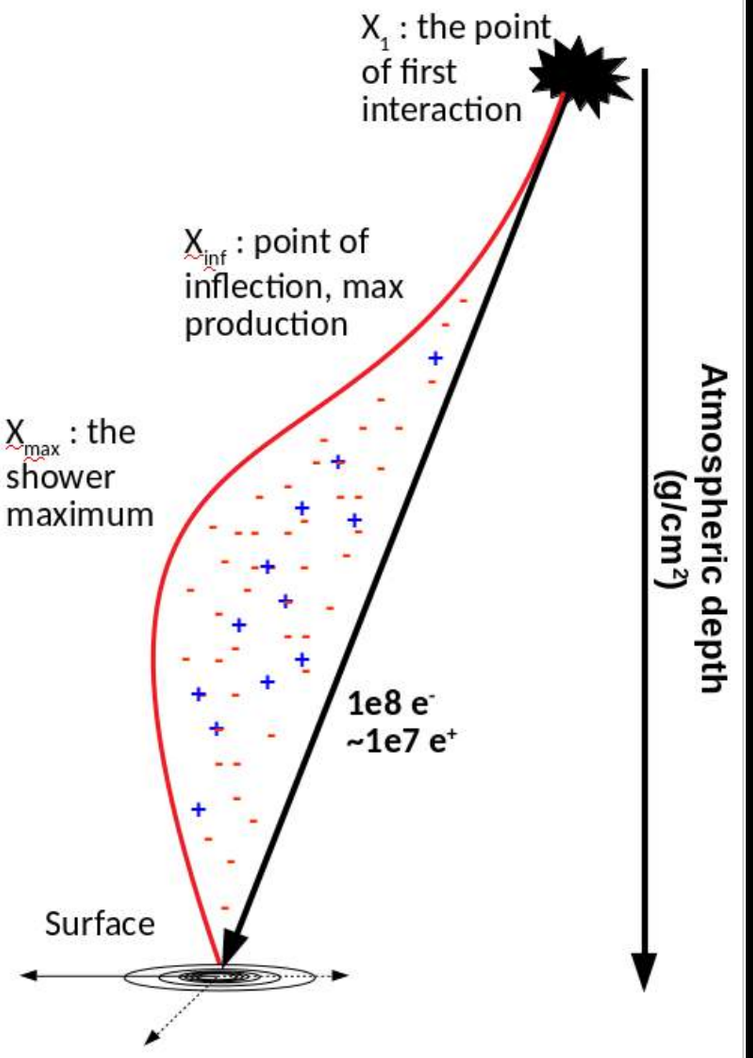
Γadio γamma

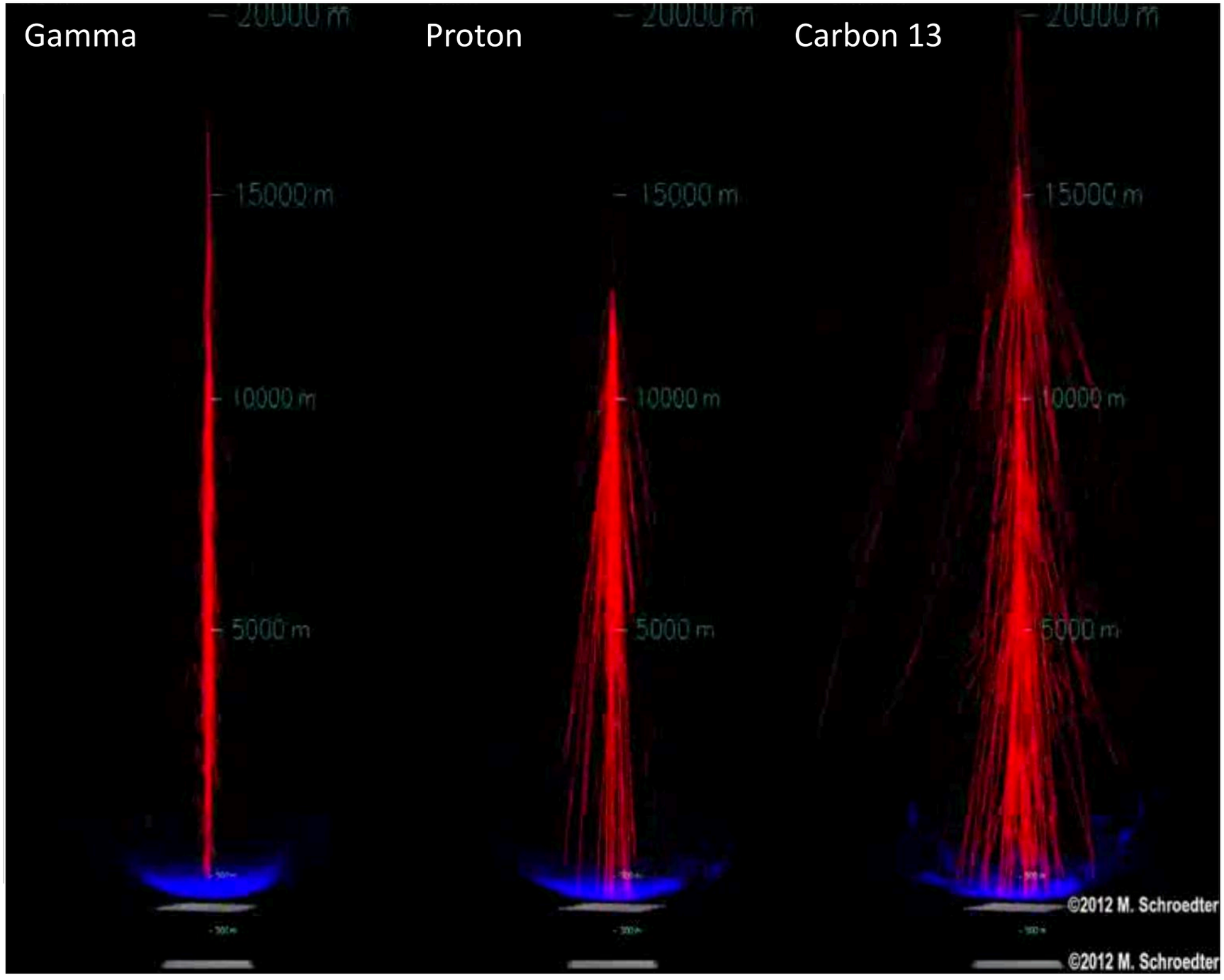
Using NenuFAR for Ultra-High Energy Gamma Ray air shower observations "à la CODALEMA"

NenuFAR Key Programme proposal

Cosmic Ray Air Showers

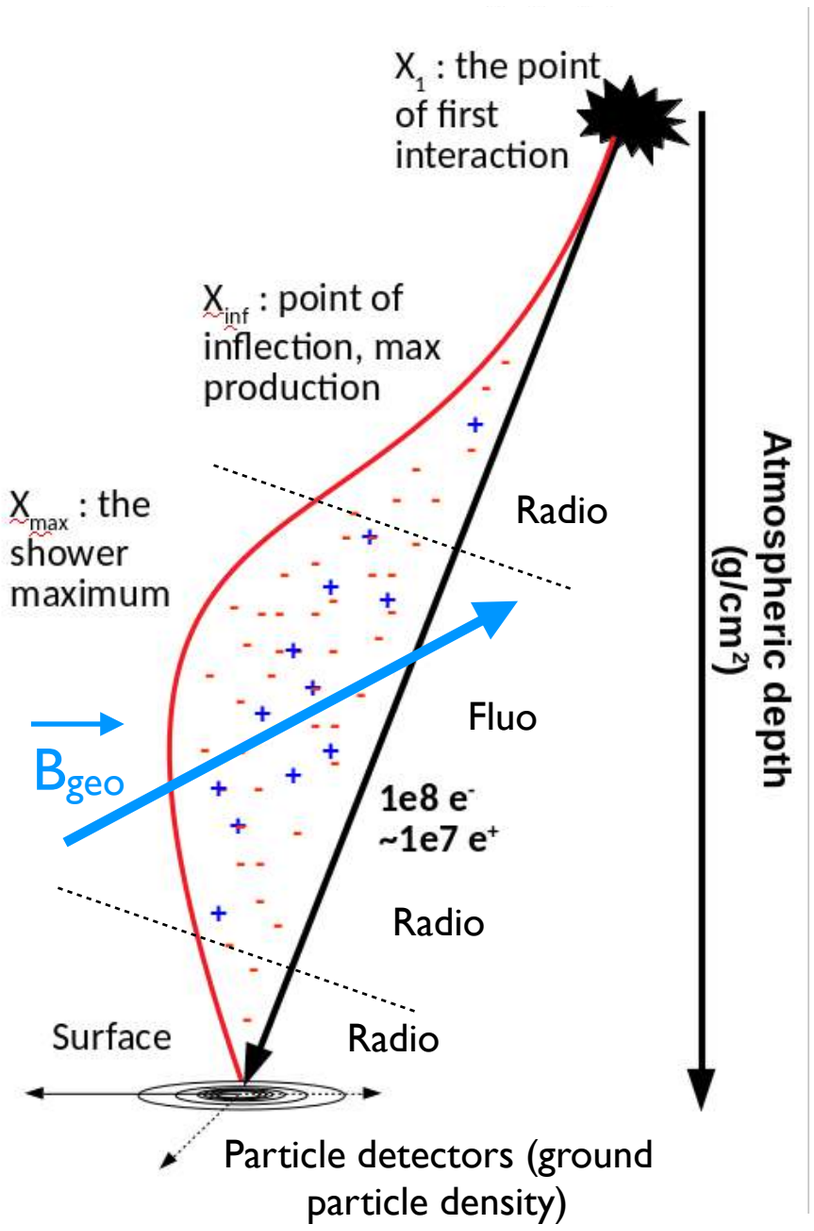
Looking for θ, Φ, (X_{core}, Y_{core}), X_{max} (nature), Energy





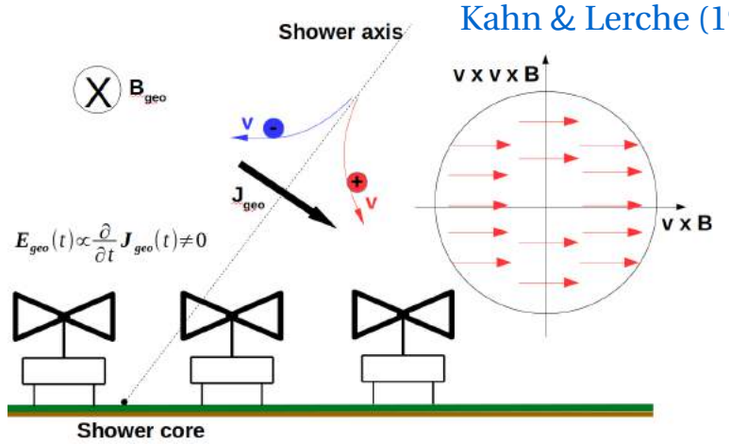
Cosmic Ray Air Shower radio-detection

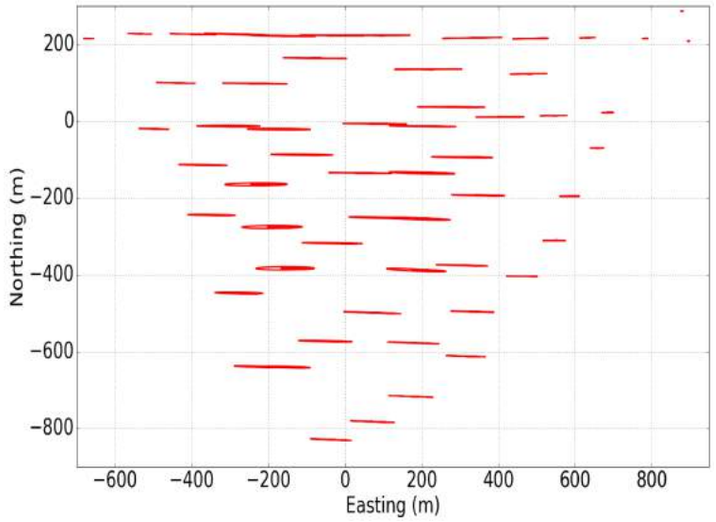
$\theta, \phi, (X_{core}, Y_{core}), X_{max}$, Energy



