Multi-wavelength observation of cosmic-ray air-showers with CODALEMA/EXTASIS

Antony Escudie[1]

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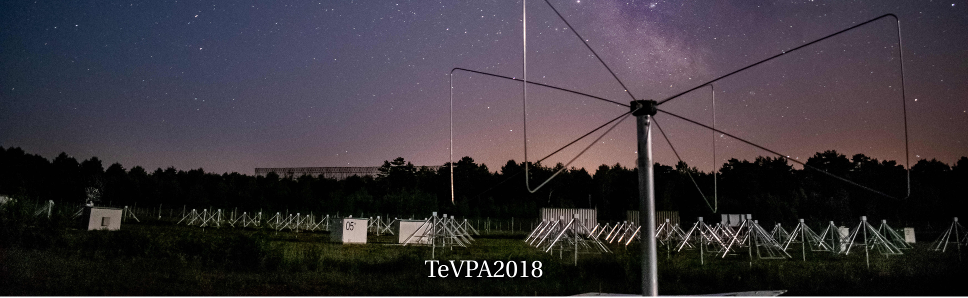
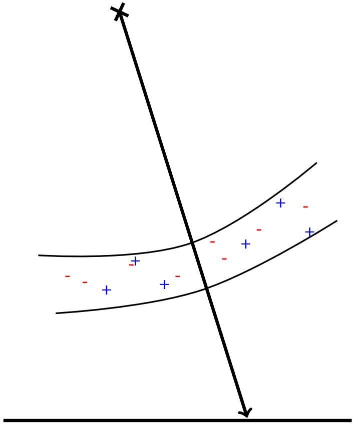
August 23, 2018



TeVPA2018

Radio-detection of cosmic-rays



- A primary CR arrives in the atmosphere, and creates an extensive air shower (EAS)
- Charged particles (e^+/e^-) in the EAS create electric field (geomagnetic + negative charge excess mechanisms)

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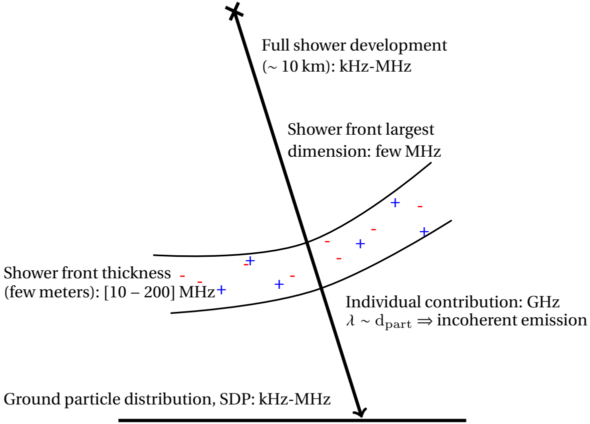

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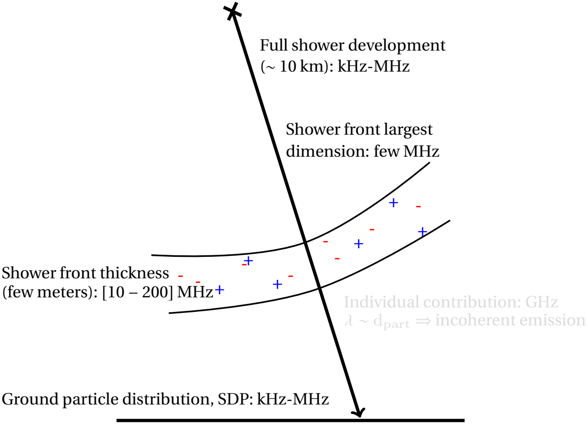

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- Charged particles (e^+/e^-) in the EAS create electric field (geomagnetic + negative charge excess mechanisms)
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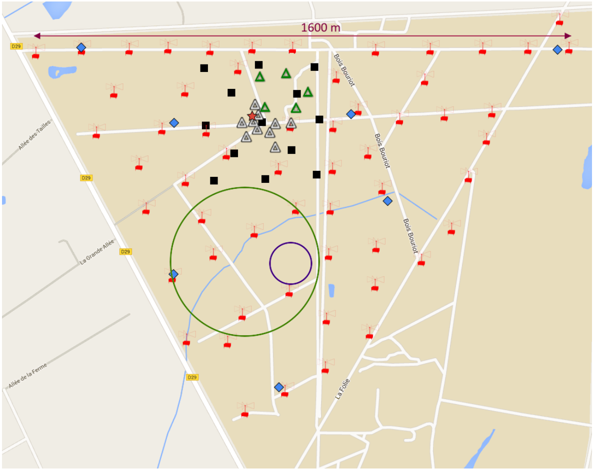
- Arrival direction (θ, ϕ), core position, composition (X_{max}), energy
- Different frequencies probe different properties of the shower

The experimental site - Nançay Observatory



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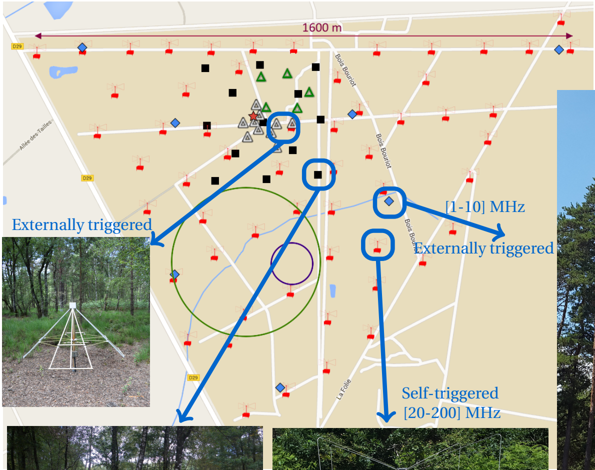


