

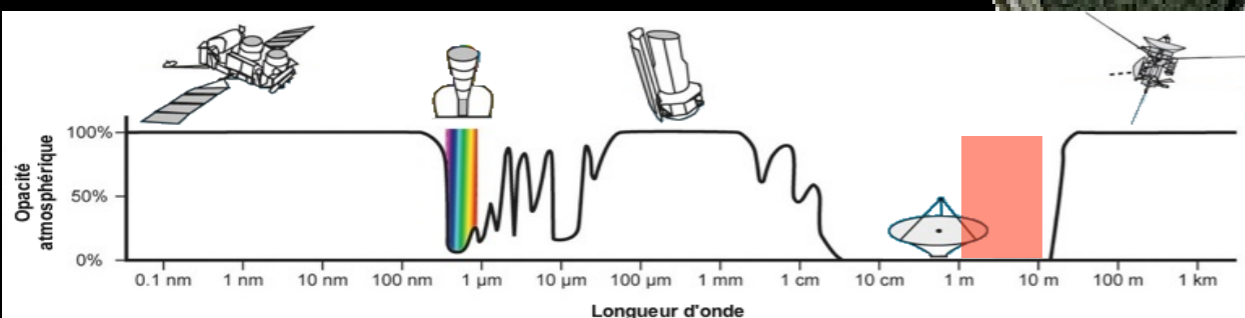
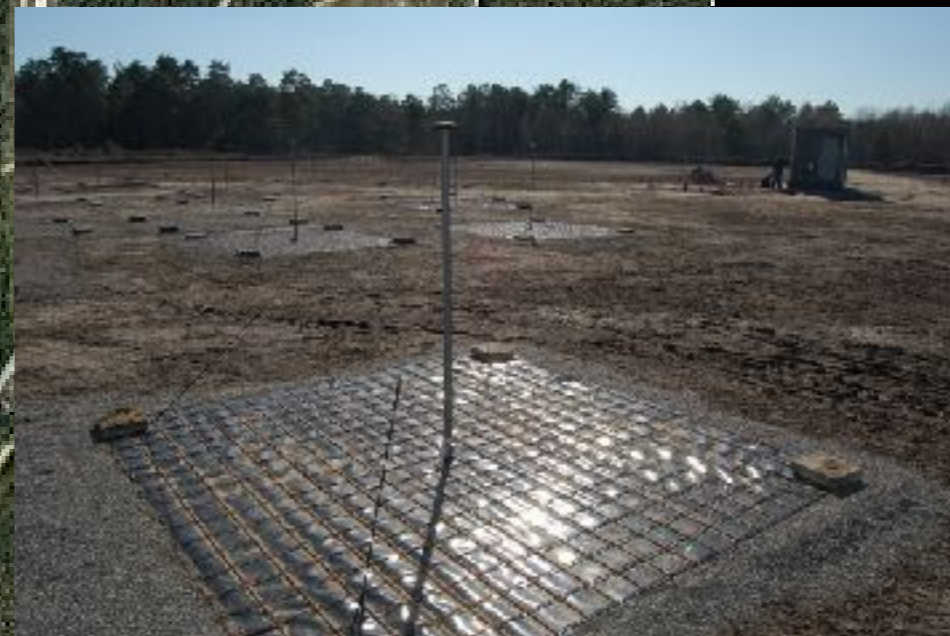
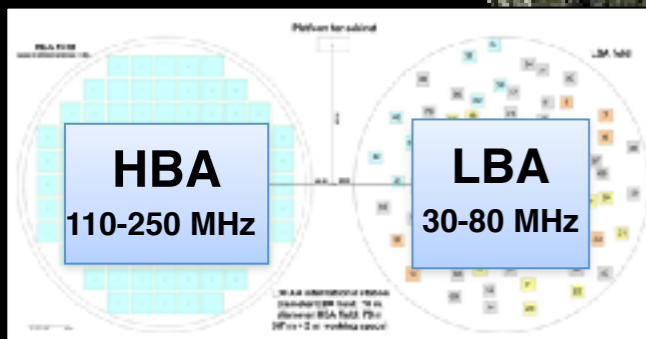
# *NenuFAR* *in 2021*

**Philippe Zarka**

*Observatoire de Paris, CNRS, PSL*

**and the NenuFAR team**

# LOFAR station in Nançay since 2010



# International LOFAR Telescope (ILT)

1<sup>st</sup> SKA pathfinder (30-250 MHz)

Birr



Chilbolton



Dutch stations

LOFAR Core (NL)

Jülich

Effelsberg



Norderstedt

Tautenburg

Unterweilenbach



Onsala



Potsdam



Baldy

Łazy



Nancay



ION

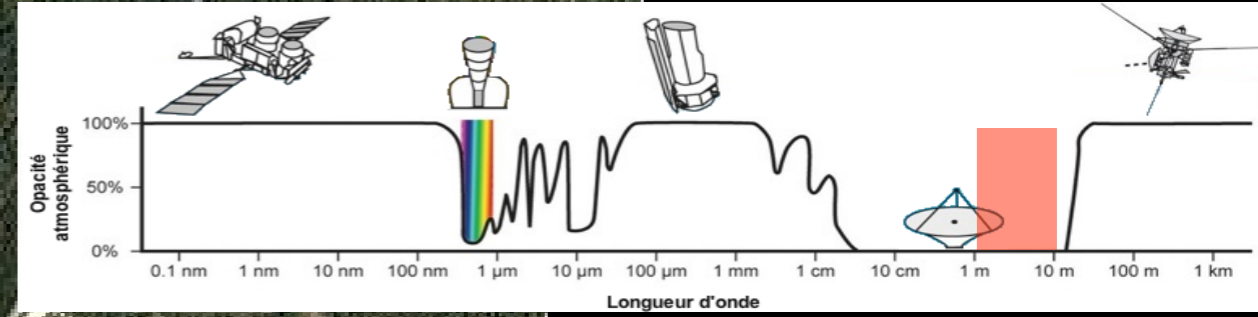
Netherlands Institute for Radio Astronomy



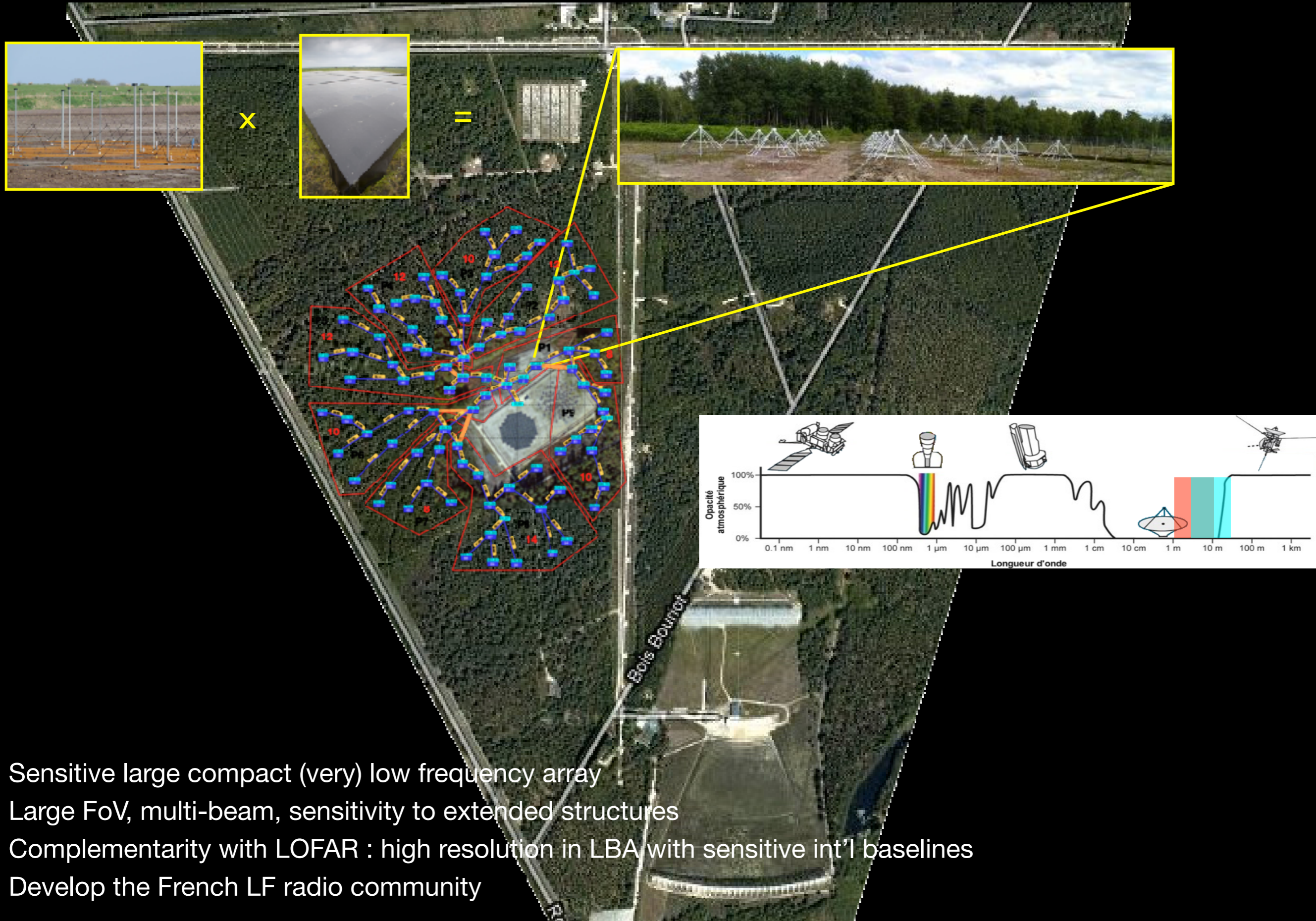
# NenuFAR : initial project = LOFAR Super Station



# From LOFAR to ...

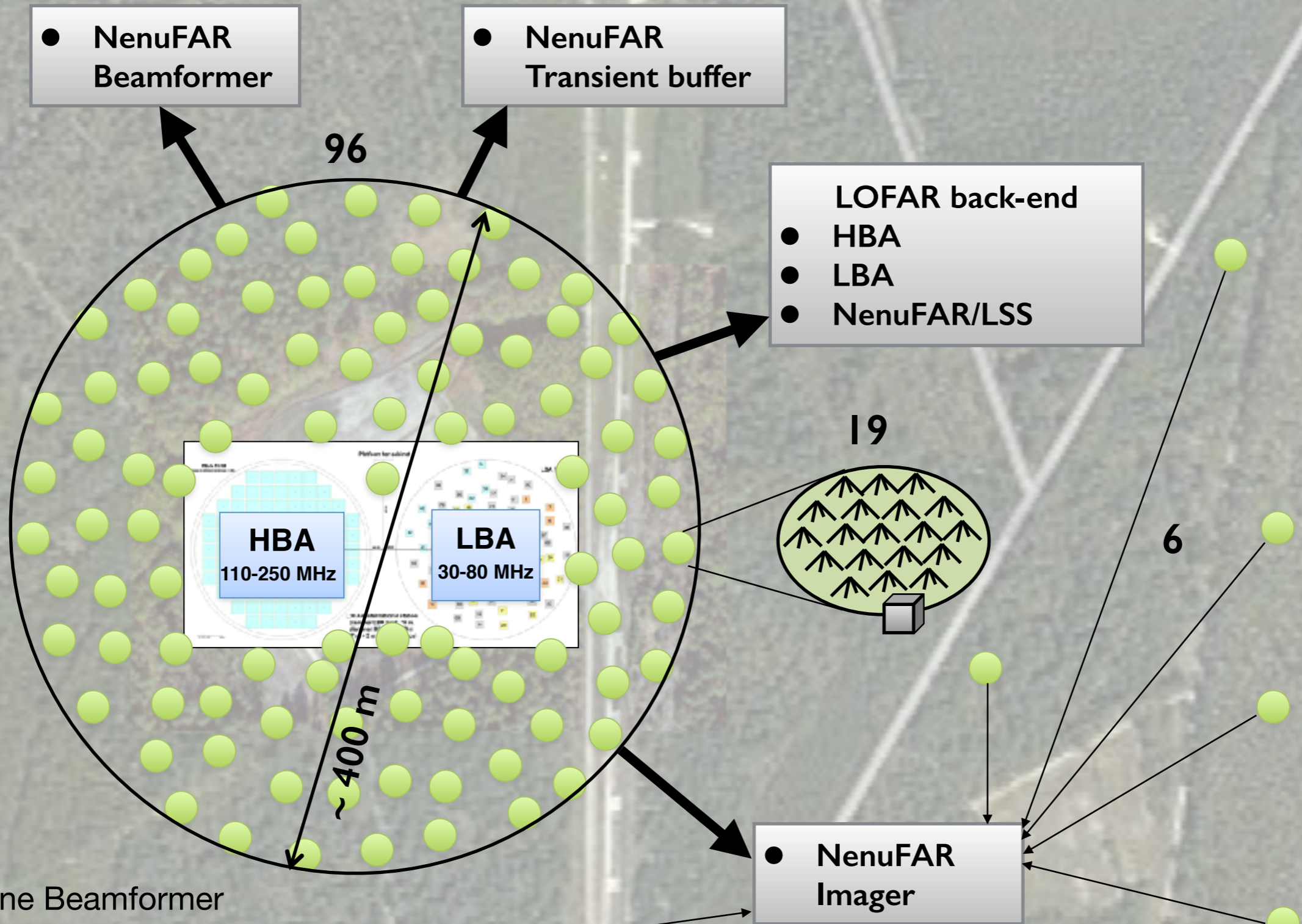


# ... NenuFAR (New extension in Nançay upgrading LOFAR)



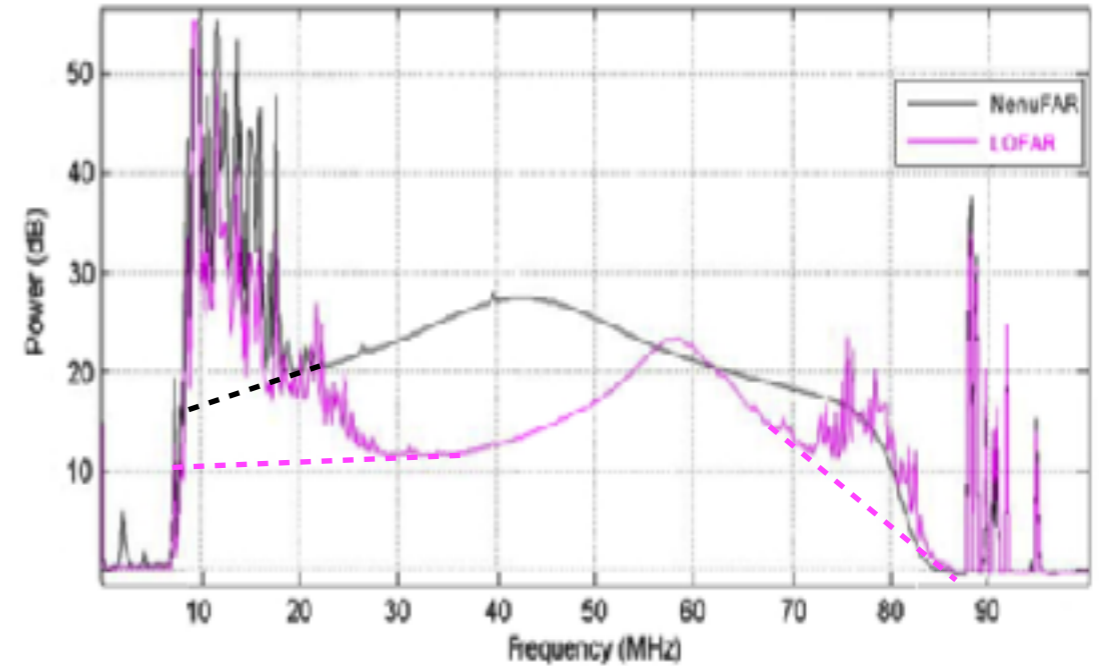
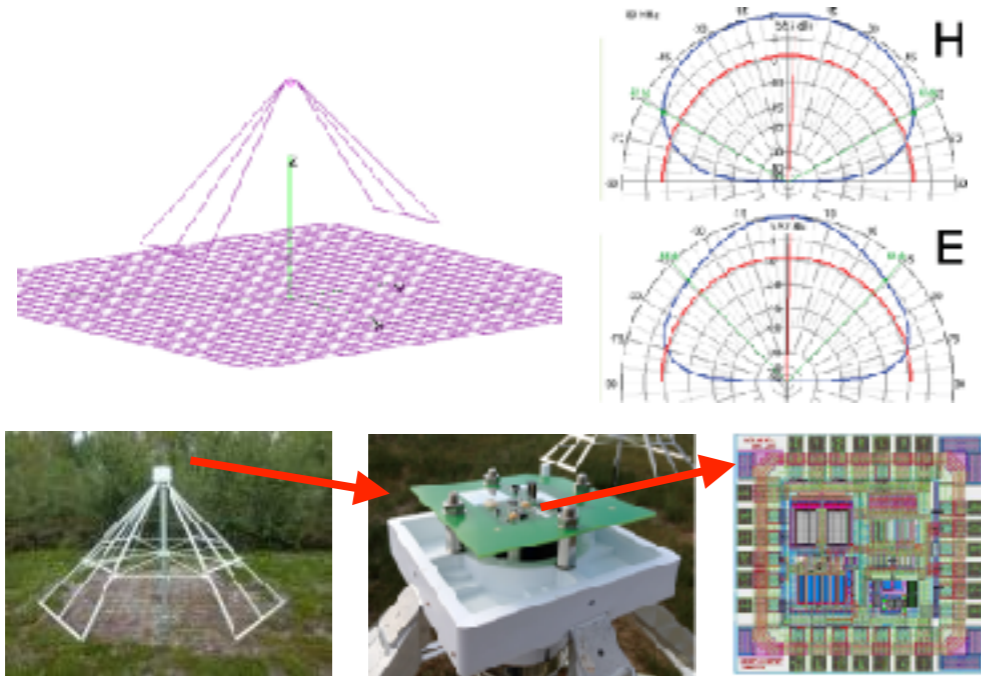
- Sensitive large compact (very) low frequency array
- Large FoV, multi-beam, sensitivity to extended structures
- Complementarity with LOFAR : high resolution in LBA with sensitive int'l baselines
- Develop the French LF radio community

# NenuFAR : SKA pathfinder in the range 10-85 MHz



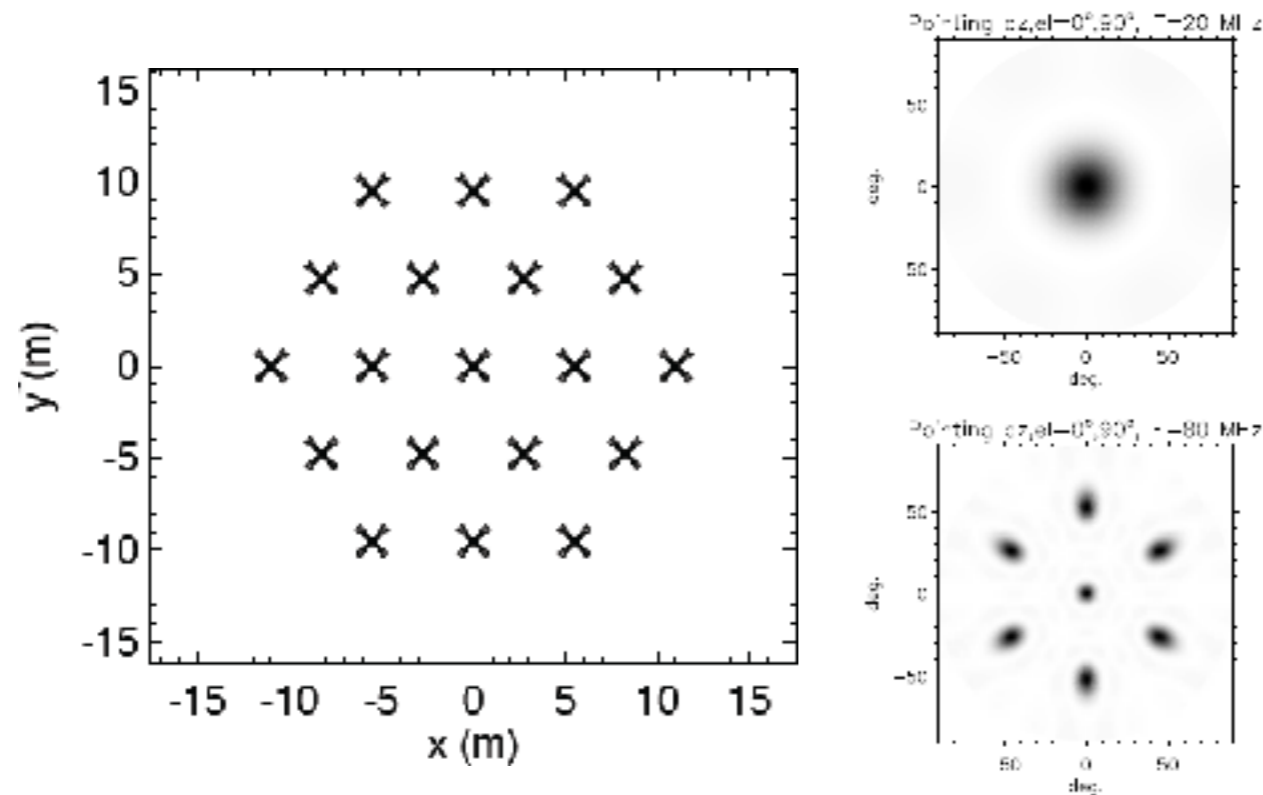
- Standalone Beamformer
- Standalone Imager
- Standalone Waveform (transient) capture
- With LOFAR : LSS + short baseline visibilities

# Sensitive antenna + preamplifier



[Girard, 2013 ; Charrier et al., 2007, 2015]

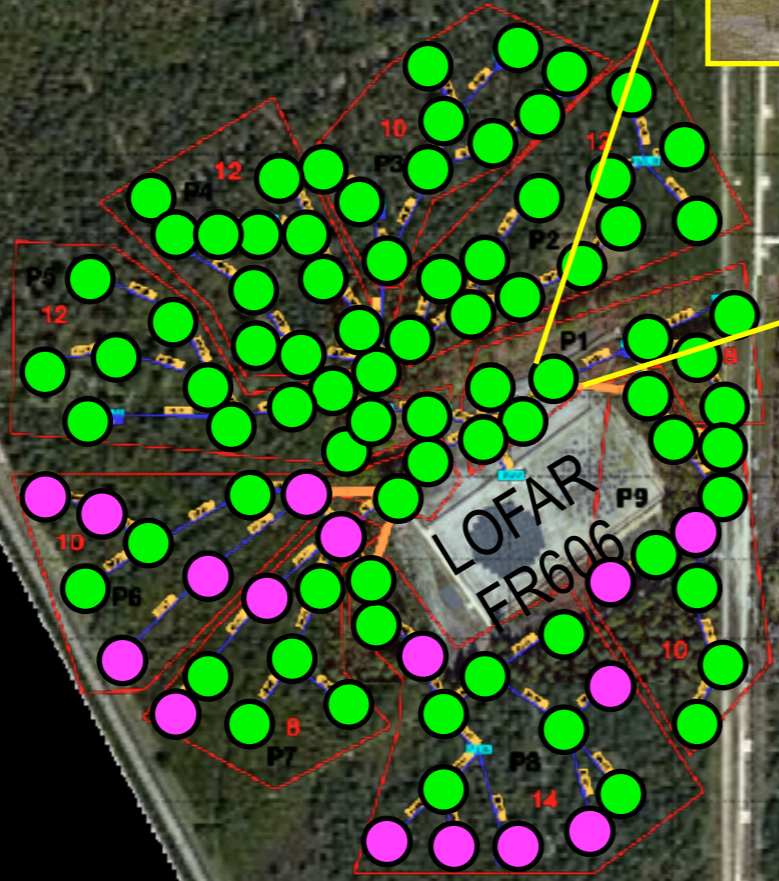
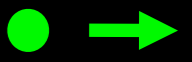
# 19-antenna analog-phased Mini-Array



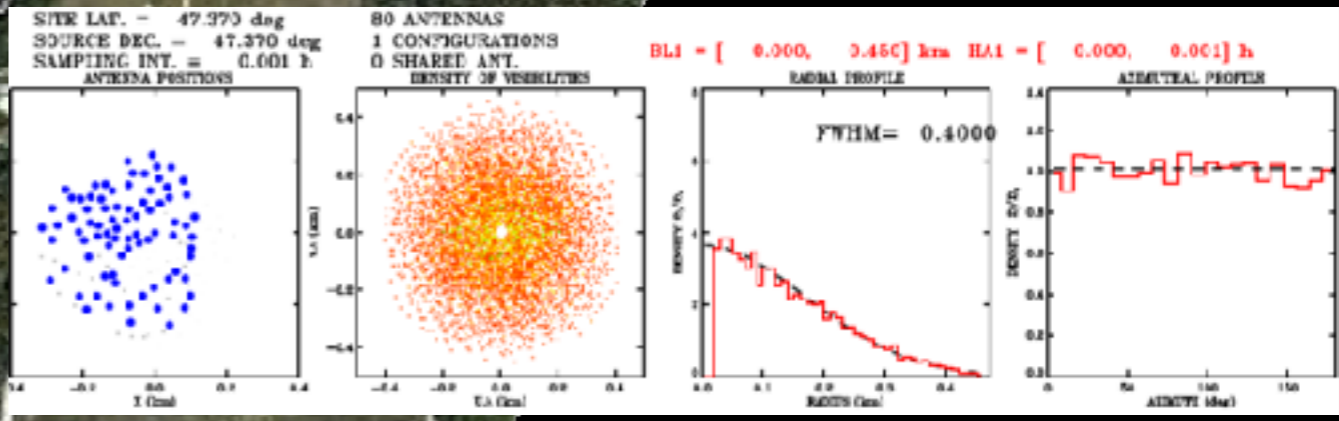
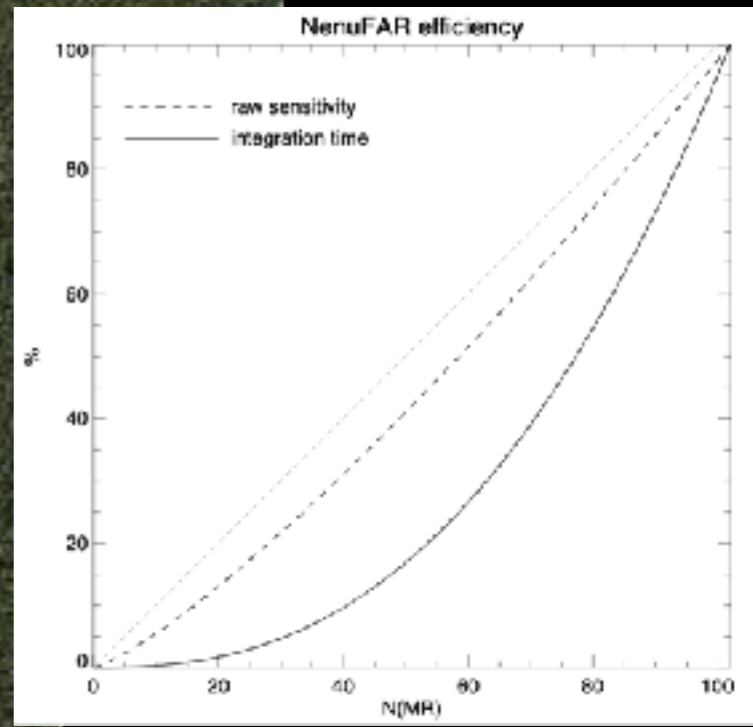
[Girard & Zarka, in prep]



