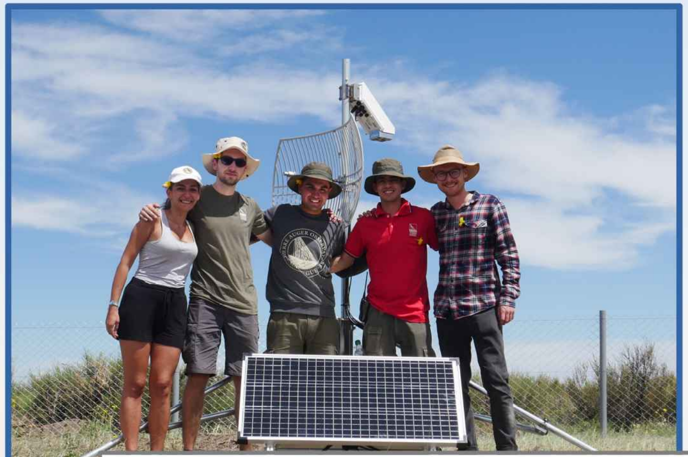
Karlsruhe Institute of Technology

UNSAM

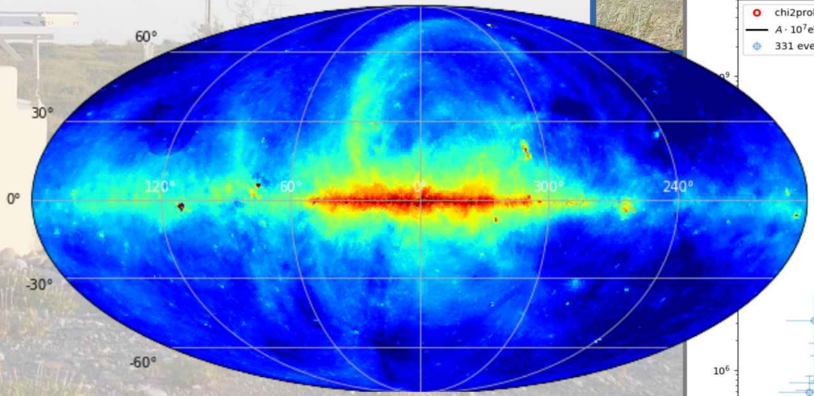
PIERRE AUGER OBSERVATORY

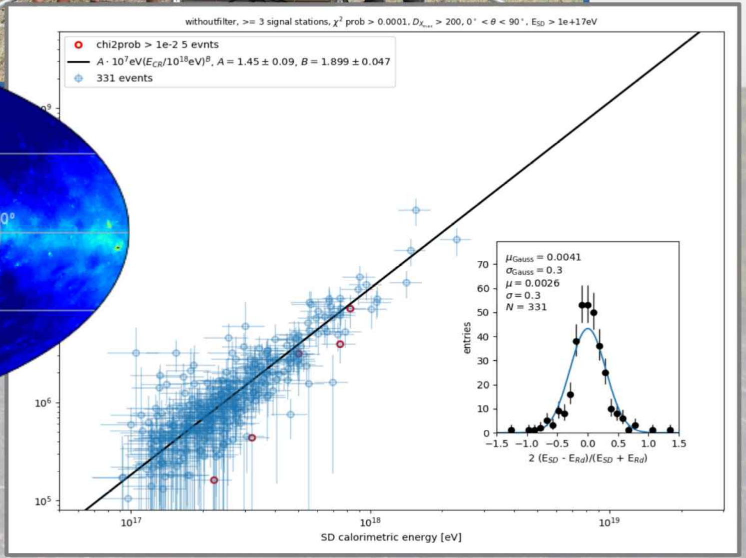
HIRSAP

Absolute measurements for and with the radio detectors at the Pierre Auger Observatory



KSETA Plenary Workshop
27th March 2023



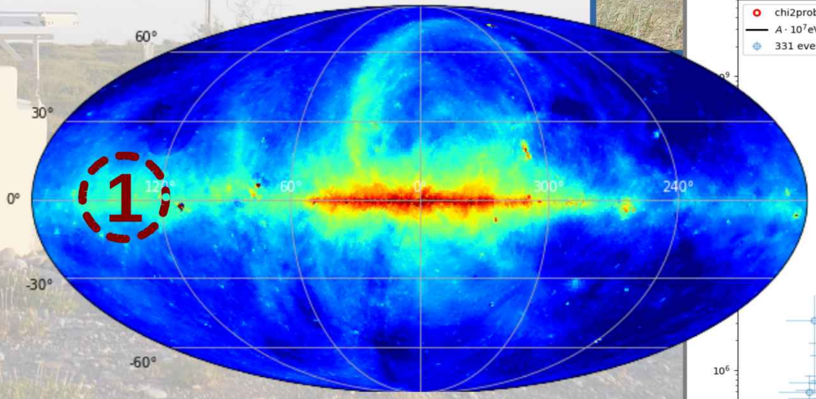


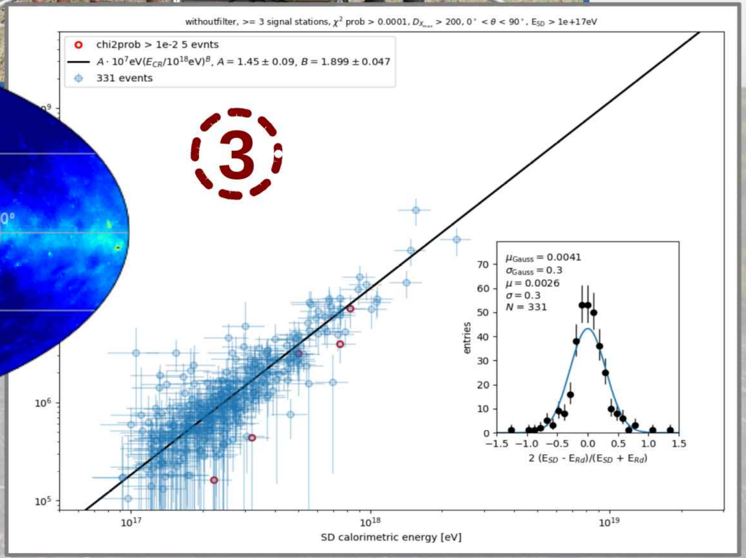
Max Büsken

Absolute measurements for and with the radio detectors at the Pierre Auger Observatory

KSETA Plenary Workshop
27^{th} March 2023

Max Büsken





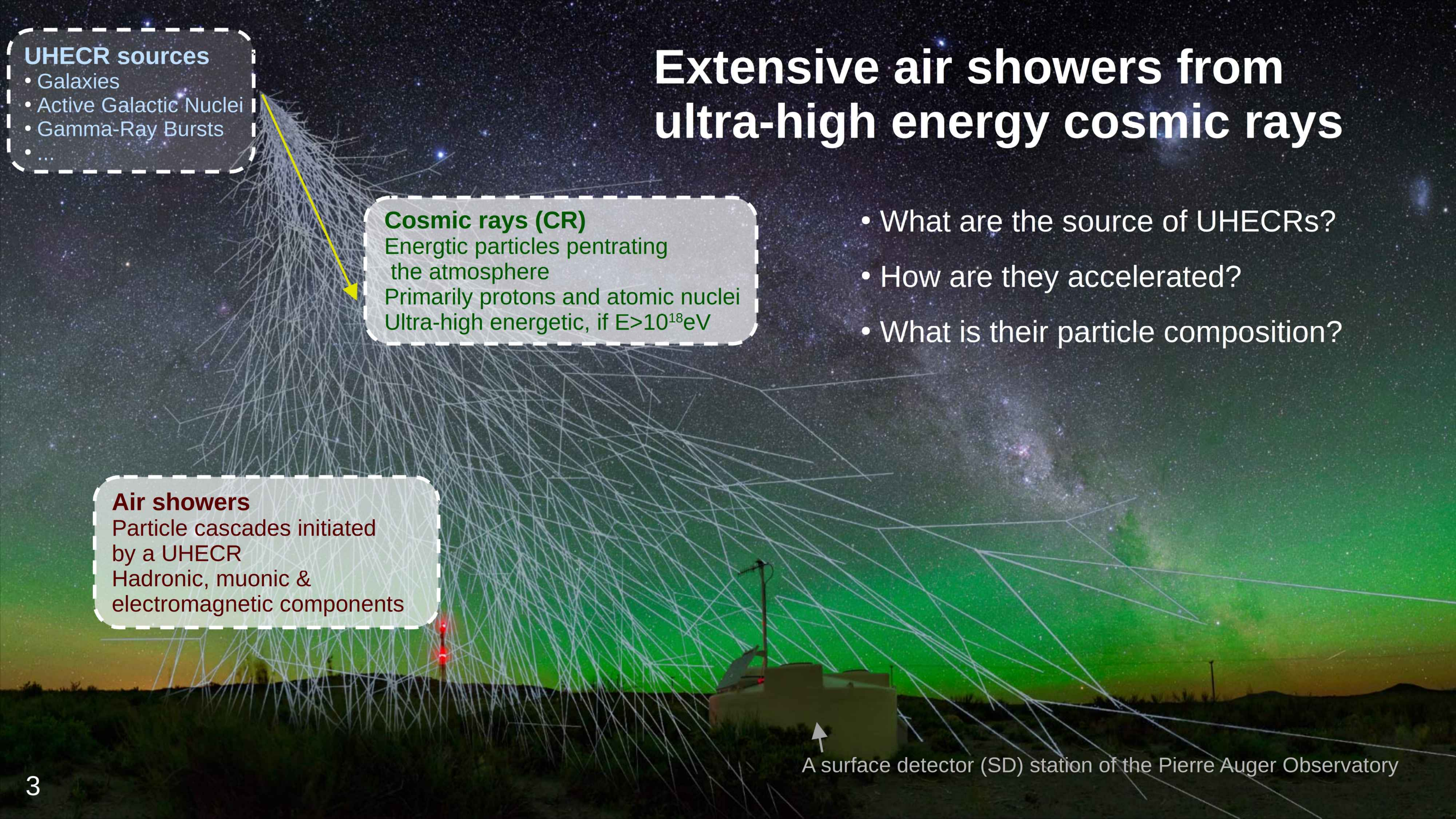
Extensive air showers from ultra-high energy cosmic rays

UHECR sources
- Galaxies
- Active Galactic Nuclei
- Gamma-Ray Bursts
- ...

Cosmic rays (CR)
Energtic particles pentrating
 the atmosphere
Primarily protons and atomic nuclei
Ultra-high energetic, if $E>10^{18}$eV

Air showers
Particle cascades initiated
by a UHECR
Hadronic, muonic &
electromagnetic components

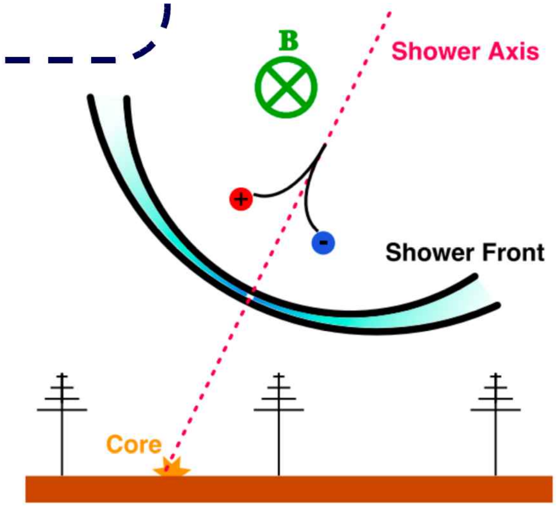
- What are the source of UHECRs?
- How are they accelerated?
- What is their particle composition?



A surface detector (SD) station of the Pierre Auger Observatory

Radio emission from cosmic-ray air showers

Electrons and **positrons** of the shower get **deflected** by the **earth's magnetic field** and emit **radiation**



Geomagnetic mechanism
(dominant)

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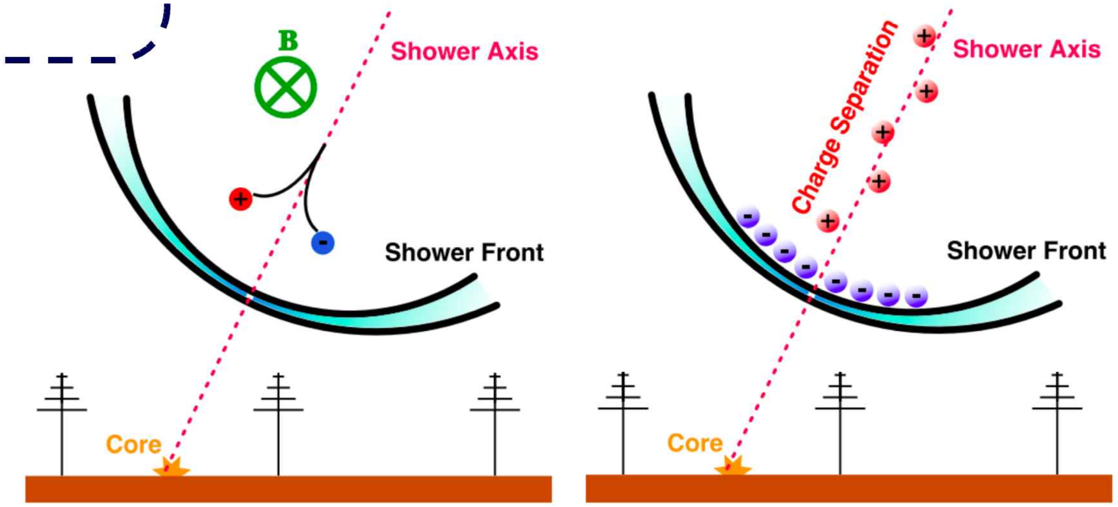

