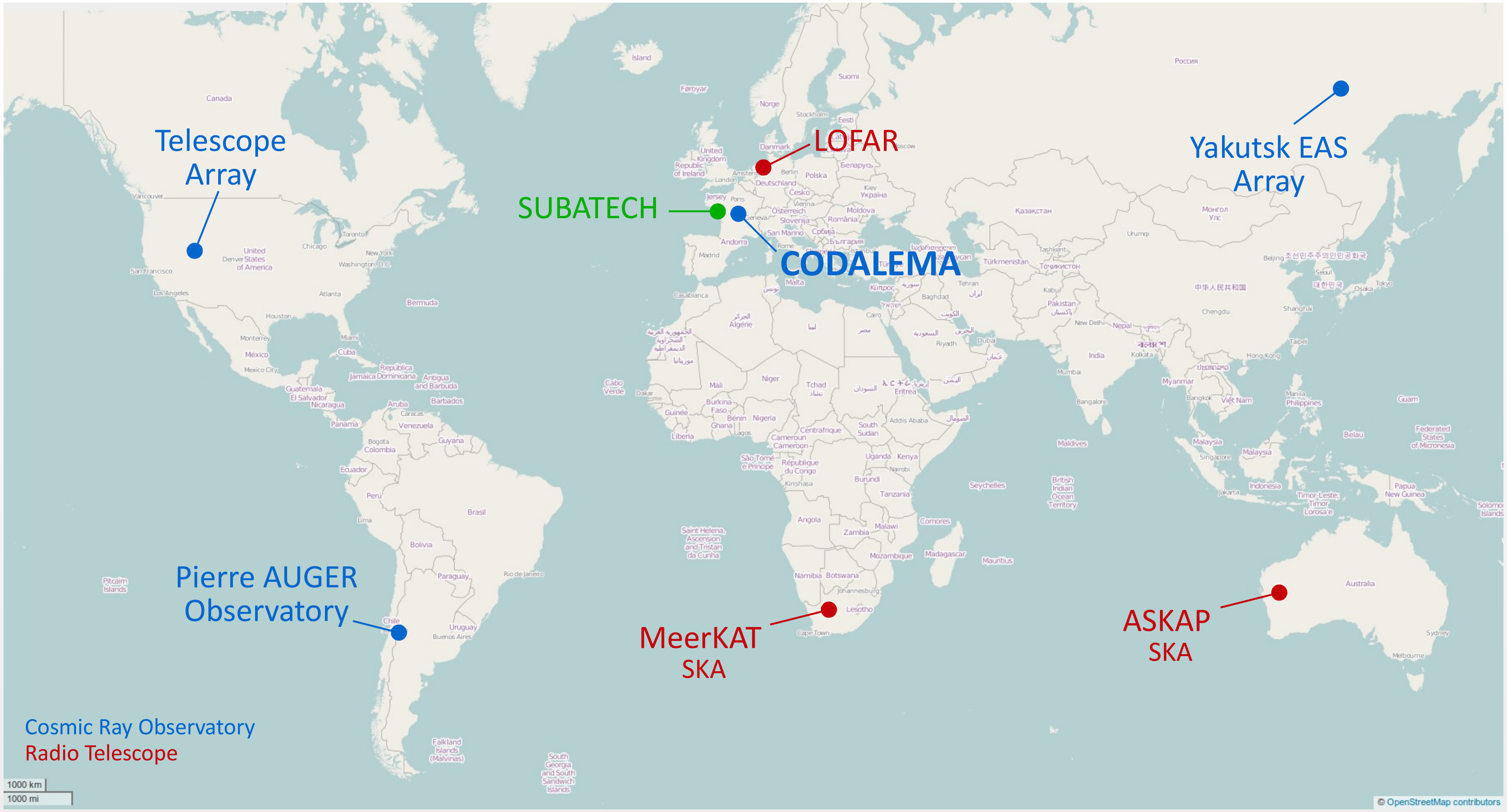
CODALEMA : the radio detection of extensive air showers



Subatech

Station de Radioastronomie de Nançay

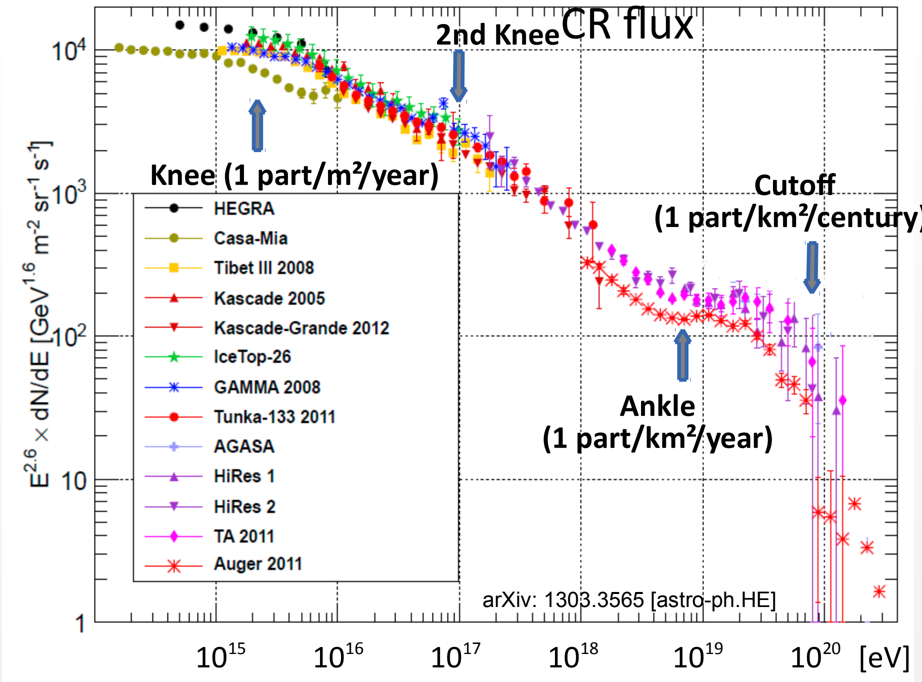
Tackling the challenges of the next generation cosmic ray observatory

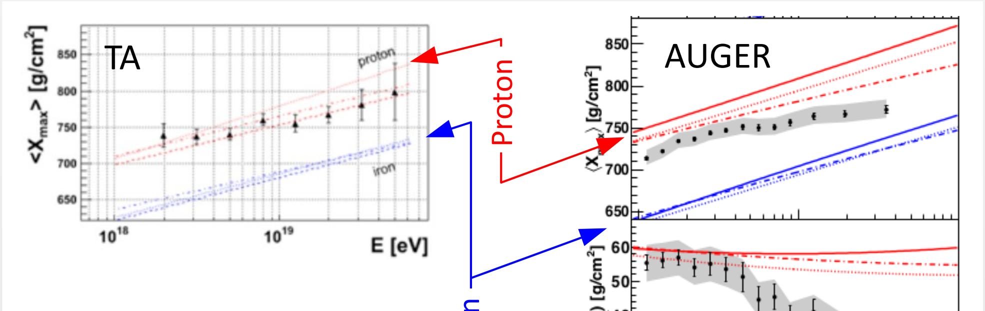
(Why, What, How, When ?)

Lilian Martin, SUBATECH Nantes, FRANCE

Observation of Ultra High Energy Cosmic Rays (UHECR)

- **An old field but still with very fondamental questions :**
  - What is the nature of the UHECR ?
  - What are the sources of UHECR ?
    - Production mechanism
    - Galactic vs extra-galactic origin
- **Some significant progresses :**
  - The spectrum is ending at the very high part
  - The HE part of the spectrum has features
  - The sky seems anisotropic



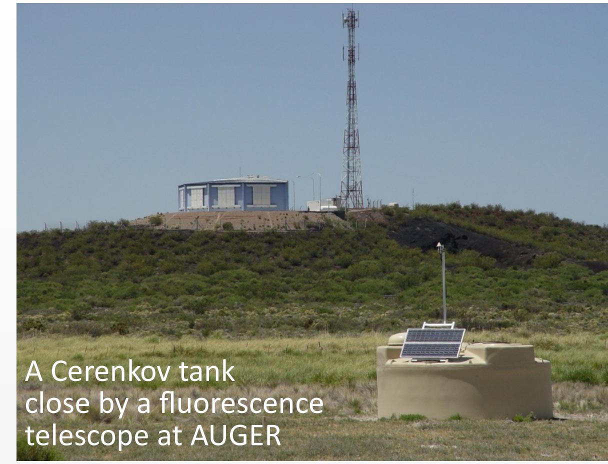


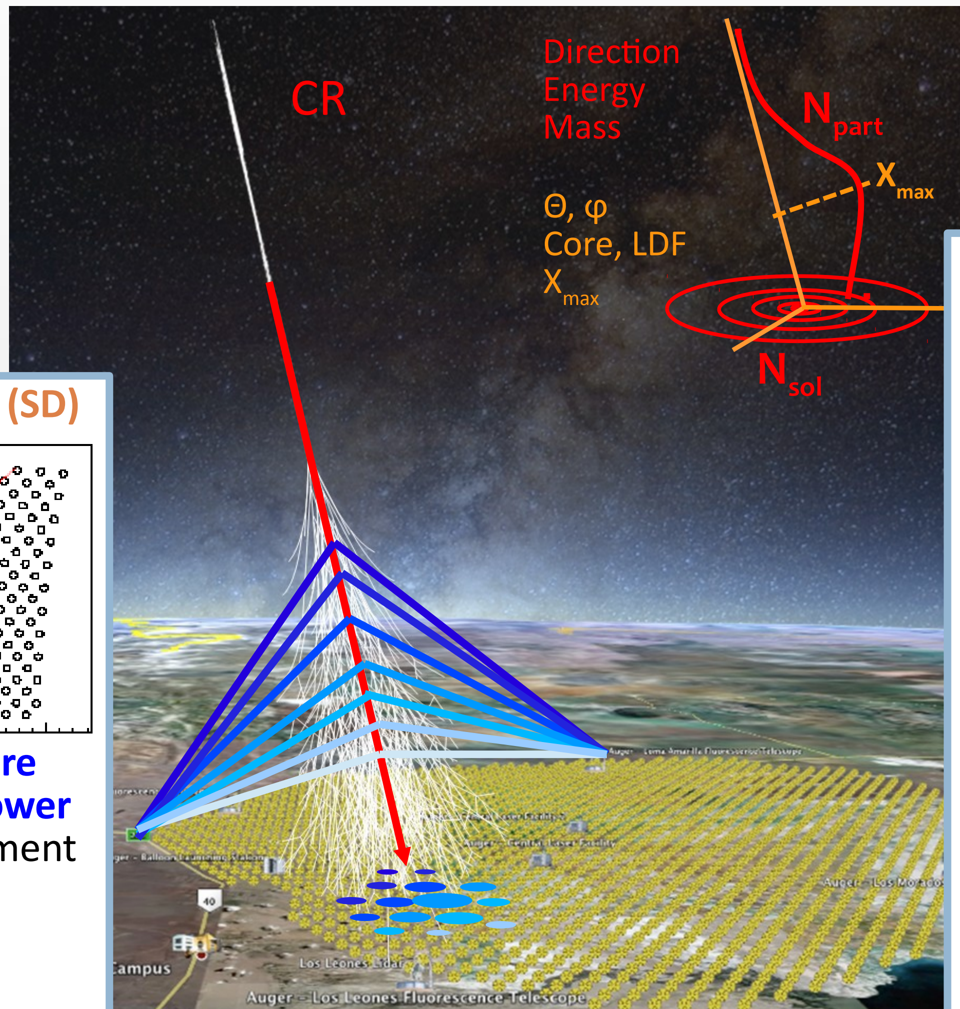
CR mass versus energy
TA : always protons
AUGER : RC gets heavier !

