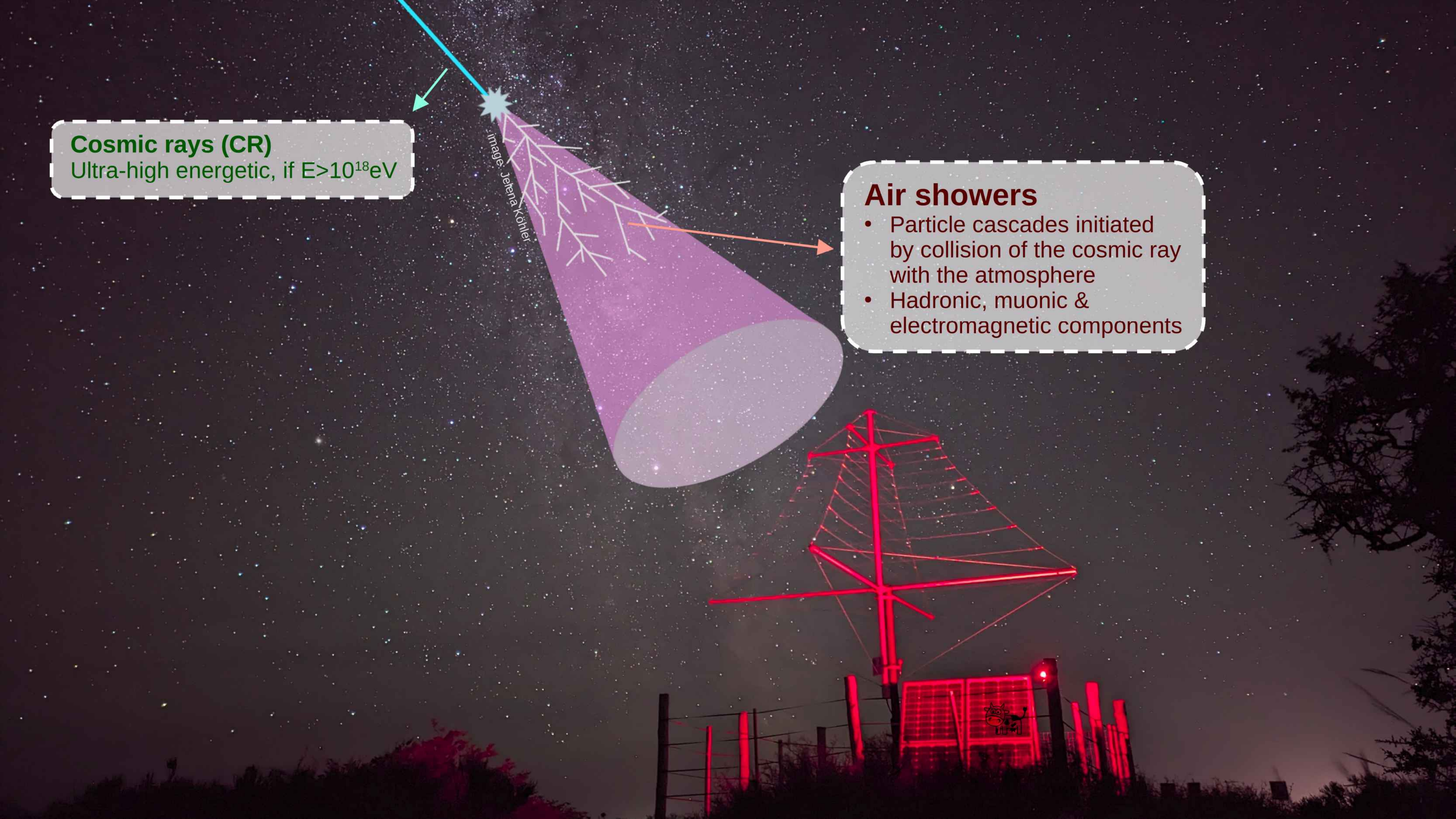
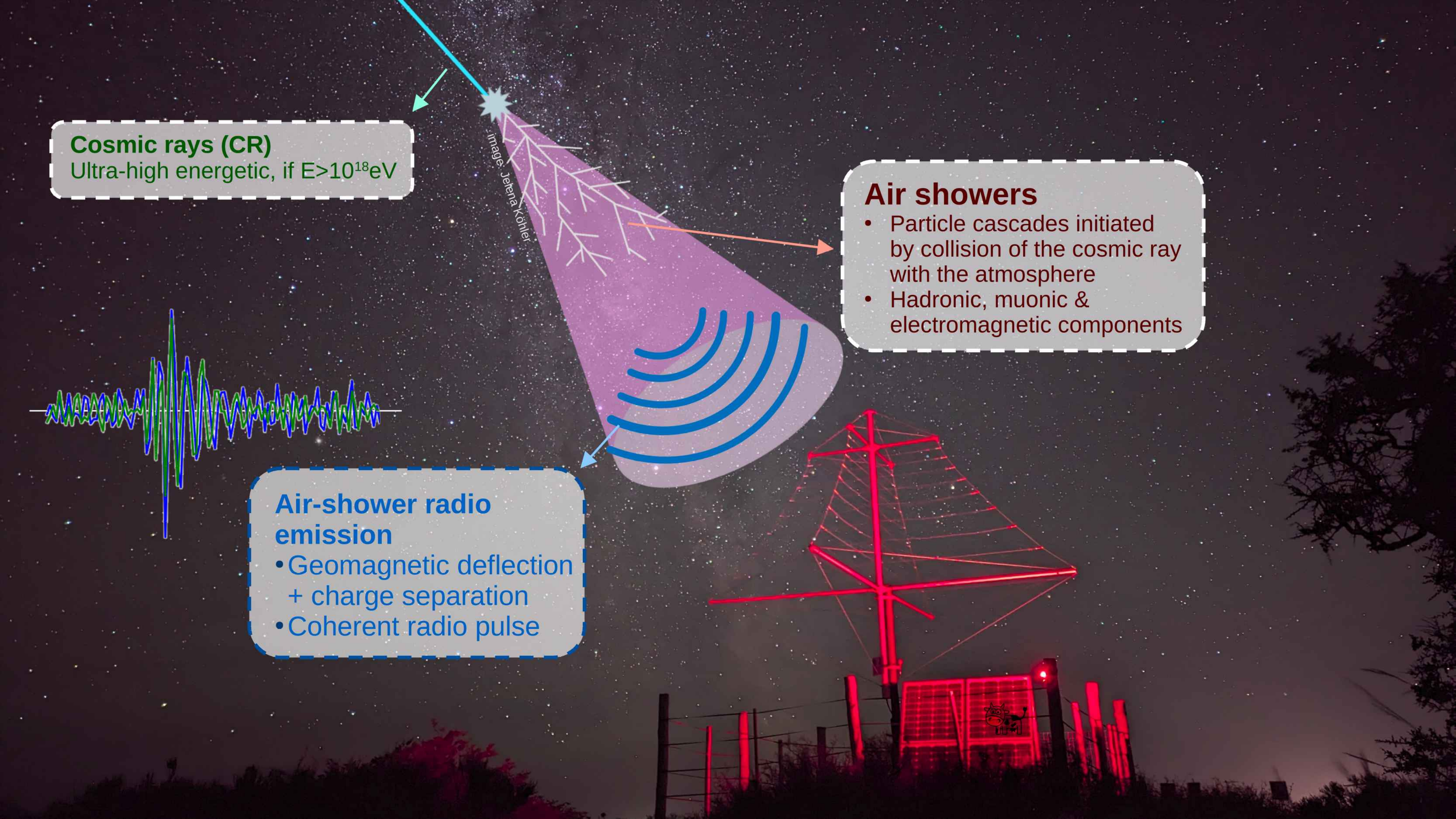
DPG Frühjahrstagung
6th March 2024

Max Büsken & Tim Huege
for the Pierre Auger Collaboration

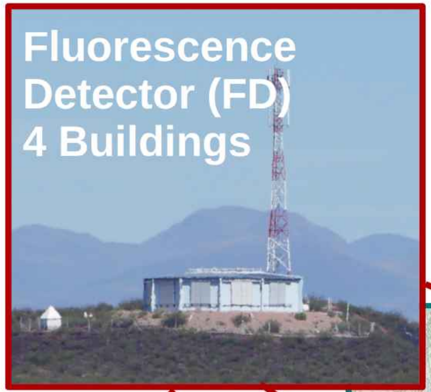
Accessing the Cosmic-Ray Energy Scale with the *Auger Engineering Radio Array*

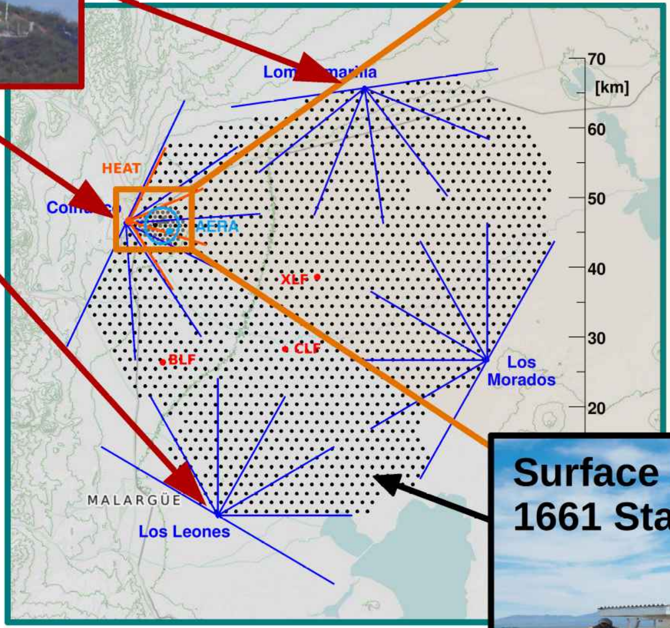
Karlsruhe Institute of Technology
UNSAM
PIERRE AUGER OBSERVATORY
HIRSAP
Bundesministerium für Bildung und Forschung

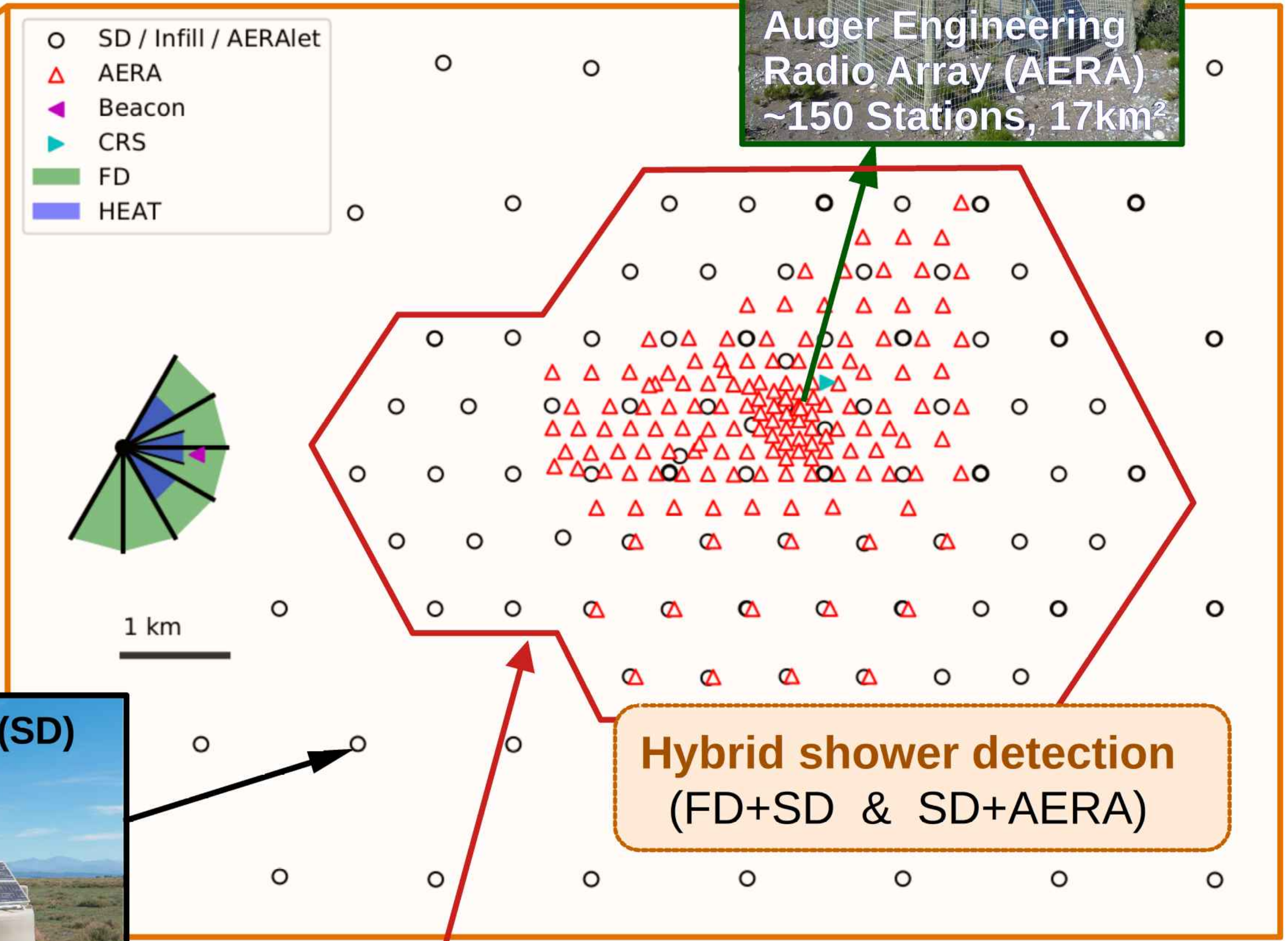

Cosmic rays (CR)
Ultra-high energetic, if E>10^18eV
Image: Jelena Köhler
Air showers
• Particle cascades initiated by collision of the cosmic ray with the atmosphere
• Hadronic, muonic & electromagnetic components


Cosmic rays (CR)
Ultra-high energetic, if E>10^18eV
Image: Jelena Köhler
Air showers
• Particle cascades initiated by collision of the cosmic ray with the atmosphere
• Hadronic, muonic & electromagnetic components
Air-shower radio emission
• Geomagnetic deflection + charge separation
• Coherent radio pulse

