COSMIC RAY RADIODETECTION

A short introduction

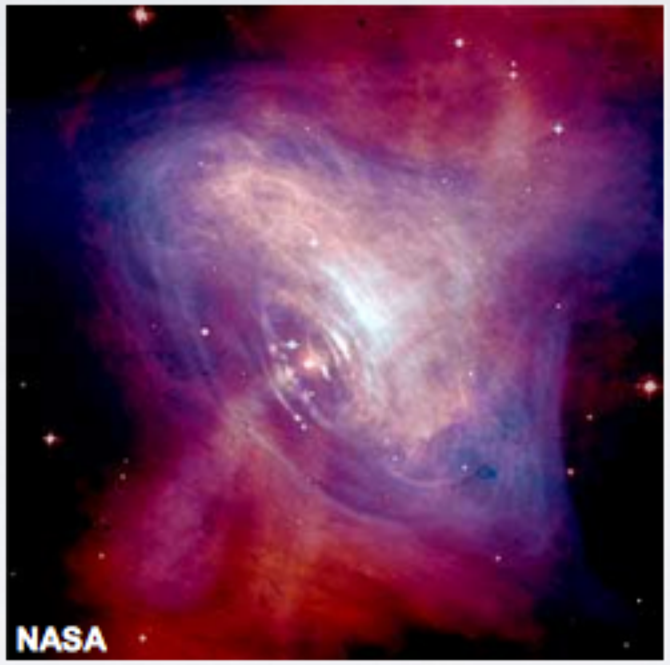
Lilian Martin & Richard Dallier
Subatech, CNRS/IN2P3 - Ecole des Mines de Nantes - Université de Nantes

Alain Lecacheux
LESIA, CNRS/INSU - Observatoire de Paris-Meudon-Nançay

MOTIVATIONS

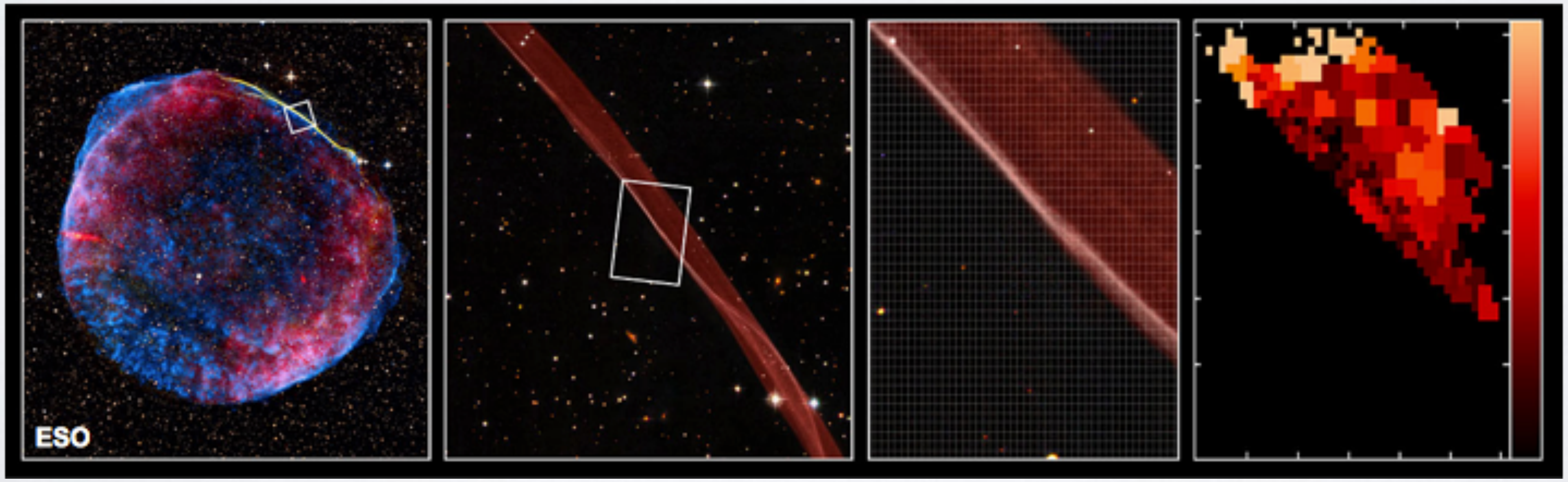
- Cosmic rays are stable and charged particles: p, He, … , Fe
- Abundance depending on their energy and mass
- **Another way to study astrophysical phenomena in the Universe**

Pulsar – Crab Nebula

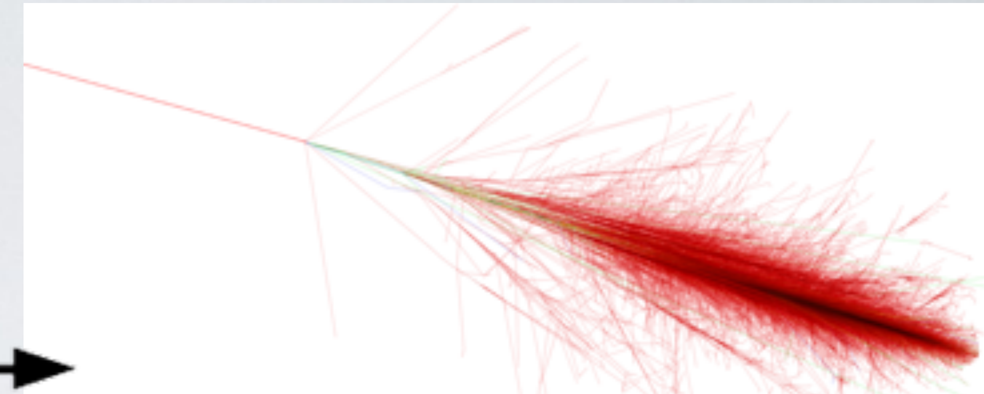


AGN - Centaurus A

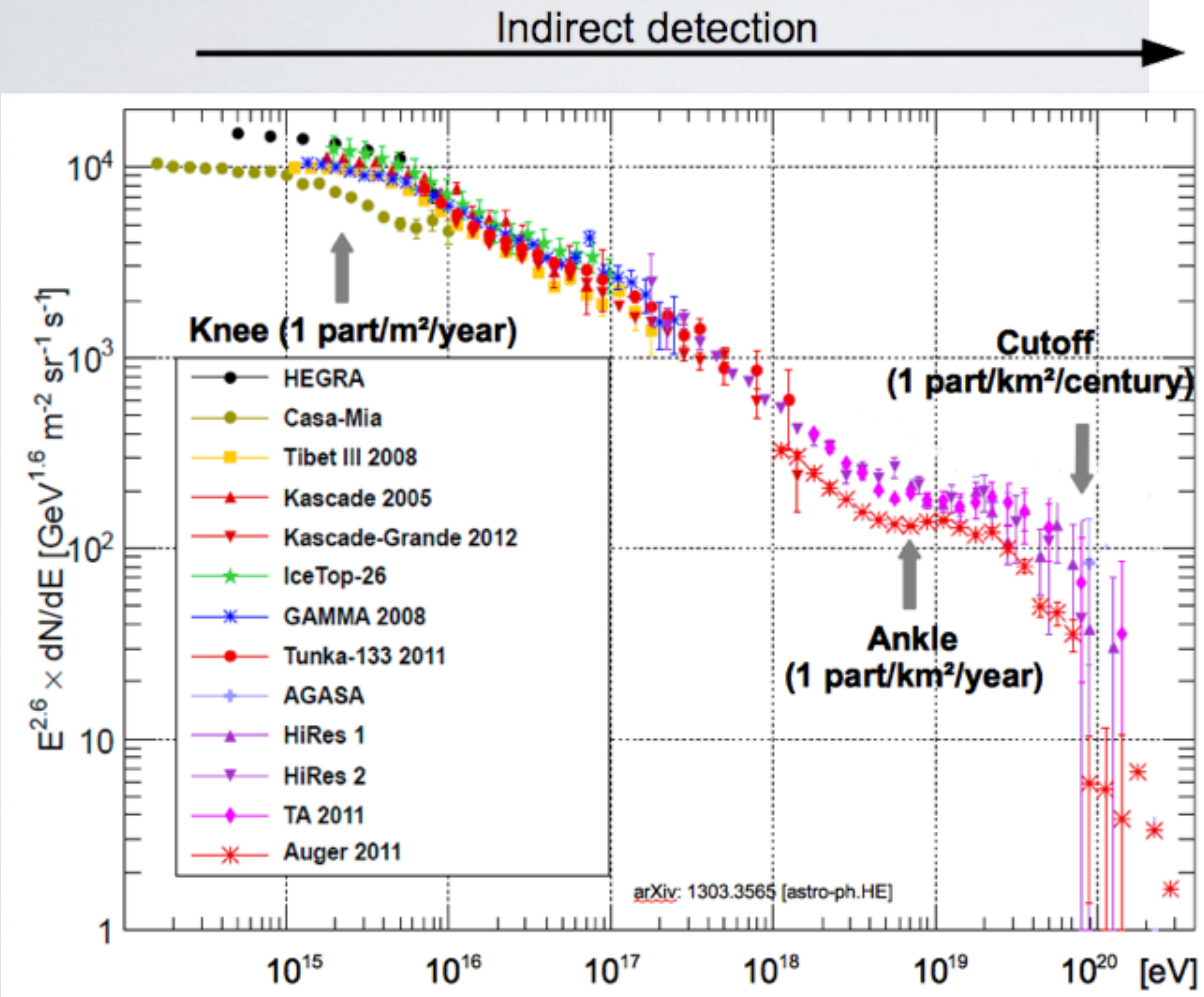
Supernova remnant – SN 1006



THE END OF THE COSMIC RAY SPECTRUM



A cosmic ray air shower



10^{15} - 10^{16} eV:
Composition: proton dominated
Source: galactic supernova

10^{16} – 4.10^{18} eV:
Composition: iron dominated
Source: galactic supernova + extragalactic ?

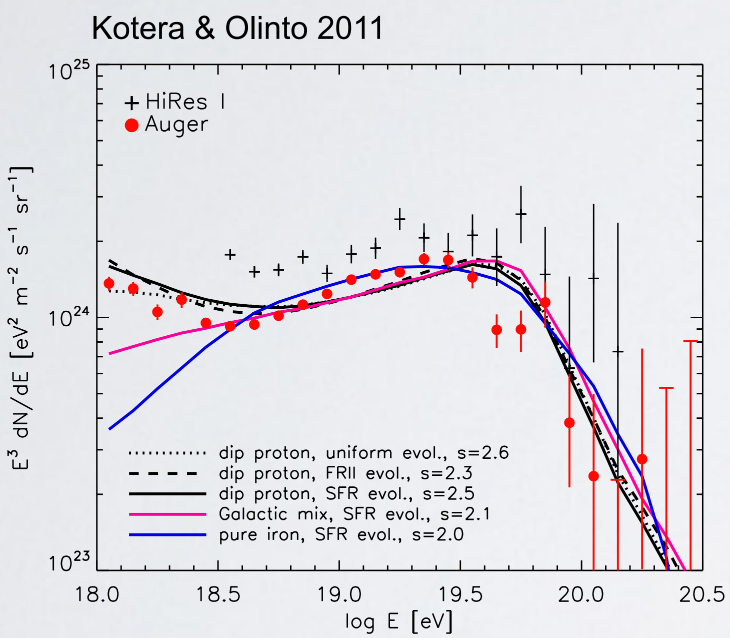
4.10^{18} – 4.10^{19} eV:
Composition: proton dominated
Source: extragalactic ?

Above 4.10^{19} eV:
Composition: ?
Source: ?

REMAINING CHALLENGES

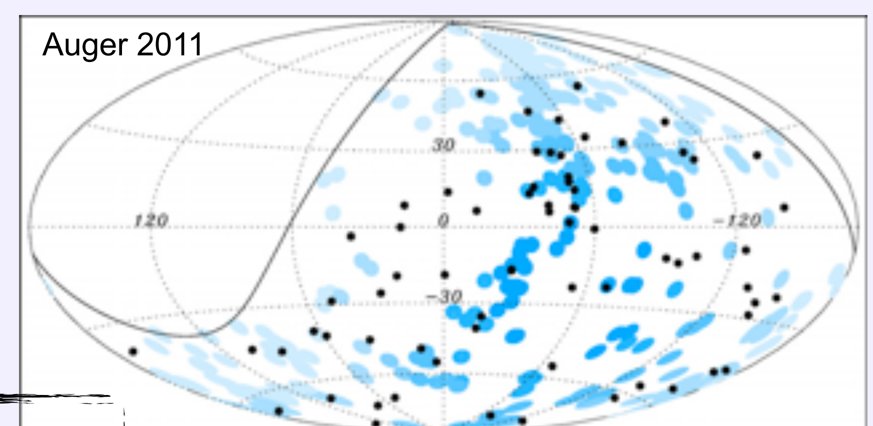
Spectrum

Ankle: galactic/extragal. transition?
e^+/e^- pair production depletion?
High energy cut off: GZK ? Source acceleration limit?
Source horizon?



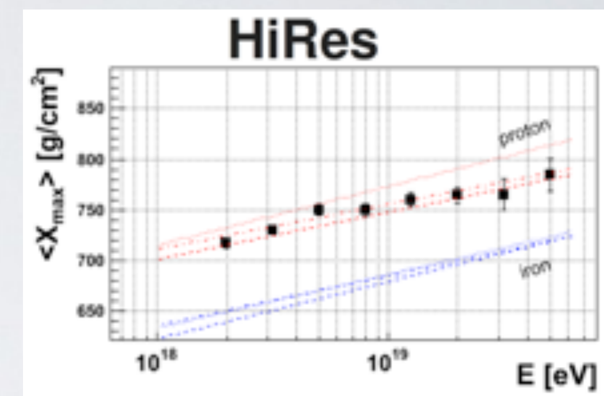
Sources

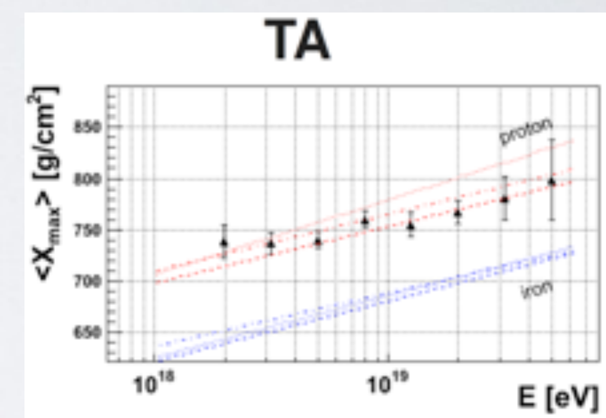
Auger : E > 55 EeV ➟ Anisotropy
HiRes/TA don't confirm !
AGN (Auger : 3σ) ? Cen-A ?

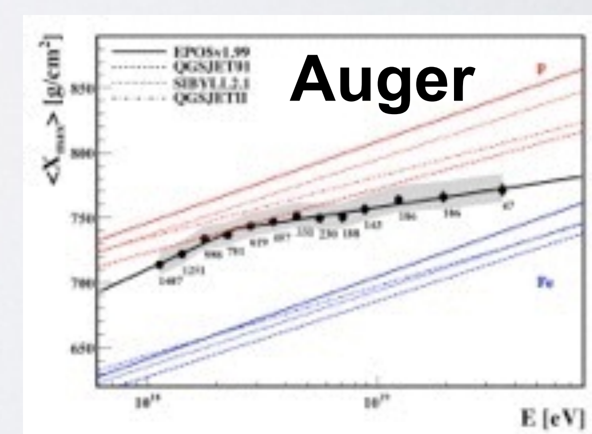


Composition

Heavier at high energy: seen by Auger, but not HiRes nor TA!
➟ Difference North/South sky ?
Statistics ? Analysis method ?







Needs

Higher statistics at high energy
Better energy resolution
Coverage of North hemisphere
Measure of spectral index & composition

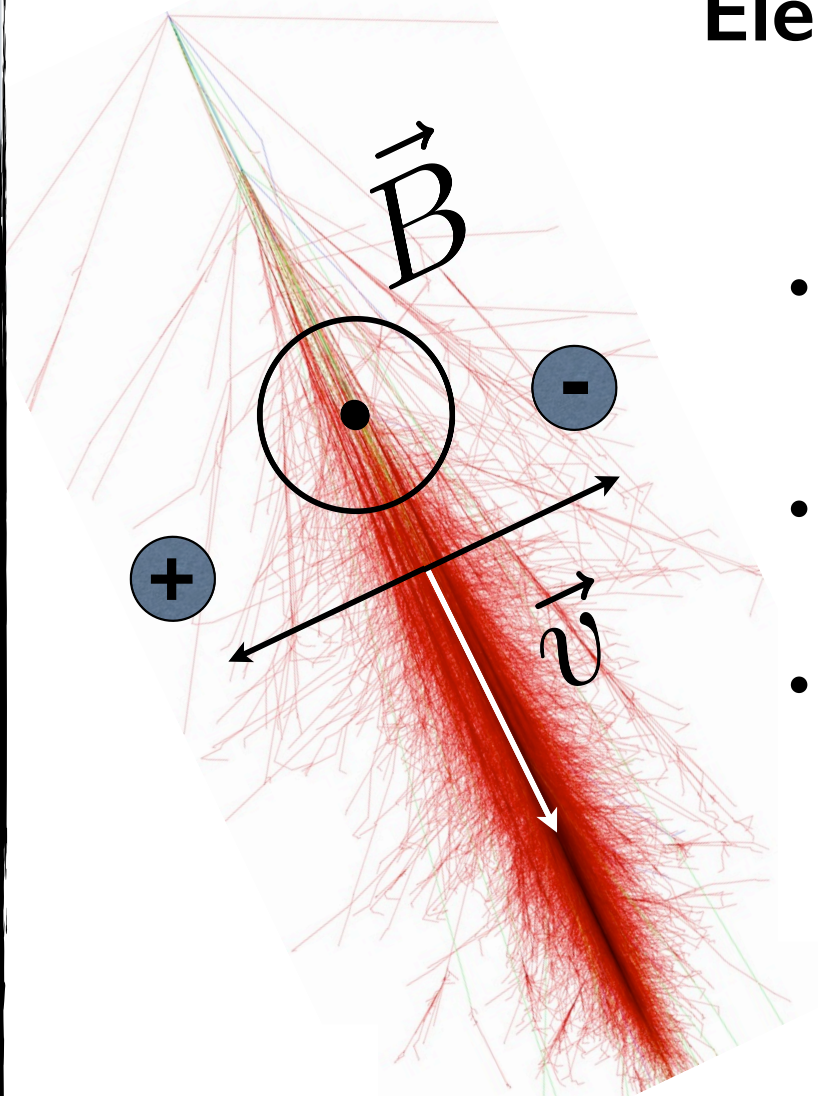
WHAT ANSWERS ?

The solution would be a new giant instrument at ground

- Higher statistics at high energies:
  detection surface 10 x S_{Auger} ⇒ 30000 km^2 !
- Energy resolution, spectral index and composition:
  more accurate measurements ⇒ Multi-hybrid detection ?
- Timeline ≲ 15 years ?

Radio detection ?

Electric field



Different approaches:

- Cerenkov radiation of negative charge excess (electron excess is ~10-20 %): Askary'an effect (1962)
- Macroscopic view: **j** current radiation ; MGMR simulation code (Werner & Scholten)
- Microscopic view: radiation of e^-/e^+ pairs in **B** ; codes REAS3 (Huege), SELFAS (Marin & Revenu), ZHAires (Alvarez-Muniz et al.)

Jodrell Bank 1964

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

Static field

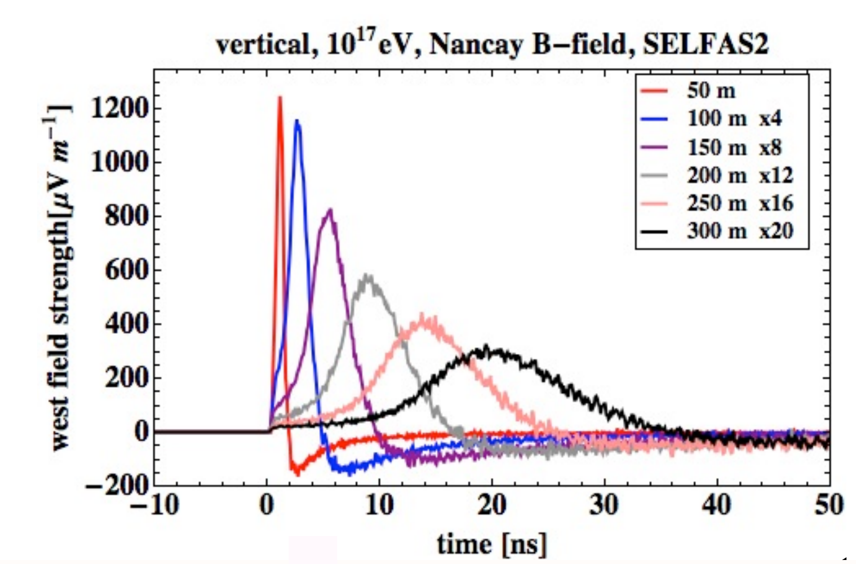
Sum of all static field contributions

Macroscopic charge variation (charge excess term)

Sum on all charges. Electron excess implies a global charge variation $Q(t) \propto N(t)$

Current variation (geomagnetic term)

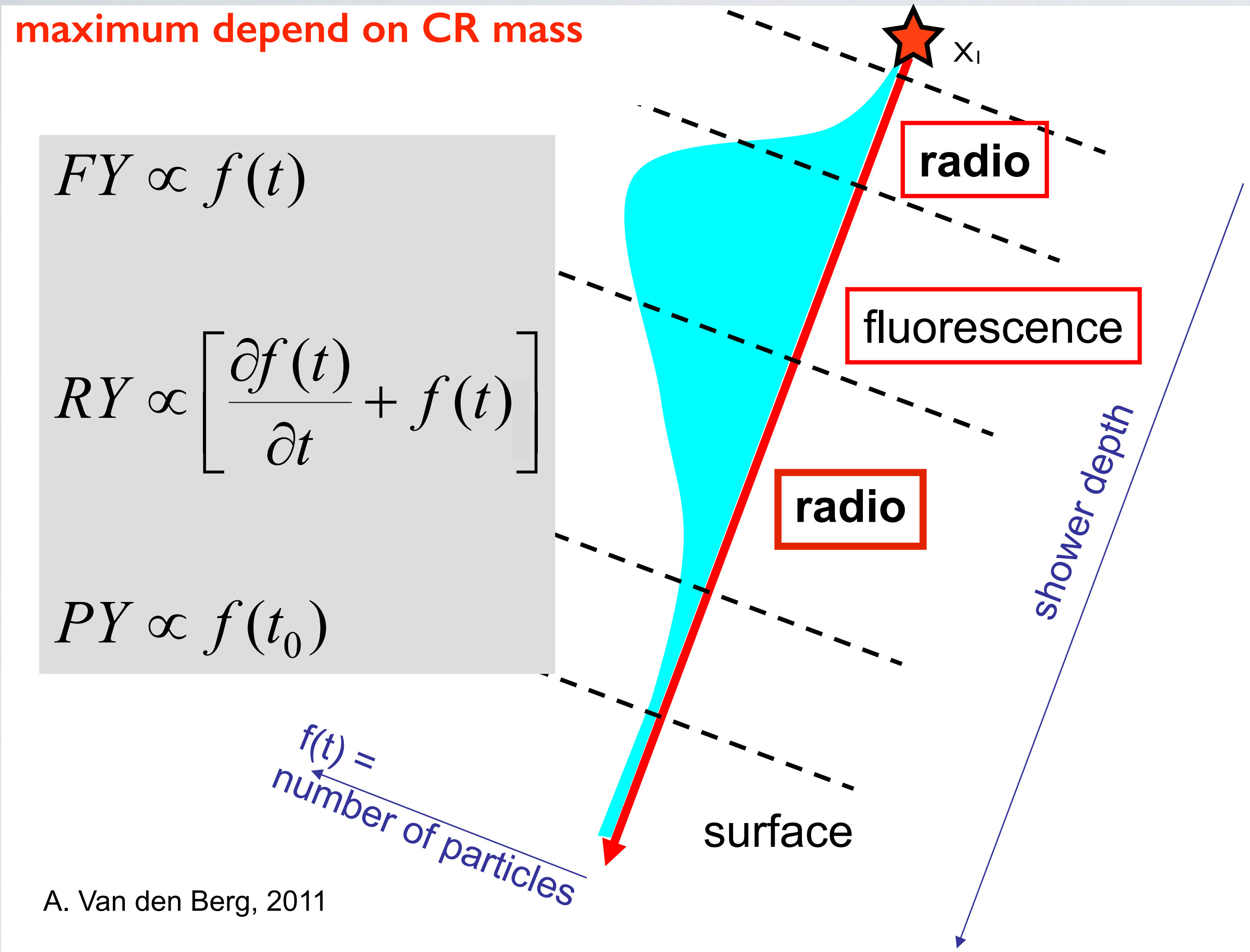
Sum of currents produced by charge (e^-/e^+) drift in **B**



