Radio detection of atmospheric air showers of particles

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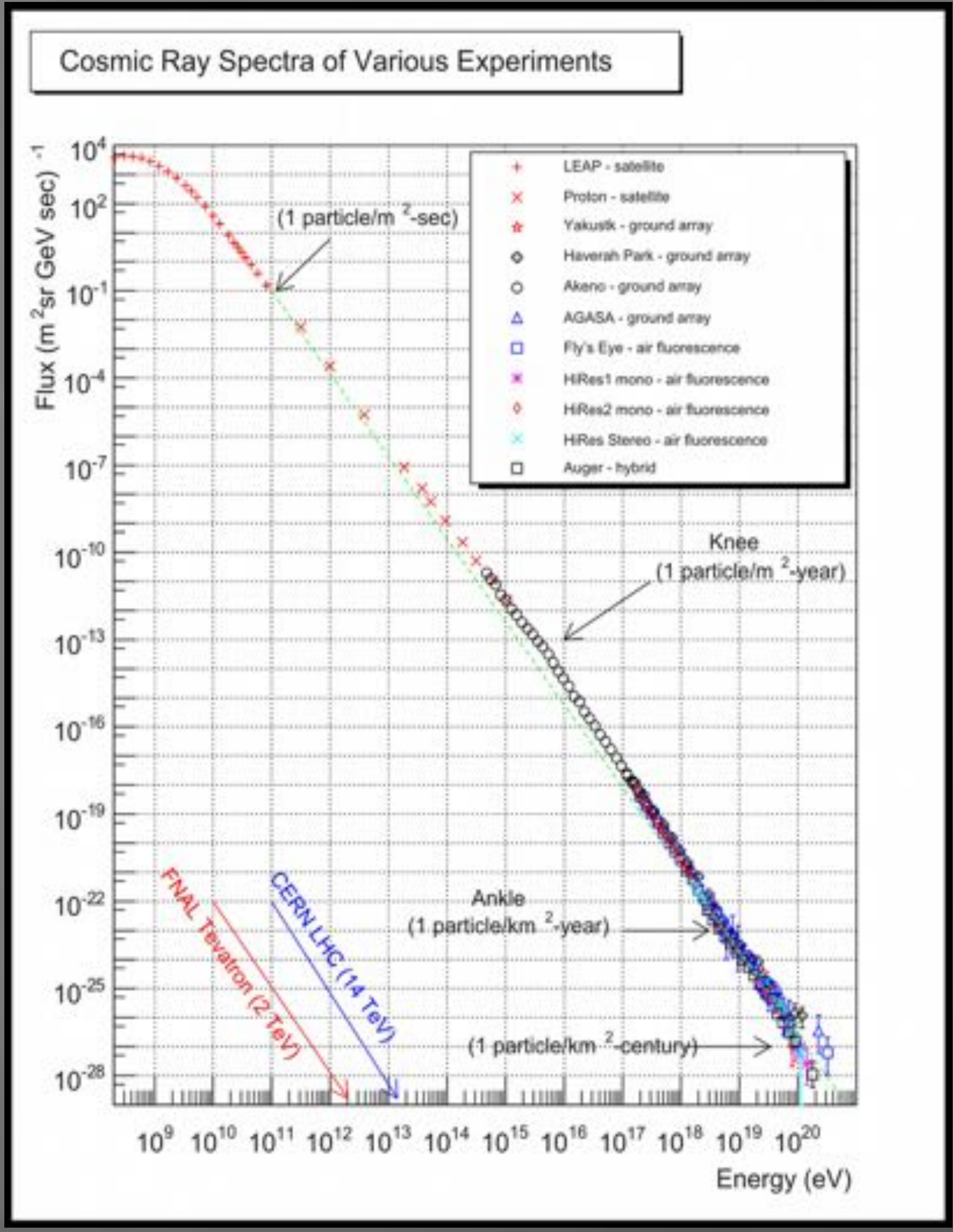
Why being interested in cosmic-rays (CRs) ?

- CRs: charged particles of extraterrestrial origin
- Coherent over 32 orders of magnitude: universal production mechanism
- Give access to high-energy cosmic phenomena
- Study of cross section at high energy (p-p, p-air): 800 times higher than the 14 TeV of the LHC
- Understanding the acceleration mechanisms
- Constraining the characteristics of sources
- Interrelationship with other messengers (γ, ν . . .)



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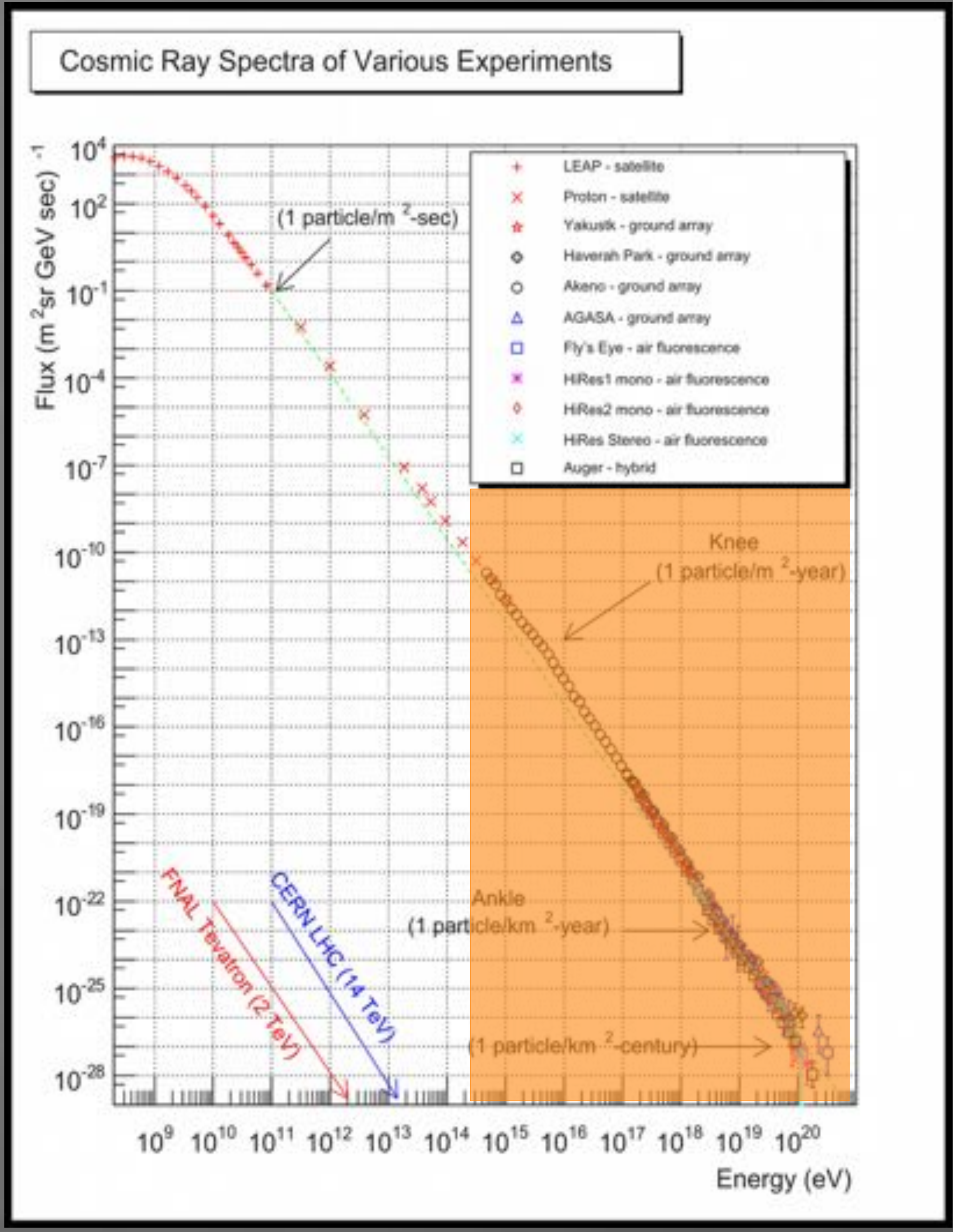
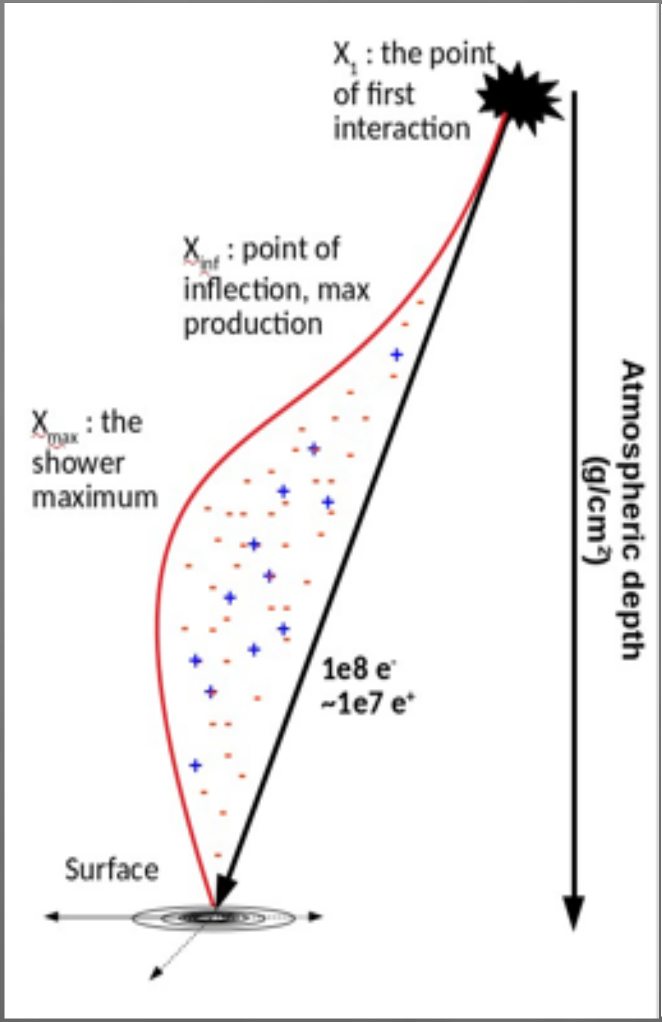


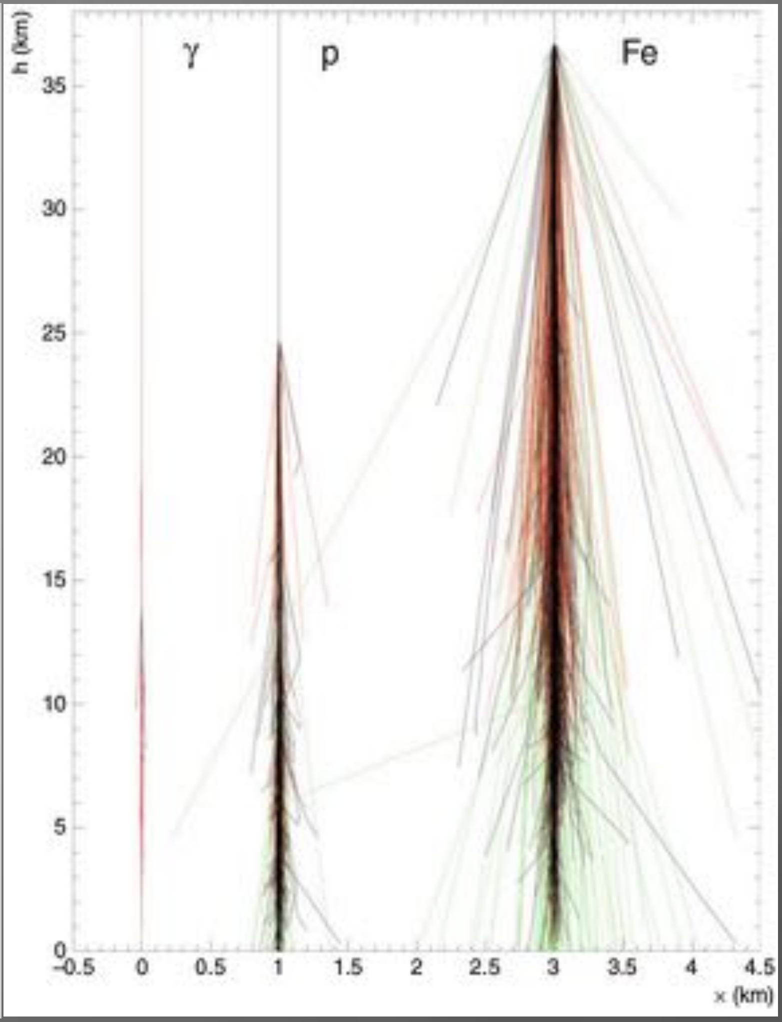
How to detect them ?

