Recent results [and improvements] from CODALEMA and the Nançay radio facilities

A multi-scale and multi-frequency environment for cosmic ray air shower radio signal detection

R. Dallier, J.L. Béney, H. Carduner, D. Charrier, L. Denis, A. Escudié, D. Garcia Fernandez, F. Gaté, A. Lecacheux, F. Lefevre, L. Martin, B. Revenu, L.M Rigalleau

- Motivations for Nançay setup
- Presentation of instruments
  - CODALEMA-3
  - EXTASIS
  - Compact Array & Composite Trigger
  - NenuFAR
- Illustration of performances
- Outlook

Motivations

To explore new or neglected ways of exploitation of the radio signal emitted by EAS

Lacks

Determination of X_{max}: seems needing high antenna density (contradictory with high energies)

Covering large areas: standalone detectors, but either reject parasitic transients (self-triggering) or use scintillators (slave mode)

Detection range in classical [30-80] MHz band too short (sensitivity too low)

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Solutions?

Look at high frequencies?

Very selective, composite radio trigger with several antennas (increased sensitivity)?

Look at low frequencies?
3-polarization detection?

Observe mainly inclined showers with sparse arrays?

Could radio detectors be "stand alone"?

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Some of these topics are explored with several instruments individually - *This conference*

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LOFAR HBA - Rossetto, #33 (follows)
ANITA - Deaconu, #38 (friday)
EVA - Pfendner, #44 (friday)

GNO (ν) - Wissel, #4 (today)
LOFAR - Bonardi, #34 (today)
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(former attempts on LOPES & AERA)

T-REX - Schröder, #2 (wednesday)
AERA - Kambeitz, #22 (friday)

(sorry if I forgot some names!)

Motivations

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Solutions?

CODALEMA / EXTASIS purposes

To explore all these possibilities at the same place

To help radio detection becoming a stand alone technique

Look at high frequencies?

Very selective, composite radio trigger with several antennas (increased sensitivity)?

Look at low frequencies? 3-polarization detection?

Observe mainly inclined showers with sparse arrays?

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Existing instruments:

CODALEMA 3

An array of wide band standalone stations

CODALEMA-3

[20-200] MHz

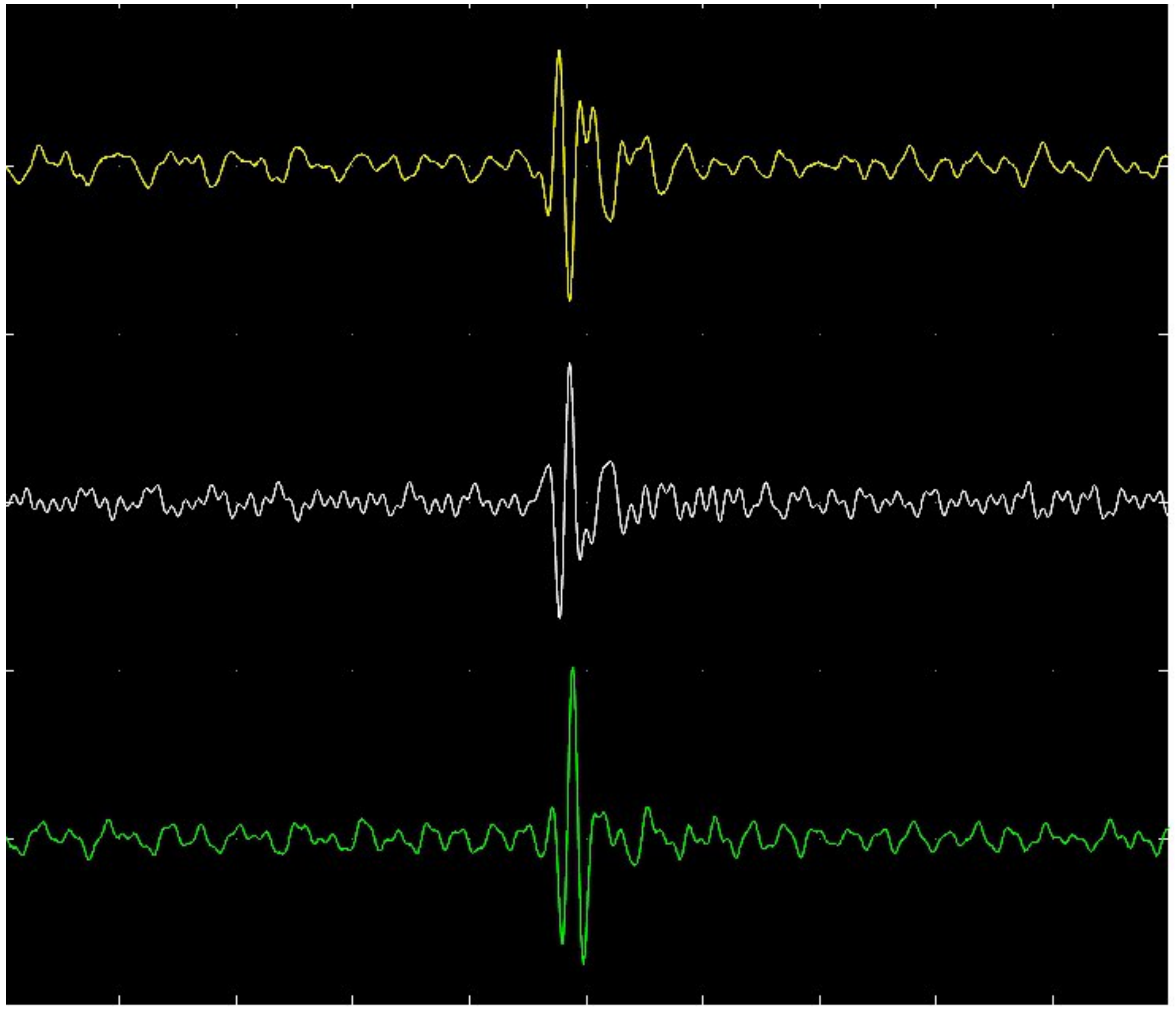
13 particle detectors (scintillators)

57 Butterfly antenna and LONAMOS LNA (exported on AERA)

"Tripole":

A newly designed 3-Polarization antenna

- 3 channels, 1GS/s, externally ("SD") triggered
- Aim: testing the "far-field" hypothesis (no longitudinal E-field component)



\EW

\SW-NE

\SE-NW

Technical data

13 particle detectors (scintillators)

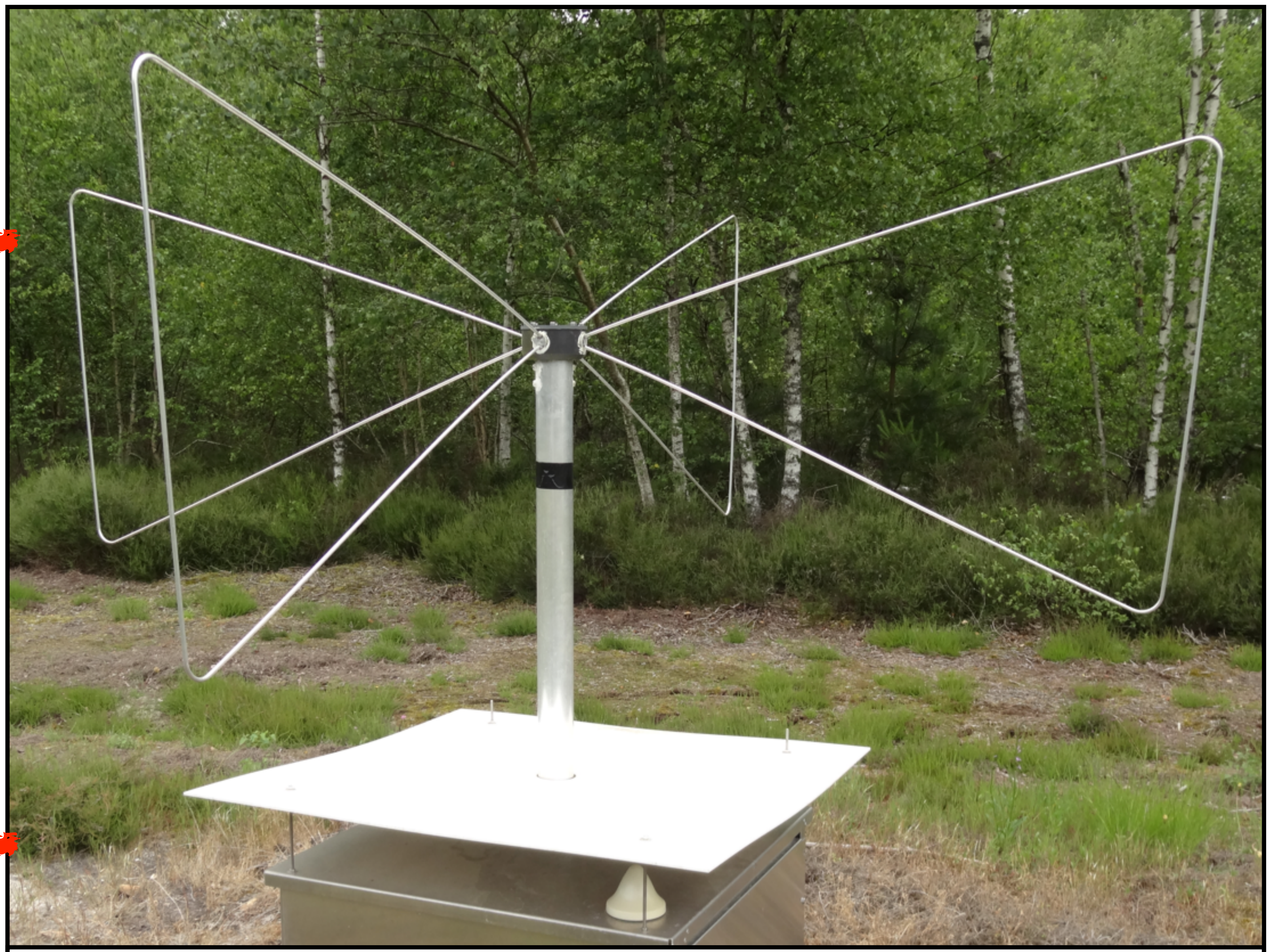
- 340 m x 340 m (0.12 km^2)
- 0.8 m x 0.8 m plastic scintillators, 4 cm thick, seen by 2 PM
- Sampling 1 GS/s, 12 bits, 2.56 µs
- Cabled array, central DAQ
- Generate a trigger signal, to be sent to any other detector (by cable or ethernet) and a GPS datation station

DATABASE
for all arrays
Event Builder

"AERA-like"
central DAQ
T3 level
Radio event
builder
Switchable

5/13 trigger
Energy range:
2.10^{16} - 5.10^{17} eV

Pure radio T3
Noise rejection
99%-100%



57 standalone radio stations

- Triangle 1600 m x 1400 m (1.1 km^2)
- Butterfly antenna, LONAMOS LNA
- Sampling 1 GS/s, 14 bits, 2.56 µs
- Frequency band [20 - 200] MHz
- Self-triggered array, local trigger (T1 & T2), local DAQ, data transfer w. fibres
- Relative datation accuracy ~5 ns
- 20 - 25 W power (depends on activity)

Existing instruments:

EXTASIS

Search for the low frequency components

Why looking at low frequencies?

year	reference	frequency	message
1970	Allan, Clay, Nature 225, 253	2 MHz	100 times higher than at 32 MHz
1970	Prescott et al, 11th ICRC 3, 717	3.6 MHz, 10 MHz	higher than geomagnetic, no detection at 10 MHz
1971	Stubbs, Nature 230, 172	2 MHz	250 times higher than at 44 MHz
1971	Hough et al, Nature 232, 14	3.6 MHz	10 times higher than geomagnetic in 20-60 MHz
1972	Felgate, Stubbs, Nature 239, 151	6 MHz	two polarizations, not only geomagnetic
1973	Clay et al, 13th ICRC 4, 2420	100 kHz	$\varepsilon_\nu \propto \nu^{-1.5}$
1973	Gregory et al, Nature 245, 86	100 kHz	large SNR, not only geomagnetic
1985	Suga et al, 20th ICRC 7, 268	50 kHz, 170 kHz, 1.6 MHz	Akeno, huge field strength vs geo-magnetic/electric
1987	Nishi, Suga, 20th ICRC 6, 125	26-300 kHz	Akeno, monopolar, 1/d, 2.5 km
1991	Castagnoli et al, 22nd ICRC 4, 363	470 kHz, 2.6 MHz	EASTOP/EASRadio, amplitude ↗ when freq ↘
1992	Baishya et al, NCimC 16, 17	2 MHz, 9 MHz	TR is not the only mechanism
1993	Kadota et al, 18th ICRC 4, 262	30 kHz-3 MHz	AGASA, mono/bi polar

Review by B. Revenu, 2014

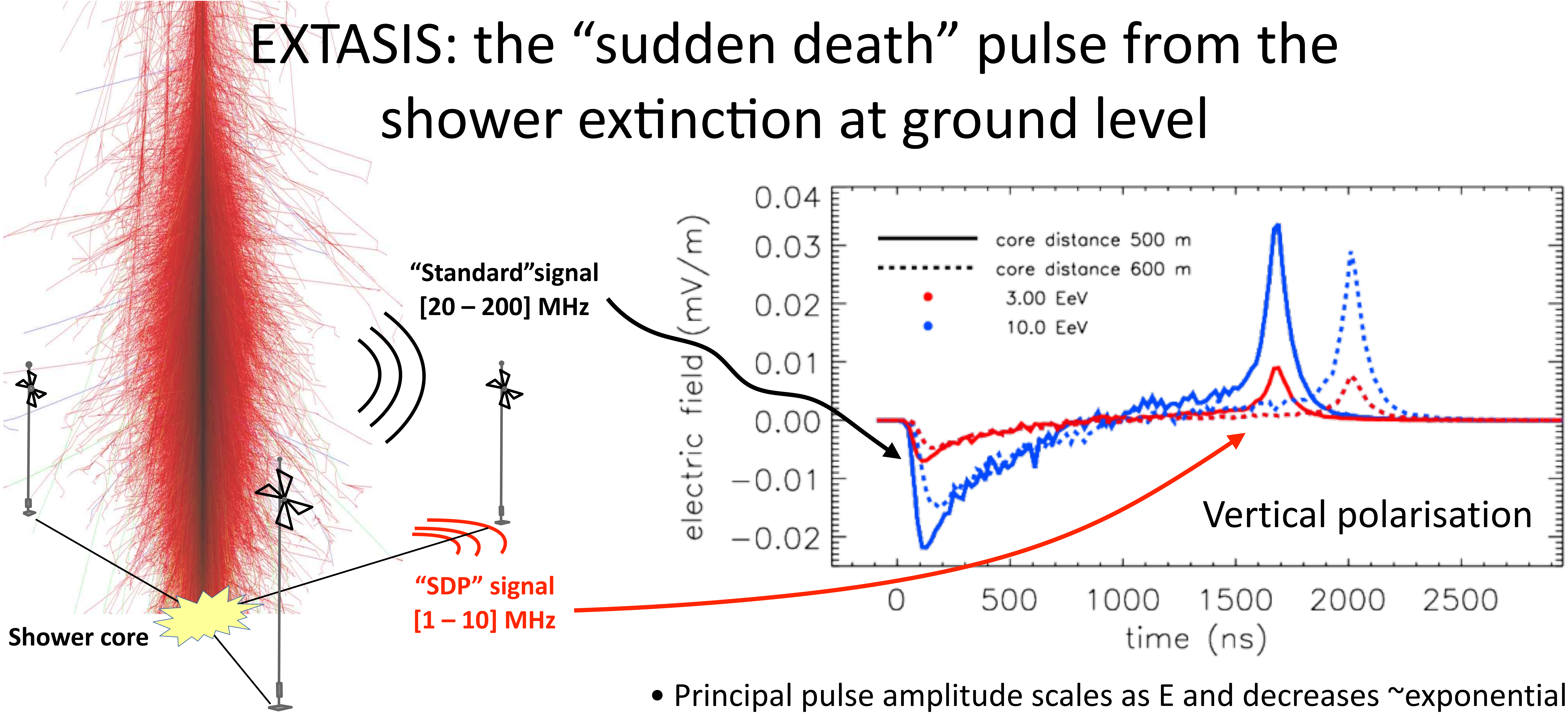
Why looking at low frequencies?

year	reference	mechanism
1957	Wilson, Phys. Rev. 108, 155	geoelectric, recombination
1968	Charman, J. Atm. Terr. Phys. 30, 195	geoelectric, acceleration of electrons
1972	Allan, Nature 237, 384	maximum coherence
1983	Kaneko et al, 18th ICRC 11, 428	charge-excess in air and at the ground
1985	Nishimura, 20th ICRC 7, 308	TR of electrons on the ground
1985	Suga et al, 20th ICRC 7, 268	TR of electrons on the ground
1978	Sivaprasad, Aust. J. Phys. 31, 439	geoelectric, acceleration of electrons

Review by B. Revenu, 2014

- Theories were not complete
- The “classical” signal should be seen at low frequencies
- But if there was “another” process?

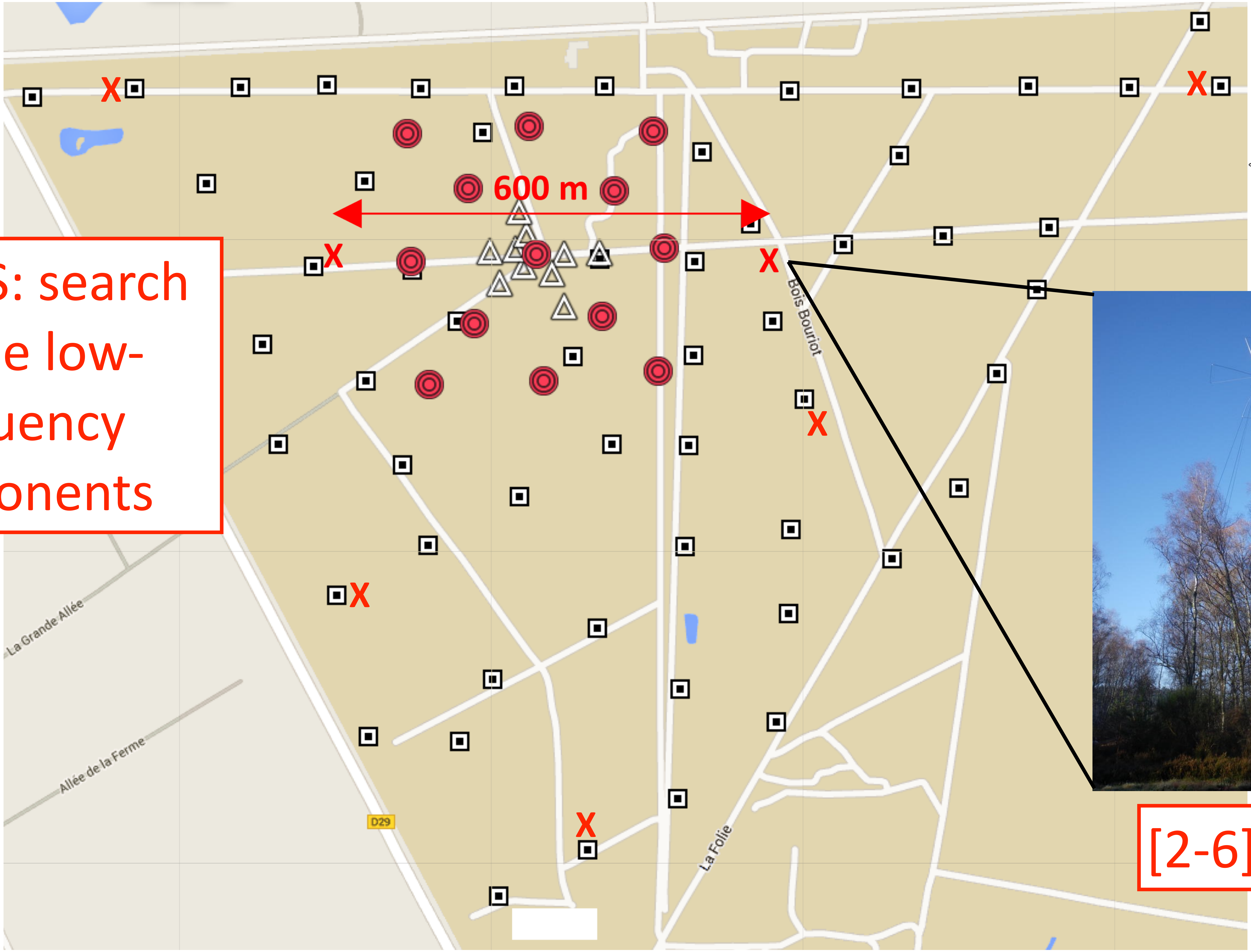
EXTASIS: the "sudden death" pulse from the shower extinction at ground level

