Exploiting the radio signal from air showers: the AERA progress

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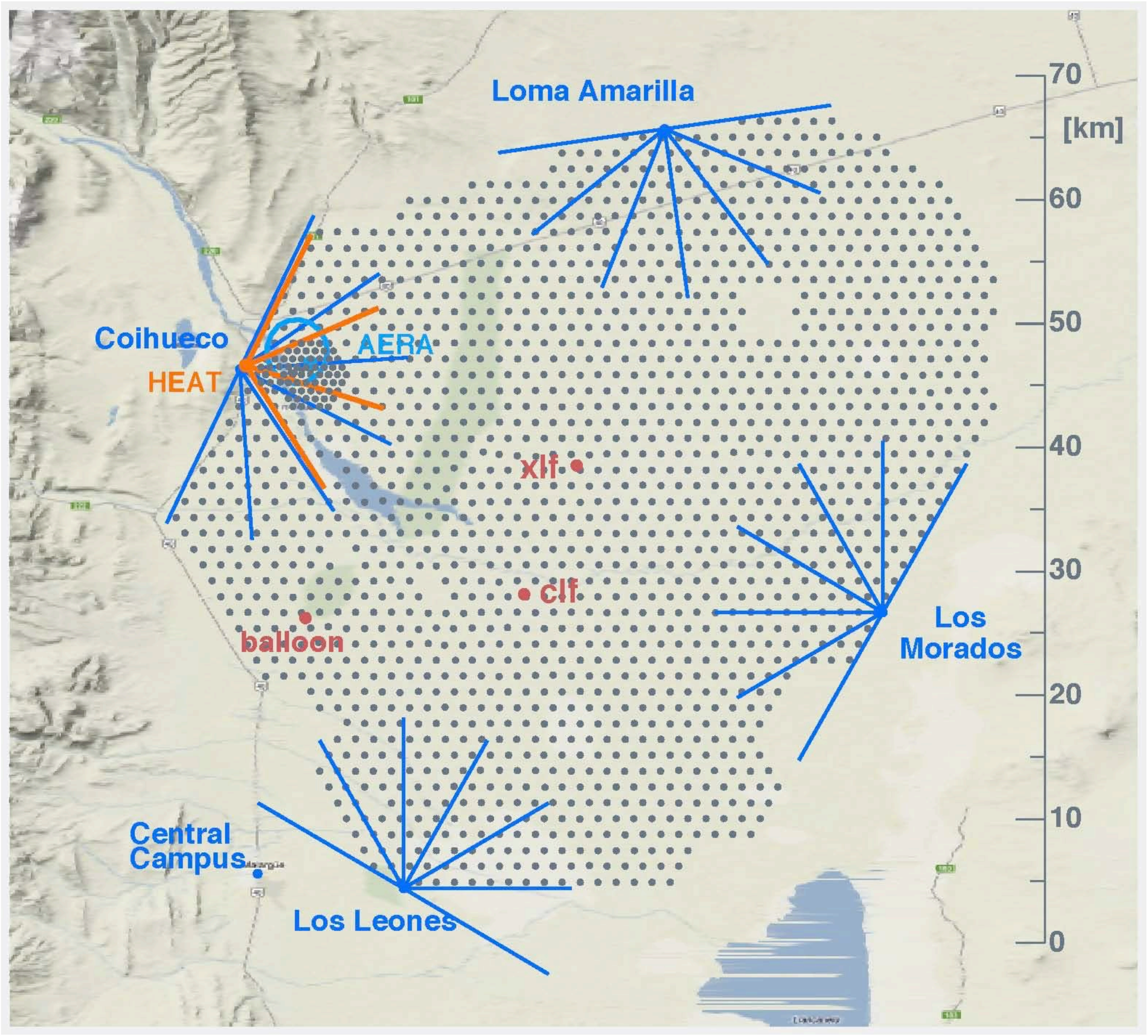
Where?

The Pierre Auger Observatory

- 1660 Cherenkov tanks (SD)
- 3000 km^2
- 4 fluorescence sites (FD, 27 telescopes)

Auger Engineering Radio Array (AERA)

- the largest cosmic ray radio array in the world



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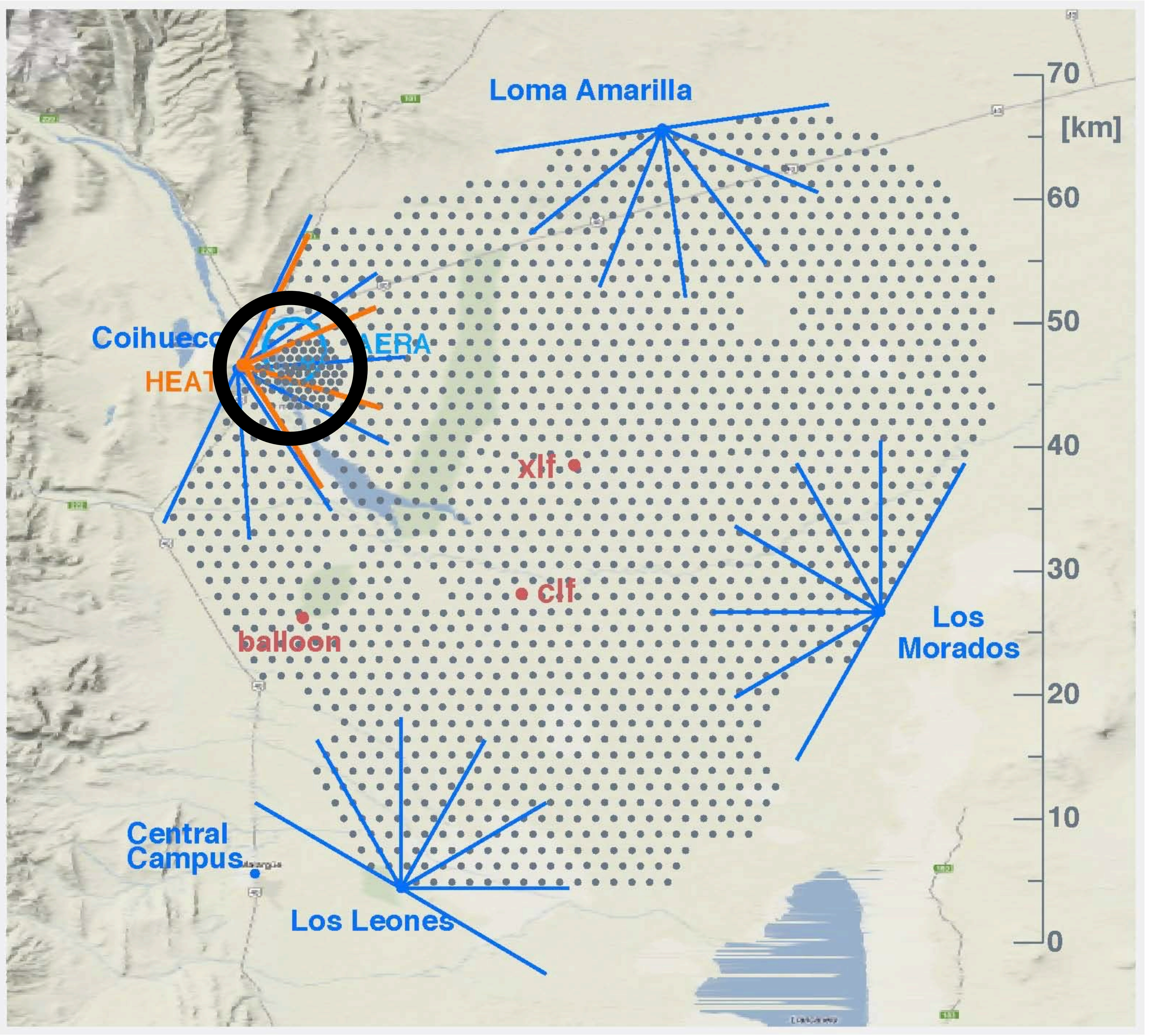

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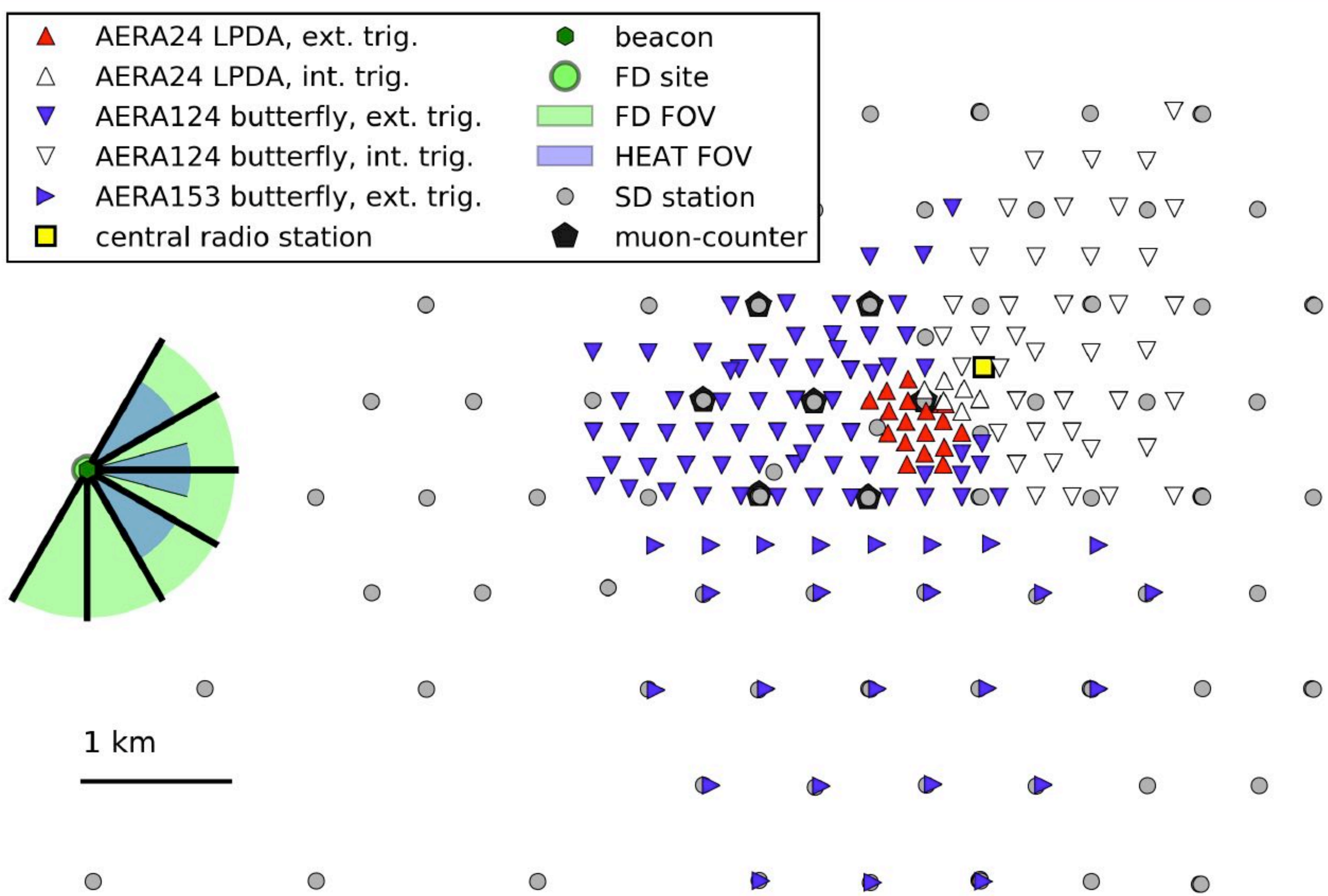
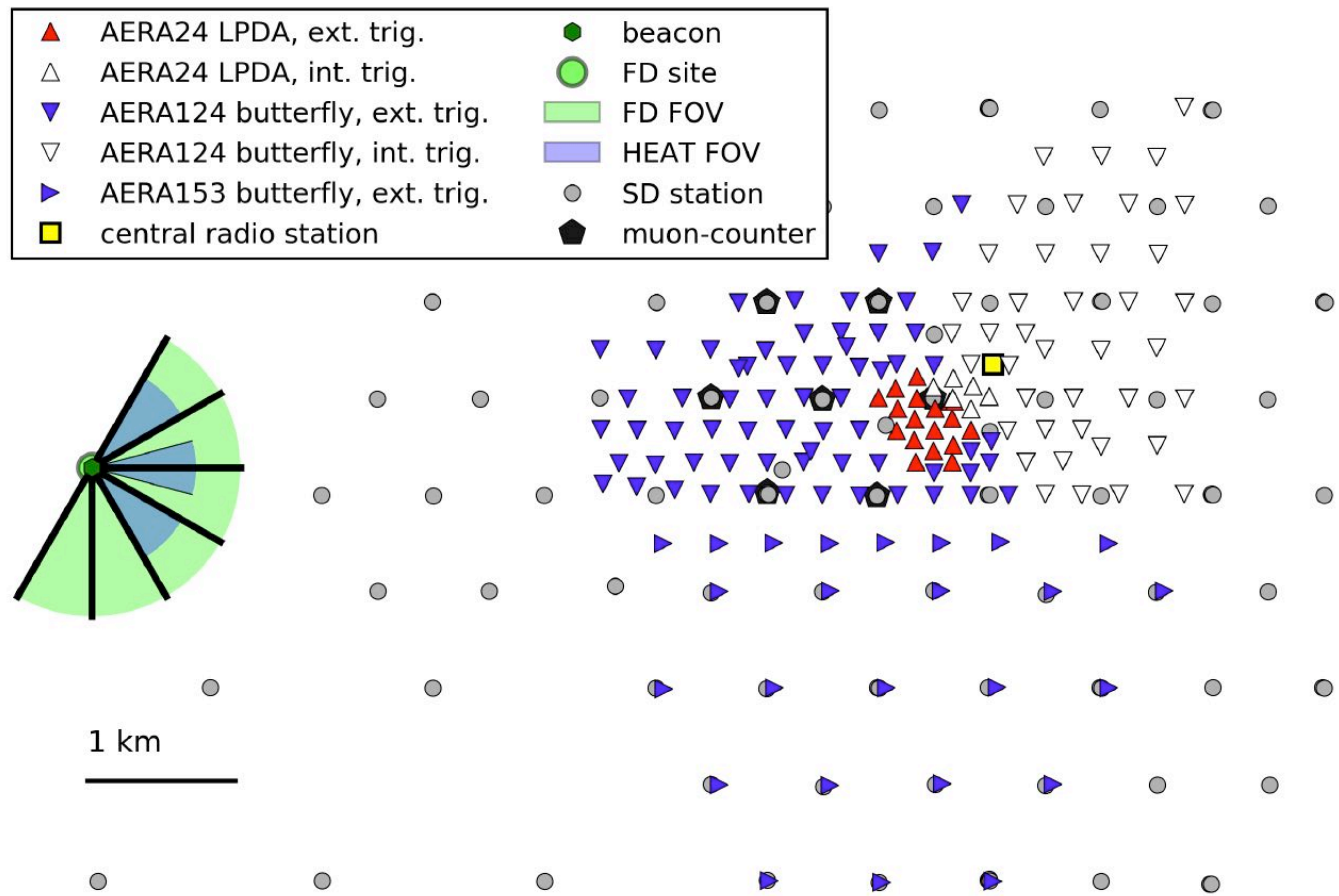
Auger Engineering Radio Array (AERA)



Where?

Auger Engineering Radio Array (AERA)

2011: 24 stations, 0.4 km²

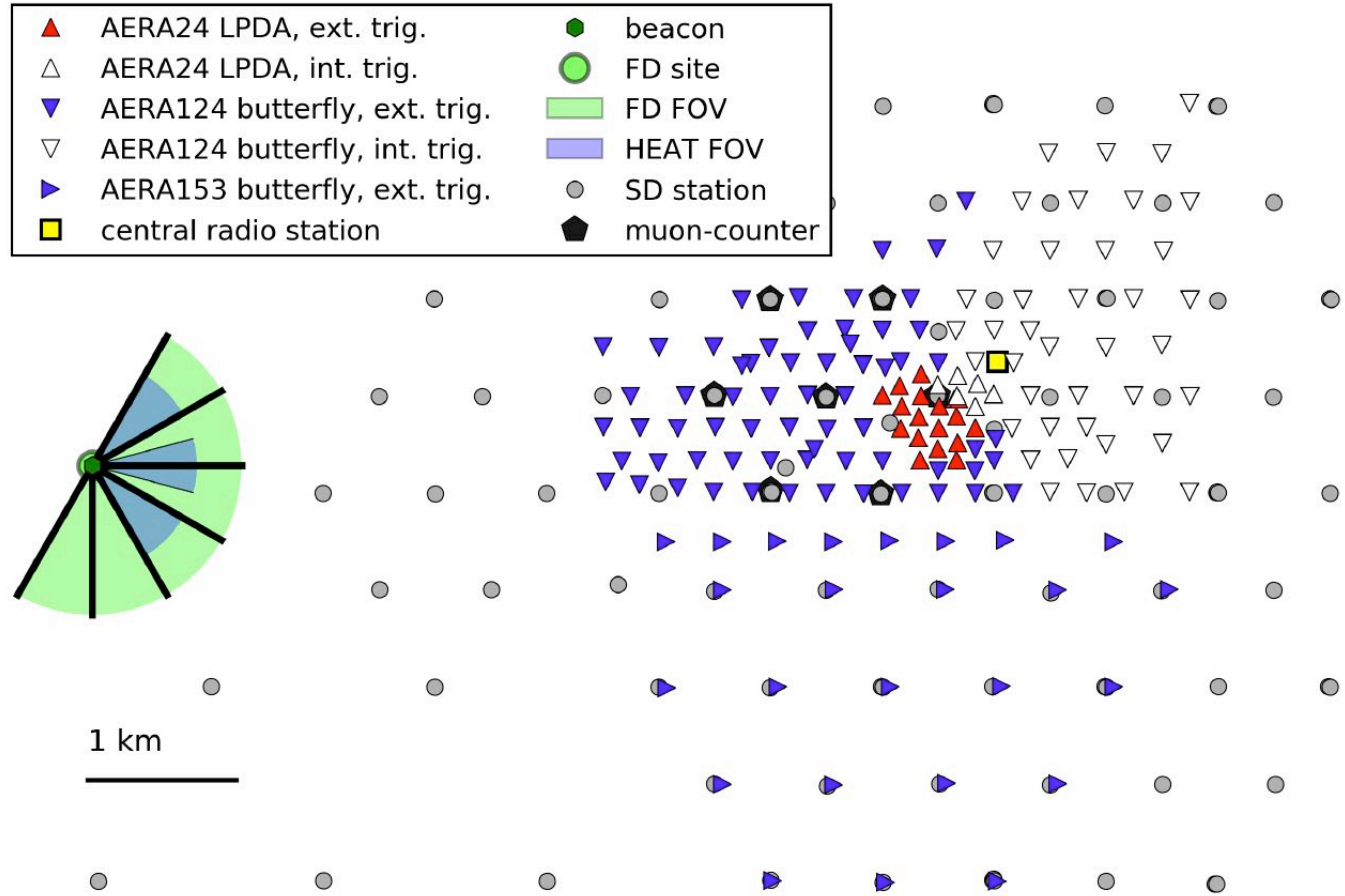


Where?

Auger Engineering Radio Array (AERA)

2011: 24 stations, 0.4 km²

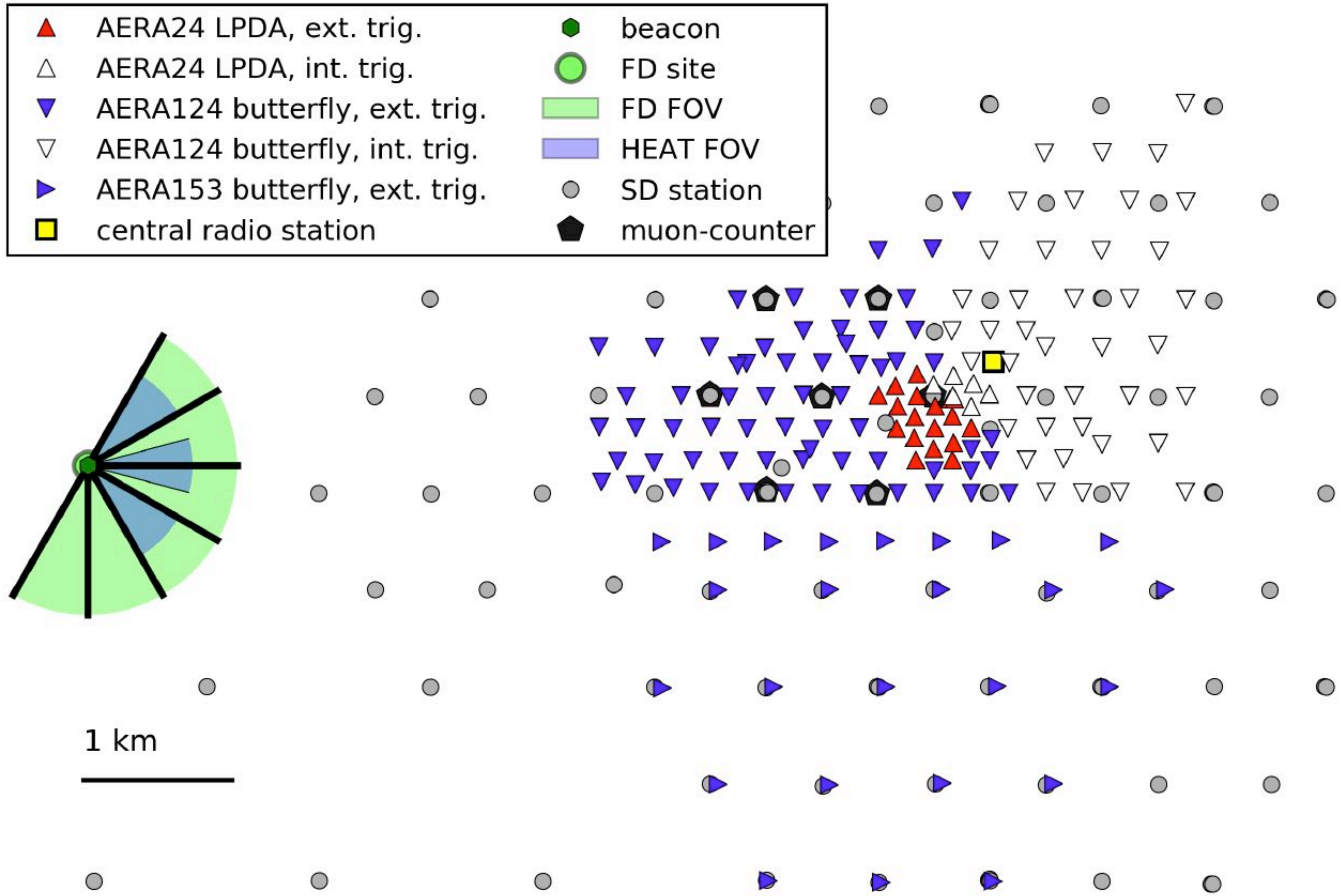
2013: 124 stations, 6 km²



Where?

Auger Engineering Radio Array (AERA)

2011: 24 stations, 0.4 km²
2013: 124 stations, 6 km²
2015: 153 stations, 17 km²



How?

wifi for communication (central DAQ, remote computers)

GPS antenna for timing accuracy

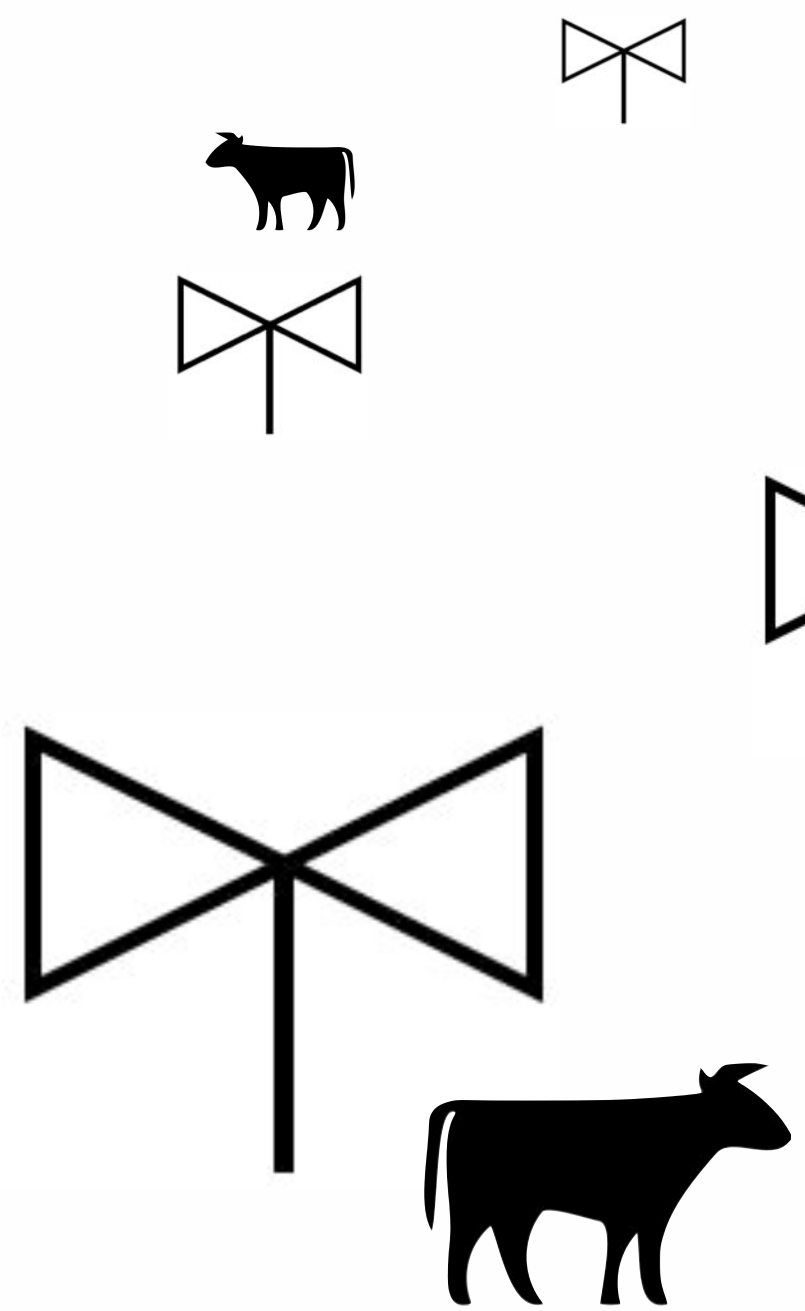
electronics + local DAQ: self-trigger, external trigger, monitoring...

effective freq. range: 30-80 MHz
sampling freq.: 180 MHz or 200 MHz
EW and NS polarizations

antenna+amplifier (LPDA, Butterfly)

solar panel

How?

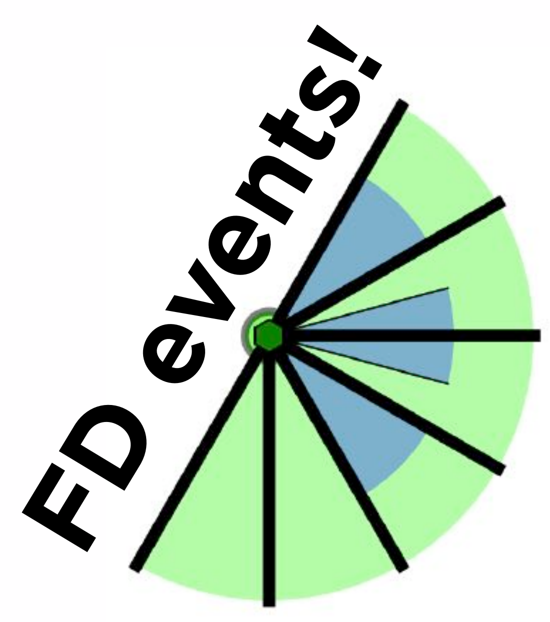


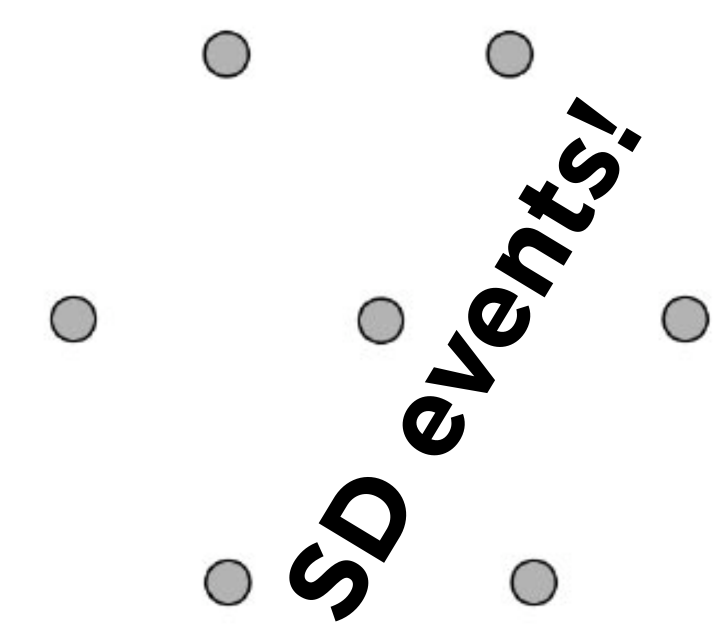
central DAQ:

- gets timestamps from stations
- computes coincidences
- asks for raw data (self trigger)

+

- gets trigger information from SD and FD
- asks for raw data (external trigger)





Why?

