Latest results of the CODALEMA experiment: cosmic rays radio-detection in a self-trigger mode

ECRS 2012 - Moscow

By Diego Torres Machado

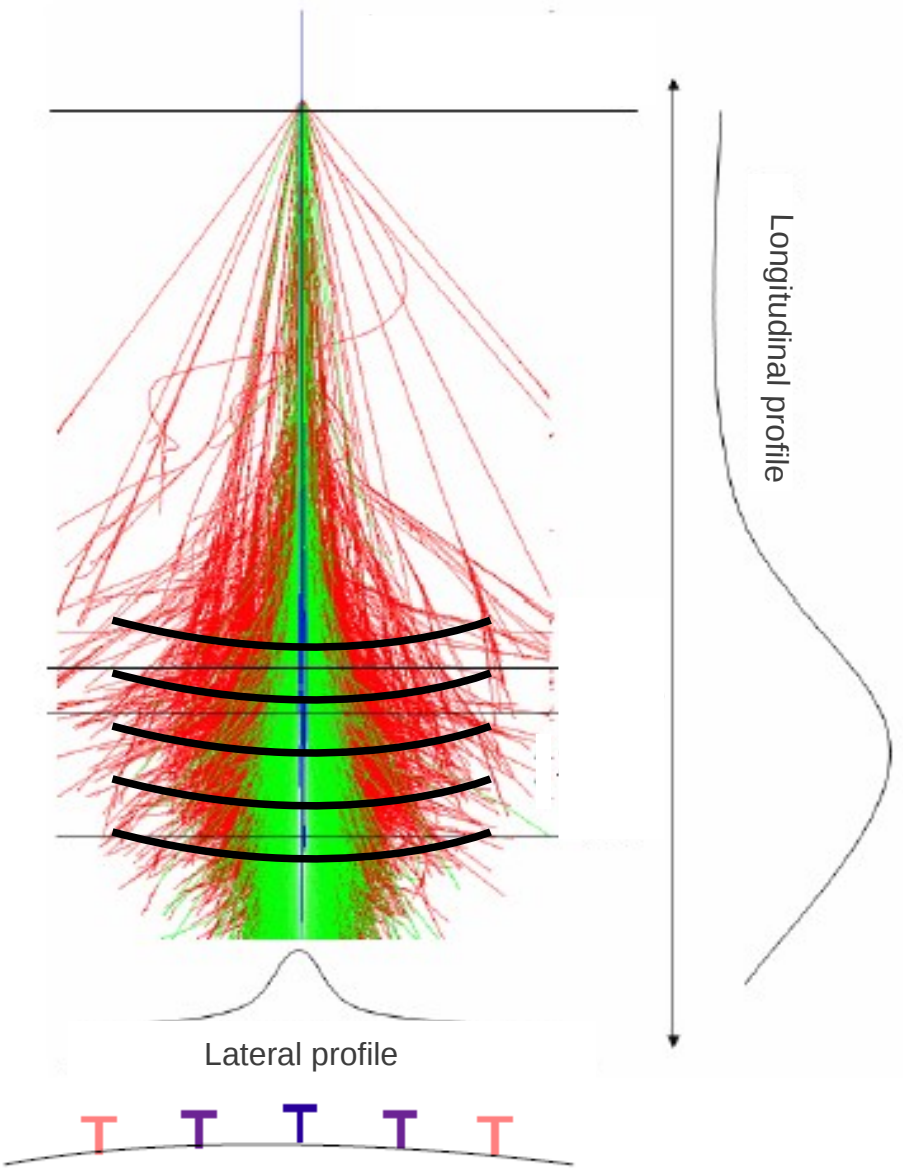
Astroparticles group at SUBATECH, Nantes

The purpose

From air showers parameters:

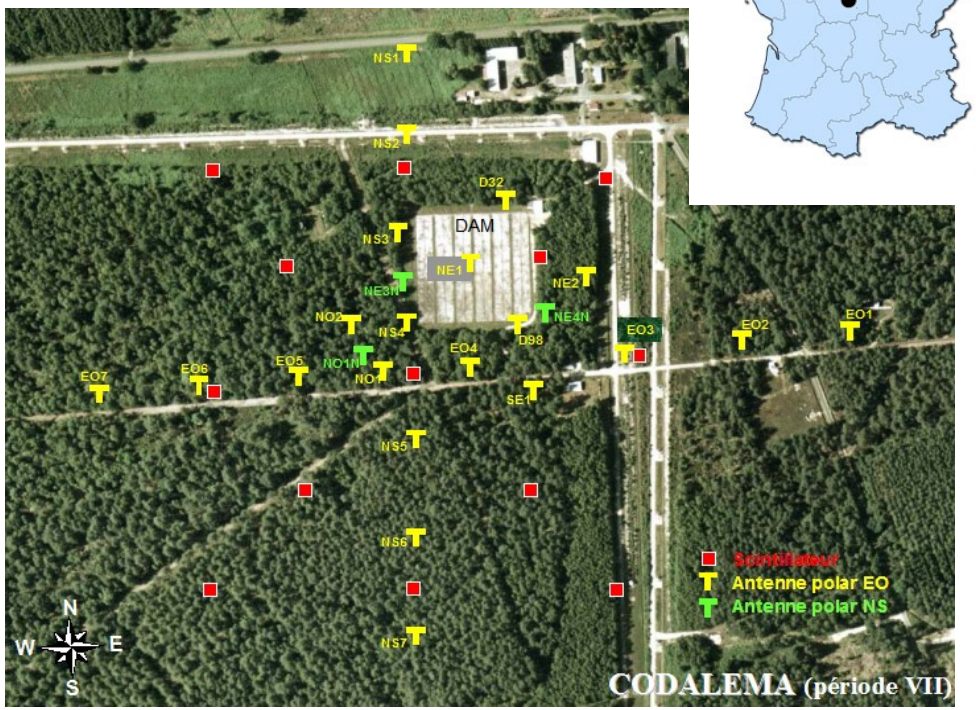
- **Arrival direction** of events & angular resolution of the array
- **Energy estimator**: correlation between **E** and primary cosmic ray energy
- **Composition** at 10^{16} – 10^{18}eV (signal contains information about the entire shower development)

Self-sufficiency of the radio detection & mastering a large radio array

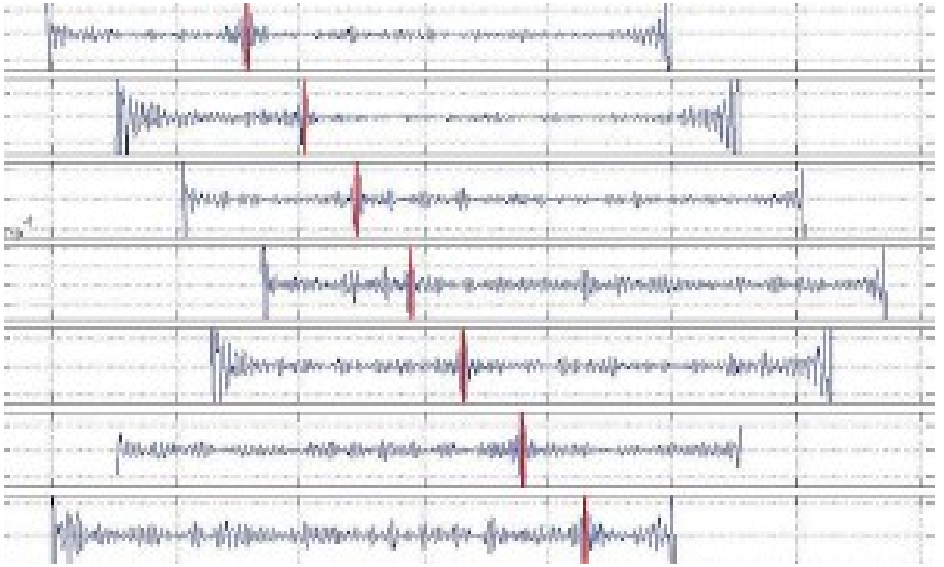


CODALEMA 2

Nançay Observatory



- Working since 2006
- 21 antennas (EW) + 3 antennas (NS)
- 17 scintillators
- Covered surface: 0.25 km² → 2nd knee
- Sensitivity to the galactic background radiation



Dipole antenna

Particle detector

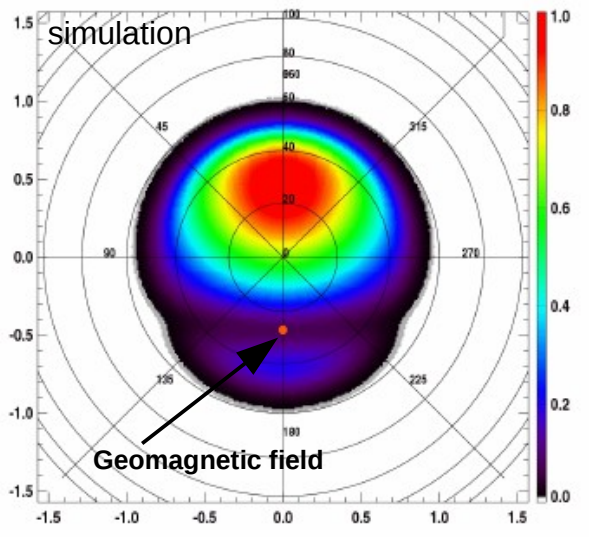
CODALEMA 2: emission mechanisms

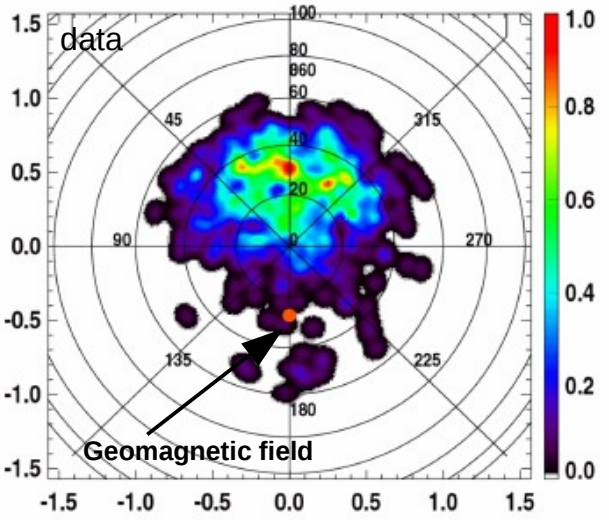
First order: geomagnetic effect

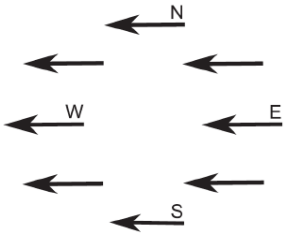
Ardouin D et al 2009 Astropart. Phys **31** 192-200

- Time varying transverse current
- Signal strength $\propto \mathbf{v} \times \mathbf{B}$
- Purely linear polarization
- Electric field aligned with $\mathbf{v} \times \mathbf{B}$