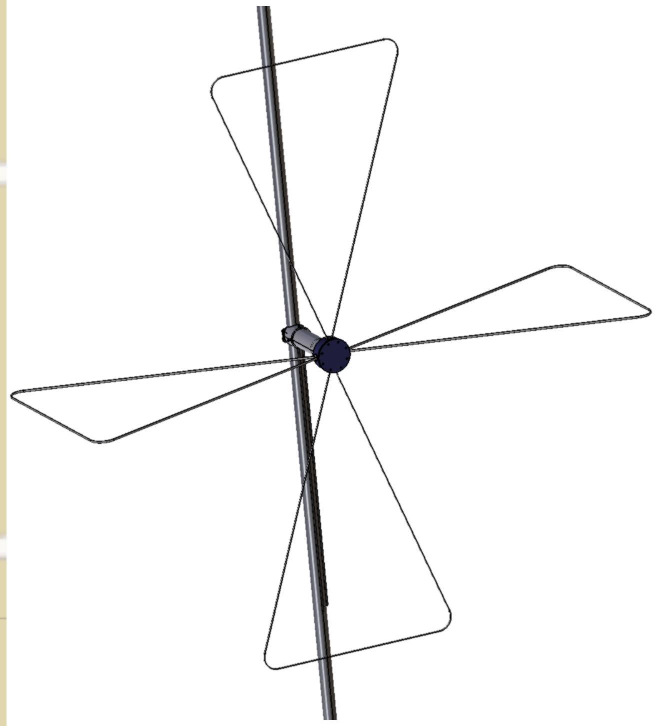


Easy core location by triangulation at ground level

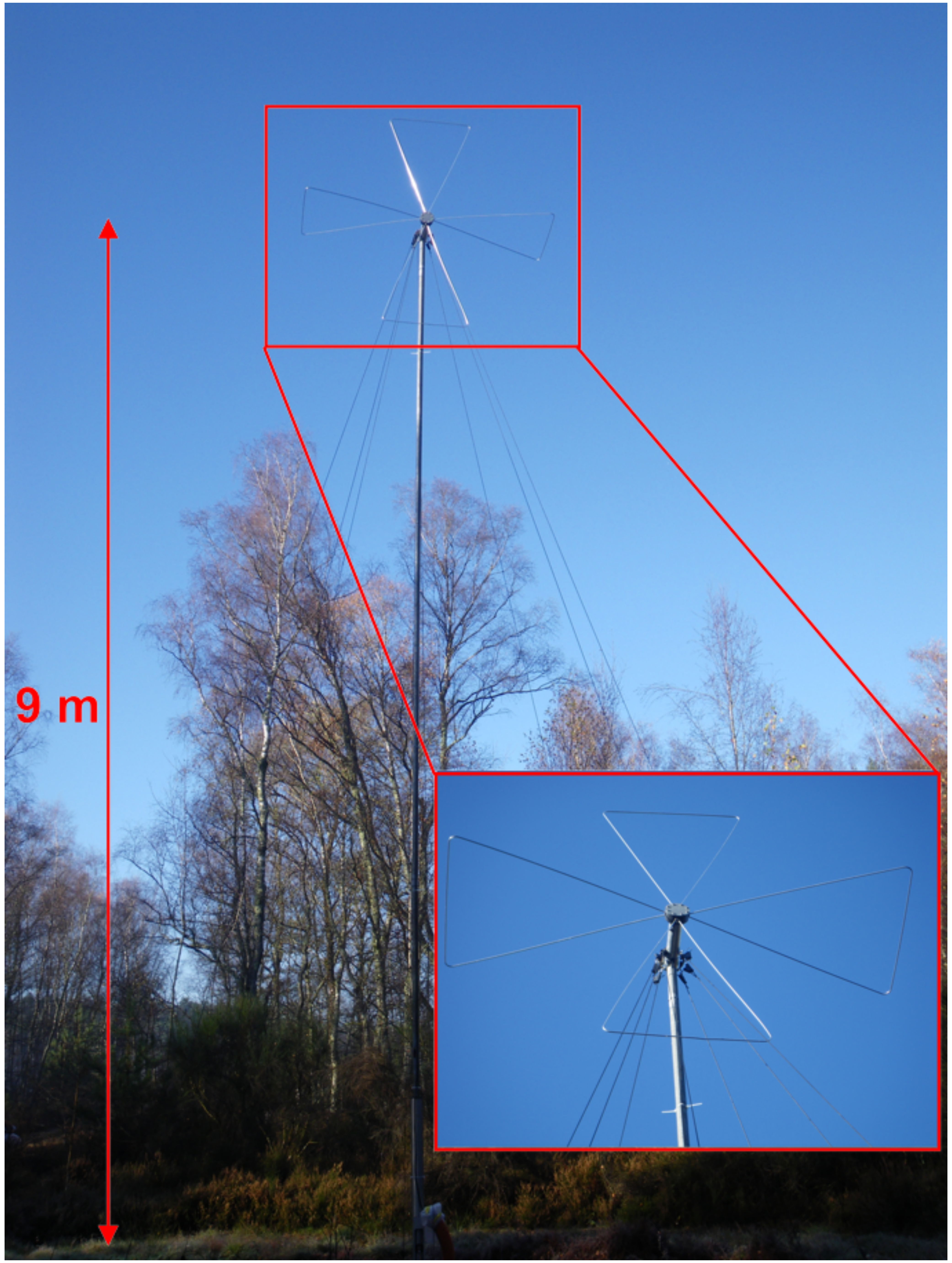
- Principal pulse amplitude scales as E and decreases ~exponentially but SDP amplitude scales as E and decreases as $1/d_{core}$
- Polarisation lies in the plane transverse to the (observer-shower core) direction

EXTASIS: search for the low-frequency components





[2-6] MHz



- Butterfly type + modified LONAMOS LNA
- Vertical and NS polarisations
- The optimized 9 m pole acts as a part of the antenna
- Currently 2 antennas, 600 m apart
- Soon: 7 antennas over ~1 km^2
- Several versions since ~1.5 years
- First: sampling 18 MS/s, 8 bits, 1 ms
- Soon: sampling 0.5 GS/s, 8 bits, 10 ms
- Frequency band [2 - 6] MHz (low-pass limited)
- Externally-triggered array, distribution by ethernet for the 5 new antennas
- Signal is difficult to find! (not found on AERA LF)

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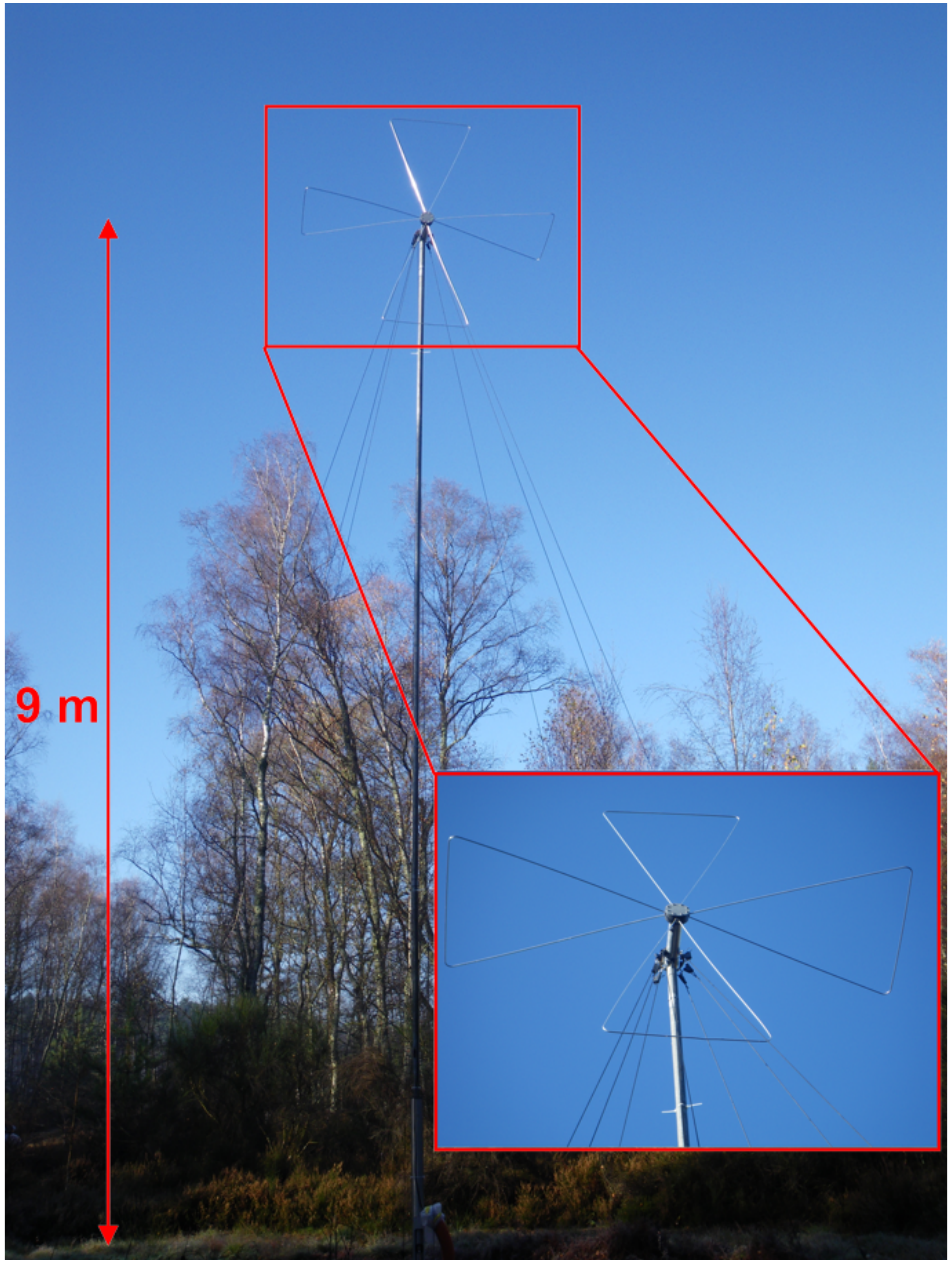
thernet for

A LF)



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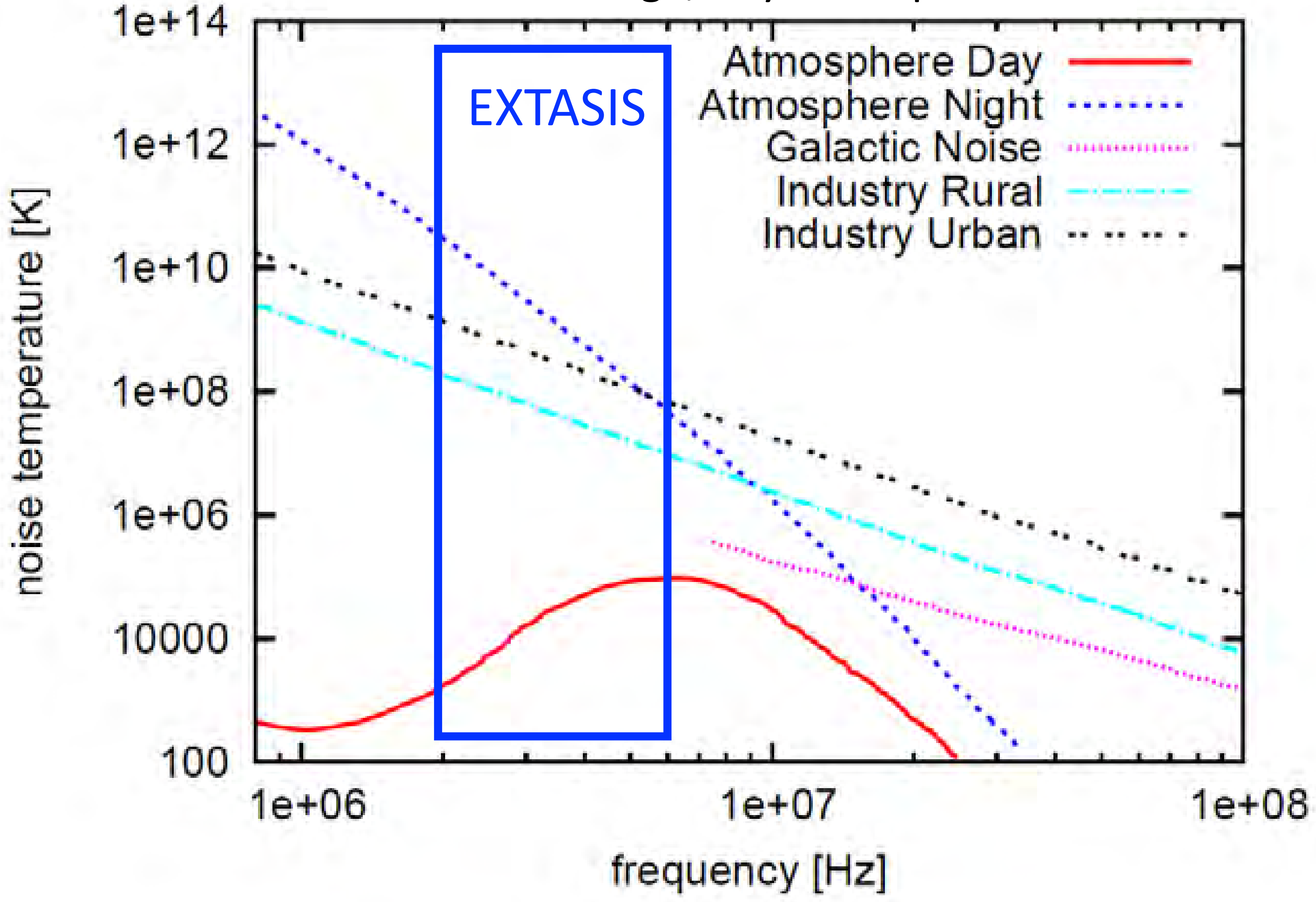
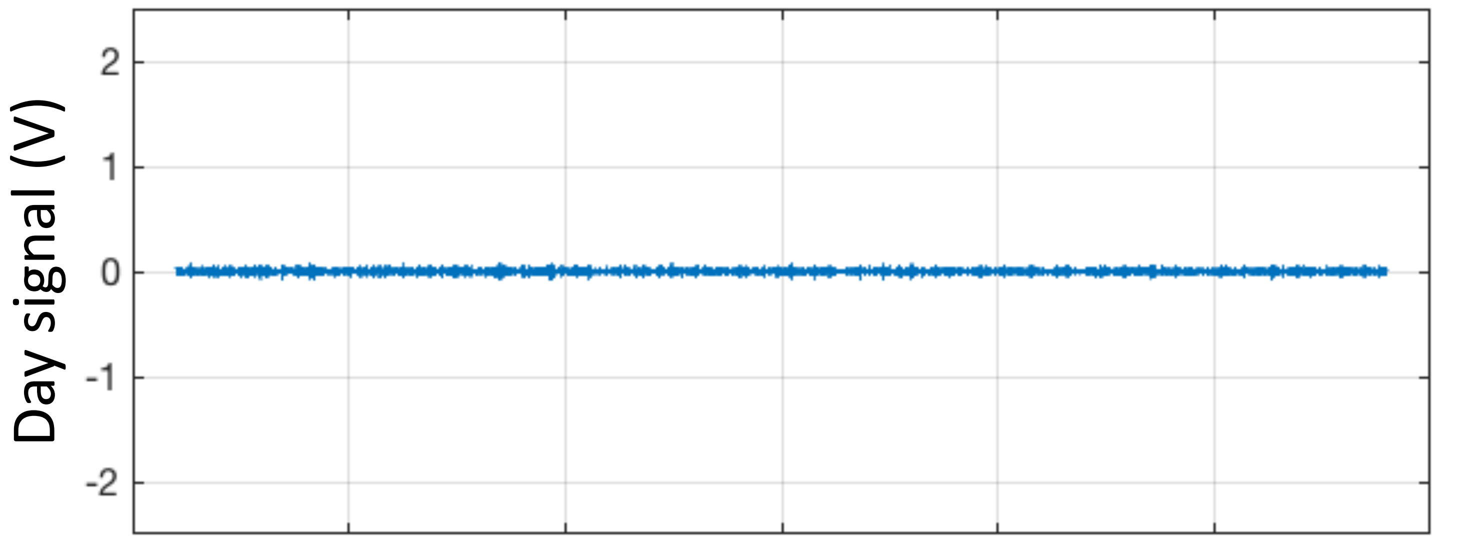
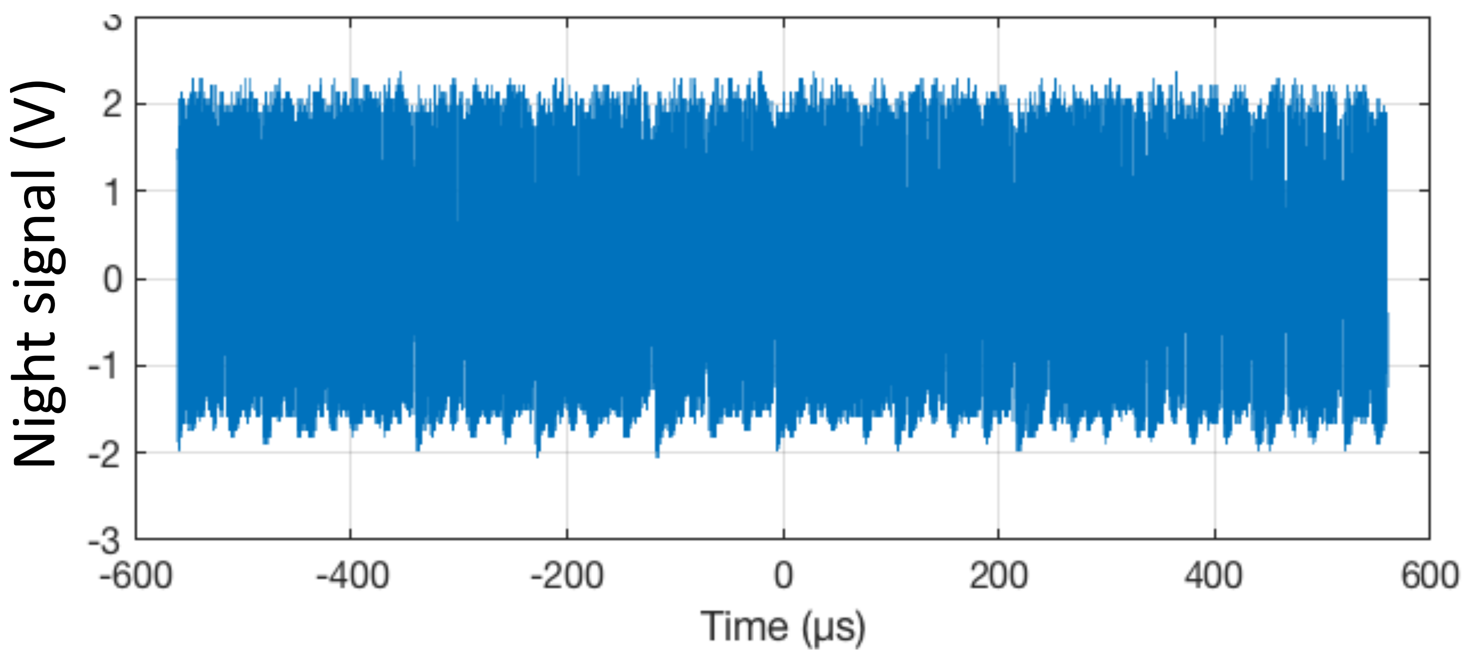
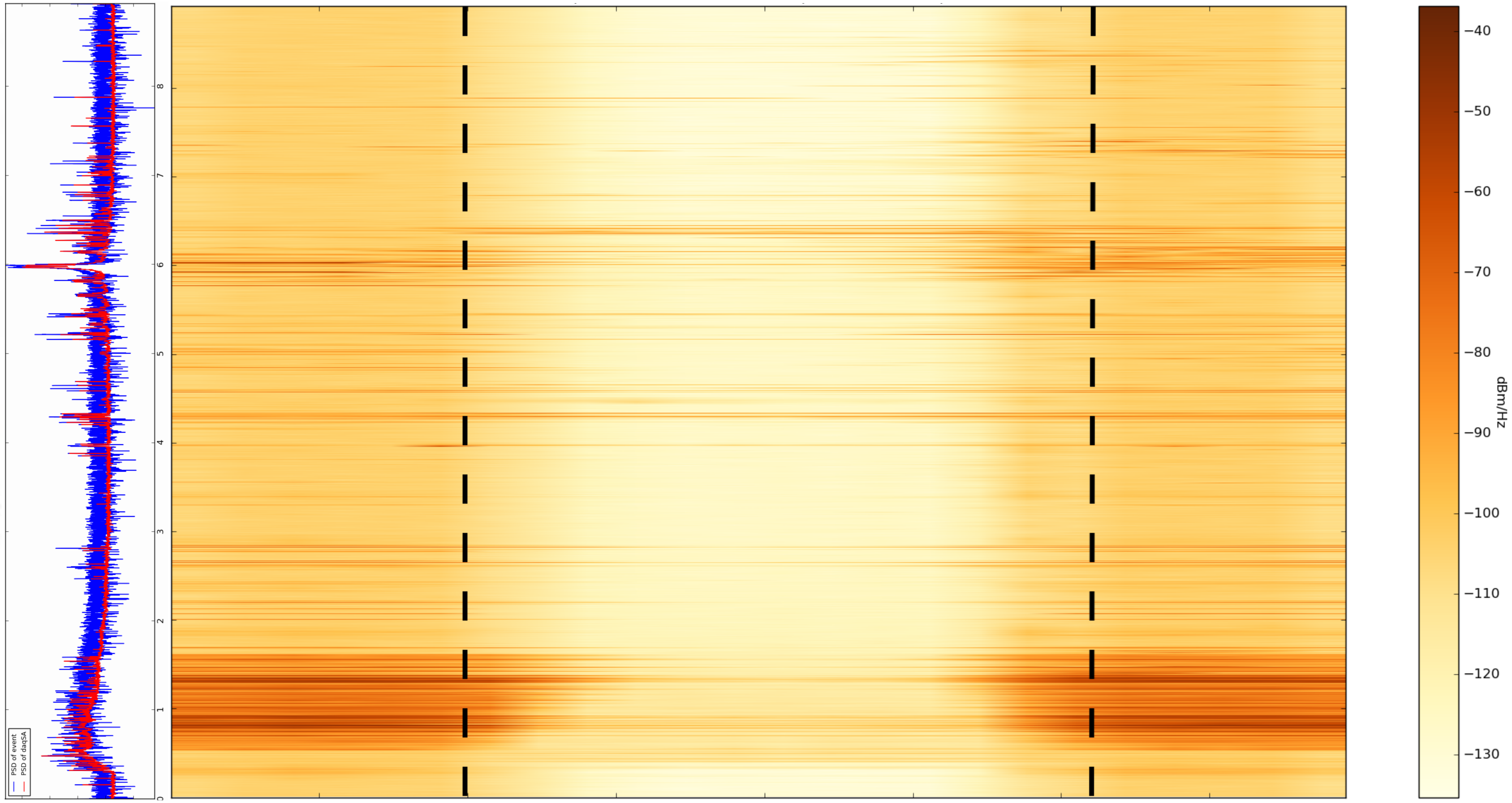
Why it is so hard to work at low frequencies

