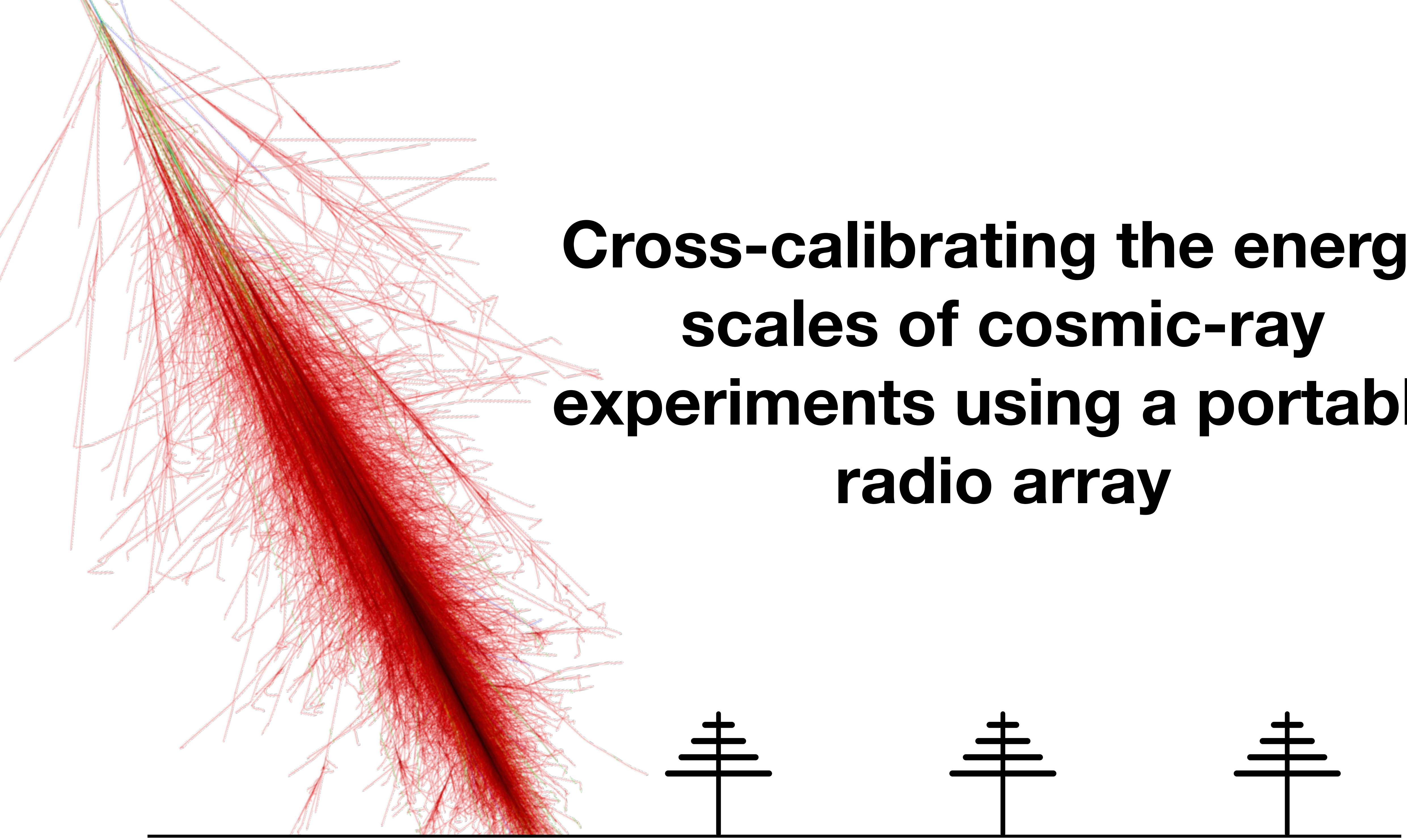
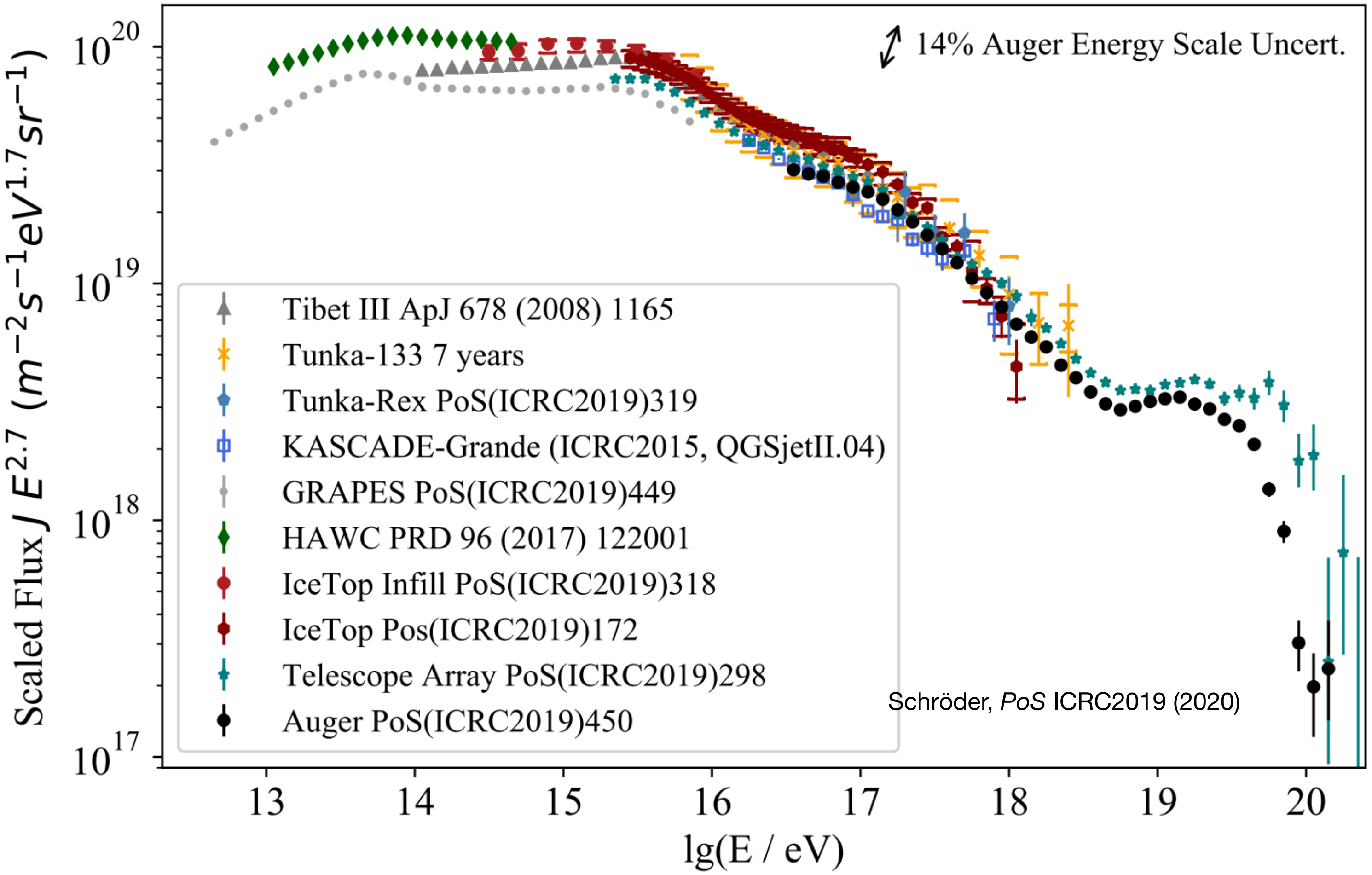


Cross-calibrating the energy scales of cosmic-ray experiments using a portable radio array

A. Bonardi, S. Buitink, A. Corstanje, K. D. de Vries, H. Falcke, B. M. Hare, J. R. Hörandel, T. Huege,
G. Krampah, P. Mitra, K. Mulrey*, A. Nelles, H. Pandya, J. P. Rachen, E. Santiago, L. Rossetto,
O. Scholten, R. Stanley, S. ter Veen, T. N. G. Trinh, T. Winchen

*kmulrey@vub.be

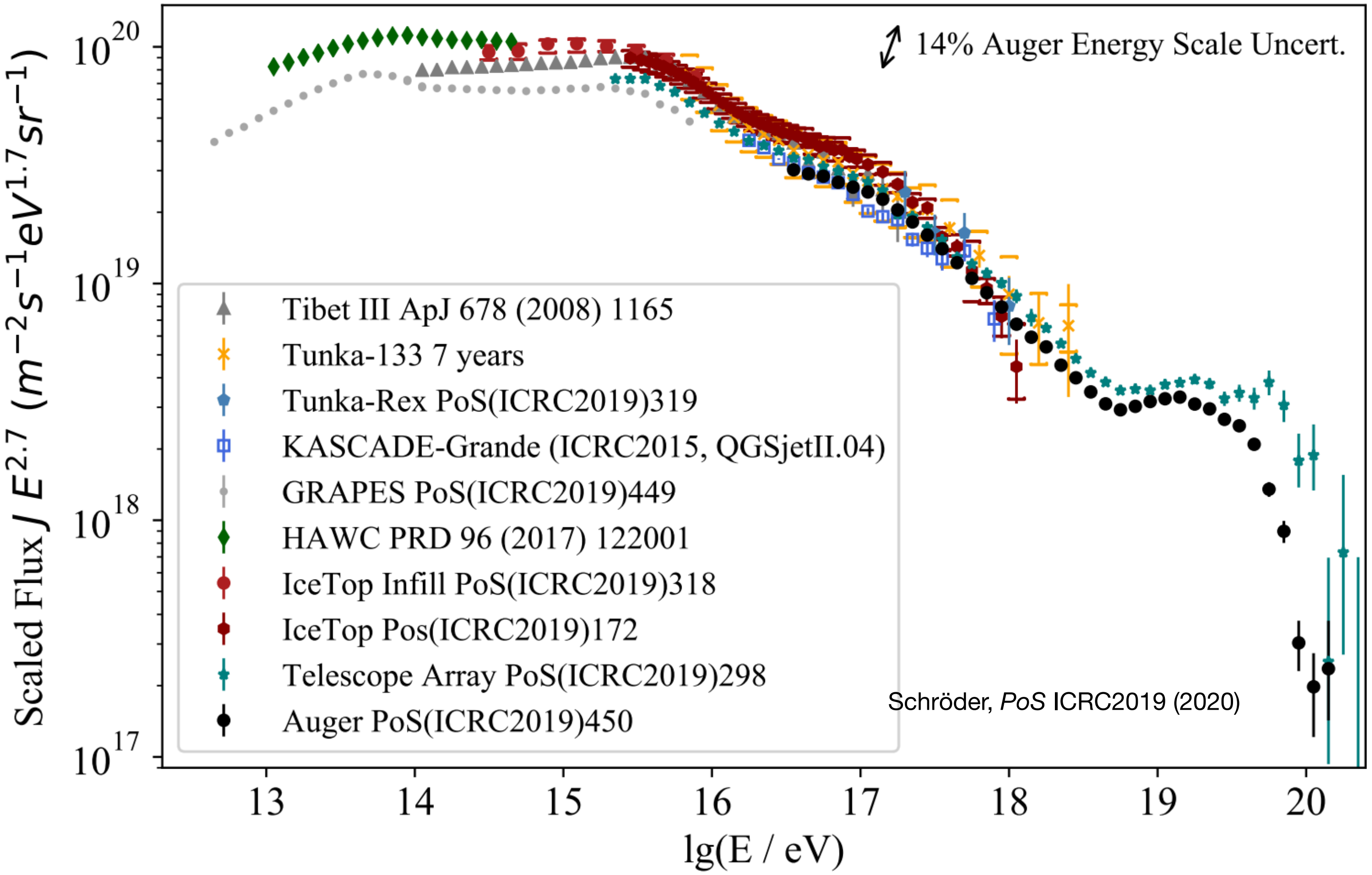
Motivation



Schröder, *PoS* ICRC2019 (2020)

- Energy scales between different experiments differ, must be scaled in order to achieve a global spectrum
- Difficult to directly compare energy reconstruction (different detection methods, systematics, etc.) between experiments

Motivation

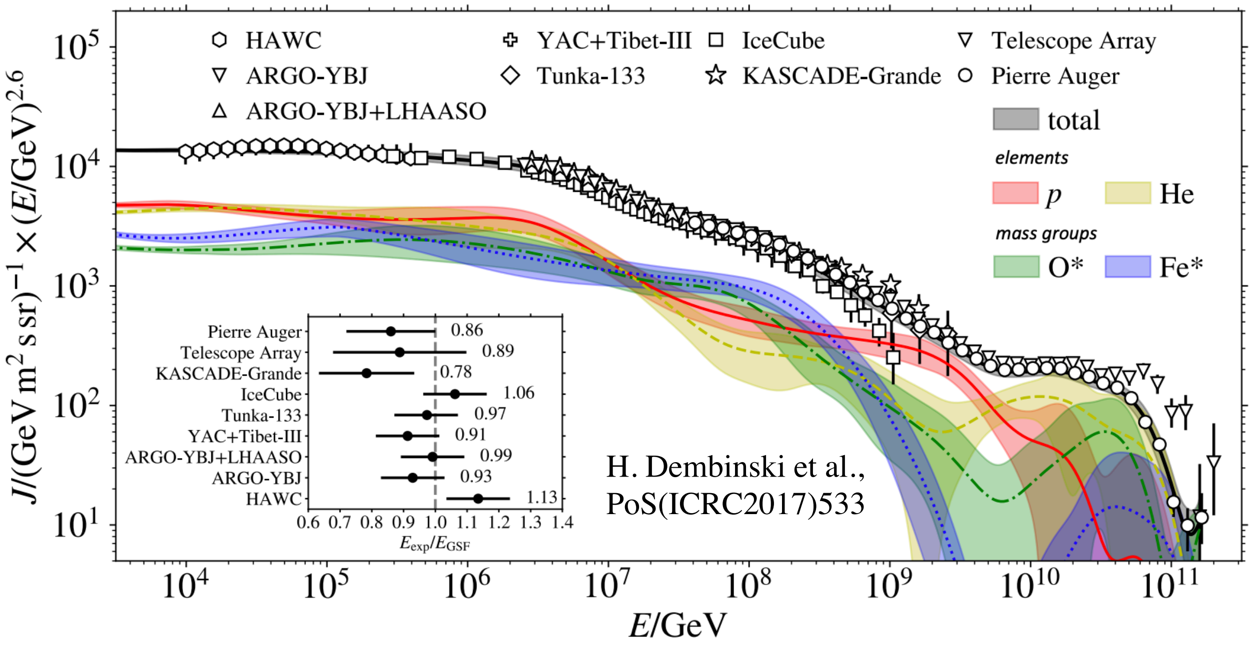


Schröder, *PoS* ICRC2019 (2020)

- Energy scales between different experiments differ, must be scaled in order to achieve a global spectrum
- Difficult to directly compare energy reconstruction (different detection methods, systematics, etc.) between experiments
- ***A universal energy scale is critical for understanding cosmic ray sources and acceleration***

Motivation

A common energy scale has been derived using a data driven using a Global Spline fit (H. Dembinski et al., PoS(ICRC2017)533



H. Dembinski et al., PoS(ICRC2017)533

Can a global energy scale be determined experimentally?

