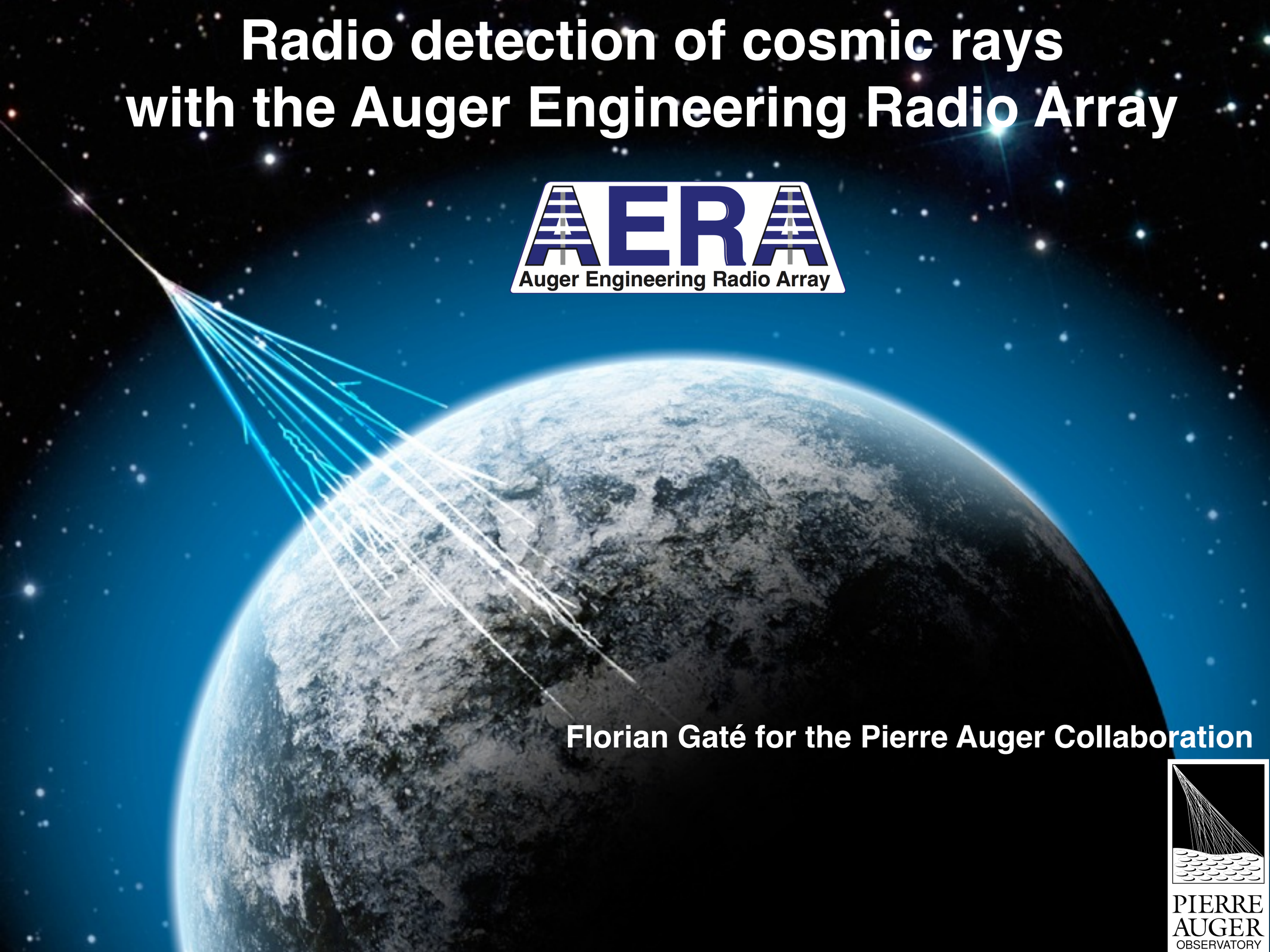
Radio detection of cosmic rays with the Auger Engineering Radio Array

AERA
Auger Engineering Radio Array



Florian Gaté for the Pierre Auger Collaboration

PIERRE AUGER OBSERVATORY

The Pierre Auger Observatory

- **Located in Malargüe, Argentina**
- **world's largest cosmic ray detector (3000 km^2)**

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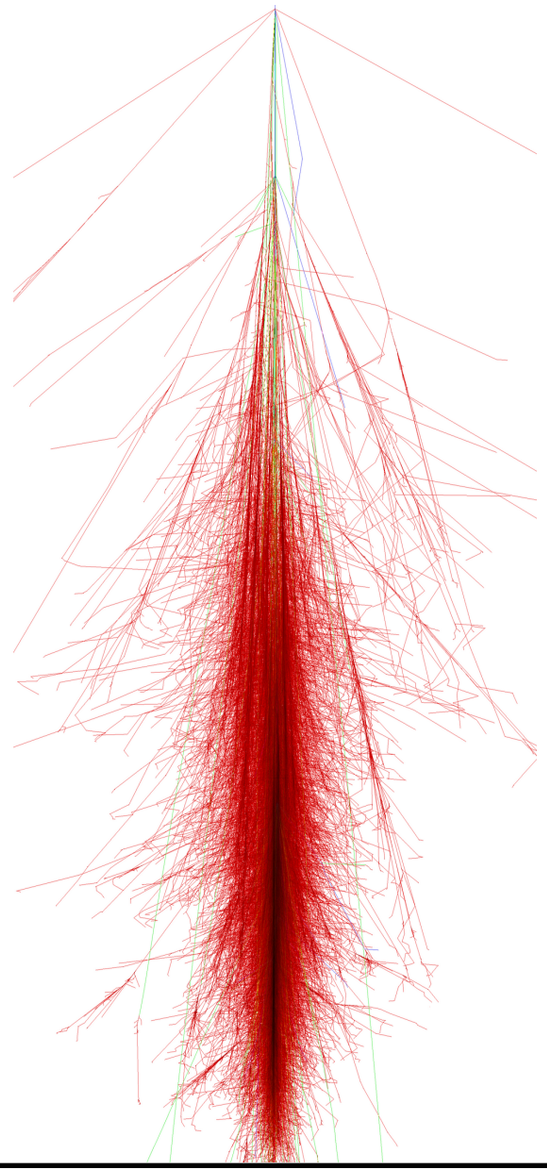
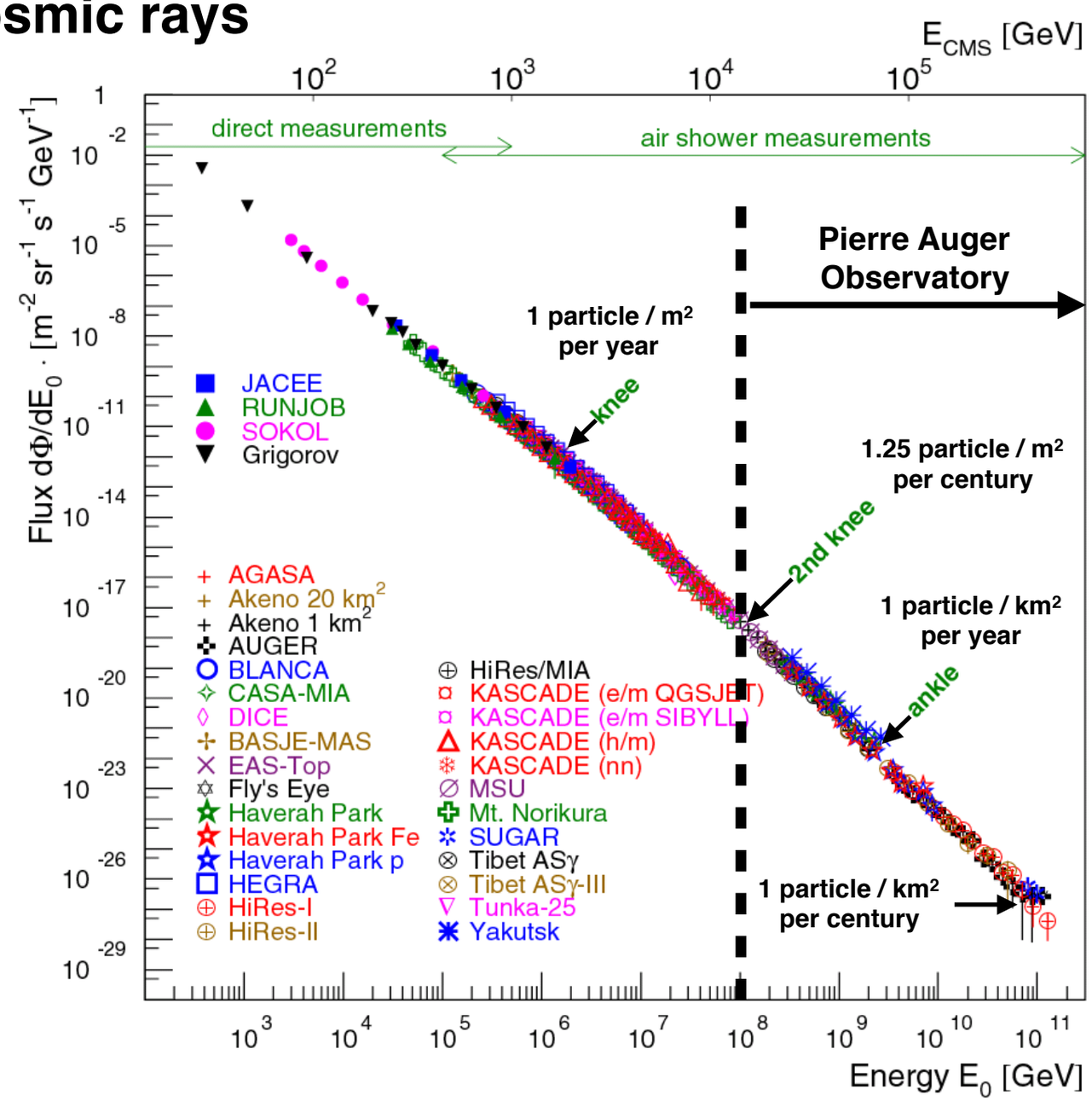
  $E > 10^{17}$ eV





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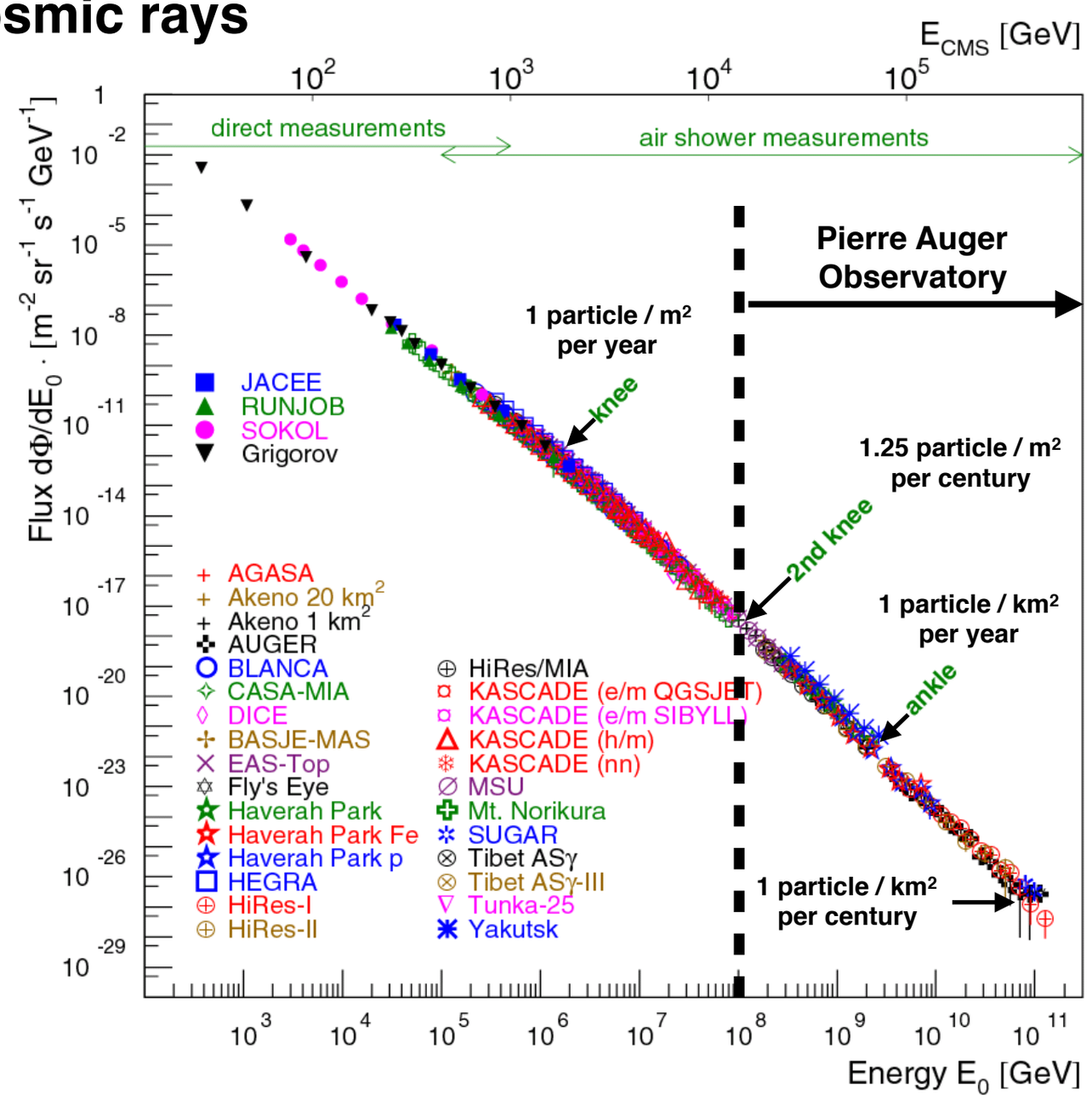
  $E > 10^{17}$ eV
- physics goals
  - sources
  - acceleration mechanisms
  - origin of the cut-off
  - mass composition



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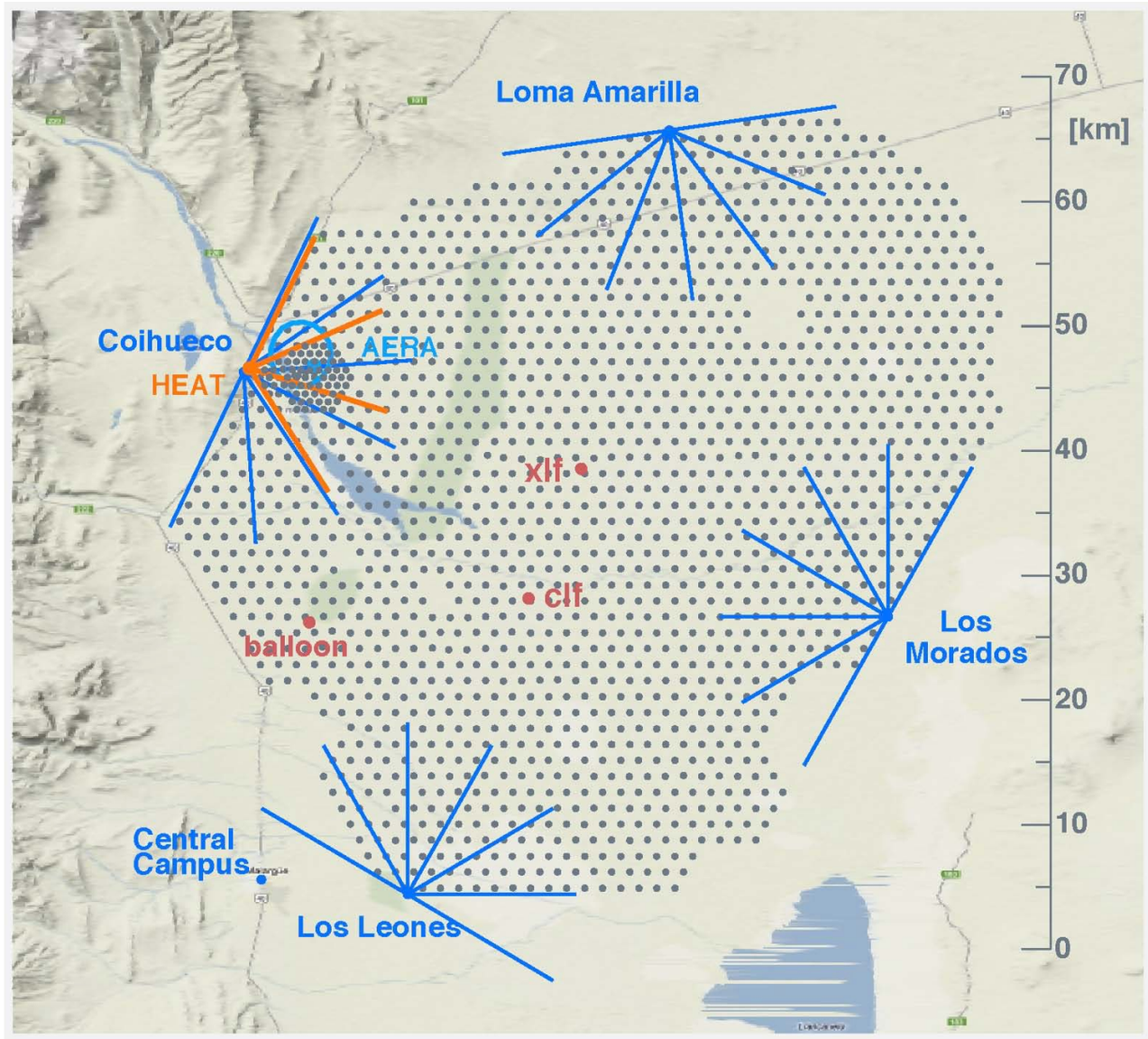
- 4 fluorescence sites (27 telescopes)



