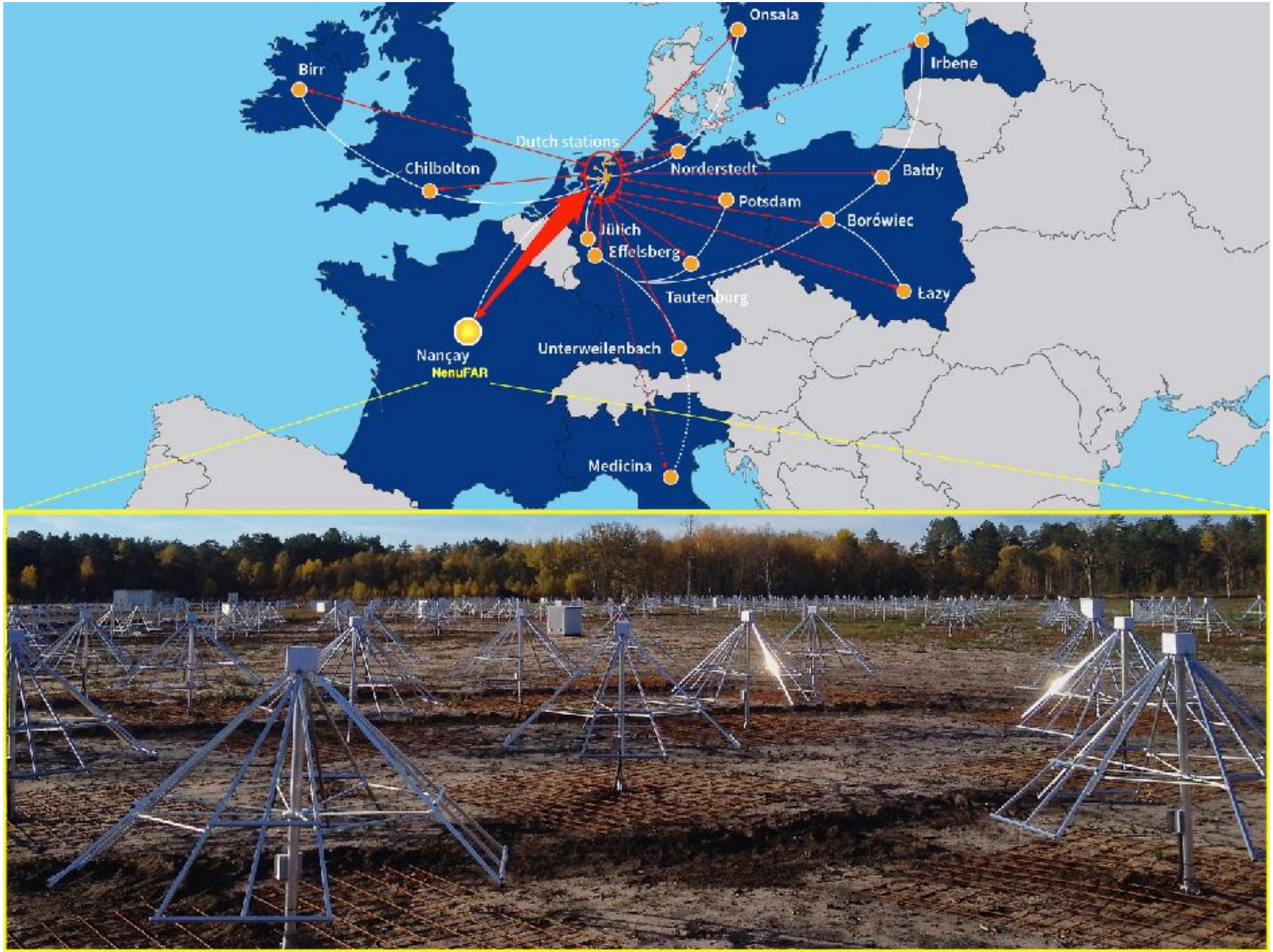
NenuFAR : the French SKAO pathfinder

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

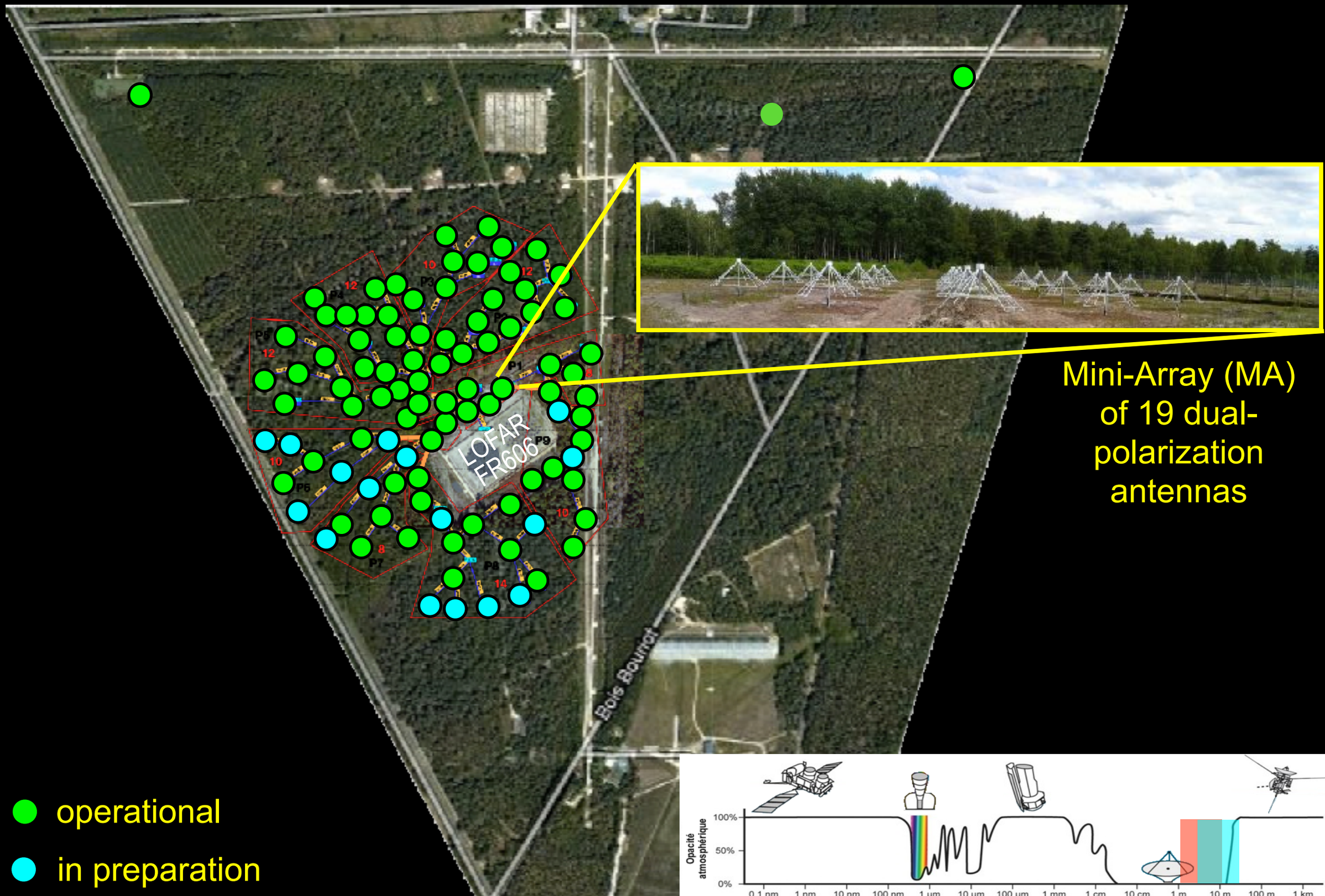
600 Gbits/s
de volume de données
traitées en temps réel
24/7

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**

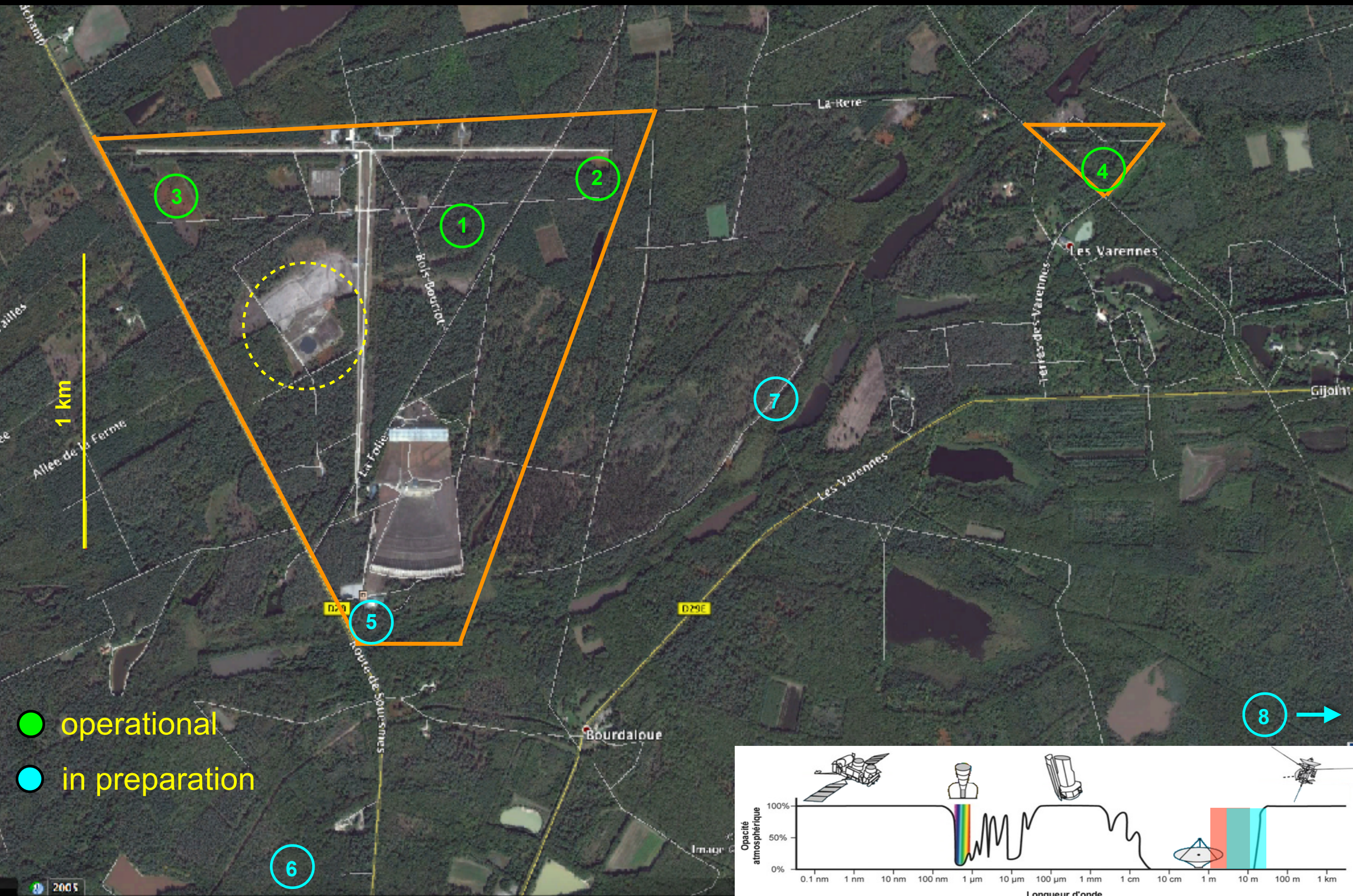
Built around the French LOFAR station in Nançay
Made of ~100 MA : Core (80 MA / 96) + Remote (4 MA)