➡ N-S asymmetry in arrival directions







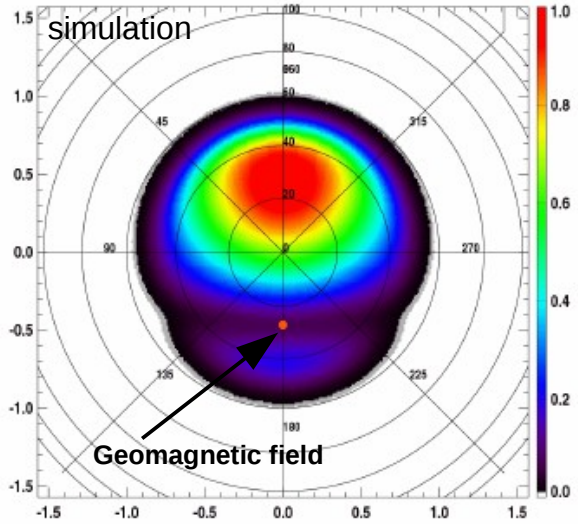
CODALEMA 2: emission mechanisms

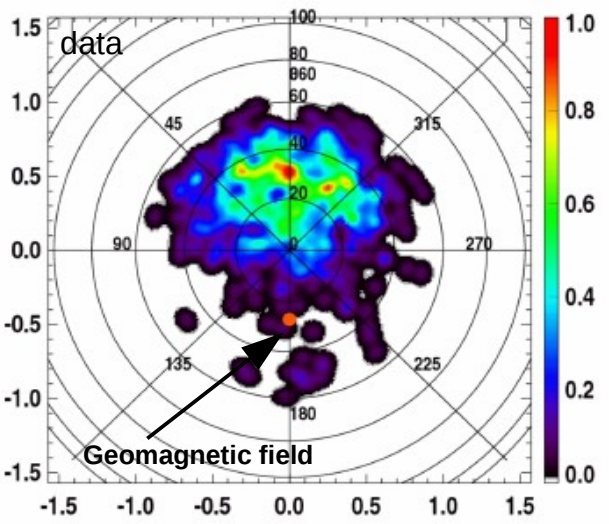
First order: geomagnetic effect

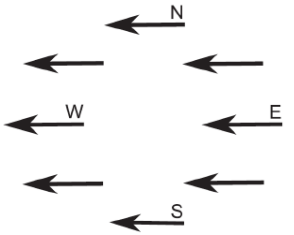
Ardouin D et al 2009 Astropart. Phys **31** 192-200

- Time varying transverse current
- Signal strength $\propto \mathbf{v} \times \mathbf{B}$
- Purely linear polarization
- Electric field aligned with $\mathbf{v} \times \mathbf{B}$

➡ N-S asymmetry in arrival directions







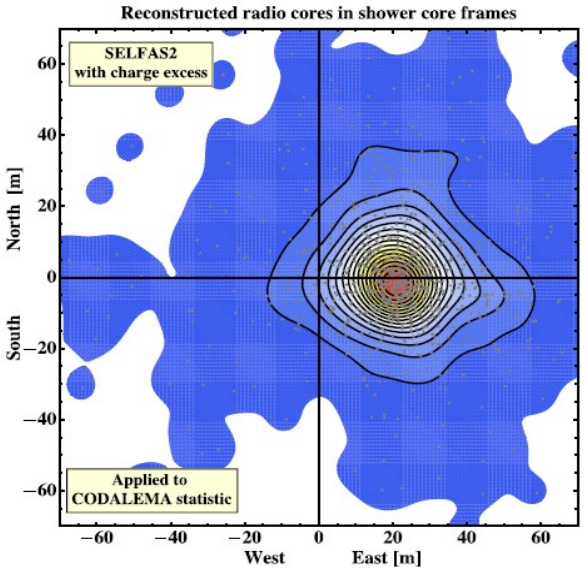
Second order: Charge excess

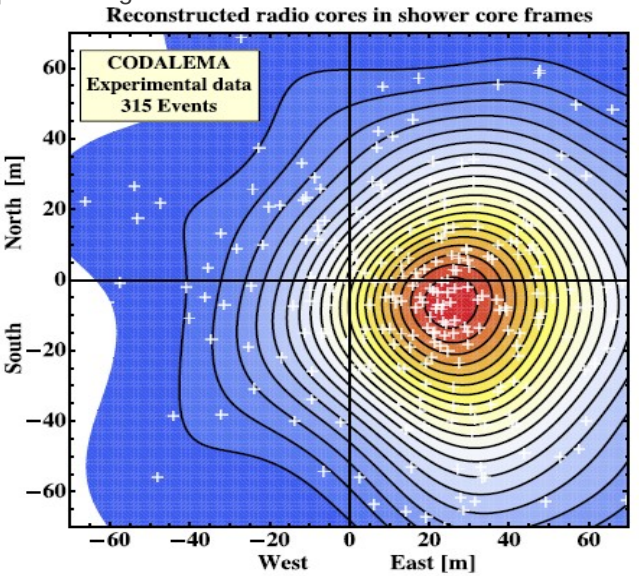
+

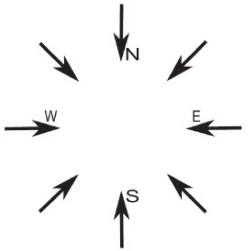
Lecacheux A, Belletoile A, proc of the 31st ICRC 2009
Marin V et al B 2012: http://arxiv.org/abs/1203.5248v1

- Time varying charge excess
- Purely linear polarization
- Electric field radially oriented, varies with observer location relative to core

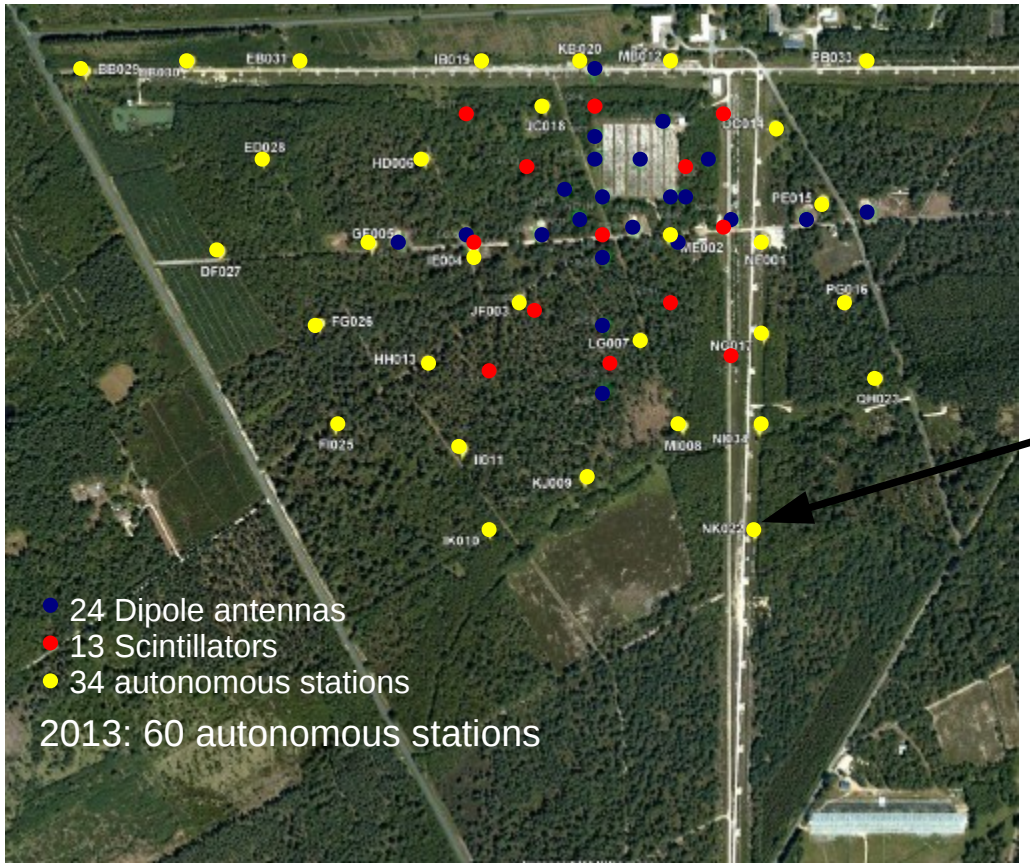
➡ Systematic shift between particle and radio cores



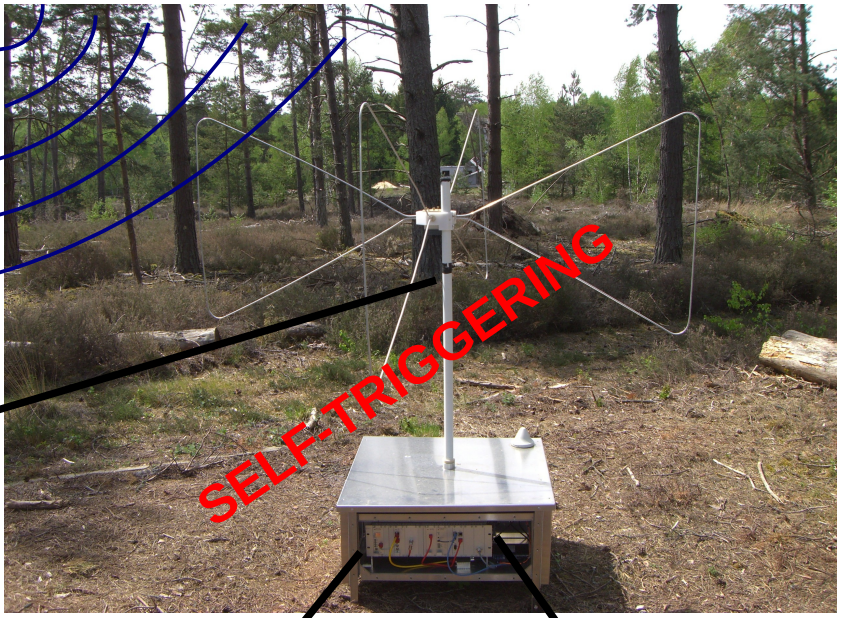




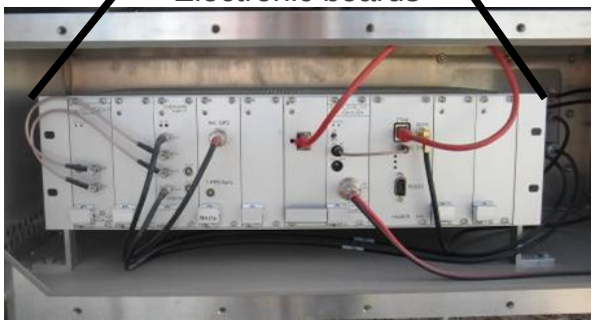
CODALEMA 3: the autonomous antenna array



The butterfly antenna



Electronic boards



Antenna deployed at CODALEMA & RAuger

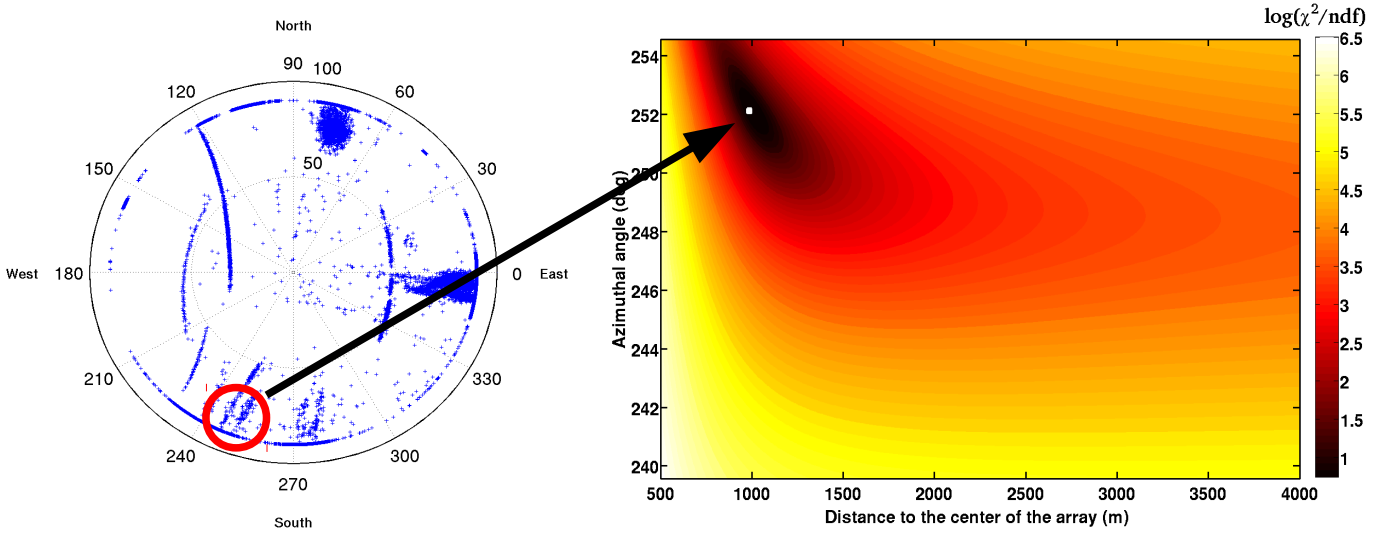
- Area: 0.5km² → more statistics in 10^{16} – 10^{18}eV energy range
- EW **&** NS horizontal polarizations
- Better understanding of lateral profiles
- R&D for future giant & hybrid detectors (AERA, Auger next...)

