

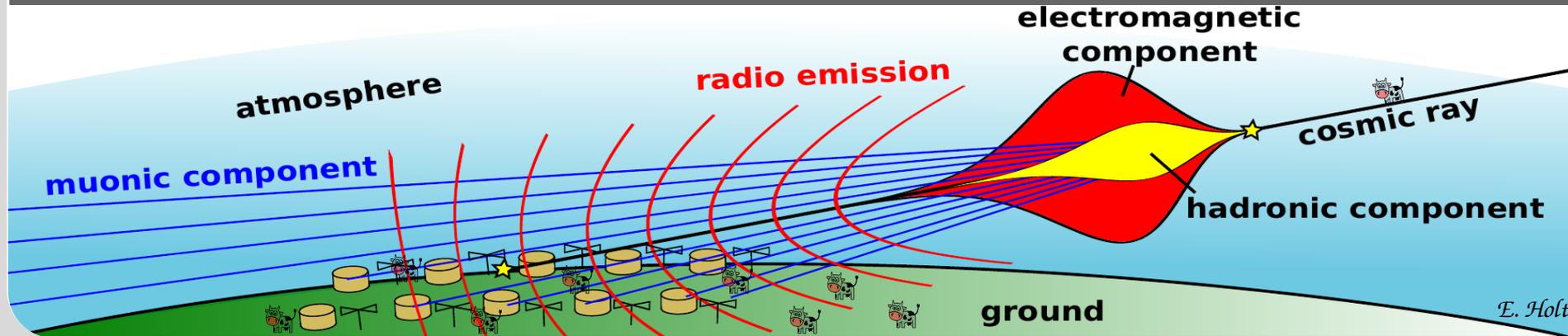
# The AugerPrime Radio Detector

Felix Schlüter for the Pierre Auger Collaboration

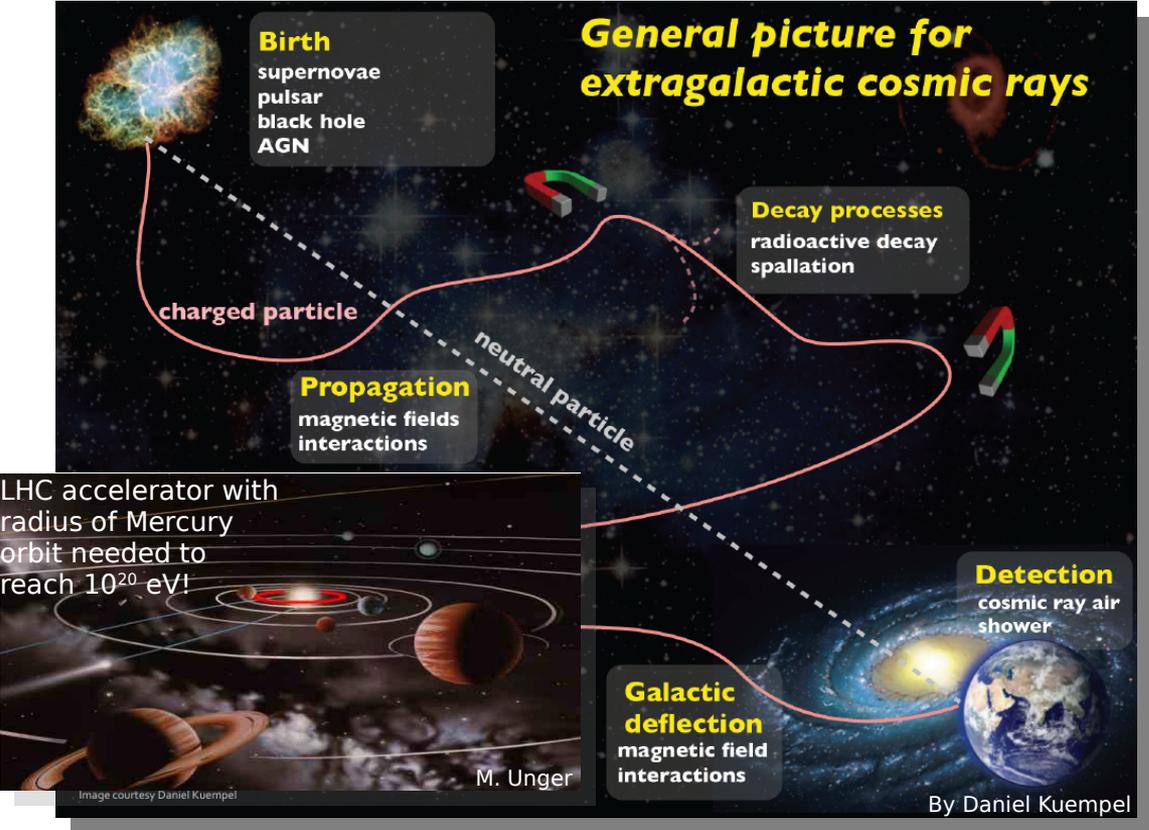
TIPP - Virtual, 25 May 2021

Institute for Astroparticle Physics (IAP)

Instituto de Tecnologías en Detección y Astropartículas (ITeDA)



# Ultra-High Energy Cosmic Ray



## ■ UHECR

- Get deflected by magnetic field
- Rare  $< 1 / (\text{km}^2 \text{ yr})$
- (Relatively) easy & efficient to measure
- Protons, ..., iron nuclei

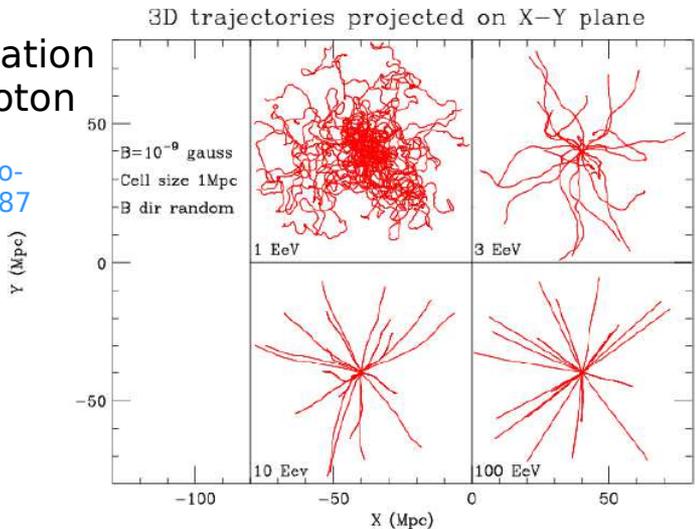
## ■ Open questions:

- Sources
- Acceleration mechanism
- ...

# Key information: Mass (Charge) of UHECR

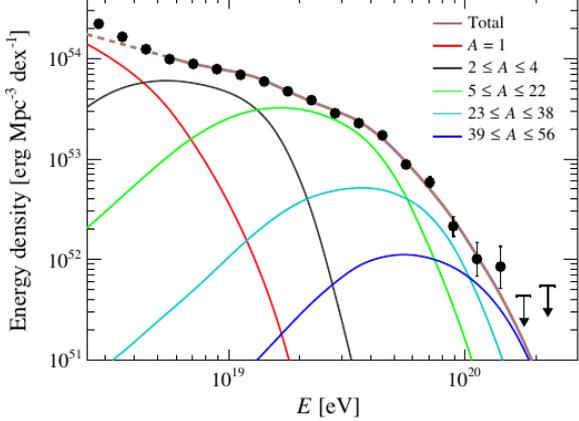
## Propagation of a proton

J. Cronin  
arXiv:astro-ph/0402487



- High energetic protons point back to source (heavy particles still get deflected)
- Separation of protons (light particles) would enable cosmic ray astronomy

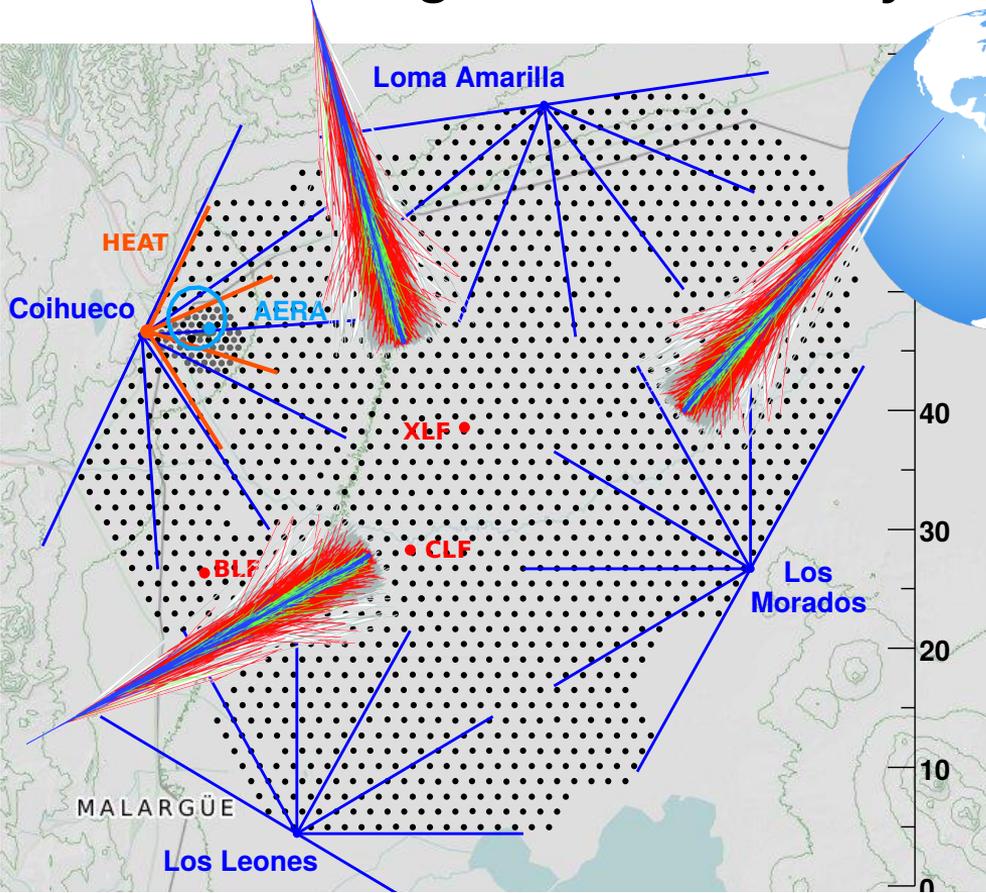
## Energy spectrum



Auger, PRL 125, 121106 (2020)

