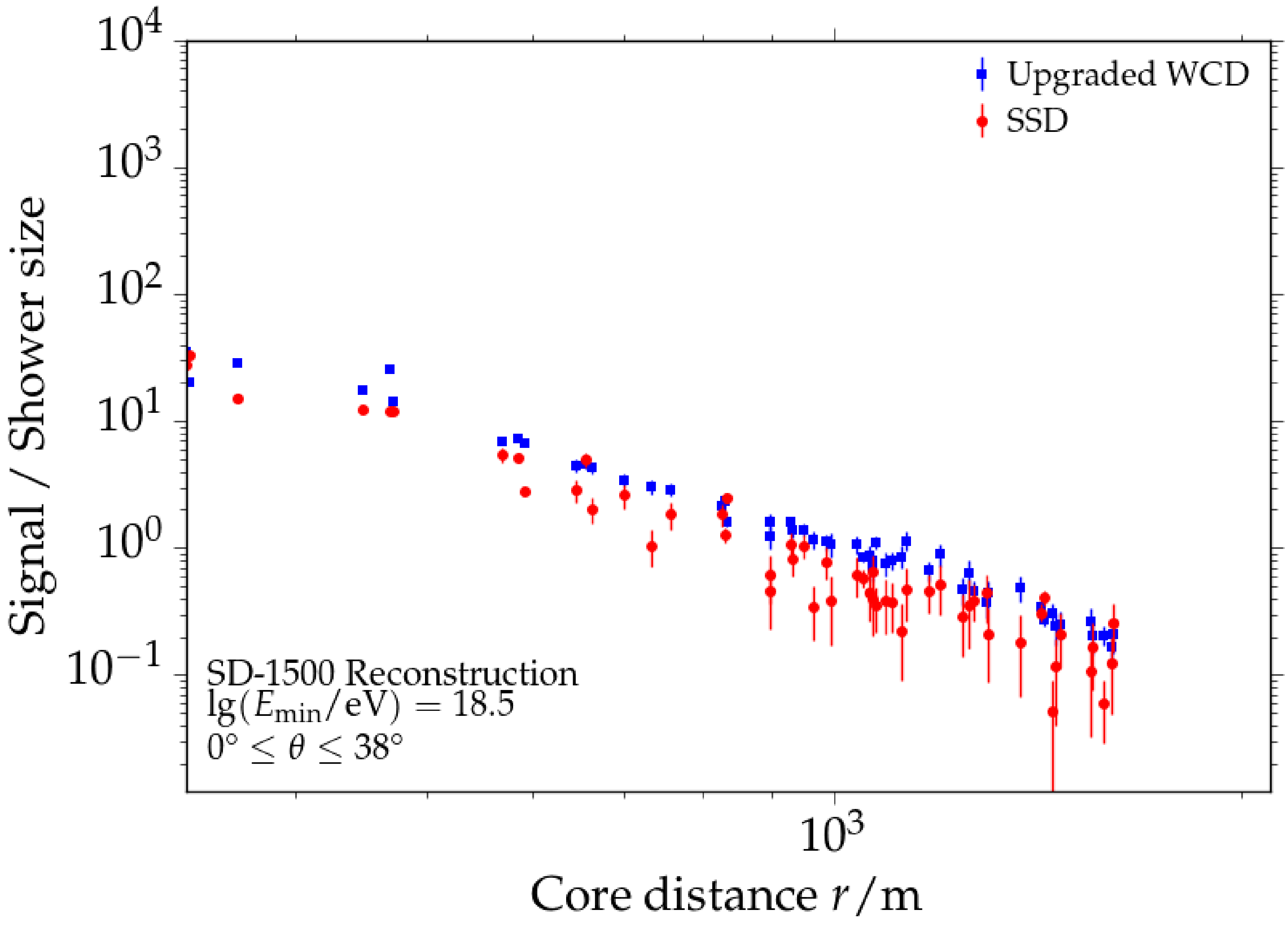
- **Deployment** of **SSDs** taking place
  → more data coming soon
- Ongoing **reconstruction** with **scintillators**
  → mass discrimination