- **Still some major open issues :**
  - Origin of the spectrum ultra-high energy fall out : GZK cutoff or source limits ?
  - Nature of cosmic rays : p or Fe ?
  - No source pointing capabilities (yet or if any ?)
- **Larger statistic AND particle identification needed !**

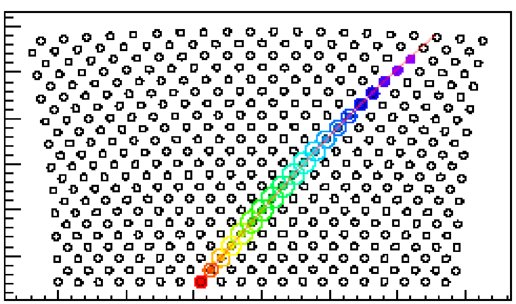
Conventional UHECR detection techniques

Two detection techniques are basically used nowadays to observe and to characterize UHECR :
Plastic scintillators (TA) or Cerenkov tanks (AUGER) and fluorescence telescopes (TA and AUGER)





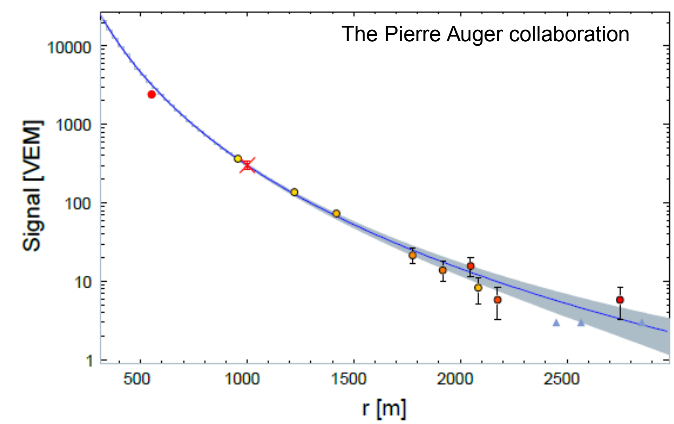
Fluorescence detectors (SD)



Sampling the atmosphere excitation along the shower

+ Calorimetric measurement
+ Energy + X_{max} ∝ mass
- Low duty cycle
- Stereoscopic vision

Surface detectors (SD)



Sampling the particle density on the ground

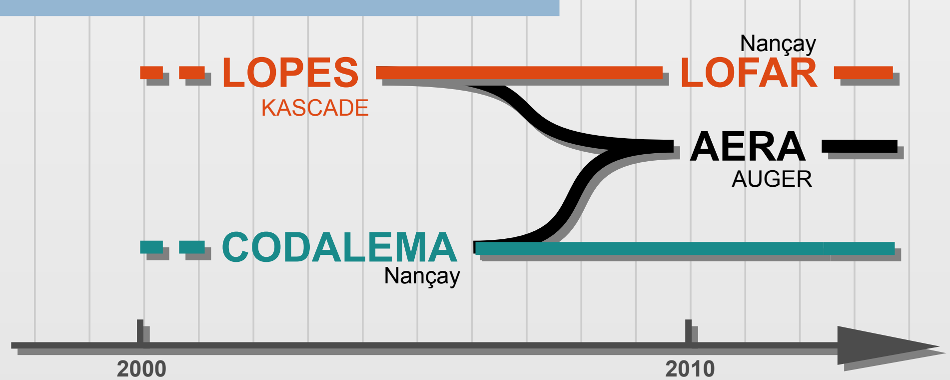
+ High duty cycle
+ Well developed and understood
- Only the shower end is analyzed
- Strongly model-dependent for energy computation

The radio detection of cosmic rays

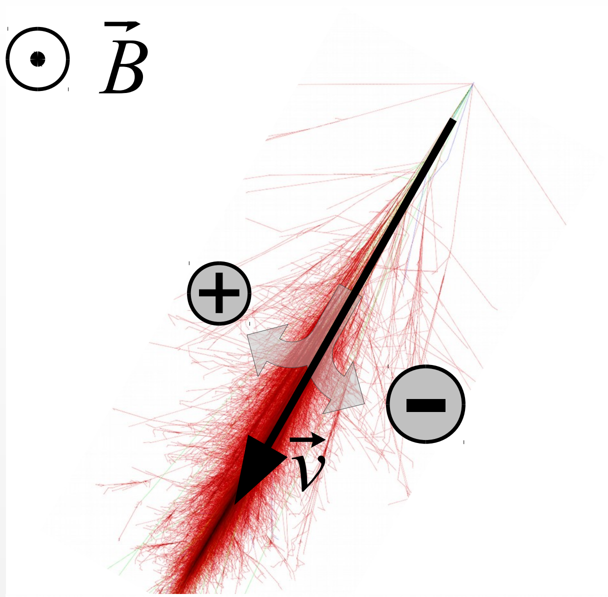
- **Larger and better at ultra high energies**
  - High duty cycle and very large surface to reach significant statistics
  - Event by event particle identification
- **International Symposium on Future Directions in UHECR Physics (UHECR2012)**
  - « Light » upgrades of the big instruments on short time scale and toward low energies
  - Pursue the R&D activities on alternative solutions for a possible future giant instrument

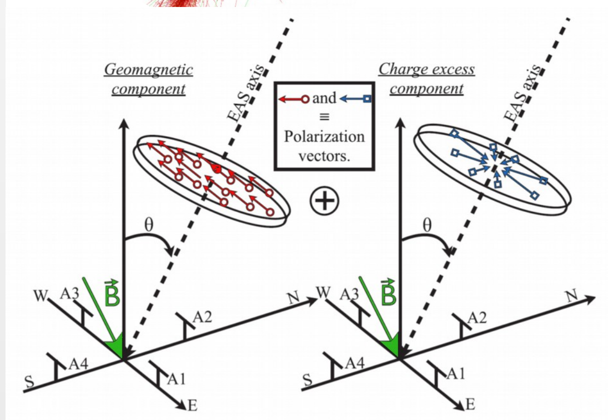
Aims of the radio detection R&D
- A complete technique : direction, energy, mass...
- A competitive technique : efficiency, duty cycle, robustness, cost ...

- **The (long) history radio detection of EAS**
  - 1960 : prediction for a Cerenkov signal in the radio domain (Askaryan)
  - 1962 : geomagnetic effect predicted (Khan and Lerche)
  - 1965 : first experiments (Jelley et al)
  - 1975 : the book is closed
    - Various but incoherent results
    - Technical difficulties
    - Rise of particle and fluo. detection
- **The renaissance of the radio detection**
  - Early 2000 : CASA-MIA, EAS-TOP then LOPES and CODALEMA
  - Mid-2000 : AERA, strong theoretical activities
  - Early 2010 : LOFAR, GHz measurements



Radio emission from Extensive Air Showers





The different mechanisms induce specific polarization patterns for the radio signal

Air shower = - and + charges moving in a medium and a magnetic field

Different approaches to describe the resulting electric field :

- Cerenkov radiation due to the charge excess (about 20 to 30% more electrons) : Askaryan effect (1962)
- Macroscopic models : radiation induced by a net current ; MGMR, EVA codes...
- Microscopic approach : e+ and e- radiation in the geomagnetic field B ; REAS3, SELFAS, ZHAires codes...

Predictions are now rather similar : we understand the signal formation

$$E(x,t)=\frac{1}{4\pi\epsilon_0}\left\{\left[\frac{nq(t_{ret})}{R^2(1-\beta\cdot n)}\right]_{ret}+\frac{1}{c}\frac{\partial}{\partial t}\left[\frac{nq(t_{ret})}{R(1-\beta\cdot n)}\right]_{ret}+\frac{1}{c^2}\frac{\partial}{\partial t}\left[\frac{vq(t_{ret})}{R(1-\beta\cdot n)}\right]_{ret}\right\}$$

Static field
Sum of all static contributions

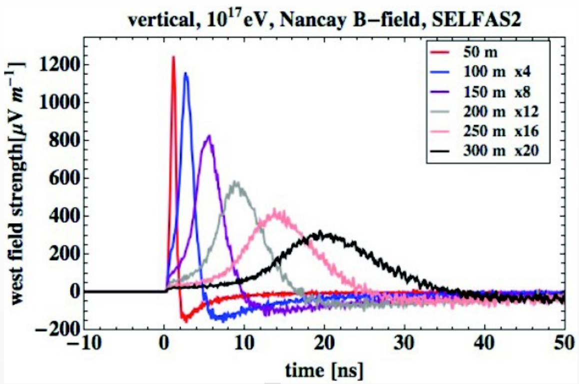
Charge variation (charge excess term)
Sum of all charges. The electrons excess induces a net charge

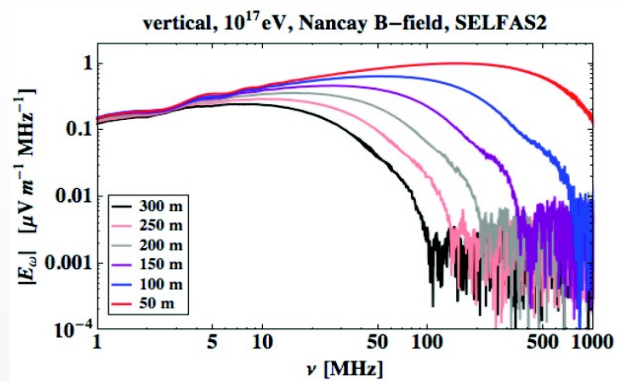
Current variation (geomagnetic term)
Sum of the current produced by the e+/e- deflected by the B field

SELFAS formalism (V.Marin et al.)
Effects of the air refractive index are no included in this formula

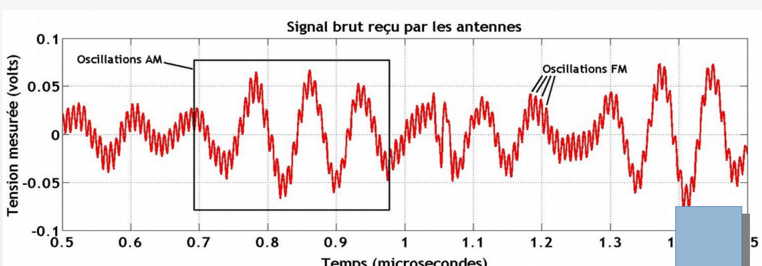
The overall radio signal is correlated to the full shower development