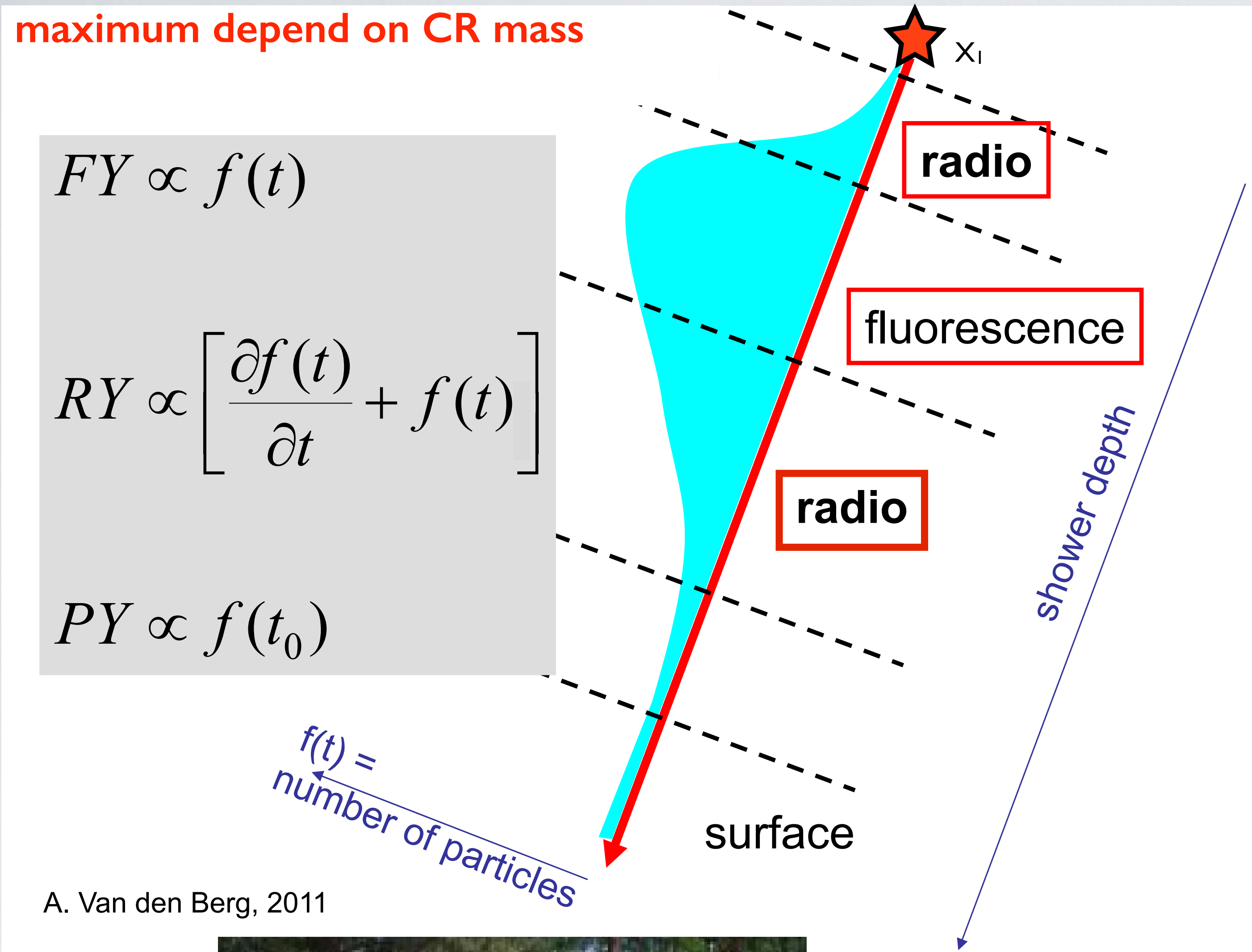
Marin and Revenu, 2012

Radio signal is correlated to the complete air shower development

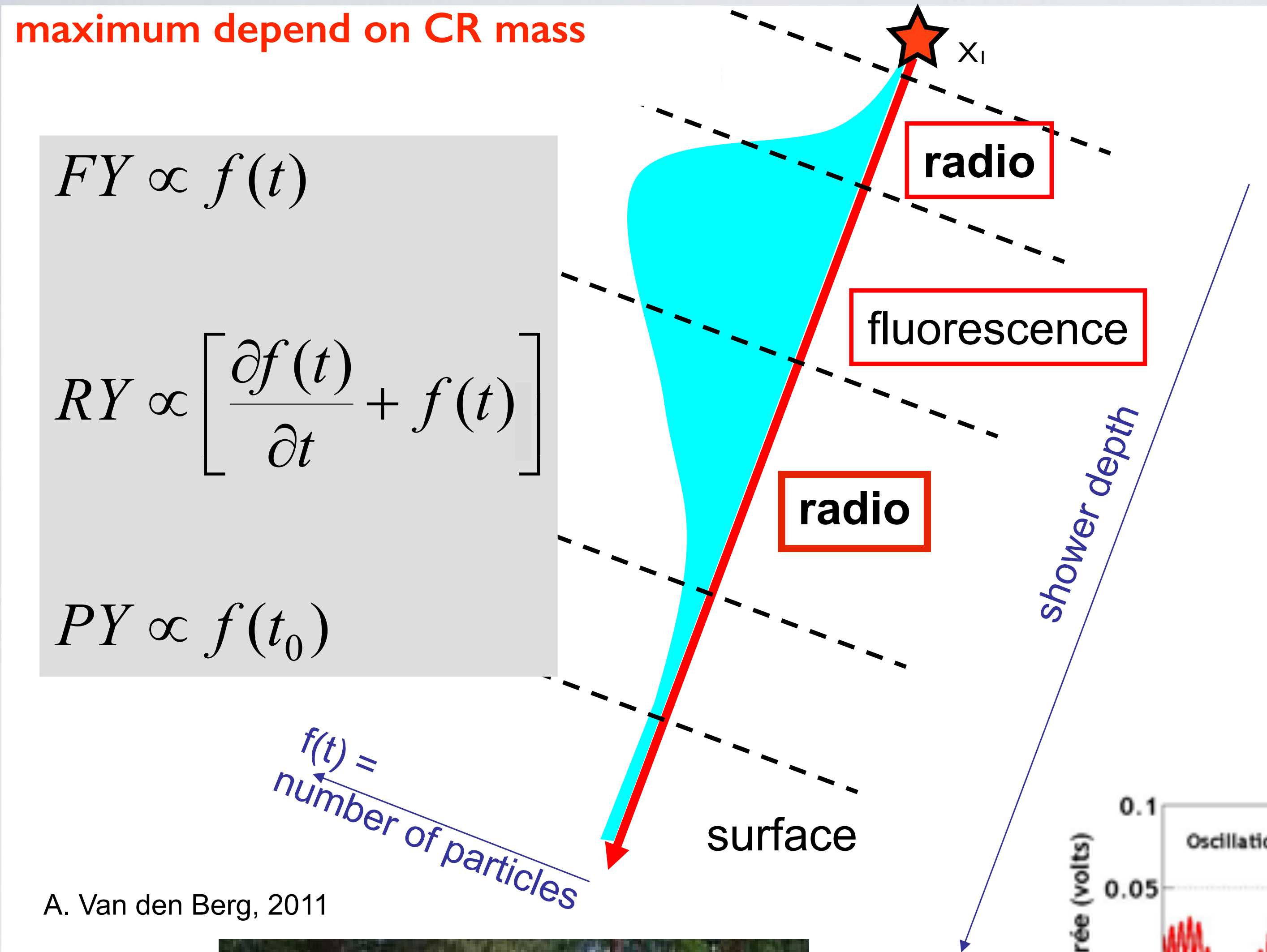
First interaction altitude and charge production maximum depend on CR mass

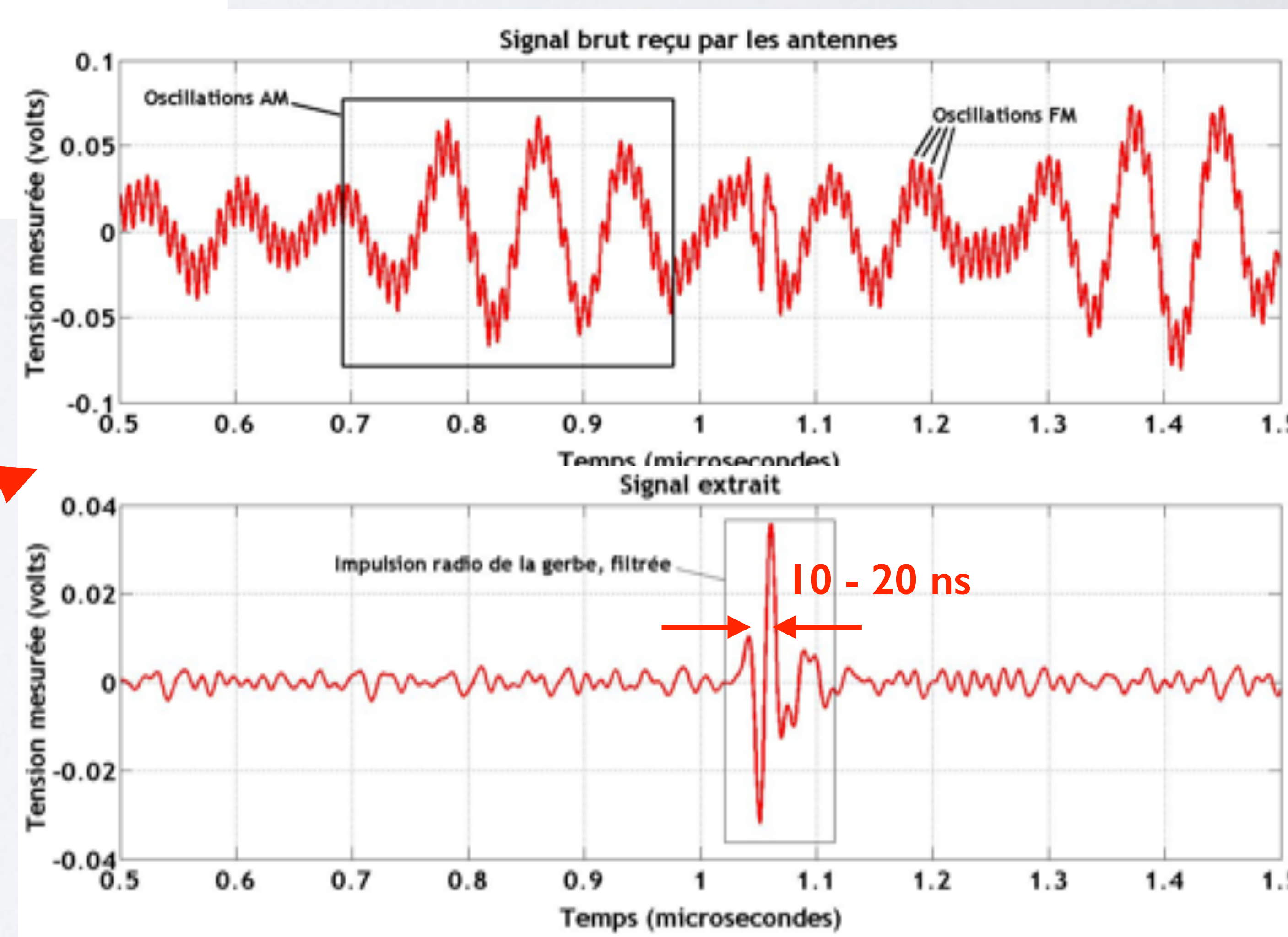


First interaction altitude and charge production maximum depend on CR mass



First interaction altitude and charge production maximum depend on CR mass



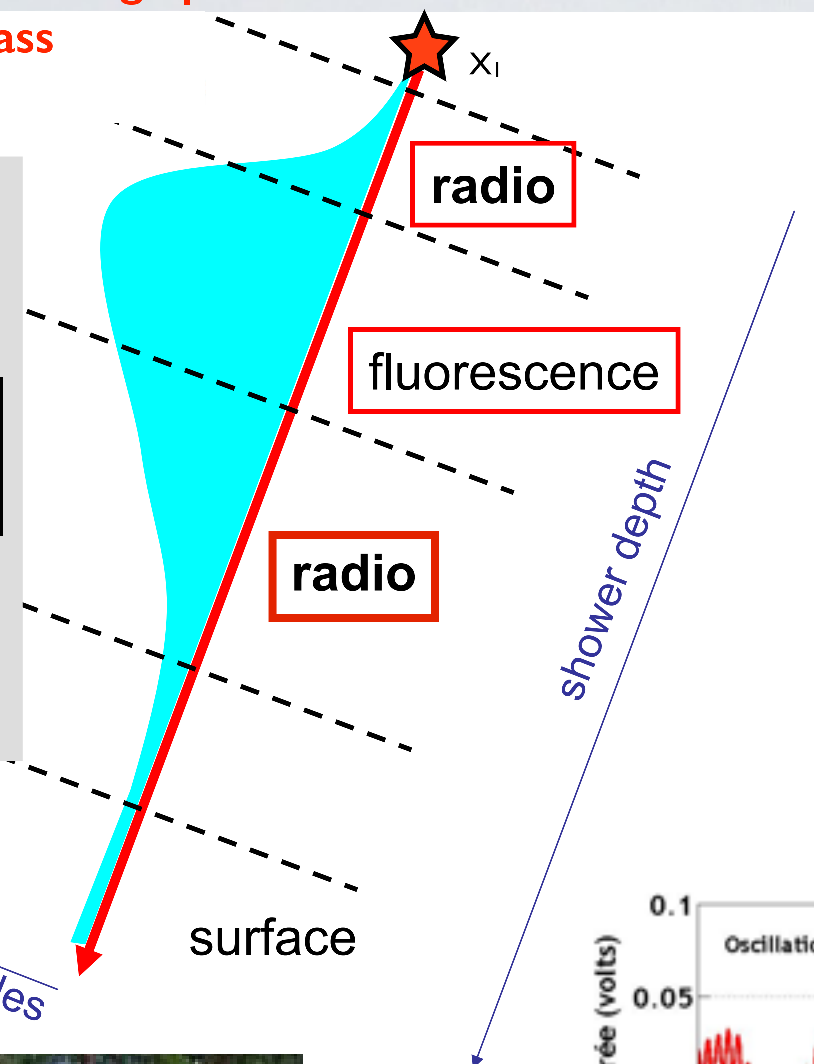


First interaction altitude and charge production maximum depend on CR mass

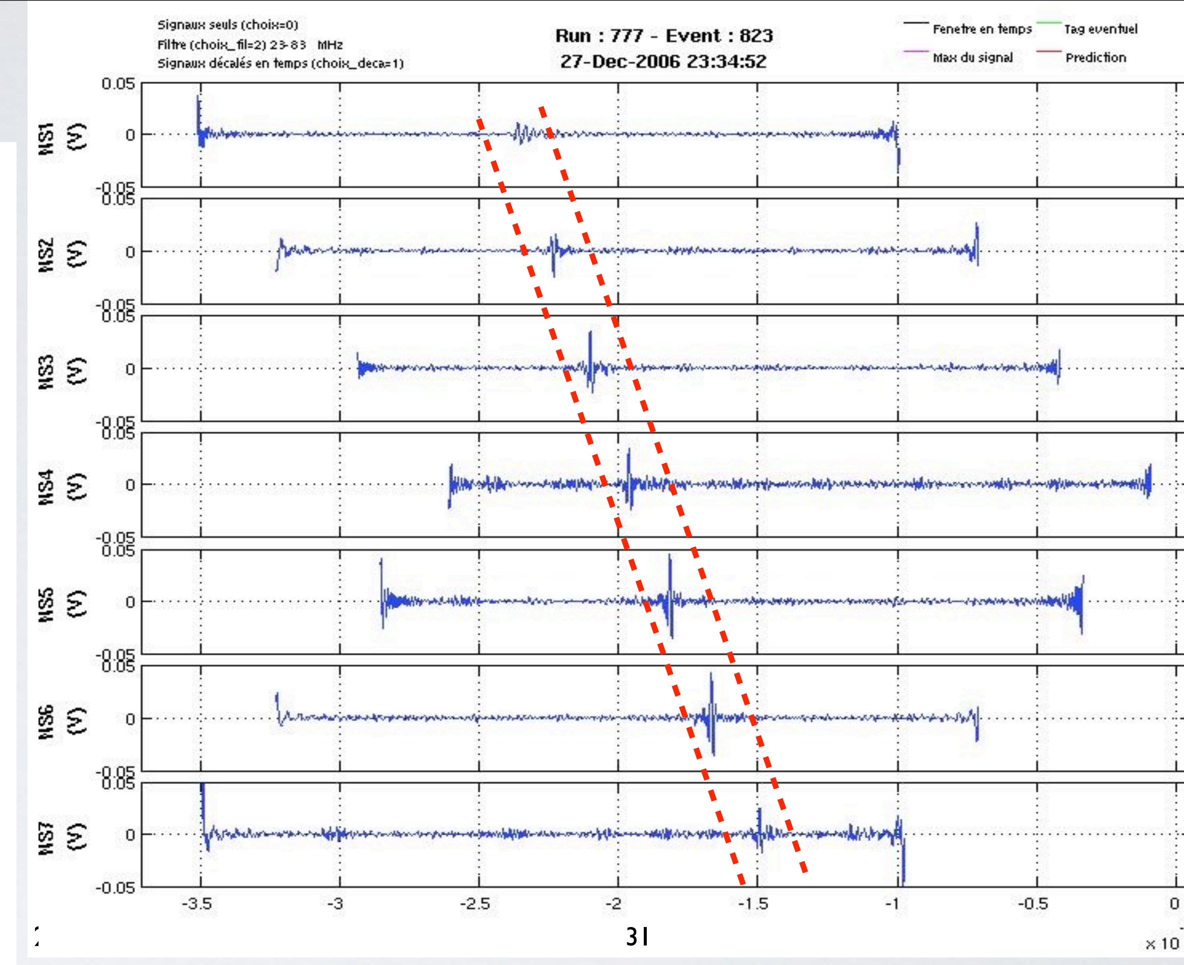
$$FY \propto f(t)$$

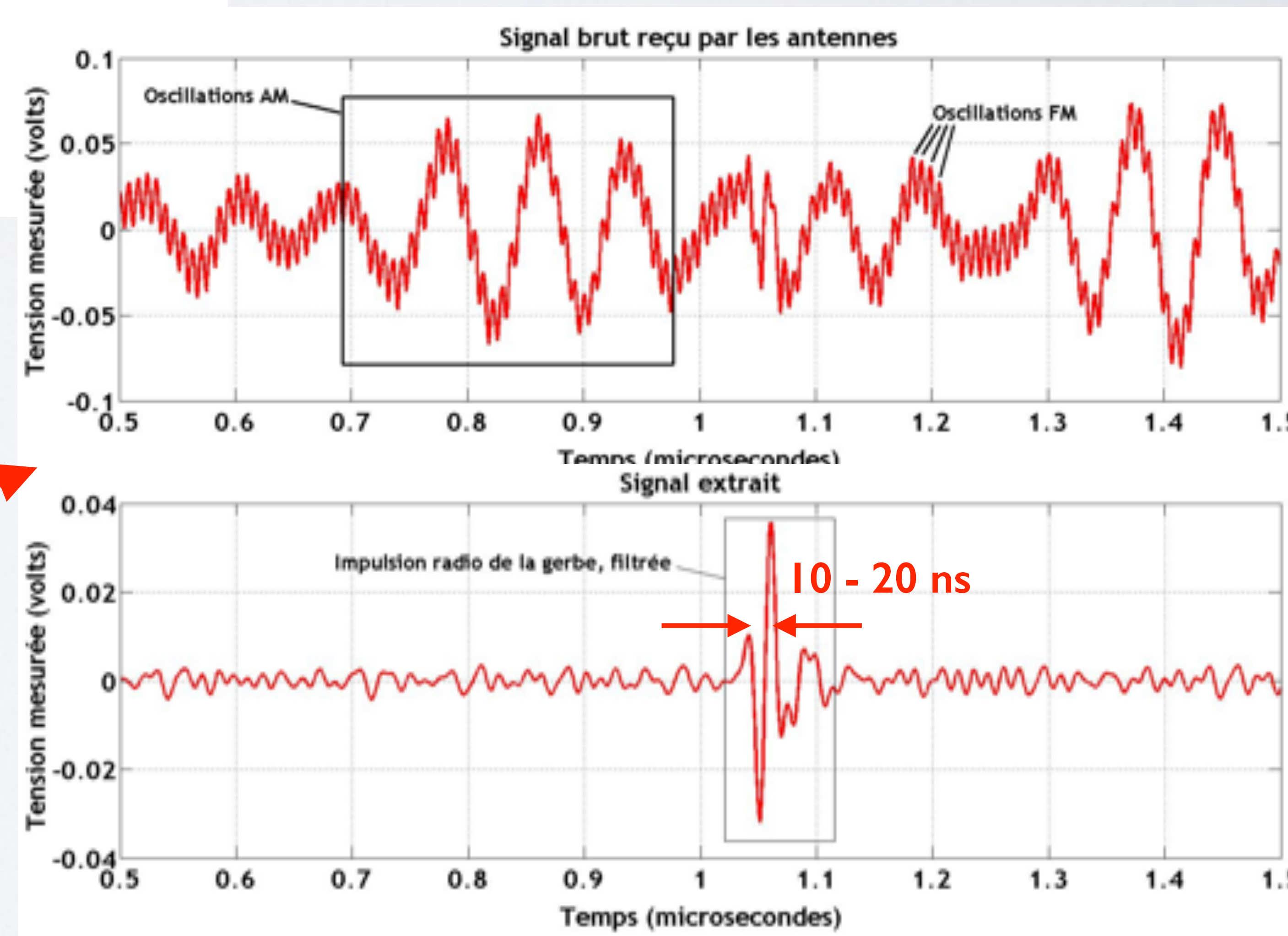
$$RY \propto \left[\frac{\partial f(t)}{\partial t} + f(t)\right]$$

