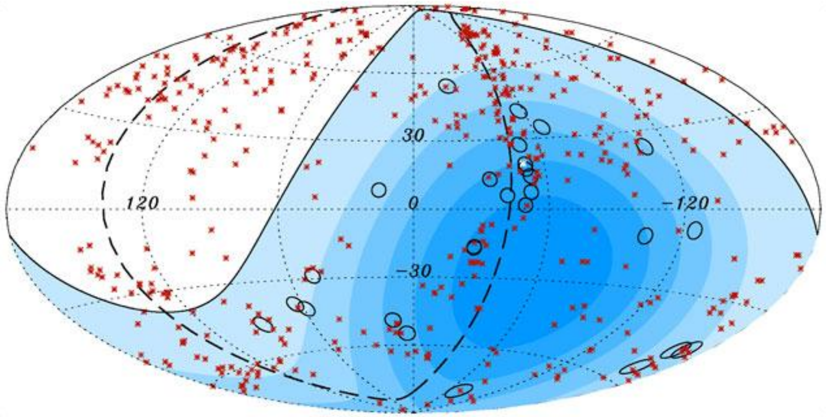
Status et perspectives de la radiodétection des grandes gerbes cosmiques

P. Lautridou LPCC 19/11/2010

La Problématique des rayons cosmiques ayant des énergies de l'ordre du Joule (~ 10^{19} eV)

- Quelles sont ces particules ?
- D'où viennent-elles ?
- Y a t'il une limite à leur énergie ?



Auger data 2008

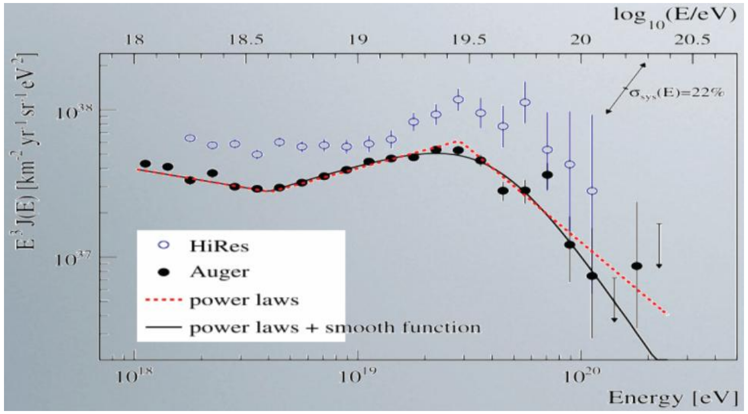
=>Astronomie des Hautes Energie ?

=> Structure des champs mag.?
=> Mécanismes d'accélération ?

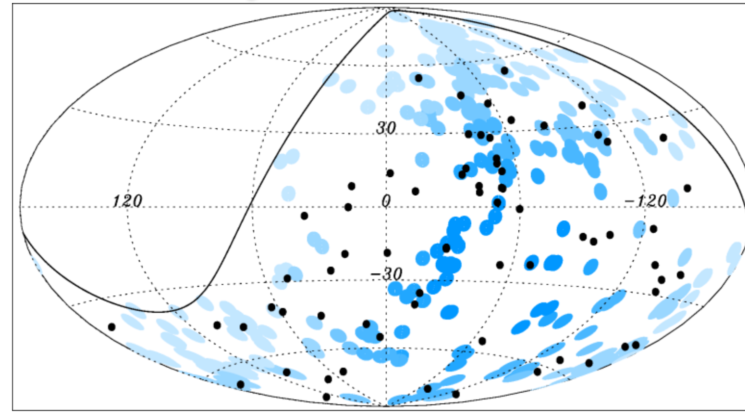
=>Physique des interactions au Joule ?

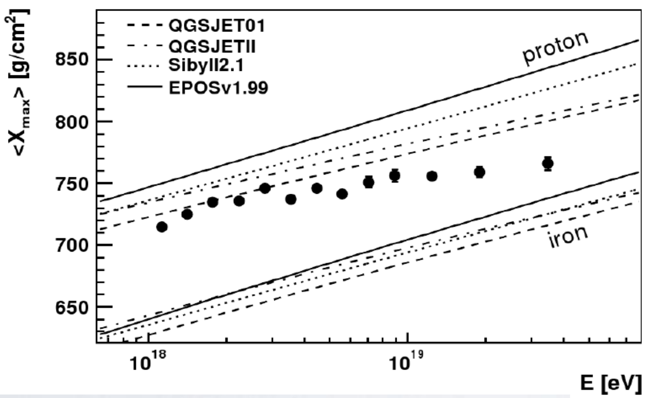
+ Physique de l'atmosphère, Radioastronomie (réseau réparti, pulse géant)...

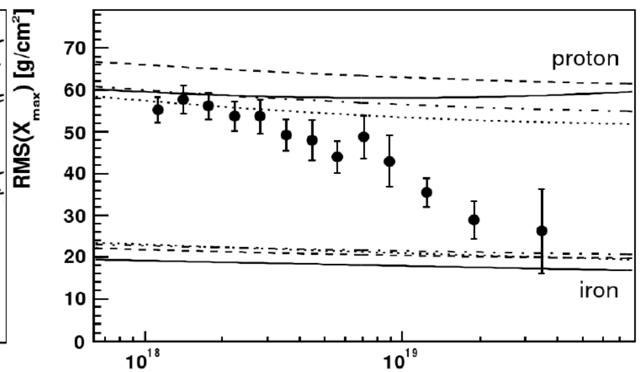
Results in 2010 (AUGER)



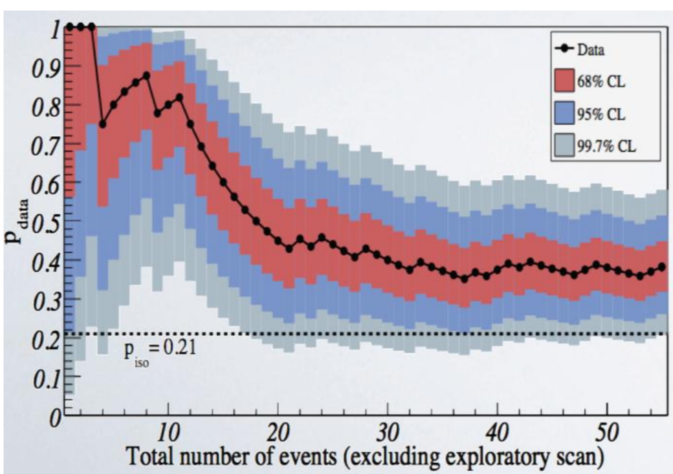
GZK (20σ)
and
Anisotropy (3σ)



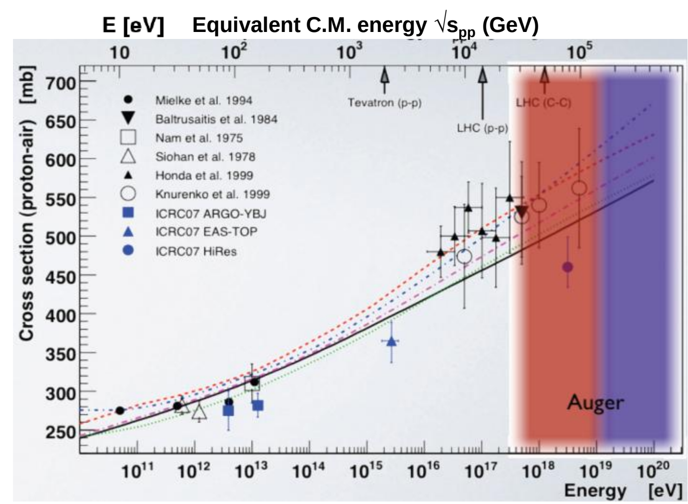




Fe rather than p ?
(with current models)



Anisotropy genuine ?
or change in Xsec at
highest énergies ?

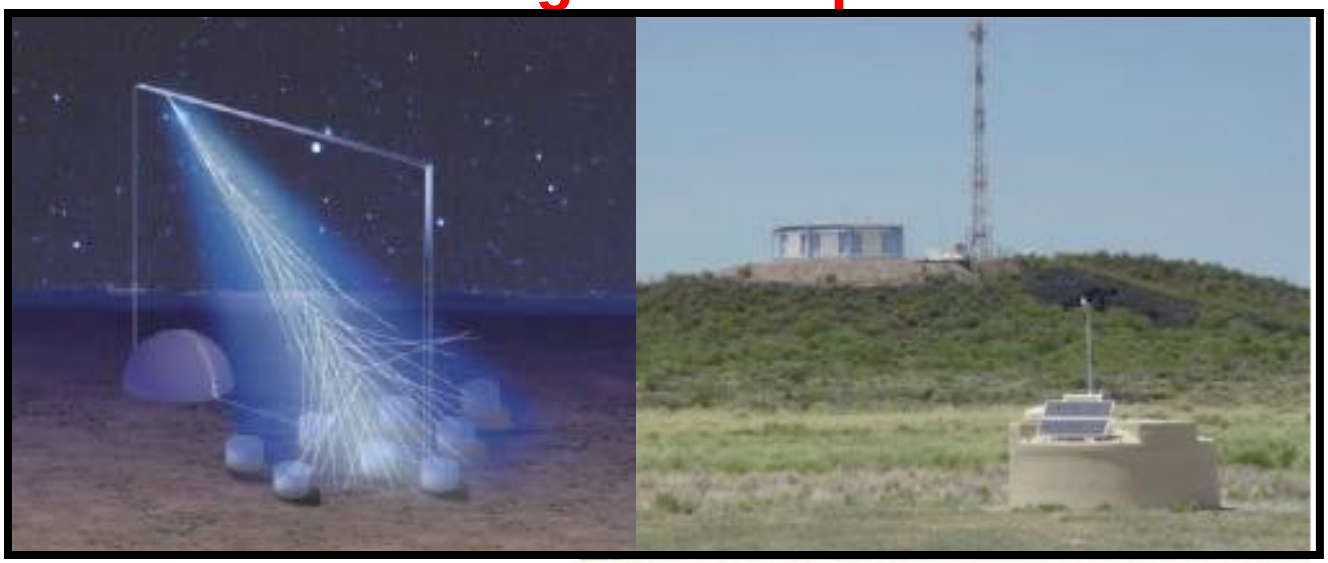


Des techniques expérimentales standards à la radiodétection

=>Des détecteurs géants comme le « Pierre AUGER Observatory » en Argentine ~3000 km^2 ou le T.A. au USA

- Les détecteurs de particule au sol => Pb des gerbes inclinées
- Les détecteurs de fluorescence => Pb du cycle utile de 10%

=>Besoin de détecteurs + grands & performants =>COUT



Rechercher d'autres solutions…

La radiodétection

1962: **Prédiction théorique** - effet Askar'yan

1964-65: **Première expérience** - T.C. Weekes

Milieu 70 ': **Méthode délaissée** difficultés d'interprétation et de détection + succès d'autres techniques

Fin 90 ': **Redécouverte dans milieux denses (glace, sel) =>neutrinos**

En 1999: **Preuve du principe sur accélérateur (sable, D. Saltzberg,)**

En 2000 : **Expérience sur CASA-MIA (K.Green et al., 2003, N.I.M. A, 498)**

En 2002 ← **Expérience LOPES sur KASCADE => Analyse fréquentielle**

Expérience CODALEMA de SUBATECH => Forme d'onde

En 2005 ← **H. Falcke et al., Nature, May 19, 2005**

P. Lautridou et al. NIM A555 2005

En 2006 prospectives sur PAO, en 2008 sur 21CMA (TREND), en 2010 émission free-free.... multi-sites, multi-capteurs, multi-analyses, multi-Messagers

Mécanismes d'émission radio

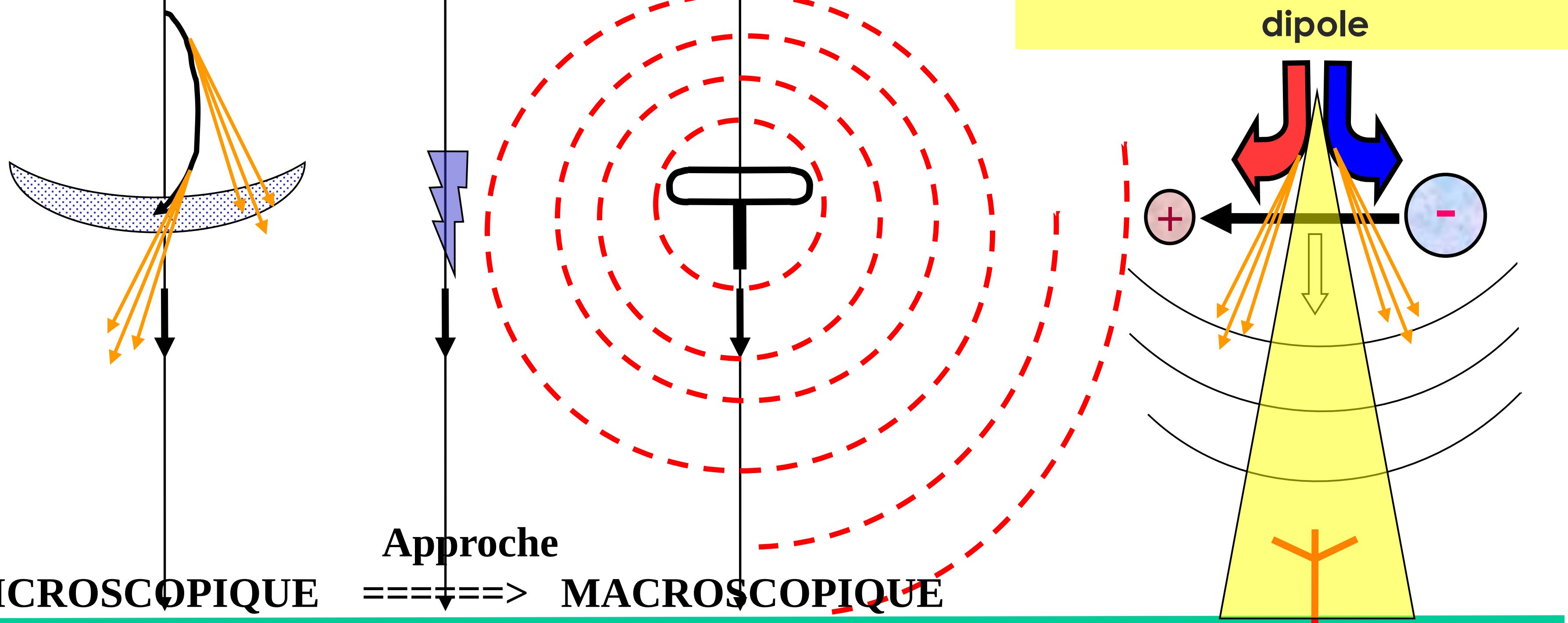
Dans le ciel…

Galette de Milliard de Particules… ➡ Fil Électrique… ➡ Antenne d'émission…

qui se dirige vers le sol à la vitesse de la lumiere !!!

90% de γ (>50keV)
9% d'ē (>250keV)
0,9% μ (>1GeV)
0.1% hadrons

- Excès de charge: e-/e+
  monopole
- Effet géomagnétique F=qVxB
  dipole



Approche

MICROSCOPIQUE ======> MACROSCOPIQUE

Geo-synchrotron

Courant dipolaire

+ Emission Cerenkov ?

ANTENNE DE DETECTION

Modelisations

•**Monte-Carlo: microscopic description**

Spectrum Analysis in frequency space

REAS3: Corsica + geosynchrotron

ReAIRES: Géomagnétic effect

-Semi-analytical: macroscopic description

Waveform analysis in time space

MGMR: Extraction of simple laws + Dipole current

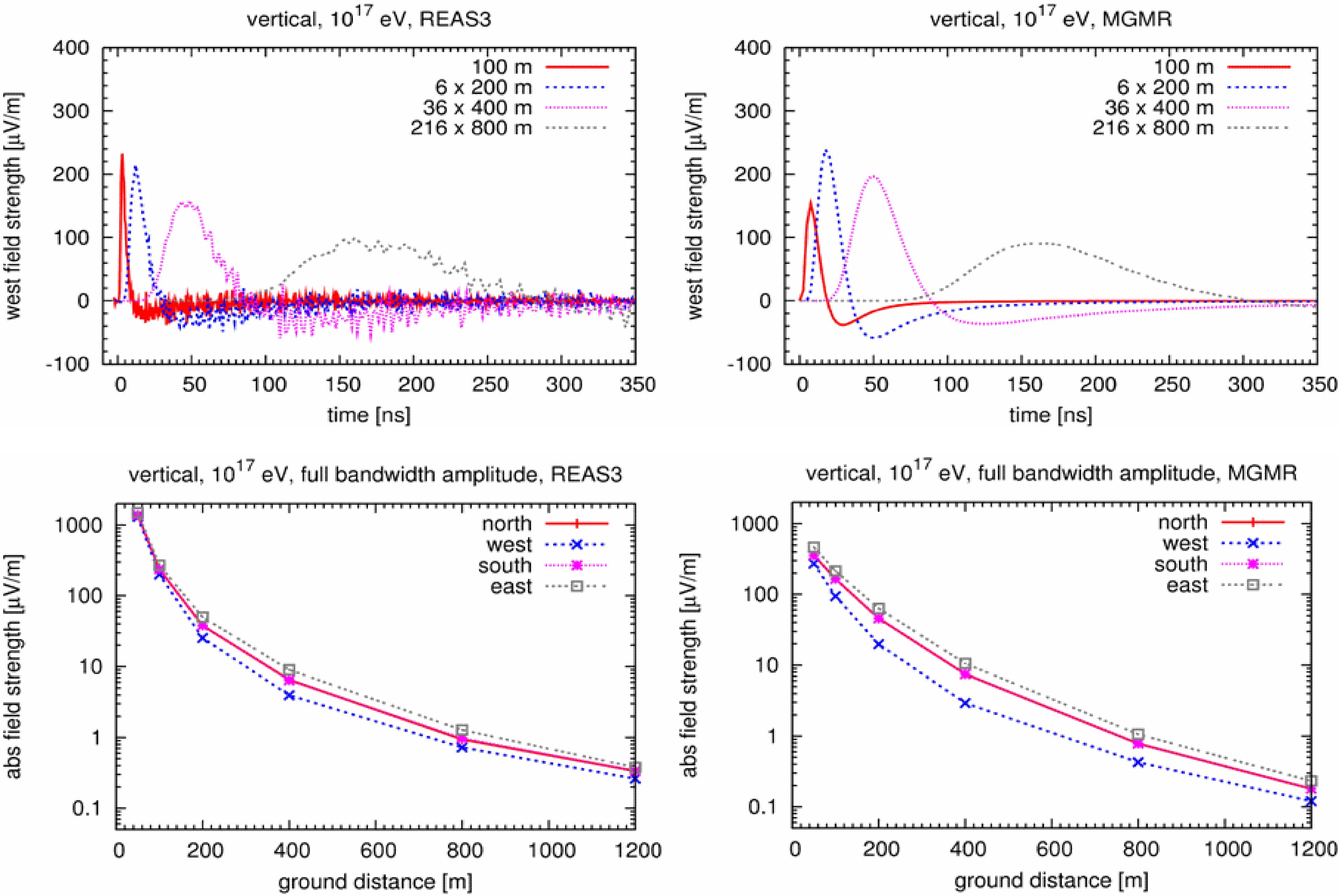
+ Several toy models: test of specific points

- Coulomb emission (+geomagnetic effect)
- boosted model (+ refractive index of Air + Cerenkov emission)
- Wire model, Compton Inverse model, etc.