- Study of the secondary charged particles induced by the interaction of the primary CR with the atmosphere components ⇒ Extensive Air Shower (EAS)

- Methods of detection: fluorescence, particle detectors, Cherenkov tank

- Extracting primary characteristics: Xmax=nature, energy, arrival direction





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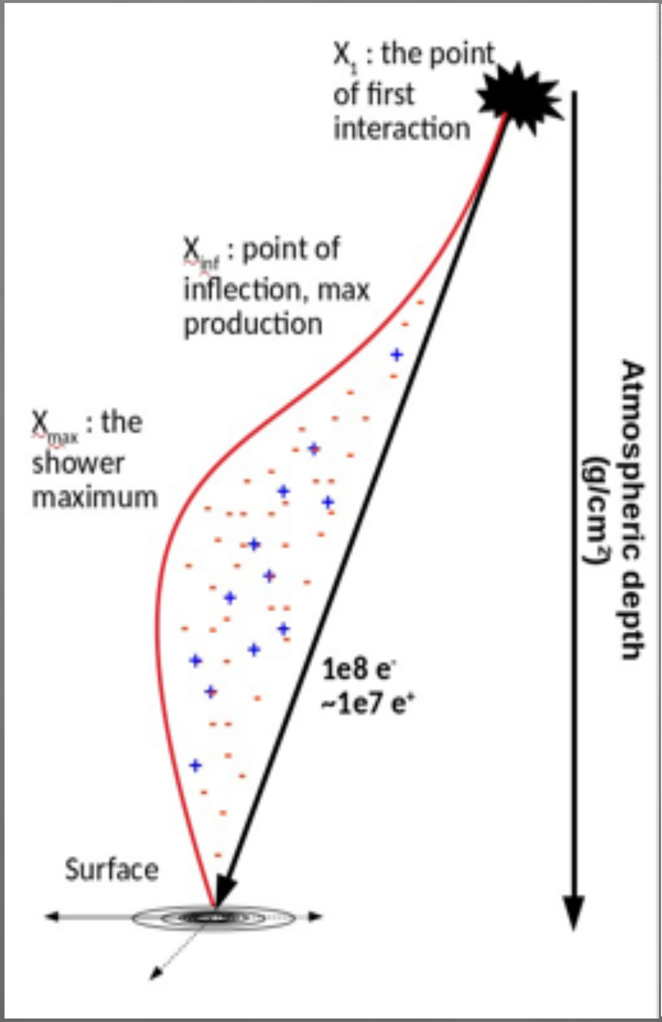

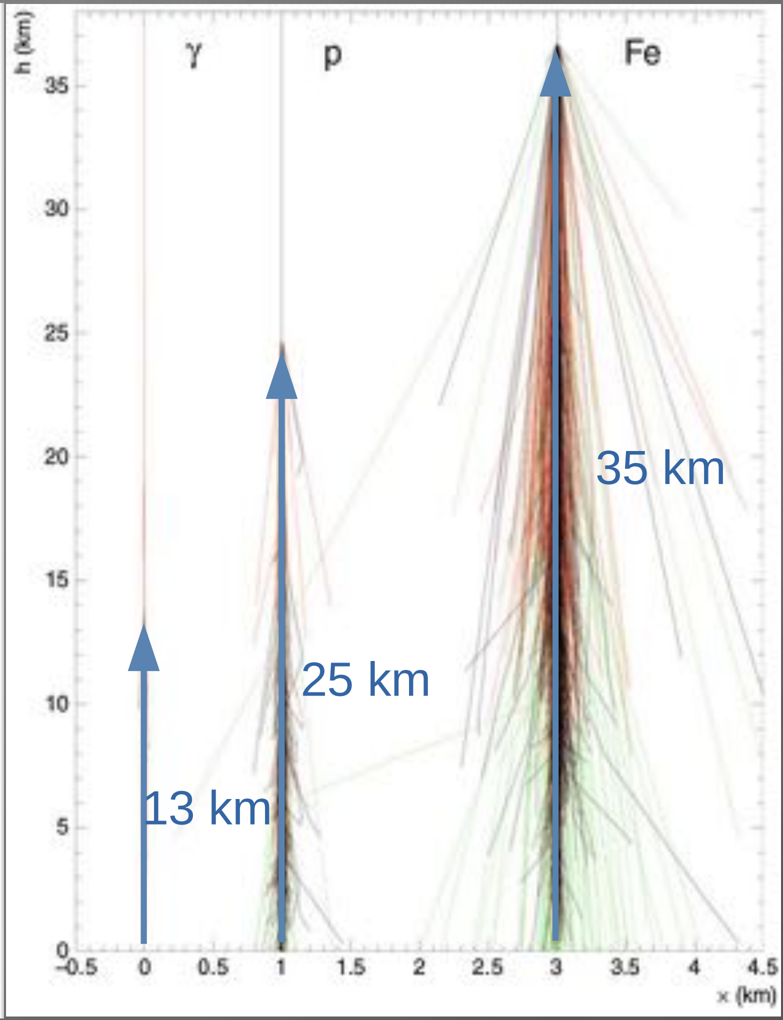

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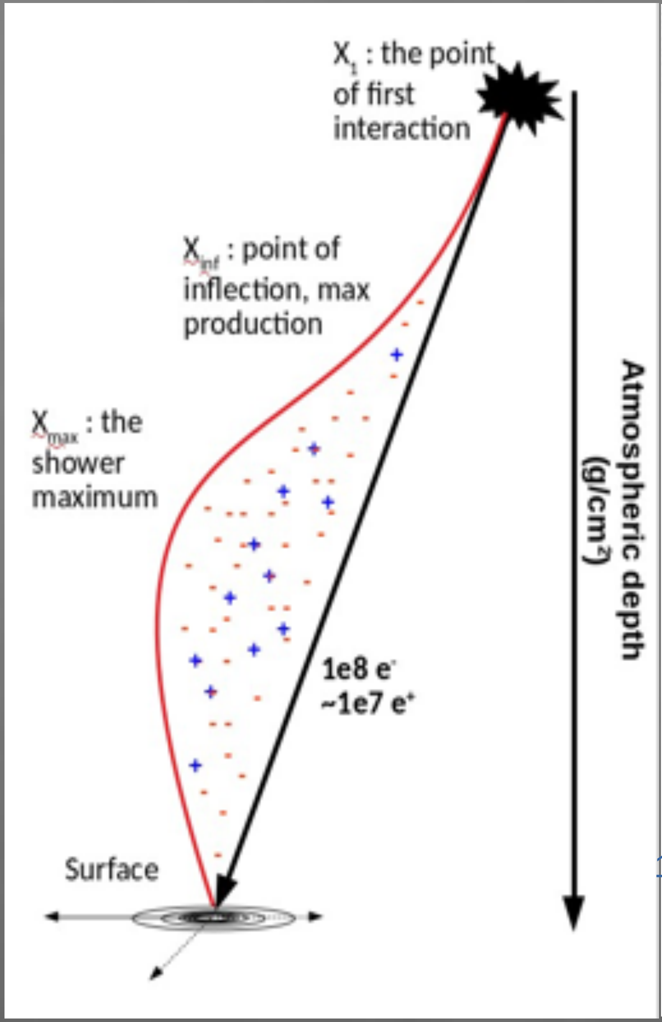