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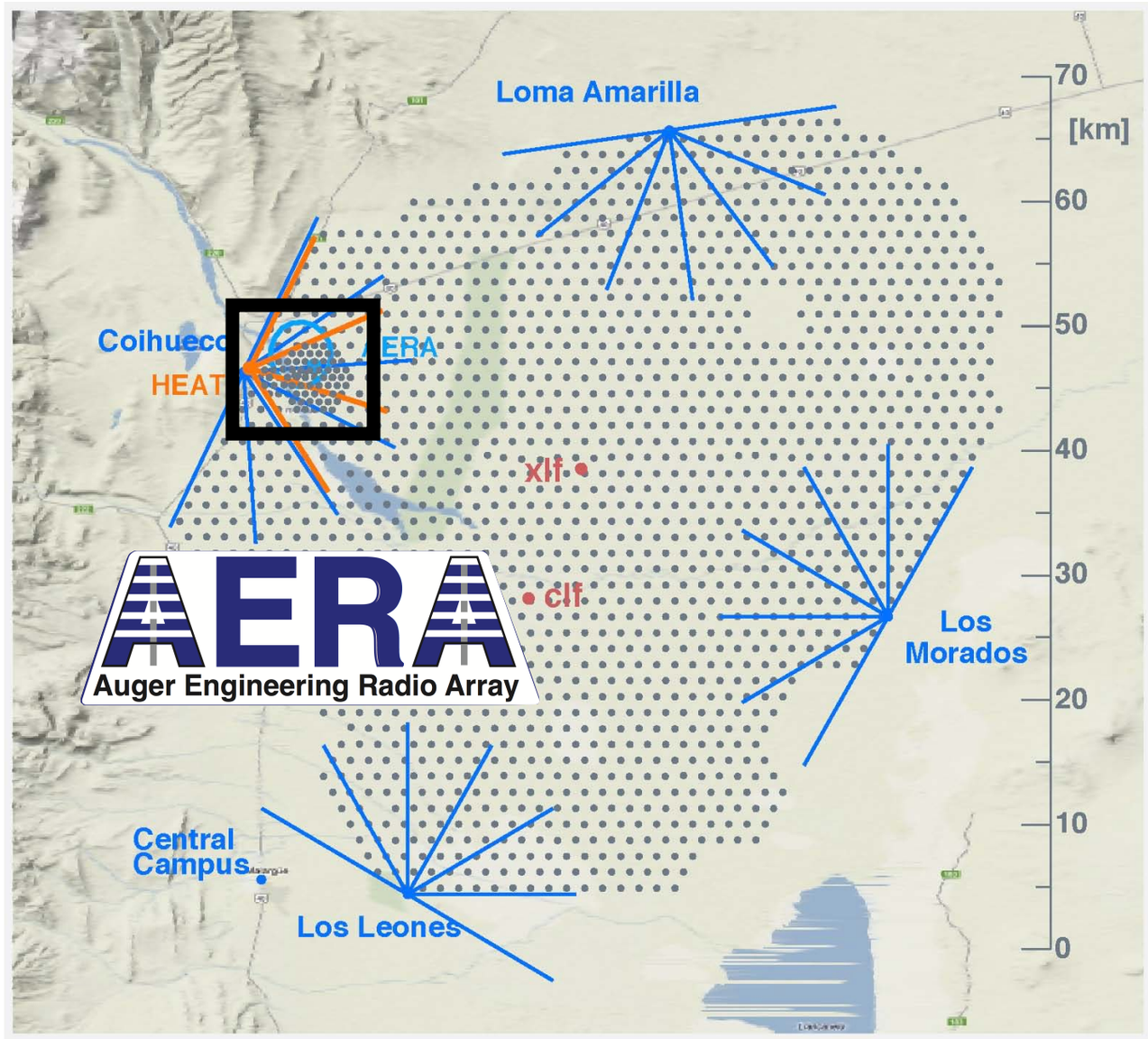
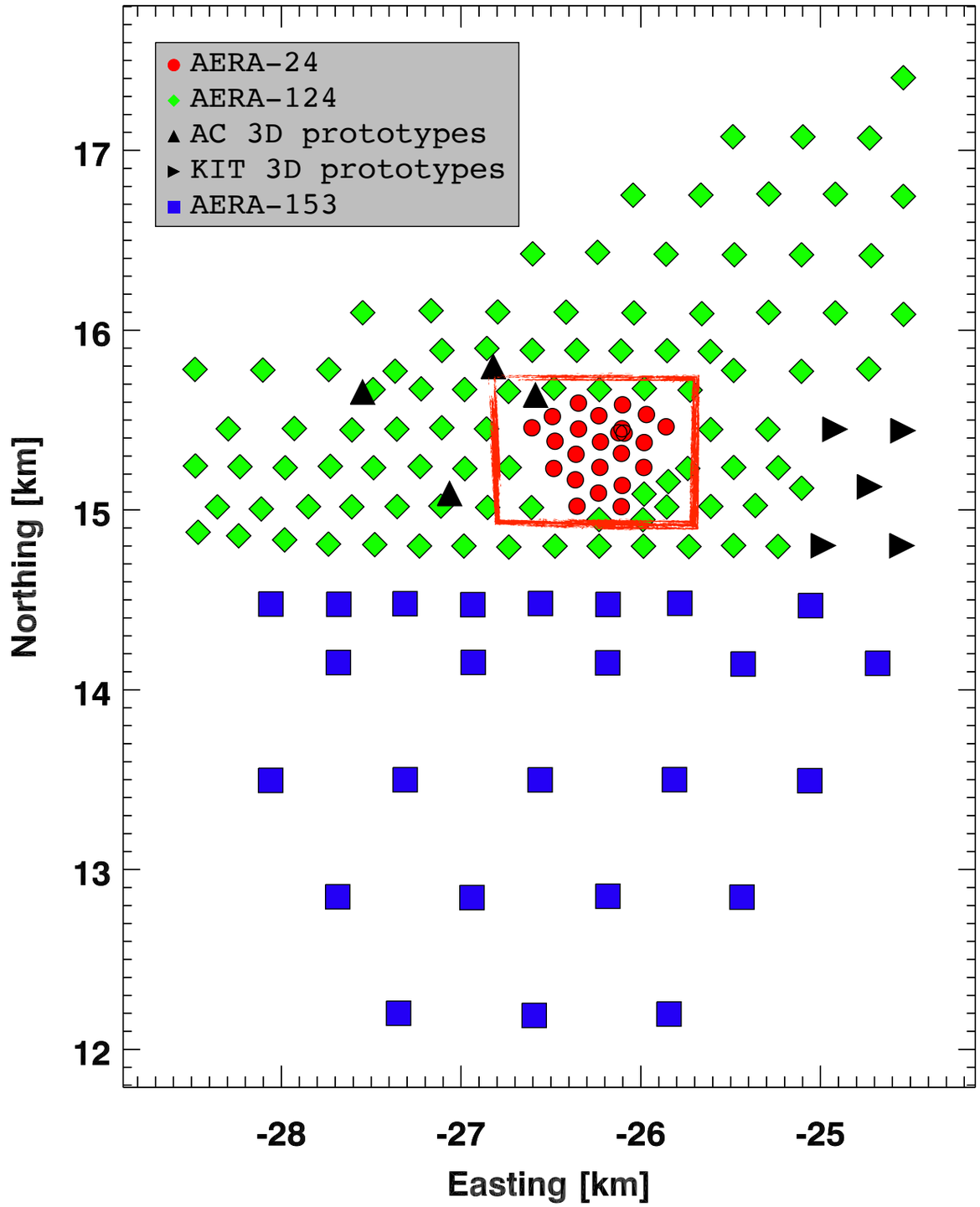
coincident measurements



AERA

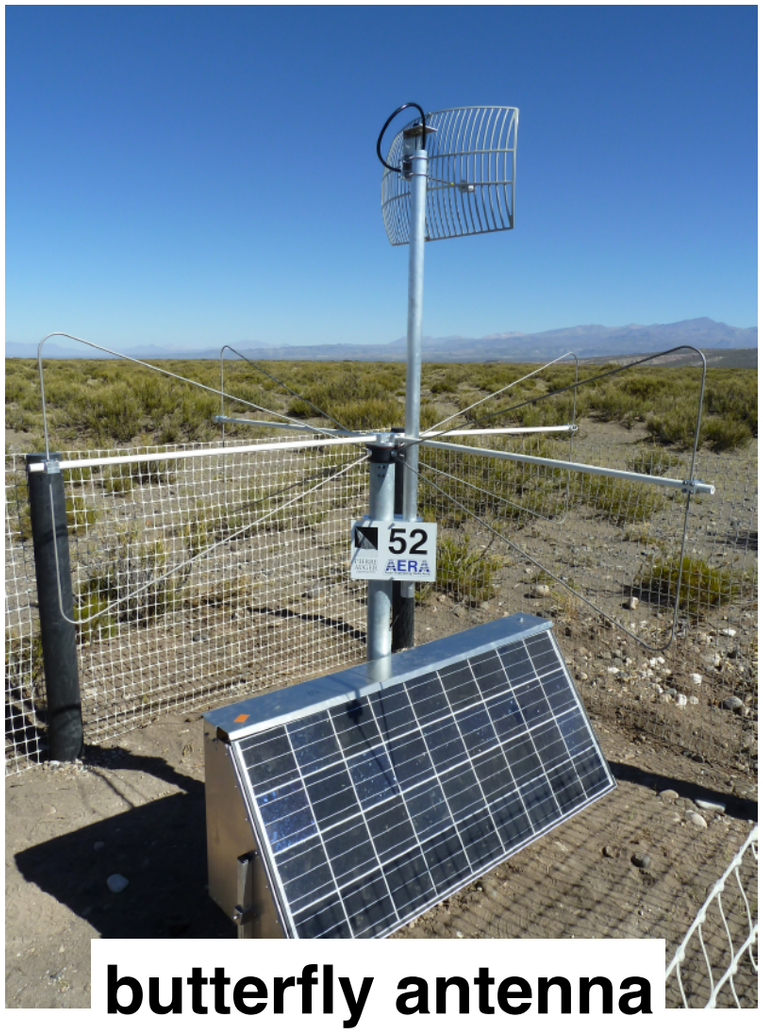
- **Deployment and spacing:**
  - **2011: Phase I - 24 stations - 144 m**

log-periodic antenna

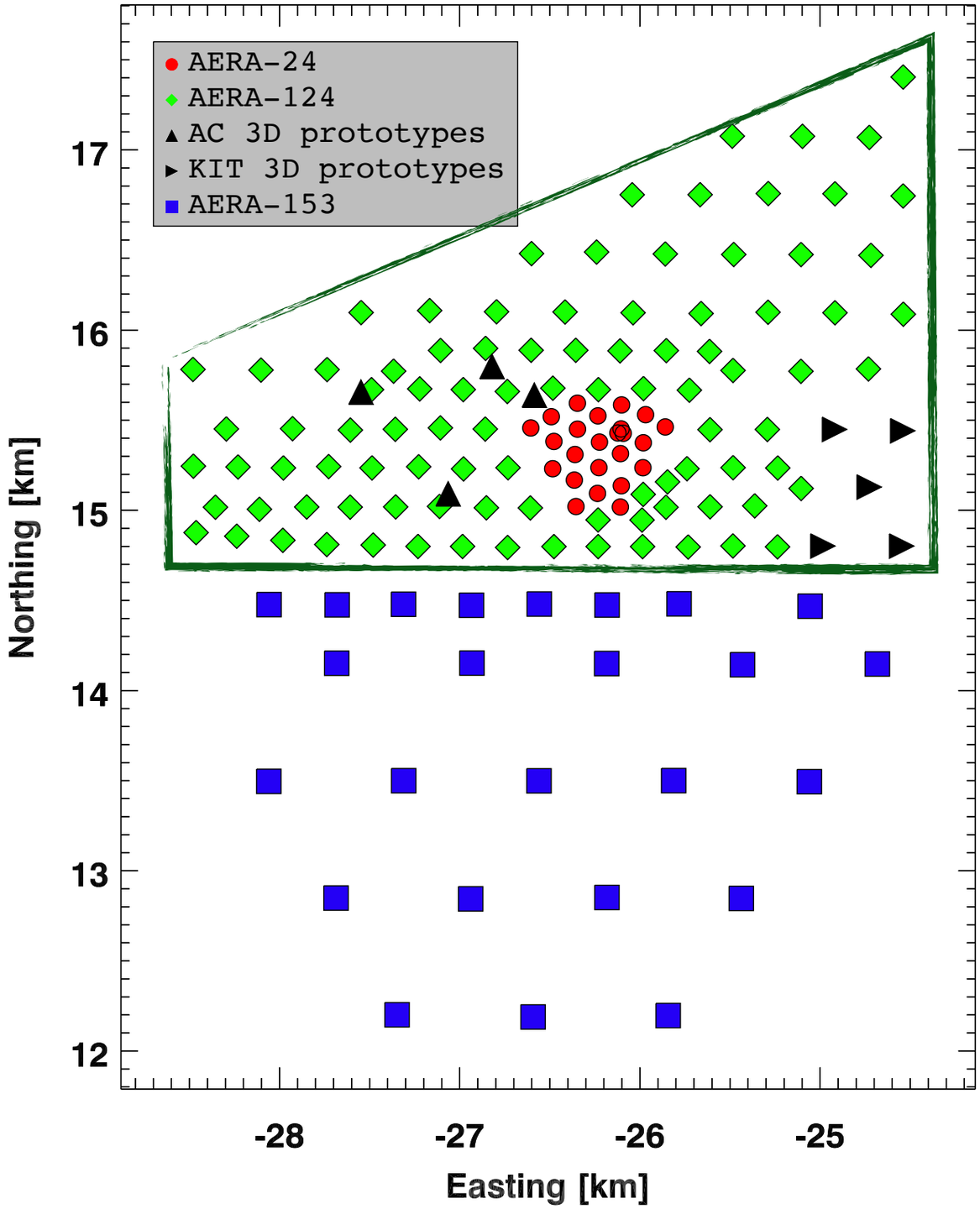


AERA

- **Deployment and spacing:**
  - **2011: Phase I - 24 stations - 144 m**
  - **2013: Phase II - 124 stations - 250 & 375 m**