=>Fréquency analysis (1970) => Waveform analysis + Trigger capabilities (2000)

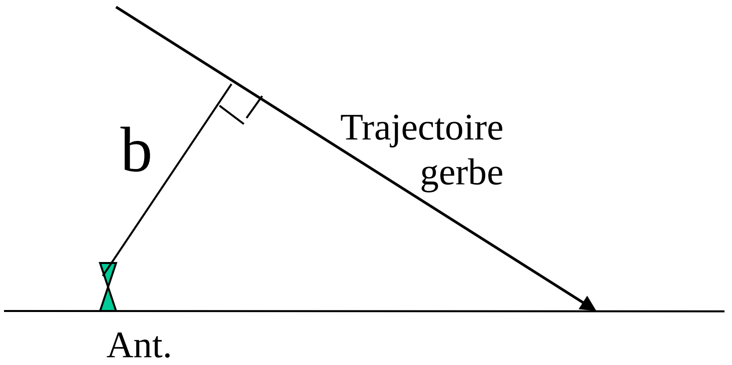
=> Since 2009 great unification of the theoritical results but... field extend & frequency spectra not yet in full agrement with experimental results

Results of the modelisations

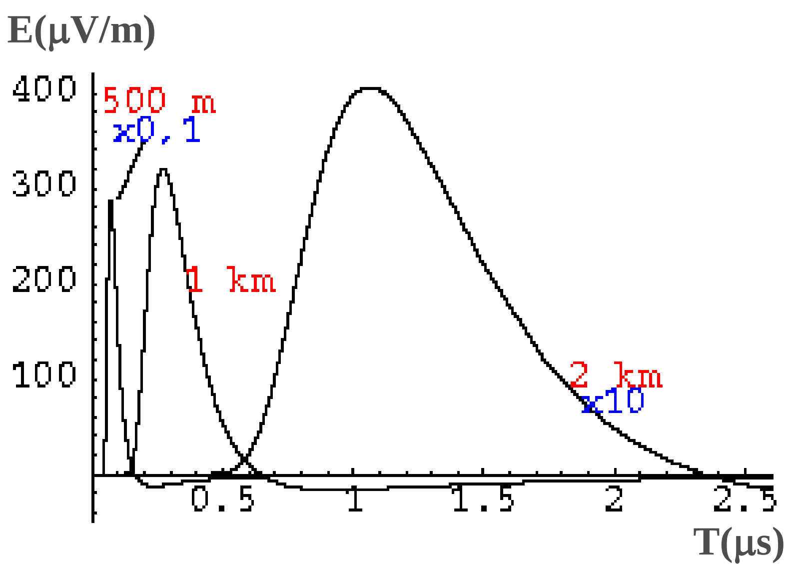


Démarche expérimentale de CODALEMA en 2001

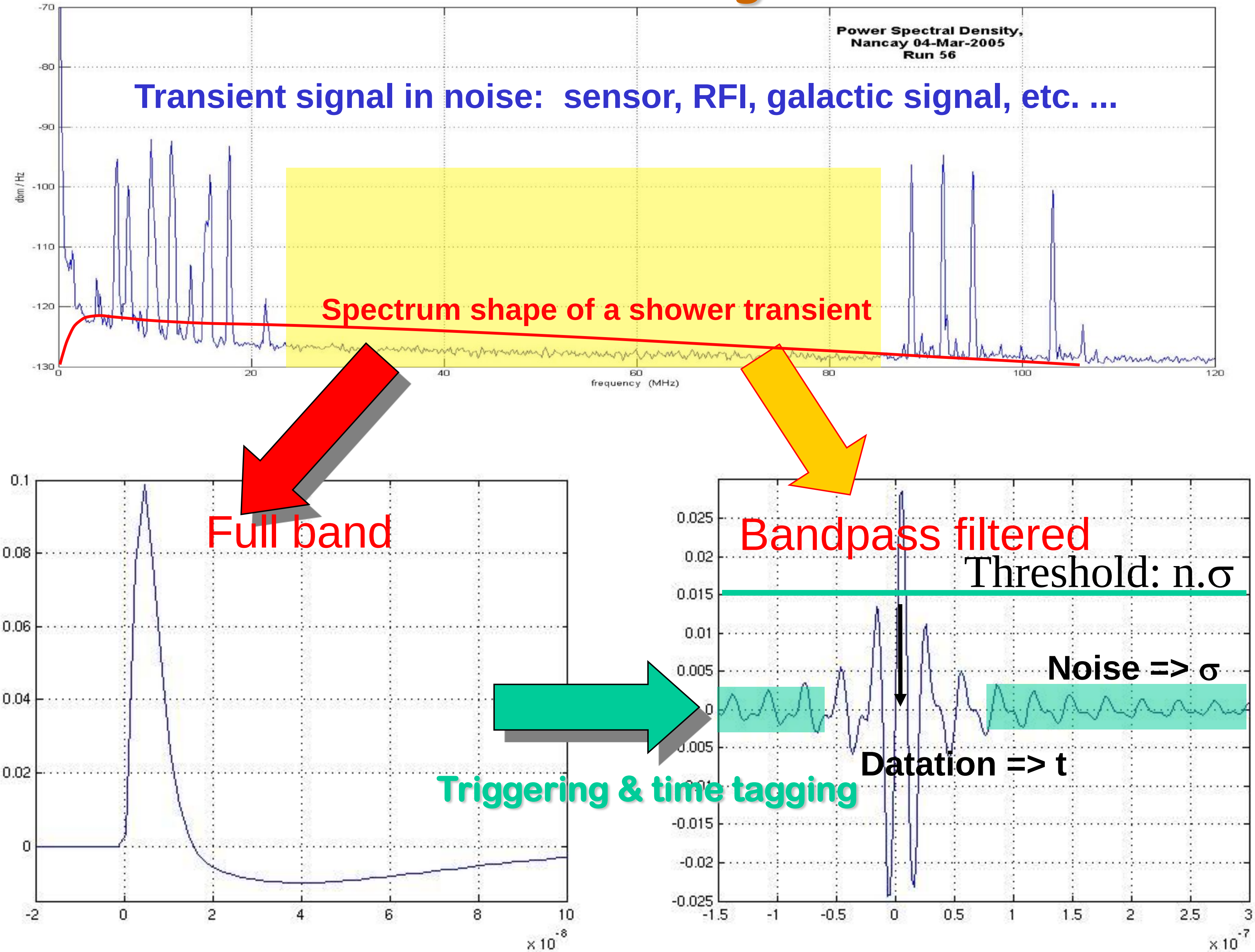
- **Simulation théorique:** Informations contenues dans la forme du signal
  - Amplitude (>1μV/m) => énergie
  - Durée (~100 ns) => paramètre d'impact (b)
  - Forme d'onde => nature des particules



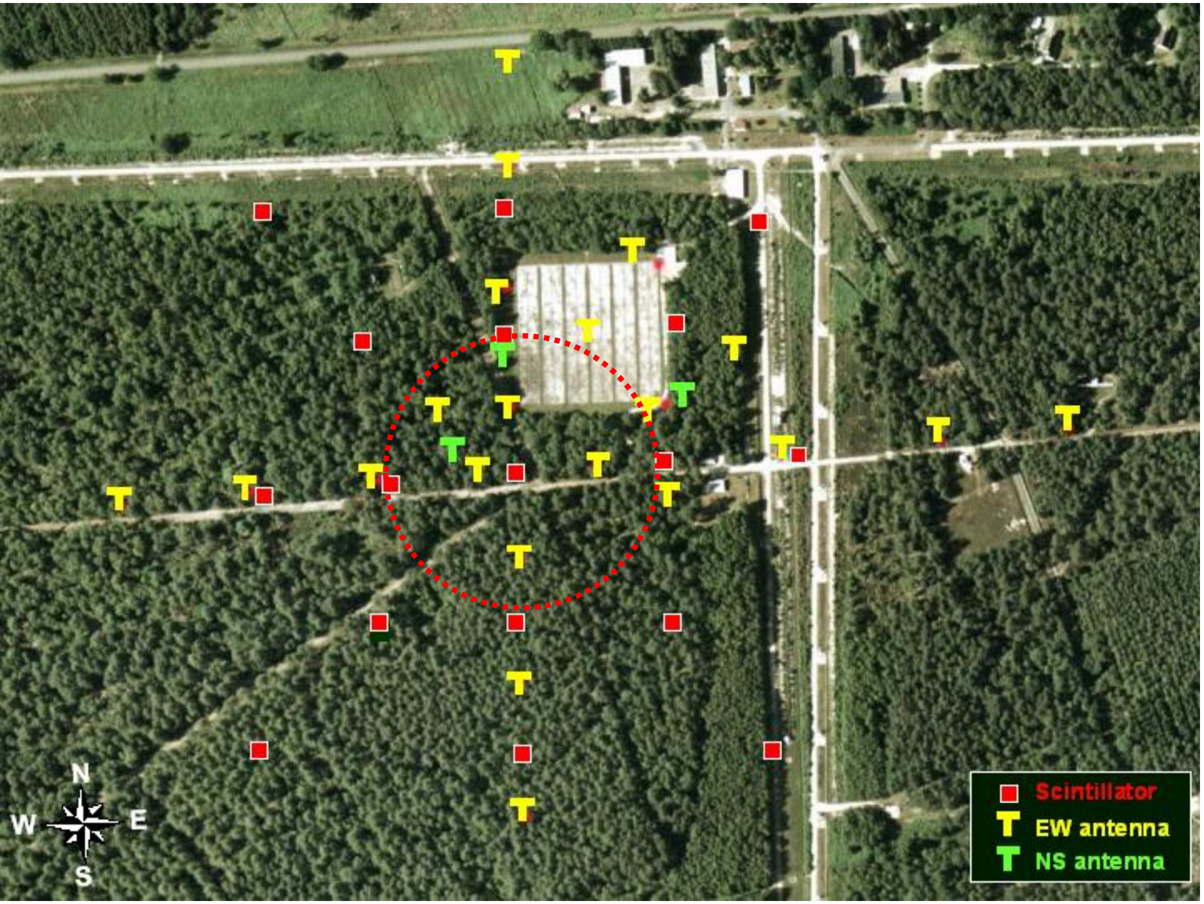
- **Mesures expérimentales:**
  - Evts rares (trigger~10^{-3} Hz)
  - Analyse temporelle du signal=>direction d'arrivé
  - Analyse de l'amplitude =>Extraction de l'énergie du primaire



Transient recognition



CODALEMA experimental setup in 2009



Radio arrays

-24 dipole antennas
cross: 600 m x 500 m
21 ant. in E-W polarization
3 ant. in N-S polarization

-DAM
18 blocs of 8 phased log-spiral antennas
Operating in transient mode

12 bits ADC
@ 1 GSample/s

Particle array

17 scintillator stations square 350 m x 350 m

Trigger : the 5 central particle stations

Internal Showers : Higher Signal in central stations

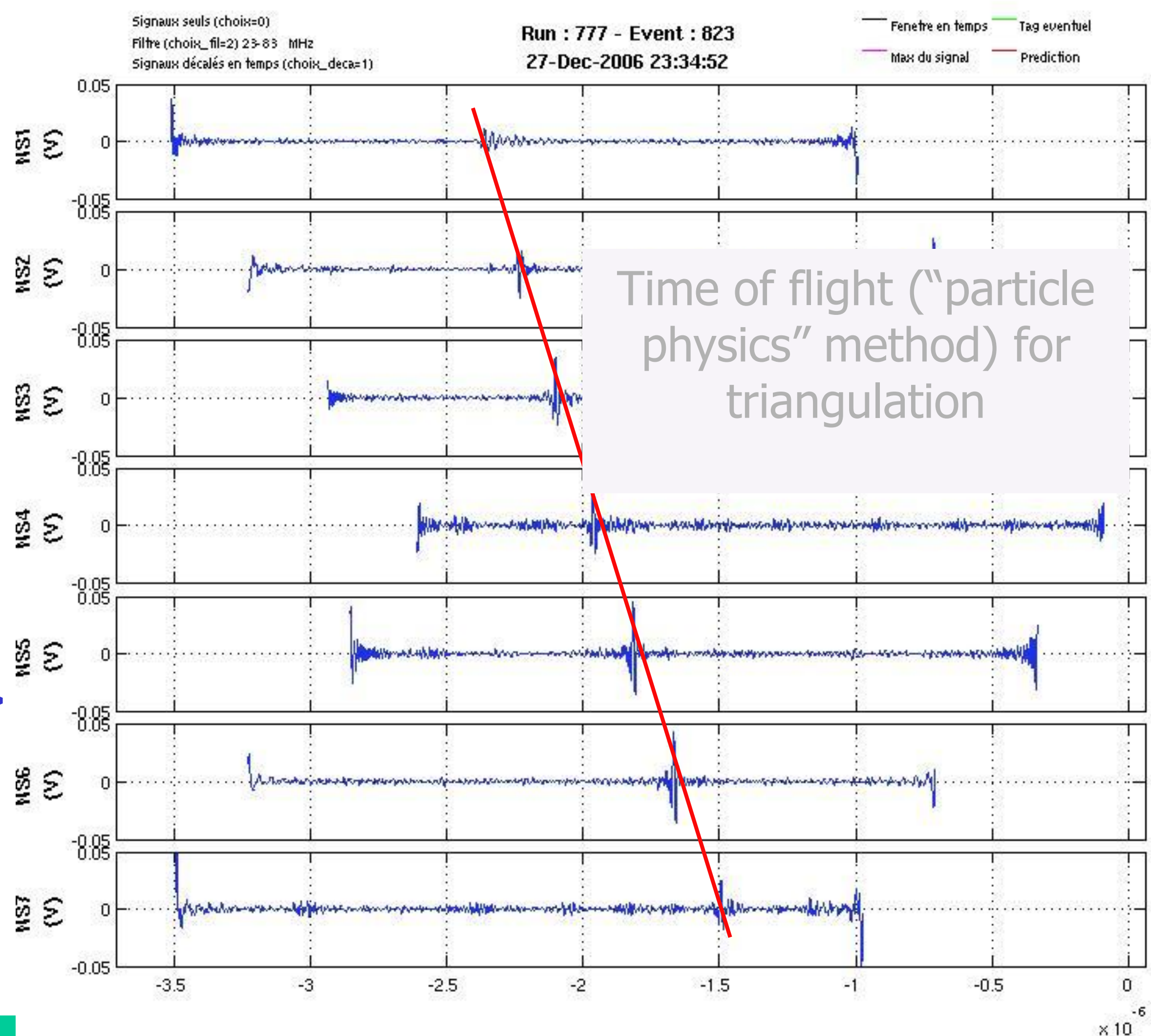
Core Position + Direction + Energy (via CIC method)

CODALEMA illustrative example

Wide bandwidth recording (here 1-250 MHz)

Narrow band filtering (here 23-83 MHz)

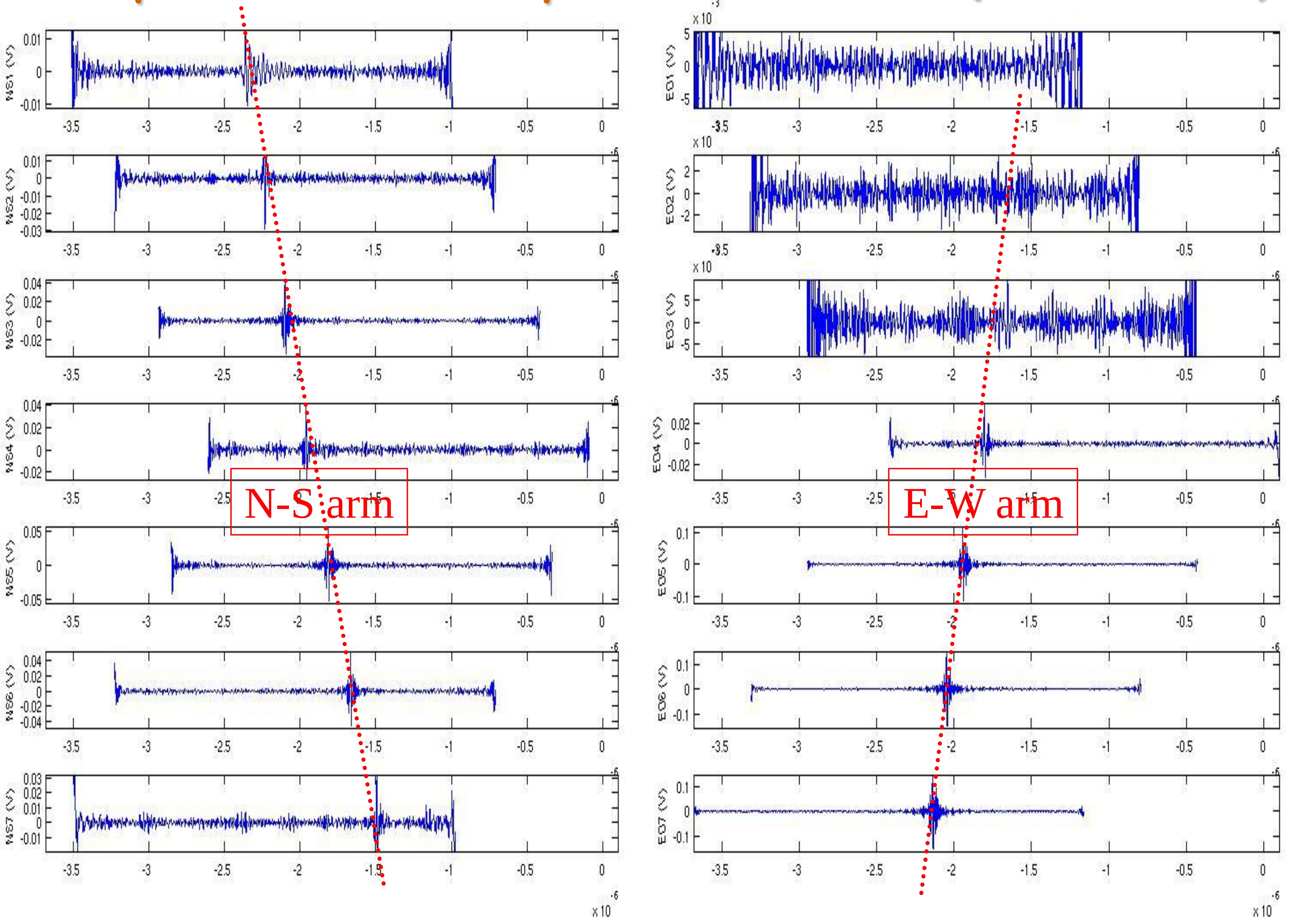
•Amplitude => Tagging
•Time => Direction
•Electric field profile => Core location, Energy



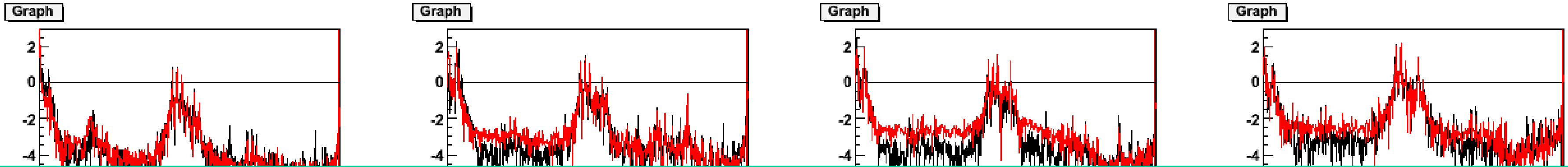
Ant. by Ant. analysis & Evt by Evt analysis

Correlations with particles

A dipôle event in E-W pol. @ E~$10^{17.5}$ eV (23-130 MHz)



Associated frequency spectra



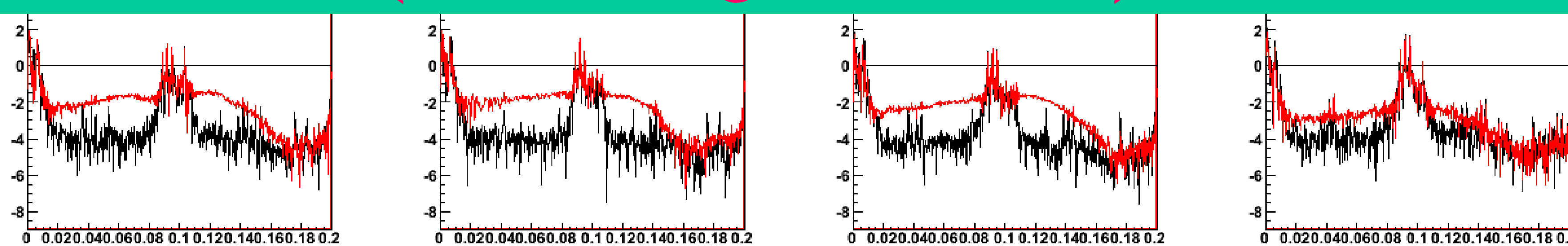
Various antennas (Log-Spiral, Dipoles) &Various electronics (LNA,VME or Scope ADC, Filters) tested…

=>The detection method is robust, the signal is firm: independent of the antenna and electronics

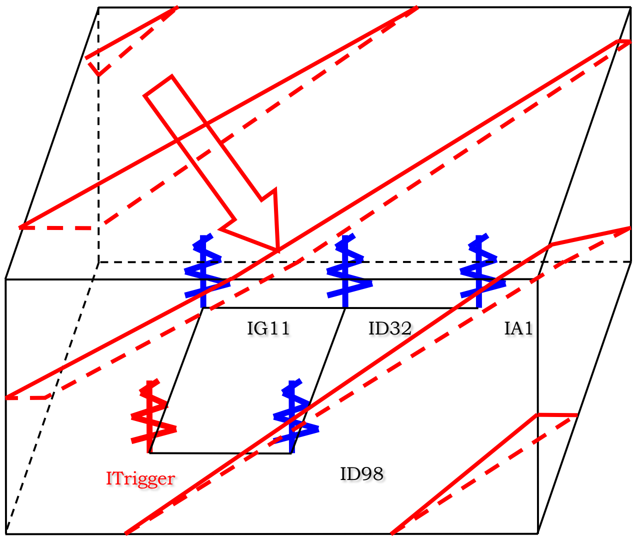
BUT:

Detection < 10 MHz not efficient enough @ Nançay (better @ PAO)

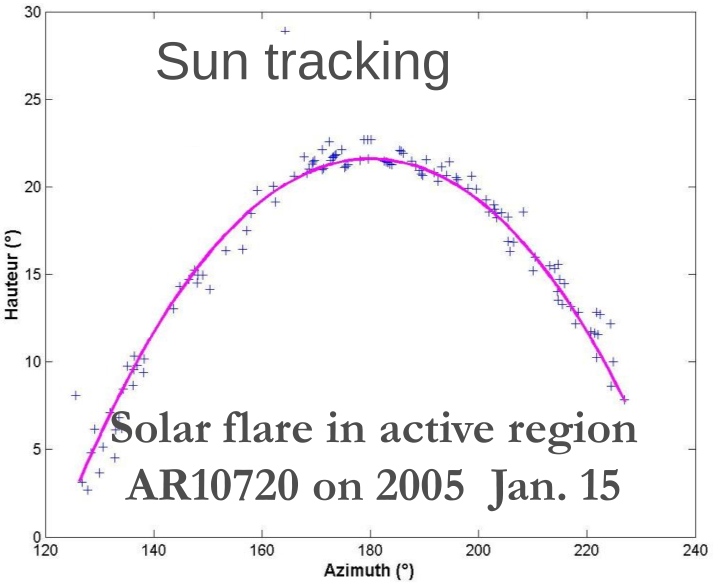
Detection > 100 MHz : Intermittent transmiters make the detection random @ Nançay (but efficient @ RF clean sites)

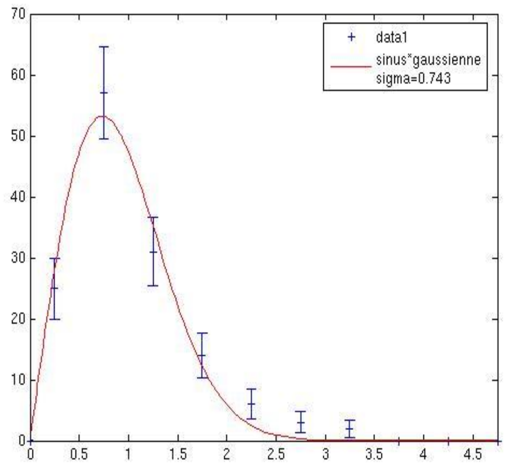


Triangulation performances
(using Solar bursts)



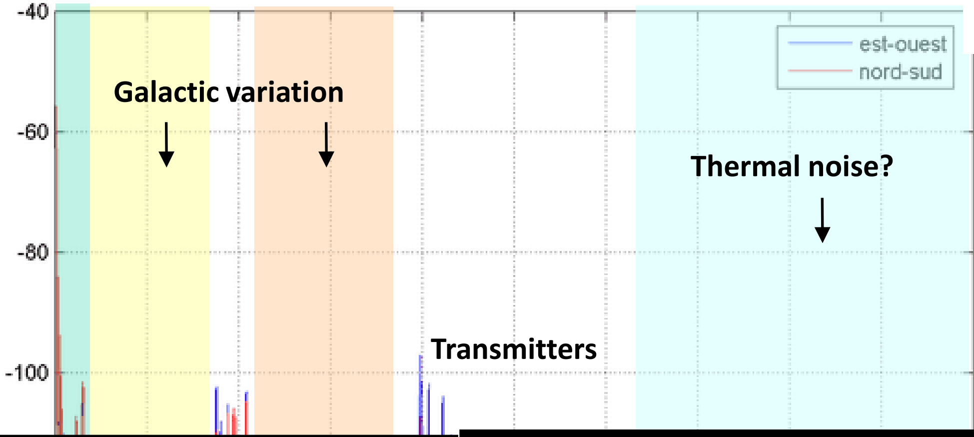
•Assume plane front waves
• Use arrival times of the transient



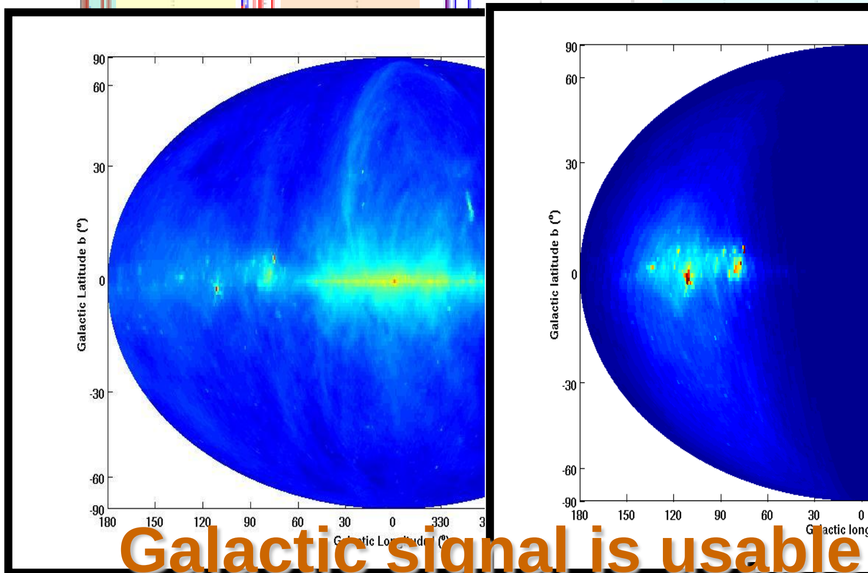


=> Angular Resolution Residues σ= 0.74 °
(level arm of 200m and 4 antennas)

Field calibration method
(using Galactic emission)

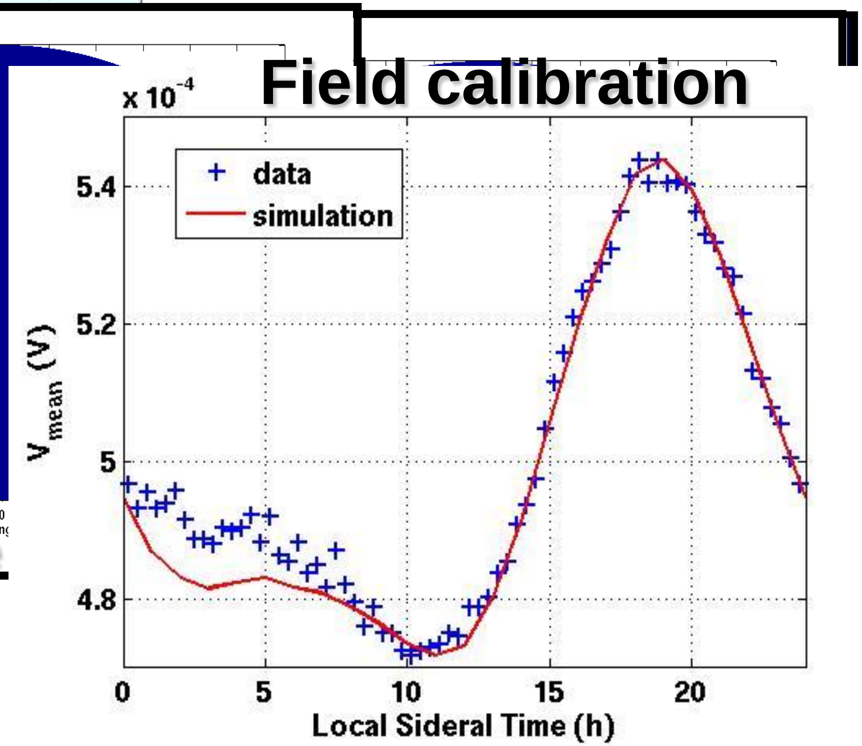


Exposure recurrence: 23h56

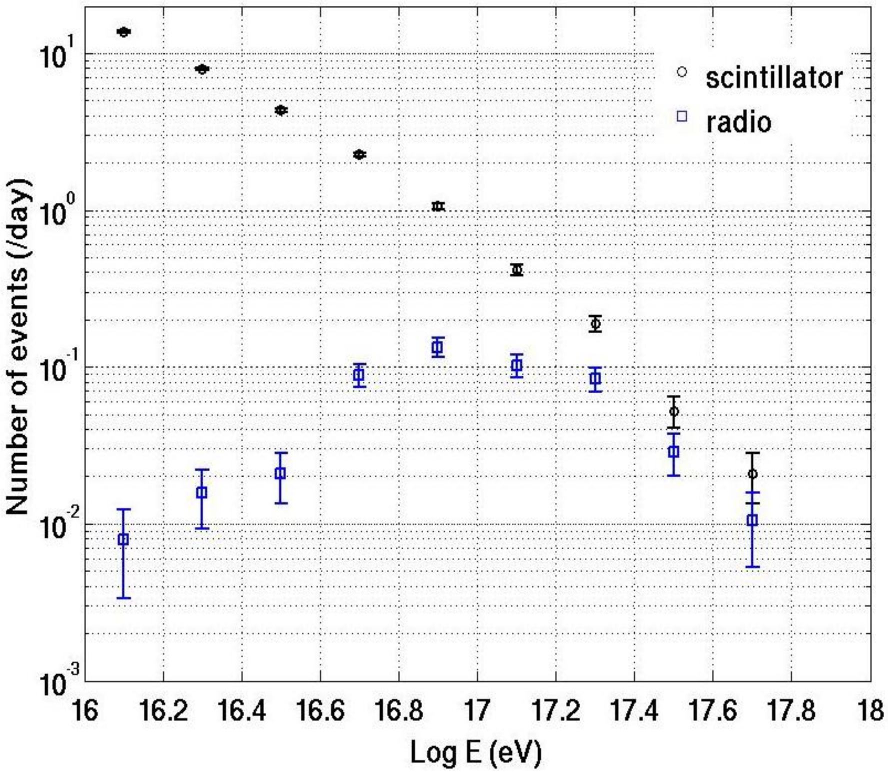


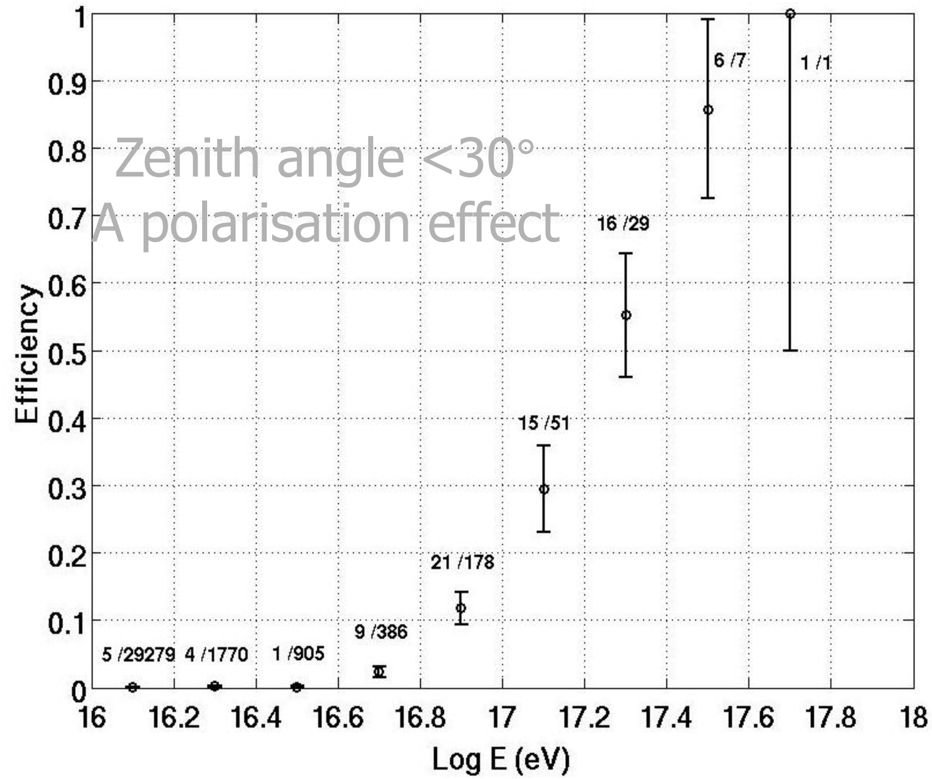
Galactic signal is usable

Field calibration



Radio detection efficiency

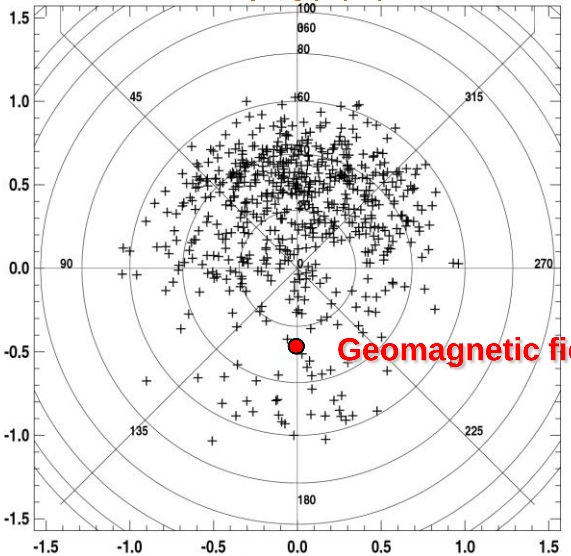




Full efficiency reached @10^{18} eV with E-W polarization
Expected improvements using the detection of the full states of polarisation ?

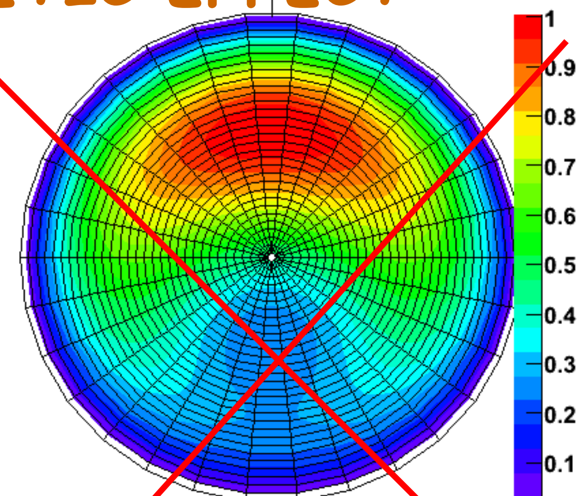
Is there a lack of efficiency ? ⇒ sky coverage due to antenna lobe effects ? etc.

Emission Mecanism



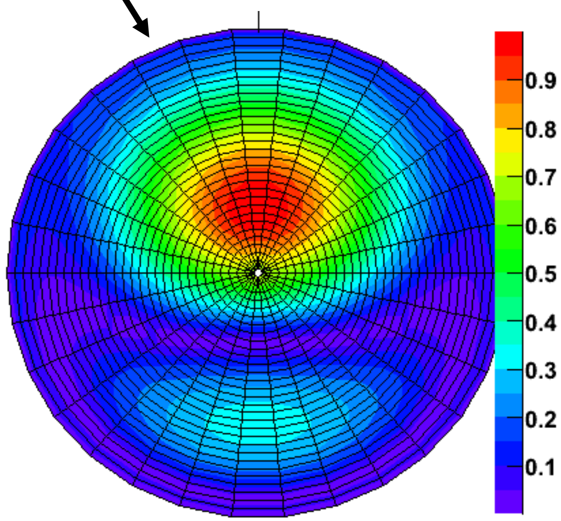
=>Detection at threshold correlated to arrival directions

=>GEOMAGNETIC EFFECT



LOPES interpretation

Nat. 2007

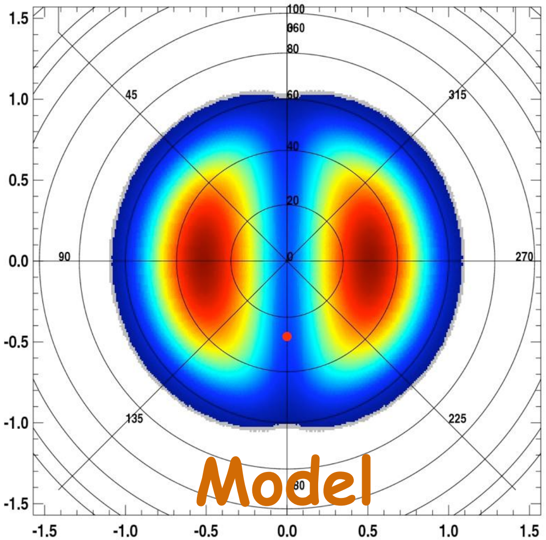


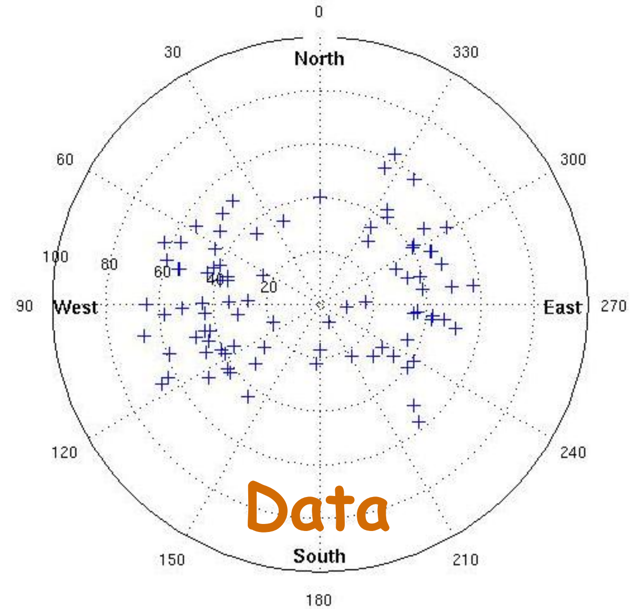
CODALEMA toy-model & AIRES calculations

Astro.Part. Phys. 2009

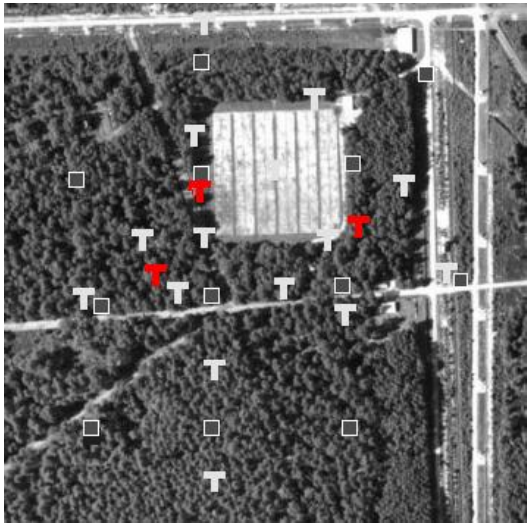
$$=> E \sim |VxB|_{E-W}$$

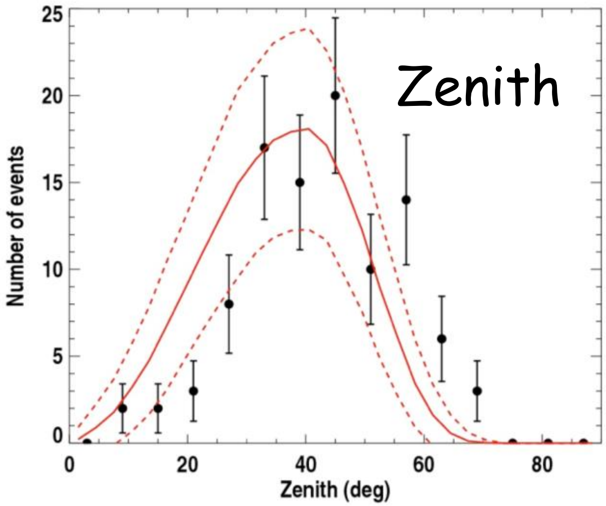
Is the vxB model valid for the N-S polarization ?