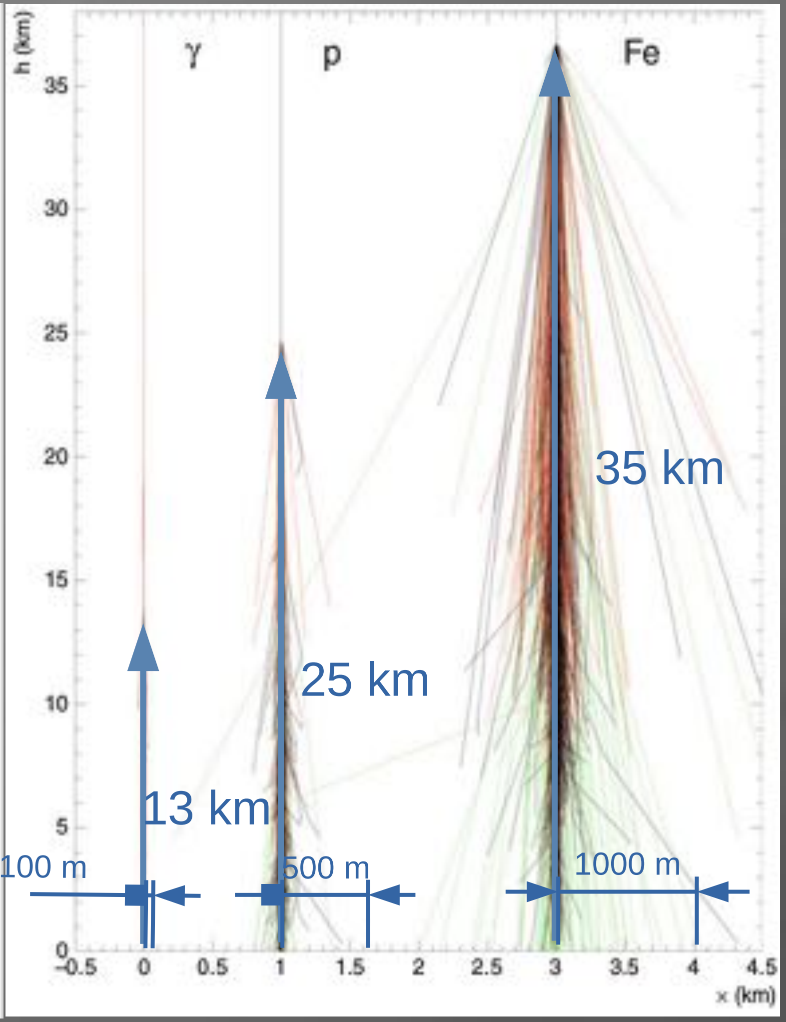

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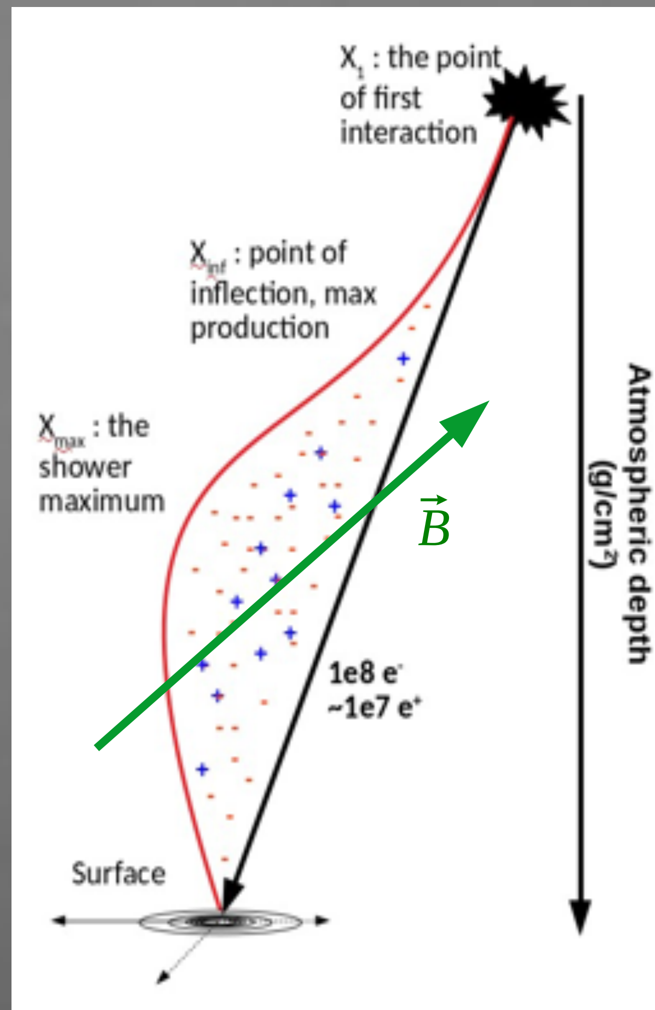
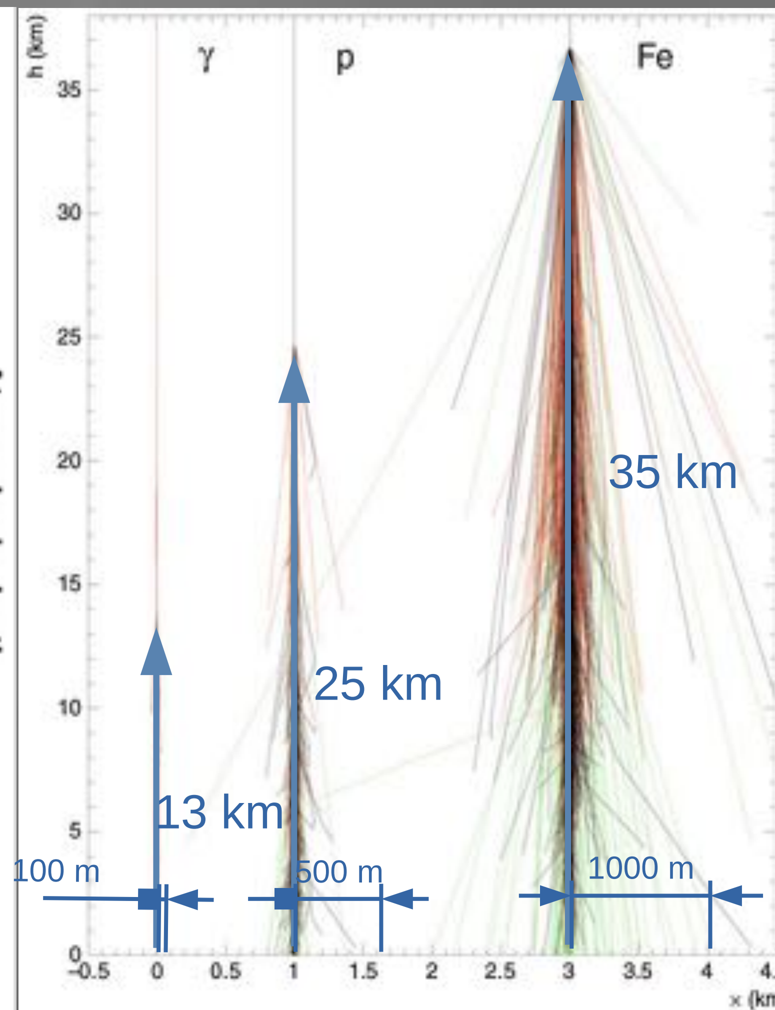
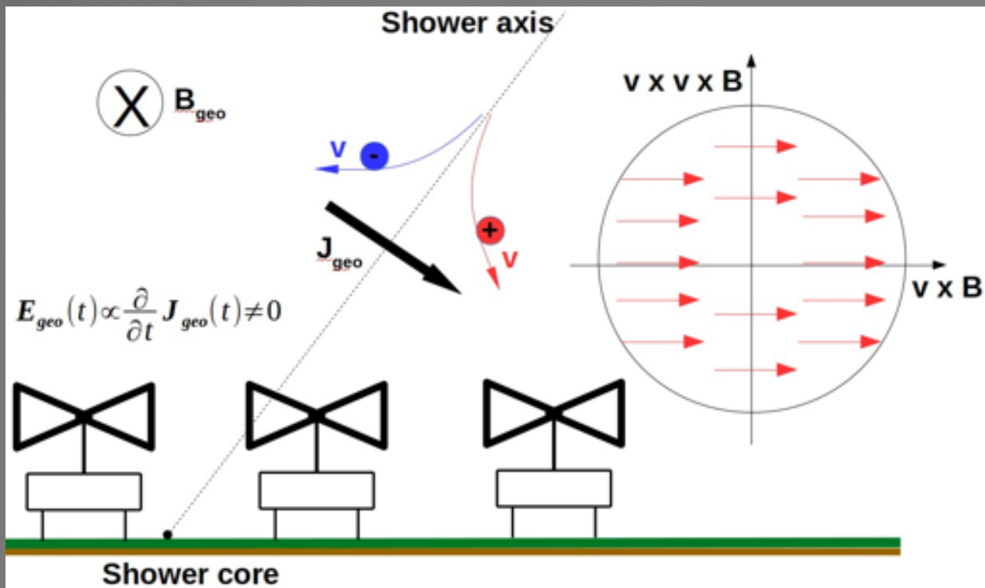
- Charged particles in movement + magnetic field ⇒ electric field emission ⇒ radio detection



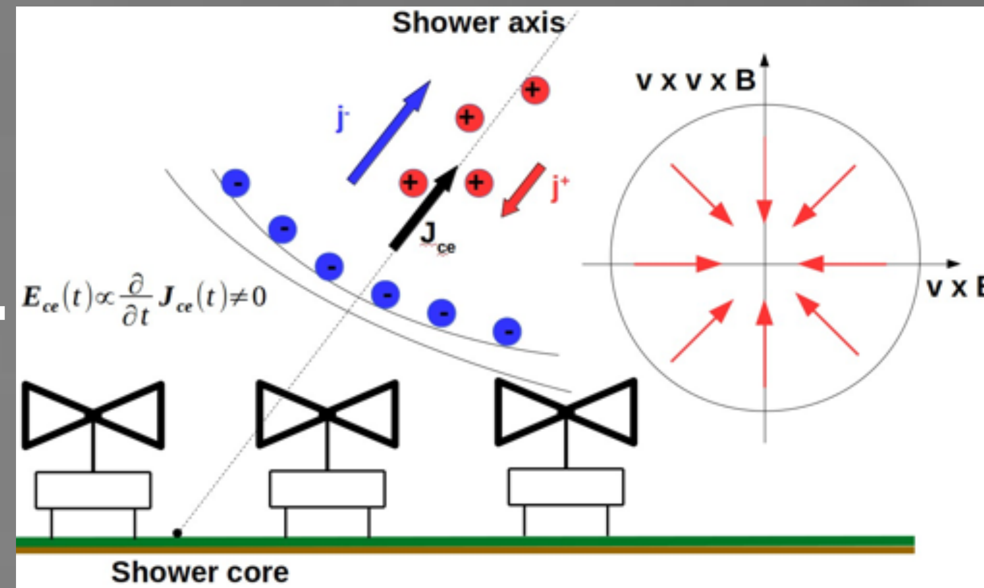


Radio emission from EAS – SELFAS3

Geomagnetic mechanism



Charge excess mechanism



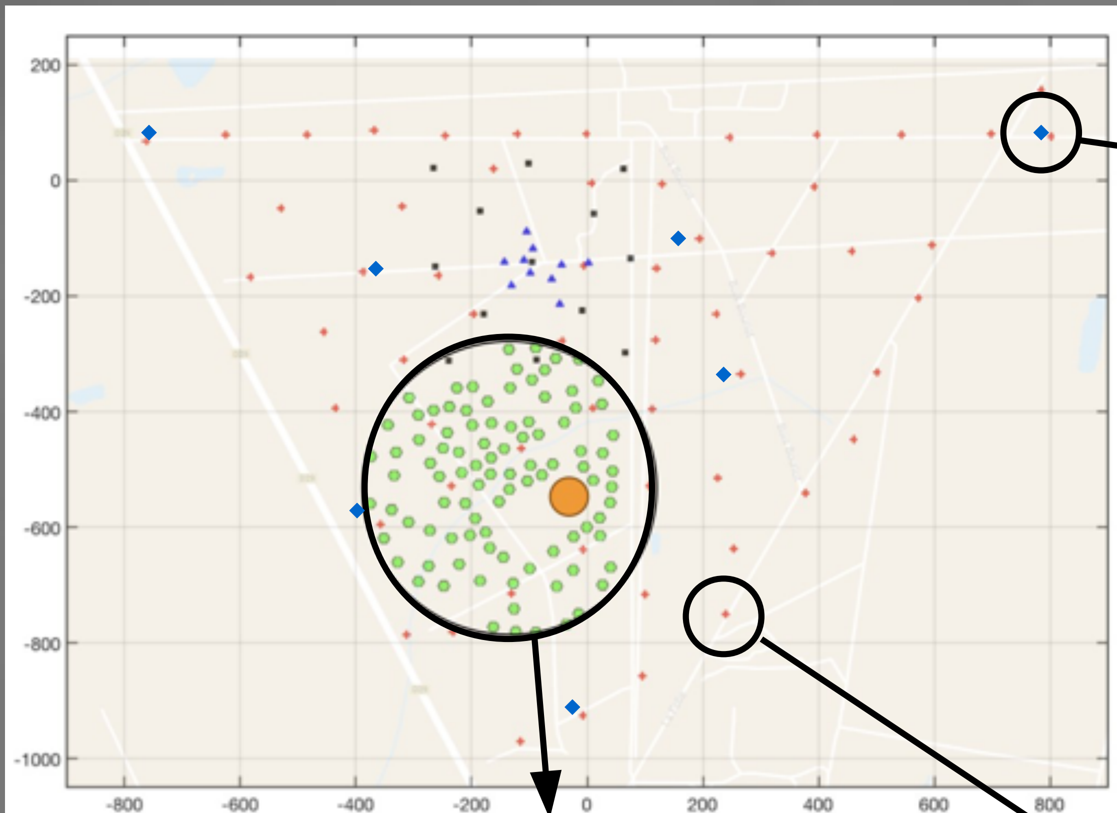
$$\mathbf{E}(\mathbf{x},t) = \frac{1}{4\pi\epsilon}\int \mathrm{d}^3x' \left[\frac{\hat{\mathbf{R}}}{R}[\rho(\mathbf{x}',t')]_{\mathrm{ret}} + \frac{\hat{\mathbf{R}}}{c_n R}\left[\frac{\partial\rho(\mathbf{x}',t')}{\partial t'}\right]_{\mathrm{ret}} - \frac{1}{c_n^2 R}\left[\frac{\partial\mathbf{J}(\mathbf{x}',t')}{\partial t'}\right]_{\mathrm{ret}}\right]$$

$$\begin{aligned}\rho(\mathbf{x}',t') &= -q\delta^3(\mathbf{x}'-\mathbf{x}_1)\Theta(t'-t_1)\\ &\quad +q\delta^3(\mathbf{x}'-\mathbf{x}_1)-\mathbf{v}(t'-t_1))[\Theta(t'-t_1)-\Theta(t'-t_2)]\\ &\quad +q\delta^3(\mathbf{x}'-\mathbf{x}_2)\Theta(t'-t_2)\end{aligned}$$

Charge conservation: implemented in SELFAS3 simulation code

GDAS : treatment of the atmosphere: *Astroparticle Physics, 98:38 – 51, 2018*

The experimental site – Nançay Radio Observatory



EXTASIS - [1,7-3,7] MHz

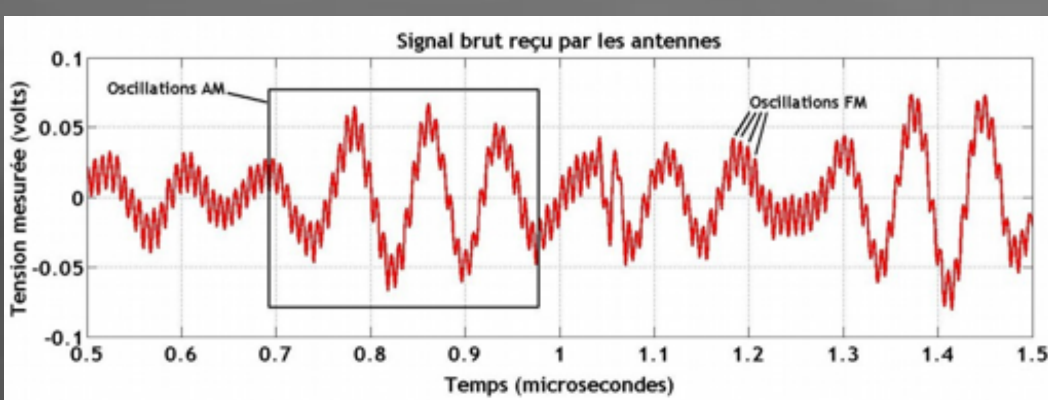
NenuFar - [10-85] MHz

CODALEMA - [20-200] MHz

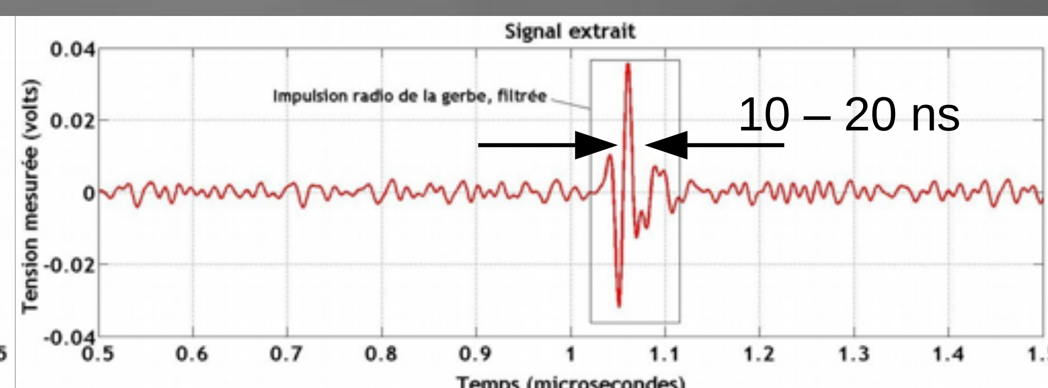
How does it work ?