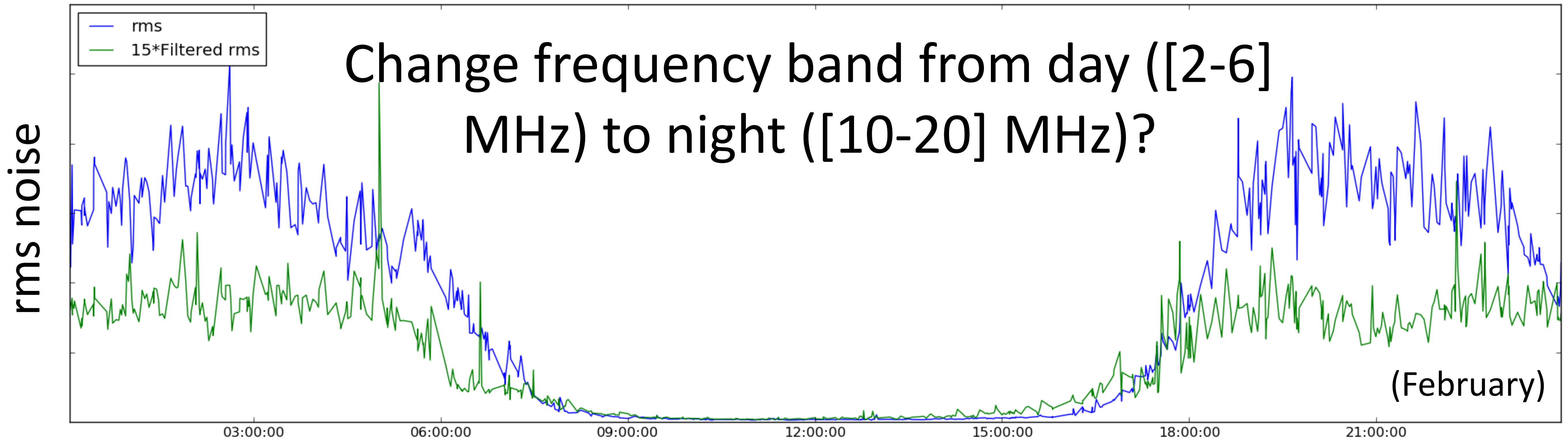
From Tim Huege, Physics Reports 620









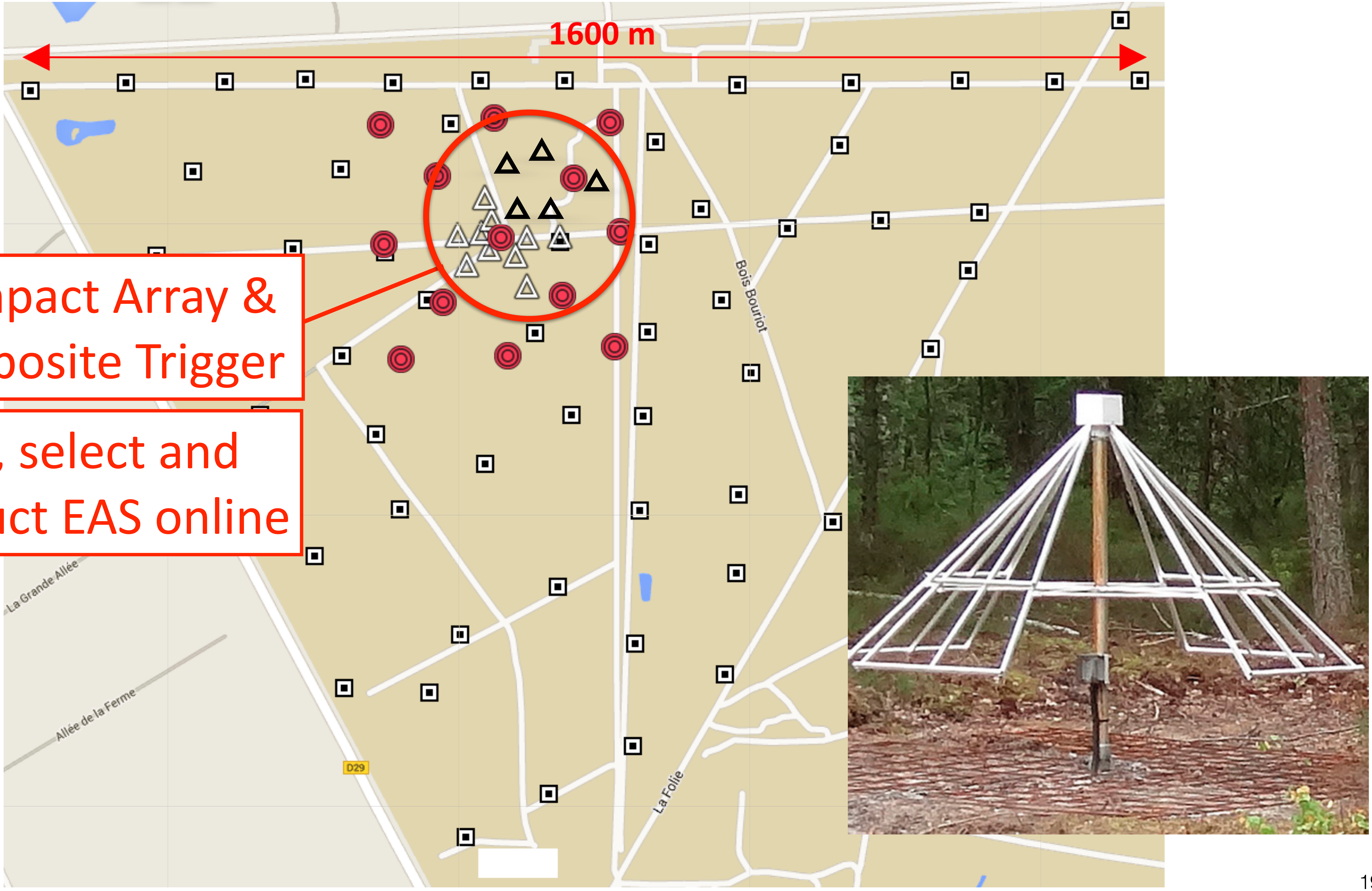


Change frequency band from day ([2-6] MHz) to night ([10-20] MHz)?

Instruments in progress:

The Compact Array & the Composite Trigger

Clustering and increasing selectivity & sensitivity



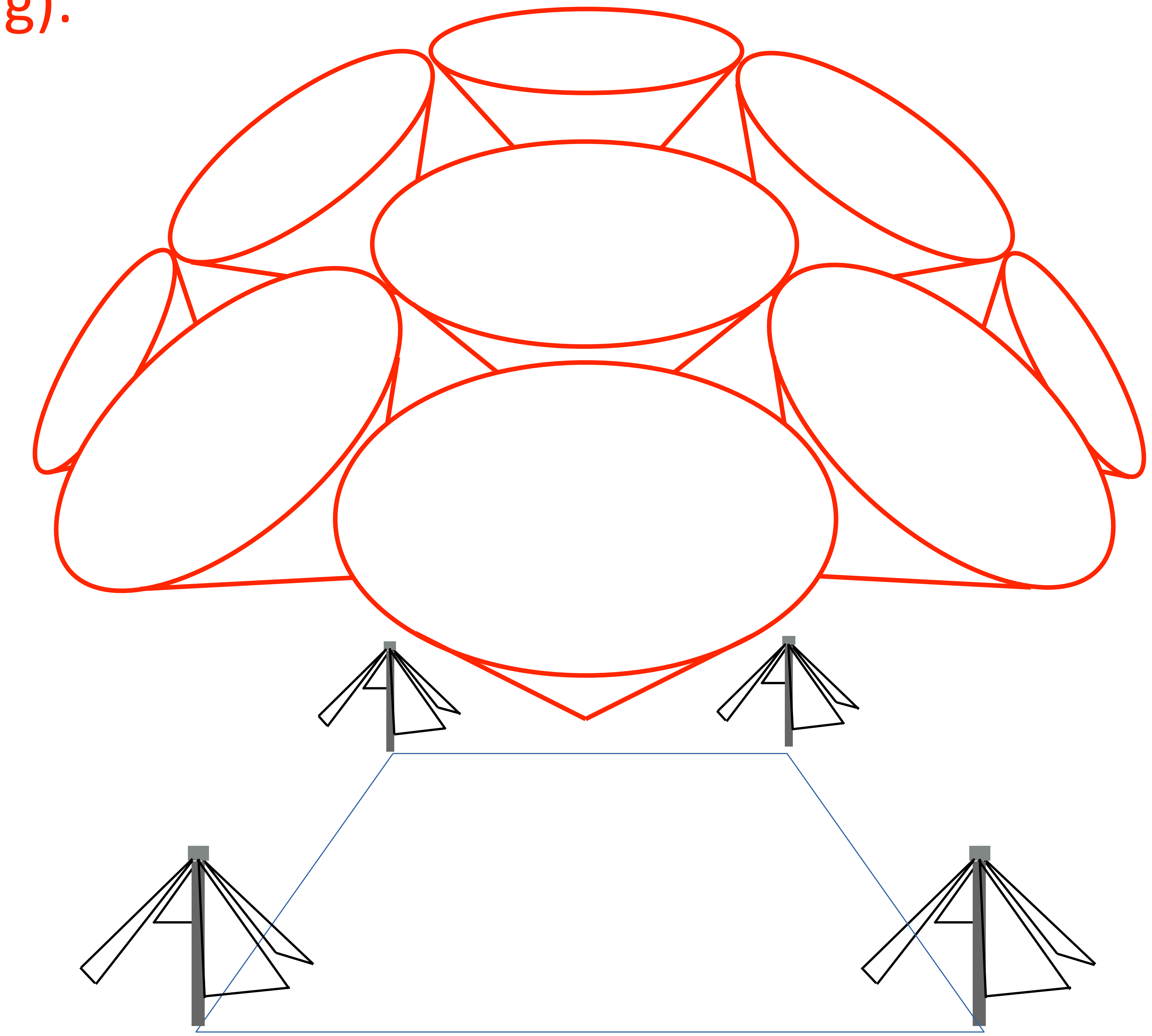
The Compact Array & the Composite Trigger

Detect, select and reconstruct EAS online

Aim: building a composite trigger, able to detect and select online the EAS events by testing in real time all sky directions at once

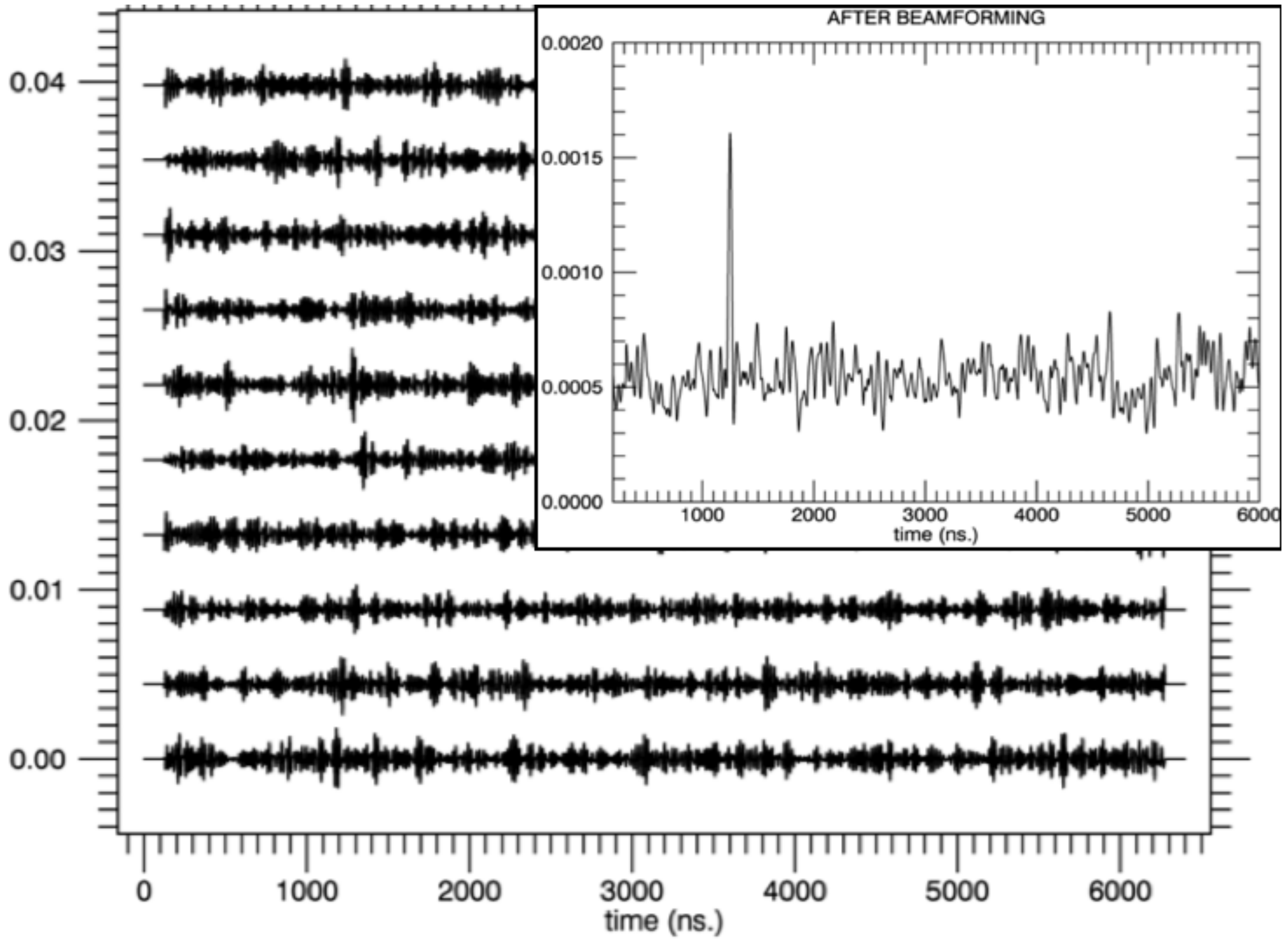
Compact array (working):

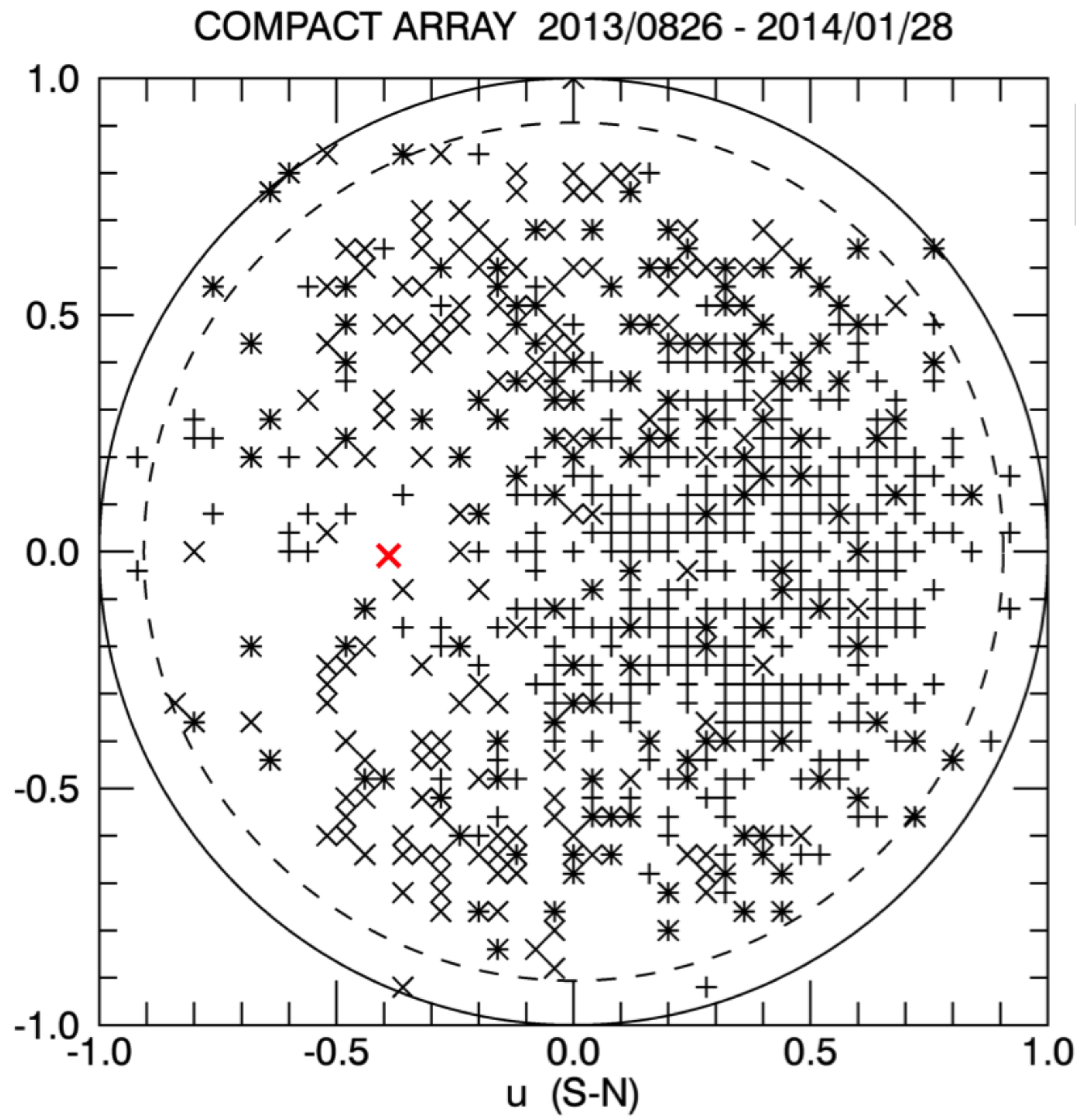
- 10 antennas (+LNA)
- NS & EW polarisation
- 5-branch star array
- 24 to 146m spacing
- SD triggered
- 6 µs snapshot
- 400 MS/s
- [10-200] MHz
- Works offline as an interferometer
- Sensitivity x $\sqrt{10}$
- Active since 2013
- Used as a test bench for the composite trigger



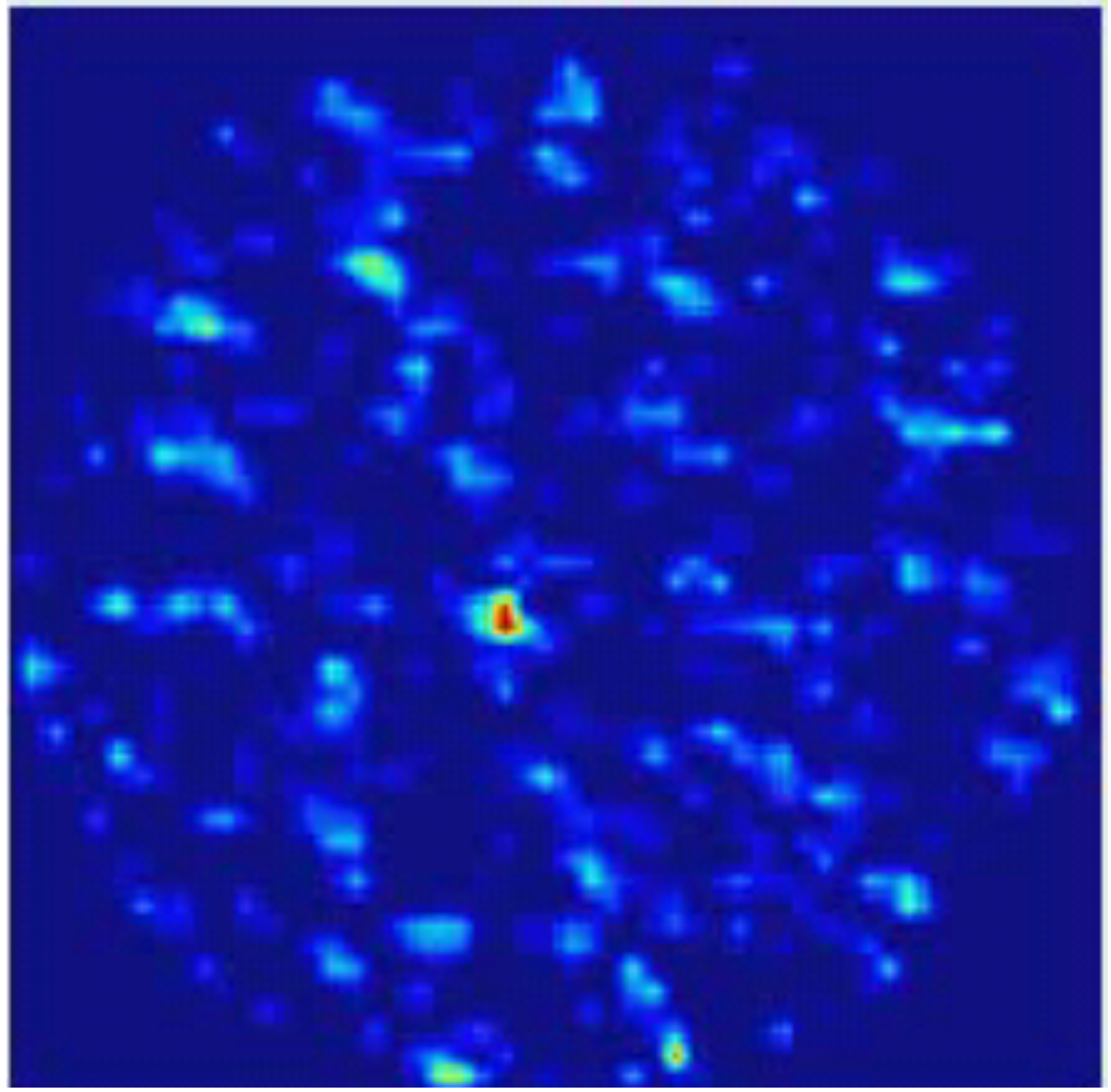
Composite trigger (still in progress):

