

# The NenuFAR project\*

\* New Extension in Nançay Upgrading LOFAR

**P. Zarka<sup>1</sup>, M. Tagger<sup>2</sup>, L. Denis<sup>3</sup>, J. Girard<sup>1,4</sup>,  
& the NenuFAR-France team<sup>5</sup>**

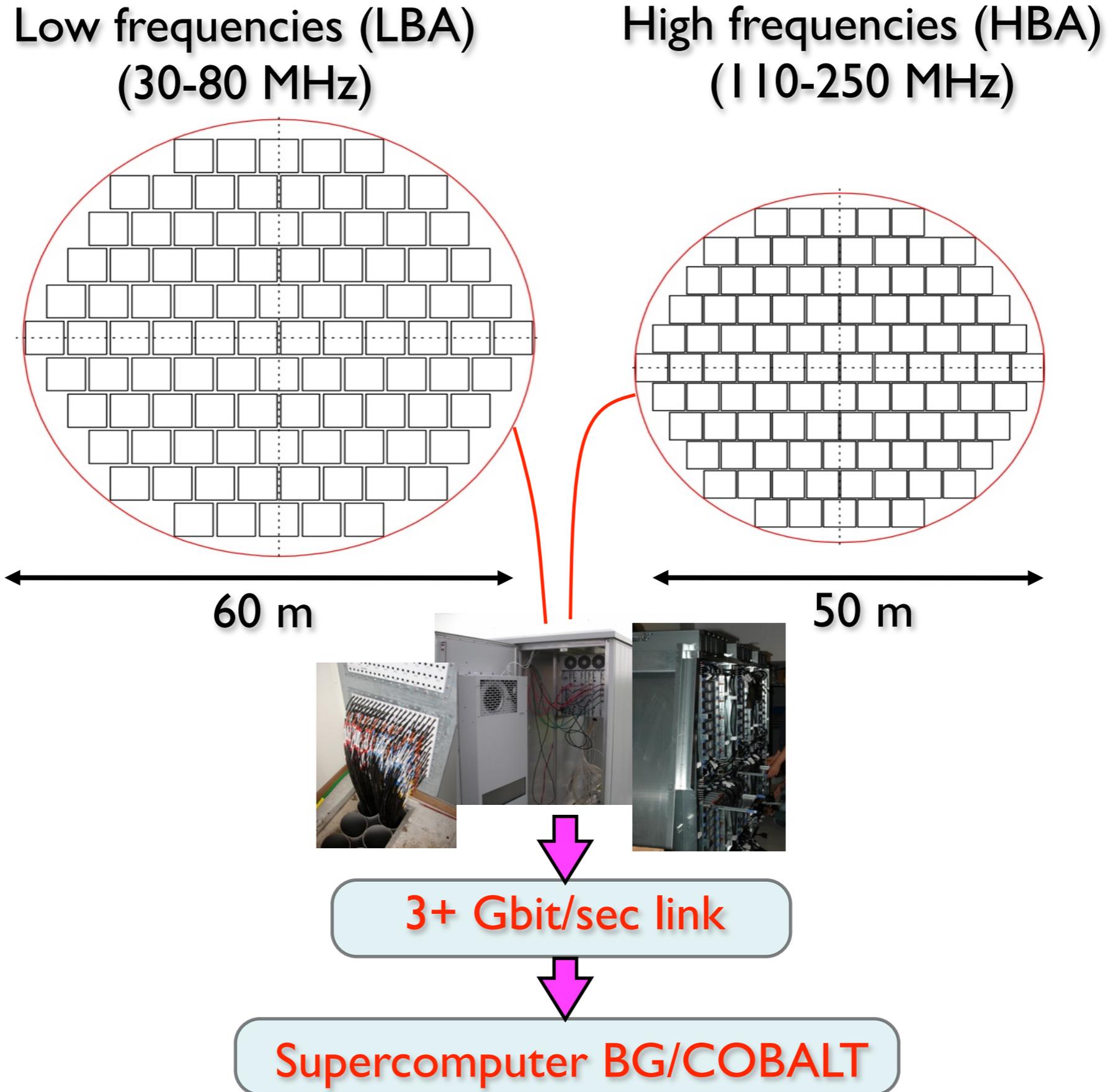
*<sup>1</sup>LESIA-OP, <sup>2</sup>LPC2E-Orléans, <sup>3</sup>USN-OP, <sup>4</sup>CEA-Saclay,*

*<sup>5</sup>Everywhere in France especially in Nançay*

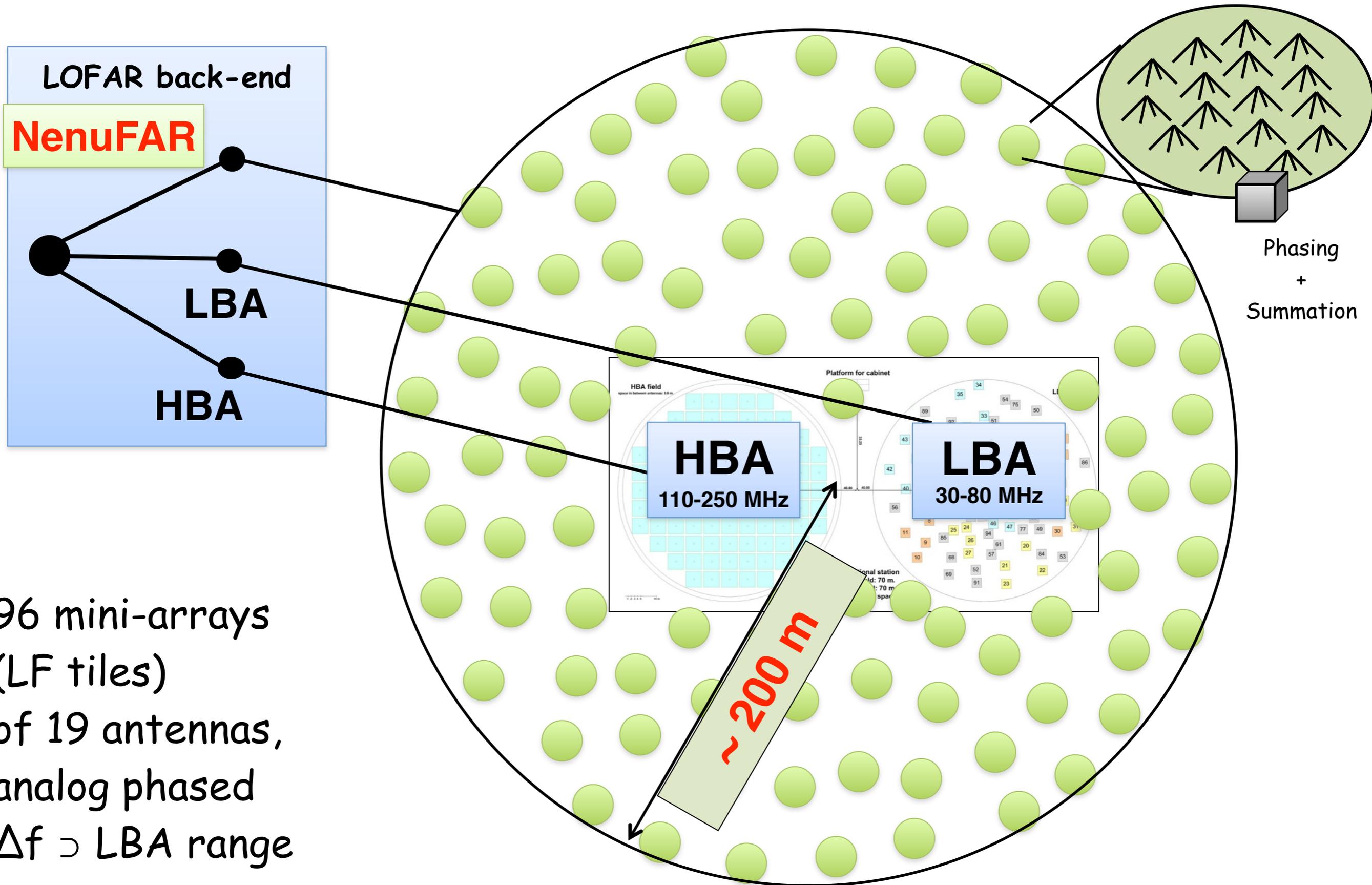
# LOFAR station in Nançay : FR606



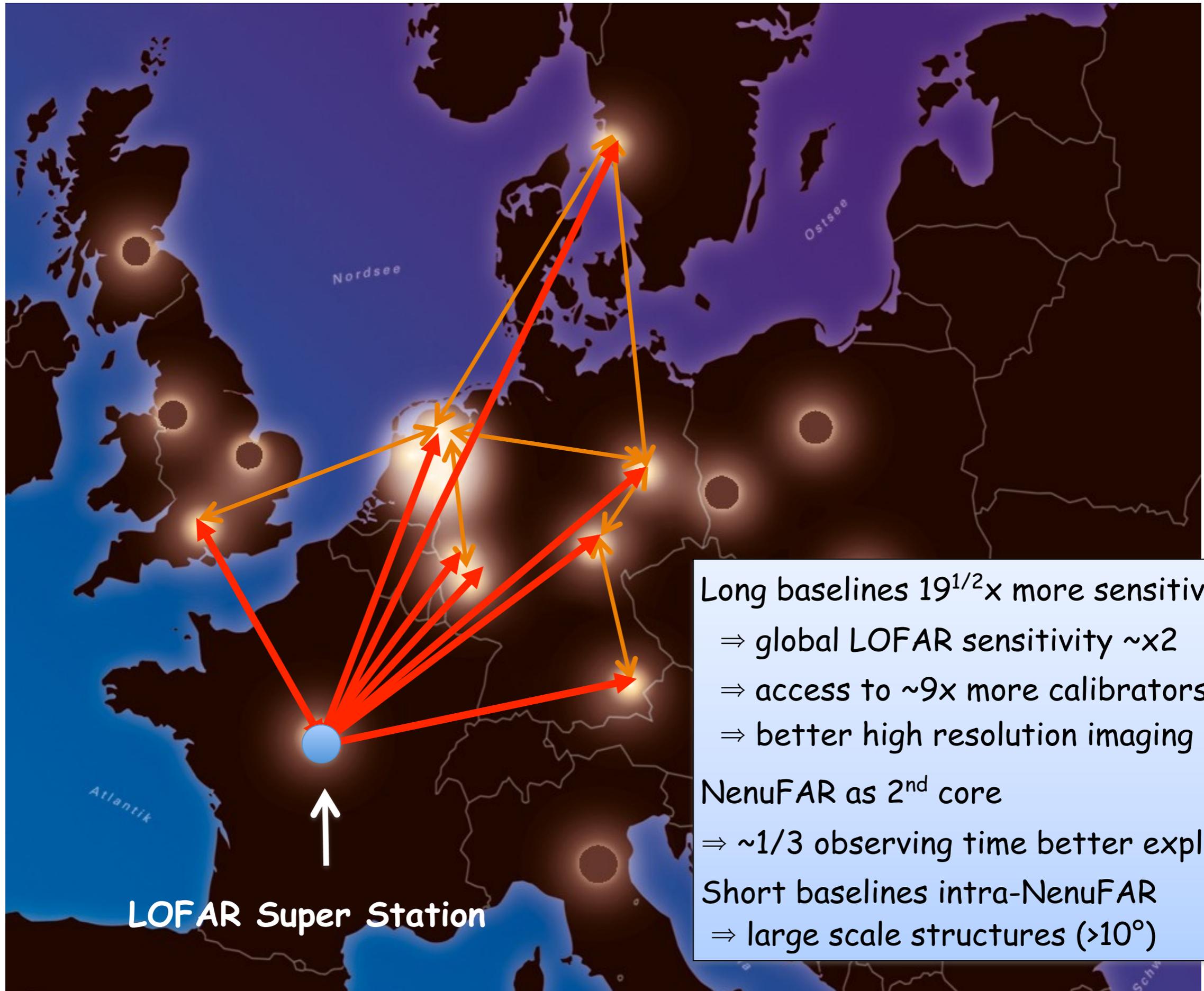
# LOFAR station in Nançay : FR606



# The NenuFAR concept : giant local phased array + interferometer



# What NenuFAR will bring ?



Long baselines  $19^{1/2}$ x more sensitive  
⇒ global LOFAR sensitivity  $\sim$ x2  
⇒ access to  $\sim$ 9x more calibrators  
⇒ better high resolution imaging