# Mini-Array distribution : core

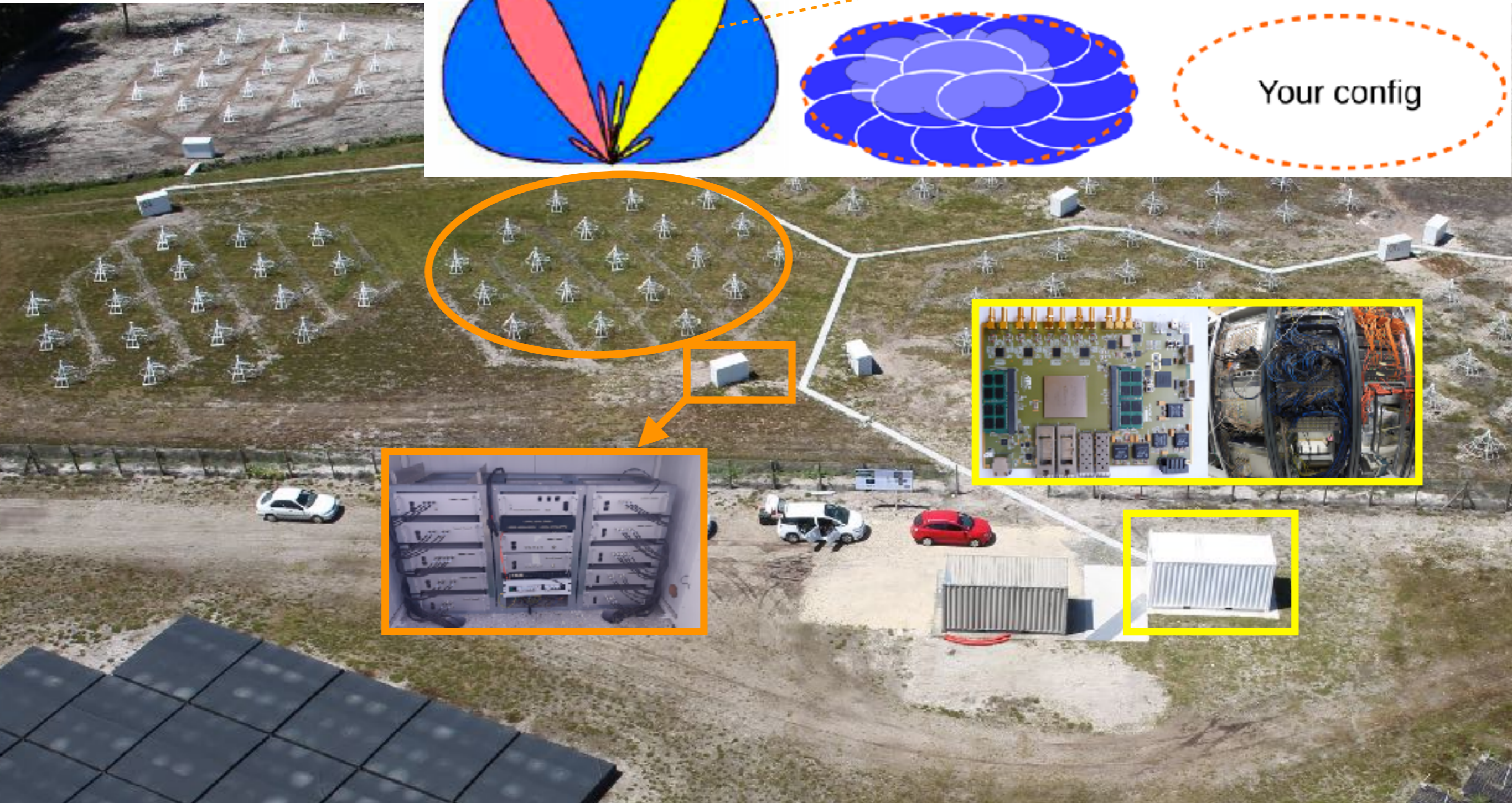


- operational
- to be built

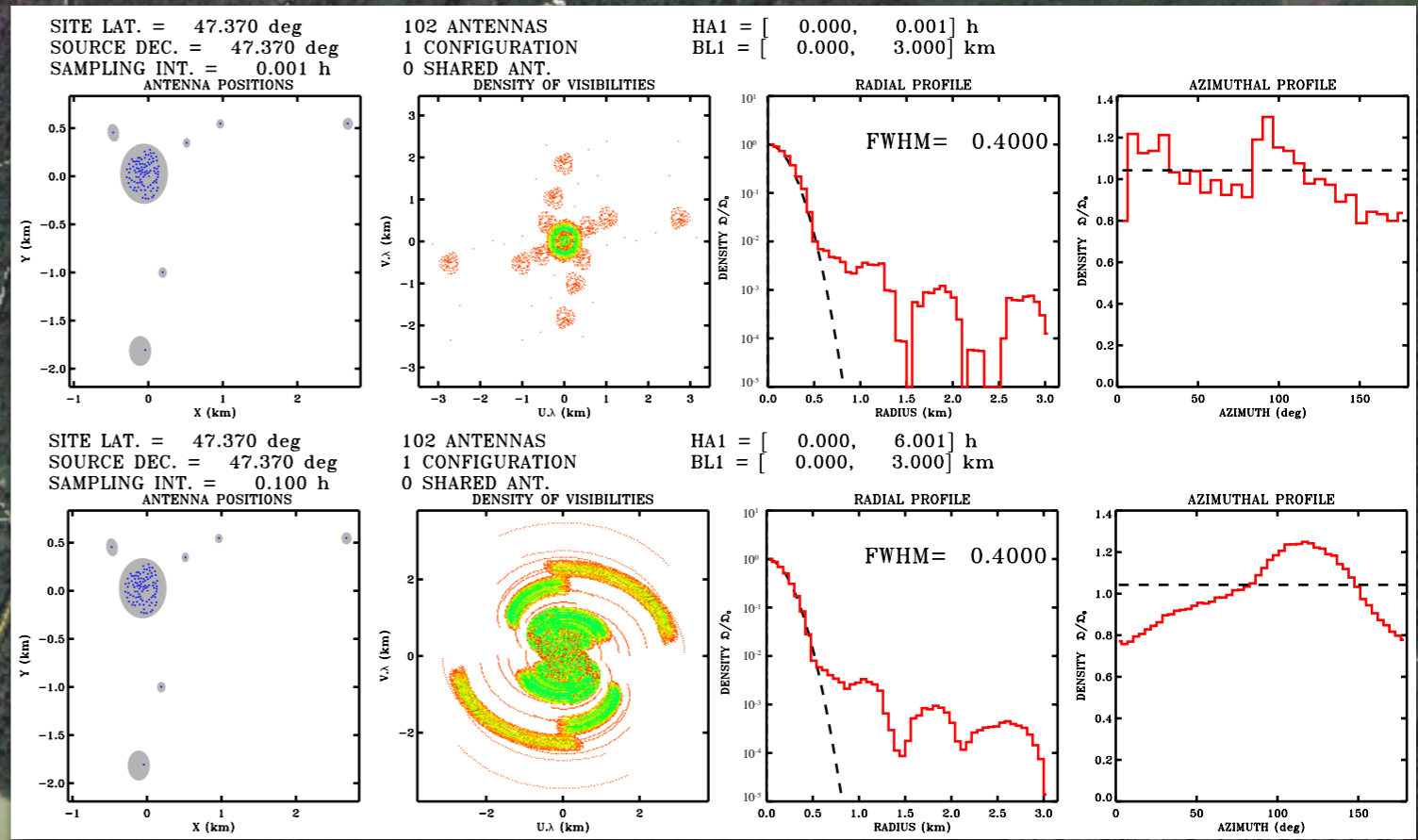
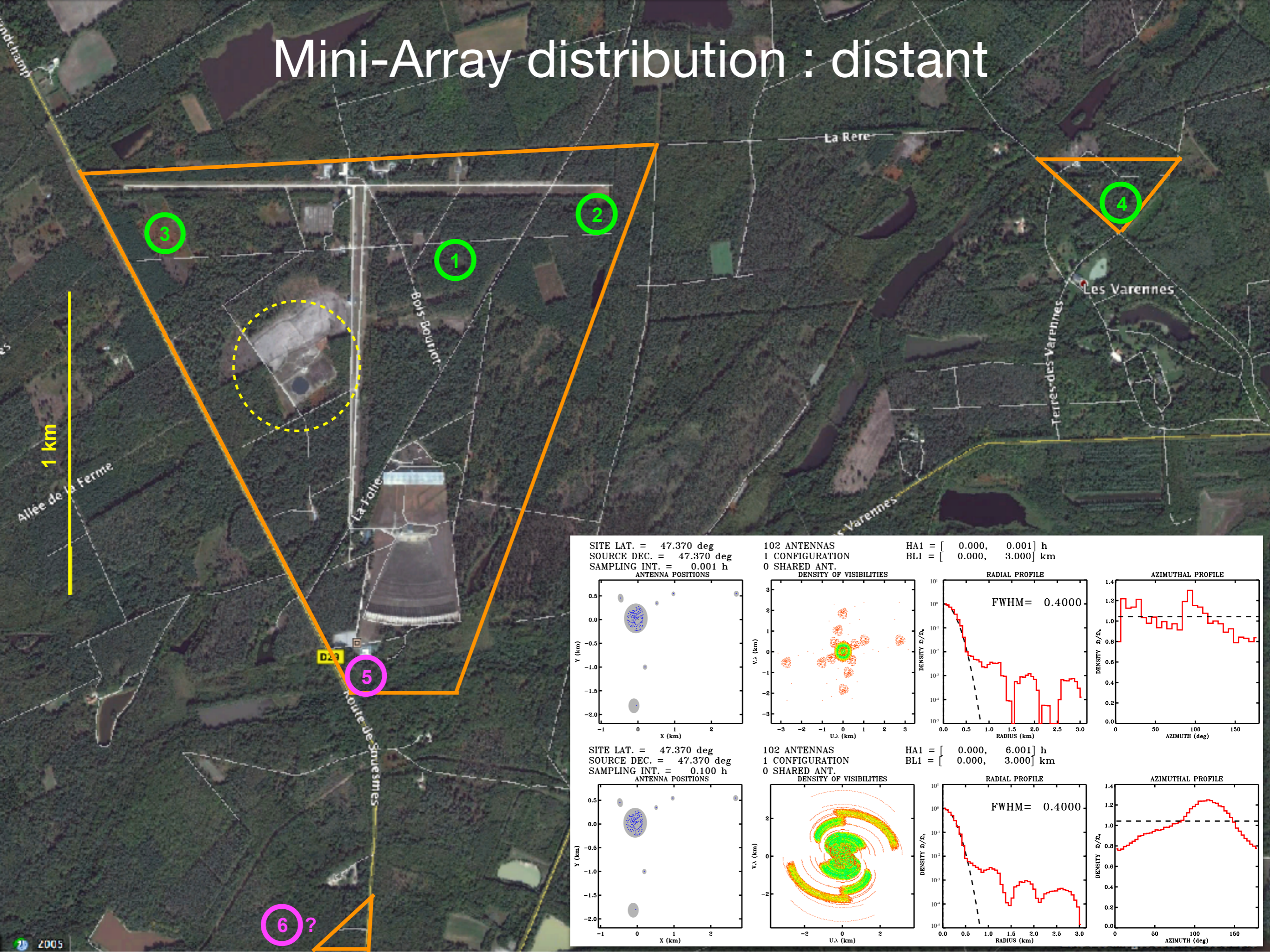


# Analog + Digital beamforming

- 768 beamlets ( $f_c, \delta f = 200 \text{ kHz}, \theta, \phi$ )



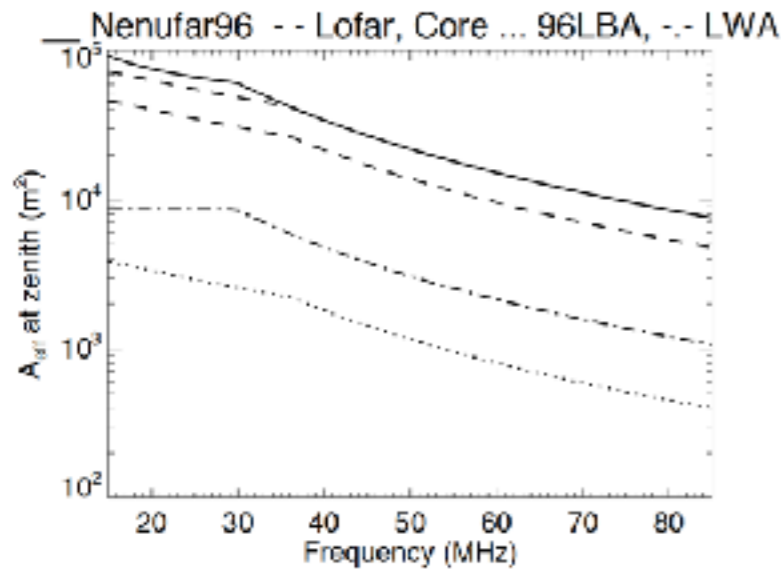
# Mini-Array distribution : distant



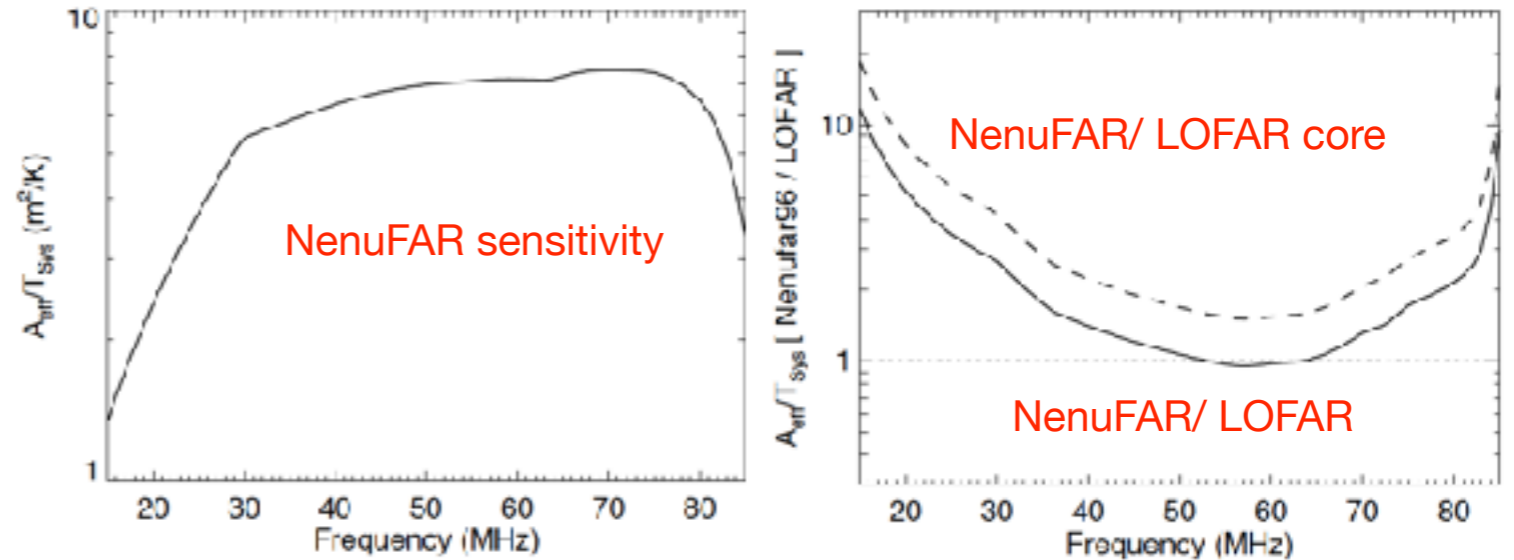
6 ?

# $A_{\text{eff}}$ , Sensitivity, Angular resolution

$A_{\text{eff}}$



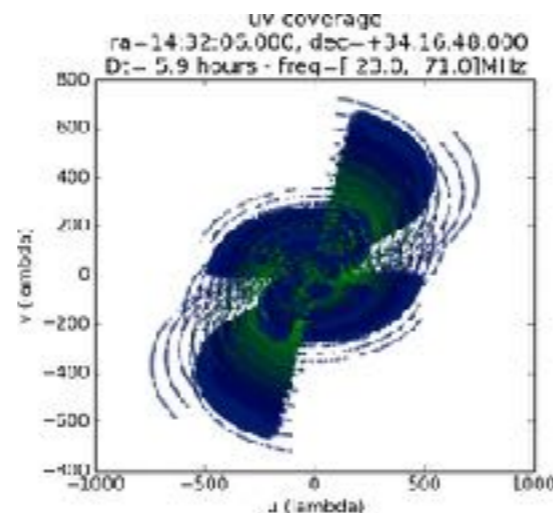
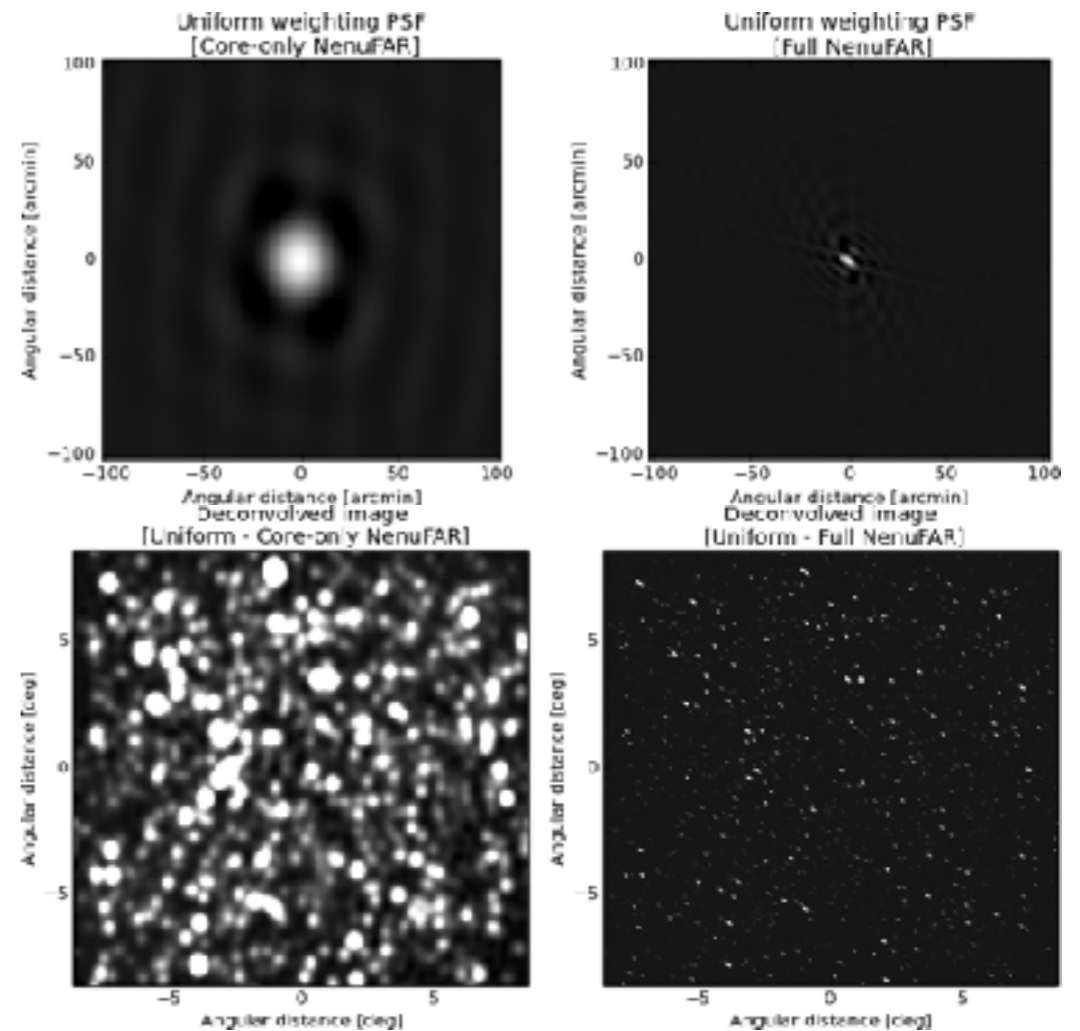
Sensitivity



[P. Zarka]

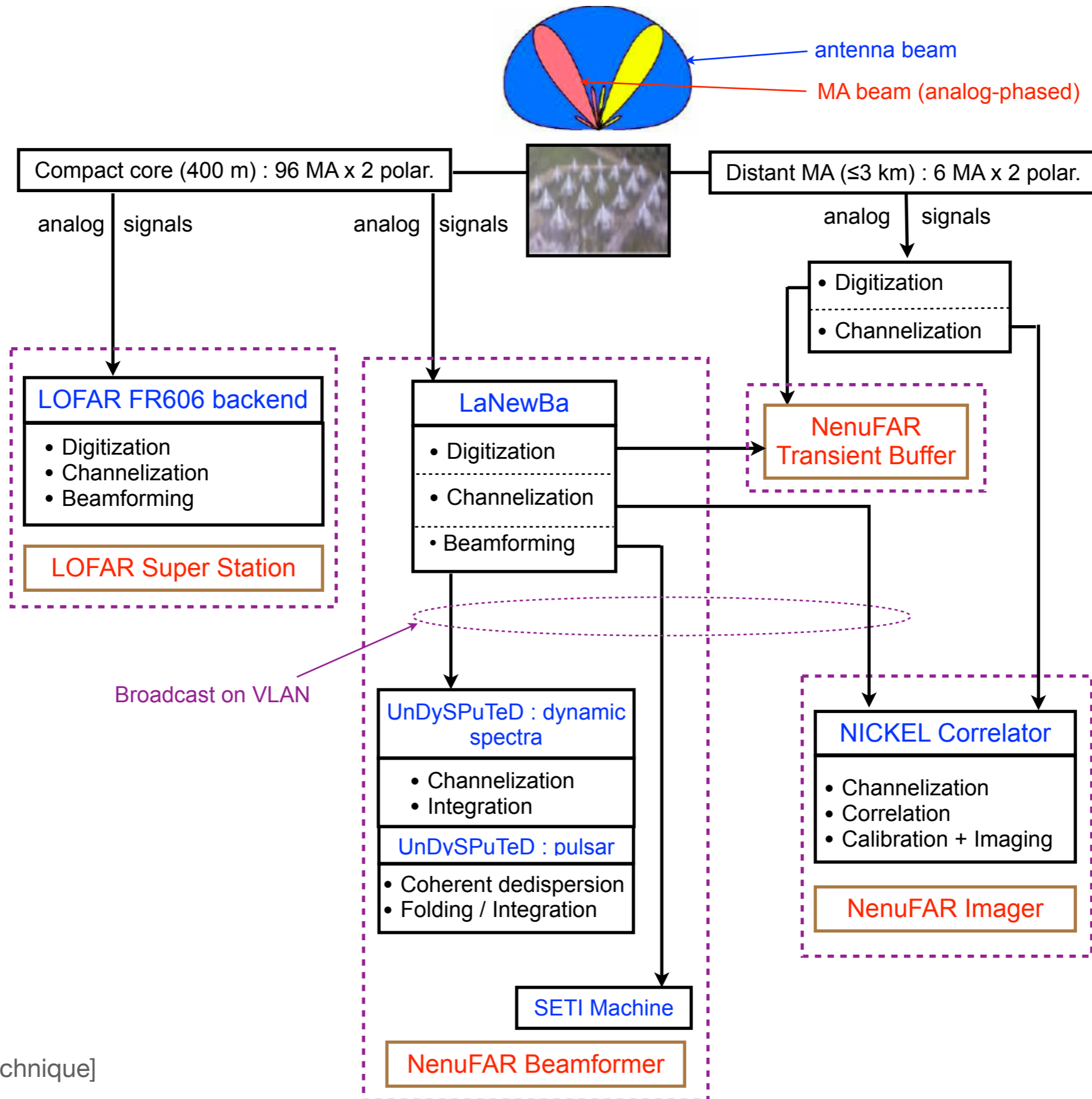
Angular resolution:

- $MA \sim 700/f^\circ$
- NenuFAR core  $\sim 43/f^\circ$
- with distant  $MA \sim 400/f \text{ arcmin}$

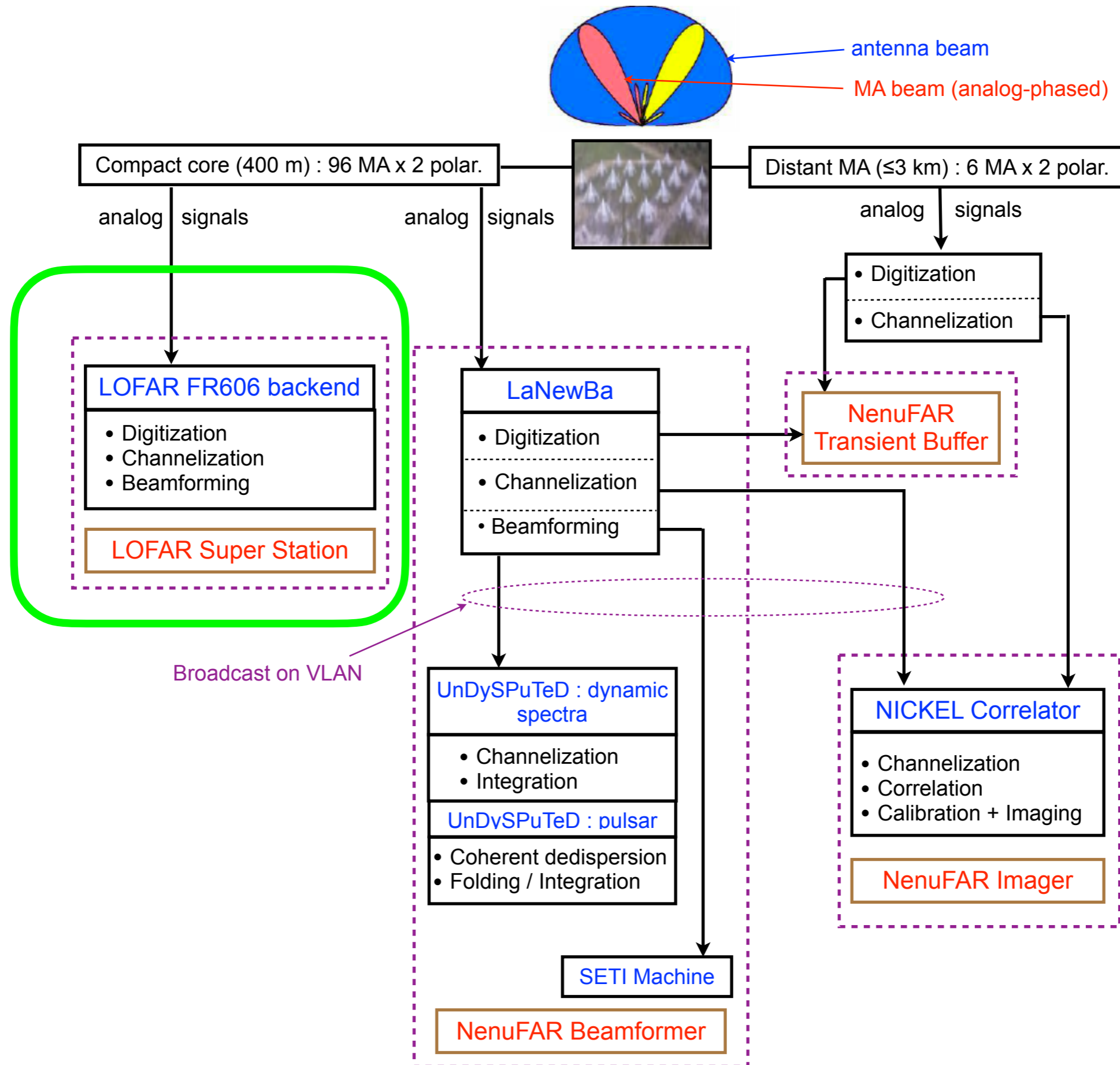


[C. Tasse]

