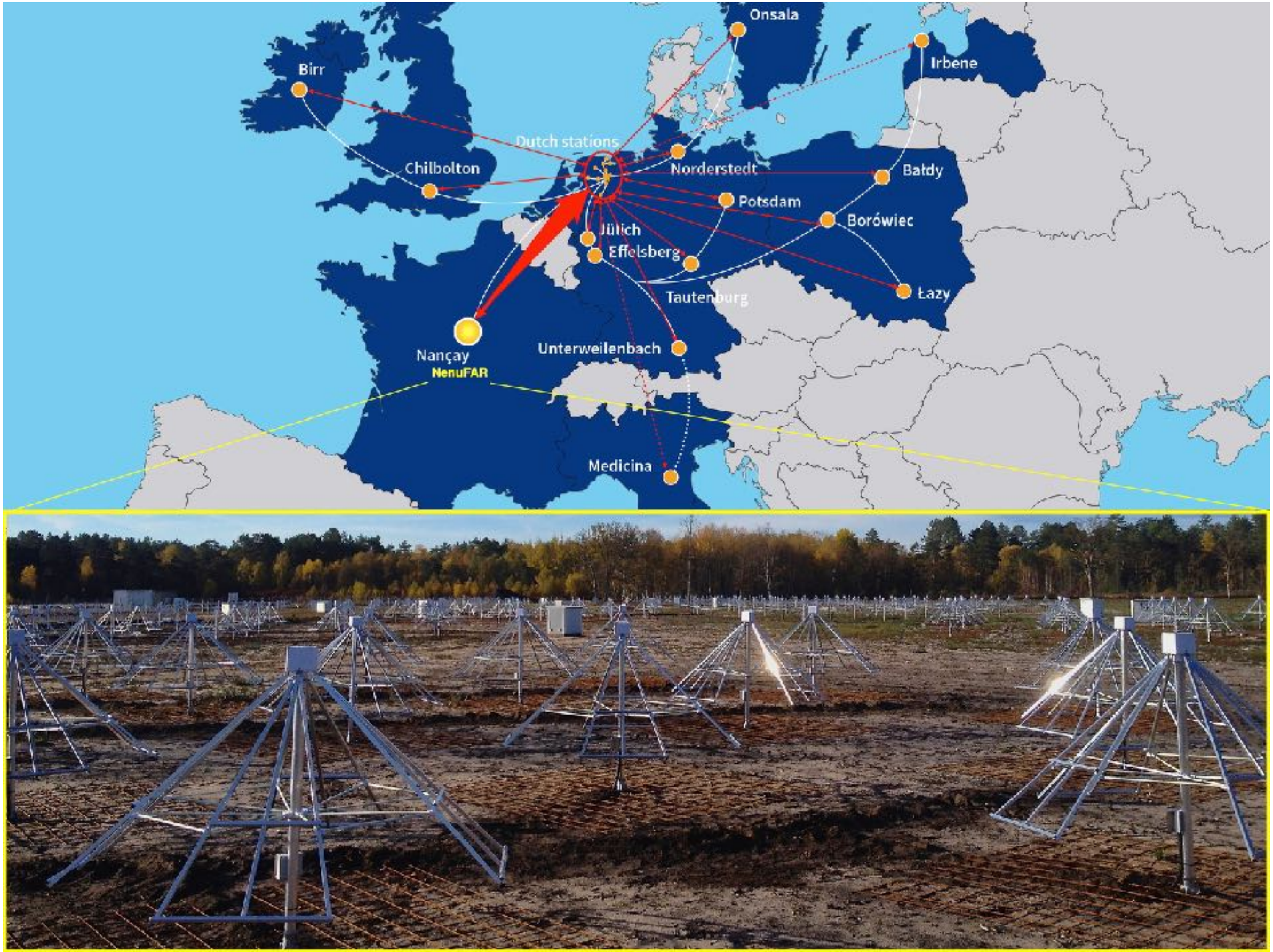
NenuFAR: status and outlook

Philippe Zarka
& the NenuFAR-France collaboration

The french very large Low-Frequency Radiotelescope



NenuFAR

en chiffres...

3 instruments **en 1**
réseau phasé autonome
imageur autonome
super station LOFAR

60 000 m²
d'aire effective
à 25 MHz

un réseau total
de **1 938** antennes
situé à Nançay

10 à 85 MHz
de gamme de fréquence
(longueurs d'onde
de 3,5 m à 30 m)

96
mini-réseaux

19
antennes dans
1 mini réseau

6
mini-réseaux
distants

3 km
de distance
au mini-réseau
le plus éloigné

400 m
de diamètre au
cœur du réseau

600 Gbits/s
de volume de données
traitées en temps réel
24/7

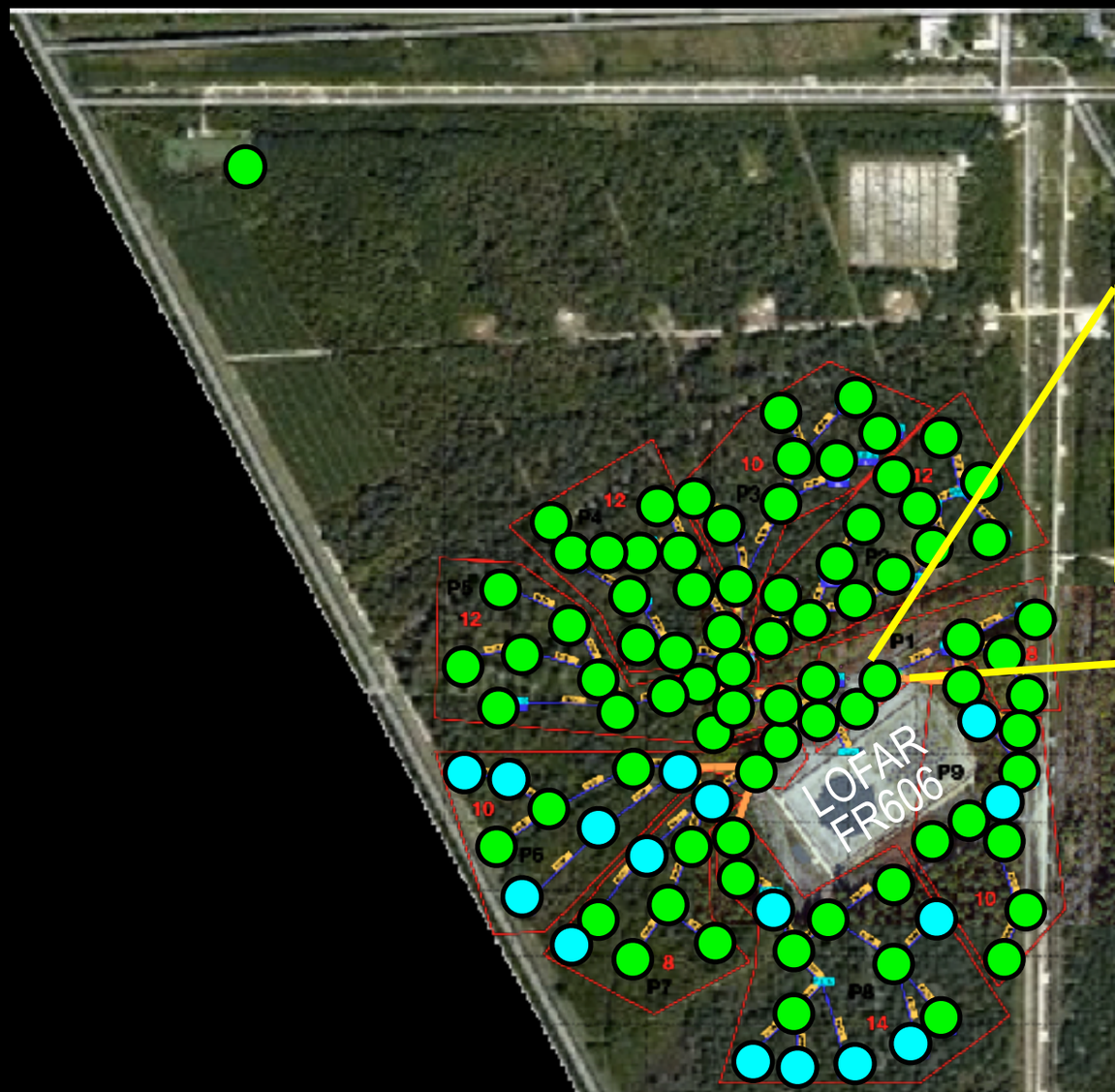
180 km
de câbles
coaxiaux

10 Po
de données brutes
traitées par an

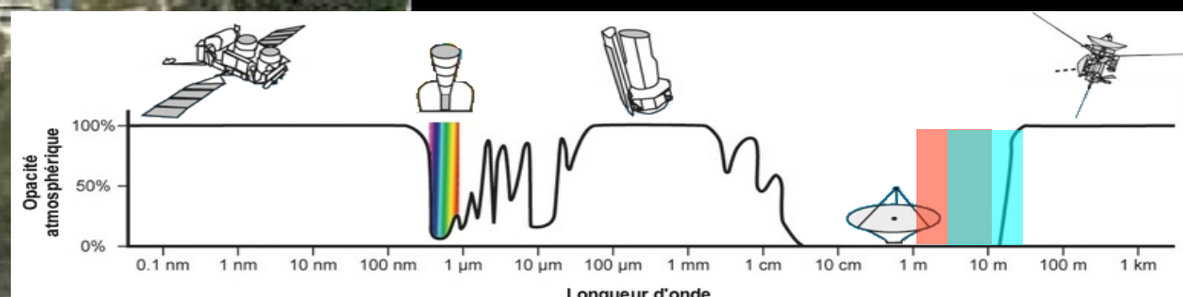
- **First proposed as a LOFAR super station (2008)**
- **NenuFAR = New extension in Nançay upgrading LOFAR (named in 2011)**
- **But first implemented as standalone sensitive large LF compact array (≥2014)**
- **Labelled official SKA pathfinder (2014)**
- **Inaugurated in 2019**

Built around the French LOFAR station in Nançay
Made of 84/104 MA : Core (80/96 MA) + Remote (4/8 MA)

Mini-Array (MA) of 19 dual-polarization antennas



- operational
- in preparation



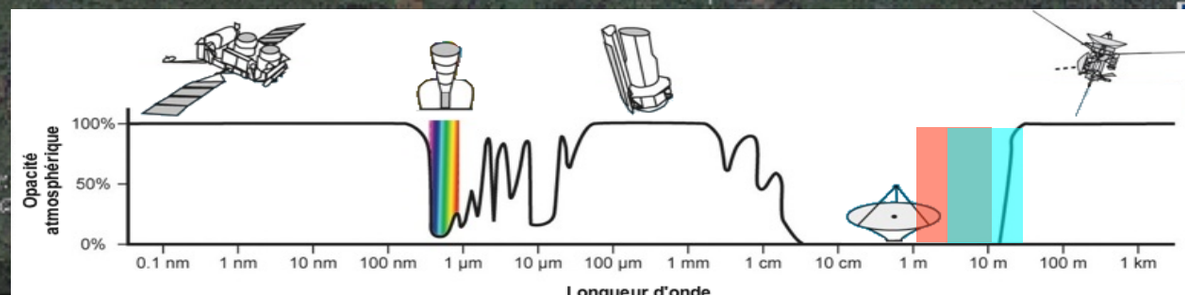
Completion expected in 2024 :
Core 96 MA + 8 remote MA

1
2
3
4
5
6
7
8

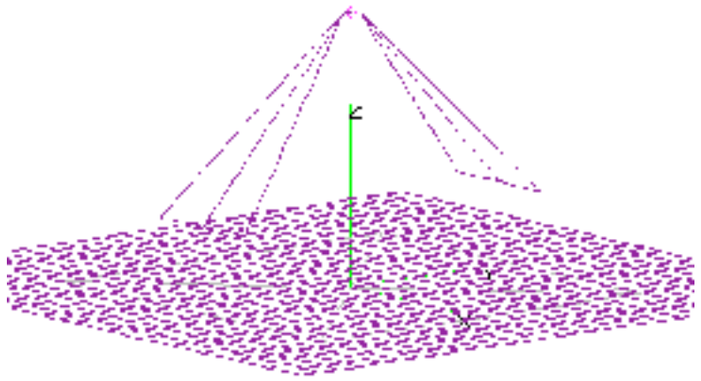
1 km

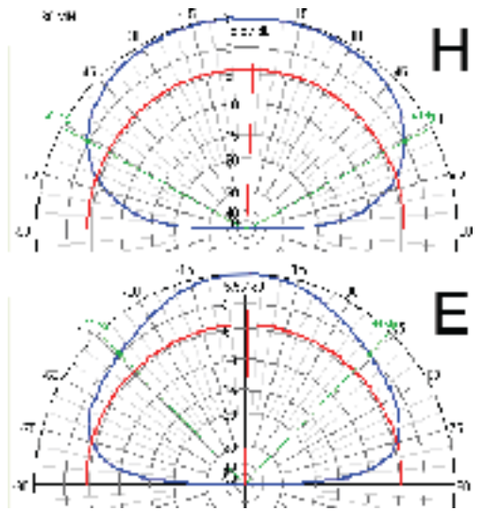
operational

in preparation



Mix of external technology …

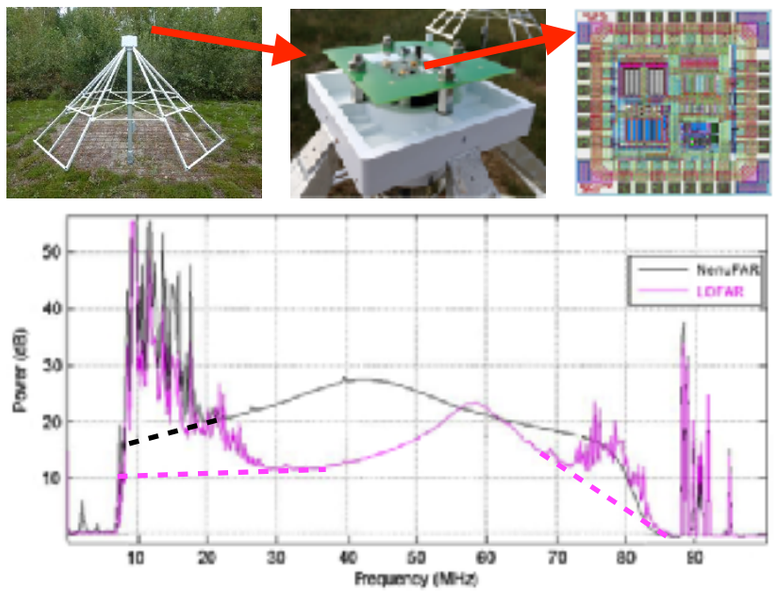




LWA radiator [Hicks et al., 2012]

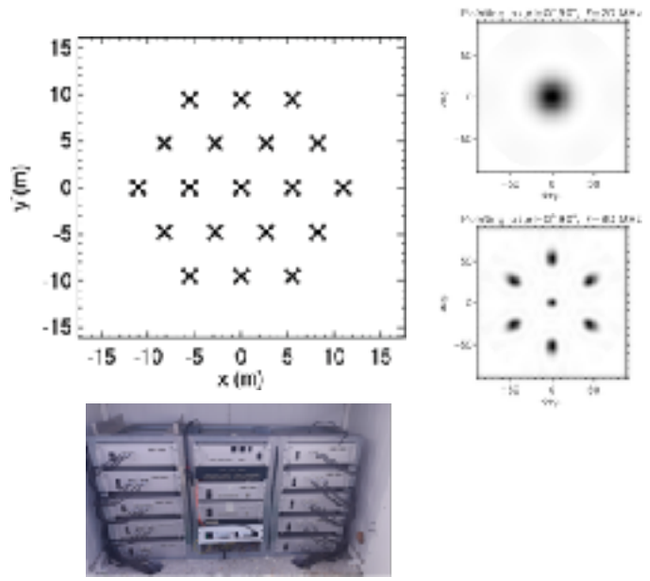
COBALT2 correlator … [Pandey, Viou et al.]