Shower physics

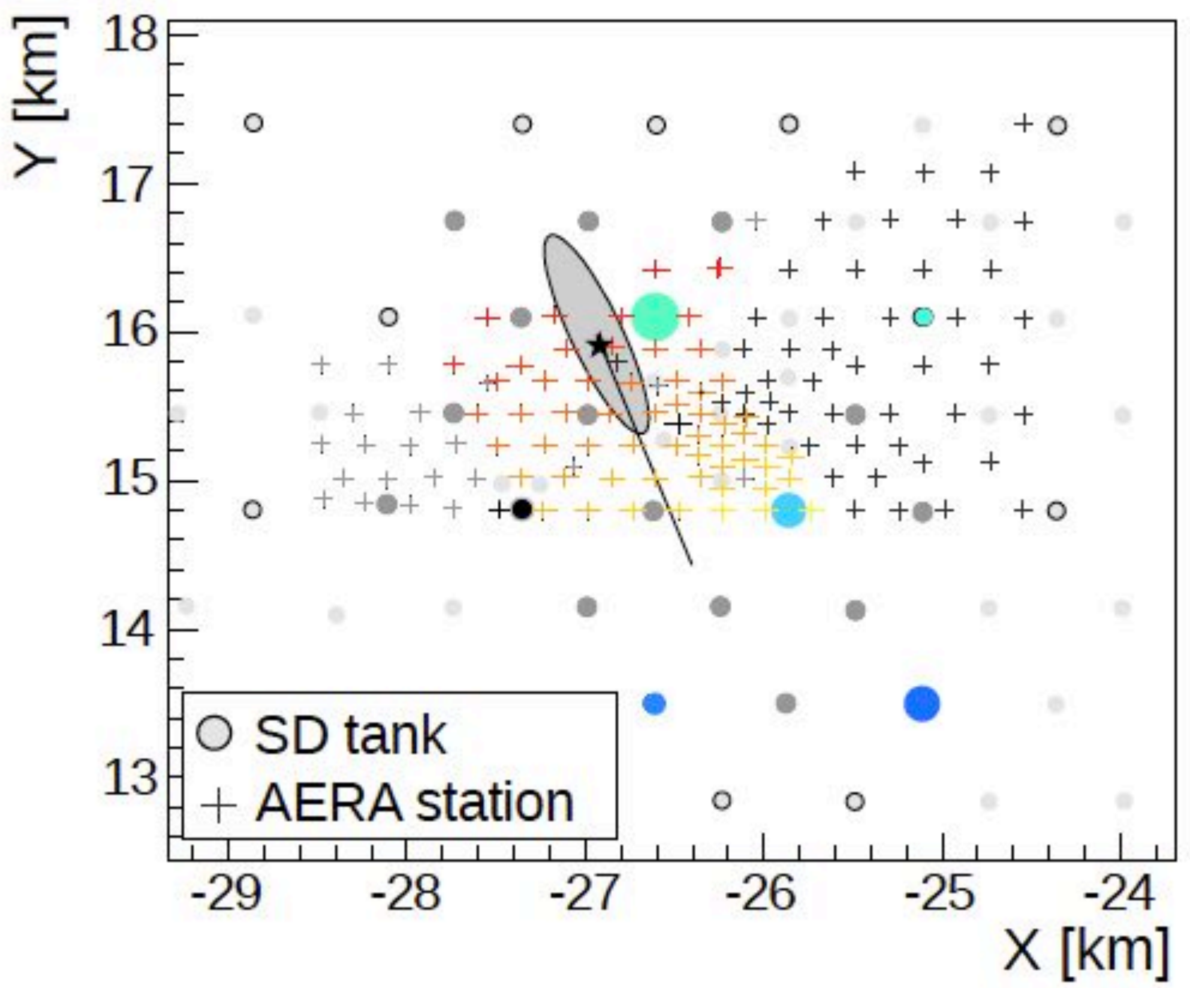
- fine details of the electric field emission mechanisms
- e+/e- and muons distributions

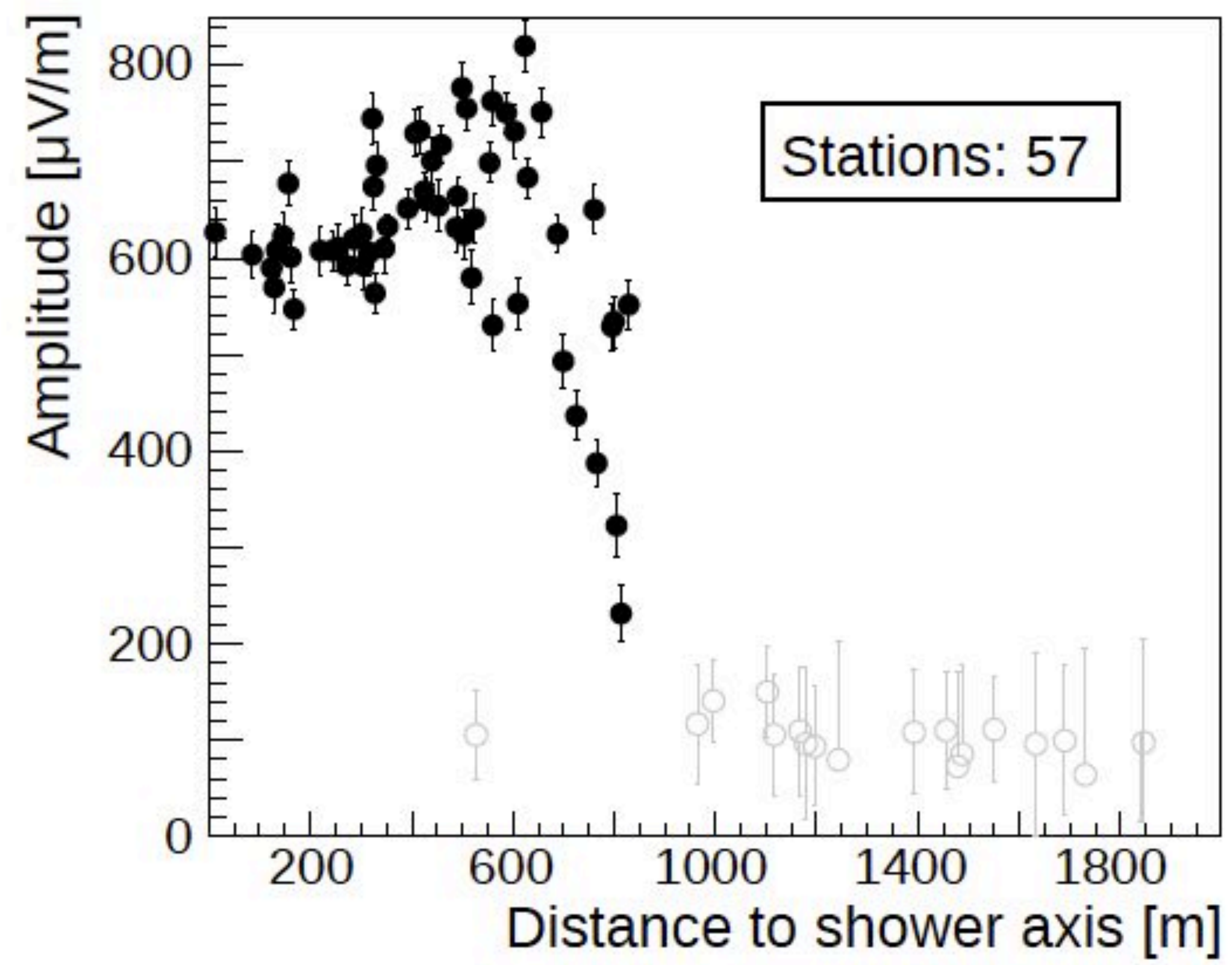
Cosmic ray physics above 1 EeV

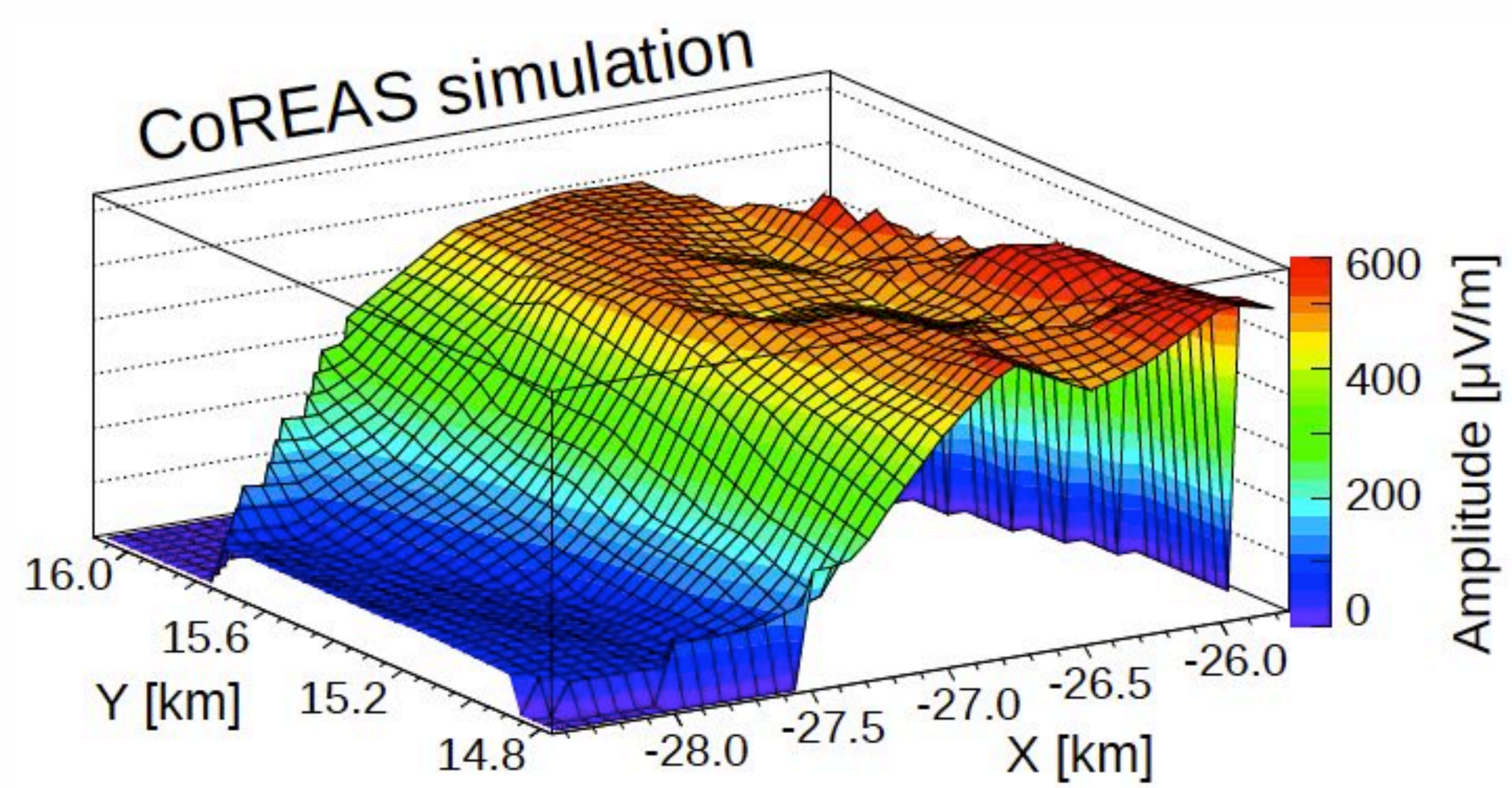
- calorimetric energy measurement (and spectrum)
- energy scale of Auger (FD)
- composition through X_{max} with ~100% duty cycle, in particular in the transition region
- inclined showers (large acceptance)

Geophysics

- study of atmospheric electric fields
- lightning/CR correlation



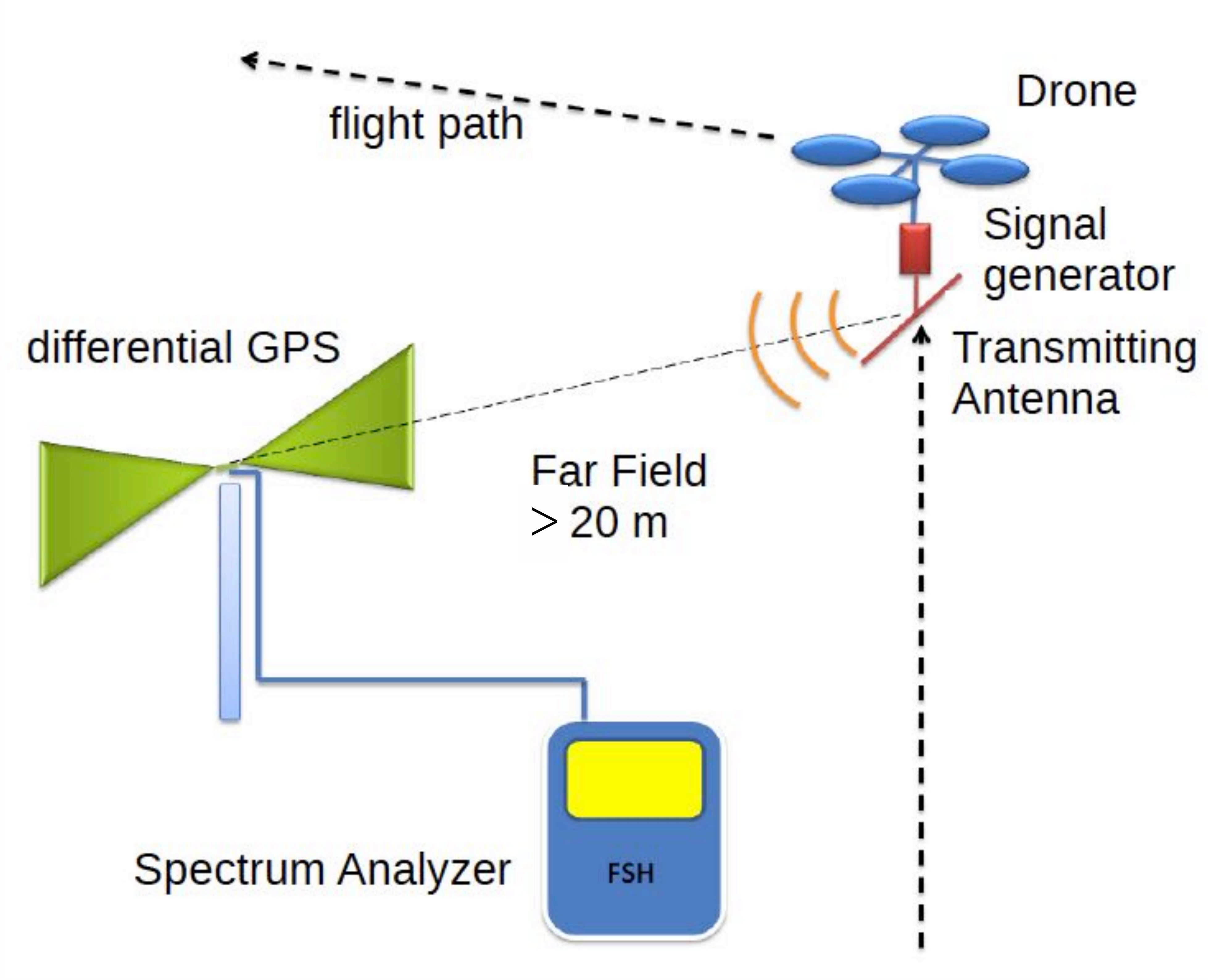




I. Understanding the detector

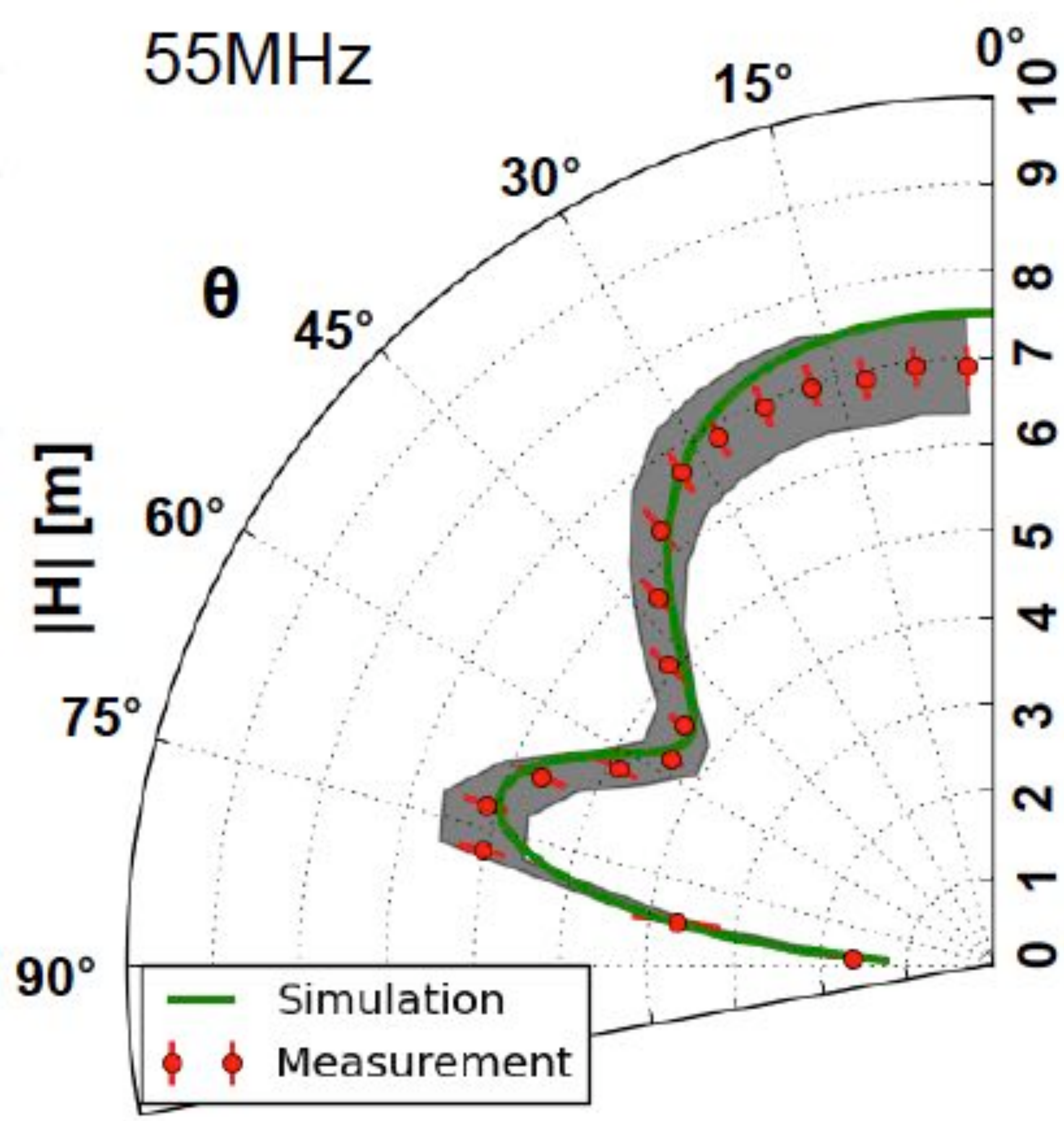
Amplitude calibration

direct calibration using a pulser on a drone



vector effective length:

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



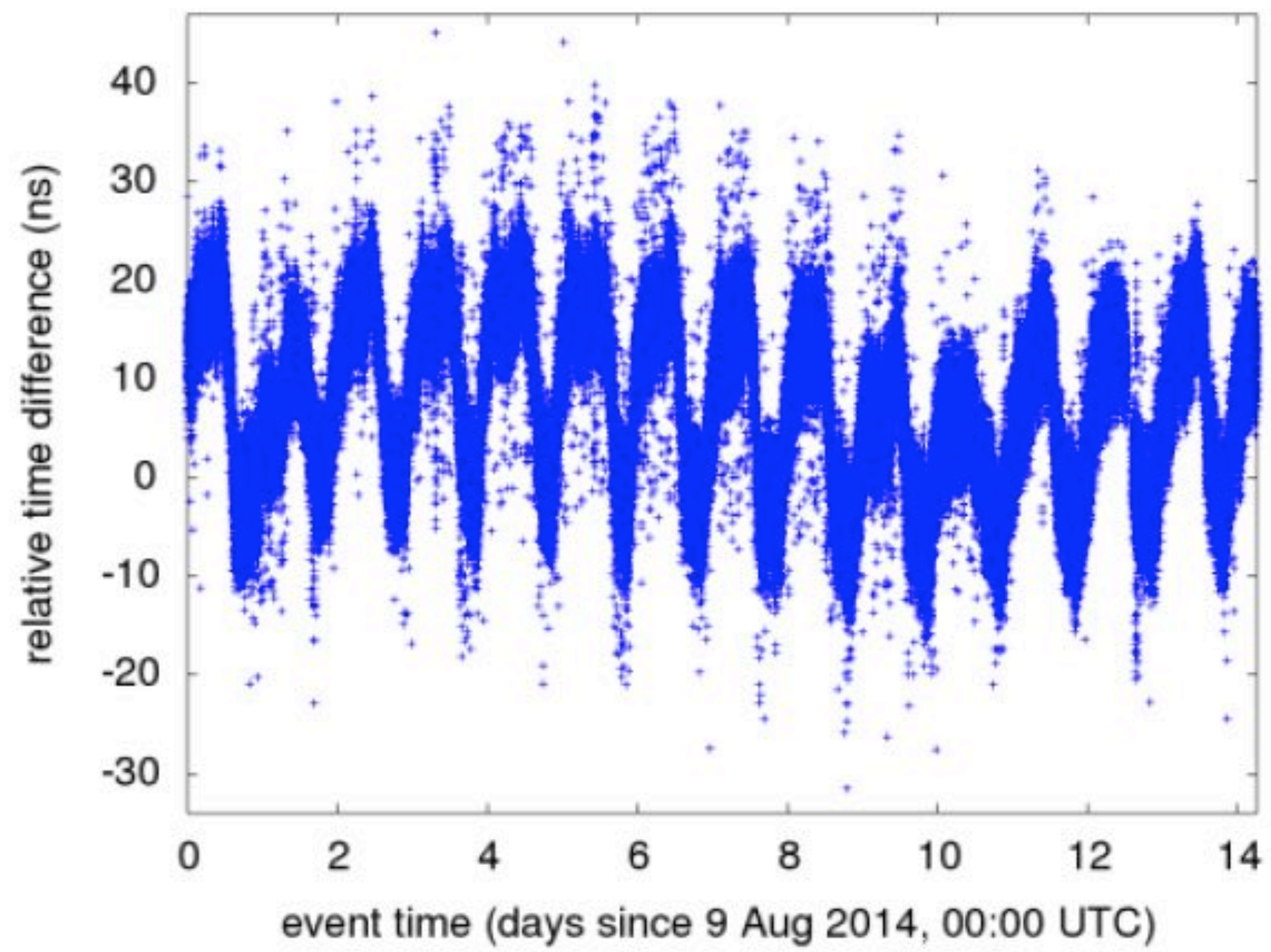
overall uncertainty: **14%** (antenna response+full electronics chain)

Time calibration

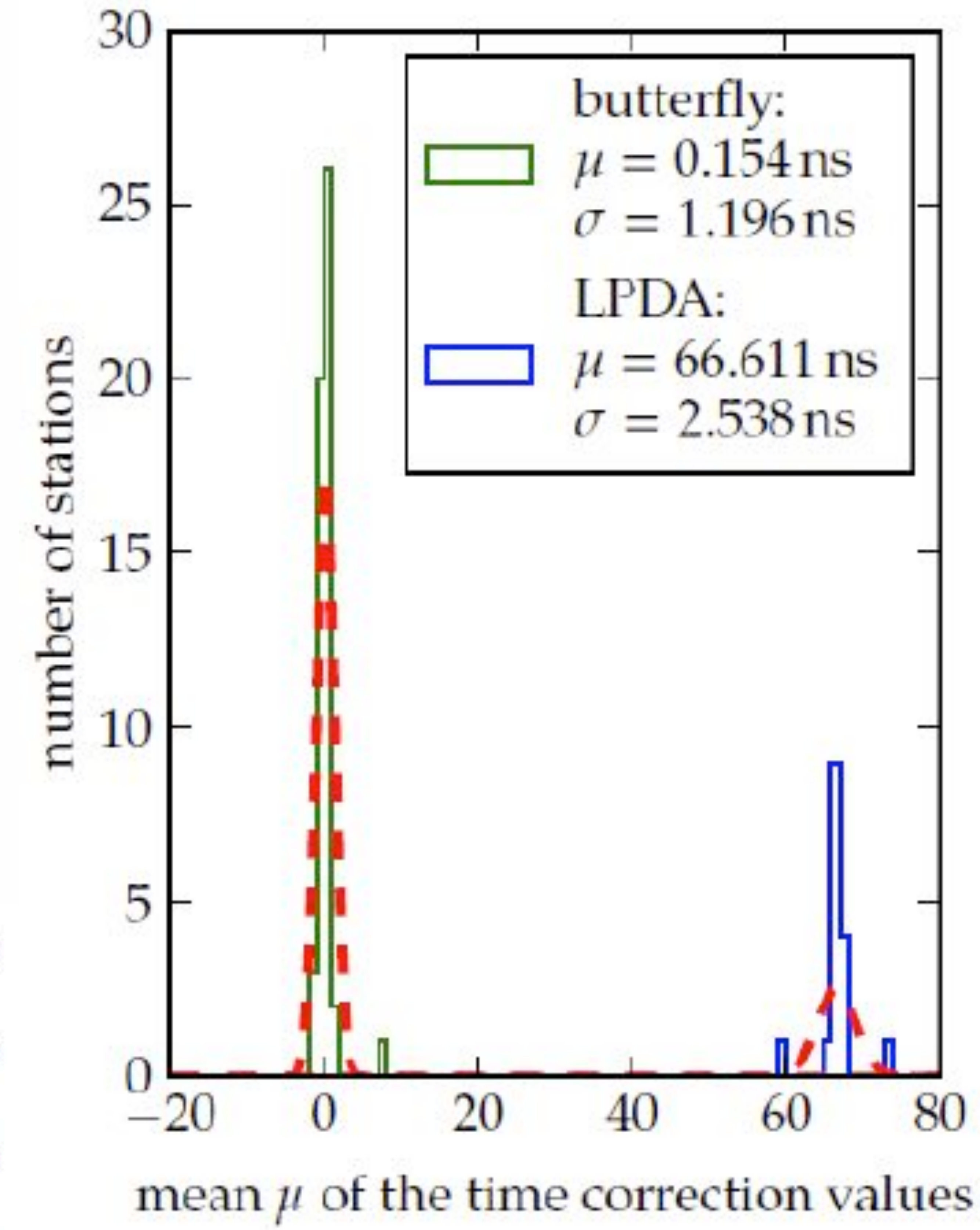
correct for GPS drifts by comparing time differences between two stations using a distant beacon and airplane transits over AERA

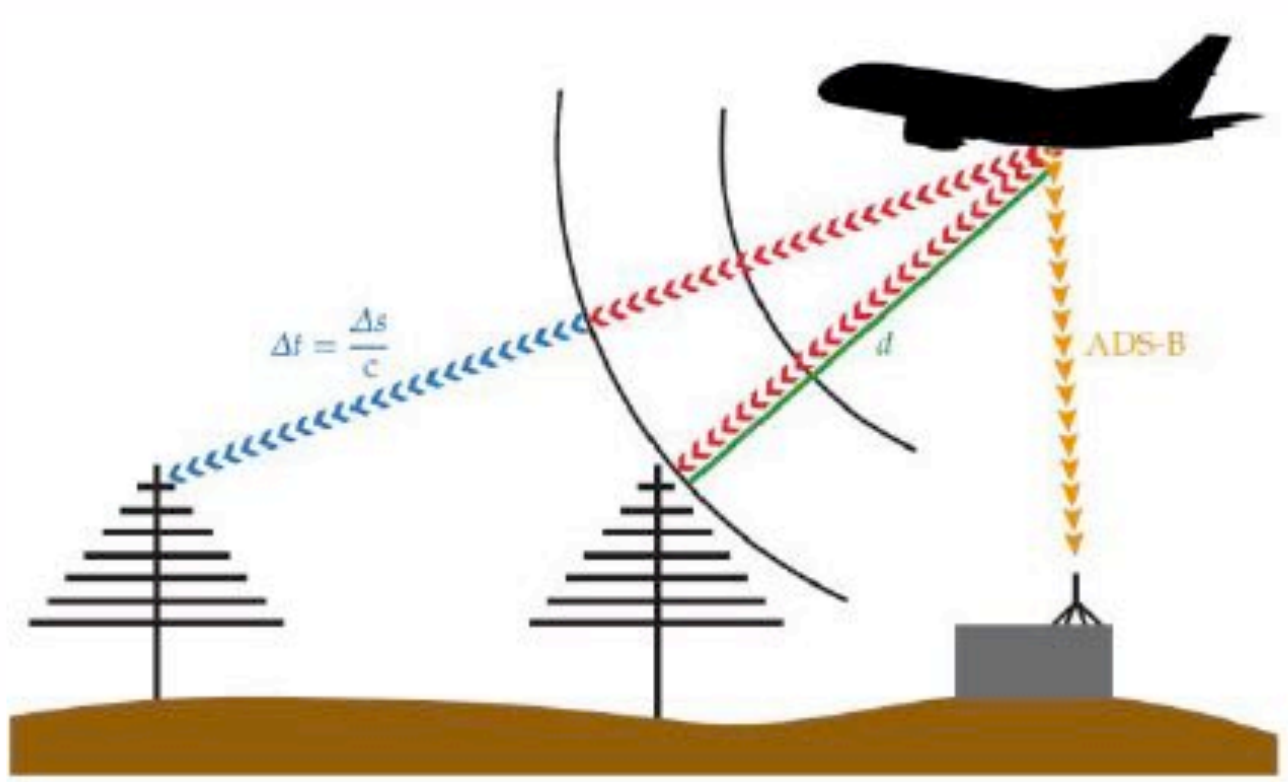
time accuracy around 30 ns!