Measuring the radio electric signal

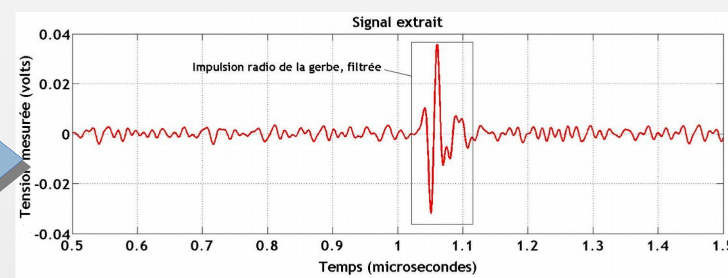




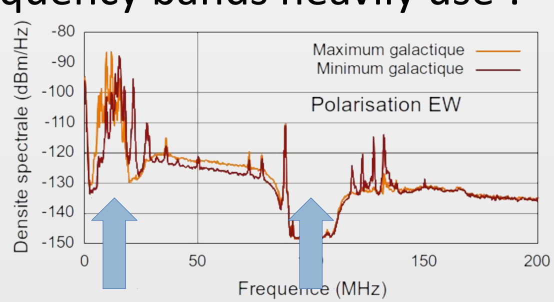
Short bipolar transient expected ! Pulse height and duration strongly variating with distance. Energy spreads mostly in decametric and metric bands (few MHz to few 100 MHz)



Sensitive and wide-band decametric antenna
Fast sampling over a short duration



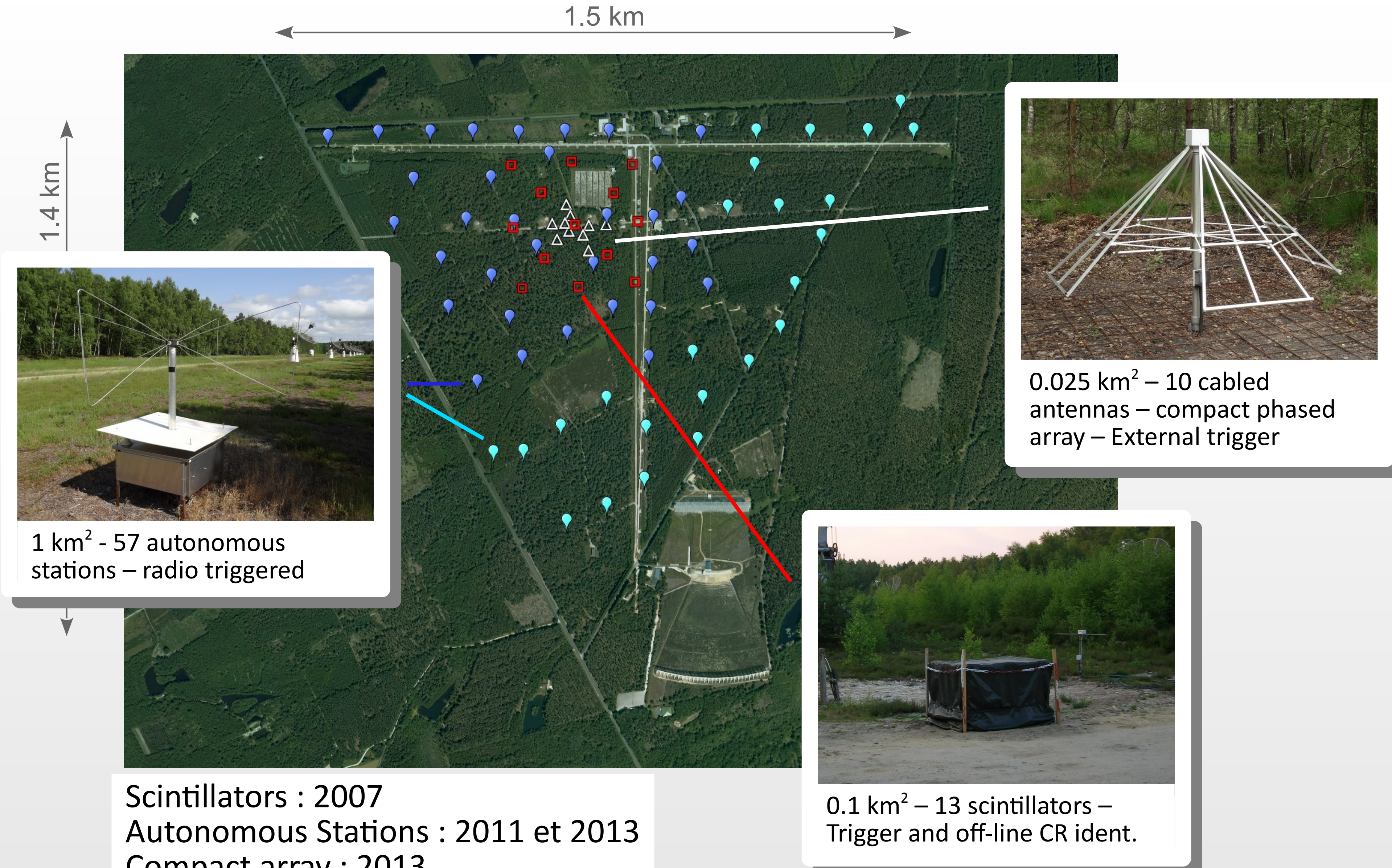
Frequency bands heavily use !



Filtering of the AM and FM bands

Detection « à la » particles : the electric field is sampled using an array of antennas on the ground

CODALEMA : An ensemble of instruments at Nançay



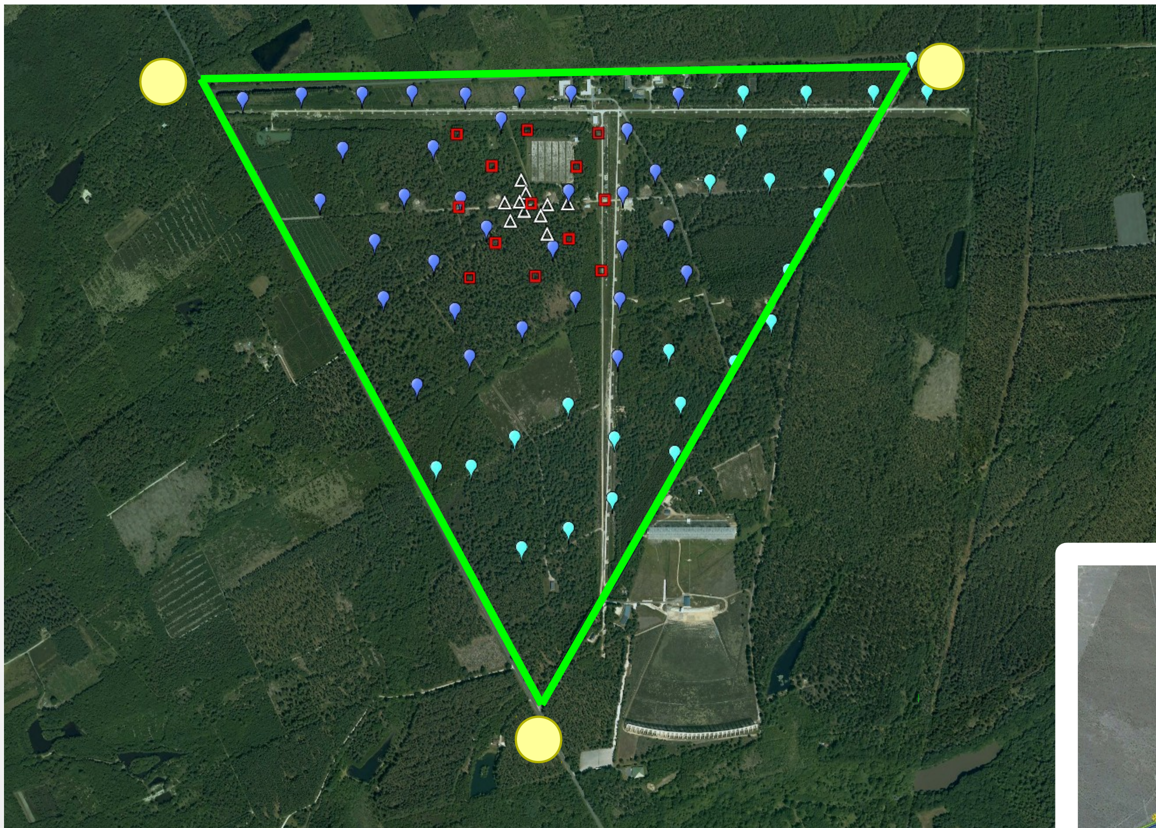
1 km^2 - 57 autonomous stations – radio triggered

0.025 km^2 – 10 cabled antennas – compact phased array – External trigger

0.1 km^2 – 13 scintillators – Trigger and off-line CR ident.

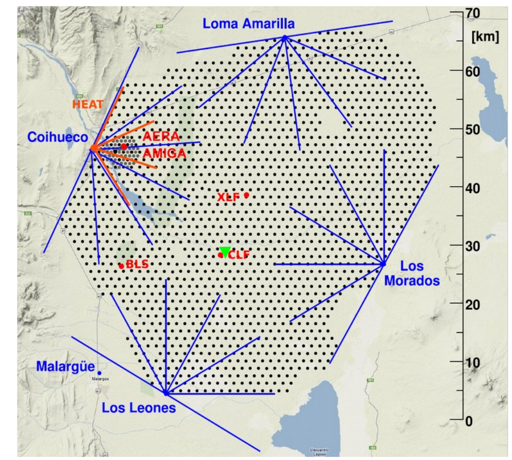
Scintillators : 2007
Autonomous Stations : 2011 et 2013
Compact array : 2013

Comparing CODALEMA to AUGER

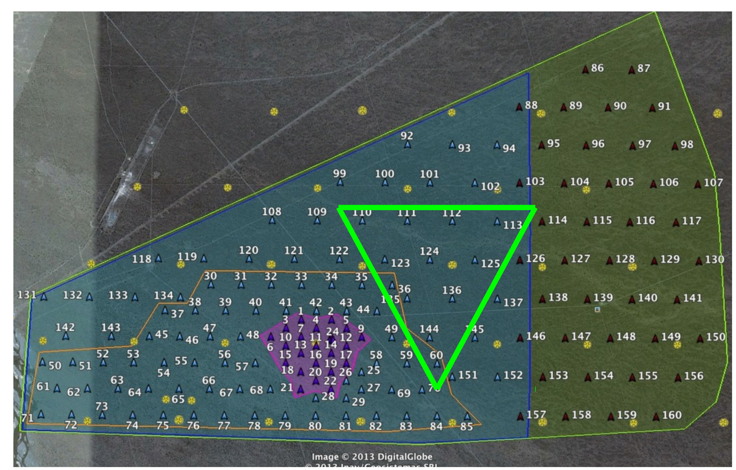


CODALEMA is equivalent to an elementary cell of the AUGER surface detector !
CODALEMA is about 10 times smaller than AERA.