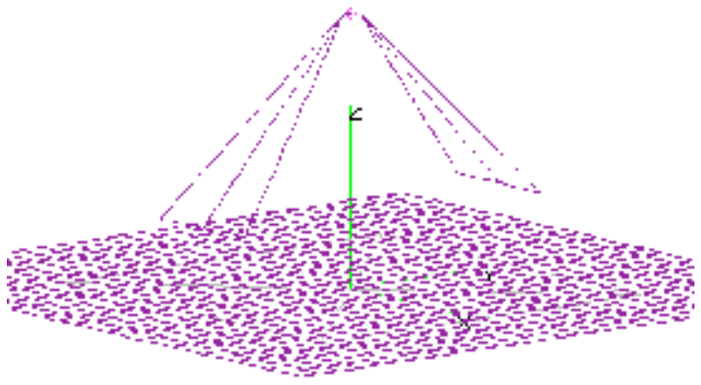
Mini-Array (MA) of 19 dual-polarization antennas

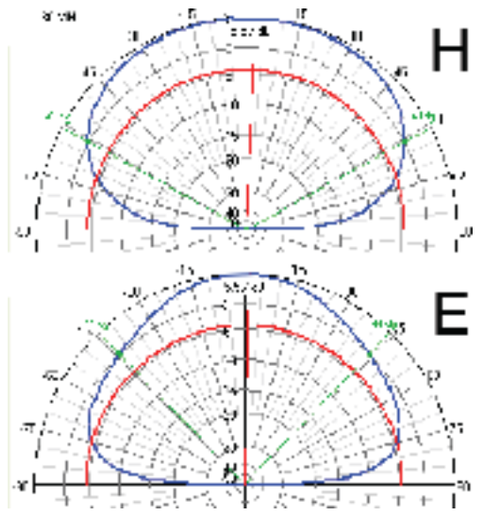
- operational
- in preparation

Near completion: core in 2023, funding request for last 4 remote MA



Mix of external technology …

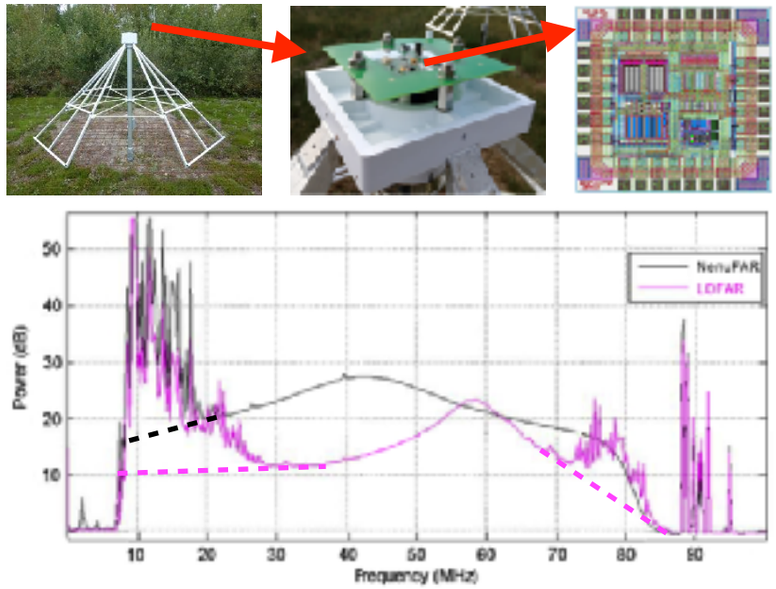




LWA radiator [Hicks et al., 2012]

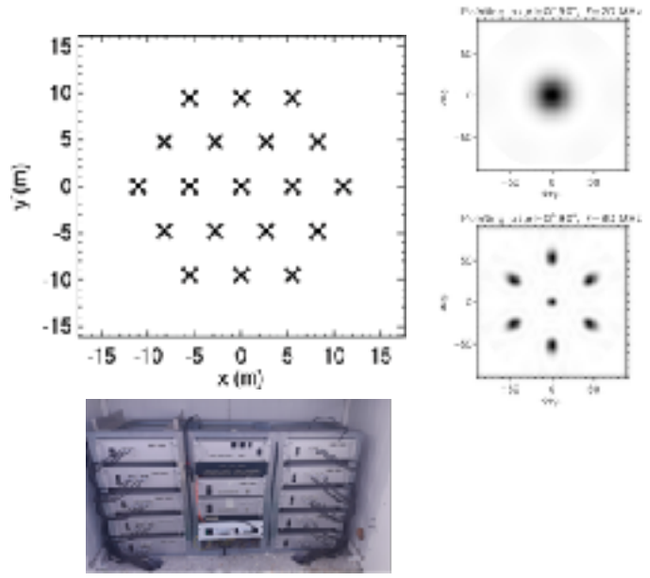
COBALT2 correlator … [Viou et al., 2020]

… and original internal developments



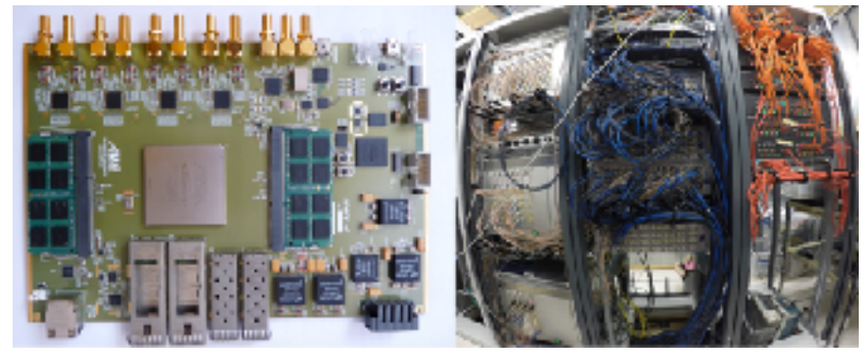
Antenna preamplifier

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



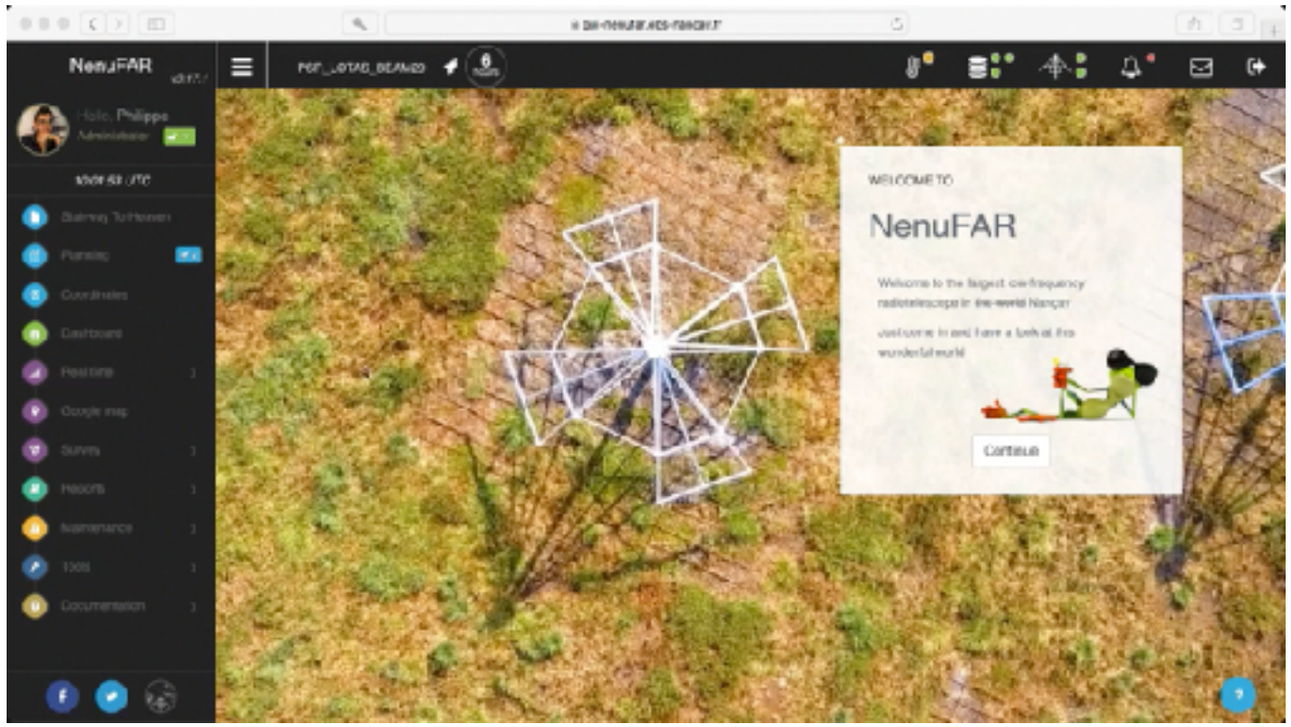
Mini-array topology & phasing

[Girard & Zarka, 2022]



Beamformed receivers

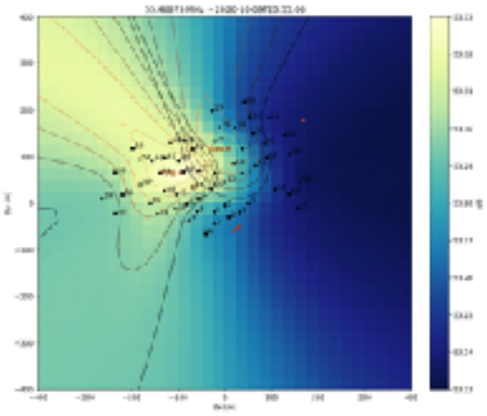
[Cognard, Bondonneau et al.]