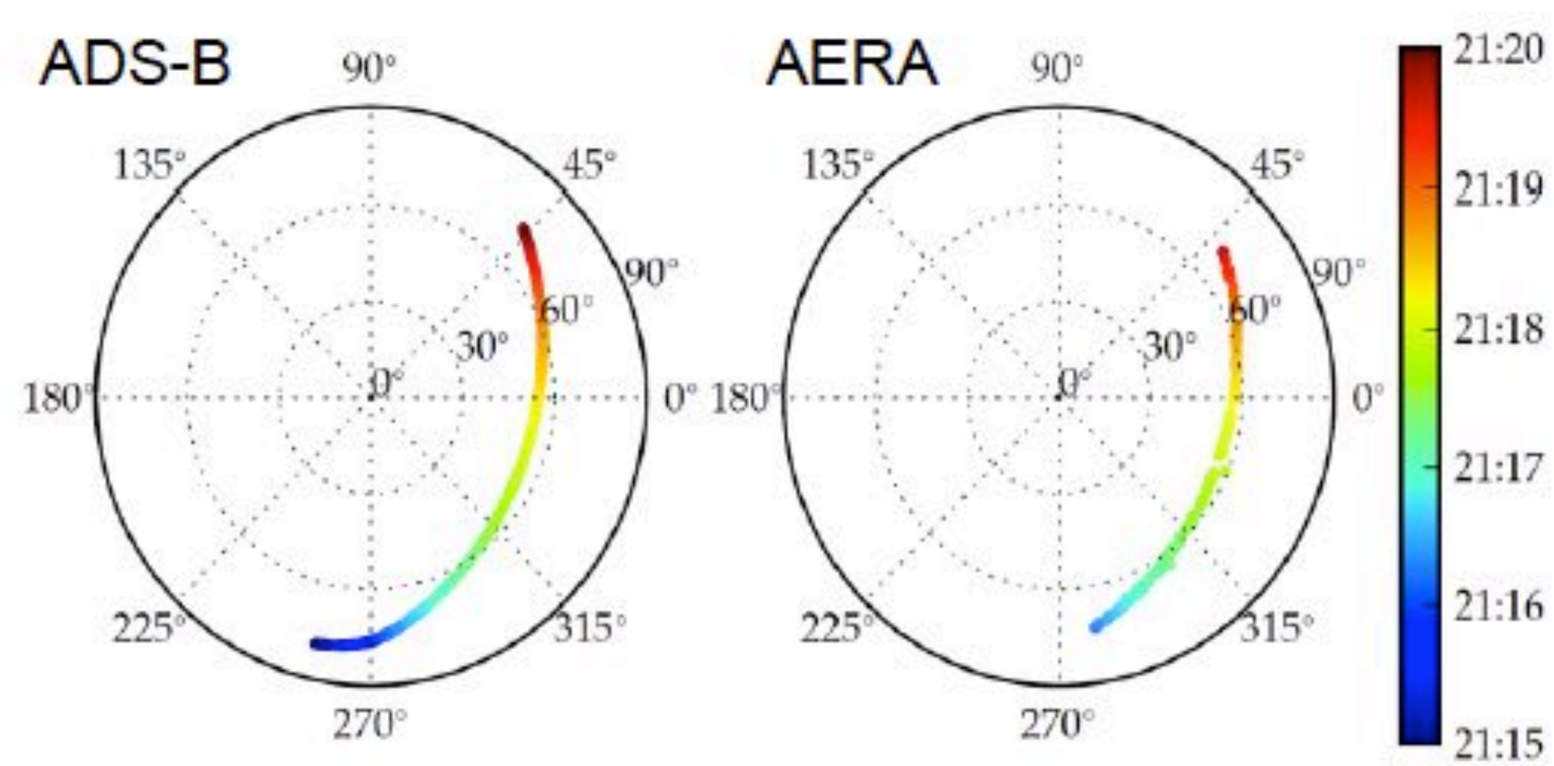
GPS time drift over 2 weeks



Auger collab. JINST 11 (2016) P01018







overall uncertainty: **2 ns**

II. Understanding the source of the signal

Emission mechanism

$$-\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{\beta}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

Geomagnetic contribution

Emission mechanism

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$$\vec{E}_{\text{geo}} \propto \vec{\beta} \times \vec{B}$$

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from **measurements** of the electric field in the EW and NS polarizations, we can compute the polar. angle:

$$\phi_{\rm mes} = \arctan(E_{\rm NS}/E_{\rm EW})$$

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and compare it to the **expected** polar. angle:

$$\phi_{\mathrm{exp}} = \arctan((\vec{\beta} \times \vec{B})_{\mathrm{NS}} / (\vec{\beta} \times \vec{B})_{\mathrm{EW}})$$

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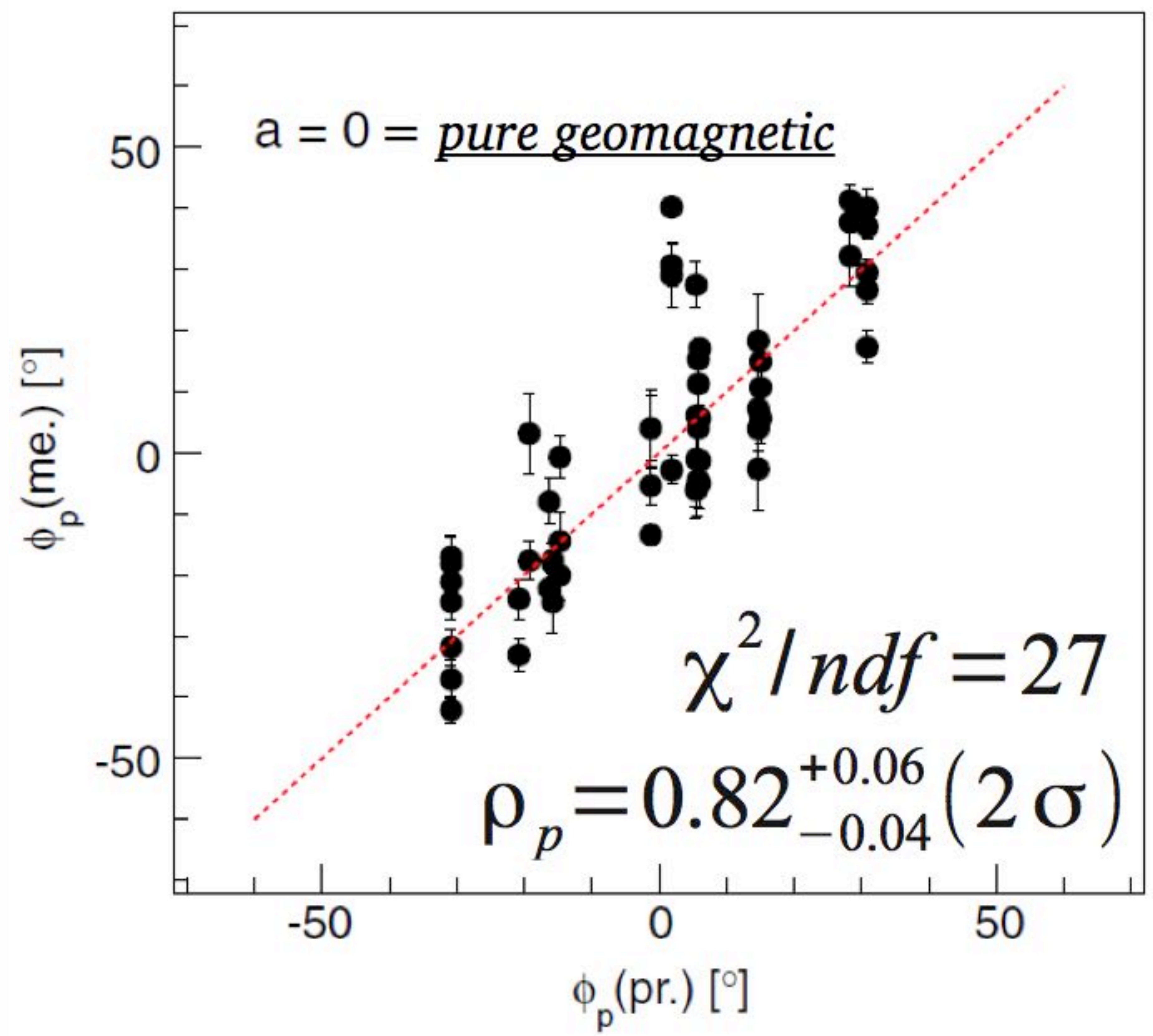
AERA data



Auger collab., Phys. Rev. D 89, 052002 (2014)

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The geomagnetic mechanism is dominant!

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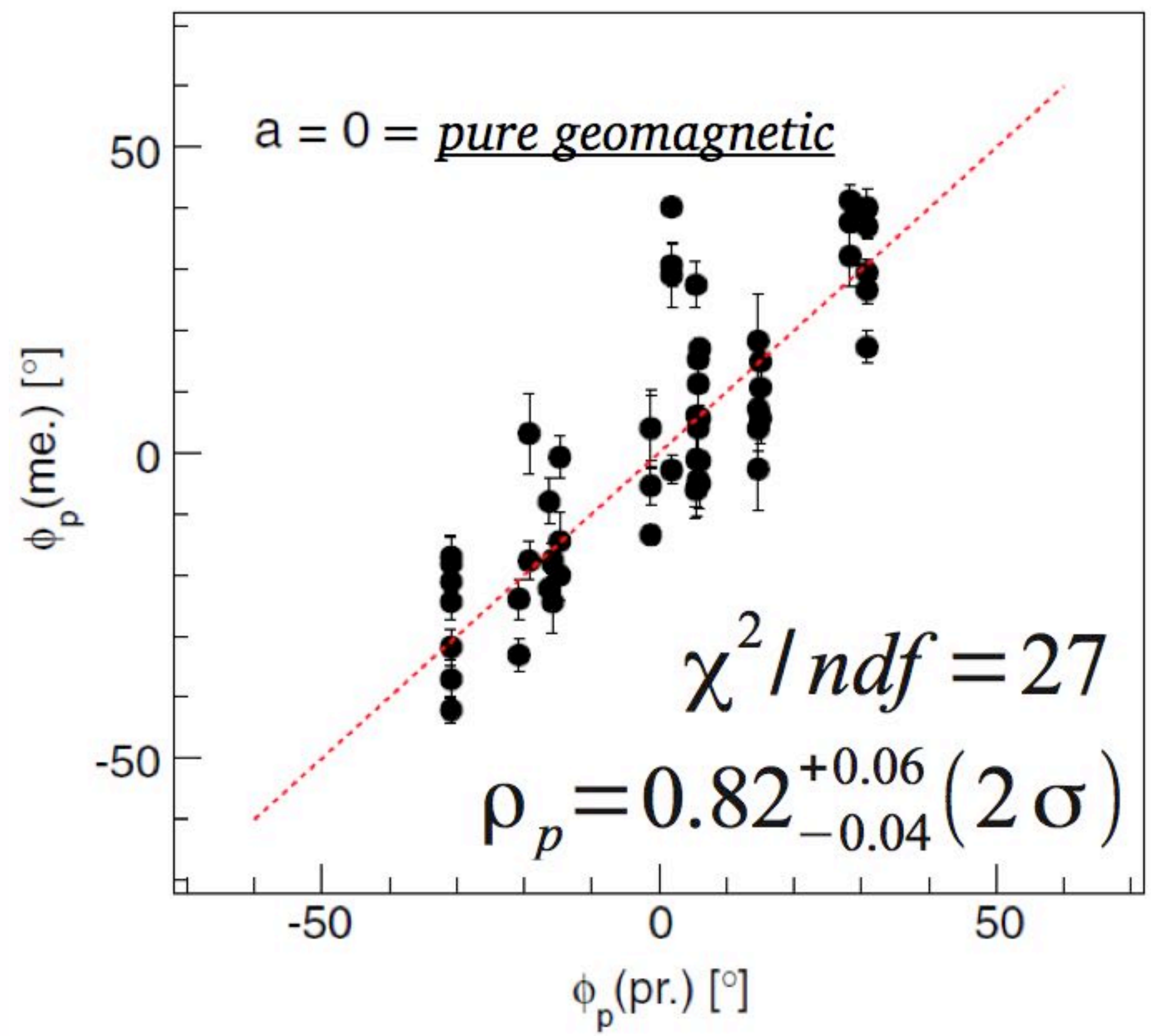

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Emission mechanism

Charge excess contribution

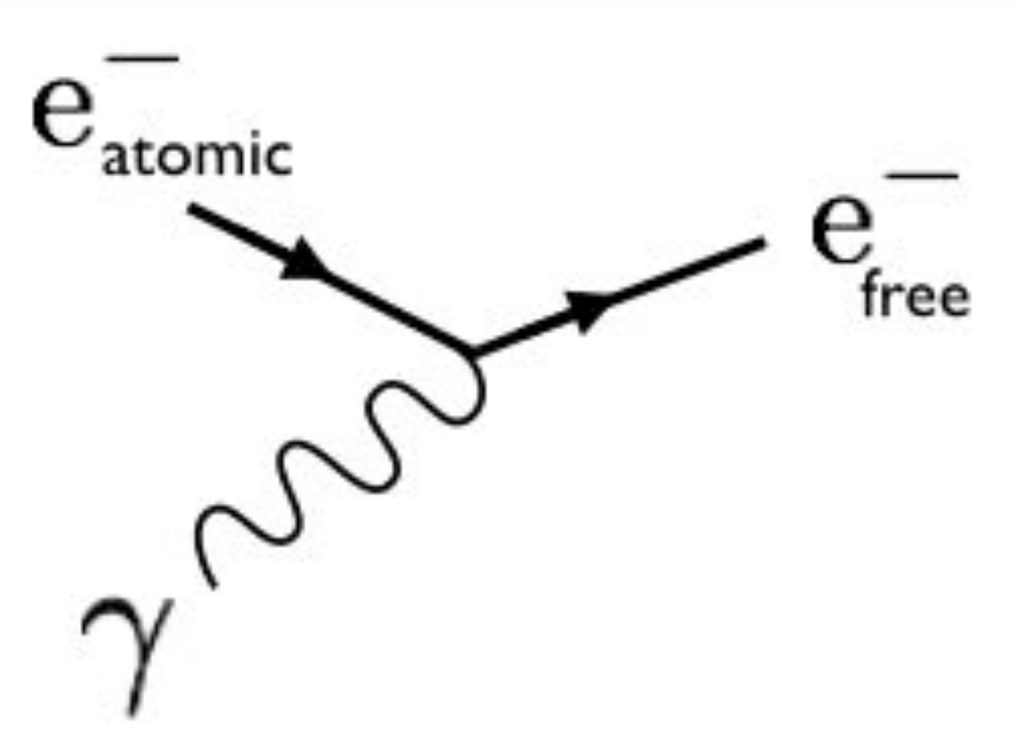
$$+\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}^{N}\frac{q_i\,\vec{n}_i}{R_i(1-\eta\vec{\beta}_i\cdot\vec{n}_i)}$$

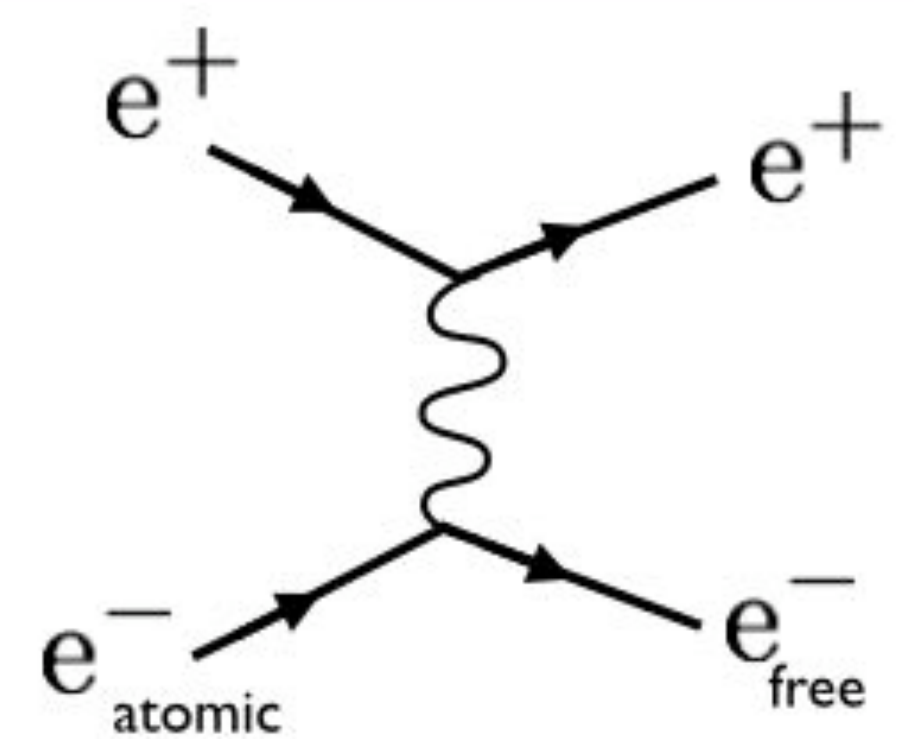
(Askaryan 1962, 1965)

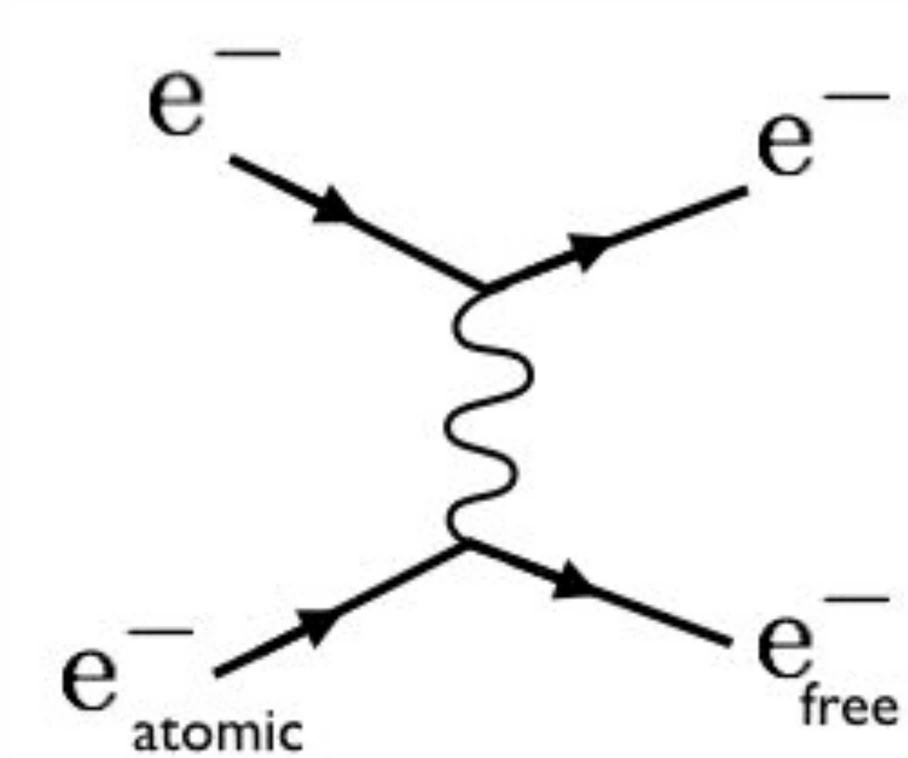
No net electric field if $n_{e+} = n_{e-}$

but $n_{e+} < n_{e-}$ because:

- in flight e+ annihilation
- electrons are extracted from the medium (Compton, Bhabha, Moeller)







excess of electrons: net electric field, radial polarization pattern, depends on the observer's location

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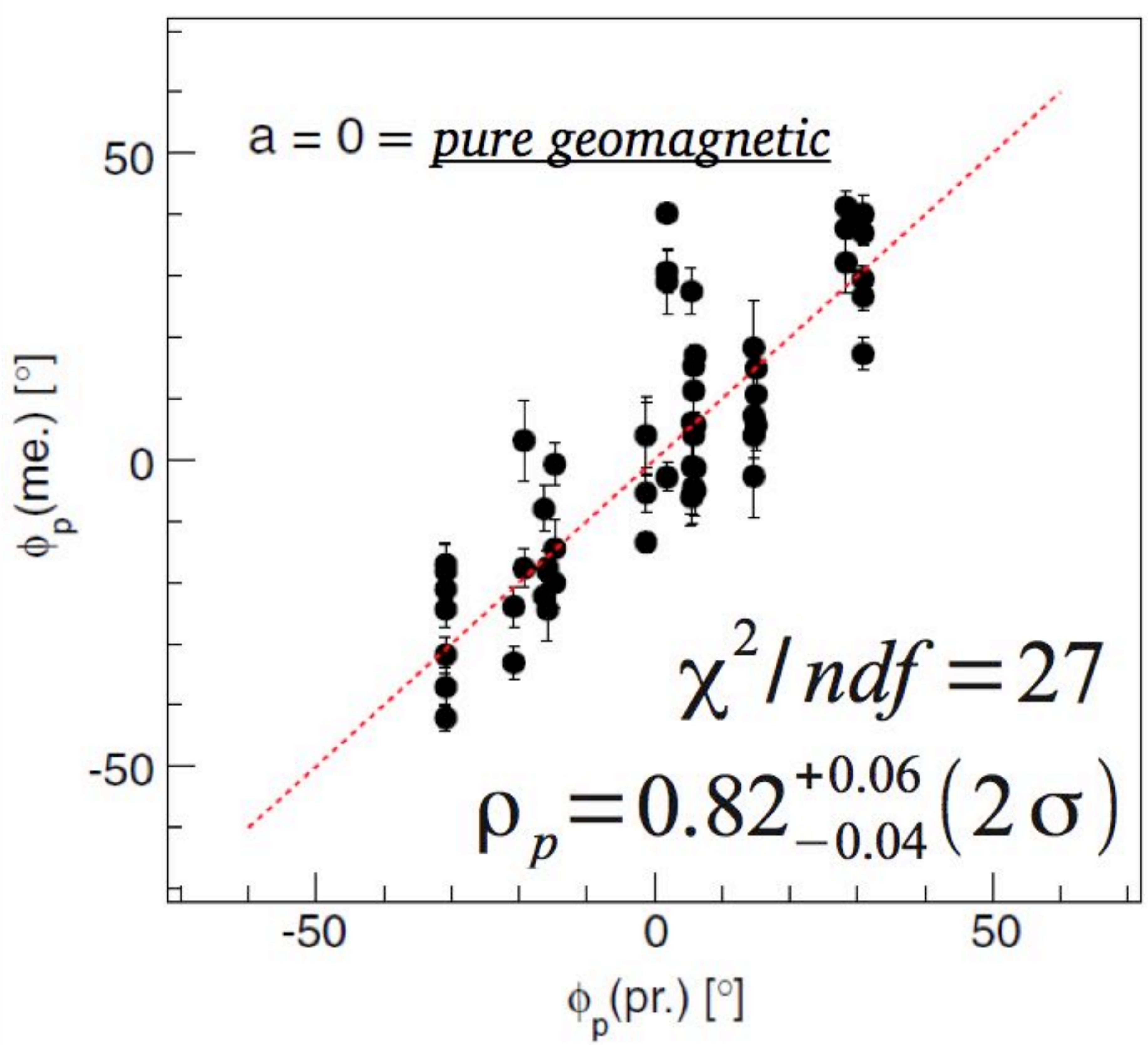