- Interpretation of energy spectrum depends on mass composition

# The Pierre Auger Observatory

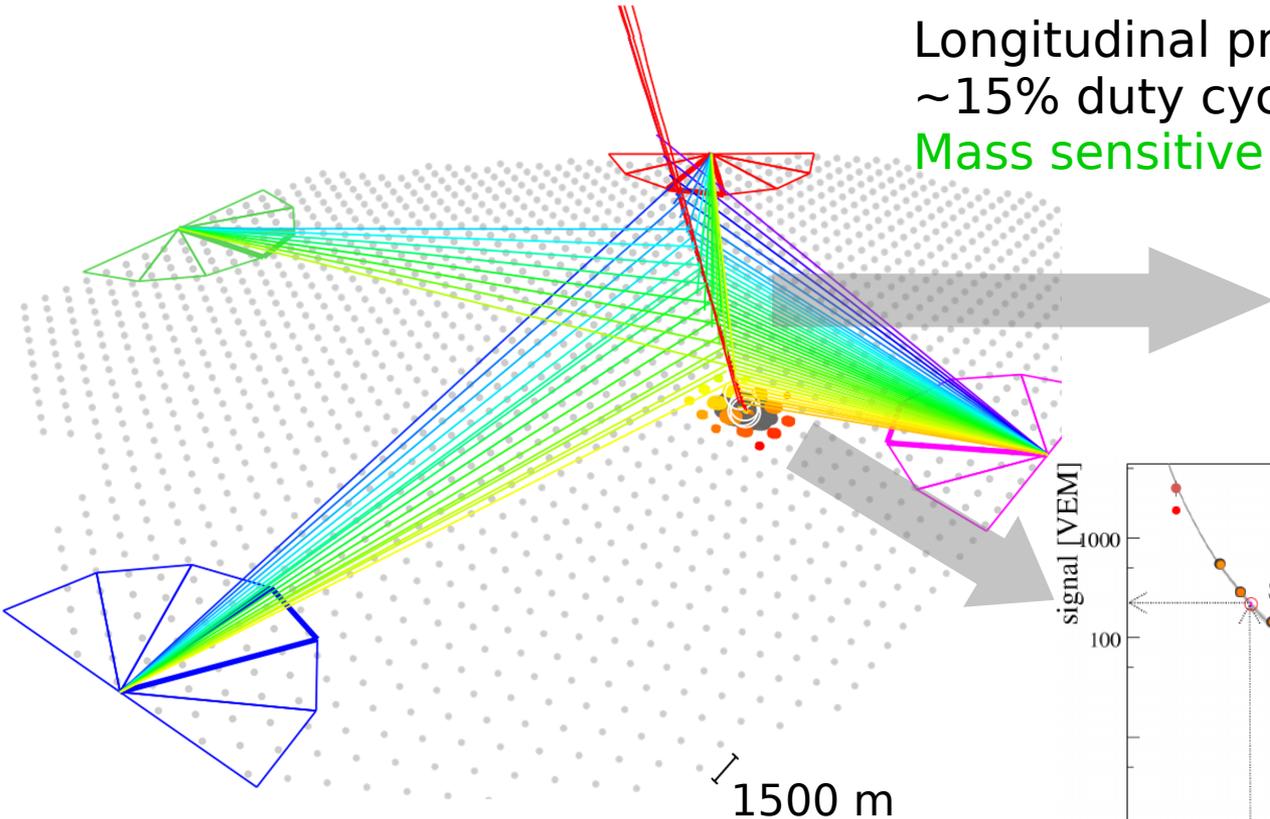


Fluorescence Detector (FD):  
27 telescopes  
at 4 sites

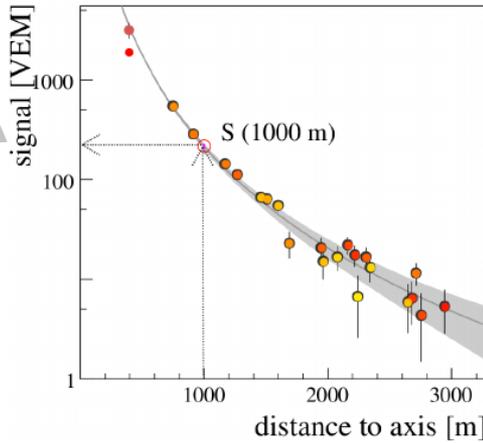
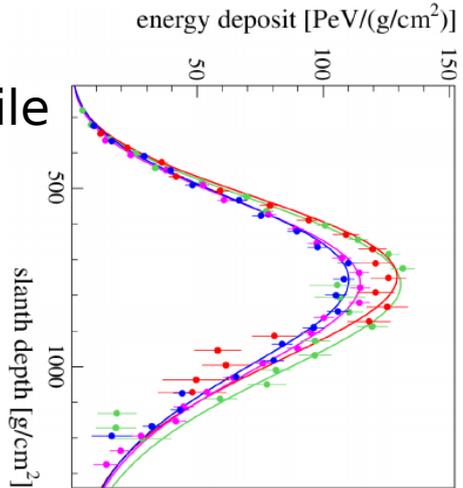
Surface Detector (SD):  
1660 WCD stations  
on 3,000 km<sup>2</sup>

WCD

# Hybrid Detection with Auger

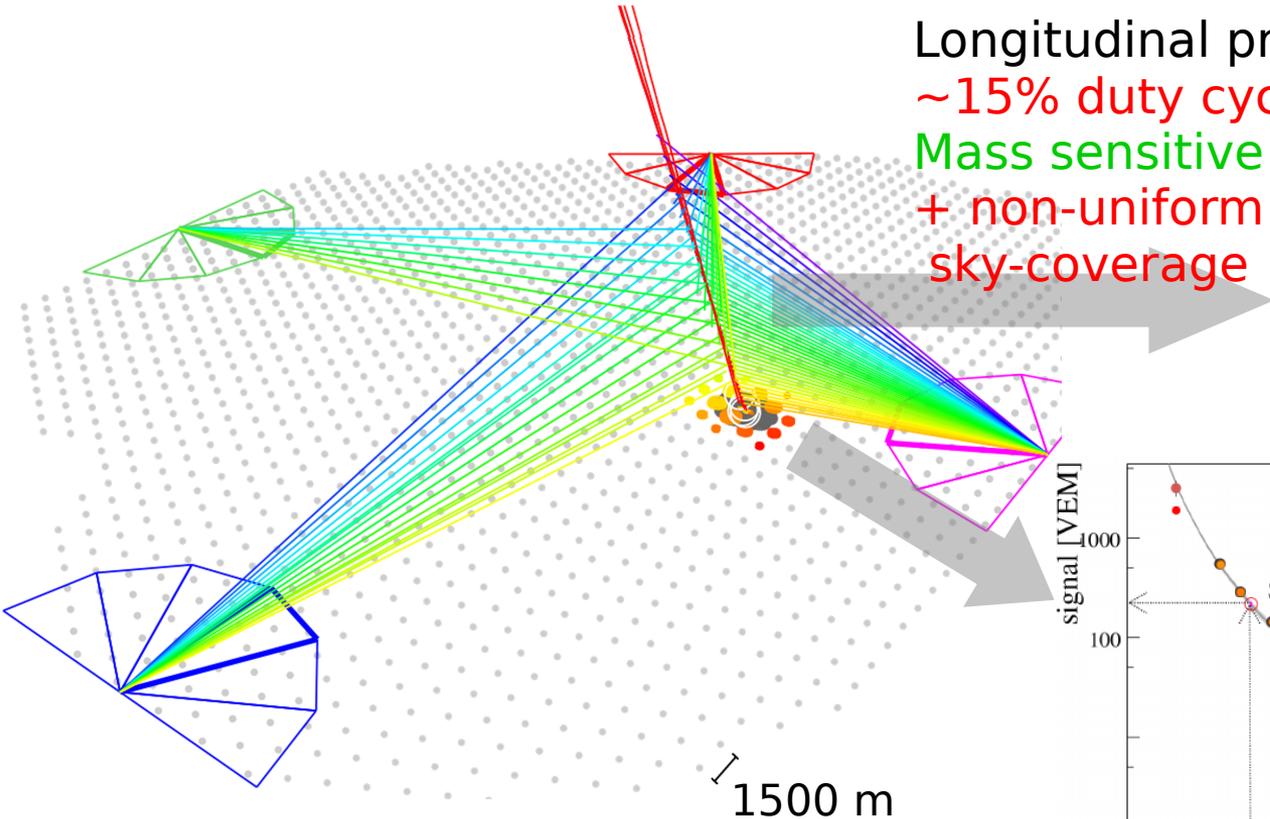


Longitudinal profile  
~15% duty cycle  
Mass sensitive

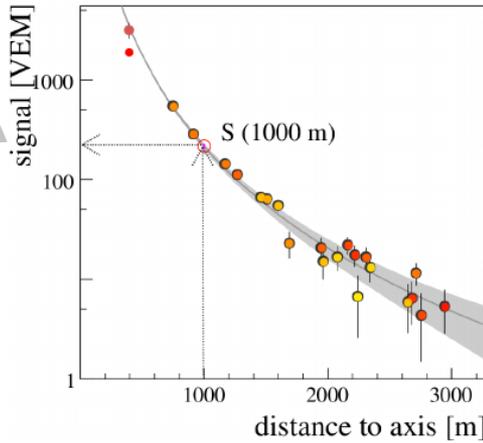
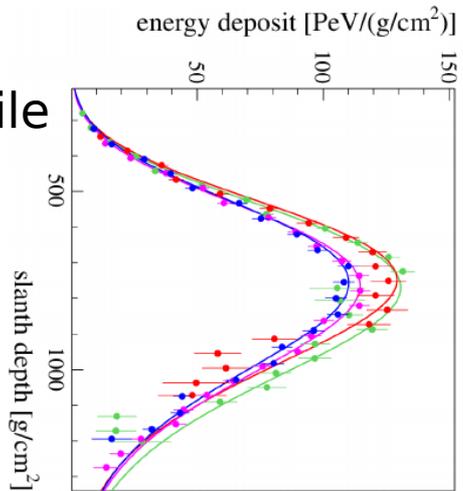


Lateral distribution  
~ 100% duty cycle  
Mass insensitive

# Hybrid Detection with Auger



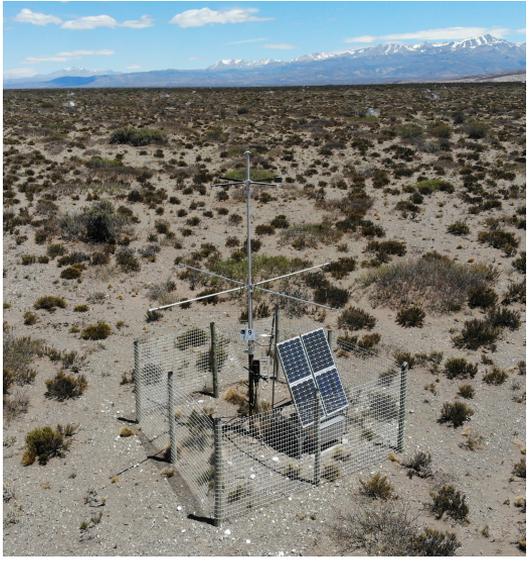
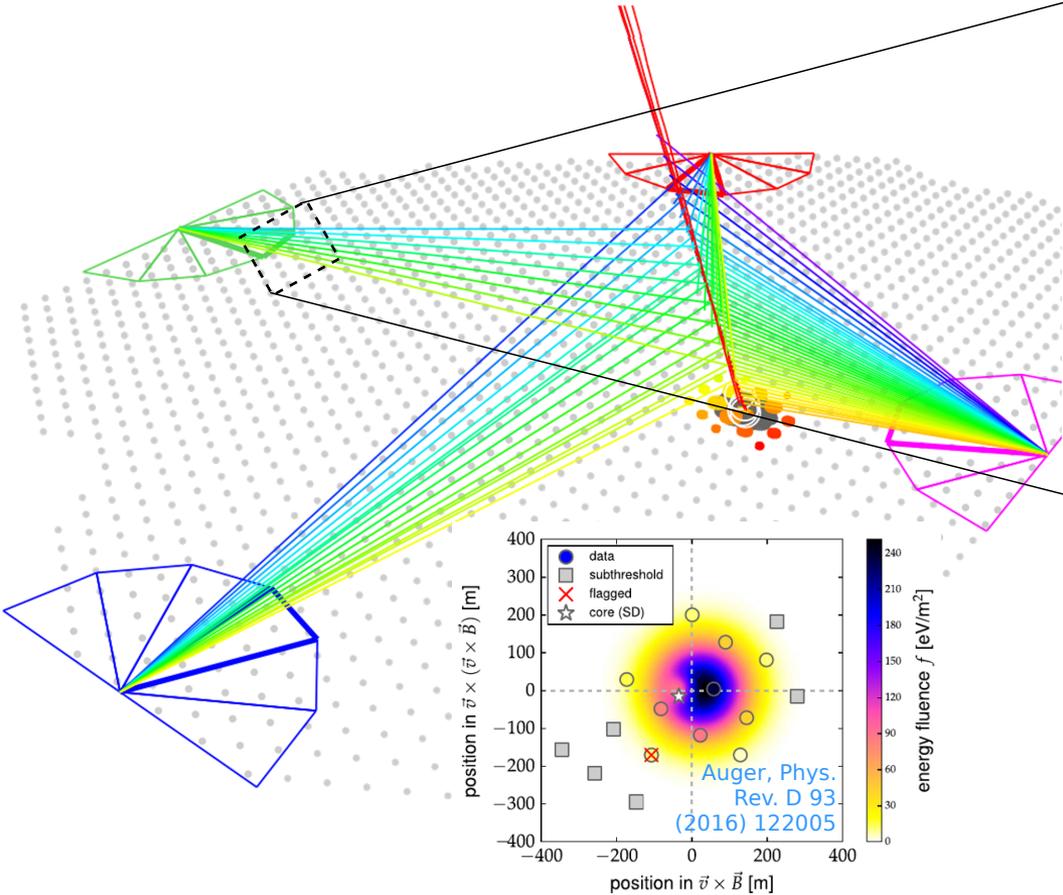
Longitudinal profile  
~15% duty cycle  
Mass sensitive  
+ non-uniform sky-coverage



Lateral distribution  
~ 100% duty cycle  
Mass insensitive

# Radio at Auger: AERA

## Auger Engineering Radio Array



Operation since 2010,  
153 antennas, 17  $\text{km}^2$ :

- Vertical showers ( $< 60^\circ$ )
- $\lg(E/\text{eV}) = 17.5 - 18.5$
- First inclined air showers detected [Auger, JCAP 10 \(2018\) 026](#)

# AugerPrime

Goal: Mass sensitive measurement  
with large exposure & sky-coverage

➔ Muon-Electron separation



# AugerPrime

Goal: Mass sensitive measurement  
with large exposure & sky-coverage

➔ Muon-Electron separation

- Surface-Scintillator Detector (**SSD**):  
Muon-electron separation for  
**vertical showers ( $\theta \lesssim 55^\circ$ )** (see  
poster 426, tomorrow 26.5)

