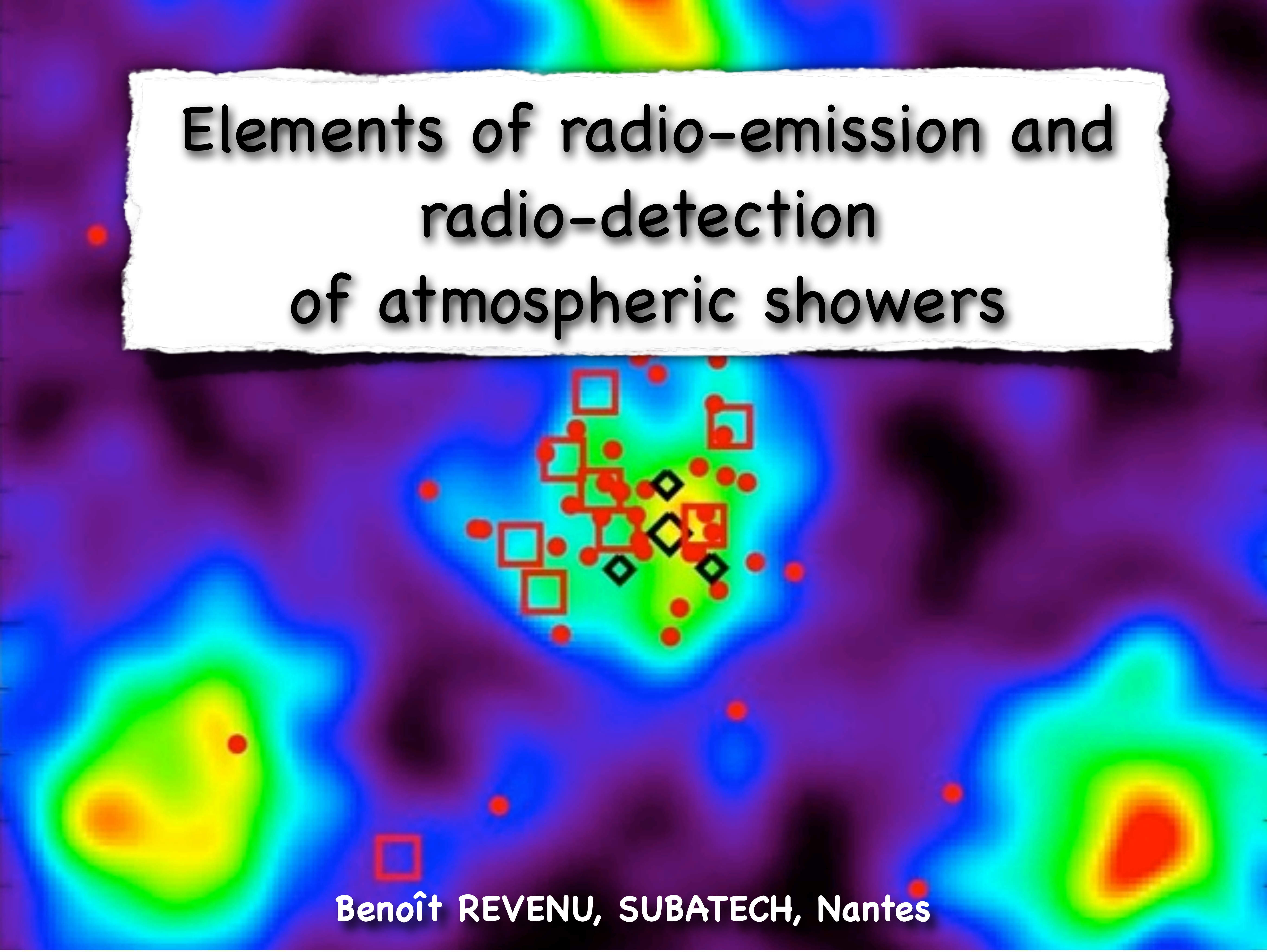
Elements of radio-emission and radio-detection of atmospheric showers



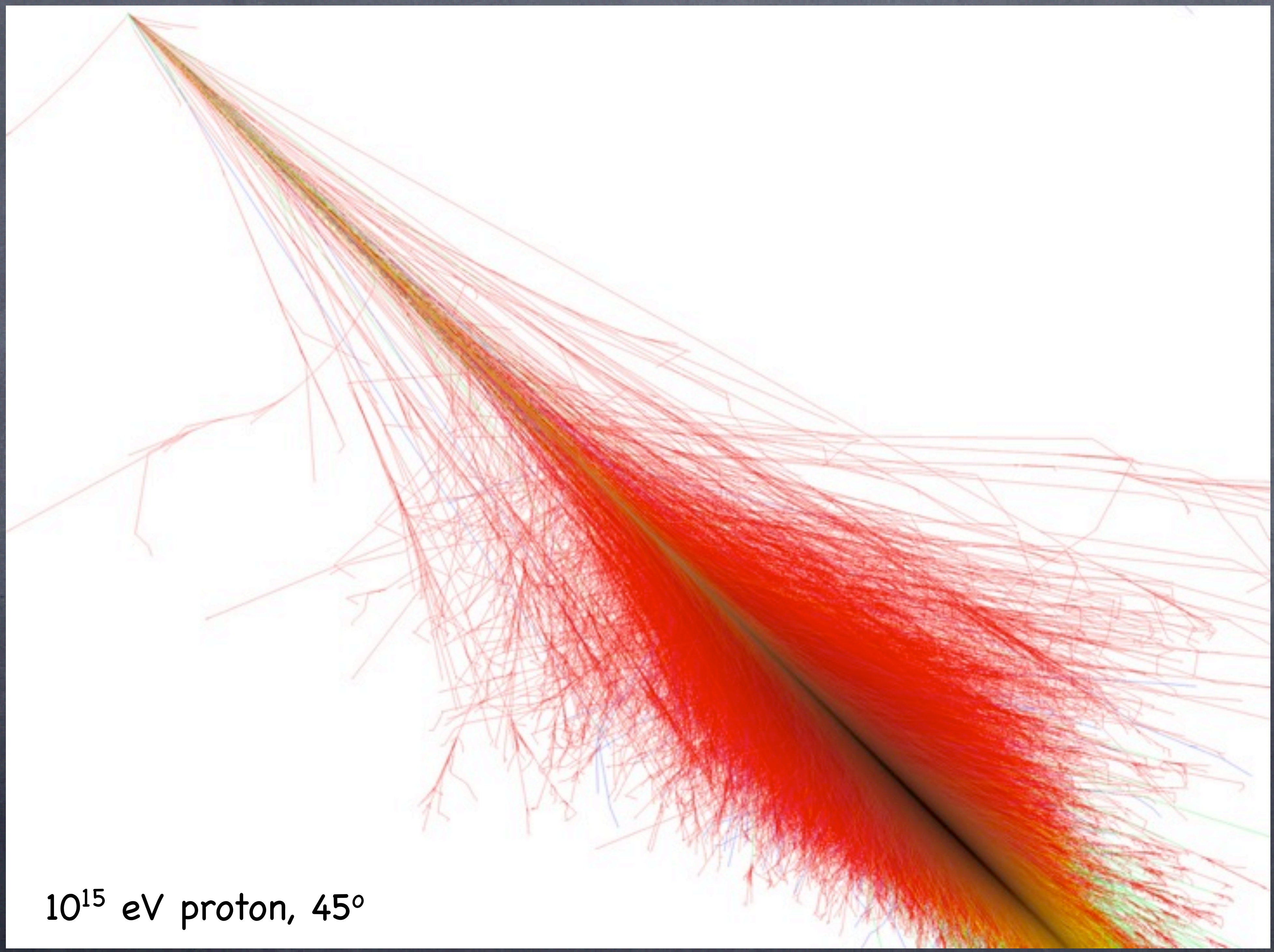
Benoît REVENU, SUBATECH, Nantes

Outlook

- Introduction
  - some numbers on atmospherical showers
  - secondary particles and fluorescence light
- Emission of the electric field
  - orders of magnitude with Coulomb
  - polarisation with the radiative contribution
- Radio detection
  - in Nançay (CODALEMA) and in Malargüe (Auger)
  - the future

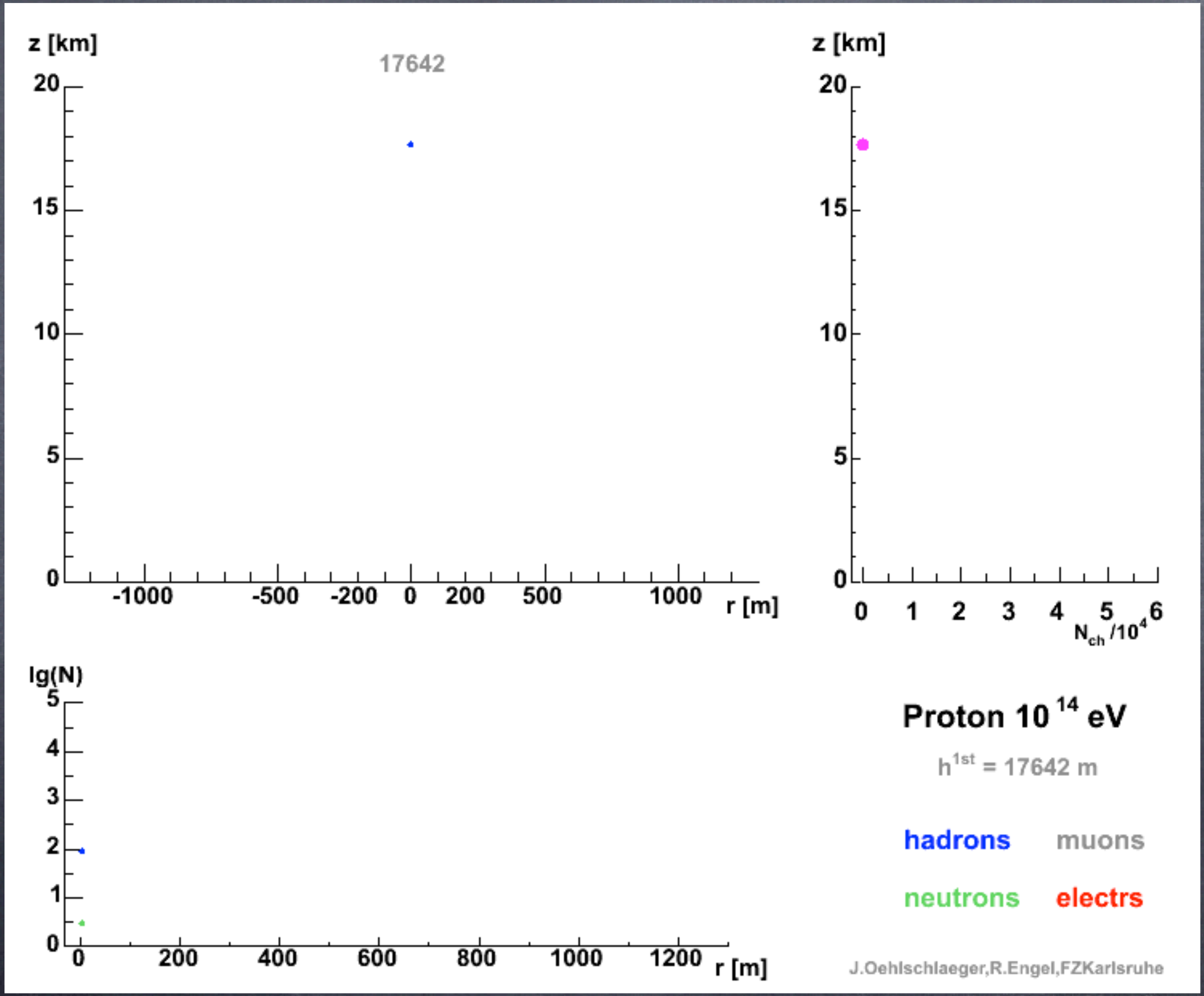
Shower composition

99 % of gammas, electrons, positrons, 0.9 % of muons

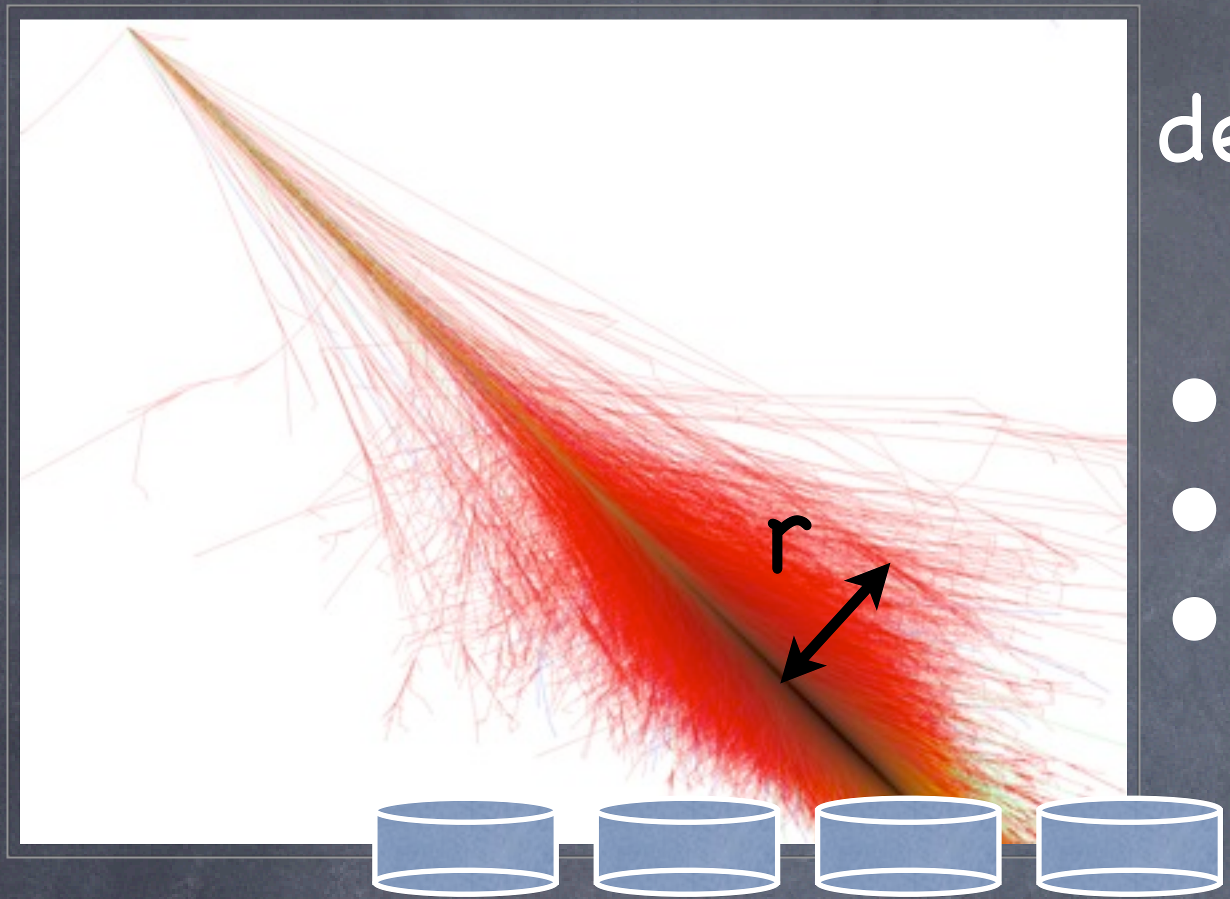


F. Schmidt, "CORSIKA Shower Images", http://www.ast.leeds.ac.uk/~fs/showerimages.html

Shower composition

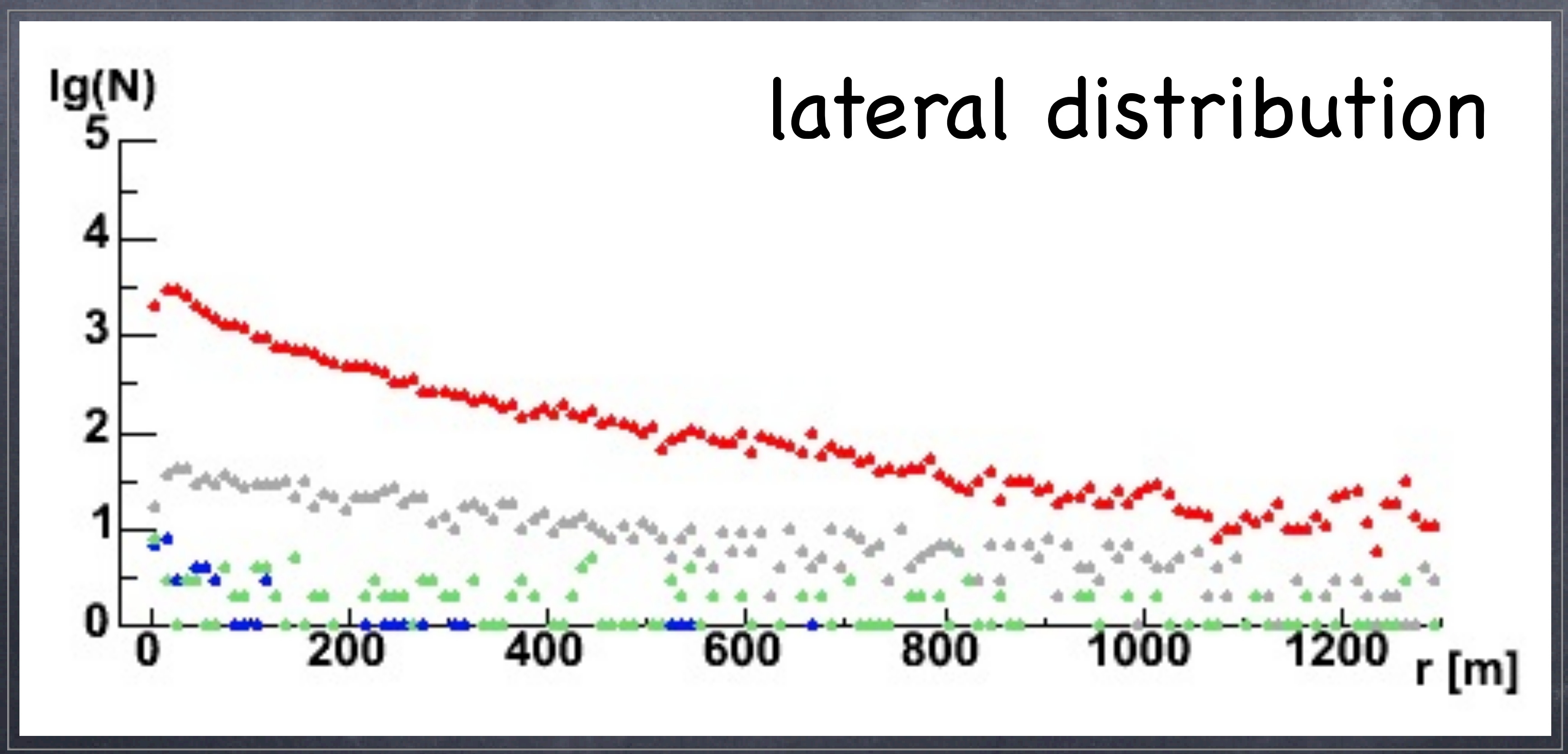


Shower composition



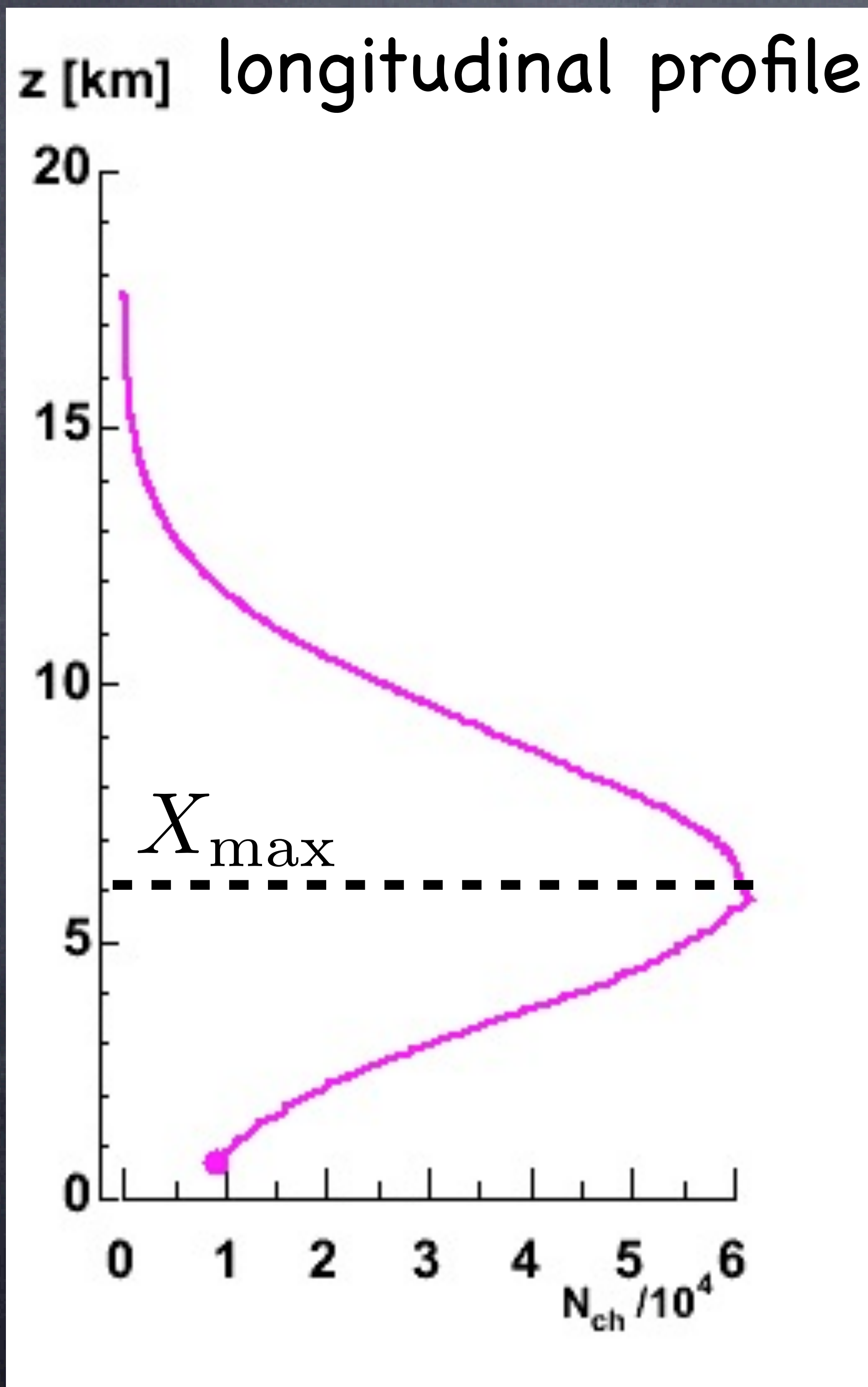
detection of the ground particles

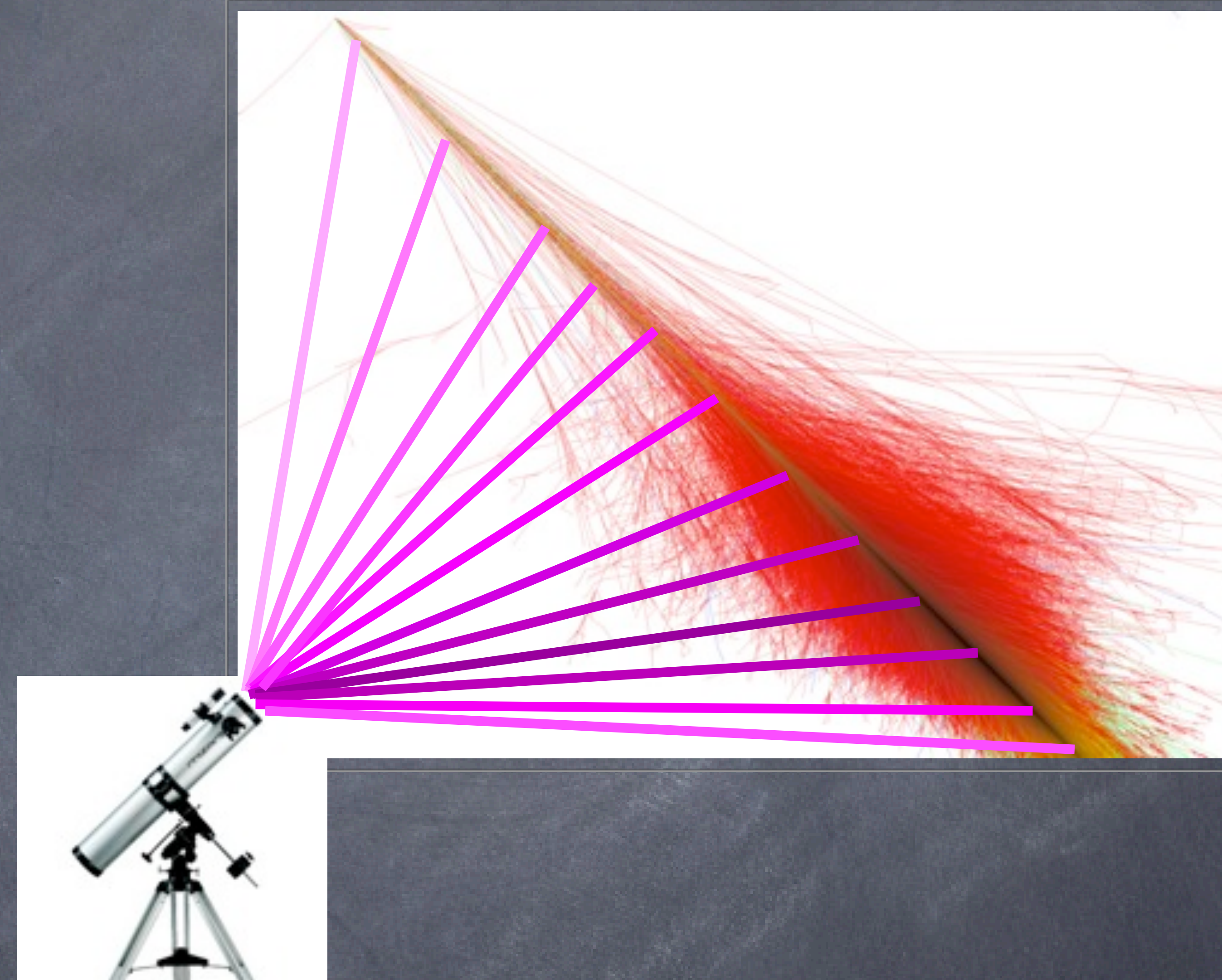
- estimate of the arrival direction
- estimate of the primary energy
- constraints on the nature of the primary



Shower composition

detection of the fluorescence light





$X_{\max}$: depends on the nature and the energy of the primary

calorimetric measurement

effective time around 10%

Radio-emission: electric field

at EeV energies, huge number of secondary particles (few 10^8)

$$\vec{E} = \frac{e}{4\pi\varepsilon_0}\left[\frac{\vec{n}-\vec{\beta}}{\gamma^2 R^2 (1-\vec{\beta}.\vec{n})^3} + \frac{\vec{n}\times((\vec{n}-\vec{\beta})\times\vec{\beta}')}{Rc(1-\vec{\beta}.\vec{n})^3}\right]_{\mathrm{ret}}.$$

Lorentz force

Coulombian scattering with other charges

the complete computation is impossible

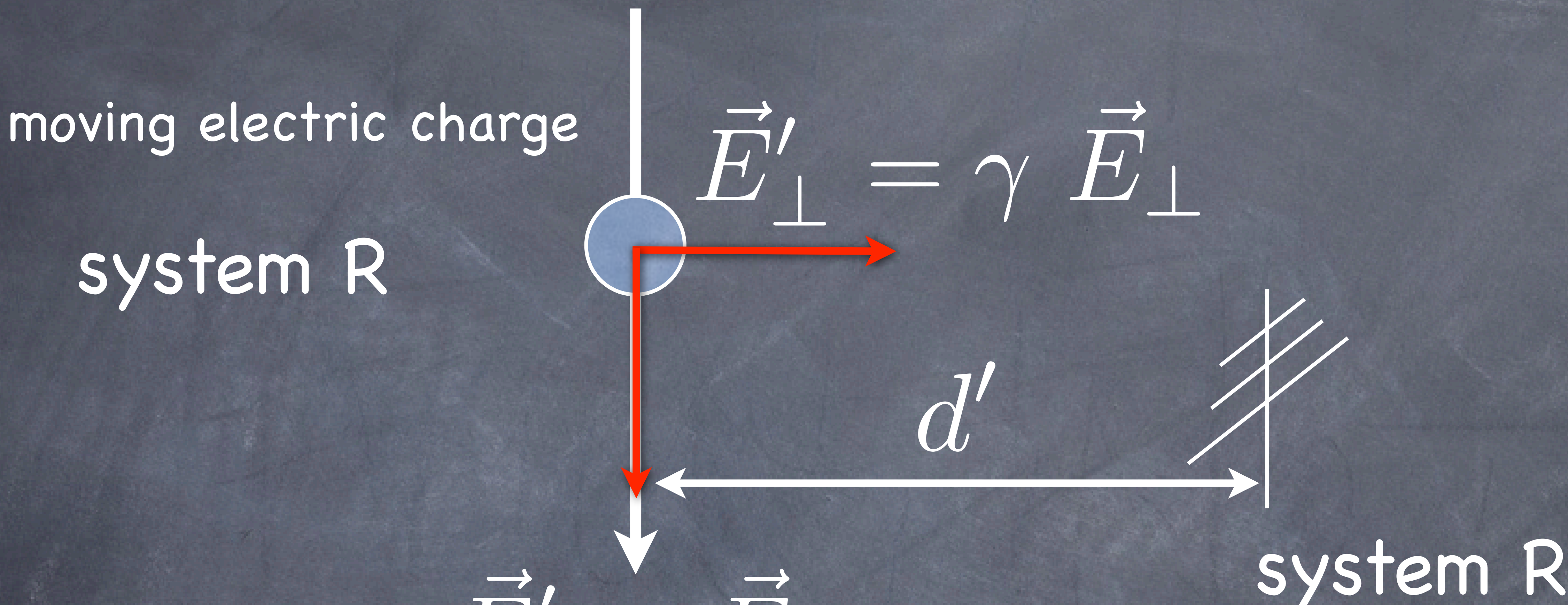
choice between 2 descriptions:

microscopic and macroscopic

Radio-emission: Coulombian approach

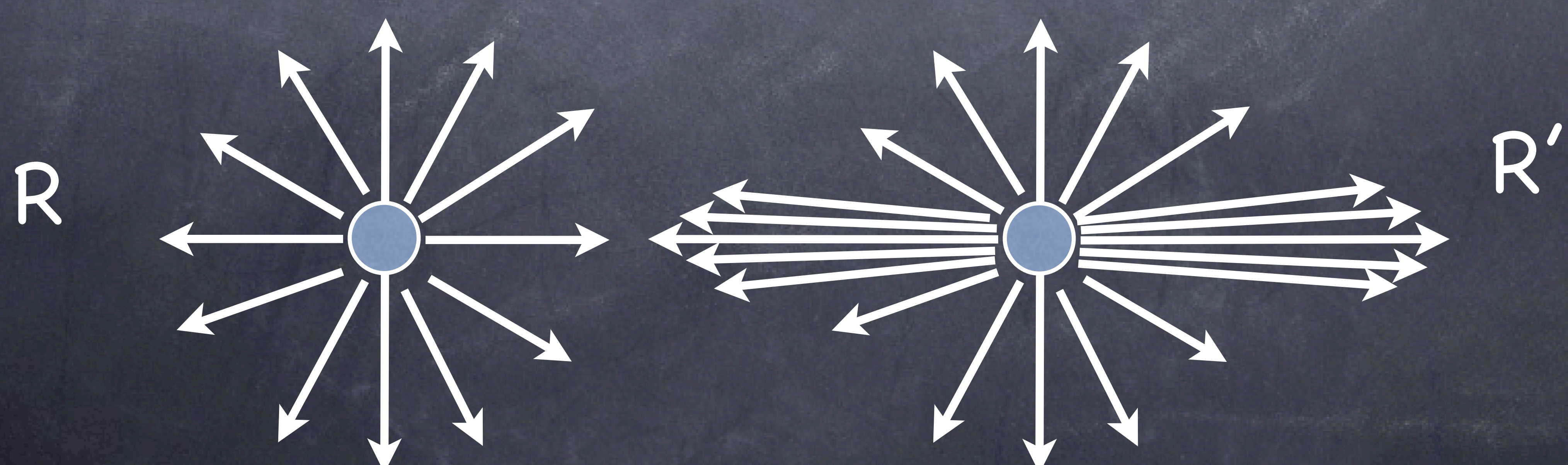
But before this, to get the orders of magnitude, consider only the Coulombian contribution to the electric field