Geomagnetic mechanism

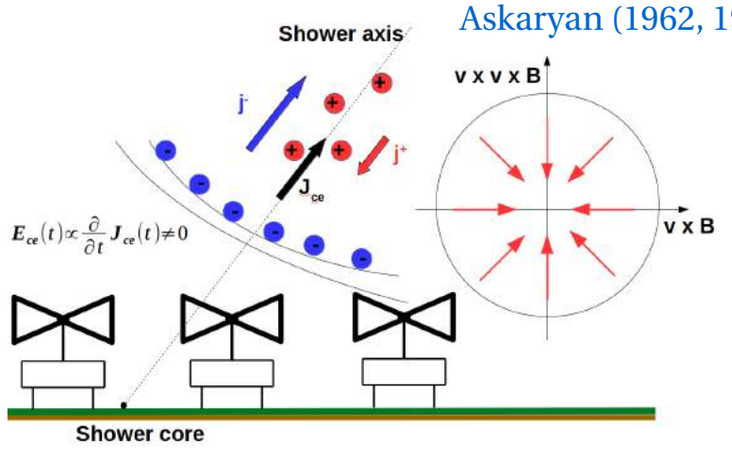
Kahn & Lerche (1967)

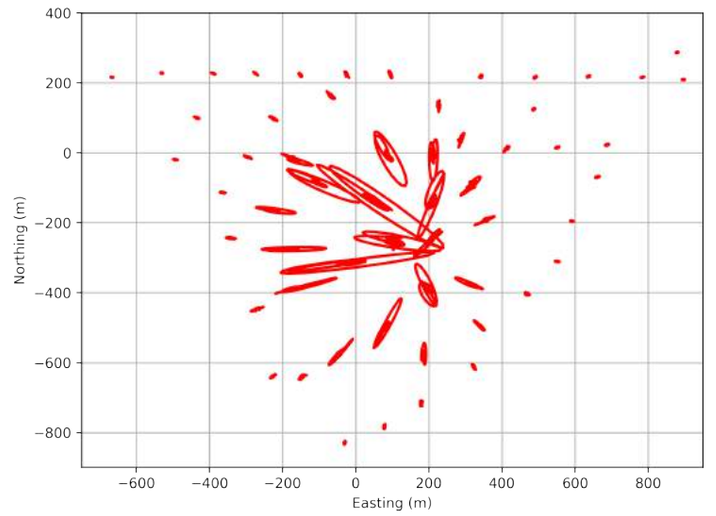




Charge excess mechanism

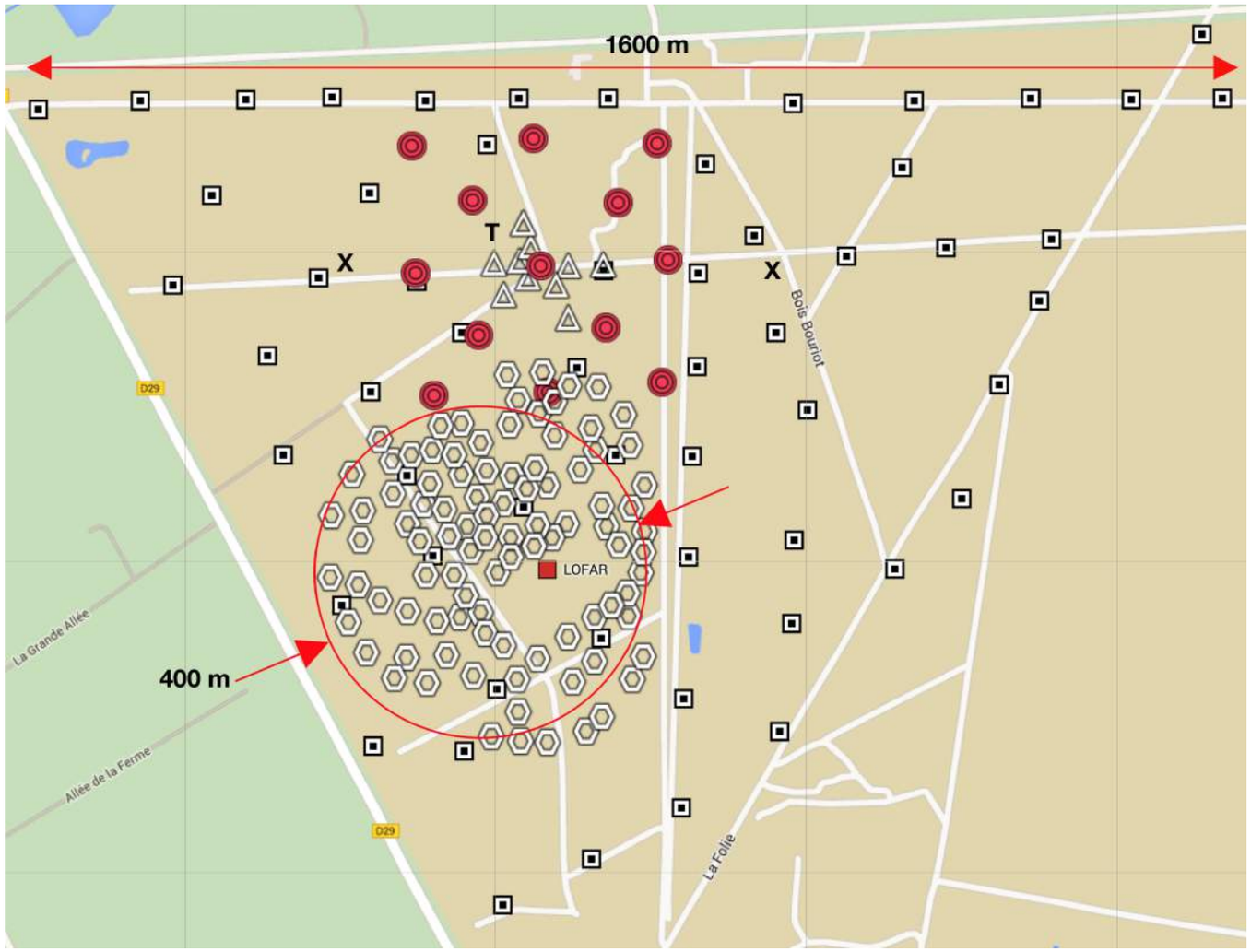
Askaryan (1962, 1965)



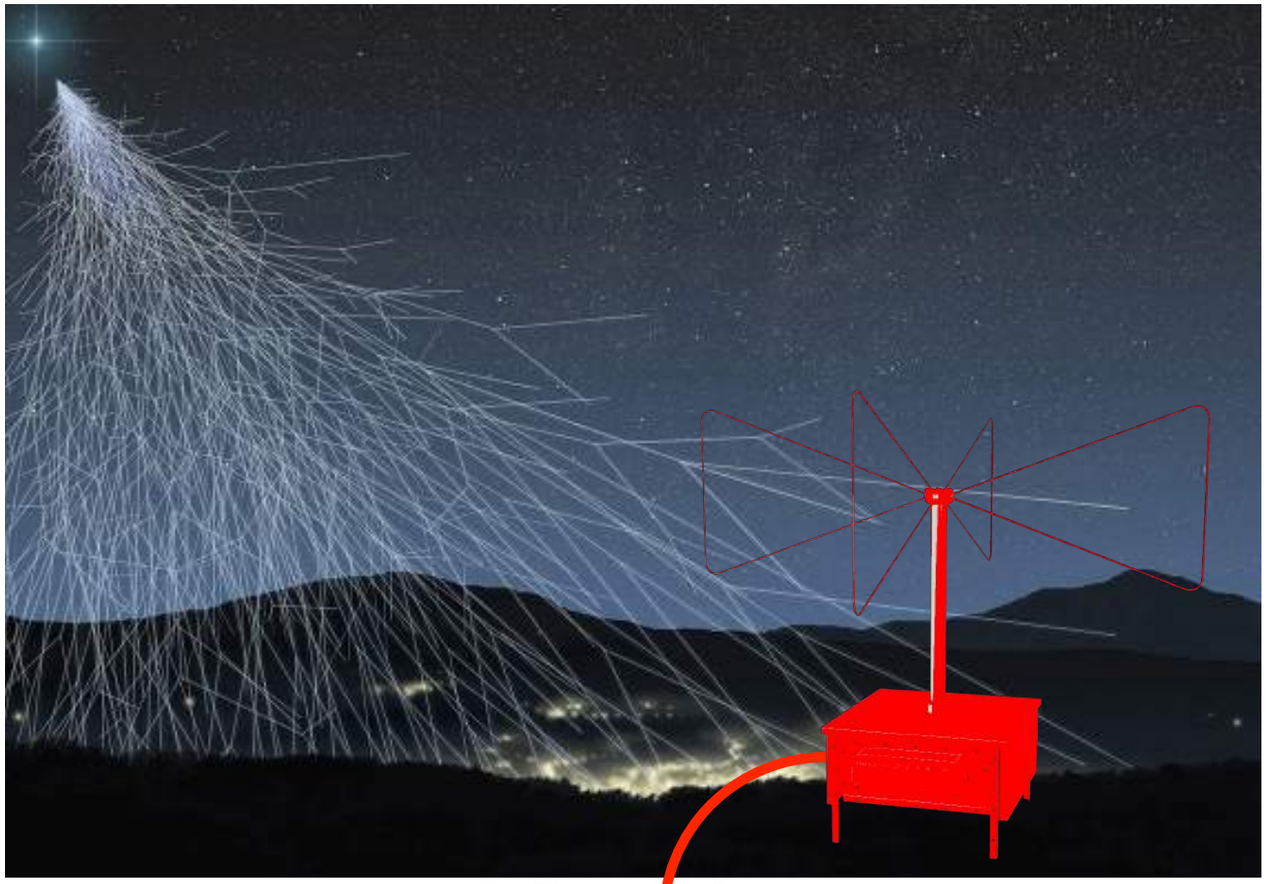


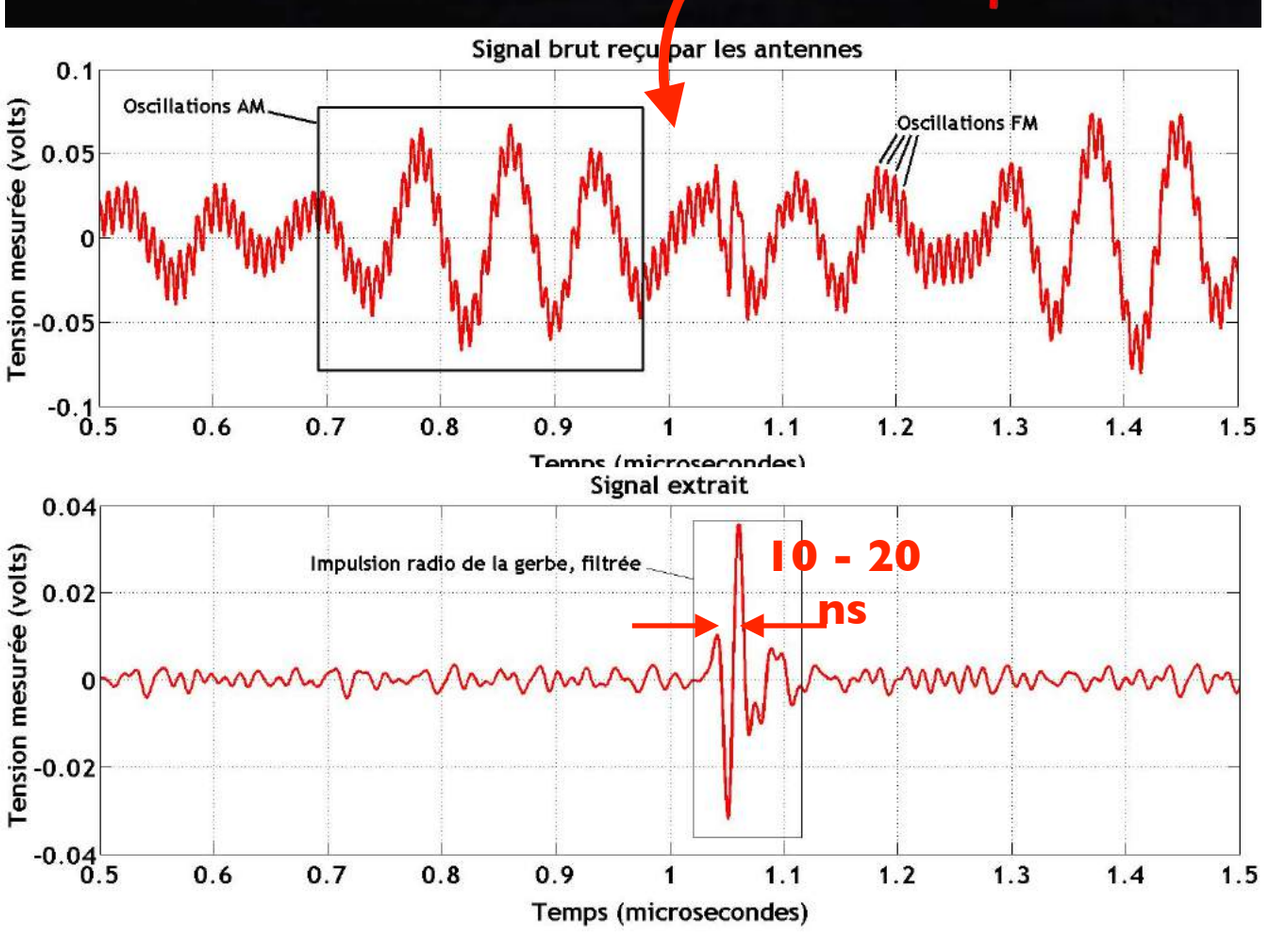
NenuFAR and CODALEMA

- CODALEMA antennas cover the complete Nançay area, surround NenuFAR
- 4 arrays: autonomous stations, compact array (CA), low frequency array (LF) and scintillator (particle detector) array
- Particle detector triggers CA and LF
- Particle trigger can be distributed outwards