- 5 antennas
- Circular polarisation
- [30-80] MHz
- Self detecting mode
- Continuous sampling @100 MHz
- Real-time software (GPU 5 Tflops)
- For each successive time-window corresponding to the array time aperture (500 ns): generate ~2000 beams in sky (~2° apart) via beamforming, and search for beam(s) containing signal above some intensity threshold

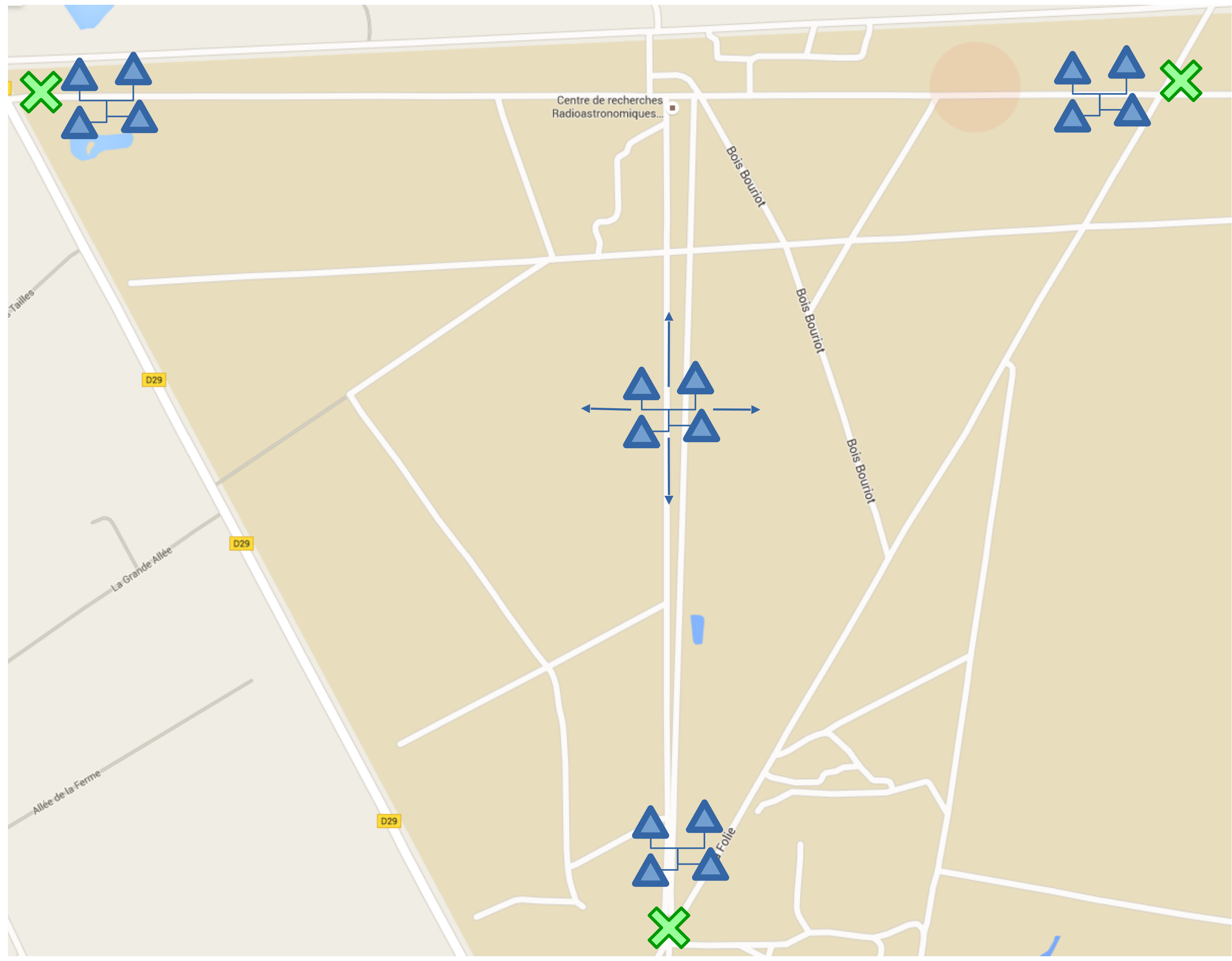




SD triggered mode: offline reconstruction of 1000 events out of 80000 triggers



A. Lecacheux - ARENA2014

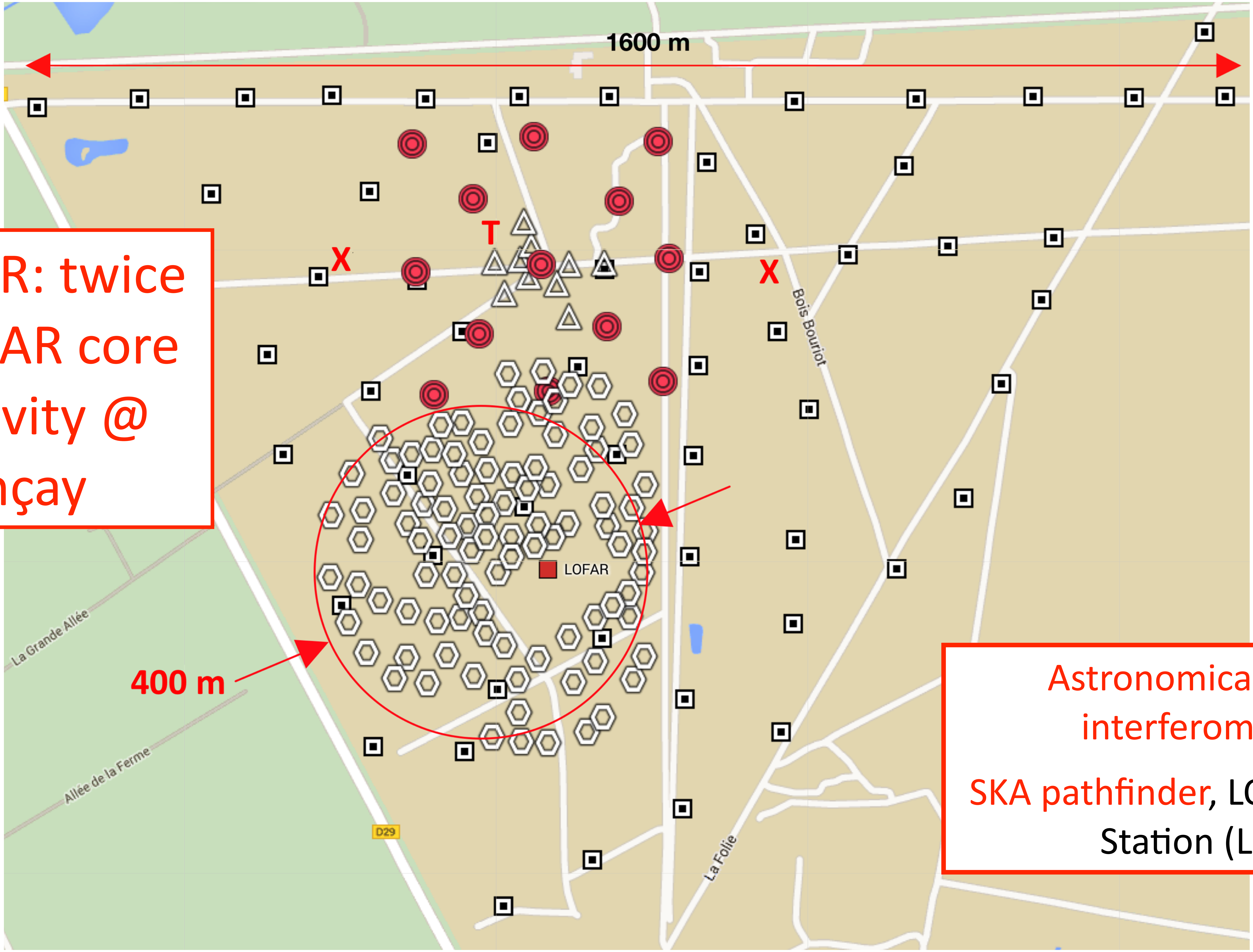


Towards a very efficient and wide frequency band sparse array?

Instruments in progress/project:

NenuFAR

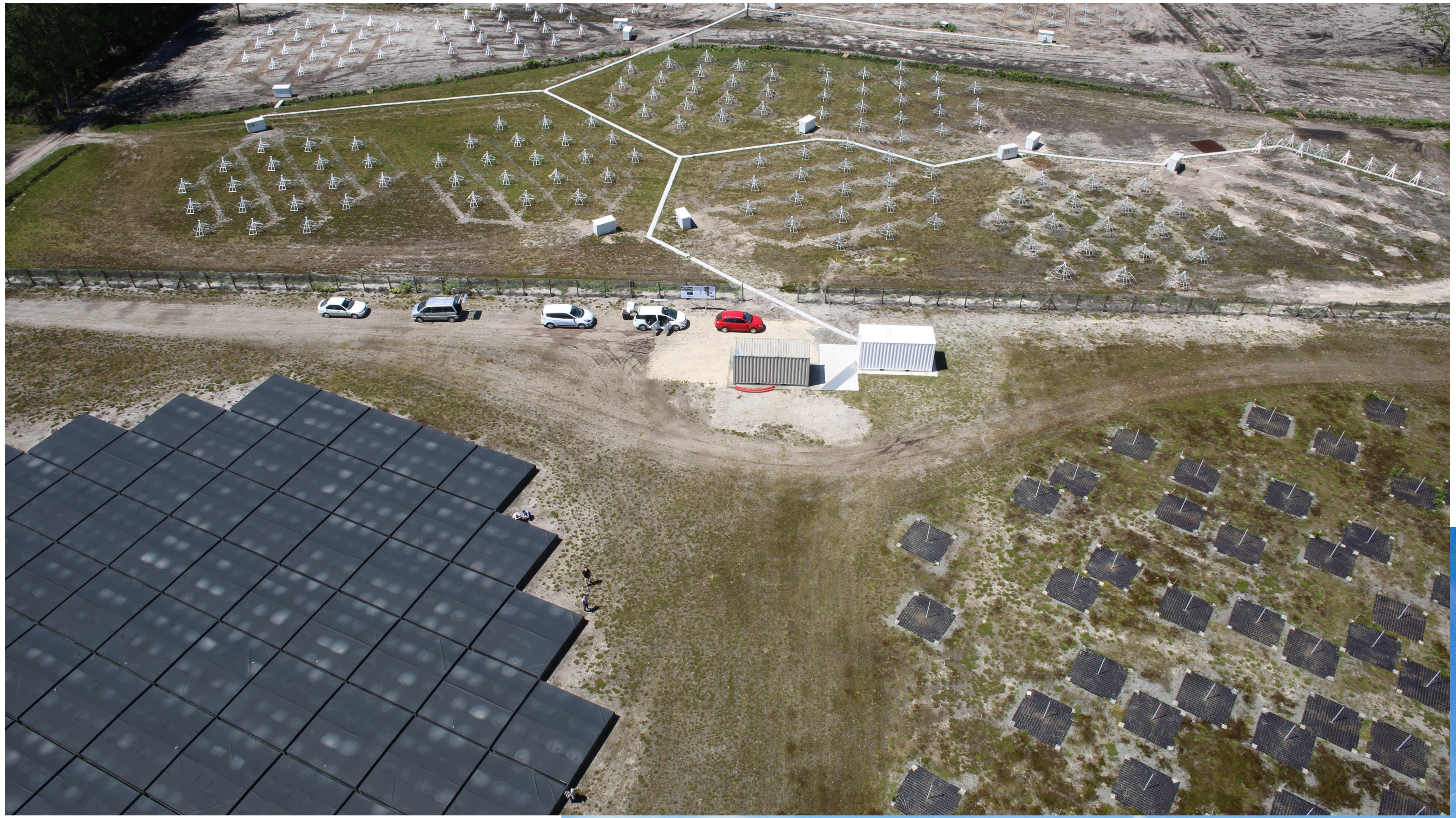
A radiotelescope for EAS and a pathfinder for SKA-EAS?

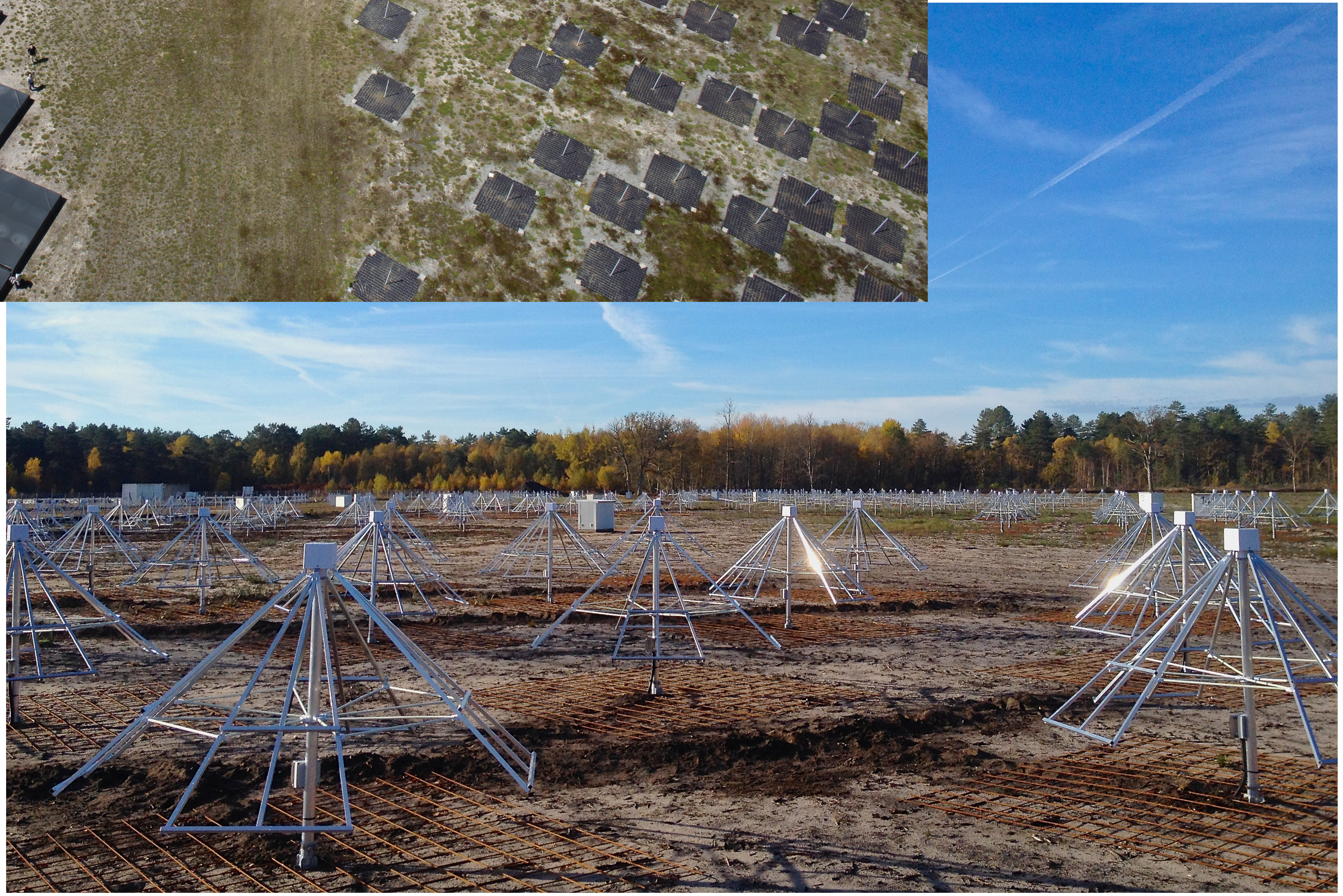


NenuFAR: twice the LOFAR core sensitivity @ Nançay

Astronomical radio interferometer

SKA pathfinder, LOFAR Super Station (LSS)





96 arrays of 19 antennas (Compact Array type) in dual polarization [10-80] MHz

96 out of the 1824 antennas (1/array) devoted to UHECR detection (ext. trigger)

Transient Buffer Board (to be implemented)

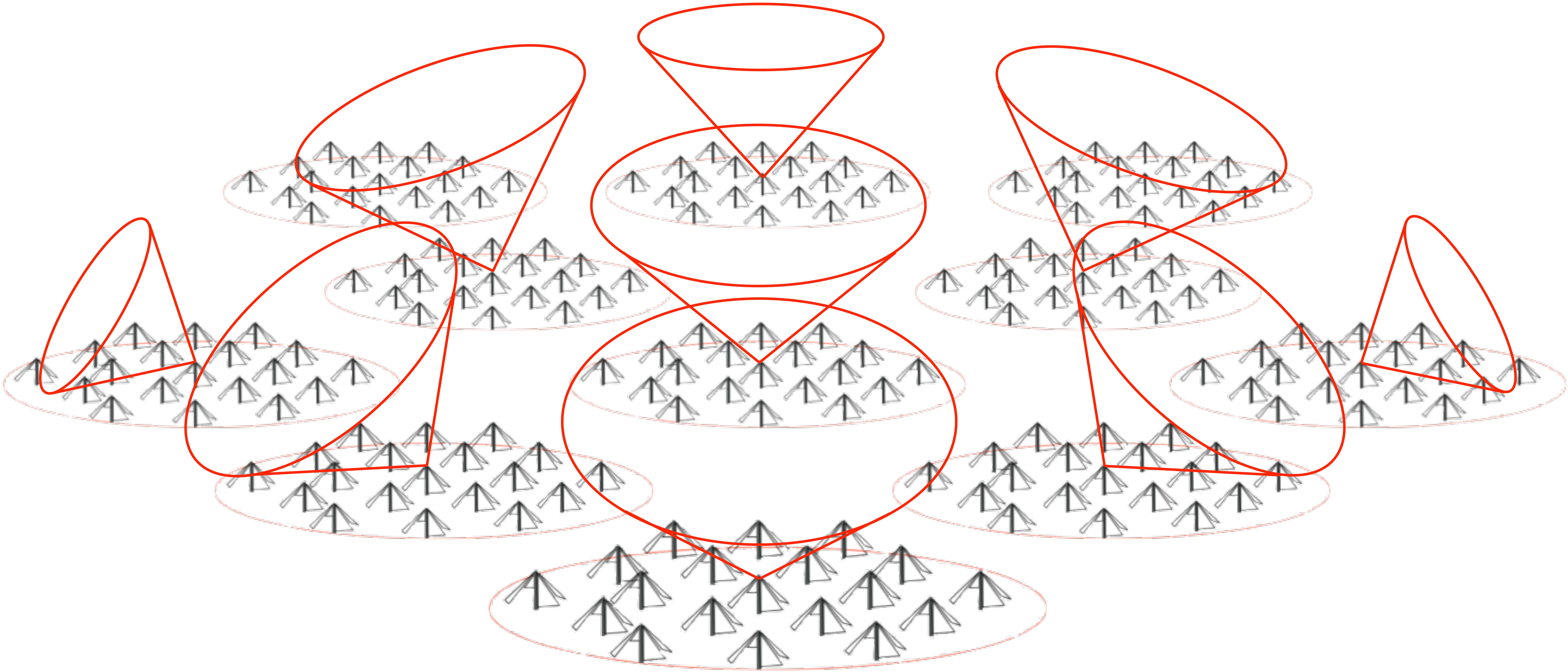
Currently 22 arrays installed

52 arrays in Nov. 2017

Completion to 96 arrays foreseen late 2018

Anyone can apply for observations

Another possible use in dedicated observation mode (not 100% of time): phasing each mini array in different directions, the whole covering all the sky ("Compact Array" mode)