BUT: sensitivity to the radio frequency interferences

Standalone detection: rejection modes & reconstruction

Spherical reconstruction of the wave front (offline)

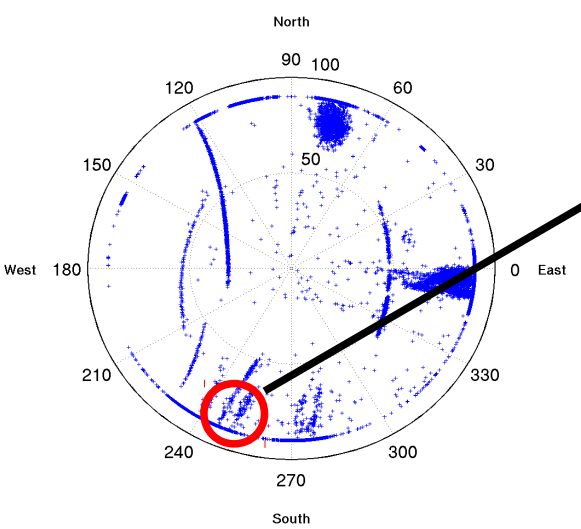
- Sensitivity to the initial conditions
- High accuracy required about antenna's position and timing of events

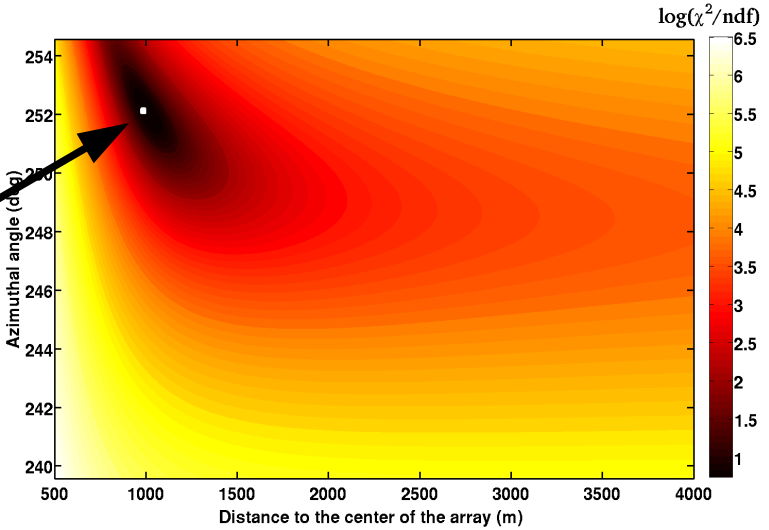


Standalone detection: rejection modes & reconstruction

Spherical reconstruction of the wave front (offline)

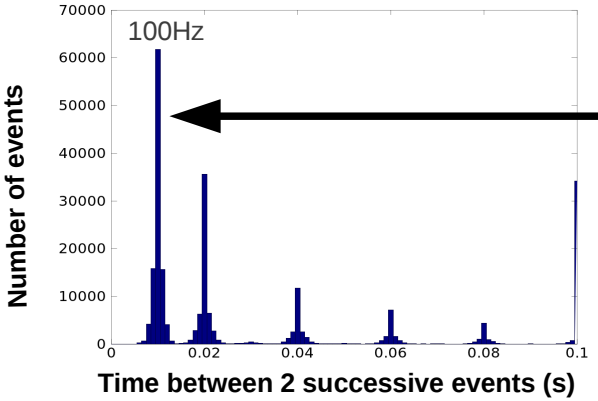
- Sensitivity to the initial conditions
- High accuracy required about antenna's position and timing of events





Rejection of periodic events (online)

- Radio environment of each antenna



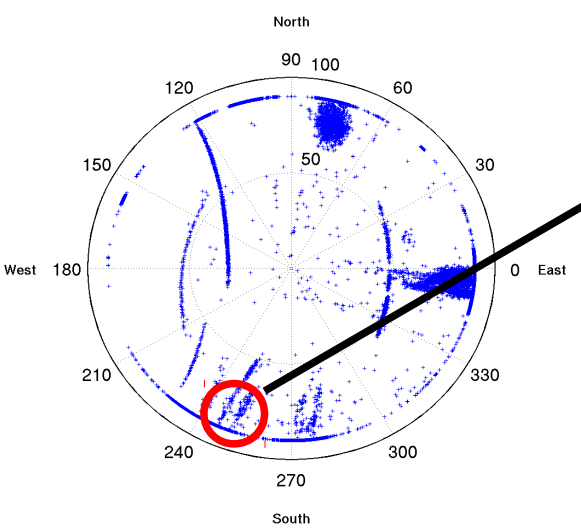
Transformer

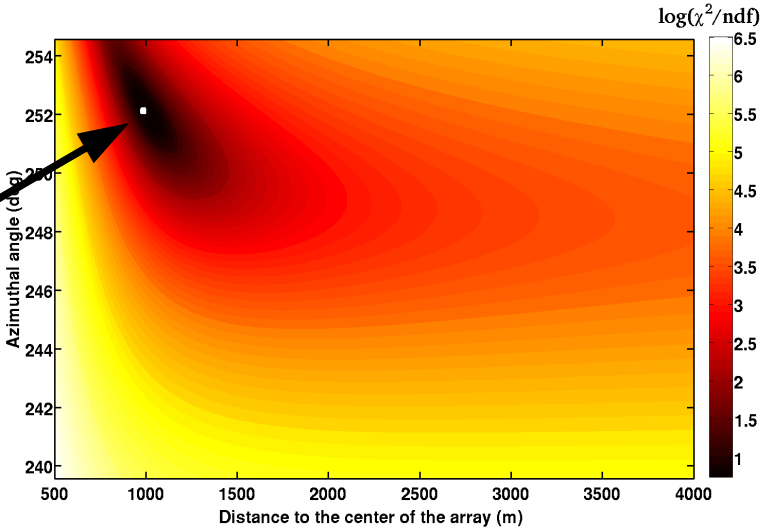
Has been implemented successfully!

Standalone detection: rejection modes & reconstruction

Spherical reconstruction of the wave front (offline)

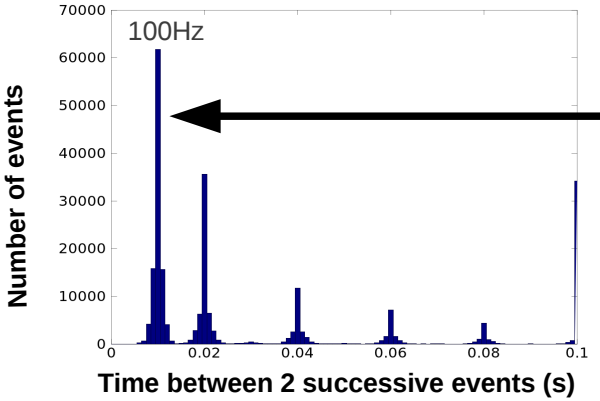
- Sensitivity to the initial conditions
- High accuracy required about antenna's position and timing of events





Rejection of periodic events (online)

- Radio environment of each antenna

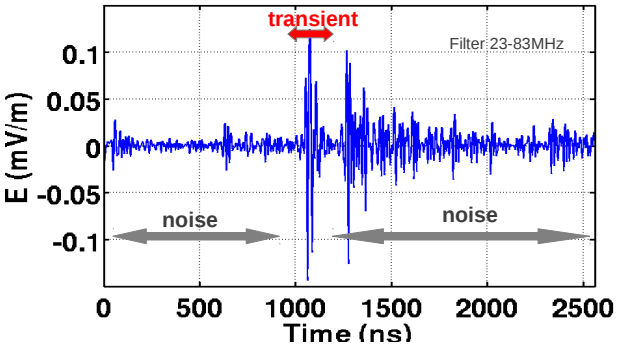


Transformer

Has been implemented successfully!

Wave shape analysis (online)

- Expected transient coming from an EAS: < 100ns

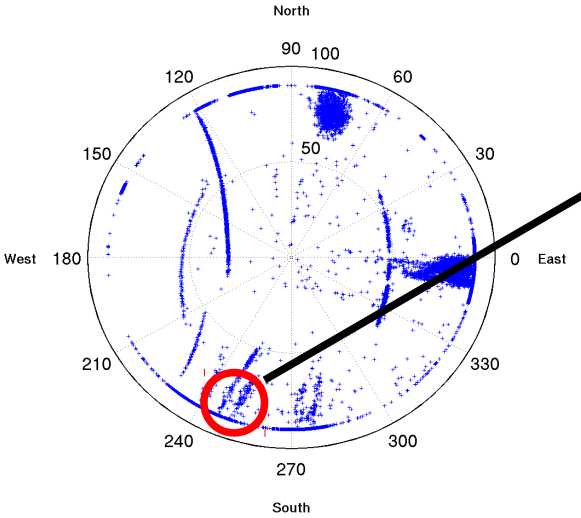


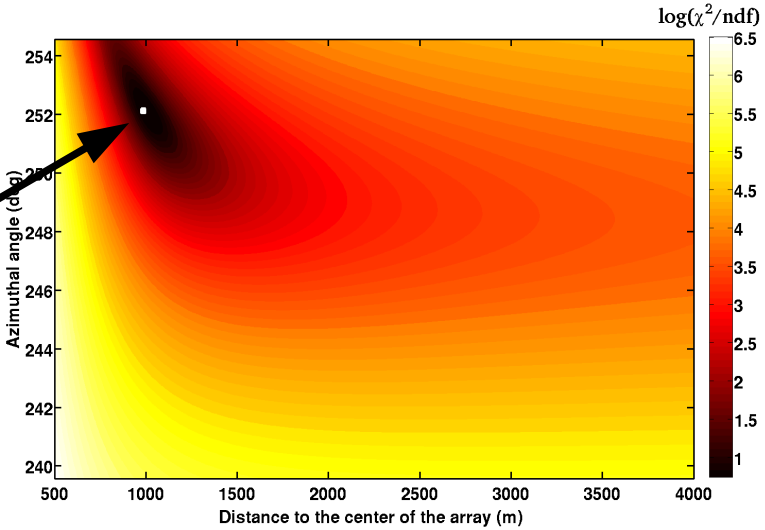
A. Bellétoile: Auger GAP-2011-47

Standalone detection: rejection modes & reconstruction

Spherical reconstruction of the wave front (offline)

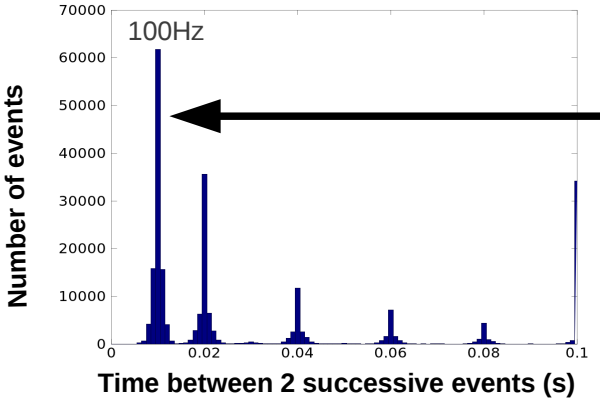
- Sensitivity to the initial conditions
- High accuracy required about antenna's position and timing of events





Rejection of periodic events (online)

- Radio environment of each antenna



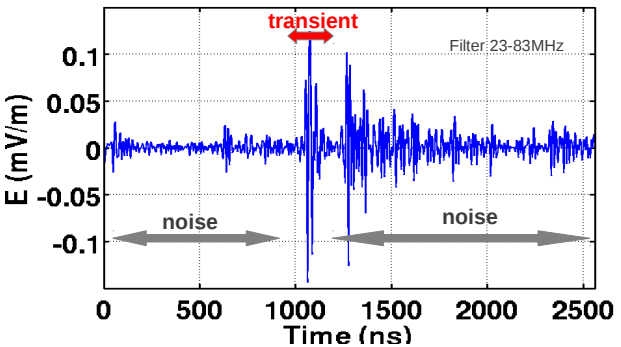
Transformer

Has been implemented successfully!