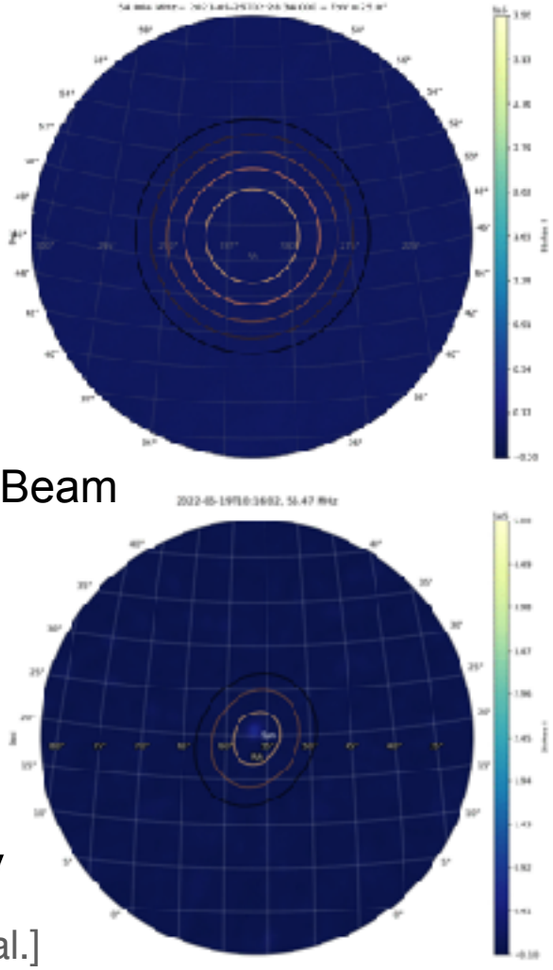
Virtual Control Room

[Taffoureau et al., 2020]

Near-field



Beam



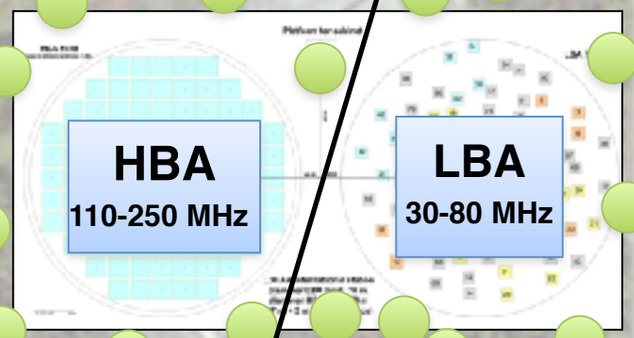
NenuFAR-TV

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

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

- NenuFAR Beamformer
- NenuFAR Waveform (Transient) buffer

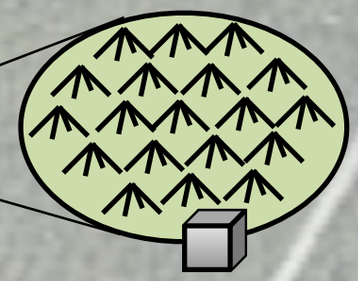
96



~ 400 m

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

19

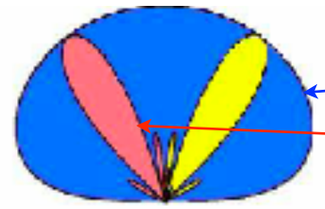


4-8

- 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

LaNewBa

- Digitization
- Channelization
- Beamforming

NenuFAR Transient Buffer

Broadcast on VLAN

UnDySPuTeD : dynamic spectra

- Channelization
- Integration

UnDySPuTeD : pulsar

- Coherent dedispersion
- Folding / Integration

SETI Machine

NenuFAR Beamformer

NICKEL Correlator

- Channelization
- Correlation
- Calibration + Imaging

NenuFAR Imager

- 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'
- Sensitivity ≥ LOFAR
- LSS mode in preparation + test (MoU)

[C. Viou, Project Manager]

Science organization

- Early Science, shared-risk phase : 1/7/2019 - 30/11/2022, ~12 active Key Projects
- Call#1 for Open time: 7 → 9/2022, 3 more PI proposals
- Cycle 1 starts 1/12/2022
- Pressure on observation time up to x2 at night.

  - 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.)

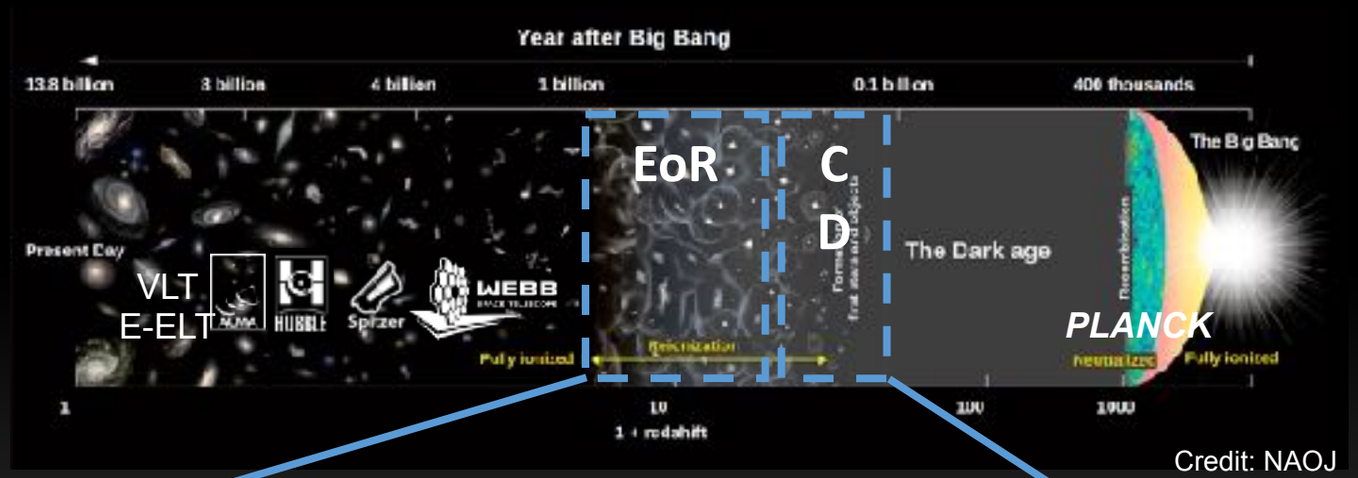
  + Formation of students, Radio-Amateurs group

NenuFAR Cosmic Dawn KSP

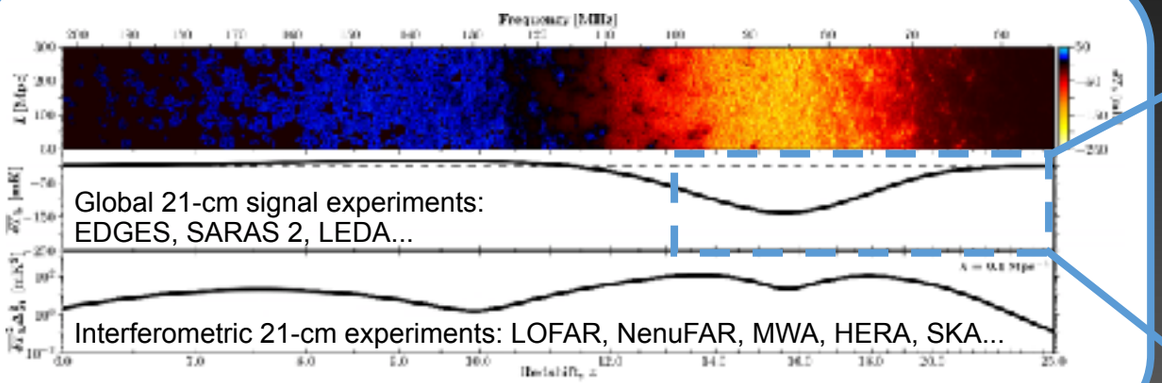
AIM - *Detect and interpret the power spectrum of the 21-cm signal from the Cosmic Dawn*

Status: +1000h observed. More observations ongoing.

[Mertens et al., in prep]