butterfly antenna



AERA

- **Deployment and spacing:**
  - **2011: Phase I - 24 stations - 144 m**
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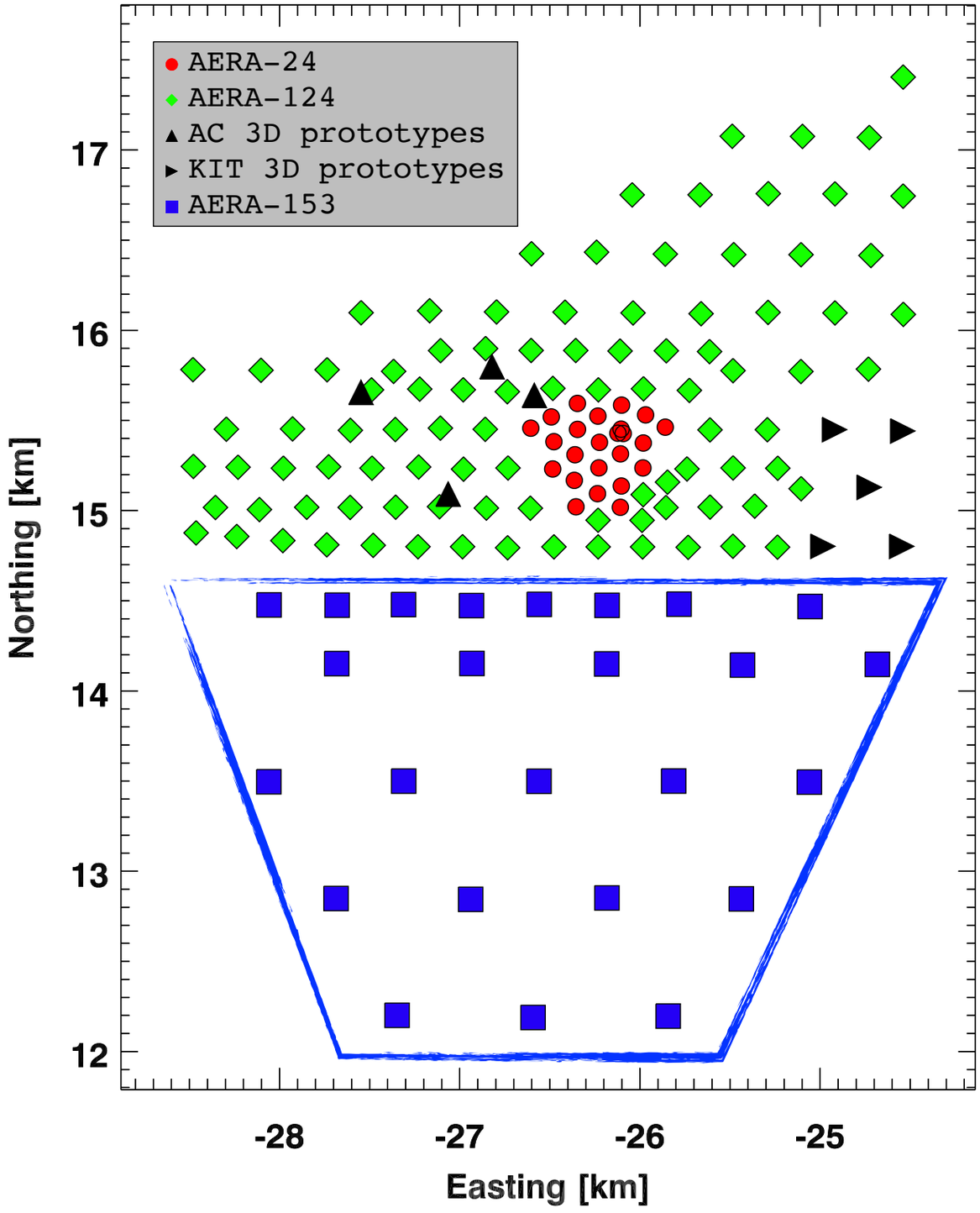
  - **2015: Phase III - 153 stations - 750 m**

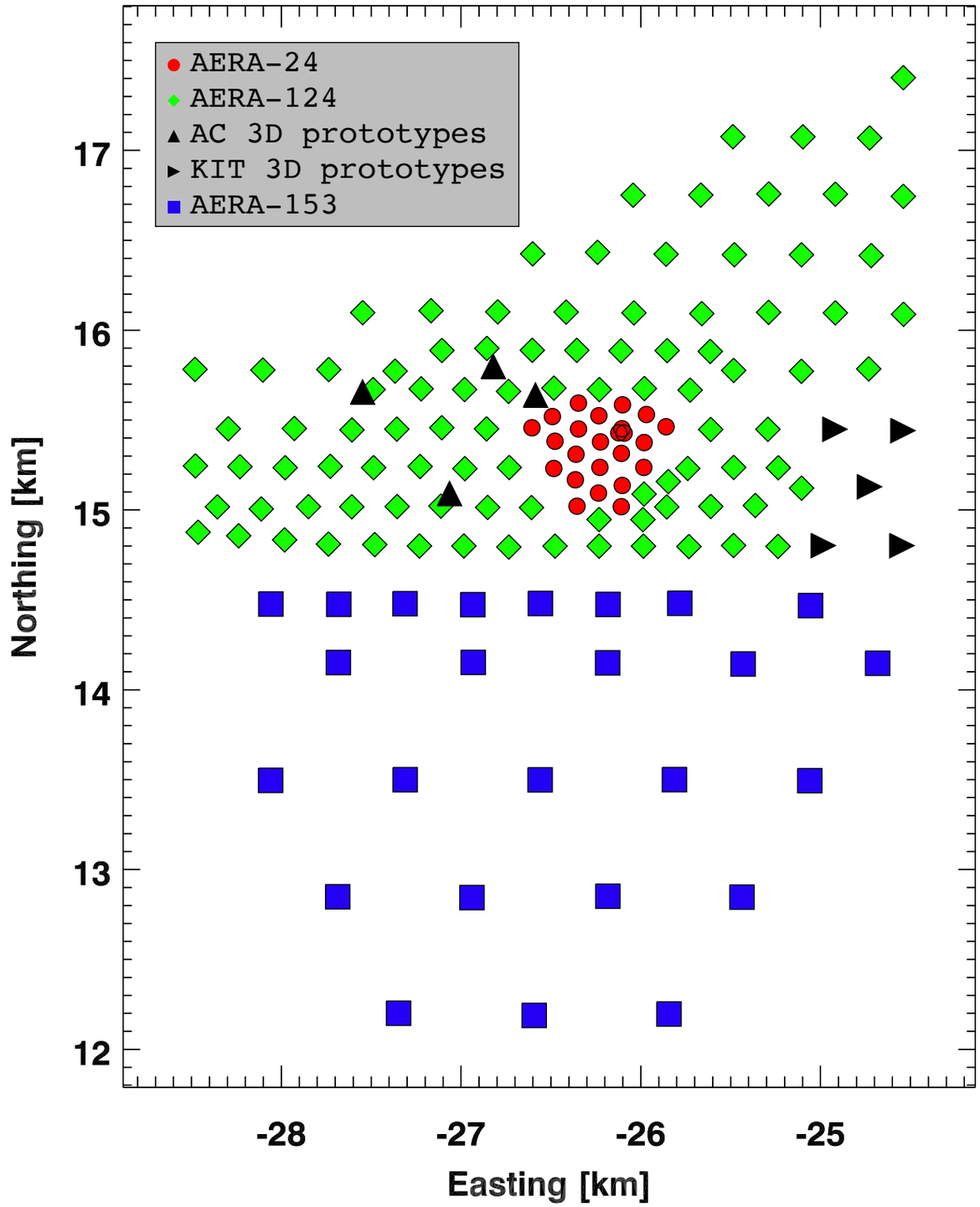
butterfly antenna



AERA

- Deployment and spacing:
  - 2011: Phase I - 24 stations - 144 m
  - 2013: Phase II - 124 stations - 250 & 375 m
  - 2015: Phase III - 153 stations - 750 m
- 153 radio stations on 17 km^2
- calibrated in time and amplitude
- duty cycle ~100%

- 30 - 80 MHz
- two horizontal polarizations
- energy range: E > 10^{17} eV
- shower physics:
  - arrival direction
  - core position
  - energy
  - mass composition



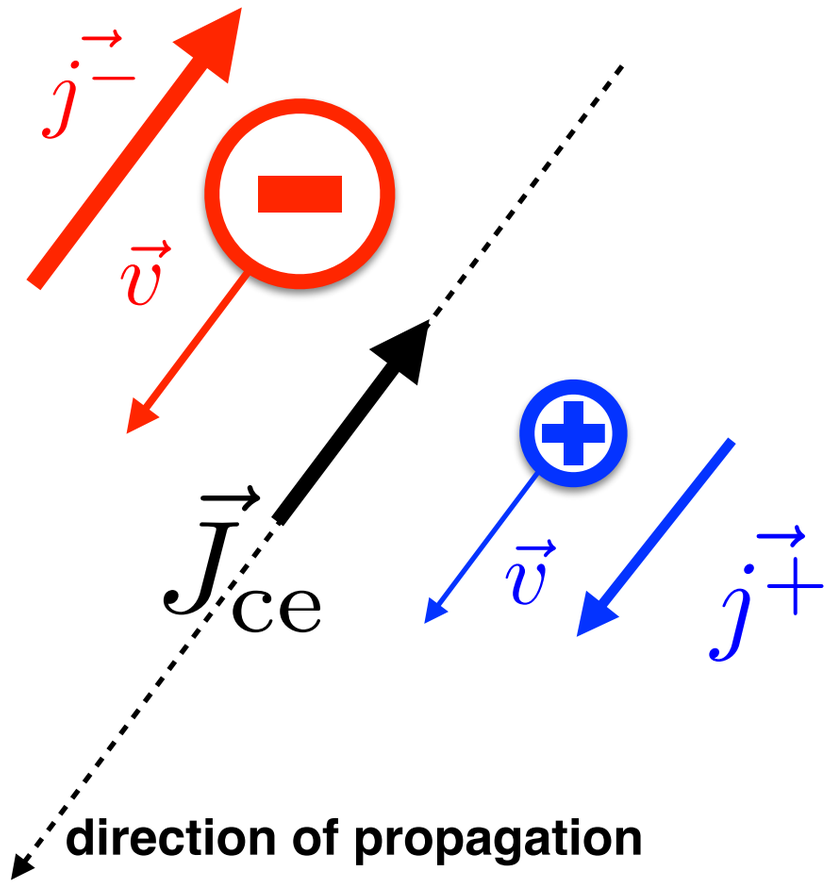
Emission mechanisms

- **Charge excess mechanism**

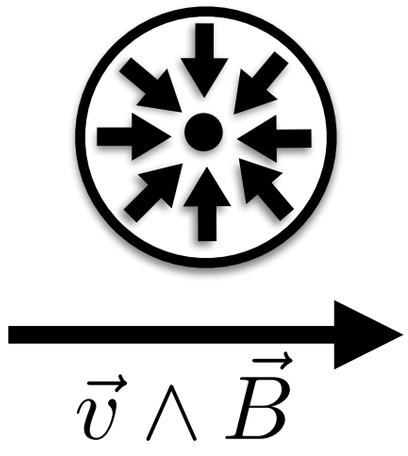
Excess of negative charges

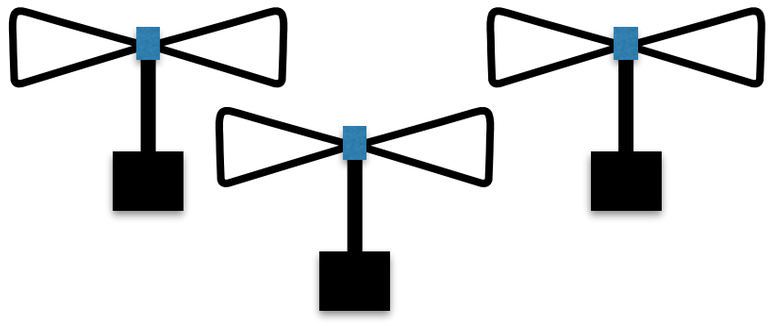
$$\vec{J}_{\rm ce} = \vec{j^-} + \vec{j^+}$$

$$\vec{E}_{\rm ce}(t) \propto \frac{\partial}{\partial t}\vec{J}_{\rm ce}(t)$$



Radially polarized around shower axis





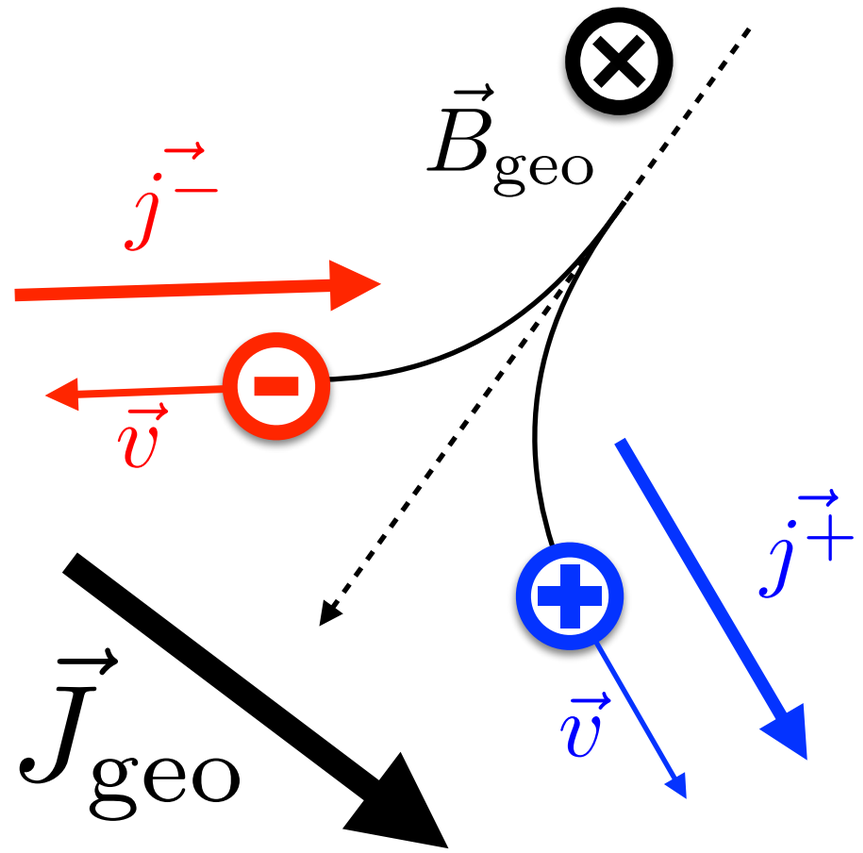
Emission mechanisms

- **Geomagnetic mechanism**

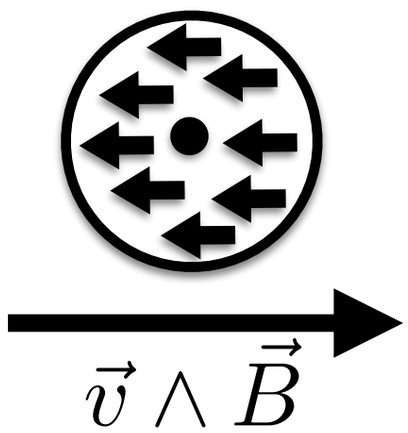
Lorentz force applied to secondary particles

