Radio Detection of High Energy Cosmic Ray Air Showers

A short review

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(CODALEMA and Radio@Auger collaborations)

XXth RENCONTRES DE BLOIS
18th - 23rd May 2008
"Challenges in Particle Astrophysics"

Château de Blois (France)

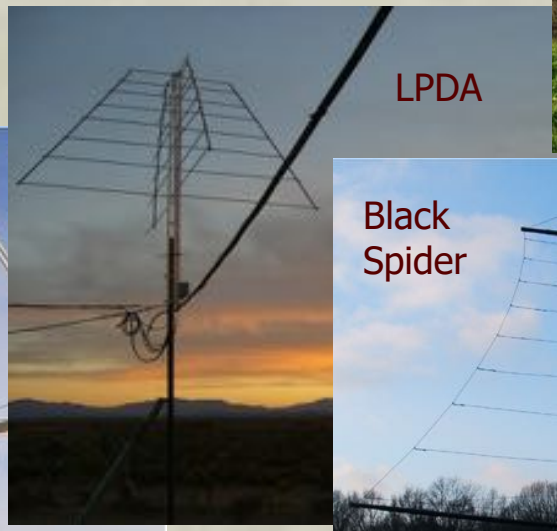
Historical review

1962	Theoretical prediction - Askar'yan effect
1964-65	First experiment - T.C. Weekes
Mid 70's	Abandoned (difficulties of interpretation and detection + success of other techniques)
End 90's	Re-investigated in dense media (ice, salt) $\Rightarrow$ neutrinos
1999	Proof of principle on accelerator (sand, D. Saltzberg,)
2000	Experience on CASA-MIA (K. Green et al., 2003, N.I.M. A, 498) Try on EAS-Top (Italy) $\Rightarrow$ no convincing results
2002	LOPES Experience on KASCADE (FZK) CODALEMA Experience @ Nançay Radio Observatory
2005-2007	New theoretical approaches: microscopic models based on MC calculations (Huege & Falcke), macroscopic models based on semi-analytical formulae (Scholten, Werner & Rusidy)
2006	Prospectives on AUGER-South

General properties

Radio detection:

- Is a bolometric method (uses atmosphere as a calorimeter) ⇒ macroscopic properties of the shower
- Gives access to longitudinal development of the shower, at large distances
- Is sensitive to inclined showers ⇒ neutrinos ?
- Presents a high duty cycle, is cheap
- Is few technology and method dependent ⇒ robust



Two current and major experiments:

LOPES and CODALEMA

CODALEMA @ Nançay

21 dipole antennas in EW polarization ▽

3 dipole antennas in NS polarization ▽

13 particle detectors (trigger) ■

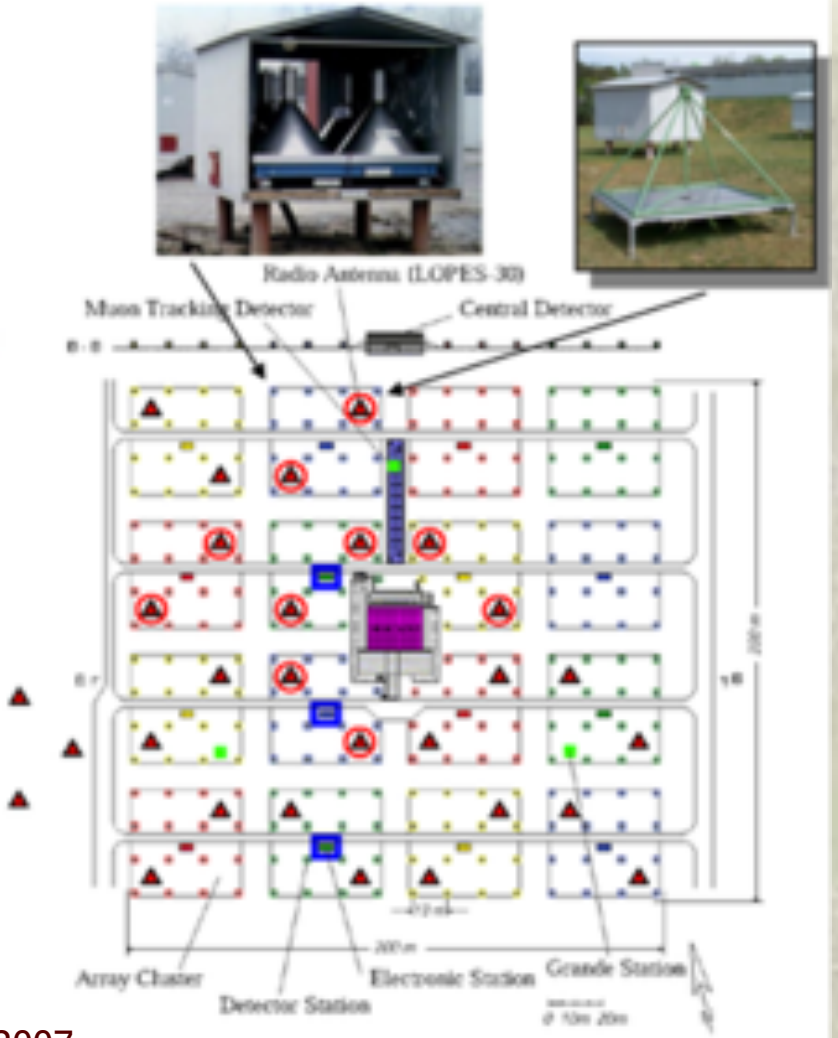
Data Acquisition:
- 12 bits ADC
- Sampling: 1 GHz

Antennas: "+" of 600 m x 500 m

Scintillators: "□" of 350 m x 350 m

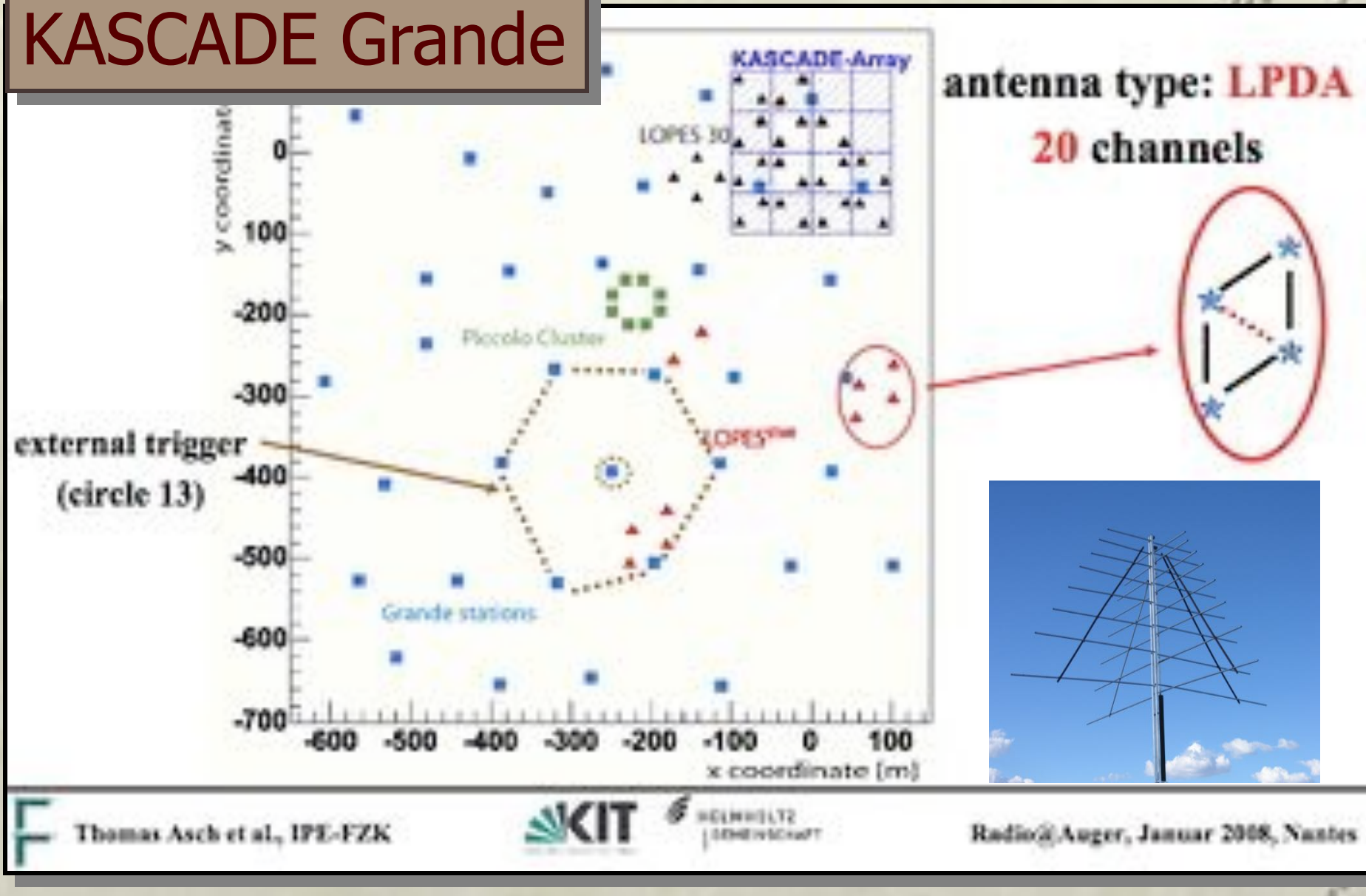
LOPES: LOFAR PrototypE Station

- 10 antenna prototype at KASCADE (all 10 antennas running)
- triggered by large event (KASCADE) trigger (10 out of 16 array clusters)
- offline correlation of KASCADE & LOPES (not integrated yet into the KASCADE DAQ)
- KASCADE can provide starting points for LOPES air shower reconstruction
  - core position of the air shower
  - direction of the air shower
  - size of the air shower
- Now: 30 antennas have been installed and take data
- Software and data archive on multi-TB raid system
- >1 Million events in database



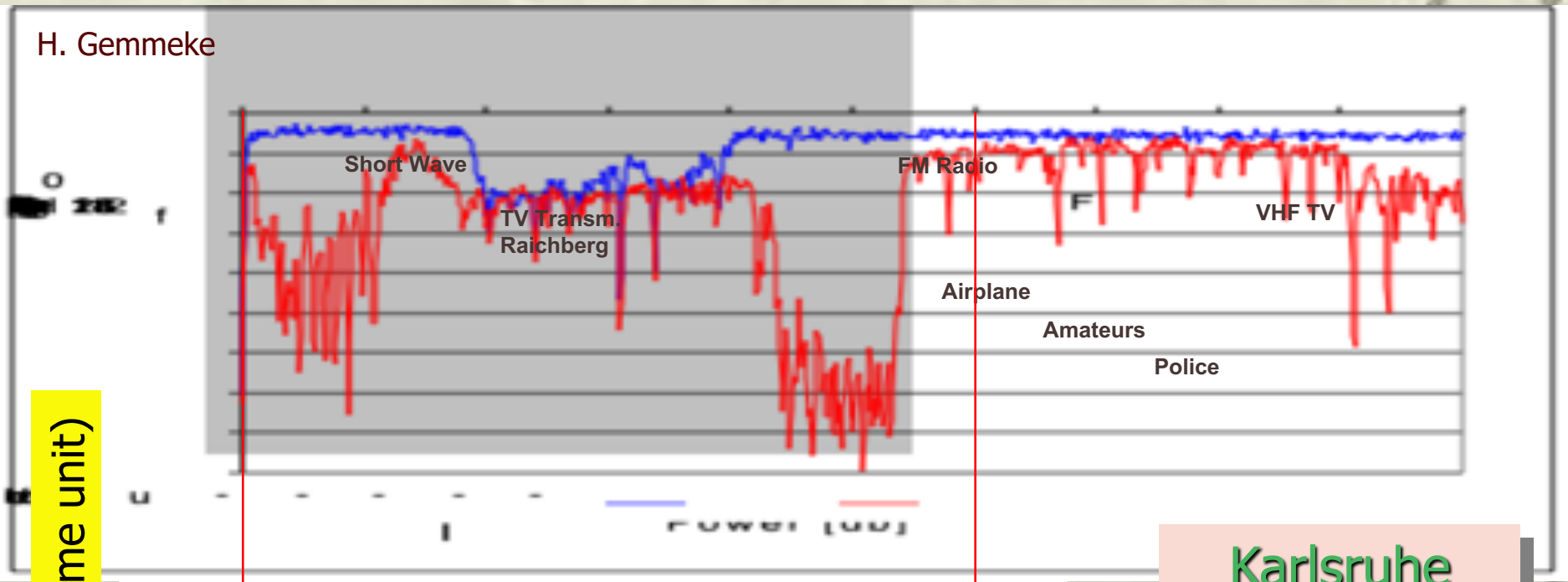
H. Falcke, May 2007.

