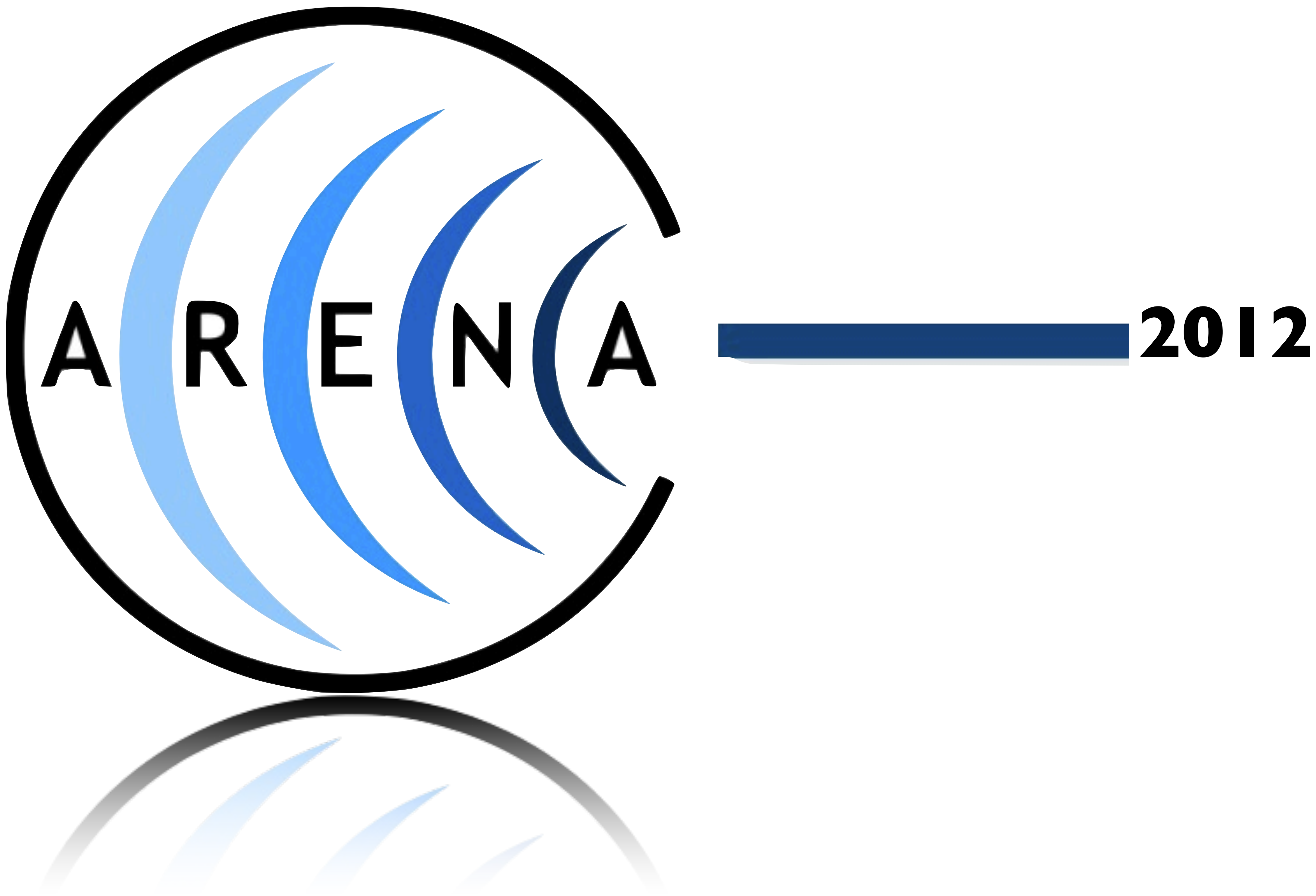
Overview of MHz air shower radio experiments and results

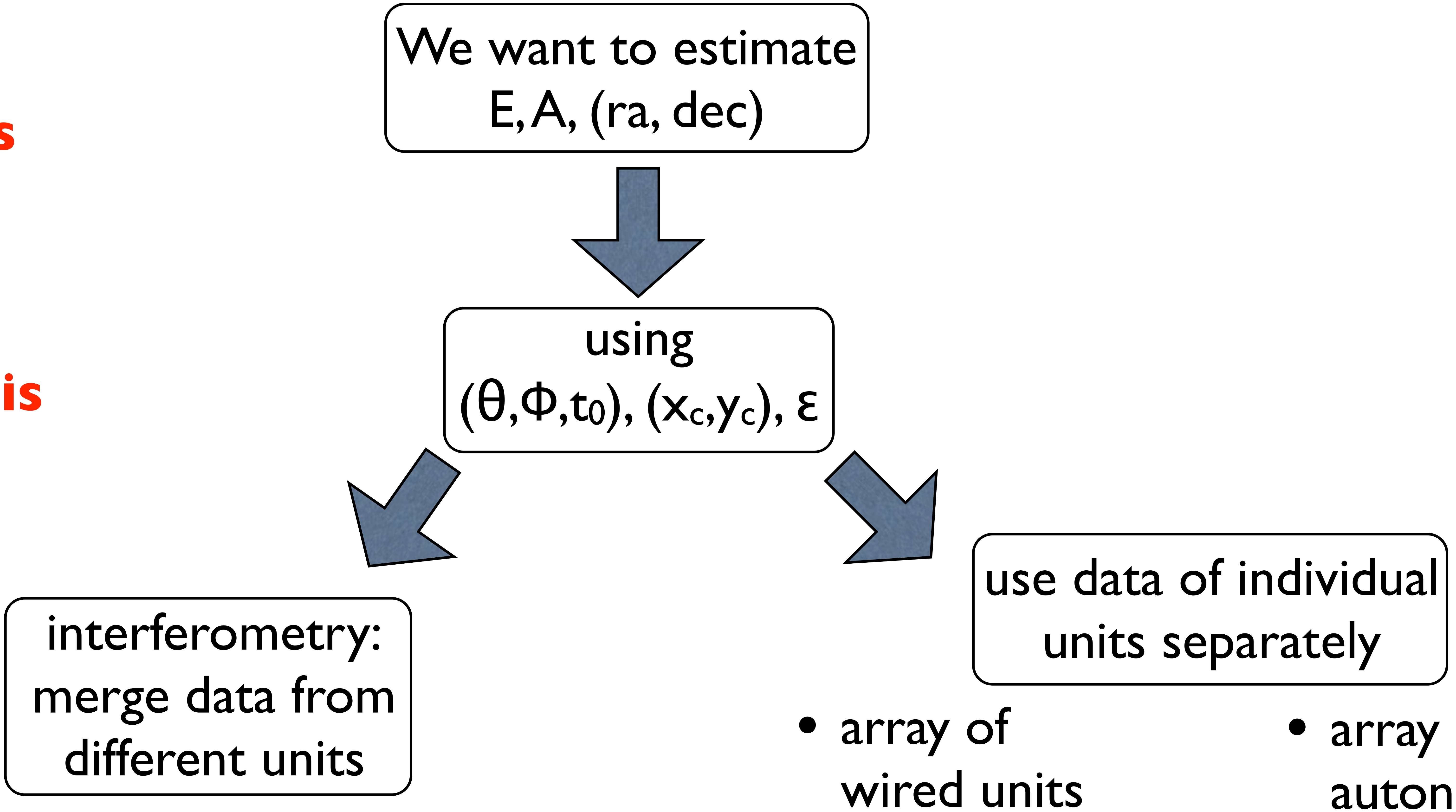


Aims

- **arrival direction in the sky** (ra, dec): under control
- **energy of the primary**: work ongoing, correlation electric field with primary energy provided by another detector (SD and/or FD)
- **nature of the primary**: work ongoing, need another detector (FD)
- **angular reconstruction**: under control
- **emission mechanisms**: through polarization, geomagnetic and charge-excess identified (different polarization patterns)
- **LDF and core position**: work ongoing

and then (only then), we will answer to the FAQ:
what about a huge radio array over tens or thoudands of km^2?

From data to physics



physics/ astrophysics

We want to estimate E, A, (ra, dec)

data analysis

using (θ,Φ,t_0), (x_c,y_c), ε

technics

interferometry: merge data from different units

LOPES

good solution
if the site is noisy

use data of individual units separately

- array of wired units

CODALEMA 1,2
MAXIMA
TREND, LOFAR+LORA,
RASTA, Tunka-Rex...

- array of fully autonomous units

CODALEMA3
RAuger 1,2
AERA
EASIER MHz...

Howto

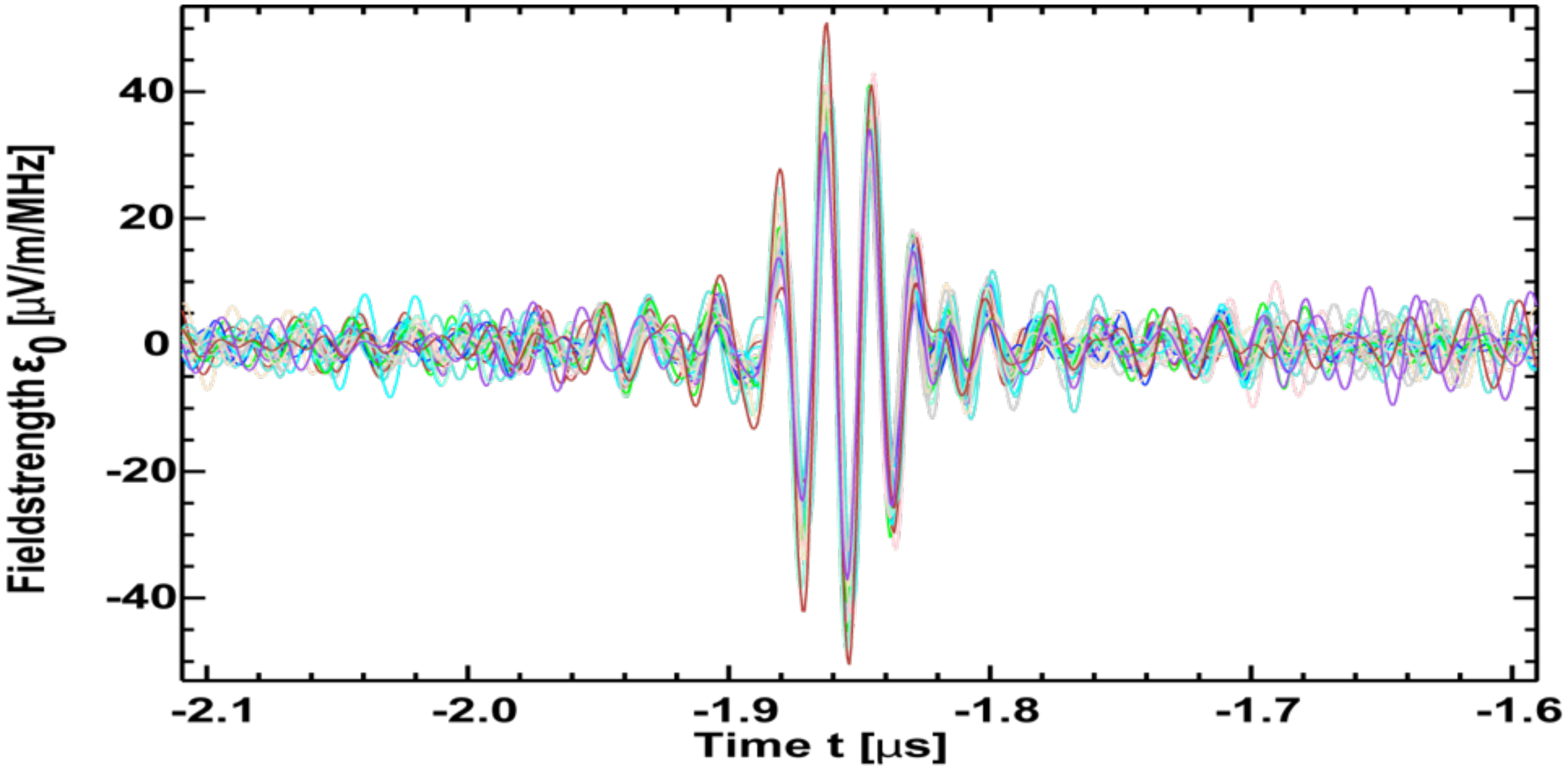
I. Interferometry, example of the LOPES experiment

- digital radio interferometer
- triggered by KASCADE
- energy range $10^{16.8}$-10^{18} eV
- shower reconstruction provided by KASCADE (also N_e, N_μ)
- radio-noisy environment: low sampling frequency 80 MHz
- signal filtered within [40,80] MHz

Howto

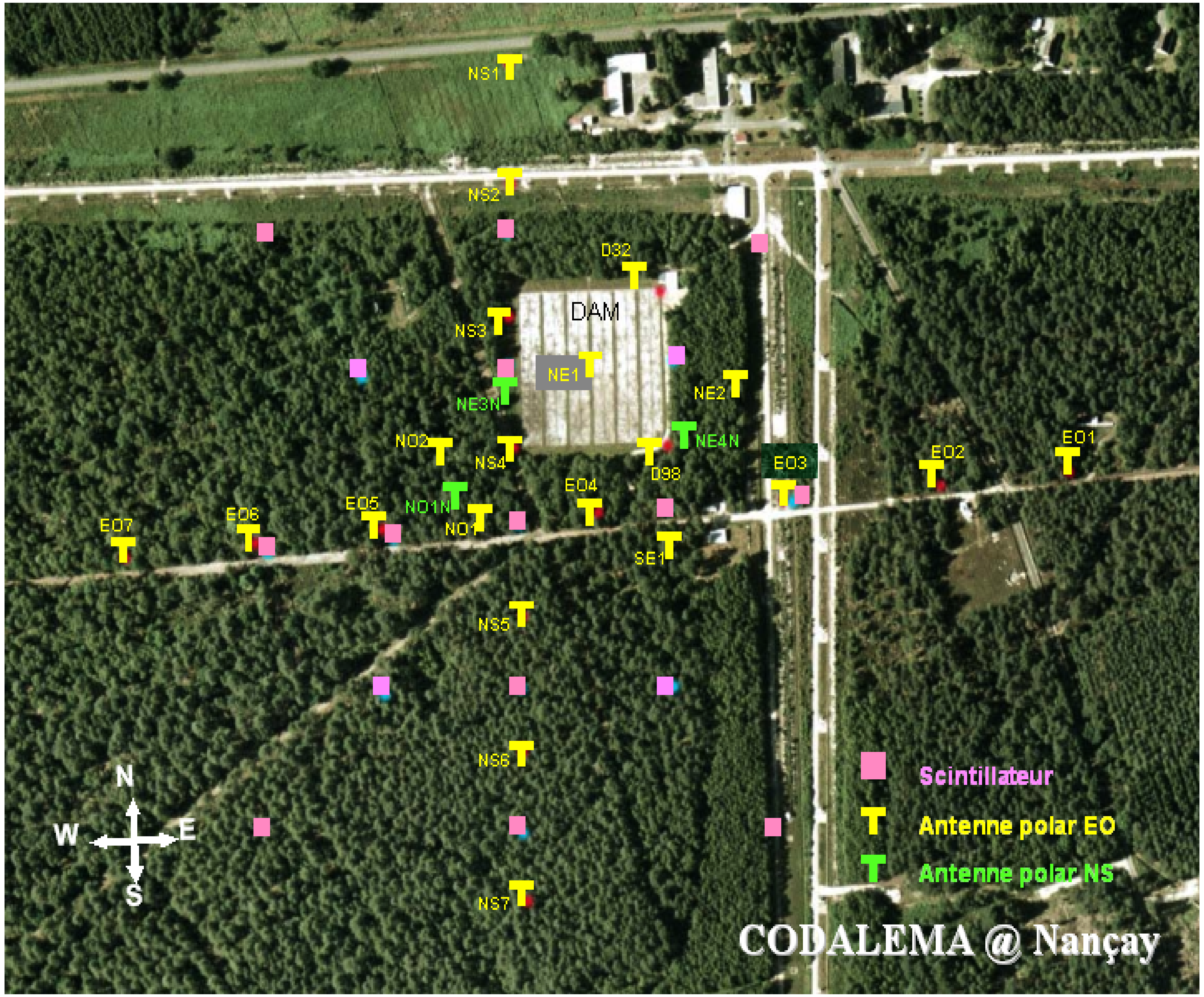
I. Interferometry, example of the LOPES experiment

After time calibration, amplitude calibration, filtering and cleaning,
cross-correlation beam forming
provided the shower geometry (KASCADE), compute the expected arrival time in the antennas and "synchronize radio data"



Howto

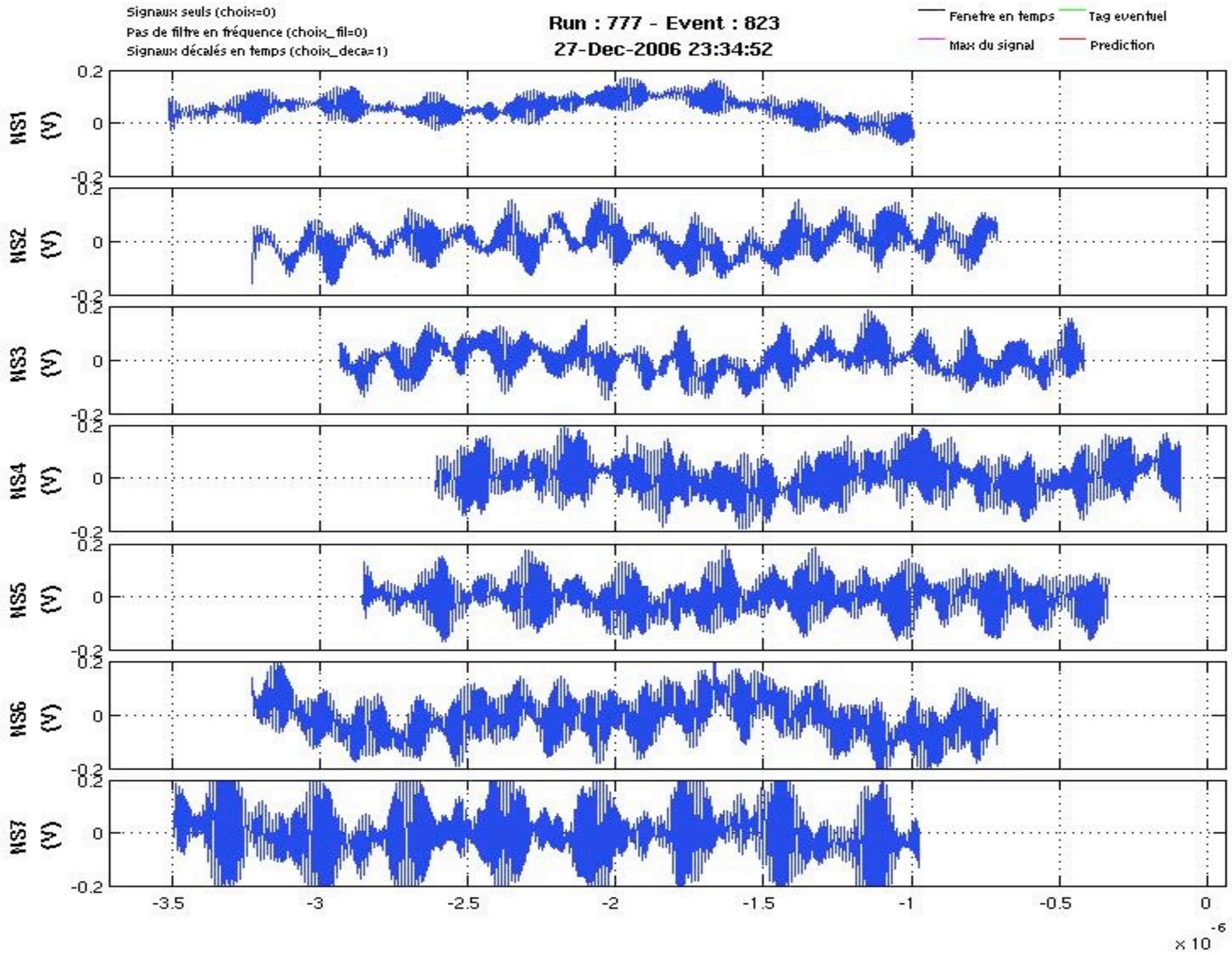
II. Particle physics-like radio detector, example of the CODALEMA2 experiment



- radio-quiet site
- array of **21 EW** and **3 NS** antennas, step of 85 m, 2 arms of 600 m length
- DAM: 144 log-periodic antennas 80x80 m^2
- 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
- MATACQ ADC: 12 bits, 1 GHz, 2500 samples

Howto

II. Particle physics-like radio detector, example of the CODALEMA2 experiment



Howto

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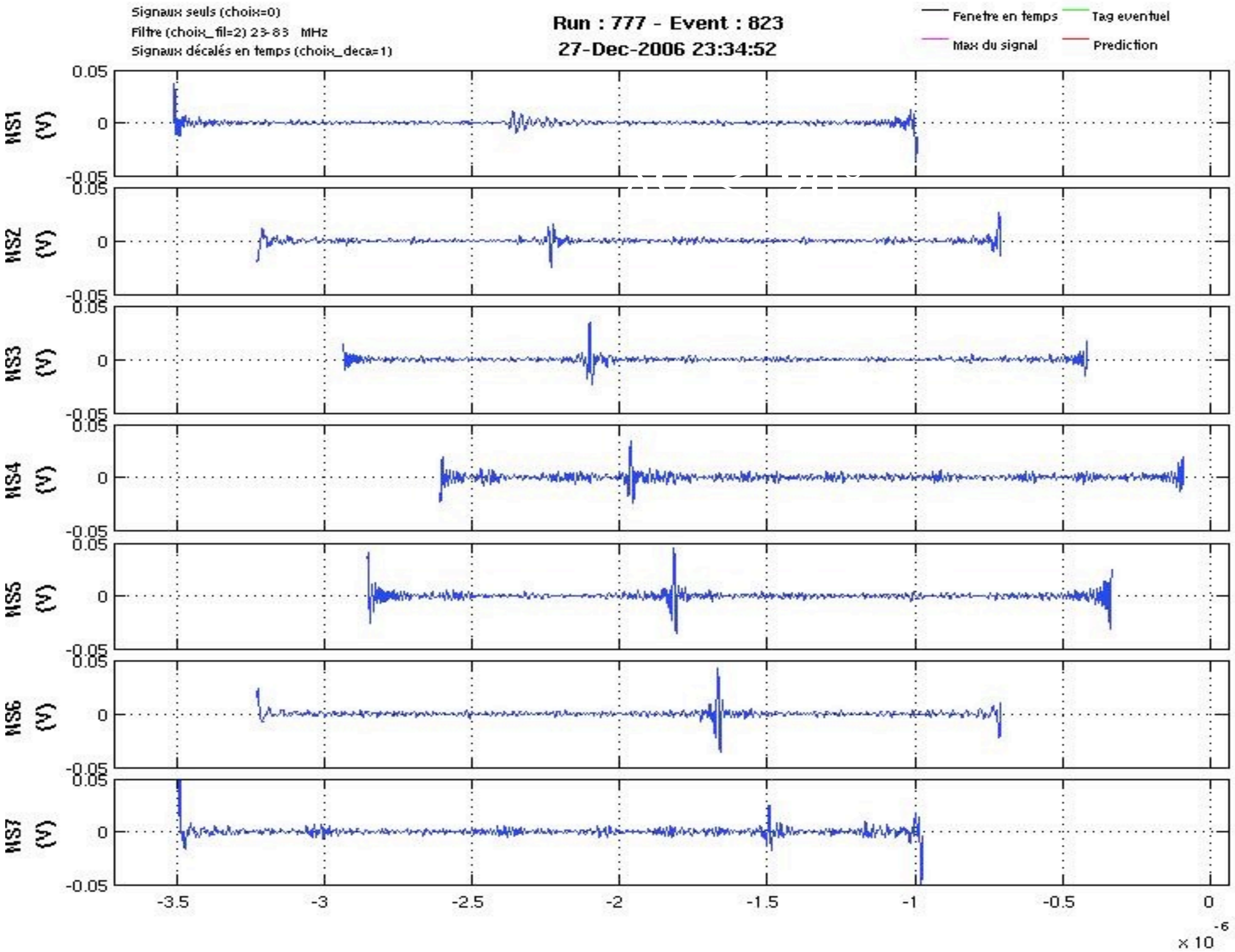

Howto

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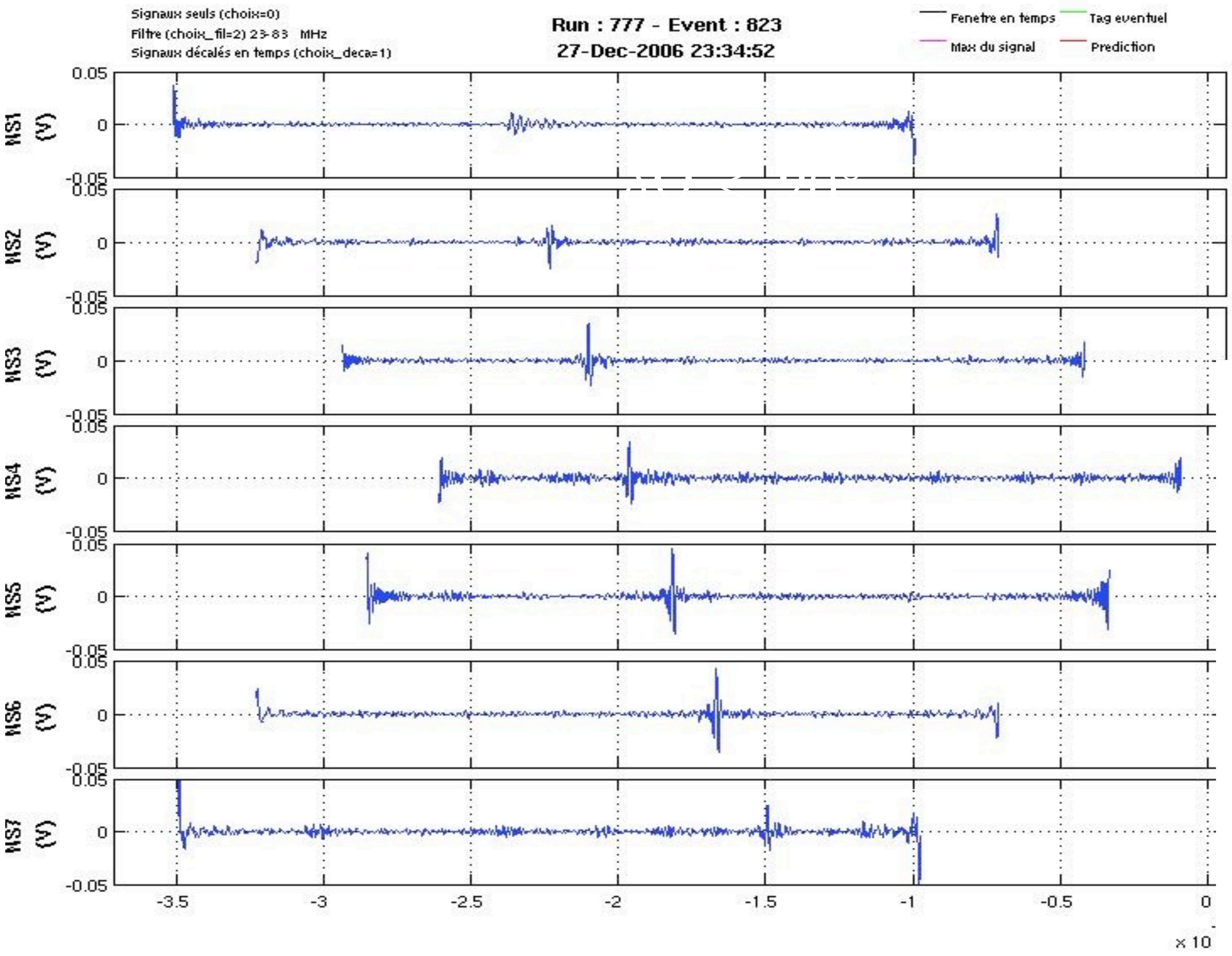
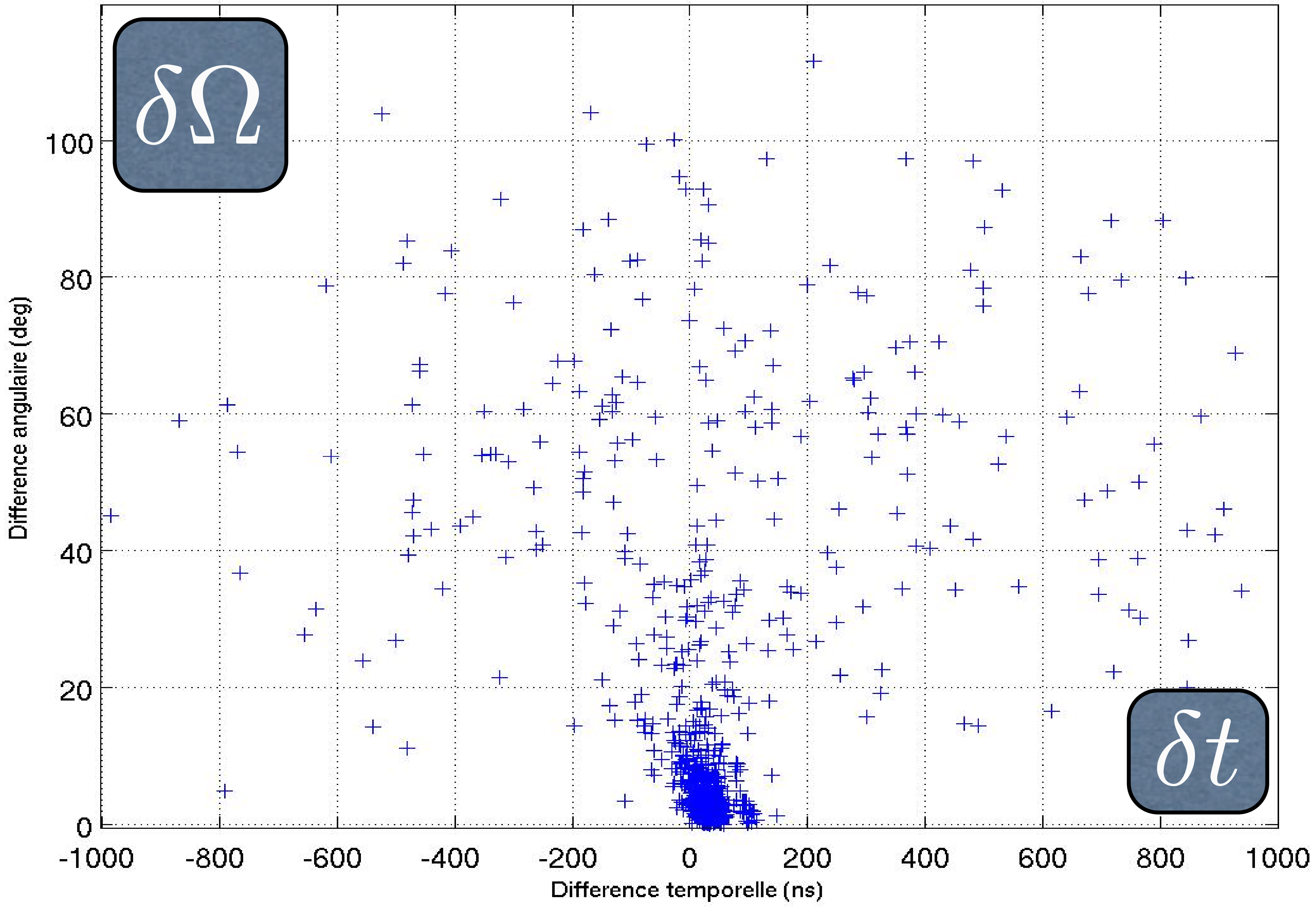