$$PY \propto f(t_0)$$

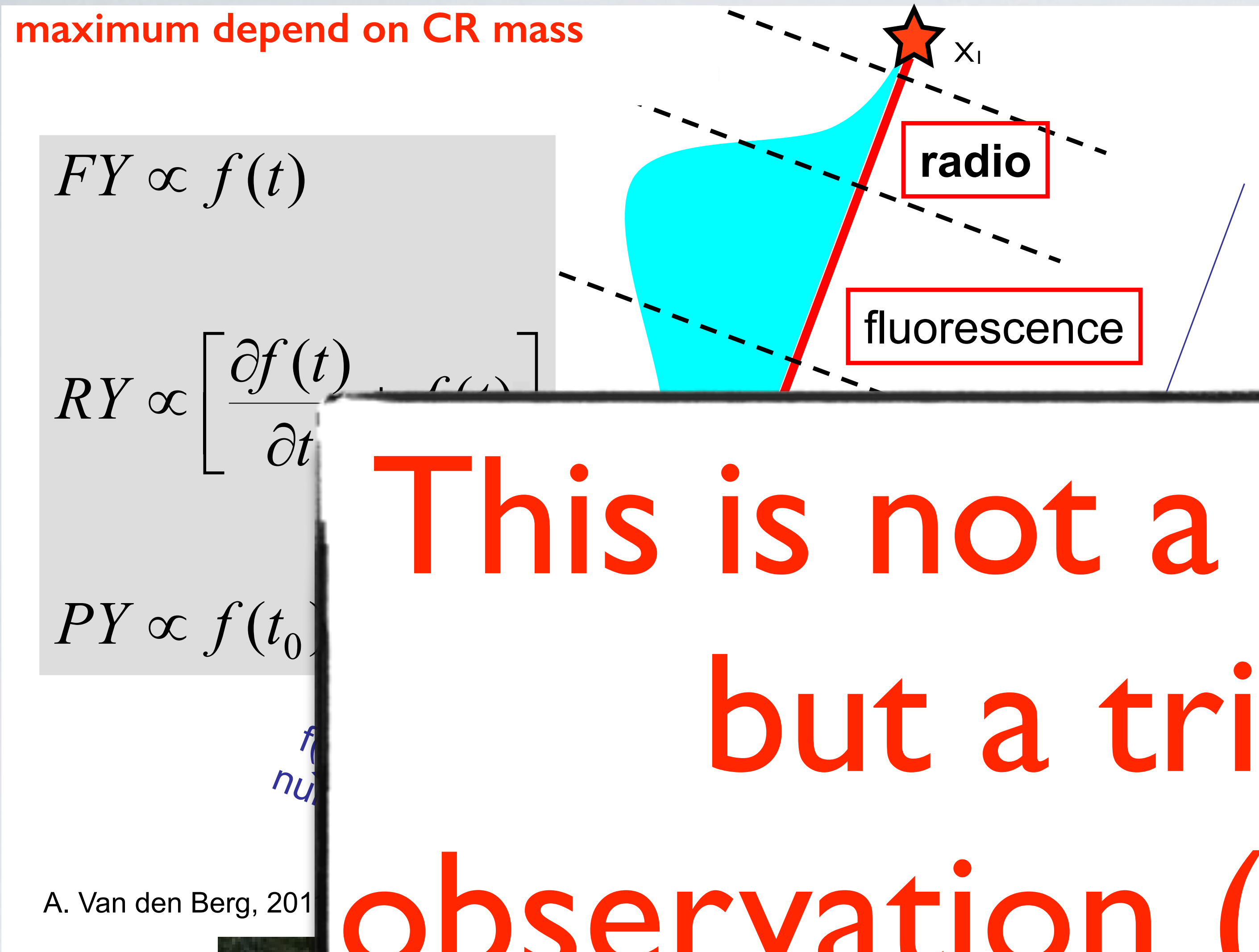


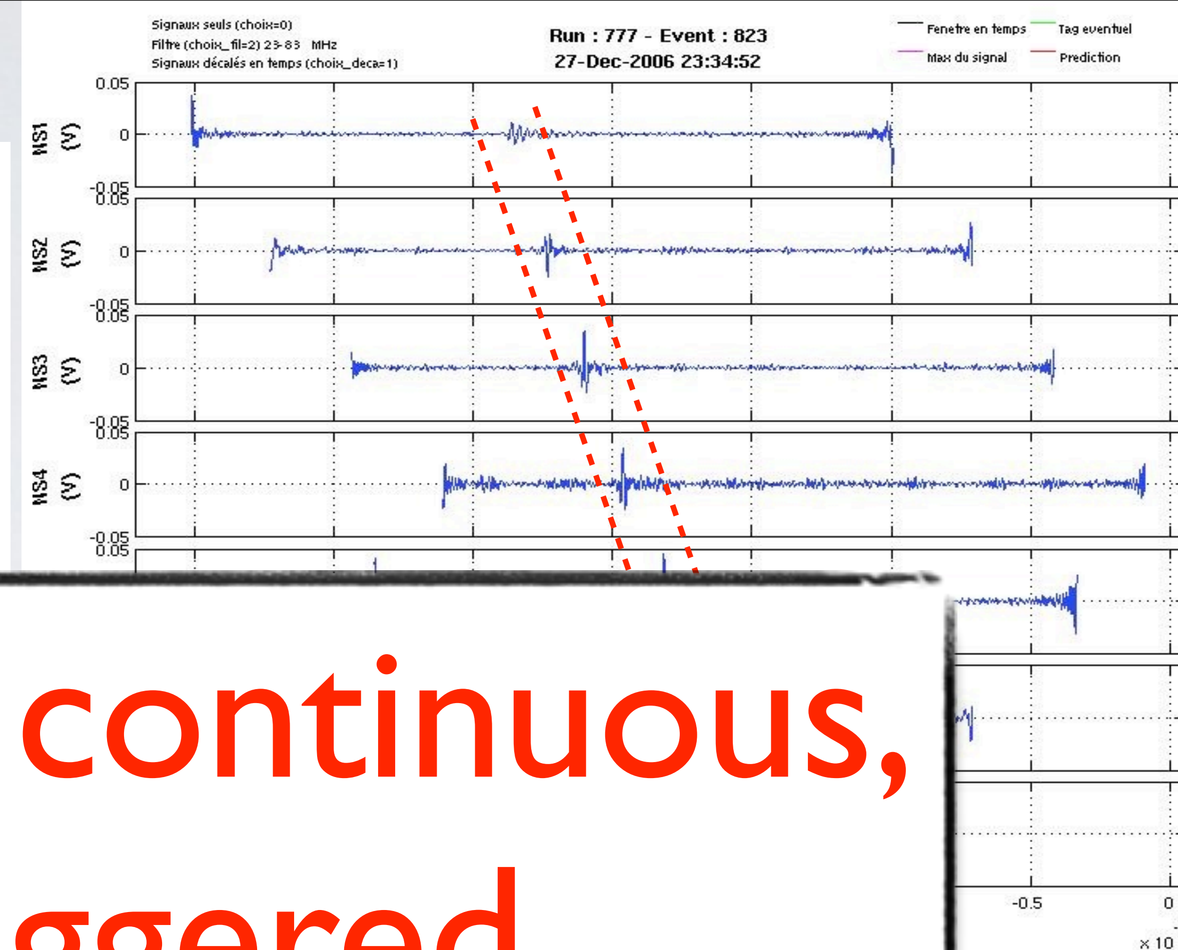
A. Van den Berg, 2011

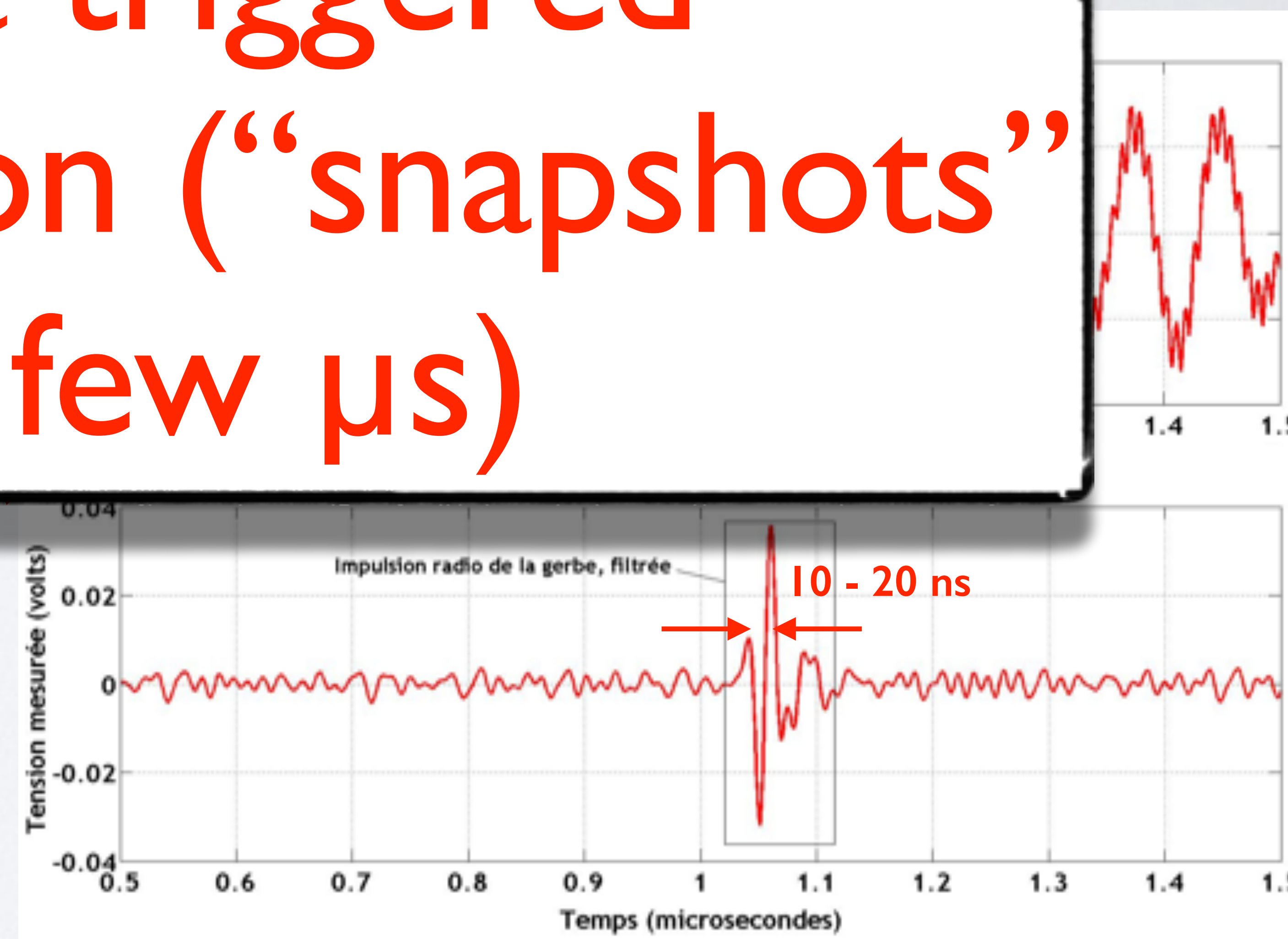




First interaction altitude and charge production maximum depend on CR mass

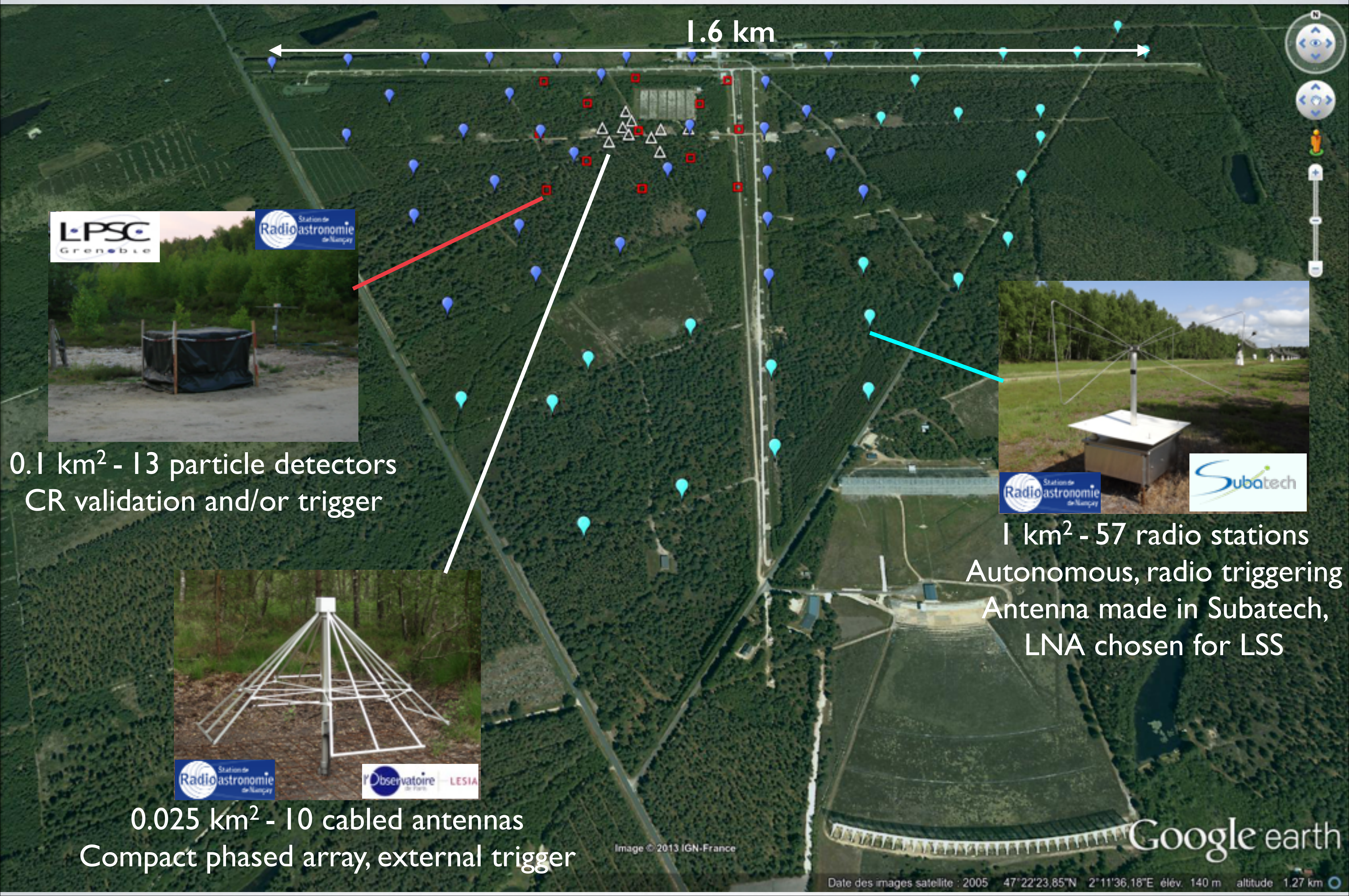




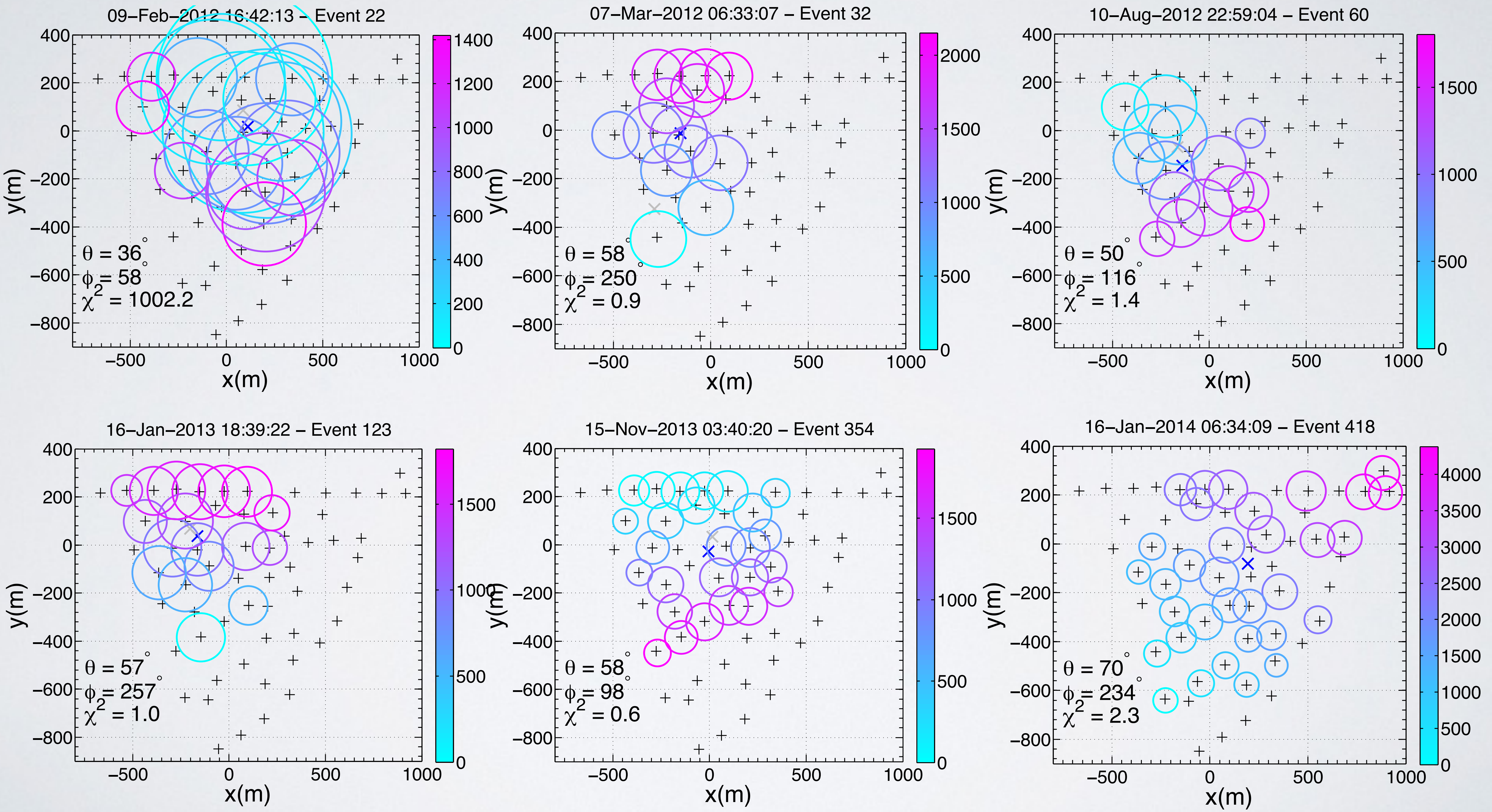


This is not a continuous, but a triggered observation ("snapshots" of few µs)

CODALEMA (NANÇAY, SINCE 2003)

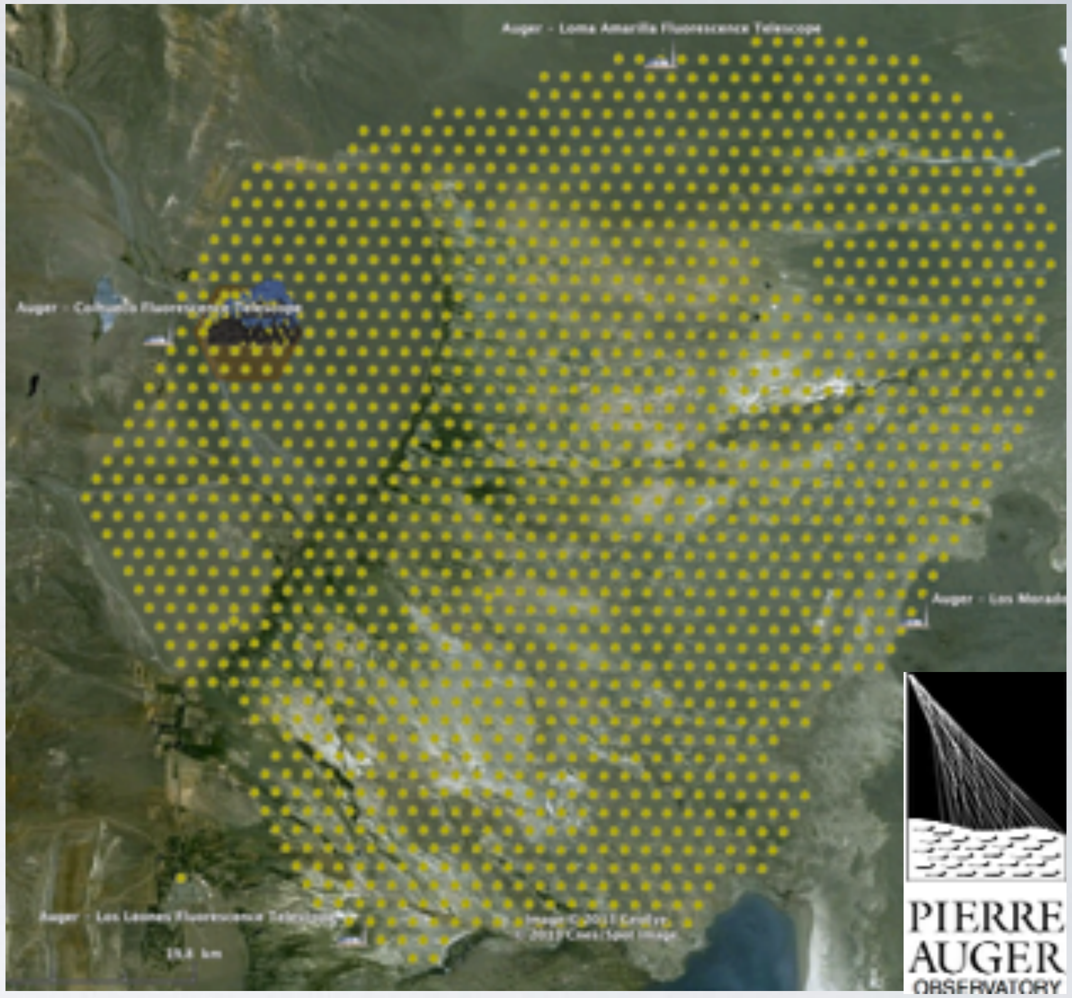


SOME BIG EVENTS



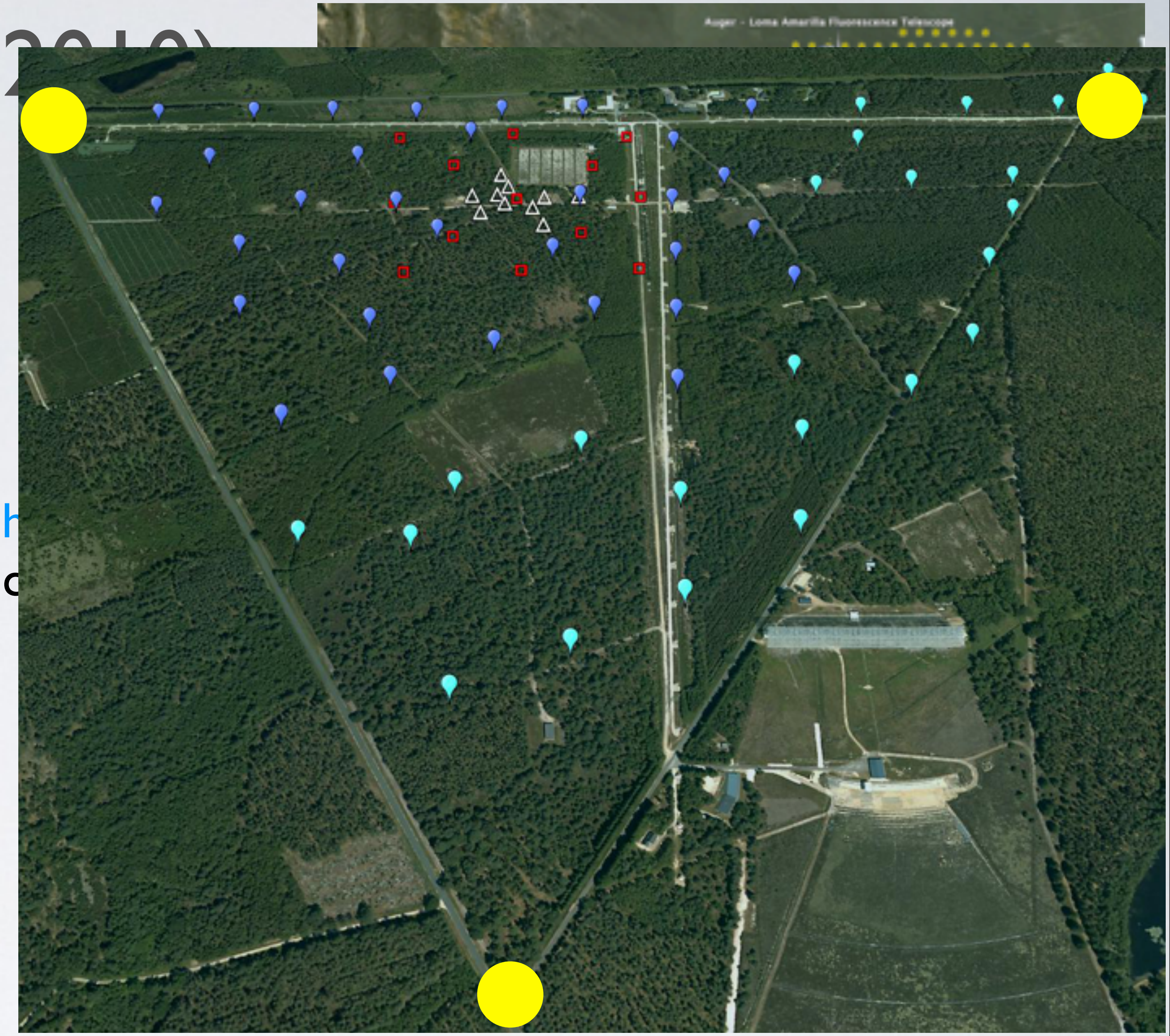
AERA (AUGER, SINCE 2010)

- RAuger prototype (F) in 2007 until 2010
- RAuger 2 in 2010 until 2013
- 24 autonomous stations late 2010
- 124 autonomous stations (7 km^2, may 2013)
- 160 foreseen (~13 km^2)
- Self-triggered and externally triggered
- Antenna, EMC housing, central DAQ: Subatech
- Local electronics, ADC, local & central DAQ, comms, monitoring: other 10 D, NL, F, R and P labs
- 3 grid steps (144m, 250m & 375m)



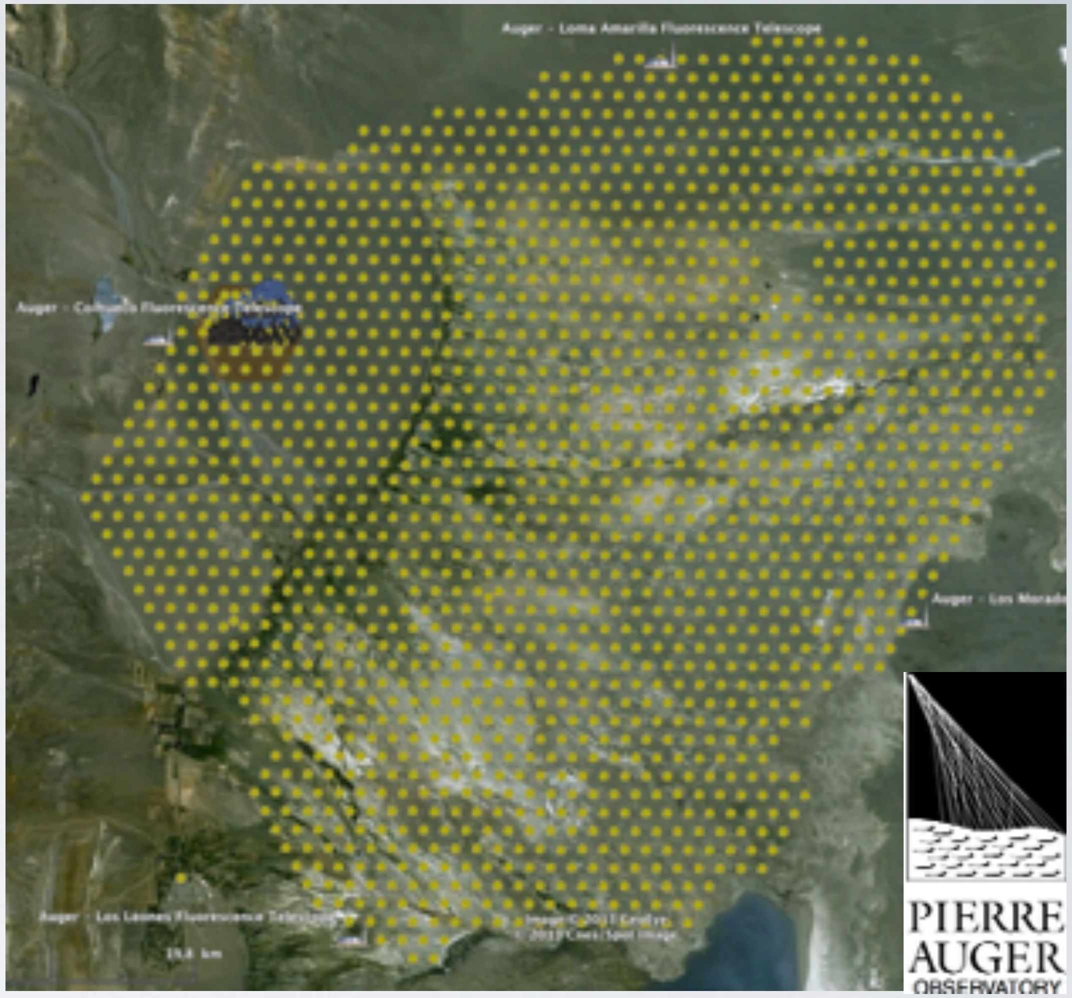
AERA (AUGER, SINCE 2010)

- RAuger prototype (F) in 2007 until 2010
- RAuger 2 in 2010 until 2013
- 24 autonomous stations late 2010
- 124 autonomous stations (7 km^2, may 2013)
- 160 foreseen (~13 km^2)
- Self-triggered and externally triggered
- Antenna, EMC housing, central DAQ: Subatech
- Local electronics, ADC, local & central DAQ, c
  monitoring: other 10 D, NL, F, R and P labs
- 3 grid steps (144m, 250m & 375m)