The Pierre Auger Observatory



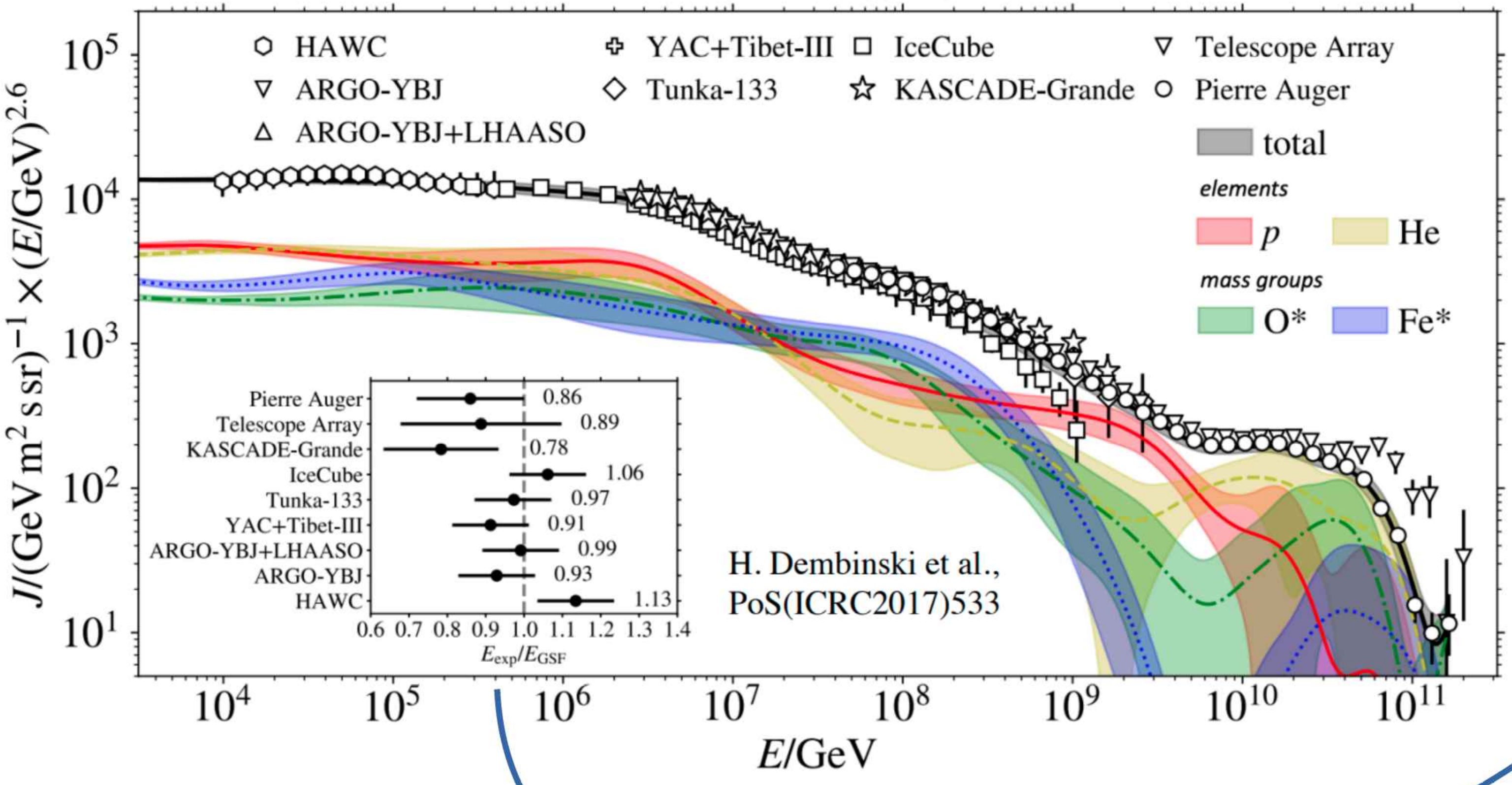




Infill region with denser detector spacing

Importance of the cosmic-ray energy scale

Cosmic-ray energy spectrum

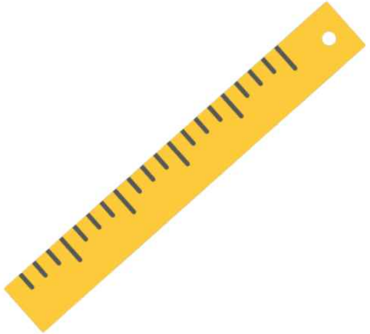


- Cosmic-ray (CR) energy is base ingredient in many analyses,

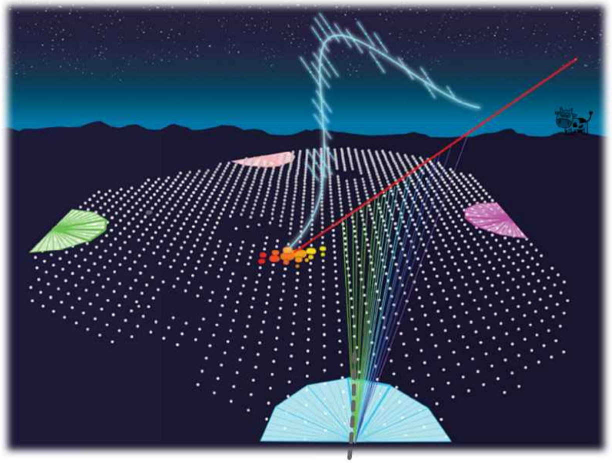
  e.g. CR energy spectrum

- Value of reconstructed energy bound to the observatory's energy scale
  - Absolute determination crucial

i.e. "did we apply the ruler correctly?"



Energy scales at the Pierre Auger Observatory



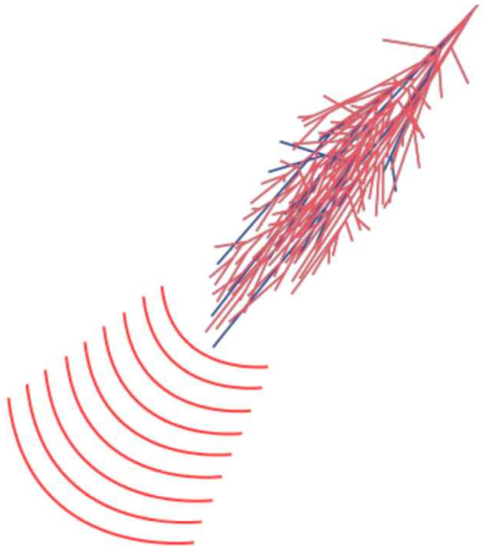
Need precise determination of cosmic-ray energy E_{CR}

established (FD):

alternative (Radio):

Energy scale defined by the **fluorescence yield**

Energy scale defined by **classical electrodynamics** in MC air-shower simulations



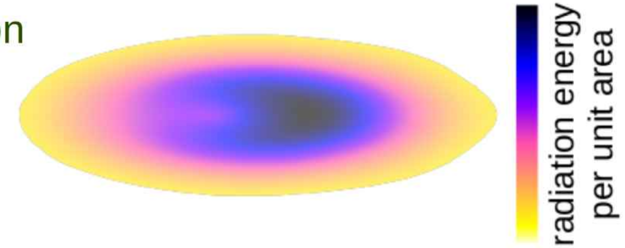
Total number of fluorescence photons proportional to cosmic-ray energy

$$N_{\gamma,\,\mathrm{fluorescence}} \propto E_{CR}$$

Measured in the laboratory
M. Ave et al. [AIRFLY Collaboration] Astropart. Phys. 42 (2013) 90.

High-precision simulations:

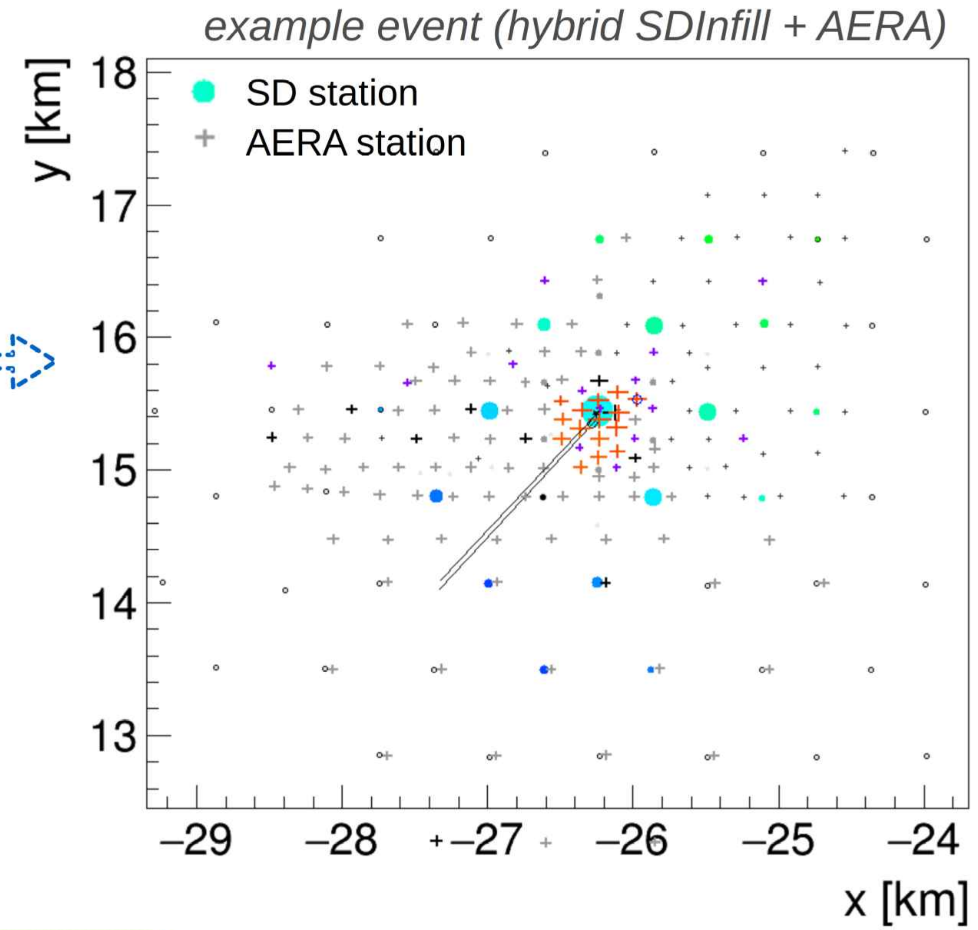
- Corsika: particle cascade
- CoREAS: radio emission from classical electrodynamics

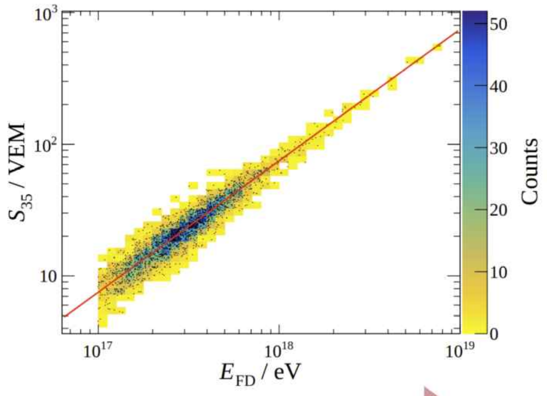


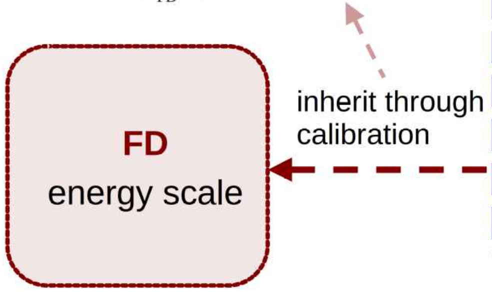
How to compare the scales?

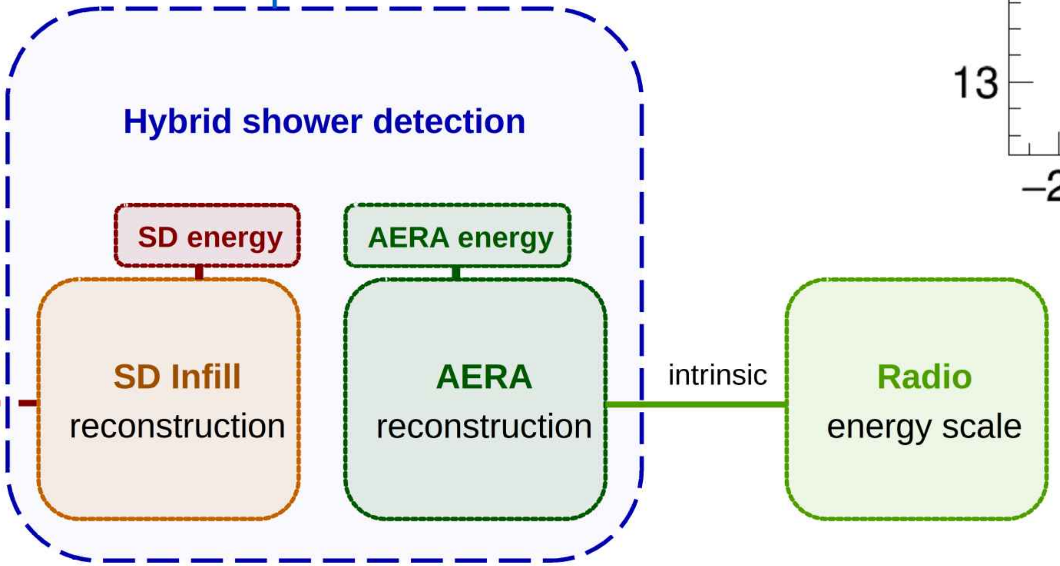
Comparing energy scales

Shower dataset:
- Full AERA operation since 2013
- Number of reconstructable hybrid events after quality cuts ~1000