$(\theta,\ \phi,\ t_0)_{\text{scintillator}}$

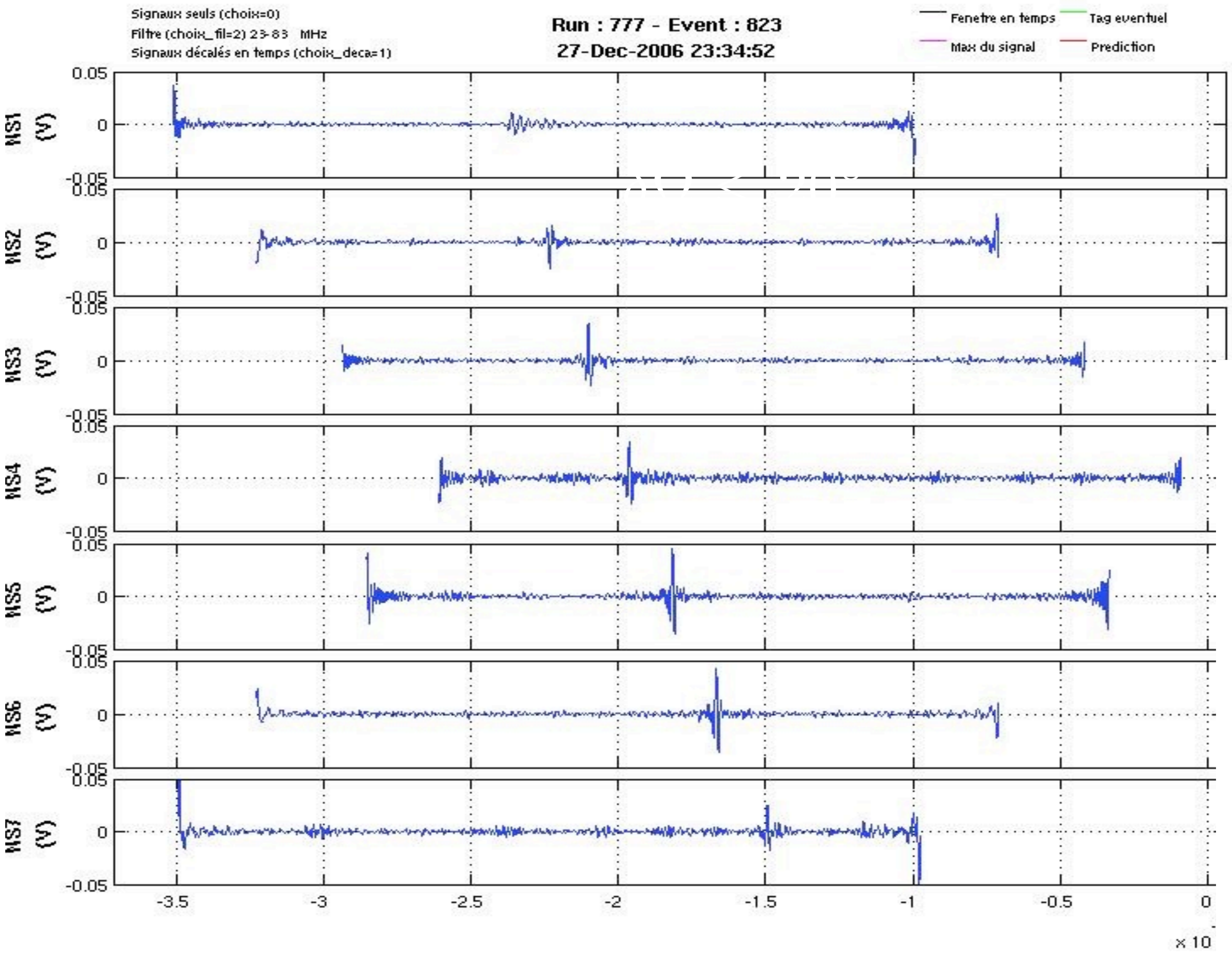
$(\theta,\ \phi,\ t_0)_{\text{radio}}$

$|\delta t| \leqslant 100\ \text{ns}$ $\delta\Omega \leqslant 20^\circ$



Howto

II. Particle physics-like radio detector, example of the CODALEMA2 experiment



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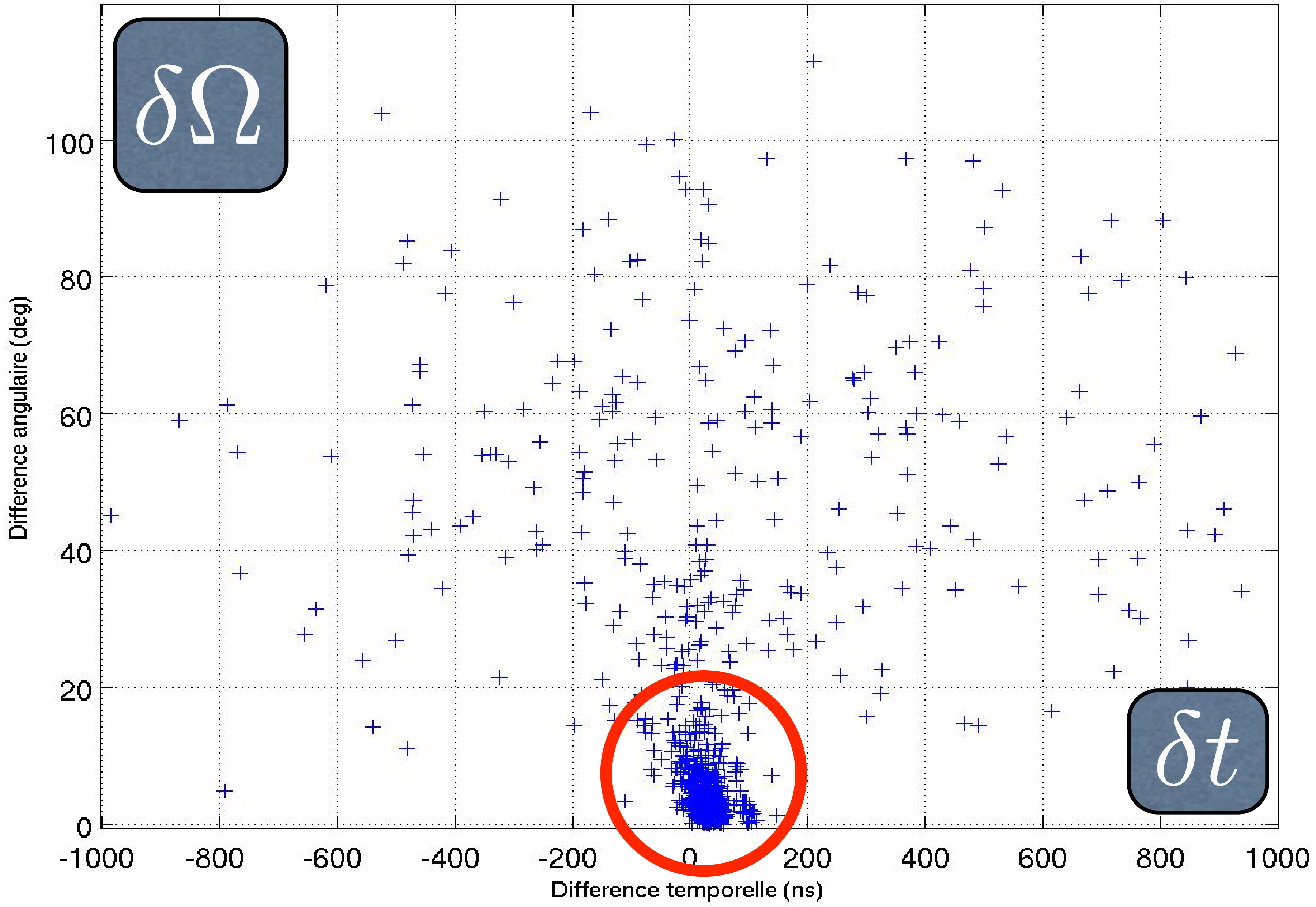


Electric field

(description adopted in SELFAS for instance)

$$\boldsymbol{E}_{tot}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\left\{ \sum_{i=1} \left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i^2(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)} \right]_{\mathrm{ret}} + \frac{1}{c}\frac{\partial}{\partial t} \sum_{i=1} \left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)} \right]_{\mathrm{ret}} - \frac{1}{c^2}\frac{\partial}{\partial t} \sum_{i=1} \left[\frac{\boldsymbol{v}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)} \right]_{\mathrm{ret}} \right\}$$

Static field

Summation of all individual static contributions

Macroscopic charge variation

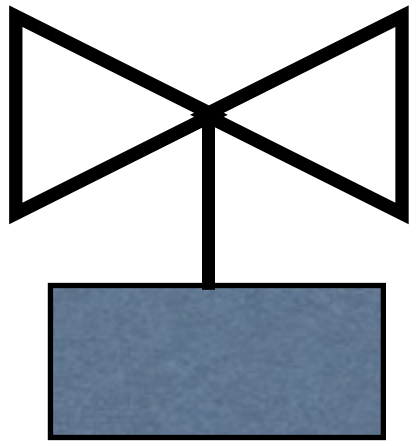
Summation of all individual charges. The e$^-$ excess implies a global charge variation Q(t)= α N(t)

Current variation

Summation of all individual currents, systematic opposite drift of e- and e+ in **B**

Signal correlated to the complete shower development !

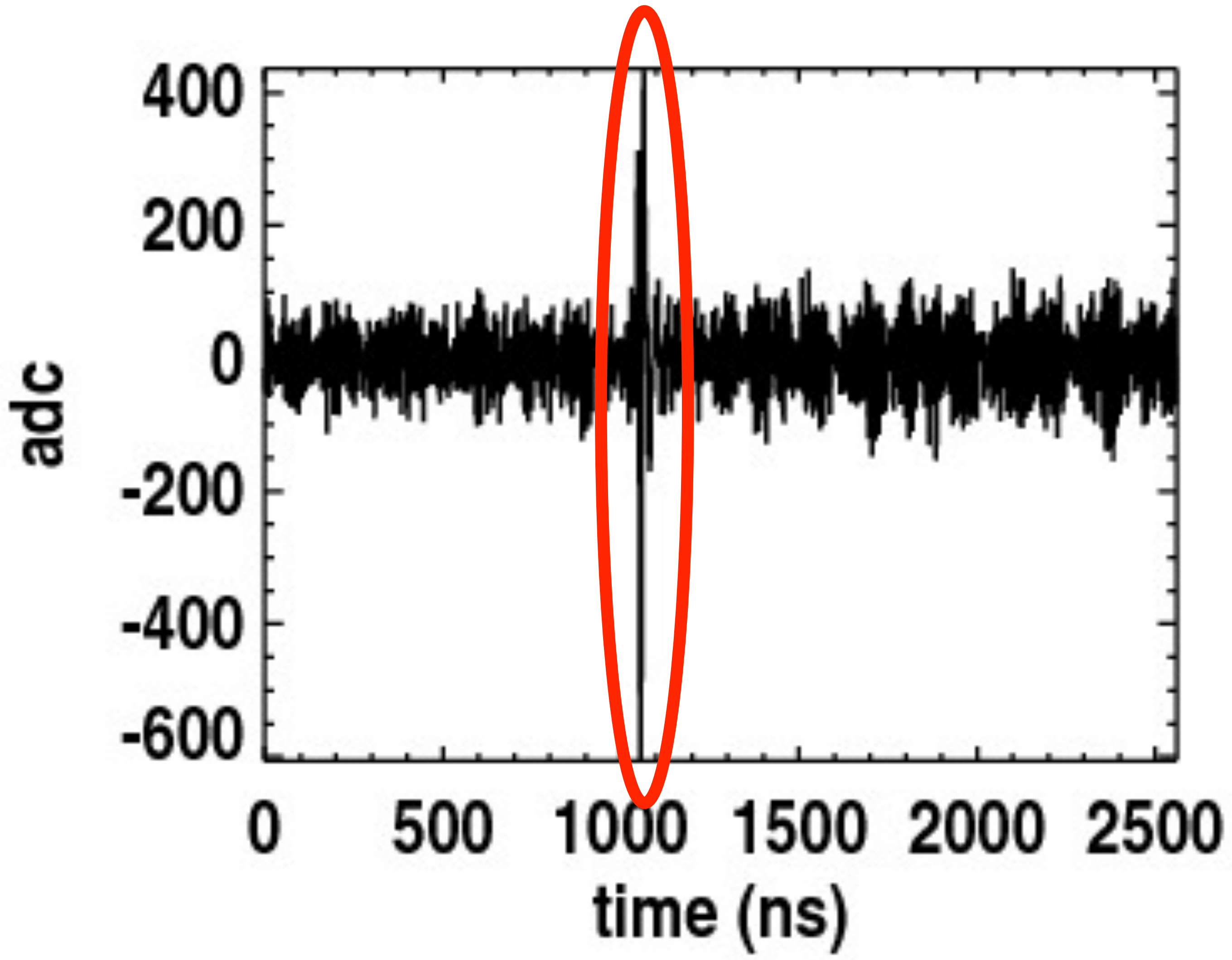
What can we learn from this electric field?



Angular resolution

all experiments provide e-field(t) for one detector:

- identification of the main pulse due to the cosmic ray
- then use a timing reference (GPS) to tag the pulse

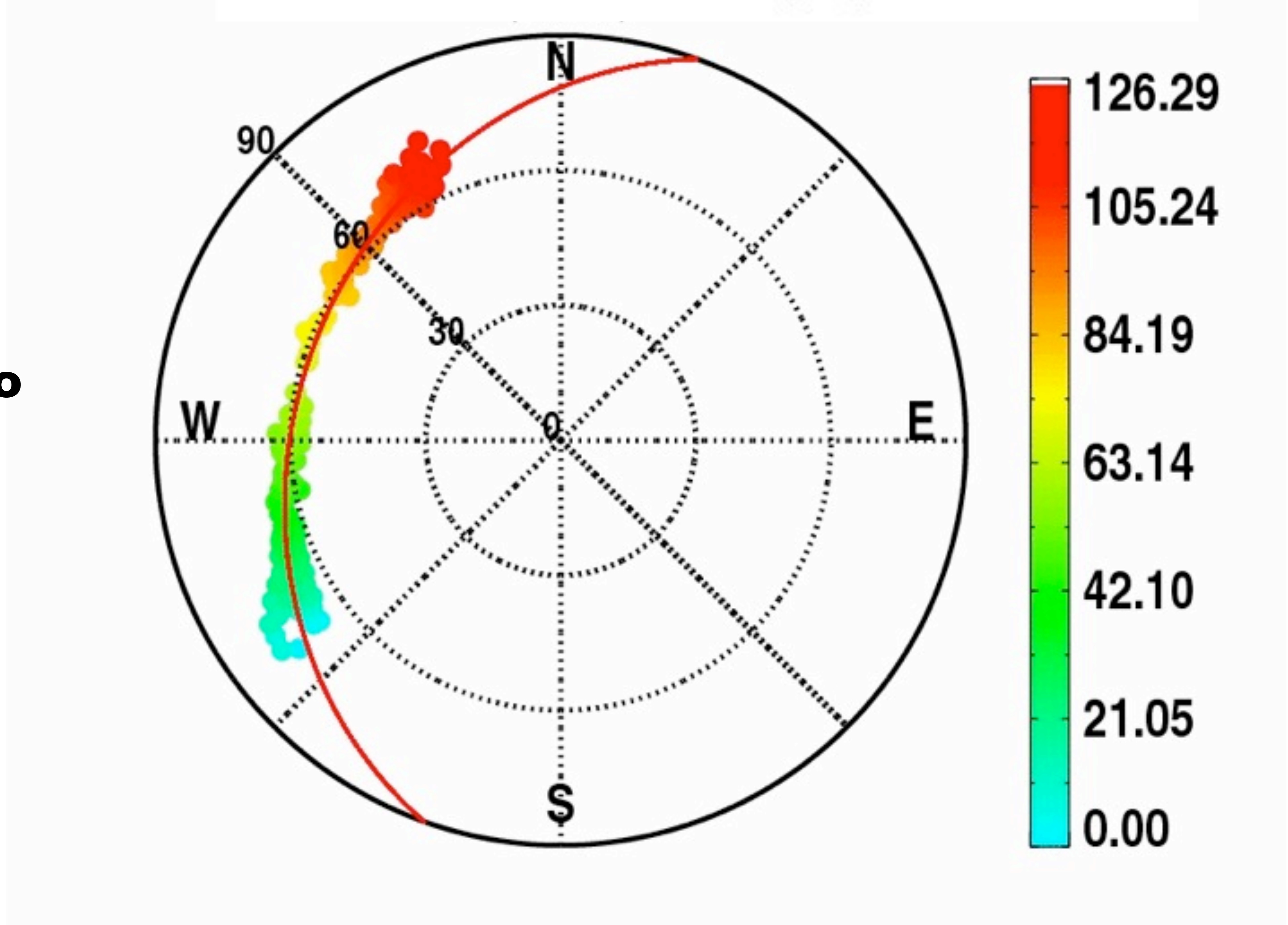


then electric field has been detected at (x,y,z,t)

3 non-aligned detectors leads to (θ,Φ)

Angular resolution better than 0.5°

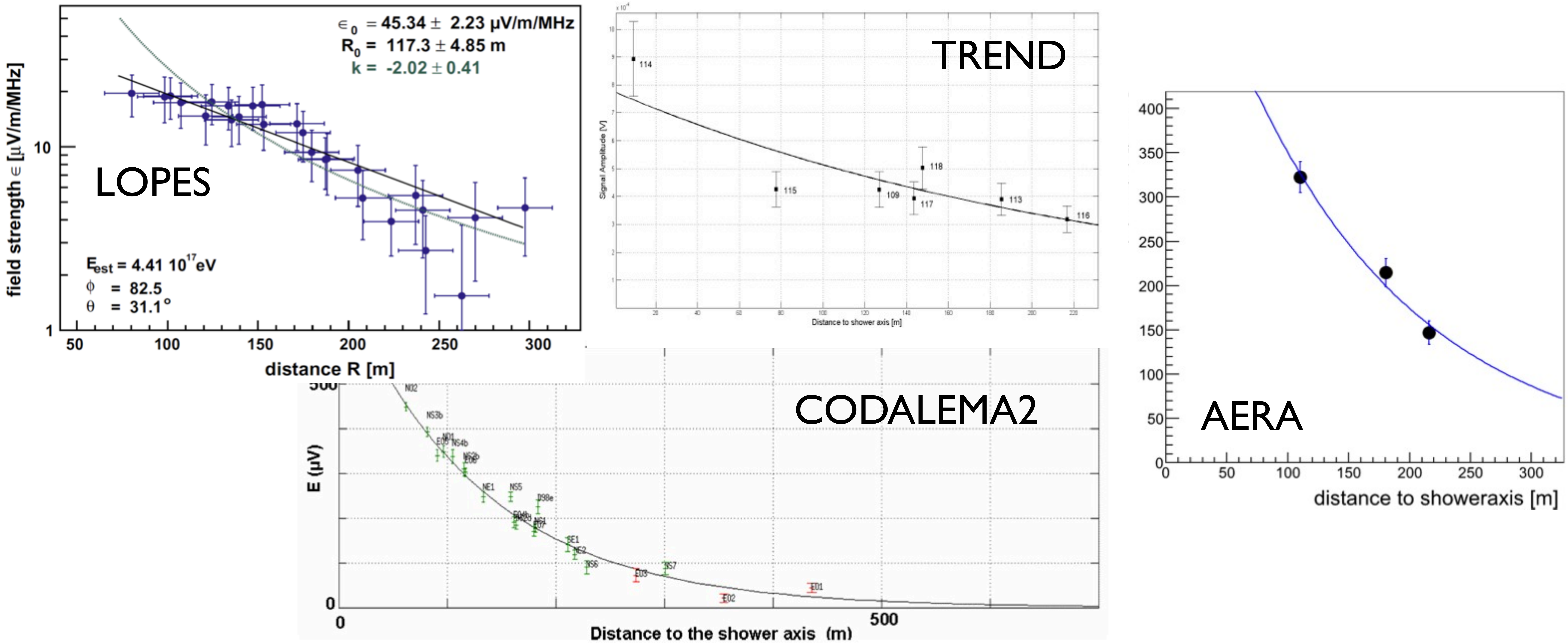
(much better than a typical SD)



Lateral Distribution Function

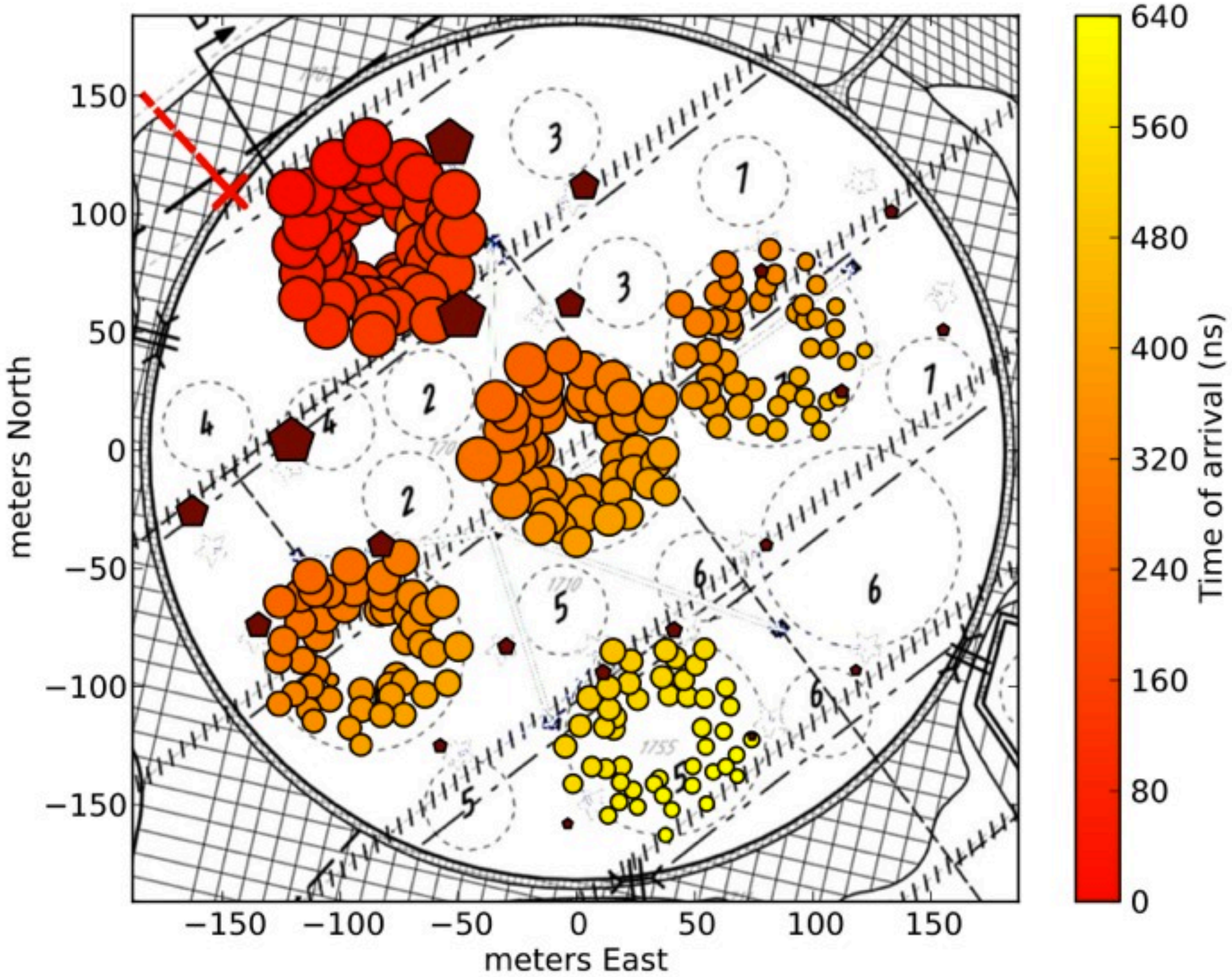
For N stations, draw e-Field = f(axis distance)

For a pure exponential profile: most of the events are OK
some of them are **flat** for antennas close to the shower axis

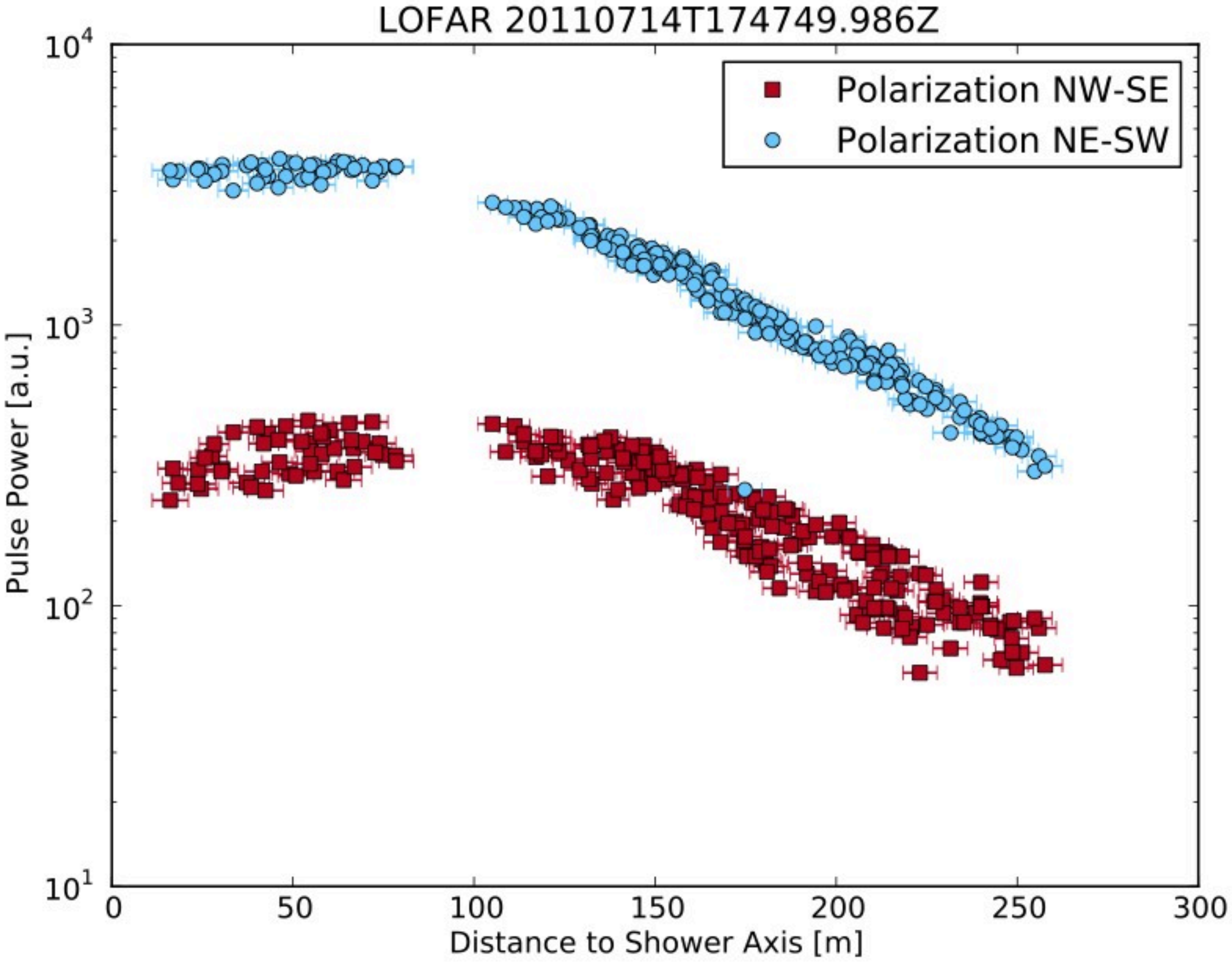


Lateral Distribution Function

LOFAR/LORA

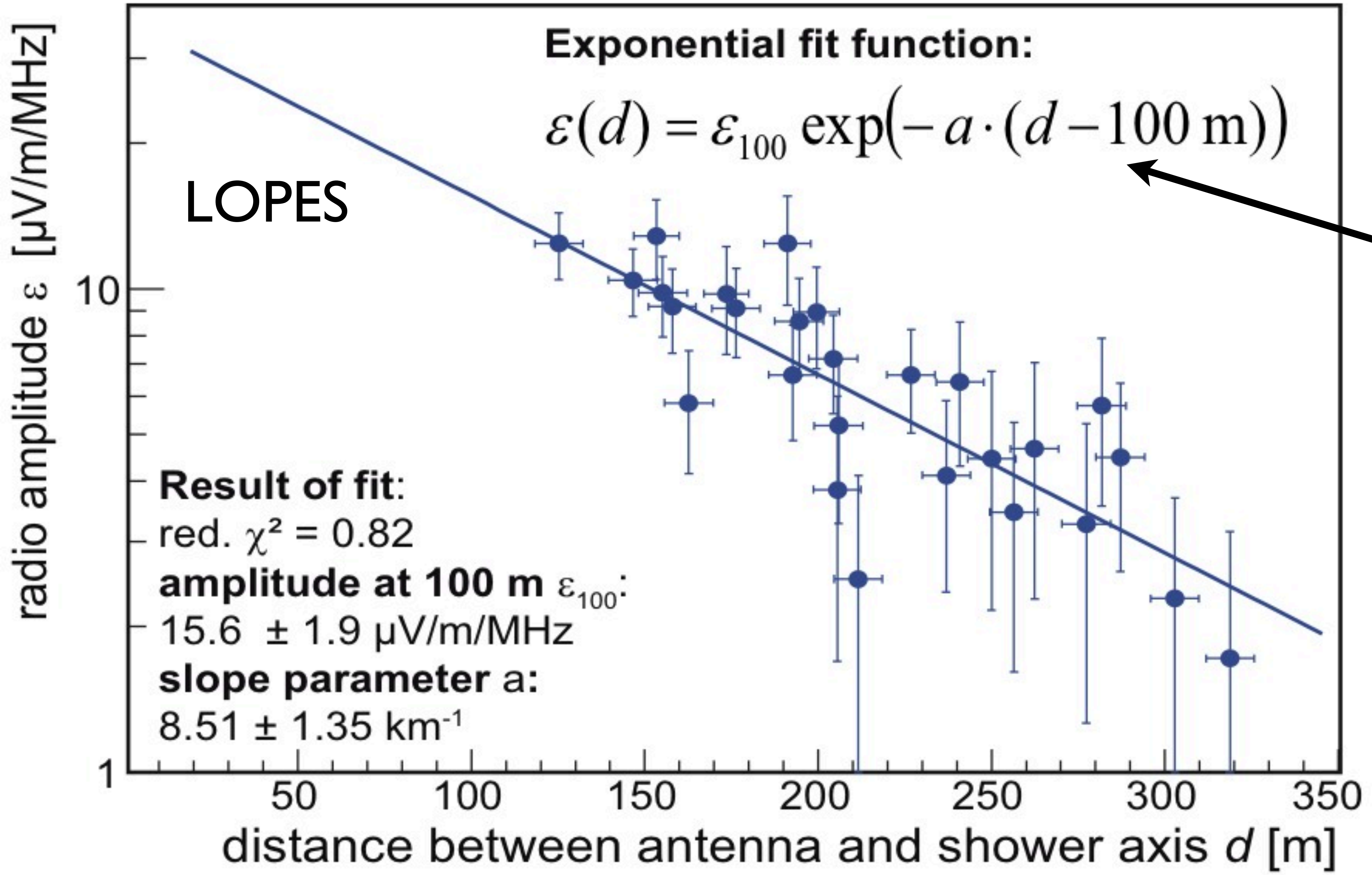


(see talk of A. Nelles)