- Detection of the radio pulse emitted during the EAS development
- Sensitive, wide-band (20-200 MHz), standalone,independent and autonomous antenna
- Analog triggering on threshold, fast sampling over a short duration: 1GS/s over 2,56 µs
- The electric field is sampled using an array of antennas on the ground
- CRs come from all directions ⇒ need to observe the entire sky ⇒ **wide individual antenna lobe**

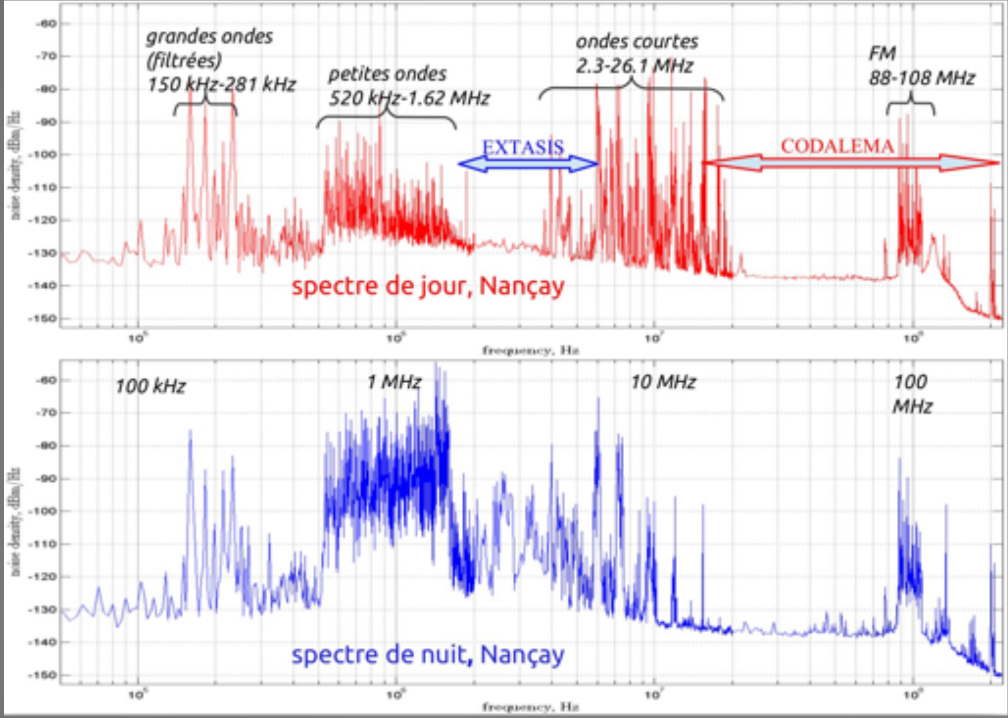
Full band signal



Filtered signal



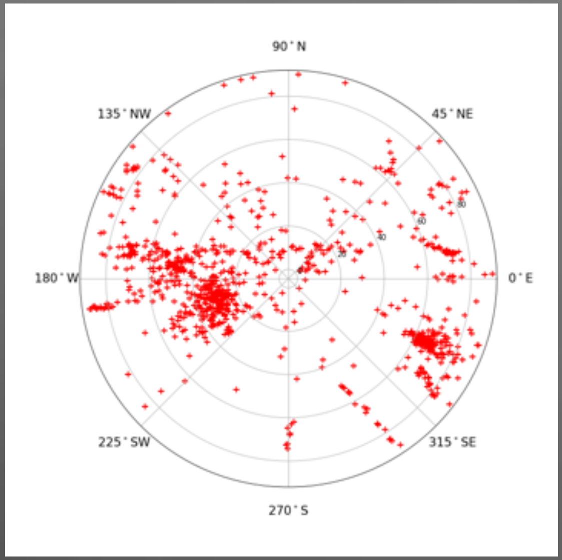
The transient environment at Nançay

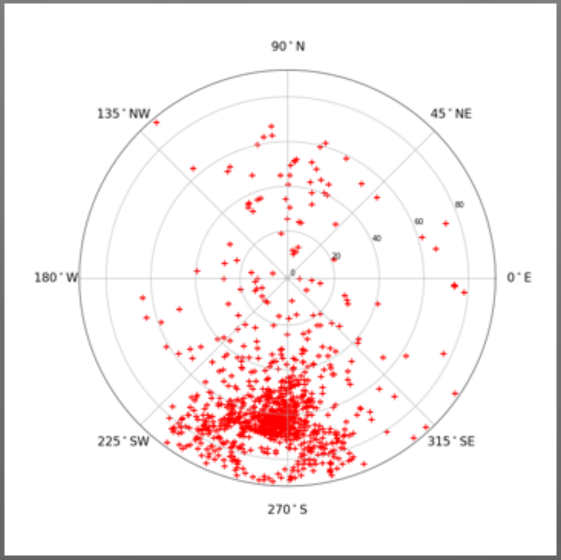


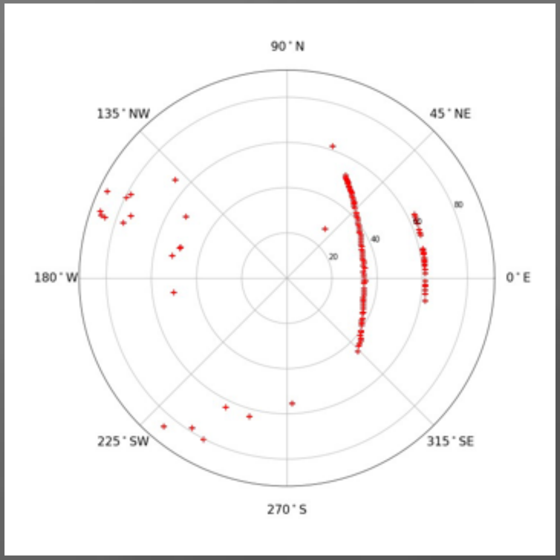
A large variety of parasitic sources:

- Plane tracks
- Poorly reconstructed sources
- Clear sources at specific azimuths
- AM and FM broadcasts
- Noise rejection algorithms inline (99 %) + offline (99% of the 1% remaining)

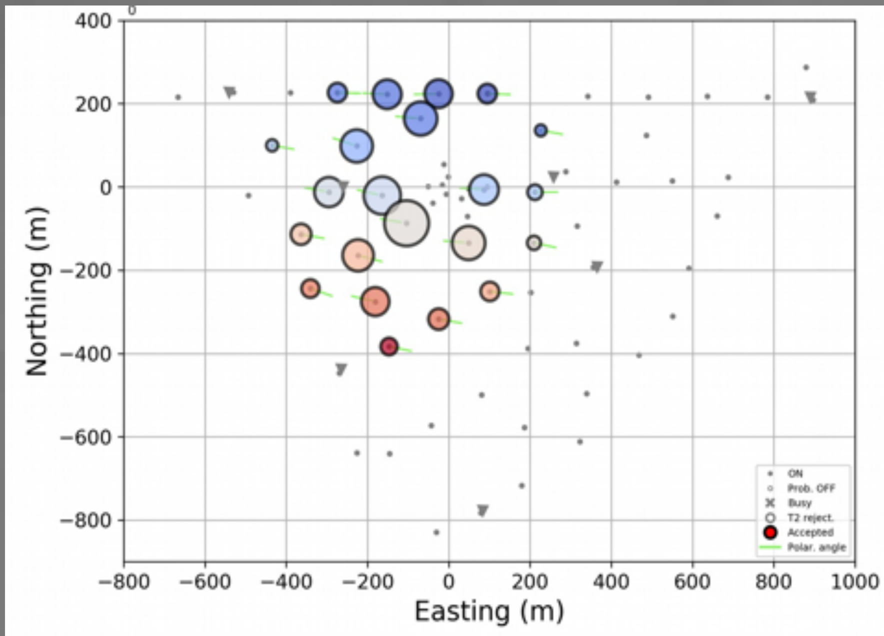
Sky map of reconstructed Directions Of Arrival



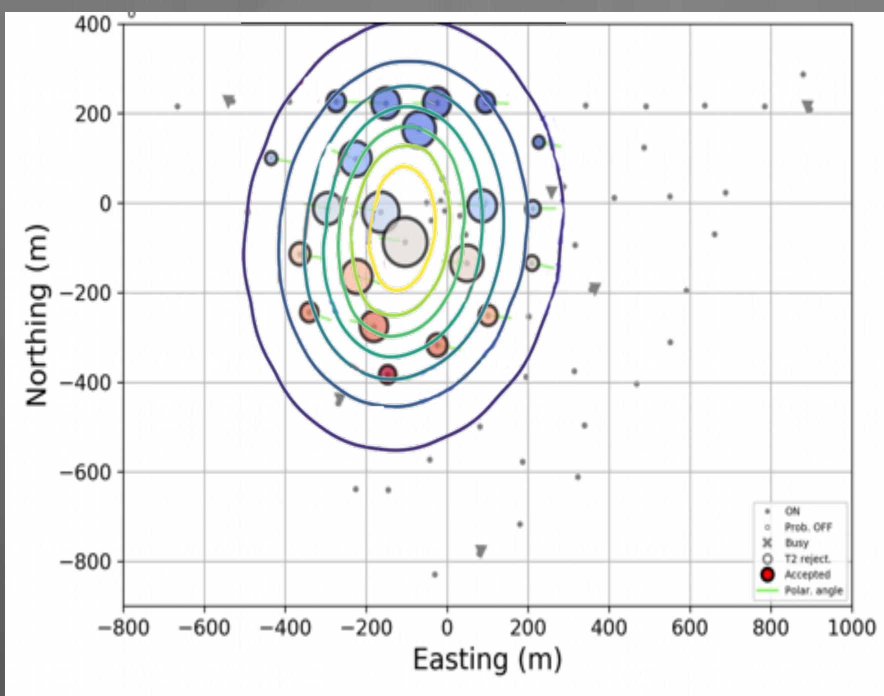


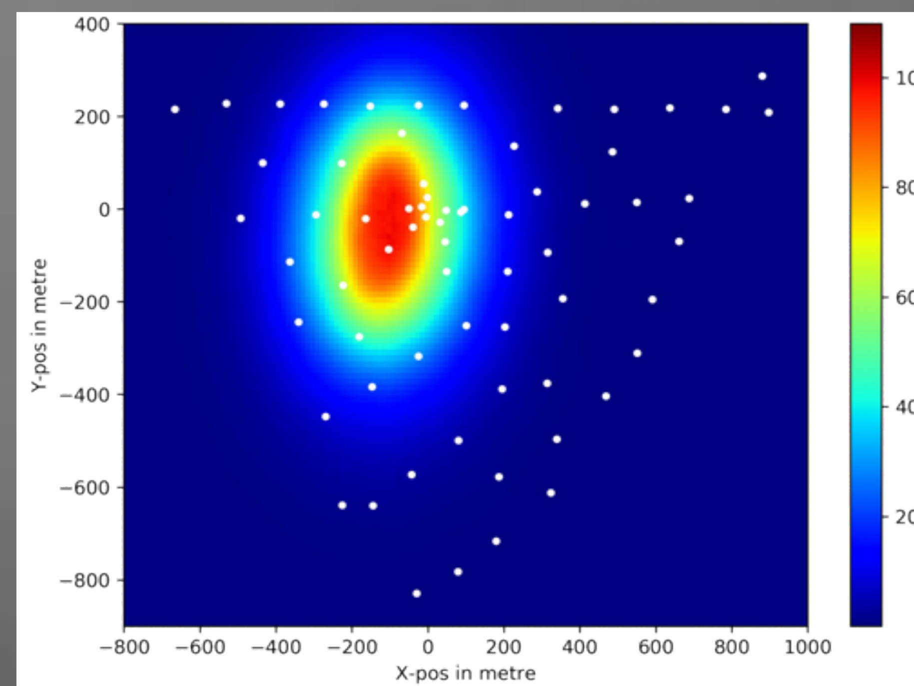


Estimating the shower parameters



- Direction of Arrival reconstructed using arriv   al times
- Core postion, composition and energy reconstructed through MC simulations