Radio-emission: Coulombian approach



$$\vec{E}'_{\perp} = \gamma\ \vec{E}_{\perp}$$

$$\vec{E}'_{\parallel} = \vec{E}_{\parallel}$$



Radio-emission: Coulombian approach

$$E'_{\perp} = \frac{\gamma\, q\, d'}{4\pi\varepsilon_0 \left(\gamma^2\beta^2c^2t'^2 + d'^2\right)^{3/2}}$$

origin of times: when the impact parameter is the smallest

from FD: the number of charges is proportionnal to the primary energy

true also for the field! (proportionnal to q)

$$||\vec{E}|| \propto E_p$$

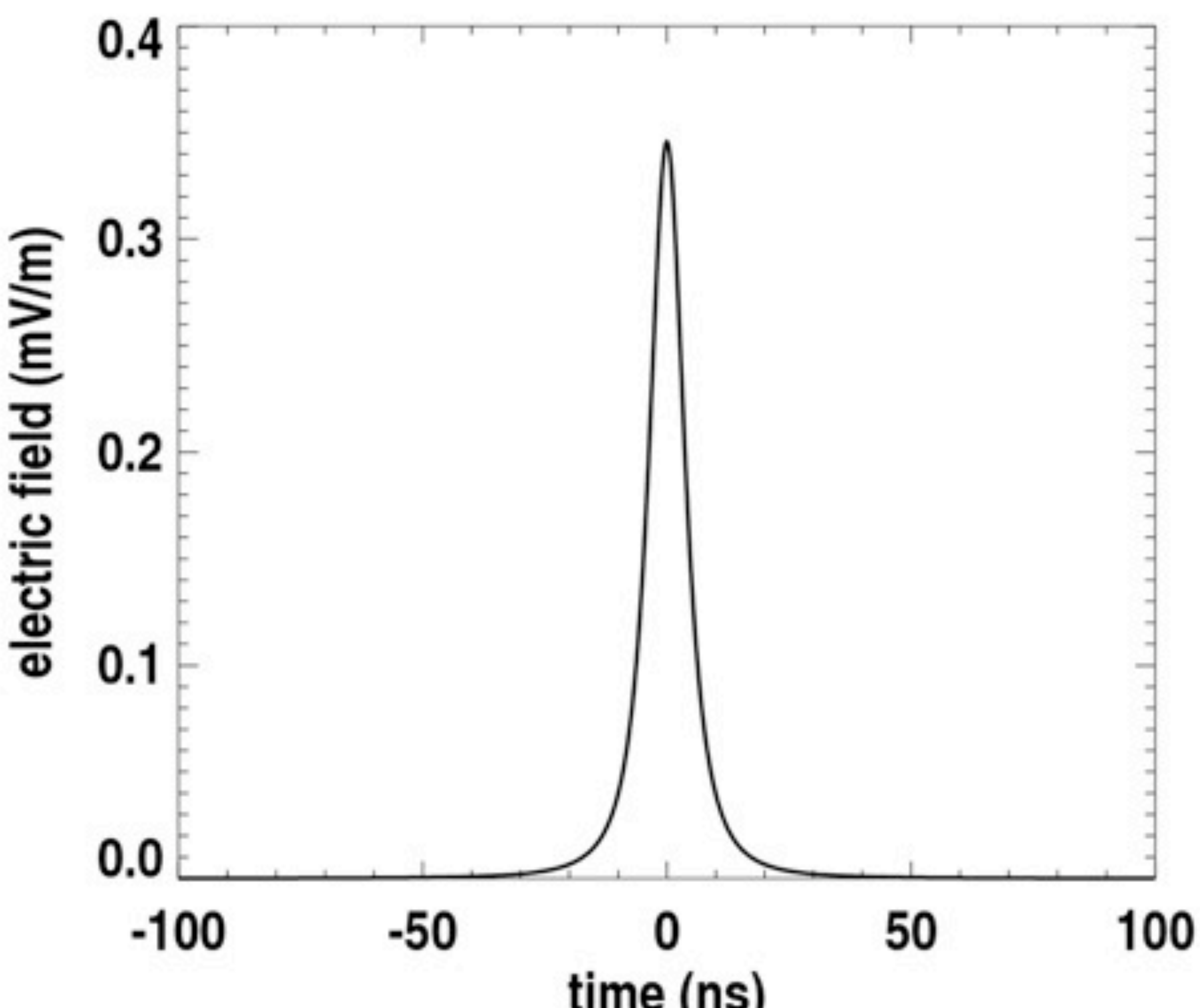
30 MeV e^- ($\gamma \sim 60$), 2.10^8 e^- at Xmax (2×10^{17} eV shower), e^- in excess at the level of 20%

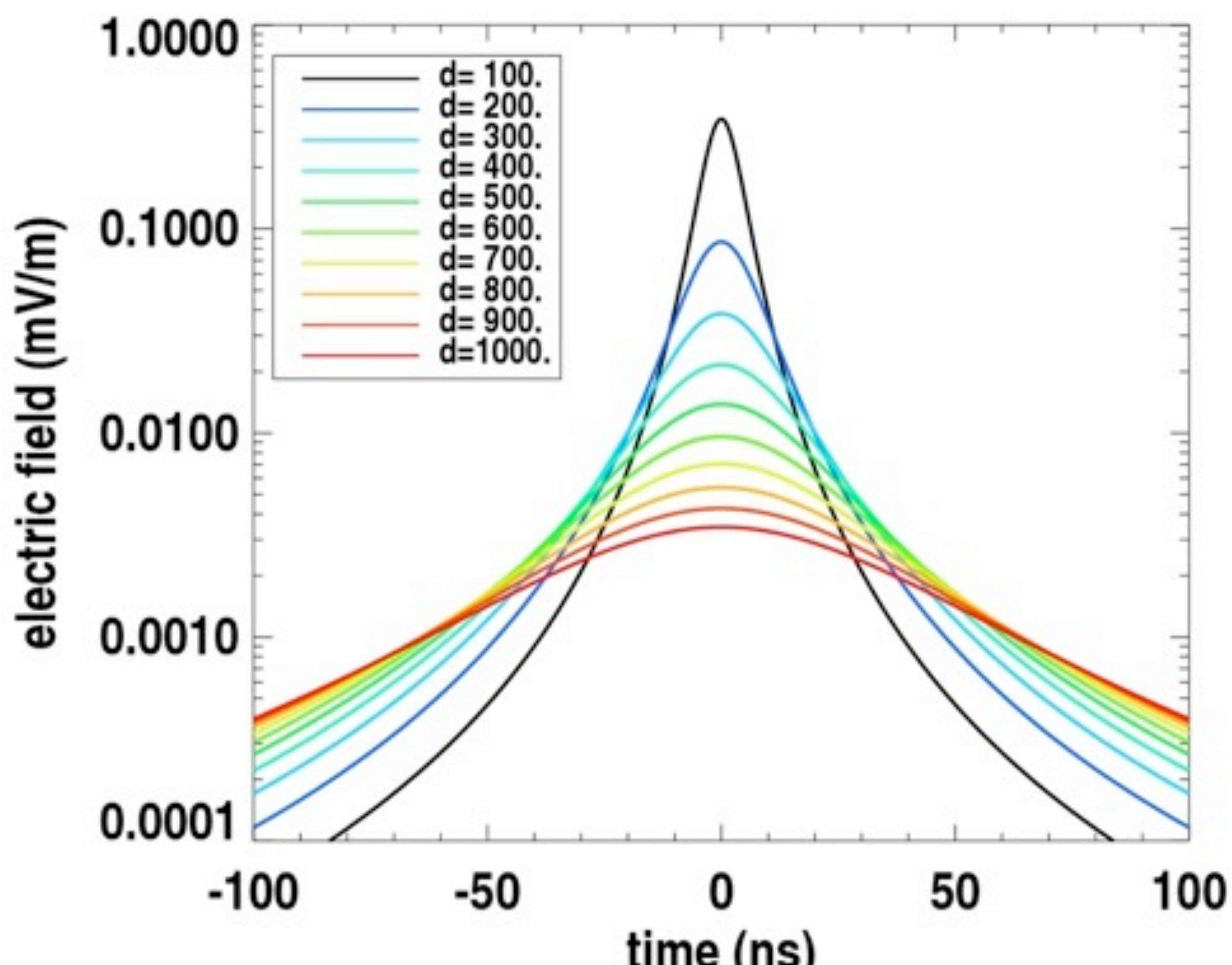
Radio-emission: Coulombian approach

$$E_{\max} = \frac{\gamma\, q}{4\pi\varepsilon_0\, d^2}, \quad \tau = \frac{d}{\gamma\, c}$$

0.1 mV/m for d = 100 m

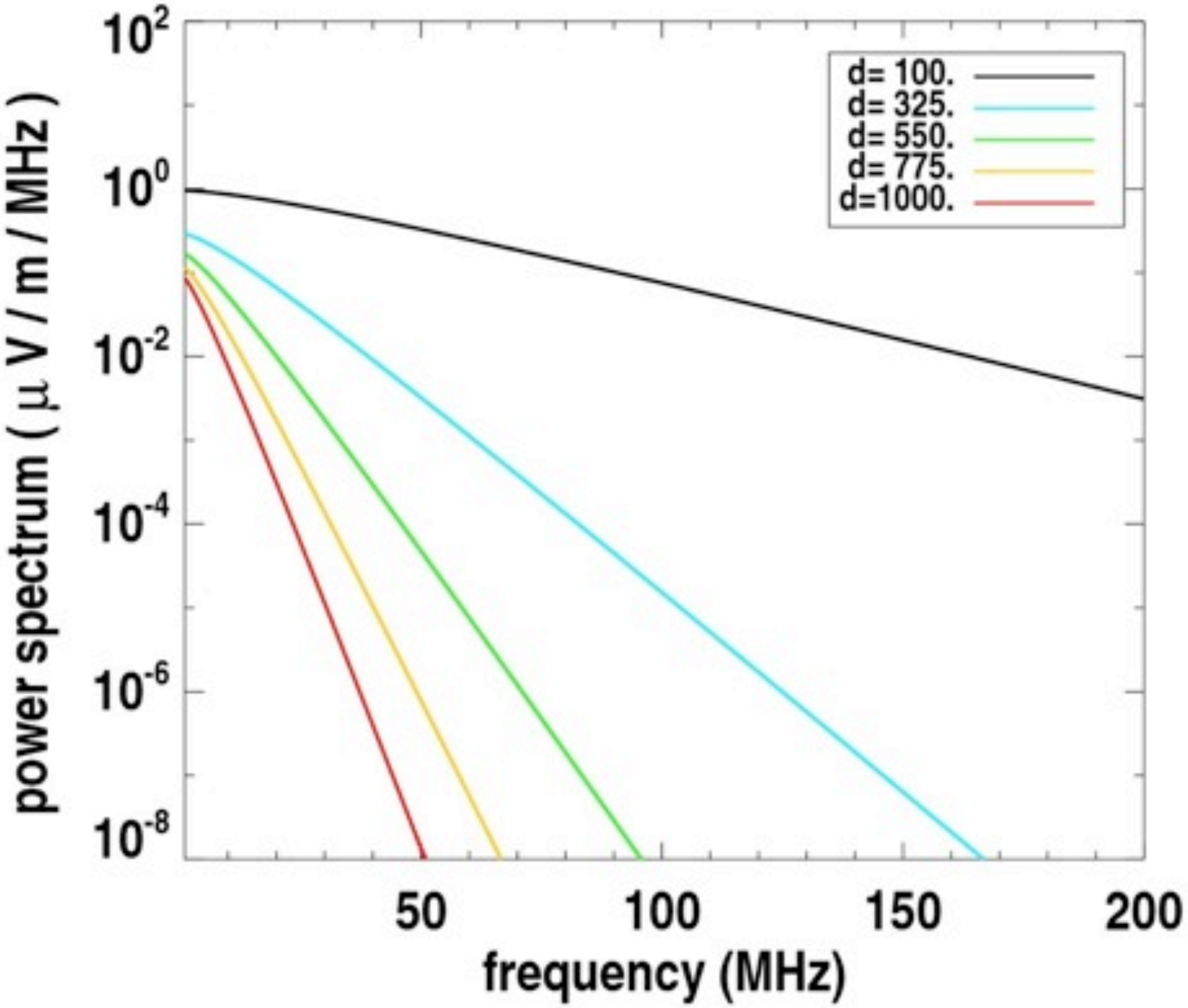
monopolar pulse,
duration is 5 ns FWHM

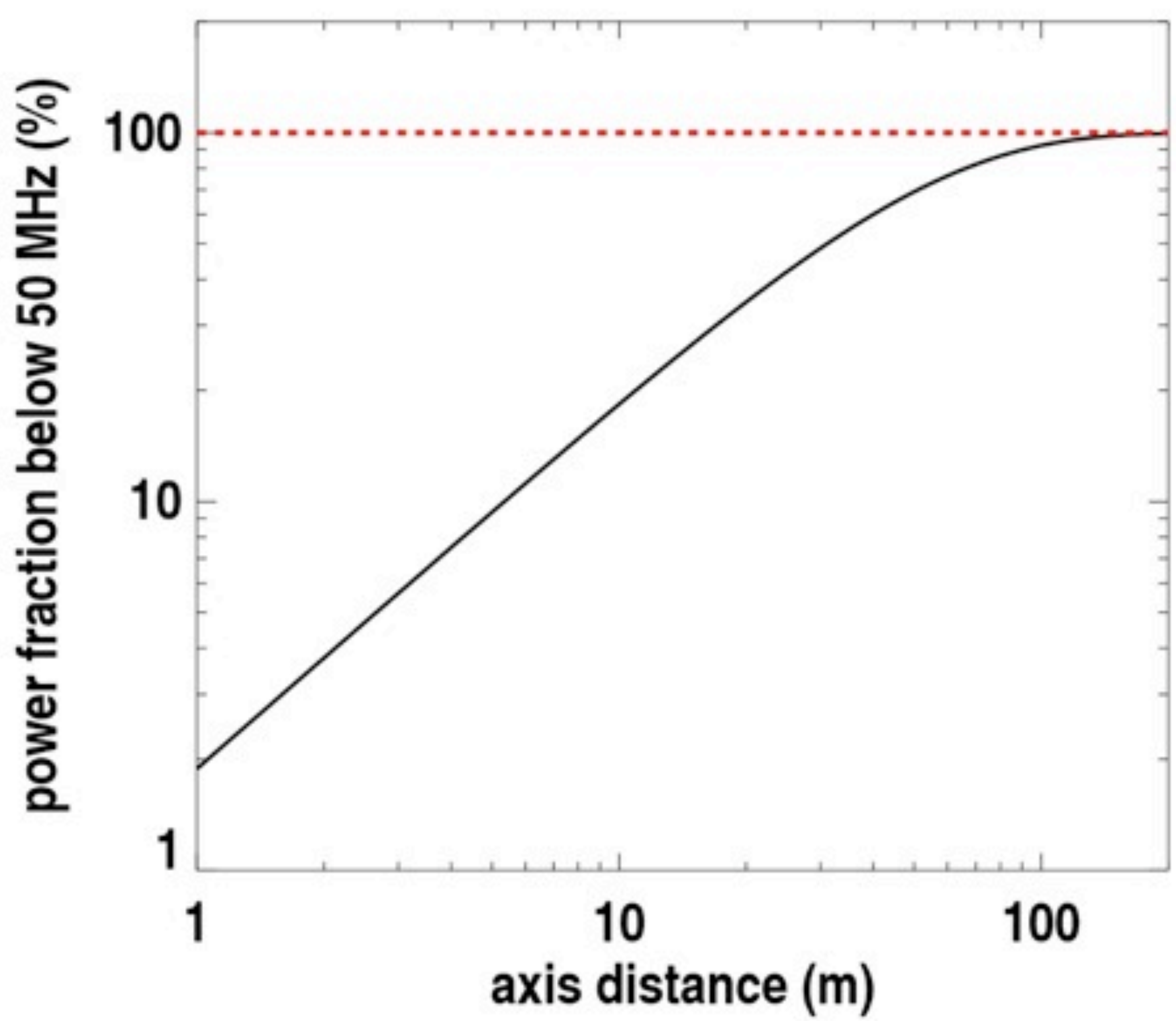




Radio-emission: Coulombian approach

Frequency spectrum





important to detect the electric field at low frequencies to be able to see distant showers

Radio-emission: Coulombian approach

what we learnt with the Coulombian approach

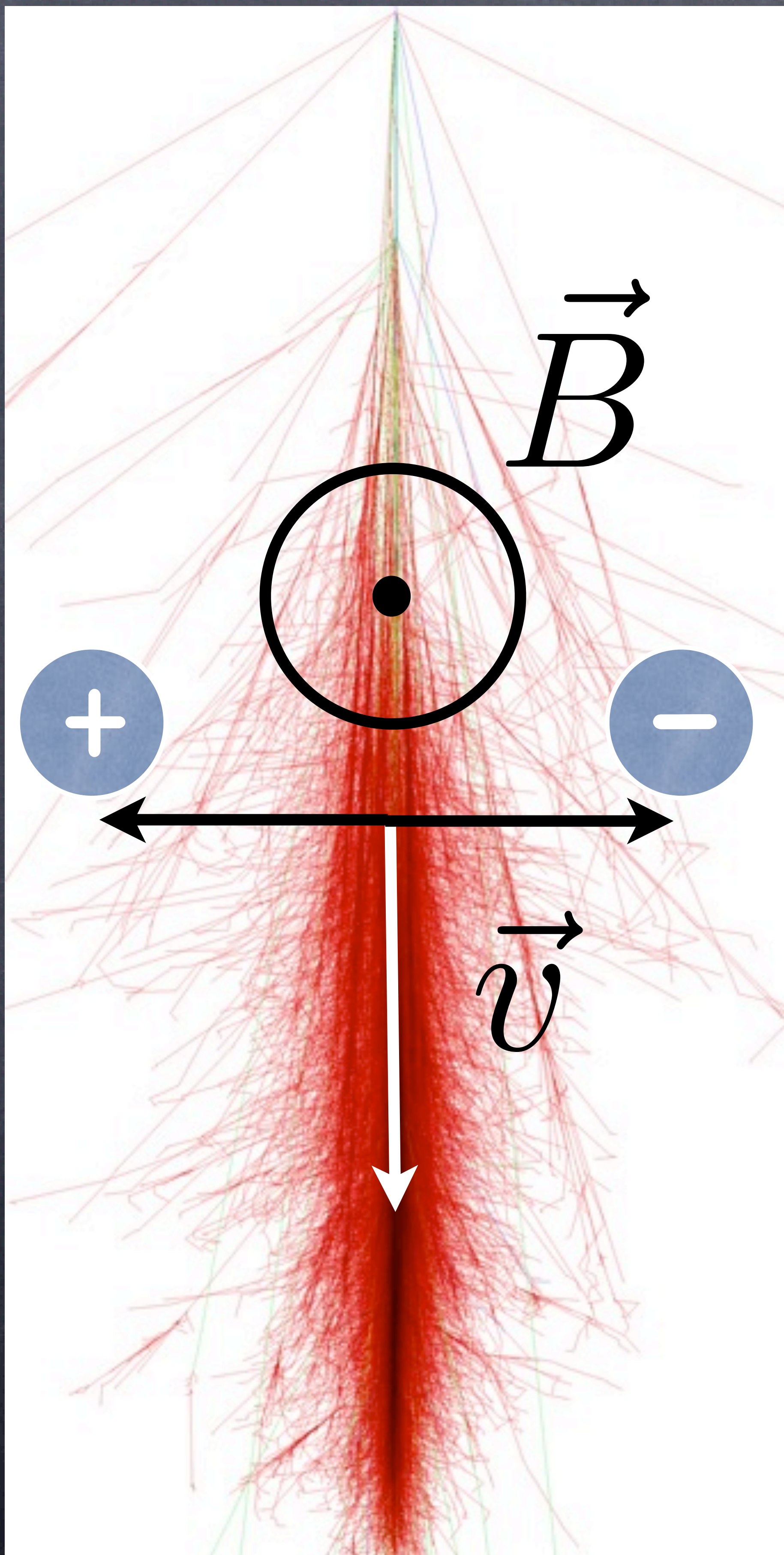
- the electric field is proportionnal to the number of charges and consequently to the primary energy
- the signal is in the [1-200] MHz band
- we need a large bande antenna to detect distant showers
- we need a sensitive antenna to be able to detect electric fields below mV/m
- choose a radio-quiet site to limit human pollution

Radio-emission: some details

we must take into account other phenomenons

- the air index varies with altitude and weather conditions (Cerenkov)
- the shower is not 1D, we must consider the lateral and longitudinal distributions
- the shower front thickness is of the order of few meters corresponding to frequencies between 1 MHz and 200 MHz (scales as N^2, in the coherence domain)
- $\vec{B}$ systematically separates the charges with the Lorentz force

Radio-emission: different descriptions



Macroscopic or microscopic...

- Cerenkov emission from the excess of electrons (10-20 % excess), effet Askaryan
- current emission, $\vec{j}$ $A^\mu \propto \int j^\mu / R$
- coherent synchrotron emission of the e^+/e^- pairs
- radiative field of the accelerated charges in the magnetic field
- boosted Coulombian field
- shower polarisation (dipole)

year	theory	experiments
1962	Askaryan: Cerenkov from electrons	
1965	Kahn and Lerche: charge excess, transverse current (dominant), dipole	Jelley, first radio pulses in coincidence with Geiger counters
1970		Allan's parameterisation : $\mathcal{E}_\nu = 20 \left(\frac{E_P}{10^{17}\ \mathrm{eV}} \right) \sin\alpha \cos\theta \exp\left(-\frac{R}{R_0(\nu,\theta)} \right)$.
1970	End of the radiodetection	
2000	New technologies: reborn of radio	
2003	Falcke, Gorham, Huege: synchrotron coherent emission of the e^+/e^- pairs	CODALEMA, LOPES
2005	DuVernois, Cai, Kleckner: radiative emission of the charged particles	CODALEMA, LOPES
2007 2008	Scholten, Werner: transverse current Meyer, Lecacheux, Ardouin: boosted coulombian field, Cerenkov	CODALEMA, LOPES, RAuger
2009, 2010		CODALEMA, LOPES, RAuger, AERA CODALEMA phenomenology: $\vec{v} \times \vec{B}$

Radio-emission: different signatures

- Cerenkov from e^-: no directional signature ; dominant effect in a dense material (water, ice....): GLUE, ANITA, RICE, SALSA
- transverse current: bipolar pulse, polarisation along v X B, peak due to the early stages of the shower, the field is due to the longitudinal development
- e^+/e^- synchrotron: monopolar pulse, peak due to the shower maximum
- radiative field from accelerated particles: monopolar pulse, polarisation along v X B
- Coulombian field: due to the low energy part of the shower, no directional signature

summary: the field is due to the shower development and some models predict a v X B dependence

Radio-emission: geomagnetic signature

the radiative contribution

Coulomb, near field

radiative, far field

$$\vec{E} = \frac{e}{4\pi\varepsilon_0}\left[\frac{\vec{n}-\vec{\beta}}{\gamma^2 R^2 (1-\vec{\beta}.\vec{n})^3} + \frac{\vec{n}\times((\vec{n}-\vec{\beta})\times\vec{\beta}')}{Rc(1-\vec{\beta}.\vec{n})^3}\right]_{\rm ret}.$$

with

$$t_{\rm obs} = t + \frac{|R(t)|}{c} \qquad \vec{\beta}' = \omega\vec{\beta}\times\vec{b} \qquad \omega = \frac{eB}{\gamma m}$$

$$\vec{b} = \frac{\vec{B}}{B}$$

Lorentz!

synchrotron frequency

$$\vec{E}_{\rm radiative} \propto \vec{\beta}\times\vec{B}$$

Radio-emission: geomagnetic signature

model self consistence:

$$\frac{(\vec{v} \times \vec{B})_z}{(\vec{v} \times \vec{B})_{\mathrm{NS}}} = \frac{E_z}{E_{\mathrm{NS}}} = \mp \tan \theta_B$$

following N or S hemisphere

constant value!

but the vertical signal may be hard to detect
because of human activities

Radio-emission: geomagnetic signature

$$\vec{E}_{\mathrm{radiative}} \propto \vec{\beta} \times \vec{B}$$

Allan's formula (1970):

$\mu\mathrm{V.m}^{-1}.\mathrm{MHz}^{-1}$

$$\mathcal{E}_\nu = 20 \left(\frac{E_P}{10^{17}\ \mathrm{eV}} \right) \sin\alpha \cos\theta \exp\left(-\frac{R}{R_0(\nu, \theta)} \right) .$$

proportionnal to primary energy

$$\frac{|\vec{\beta} \times \vec{B}|}{\beta B}$$

atmospherical attenuation

exponential decrease with axis distance

Radio-technique: potentialities

- arrival direction and core position: triangulation with GPS timing and lateral distribution (like a SD)
- energy: electric field proportional to primary energy and due to the longitudinal development (like a FD)
- effective time close to 100 % (thunderstorms periods)
- cheap detector! (around 4 000 euros for a fully autonomous station, 1/3 of a Auger tank)

⇓

test with hybrid experiments

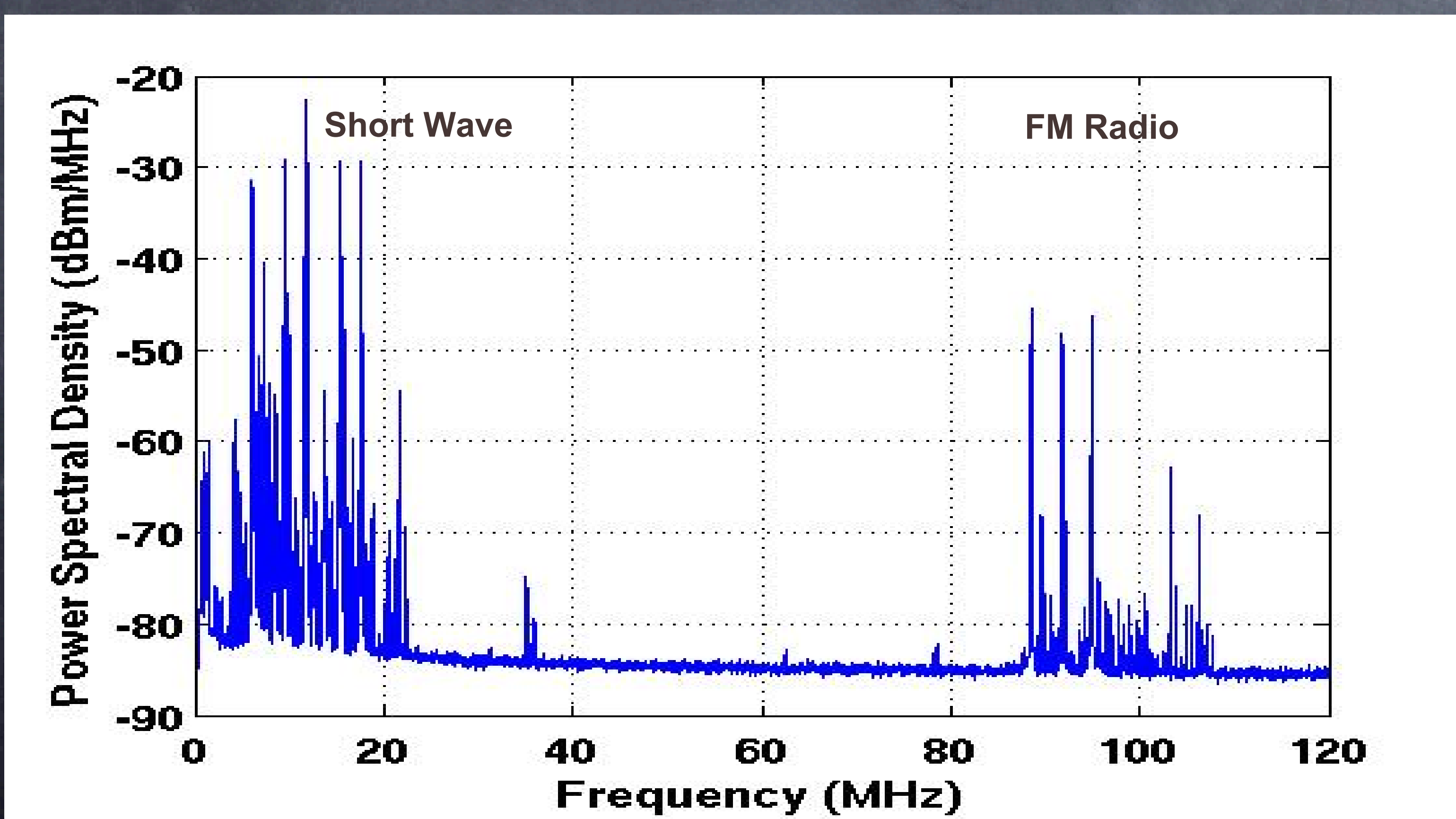
(CODALEMA, LOPES)