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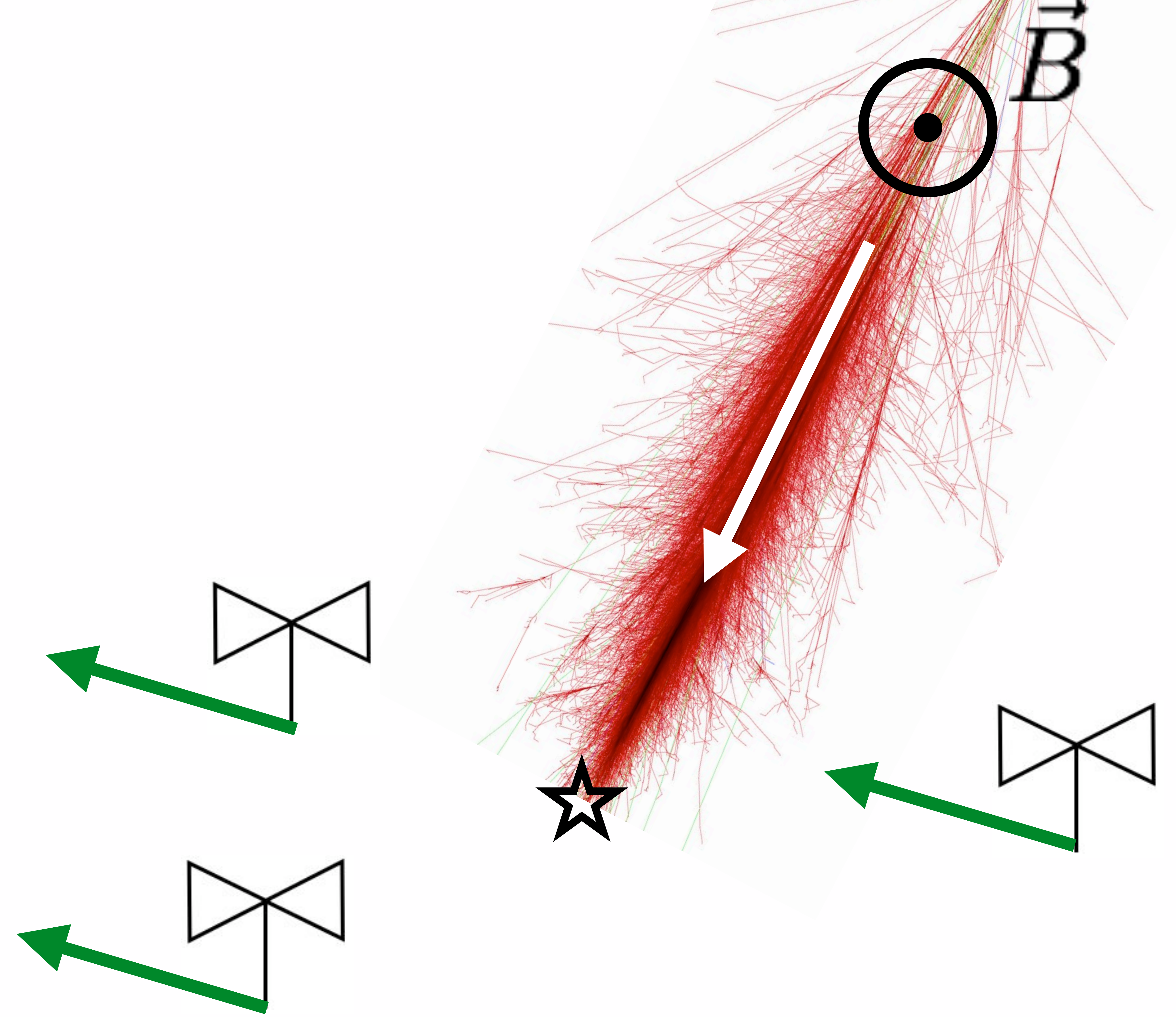

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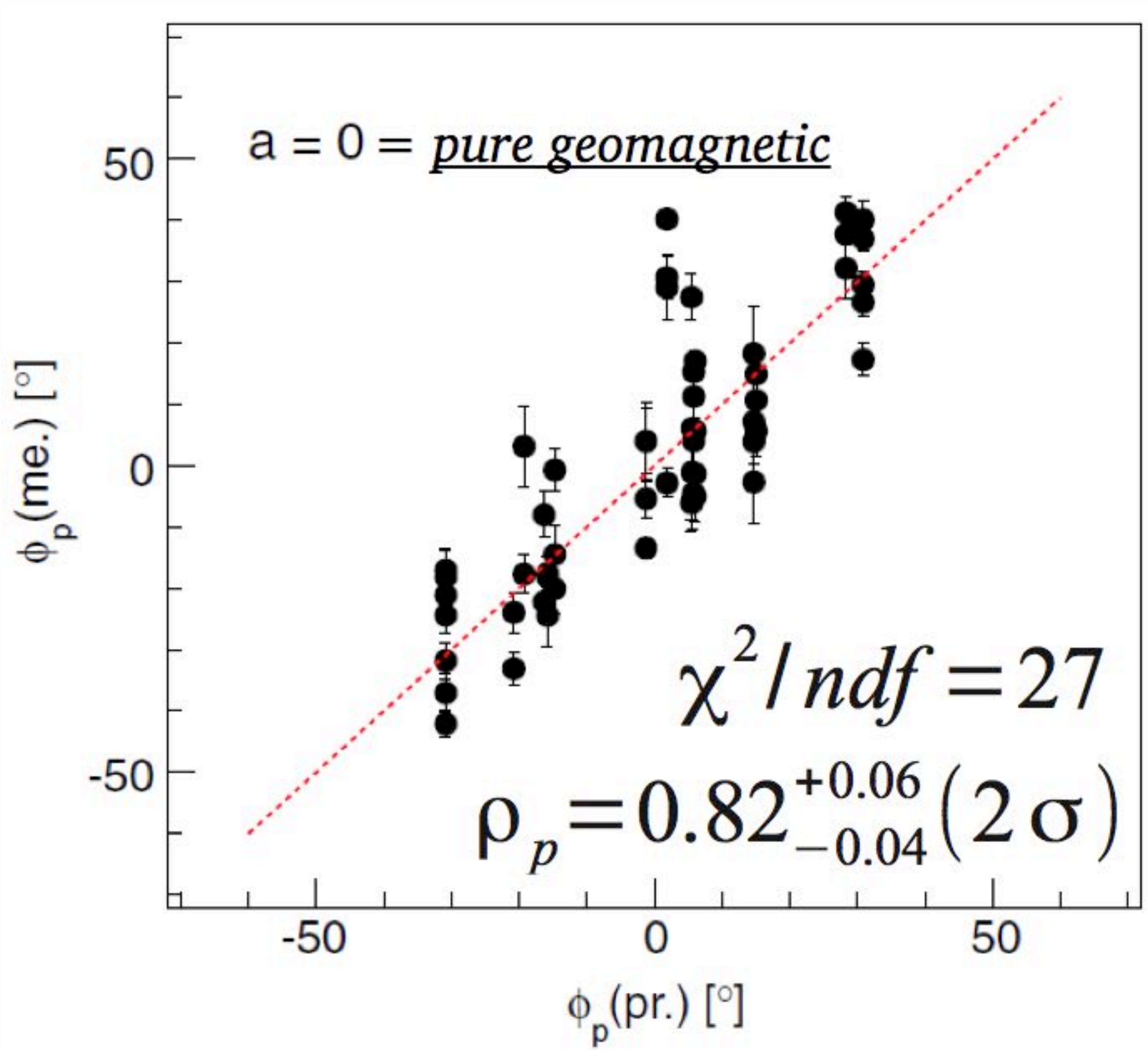

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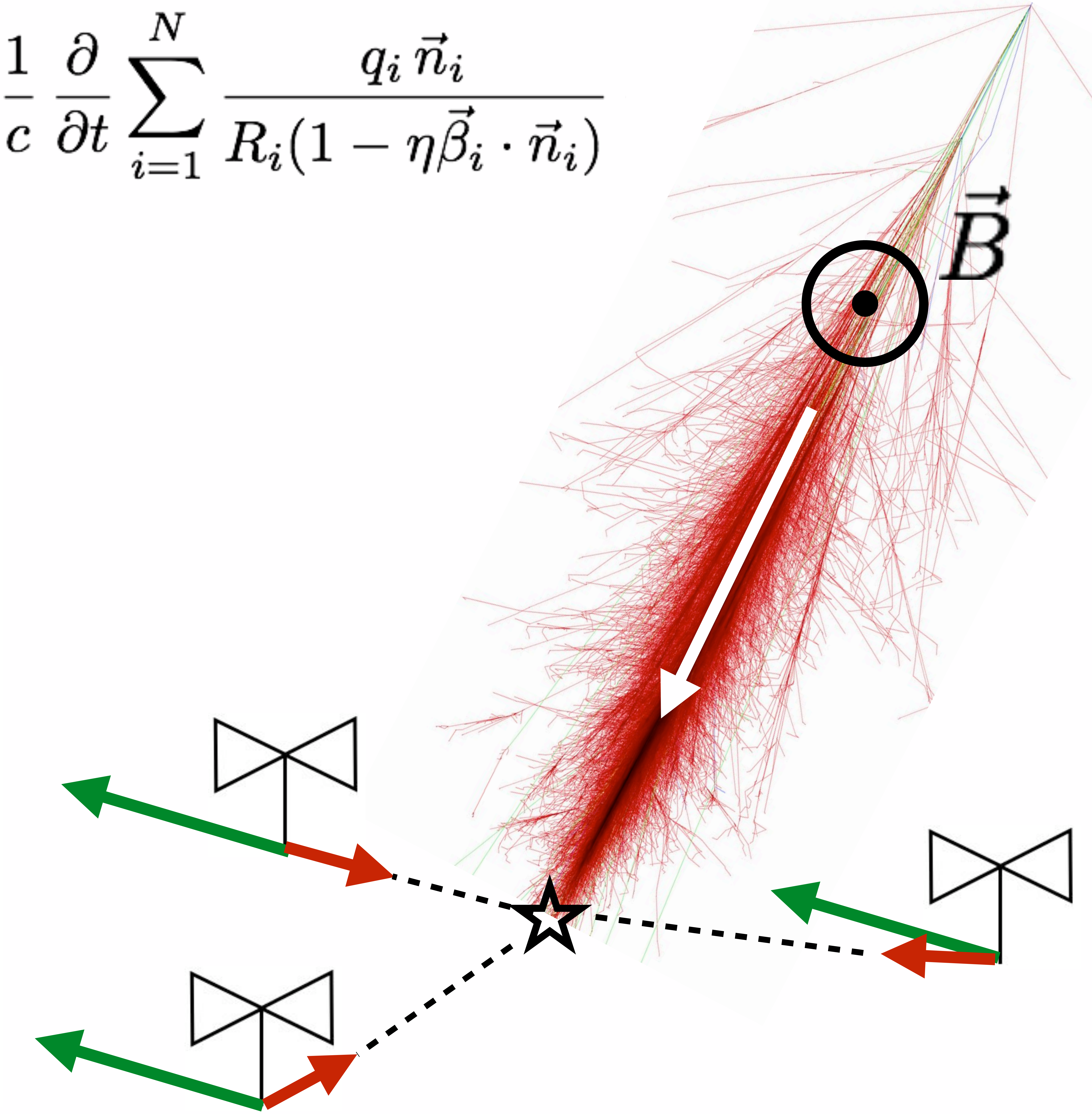

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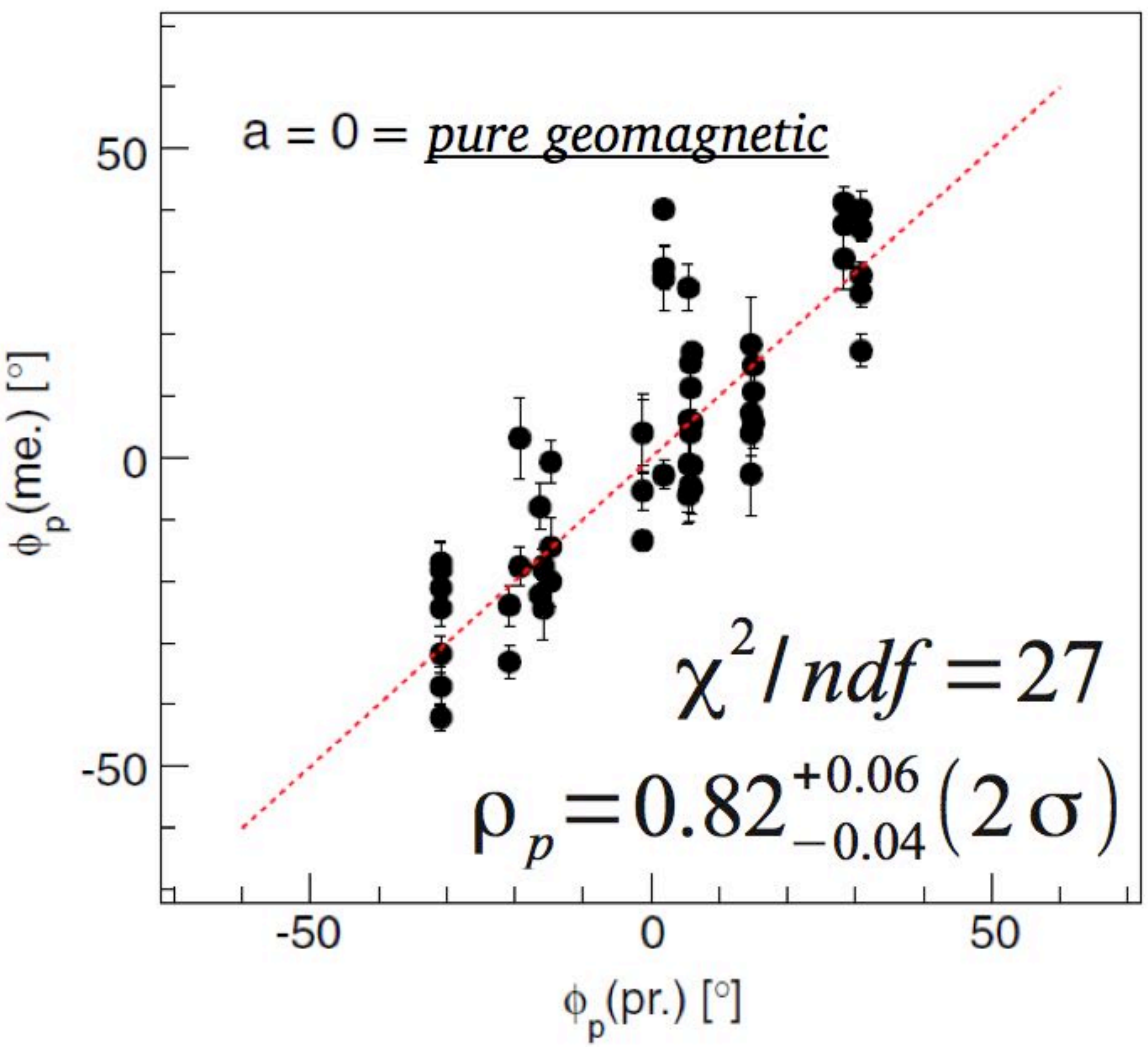

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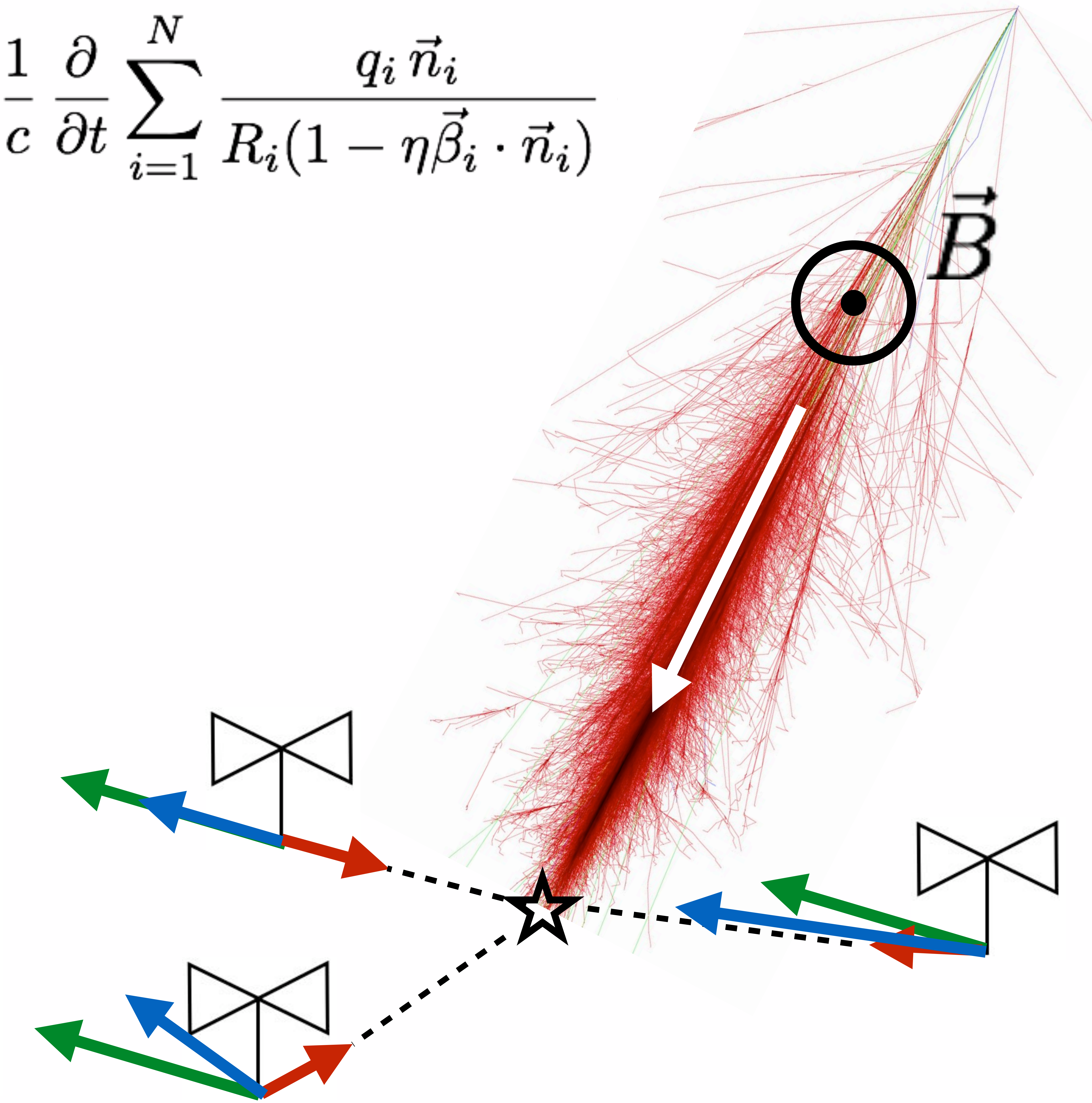

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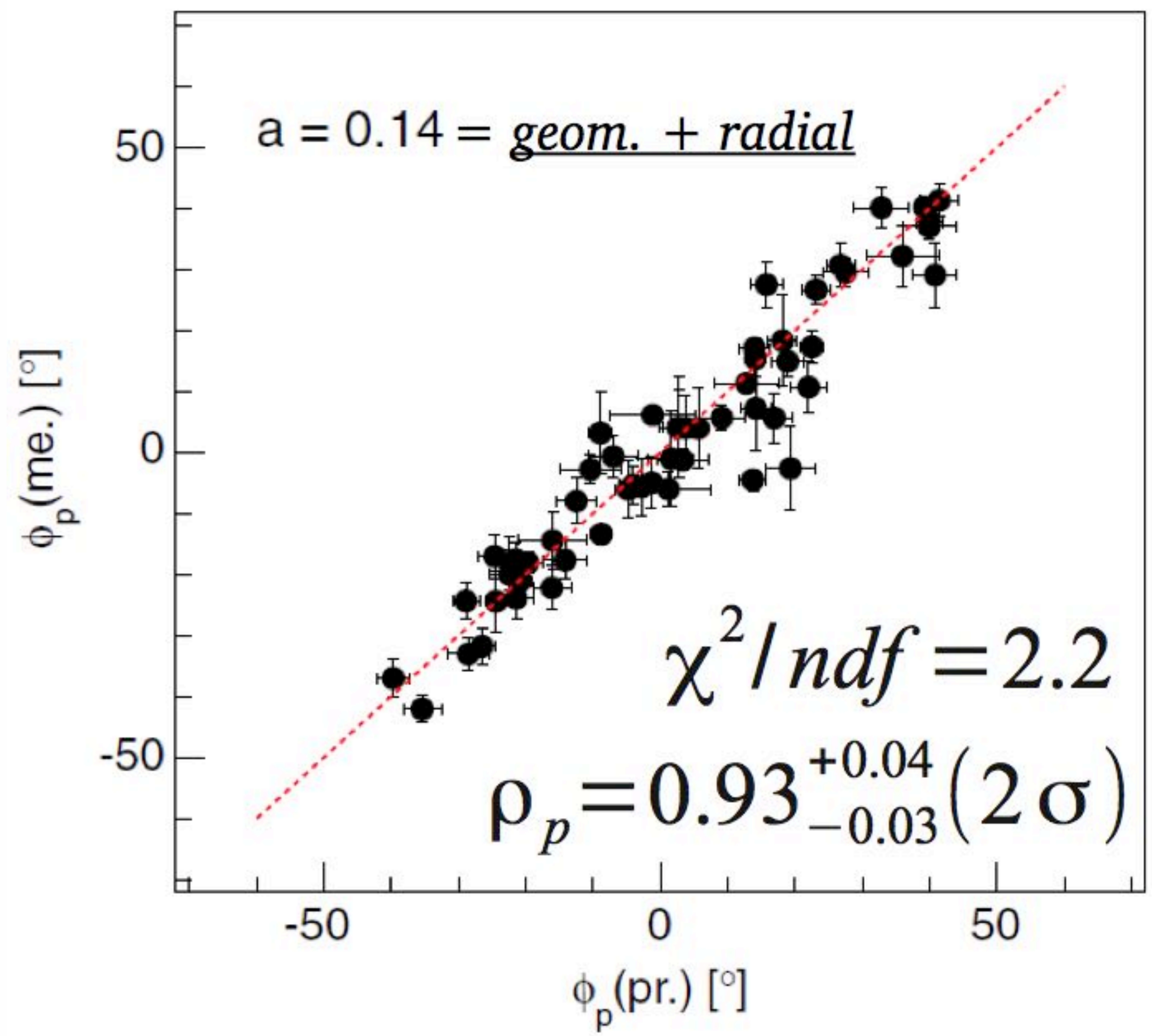

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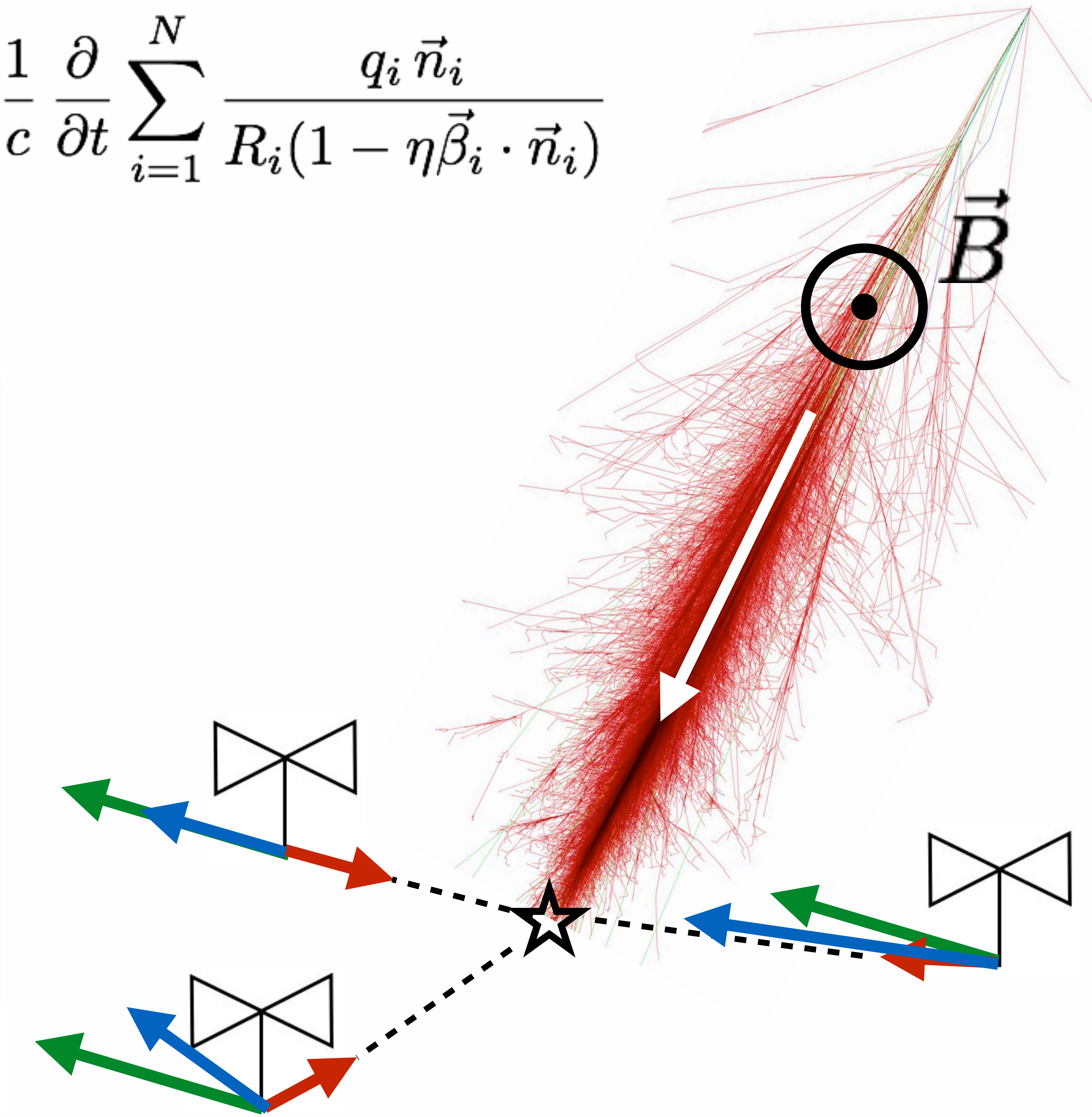


III. Extracting CR characteristics (energy, X_{max})

Lateral distribution function: **energy** estimation

two mechanisms interfere: we loose azimuthal symetry

need 2D LDF, here difference of 2 Gaussians computed from dedicated simulations (using CoREAS)

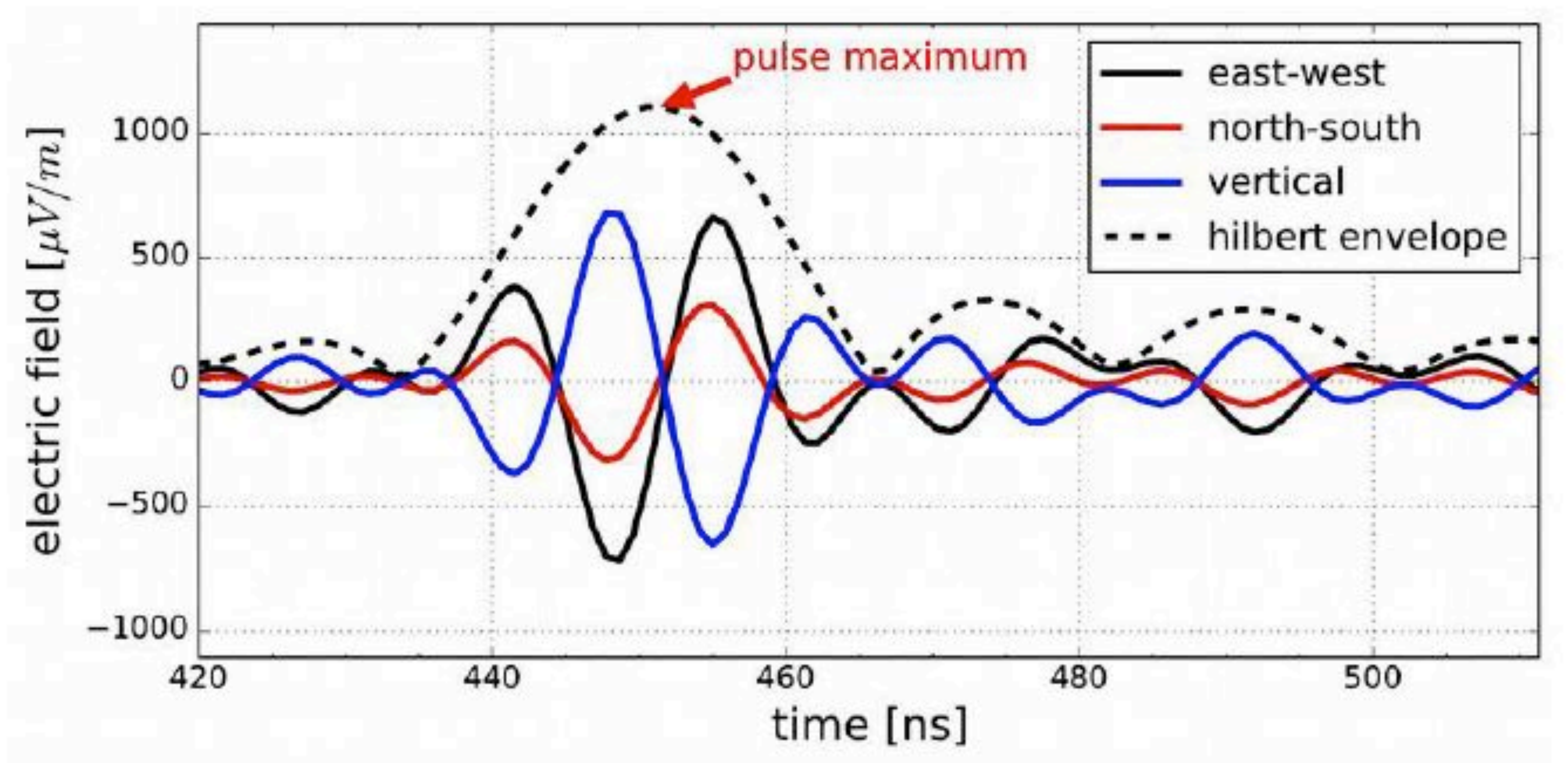
Nelles et al., Astropart. Phys. 60, 13 (2015)