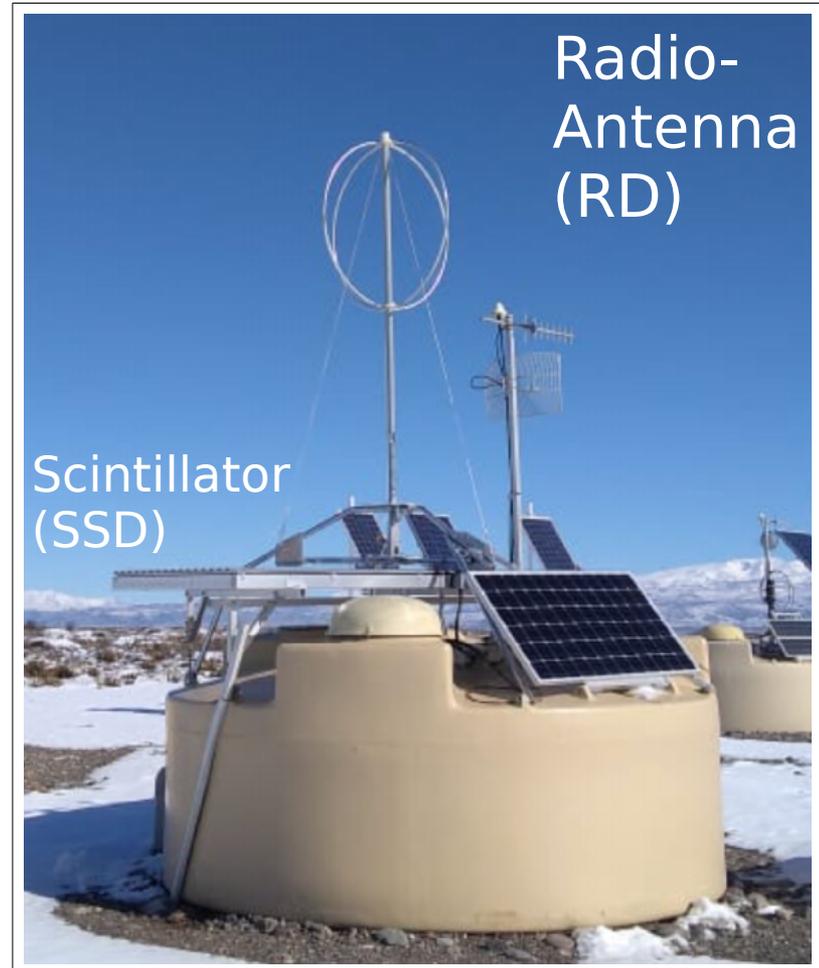


# AugerPrime

Goal: Mass sensitive measurement with large exposure & sky-coverage

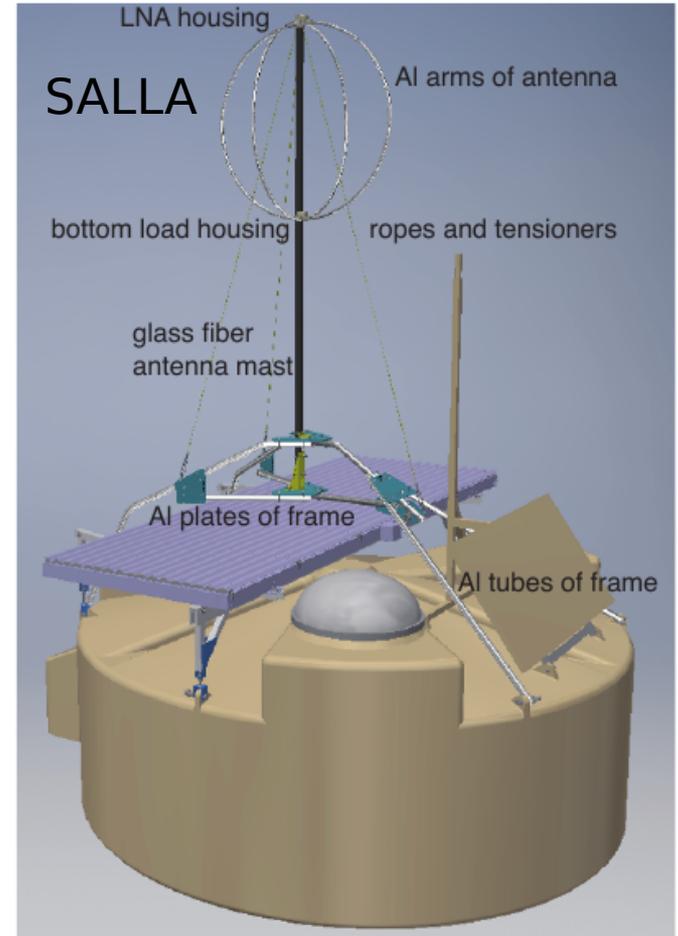
➔ Muon-Electron separation

- Surface-Scintillator Detector (**SSD**): Muon-electron separation for **vertical showers ( $\theta \lesssim 55^\circ$ )** (see poster 426, tomorrow 26.5)
- The Radio Detector (**RD**): Muon-electron separation for **inclined showers ( $\theta \gtrsim 65^\circ$ )**

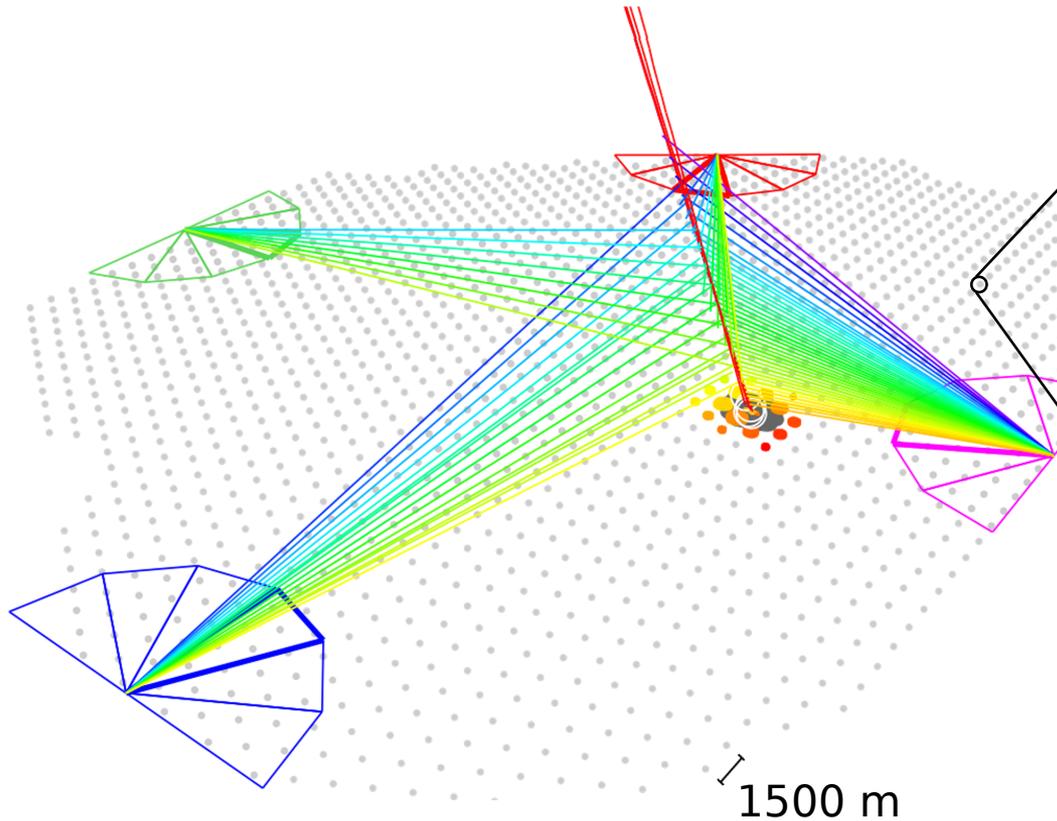


# AugerPrime Radio Detector

- Fully integrated in existing infrastructure
  - Triggering and DAQ from SD
- Short Aperiodic Loaded Loop antennas (SALLAs)
  - Di-polarized signals in 30-80 MHz, sampled with 250 MHz
  - Refined design for higher sensitivity
- Energy and band-width budget:
  - Solar powered: budget < 3W
  - 20+ year-old wire-less COMMS



# AugerPrime Radio Detector



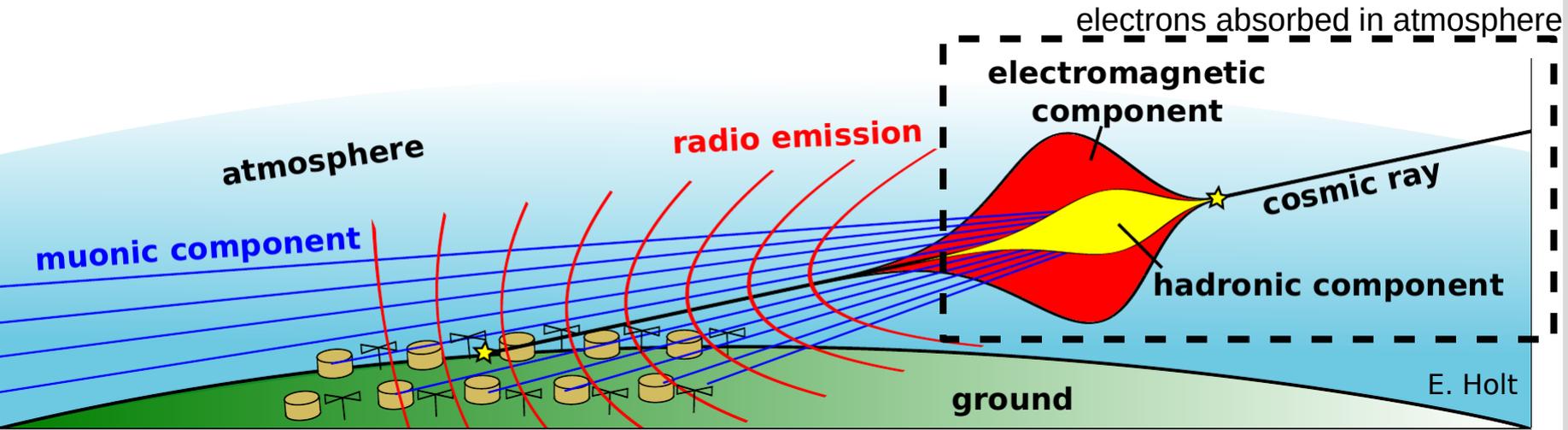
x 1660



- Deployment ~ 2021 - 2023  
1660 antennas, 3000 km<sup>2</sup>:
- Inclined showers ( $> 65^\circ$ )
  - $\lg(E / \text{eV}) \gtrsim 18.8$