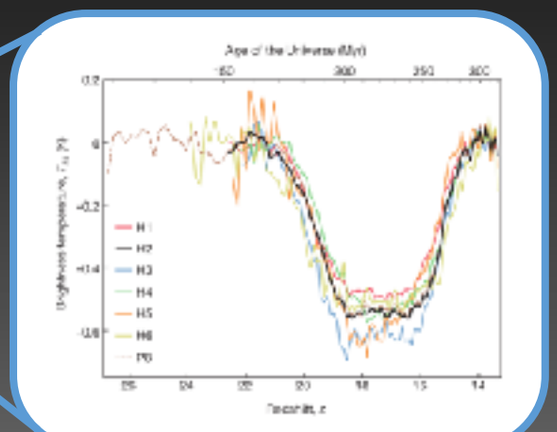


Credit: NAOJ



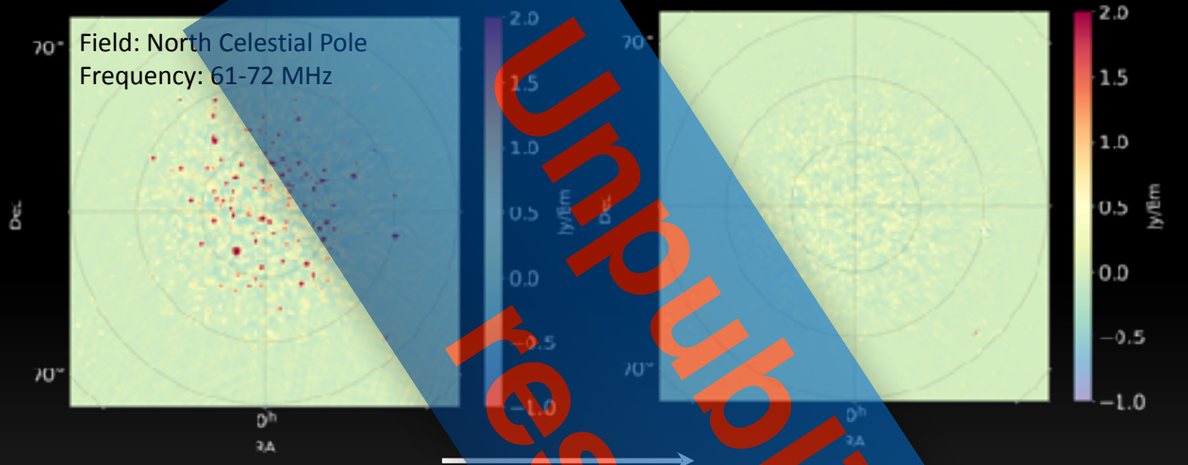
Credit: Mesinger & Greig

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



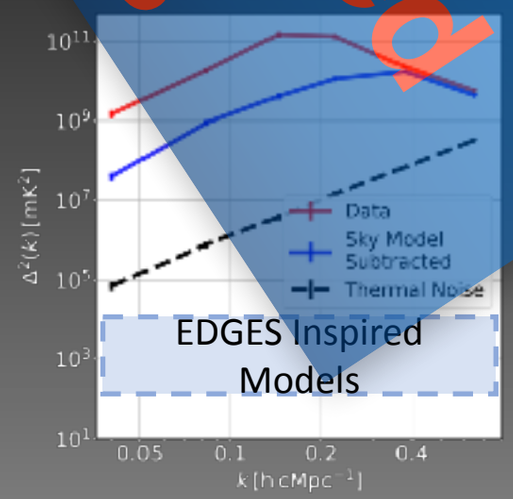
Need "exotic" model to be explained

Single night Observation: Preliminary Results



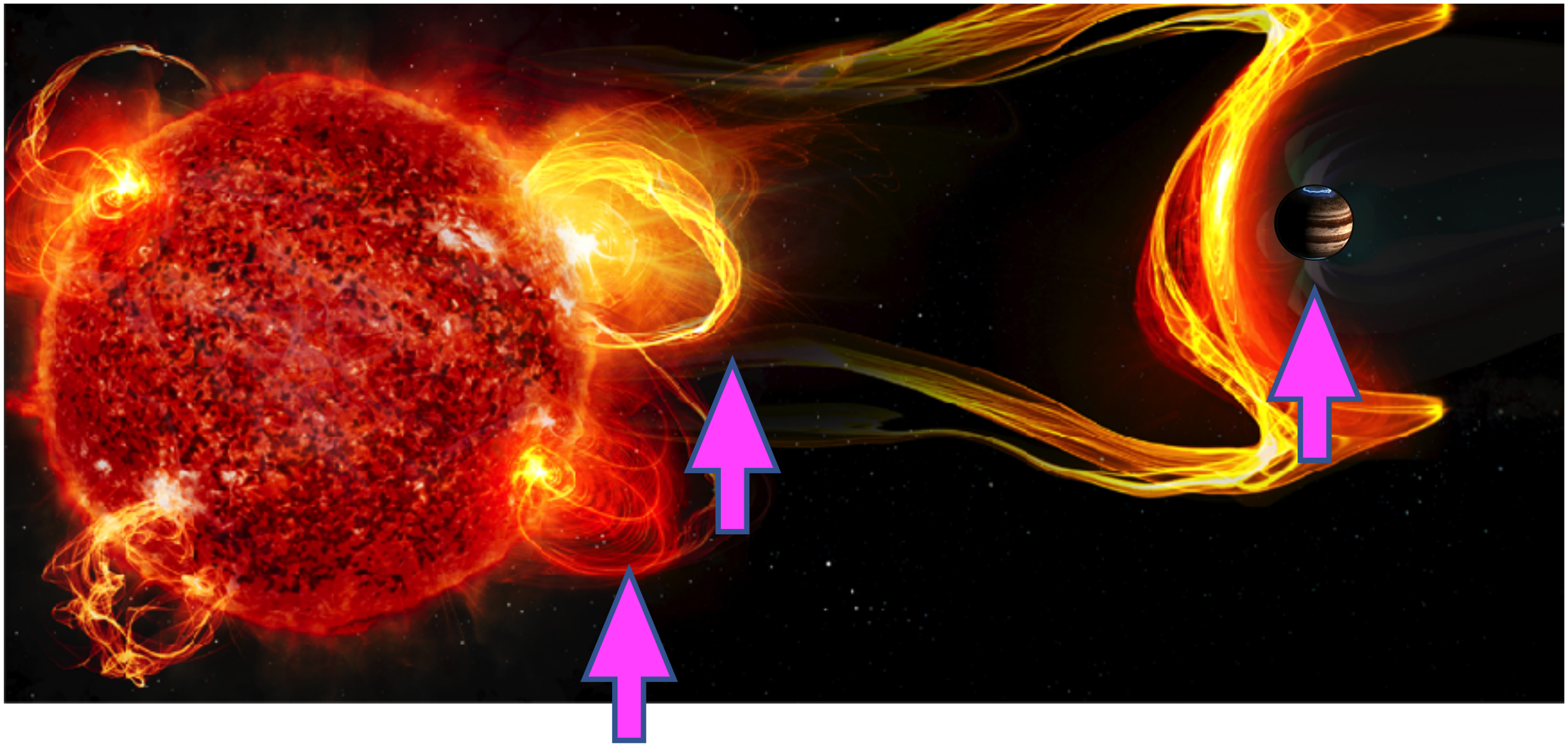
Calibration and Sky Model Subtraction

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



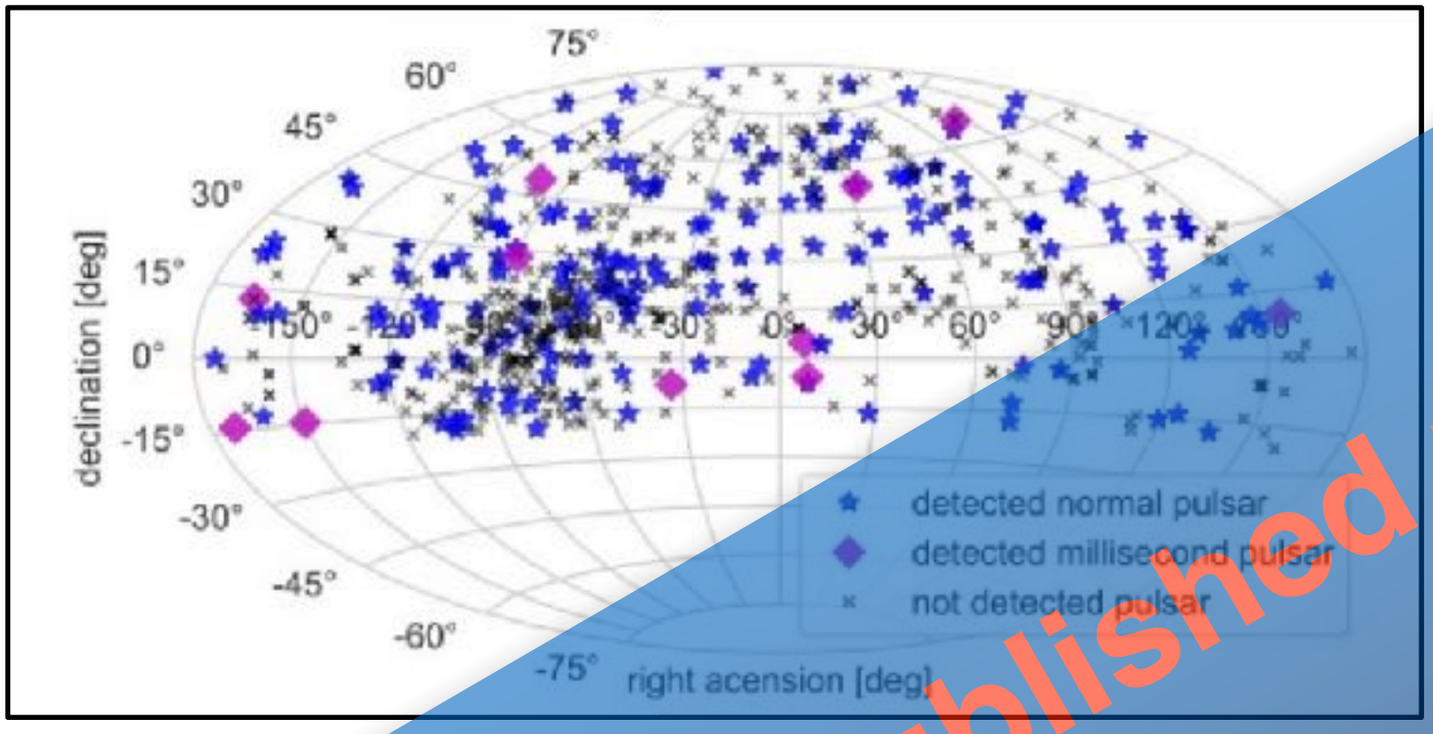
Unpublished results

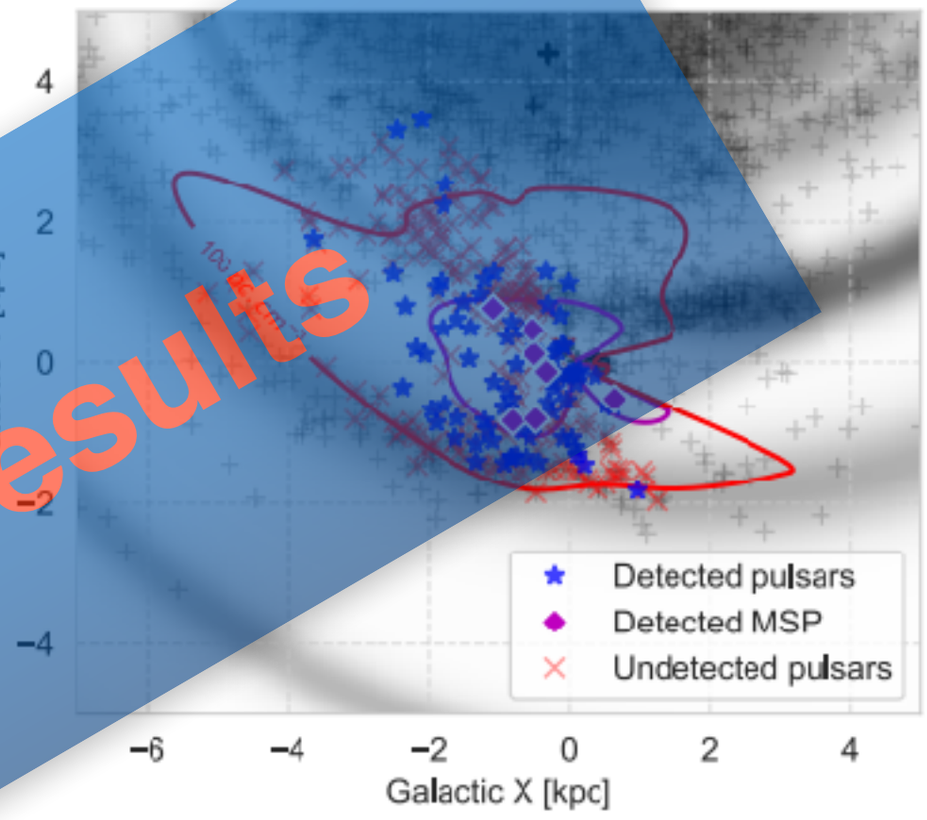
Exoplanets & Stars Key Project



- Source selection, RFI & strong sources mitigation
- Pipeline under development following LOFAR beamformed + MODS/DynSpecMS
- → statistical detections
  + first stellar dynamic spectra with LOFAR ~150 MHz [Tasse, Zarka, et al., in prep]
- → exoplanets with NenuFAR ≤ 85 MHz ?
  EXORADIO ERC advanced project (P. Zarka)