+ LOPES^{STAR} and KASCADE Grande

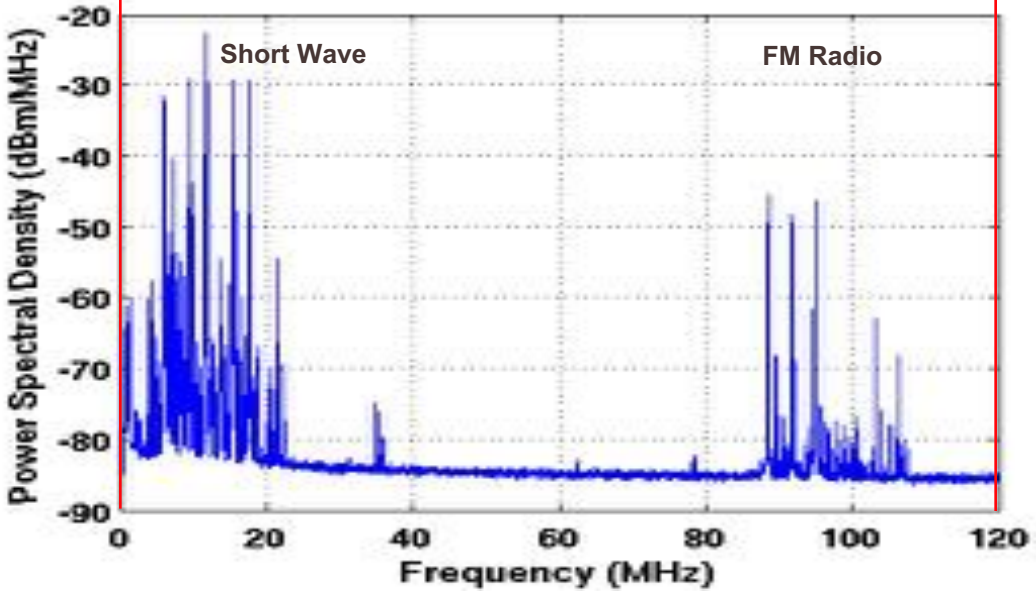


Problem: RFI noise

H. Gemmeke



(Not the same unit)



Karlsruhe
(not so Ruhe..)

Nançay

Wide band recording is possible (at high sampling rate)

Different sites, different antennas, different methods

Particle detector triggers on a CR event

Radio signal (waveform) is recorded on antennas

Offline processing to find if CR radio signal has been detected

Filtering wide band + simple voltage threshold $\Rightarrow$ radio shower signal independent from particle detector, on each antenna for one event

RFI suppression + time scaling using particle detector information (beam forming) + sum of amplitudes of all antennas for one event

CODALEMA

"Transient method" (particle physics)

Study of V(t)

LOPES

"Stationary method" (astronomy)

Study of V(ν)