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

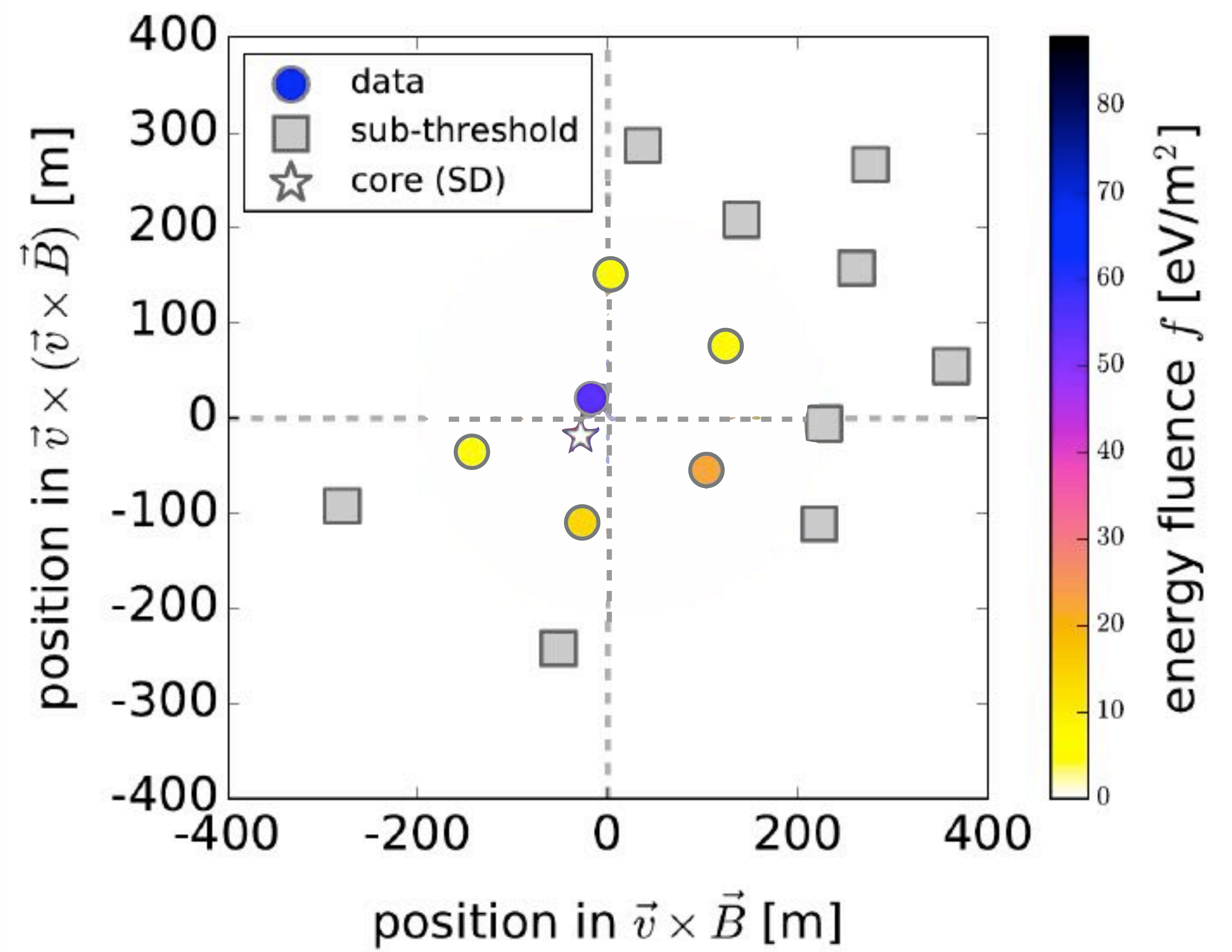
For a single radio station:

1. compute E-field vs time

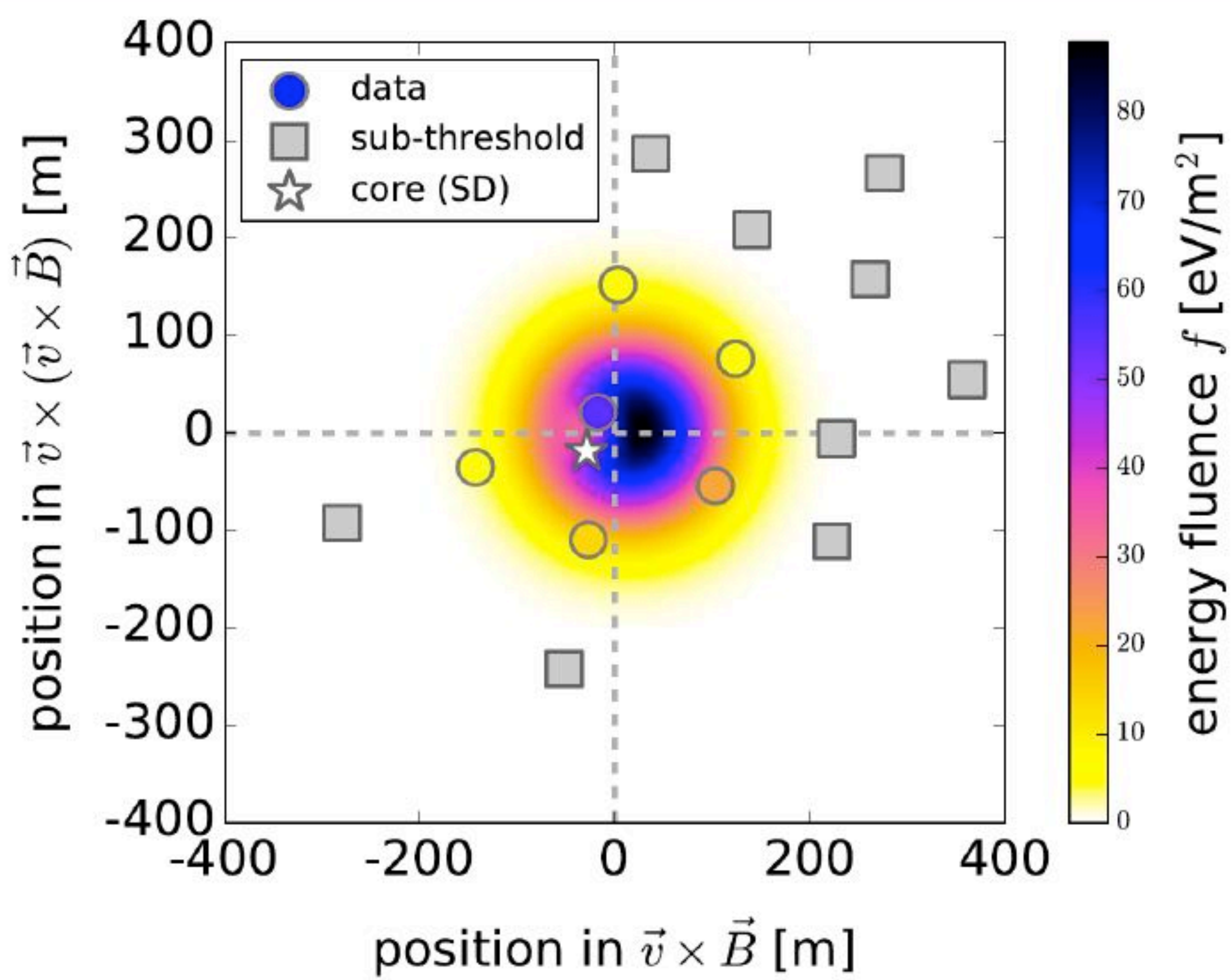
2. integrate the Poynting vector to get the energy fluence (eV/m^2)



Energy estimation: single station data, eV/m^2



Energy estimation: 2D LDF best fit



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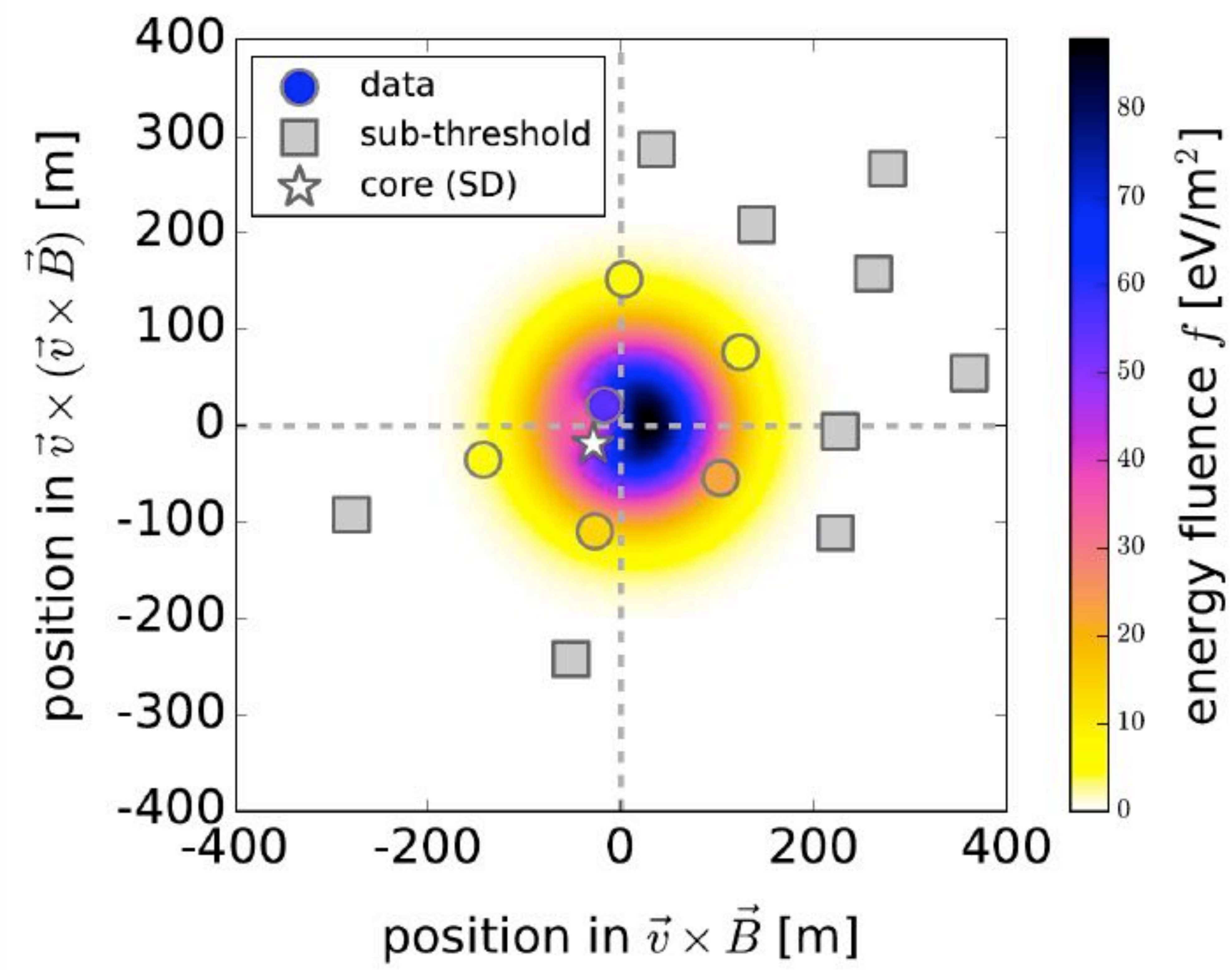
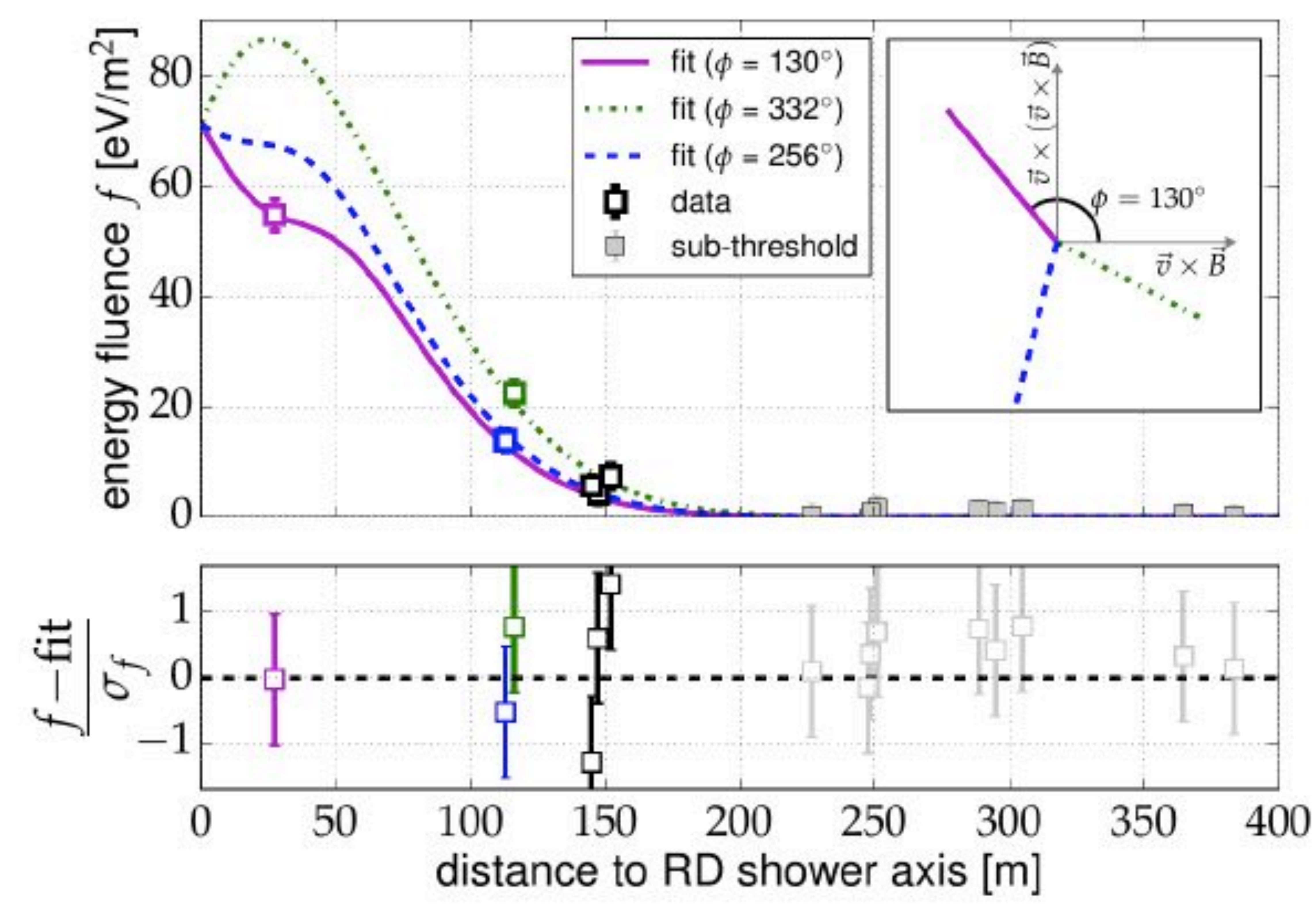
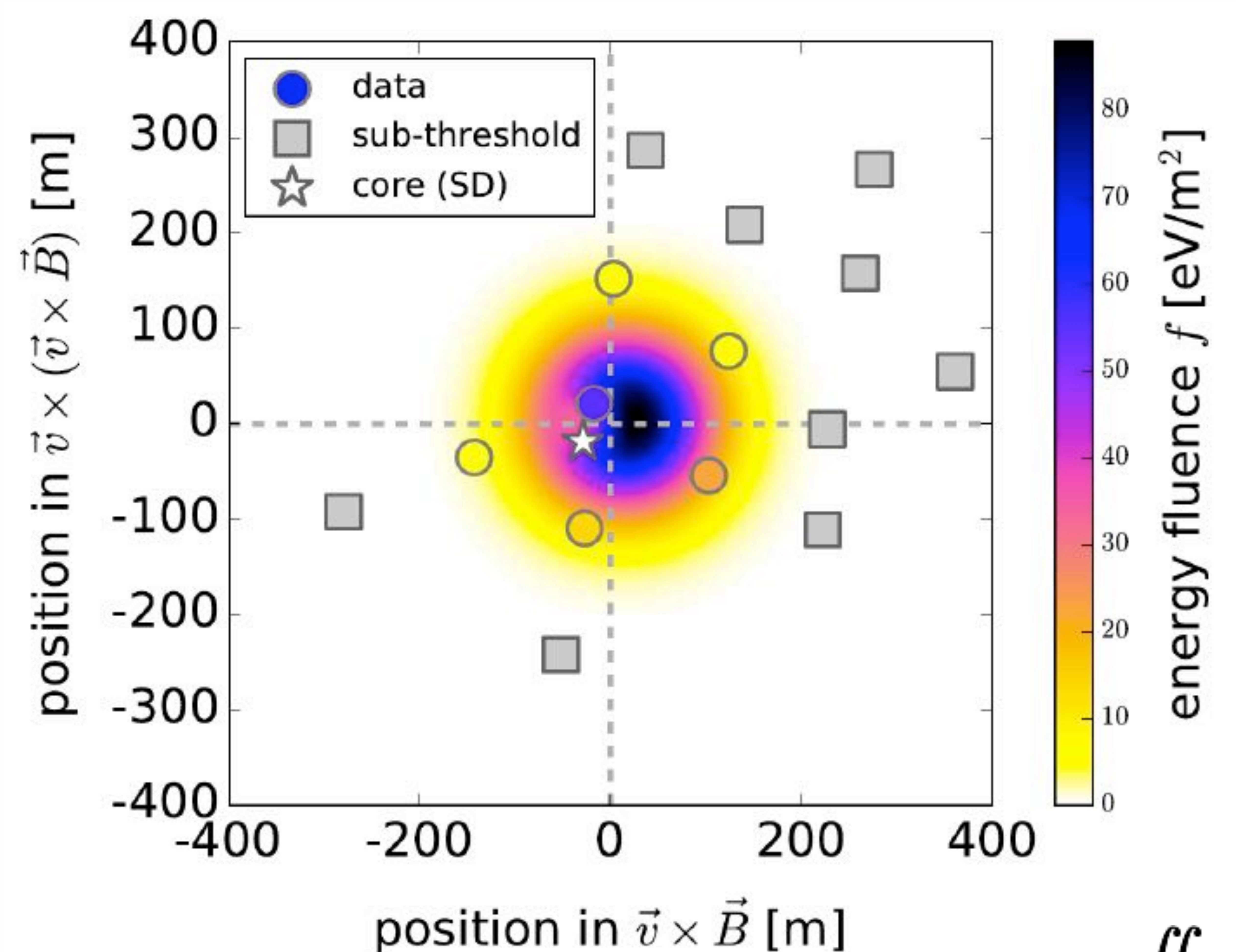


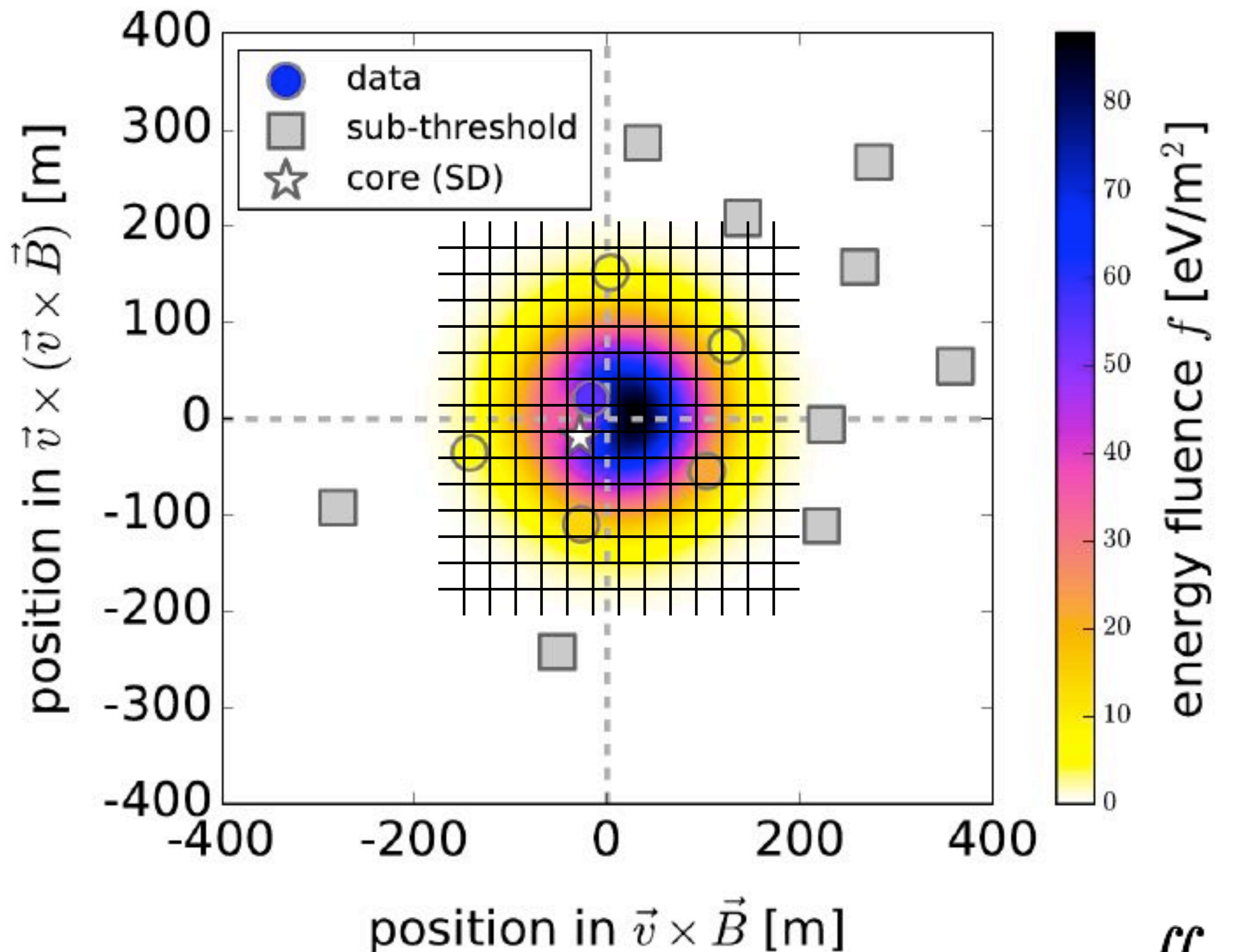


Energy estimation: 2D LDF integration



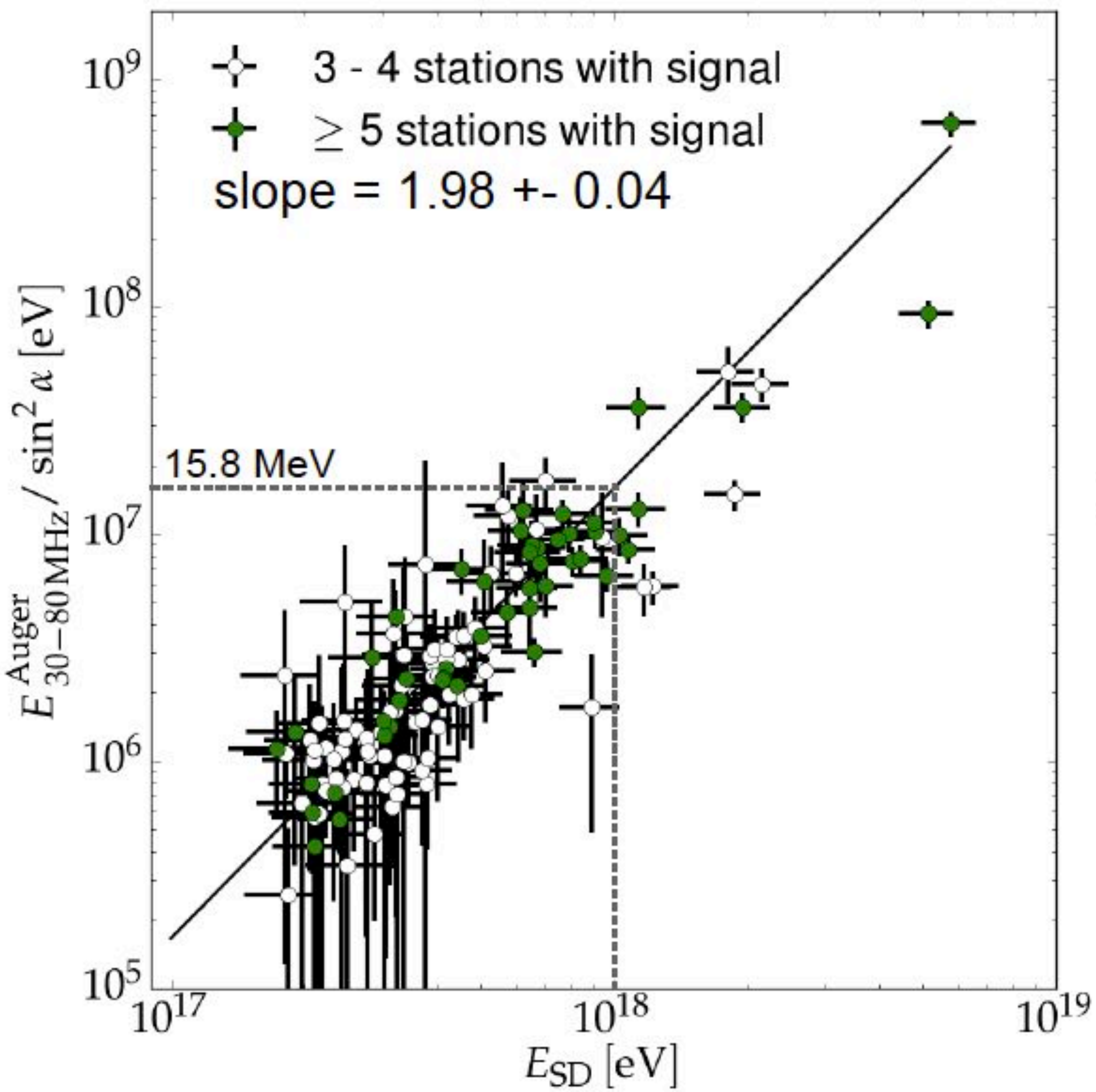
$$E_{\text{radio}} = \iint \text{LDF}(x, y)\, \mathrm{d}x\, \mathrm{d}y$$