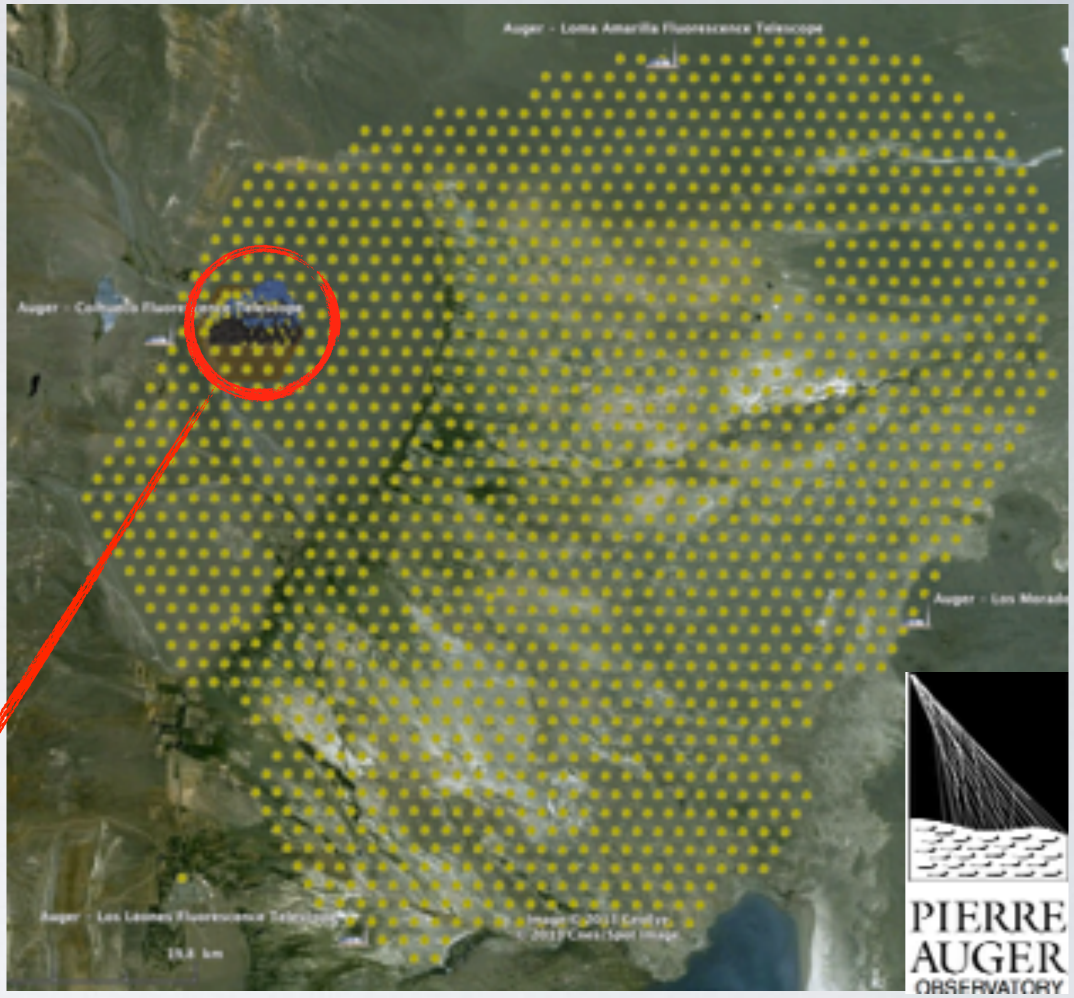
AERA (AUGER, SINCE 2010)

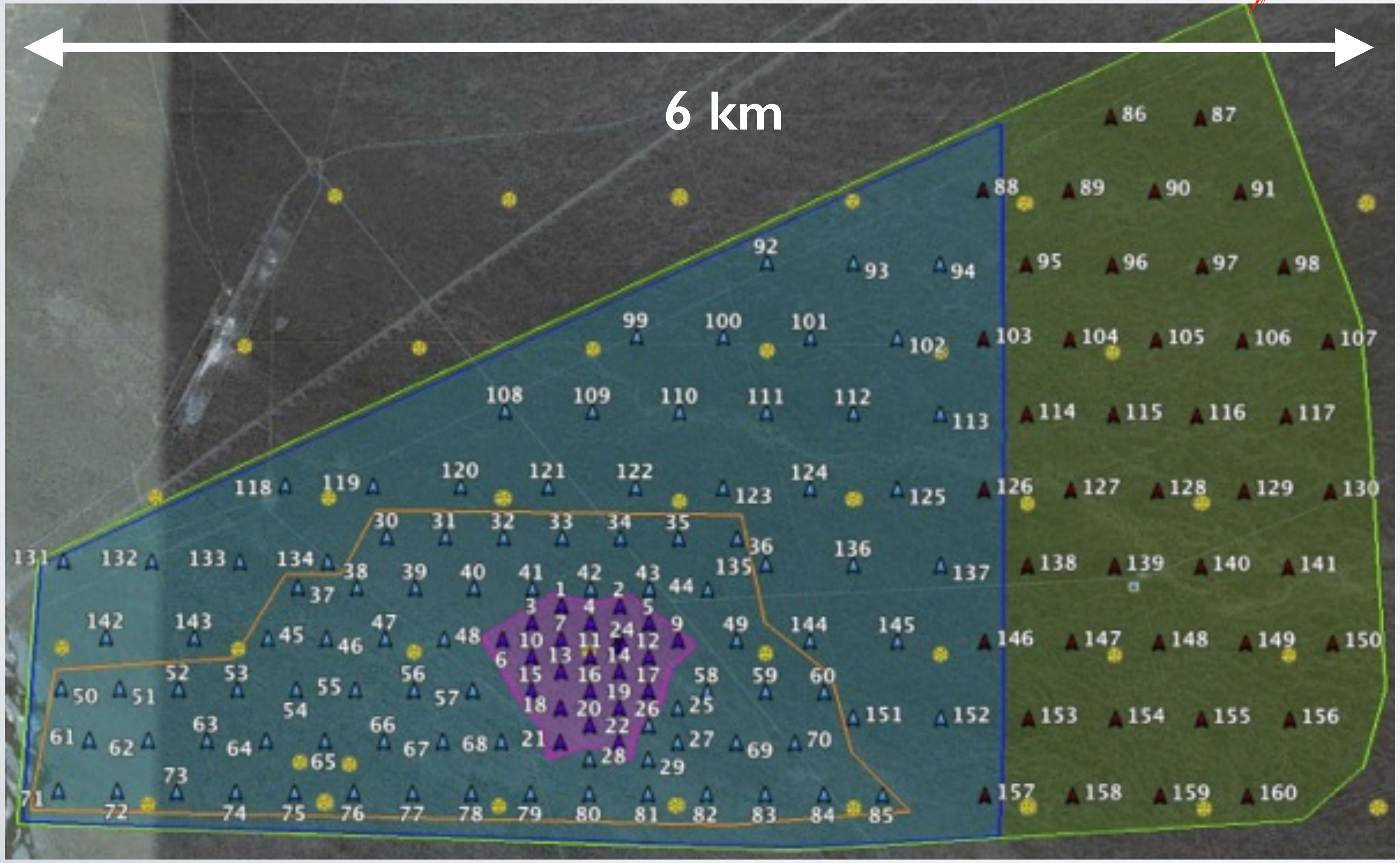
- RAuger prototype (F) in 2007 until 2010
- RAuger 2 in 2010 until 2013
- 24 autonomous stations late 2010
- 124 autonomous stations (7 km^2, may 2013)
- 160 foreseen (~13 km^2)
- Self-triggered and externally triggered
- Antenna, EMC housing, central DAQ: Subatech
- Local electronics, ADC, local & central DAQ, comms, monitoring: other 10 D, NL, F, R and P labs
- 3 grid steps (144m, 250m & 375m)



AERA (AUGER, SINCE 2010)

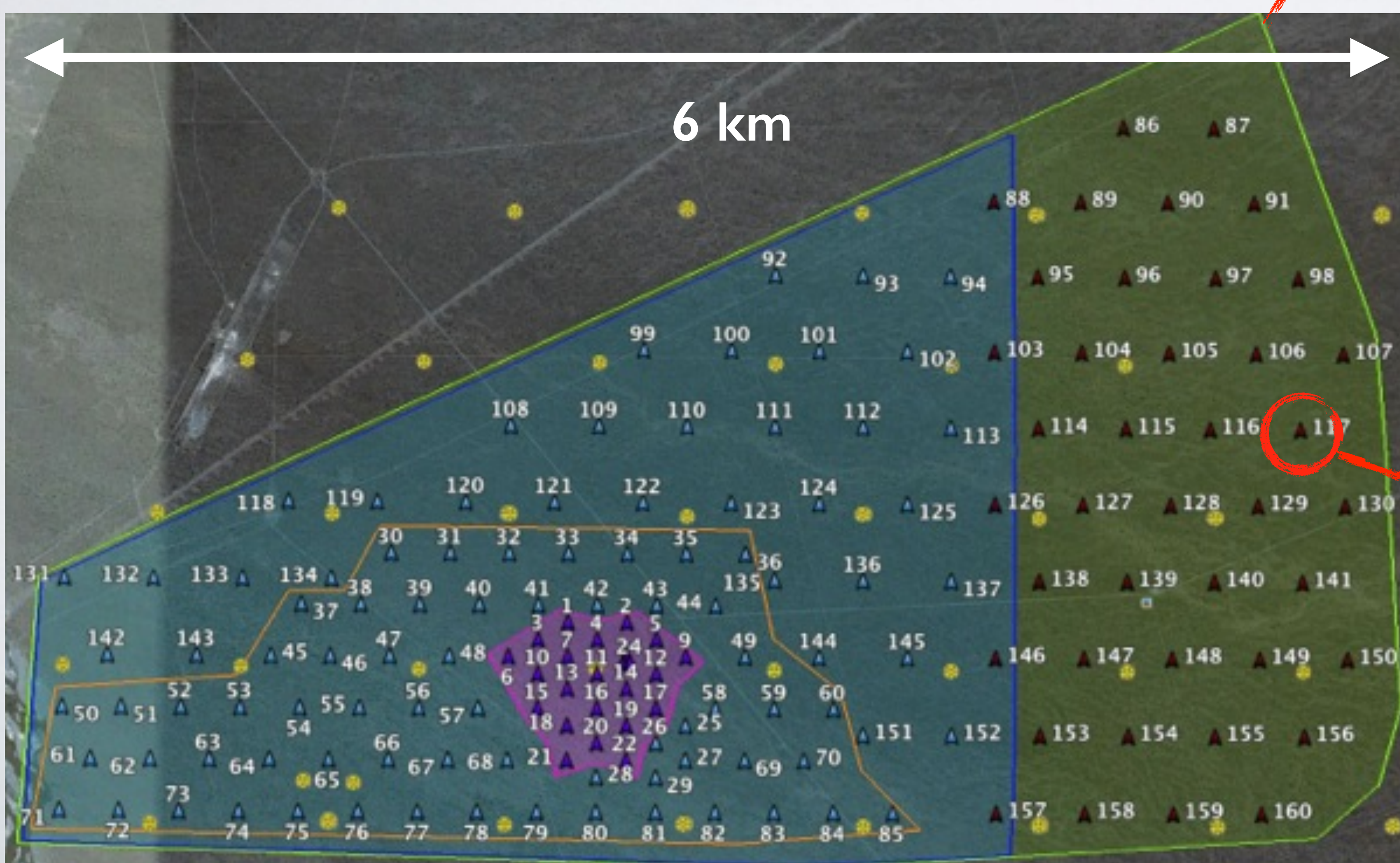
- RAuger prototype (F) in 2007 until 2010
- RAuger 2 in 2010 until 2013
- 24 autonomous stations late 2010
- 124 autonomous stations (7 km^2, may 2013)
- 160 foreseen (~13 km^2)
- Self-triggered and externally triggered
- Antenna, EMC housing, central DAQ: Subatech
- Local electronics, ADC, local & central DAQ, comms, monitoring: other 10 D, NL, F, R and P labs
- 3 grid steps (144m, 250m & 375m)



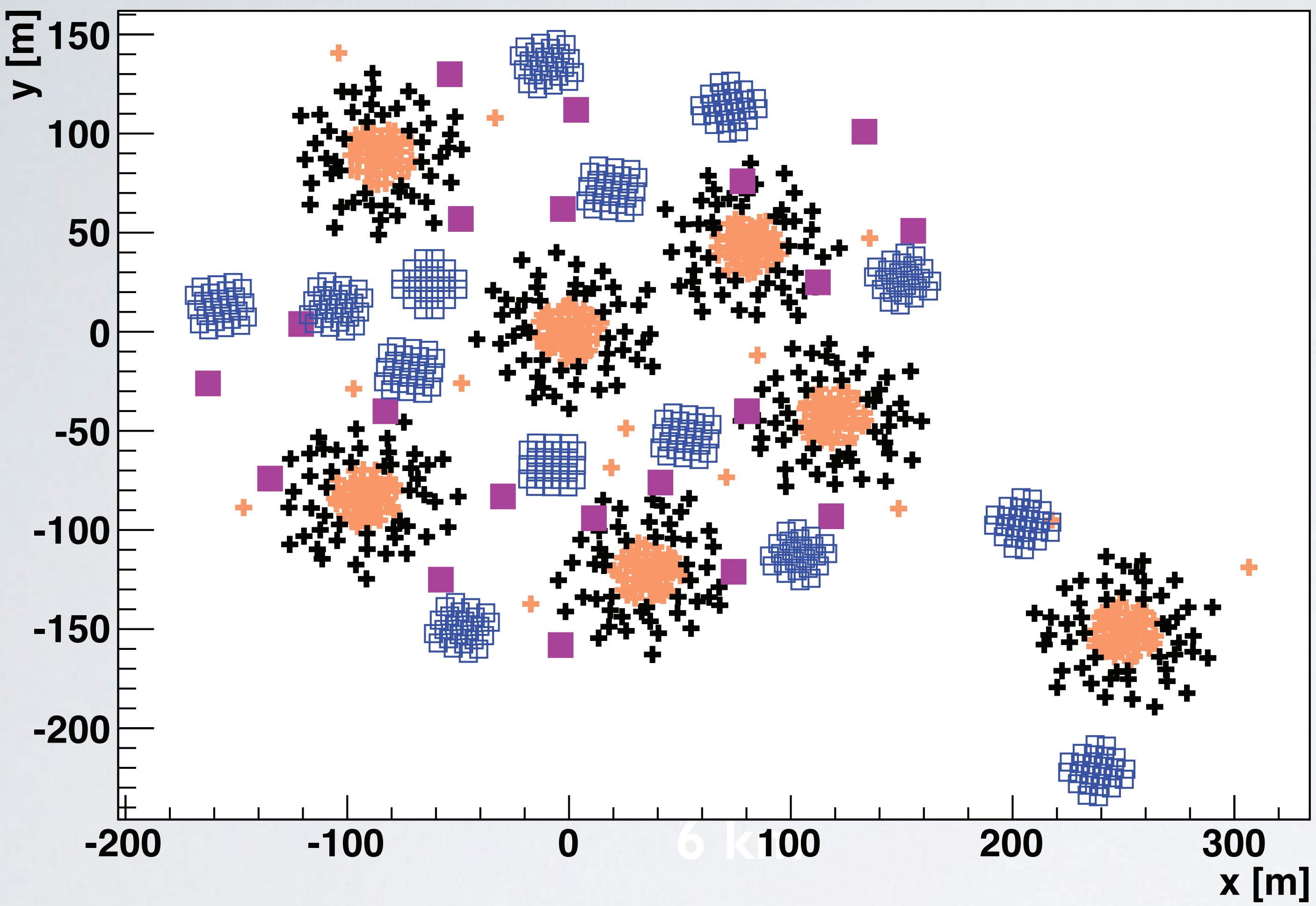


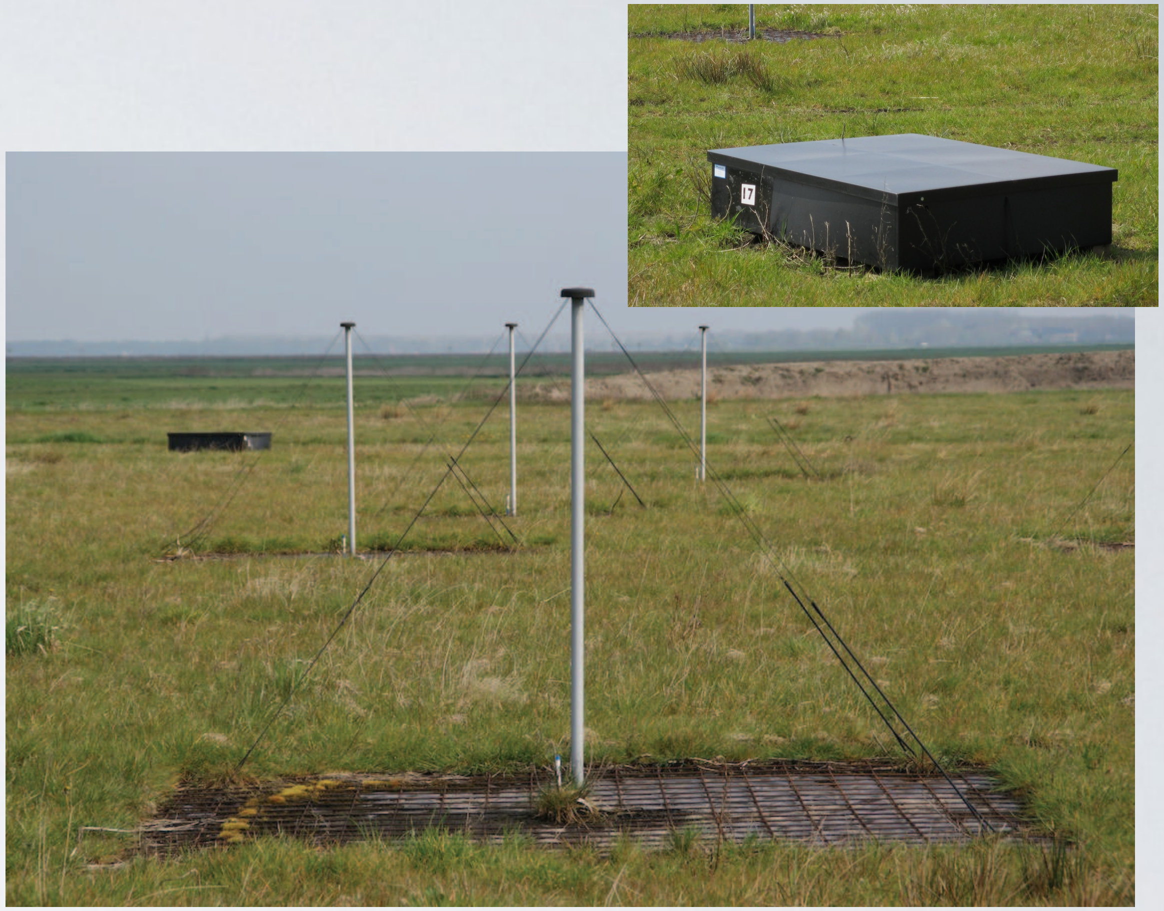
AERA (AUGER, SINCE 2010)

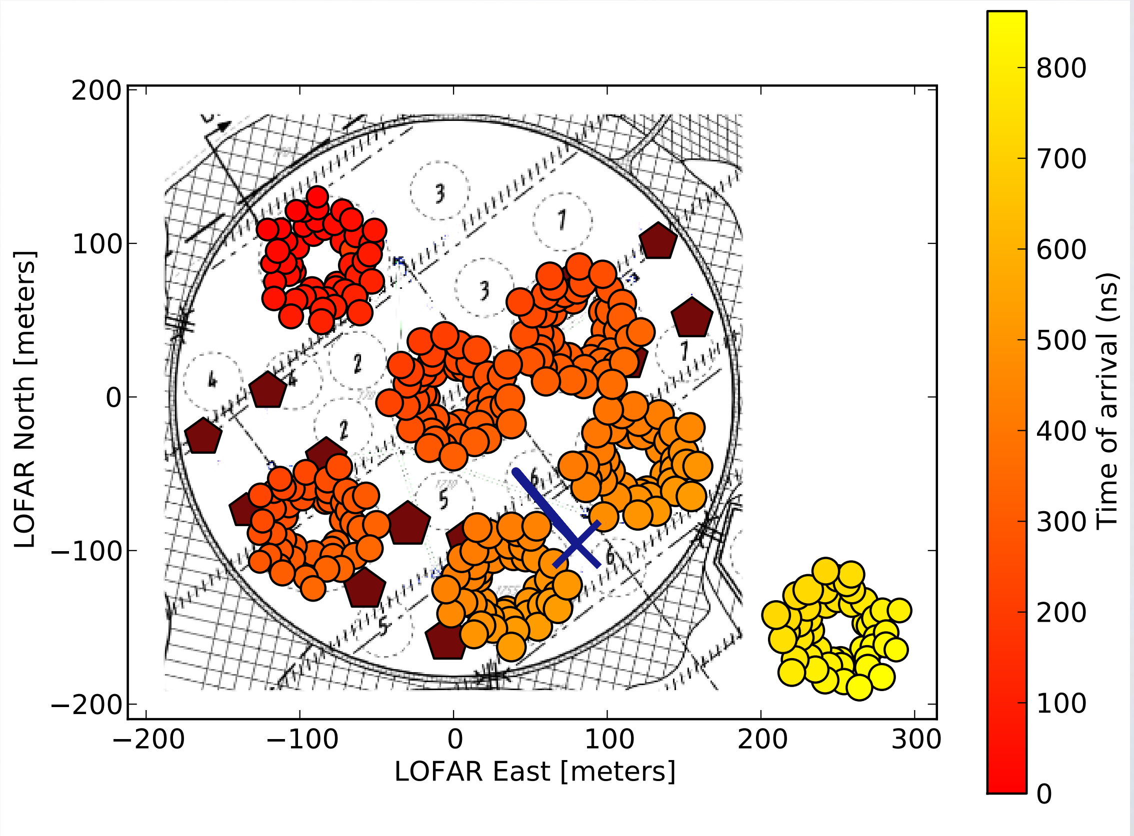
- RAuger prototype (F) in 2007 until 2010
- RAuger 2 in 2010 until 2013
- 24 autonomous stations late 2010
- 124 autonomous stations (7 km^2, may 2013)
- 160 foreseen (~13 km^2)
- Self-triggered and externally triggered
- Antenna, EMC housing, central DAQ: Subatech
- Local electronics, ADC, local & central DAQ, comms, monitoring: other 10 D, NL, F, R and P labs
- 3 grid steps (144m, 250m & 375m)



LOFAR (NL, SINCE 2011)





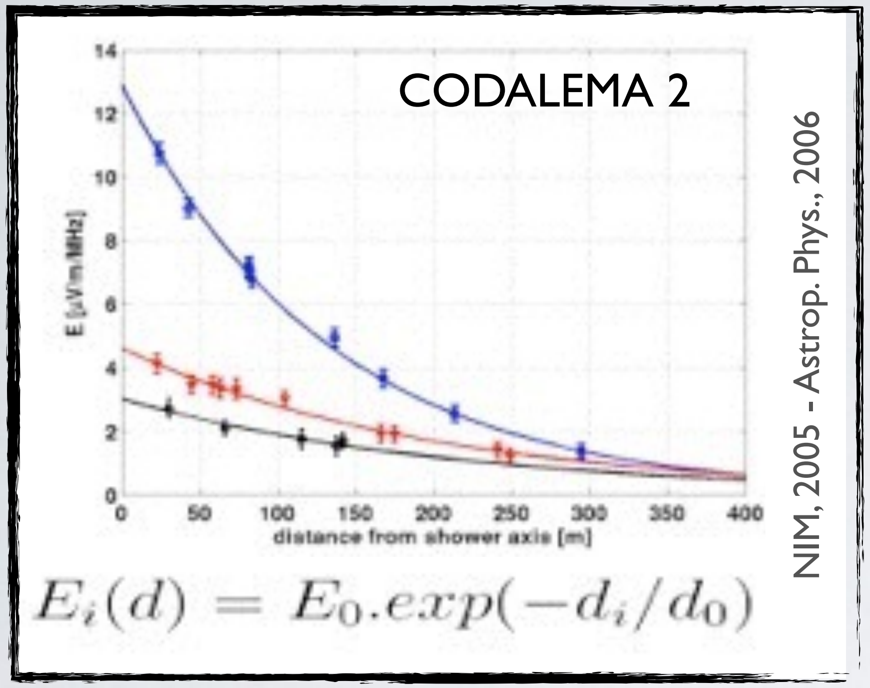


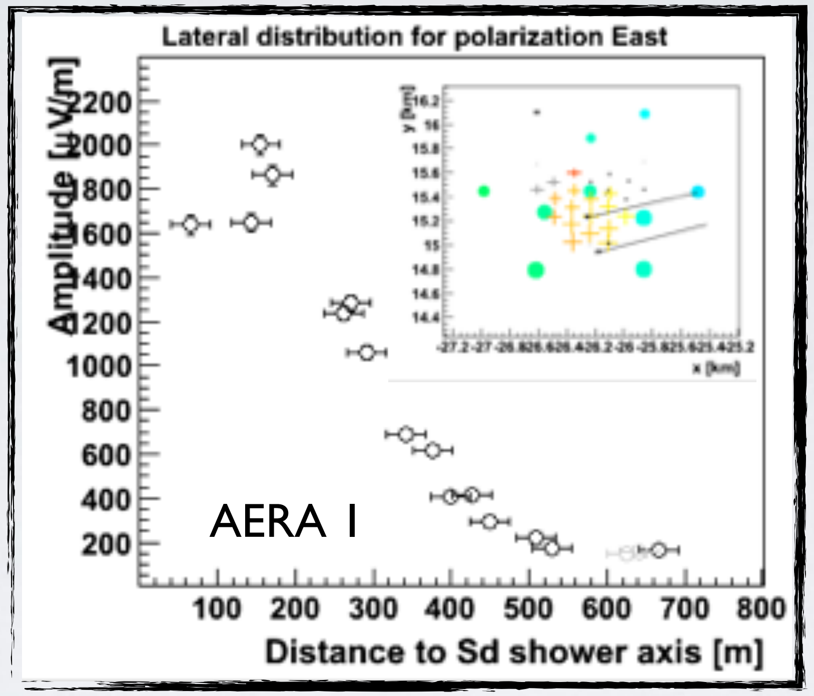
- Externally triggered by LORA (20 particle detectors)
- Currently only equipped in the very core (0.1 km^2) "Superterp"
- Very high antenna density (~600 units)
- Mainly low frequency band (30-80 MHz) is used
- Cosmic ray observation mode is superimposed to normal observation mode (not a dedicated observing time)