Wave shape analysis (online)

- Expected transient coming from an EAS: < 100ns

A. Bellétoile: Auger GAP-2011-47

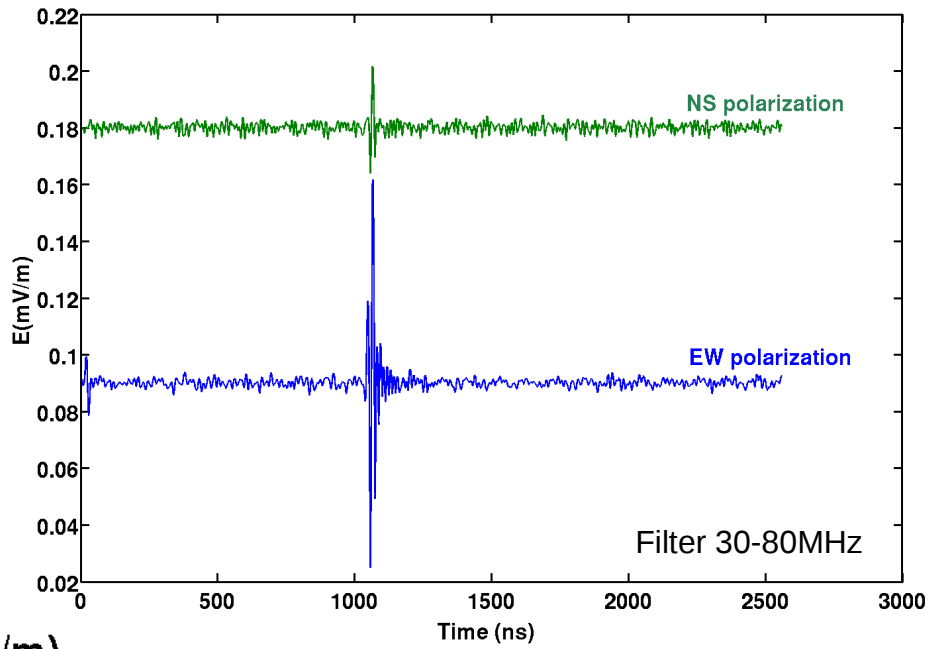


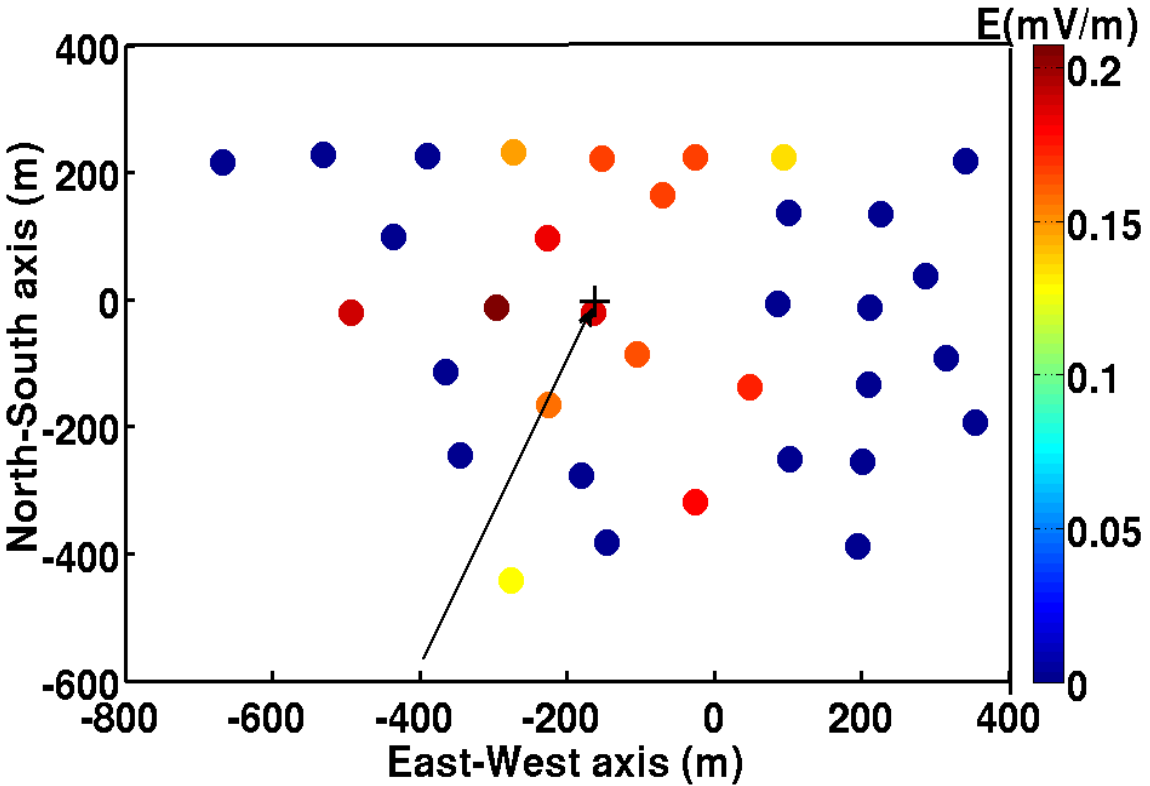
- ✔ Several noise sources located
- ✔ 50-80% of rejection for periodic events
- ✔ Up to 90% of rejection using wave shape analysis in time domain

EAS detection & polarization

Large multiplicity event observed by all the dipole array & 14 self-triggering antennas

- Several stations “off” at this moment
  → not perfect reconstruction of the core
- Inclined air shower (θ = 58°)
  → exponential profile does not works
- EAS coming from the South
  → Larger charge excess relative contribution ?
- No data available from scintillators
  → no energy estimation

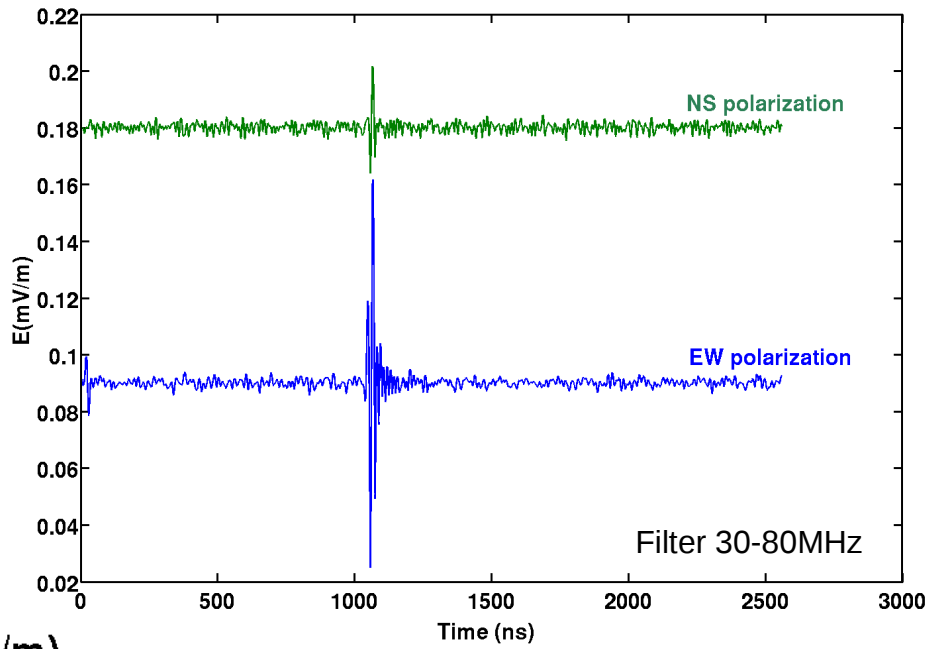


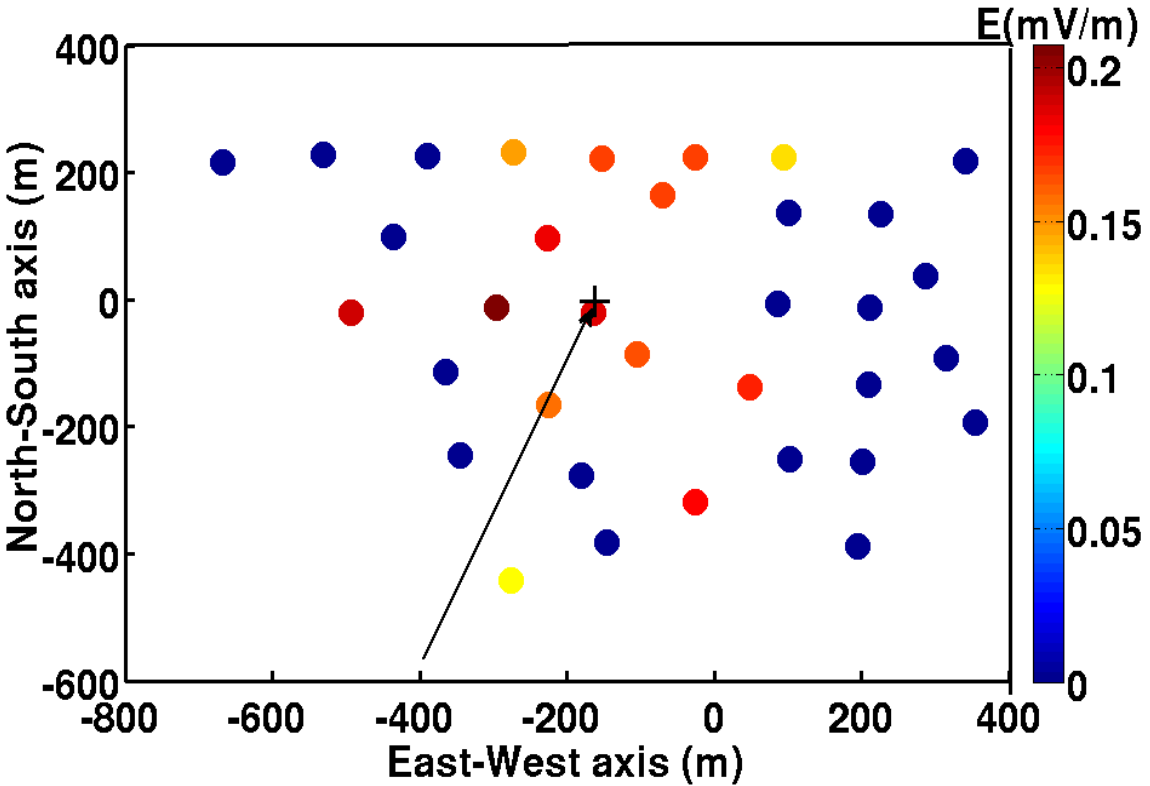


EAS detection & polarization

Large multiplicity event observed by all the dipole array & 14 self-triggering antennas