Geomagnetic mechanism *(dominant)*

Charge-excess mechanism

More **electrons from air ionization** + **annihilation of positrons**

➜ **excess of negative charges** in the shower front

➜ produces **radio pulses**

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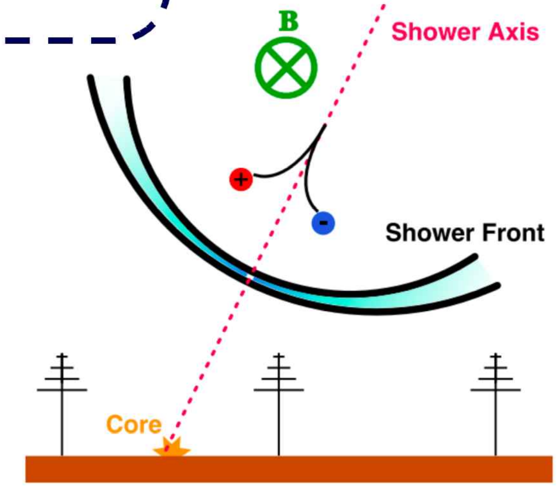
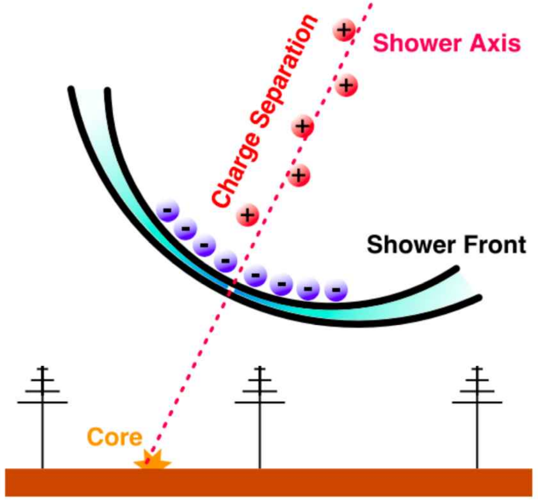


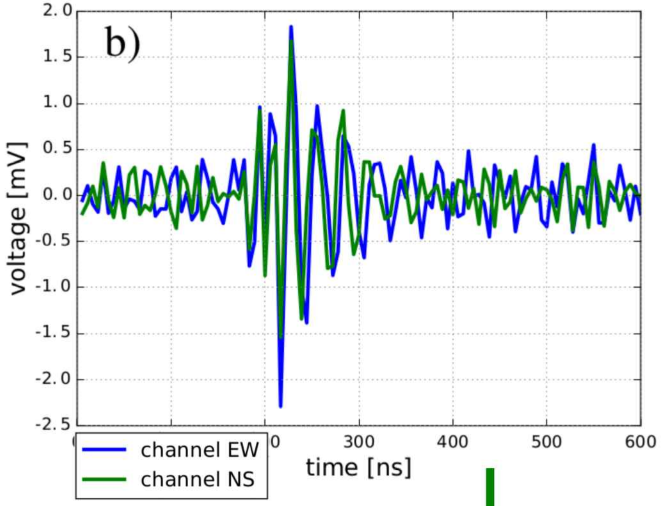
Geomagnetic mechanism
(dominant)



Charge-excess mechanism

Typical used **frequency range:**
few 10 MHz - few 100 MHz

In antenna: ultra short radio pulse



More **electrons from air ionization** + **annihilation of positrons**

→ **excess of negative charges** in the shower front

→ produces **radio pulses**

Reconstruct properties of the shower and primary particle:

- Energy *E*
- Arrival direction θ, φ
- Particle type
- ...

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Radio emission from cosmic-ray air showers

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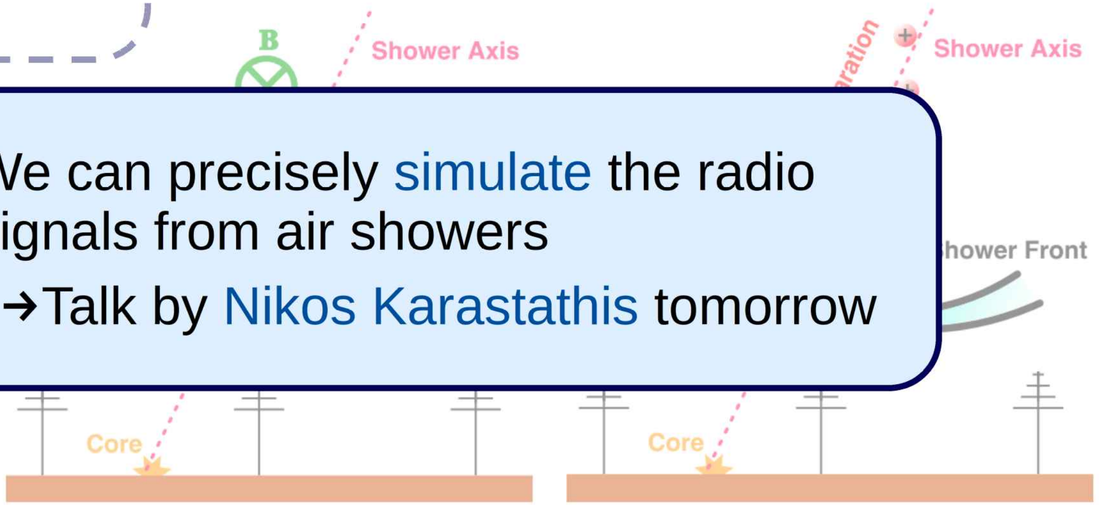

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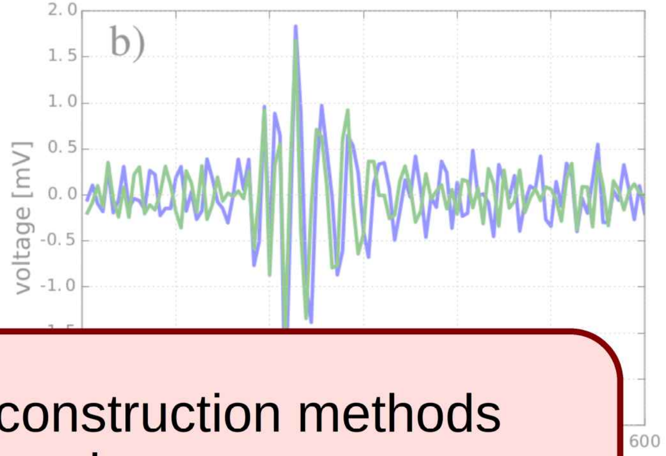

We can precisely simulate the radio signals from air showers

→Talk by Nikos Karastathis tomorrow

Proper signal reconstruction methods are being developed

→Talk by Sara Martinelli on Wednesday

More **electrons from air ionization** + **annihilation of positrons**

→ **excess of negative charges** in the shower front

→ produces **radio pulses**

Reconstruct properties of the shower and primary particle:

- Energy E
- Arrival direction θ, φ
- Particle type
- ...

Geomagnetic mechanism *(dominant)*

Charge-excess mechanism

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Chapter 1

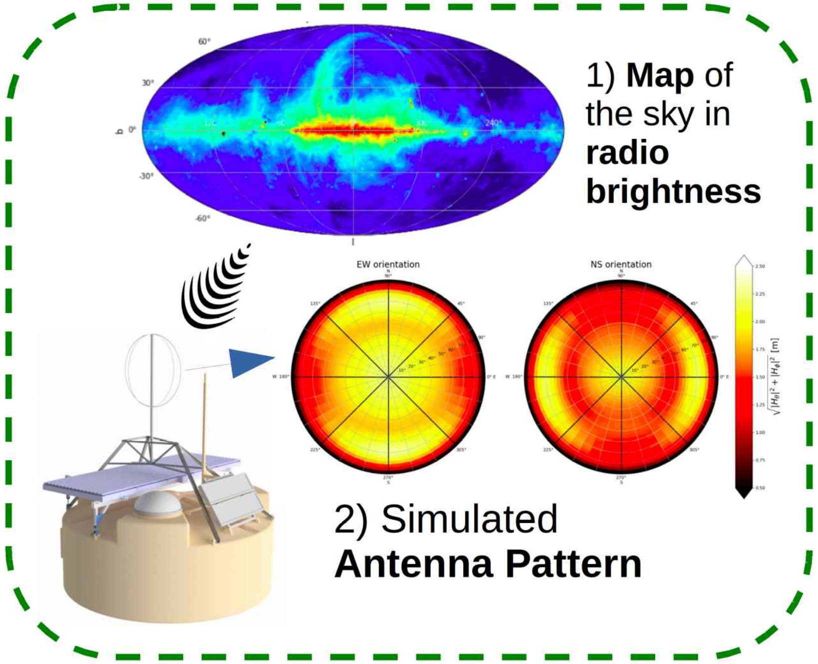
„You probably have radio background.“

„Of course, let’s use it.“

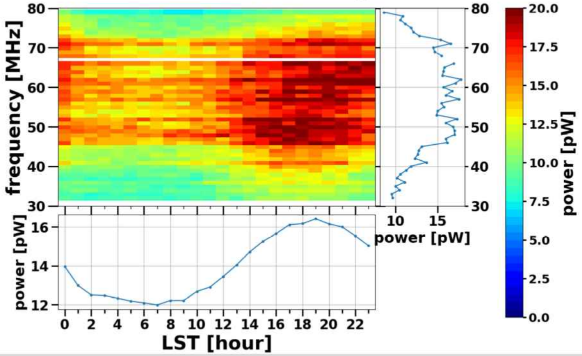
Absolute calibration of radio detectors

- High-level physics analyses require an absolute calibration of the antenna
- Background (typically) dominated by the Galactic radio emission
- New method: Galactic calibration
  - Compare strength of measured noise with predictions from sky models
  - Need an estimate of uncertainties on absolute scale of the prediction

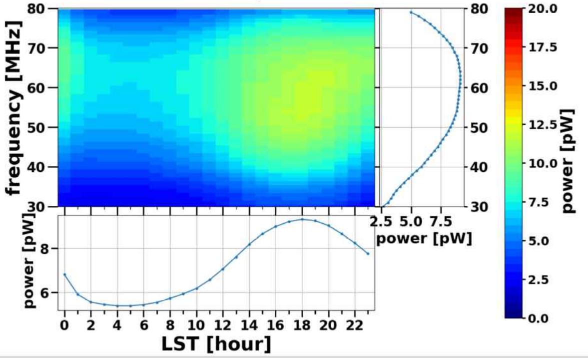
→ Comparison study of prediction models



measured background



simulation/prediction



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Comparison of radio sky models

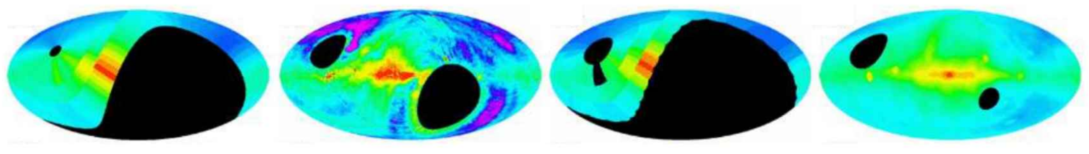
- 8 Models for predicting the radio sky:
  - LFmap
  - LFSM
  - GSM2008
  - GSM2016
  - Haslam (not considered in comparison)
  - GMOSS
  - SSM
  - ULSA

- Method: Inter-/extrapolate reference maps (spatially & in frequency)

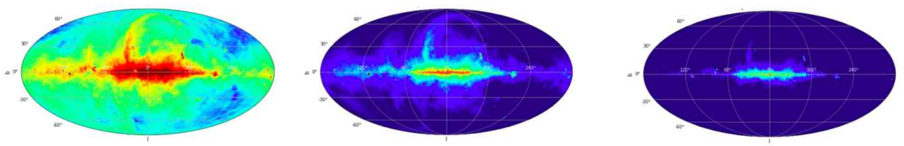
  $\rightarrow T_{\mathrm{Sky}}(\nu; l, b)$

Brightness temperature:
The temperature, that a black body with the same brightness would have

Reference maps/surveys



Sky Model



Model output

➔ Evaluate level of agreement as estimator for prediction accuracy

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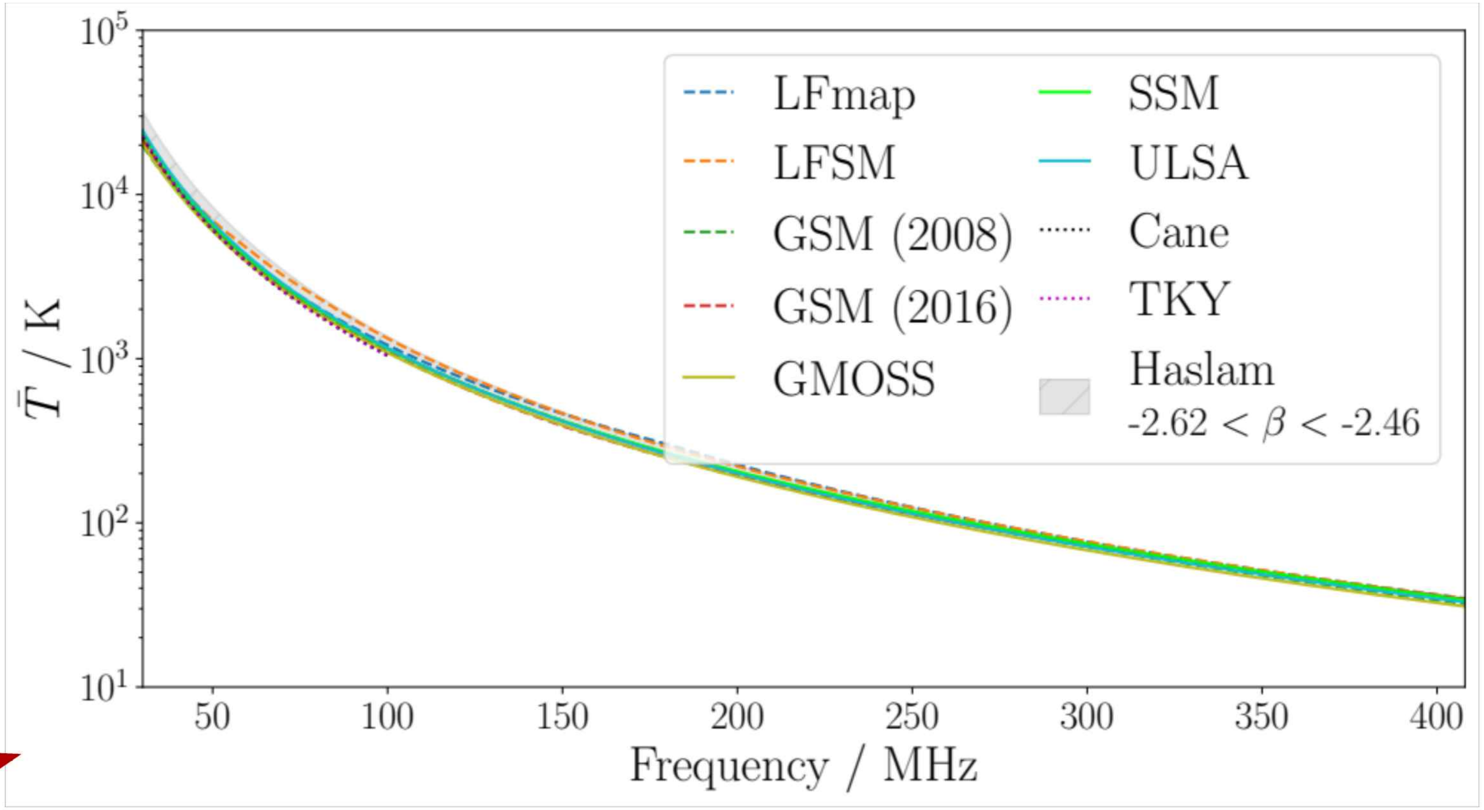
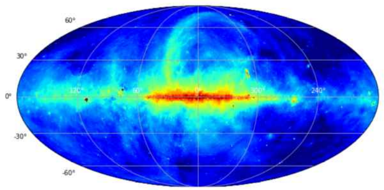
Radio sky background models