# Receivers and signal path



# Receivers and signal path

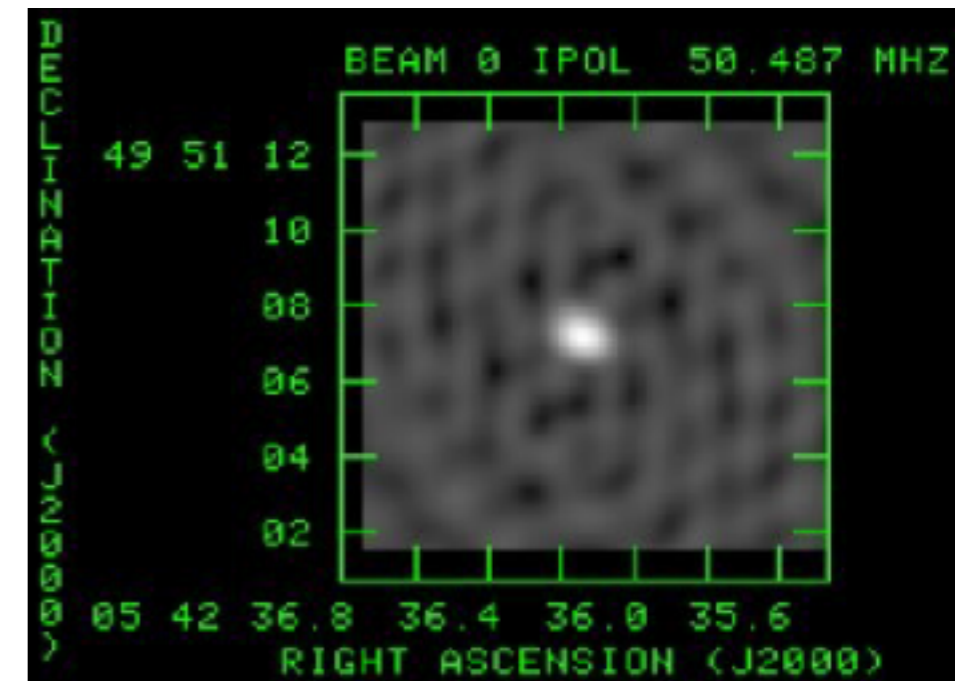
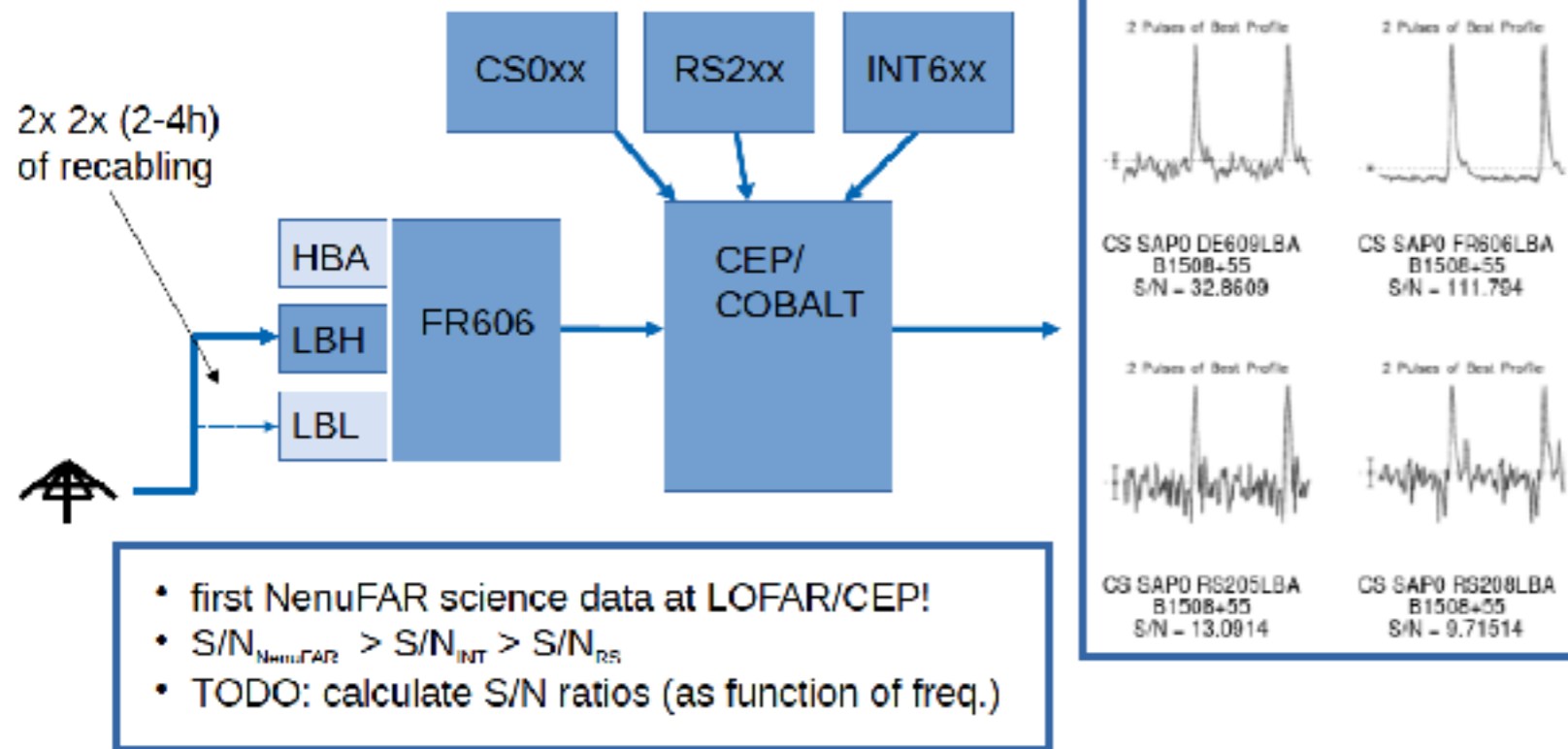


# LOFAR super station mode : in progress

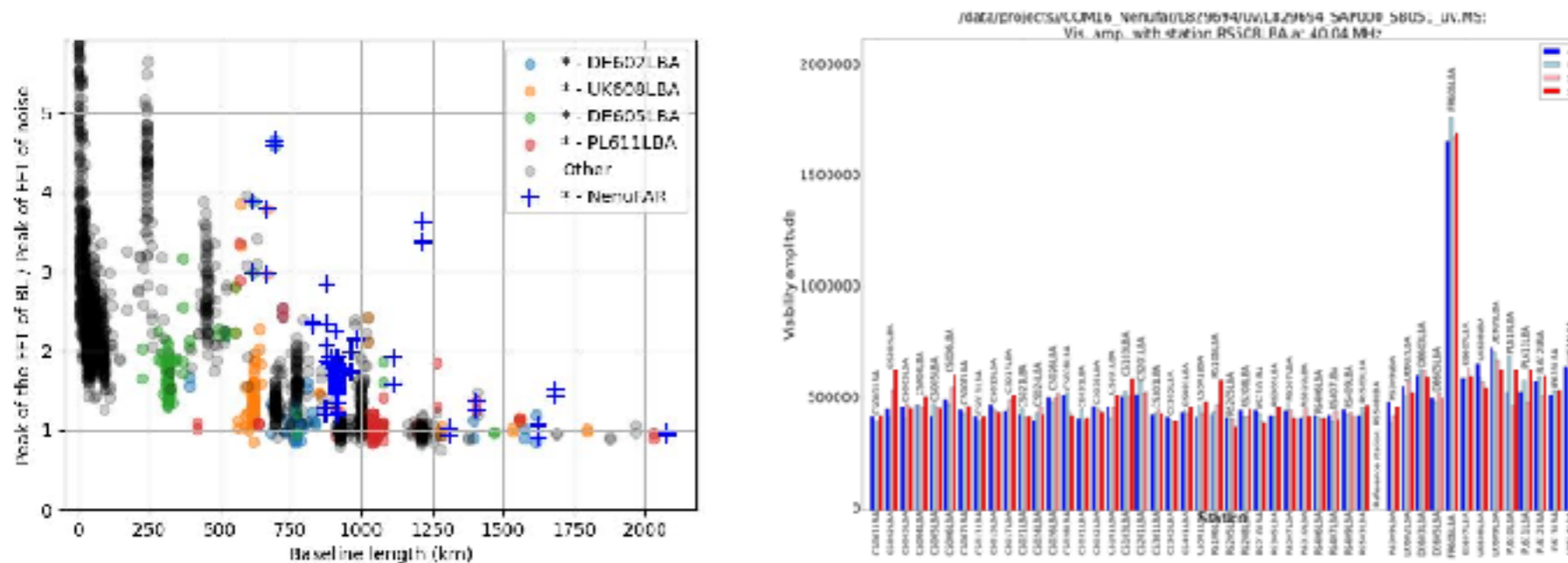


# LOFAR super station mode : in progress

## Fly's Eye observation of pulsar B1508+55



- first NenuFAR-ILT image!
- imaging is possible!
- only 2 MHz of data





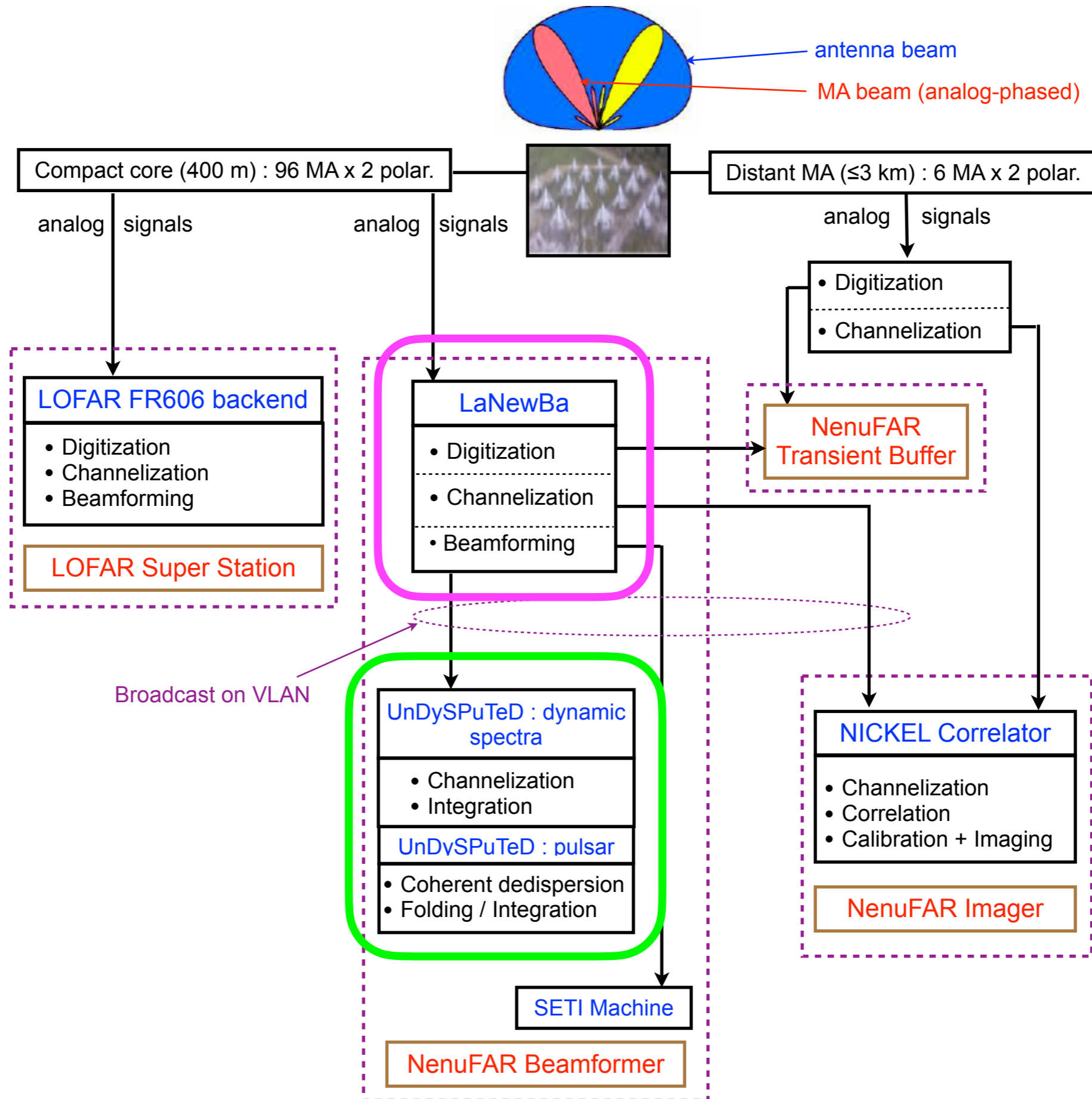
# Science organization

- « Early Science » phase  $\geq$  1/7/2019, for 7 semesters, until 1/12/2022

## Key / Pilot programs

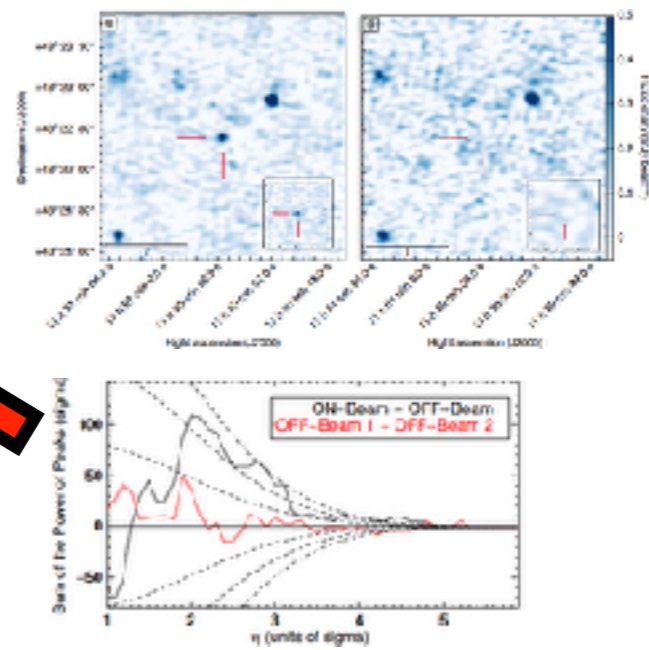
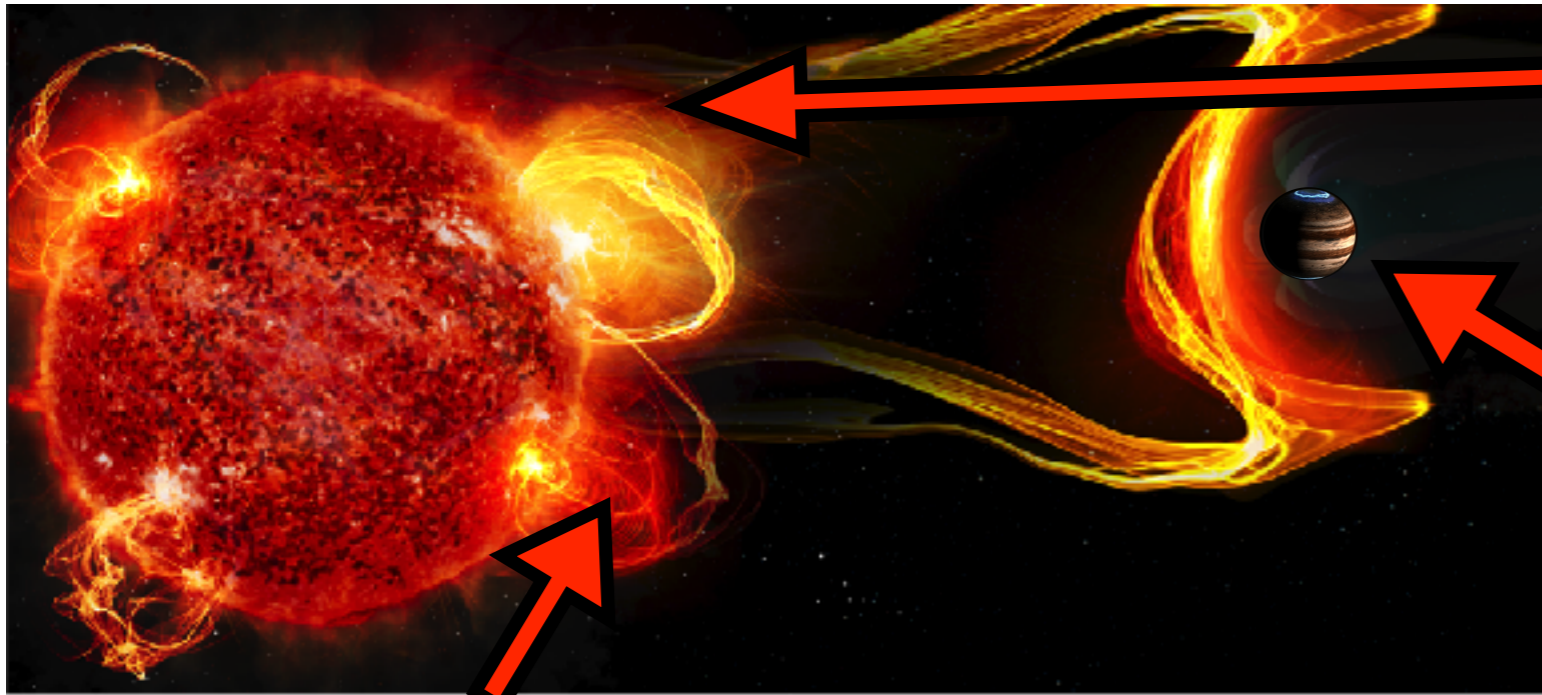
- ES01 Cosmic Dawn KP (Koopmans, Semelin et al.)
  - ES02 Exoplanets & Stars KP (Zarka, Lamy et al.)
  - ES03 Pulsars KP (Grießmeier et al.)
  - ES04 Transients KP (Corbel, Girard et al.)
  - ES05 Fast Radio Bursts PP (Decoene, Zarka et al.)
  - ES06 Planetary Lightning KP (Grießmeier et al.)
  - ES07 Joint Jupiter studies KP (Yerin, Lamy et al.)
  - ES08 Cluster of galaxies & AGNs KP (Pommier et al.)
  - ES09 Cluster Filament & Cosmic Magnetism PP (Bonnassieux et al.)
  - ES10 Radio recombination lines PP (Gusdorf et al.)
  - ES11 Sun KP (Carley, Masson et al.)
  - ES12 Radio Gamma KP (Dallier et al.)
  - ES13 SETI KP (Hellbourg et al.)
  - ES14 Cas A PP (Konovalenko et al.)
  - ES15 Large Scale Background Survey PP (Sidorchuk et al.)
- + Formation of students, Radio-Amateurs group*

# Receivers and signal path



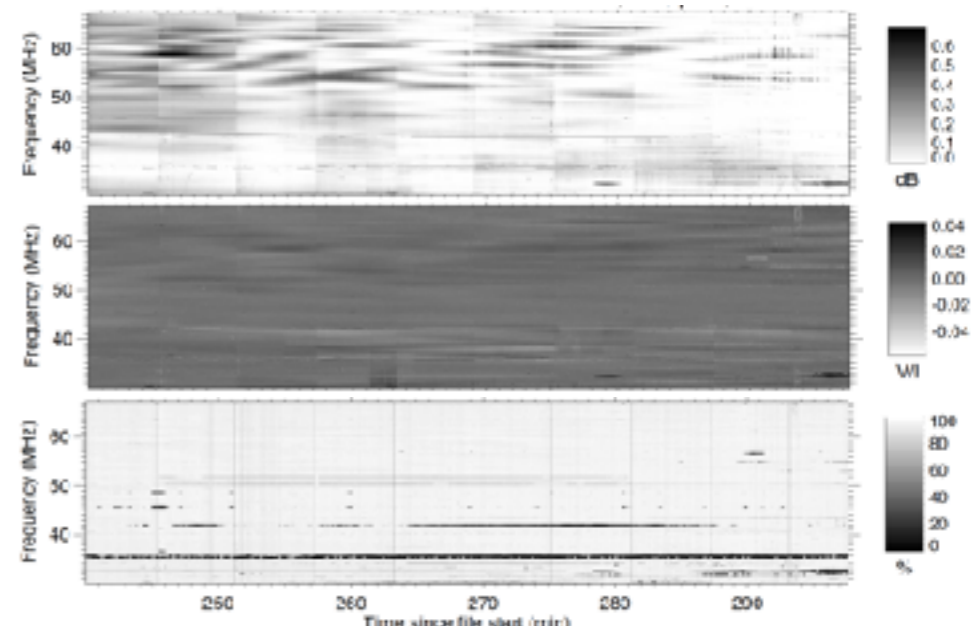
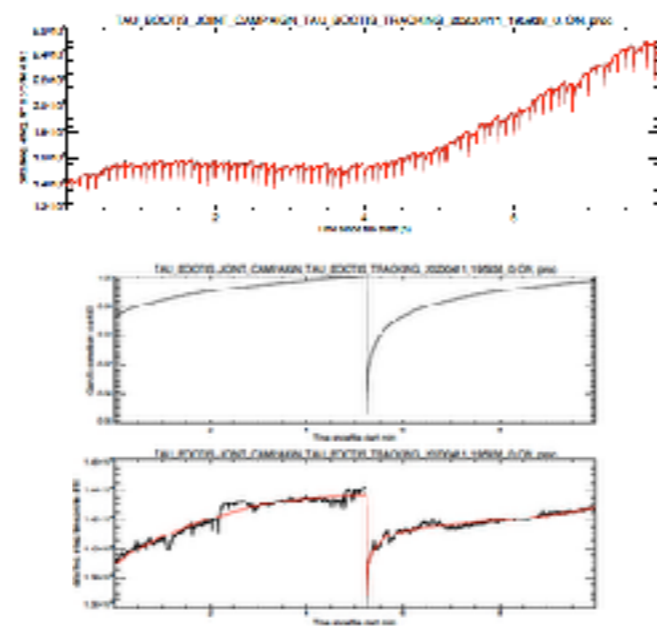
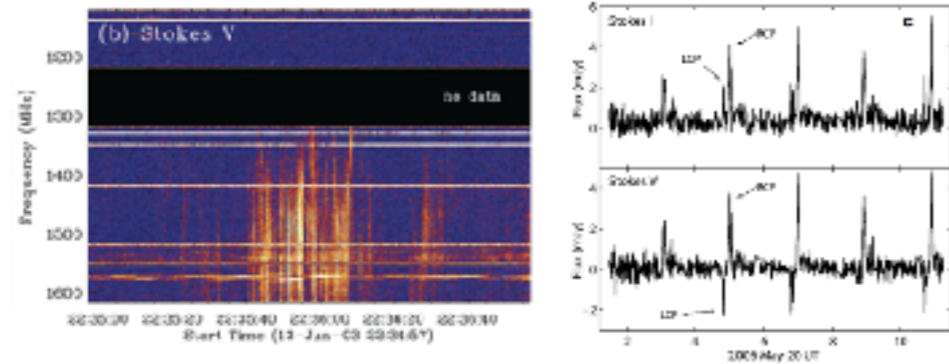
# ES02: Exoplanets & Stars