CODALEMA waveform processing principle

Radio transmitters

✓ Mask the transient

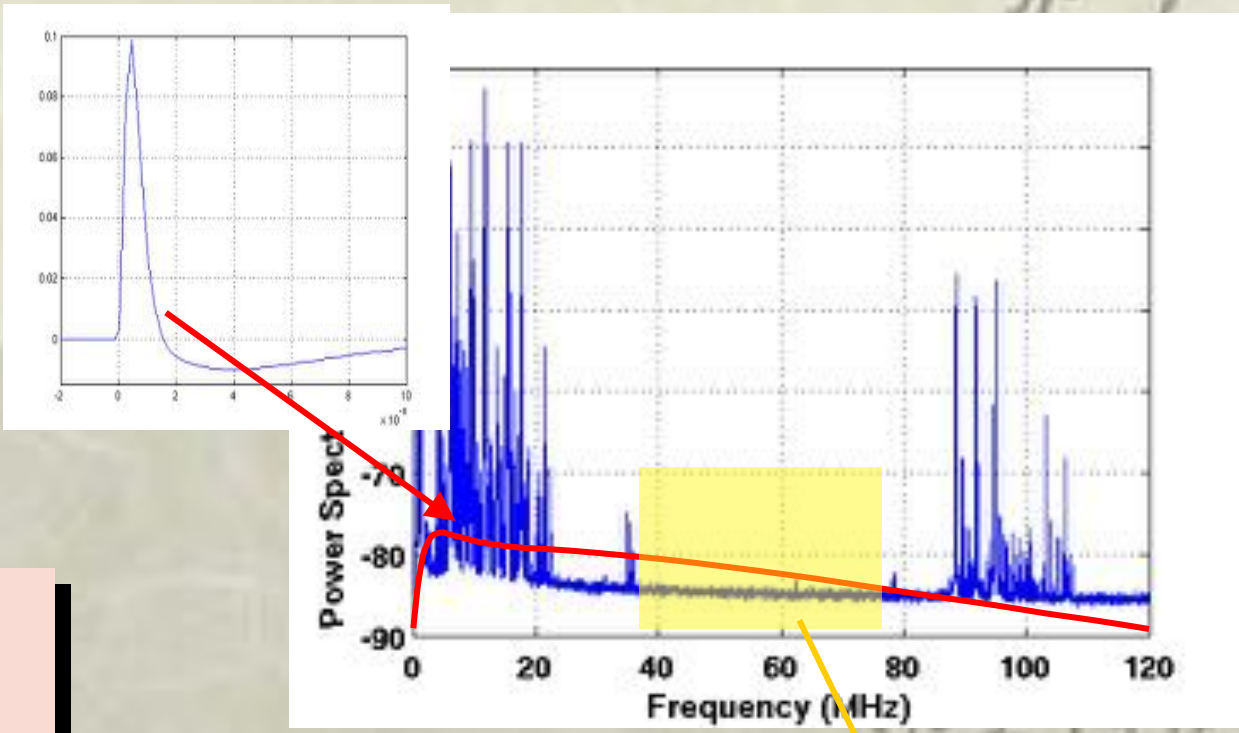
Filtered waveform

✓ Keeps transient nature

Applying a threshold

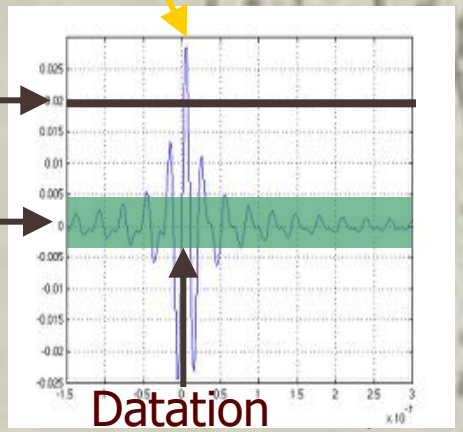
✓ Triggering on amplitude

✓ Datation of the pulse



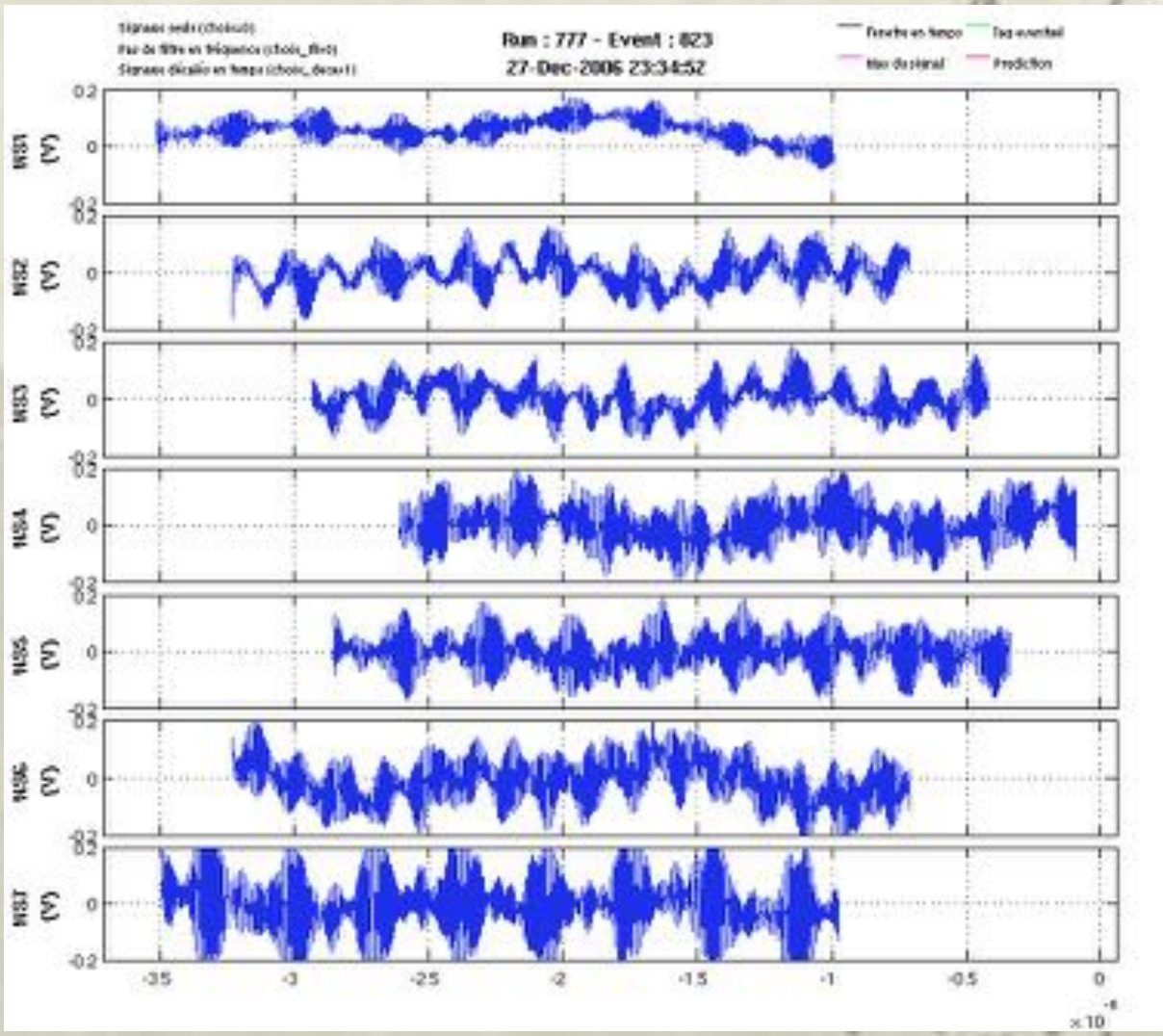
Voltage threshold

Estimated noise: σ_b



CODALEMA illustrative example

Wide bandwidth recording (1-250 MHz): transients are hidden by transmitters



CODALEMA illustrative example

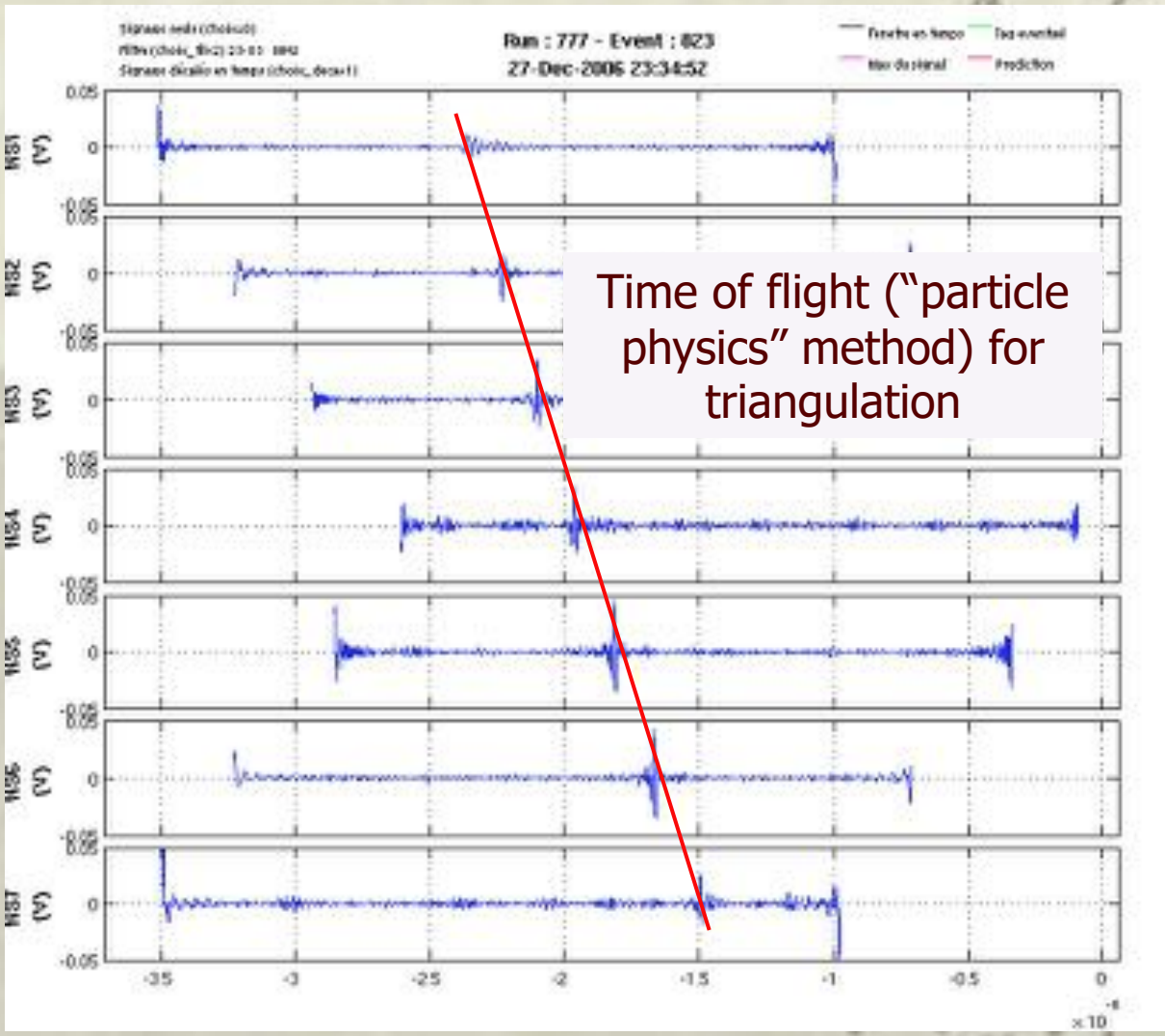
Wide bandwidth recording (1-250 MHz): transients are hidden by transmitters

Narrow band filtering (here 23-83 MHz)

Radio signal gives independent parameters:

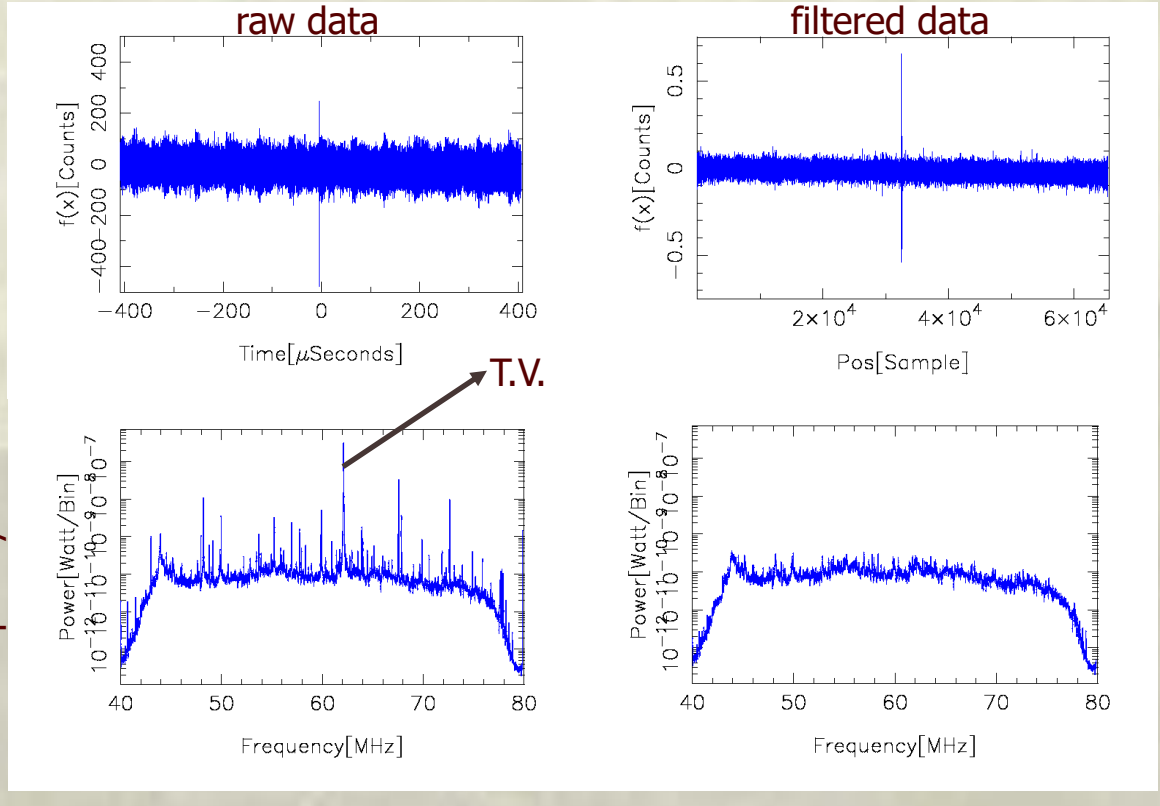
Direction by triangulation, core position, shower field profile (sampled antenna by antenna)…

Correlation with particles (time, arrival direction)



CR event selection
(rate: ~ 1/day > 5 10^{16} eV)

LOPES waveform processing principle



Very noisy environment + low sampling (80 MS/s)

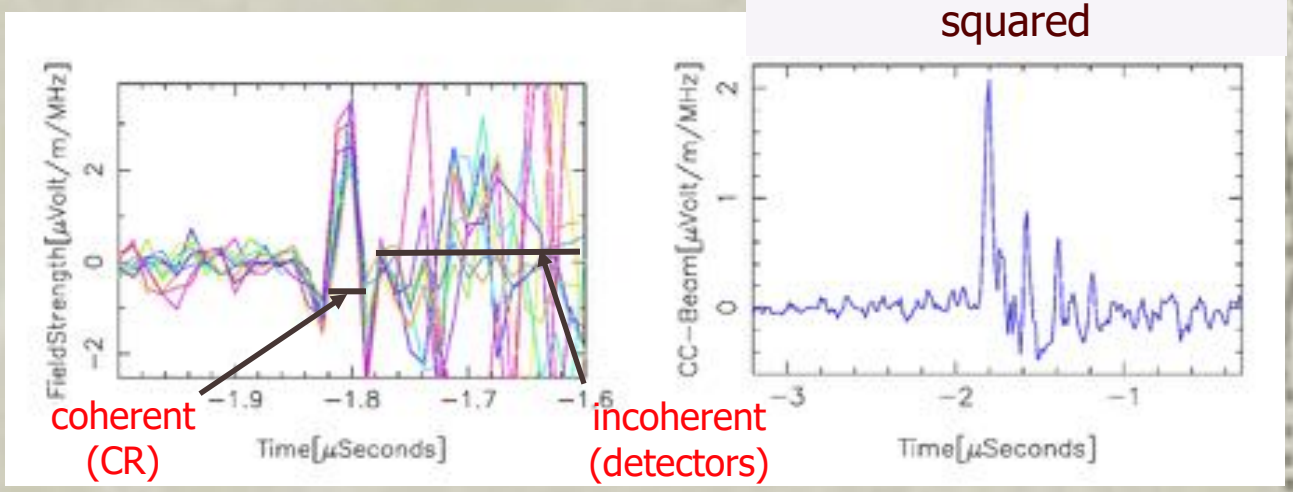
⇒ Narrow band

RFI suppression

Sum of delay-corrected E-field from all antennas, squared

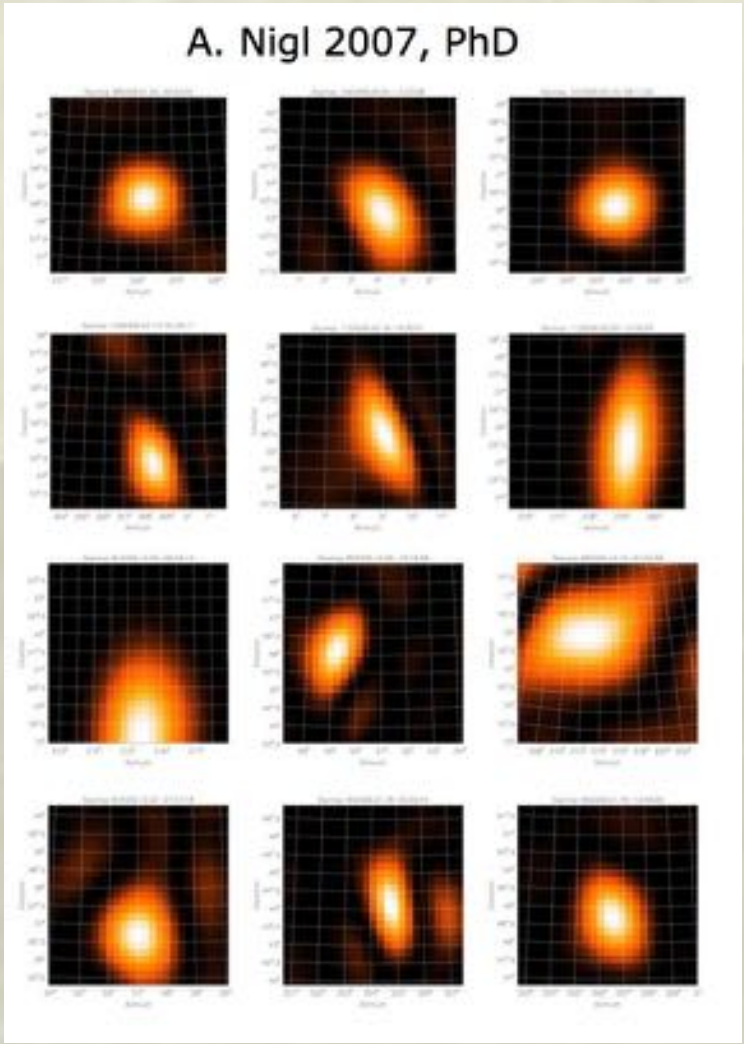
Electric field at each antenna corrected for arrival direction of CR with the help of KASCADE data