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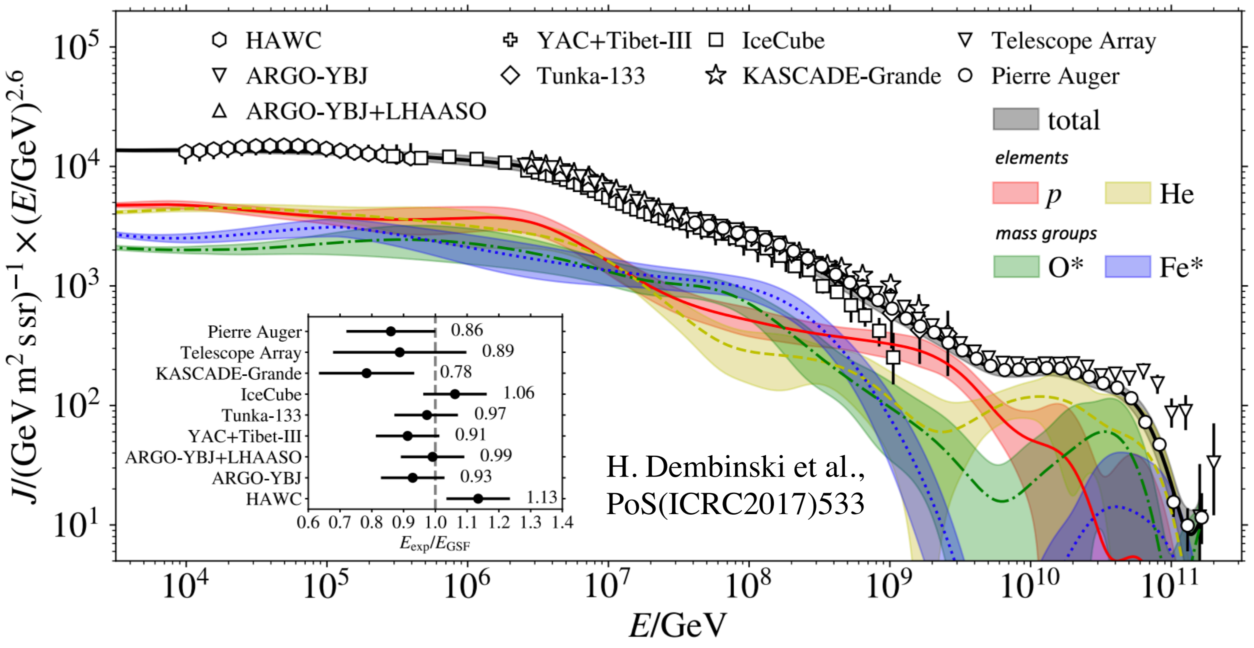
A common energy scale has been derived using a data driven using a Global Spline fit (H. Dembinski et al., PoS(ICRC2017)533



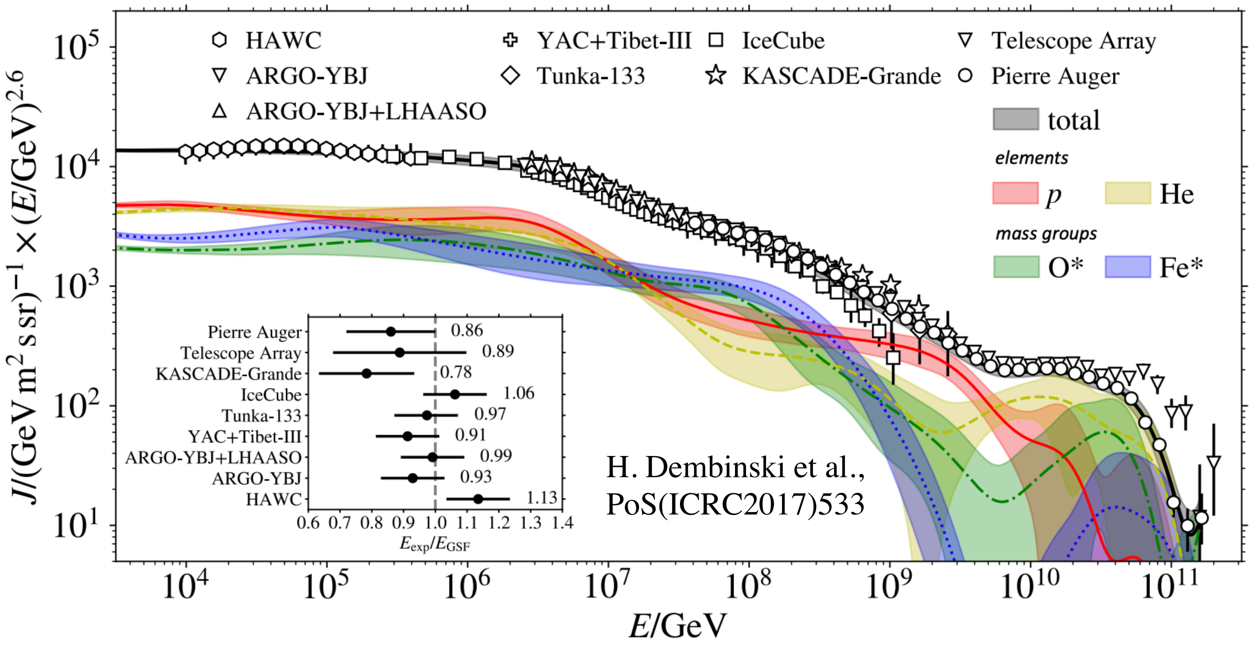
H. Dembinski et al., PoS(ICRC2017)533

Can a global energy scale be determined experimentally?

Cosmic-ray energy cross-calibration array

Motivation

A common energy scale has been derived using a data driven using a Global Spline fit (H. Dembinski et al., PoS(ICRC2017)533

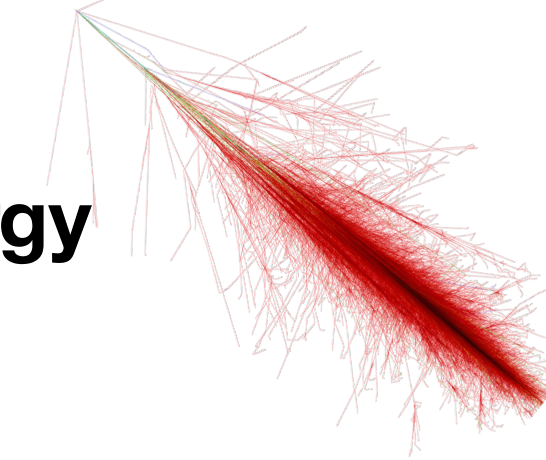


H. Dembinski et al.,
PoS(ICRC2017)533

Can a global energy scale be determined experimentally?

Cosmic-ray energy cross-calibration array → **1. Radiation Energy**

universal measurement



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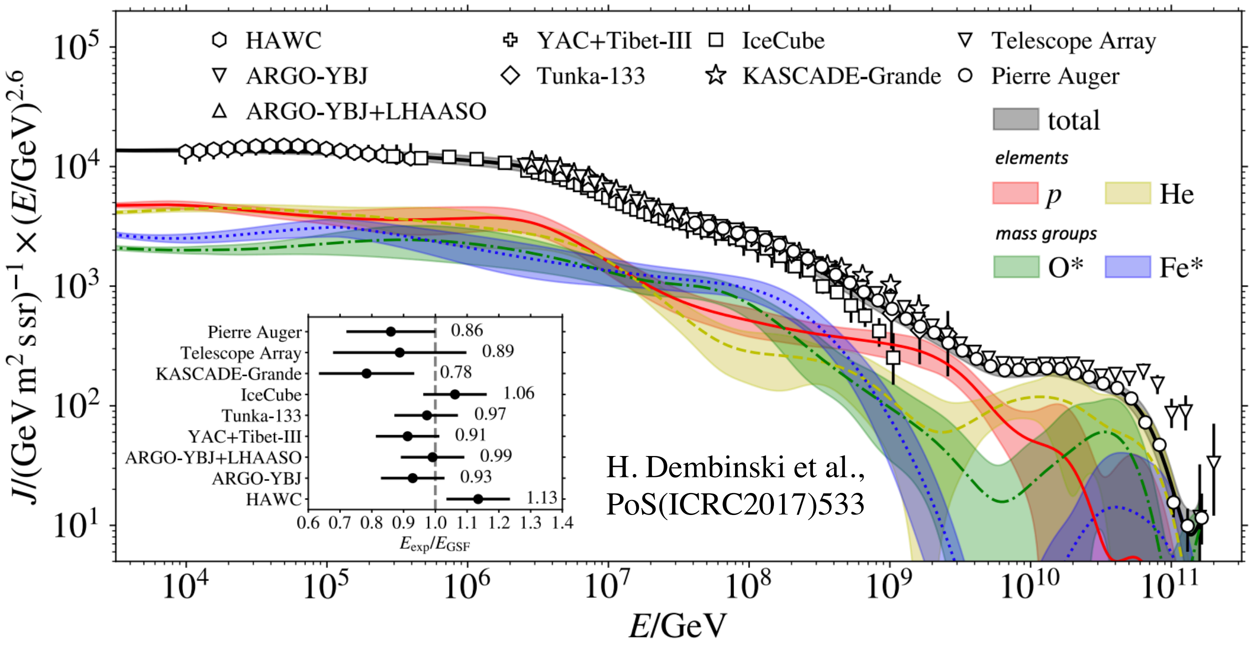
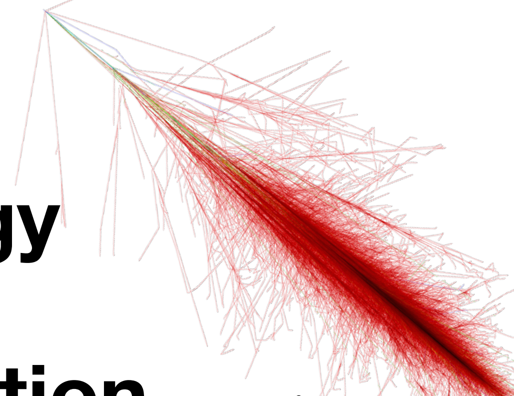


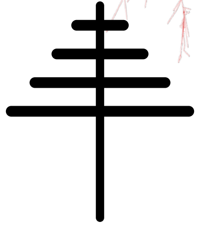
H. Dembinski et al., PoS(ICRC2017)533

Can a global energy scale be determined experimentally?

Cosmic-ray energy cross-calibration array

1. Radiation Energy
   universal measurement
2. Common detection system
   minimal systematic uncertainties





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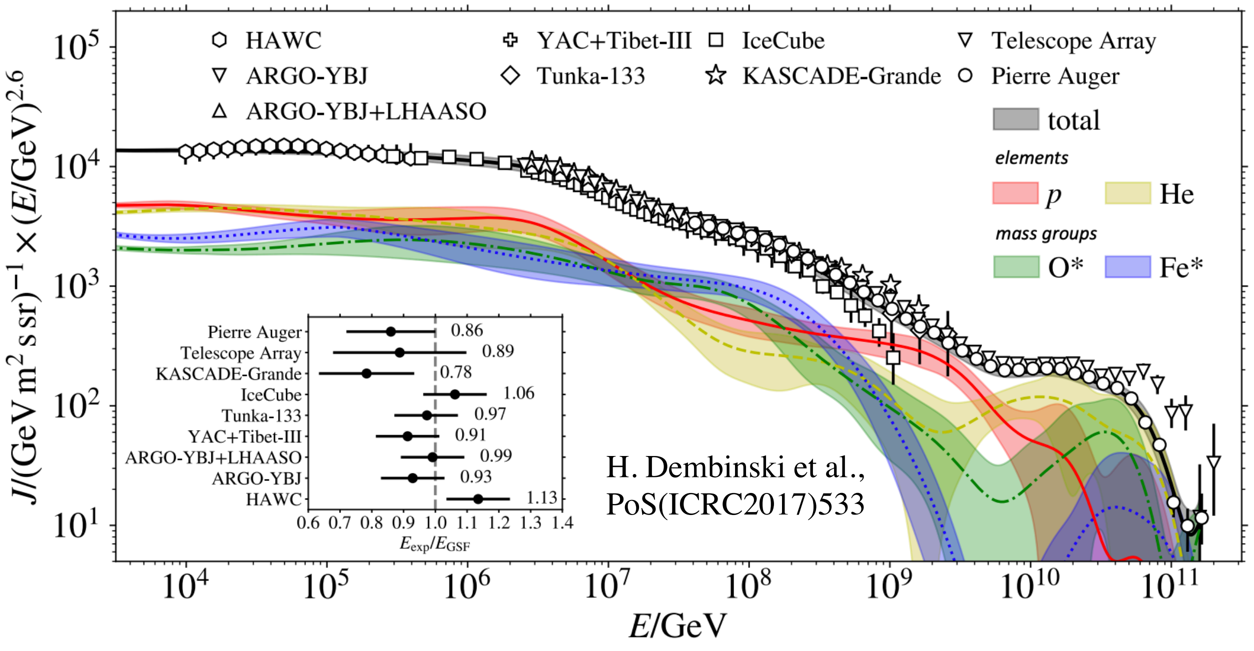
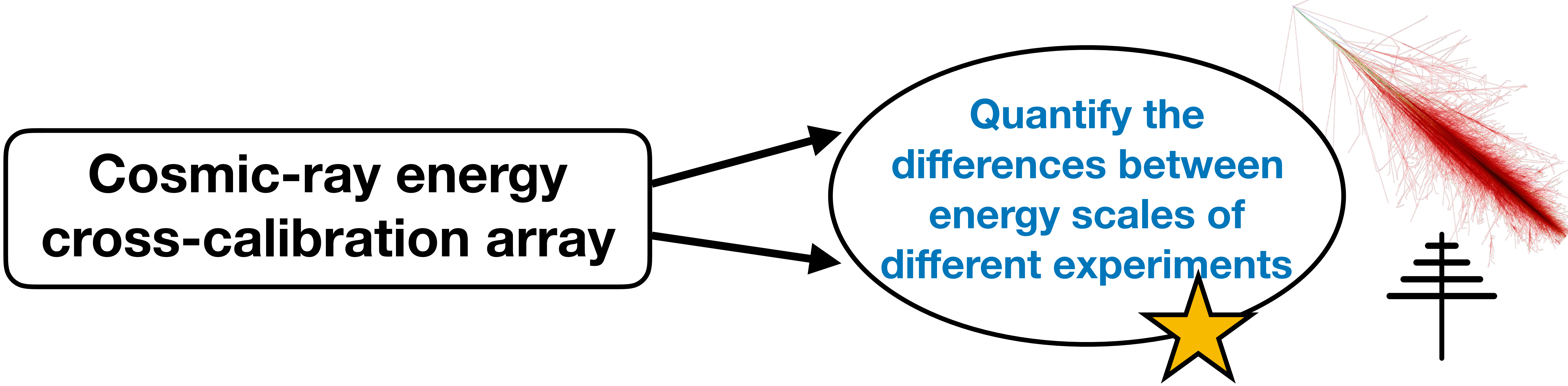


Can a global energy scale be determined experimentally?



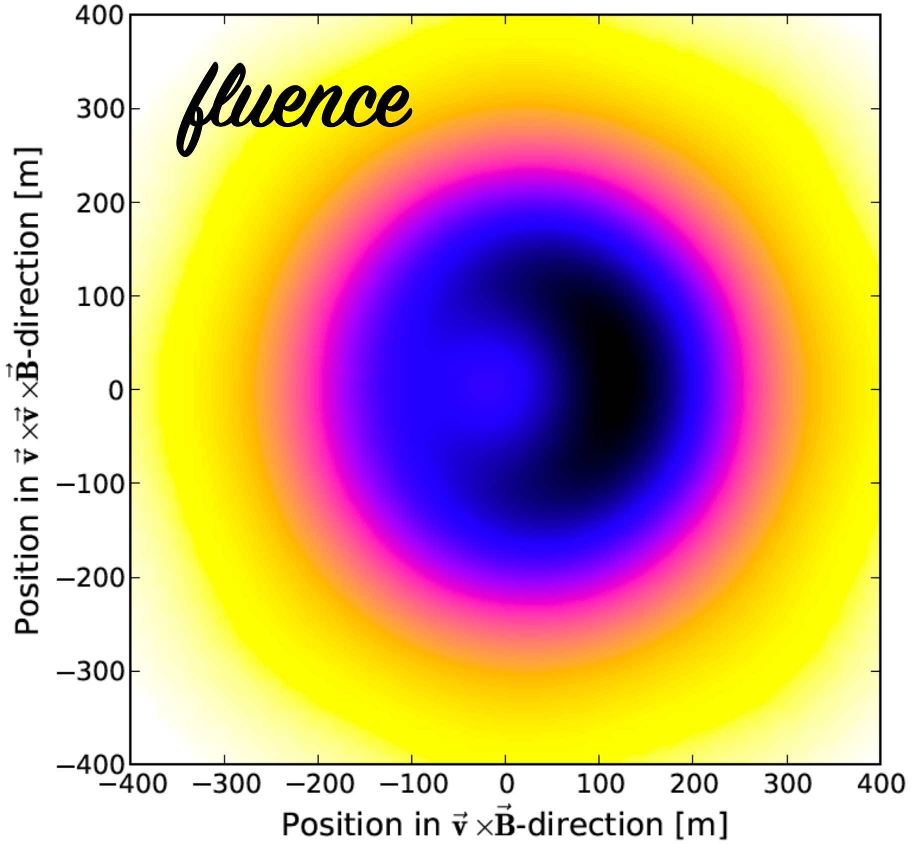
Cosmic-ray energy cross-calibration array

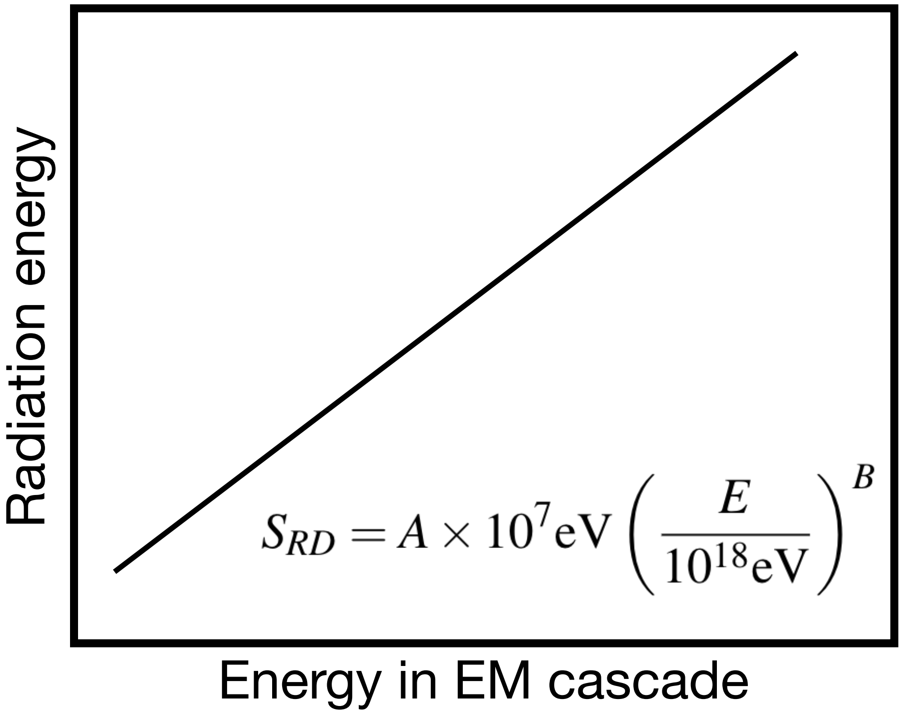
Quantify the differences between energy scales of different experiments