# Inclined air showers with AugerPrime

- Goal: Disentangle **muonic** and **electromagnetic** shower components

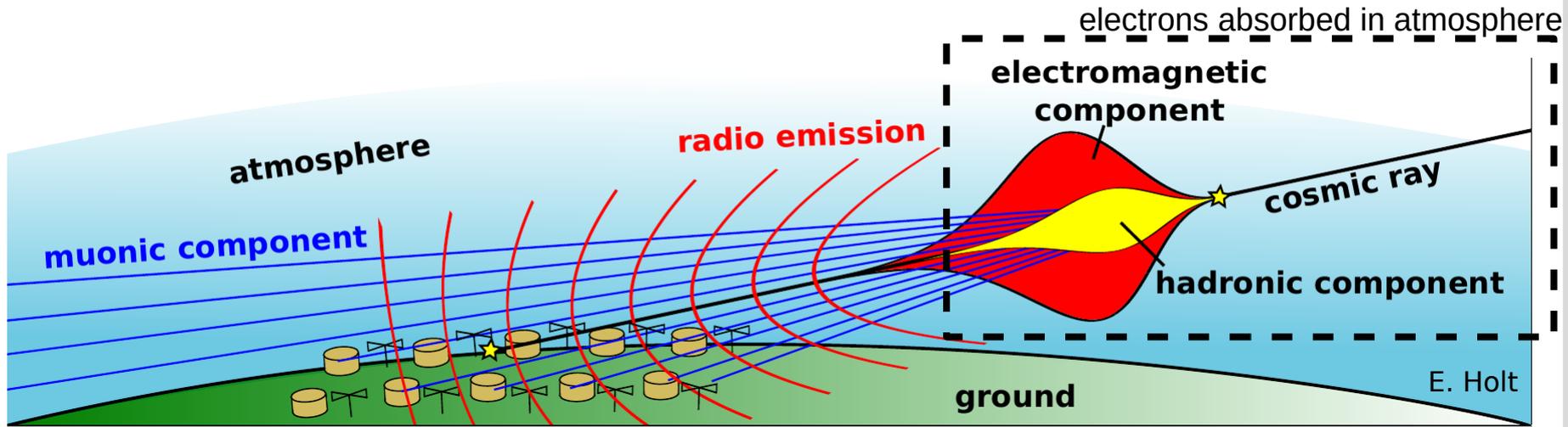


- **Muonic component** via water-Cherenkov tanks

- **Electromagnetic component** via radio antennas

# Inclined air showers with AugerPrime

- Goal: Disentangle **muonic** and **electromagnetic** shower components

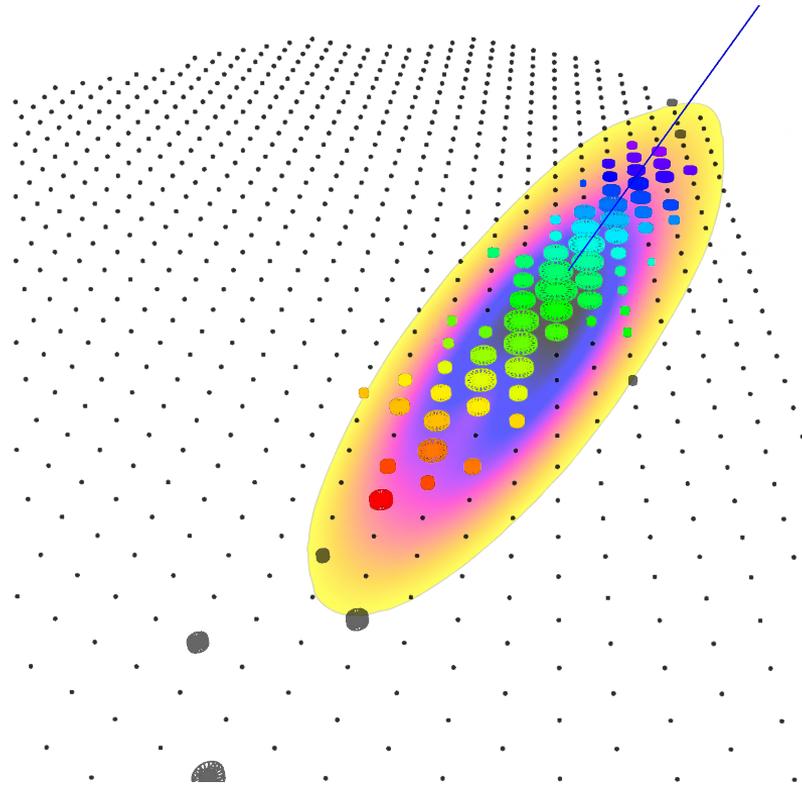


- **Muonic component** via water-Cherenkov tanks

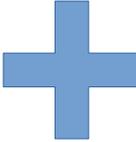
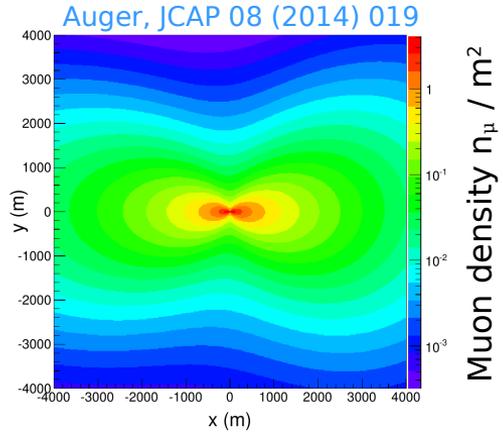
- **Electromagnetic component** via radio antennas

Muon-electron separation by atmosphere → very pure separation 👍

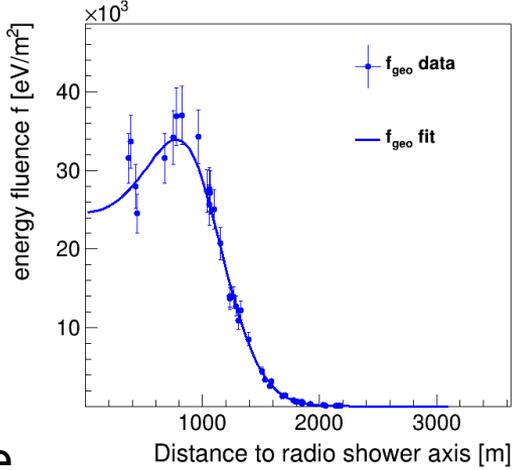
# Inclined air showers with AugerPrime



Muons at ground



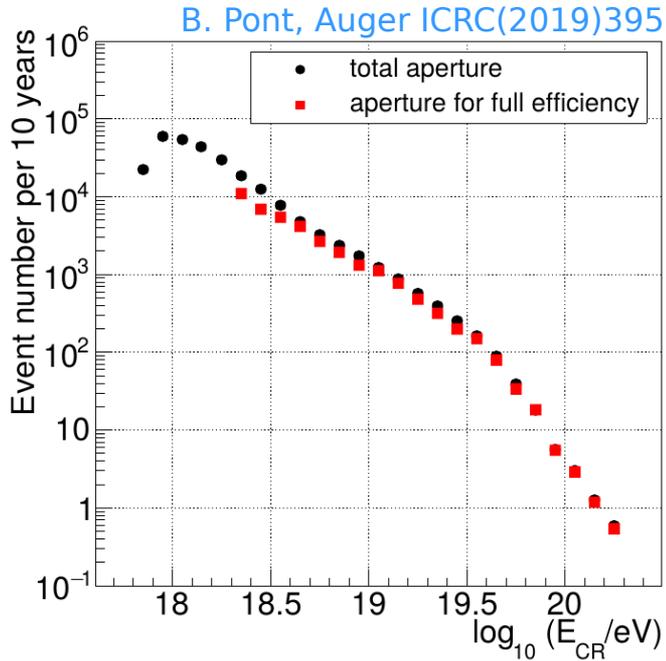
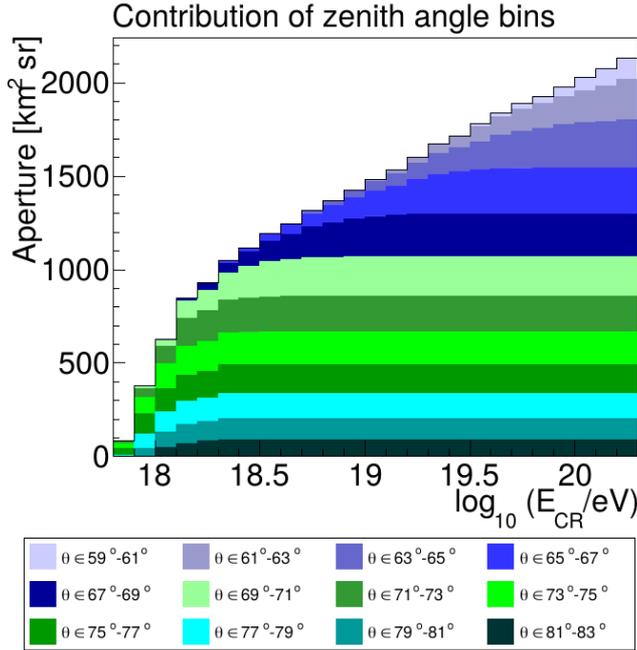
Electromagnetic radiation at ground



Mass sensitivity with  $\sim 100\%$  duty cycle

# Event statistics – 10 years of operation

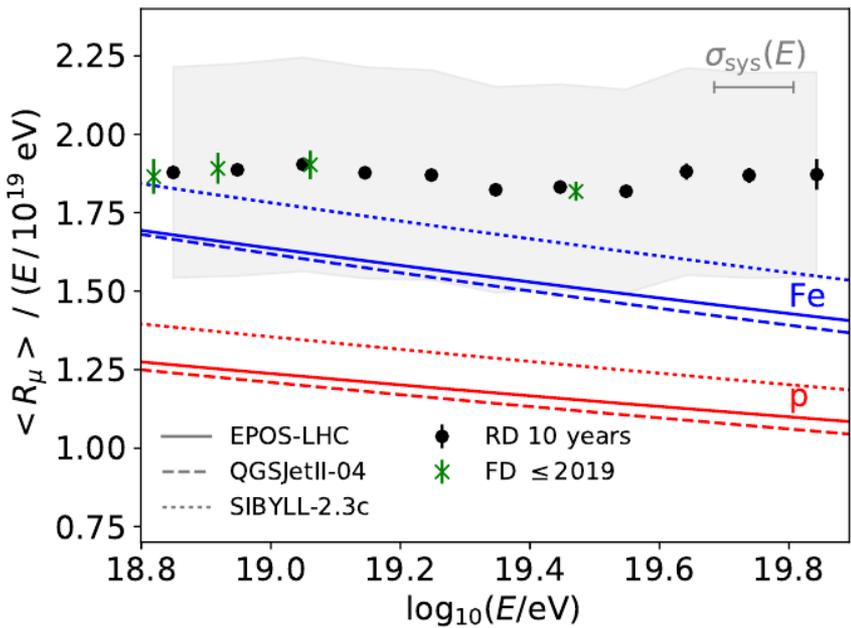
- Efficiency estimated with LDF model
- Aperture for 3000km<sup>2</sup> array
- Using measured Auger flux → Expected event statistics



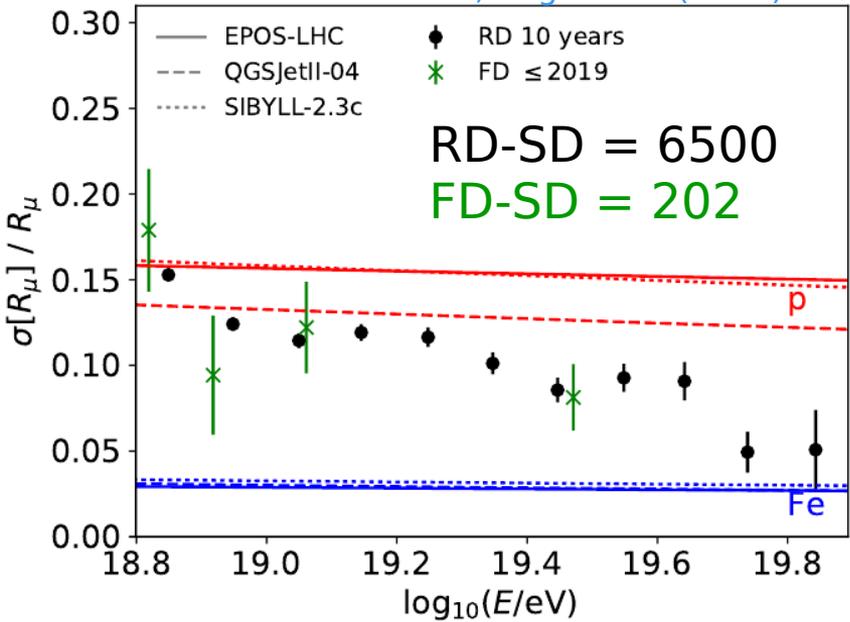
→ in 10 years: 6500 events with  $\lg E > 18.8$

# Measurement of the muon number $R_\mu$

- Composition sensitive variable
- RD: Toy data (inter-/extrapolation of FD data) with expected 10-year statistics – demonstrate statistical accuracy