- Compare models by average sky temperature
- Studied frequency range: 30 - 408 MHz
- *Cane*, *TKY* and *Haslam* are simple parametrizations / less sophisticated models
  ➔ not included in the comparison





average over sky

$$\bar{T} = \frac{1}{4\pi}\int_{-\pi}^{\pi} dl \int_{\frac{-\pi}{2}}^{\frac{\pi}{2}} db \cos{(b)} T(l,b)$$

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Radio sky background models

- Compare models by average sky temperature
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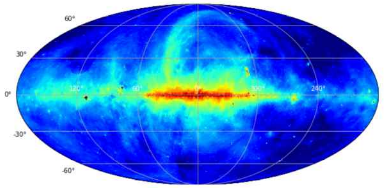
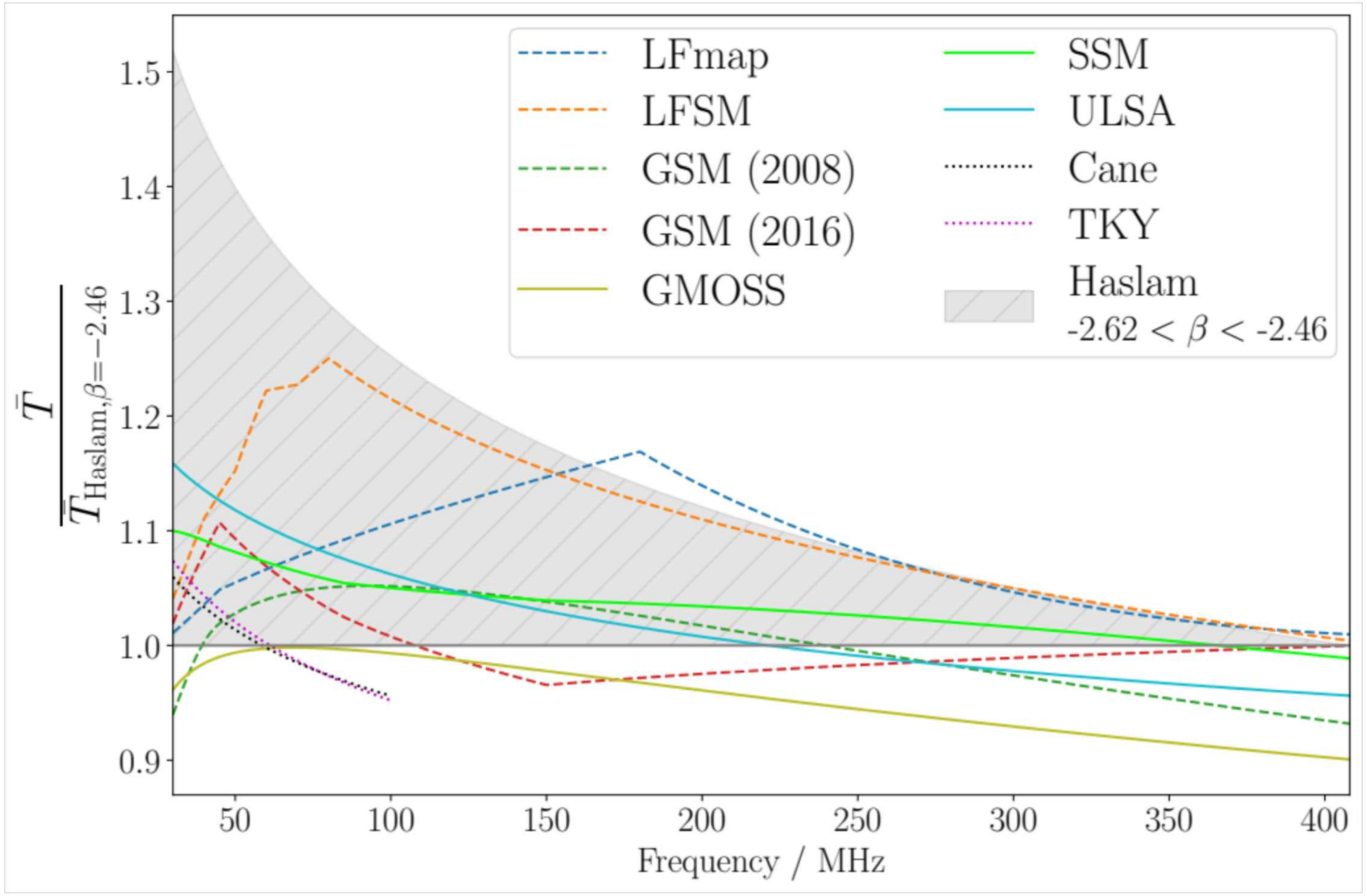


average over sky



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1

Model-by-model agreement

- Integrate over frequency
  - ➔ Quantify direct comparison between any 2 models
- Global agreement at 14.6%

$$\frac{\sigma_T}{T} \approx \frac{\sigma_P}{P} \approx 2\frac{\sigma_V}{V} \approx 2\frac{\sigma_E}{E}$$

➔ Error on CR energy: ~7%

m₁ \ m₂	LFmap	GSM08	GSM16	LFSM	GMOSS	SSM	ULSA
LFmap		4.6%	0.7%	-7.3	7.3%	-1.8%	-4.8%
GSM08	-4.6%		-3.8%	-11.9%	2.7%	-6.4%	-9.3%
GSM16	-0.7%	3.8%		-8.1%	6.5%	-2.5%	-5.5%
LFSM	7.3%	11.9%	8.1%		**14.6%**	5.5%	2.6%
GMOSS	-7.3%	-2.7%	-6.5%	-14.6%		-9.1%	-12.0%
SSM	1.8%	6.4%	2.5%	-5.5%	9.1%		-2.9%
ULSA	4.8%	9.3%	5.5%	-2.6%	12.0%	2.9%	

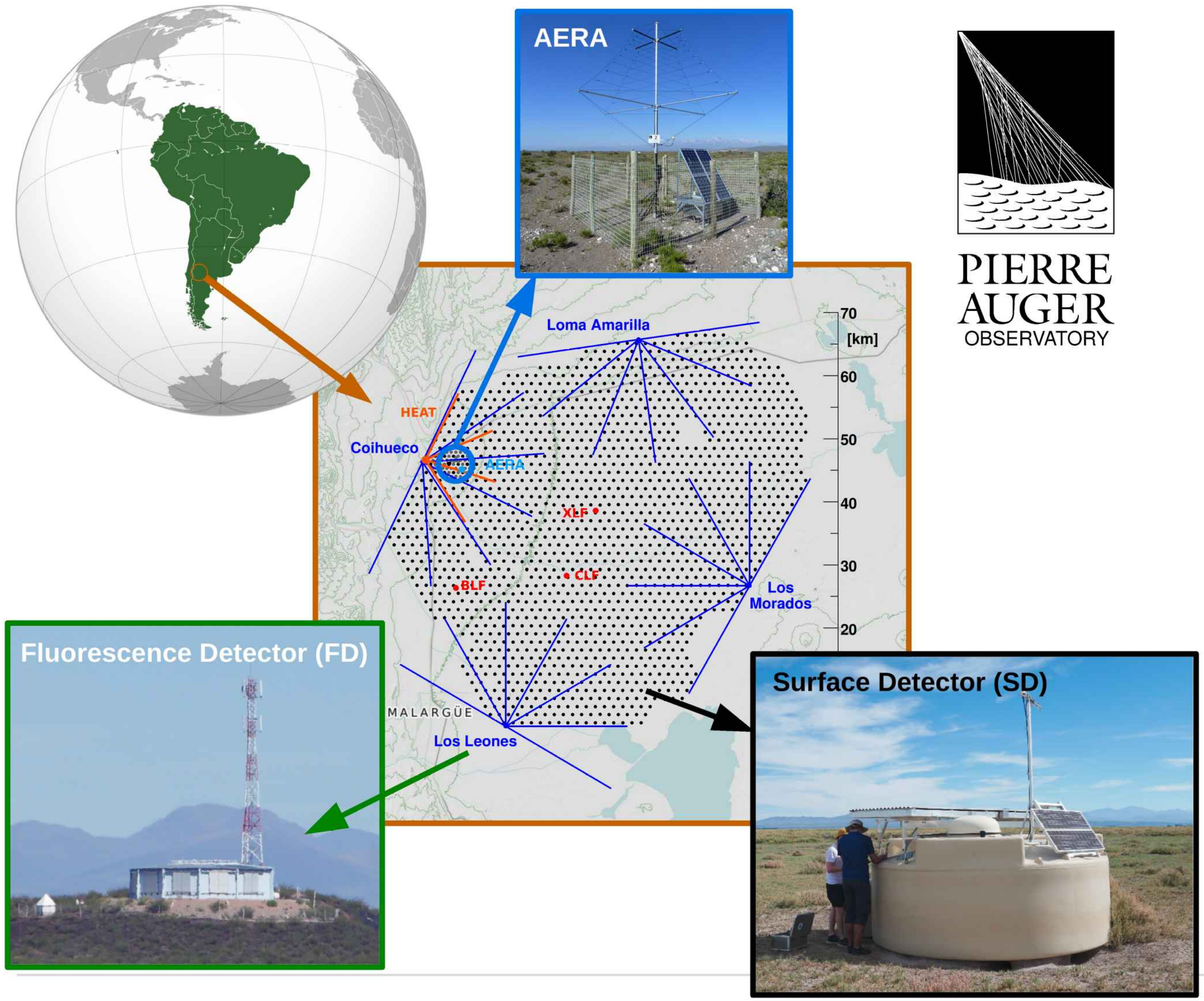
diagonal

$$r_{\mathrm{m_1,m_2}} = 2 \cdot \frac{\int_{30\mathrm{MHz}}^{408\mathrm{MHz}} T_{\text{sky, average; m}_1}(\nu) - T_{\text{sky, average; m}_2}(\nu)\, d\nu}{\int_{30\mathrm{MHz}}^{408\mathrm{MHz}} T_{\text{sky, average; m}_1}(\nu) + T_{\text{sky, average; m}_2}(\nu)\, d\nu}$$

Chapter 2

„What if there is a thunderstorm during an air shower?“

The Pierre Auger Observatory



- Largest ground-based observatory for ultra-high energy cosmic rays (UHECRs)
  - Study their origin, mass composition, acceleration mechanisms,...
- Hybrid detection of extensive air showers:
  - Fluorescence Detectors (FD)
  - Water Cherenkov Detectors
  - Scintillator Surface Detectors
  - Underground Muon Detectors
  - Radio Detectors

→ Auger Engineering Radio Array (AERA):
>150 antenna stations, 30-80 MHz
17 km² array, >10 years operation

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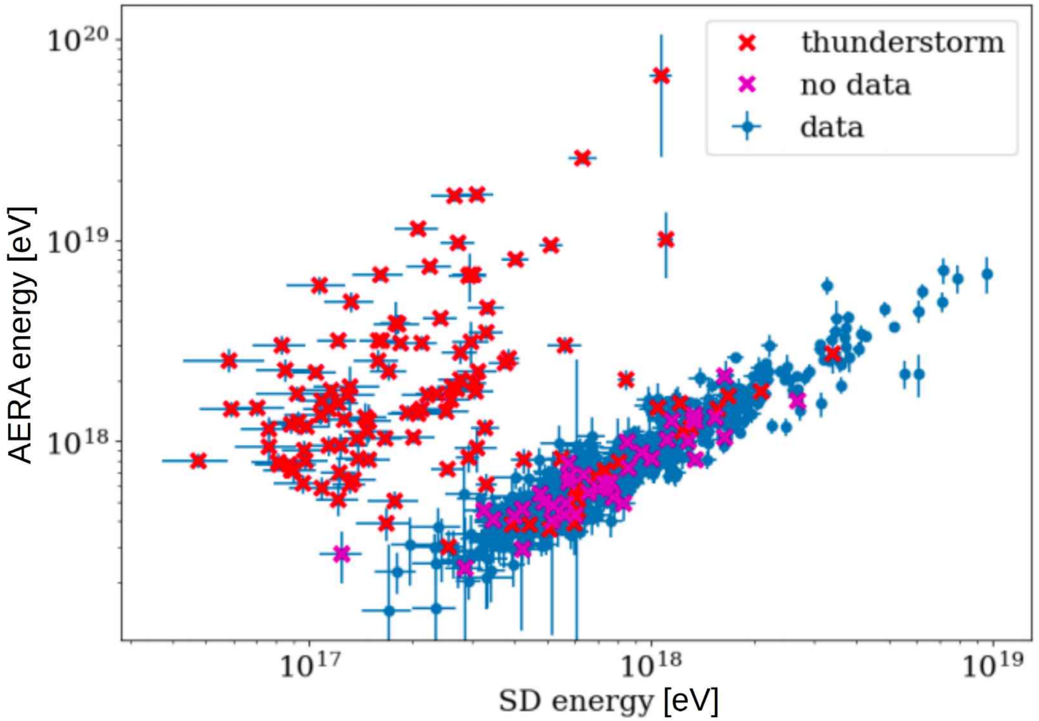
Radio detection during thunderstorms at AERA

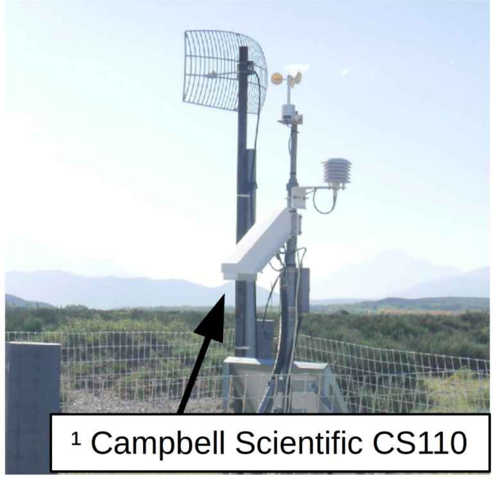


↳ Event-by-event energy estimators from the Radio Detector (AERA) vs. Surface Detector

- Atmospheric electric fields during thunderstorms heavily influence radio signals from air showers
- Affected events not interpretable

Solution:

- Monitor the electric field and thunderstorms (TS) with Electric Field Mills (EFMs)
  → Flag TS periods
- Two EFMs[1] at AERA running stable & autonomously (10+ years)



[1] Campbell Scientific CS110

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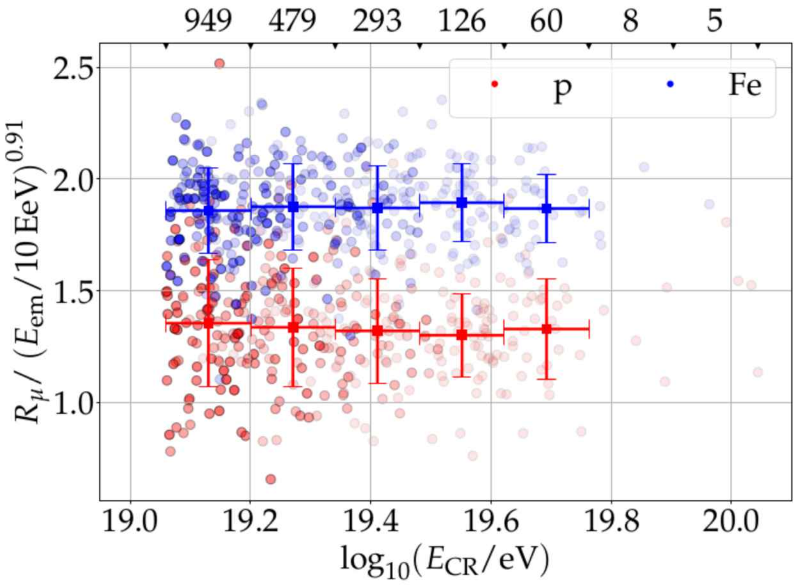
AugerPrime: the new radio detector

- AugerPrime upgrade of the Pierre Auger Observatory
- A major part: new Radio Detector (RD)
  - "SALLA" on each surface detector station (1661)
    (short aperiodic loaded loop antenna)
  - Will detect inclined air showers, i.e. θ>65°
  - CR mass discrimination for hybrid detections with the water-Cherenkov detectors expected



  - Mass deployment started this month
    ➜ expect to finish by the end of 2023

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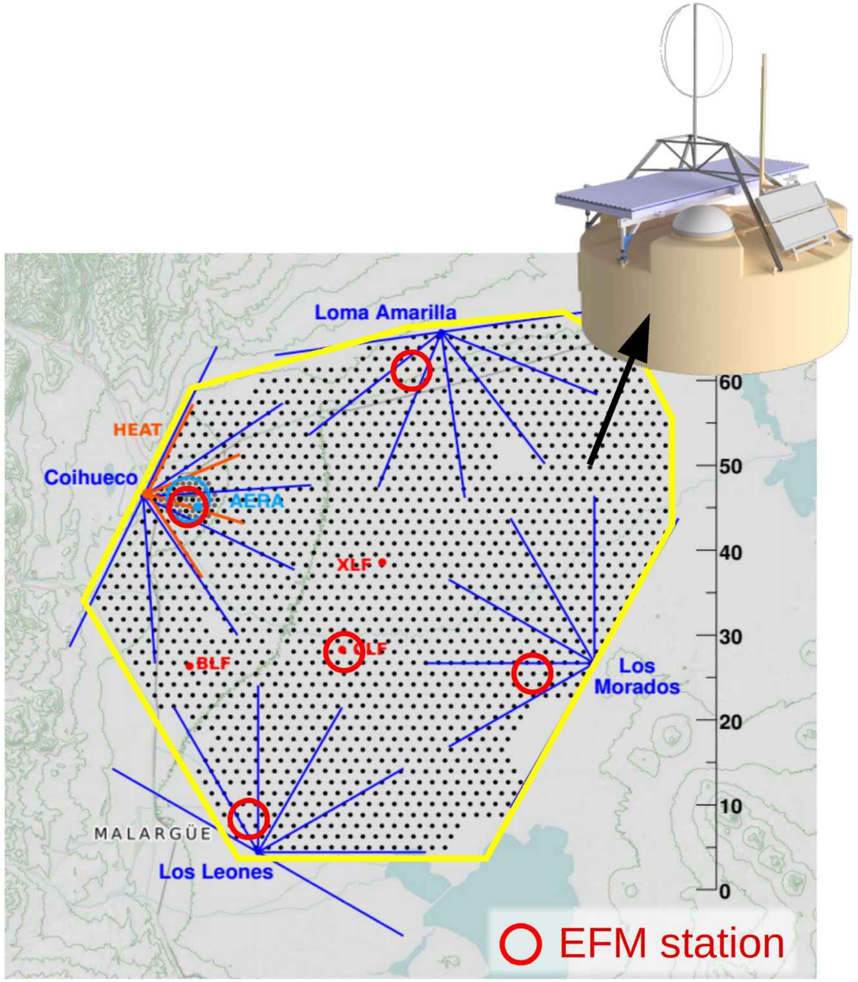
A new network of electric field mills



AugerPrime upgrade:

- new RD on > 3000 km² array
- Need E-field monitoring on larger scale

Goals:

- Track thunderstorms
- Smart flags based on shower direction and cloud movement

New network of Electric Field Mills (EFM)

- 5 new EFMs spread over the array
  - Autonomous, remote operation for 10+ years
  - Absolute calibration of E-field measurement

    → requirements for station design

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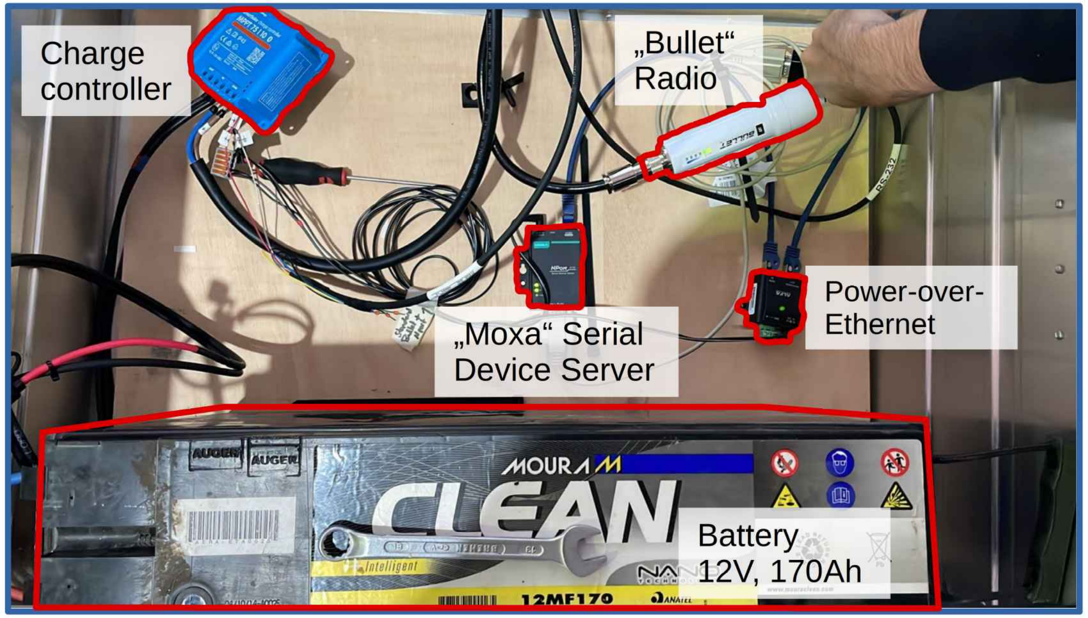
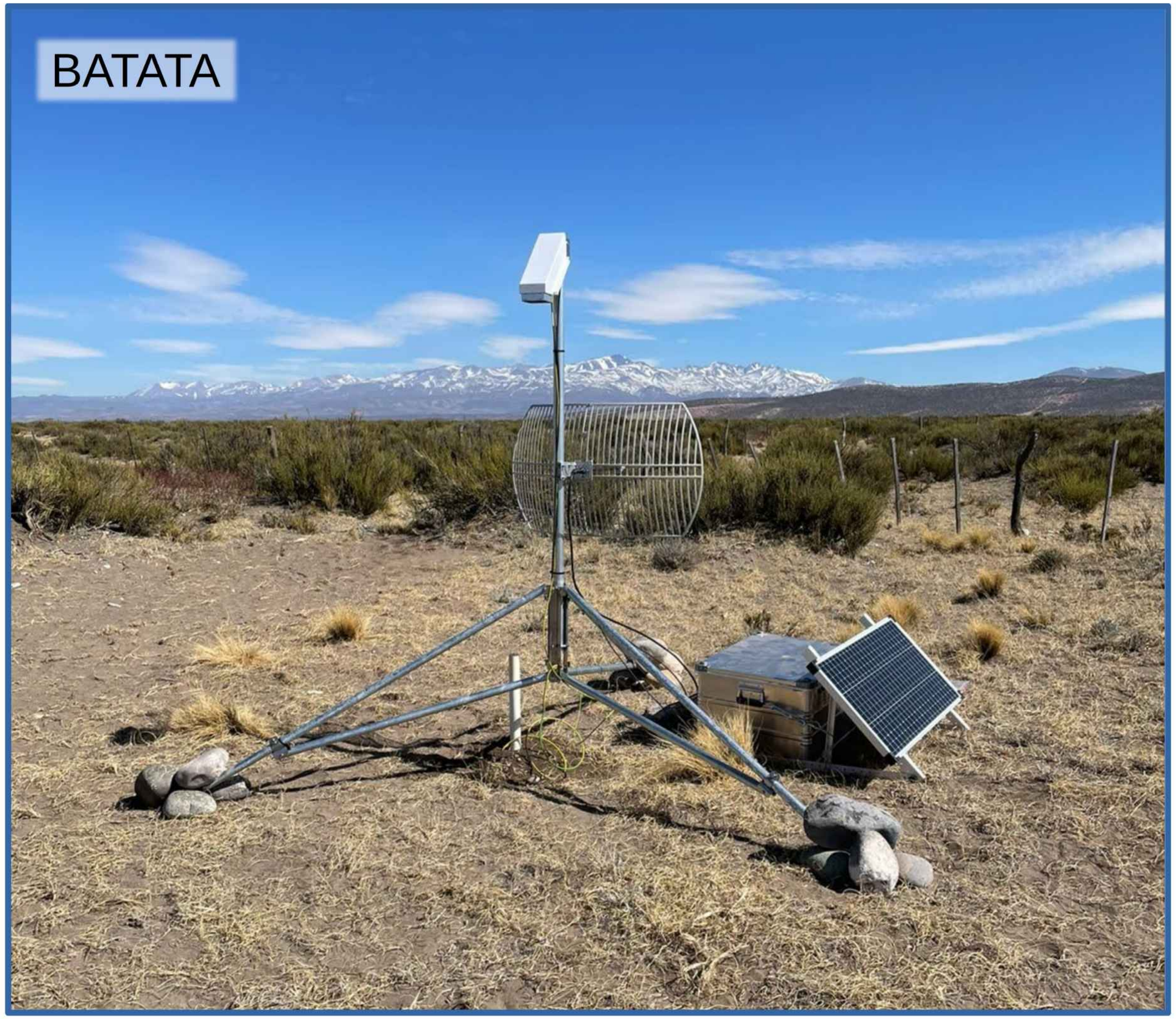
Deployment

- First station installed in August 2022 by colleagues
- Successful deployment ✔
- First data looked fine ✔





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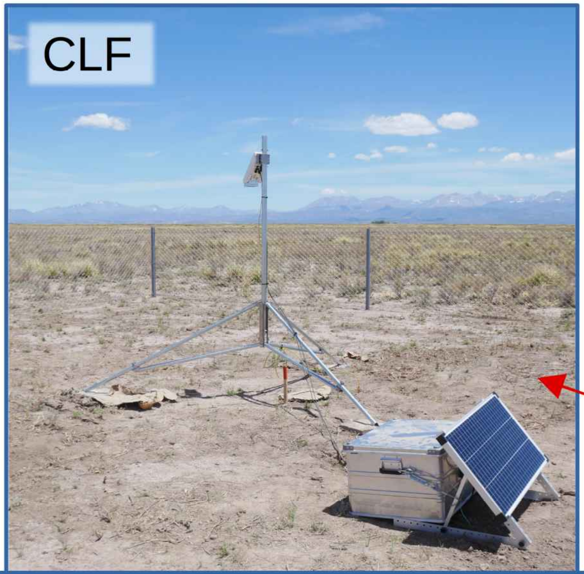
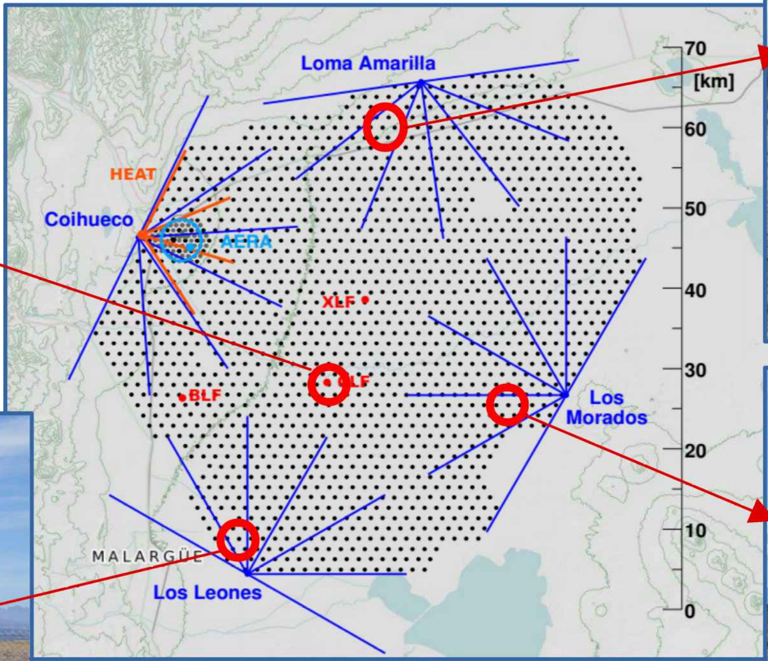
Deployment