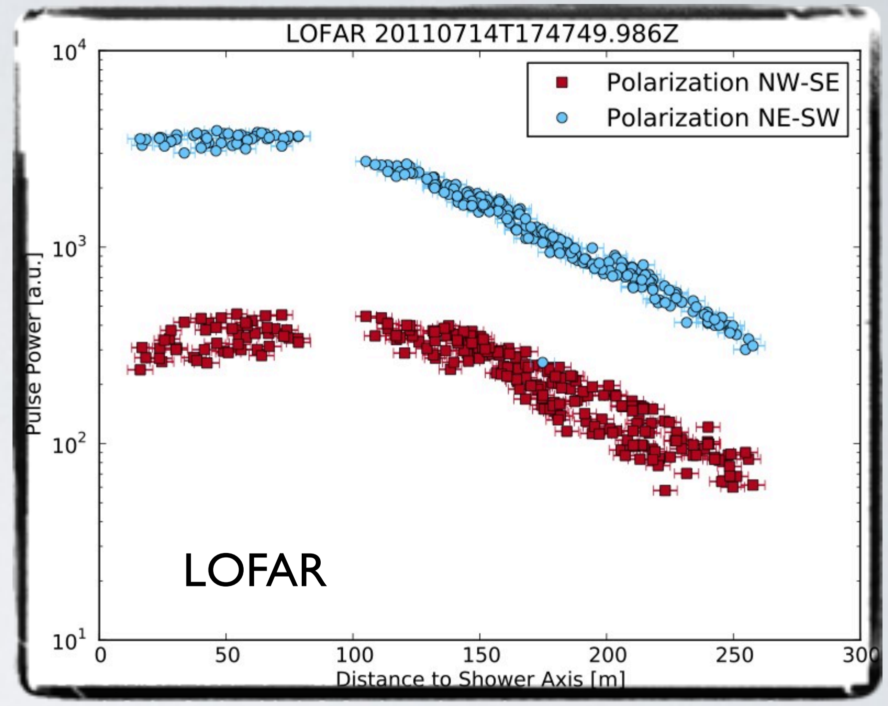
RADIO RESULTS - 1

Lateral field profile and energy correlation

E0, d0, (X0,Y0) - E0 ∝ Ep



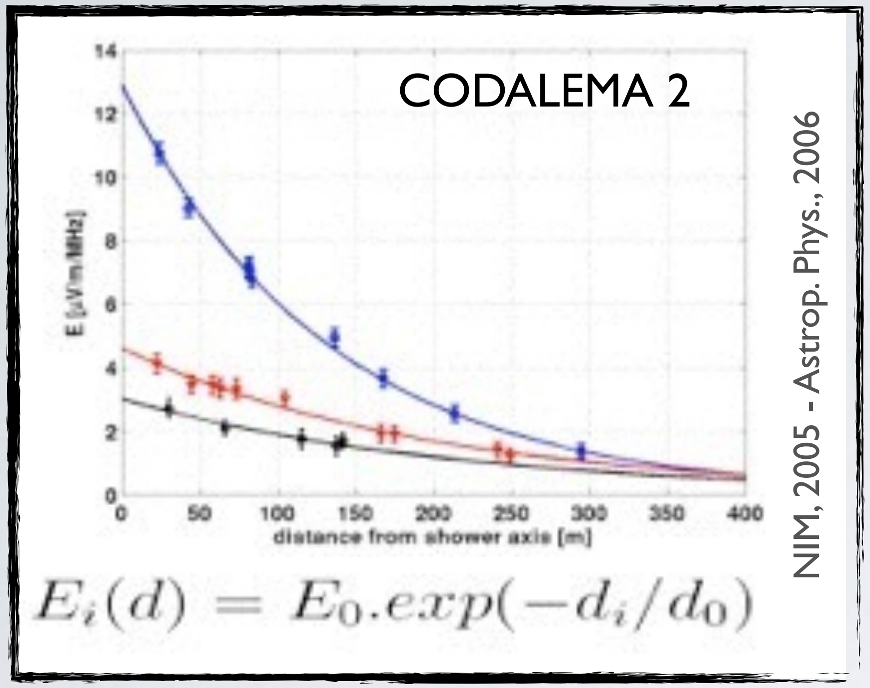


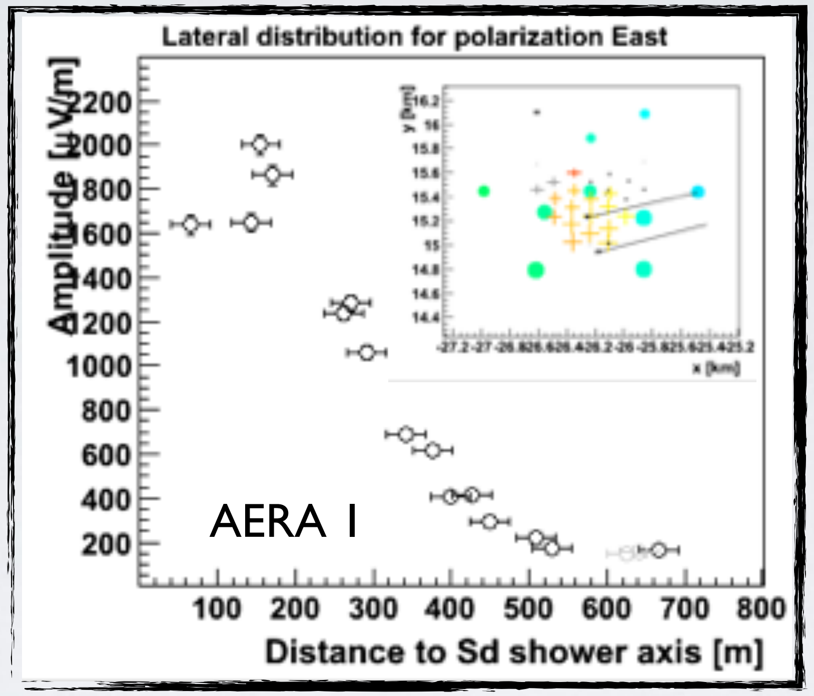


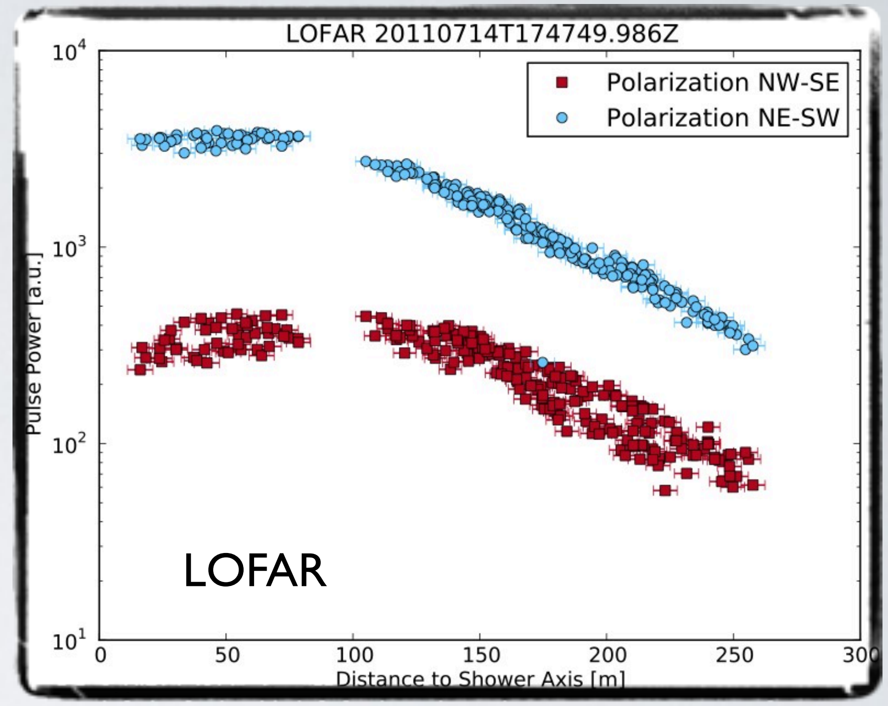
RADIO RESULTS - 1

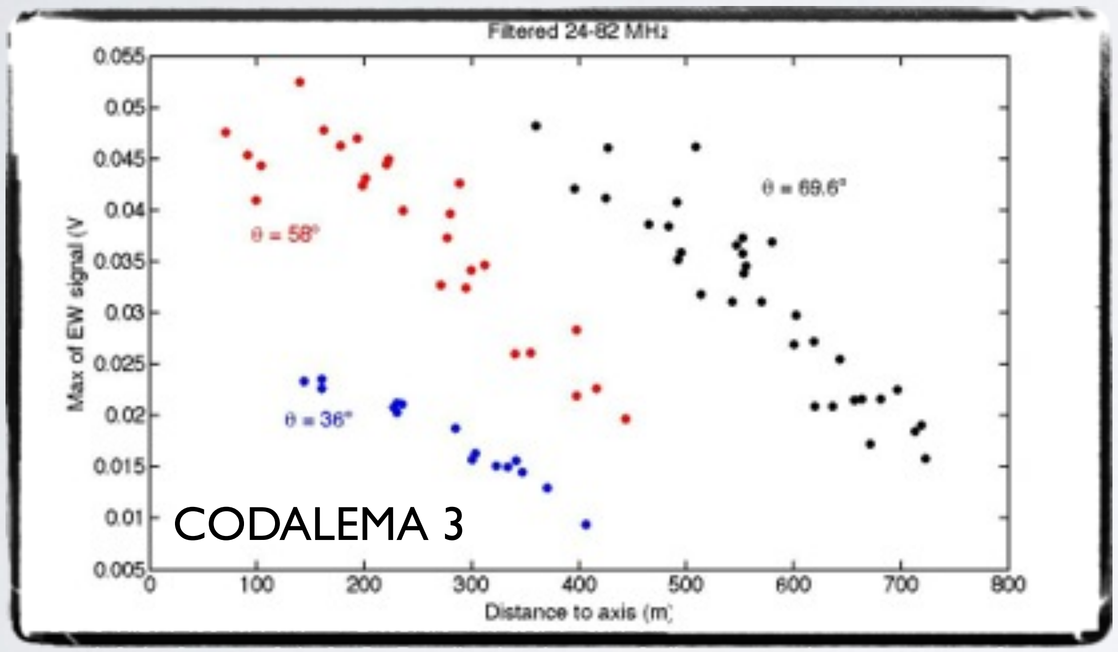
Lateral field profile and energy correlation

E0, d0, (X0,Y0) - E0 ∝ Ep



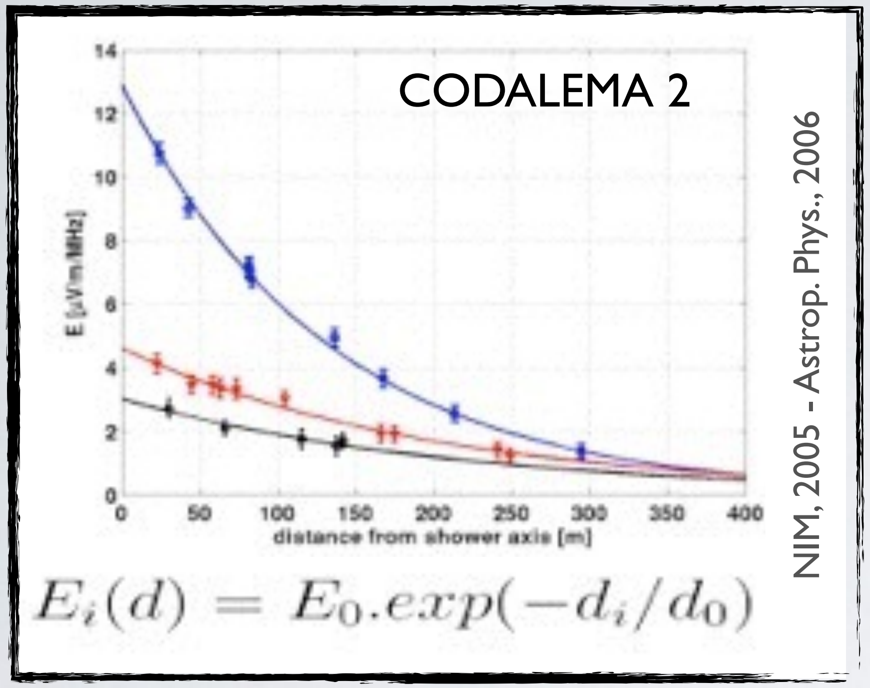


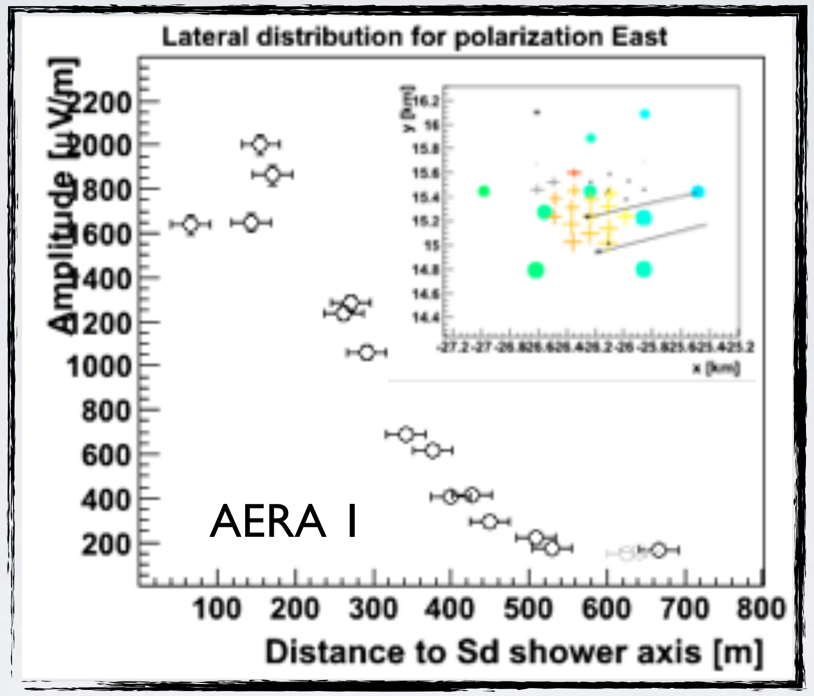


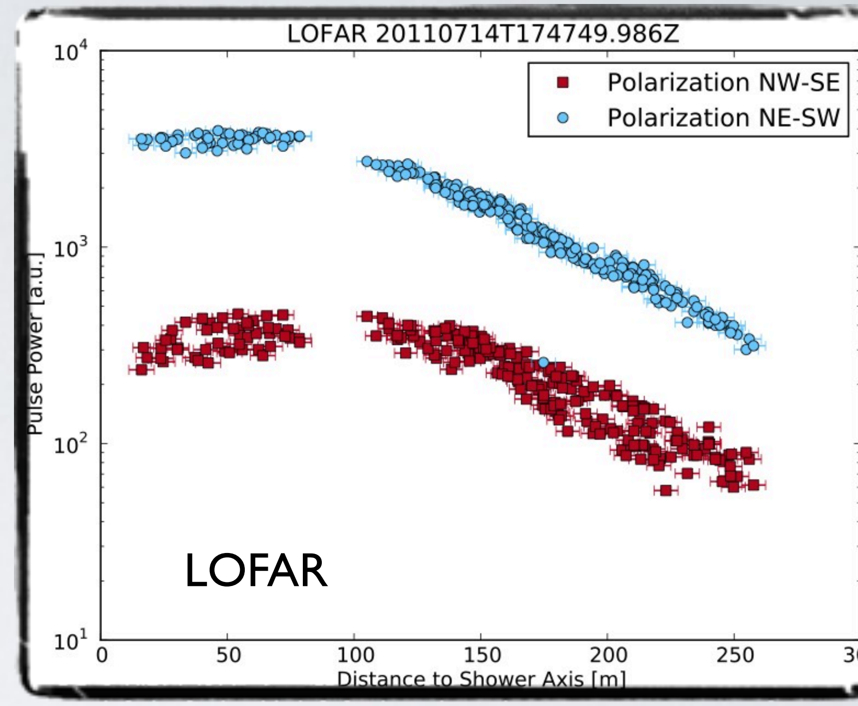


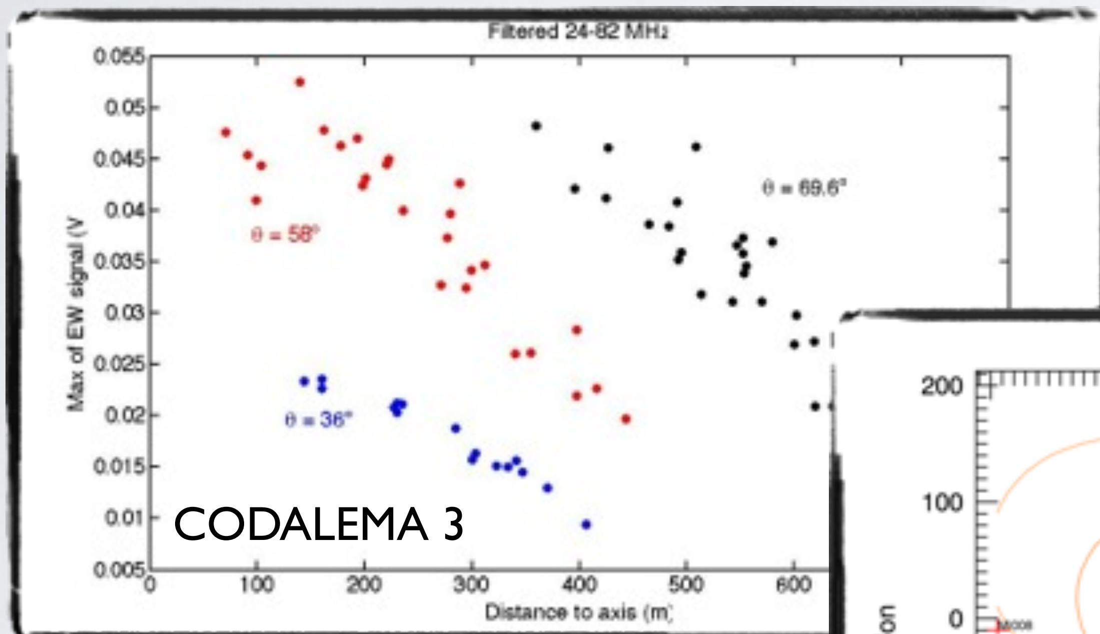
RADIO RESULTS - I

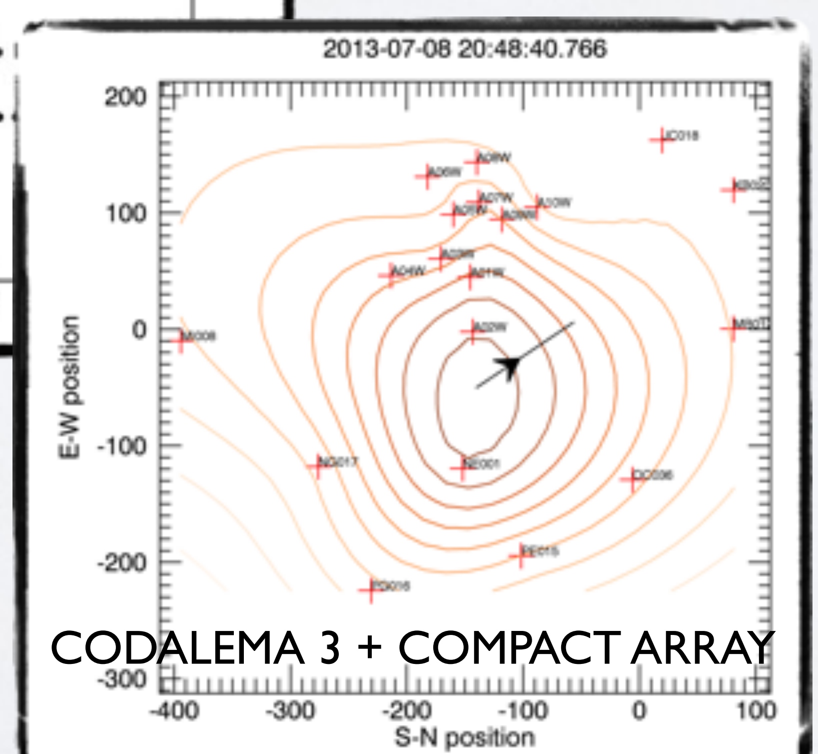
Lateral field profile and energy correlation
E0, d0, (X0,Y0) - E0 ∝ Ep







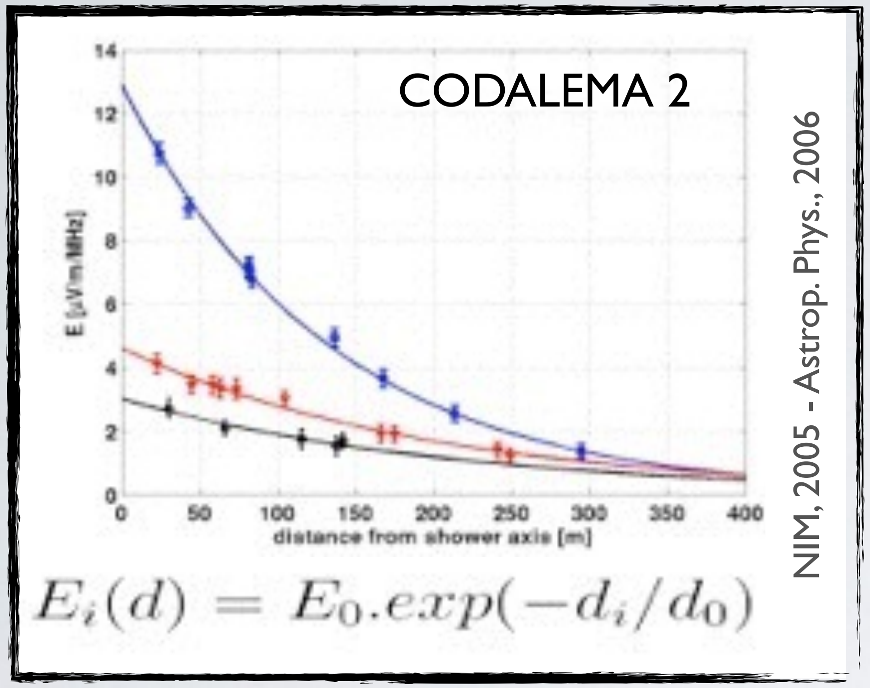


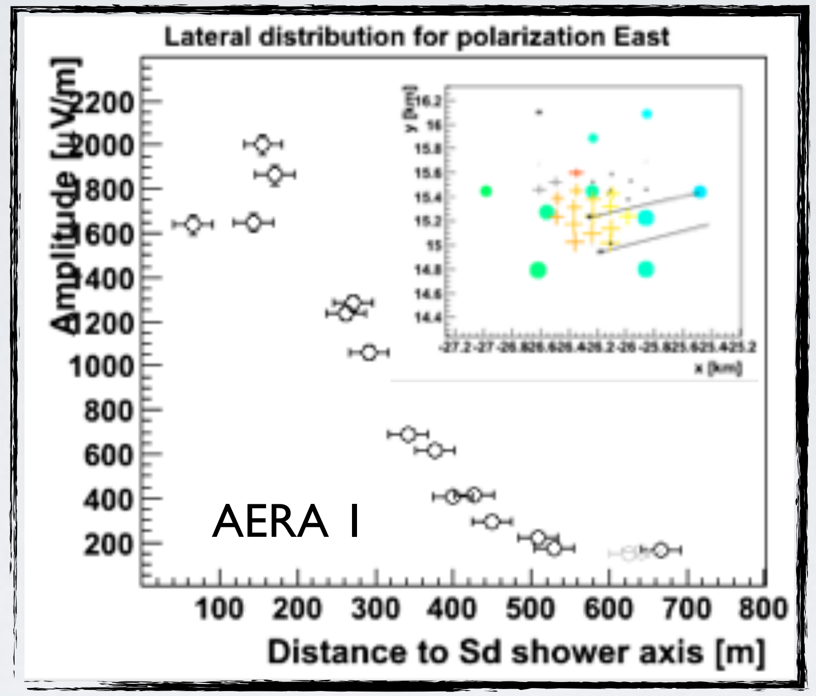


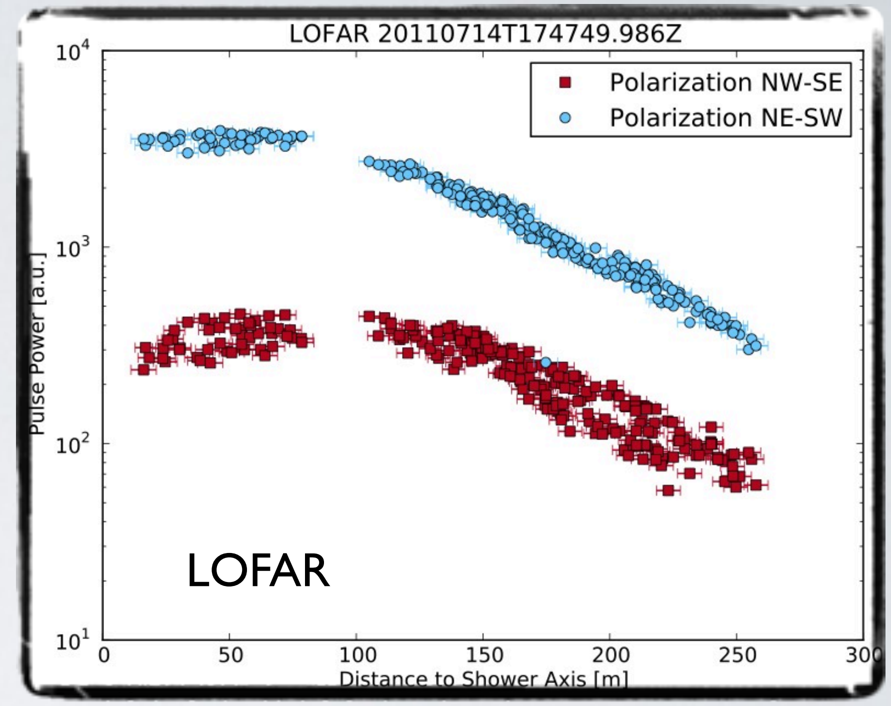
RADIO RESULTS - I

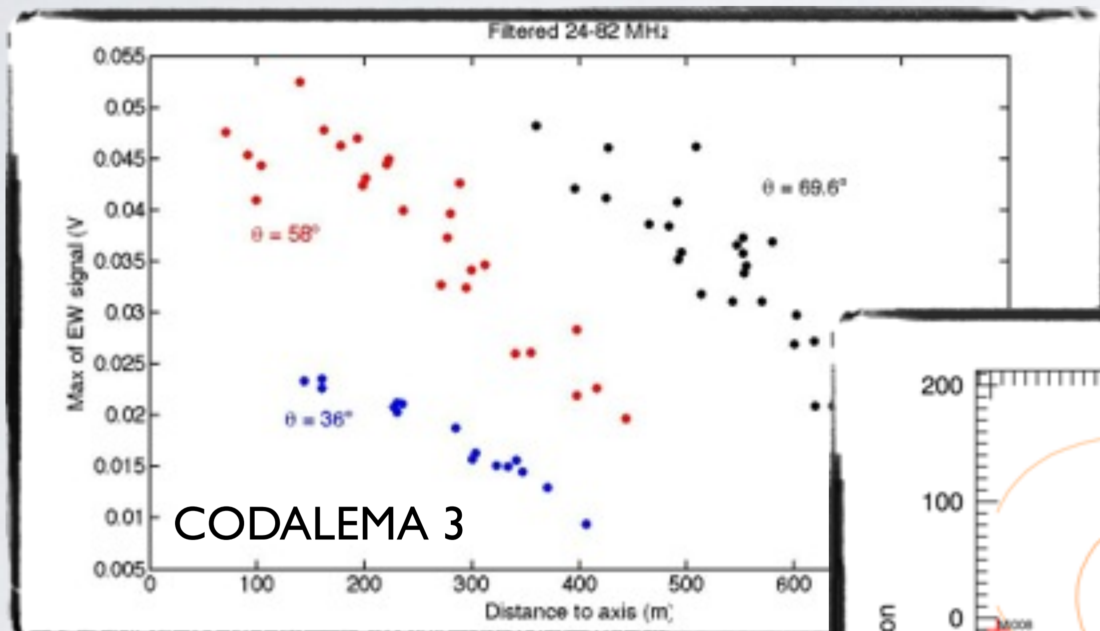
Lateral field profile and energy correlation