Lateral Distribution Function

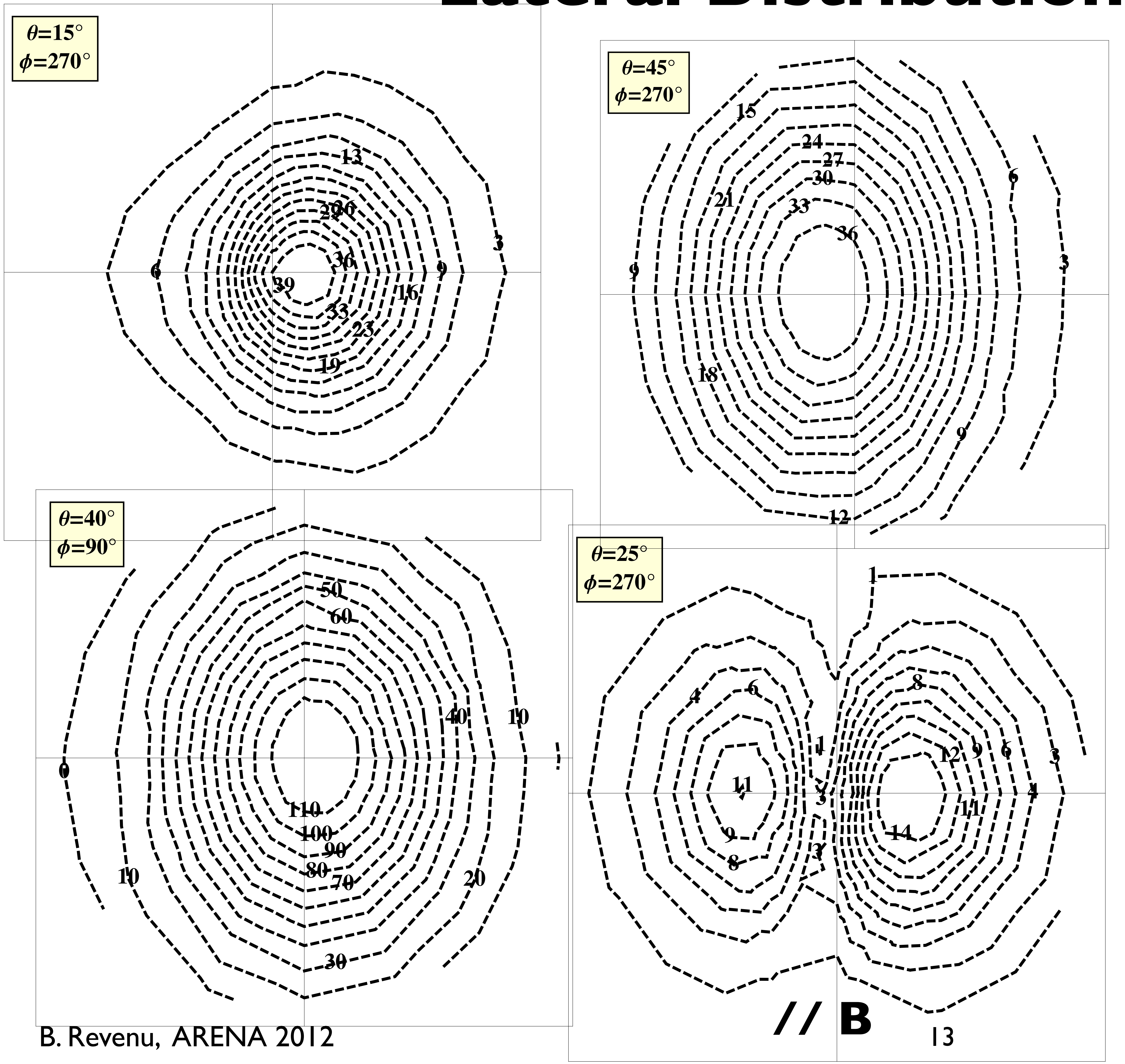
LOPES, Phys. Rev. D 2012, arXiv:1203.397v1



modified
exponential function

(see talk of F. Schröder)

Lateral Distribution Function

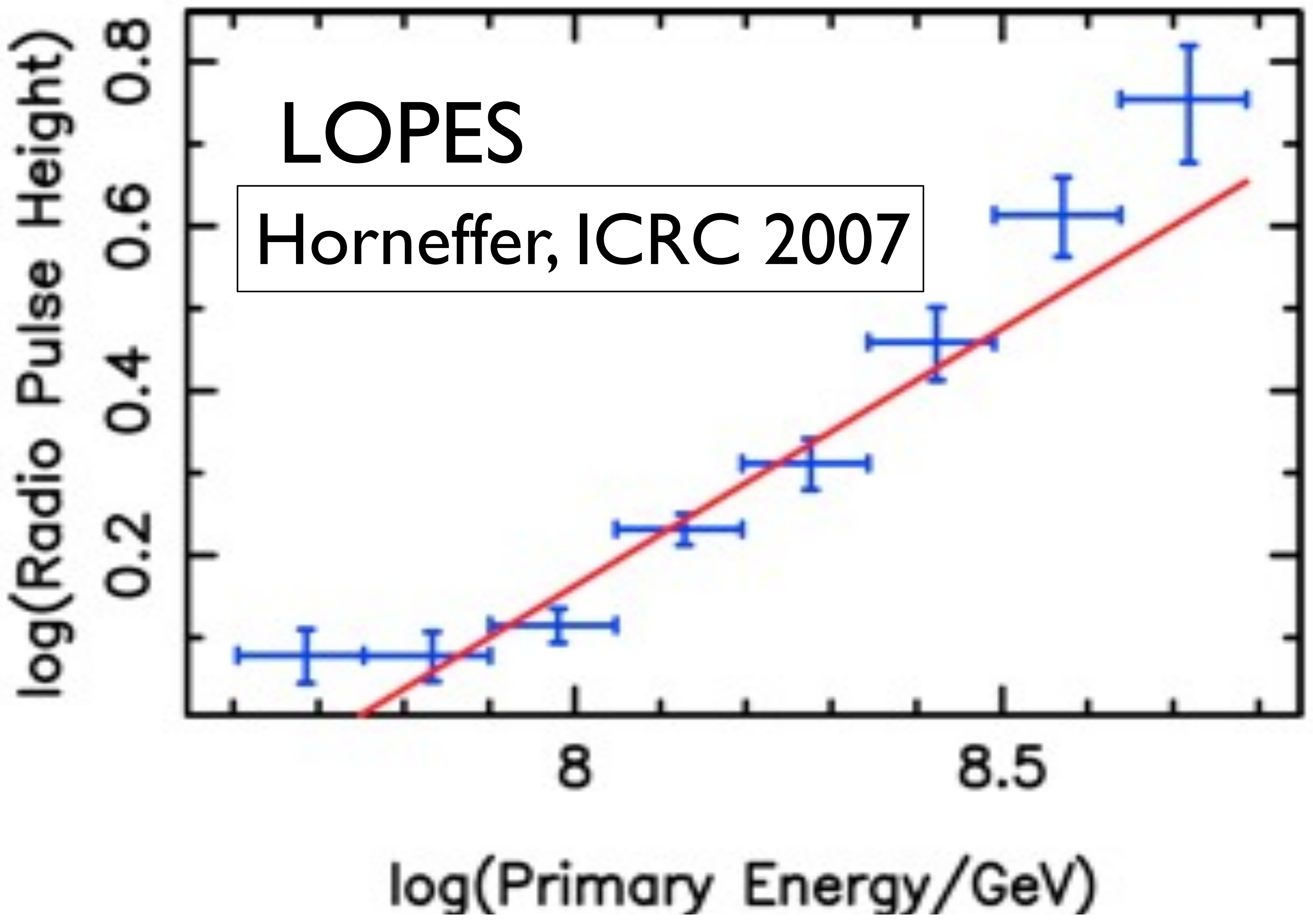


Sample showers 10^{17} eV
EW polarization on the ground
no simple pattern,
no cylindrical symmetry

need a more complicated 2D-LDF
(mainly if you don’t measure all
polarizations)

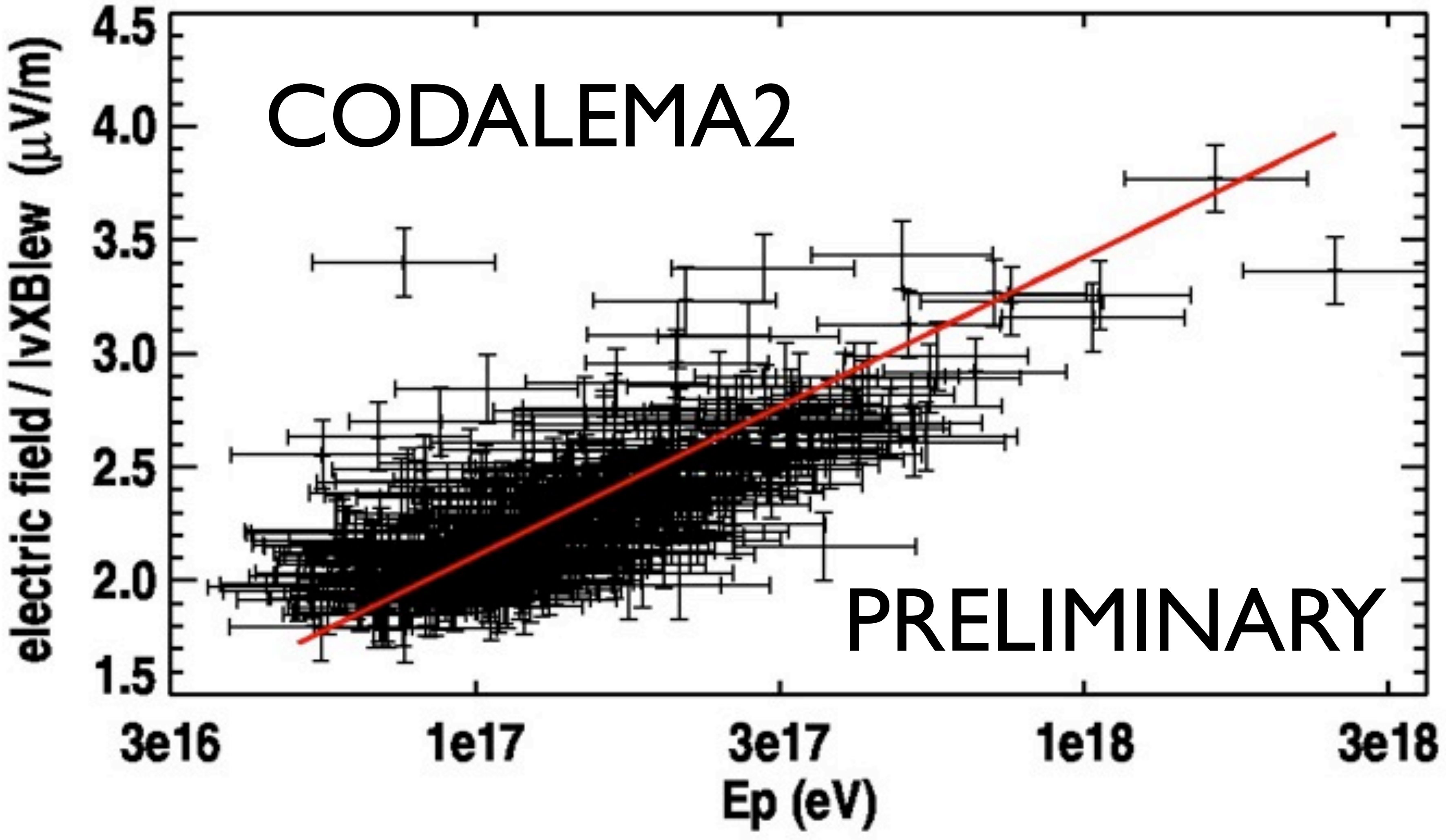
After a choice of the LDF, compute
the electric field at specific distance
(on-axis for instance) and search
for correlation with primary energy

Correlation electric field/primary energy


LOPES

Horneffer, ICRC 2007

AERA
see talk from C. Glaser

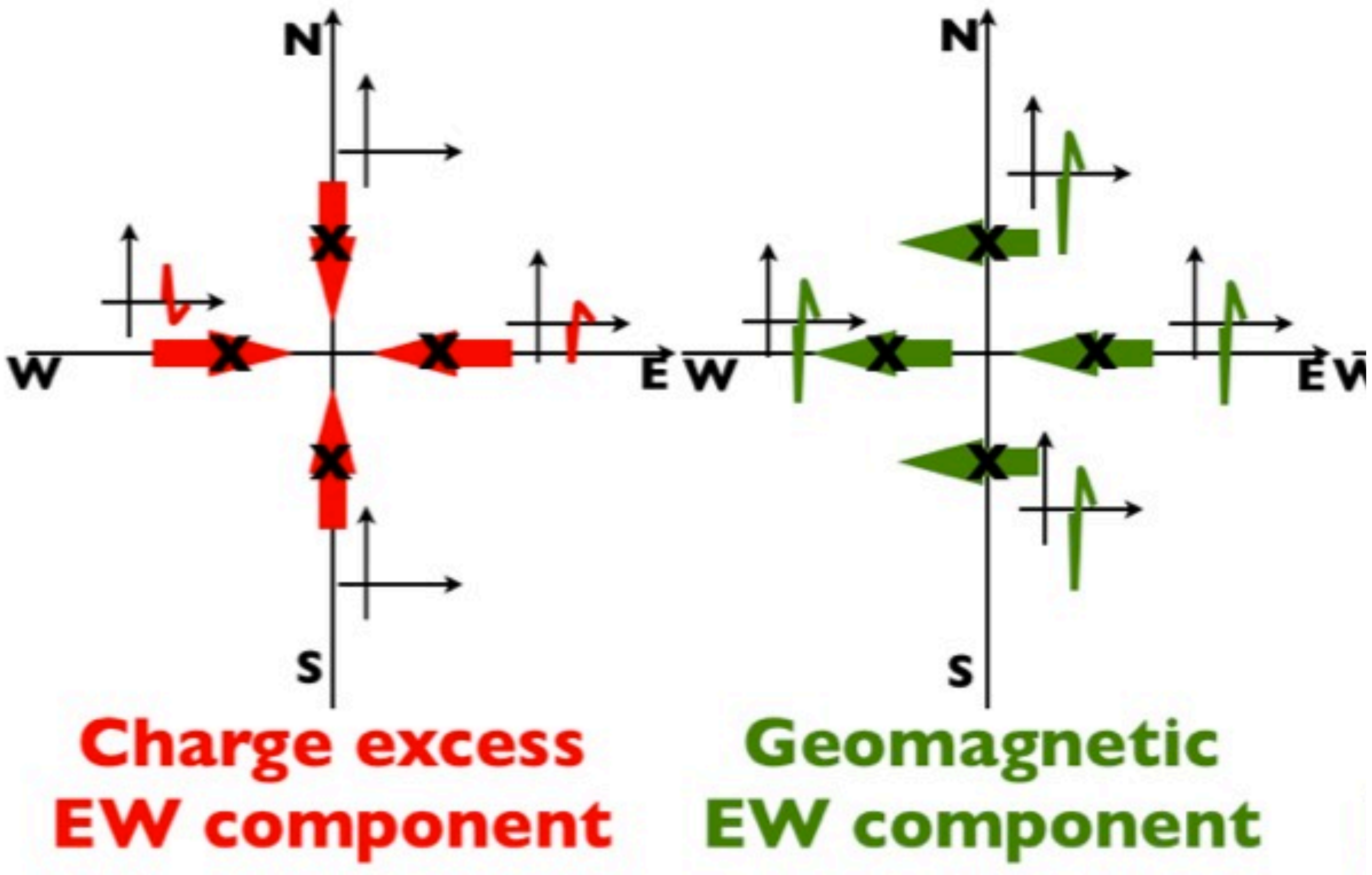

CODALEMA2

PRELIMINARY

- needs proper deconvolution of the antenna response
- needs reliable energy estimation (SD, FD)
- needs full study of systematic errors with their possible correlations

Emission mechanisms

$$\boldsymbol{E}_{tot}(\boldsymbol{x},t) = \frac{1}{4\pi\epsilon_0}\left\{\sum_{i=1}\left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i^2(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)}\right]_{\rm ret} + \frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}\left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)}\right]_{\rm ret} - \frac{1}{c^2}\frac{\partial}{\partial t}\sum_{i=1}\left[\frac{\boldsymbol{v}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)}\right]_{\rm ret}\right\}$$



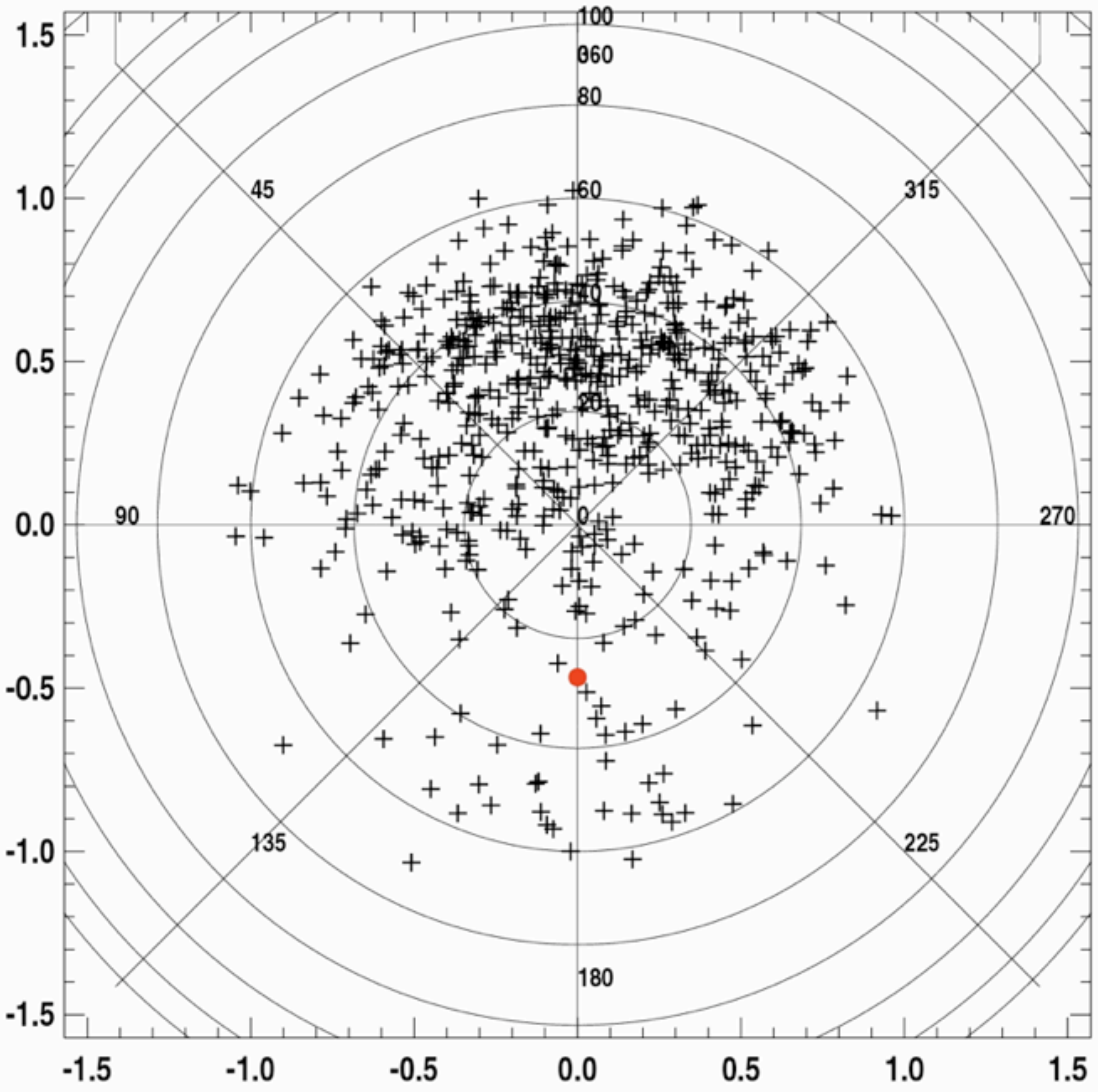
Two main mechanisms with two different polarization patterns!

The geomagnetic component is dominant

The charge-excess component is probably observed

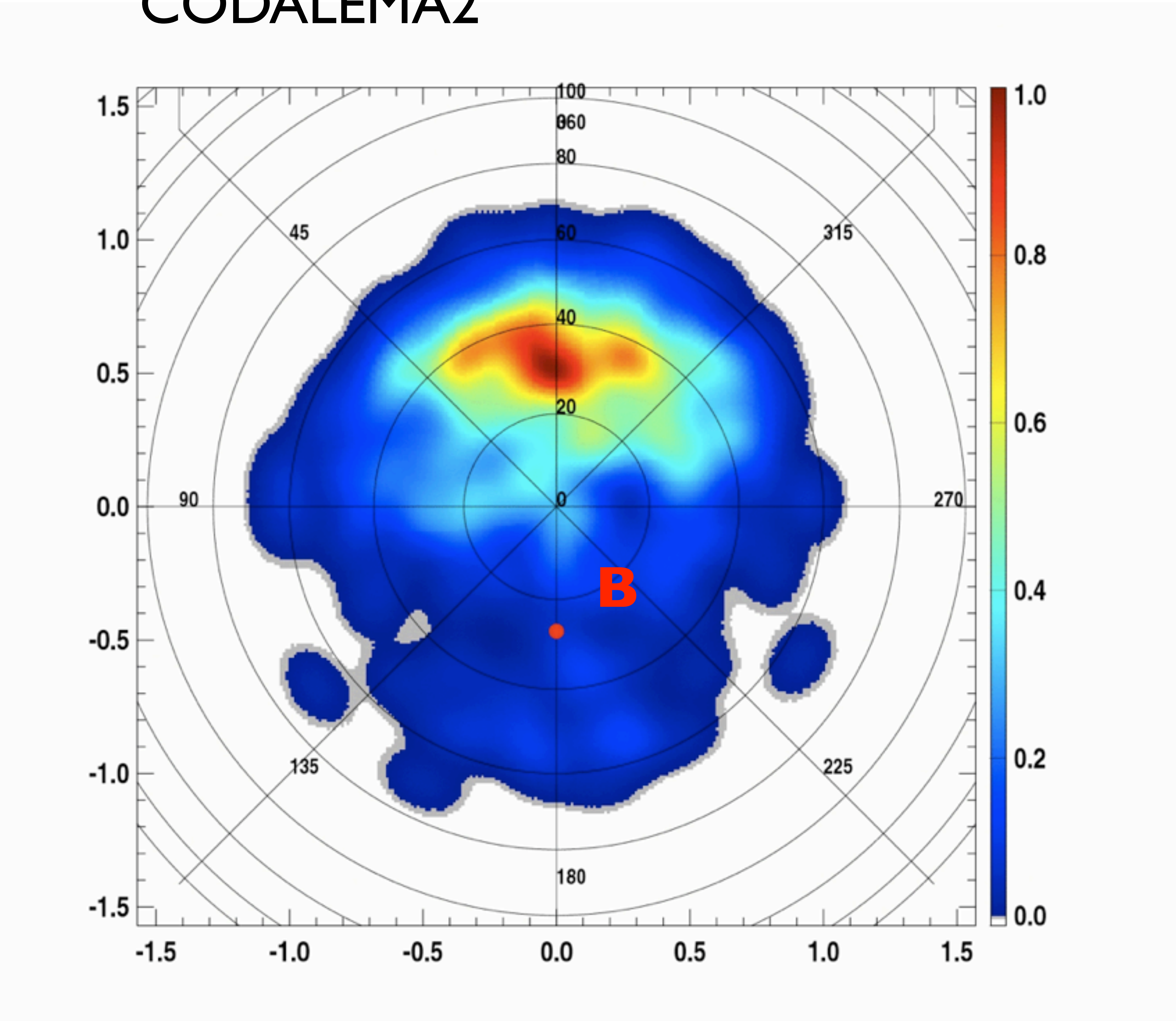
The geomagnetic component

CODALEMA2



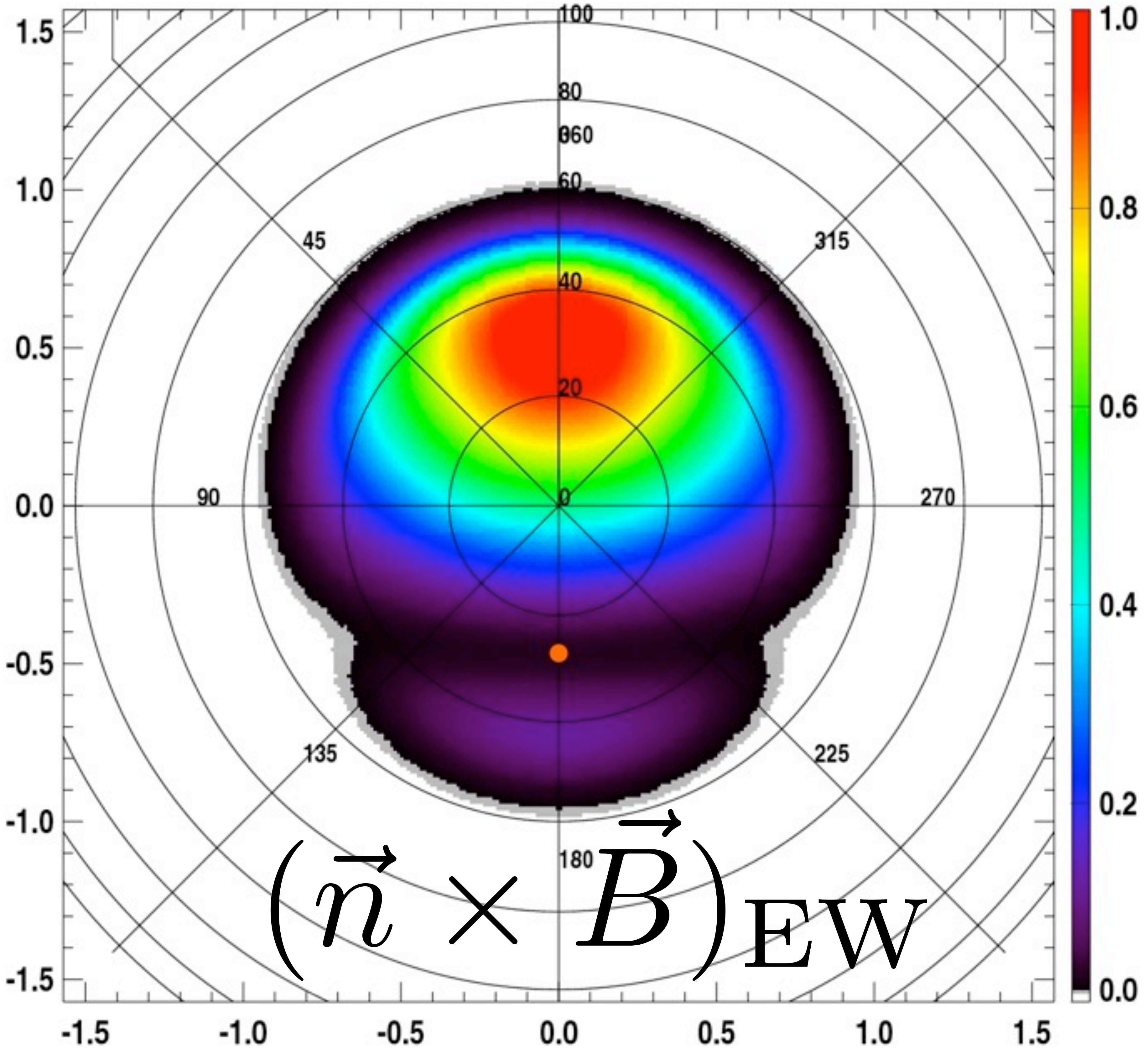
The geomagnetic component

CODALEMA2



The geomagnetic component

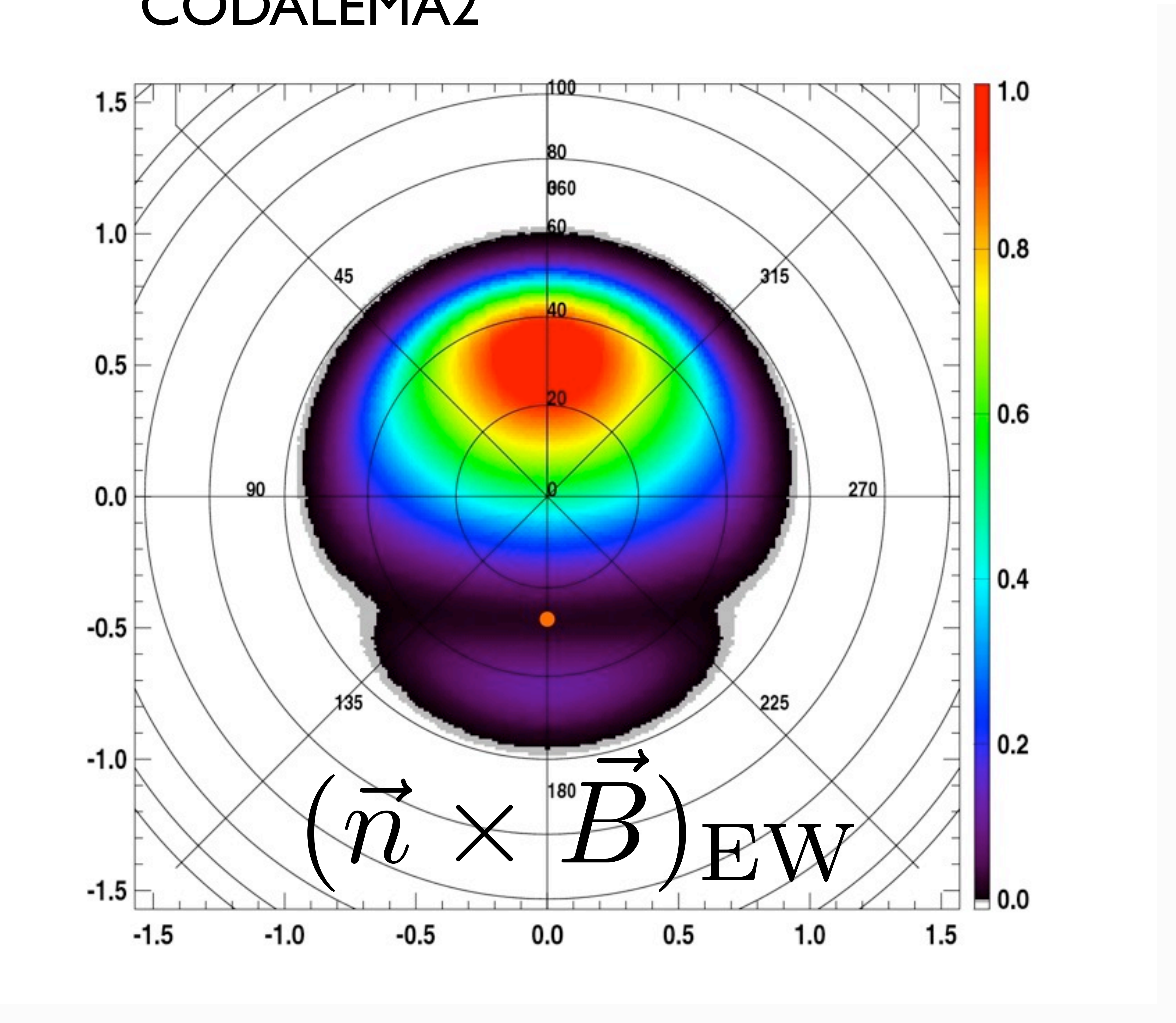
CODALEMA2



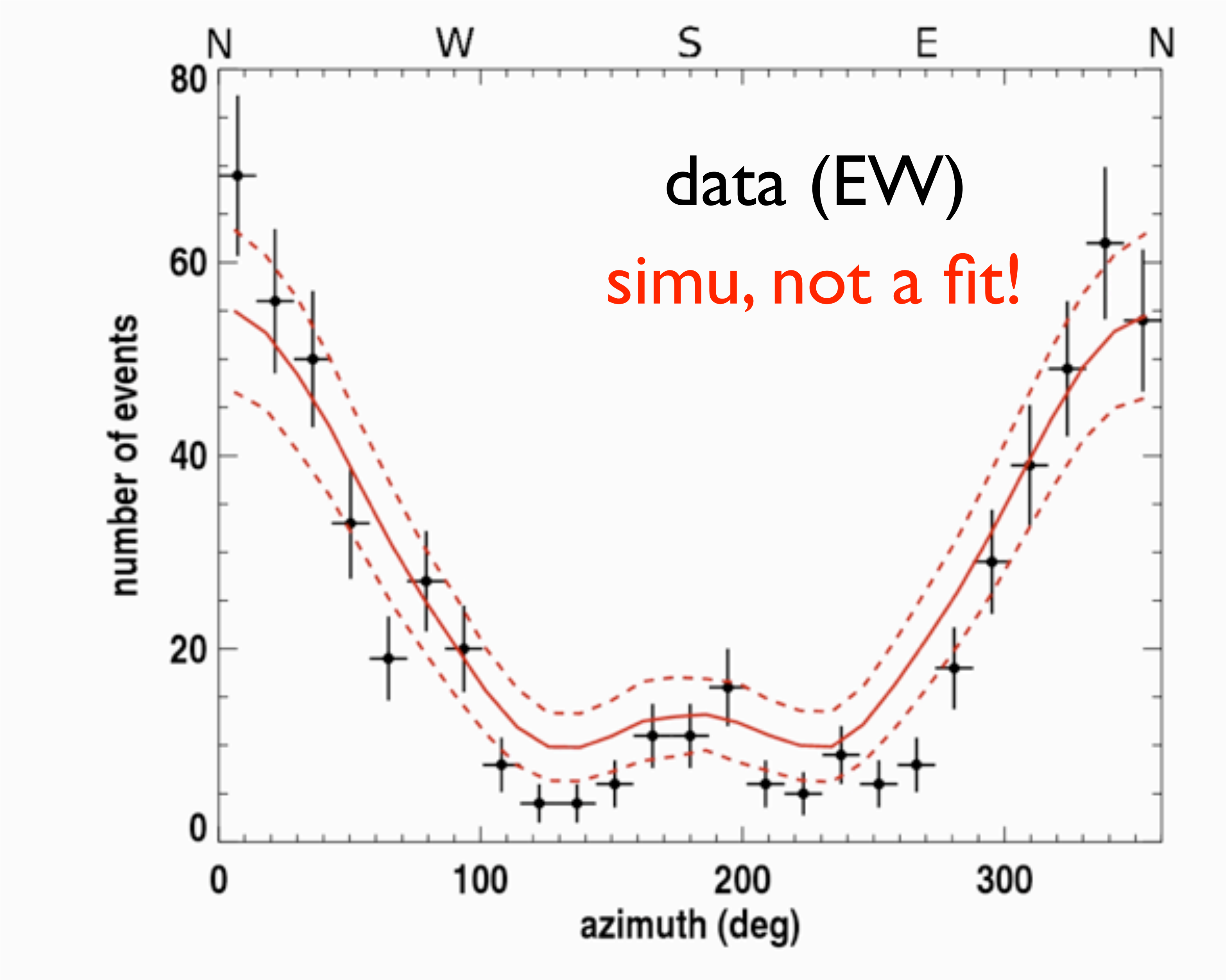
$$(\vec{n} \times \vec{B})_{\mathrm{EW}}$$