- Comparative exo-magnetospheric physics & stellar activity



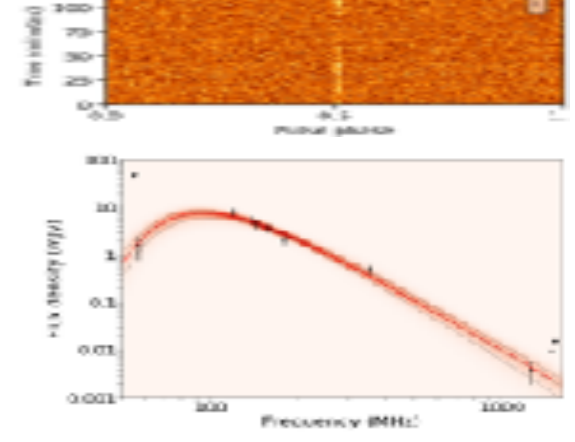
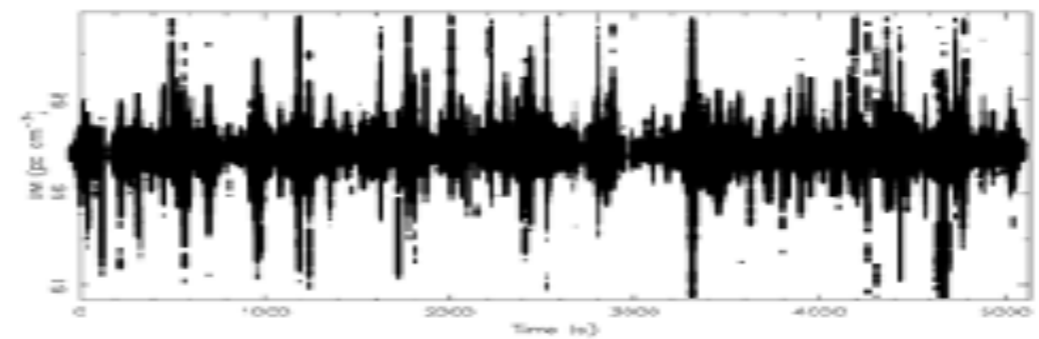
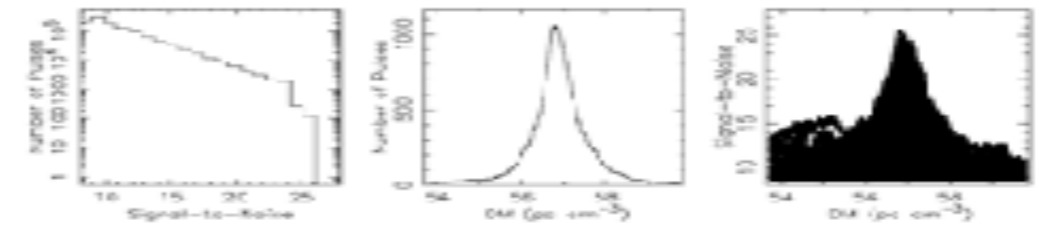
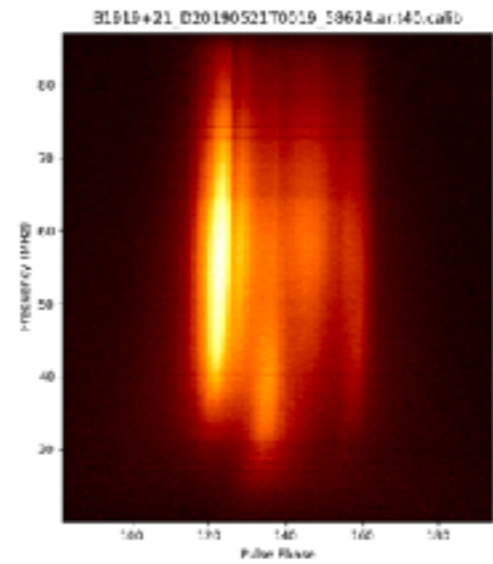
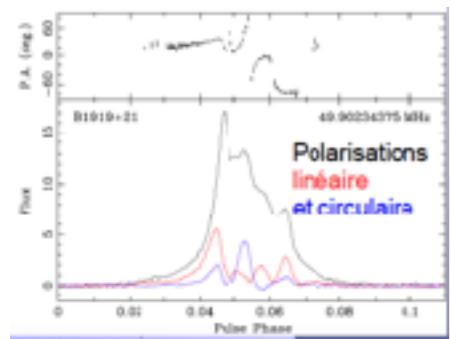
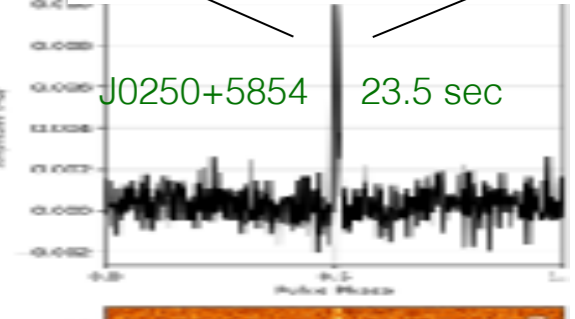
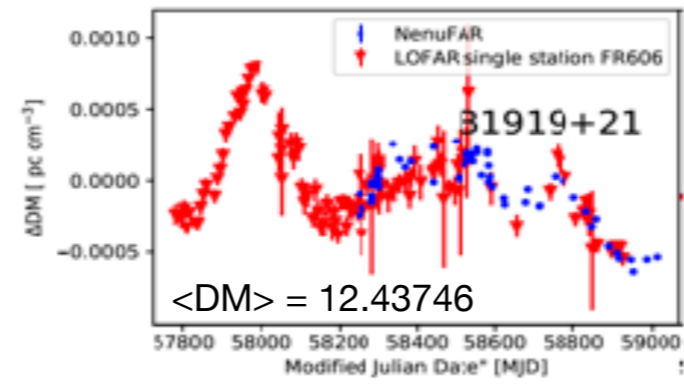
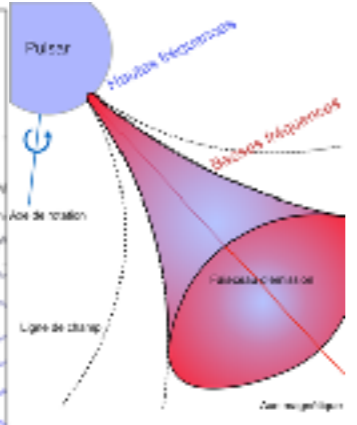
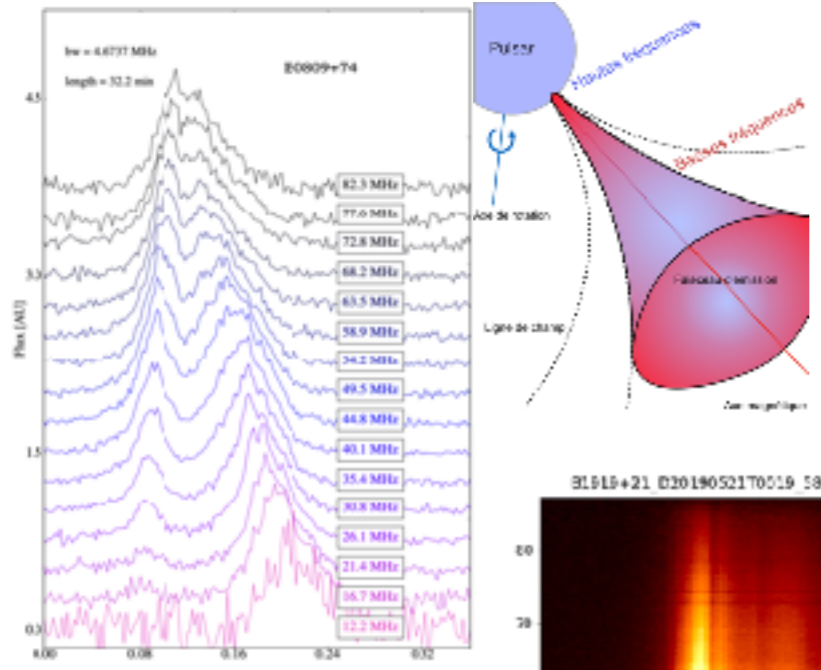
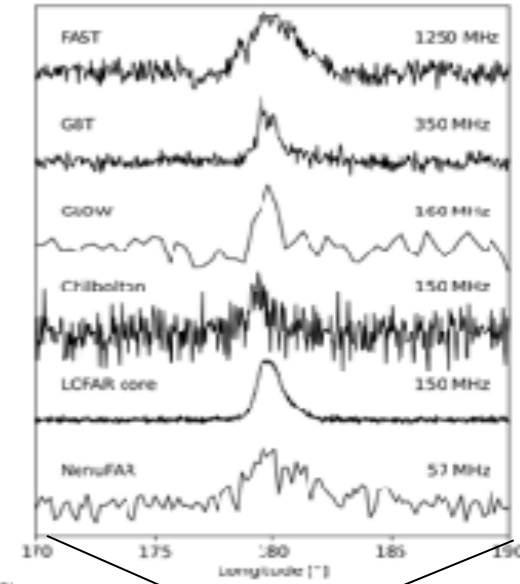
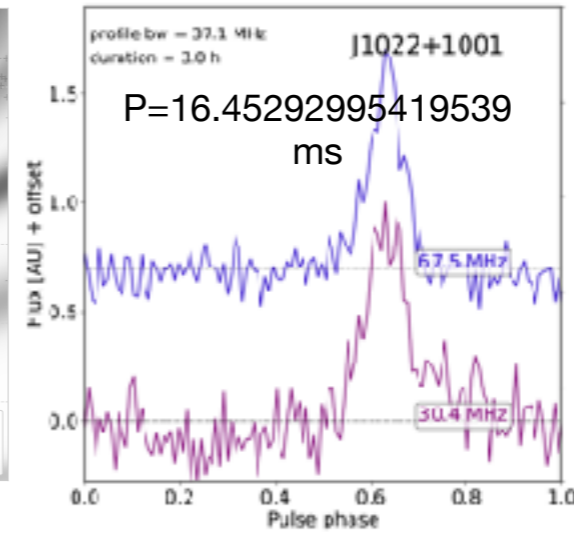
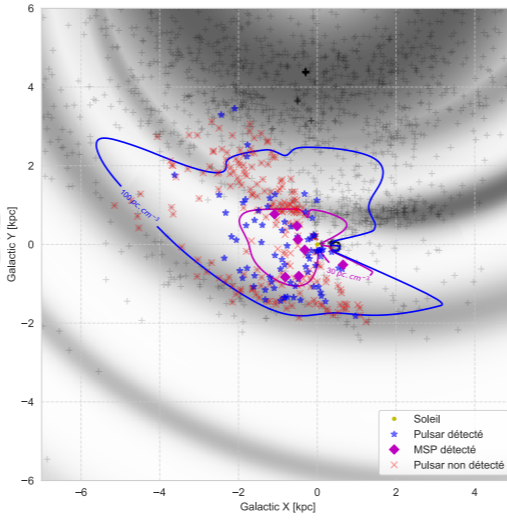
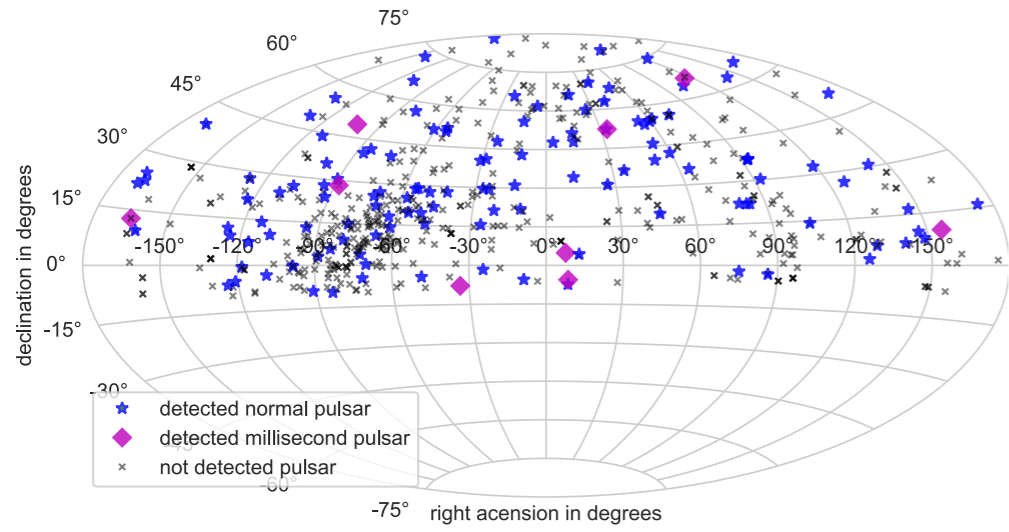
[Vedantham et al., 2020 ; Turner et al., 2021]

[Osten & Bastian, 2006 ; Hallinan et al., 2007]



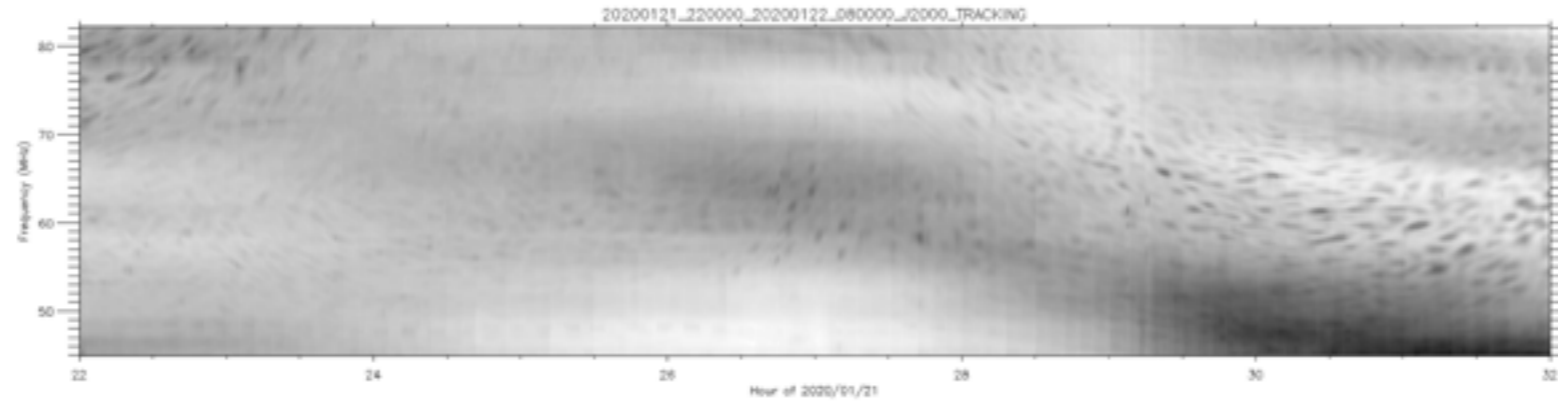
- Pre-processing pipeline operational, processing in progress ; observations // LOFAR

# ES03: Pulsars

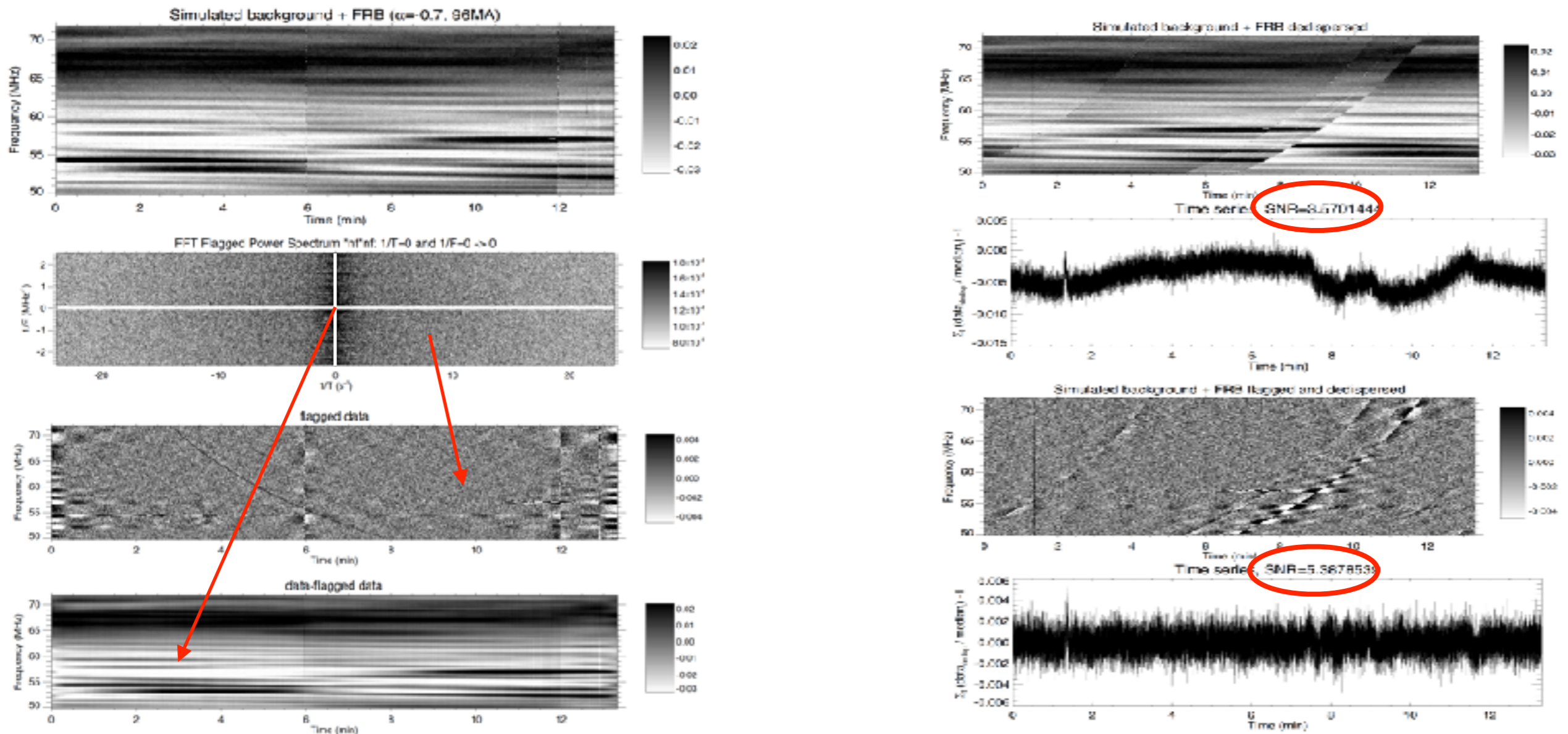


# ES05: Fast Radio Bursts

[V. Decoene & P. Zarka]



- Pre-processing pipeline operational, processing in progress ; observations // LOFAR

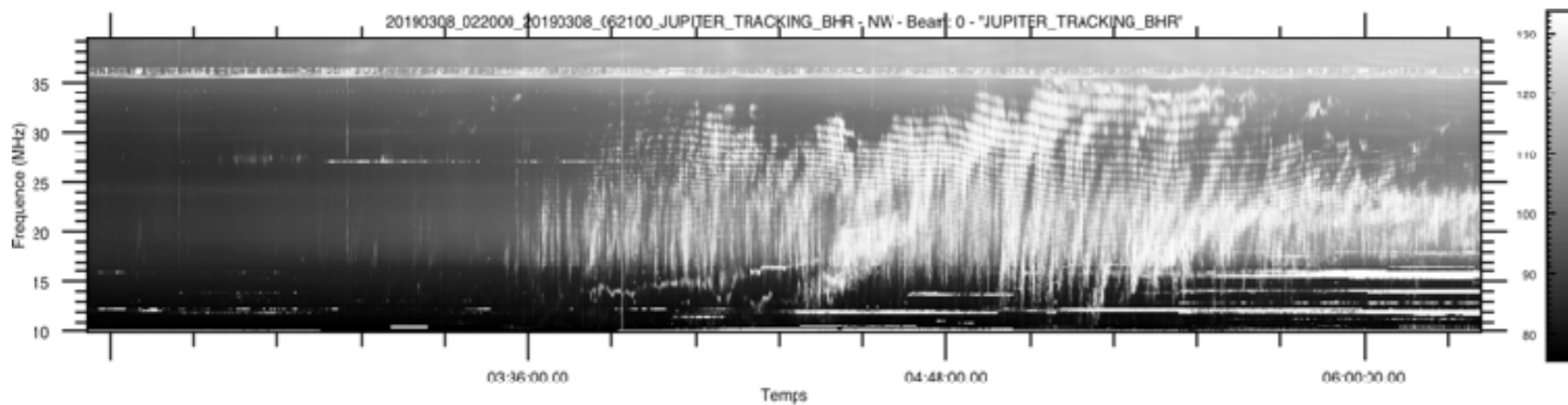
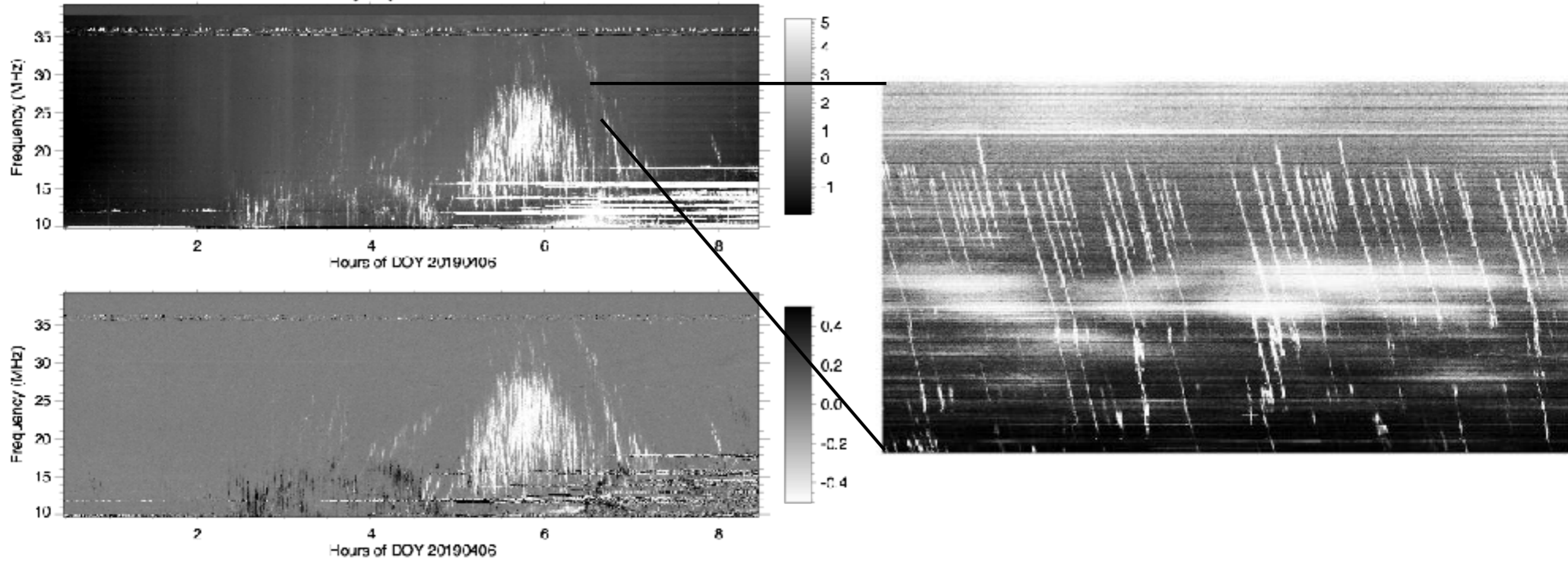


- Benchmarked on PSR0329.54 and on FRB simulations + real data

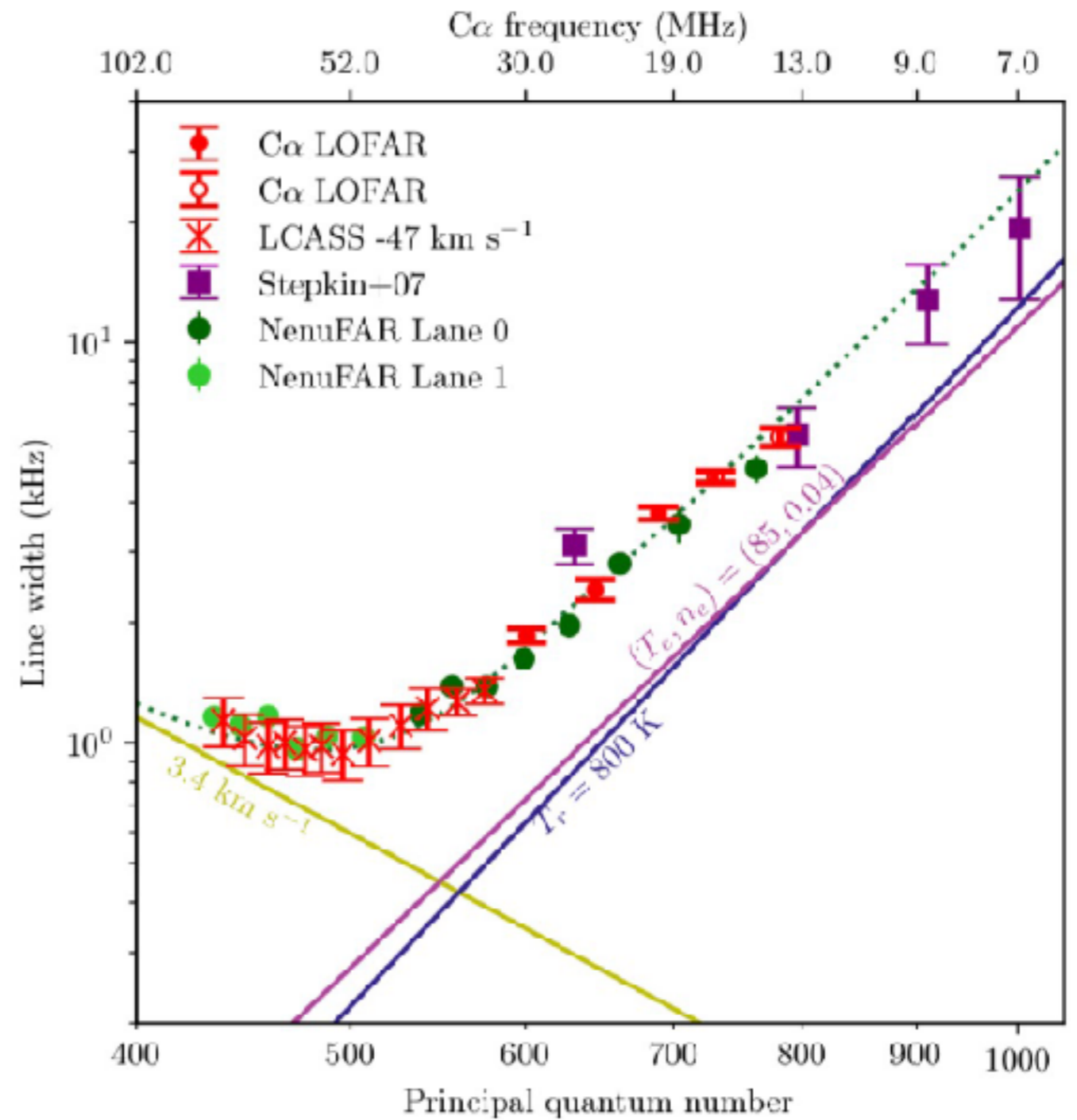
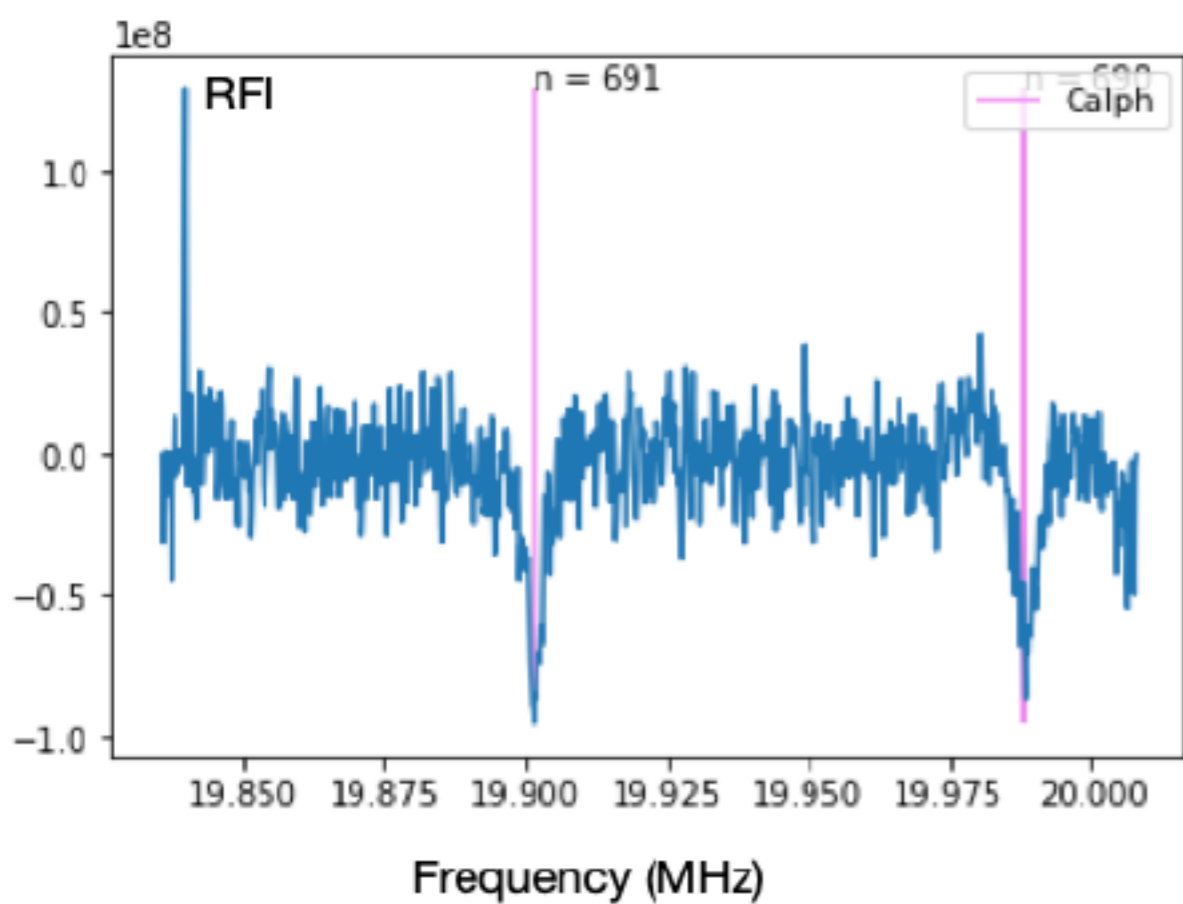
# ES07: Jupiter