… and original developments



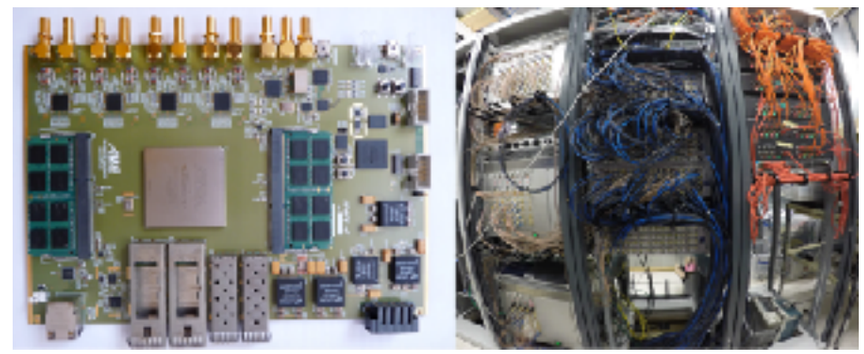
Antenna preamplifier

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



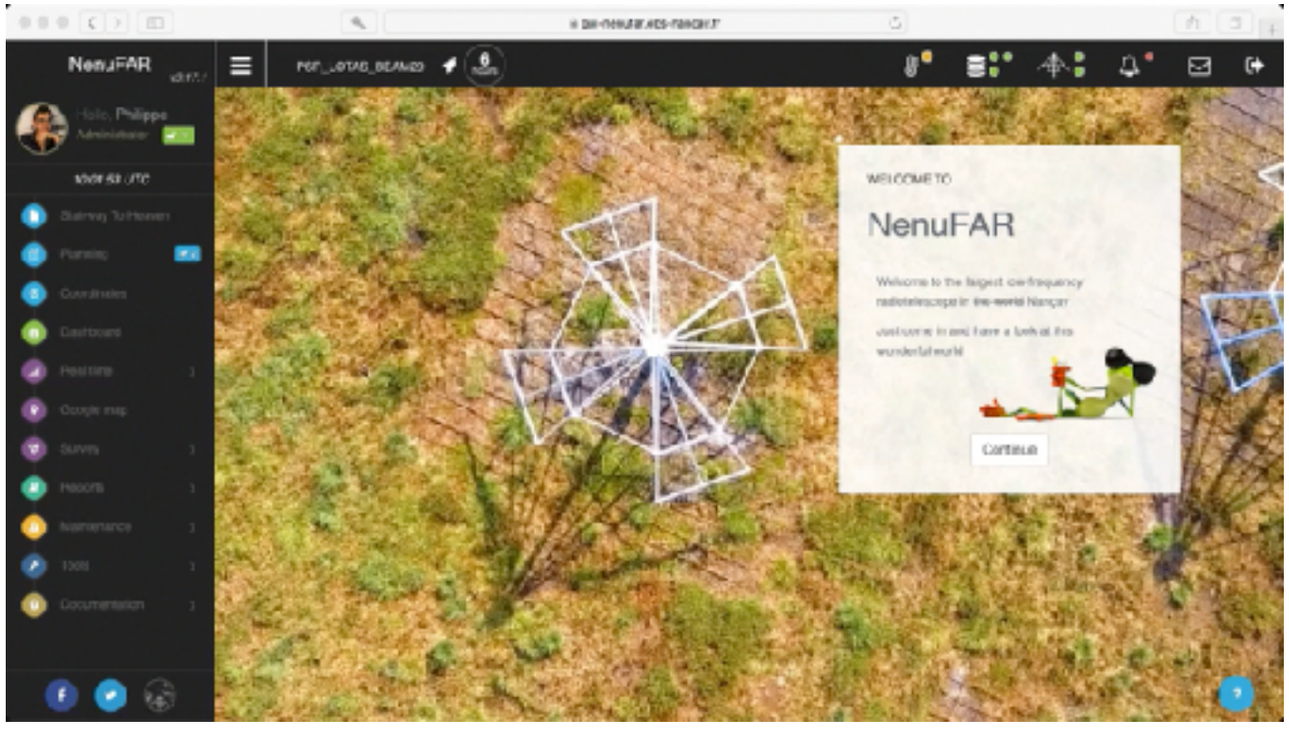
Mini-array topology & phasing

[Girard & Zarka, 2023]



Beamformed receivers

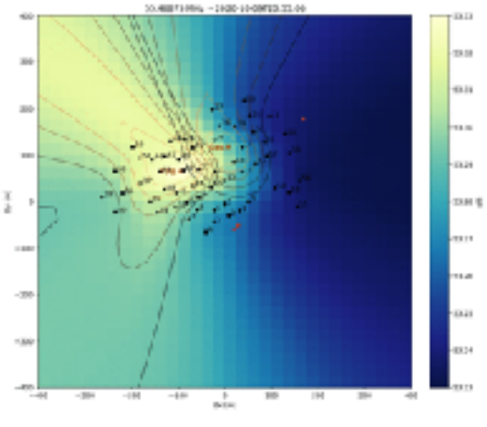
[Cognard, Bondonneau et al.]



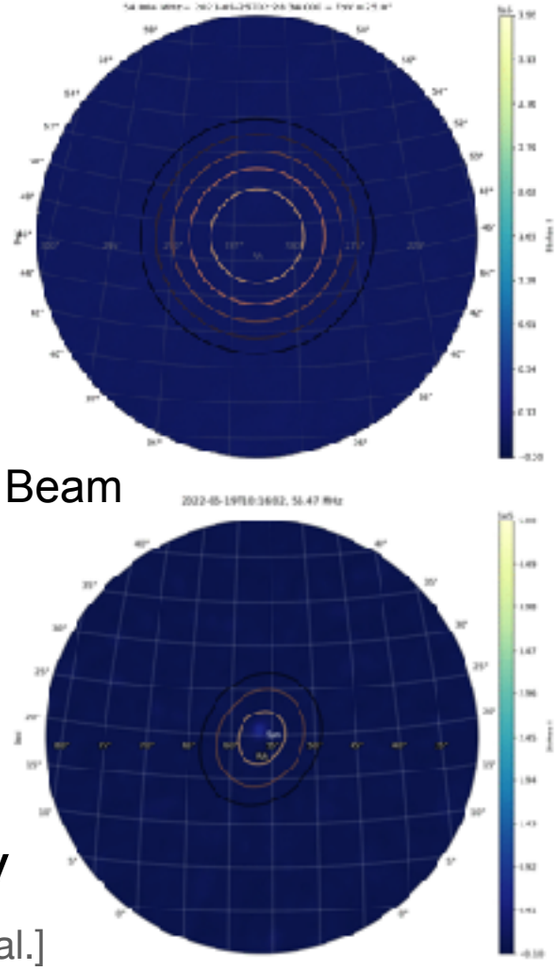
Virtual Control Room

[Taffoureau et al., 2020]

Near-field



Beam



NenuFAR-TV

[A. Loh, F. Mertens et al.]

4 instruments in 1: Beamformer / Imager / Waveform / LSS

- NenuFAR Beamformer
- NenuFAR Waveform (Transient) buffer

96

HBA
110-250 MHz

LBA
30-80 MHz

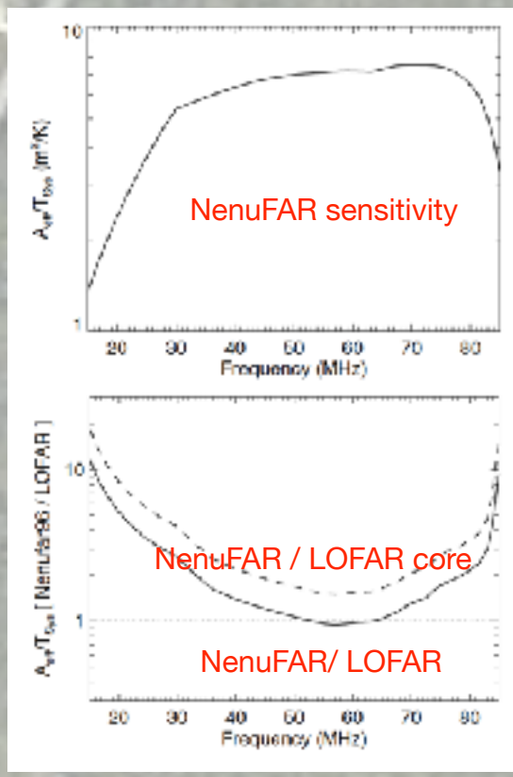
~ 400 m

LOFAR back-end
- HBA
- LBA
- NenuFAR/LSS

19

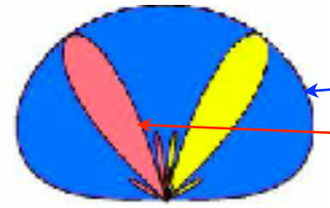
8

- NenuFAR Imager



- Sensitive large compact (very) low frequency array
- Large FoV, multi-beam, sensitive to extended structures
- Complementary with LOFAR : high resolution in LBA with sensitive int'l baselines

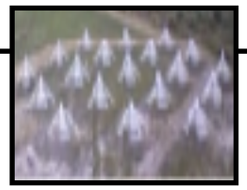
Receivers and signal path



antenna beam

MA beam (analog-phased)

Compact core (400 m) : 96 MA x 2 polar.



Distant MA (≤3 km) : 6 MA x 2 polar.

analog signals

analog signals

analog signals

- Digitization
- Channelization

LOFAR FR606 backend

- Digitization
- Channelization
- Beamforming

LOFAR Super Station

- Correlation
- Calibration + Imaging

LOFAR

LaNewBa

- Digitization
- Channelization

- Beamforming

B H R

SDO

TBB

UnDySPuTeD : dynamic spectra

- Channelization
- Integration

UnDySPuTeD : pulsar

- Coherent dedisp.
- Folding / Integ.

SETI Machine

Thetis, BCB

NenuFAR Standalone Beamformer

NenuFAR Correlator : NICKEL + COPER

- Channelization
- Correlation
- Calibration + Imaging

NenuFAR Standalone Radio Imager

- RadioGAGa trigger

NenuFAR Transient Buffer

- Beamforming (down to 300 µsec & 100 Hz, <1 Hz with SETI receiver), in 30'-2° beams
- Waveform capture (200 MHz & n x 200 kHz)
- Imaging with resolutions down to 3'-5'

[C. Viou, Project Manager]

Science organization

- Early Science, shared-risk phase : 1/7/2019 - 30/11/2022, ~12 active Key Projects
- Semester calls for Open time since 9/2022 (PI proposals ; most KP continue)
- Cycle 1 : 1/12/2022-31/5/2023 ; Cycle 2 started 1/6/2023
- Pressure on observation time x1.3 to x2 at night

- Cycle 1 programs
  - LT01 Cosmic Dawn (Koopmans, Semelin et al.)
  - LT02 Exoplanets & Stars (Zarka, Lamy et al.)
  - LT03 Pulsars (Grießmeier et al.)
  - LT04 Transients (Corbel, Girard et al.)
  - LT05 Fast Radio Bursts (Decoene, Zarka et al.)
  - LT06 Planetary Lightning (Grießmeier et al.)
  - LT07 Joint Jupiter studies (Yerin, Lamy et al.)
  - LT09 Galaxies, Cluster Filament & Cosmic Magnetism (Bonnassieux et al.)
  - LT10 Radio recombination lines (Gusdorf et al.)
  - LT11 Sun (Briand, Masson et al.)
  - LT12 Radio Gamma (Dallier et al.)
  - LT13 SETI (Hellbourg et al.)
  - RP1A Faraday tomography of Galactic diffuse polar in 3C196 field (Bracco)
  - RP1B Low-Frequency Sky Survey (Girard, Sidorchuk et al.)
  - RP1C Free-free absorption in Cas A PP (Stanislavsky, Konovalenko et al.)