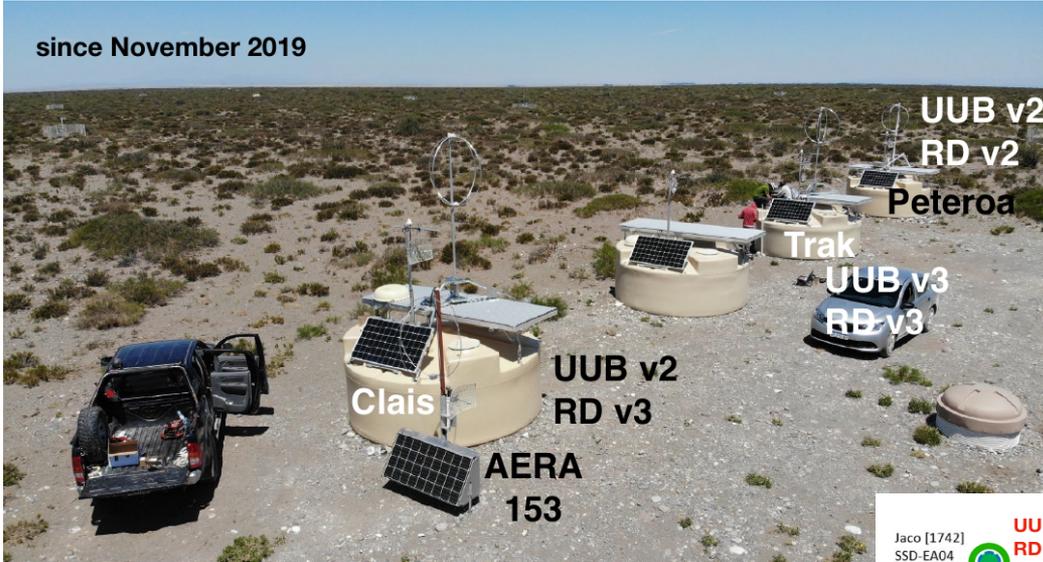


B. Pont, Auger ICRC(2019)395



# RD Engineering Array

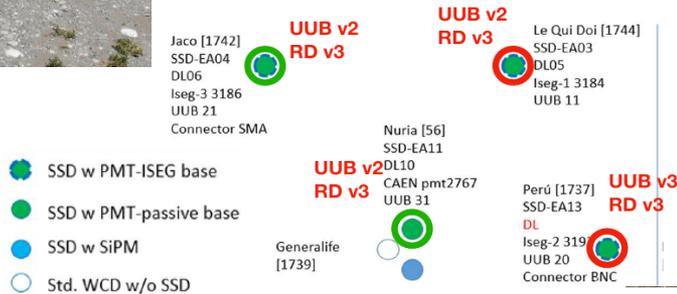
Antennas deployed in test area



4 Antennas in regular array (2 triangle) with readout electronics

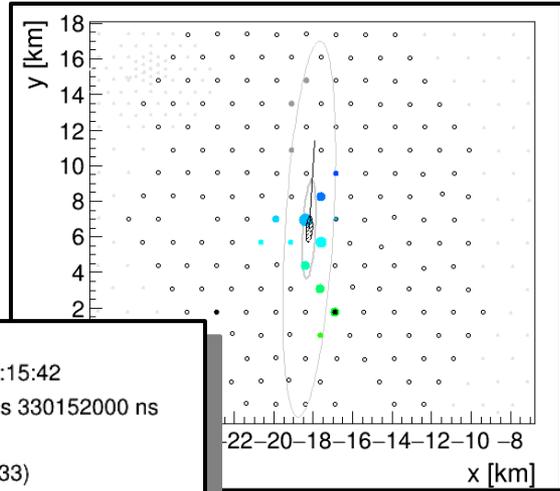


10 antennas in final design by the end of July



# First Air Showers

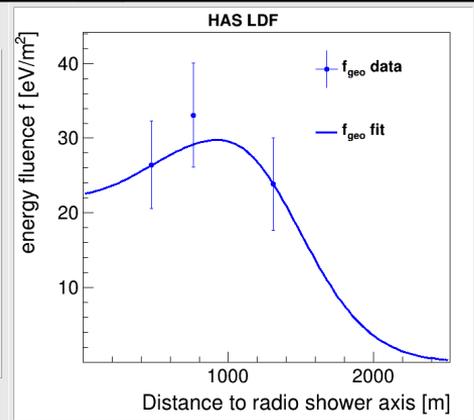
“air-shower signal in 3 antennas in coincidence with the SD”



```

pions |
4+/-34.3 muV/m  24.2+/-13.3 eV/m^2  SNR=48  d=1288.63 m
32.4 muV/m  30.7+/-9.2 eV/m^2  SNR=67.5  d=454.24 m
93.7+/-36.1 muV/m  35.8+/-17.3 eV/m^2  SNR=75.4  d=725.372 m
59.8 muV/m  2.1+/-0.8 eV/m^2  SNR=4.7  d=2104.8 m

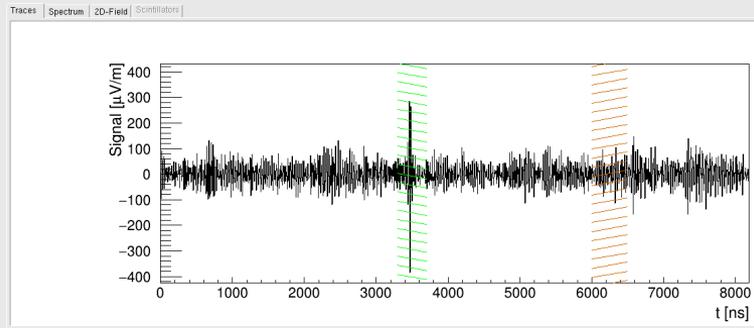
beta = not calculated  Time Residual = 0 +/- 13.5 ns
n Status: not rejected  Saturation Status: not saturated
Peak = 3472 ns  Signal Window = [ 3300 ns ... 3700 ns ]
Correction by GPS | Beacon | Calibration: not set | not set | not set
Direction | Observ Angle: not calculated | not calculated  a: not calculated
    
```



**Event 59233851 :-)**  
 Time (UTC): 2020/7/16 22:15:42  
 Time (GPS): 1278972960 s 330152000 ns  
 Trigger: 4C1; 6T5 T5Has  
 Stations: 12 (Acc: 2, Bad: 33)

**Global reconstruction (LDF + axis) (5)**  
 $E = (2.89 \pm 0.65) \times 10^{18} \text{ eV}$   
 $(\theta, \phi) = (83.4 \pm 0.4, 87.0 \pm 0.1) \text{ deg}$   
 $(x, y) = (-18.21 \pm 0.11, 6.43 \pm 0.50) \text{ km}$   
 $N_{19} = 0.5 \pm 0.1$   
 radius =  $99.78 \pm 0.50 \text{ km}$

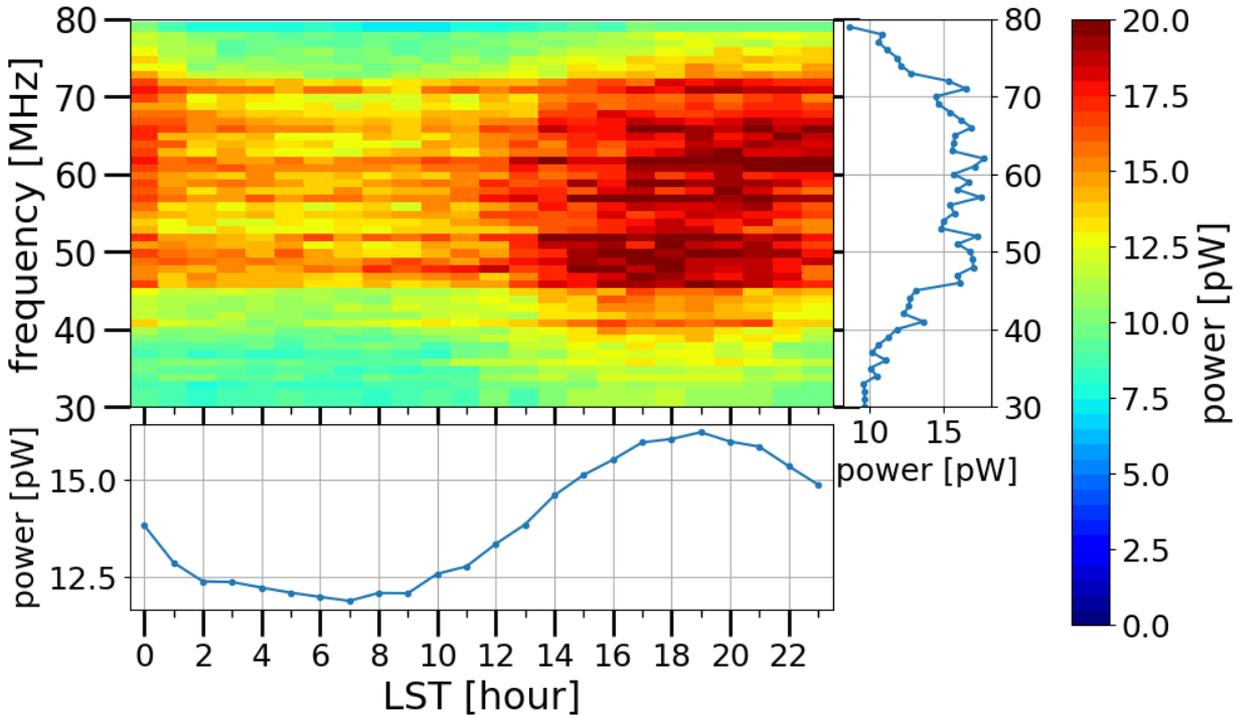
**Monitoring**  
 average stations age: 13.4 yr



“fully calibrated, reconstruction in place!”

# First Measurements of the galactic background

- Emission from galactic center acts as standard candle
  - Modulation with sidereal day
  - Calibration source!



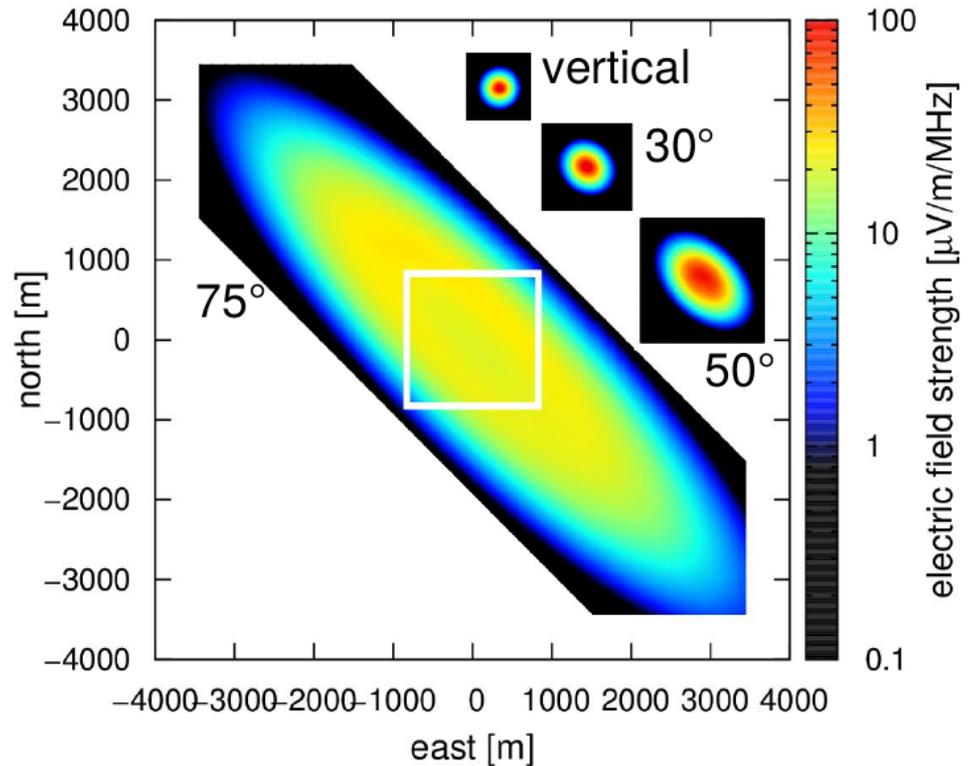
# The AugerPrime Radio Detector

- Design finalized, deployment starts end of the year
- First air shower measured, galactic modulation observed  
→ design works!
- RD will increase AugerPrime sky-coverage of mass sensitive measurements
- Muon-electron separation with RD will provide high-purity, high-statistic measurements of the mean muon number
- Event-by-Event discrimination of protons is under investigation
- Hybrid measurement provide a wealth of information to be exploited in the future

Thanks!

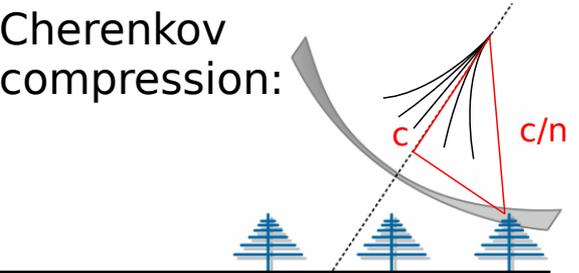
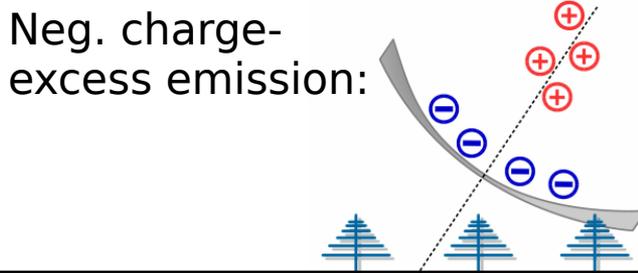
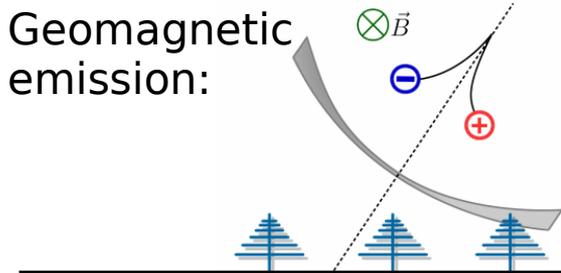
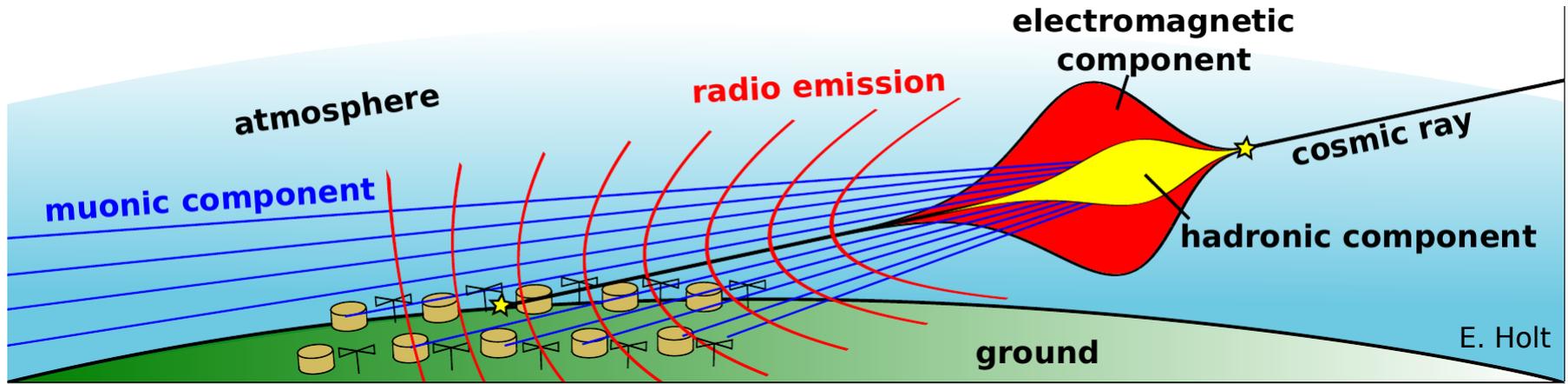
# Inclined air showers with radio