CODALEMA is not a large scale (i.e. high energy) cosmic ray observatory.

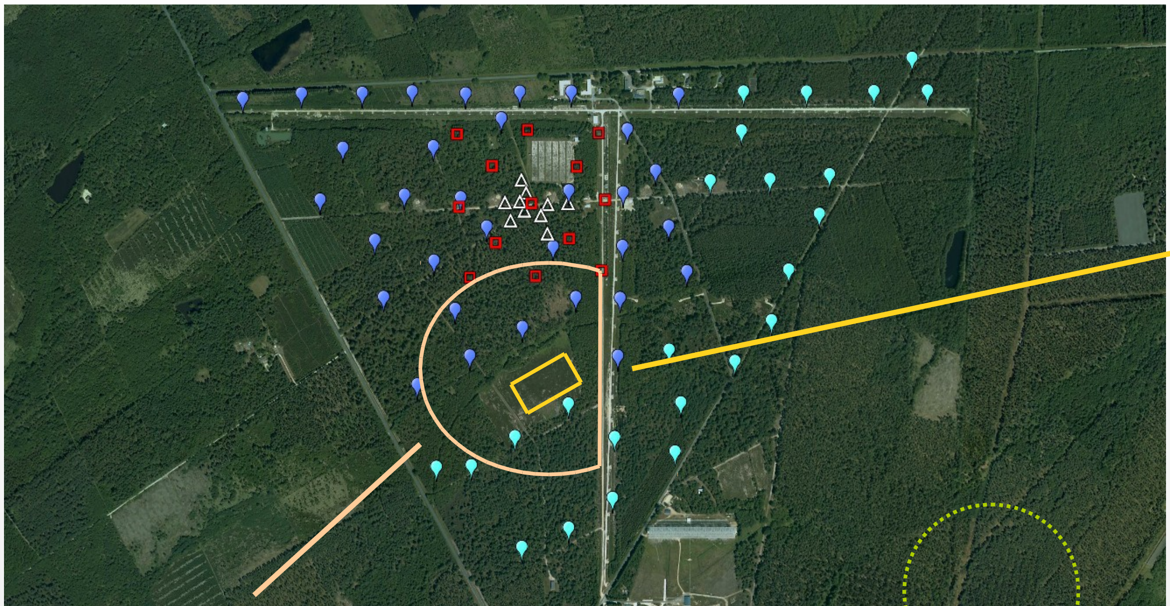


AUGER surface detector – 1600 tanks – 3000 km^2



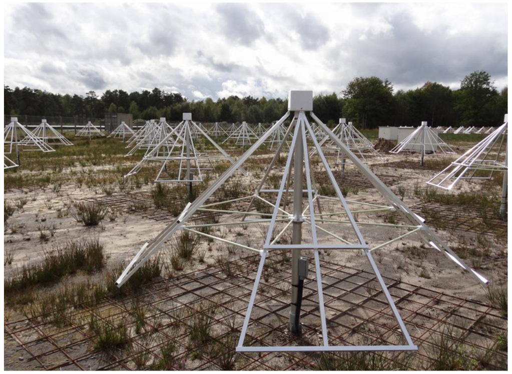
AUGER radio array prototype : AERA – 160 radio stations – 13 km^2 – hybrid detection

Comparing CODALEMA to LOFAR



The LOFAR international station at Nançay – 192 antennas


LOFAR superterp (Netherlands) – 21x96 antennas – Ø = 350 m


The NenuFAR project (Nançay) – 19x96 antennas – Ø = 400 m

CODALEMA covers a surface bigger than the LOFAR superterp in the Netherlands.

CODALEMA = LOFAR LBA+HBA antennas combined
CODALEMA surrounds the NenuFAR array
3 complementary instruments...

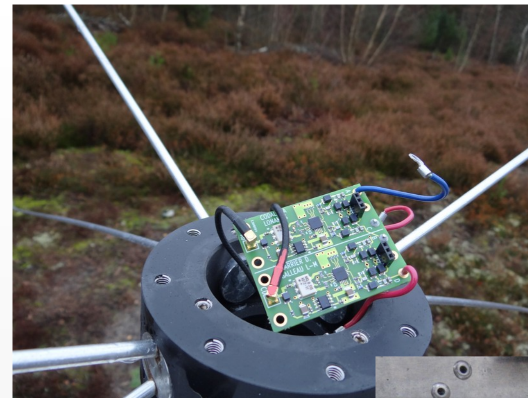
The autonomous station array

Development of an new radio detection station and a station array at Nançay :

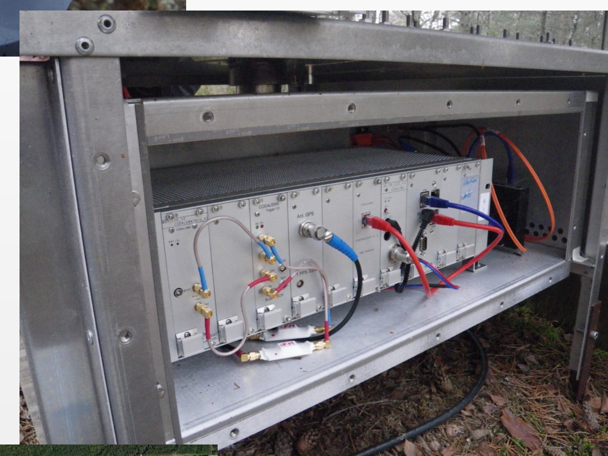
- To design a possible sensor for a next generation observatory : an autonomous radio trigger
- To handle and master a prototype of an antenna array : an ensemble of several tens of detection stations in a known site (closeness, simplicity)
- To increase the capabilities of CODALEMA to perform detailed measurement of Extensive Air Showers : a new antenna design.

Instrumental key items

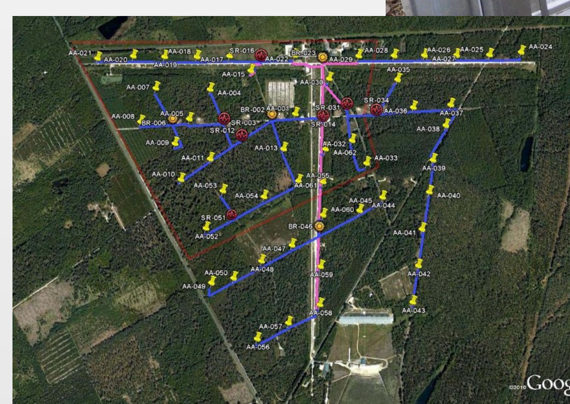
- A robust, linear wide-band antenna : a dedicated LNA and successful design (exported in AERA and NenuFAR)
- Modular (one board=one function) , on-board and upgradeable electronics : Power, GPS, Trigger, Comm., ADC, PC...
- Radio self pollution limited : electromagnetic compatibility of the crate and the mechanical box tested in an anechoic chamber and on site.
- A power network and a computing network (10 km of buried power cables and optical fibers) : no solar panels nor radio comm. network to deal with (problem common to all scattered arrays)
- Analog first level trigger (orthogonal choice compared to AERA). No permanent digitization of the signals : a controlled energy budget (~20W per station)



The dual channel low noise amplifier integrated into the antenna head

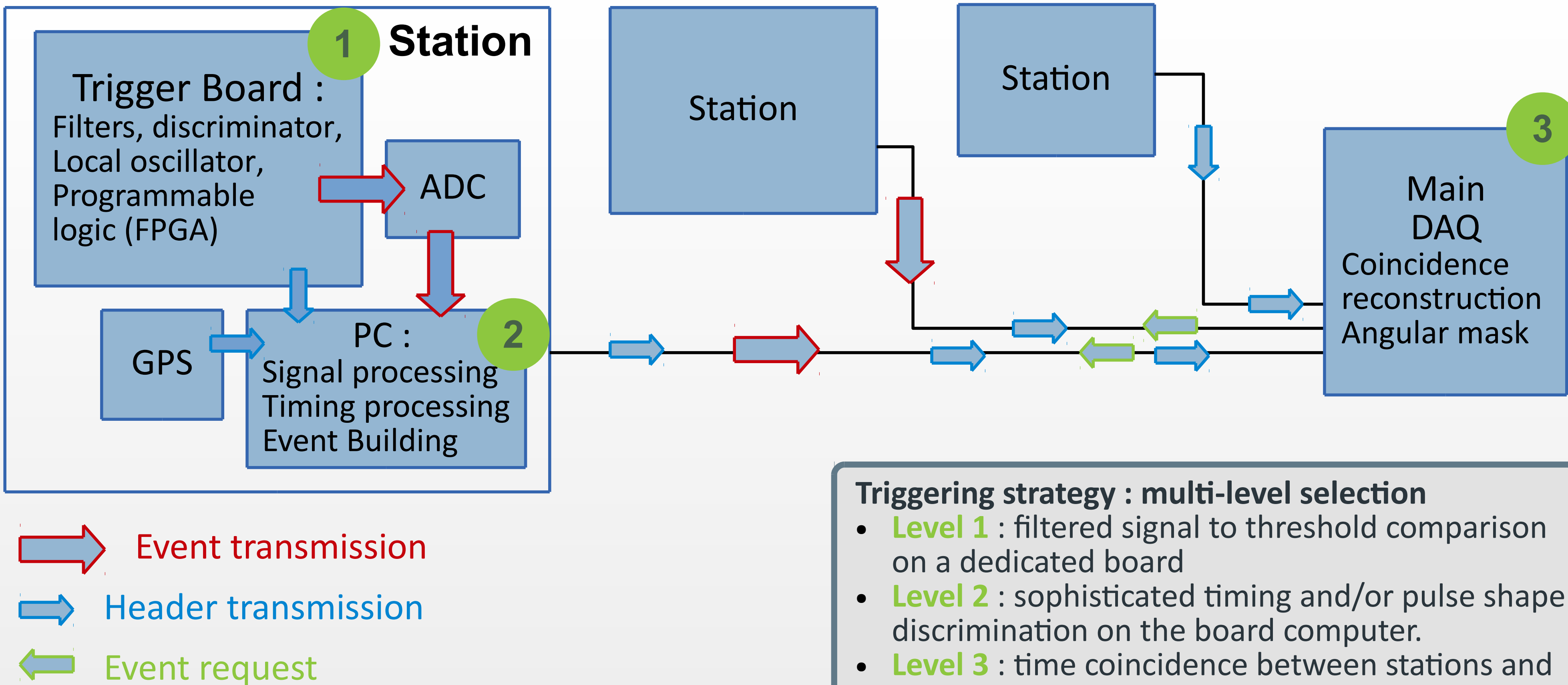


A double EMC barrier: crate and box with metallic seals



10 km of cuttings and gutters along the forest tracks and the roads.