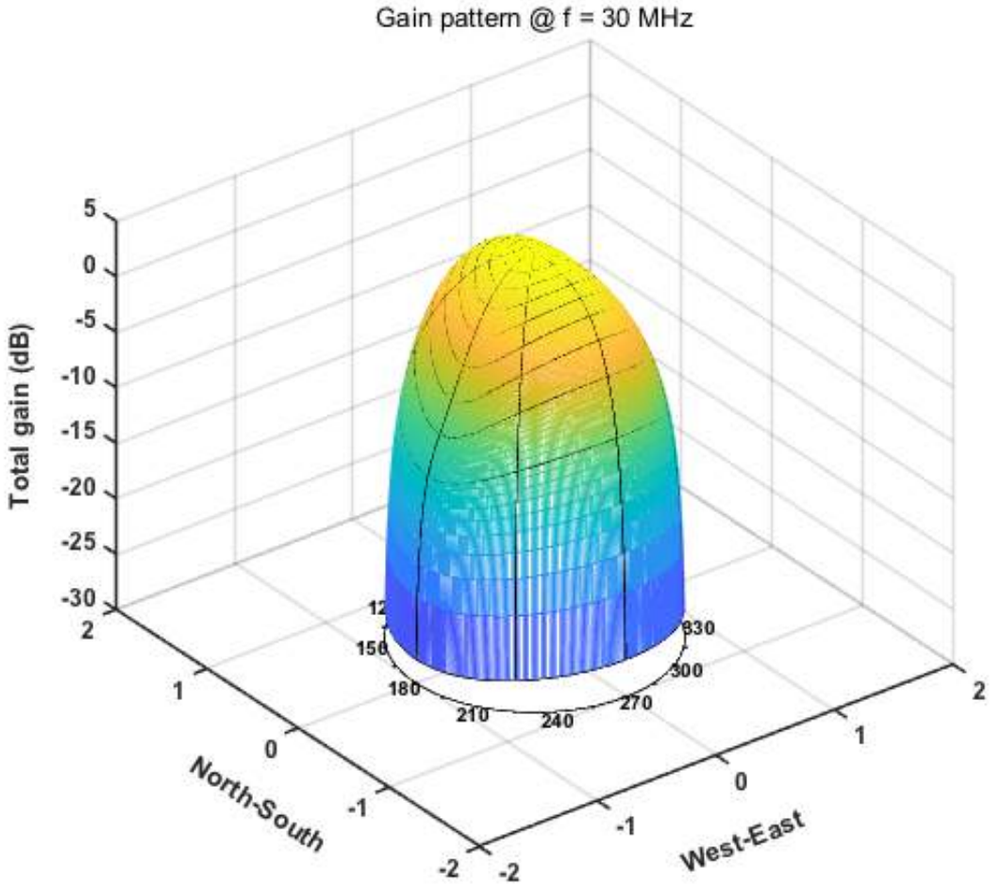


CODALEMA & Cosmic rays: detection of the transient radio pulse emitted by the secondary particles of the air shower



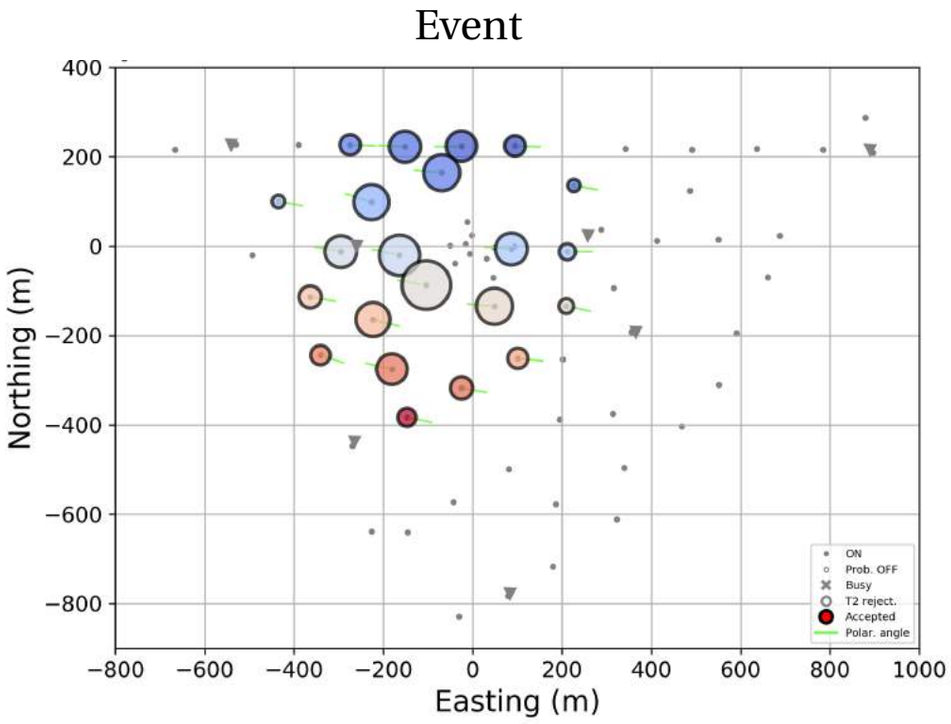


- Analogic self-trigger electronics
- 2.5 µs snapshots recording (GPS datation), 1 GS/s
- Standalone, independent an autonomous detection stations, very wide band (20-200 MHz)
- Arrival direction not predictable, need to observe the whole sky (wide individual antenna lobe)

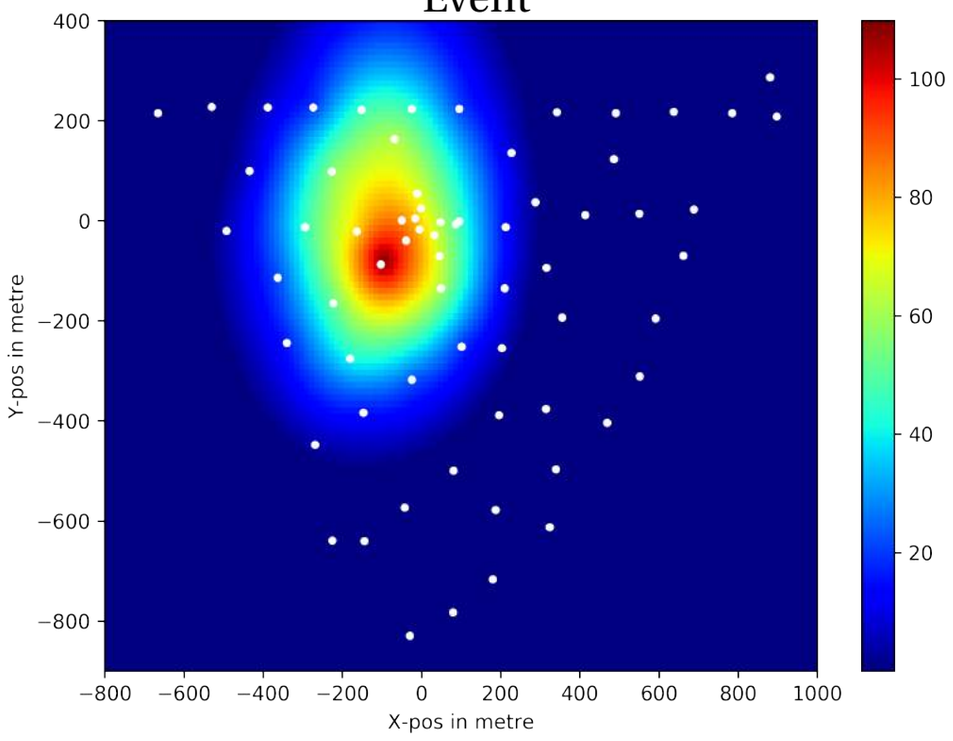


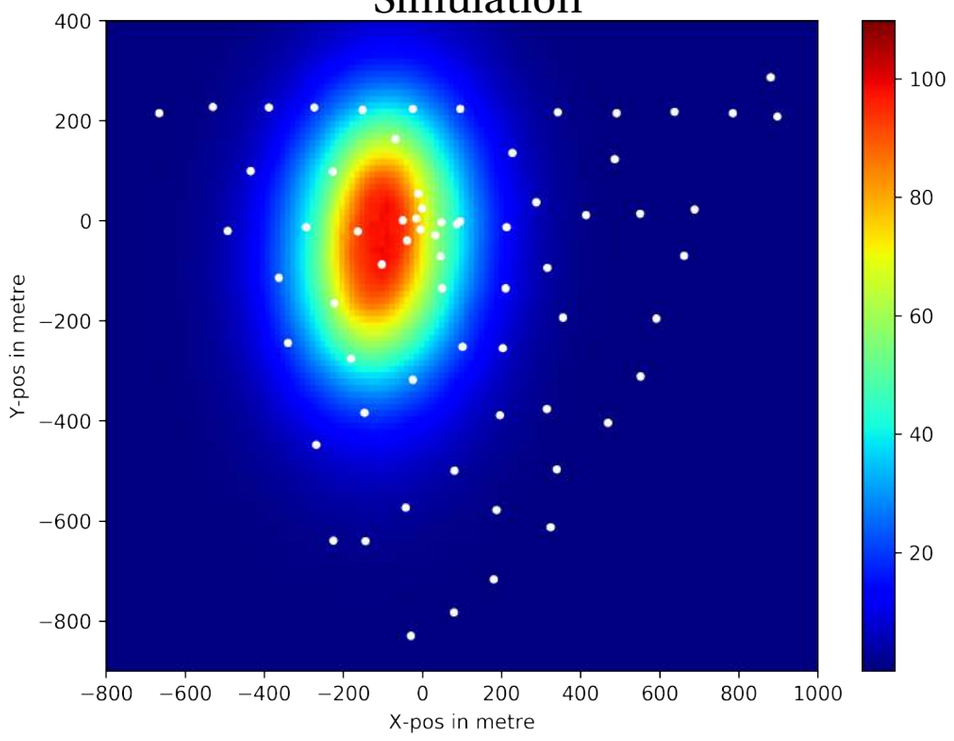
- Information on the shower and on the primary CR taken from the ground electric field profile, over several detection stations