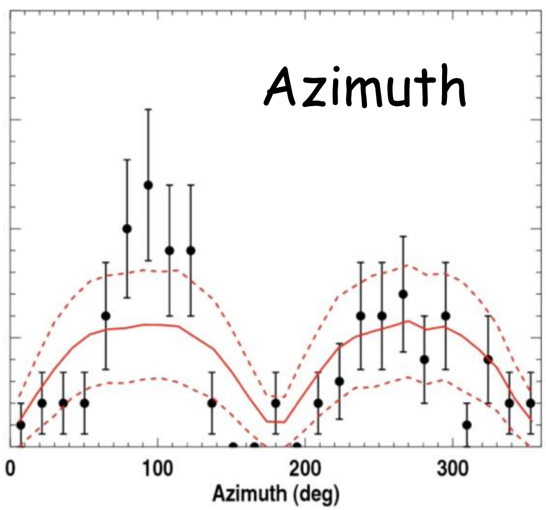




3 N-S antenna in the array





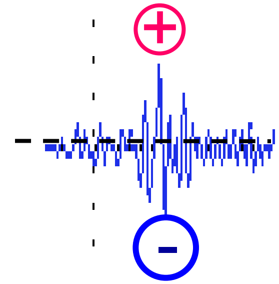


The statistic is lower but at the first look :
YES

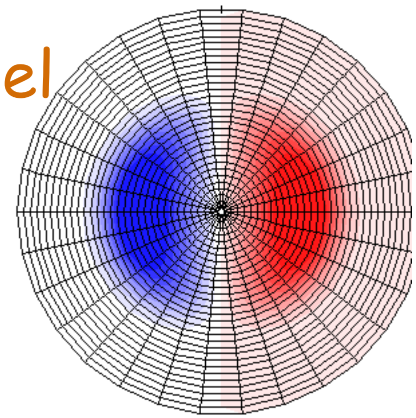
Is that the model reflects the polarity of the pulse ?

-The filtered Signal keeps the polarity of the full band signal

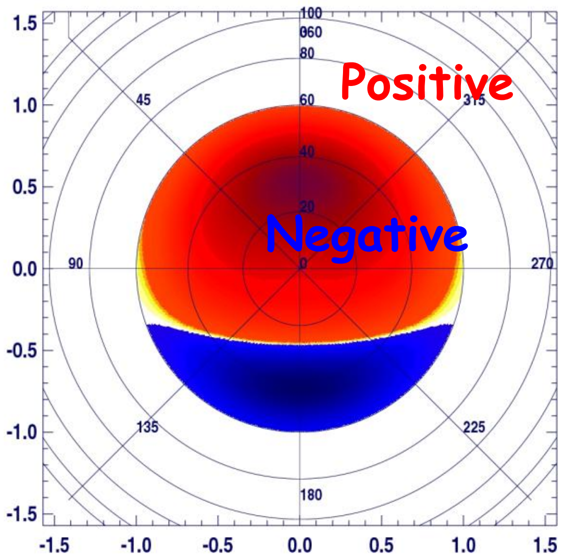
-The sign of the event is given by the sum of the polarities



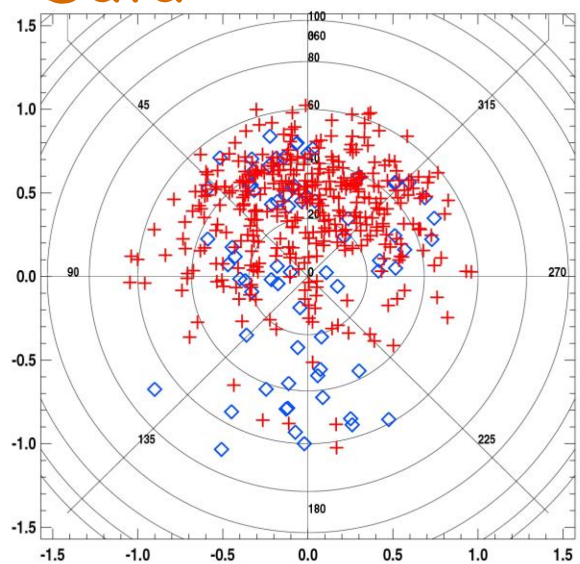
Model



Model

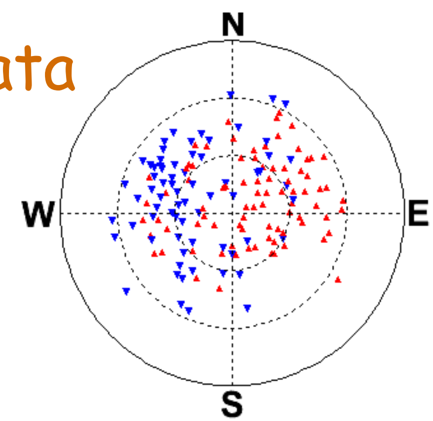


Data



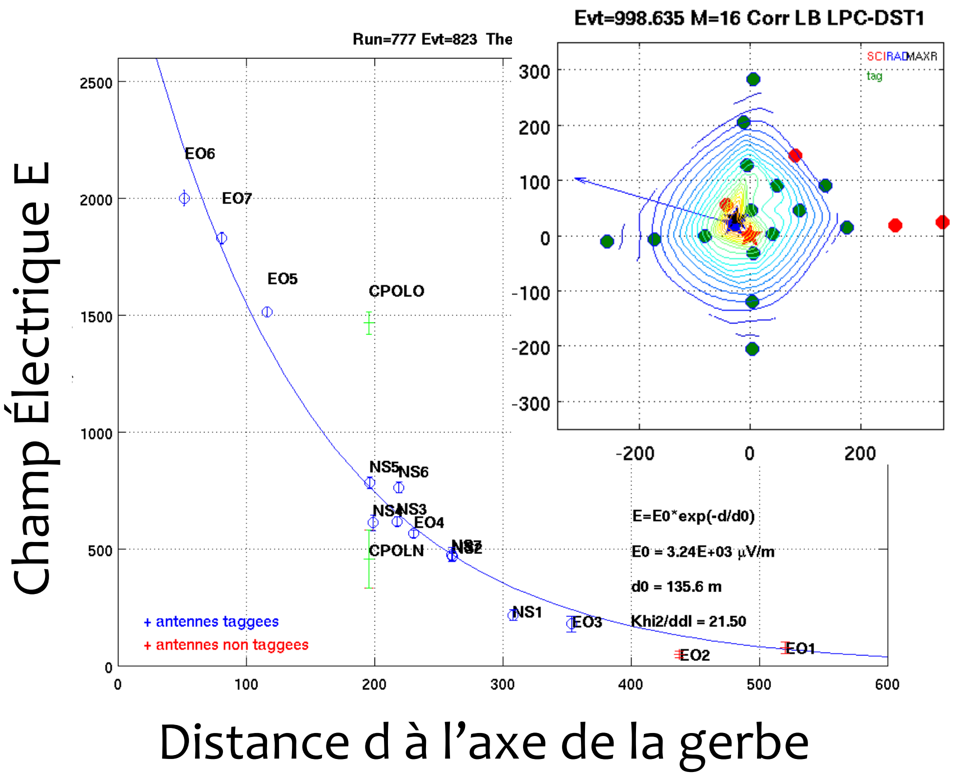
E-W polarization

Data



N-S polarization

Energy calibration (Preliminary)

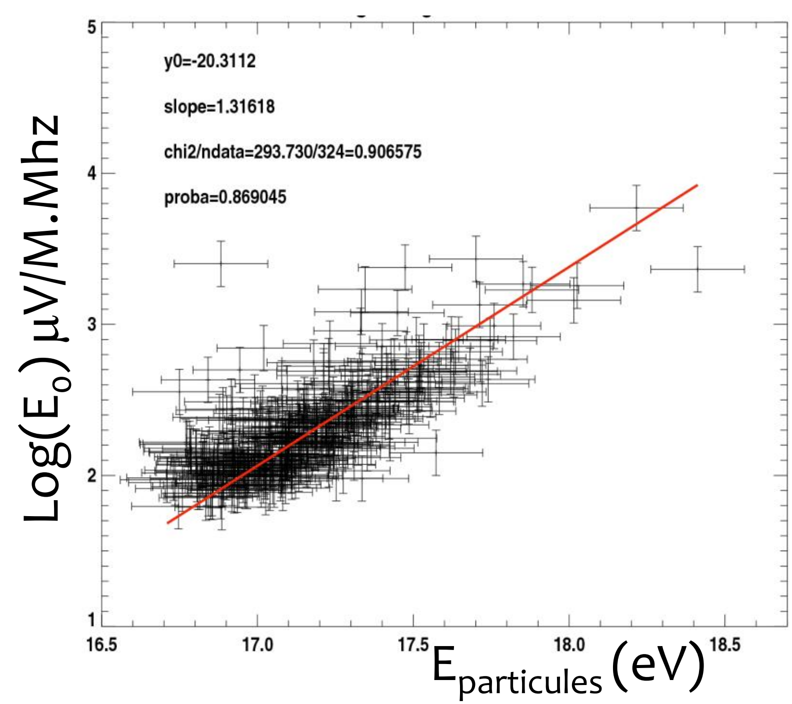


Interpretation of the profile with the ALLAN formula:

$E = E_0.\exp(-d/d_0)$

=> Allows to deduce E_0 after fit

=> Try E_0 as energy estimator for radio

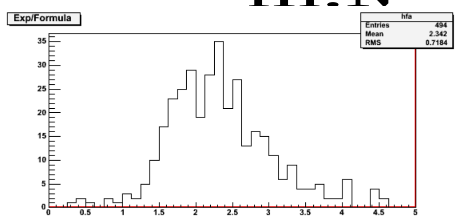


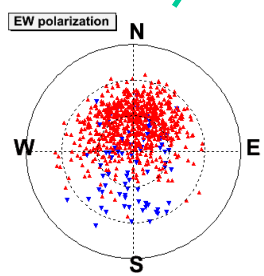
With σ_{Part} ~ 30 % => σ_{Radio} ~ 15 %
(LOPES ICRC 2007: 27 %)

=> Expected improvements using E-W + N-S detection

From CODALEMA results to simulations codes => overall parameterization

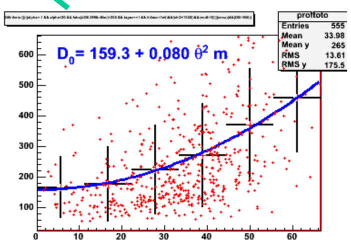
$E_0 = 23 \frac{\mu V}{m.M}$





$F(\theta) = \cos$

for 'historical' reasons. Need statistics @ high zenith angle to refine.



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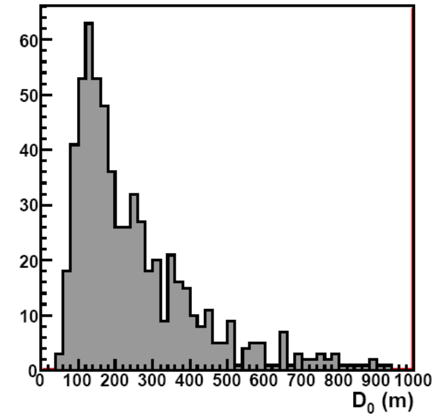
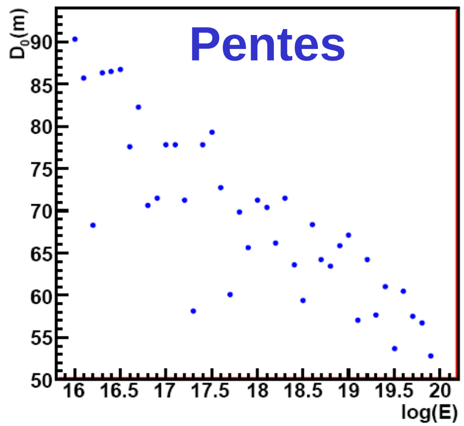
⇒Applied to radio-detection networks (CODALEMA, AERA…)

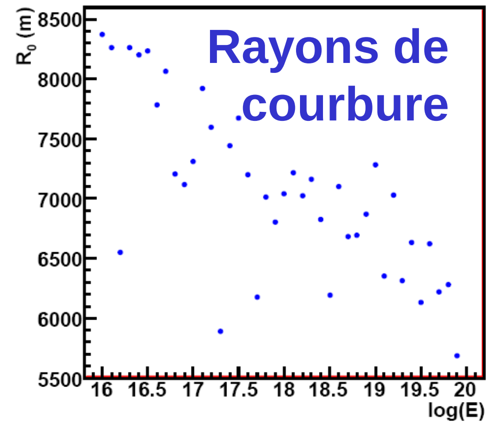
Effects of array pitch, shape, magnetic field, altitude, detection threshold, acceptance, multiplicity, bandwidth, polarisation…

Corrélations des observables: un pulse à résoudre....

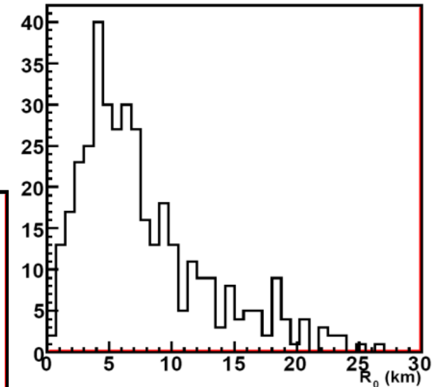


Comprendre la variabilités des profils

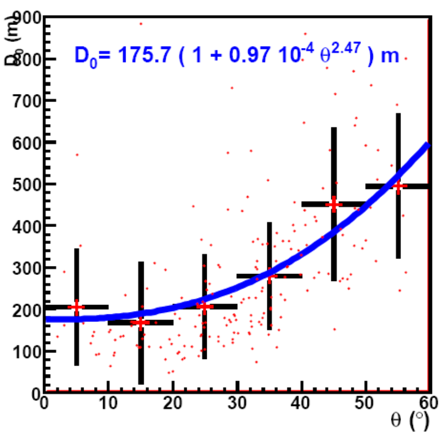




Simulations AIRES



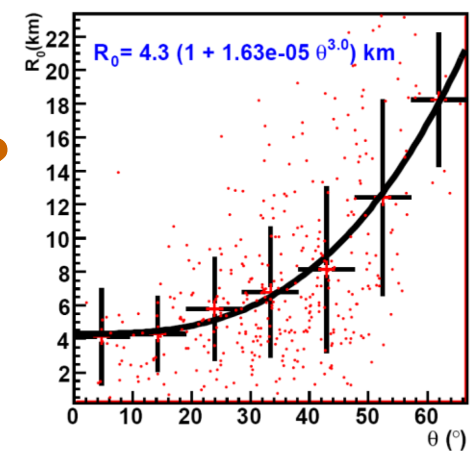
Comprendre la variabilité des courbures



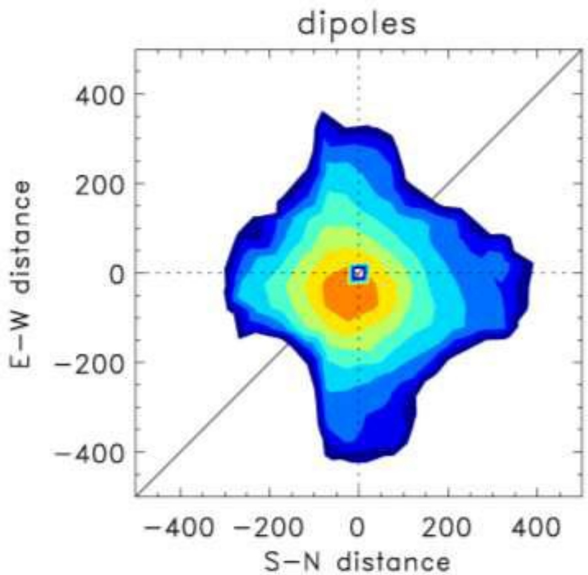
Effet du Xmax ?

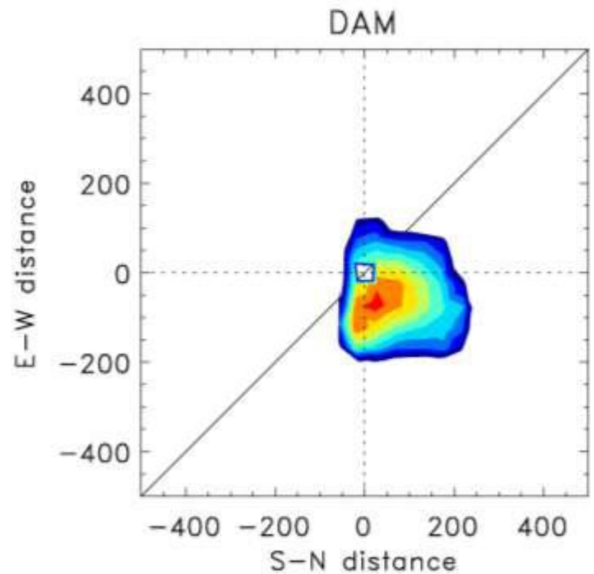
Altitude première Interaction ?

$\Rightarrow$Identification du primaire?

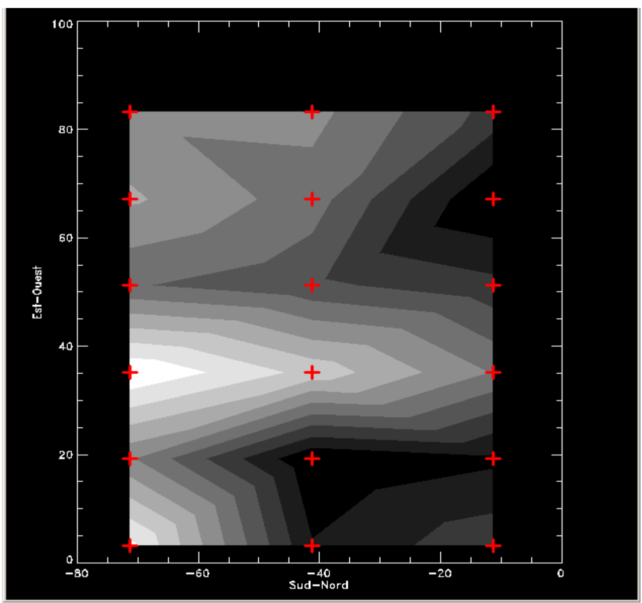


Interprétations des nouvelles observations



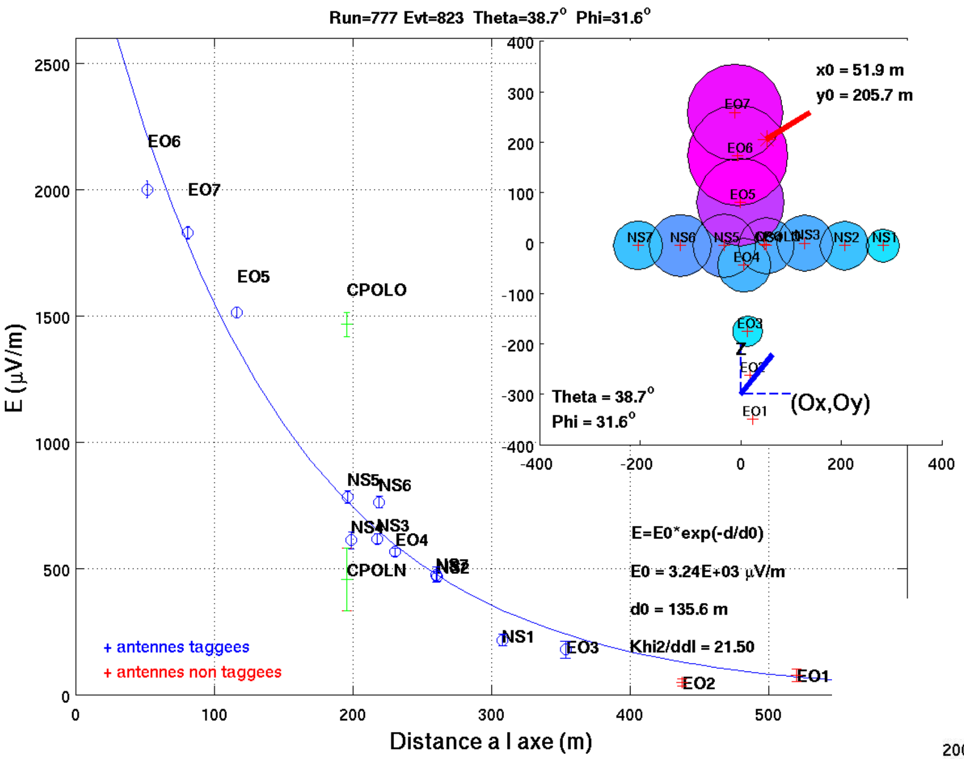


Décalage des pieds de gerbe radio vers l'Est ???



Topologie du champ électrique à courte distance ???