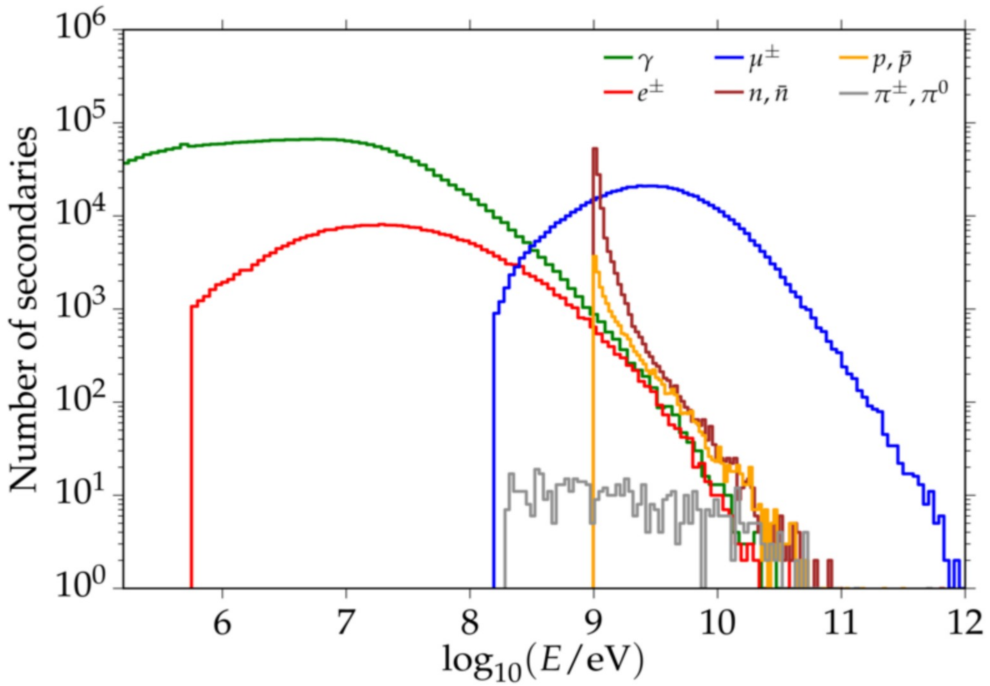


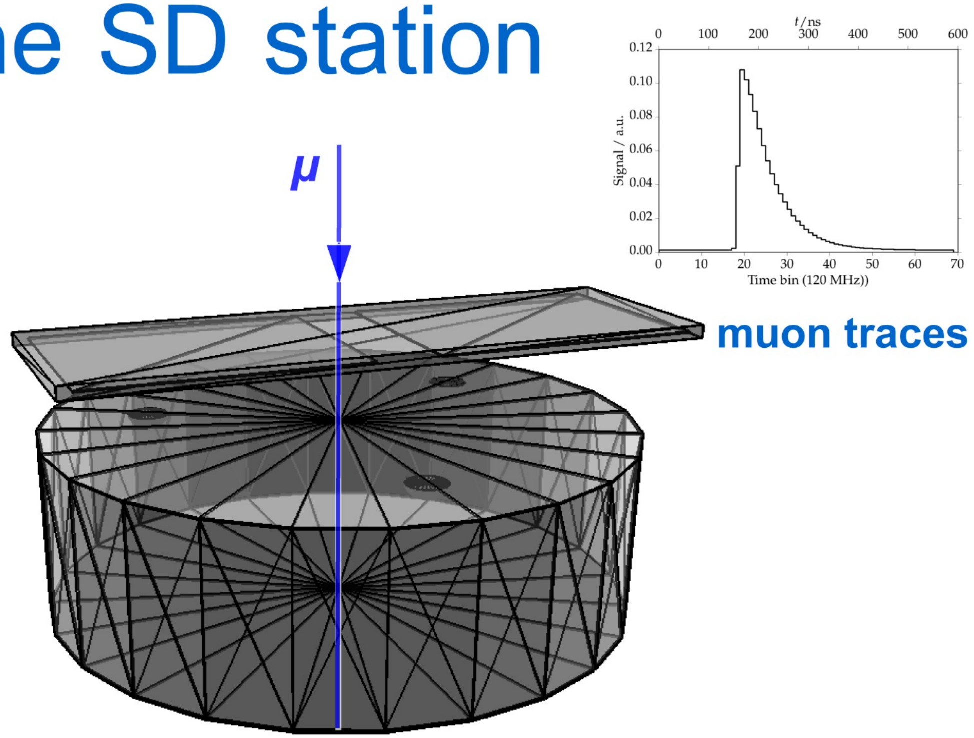
backup


Upgraded WCD
SSD
10^4
10^3
10^2
10^1
10^0
10^{-1}
Signal / Shower size
SD-1500 Reconstruction
$\lg(E_{\min}/\mathrm{eV}) = 18.5$
$0° \leq \theta \leq 38°$
10^3
Core distance r / m

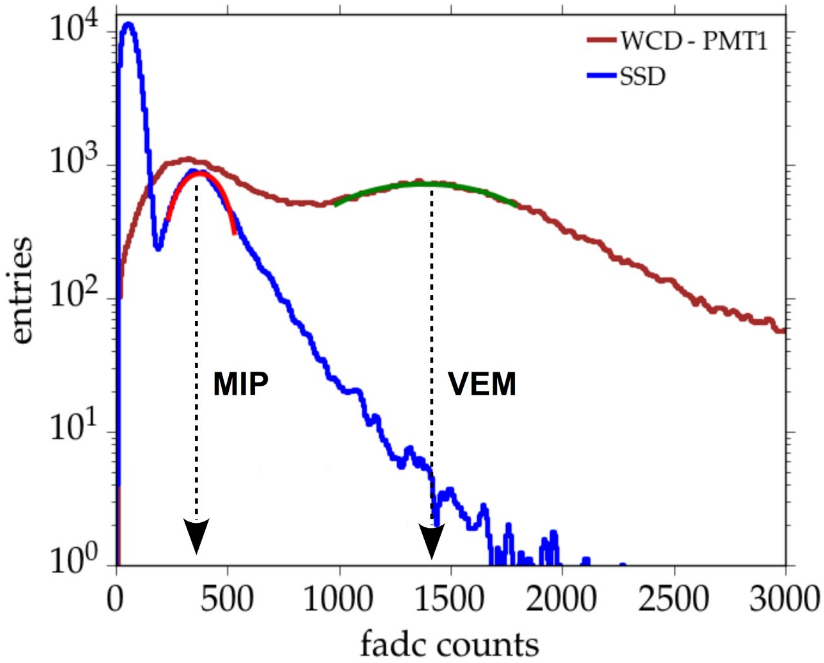
Calibration of the SD station

flux of secondaries from low energy showers





charge histograms



- atmospheric background flux ~1000 particles $m^{-2}\ s^{-1}$
- **histogram** of recorded signals used for **calibration**
- signals expressed in units of:
  - **VEM** (*Vertical Equivalent Muon*) for **WCD** signals
  - **MIP** (*Minimum Ionizing Particle*) for **SSD** signals