Concept

Use radiation energy to compare energy scales

- energy emitted by the air shower in the form of radio waves
- integral of energy fluence on ground
- scales with energy in electromagnetic components of the air shower

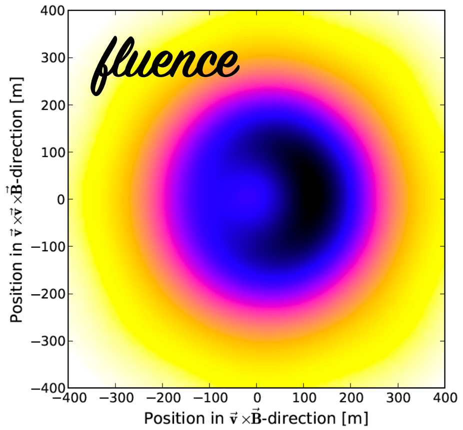


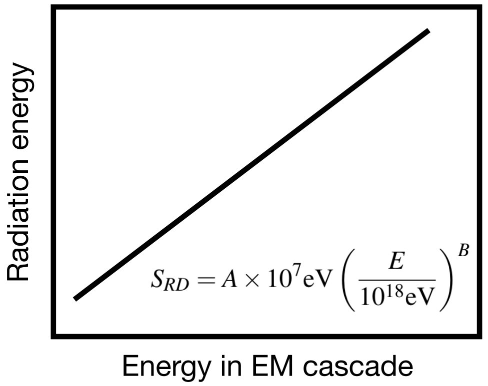


$$S_{RD} = A \times 10^{7}\mathrm{eV}\left(\frac{E}{10^{18}\mathrm{eV}}\right)^{B}$$

Concept

Use radiation energy to compare energy scales





Make it universal…

corrected radiation energy

radiation energy

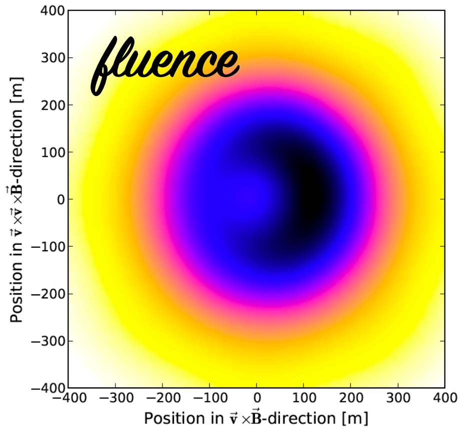
$$S_{RD} = \frac{E_{\mathrm{rad}}}{(a'^2 + (1 - a'^2))\sin^2\alpha(\frac{B_{\mathrm{Earth}}}{0.243\mathrm{G}})^{1.8}}$$

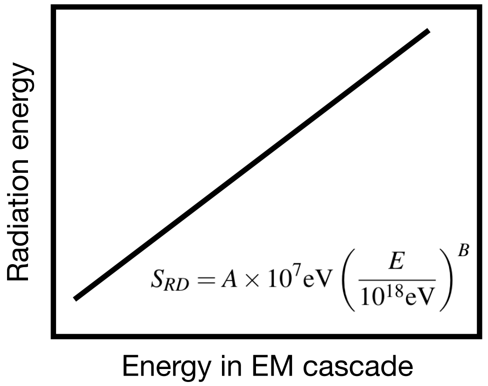
a = parametrization of the charge-excess fraction
B_{Earth} = local magnet field
α = angle between shower axis and B_{Earth} axis

Method from:
C. Glaser, et al. JCAP, 1609(09):024, 2016

Concept

Use radiation energy to compare energy scales





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B_{Earth} = local magnet field
α = angle between shower axis and B_{Earth} axis

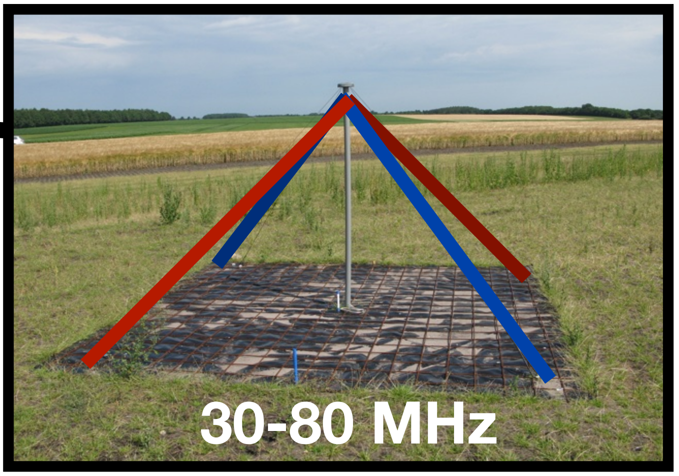
Corrected radiation energy is a universal quantity that can be directly compared between experiments

Method from:
C. Glaser, et al. JCAP, 1609(09):024, 2016

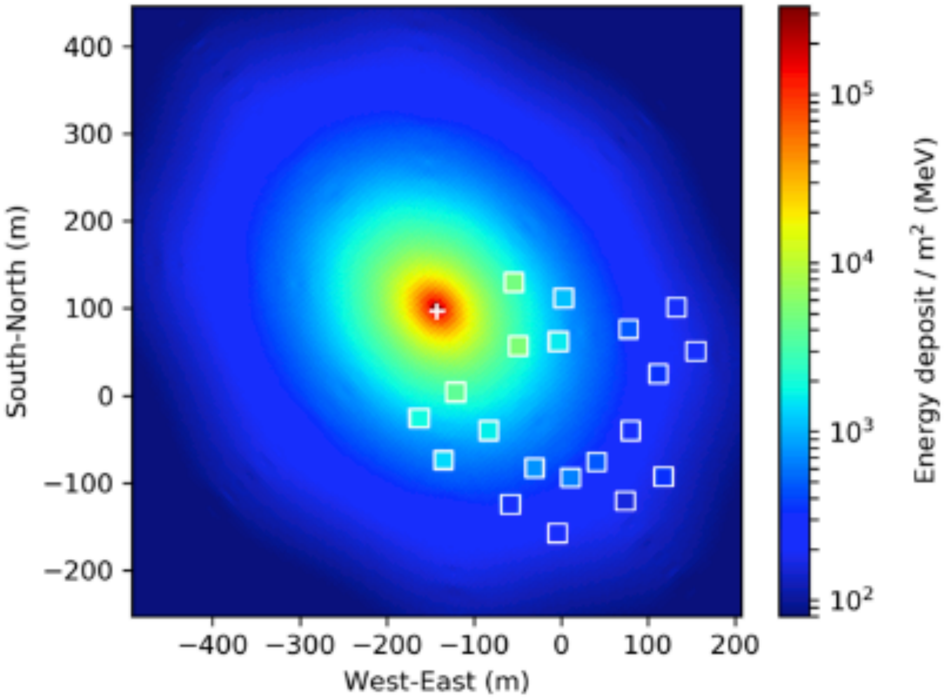
Example: LOFAR

LOFAR Radboud air shower Array (LORA)

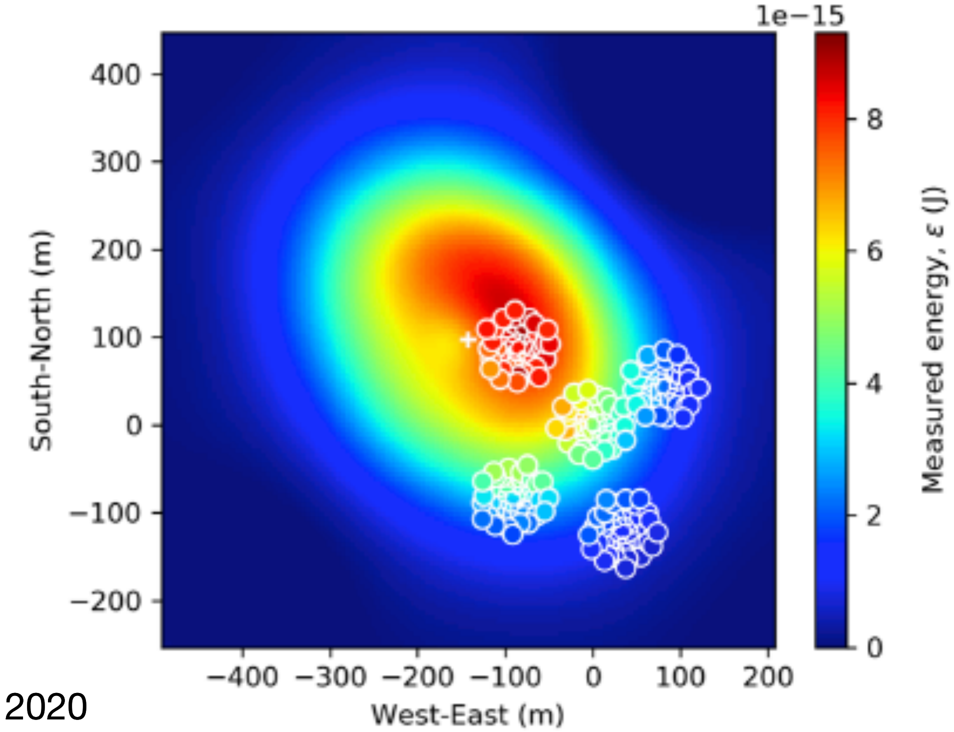
Low Frequency Array (LOFAR)