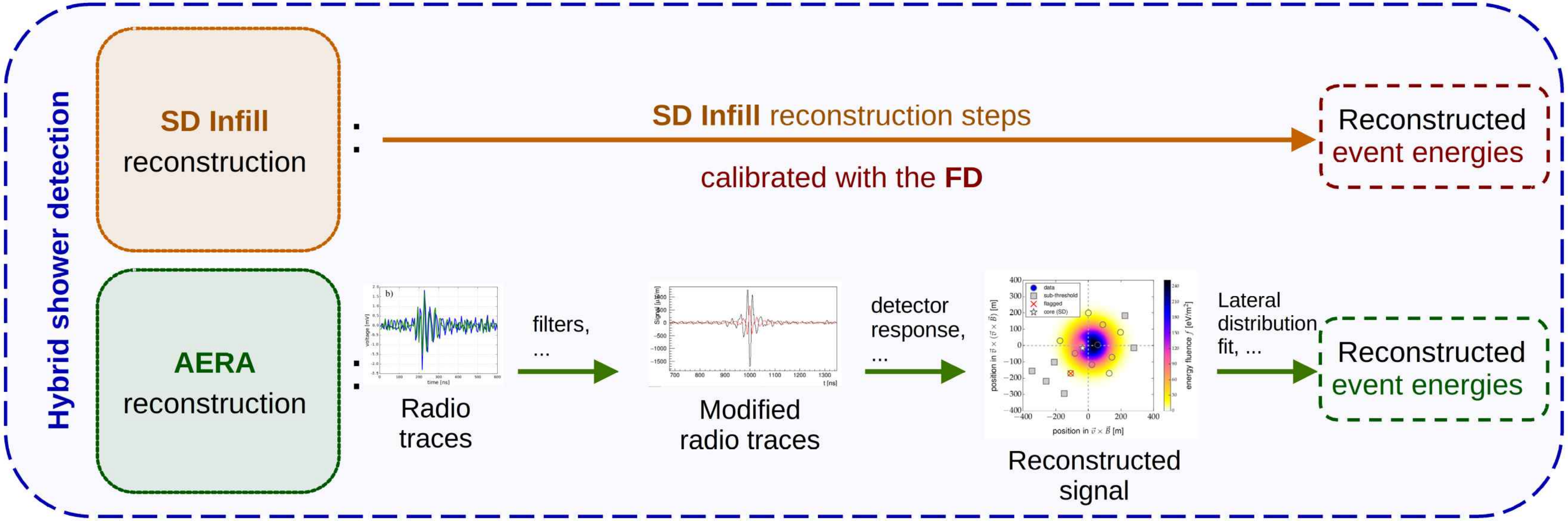




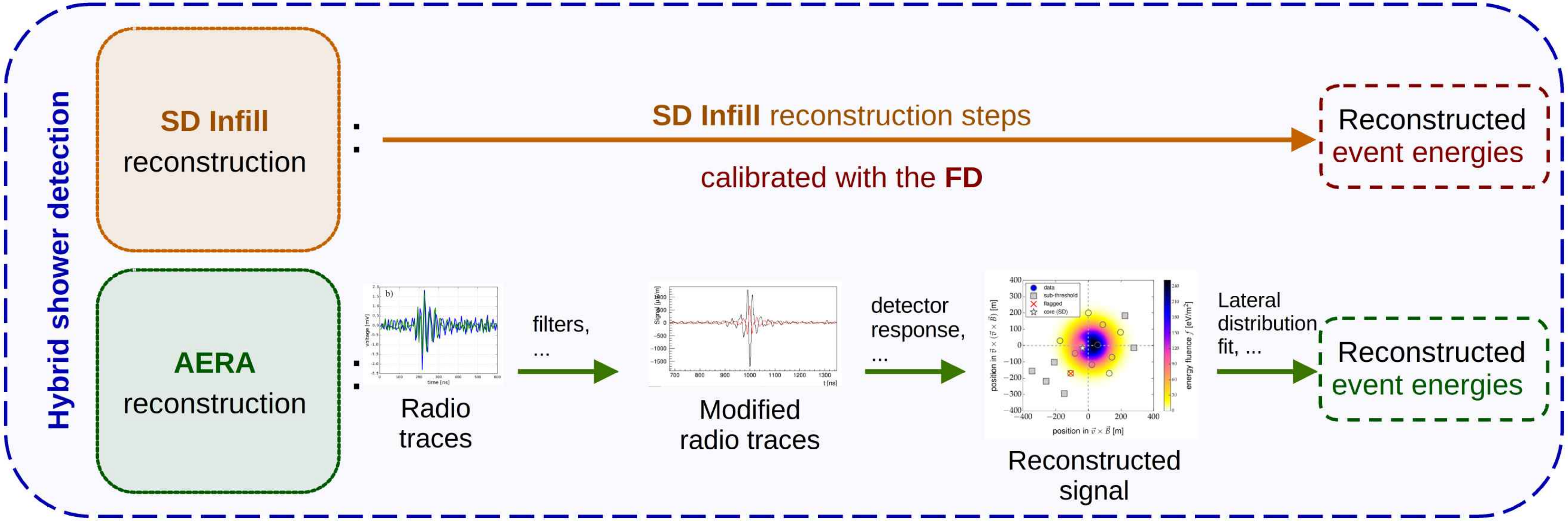




Comparing energy scales



Comparing energy scales

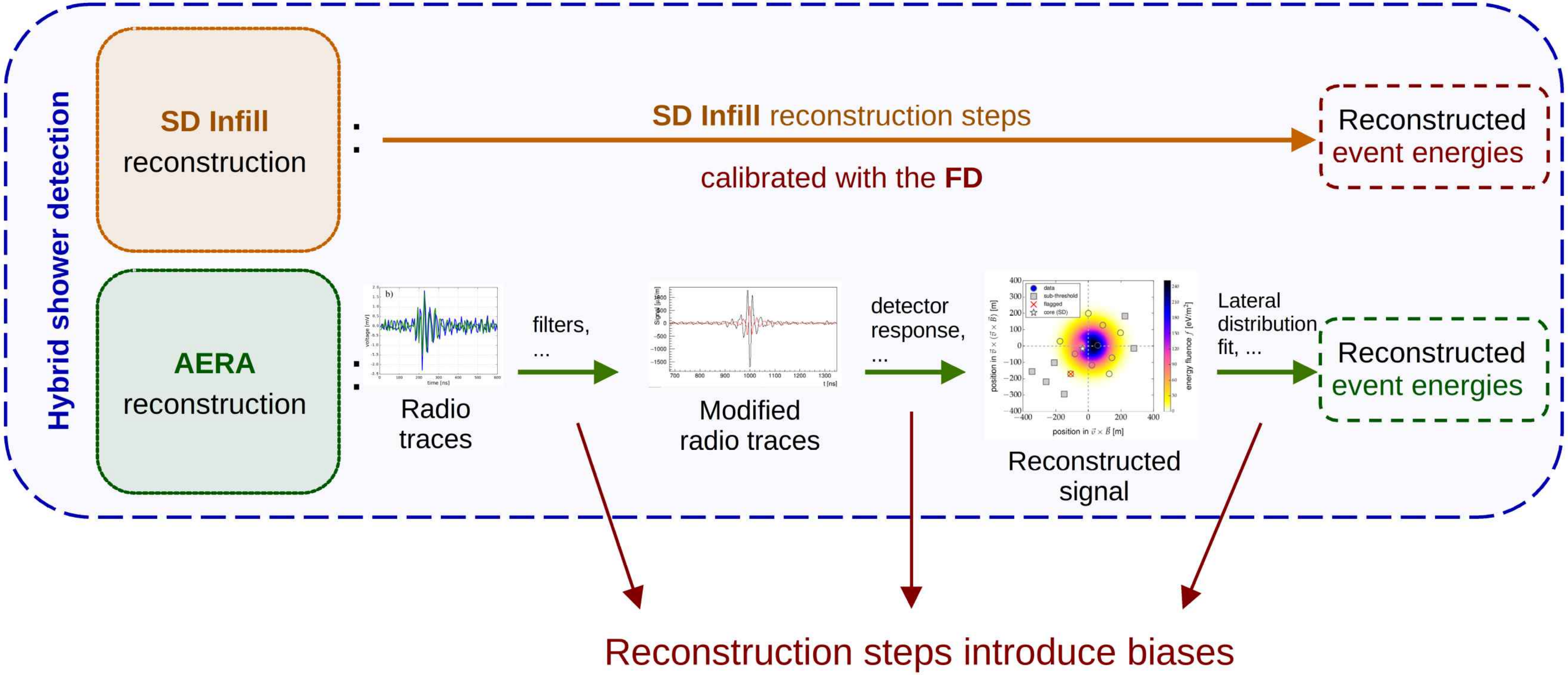


Good calibration of the radio detector is crucial

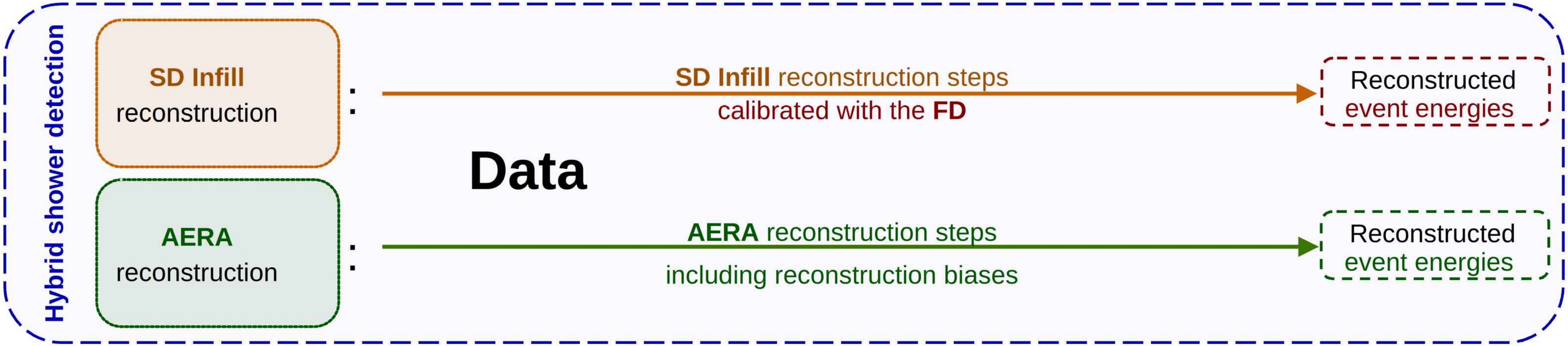
Some important steps:

- Electronics calibration in the laboratory (amplifiers,…)
- Description of detector response (simulation of directional sensitivity,…)
- Absolute signal calibration (Galactic background as a reference,…)
- ...

Comparing energy scales

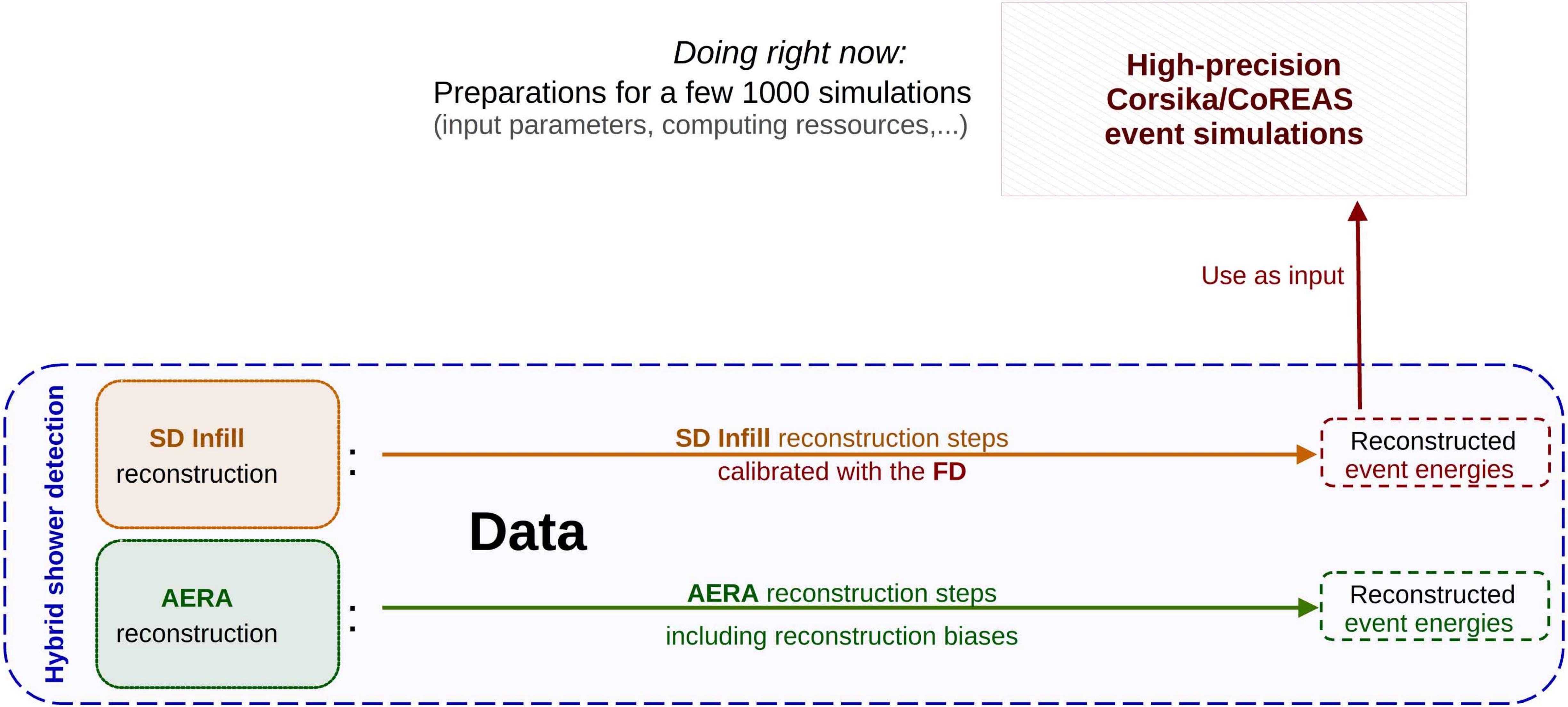


Comparing energy scales

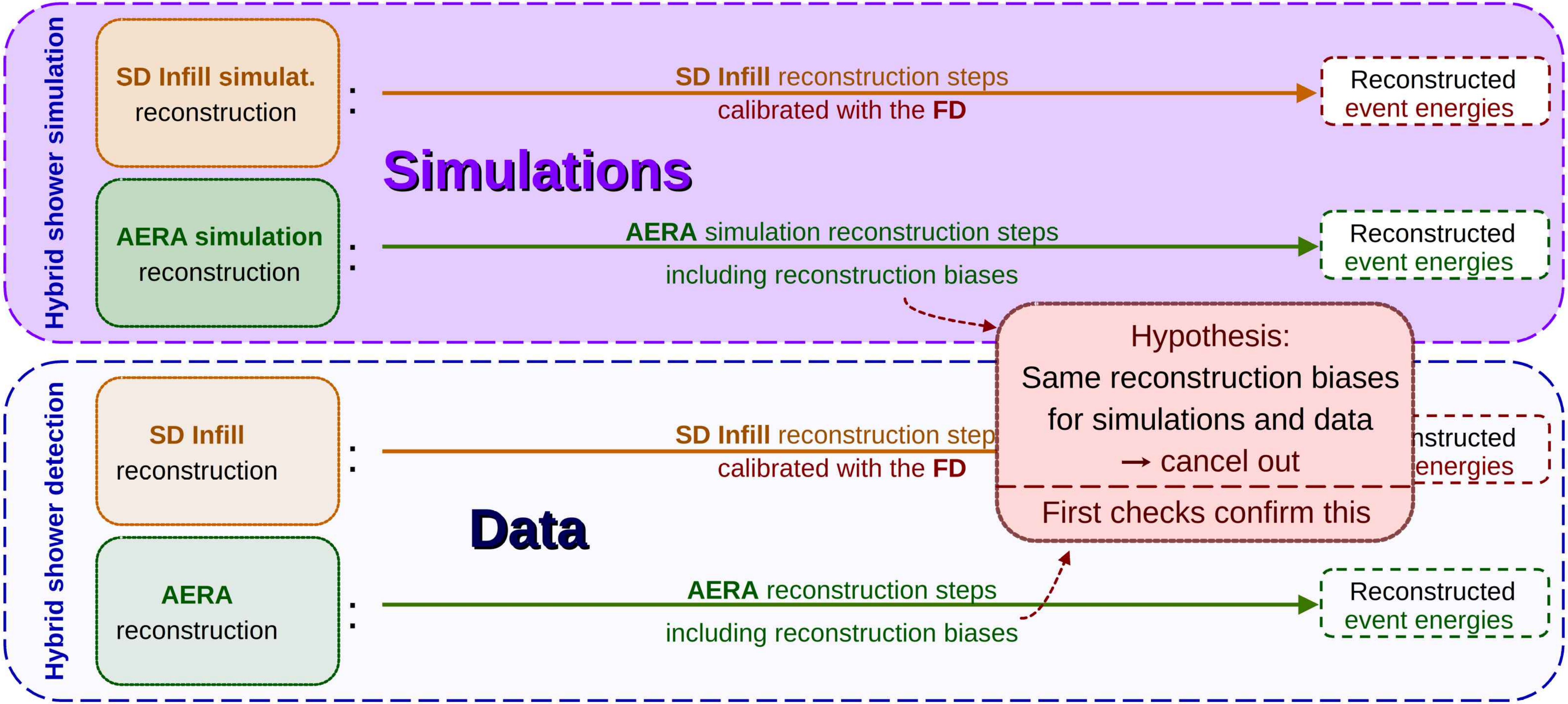


Comparing energy scales

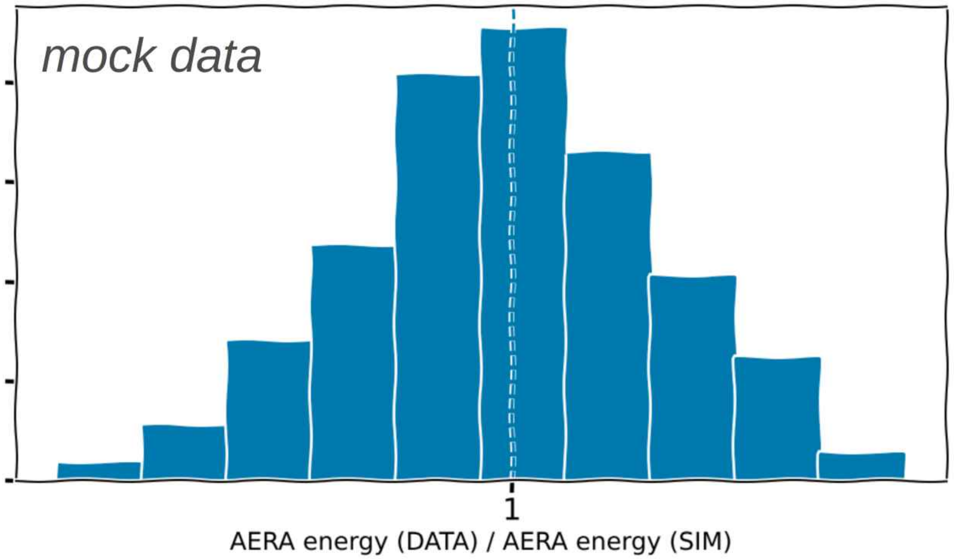
Doing right now:
Preparations for a few 1000 simulations
(input parameters, computing ressources,...)



Comparing energy scales



Comparing energy scales



Comparing (biased) SD/AERA measurements with (biased) simulations

Summary

- Radio arrays can independently probe the cosmic-ray energy scale, next to the established access via fluorescence telescopes
- Preparing approach to directly compare CR energy scales at the Pierre Auger Observatory from AERA and the FD:
  - Equalized reconstructions of data and simulations to cancel out rec. biases

Outlook

- Do comparison with new high-precision simulations
- Study systematics
  → biases and uncertainties

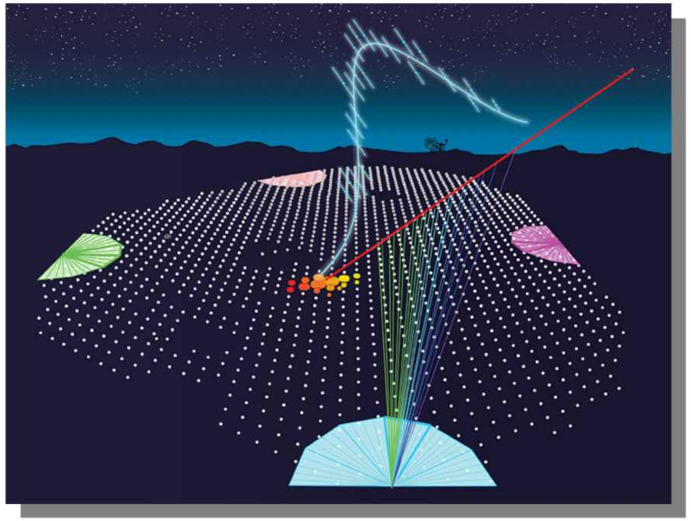
Backup

Accessing the cosmic-ray energy scale

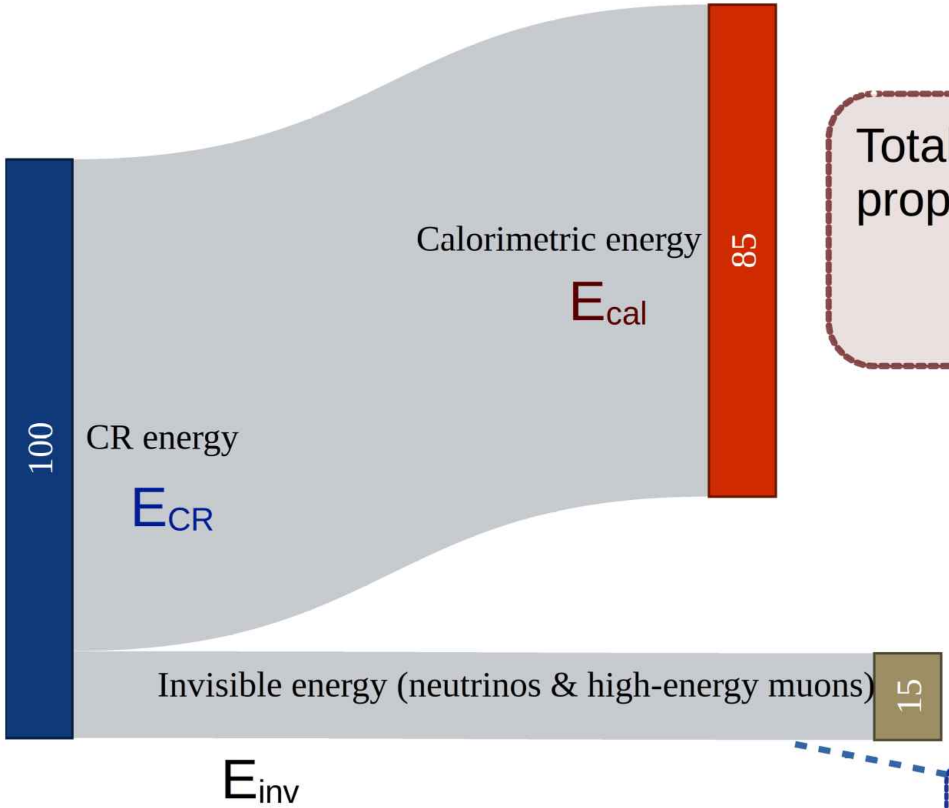
with the Auger Fluorescence Detector (FD)