CODALEMA : the triggering strategy



Triggering strategy : multi-level selection

- **Level 1** : filtered signal to threshold comparison on a dedicated board
- **Level 2** : sophisticated timing and/or pulse shape discrimination on the board computer.
- **Level 3** : time coincidence between stations and angular reco. on a master computer.

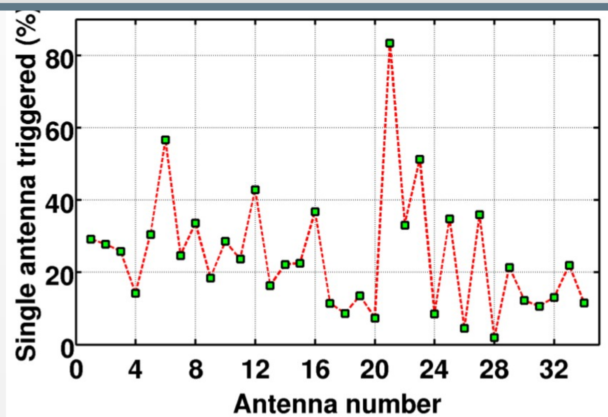
Storing and data saving scheme

- After L1 : full event are stored locally
- After L2 : event header at sent by the station
- After L3 : full events are requested and sent by the stations involved in the coincidences

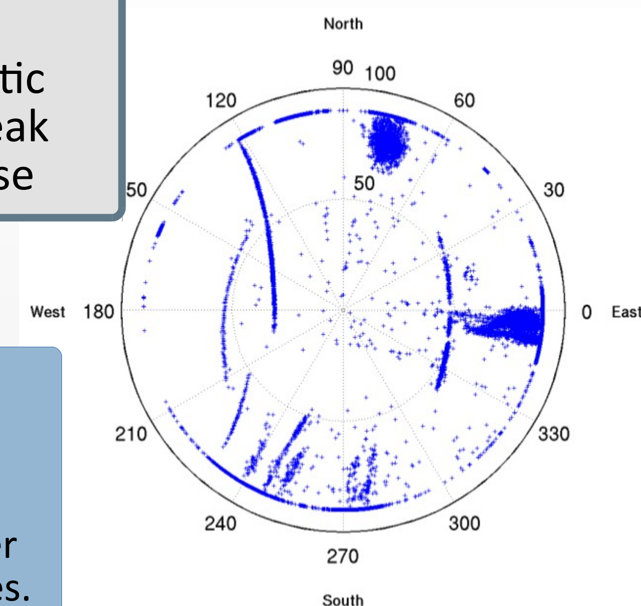
Data format developed for and adopted from AERA (AUGER).
Data are stored off-line in a Firebird db for monitoring, mining and archiving.

The transient sky : a brand new world

A large fraction of the events concerns only one or few stations : very local noise sources

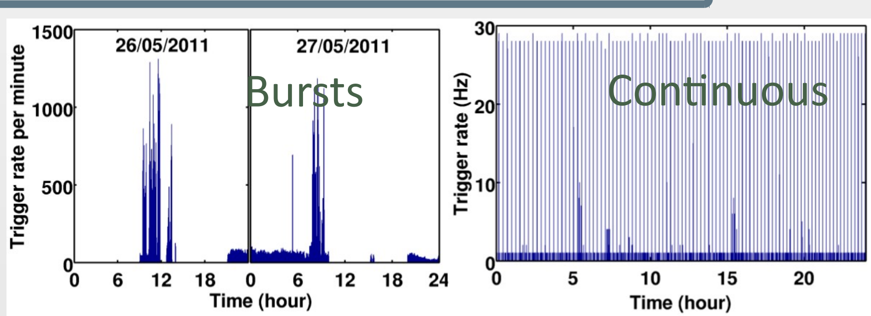


A typical day at Nançay :
mobile vs static
intense vs weak
spot vs diffuse



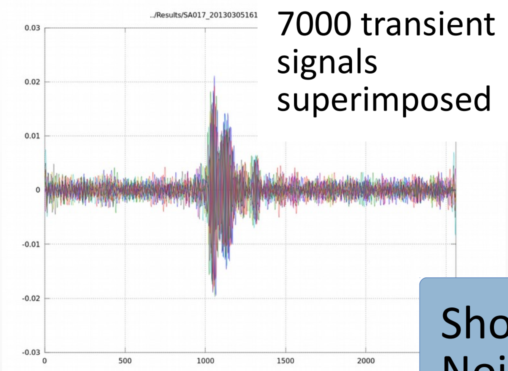
Despite a very severe regulation in term of RFI, the radio-astronomy station of Nançay is surrounded by various parasitic transient sources : planes, power lines, power transformers, fences.

Permanent signals or periodic bursts : identity of the sources



A large fraction of the transient sources has been identified, characterized and localized
Selected strategy : Do not turn them off. Try to become immune to their emission ! Human activities are (almost) everywhere...

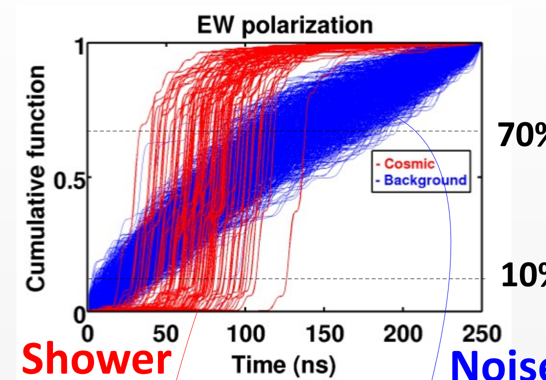
Transient noise rejection methods



7000 transient signals superimposed

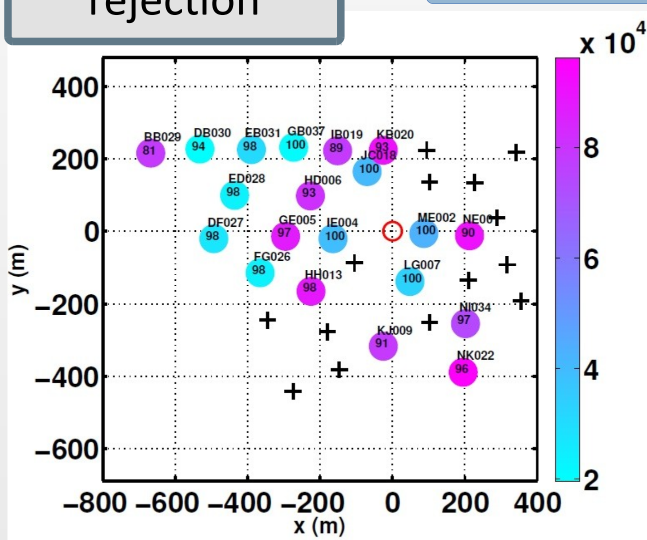
Wave form selection

Normalized cumulative V^2



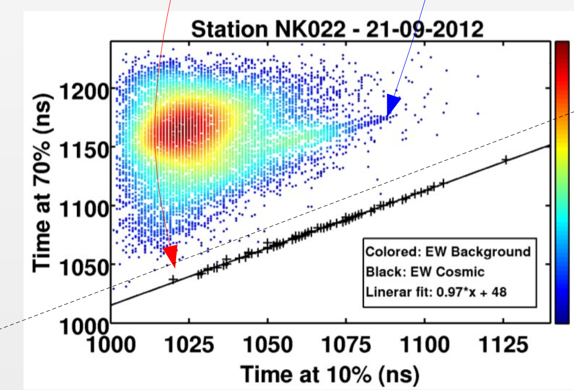
Shower/noise signals are short/long.
Noise signals are similar, with secondary pulses and often periodic.
Wave form, energy or occurrence selection

Parasitic signal rejection



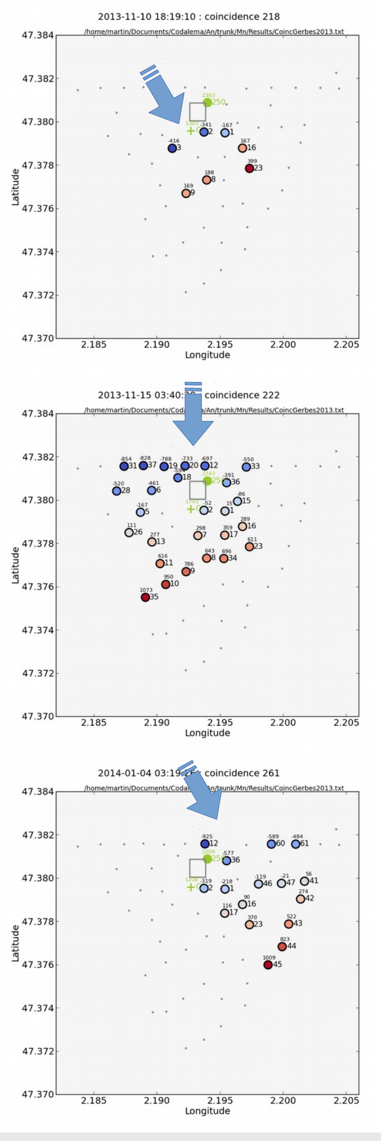
Rejection yield : 94.2 % (T2)
To be implemented in the T1 level
Optimization at the T2 et T3 levels

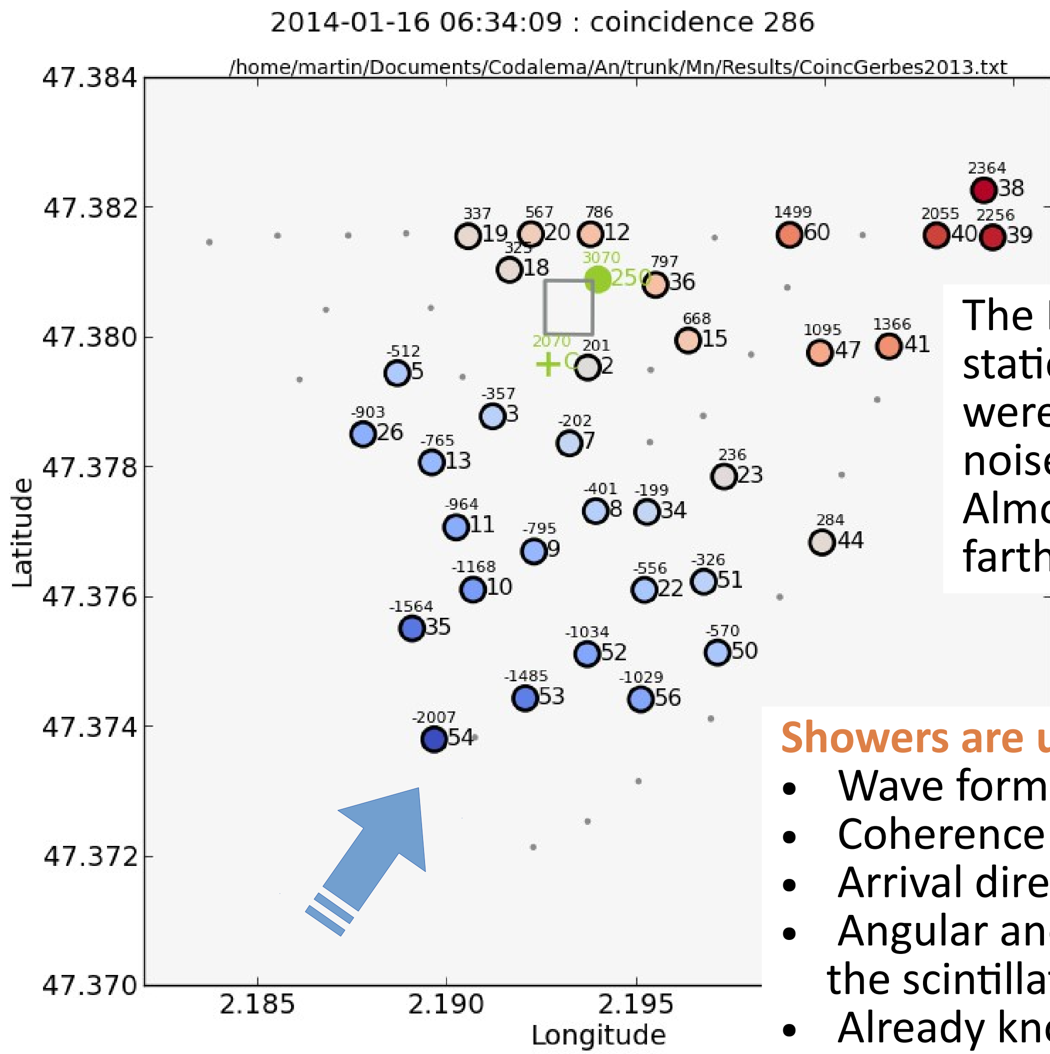
Rejection above the shower signal accumulation line