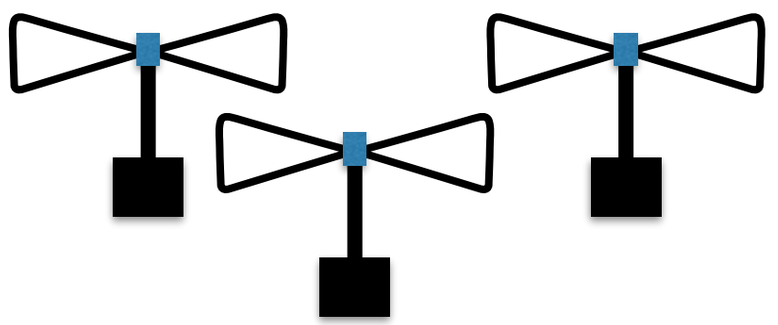
$$\vec{J}_{\mathrm{geo}} = \vec{j^-} + \vec{j^+}$$

$$\vec{E}_{\mathrm{geo}}(t) \propto \frac{\partial}{\partial t}\vec{J}_{\mathrm{geo}}(t)$$



Polarized in the direction of the Lorentz force



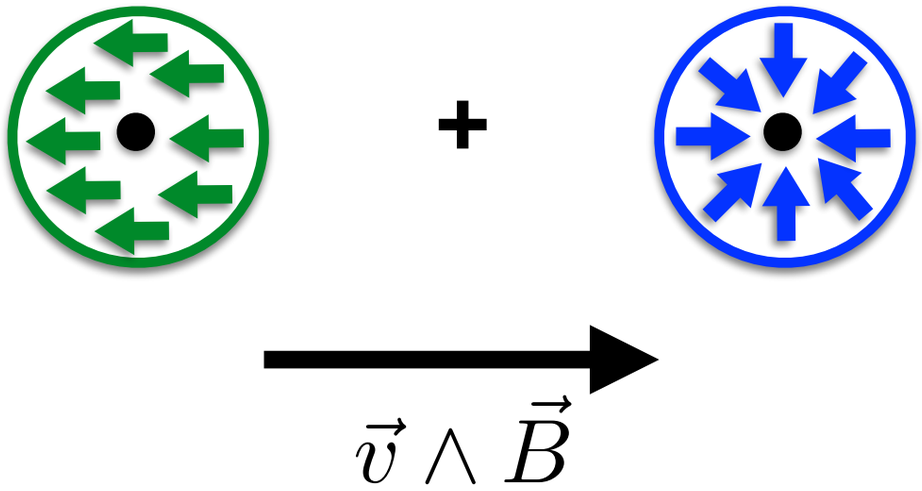


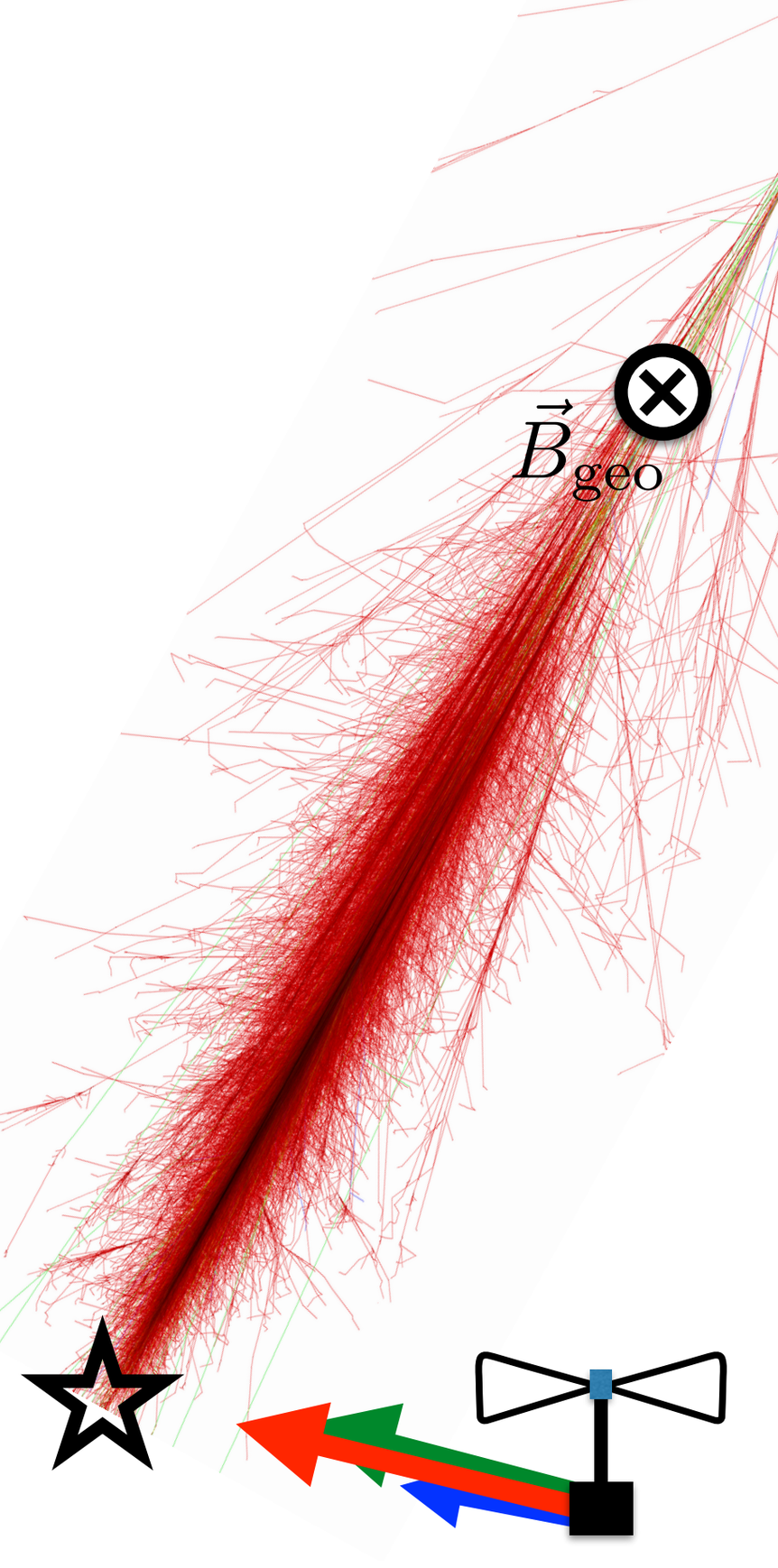
Emission mechanisms

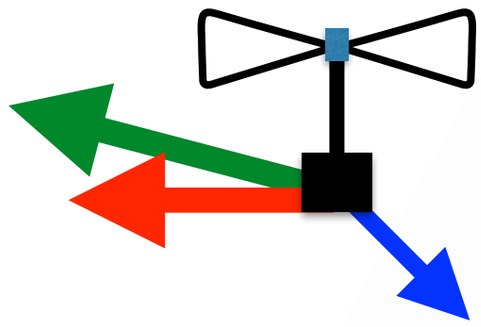
- **Total electric field**

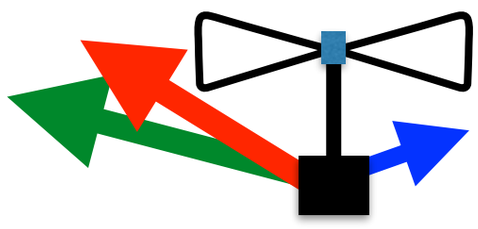
composition of the two effects

geomagnetic **charge excess**









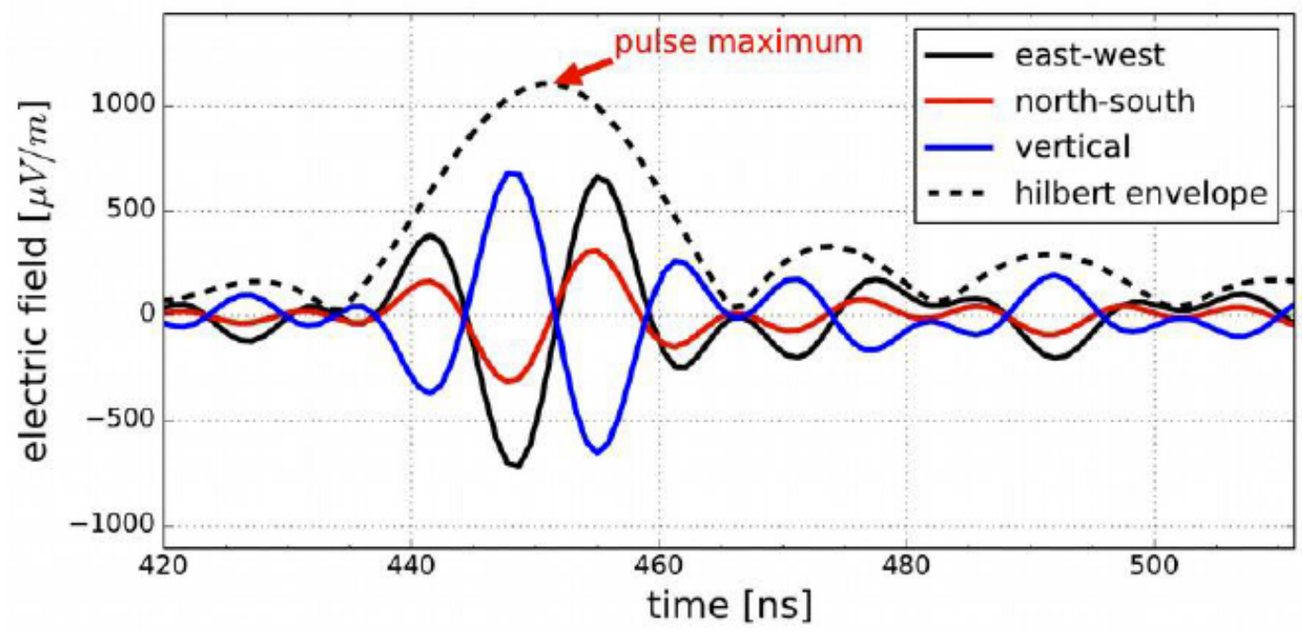
leads to asymmetry around the shower axis and complex pattern at the ground level:

Energy measurement

compute the total electric field from the three polarization components

with vertical polarization from the arrival direction

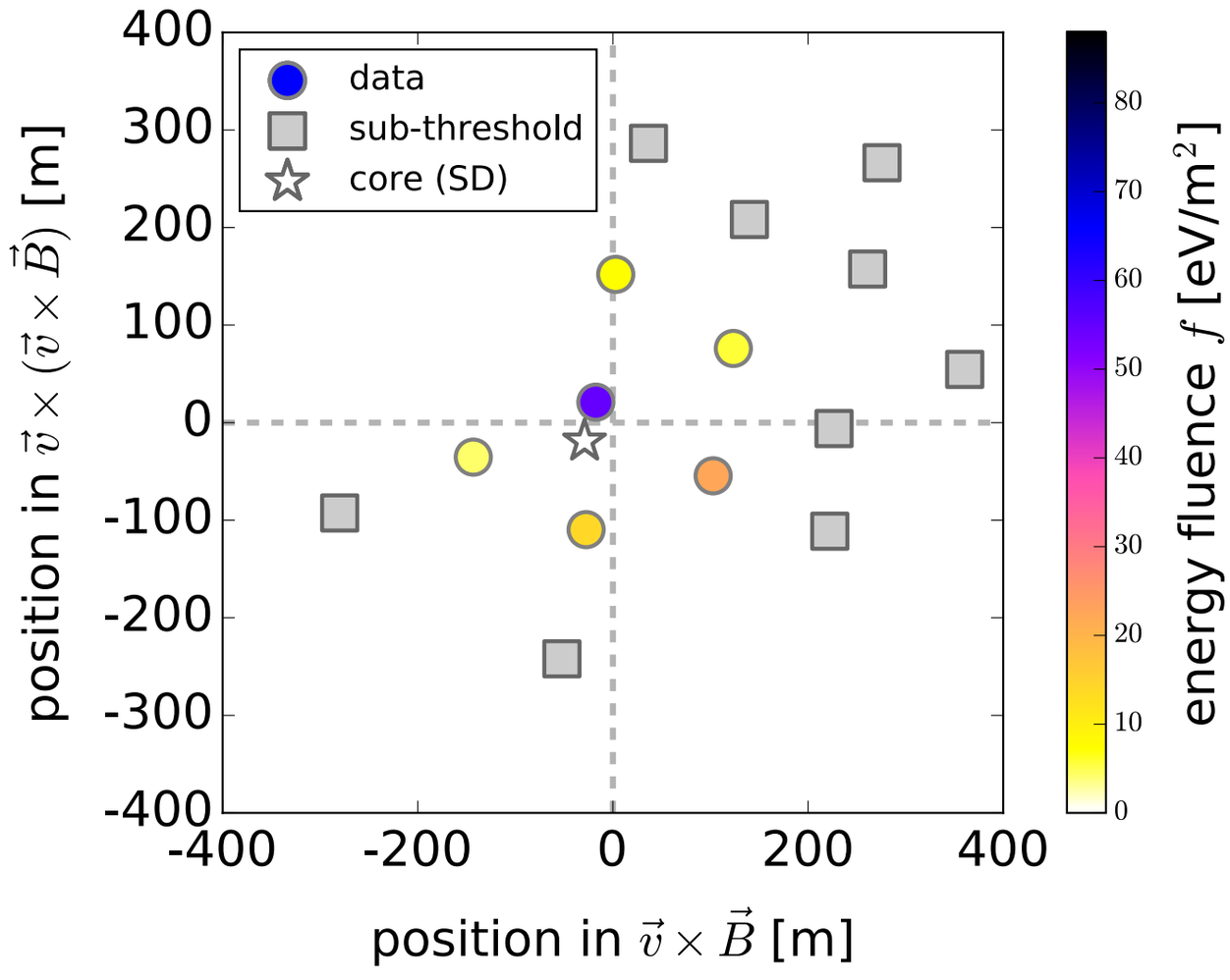
electric field Vs time



energy estimator calculated for all stations

Integration of the Poynting vector over time

energy fluence (eV/m²)

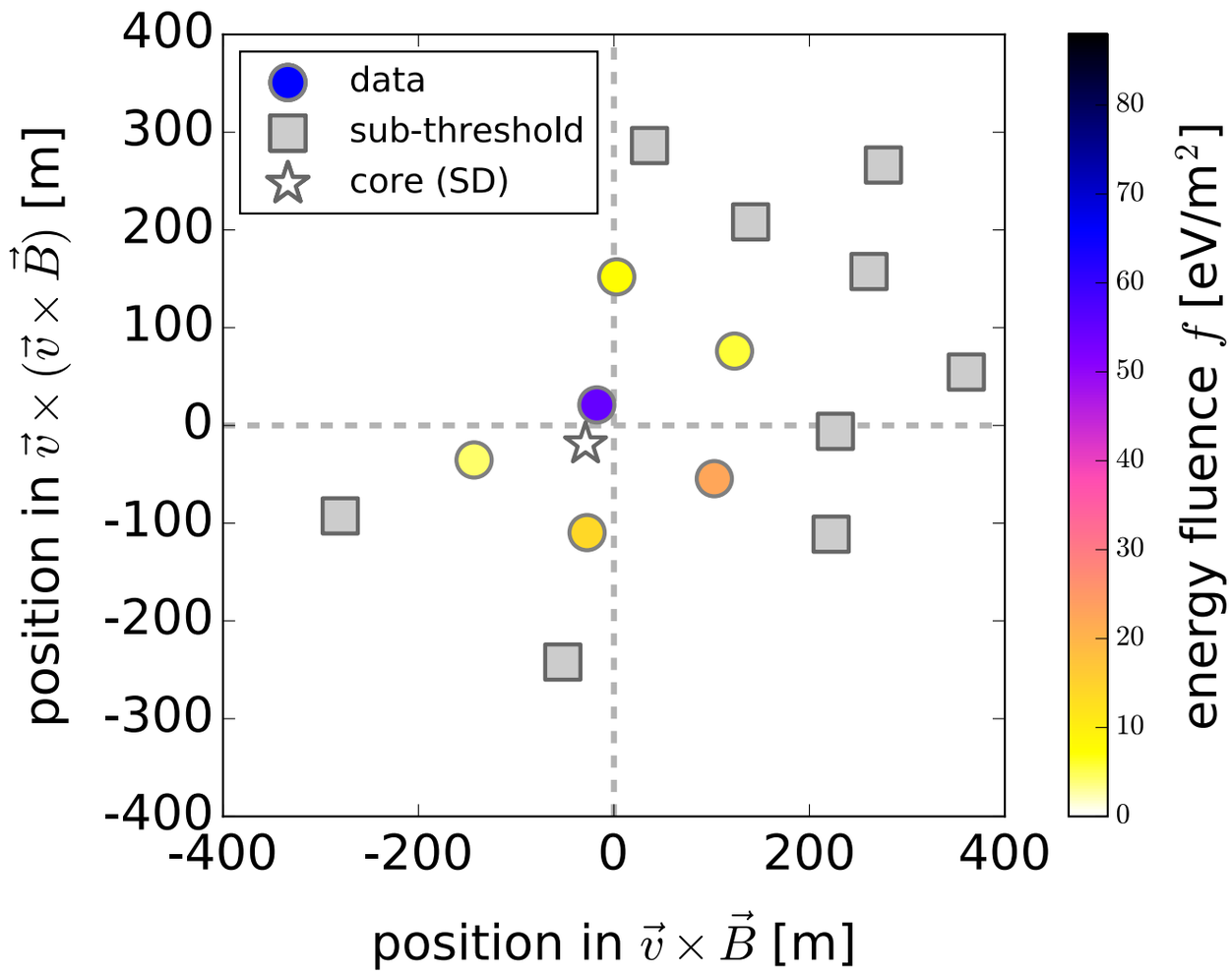


Energy measurement

Fit a 2D model that accounts for asymmetry around the shower axis

$$\mathrm{LDF}(\mathbf{r}) = A\left[\exp\left(\frac{-(\mathbf{r}+C_1\mathbf{e}_{\mathbf{v}\times\mathbf{B}}-\mathbf{r}_{\mathrm{core}})^2}{\sigma}\right) - C_0\exp\left(\frac{-(\mathbf{r}+C_2\mathbf{e}_{\mathbf{v}\times\mathbf{B}}-\mathbf{r}_{\mathrm{core}})}{(C_3 e^{C_4\sigma})^2}\right)\right]$$