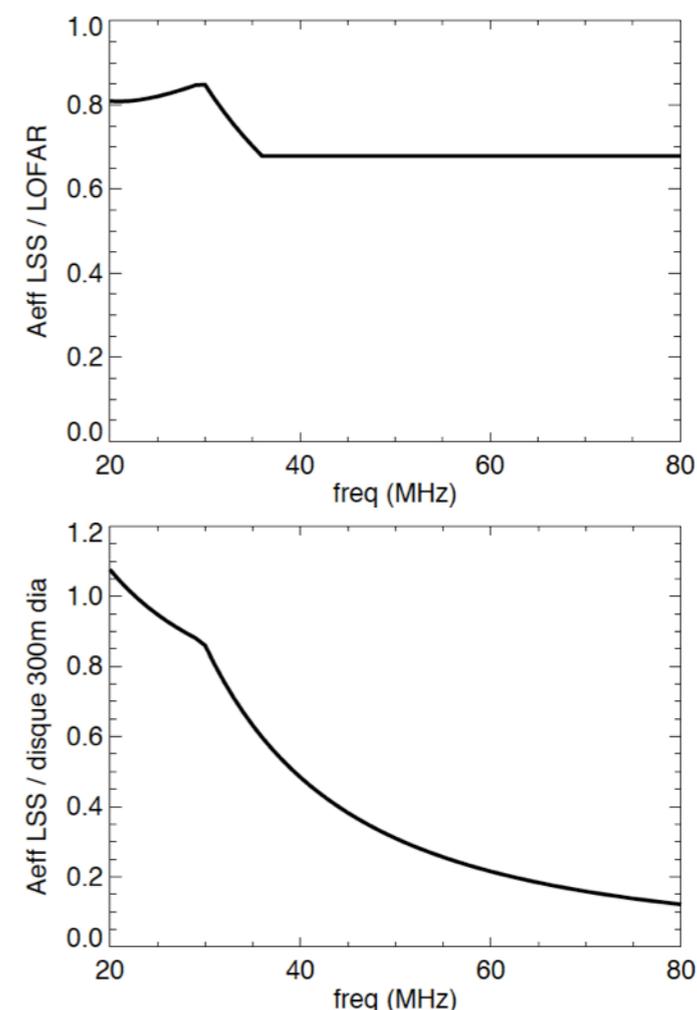
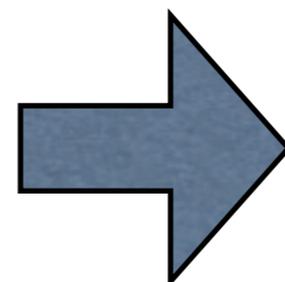
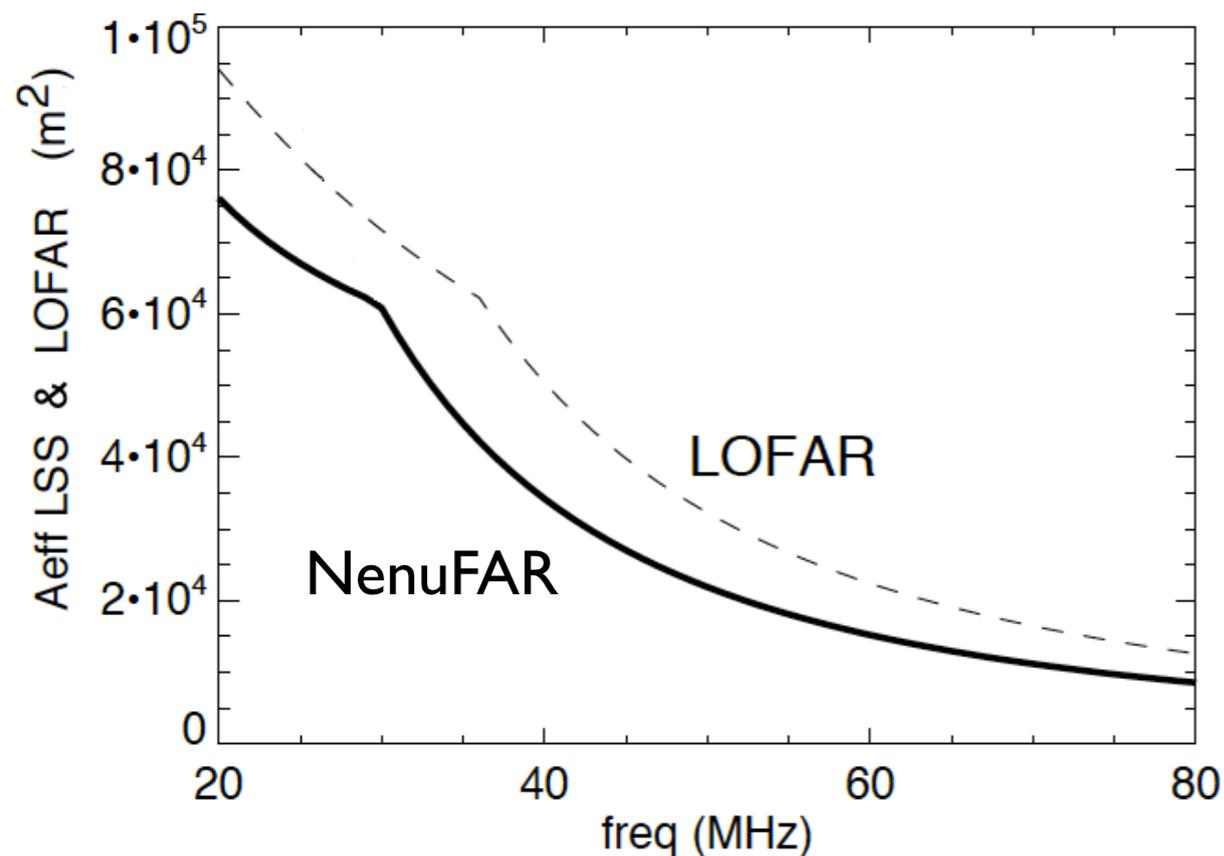
NenuFAR as 2<sup>nd</sup> core

⇒  $\sim$ 1/3 observing time better exploited

Short baselines intra-NenuFAR

⇒ large scale structures ( $>10^\circ$ )

# What NenuFAR will bring ?



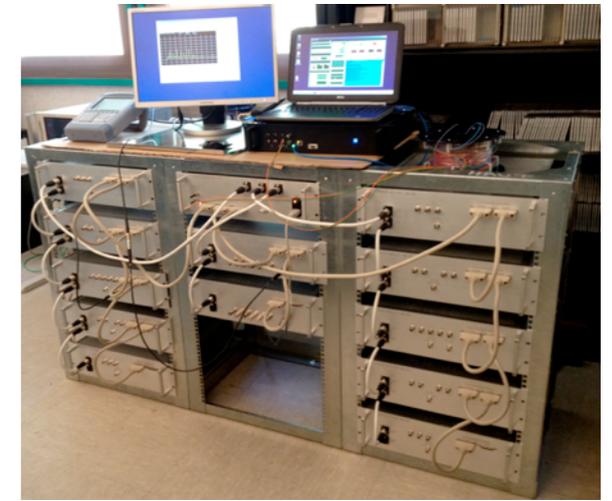
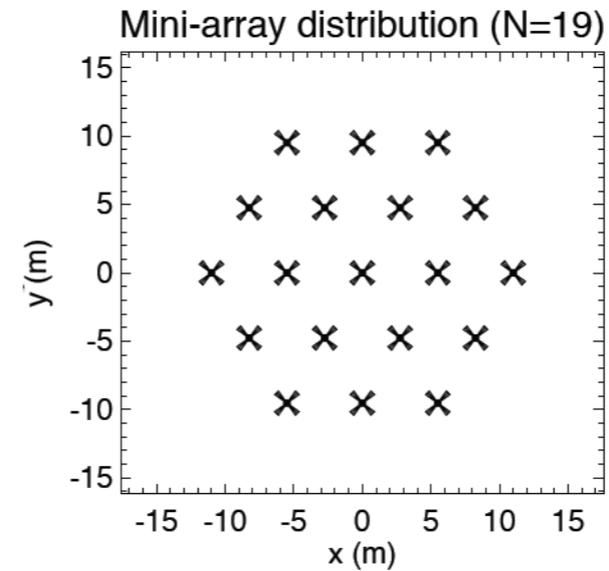
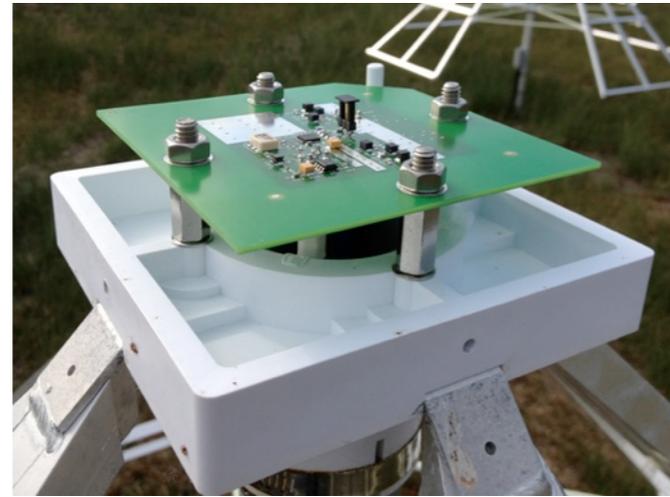
Large standalone instrument («LF Arecibo» in Nançay) with high instantaneous sensitivity

- ~19x the sensitivity of an international LOFAR station in LBA range
  - $A_{\text{eff}} = 70\text{-}80\% \times A_{\text{eff}} \text{ LOFAR LBA} = 190\% \times A_{\text{eff}} \text{ LOFAR core LBA}$
  - Access to VLF (10-85 MHz)
  - 2 full-band (75 MHz) full-polarization simultaneous coherent tied-array beams
- ⇒ coherent TAB mode > 2x more efficient than LOFAR
- ⇒ Instantaneous polarized imaging with 256 pixels in 8°-60° FoV within TBD bandwidth

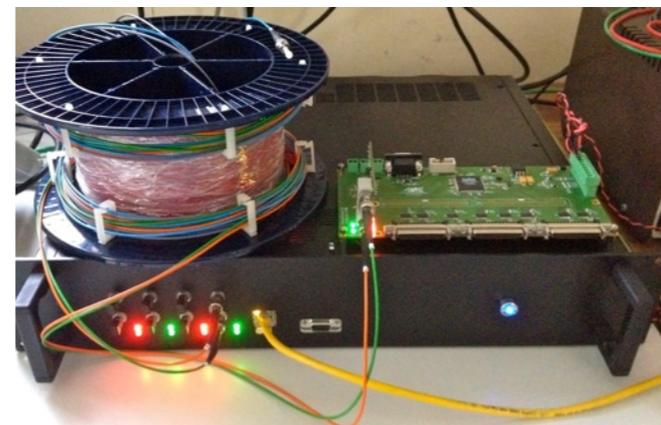
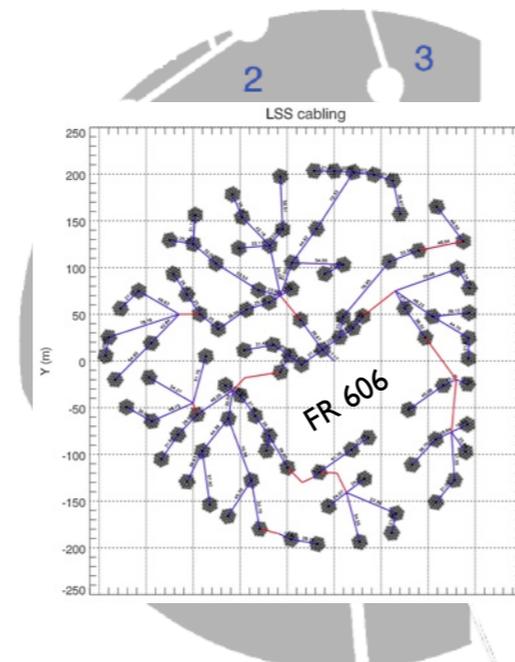
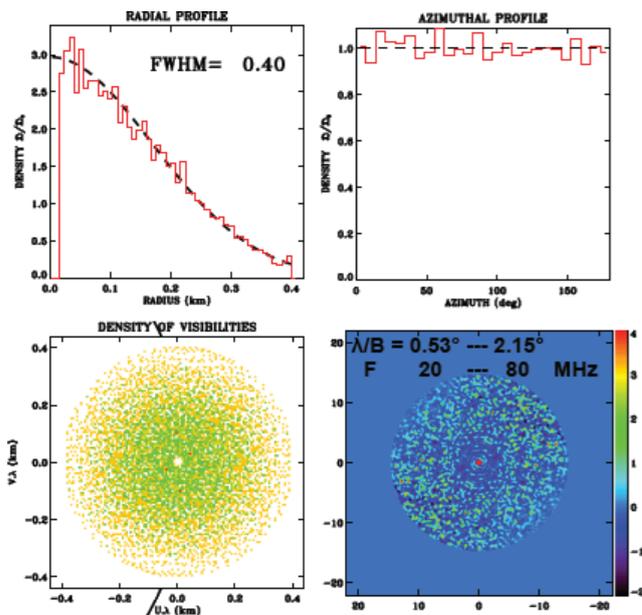
# Designing + Prototyping Nenufar

ANR program 9/2009 2/2013

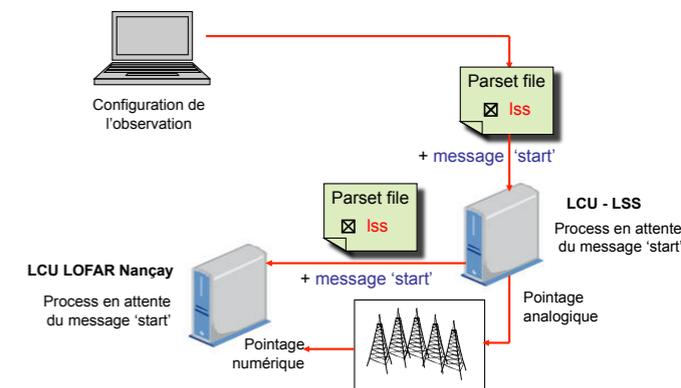
<https://nenufar.obs-nancay.fr/lss/> (ask for passwd)



- Study of all aspects of the project : antenna, preamp., distribution mini-arrays & global, phasing, cabling/trenches, silent control/command, dialog with LOFAR



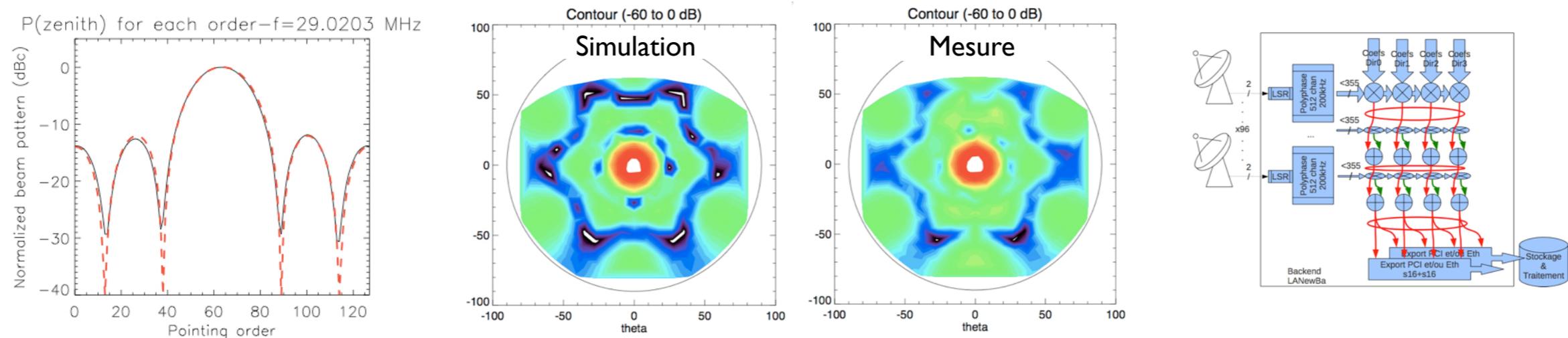
Mode standalone



# Designing + Prototyping Nenufar

ANR program 9/2009 2/2013

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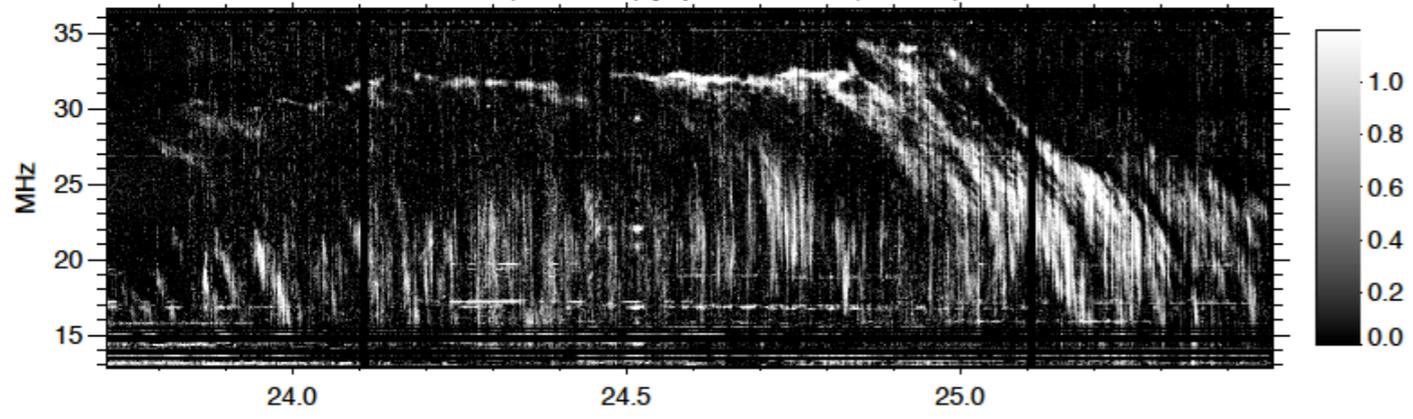
- Construction of 3 mini-arrays (x 2 polarizations) + dedicated test receiver
- Definition of a standalone dedicated NenuFAR receiver (Nançay/ALSE)  
⇒ "duty-cycle" ~100% in the analog mini-array beam
- Industrialization studies, site study (ONF), costing, sub-contracting, schedule