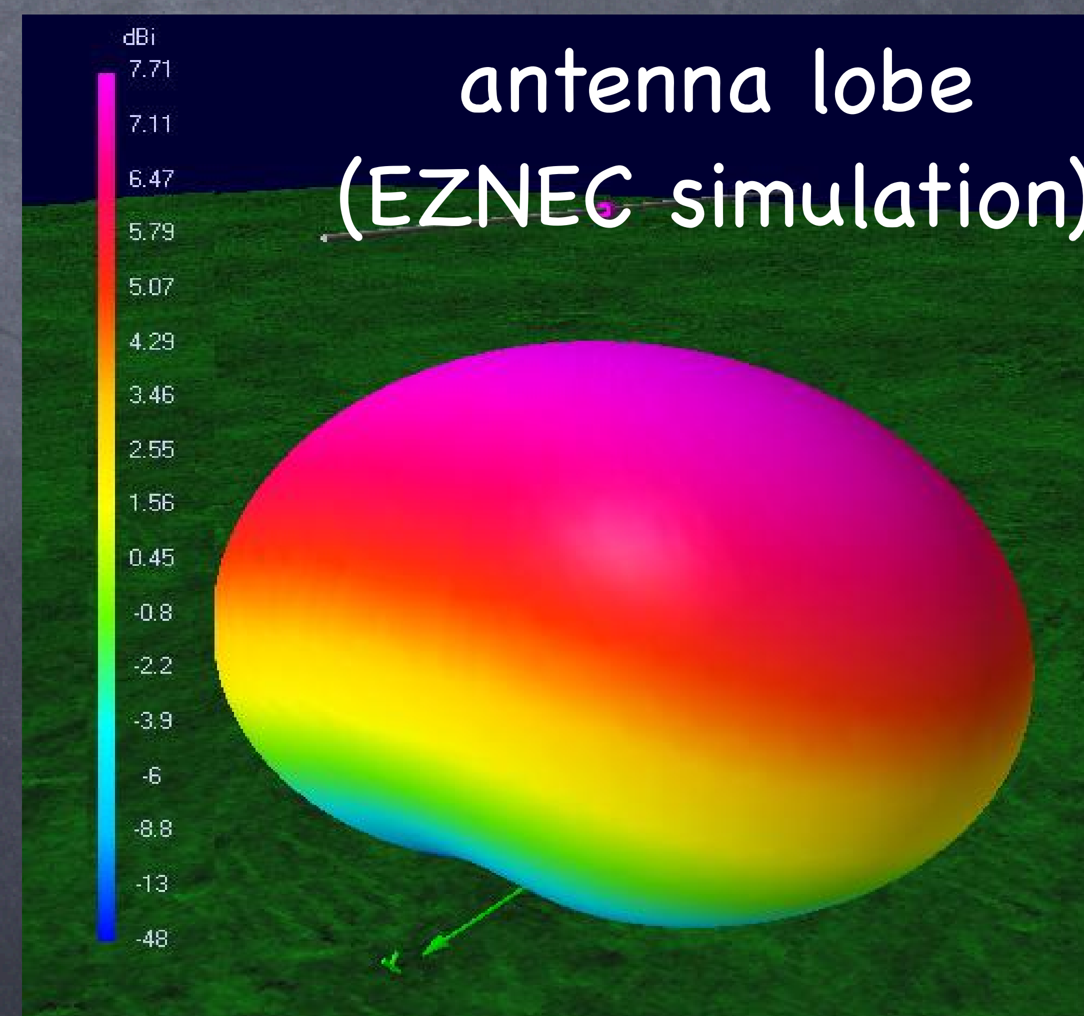
Radio-detection of atmospheric showers

the CODALEMA experiment

Construct an appropriate antenna

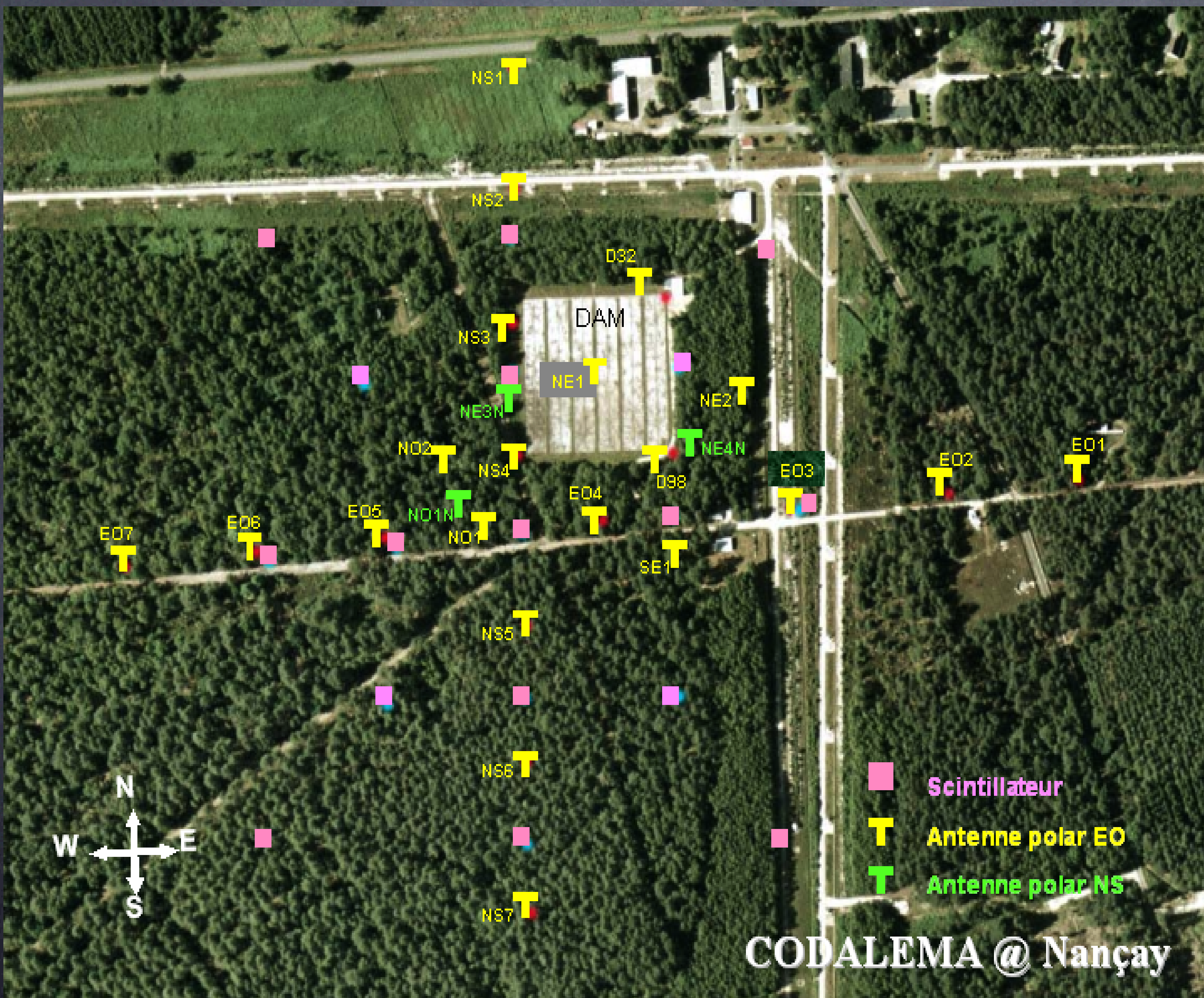
- dipolar active antenna
- 1.2 m length, 10 cm wide
- 1 m above ground
- gain 30 dB LNA
- bandwidth 80 kHz-230 MHz
- quasi isotropic lobe





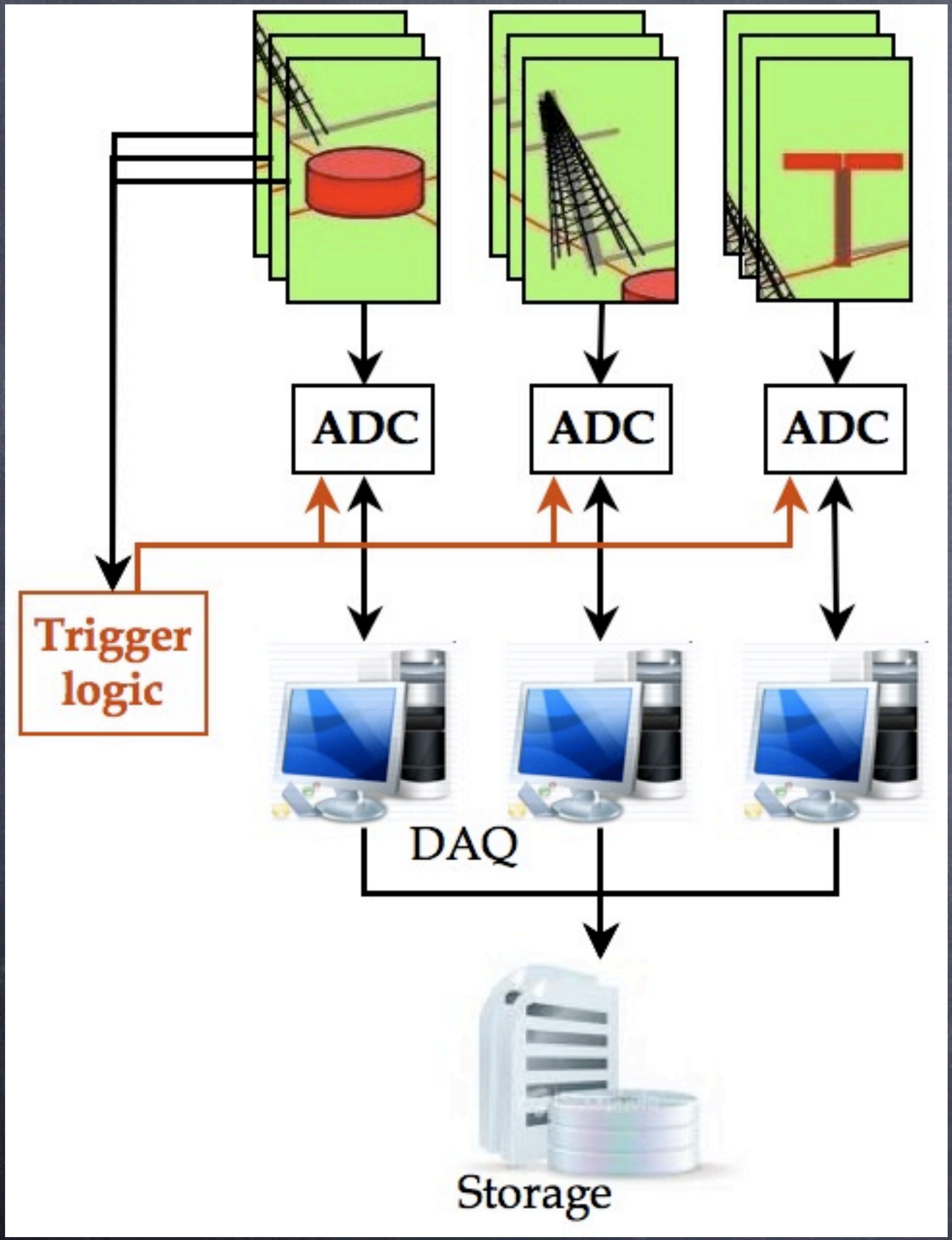
CODALEMA

in the Nançay radiotelescope site (center of France)



- array of 17 scintillators, step of 80 m, 300m x 300m : **CODALEMA trigger**
- energy threshold around 10^{15} eV (knee region), full acceptance at 10^{16} eV
- array of 21 antennas in EW polarisation and 3 in NS polarisation, step of 85 m, 2 arms of 600 m length
- DAM: 144 log-periodic antennas 80x80 m^2

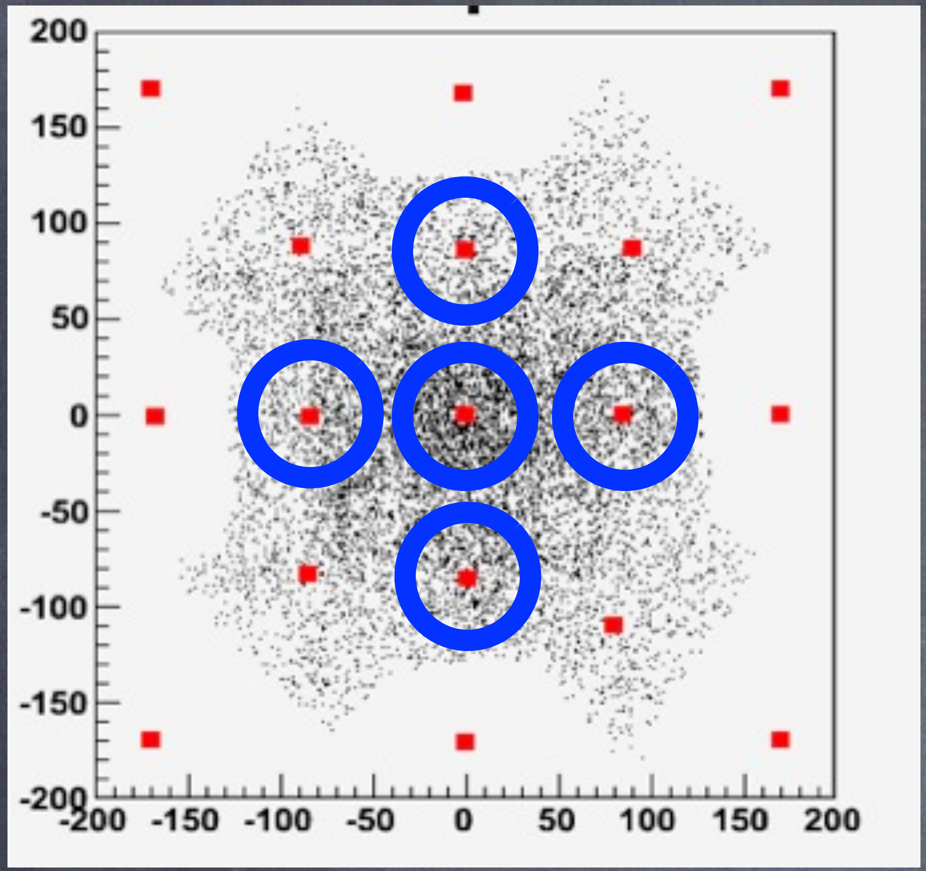
CODALEMA



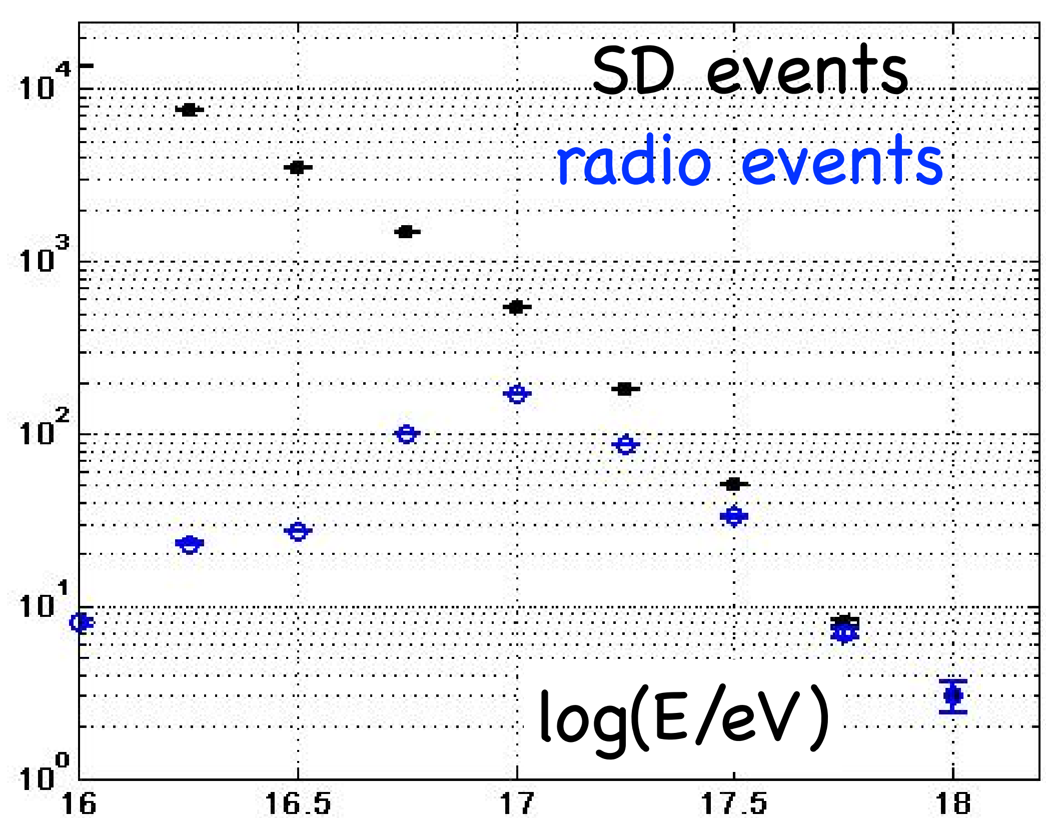
trigger: remote control of the thresholds and trigger conditions

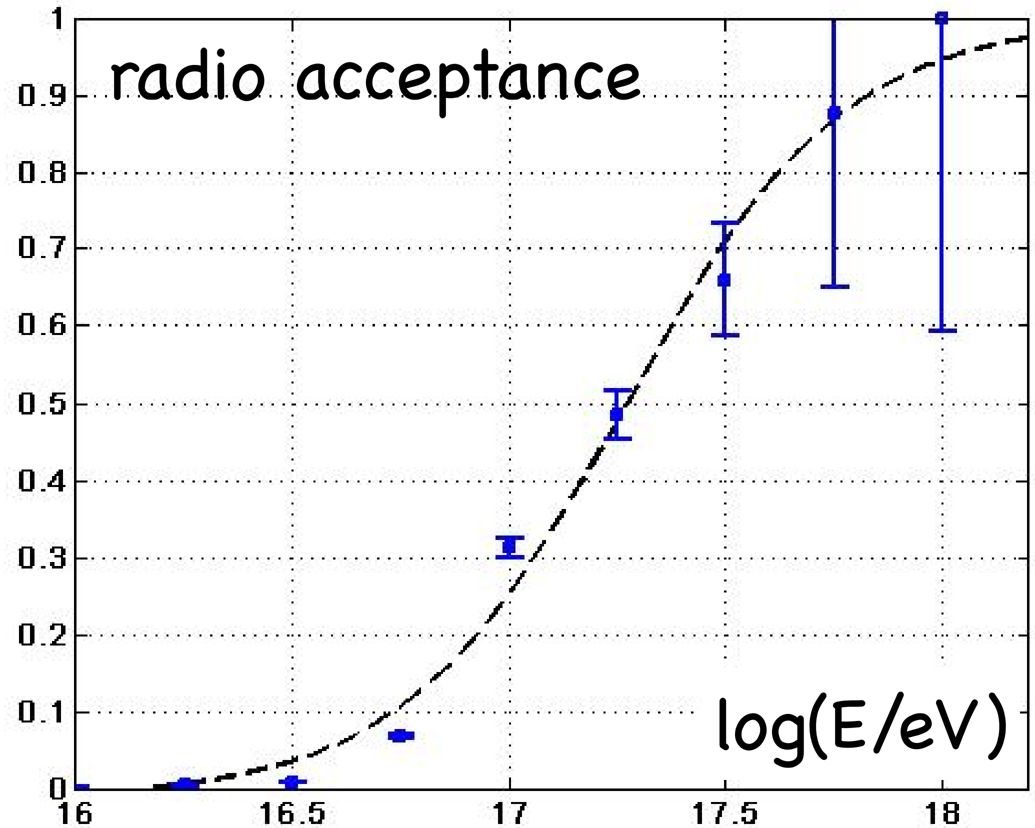
MATACQ ADC : 300 MHz, 12 bits, 1 Gs/s, 2500 samples

CODALEMA

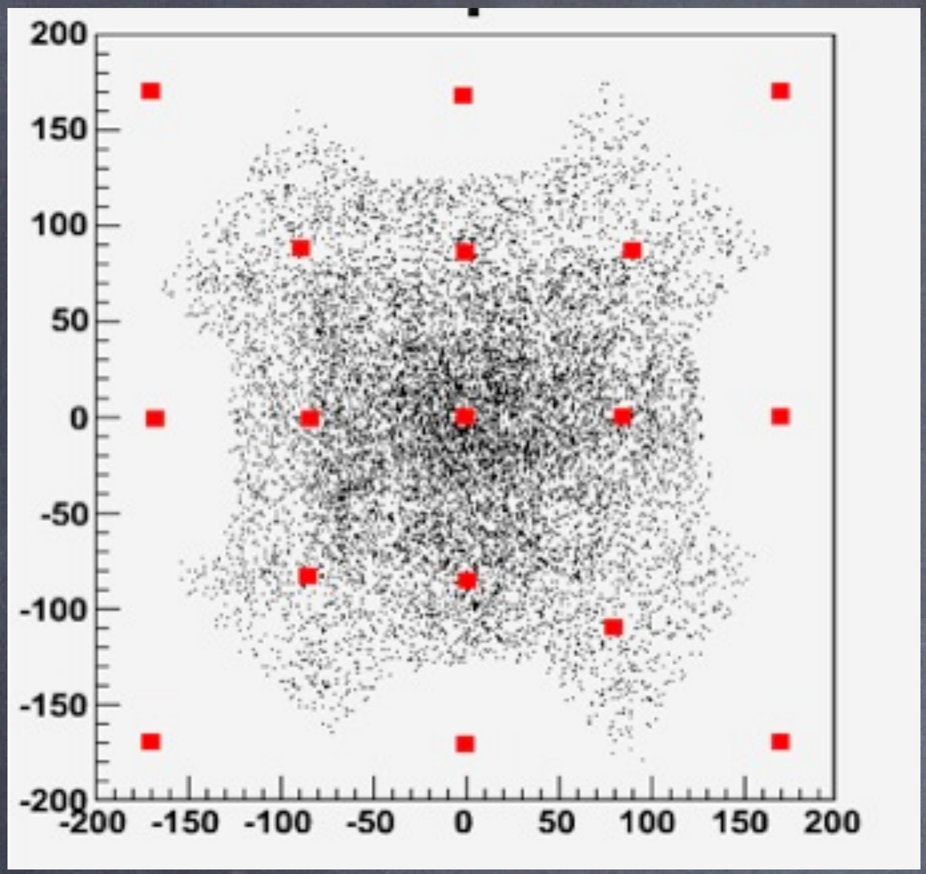


- condition for 1 scintillator: peak>0.3 VEM
- trigger: the 5 central stations wihtin 600 ns
- trigger rate: 7 min
- internal event: the scintillator with maximal signal is not on the edges (good reconstruction of core and energy)
- external event: axis direction only
- 50 000 internal events in 2 years $\theta \leqslant 50^\circ$





CODALEMA



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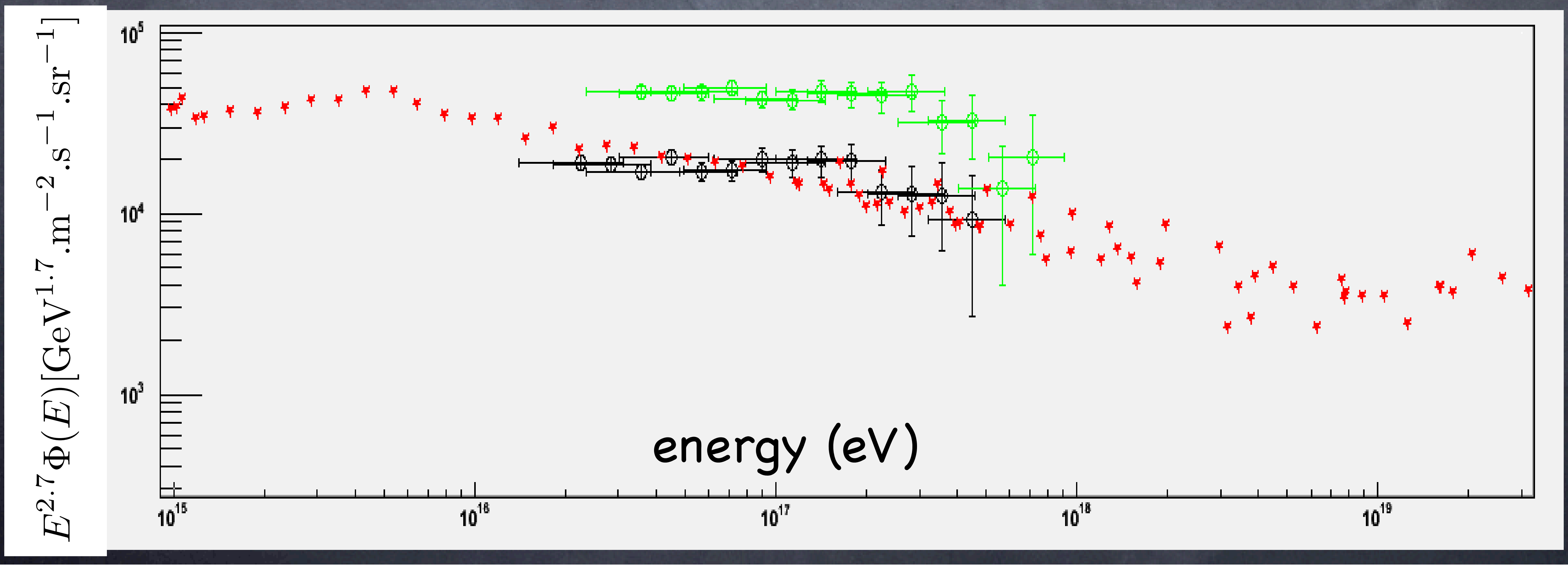
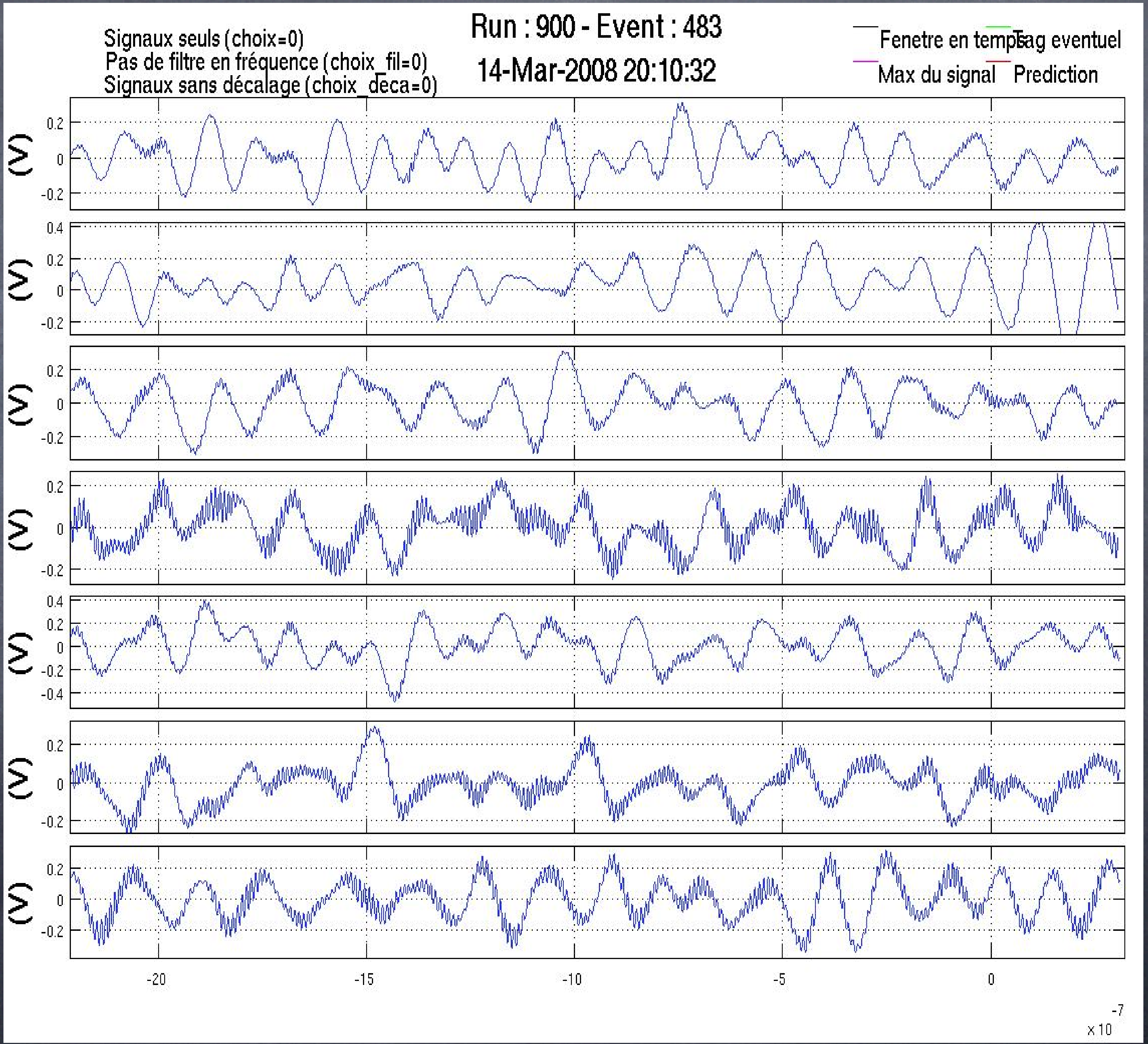


