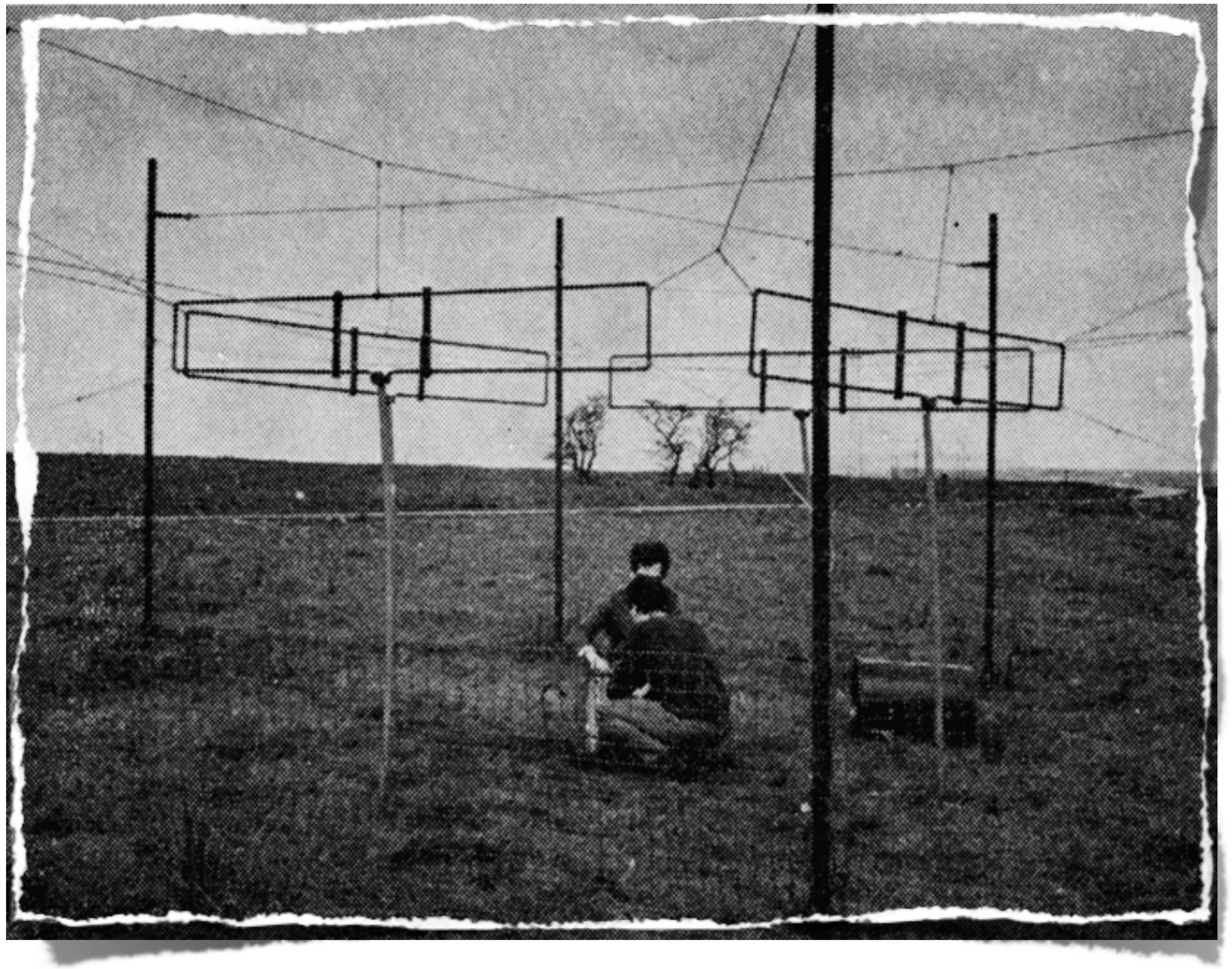
HE cosmic rays (ground-based) experiments in the MHz domain

Radio Simulations for Neutrino and Cosmic Ray Detectors, OSU, Feb 2012

Radio detection: back to the 60s

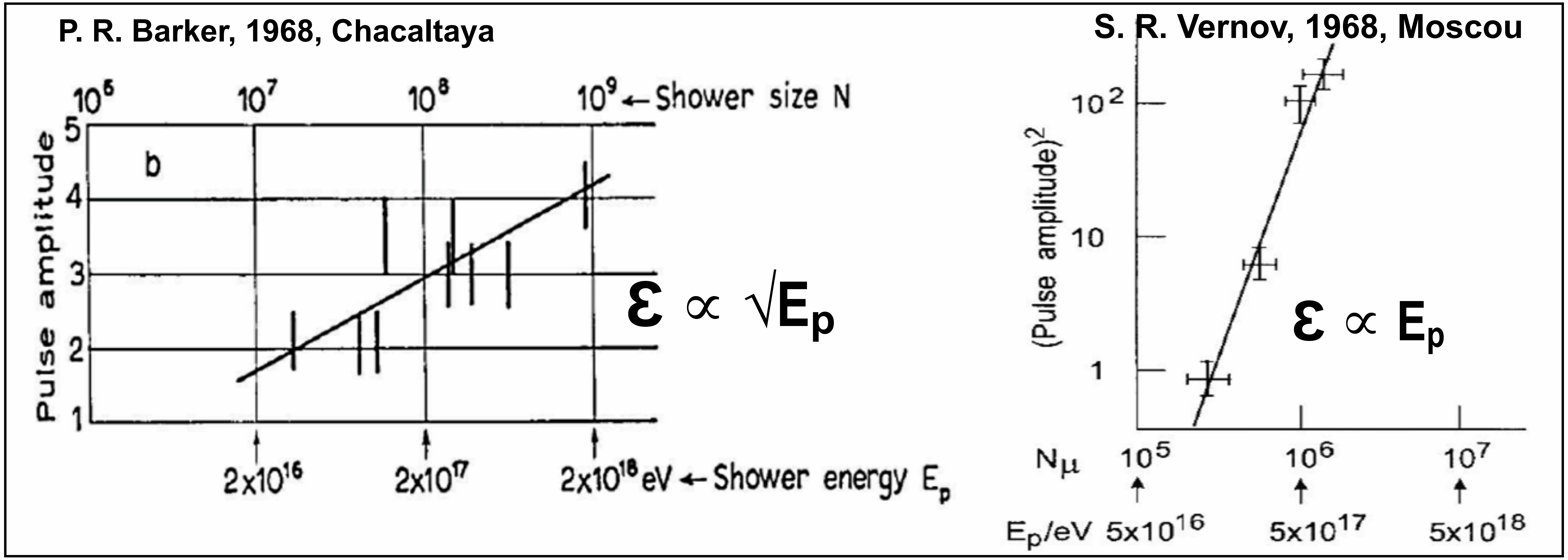
Jodrell Bank 1964



Haverah Park 1968

Radio detection: back to the 60s

- 1962: Askaryan, theory, Cerenkov in radio, electric field from charge-excess
- 1964-65: Kahn & Lerche, theory, geomagnetic contribution should be dominant
- 1964-65: Jelley et al, first experiments in the MHz range
- 1968: unclear situation: coherence? incoherence?

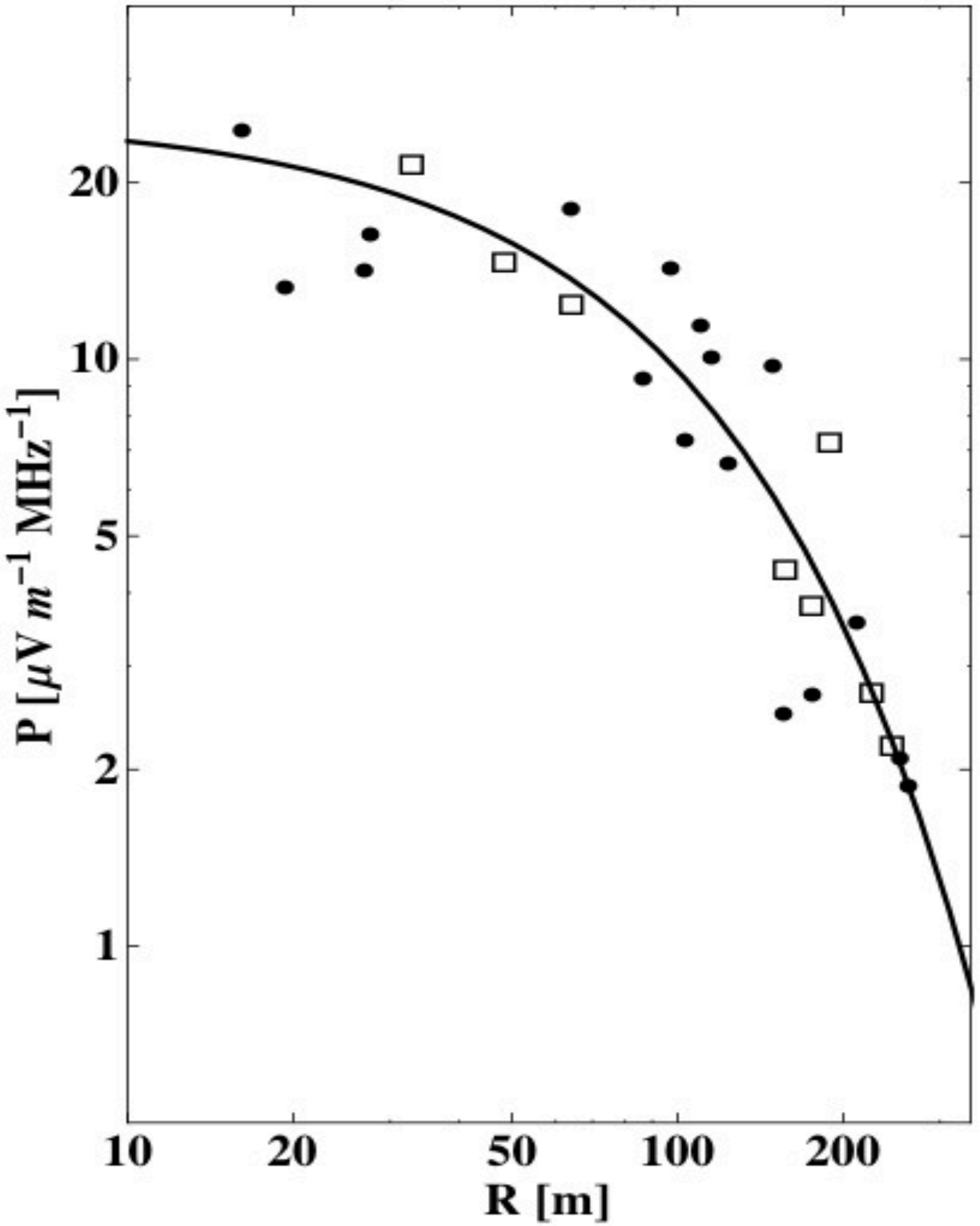

P. R. Barker, 1968, Chacaltaya

$\varepsilon \propto \sqrt{E_p}$

S. R. Vernov, 1968, Moscou

$\varepsilon \propto E_p$

Radio detection: back to the 60s



- "finally", synthesis in1971 by Allan electric field strength with axis distance:

$$\xi_\nu = 20\frac{E_p}{10^{17}}\sin(\alpha)\cos(\theta)\exp(-\frac{R}{R_0(\nu,\theta)}) \quad \mu\mathrm{V.m^{-1}.MHz^{-1}}$$

- 1975: radio data interpretation not easy + DAQ limitations ➝ people prefer conventional techniques, no more advances in radio until ~2000

Radio detection since 2000

- 2000: re-investigation of radio in dense media (ice, salt) for neutrinos detection (in sand, D. Saltzberg)
- 2000: setup on CASA-MIA and EAS-TOP: no detection
- 2003: first modern experiments CODALEMA (Nançay radio observatory, France) & LOPES (Karlsruhe, Germany)
- since 2003: theoretical developments (microscopic, macroscopic descriptions) leading to several simulation codes
- since 2006: new experiments, mainly in an autonomous mode

Electric field

(description adopted in SELFAS)

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

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 the magnetic field

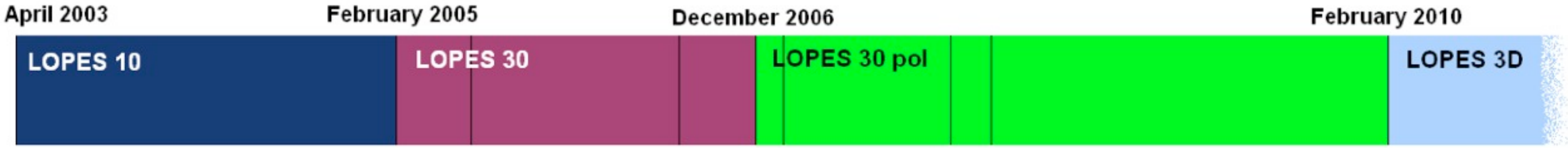
Signal correlated to the complete shower development !

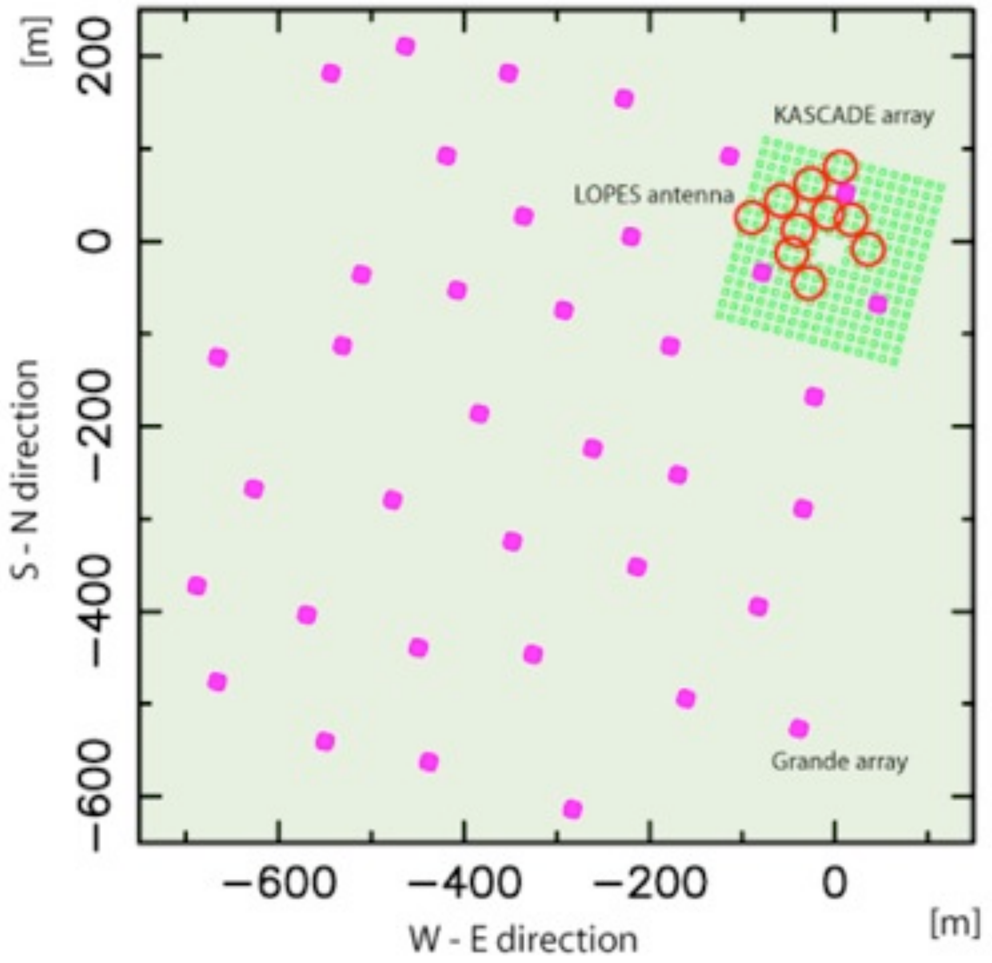
(some) Modern radio experiments

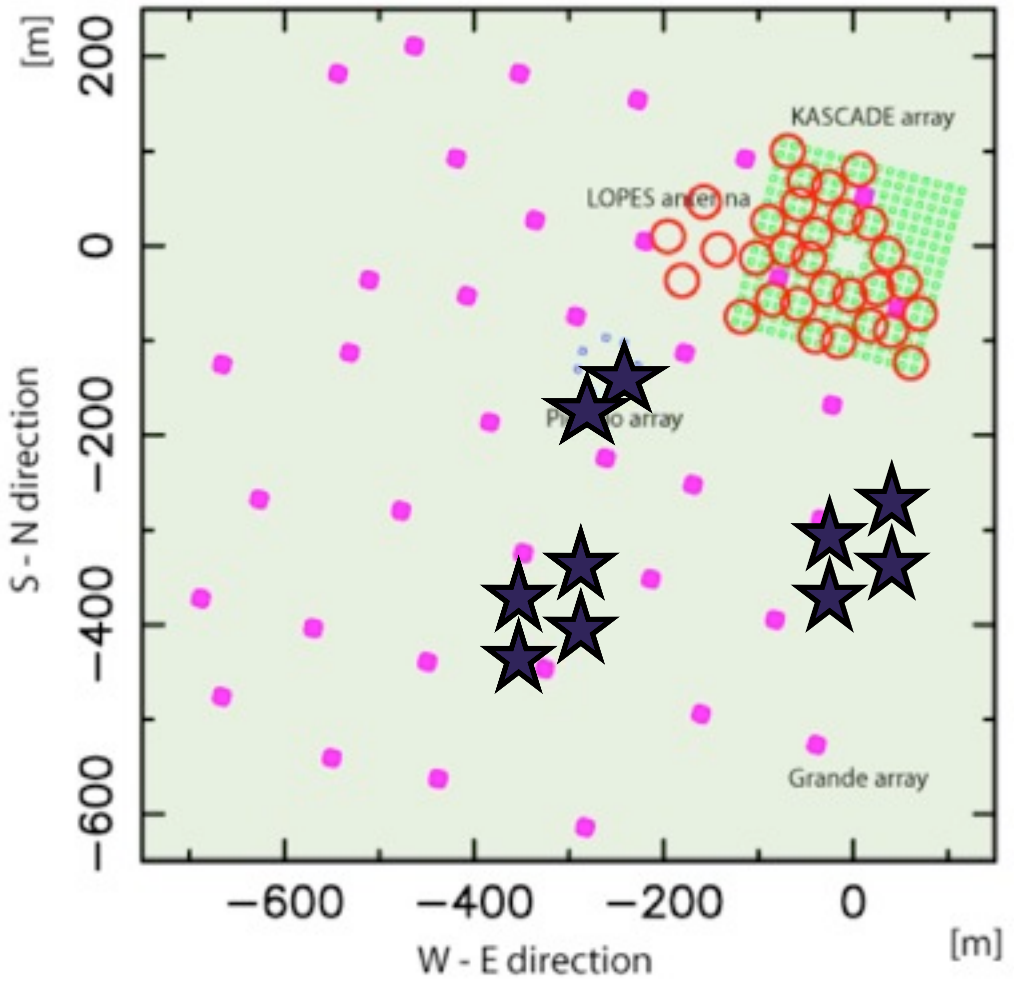
- LOPES
- CODALEMA
- TREND
- Radio-detection in Argentina
  - pre-AERA setups
    - RAuger
    - MAXIMA
  - AERA
  - EASIER
- the RASTA project

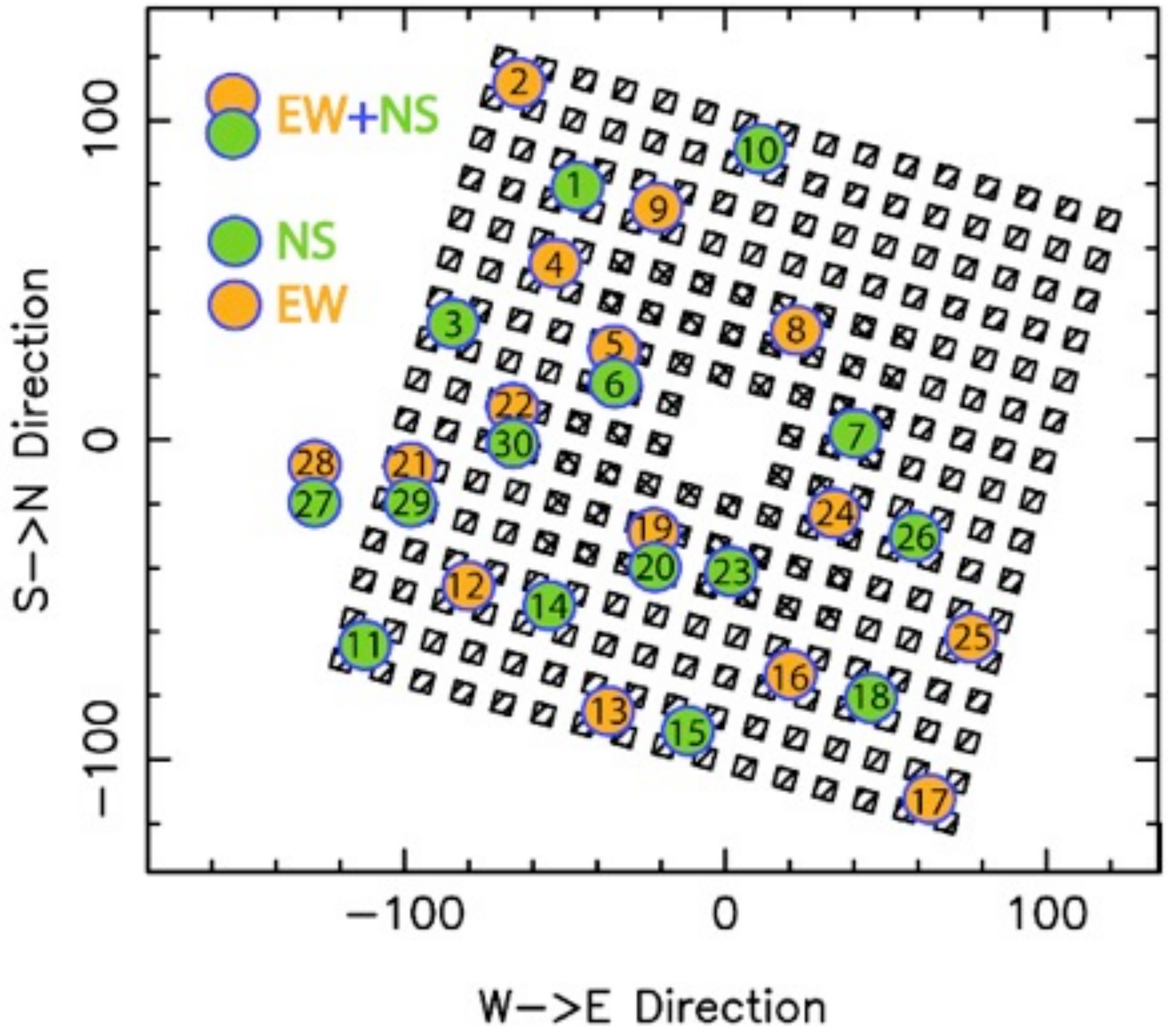
The LOPES experiment

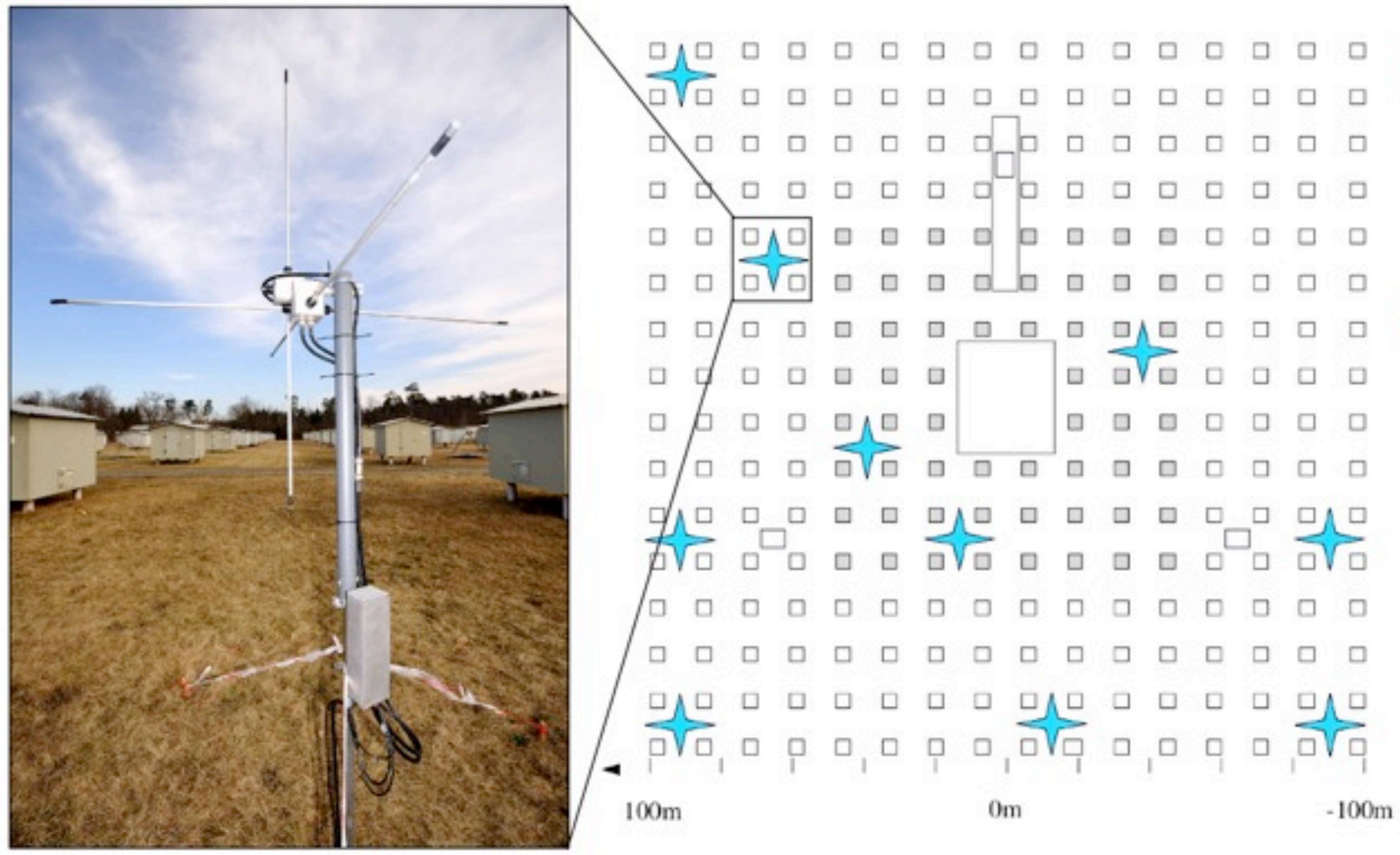
- triggered by the KASCADE experiments
- energy range $10^{16.8}$-10^{18} eV
- shower geometry from KASCADE
- interferometry mode (phased array)
- detailed characteristics also provided (N_e, N_μ, ...)
- radio-noisy environment: low sampling frequency 80 MHz



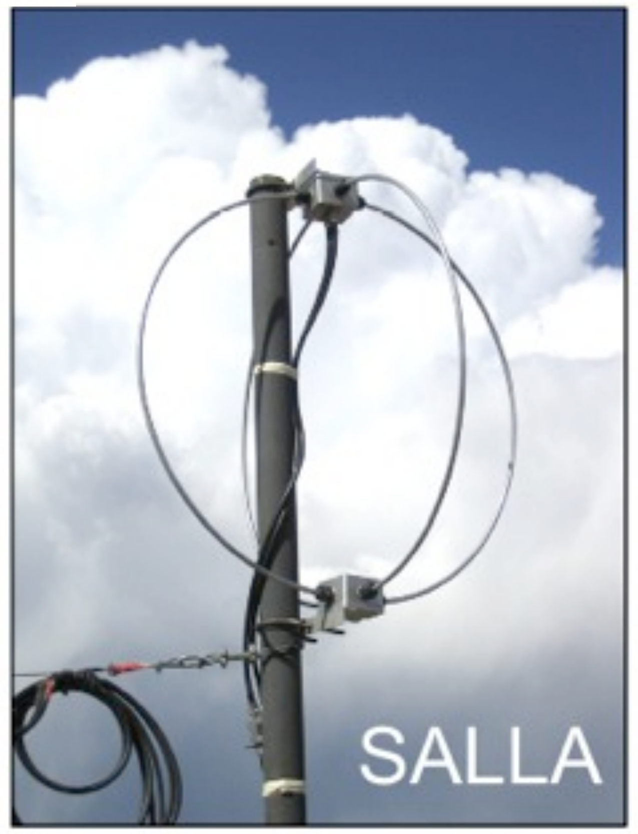






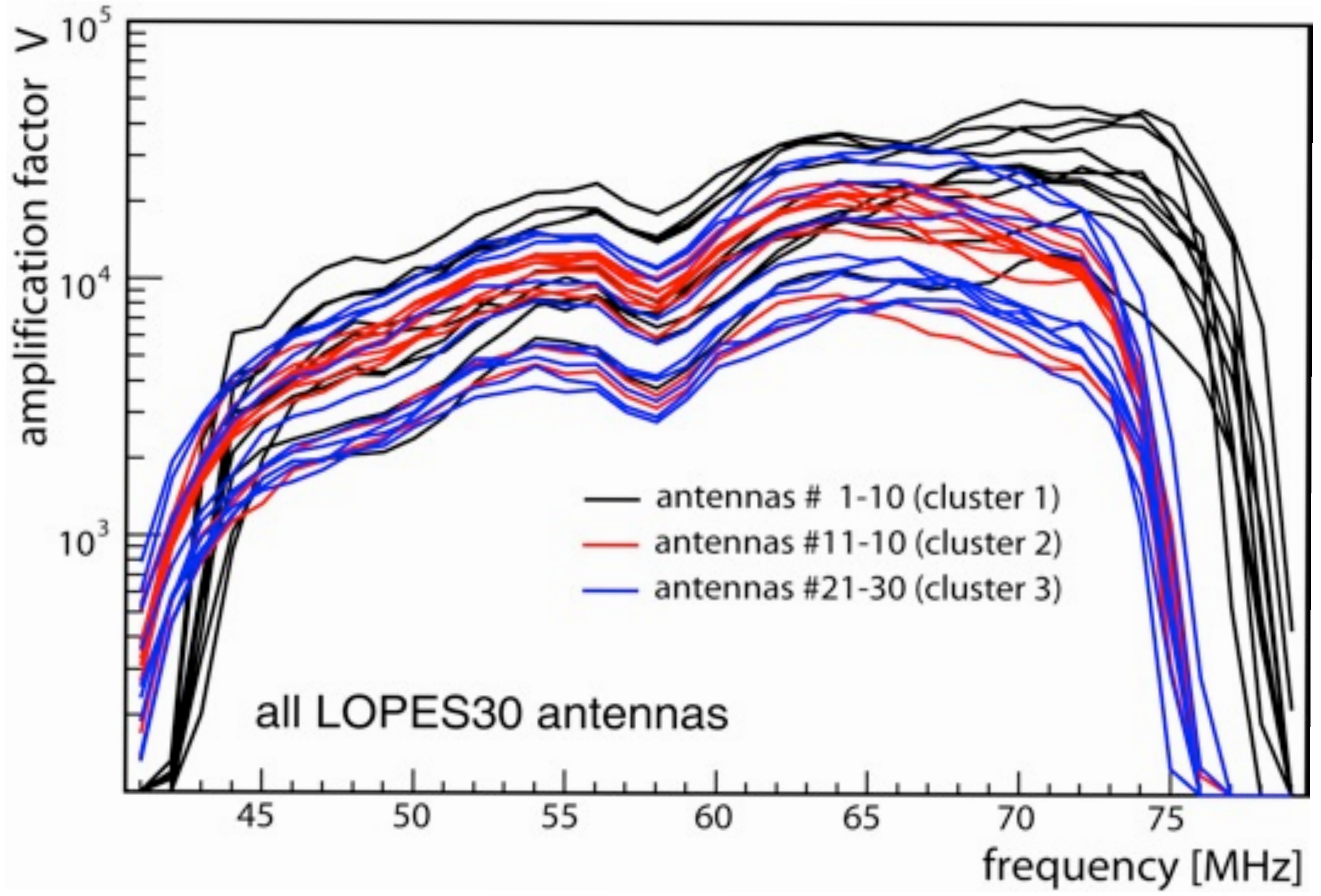


- 10 tripole antennas (NS, EW, vertical)
- kept readout from LOPES

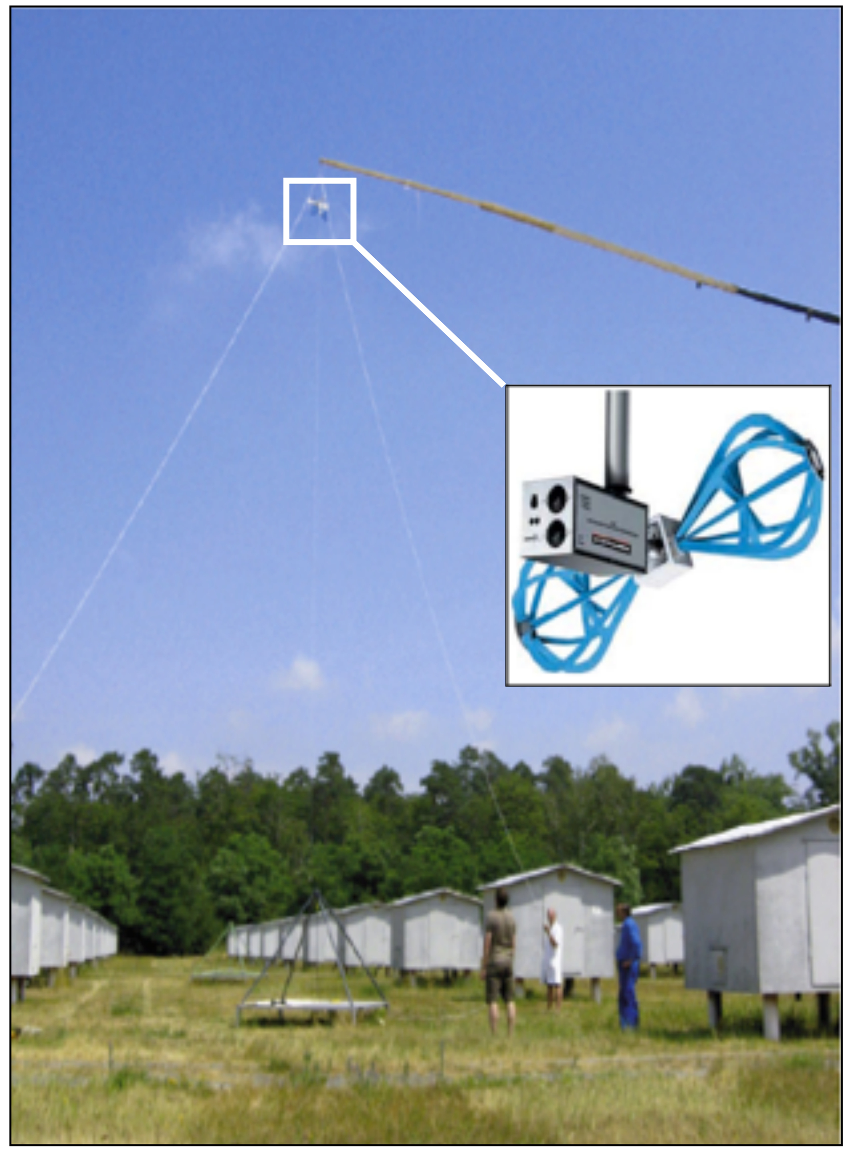


The LOPES experiment

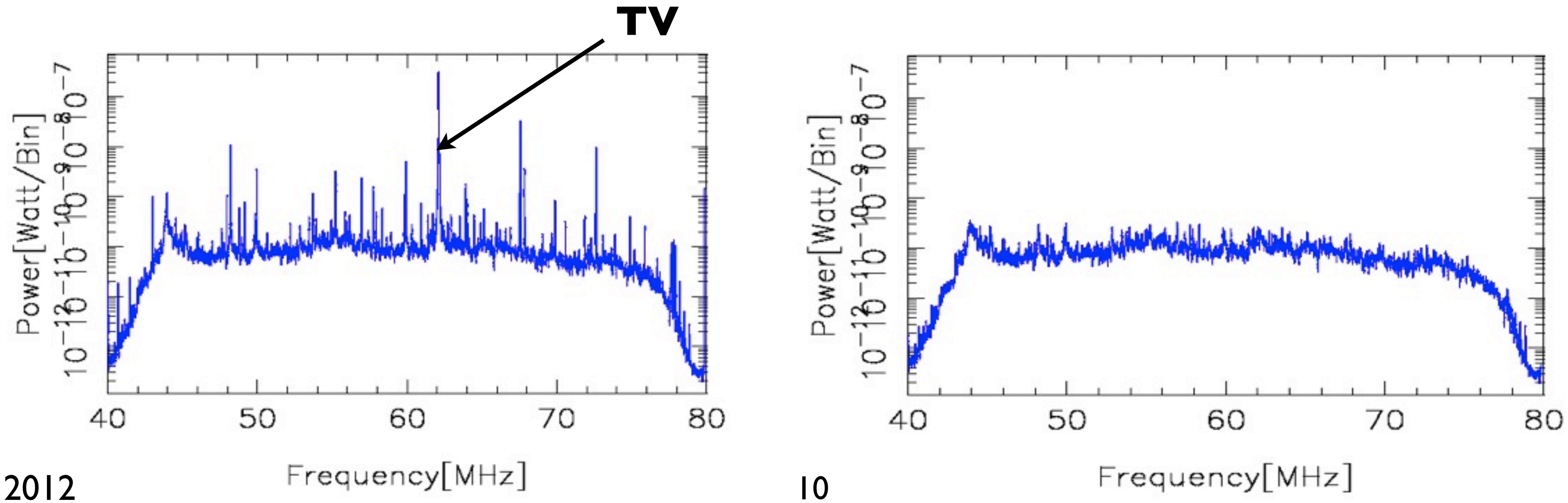
I. Amplitude calibration



systematic error of
~ 20%



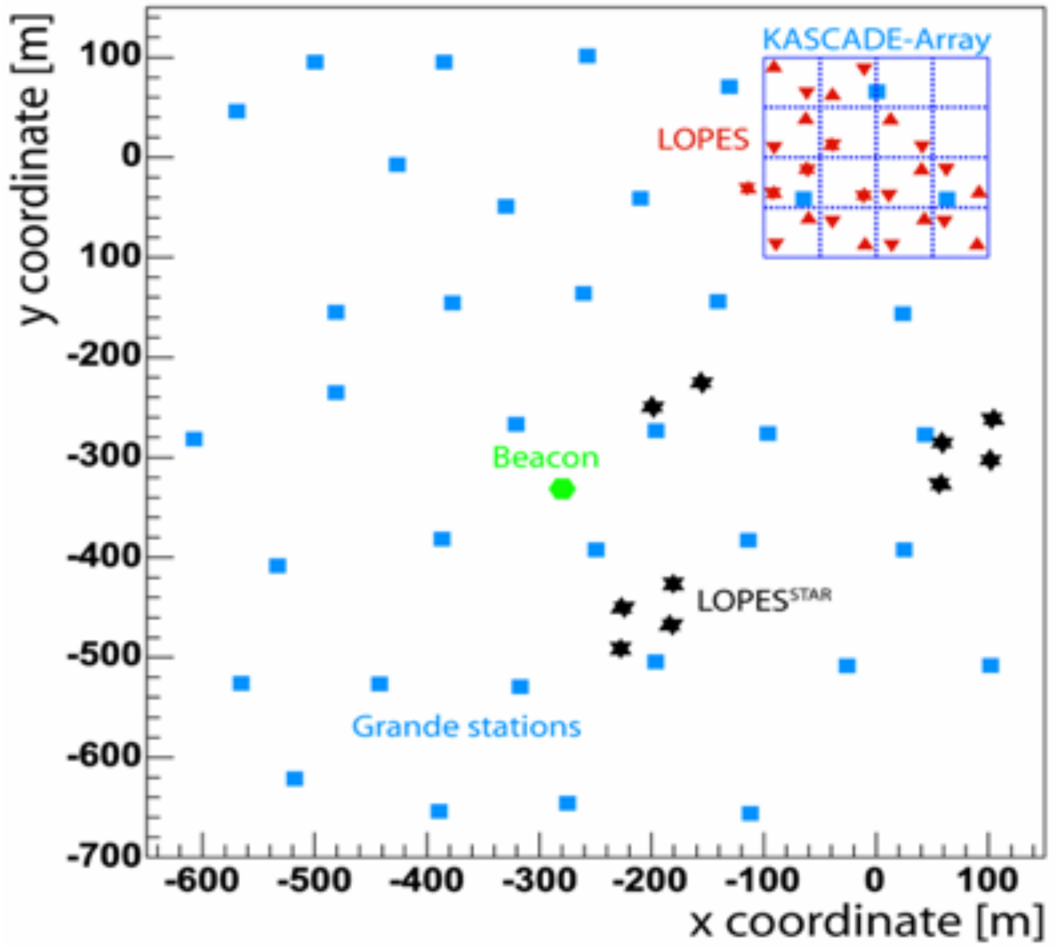
II. Digital filtering of narrow-band RFI



The LOPES experiment

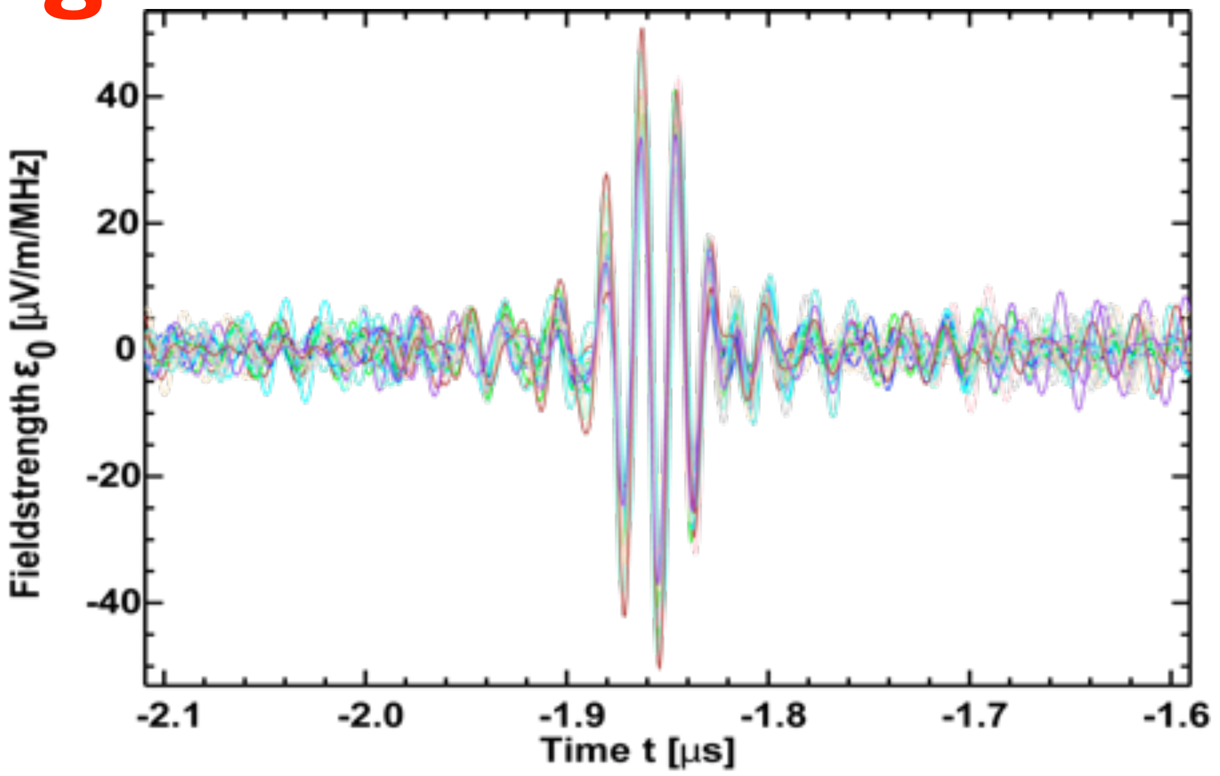
III. Time calibration

Use TV transmitter (LOPES10) and beacon (LOPES30)
with the beacon, a time resolution of ~ 1 ns is acheived



IV. Digital beam-forming

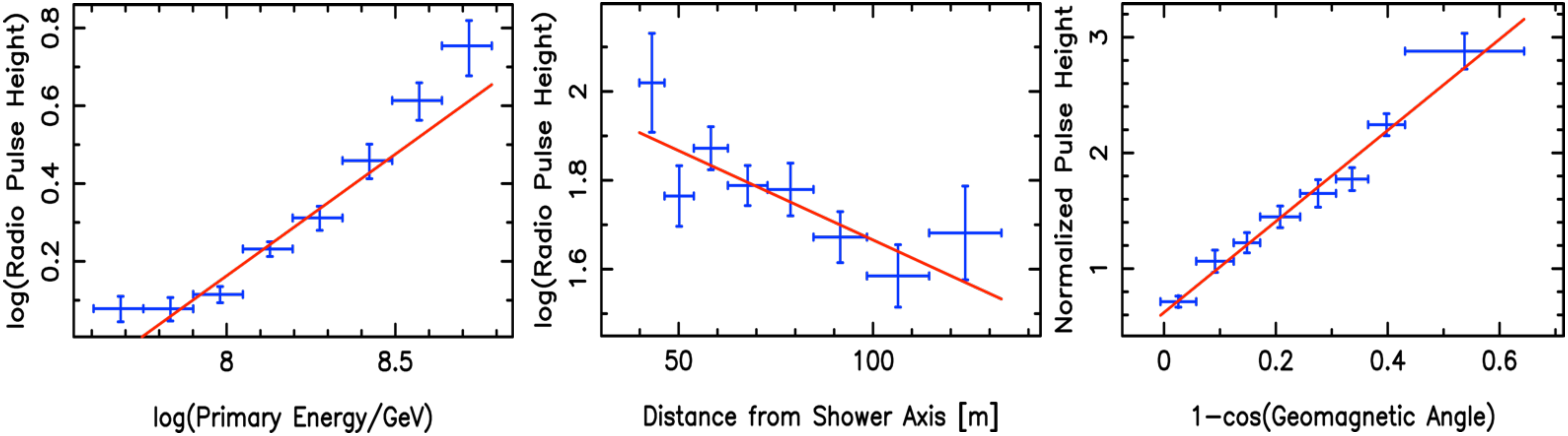
From the shower geometry (KASCADE),
compute the expected arrival time in the antennas and
“synchronize radio data” (criteria: maximum correlation)