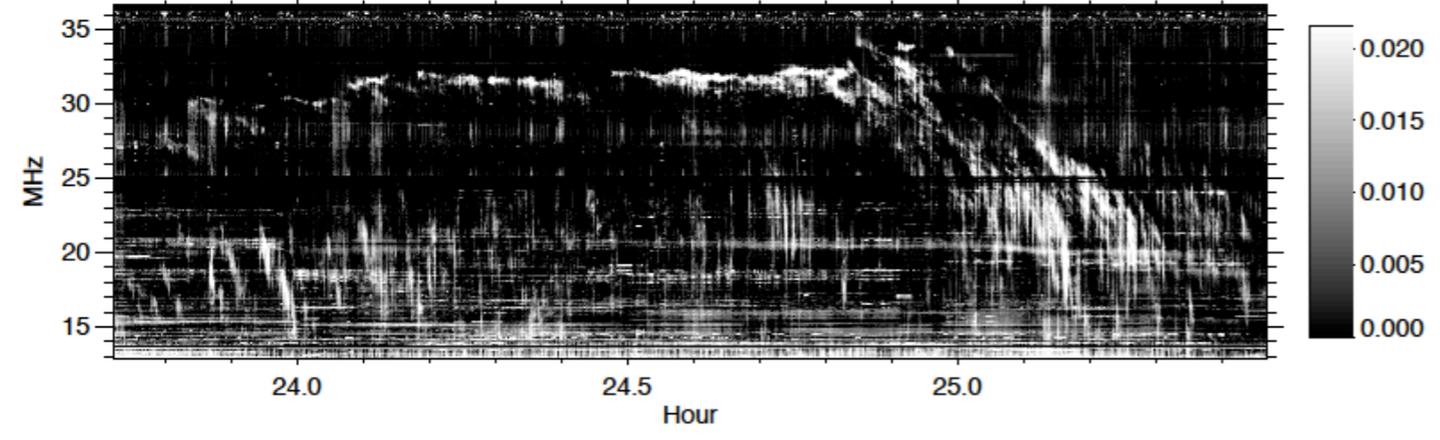
# NenuFAR / DAM calibration (1 antenna)



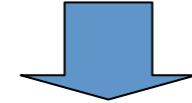
DAM (LH+RH) jupiter rebin (>80%)



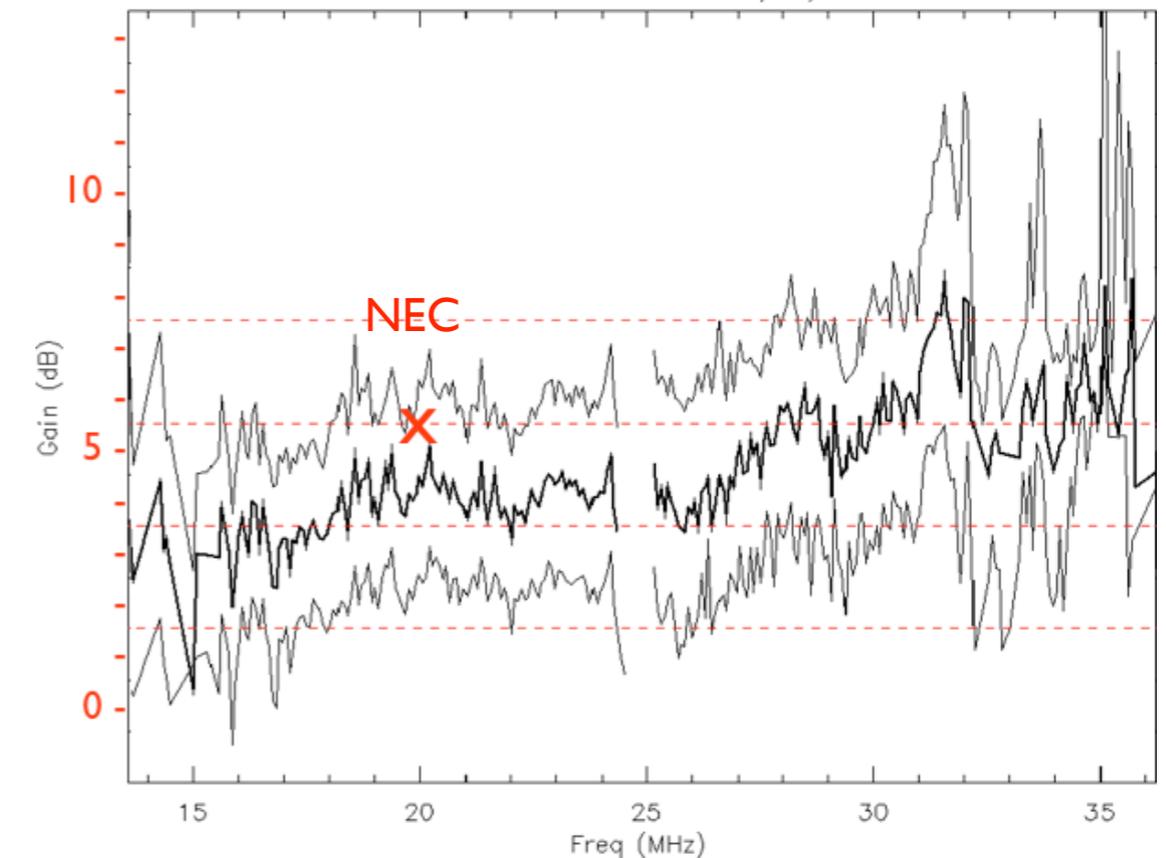
LSS (LH+RH) jupiter rebin (>80%)



$$\frac{(S_{\text{jup}} / S_{\text{gal}})_{\text{DAM}}}{(S_{\text{jup}} / S_{\text{gal}})_{\text{LSS}}} = \frac{\Omega_{\text{LSS}}}{\Omega_{\text{DAM}}} = \frac{G_{\text{DAM}}}{G_{\text{LSS}}}$$

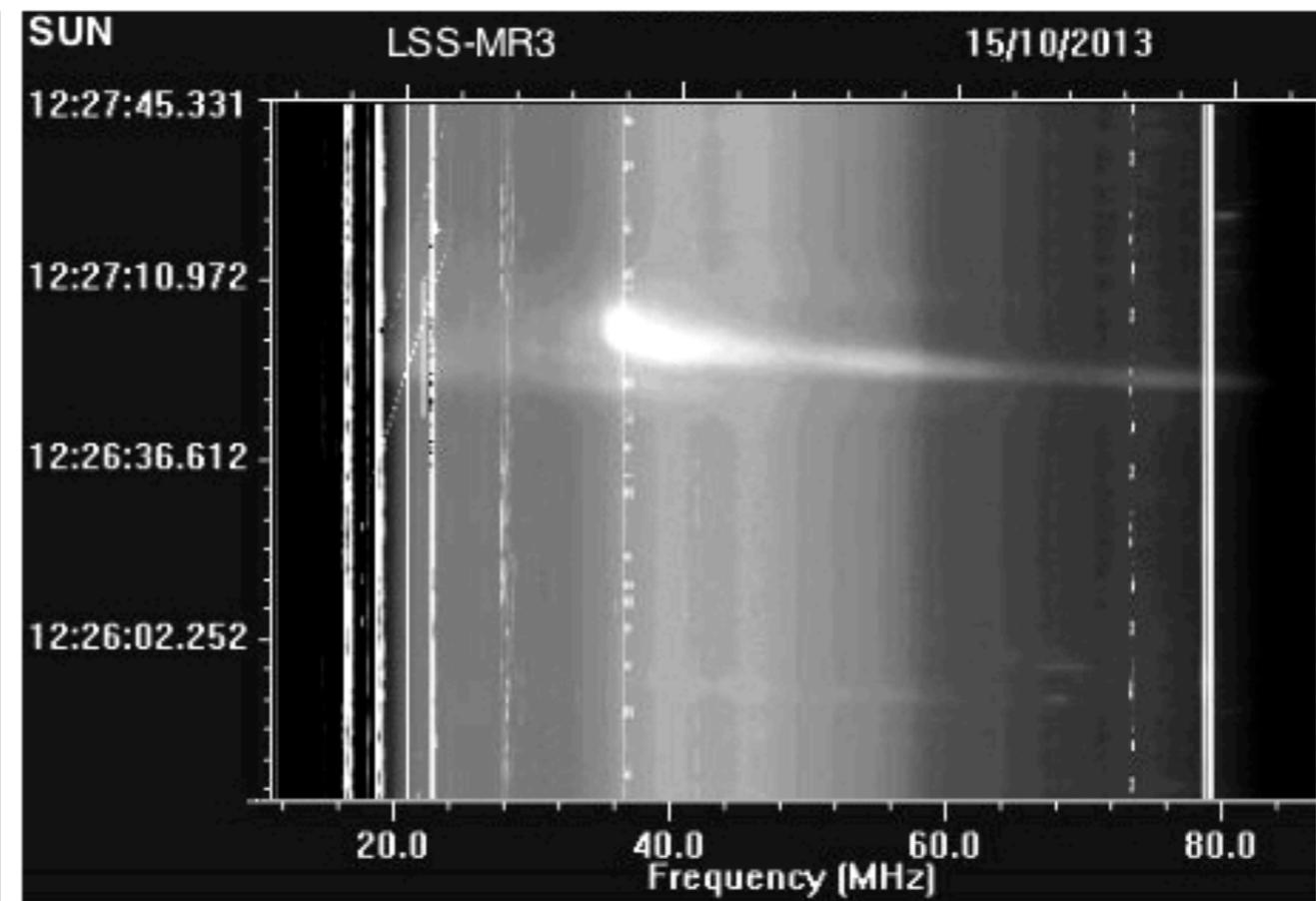
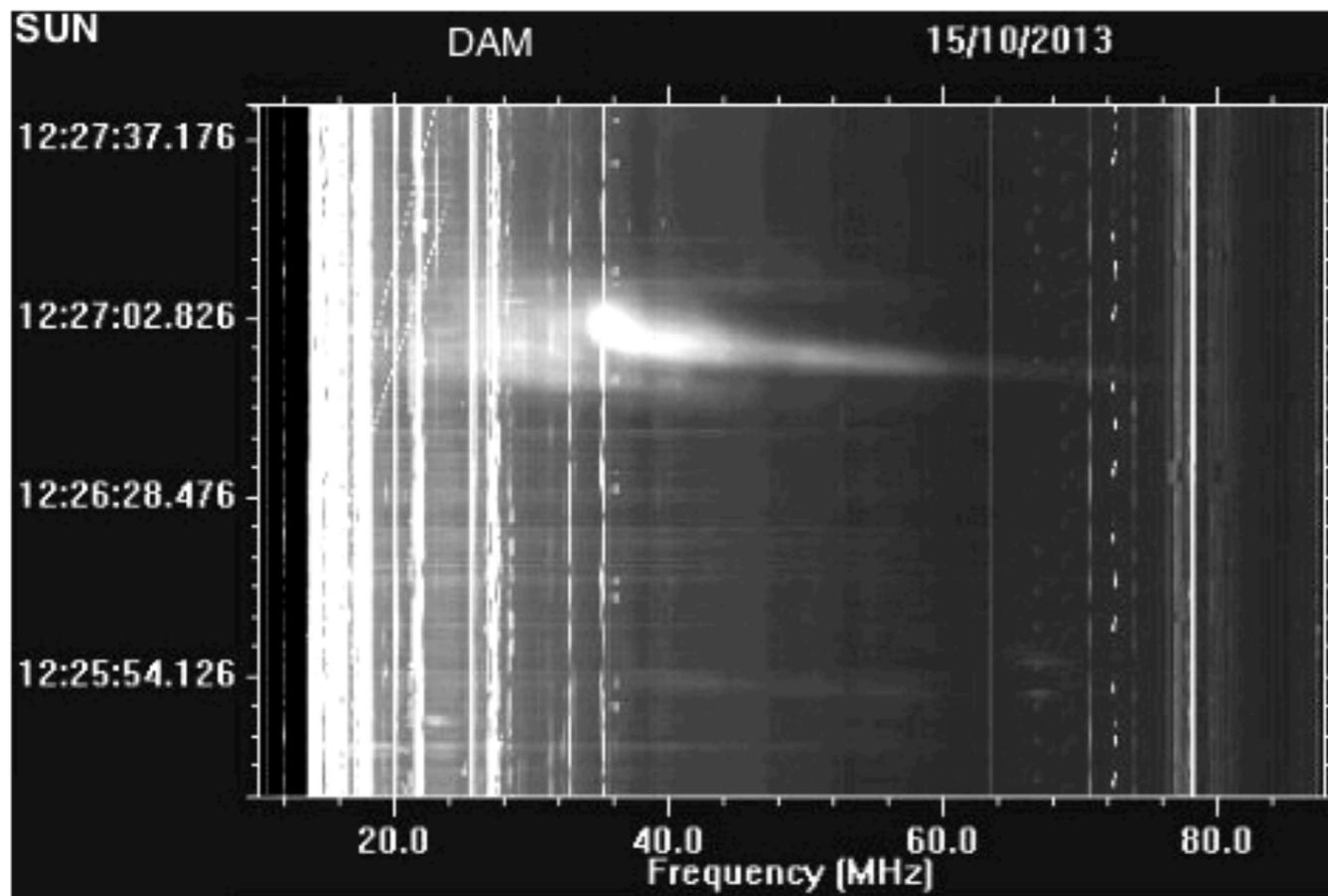