Particle footprint

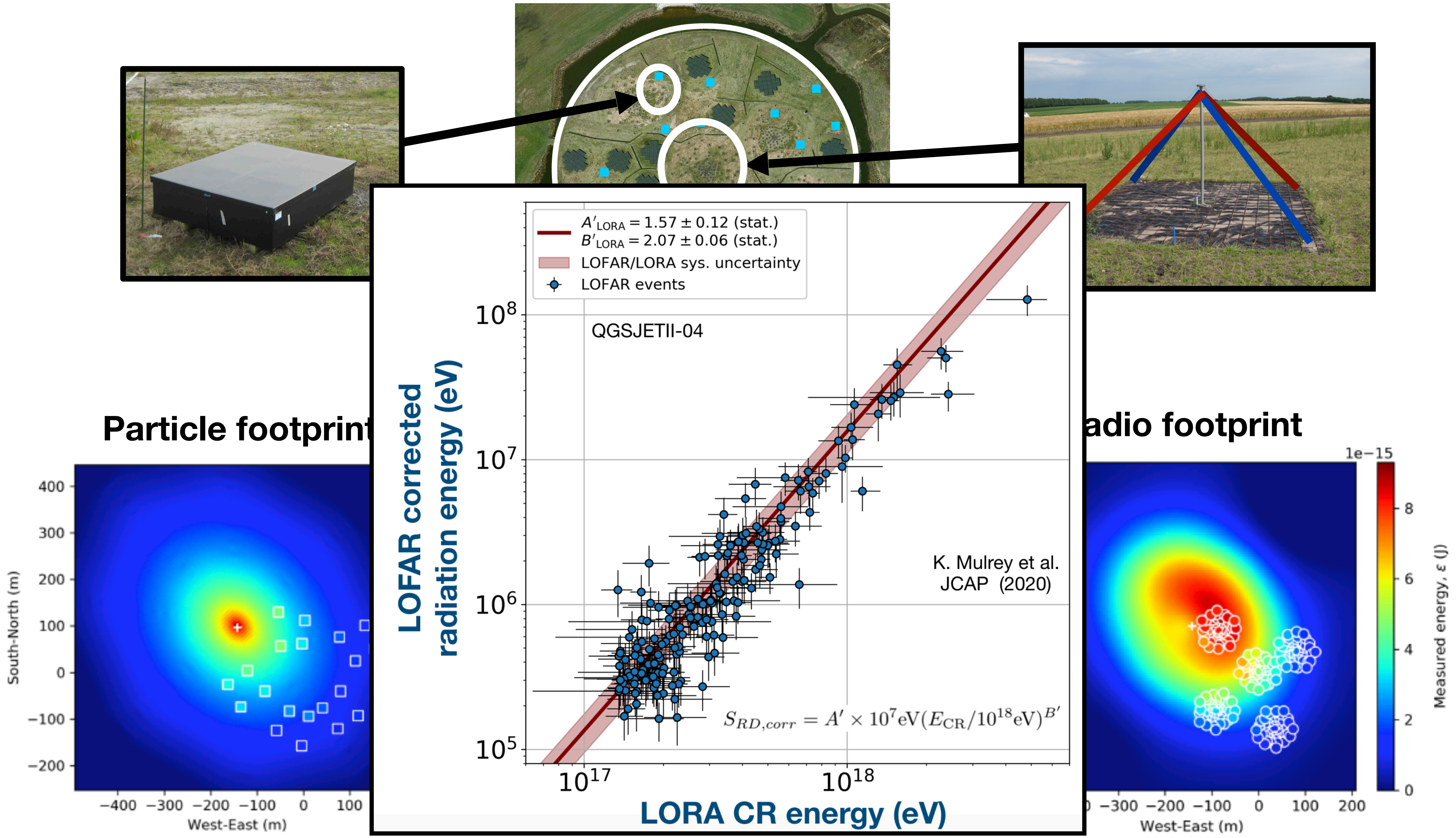


Radio footprint

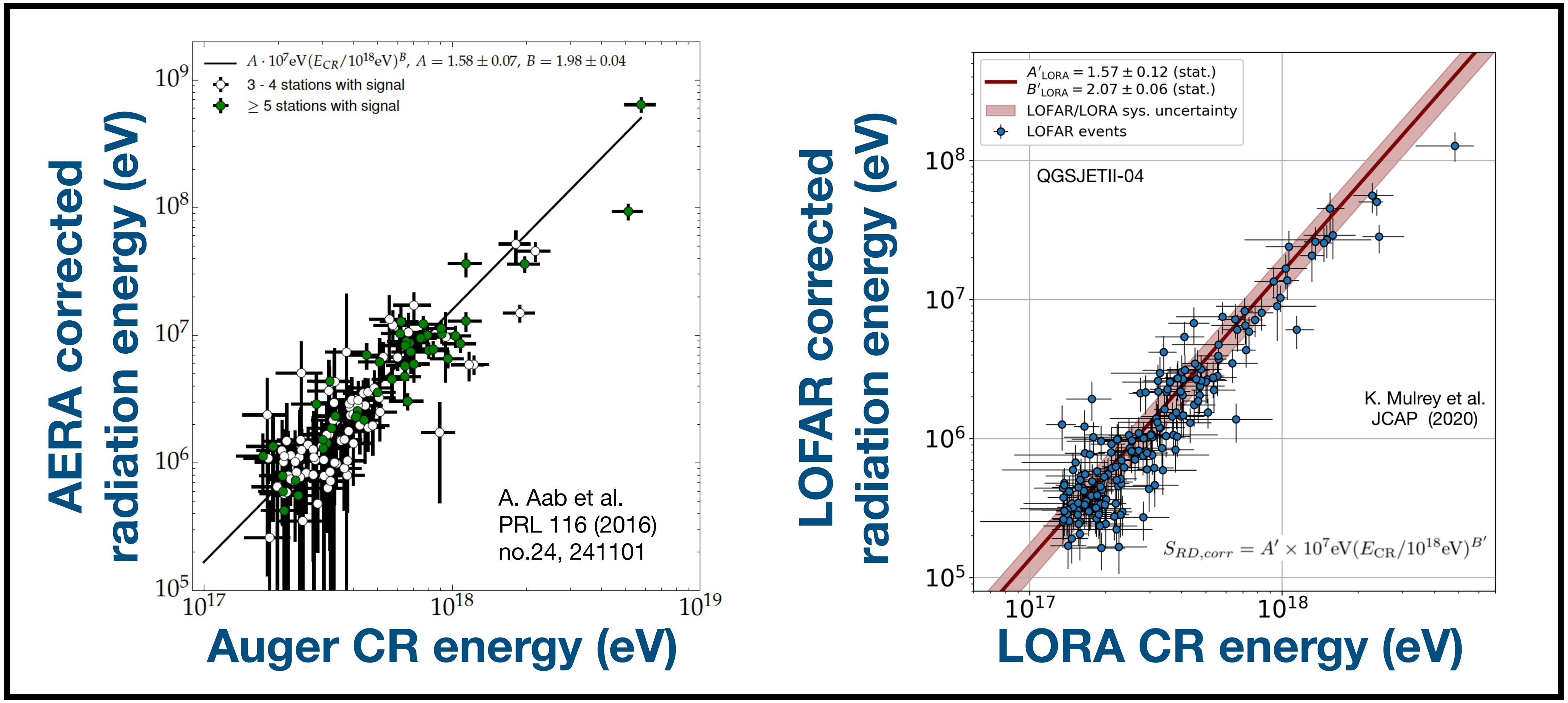


Mulrey et al. JCAP 2020

Example: LOFAR

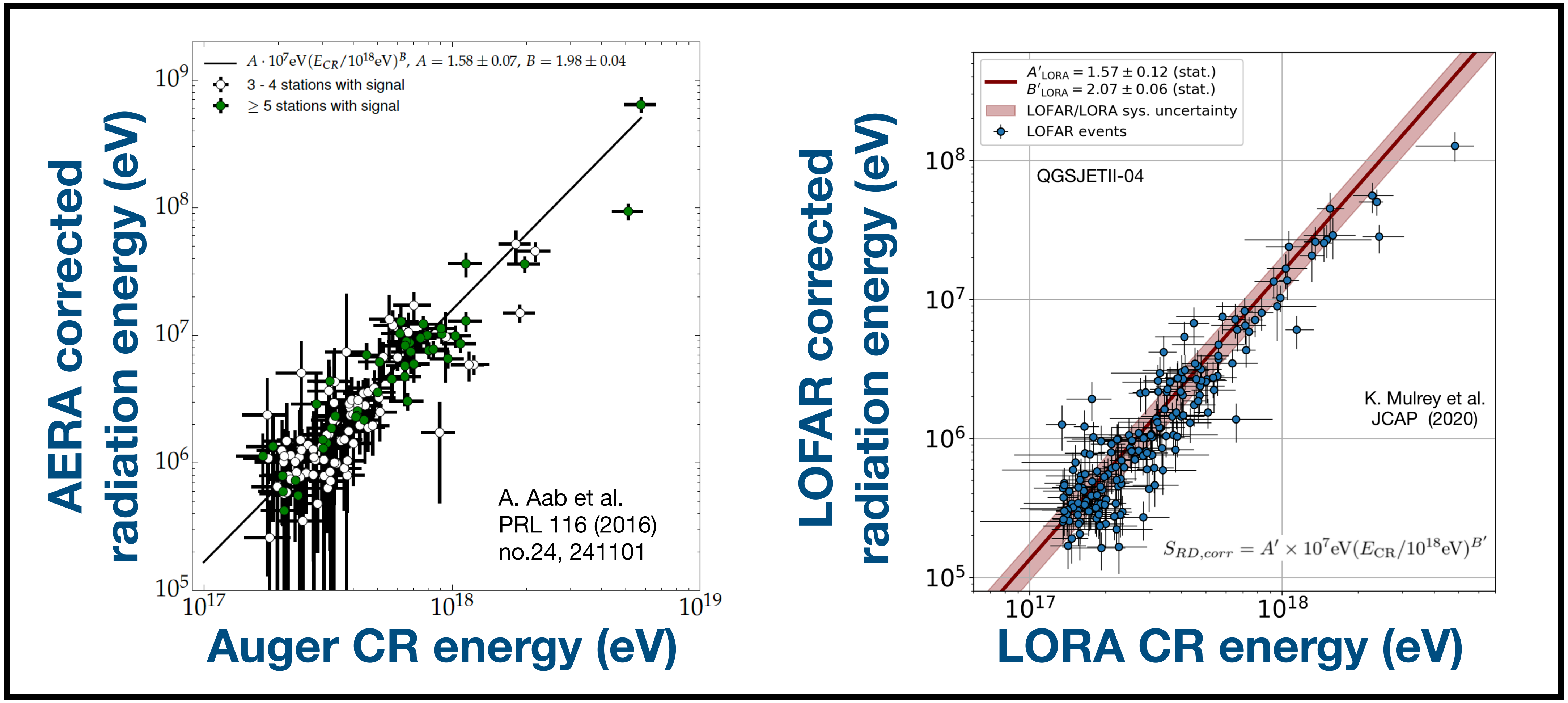


Example: LOFAR + Auger



At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

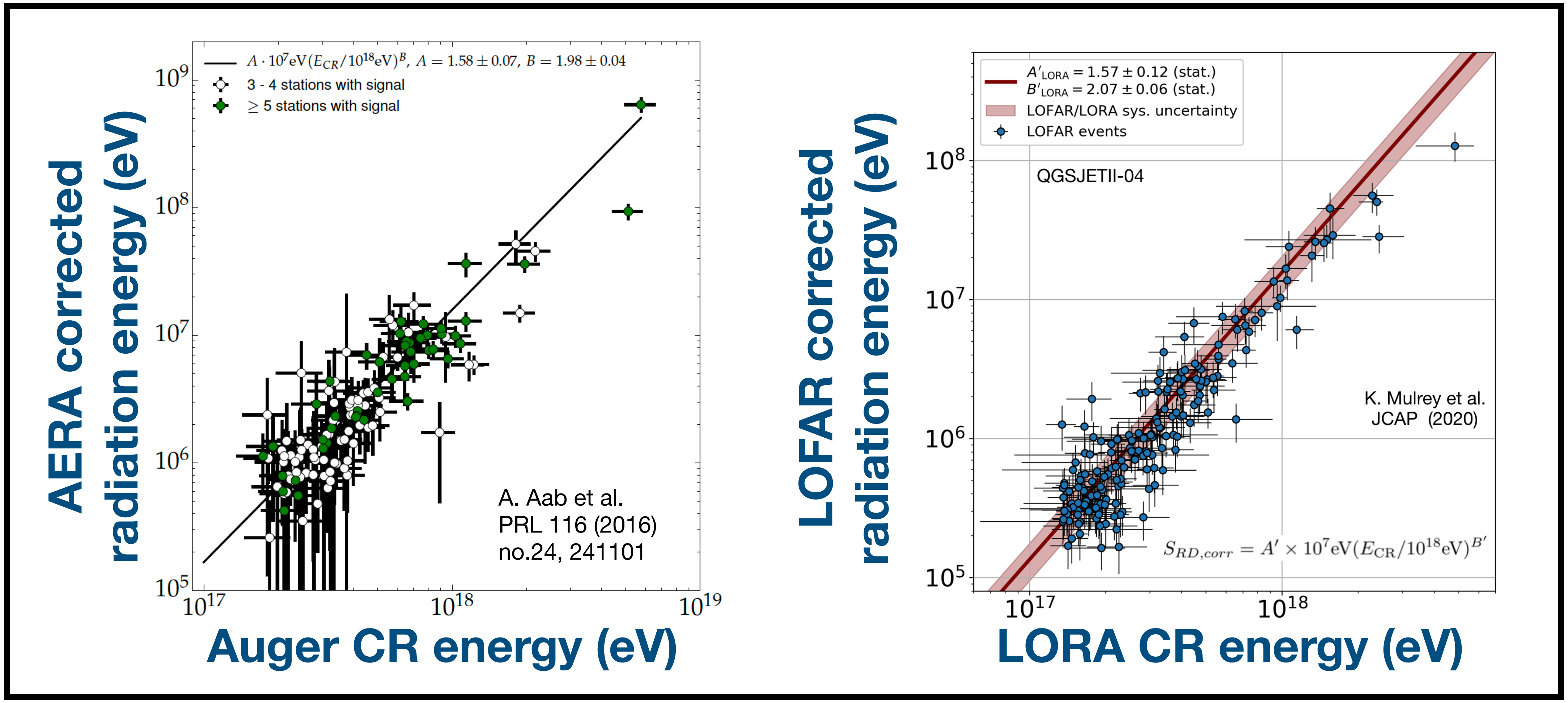
Example: LOFAR + Auger



At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

How can we improve this?

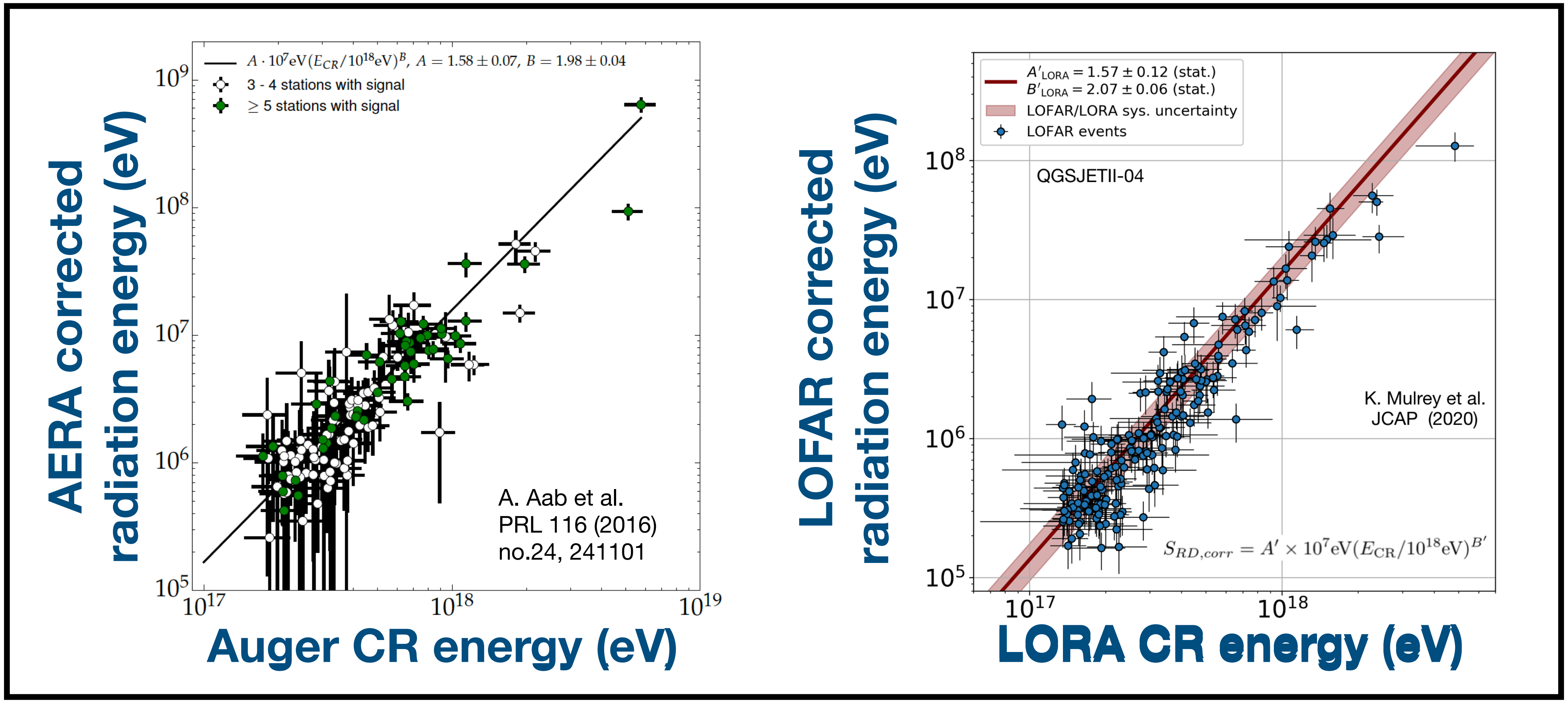
Example: LOFAR + Auger



At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

- **14% uncertainty AERA antenna calibration**
- **13.6% uncertainty LOFAR radiation energy (dominated by antenna calibration)**

Example: LOFAR + Auger

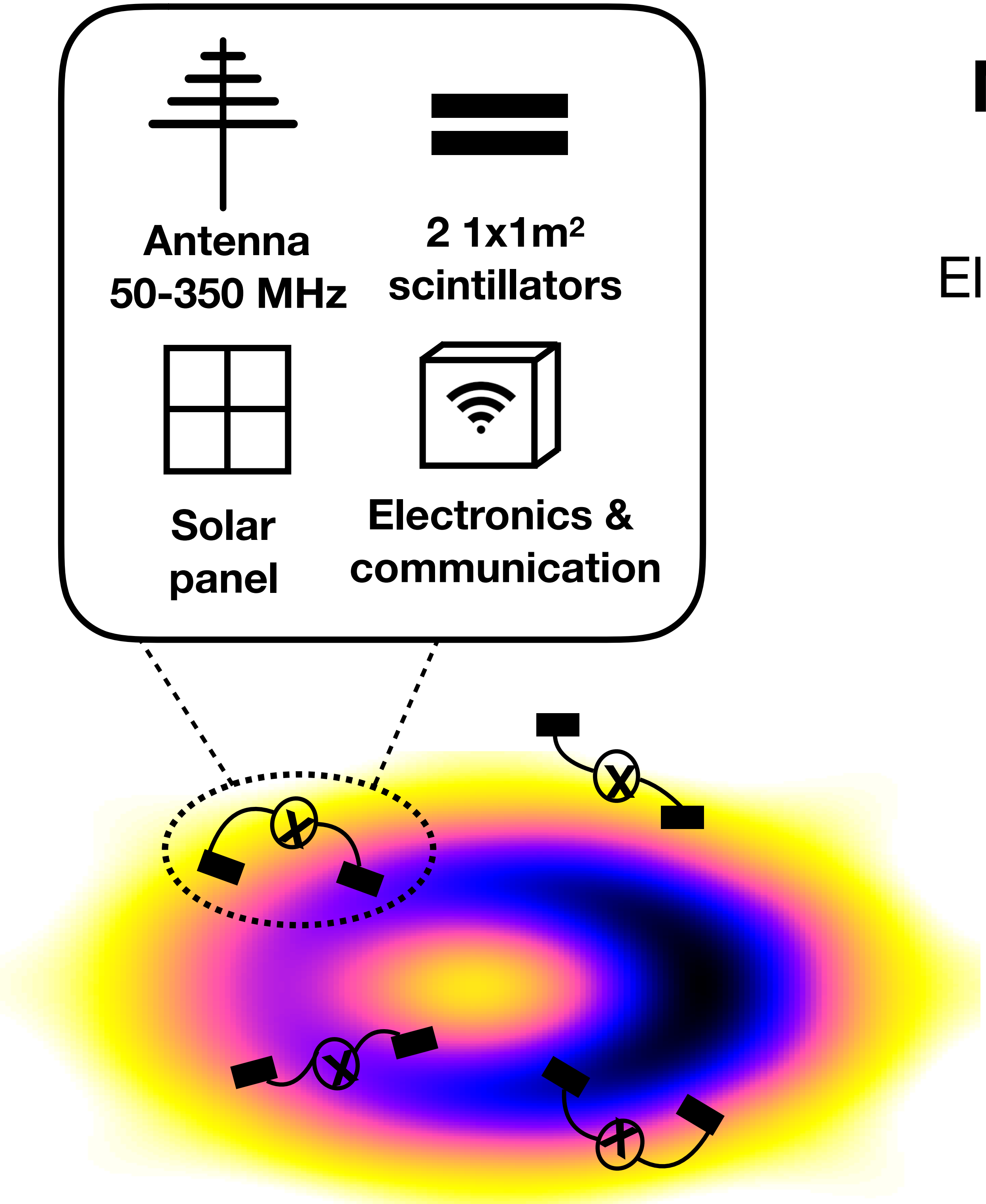


At a radiation energy of 1 MeV, the energy scales of Auger and LORA agree to within 6 ± 20 %

- **14% uncertainty AERA antenna calibration**
- **13.6% uncertainty LOFAR radiation energy (dominated by antenna calibration)**

Measure the radiation energy with the same array!

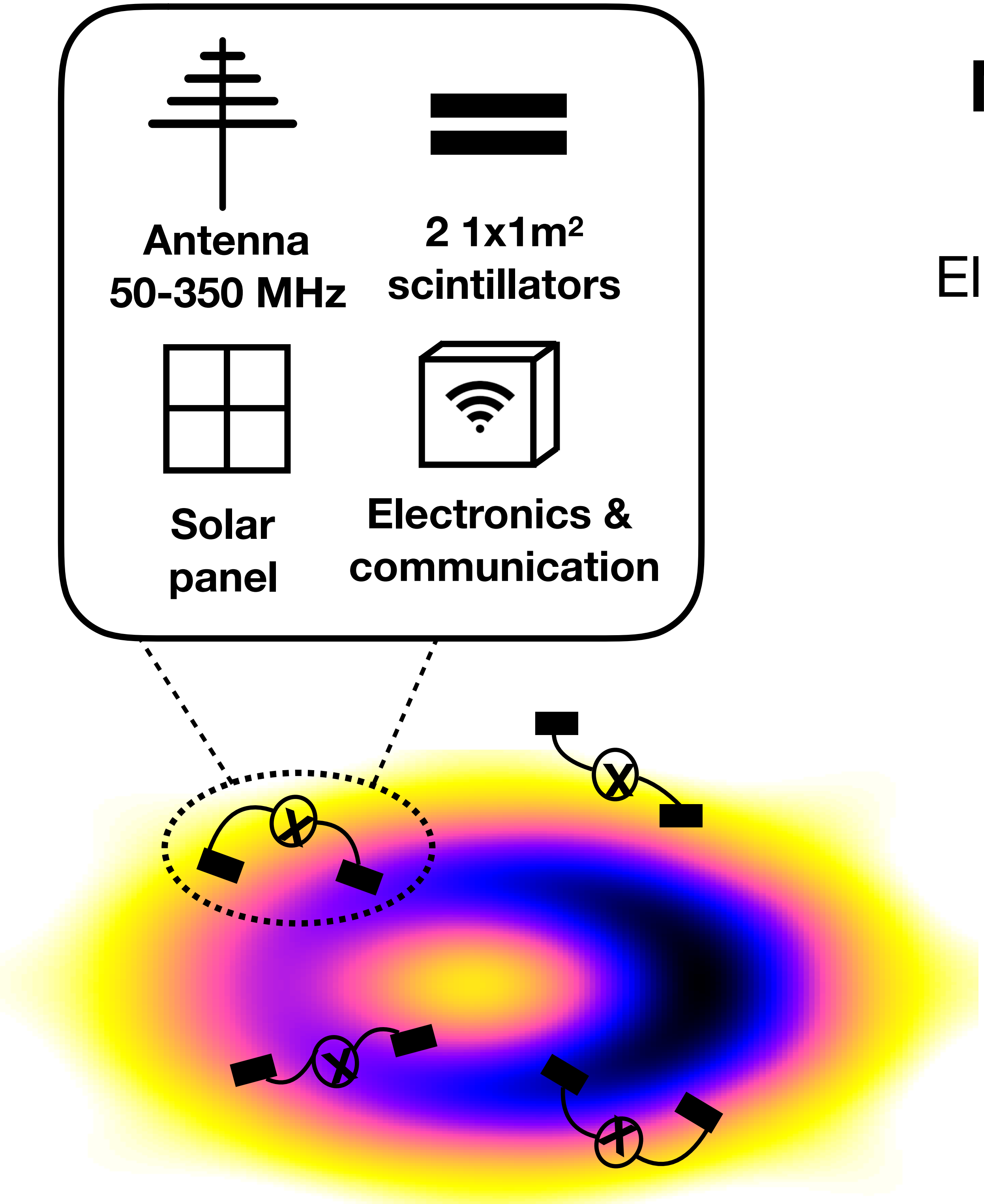
Cross-calibration array



Measure the radiation energy with the same array!