Effective area: 19 x single LBA station

CODALEMA 3 / EXTASIS

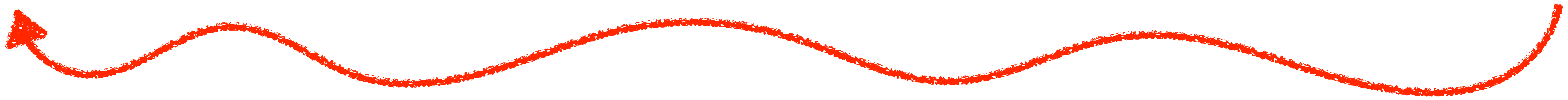
Illustration of the performances

A multi-hybrid event, X_{max} reconstruction

wide band advantage and polarisation features

R. Dallier - ARENA2016

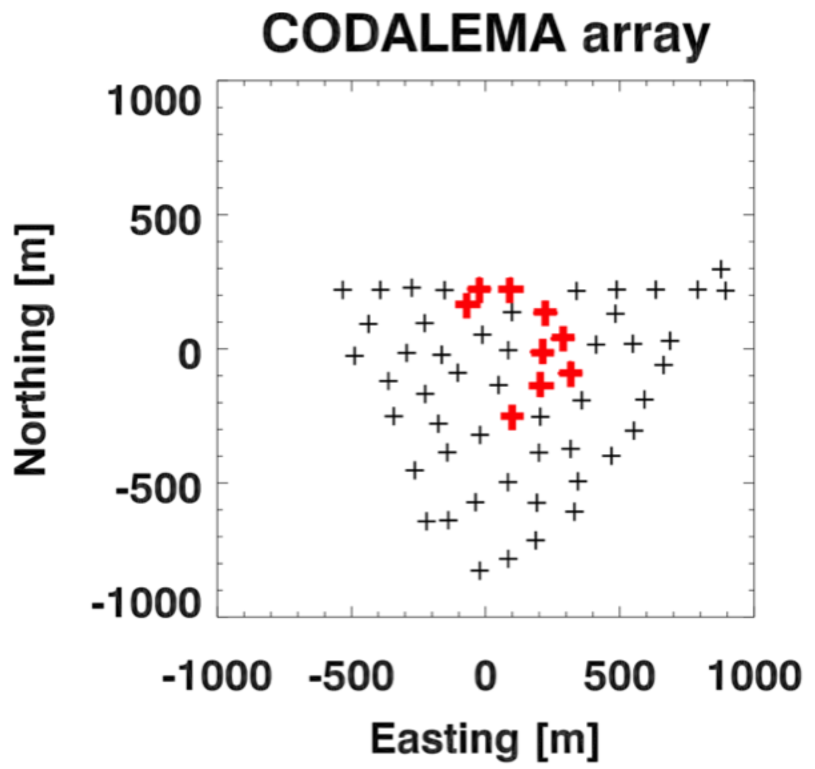
Raw signals (V) E-Fields (V/m) SELFAS Simulation (V)

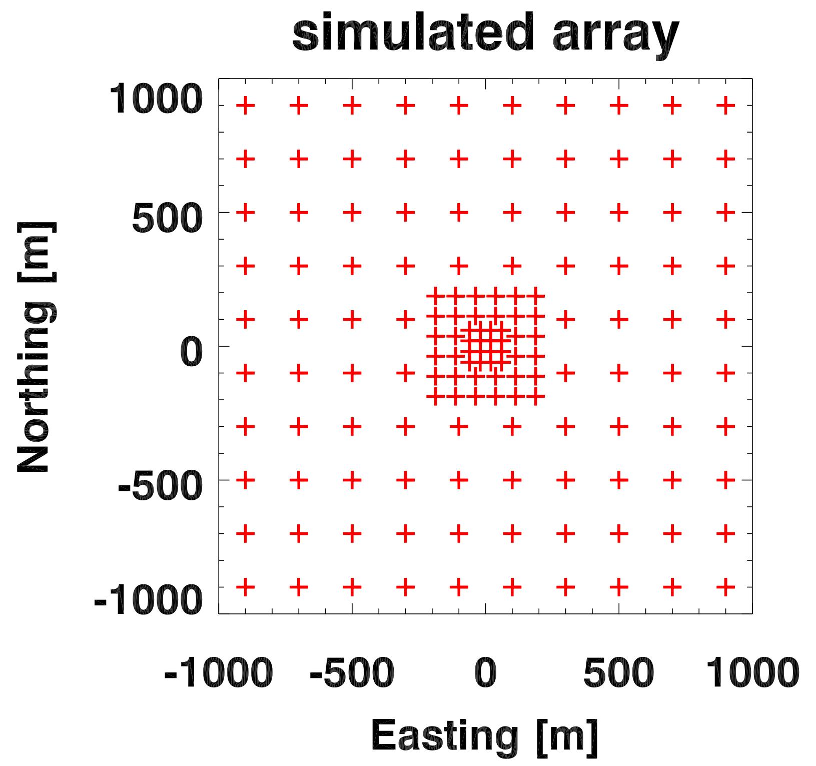


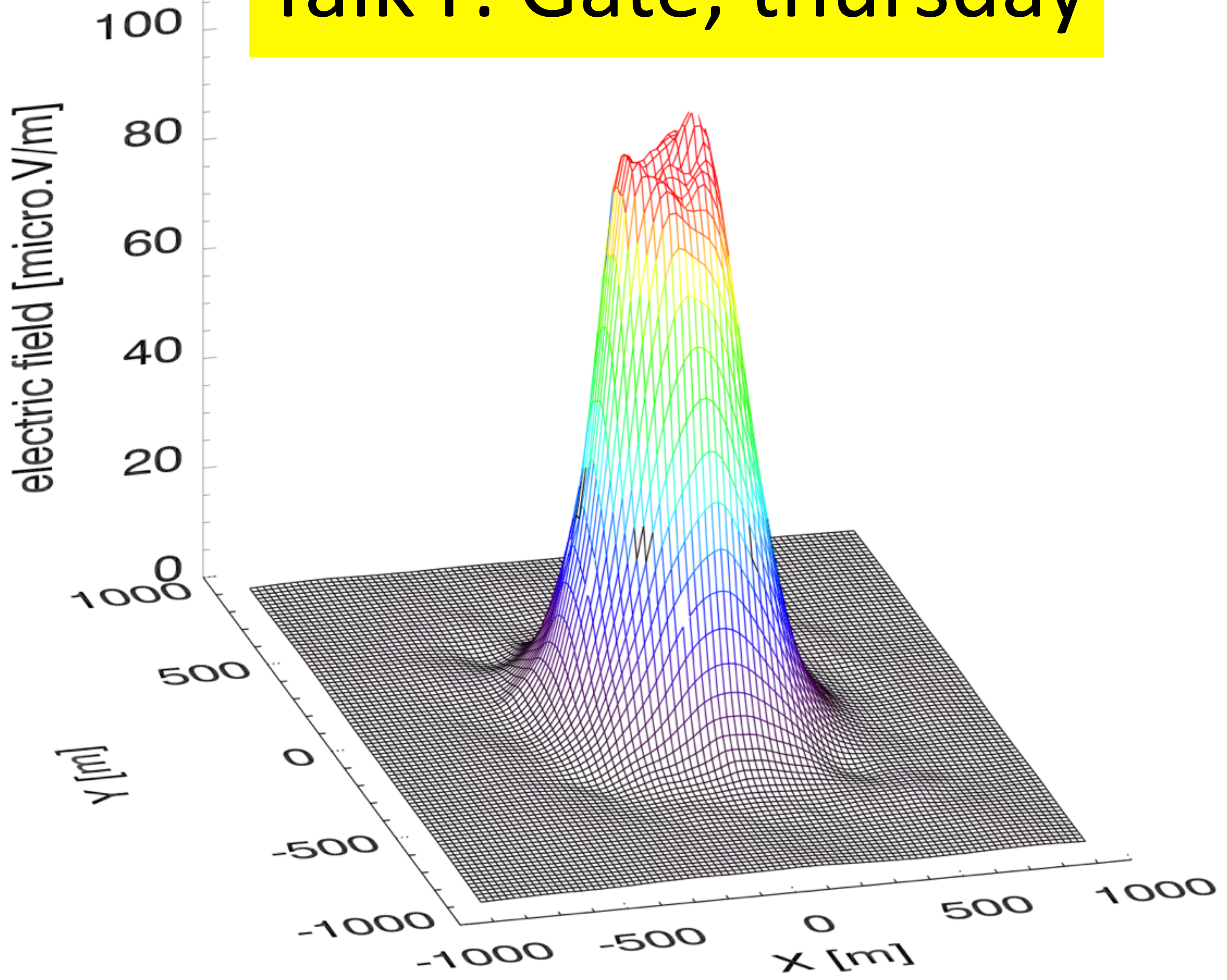
SELFAS simulation

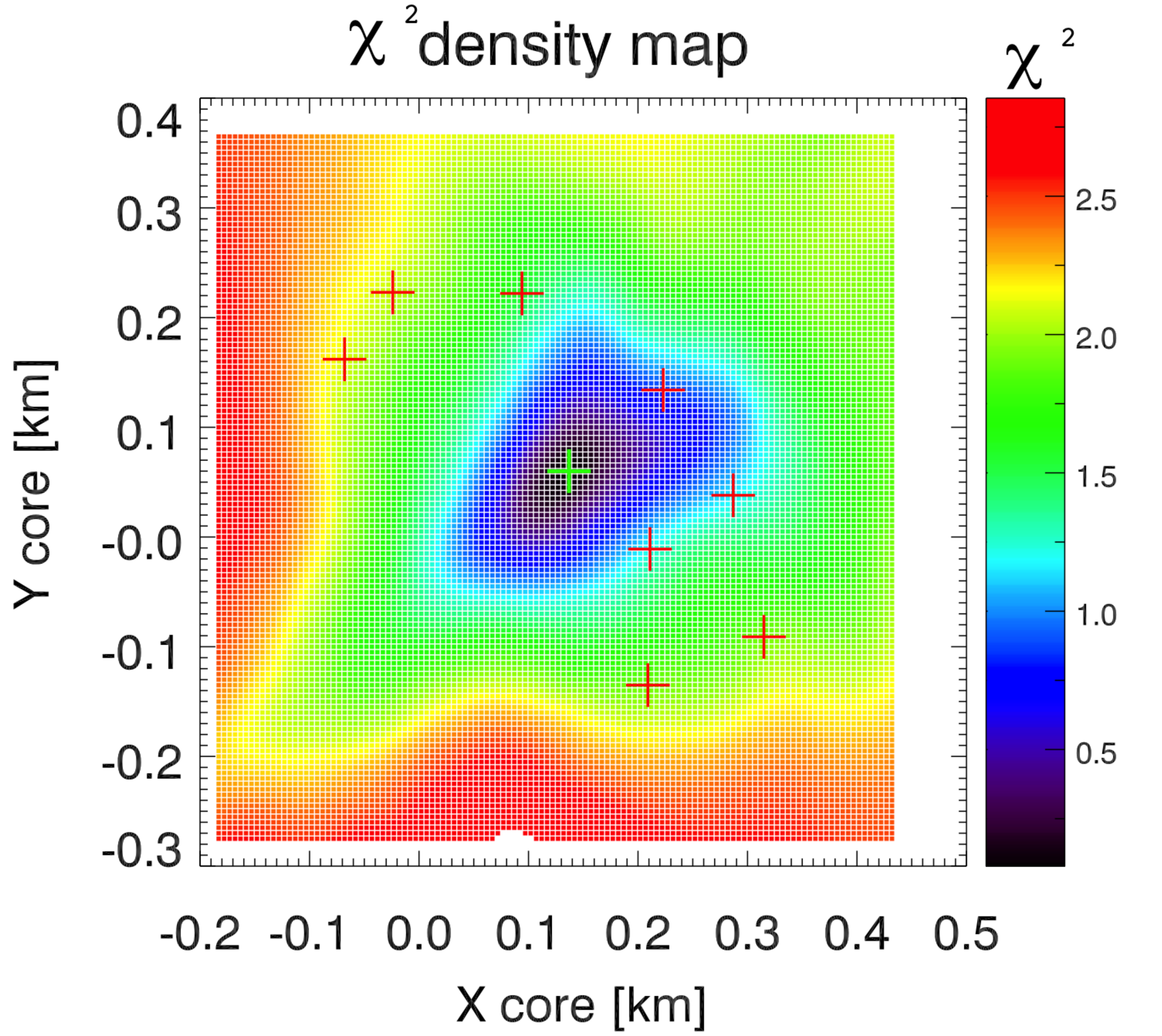
- Search for best core position
- Search for best 2D-LDF match
- Recover EAS X_{max} & Energy

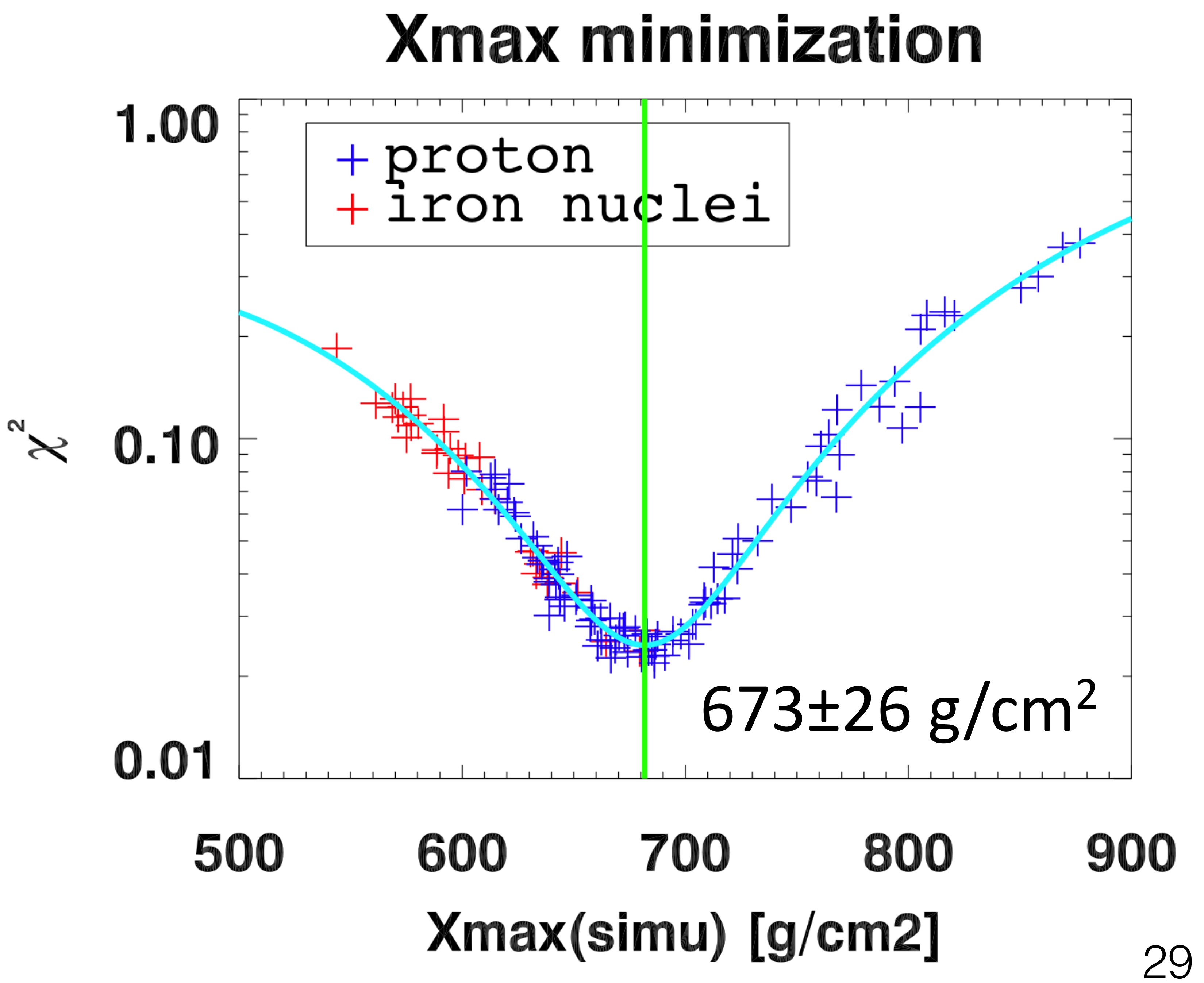
Pure radio method
Talk F. Gaté, thursday