Externally triggered

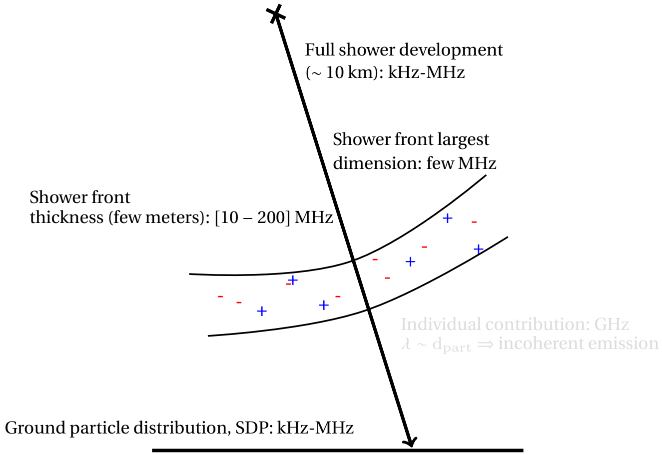
[1-10] MHz

Externally triggered

Self-triggered
[20-200] MHz

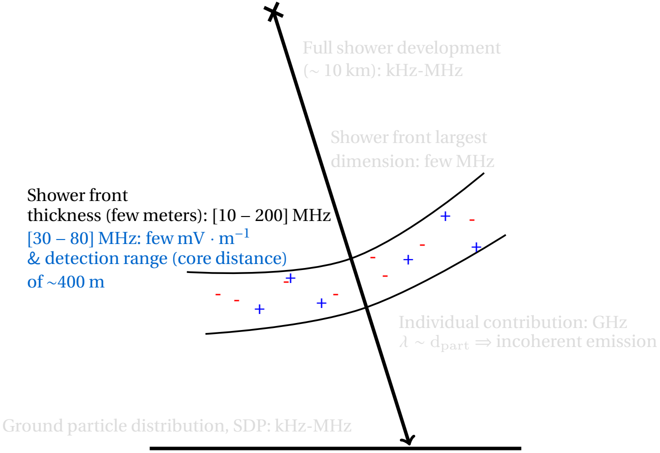
CODALEMA results

[20 – 200] MHz



CODALEMA results

[20 – 200] MHz



Progress in simulation - SELFAS3

- Classically, working under "far-field" assumption: SELFAS2, ZHAireS or CoREAS
- Low frequency (<10 MHz) radio emission of EAS needs a new treatment including near-field effects (d$\sim\lambda$)
- At 1 MHz, and R =100 m: $\frac{2\pi f}{c} R \sim 2 \Rightarrow$ Near field!

$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\epsilon}\int d^3x' \left(\left[\frac{\rho(\mathbf{x}',t_{ret})\mathbf{r}}{R^2(1-n\beta\cdot\mathbf{r})} \right]_{ret} + \frac{n}{c}\frac{\partial}{\partial t}\left[\frac{\rho(\mathbf{x}',t_{ret})\mathbf{r}}{R(1-n\beta\cdot\mathbf{r})} \right] - \frac{n^2}{c^2}\frac{\partial}{\partial t}\left[\frac{\mathbf{J}(\mathbf{x}',t_{ret})}{R(1-n\beta\cdot\mathbf{r})} \right]_{ret} \right)$$

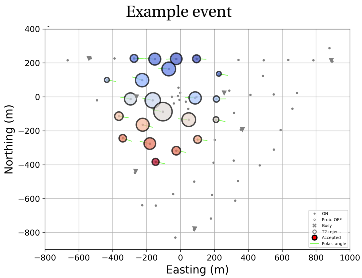
Charge must be conserved: D. García-Fernández *et al.*, Phys. Rev. D 97, 103010, 2018, implemented since 2018

Charge density ρ, refractive index n $\Rightarrow$ atmosphere description $\rho(z)$ $(g \cdot cm^{-3})$, n(z)

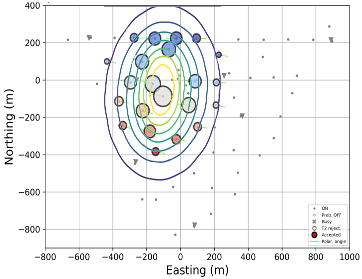
Upgrade of SELFAS with a state-of-the-art treatment of the atmosphere: F. Gaté *et al.*, Astroparticle Physics, 98:38 – 51, 2018

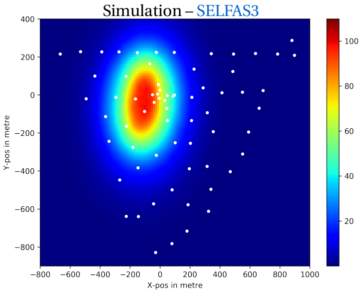
- USstandard: $\Delta X_{max} = 34.1\ g \cdot cm^{-2}$, $\sigma_{X_{max}} = 8.9\ g \cdot cm^{-2}$
- GDAS: $\Delta X_{max} = 0.1\ g \cdot cm^{-2}$, $\sigma_{X_{max}} = 2.4\ g \cdot cm^{-2}$