  + Formation of students, Radio-Amateurs group

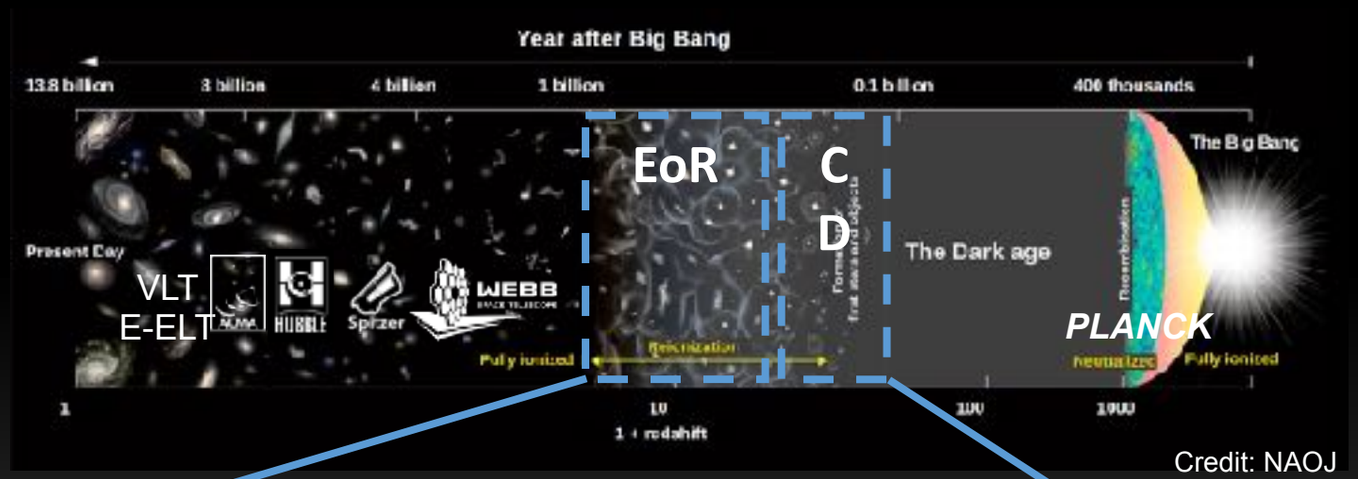
NenuFAR Cosmic Dawn KSP

AIM - *Detect and interpret the power spectrum of the 21-cm signal from the Cosmic Dawn*

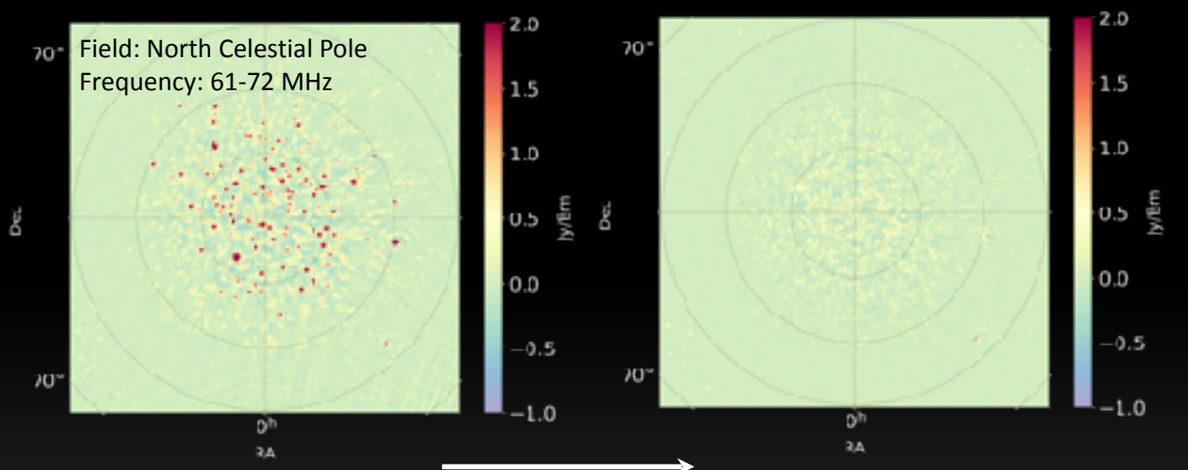
Status: +1000h observed. More observations ongoing.

[Mertens et al., in prep]

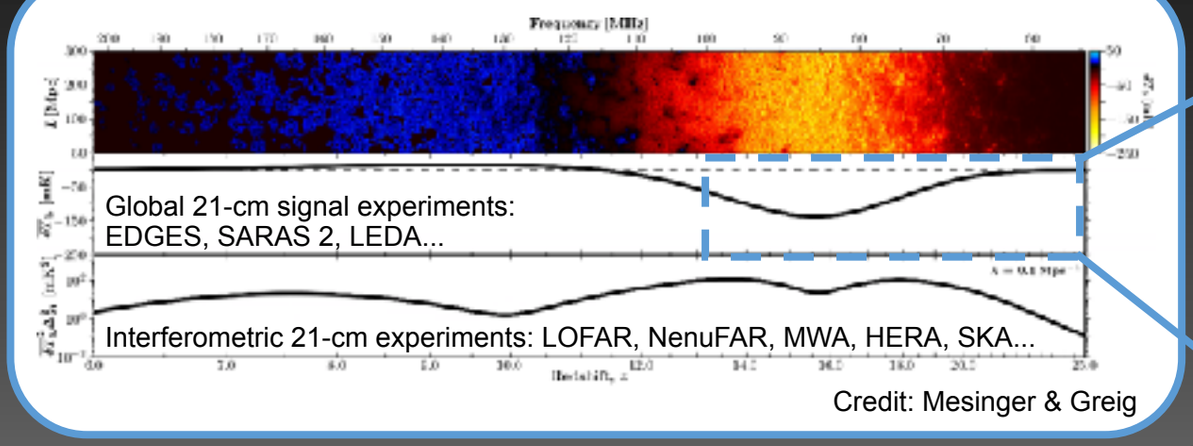
Single night Observation: Preliminary Results



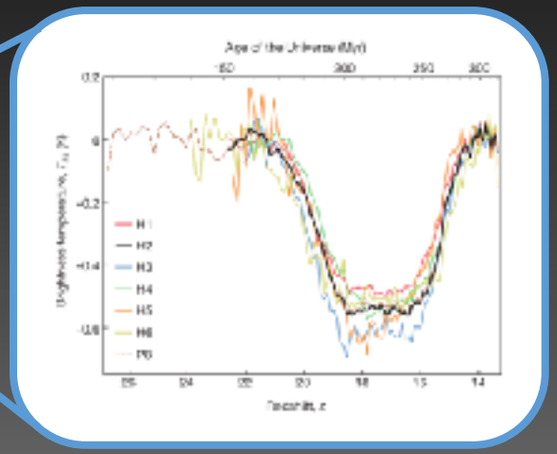
Credit: NAOJ



Calibration and Sky Model Subtraction



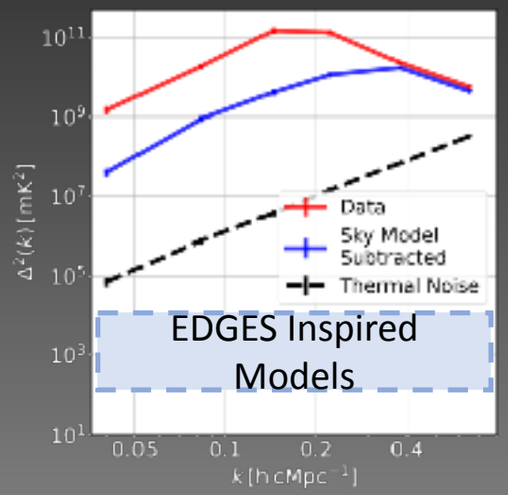
Credit: Mesinger & Greig



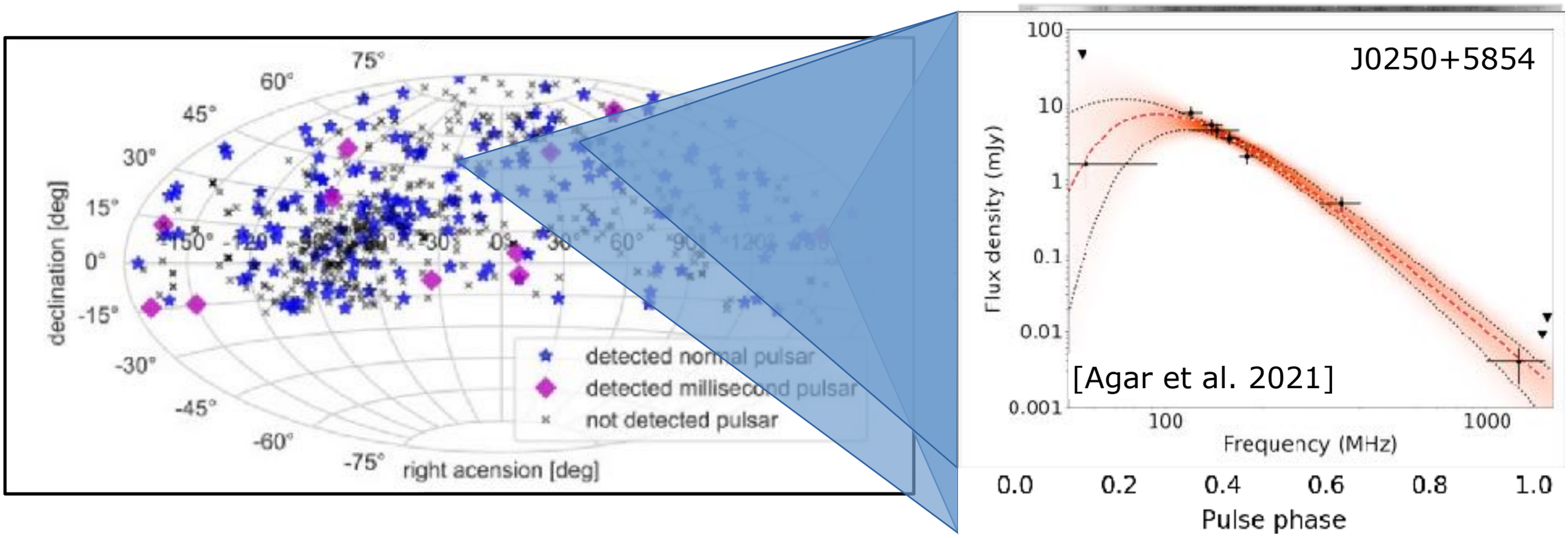
21-cm absorption profile observed by EDGES
(Bowman et al., Nature, 2018)

Need "exotic" model to be explained

Power Spectrum (~11h data)
Before residual foreground subtraction



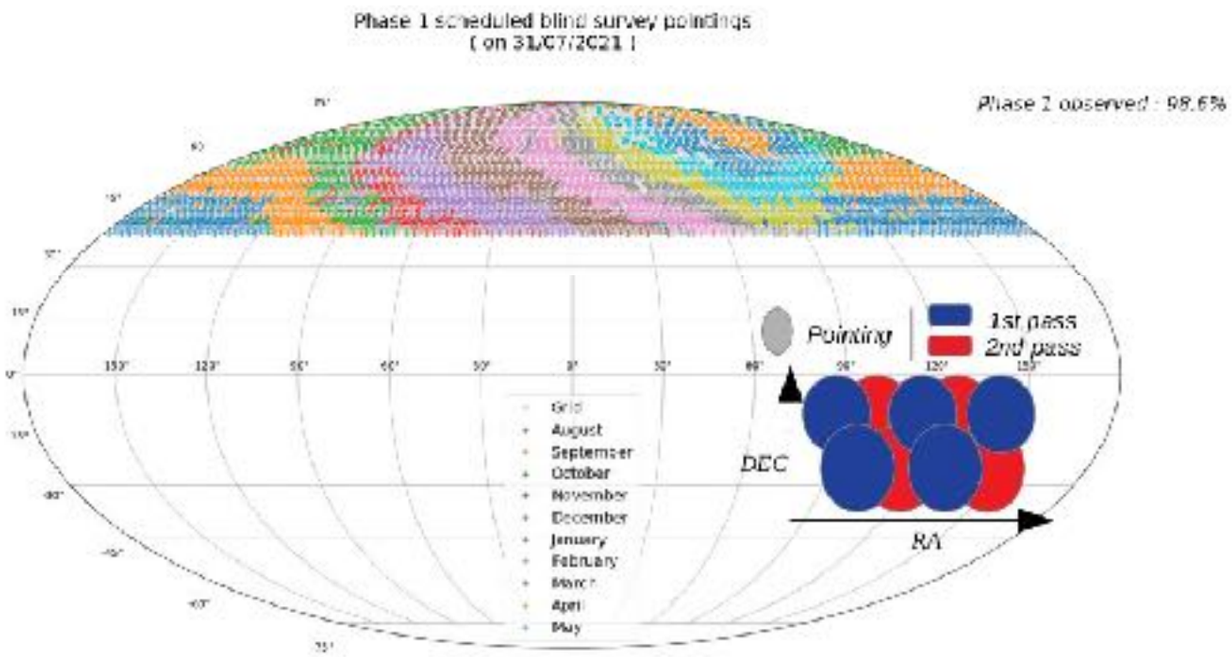
Pulsar census & MSPs



- Observation of 711 known pulsars
- DEC > -20°, DM < 100 pc/cm^3 (nearby pulsars)
- 184 pulsar detected (~100 for the first time <100 MHz)
- 11 MSPs detected (7 for the first time <100 MHz)
- next steps: study of scattering, pulsar spectra, turnover, …

[Bondonneau et al., A&A 2021; Agar et al., MNRAS 2021; Bilous et al., A&A 2022; Bondonneau et al., in prep.]