The geomagnetic component

CODALEMA2



$(\vec{n} \times \vec{B})_{\mathrm{EW}}$

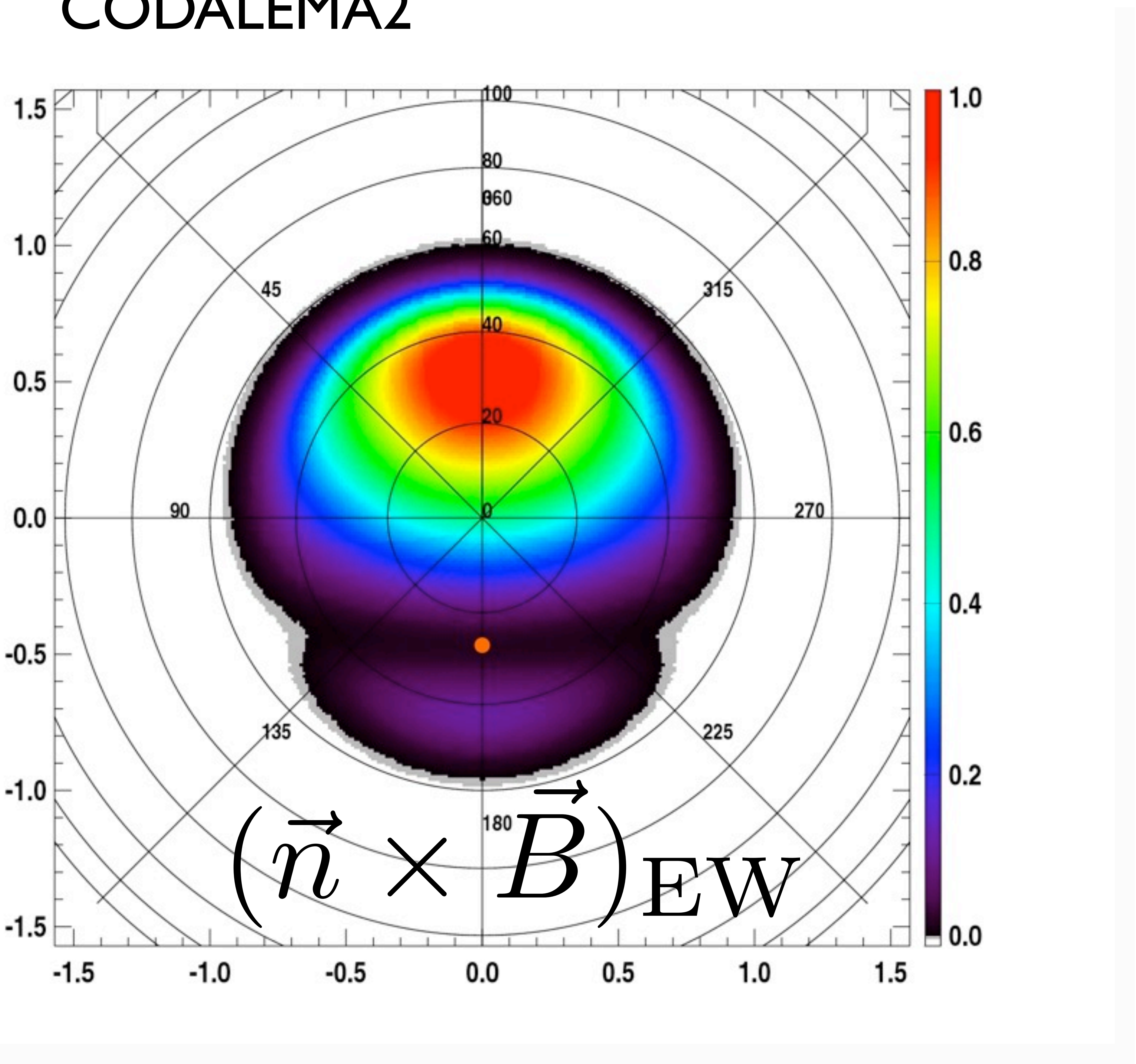


data (EW)

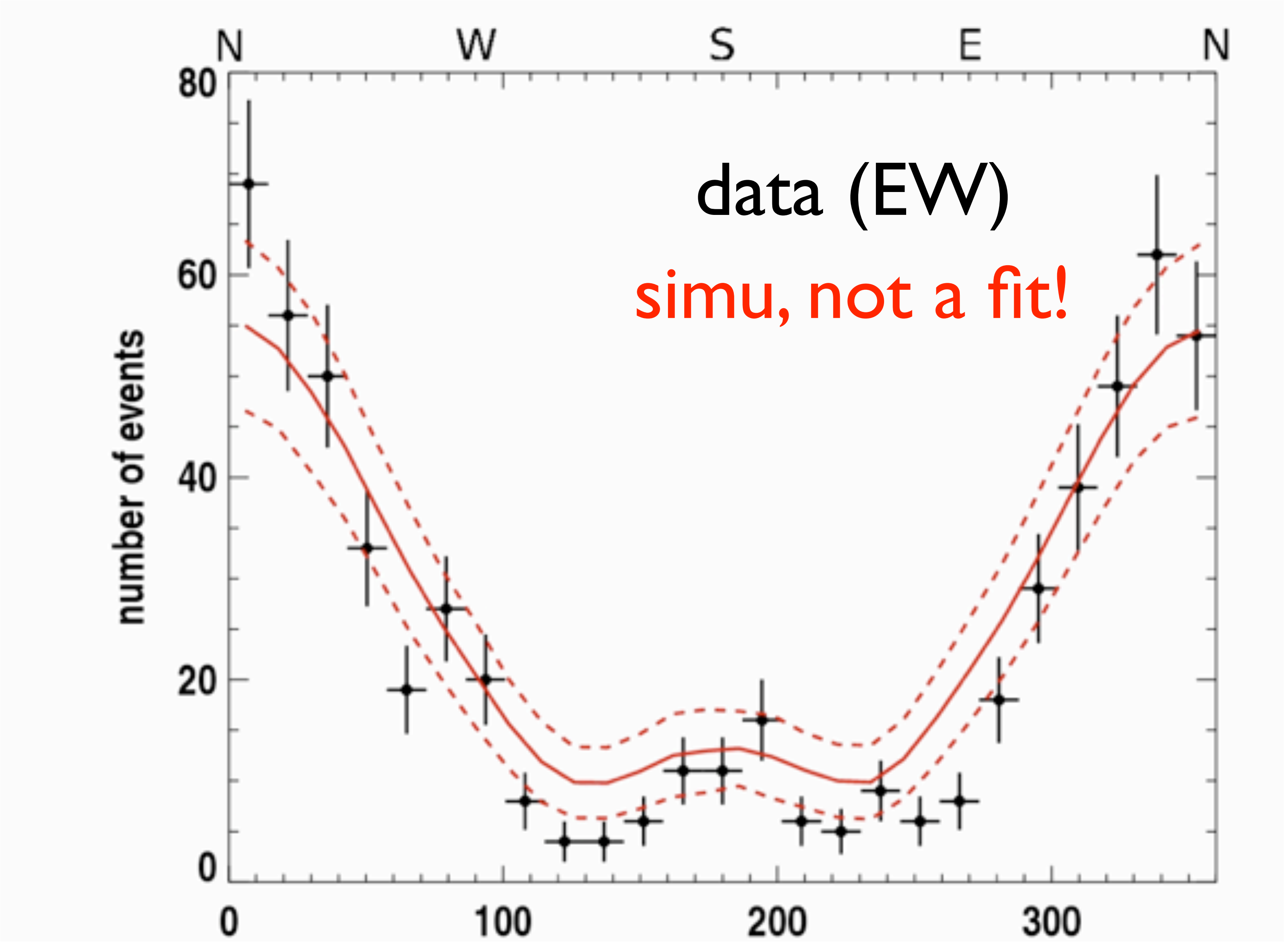
simu, not a fit!

The geomagnetic component

CODALEMA2

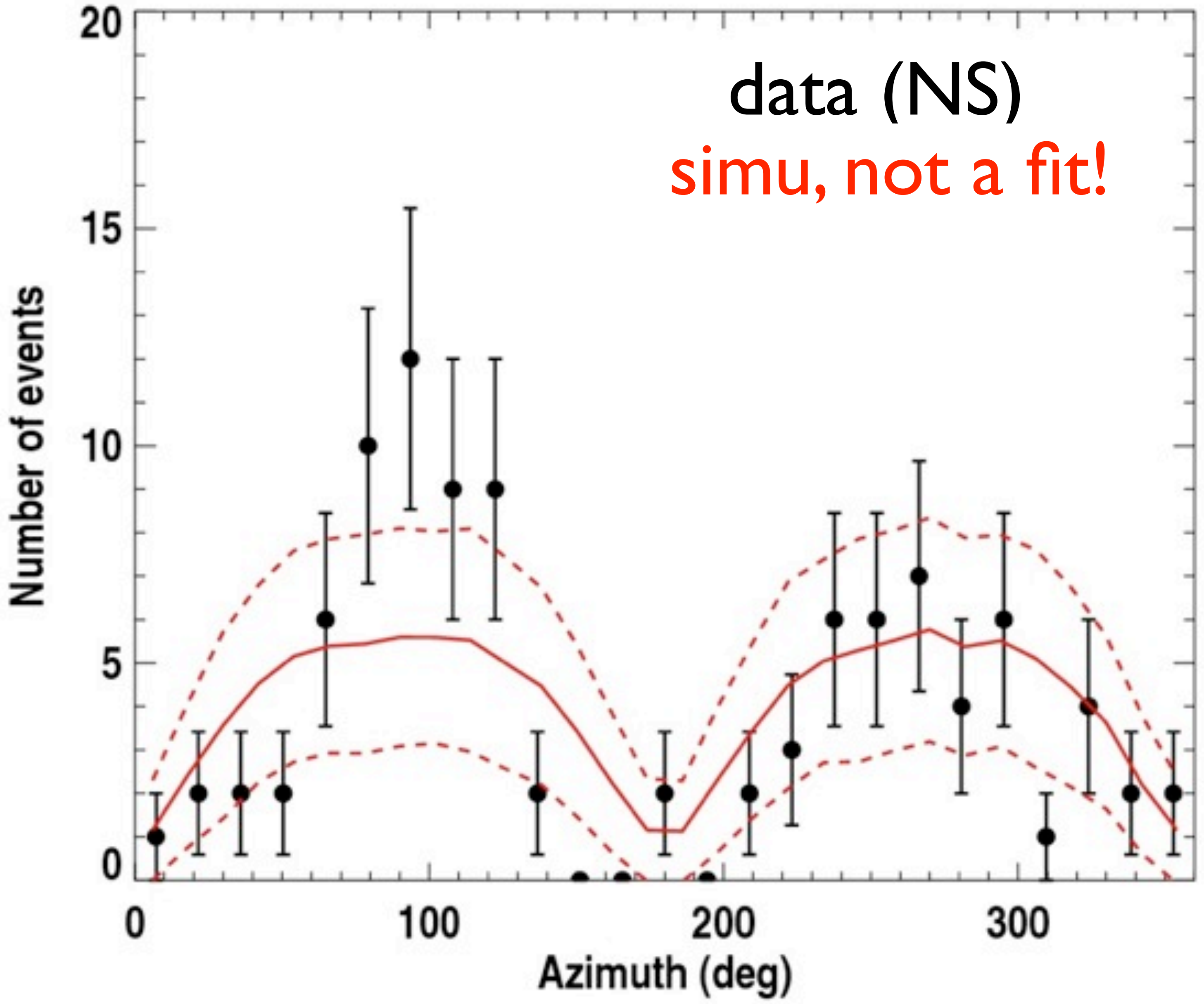


$$(\vec{n} \times \vec{B})_{\mathrm{EW}}$$



data (EW)

simu, not a fit!

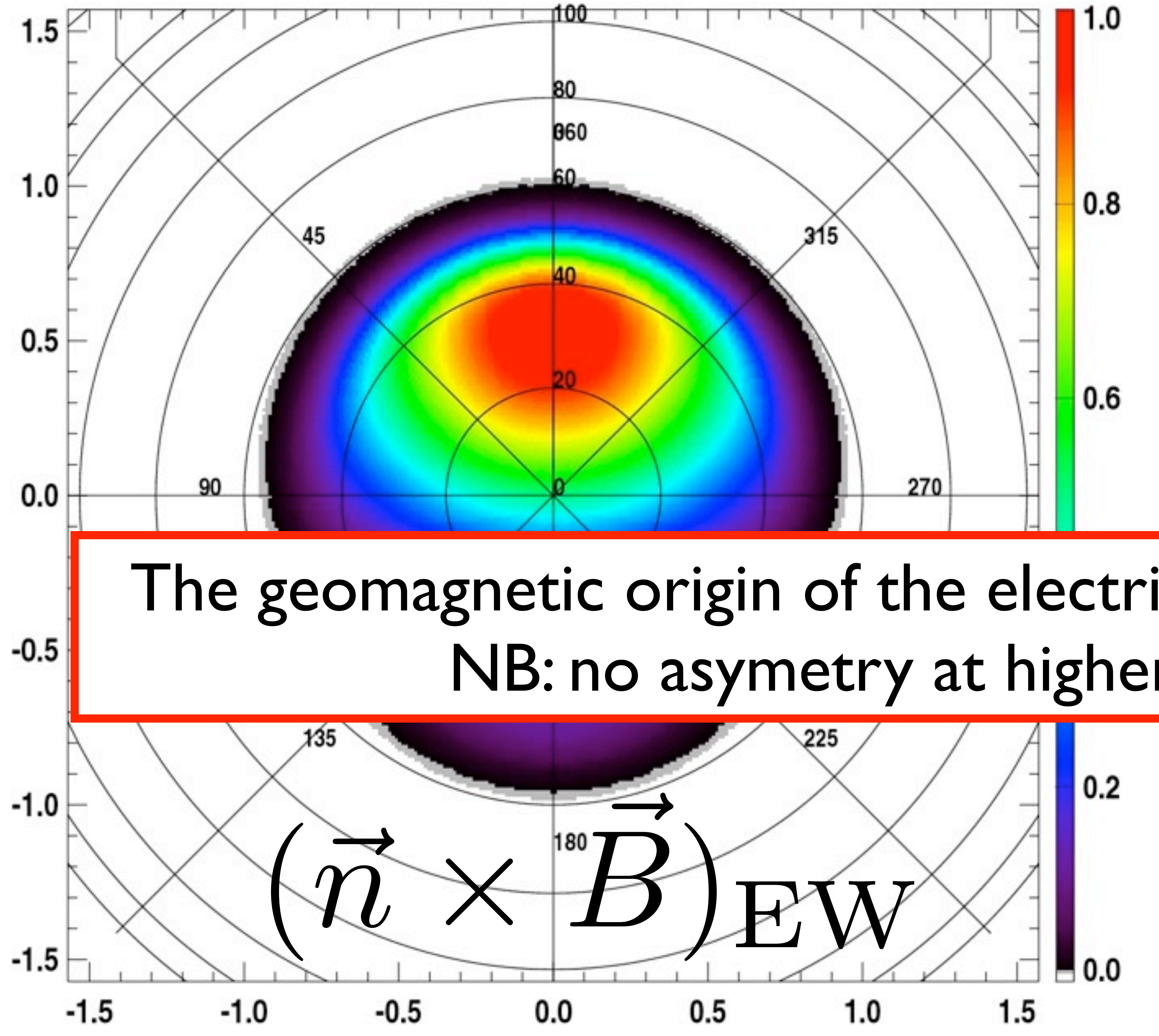


data (NS)

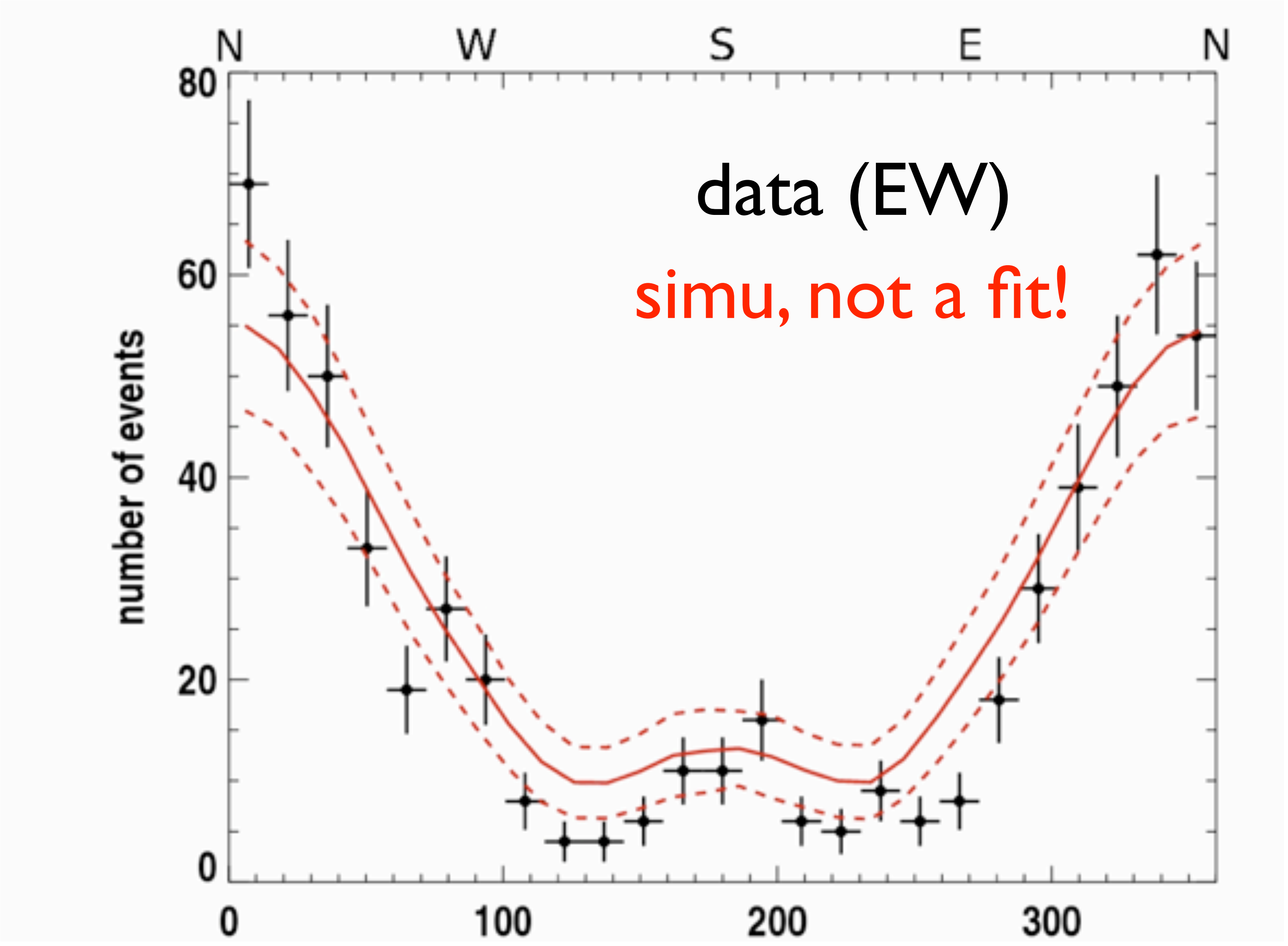
simu, not a fit!

The geomagnetic component

CODALEMA2



$(\vec{n} \times \vec{B})_{\mathrm{EW}}$

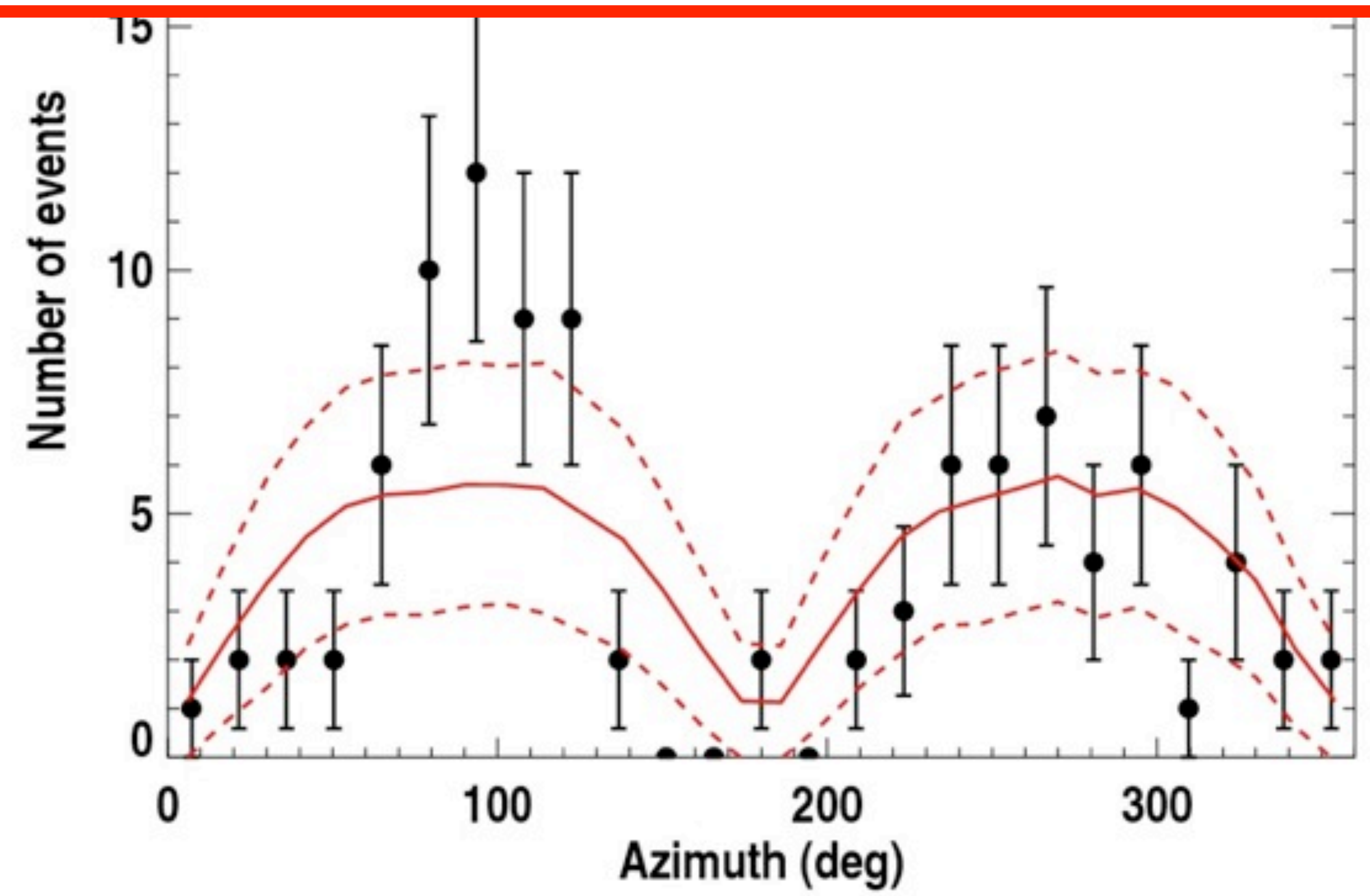


data (EW)

simu, not a fit!

The geomagnetic origin of the electric field is well-established in both polarizations

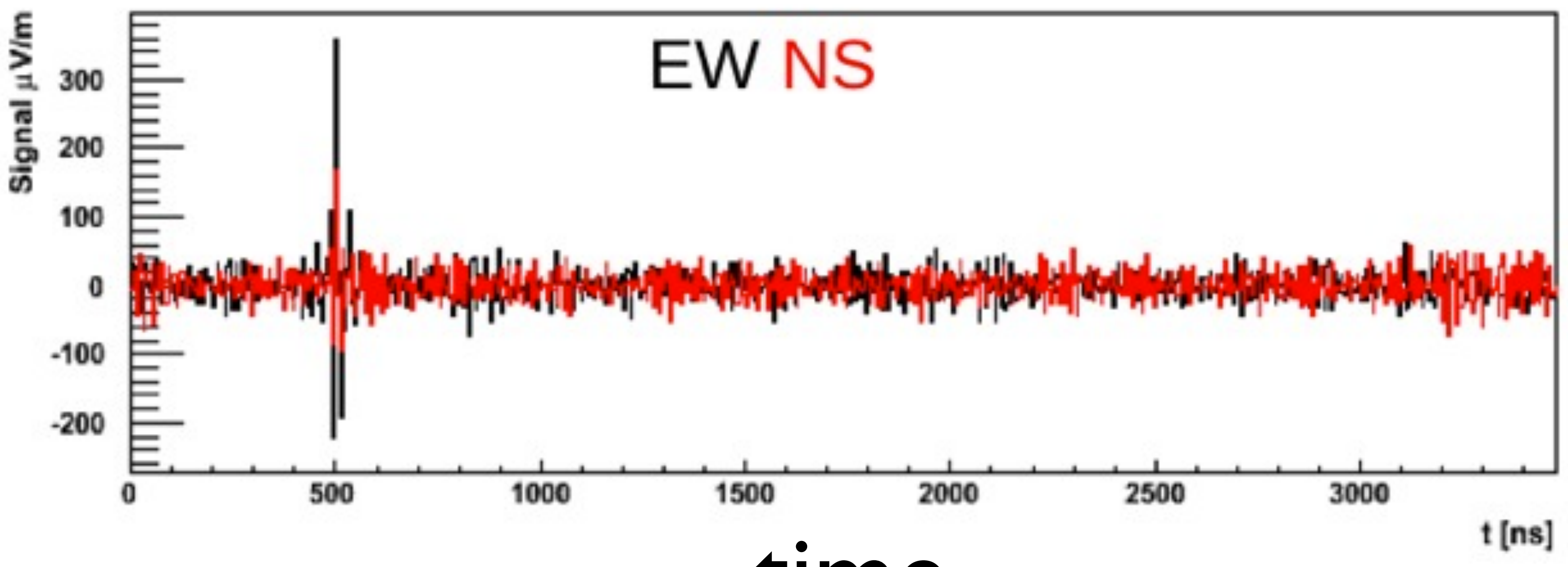
NB: no asymetry at higher energies, this is a threshold effect