Nelles et al., Astropart. Phys. 60, 13 (2015)



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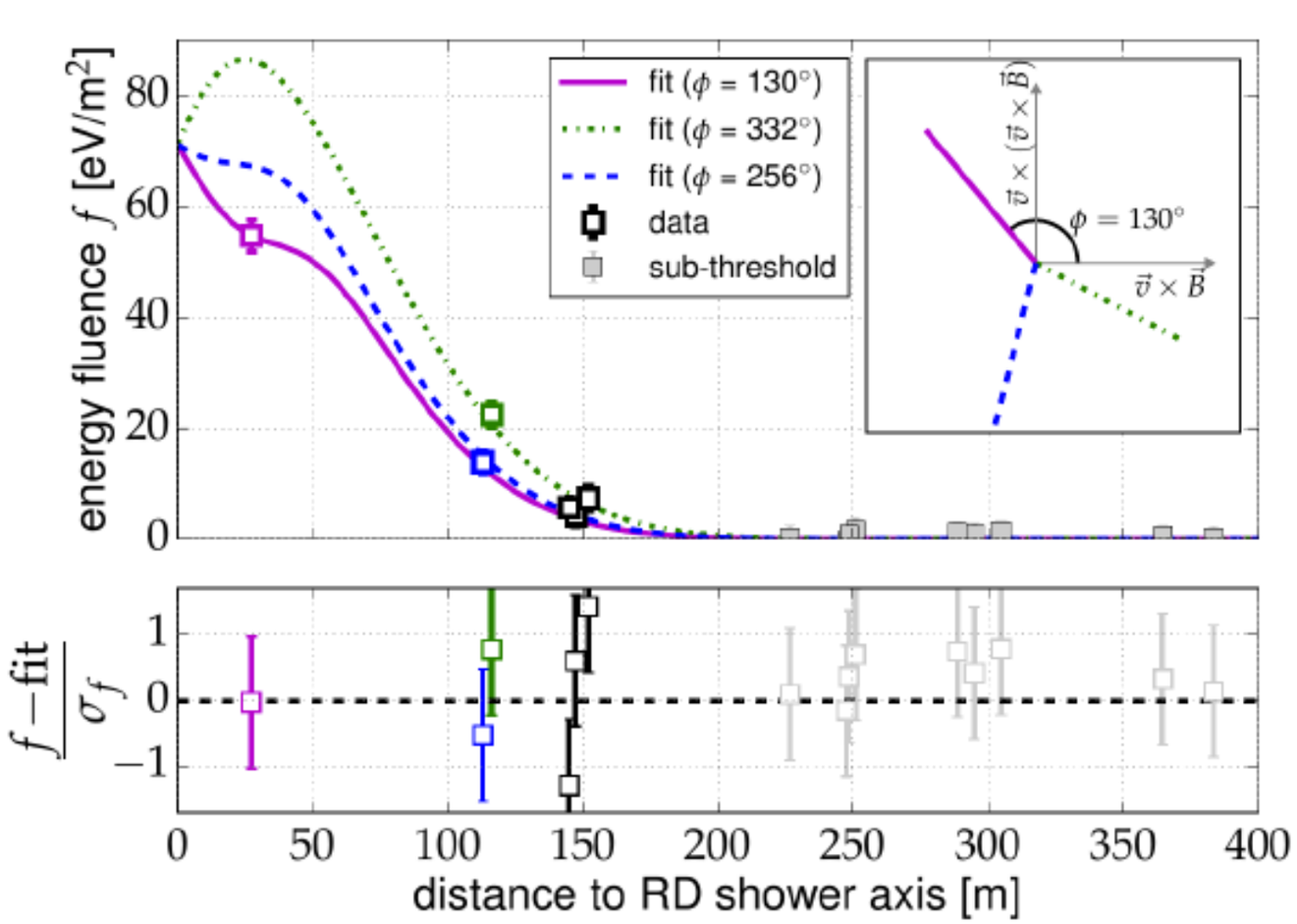

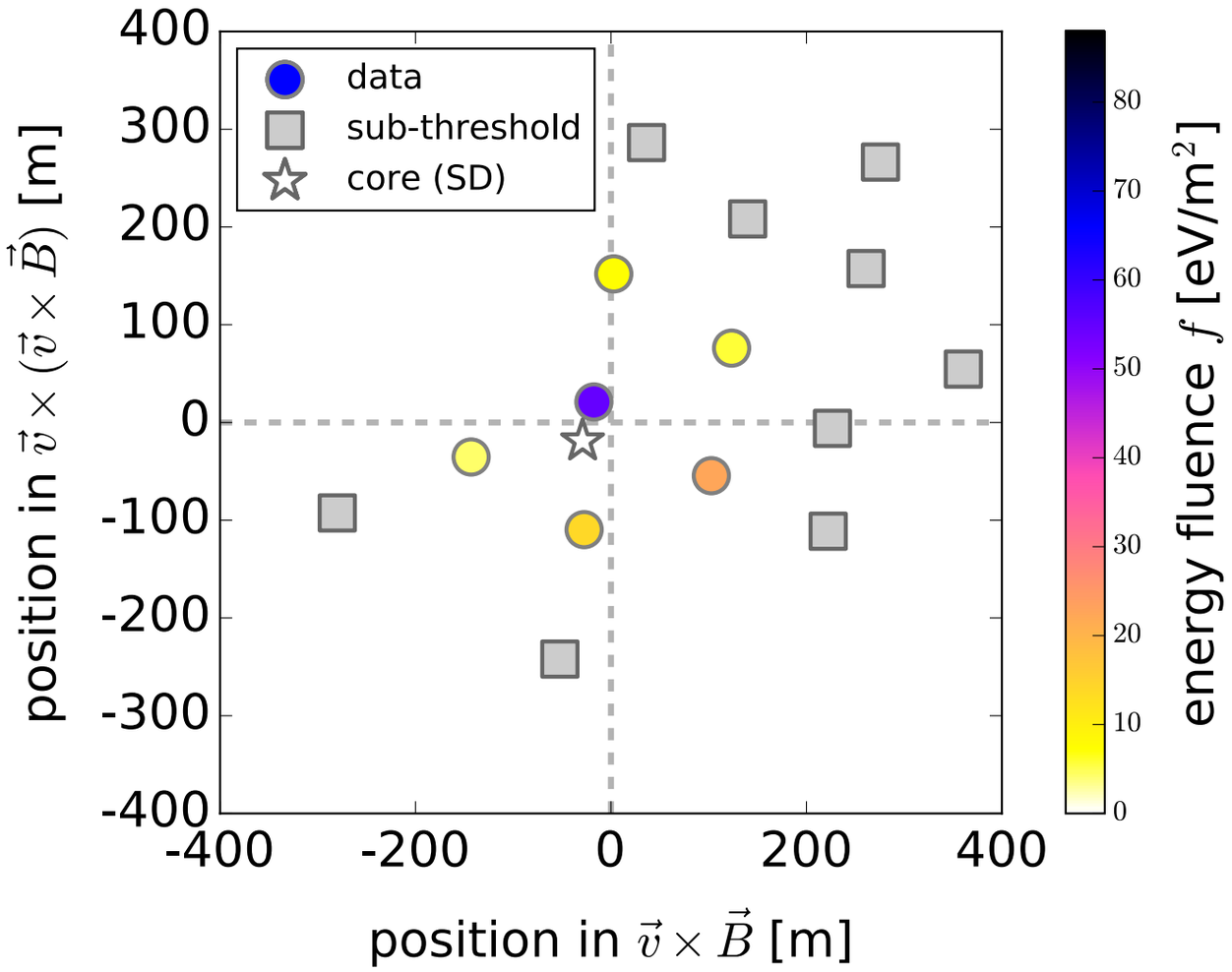

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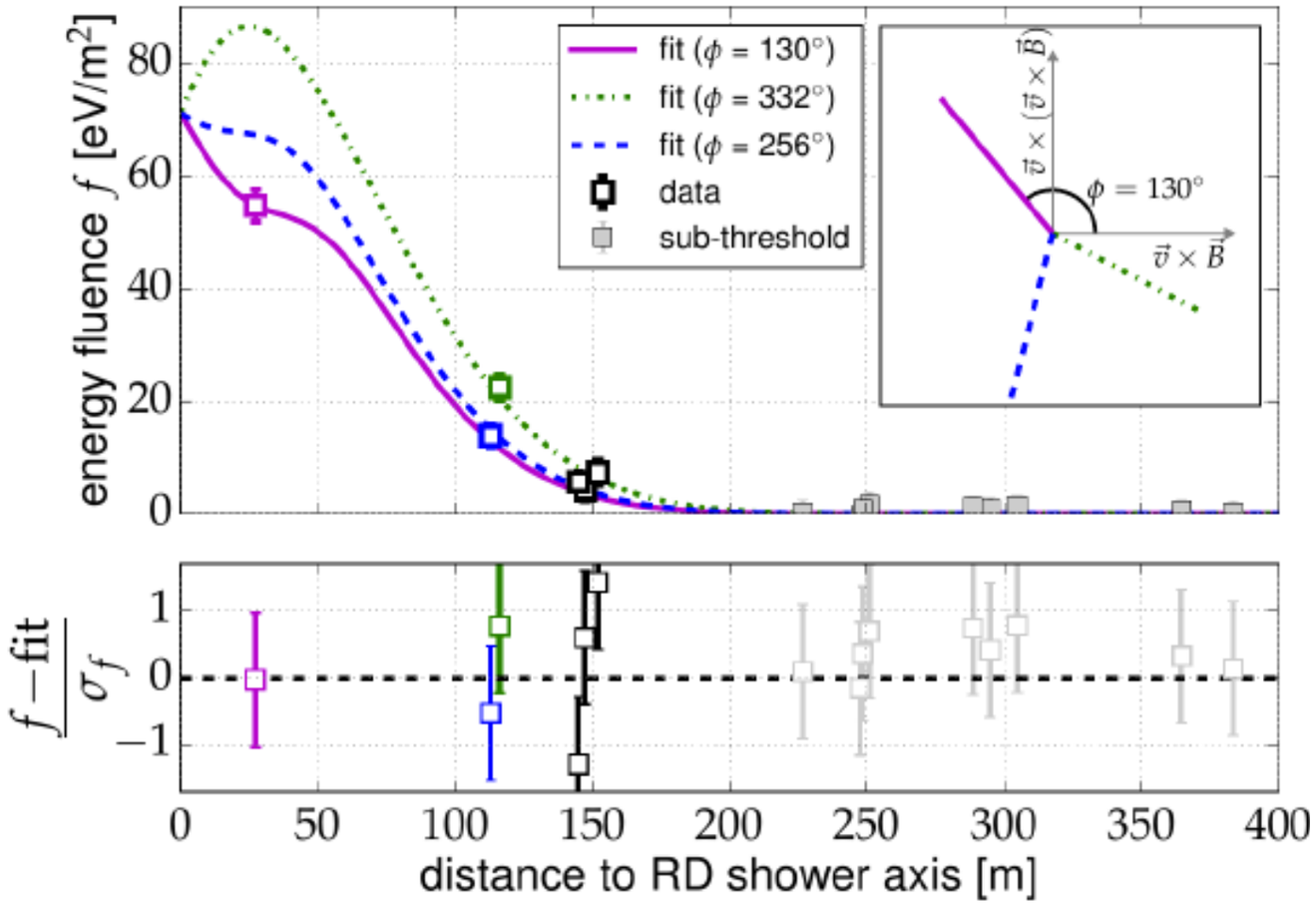
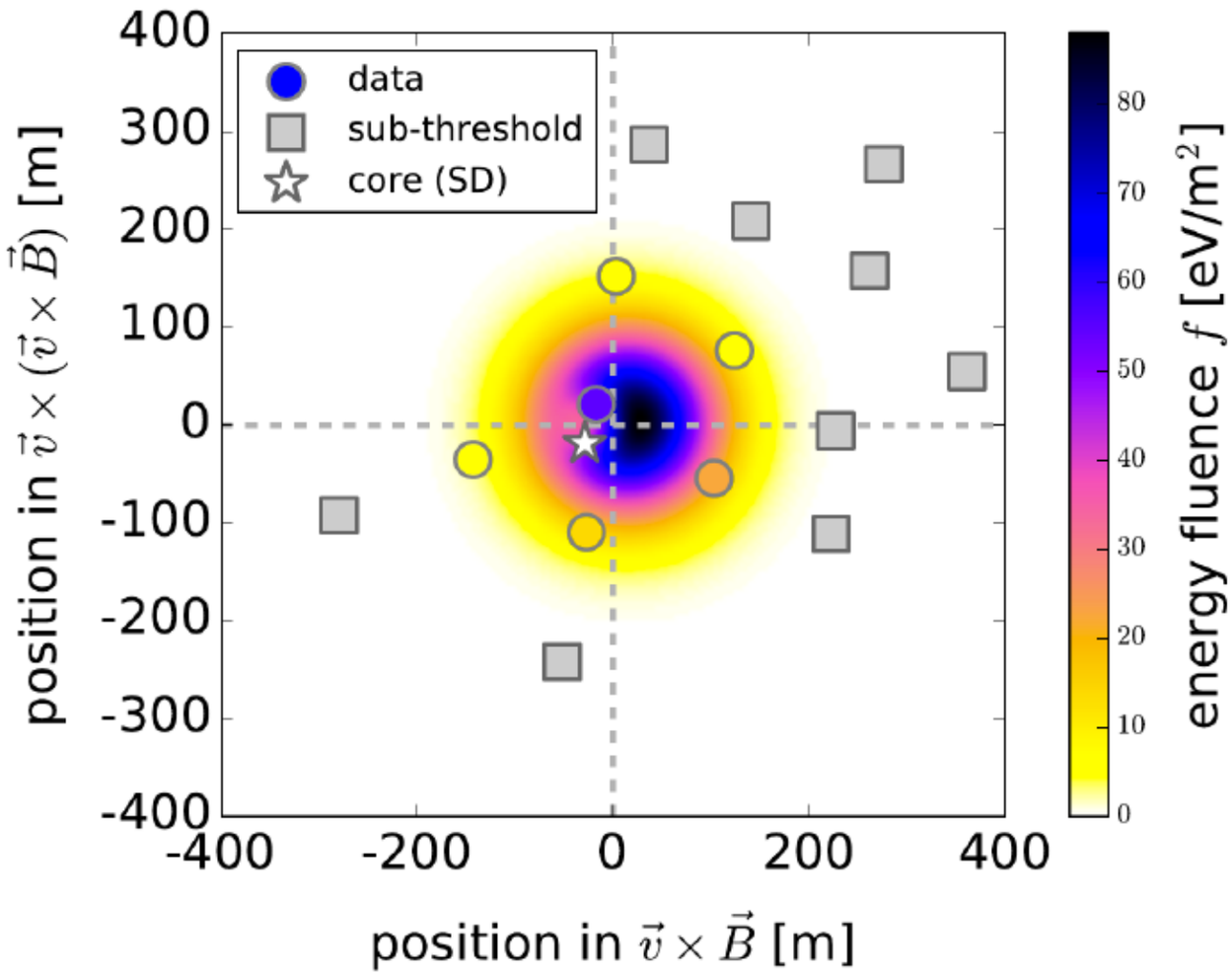
$$E_{\mathrm{radio}} = \iint \mathrm{LDF}(x,y)\,\mathrm{d}x\,\mathrm{d}y$$