[L. Lamy & S. Yerin]

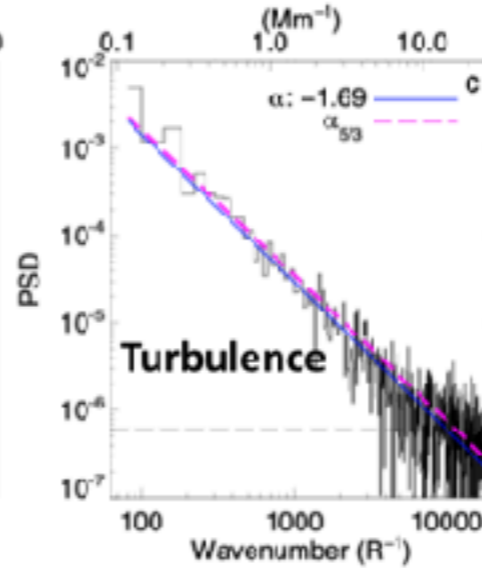
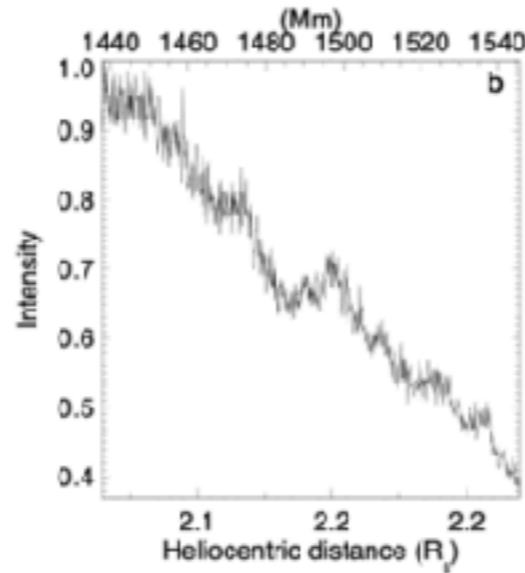
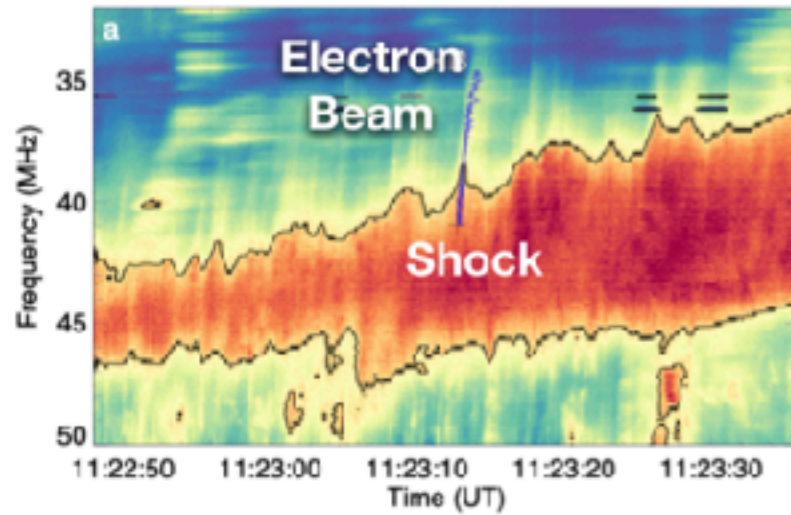
NenuFAR/DynSpec - Stokes S and V



# ES10: RRLs

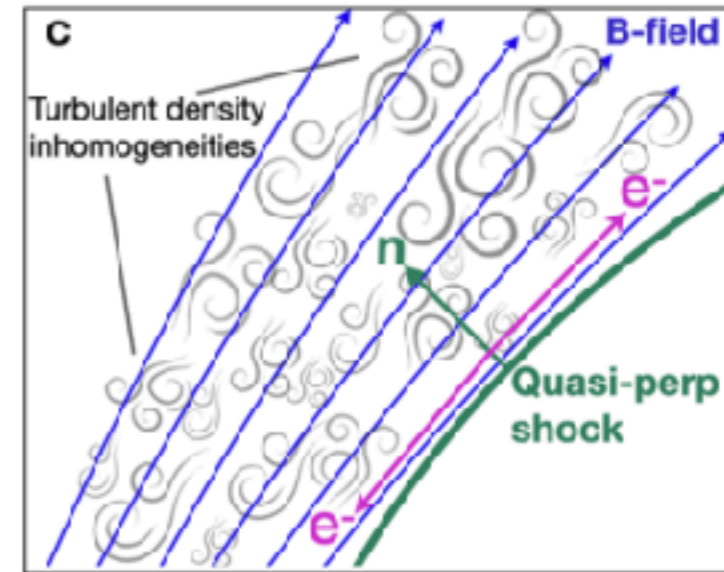
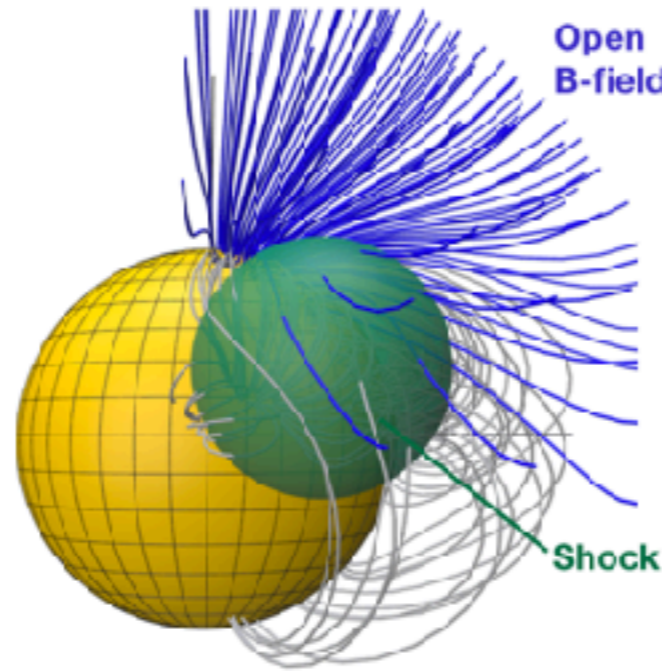
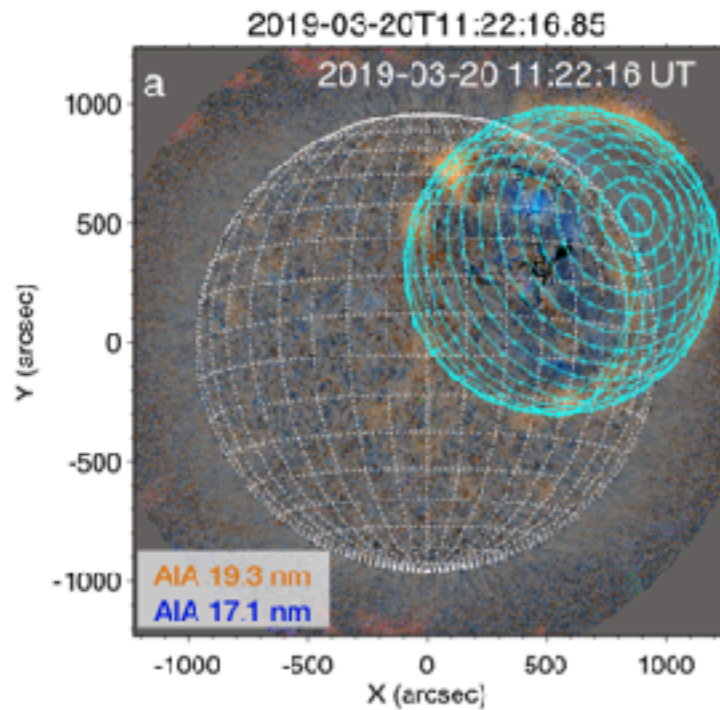


# ES11: Sun



## Results:

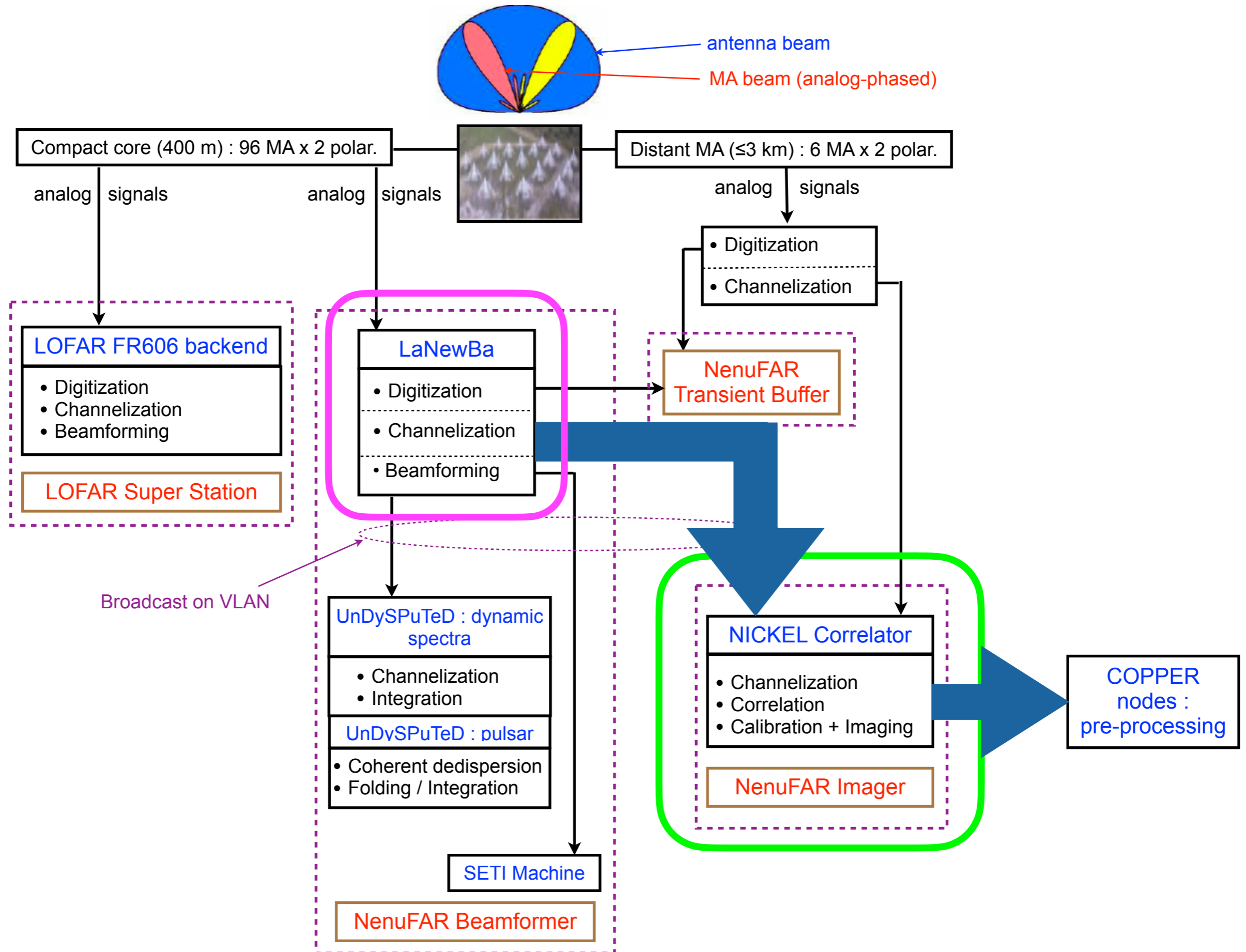
- First observations of particle acceleration in turbulence in the solar corona
- Important for acceleration mechanisms + radio emission generation



[Carley et al., ApJ, 2021]

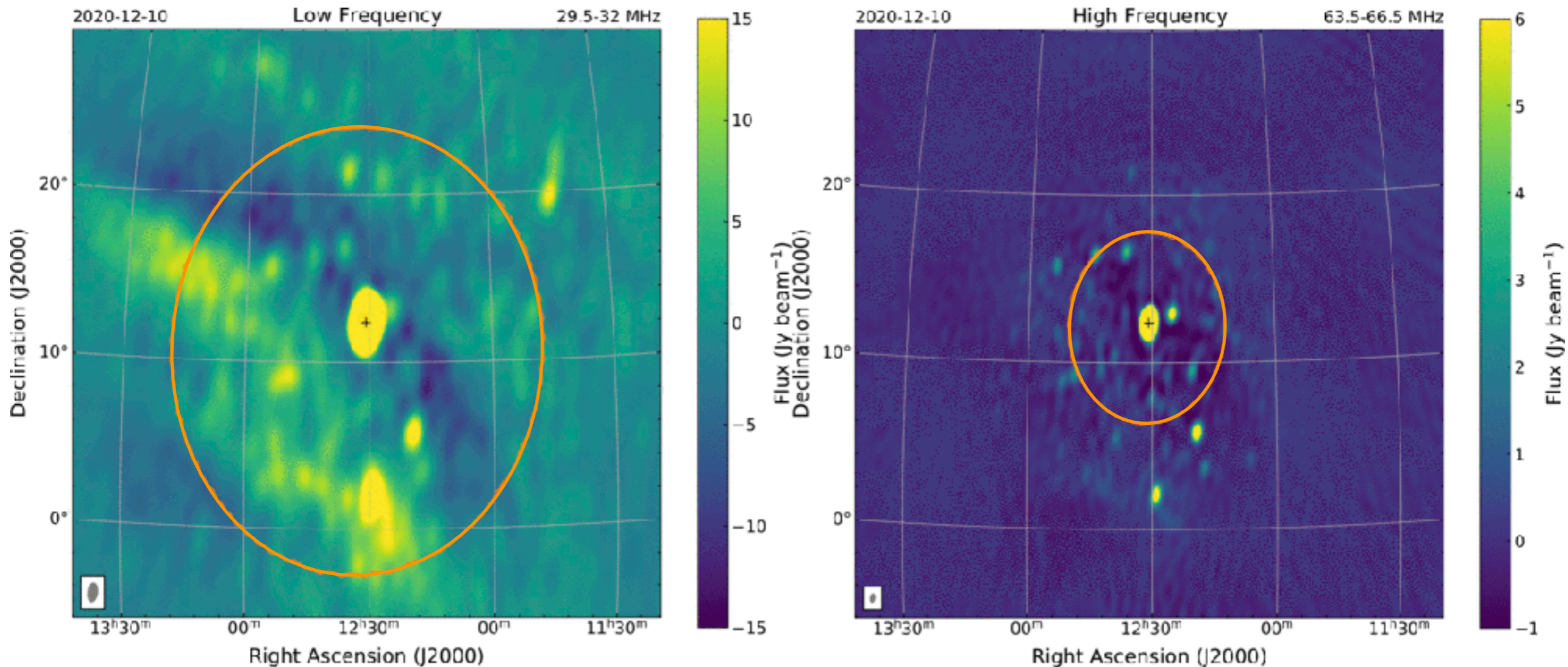


# Receivers and signal path



# NICKEL correlator : first light (Virgo-A)

NenuFAR Imager Correlation Kluster Elaborated from LOFAR's

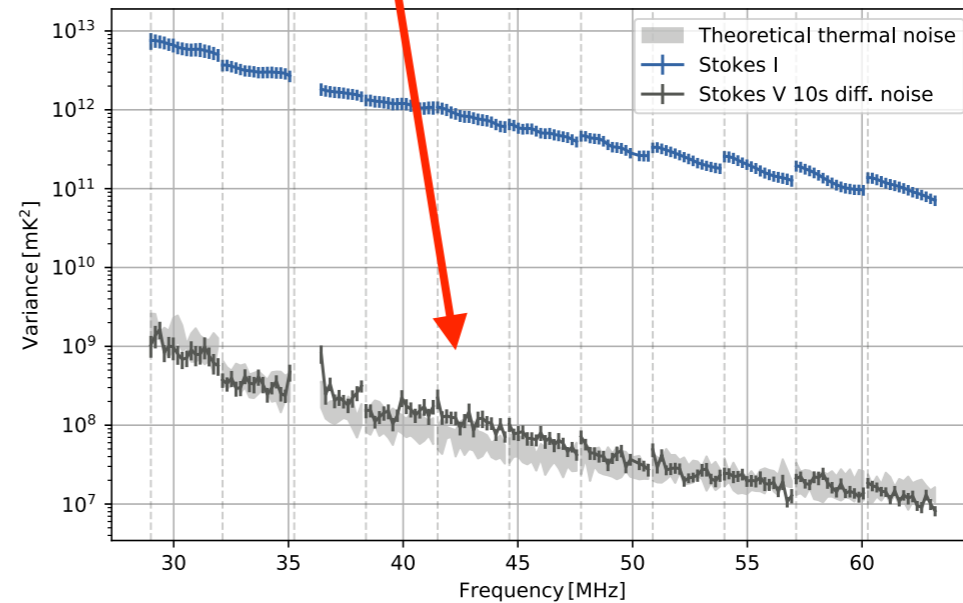
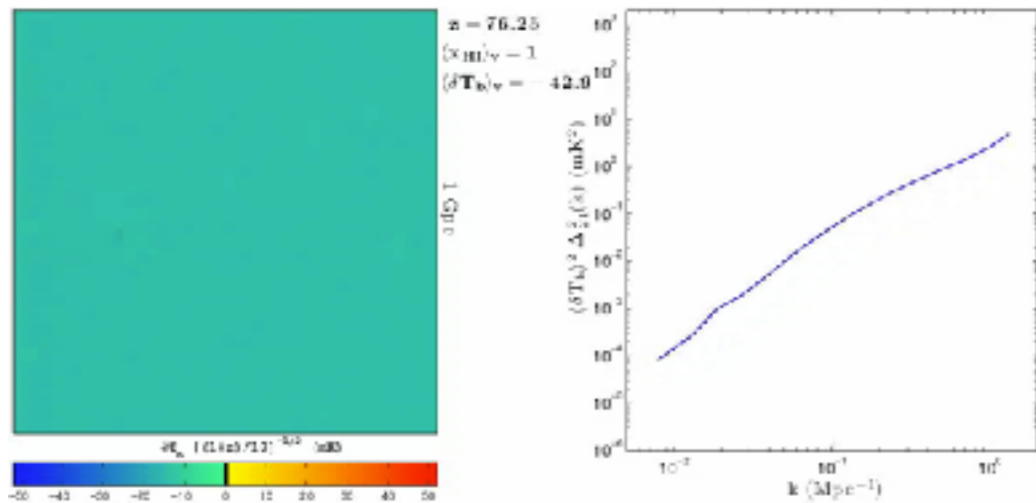
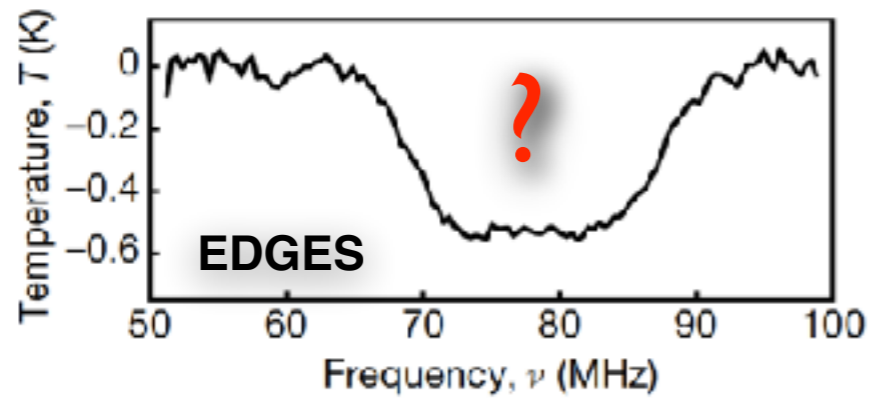
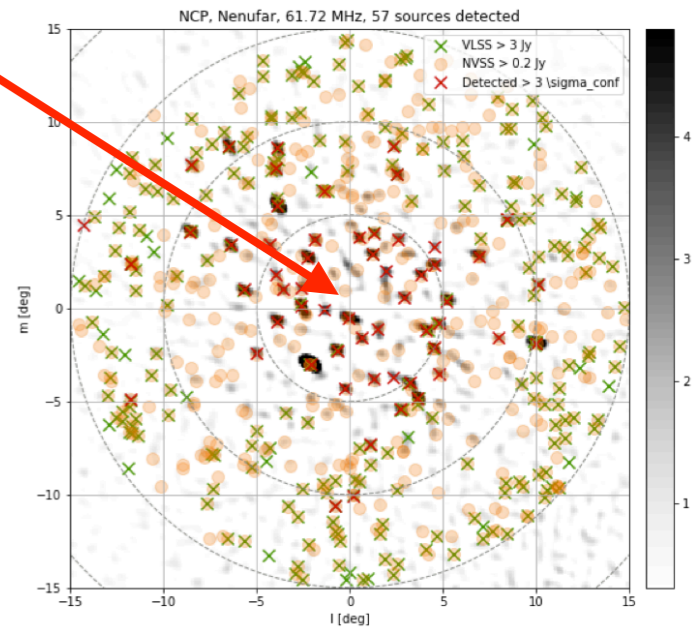
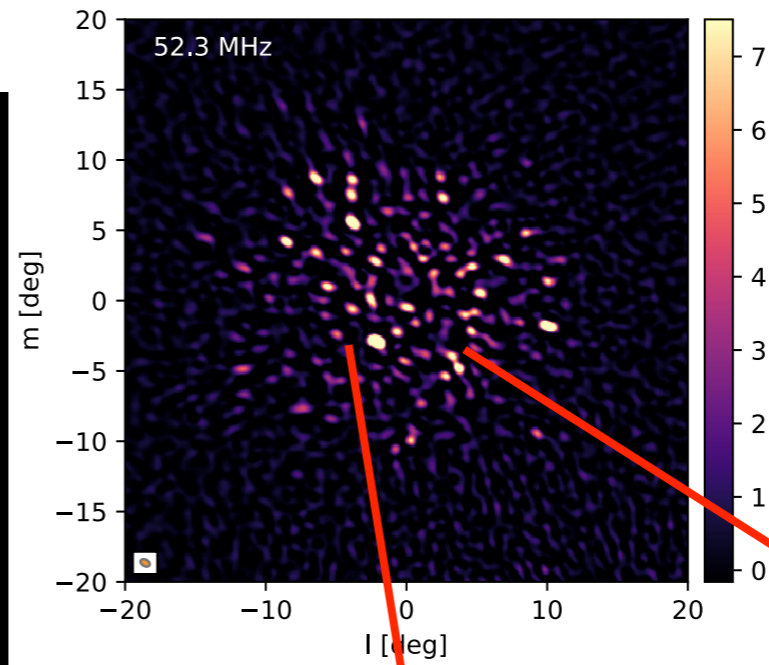
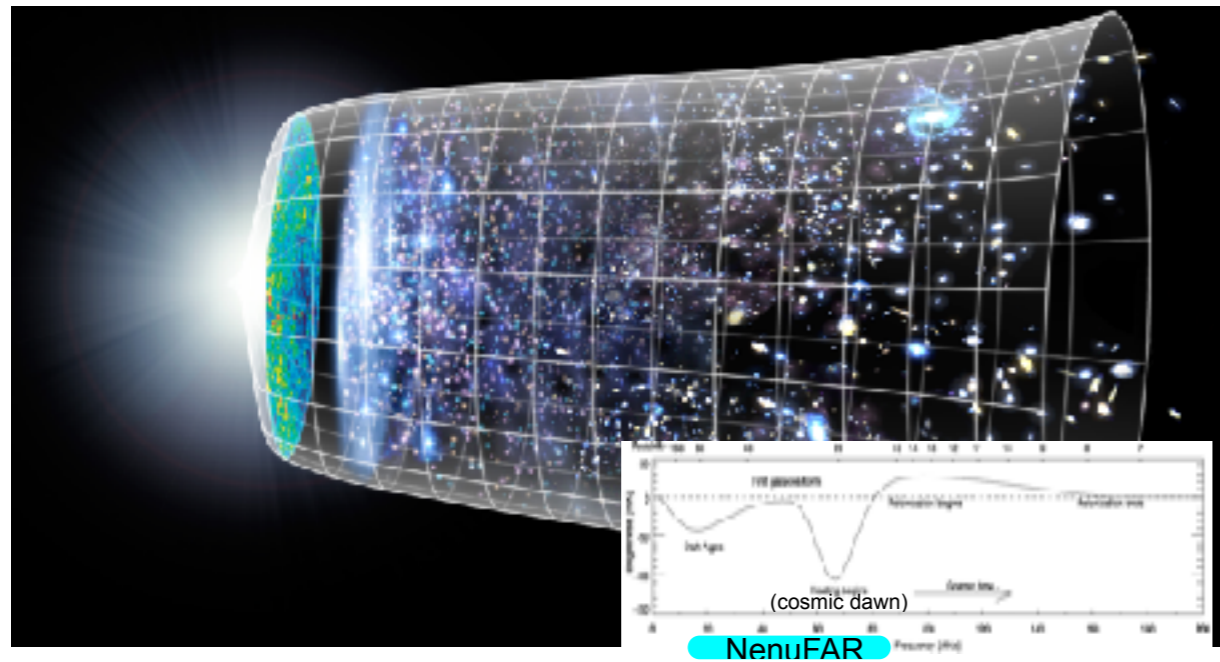


- <https://nenufar.obs-nancay.fr/2021/01/06/premiere-lumiere-du-nenufar-radio-imager/>
- <https://www.astron.nl/dailyimage/main.php?date=20210201>