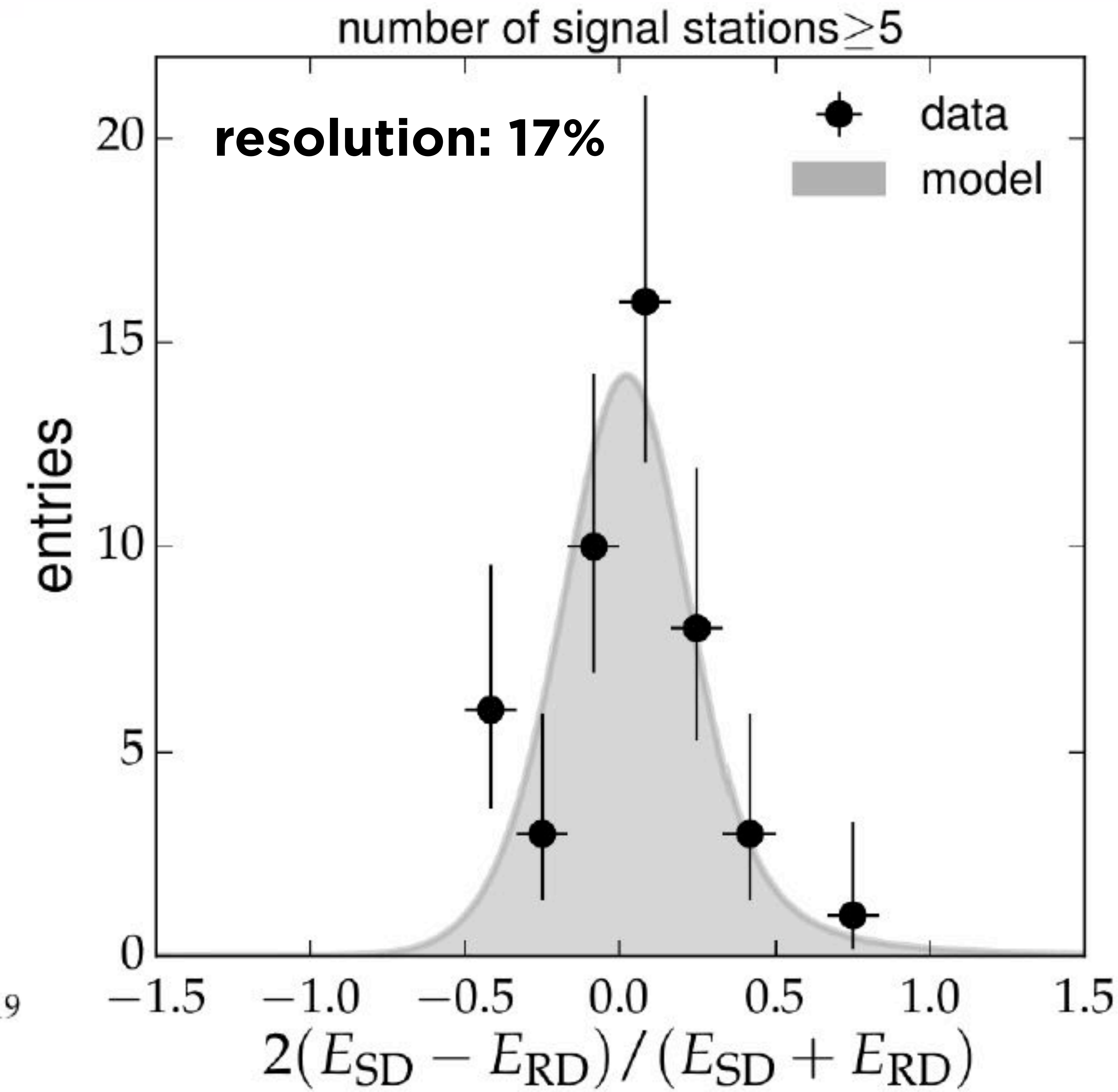
Energy estimation: 2D LDF integration



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

using events in coincidence with Auger SD,
compare the deposited energy with the SD energy:





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

Calorimetric energy estimation

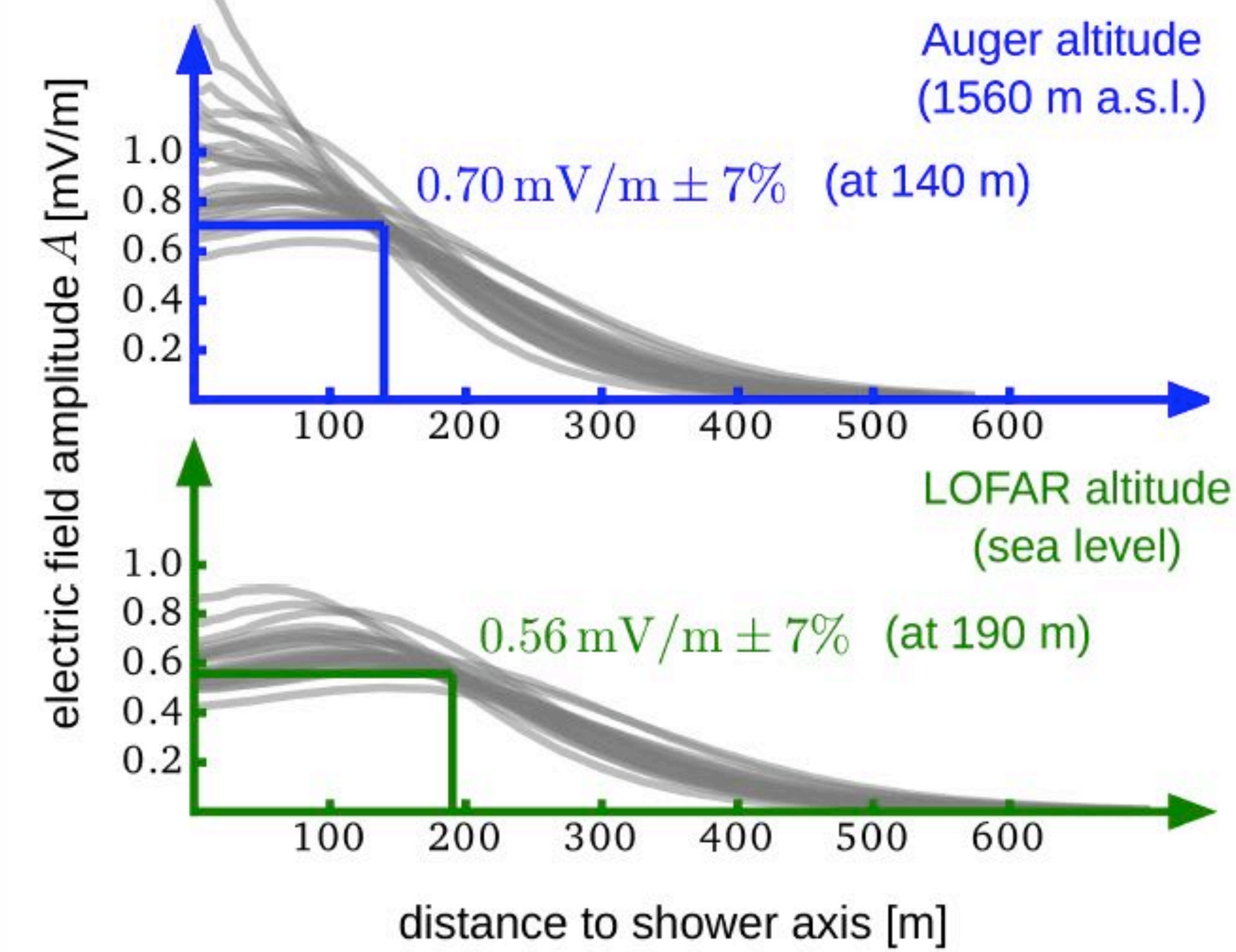
this provides a calorimetric energy estimation from the **radiated energy** in [30-80] MHz:

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

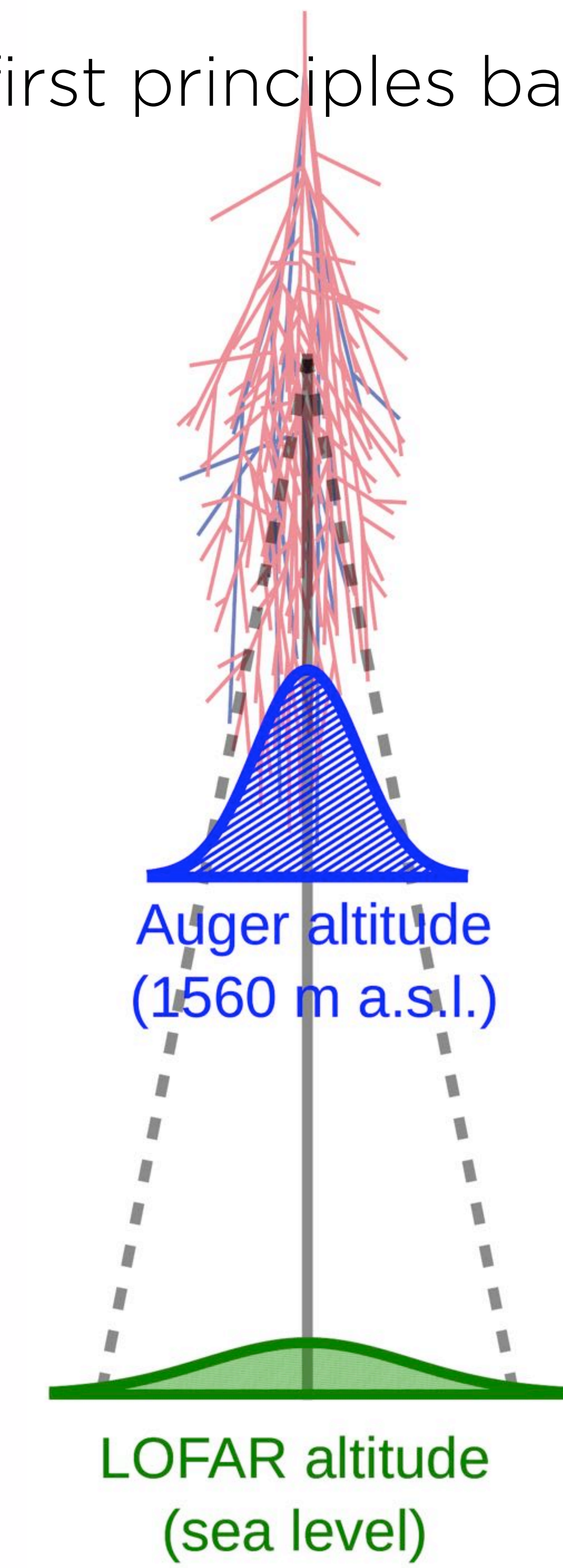
Auger collab., PRL 116, 241101 (2016)
Auger collab., PRD 93, 122005 (2016)

- 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:



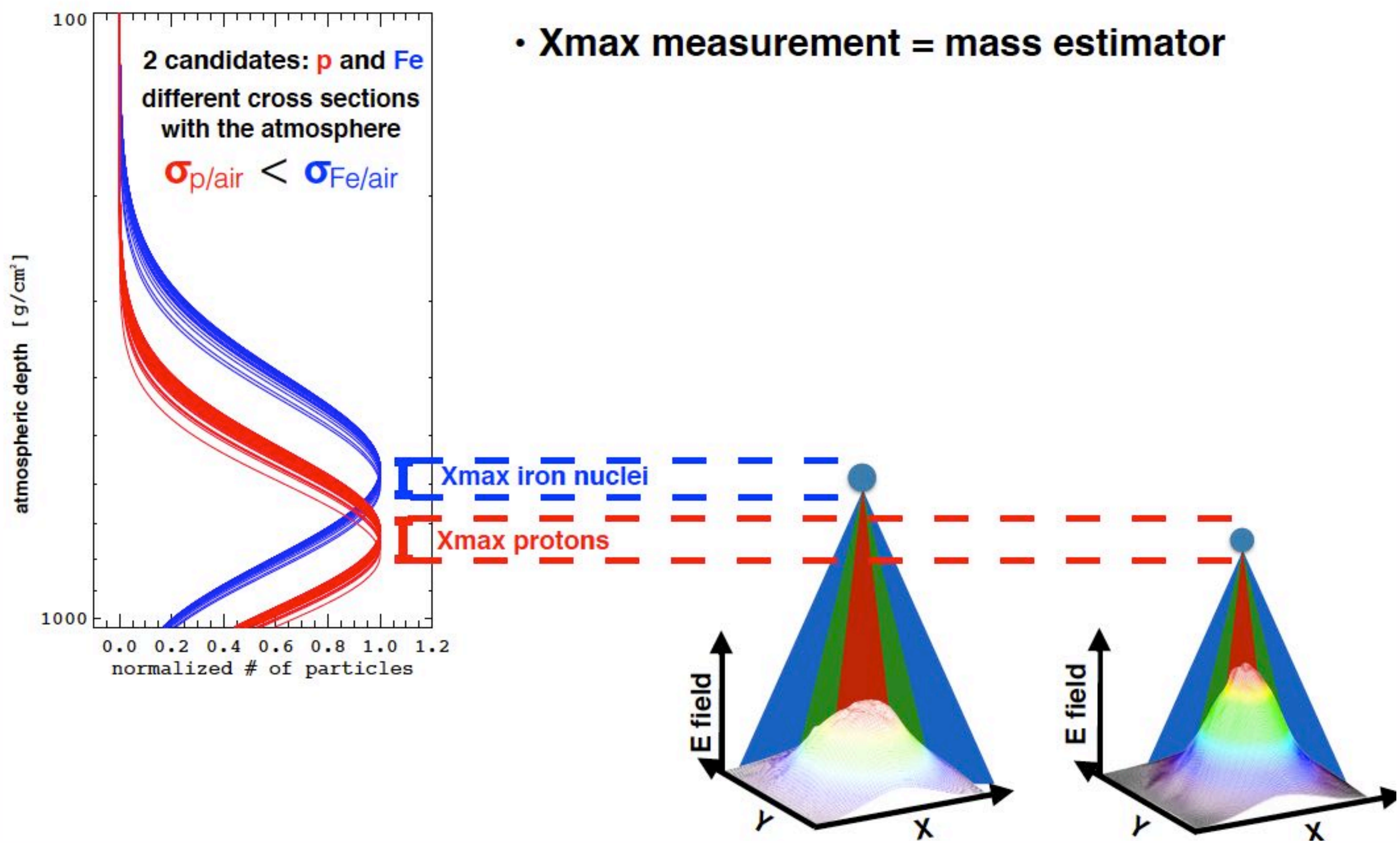
two different amplitudes at two different optimal axis distances!



but the same radiated energy: 11.9 MeV

X_{max} determination

strong correlation between the X_{max} and the shape of the 2D LDF



X_{max} determination

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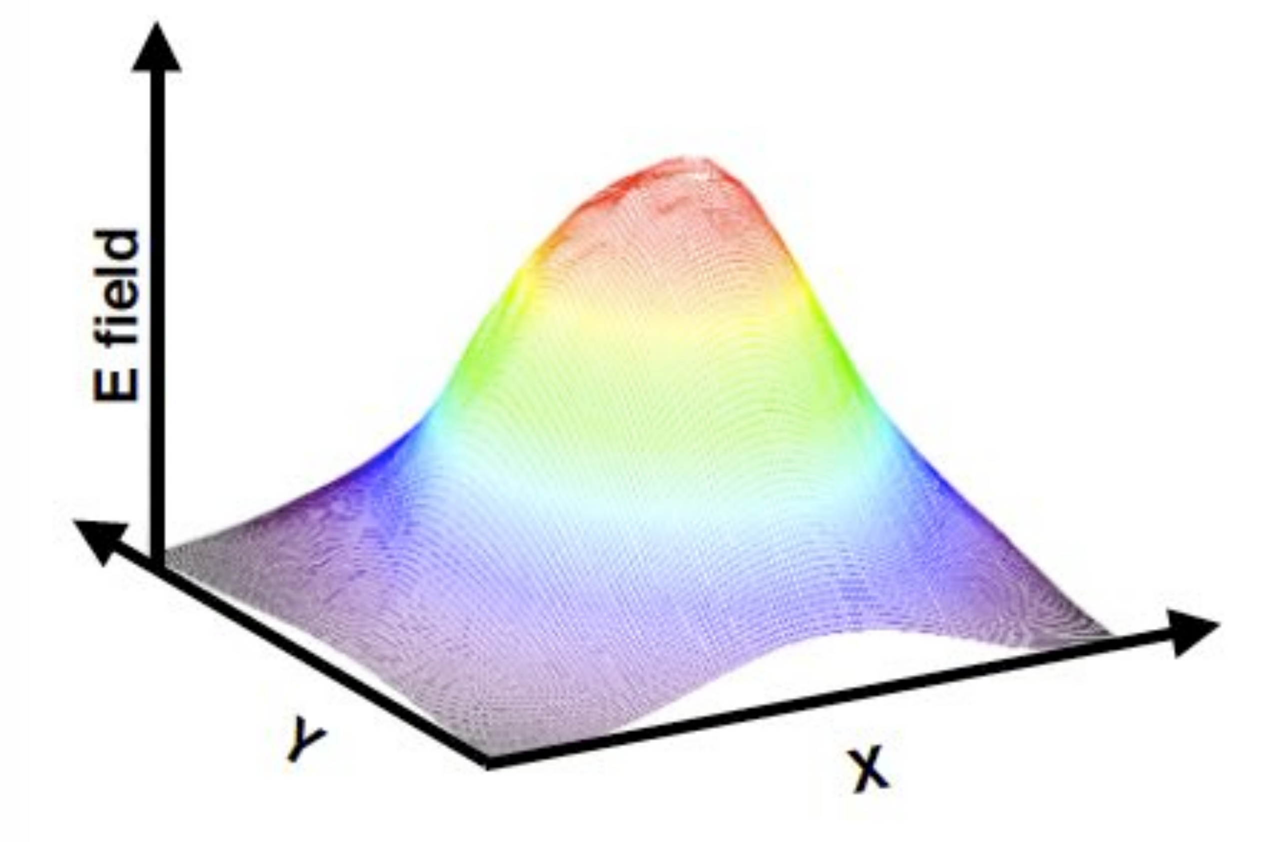
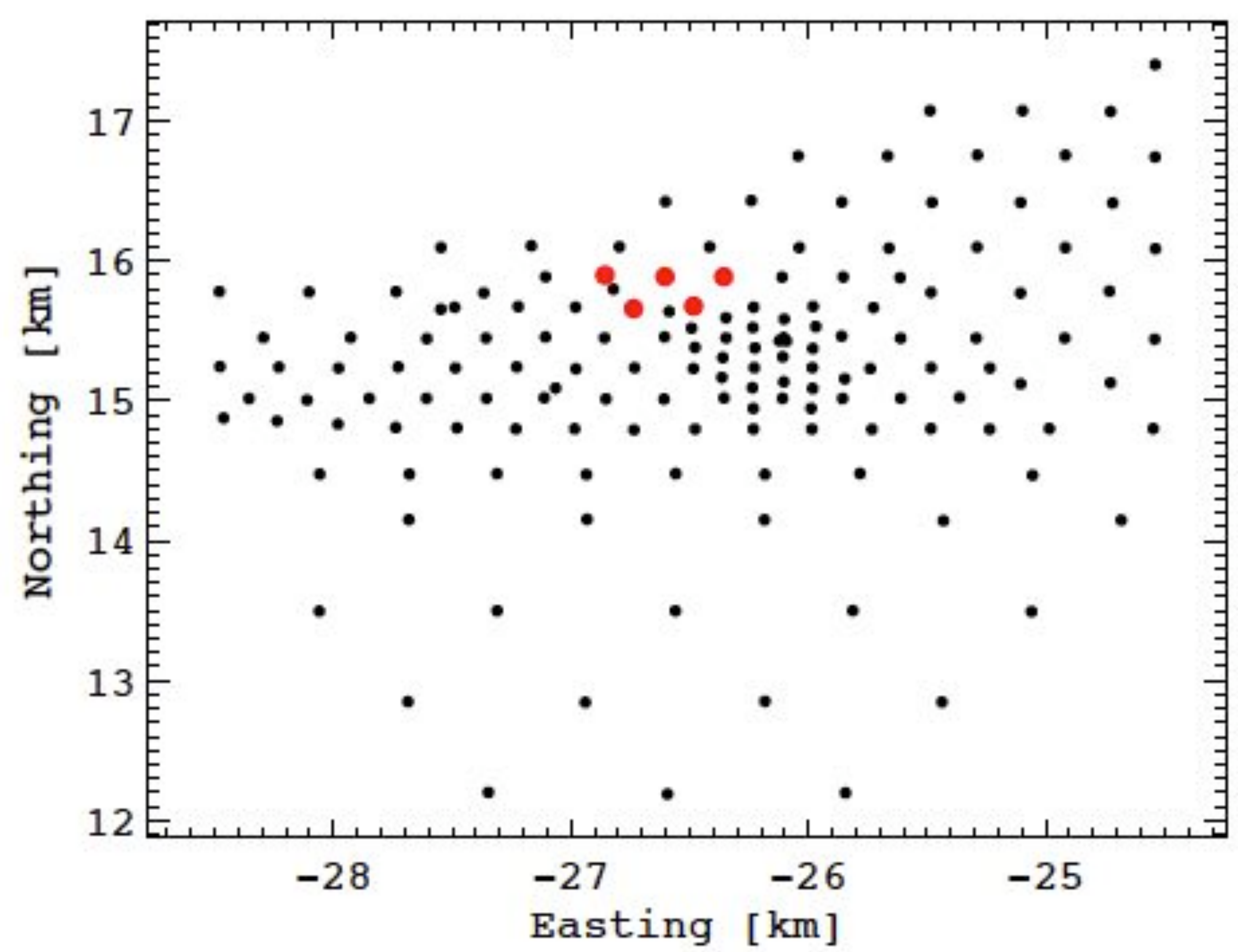
3 methods currently studied in AERA, example of the amplitude method
interpolate simulated (SELFAS) electric field at the measurement positions

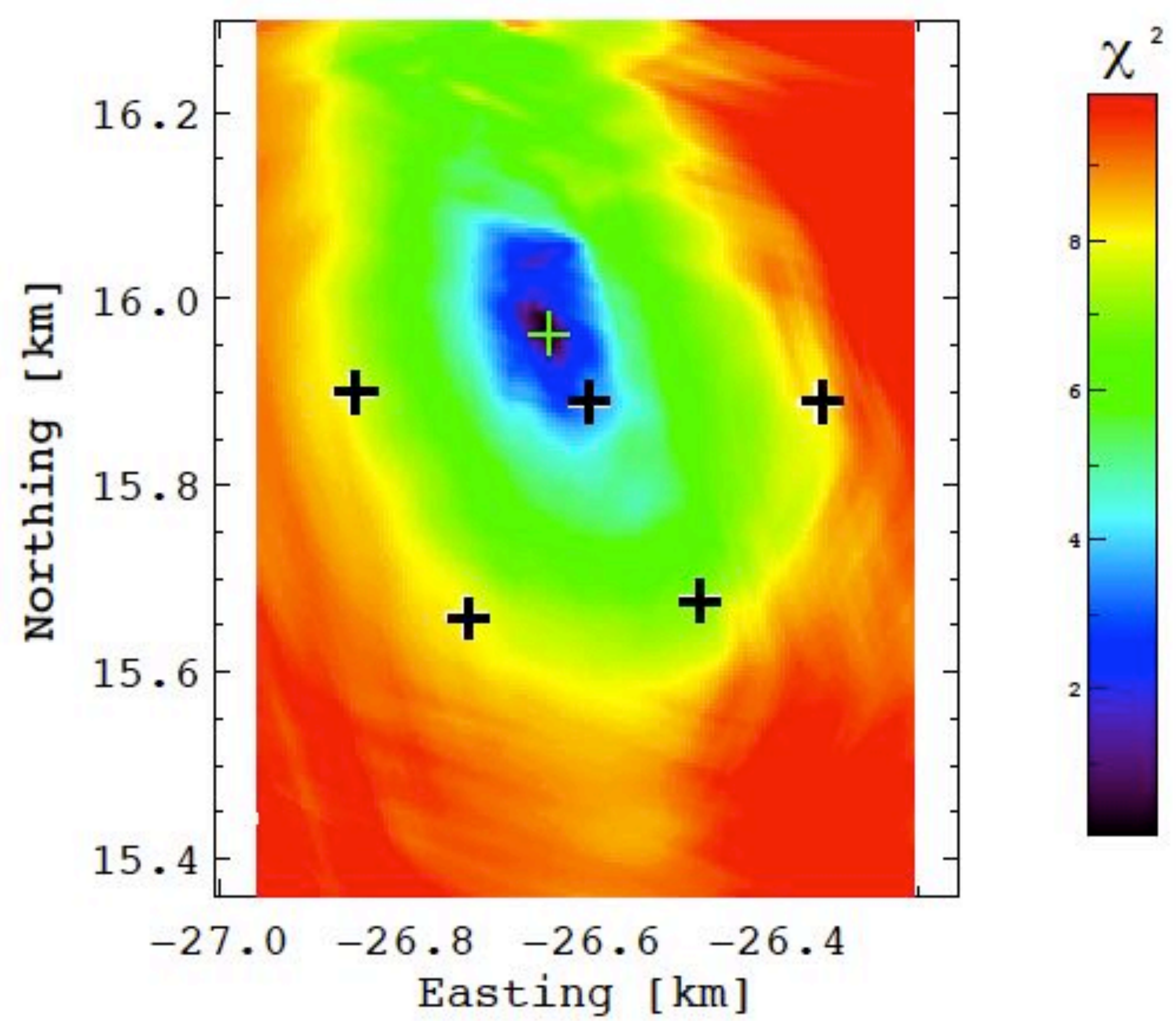


simulate the shower using the radio (θ,Φ) and assume 1 EeV



compare expected values to data

obtain best core position



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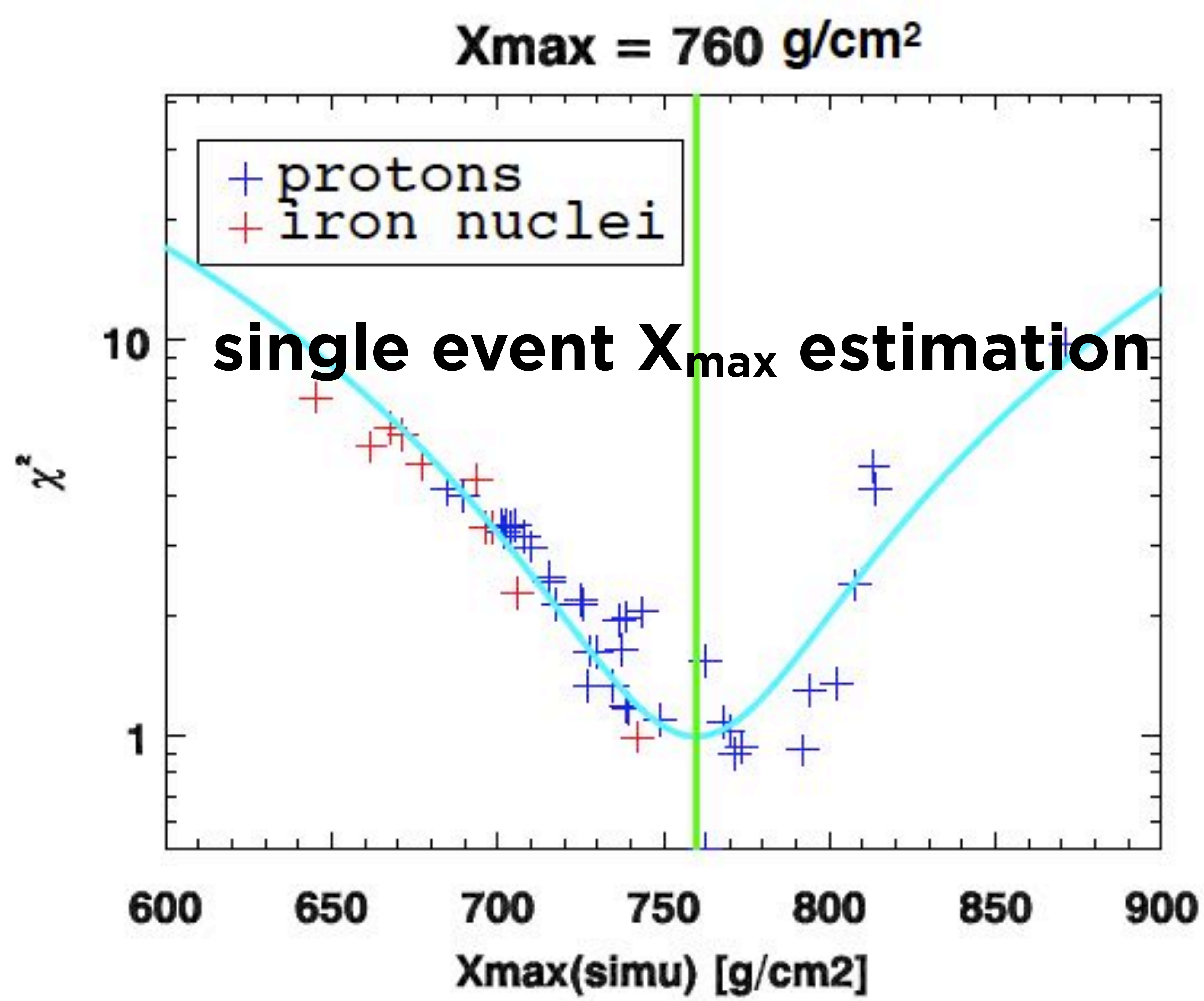
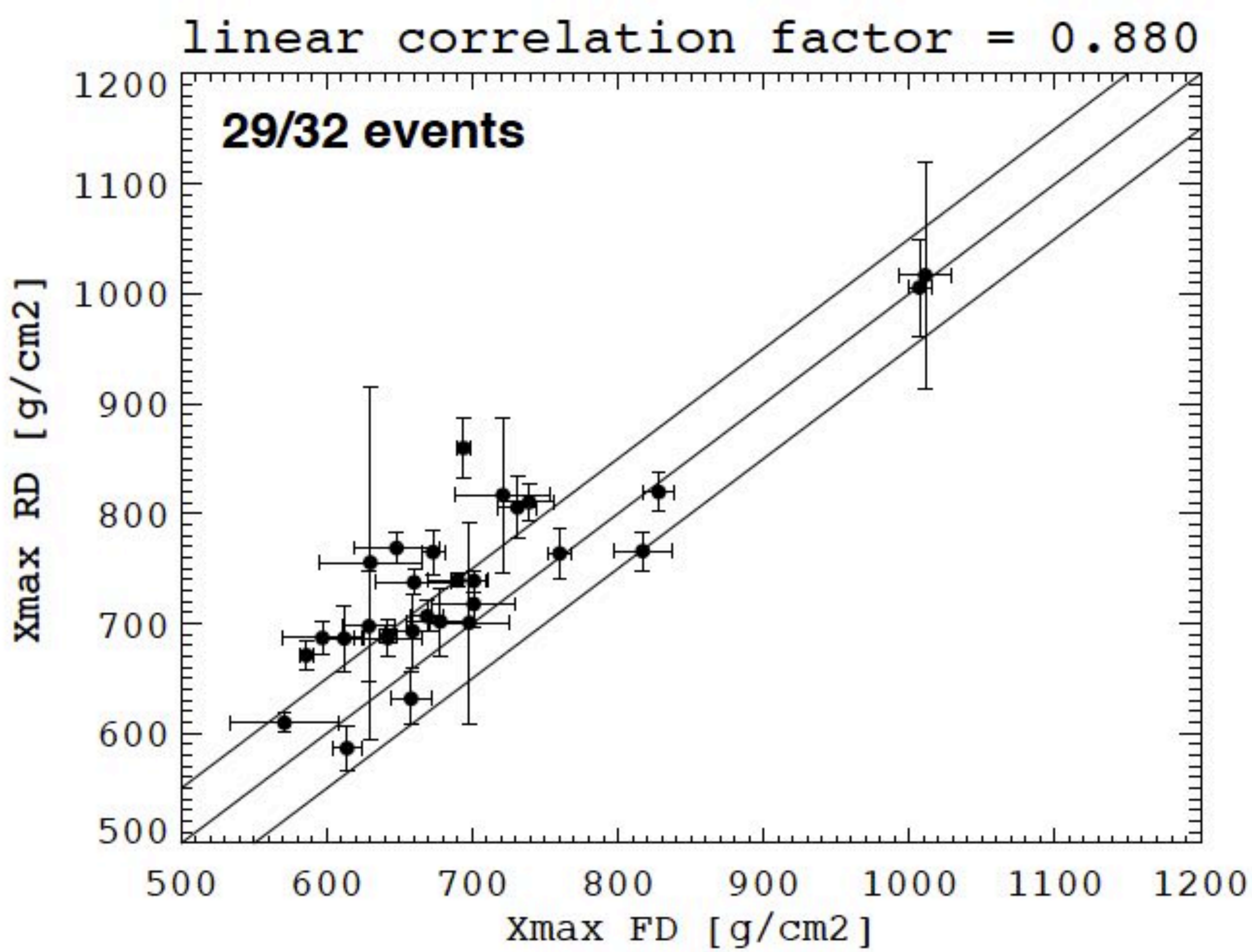