Eliminate uncertainties on the comparison due to antenna calibration, system response, …

Cross-calibration array



Antenna 50-350 MHz

2 1x1m^2 scintillators

Solar panel

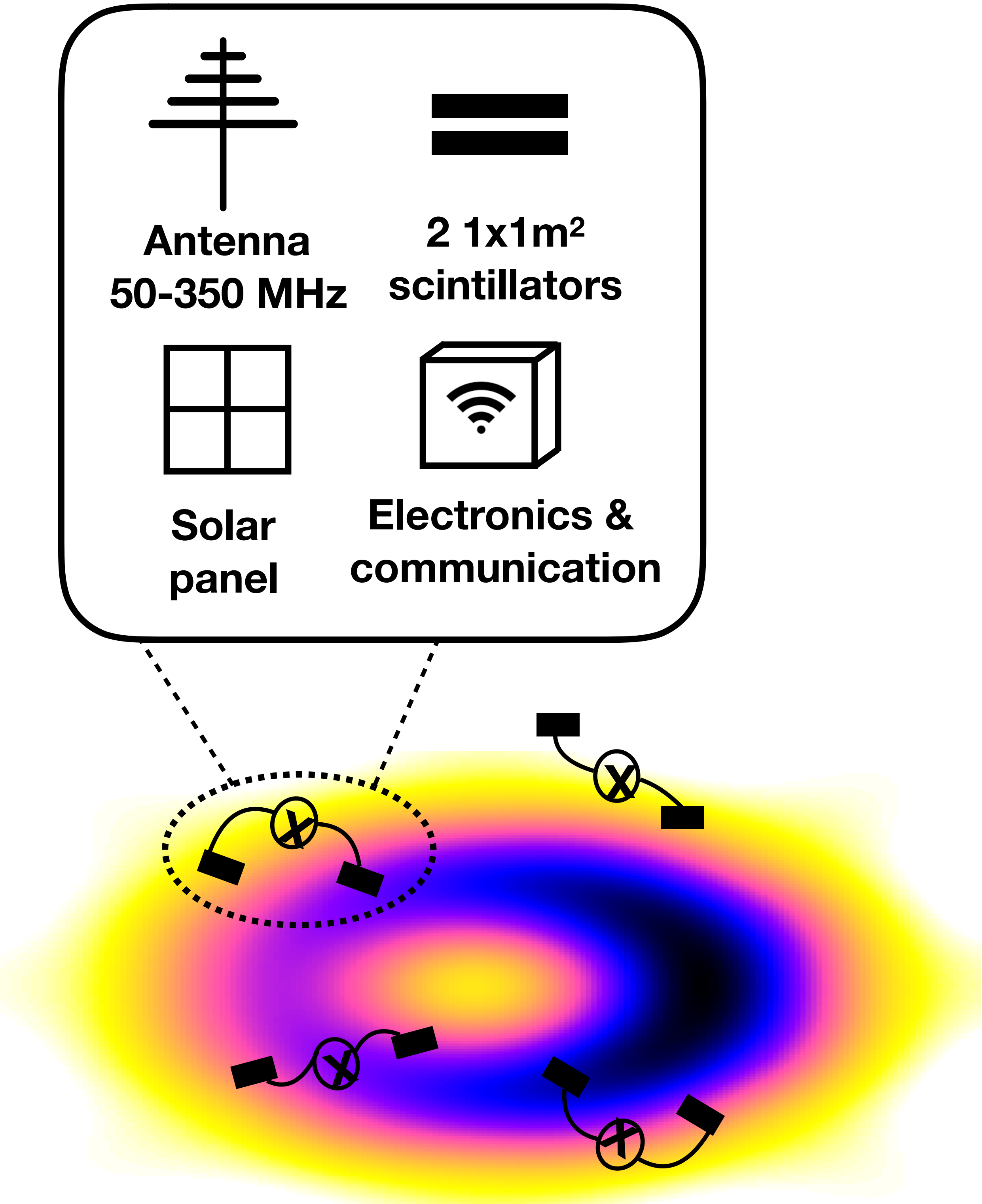
Electronics & communication

Measure the radiation energy with the same array!

Eliminate uncertainties on the comparison due to antenna calibration, system response, …

- ***Autonomous***: self triggering, independent energy measurement, no/minimal interference with main experiment
- ***Portable***: can be deployed at different sites, spacing can be adjusted to probe different energy regimes

Cross-calibration array



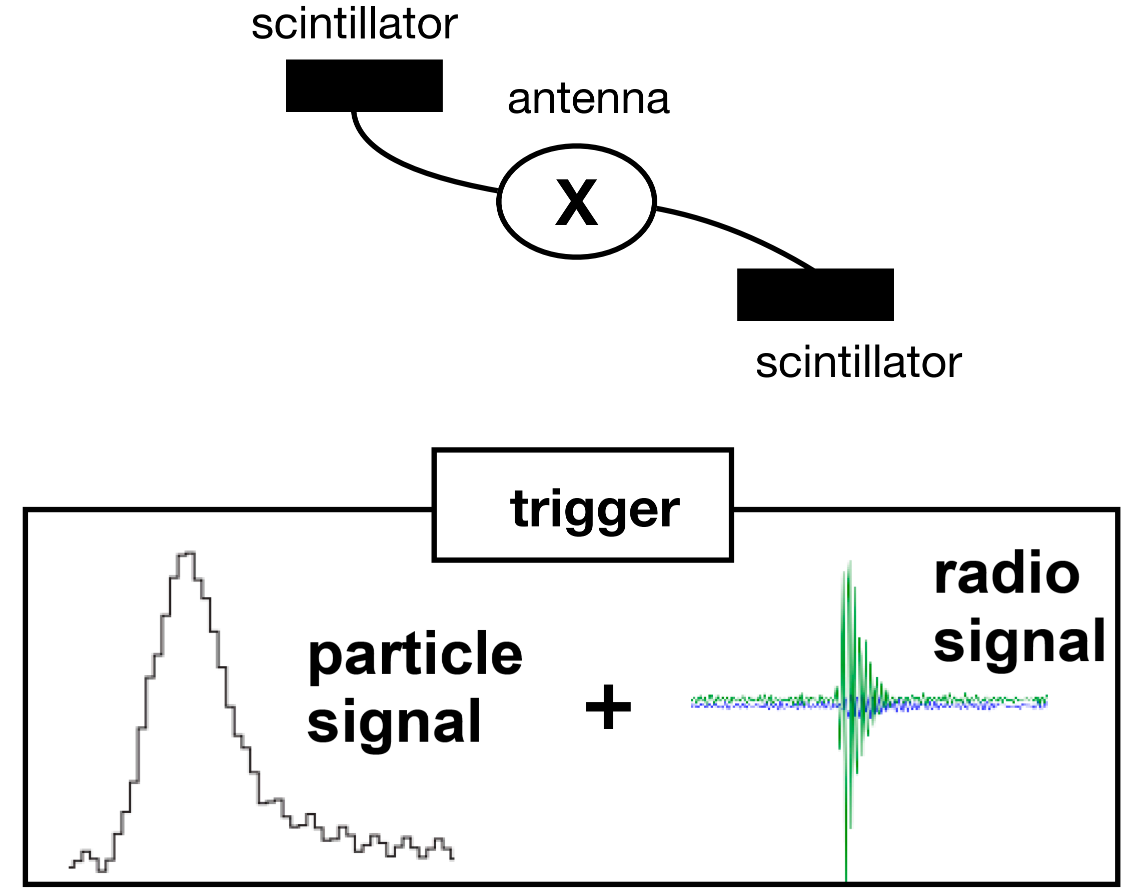
Antenna
50-350 MHz

2 1x1m^2
scintillators

Solar
panel

Electronics &
communication

Triggering: radio + particle



scintillator

antenna

scintillator

trigger

particle
signal

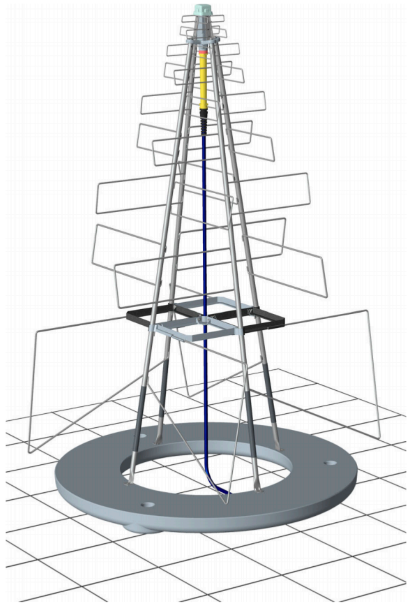
+

radio
signal

Particle: ensures a cosmic ray ✓

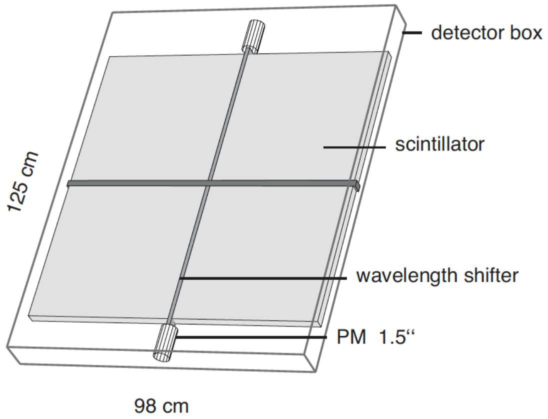
Radio: Strong radio signal / usable event ✓

Cross-calibration array



Antenna: SKA log-periodic (v2)

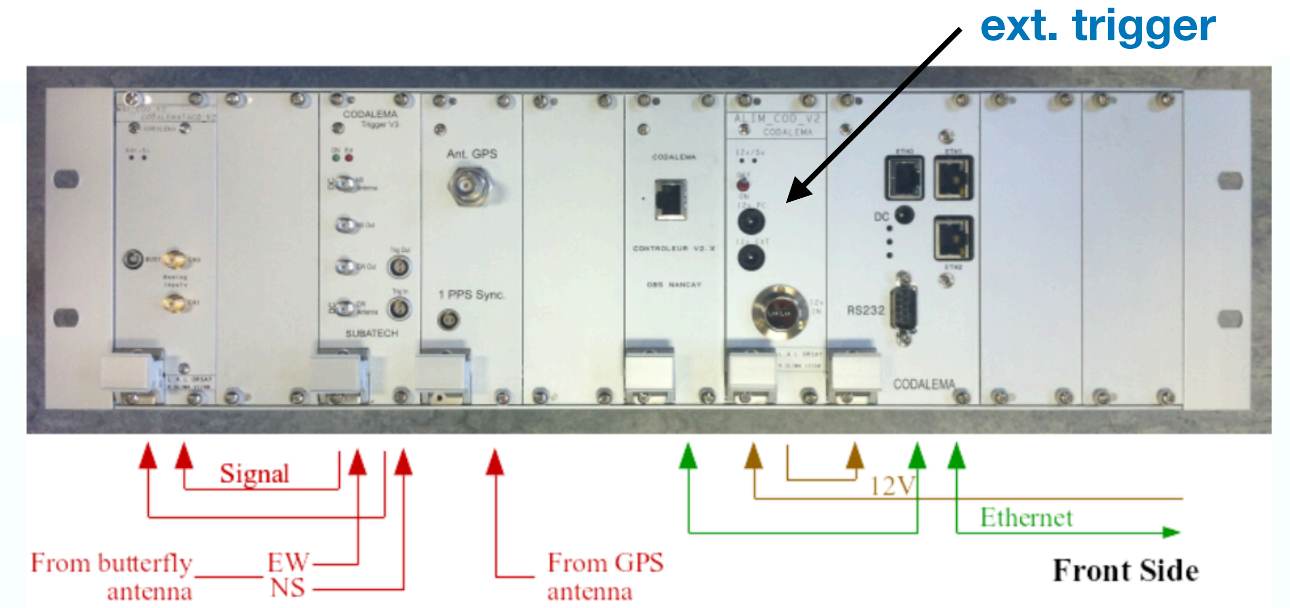
- High gain, smooth response up to 350 MHz
- Well modeled
- Used in SKA, IceTop radio



Scintillators: KASCADE

- ~1m^2
- Well understood

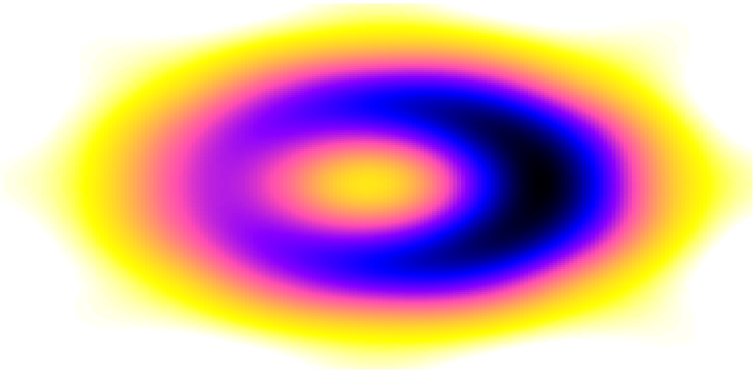
CODALEMA electronics



- 1 GS/s sampling
- 14 bit depth
- 2.56 μsec traces
- 15 ns relative accuracy
- 20-25 W power
- External / logic triggering

Radiation Energy Reconstruction

1. Integrate fluence to get radiation energy (2D LDF)

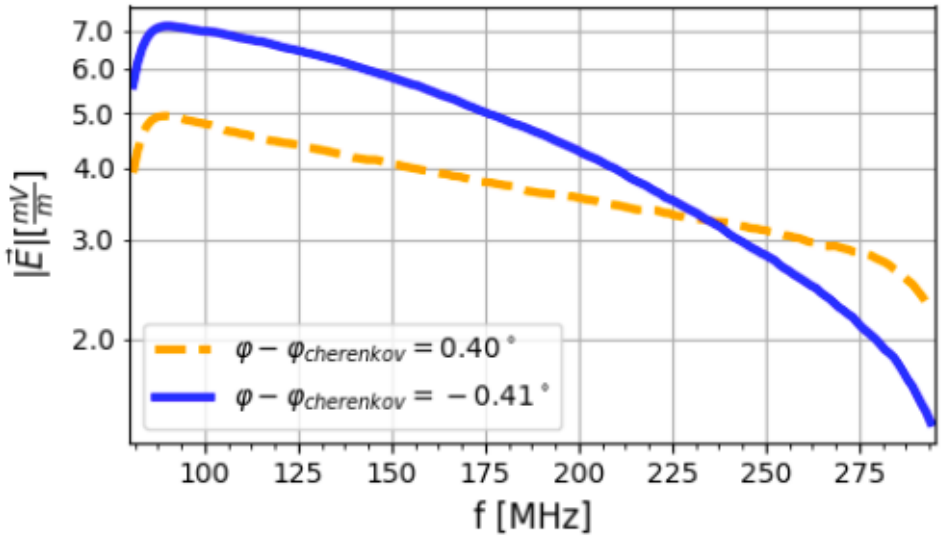


$$f = \varepsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$$

A. Aab et al.
PRL 116 (2016)
no.24, 241101

- Only 5 stations- use direction/core info from host experiment
- Develop model for 50-350 MHz footprint
- Resolution ~20% (30-80 MHz)

2. Use broadband spectral information (ARIANNA style)



$$\begin{pmatrix} \mathcal{E}_\theta \\ \mathcal{E}_\phi \end{pmatrix} = \begin{pmatrix} A_\theta \\ A_\phi \end{pmatrix} 10^{f \cdot m_f} \exp(\Delta j)$$