⇒ 6 NICKEL nodes + 5 COPPER nodes

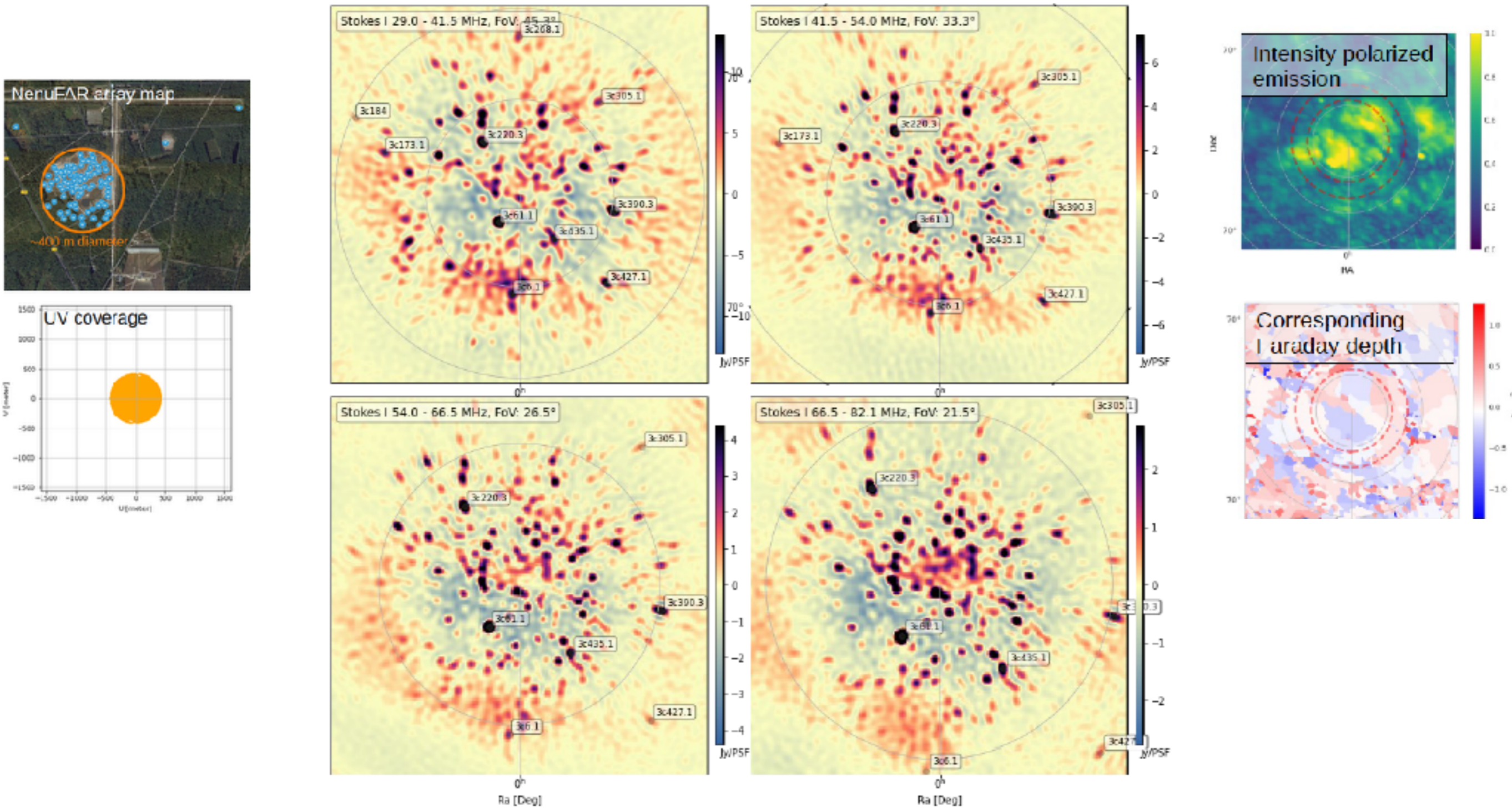
⇒ Pre-processing / Calibration / Imaging ... pipelines in development

# ES01: Cosmic Dawn

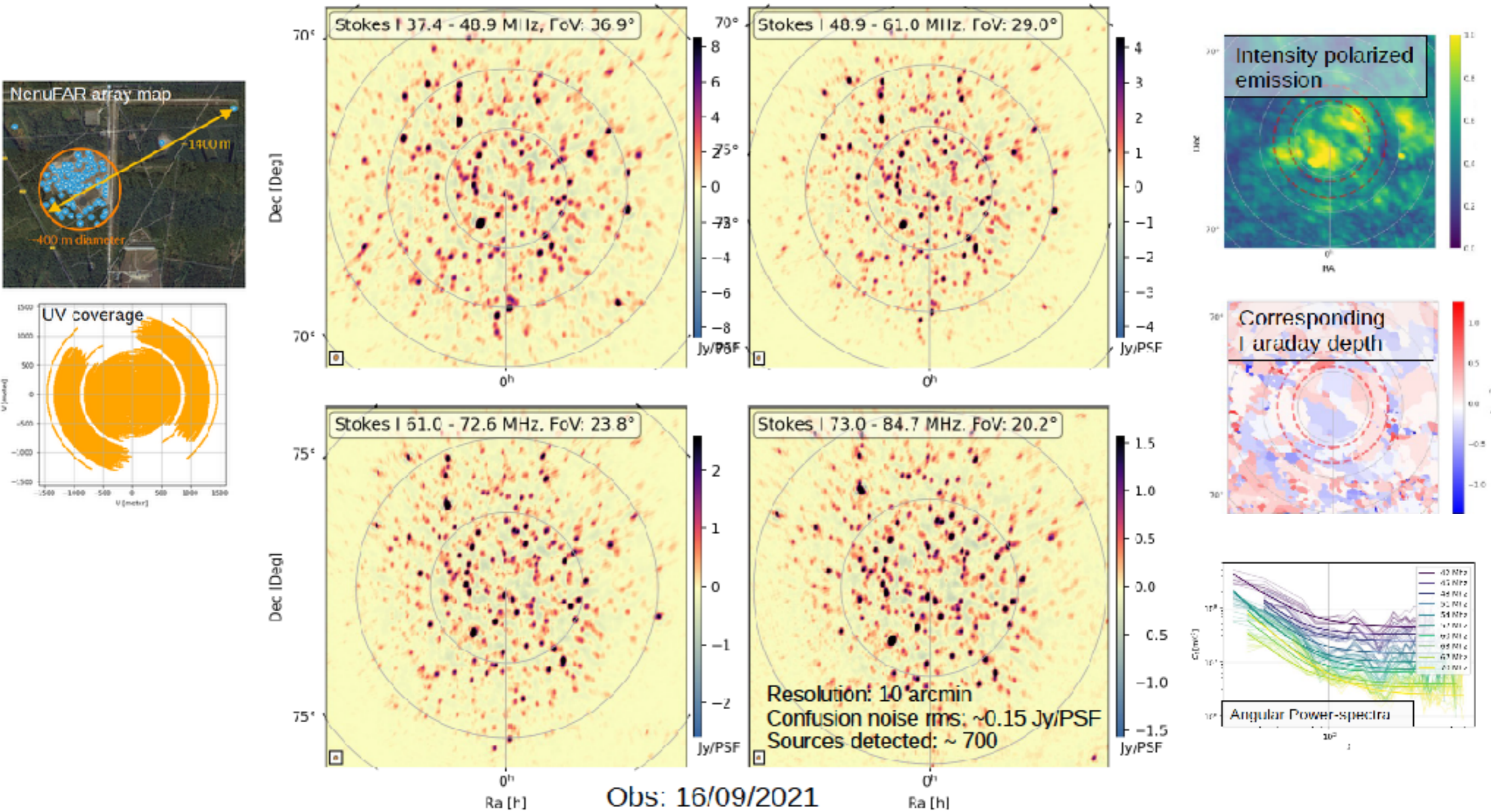


# ES01: Cosmic Dawn (NCP imaging)

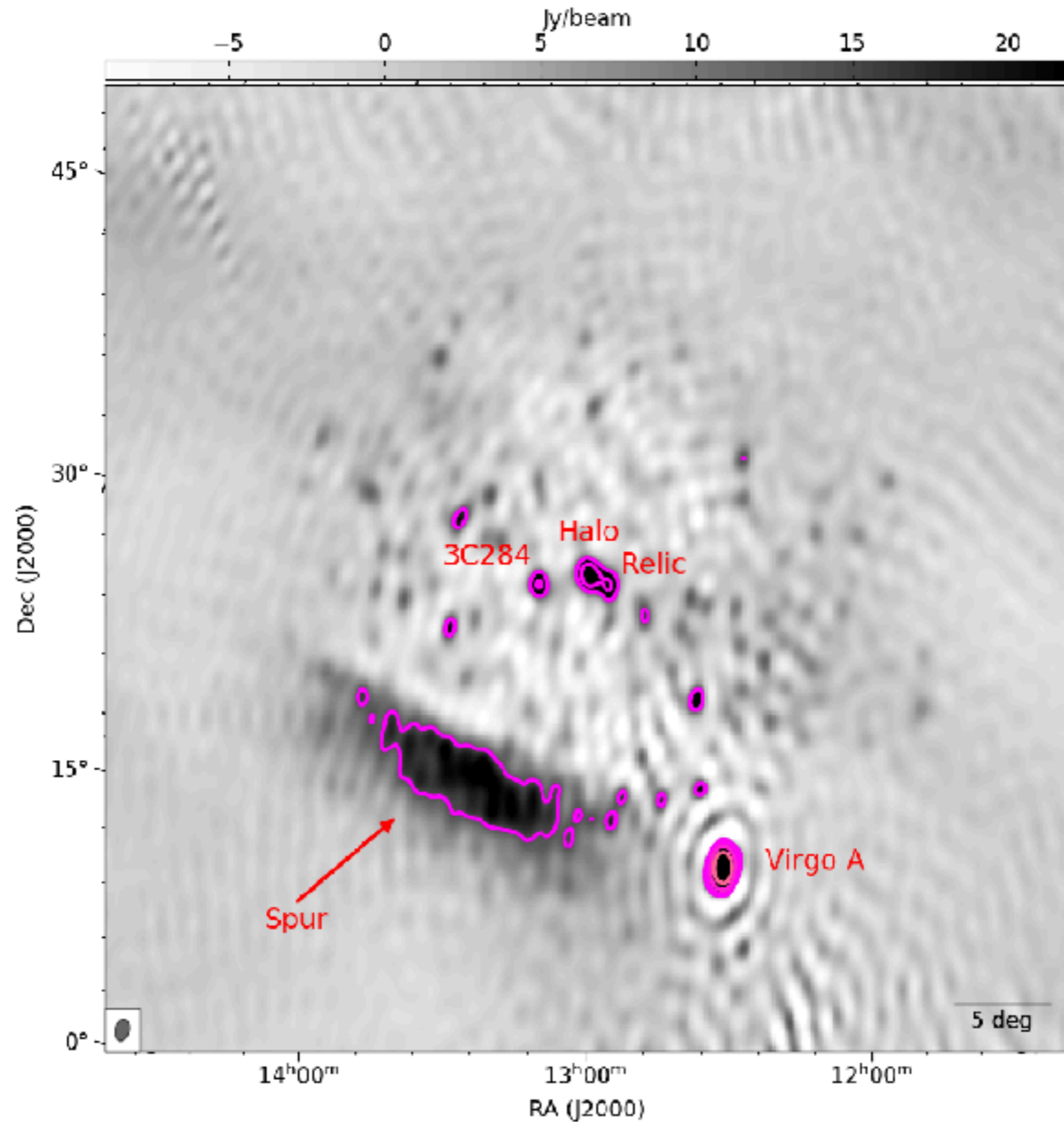
## North Celestial Pole – NenuFAR



# ES01: Cosmic Dawn (NCP imaging)

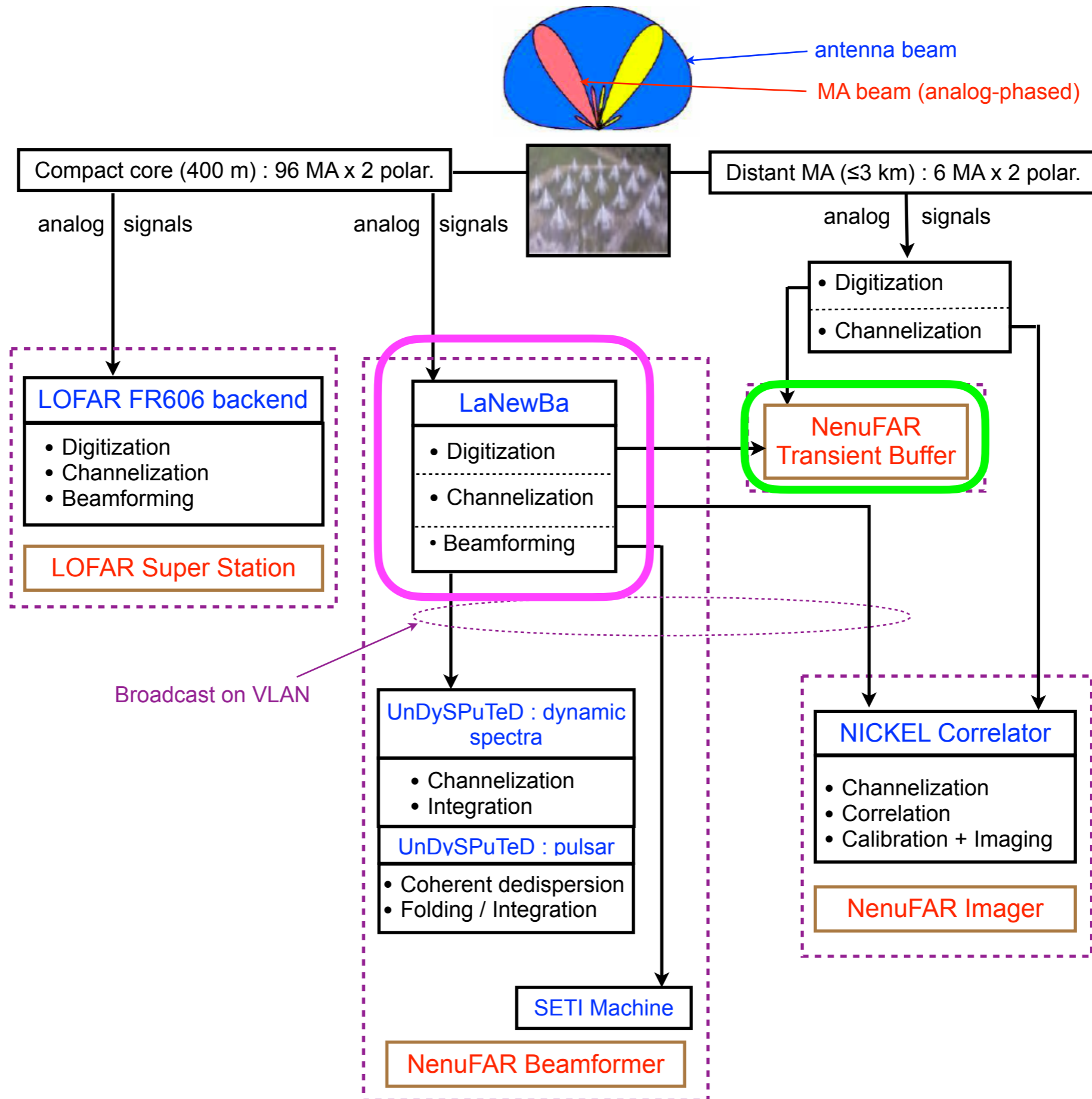


# ES09: Cluster filaments & Cosmic magnetism



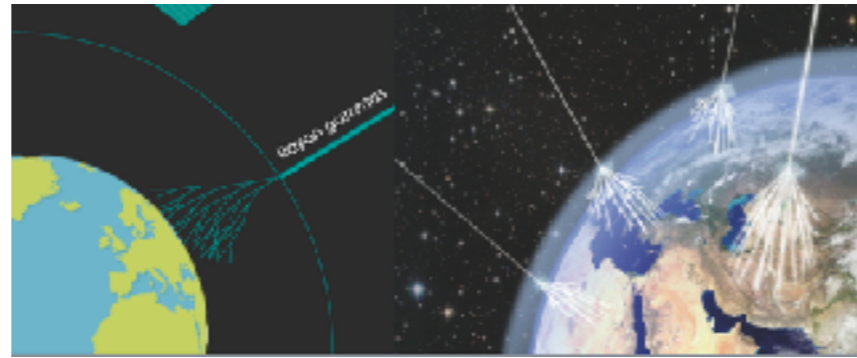
[Bonnassieux et al., 2021]

# Receivers and signal path



# ES12: Radio Gamma

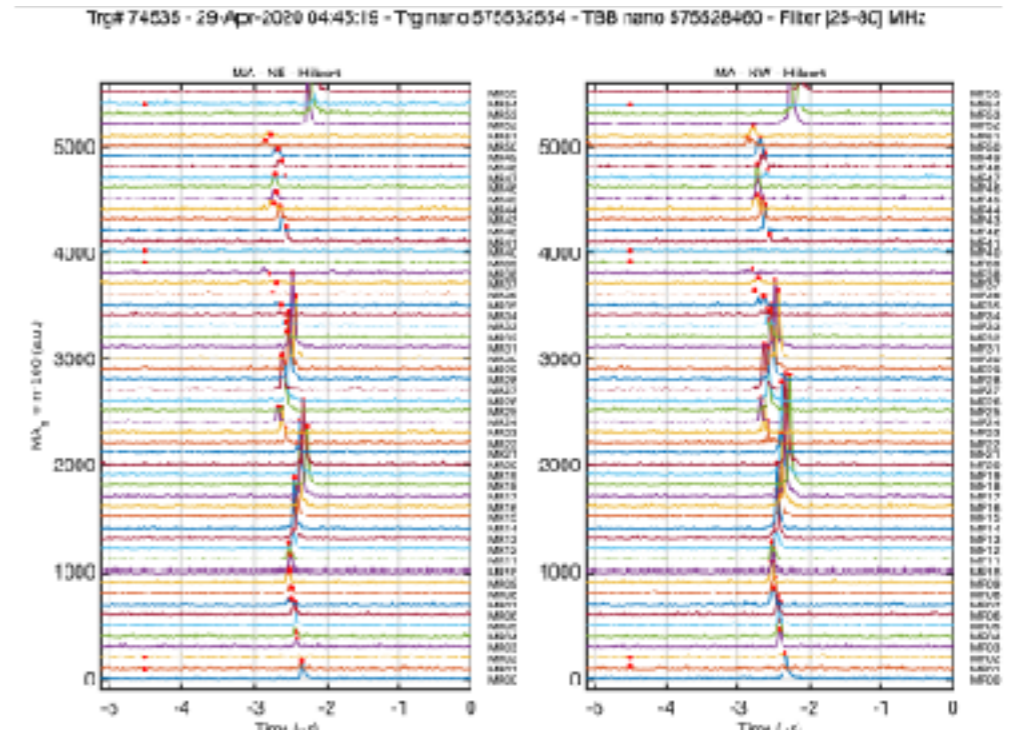
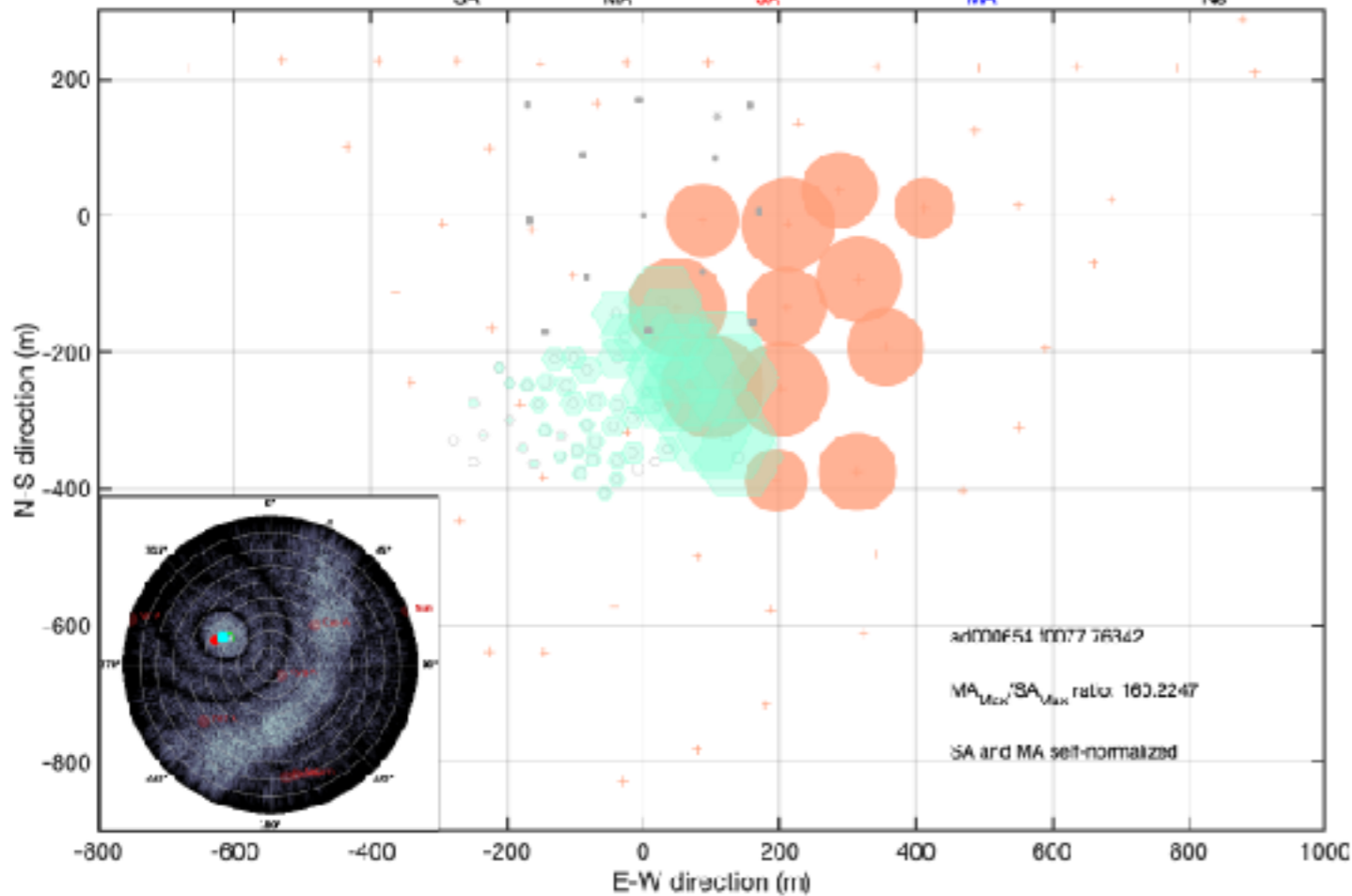
[R. Dallier & L. Martin]



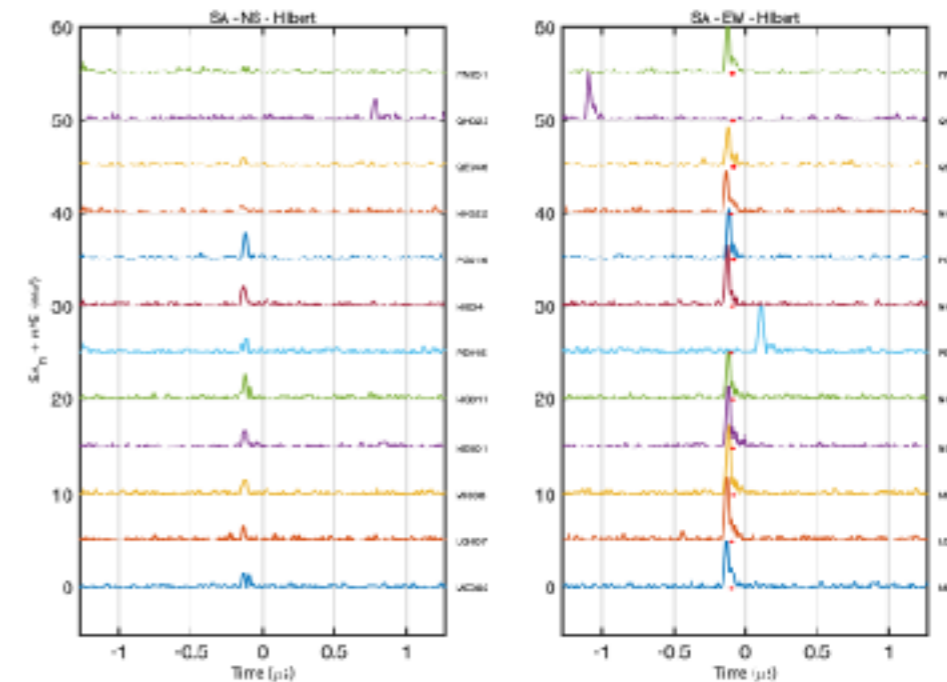
Événement "rayon cosmique" vu par CODALEMA et NenuFAR sur déclenchement scintillateurs *par hasard* dans la direction de pointage de NenuFAR

TBB →

Event: 29-Apr-2020 04:45:19 • Mult<sub>SA</sub> = 12 • Mult<sub>MA</sub> = 51 •  $[\theta, \phi]_{SA} = [36, 157]$  •  $[\theta, \phi]_{MA} = [33, 150]$  •  $[E, Az]_{NB} = [50, 303]$



ev000654.0077 76342 - 29-Apr-2020 04:45:19 - Min. na 575528497 - MC250 na 575532554 - Filter [25-30] MHz



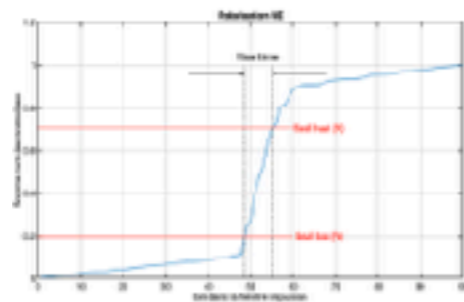
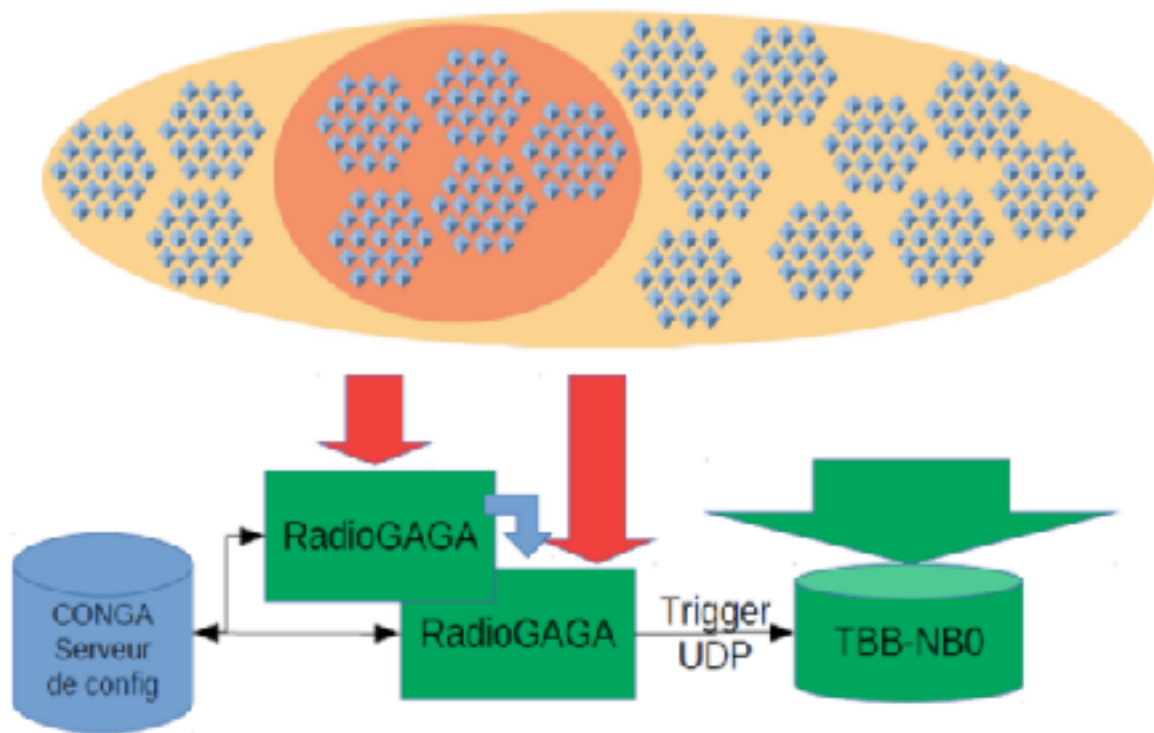
CODALEMA



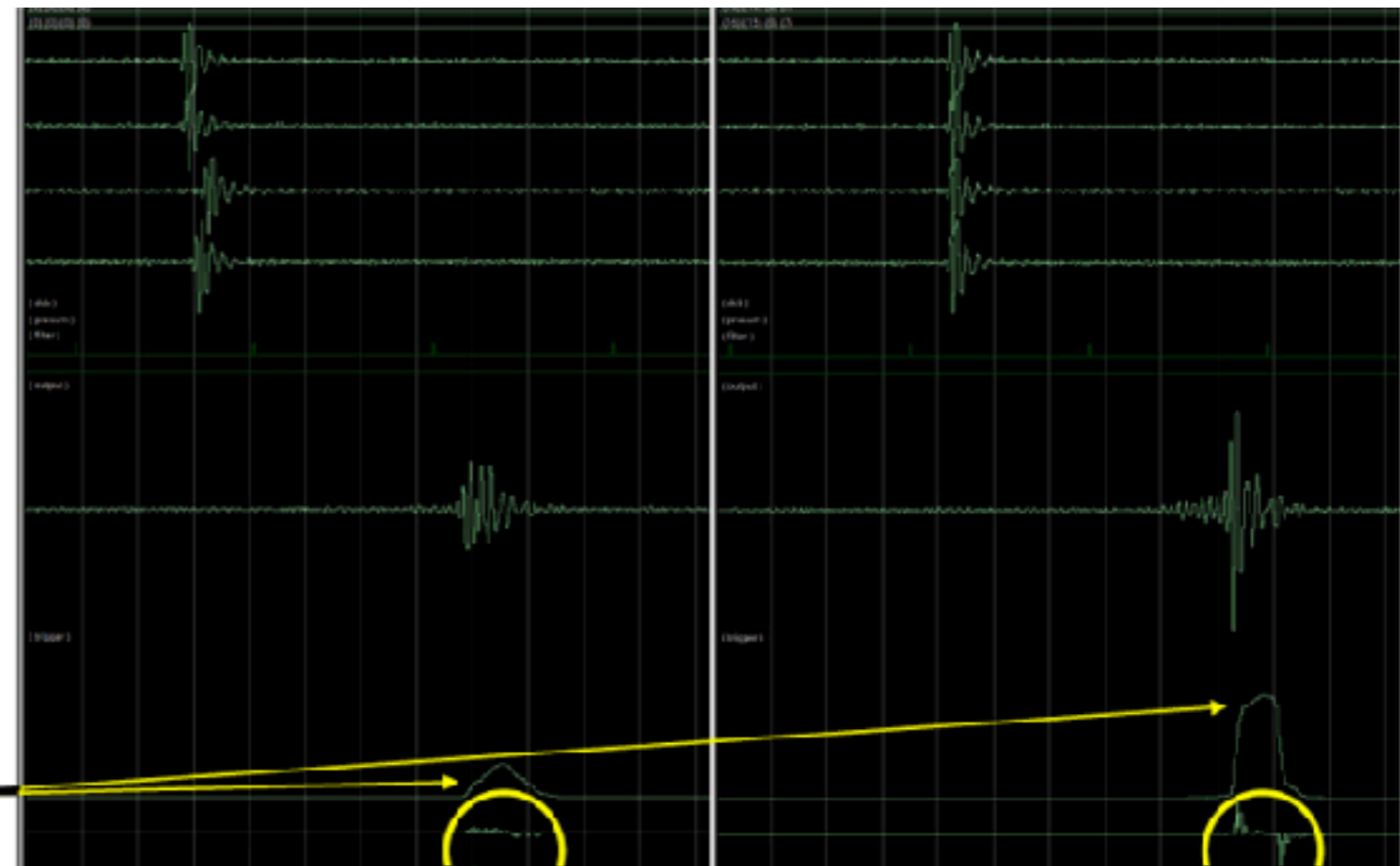
# ES12: Radio Gamma : Trigger RadioGaGa

- Digital phasing of several Mini-Arrays for having a more sensitive trigger

[T. Berthet et al.]