- Several stations “off” at this moment
  → not perfect reconstruction of the core
- Inclined air shower (θ = 58°)
  → exponential profile does not works
- EAS coming from the South
  → Larger charge excess relative contribution ?
- No data available from scintillators
  → no energy estimation





Signal range ≥ 760m for 0.5km²

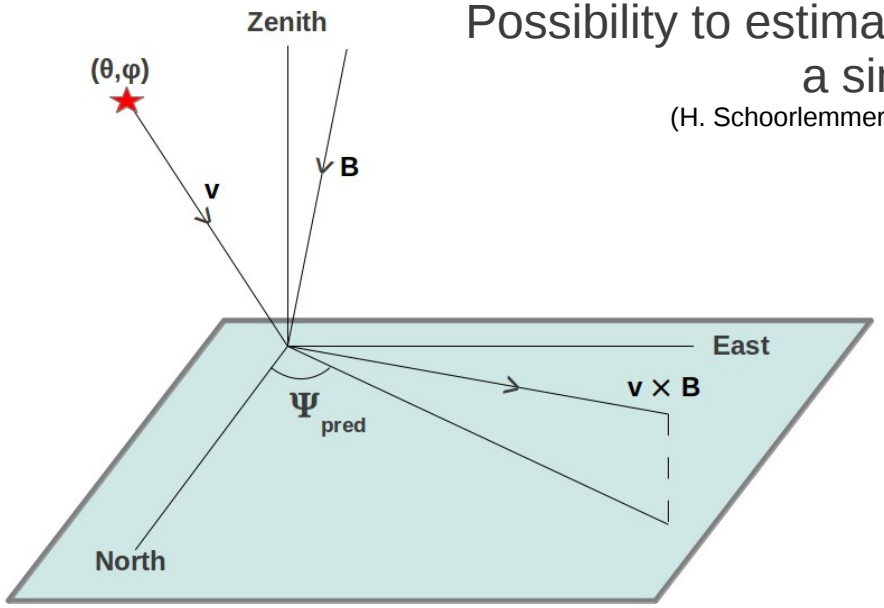
EAS detection & polarization

Butterfly antenna provides both EW and NS polarizations of the electric field

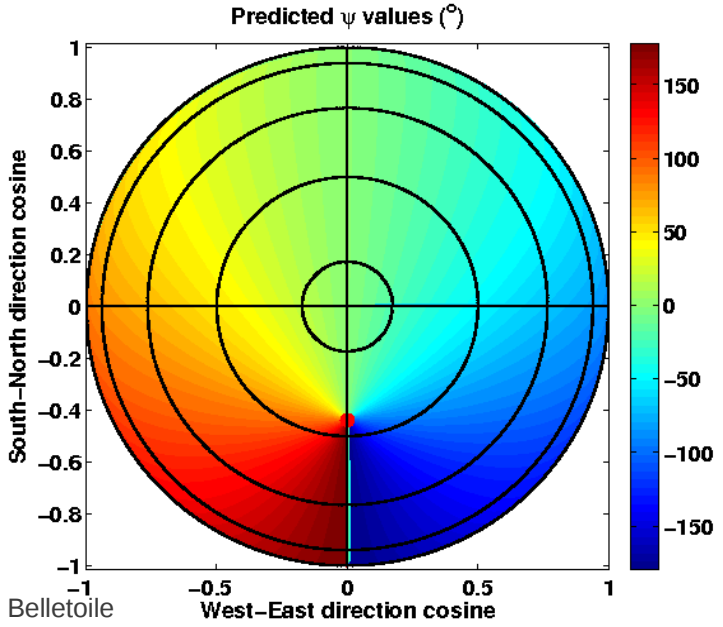
⇩

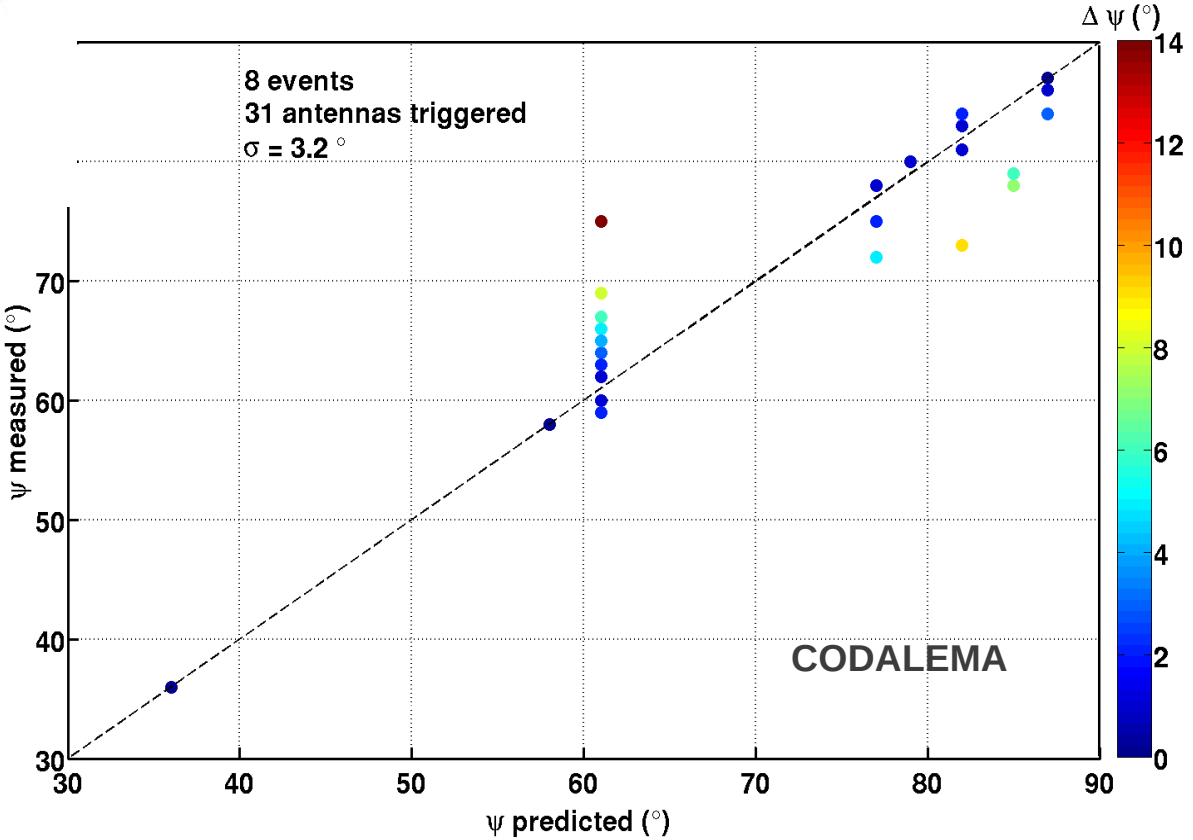
Possibility to estimate **polarization angles** using a single antenna

(H. Schoorlemmer ARENA 2010; A. Belletoile ICRC 2011)



$$\tan \Psi_{meas} = \frac{\vec{E}_{EW}}{\vec{E}_{NS}}$$





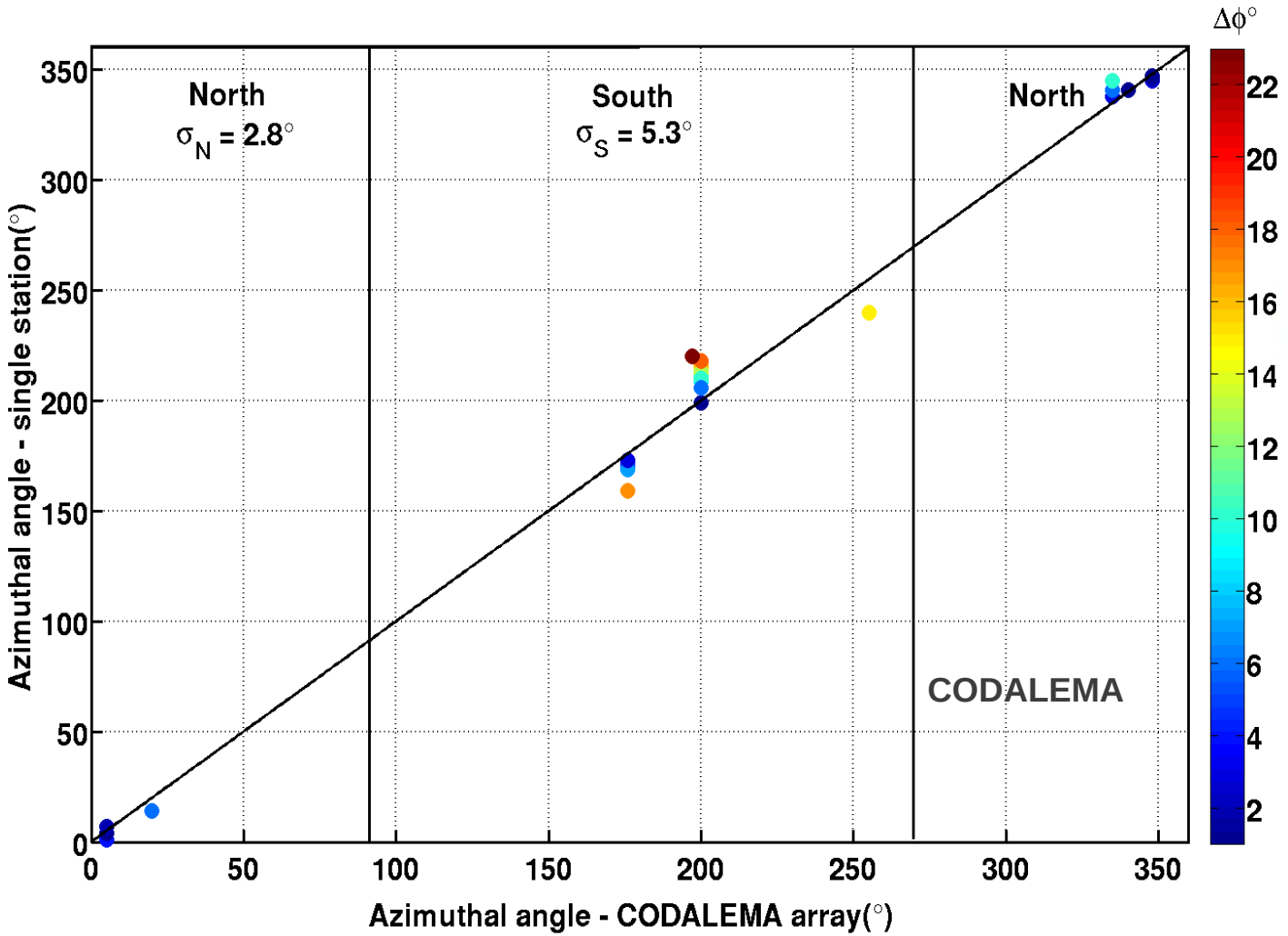
EAS detection & polarization

Butterfly antenna provides both EW and NS polarizations of the electric field

⇩

Possibility to estimate **azimuthal angles** using a single antenna

(AERA GAP-note 2012-042 B. Revenu)



$$\vec{E} \propto q(\vec{v} \times \vec{B})$$

implies

$$\tan \Phi_{radio} = -\frac{\vec{E}_{EW}}{\vec{E}_{NS}} \cos^2 \theta_B$$

- ✔ Good agreement (1st order)
- ✔ Need more statistics
- ✔ Take into account others effects