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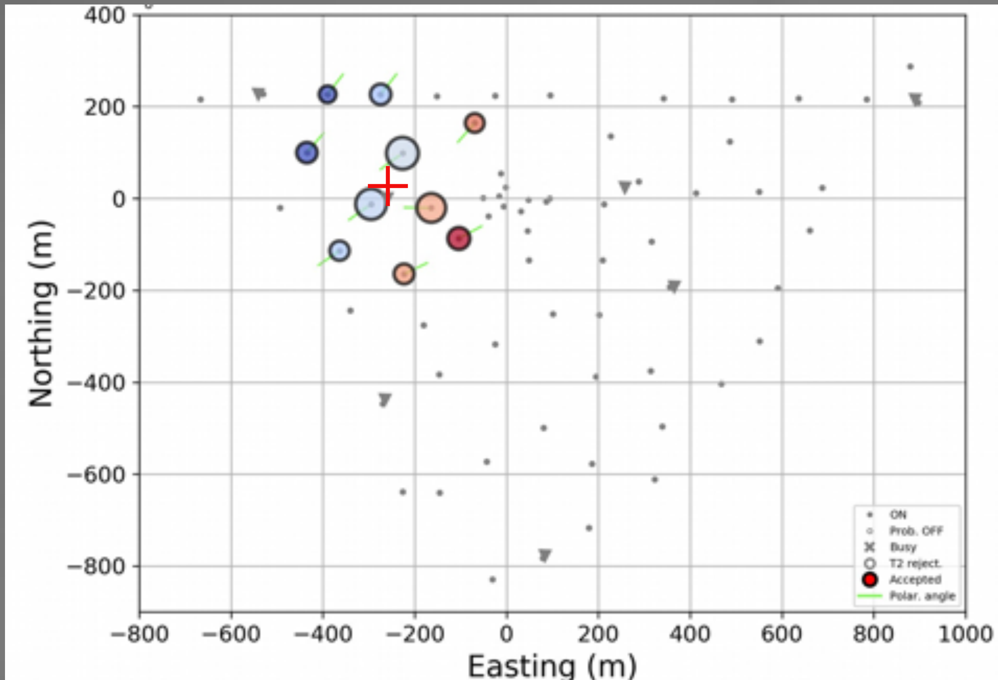
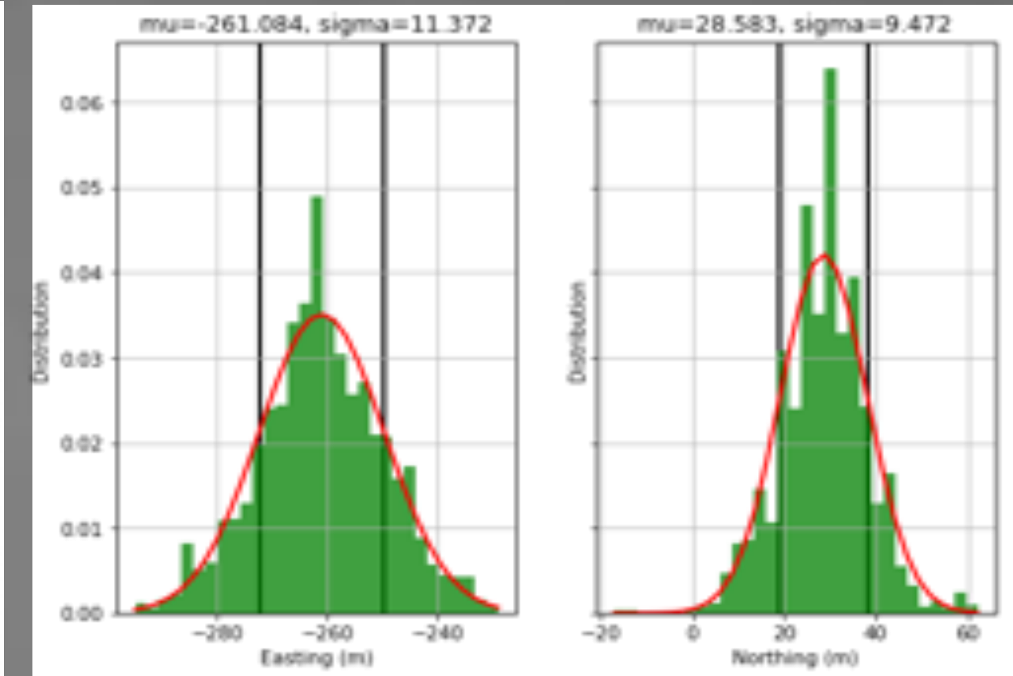
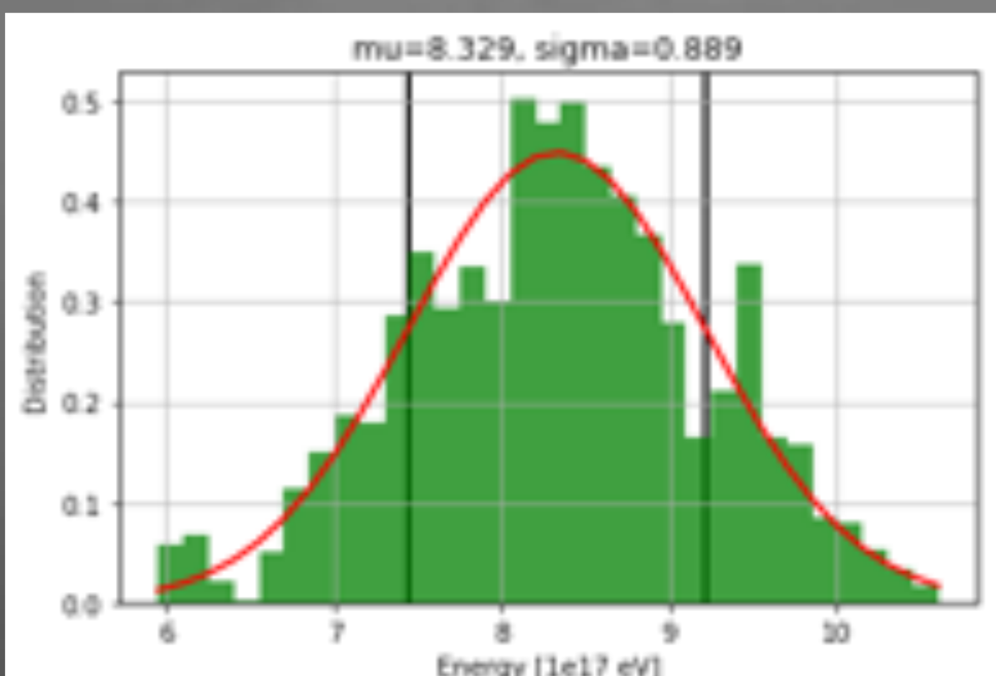
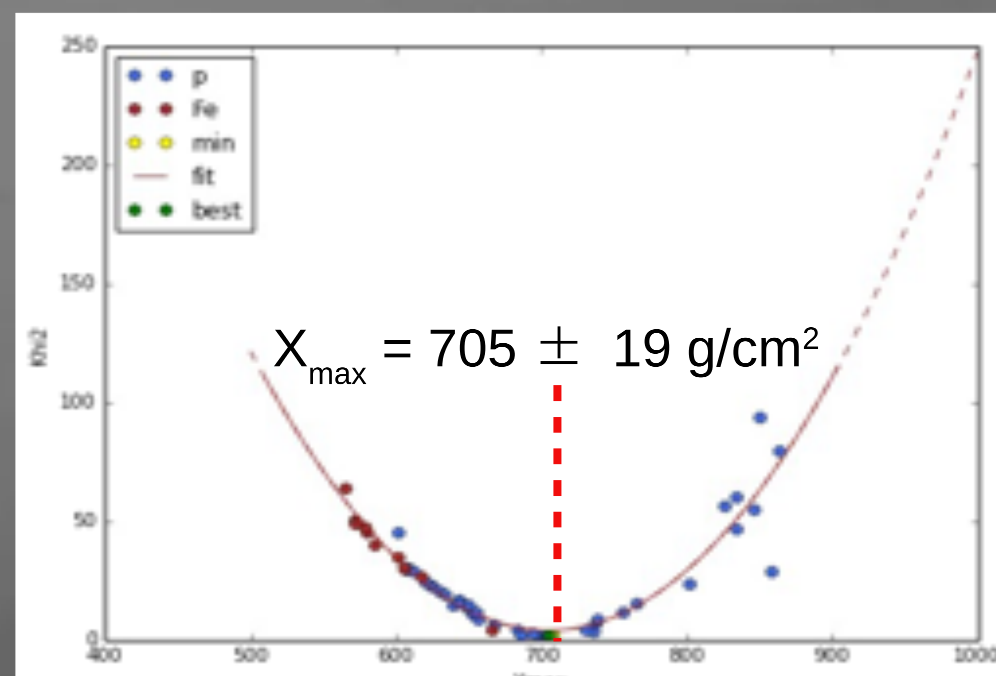
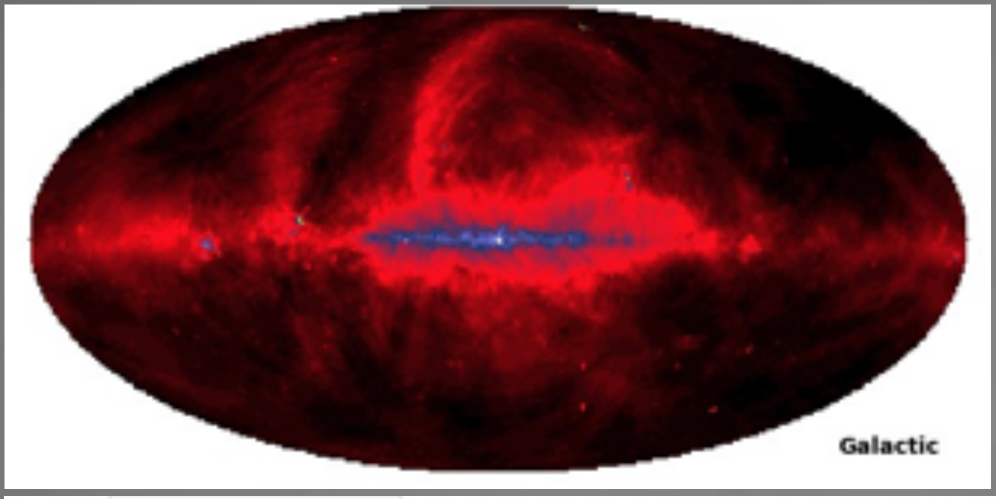