FD principle:

Shower particles excite air molecules
→ emit fluorescence light



E_{cal}: All energy deposited in the atmosphere



Total number of fluorescence photons proportional to calorimetric energy

$$N_\gamma \propto E_{cal} \propto E_{CR}$$

FD probes absolute CR energy scale

Can be corrected for
Phys. Rev. D 100, 082003 (2019)

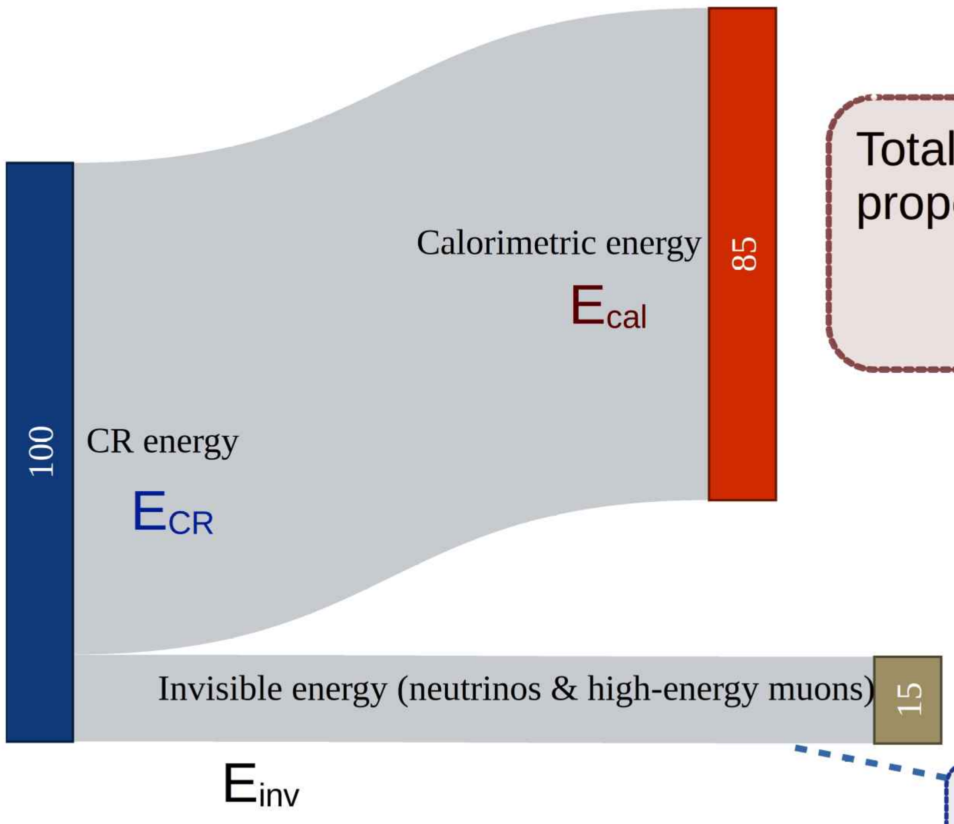
Consequence for SD:

SD calibrated from hybrid events
► SD inherits FD energy scale

Accessing the cosmic-ray energy scale

with the Auger Fluorescence Detector

E_{cal}: All energy deposited in the atmosphere



Total number of fluorescence photons proportional to calorimetric energy

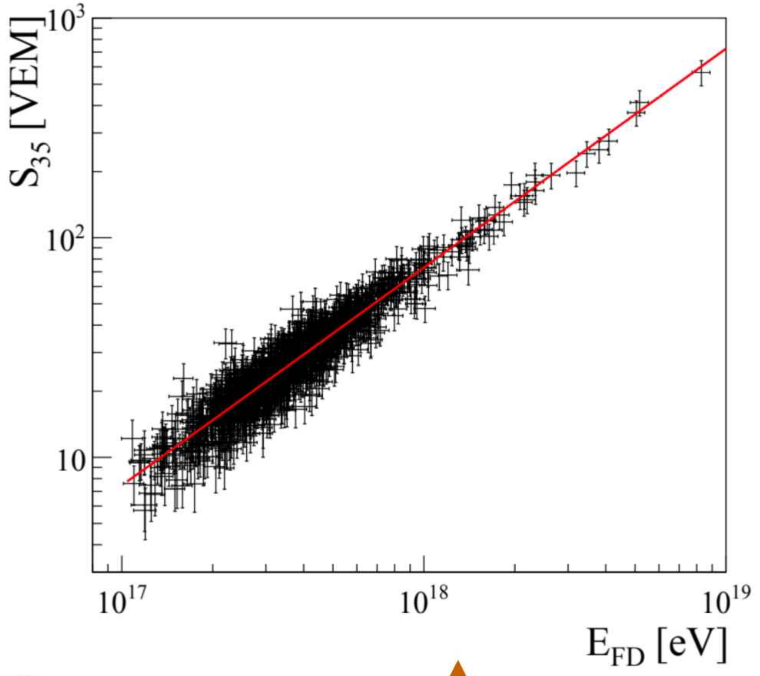
$$N_\gamma \propto E_{cal} \propto E_{CR}$$

FD probes absolute CR energy scale

Can be corrected for

Phys. Rev. D 100, 082003 (2019)

energy estimator from SD



energy estimator from FD

Consequence for SD:

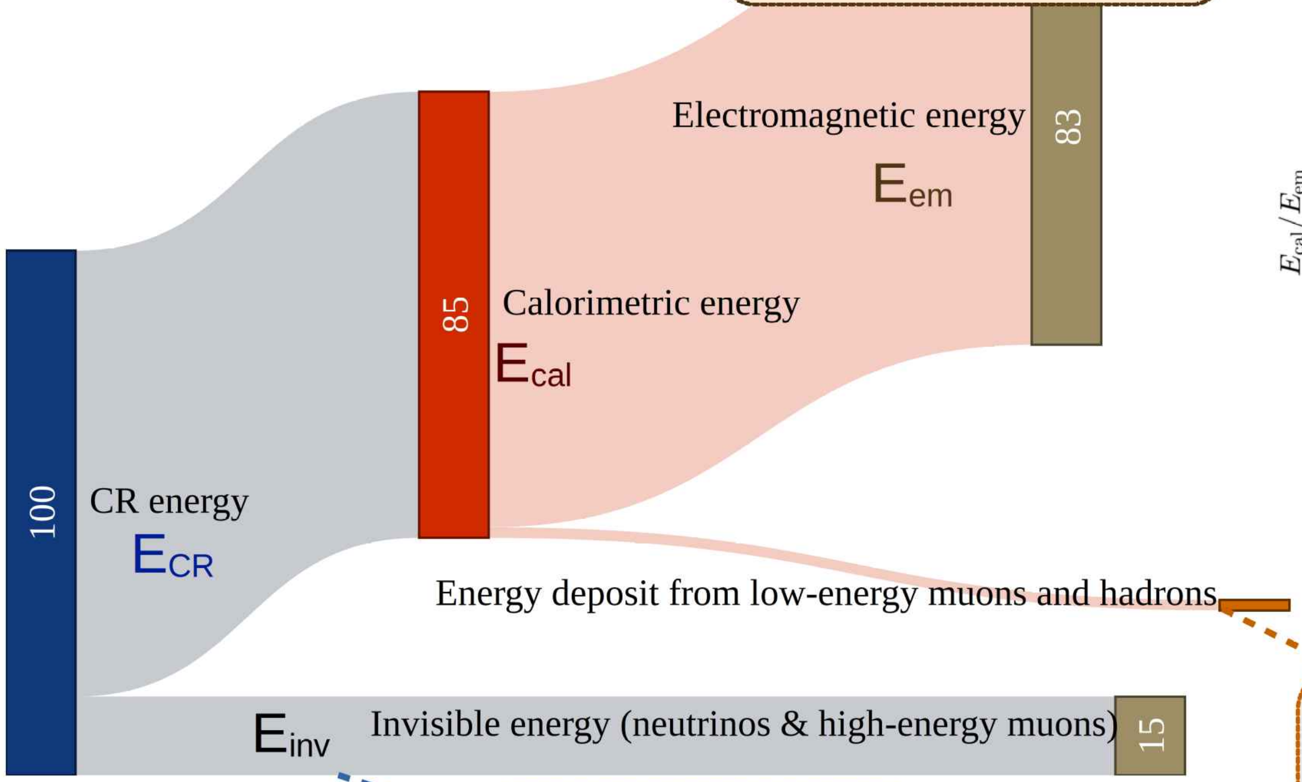
SD calibrated from hybrid events

▸ SD inherits FD energy scale

Accessing the cosmic-ray energy scale

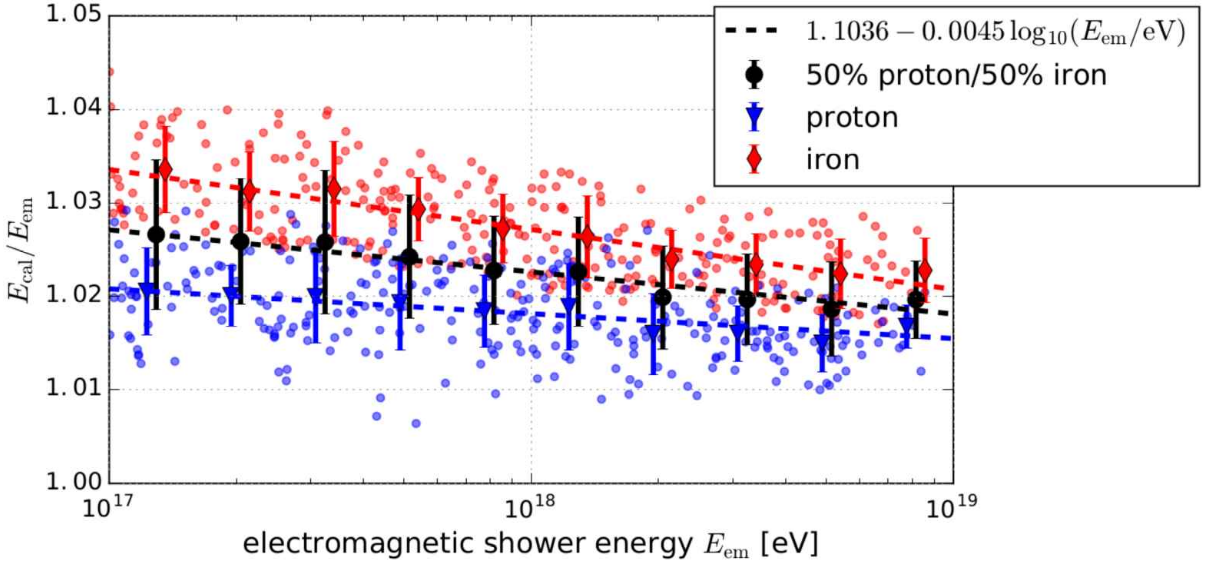
with AERA

E_{em}: All energy deposited in the atmosphere **by e^+, e^-, ɣ**



Can be corrected for

Phys. Rev. D 100, 082003 (2019)



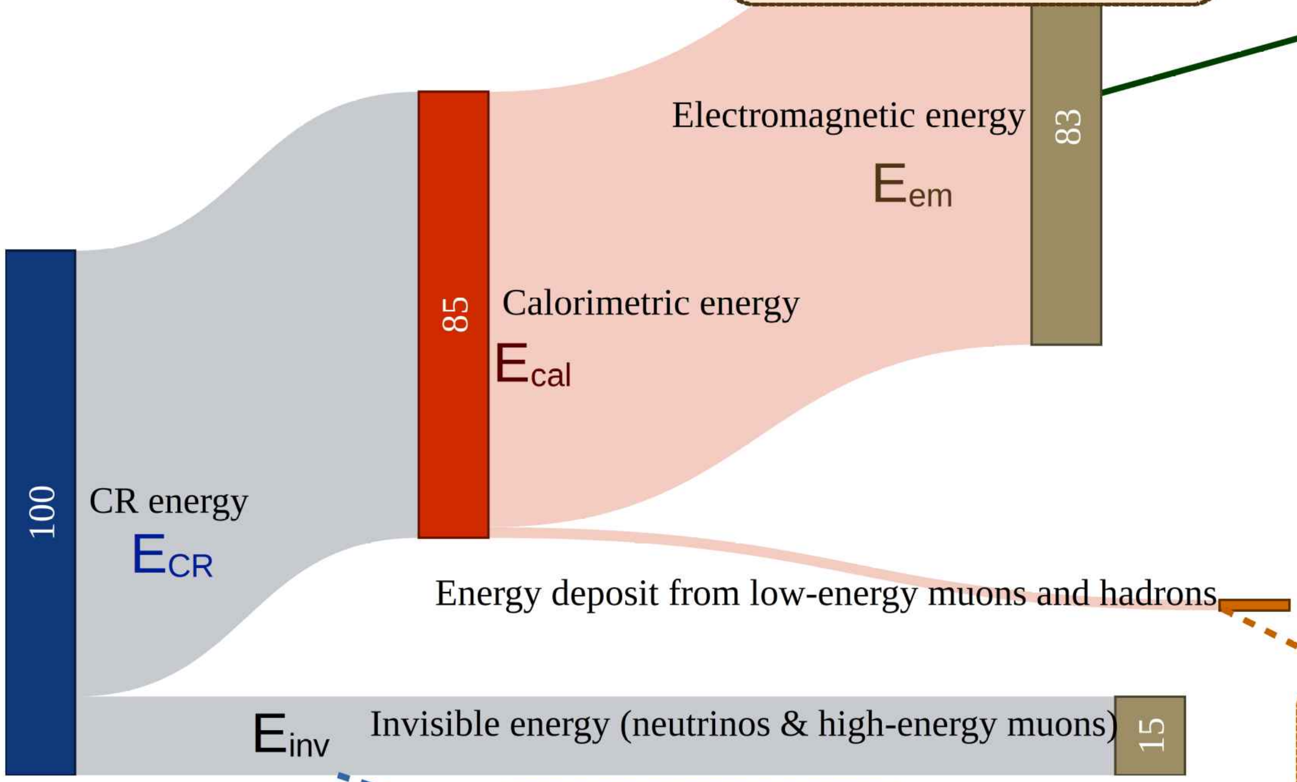
Difference between E_{cal} and E_{em}

- can be corrected for: 2.3% @ 10^{18}eV

Accessing the cosmic-ray energy scale

with AERA

E_{em}: All energy deposited in the atmosphere **by e^+, e^-, γ**



Can be corrected for

Phys. Rev. D 100, 082003 (2019)

Difference between E_{cal} and E_{em}

▸ can be corrected for: 2.3% @ 10^{18}eV

Radiation energy E_{rad} → E_{rad}: All energy deposited in the atmosphere **in form of radio waves**