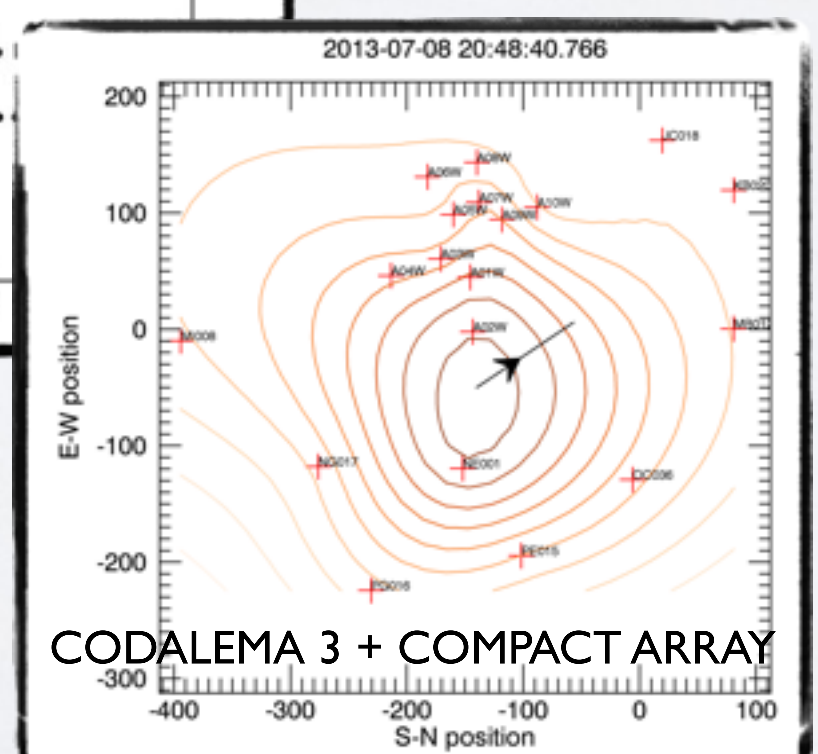
E0, d0, (X0,Y0) - E0 ∝ Ep

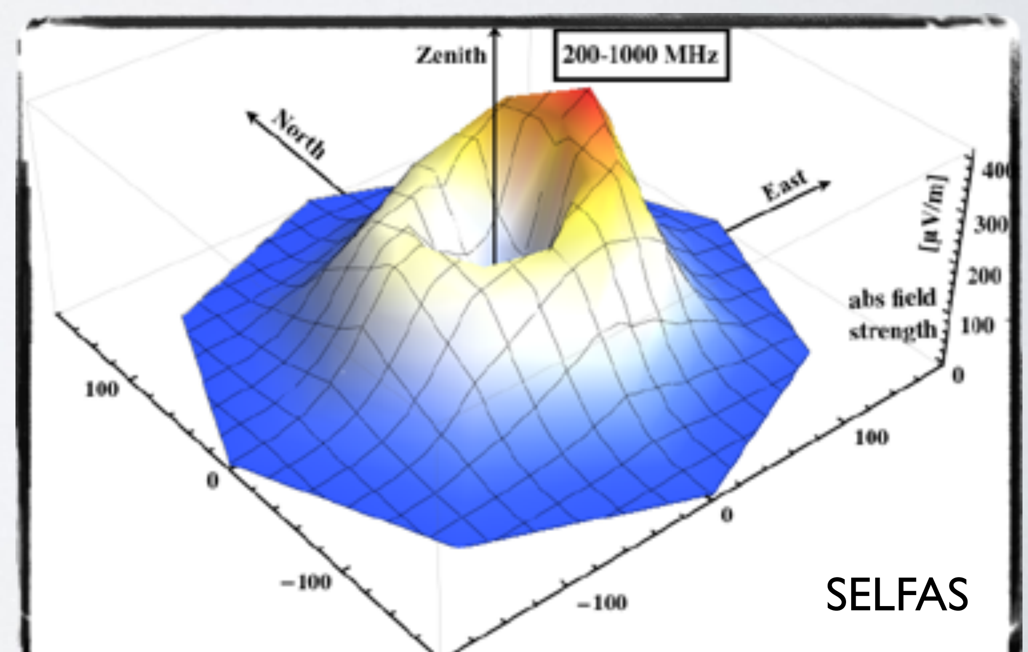






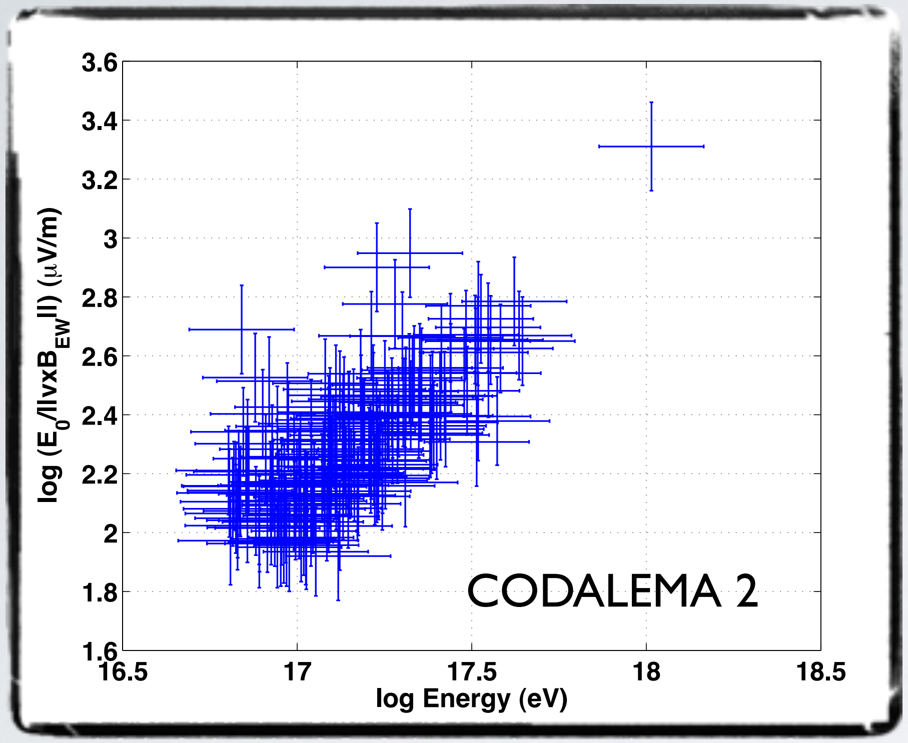


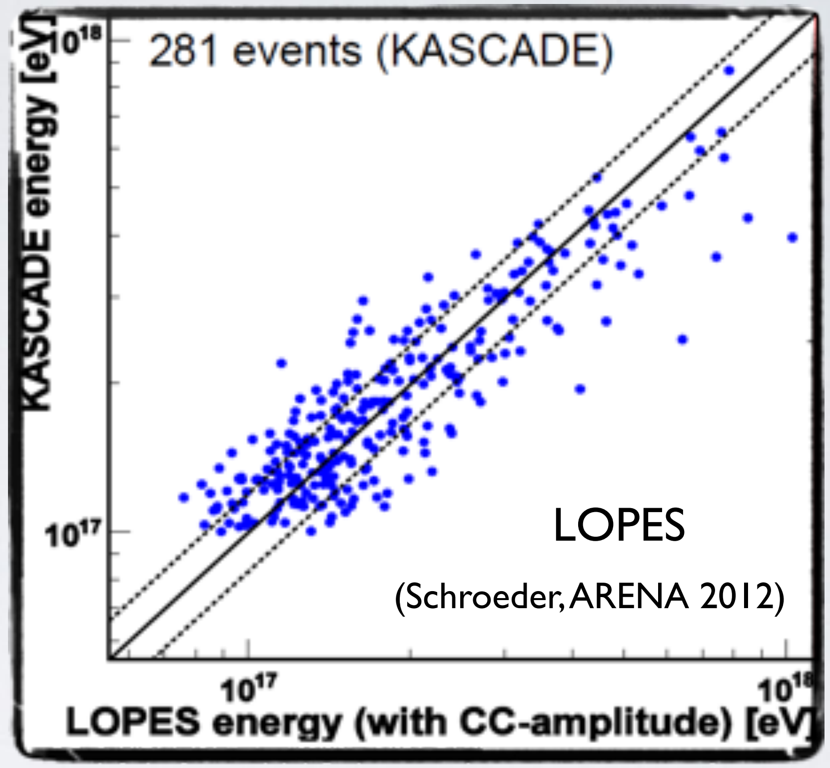


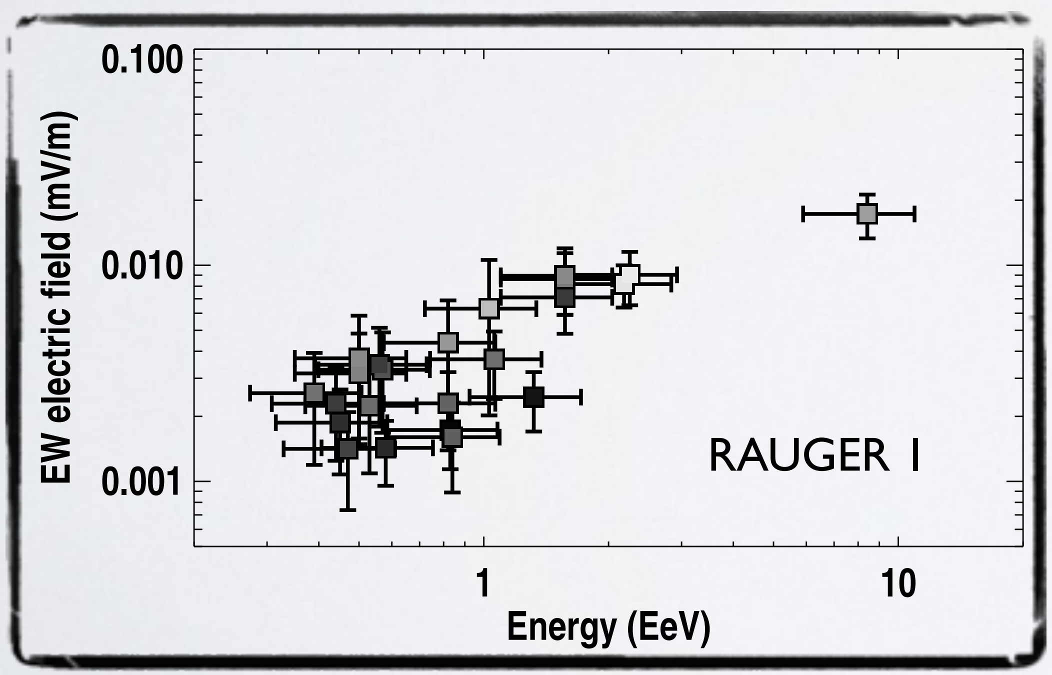


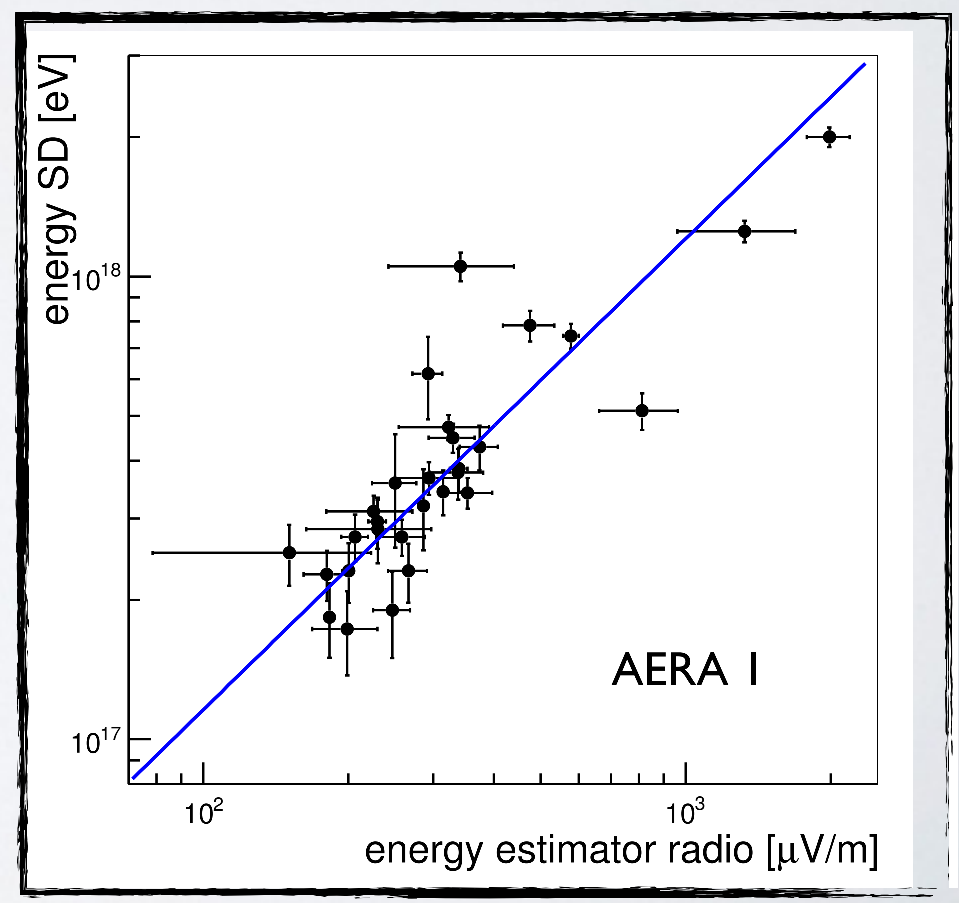
RADIO RESULTS - 1

Lateral field profile and energy correlation
E0, d0, (X0,Y0) - E0 ∝ Ep



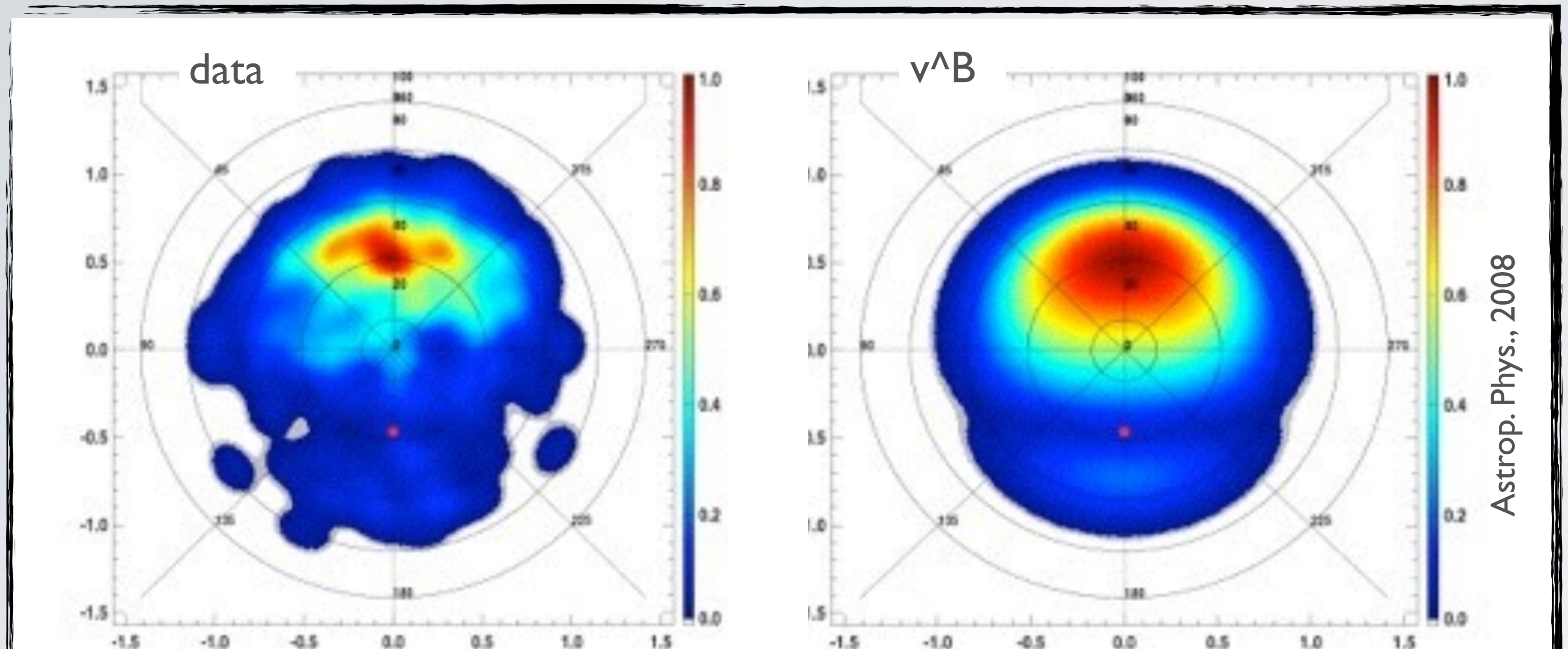






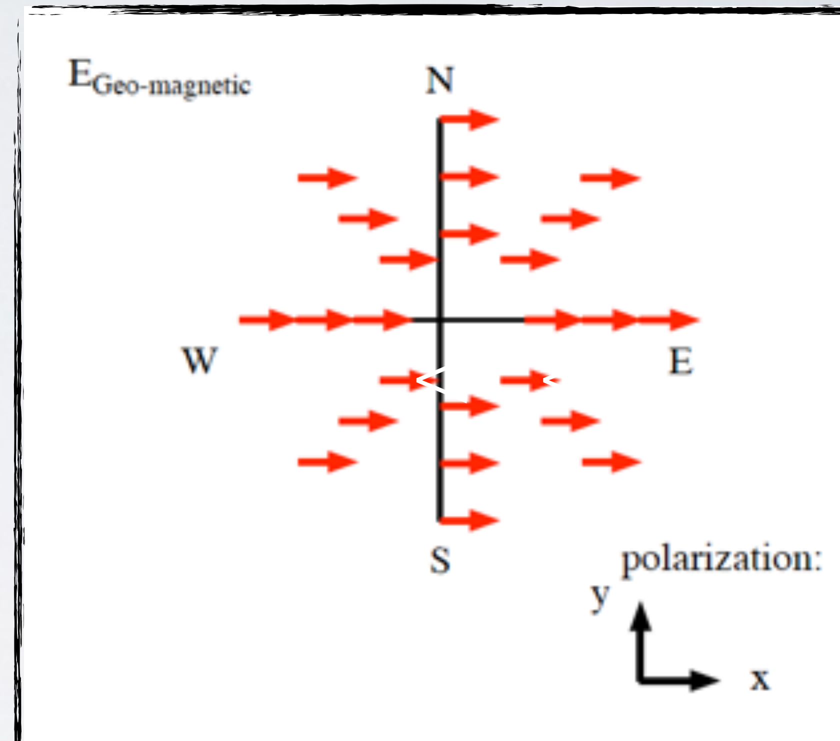
RADIO RESULTS - 2

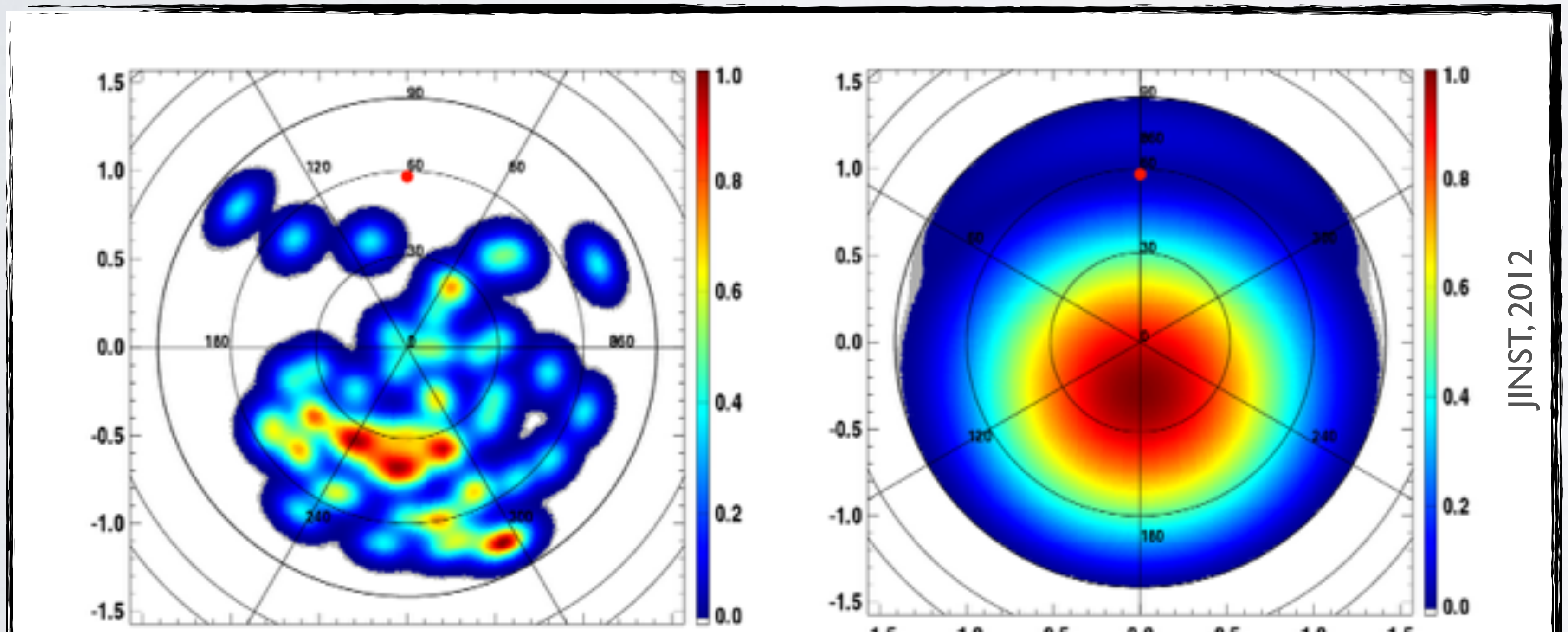
Geomagnetic contribution
$E \propto v \wedge B$, polarization → $f(\theta,\varphi)$