- Other 4 stations deployed in November 2022



- Smooth deployment ✔
- 3 of 4 remote links functional

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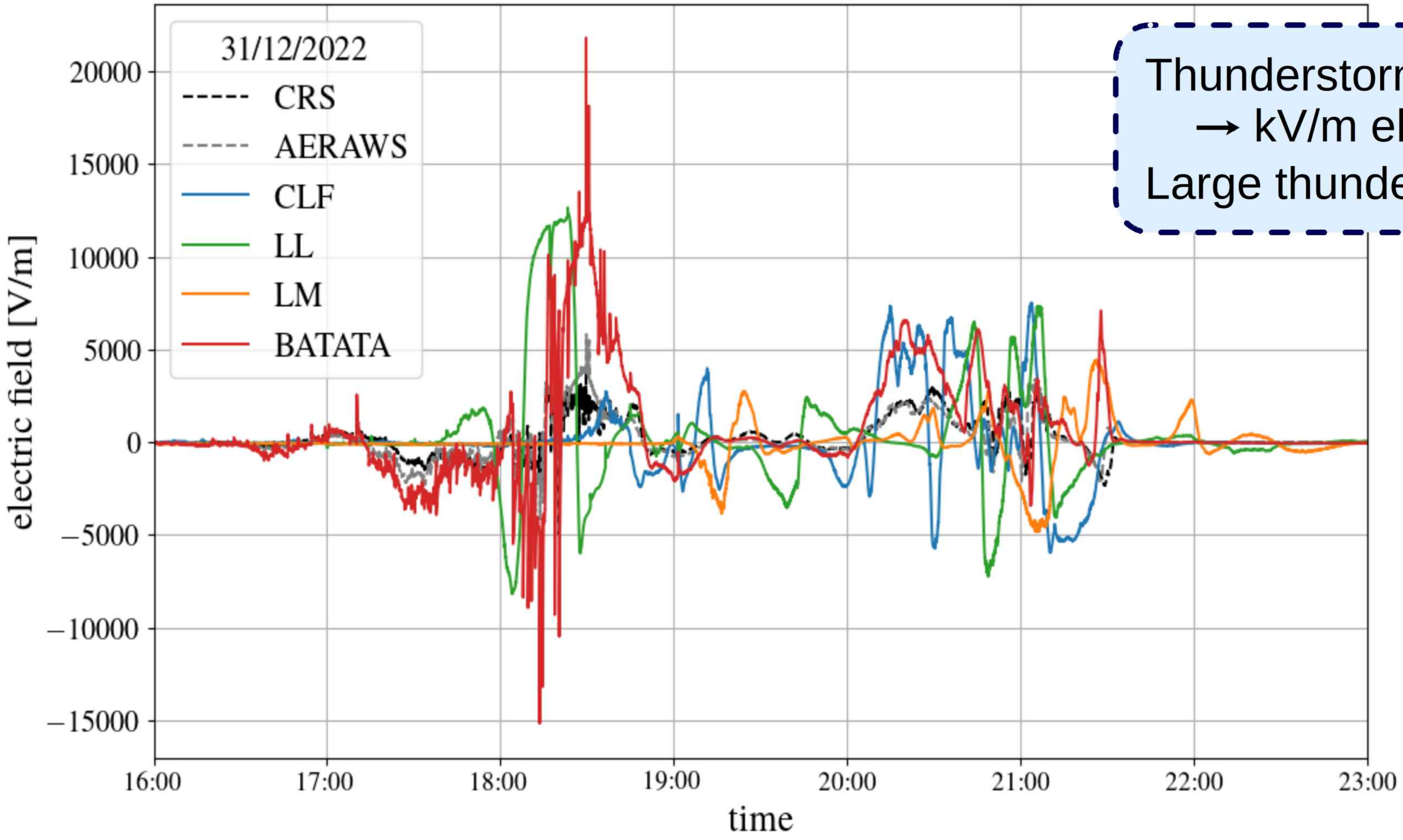
2

E-field data



Thunderstorm conditions
→ kV/m electric field
Large thunderstorm seen in all stations

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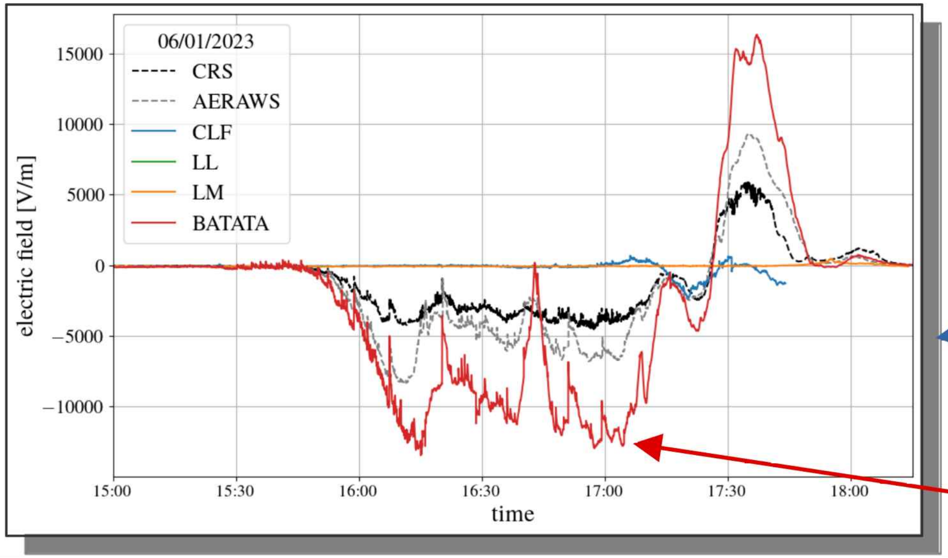
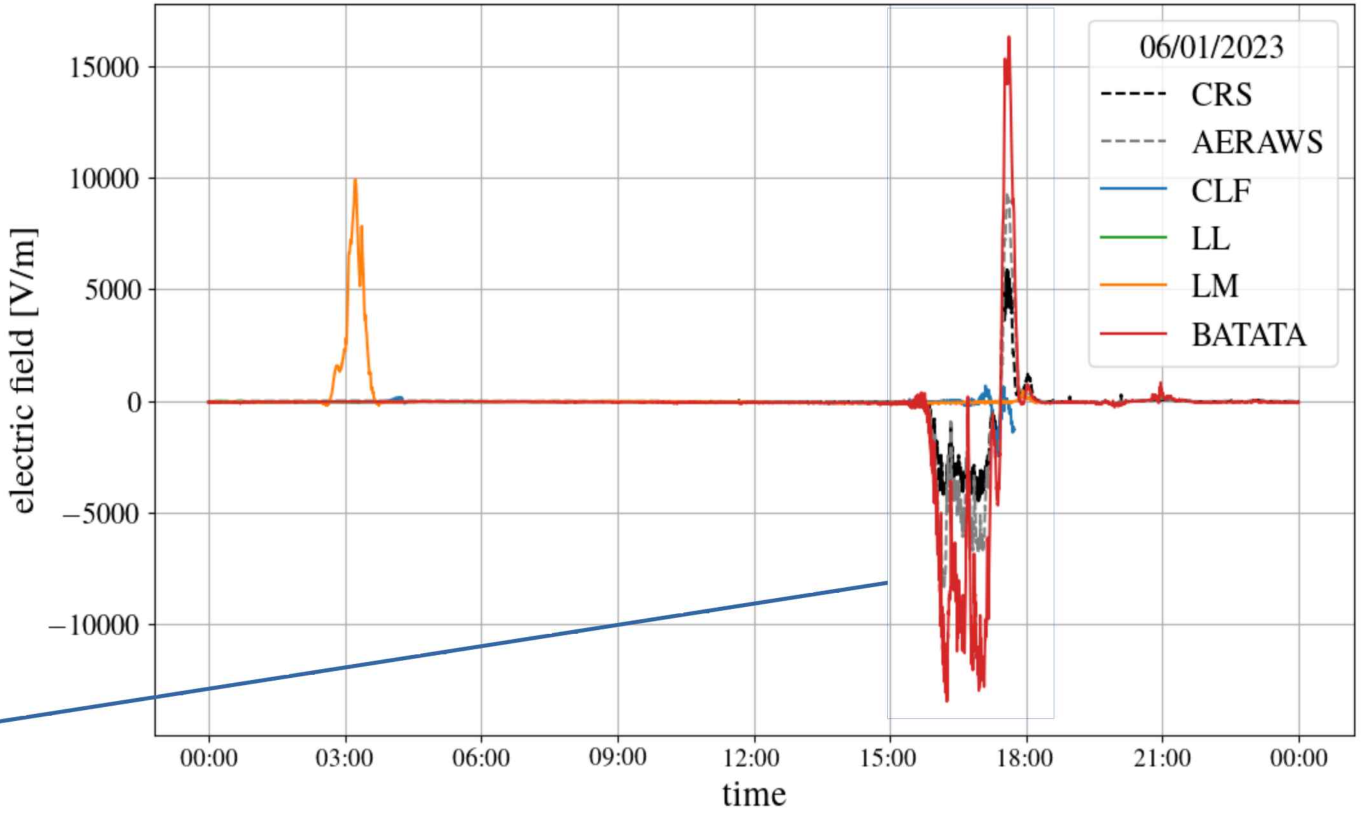
E-field data

- Thunderstorms / clouds only seen in single stations
  - Variety in scale of thunderclouds
- Difference of effective gain between calibrated and uncalibrated EFMs





BATATA station with absolute calibration

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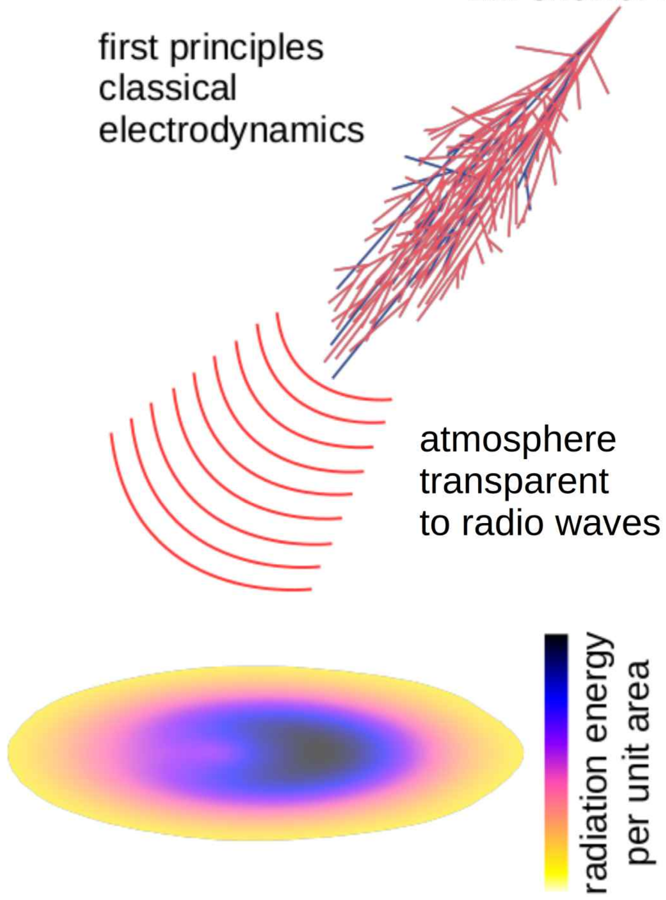
Chapter 3

„What can you do with a radio detector with an absolute calibration?“

(connecting to Chapter 1)

The cosmic-ray energy scale with AERA

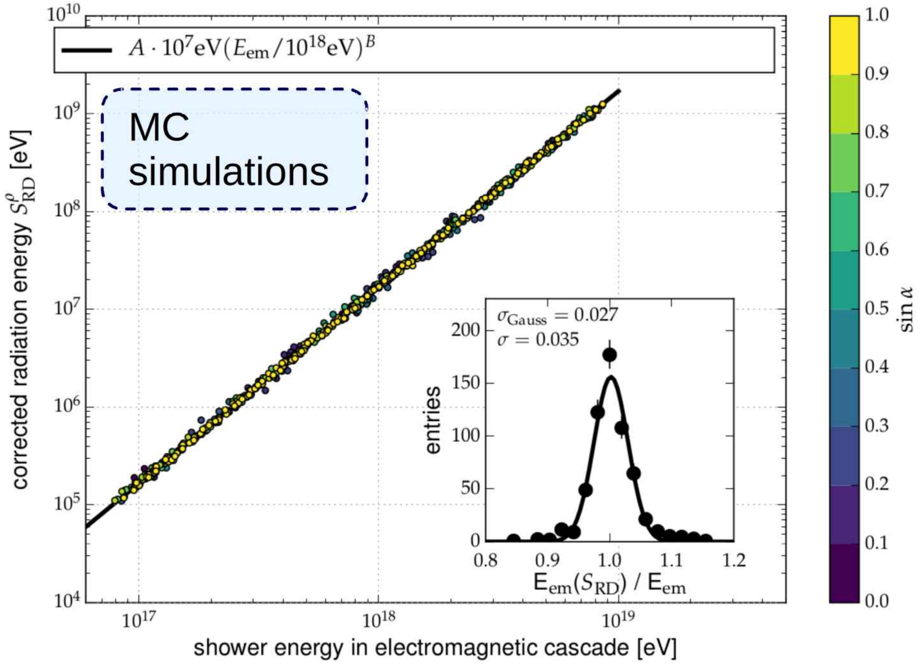
Theoretical calculation



Electromagnetic energy E_{em}
All energy deposited by the electromagnetic shower component (e^-,e^+,γ) in the atmosphere

Radiation energy $S^{\rho\theta}_{RD}$
All energy from shower emitted in form of radio waves

$$S^{\rho\theta}_{\mathrm{RD}} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV} \right)^{1.978}$$