Corrected "" S_{rad} → S_{rad} = E_{rad} *corrected for*

- B-field strength and angle
- Air density at Shower maximum

Corrected radiation energy proportional to electromagnetic energy

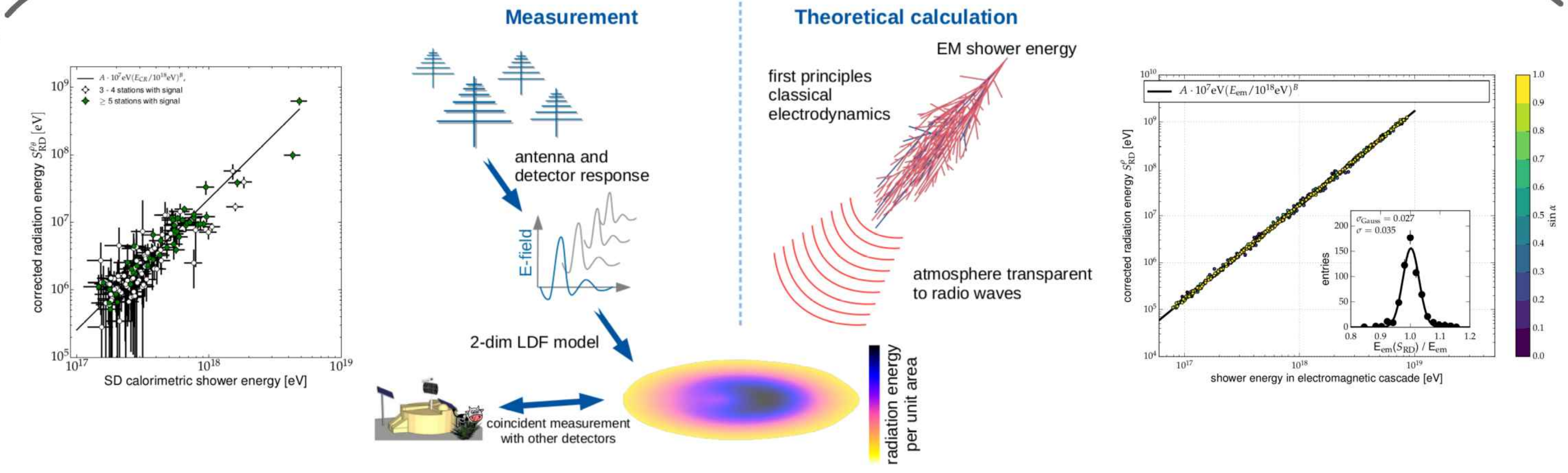
$$S_{rad} \propto E_{em} \propto E_{CR}$$

→ *Independent energy scale access*

Comparing FD and radio energy scales

- Two individual energy scale accesses call for comparing them
- One recipe worked out by C. Glaser
- Based on hybrid SD-AERA-showers and a high-precision simulation study

Recipe introduced by C. Glaser (PhD thesis, 2017)



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

Allows to compare CR energy scales from FD and radio

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

Aiming to determine a universal/academic radio energy scale

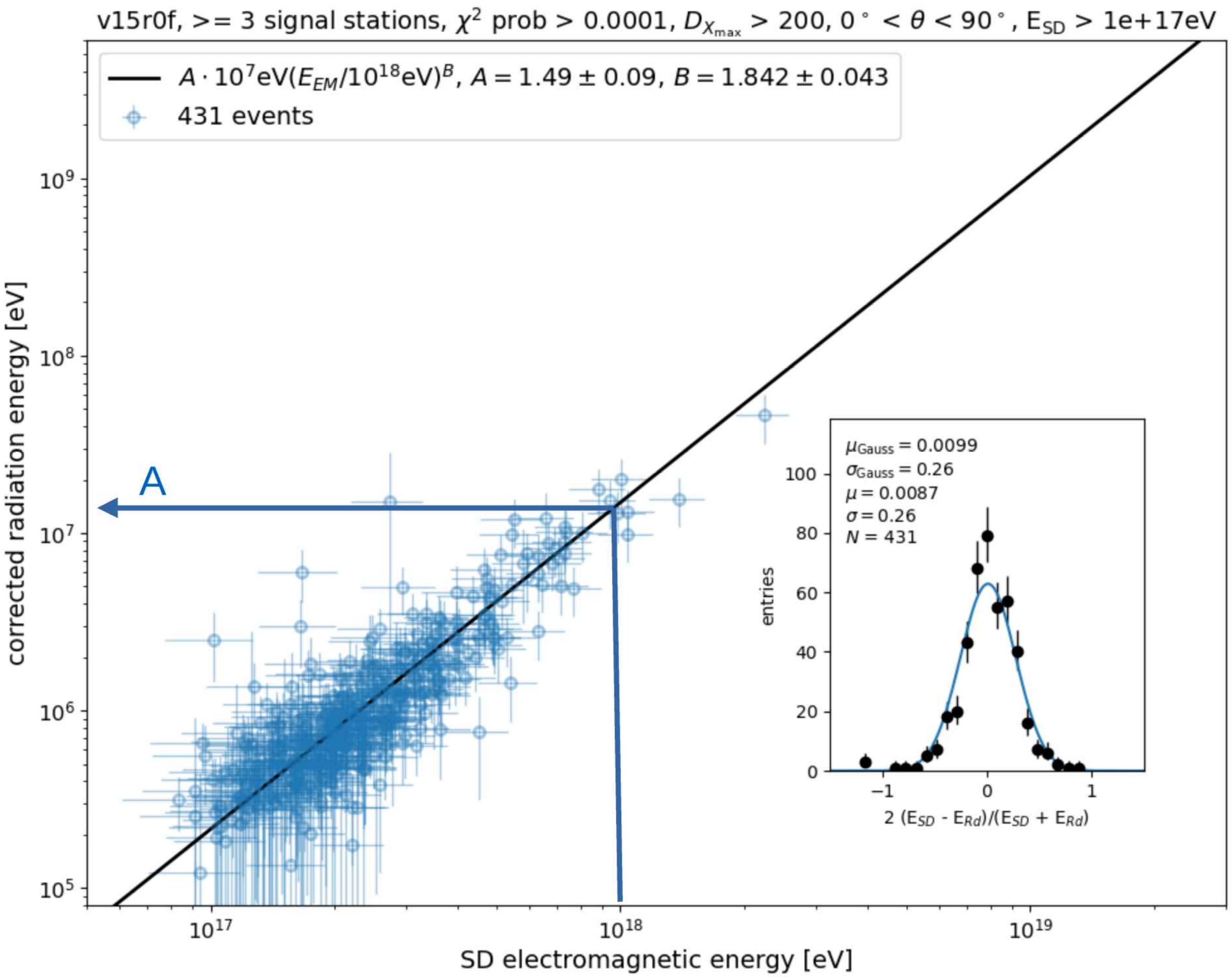
Calibration fit from hybrid showers (SD-AERA)

- Fit S_{rad} from AERA reconstruction to E_{em} from SD reconstruction

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

- A: “how much energy from a 10^{18}eV shower is transformed into radio waves“
- B: Scaling of S_{rad} with E_{em}

Disclaimer: Shown fit values for A and B are very preliminary and not to be compared to previous analyses



Calibration fit from hybrid showers (SD-AERA)

- Fit S_{rad} from AERA reconstruction to E_{em} from SD reconstruction

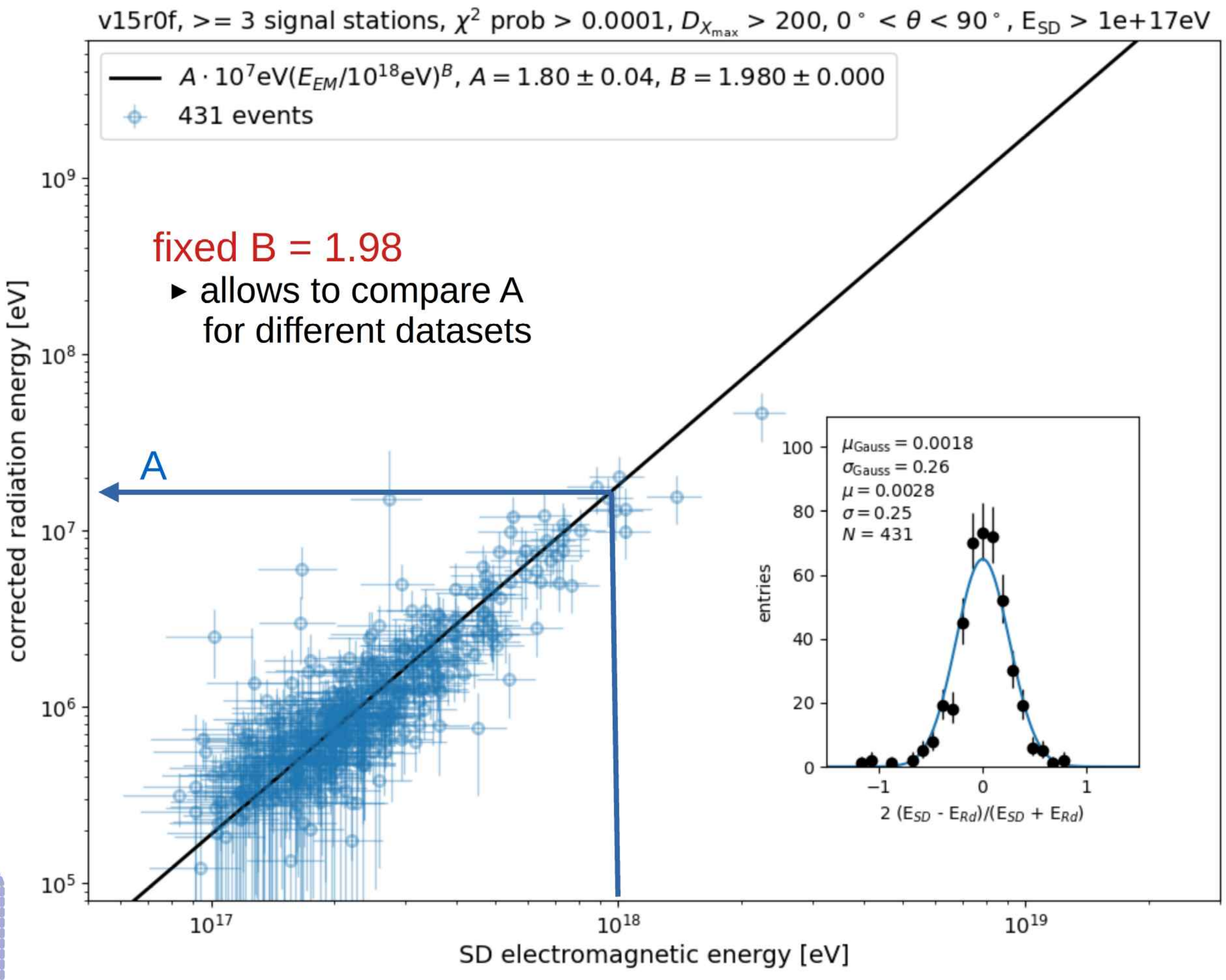
$$S_{\mathrm{RD}}^{\rho\theta} = A \times 10^7 eV \left(\frac{E_{\mathrm{SD,em}}}{10^{18} eV} \right)^B$$

- A: “how much energy from a 10^{18}eV shower is transformed into radio waves“
- B: Scaling of S_{rad} with E_{em}

  expectation B = 1.98*

  [JCAP 09(2016)024]

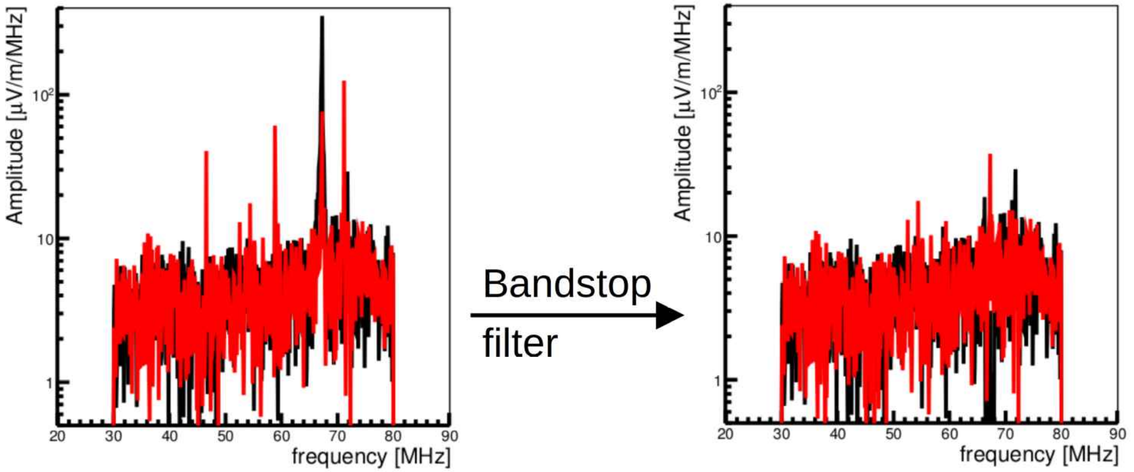
*deviation from quadratic scaling originates from using the zenith angle only to approximate the air density correction, instead of using Xmax



Reconstruction biases in data and simulations

- Steps in AERA reconstruction with multiple choices:
  - Noise filter
  - Signal estimation method (energy fluence)
  - ...
- Tested SD-AERA calibration fit with fixed B=1.98
  - Check relative change in fitted A
  - Changes very similar for data and simulations

AERA frequency spectra (red + black: 2 polarizations)



by C. Glaser

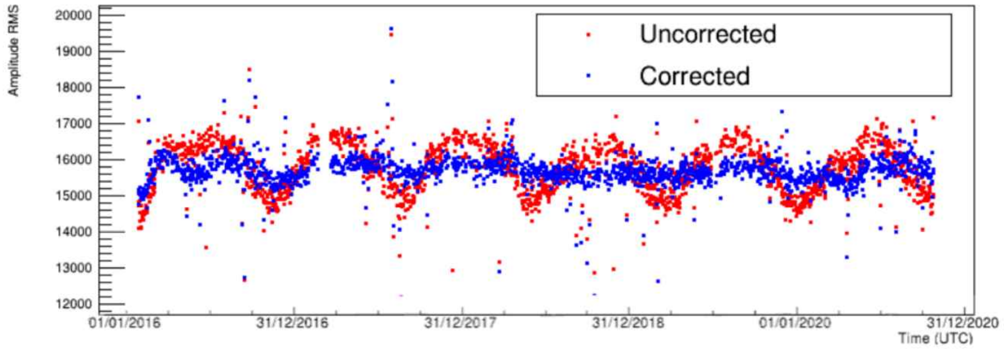
Test	Description	Relative change in A (data)	Relative change in A (simulations)
Noise filters	no filter	-	-
	Bandstop	-12.2%	-11.6%
	Sinewave suppressor	-2.9%	-1.9%
Signal estimation methods	Offline method	-	-
	Method with background subtraction	-5.2%	-6.2%

General reconstruction improvements & advancements

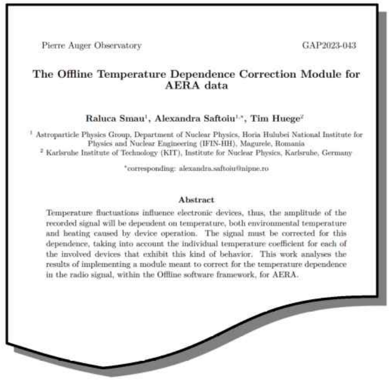
Testing the temperature correction..

Correcting temperature dependence of amplifiers

Raluca Smau, Alexandra Saftoiu



GAP *2023-043*



Pierre Auger Observatory GAP2023-043

The Offline Temperature Dependence Correction Module for AERA data

Raluca Smau[1], Alexandra Saftoiu[1,*], Tim Huege[2]

[1] Astroparticle Physics Group, Department of Nuclear Physics, Horia Hulubei National Institute for Physics and Nuclear Engineering (IFIN-HH), Magurele, Romania
[2] Karlsruhe Institute of Technology (KIT), Institute for Nuclear Physics, Karlsruhe, Germany

*corresponding: alexandra.saftoiu@nipne.ro

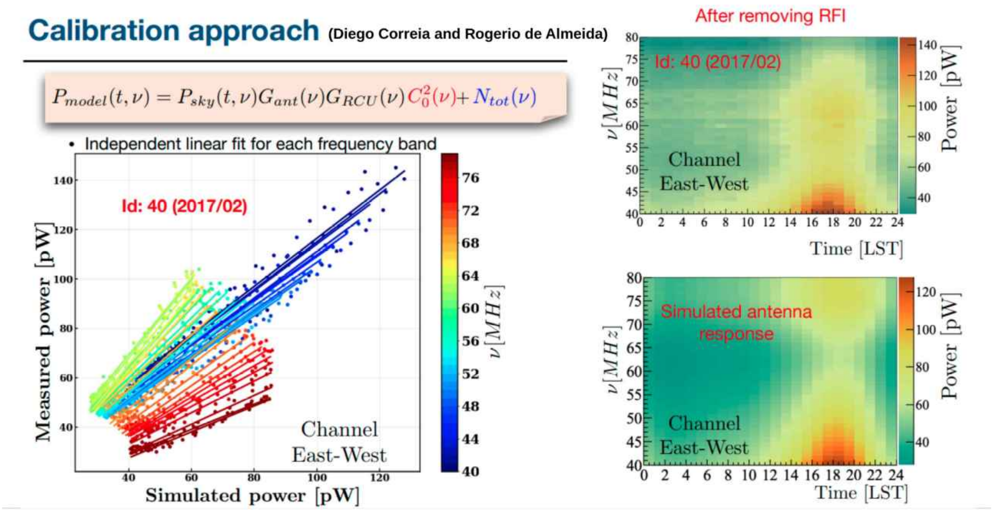
Abstract

Temperature fluctuations influence electronic devices, thus, the amplitude of the recorded signal will be dependent on temperature, both environmental temperature and heating caused by device operation. The signal must be corrected for this dependence, taking into account the individual temperature coefficient for each of the involved devices that exhibit this kind of behavior. This work analyses the results of implementing a module meant to correct for the temperature dependence in the radio signal, within the Offline software framework, for AERA.