LSS antenna Gain – from 25,50,75% levels





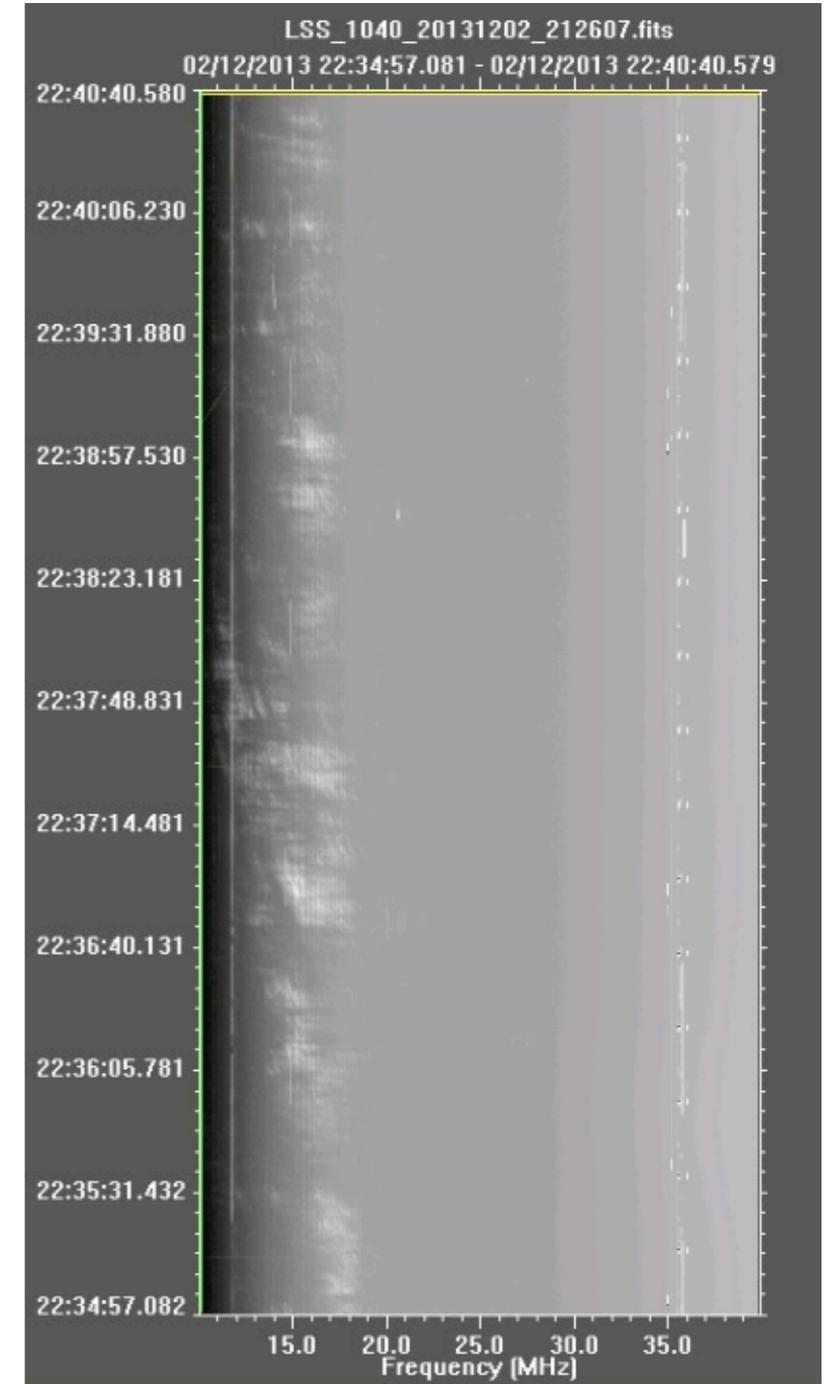
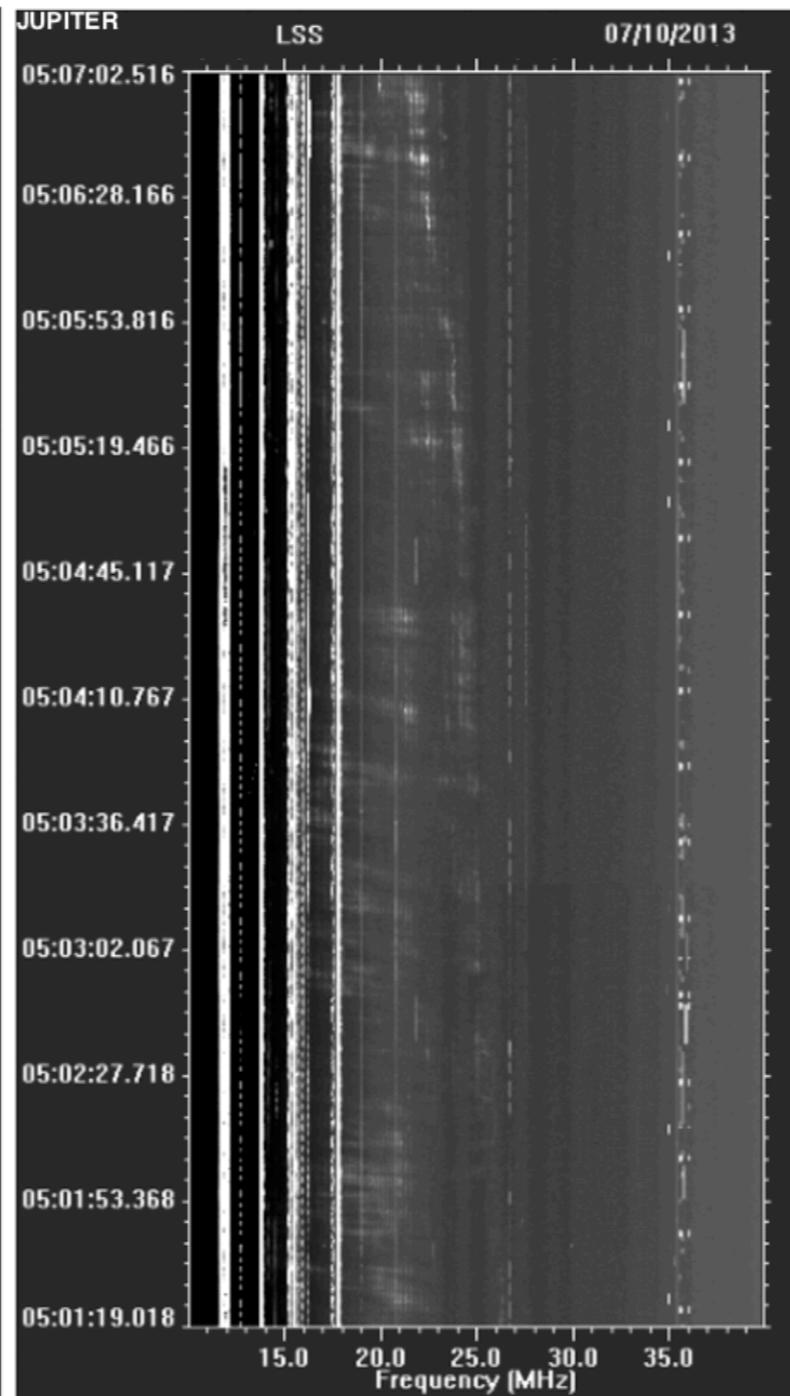
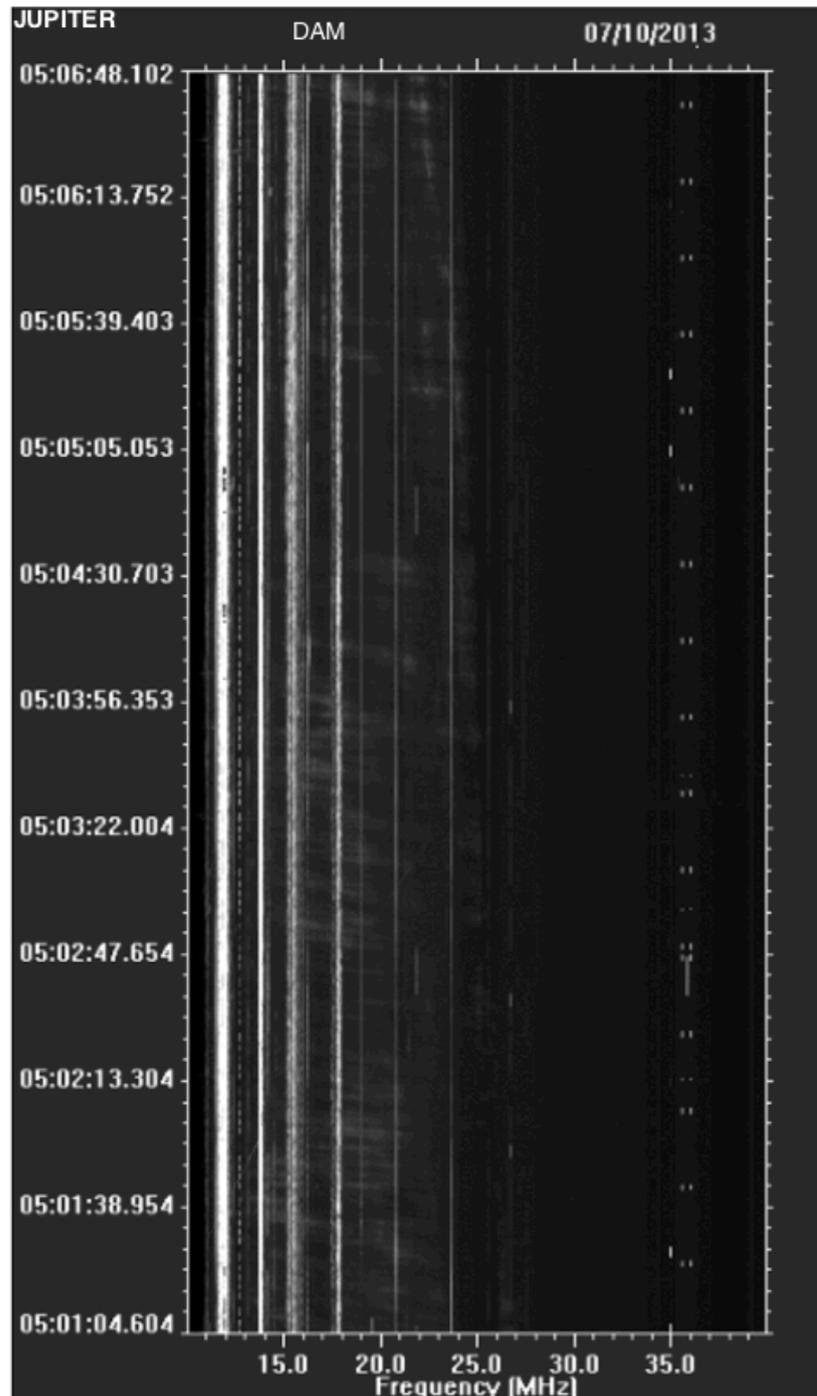
# NenuFAR / DAM calibration (1 mini-array)



Solar type III



# NenuFAR / DAM calibration (1 mini-array)



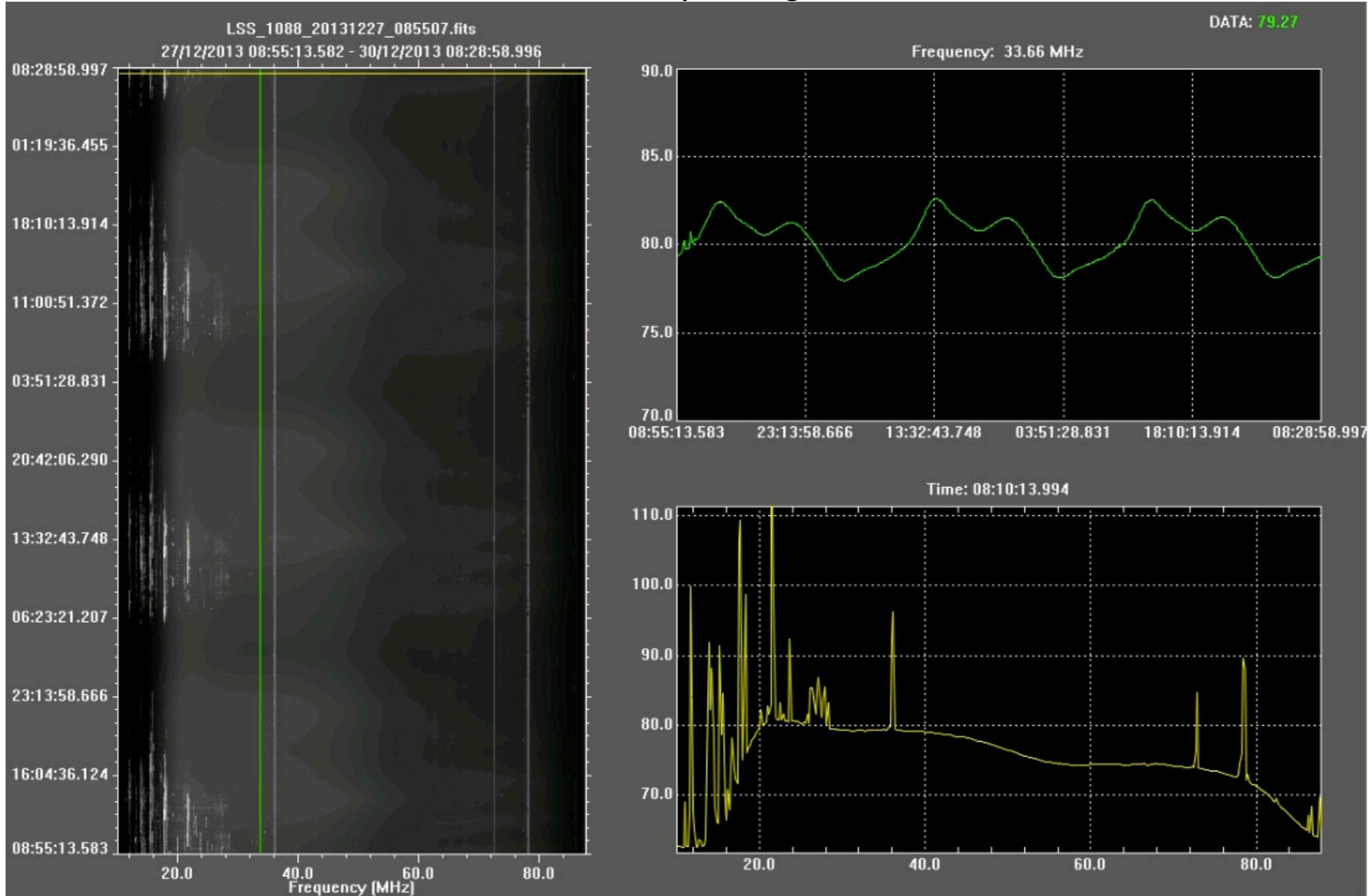
Jovian DAM

down to 10 MHz

# NenuFAR / DAM calibration (1 mini-array)



Zenith pointing



# Technical characteristics of NenuFAR

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

- Giant phased array LOFAR-compatible
- 1824 antennas : 96 mini-arrays of 19 antennas each
- Diameter ~400 m
- Collective area ~ 62 000 m<sup>2</sup> @ 30 MHz ( $\propto \lambda^2$ )
- Frequency range = 10-85 MHz ( $\lambda=3.5-30\text{m}$ )
- Broad FoV (8°-60°), pointing -23° → +90°
- Resolution ~ 1° (Standalone) - 0.1 " (LSS)
- Resolutions  $\ll 1$  msec  $\times$  1 kHz (TBD), Full polarization (4 Stokes)
- Sensitivity  $< 10$  mJy ( $10^{-28}$  Wm<sup>-2</sup>Hz<sup>-1</sup>) [+confusion]
- Privileged access for french community
- SKA-Low pathfinder