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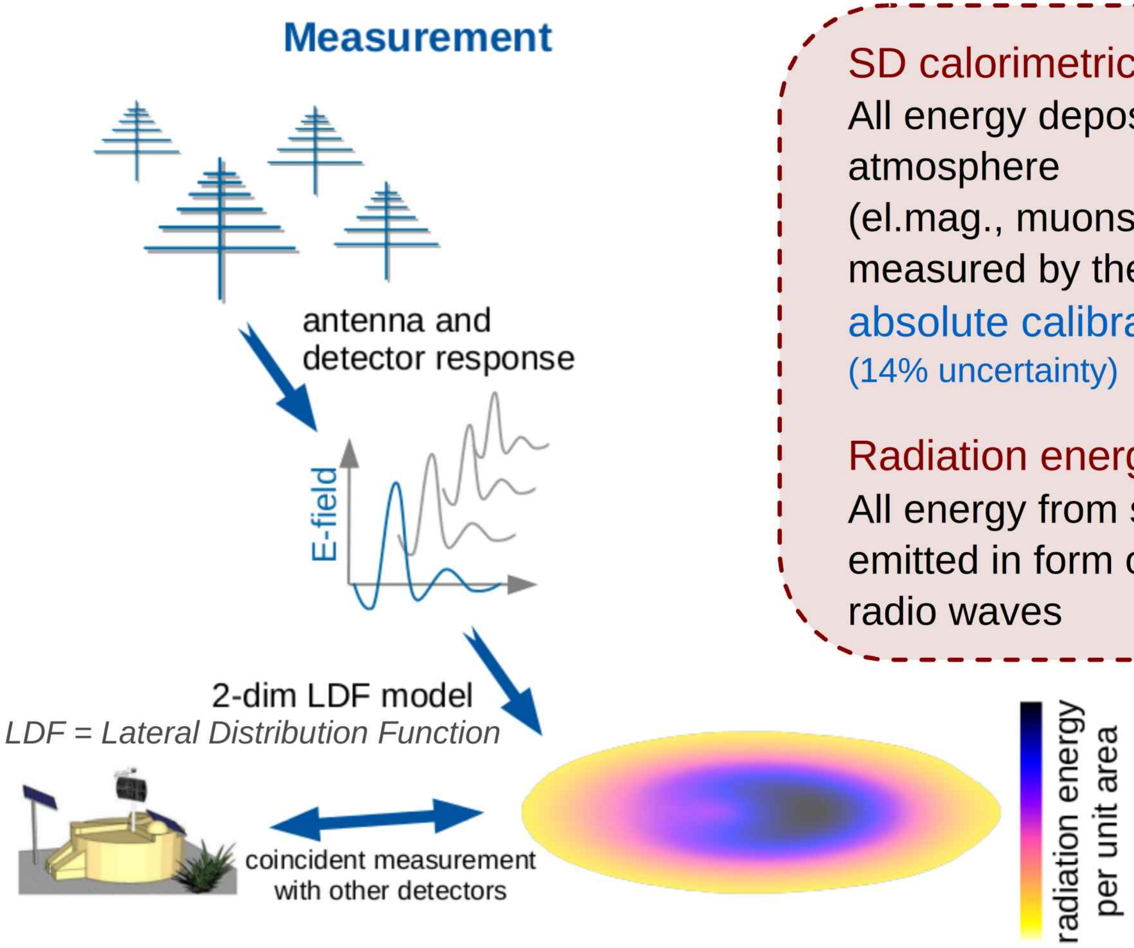
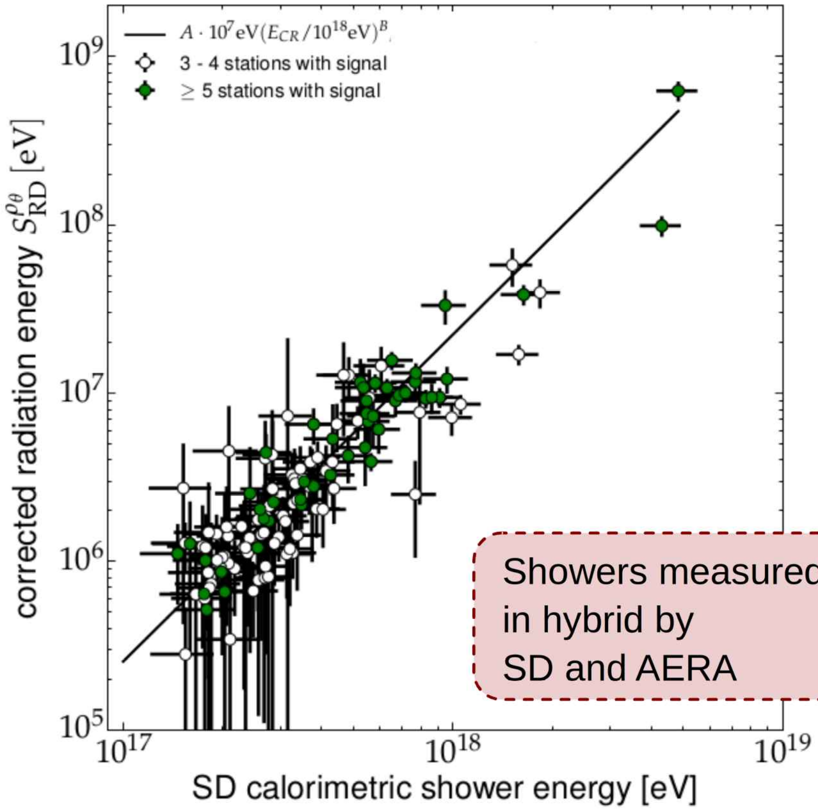
The cosmic-ray energy scale with AERA



SD calorimetric energy $E_{SD,cal}$
All energy deposited in the atmosphere
(el.mag., muons, hadrons)
measured by the SD
absolute calibration from FD
(14% uncertainty)

Radiation energy $S^{\rho\theta}_{RD}$
All energy from shower emitted in form of radio waves

$$S^{\rho\theta}_{\mathrm{RD}} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV}\right)^B$$



Showers measured in hybrid by SD and AERA

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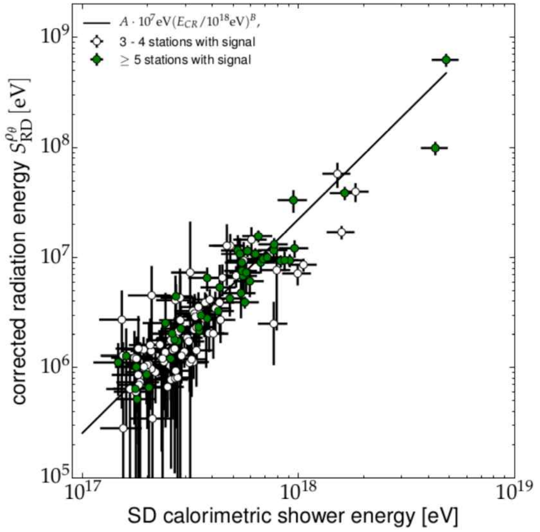
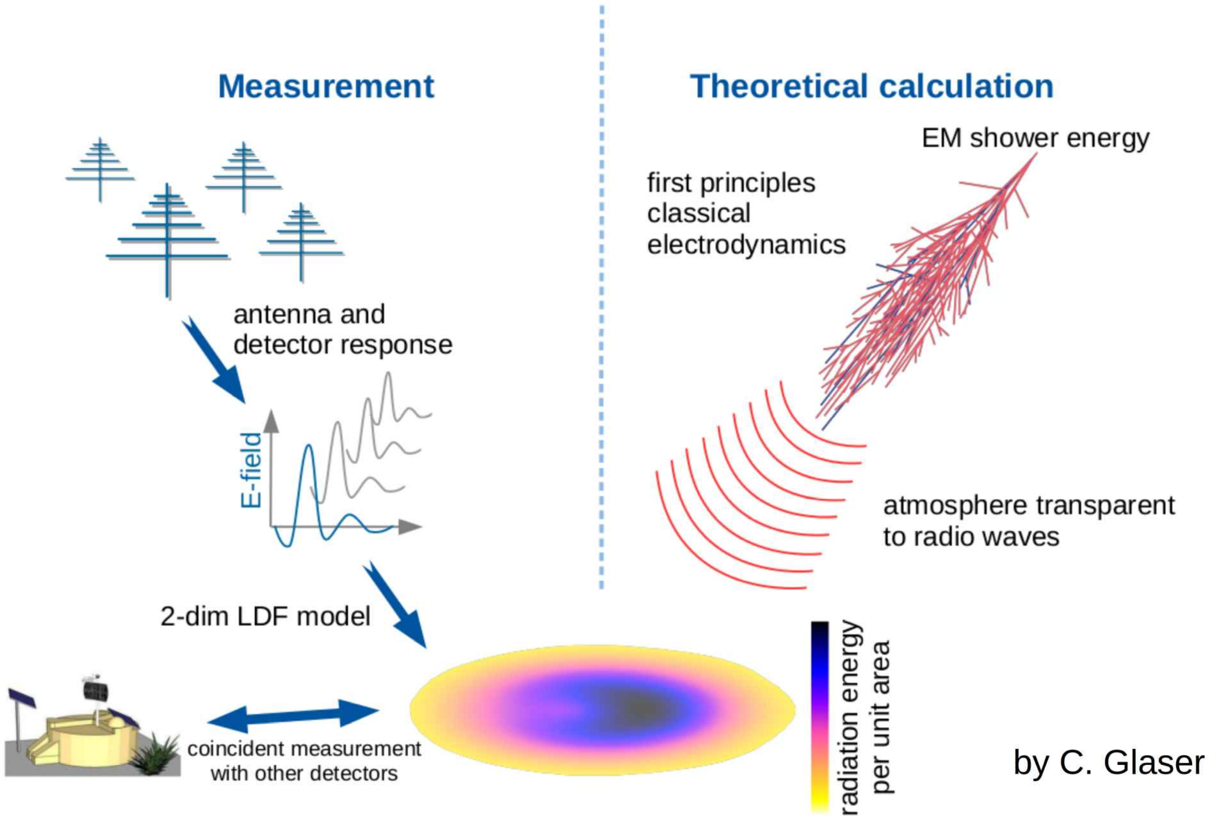
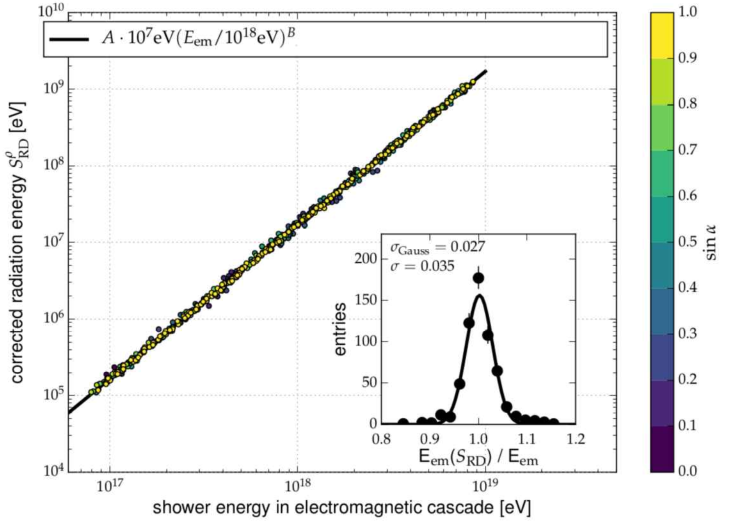
3

The cosmic-ray energy scale with AERA





by C. Glaser



$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV}\right)^B$$

Allows to compare CR energy scales from FD and radio

$$S_{\mathrm{RD}}^{\rho\theta} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV}\right)^{1.978}$$

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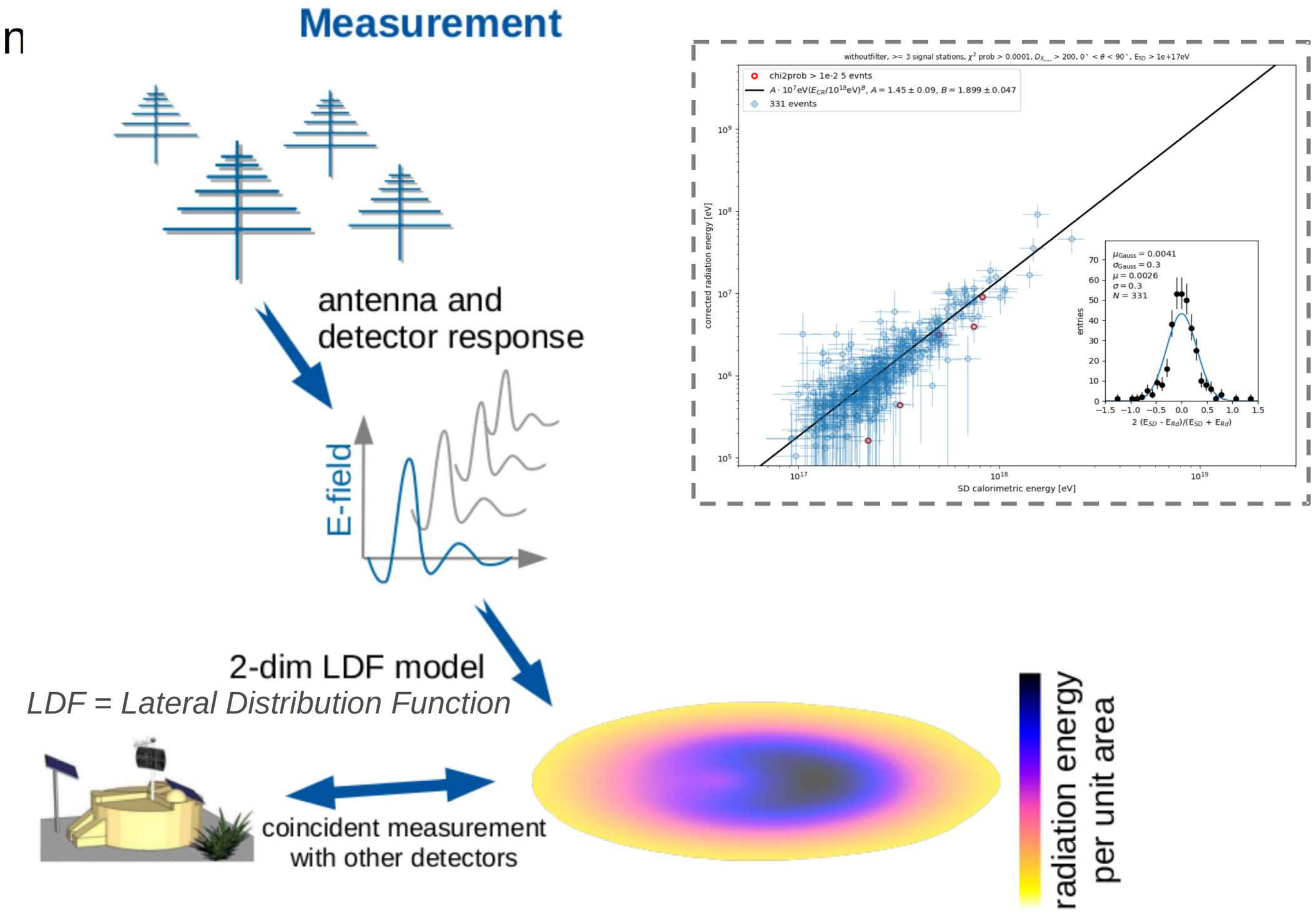
3

The cosmic-ray energy scale with AERA

- Previous measurements of the absolute radiation energy had statistical limitations and needed improvement in error estimates
- New data analysis with
  - More data
  - Improved event reconstruction
    - Galactic calibration
    - Signal reconstruction
- Comparison of radio and FD energy scales



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Summary & Outlook

- Absolute calibration of the Auger radio detectors using the Galactic emission
  - Systematic uncertainty on predicted Galactic emission:

    14.6% on T_{sky} → ~7% on reconstructed E_{CR}

- New network of Electric field mills deployed
  - Thunderstorm monitor for the new radio detector on a large scale
  - Setup designed with an absolute calibration of the EFMs

- Next: Absolute measurement of cosmic-ray energy scale with radio

Pioneered for AERA applicable to new Auger Radio Detector later

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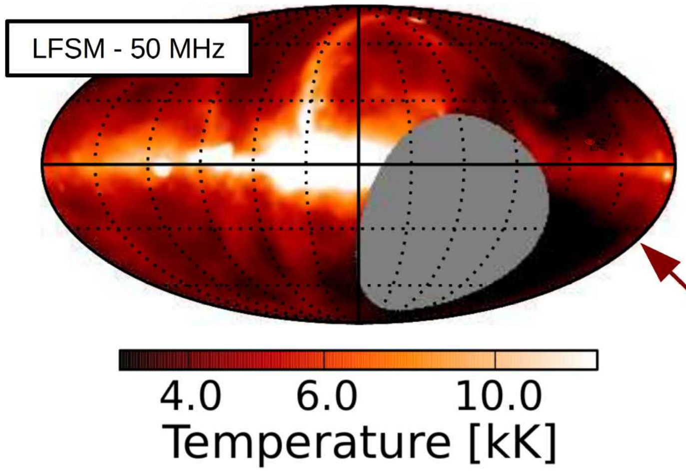
Backup

①

Reference Maps



- Overview of reference maps:
  - relative scale uncertainty < 20%
  - zero level error (offset) < 12% of average T_{Sky}
- Models are correlated

Accuracy of the temperature scale: $T_{\text{true}} = a \cdot T_{\text{obs}} + b$

$$\frac{\sigma_T}{T} \approx \frac{\sigma_P}{P} \approx 2\frac{\sigma_V}{V} \approx 2\frac{\sigma_E}{E}$$

map No.	frequency ν/MHz	covered declination	relative scale uncert./%	zero level error/K	zero level error norm. to average/%
1	10	$-6° < \delta < 74°$	9*	$2 \cdot 10^4$	7.0
2	22	$-28° < \delta < 80°$	16	$5 \cdot 10^3$	11.5
3	40	$-40° < \delta < 90°$	20	10	0.1
4	45	$-90° < \delta < 65°$	10/15	125†	1.5
5	50	$-40° < \delta < 90°$	20	10	0.2
6	60	$-40° < \delta < 90°$	20	10	0.2
7	70	$-40° < \delta < 90°$	20	10	0.3
8	80	$-40° < \delta < 90°$	20	10	0.5
9	85	$-25° < \delta < 25°$	7	120	6.7
10	150	$-25° < \delta < 25°$	5	40	9.2
11	178	$-5° < \delta < 88°$	10	15	5.3
12.a	408 (1982)	$-90° < \delta < 90°$	10/5	3	8.8
12.b	408 (2003)	$-90° < \delta < 90°$	10/5	3	8.8
12.c	408 (2015)	$-90° < \delta < 90°$	10/5	3	8.8

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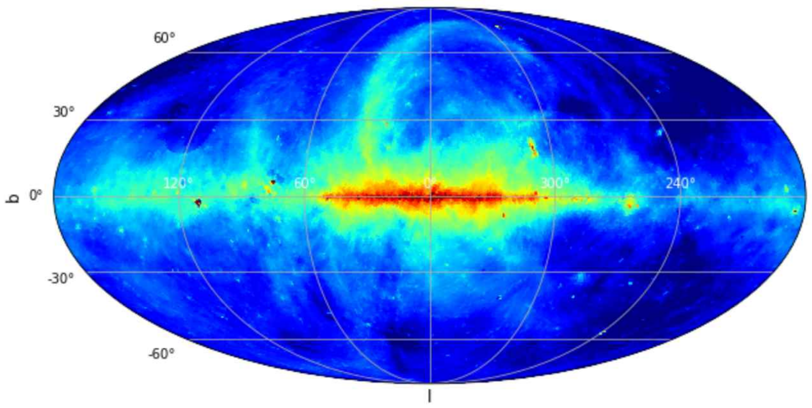
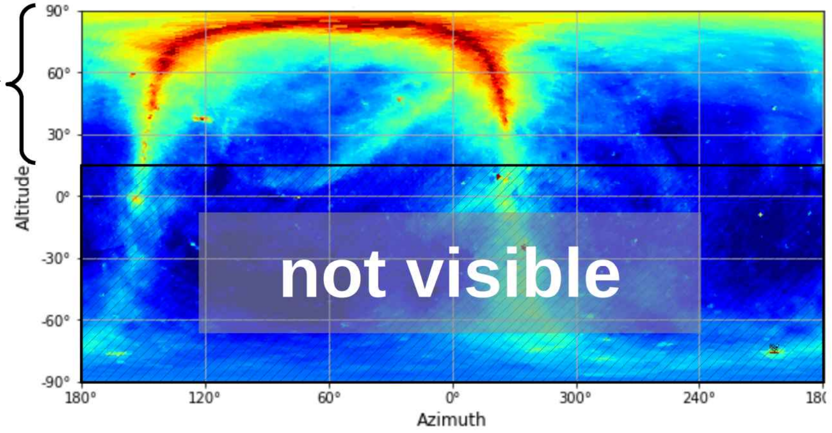
1

From Global Sky to Selected Radio Array

- Instead of the total sky use the local sky (15°-90° elevation) at the site a radio array
  - ➔ average over LST



convert



- Compare based on the frequency band of the Auger radio detectors
  - ➔ For Auger, models agree within 11.7%
  - ➔ For other radio arrays, agreement between 15% and 22%

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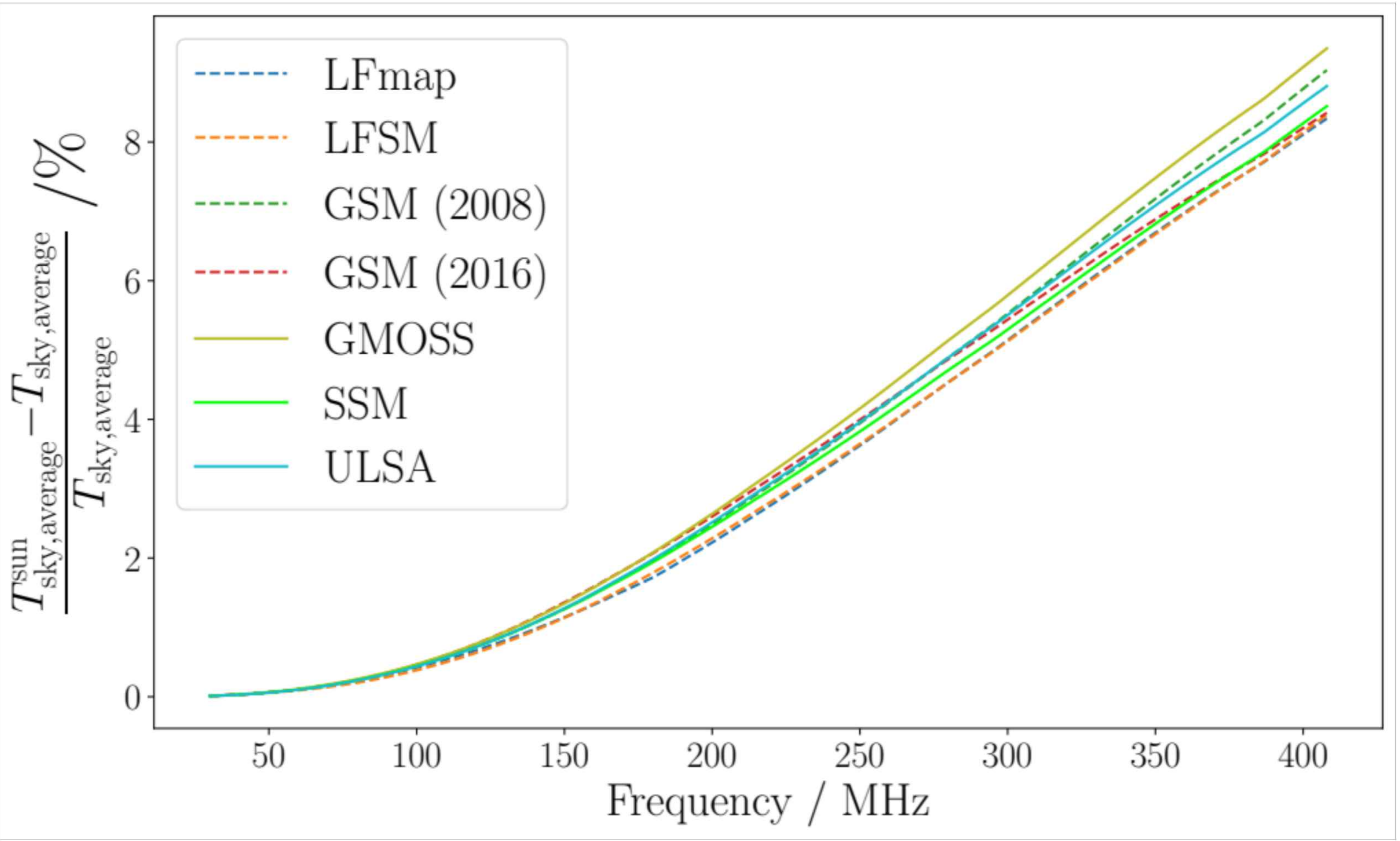
Influence of quiet Sun

- Additional source of radio emission in the sky
- Relative influence on average T_{sky} negligible for Auger
- Relevant for arrays at higher frequencies



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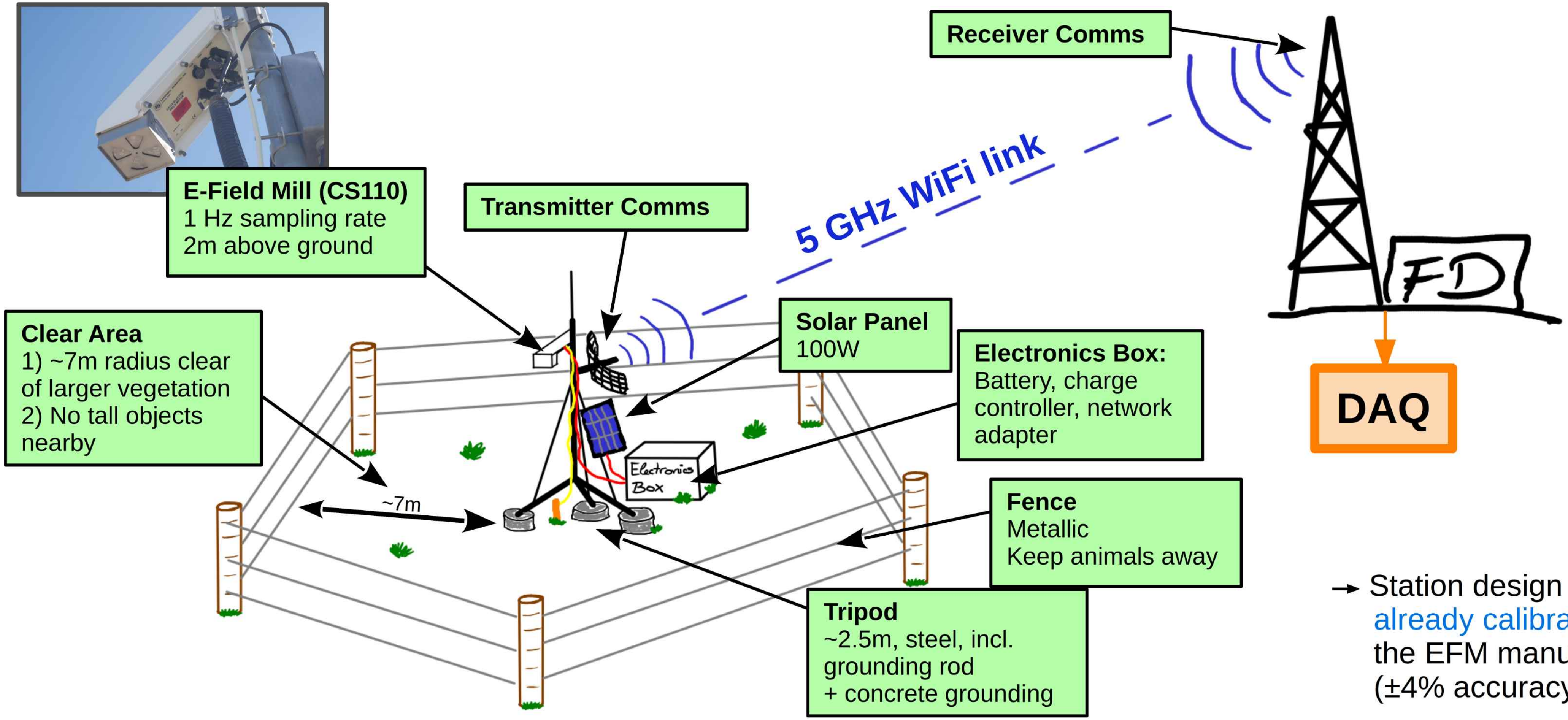
EFM Station Design



→ Station design already calibrated by the EFM manufacturer (±4% accuracy)