..and Galactic calibration

Absolute calibration using dominating Galactic background as reference

Diego Correia & Rogerio de Almeida



GAP *2023-036*

Pierre Auger Observatory GAP2023_036

AERA Galactic Calibration implementation within Offline

D. Correia dos Santos[1], R. M. de Almeida[1],

Universidade Federal Fluminense, RJ, Brazil[1]

Abstract

A comprehensive understanding of the antenna response is crucial to achieve accurate interpretation of the AERA data. Thus, careful calibration of the antennas is essential. This note provides a detailed explanation of how to perform an absolute calibration using the radio emission from the Galaxy. The approach involves propagating a model of the entire radio sky through the system response, which encompasses the antenna, filters, and amplifiers. The resulting output is then compared with the averaged spectra recorded by stations. We provide a comprehensive description of the modules designed to obtain calibration constants and correct traces within the Offline framework.

Temperature correction & Galactic calibration

- Offline modules recently finalized
- No big change with temperature correction
- Large influence of sky model choice ☐ in Galactic calibration

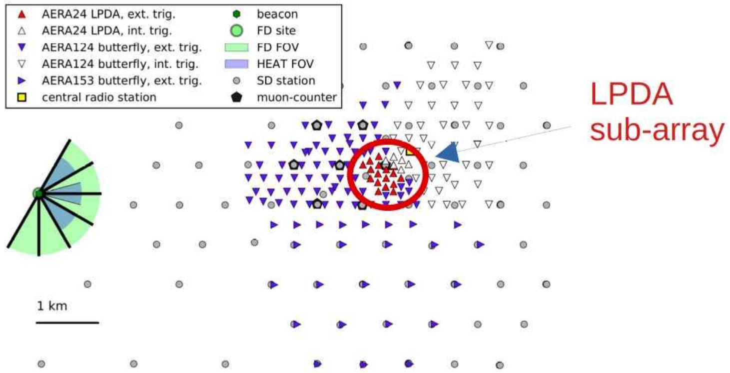
  → will use **average cal. constants** & estimate systematic uncertainties

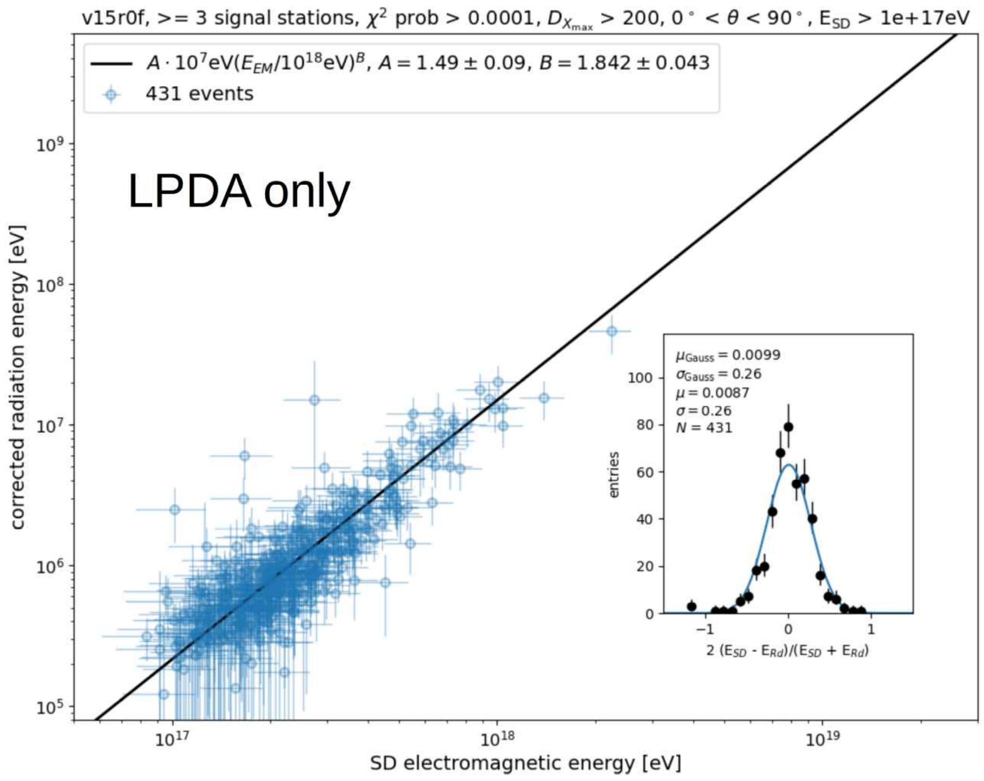
  → average change in A small

description	relative change in A
without temp-corr. & Gal. cal.	-
temp-corr. only	1.8%
LFmap	7.8%
GSM	1.8%
GSM16	-7.7%
LFSM	3.0%
GMOSS	5.4%
SSM	0.0%
ULSA	-10.8%
"Average model"	-3.0%

Fully including Butterfly antennas

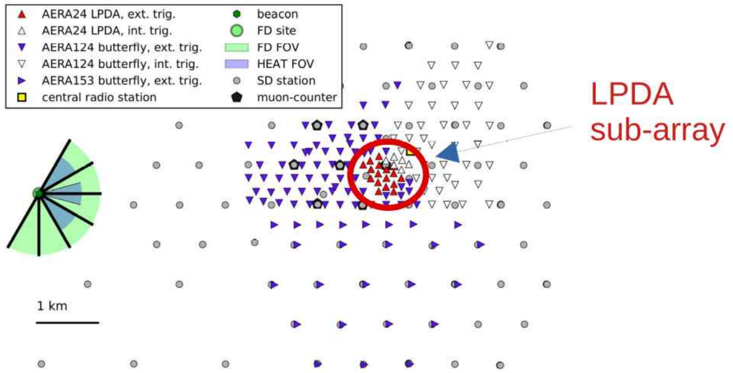
- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations



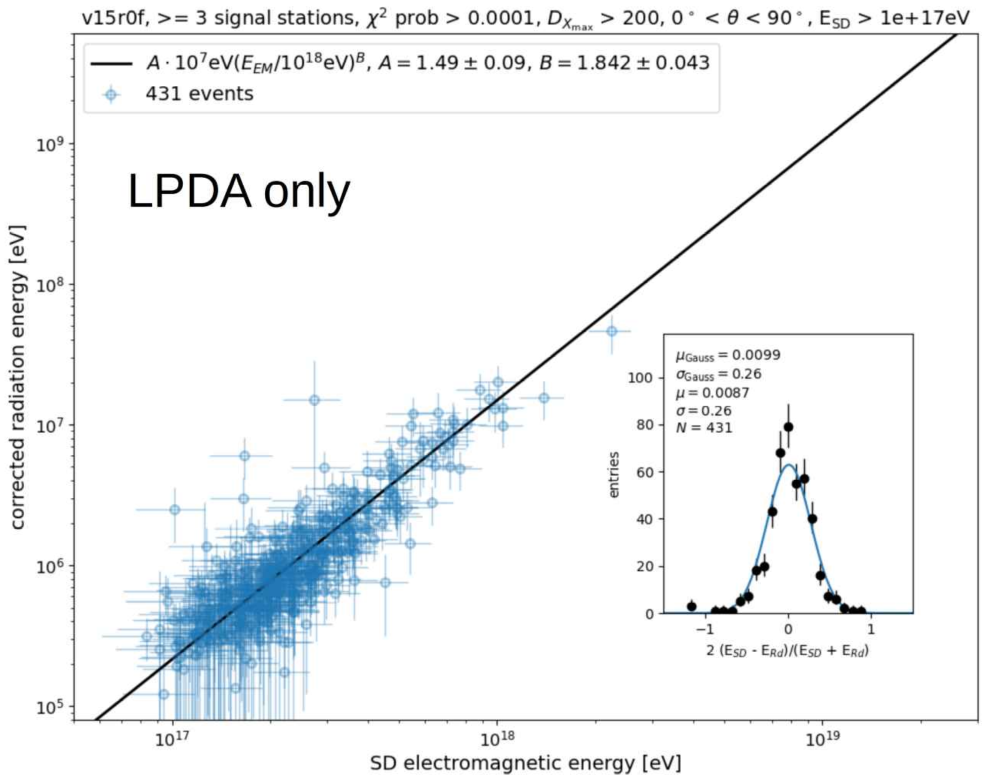


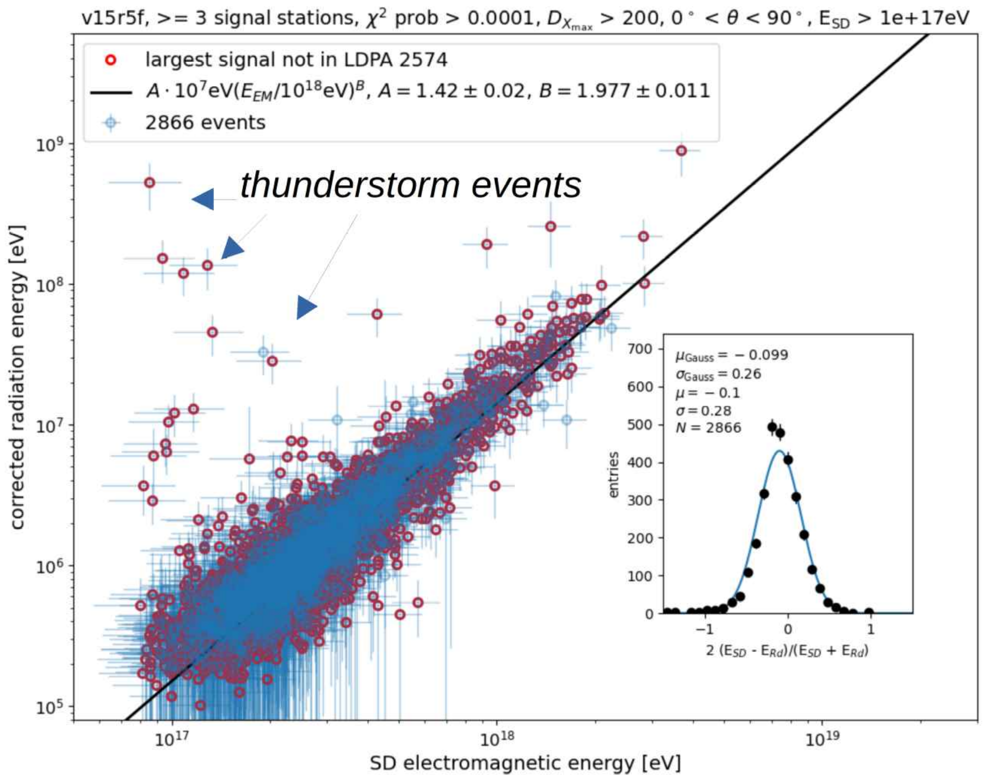
- LPDA:
  Antenna response well understood
- Butterfly:
  - Previous drone measurement did not agree well with simulated antenna response pattern
    - Several investigations questioning validity of that drone measurement
  - Tests suggest: simulated pattern safe to use
    - To be confirmed from ongoing drone campaign

Fully including Butterfly antennas



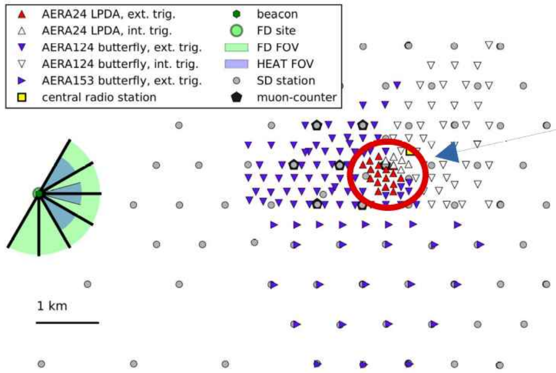
- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations
  - Fully including Butterfly stations increases statistics greatly
  - Gain in statistics allows to set stricter quality cuts / energy threshold



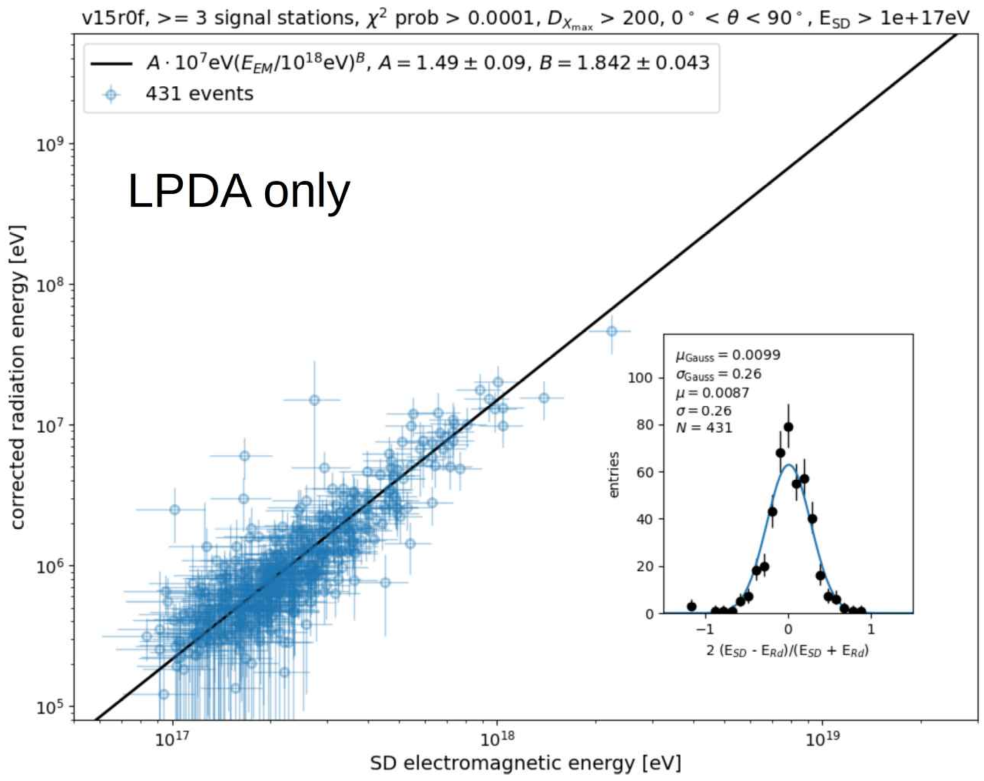


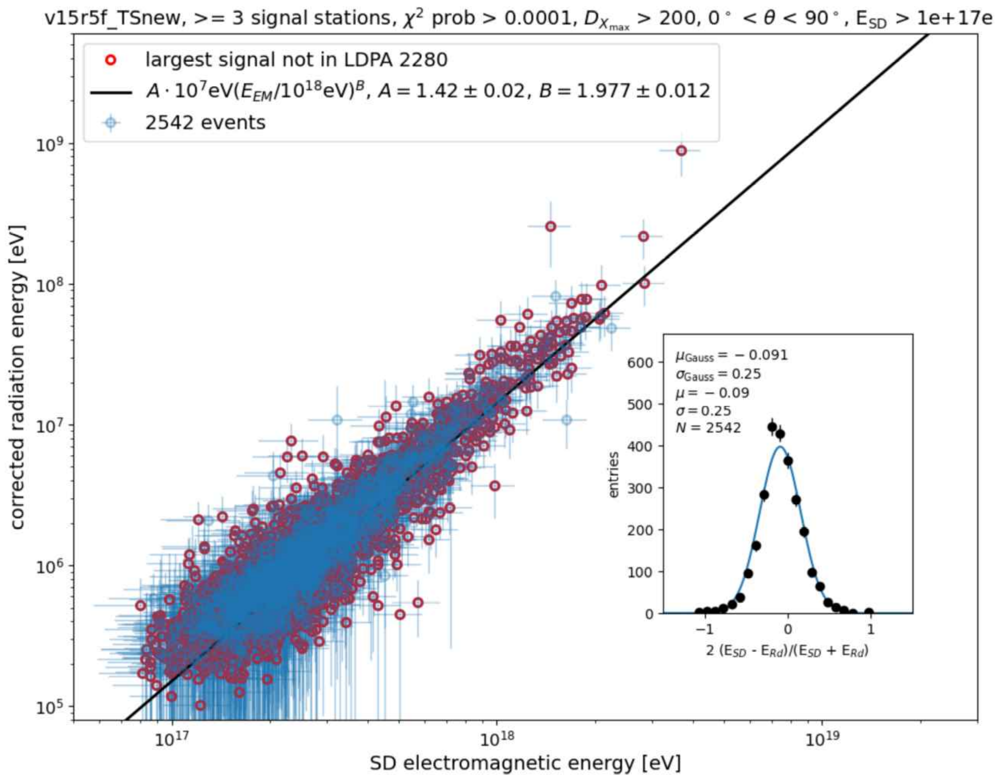
Fully including Butterfly antennas

- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations
  - Fully including Butterfly stations increases statistics greatly
  - Gain in statistics allows to set stricter quality cuts / energy threshold