# NenuFAR Operating modes

- LOFAR-ILT (LSS) → high angular resolution
- LOFAR-single station → high spectral resolution
- Standalone (in // to above within Mini-Array analog FoV)
  - N(=2) beams, full band, with maximum time resolution  
+ ARTEMIS-like backend
  - ~256 pixels imaging within TBD bandwidth / a few sec
- Transient Buffer Boards (waveform)
- Data policy → cf. M. Tagger's talk

• Phasing / scale :	antenna	Mini-Array	NenuFAR
• Beaming :	$\sim 2 \pi$	$8^\circ - 60^\circ$	$0.5^\circ - 4^\circ$



# NenuFAR Science

- Standalone : all science topics requiring high-sensitivity & large FoV,  
no high angular resolution

dark ages

pulsars, RRATs

flaring/dwarf stars, exoplanets

SS planets - lightning/TLEs

blind transient searches

- LSS : high angular resolution imaging

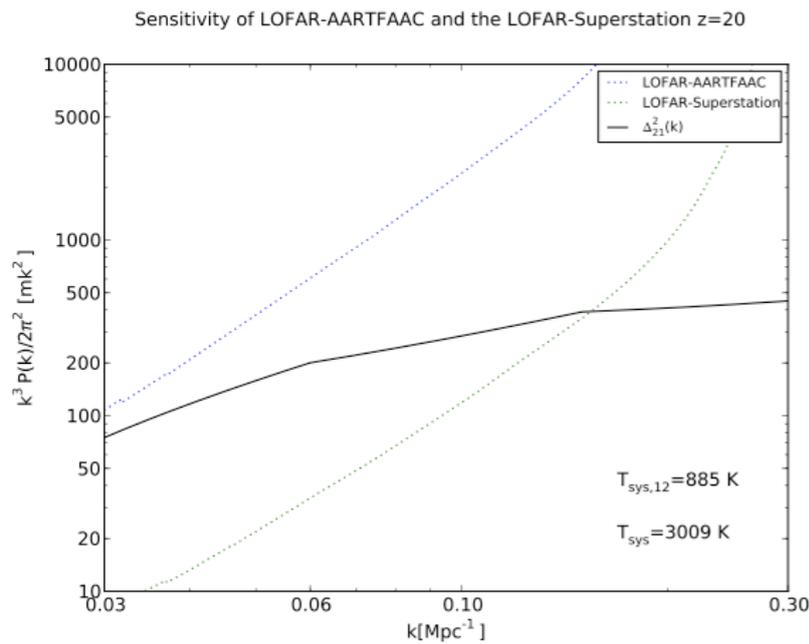
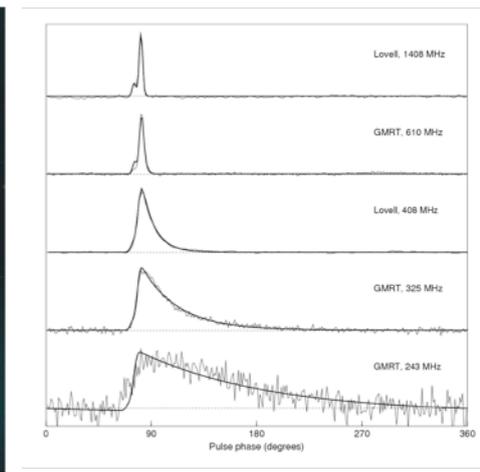
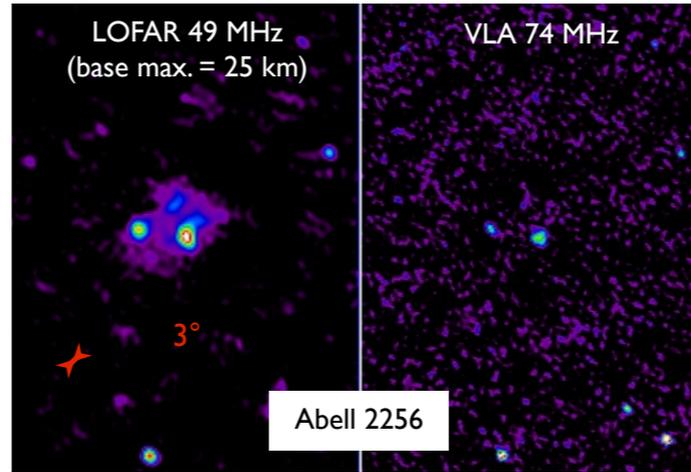
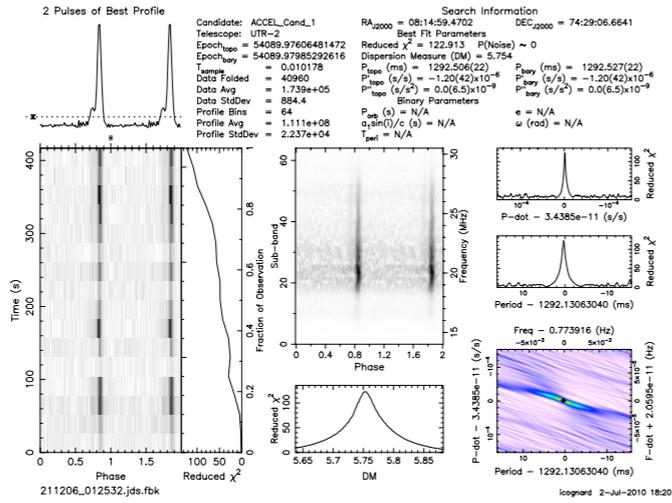
Galaxy formation

ISM structure

small-scale B fields

→ cf. preliminary LSS & NenuFAR-I science cases

# NenuFAR Science



- Cosmology (dark ages) and galaxy formation
  - Structure of Galactic Interstellar Medium
  - Pulsars & Rotating radio transients (RRATs)
  - Binary/flaring stars & Exoplanets
  - The Transient Universe
  - Light flashes in Terrestrial and Planetary atmospheres
- ⇒ LSS standalone, LSS+LOFAR, LSS//LOFAR

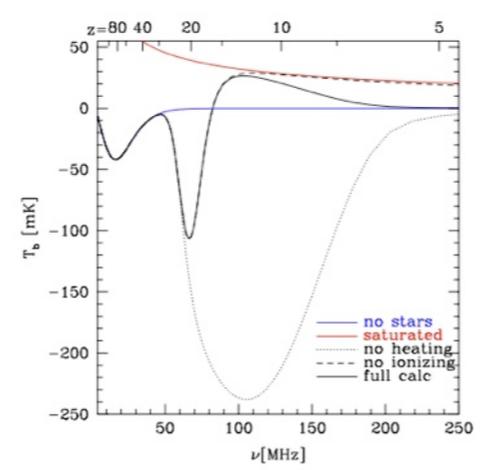
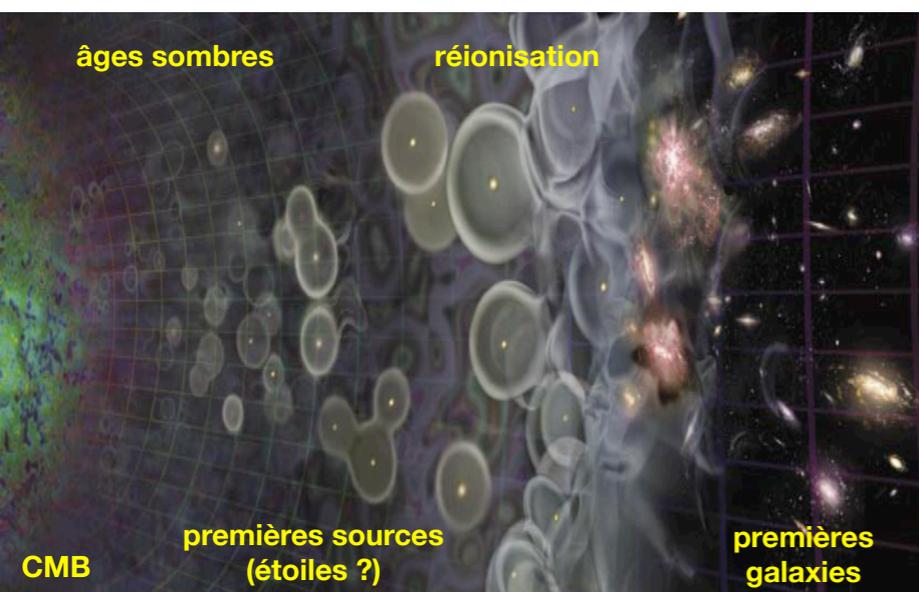
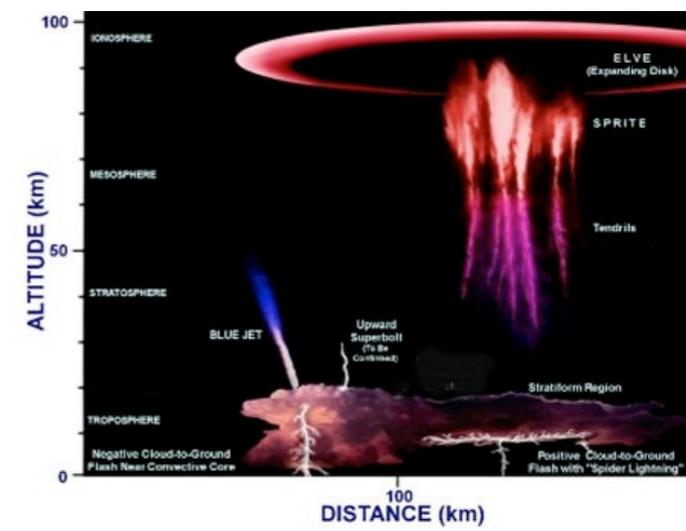
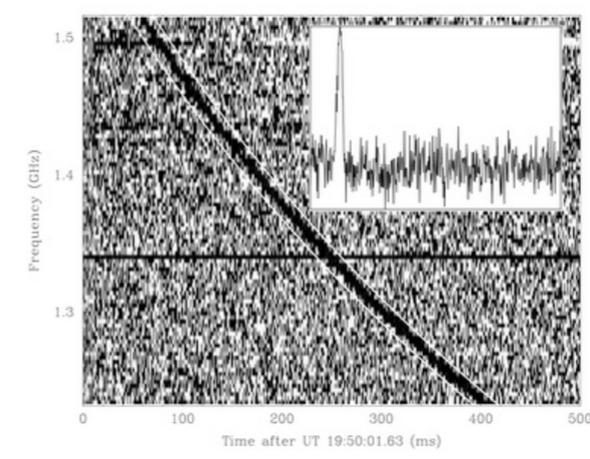


FIG. 1 (color online). Evolution of the 21 cm global signal for different scenarios. Solid blue curve: no stars; solid red curve:  $T_S \gg T_\gamma$  and  $x_H = 1$ ; black dotted curve: no heating; black dashed curve: no ionization; black solid curve: full calculation.



# The context of NenuFAR

- / LOFAR : 2x larger than the core, instantaneous sensitivity, duty-cycle
  - / VLA, GMRT : broad coverage of LF range,  $A_{\text{eff}}$
  - / UTR-2 : frequency range, polarization
  - / GURT : 256 pixels imaging
  - / LWA, OLWA :  $A_{\text{eff}}$ , LSS-mode
  - / AARTFAAC:  $A_{\text{eff}}$
  - / SKA : earlier, national
- complementary to all !