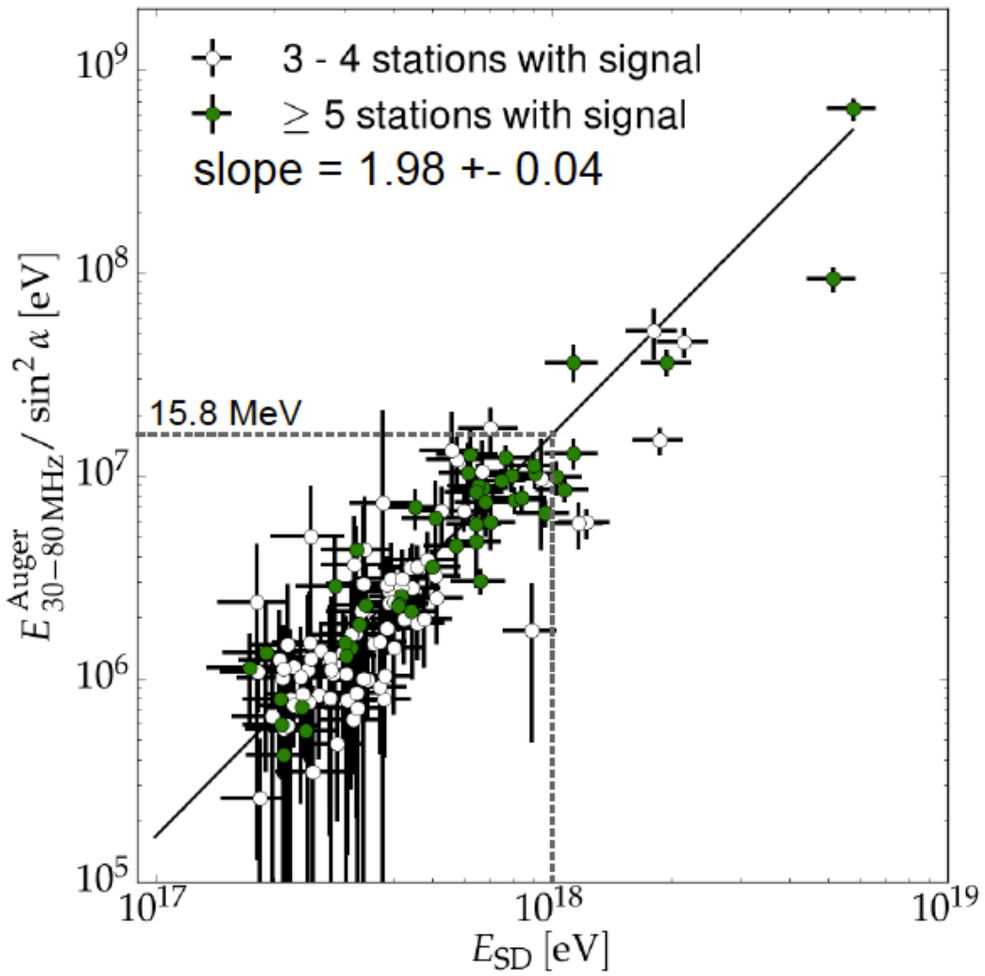


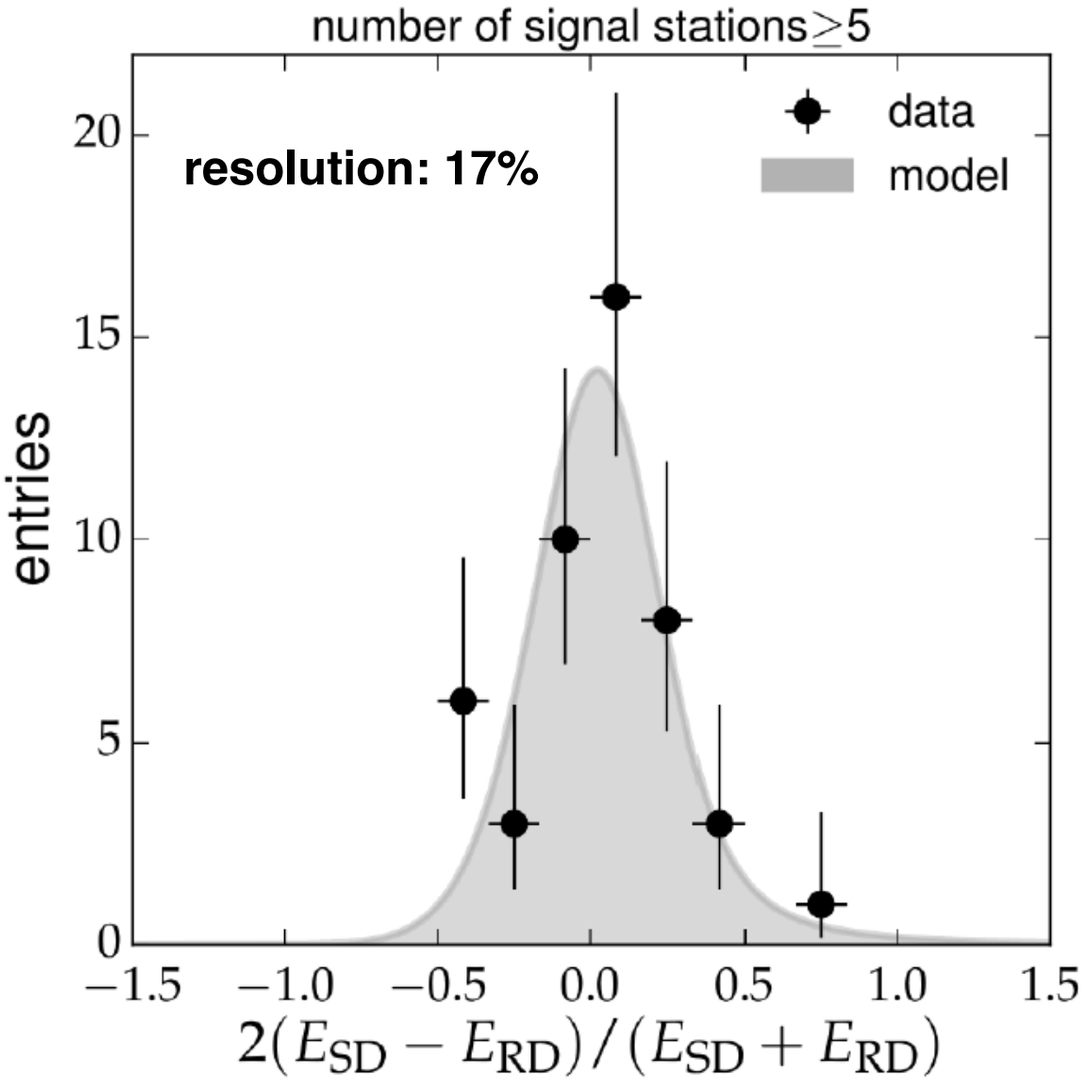


Energy measurement

Correlation between the deposited radio energy and SD energy for coincident measurements

Auger collab., PRL 116, 241101 (2016)
Auger collab., PRD 93, 122005 (2016)

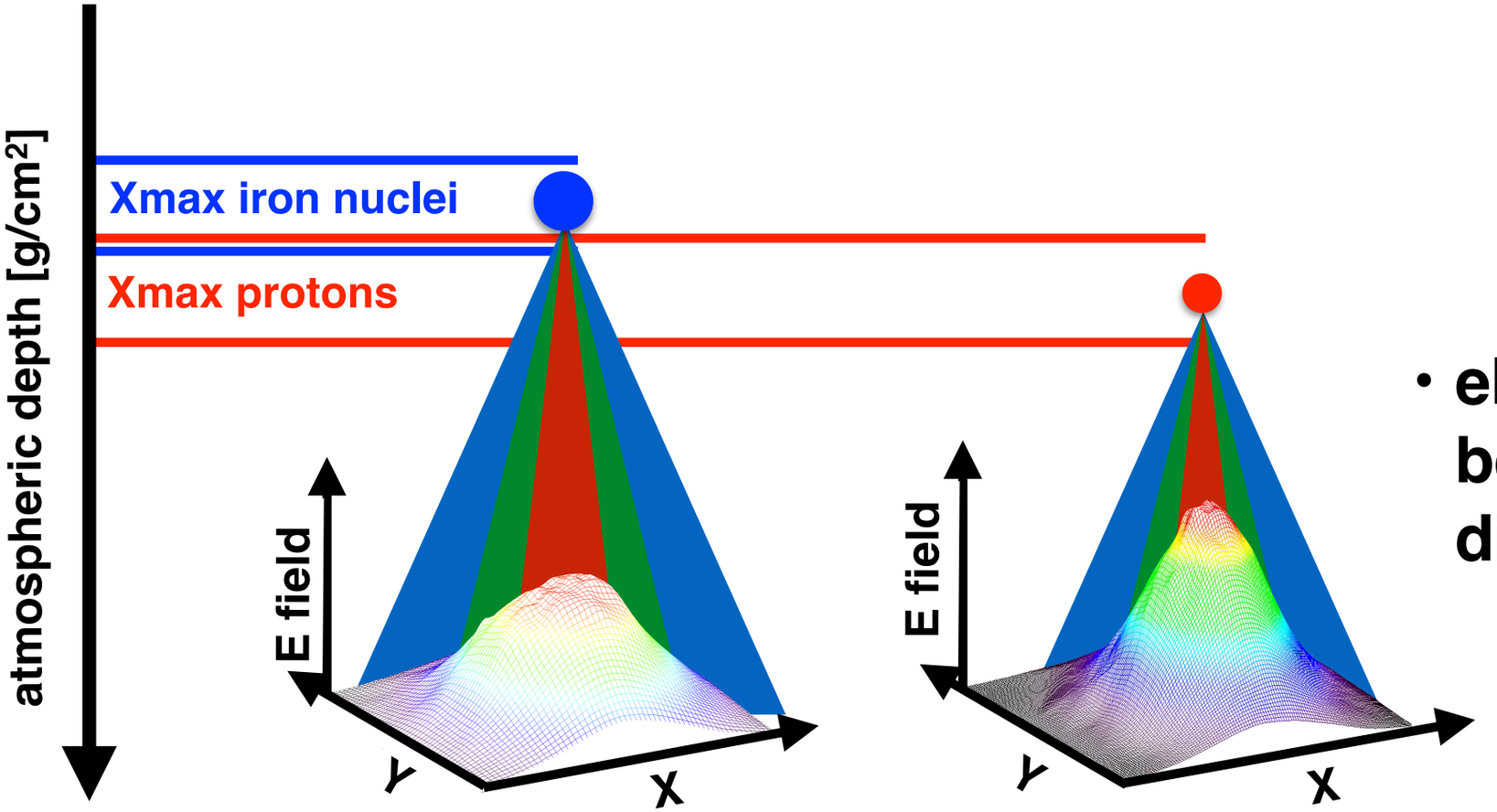




Energy measurement from radio signal!

Mass composition

- Xmax correlated to the mass of the primary

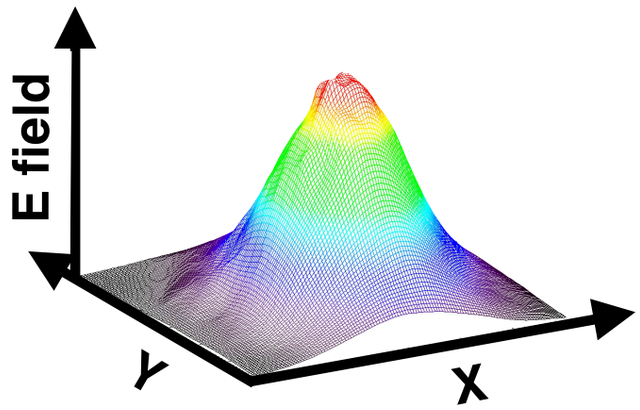


- electric field highly beamed toward the direction of propagation

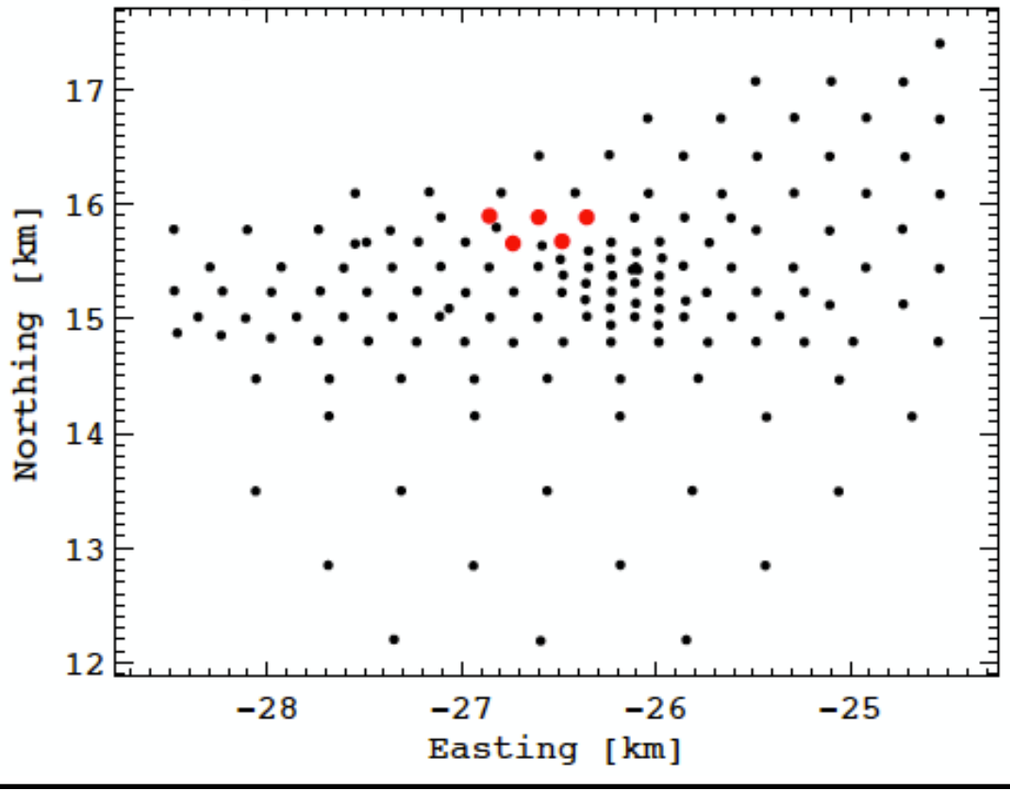
- strong correlation between the LDF and Xmax
- Xmax reconstruction from the amplitude or energy fluence with a duty cycle close to 100% (14% for fluorescence)