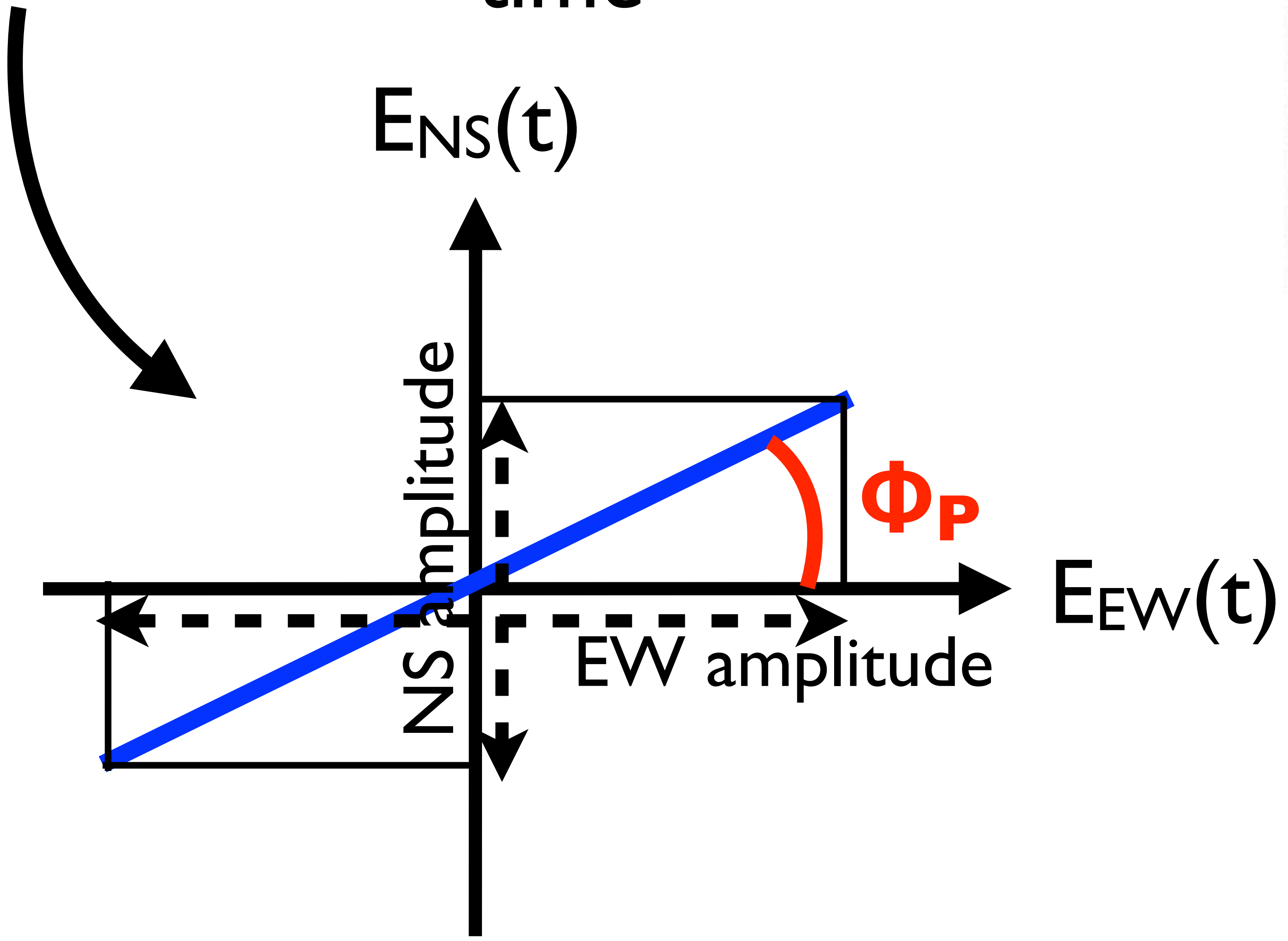
The geomagnetic component

measured polar. angle: $\phi(t_i) = \arctan(U(t_i)/Q(t_i))/2$

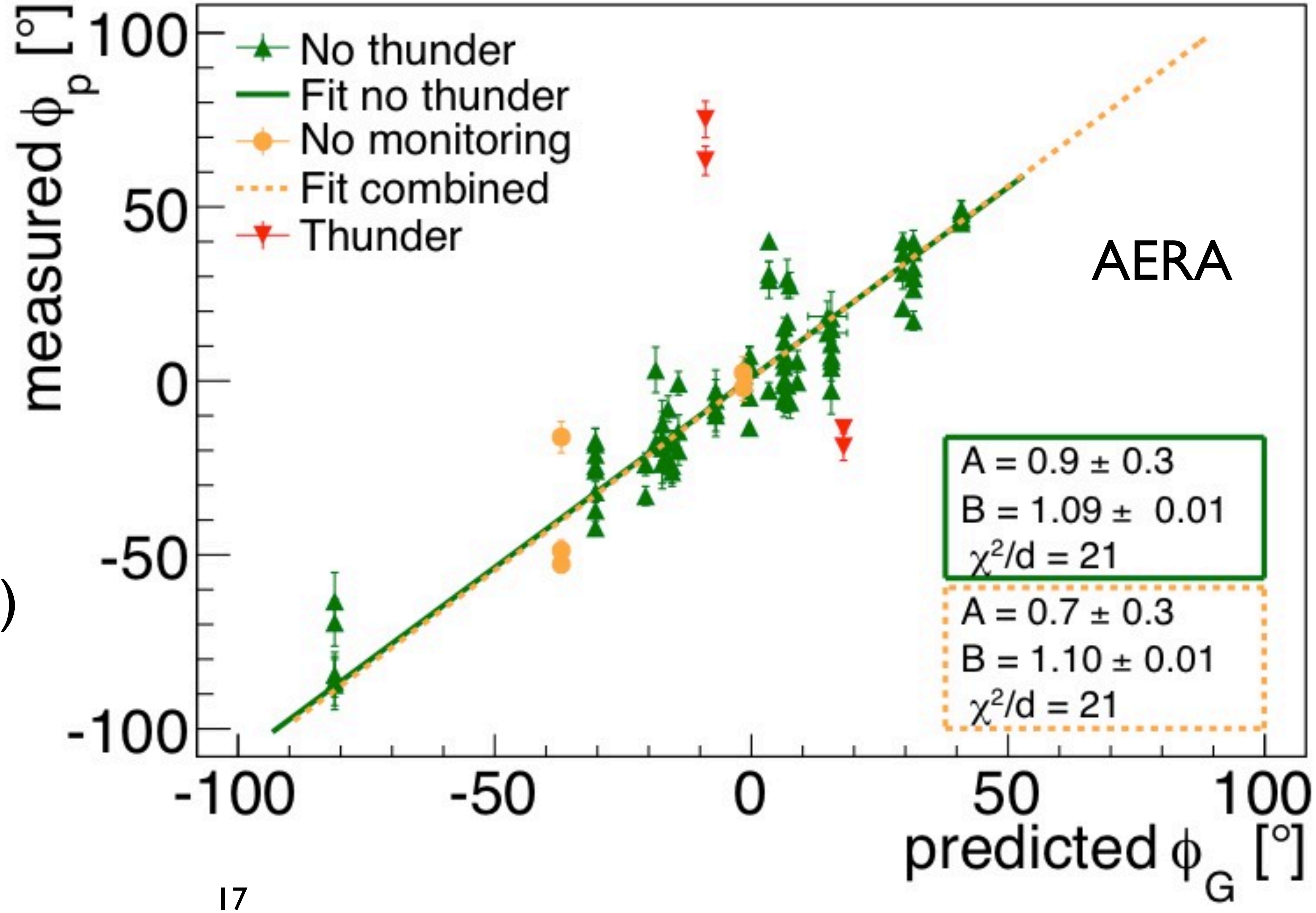
nXB polar. angle: $\phi_{\mathrm{mag}} = \arctan((\vec{n} \times \vec{B})_{\mathrm{NS}}/(\vec{n} \times \vec{B})_{\mathrm{EW}})$



time

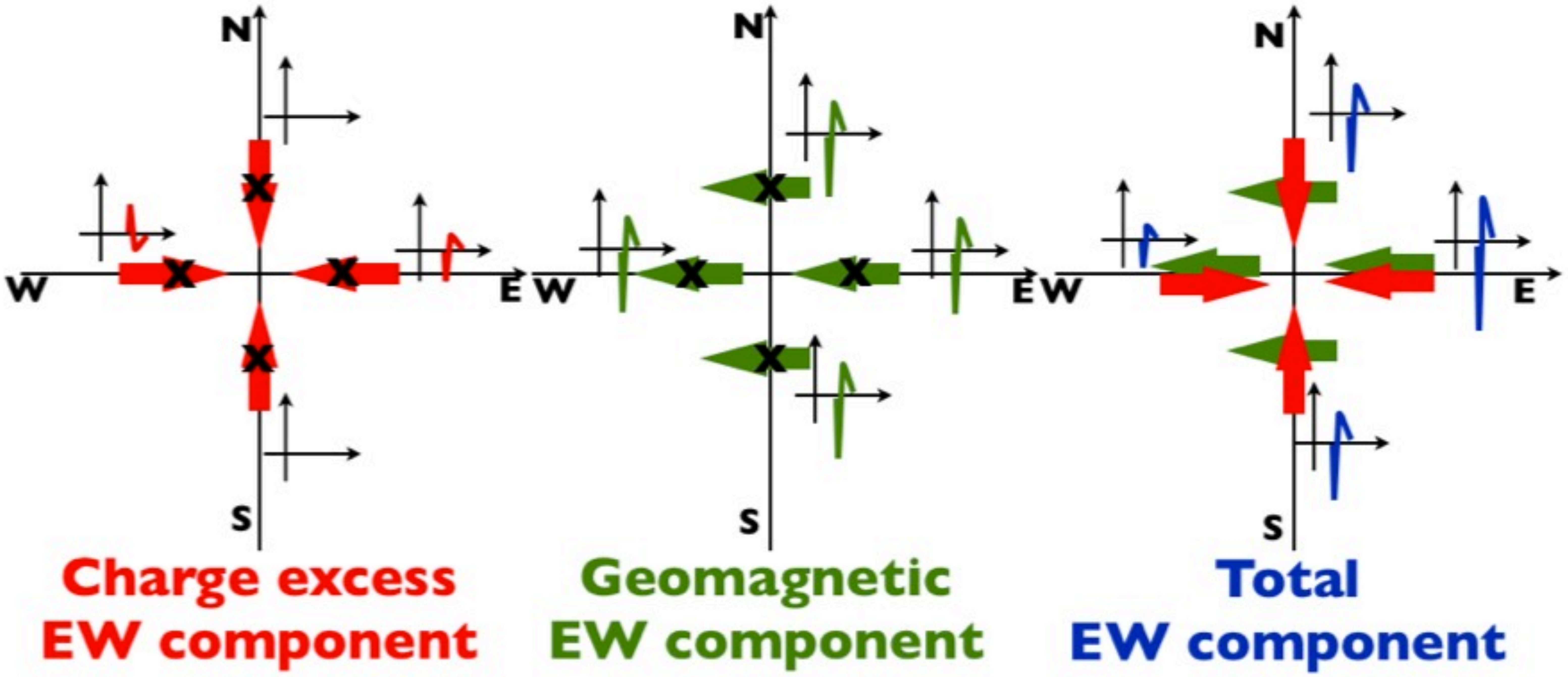


Schoorlemmer, ICTAPP 2011



The charge-excess component

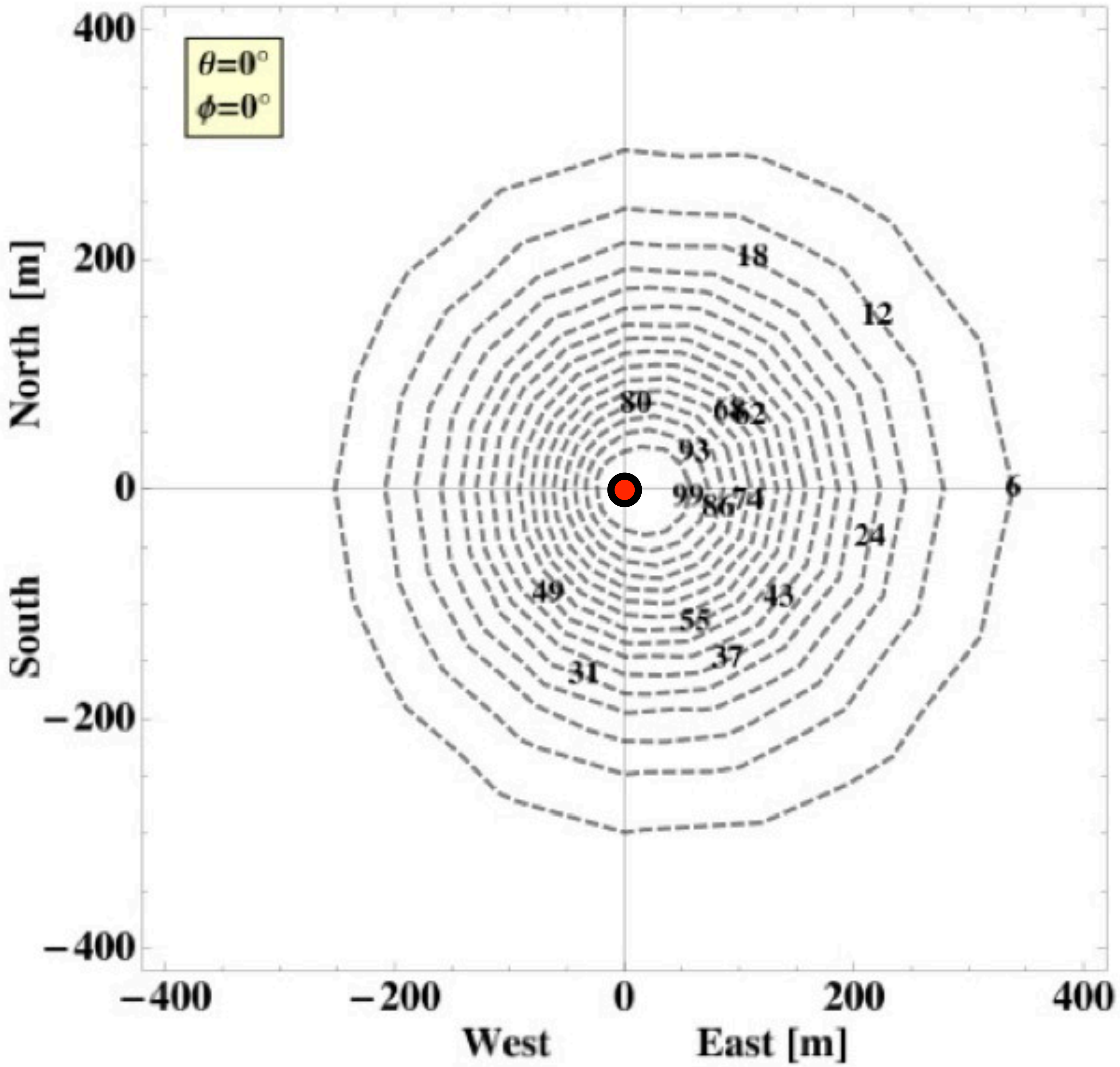
Secondary effect: example of a vertical shower



The charge-excess component

Secondary effect: example of a vertical shower

$$\frac{1}{c}\frac{\partial}{\partial t}\sum_{i=1}\left[\frac{\boldsymbol{n}_i q_i(t_{ret})}{R_i(1-\boldsymbol{\beta}_i.\boldsymbol{n}_i)}\right]_{\mathrm{ret}}$$



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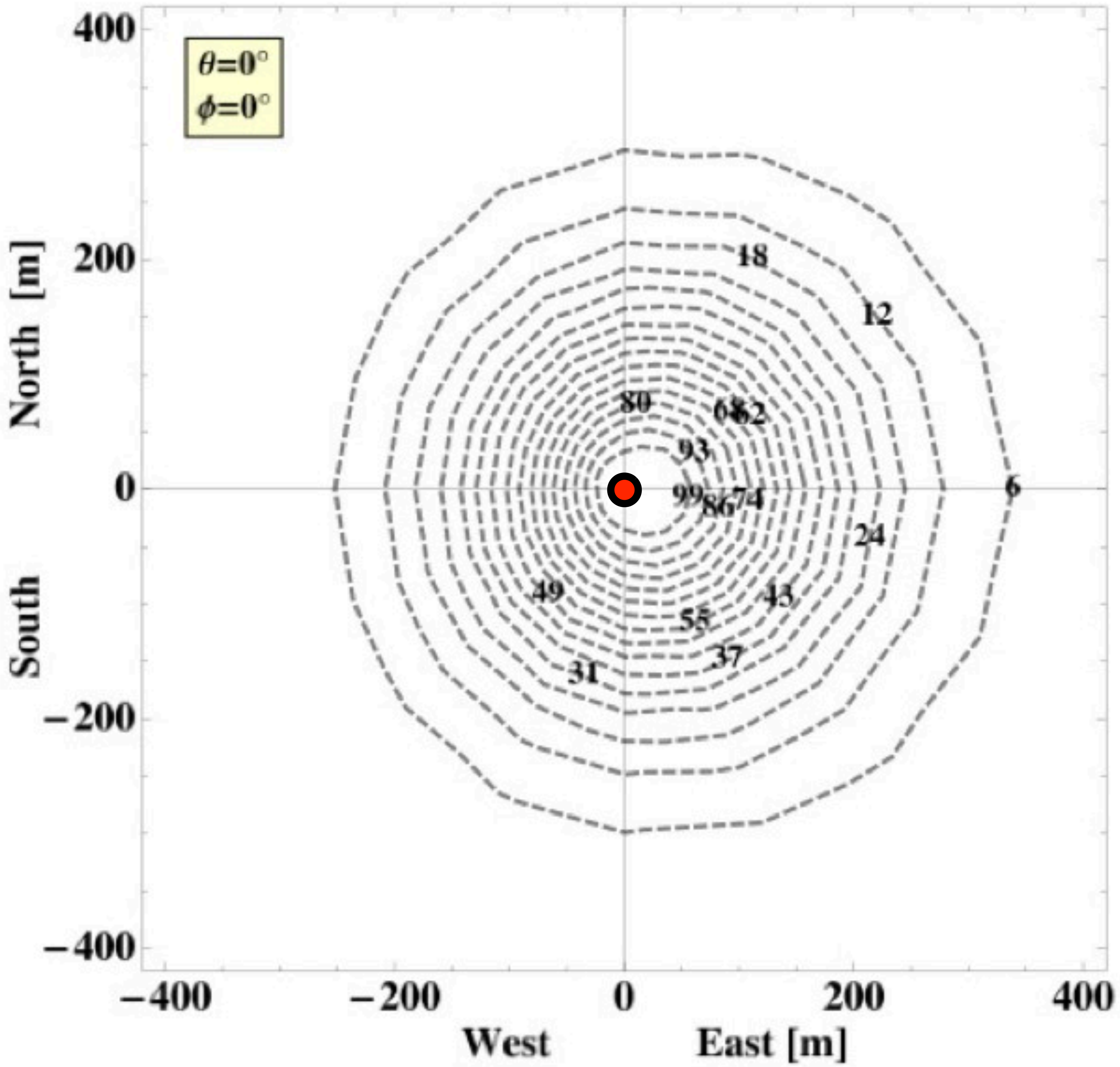
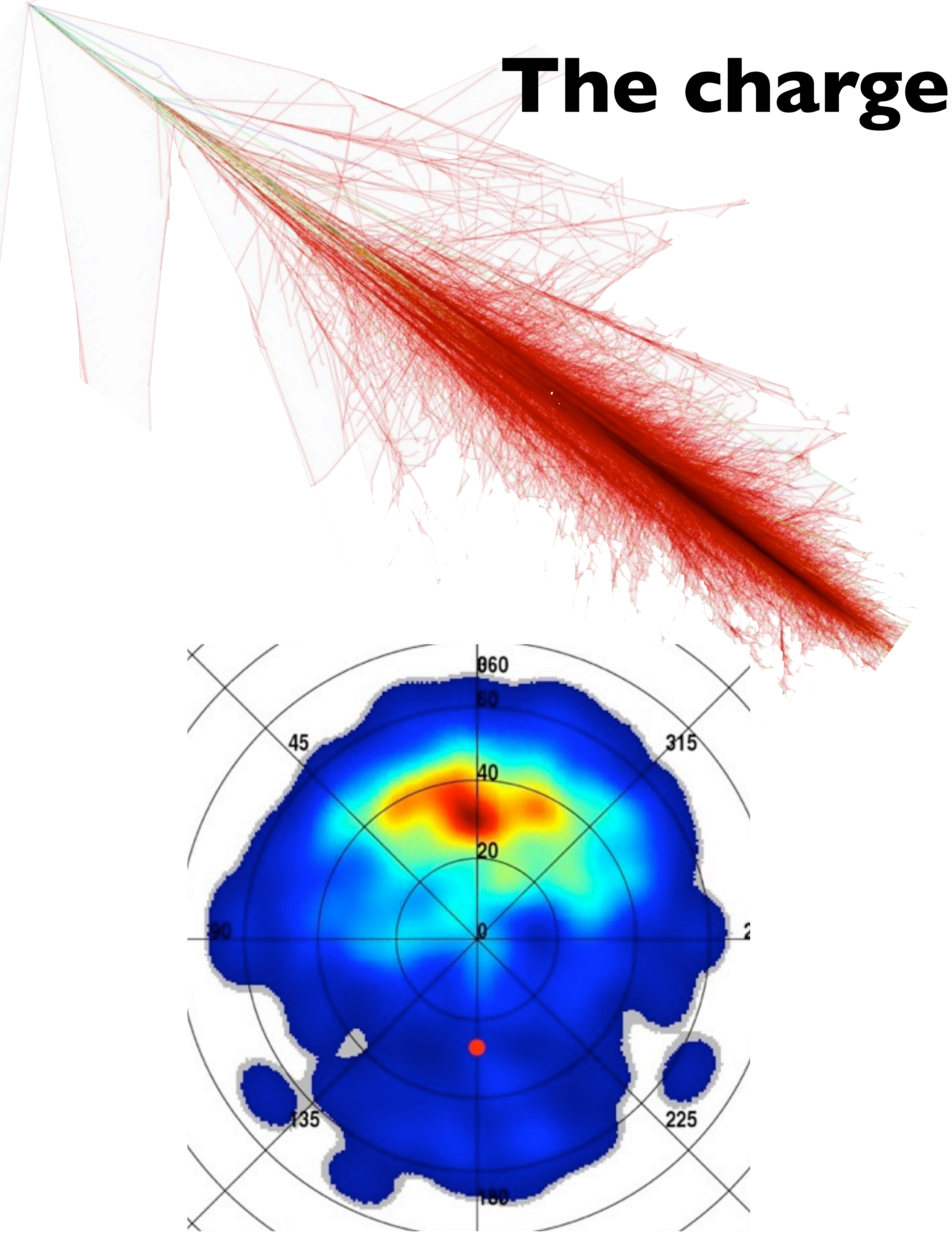


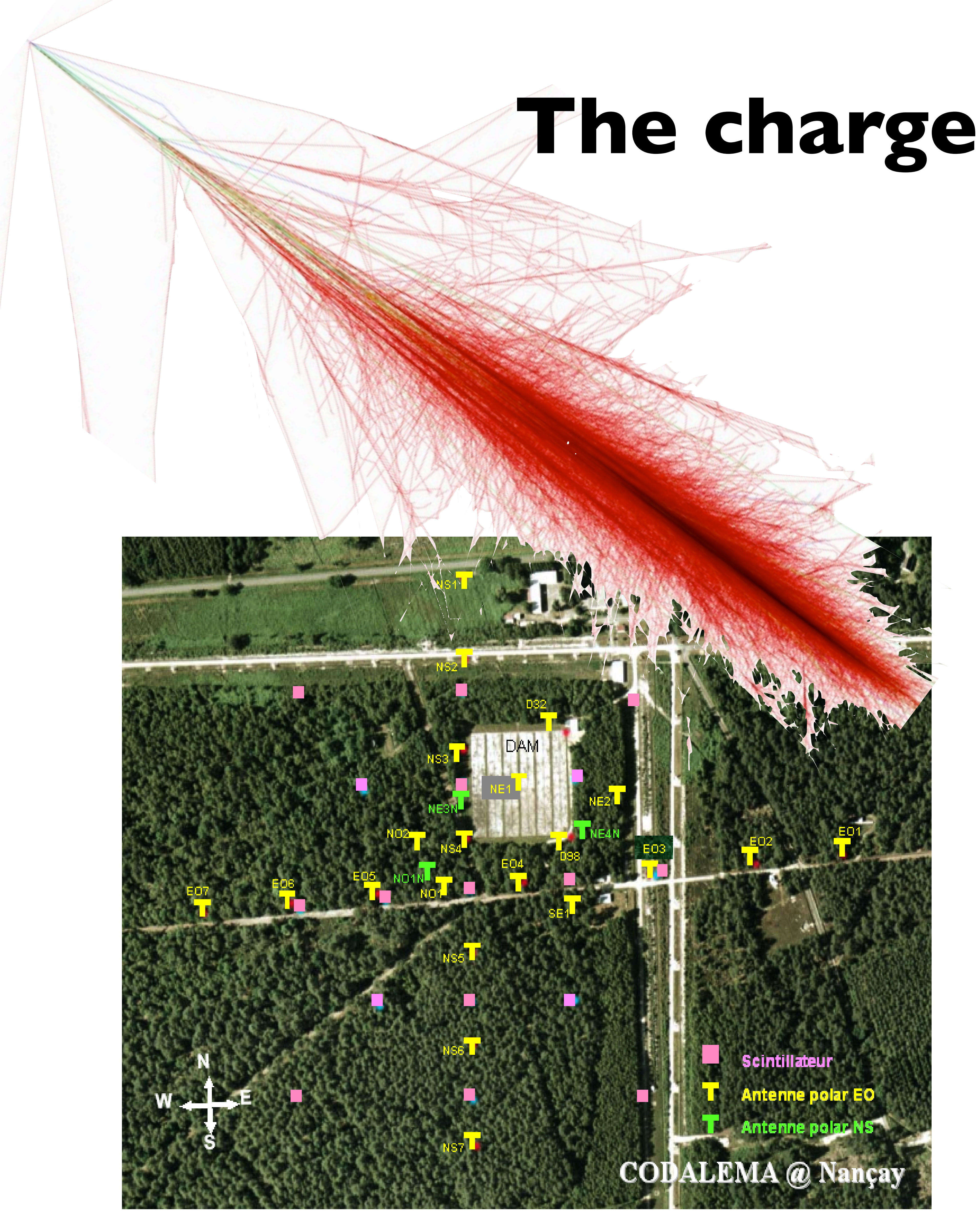
The EW-electric field profile
is shifted to the east
wrt the particle shower core
signature in the data ?

The charge-excess component



1) simulate N showers following the observed distribution (skymap and particle core positions)

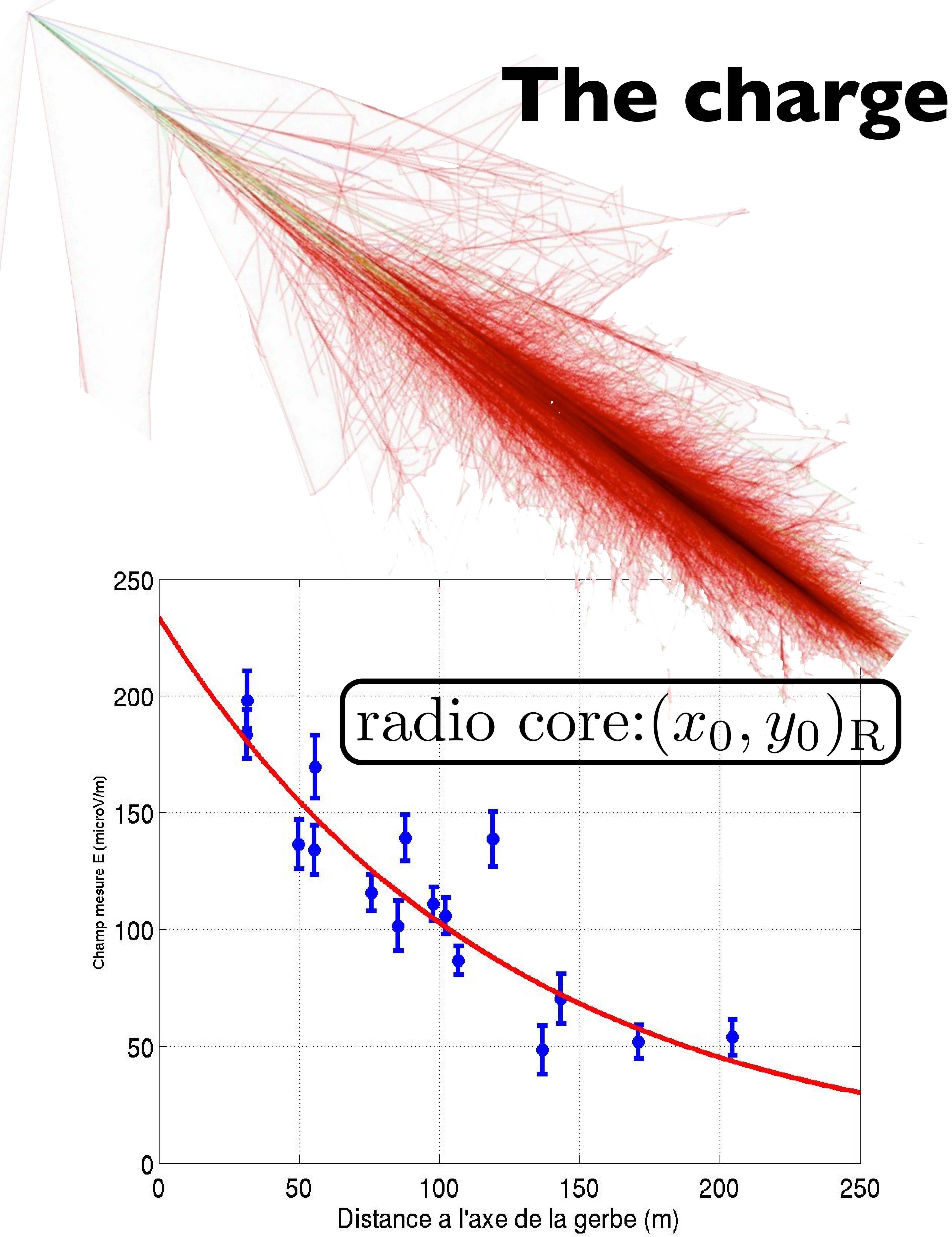
The charge-excess component



1) simulate N showers following the observed distribution (skymap and particle core positions)

2) compute the electric field for each antenna, at the same positions than the CODALEMA array (EW)

The charge-excess component



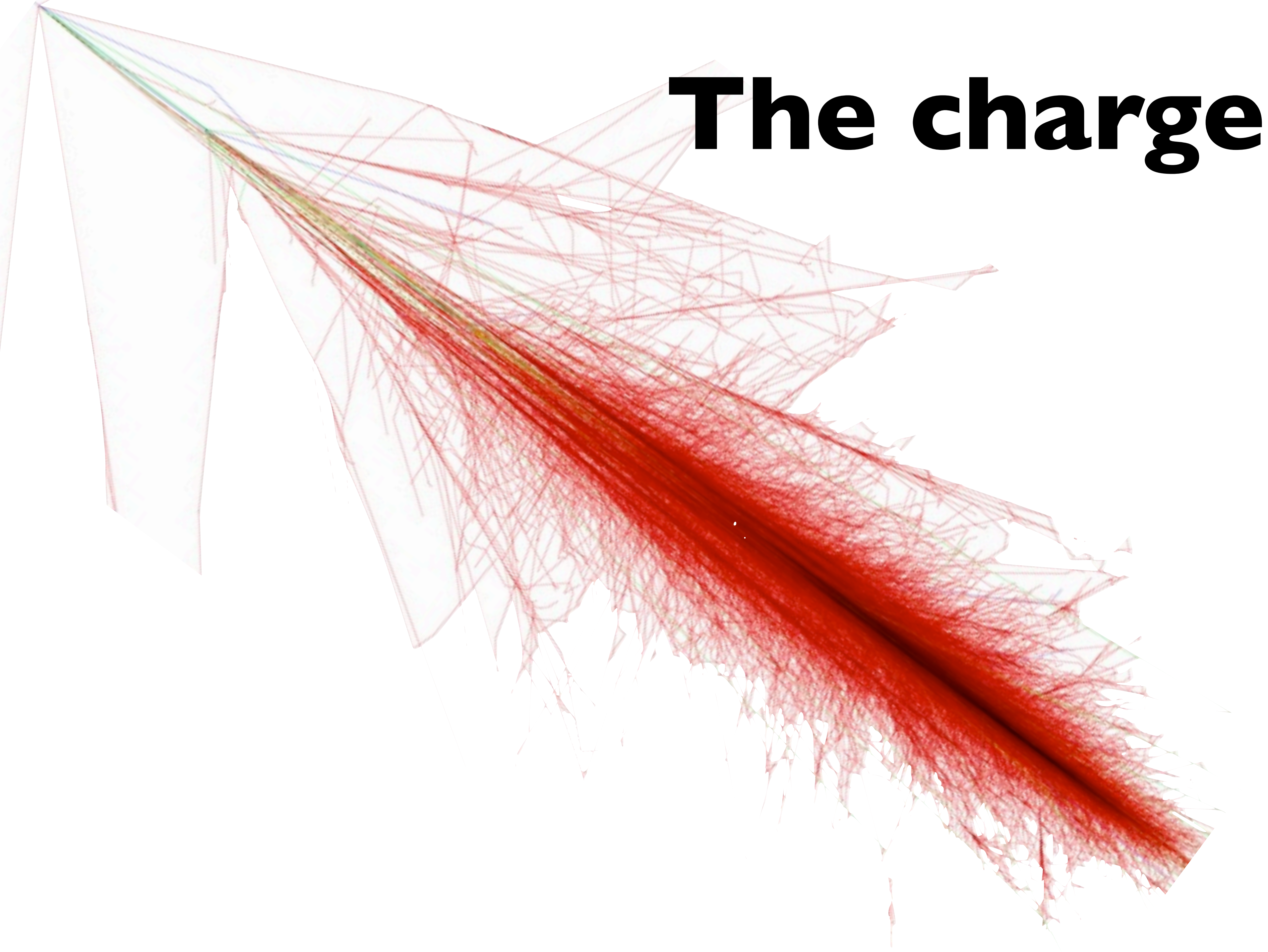
radio core:$(x_0, y_0)_{\mathrm{R}}$

1) simulate N showers following the observed distribution (skymap and particle core positions)