CODALEMA

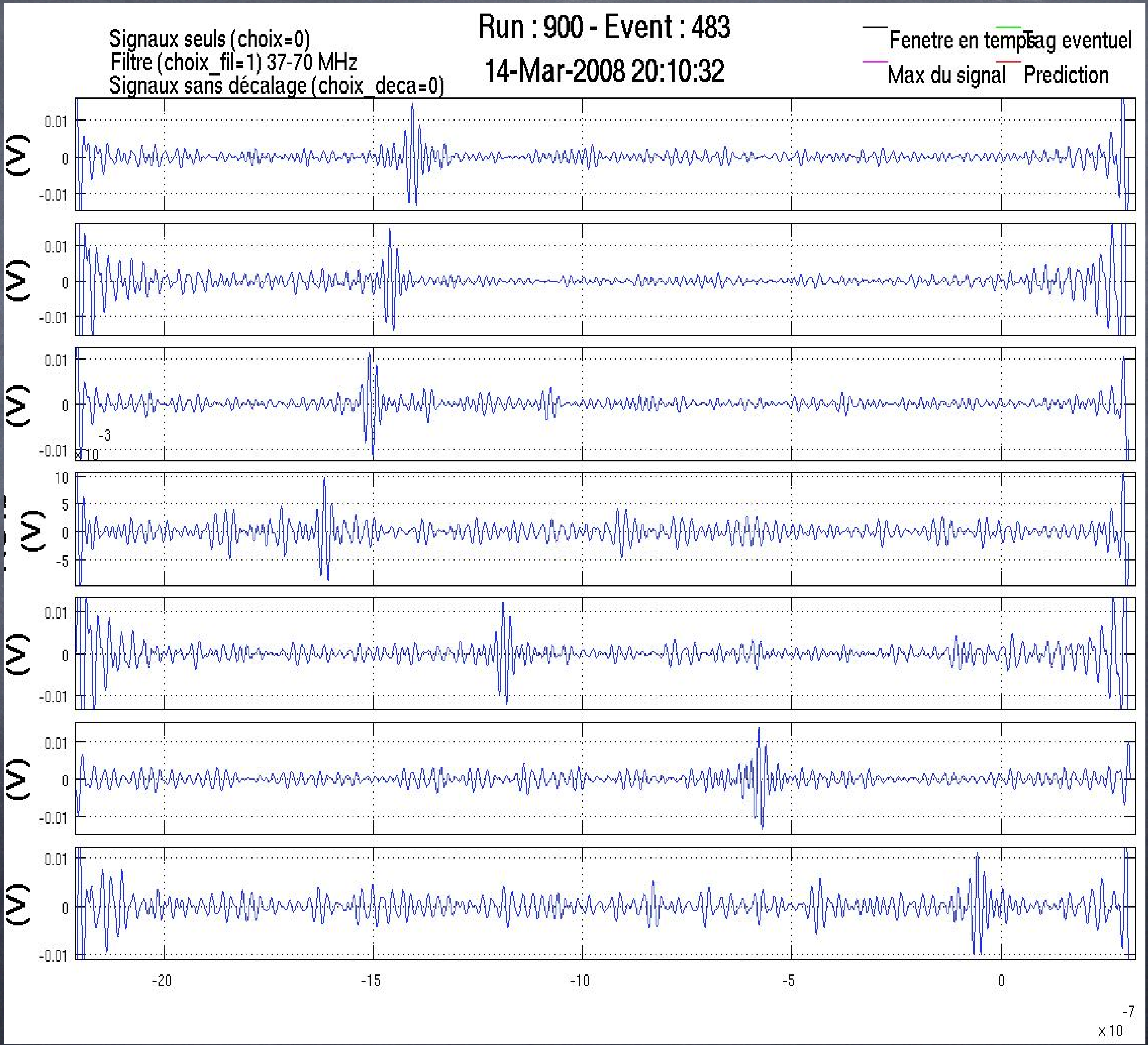
trigger scintillator

record radio data, 1 Gs/s, 2.5 μS



CODALEMA

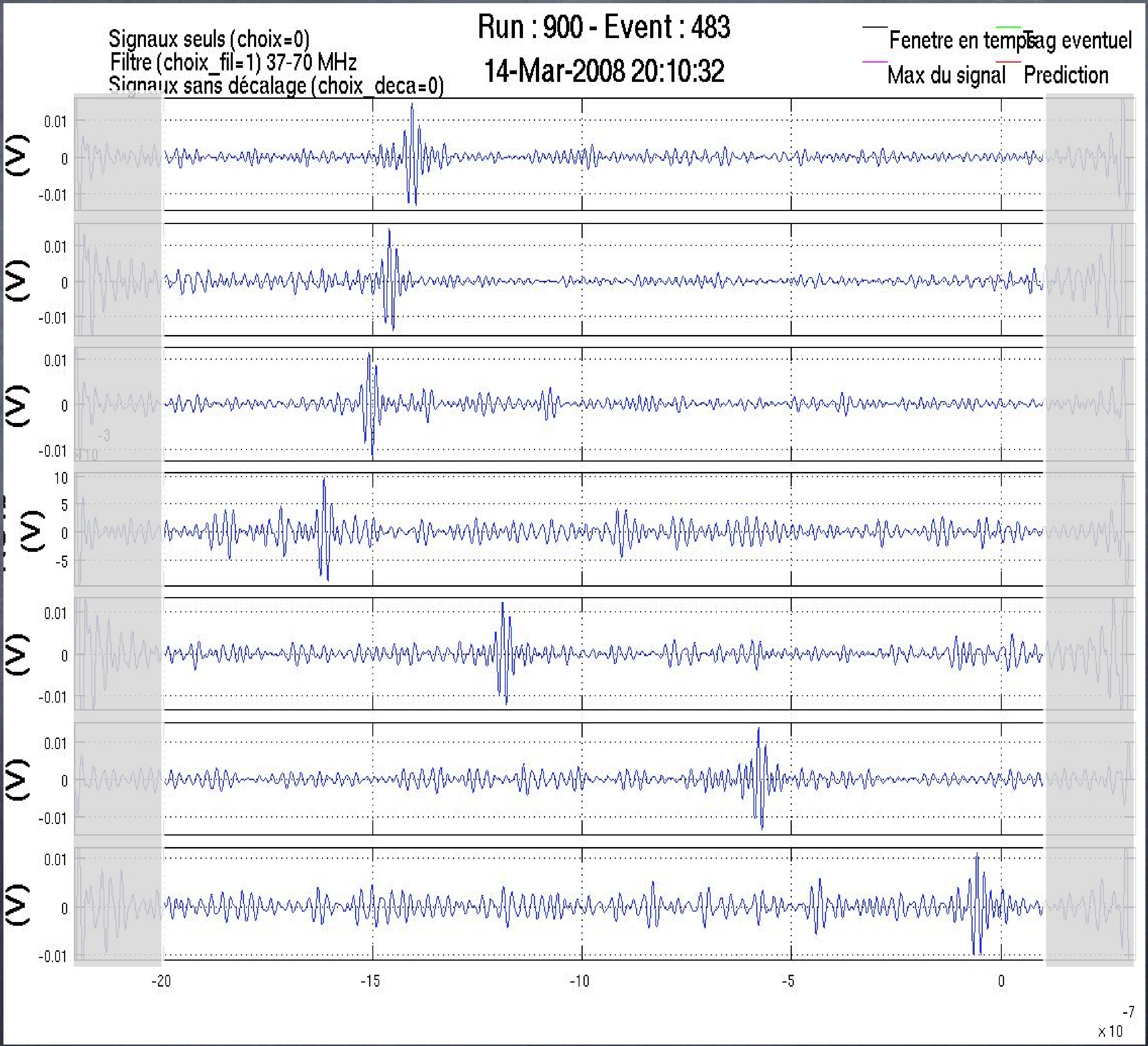
numeric filter
in the band
23-82 MHz



CODALEMA

numeric filter in the band **23-82 MHz**

kill Gibbs regions

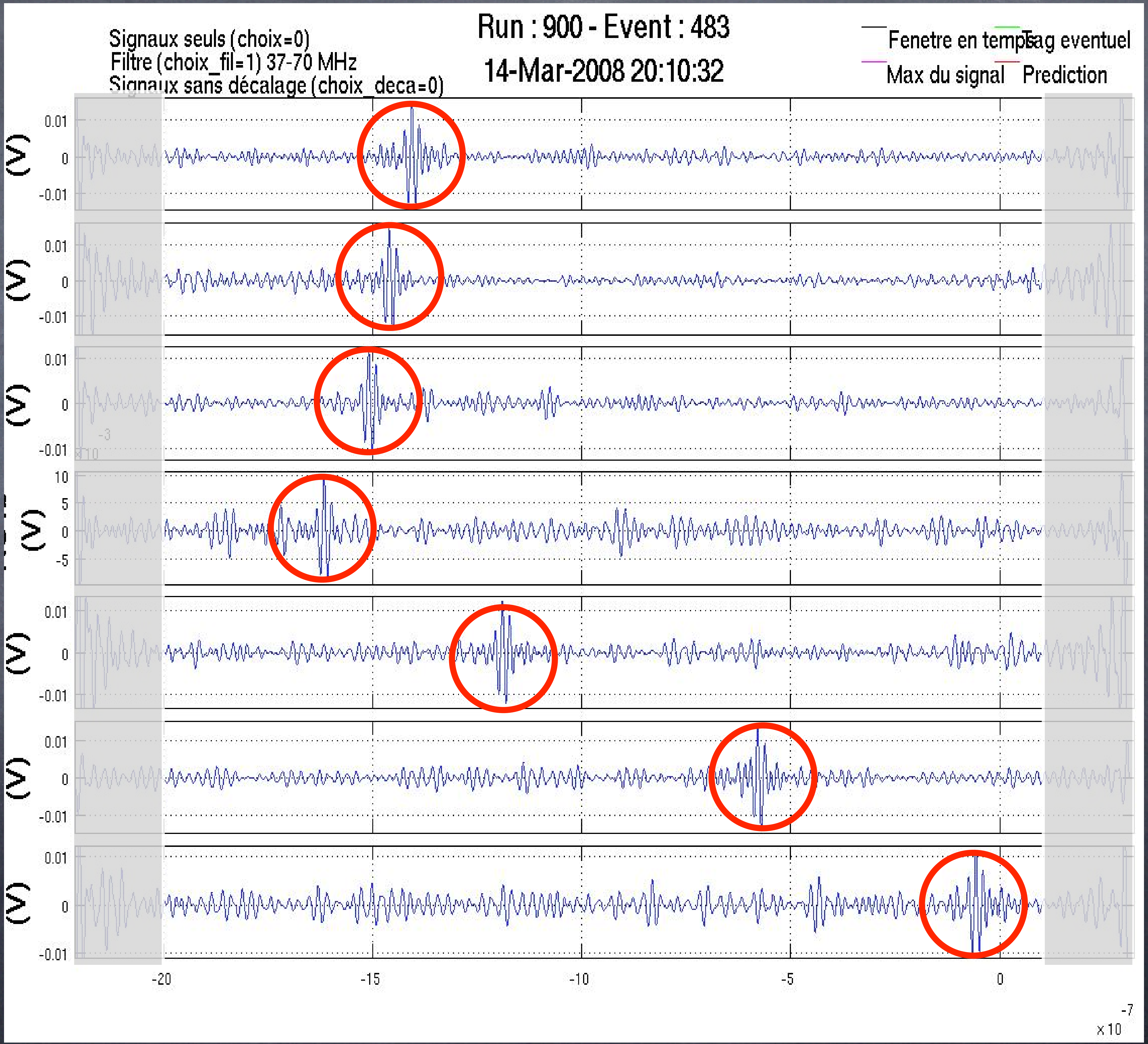


CODALEMA

numeric filter in the band 23-82 MHz

kill Gibbs regions

detect transients

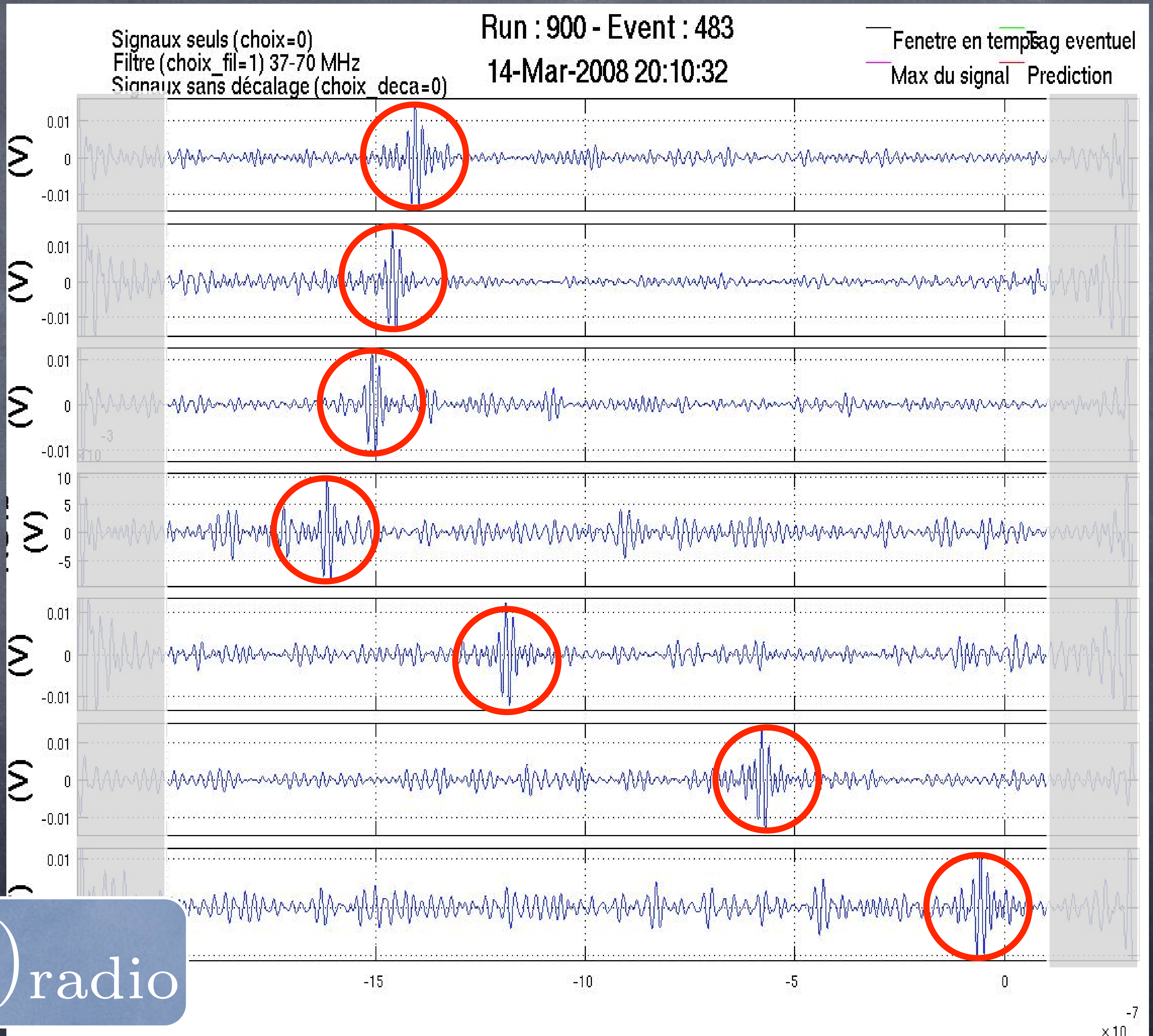


CODALEMA

numeric filter
in the band
23-82 MHz

kill Gibbs
regions

detect
transients



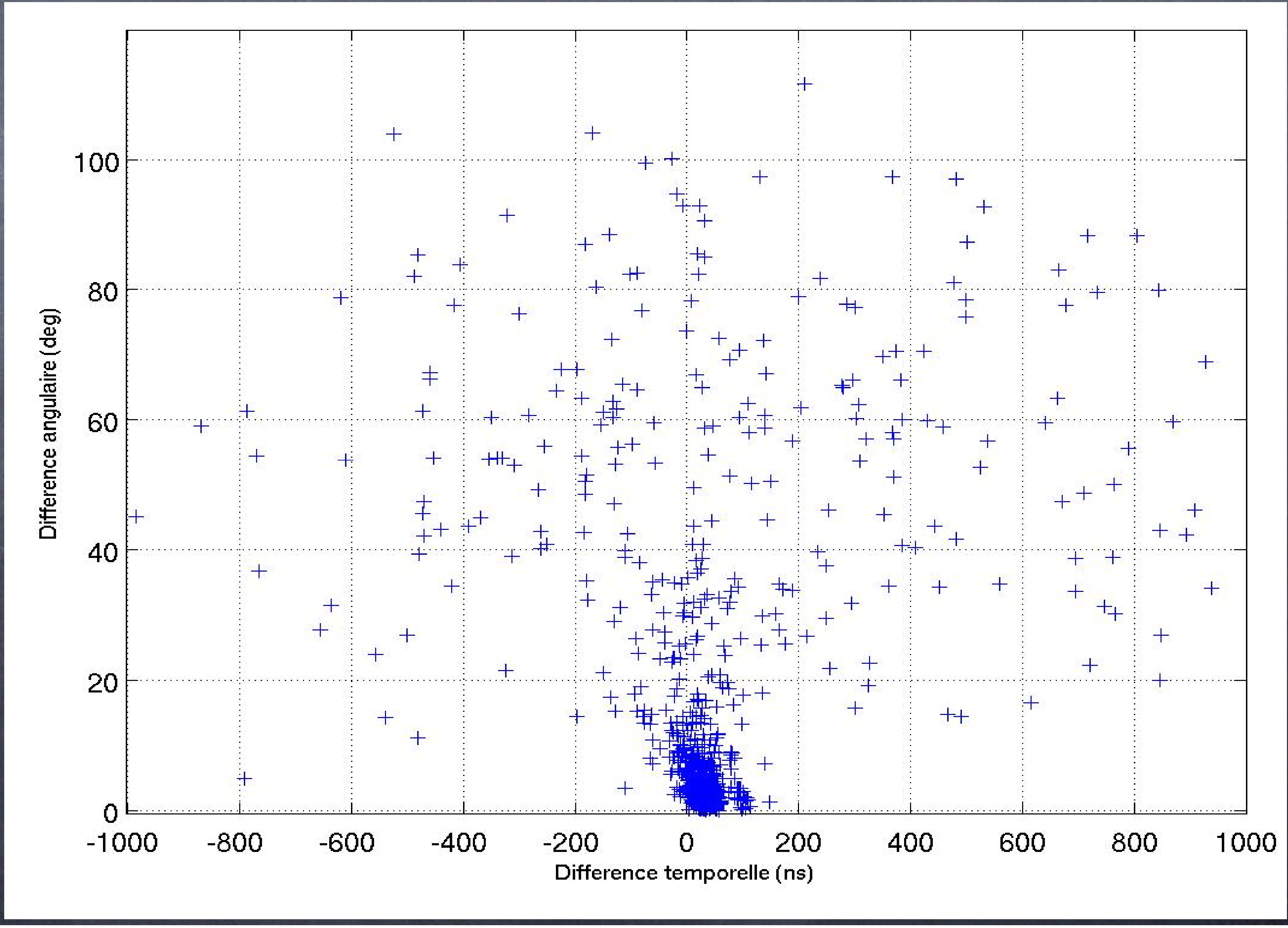
$$(\theta,\ \phi,\ t_0)_{\rm radio}$$

CODALEMA

identification of cosmic rays: comparison of the radio/scintillator reconstructions

$(\theta,\ \phi,\ t_0)_{\text{radio}}$ $(\theta,\ \phi,\ t_0)_{\text{scintillator}}$

$\delta\Omega,\ \delta t$



27/11/06-20/03/08
355 effective days
619 coincidences
(internal and external)

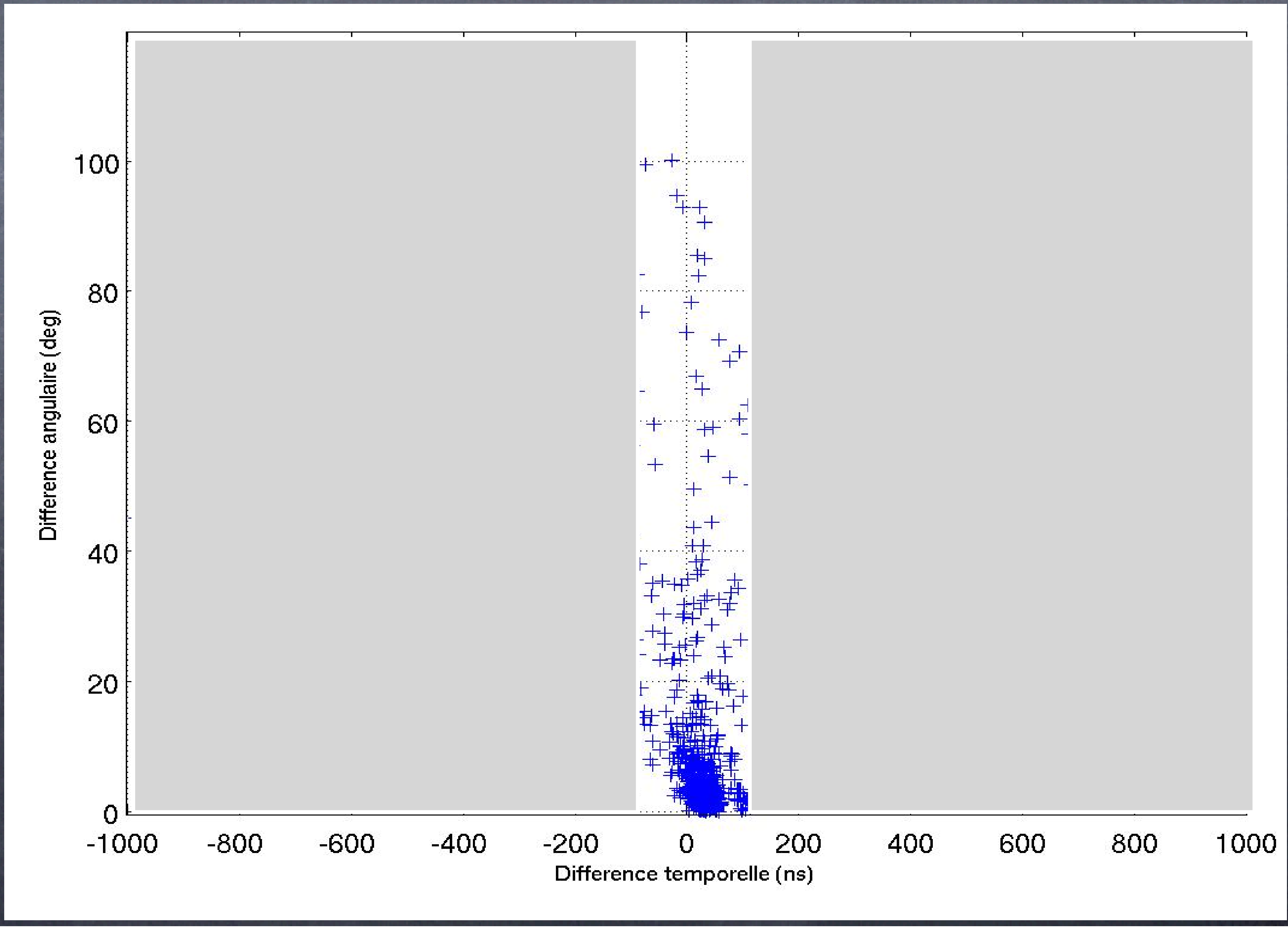
CODALEMA
identification of cosmic rays: comparison of the radio/scintillator reconstructions

$(\theta,\ \phi,\ t_0)_{\mathrm{radio}}$

$(\theta,\ \phi,\ t_0)_{\mathrm{scintillator}}$

$\delta\Omega,\ \delta t$

$|\delta t| \leqslant 100\ \mathrm{ns}$



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$$(\theta,\ \phi,\ t_0)_{\text{radio}}$$

$$(\theta,\ \phi,\ t_0)_{\text{scintillator}}$$

$$\delta\Omega,\ \delta t$$

$$|\delta t| \leqslant 100\ \text{ns}$$

$$\delta\Omega \leqslant 20^\circ$$

27/11/06-20/03/08
355 effective days
619 coincidences
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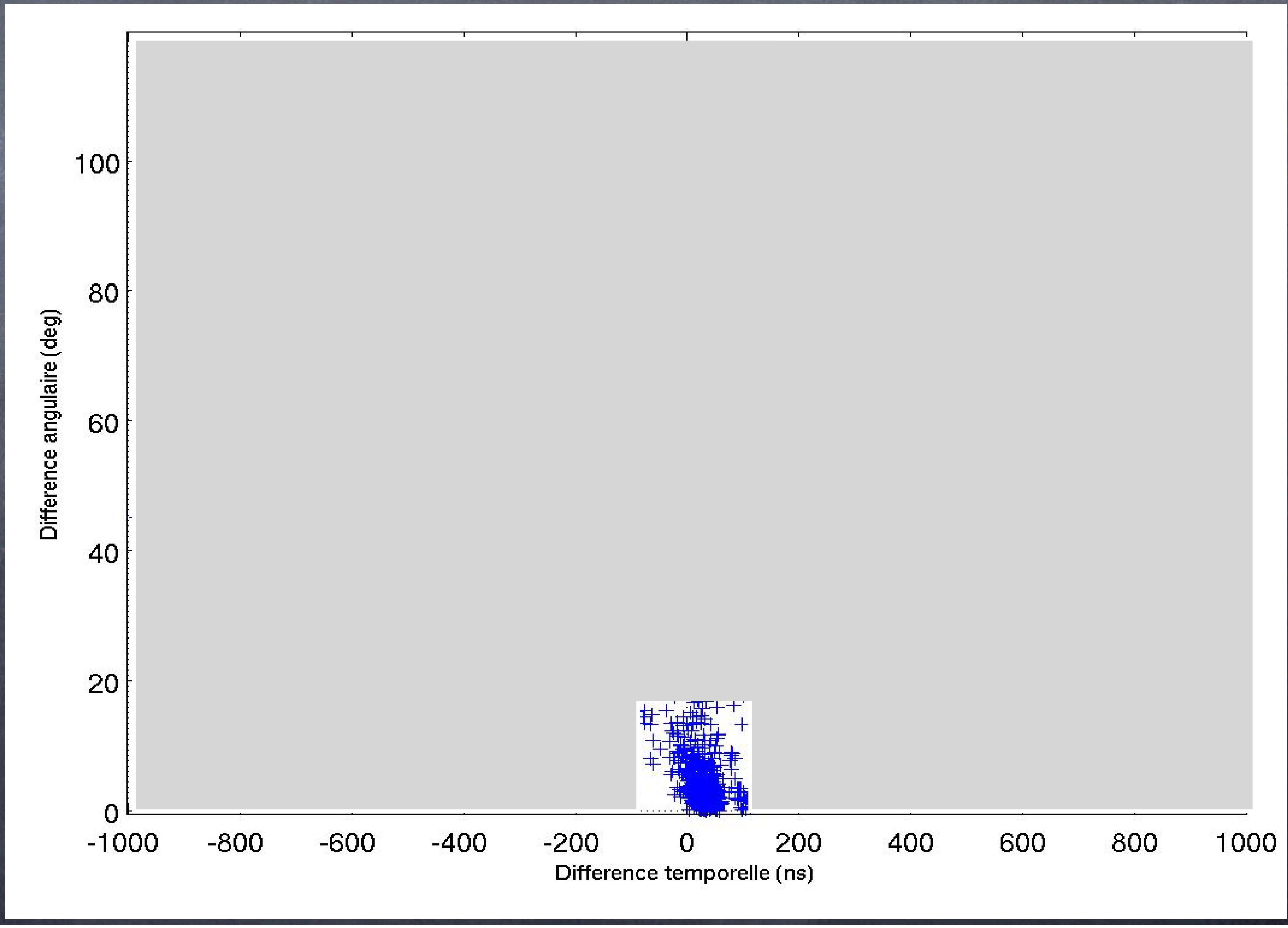
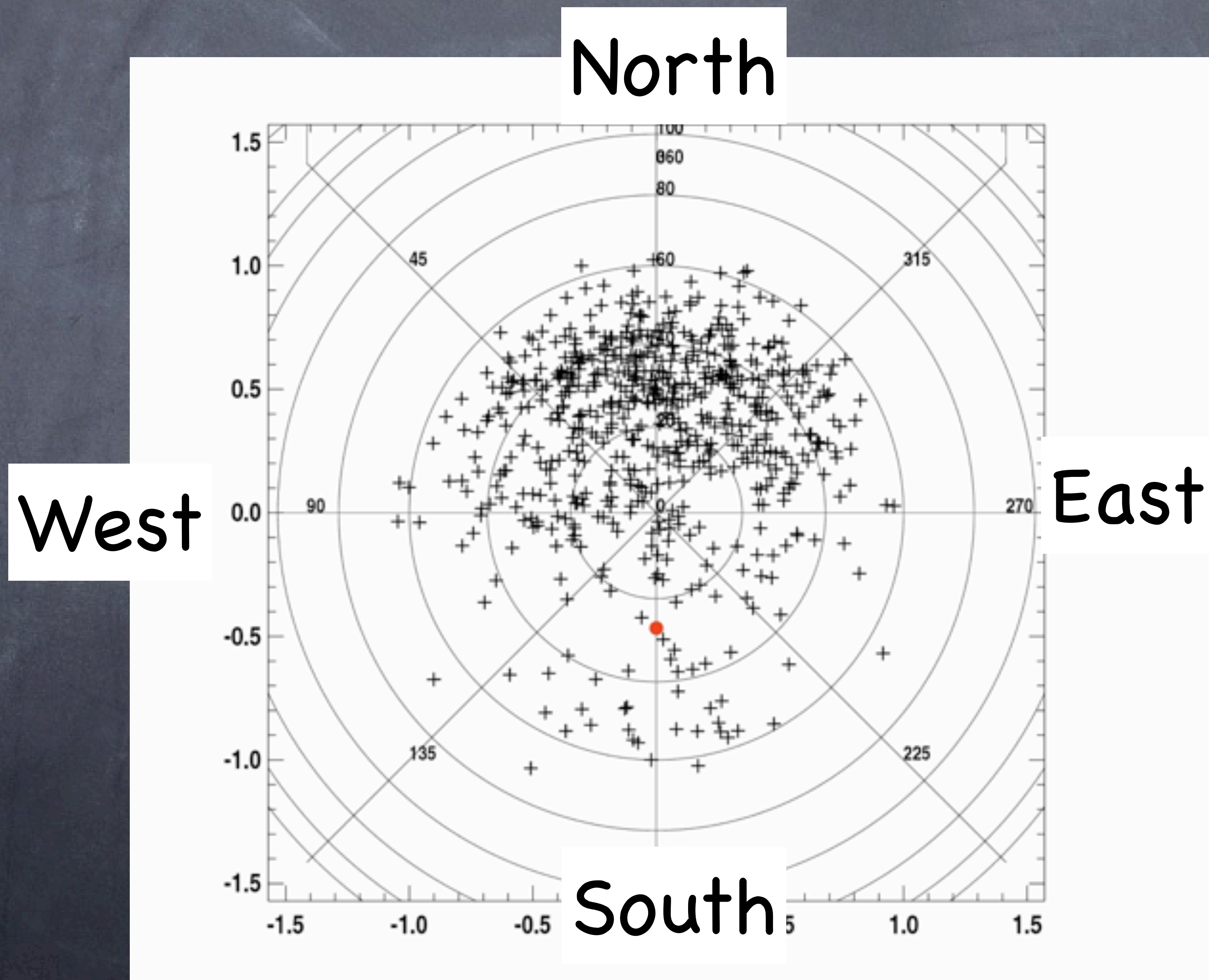