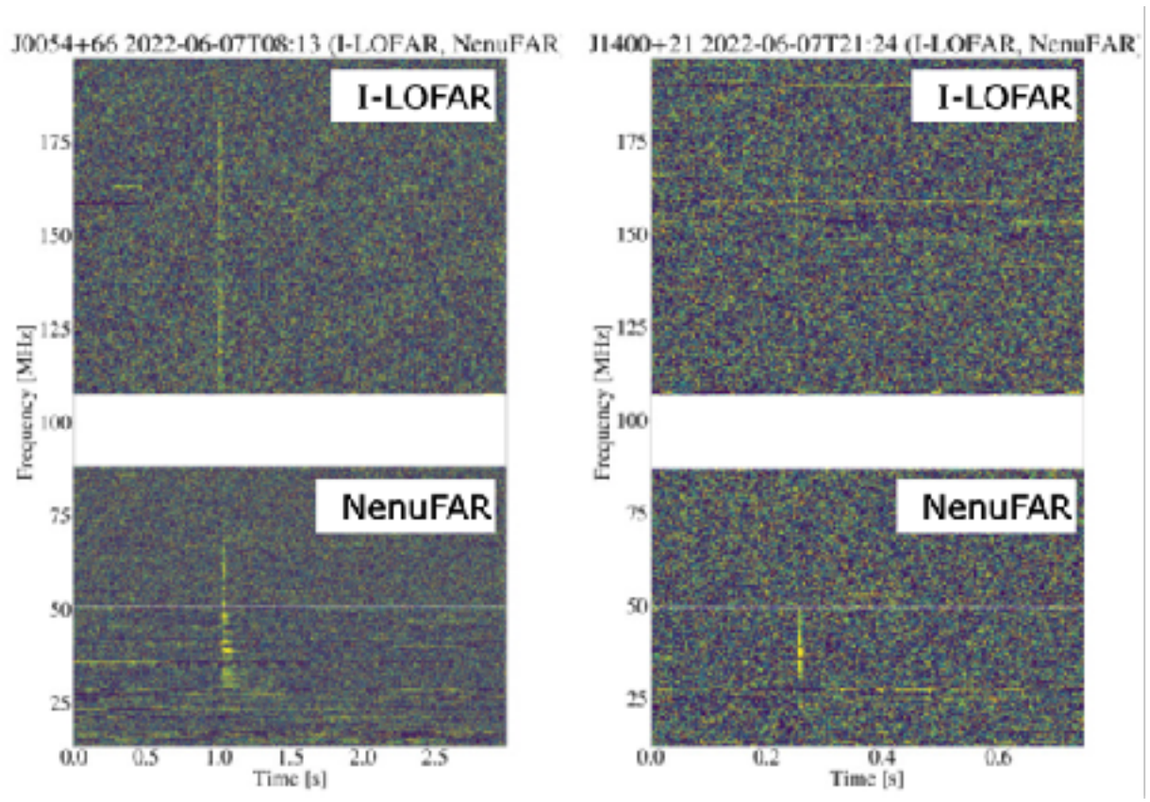
Pulsar blind survey



- searching unknown pulsars δ>39°
- 39-77 MHz, DM<70 pc/cm^3 & P>80 ms
- 7692 pointings: observations 2020-2022
- first "candidates"

[Brionne et al., submitted]

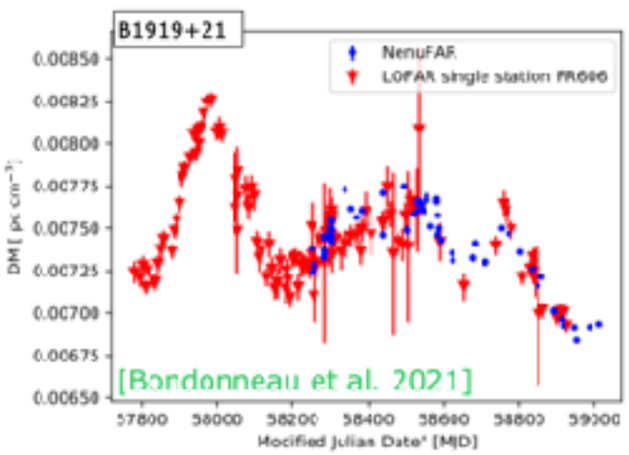
RRATs

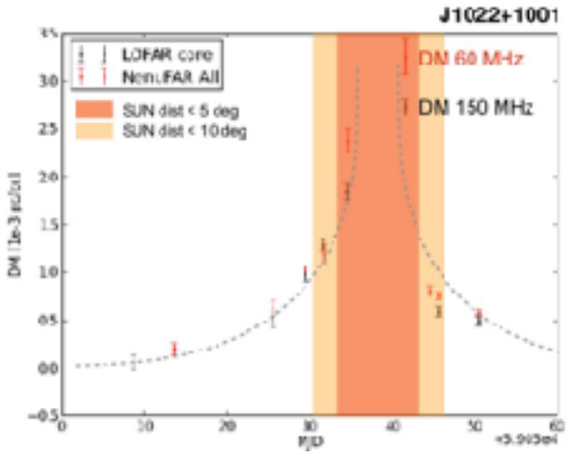


- 1 RRAT previously known ≤100 MHz
- 25 observed win NenuFAR → 7 detected
- simultaneous obs. with LOFAR HBA (IE613)

[McKenna et al. in prep.]

Ionized ISM

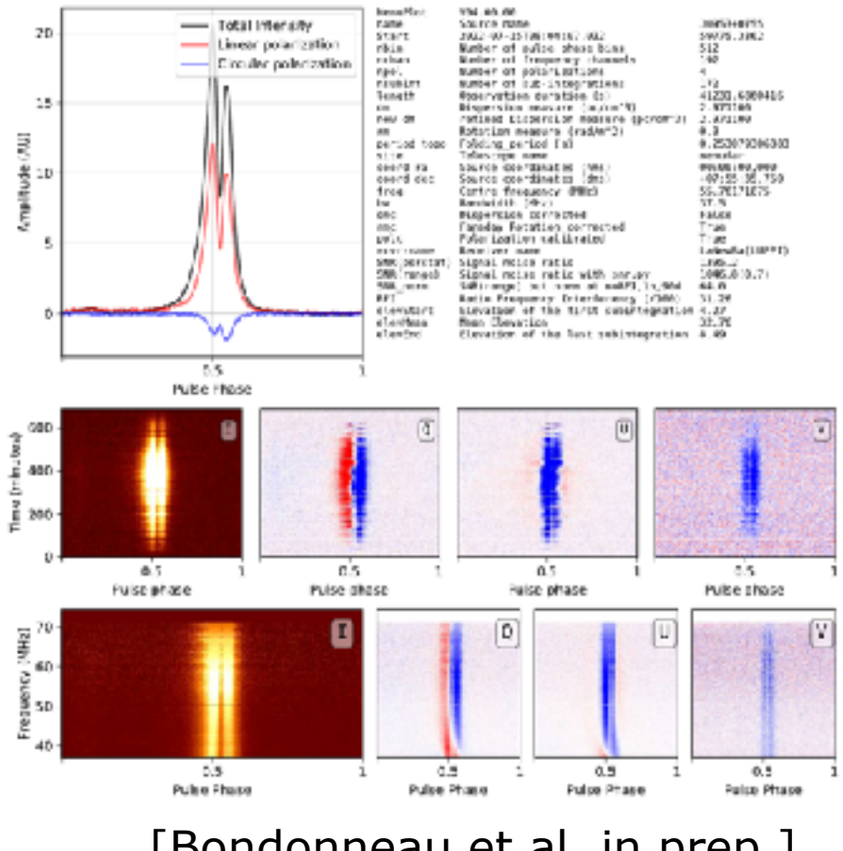




- NenuFAR: high sensitivity & low frequencies
  → precision of ~10^{-5} pc/cm^3 on DM
  → DM monitoring, statistics of "DM events"
  → improve timing (e.g. for PTA)
- DM versus apparent distance to Sun
- DM jump due to a CME
  → under study

  [Wu et al., MNRAS 2023 ; Tiburzi et al., in prep; Zahraoui et al., in prep]

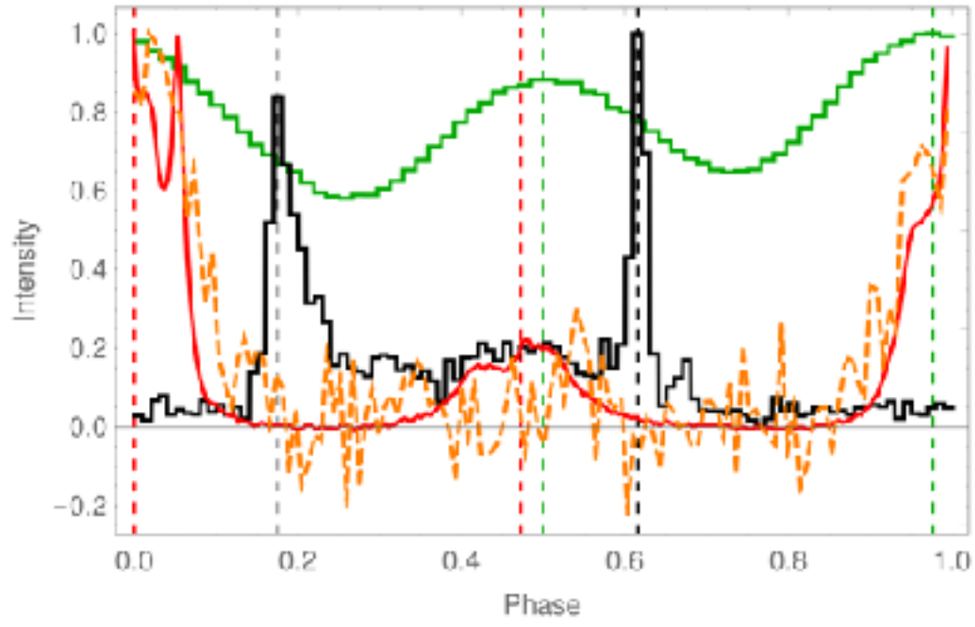
Polarization



[Bondonneau et al. in prep.]

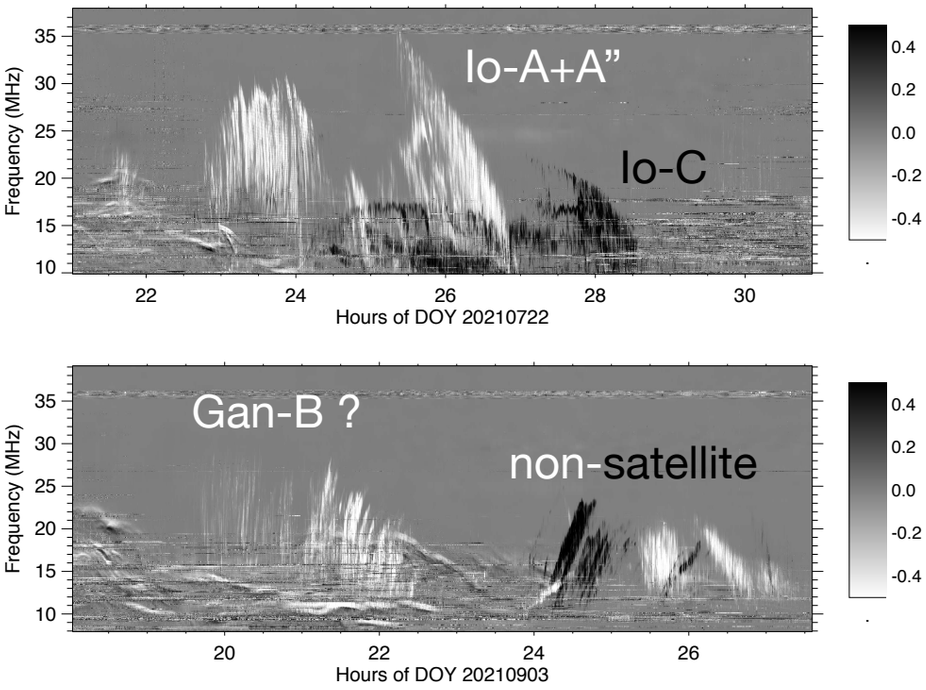
Multi-λ

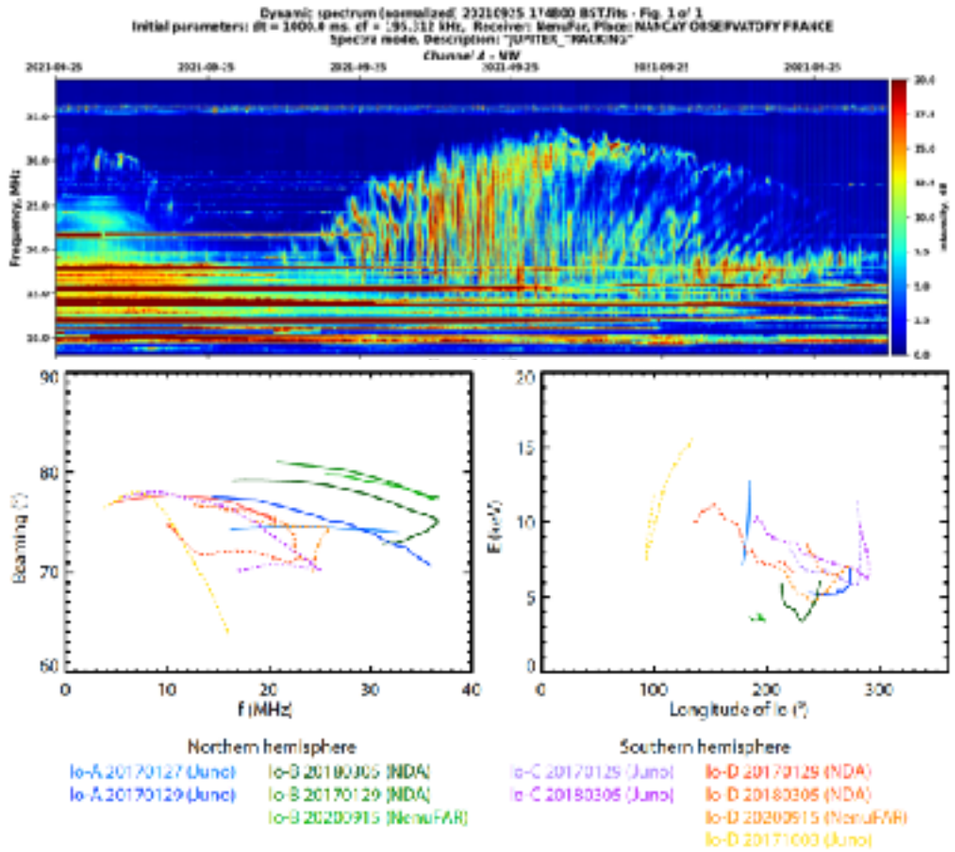
- J0030+0451 MSP observed by FERMI/LAT (γ), NICER (X-rays), NRT (GHz), NenuFAR
  [Pétri et al., submitted]