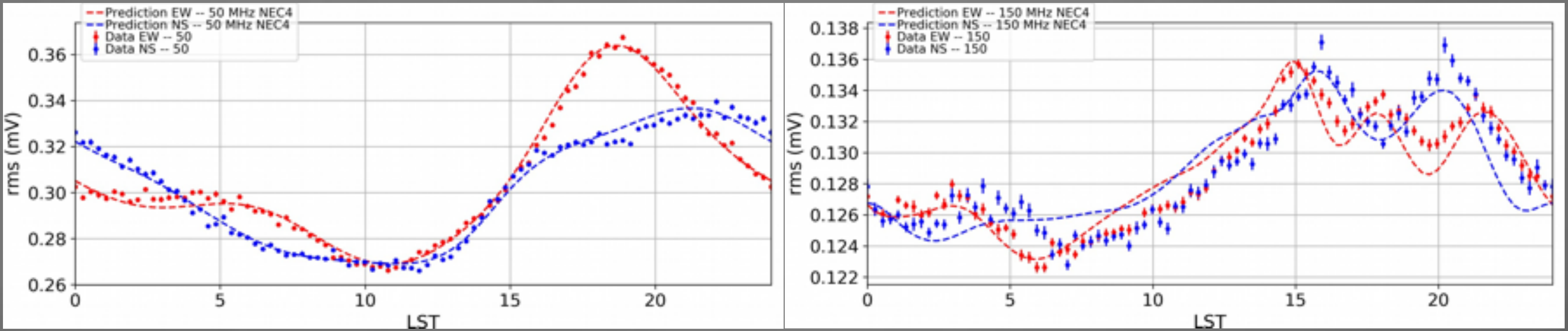


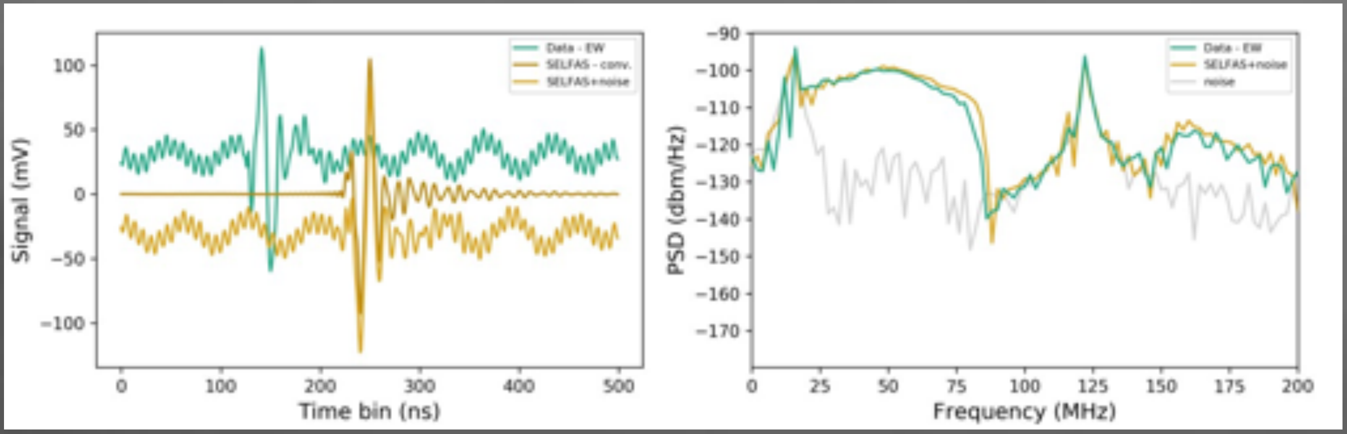


Good knowledge of the radio instrument



- Use of the Galactic radio emission as an absolute source for the calibration of the radio detectors of CODALEMA
- Galactic model: Global Sky Model





- Instrument and simulations very well mastered, strong agreement on [1-200] MHz

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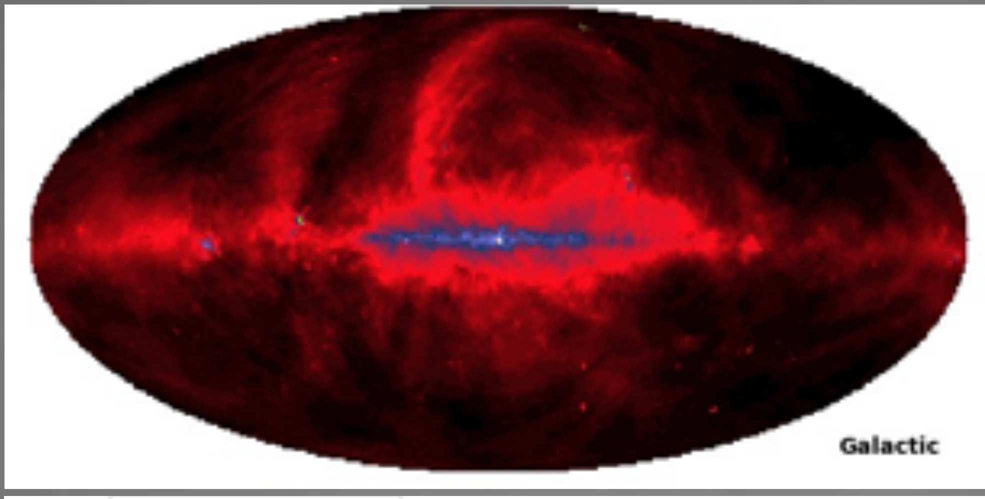

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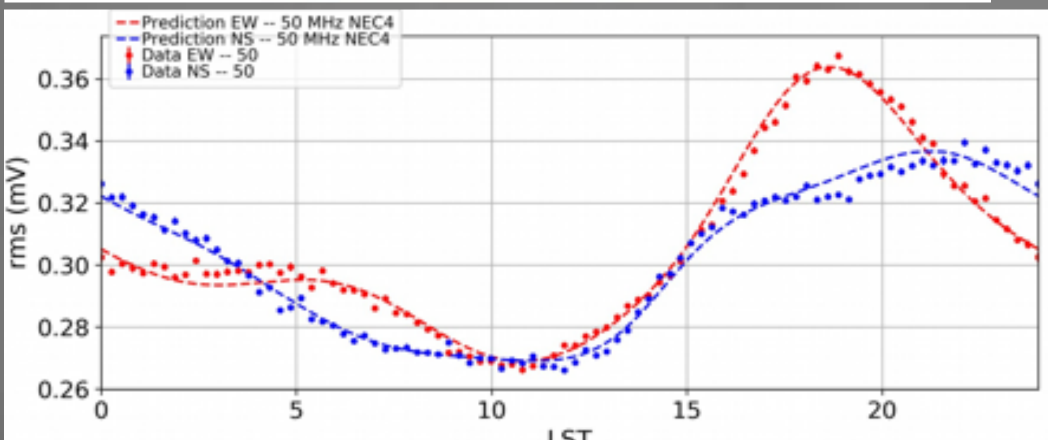