# The context of NenuFAR

- Hardware fully defined, except dedicated receiver (ongoing)
- Probably best operating LF antenna+preamp (except ~ GURT)
- Receiver definition still in progress (flexibility exists)
  - capabilities of NenuFAR will increase as those of the receiver  
(beams,  $\Delta f$ , correlation...)
  - major goal and effort

Equipe NenuFAR-France : ~ 25 chercheurs + 15-20 ITA (incl. 3 young scientists AA-CNAP)

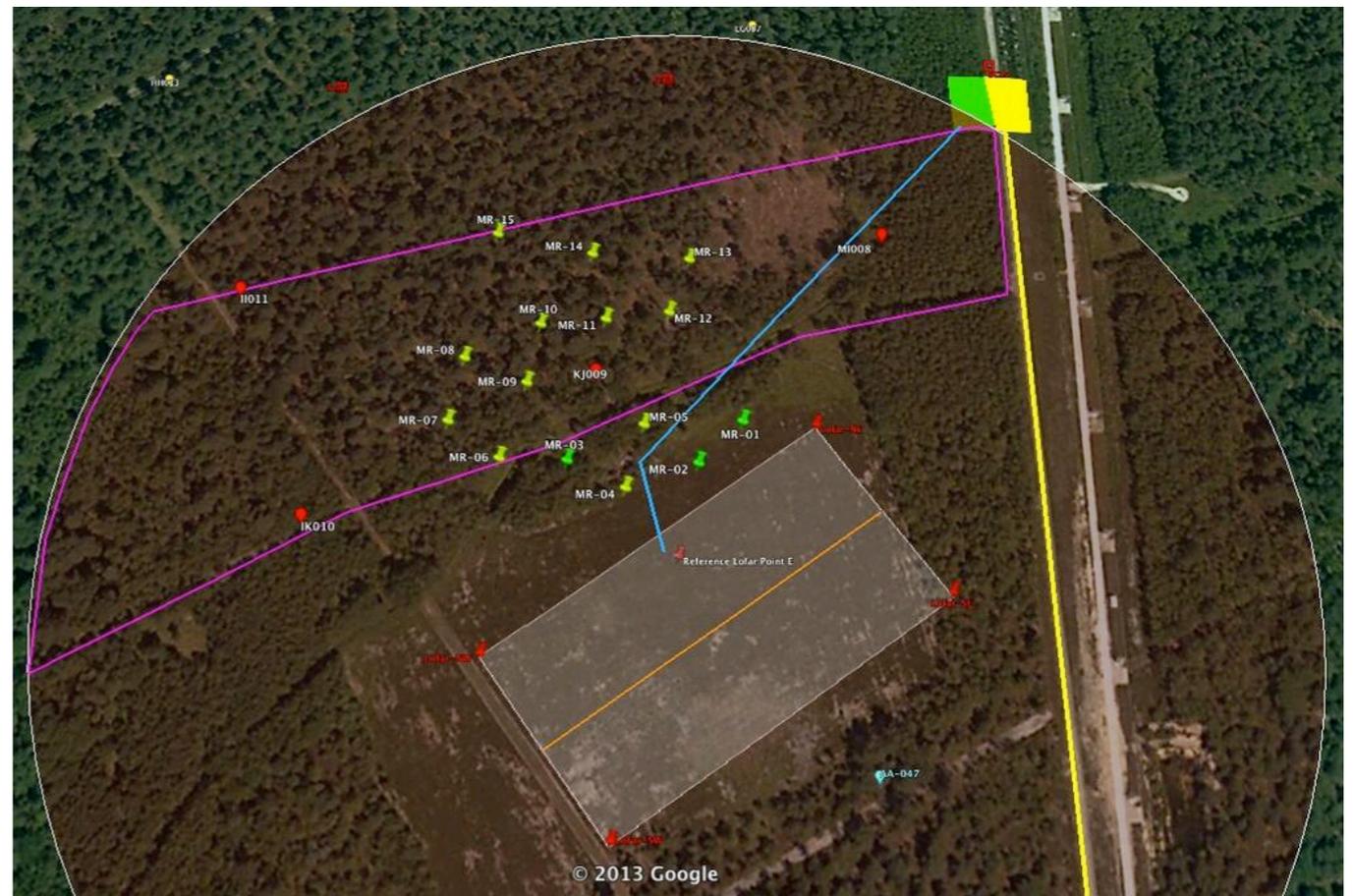
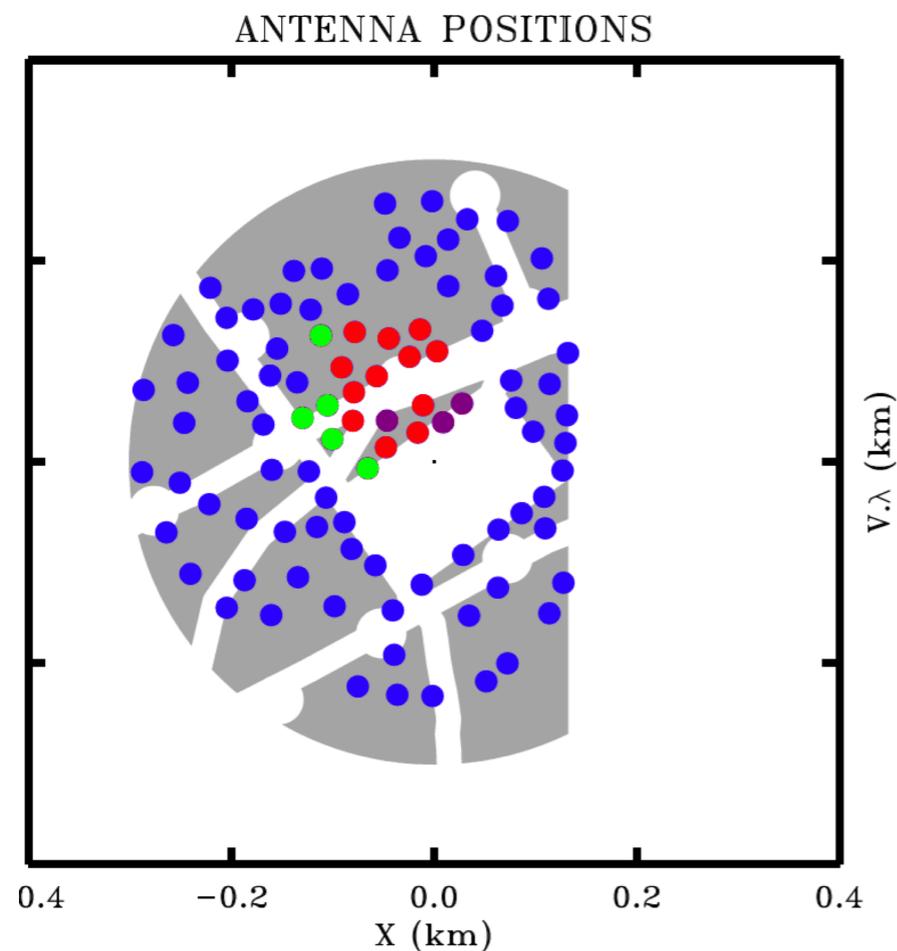
Laboratoires impliqués dans la réalisation : Nançay, LESIA, GEPI, LERMA, LPC2E, Prisme, Subatech, IRA Kharkov, SRI Graz (soutien OP, ESEP)

Laboratoires utilisateurs : OP (LESIA, GEPI, LERMA, LUTh), CEA/Sap-DASE-AIM, IAS, IAP, E. Polytechnique, ENS/LRA, APC, IN2P3, LPC2E, Nançay, OCA, IRAP ...

# NenuFAR status

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

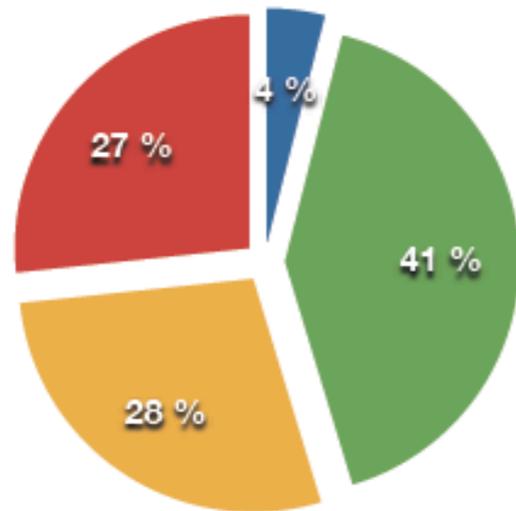
- Construction cost :  $\sim 4.5$  M€
- Low operation cost
- $\geq 1$  M€ secured in 2013 ; 0.5 - 1 M€ expected in 2014 ...
- Phase 1 (NenuFAR-1) received green light from OP/OSUC/UO (15/11/2013)
  - construction or  $\geq 15$  mini-arrays started, operational in  $\sim 1$  year



# NenuFAR status

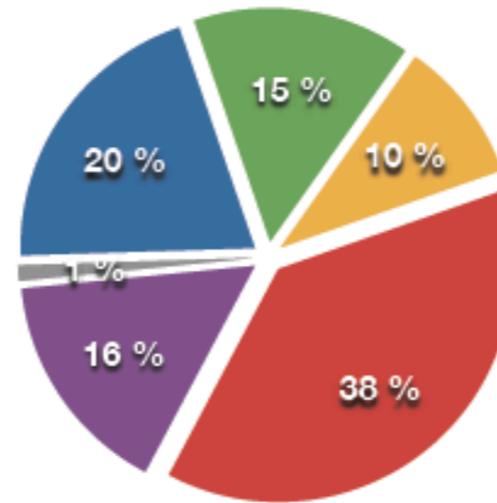
<https://nenufar.obs-nancay.fr>

NenuFAR-1 (15 MR) - Budget disponible: 1160,39 Ke



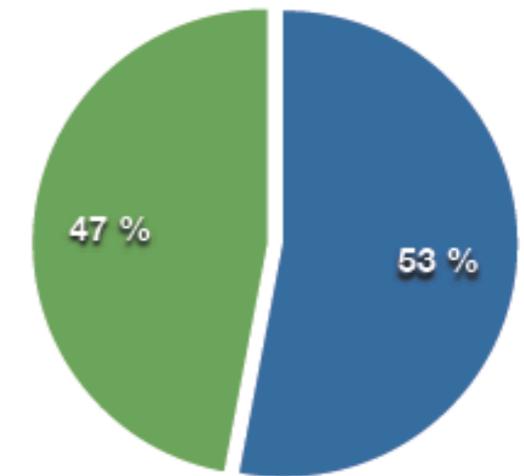
- Financement Autriche
- Prêt PSL
- Financement Région
- Contribution DIM-ACAV

NenuFAR-1 (15 MR) - Budget prévisionnel: 1042,58 Ke

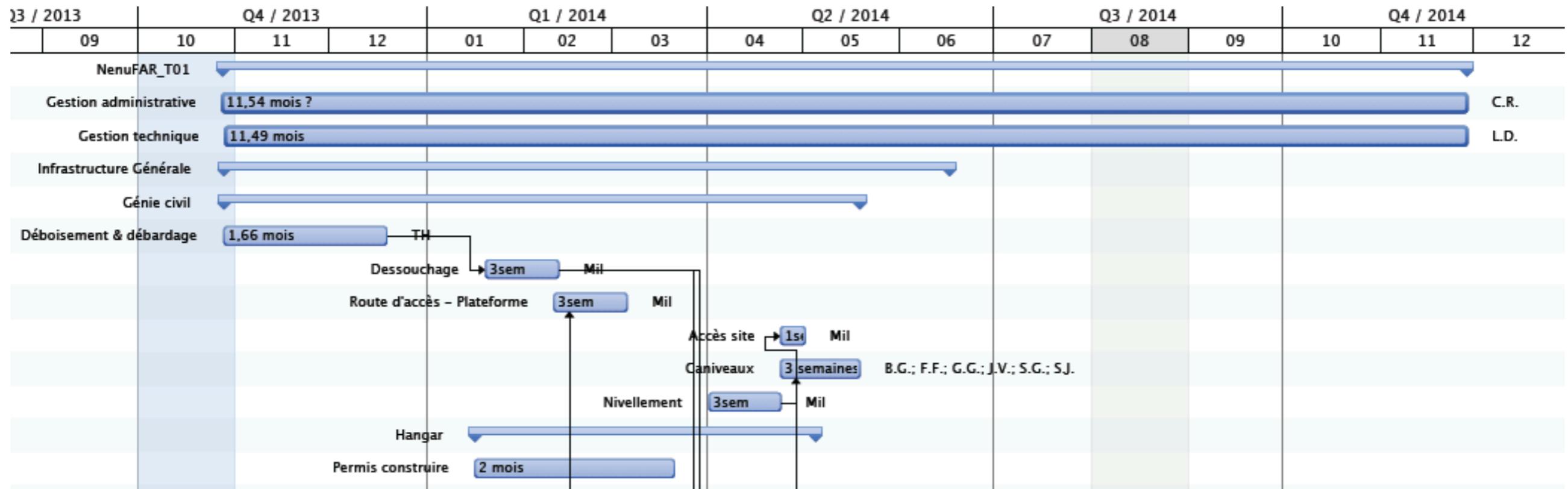


- Infrastructure
- Antennes et amplificateurs
- Câbles coaxiaux, racks, assemblage phasage
- Phasage, contrôle commande
- Récepteur
- Divers

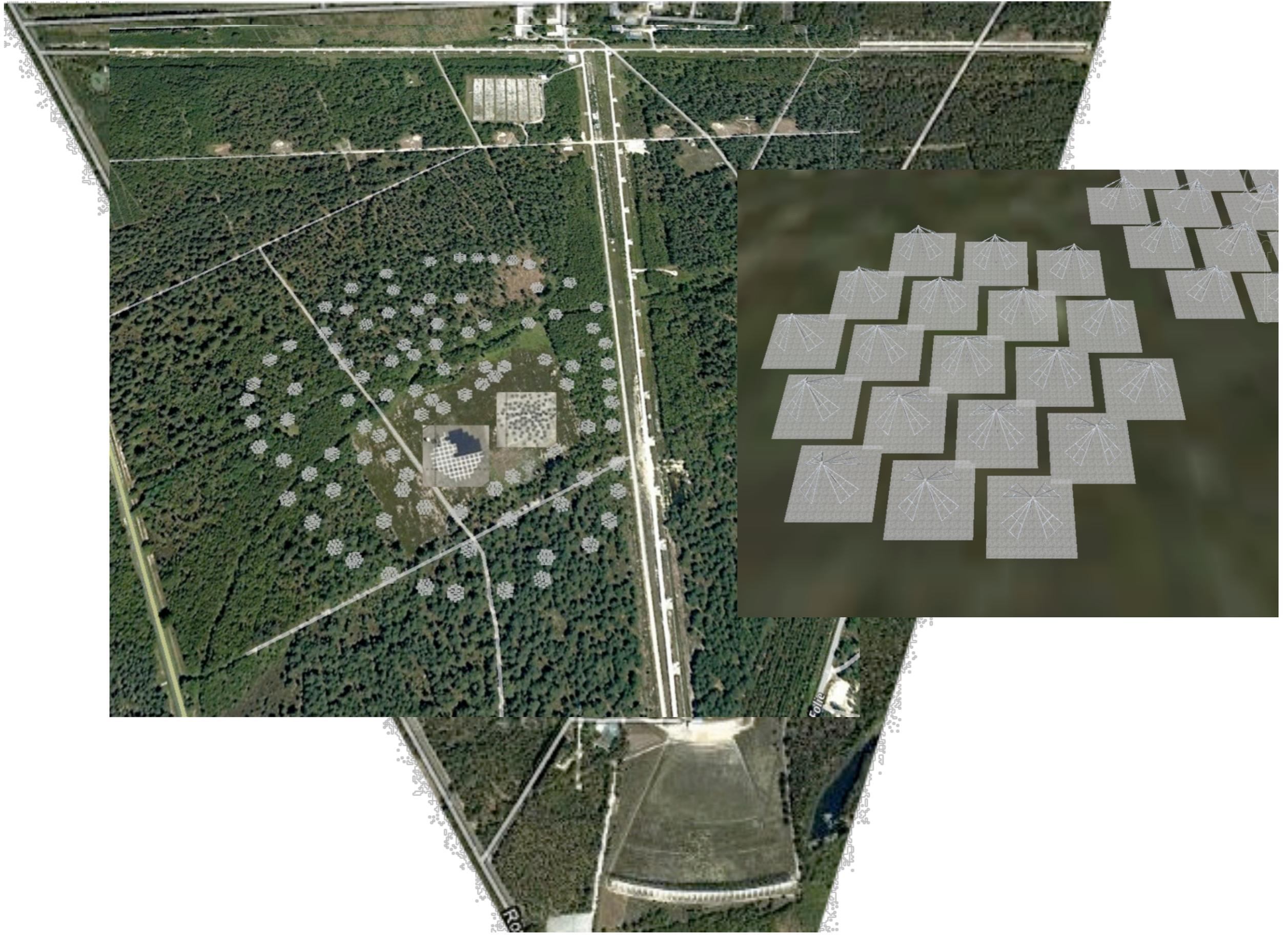
NenuFAR-1 (15 MR) - En cours



- A engager
- Engagé



# Tomorrow NenuFAR ...



The background is a collage of green leaves, some showing brown spots. Overlaid on the leaves are numerous circular images of the NenuFAR antenna array, which consists of a central white structure with multiple black legs extending outwards. The text 'NENUFAR' is written in a stylized, red, outlined font across the middle of the collage.