CODALEMA

arrival directions (internal and external events) distribution on the sky, in local coordinates: strong asymetry



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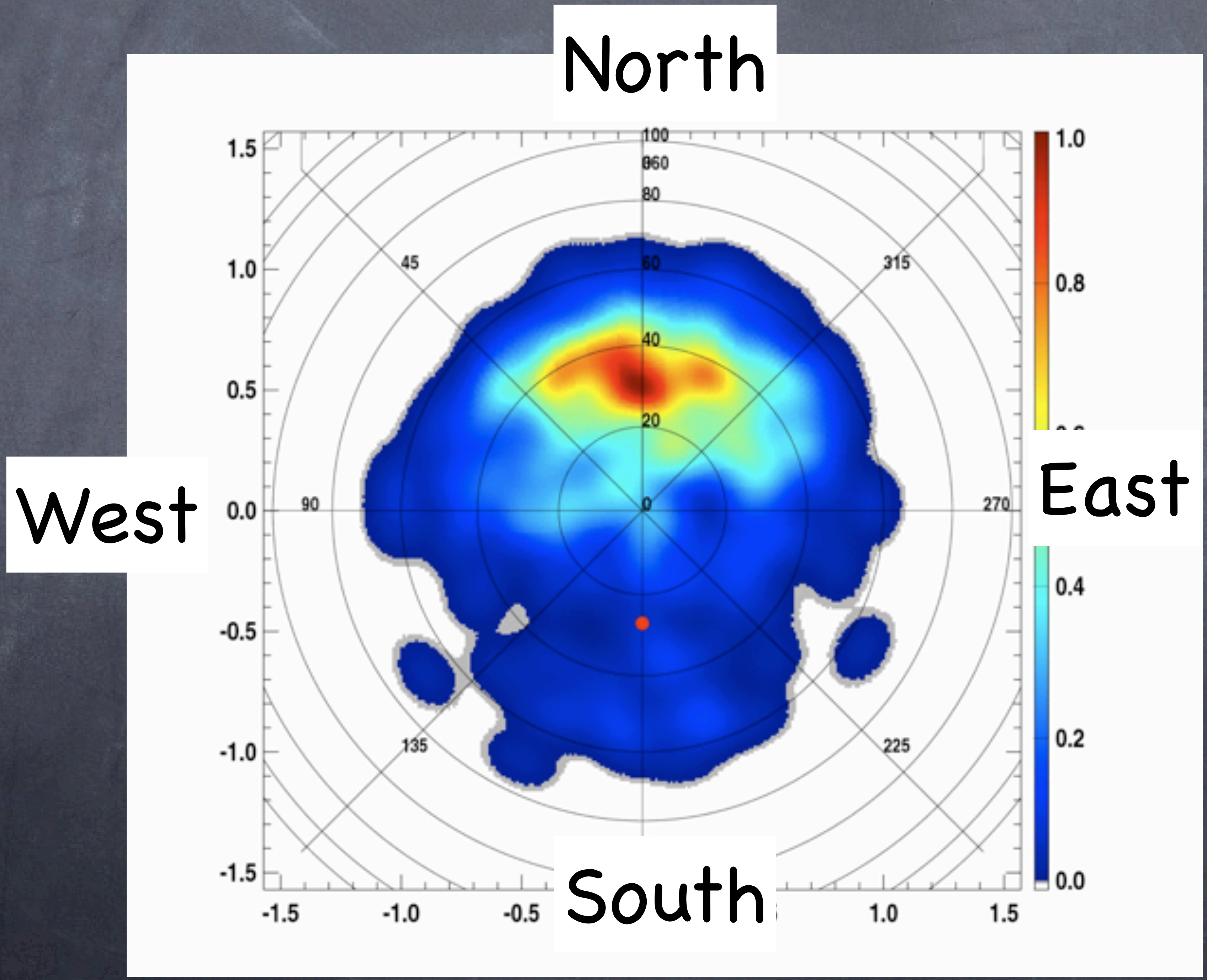

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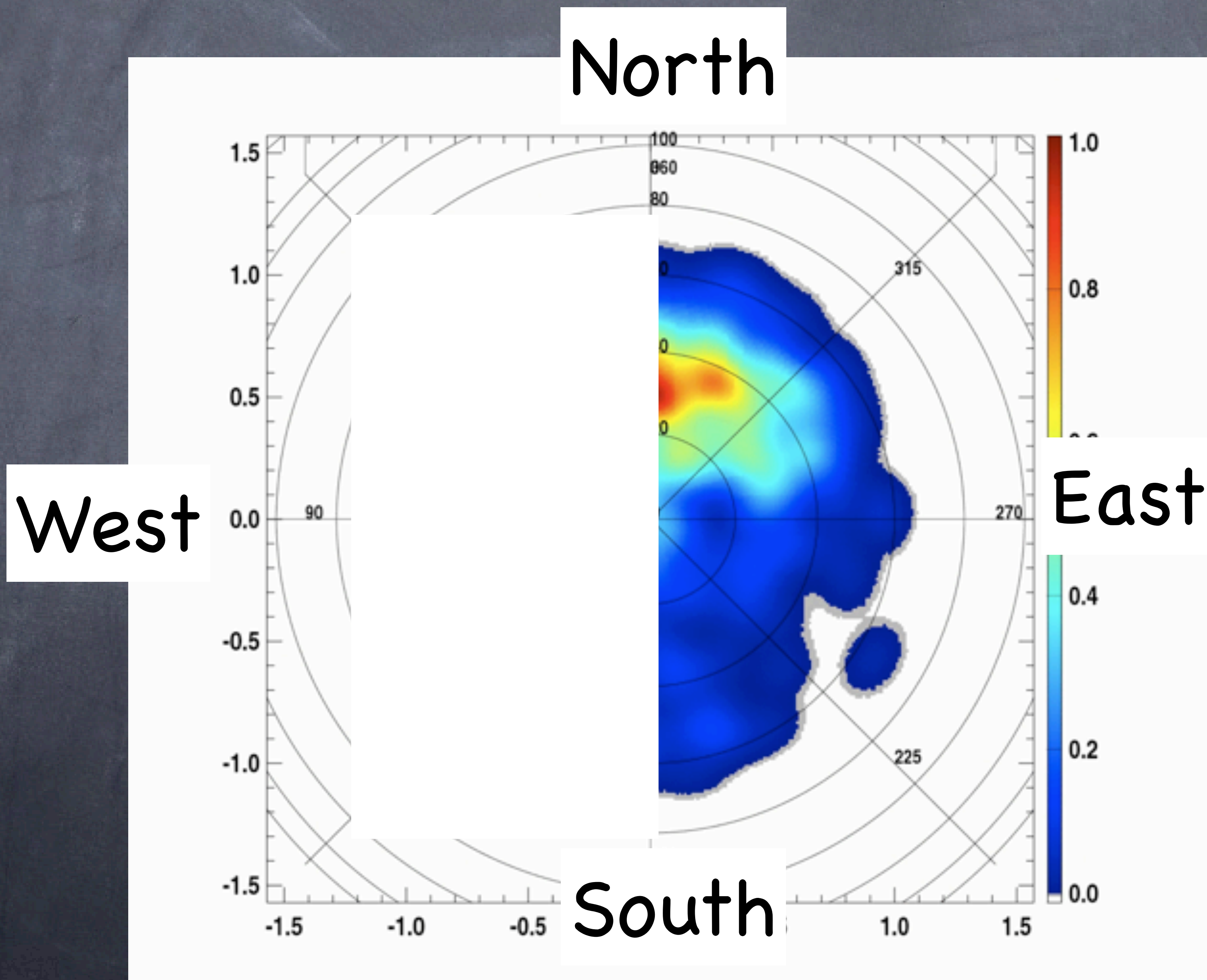

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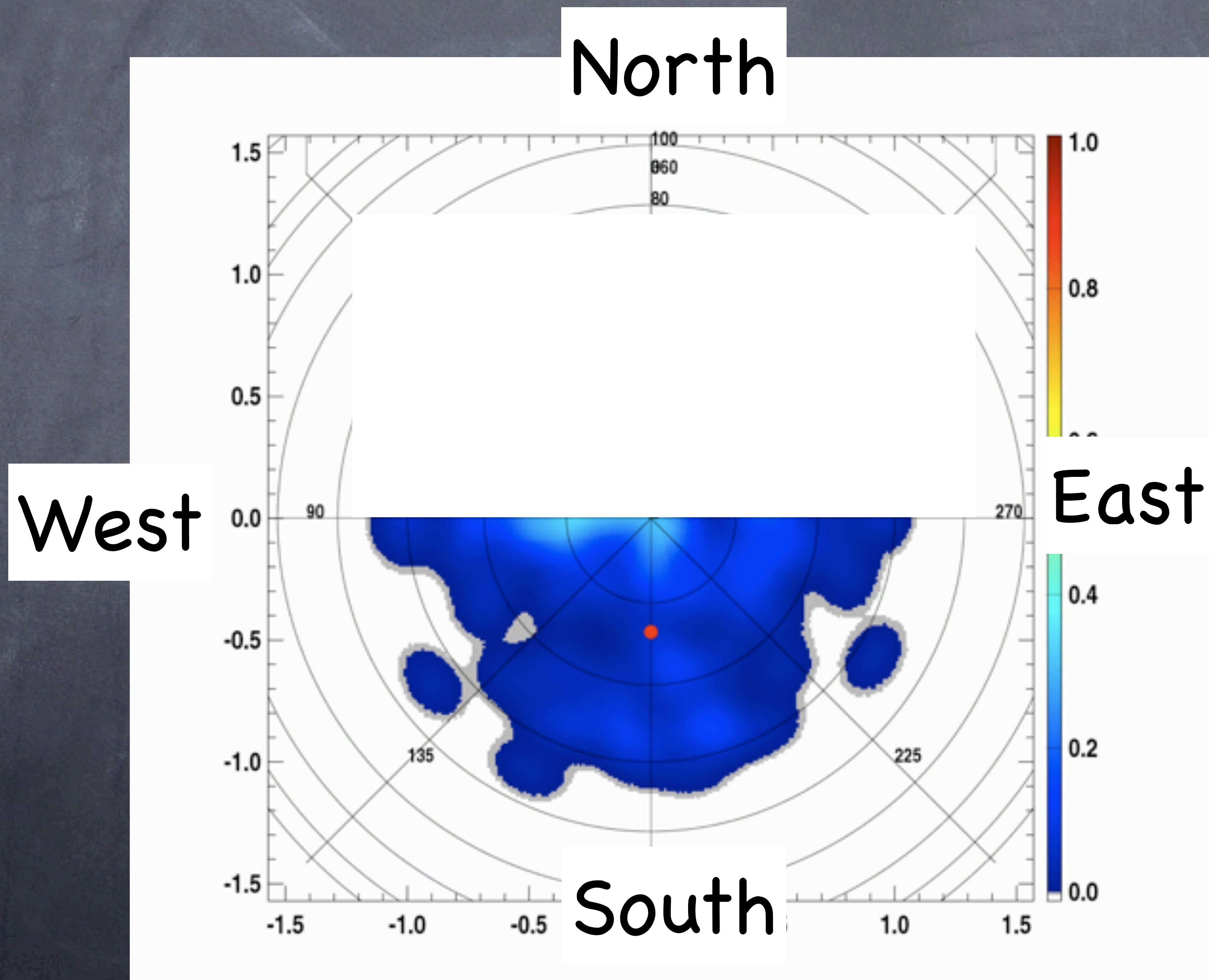
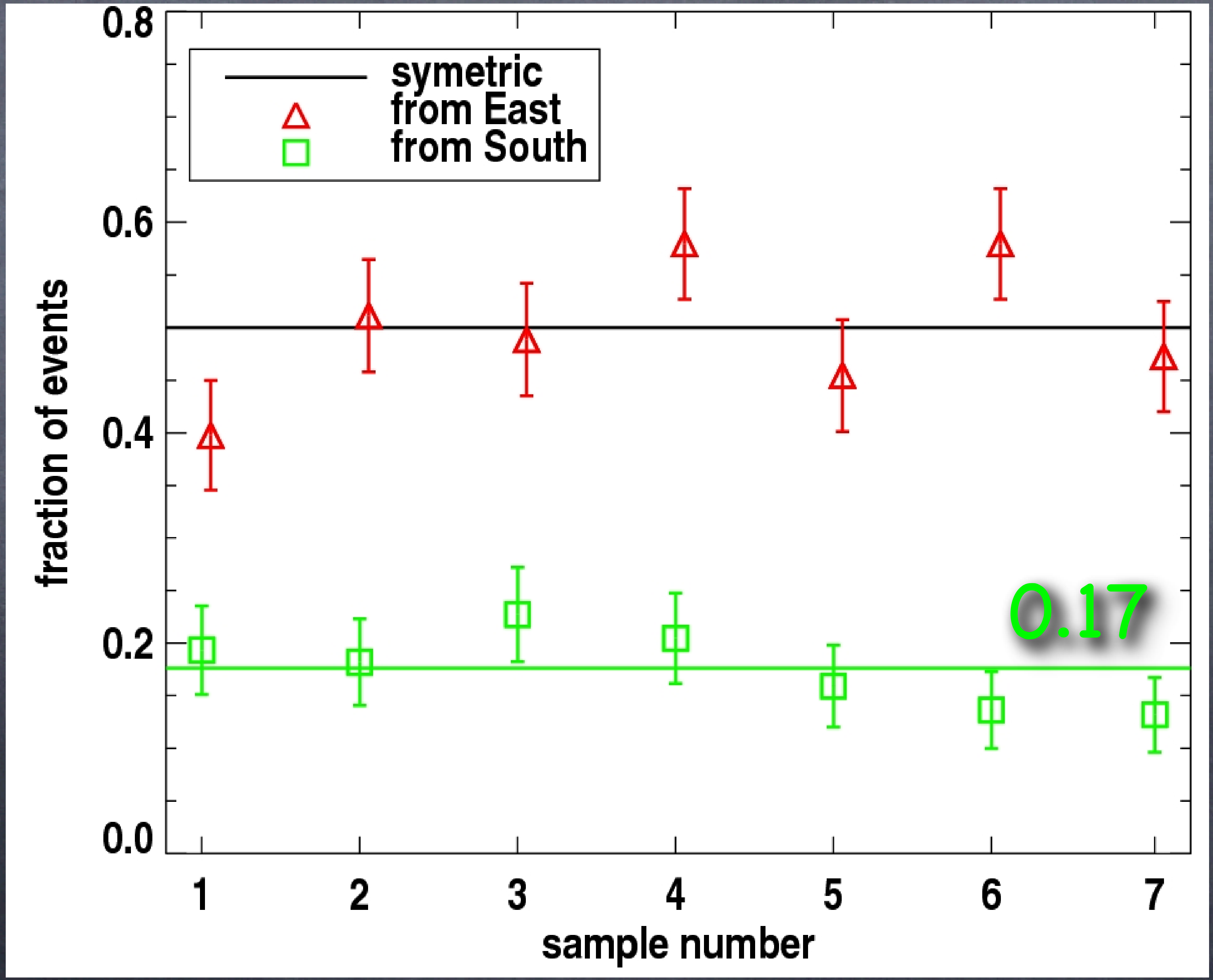


CODALEMA

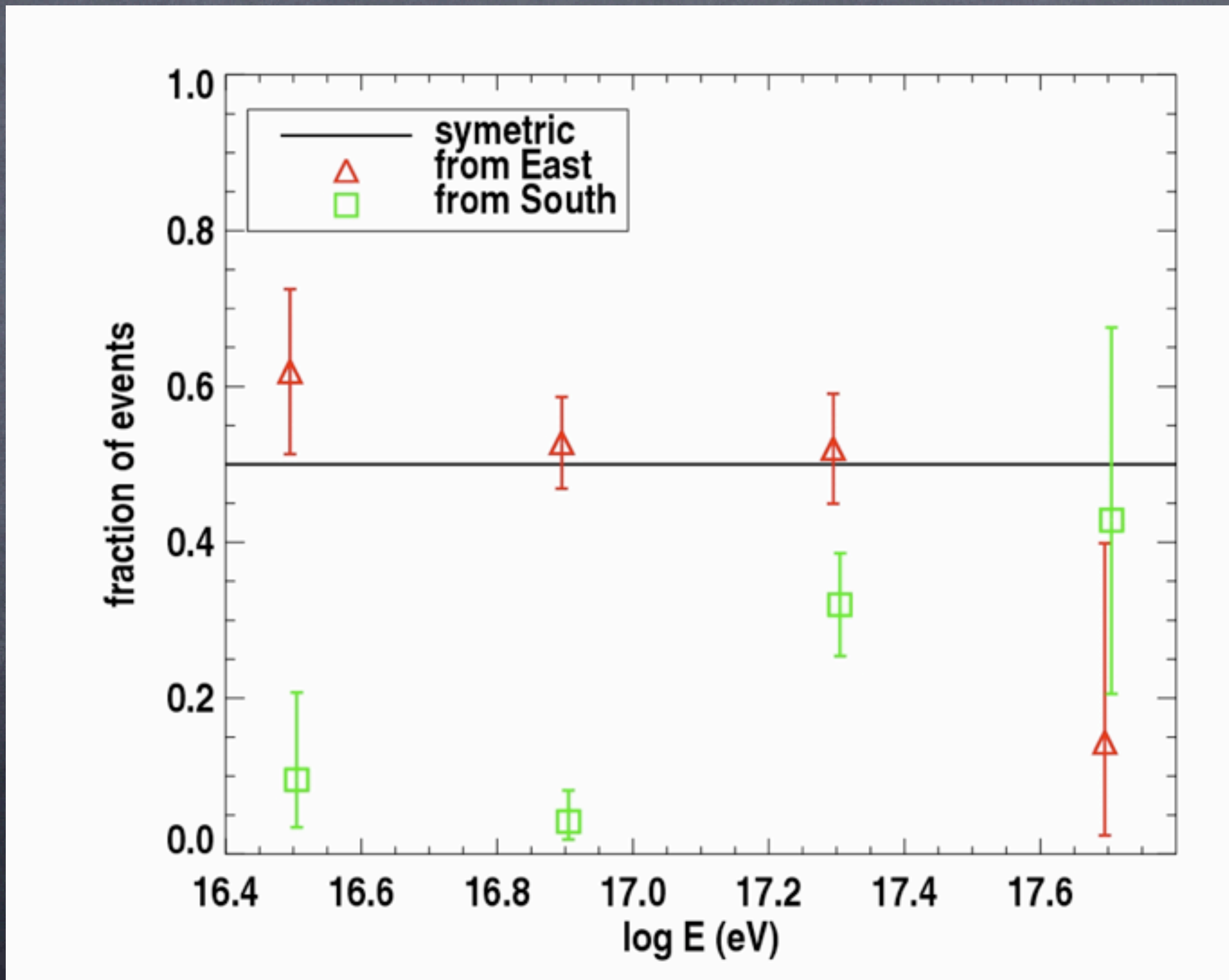
the observed asymetry is stable in time
(checked on 7 subsets with same number of events)

4.8 times more events from the North



CODALEMA

asymetry as a function of energy
(internal events only)



CODALEMA

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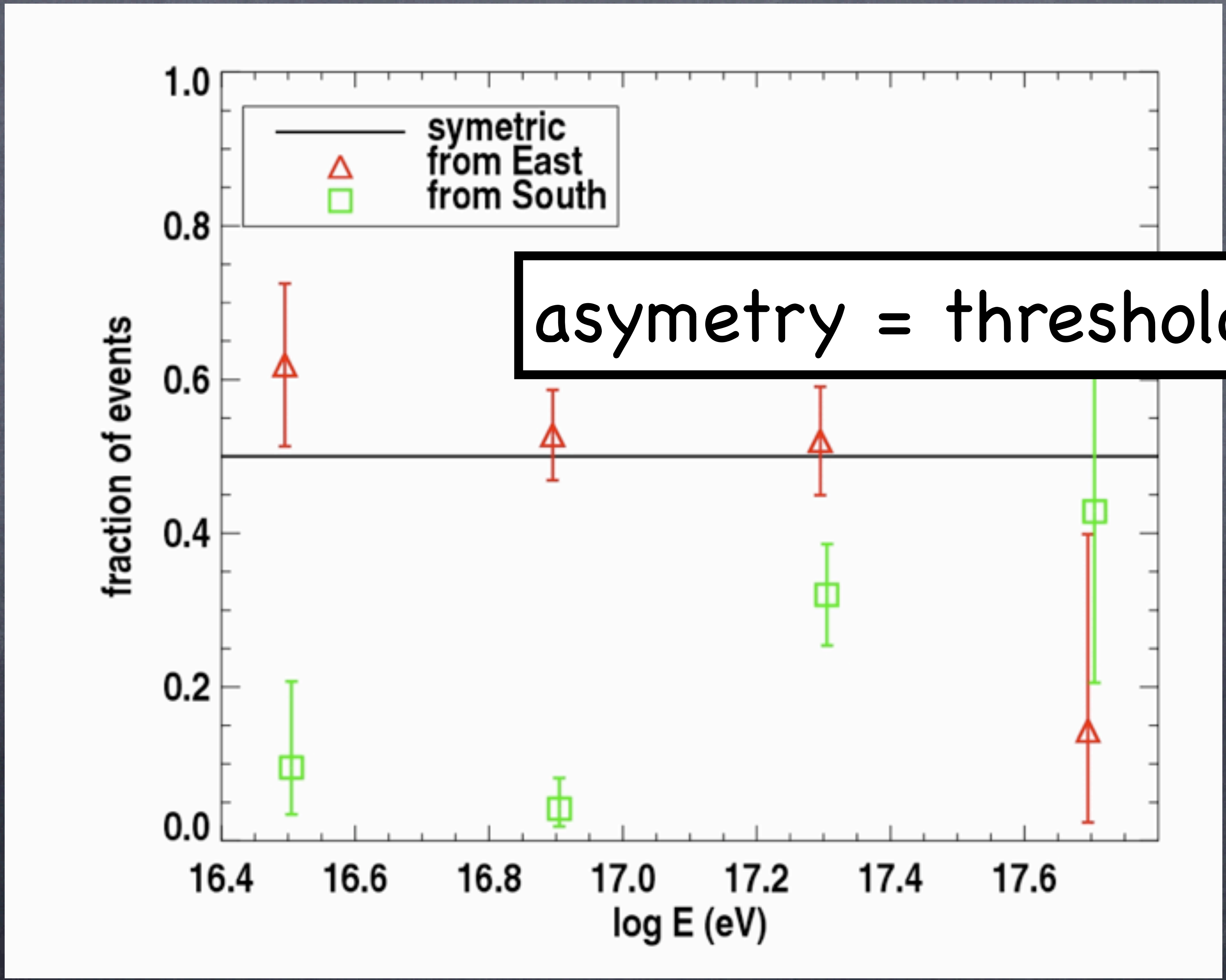


asymetry = threshold effect

CODALEMA

BUT

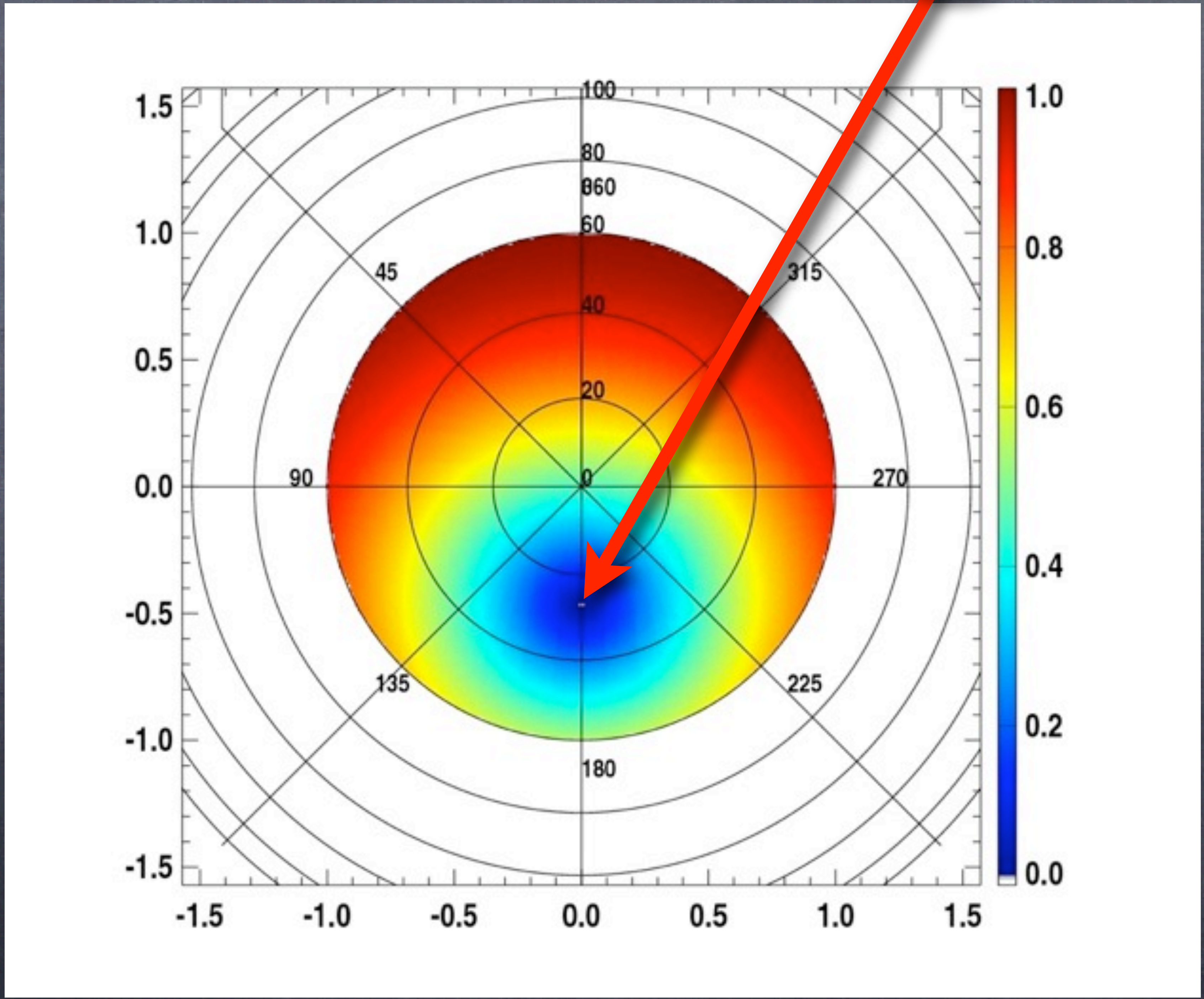
$$\vec{E}_{\mathrm{radiative}} \propto \vec{\beta} \times \vec{B}$$

hypothesis: the probability to trigger is proportionnal to the norm of the electric field this permits to construct an event density map according to this geomagnetic model

CODALEMA

ingredients:

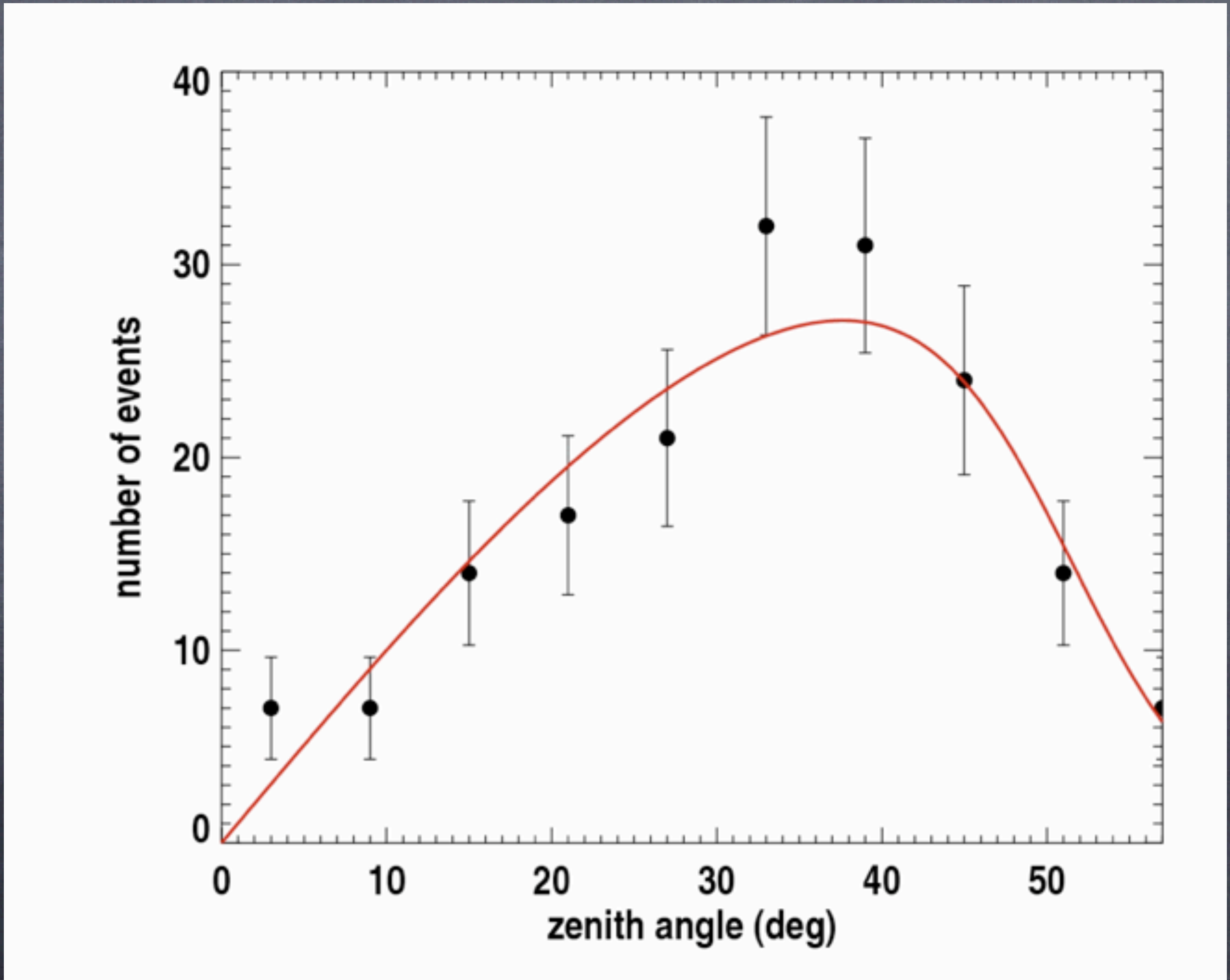
$$\vec{E}_{\mathrm{radiative}} \propto \vec{\beta} \times \vec{B}$$