Estimating the shower parameters

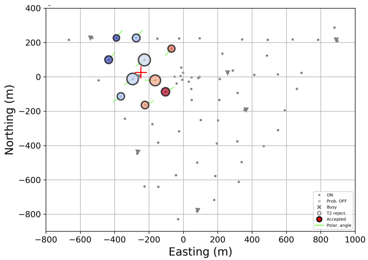


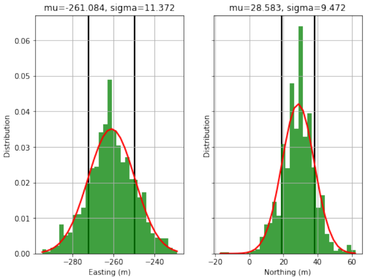
- θ, ϕ reconstructed using arrival times
- Core position, composition (X_{max}) and energy reconstructed trough MC simulations

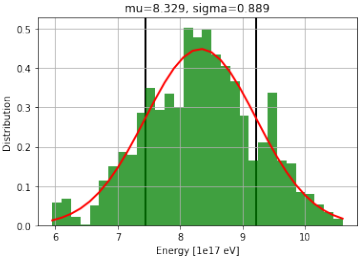


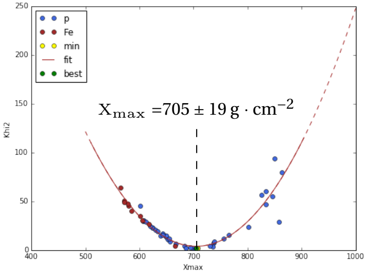


Estimating the shower parameters



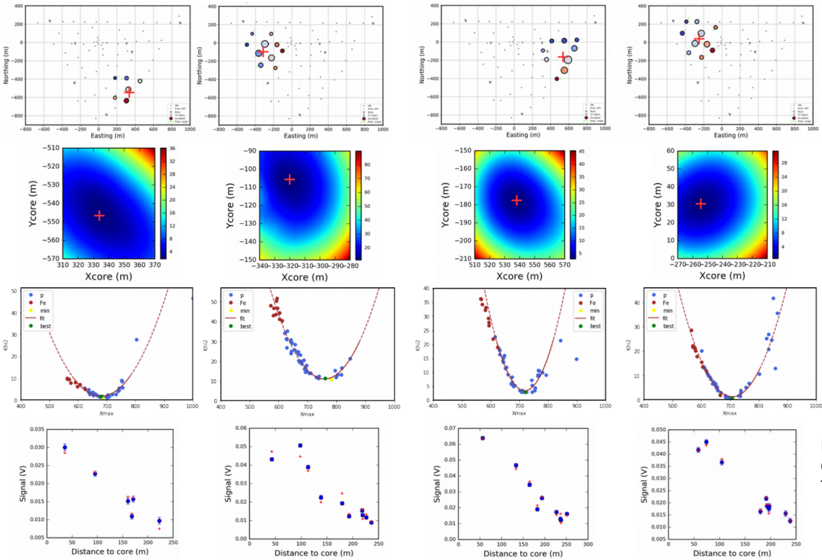






$$X_{max} = 705 \pm 19\,\mathrm{g \cdot cm^{-2}}$$

From Lilian Martin, ICRC2017



Amplitude footprint

χ^2 vs core location

χ^2 vs X_{max}

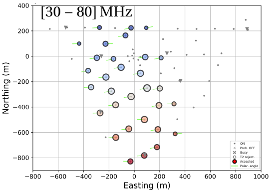
Lateral distribution function

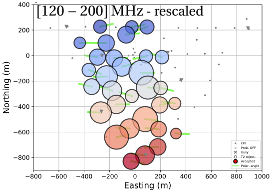
•Data

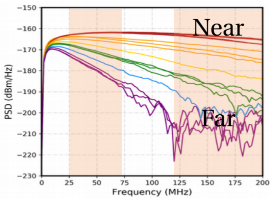
+SELFAS

Importance of the [120 – 200] MHz region

Inclined event ($\theta = 55°$)







Work in progress

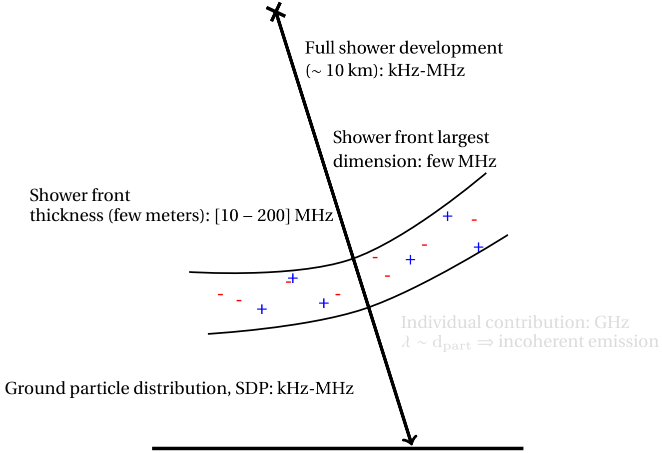
Radio-reconstruction of inclined event in [30 – 80] MHz difficult

Radio-reconstruction much better including the HF band: $\chi^2_{[30-200]} = \chi^2_{[30-80]}/3$

Continuity in the spectra, their content is precious $\Rightarrow$ only CODALEMA can do that!