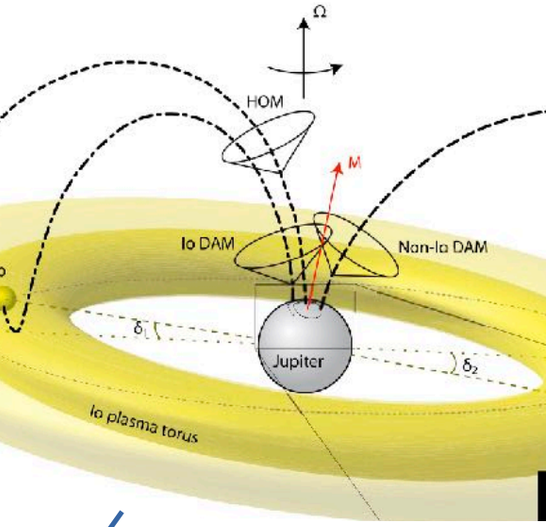
NenuFAR Jupiter KSP

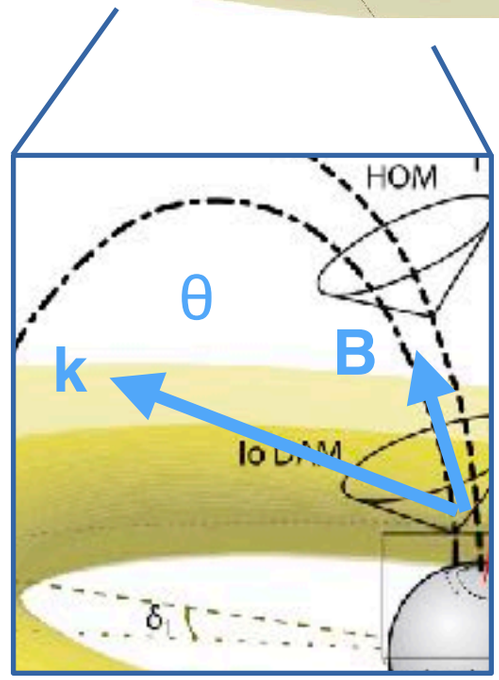
- High sensitivity obs. **in support to Juno** // UTR-2: dynamic spectra (84 msec x 12 kHz) & waveform
  → faint emissions, fine structures

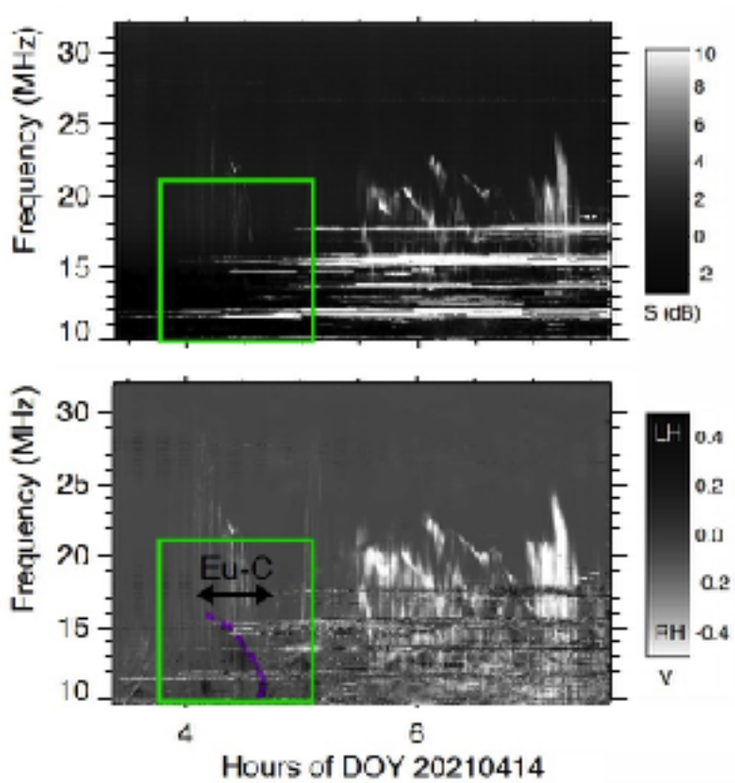


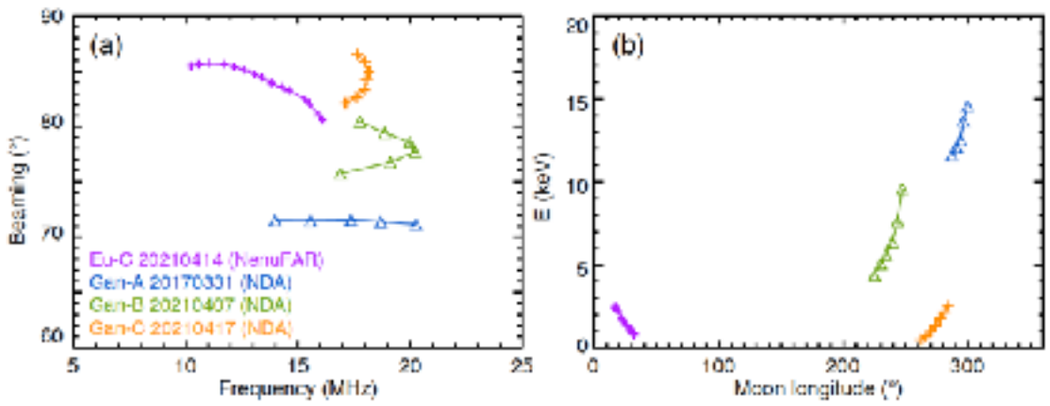


[Lamy et al., JGR 2022]



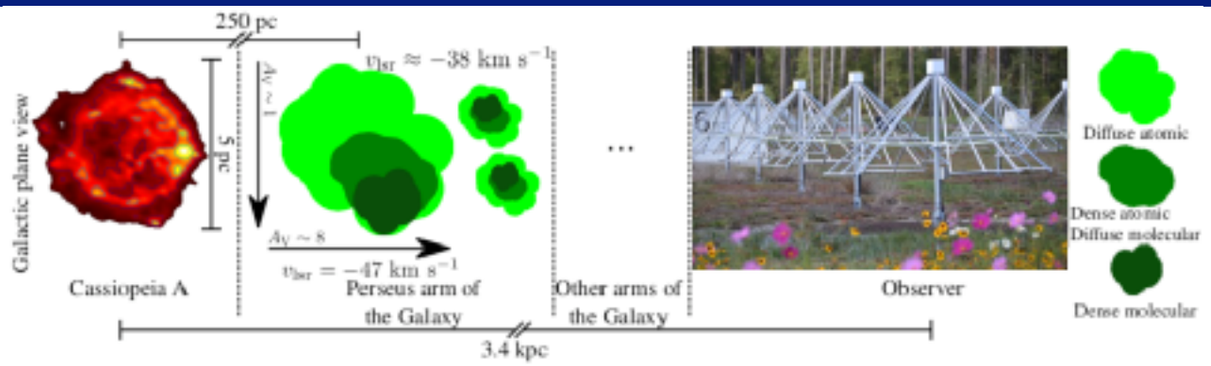




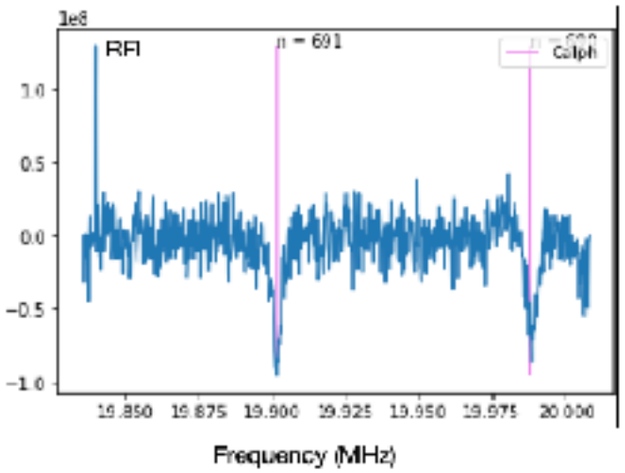


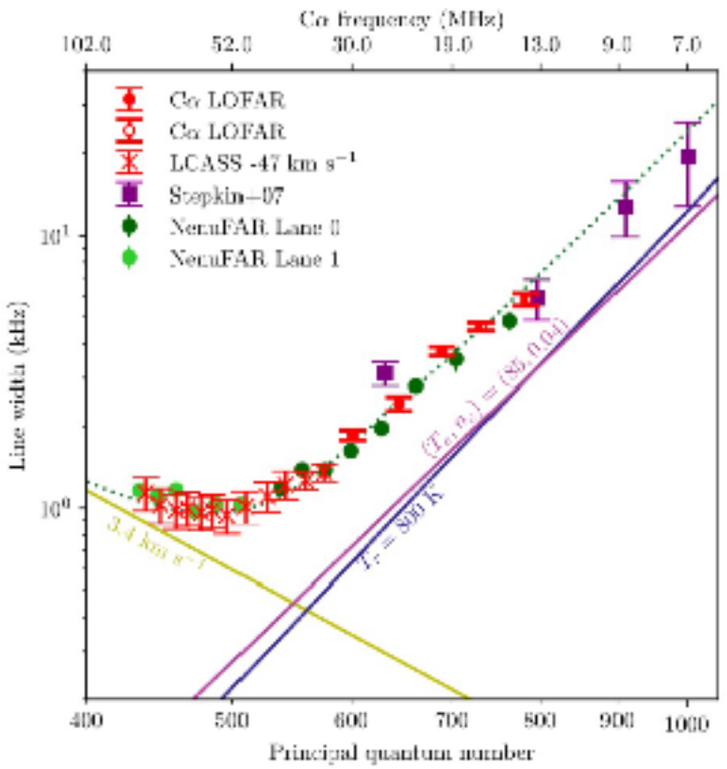
[Lamy et al., PRE9, 2022]

Radio recombination lines in the ISM



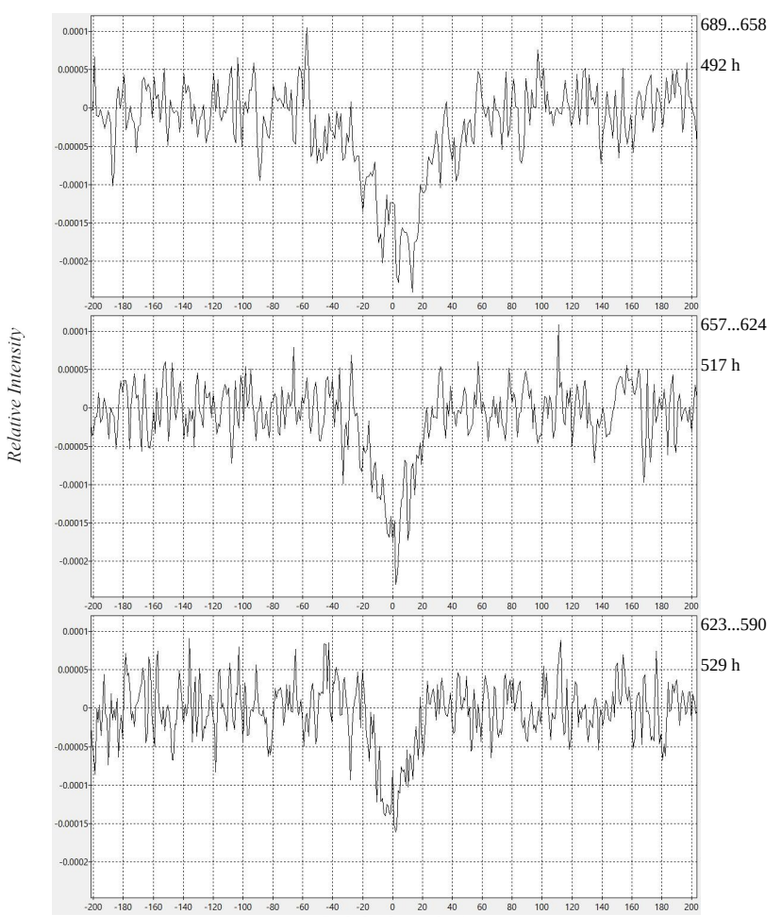
- High SNR detection

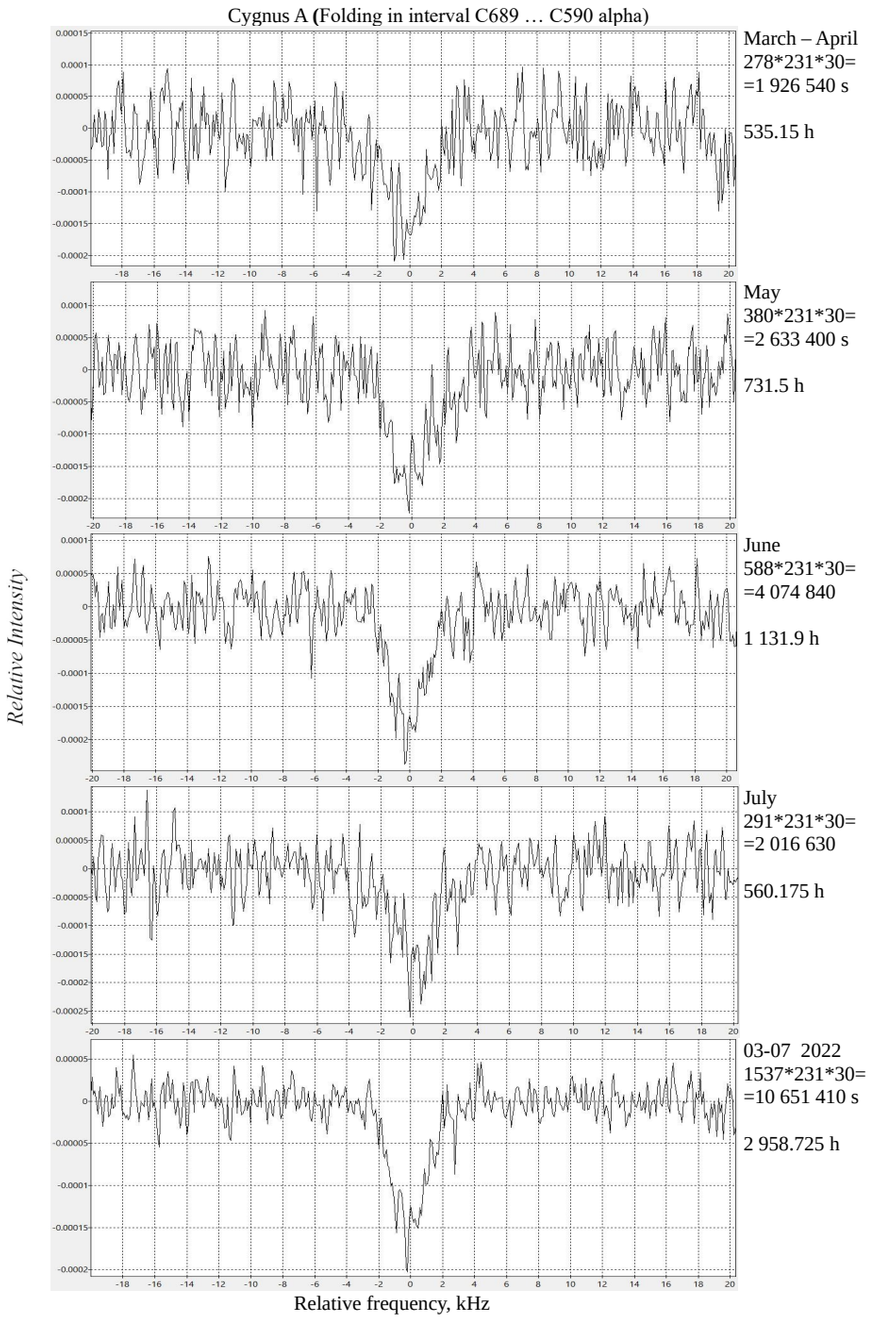




[Cros et al., in prep.]