CODALEMA

ingredients:

use the zenithal trigger distribution

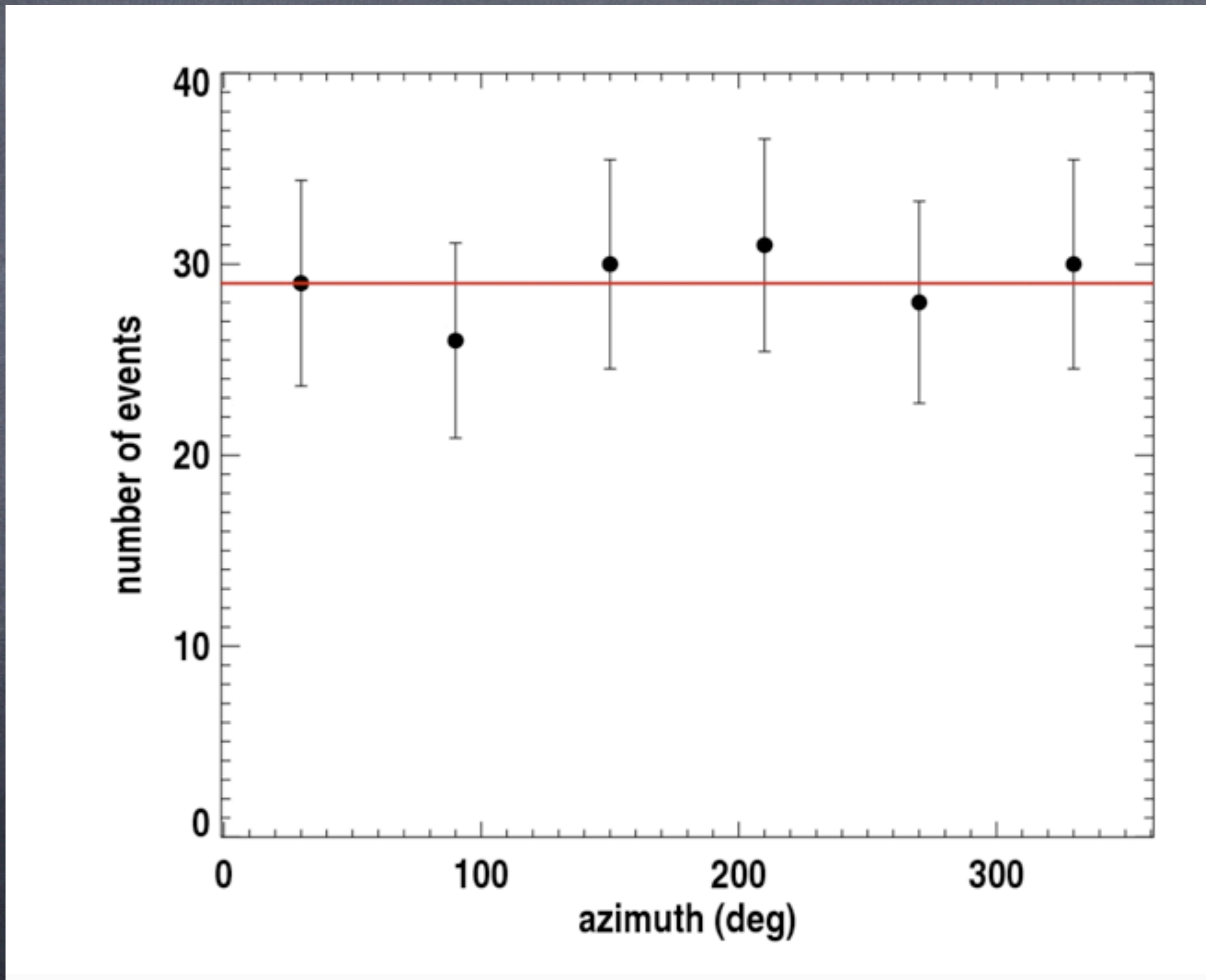


$$\frac{\mathrm{d}N}{\mathrm{d}\theta}$$

CODALEMA

ingredients:

use the azimutal distribution of the trigger

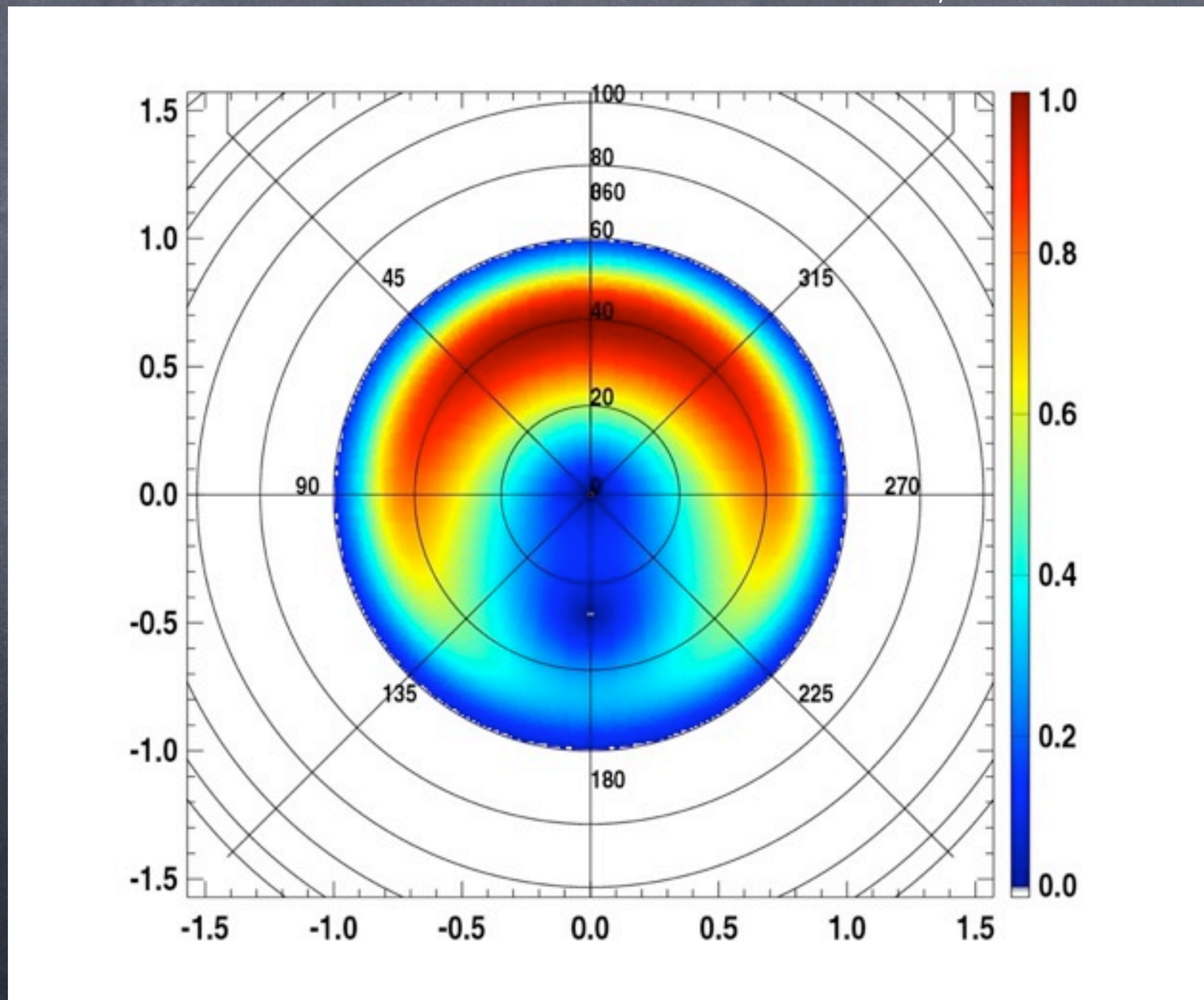


$$\frac{dN}{d\theta}$$

$$\frac{dN}{d\phi}$$

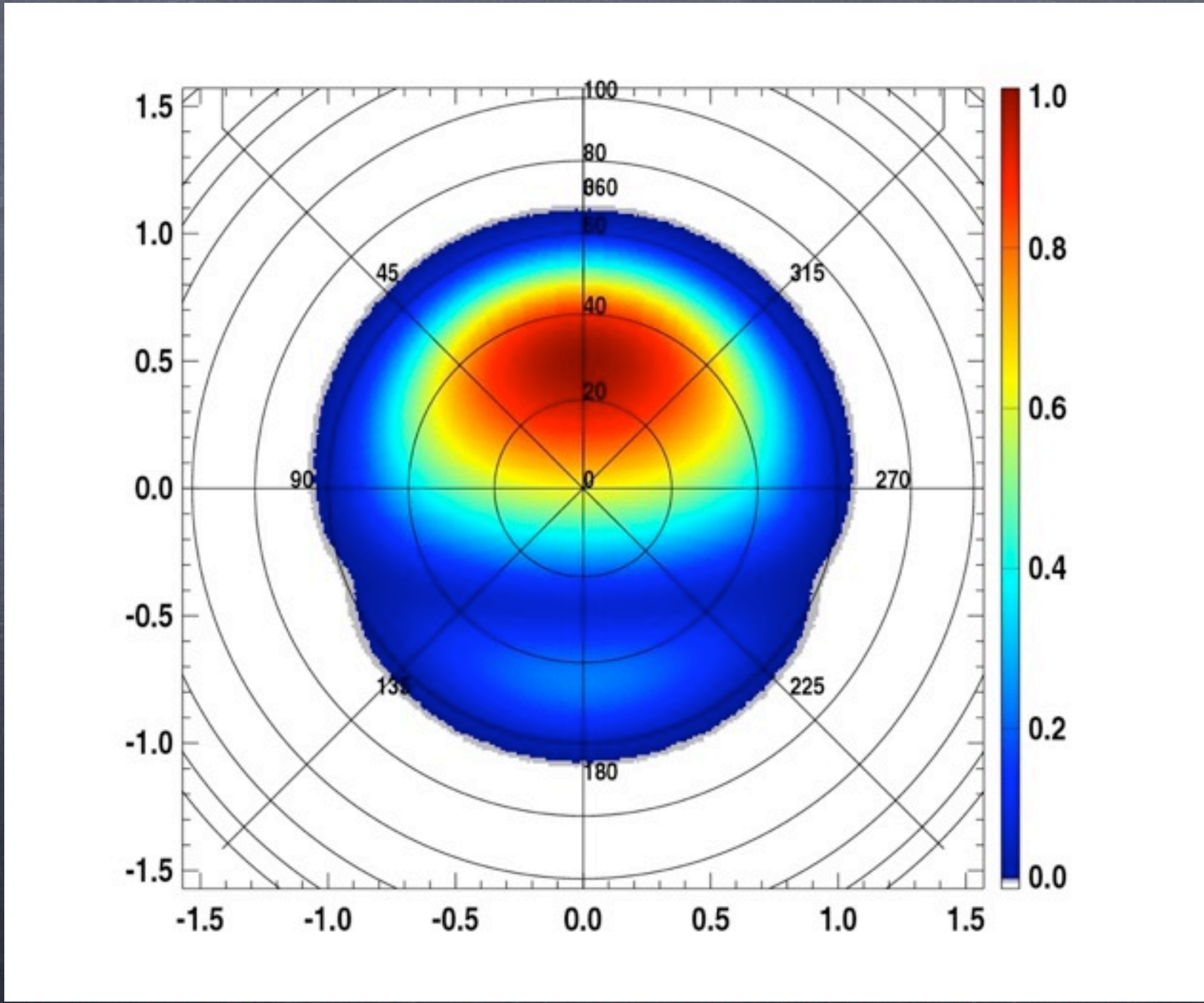
CODALEMA

$$(\vec{\beta} \times \vec{B}) \cdot \frac{\mathrm{d}N}{\mathrm{d}\theta} \cdot \frac{\mathrm{d}N}{\mathrm{d}\phi}$$



CODALEMA

$$(\vec{\beta} \times \vec{B})_{\mathrm{EW}} \cdot \frac{\mathrm{d}N}{\mathrm{d}\theta} \cdot \frac{\mathrm{d}N}{\mathrm{d}\phi} \cdot \frac{1}{\sin\theta}$$



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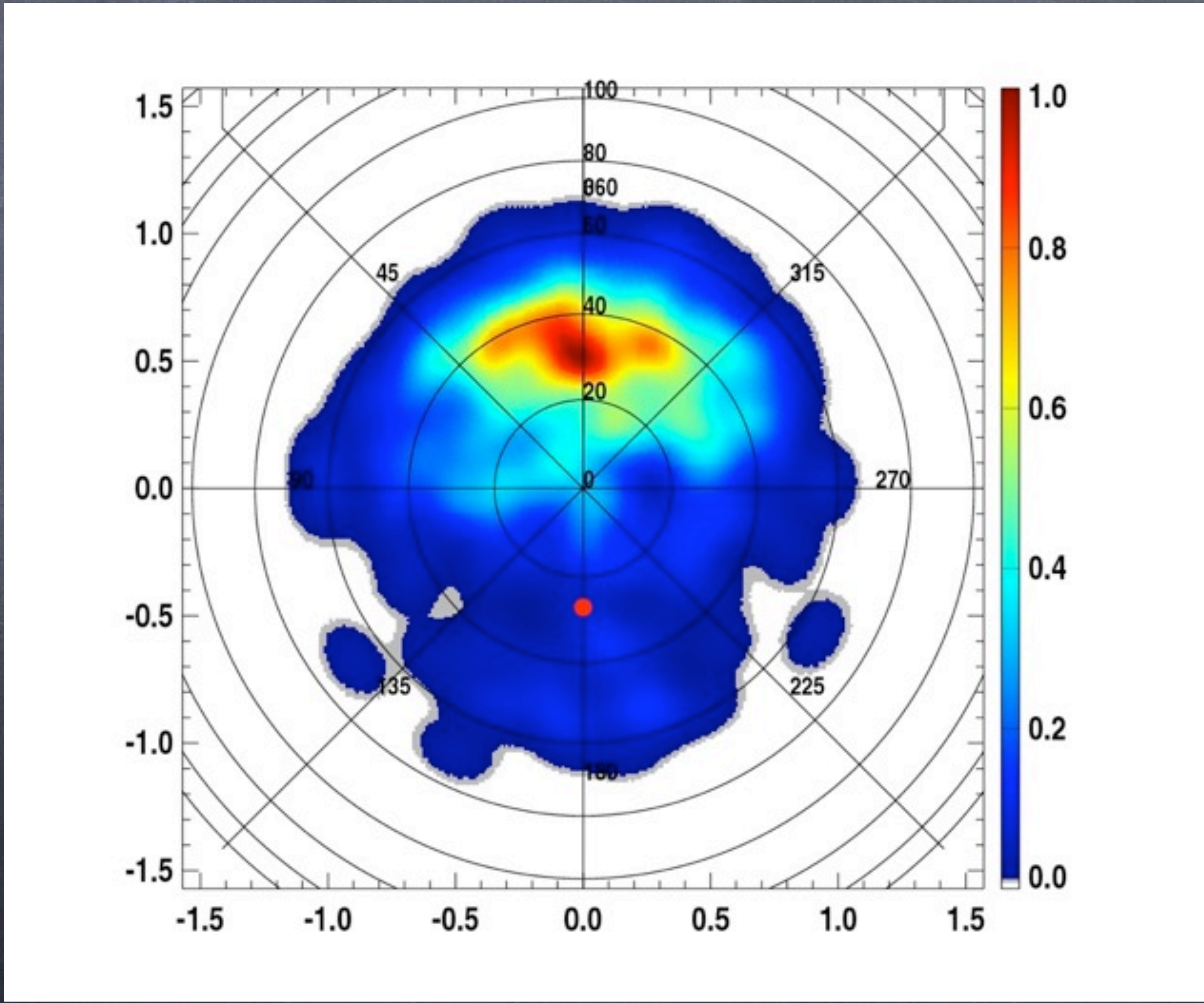
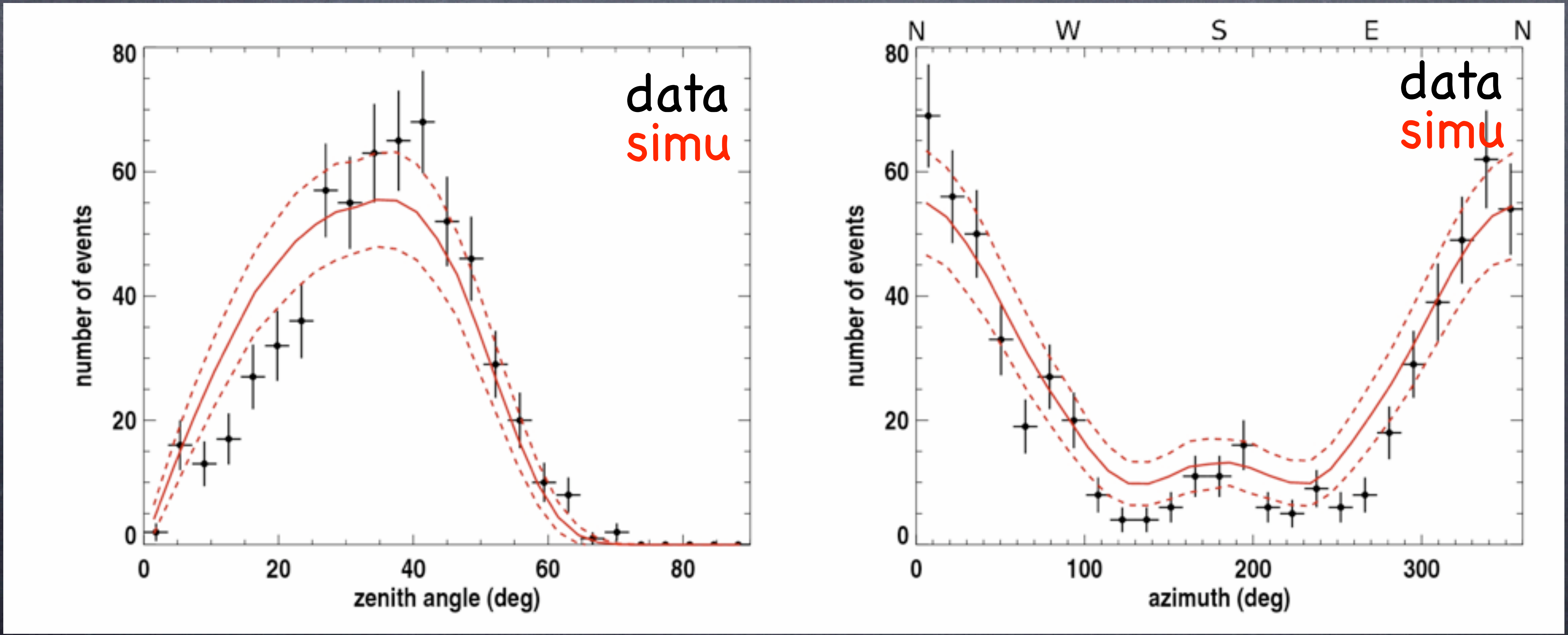
At first sight it is very encouraging
check further with MC simulations



CODALEMA

Test with Monte-Carlo simulation:
draw N sets of p simulated events following the theoretical skymap, p being the actual number of real events in the CODALEMA dataset and compute the angular distributions

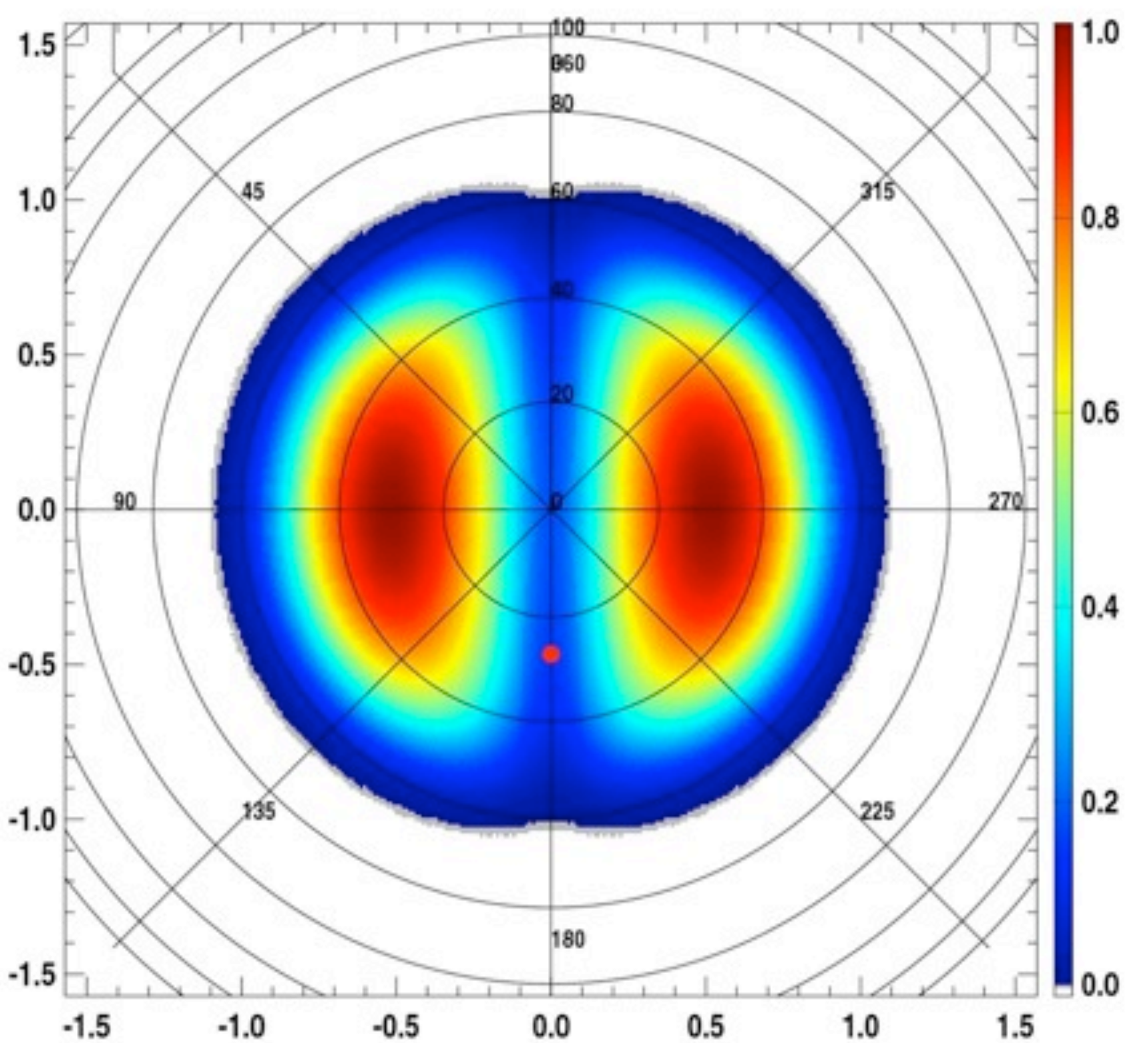


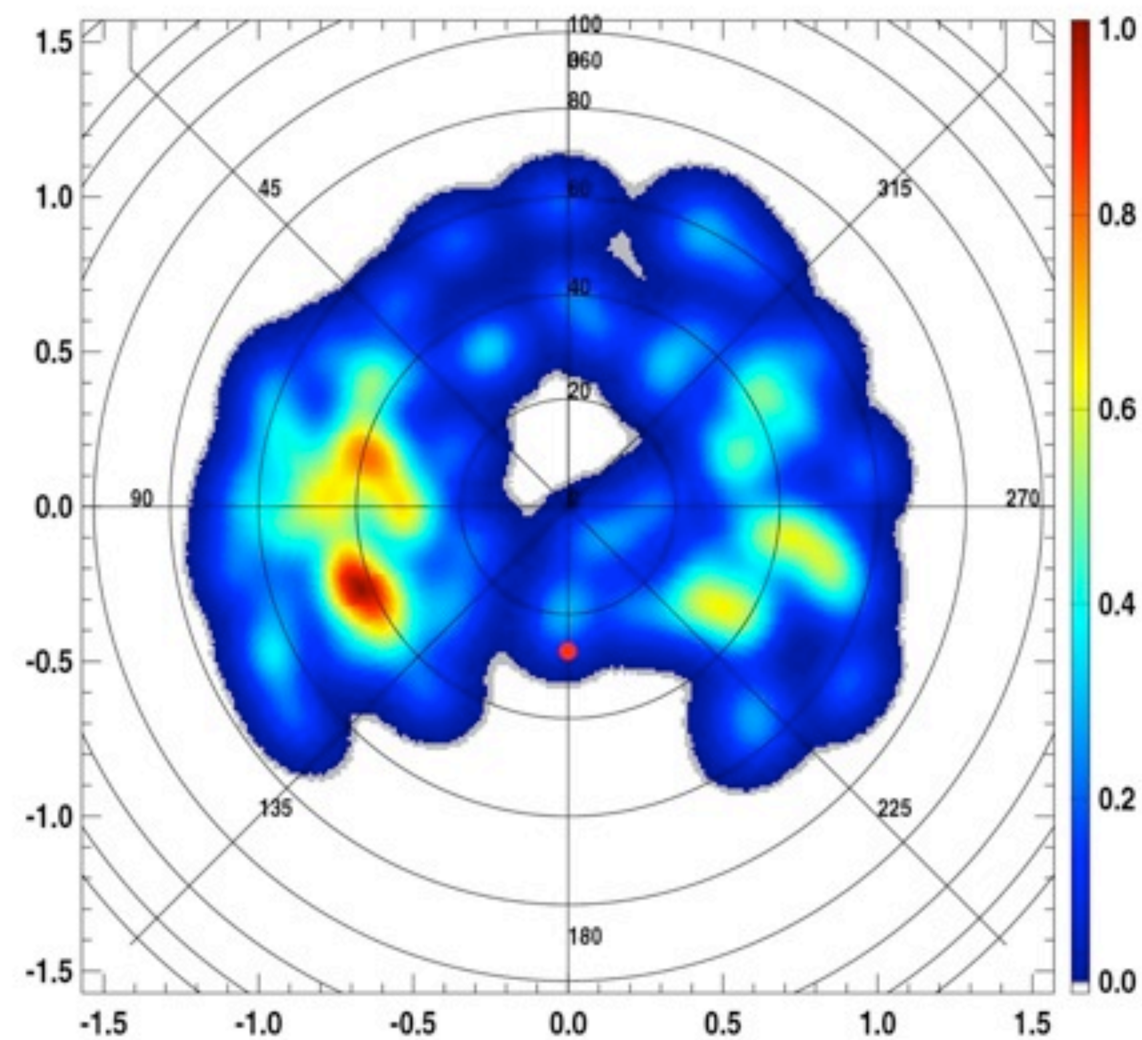
CODALEMA

good results also in the NS polarisation
(but only 3 antennas and small amount of data)

$$(\vec{\beta} \times \vec{B})_{\rm NS} \cdot \frac{{\rm d}N}{{\rm d}\theta} \cdot \frac{{\rm d}N}{{\rm d}\phi} \cdot \frac{1}{\sin\theta}$$