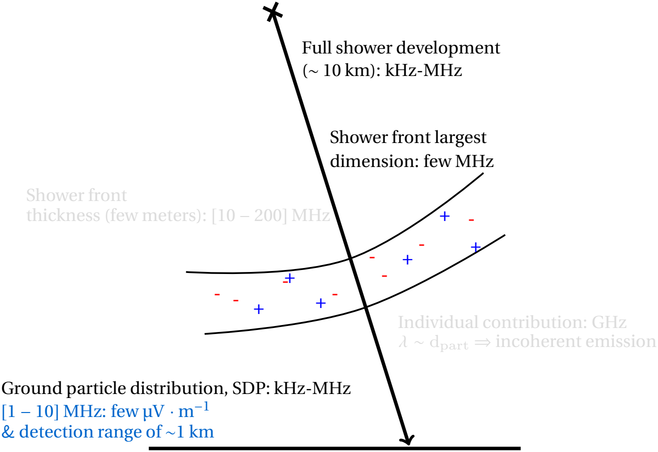
EXTASIS results

[1 – 10] MHz



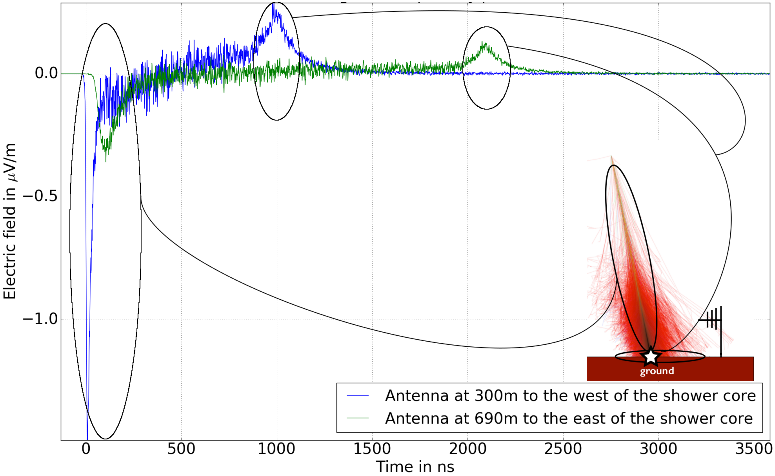
EXTASIS results

[1 – 10] MHz



Low-frequency counterpart in the radio signal

Simulation of vertical proton at 10^{17} eV, signal observed in the vertical polarization



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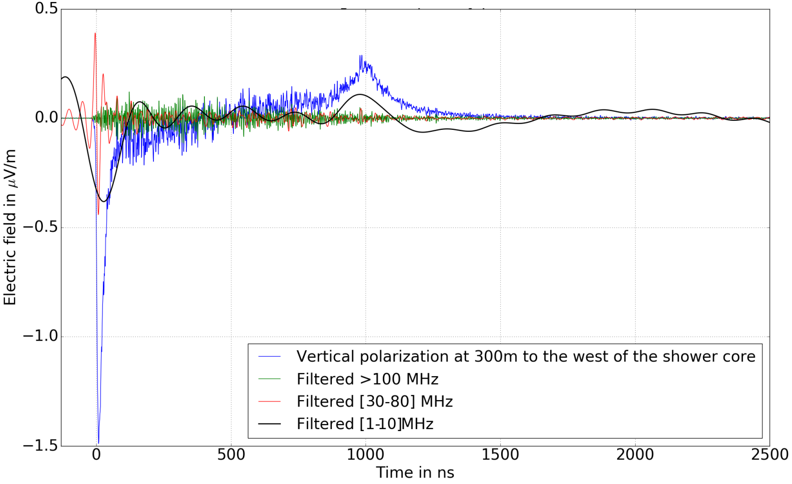
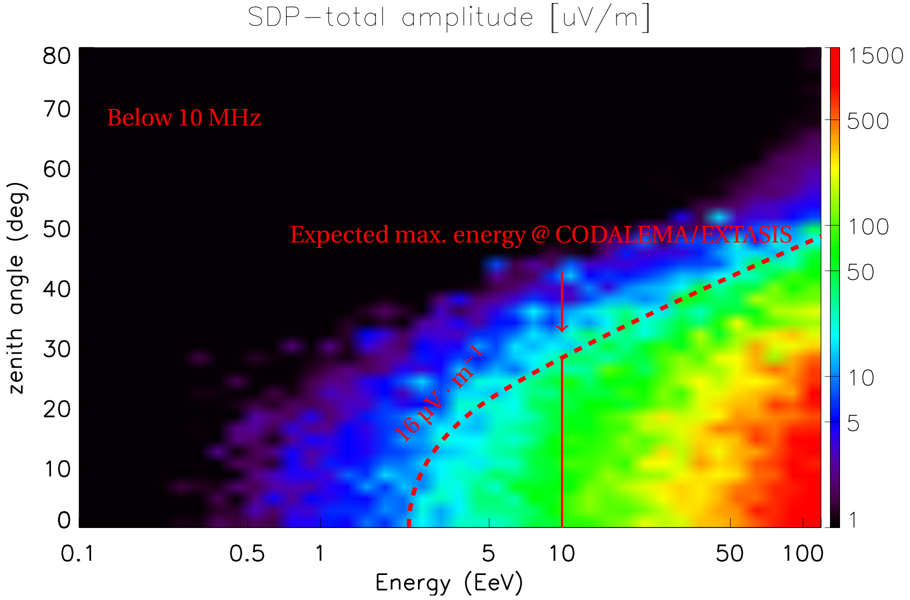