2) compute the electric field for each antenna, at the same positions than the CODALEMA array (EW)

3) compute the radio core position using an exponential profile

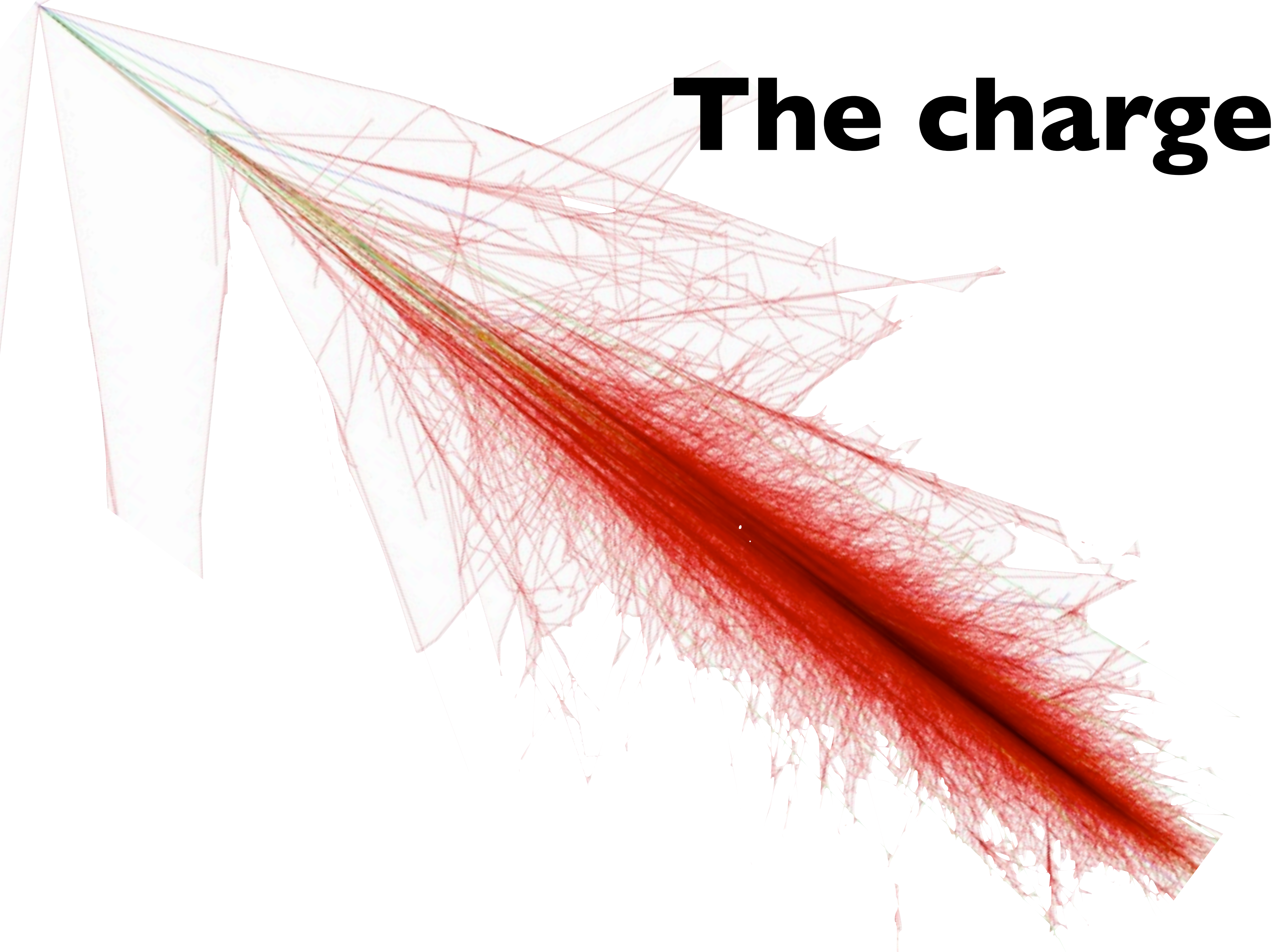
The charge-excess component



1) simulate N showers following the observed distribution (skymap and particle core positions)
2) compute the electric field for each antenna, at the same positions than the CODALEMA array (EW)
3) compute the radio core position using an exponential profile
4) study the relative position of the radio core position wrt the particle core position

$$\boxed{\delta\vec{R}_{\mathrm{core}} = (x_0, y_0)_{\mathrm{R}} - (x_0, y_0)_{\mathrm{S}}}$$

The charge-excess component



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1) simulate N showers following the observed distribution (skymap and particle core positions)

2) compute the electric field for each antenna, at the same positions than the CODALEMA array (EW)

3) compute the radio core position using an exponential profile

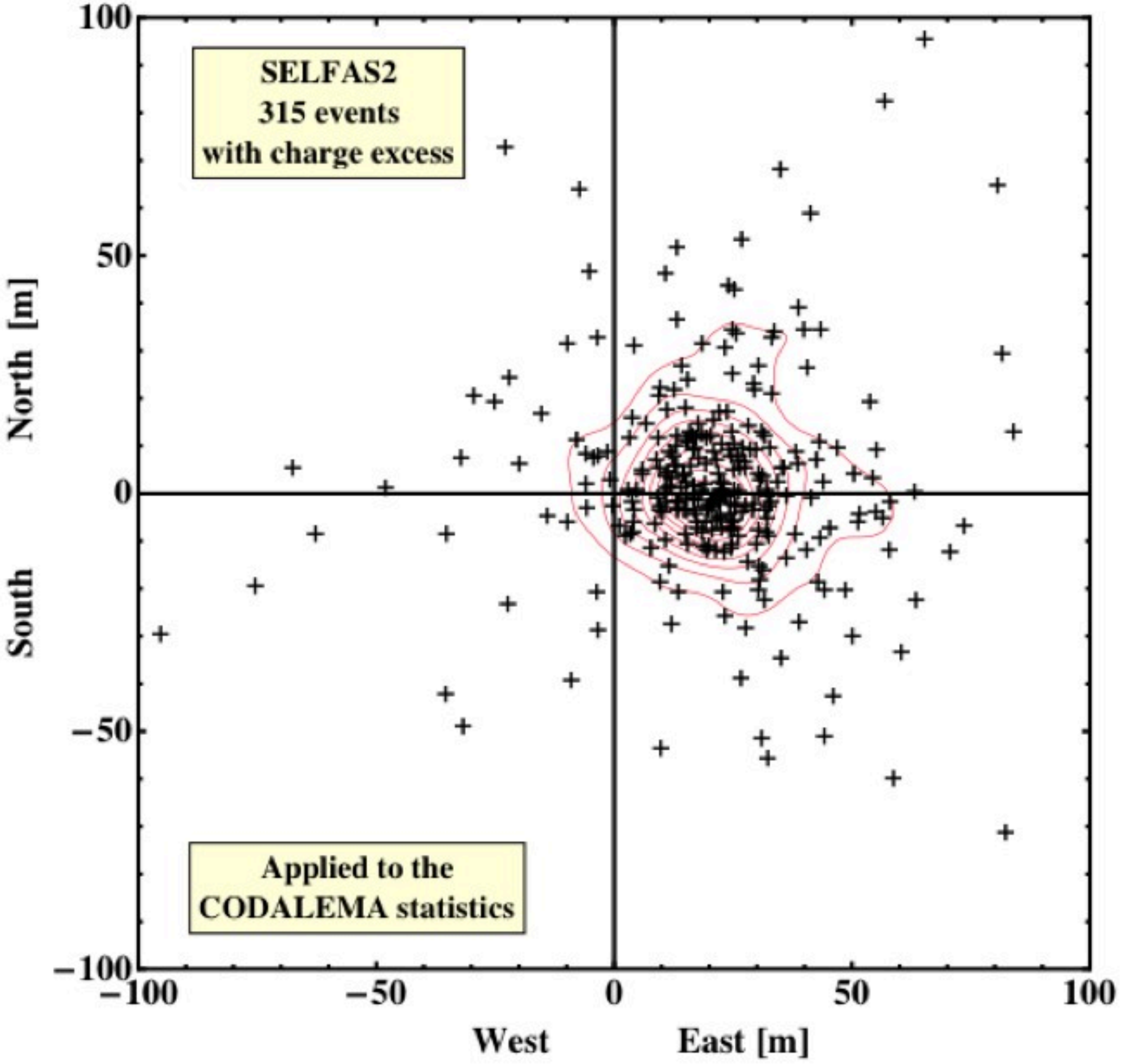
4) study the relative position of the radio core position wrt the particle core position

5) do it once with charge excess, once without charge excess in the simulation

Marin, ICRC 2011

The charge-excess component

$$\delta\vec{R}_{\rm core} = (x_0, y_0)_{\rm R} - (x_0, y_0)_{\rm S}$$



Marin, ICRC 2011

The charge-excess component

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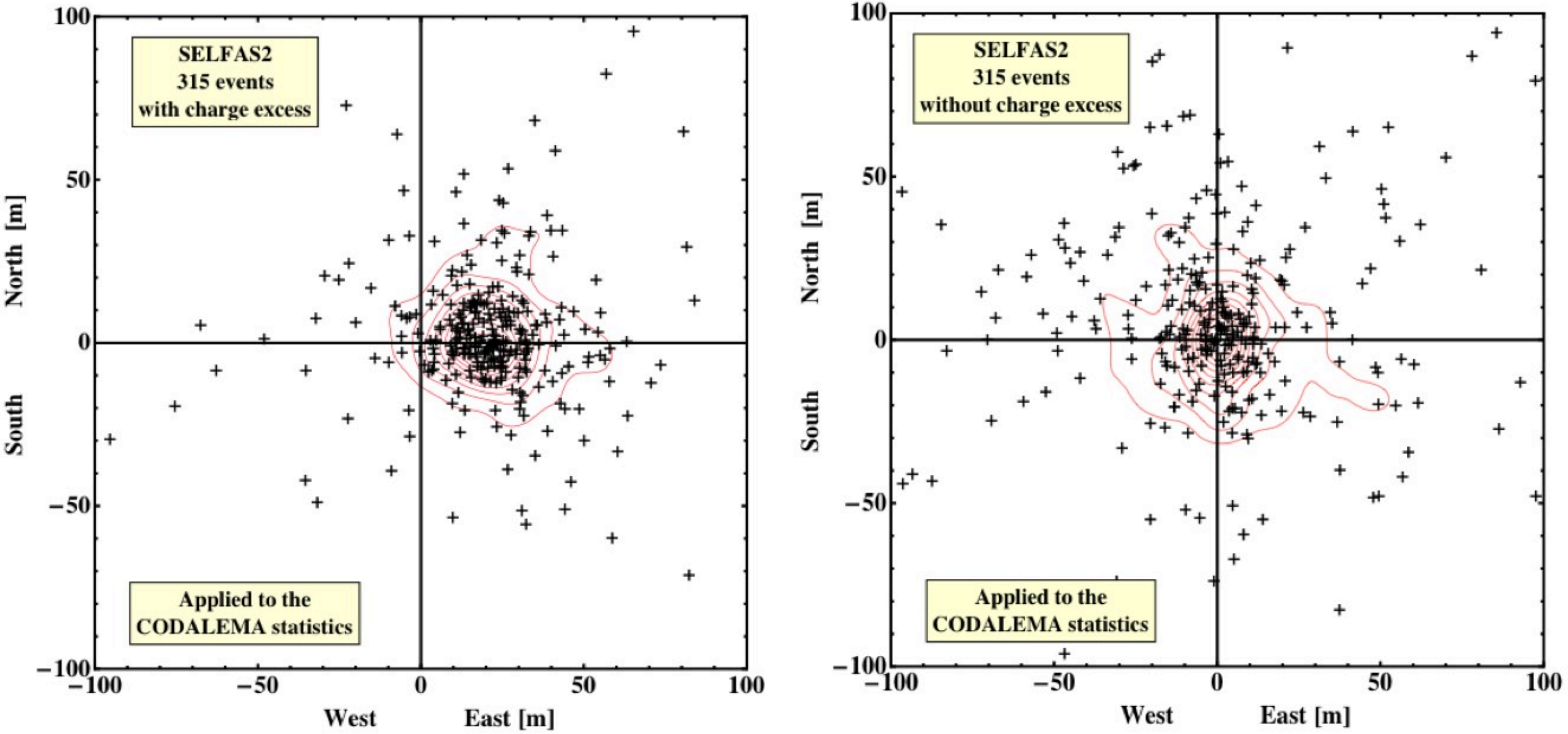

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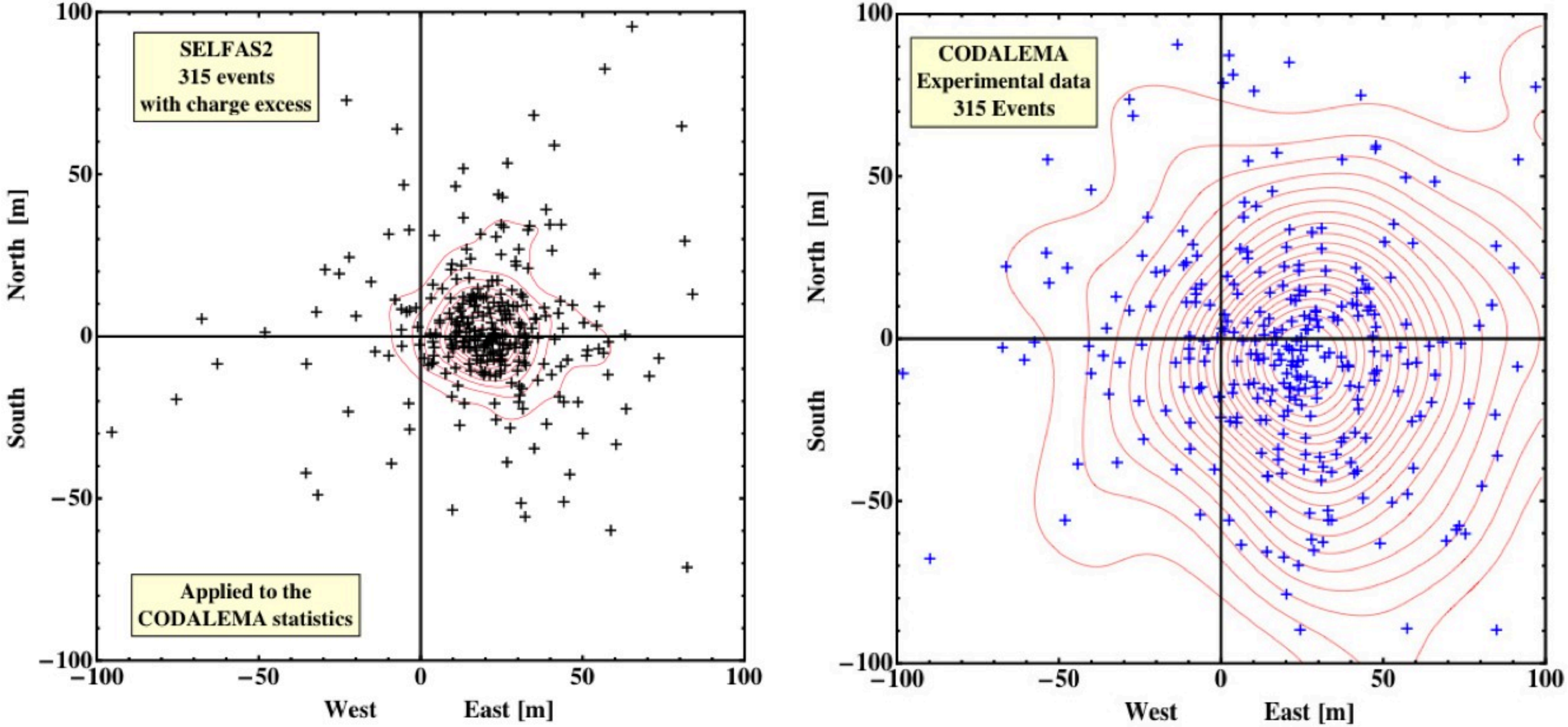
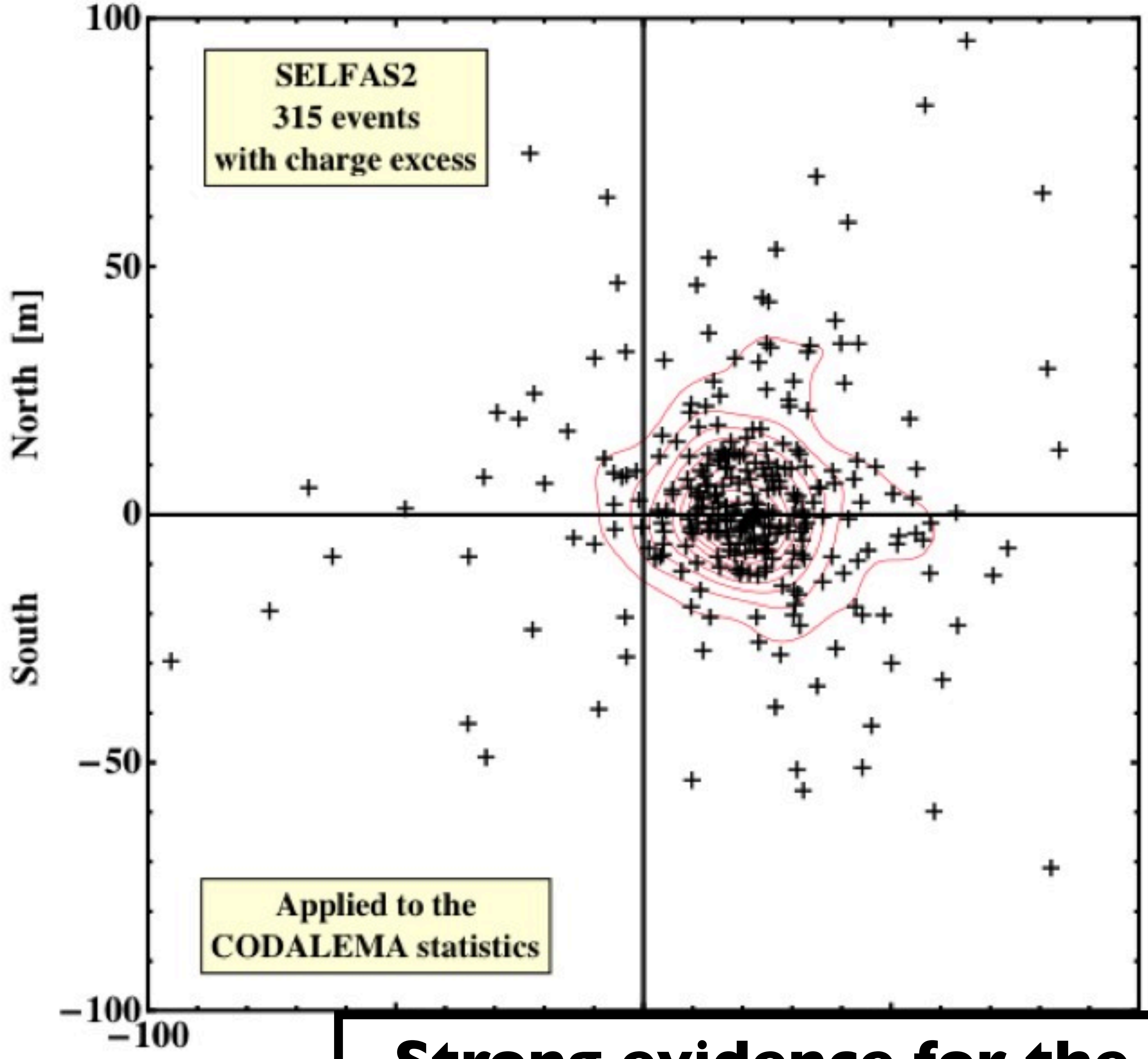
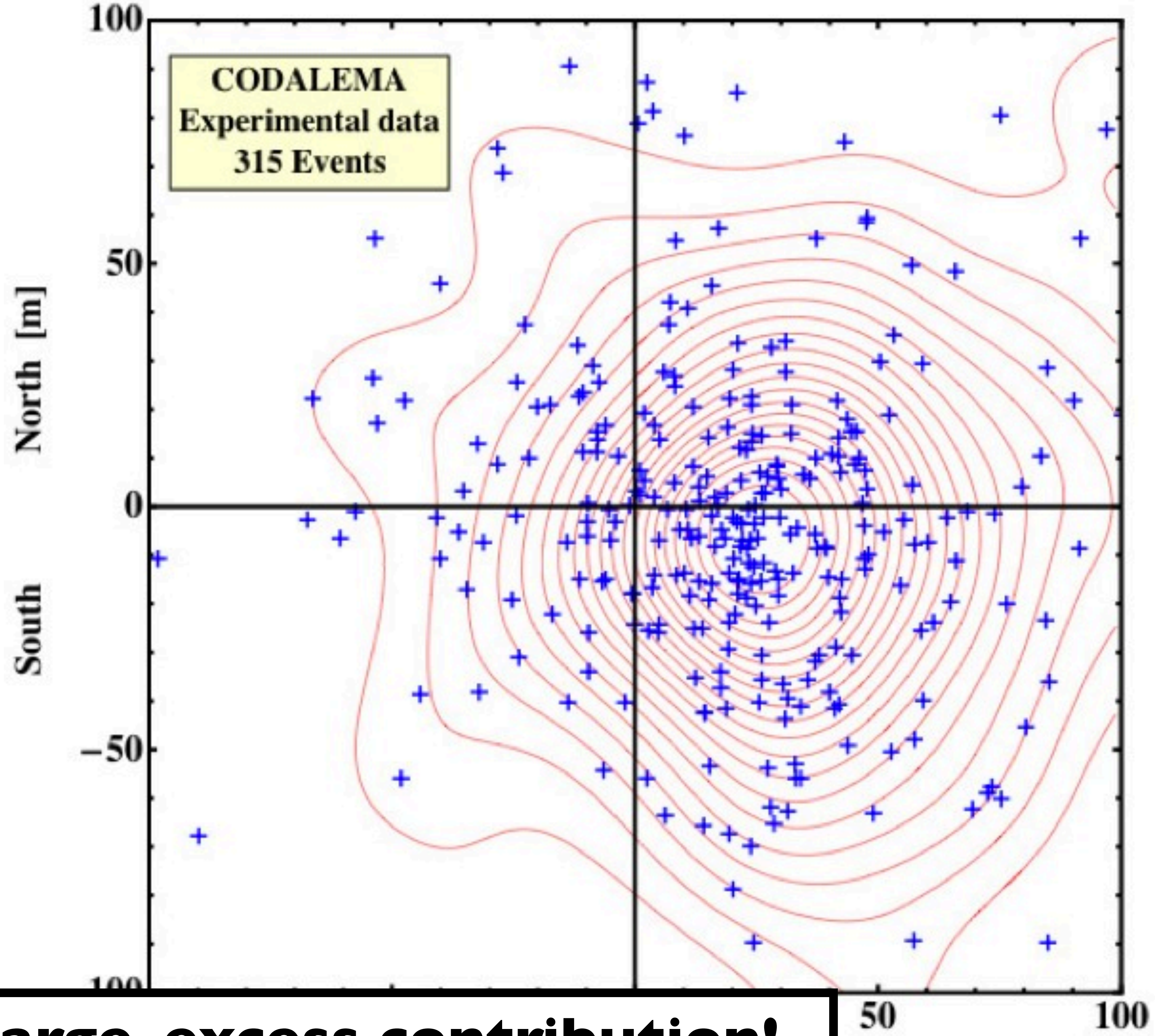


Marin, ICRC 2011

The charge-excess component

$$\delta\vec{R}_{\mathrm{core}} = (x_0, y_0)_{\mathrm{R}} - (x_0, y_0)_{\mathrm{S}}$$

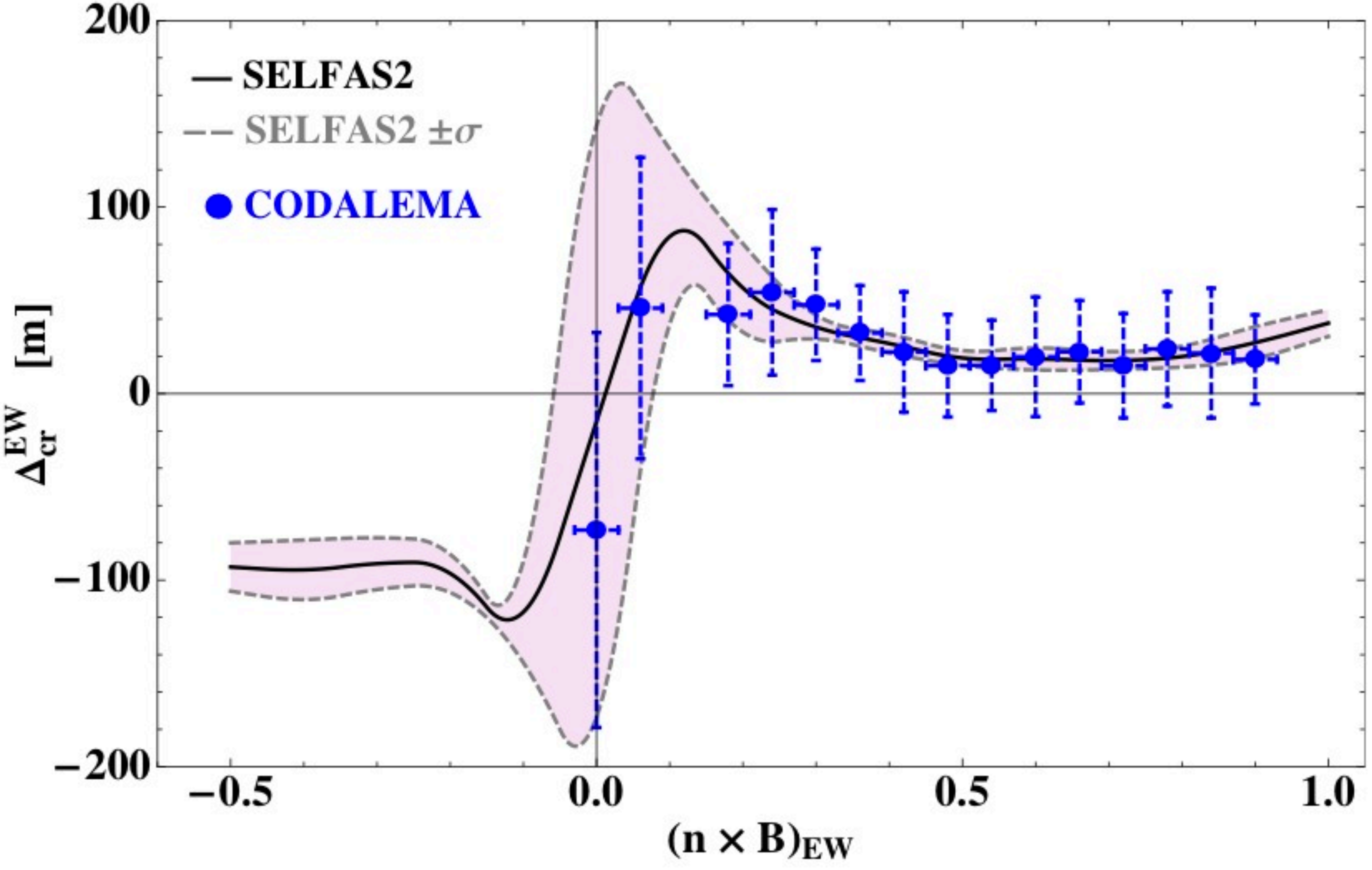




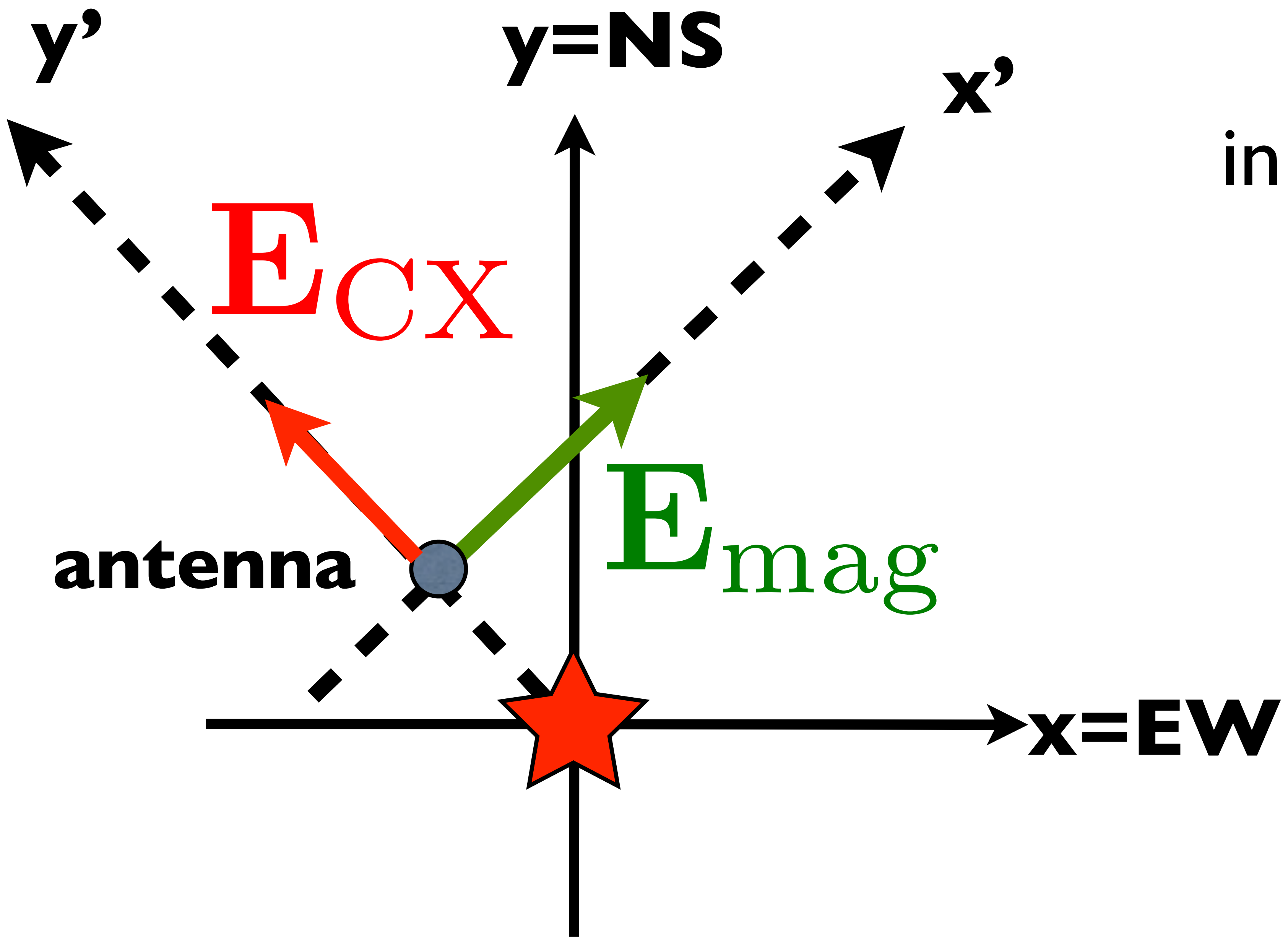
Strong evidence for the charge-excess contribution!