⇒ Time scaling (beam forming)

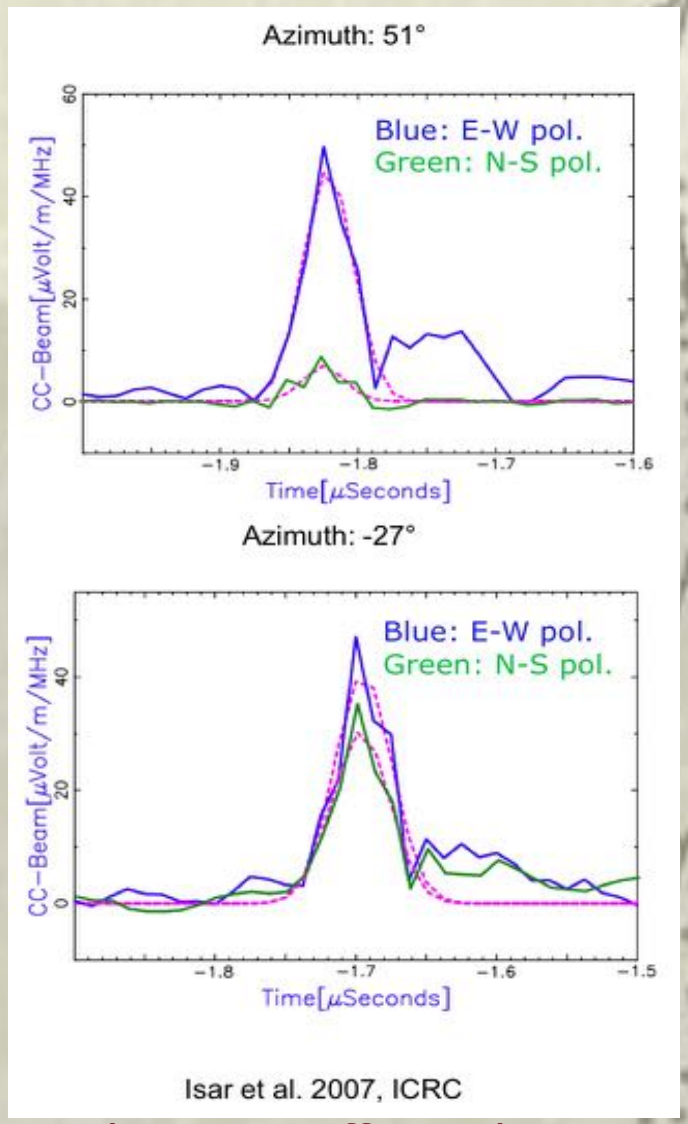


H. Falcke et al. Nature May 2005.

LOPES illustrative example



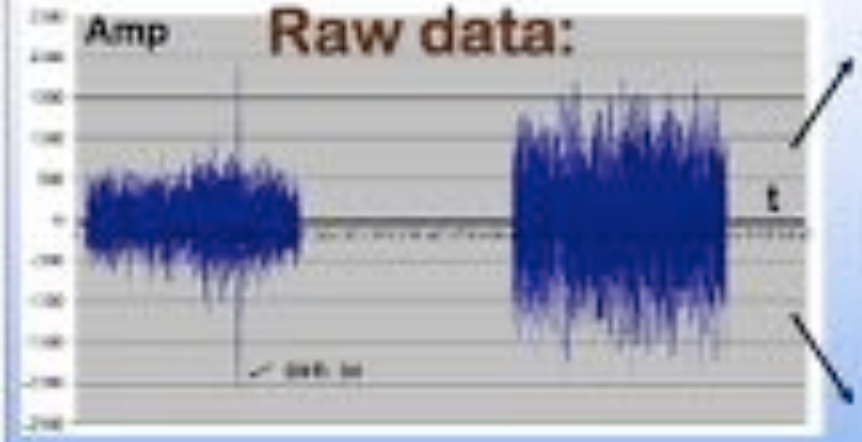
Beam forming in each sky direction ⇒ imaging of shower pulse
Correlation/interferometry ("astronomical" method) for triangulation



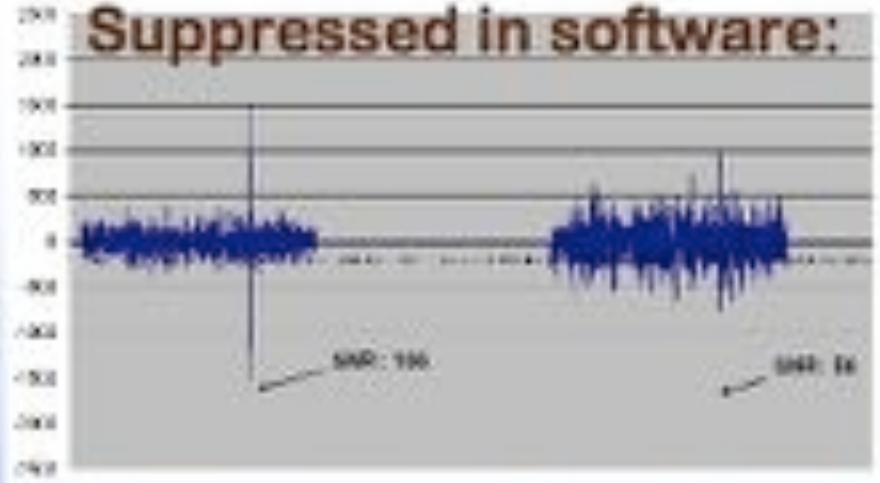
Polarization effect coherent with theoretical prediction

LOPES^{STAR} illustrative example

RFI suppression + triggering online in hardware



Real shower event, measured with LOPES^{STAR} at FZK



⇒ "CODALEMA like" data (antenna by antenna)

Main results on HECR radio signal properties:

A comparative and complementary view

What we have to question:

1 EAS Energy threshold

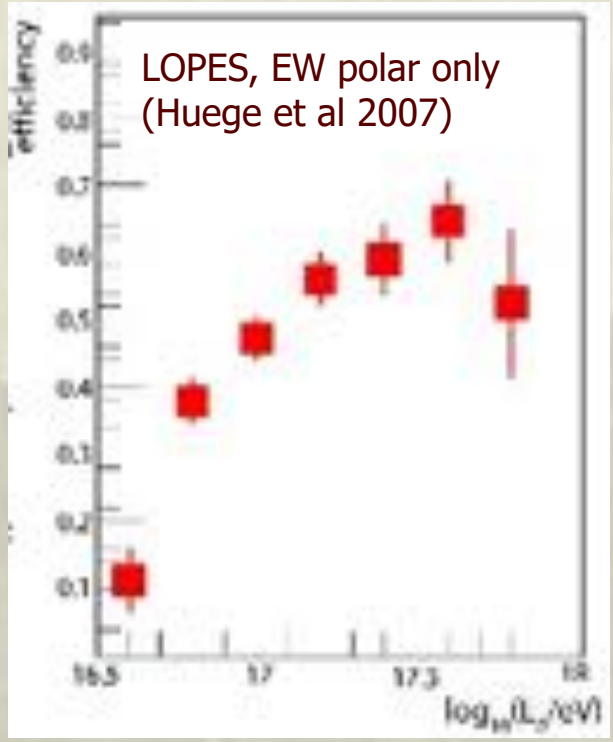
2 GeoMagnetic field dependence

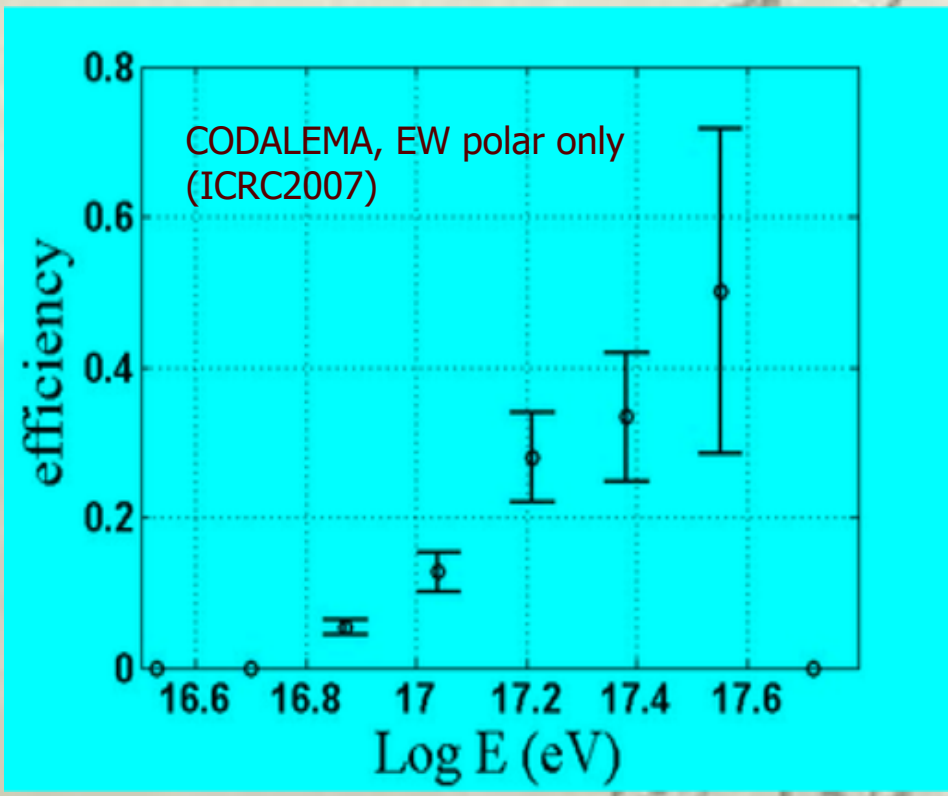
3 EAS electric field profile

4 EAS electric field extent

5 Shower energy dependence

1 - Radio detection energy threshold



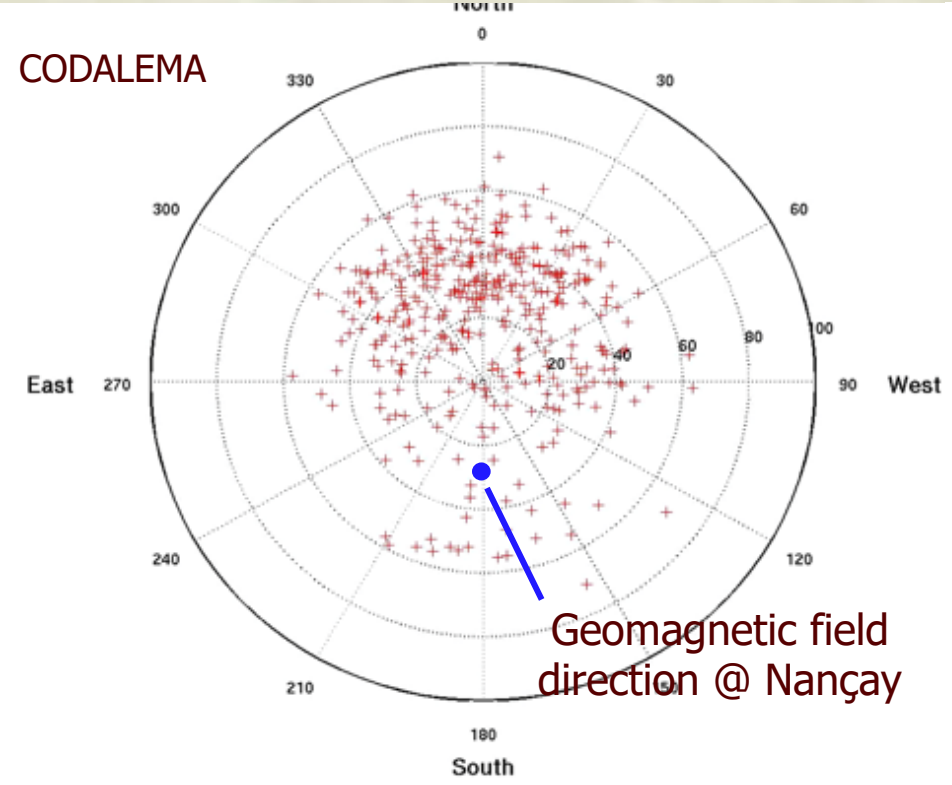


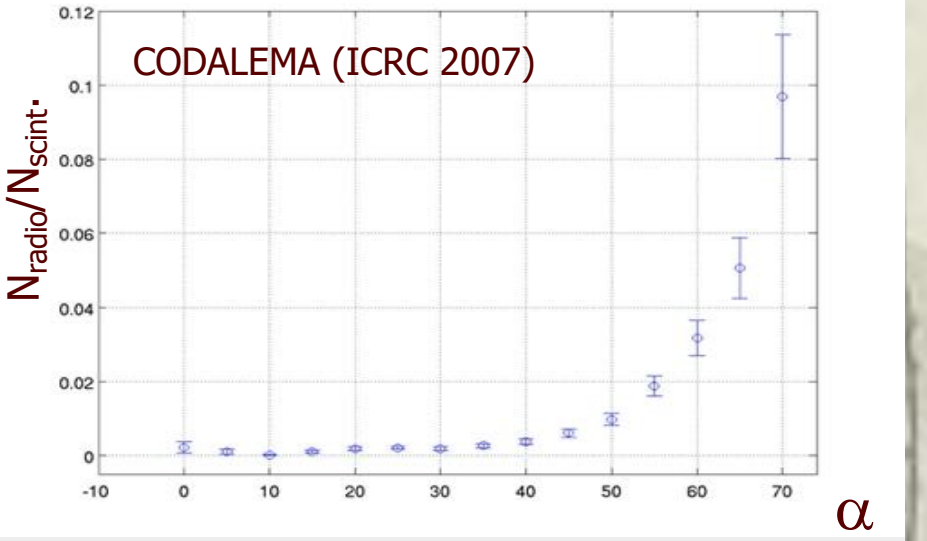
Current setup efficiency

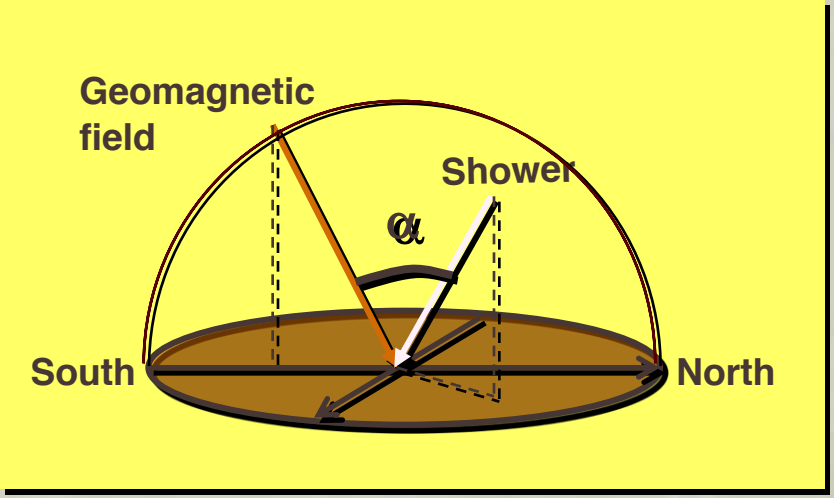
- Threshold ~ 4 to 6 10^{16} eV
- Needs two polarizations (EW and NS) !
- Full efficiency > 10^{18} eV ?
- Still a lack in efficiency ⇒ sky coverage ?

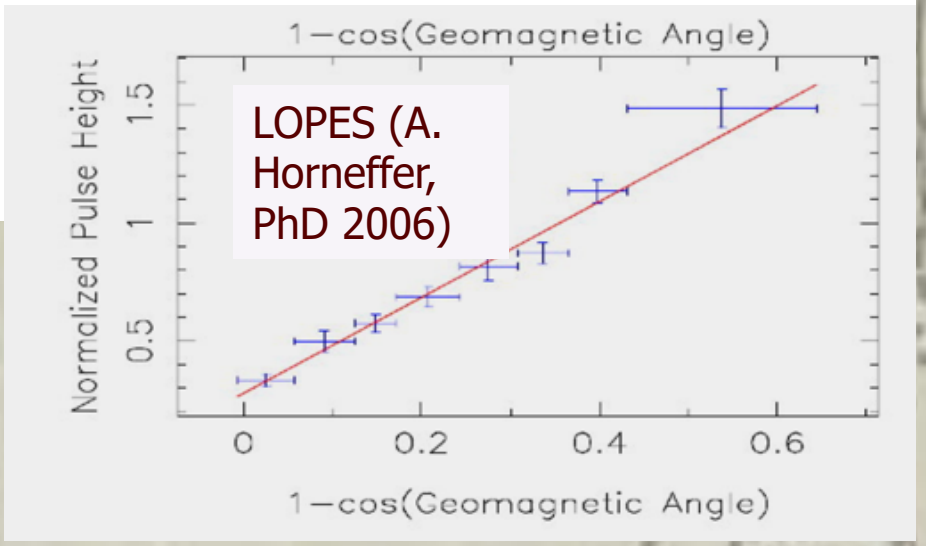
CODALEMA simulations: full efficiency with only EW polar is indeed reached (Riviere et al, 2008, tbp)

2 - GeoMagnetic field dependence









CLEAR DEPENDENCE WITH α, BUT...

why vs (1 - cos α) rather than (sin α□ ?

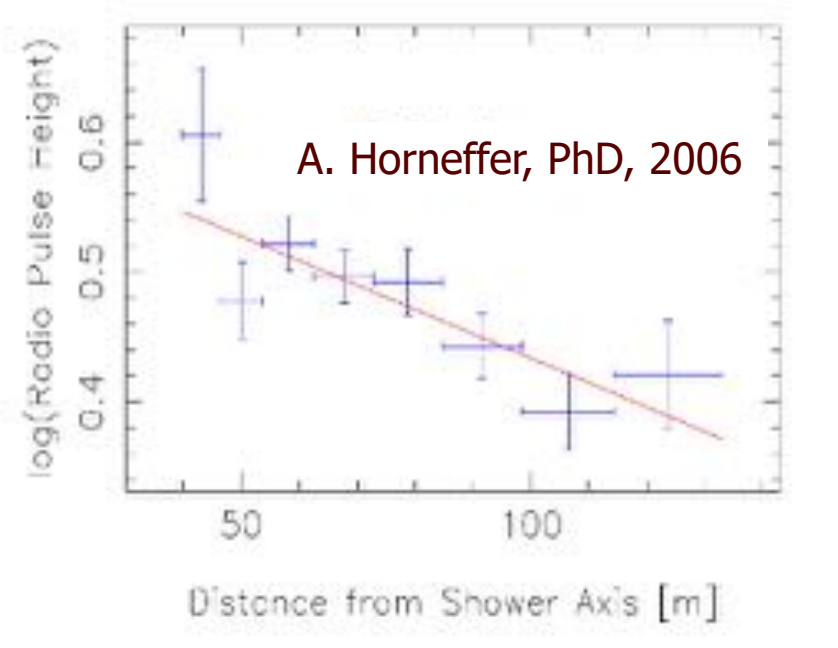
3 - EAS electric field profile

From H.R. Allan (1971), Huege & Falcke (2005) :

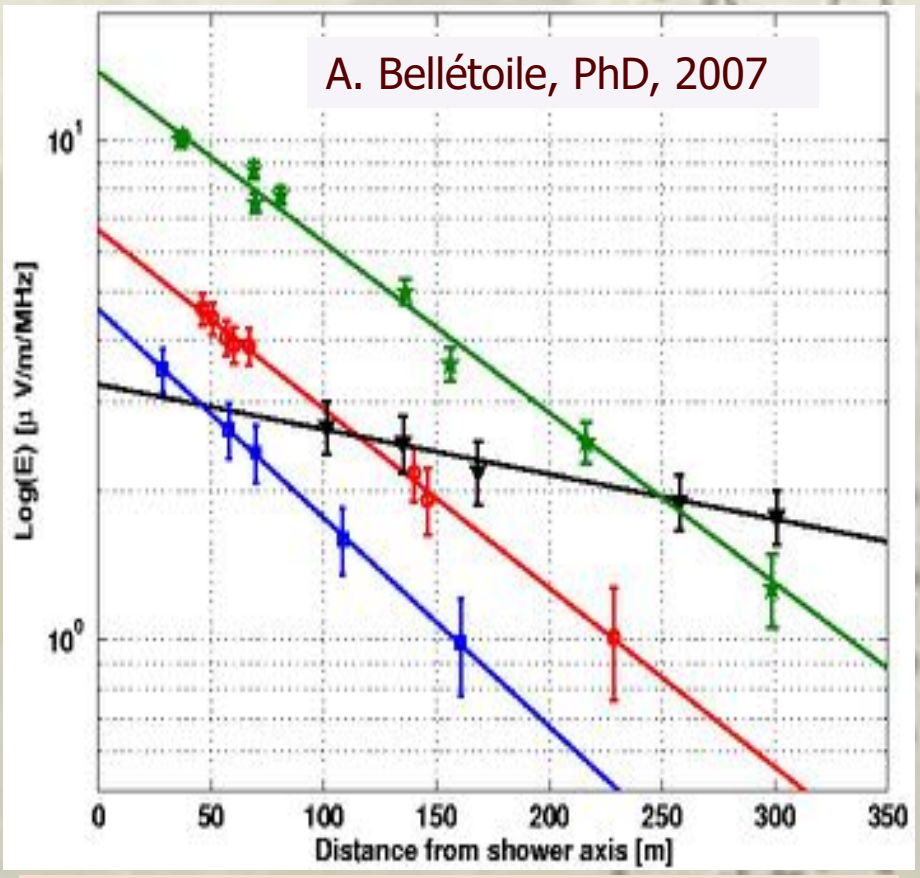
Exponential fit of radial dependence in the shower-based coordinate system

$$E(d) \propto E_0 \exp\left[\frac{-d}{d_0}\right]$$

(d = distance to the shower core)