Estimating the shower parameters

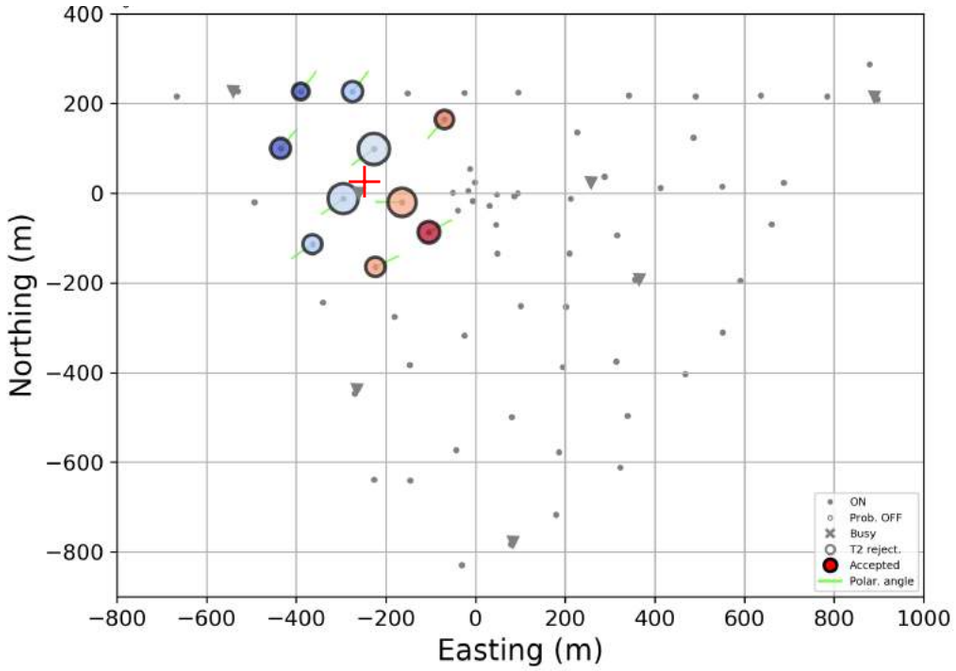


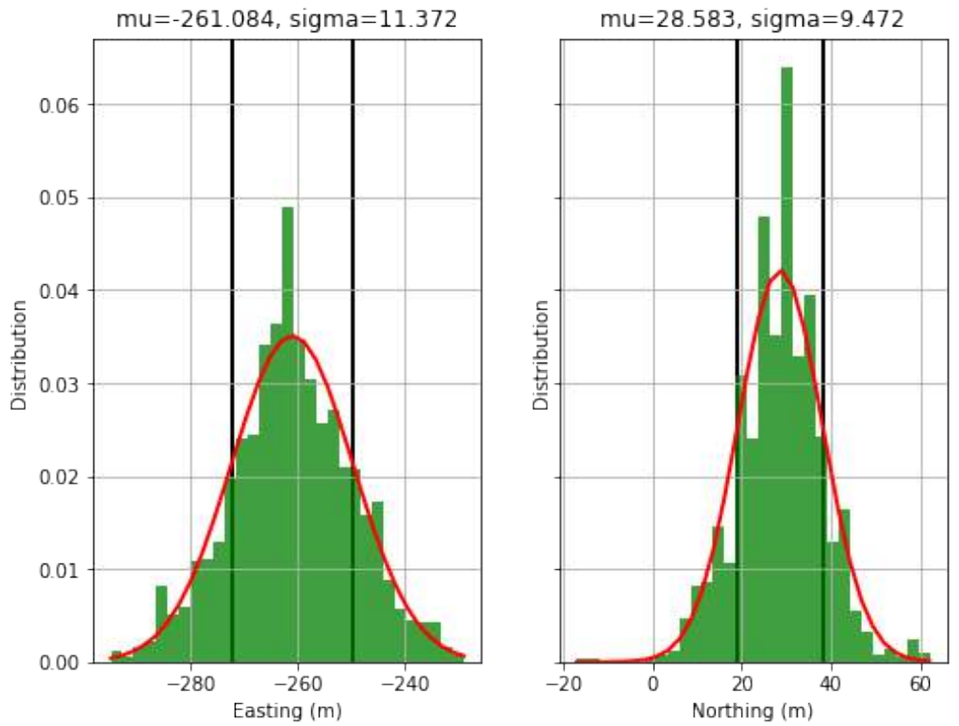
$\theta, \phi, (\mathrm{X_{core}}, \mathrm{Y_{core}}), \mathrm{X_{max}}$, Energy

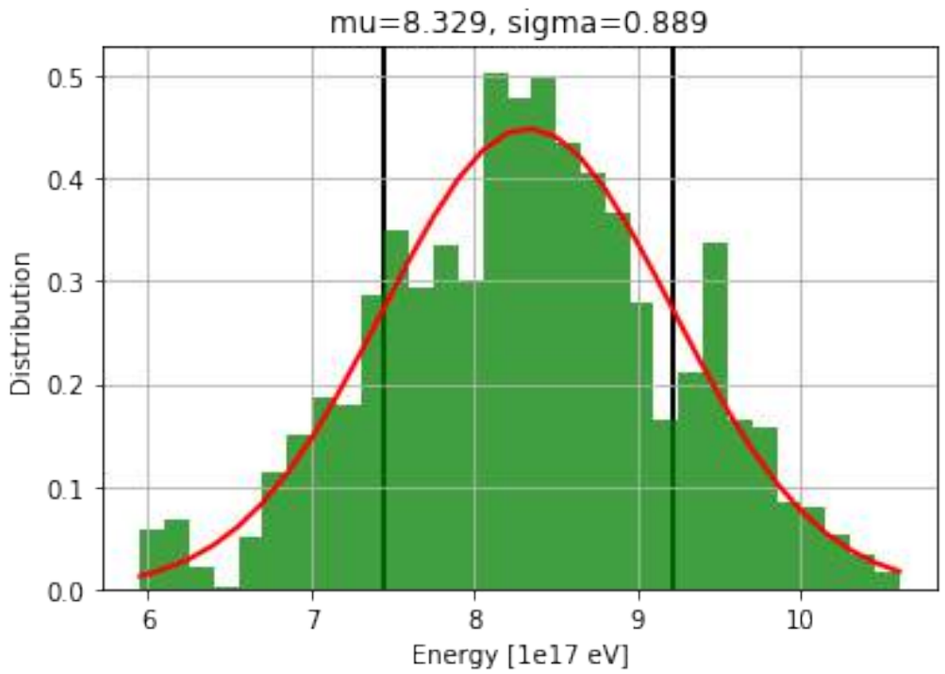


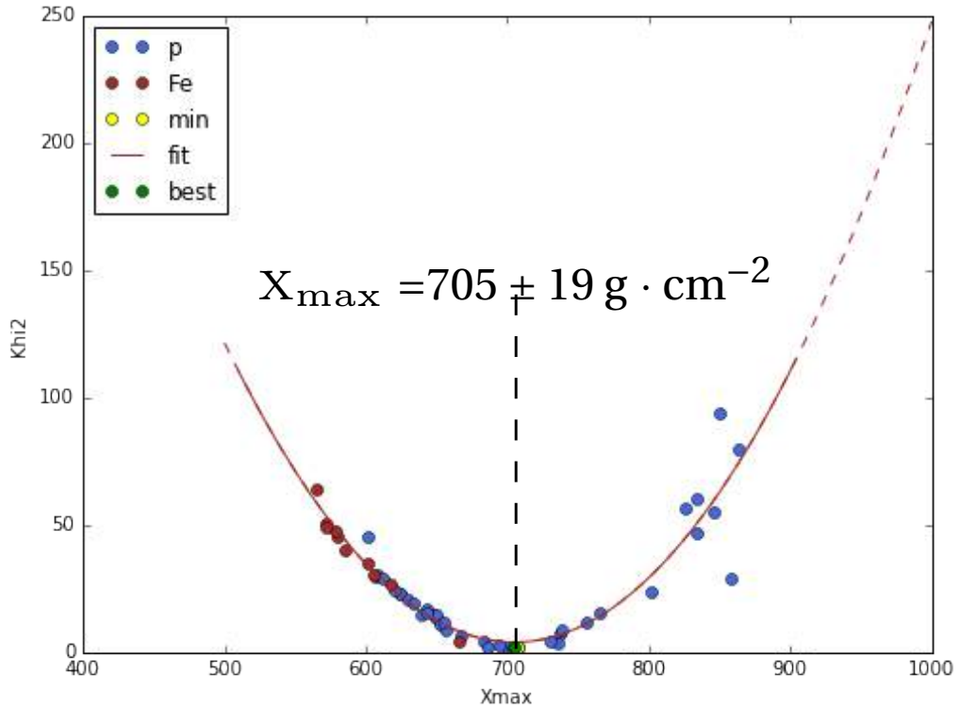


Estimating the shower parameters

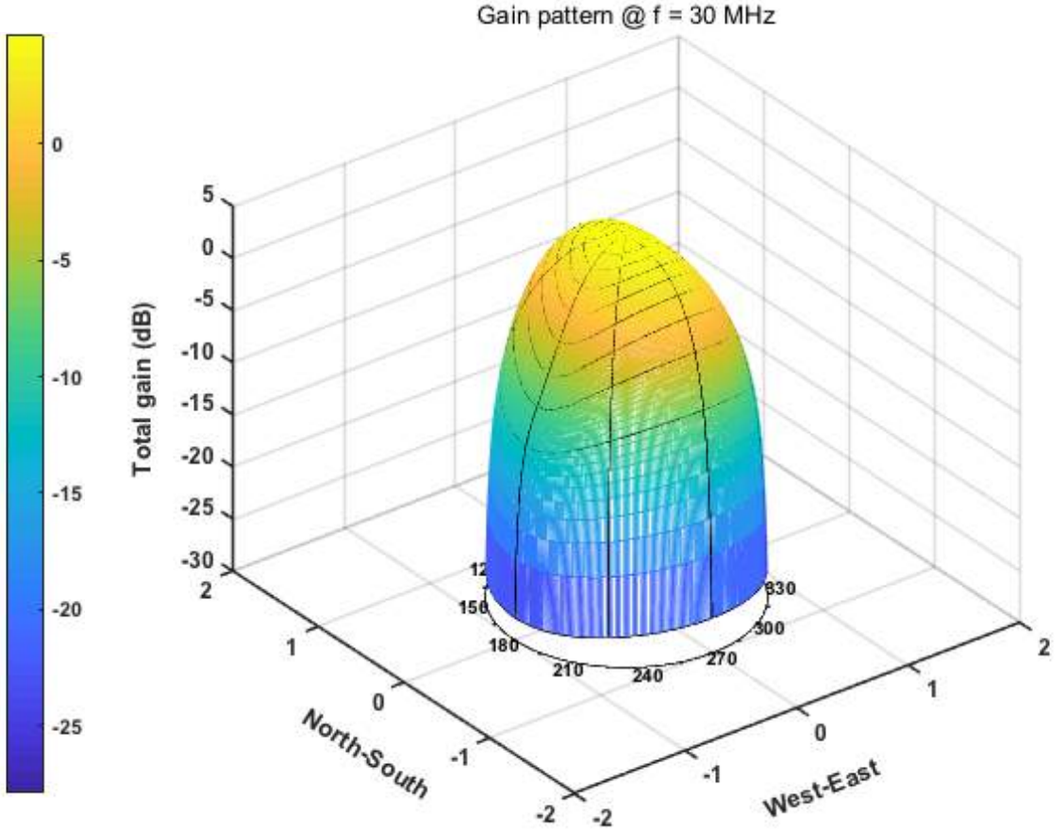








CODALEMA & Cosmic Rays: arrival direction not predictible, need to observe the whole sky (wide individual antenna lobe, self-trigger)



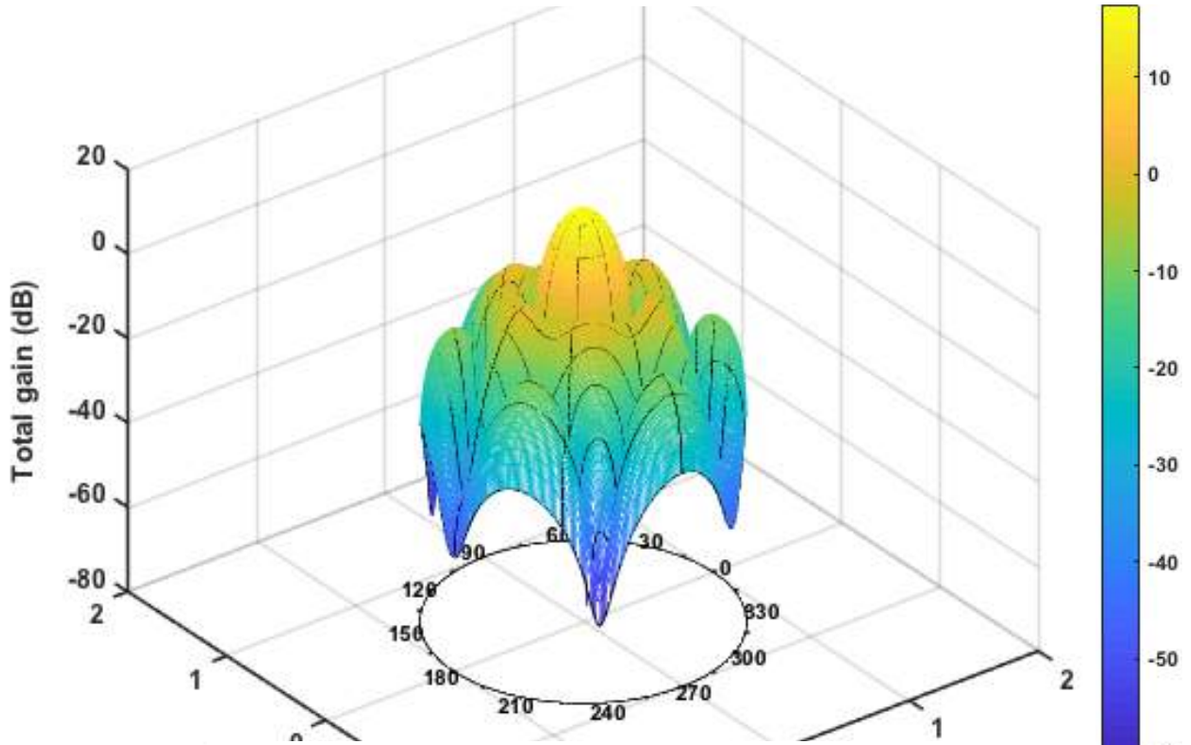
But what if we knew in advance where the shower came from?