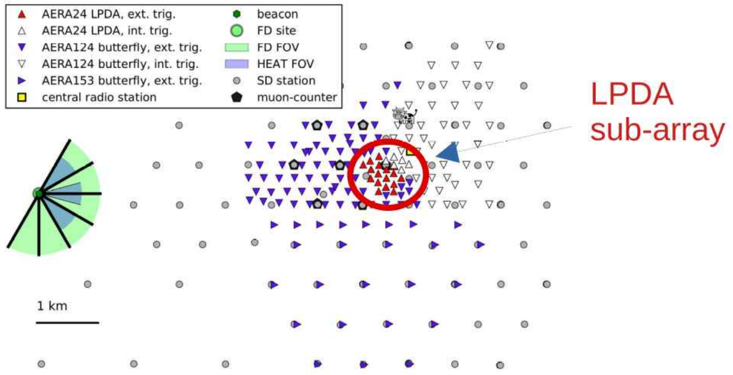


LPDA sub-array

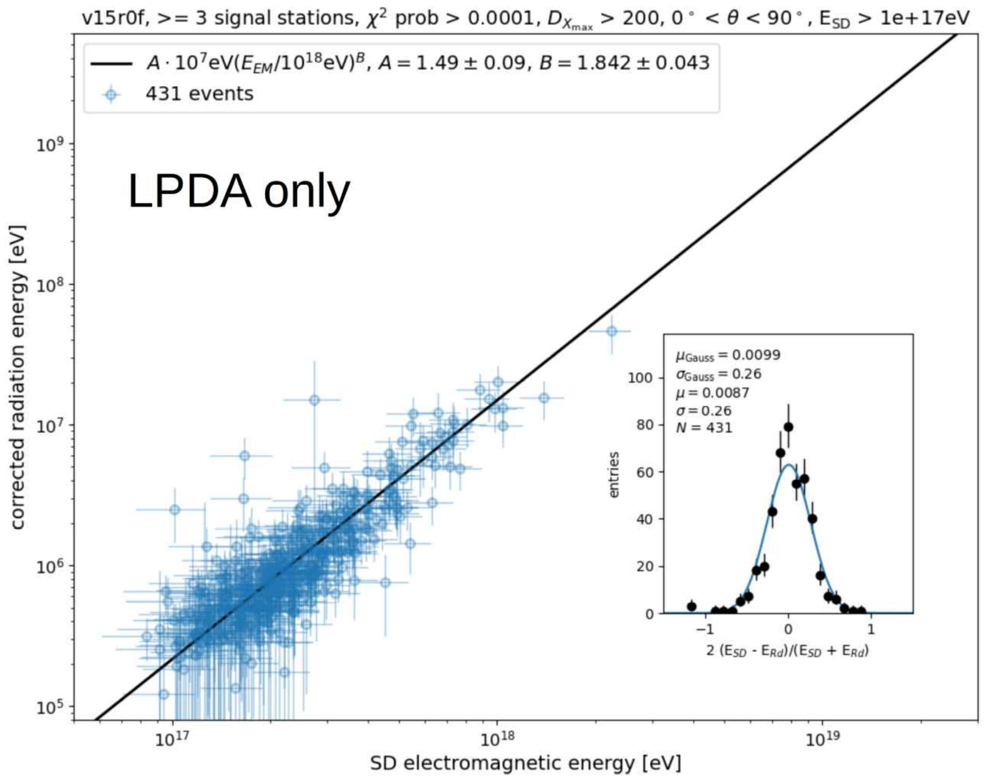


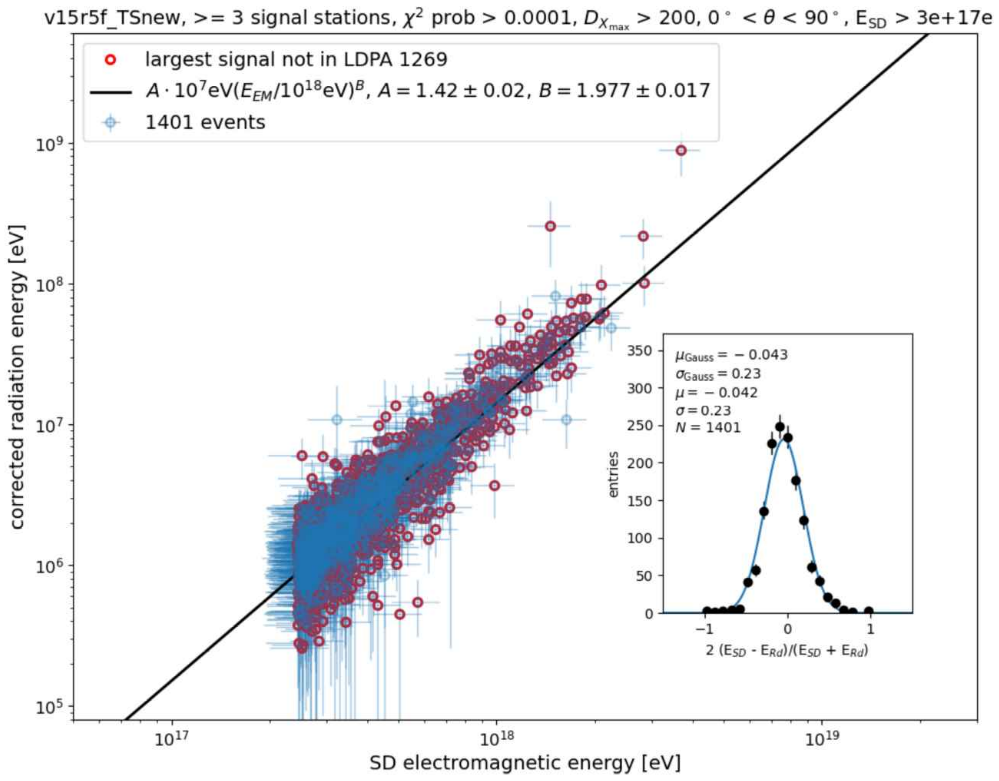


Fully including Butterfly antennas



- AERA antenna types: LPDA & Butterfly
- So far: basically only used LPDA stations
  - Fully including Butterfly stations increases statistics greatly
  - Gain in statistics allows to set stricter quality cuts / energy threshold



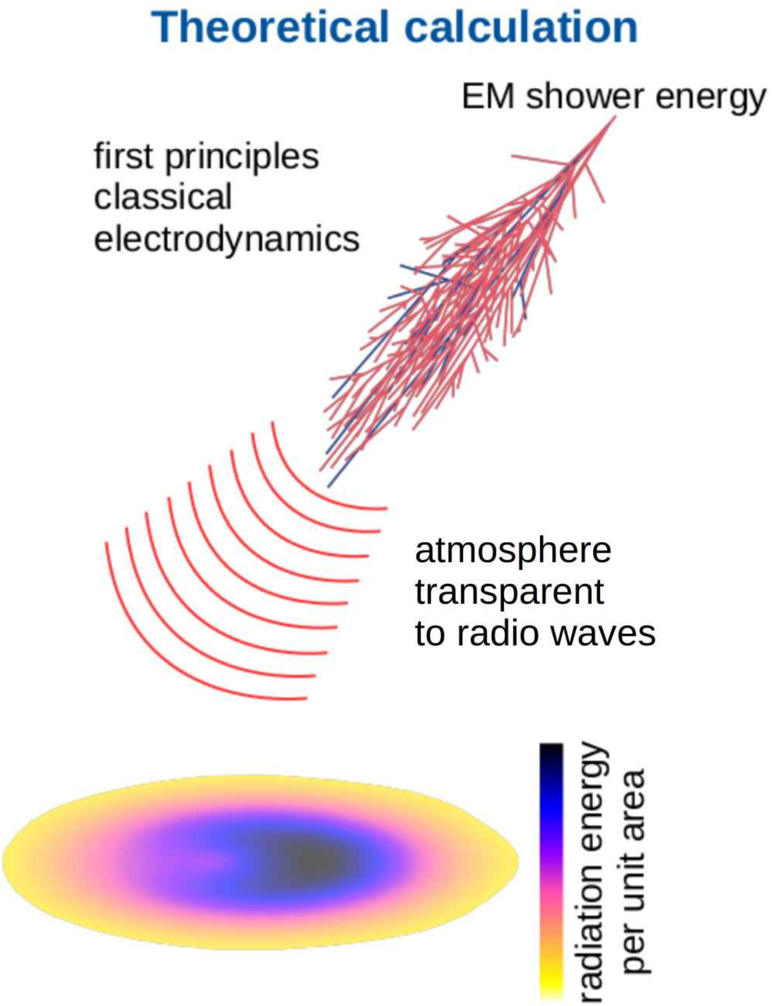


Simulations by V. Lenok

Table 3.2: List of the parameters used for the CORSIKA simulations.

Name of parameter	Set value
Cosmic-ray nuclei (PRMPAR)	H and Fe
Observation level (OBSLEV)	1570 m a.s.l.
High-energy hadron interaction model	QGSJetII-04
Low-energy hadron interaction model	URQMD 1.3cr
Energy cuts for hadrons, muons, electrons, and photons correspondingly (ECUTS)	0.3 GeV 50 MeV 250 keV 250 keV
Outer radius of NKG electron distribution (RADNKG)	5 km
Electron multiple scattering length factor (STEPF)	0.5
Using NKG and/or EGS4 (ELMFLG)	T T
Muon multiple scattering angle (MUMULT)	T
Magnetic field	according to WMM
Atmosphere model	GDAS, curved

The cosmic-ray energy scale with AERA

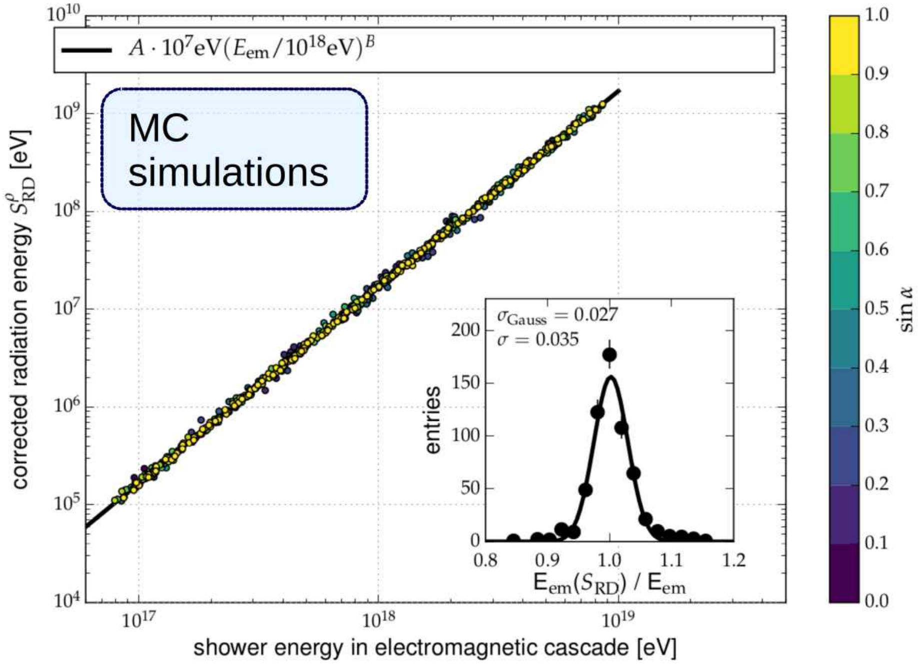


transferable to calorimetric/
cosmi-ray energy

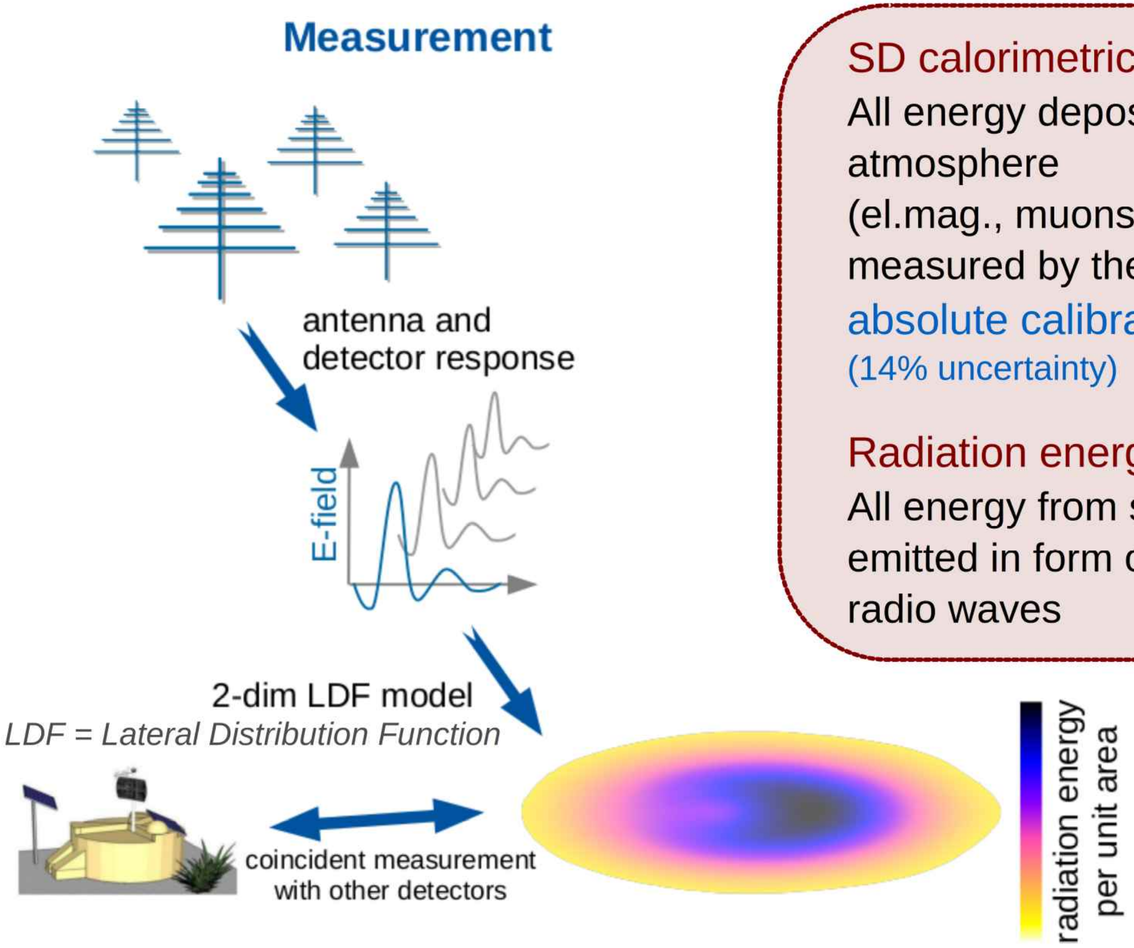
Electromagnetic energy E_{em}
All energy deposited by the electromagnetic shower component (e^-,e^+,γ) in the atmosphere

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

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



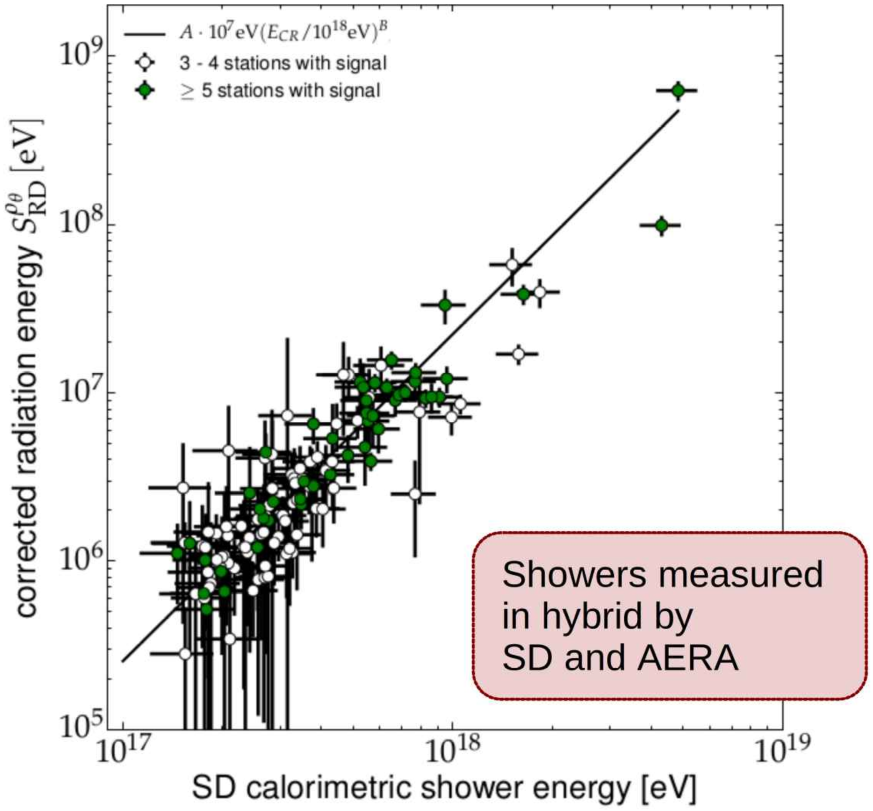
The cosmic-ray energy scale with AERA



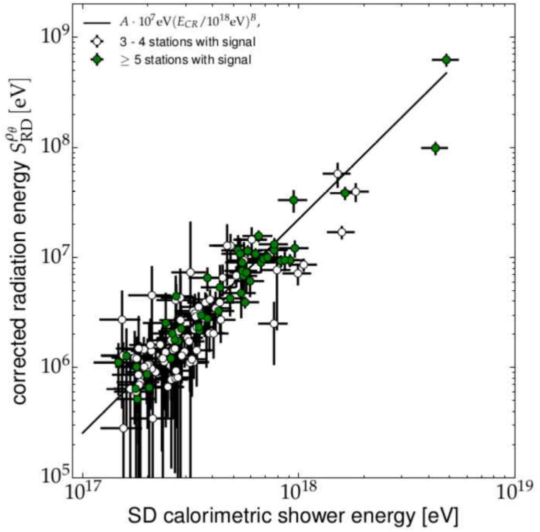
SD calorimetric energy $E_{SD,cal}$
All energy deposited in the atmosphere
(el.mag., muons, hadrons)
measured by the SD
absolute calibration from FD
(14% uncertainty)