Marin, ICRC 2011

The charge-excess component



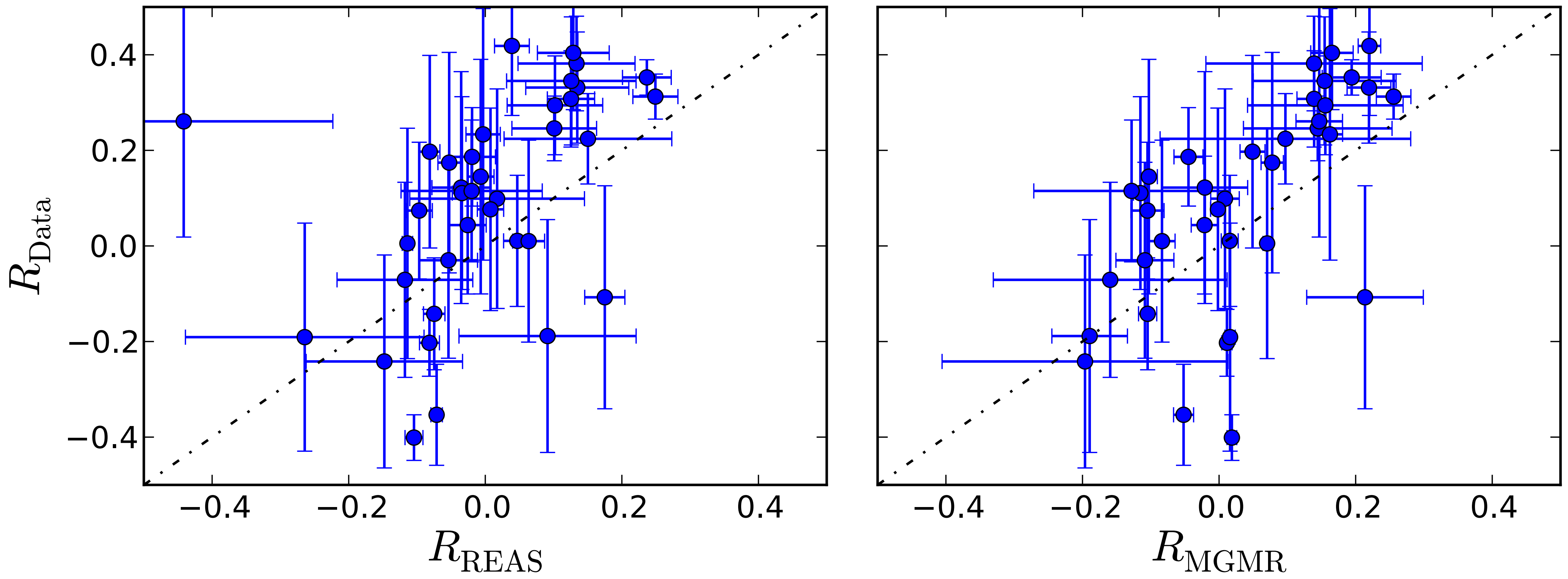
The charge-excess component



in (x',y'), define:

$$\boxed{R = \frac{\sum_{i=1}^{N} E_{x'}(t_i)\, E_{y'}(t_i)}{\sum_{i=1}^{N} E^2_{x'}(t_i) + E^2_{y'}(t_i)}}$$

if no charge excess: R=0 compare R_{data} and R_{sim}



X^2/dof values	**nxB only**	**nxB+charge excess**
MGRM	**6.08**	**2.53**
REAS	**6.28**	**2.64**

Hint for the charge-excess mechanism

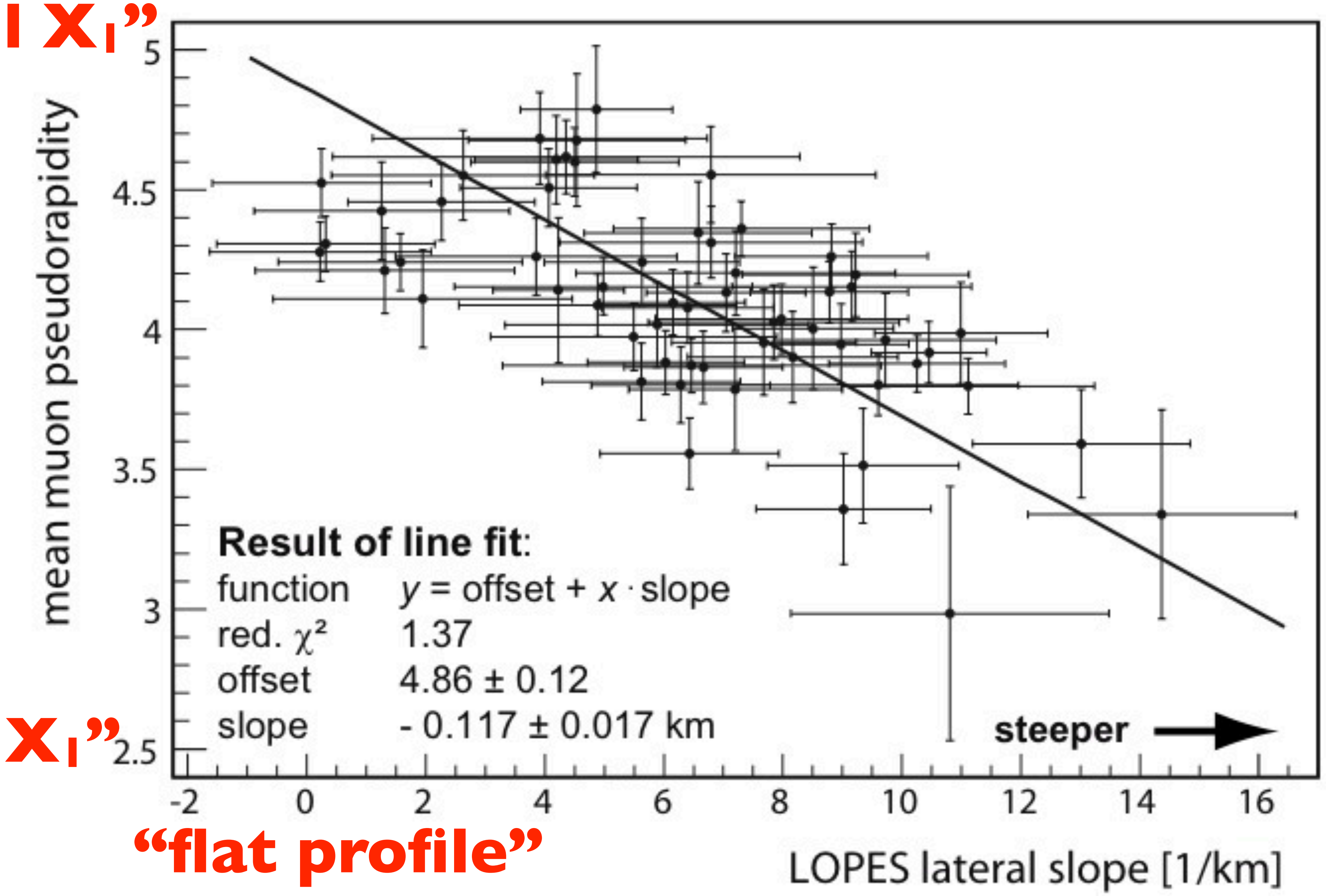
Correlation with shower development (nature of the primary)

LOPES, Phys. Rev. D 2012, arXiv:1203.397v1

correlation between slope of the LDF and mean muon pseudorapidity
the radio signal is sensitive to the longitudinal development of air showers

"small X_1"

"large X_1"



"flat profile"

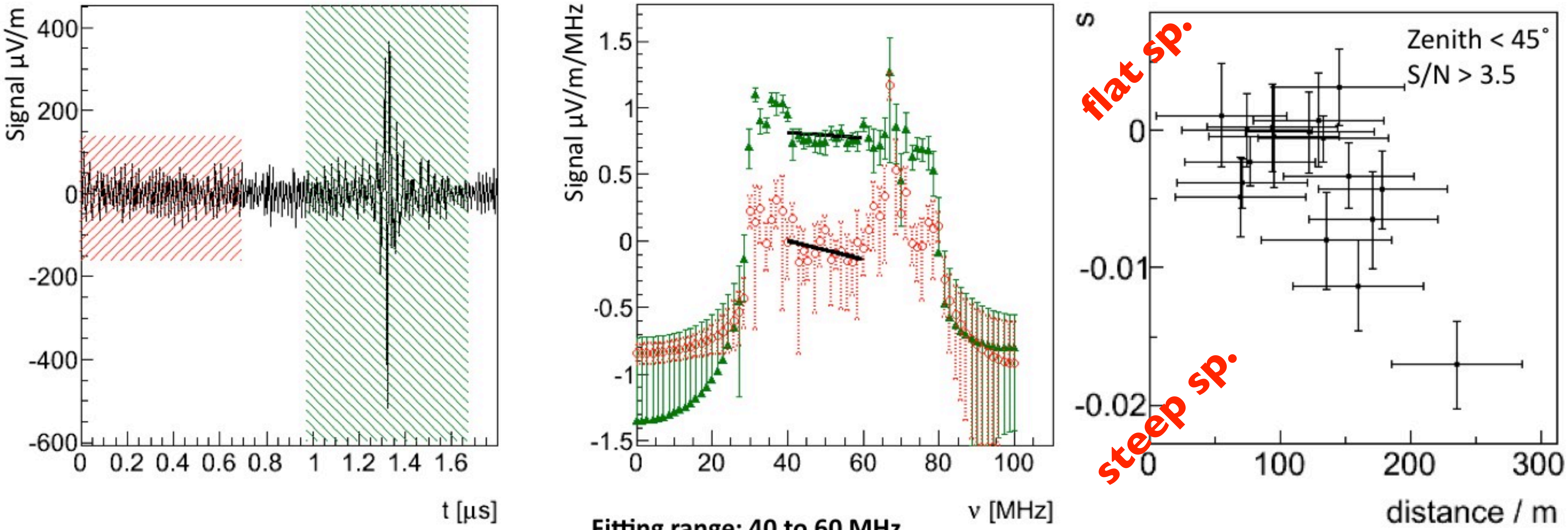
"steep profile"

(see also talk of N. Palmieri, LOPES and X_{max})

Correlation with shower development (nature of the primary)

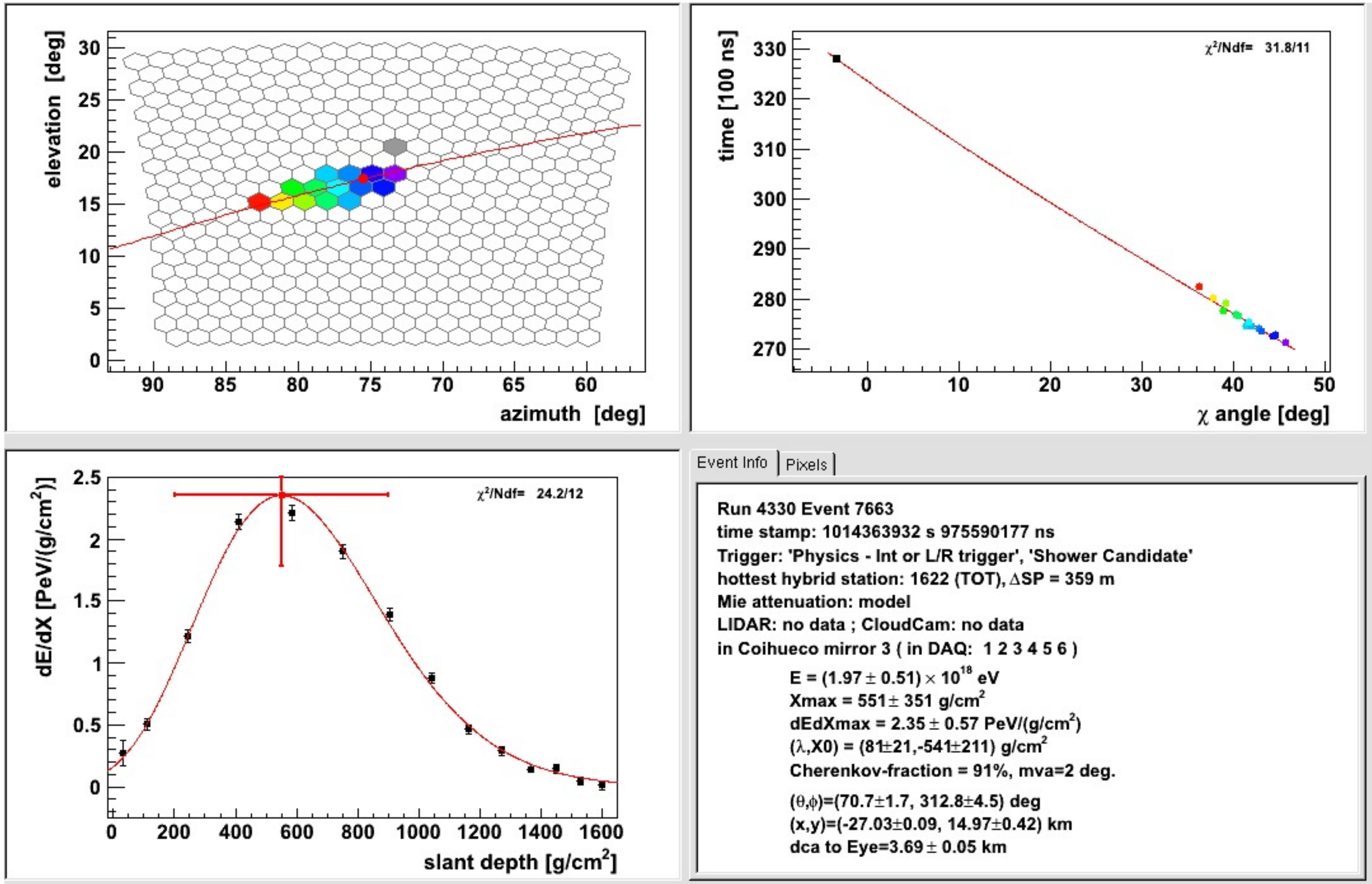
The time shape of the signal depends on the line of sight: influence on the power spectrum
Fit the slope of the power spectra: the slope depends on the shower geometry

(see talk of S. Grebe)



Fitting range: 40 to 60 MHz

Correlation with shower development (nature of the primary)

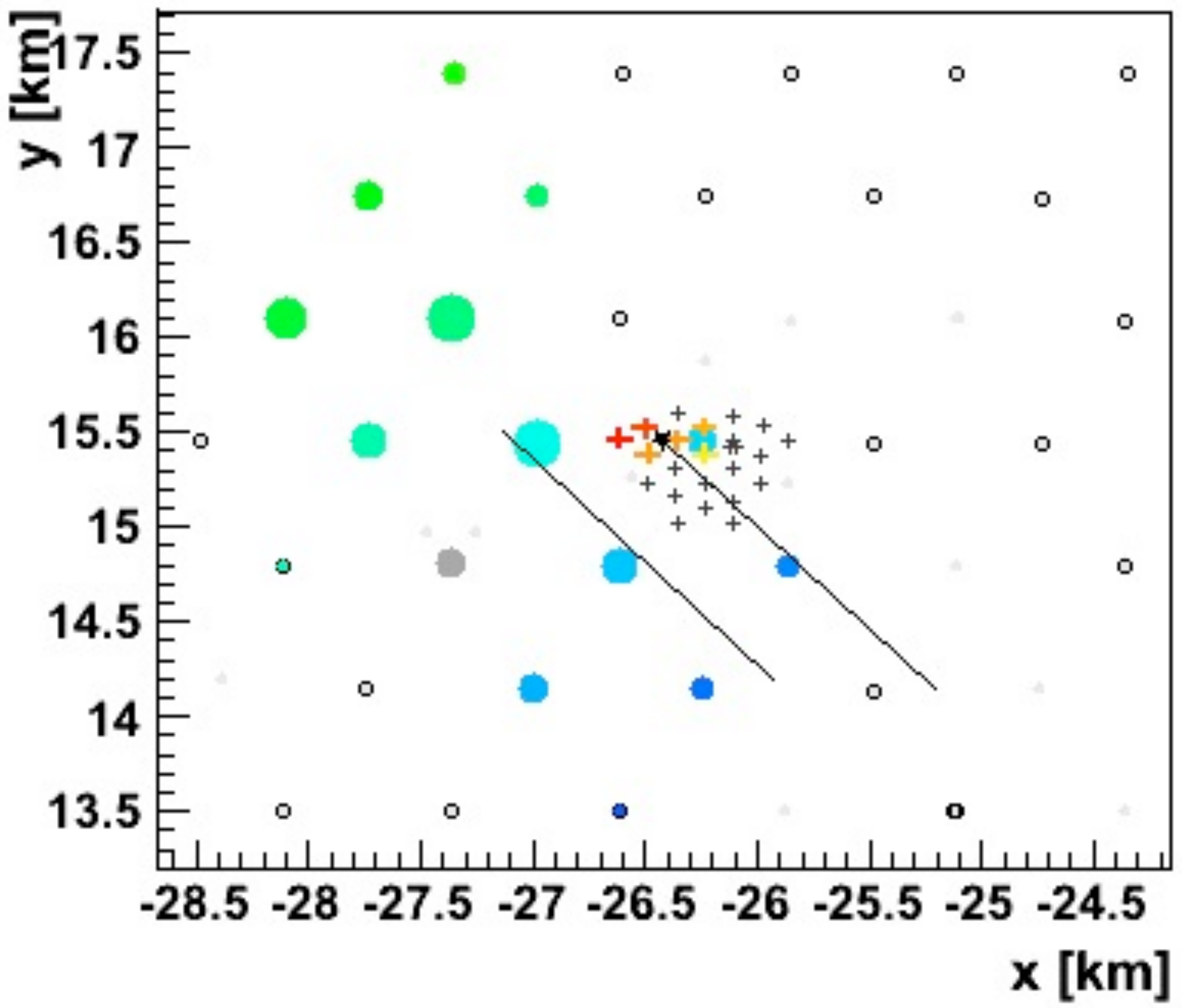


Run 4330 Event 7663
time stamp: 1014363932 s 975590177 ns
Trigger: 'Physics - Int or L/R trigger', 'Shower Candidate'
hottest hybrid station: 1622 (TOT), ΔSP = 359 m
Mie attenuation: model
LIDAR: no data ; CloudCam: no data
in Coihueco mirror 3 (in DAQ: 1 2 3 4 5 6)

E = (1.97 ± 0.51) × 10^{18} eV
Xmax = 551± 351 g/cm^2
dEdXmax = 2.35 ± 0.57 PeV/(g/cm^2)
(λ,X0) = (81±21,-541±211) g/cm^2
Cherenkov-fraction = 91%, mva=2 deg.

(θ,ϕ)=(70.7±1.7, 312.8±4.5) deg
(x,y)=(-27.03±0.09, 14.97±0.42) km
dca to Eye=3.69 ± 0.05 km

AERA experiment: uses
uses data and reconstruction
from SD and FD !
(see talk of M. Melissas)



Synthesis

At first order **E = n X B** in both amplitude and polarization (almost all experiments), in both hemispheres

Close to the shower axis: Cerenkov

“LDF anomaly”: flat for antennas close to the shower axis; departure from an pure exponential dependence with axis distance

The charge-excess mechanism is (almost) detected:
- signature in the polarization angle (AERA & MAXIMA setup)
- signature on the radio core positions (CODALEMA)

Signal depends on: angle to geomagnetic field, distance to shower axis, position of the detector wrt shower core and frequency band

Radio signal sensitive to the shower development: indication in the data (not only in simulations!)

ARENA 2012

Codalema 3

The station

Butterfly antenna, EW & NS polarization measurement

GPS based timing system, resolution of the order of 5 ns,

Analog trigger board,

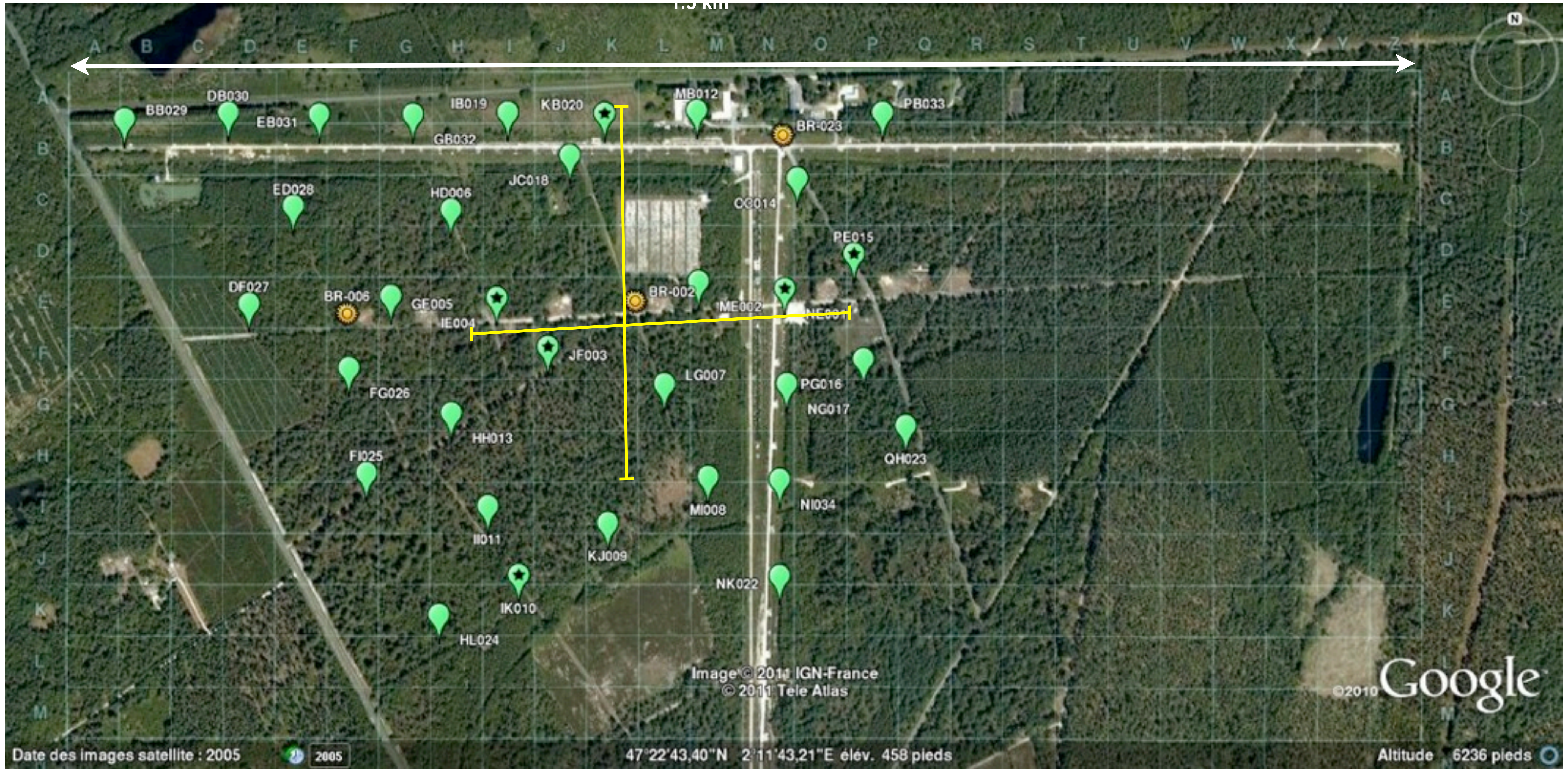
2 ADC channels(1GHz 2560 pts 14 bits),

Embedded PC

Optical fiber

external power supply (cables) but designed for batteries

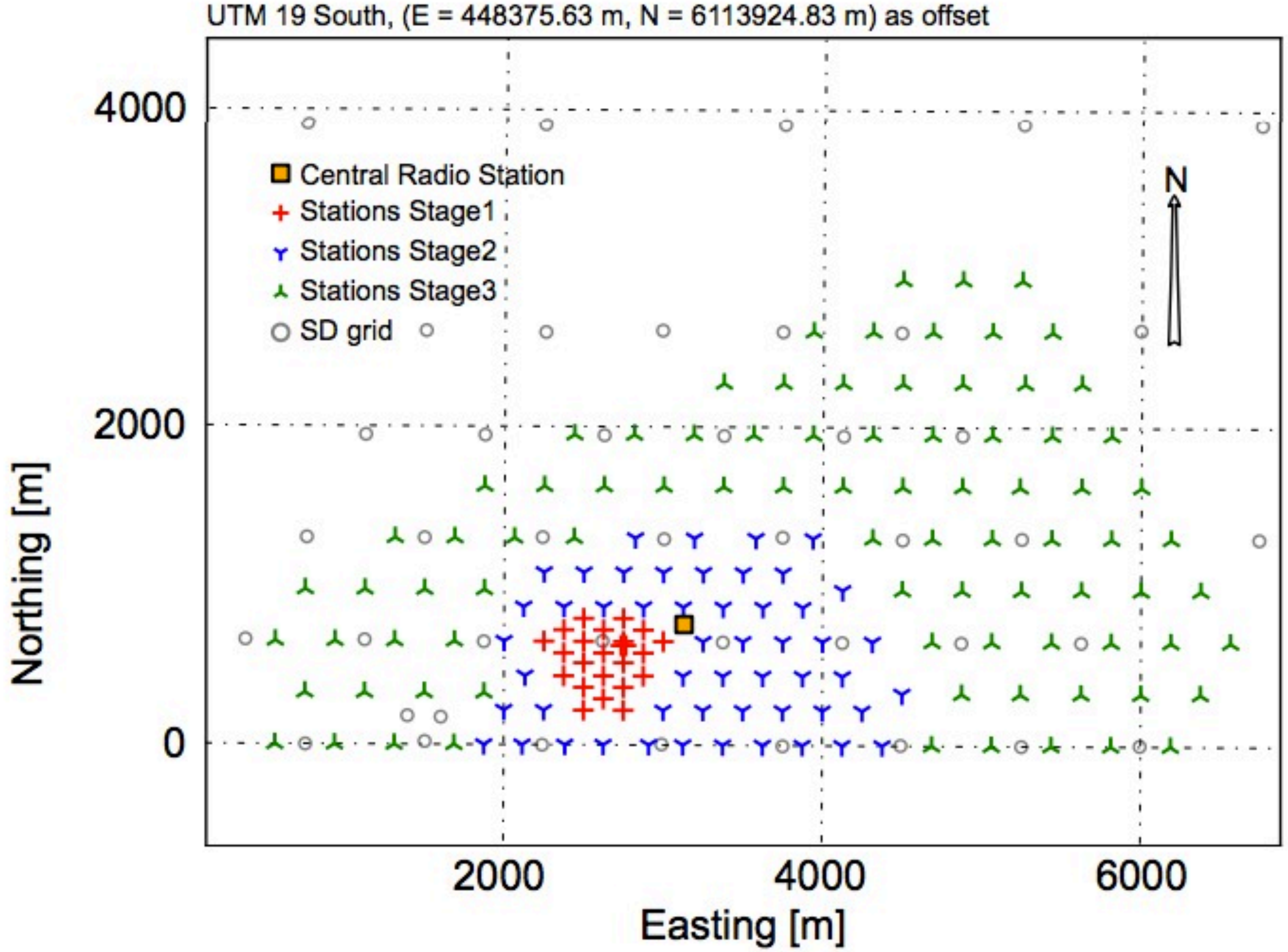
Design validated at the Pierre Auger Observatory