The stations and the array can be optimized but the are already functioning EAS have been steadily measured since more than a year.

Observing and analyzing cosmic ray events



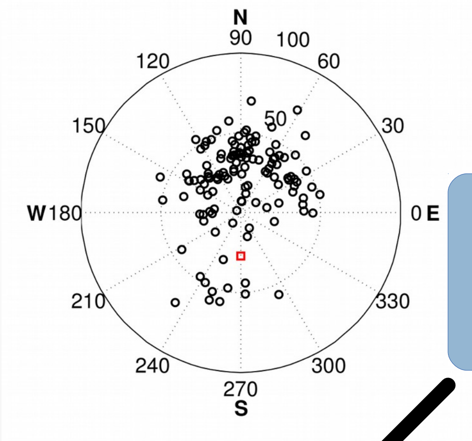


The EAS has been seen by 33 stations. Missing stations were busy (triggering on noise transients).
Almost 1.5 km between the farthest stations.

Showers are unambiguously identified :

- Wave form and spectral signature
- Coherence of the GPS times
- Arrival direction above the horizon
- Angular and temporal coincidence with the scintillator array
- Already known properties are clearly emerging : arrival direction anisotropy, electric field lateral distribution

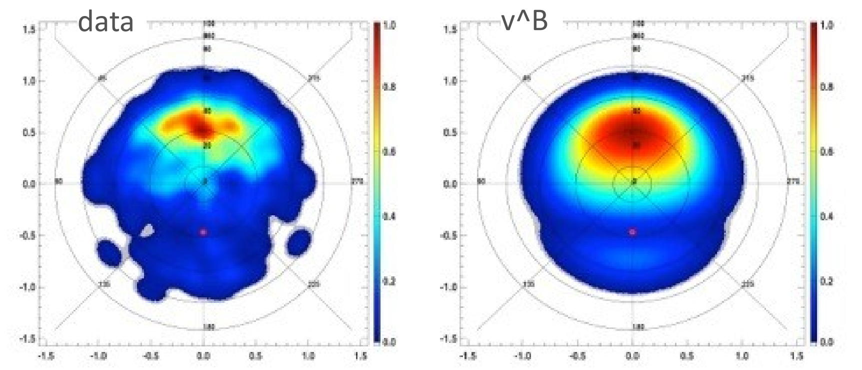
Measuring the basic shower properties



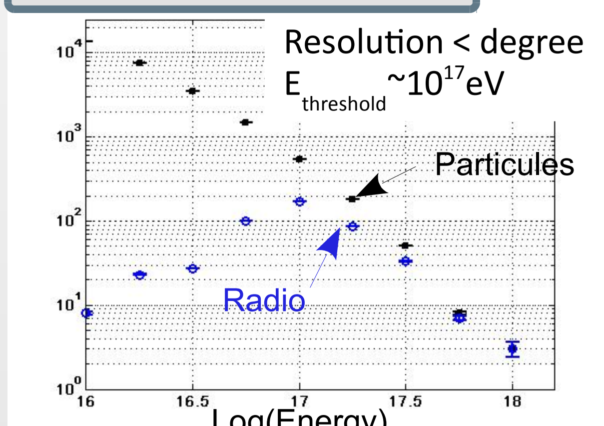
Arrival times and directions

Radio signal production mechanisms

The geomagnetic field is the main player !

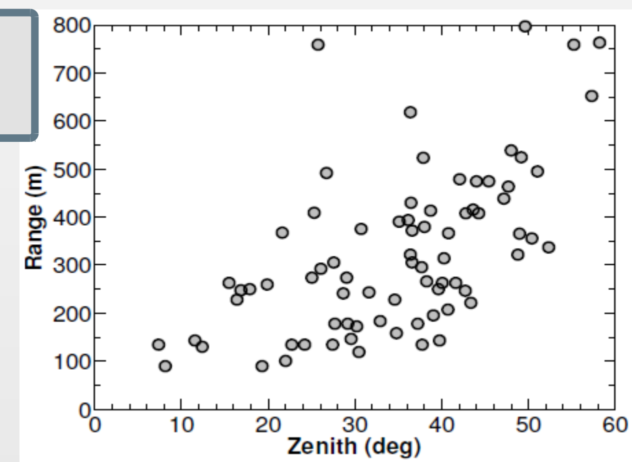


Angular resolution
Threshold and
detection efficiency



Wave front curvature : spherical, parabolic, conical ?
Correlation with the maximum emission point ?

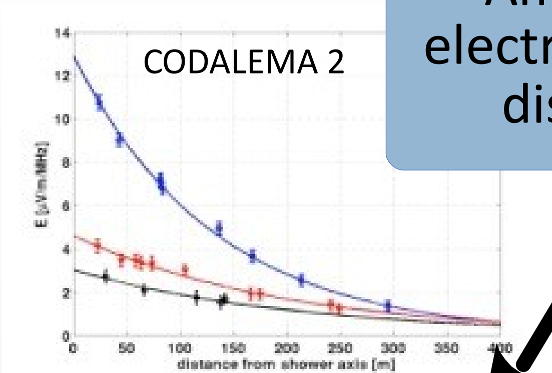
Angular acceptance
Radio « range »



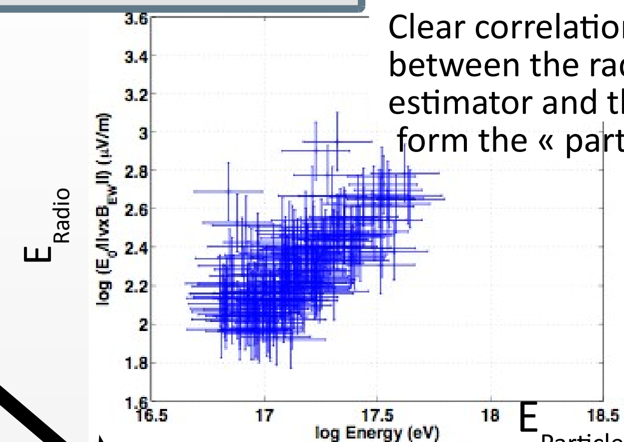
Radio “sees” at several hundreds of meters.
Radio “sees” very inclined showers

Measuring the basic shower properties

Amplitudes et electric field lateral distributions

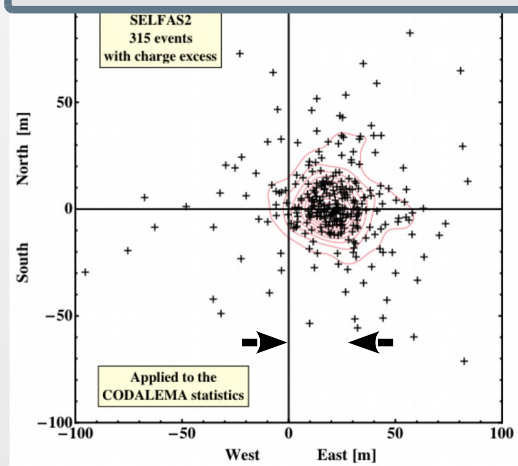


Energy estimator



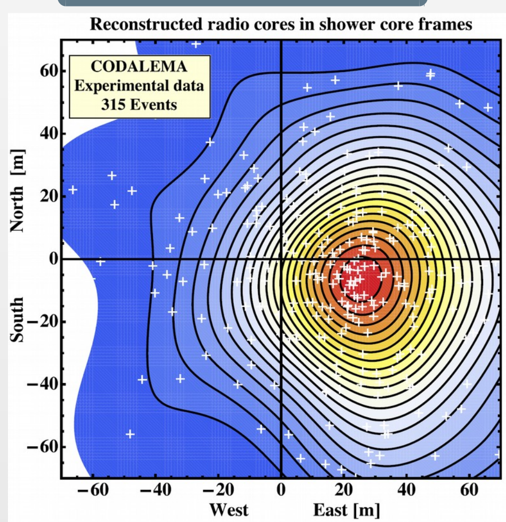
Clear correlation between the radio estimator and the energy form the « particles »

Radio signal production mechanism



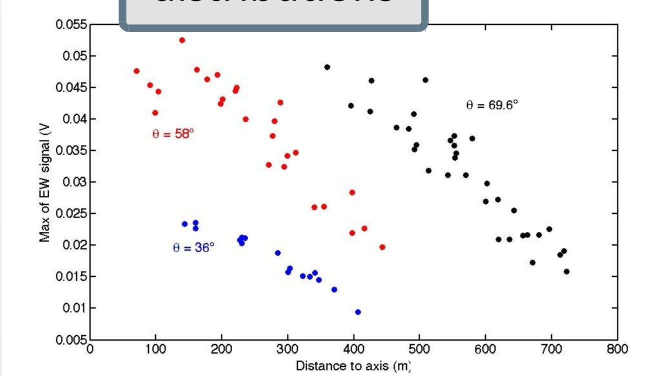
The charge excess effect explains the systematic core shift of 20m