Corrected radiation energy

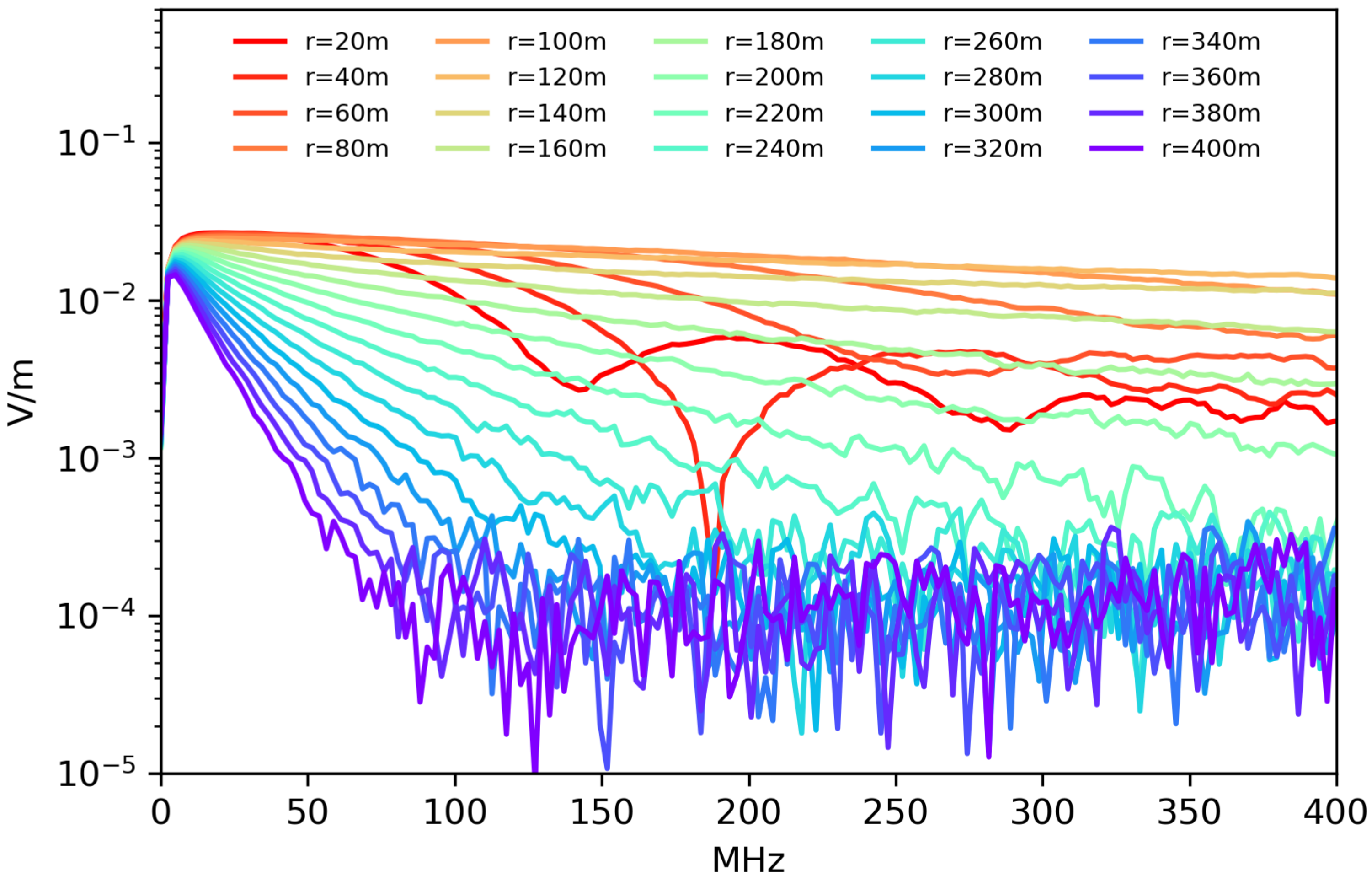
$$\frac{\sqrt{\Phi'_E}}{E_{shower}} = A \cdot \exp(-s \cdot (|m_f| \cdot \mathrm{GHz})^{0.8})$$

Welling et al.
***JCAP* 10 (2019) 075**

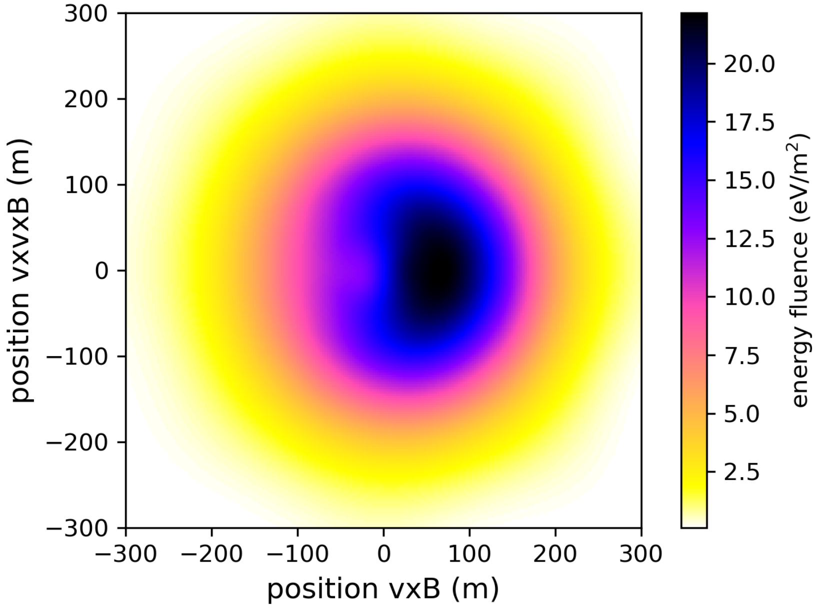
- Make use of spectral information to determine where you are w.r.t the Cherenkov cone
- Single antenna reconstruction?
- Resolution ~15%

Radiation Energy Reconstruction

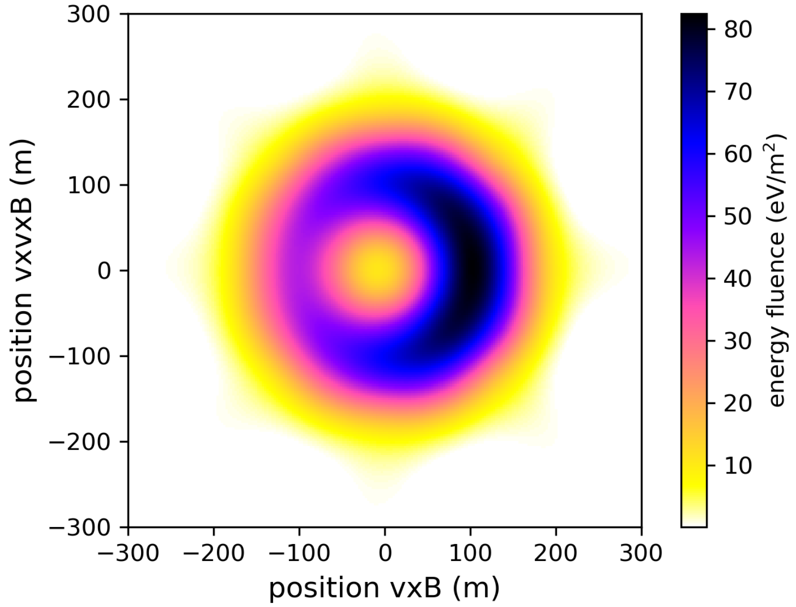
Geomagnetic signal on vxvxB arm
E~10^{17}eV
Xmax=640 g/cm^2
zenith=33°



30-80 MHz



50-350 MHz



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Xmax=640 g/cm^2
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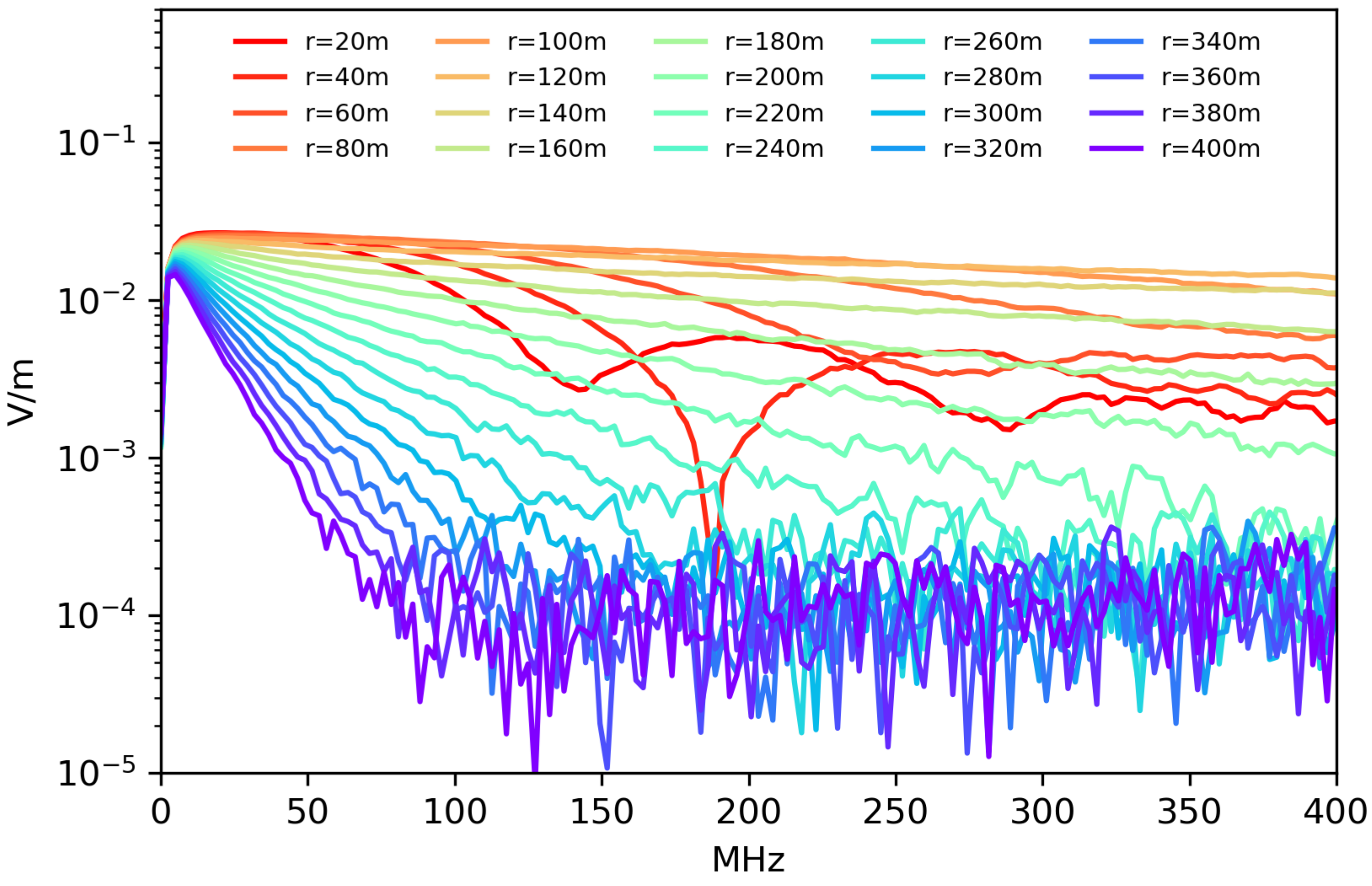
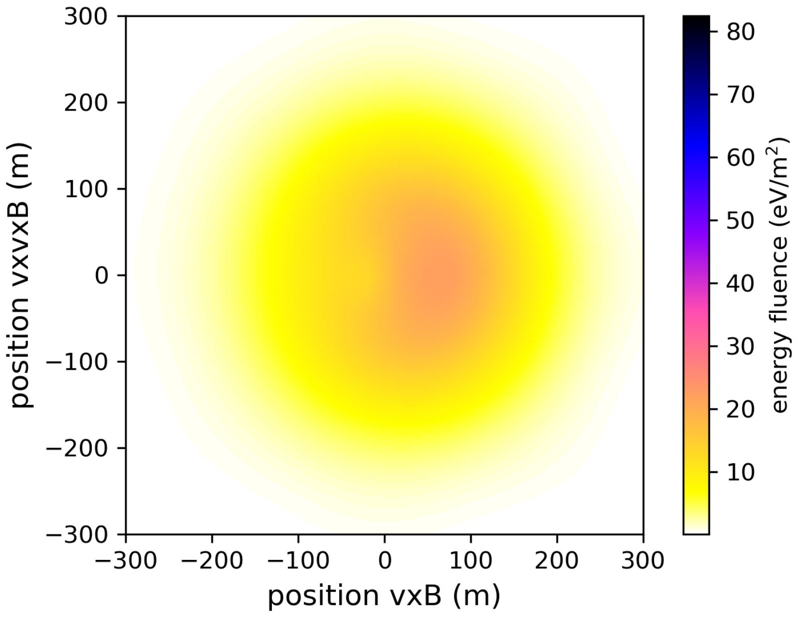
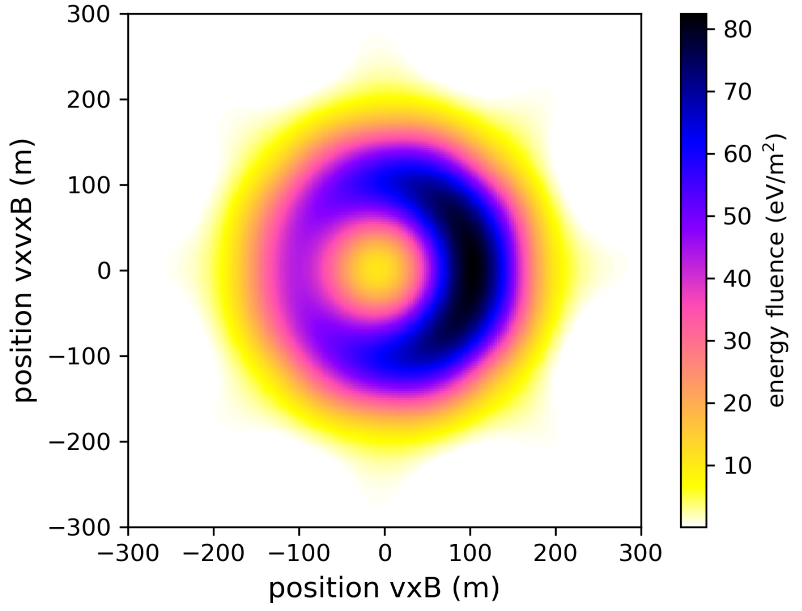


Energy reconstruction: work in progress

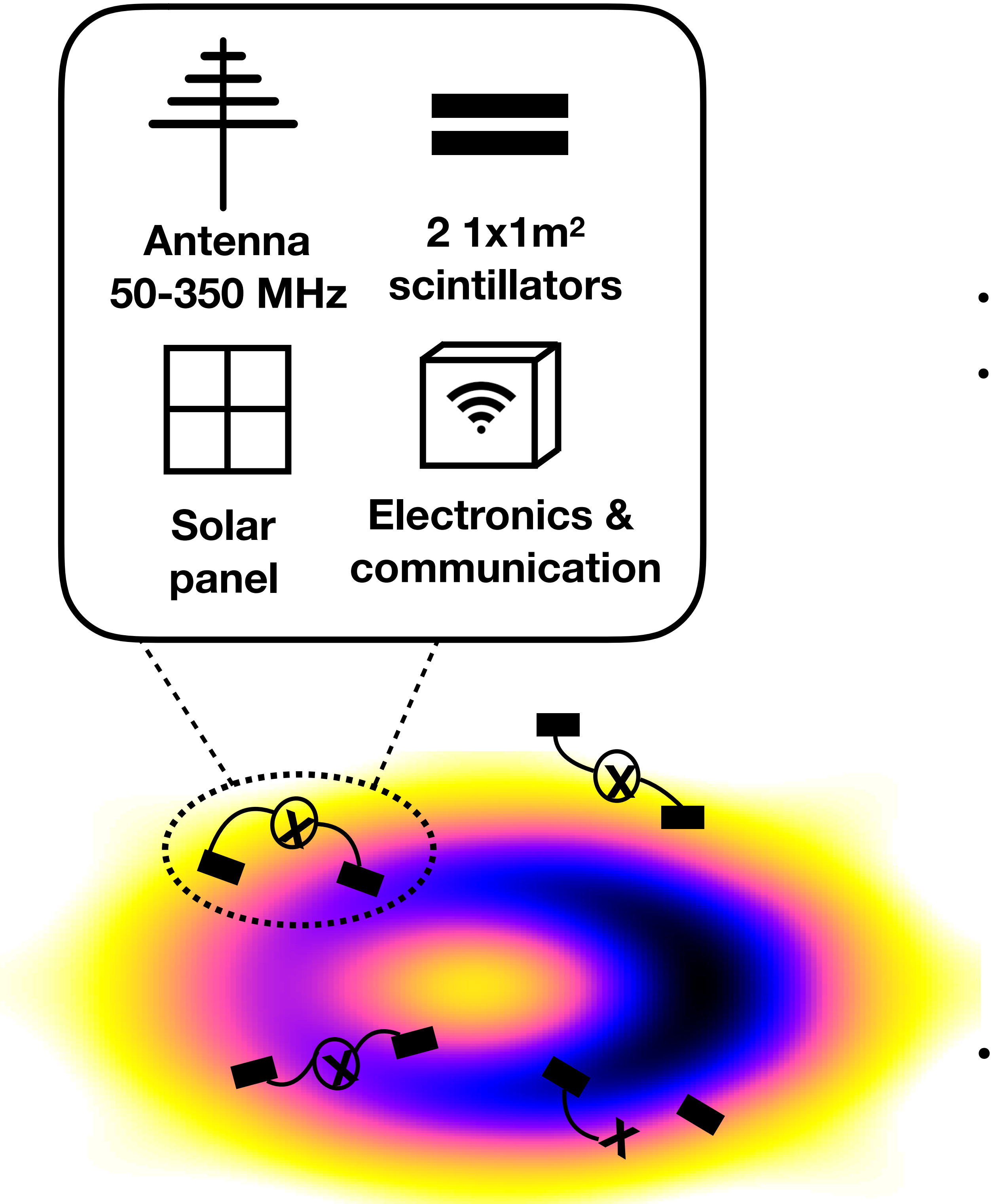
30-80 MHz



50-350 MHz

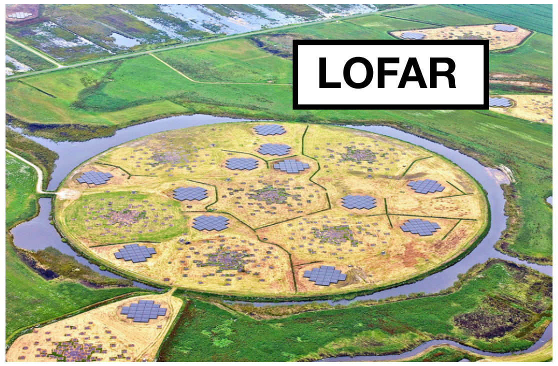


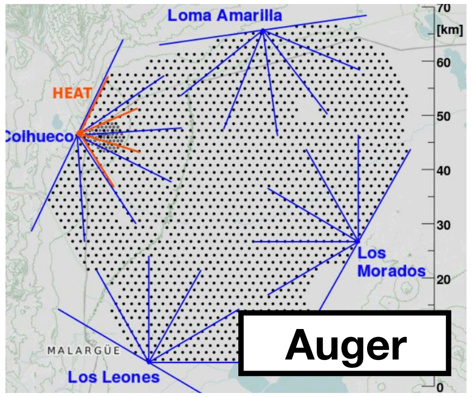
Radiation Energy Reconstruction



Timeline

- ***Prototype design and assembly*** 2020-2021
- ***Deployment***: 2021-2022 @ **LOFAR**, 2022 @ **Auger**