- Vertical: strongly beamed emission
  - small footprint
  - strong signal
- Inclined: strongly projected emission
  - Large footprints
  - weaker signals
- Inclined air shower allow to measure with radio antennas on sparse arrays and large areas to reach high exposure



T. Huege, A. Haungs, UHECR2014, [arXiv:1507.07769](https://arxiv.org/abs/1507.07769).

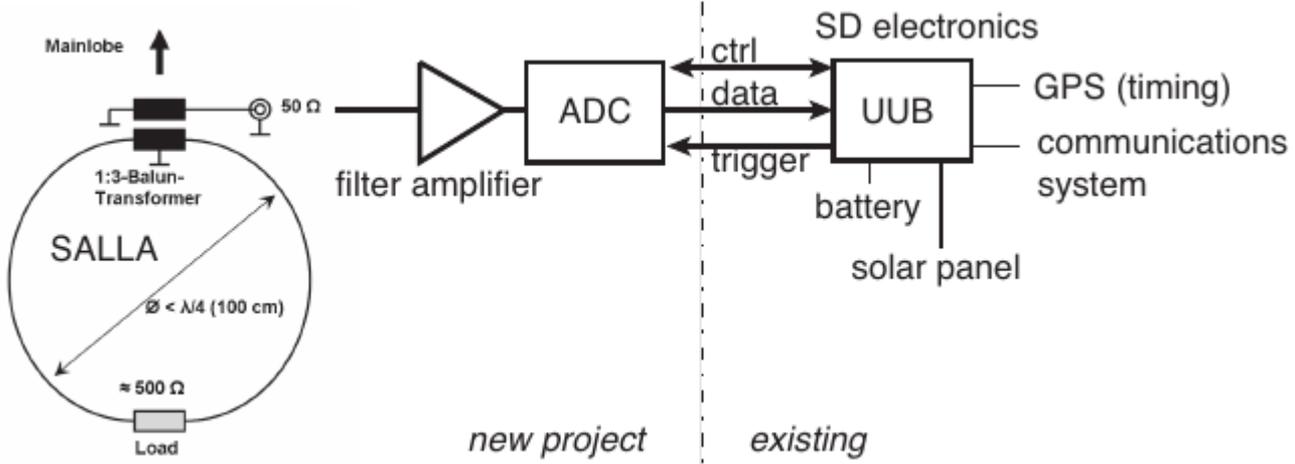
# Inclined air showers with AugerPrime



C. Glaser

# Integration into Auger SD

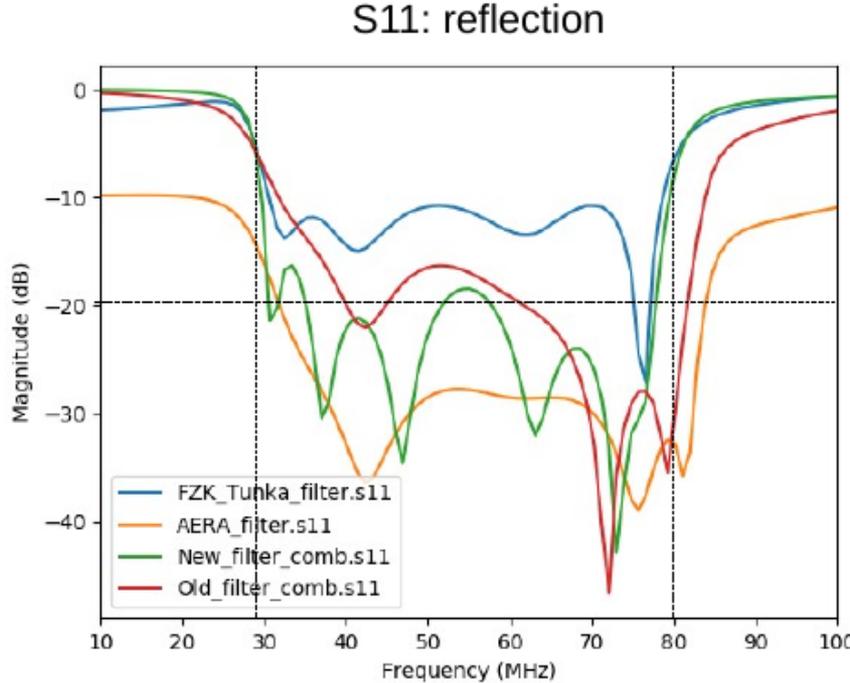
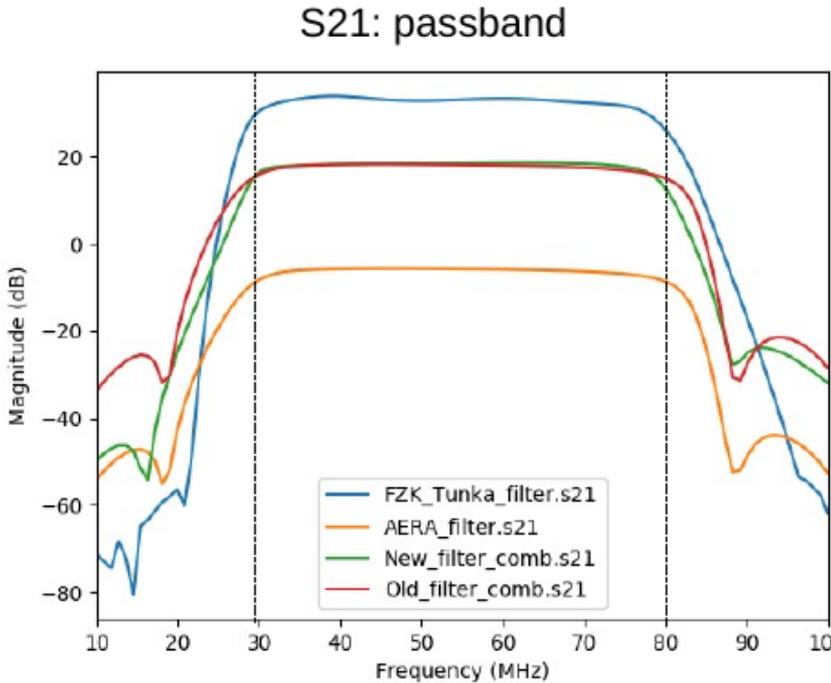
- RD built on top of SD:



SALLA: Initially developed for AERA (Auger) → deployed at Tunka-Rex, → improved design for better signal-to-noise ratio for RD

# Electronic development

Gain is tuned to optimally detect the galactic modulation  
We do not expect saturation to be a problem



2020-03-20

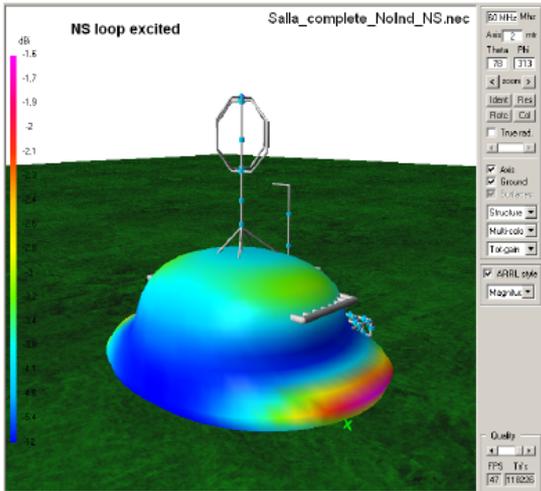
RD electronics update

11

# Antenna response

- Direction sensitivity of antennas are being studied
  - Simulations & Octocopter measurement campaigns

## 4nec2

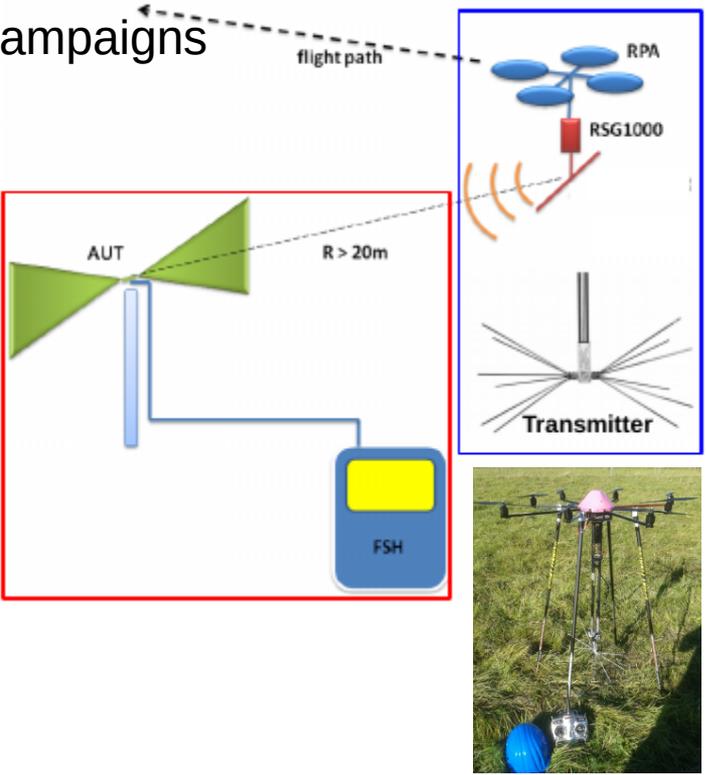


- Measuring transmitted signal 30 – 80 MHz, 5 MHz steps

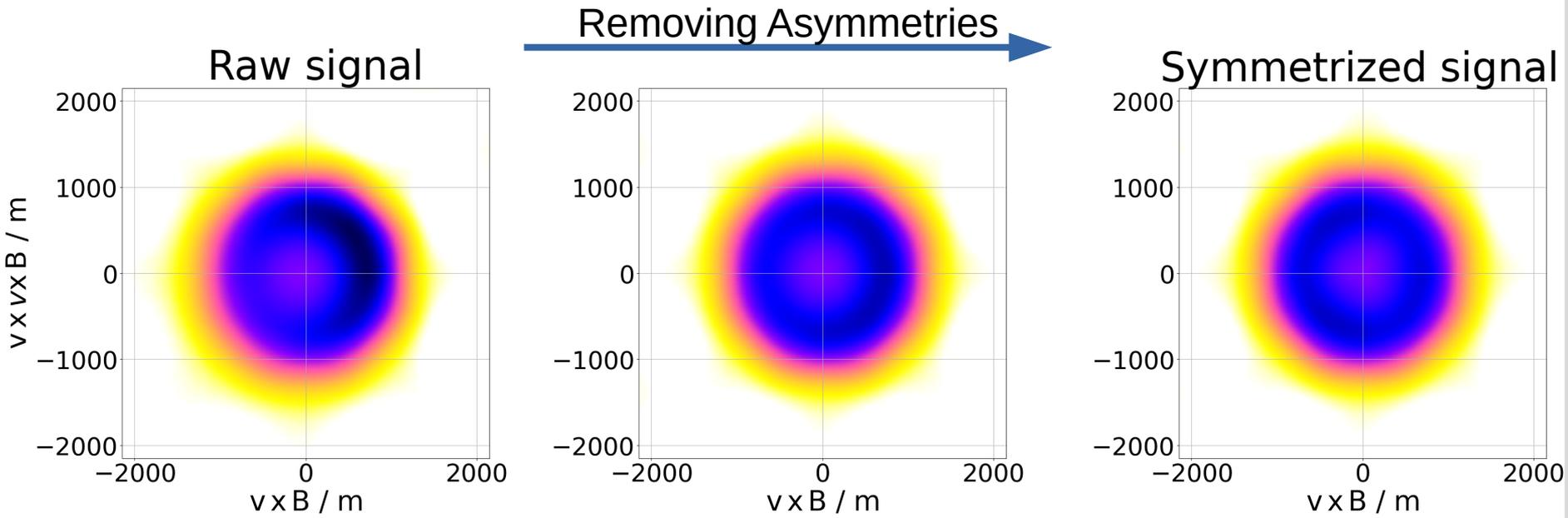
$$|H| = \sqrt{\frac{4 \cdot \pi \cdot Z_A}{Z_0} \cdot R \cdot \sqrt{\frac{P_r}{G_t \cdot P_t}}}$$