Location of the shower core



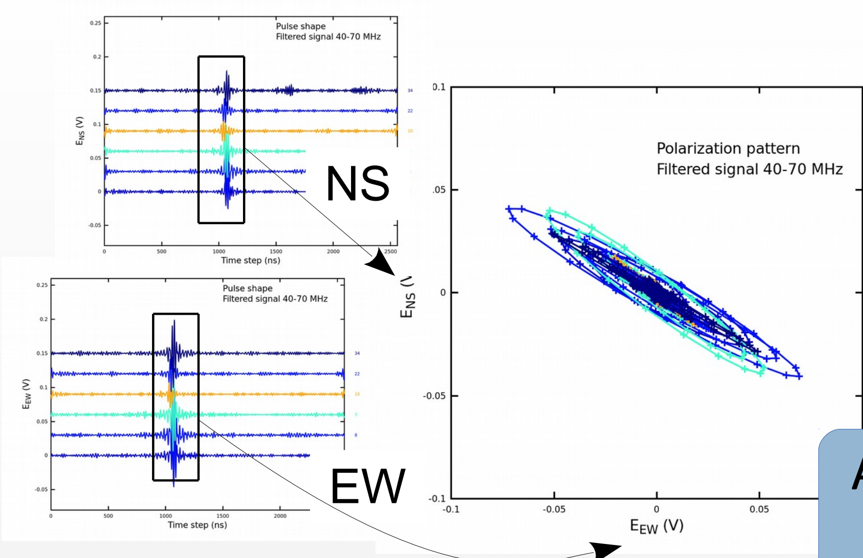
The « radio » shower core is correlated to the « particles » shower core

Shape of the lateral distributions

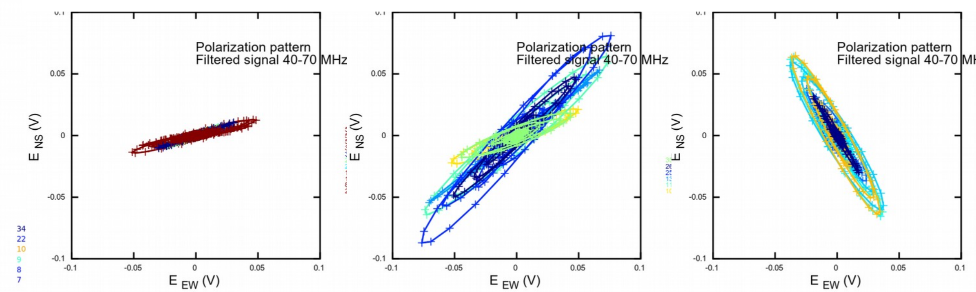


Lateral distributions are often strongly irregular : the electric field ground patterns are complex and thus rich

Beyond basic properties : signal polarization



Radio signals are strongly polarized !



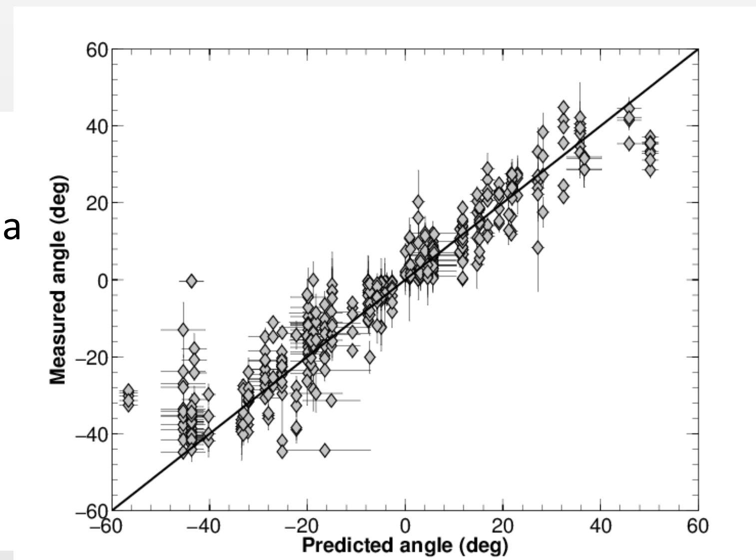
Amplitudes and polarization

Stokes parameter analysis : for each event and and antenna

$$Q=\frac{1}{n}\sum_{i=1}^{n}(E_{EW,i}^2-E_{NS,i}^2)$$

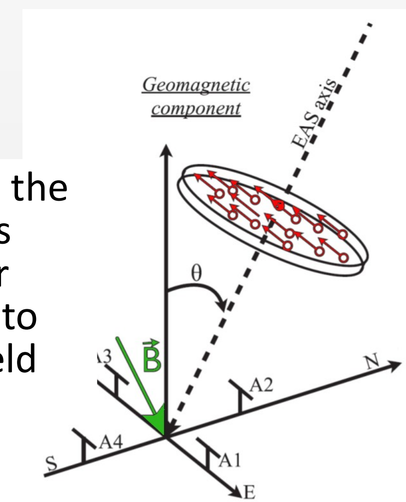
$$U=\frac{2}{n}\sum_{i=1}^{n}(E_{EW,i}E_{NS,i})$$

$$\psi_{meas.}=\frac{1}{2}\tan^{-1}\left(\frac{U}{Q}\right)$$



Transverse current : the signal polarization is given by the shower orientation relative to the geomagnetic field

$$\psi_{Pred.}=\tan^{-1}\left(\frac{(\vec{v}\times\vec{B})_{NS}}{(\vec{v}\times\vec{B})_{EW}}\right)$$

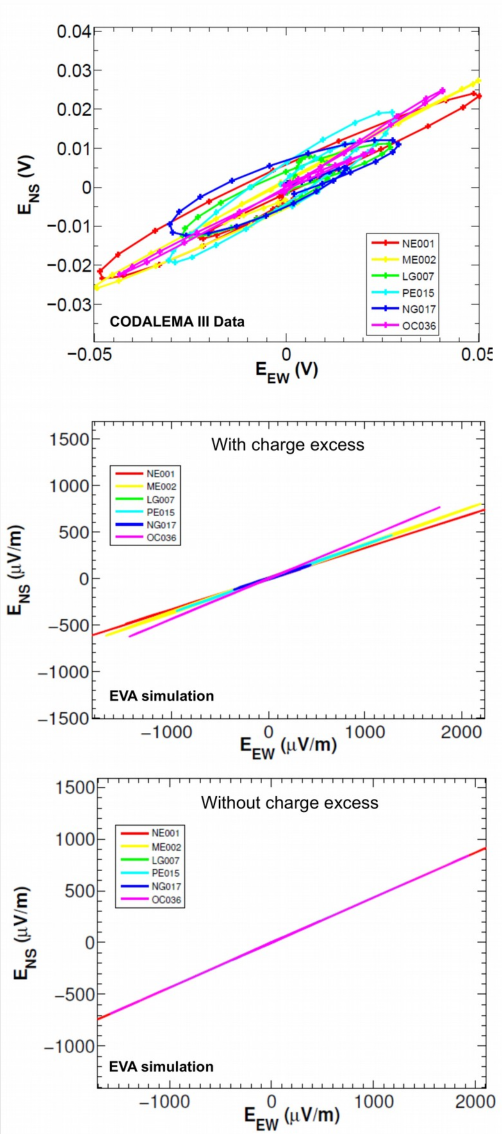


Strong correlation with the predicted angle

Arrival direction ↔ Polarization !

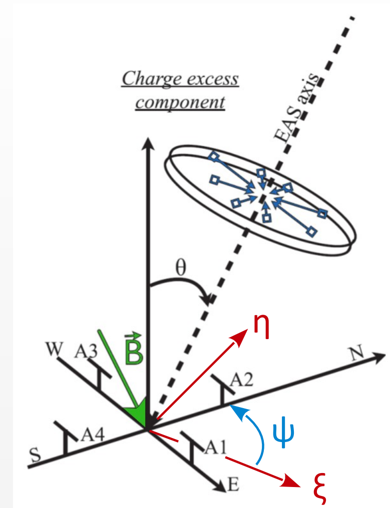
Shower – Noise discrimination !

Beyond basic properties : signal polarization



Amplitudes and polarization

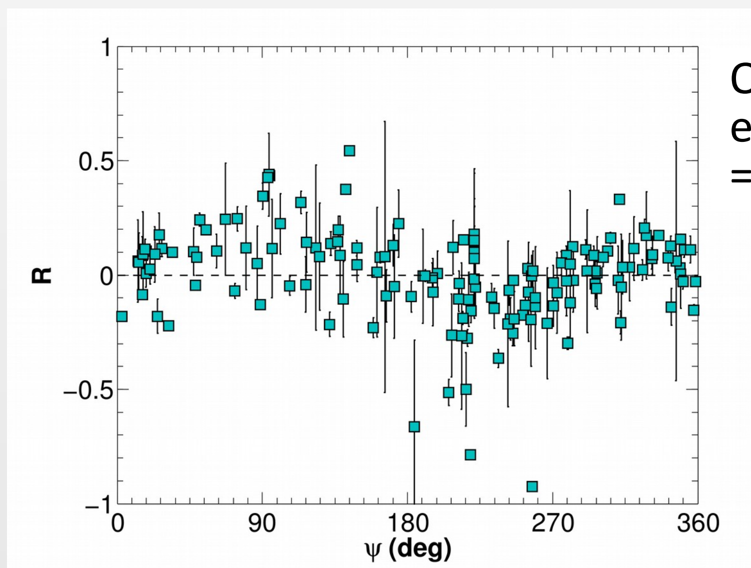
On an event basis : polarization angles are systematically scattered around the mean value.



The polarization is computed in a (ξ,η) frame specific to each shower (where the transverse current contribution cancels out) :

$$R(\psi) = \frac{2\sum_{i=1}^{n}(E_{\xi,i}E_{\eta,i})}{\sum_{i=1}^{n}(E_{\xi,i}^2 + E_{\eta,i}^2)}$$

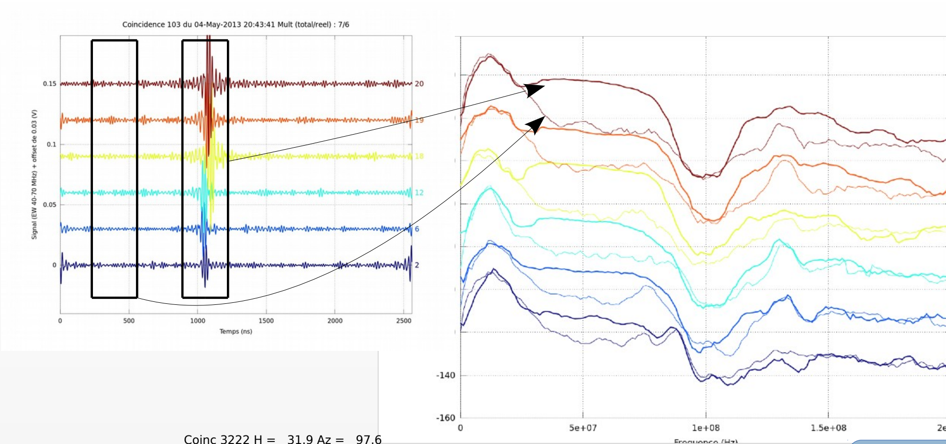
A radial contribution appears as a sinusoid !