Comprendre la variabilité des profils

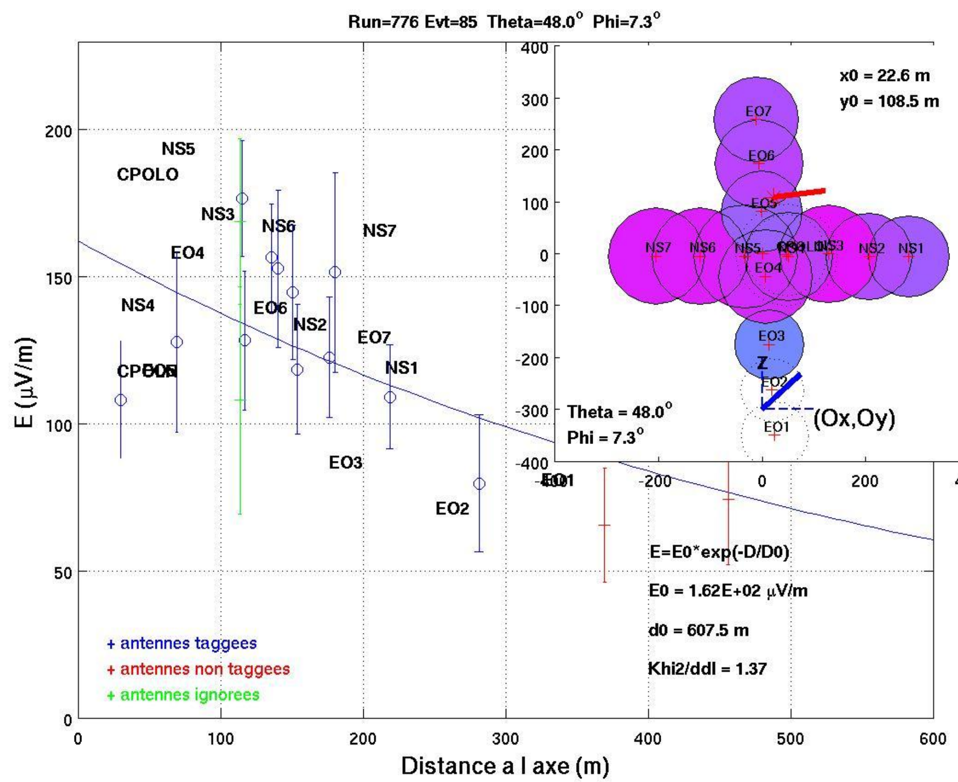


=>Profils exponentiels?

-Effets d'environnement?

=> Effets d'environnement faibles (thèse T.Garçon – déc. 2010)

-Effet du primaire?

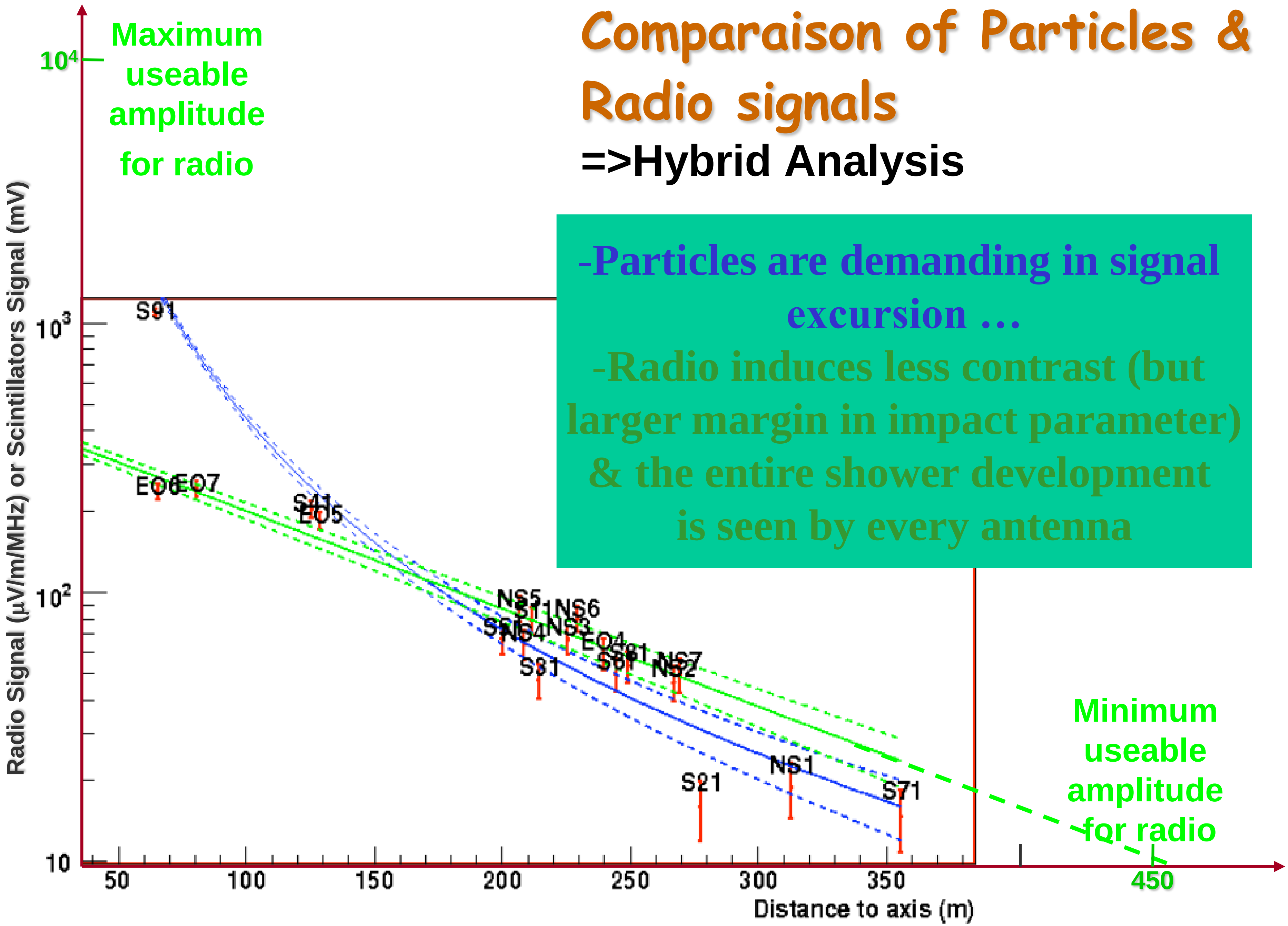


Comparaison of Particles & Radio signals

=>Hybrid Analysis

-Particles are demanding in signal excursion …

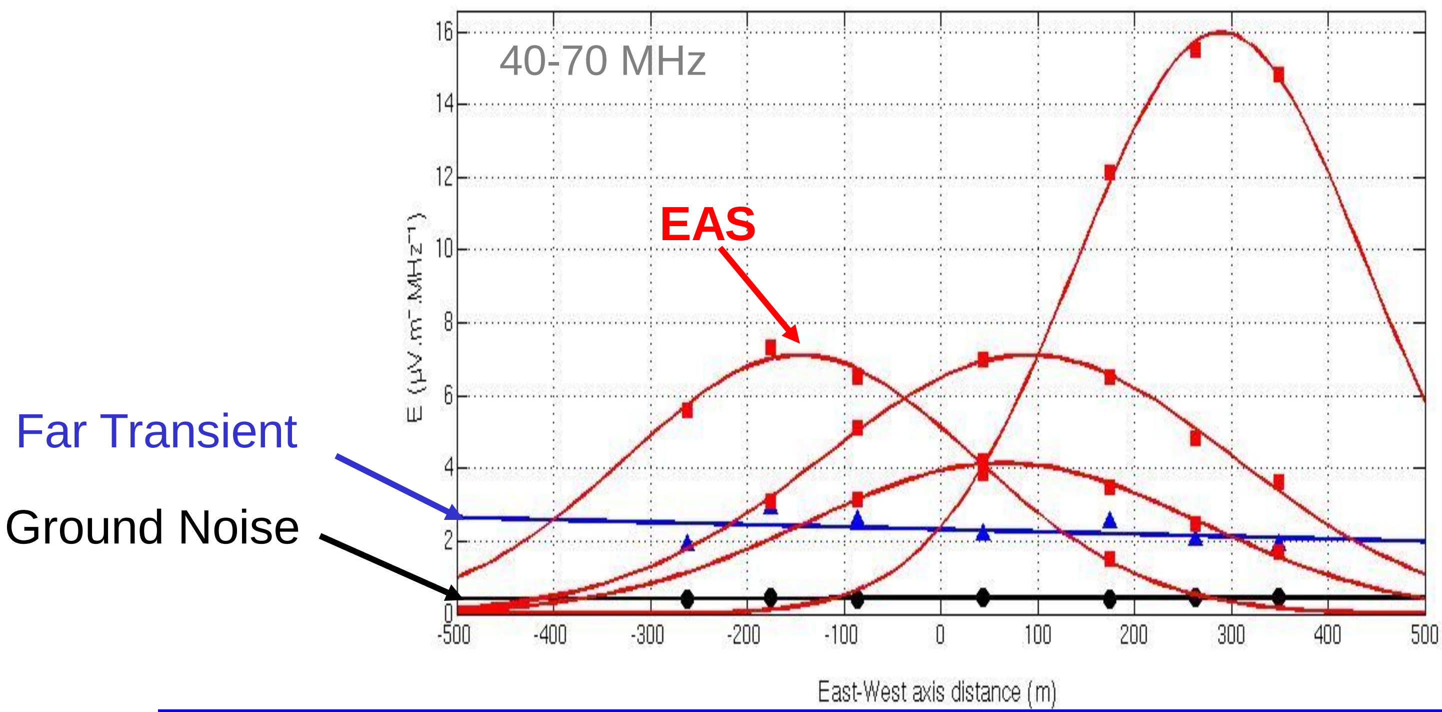
-Radio induces less contrast (but larger margin in impact parameter) & the entire shower development is seen by every antenna



Electric Field topologies

Variable antenna multiplicity (limited array)

The entire shower development is seen by every antenna

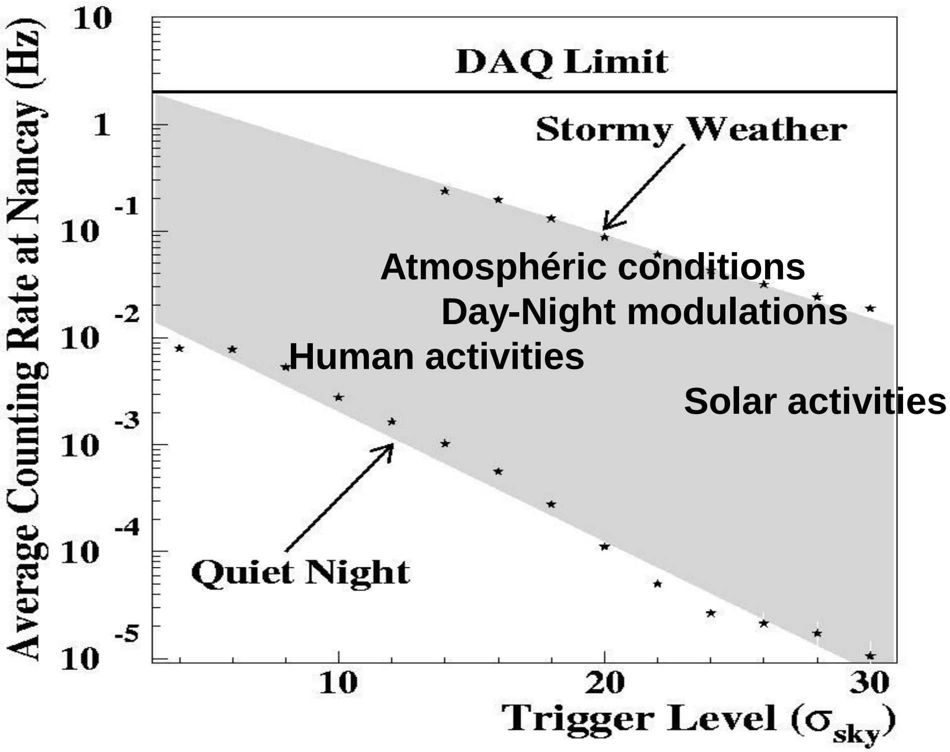


Free of particle ground density fluctuations

Field topology is a desive criterion of selection in stand alone mode

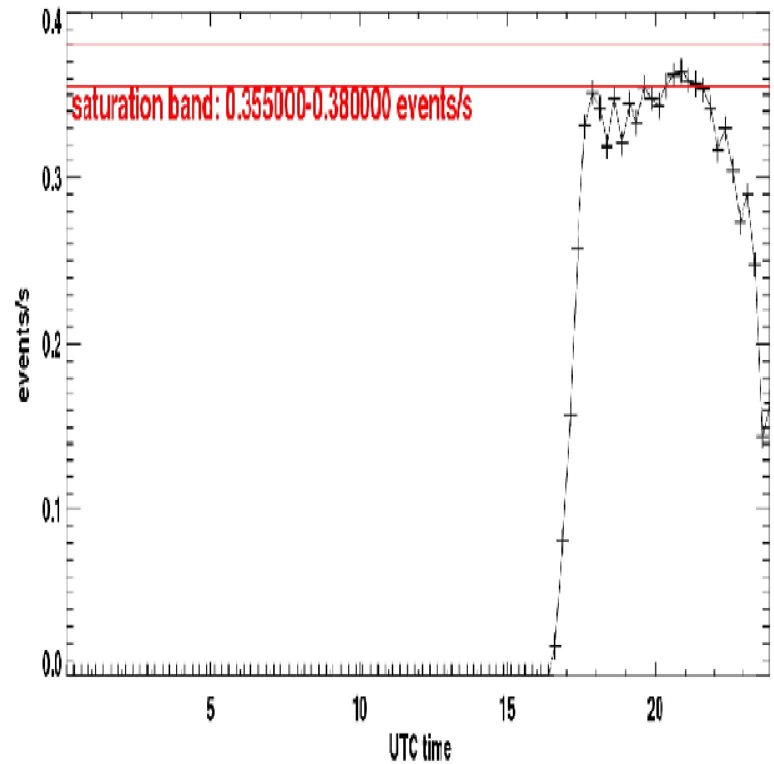
Trigger capability & Transient background

2004 : Trigger rate in 33-65 band with 1 antenna @ Nancay



=> Triggering with antenna is possible in stand alone mode

2006 : Trigger rate in 50-70 band with 1 antenna @ PAO



Trigger Rates depend of the site (& of the frequency band)…

Evolution of the sensor concepts from 2002 to 2009

Compacité

Sensibilité

Log-Spiral Antennas (2005)

Circular polarization

Diameter = 5m

Heigh = 6m

Active Short (2006) Fat Dipoles

length = 1.21m

height = 1m

Self-Contained Radio Station (2008)

Multi polarization

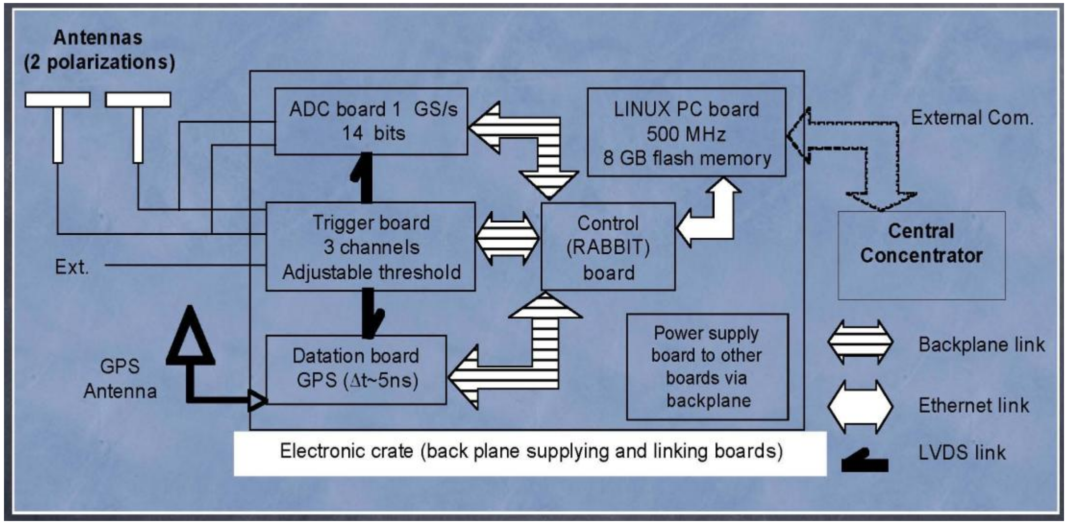
f_{middle} ~ 65 MHz

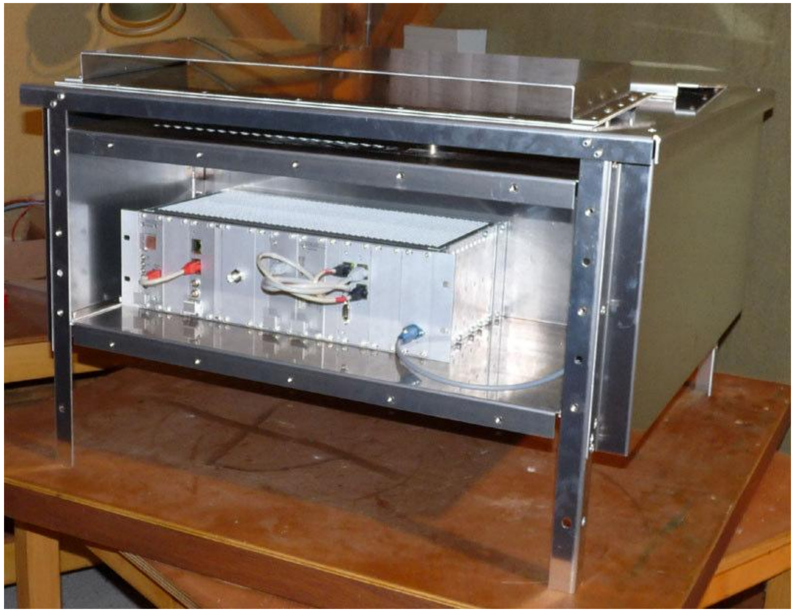
length = 3.22m

height = 1.40m

3KE/station

Electronics





- 2 polarization states

- GPS timing resolution: 2.5 ns
- Trigger: @ galactic threshold
- Acq. rate: 25 evt/s

+ Open solutions for
- Outer world: WiFi, GSM, 3G, Ethernet…
- Power: Solar, Wind, 220V…
- Consumption: 20 W

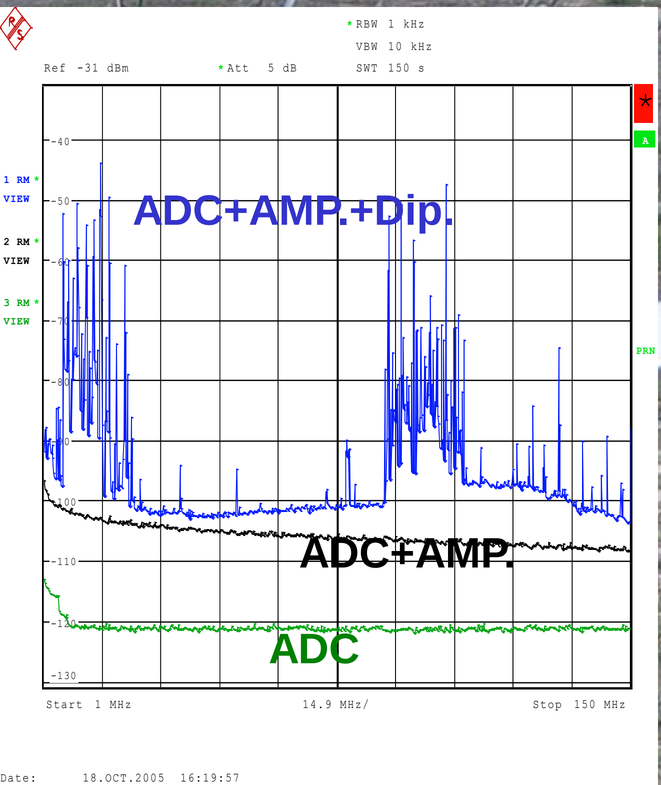
ADC+Alim.+ Backplane(LAL),
Trigger+crate+integ.+ant. (SUBATECH),
GPS(LAOB), Control(Nançay),
PC+COM.(commercial)