- Cyg A studies

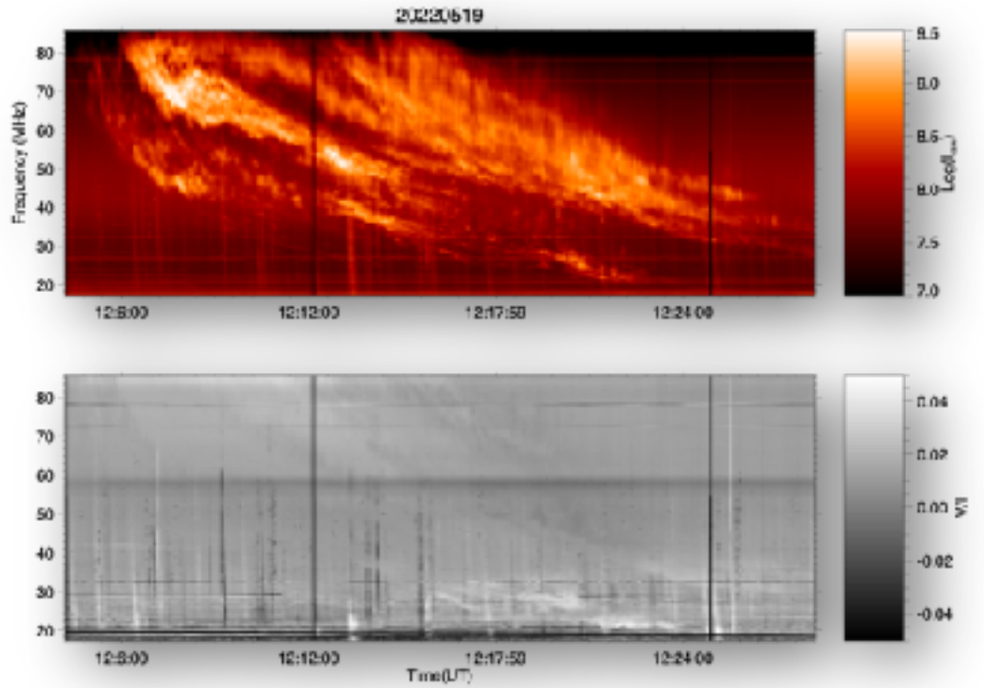




Solar KSP

Key questions:	✓ Acceleration mechanisms	✓ Emission mechanisms in quiet or active regions
	✓ Transfer and dissipation of energy Sun → IP	✓ e- beams escaping solar atm., Turbulence
Constraints:	Fast emissions (sub-sec. → 10s minutes), eruptive, unpredictable	

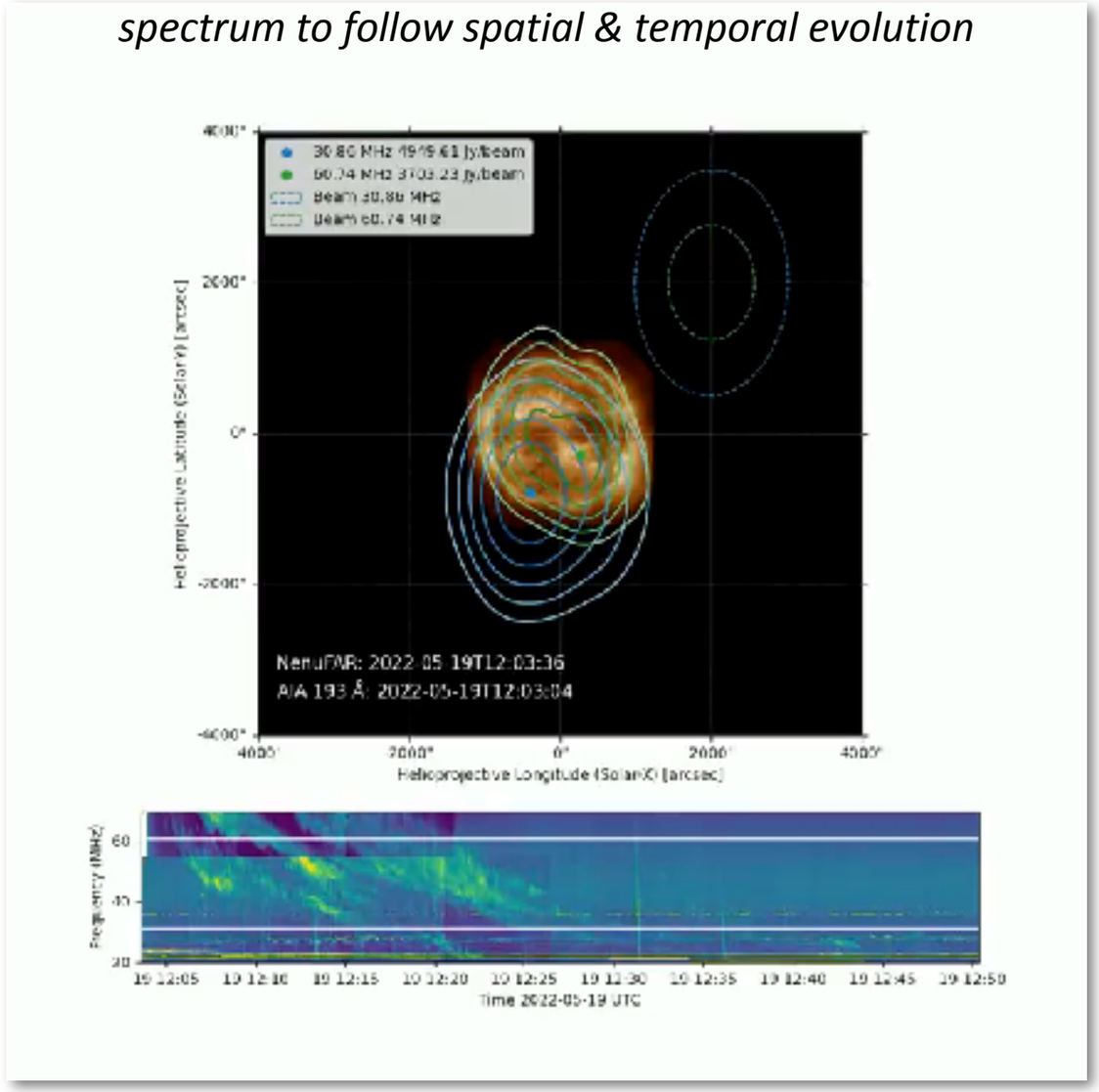
NenuFAR high sensitivity, polarization, dynamic spectra + imaging



Long-lived, highly-structured weakly polarized shock-related emissions …

Short-lived, narrow-banded, highly polarized emissions

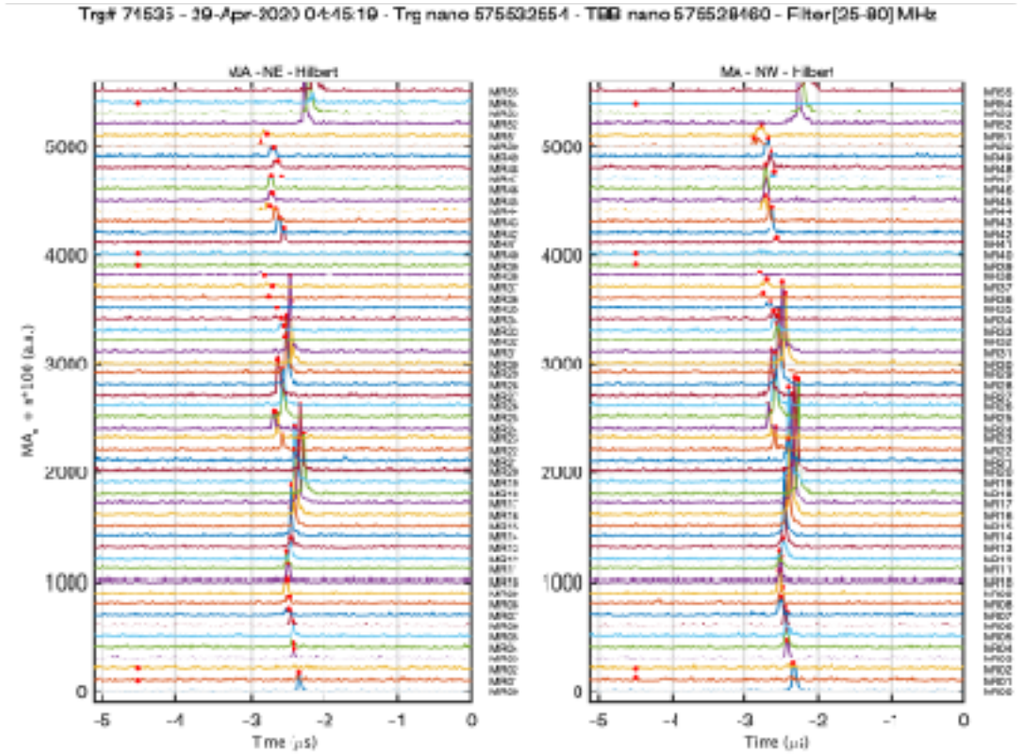
Highly dynamical phenomena: imaging + dynamic spectrum to follow spatial & temporal evolution

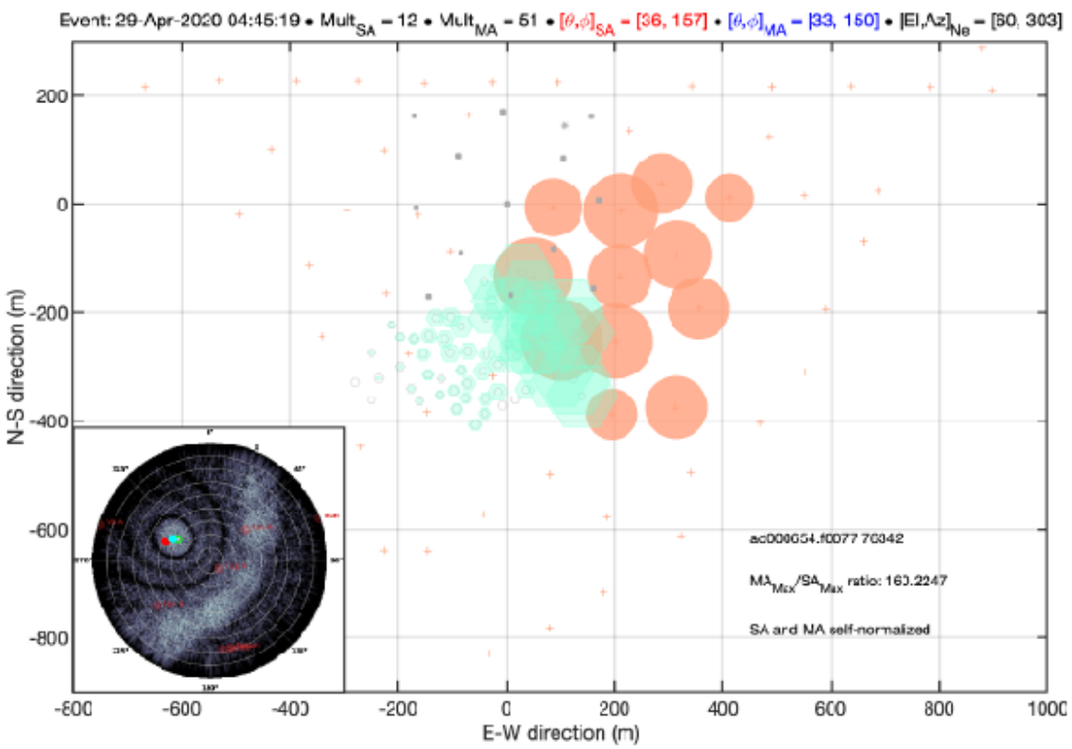


[Briand et al., 2022 ; Murphy et al., in prep.]