Pulsar census



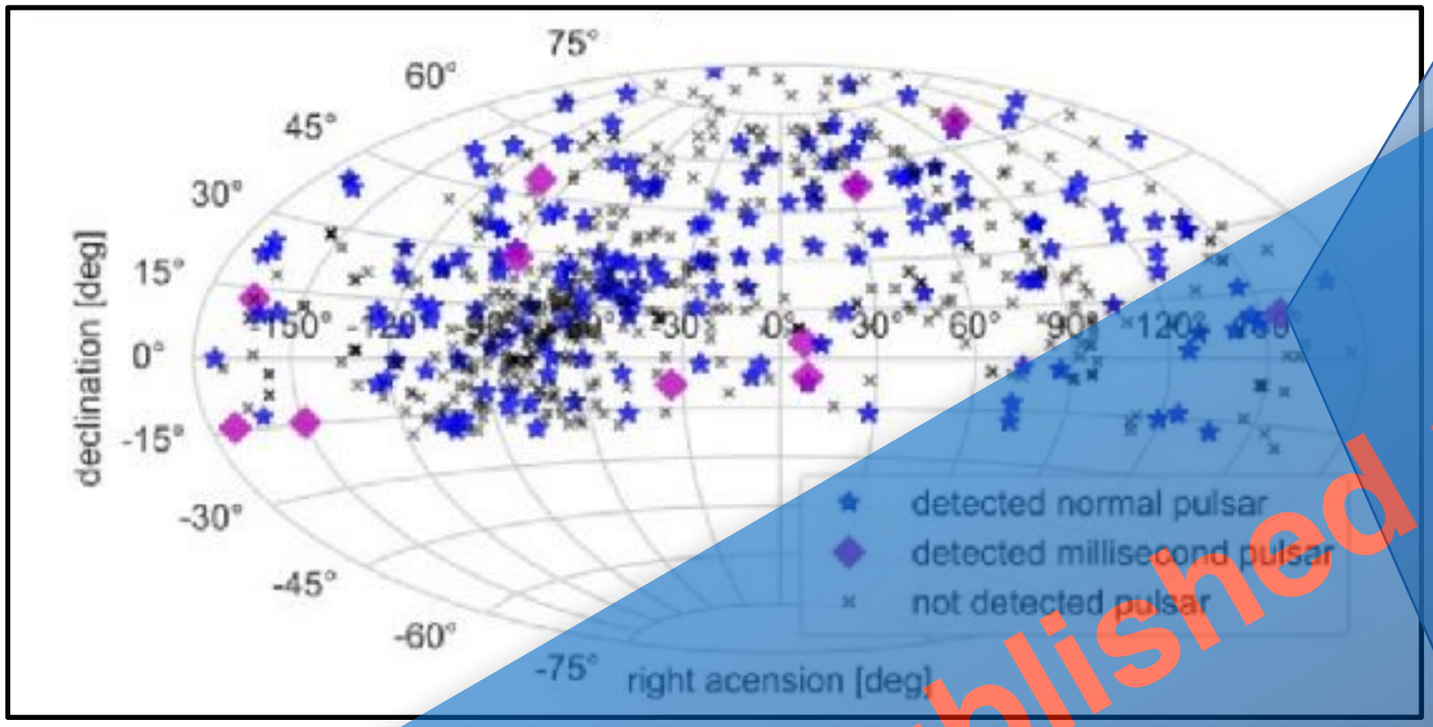


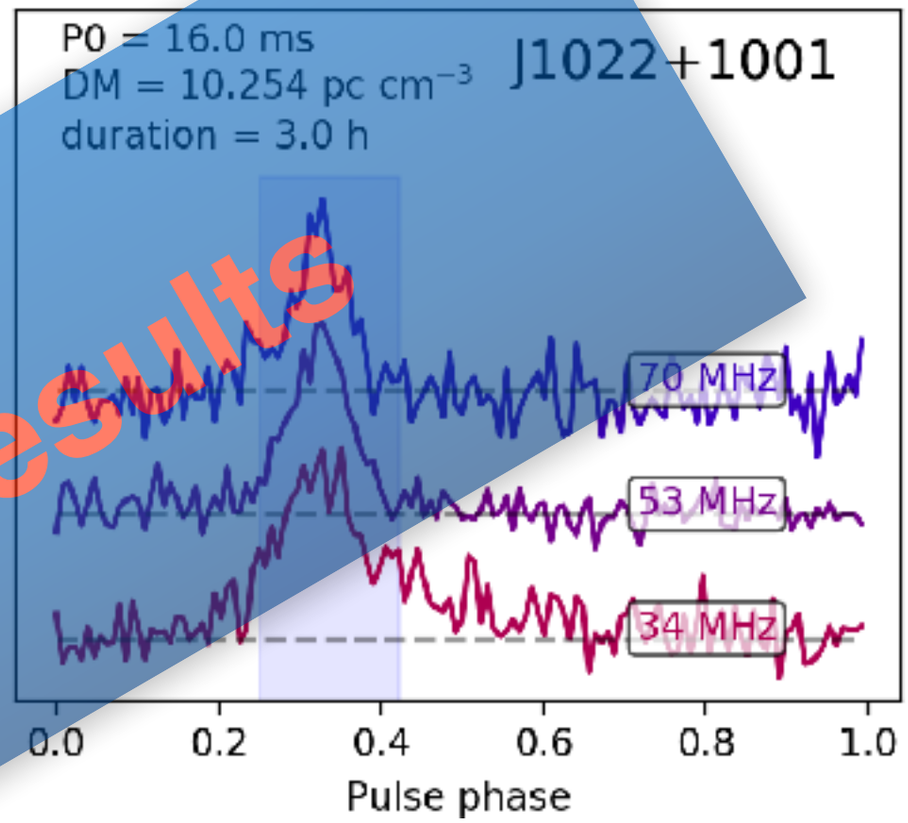
Unpublished results

- observation of 711 known pulsars
- DEC > -20°, DM < 100 pc/cm^3 (nearby pulsars)
- 184 pulsar detected (~100 for the first time <100 MHz)

[Bondonneau et al. in prep.]

Pulsar census & MSPs





- observation of 711 known pulsars
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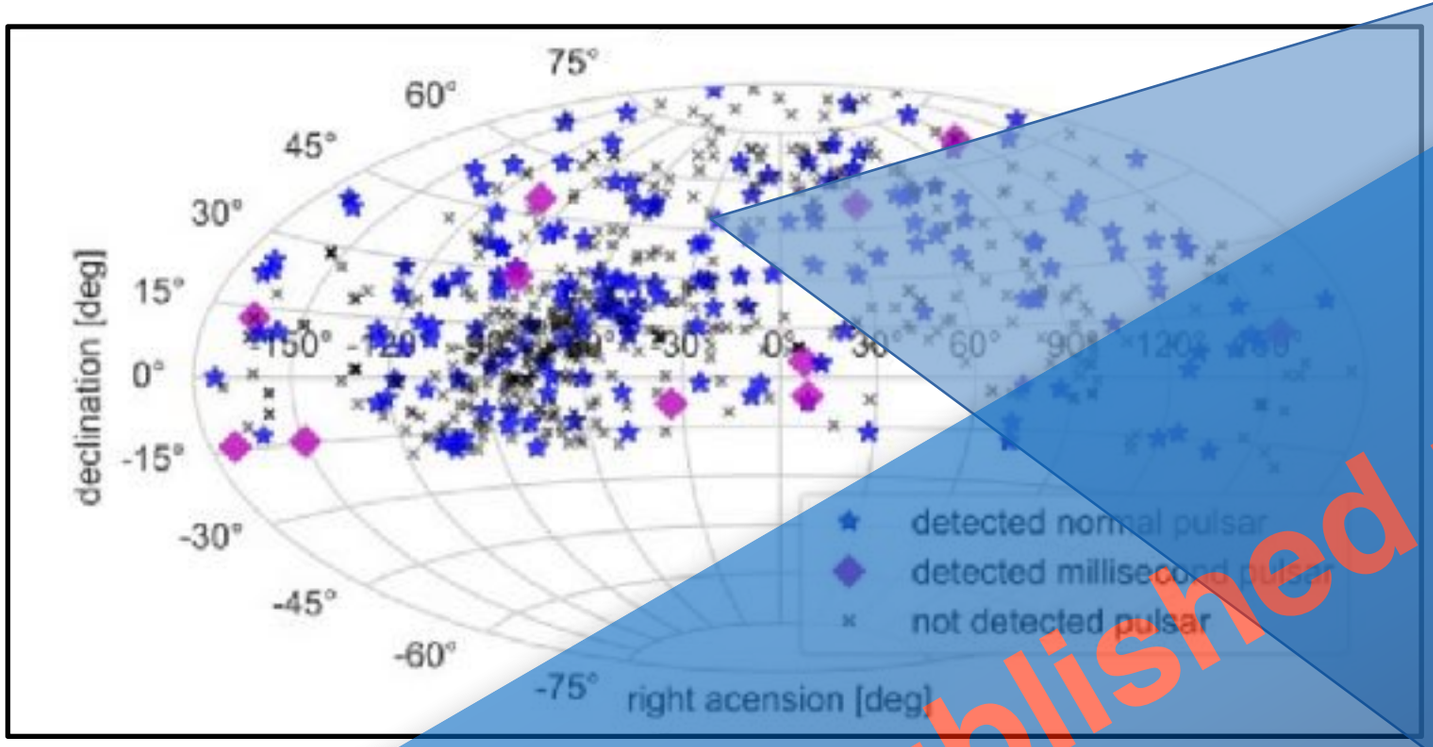
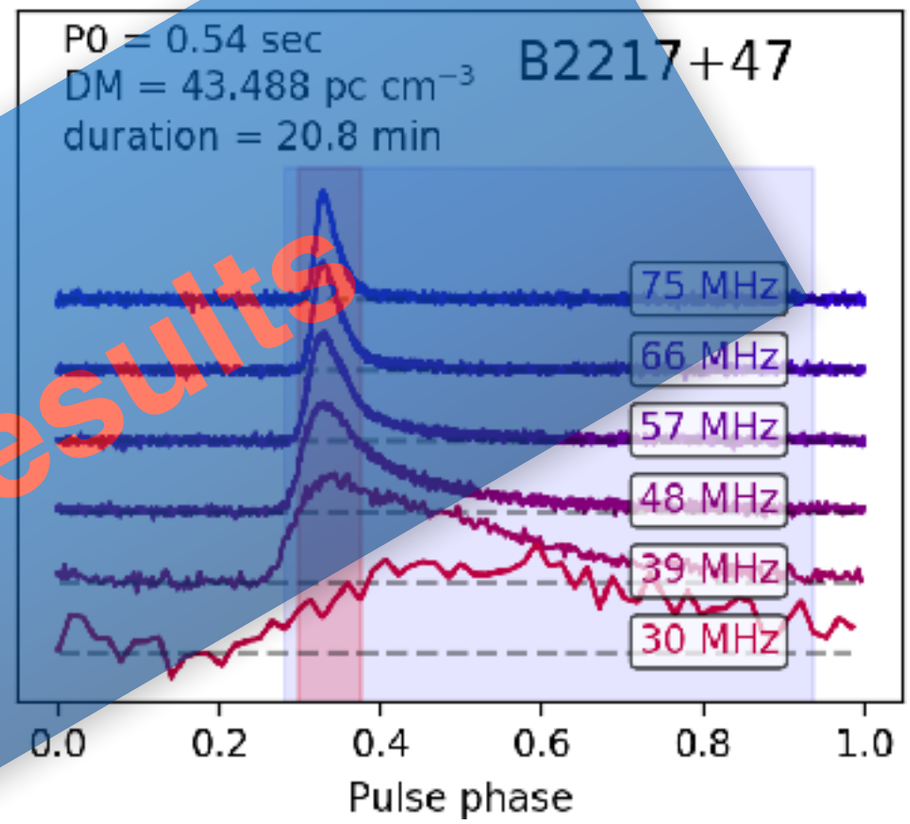
- 11 MSPs detected (7 for the first time <100 MHz)

[Bondonneau et al. in prep.]