⇩

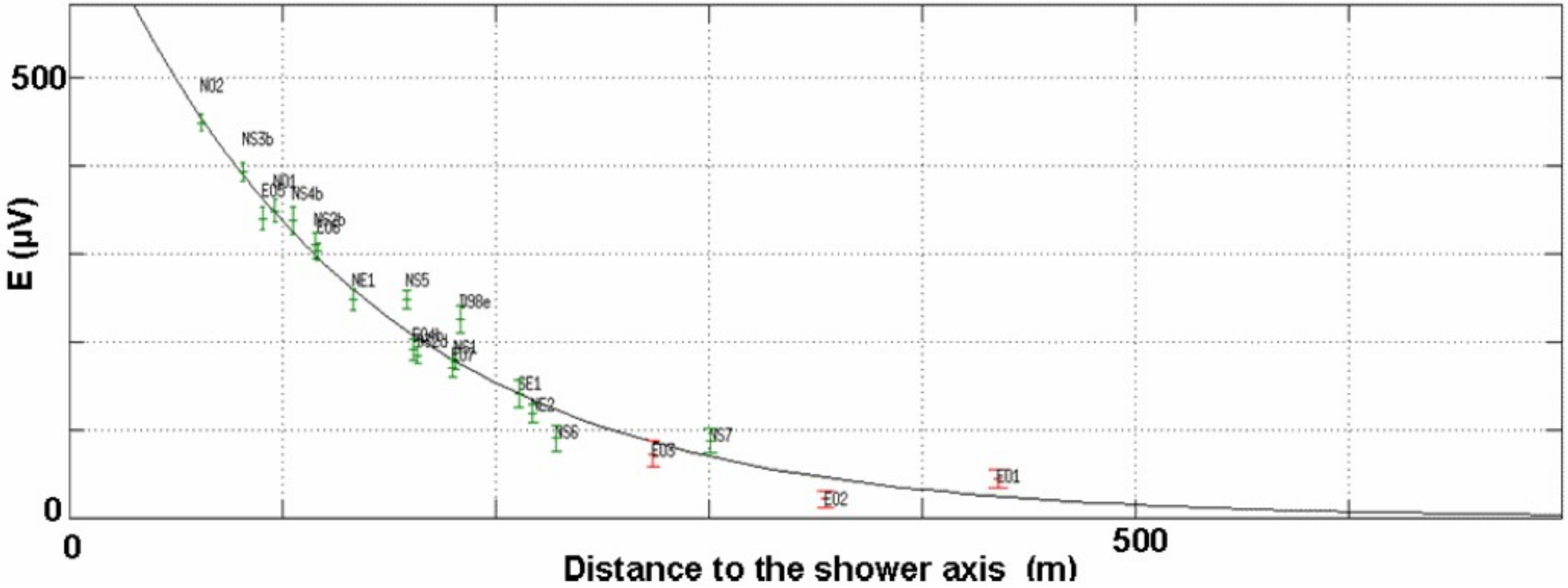
Crucial to understand the emission mechanisms

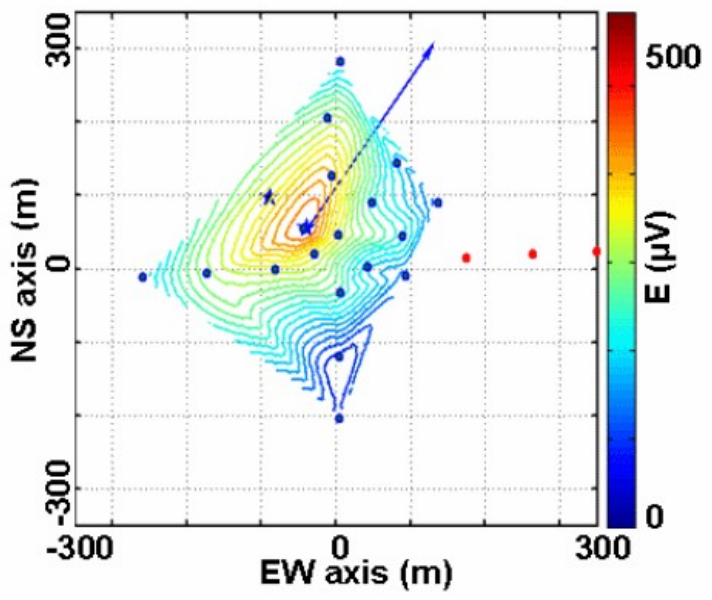
Outlook

- Main mechanisms of radio emission by EAS identified
- Control of the anthropic sources
- Deployment of CODALEMA 3 (34 + 26 standalone stations)
- R&D for self-triggered system, signal range and detection efficiency
- Polarization provides informations about emission mechanisms