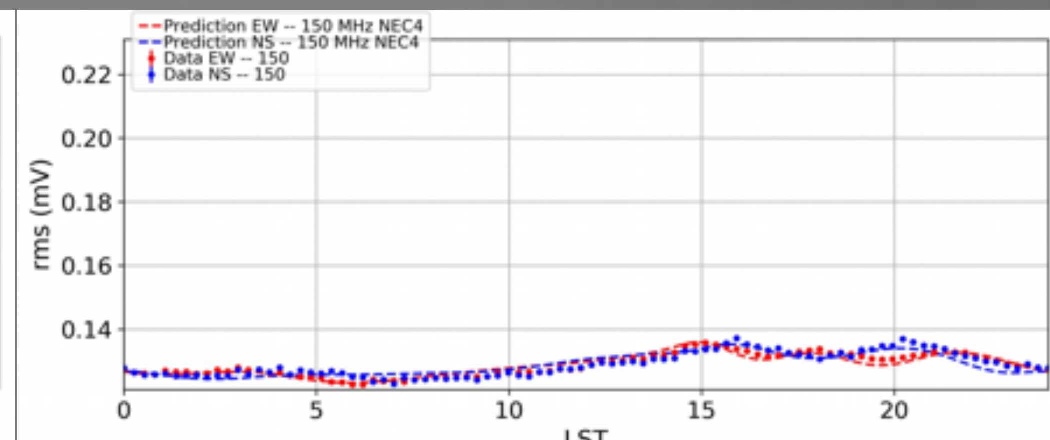

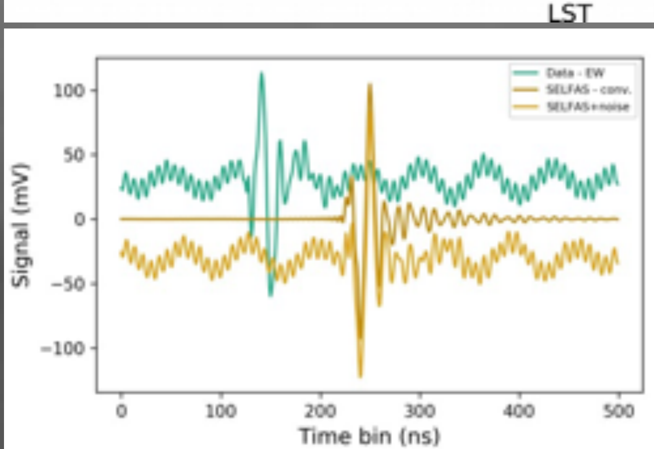

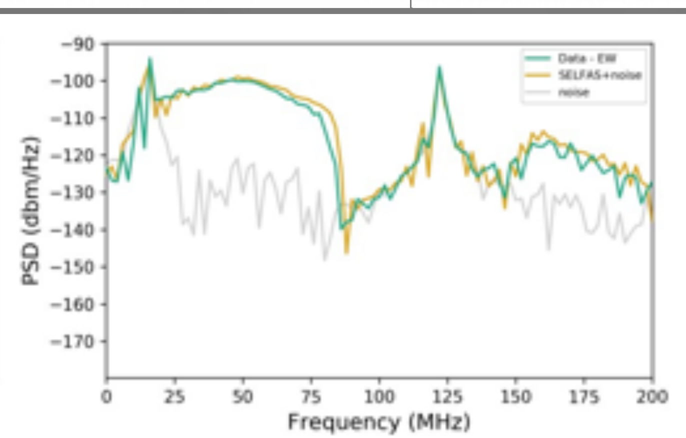

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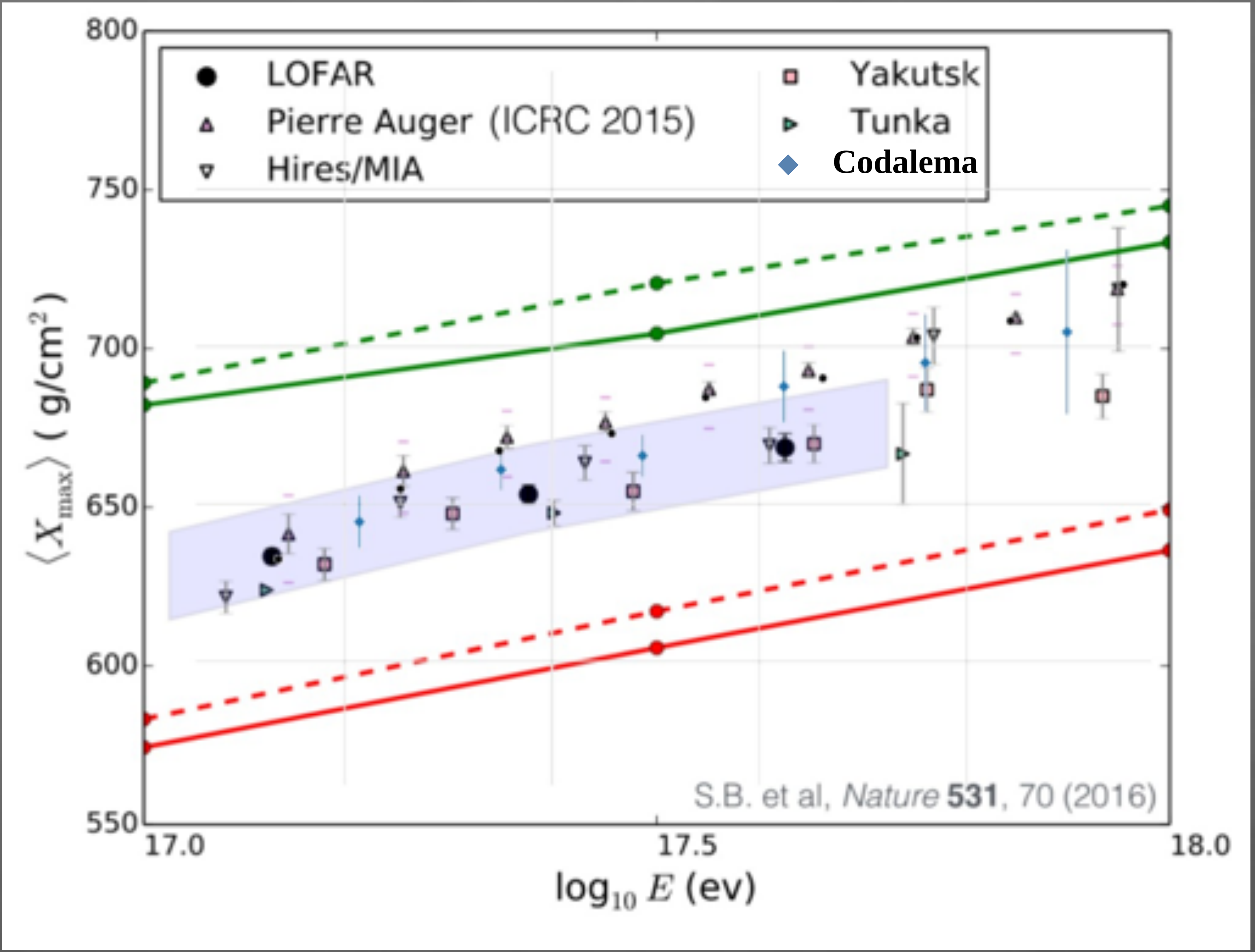
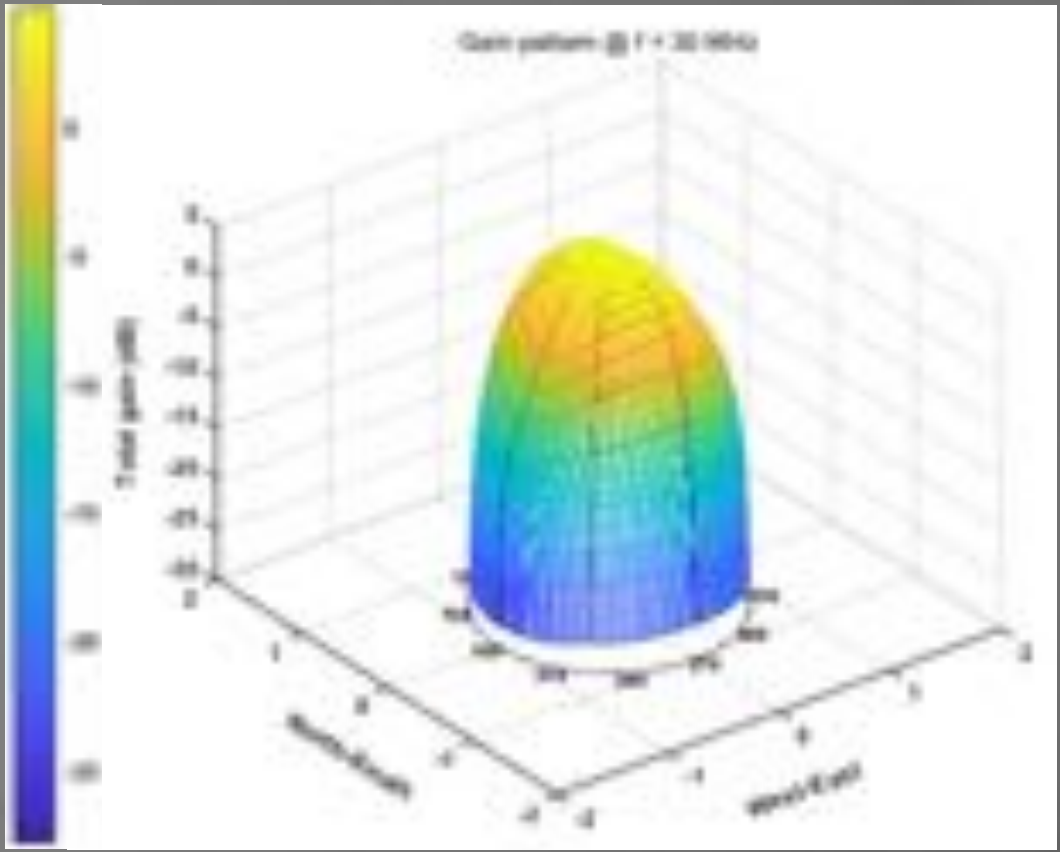
To the mass composition using the radio signal



CODALEMA & Cosmic Rays:

- arrival directions not predictible
- need to observe the whole sky
  ⇒ wide individual antenna lobe, self-trigger
- Energy threhold for radio ~ $10^{16.5}$ eV
- ⇒ impossibility to observe gamma ray showers of ~ 10^{14} - 10^{15} eV



But what if we knew in advance where the shower came from?

Gamma photons:

- Science case: currently, gamma astronomy till ~ 100 TeV (HAWC), [100 TeV-1 PeV] unaccessible with current telescopes, low duty cycle due to constraints on observation conditions (no Moon, no clouds...)
- Source may be known *a priori* (H.E.S.S., MAGIC, VERITAS… catalogs)
- Gamma shower: the energy is lower than for CR ⇒ Need to increase detection sensitivity ⇒ To combine several antennas and to point toward sources (possible with NenuFAR by combining the antennas of the mini-arrays (MA), and by combinin the mini-arrays themselves !)

Gain 1 MA ~20 dB (vs 0 dB for single antenna) + Observation duty cycle 100%

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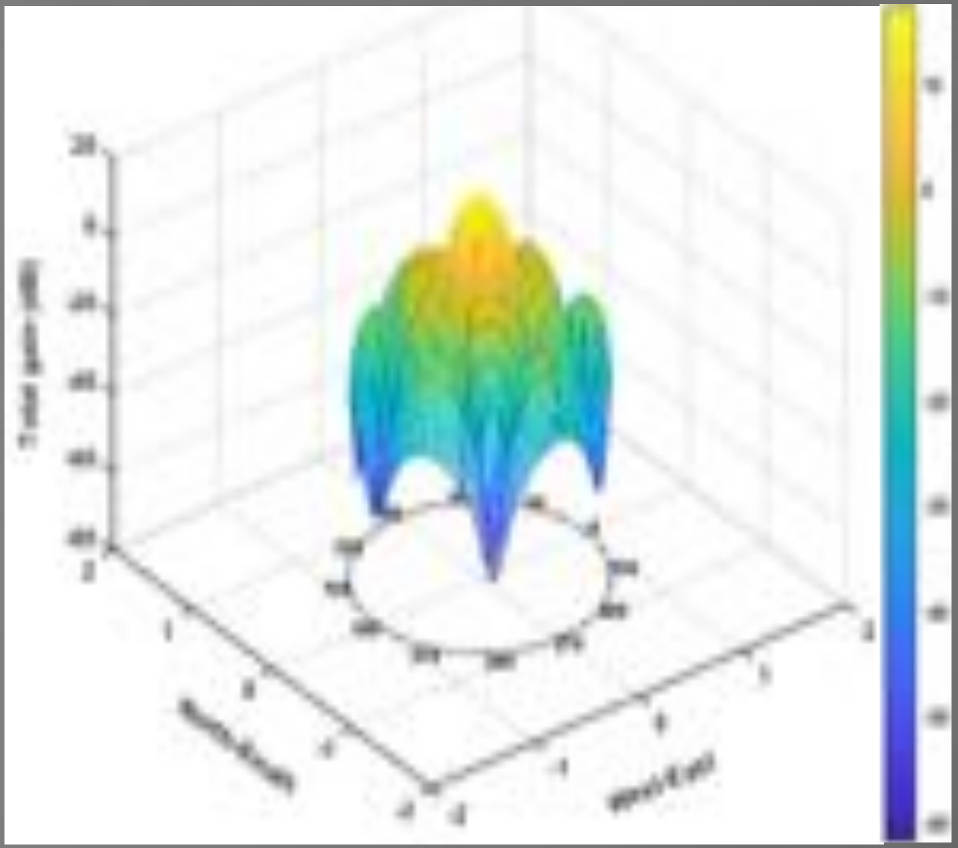

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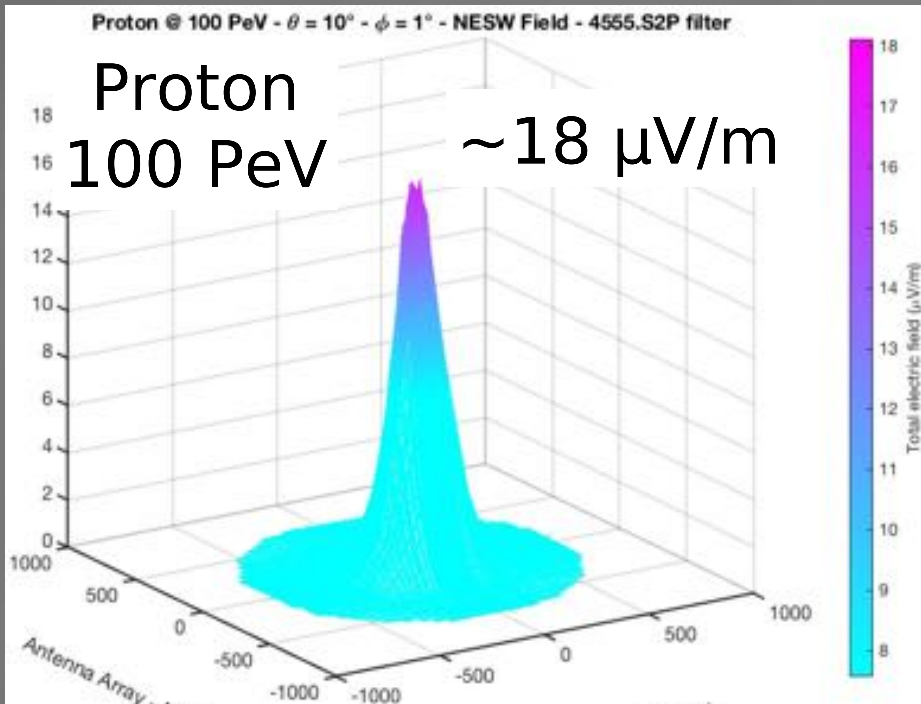
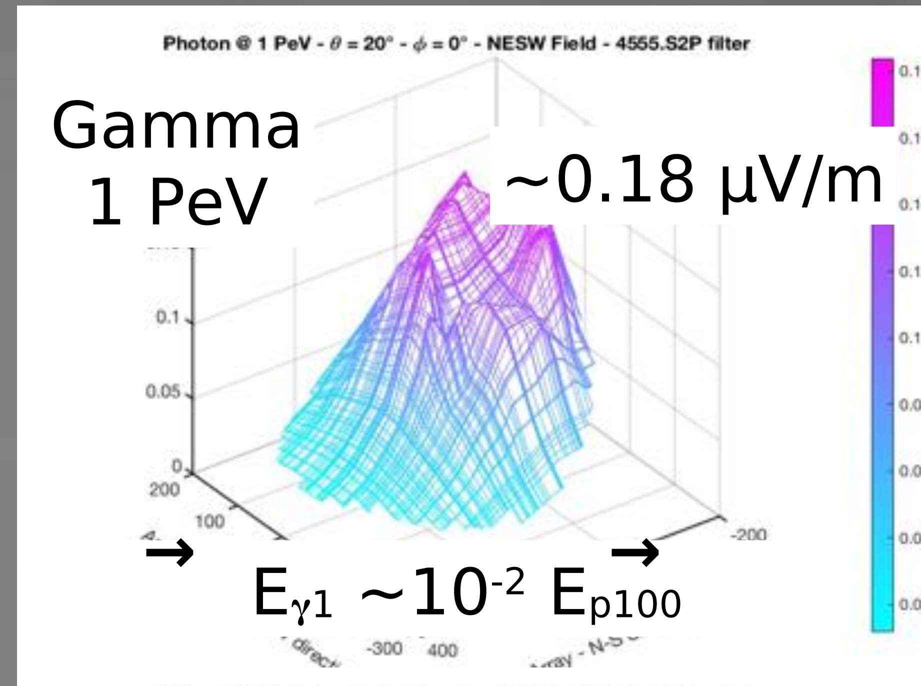
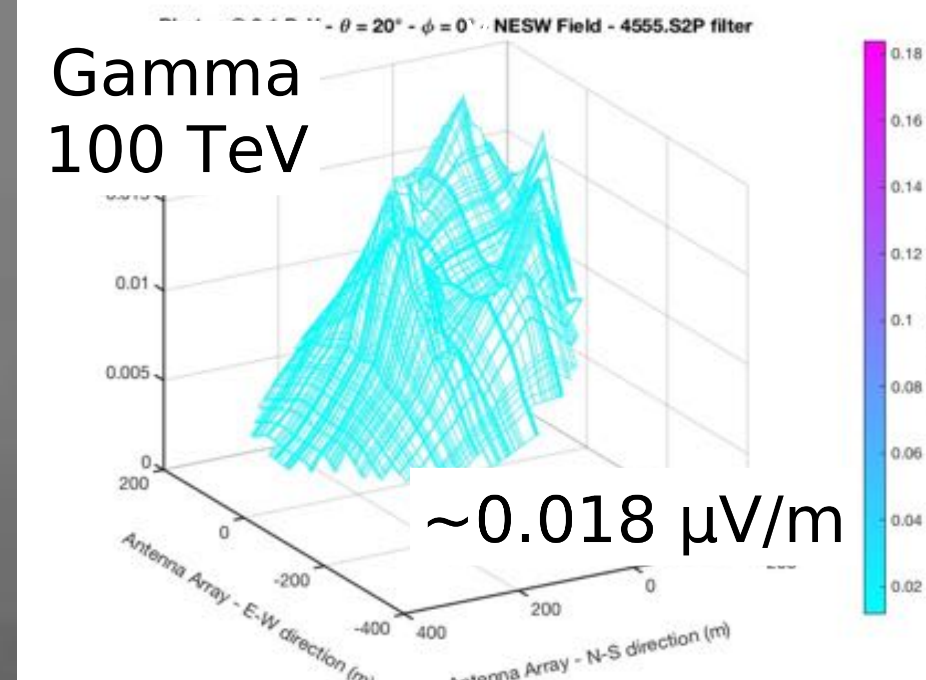
Ground profile for gamma shower