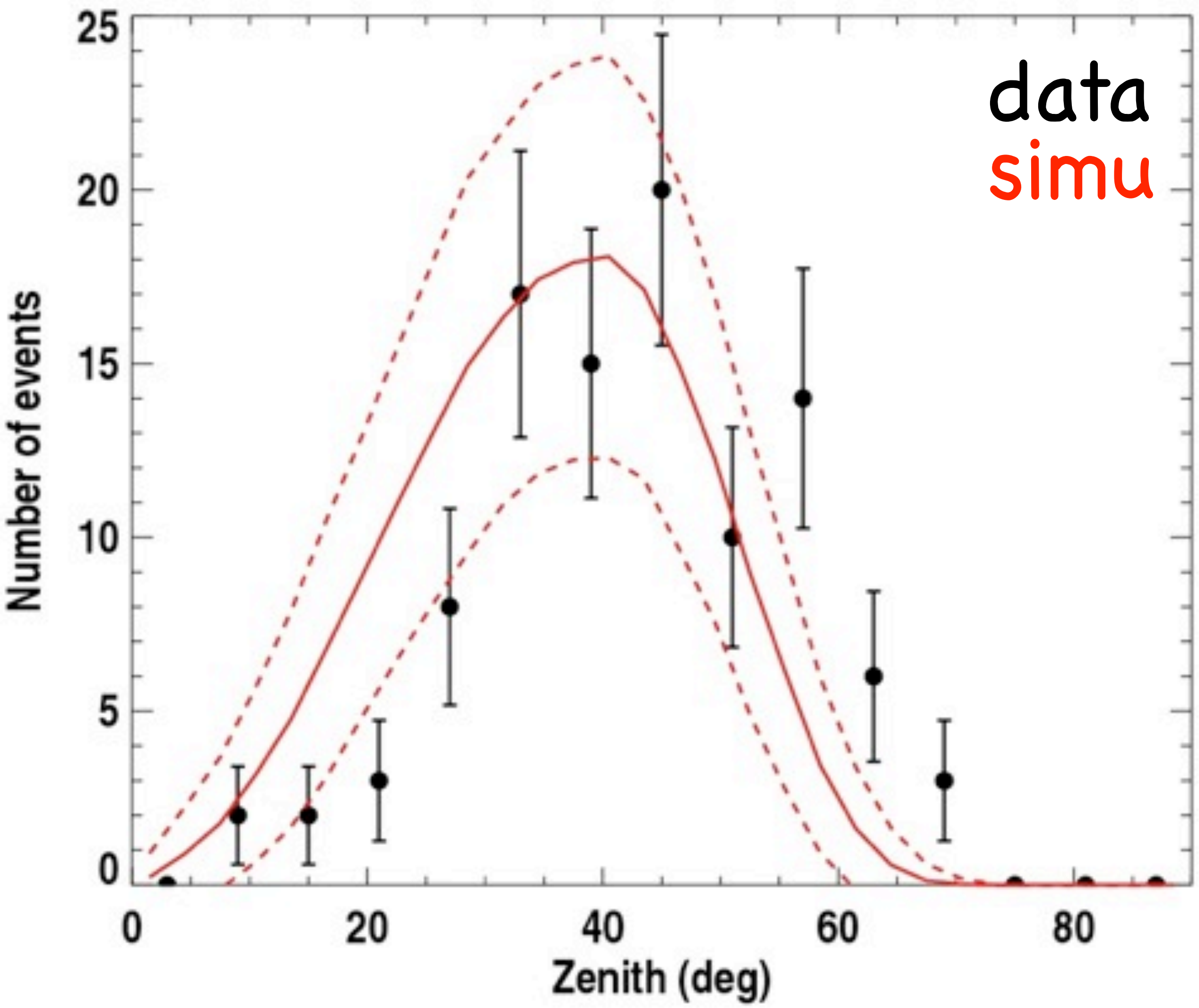
NS polarisation observed skymap

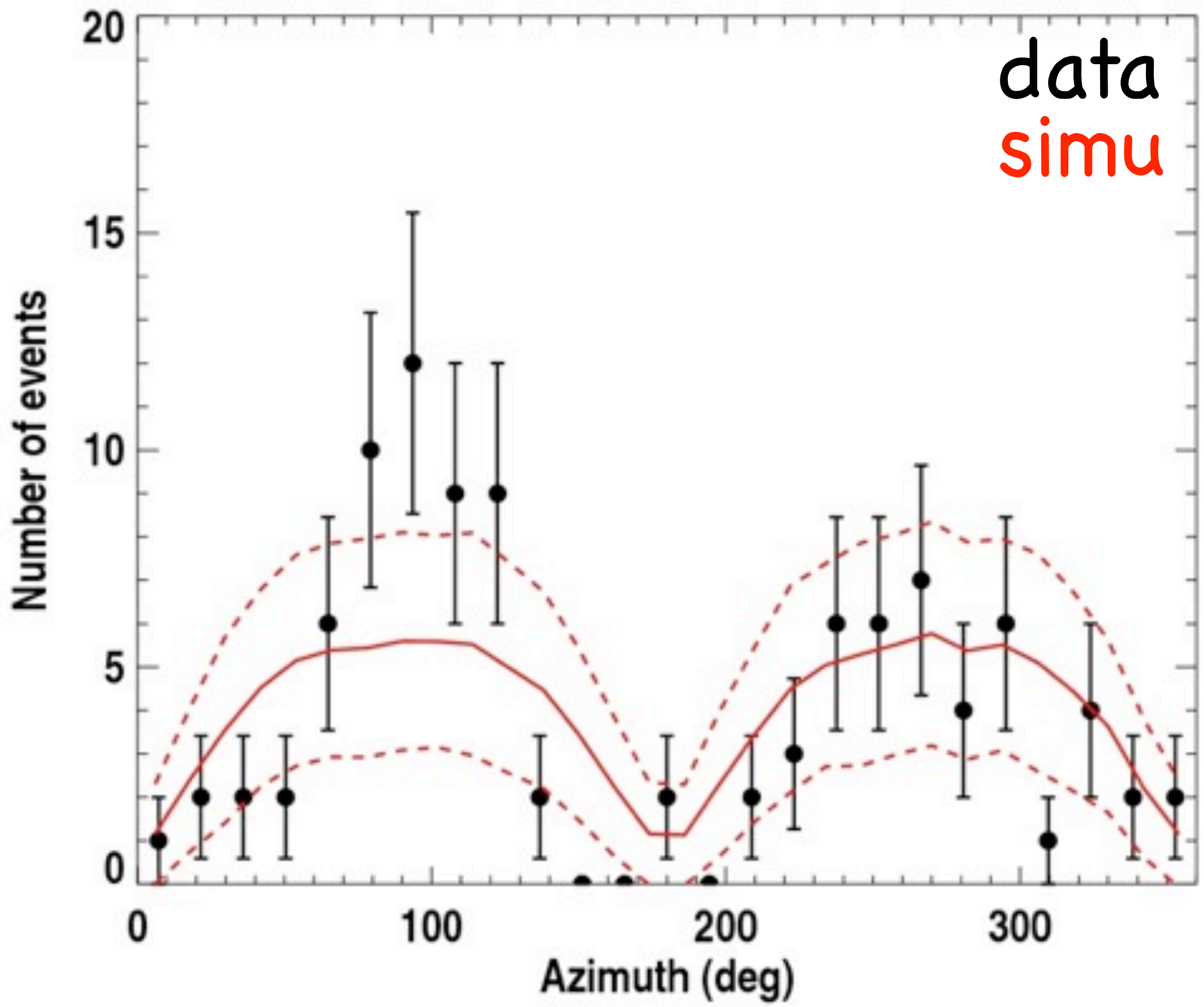




CODALEMA

comparison with MC simulation in the NS polarisation





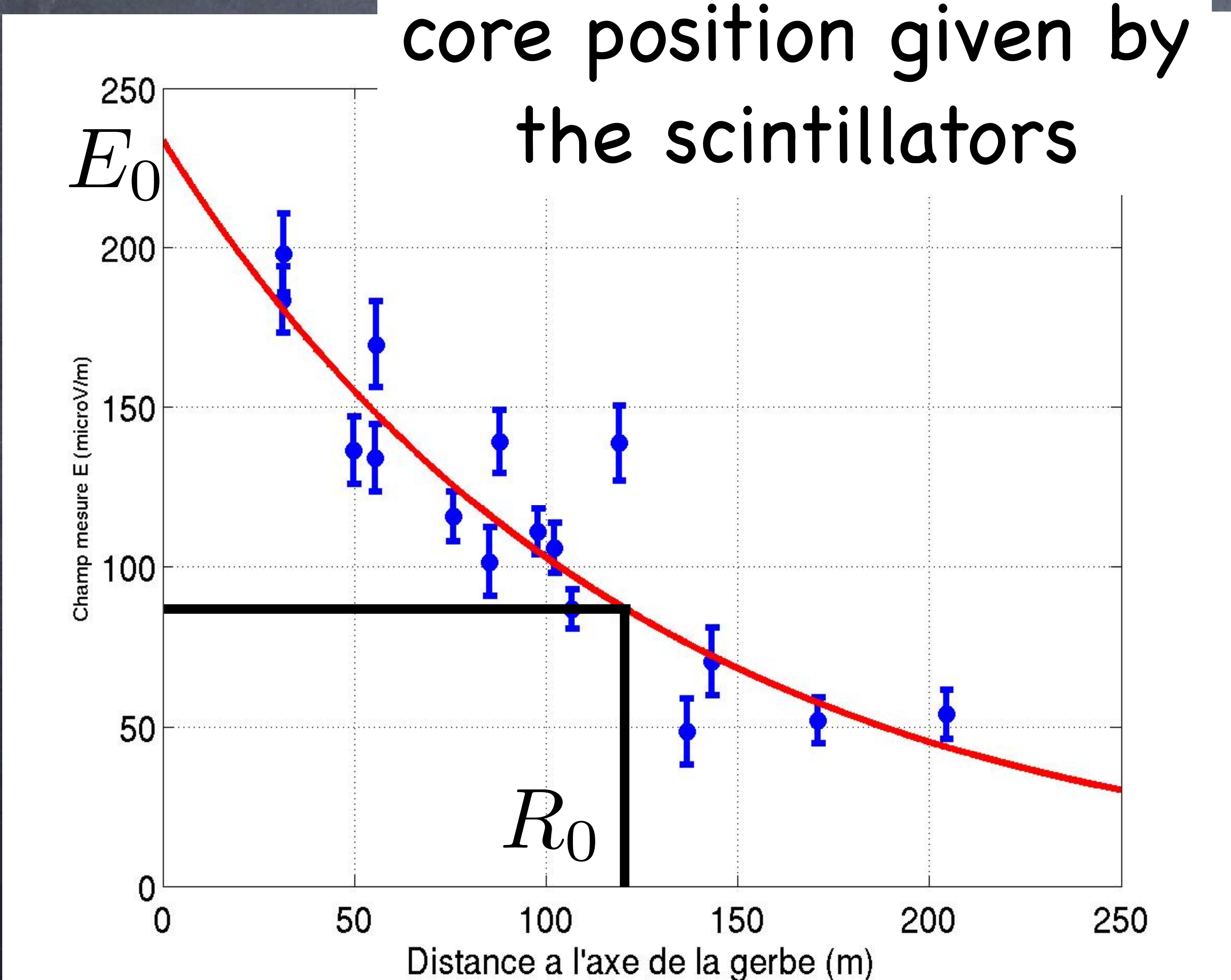
CODALEMA

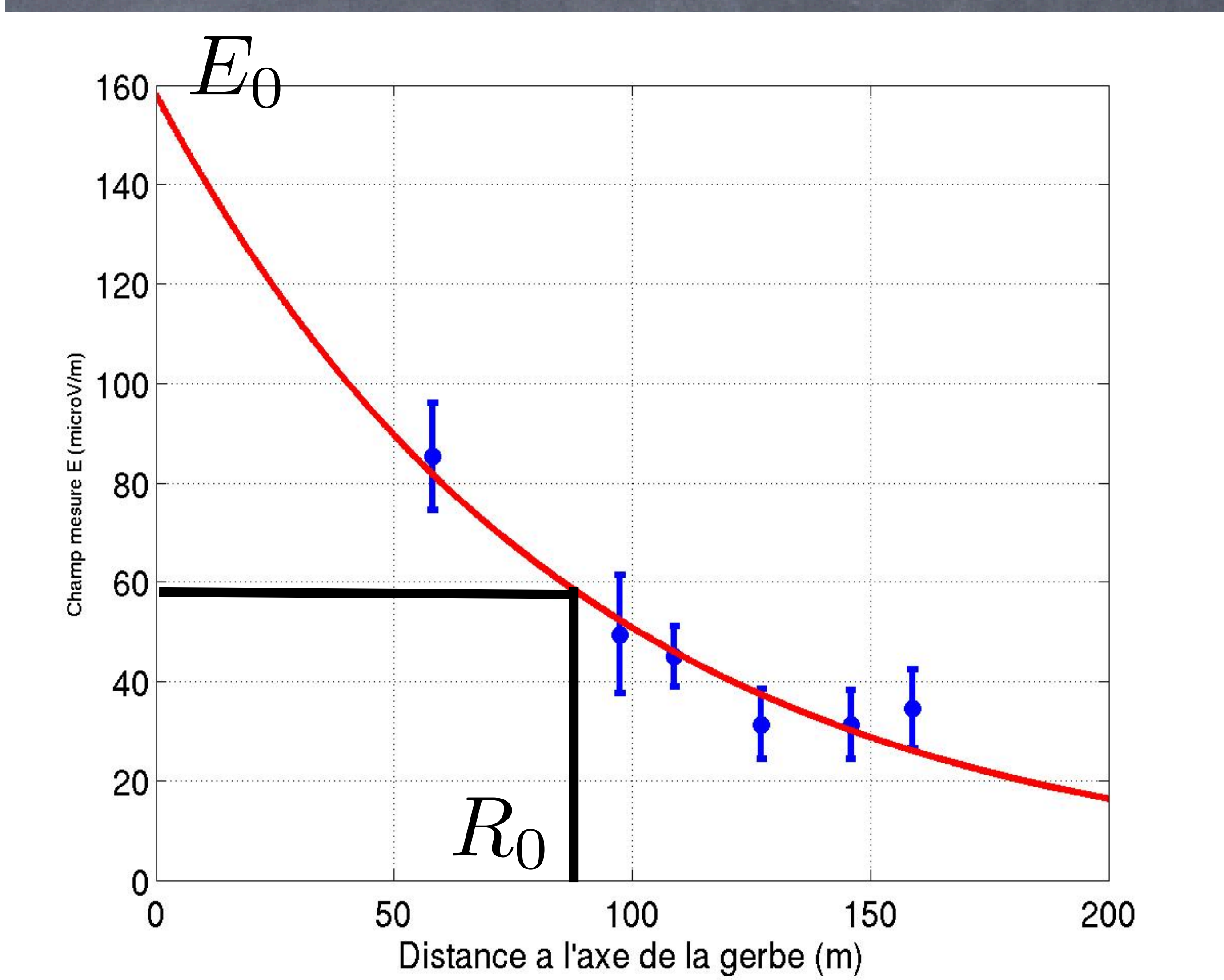
electric field from primary energy

$$\mathcal{E}_\nu = 20\left(\frac{E_P}{10^{17}\ \mathrm{eV}}\right)\sin\alpha\cos\theta\exp\left(-\frac{R}{R_0(\nu,\theta)}\right).$$

$\varepsilon \propto E_0\ \exp(-R/R_0)$ is like a LDF

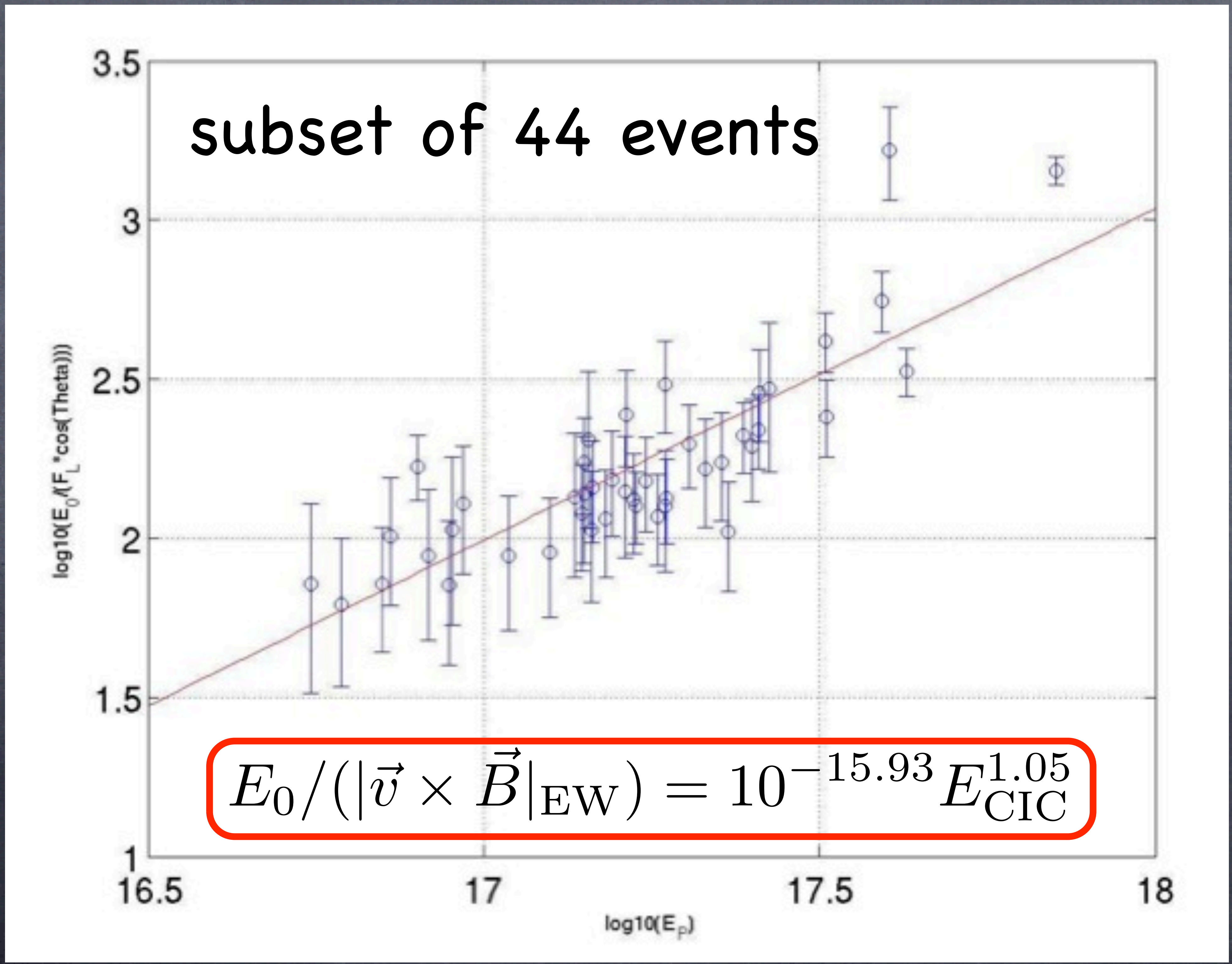
core position given by the scintillators





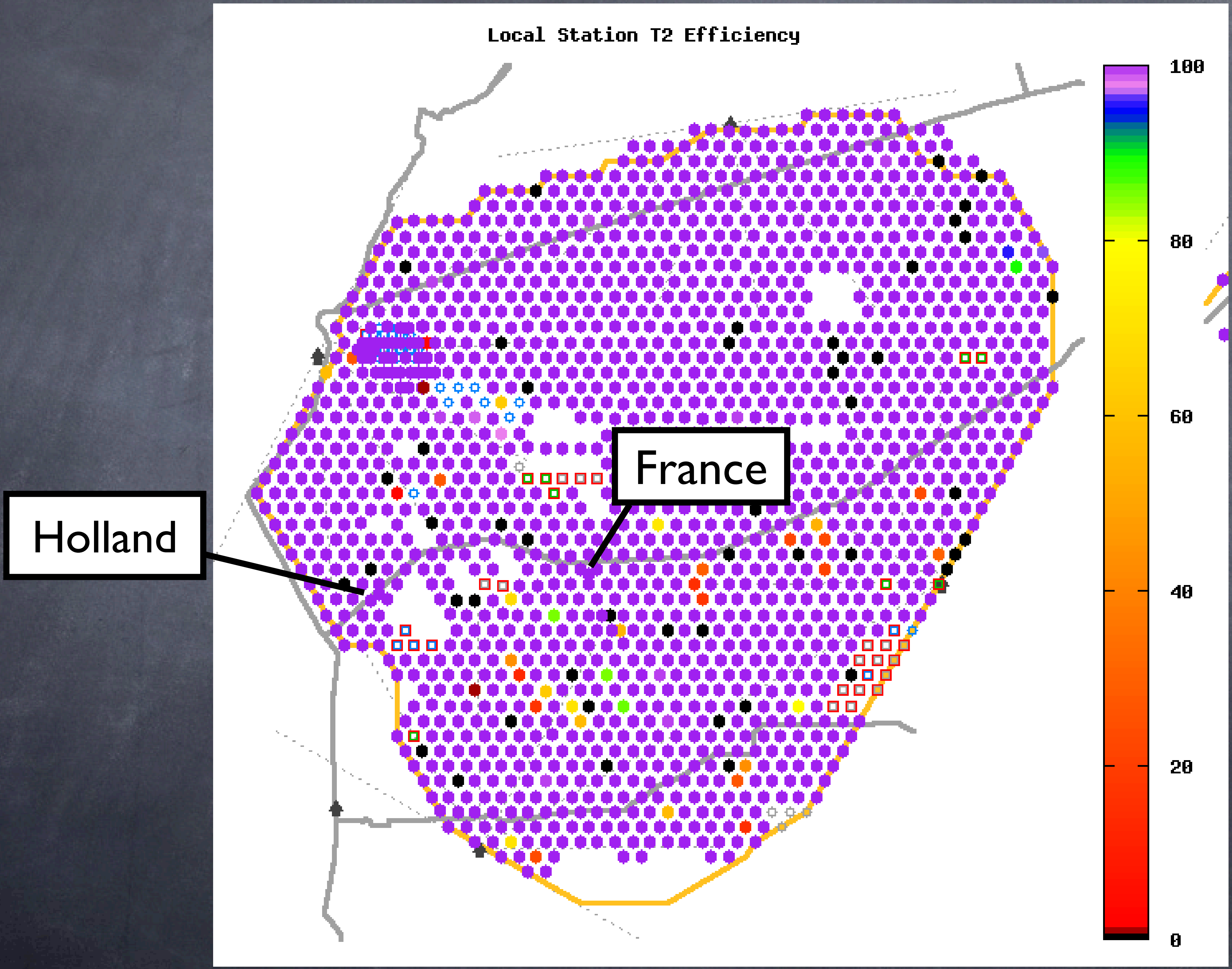
CODALEMA

correlation between the electric field and the primary energy



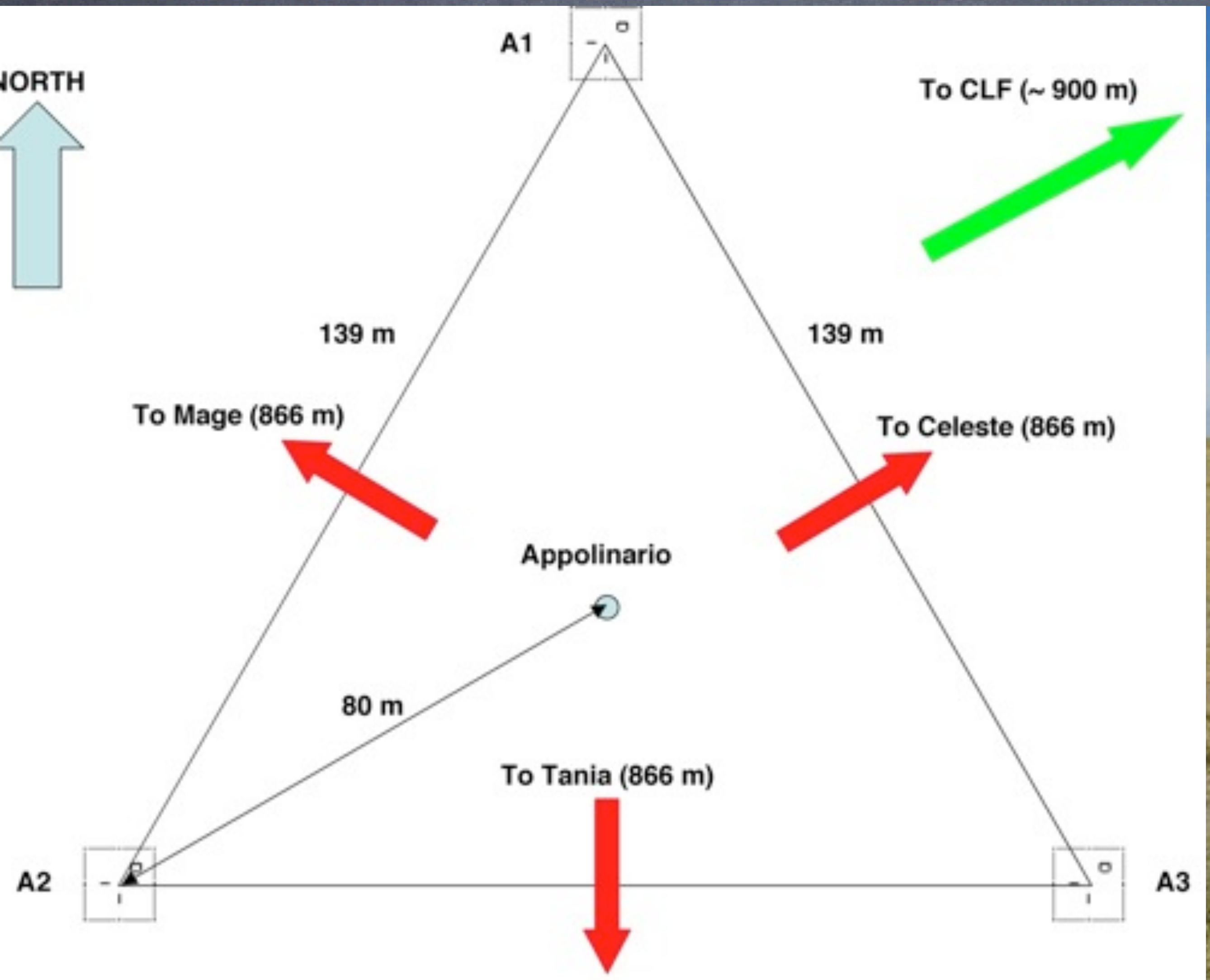
$$E_0/(|\vec{v} \times \vec{B}|_{\mathrm{EW}}) = 10^{-15.93} E_{\mathrm{CIC}}^{1.05}$$

Radio detection in Argentina

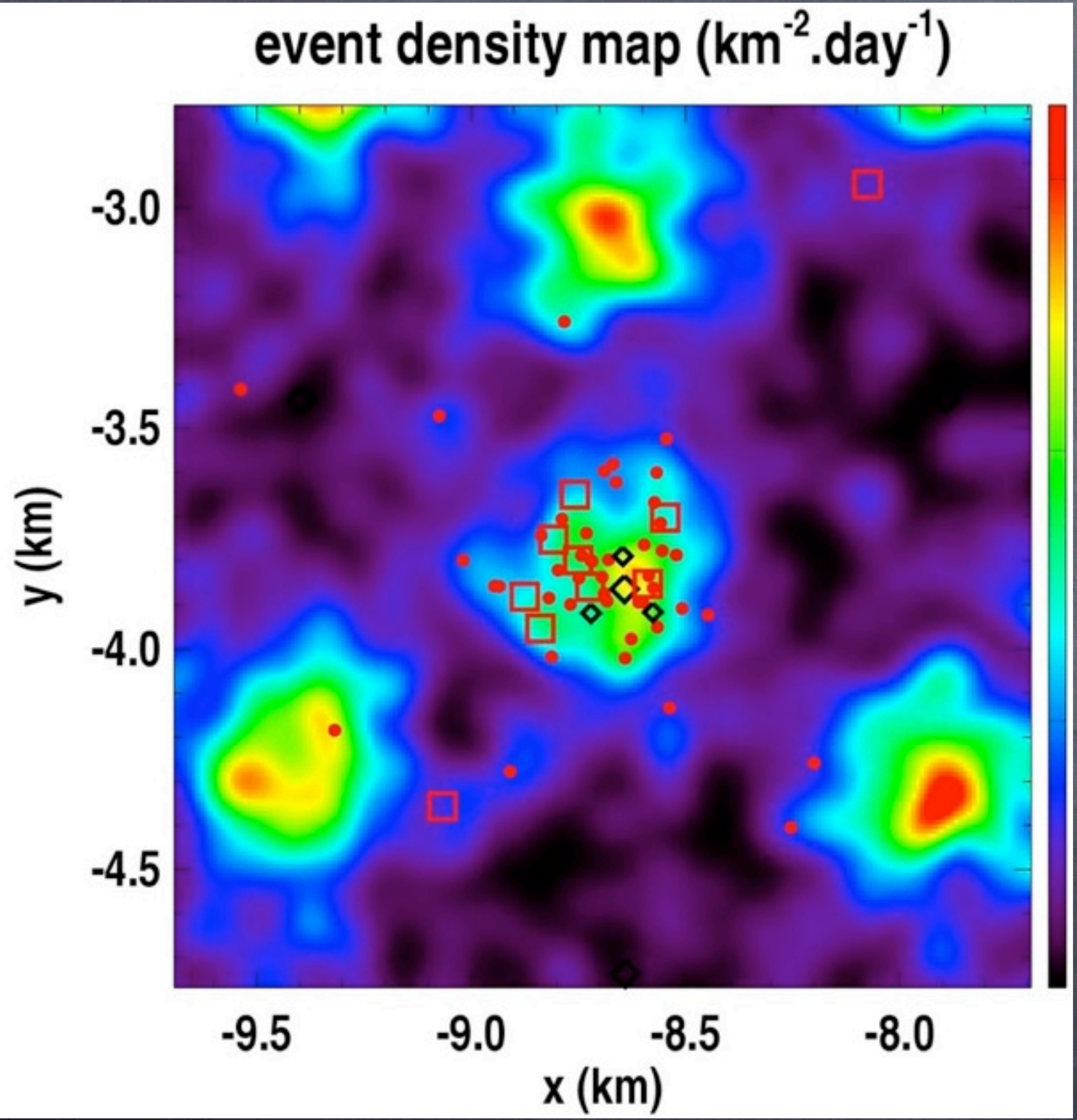


Radio detection in Argentina

first prototype fully autonomous (acquisition, WIFI transfer, solar panels and batteries)
same CODALEMA dipolar antenna
2 polarisation measurements
offline detection of coincidences with Auger SD



Radio detection in Argentina



first coincidence in July 2007

57 events in coincidence with Auger SD (up to Feb 2010)

coincidences with showers up to 1 km from the antenna (axis distance)

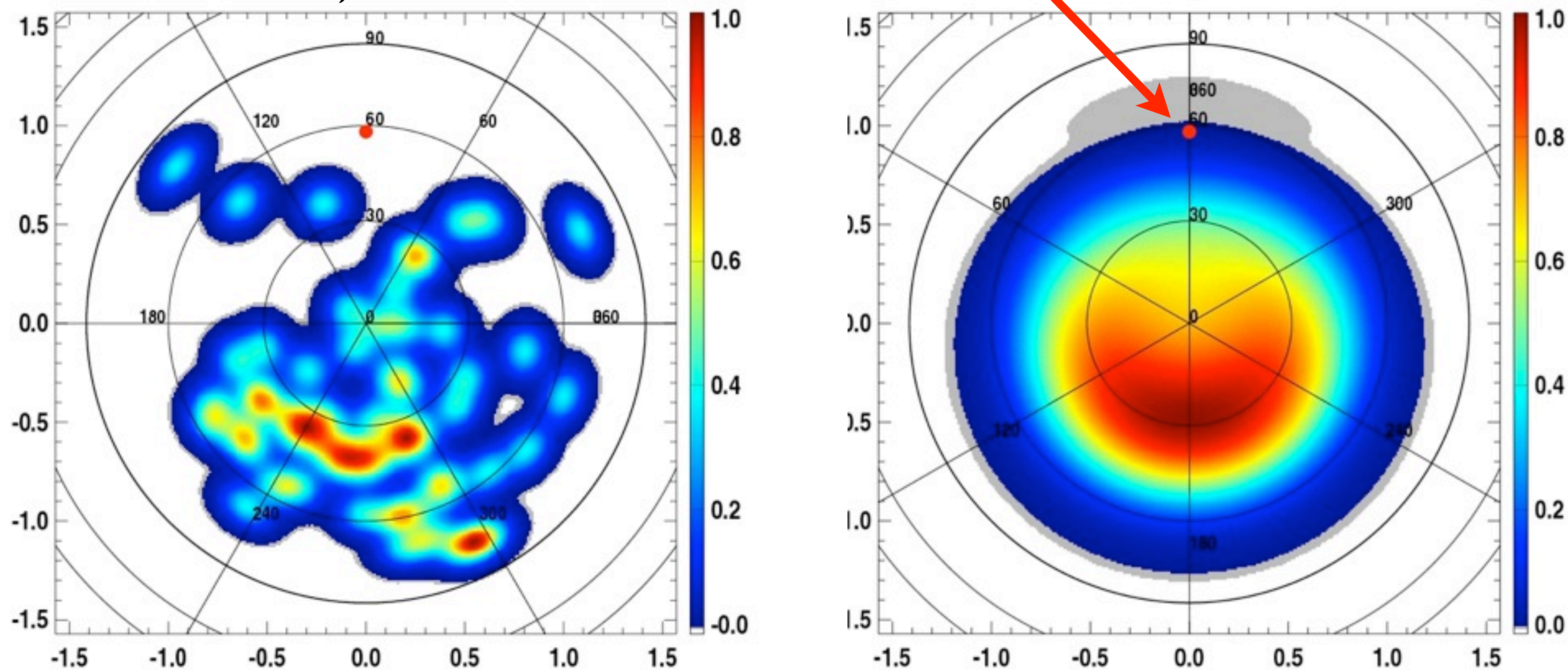
capacity to detect horizontal showers

Radio detection in Argentina

Auger events seen by the radio setup

$$(\vec{\beta} \times \vec{B})_{\mathrm{EW}} \cdot \frac{\mathrm{d}N}{\mathrm{d}\theta} \cdot \frac{\mathrm{d}N}{\mathrm{d}\phi} \cdot \frac{1}{\sin\theta}$$