Gamma photons: source may be known *a priori* (H.E.S.S., MAGIC, VERITAS… catalogs)

⚠ γ shower: energy lower than for CR, thus $\vec{E}$ lower

? ⇒ Increase detection sensitivity

⇒ To phase several antennas and to point toward sources

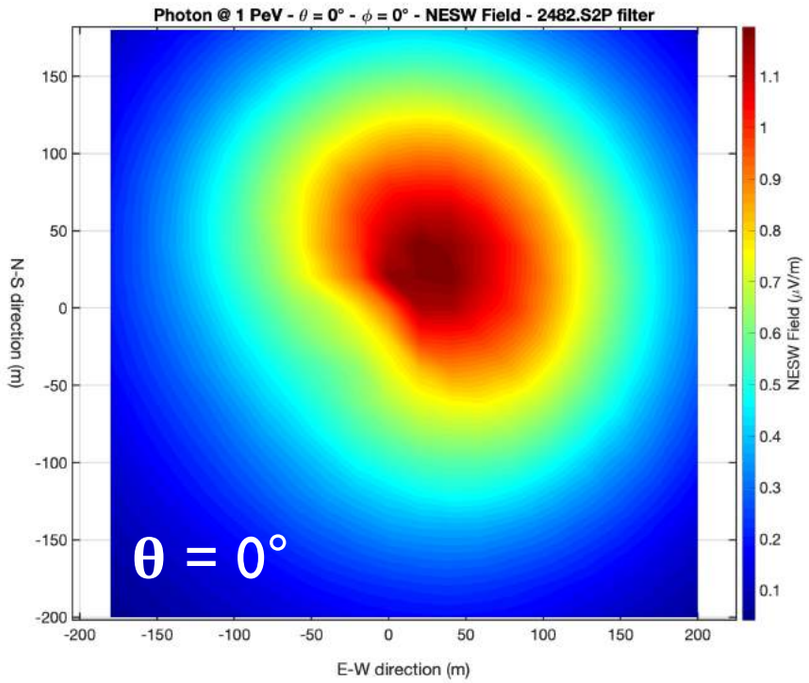


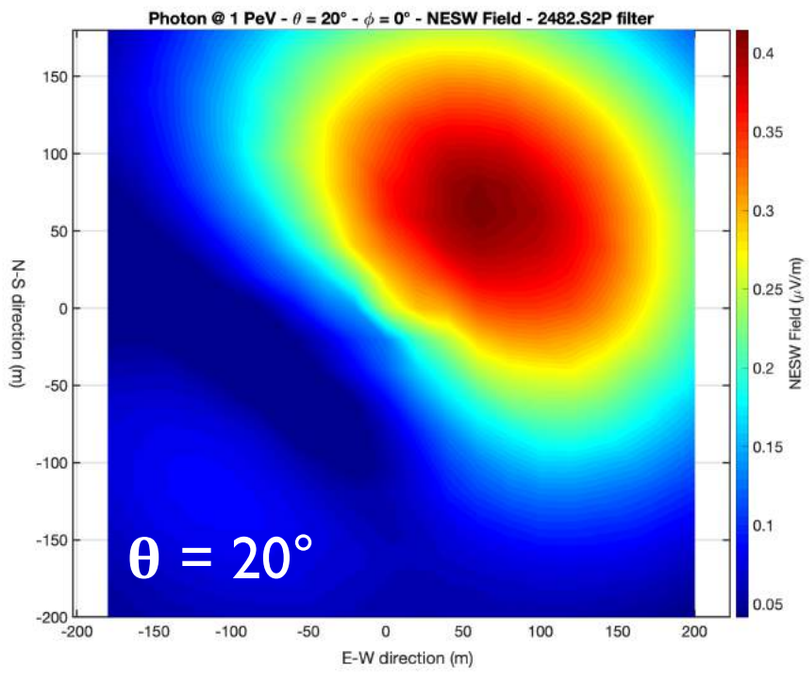
Gain 1 MA ~20 dB (vs 0 dB for single antenna)

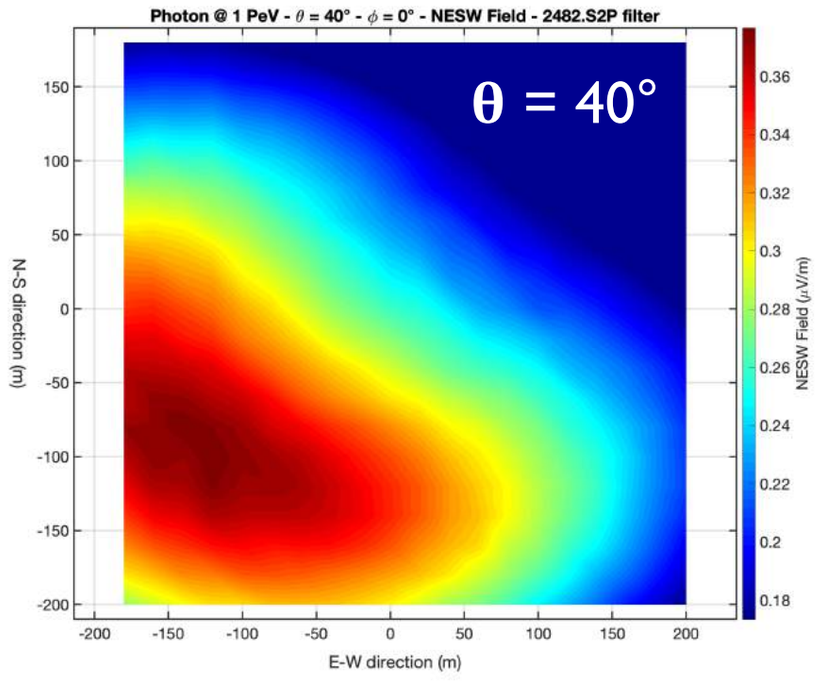
Trigger → read the whole NenuFAR array (TBB) to get the ground electric field footprint, and reconstruct the photon energy "à la CODALEMA"

Observation duty cycle 100%

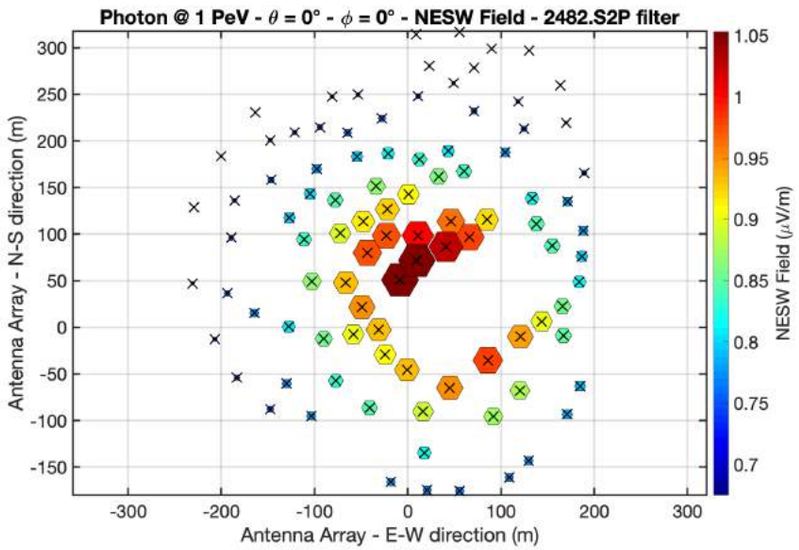
Ground profile for gamma shower (extension ~ NenuFAR diameter)