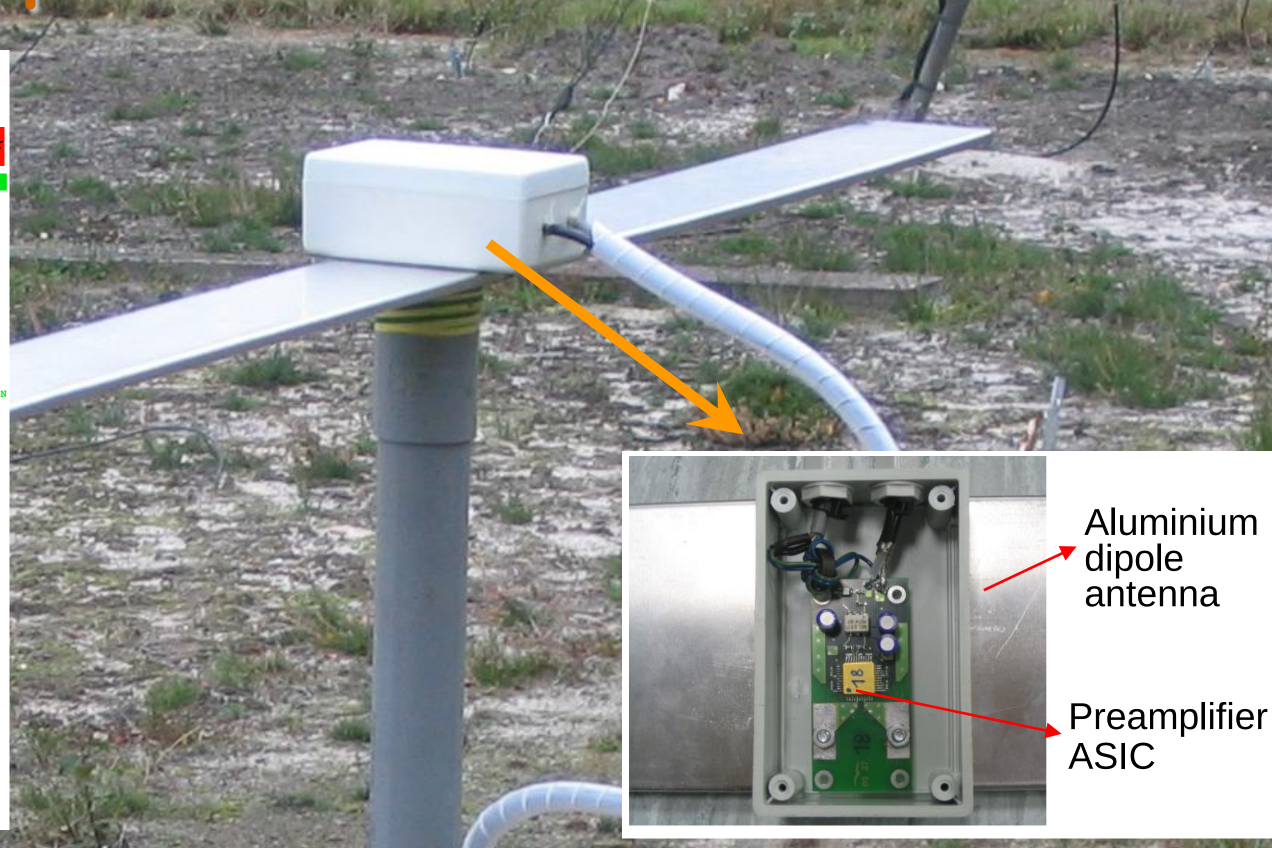
+ Enbedded mini-switch (housed in the inner box)

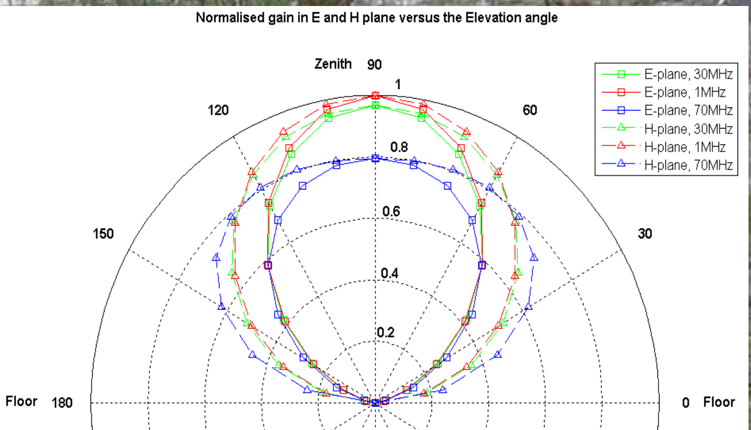
+ Enbedded transformer 220-12V (housed in the outer box)

for CODALEMA-Phase 3 @Nançay

Développements Antennes-LNA





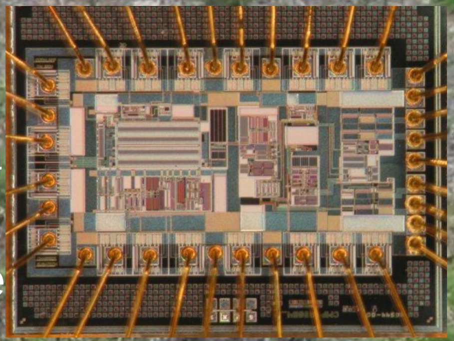


ASIC AMS BiCMOS 0.8 μ

Gain 48-55 dB, 0.8 nV.Hz$^{-1/2}$, 0-250 MHz

PCB associé + filtrage adapté à chaque site

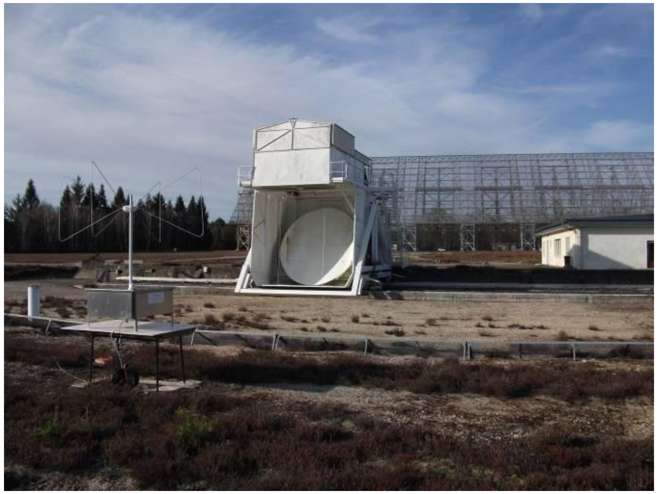
Réponse de la chaîne maîtrisée

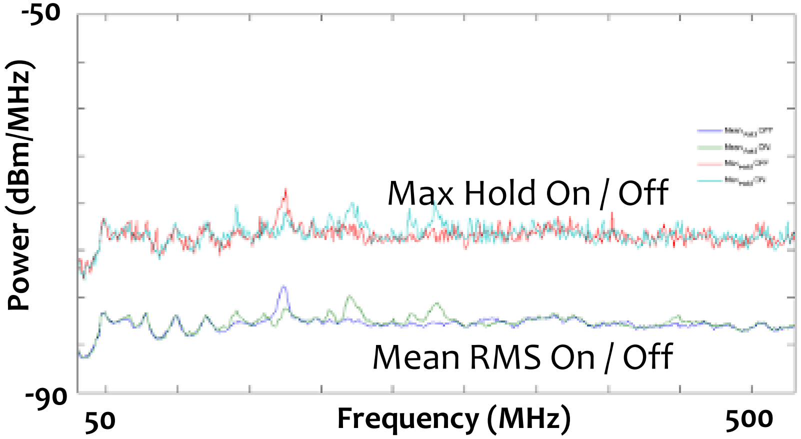


Electromagnetic compatibility (EMC)

Tests of noise produced by the autonomous station :
•Antennas @ 1 m of the electronic box (0.8 nV.Hz$^{-1/2}$)
•anechoic chamber, radioheliograph array and radiotelescope measurements







- No noise radiated between 10 MHz and 4 GHz
- No self-induced triggering

⇨ **Green light for installation @ Nançay**

The Radiodetection constellation in 2010

Depuis 2001
@Nançay & @FZK
CODALEMA & LOPES
UHECR ~10^{17} eV

2007@ARAGATS
LPTA Montpellier
$\gamma \leq 10^{16}$ eV + Detection in near field
3 ant.+ARAGATS
2006@RT Nançay
γ @ TeV

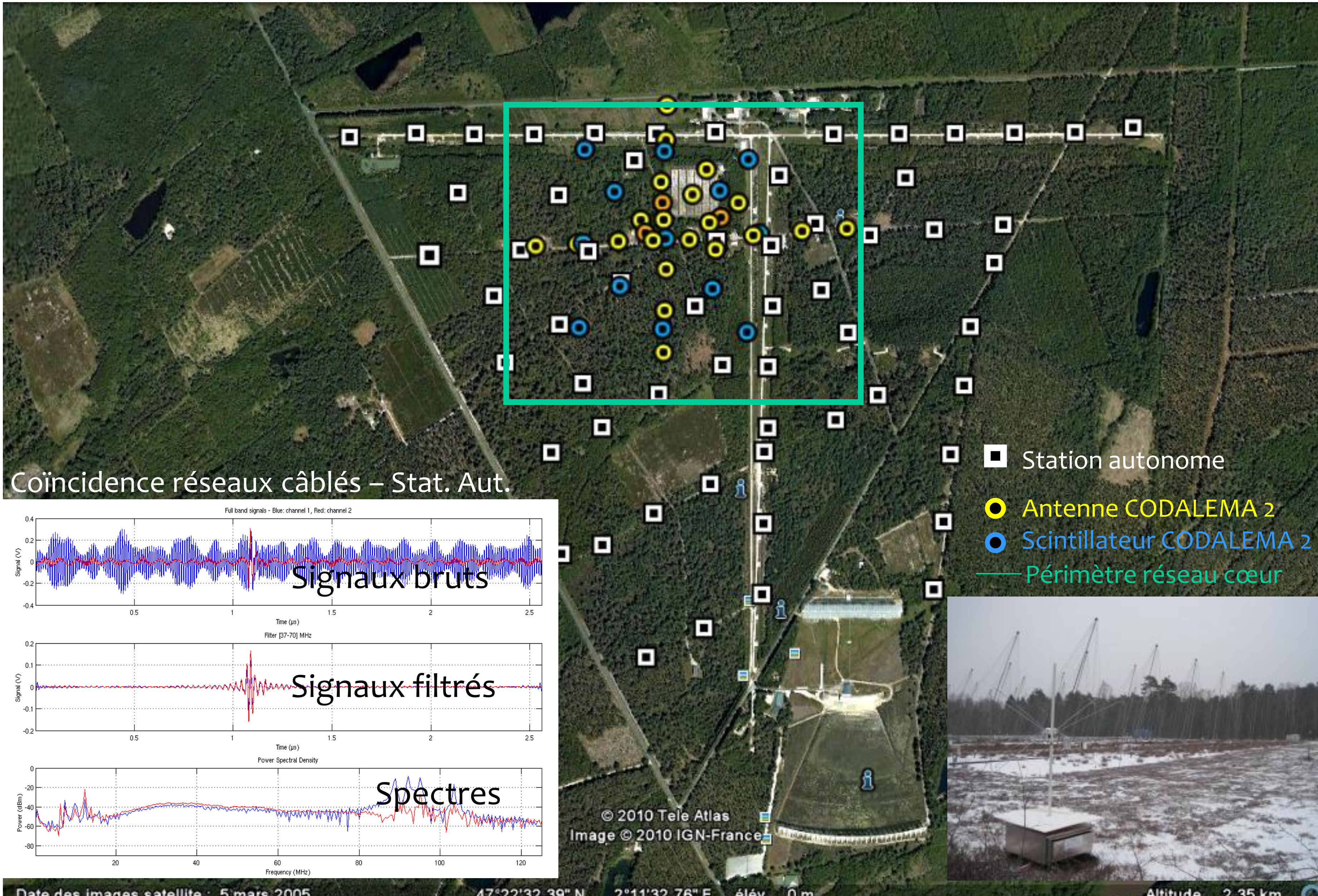
2006@AUGER
UHECR ~10^{18} eV
6 autonomous ant. + SD

2008@AUGER-AERA
UHECR ~10^{18} eV
20 km2 autonomous ant.

In 2008@21CMA-TREND
Horizontal EAS
ν_τ ~10^{17} eV
4 autonomous ant.

2009@AUGER
UHECR ~10^{18} eV
Free-Free emission in GHz
EASIER, MIDAS, AMBER

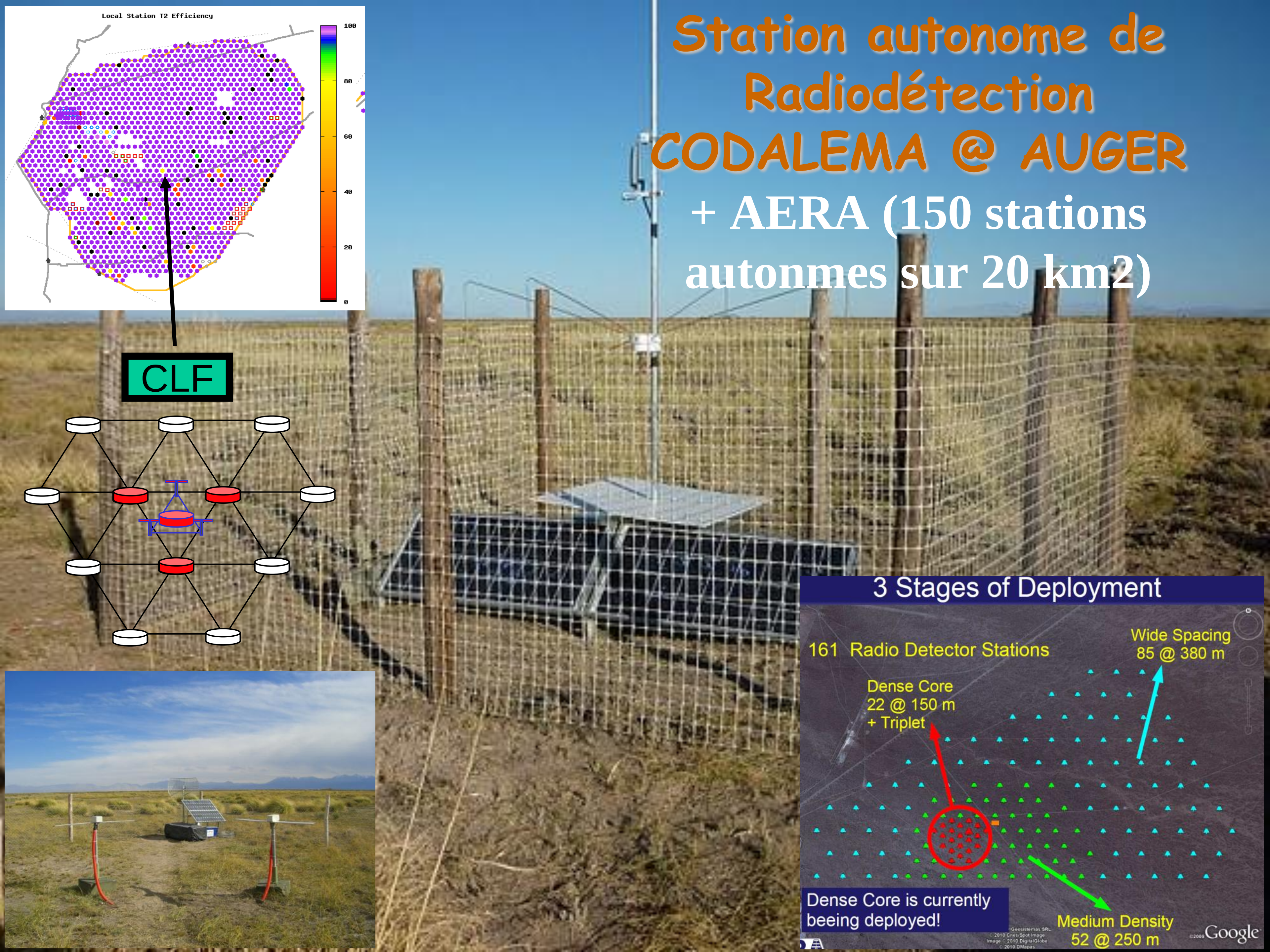
CODALEMA 3 : un réseau multi-échelle



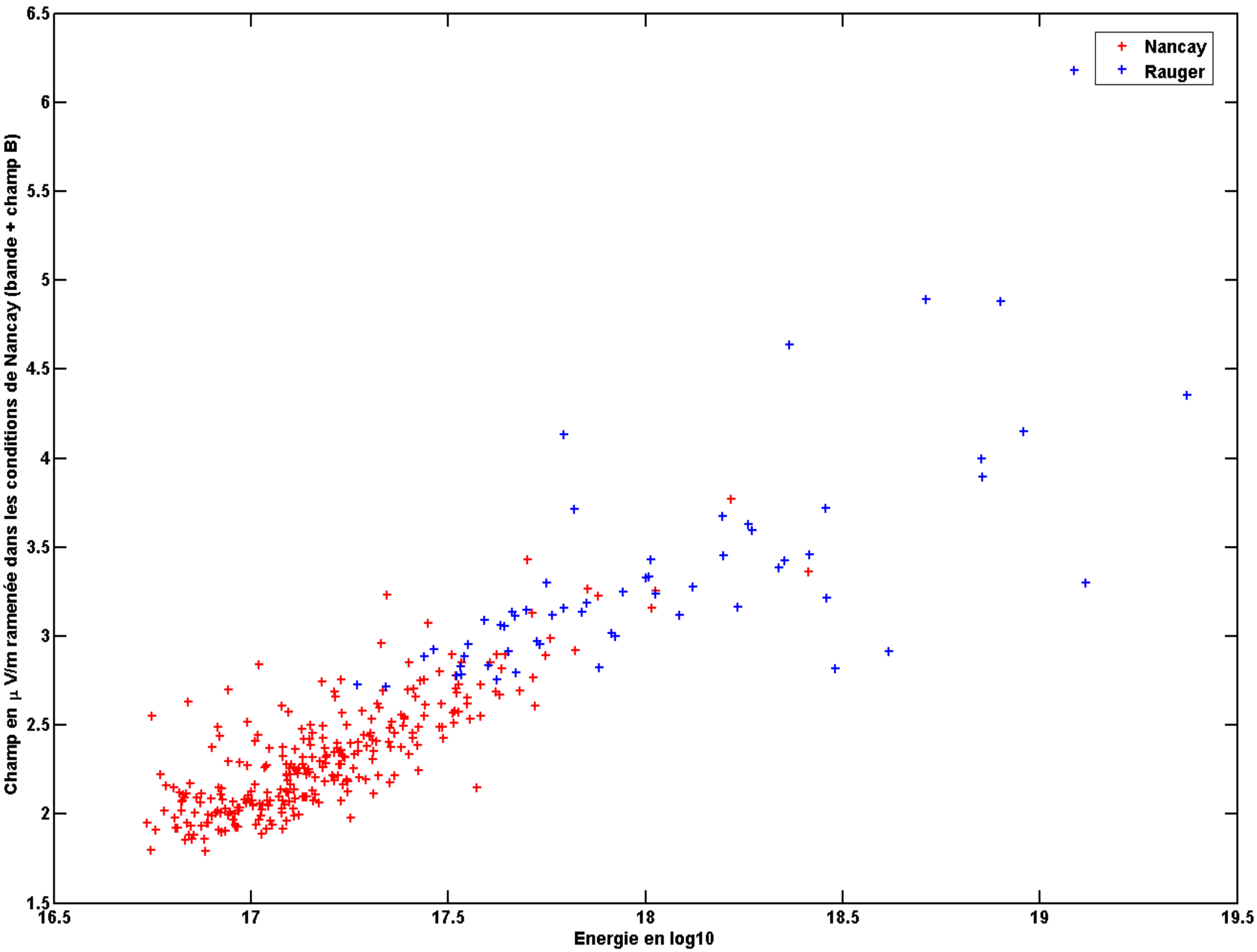
CODALEMA 3 (2011-2015) : de nouveaux instruments pour des analyses plus riches

- **Déclenchement impulsionnel pour le DAM**

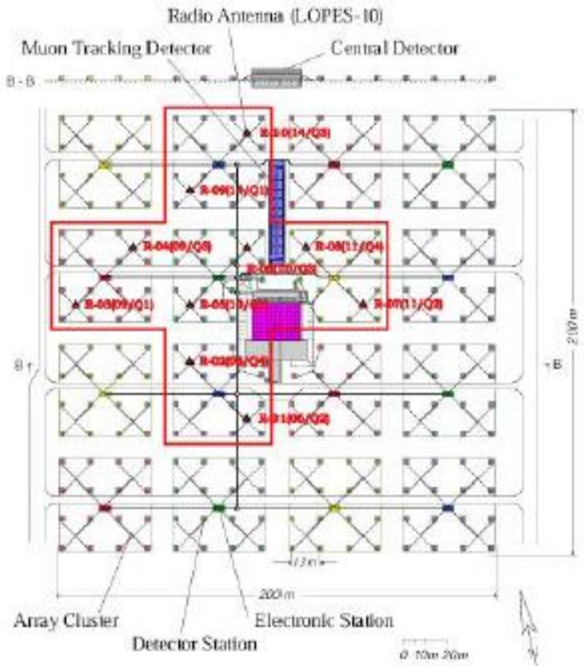
- **Expérience de radio détection en 3D (SUBATECH, LESIA-Nançay, CNET)**
  - Vol d'un ballon équipé d'une station autonome au dessus du réseau câblé CODALEMA.
  - Vers Novembre 2010 et en collaboration avec le CNES.
  - Mesure du champ électrique en 3D


Station autonome de Radiodétection CODALEMA @ AUGER
+ AERA (150 stations autonmes sur 20 km2)
Local Station T2 Efficiency
100
80
60
40
20
0
CLF
3 Stages of Deployment
161 Radio Detector Stations
Wide Spacing
85 @ 380 m
Dense Core
22 @ 150 m
+ Triplet
Dense Core is currently beeing deployed!
Medium Density
52 @ 250 m
Google

Un atout pour l'étalonnage en énergie ...