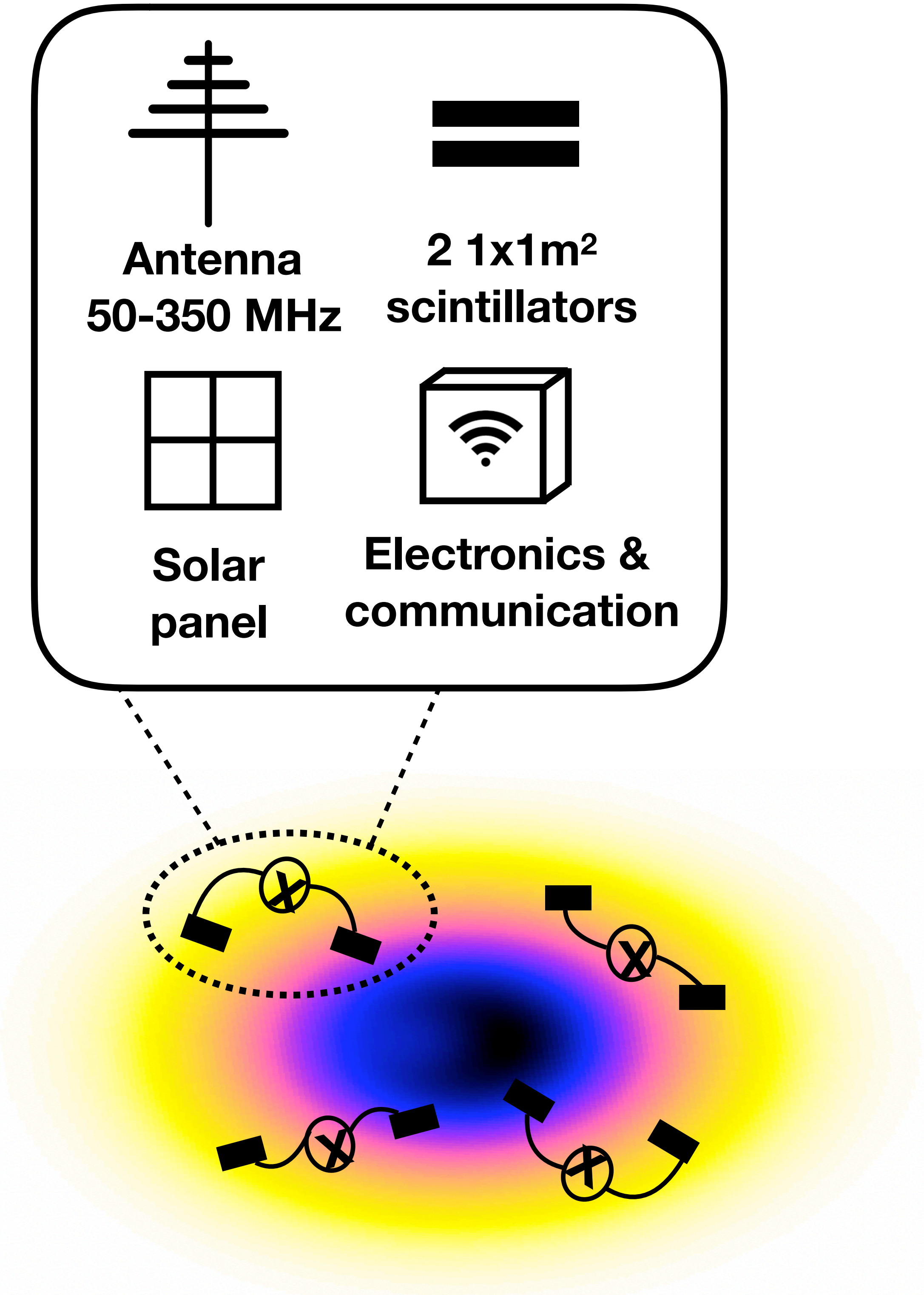




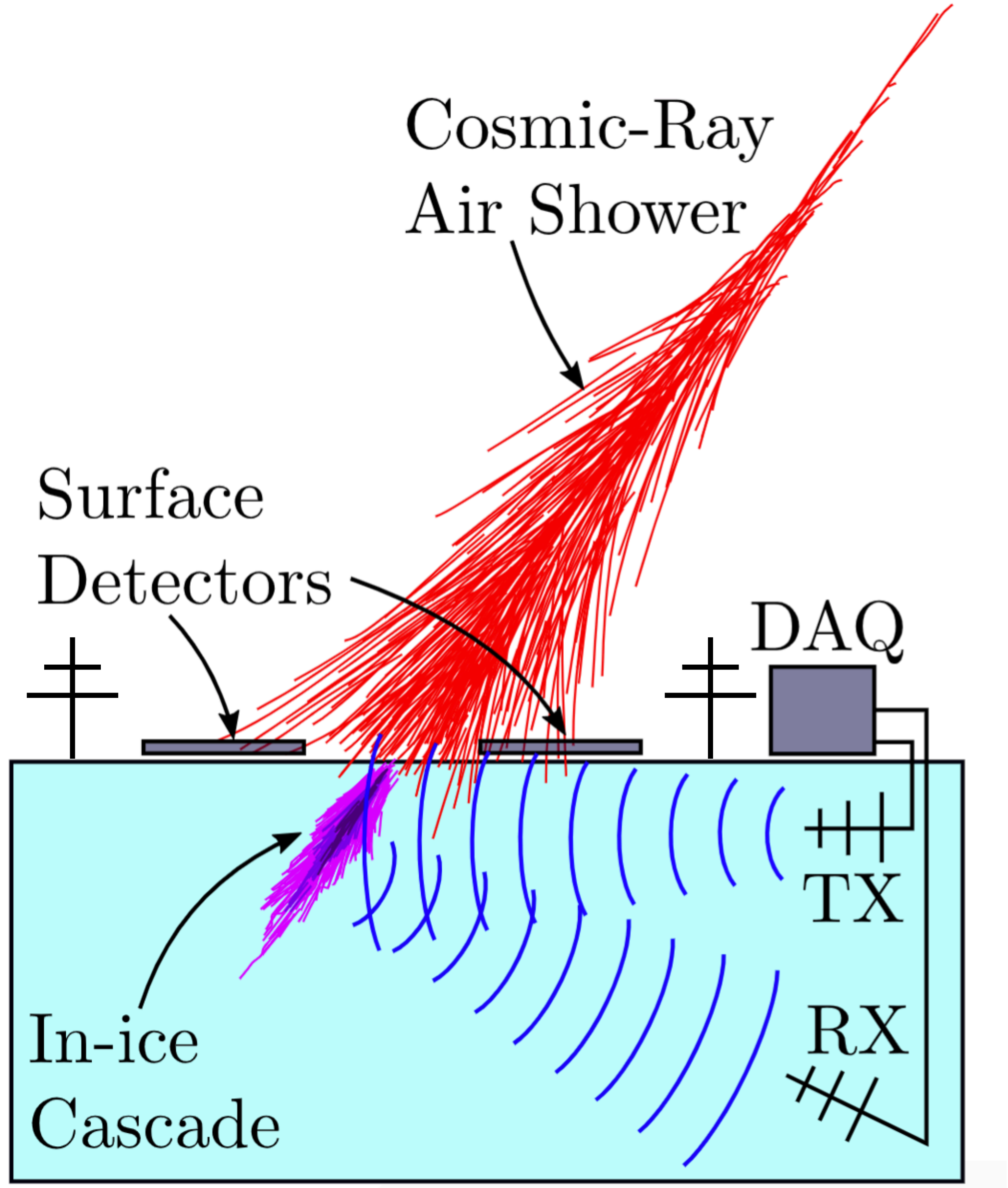
Collect ~ 300 events at each location

- ***Longterm*:** deploy at other experiments

RET-CR Surface array



Radar Echo Telescope



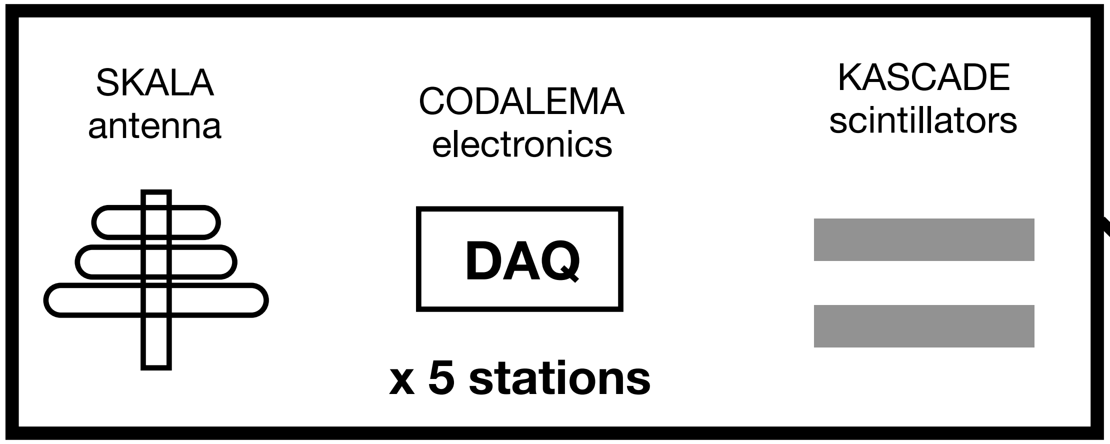
ICRC2021
1032
1214
1147

RET-CR
K. de Vries,
S. Prohira
et al.