- Using octocopter to cover different directions → several flights
- Transmitter alignment ↔ Signal polarization

$$\vec{H} = H_\phi \vec{e}_\phi + H_\theta \vec{e}_\theta$$



# Reconstruction model for inclined air showers



Projecting in shower plane aligned with magnetic field

Correcting for Early-Late Effect:

Subtracting Charge-Excess

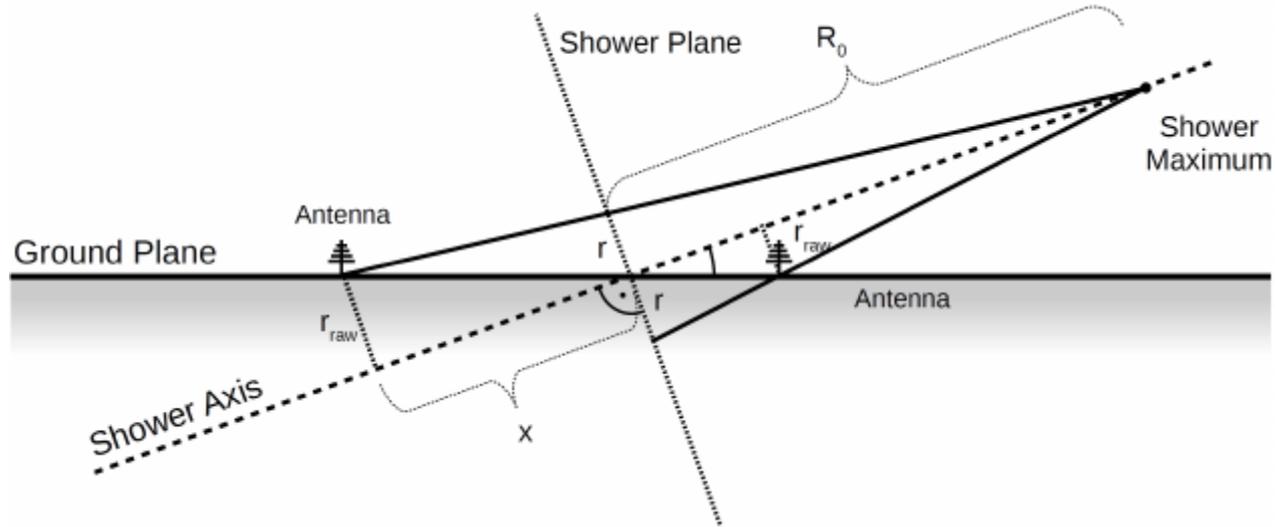
Signal:  $f = f_{vxB}$

$f = f_{vxB} c_{el}$

$f_{geo} = f_{vxB} c_{el} a_{CE}$

# Early-Late Correction

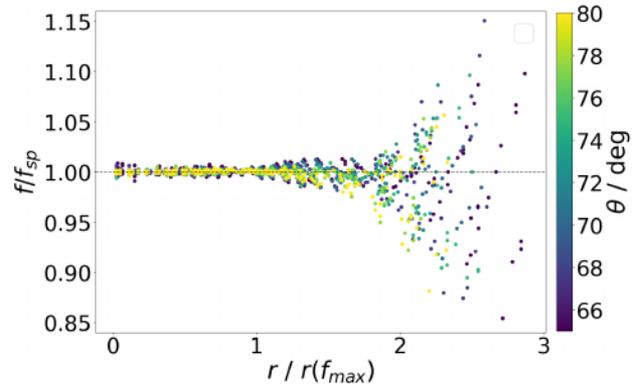
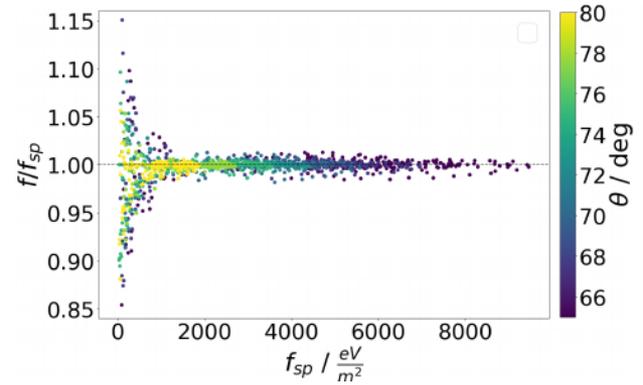
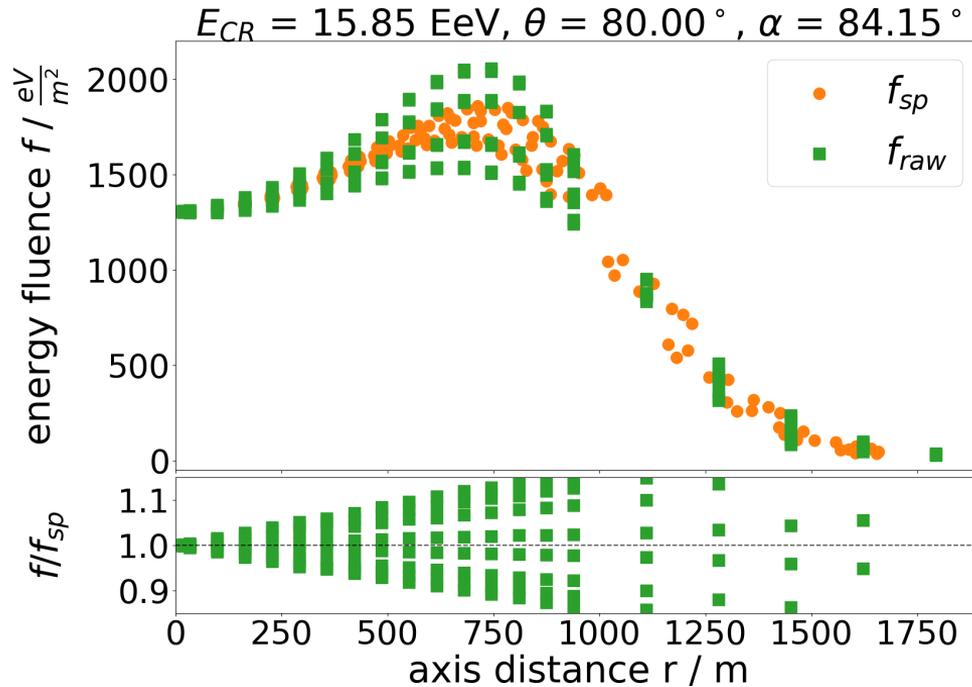
- Correct geometrical projection effects:



$$f = f_{\text{raw}} \cdot \left( \frac{R}{R_0} \right)^2 \quad r = r_{\text{raw}} \cdot \frac{R_0}{R} \quad R \equiv R_0 + x$$

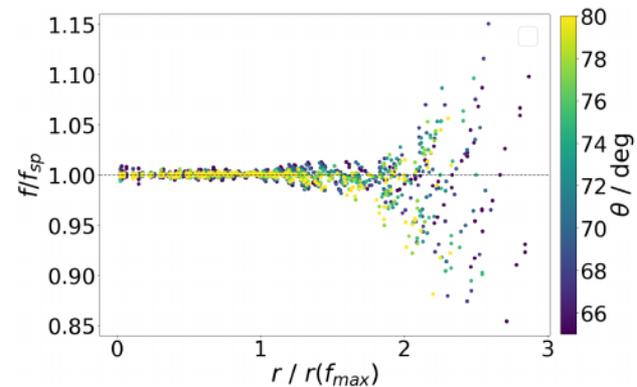
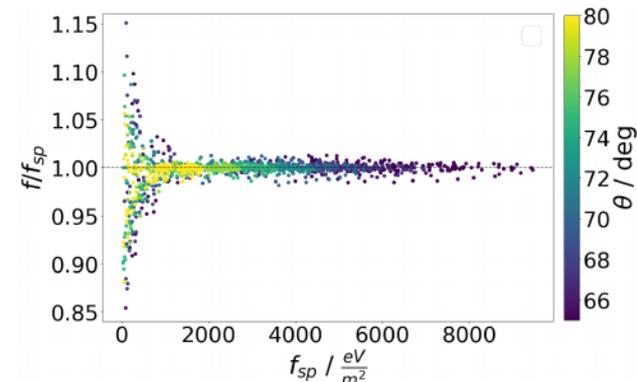
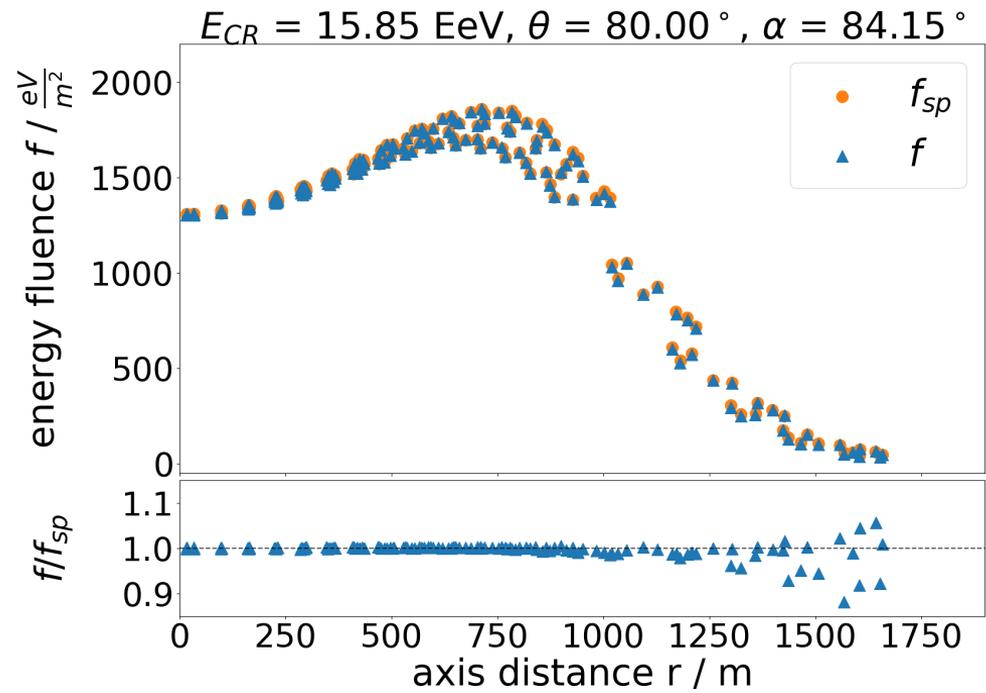
# Early-Late Correction