width of residuals: 40 g/cm^2

Conclusion

- AERA is properly calibrated, covers 17 km^2 and produces high-quality data in correlation with showers detected by all detectors of the Pierre Auger Observatory

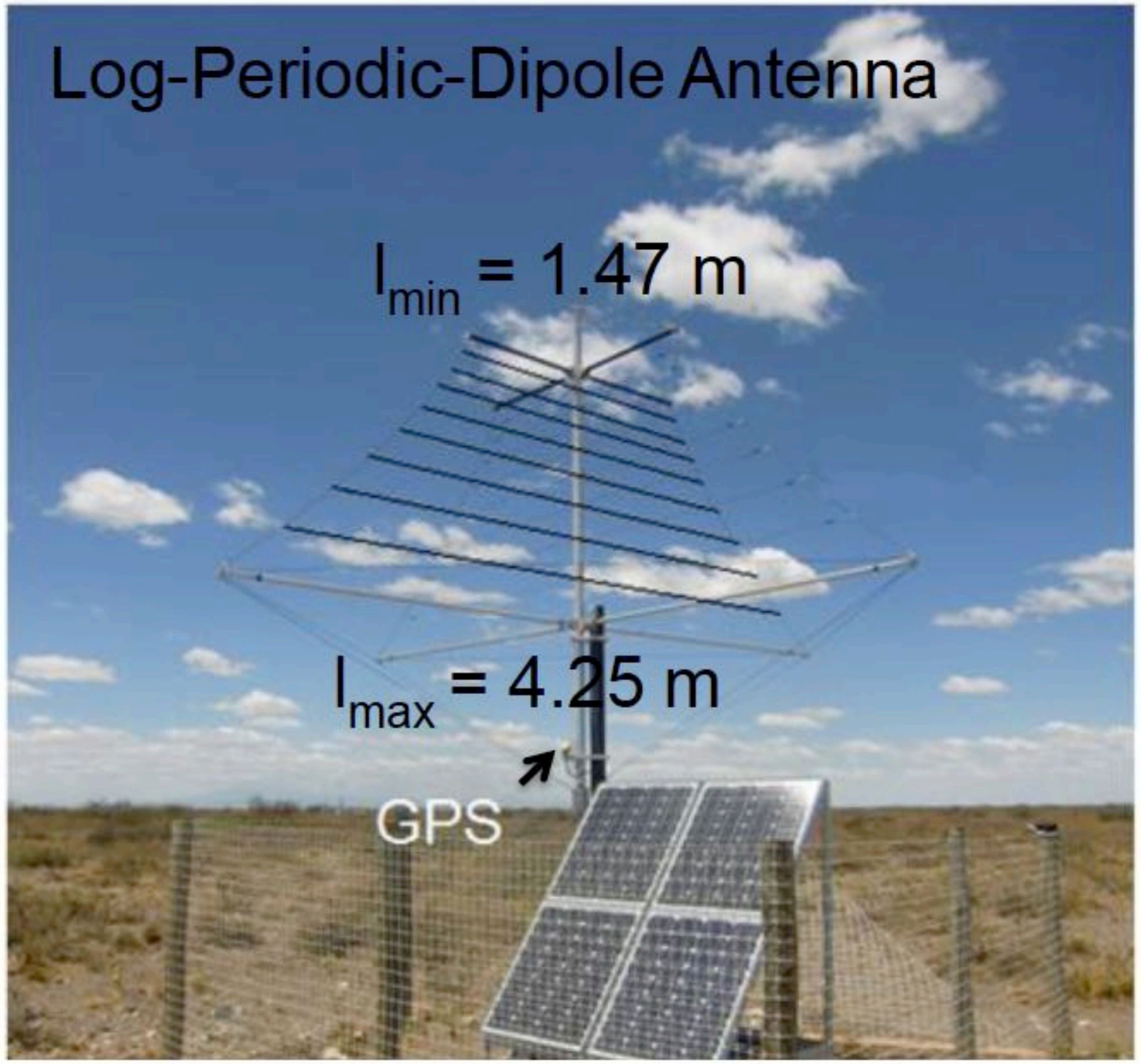
- the source of the radio signal is relatively well understood

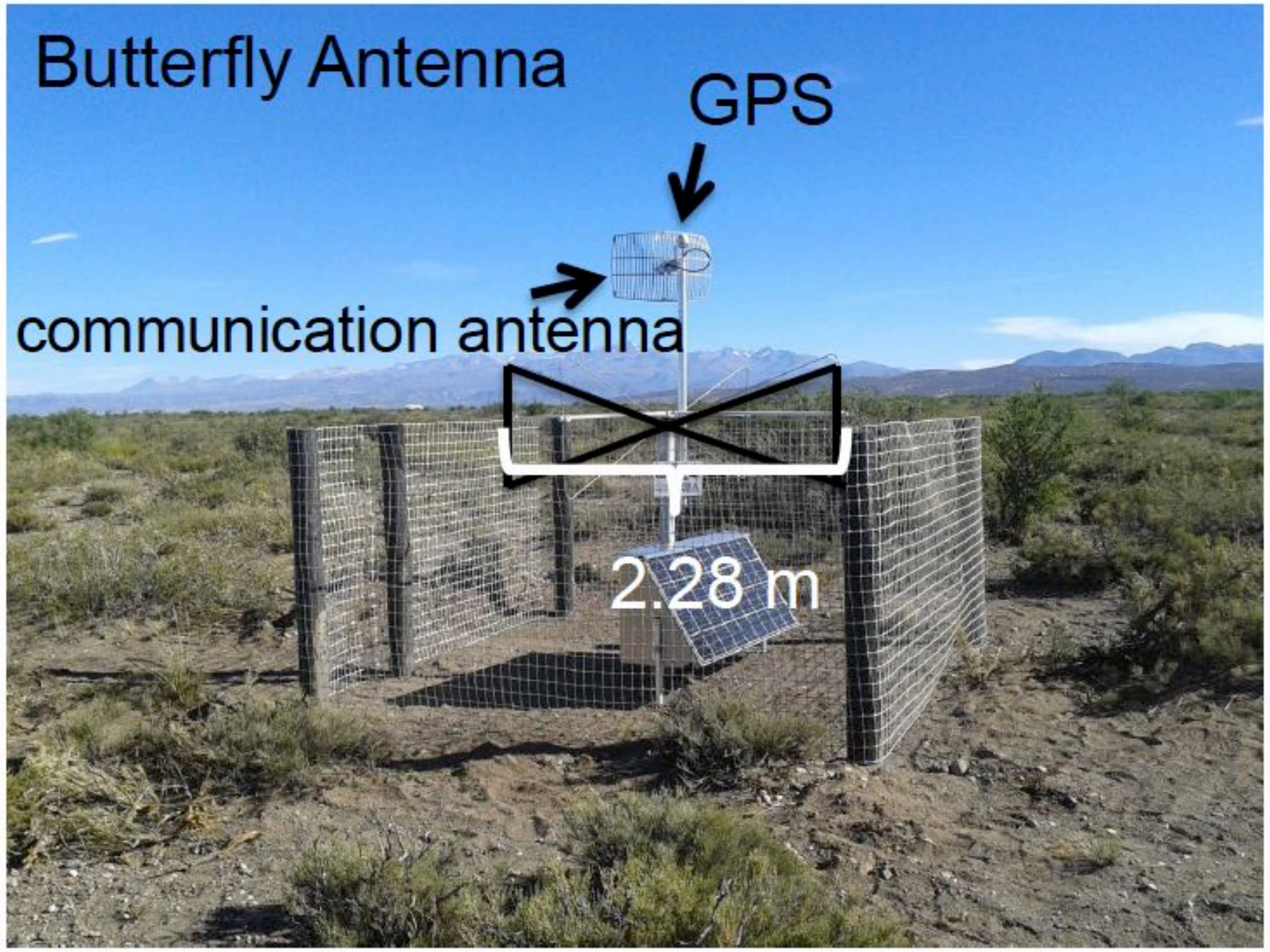
- Energy:
  - the primary energy is partly released as radiation energy in a calorimetric way: 1 EeV => 16 MeV in [30-80] MHz
  - the energy resolution using the radio signal is 17%
  - this provides a new independent energy scale for CR experiments

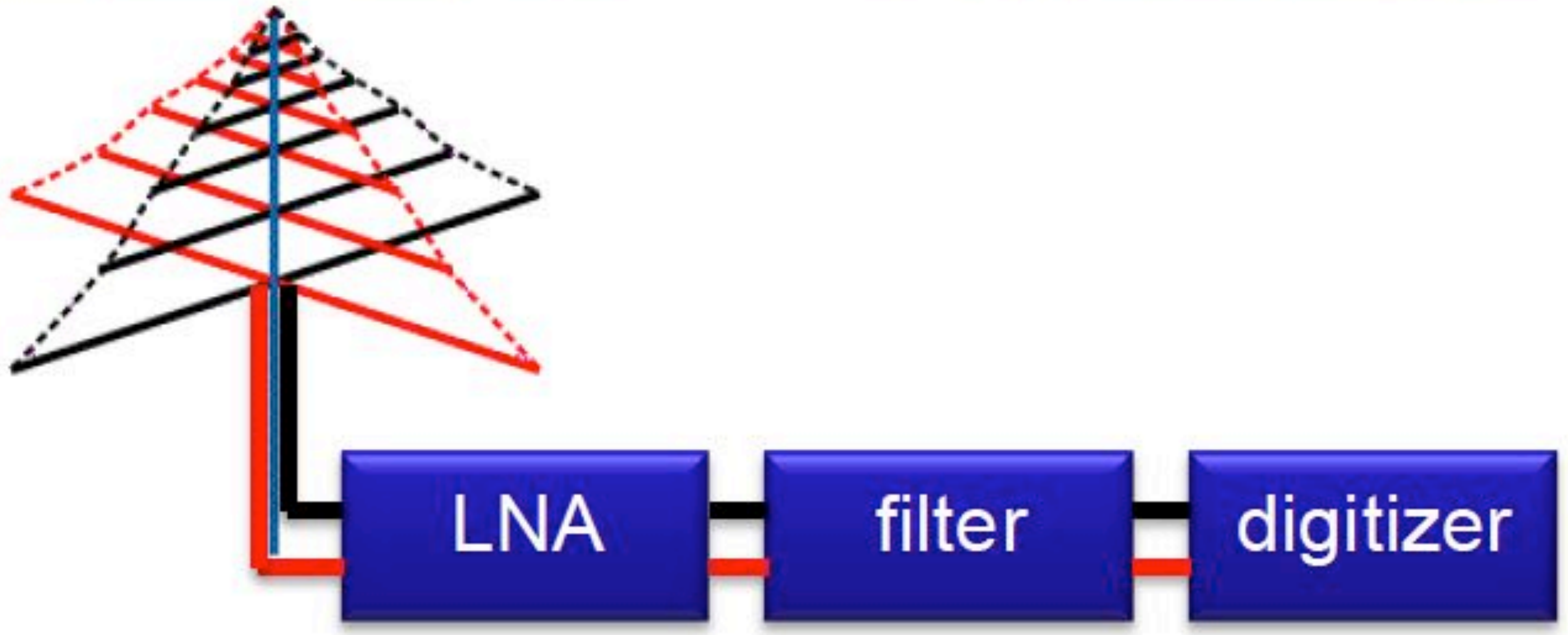
- Composition:
  - we work on a systematic measurement of Xmax, for each event, with a ~100% duty cycle
  - we expect around 40 g/cm^2 resolution

- data analysis of the full array ongoing, we aim at providing results on the energy spectrum and composition in the transition region

RICAP 16



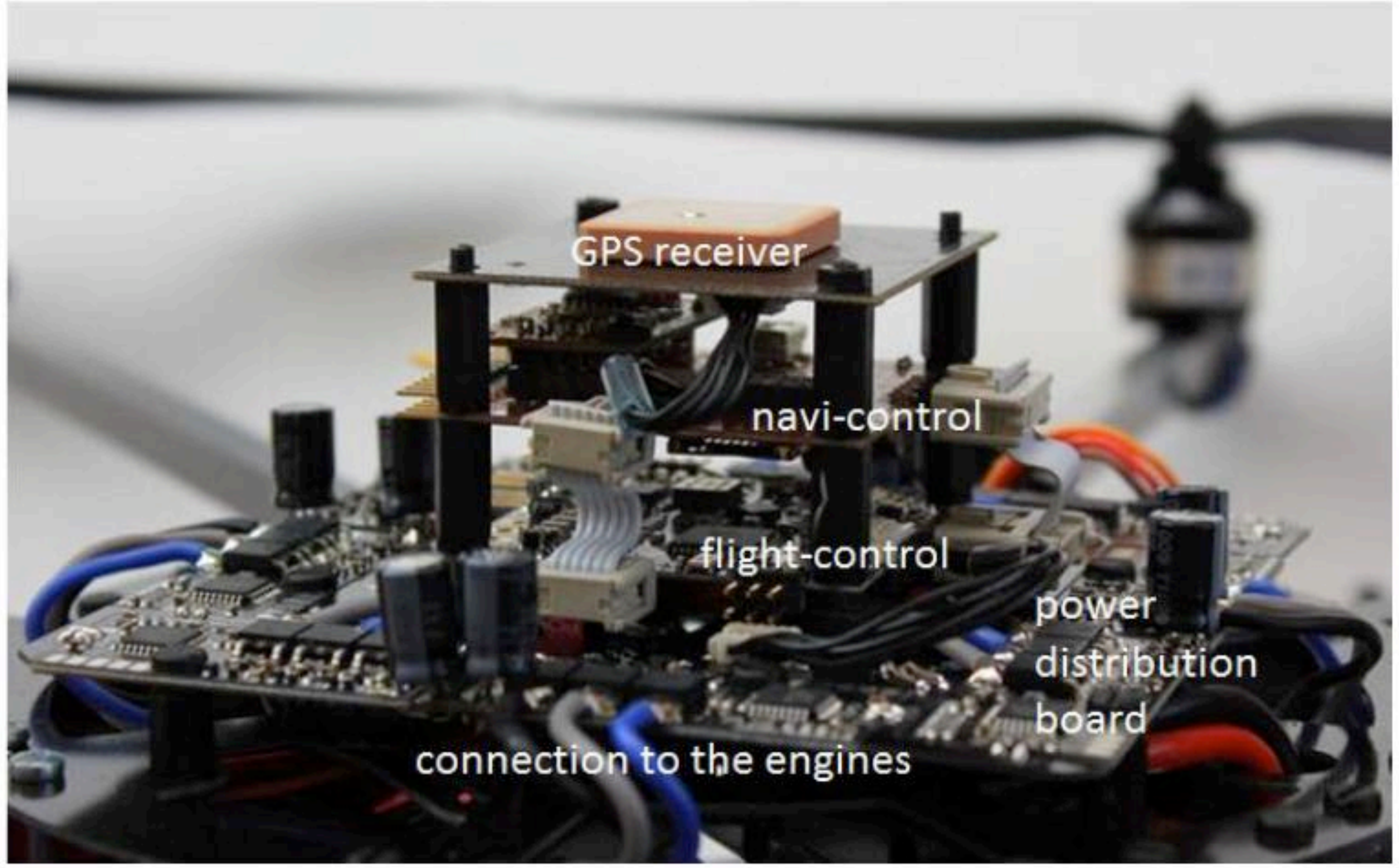




5

- 2 different radio station types
- NS and EW polarized antenna
- antenna alignment:
  to magnetic north with precision < 1°
- bandwidth: 30MHz - 80MHz
- autonomous radio station
- power consumption: ~10W

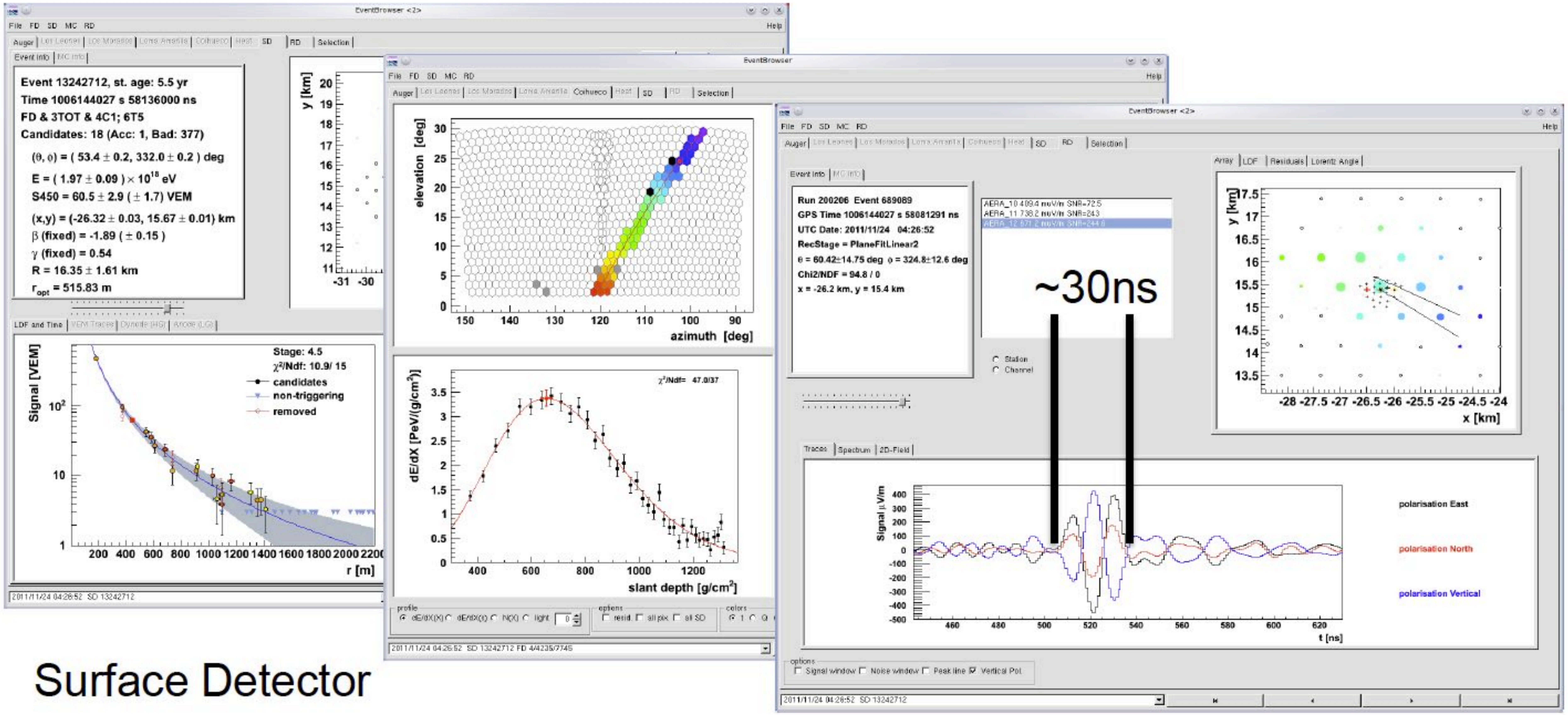
(Raphael Krause, Vienna 2016)



- power: 6600 mAh Lipo 13-16V
- payload: ~2000g
- mass: 2545g (including 715g accumulator)
- flight time: 25min/9min (wo/w payload)
- barometer → elevation
- gyroscope → inclination
- acceleration sensor → angular speed
- GPS → position

9

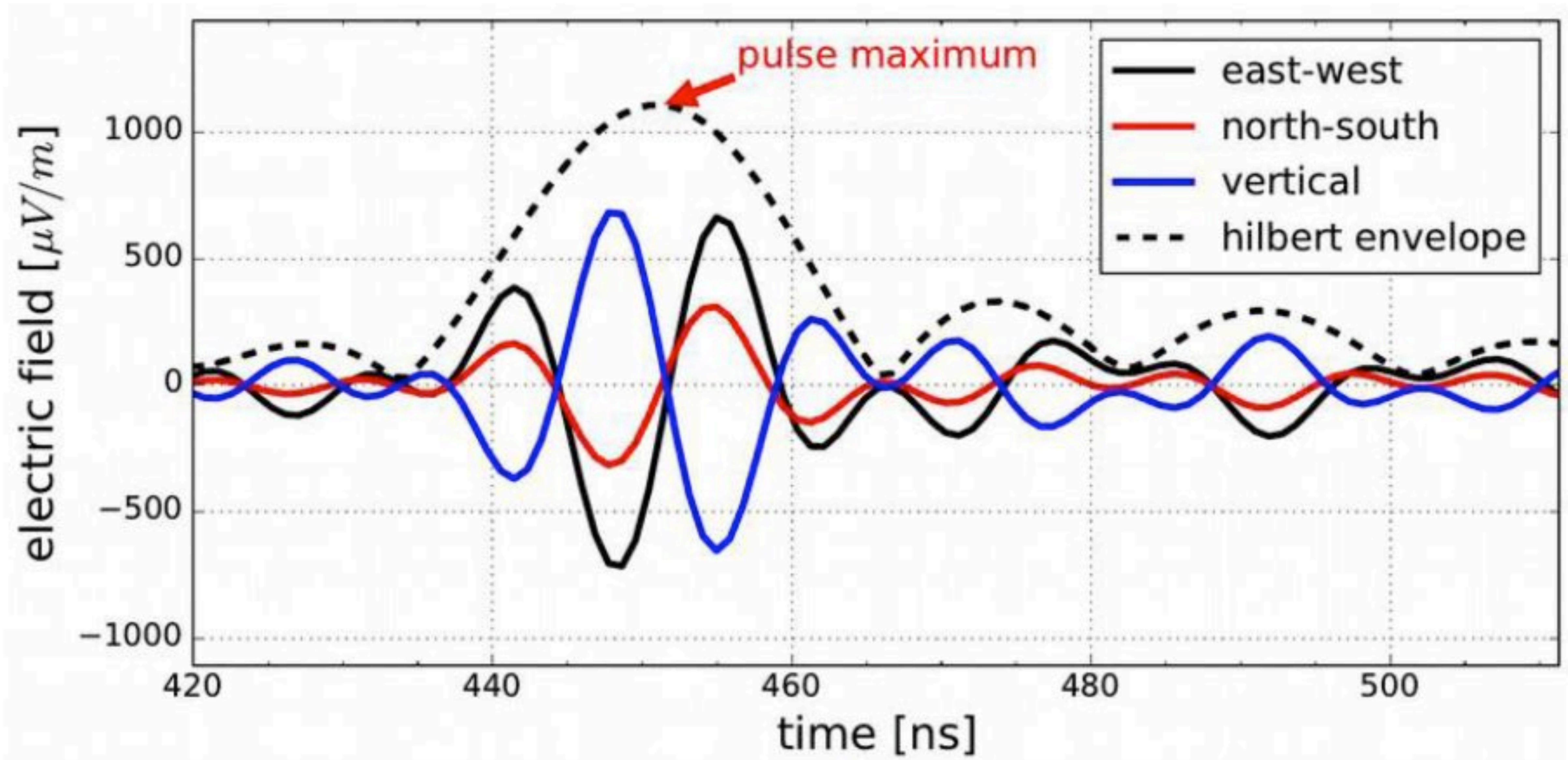
Vienna Conference on Instrumentation 2016
Raphael Krause | RWTH Aachen University | 18.02.2016



Surface Detector

Fluorescence Detector

Radio Detector



- window around maximum of Hilbert envelope
- energy fluence in eV/m^2
  - → time integral of Poynting vector
  - → noise expectation subtracted
  - → $u = \varepsilon_0 c \left(\Delta t \sum_{t_1}^{t_2} |\vec{E}(t_i)|^2 - \Delta t \frac{t_2 - t_1}{t_4 - t_3} \sum_{t_3}^{t_4} |\vec{E}(t_i)|^2 \right)$

(Christian Glaser, ARENA 2016)

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

C constants obtained from CoREAS simulations

⩽ 5 stations: get Λ and σ

⩾5 stations : get Λ, σ, rcore

TABLE III. Parameters C_0 - C_4 of Eq. (4). $C_3 = 16.25\,\mathrm{m}$ and $C_4 = 0.0079\,\mathrm{m}^{-1}$. The zenith-angle dependent values used to predict the emission pattern are given for zenith angle bins up to 60°.