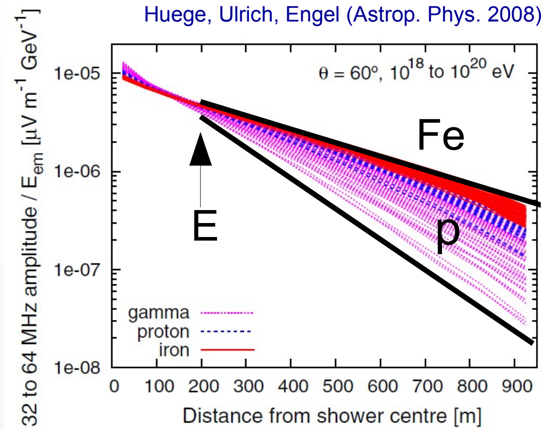


Oscillation in the experimental distribution = charge excess effect

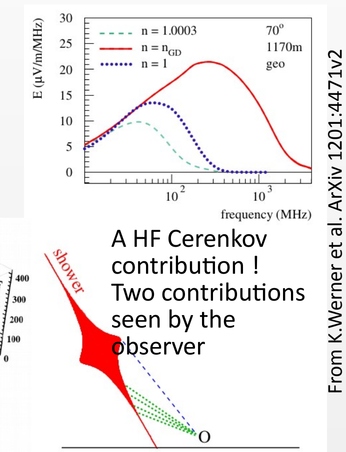
Location around the shower core ↔ polarization dispersion !
The shower can be localized from the polarization values.
More precise than lateral distribution of the electric field ?

Beyond basic properties : frequency studies



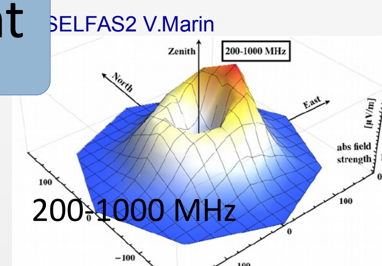


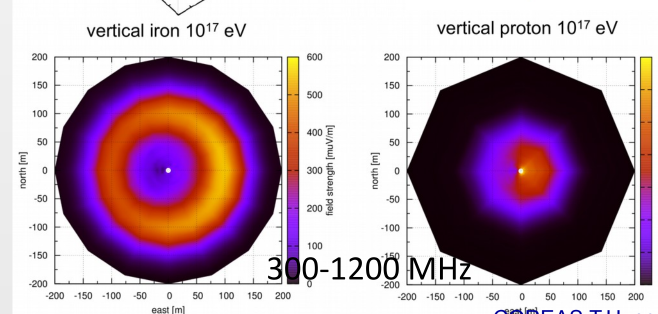
(E_{f1}/E_{f2}) ratio :
Energy measurement
Mass discrimination



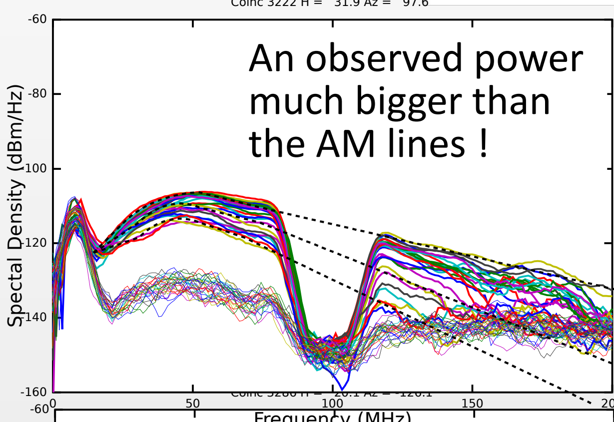
A HF Cerenkov contribution !
Two contributions seen by the observer

Spectral content

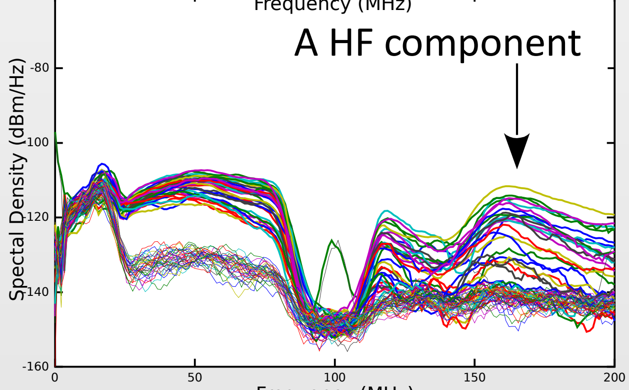




The Cerenkov effect induces discriminating HF contributions !



A spectrum shape changing with the antenna : variation with the distance to the shower !



Frequency : Information on the position, energy and mass of the CR

One needs a sensitive, wide-band and mastered antenna

Precise antenna response deconvolution. On going work !

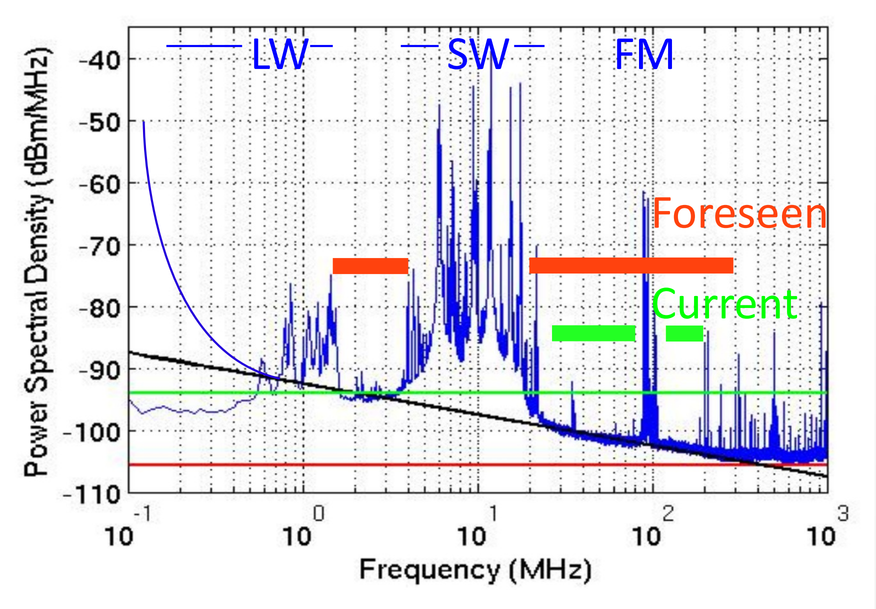
Conclusions : Is the radio detection technique ready ?

- **A comprehensive and accurate technique ?**
  - **Production process : OK**
    - The electric field production mechanisms (geomagnetic, charge excess, refractive index) are known and controlled over a large frequency range (few MHz to GHz)
    - Models are various and are (now) producing similar predictions
    - Complex electric field patterns observed are nicely matched by simulations
  - **Arrival direction of the CR : OK**
    - Reconstruction by individual timing or interferometry
    - Sub-degree angular resolution
  - **Energy of the CR : OK**
    - Radio signal amplitude and energy correlations
    - Energy resolution of the order of 10-20% is achievable (radio can probably do better)
    - Fine comparison with models will bring higher precision
  - **Mass of the CR : COMING UP**
    - The less measured observable so far
    - Good sensitivity to the X_{max} has been claimed (LOFAR) by comparison to simulations
    - Sensitivity to the longitudinal development of the shower is under study.
    - Several directions are explored : spectrum slope, wave front curvature, Cerenkov contribution...

Conclusions : Is the radio detection technique ready ?

- **A competitive technique ?**
  - **Large scale array prototypes (AERA, LOFAR) are producing results but not for UHECR yet**
  - **Duty cycle : OK (ALMOST)**
    - No particular natural show stopper besides lightnings.
    - Human made parasitic transients is the most troublesome factor : Efficiency is fine but purity is very low.
    - Optimization of the trigger strategies.
    - Development of an on-line composite trigger (CODALEMA compact array), T3 trigger (CODALEMA and AERA) masking noise arrival direction.
    - At worst antenna + scintillator patch combination
  - **Range : TO BE IMPROVED**
    - The electric field quickly vanish with the distance to the shower in the current observation band. Very good sensitivity to inclined showers.
    - Optimization of the signal to noise ratio combined to optimized triggers
    - Polarization and spectrum can reduce the number of sensors
    - Extend the antenna range down to lower frequencies (down to 15 MHz and below the AM lines)
  - **Cost, simplicity, robustness... : OK BUT TO BE WORKED OUT**
    - The sensor is a simple, compact, easy to deploy. No fluid, no light-tightness needed.
    - The sensor is rather cheap and the energy budget is controlled.
    - No integration efforts have been done yet but some ideas emerge (all-in-one solution, smart phone technologies)

Conclusions : still new directions to explore

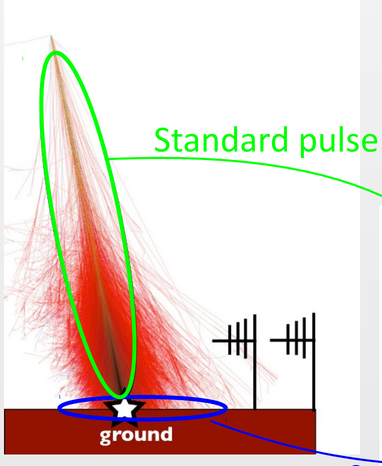


Increasing the comprehensive measurements :

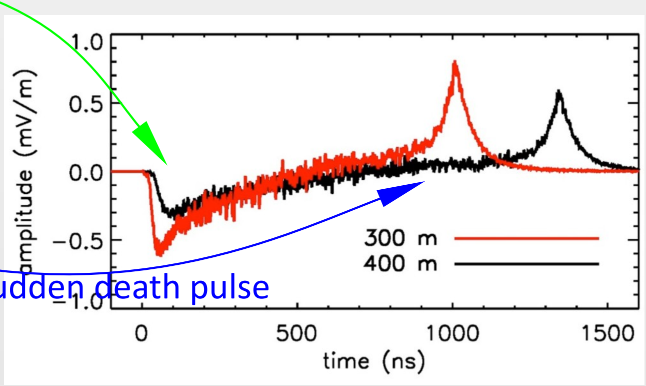
Improving the sensitivity toward low frequencies (down to 10-15 MHz and 1.5-4 MHz) : extending the range !
Improving the sensitivity toward high frequencies (150 to 300 MHz) : looking for the Cerenkov signal.
The LNA is ready : adaptation of the radiators and the front end filters.

Measuring the electric field vertical component : adding a third radiator. Stronger constraint on the models, higher sensitivity to the EAS properties.
The station is ready : available slot for a additional digitization board.

Investigating the signal associated to the shower hitting the ground (sudden death pulse)



Fast and coherent deceleration of particles



Low frequency (<20 MHz)
mostly vertical polarization.
1/d attenuation
scale with E
Provide the shower core location
Provide a precise clock for absolute timing of the shower development (sensitivity to X_{max})

Hints for observations in the past !
Predicted by various models
EXTASIS project at SUBATECH AND Nancay