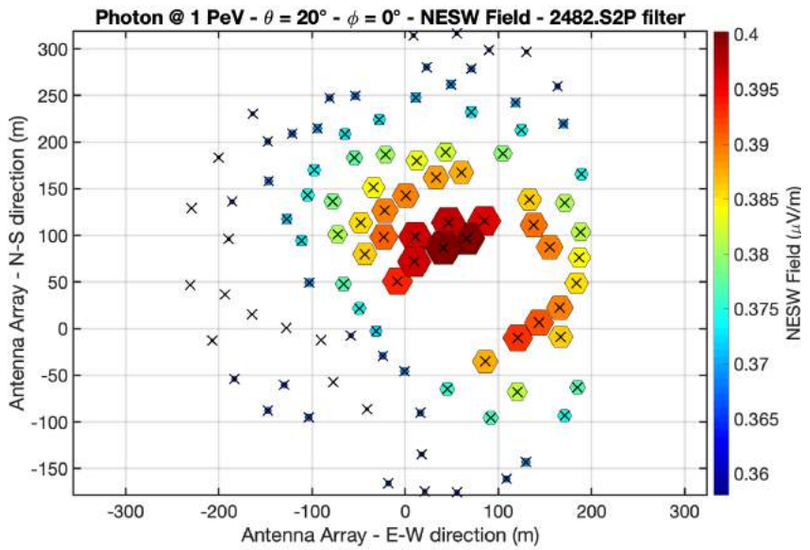


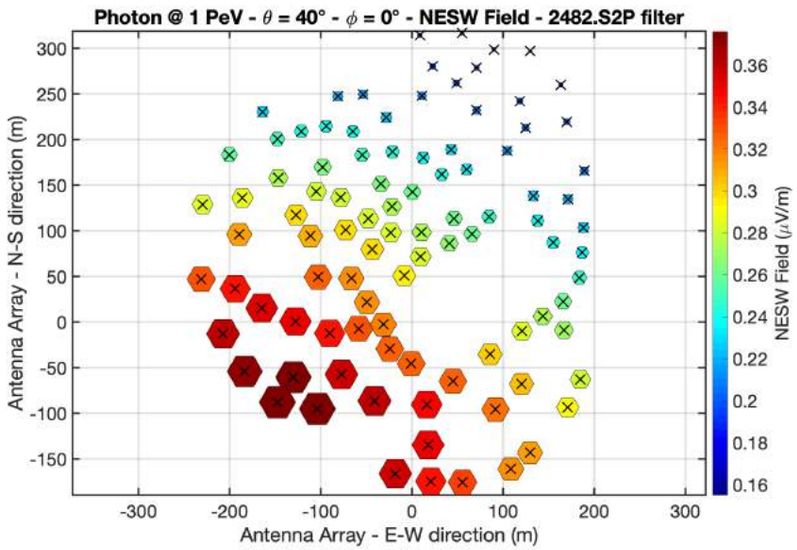




I PeV - [24-82] MHz

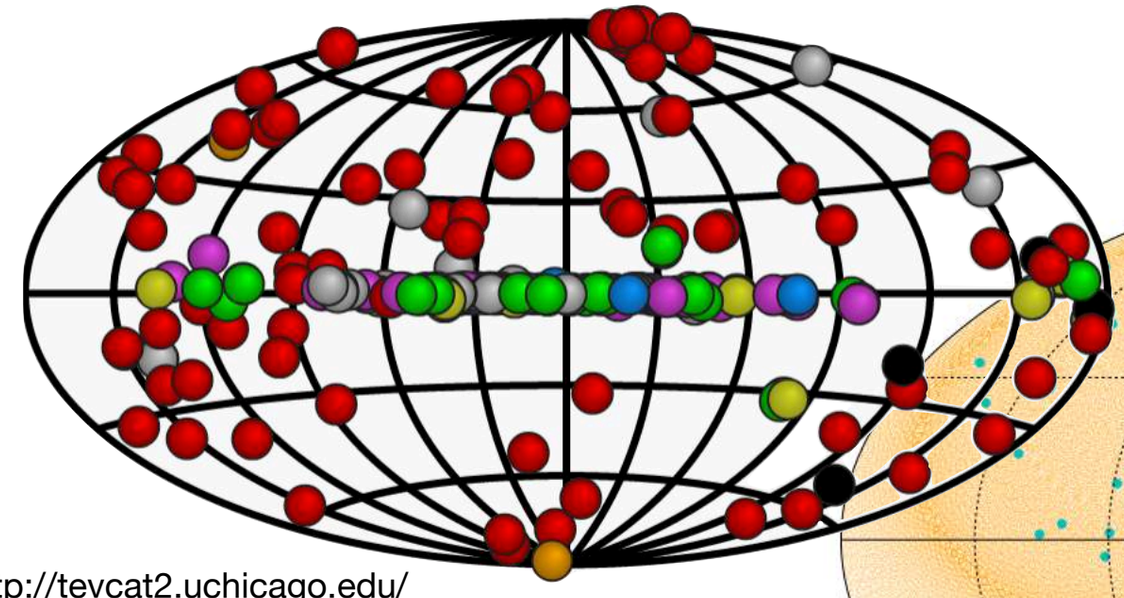




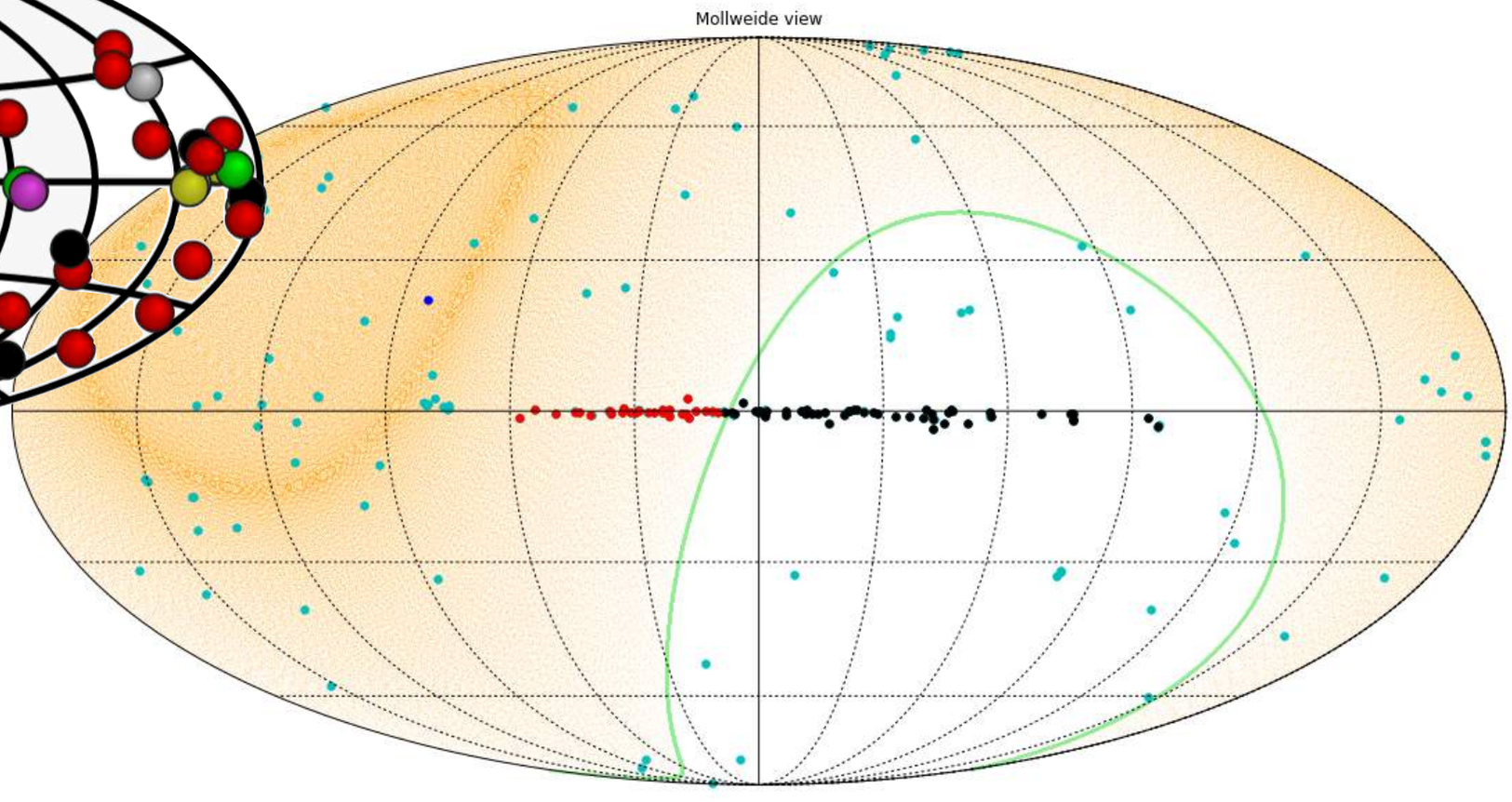


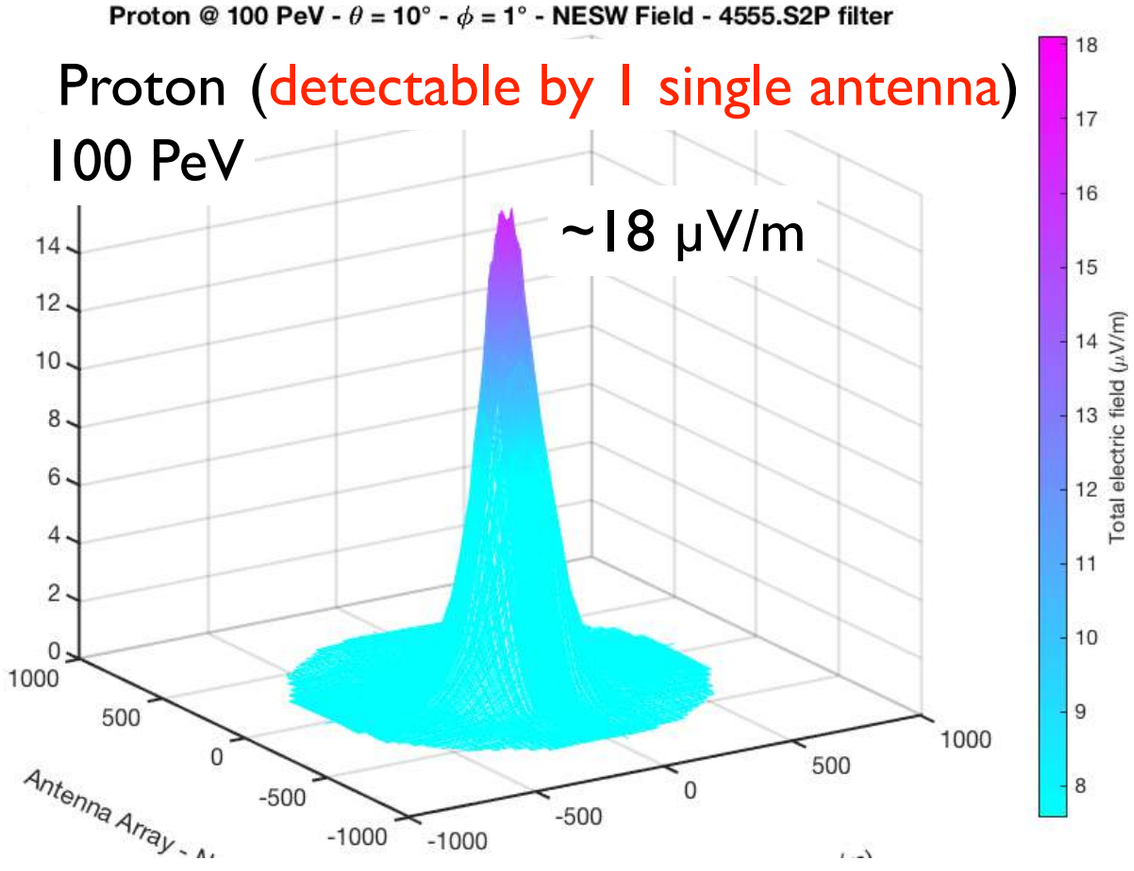
But are there gamma sources @ PeV ?

- So-called "PeVatrons" are expected in or close to the Galactic Centre
- The latter is not visible for NenuFAR…
- Extragalactic sources are not in the scope of > 100 TeV gamma rays
- Could be of great interest to reach ~100 TeV sensitivity (H.E.S.S., Magic, Veritas… catalogs)