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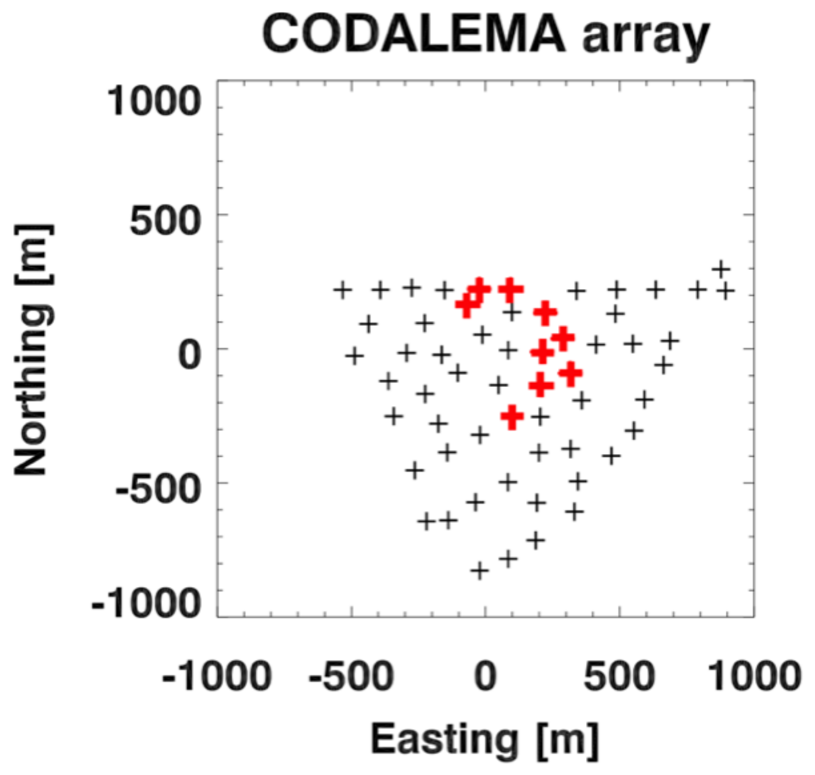
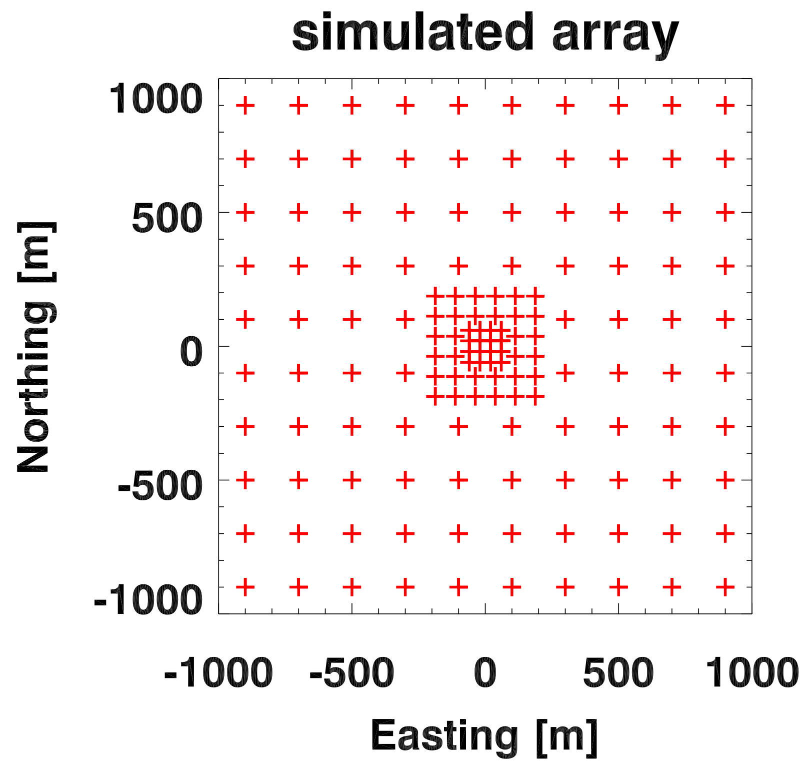
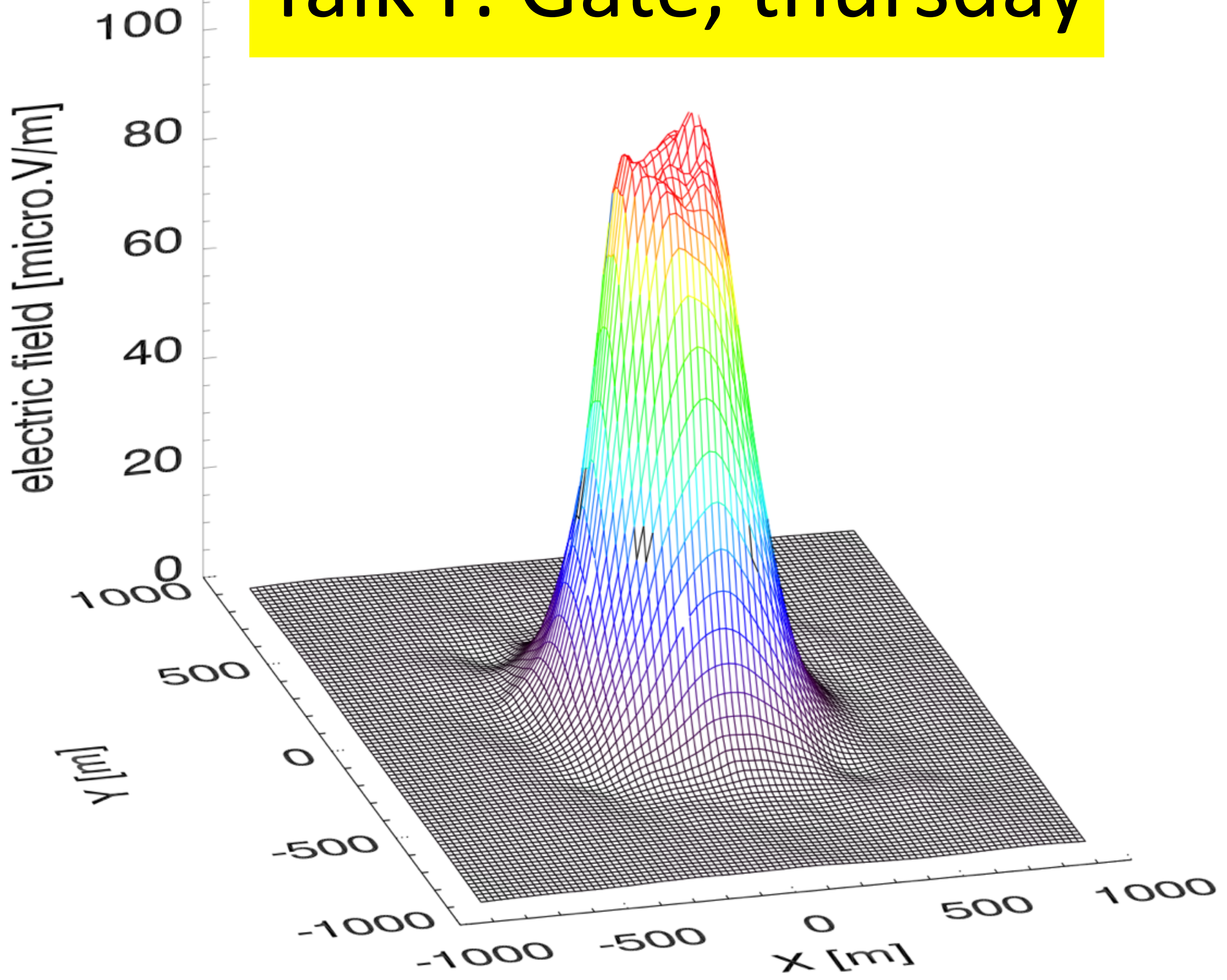
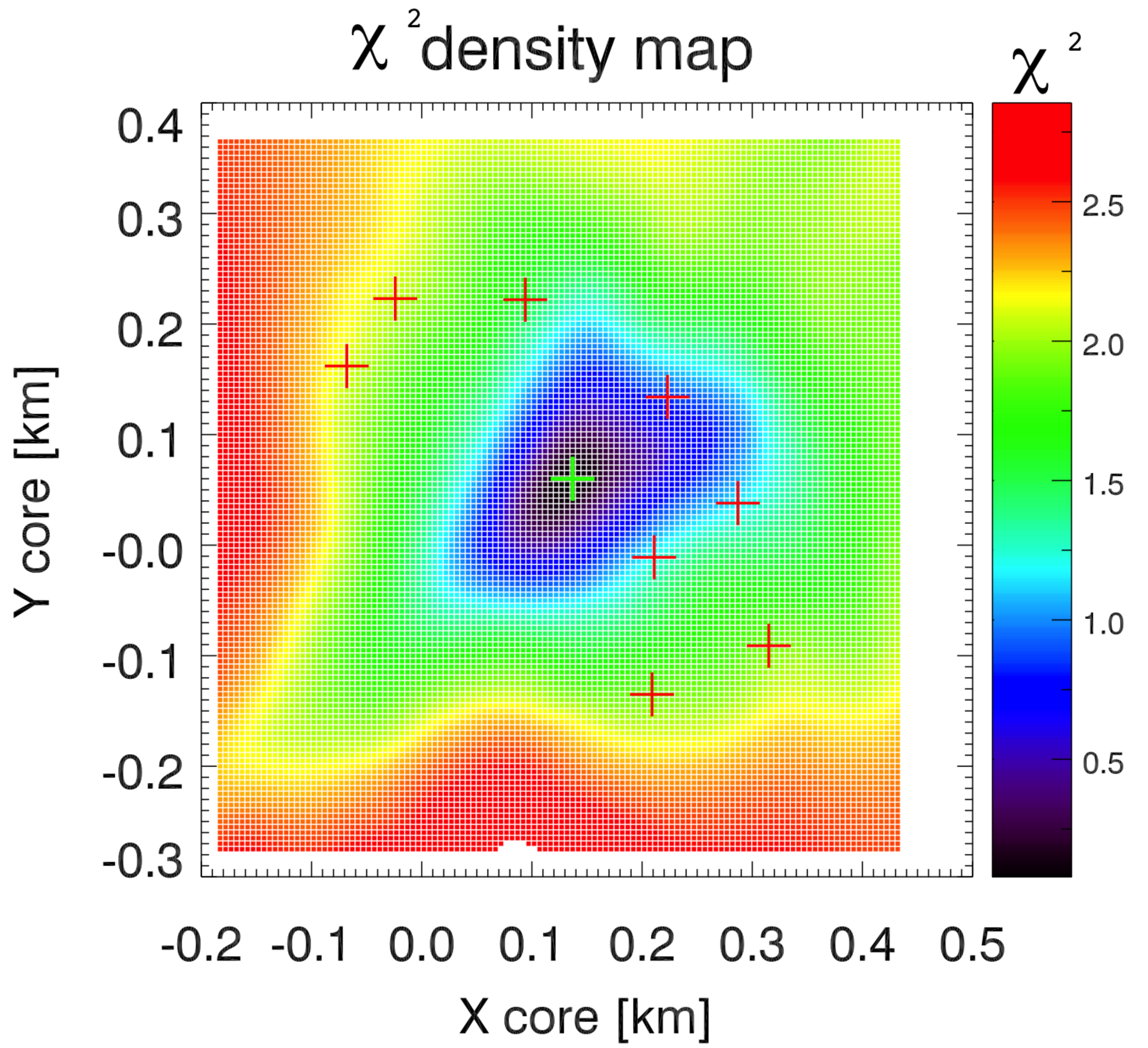
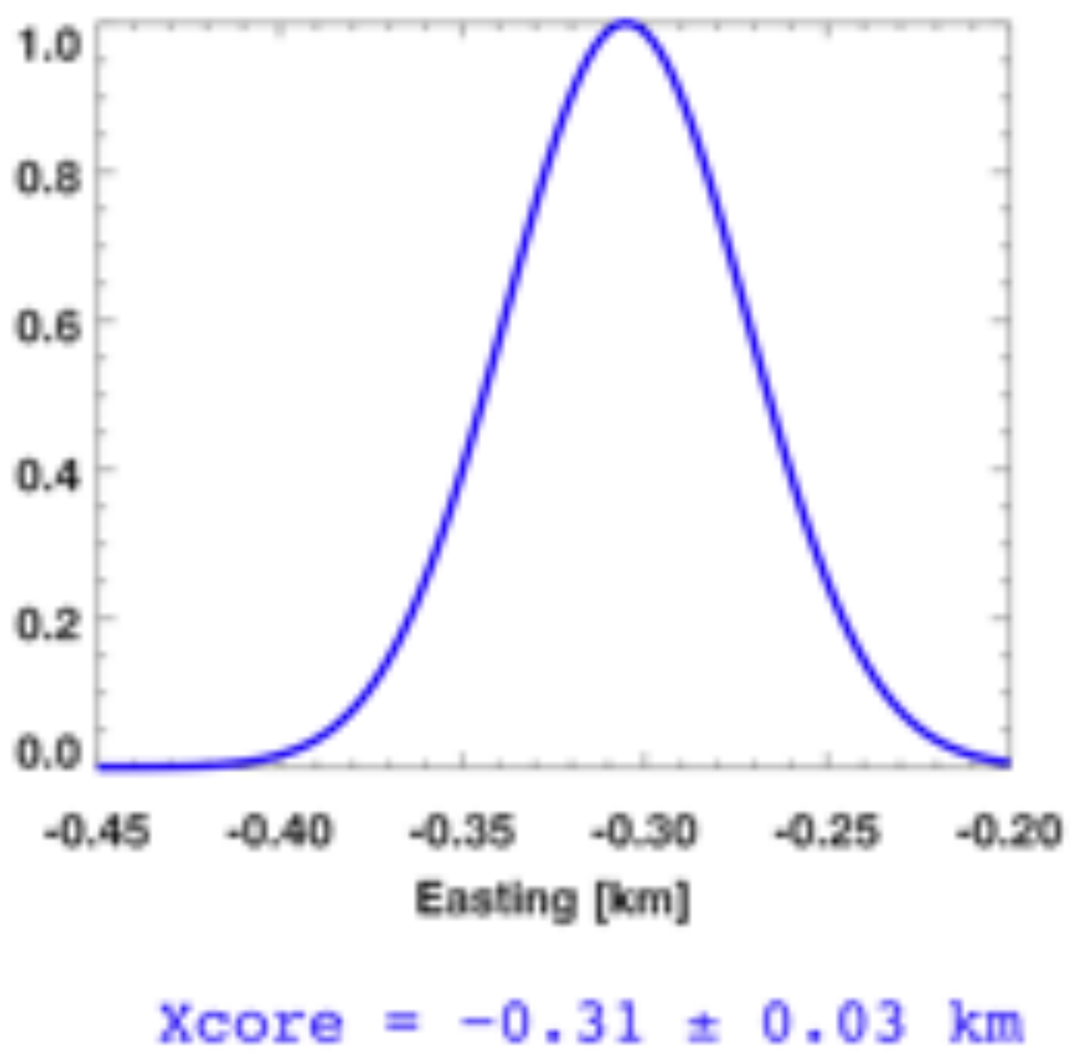