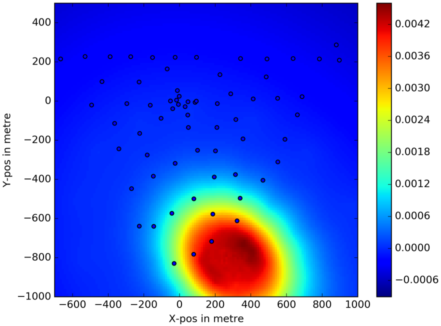
The sudden death signal



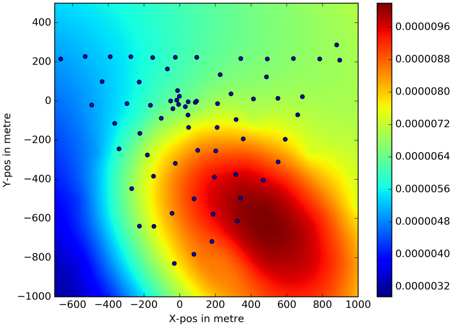
Detection range

Simulations ($V \cdot m^{-1}$) show a wider 2D profile at low frequencies

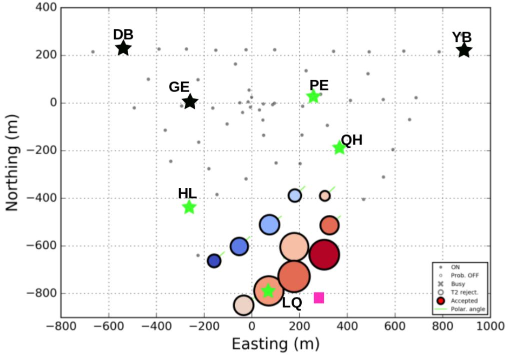
[30 – 80] MHz



[1 – 5] MHz



Illustrative example of LF detection

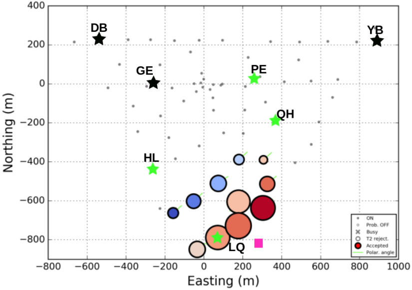


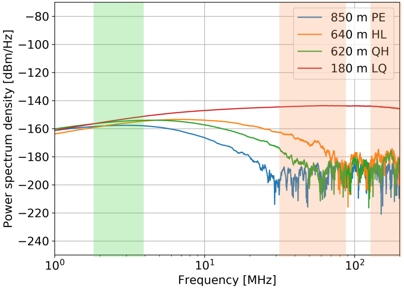
PE at 850 m ⇒ only LF signal
(16 μV/m)
QH at 620 m ⇒ only LF signal
HL at 640 m ⇒ only LF signal
LQ at 180 m ⇒ HF & LF signal

Arrival directions:

- $\theta_{\mathrm{LF}} = 31°$, $\Phi_{\mathrm{LF}} = 146°$
- $\theta_{\mathrm{SA}} = 40 \pm 1°$, $\Phi_{\mathrm{SA}} = 145 \pm 1°$
- $\theta_{\mathrm{SC}} = 33 \pm 6°$, $\Phi_{\mathrm{SC}} = 143 \pm 7°$

Illustrative example of LF detection

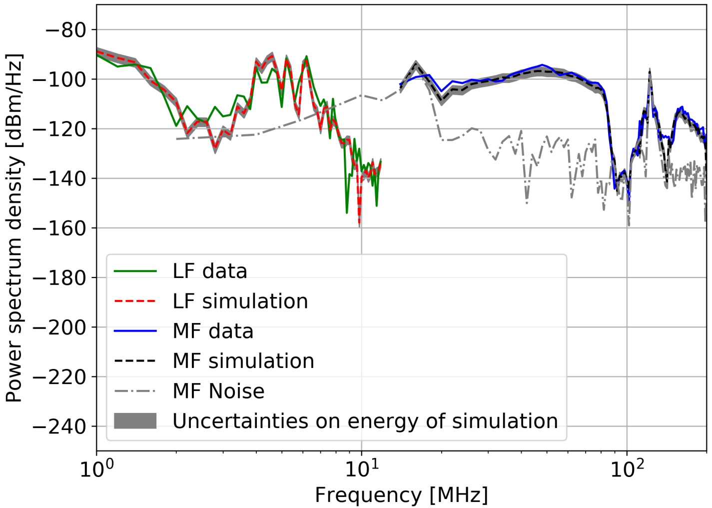




Summary at LF

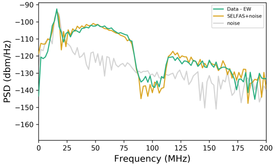
- LF counterpart of shower development detected
- Larger detection range, weaker signal
- Sudden death signal still not seen ⇒ Auger
- Strong correlation with atmospheric electric field
- LF signal seems not very promising (very few events, low efficiency): 20 LF events seen since March 2017

Illustrative example of LF detection



- CODALEMA/EXTASIS: very wide [1-10] + [20 – 200] MHz, routinely multi-wavelength observation of cosmic-ray air-showers in 10^{16} – 10^{18} eV, self-triggered stations in [20 – 200] MHz

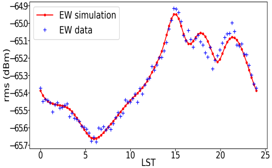
- Instrument and simulations very well mastered, strong agreement



- Estimation of shower parameters using the radio signals (θ, ϕ, (X_{core},Y_{core}), X_{max}, Energy) in [20 – 200] MHz, using both polarizations independently ⇒ CR composition from CODALEMA upcoming

- Low-frequency signal seems not very promising

- Difficult to extract parameters for inclined showers ⇒ use of the HF counterpart



CODALEMA/EXTASIS are smart, powerful instruments in a unique environment

Thank you for listening !