The LOPES experiment

Horneffer, ICRC 2007

Main LOPES results



$$\varepsilon_{\mathrm{EW}} = A\ (1 + B - \cos\alpha)\ \cos\theta\ \exp\left(-\frac{R}{R_0}\right)\ \left(\frac{E}{10^{17}\ \mathrm{eV}}\right)^{\gamma}\ \mu\mathrm{V/m/MHz}$$

$$A = 10.9 \pm 1.1$$

$$B = 1.16 \pm 0.02$$

$$R_0 = 202 \pm 64\ \mathrm{m}$$

$$\gamma = 0.94 \pm 0.03$$

The LOPES experiment

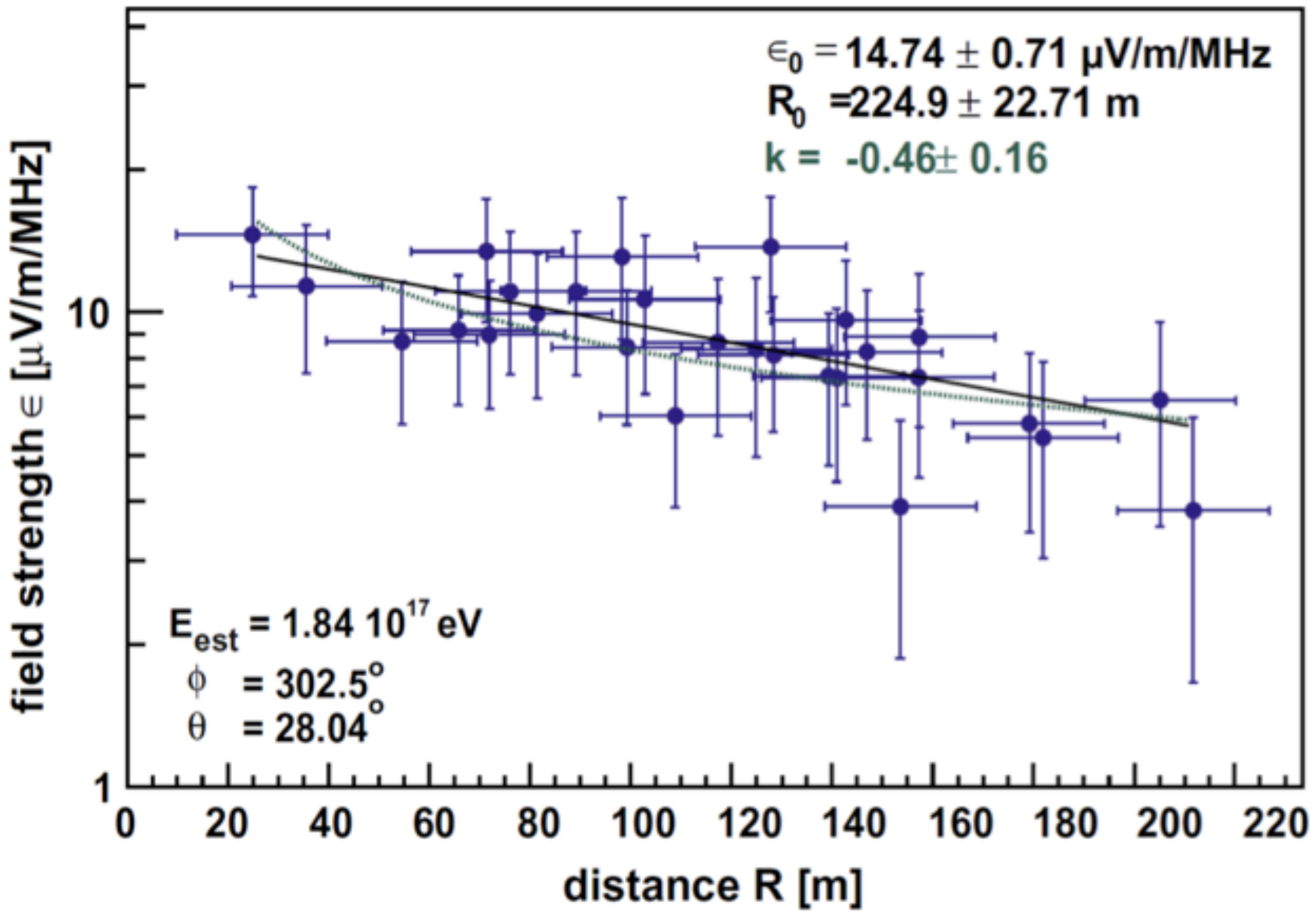
Apel et al, APP 2010

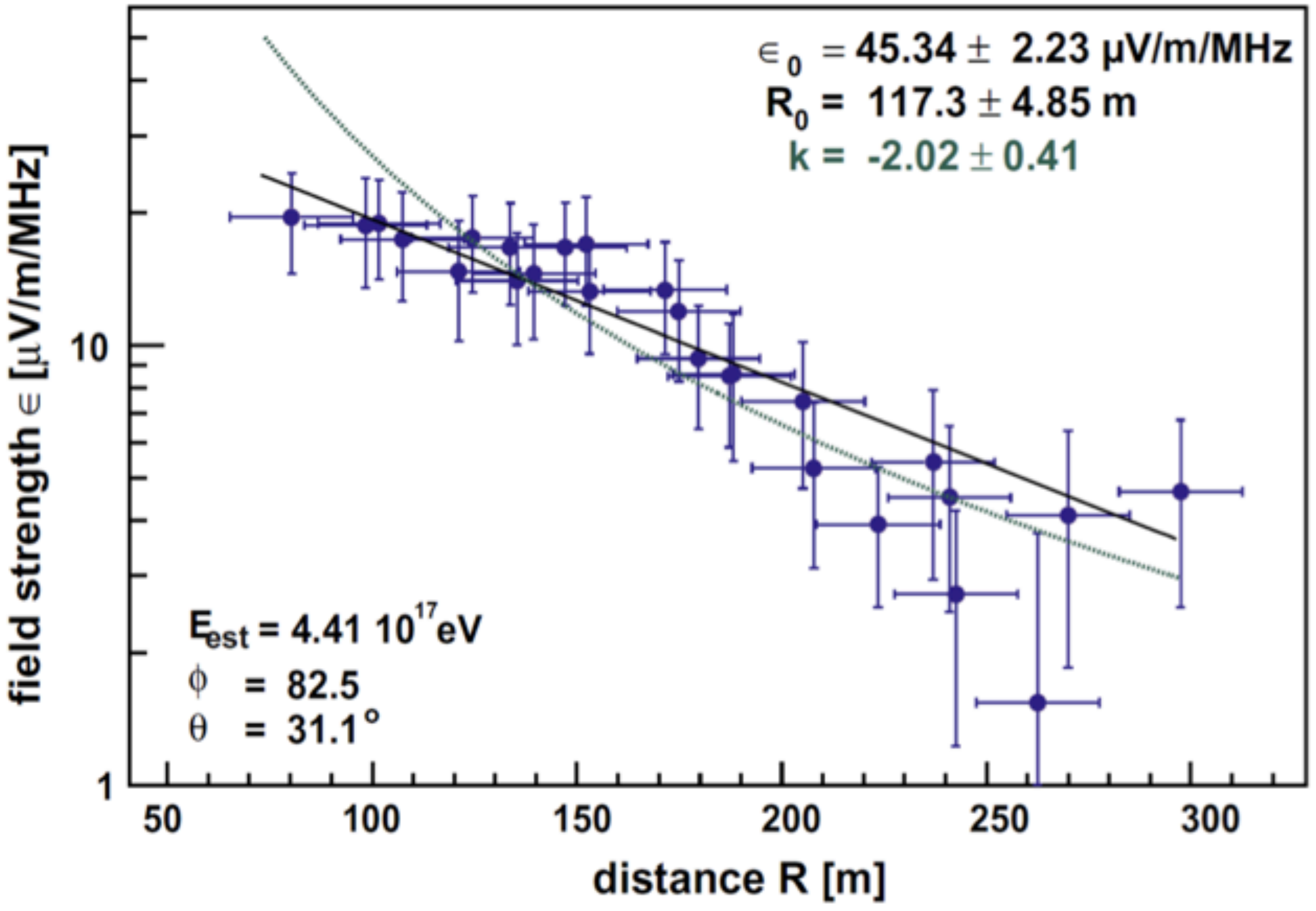
Main LOPES results

Electric field profile

~80% of the events have a good exponential profile

~20% of them are flat for antennas close to the shower axis



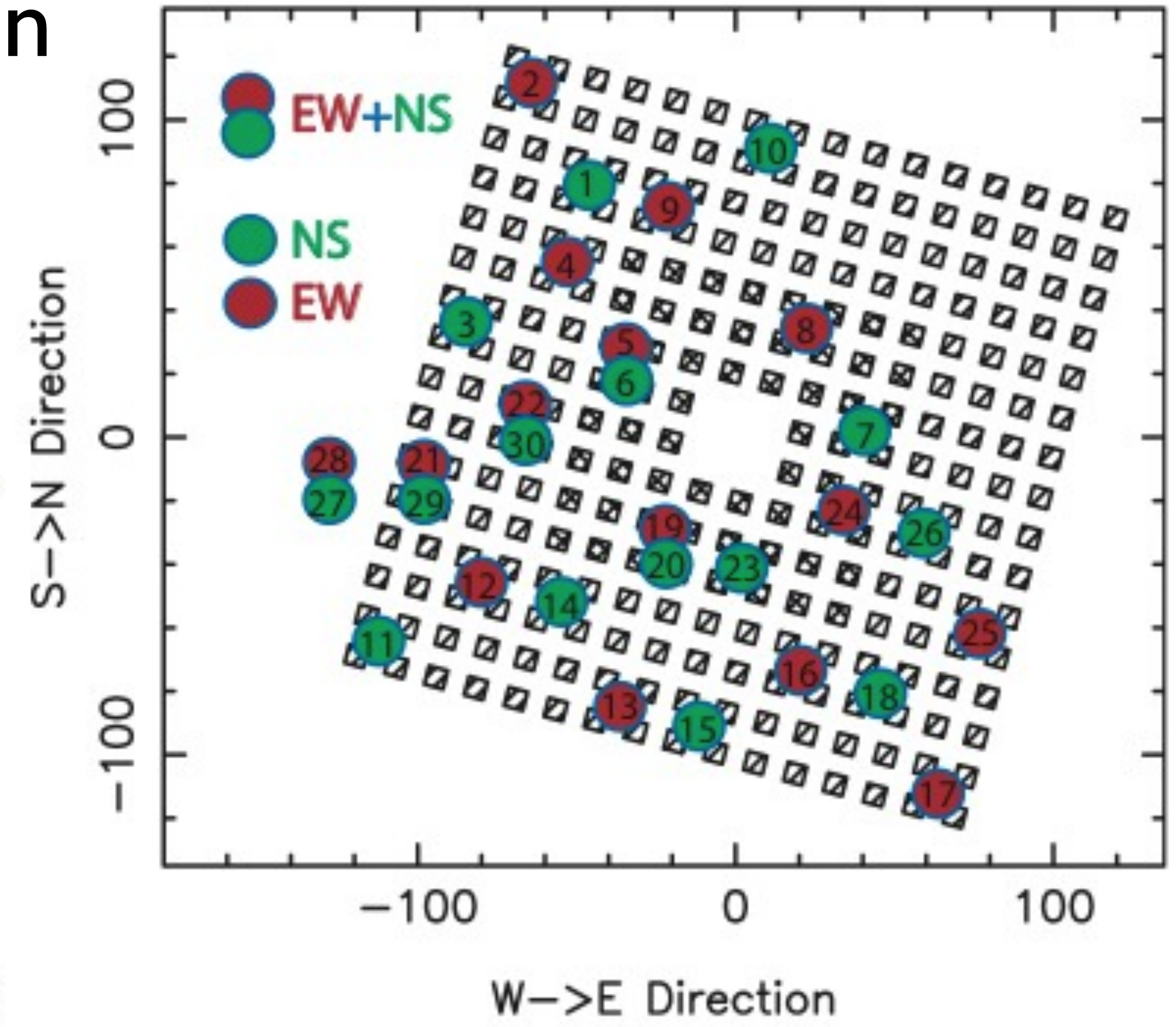


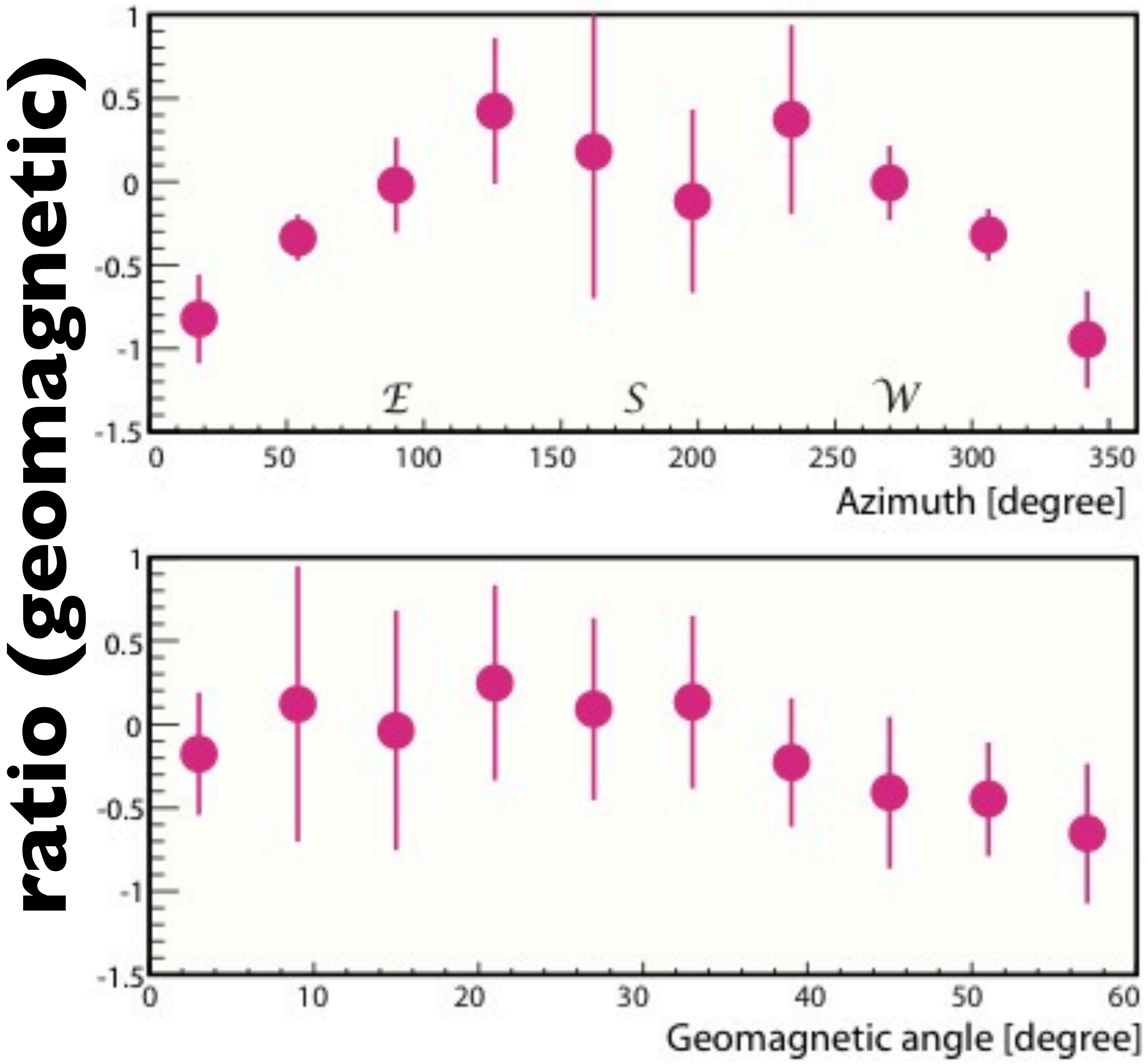
The LOPES experiment

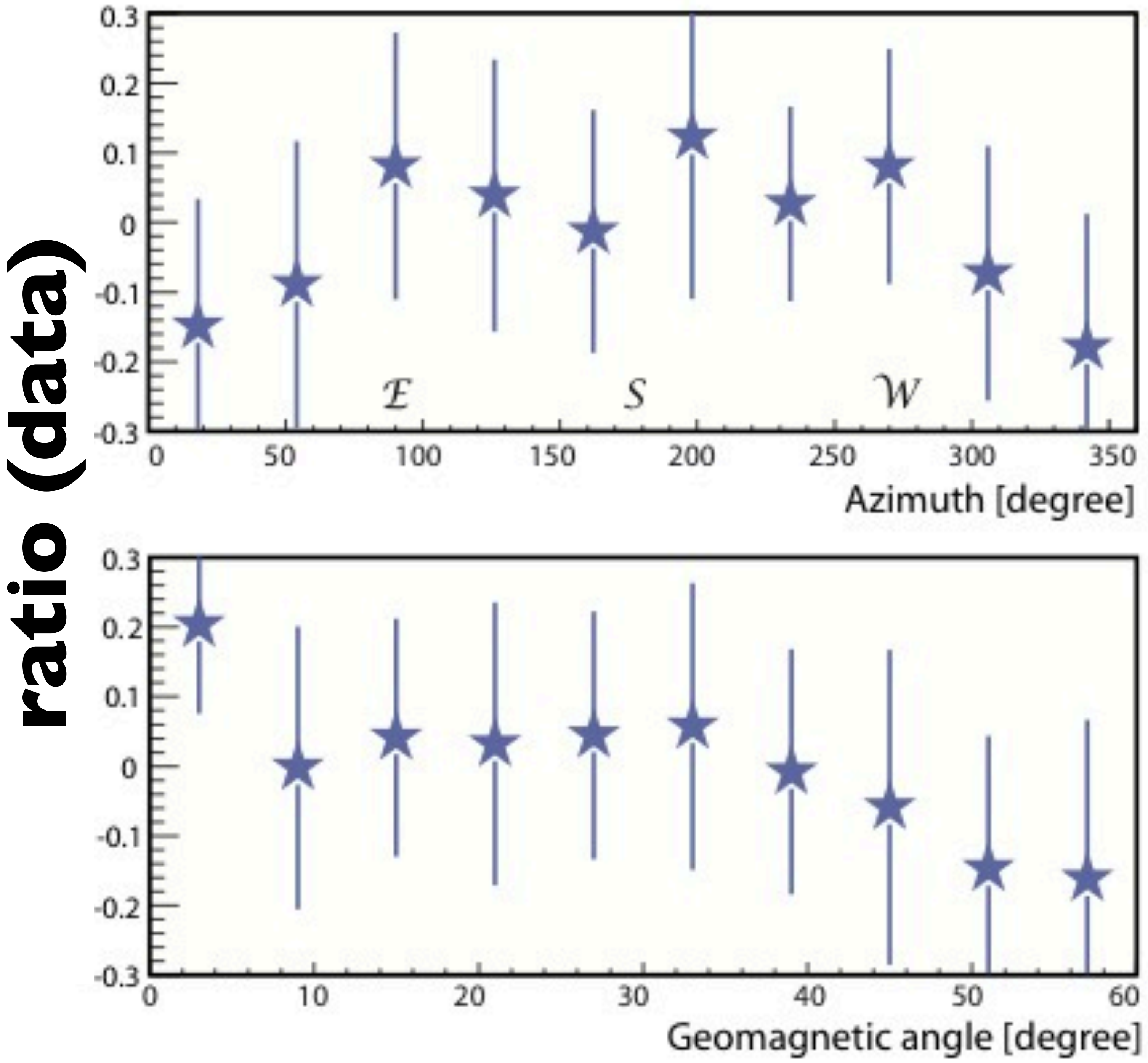
Isar et al, ICRC 2009

Main LOPES 30 Pol results

15 antennas measure the EW polarization
15 antennas measure the NS polarization
5 antennas measure both EW and NS



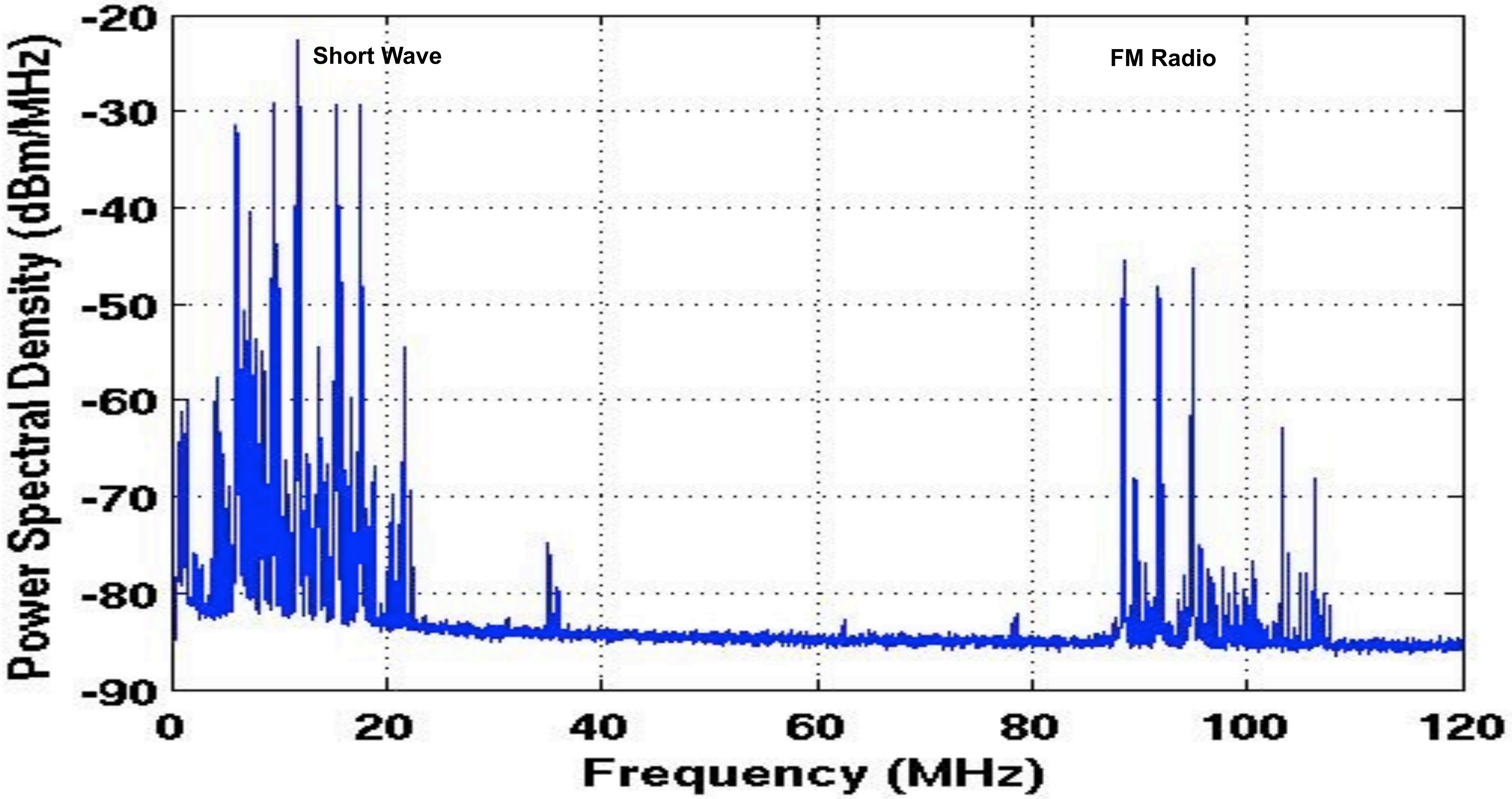


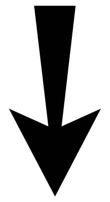


data in good agreement
with v X B at first order

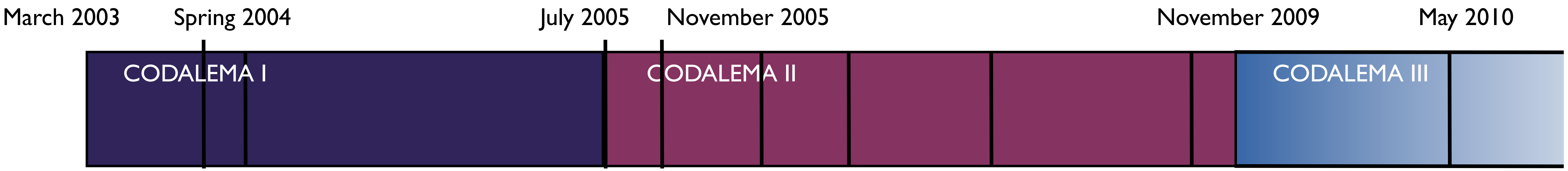
The CODALEMA experiment

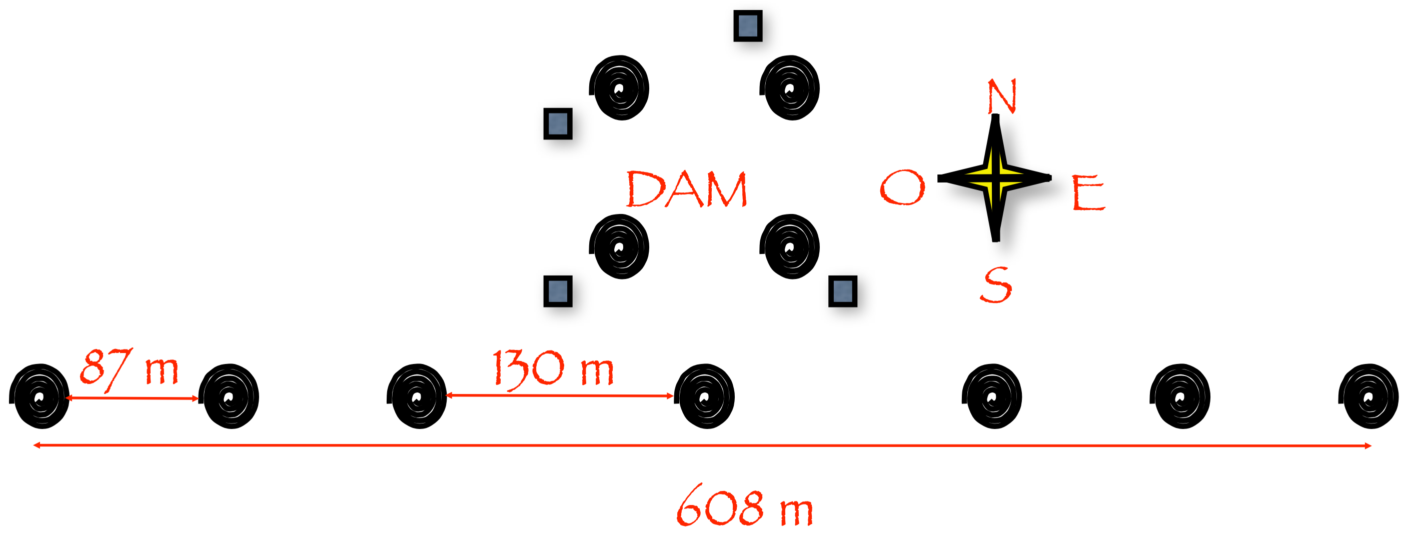
The site in Nançay is radio-quiet:
protected aera dedicated to radio-astronomy

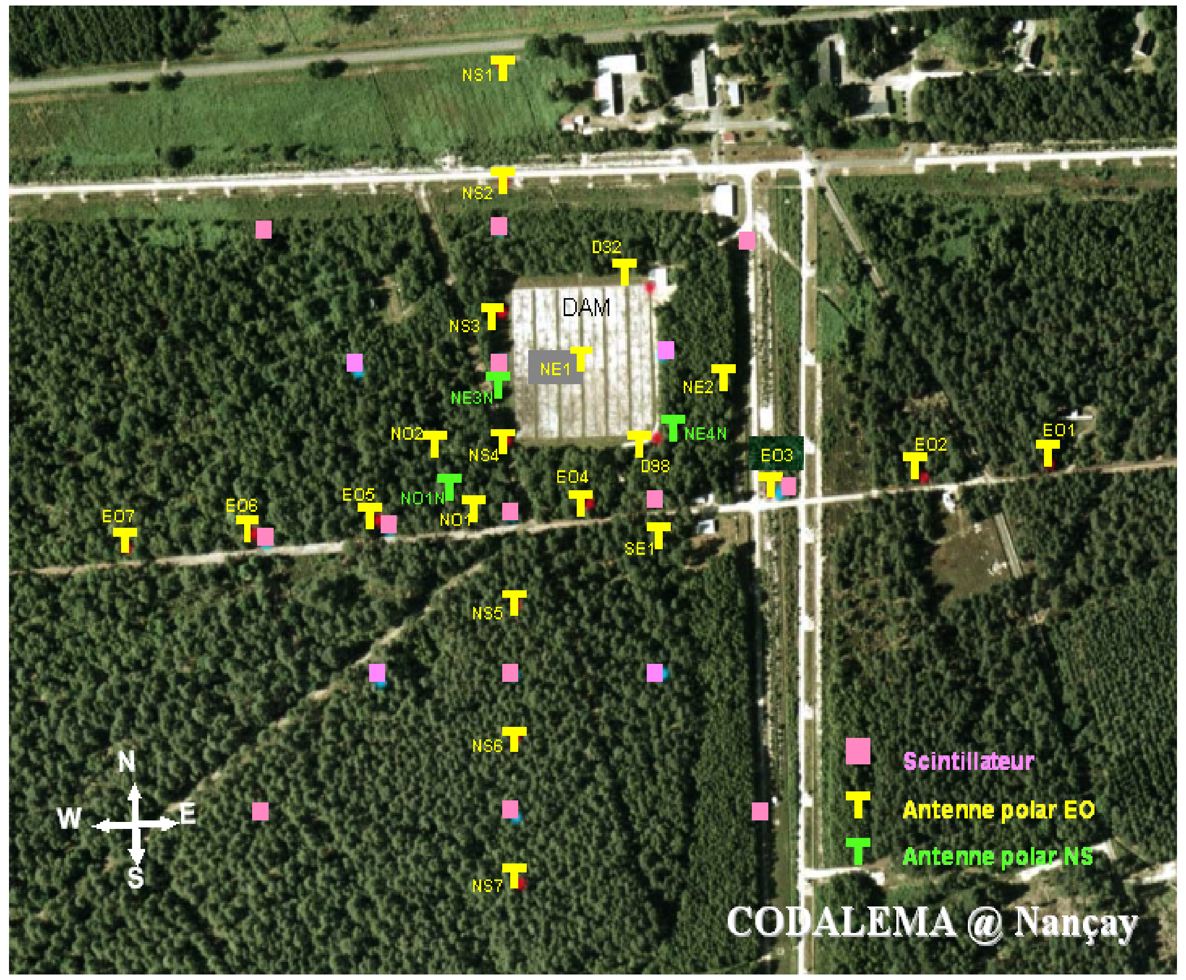


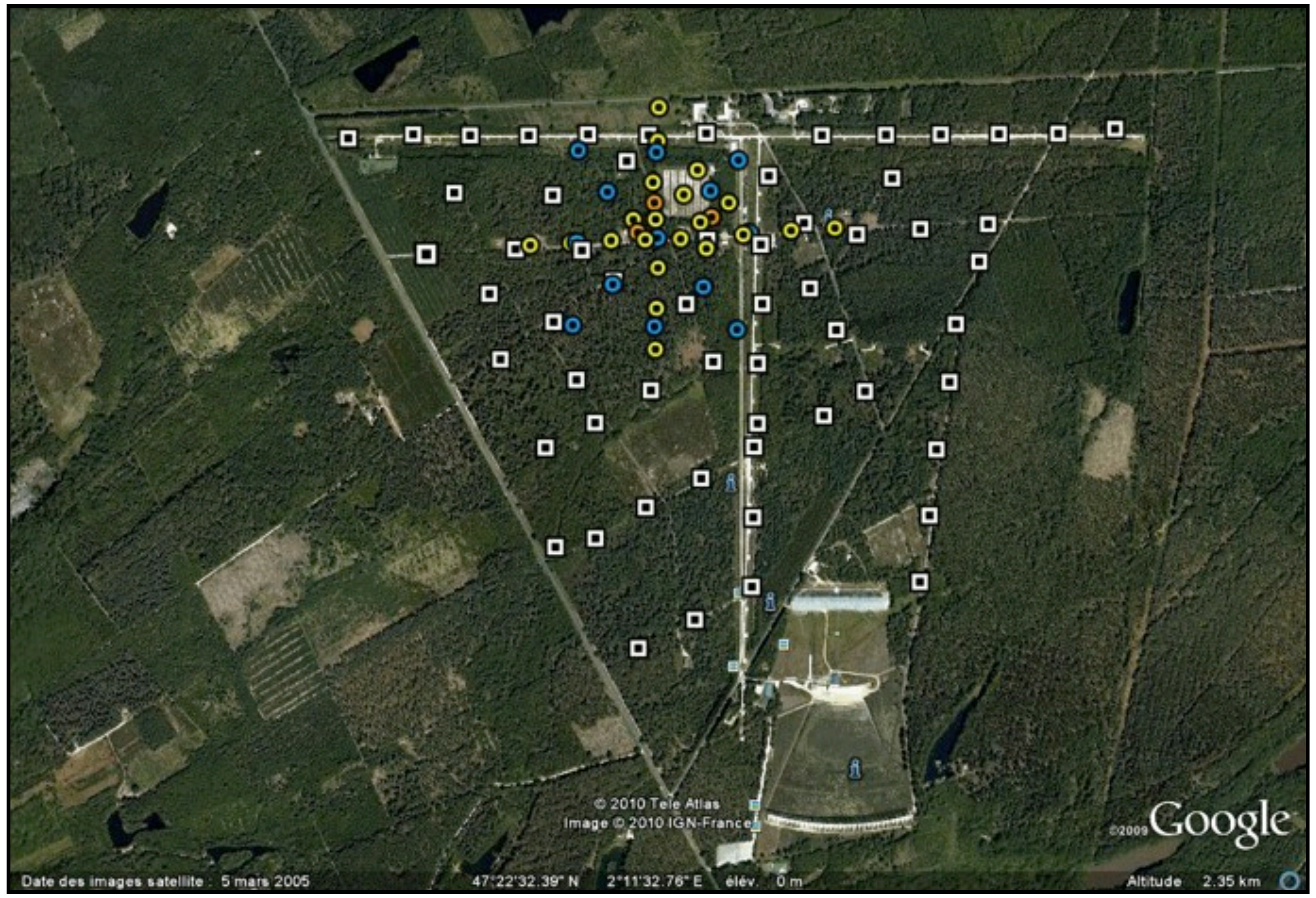


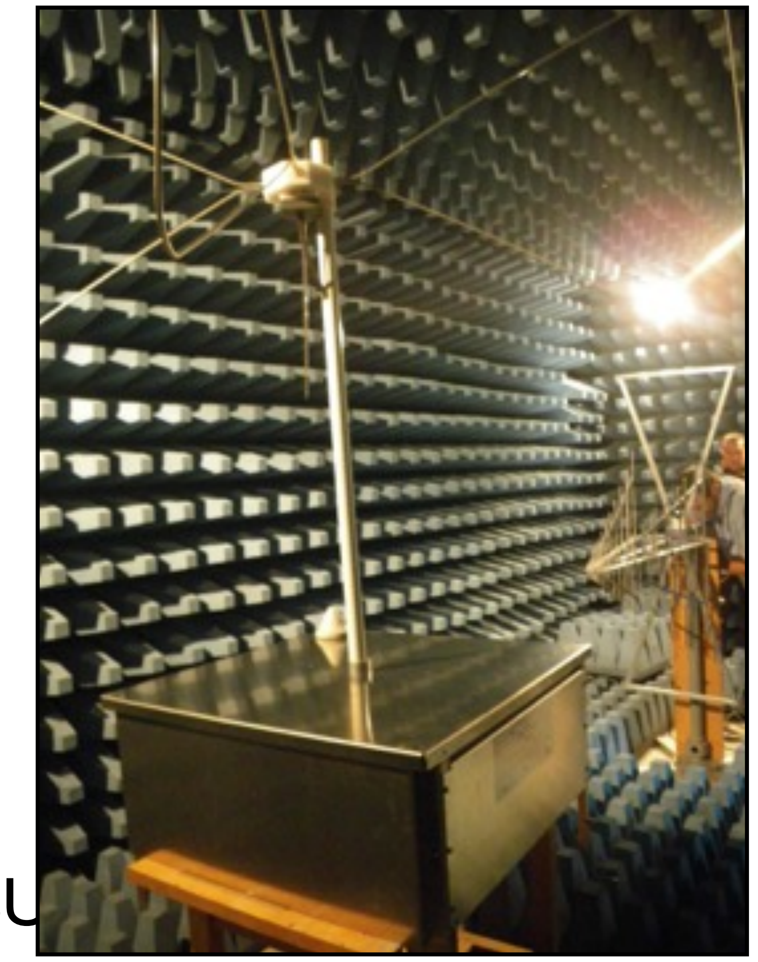
High sampling frequency 1 GHz
Possible to use data up to ~ 250 MHz
use a particle detector to trigger the radio array


March 2003
Spring 2004
July 2005
November 2005
November 2009
May 2010
CODALEMA I
CODALEMA II
CODALEMA III

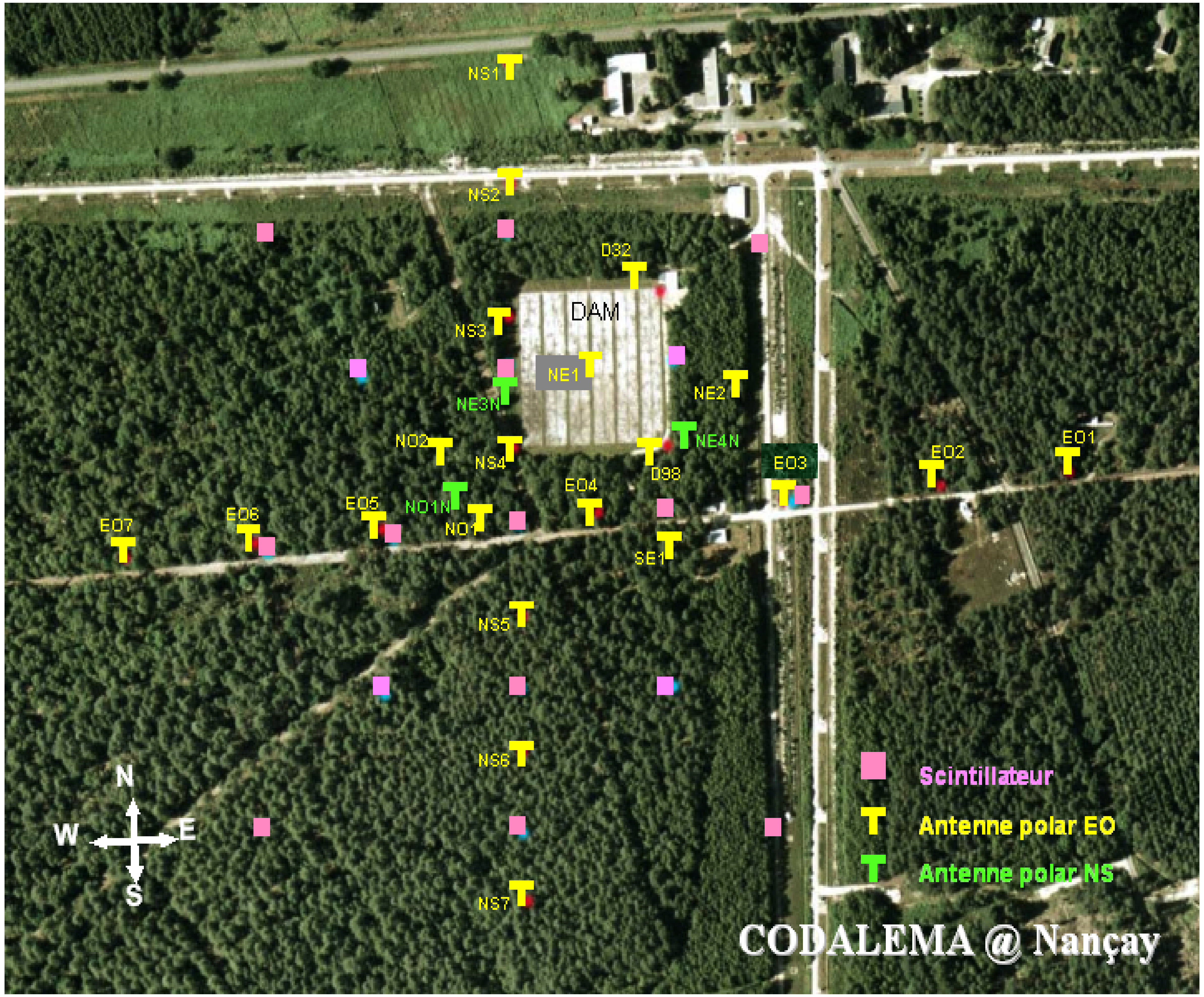

DAM
N
O
E
S
87 m
130 m
608 m


NS1
NS2
D32
DAM
NS3
NE1
NE2
NE3N
NE4N
NO2
NS4
D98
EO3
EO2
EO1
EO4
EO5
NO1N
NO1
EO6
EO7
SE1
NS5
NS6
NS7
N
W
E
S
Scintillateur
Antenne polar EO
Antenne polar NS
CODALEMA @ Nançay


© 2010 Tele Atlas
Image © 2010 IGN-France
©2009 Google
Date des images satellite : 5 mars 2005
47°22'32.39" N 2°11'32.76" E élév. 0 m
Altitude 2.35 km



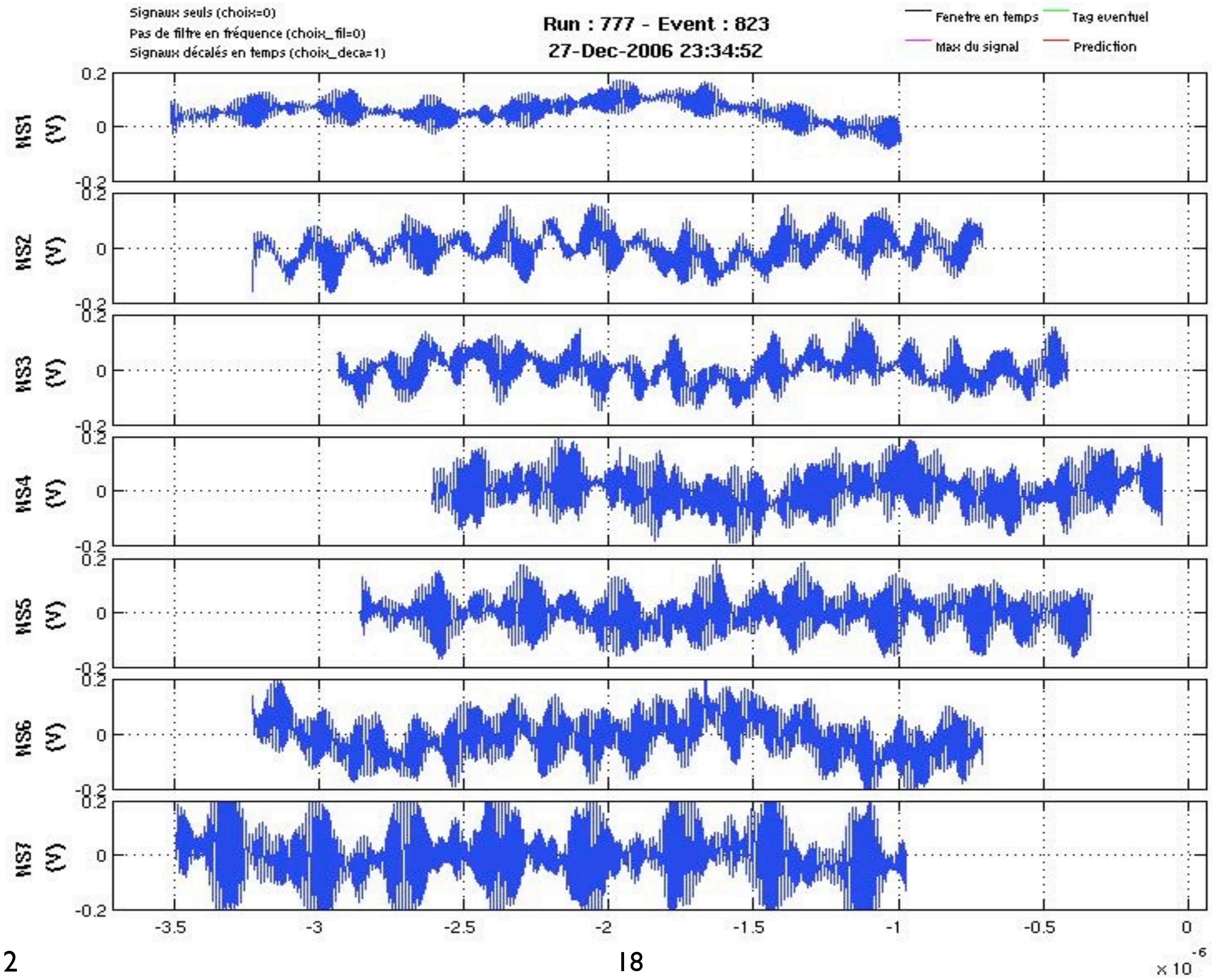
The CODALEMA experiment



- array of **21 EW** antennas and **3 in NS**, 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 Gs/s, 2500 samples

The CODALEMA experiment (EW data)

Read radio data after a particle trigger:



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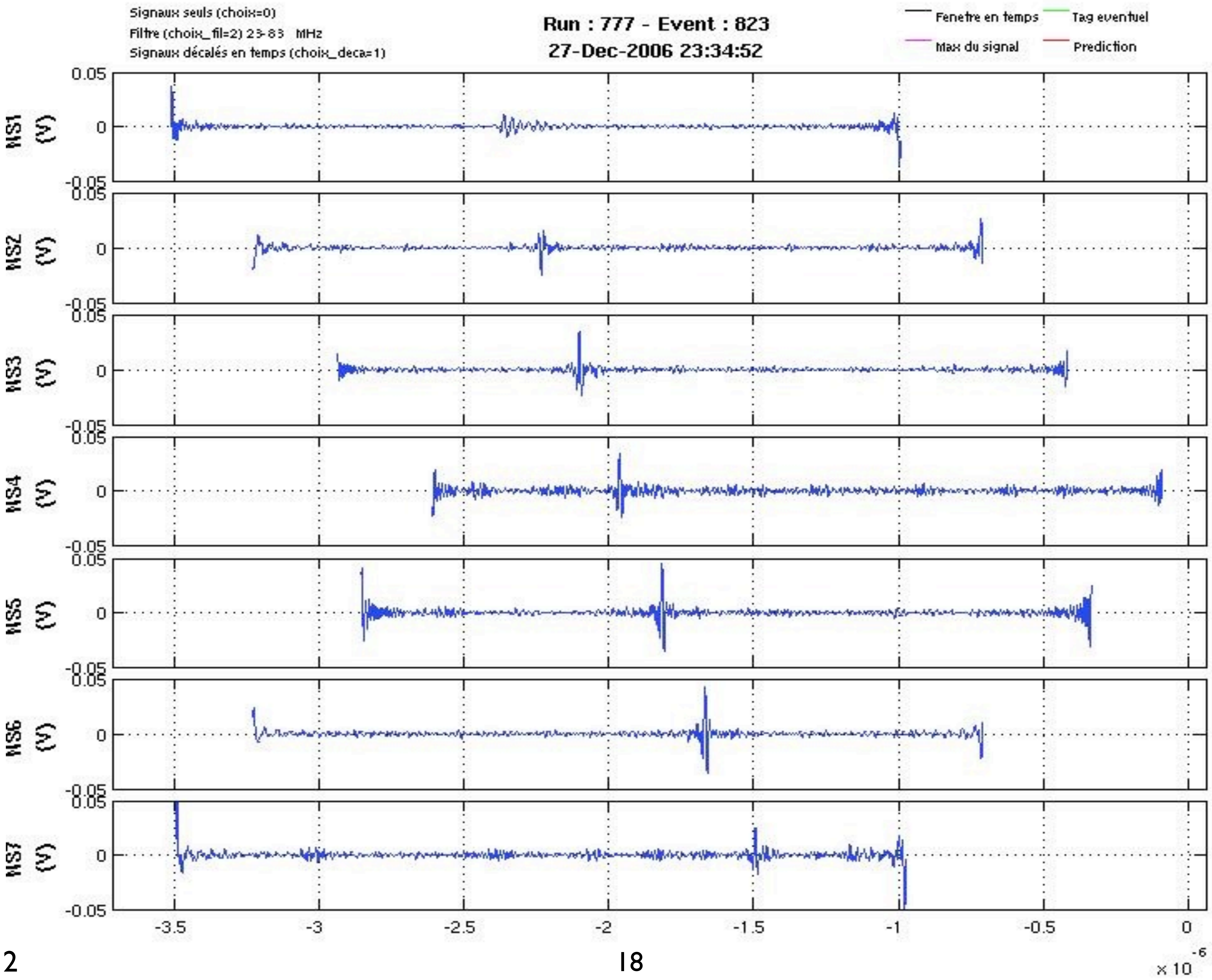

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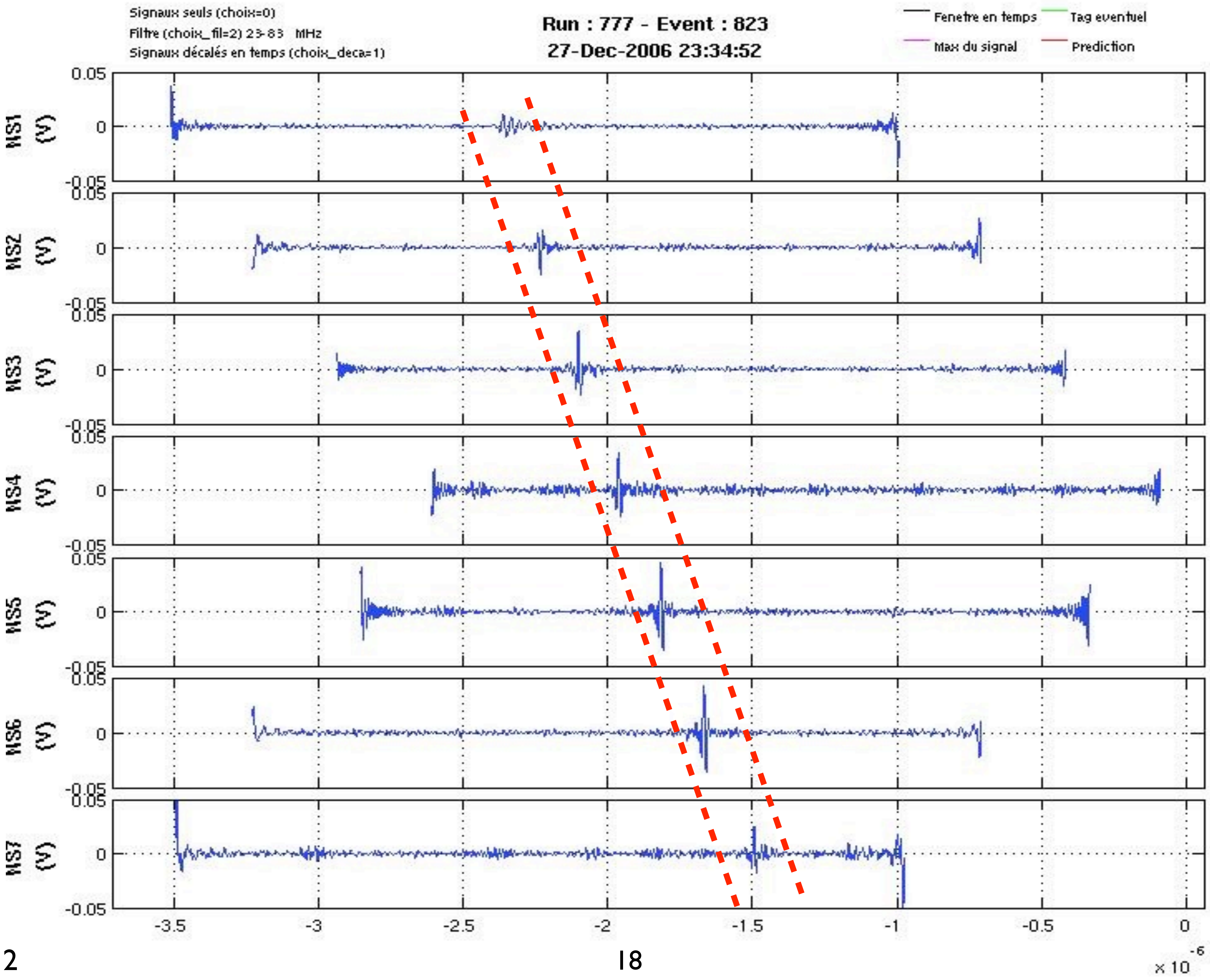
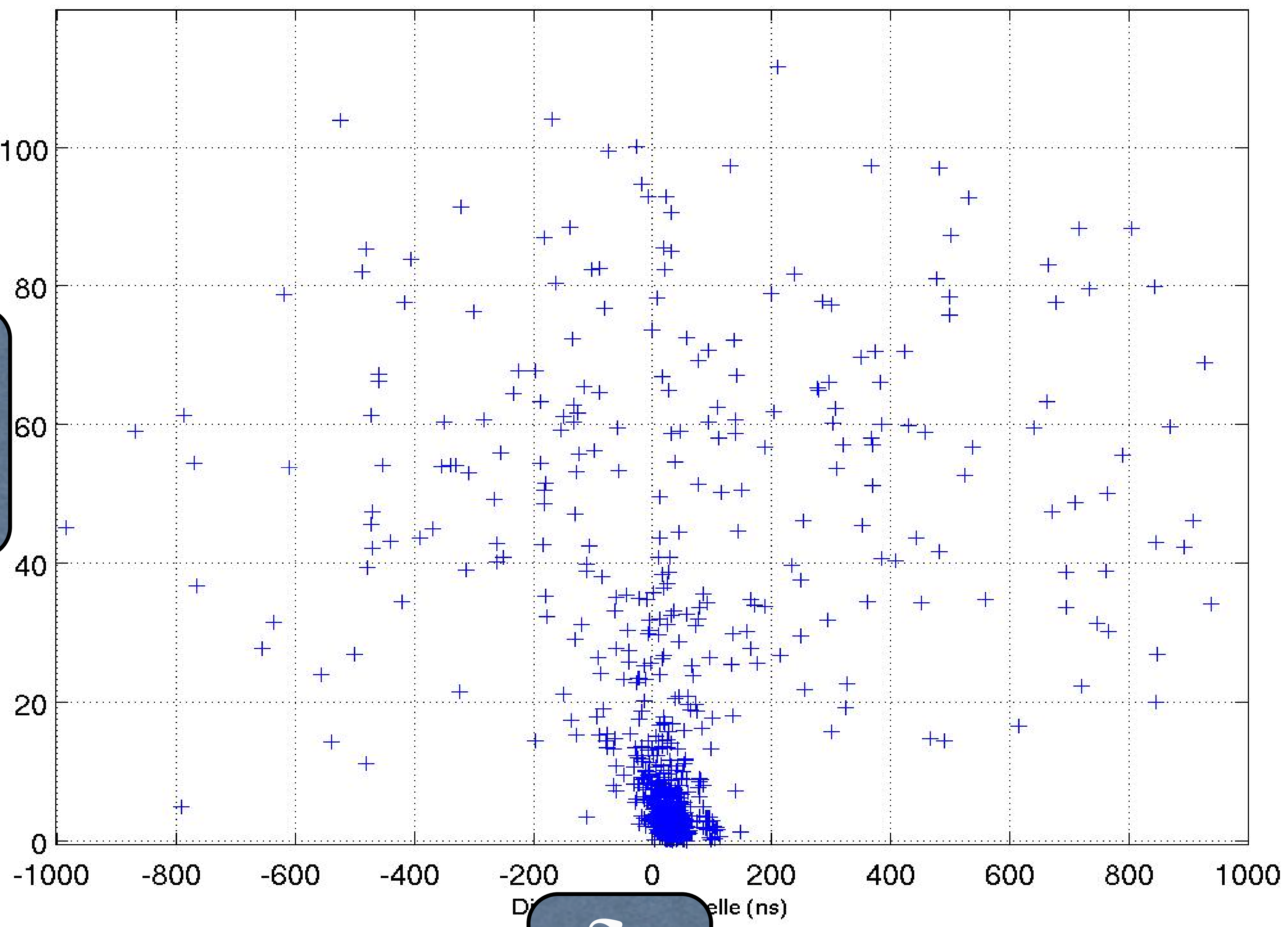


The CODALEMA experiment (EW data)

Two independent reconstructions:

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



$\delta\Omega$

δt

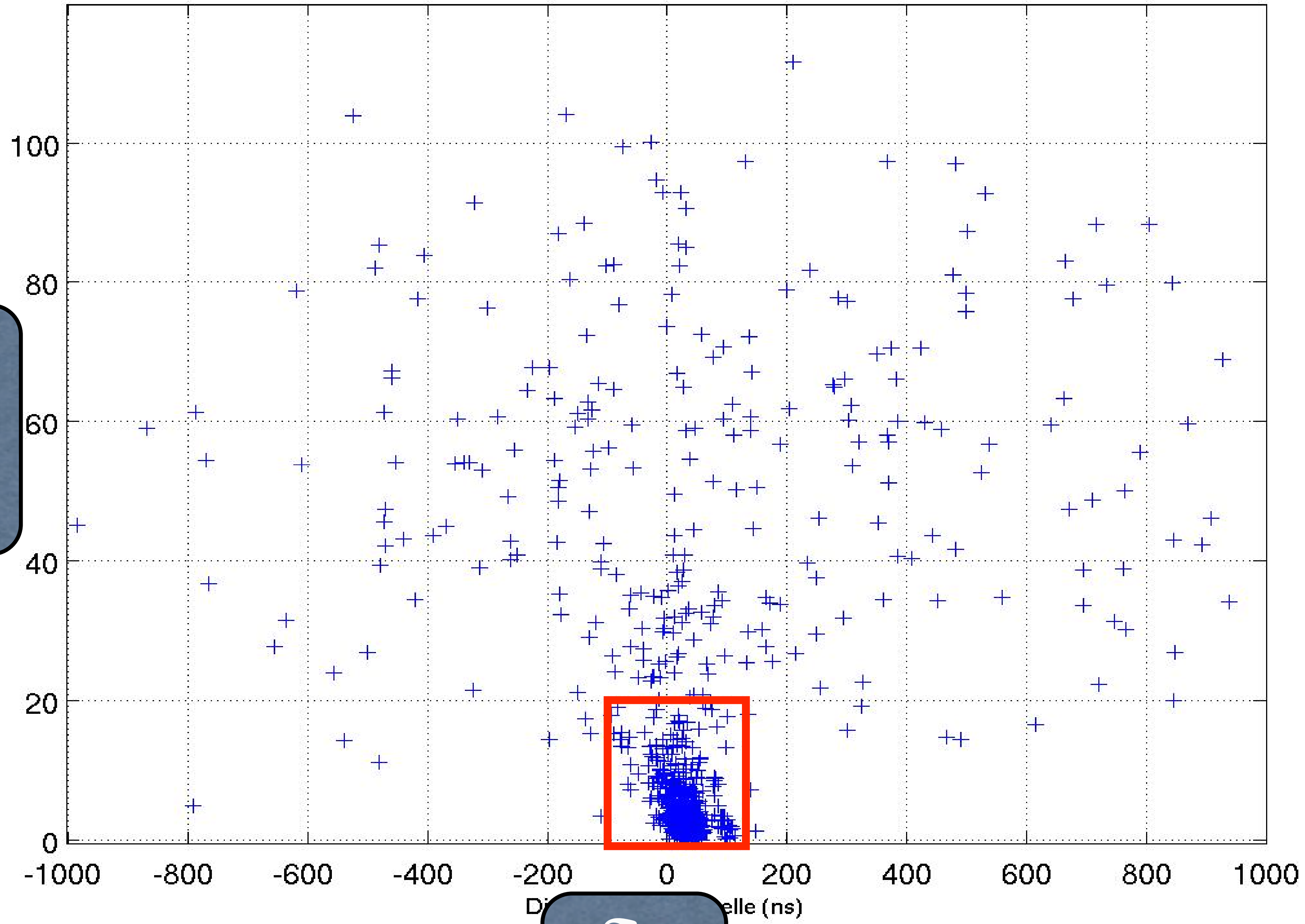
The CODALEMA experiment (EW data)

Two independent reconstructions:

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

Search for coincidences by comparison of arrival time and arrival direction

$|\delta t| \leqslant 100\ \mathrm{ns}$ $\delta\Omega \leqslant 20°$



$\delta\Omega$

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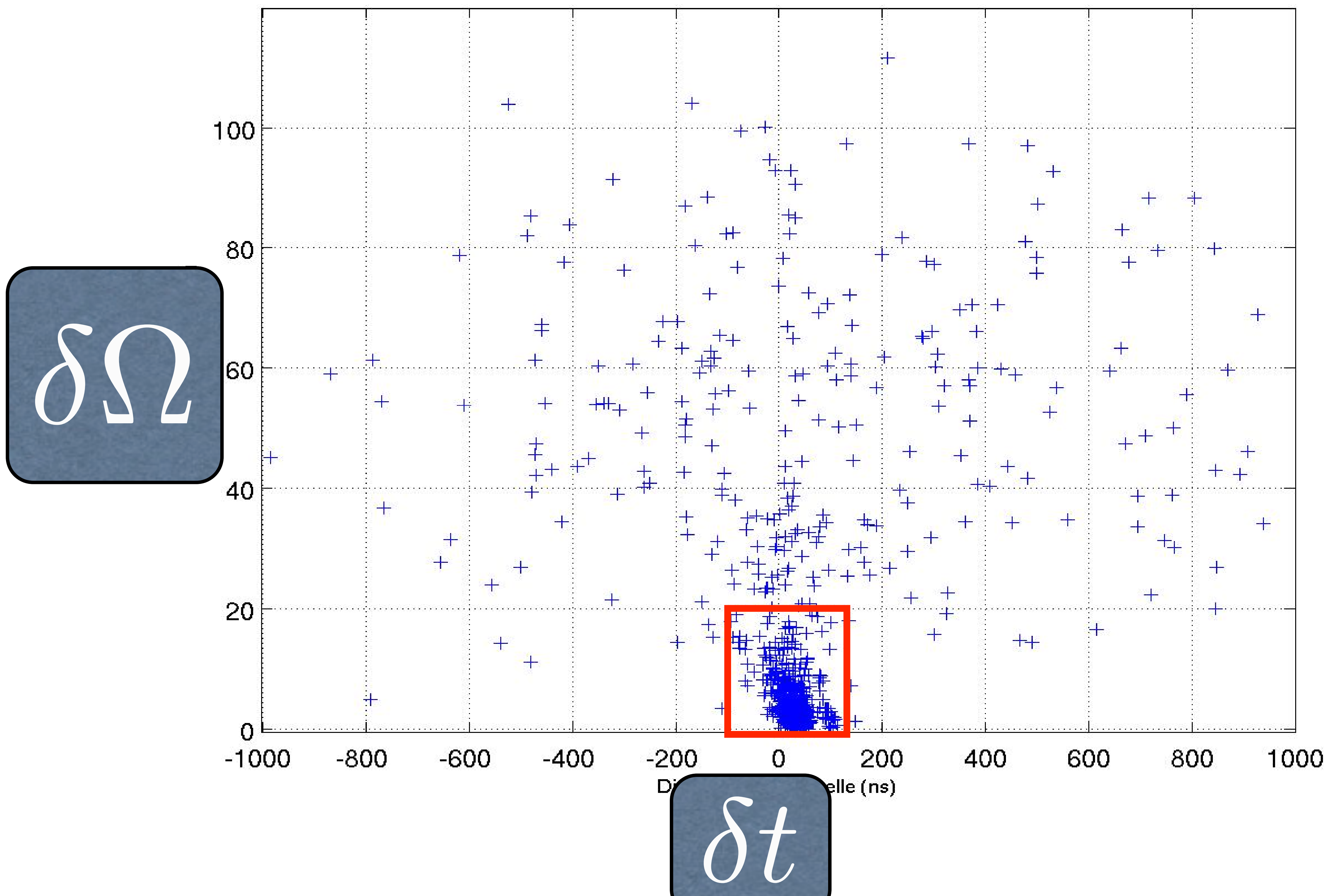

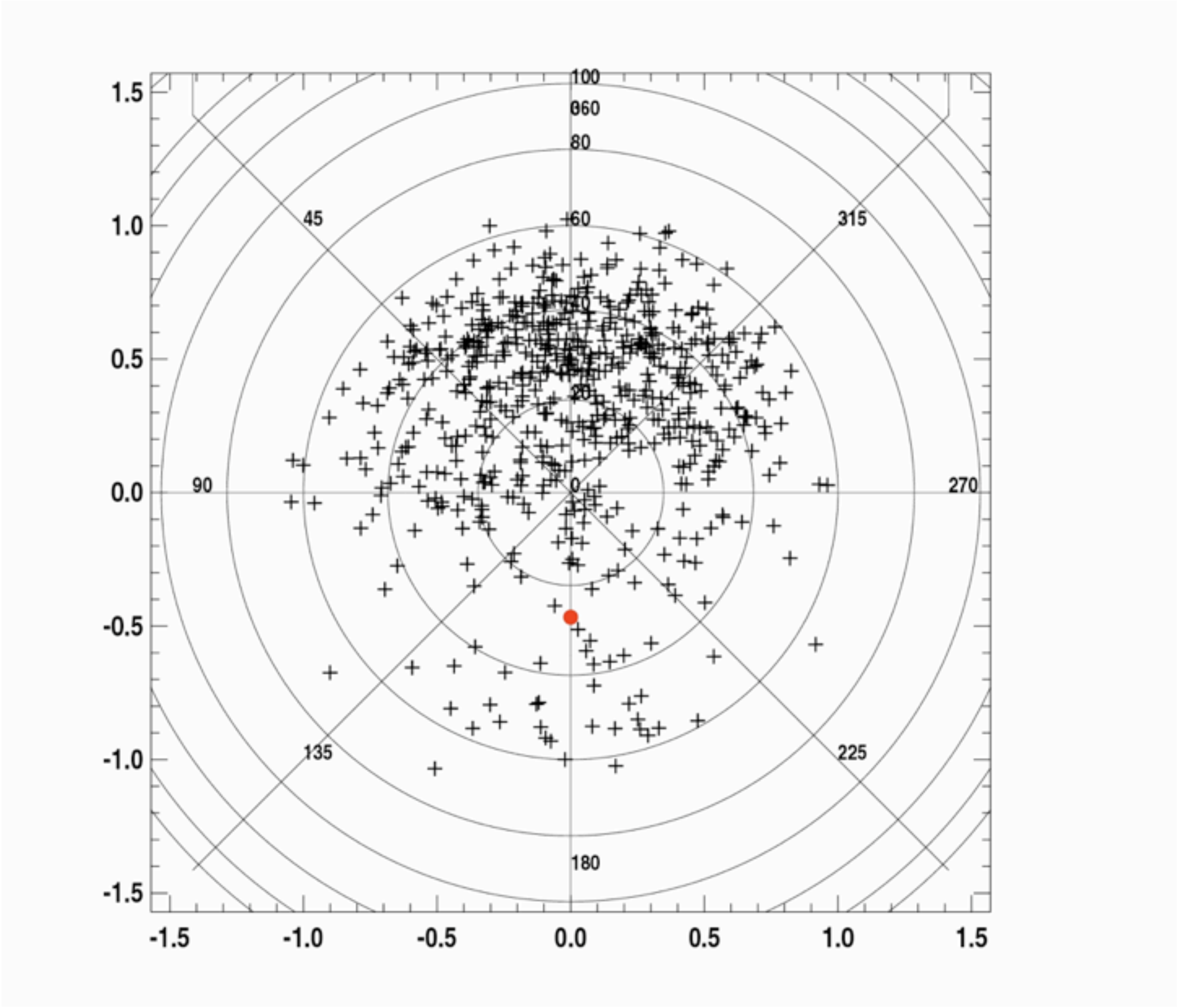

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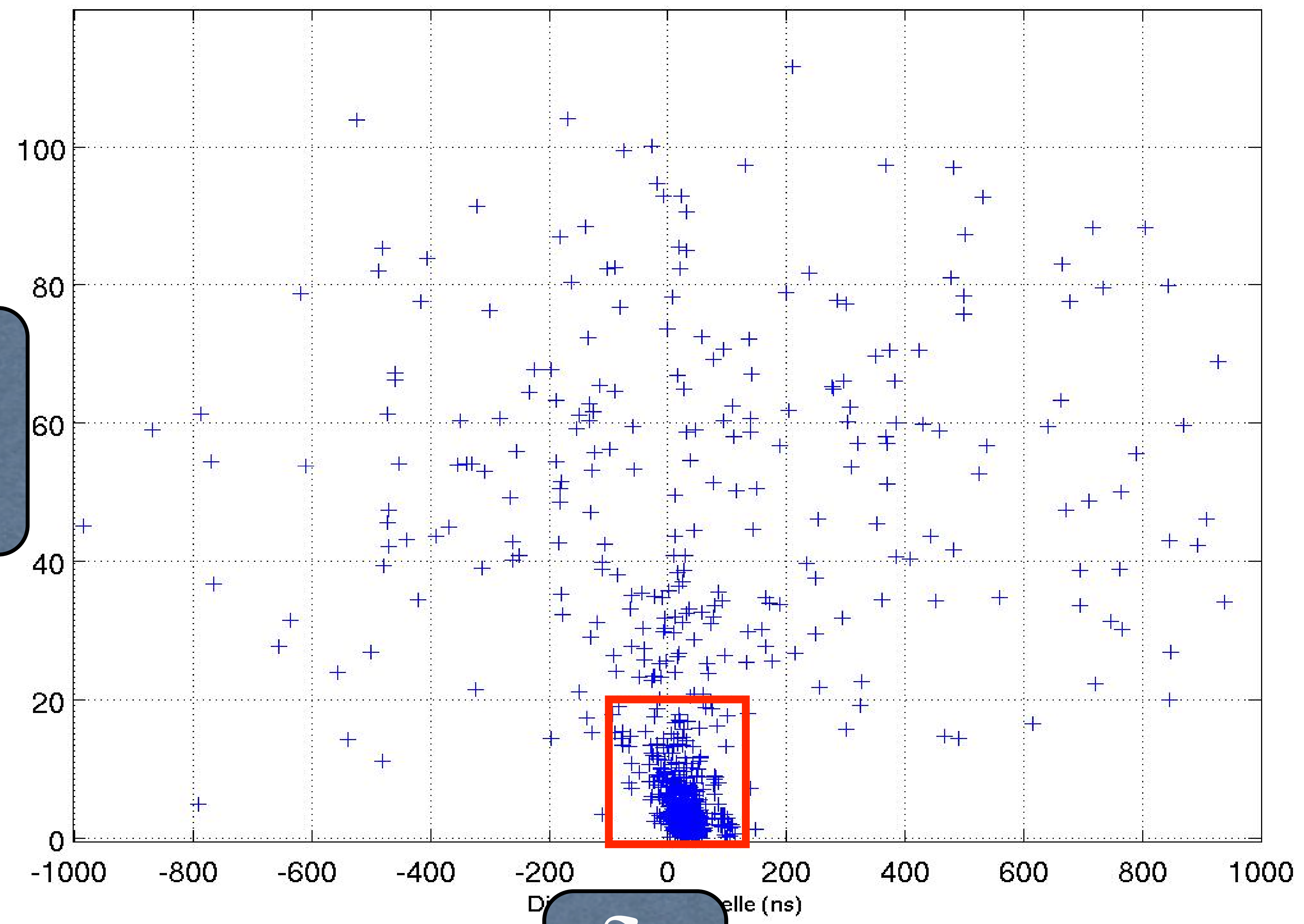
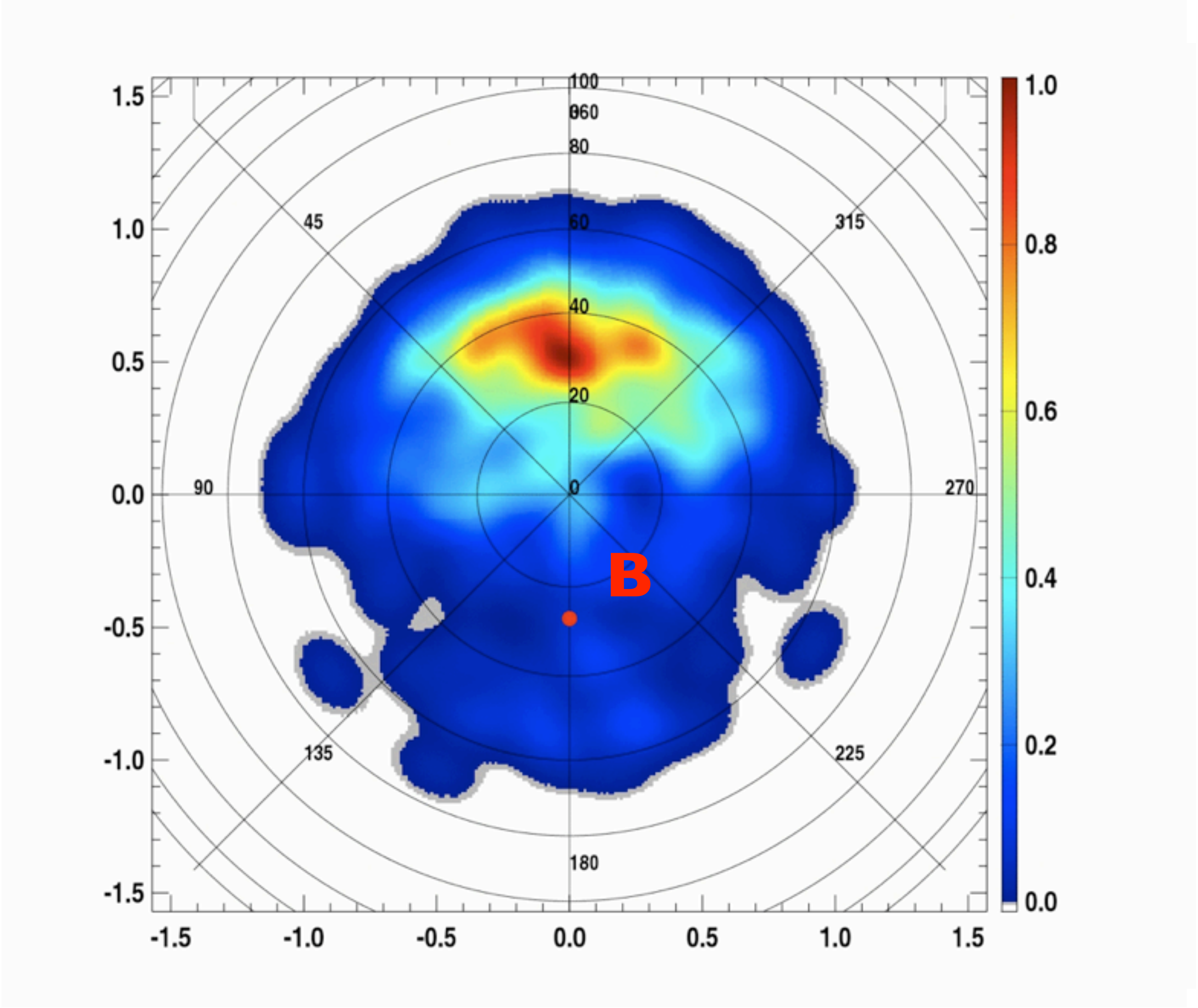


$\delta\Omega$

δt



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Two independent reconstructions:

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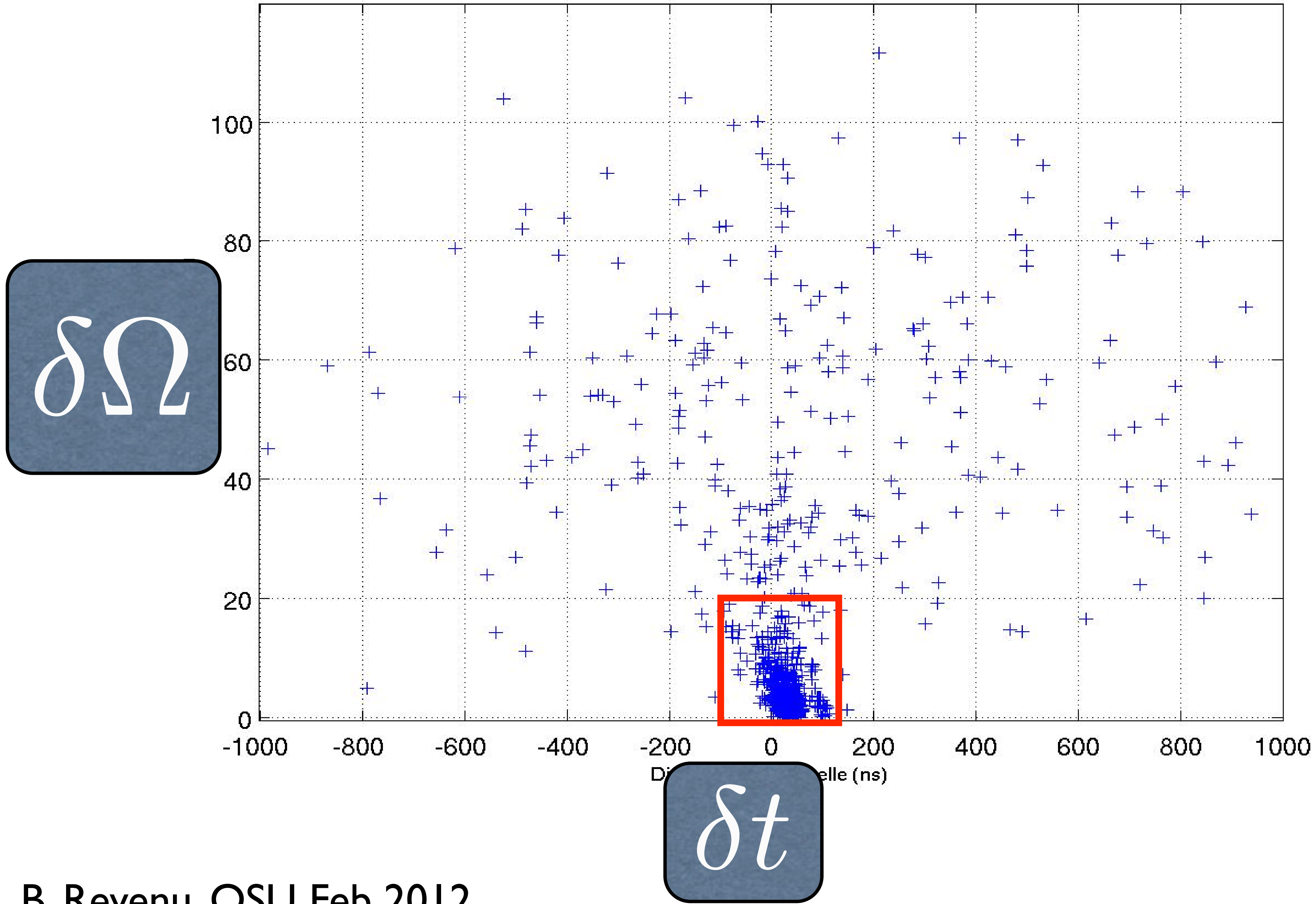

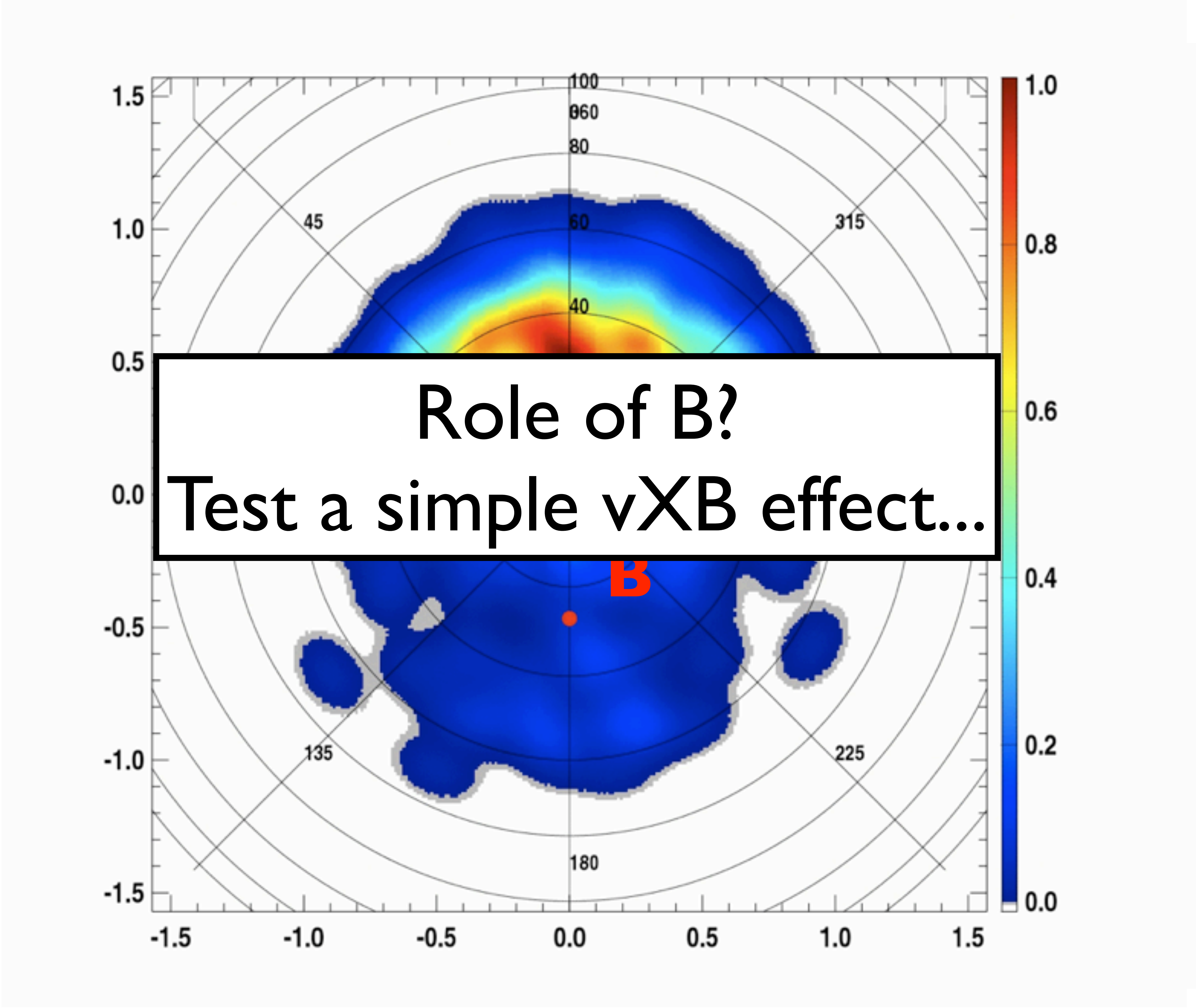

Role of B?

Test a simple vXB effect...

The CODALEMA experiment (EW data)

Two independent reconstructions:

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

Search for coincidences by comparison of arrival time and arrival direction

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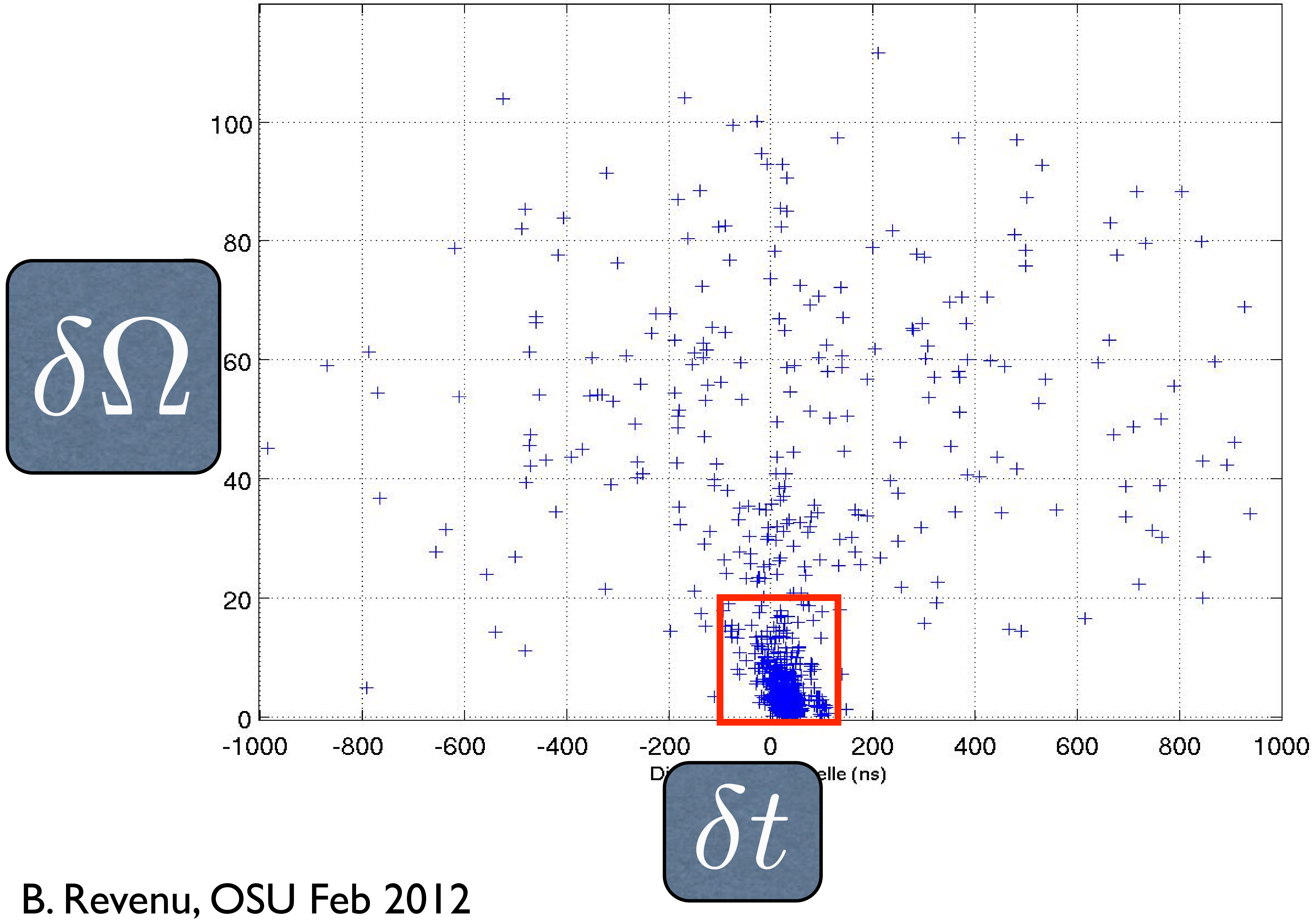
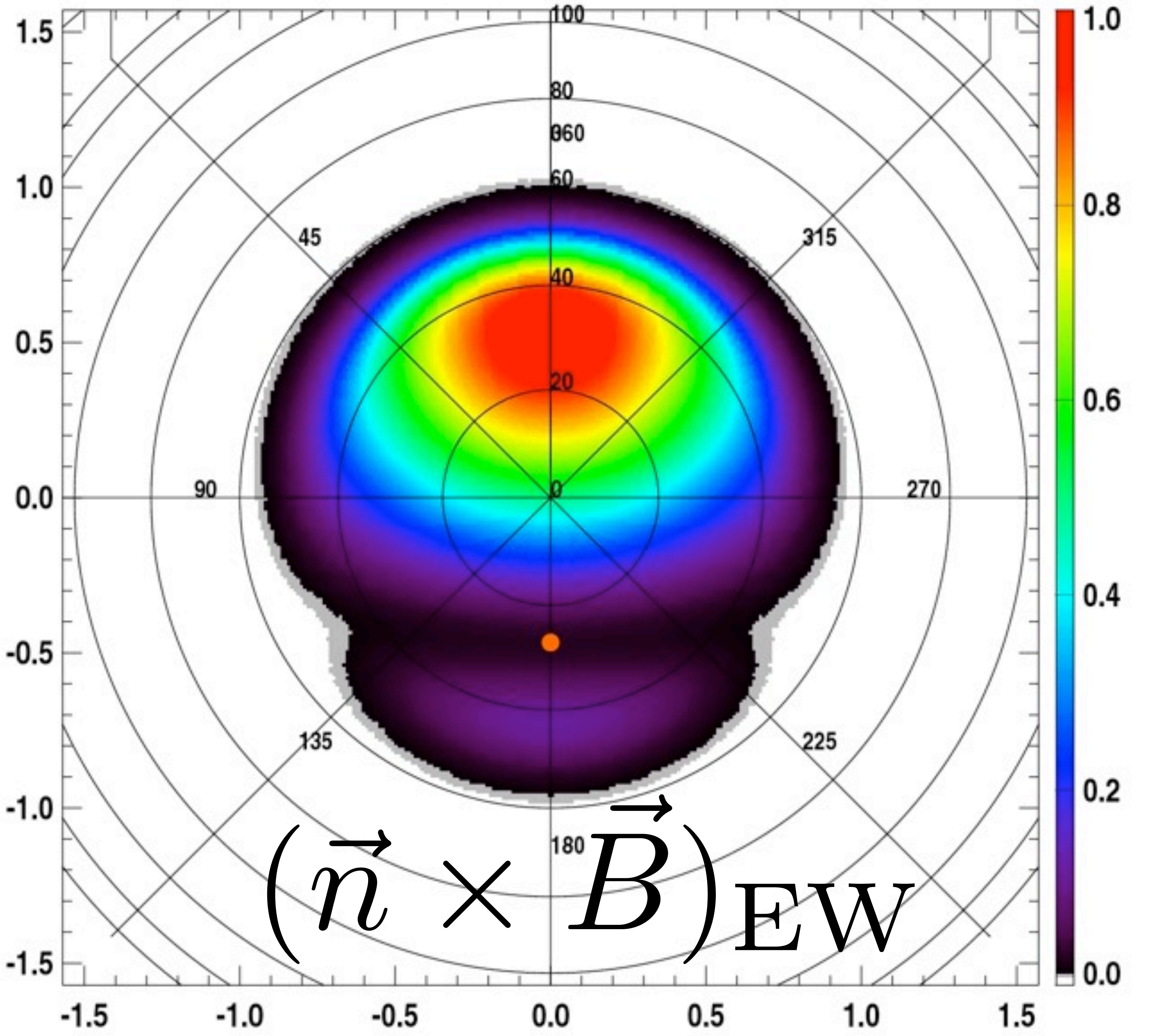
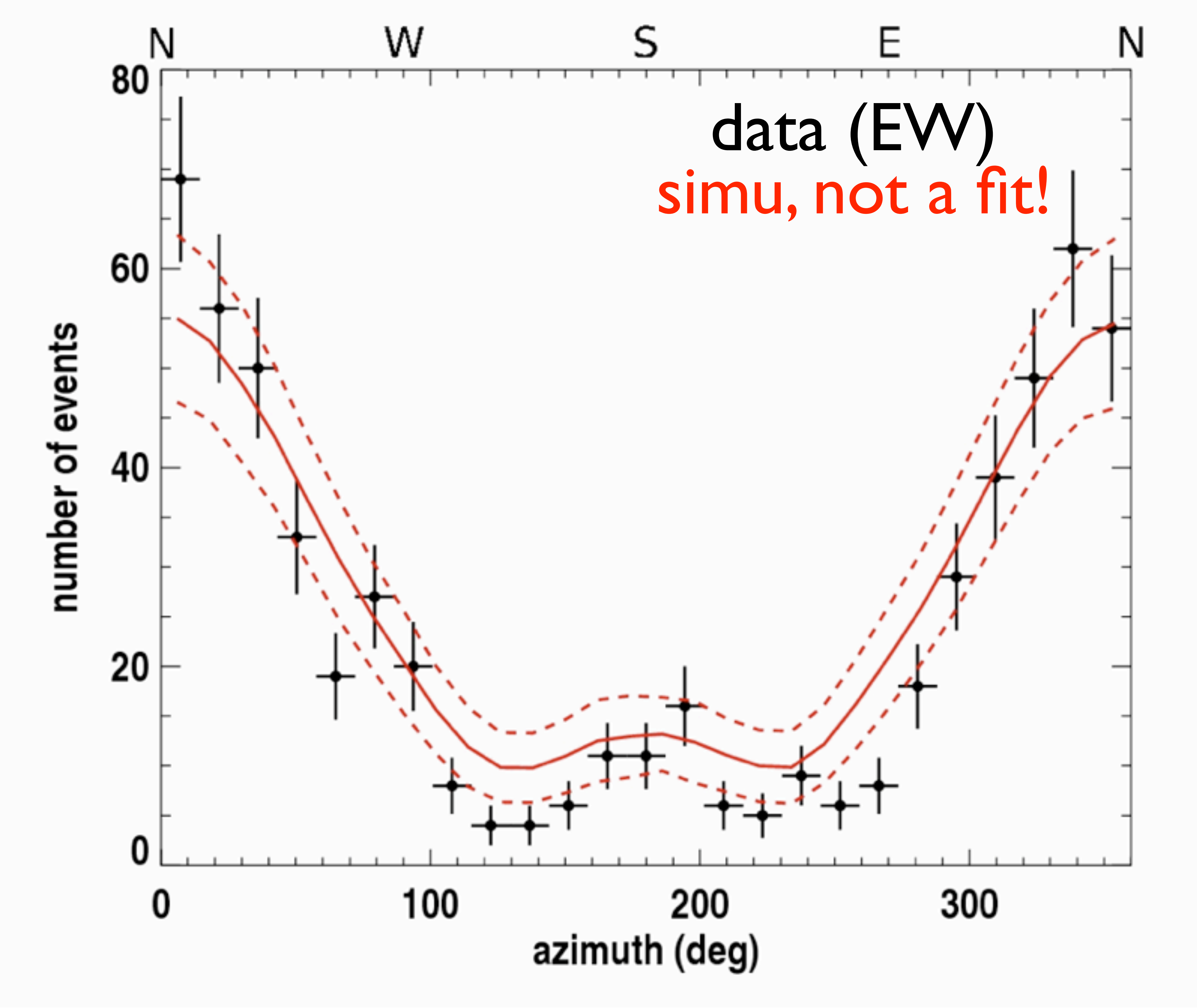




The CODALEMA experiment (EW-NS data)

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



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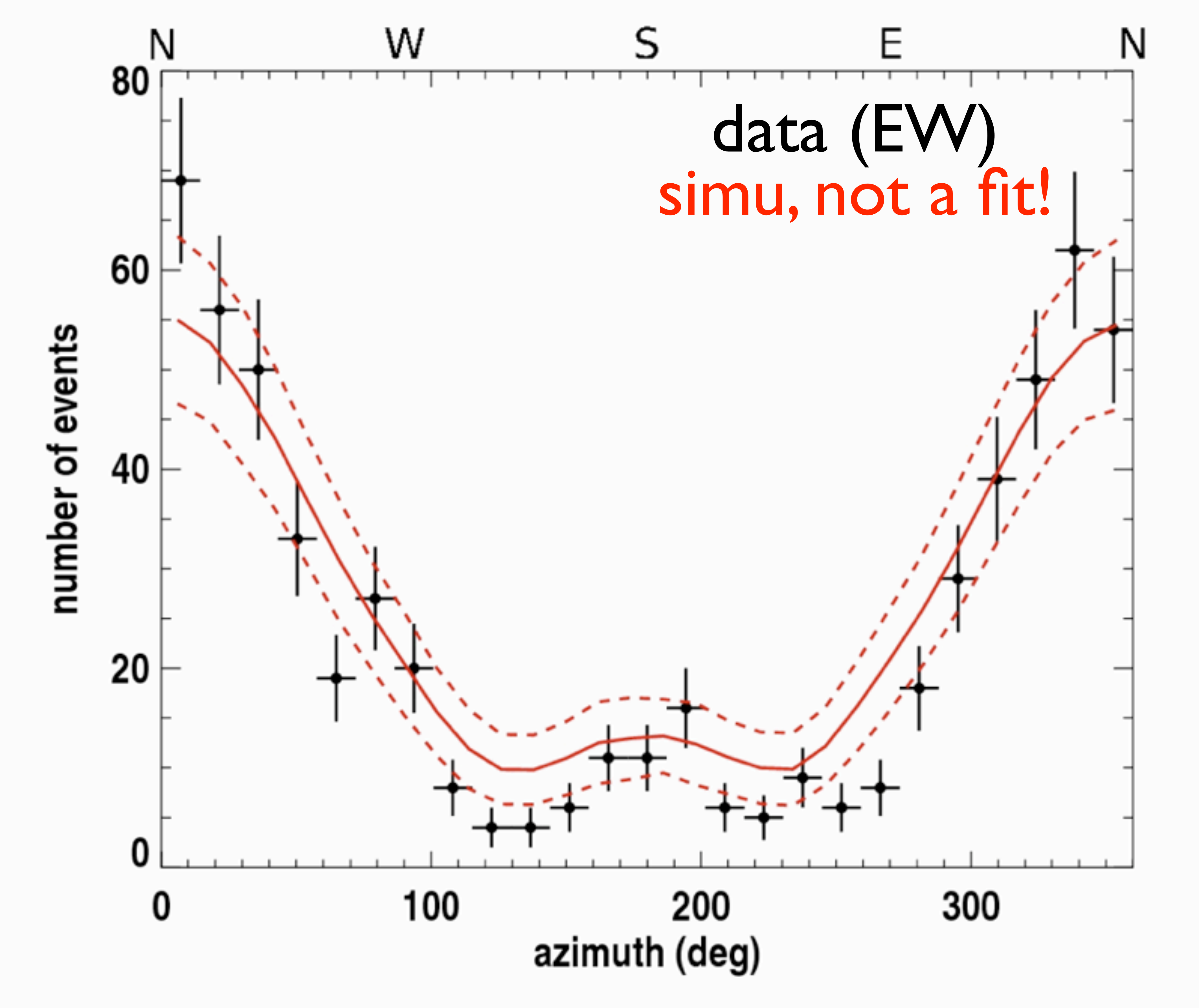
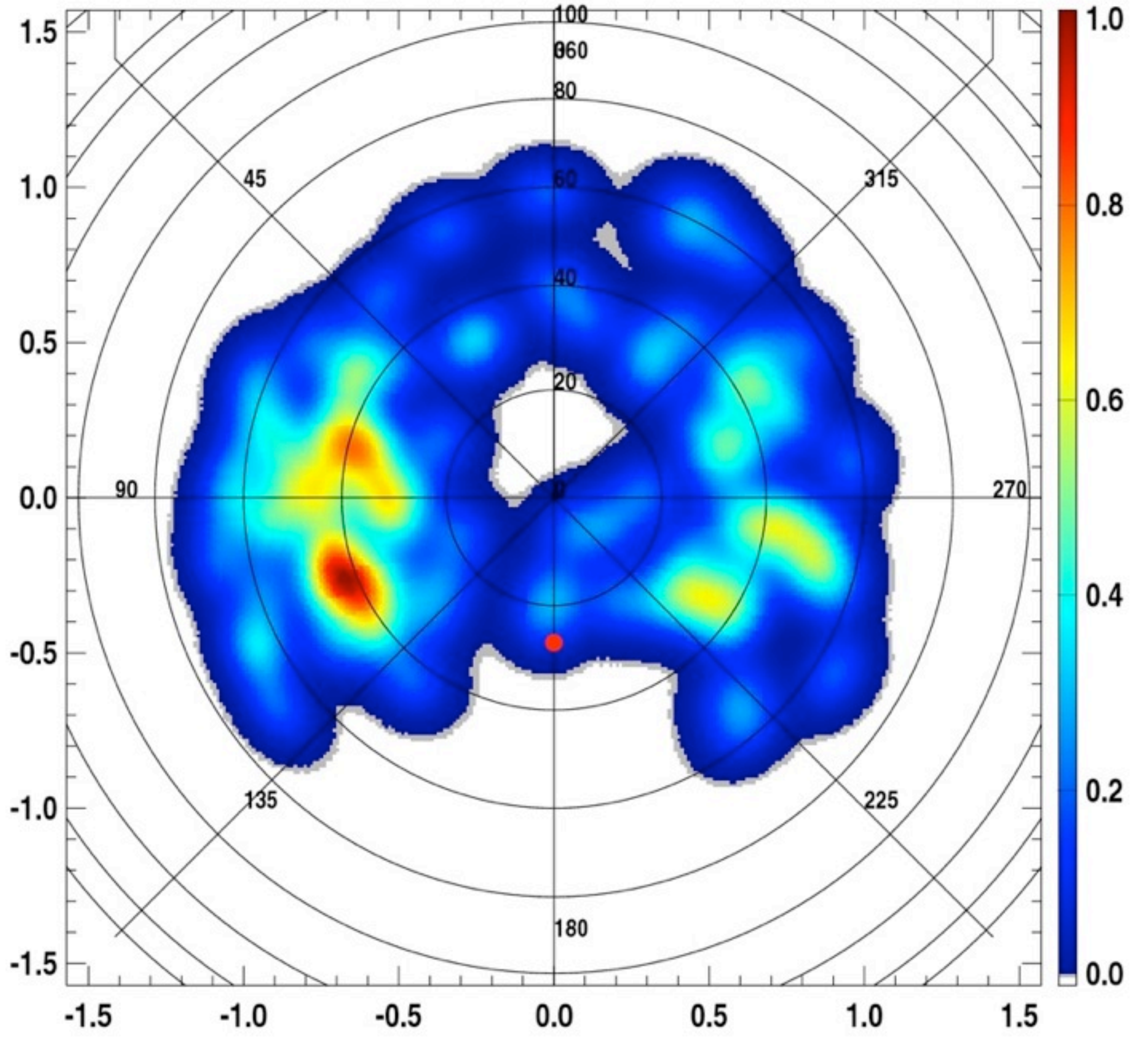

data (EW)
simu, not a fit!



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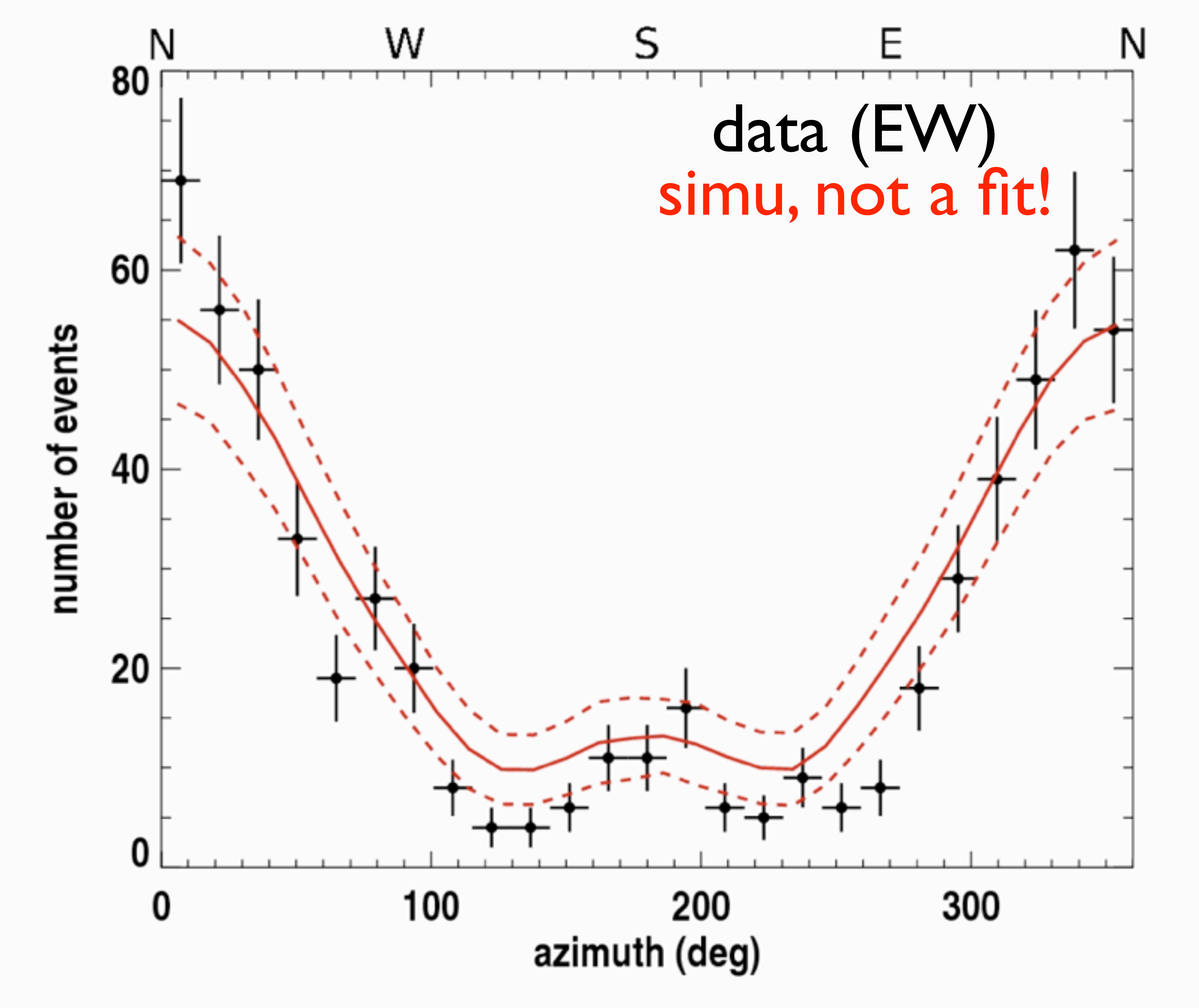

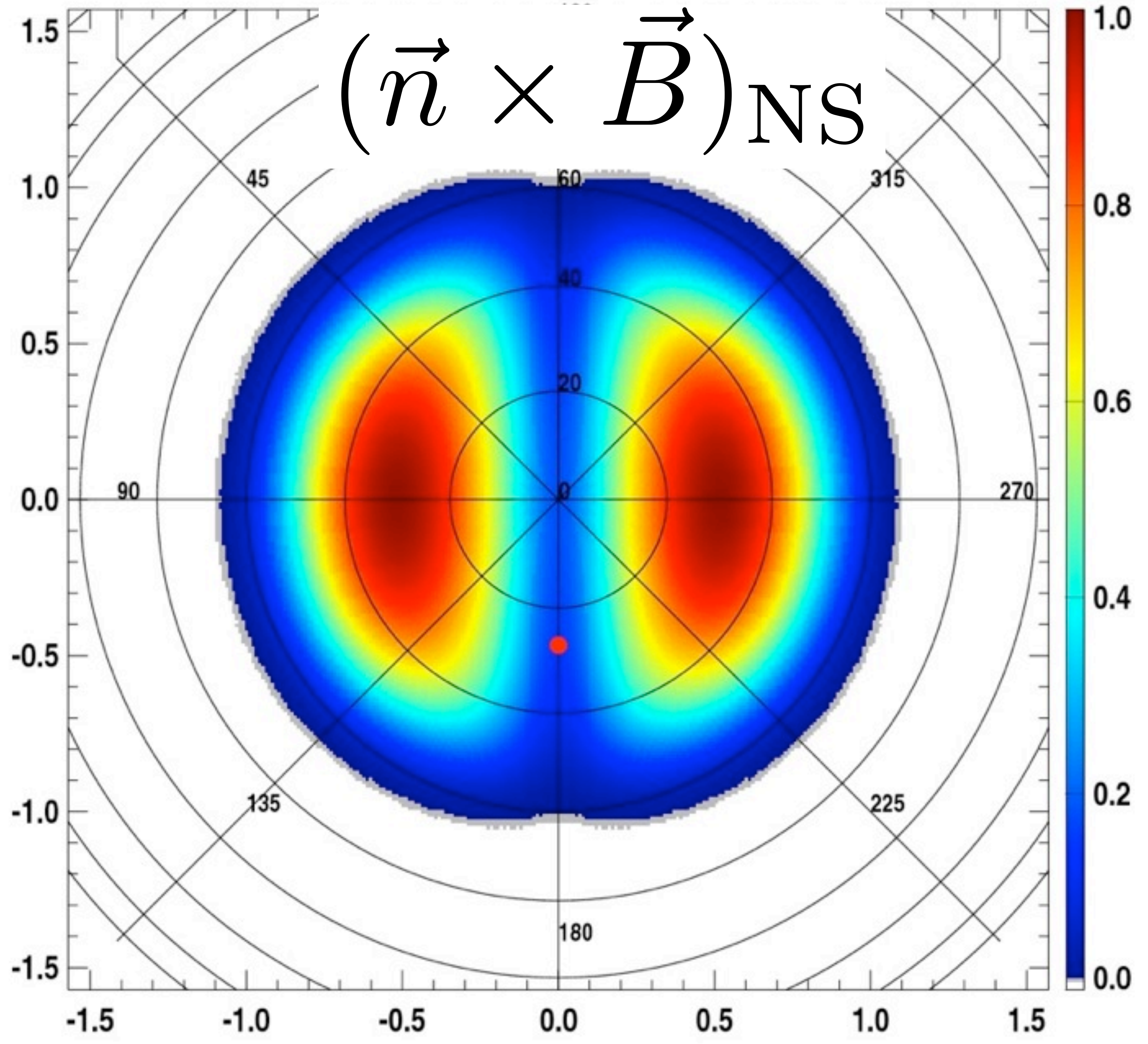

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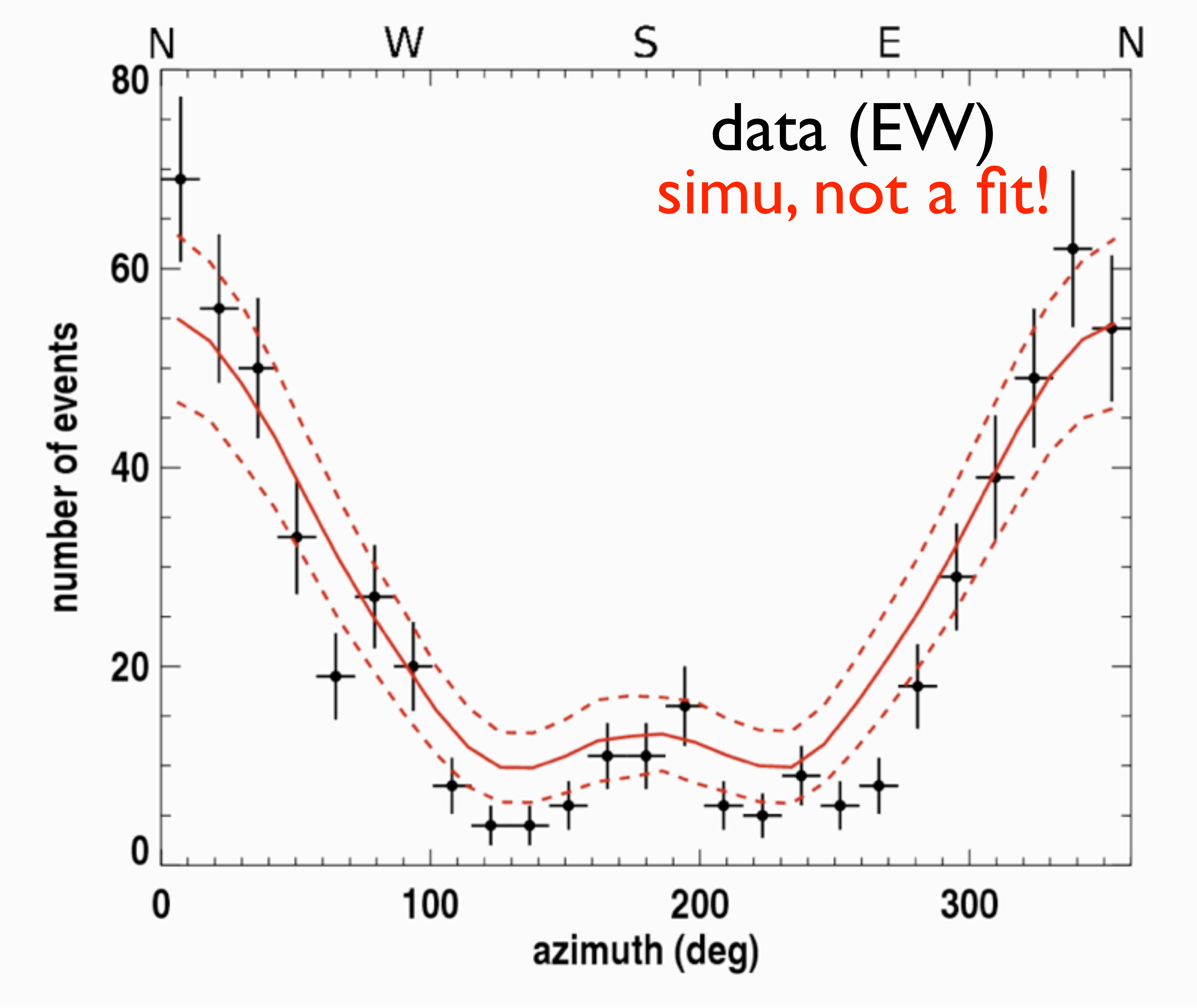