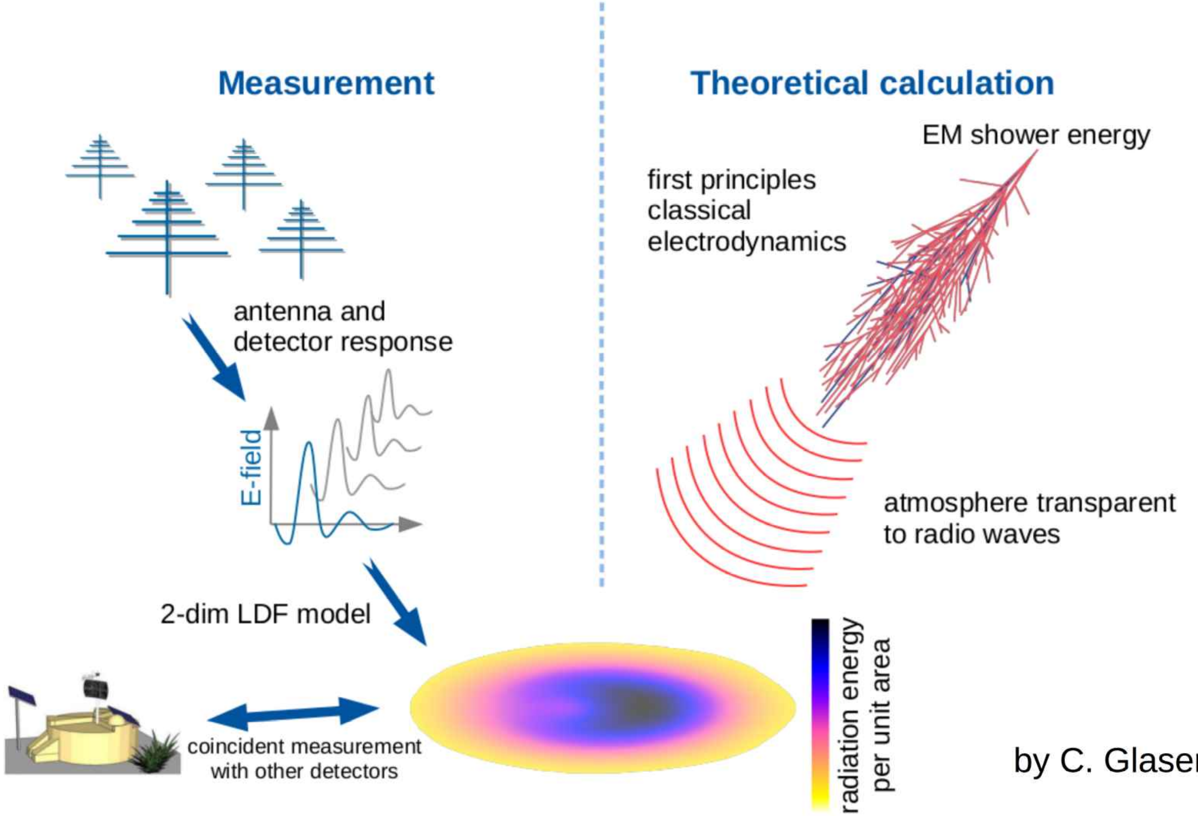
Radiation energy $S^{\rho\theta}_{RD}$
All energy from shower emitted in form of radio waves

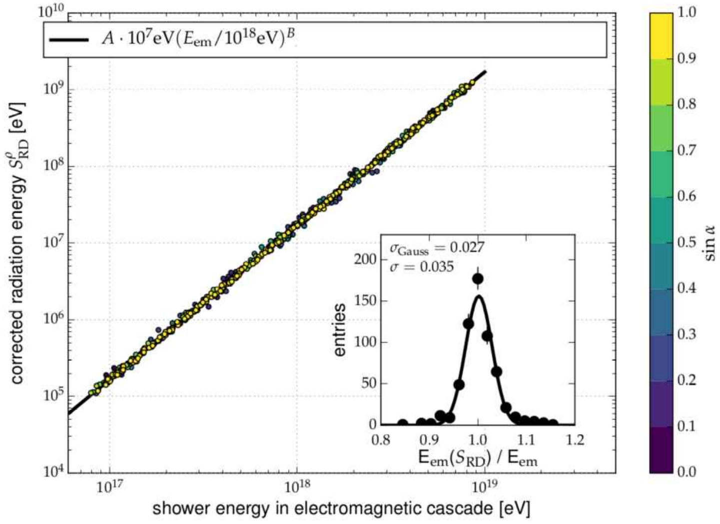
$$S^{\rho\theta}_{\mathrm{RD}} = A \times 10^{7} eV \left(\frac{E_{\mathrm{SD,cal}}}{10^{18} eV} \right)^{B}$$



The cosmic-ray energy scale with AERA







by C. Glaser

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

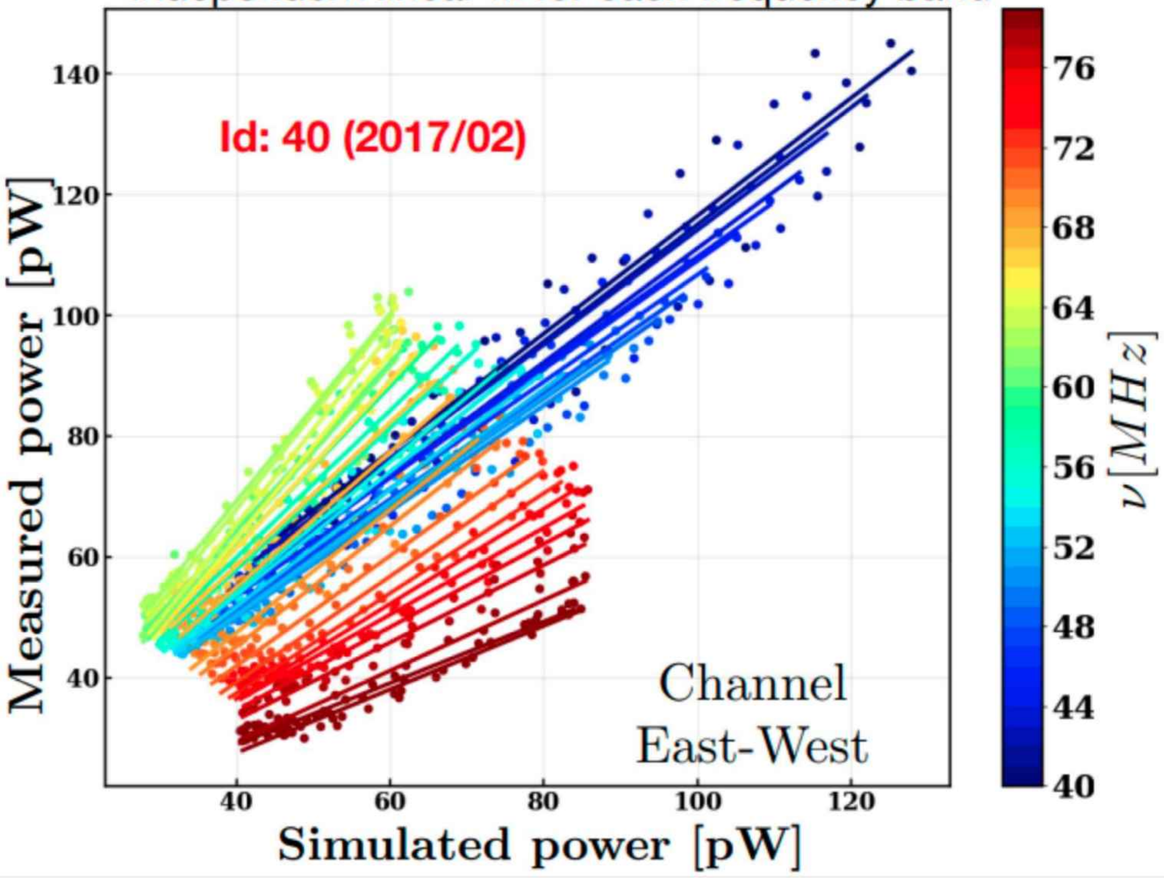
Allows to compare CR energy scales from FD and radio

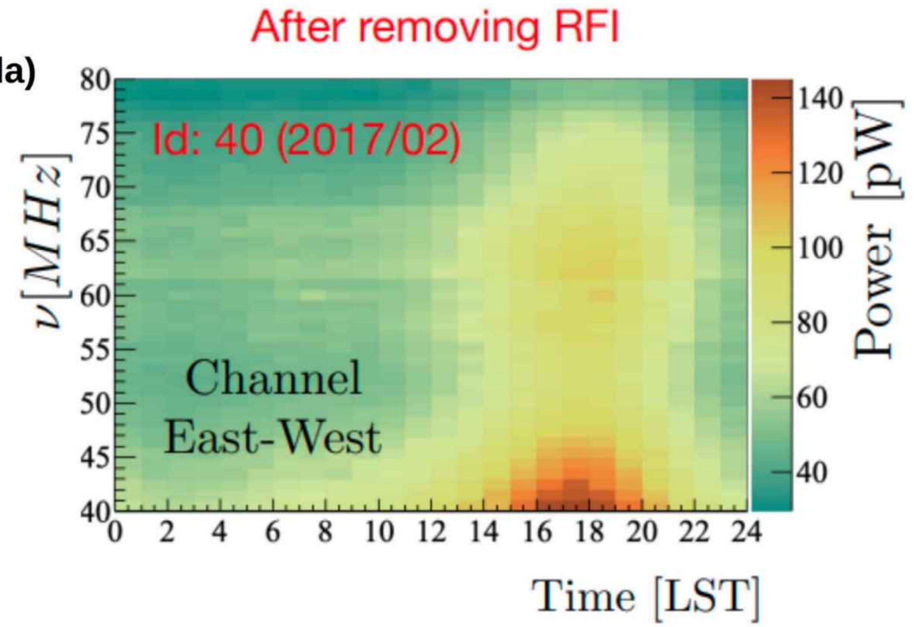
$$S_{\mathrm{RD}}^{\rho\theta} = 1.639 \times 10^7 eV \left(\frac{E_{\mathrm{em}}}{10^{18} eV} \right)^{1.978}$$

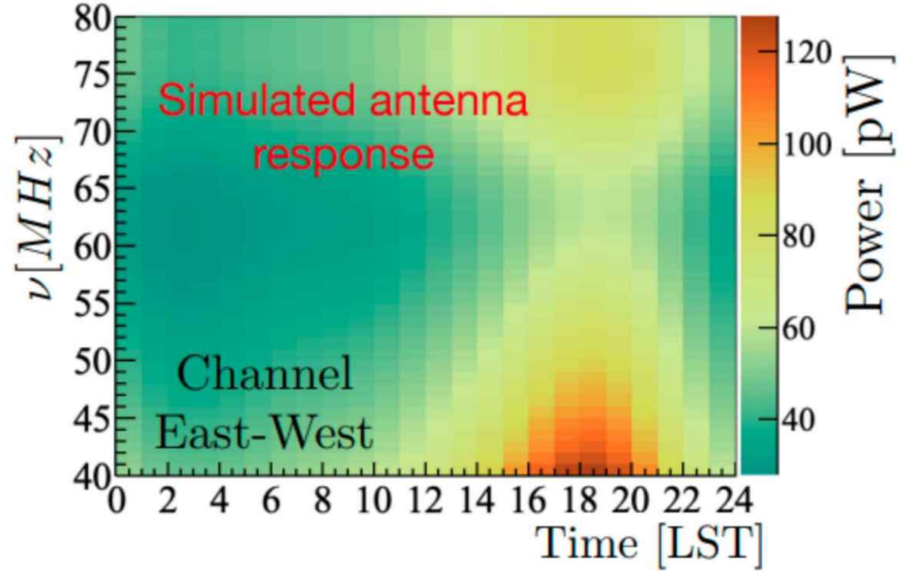
Calibration approach (Diego Correia and Rogerio de Almeida)

$$P_{model}(t,\nu) = P_{sky}(t,\nu)G_{ant}(\nu)G_{RCU}(\nu)C_0^2(\nu) + N_{tot}(\nu)$$

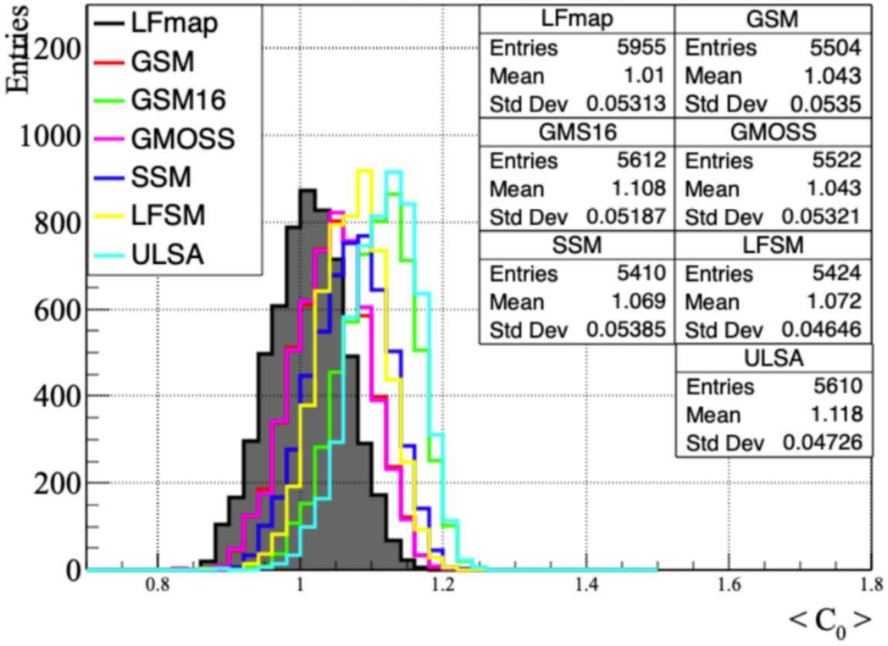
- Independent linear fit for each frequency band







Distribution of average C0 from 2016 to 2020 for both channels



dataset	description	events	A [10^7eV]	B	dataset overlap with 16r0f	A (fix B)	relative change in A
v16r0f	-	398	1.42 ± 0.09	1.868 ± 0.046		1.64 ± 0.04	
v16r1f	temp-corr. only	364	1.48 ± 0.10	1.889 ± 0.047		1.67 ± 0.04	1.8%
v16r3f	LFmap	233	1.90 ± 0.19	2.008 ± 0.076	187	1.79 ± 0.07	7.8%
v16r4f	GSM	230	1.72 ± 0.19	1.969 ± 0.084	189	1.69 ± 0.06	1.8%
v16r5f	GSM16	230	1.60 ± 0.16	1.980 ± 0.073	190	1.55 ± 0.06	-7.7%
v16r6f	LFSM	232	1.62 ± 0.16	1.987 ± 0.075	192	1.70 ± 0.06	3.0%
v16r7f	GMOSS	231	1.74 ± 0.20	1.973 ± 0.086	190	1.76 ± 0.06	5.4%
v16r8f	SSM	235	1.68 ± 0.18	1.956 ± 0.081	195	1.68 ± 0.06	0.0%
v16r9f	ULSA	224	1.46 ± 0.17	1.938 ± 0.085	186	1.48 ± 0.05	-10.8%