CODALEMA 2

NORTH



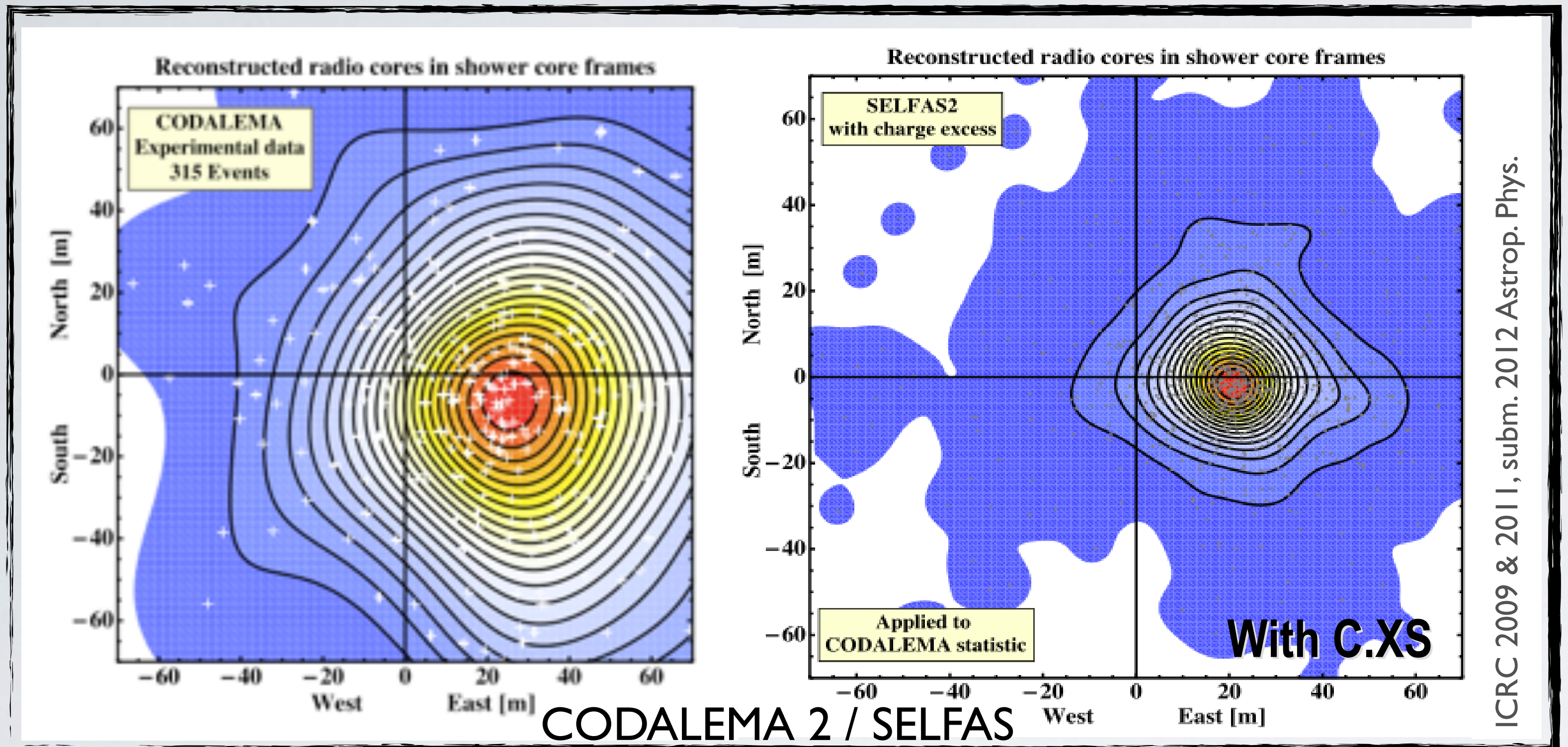


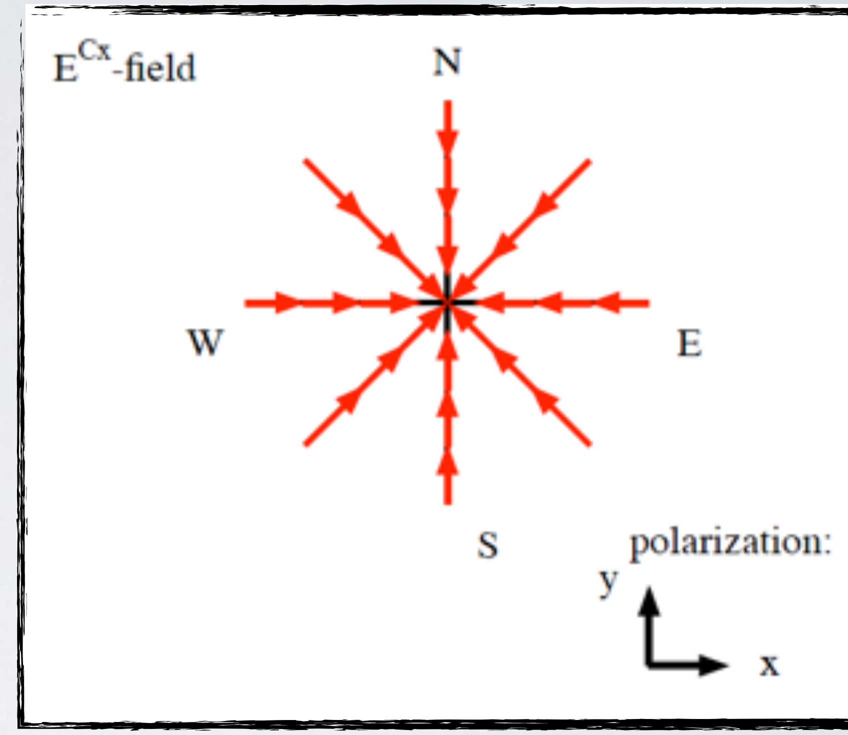
RAUGER 1

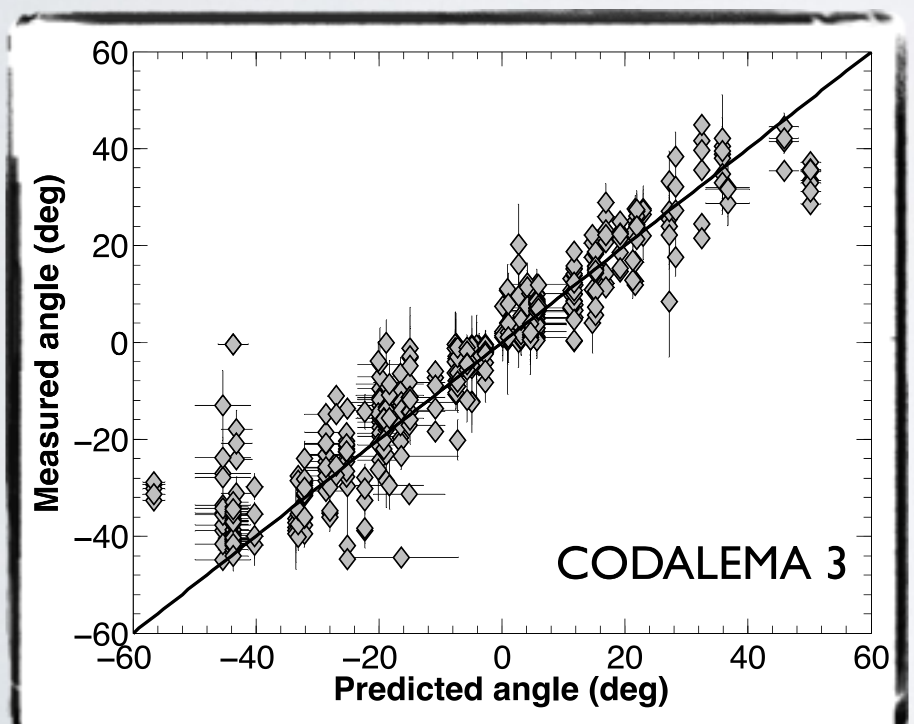
SOUTH

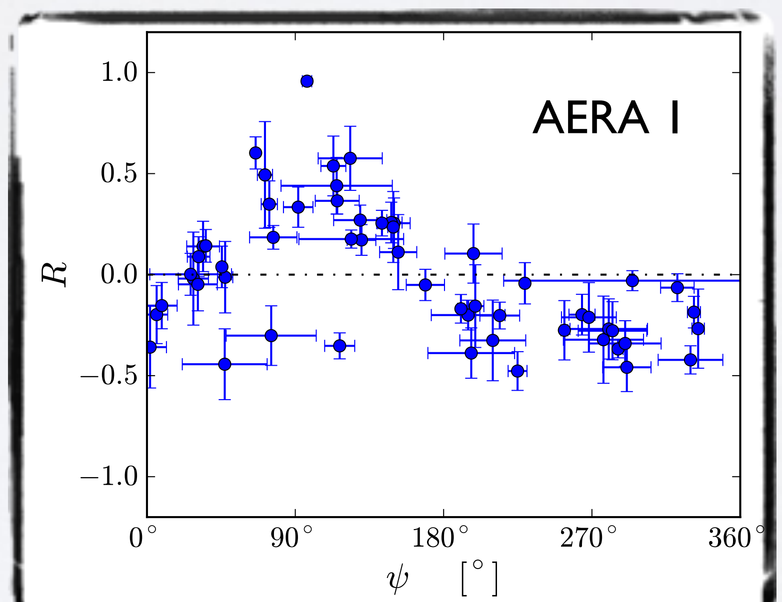
RADIO RESULTS - 3

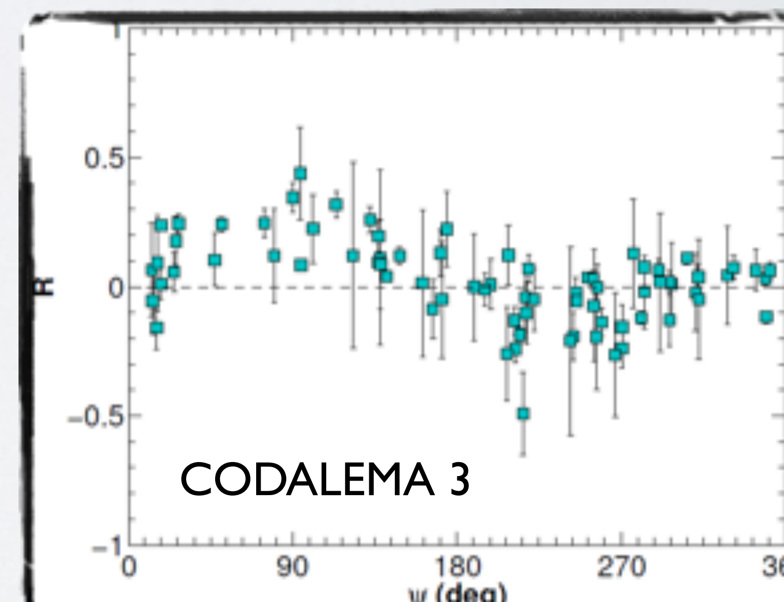
Charge excess contribution
2nd order, polarization → observer
Radio core vs particle core shift





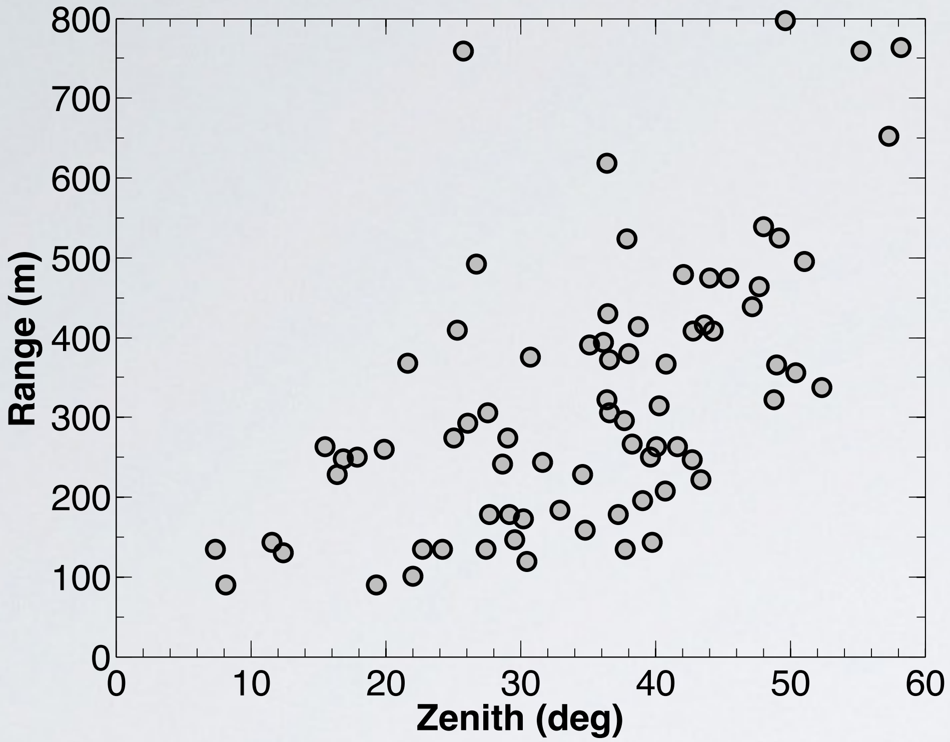


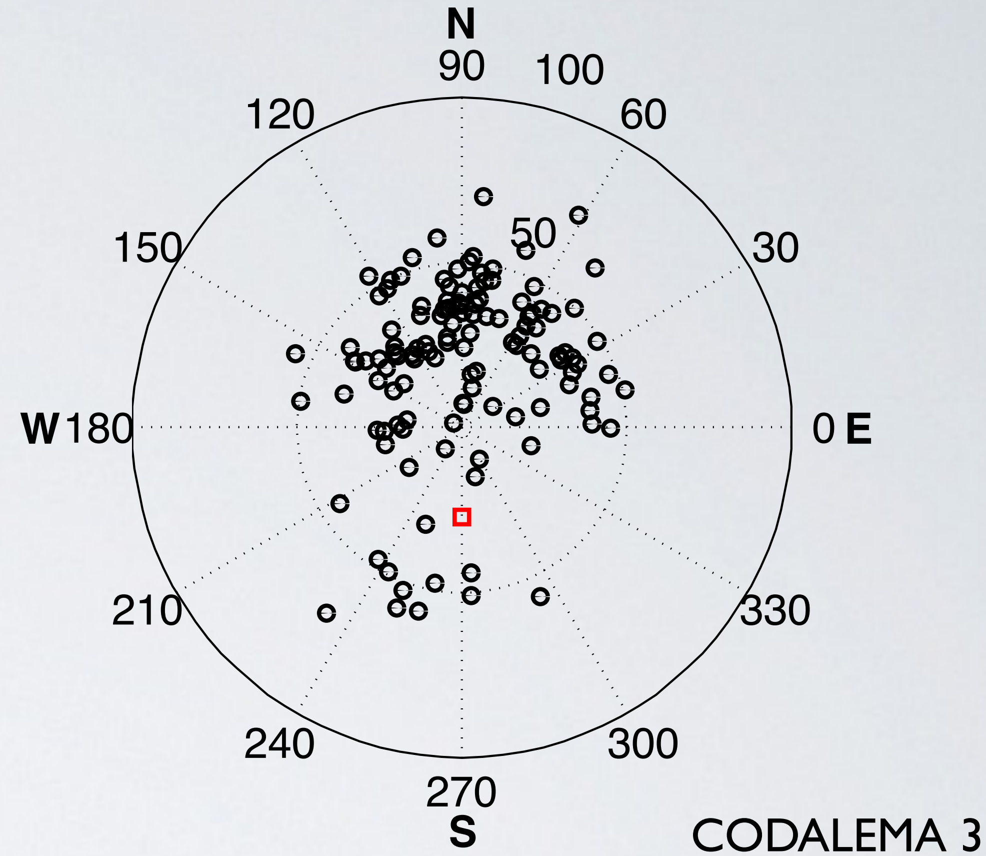


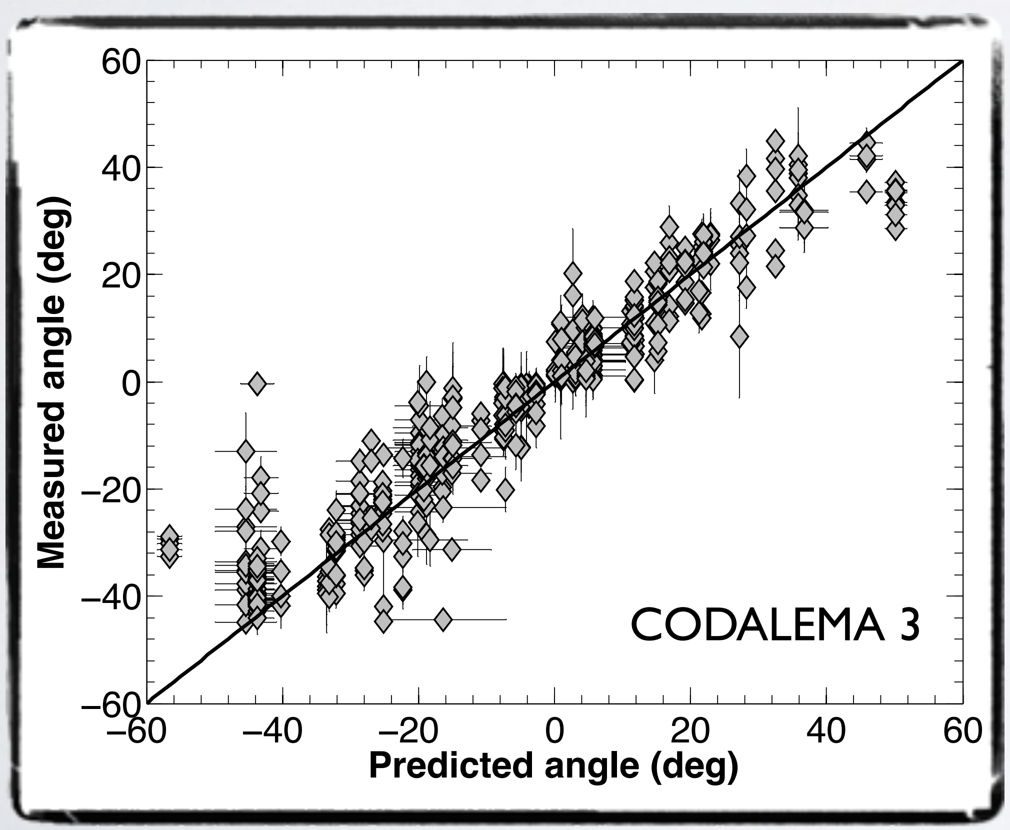


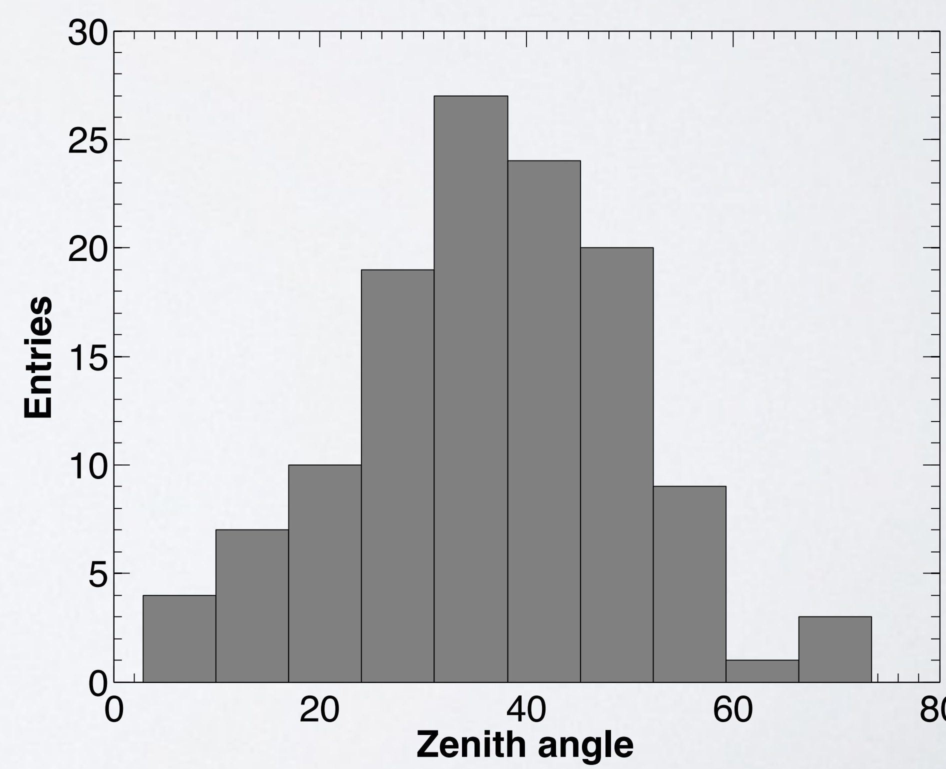
OUTLOOK

- Ultra-High Energy Cosmic Rays
  - ✓ Involves astrophysics & particle physics
  - ✓ Community ➟ needs for a new instrument
  - ✓ Augmentation of statistics, discrimination of composition, energy resolution
- Radio detection of cosmic rays
  - ✓ Key method for the future ?
    - French competence - great opportunity !
    - CODALEMA and Nançay (includes LOFAR and LSS) as a development base
  - ✓ AERA : multi-hybrid on Auger - pertinence of the method, R&D difficult on site
  - ✓ Still to find the composition-related radio observable
  - ✓ A new way to observe very fast transients: potential new window in radioastronomy ?
- Links with LOFAR and SKA
  - ✓ High sensor (antenna) density: very fine shower profile
  - ✓ Ability to discriminate showers on radio signal only (aim of compact array @ CODALEMA)
  - ✓ From compact array to LSS/NenuFAR: see discussion tomorrow…

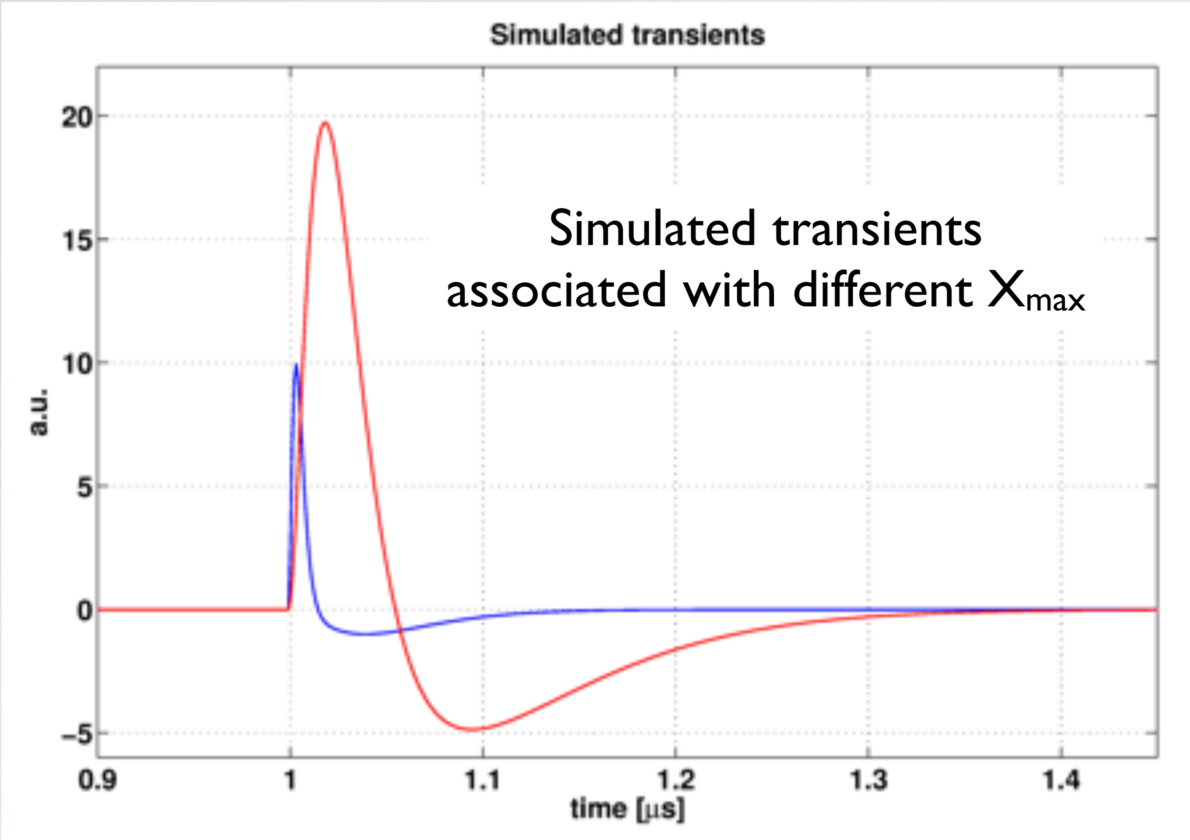

Range (m)
Zenith (deg)
0 100 200 300 400 500 600 700 800
0 10 20 30 40 50 60

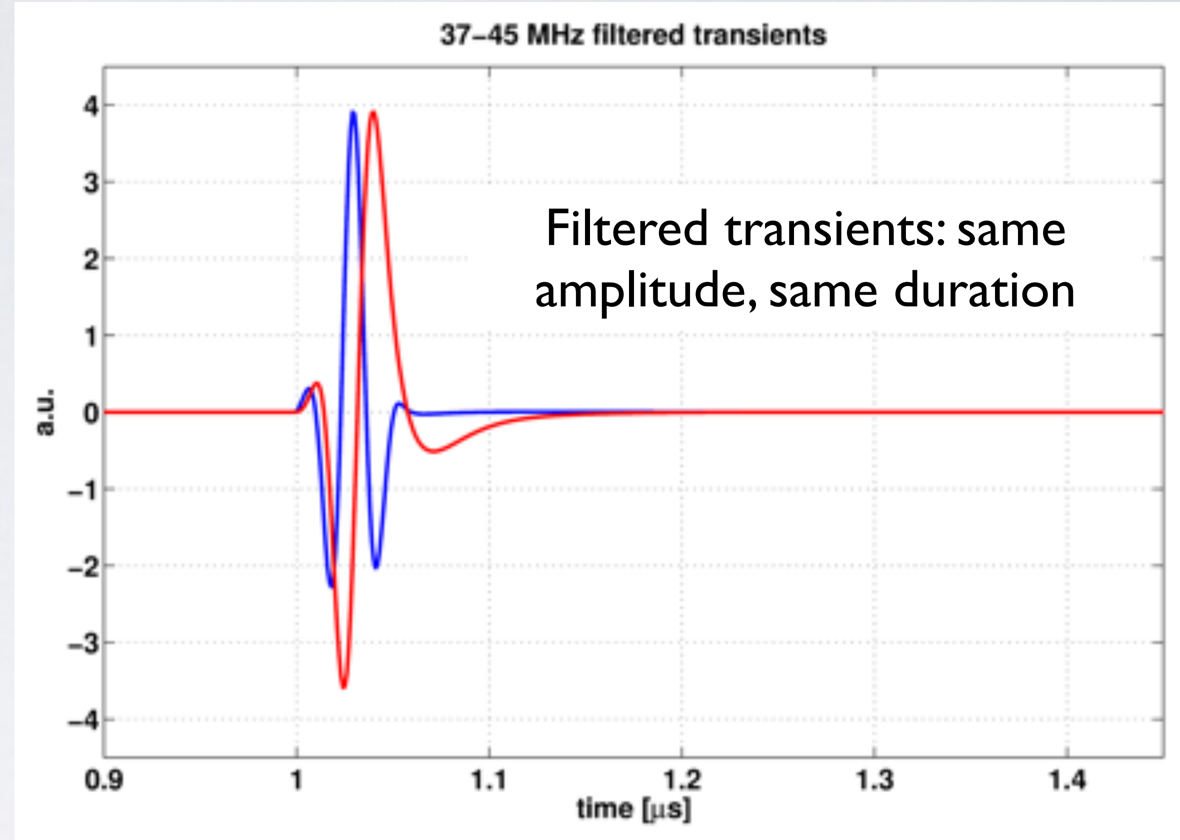

N
90
100
120
60
150
50
30
W180
0 E
210
330
240
300
270
S
CODALEMA 3

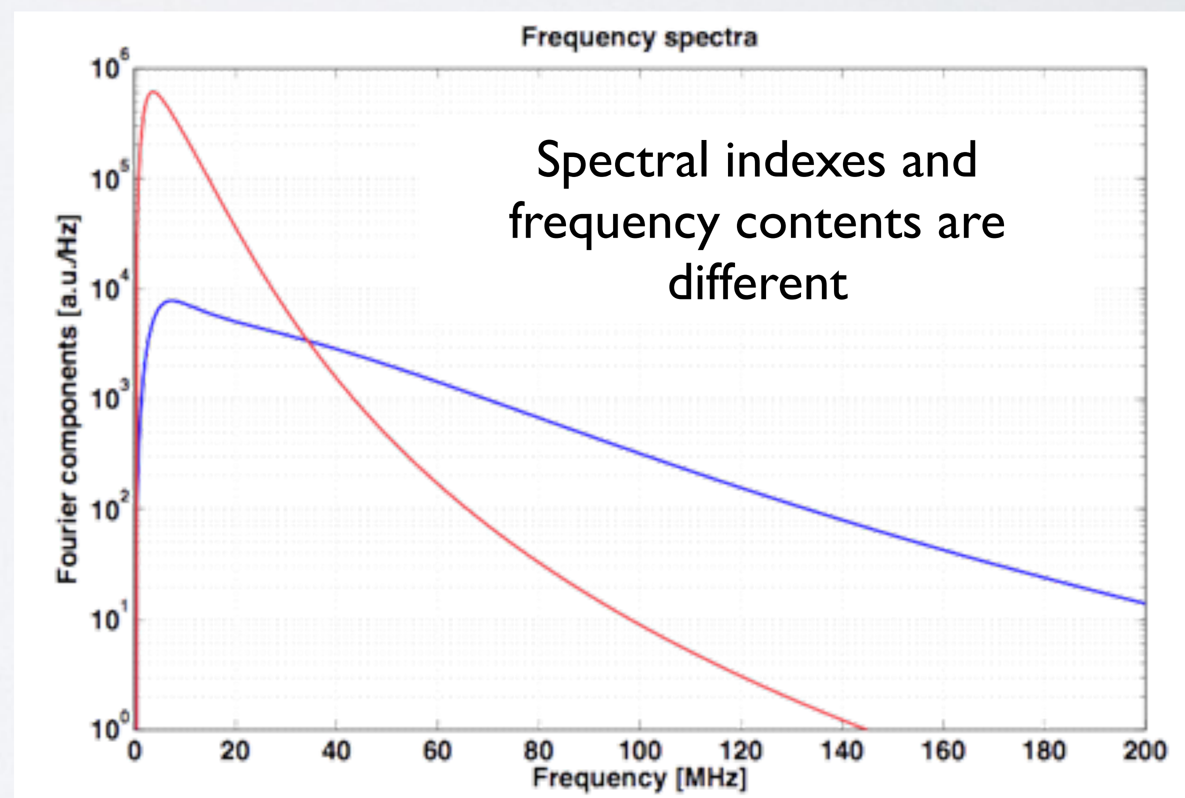

Measured angle (deg)
Predicted angle (deg)
60 40 20 0 −20 −40 −60
−60 −40 −20 0 20 40 60
CODALEMA 3