Back-up

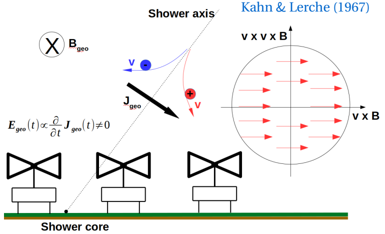
Geomagnetic emission mechanism:

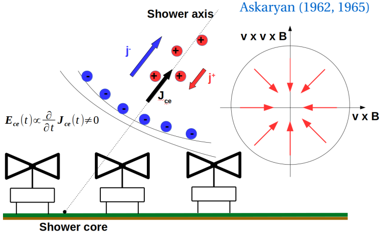
- Earth magnetic field, $\vec{F} = q\vec{v} \times \vec{B}$
- Resulting current perpendicular to the shower axis ⇒ time variation ⇒ pulses of electromagnetic radiation
- Polarized along $\vec{v} \times \vec{B}$

+

Charge excess emission mechanism:

- Negative charge excess ≈ 10 - 20 % ⇒ medium ionized by the air shower particles
- Linear polarization with electric field vectors oriented radially
- Time-varying charge excess ⇒ pulses of electromagnetic radiation





⇒ Sum of the two contributions: interferences

Hardware

13 scintillators since 2005

- → 340 m×340 m (0.12 km^2)
- → Sampling 1 GS/s, 12 bits, 2.56 µs
- → Generate a trigger signal, to be sent to any other detector and to a GPS datation station

5/13 trigger
10^{16} to 10^{18} eV

- → Database for all arrays
- → Event builder

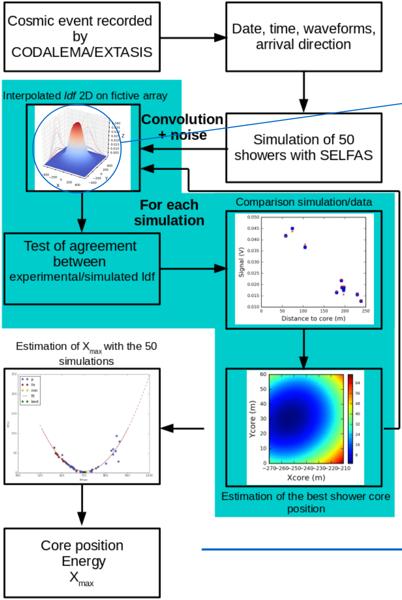
- → “AERA like” central DAQ
- → T3 level
- → Radio event builder
- → Pure radio T3
- → Noise rejection ∼ 100 %

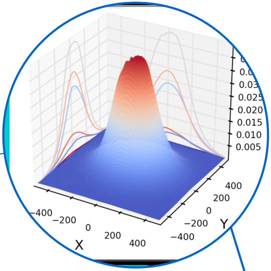
7 LF antennas since 2017

- → Butterfly antenna
- → Modified LONAMOS LNA
- → Externally triggered by SC
- → 9 m height
- → Frequency band [1 – 10] MHz

57 SA since 2013

- → Triangle 1600 m×1400 m (1.1 km^2)
- → Butterfly antenna, LONAMOS LNA
- → Sampling 1 GS/s, 14 bits, 2.56 µs
- → Frequency band [20 – 200] MHz
- → Self-triggered array, local trigger (T1 & T2), local DAQ, data transfer w. fibres
- → Relative datation accuracy ∼ 5 ns





$$\chi^2 = \frac{1}{N_{dof}-3} \sum_{ant} \frac{(A_{ant} - \alpha \mathscr{F}(x_{ant} - x_{core}, y_{ant} - y_{core}))^2}{\sigma_{ant}^2}$$

Combination of (X_{core}, Y_{core}) and α with the lowest χ^2 is the most probable set of values.

Process a set of SELFAS simulations (40p, 10Fe) per event to sample the X_{max} range.

Compare the lowest χ^2 values versus X_{max}.

The lowest χ^2 determines overall most probable (X_{core}, Y_{core}), E=$\alpha \times 10^{17}$ eV and X_{max}.

Before:

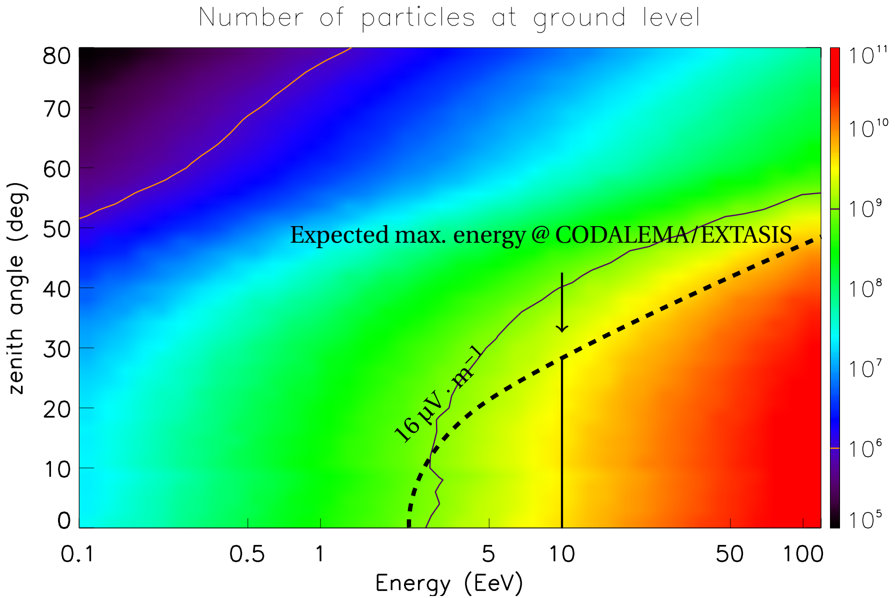
$$\chi^2 = \frac{1}{N_{\mathrm{dof}} - 3} \sum_{\mathrm{ant}} \left(\frac{(A_{\mathrm{ant}} - \alpha \mathscr{F}(x_{\mathrm{ant}} - x_{\mathrm{core}}, y_{\mathrm{ant}} - y_{\mathrm{core}}))^2}{\sigma_{\mathrm{ant}}^2} \right)$$