- Geometric correction with distance to shower maximum  $d_{x_{max}}$

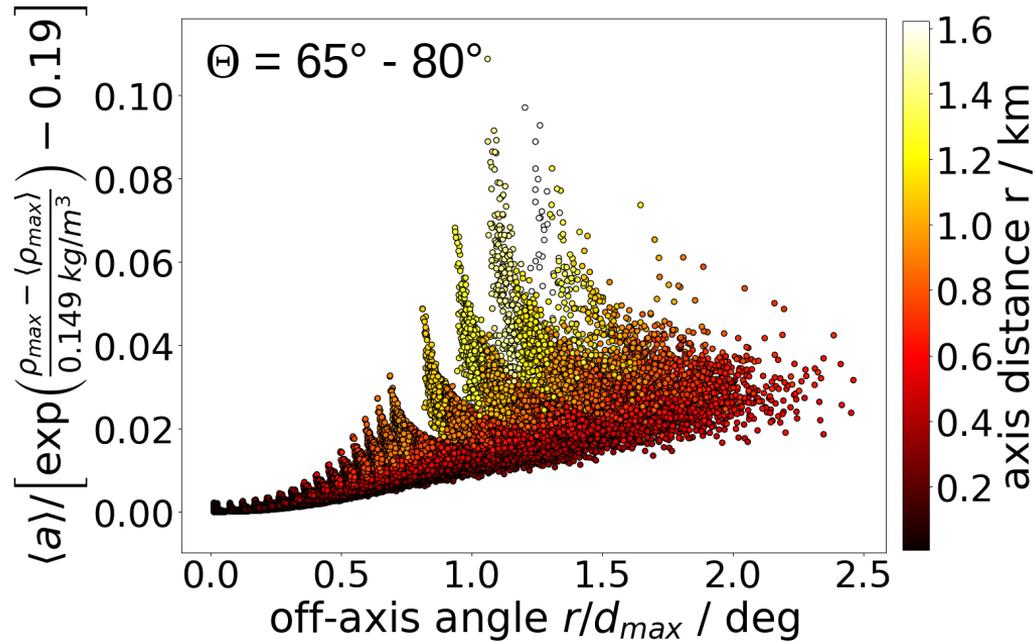


# Early-Late Correction

- Geometric correction with distance to shower maximum  $D_{x_{max}}$



# Charge-Excess Fraction

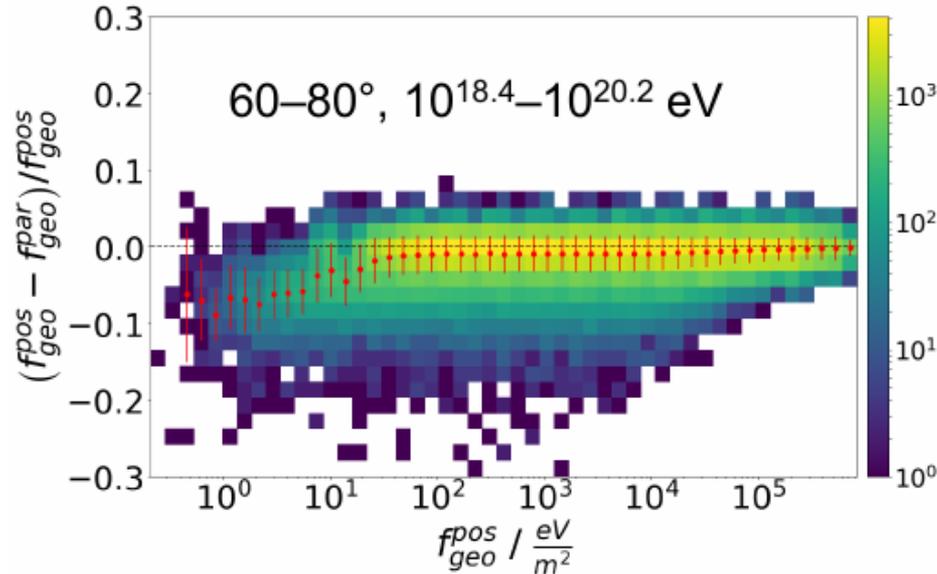


- Charge-Excess fraction determined from simulation
- $a \equiv \sin(\alpha)^2 * f_{CE} / f_{geo}$
- scales with density at shower maximum
- Parametrized with distance to shower maximum

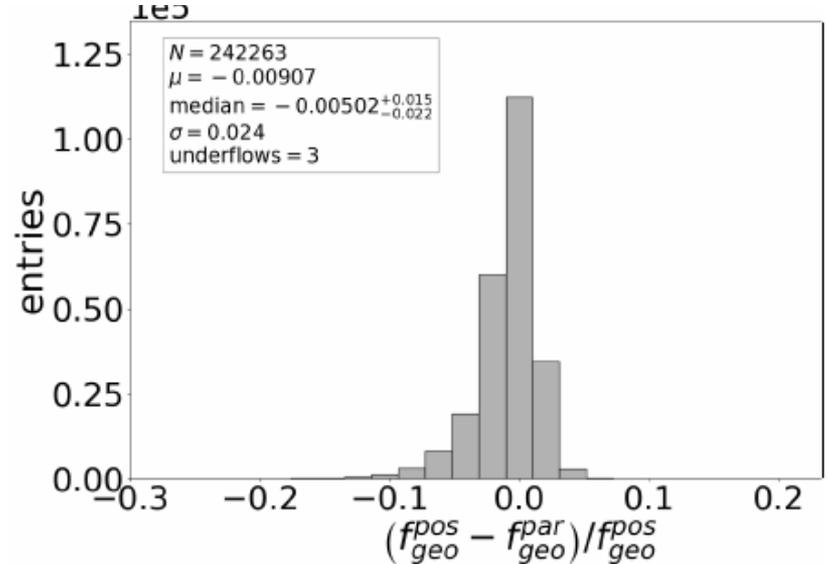
$$a(r, d_{max}, \rho_{max}) = 0.373 \cdot \frac{r}{d_{max}} \cdot \exp\left(\frac{r}{762.6 \text{ m}}\right) \cdot \left[ \exp\left(\frac{\rho_{max} - \langle \rho_{max} \rangle}{0.149 \text{ kg/m}^3}\right) - 0.189 \right]$$

off-axis angle
axis distance
atmospheric density correction

# Overall performance of symmetrization



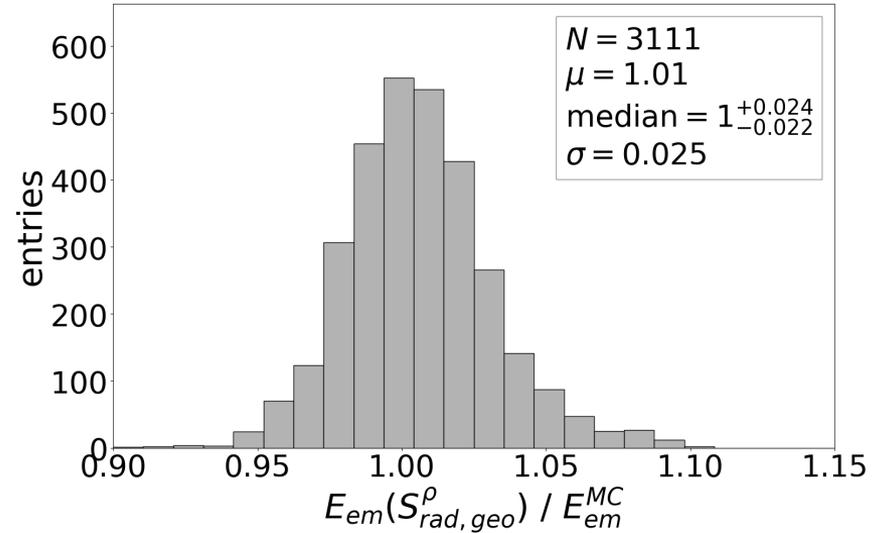
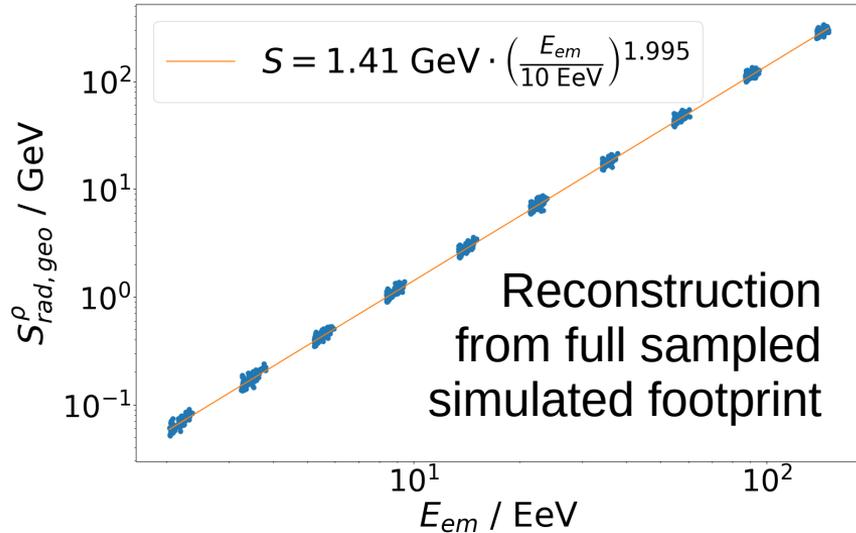
$$f_{\text{geo}}^{\text{par}} = \frac{f_{\mathbf{v} \times \mathbf{B}}}{\left(1 + \frac{\cos(\phi)}{|\sin(\alpha)|} \cdot \sqrt{a(r, d_{\text{max}}, \rho_{\text{max}})}\right)^2}$$



- average bias for all showers is below 1%, spread below 2.5%
- deviations from true geomagnetic energy fluence only at small values (not relevant for the radiation energy integration)

T. Huege, FS, L. Brenk  
POS(ICRC2019)294

# Energy reconstruction via integrated geomagnetic radiation energy

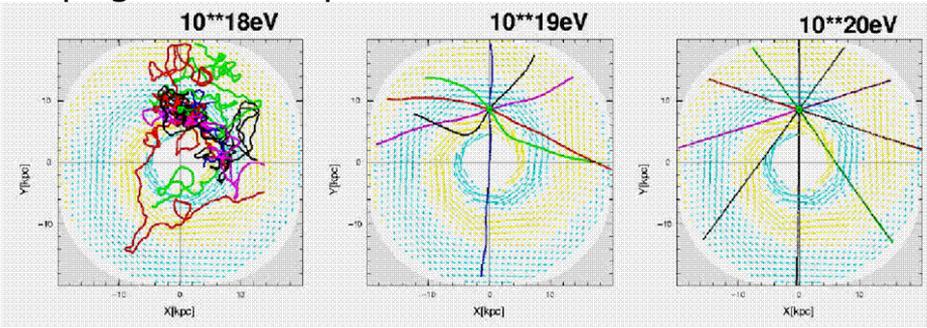


- density-corrected geomagnetic radiation energy correlates well with energy in the electromagnetic cascade, spread smaller than 3%

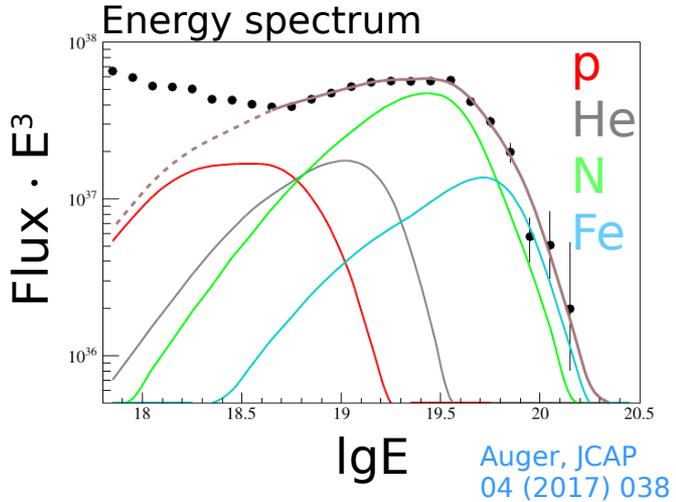
$$S_{rad,geo}^\rho = \frac{E_{rad}^{geo}}{\sin^2(\alpha)} \cdot \frac{1}{1 - p_0 + p_0 \cdot \exp[p_1 \cdot (\rho - \langle \rho \rangle)]}$$

# Key information: Mass of UHECR

Propagation of a proton



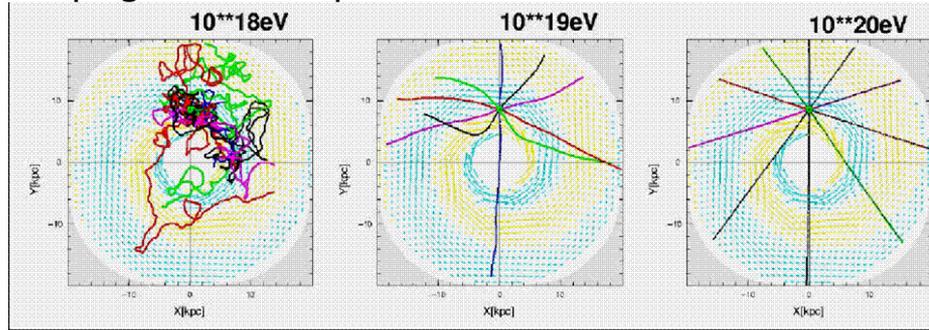
- High energetic protons point back to source (heavy particles still get deflected)
- Separation of protons (light particles) would enable cosmic ray astronomy



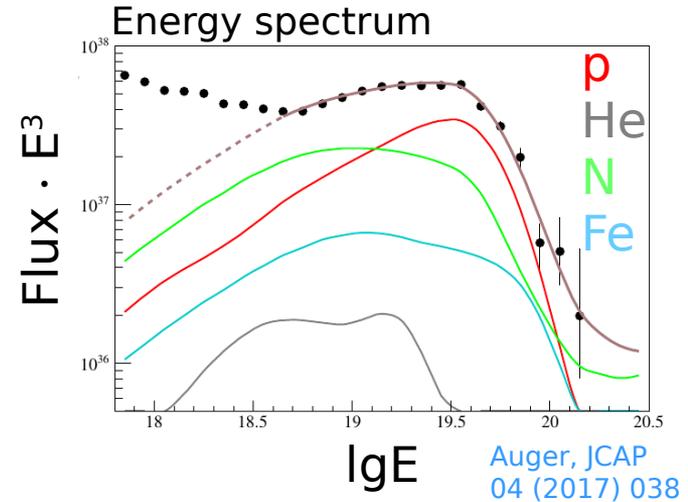
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