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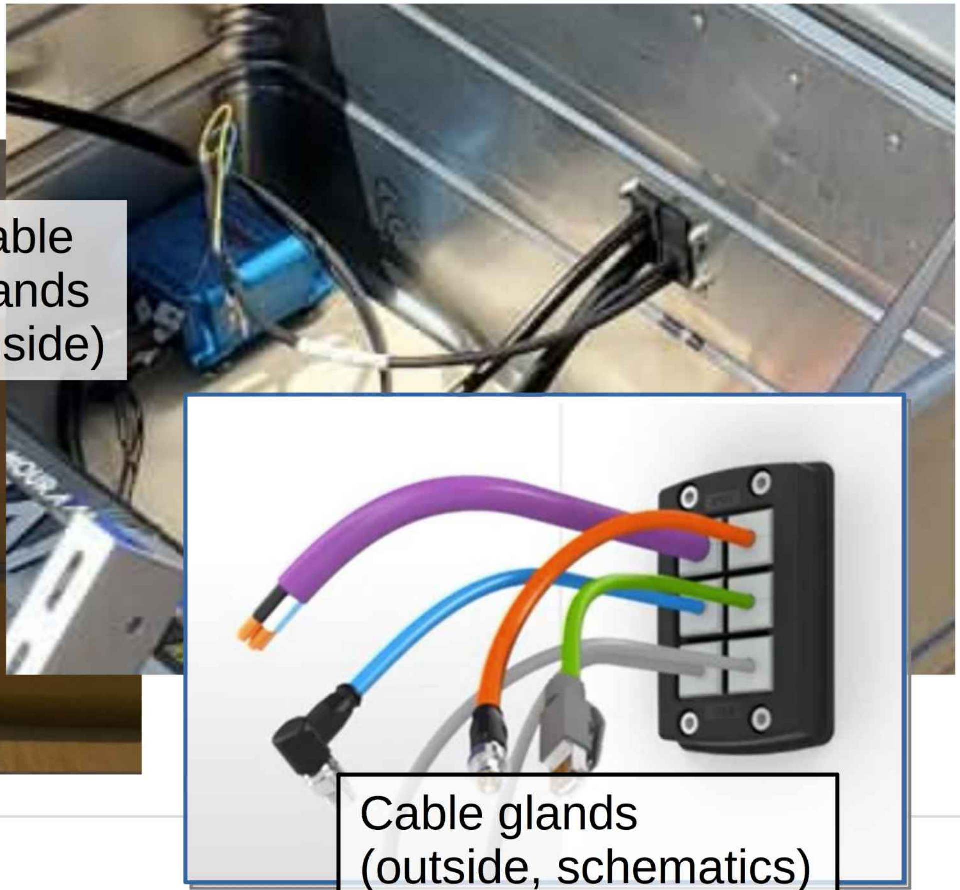
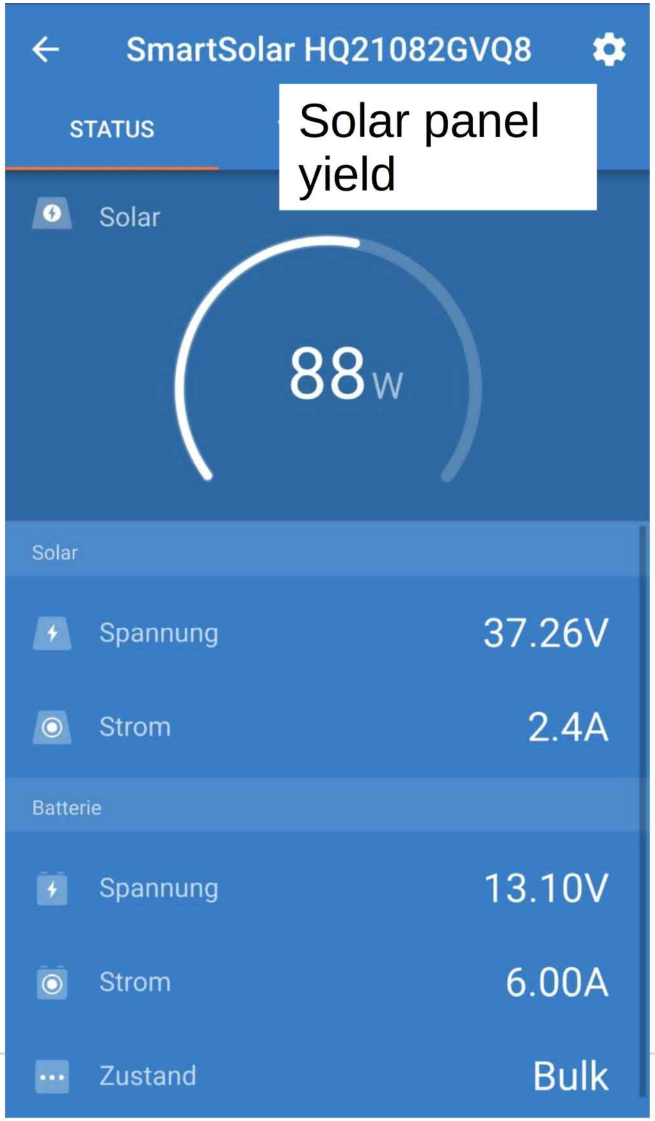
Deployment of first Station

- Power yield of solar panel looks good
- Dust- and waterproof cable glands (IP66)



Cable glands (inside)

Cable glands (outside, schematics)



Solar panel yield

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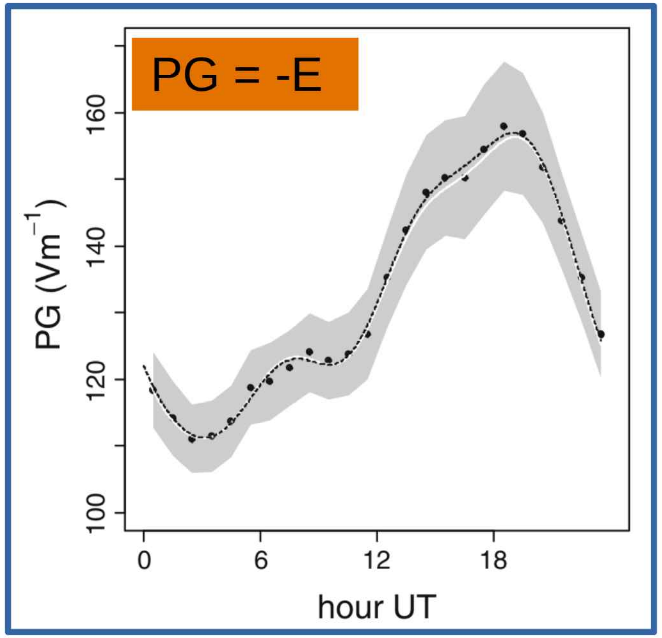
②

First E-field data

- Typical fair-weather day (±100 V/m)
- Diurnal variation as described by the „Carnegie curve“



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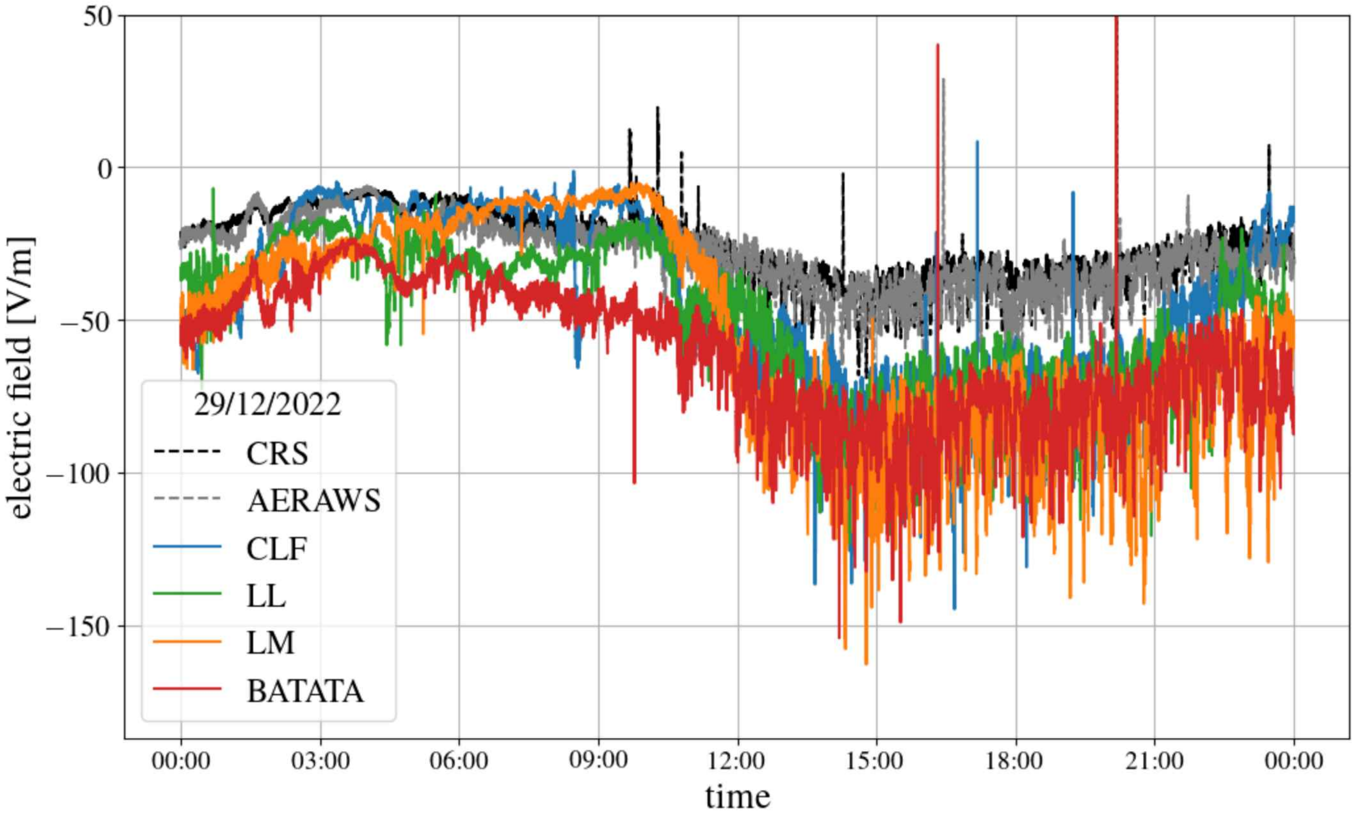

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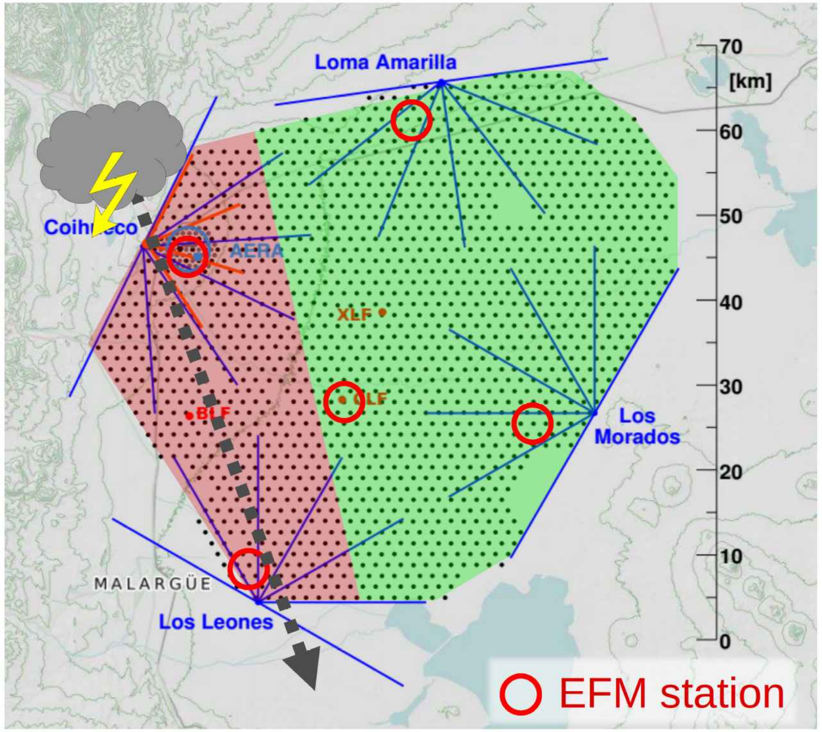
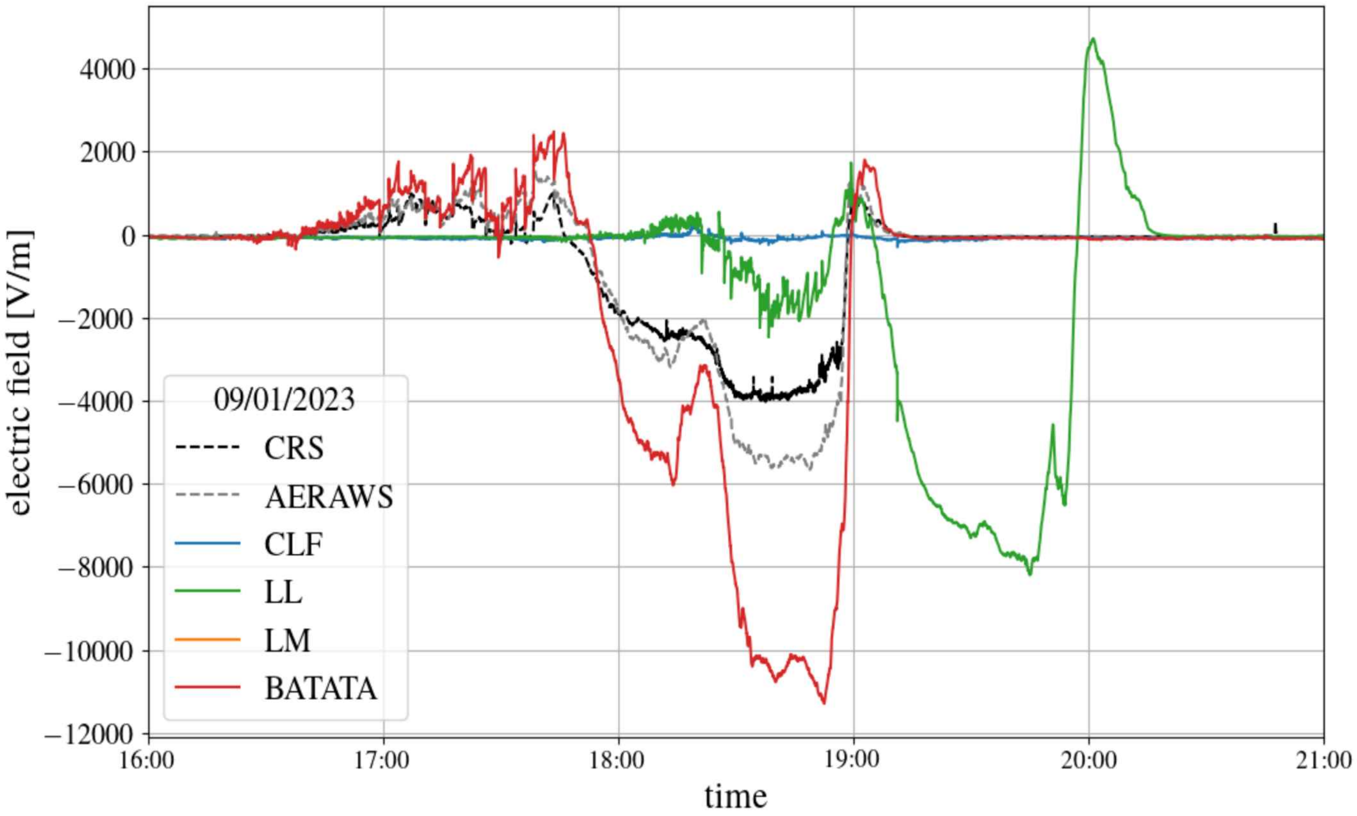
E-field data

- Thunderstorms signatures seen in multiple stations with a time shift

  → Infer movement of the cloud





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