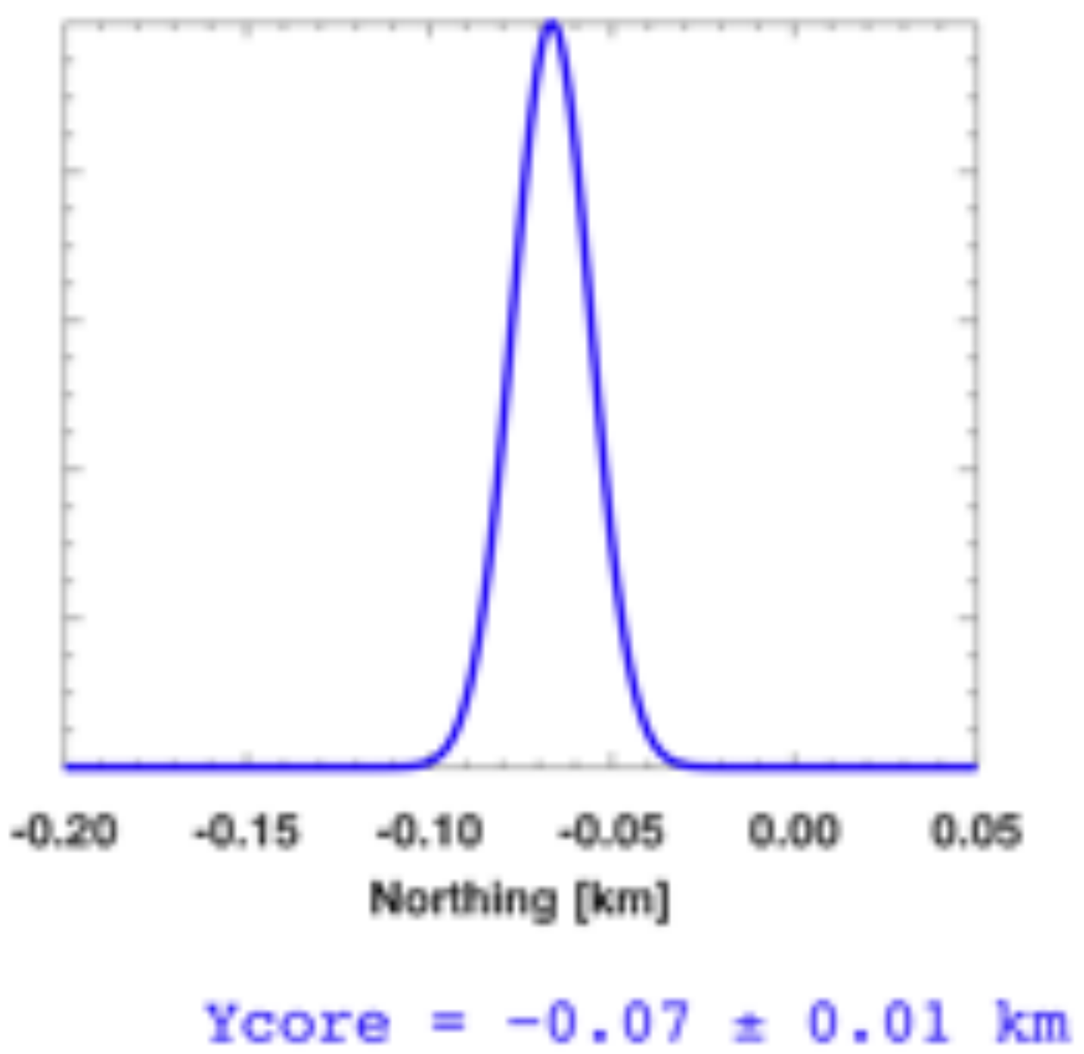




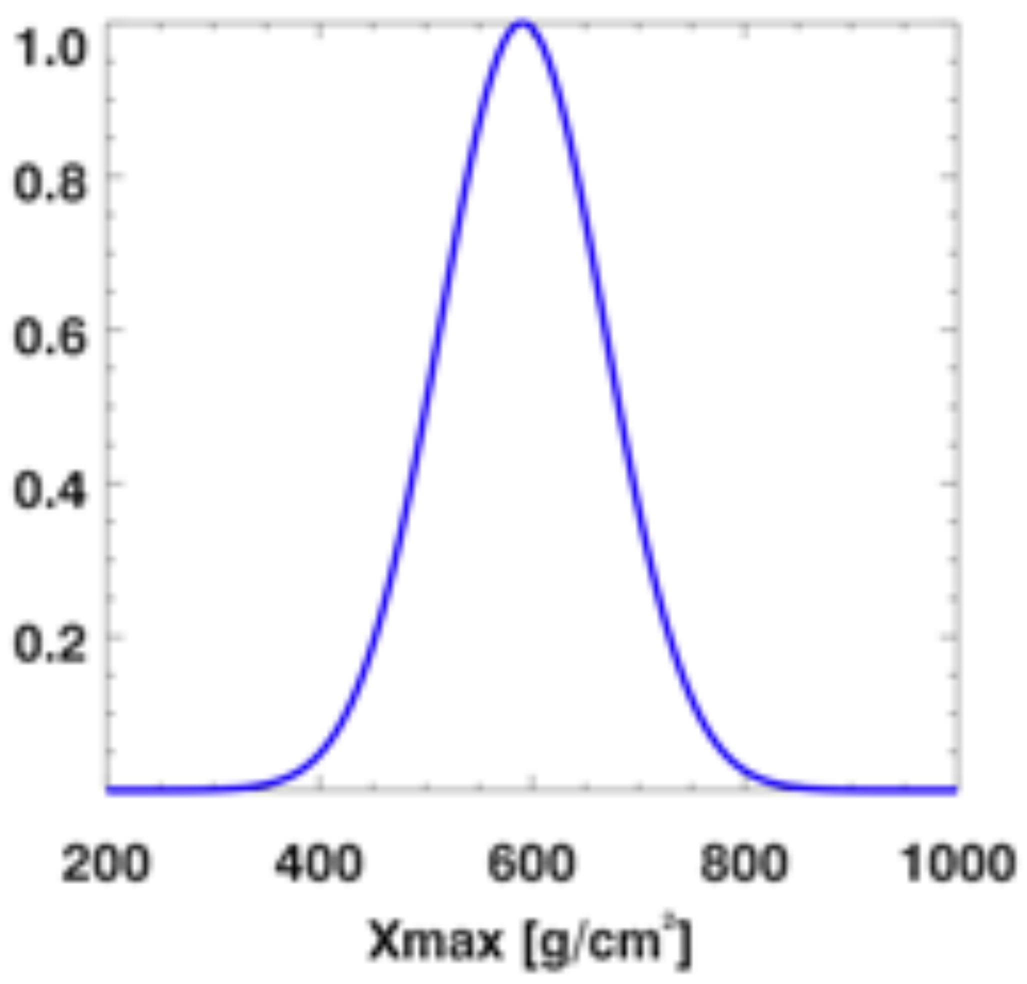


(previous event) Core position

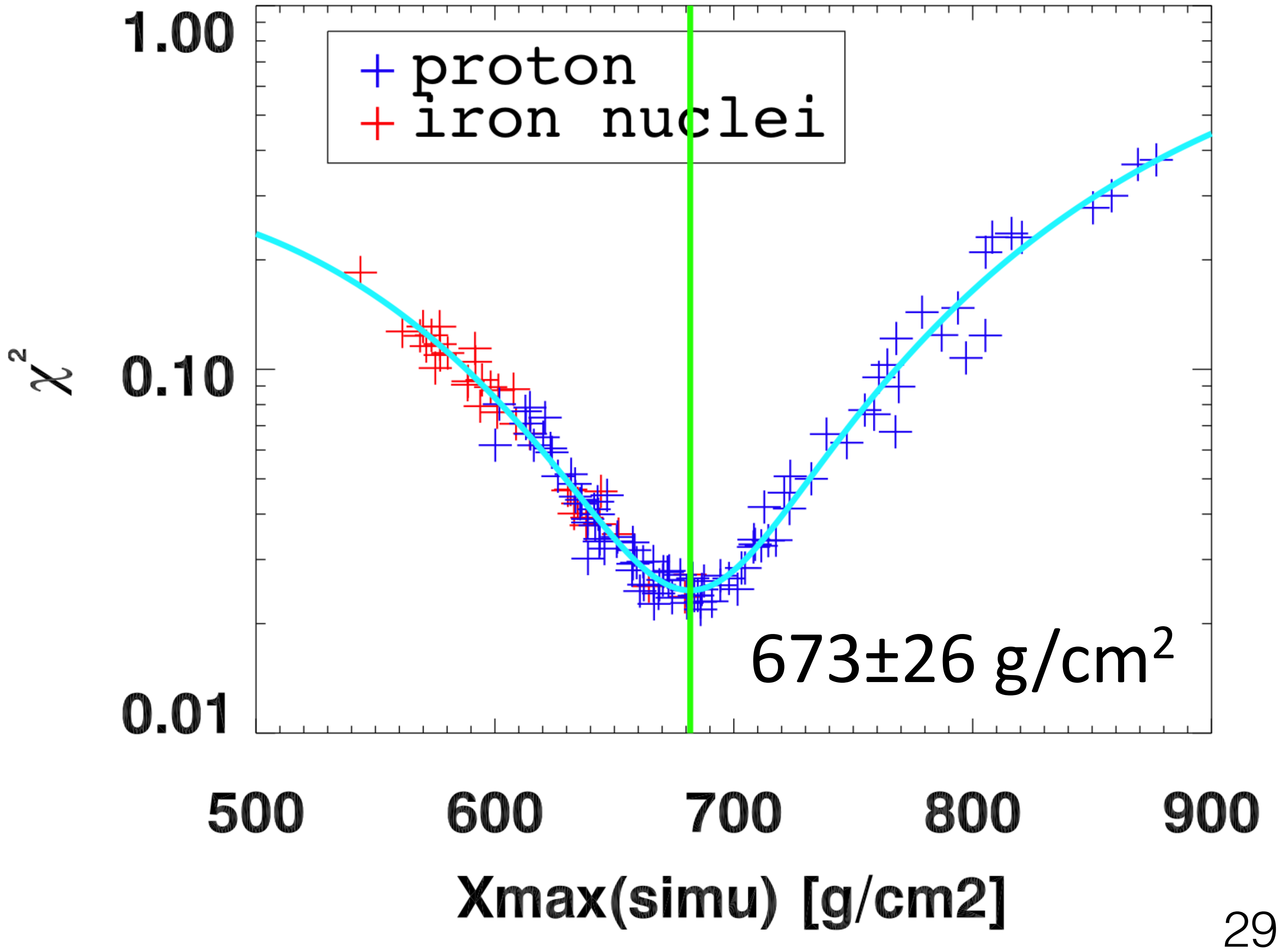




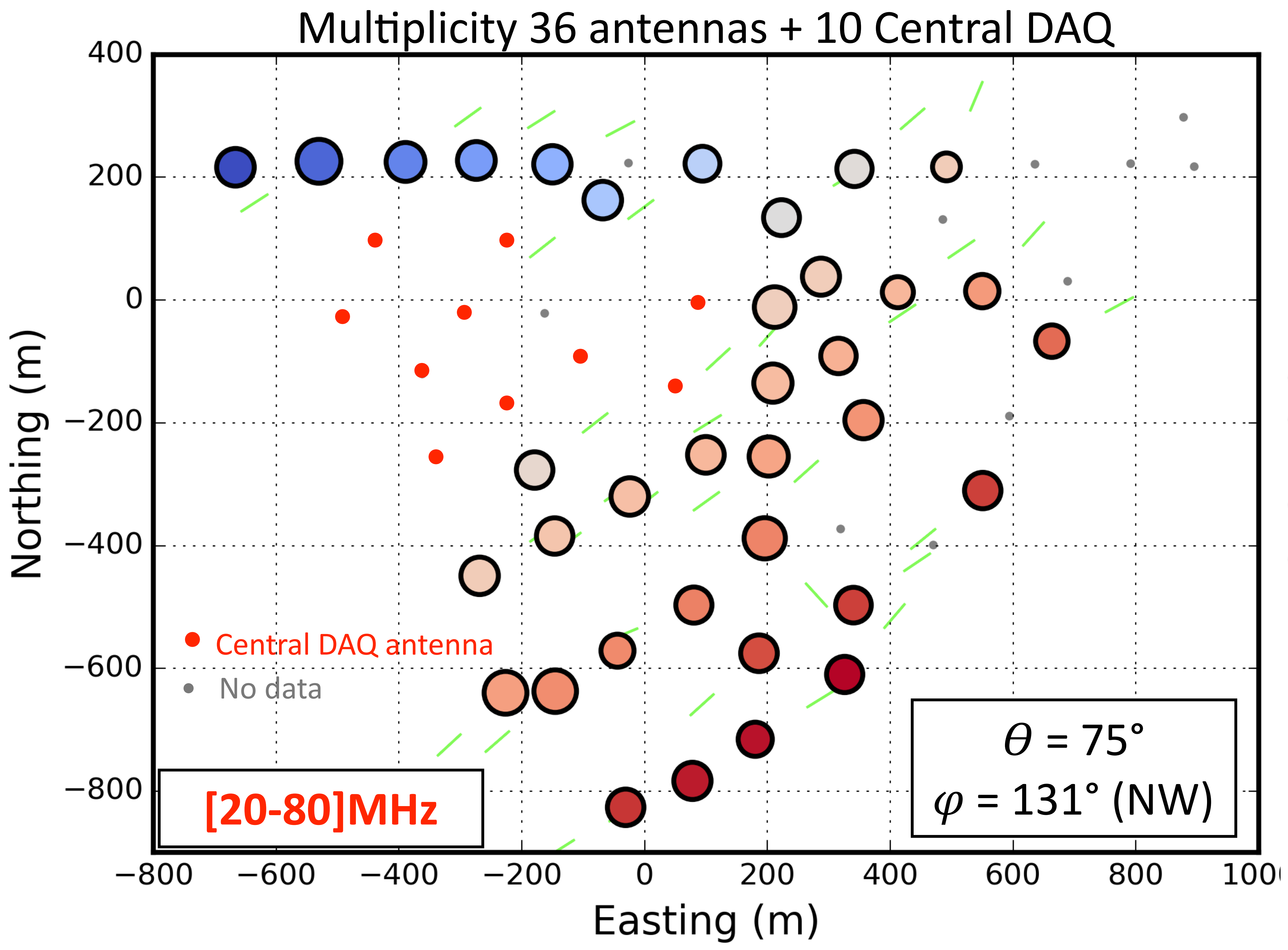
X_{max} = 591 ± 77 g/cm^2



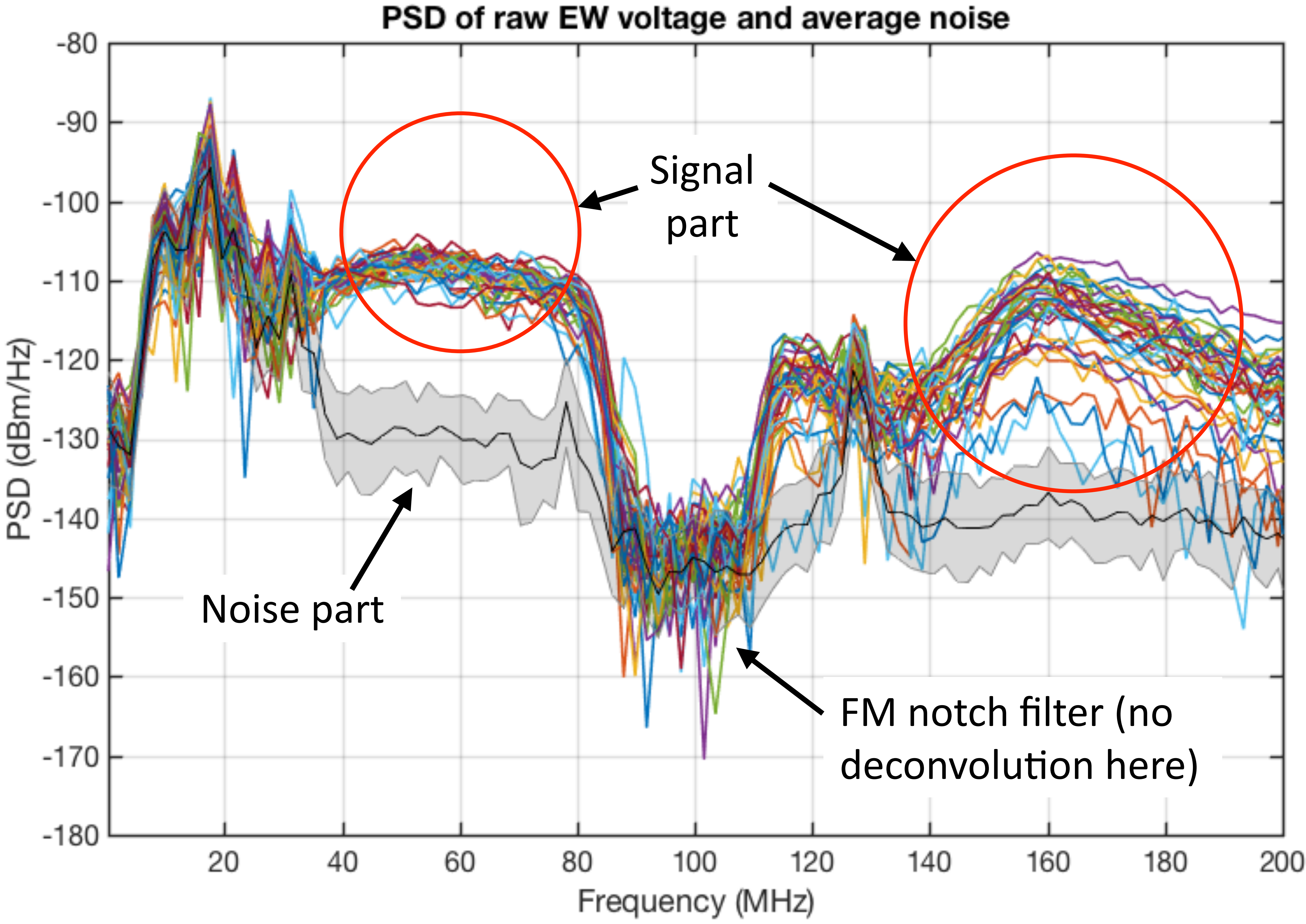
Xmax minimization



Example of high frequency signals



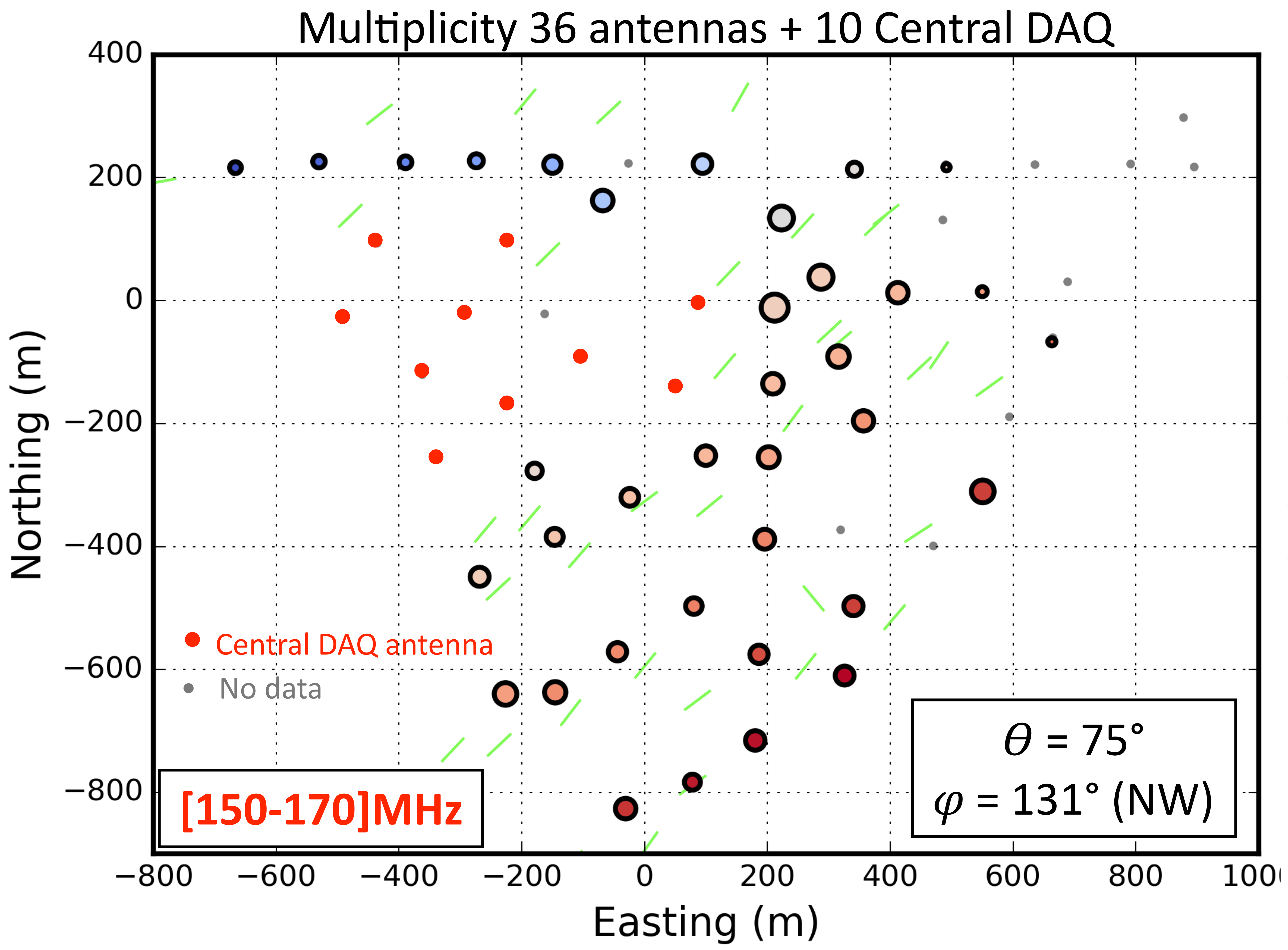
(Central DAQ signals not considered here)



Dependence on distance almost only visible above 150 MHz ⇒

Difficulty to fit a 2D profile in [20-80] MHz ⇒ difficult to get shower parameters (core, Xmax, energy) for inclined showers

Example of high frequency signals



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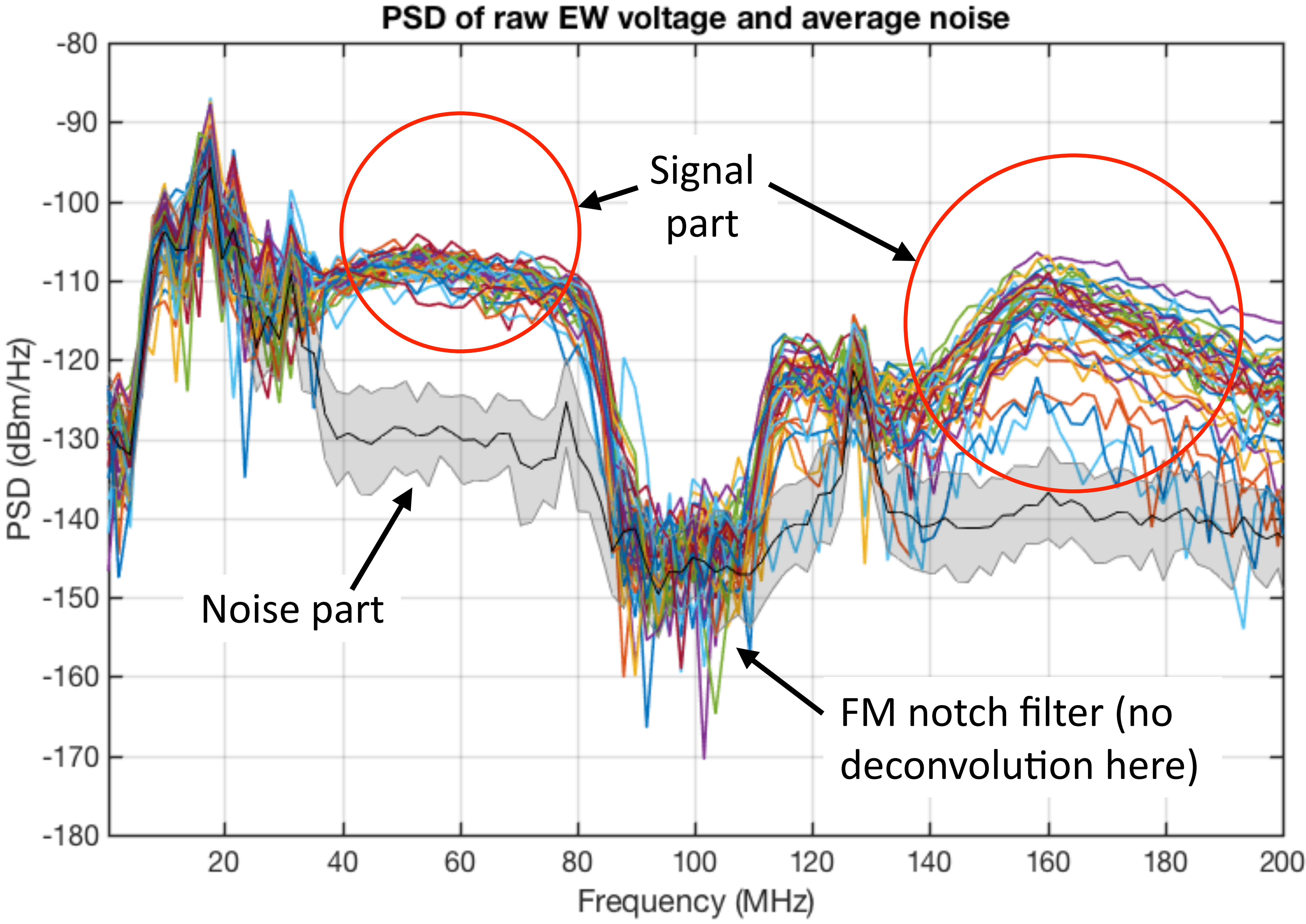
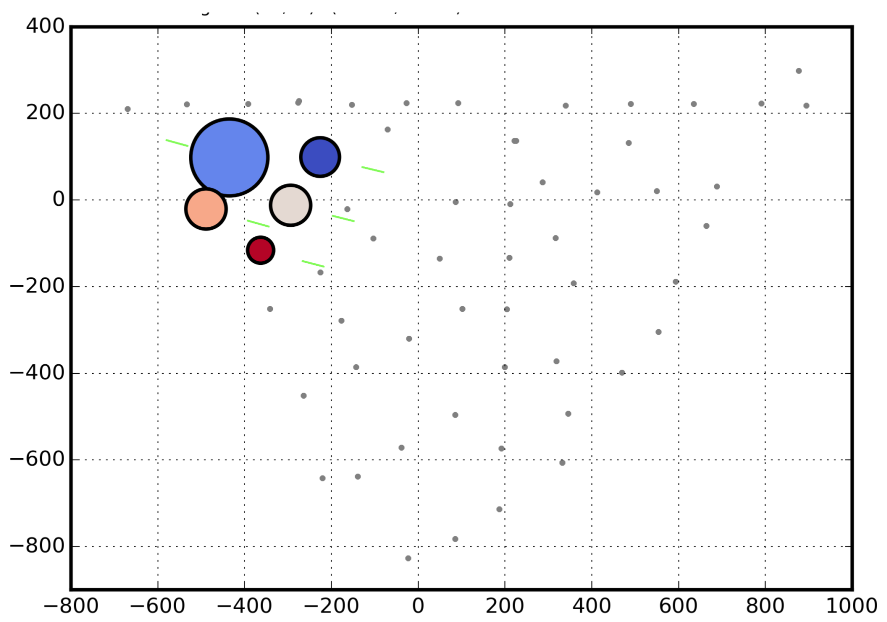


Dependence on distance almost only visible above 150 MHz ⇒

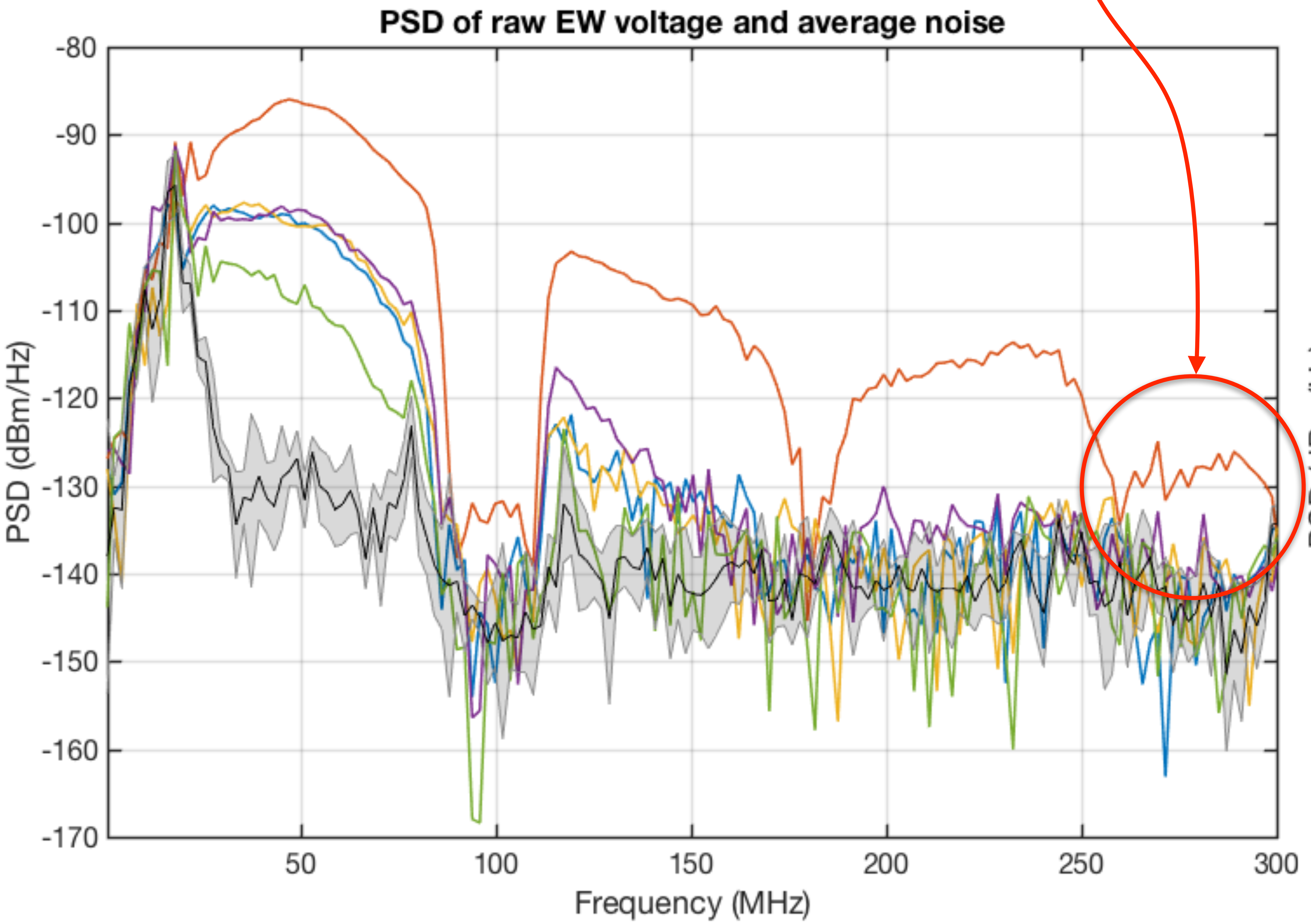
Difficulty to fit a 2D profile in [20-80] MHz ⇒ difficult to get shower parameters (core, Xmax, energy)