zenith angle	C_0	C_1[m]	C_2 [m]
$0° - 10°$	0.41	-8.0 ± 0.3	21.2 ± 0.4
$10° - 20°$	0.41	-10.0 ± 0.4	23.1 ± 0.4
$20° - 30°$	0.41	-12.0 ± 0.3	25.5 ± 0.3
$30° - 40°$	0.41	-20.0 ± 0.4	32.0 ± 0.6
$40° - 50°$	0.46	-25.1 ± 0.9	34.5 ± 0.7
$50° - 60°$	0.71	-27.3 ± 1.0	9.8 ± 1.5

X_{max}

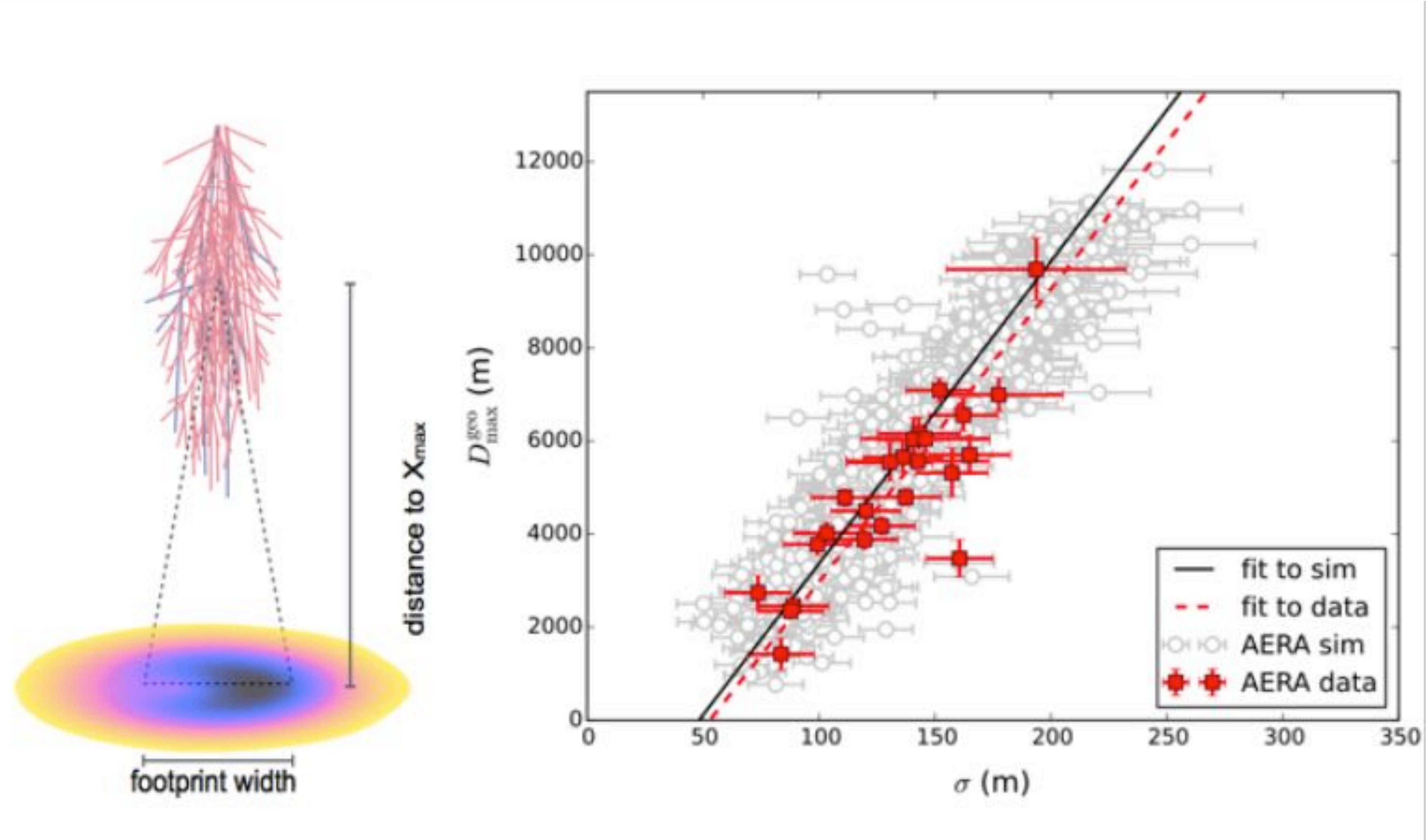
Method	A	B	C	D
model	**SELFAS** Astropart. Phys. 35 (2012) 733 – 741	**2D gaussian** Astropart. Phys. 60 (2015) 13	**CoREAS** AIP Conf. Proc. (2013) 128– 132	**ZHAireS** **horizontal components** Astropart. Phys. 59 (2014) 29
requirements	RD arrival direction	RD arrival direction	SD arrival direction SD energy	SD core (initialization) SD energy
# of simulations per event	40 p + 10 Fe	no simulation	20 p + 10 Fe	30 p + 30 Fe

(Florian Gaté, ARENA 2016)

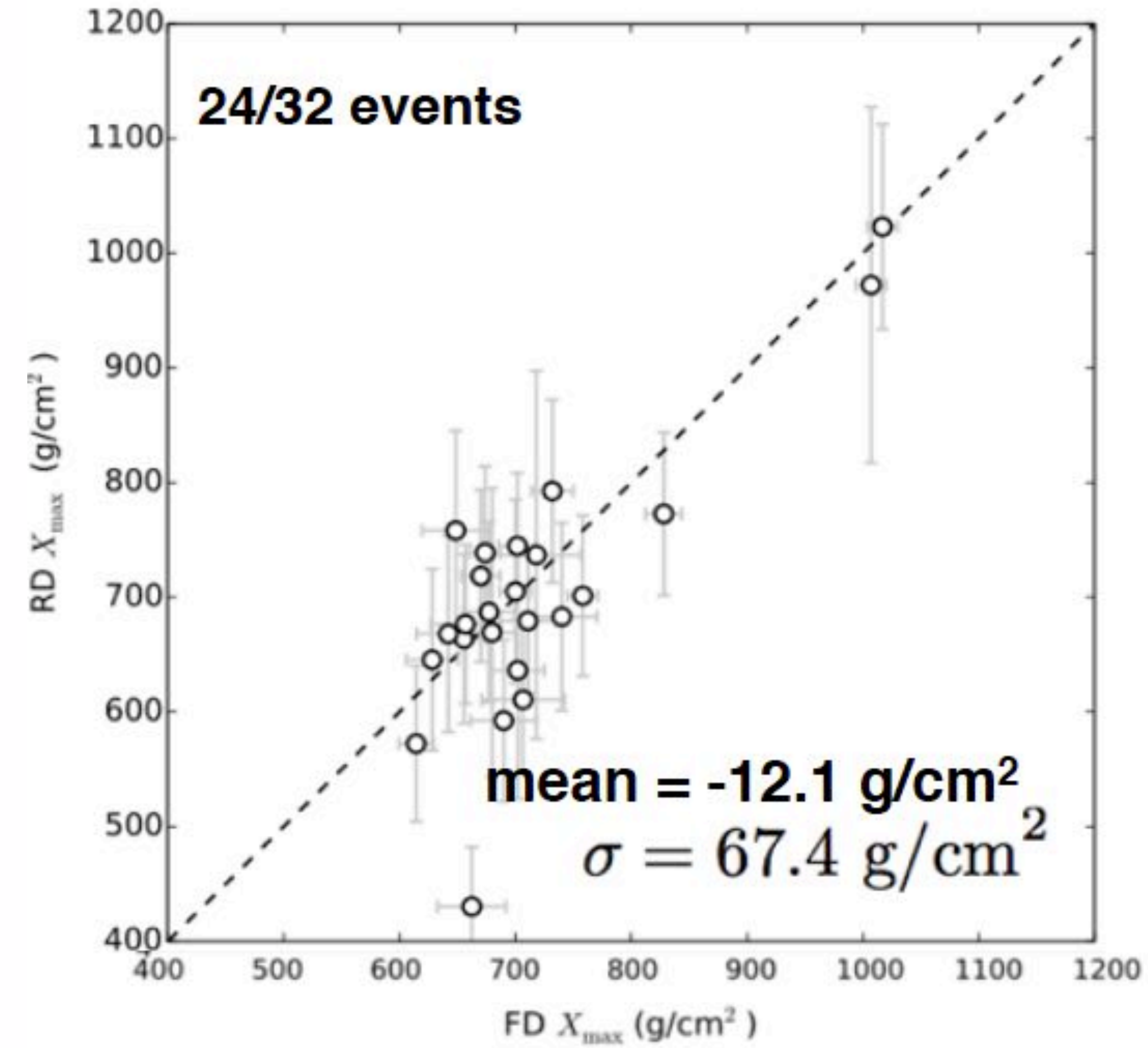
X_{max}

method based on the 2D LDF fit

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

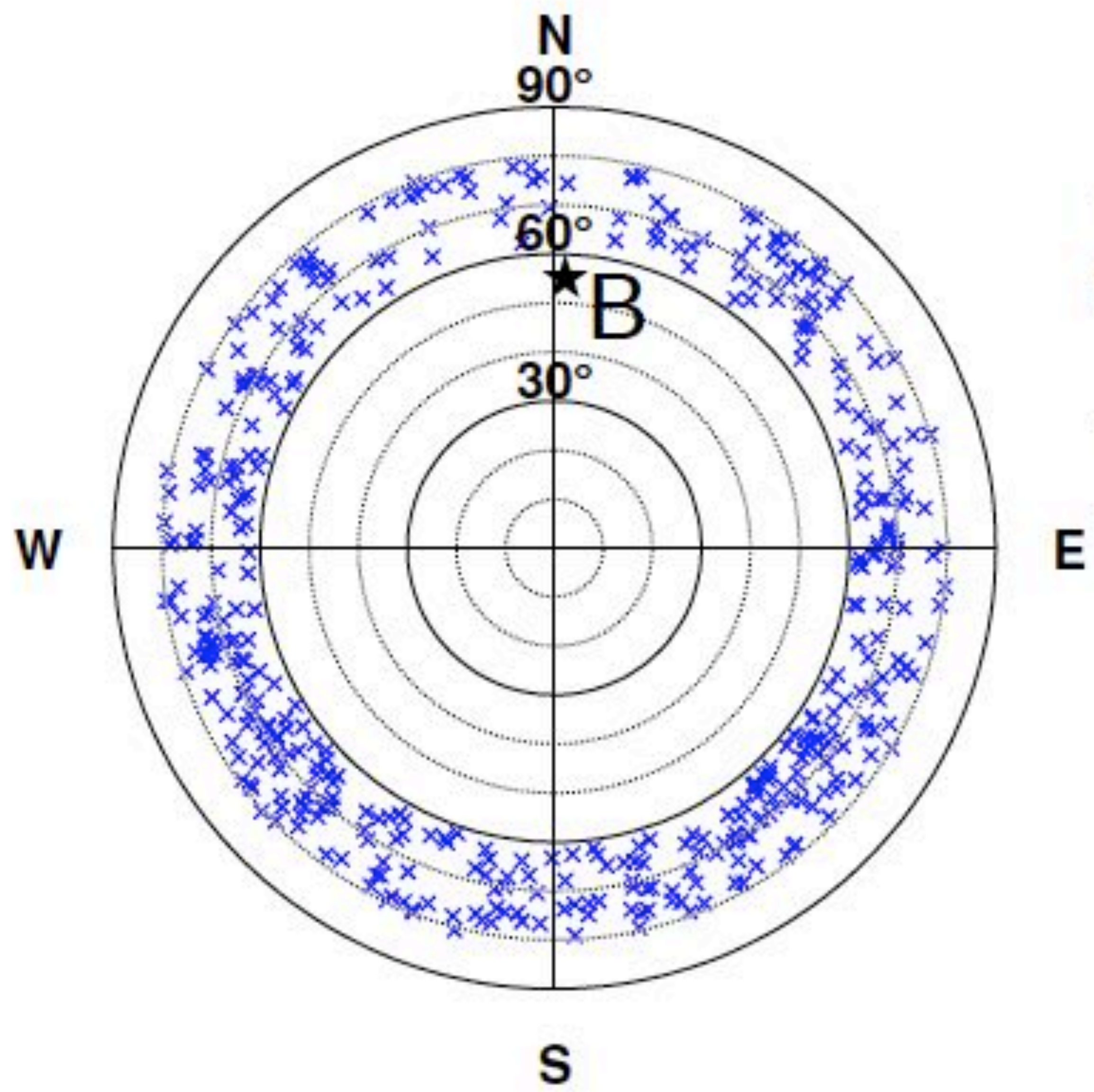


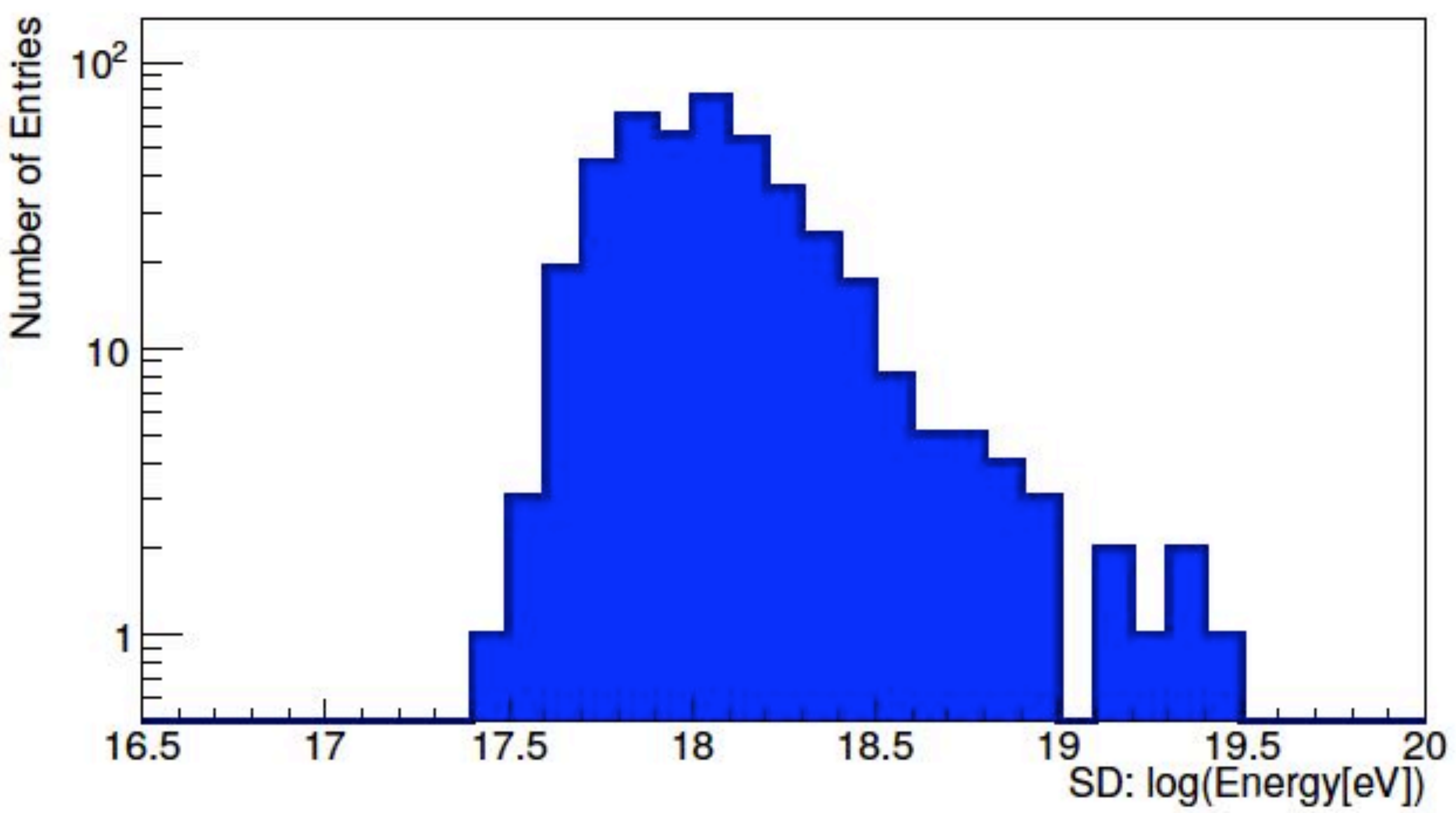
$$D^{\mathrm{geo}}_{\mathrm{max}}(X_{\mathrm{max}},\theta) = (h_{\mathrm{GDAS}}(X_{\mathrm{max}}/\cos\theta) - h_{\mathrm{Auger}})/\cos\theta$$



Horizontal showers

large multiplicity events (station spacing 750 m)



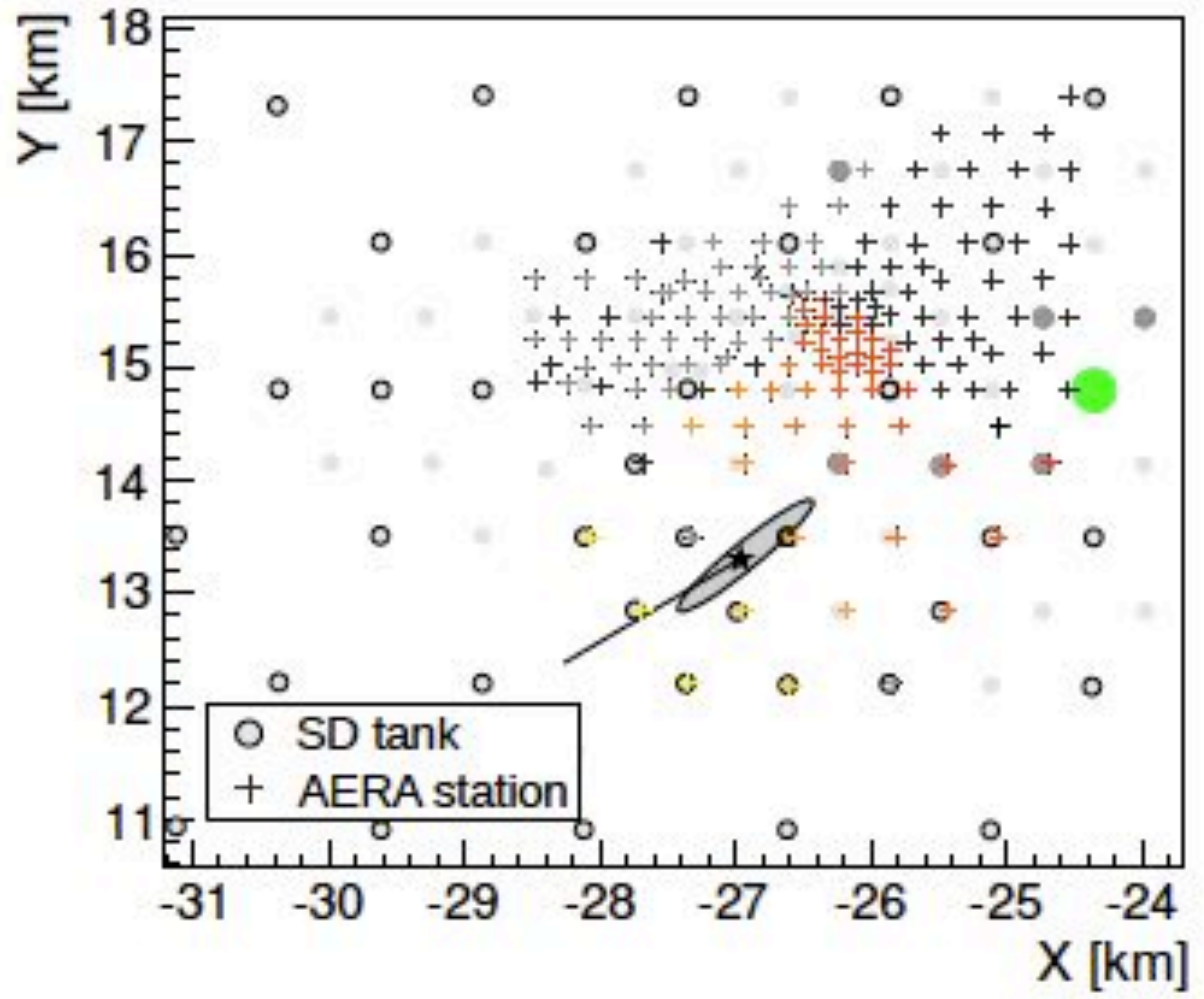


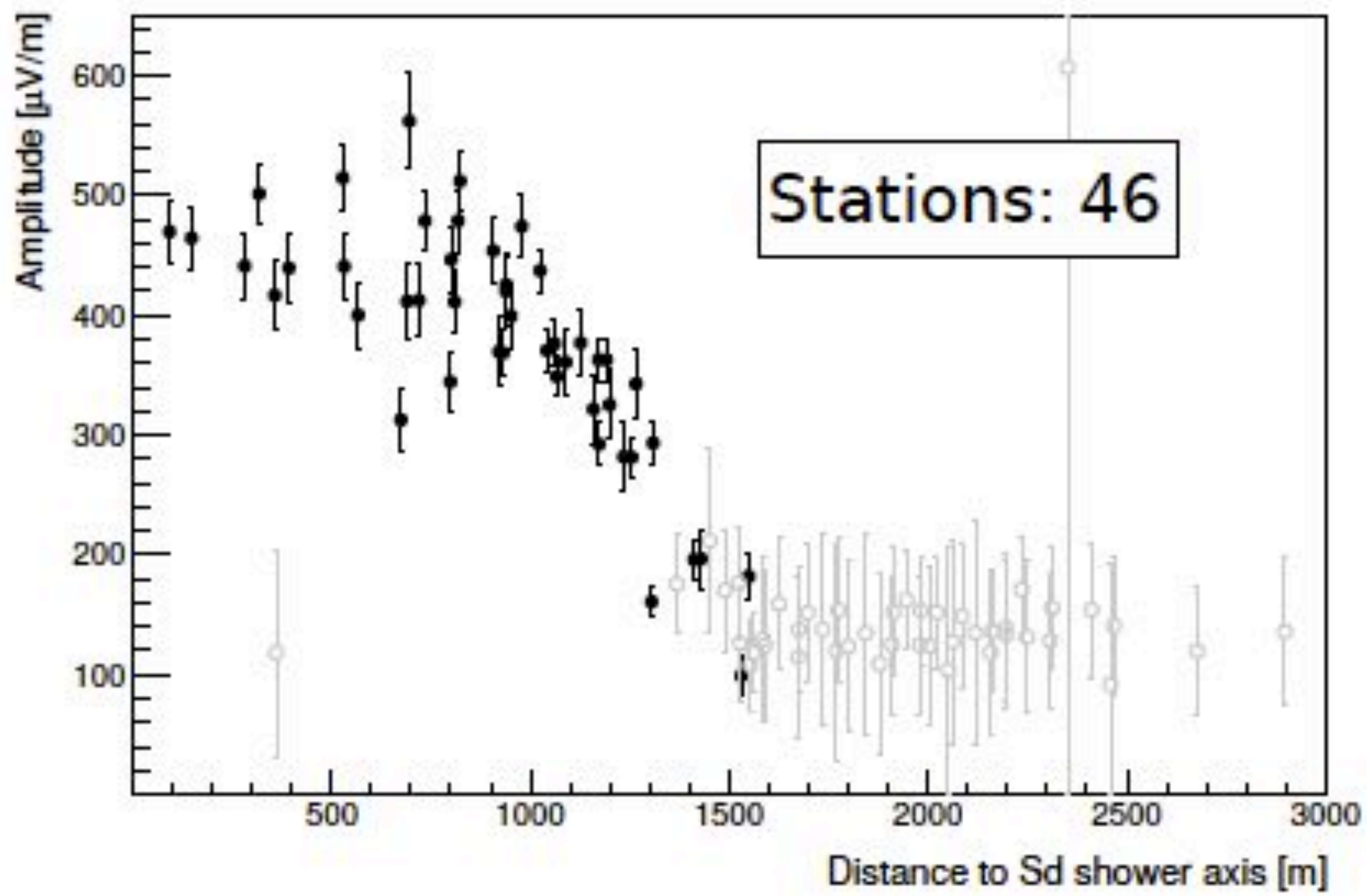
- 427 high quality horizontal radio events selected (January 1, 2012 to August 15, 2015)
- triggered and reconstructed by 1.5 km grid of surface tanks
- cut on zenith angles of 62° to 80°

(Olga Kambeitz, ARENA 2016)

Horizontal showers

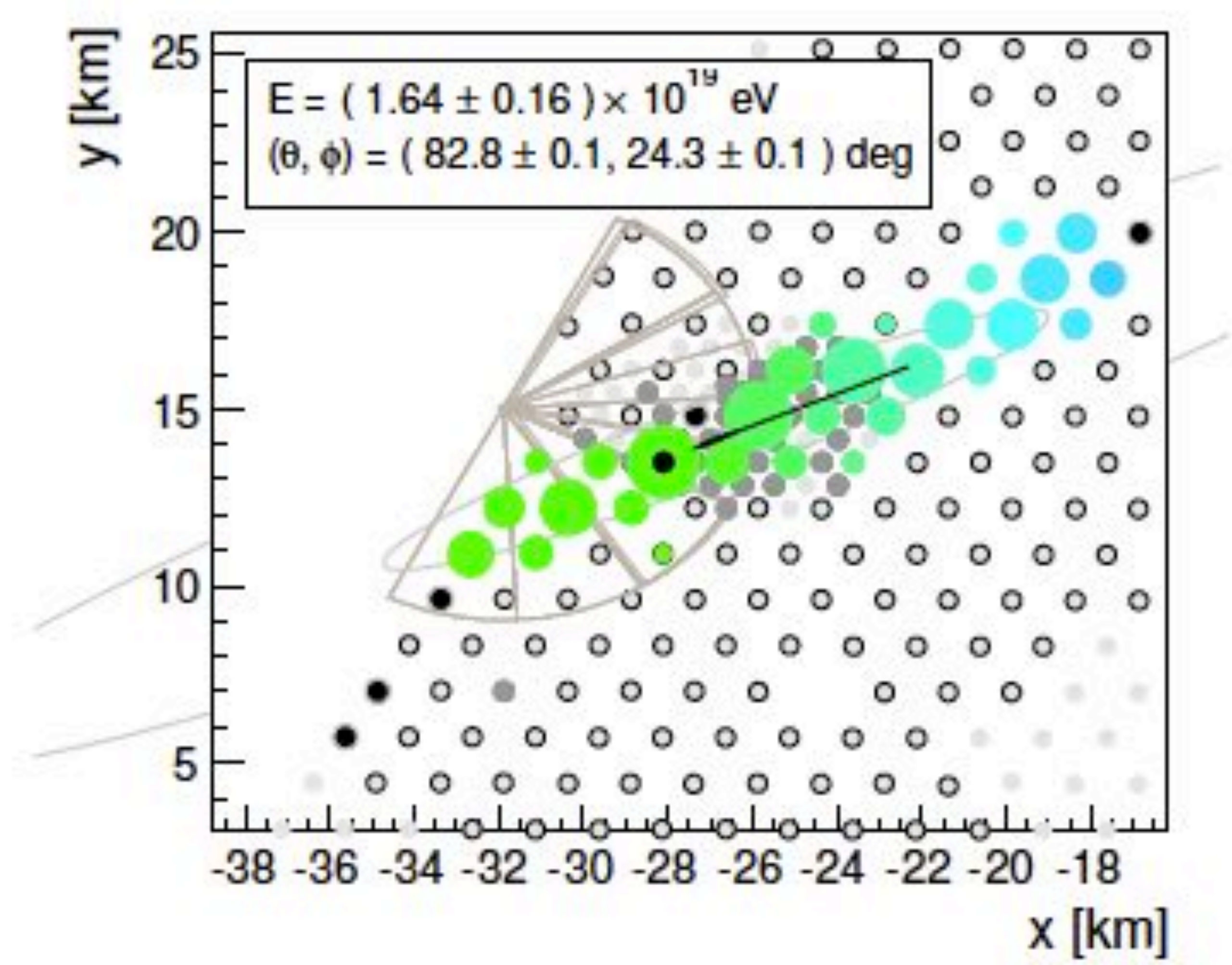
large multiplicity events (station spacing 750 m)





Horizontal showers

SD HAS



AERA