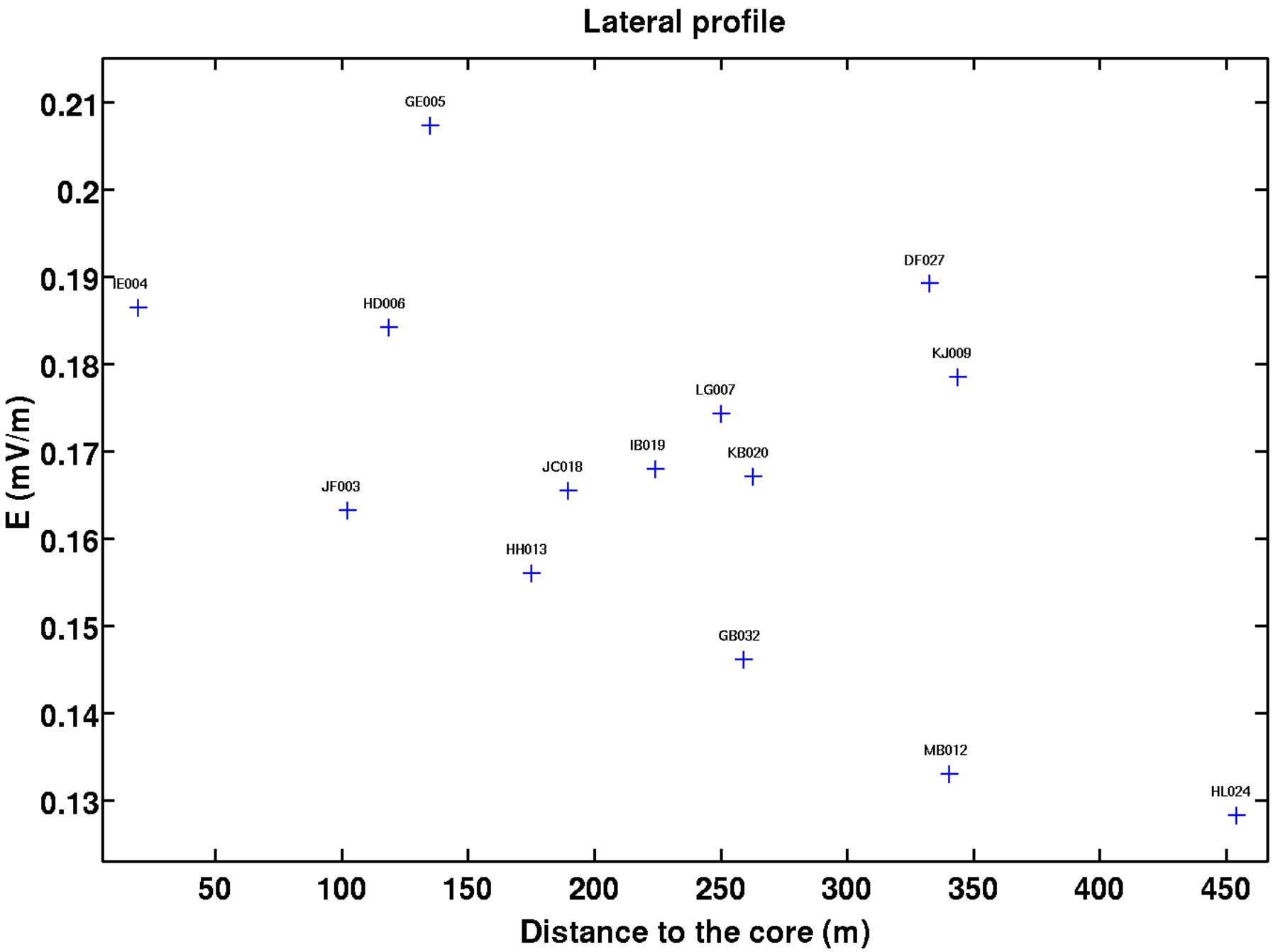
Additional slides

Lateral profile of the electric field

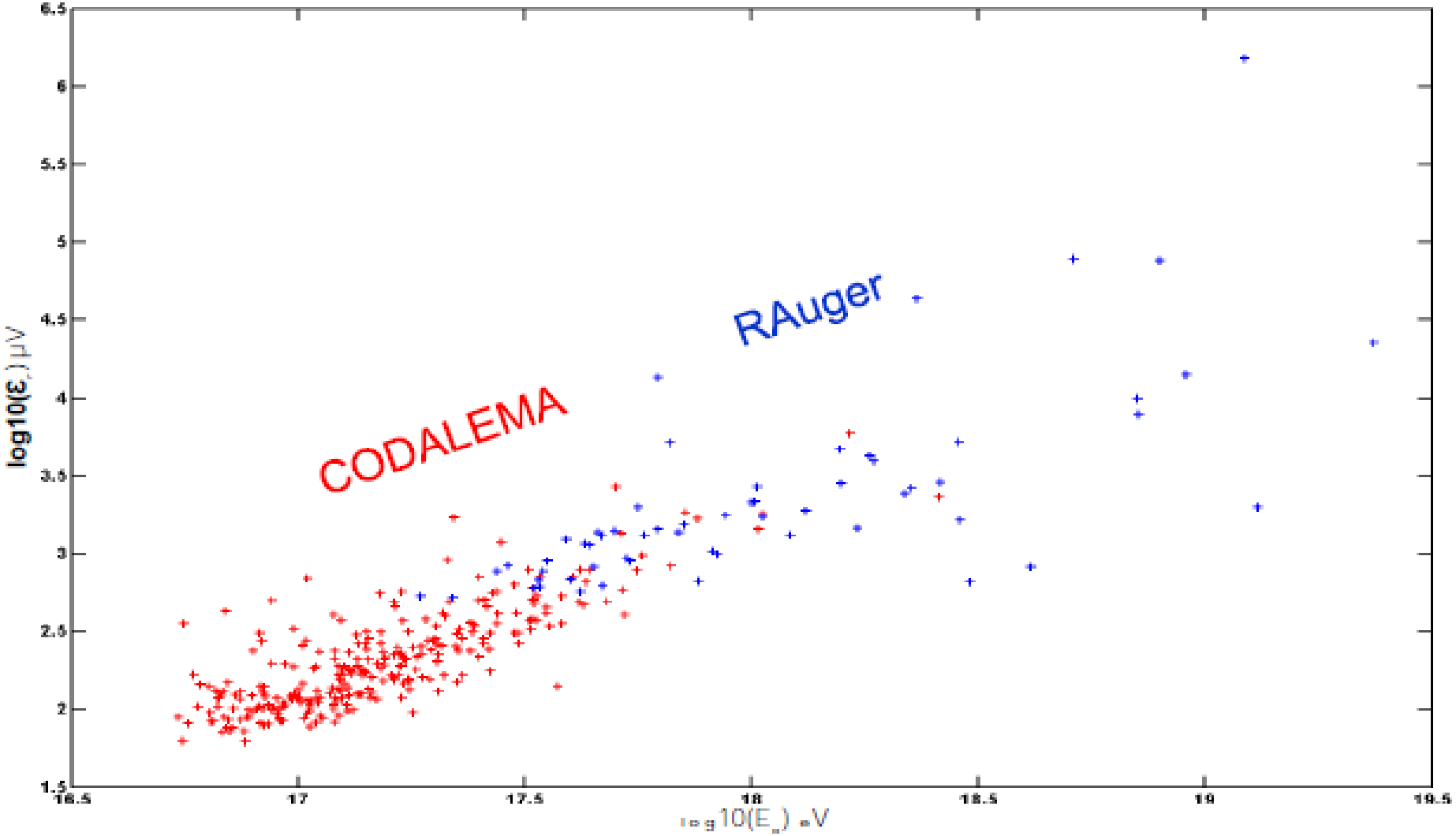




Lateral profile of the electric field: big event coming from the South



Energy estimation

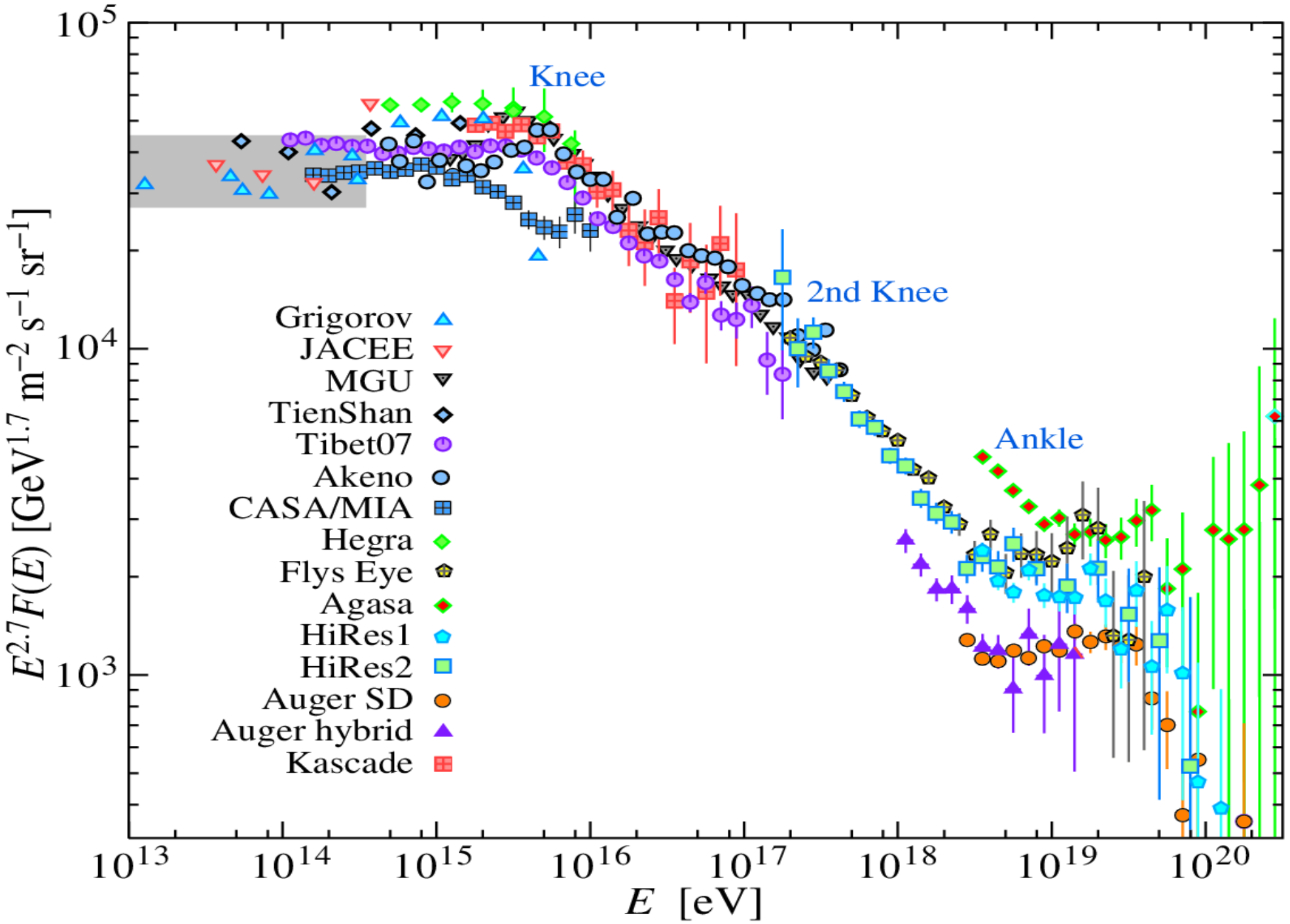


$$\varepsilon(\mu V/m/MHz) = cte.\left(\frac{E_p}{10^{17}}\right).sin\alpha.cos\theta.e^{-\frac{d}{d_0(\mu,\theta)}}$$

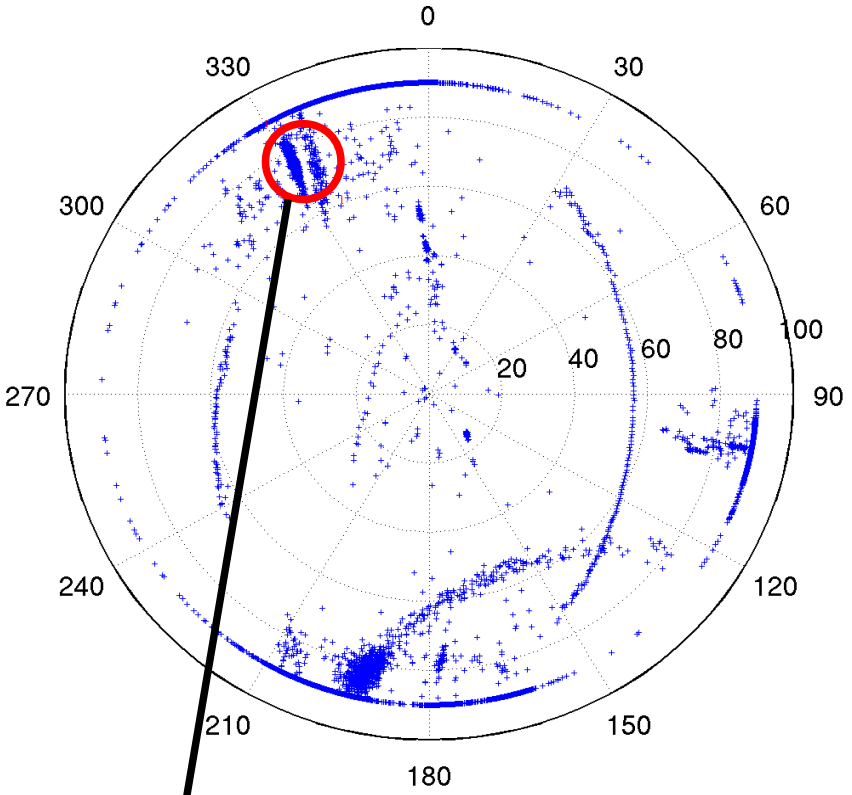
How detect them?

	Observable	Advantages	Drawbacks
Water Cherenkov Detectors Scintillators	Particle density at the ground level ↓ Lateral spread	Duty cycle~100% Direct measure of the particle density	Model-dependent for energy computation
Air Fluorescence Detectors	Nitrogen fluorescence in the atmosphere ↓ Longitudinal spread	3D shower development Detection at several km	Low duty cycle
Radio-Detection	Electric field ↓ Lateral spread of the electric field + Longitudinal spread?	High duty cycle Low cost Angular acceptance	Sensitivity to the Radio Frequency Interferences