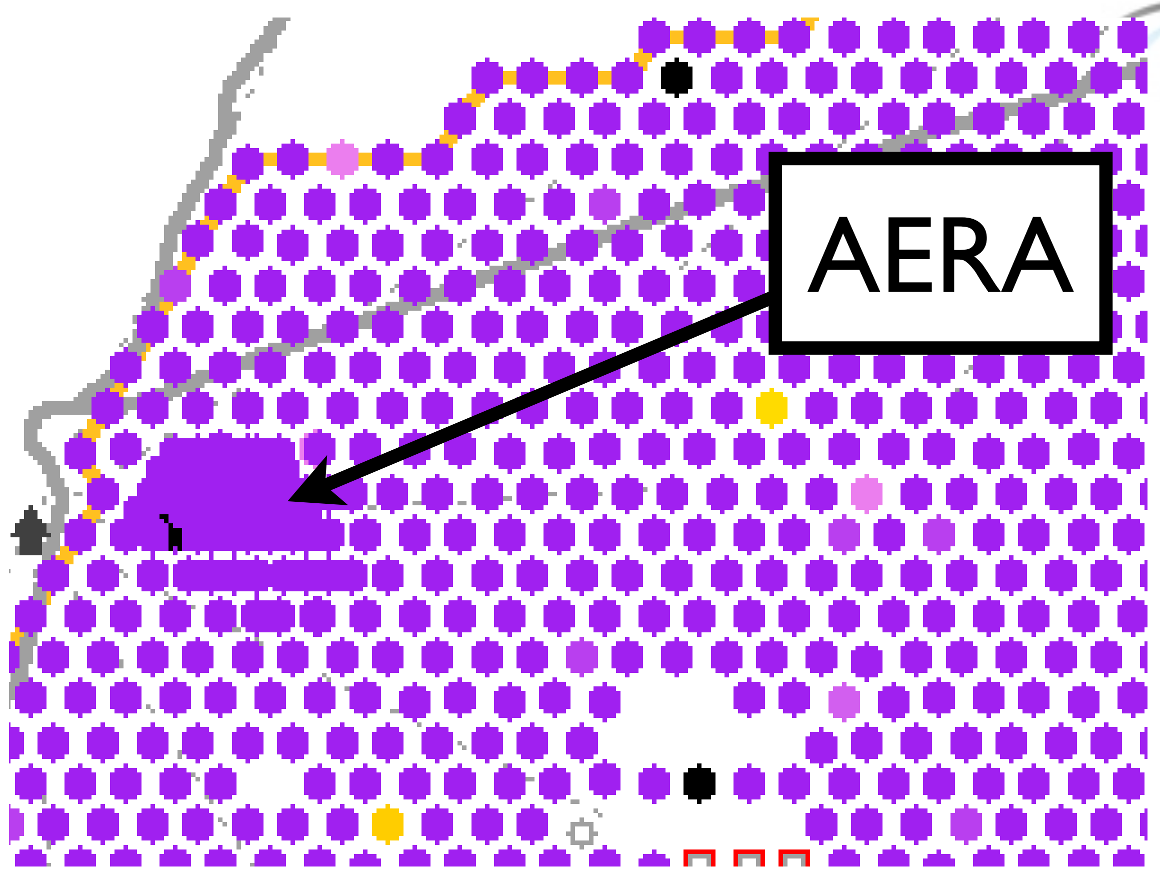


B. Revenu, ARENA 2012

AERA

running since end of 2010

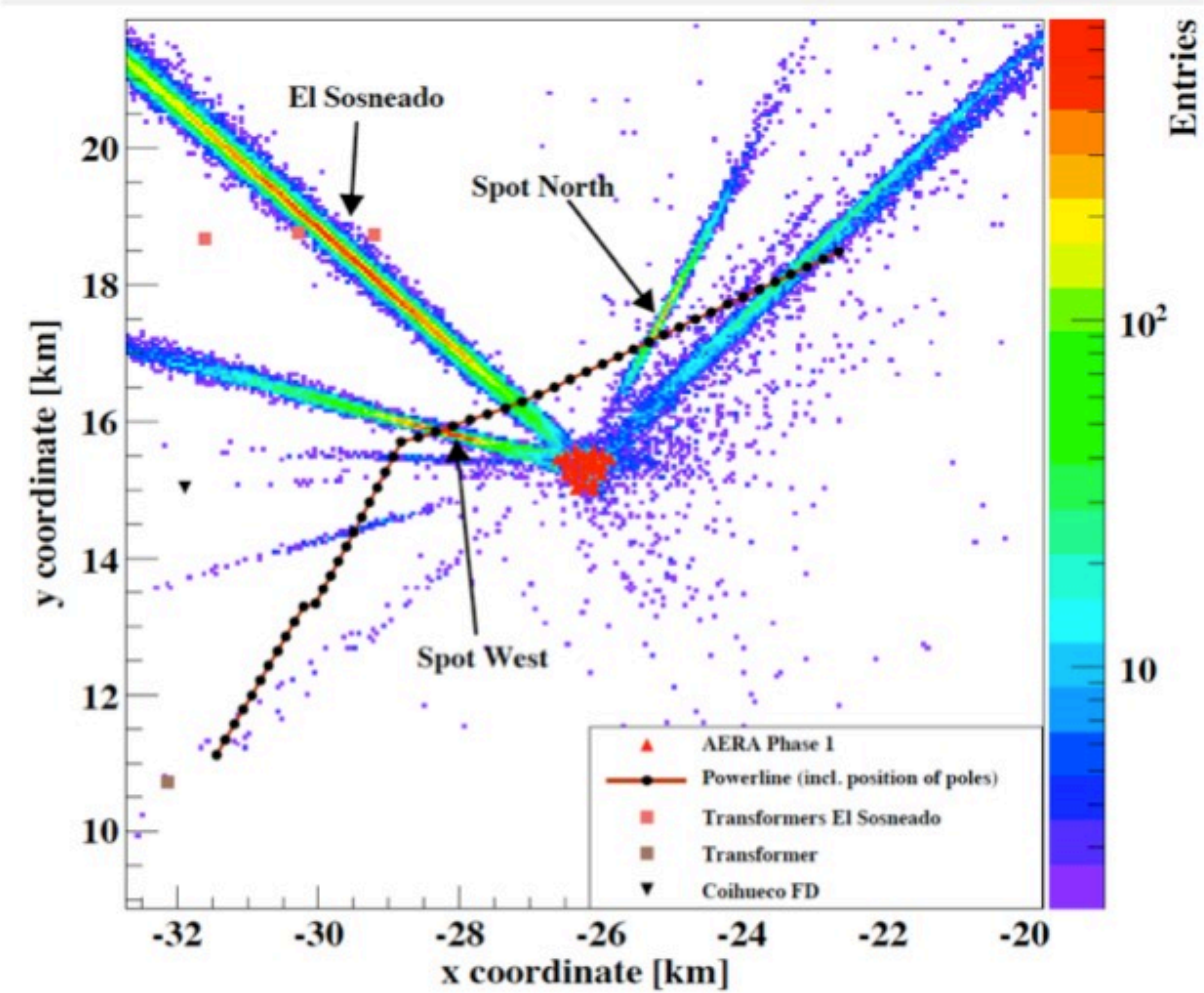




- overlap Auger Infill, HEAT, AMIGA
- self-trigger
- external trigger: SD and FD

AERA

Schoorlemmer, ICTAPP 2011

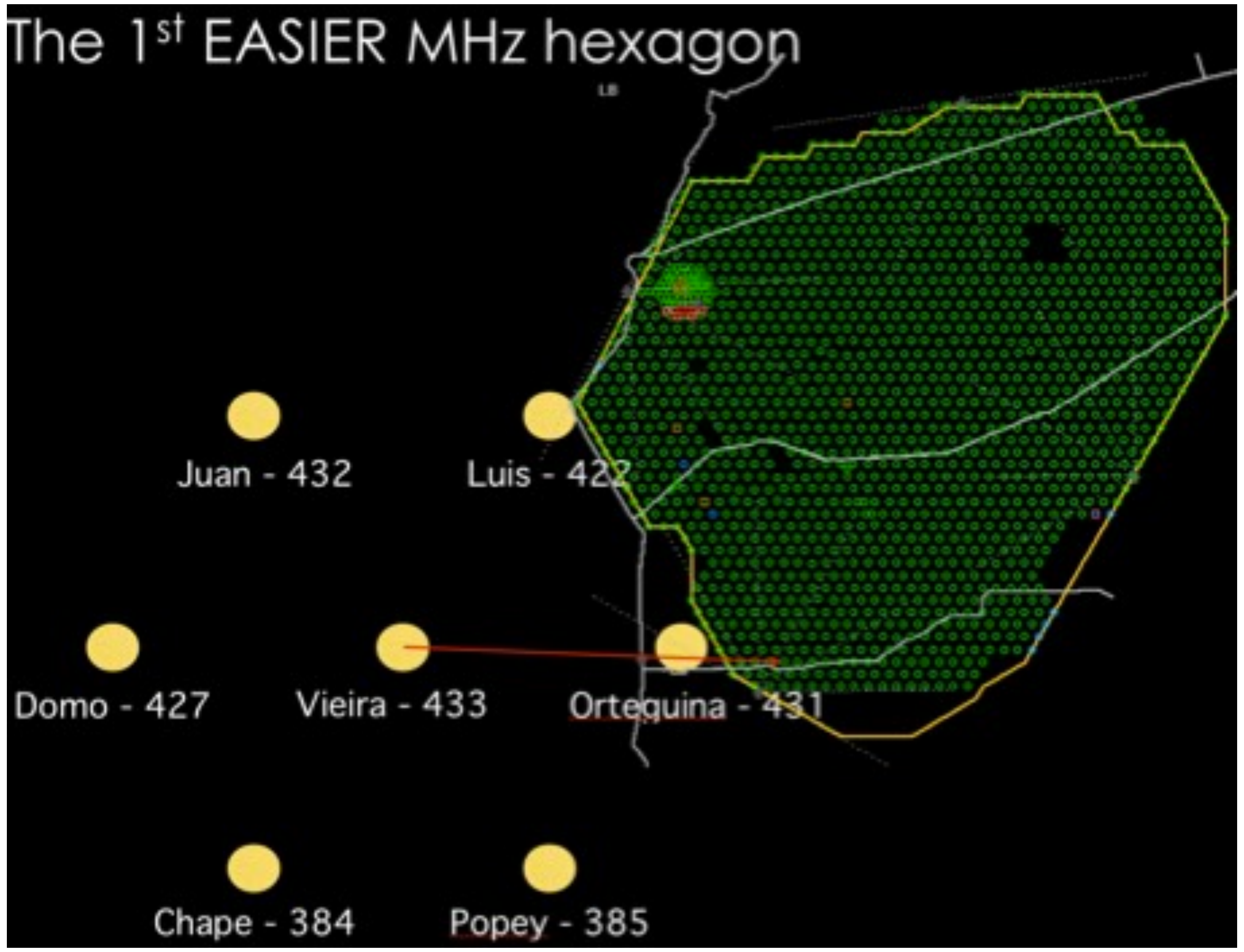


strong anthropic flux
(mainly electric converters), 50 Hz

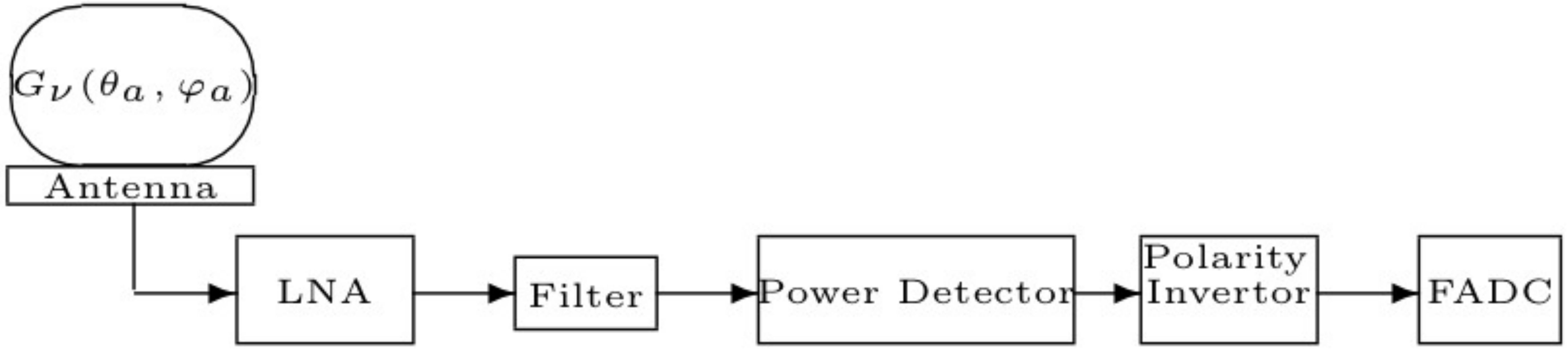
representing **MOST** of our triggers

improvements of local trigger and central trigger lead to ~ 0.1 Hz of really interesting event
(rejection factor > 98%)

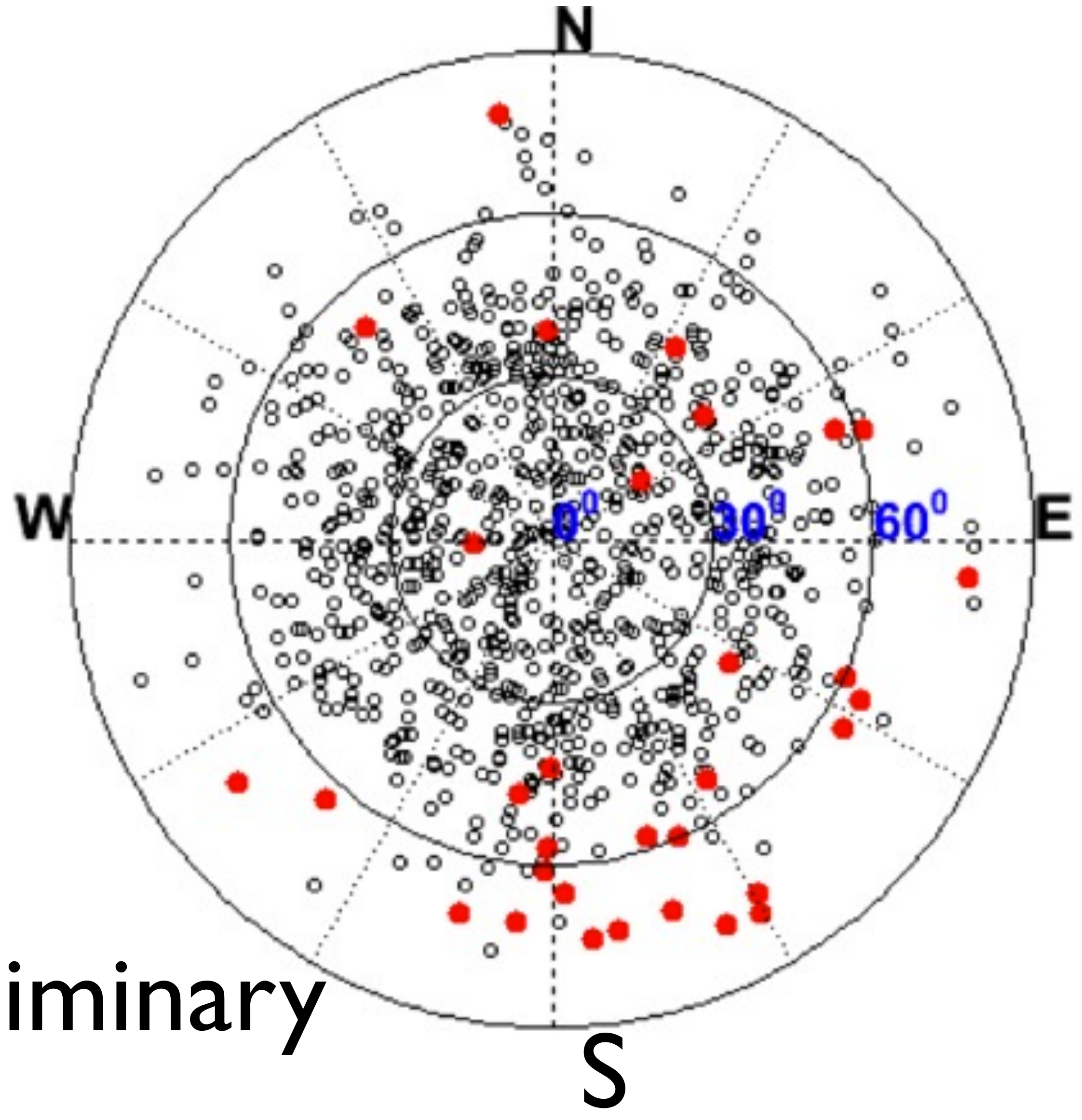
EASIER: MHz at large distance (1.5 km)



uses the CODALEMA dipolar antenna (EW polarization) and the ADC of the tank (sampling at 40 MHz), radio counterpart of a particle signal (no self-trigger)

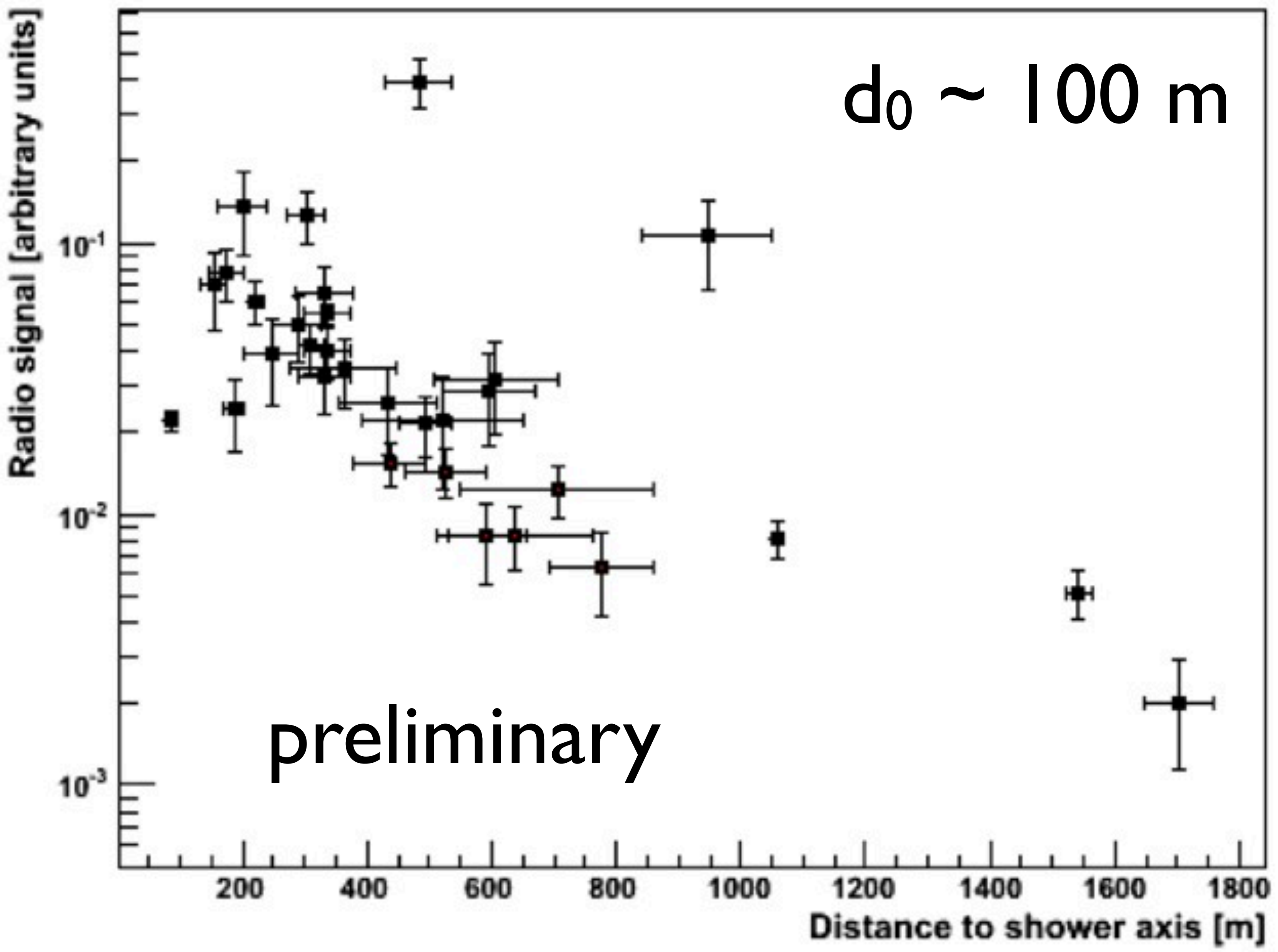


EASIER: MHz at large distance (1.5 km)



preliminary

Geomagnetic effect is observed but strong lobe effect



d_0 ~ 100 m

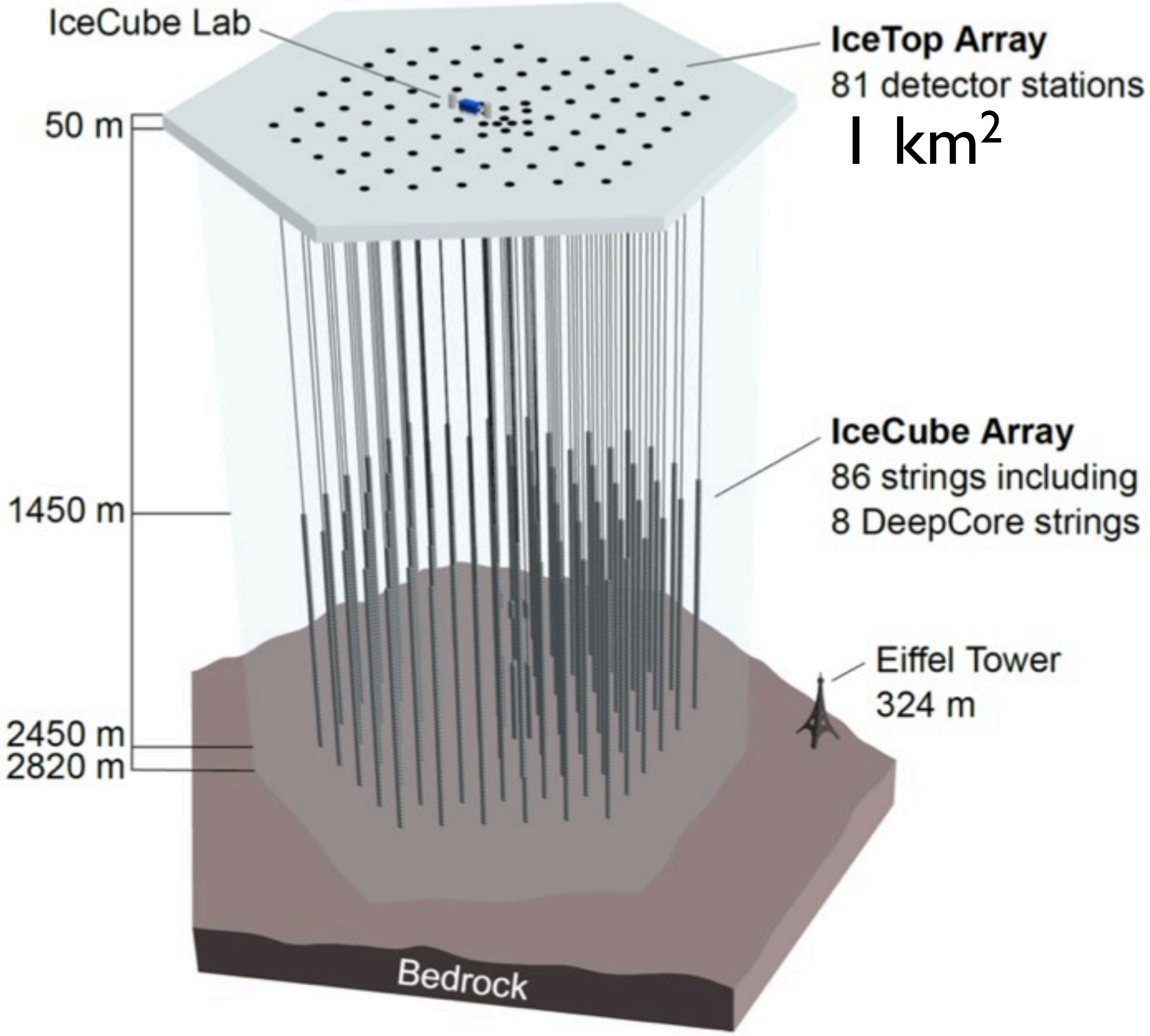
preliminary

$$\varepsilon_0 \propto \exp(-d\cos\theta/d_0)$$

(no axis distance but distance to shower maximum)

Plans for 2012: go for 50 equipped tanks with the CODALEMA butterfly antenna

The RASTA experiment



Additional detector to IceCube and IceTop
IceCube = high energy muons in ice
IceTop = surface detector of the shower
Radio detection of air showers

aim: improve the estimation of the shower composition and improve the neutrino sensitivity (better veto)

~ 1000 antennas centered on IceTop and covering ~ 10 km^2

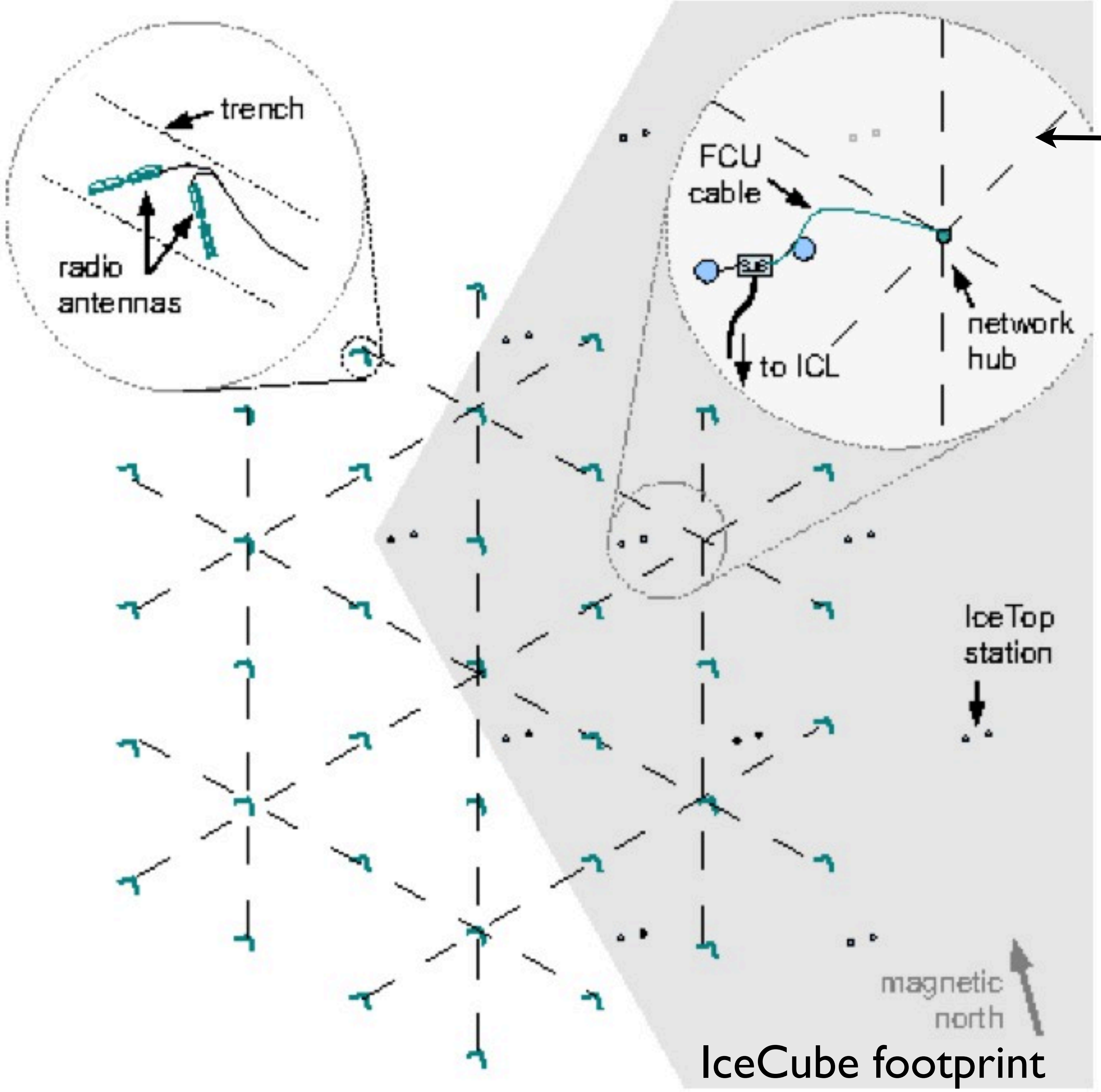
range: 10^{16} eV - ankle
zenith angle up to 60°
LOPES-like: **interferometric** radio array

The RASTA experiment

DuVernois, ICRC 2011

Antennas are in orthogonally polarized pairs

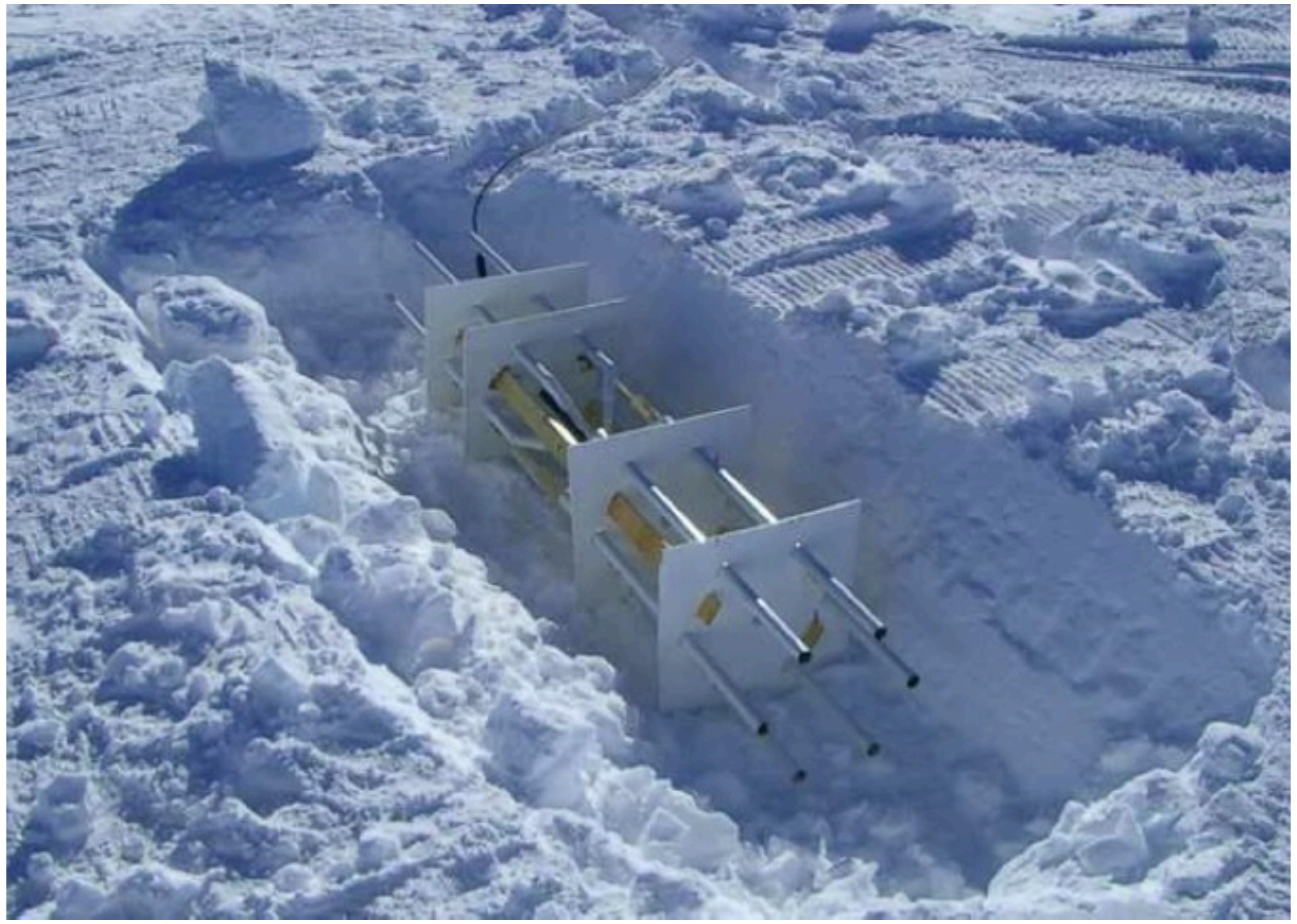
Possible RASTA configuration



IceCube footprint

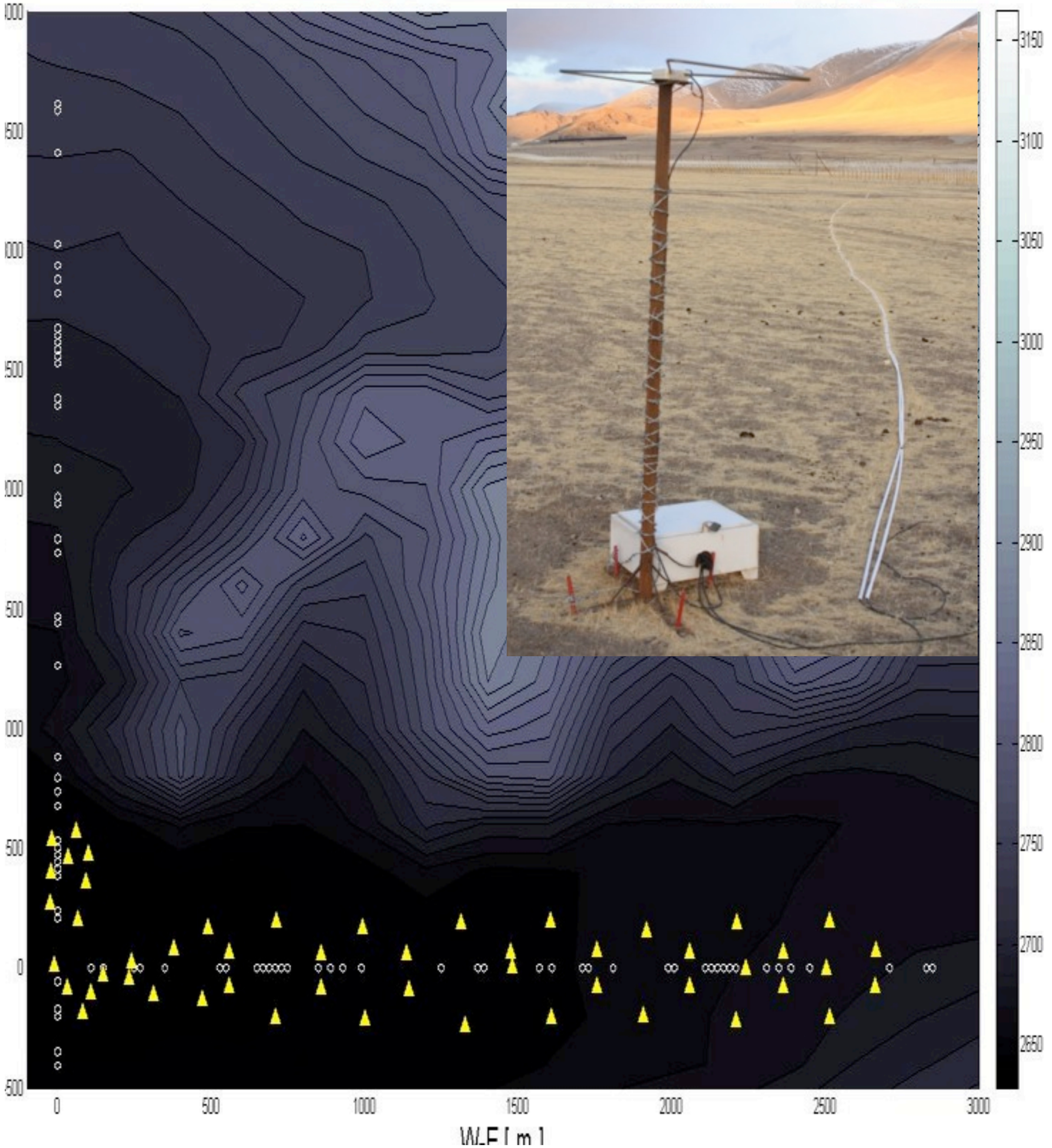
data/power line

AskaryanRadioArray fat wire dipole 25-160 MHz (used for tagging EAS events)



The TREND experiment

Martineau-Huynh, ICGAC 2011



2011: extension to 50 butterfly antennas from CODALEMA to reach 1.5 km^2

EAS candidate: $\Theta = 63°$, $\phi = 7°$, $\lambda = 241$ m