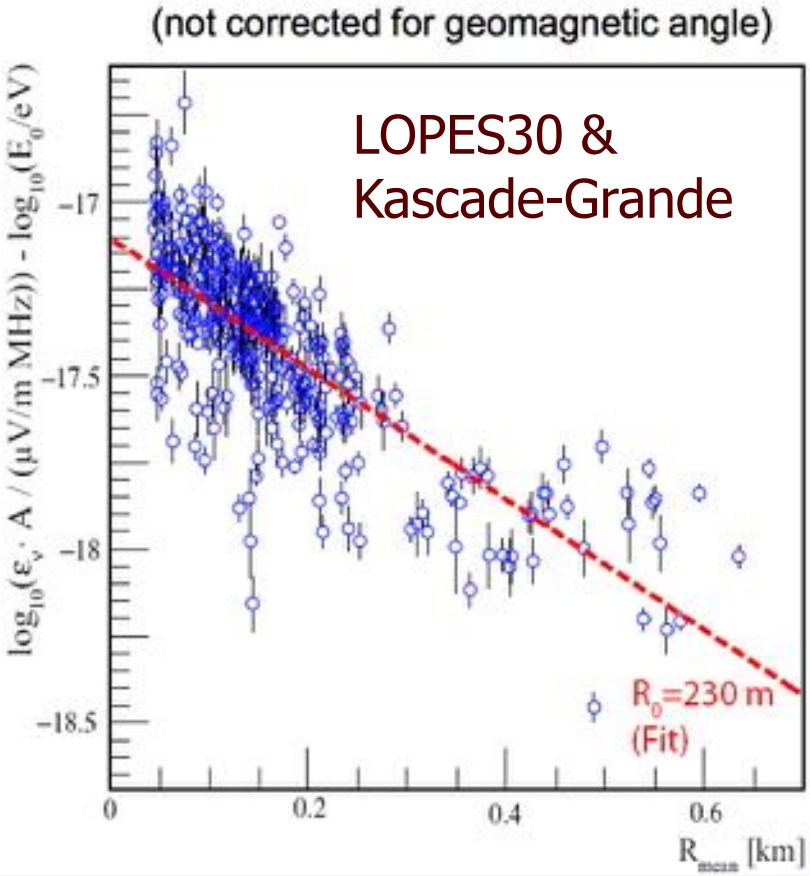


LOPES: binning on several events (no event by event information)

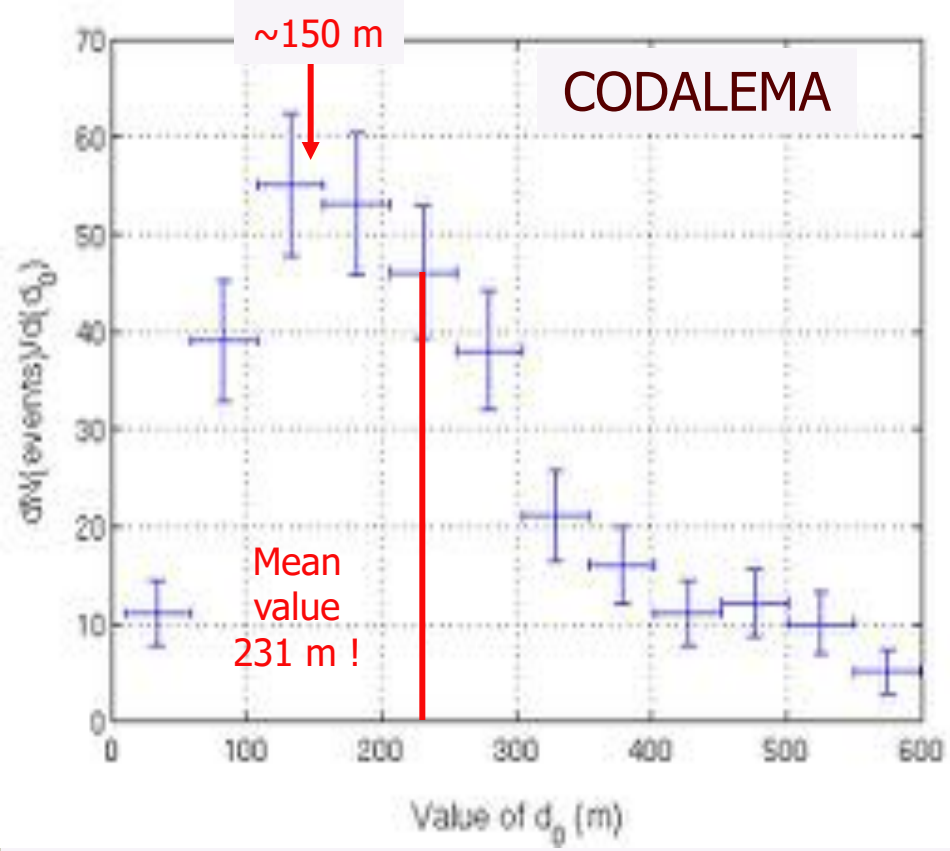


CODALEMA: event by event field measurements @ ~ 5.10^{16} eV

4 - EAS electric field extent



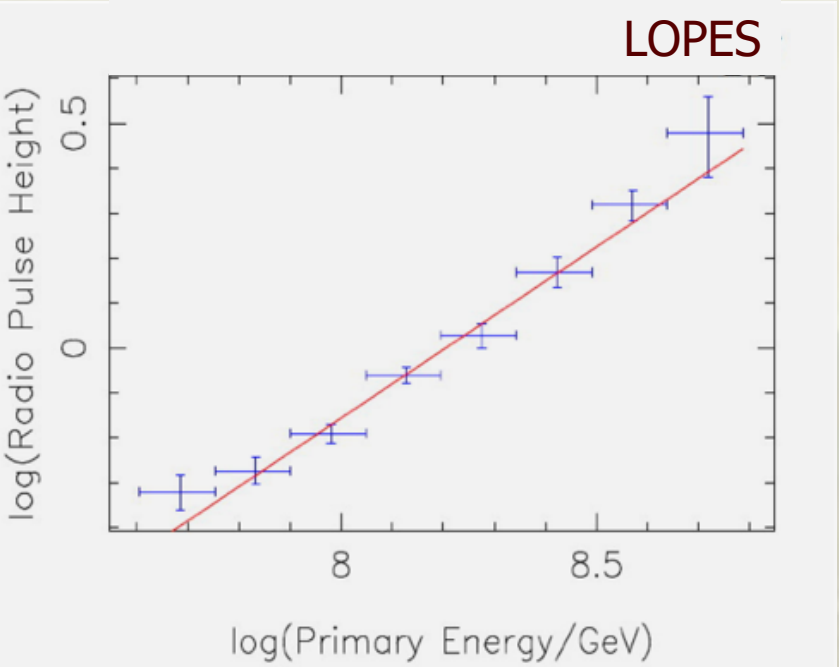
Average distance of antenna array to shower core

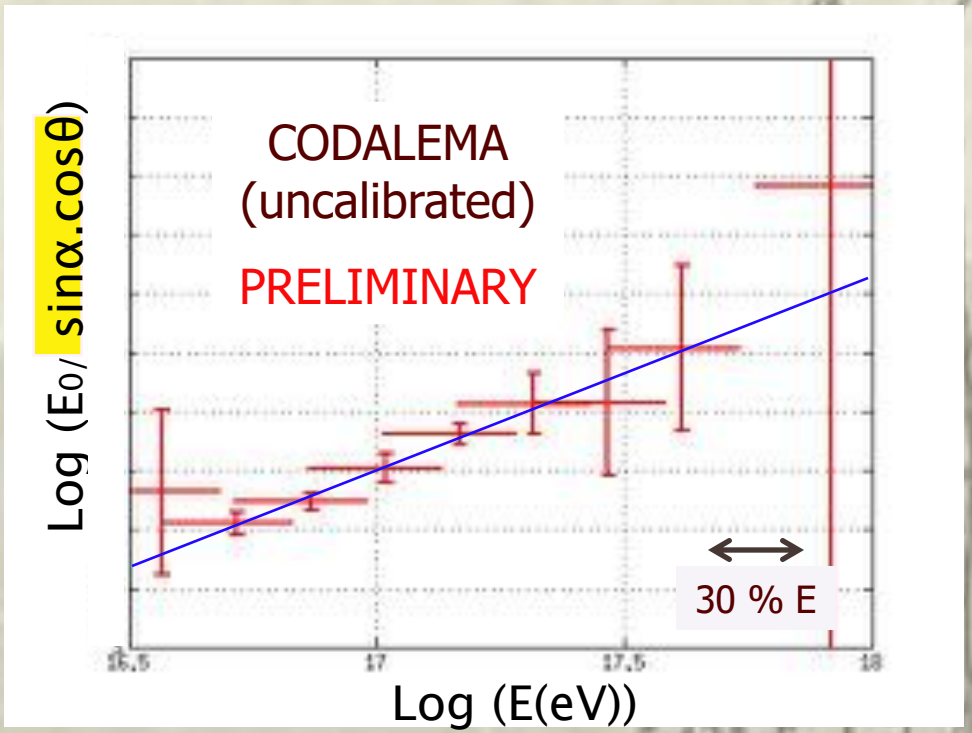


Distribution of event characteristic distances obtained by exponential fit

Characteristic extent ~ 200 m ≥ 5.10^{16} eV

5 - Shower energy dependence





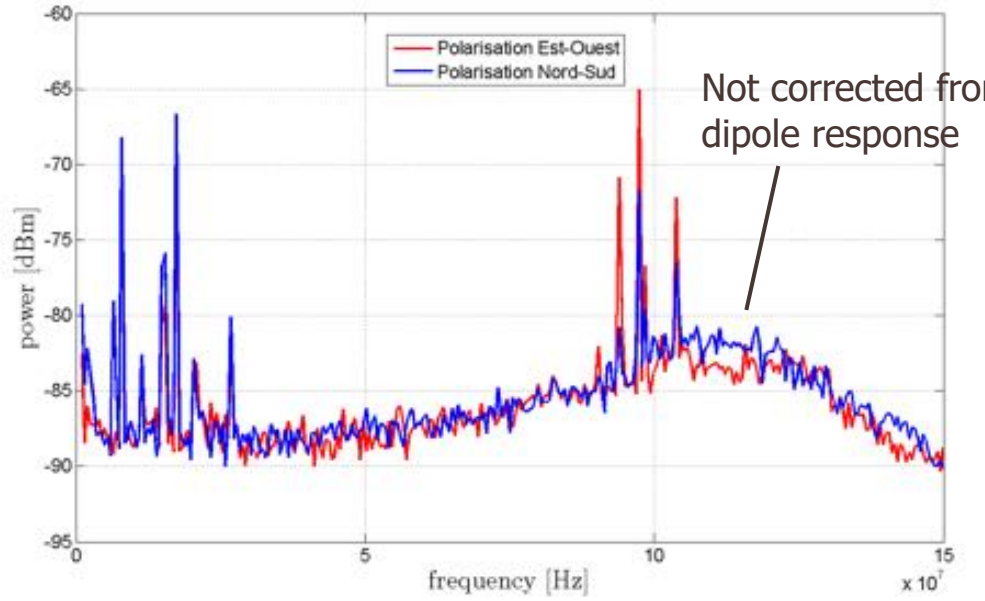
$$\varepsilon_{est,E_p} = (12 \pm 1.8)\left[\frac{\mu V}{m\ MHz}\right](1+(0.1\pm0.03)-\cos(\alpha))\cos(\theta)$$
$$\times \exp\left(\frac{-R_{SA}}{(200\pm45)m}\right)\left(\frac{E_p}{10^{17}eV}\right)^{(0.91\pm0.07)}$$

Horneffer 2006, PhD thesis
based on new absolute flux calibration and one (NS) polarization

Difficulty to work close to the energy threshold and with poor energy dynamics ⇒ Interpretation may differ, but main tendency is established

Why Radio @ Auger?