Now:

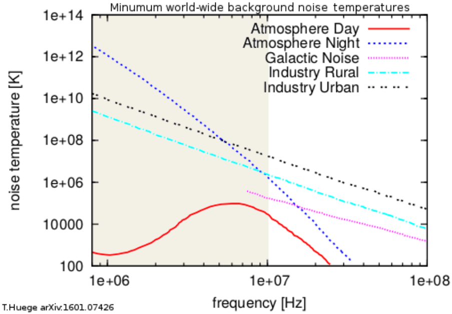
$$\begin{aligned} \chi^2 \quad = \quad & \frac{1}{N_{\mathrm{dof}} - 3} \sum_{\mathrm{ant}} \left(\frac{\left(A_{\mathrm{ant}}^{\mathrm{EW}} - \alpha \mathscr{F}^{\mathrm{EW}}(x_{\mathrm{ant}} - x_{\mathrm{core}}, y_{\mathrm{ant}} - y_{\mathrm{core}})\right)^2}{\sigma_{\mathrm{ant}}^{\mathrm{EW}\,2}} \right. \\ & \left. + \frac{\left(A_{\mathrm{ant}}^{\mathrm{NS}} - \alpha \mathscr{F}^{\mathrm{NS}}(x_{\mathrm{ant}} - x_{\mathrm{core}}, y_{\mathrm{ant}} - y_{\mathrm{core}})\right)^2}{\sigma_{\mathrm{ant}}^{\mathrm{NS}\,2}} \right) \end{aligned}$$

- Hybrid reconstruction: use of different detectors of CODALEMA/EXTASIS
- Multi-wavelength reconstruction: use of [20 – 80] MHz and [120 – 200] MHz bands
- Increasing the dof: take into account the information of both polarizations

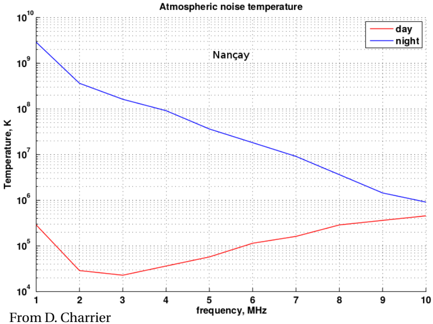
The sudden death signal



Atmospheric noise



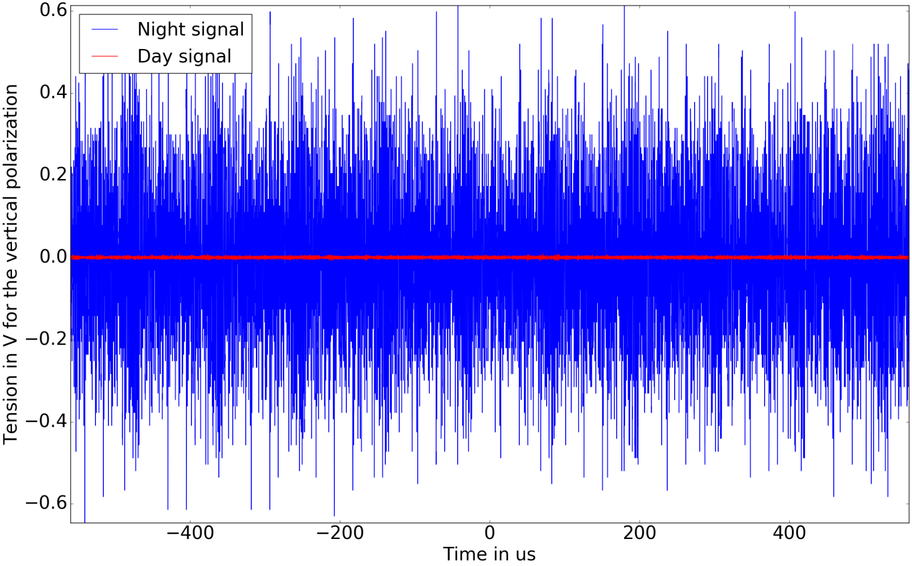
T.Huege arXiv:1601.07426



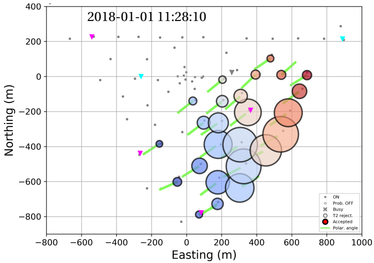
From D. Charrier

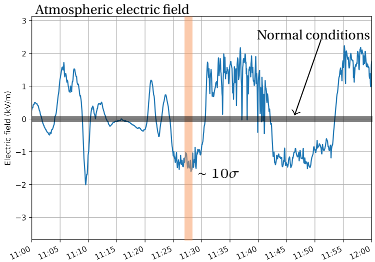
- Dominated by atmospheric and man-made noises (not the Galactic one)
- Atmospheric noise lower during day than night ⇒ duty cycle ≤ 50 %
- Analysis band: [1.7 – 3.7] MHz