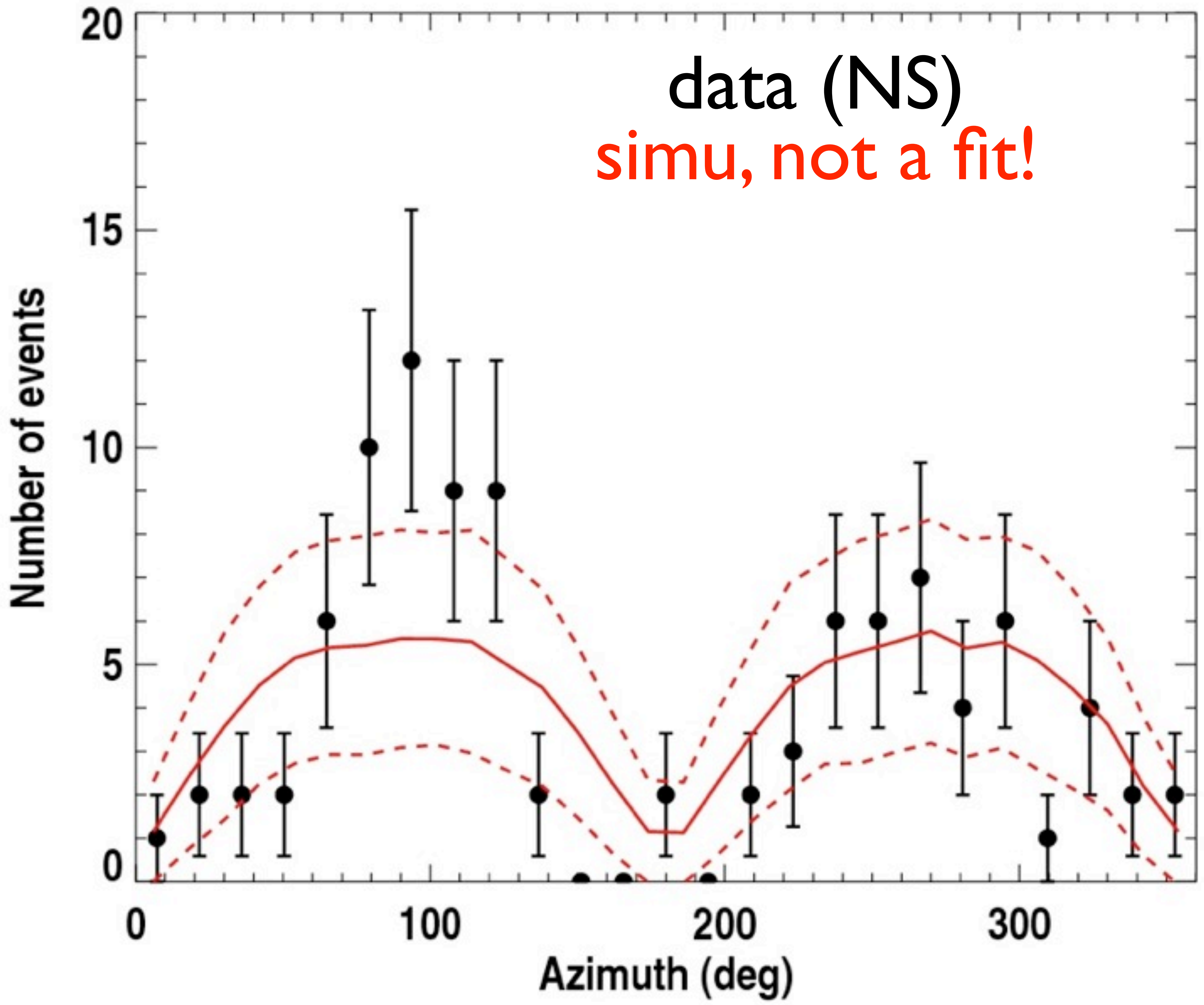

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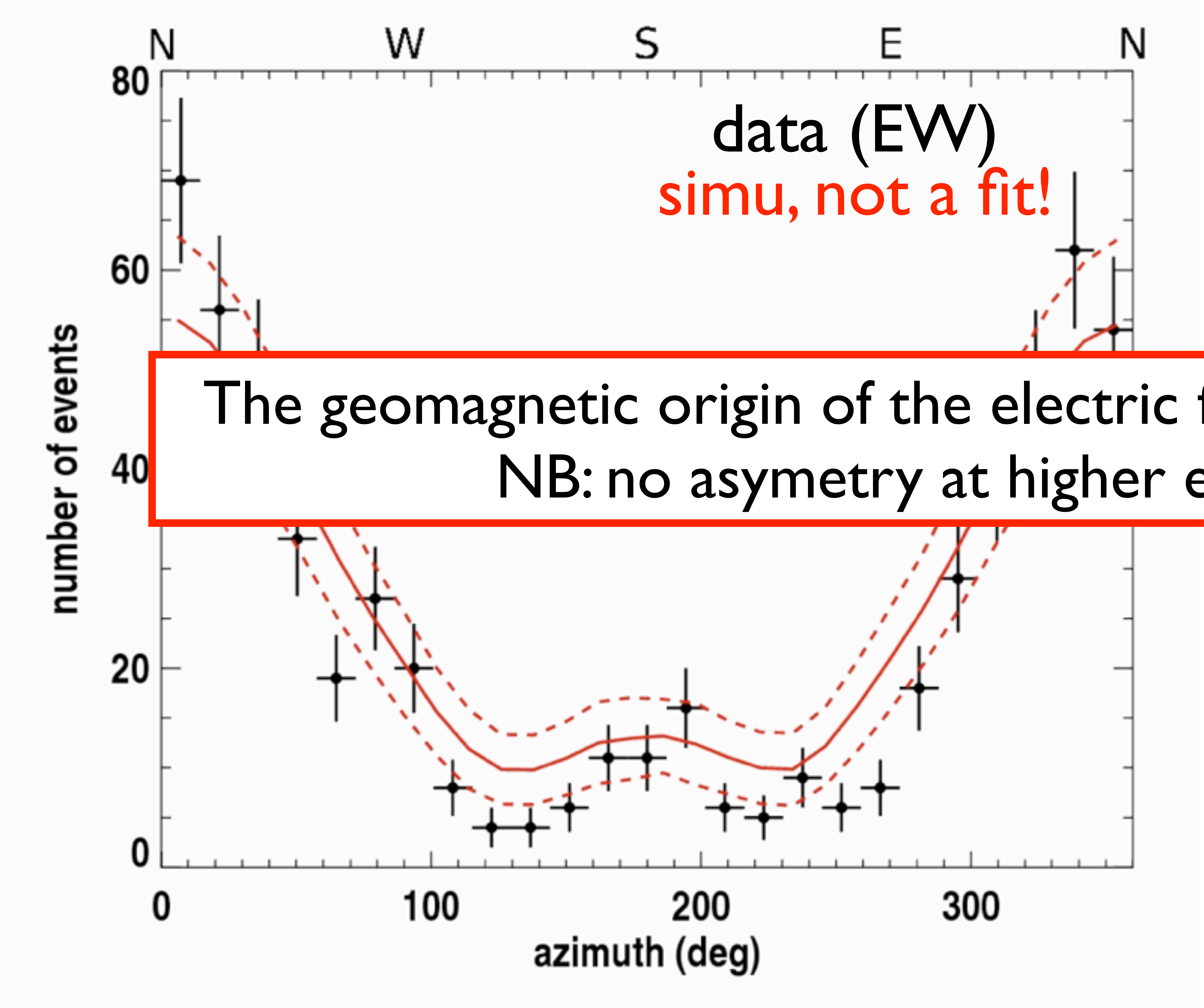
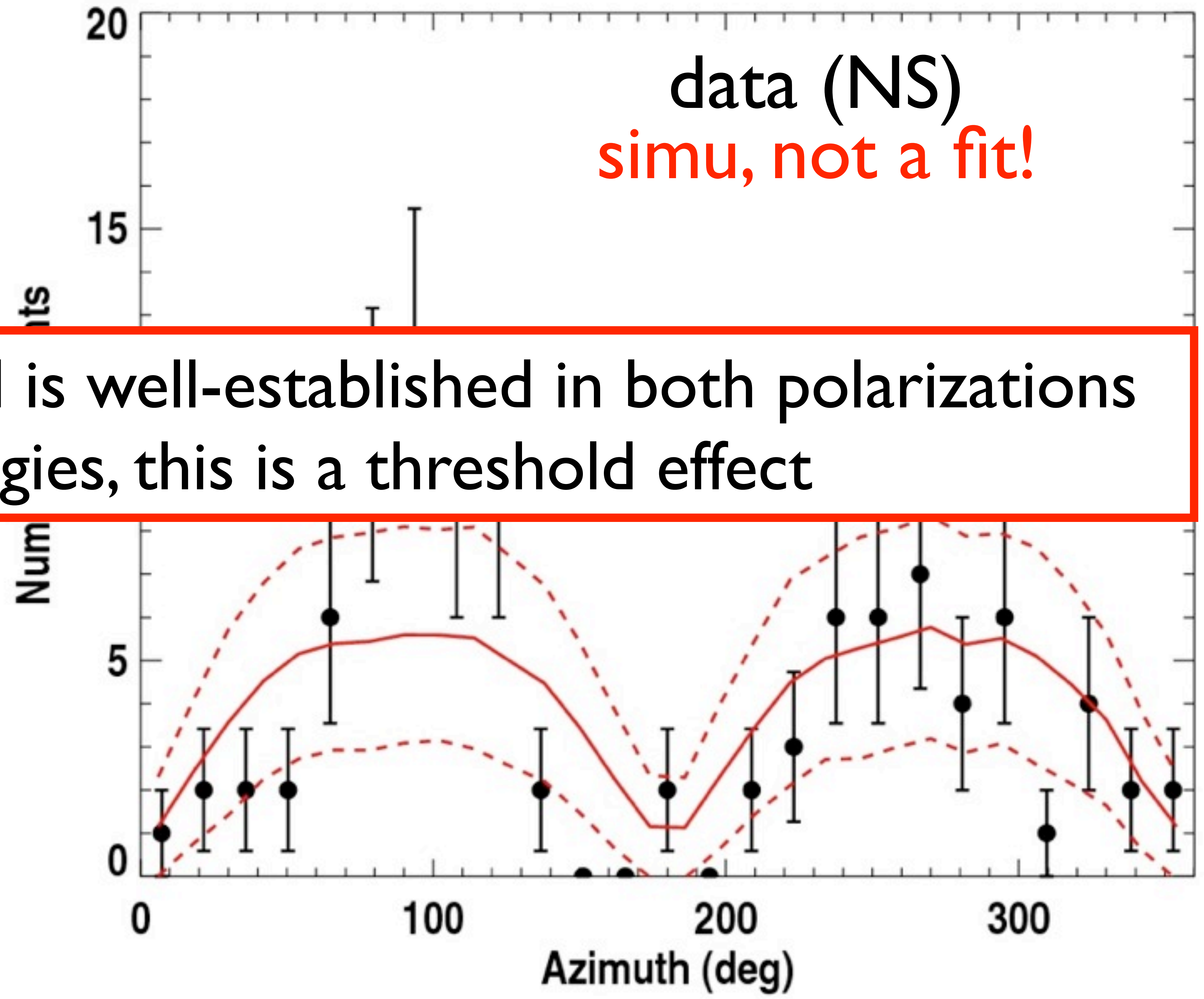




The geomagnetic origin of the electric field is well-established in both polarizations
NB: no asymetry at higher energies, this is a threshold effect

The CODALEMA experiment (EW data)

correlation between the electric field and the primary energy

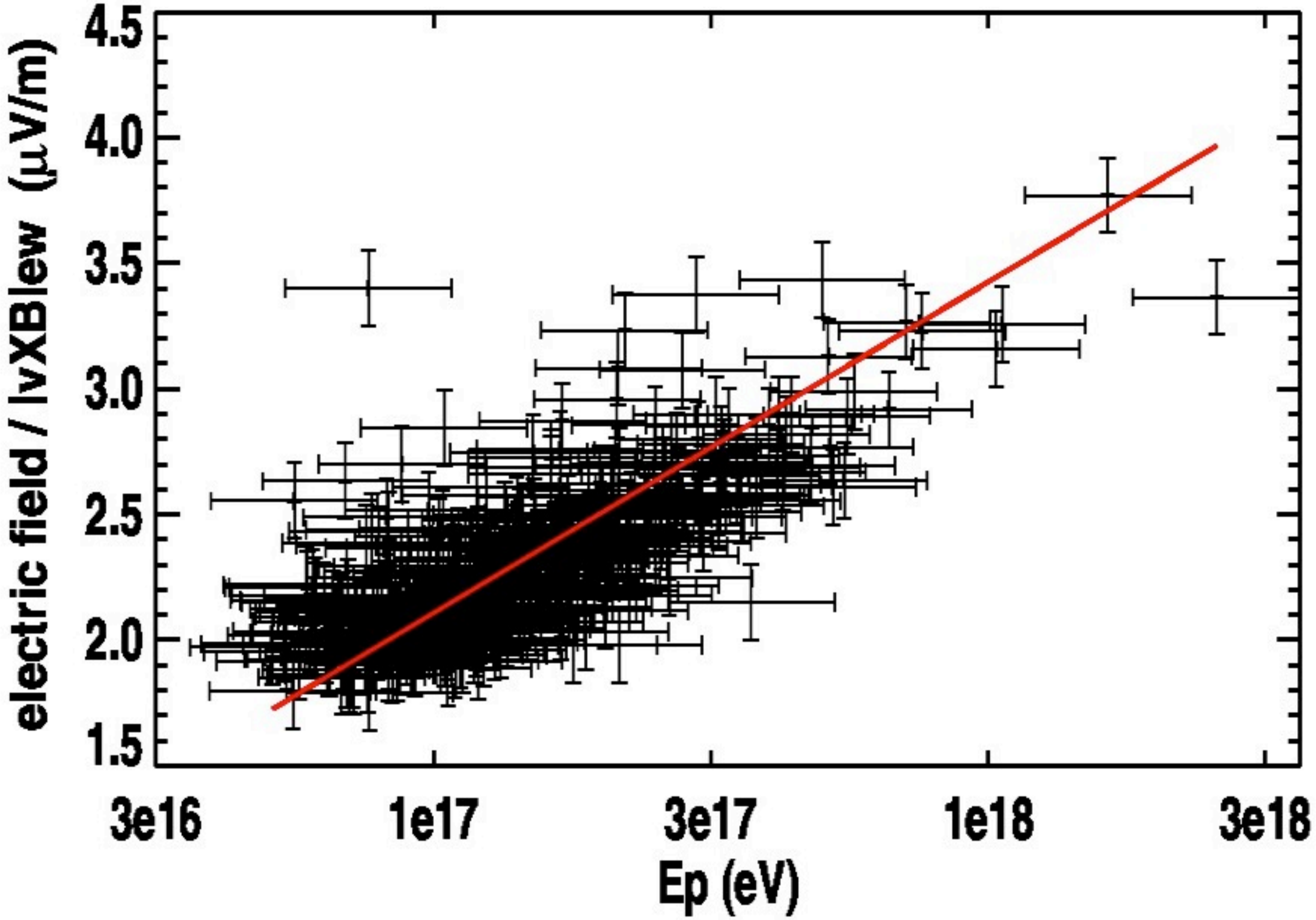
$$\mathcal{E}_0^{\mathrm{EW}} = (2.6 \pm 0.3) \left(\frac{B}{47\ \mu\mathrm{T}}\right) |(\mathbf{n} \times \mathbf{B})_{\mathrm{EW}}| \left(\frac{E}{1\ \mathrm{EeV}}\right)^{1.31 \pm 0.05} \quad \mathrm{mV/m}$$

PRELIMINARY

exponential profile assumed

strong dependence on hypothesis on the errors (systematic vs statistics and correlation or not)

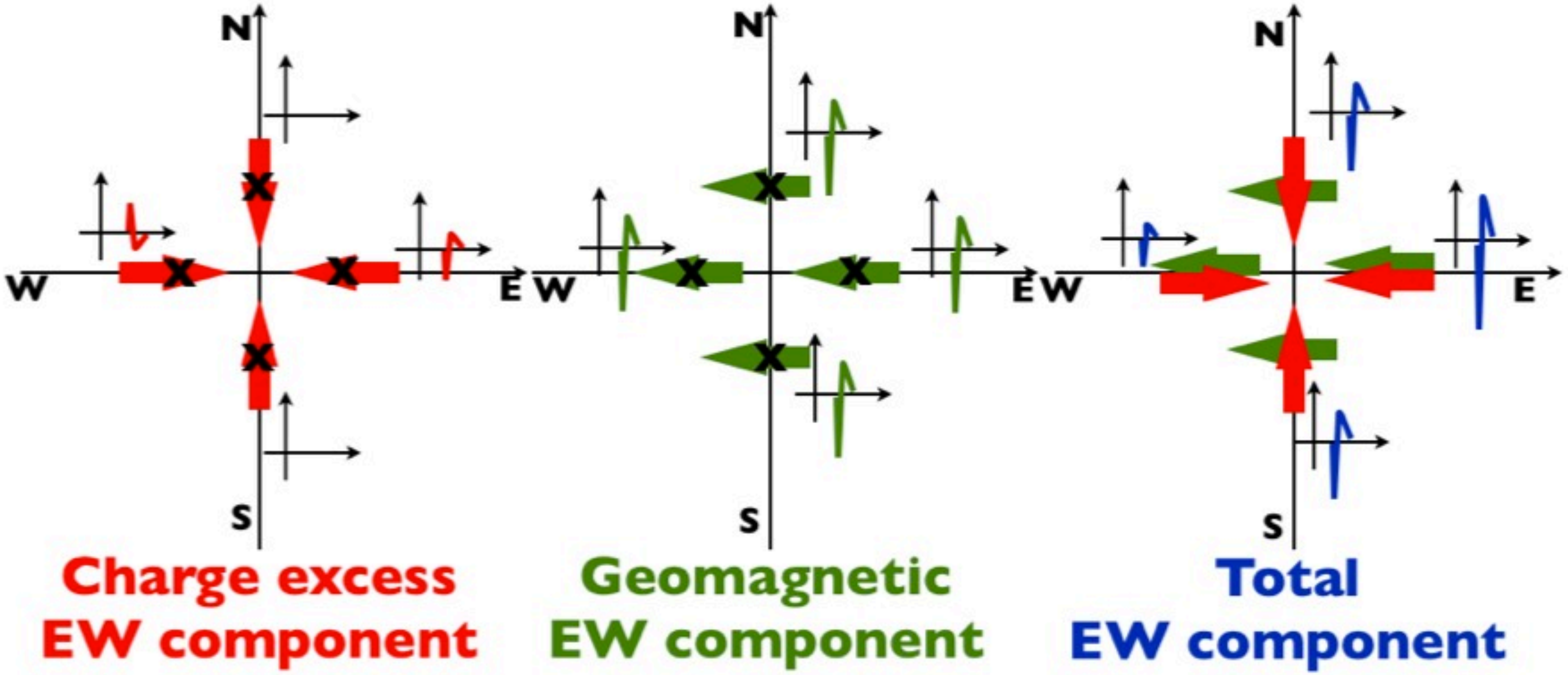
events with a flat profile observed as in LOPES



The CODALEMA experiment (EW data)

Marin, ICRC 2011

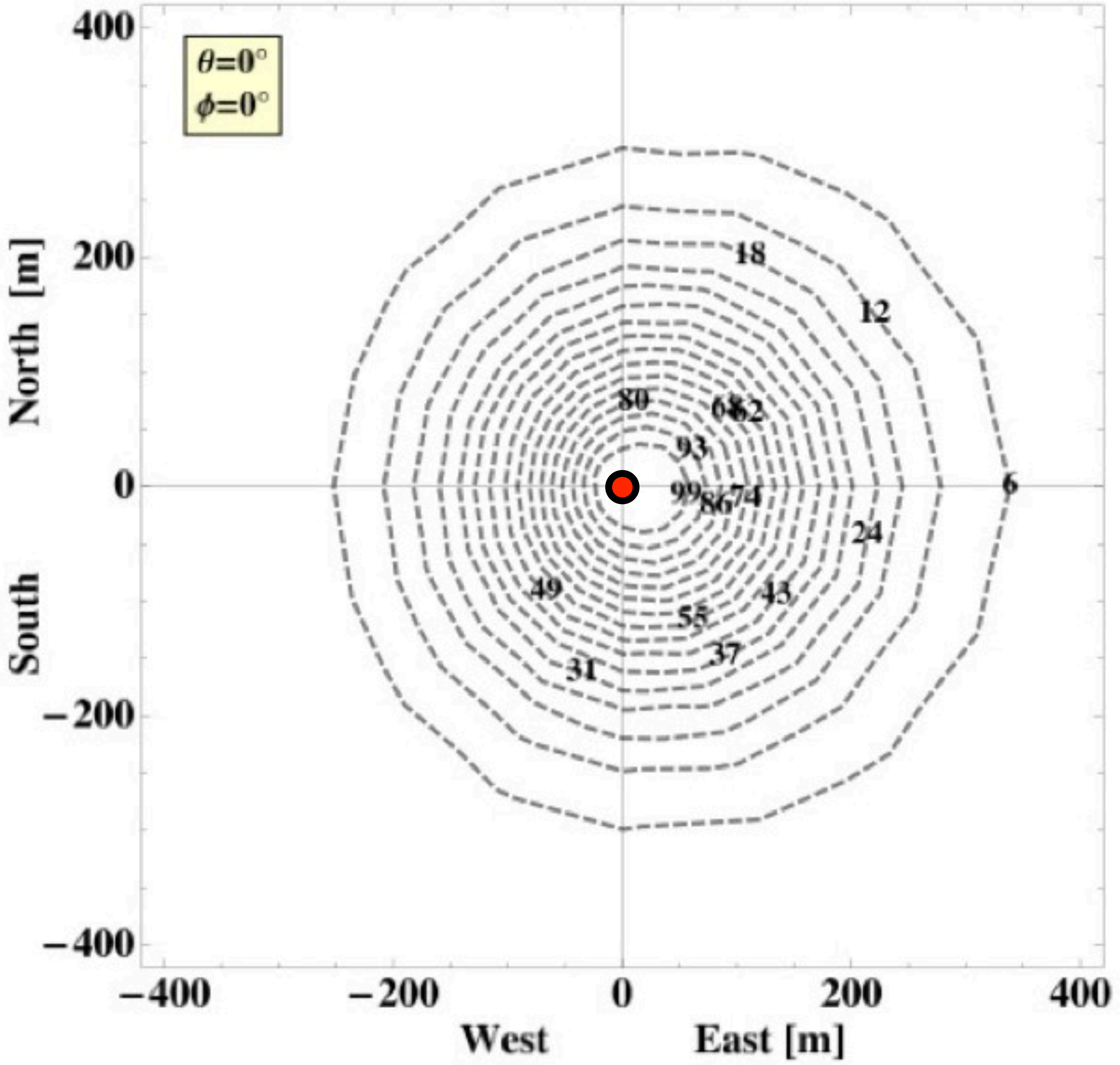
Secondary effect: the charge excess



The CODALEMA experiment (EW data)

Marin, ICRC 2011

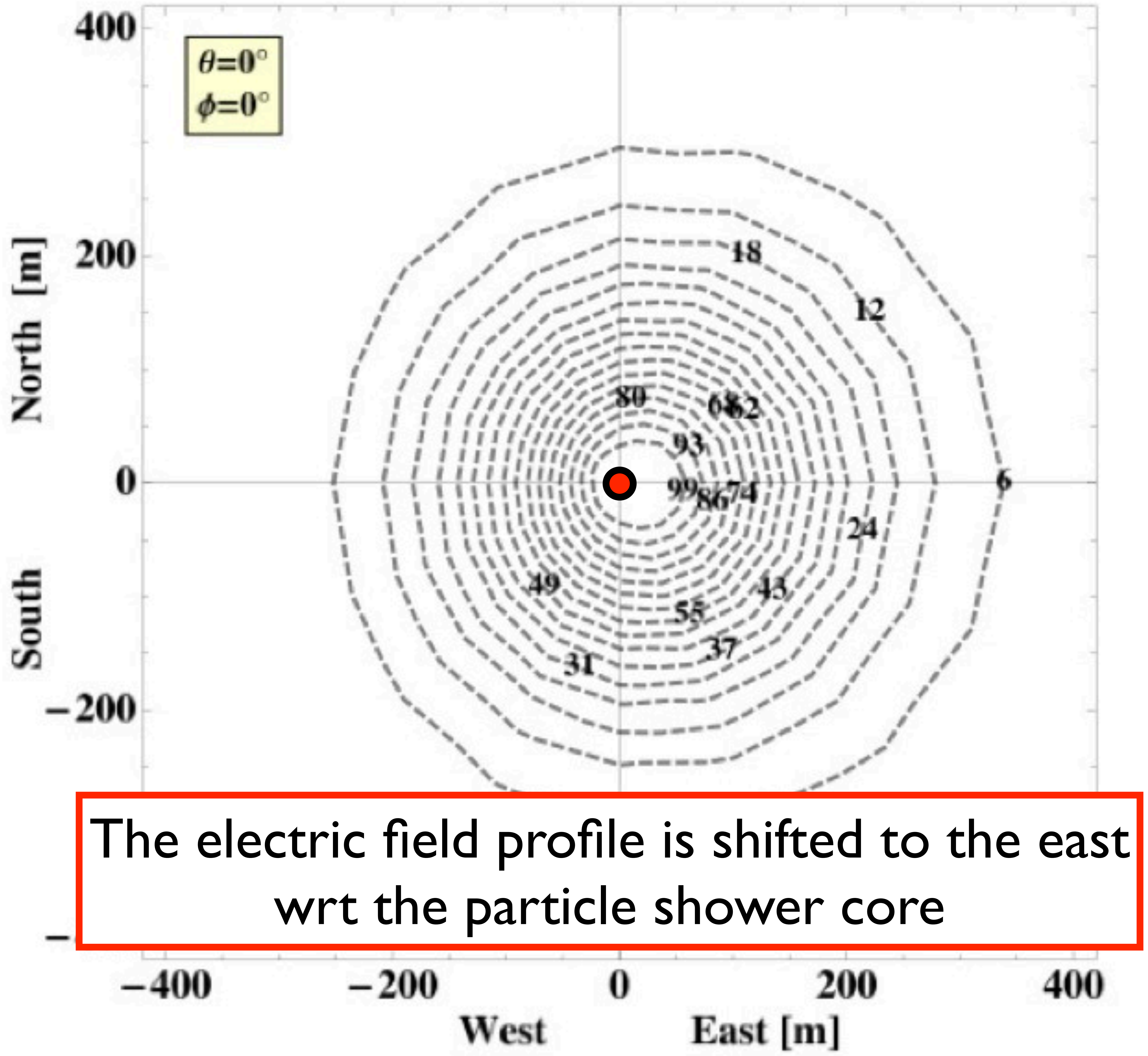
Secondary effect: the charge excess



The CODALEMA experiment (EW data)

Marin, ICRC 2011

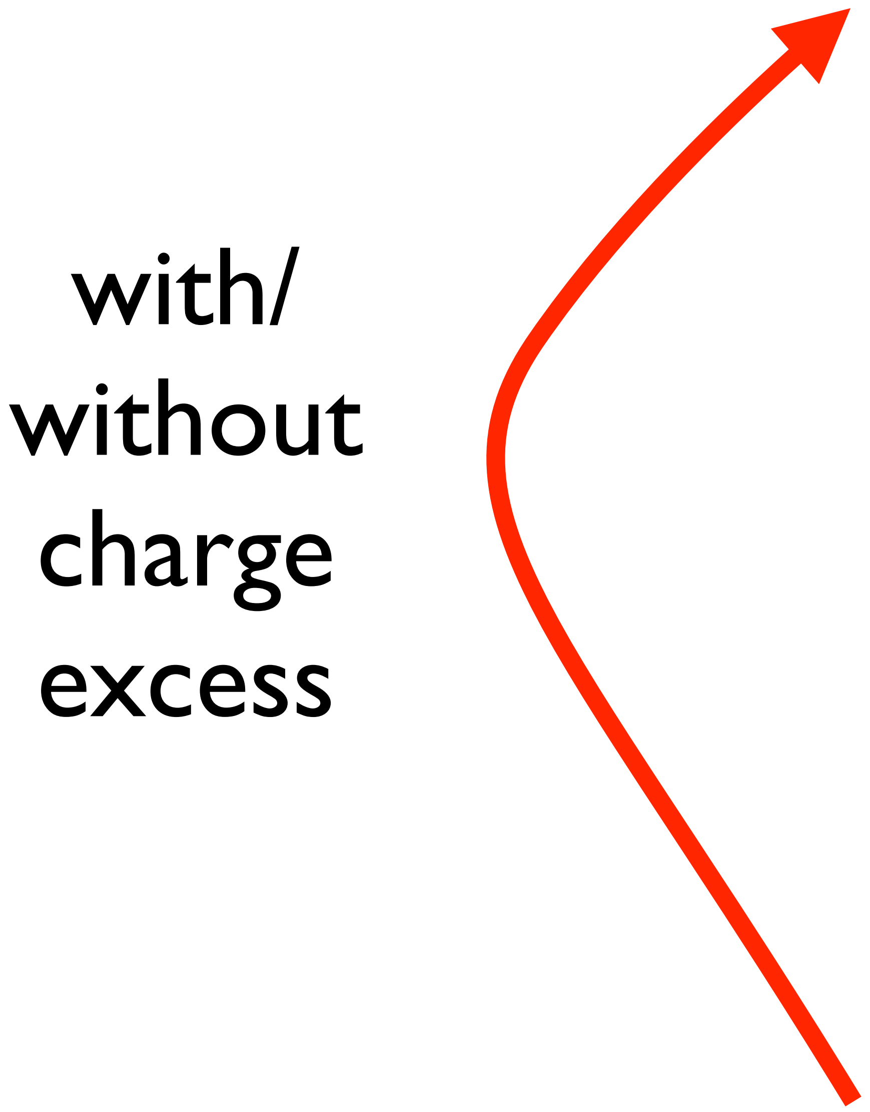
Secondary effect: the charge excess



The electric field profile is shifted to the east wrt the particle shower core

The CODALEMA experiment (EW data)

Marin, ICRC 2011



1) simulate N showers having the same arrival directions than the data (N is the number of showers actually detected), all showers have the “particle” core in (0,0)

2) compute the electric field at the same positions than the CODALEMA antennas

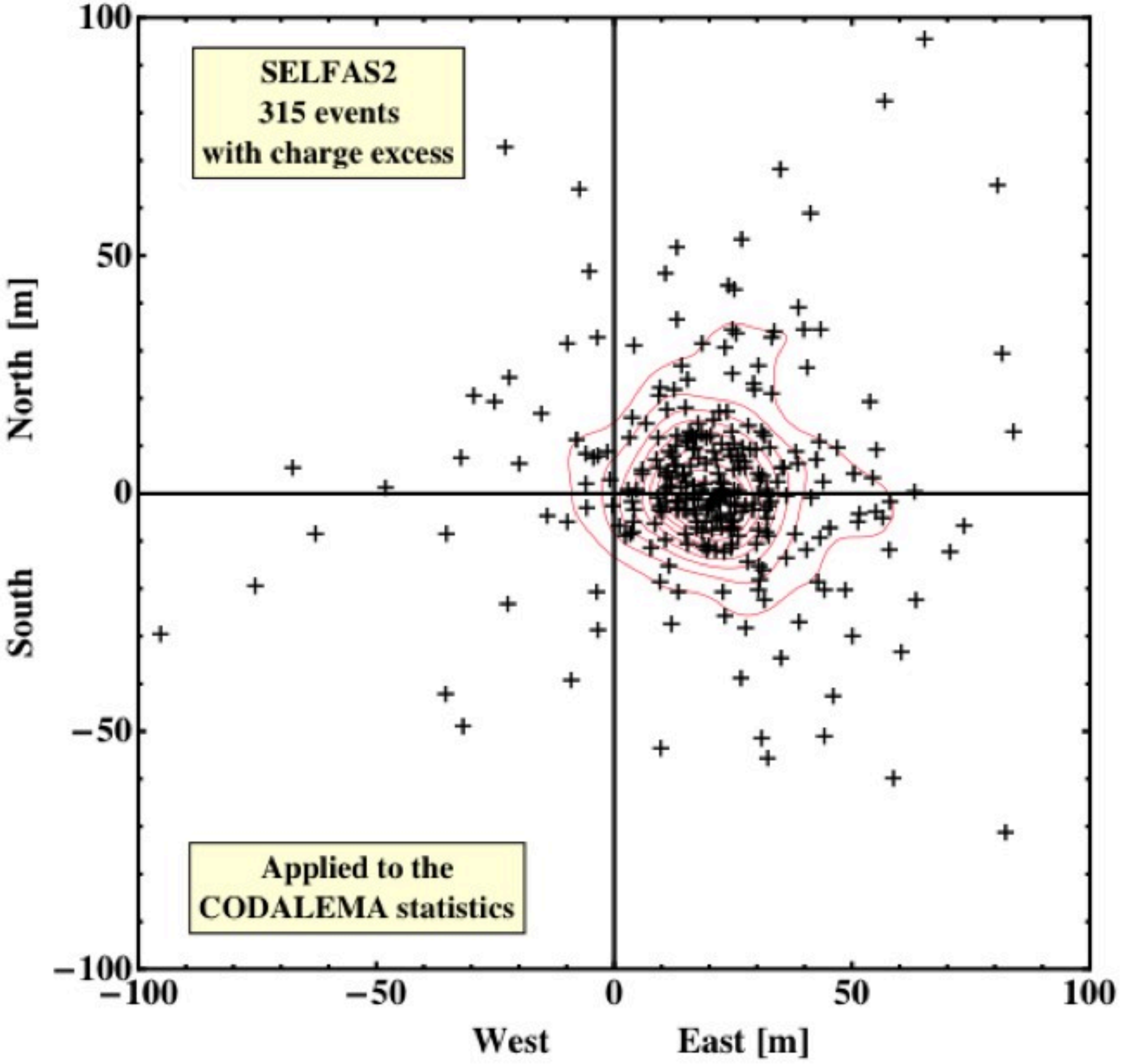
3) estimate the radio core using an exponential profile

4) compare the “particle” core position - here (0,0) - and the radio core position

The CODALEMA experiment (EW data)

Marin, ICRC 2011

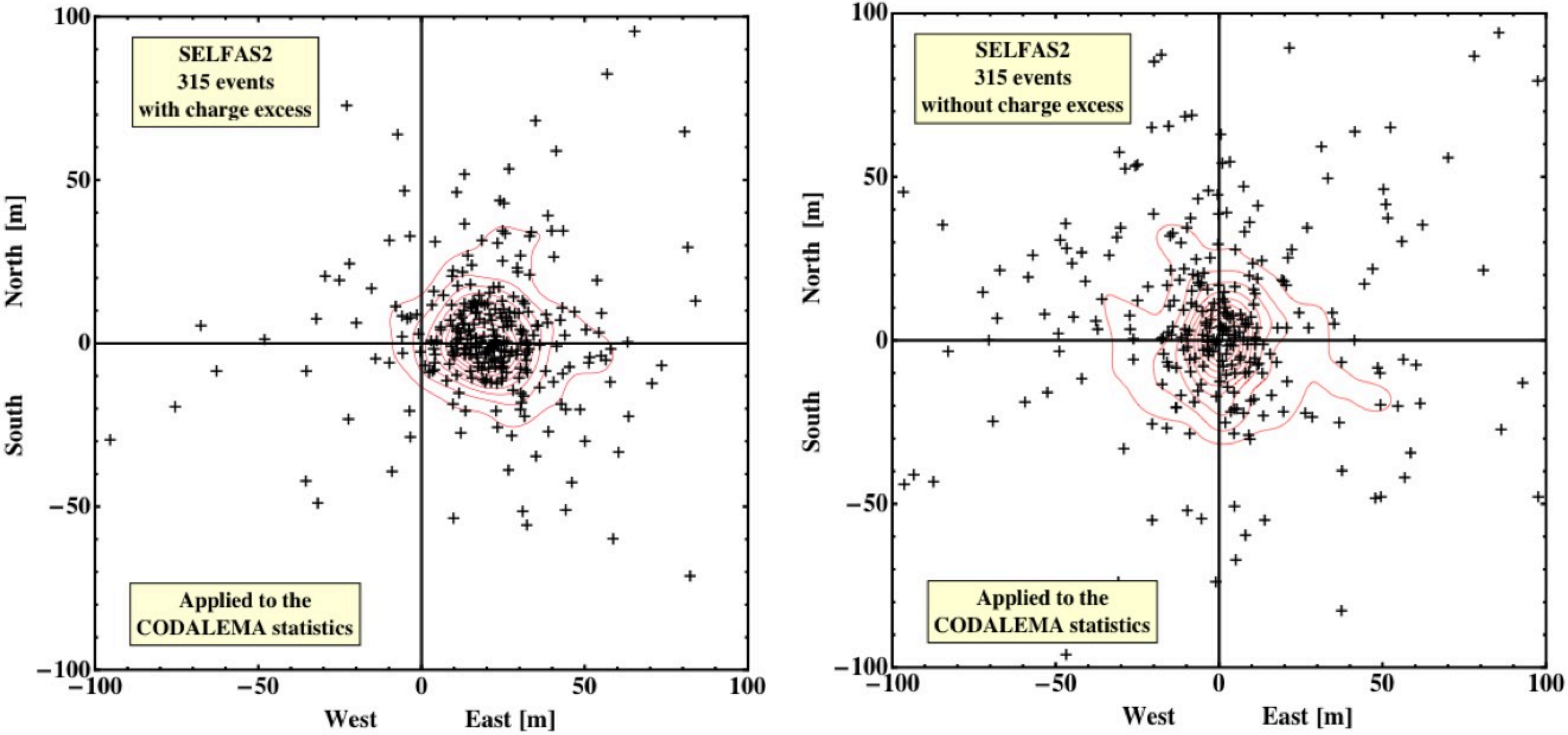
radio core positions in the reference frame of the particle shower core (simulation)



The CODALEMA experiment (EW data)

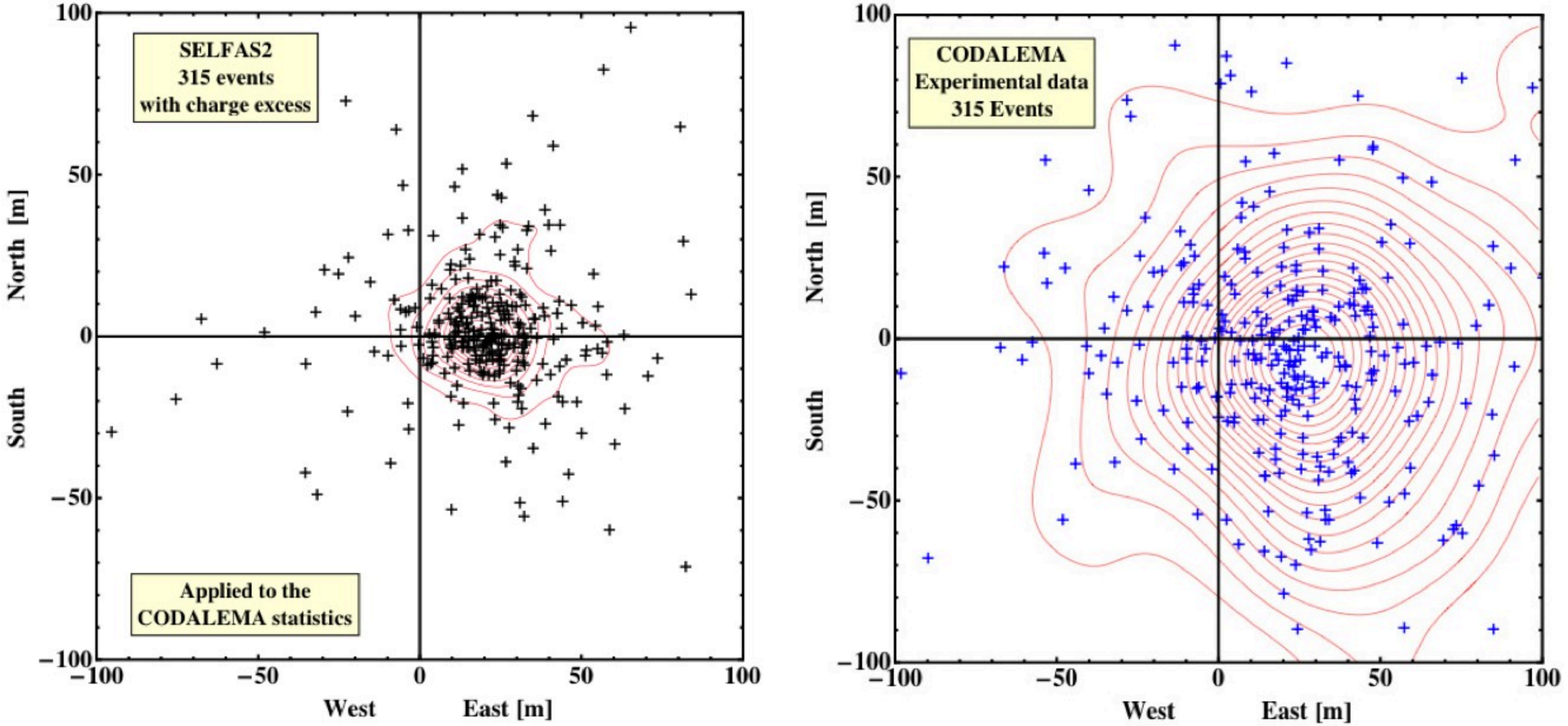
Marin, ICRC 2011

radio core positions in the reference frame of the particle shower core (simulation)



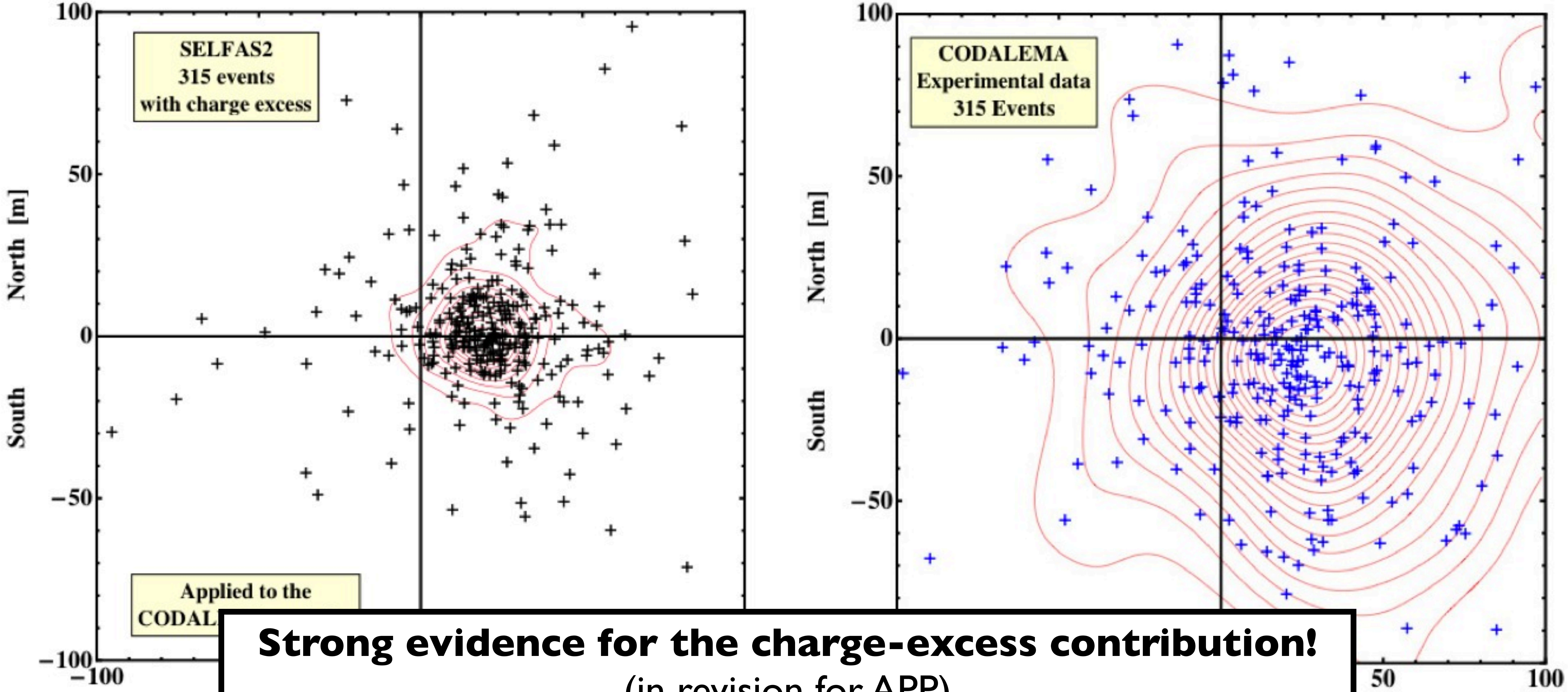
The CODALEMA experiment (EW data)

Marin, ICRC 2011



The CODALEMA experiment (EW data)

Marin, ICRC 2011



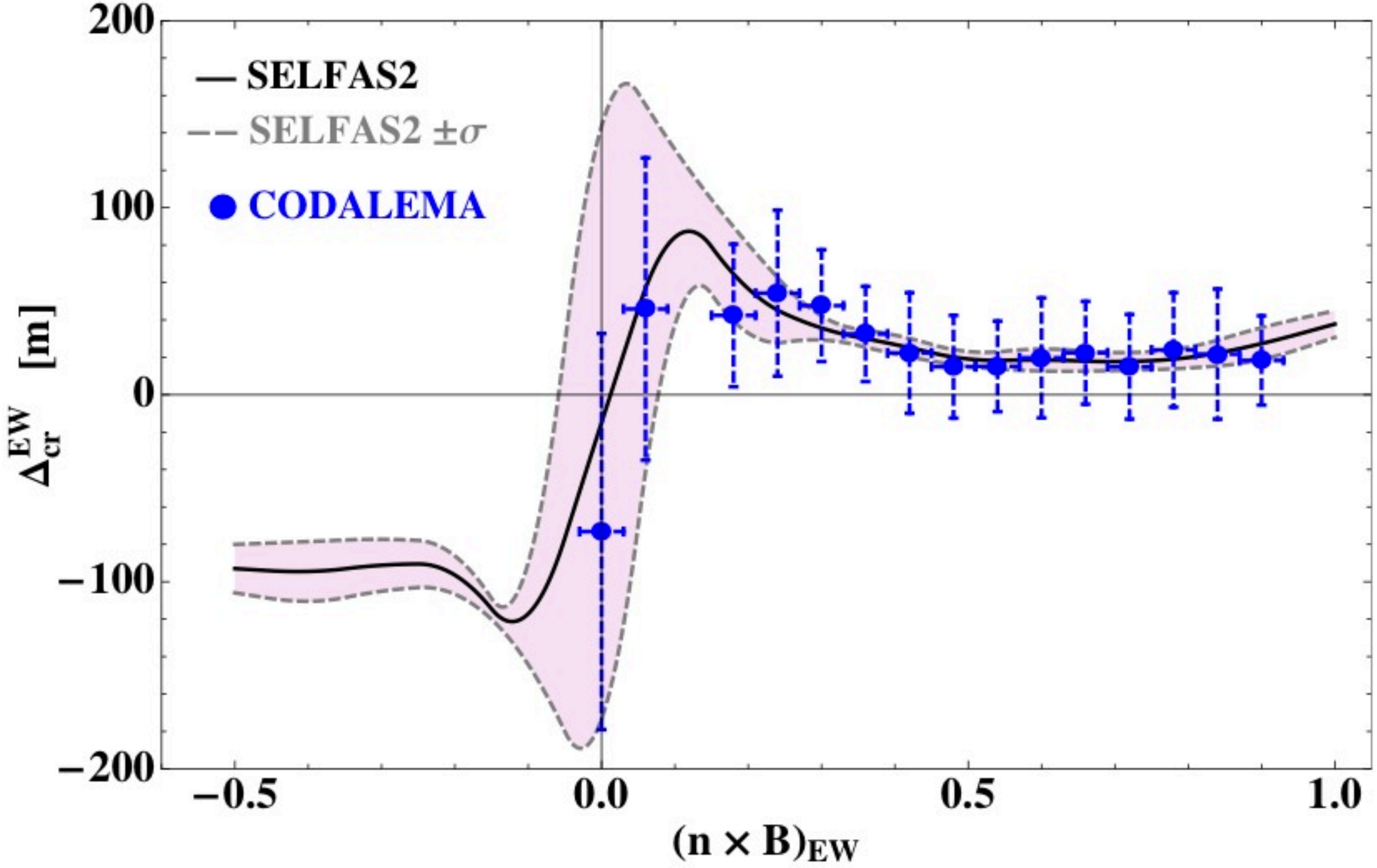
Strong evidence for the charge-excess contribution!