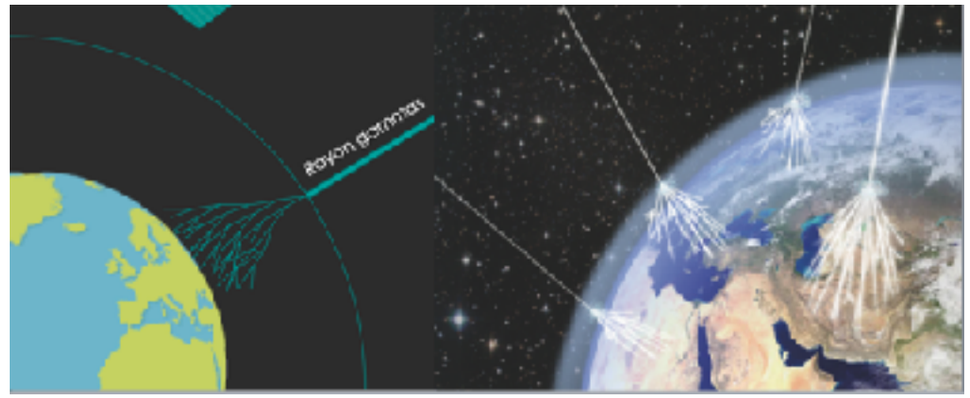
Radio Gamma KSP

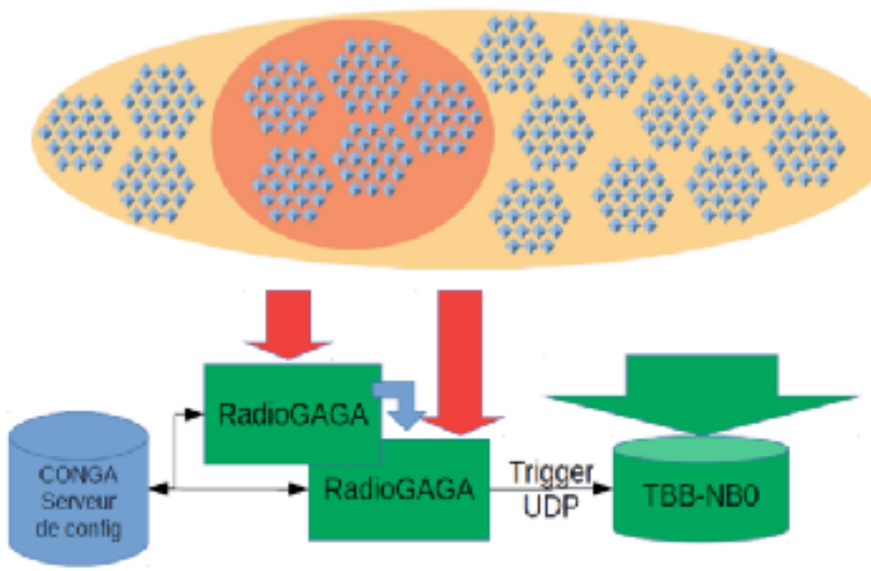
- Regular detection of Cosmic ray showers (TBB)





- RadioGaGa project : development of a sensitive trigger on phased MA → γ ray showers :

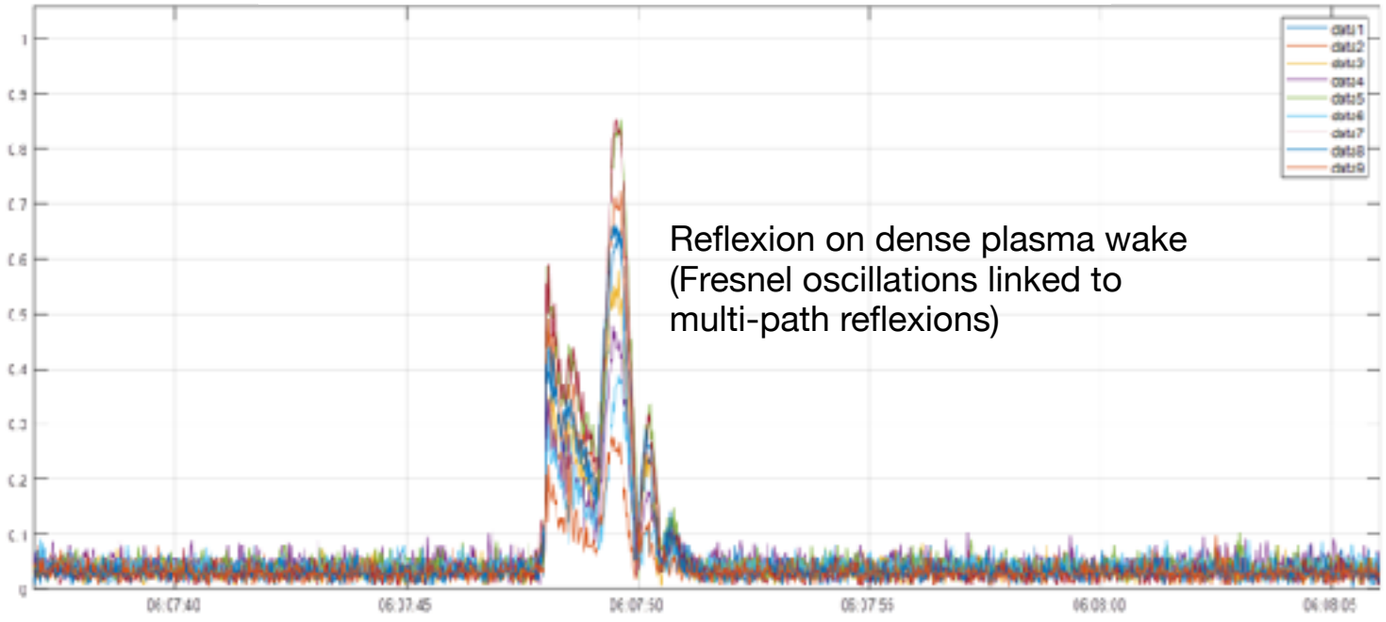




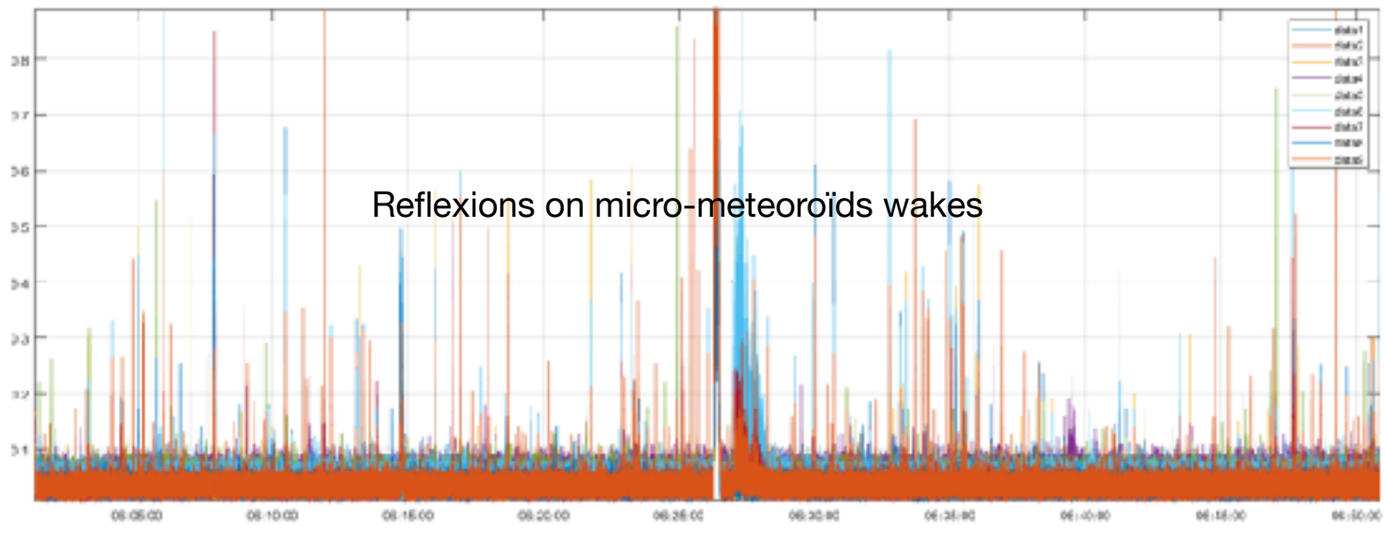
[Dallier et al., in prep.]

Radio Amateurs group

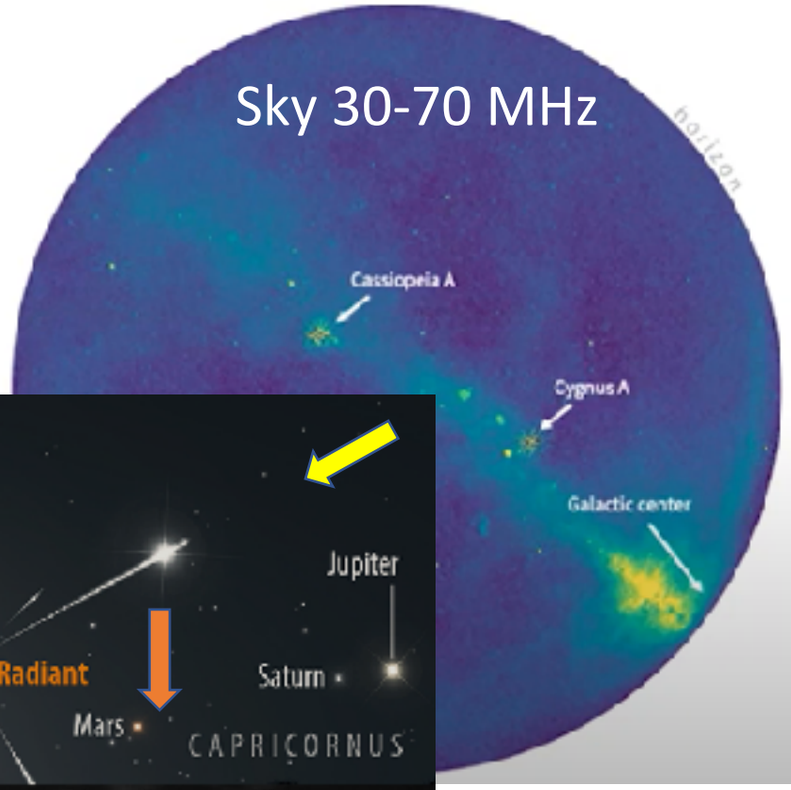
Meteor shower– Eta-Aquarids 20220605
9 individual MAs, δf = 47 Hz, δt = 20 ms

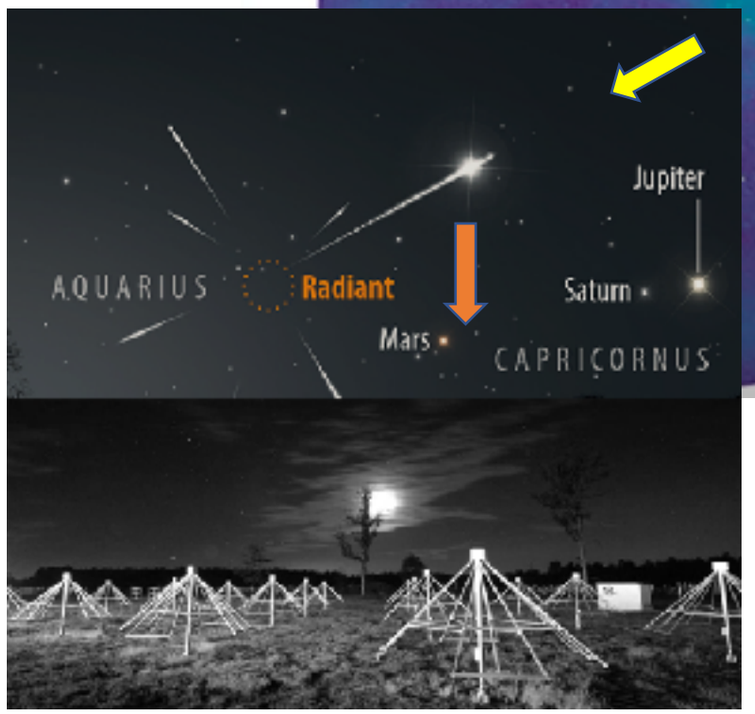


Reflexion on dense plasma wake
(Fresnel oscillations linked to
multi-path reflexions)



Reflexions on micro-meteoroïds wakes



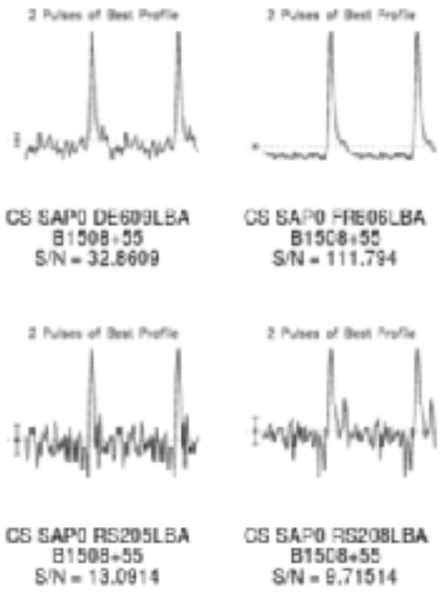


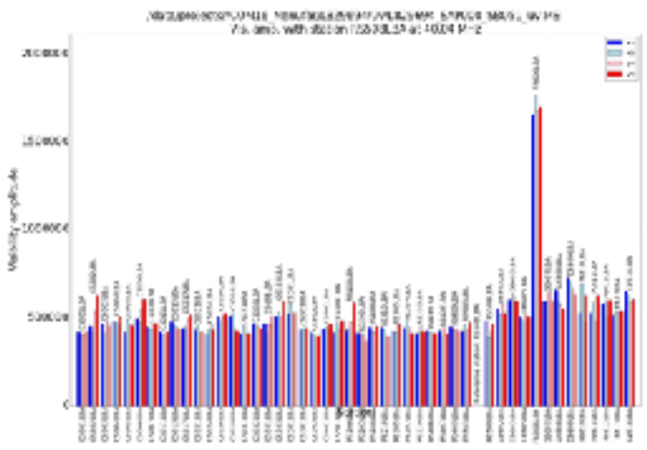
Incident radio flux
Reflected radio flux

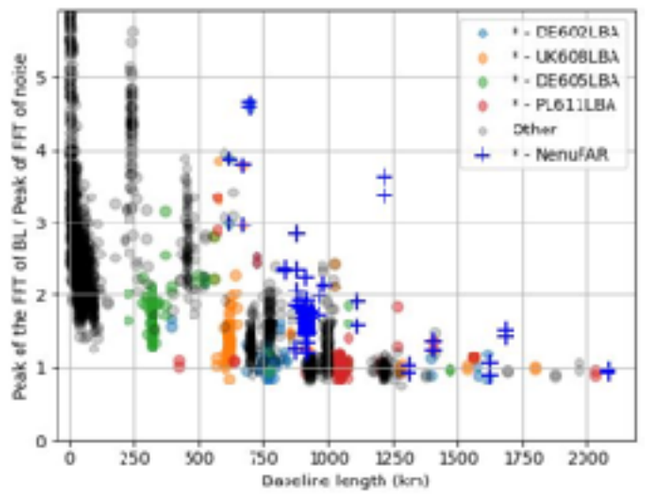
- Collaboration with FRIPON network ?
- Use of A-team sources at emitters ?