Pulsar census & MSPs





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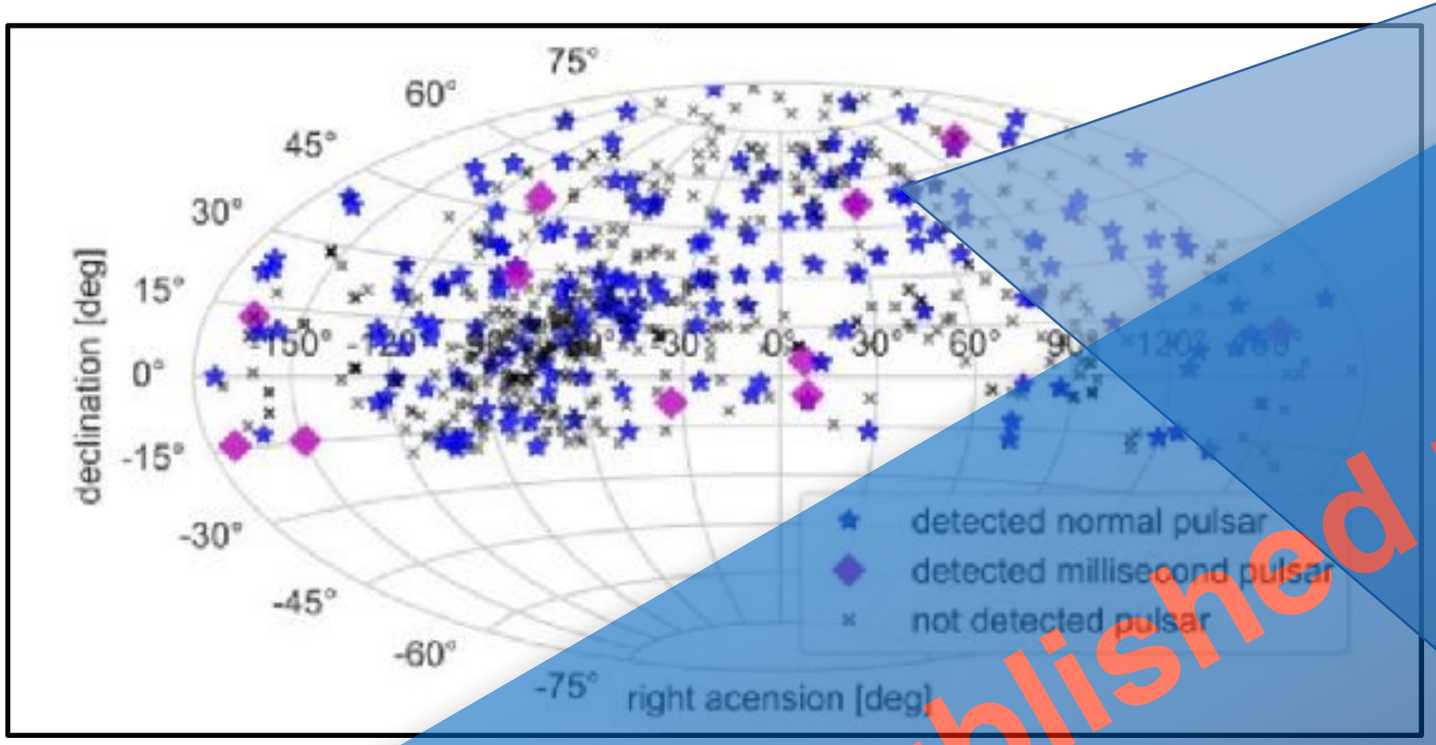
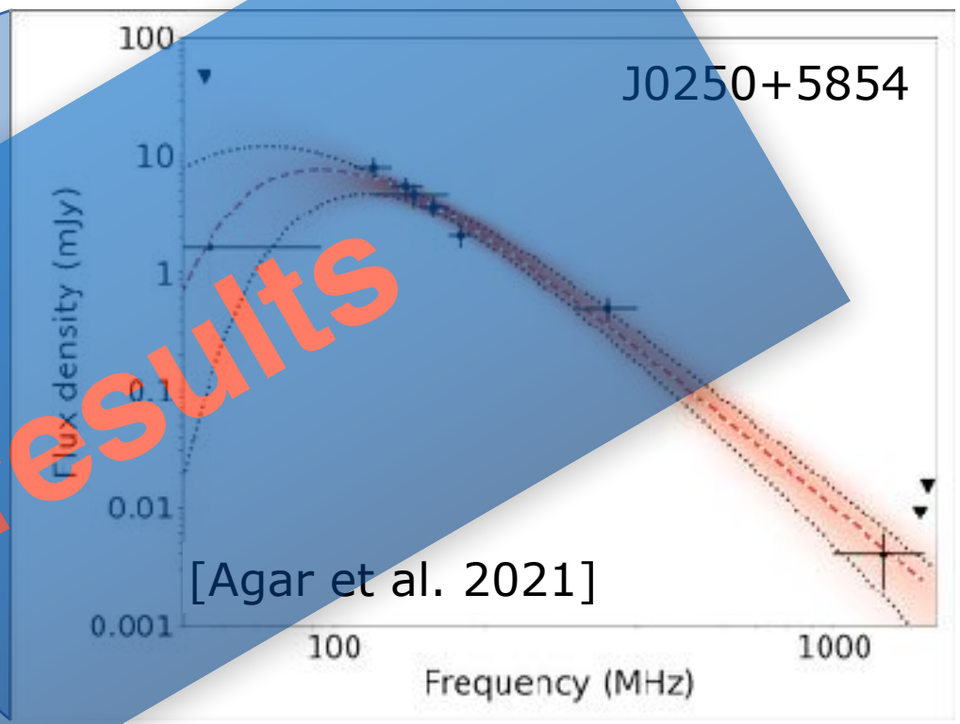
  [Bondonneau et al. in prep.]
- next steps: study of scattering, ...

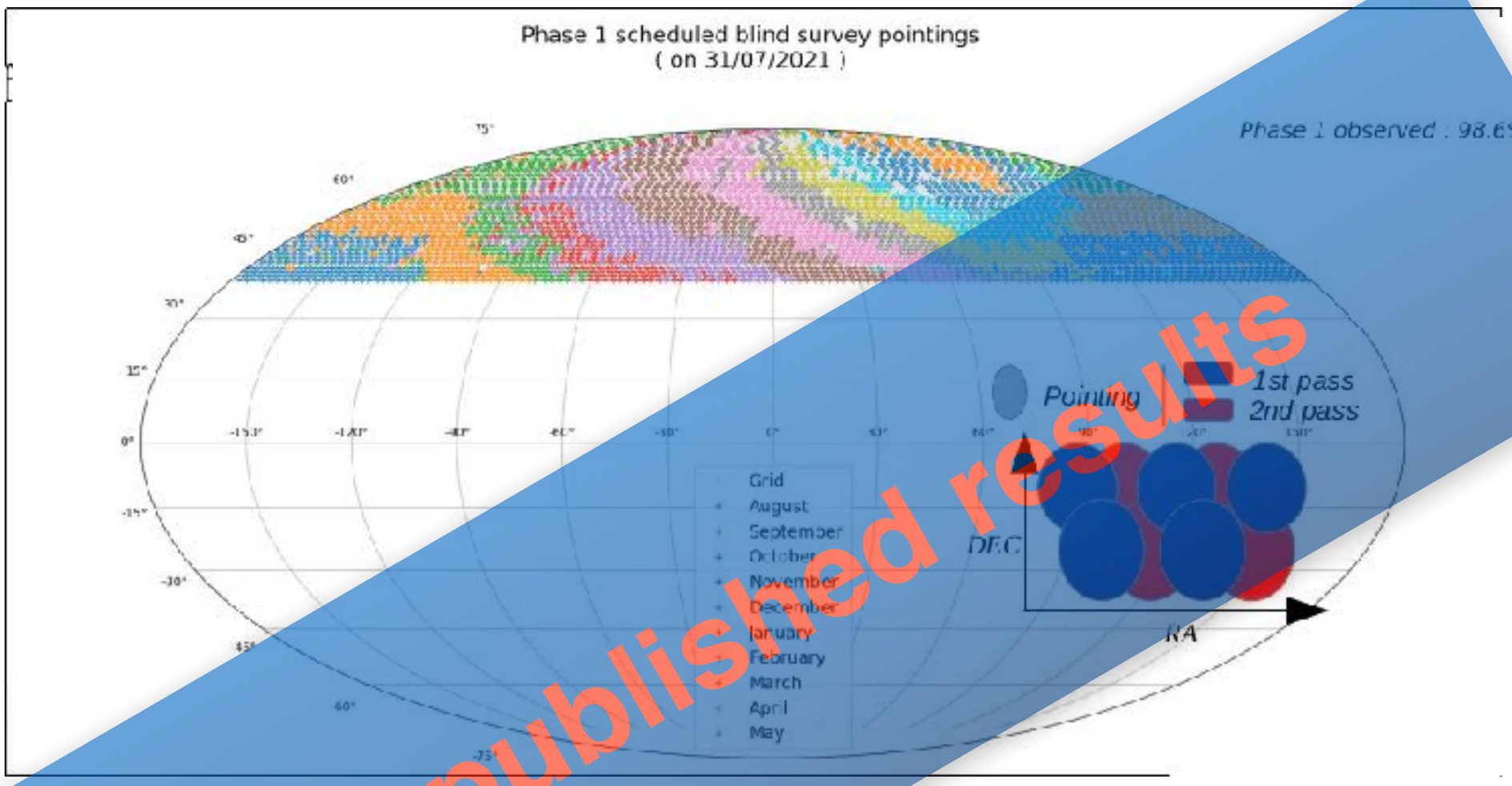
Pulsar census & MSPs





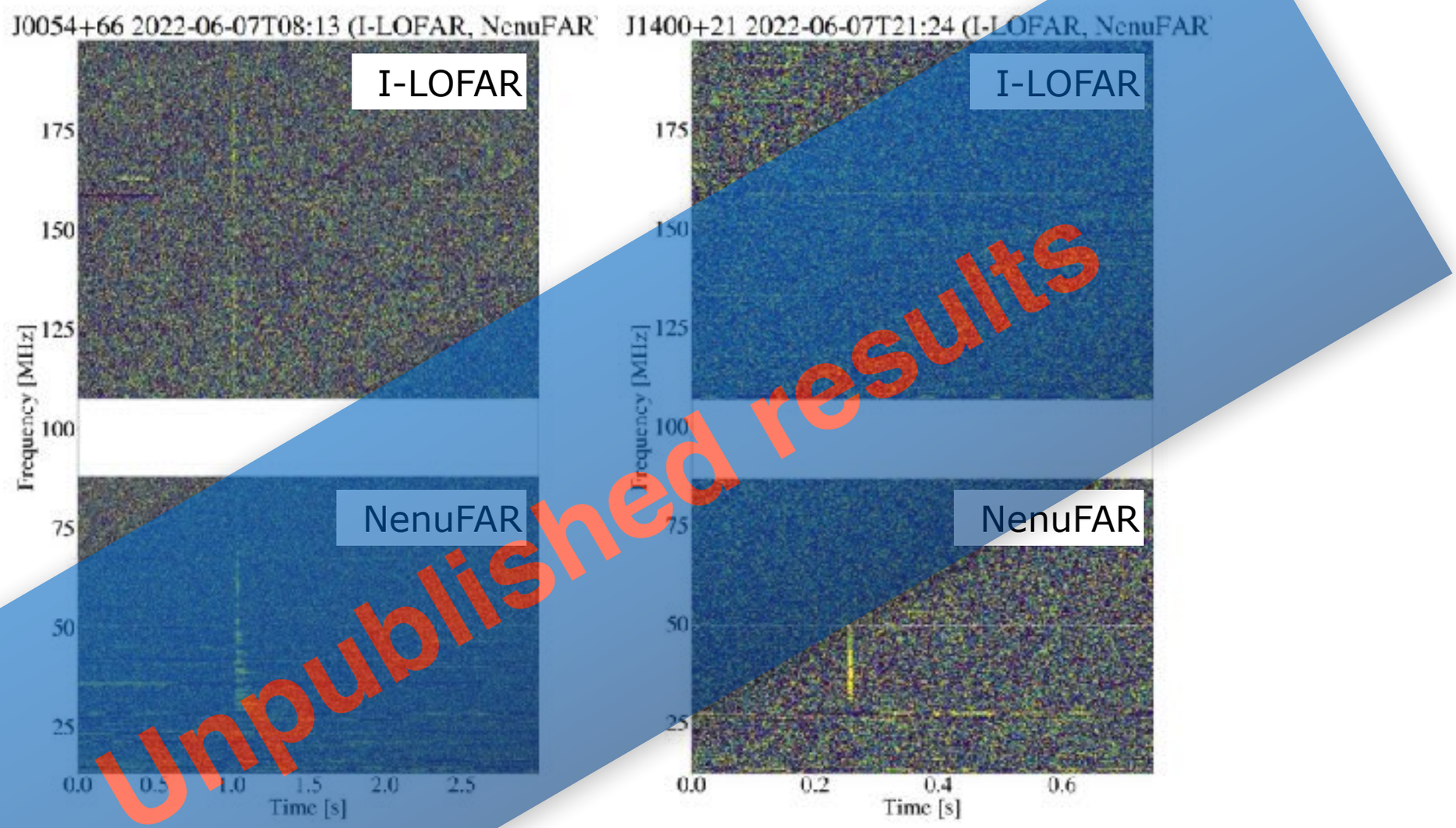
- observation of 711 known pulsars
- DEC > -20°, DM < 100 pc/cm^3 (nearby pulsars)
- 184 pulsar detected (~100 for the first time <100 MHz)
- 11 MSPs detected (7 for the first time <100 MHz)
  [Bondonneau et al. in prep.]
- next steps: study of scattering, pulsar spectra, turnover, ...