(in revision for APP)

The CODALEMA experiment (EW data)

Marin, ICRC 2011

then quantify the shift in bins of n X B:

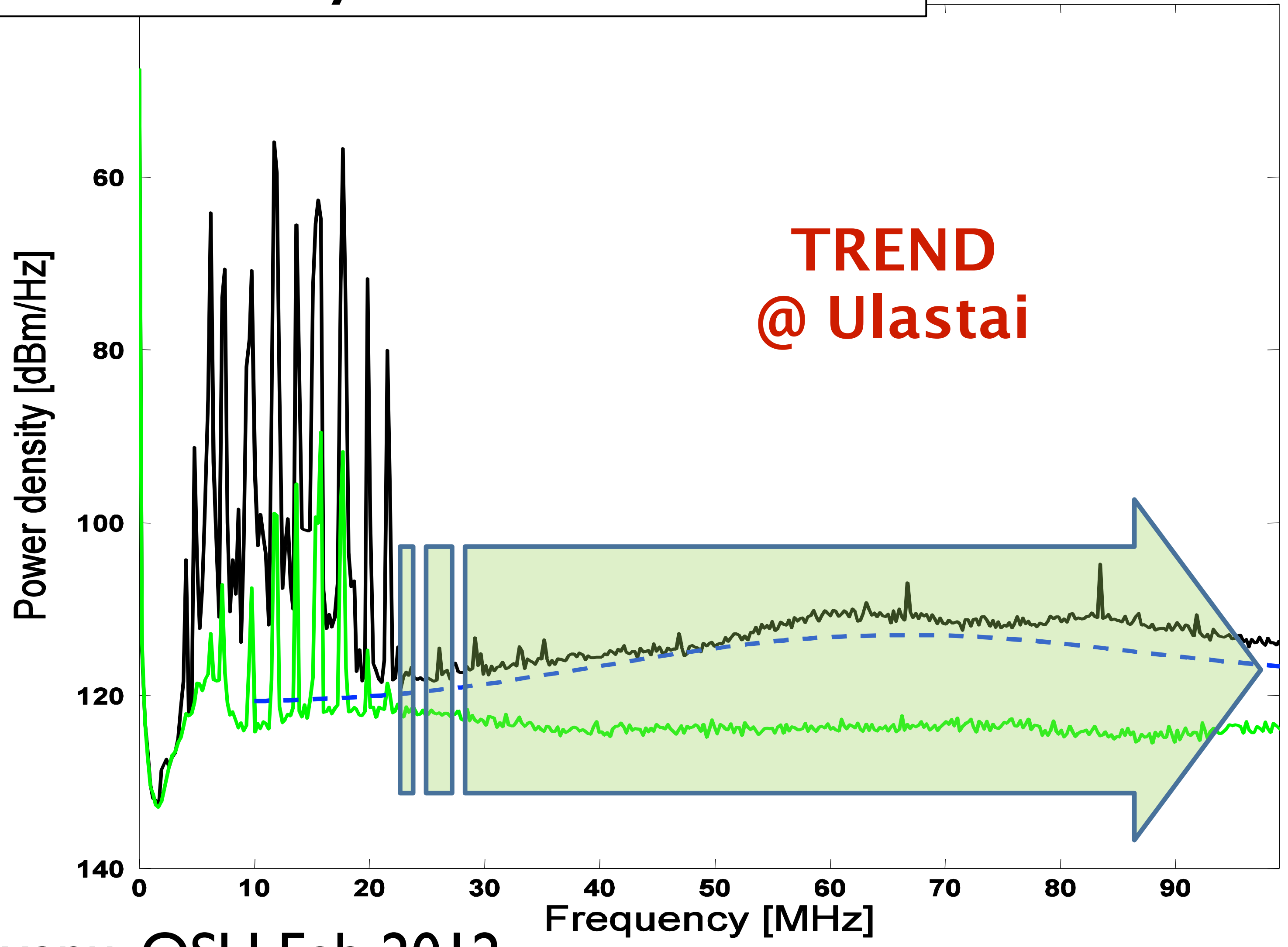


The TREND experiment

use the infrastructures of the 21CMA radio-interferometer (electronics and DAQ)

autonomous EAS radiodetection
+ high energy neutrinos

Martineau-Huynh, ICGAC 2011

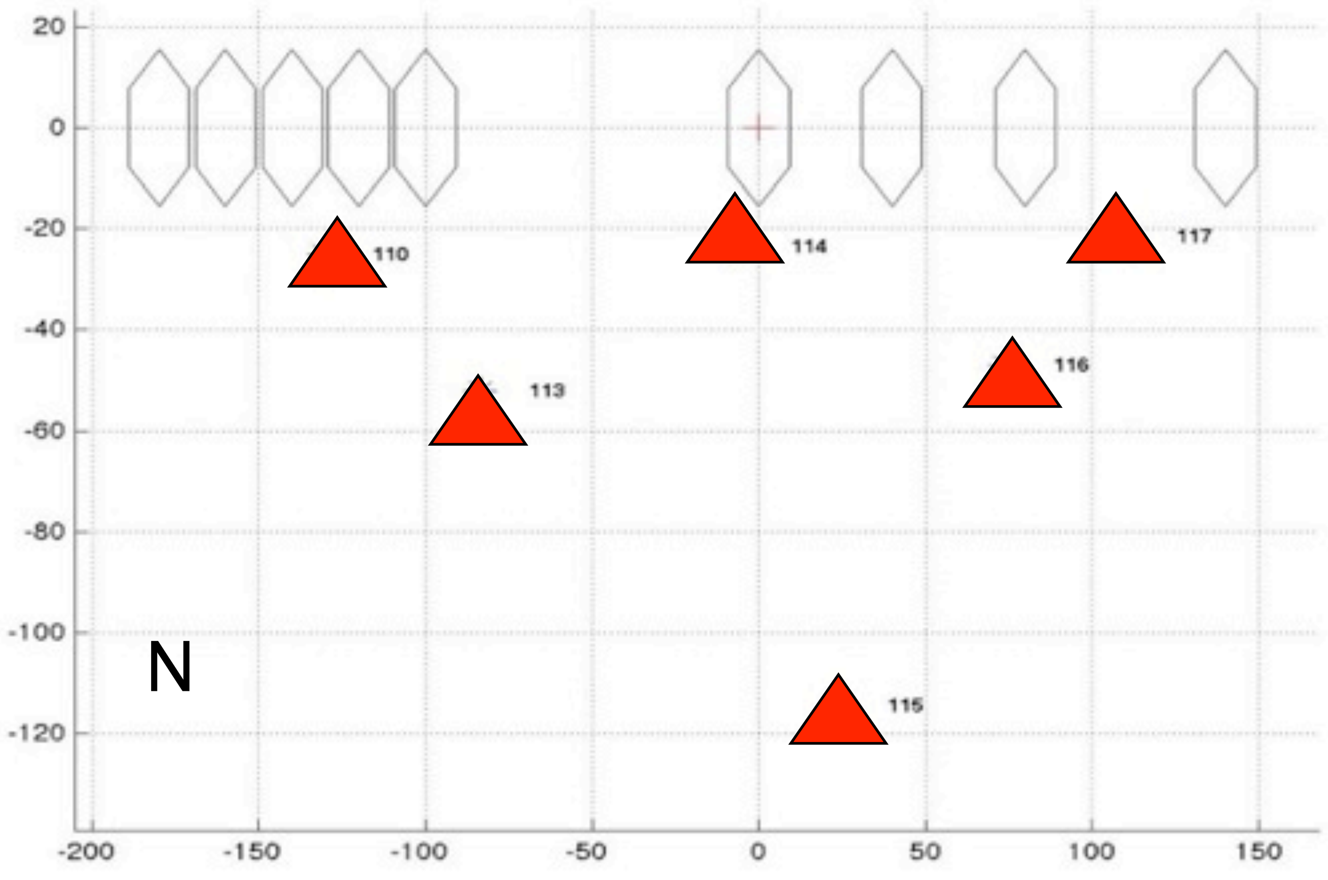


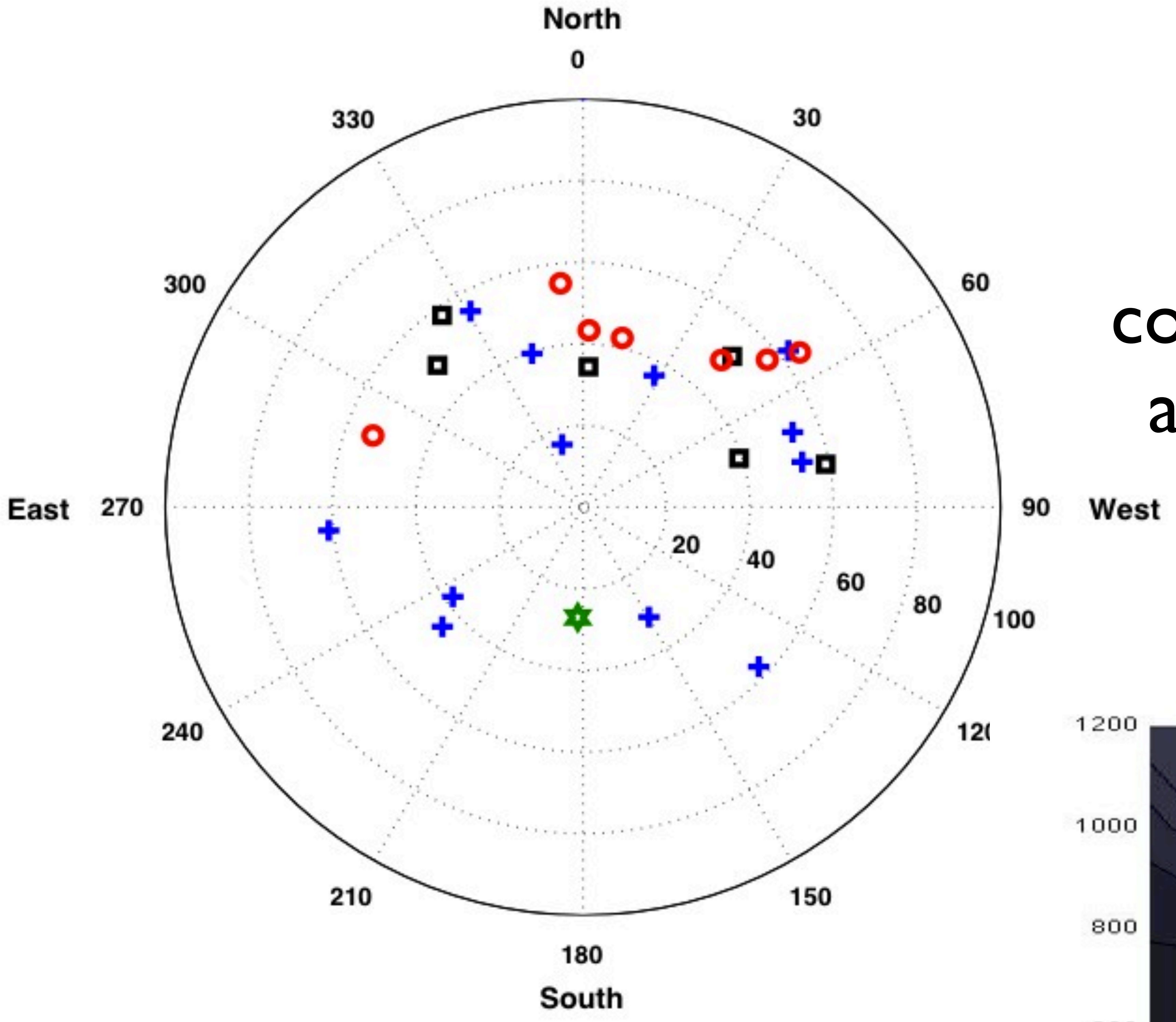
21CMA:
log-periodic antennas
3 km x 4 km

use some of them for TREND
200 Ms/s
offline analysis

The TREND experiment

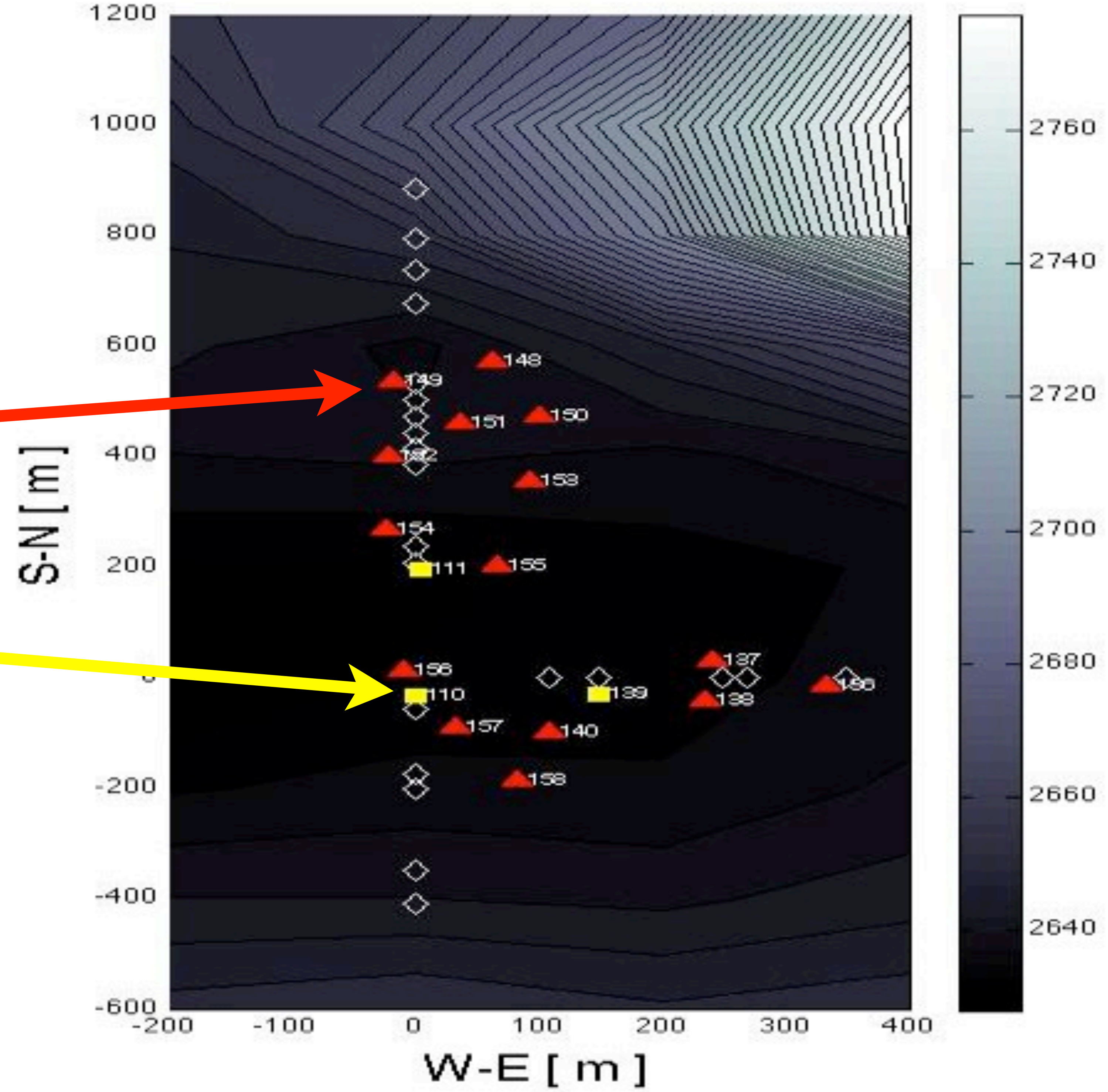
Martineau-Huynh, ICGAC 2011





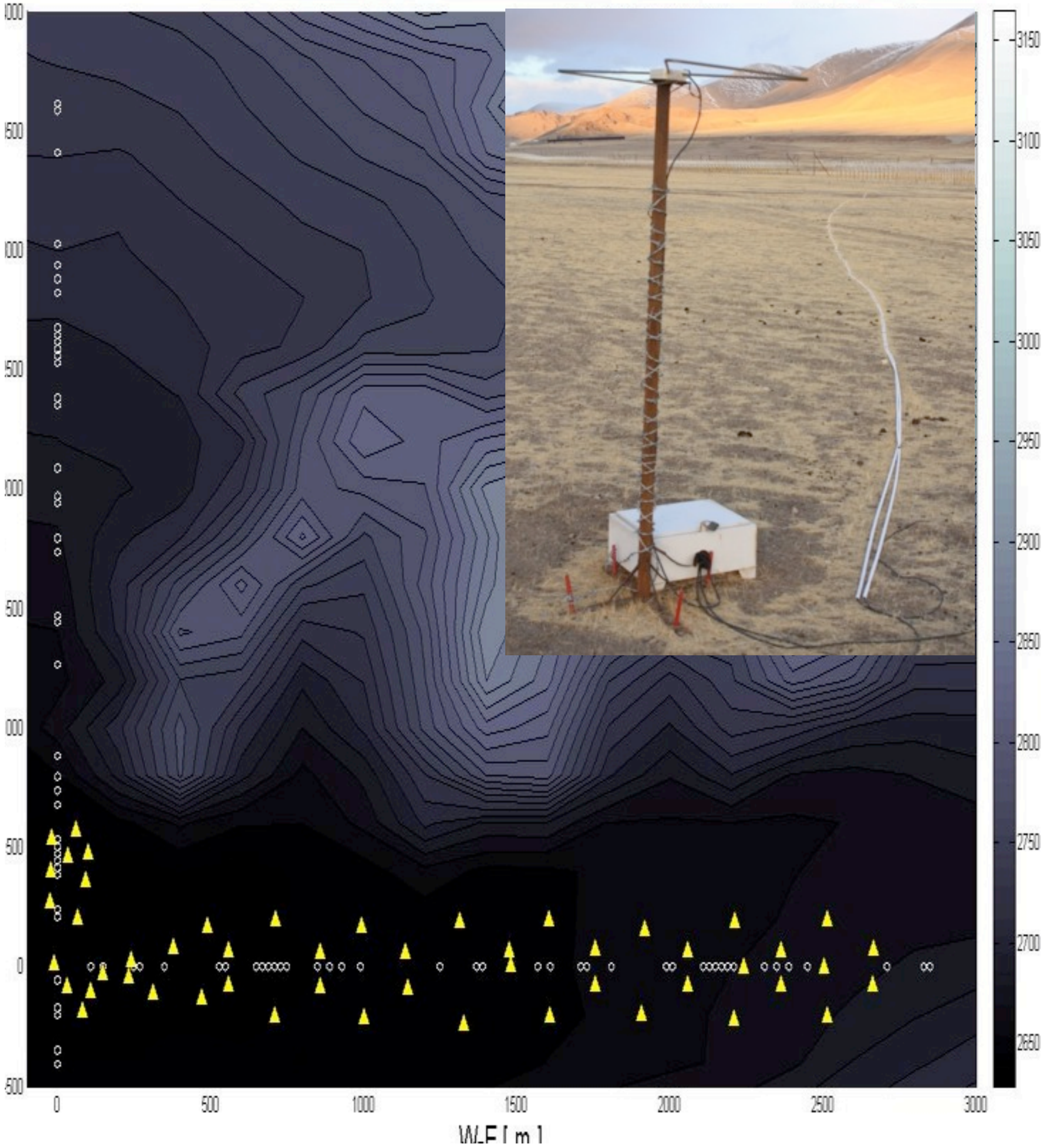
2009: validation of the concept with 6 log-periodic antennas (250m x 100m), 25 candidates

2010: array of 15 log-periodic antennas and 3 particle detectors got 13 hybrid events (6 with more than 4 antennas, reconstruction OK with scintillators)



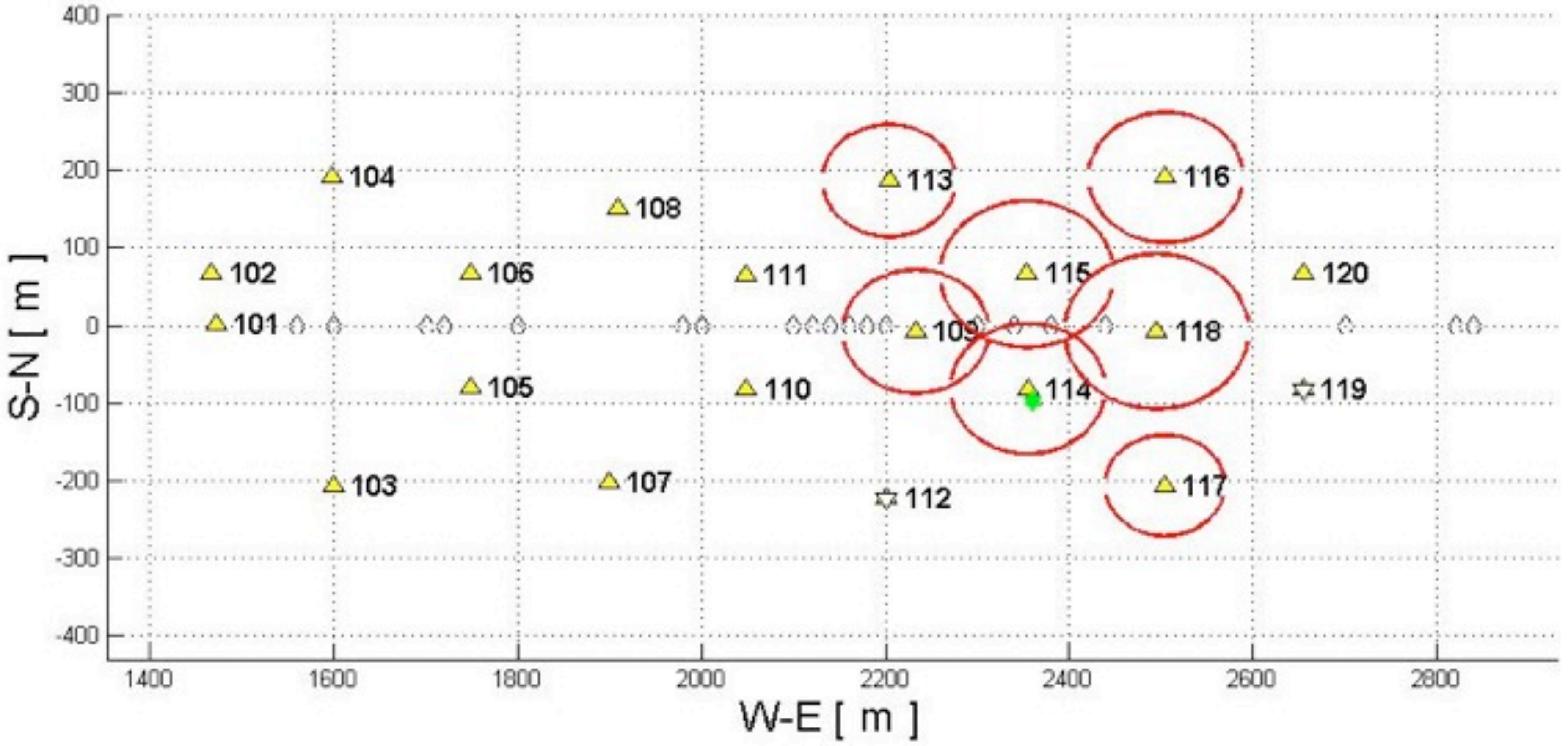
The TREND experiment

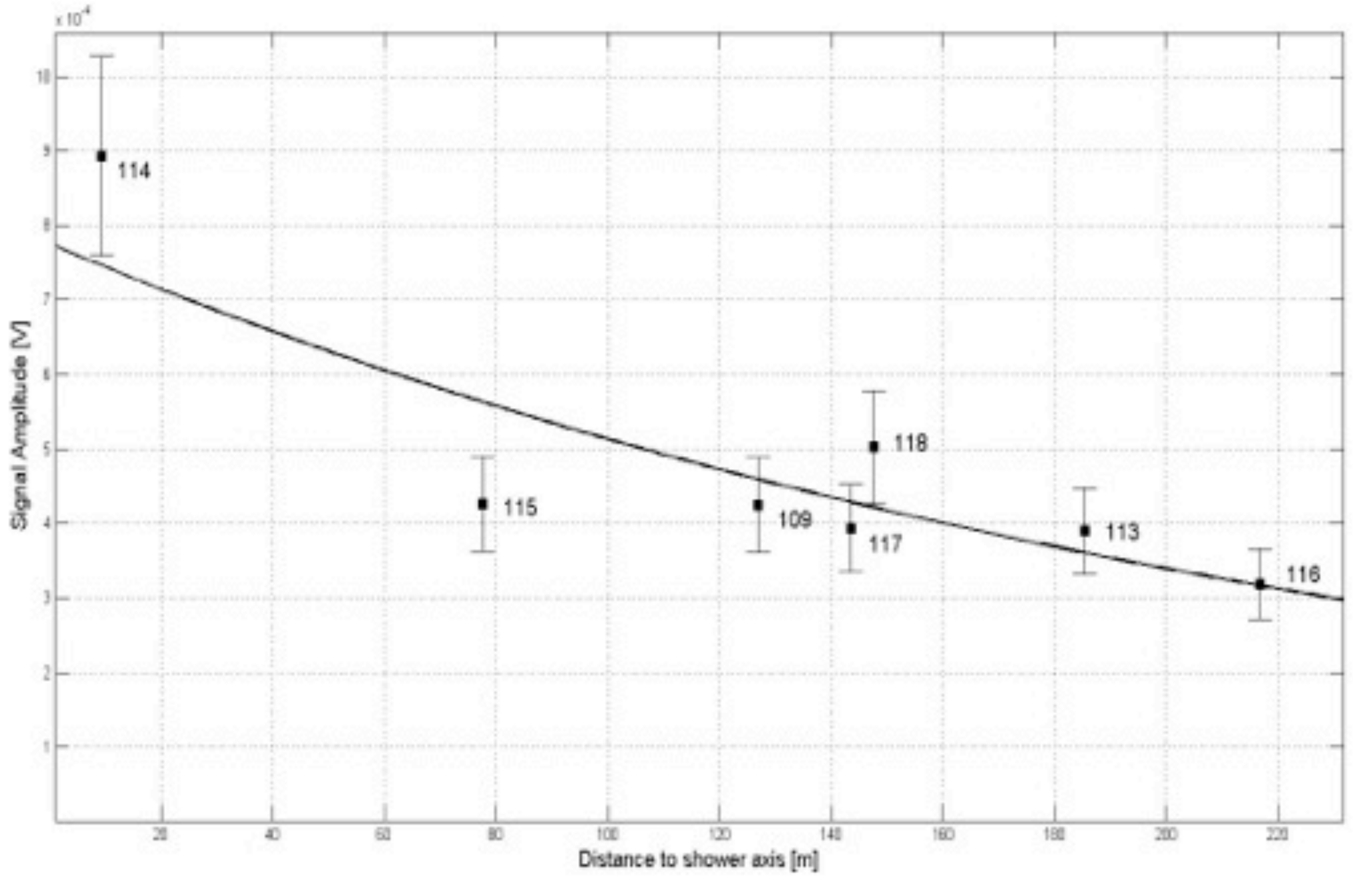
Martineau-Huynh, ICGAC 2011



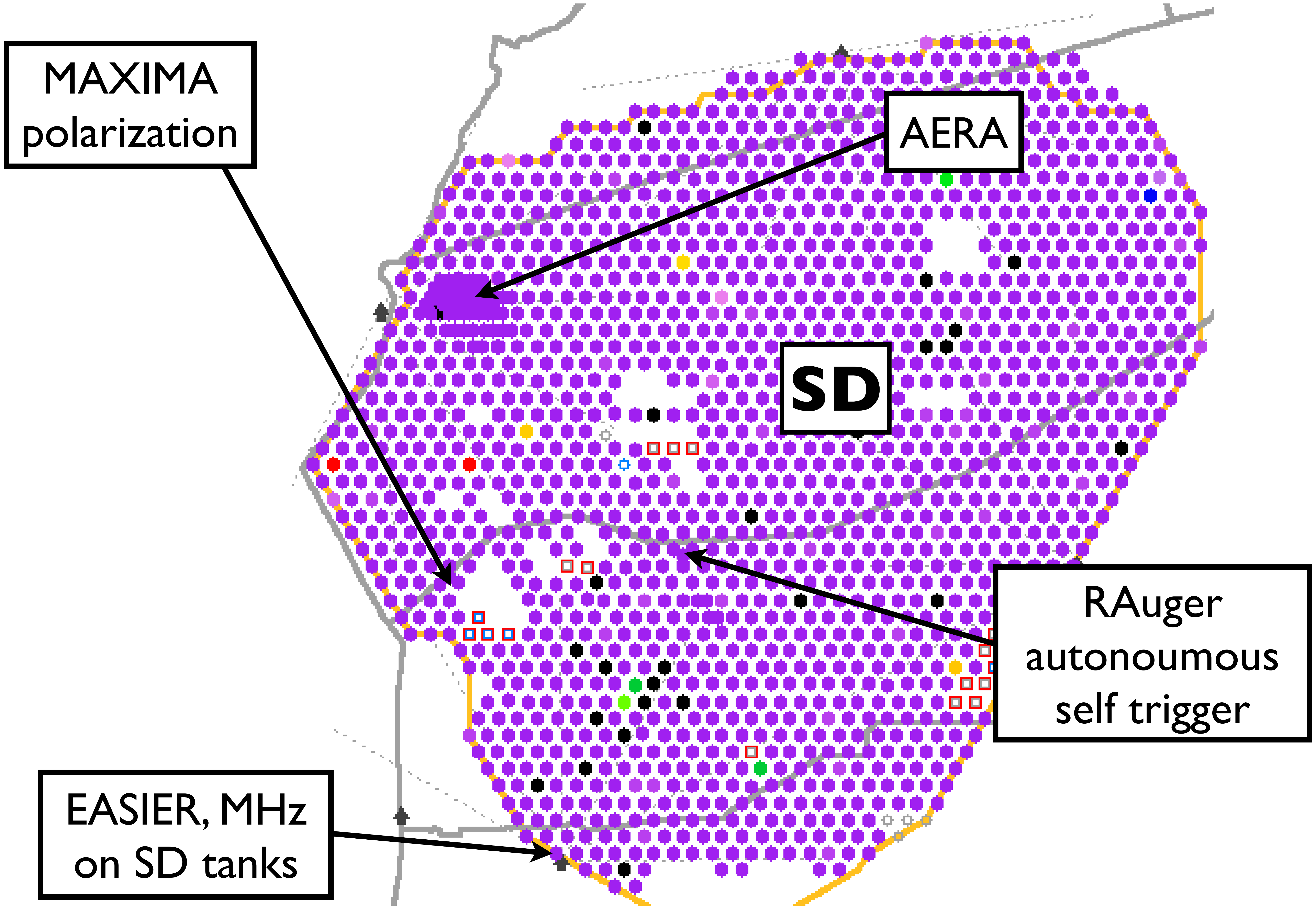
2011: extension to 50 butterfly antennas from CODALEMA to reach 1.5 km^2

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





Radio detection in Argentina



MAXIMA polarization

AERA

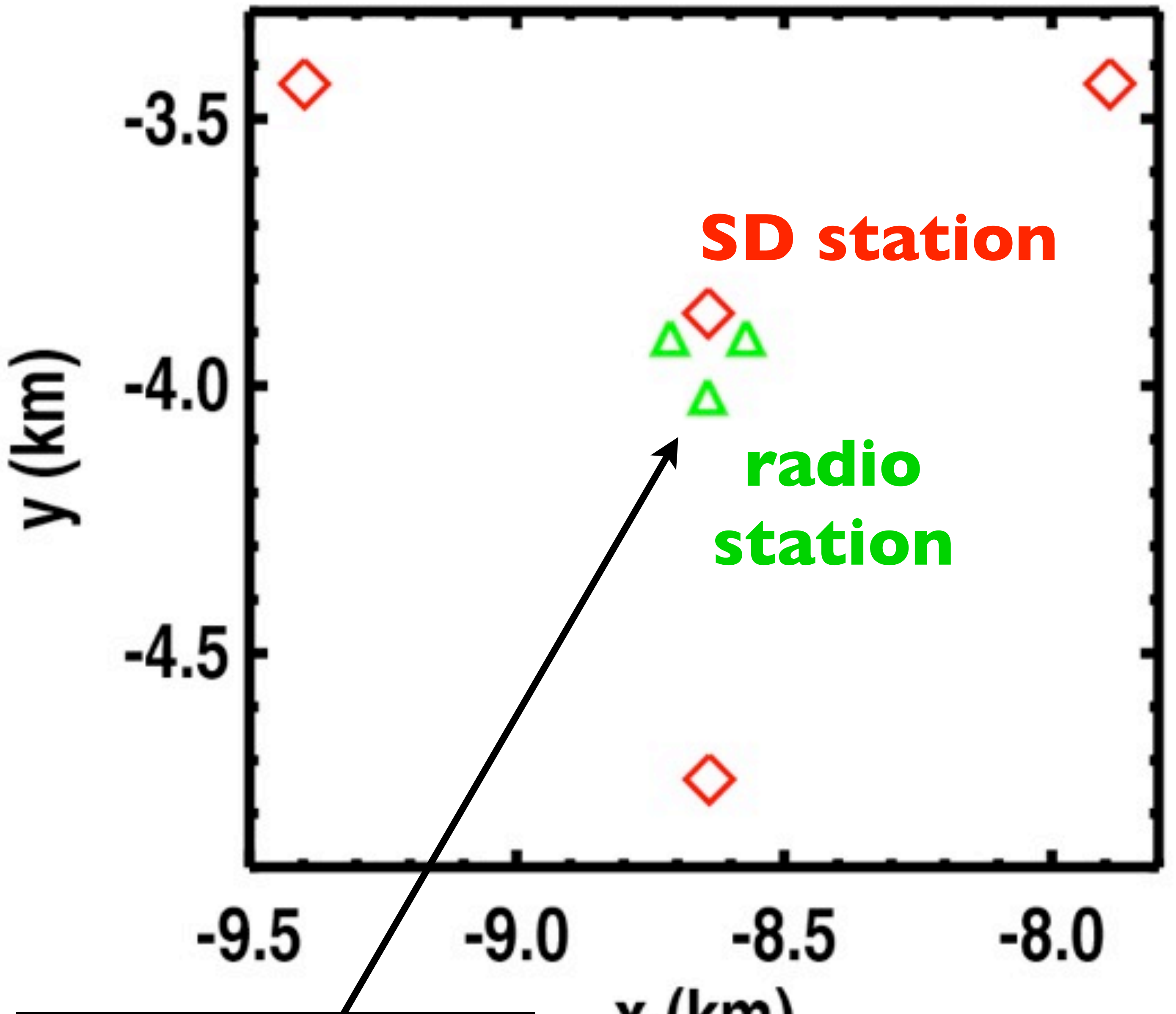
SD

RAuger autonoumous self trigger

EASIER, MHz on SD tanks

RAuger: self-trigger

Revenu, ICRC 2011

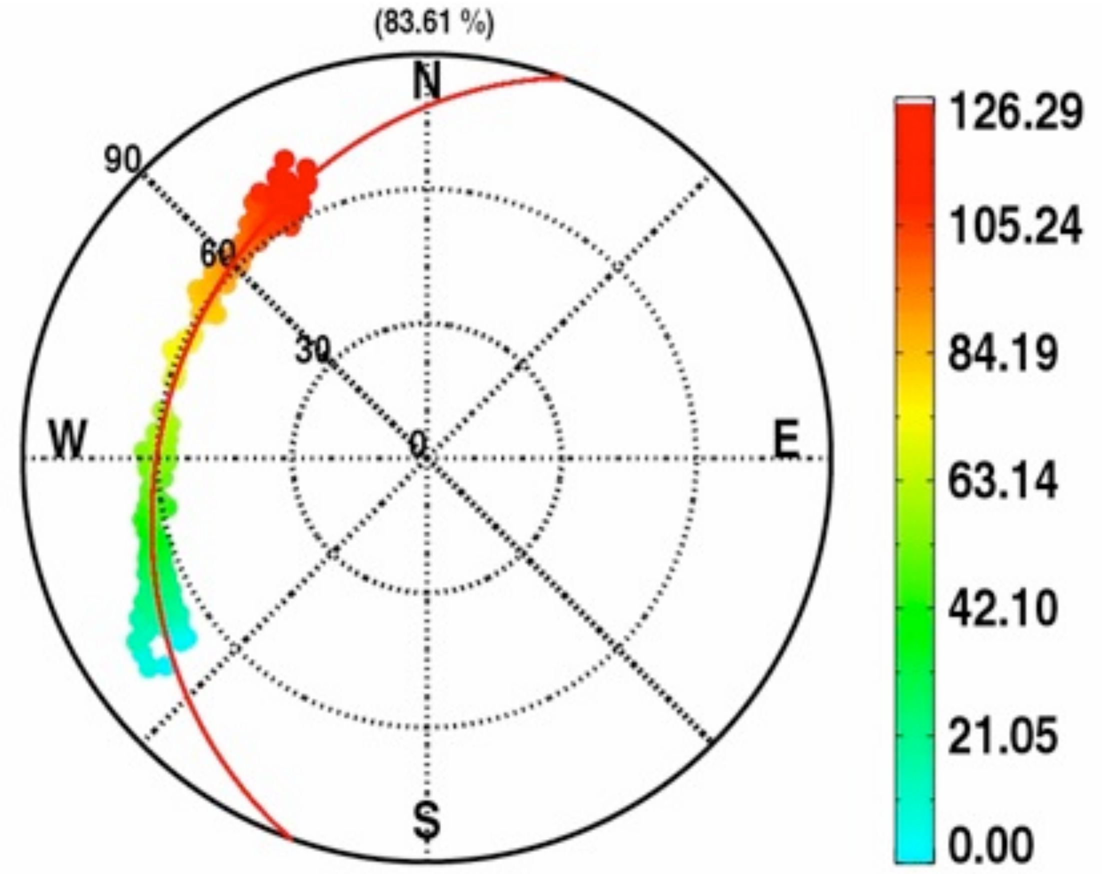


3 autonomous radio stations
with an independent trigger

140 m distance

Butterfly antenna (20-250 MHz),
in both EW and NS polarizations

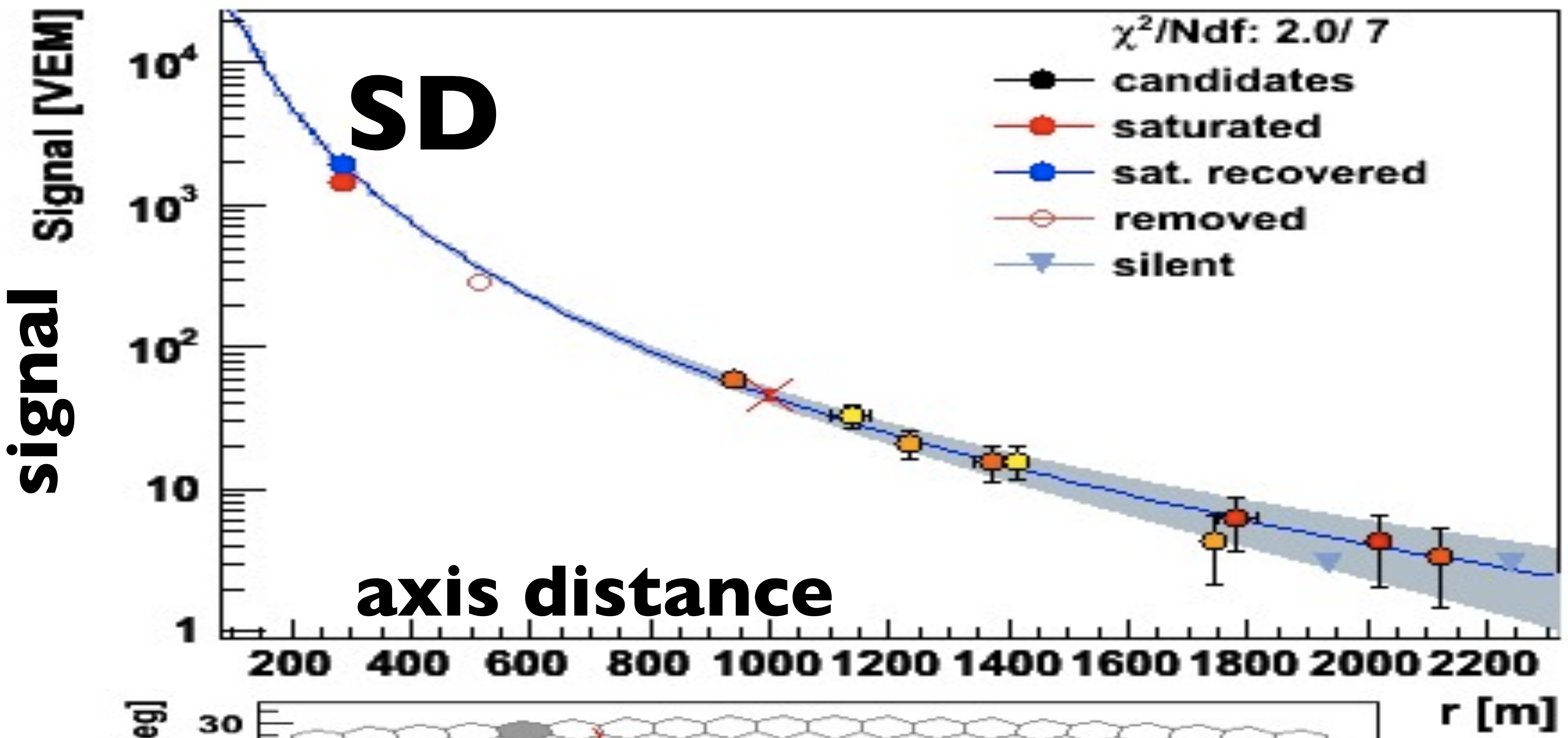
analog trigger with threshold in 45-55 MHz
sampling frequency: 1 GHz (2.5 µs)