Entries
Zenith angle
0 5 10 15 20 25 30
0 20 40 60 80

RADIO PROSPECTS - I

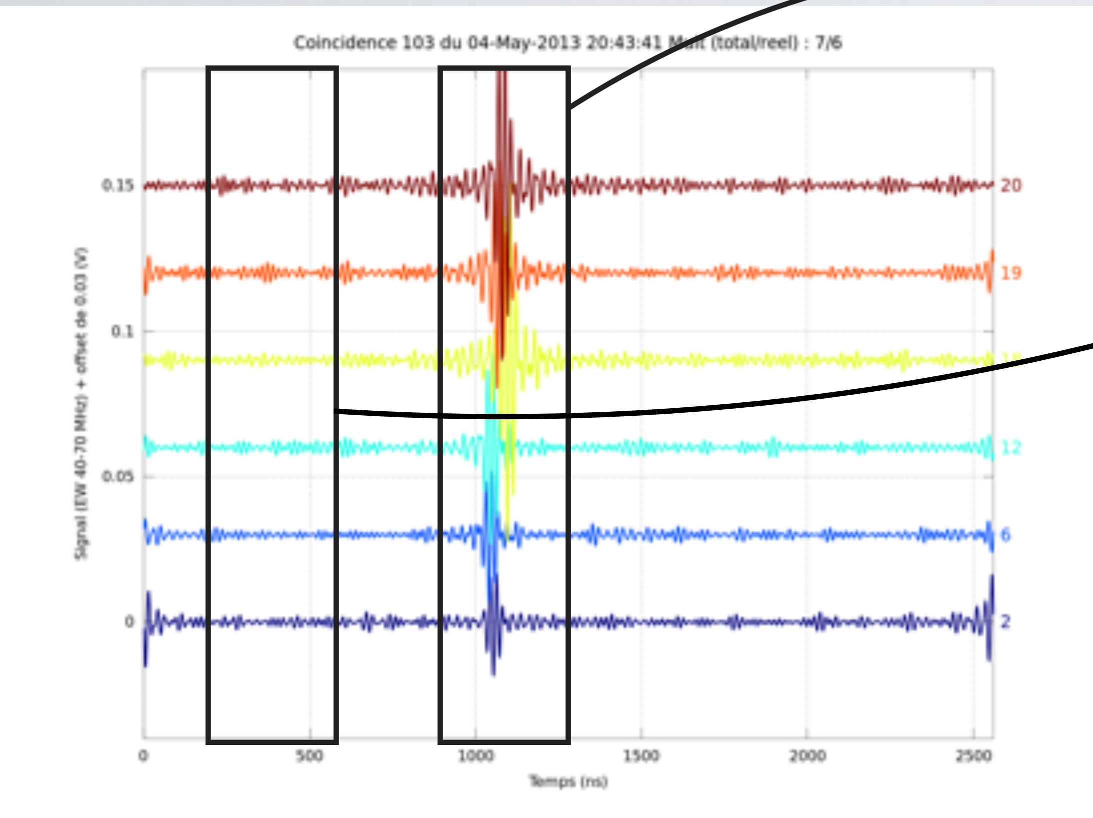


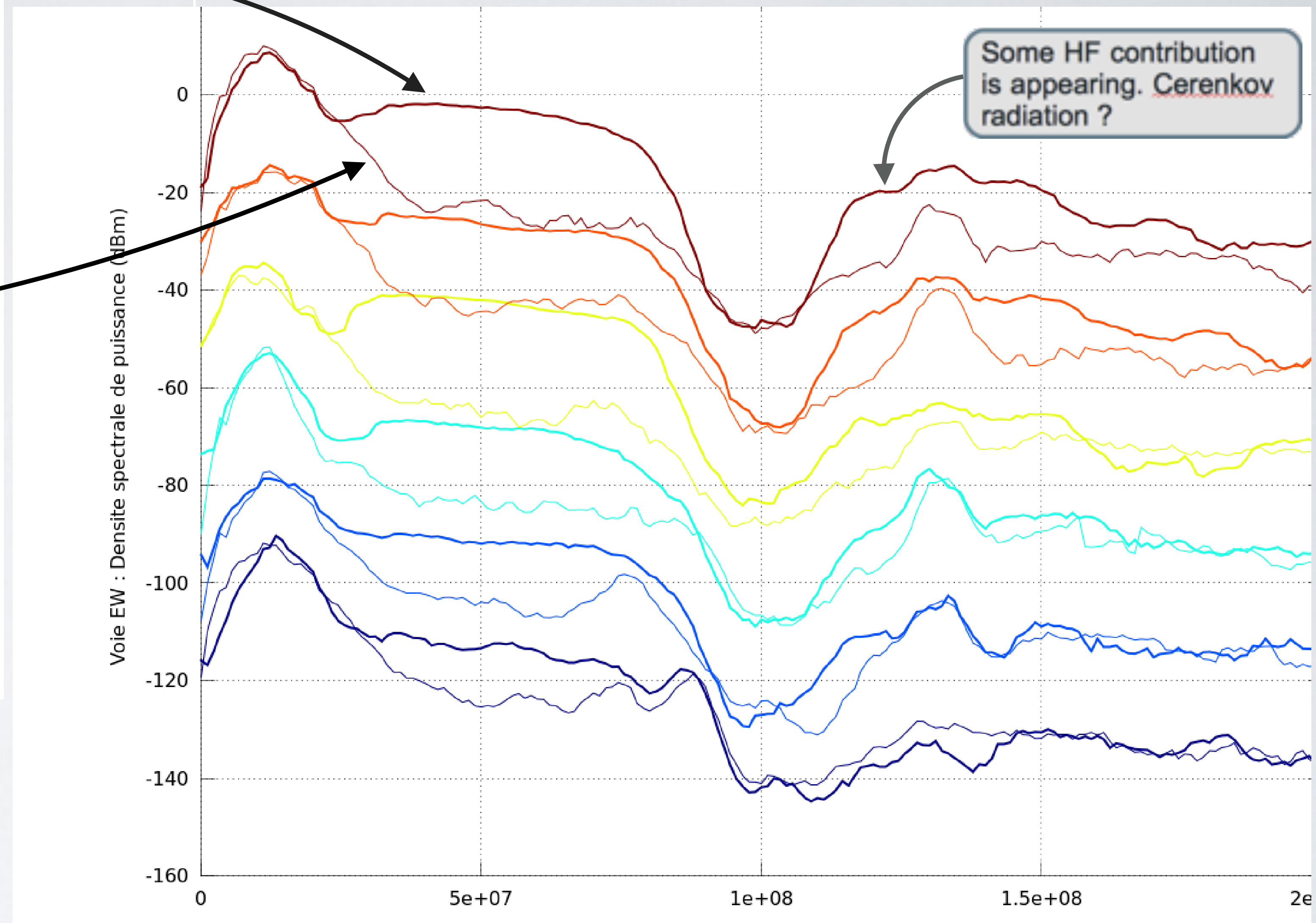


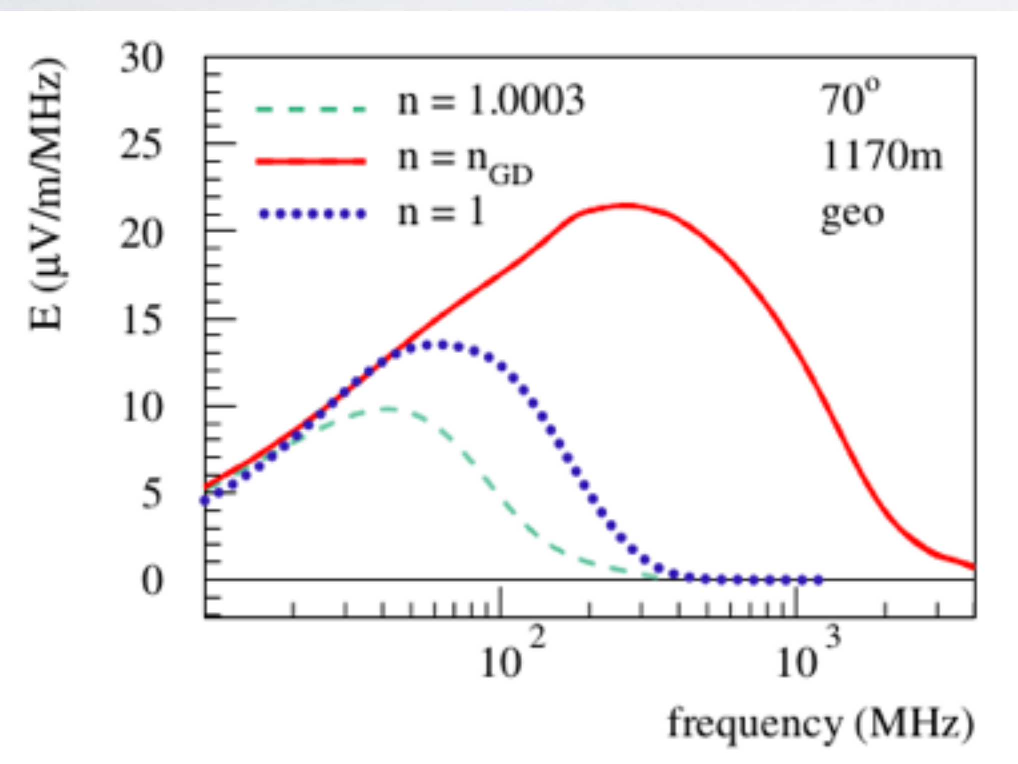


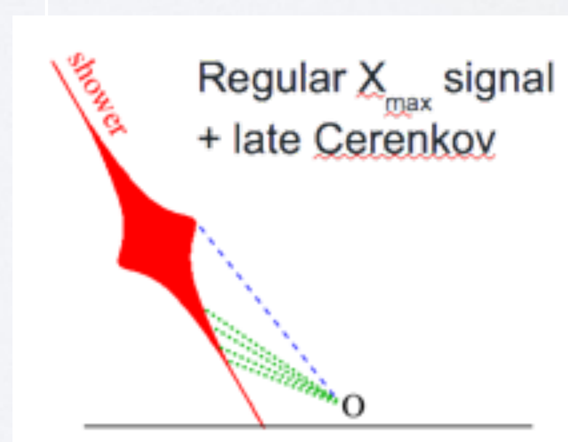
Different **EAS features** :
energy, inclination, mass (Xmax)
Or **observation conditions** :
impact parameter, orientation, under/above
induces different **pulse shapes** :
Amplitude duration, bi-polarity
Filtering the signals kills the differences
Measuring the spectrum over a wide-band preserves the sensitivity

PROSPECTS - I

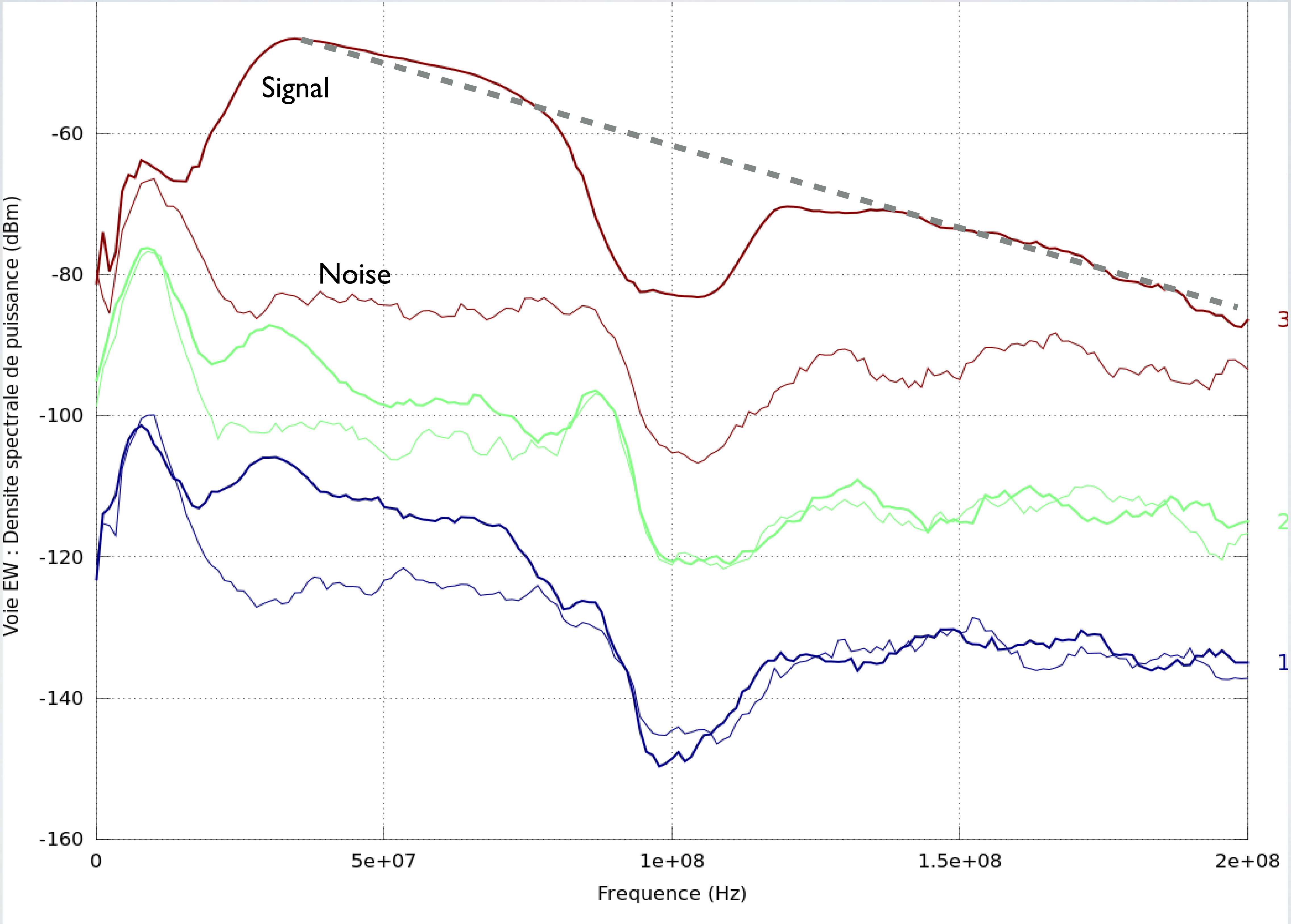

Coincidence 103 du 04-May-2013 20:43:41
0.15
0.1
0.05
0
20
19
12
6
2
0
500
1000
1500
2000
2500
Temps (ns)


Some HF contribution is appearing. Cerenkov radiation ?
Voie EW : Densite spectrale de puissance (dBm)
0
-20
-40
-60
-80
-100
-120
-140
-160
0
5e+07
1e+08
1.5e+08
Frequence (Hz)


E (μV/m/MHz)
30
25
20
15
10
5
0
n = 1.0003
n = n_GD
n = 1
70°
1170m
geo
10^2
10^3
frequency (MHz)

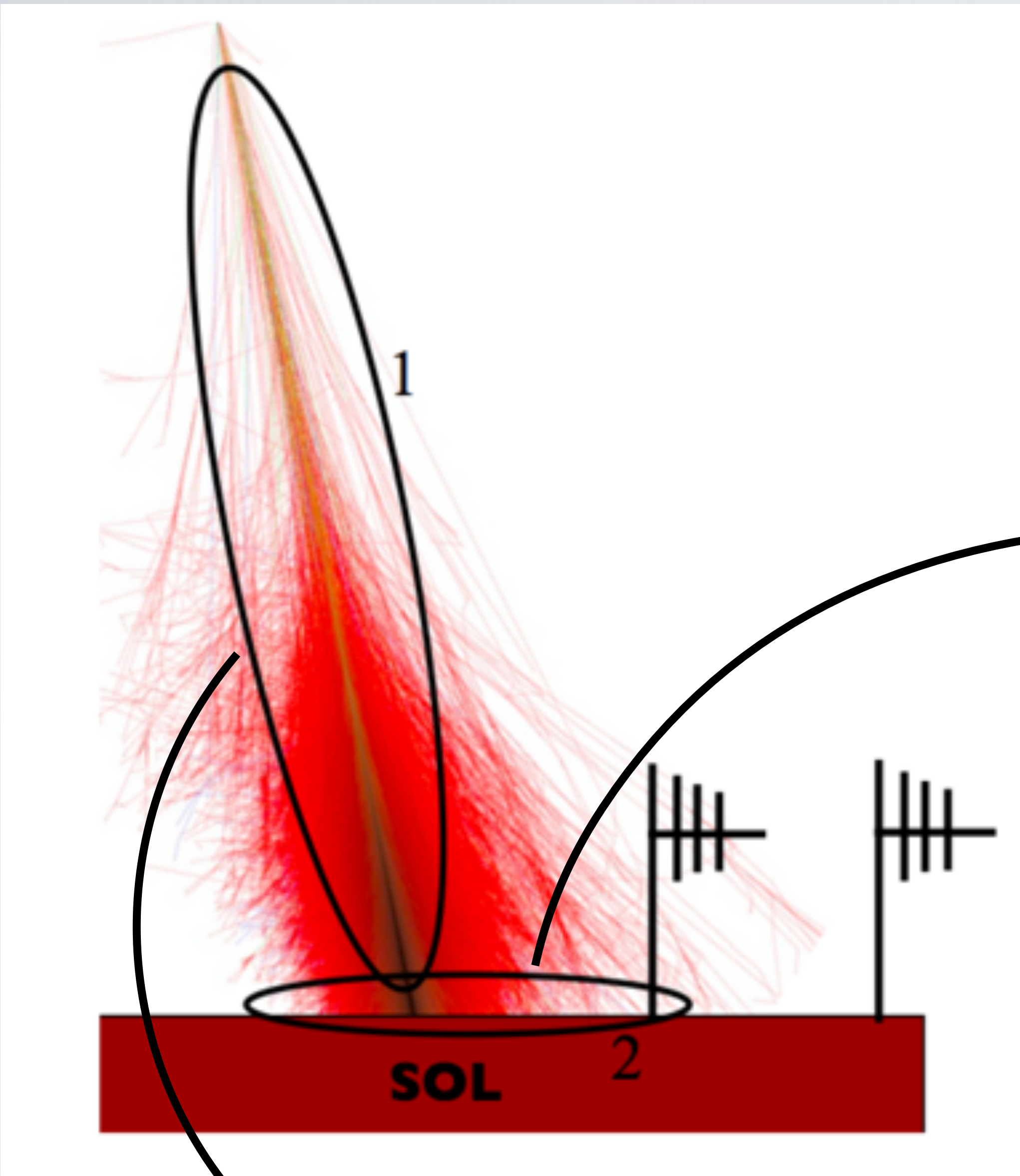

shower
Regular X_max signal
+ late Cerenkov
O

PROSPECTS - I

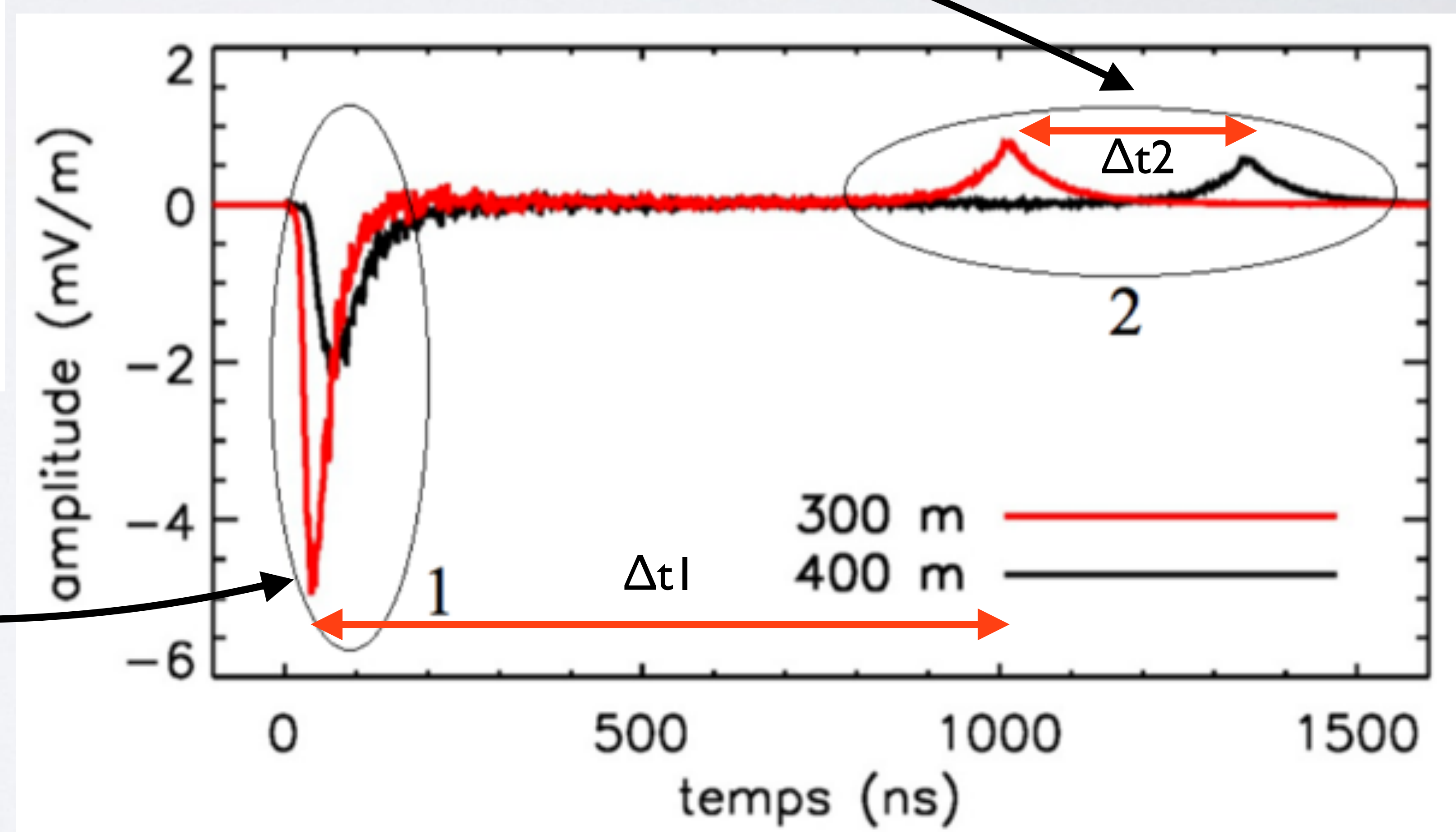

Signal
Noise
-60
-80
-100
-120
-140
-160
0
5e+07
1e+08
1.5e+08
2e+08
Frequence (Hz)
Voie EW : Densite spectrale de puissance (dBm)
3
2
1

PROSPECTS - 2

Sudden death of the shower



2: charges are strongly decelerated when arriving at ground, and gives "sudden death" signal. Time difference between 2 antennas gives shower's location. The signal is produced at low frequencies (< 10 MHz).



1: charge is varying during shower's development, and gives "main" signal. Time difference in one antenna signals gives shower's history (nature of primary?)