Pulsar blind survey



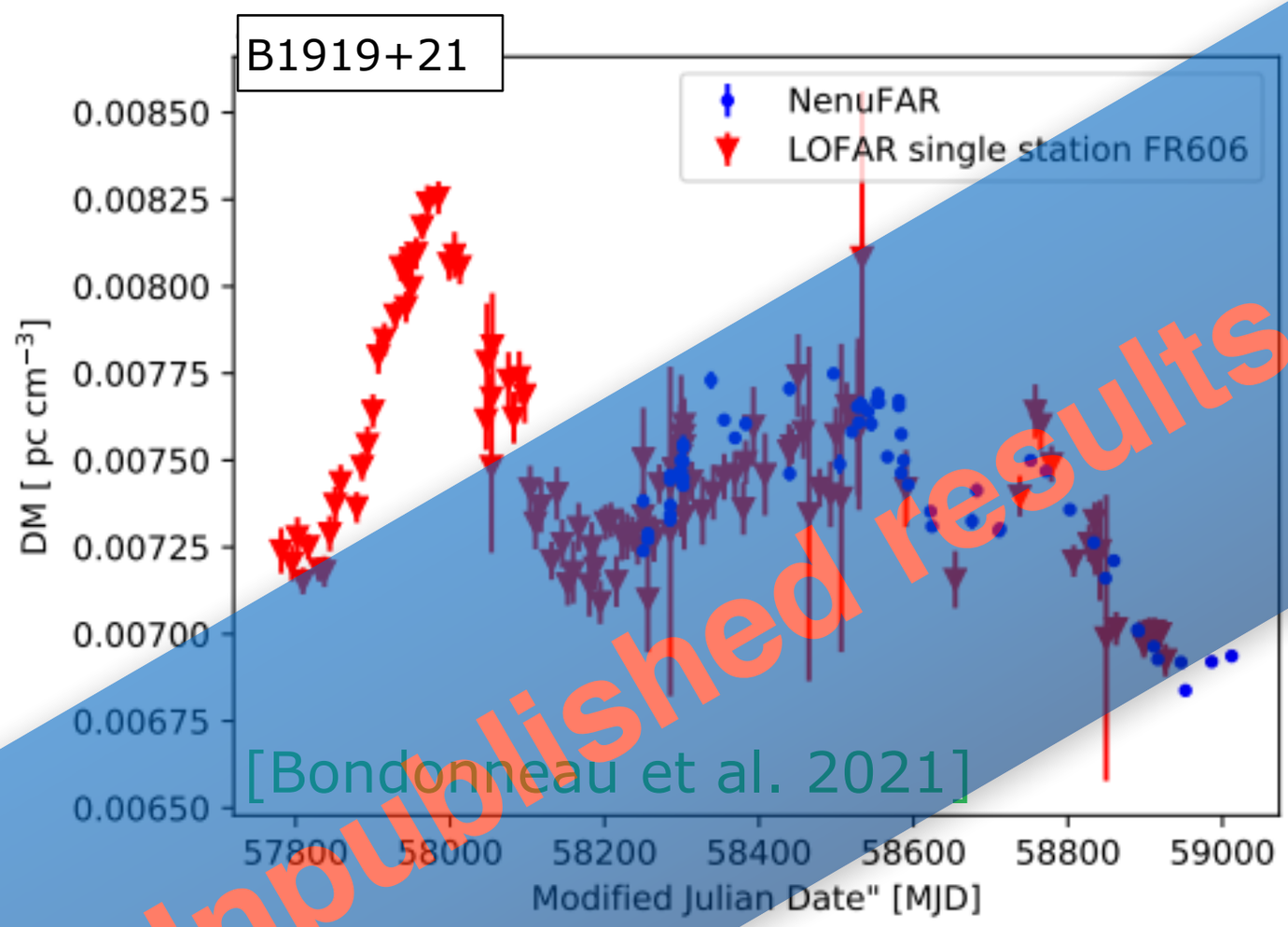
- search for unknown pulsars!
- north polar cap (DEC > 39°), 39-77 MHz
- 7692 pointings: observations 2020-2022 (94% complete)
- search space: DM < 70 pc/cm^3 & P > 80 ms
- expect: ~80-100 redetections, 0-6 discoveries
- expect slow pulsars [Tan et al. 2018, Sanidas et al. 2019]
- first “candidates” (to be re-observed 2022/12 to 2023/05) [Brionne et al. in prep.]

RRATs (rotating radio transients)



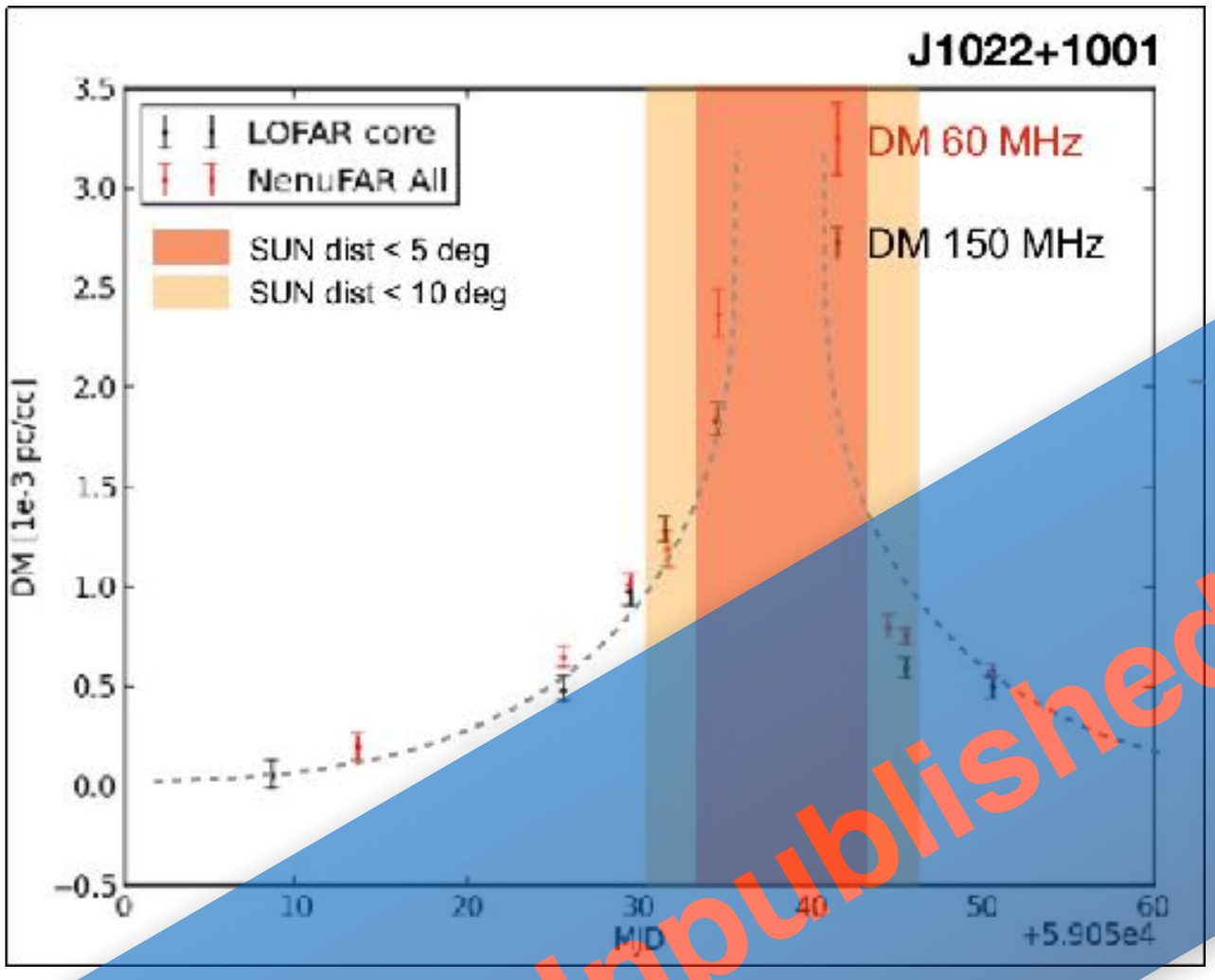
- similar to pulsars, but only few, rare pulses
- tricky (only 1 RRAT below 100 MHz known before!)
- 25 RRATs observed win NenuFAR → 7 detected
- simultaneous RRAT observations with LOFAR HBA (IE613) [McKenna et al. in prep.]