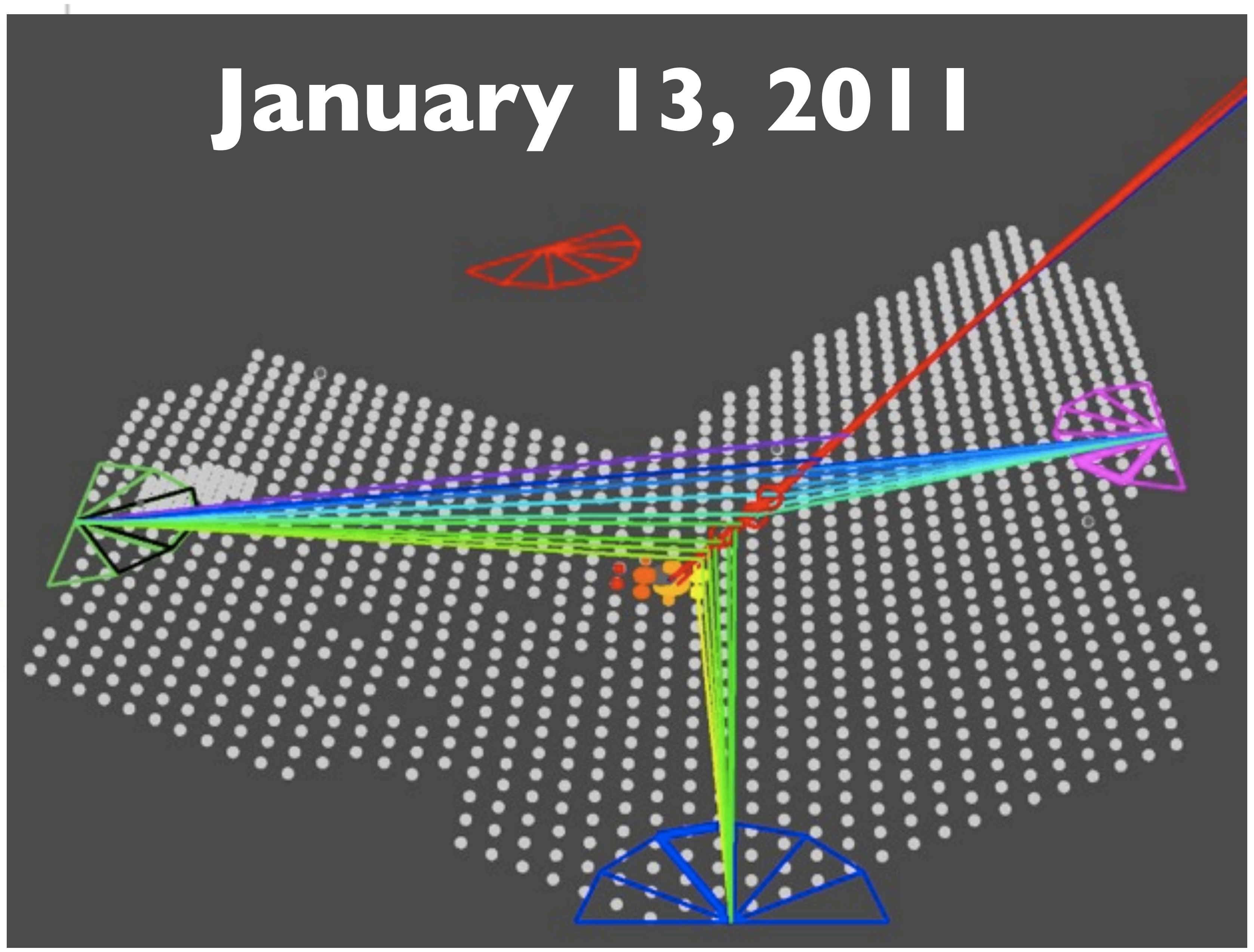


angular resolution = **0.5°**
intercalibration, polarization and lobe studies

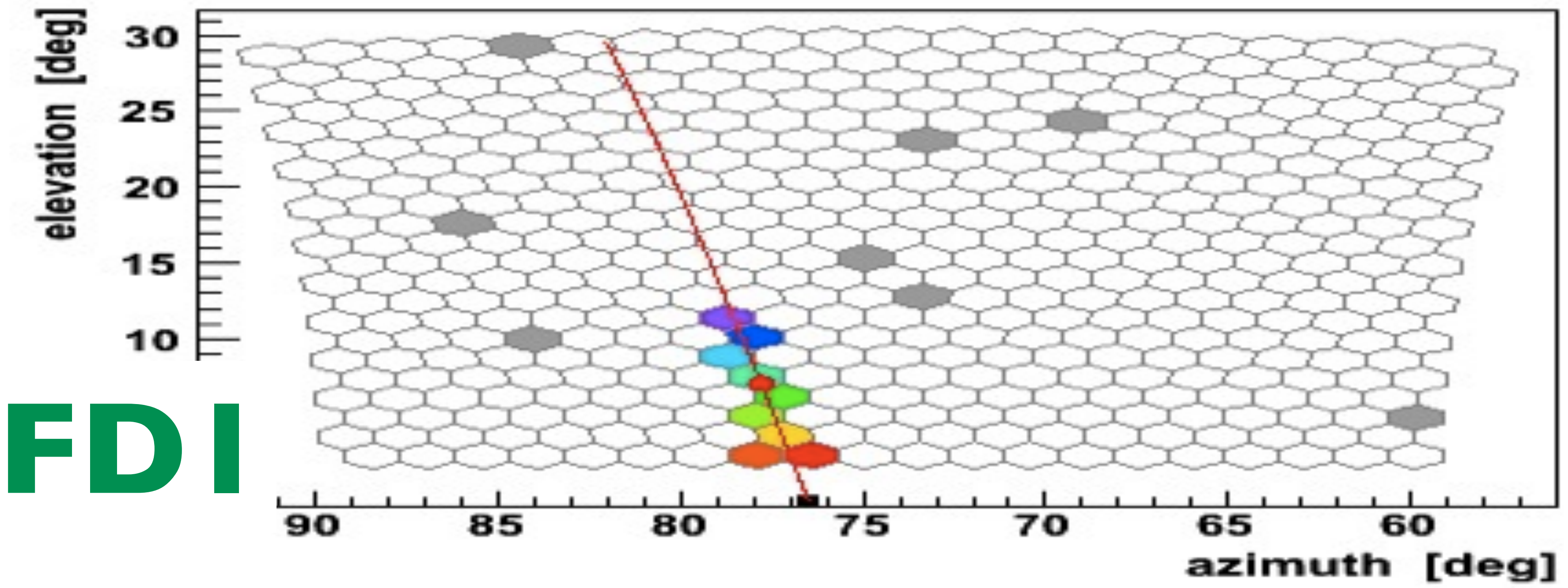
January 13, 2011

SD

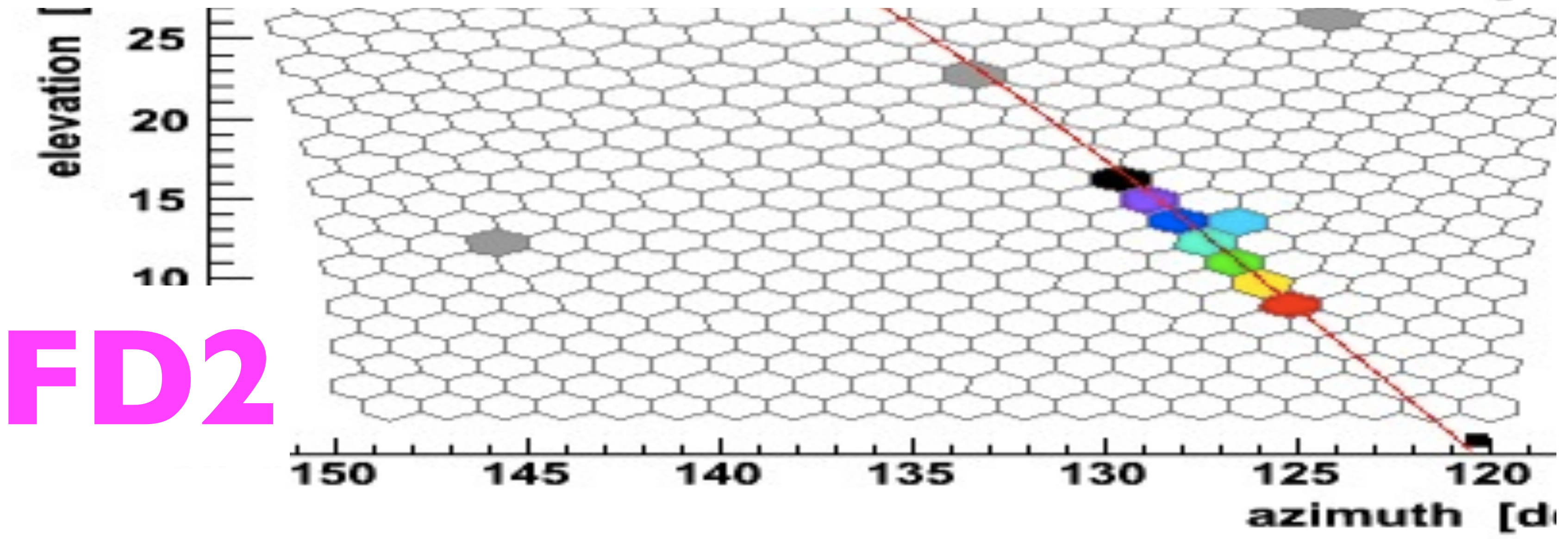




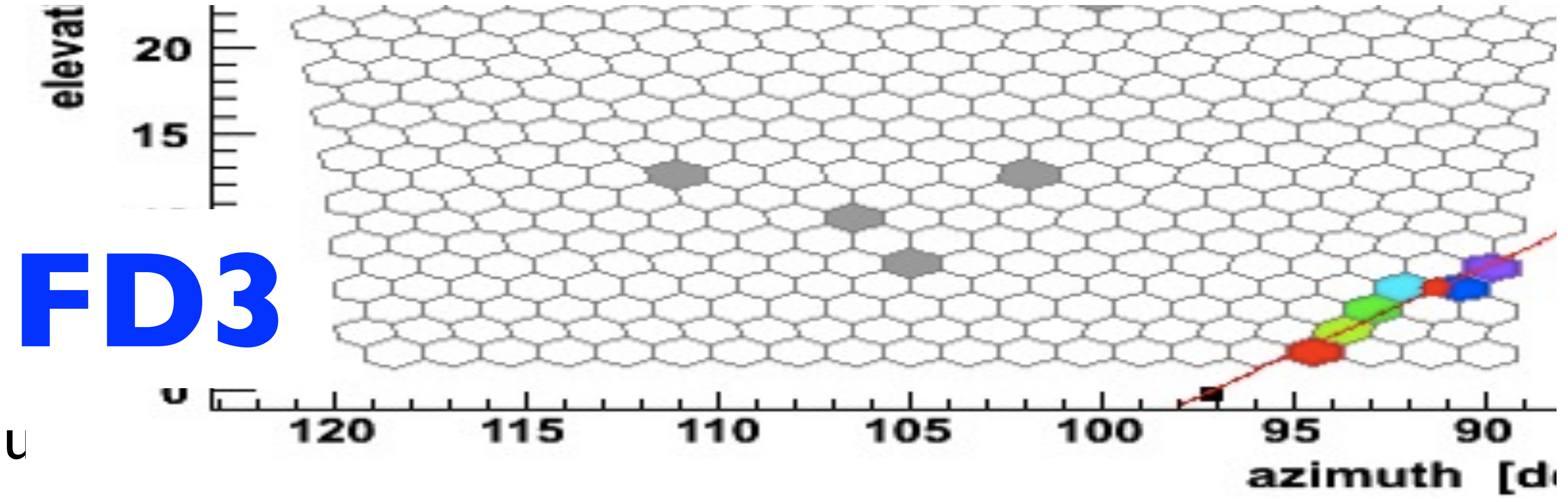
FD1



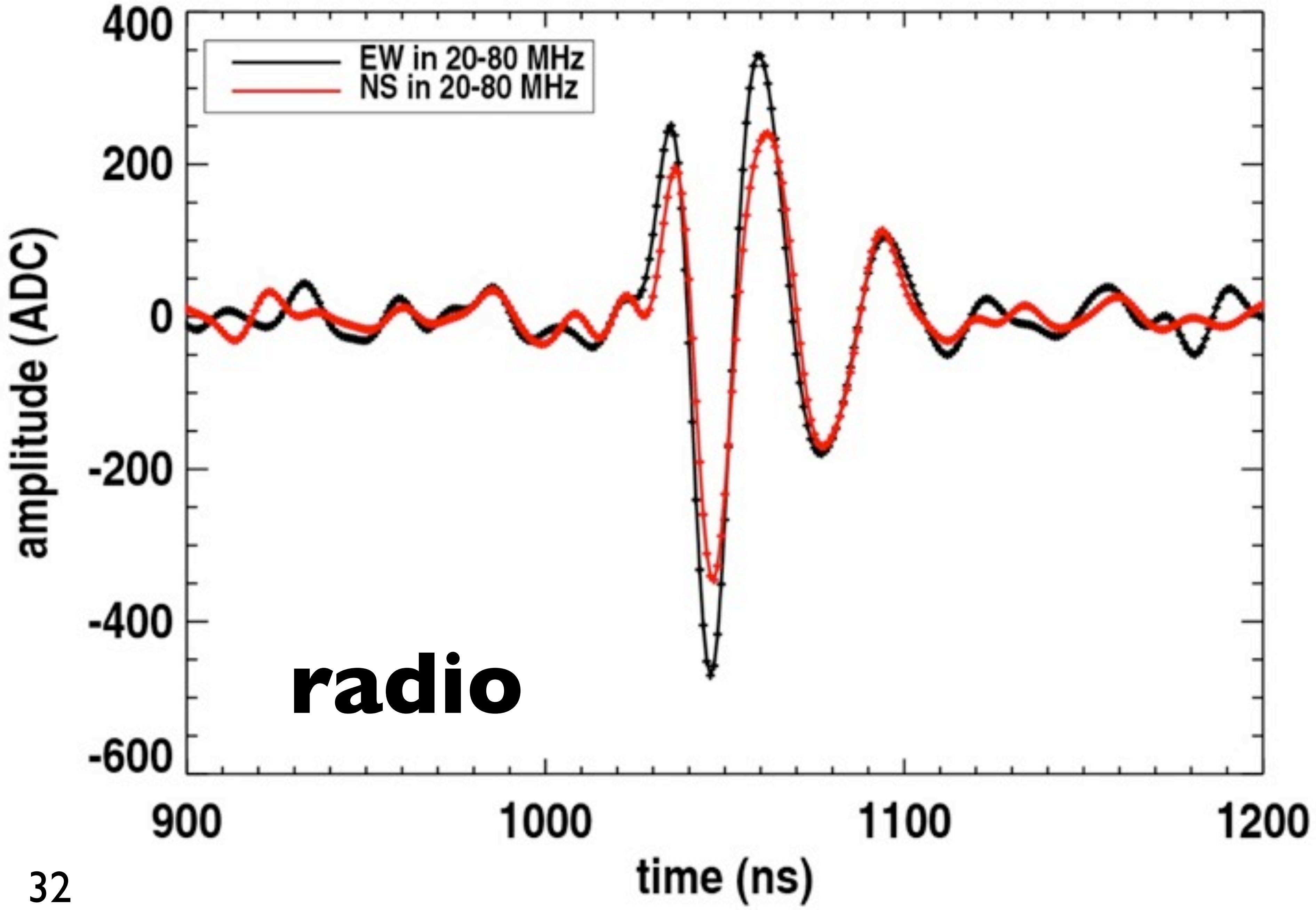
FD2



FD3



radio



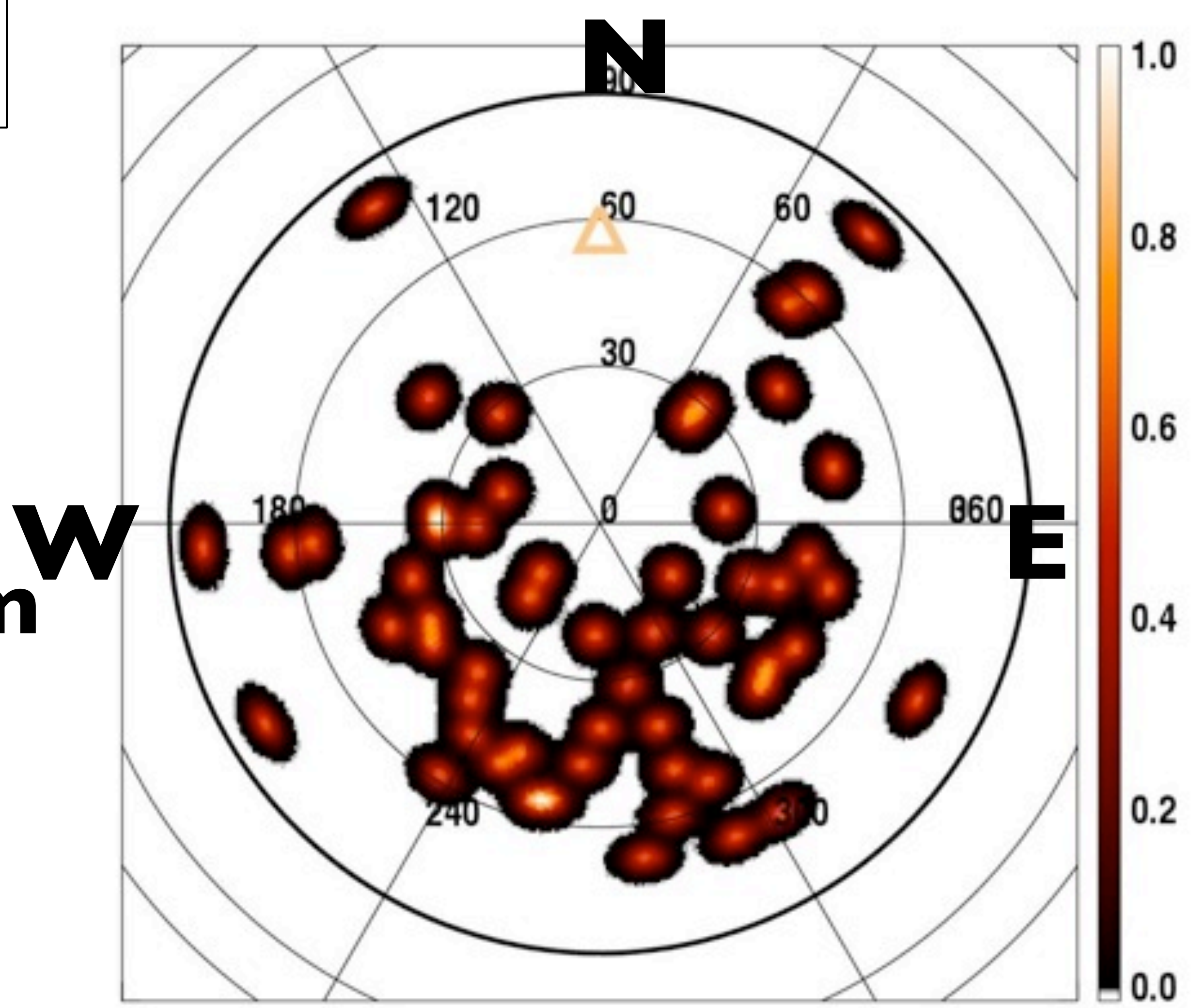
RAuger: self-trigger

Revenu, ICRC 2011

RAuger: self-trigger

Revenu, ICRC 2011

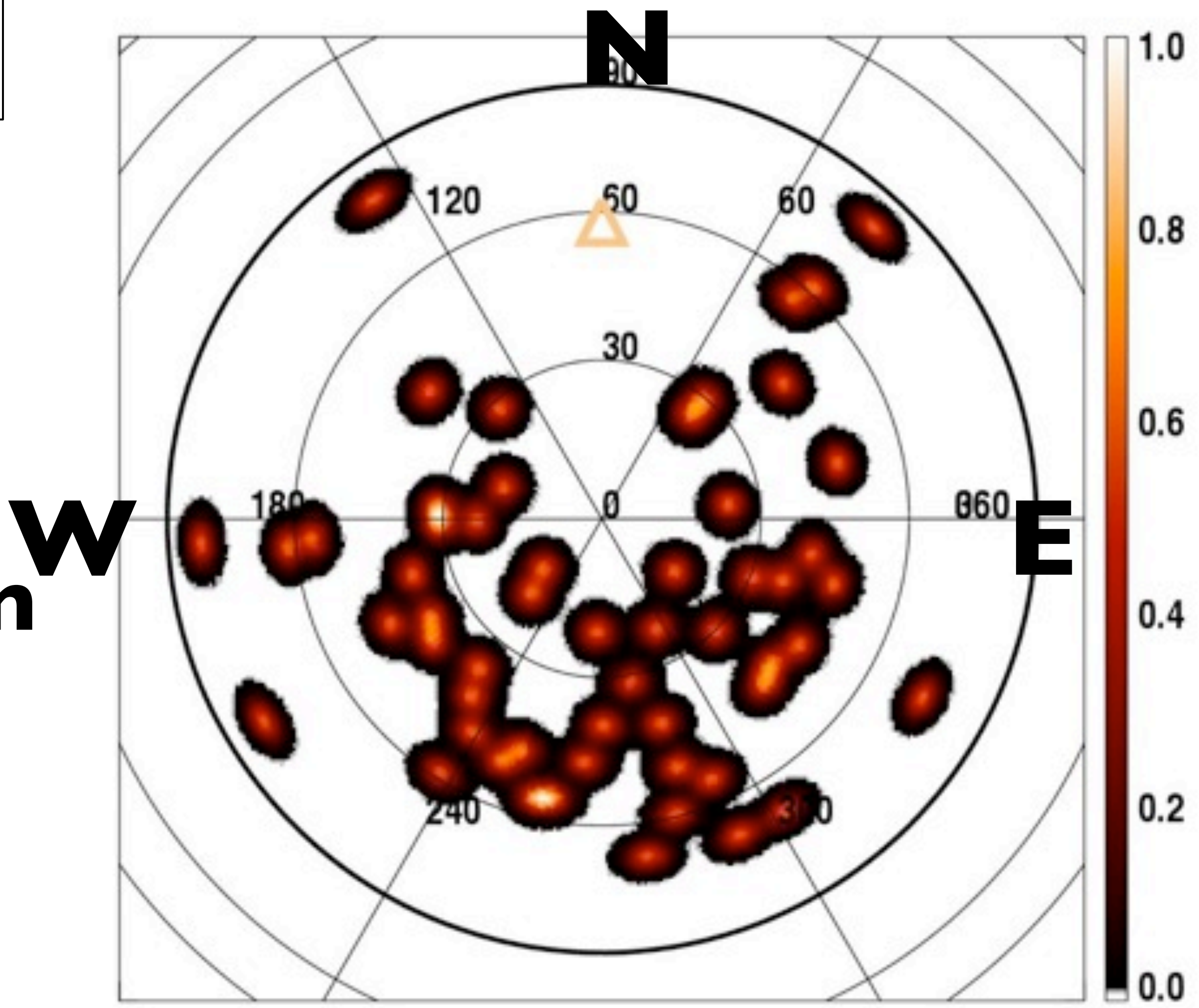
data:
76% from south

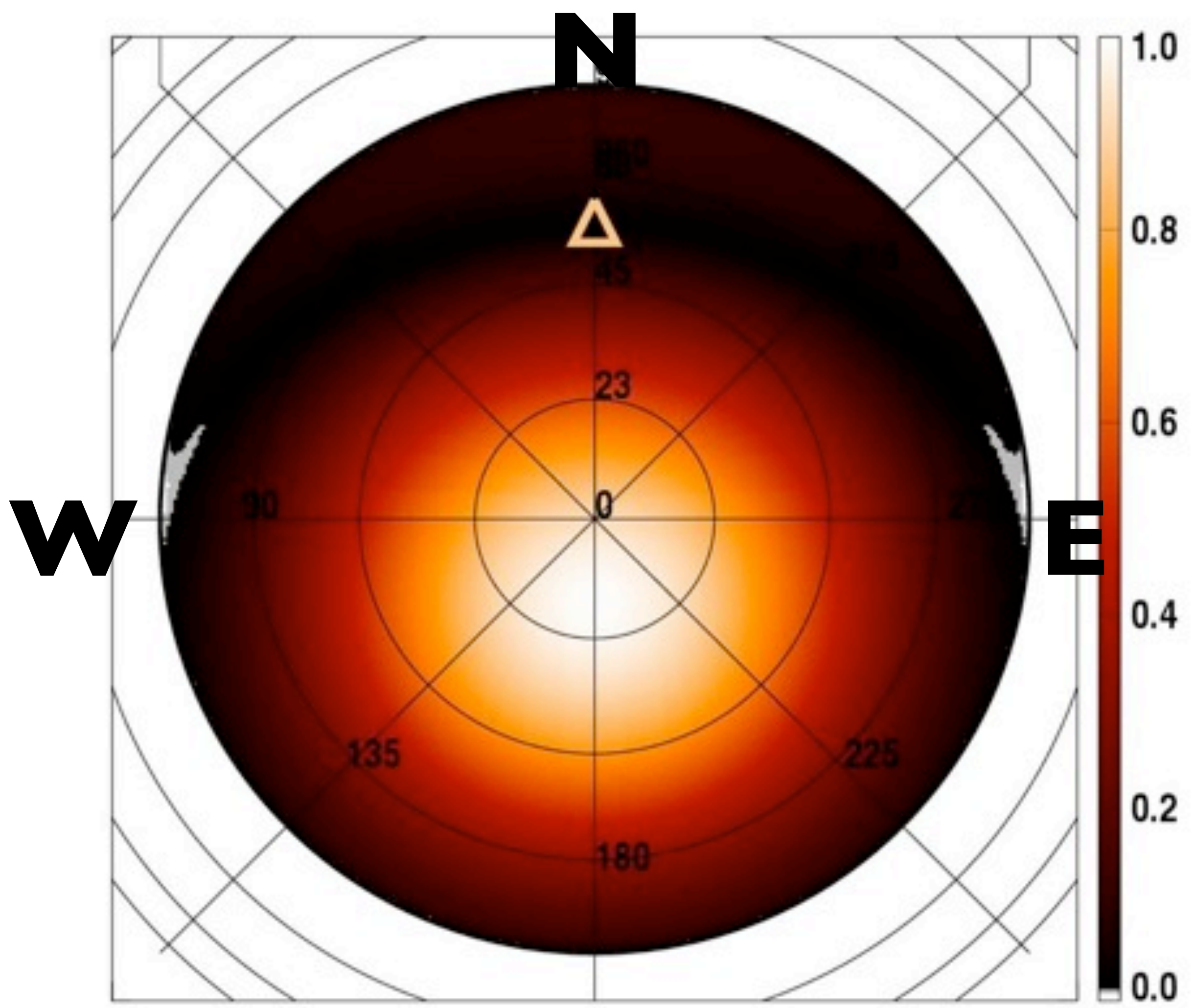


RAuger: self-trigger

Revenu, ICRC 2011

data:
76% from south



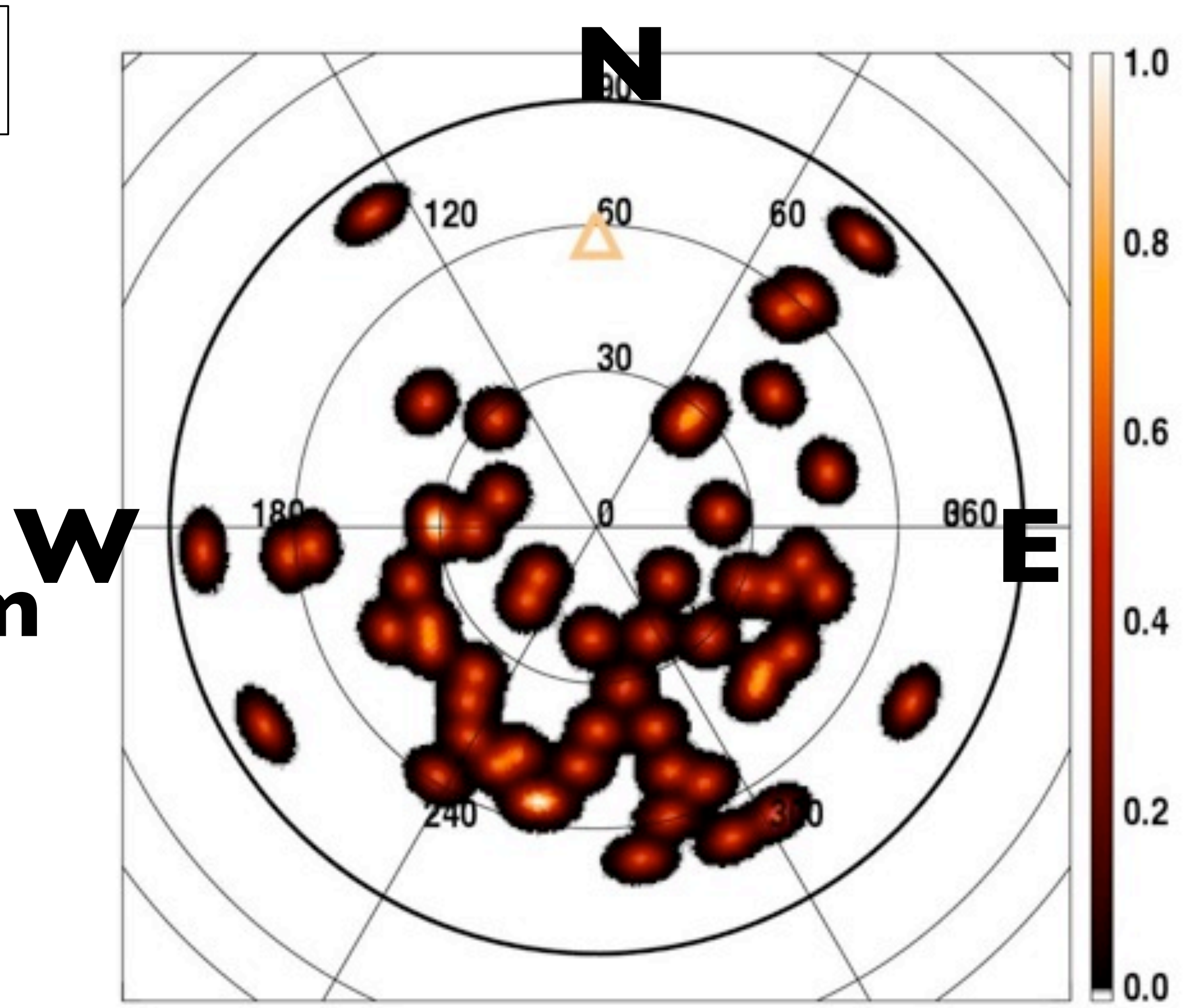


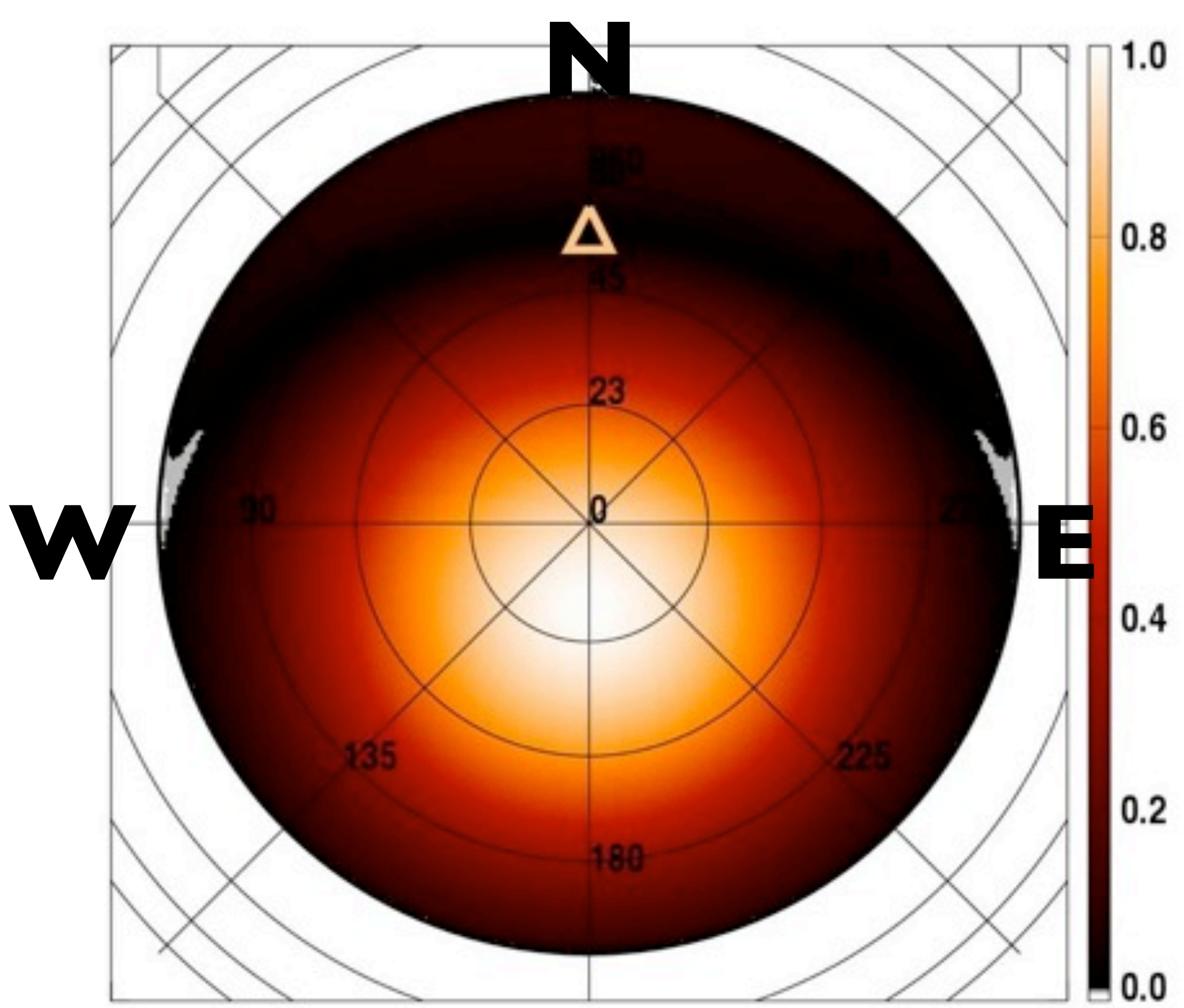
n X B:
expect
68% from
south

RAuger: self-trigger

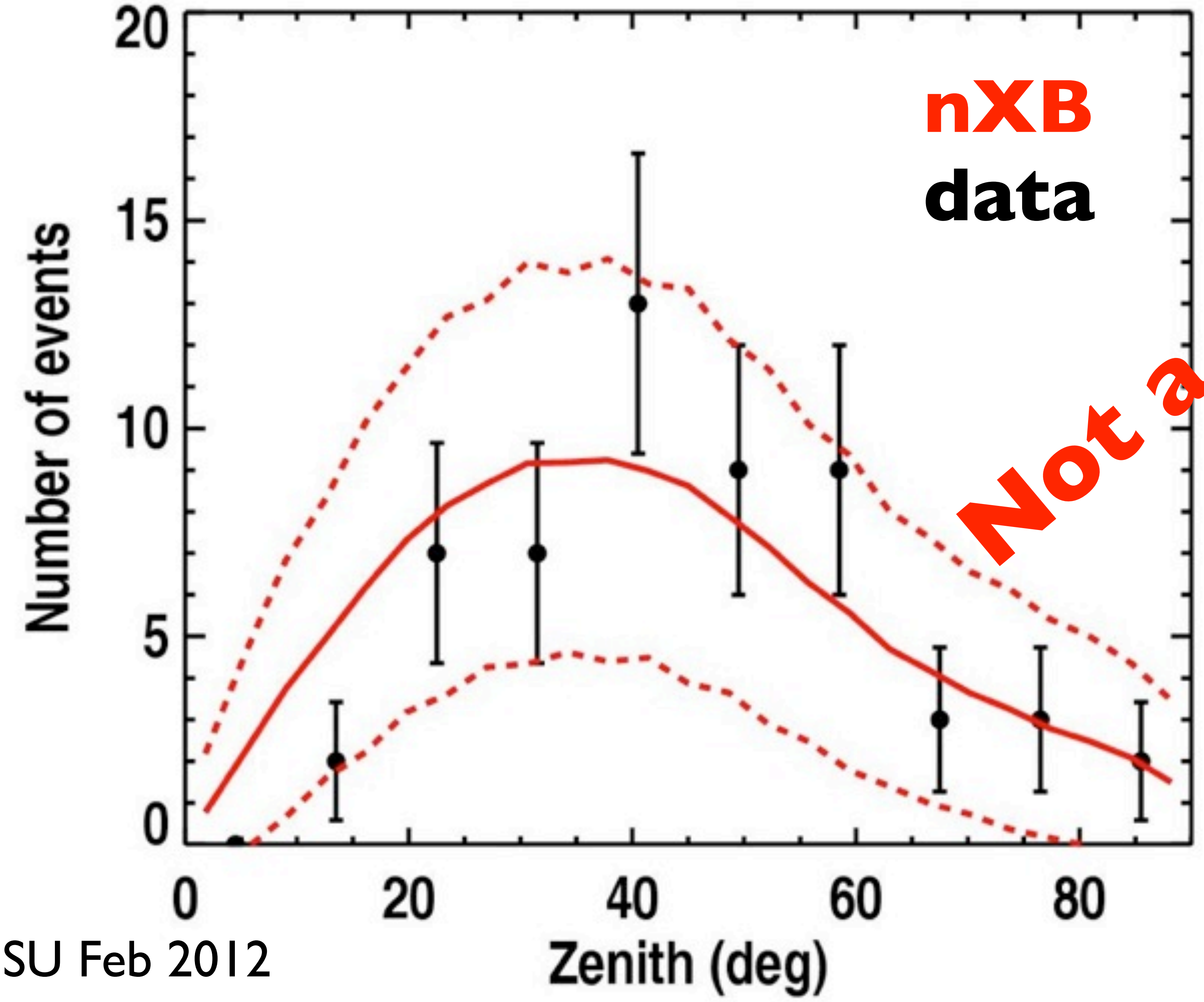
Revenu, ICRC 2011

data:
76% from south

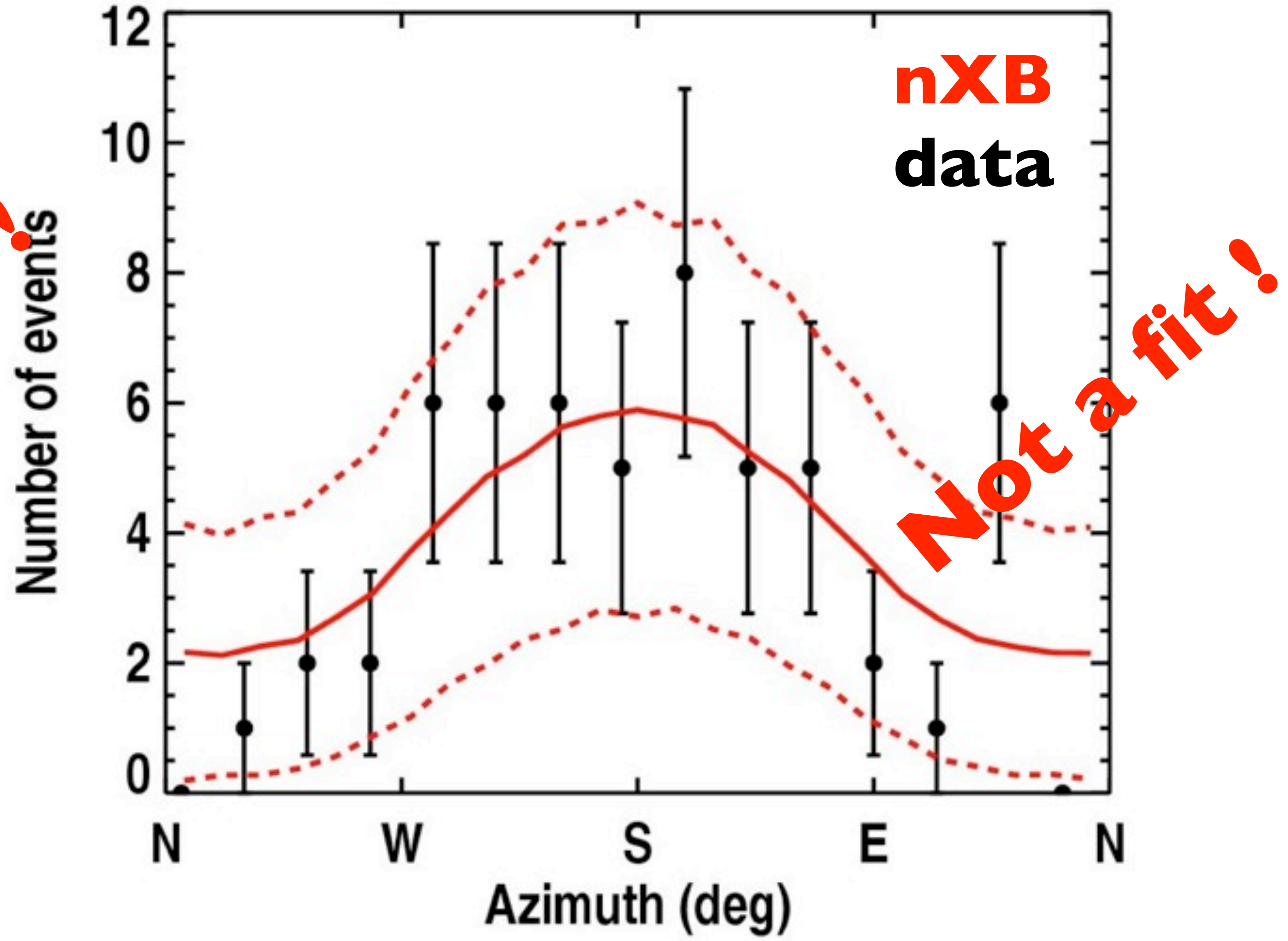




n X B:
expect
68% from south



Not a fit!

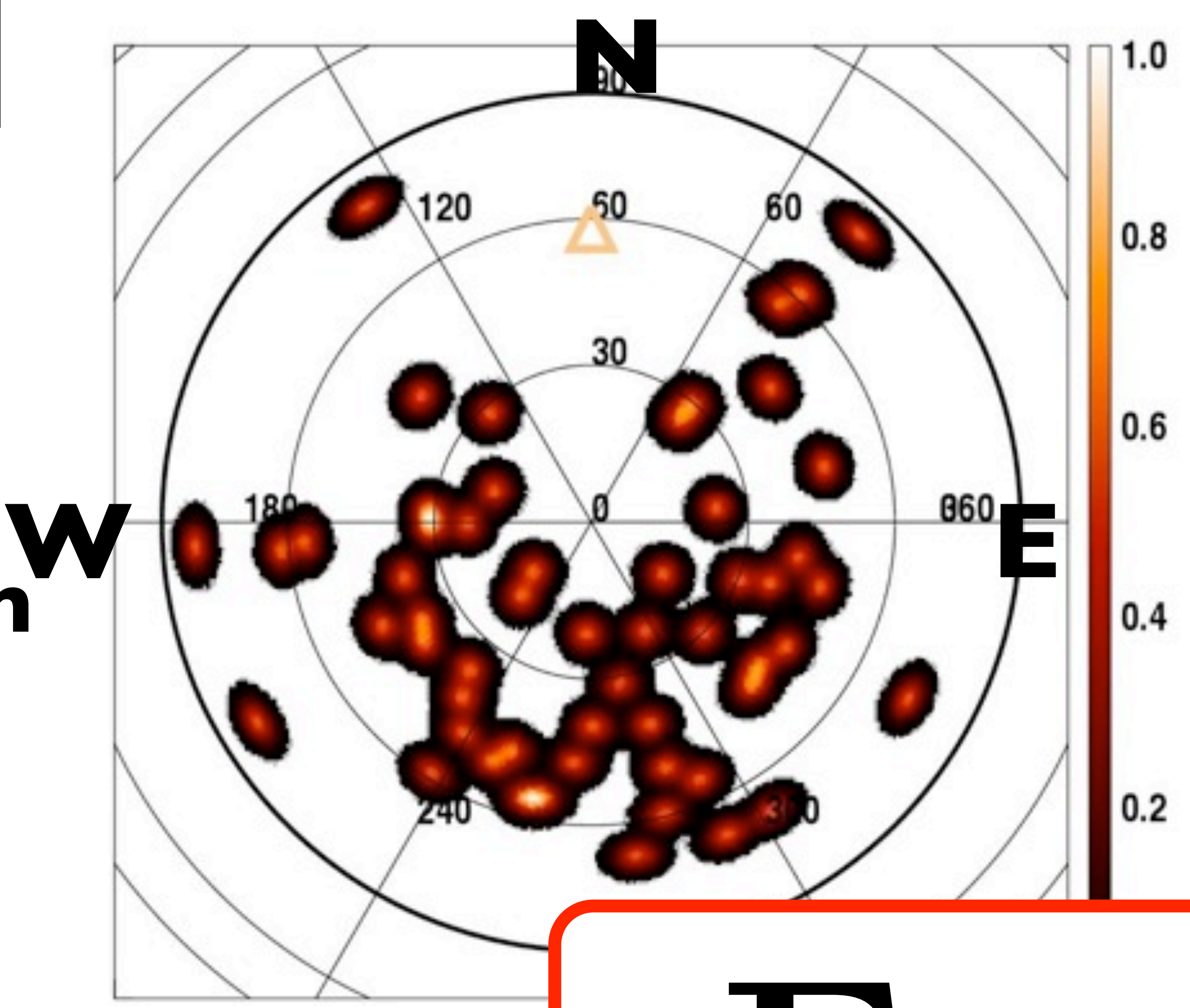


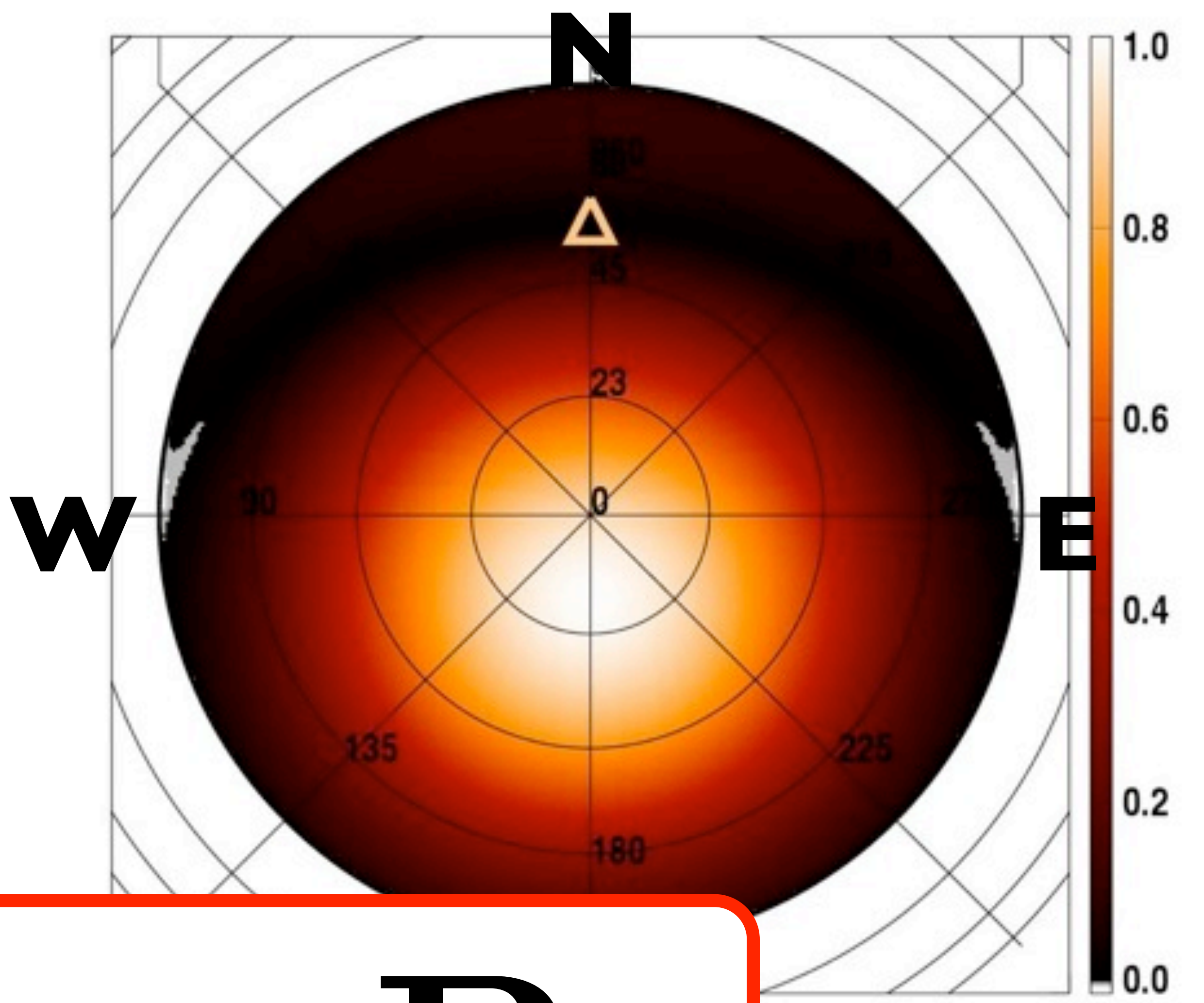
Not a fit!

RAuger: self-trigger

Revenu, ICRC 2011

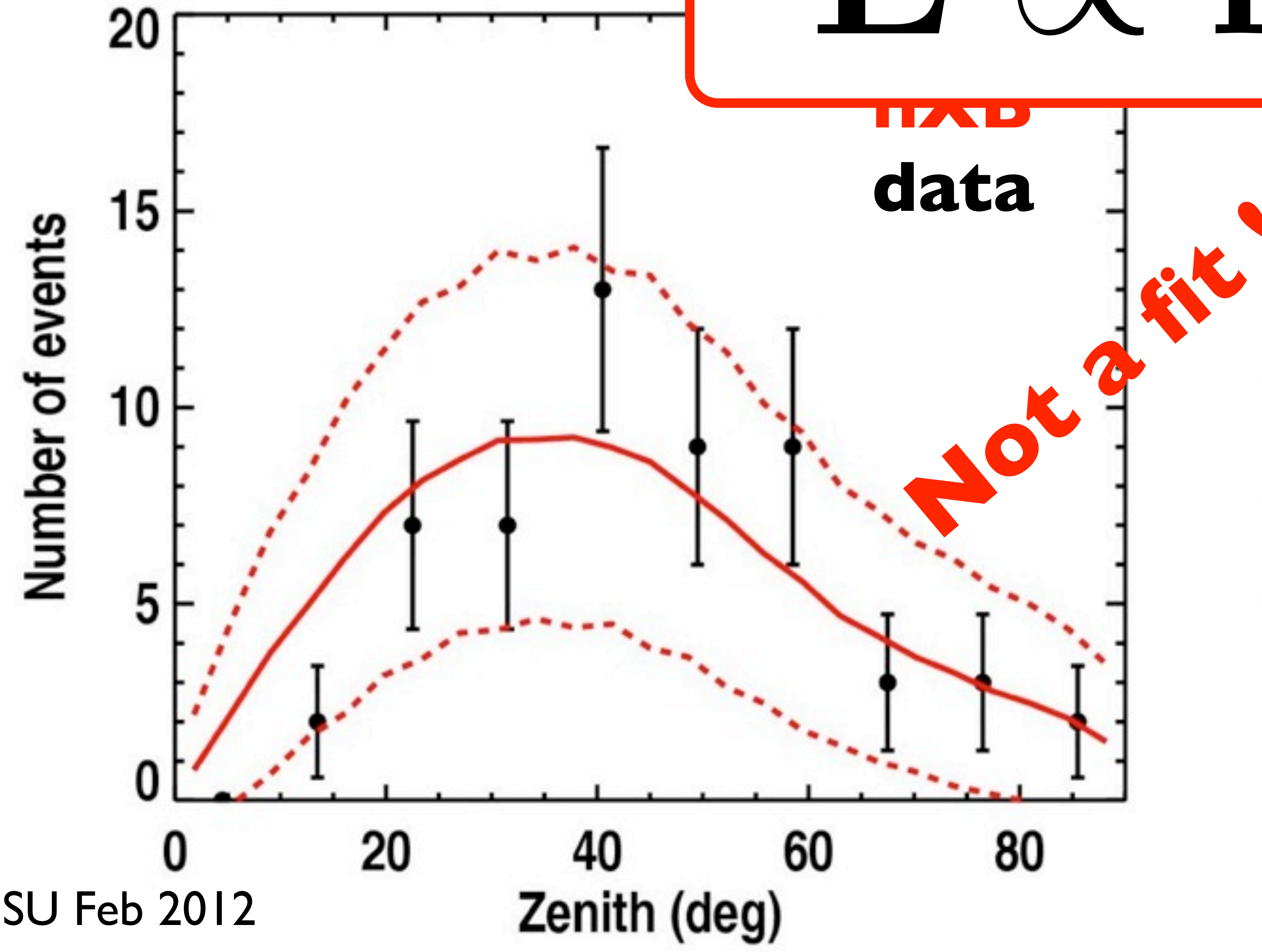
data:
76% from
south

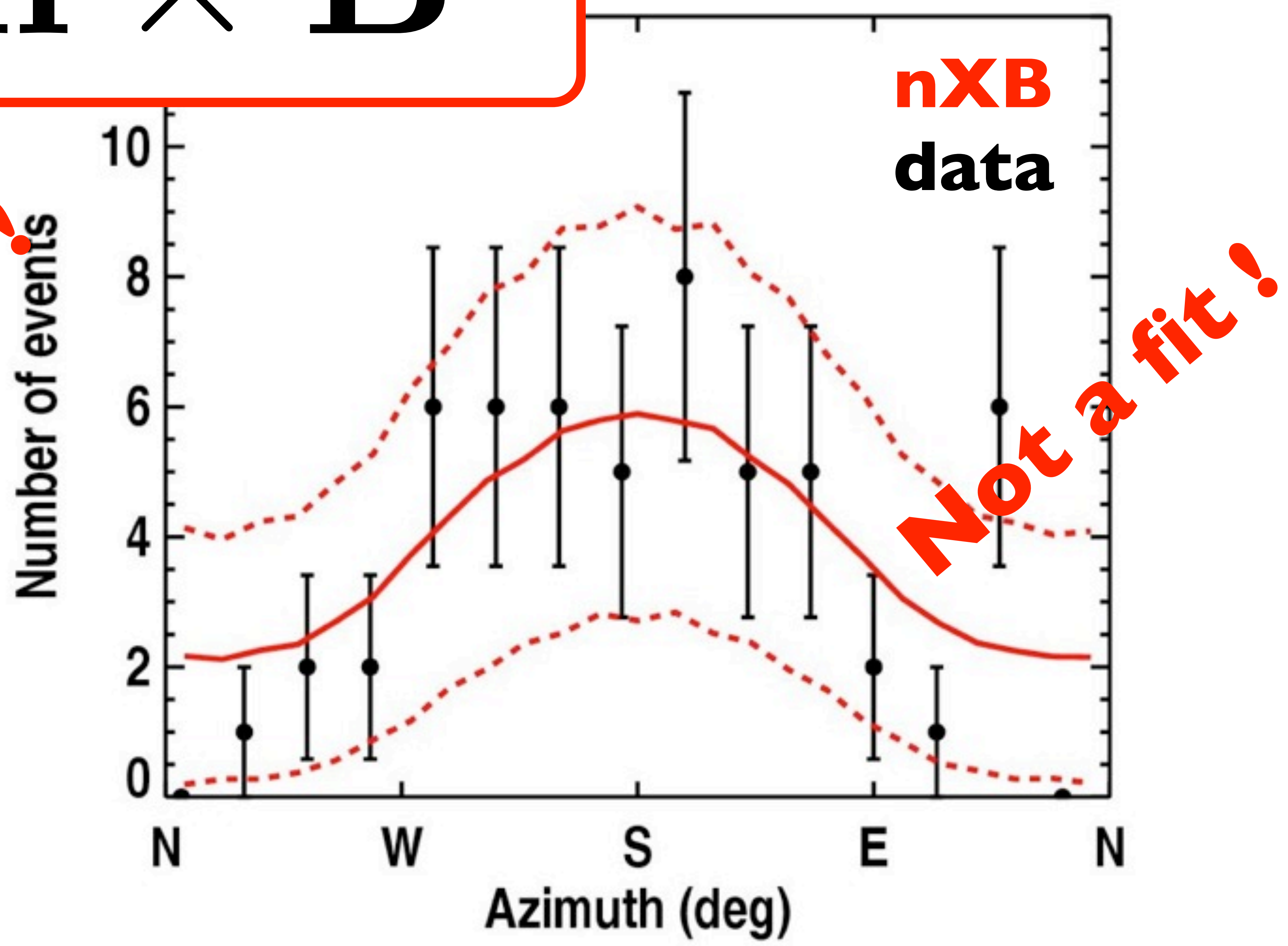




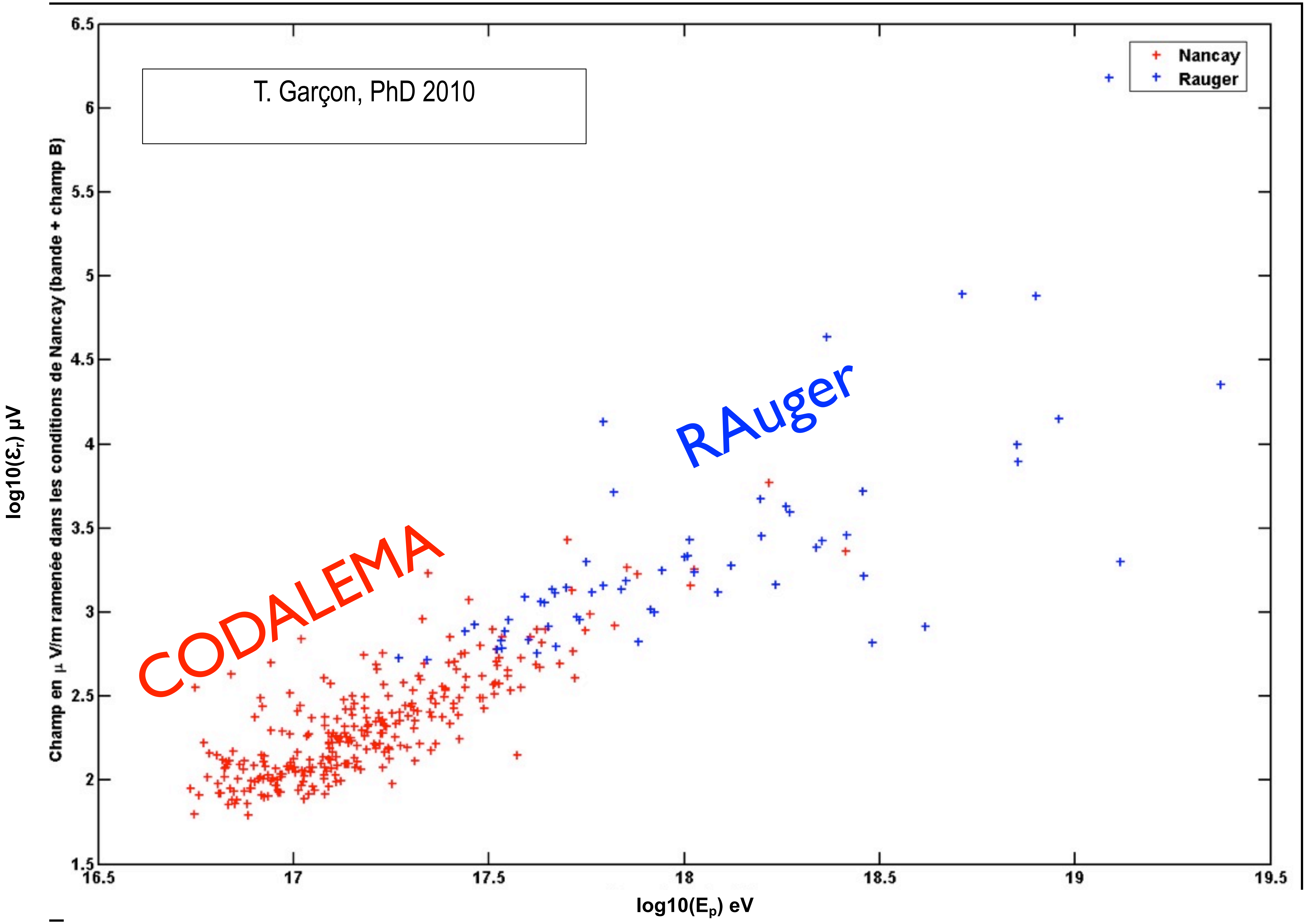
n X B:
expect
68% from
south

$$\mathbf{E} \propto \mathbf{n} \times \mathbf{B}$$



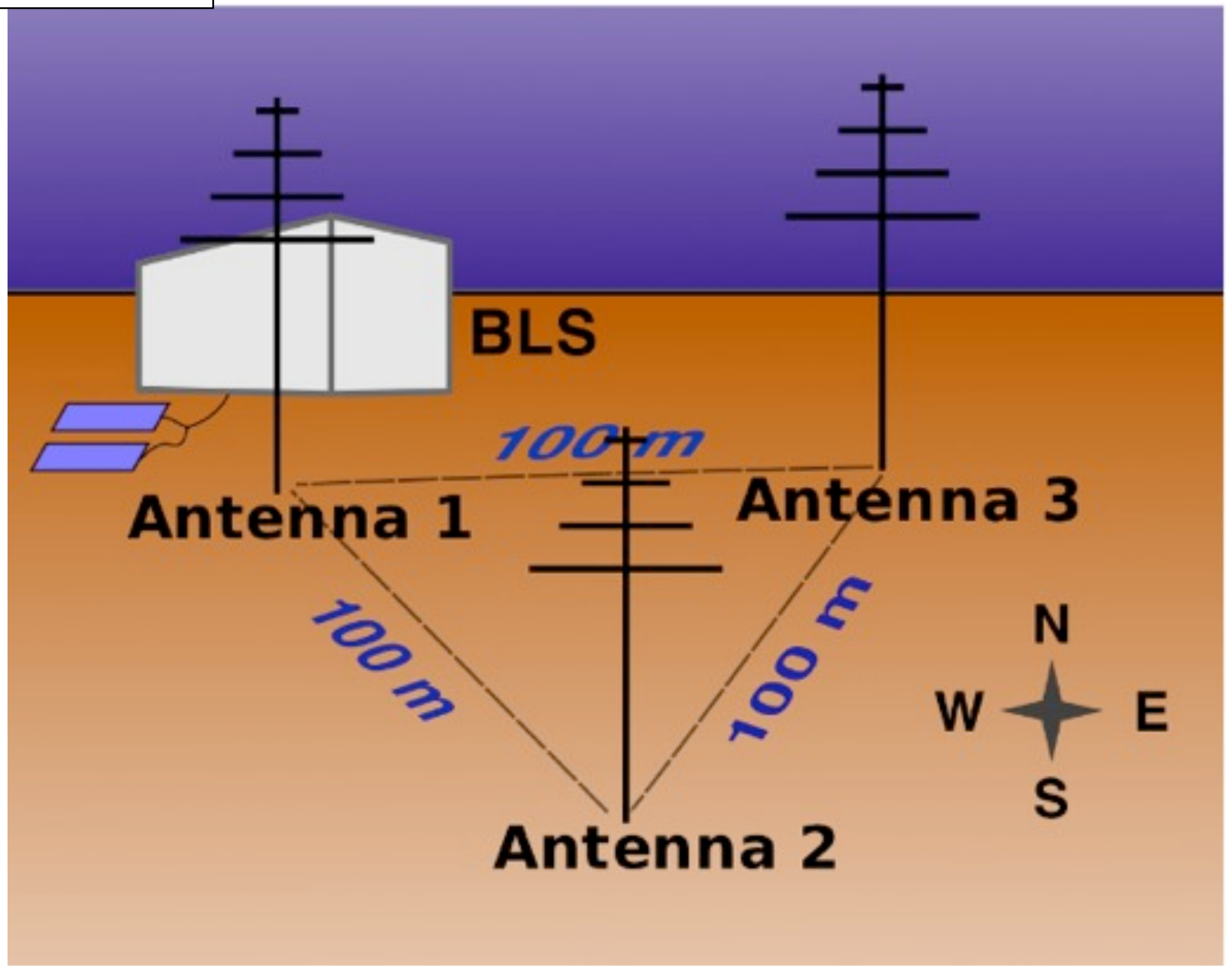


RAuger: self-trigger



MAXIMA: polarization

Revenu, ICRC 2011



LPDA, EW and NS polarizations sampling frequency 400 MHz (10 μs), data used between 40 and 70 MHz

triggered by a particle detector, 494 events in coincidence with SD, **37** signals selected (with S/N > 5)