NENUFAR

Le projet dans les temps

Tomorrow NenuFARs ?...

NenuFAR prototype in Nancay



# Complements

# NenuFAR Science case

- **Galaxy formation & Cosmology (dark ages)**

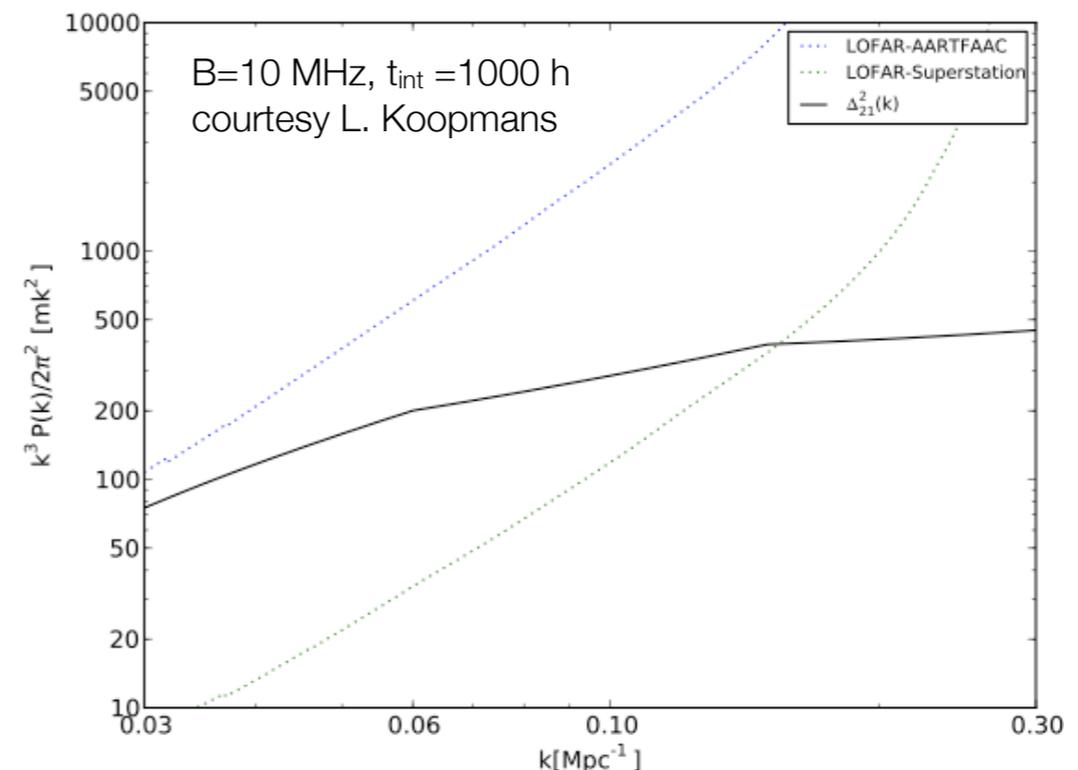
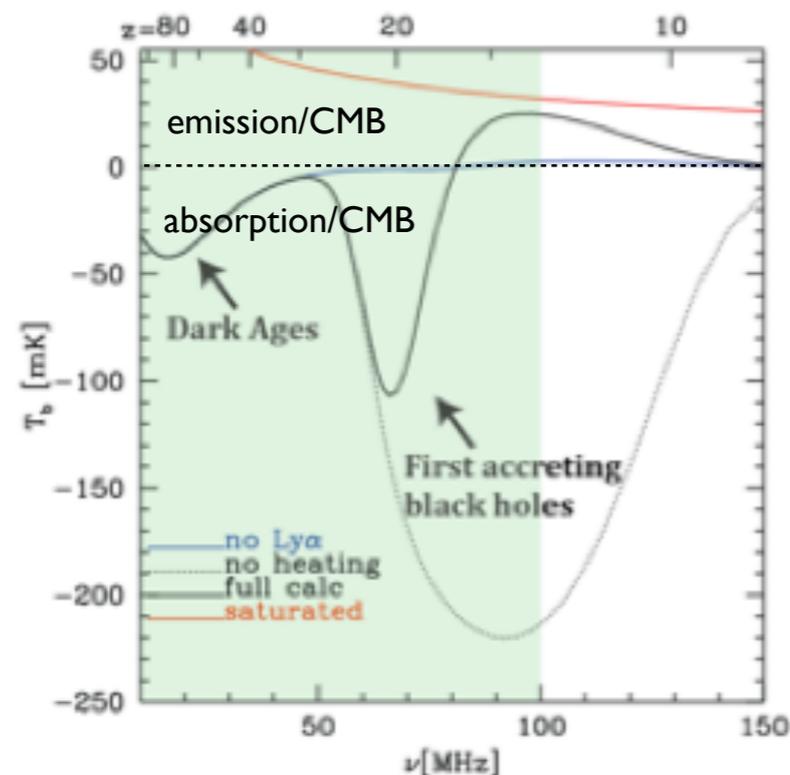
Formation of large structures (NAG at  $z < 1$ , blobs at  $z \leq 2$ , star formation in nearby galaxies, magnetic fields)

⇒ **LSS+LOFAR (sensitive long baselines)**

Signature of pre-EoR "dark ages" :

- all-sky  $H_I$  spectrum at  $z \geq 12-20$  :  $\delta T_b \sim -100 \text{ mJy} \leq \text{LBA range}$ ,  $\delta T_b/T_b \sim 10^{-6}$
- possibly larger spatial fluctuations of  $H_I$  at  $z \sim 20$

⇒ **LSS standalone + dedicated receiver (large sensitivity, accurate bandpass calibration via instantaneous cross & autocorrelation measurements)**



# NenuFAR Science case

- **Structure of Galactic Interstellar Medium**

Extended objects ( $>$  instantaneous "station" FoV  $\sim 10^\circ$  @ 30 MHz)

$\Rightarrow$  LSS+LOFAR (short baselines)

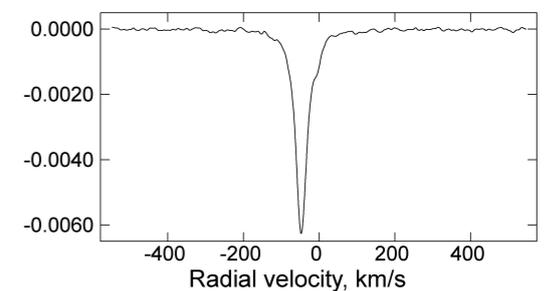
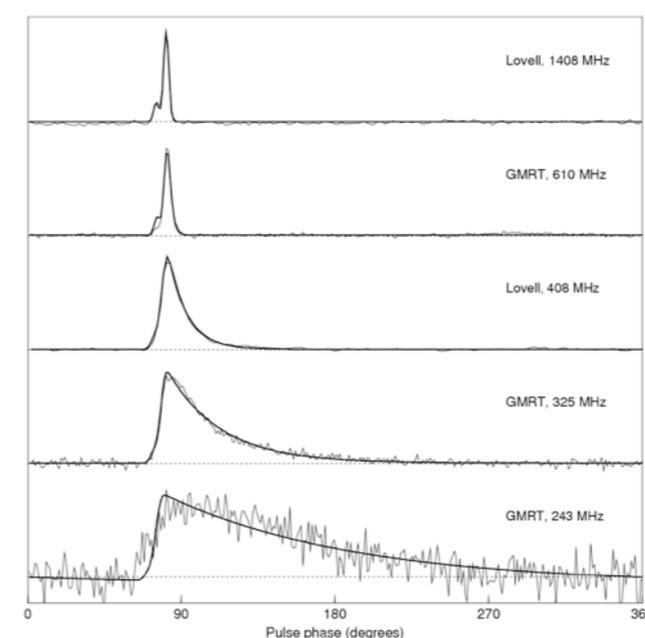
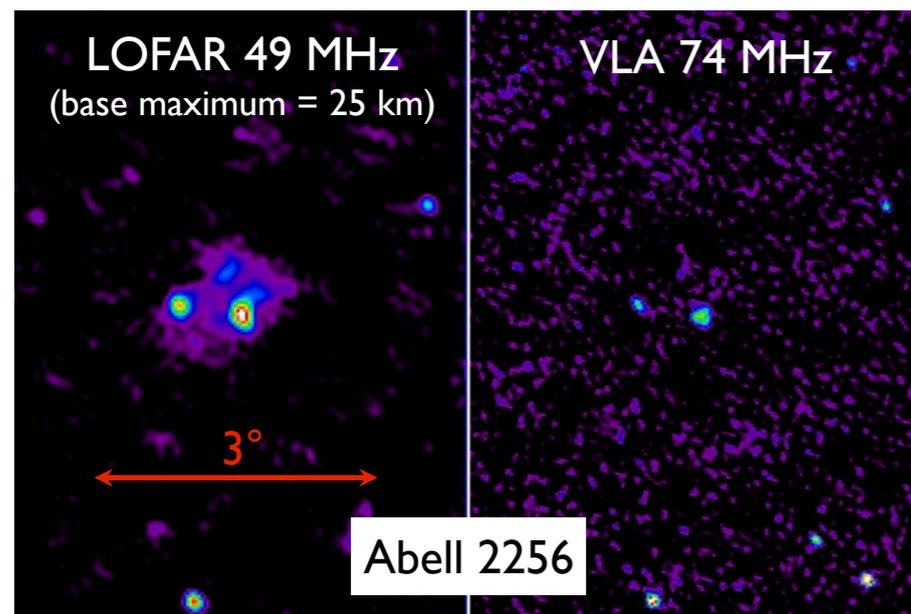
Measurement of small-scale magnetic field (RM without depolarization)

$\Rightarrow$  LSS+LOFAR (sensitive long baselines)

Maximum scale of ISM turbulence (temporal broadening of radio pulses), Atomic recombination lines

$\Rightarrow$  LSS standalone (instantaneous sensitivity, access to LF)

$\Rightarrow$  LSS+LOFAR (sensitive long baselines)

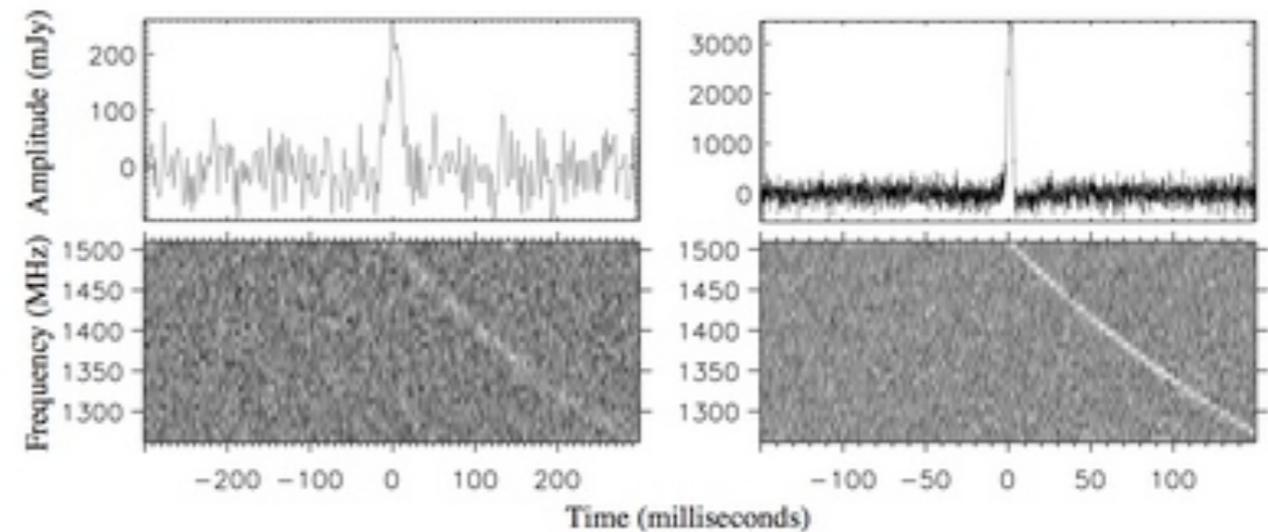
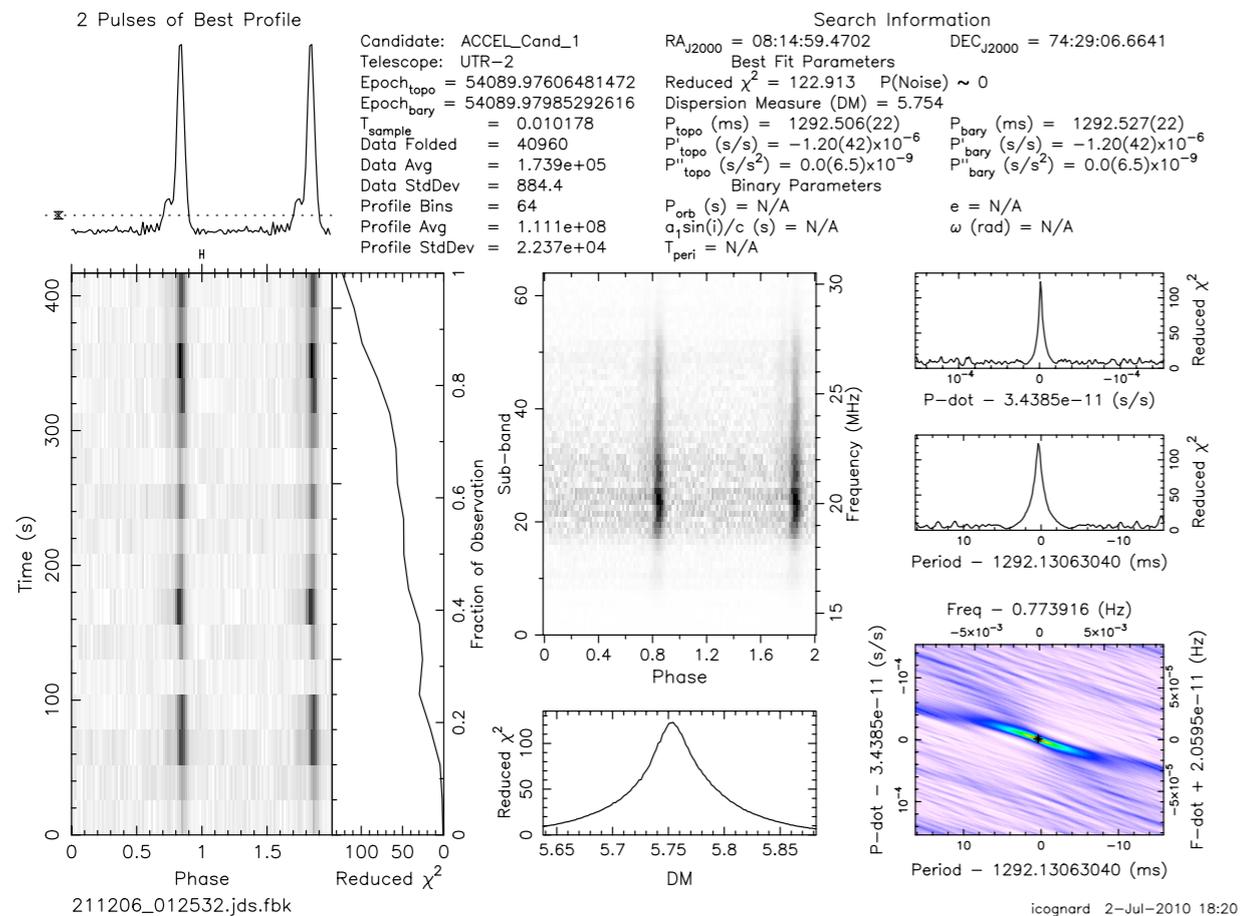