Mass composition

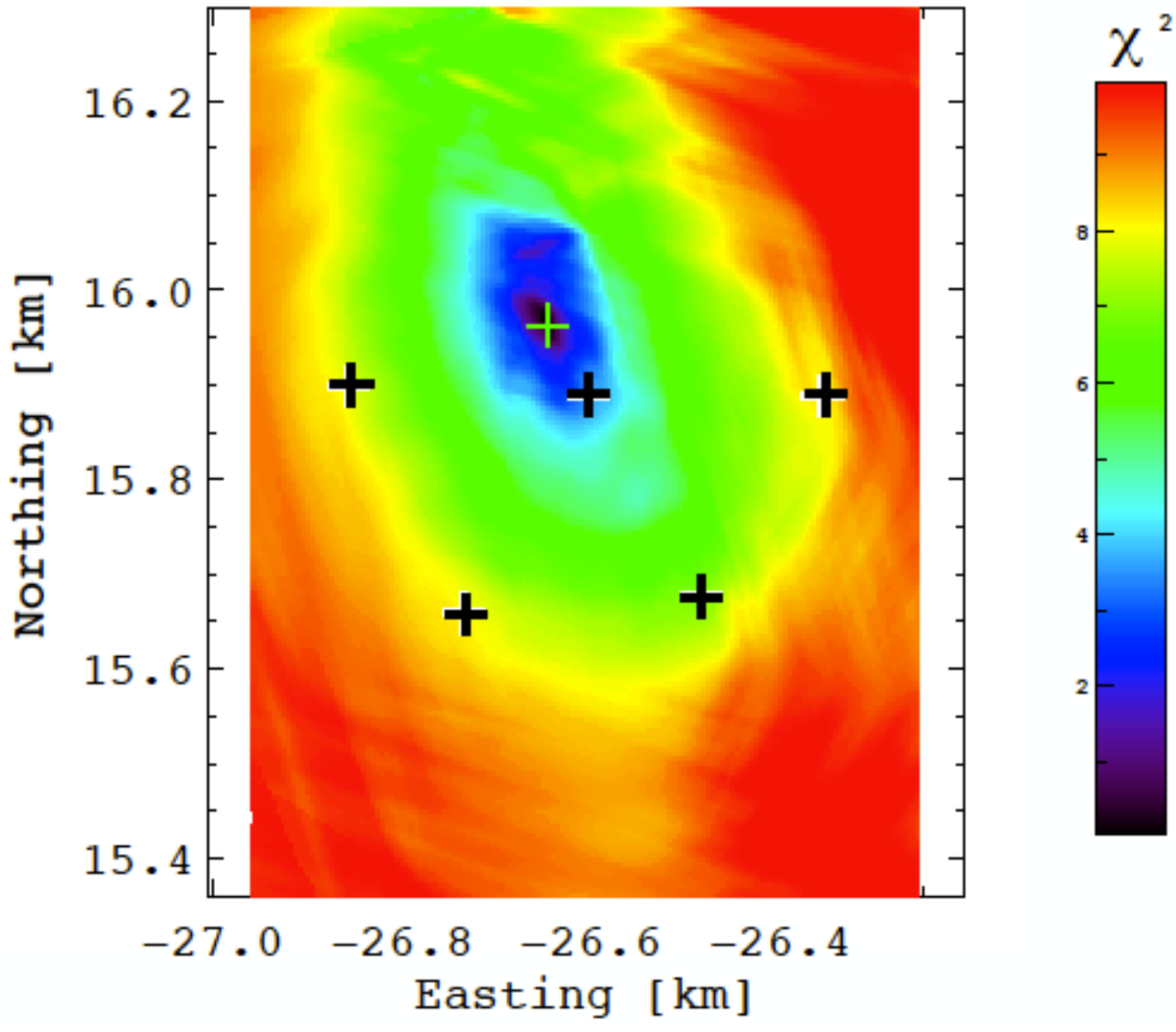
- Simulation of few LDF (radio arrival direction)



- compare simulation to data

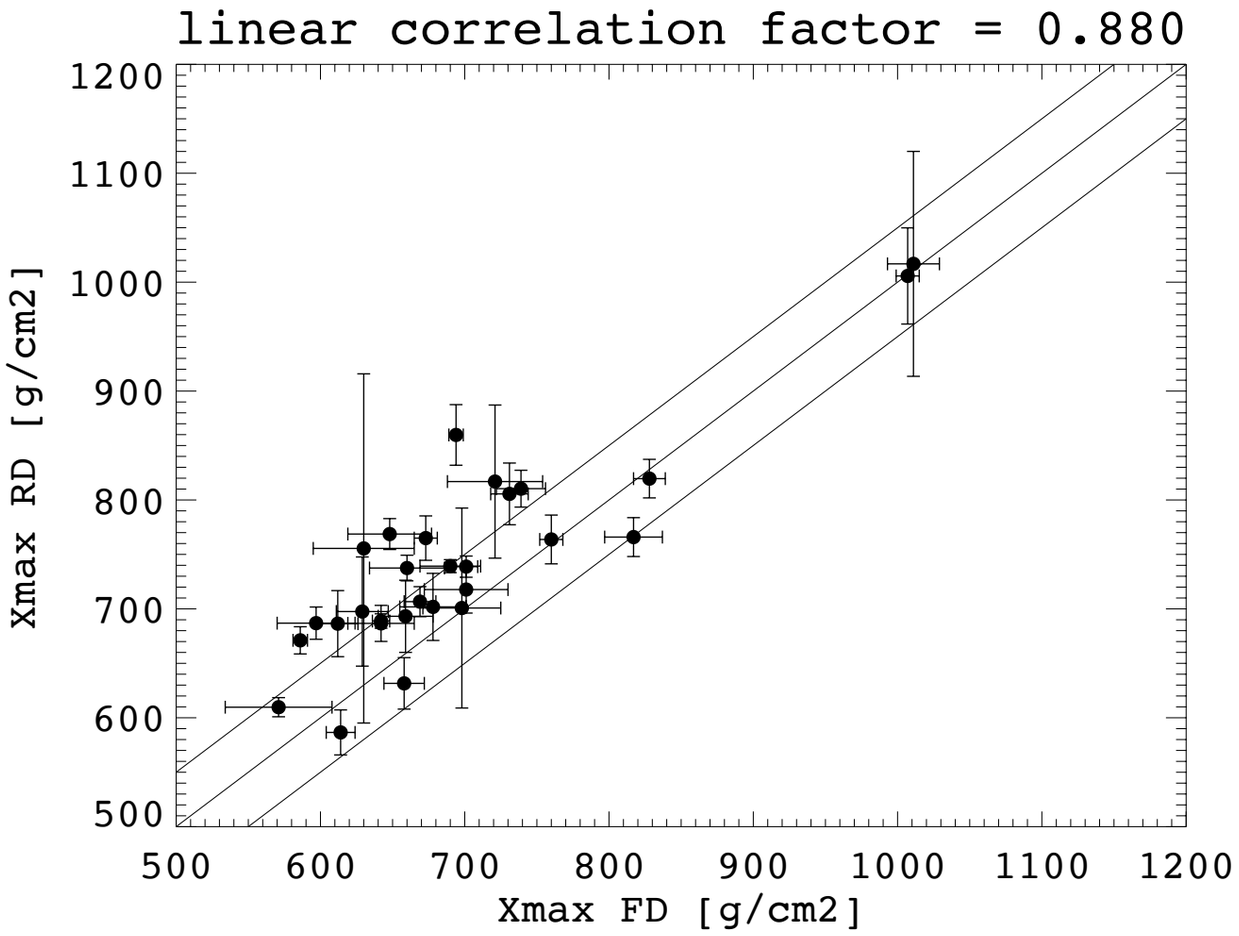


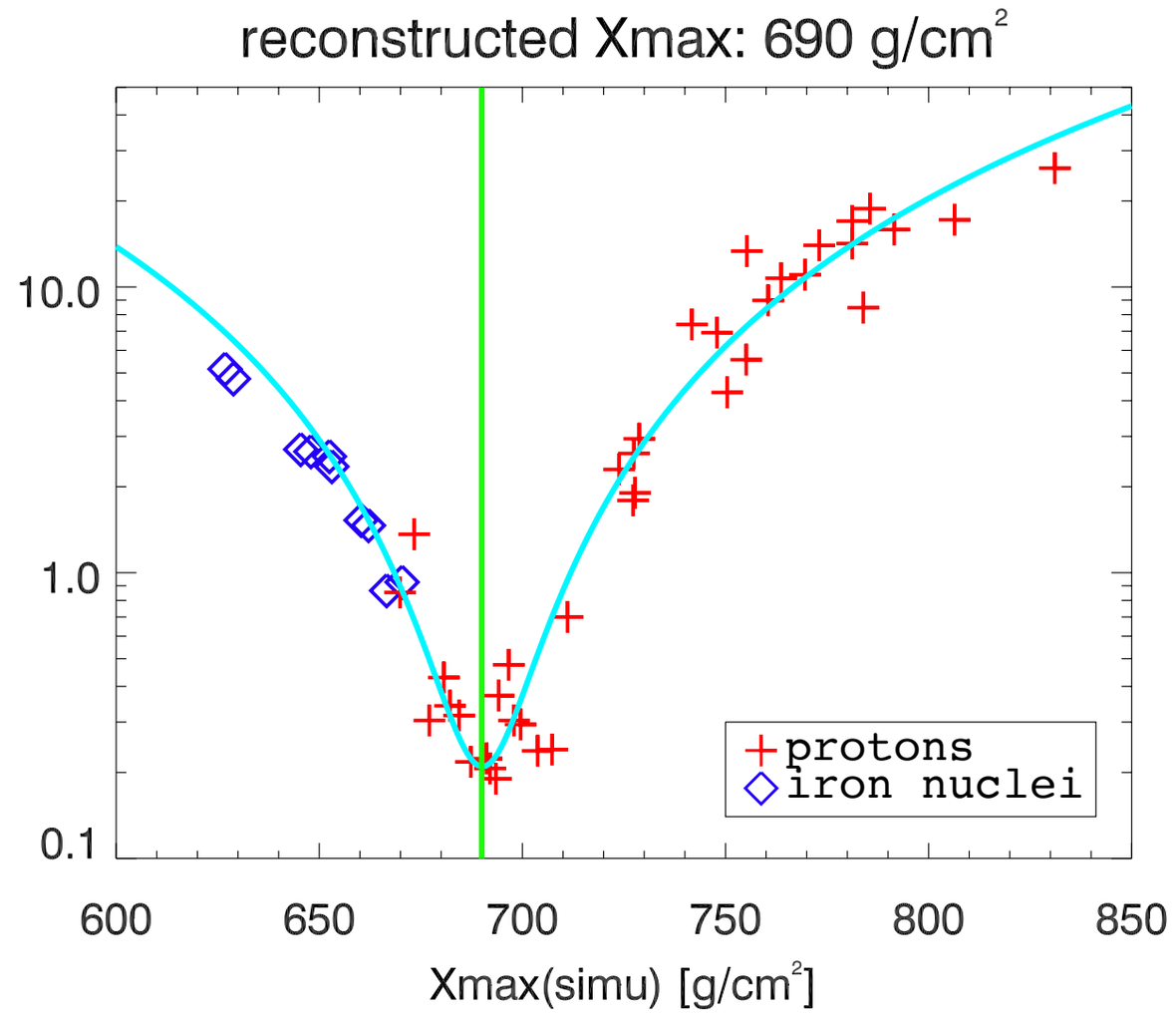
- the agreement is tested for different locations of the simulated core position to find best core position



Mass composition

- **Montecarlo on Xmax values**
- **Best agreement for an optimal Xmax**
- **Comparison to FD measurements**





- **4 methods developed for AERA**
- **width of the residuals ~40g/cm²**

Conclusions

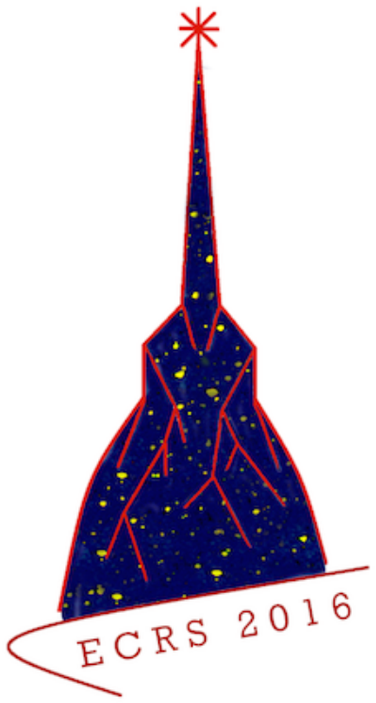
- **AERA produces high-quality data in coincidence with the fluorescence and ground detectors**

- **The emission mechanisms of the radio signal are now well understood**

- **Energy:**
  - **the primary energy is partly released as radiation energy in a calorimetric way**
  - **the energy resolution using the radio signal is 17%**
  - **this provides a new independent energy scale for CR experiments**

- **Composition:**
  - **we work on systematic Xmax reconstruction with a 100% duty cycle**
  - **The expected resolution is of 40 g/cm^2**

- **Current analysis are focused on determining the energy spectrum and mass composition in the transition region**

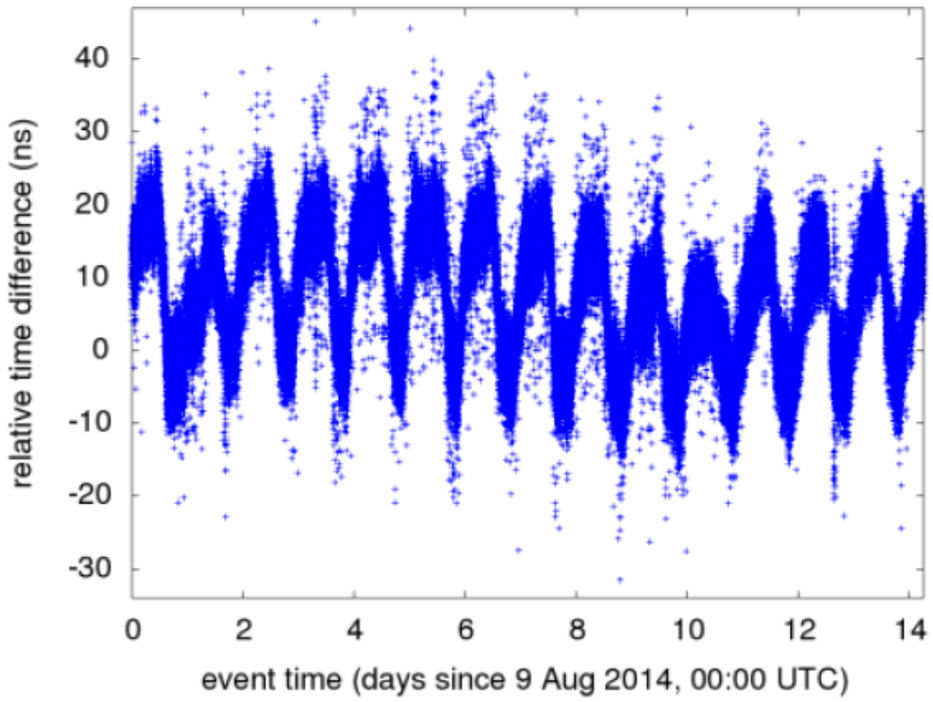


Thank you for your attention!