http://tevcat2.uchicago.edu/

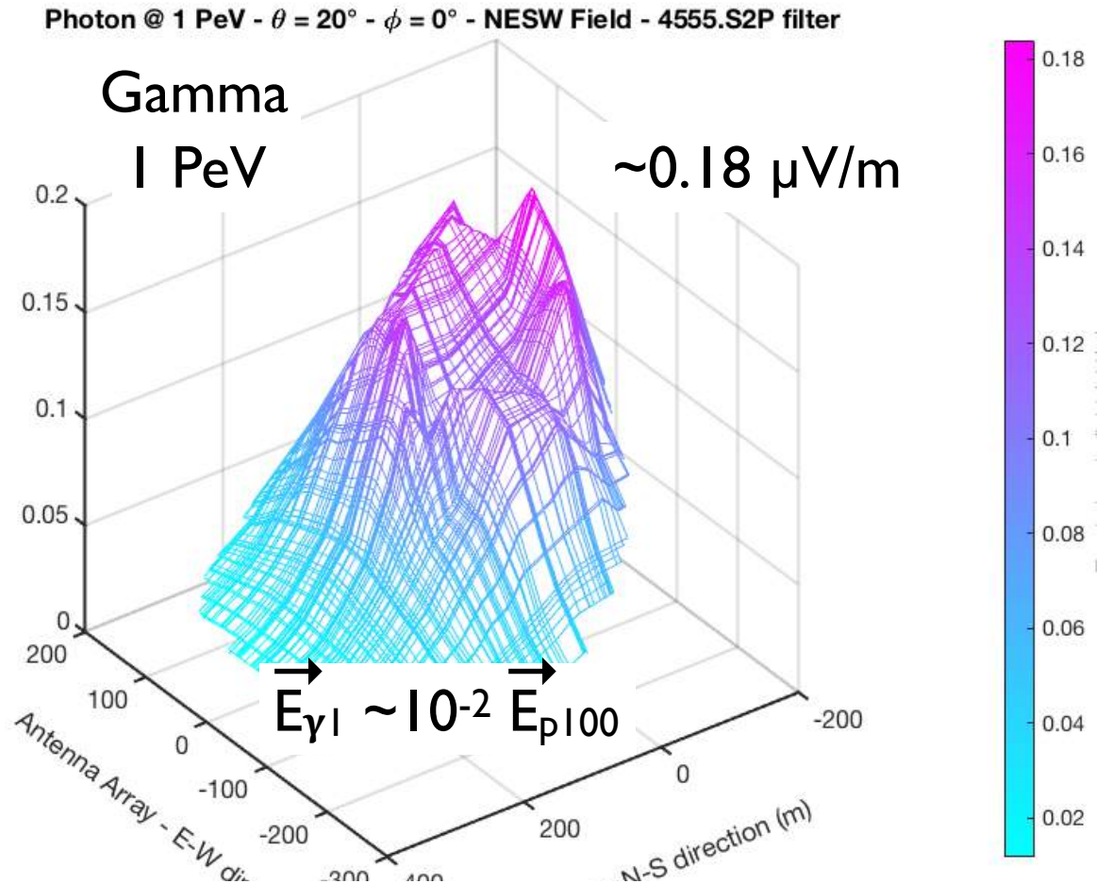


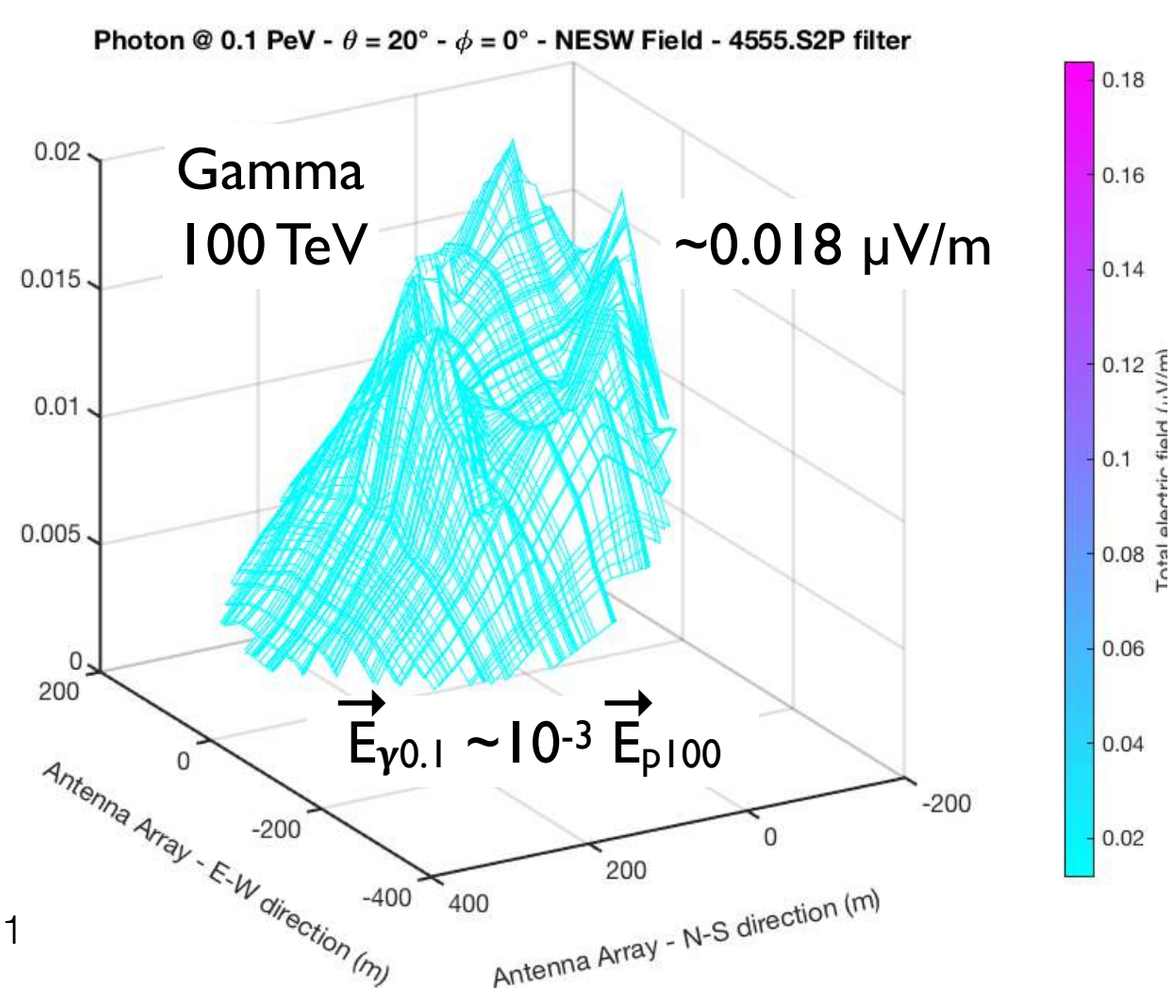


[24-82] MHz

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

How to build the trigger?

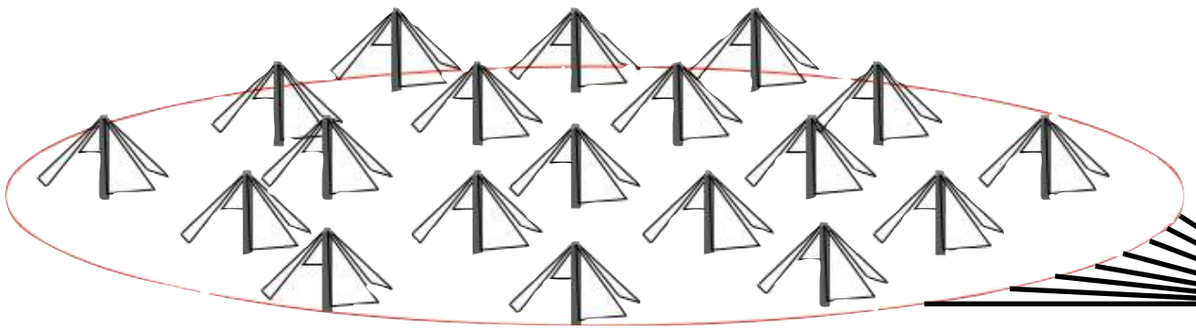




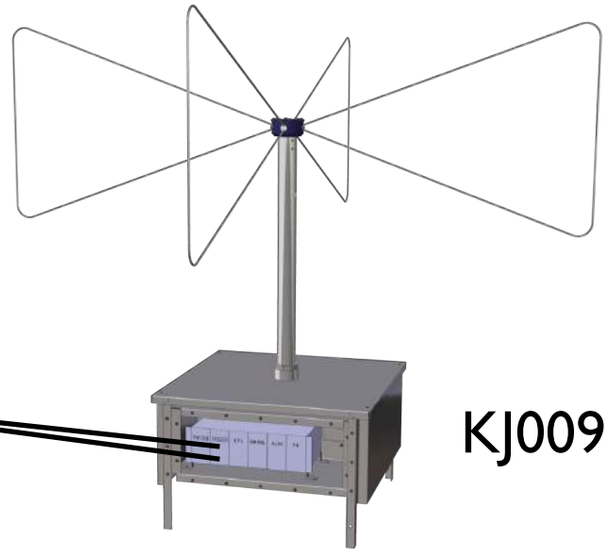
Bottleneck: the trigger - Current test status

Search for cosmic rays events in coincidence with CODALEMA

MA12



Phasing + splitter



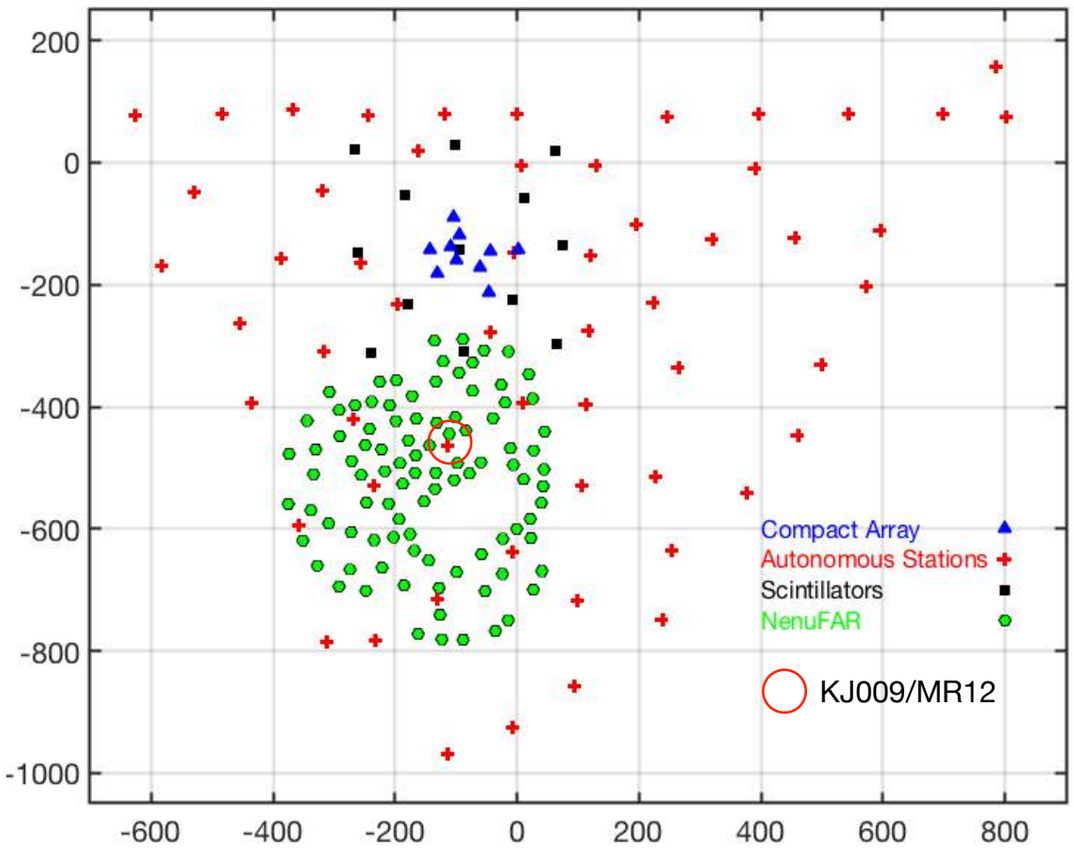
KJ009

NenuFAR container

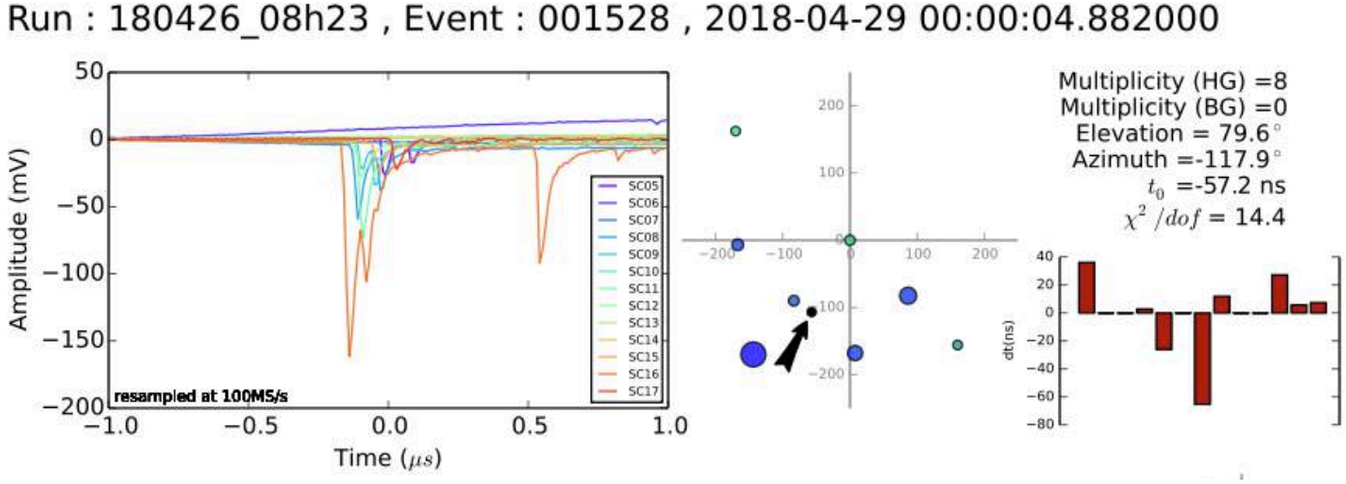
MA12 (NESW) data recorded instead of NS Butterfly antenna (25-80 MHz, trigger in 45-55 MHz)