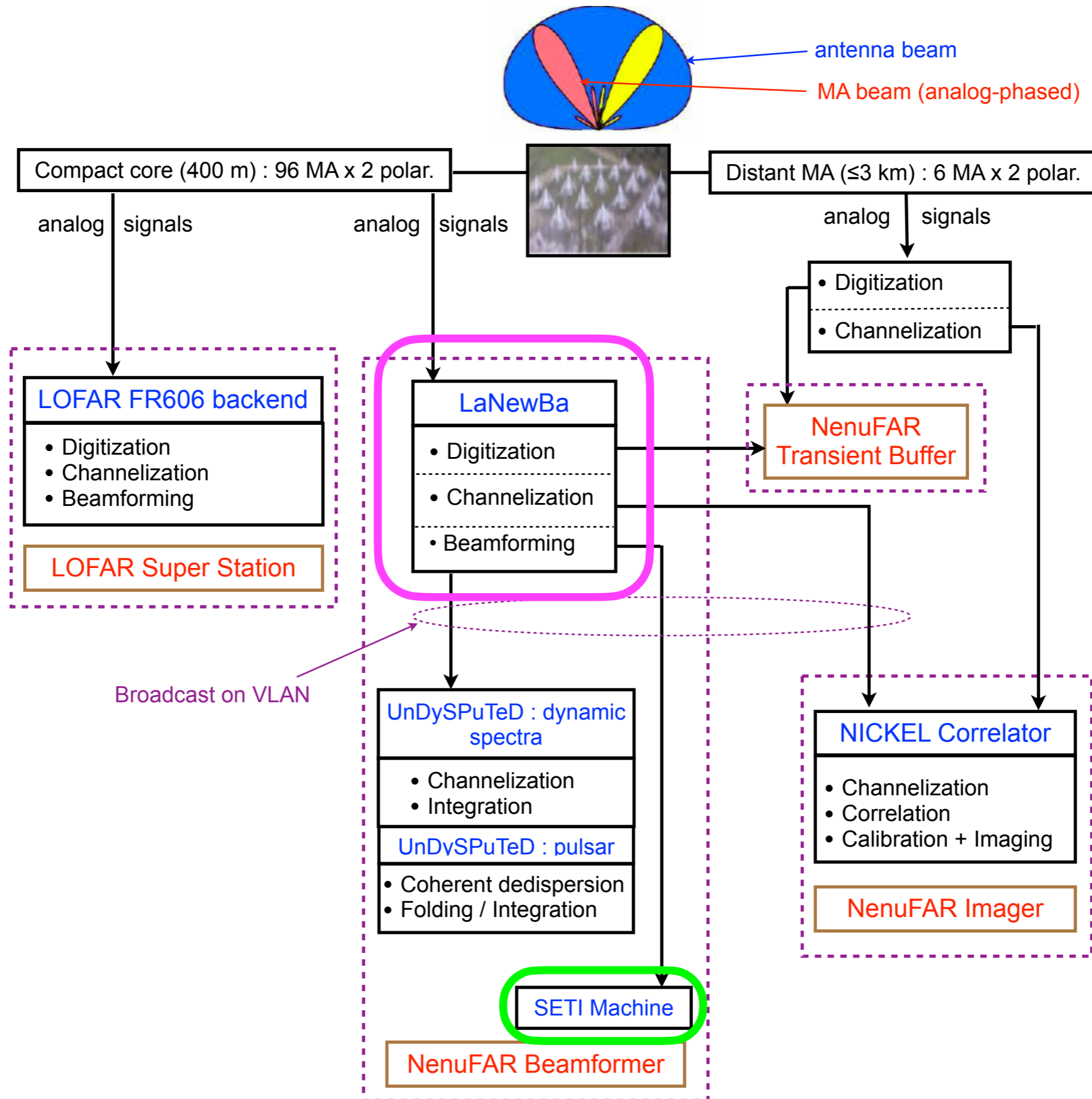
Somme cumulée  
sur fenêtre glissante



Signaux non phasés, faible **dérivée**

Signaux phasés, **dérivée** très forte

# Receivers and signal path

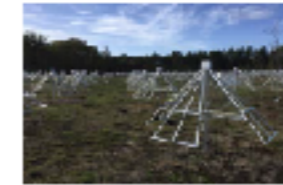


# ES13: SETI

## Current BL Observing plan for TESS targets



**Murchison Widefield Array**  
 Murchison Radio astronomy observatory, Western Australia  
 contact: Steve Croft (scroft@raam.berkeley.edu)  
 -----  
 4096 dipole array (SKA LOW precursor)  
 80 - 300 MHz  
 Extremely radio-quiet site  
 Large field-of-view allows continuous searches towards TESS targets in the southern sky.



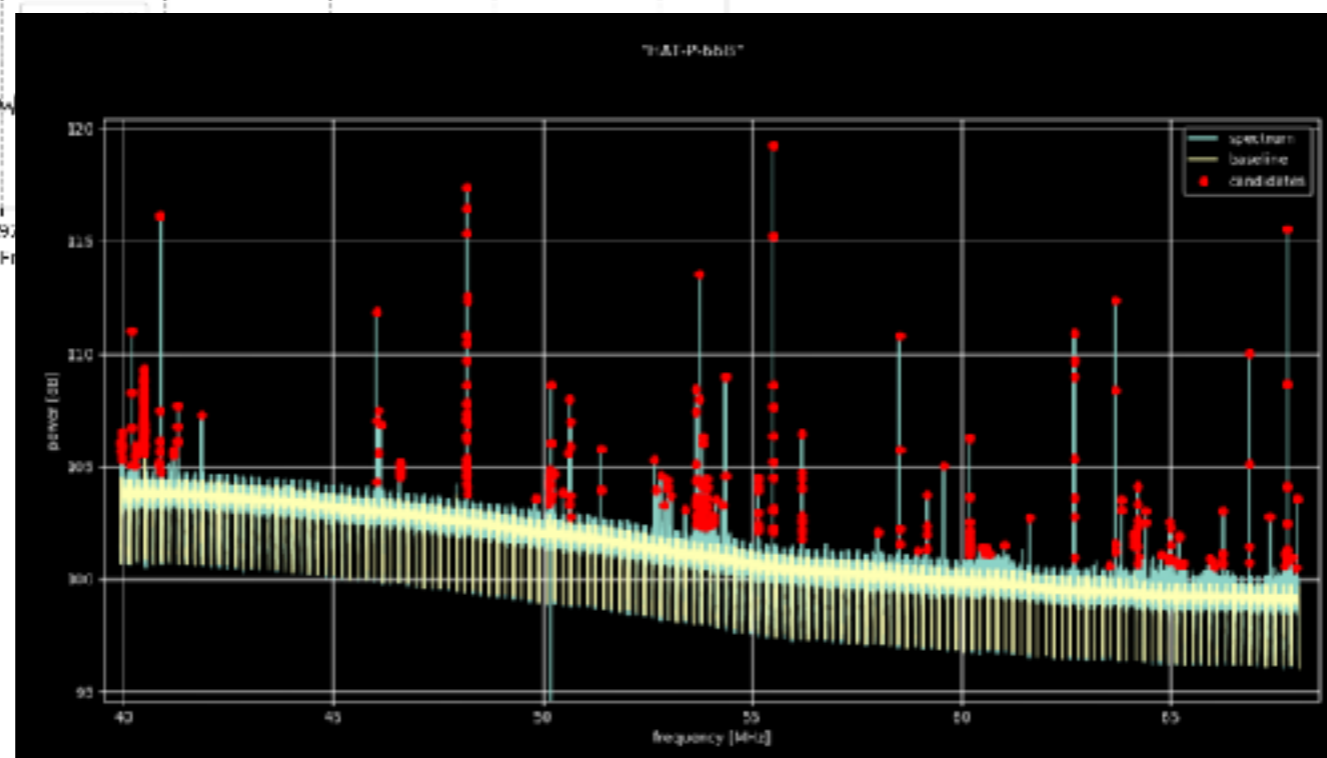
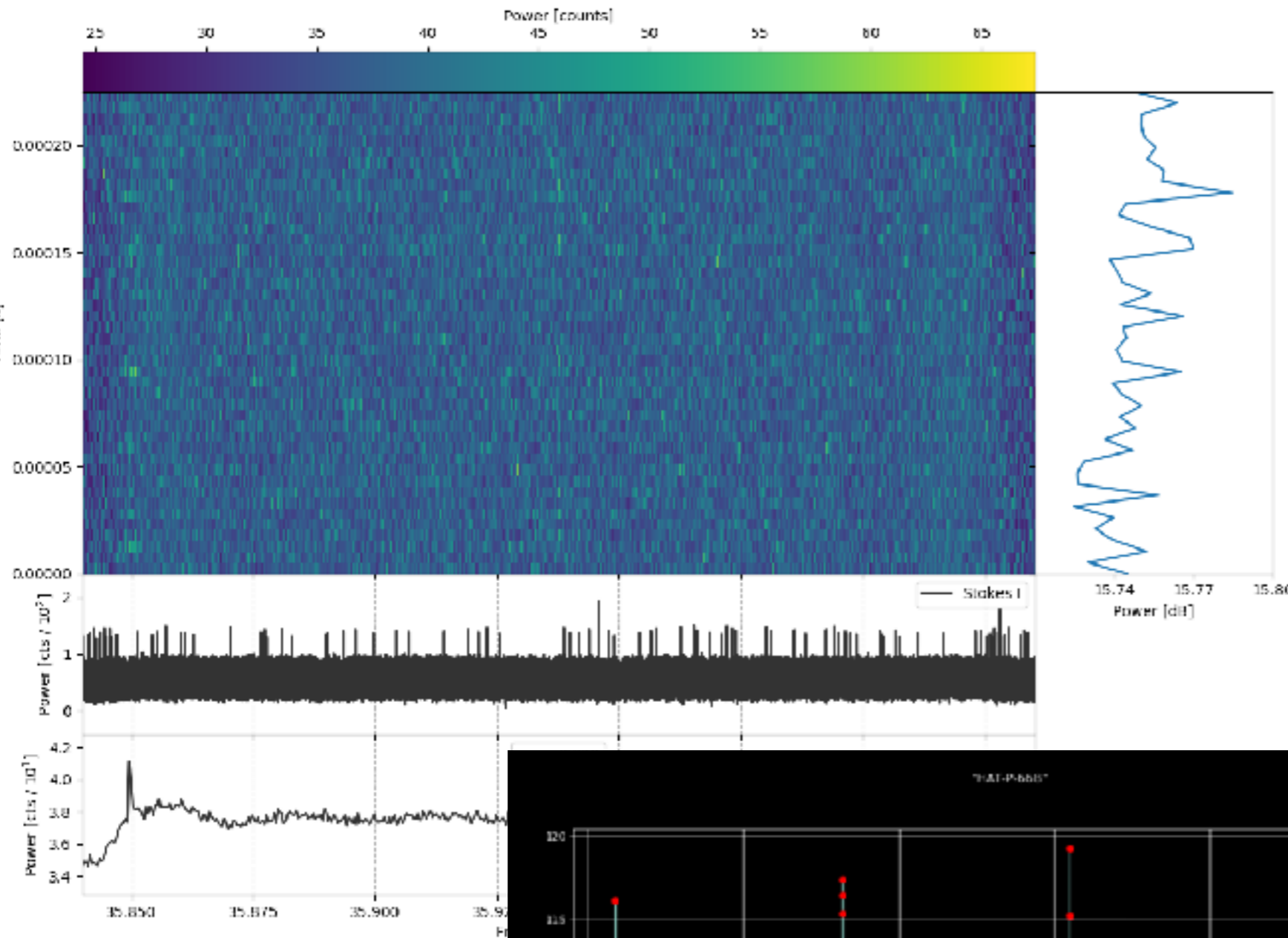
**NeuFAR Low Frequency Telescope**  
 Nançay Observatory, France  
 contact: Greg Hellbourg (greg.hellbourg@cea.fr) and Philippe Zarlin (philippe.zarlin@cea.fr)  
 -----  
 111 - 85 MHz  
 Voltage data capture enabled  
 Multichannel system allows continuous data capture  
 SETI program in observations with exoplanets (including TESS targets) is accepted as one of the Key Programs for NeuFAR commissioning program



**Parkes Observatory**  
 New South Wales, Australia  
 contact: Henry C. Price (hprice@berkeley.edu)  
 -----  
 64-meter antenna with newly-installed ultra-wide-band receiver covering 0.7 - 4 GHz  
 80 instrument: 27 GPU Nodes | 3.1 PB Storage  
 Program to followup TESS targets in the southern sky with 200 hours dedicated observations.



**Sardinia Radio Telescope**  
 Sardinia, Italy  
 contact: Andrea Melis (andrea.melis@iqg.it) and Vito Gajjar (vito.gajjar@berkeley.edu)  
 -----  
 64 m single dish antenna  
 Frequency coverage 300 MHz - 26 GHz with new planned receiver to go up to 115 GHz  
 BL instrument: 1 local node and 2 GPU nodes  
 Around 12 TESS targets will be observed across 18 - 26 GHz.



[G. Hellbourg]

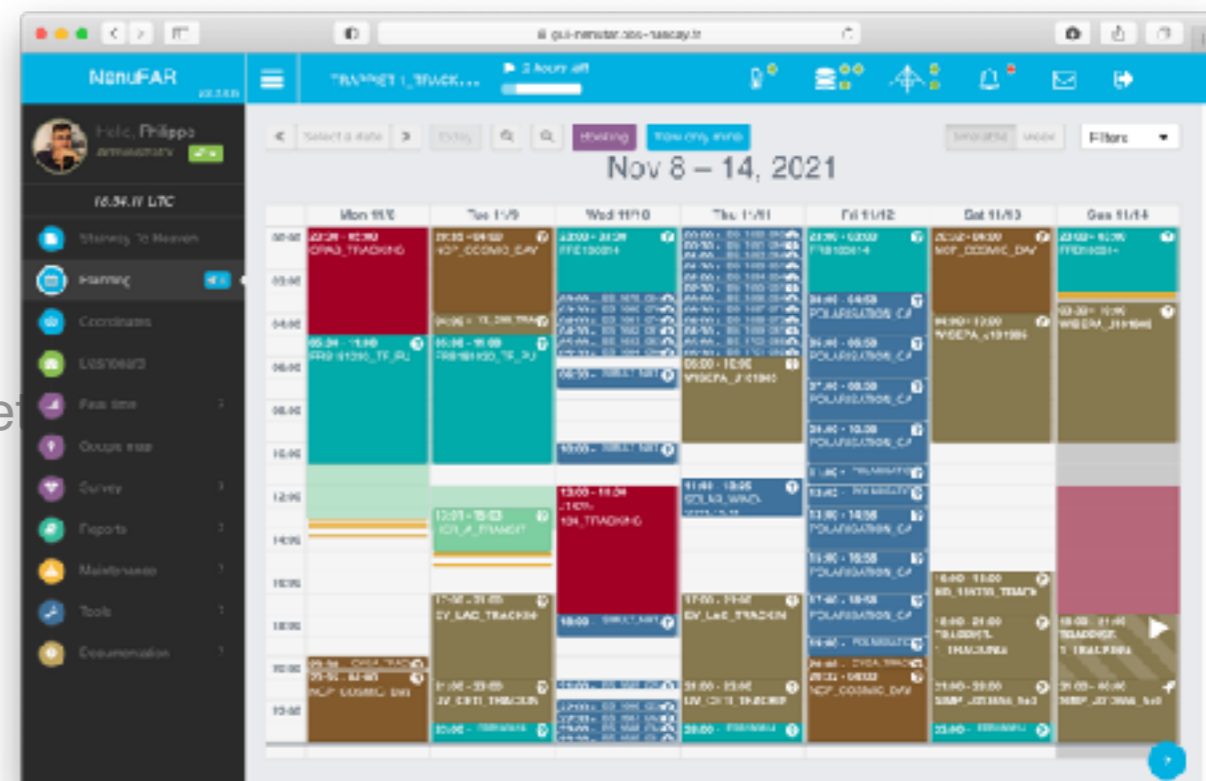
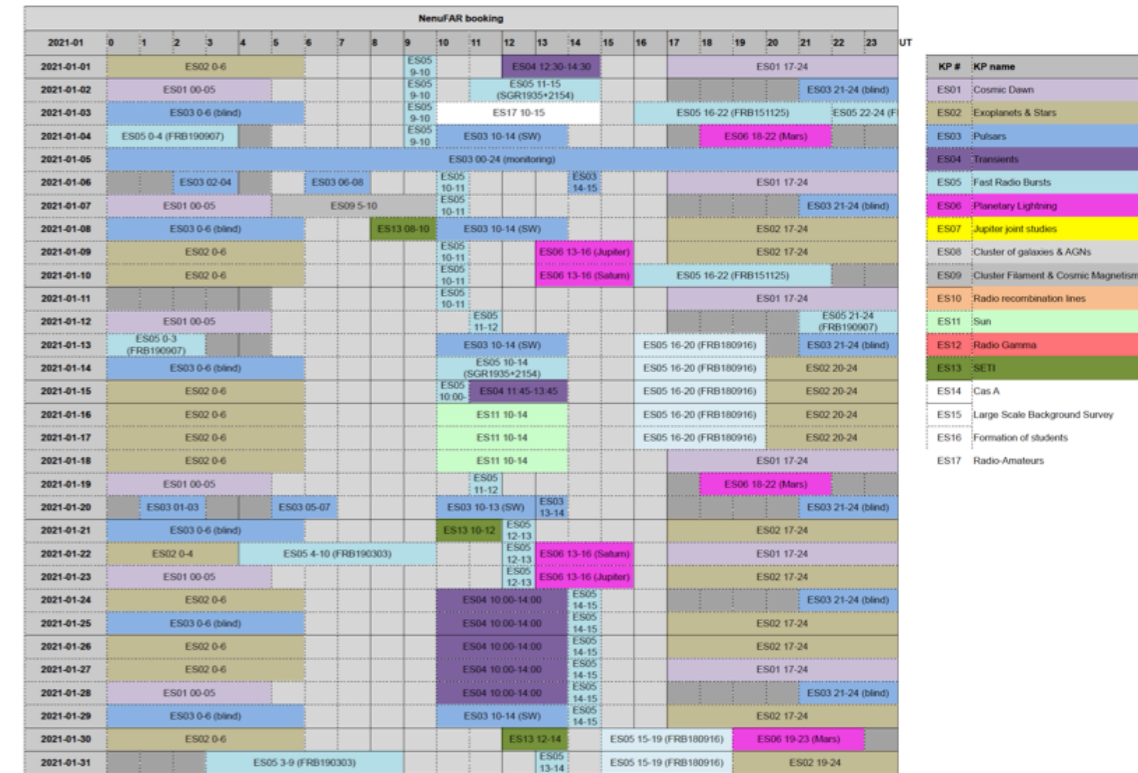
# Science organization

- « Early Science » phase  $\geq$  1/7/2019, for 7 semesters, until 1/12/2022

## Key / Pilot programs

- ES01 Cosmic Dawn KP (Koopmans, Semelin et al.)
  - ES02 Exoplanets & Stars KP (Zarka, Lamy et al.)
  - ES03 Pulsars KP (Grießmeier et al.)
  - ES04 Transients KP (Corbel, Girard et al.)
  - ES05 Fast Radio Bursts PP (Decoene, Zarka et al.)
  - ES06 Planetary Lightning KP (Grießmeier et al.)
  - ES07 Joint Jupiter studies KP (Yerin, Lamy et al.)
  - ES08 Cluster of galaxies & AGNs KP (Pommier et al.)
  - ES09 Cluster Filament & Cosmic Magnetism PP (Bonnassieux et al.)
  - ES10 Radio recombination lines PP (Gusdorf et al.)
  - ES11 Sun KP (Carley, Masson et al.)
  - ES12 Radio Gamma KP (Dallier et al.)
  - ES13 SETI KP (Hellbourg et al.)
  - ES14 Cas A PP (Konovalenko et al.)
  - ES15 Large Scale Background Survey PP (Sidorchuk et al.)
- + Formation of students, Radio-Amateurs group

- Pressure  $<$ 1 day,  $\geq$ 1 night



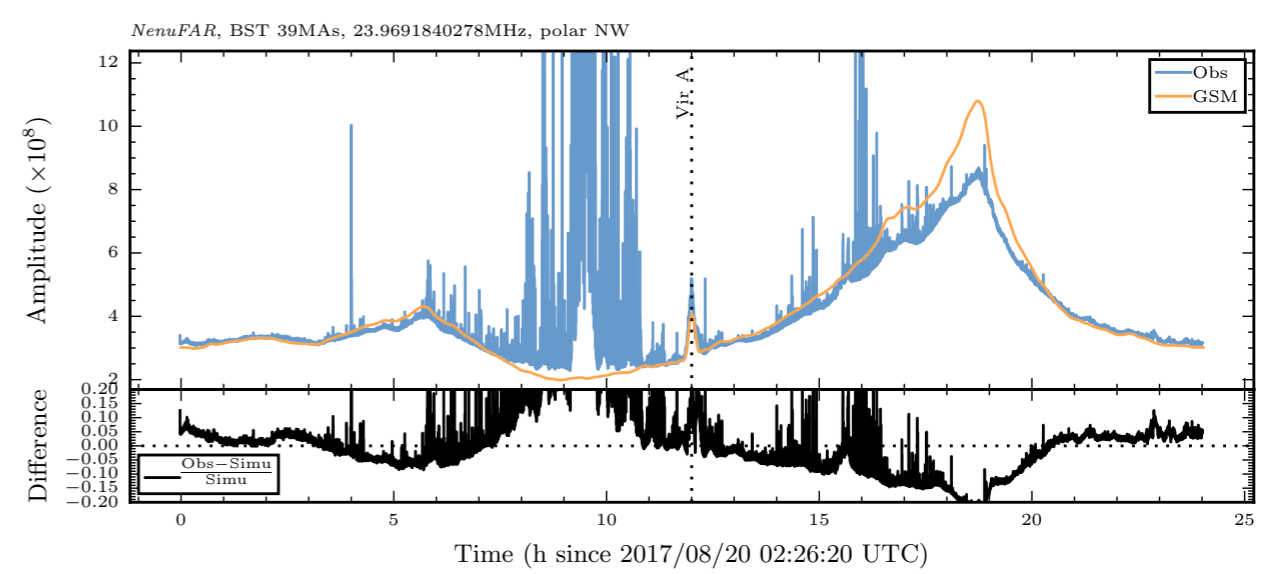
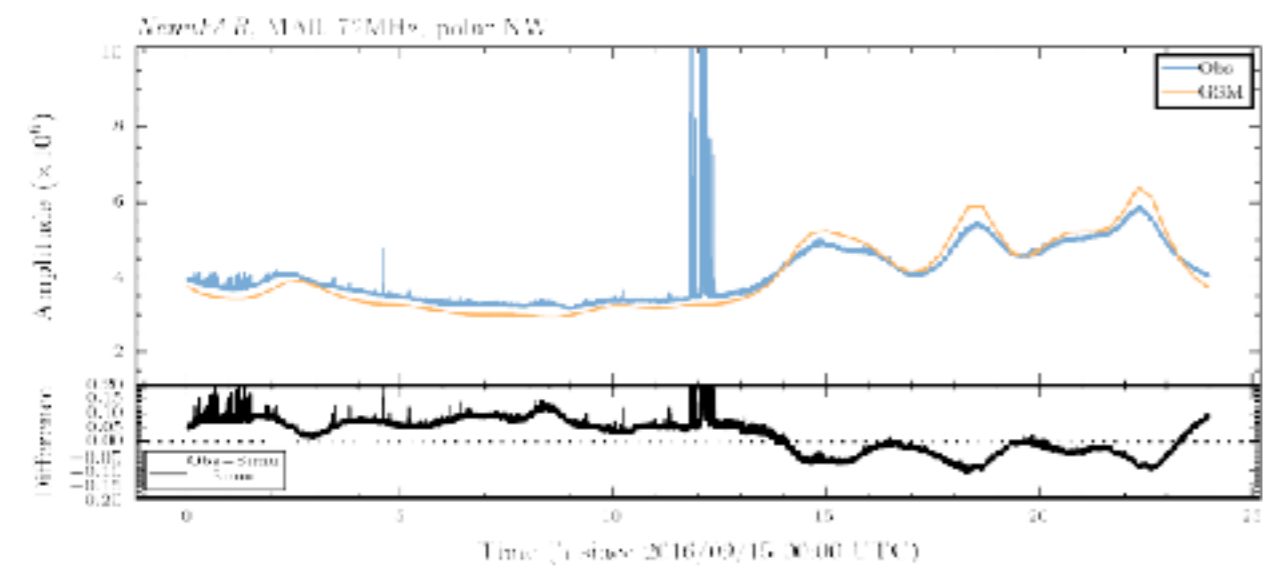
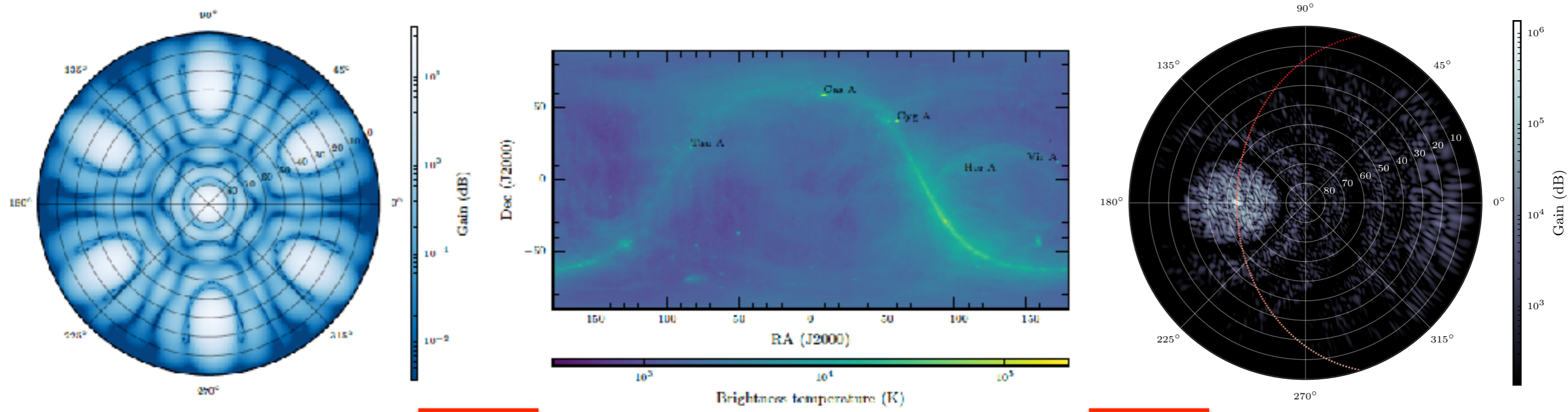
# Virtual Control Room

The screenshot displays the NenuFAR web interface. At the top, the browser address bar shows 'gui-nenufar.obs-nancay.fr'. The interface includes a dark sidebar on the left with the 'NenuFAR v3.17.1' logo and a user profile for 'Philippe Administrator'. The main content area features a 3D model of the radio telescope antenna structure overlaid on a satellite-style map of the site. A '6 hours' timer is visible in the top right. A large white overlay box on the right contains the text: 'WELCOME TO NenuFAR. Welcome to the largest low-frequency radiotelescope in the world Nancay. Just come in and have a look at this wonderful world.' Below the text is a cartoon frog character and a 'Continue' button. A sidebar on the left lists various navigation options: Stairway To Heaven, Planning, Coordinates, Dashboard, Real time, Google map, Survey, Reports, Maintenance, Tools, and Documentation.