- Extension of energy range well above 10^{18} eV (threshold some 10^{17} eV $\Rightarrow$ overlap with LOPES and CODALEMA energy ranges)
- **Merging information from 3 independent detectors should help to precise shower characteristics and nature of the primary**
- Access to very large areas (mandatory to gain statistics)
- The radio sky is very good in the pampa !



Sky background @ Auger, CLF

Prospective on Auger South

- Began in late 2006 (NL, D, F, USA, coord.: Ad van den Berg)
- Phase 1: test of different antennas and trigger concepts
- Phase 1 bis (current): setting two types of autonomous stations on the same site (BLS) for comparison purposes

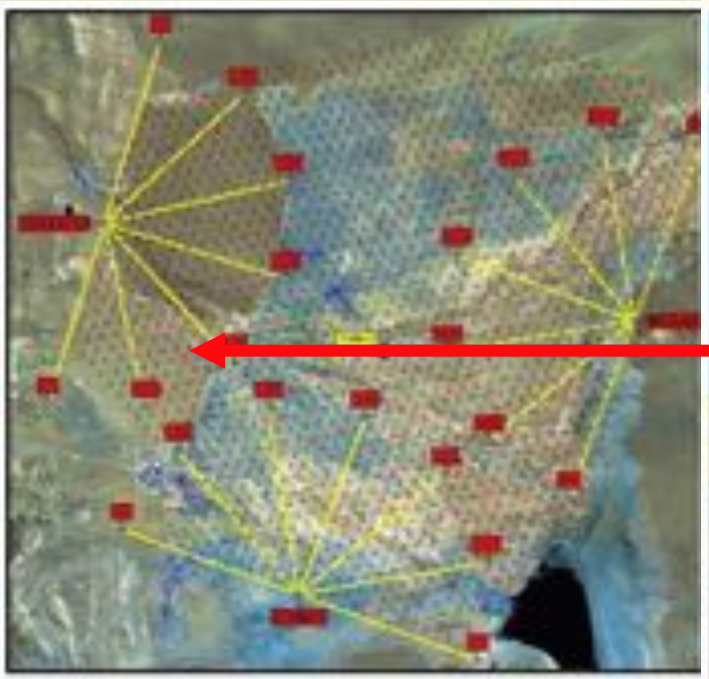
⇒ Derive technical parameters (antenna, trigger, array driving…) with benefit of LOPES and CODALEMA experience

- Phase 2 (2009-20..): setting up a 20 km^2 array for "super-hybrid" detection (SD, FD and radio)

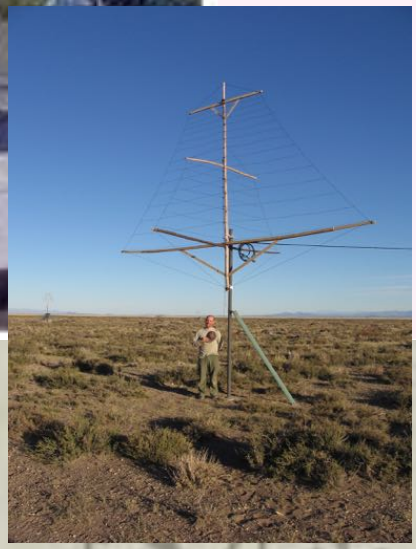
Necessitates autonomous radio detectors

Necessitates strong technical cooperation

Necessitates continuous theoretical effort



BLS

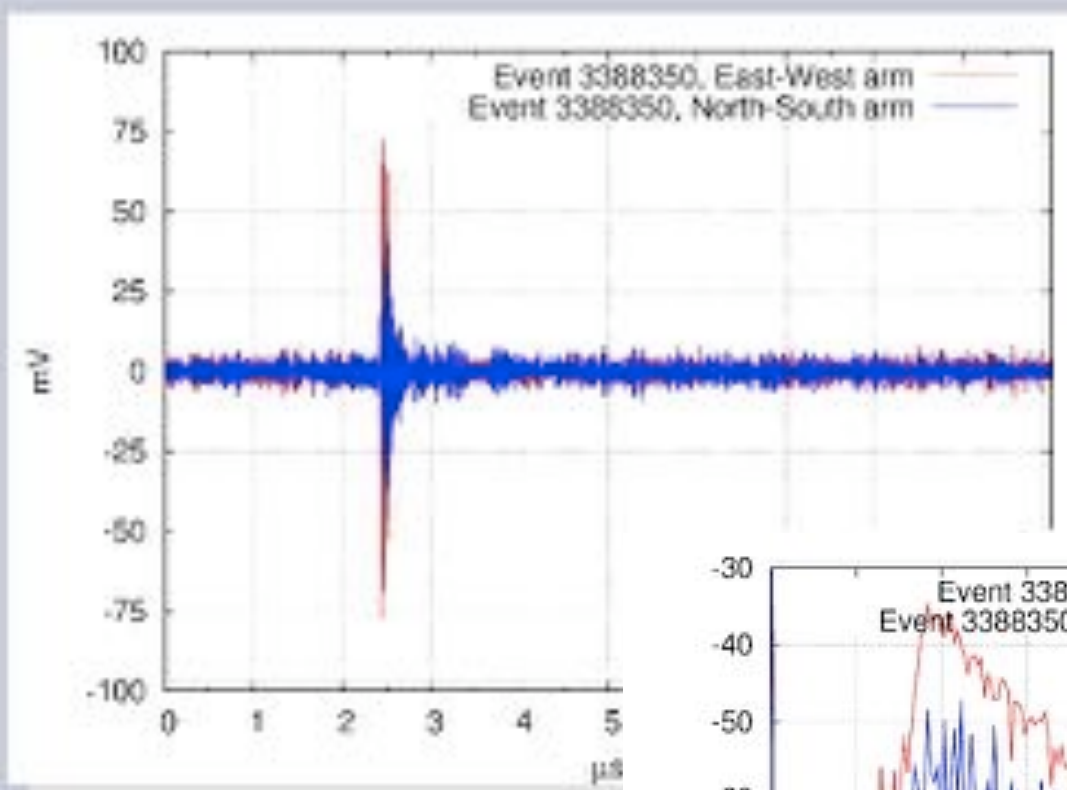


Location: BLS (NL, D, USA)

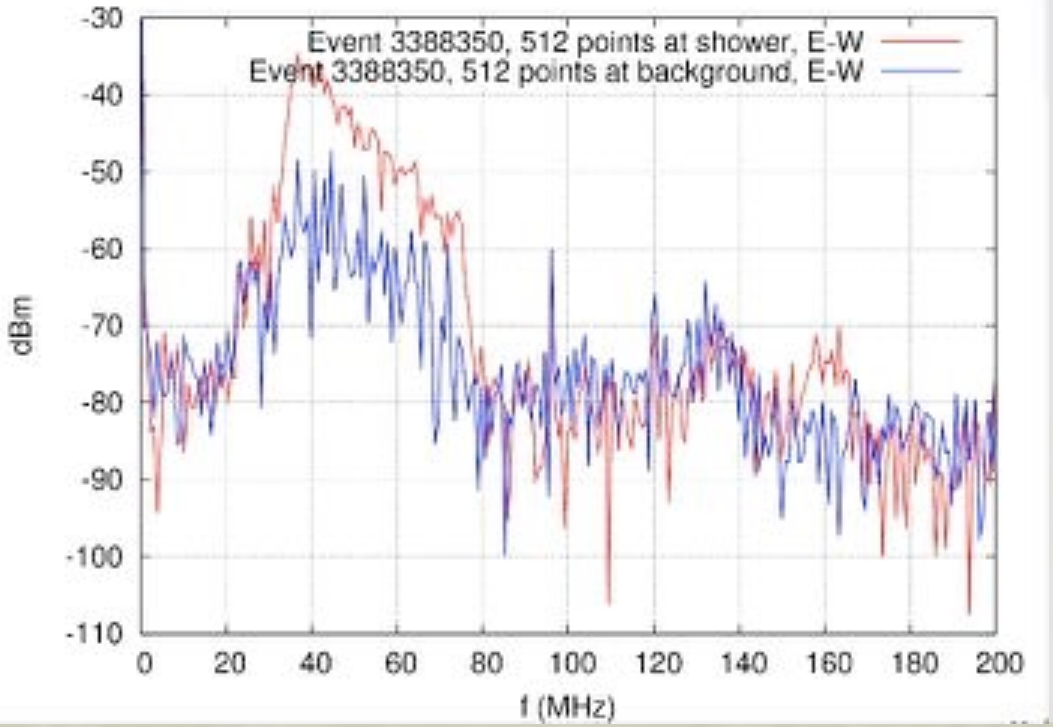
Several antennas tested, triggered by plastic scintillators

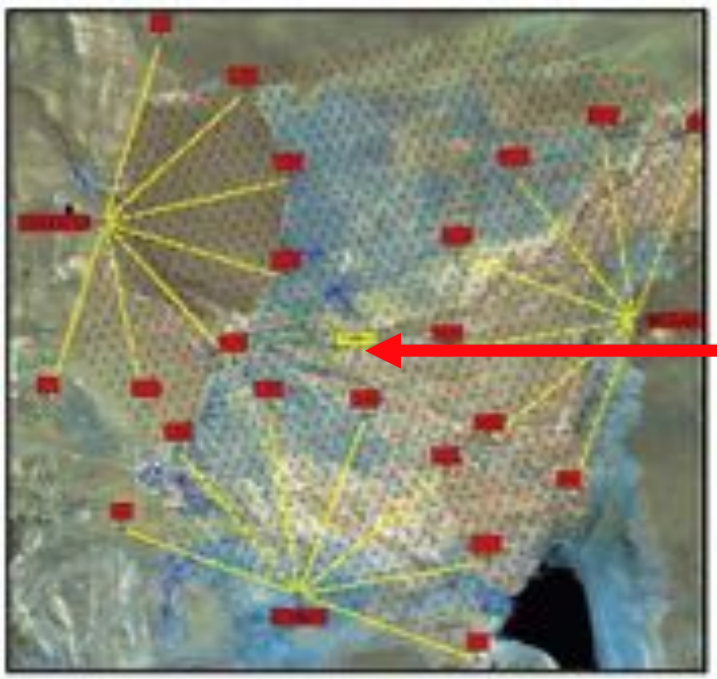
Coincidence between radio signals and Auger events were found (same principle as CODALEMA and LOPES)