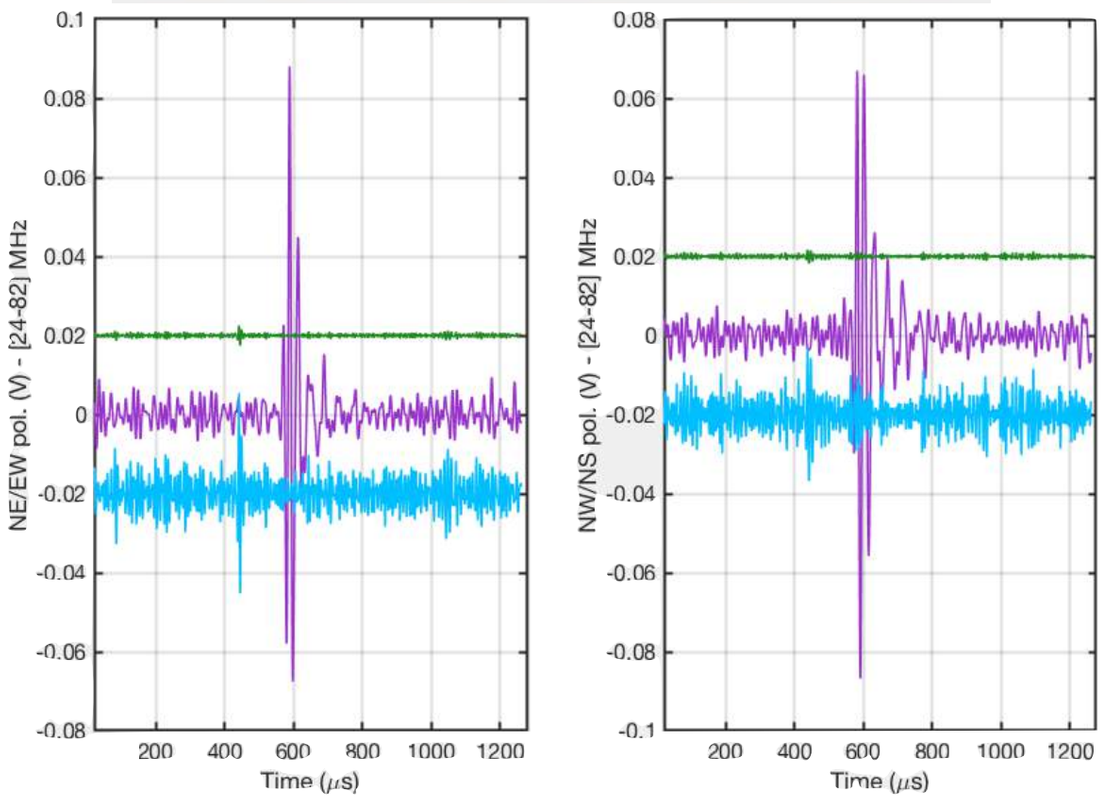
Default pointing (vertical) if no observation
Any direction during standard observation
⇒ not always a CR signal in MA12

First detection of a cosmic ray event with MA12 and CODALEMA



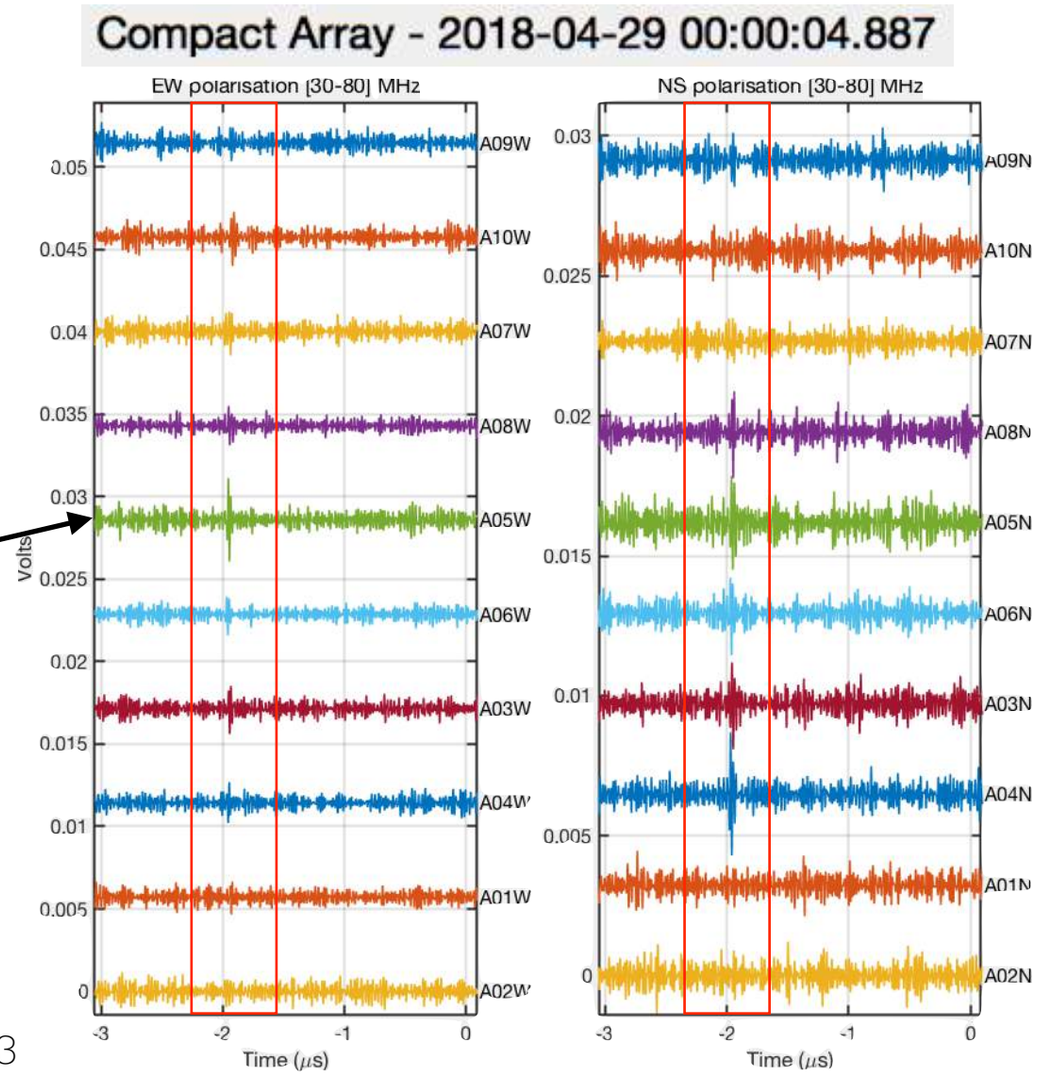
Scintillators





x1

x10



Validation of the principle

- Goal: to estimate the sensitivity of one (several) mini-arrays vs energy of the shower
- To derive the number of mini-arrays necessary to build a trigger able to reach a given shower energy sensitivity
- First stage: current operation (MA12 included in CODALEMA acquisition), ending soon
- Second stage: to use an external trigger signal (scintillators) to trigger the reading of the TBB of all the arrays (only a part of the 5 s, cosmic event time being given by the particle detector GPS datation)
- Three operation modes possible for NenuFAR on cosmic rays:
  - Current default configuration (all the MA at zenith)
  - Extraction of the signal of antenna 10 (centre) of each MA
  - Pointing each MA in a fixed direction to cover all the (half) sky (fly's eye mode)

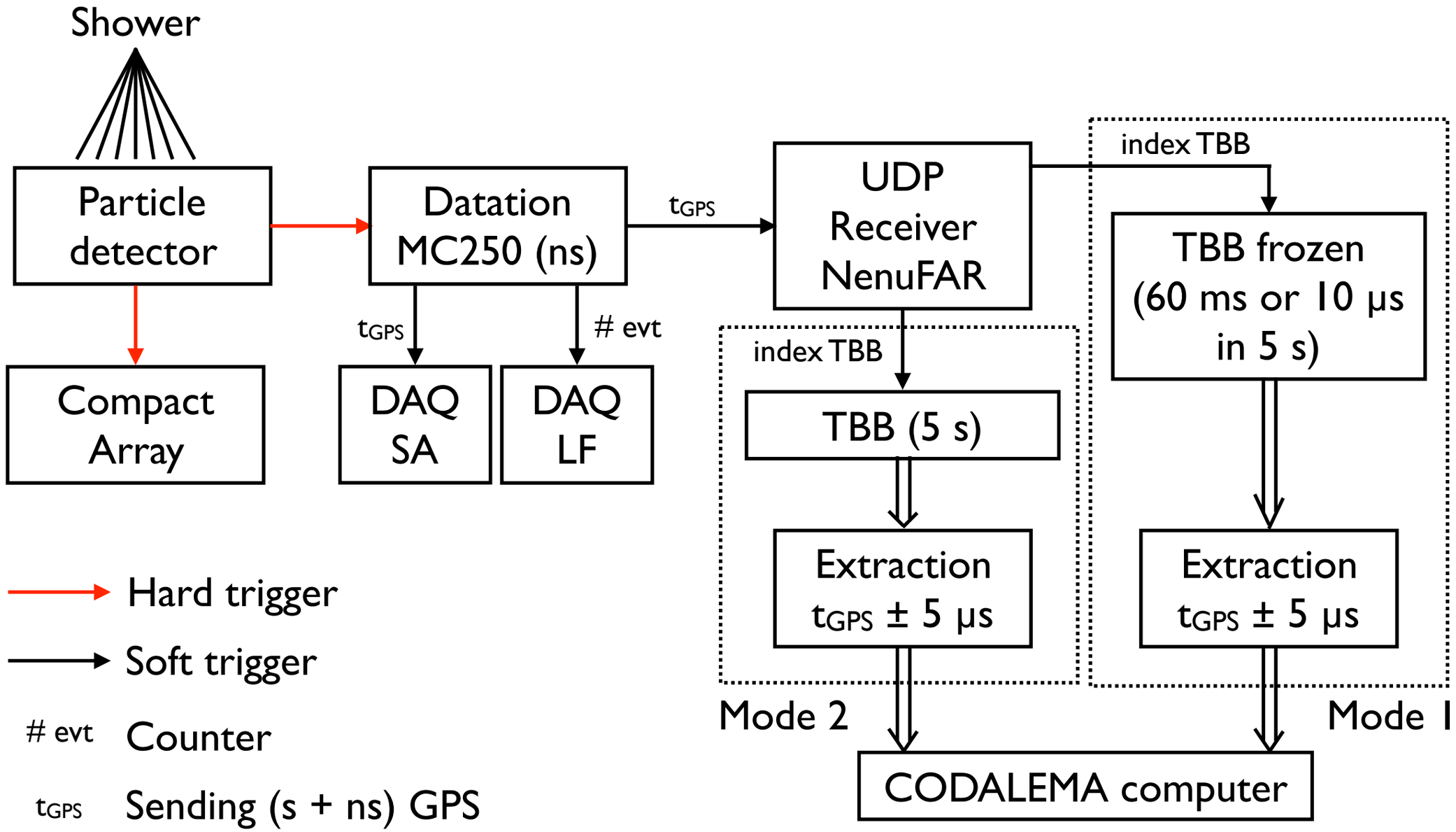
This CAN NOT be the mode used for gamma shower observation, but it is a necessary step to evaluate the sensitivity and refine the trigger needs. Could be a part of the key programme "air shower" (increases CODALEMA sensitivity).

Stage 2 functioning scheme

(*particle detector trigger + TBB reading, 2 operation modes possible*)

Mode 1: "regular" TBB operation (frozen memory + extraction of interesting memory zone)

Mode 2: "sparse" TBB operation (continuous reading + extraction of interesting memory zone)



Stage 3: observing gamma sources

- Stage 2 should help determining how many mini-arrays are necessary to reach the required sensitivity on gamma sources visible from Nançay (regular tracking mode)

- Once detected by the trigger array, reading of all TBBs just like in stage 2

- We already know that one single MA is not enough to reach (even) PeV sensitivity

- Two MA phasing solution are envisioned:
  - Digital: dedicated LaNewBa board, modified to phase 4 MA (or 8 polarisations), trigger output on built-in internal decision to trigger the TBB reading (cf Cédric Dumez). OK, provided 8 MA are enough (probably hundreds of TeV sensitivity on some sources)
  - Analog: building of a dedicated phasing cabinet, similar to the current ones but for much larger delays (on NenuFAR scale), up to 19 entries (complex, big size, cost, but feasible in principle - even if only some directions are accessible)

- In any case, need for some additional development (and money…)

To conclude

- Promising! Exploration of an energy range above HESS/CTA, potential duty cycle much higher: there is something to do there!

- Learning: stages 1 (engaged) and 2 (almost ready, depends on TBB reading). Should help dimensioning the stage 3 trigger array

- Stage 3: phasing several array in time domain (analog? digital solution? the latter should be the easiest way to do - but "only" 8 MA)

- In the meantime: improving knowledge of gamma ray fluxes above 100 TeV, improving simulations of electric fields (codes exist), selecting potential sources. To keep in touch with gamma ray community.

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…)