82% from South, 57 events



The threefold coincidence

gps = 943609544

monday 2009-Nov-30 09:45:29 UTC

ntanks=5

theta=51.0260

phi=-150.469

xcore=-8838.37

ycore=-3953.46

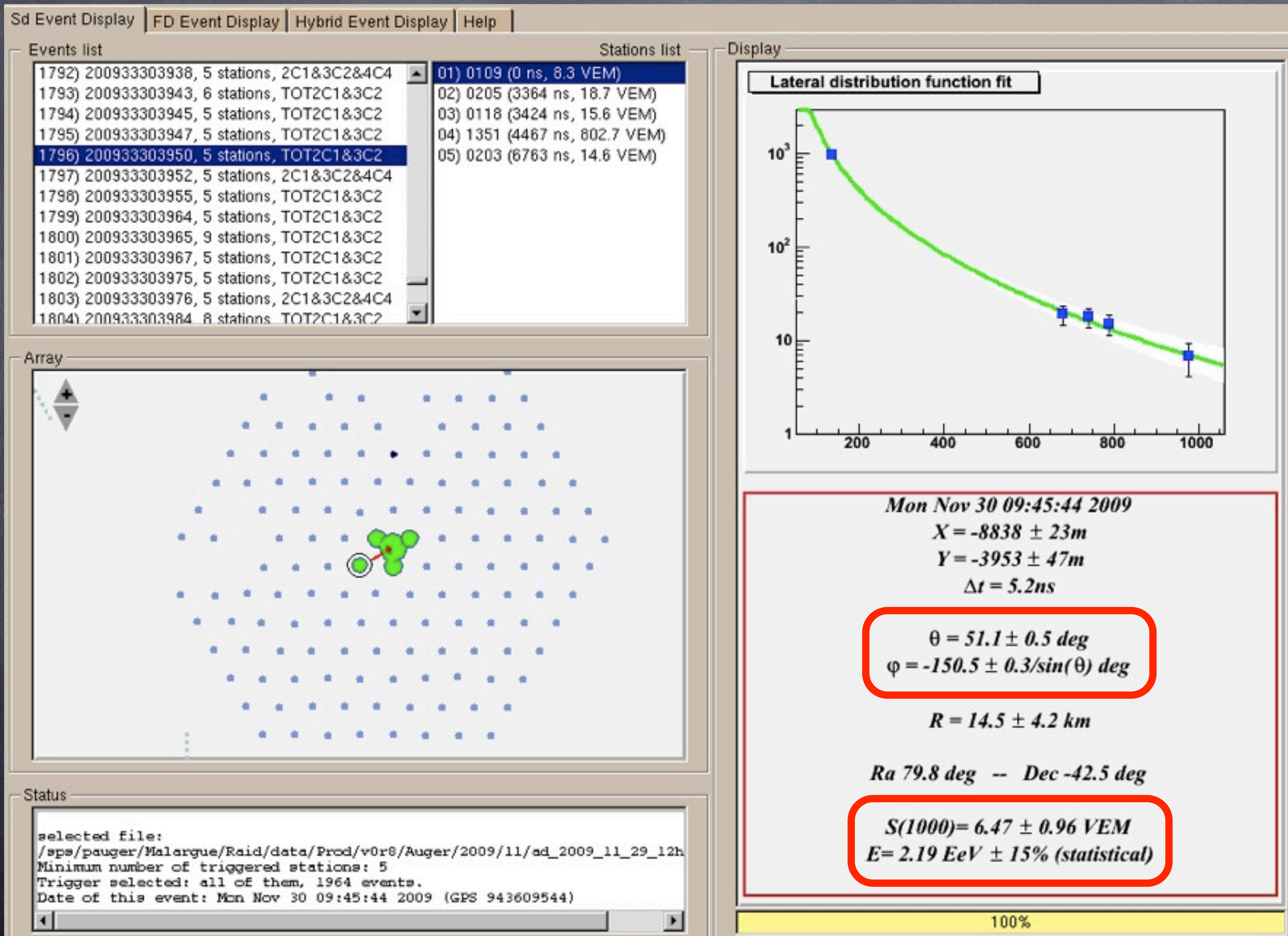
energy (EeV)=2.19300 (not CIC)

axdist-A1= 163.1177 m

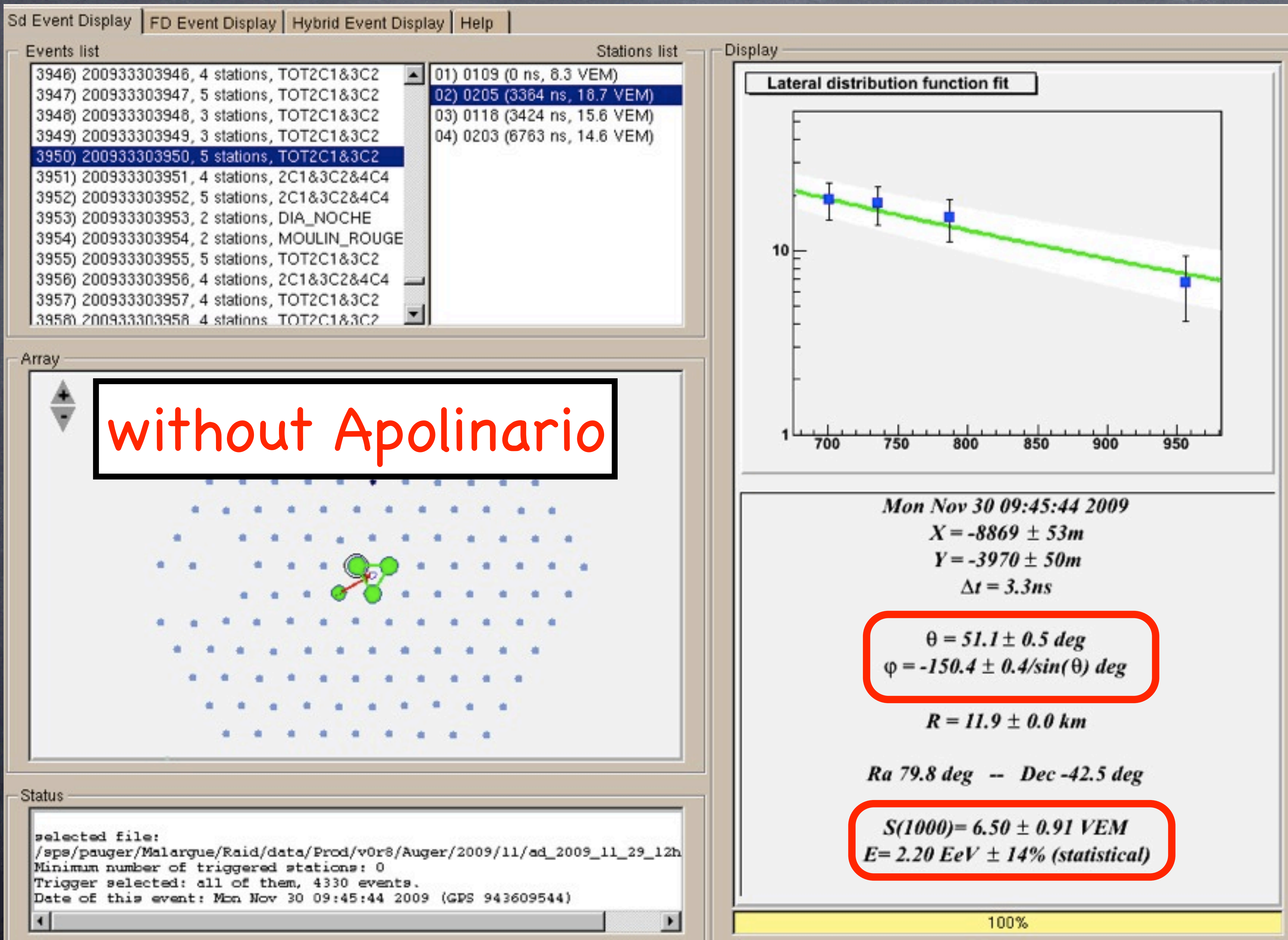
axdist-A2= 80.6342 m

axdist-A3= 183.1924 m

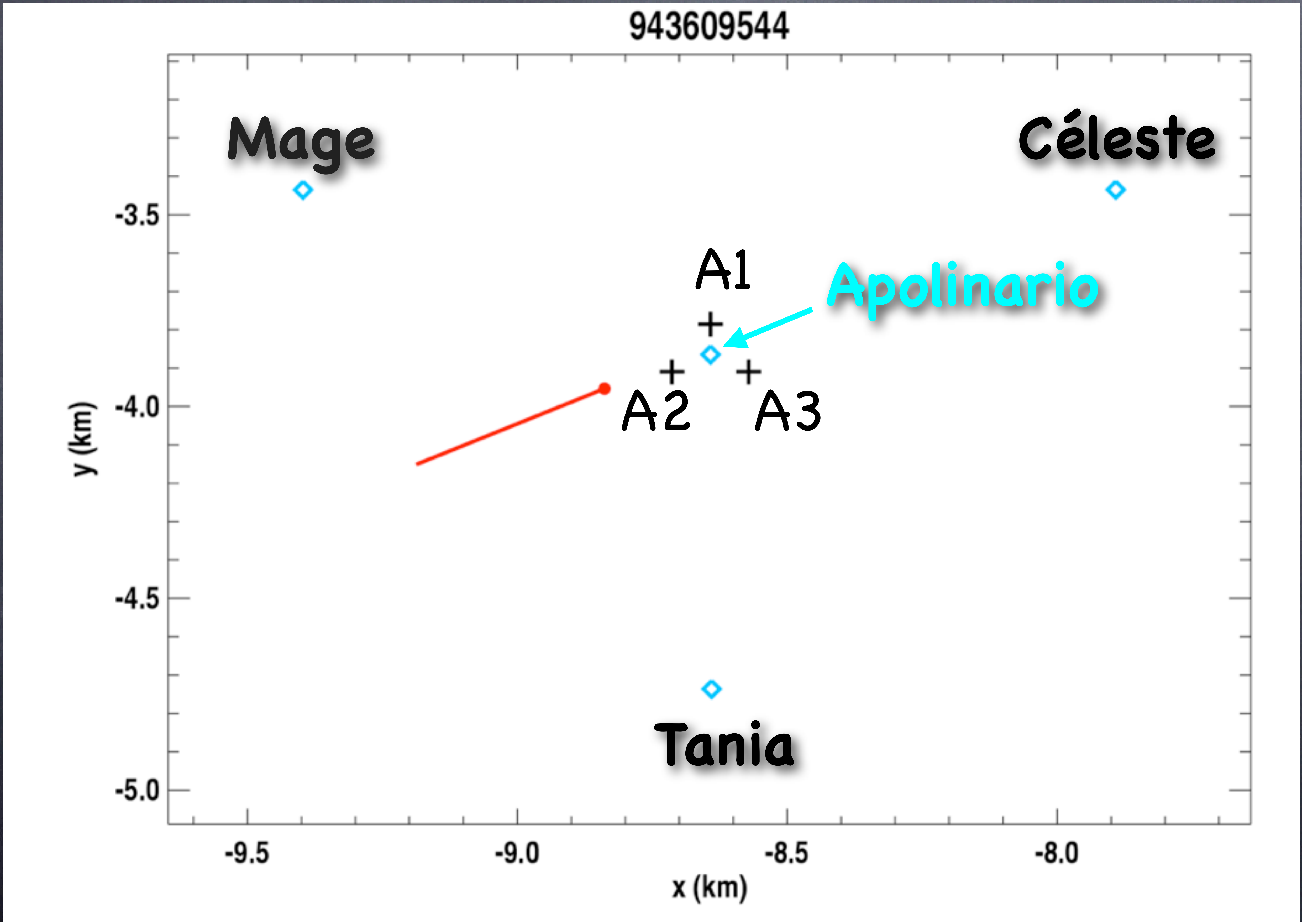
CDAS reconstruction



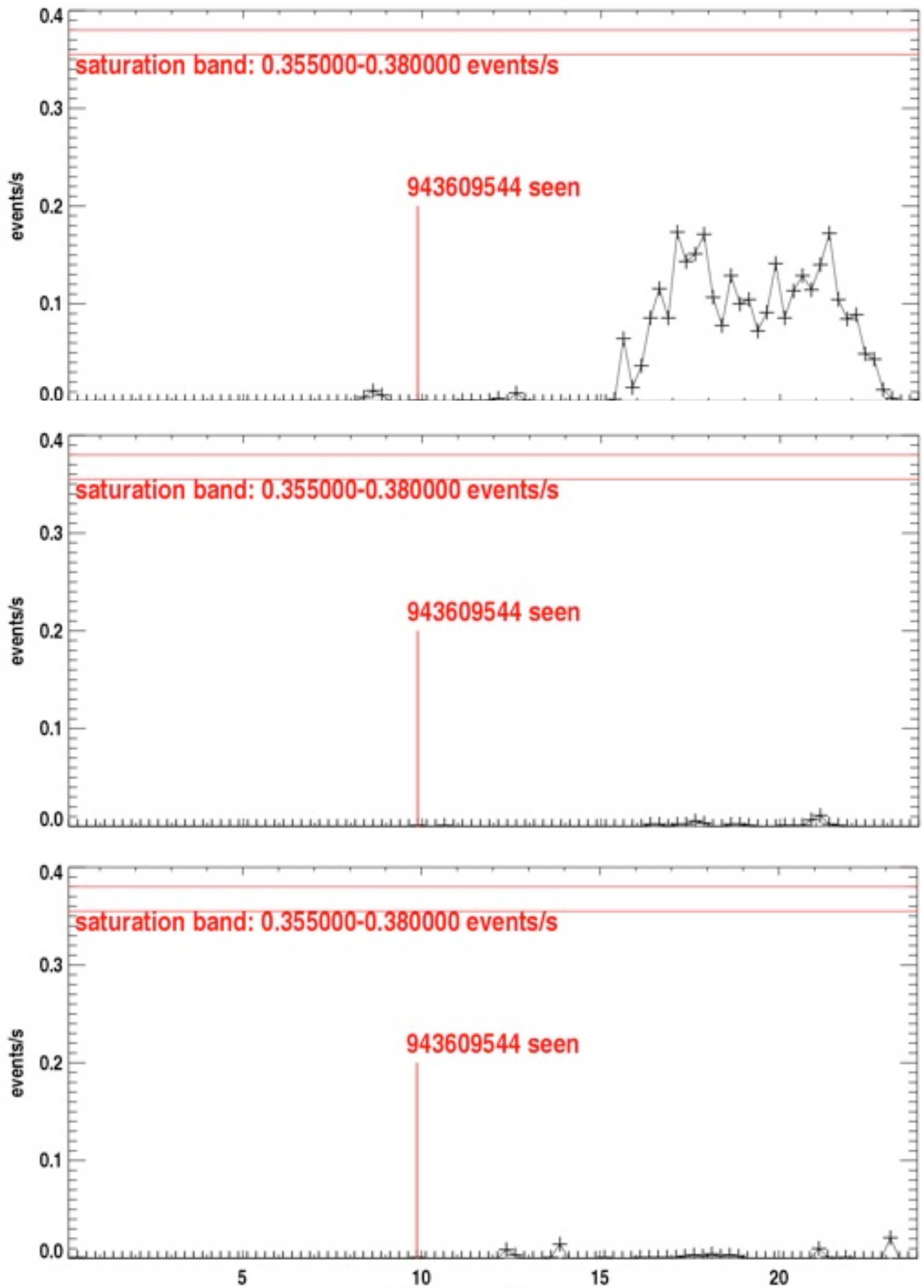
CDAS reconstruction



Radio reconstruction



Trigger rates on the 30th Nov 2009



nano A1 = 317954981

nano A2 = 317954647

nano A3 = 317954976

Radio reconstruction

nano A1 = 317954981

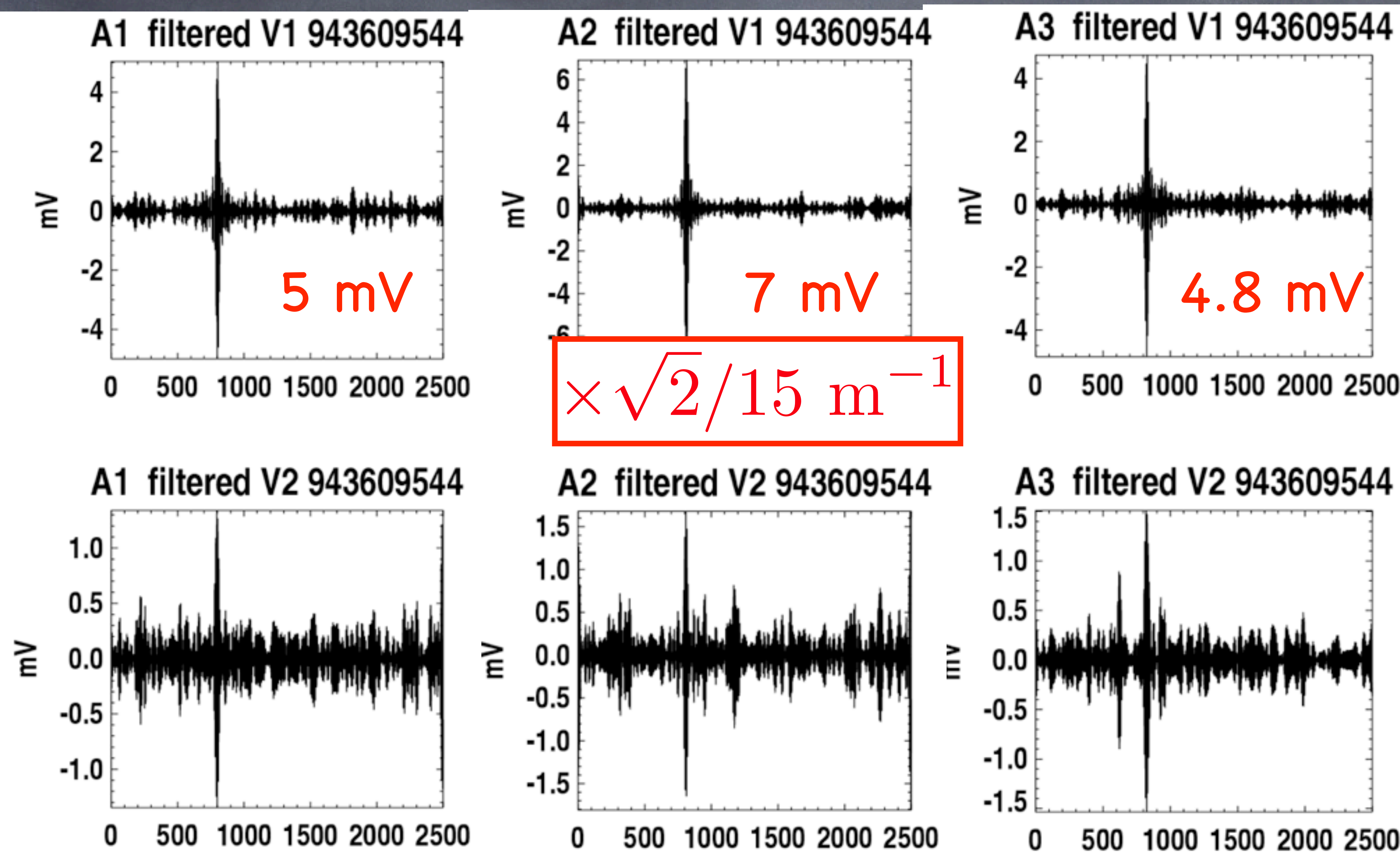
nano A2 = 317954647

nano A3 = 317954976

radio	angular difference	SD CDAS
theta = 51.37	**0.38°**	theta = 51.02
phi = 209.74		phi = 209.53

Auger angular resolution
for this θ and
multiplicity : **above 1°**

Radio reconstruction



Radio reconstruction

given the Auger SD core position
and the direction, compute the profile in the band [50-70] MHz:

$$E_i^{\mathrm{EW}} = E_0^{\mathrm{EW}} \exp(-d_i/d_0)$$

$$E_0^{\mathrm{EW}} \sim 900\ \mu\mathrm{V/m} \qquad d_0 \sim 265\ \mathrm{m}$$

$$E_0^{\mathrm{EW}}/|(\vec{v} \times \vec{B}).\overrightarrow{\mathrm{EW}}| \sim 1220\ \mu\mathrm{V/m}$$

From CODALEMA:

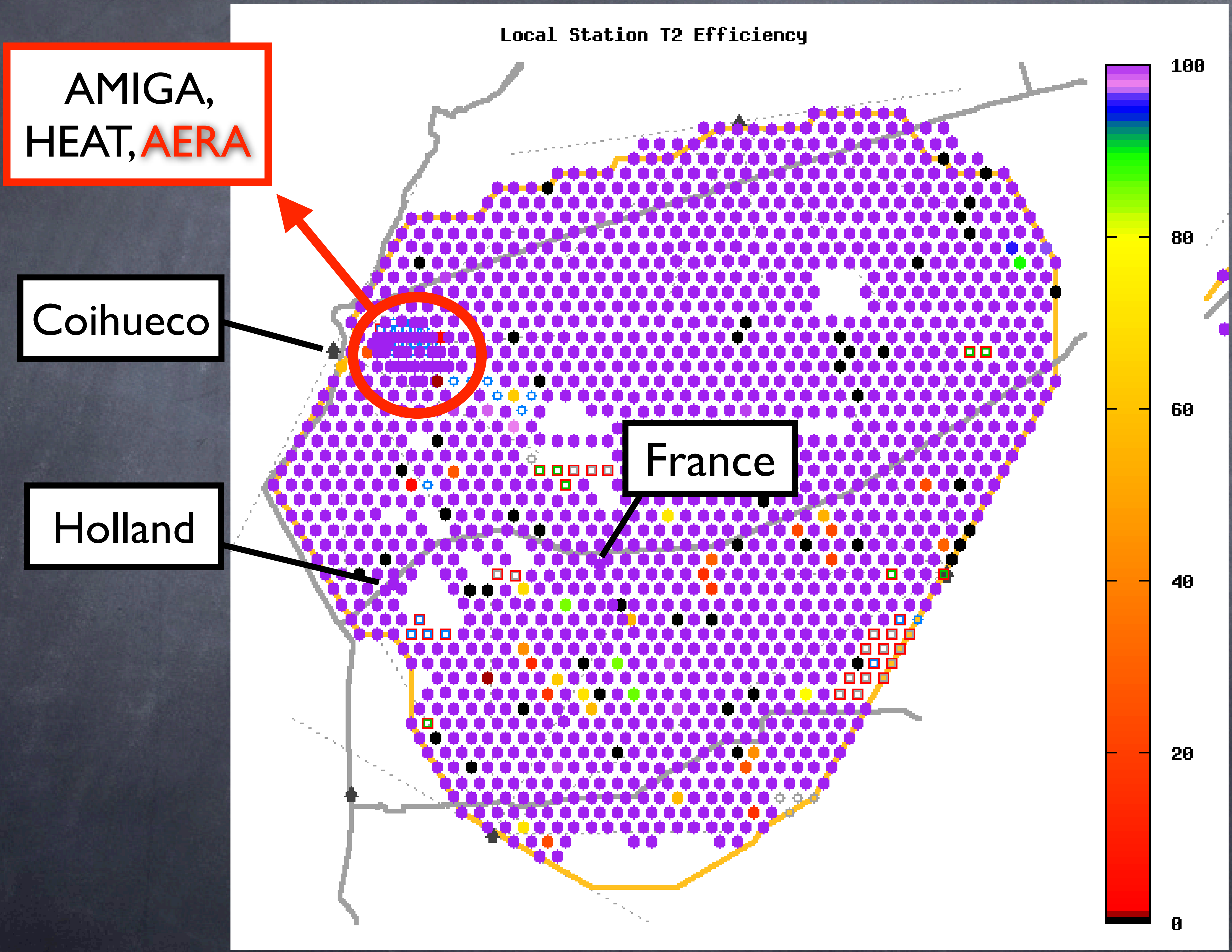
$$E_0^{\mathrm{EW}}/|(\vec{v} \times \vec{B}).\overrightarrow{\mathrm{EW}}| = 10^b {E_{\mathrm{CIC}}}^a,\ b = -15.93,\ a = 1.05$$

so that $E_{\mathrm{CIC}} = 1.29\ \mathrm{EeV}$

in very good agreement (10 %) with Auger value:

1.57 - 2.45 - **1.43 EeV** (old CIC, MC+muons, new CIC)

Radio detection in Argentina



Radio detection in Argentina, AERA

- radio signal calibration: dependence with shower parameters, in order to understand the emission mechanisms of the electric field
- check wether the radio technique is able to reconstruct correctly the shower parameters
- composition of the cosmic rays above the ankle with super-hybrid measurements (SD, FD, radio)

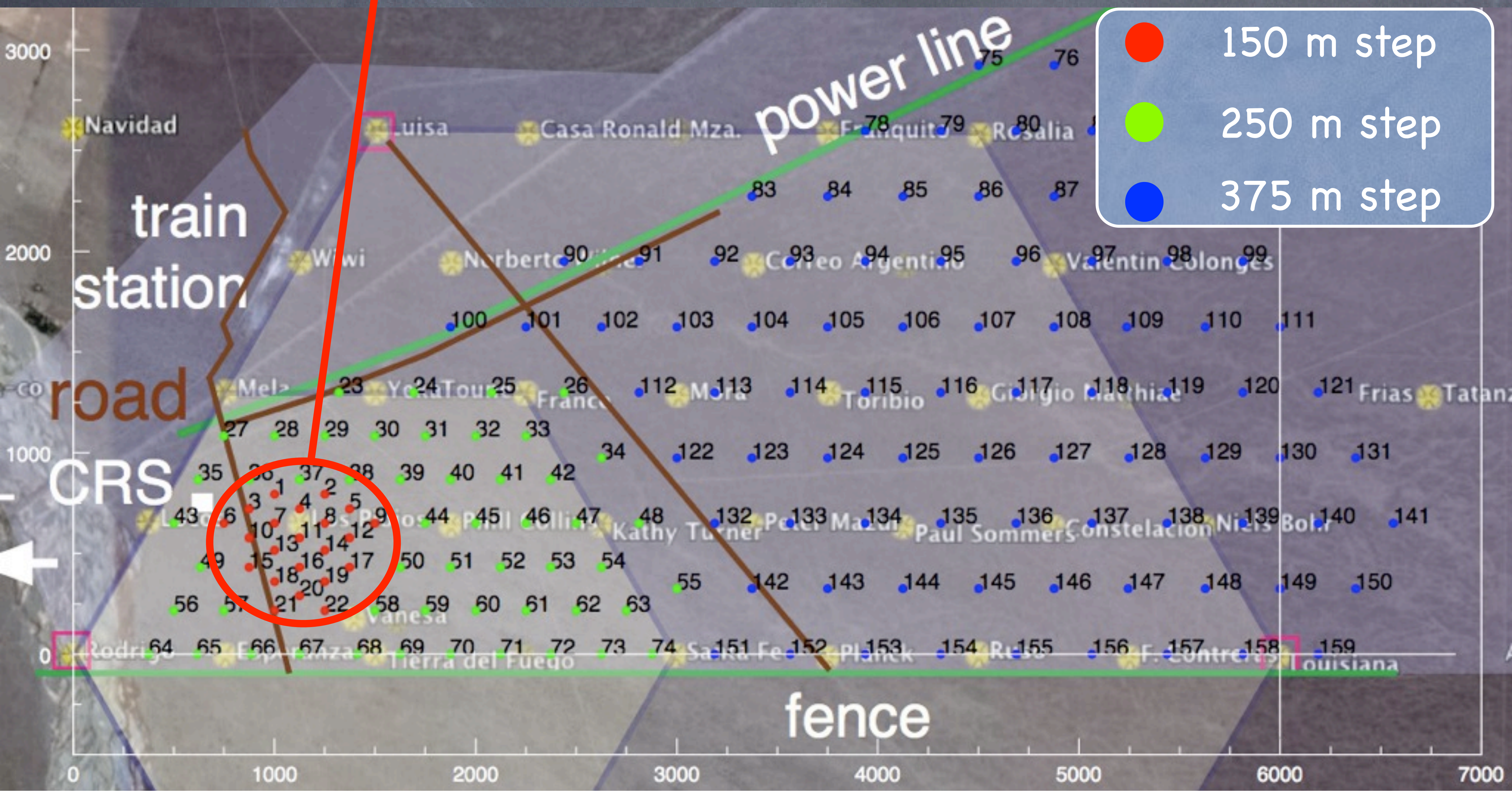
threshold around $10^{17.2}$ eV,
5 000 expected events per year,
1 000 above 10^{18} eV

Radio detection in Argentina, AERA

160 autonomous radio-stations over 20 km^2 on the AMIGA and HEAT site

frequency band 30-80 MHz

stage 1: 20-25 stations, may 2010 ?



Thanks !