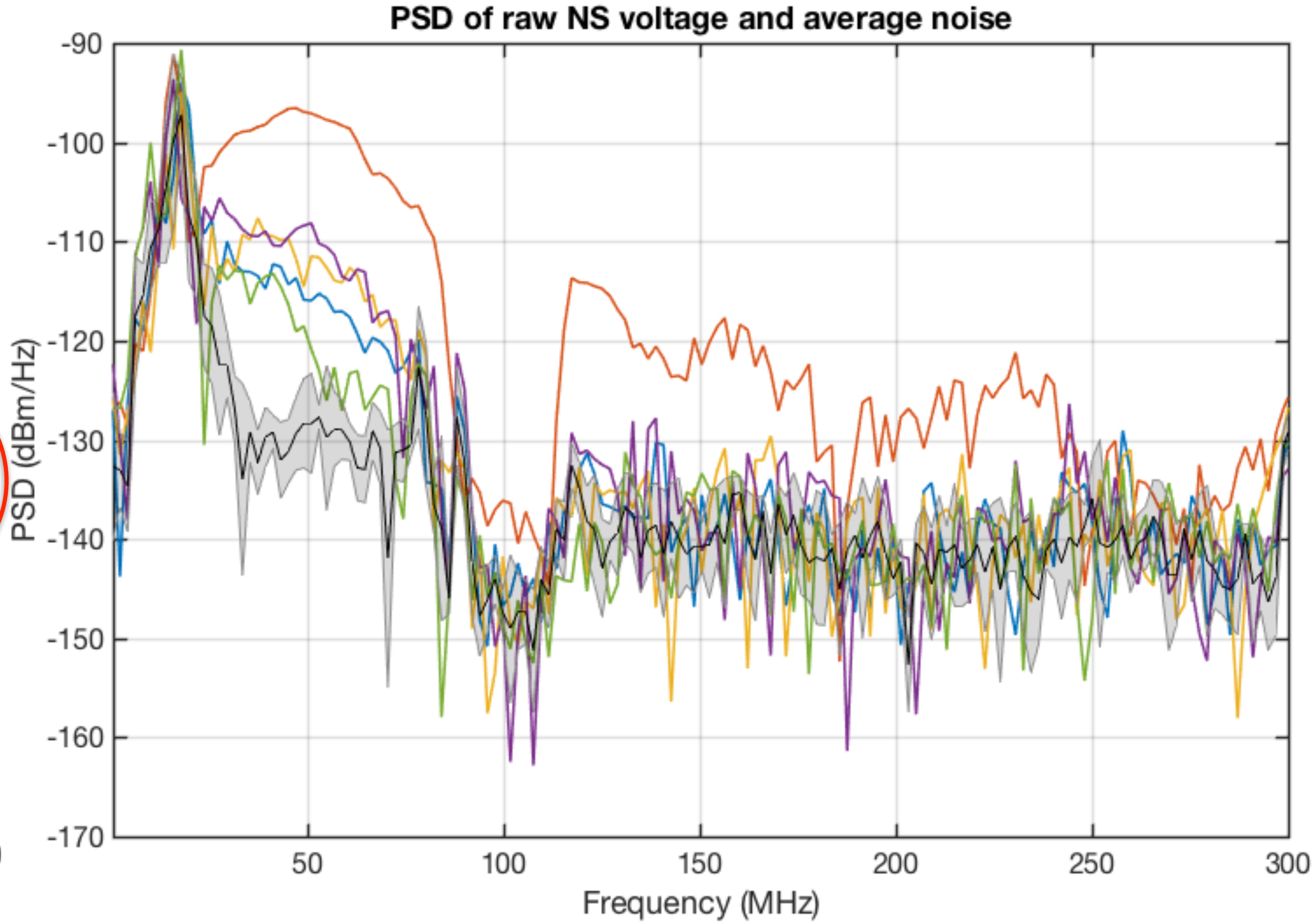
for inclined showers, while with high frequencies smaller antenna density could be enough

Even up to 300 MHz…

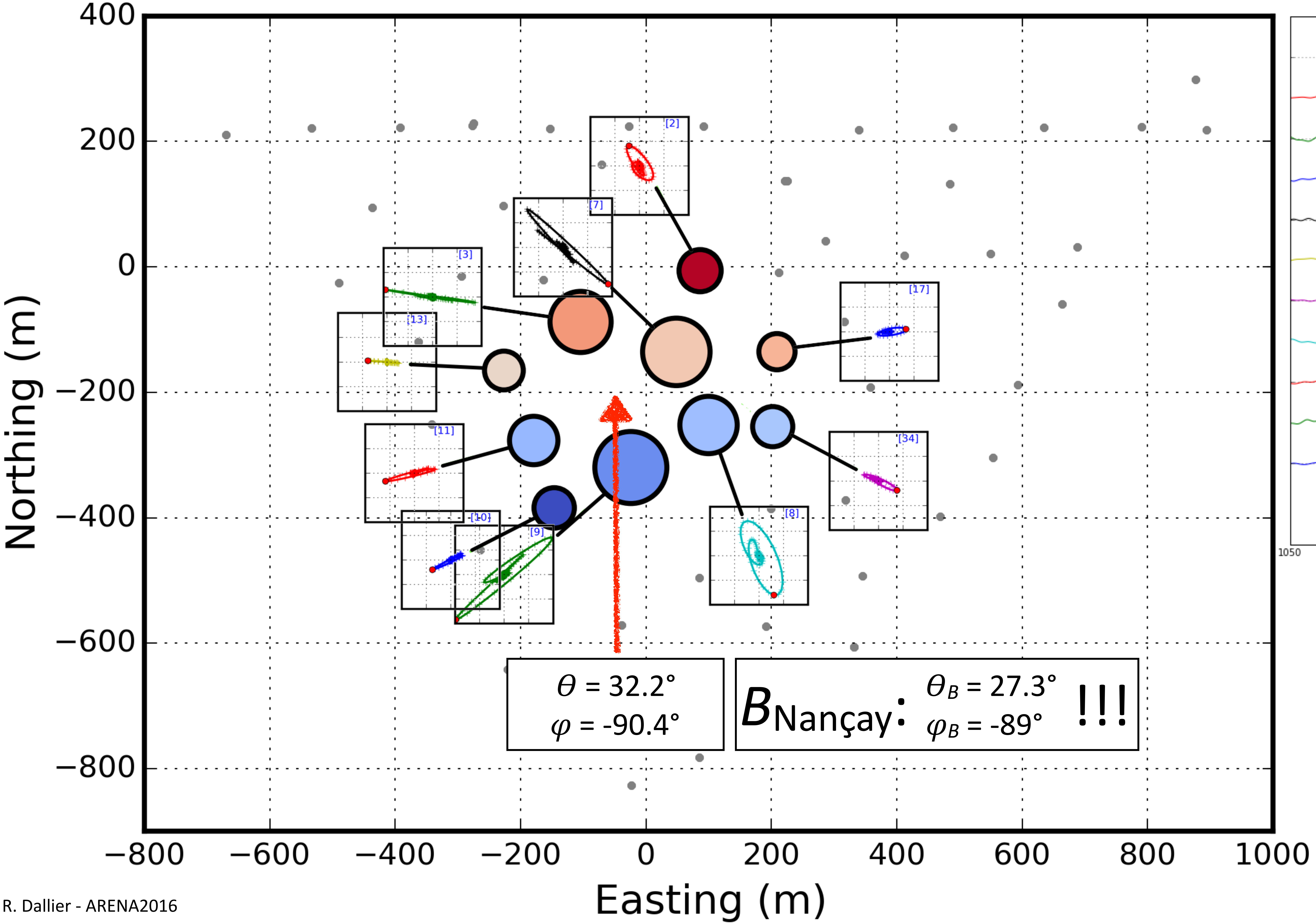


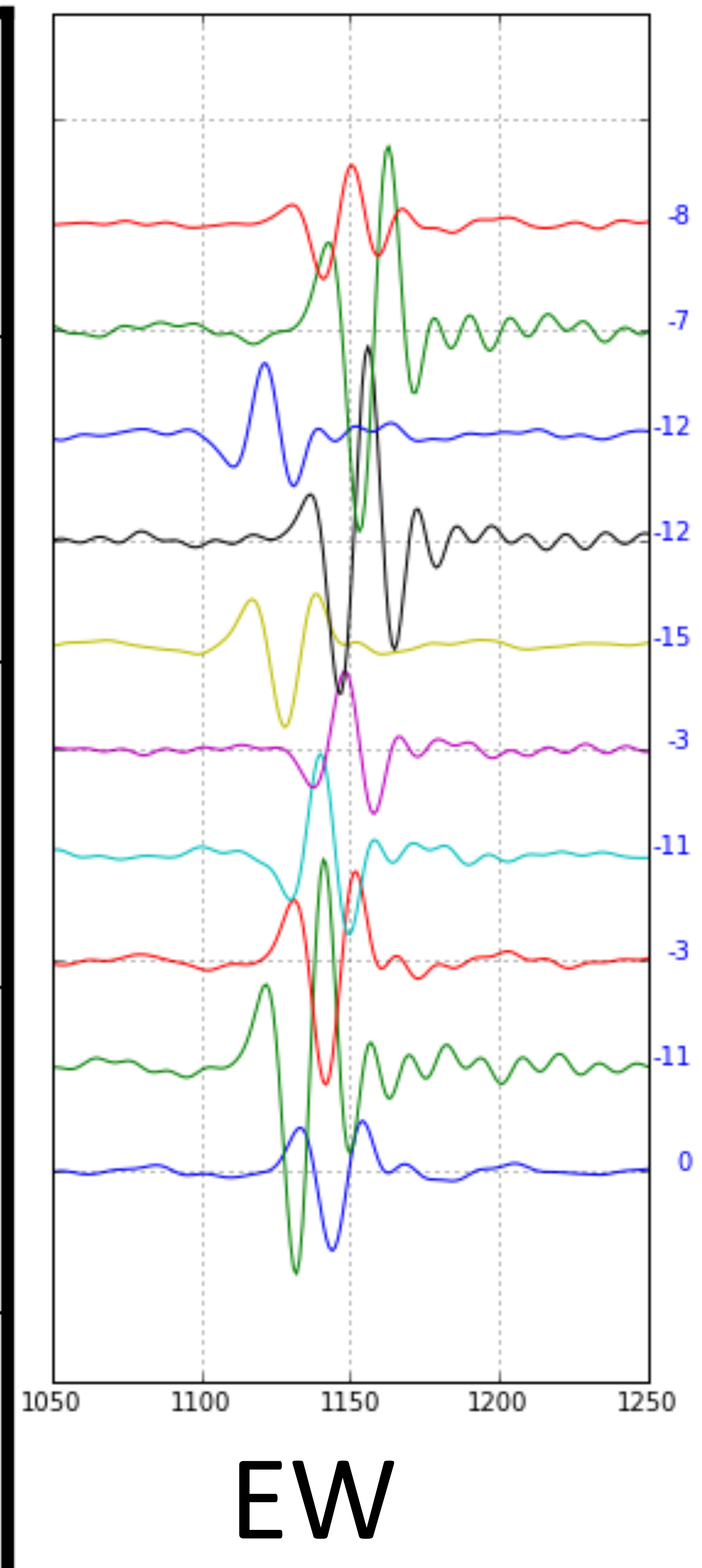
Currently the antenna response is known only up to 200 MHz, but it could be parameterized up to 300 MHz where there is still signal. Potential instantaneous band would be [20-300] MHz !

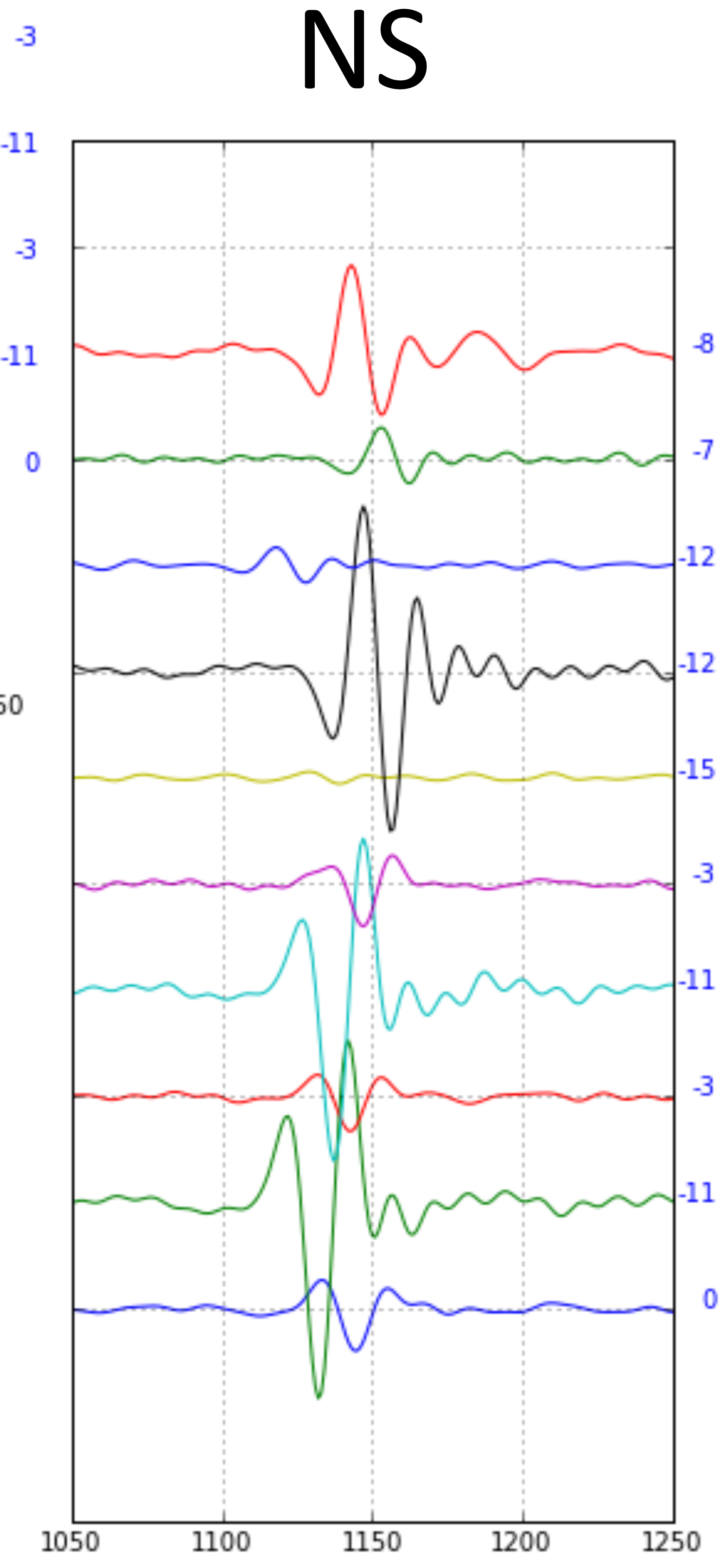




A pure charge excess event



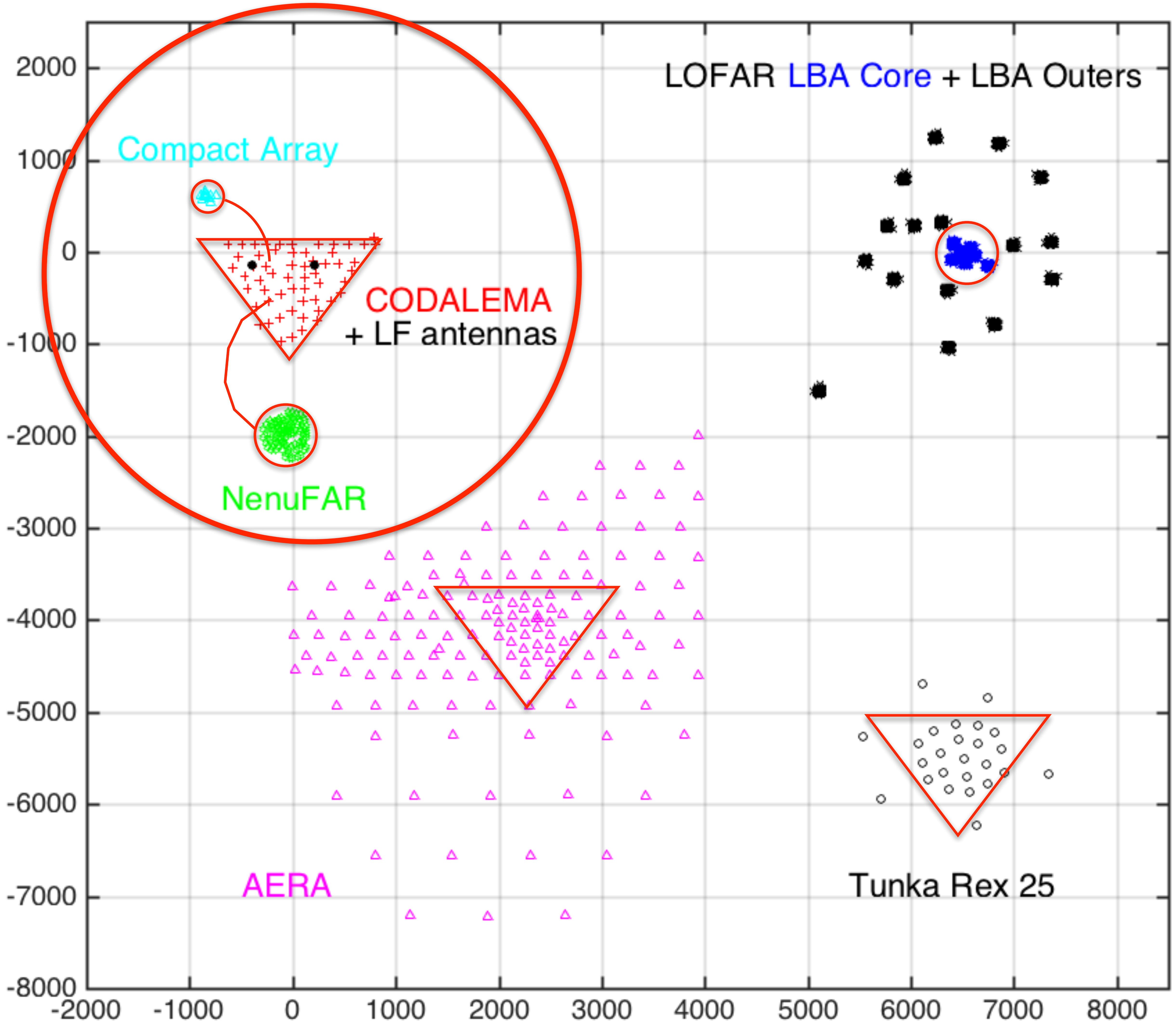


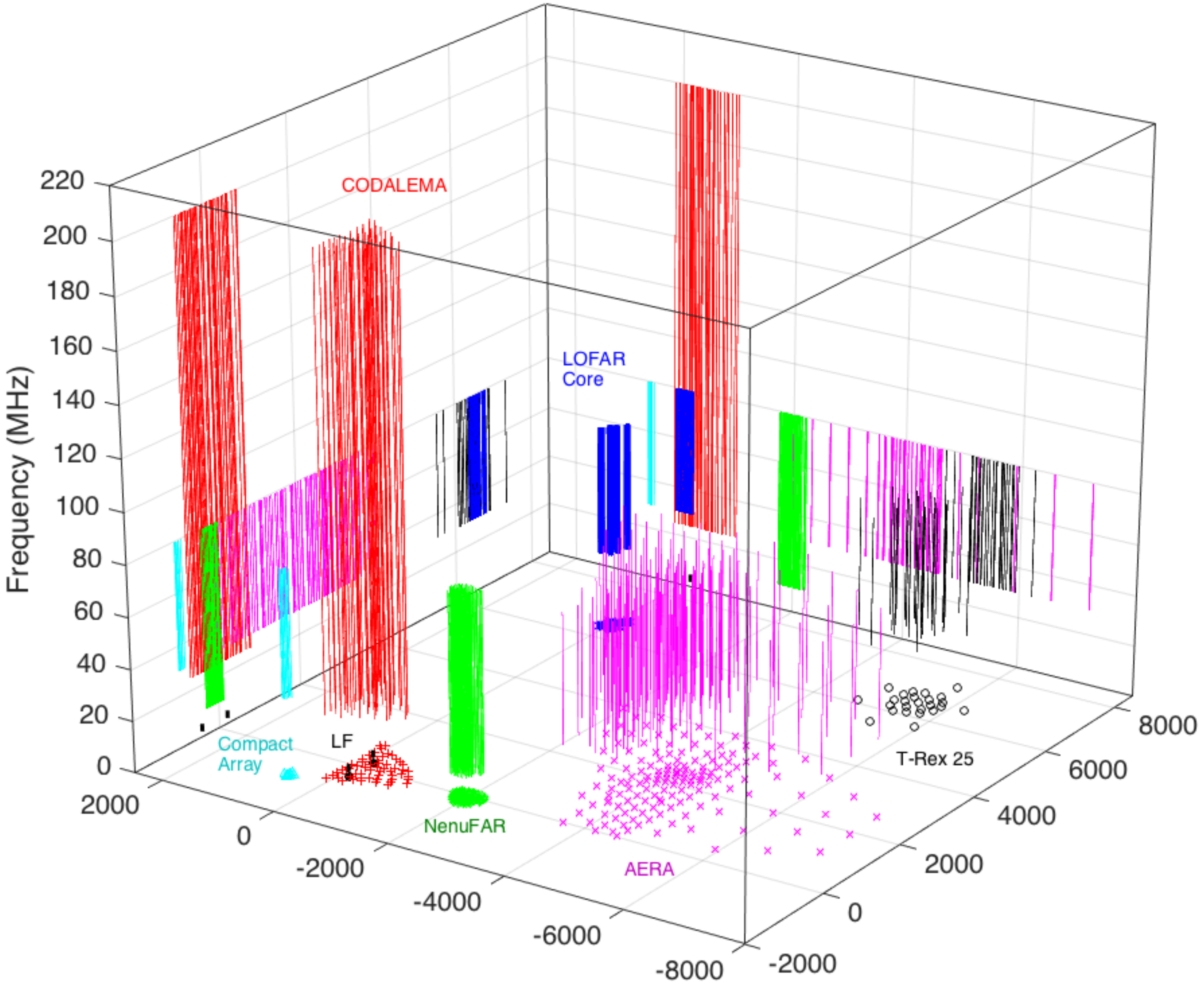


Outlook

Current or foreseen UHECR / Neutrino radio detection projects

Nançay facilities: a swiss-knife for UHECR radio detection





- Unique wide frequency band (2 - 200 MHz)
- Multi-scale antenna densities
- Test bench for future projects (e.g SKA, see T. Huege's talk on friday)
- **Anyone interested is welcome !**