ICRC: 1032
1214
1147

VUB prototype

Energy Cross Calibration array



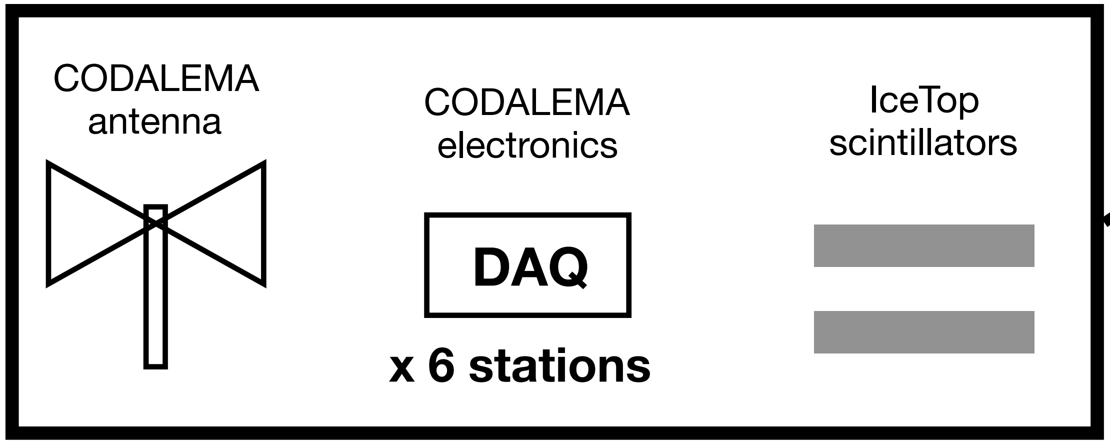
SKALA antenna

CODALEMA electronics

KASCADE scintillators

x 5 stations

RET-CR surface array



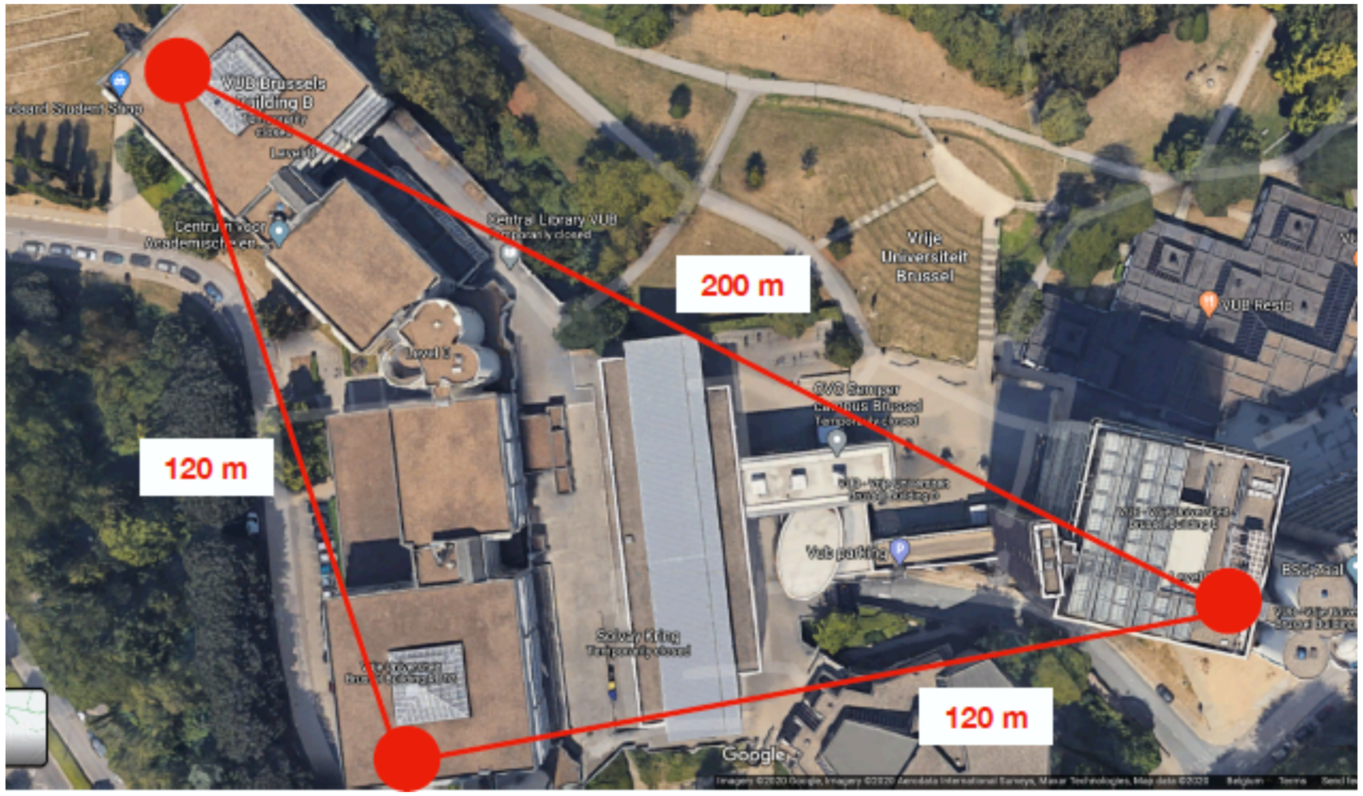
CODALEMA antenna

CODALEMA electronics

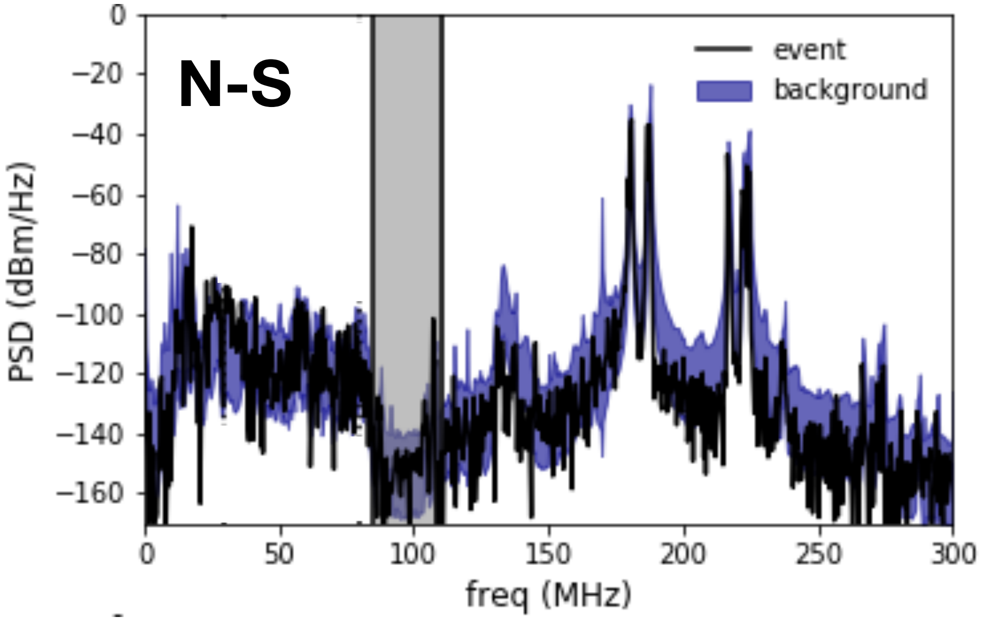
IceTop scintillators

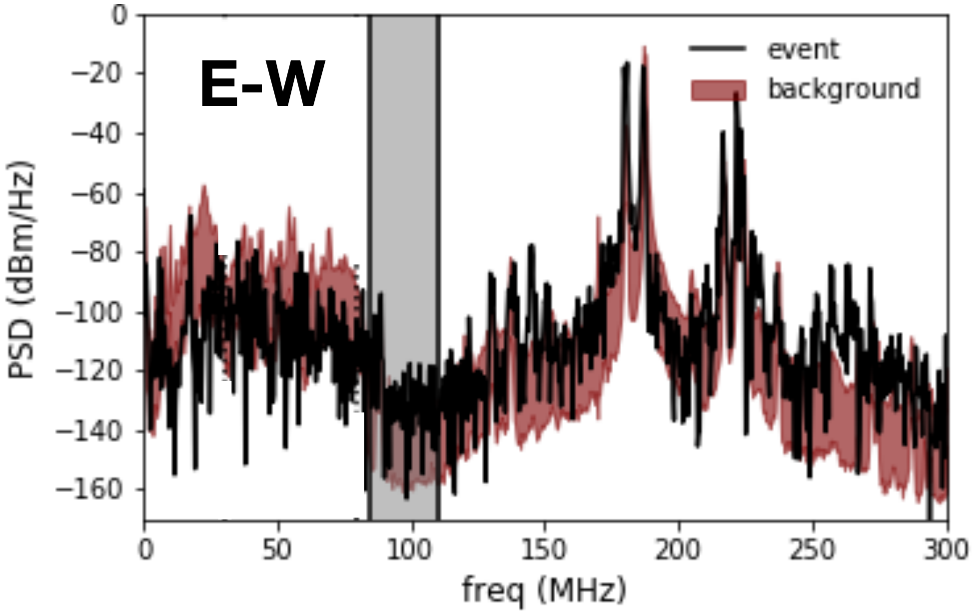
x 6 stations

Prototype deployment at the VUB 2020-2021



VUB prototype

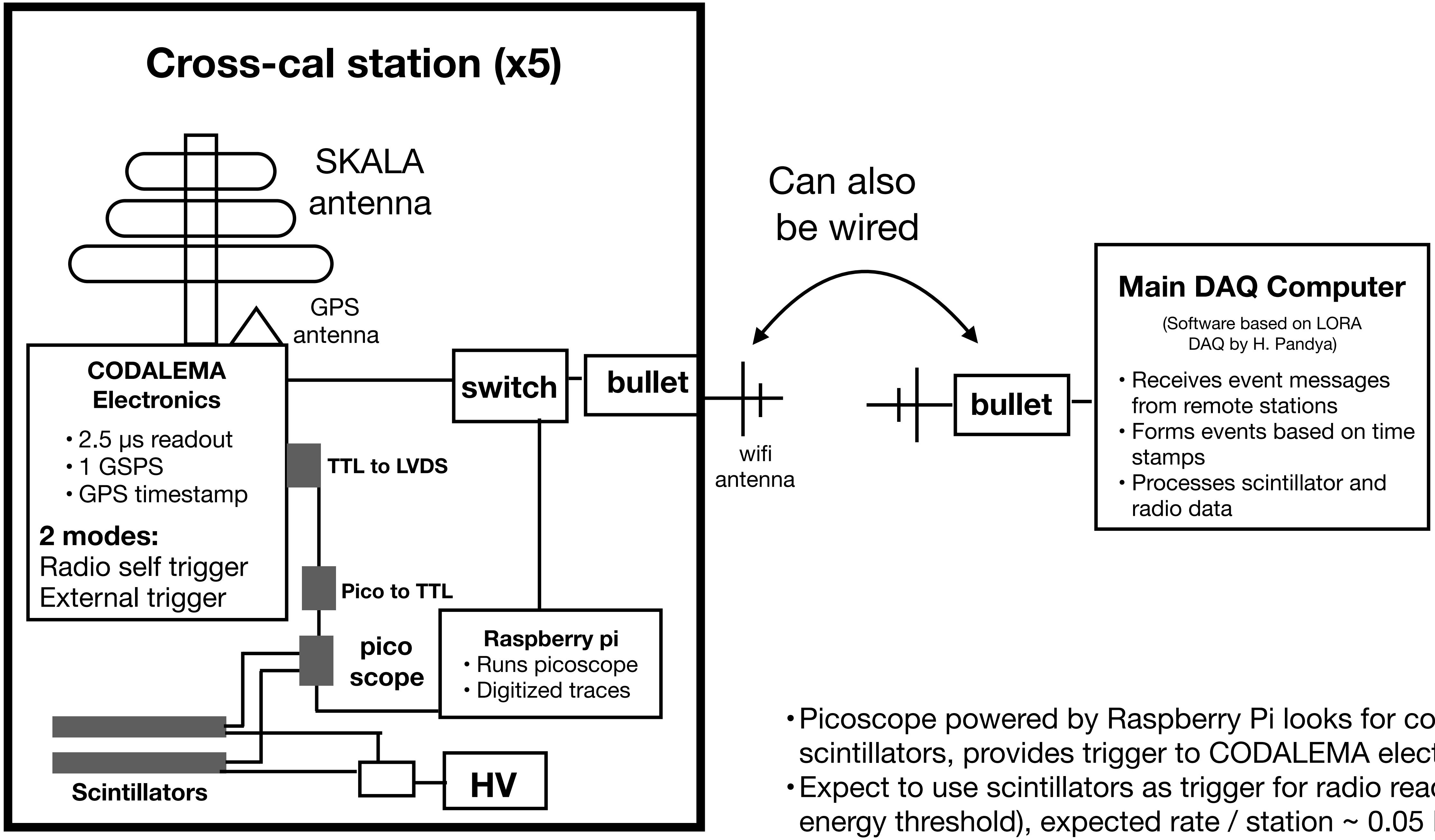




First cosmic-ray data ★

Extra

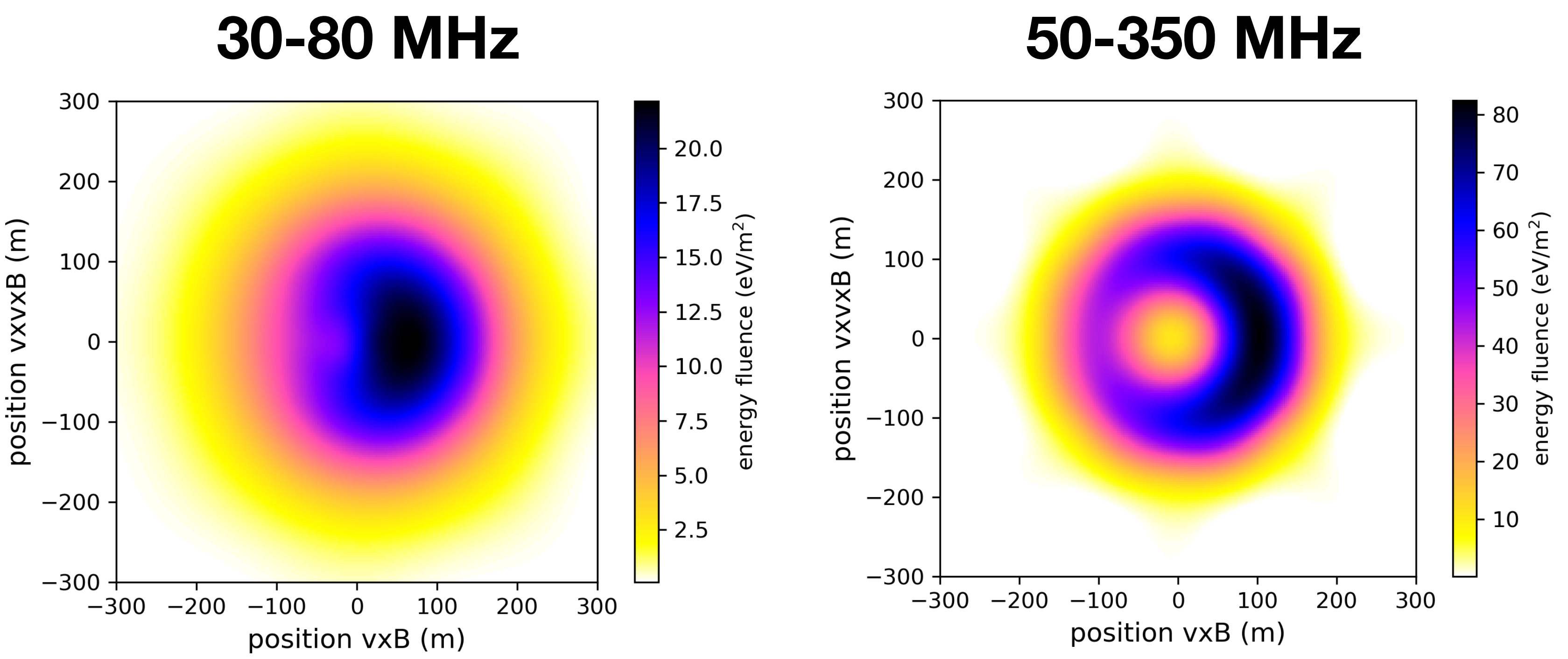
Cross-calibration array



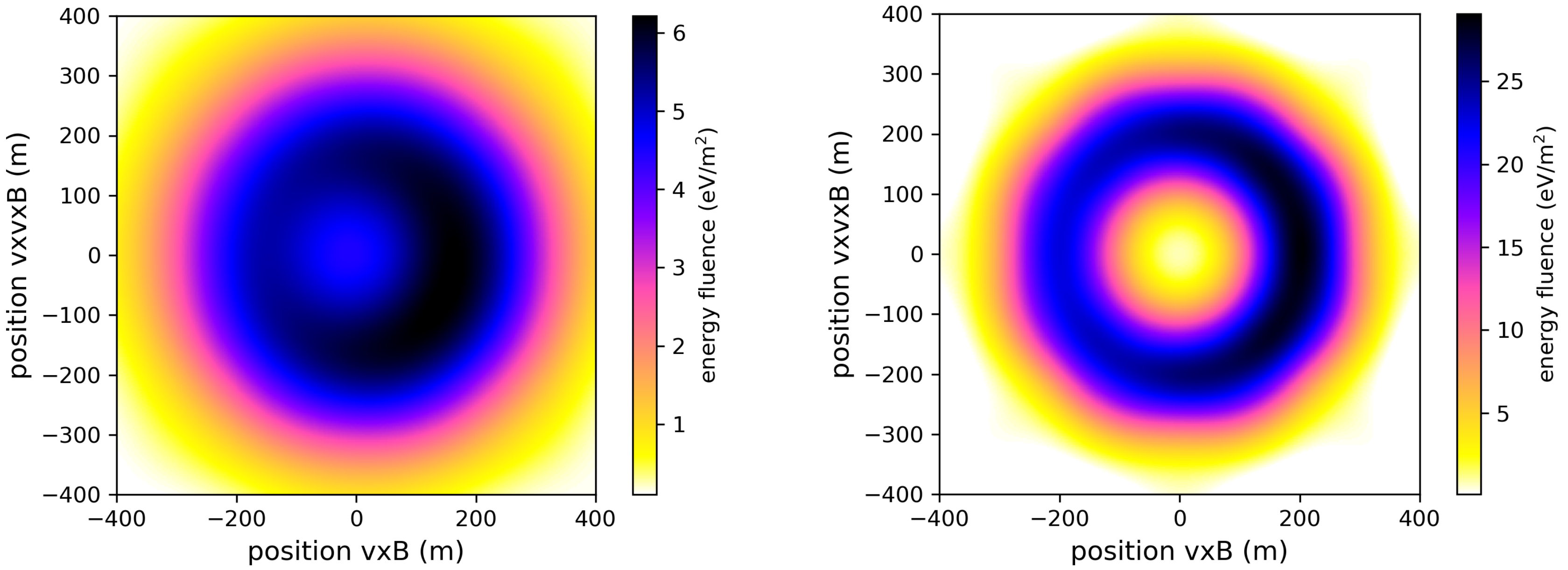
- Picoscope powered by Raspberry Pi looks for coincidence in scintillators, provides trigger to CODALEMA electronics
- Expect to use scintillators as trigger for radio readout first (lower energy threshold), expected rate / station ~ 0.05 Hz
- **Design should be compatible with LOFAR + Auger facilities**

Radiation Energy Reconstruction

$$E = 3.5 \times 10^{17}\mathrm{eV}$$
$$X_{\mathrm{max}} = 640\frac{\mathrm{g}}{\mathrm{cm}^2}$$
$$\theta = 33°$$
$$D_{\mathrm{max}} = 604\frac{\mathrm{g}}{\mathrm{cm}^2}$$

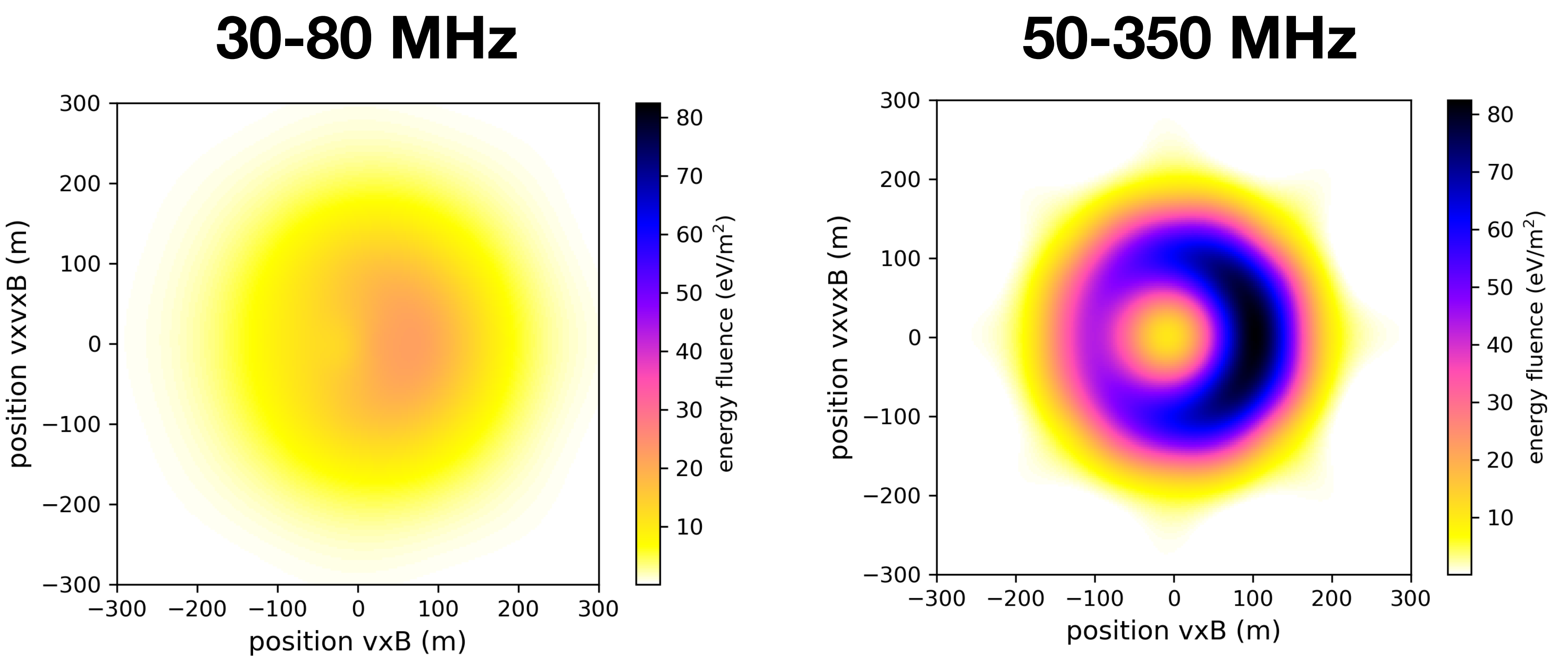


$$E = 2.1 \times 10^{17}\mathrm{eV}$$
$$X_{\mathrm{max}} = 673\frac{\mathrm{g}}{\mathrm{cm}^2}$$
$$\theta = 54°$$
$$D_{\mathrm{max}} = 1159\frac{\mathrm{g}}{\mathrm{cm}^2}$$



Radiation Energy Reconstruction

$$E = 3.5 \times 10^{17}\mathrm{eV}$$
$$X_{\mathrm{max}} = 640\frac{\mathrm{g}}{\mathrm{cm}^2}$$
$$\theta = 33°$$
$$D_{\mathrm{max}} = 604\frac{\mathrm{g}}{\mathrm{cm}^2}$$



$$E = 2.1 \times 10^{17}\mathrm{eV}$$
$$X_{\mathrm{max}} = 673\frac{\mathrm{g}}{\mathrm{cm}^2}$$
$$\theta = 54°$$
$$D_{\mathrm{max}} = 1159\frac{\mathrm{g}}{\mathrm{cm}^2}$$