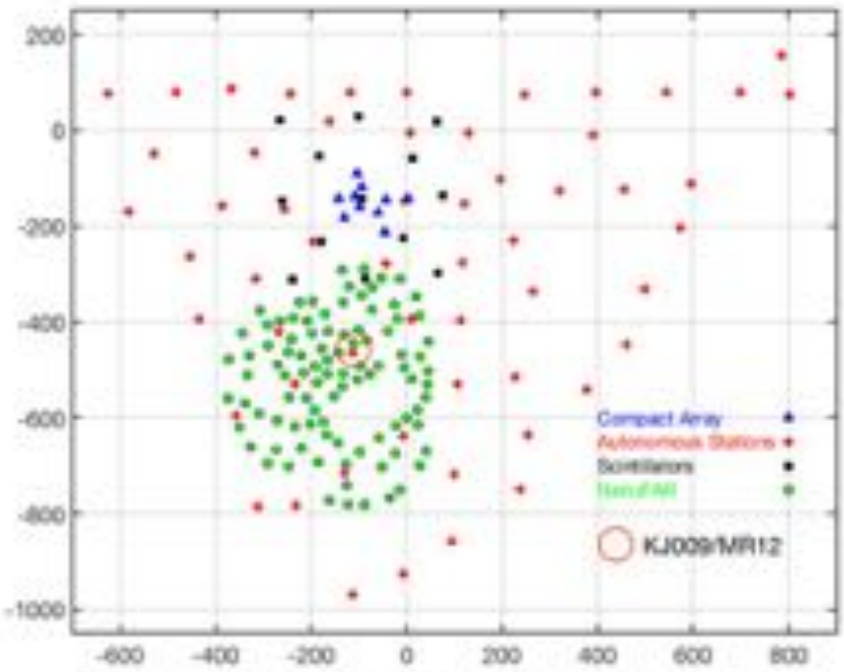


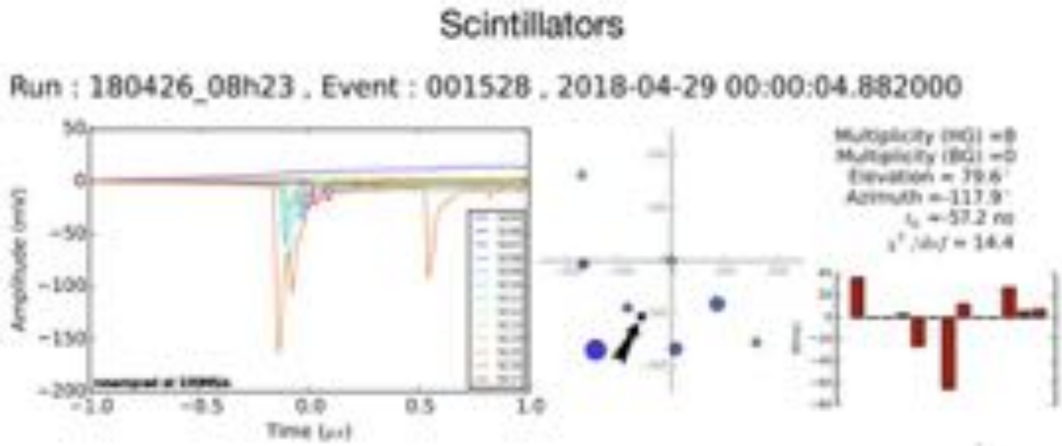


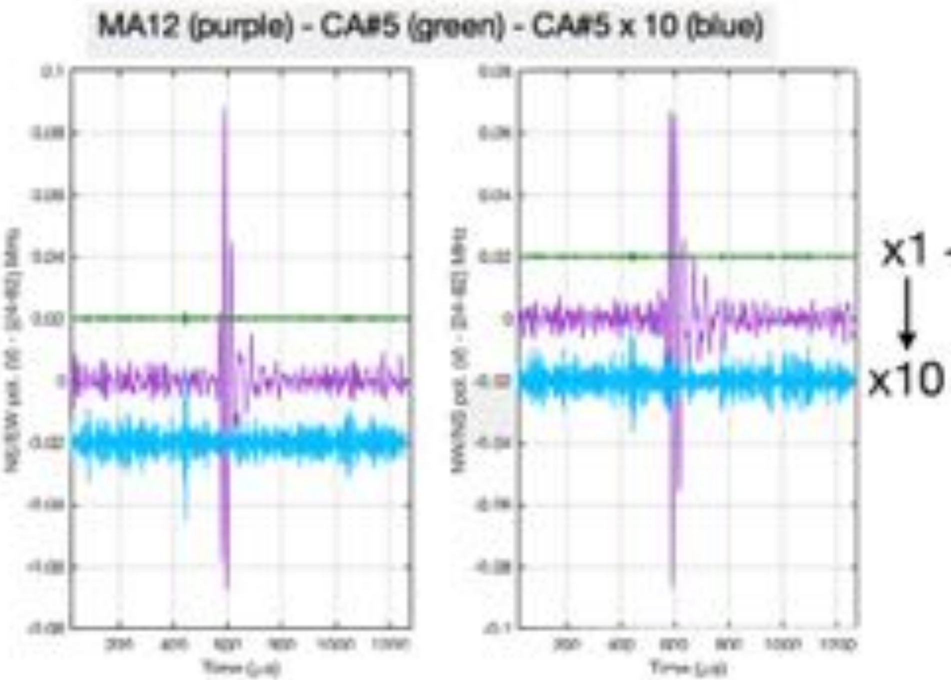


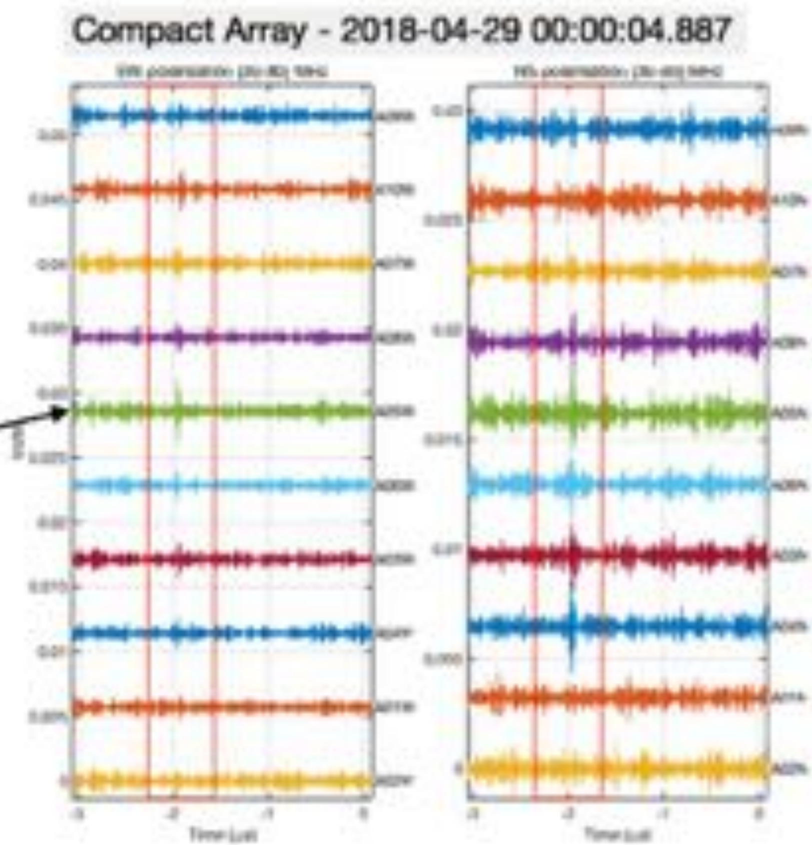
- Field profile very different for gamma vs proton
- Proportionality electric field vs energy (as expected)
- Current detection threshold (1 antenna): a few μV/m (depending on filtering band)
- For 1 PeV : ~100 antennas (5 MA)
- For 100 TeV : few hundreds (50 MA)
- ⇒ [100 TeV-1 PeV] accessible !

First detection of a cosmic ray event with MR12 and CODALEMA









Conclusion

- 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

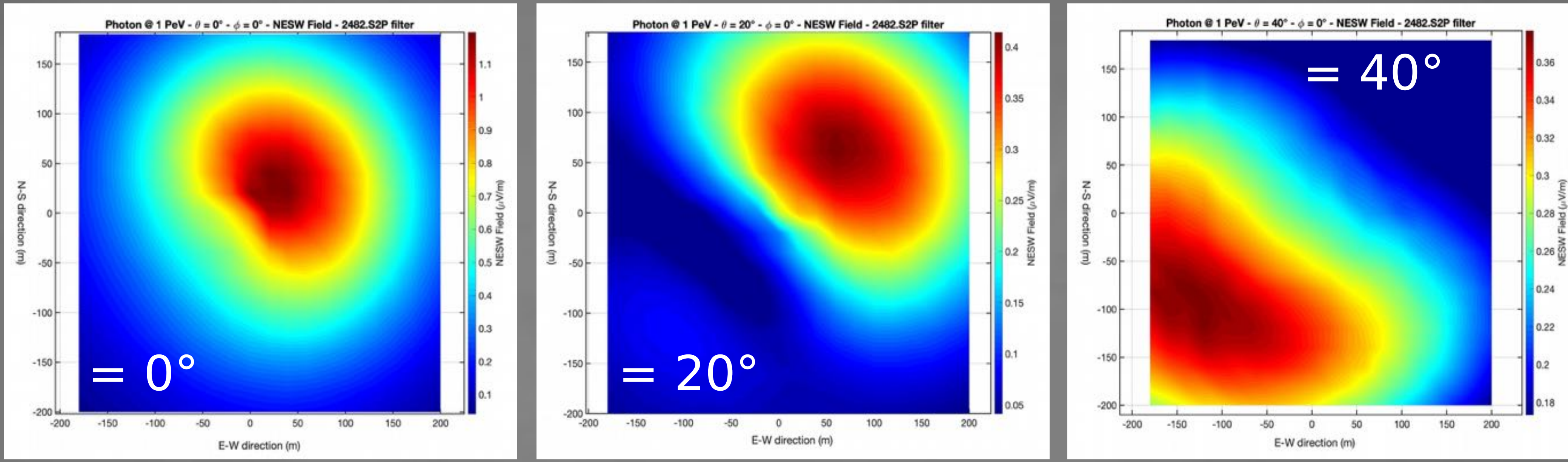
- Estimation of shower parameters using the radio signals (θ, φ, (Xcore ,Ycore), X_{max}, Energy) in [20 − 200] MHz ⇒ CR mass composition using the radio technique

- Gamma ray air shower detection: promising! Exploration of an energy range above HESS/CTA, potential duty cycle much higher: there is something to do there!

- Currently at experimental stage, a lot of work still needed (improving knowledge of gamma ray fluxes above 100 TeV, improving simulations of electric fields (codes exist), selecting potential sources…) but NenuFAR could be either a powerful instrument for northern hemisphere gamma ray sources observations, or a high-level pathfinder for the definition of a new type of instrument if interest is proven (same technique on SKA? dedicated radio array close to H.E.S.S. or CTA? long term view…)

Back-up slides

Simulated ground profile for gamma shower



1 PeV - [24-82] MHz