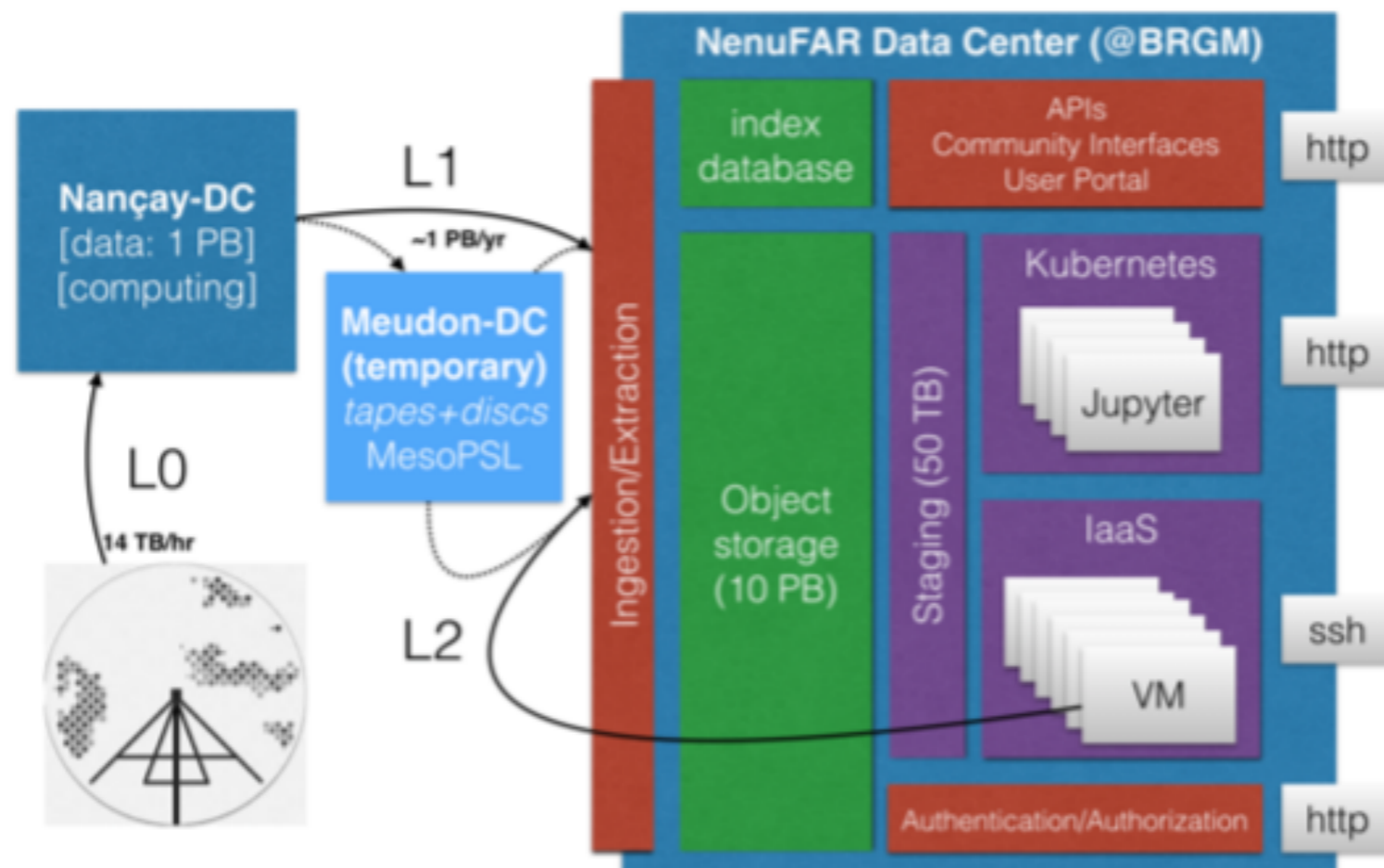
This block shows a 'SKA-France Monthly Bulletin' for November 2019. The header includes the SKA-France logo and navigation links for 'Announcements' and 'News from NenuFAR'. The main text section is titled 'Announcements' and 'News from NenuFAR'. It contains a paragraph about the NenuFAR project, describing it as a new low-frequency radio array of 1000 antennas (Virtual Antennas) in the field of radio astronomy and part of the scientific program of the French Radio Astronomy Program. It mentions the project's goal to observe the sky in the 10-100 MHz range, which is currently unexplored. The text also discusses the project's scientific goals, such as studying the evolution of galaxies and the intergalactic medium, and the role of the NenuFAR project in the SKA-France program. An inset image in the bottom right corner shows a screenshot of the NenuFAR interface, similar to the one in the main image.

[C. Taffoureau et al.]

# Simulations : nenupy



# Data storage and processing

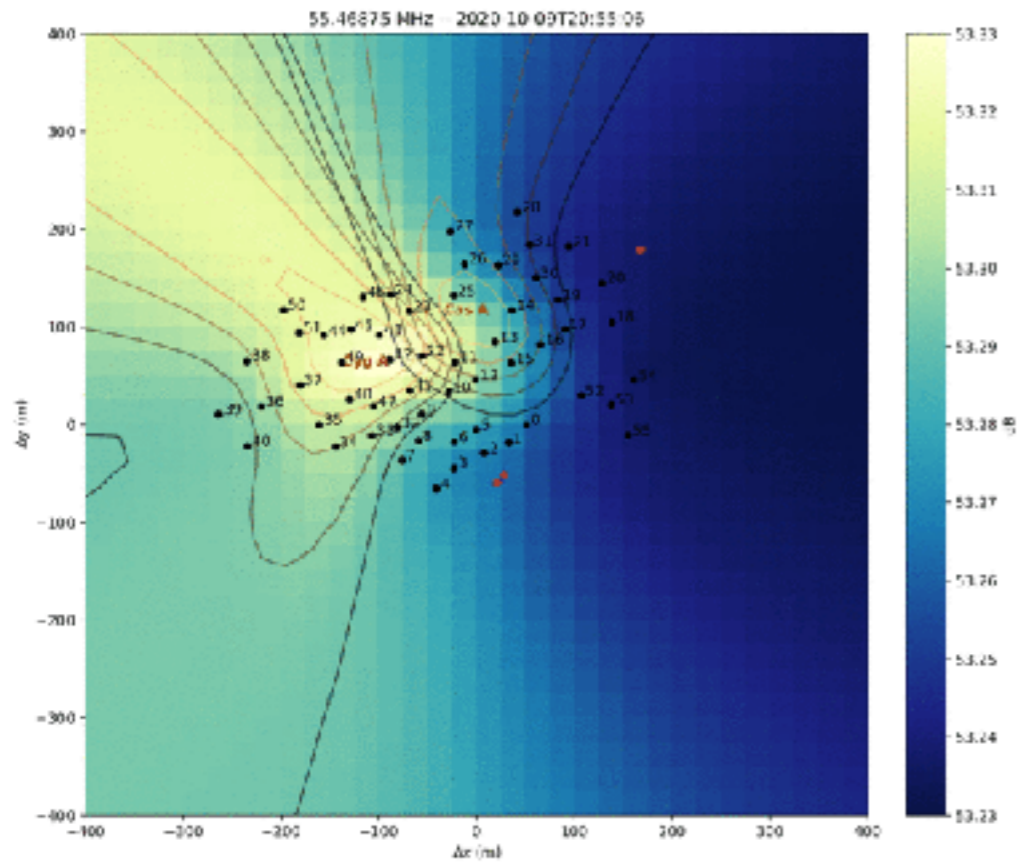


[B. Cecconi et al.]

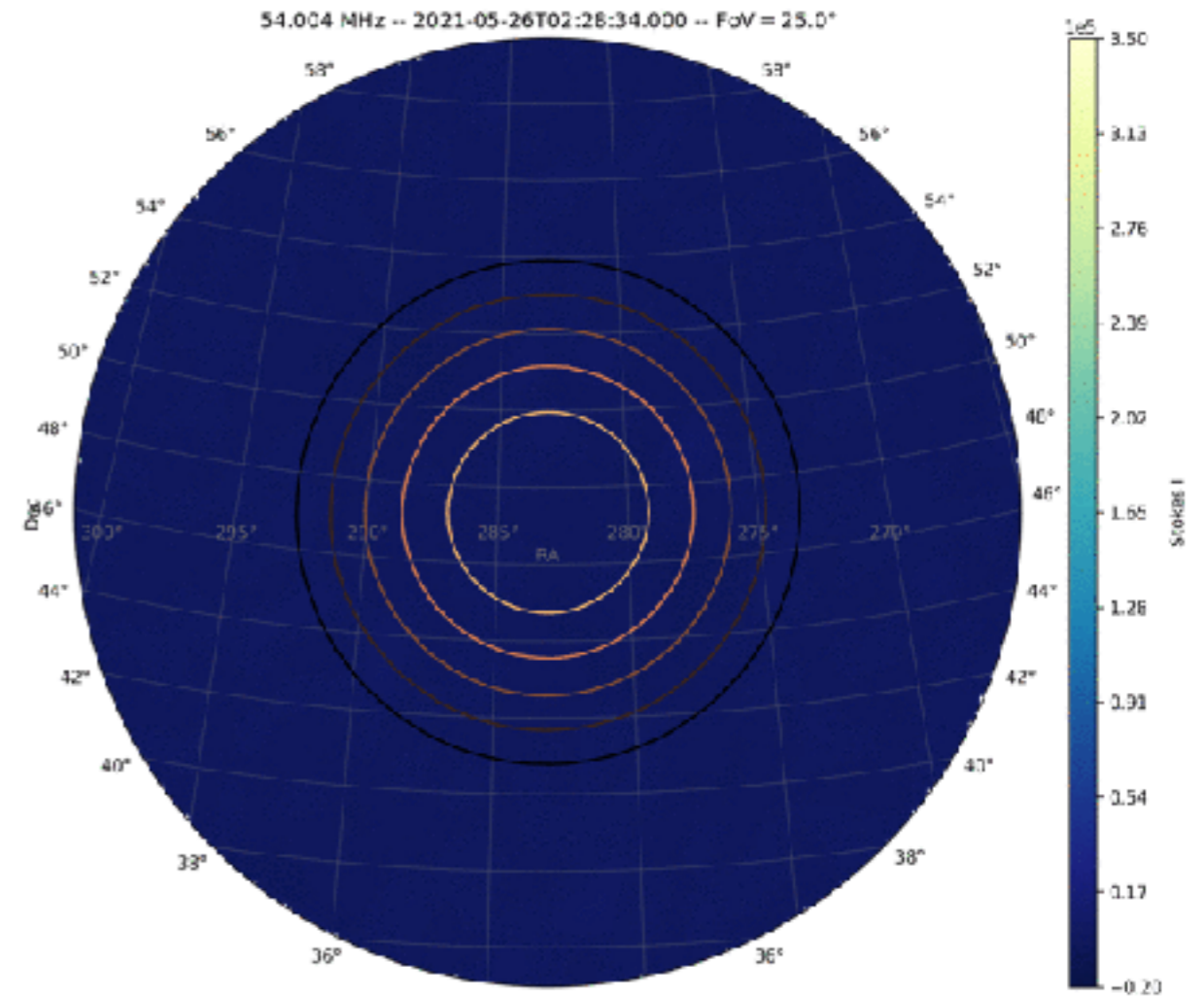
- Data: 100 GB/h beamforming, 2 TB/h imaging
- Pre-processing/reduction in Nançay
- then transfer to Data-center (in preparation with BRGM), based on cloud/docker... technologies
- in connection with GENCI, EOSC...

# NenuFAR-TV

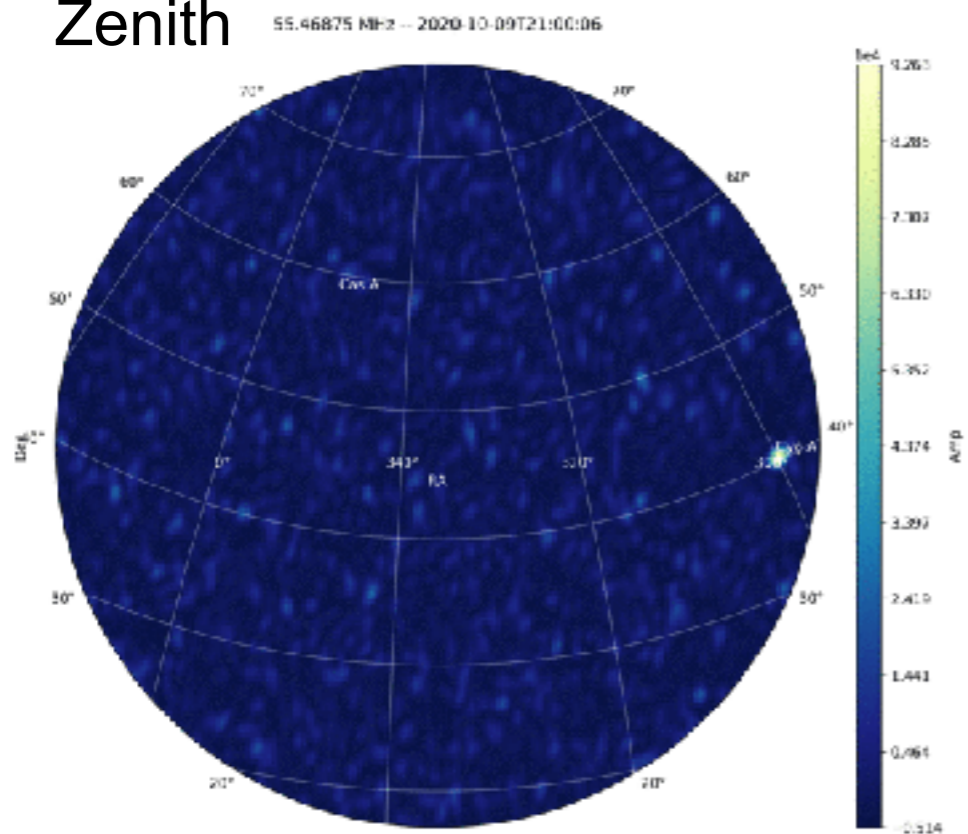
## Near-field



## Beam



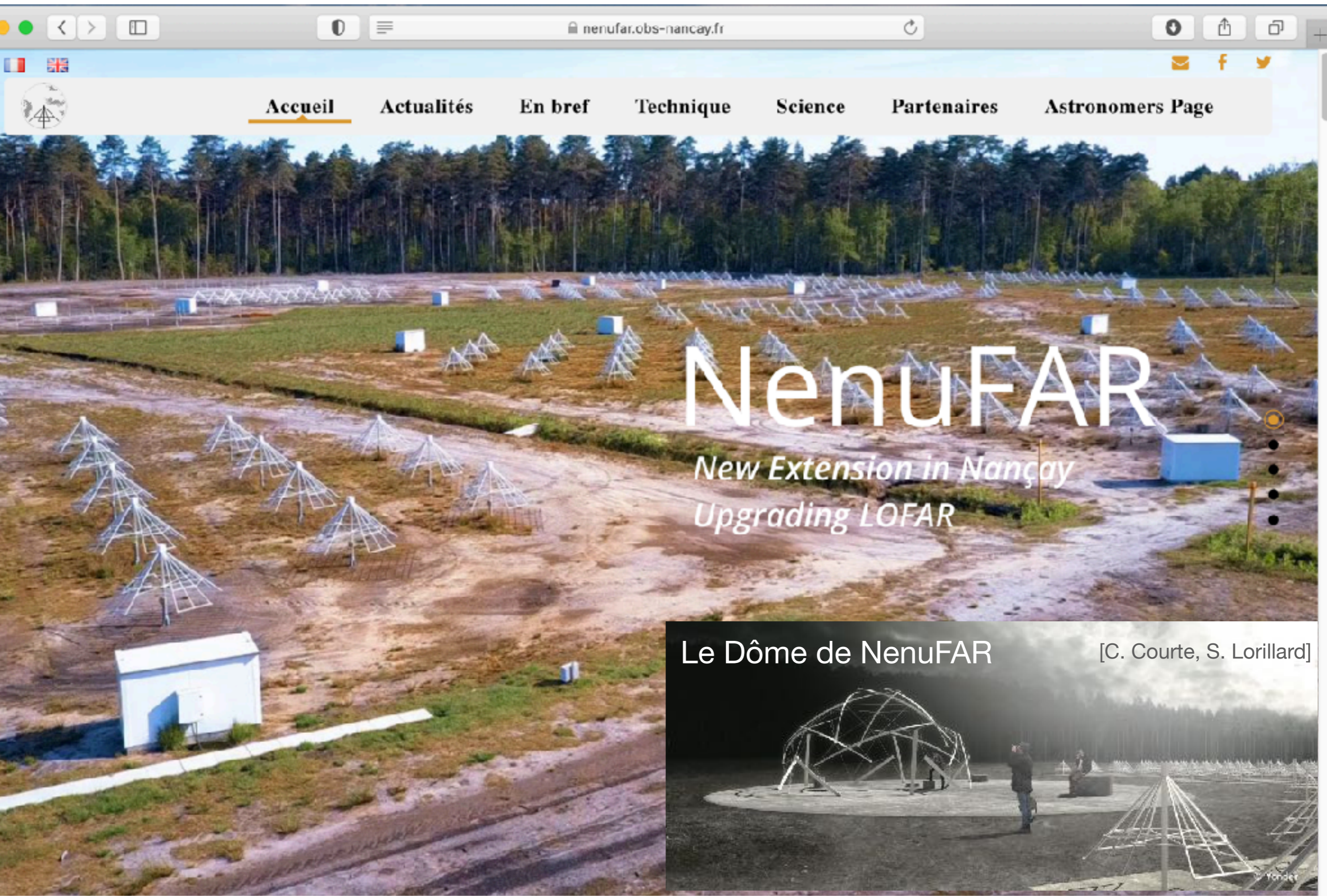
## Zenith



→ <https://nenufar.obs-nancay.fr/nenufar-tv/>



Web site : public, astronomers, news ...



The image shows a screenshot of the NenuFAR website. The browser address bar displays "nenufar.obs-nancay.fr". The navigation menu includes "Accueil", "Actualités", "En bref", "Technique", "Science", "Partenaires", and "Astronomers Page". The main content area features a large photograph of the NenuFAR antenna array under construction in a field, with a dense forest in the background. Overlaid on the image is the text "NenuFAR" in large white letters, followed by "New Extension in Nançay" and "Upgrading LOFAR" in smaller white text. A vertical navigation menu is visible on the right side of the image.

Accueil Actualités En bref Technique Science Partenaires Astronomers Page

# NenuFAR

*New Extension in Nançay  
Upgrading LOFAR*

Le Dôme de NenuFAR [C. Courte, S. Lorillard]

# Funding & Construction

- Budget secured for complete core +  $\geq 4$  distant MA (DIM-ACAV+, CPER, ERC, JSPS?...)
- Completion of NenuFAR (96 + 6 MA) & insertion in LOFAR 2.0 (LSS) expected  $\leq 2023$
- TBD: end of deployment + antenna EM simulations (origin of pointing shift?), upgraded analog pointing, 1 min./1 sec. analog/digital pointing, lower self-generated RFI ...

## Timeline

- 2009-13: Design Study
- 2014-now : Construction, Commissioning...
- 12/2018 : Call for KP proposals
- 3/2019 : 1st Users Workshop
- 1/7/2019 : Start of Early Science phase
- 3/10/2019 : Inauguration
- 17-19/11/2021 : 2nd Users Workshop
- 1/12/2022 : Start of open time (PI programs, from 10-20% to 50-75% in  $\geq 5$  years)

# How to get involved ?

- Contact the Comité Scientifique de NenuFAR ([nenufar-csn@obs-nancay.fr](mailto:nenufar-csn@obs-nancay.fr))
  - ➡ to join a KP
  - ➡ to propose a new KP
  - ➡ to be on the nenufar-news list
  - ➡ to follow NenuFAR-France project meetings
  - ➡ for any question
- Prepare to propose targeted (PI) observations by 2022Q4 (better to have first practiced within a KP)
- Analyze data distributed through the data-center (in construction)

# Lessons NenuFAR → SKA (low)

- sky is clean >50 MHz
- analog beamforming: saves computing power, electronics critical
- DynSpecMS
- VCR
- management of many modes in parallel, SETI in piggyback
- interest for LOFAR of a large coherent station, not made of sub-stations
- TV mode (monitoring, outreach)
- instrument simulations (nenupy package on github)

## Synergies NenuFAR - SKA

- complementary frequency bands
- different hemispheres
- prepare (with LOFAR) and explore feasibility of studies of Cosmic Dawn, Exoplanets, Planetary lightning, Fast Radio Bursts at LF...
- prepare the French community (now member of SKA organization)

# Publications

## Recent publications

- Bondonneau, L., and the NenuFAR-France collaboration, Low frequency pulsar observations with NenuFAR, Proc. JS 19 URSI-France, OVSQ, 26-27/3/2019.
- Dallier, R., et al., Exploration of the potential of the radio-detection technique for the detection of high-energy gamma rays, PoS(ICRC2019)655, 2019. <https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=358>
- Zarka, P., and the NenuFAR-France team, The low-frequency radio telescope NenuFAR, session J01 « New Telescopes on the Frontier », URSI GASS, 29/8-5/9/2020. <http://www.ursi.org/proceedings/procGA20/papers/URSIGASS2020SummaryPaperNenuFARnew.pdf>
- Bondonneau, L., et al., Pulsars with NenuFAR: backend and pipelines, Astron. Astrophys., 652, A34, 2021.
- Agar, C. et al., A broadband radio study of PSR J0250+5854: the slowest-spinning radio pulsar known, MNRAS, in press, 2021.
- Carley, E., et al., Observations of shock propagation through turbulent plasma in the solar corona, Astrophys. J., in press, 2021.
- Bonnassieux, E. et al., First Lights on the Cosmic Magnetism Project with NenuFAR: the Coma Cluster field, Galaxies, in press, 2021.
- Tiburzi, C., et al., Frequency-dependent dispersion measure detected during the Solar approach of PSR J1022+1001, Astron. Astrophys., submitted.
- Bilous, A., et al., Dual-frequency single-pulse study of PSR B0950+08, Astron. Astrophys., submitted.

## In preparation

- Girard, J. & P. Zarka, Optimal phased array tile configurations for LOFAR-class instruments, A&A, to be submitted.
- Mertens, F., et al., Cosmic Dawn observations with NenuFAR, to be submitted.
- Charrier, D., et al., NenuFAR antenna and preamplifier, in preparation.
- NenuFAR collaboration, The LF radiotelescope NenuFAR, Exp. Ast., in preparation.

## Theses

- Girard, J., Thèse de Doctorat, ED AA IdF, Développement de la Super Station LOFAR & Observations planétaires avec LOFAR, 21/5/2013. <https://tel.archives-ouvertes.fr/tel-00835834>
- Bondonneau, L., Thèse de Doctorat, Université d'Orléans, Première caractérisation de la population de pulsars radio à basses fréquences avec NenuFAR, 8/11/2019. <https://tel.archives-ouvertes.fr/tel-02911847>

## Internet

- Web site: <https://nenufar.obs-nancay.fr> → astronomers, news ...
- NenuFAR inauguration, 2019 : <https://www.obspm.fr/inauguration-de-nenufar-un.html>
- SKA-France Bulletins #48 of 11/2020 (VCR) and #49 of 12/2020 (NICKEL first light): <https://ska-france.oca.eu/fr/bulletins>
- NICKEL first light @ ASTRON image of the day 1/2/2021 : <https://www.astron.nl/dailyimage/main.php?date=20210201>