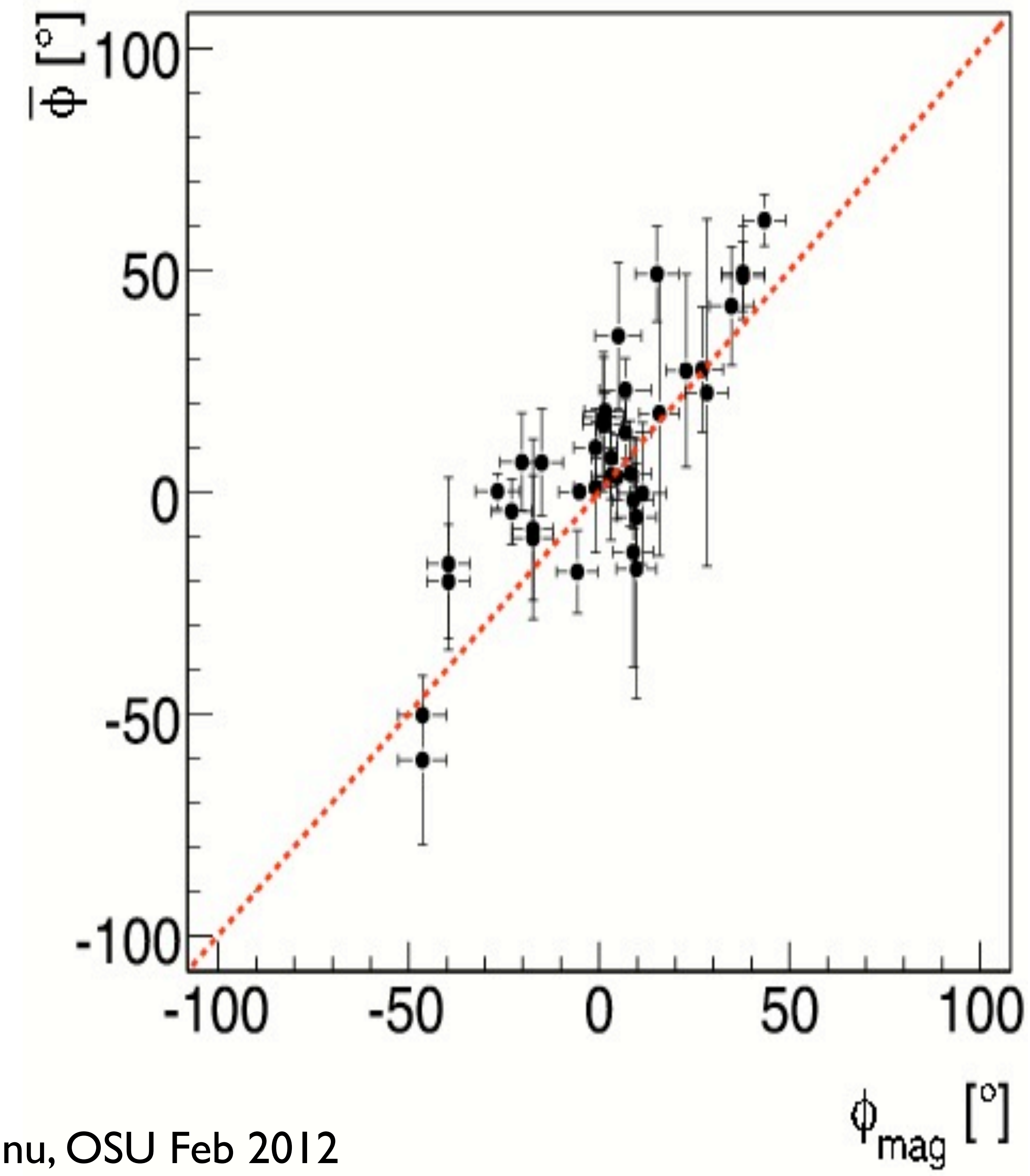
→ study the polarization of the horizontal electric field compare with expected **nXB** polarization

MAXIMA: polarization

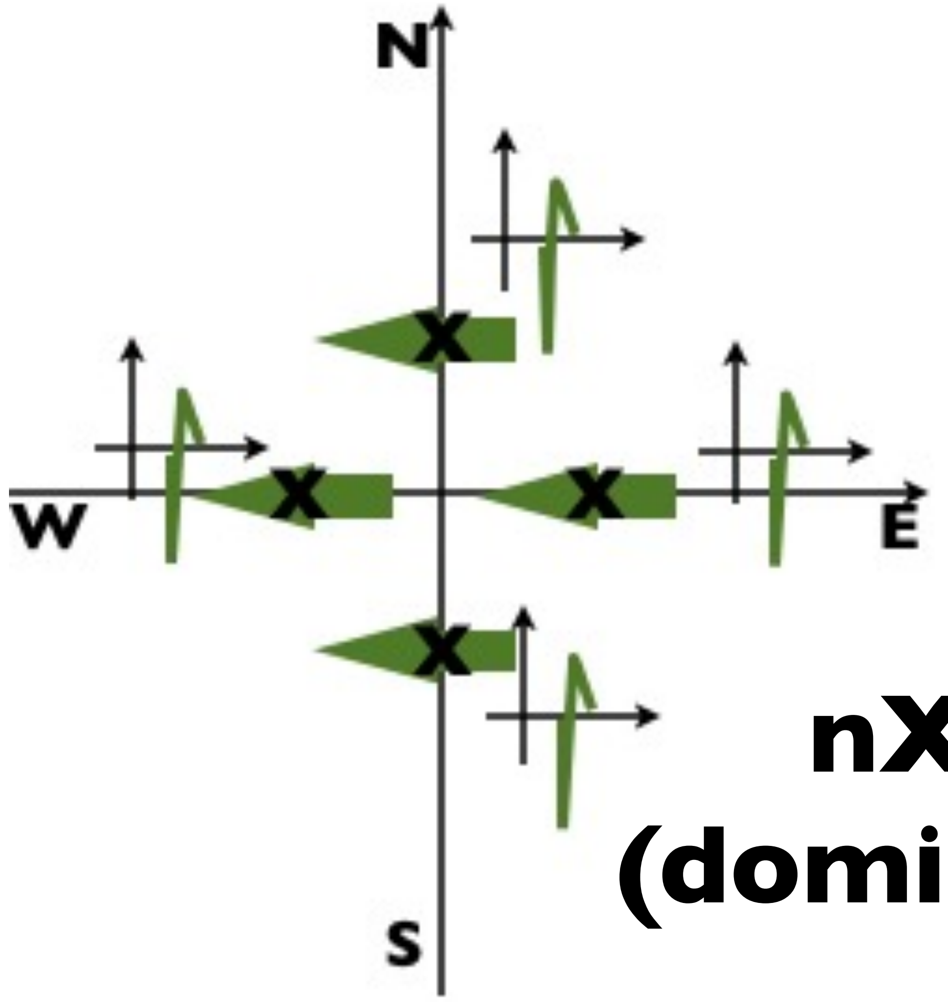
Revenu, ICRC 2011

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

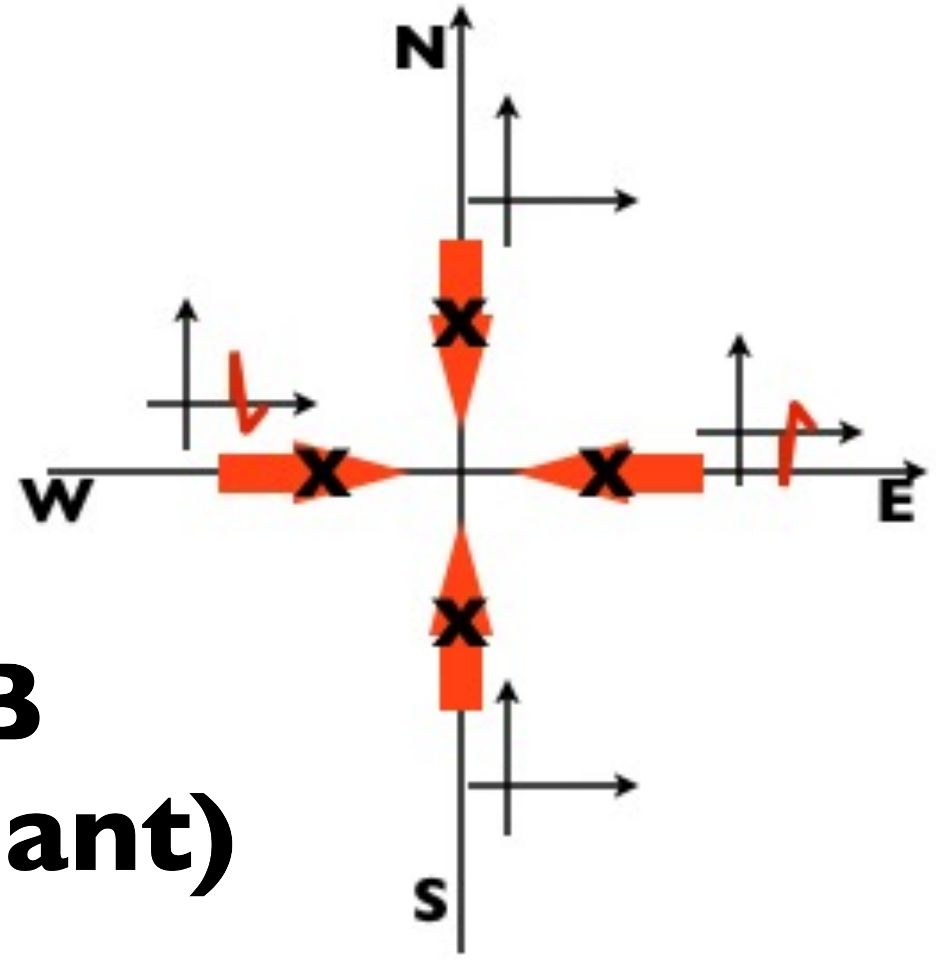
nXB polar. angle: $\phi_{\mathrm{mag}} = \arctan((\vec{n} \times \vec{B})_{\mathrm{NS}}/(\vec{n} \times \vec{B})_{\mathrm{EW}})$



- geomagnetic mechanism confirmed and dominant
- search for **secondary** effect ? different polarization patterns !



nXB (dominant)

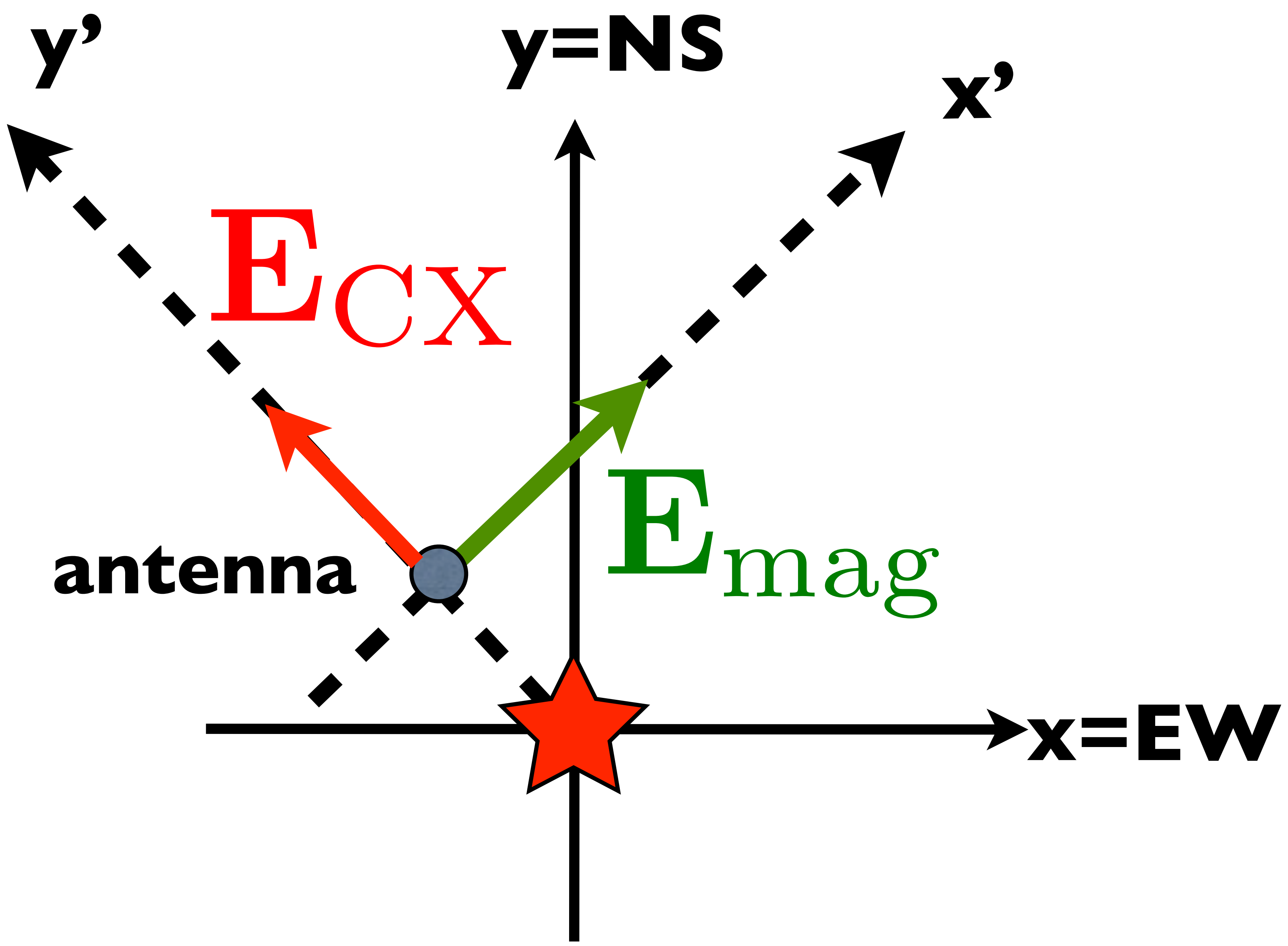


charge excess

K. Werner and O. Scholten, Astropart. Phys. 29, 393 (2008)

Revenu, ICRC 2011

MAXIMA: polarization



in (x',y'), define:

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

by construction, R=0 if pure geomagnetic contribution

compare R_{data} and R_{sim}

with simu = REAS3 and MGMR with and without charge-excess contribution

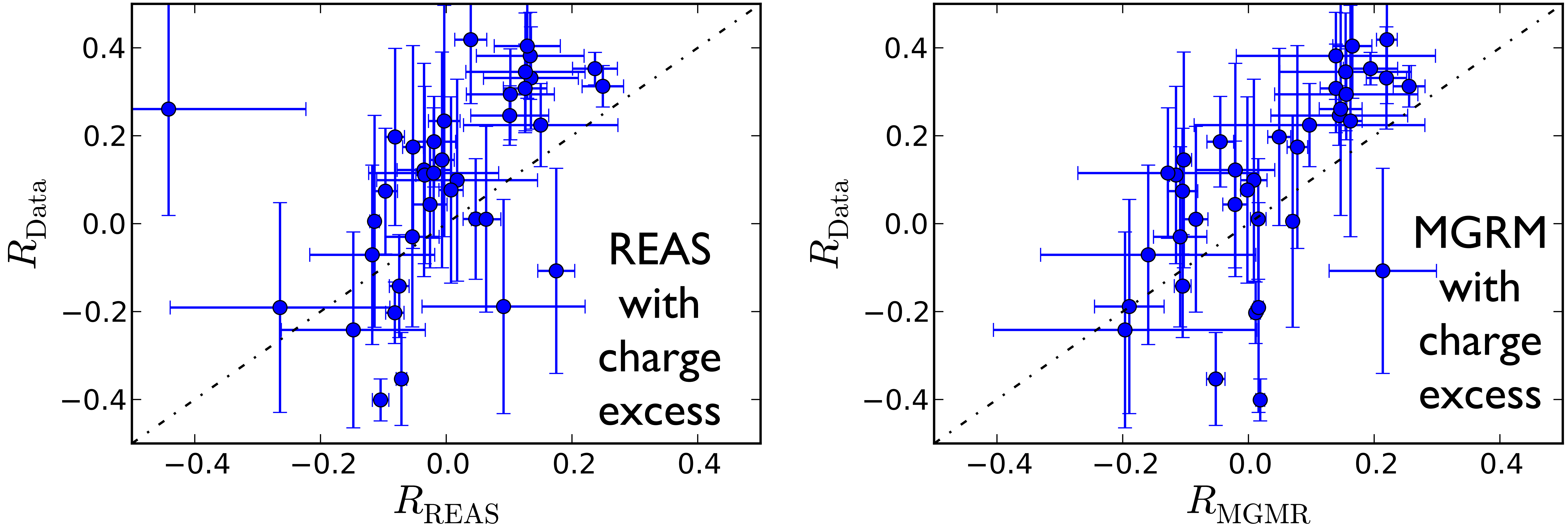
REAS3: M. Ludwig, T. Huege, Astropart. Phys., in press, doi:10.1016/j.astropartphys.2010.10.012

MGMR: K. de Vries, O. Scholten, K. Werner, Nucl. Instr. Meth. A, in press (2010) doi:10.1016/j.nima.2010.10.127

MAXIMA: polarization

Revenu, ICRC 2011

REAS3 and MGMR with charge-excess contribution

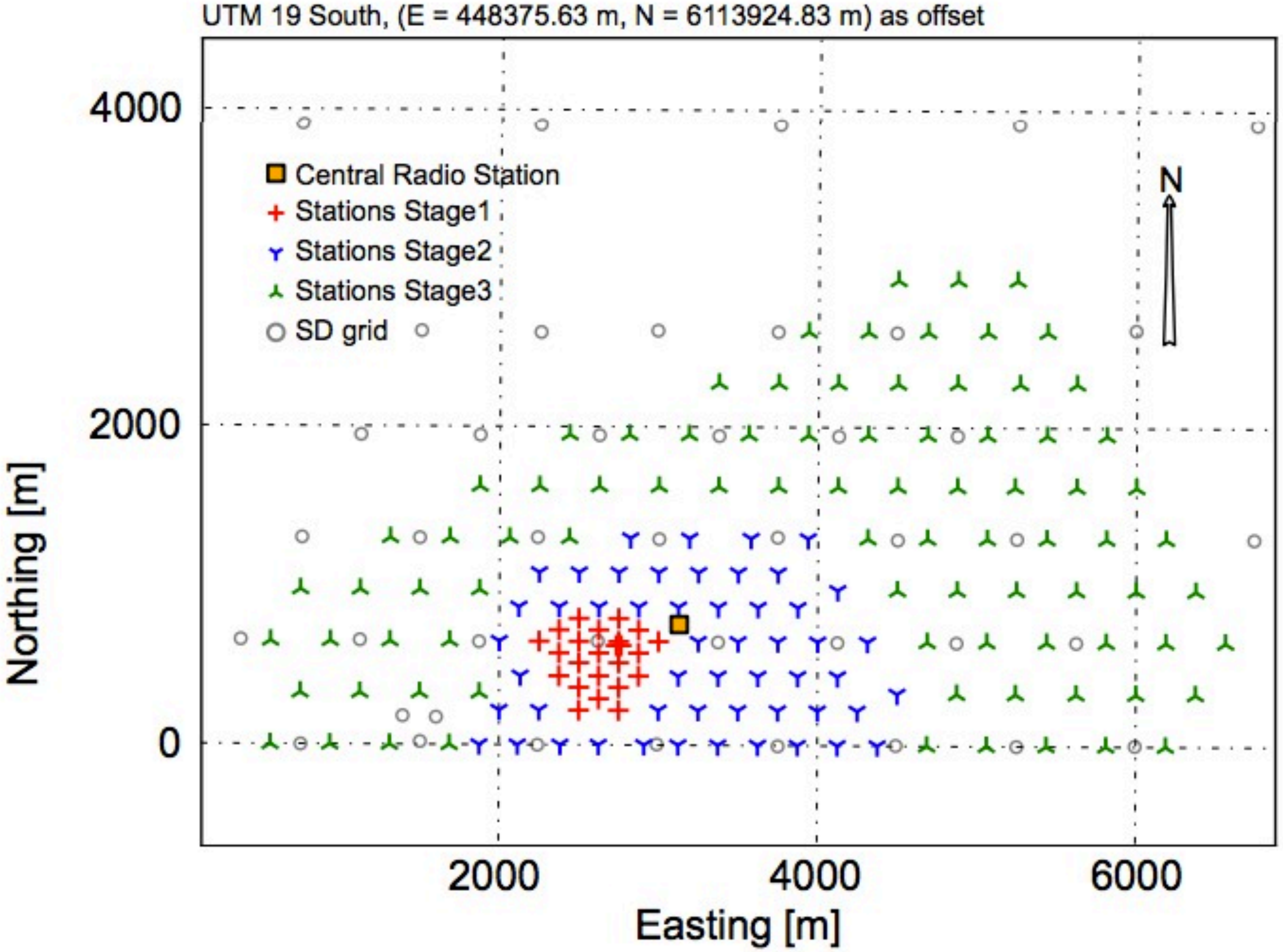


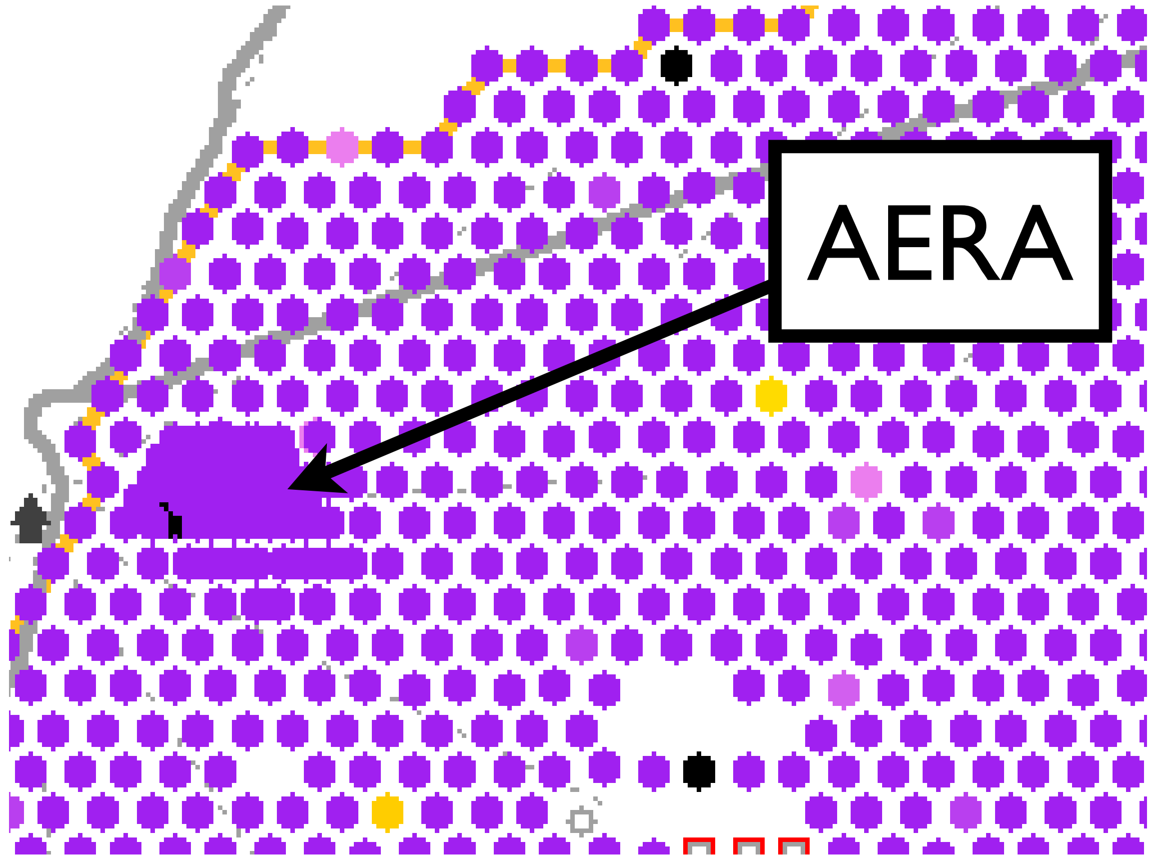
X^2/dof values	**nxB only**	**nxB+charge excess**
MGRM	**6.08**	**2.53**
REAS	**6.28**	**2.64**

Hint for the charge-excess mechanism at the PAO

AERA

running since end of 2010



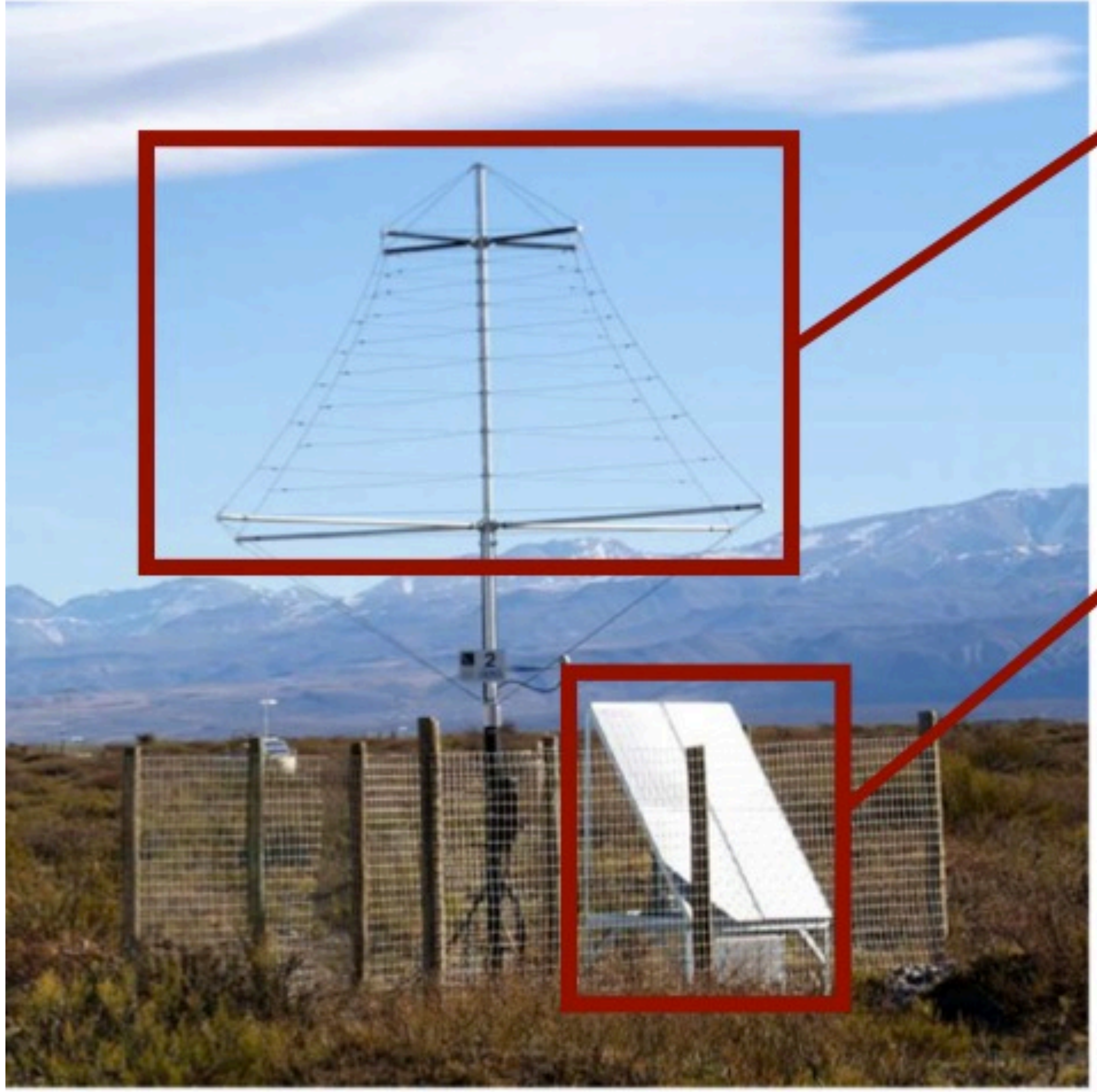


- overlap Auger Infill, HEAT, AMIGA
- self-trigger
- external trigger: SD and FD

AERA

running since end of 2010

Schoorlemmer, ICTAPP 2011



Antenna

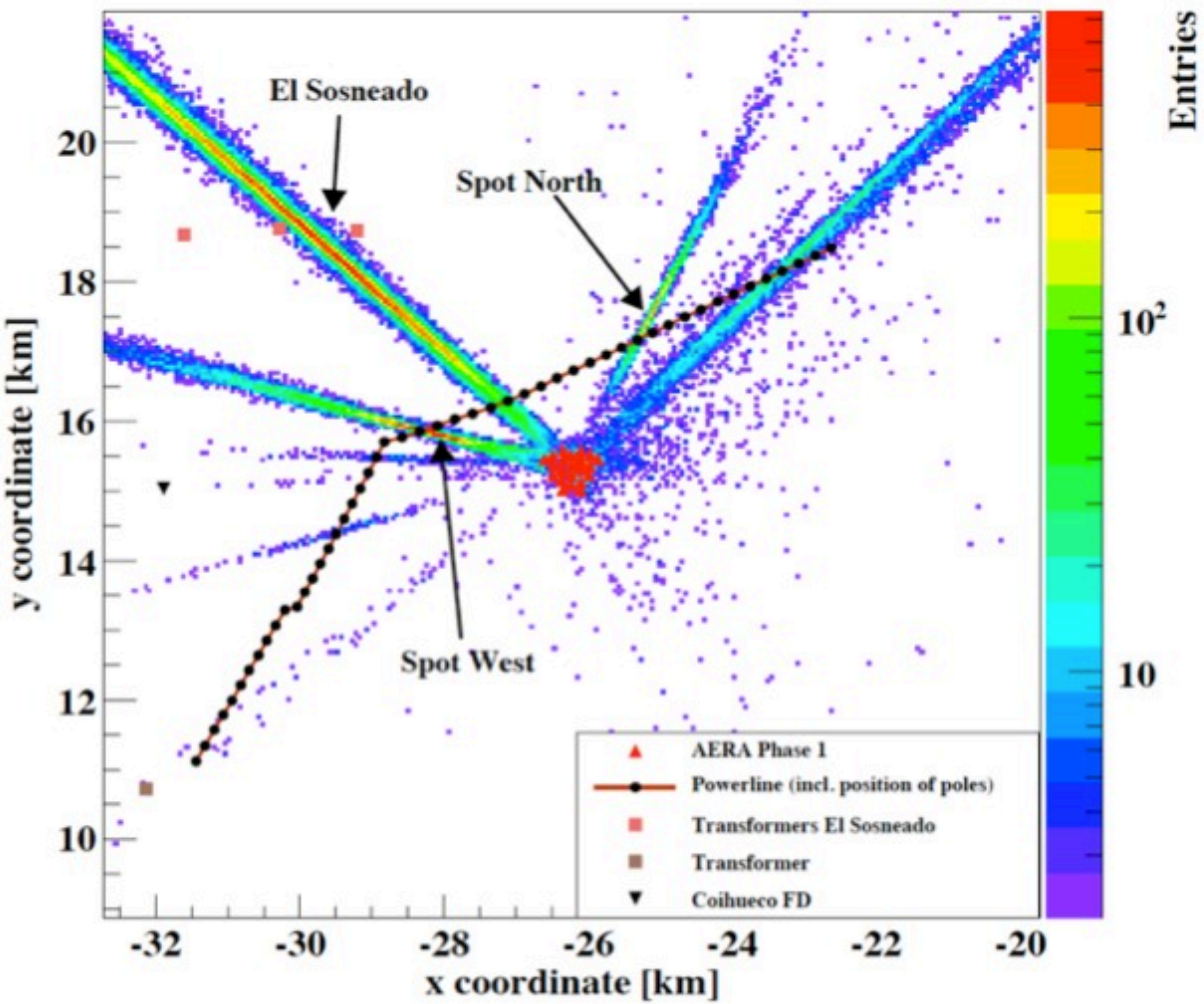
- Log Periodic Dipole Antenna.
- 30-80MHz

Electronics

- Filters
- Amplifiers
- Solar panels/batteries
- Digitizer
- Communication

AERA

Schoorlemmer, ICTAPP 2011



strong anthropic flux
(mainly electric converters), 50 Hz

representing **MOST** of our triggers

improve local triger and central trigger

AERA

~ 50 showers radio-detected, coincidences with SD and FD
polarization analysis ongoing (geomagnetic effect observed)

Kelley, ICRC 2011

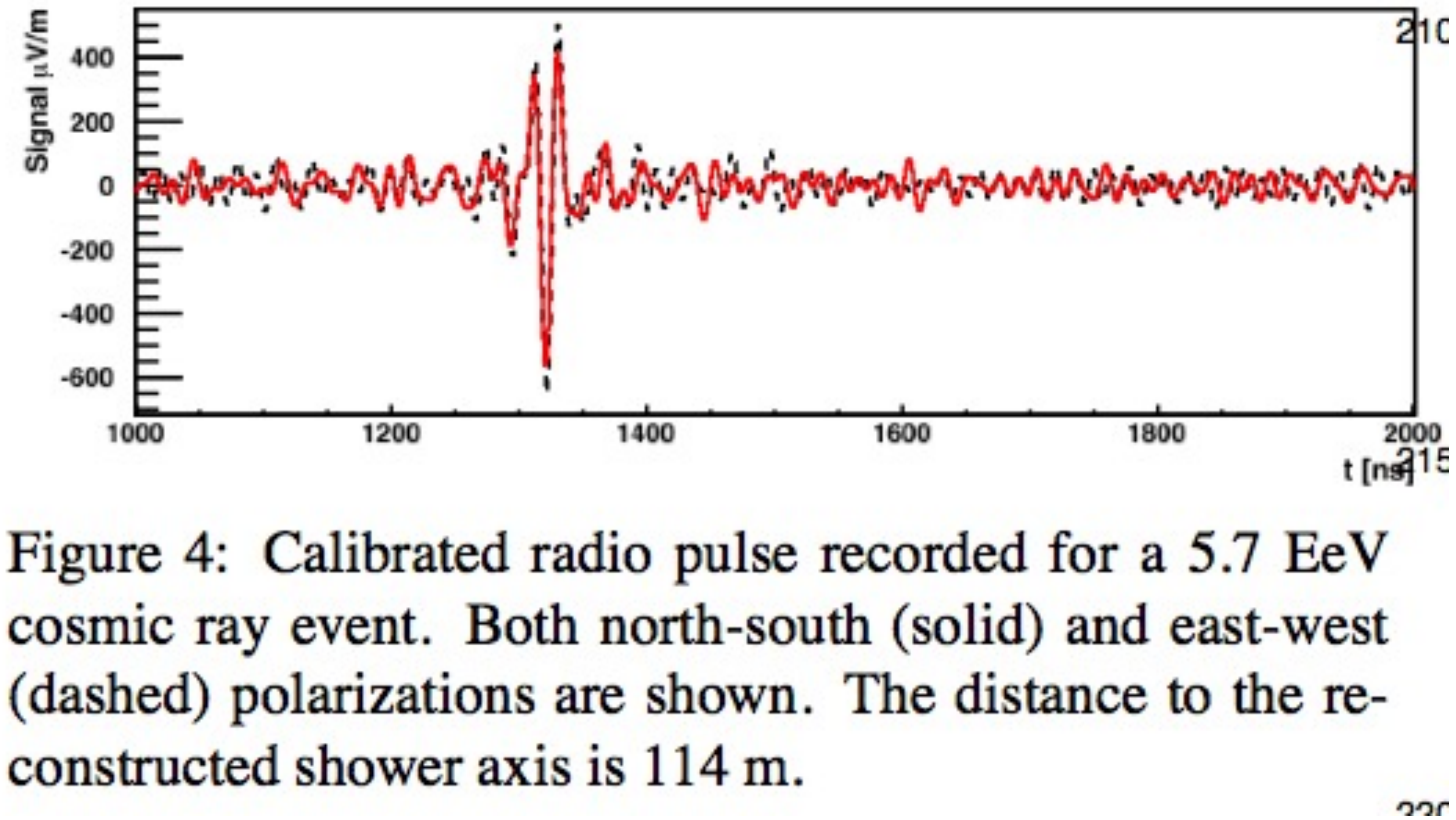
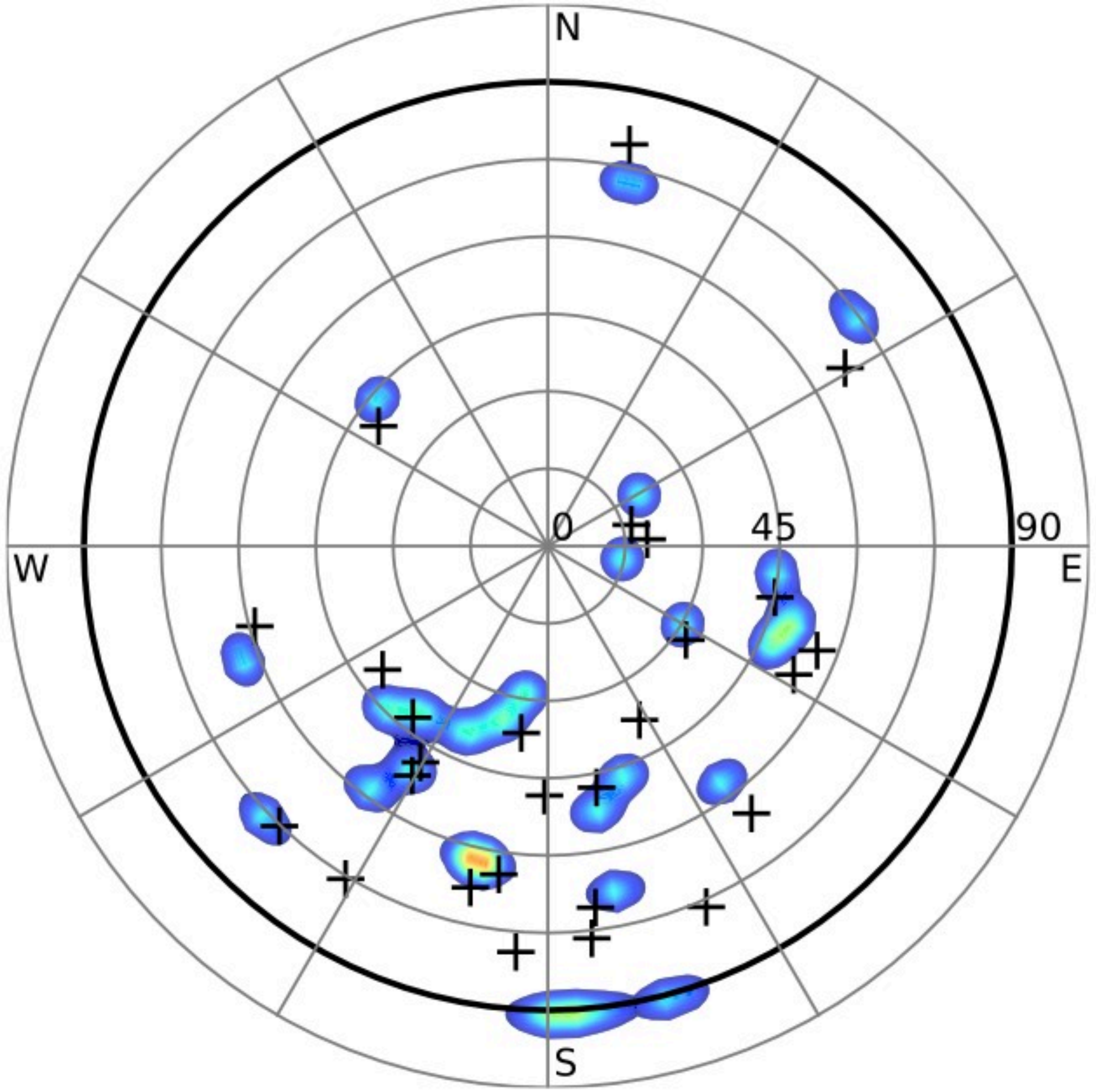


Figure 4: Calibrated radio pulse recorded for a 5.7 EeV cosmic ray event. Both north-south (solid) and east-west (dashed) polarizations are shown. The distance to the reconstructed shower axis is 114 m.

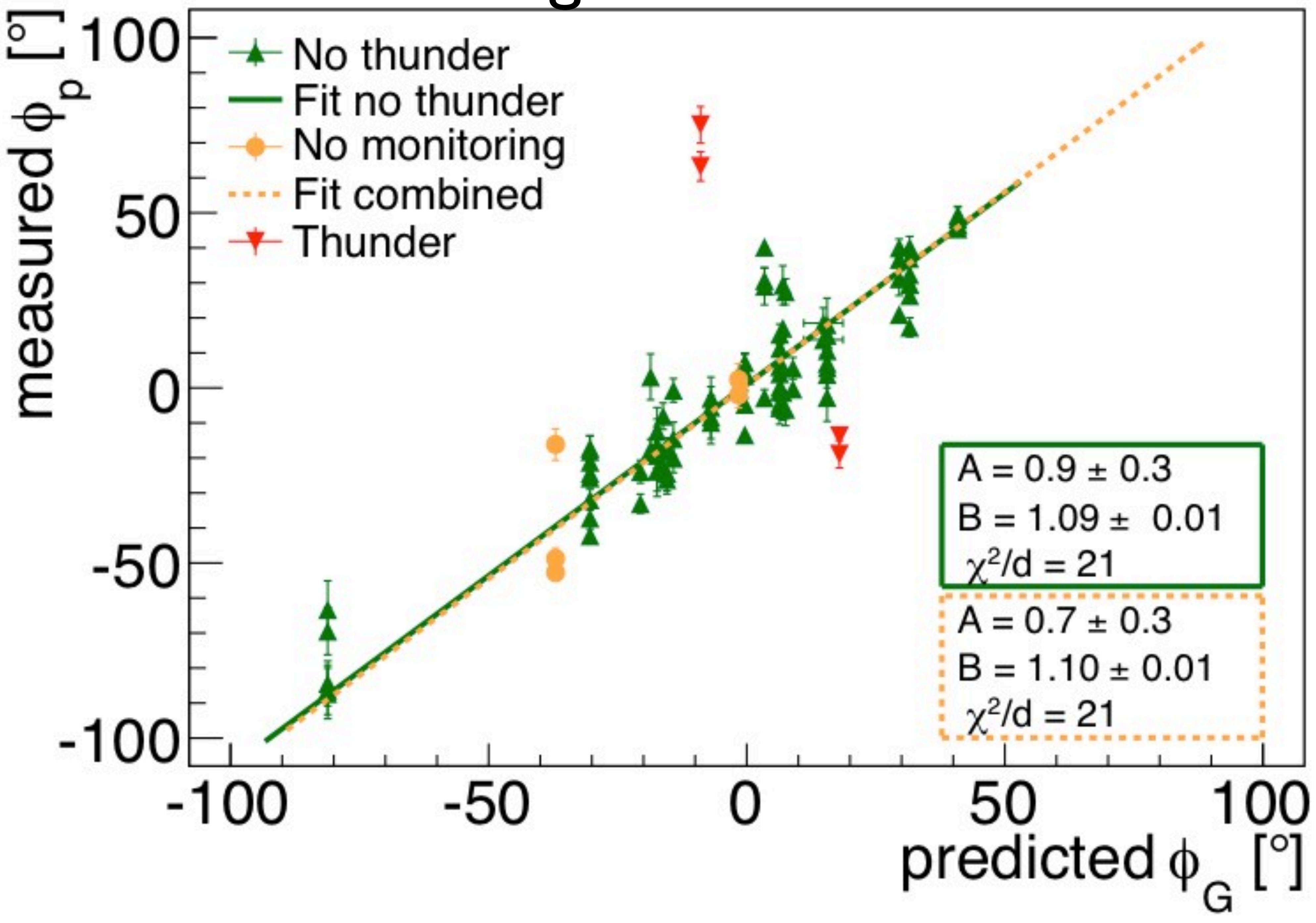
~ 0.55 evts/day
expected from simulations 1-2 evts/day