Atmospheric noise



Role of the atmospheric electric field

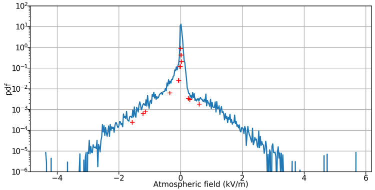




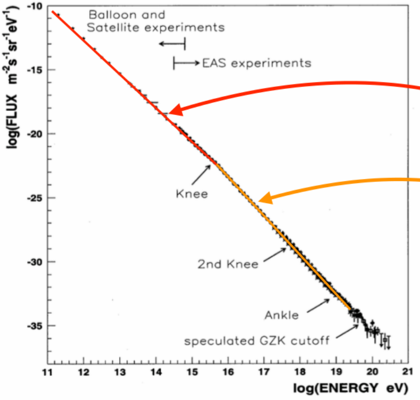
$$\overrightarrow{\mathrm{F}} = \mathrm{q} \times (\overrightarrow{\mathrm{E}}_{\mathrm{storm}} + \overrightarrow{\mathrm{v}} \wedge \overrightarrow{\mathrm{B}})$$

but

$$\overrightarrow{\mathrm{E}}_{\mathrm{storm}} \ggg \overrightarrow{\mathrm{v}} \wedge \overrightarrow{\mathrm{B}}$$



From B. Revenu



$$I_N(E) = \frac{\mathrm{d}N}{\mathrm{d}S\,\mathrm{d}t\,\mathrm{d}\Omega\,\mathrm{d}E} \quad \text{nucléons.m}^{-2}.\text{s}^{-1}.\text{sr}^{-1}.\text{eV}^{-1}$$

flux différentiel dans 10^{11}-3×10^{15} eV avec α=2.7 :

$$I_N(E) \sim 10^{19.555} \left(\frac{E}{1\text{ eV}}\right)^{-\alpha}$$

flux différentiel dans 3×10^{15} eV - 3×10^{18} eV avec α=3.1 :

$$I_N(E) \sim 10^{25.748} \left(\frac{E}{1\text{ eV}}\right)^{-\alpha}$$

flux intégré :

$$\frac{\mathrm{d}N}{\mathrm{d}S\,\mathrm{d}t\,\mathrm{d}\Omega}(E > E_0) = k\frac{{E_0}^{1-\alpha}}{\alpha - 1} \quad \text{nucléons.m}^{-2}.\text{s}^{-1}.\text{sr}^{-1}$$

$$= 50\text{ km}^{-2}\text{ min}^{-1}\text{ sr}^{-1} \text{ pour E>}10^{15}\text{ eV}$$

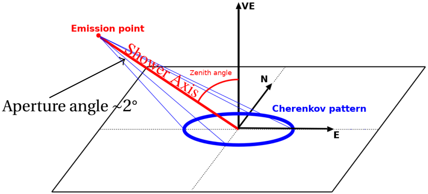
$$= 0.4\text{ km}^{-2}\text{ min}^{-1}\text{ sr}^{-1} \text{ pour E>}10^{16}\text{ eV}$$

$$\times 10 \text{ en E} \rightarrow \times 1/126 \text{ en flux}$$

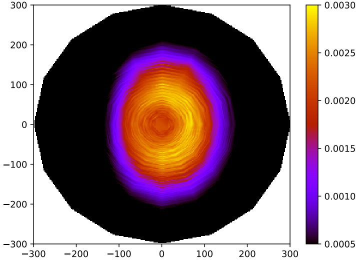
For E >1 EeV: $3.6\times10^{-2}\text{ km}^{-2}\cdot\text{d}^{-1}\cdot\text{sr}^{-1} \Rightarrow \sim 250$ showers over 3 years

Cherenkov effect

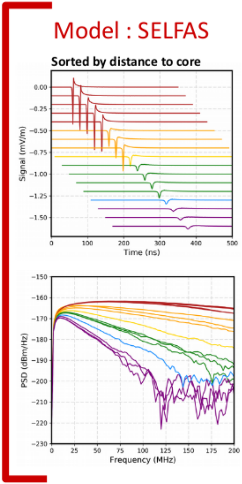
- This phenomenon occurs during the shower development in the atmosphere ⇒ radio-emission is amplified
- Signal pattern on the ground should present a ring of amplified emission

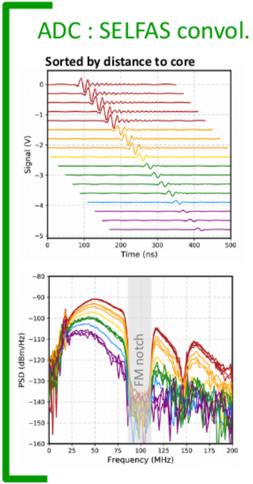


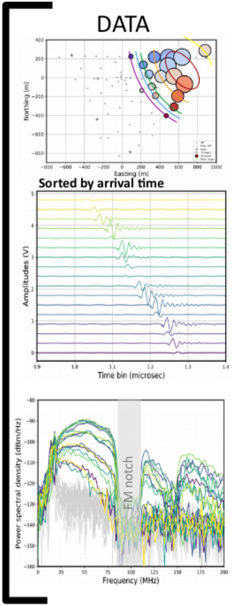
Not to scale!



Is the sensitivity preserved ?







Spectrum and amplitude variations are preserved !