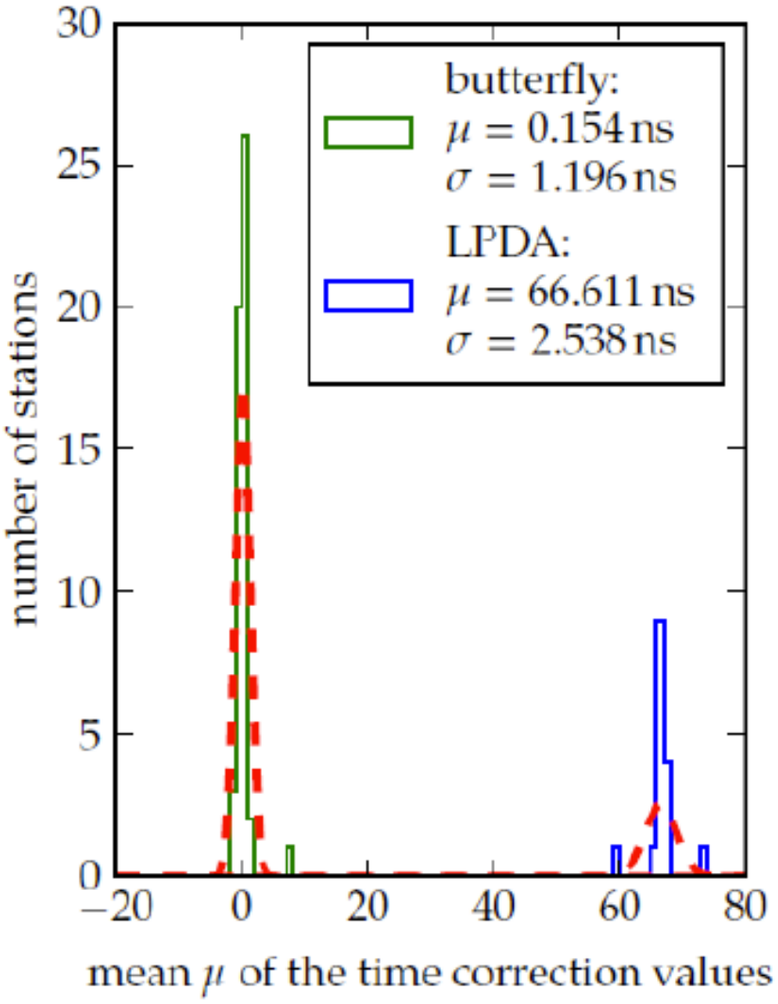
Time calibration

- **Beacon method:**

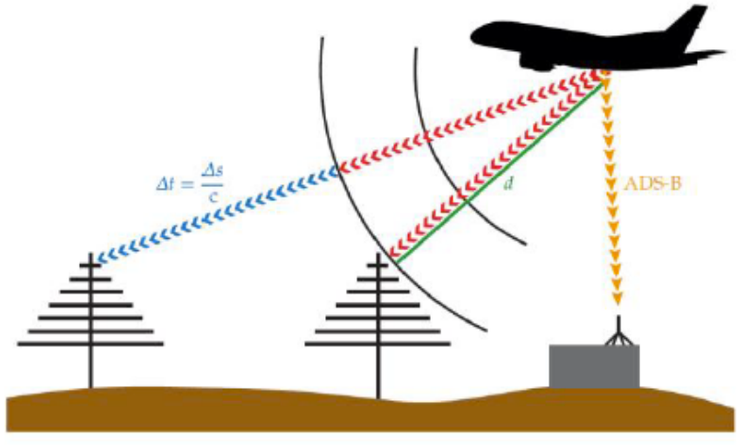
  frequencies:
  58MHz, 61MHz,
  68MHz, 71MHz

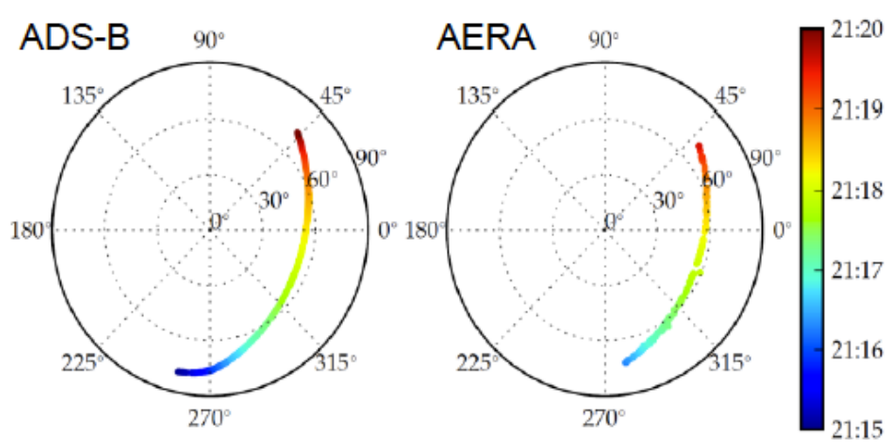


Auger collab. JINST 11 (2016) P01018



- **Air plane method: ADS-B + radio signal from air plane**

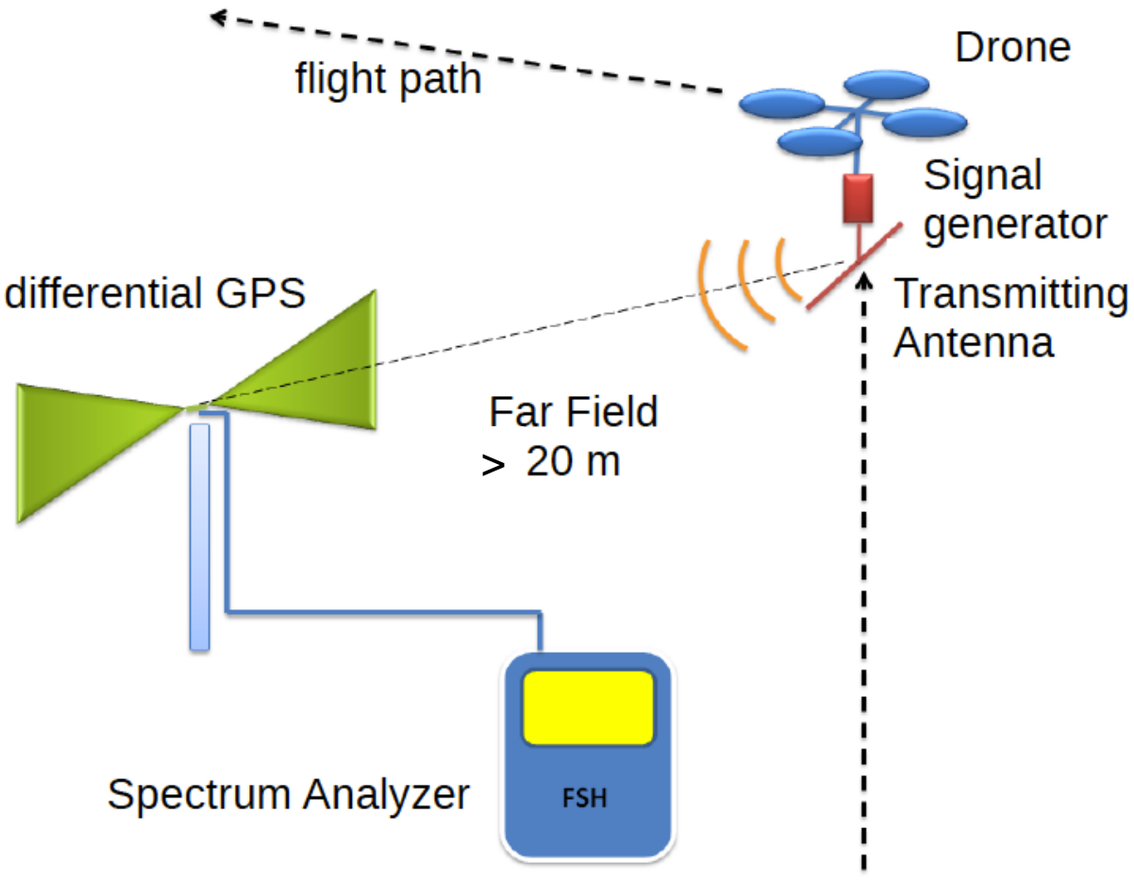




overall time precision
2 ns

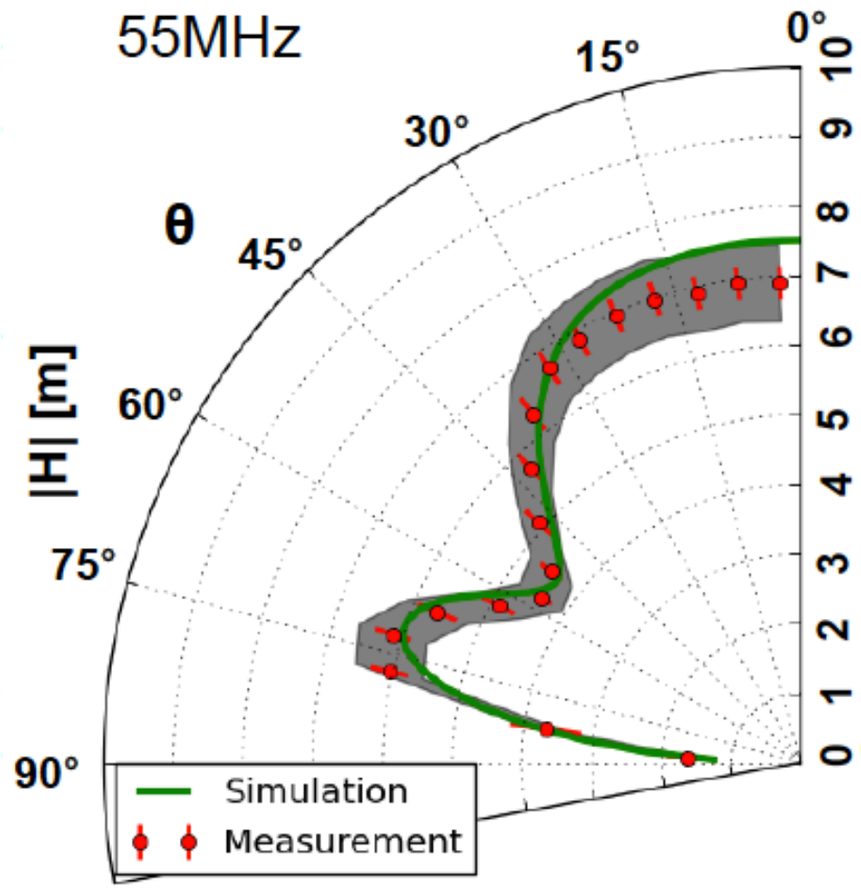
Amplitude calibration

- **Direct calibration using a pulser on a drone**



vector effective length:

$$V = \vec{H}(f, \theta, \phi) \cdot \vec{E}(f)$$



overall uncertainty: 14% (antenna response + full electronics chain)

Energy measurement

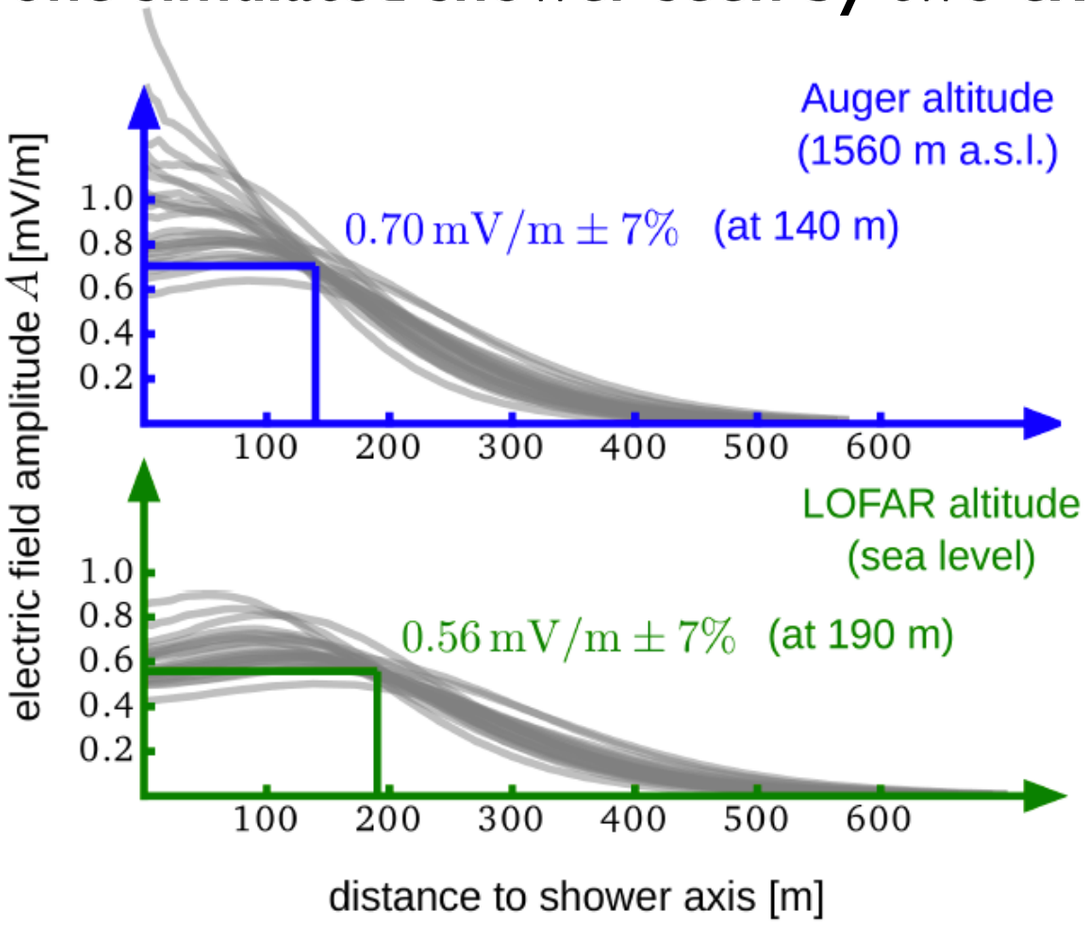
this provides a calorimetric energy estimation from the radiated energy in [30-80] MHz:

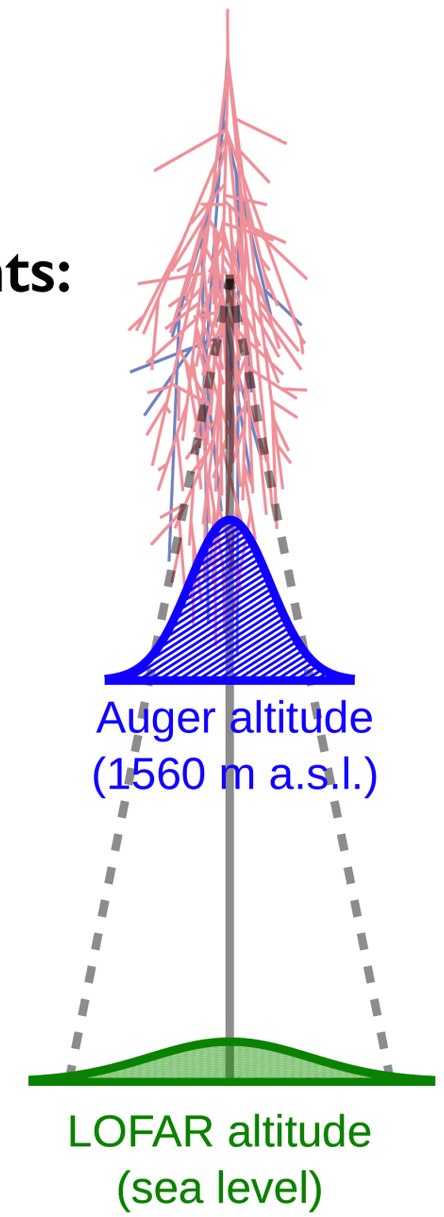
$$E_{[30;80]\ \mathrm{MHz}} = 15.8\ \mathrm{MeV} \left(\sin\alpha \frac{E}{1\ \mathrm{EeV}} \frac{B}{0.24\ \mathrm{G}} \right)^2$$

Auger collab., PRL 116, 241101 (2016)
Auger collab., PRD 93, 122005 (2016)

- **allows to calibrate the detector**
- **allows to cross-calibrate various CR experiments**
- **universal method as the atmosphere is transparent to radio waves and first principles based method**

one simulated shower seen by two experiments:





two different amplitudes at two different optimal axis distances!

but the same radiated energy: 11.9 MeV