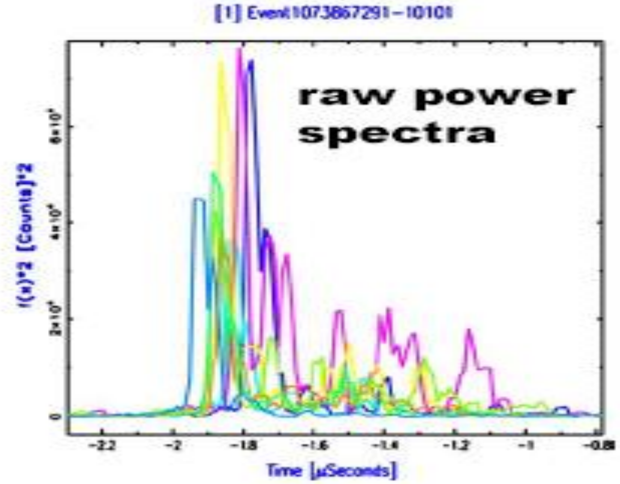
LOPES



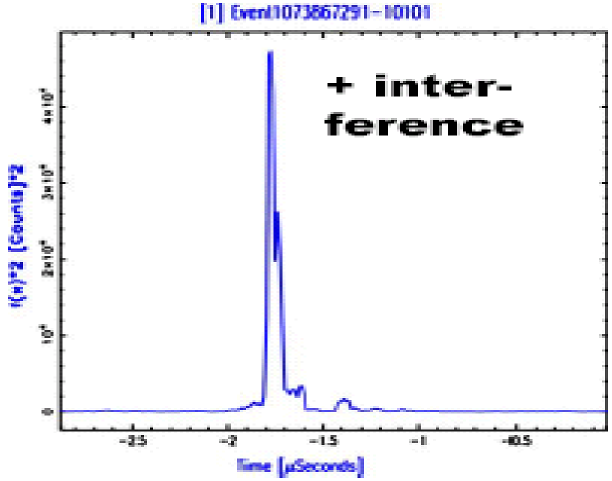
10 LOFAR antennas

Trigger KASCADE

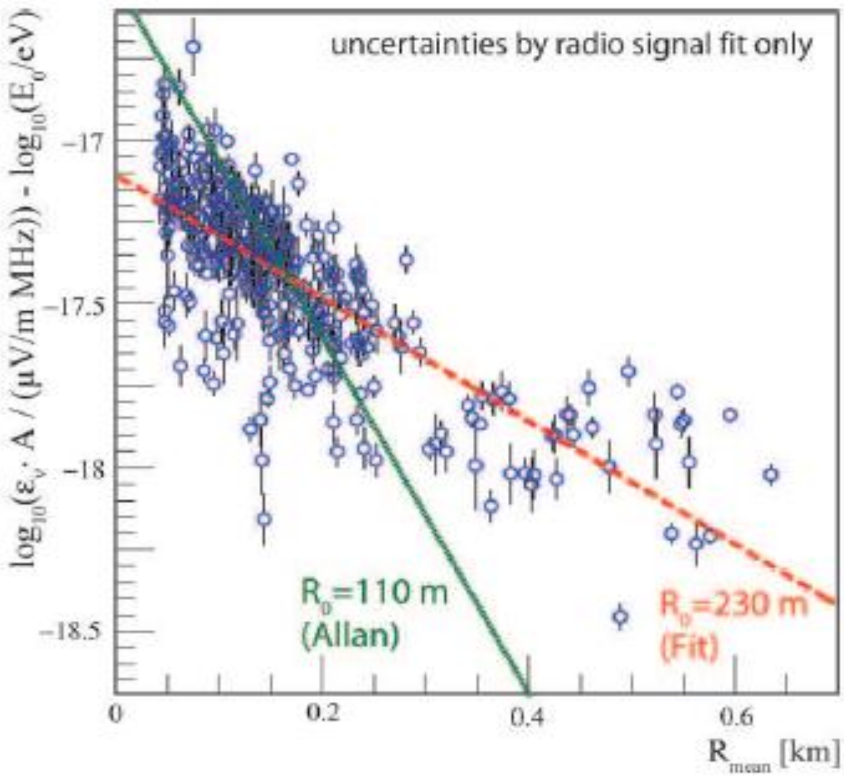
Bandwidth: 40-80 MHz + Sampling: 80 MS/s



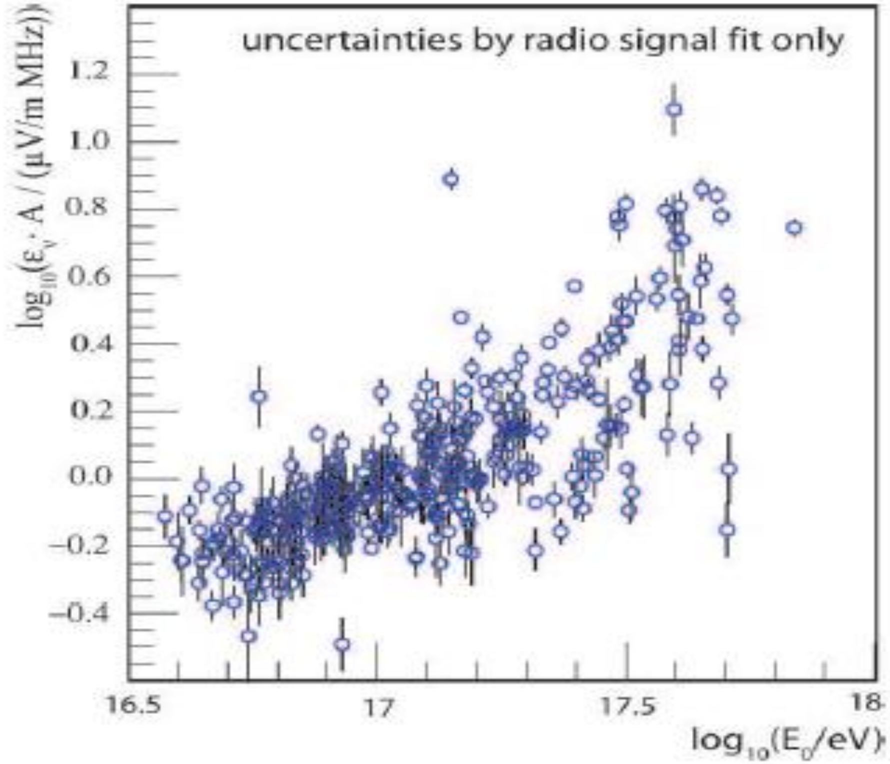
Numerical phasing



LOPES 10: Results with KASCADE-Grande



Correlation of the radio pulse height with the mean distance of the shower axis



Correlation of the radio pulse height with the primary energy of the shower

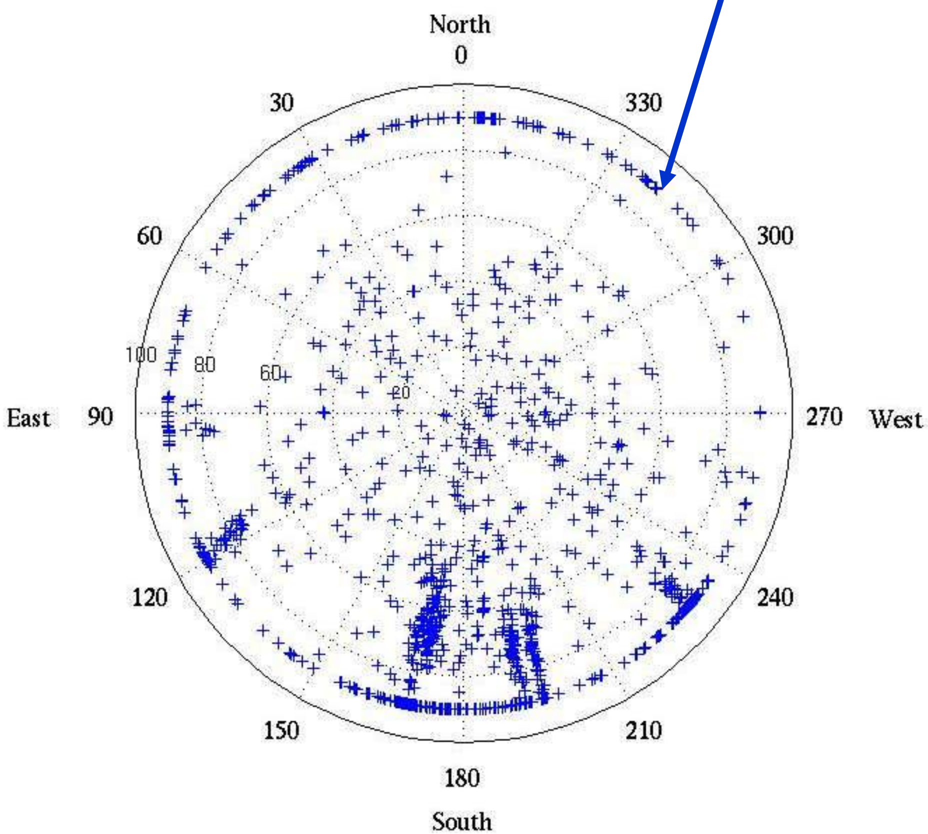
$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right](1+(0.1\pm 0.03)-\cos(\alpha))\cos(\theta)$$

$$\times \exp\left(\frac{-R_{SA}}{(200\pm 45)m}\right)\left(\frac{E_p}{10^{17}\,eV}\right)^{(0.91\pm 0.07)}$$

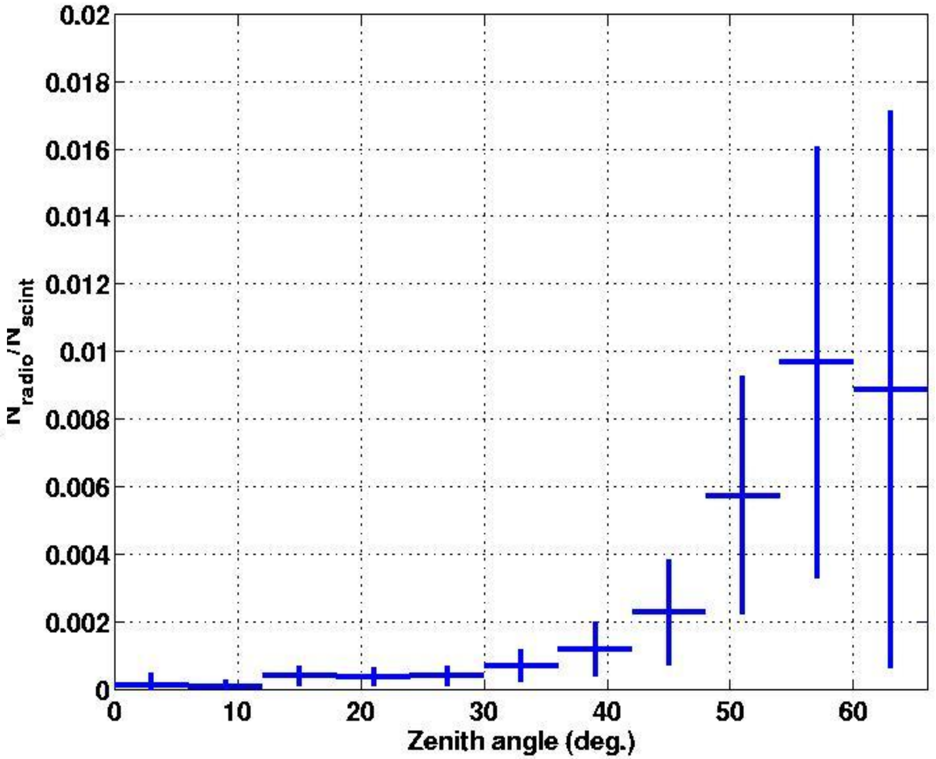
Norm
consis
MC si

Detection of horizontal EAS (2006)

Noise events in a 2 μs window around the particle trigger (Anthropic + solar + storms +….???)

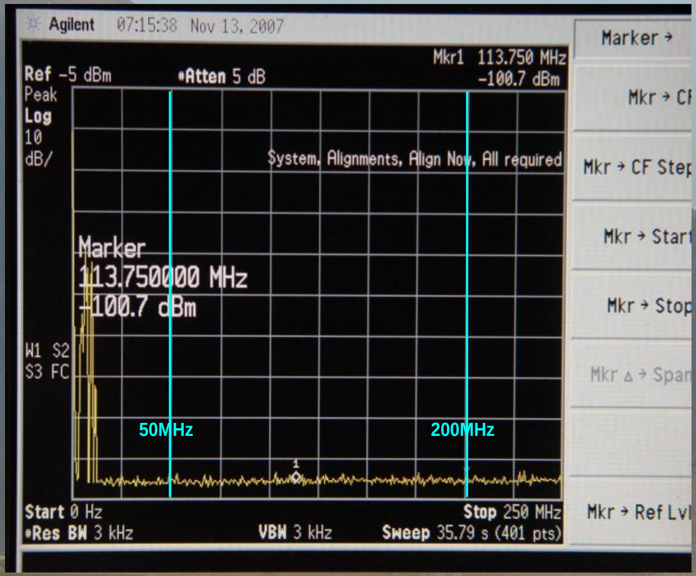


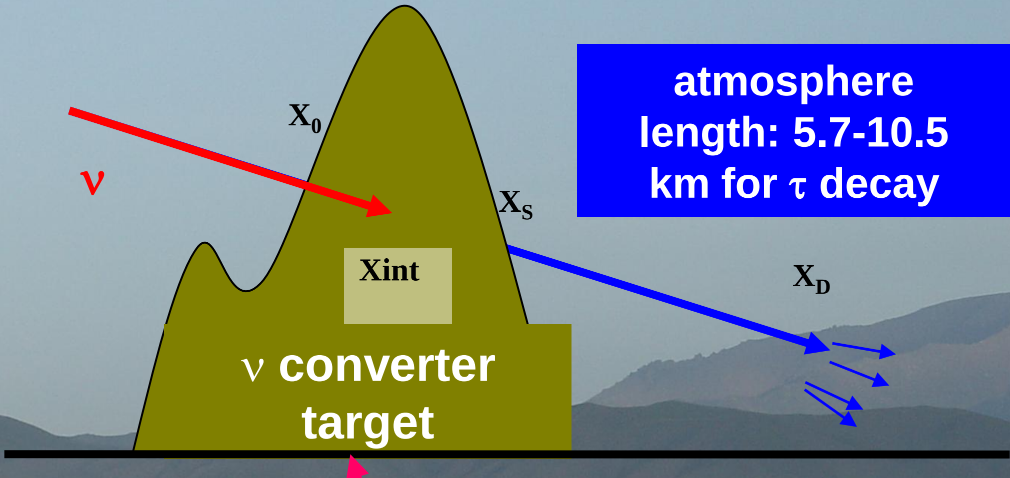
Radio / Trigger Acceptance



Radio-detection could be in nature adapted to the detection of atmospheric neutrinos ?

Tests @ 21CMA (TREND) observation of UHE neutrinos showers

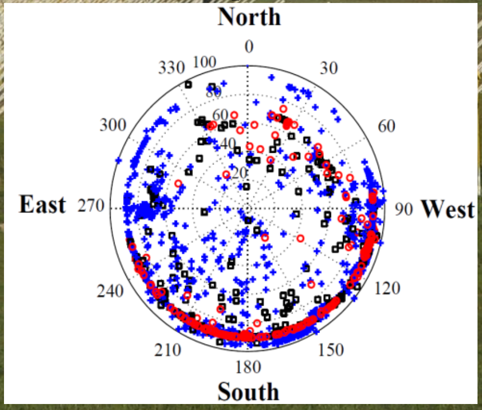


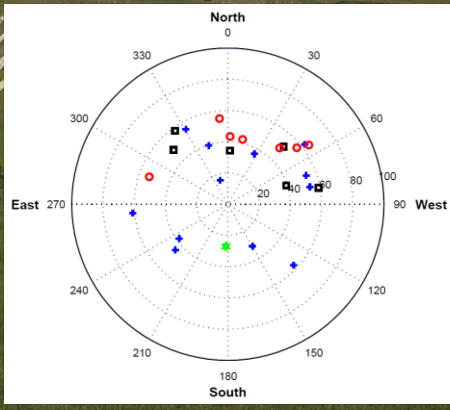


atmosphere length: 5.7-10.5 km for τ decay

Target & shield volume :
20 000 km^3
year - exposure : ~2.10 ^{20} cm^2. s

10287 (50-200 MHz) log- periodic antennas 2 arms (4km NS +3km EW)





Banc de test:

- **Techniques de détection & d'analyse différentes**
- **Gerbes inclinées**

Molecular Bremsstralhung
(Phys Rev D78 032007)

Geo-Magnetic-Radiation Model

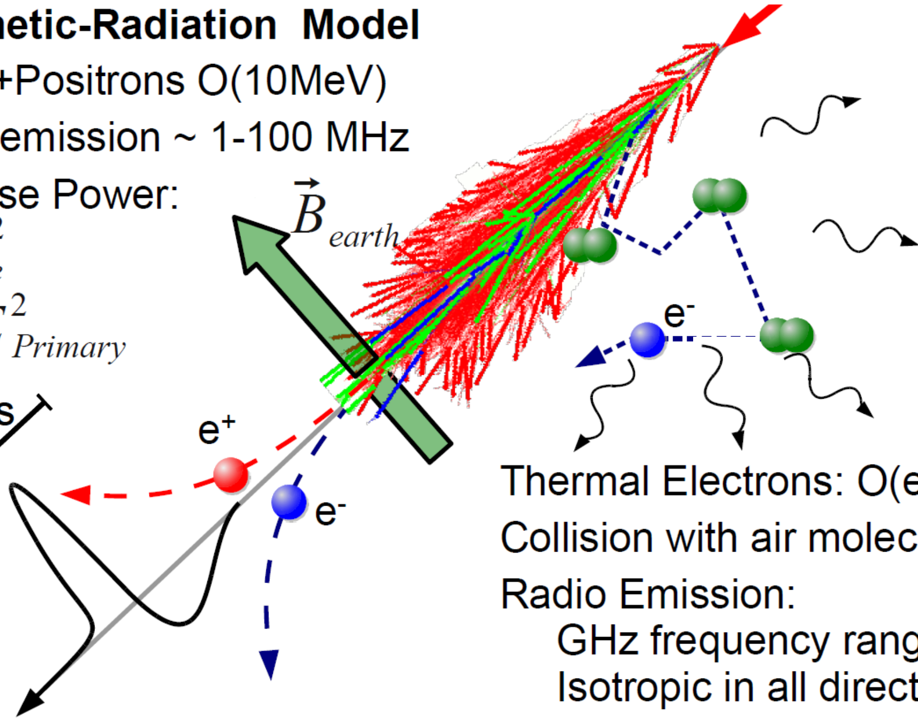
Electrons+Positrons O(10MeV)

Coherent emission ~ 1-100 MHz

Radio Pulse Power:

$\propto N_e^2$

$\propto E^2_{Primary}$



Thermal Electrons: O(eV)

Collision with air molecules

Radio Emission:

GHz frequency range

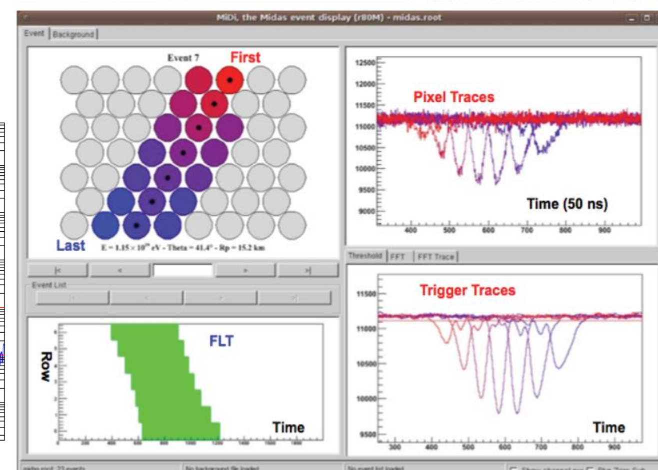
Isotropic in all directions

Molecular Bremsstrahlung

Imager

MIDAS – AMBER

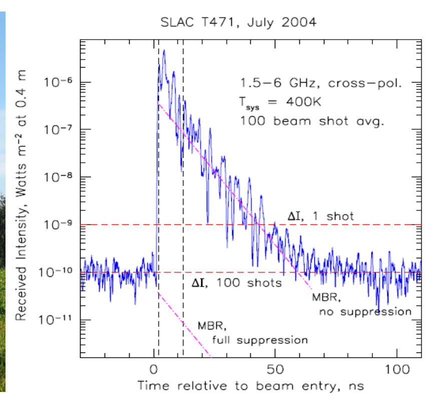
(AUGER)



Calorimetric

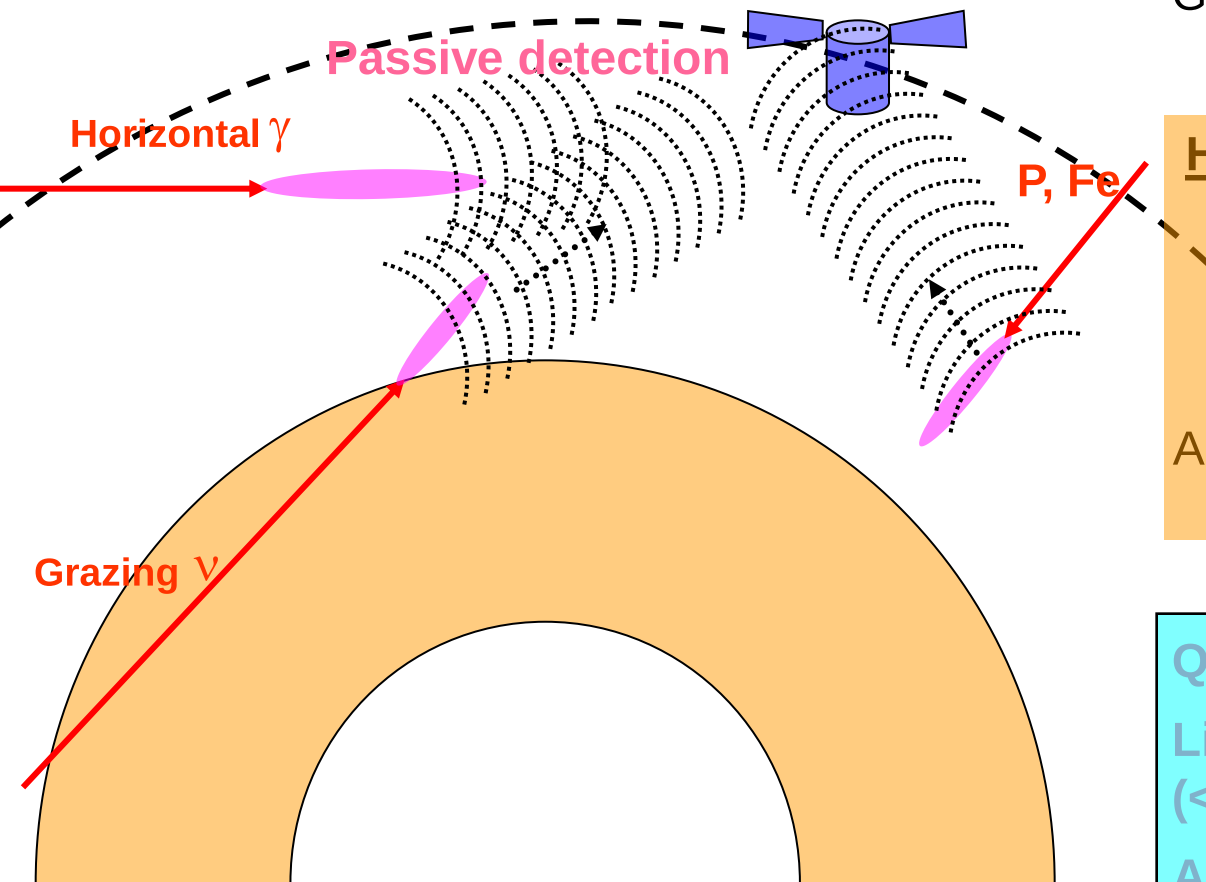
EASIER

(AUGER)



Detection of molecular excitations from the ionized trail

Showers in the low atmosphere
Detection of grazing ν, p, Fe, horizontal γ



Molecular Bremsstrahlung emission

4 π emission

Characteristic of the motion of non relativistic charges

Wide band Continuum MHz-100 GHz

H2O emission line at 22 GHz

From CO2, NO, OH, …
(upper atmosphere)

Tuned antennas

Already used in radioastronomy (ALMA, SKA)

QUESTIONS:

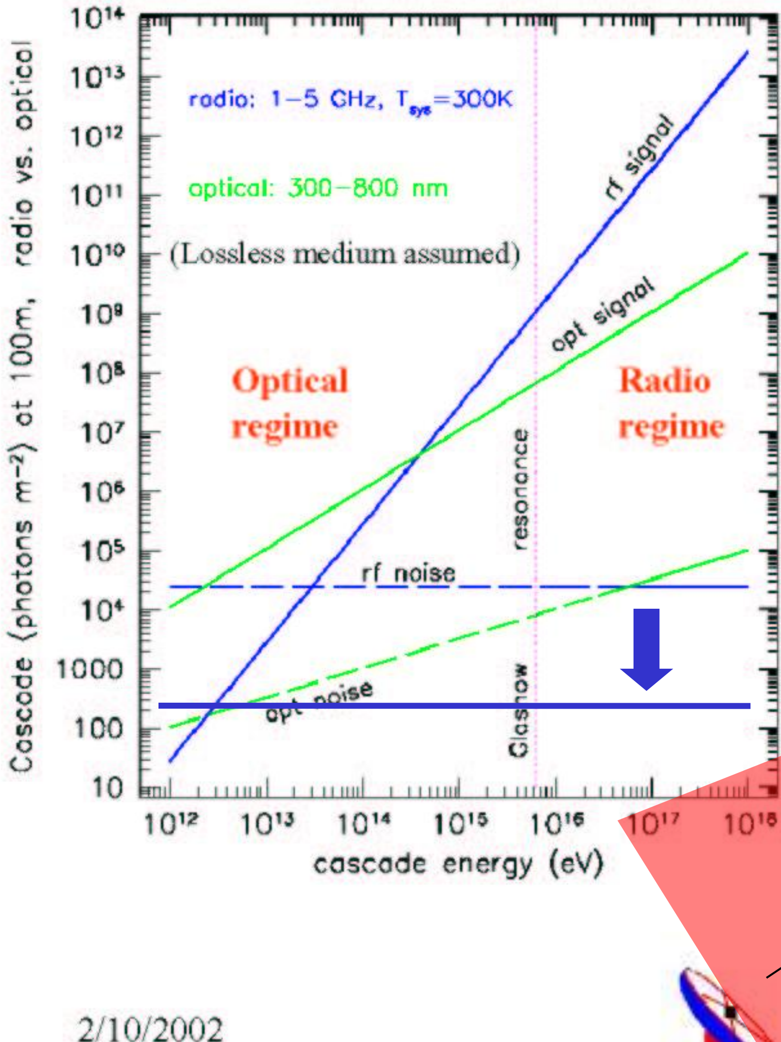
Life time of the ionized trail (< 100 ns ?, ms ?)

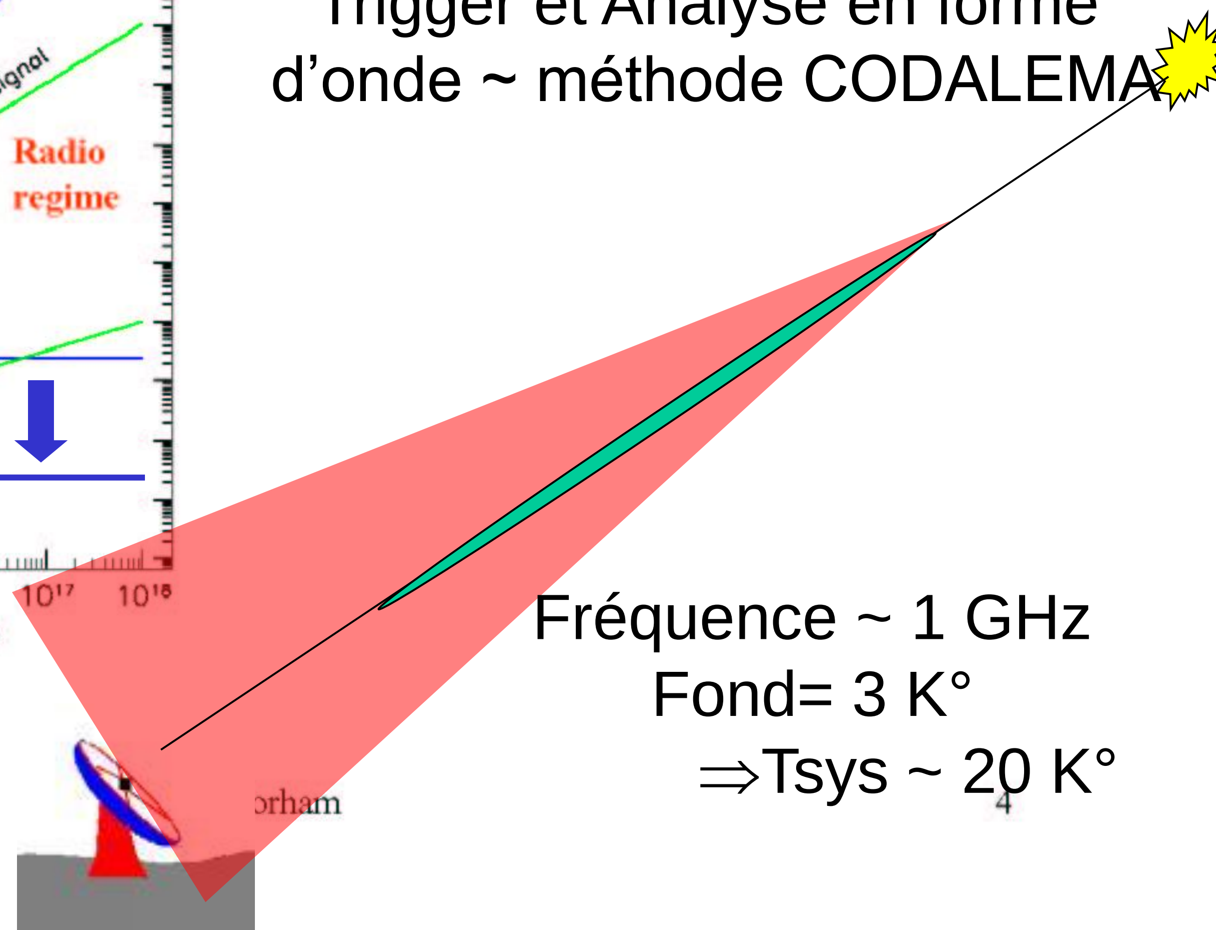
Absorption ?

Radio-Détection à la HESS vers 10^{12} eV ?

Télescope pointé (~mn d'arc @ RT de Nançay)

Détection du transitoire Č radio
Trigger et Analyse en forme d'onde ~ méthode CODALEMA





Fréquence ~ 1 GHz
Fond= 3 K°
⇒Tsys ~ 20 K°

Epilogue

- **2002-03: Principle of detection & triggering**
- **2004-05: EAS recognition, Arrival direction, Core location**
- **2006-07: Detector performances, Field topology, Threshold, Efficiency**
- **2007-08: Emission process, Energy calibration**
- **2009 : Autonomous detection**
- **2010-XXXX : Nature of the primary ?**

=>Analysis and detection methods are in stage of stabilization (see also LOPES results)

=>Theoretical developments must now be conducted at the end...

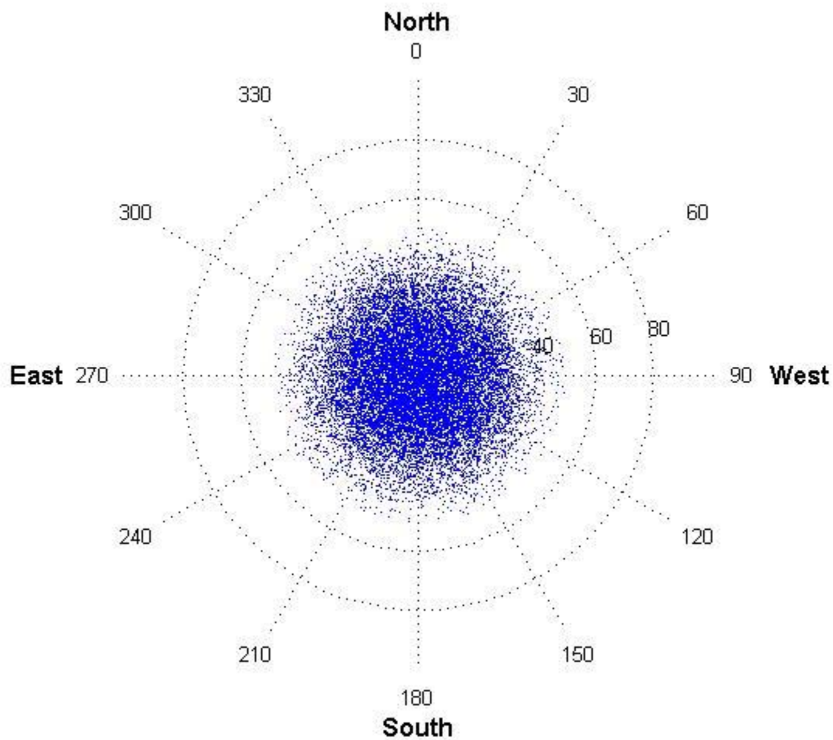
=>It as entered a phase of detailed studies of the radio emission...

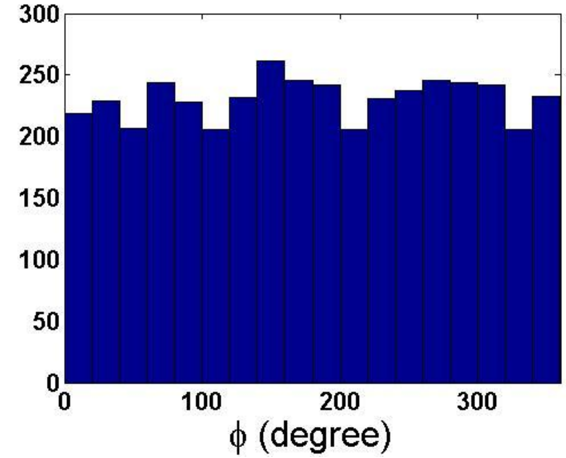
=>EAS radio detection is not far from being ready for intensive use...

=>The crippling handicap of the 60's was lifted in 2008…

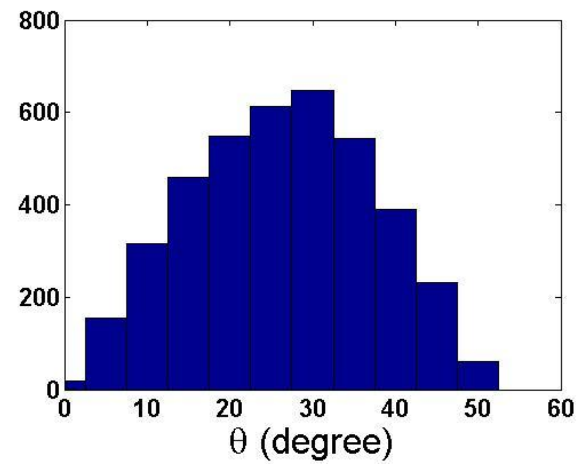
Scintillator distributions (internal)

Shower arrival direction calculated with the scintillator data





Azimuthal distribution



Zenithal distribution
Limited at $\theta < 50°$

Shower energy deduced from scintillator data
(CIC method, precision 30 %)

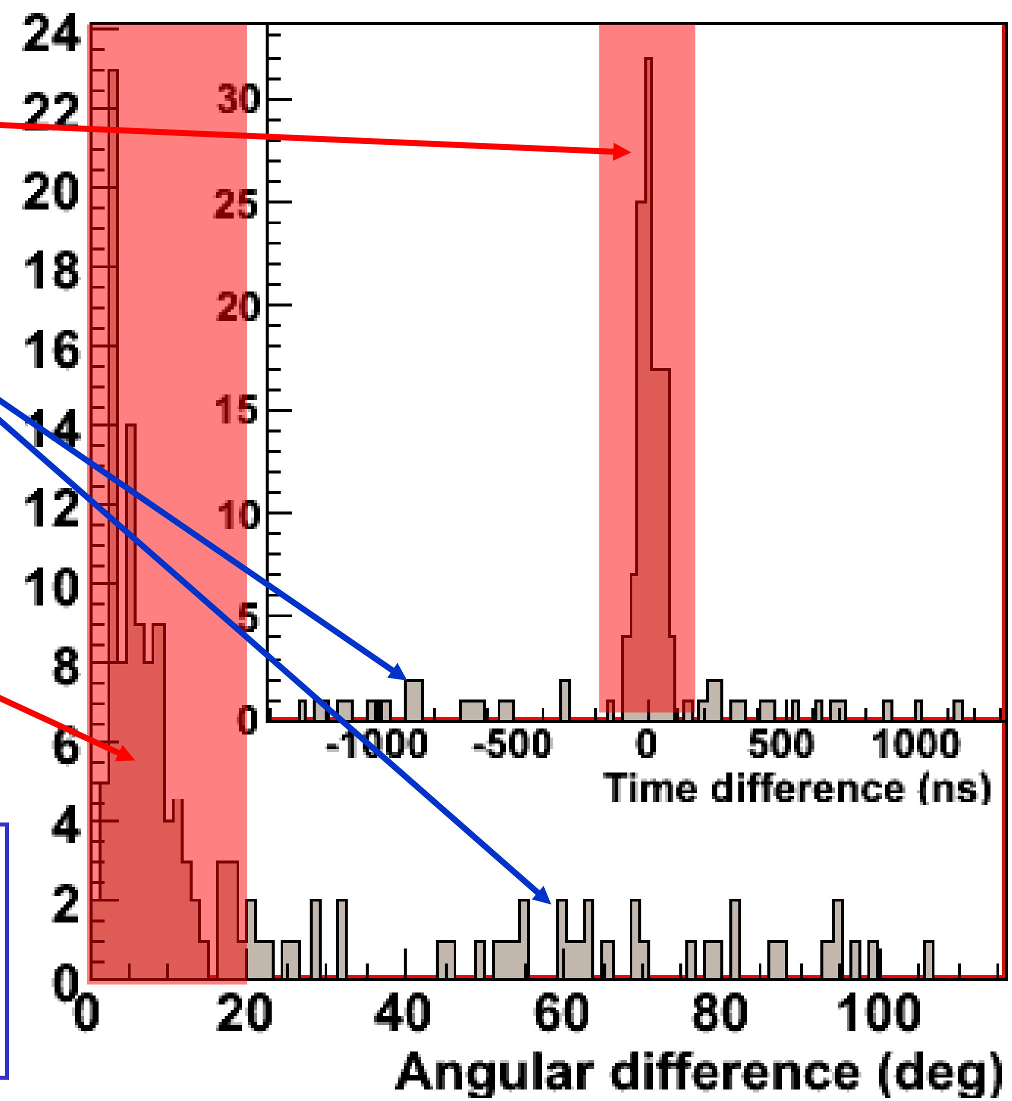
=> Energy threshold ~ 10^{15} eV

Radio-particles time & Arrival direction coincidences (for ≥ 3 antennas flagged)

Sharp peak (< 100ns)
= EAS candidates

Flat distribution
= fortuitous events

sin(Δα).Gaussian
=> σ = 4°



“Antennas” direction – “Particles” direction

Reconstruction of EAS arrival directions is proved via Radio-Detection