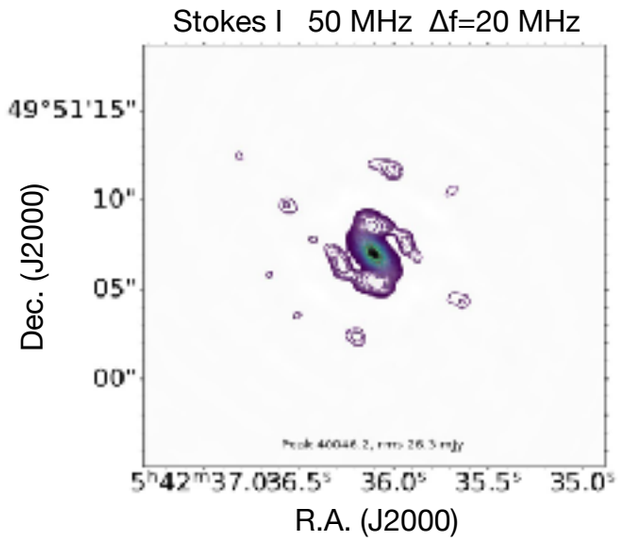
LOFAR 2.0 & LSS mode

- Functional tests with FR606 Ok [Grießmeier et al.]



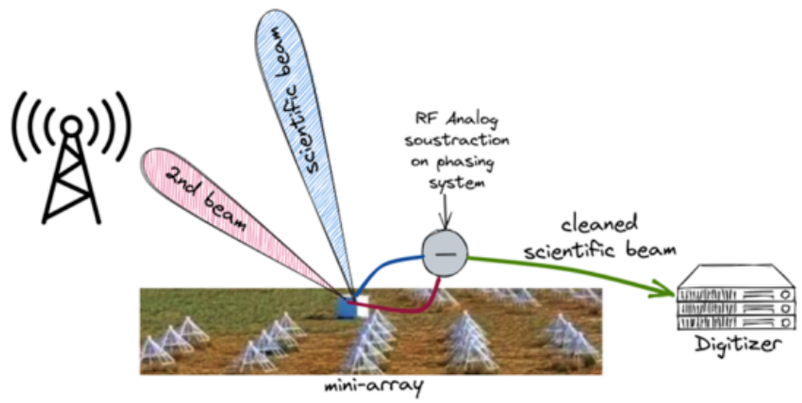






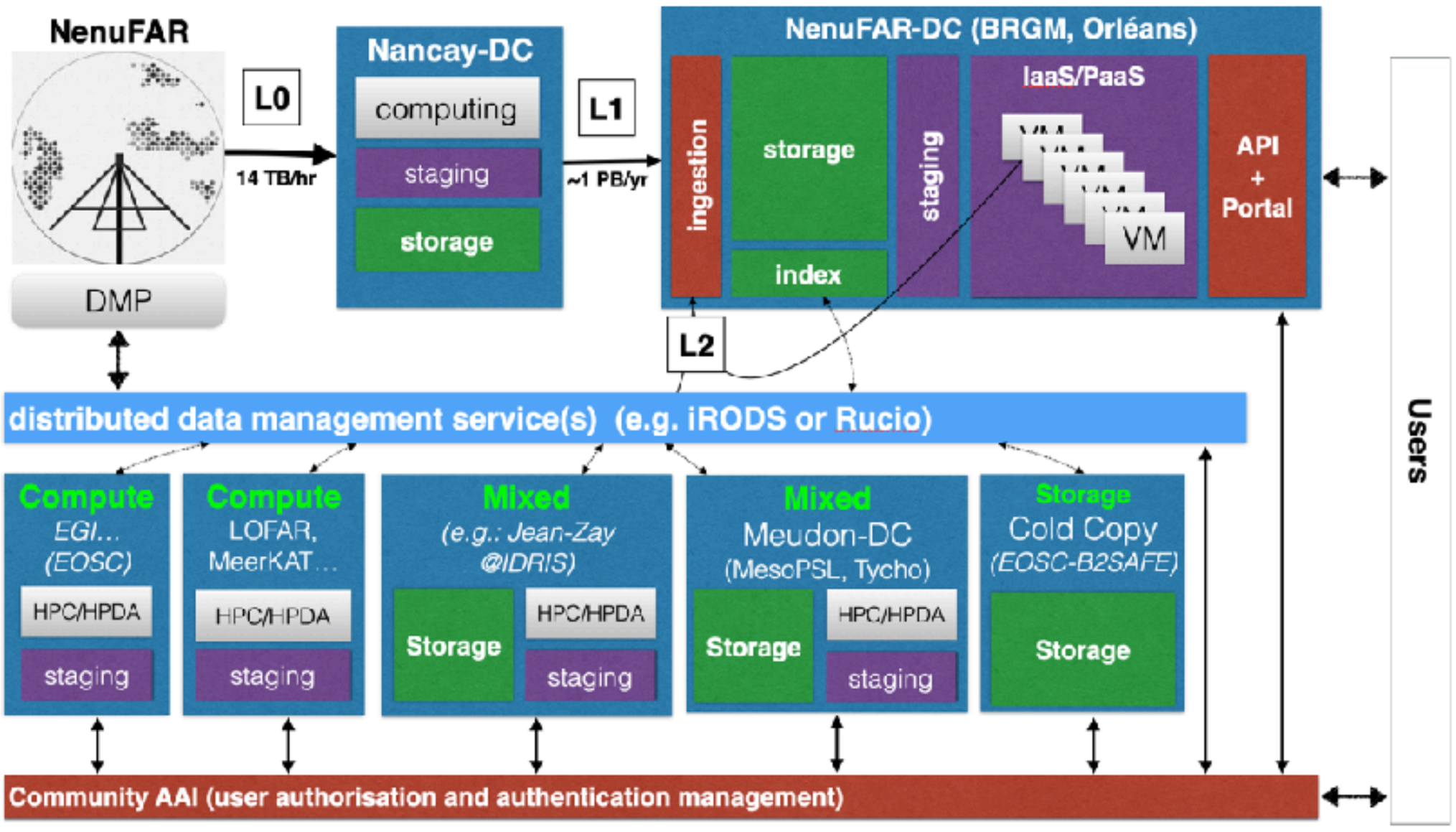
- Upgrade FR606 → LOFAR 2.0
- MoU finalized LOFAR-NenuFAR
- LSS commissioning plan [Bonnassieux et al., in prep.]

- Dual-beam ASIC
  (+signal multiplexing)
  under study



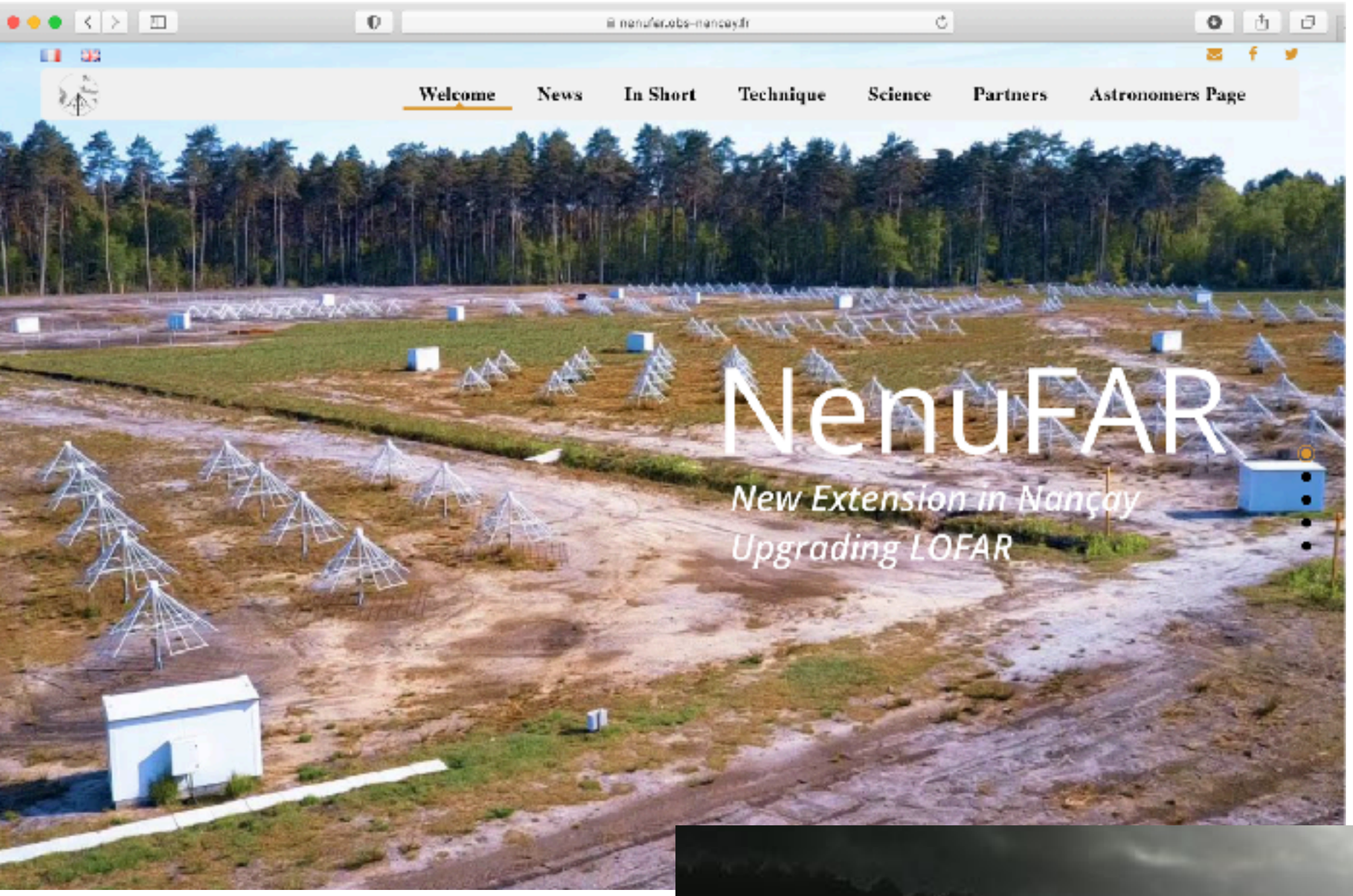
NenuFAR-Data Center

- Raw Data: ~100 GB/hour (beamforming) to ~1-2 TB/hour (imaging or waveform)
- Reduction x10-100 → Nançay Data Center + Post-Processing machines
- Development of NenuFAR-DC = Cloud-based data infrastructure, with distributed storage and computing



[B. Cecconi et al.]

Web site, Art project (Le Dôme)



[C. Courte, S. Lorillard]

Recent NenuFAR publications

Refereed / published or in press : 14

- …
- Bilous, A., et al., Dual-frequency single-pulse study of PSR B0950+08, Astron. Astrophys., A&A 658, A143, **2022**.
- Lamy, L., et al., Determining the Beaming of Io Decametric Emissions: A Remote Diagnostic to Probe the Io-Jupiter Interaction, J. Geophys. Res., 127, e2021JA030160, **2022**.
- Briand, C., et al., NenuFAR performances for solar radio observations, URSI RADIO SCIENCE LETTERS, Vol. 4, **2022**.
- Girard, J. & P. Zarka, Toward optimal phased array tile configurations for large new generation radiotelescopes and application to NenuFAR, A&A, 672, A80, **2023**.
- Ziwei Wu, et al., Pulsar Scintillation Studies with LOFAR: II. Dual-frequency scattering study of PSR J0826+2637 with LOFAR and NenuFAR, MNRAS, 520, 5536-5543, **2023**.

Non-refereed or Proceedings / published or in press : 27

Submitted :

- Pétri , J., et al., Constraining the magnetic field geometry of the millisecond pulsar PSR J0030+0451 from joint radio, thermal X-ray and γ -ray emission, A&A, submitted.
- Tiburzi, C., et al., Frequency-dependent dispersion measure detected during the Solar approach of PSR J1022+1001, A&A, submitted.
- Brionne, M., et al., The NenuFAR Pulsar Blind Survey (NPBS): I. Survey overview and validation, A&A, submitted.
- Shaw, A.K., et al., Studying the Multi-frequency Angular Power Spectrum of the Cosmic Dawn 21-cm Signal, MNRAS, submitted.

In preparation : many, incl.

- NenuFAR collaboration, The LF radiotelescope NenuFAR, Exp. Ast., to be submitted.

Theses : 4

- Girard, J., Thèse de Doctorat, ED AA Ile-de-France, 2009-2013 : Développement de la Super Station LOFAR & Observations planétaires avec LOFAR, 21/5/2013. http://tel.archives-ouvertes.fr/tel-00835834
- Bondonneau, L., Thèse de Doctorat, Université d'Orléans, 2016-2019, Première caractérisation de la population de pulsars radio à basses fréquences avec NenuFAR, 8/11/2019. https://tel.archives-ouvertes.fr/tel-02911847
- Brionne, M. Thèse de Doctorat, Université d'Orléans, 2019-2022, NenuFAR blind pulsar survey, soutenue le 28/2/2023.
- Mauduit, E., Thèse de Doctorat, ED AA Ile-de-France, 2021-2024, Recherche et étude des exoplanètes en radio avec NenuFAR (et préparation de SKA).