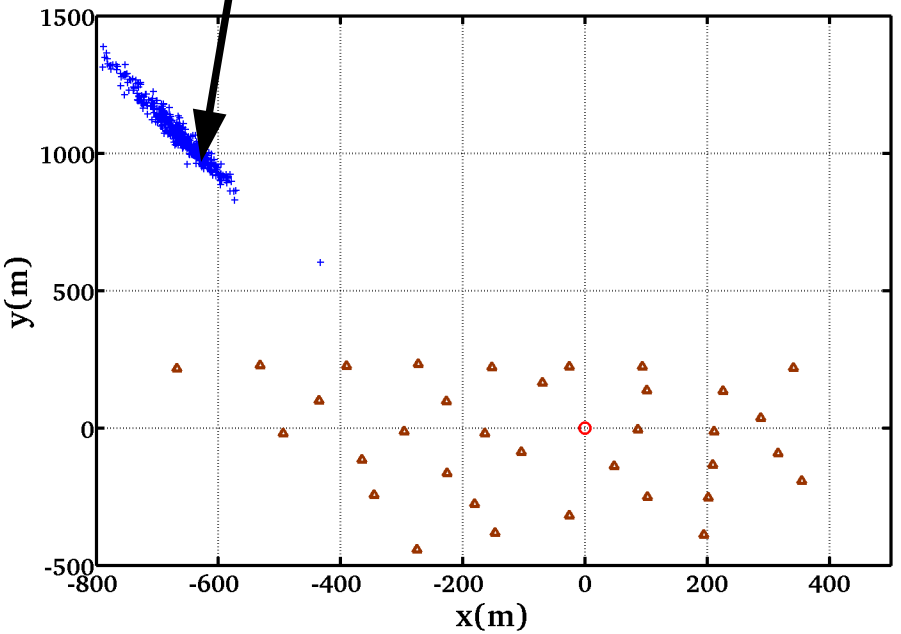
Spectrum at ultra high energy

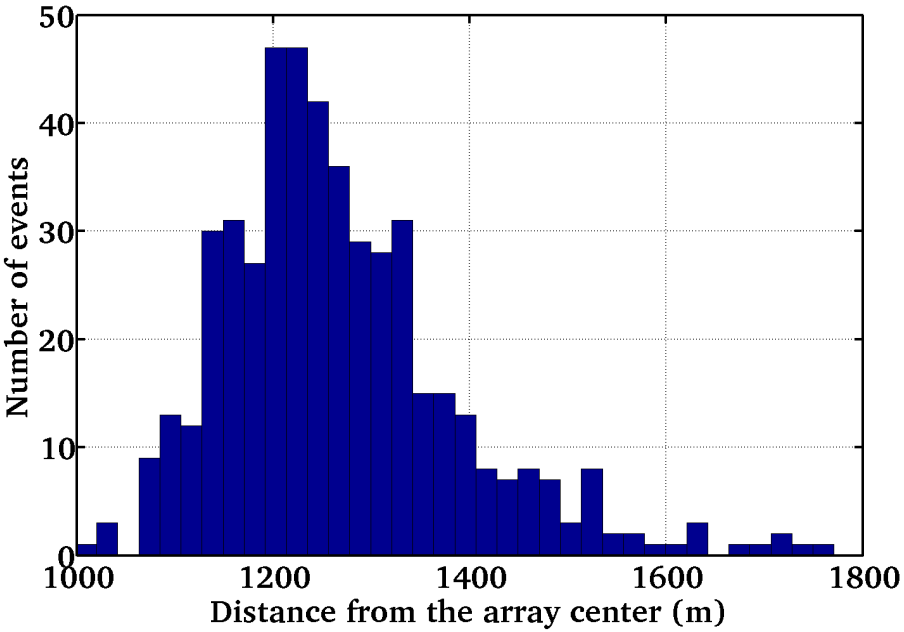


Spherical reconstruction of the background sources

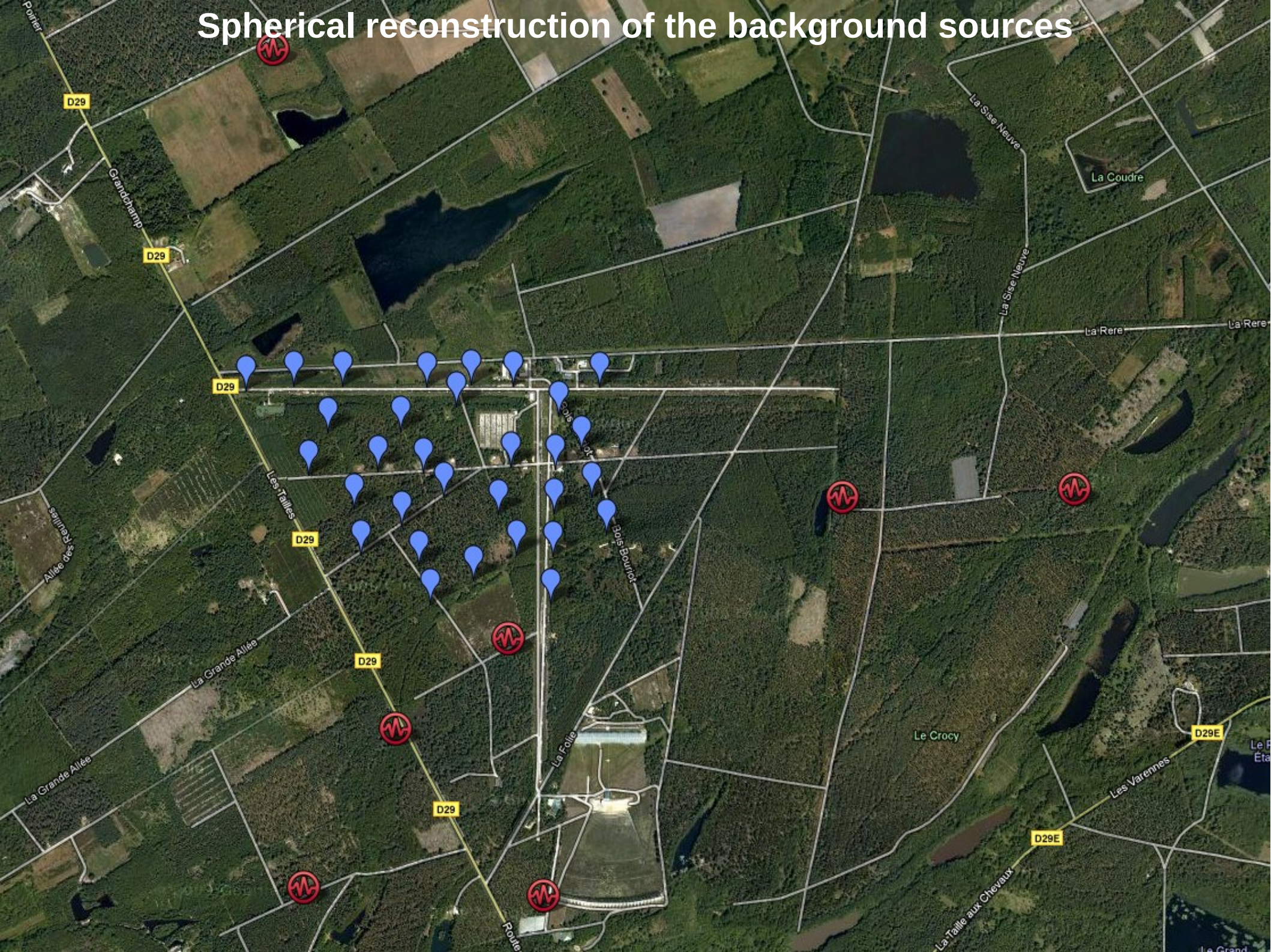


$$\chi^2 = \sum_{i=1}^{m}((x_i - x_0)^2 + (y_i - y_0)^2 + (z_i - z_0)^2 - c^2(t_i - t_0)^2)^2$$

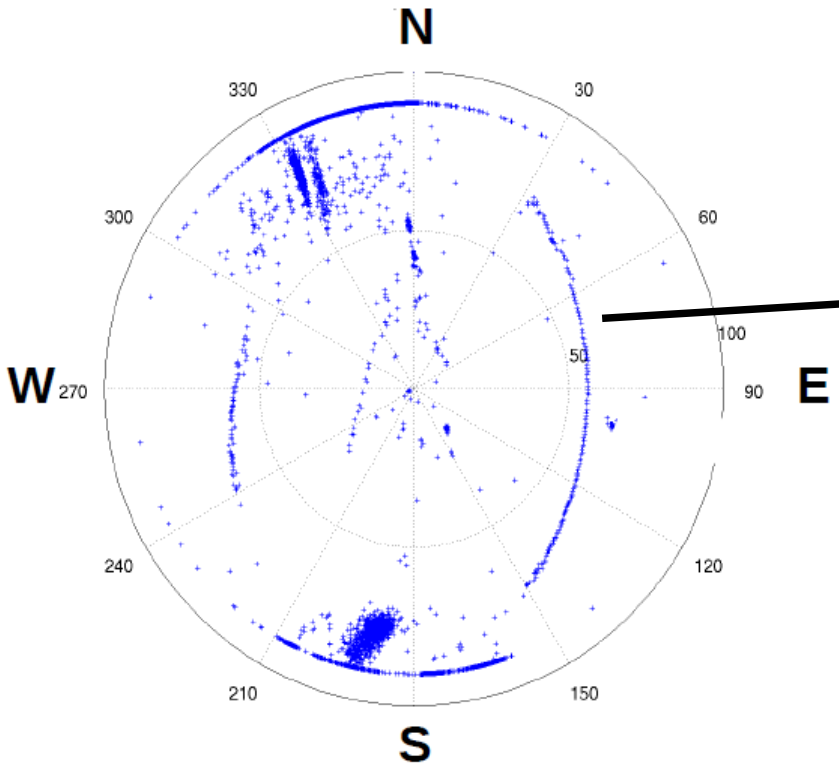


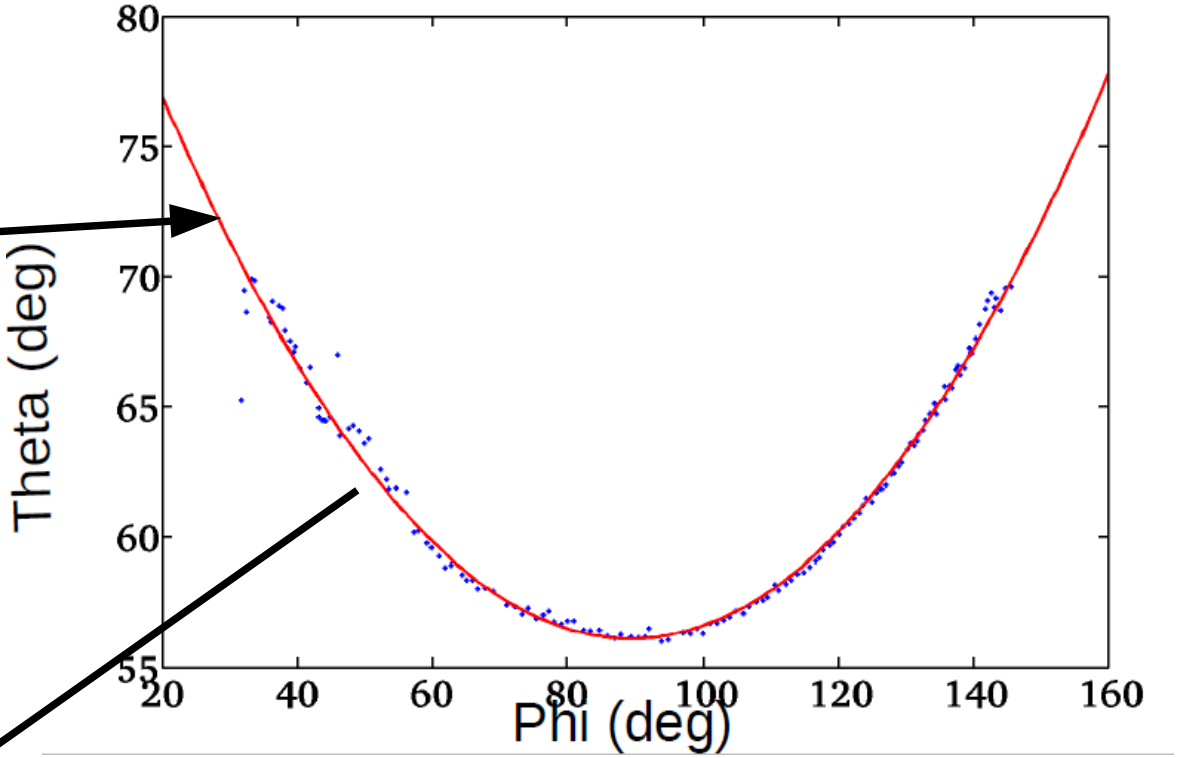


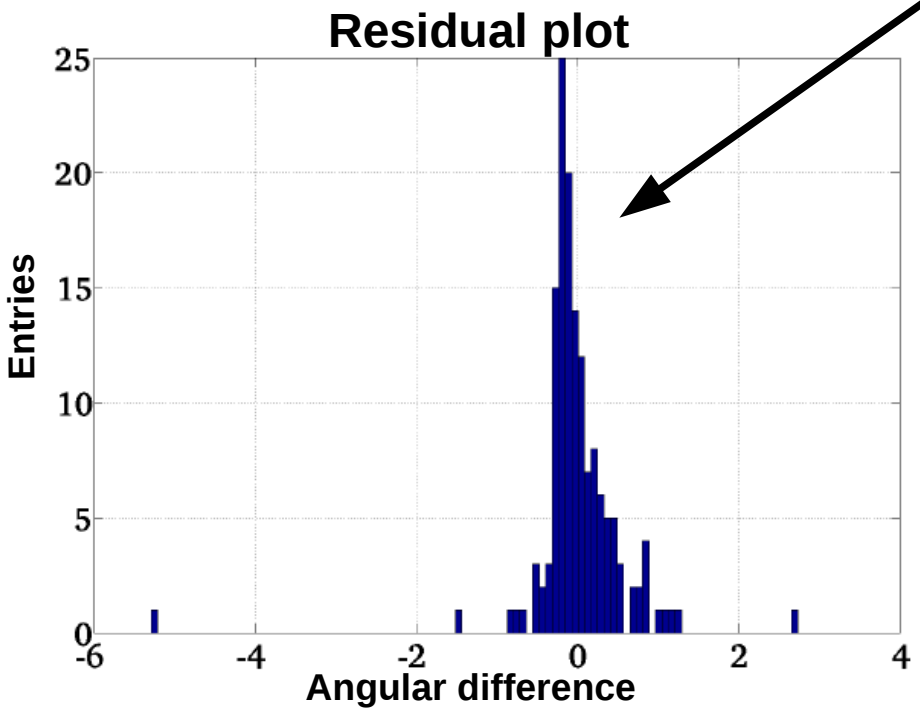
Spherical reconstruction of the background sources



Standalone array resolution







Angular resolution better then 0.4° at 1σ