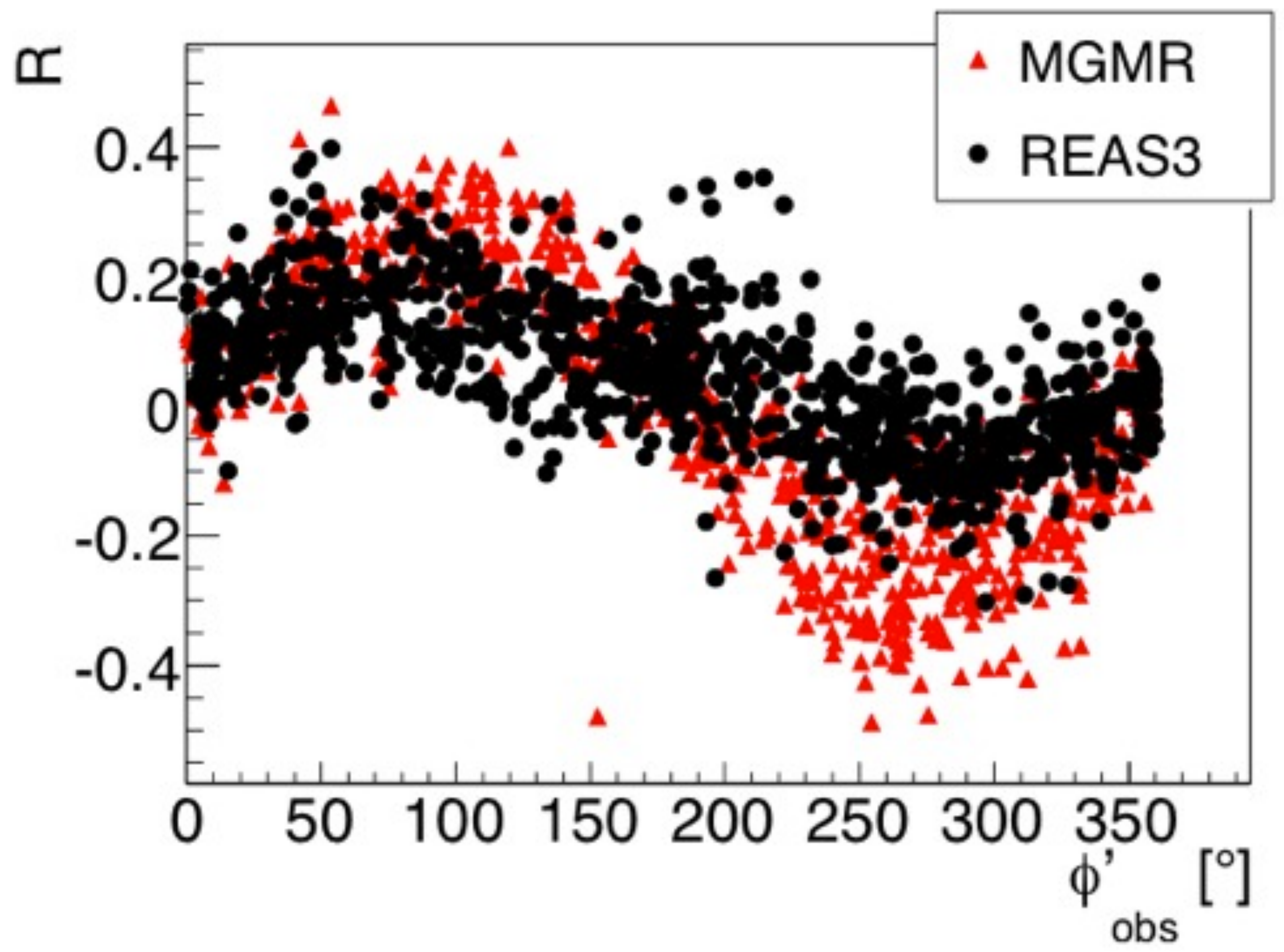


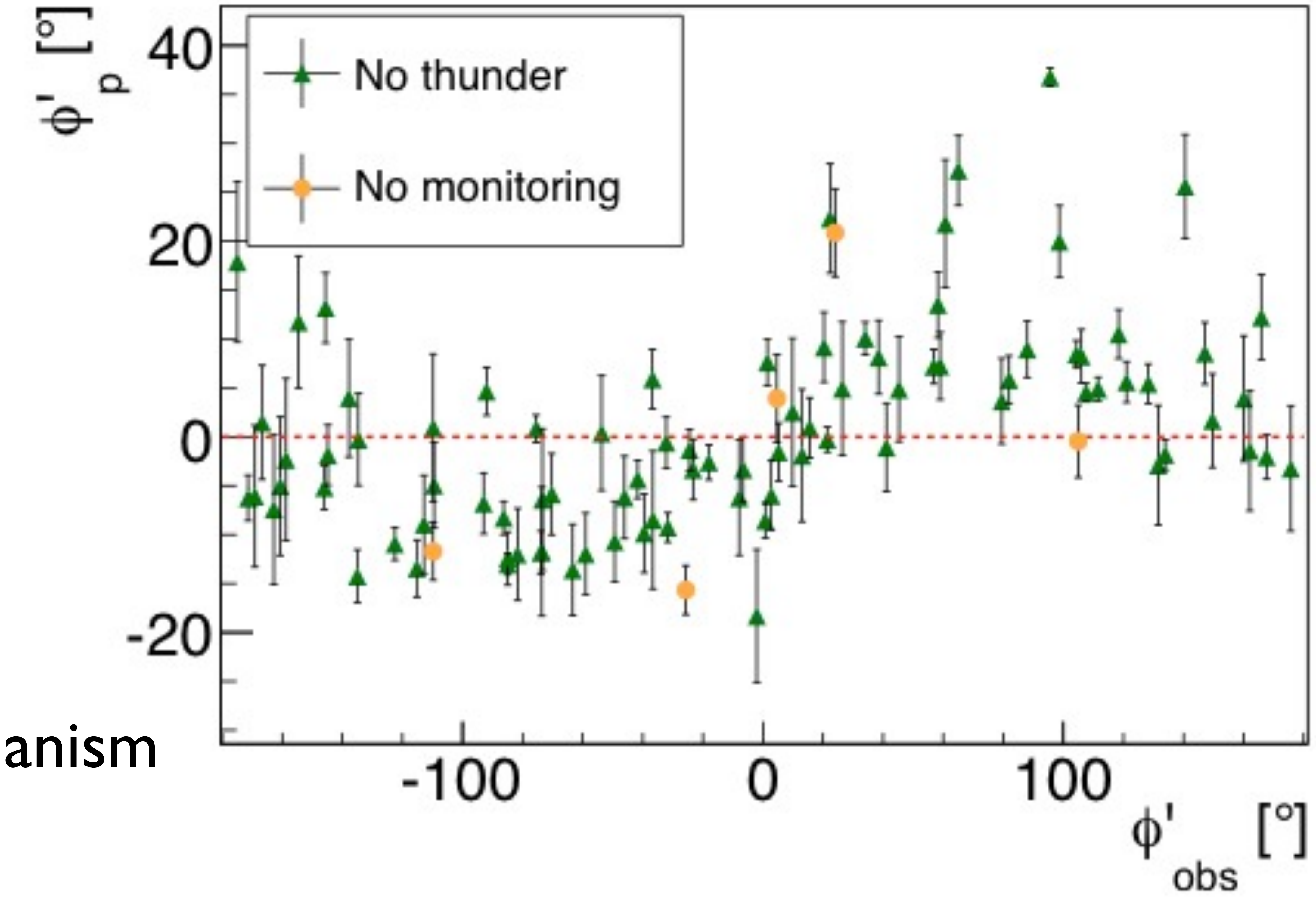
Schoorlemmer, ICTAPP 2011

AERA

Geomagnetic effect dominant

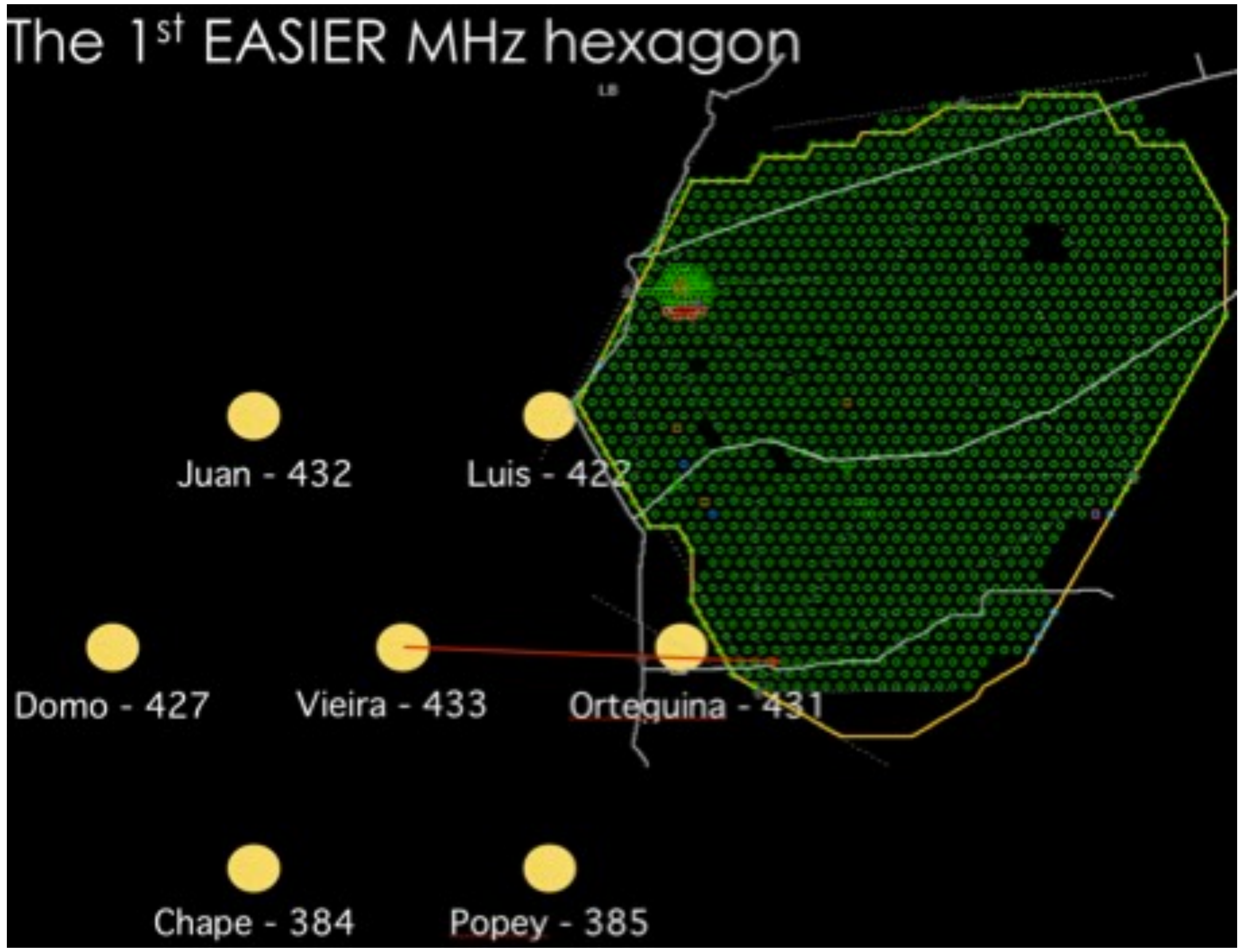




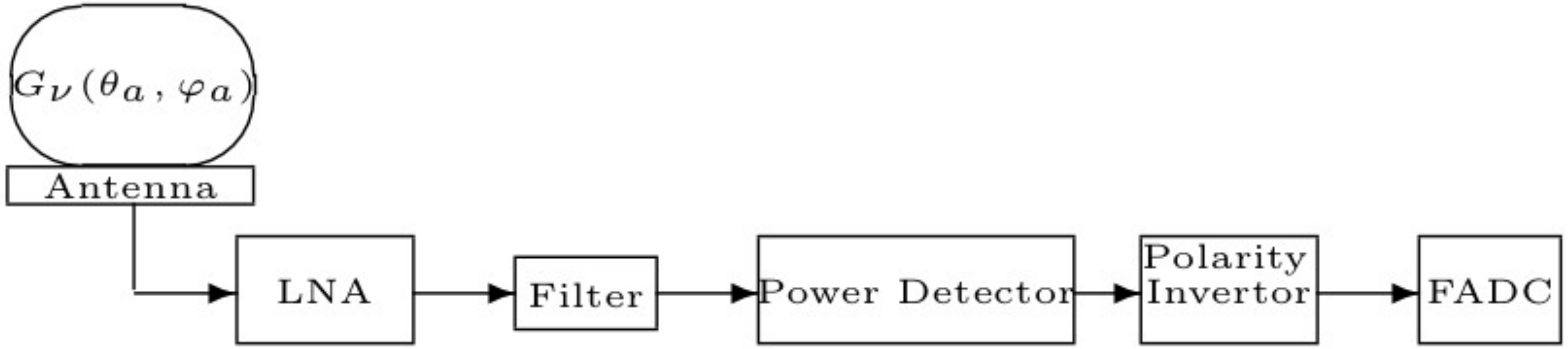


Hint for the charge-excess mechanism

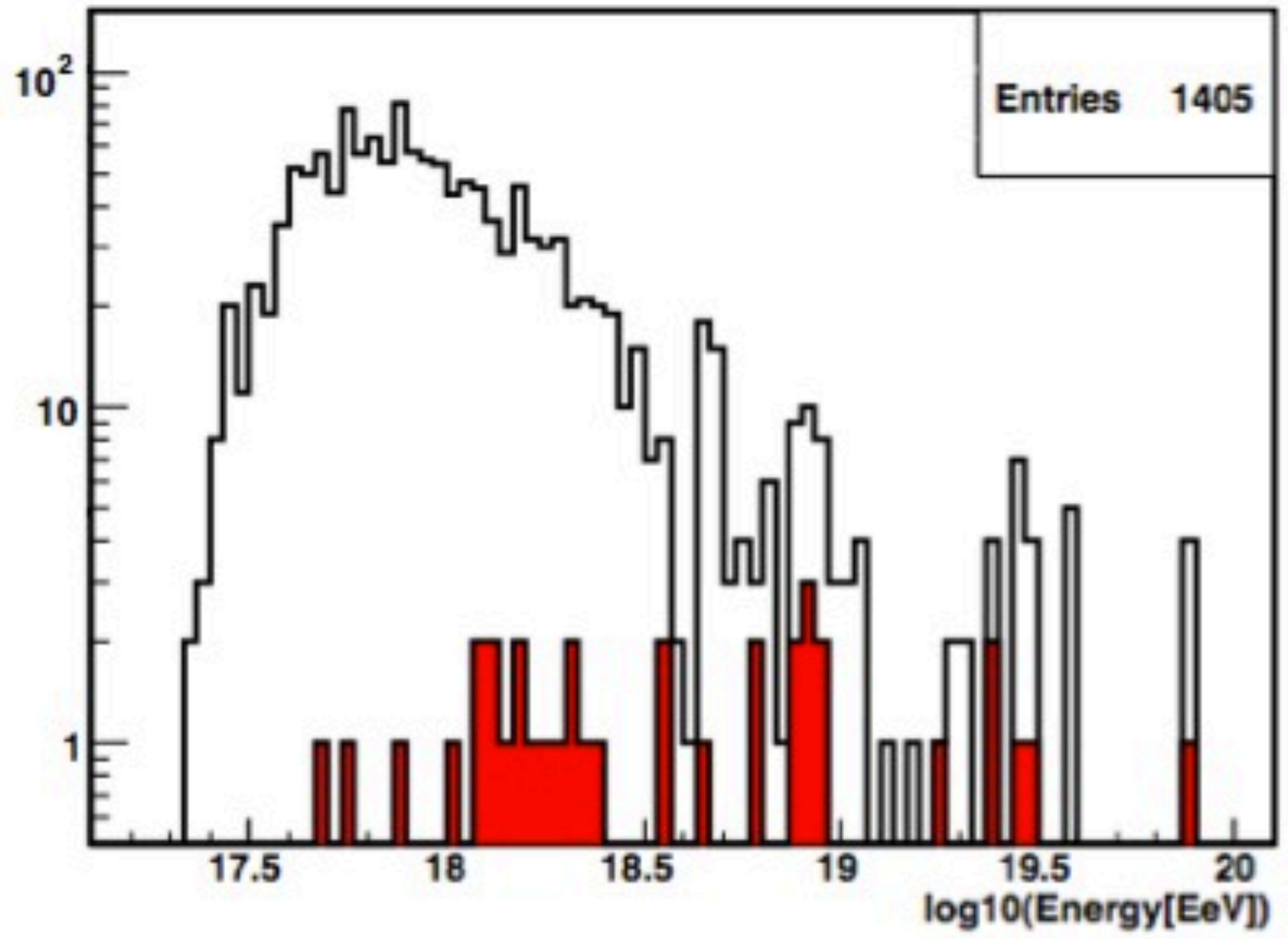
EASIER: MHz at large distance (1.5 km)

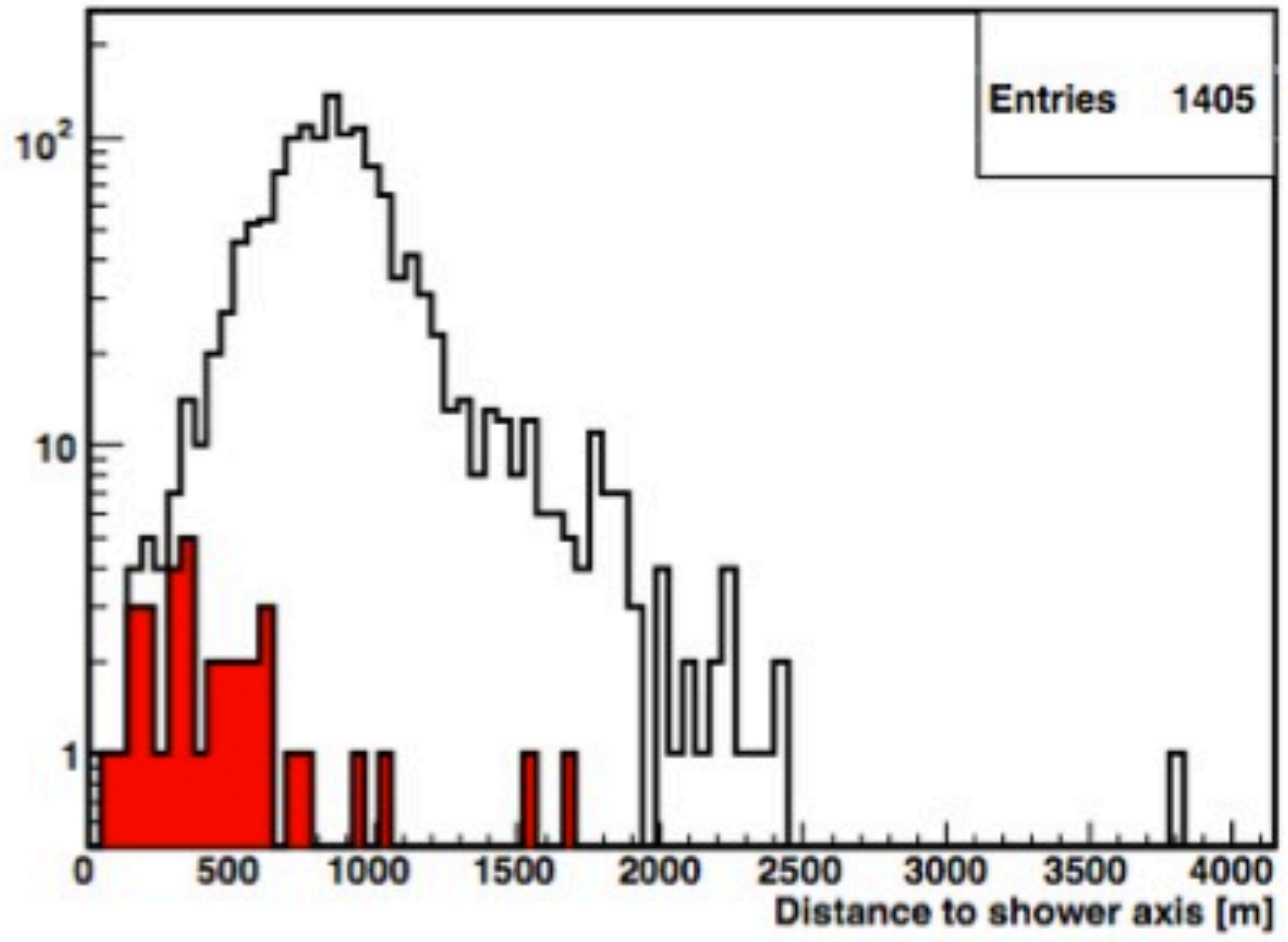


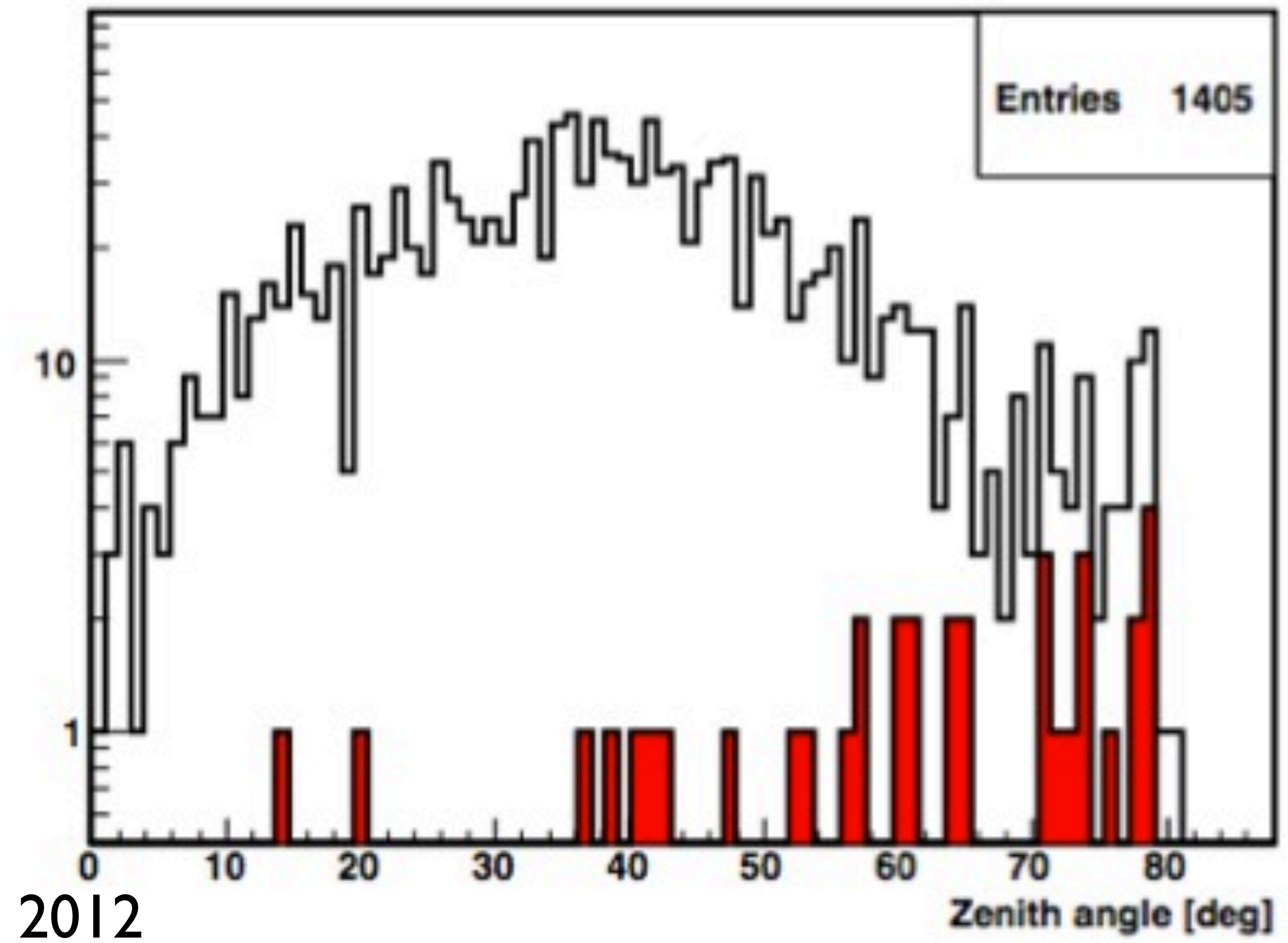
uses the CODALEMA dipolar antenna (EW polarization) and the ADC of the tank (sampling at 40 MHz), radio counterpart of a particle signal (no self-trigger)

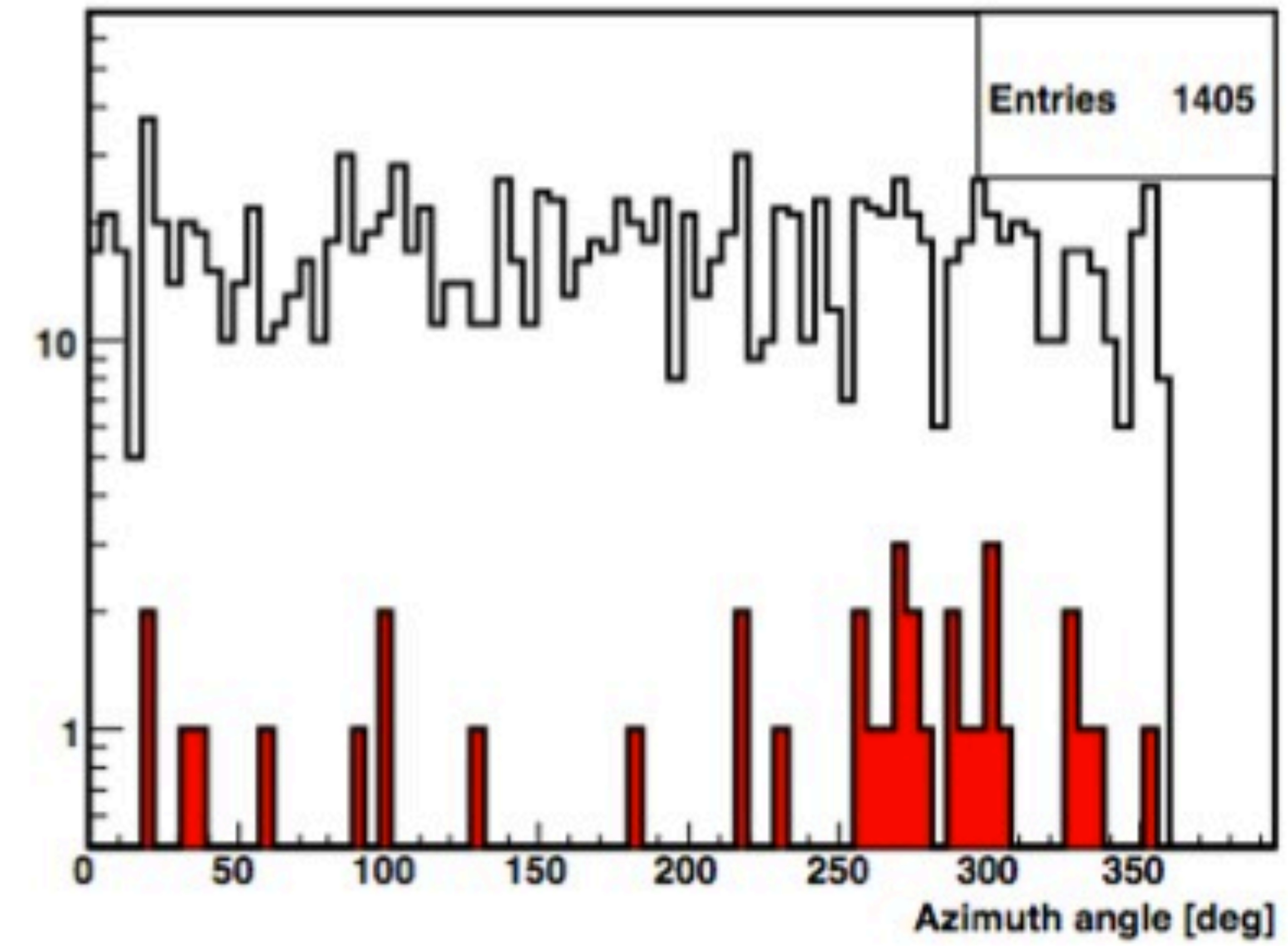


EASIER: MHz at large distance (1.5 km)

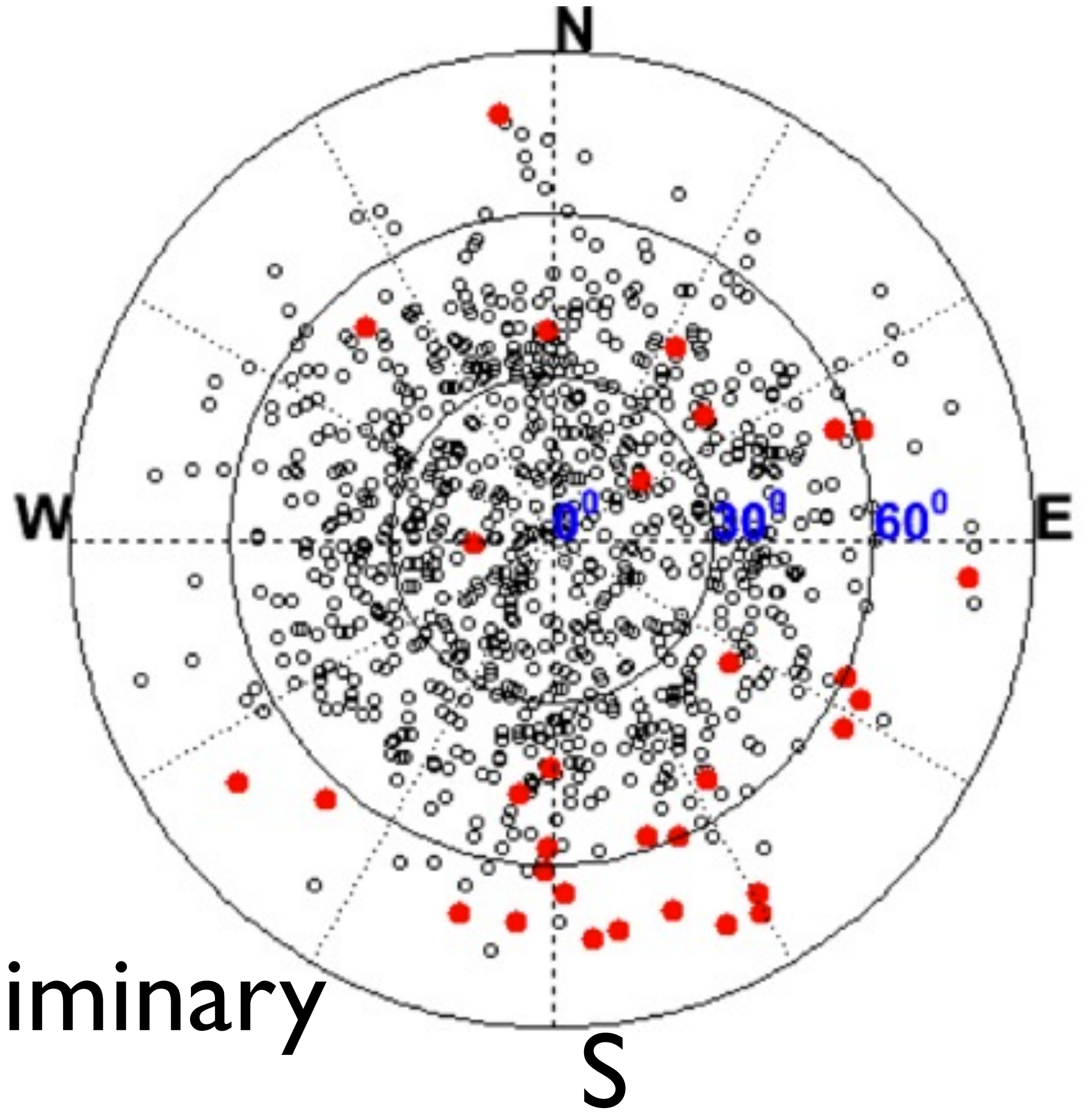






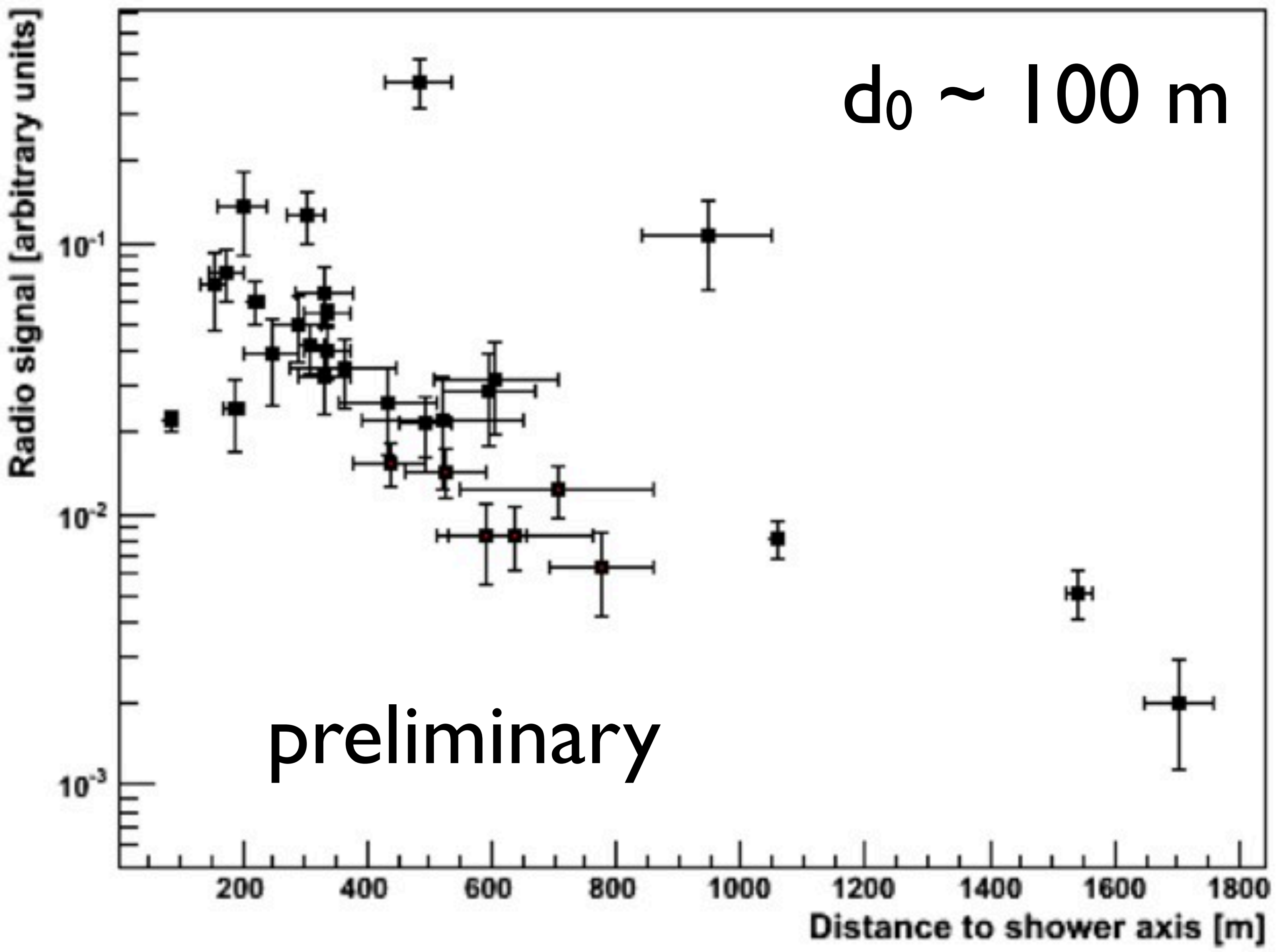


EASIER: MHz at large distance (1.5 km)



preliminary

Geomagnetic effect is observed but strong lobe effect



d_0 ~ 100 m

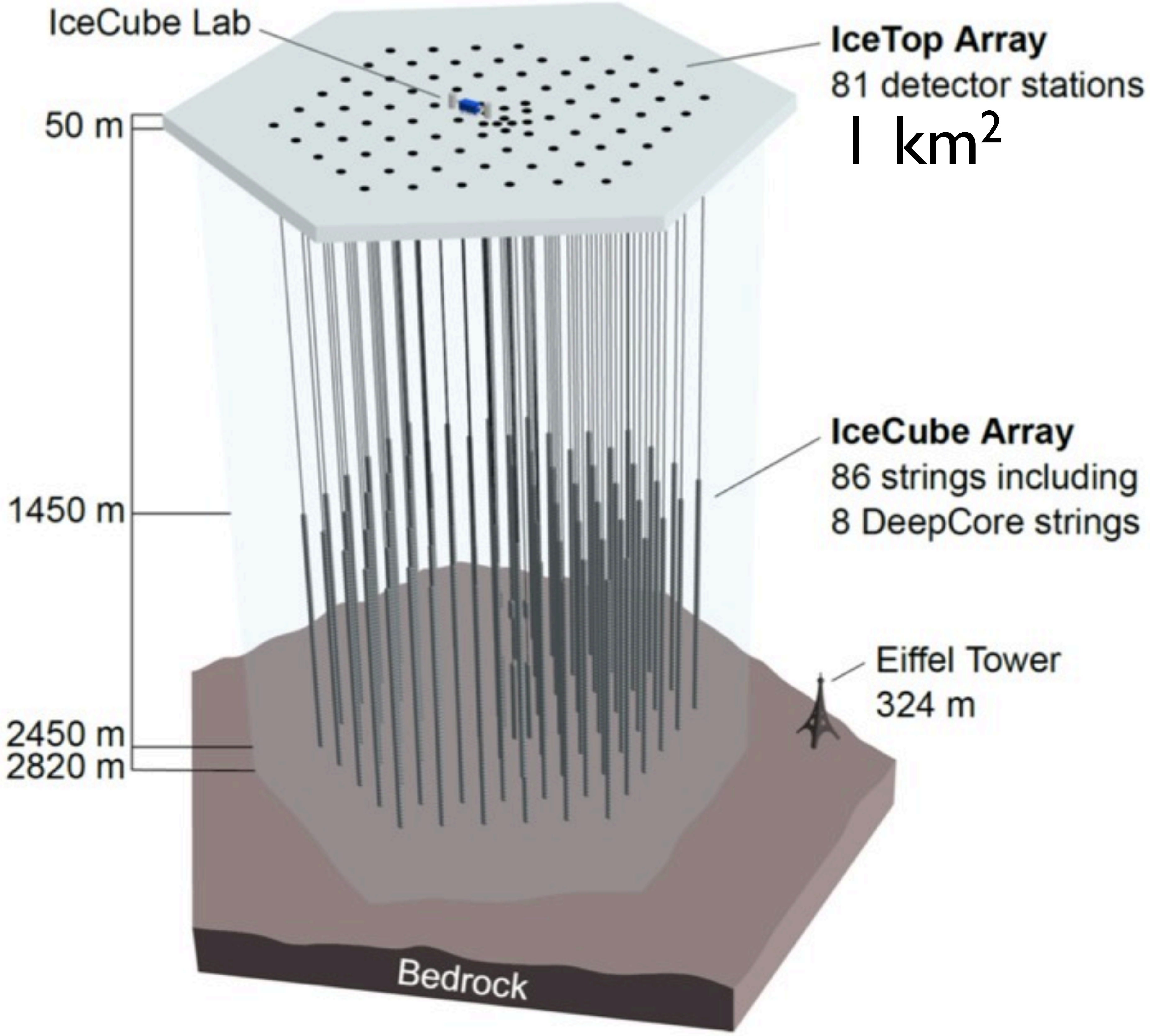
preliminary

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

(no axis distance but distance to shower maximum)

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

The RASTA experiment



1 km^2

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)

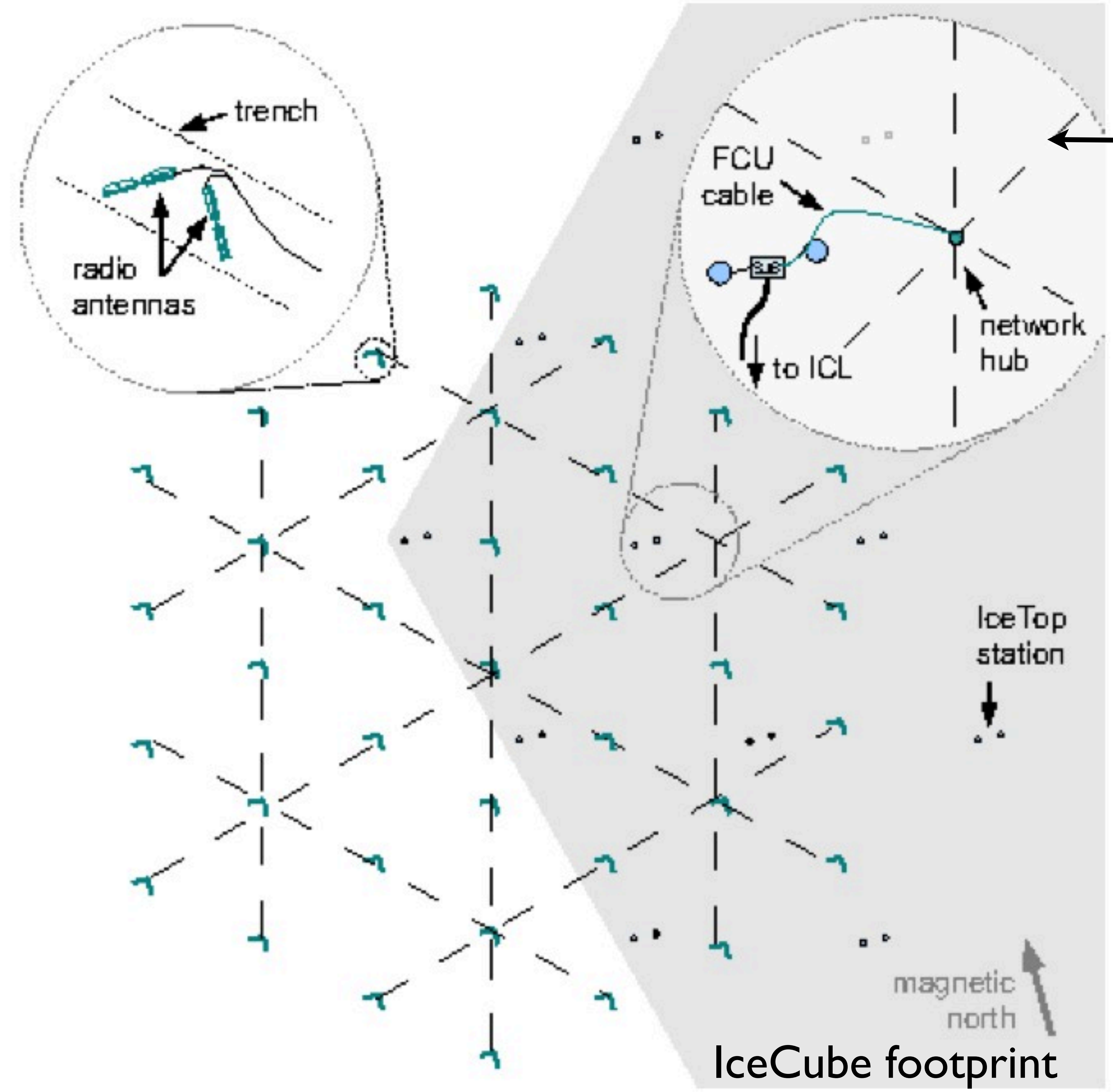
~ 1000 antennas centered on IceTop and covering ~ 10 km^2

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

The RASTA experiment

DuVernois, ICRC 2011

Possible RASTA configuration

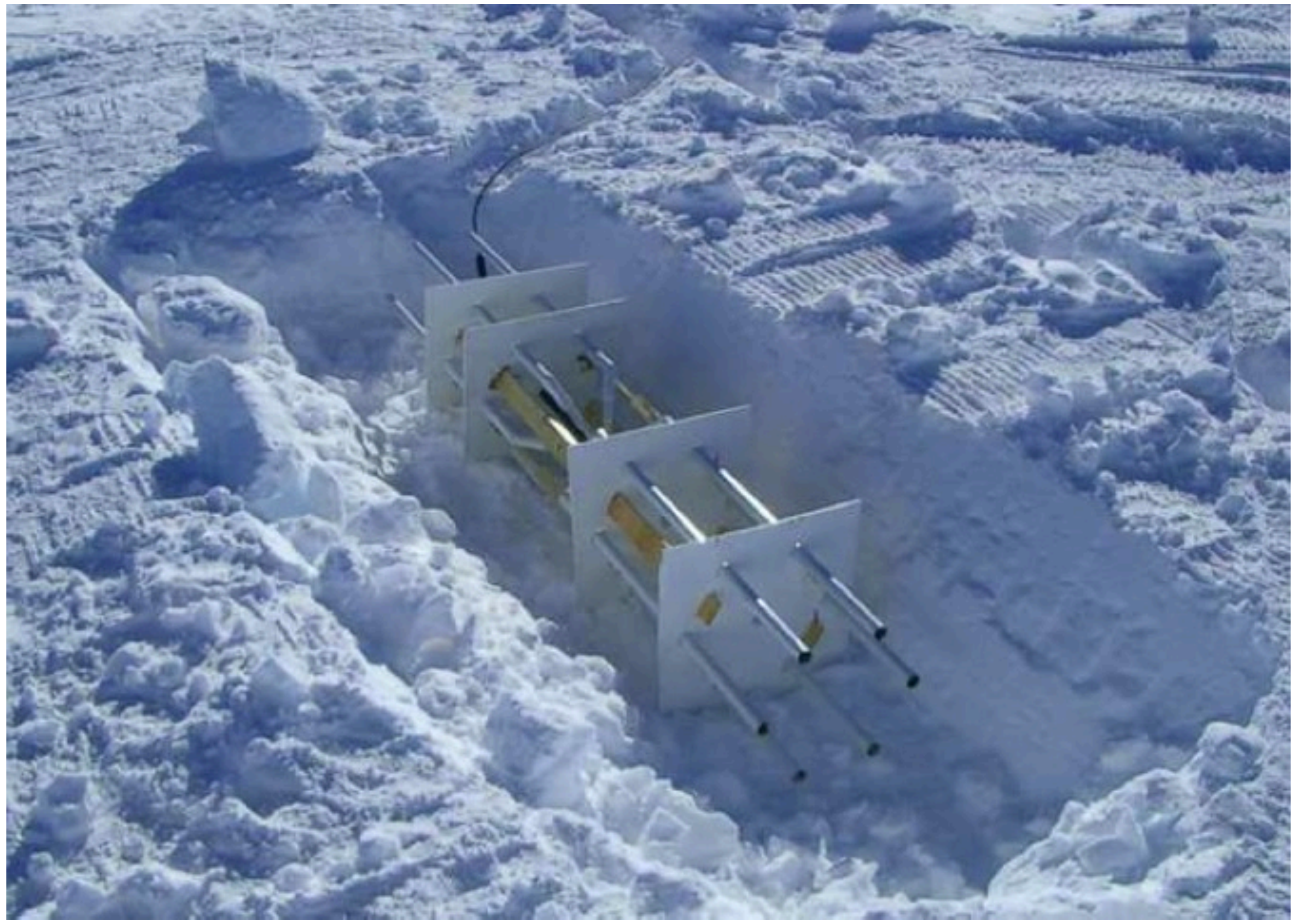


IceCube footprint

Antennas are in orthogonally polarized pairs

data/power line

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



Synthesis

Many advances since 2002: at first order **E = n X B** in both amplitude and polarization (almost all experiments), in both hemispheres

Close to the shower axis: Cerenkov (higher frequencies: LOFAR, ANITA)

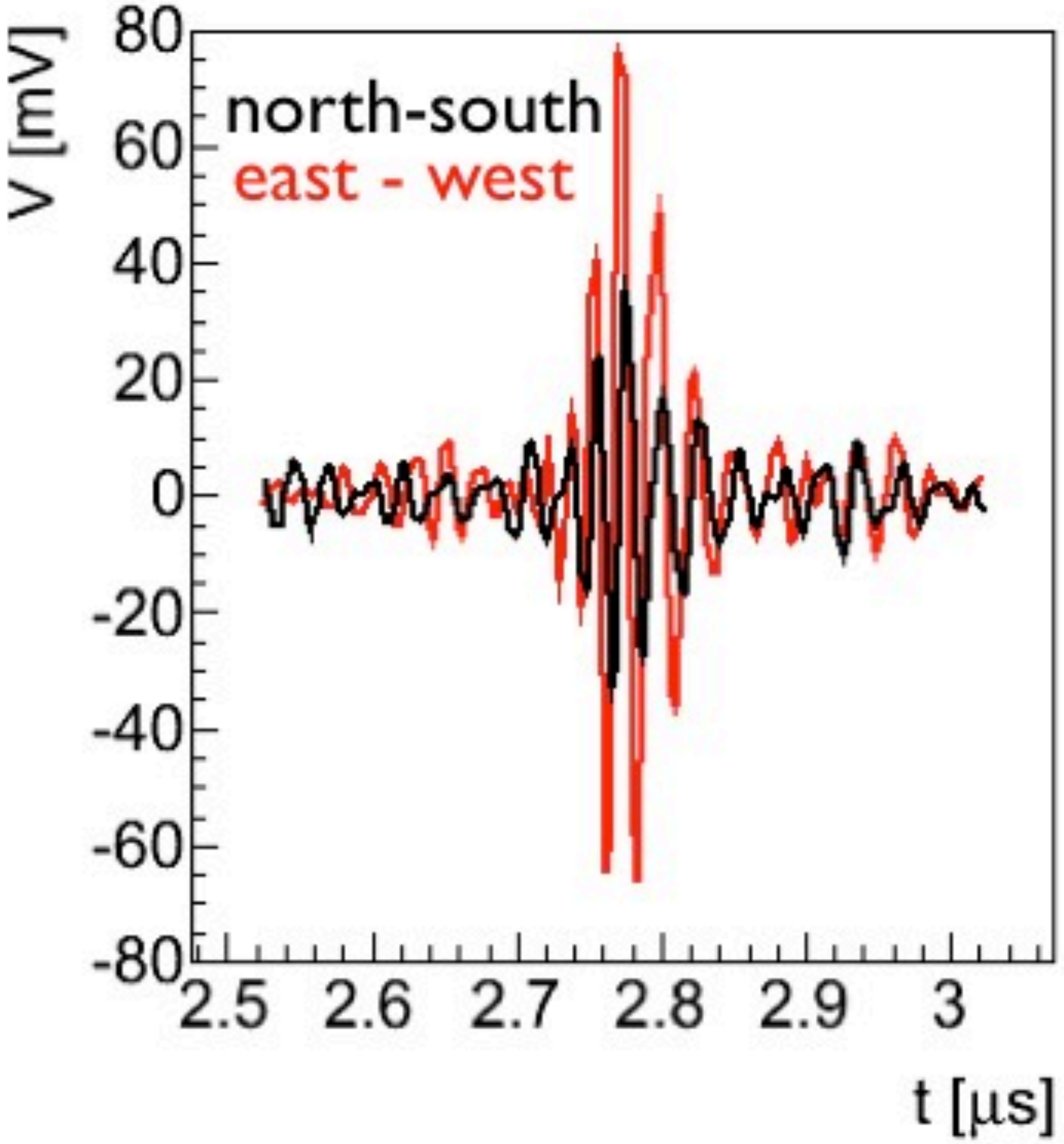
"LDF anomaly": flat for antennas close to the shower axis; departure from an pure exponential dependence with axis distance

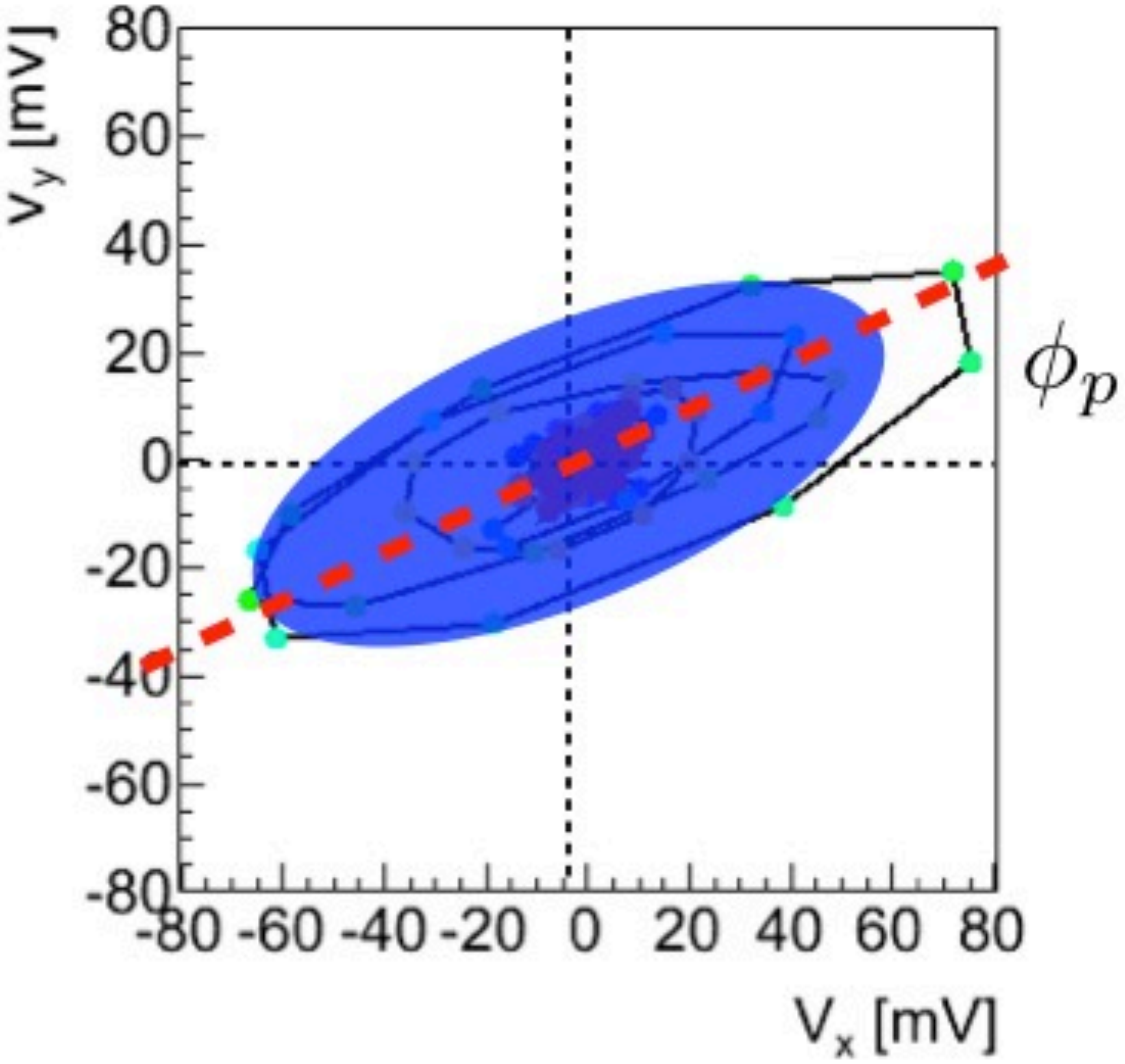
The charge-excess mechanism is (almost) detected:
- signature in the polarization angle (AERA & MAXIMA setup)
- signature on the radio core positions (CODALEMA)

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

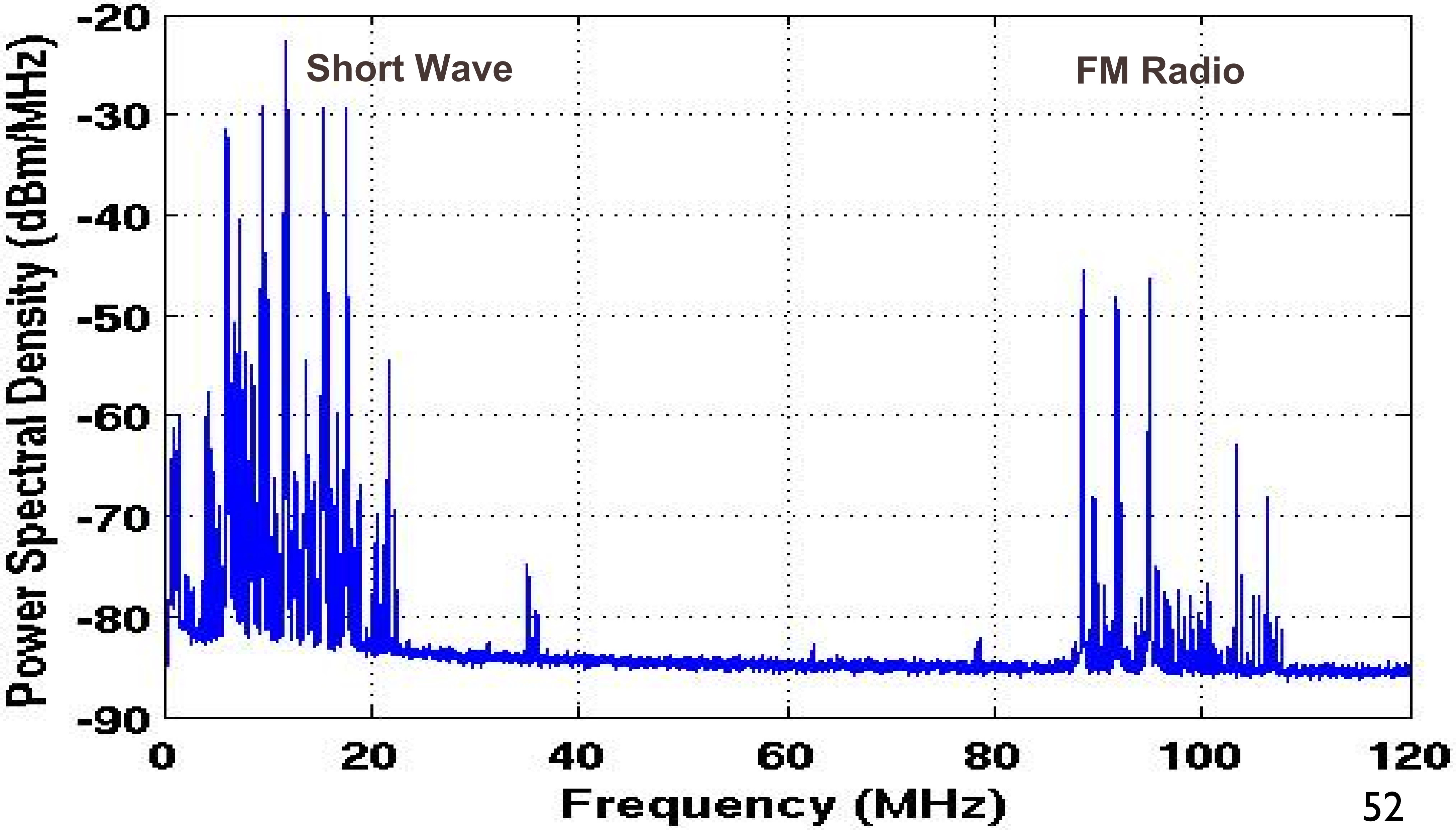
One of the most important point is the triggering algorithm (hardware/software) to improve the detection efficiency

At this moment, we don't know if a giant radio-array is promising or not


V [mV]
80
60
40
20
0
-20
-40
-60
-80
north-south
east - west
2.5
2.6
2.7
2.8
2.9
3
t [μs]


V_y [mV]
80
60
40
20
0
-20
-40
-60
-80
-80
-60
-40
-20
0
20
40
60
80
V_x [mV]
ϕ_p

The CODALEMA experiment



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