BLS: First results



Event 3388350





Pierre Auger Observatory

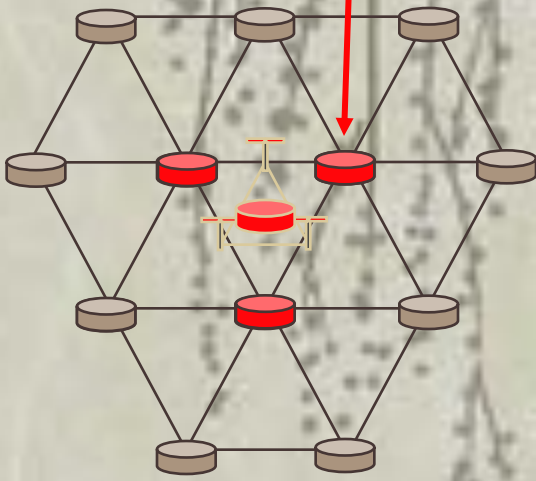
Central Laser Facility

SD Tank

Location: CLF

(F)

3 self triggered, fully autonomous stations based on CODALEMA experience



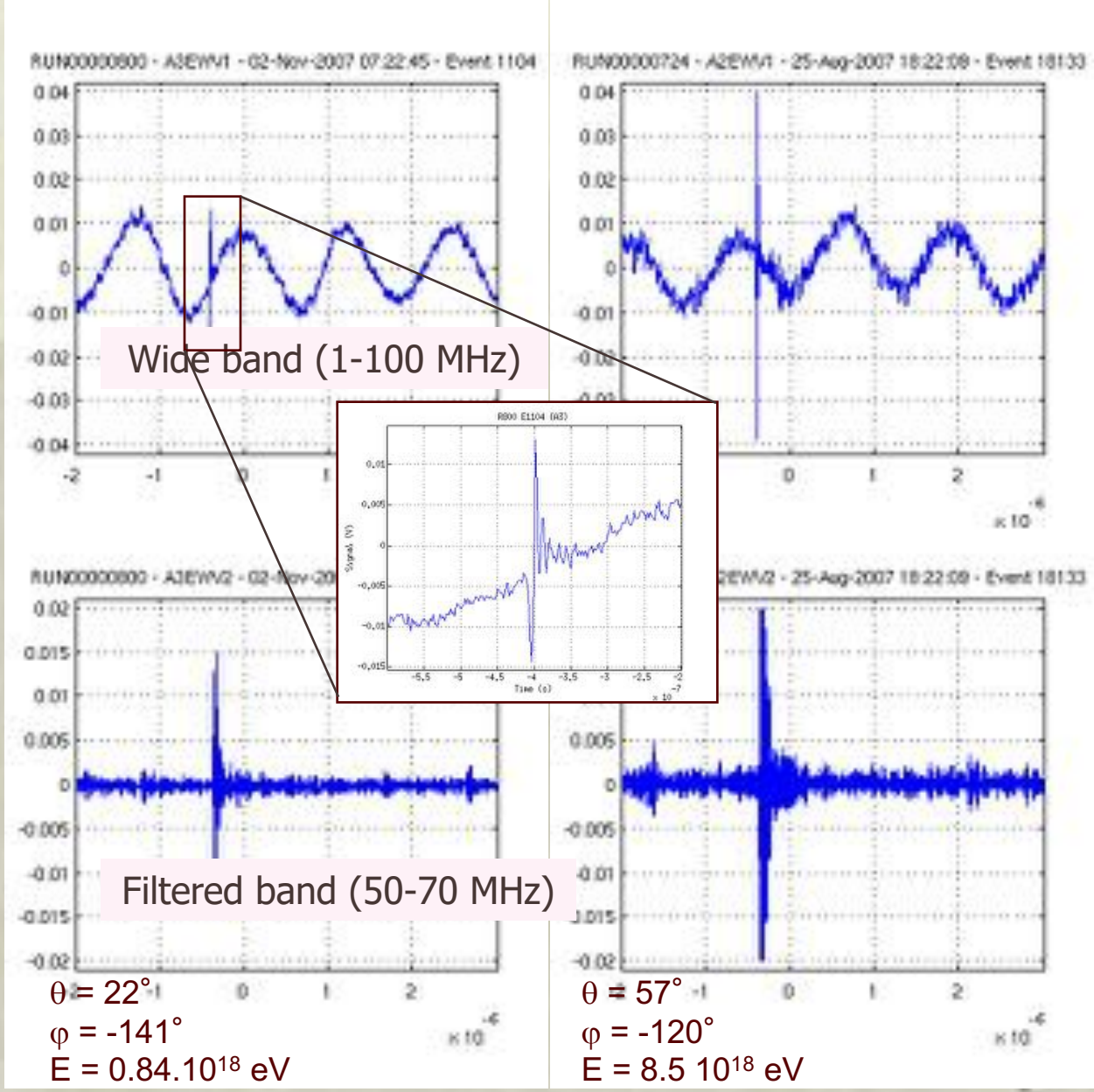
Self-triggered antennas: first events

First CR events ever detected independentely by a radio system!

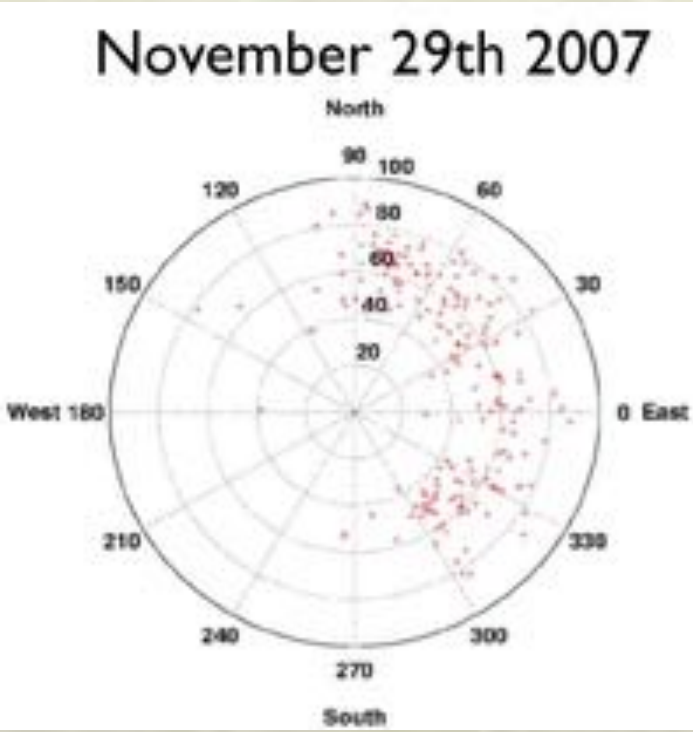
22 coincident events with Auger since July 2007, 9 since February (stable)

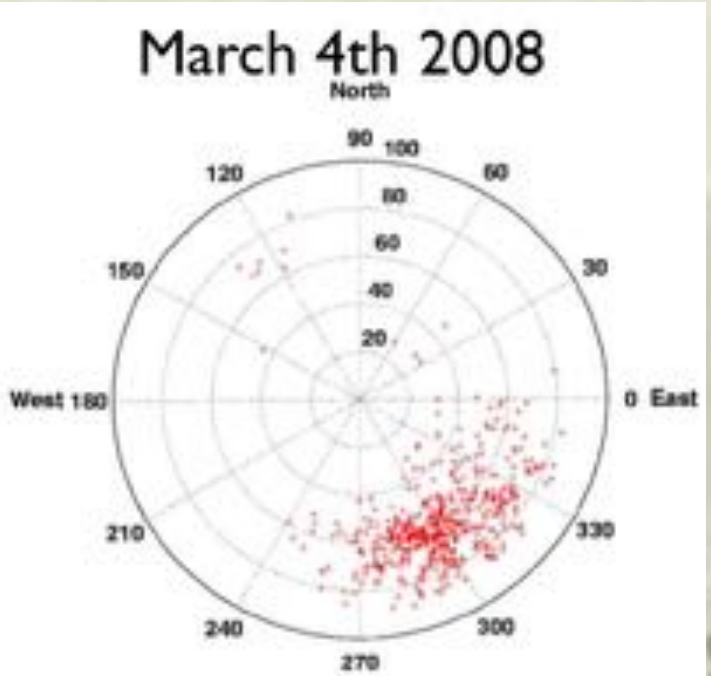
Still need a particle detector to confirm the detection by exploring time coincidences between the two systems

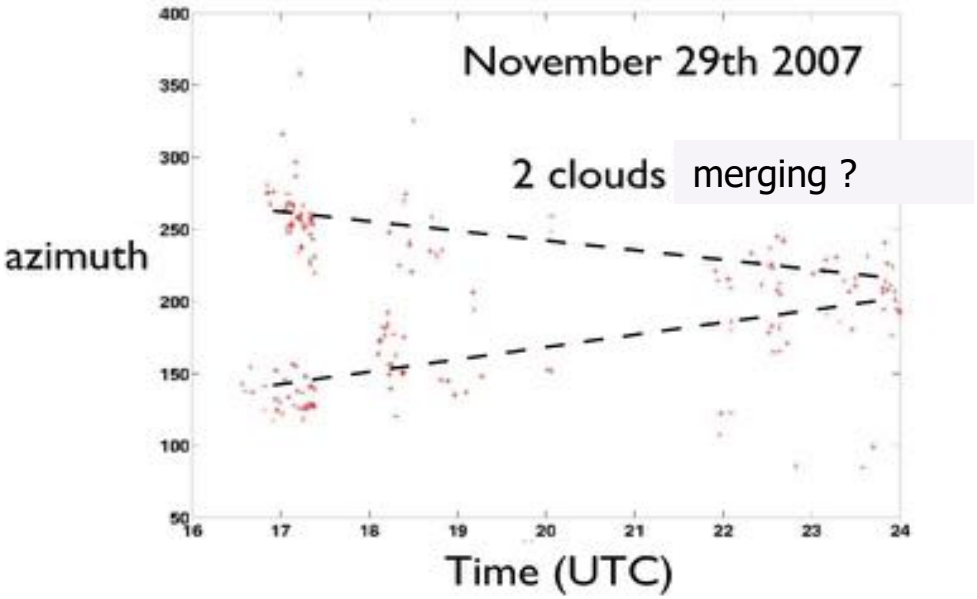
New generation of autonomous radio stations is coming soon (2 design)



Triangulation on storms







Outlook

✓Radiodetection of cosmic rays works and is roughly independent of the antenna and electronics, provided the adapted method is chosen ⇒ **The physics is robust, the signal is firm**

✓Signal is driven mainly by geomagnetic effects (not necessarily geosynchrotron) ⇒ **Theoretical work is still needed despite strong advances and good predictions**

✓Current results concern energies close to the threshold: analysis is difficult, interpretation may differ, but main tendencies are defined ⇒ **Need to extend energy range**

✓Radio is very promising for detecting inclined air showers (neutrinos ?), transient radiodetection also foreseen on other sites (LOFAR in Europe, 21CMA in China…) ⇒ **The method is spreading**

⇒ **A super hybrid detector covering a large area on Auger should help making strong progress on all those scopes**

✓**Byproduct:** fast transient radio detection method can open new windows also on purely astronomical fields (pulsars, Cerenkov observations of γ-ray from nearby sources…)