# NenuFAR Science case

- Pulsars & Rotating radio transients (RRATs)

Detection, especially at LF, Nature of RRATs, Giant Pulses, Physics of the environment of compact objects, Planets orbiting pulsars ?

⇒ LSS standalone (sensitivity + FoV = high efficiency for discovery, access to LF)



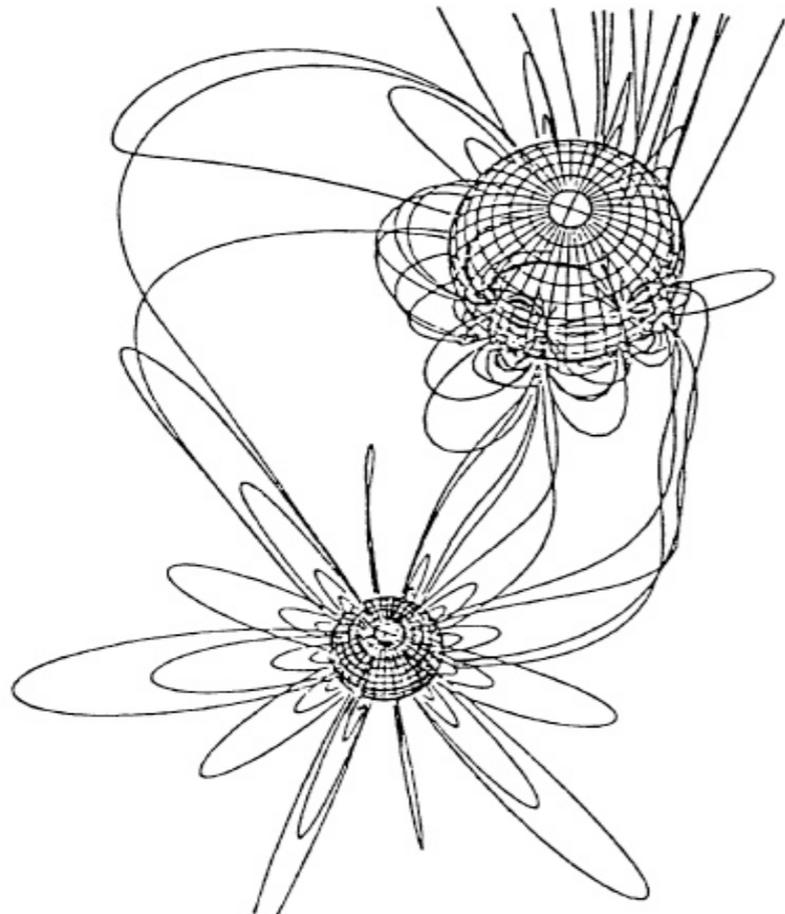
# NenuFAR Science case

- **Binary/flaring stars & Exoplanets**

Existence and characteristics of radio emission, Star-Planet plasma Interactions, Comparative magnetospheric physics, Implications on habitability.

⇒ *LSS standalone (TAB sensitivity, access to LF, large duty-cycle)*

⇒ *LSS+LOFAR, LSS//LOFAR (global sensitivity, mitigation / RFI & ionosphere)*

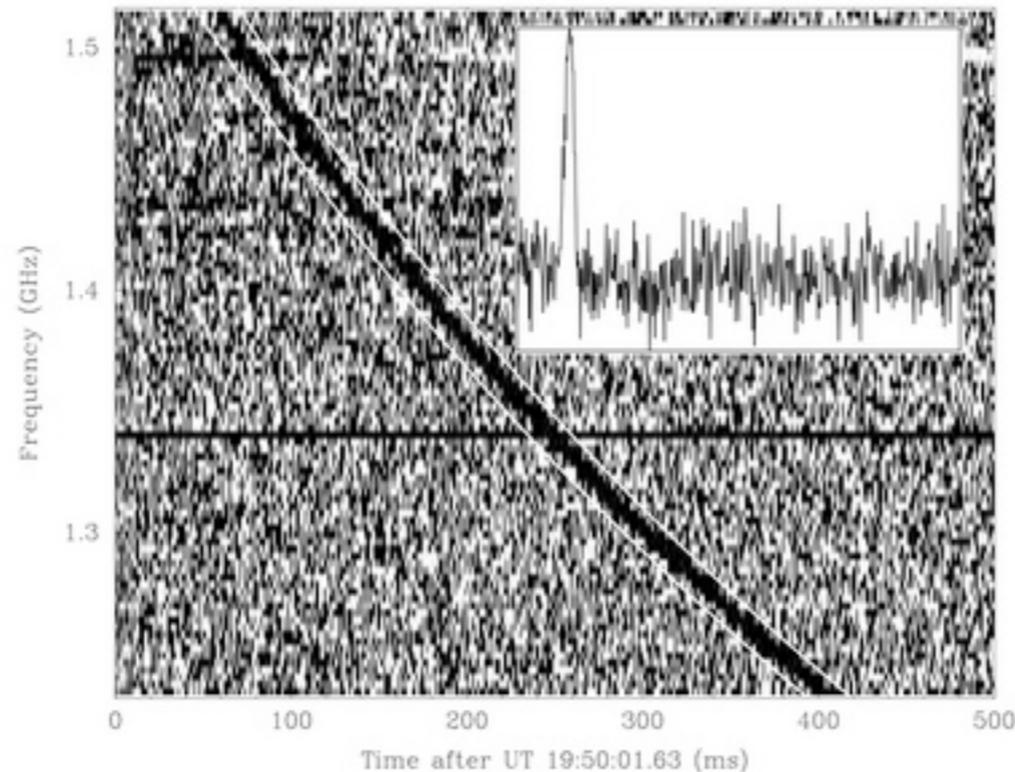


# NenuFAR Science case

- **The Transient Universe**

Exhaustive blind exploration, temporal & spectral scales of (dispersed) pulses, nature of emitters (GRB, CR, neutrinos/Moon, Gravitational Wave counterparts, serendipity...)

⇒ LSS standalone + ARTEMIS backend (coherent or incoherent TAB sensitivity, extended TBB, access to LF, large duty-cycle)

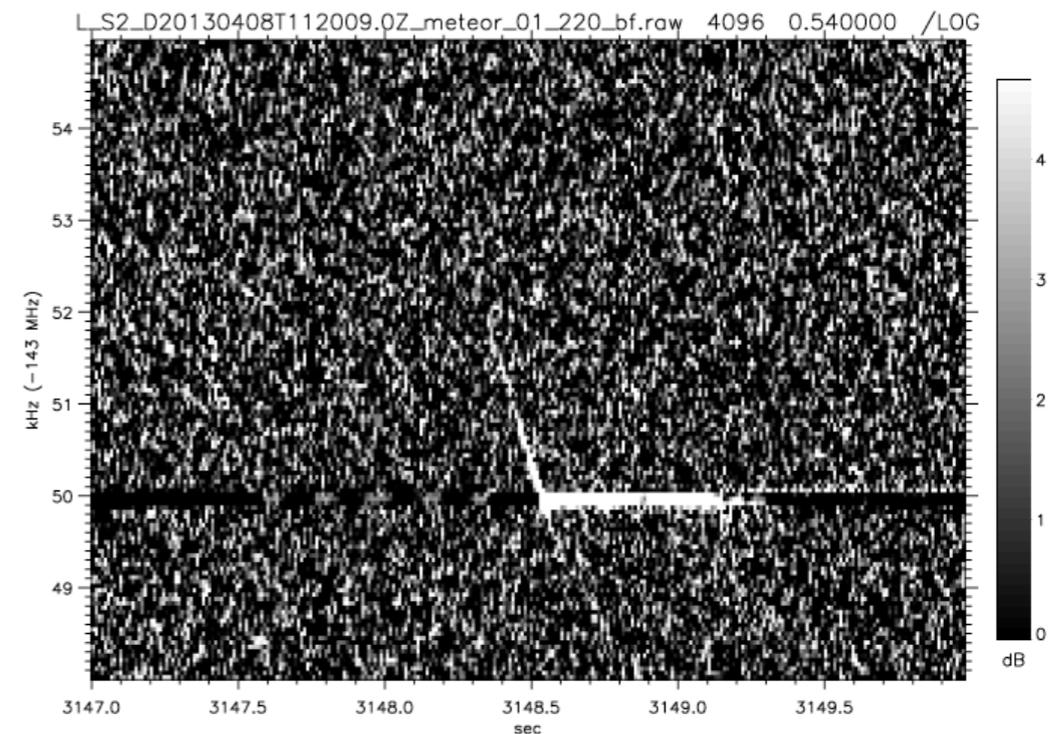
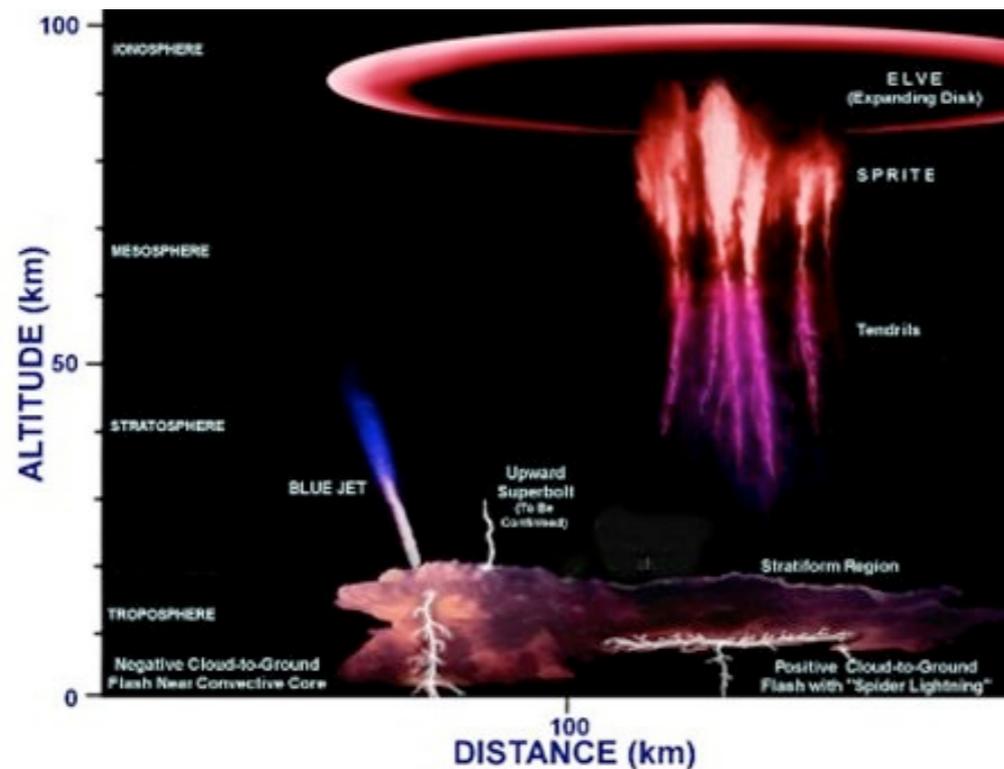


# NenuFAR Science case

- Light flashes in Terrestrial and Planetary atmospheres

Radio counterpart of TLEs, sprites, meteors... : origin, local distribution & dynamics, temporal & spectral scales, physical processes...

⇒ LSS standalone (coherent or incoherent TAB sensitivity, extended TBB, access to LF, large duty-cycle)



- Solar System radiophysics

Ionospheric scintillation & opacity, Solar & Jovian bursts, IP scintillation, active studies, meteor trails ...

# Operating modes & data policy

- being discussed by ILT ...
- NenuFAR ~ super-LBA field, optional use by LOFAR
- dedicated receiver captures the signal before entering the LOFAR back-end 100% of the time
- no use of LOFAR hardware in standalone mode
- main goal: optimize the scientific return of both LOFAR & NenuFAR
- NenuFAR-within-LOFAR freely programmed by the LOFAR PC, FLOW builder's list
- NenuFAR standalone use programmed by a FLOW PC (exchange 1 PC member ?)
- sub-arrays (NenuFAR as second core) TBD
- single station mode TBD