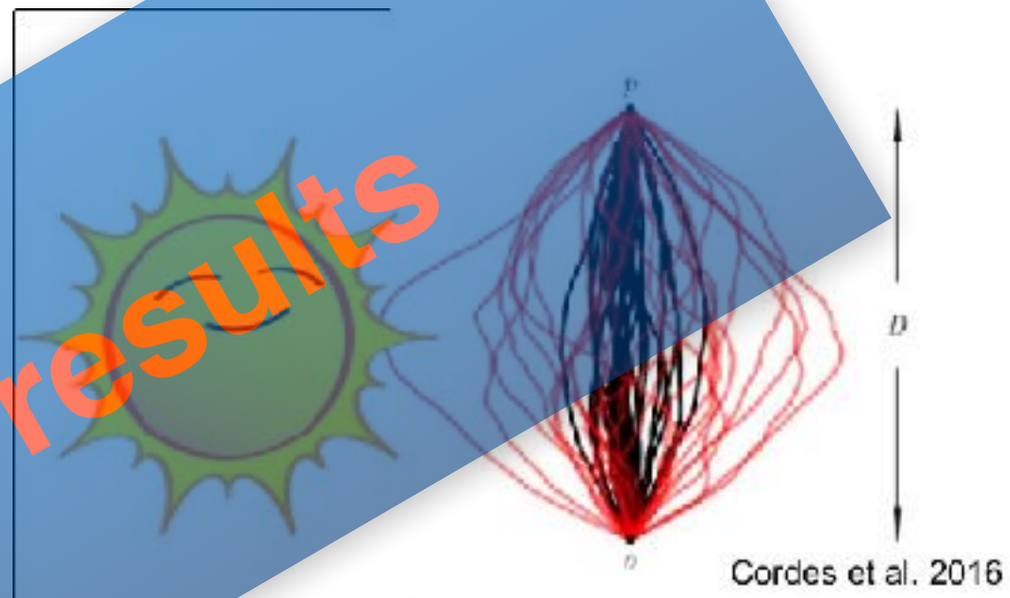
Ionized interstellar medium



- 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 pulsar timing arrays)

Heliosphere





Unpublished results

- DM contribution of solar wind
- observation near solar conjunction
- wider signal path at low frequencies [Cordes et al. 2016]

  → expect frequency-dependent DM
- different DM observed LOFAR-HBA ↔ NenuFAR

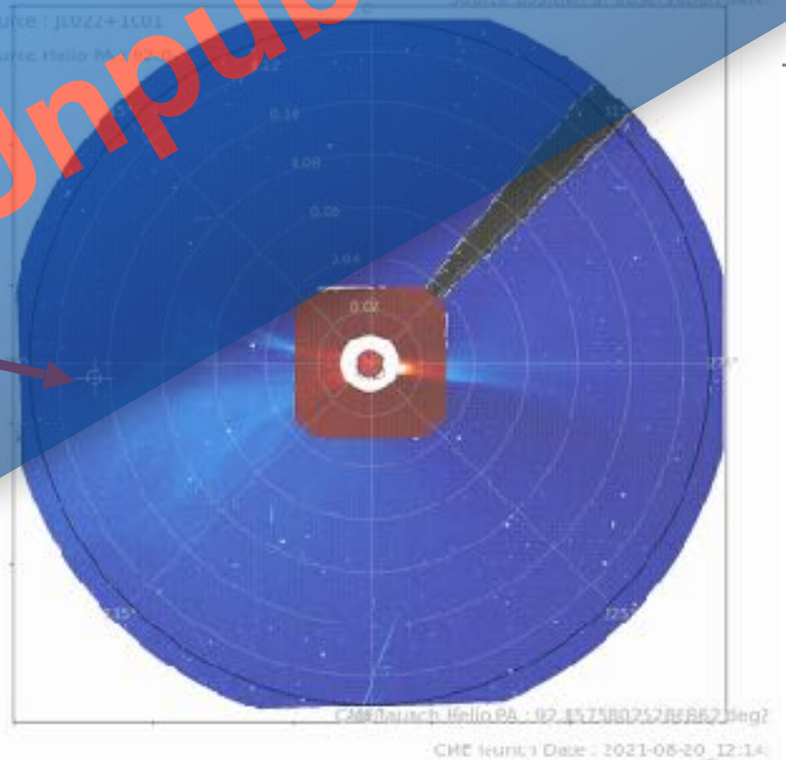
  → more observations 2022/09 → under analysis [Tiburzi et al. in prep.]

CME

DM shift for
LOFAR and NenuFAR
(simult. observations)

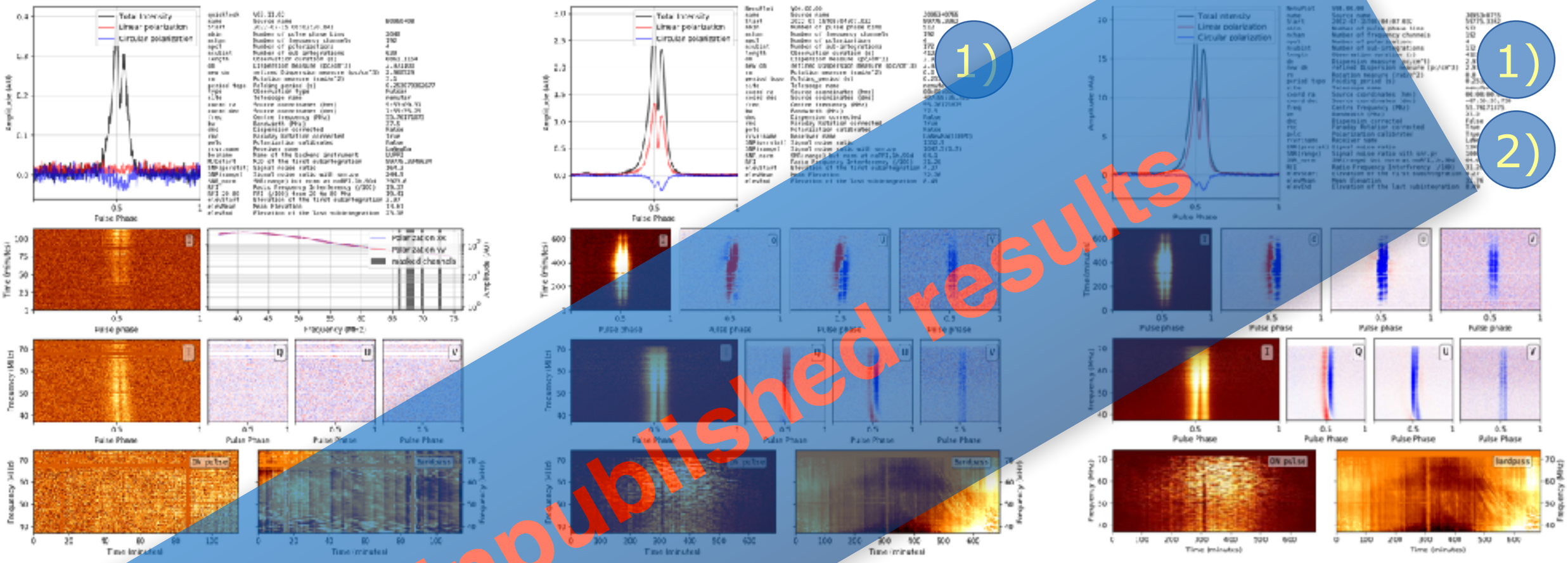
Unpublished results

J1022+1001



a CME in the line of sight
→ a jump in DM
[Zahraoui et al. in prep.]

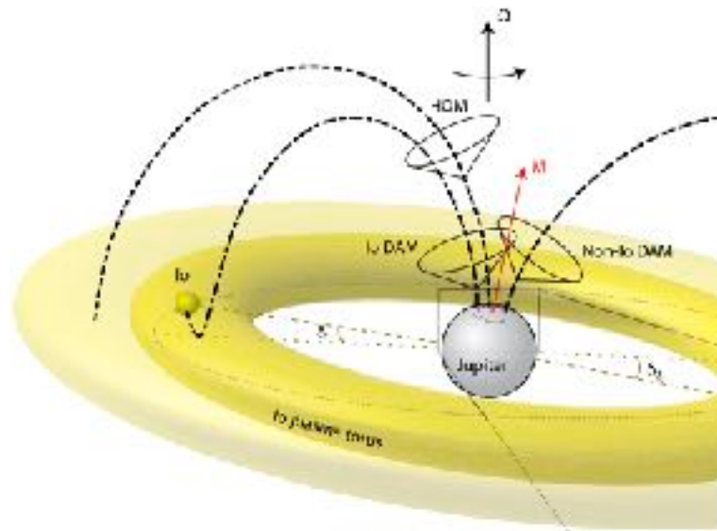
Pulsar polarization



polarisation observations require:

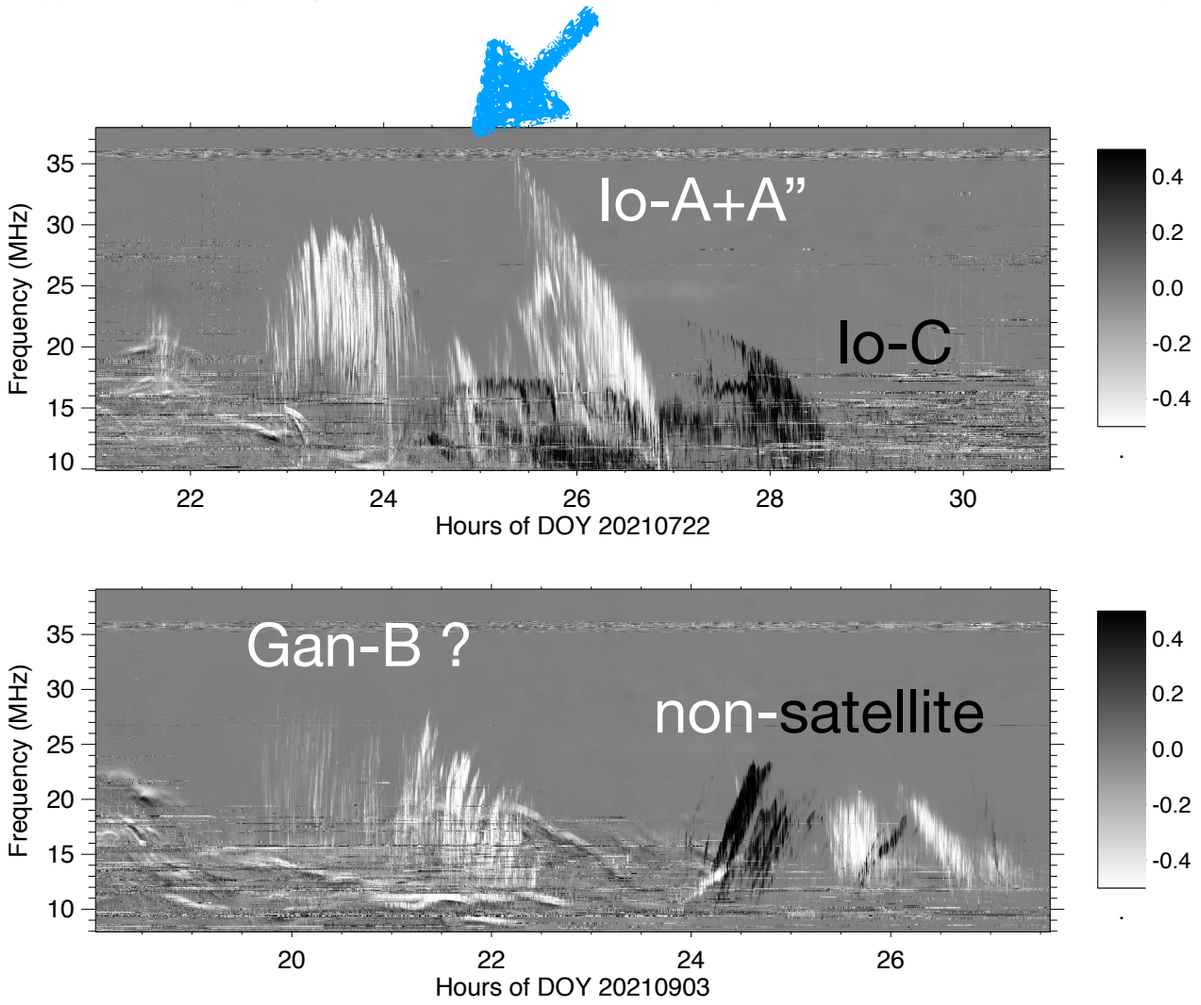
1) RM_{iono} → solved for strong pulsars
2) parallactic angle correction → solved
3) polarisation calibration → working on this
   observation of 108 bright pulsars next semester
   compare/fit to RVM model

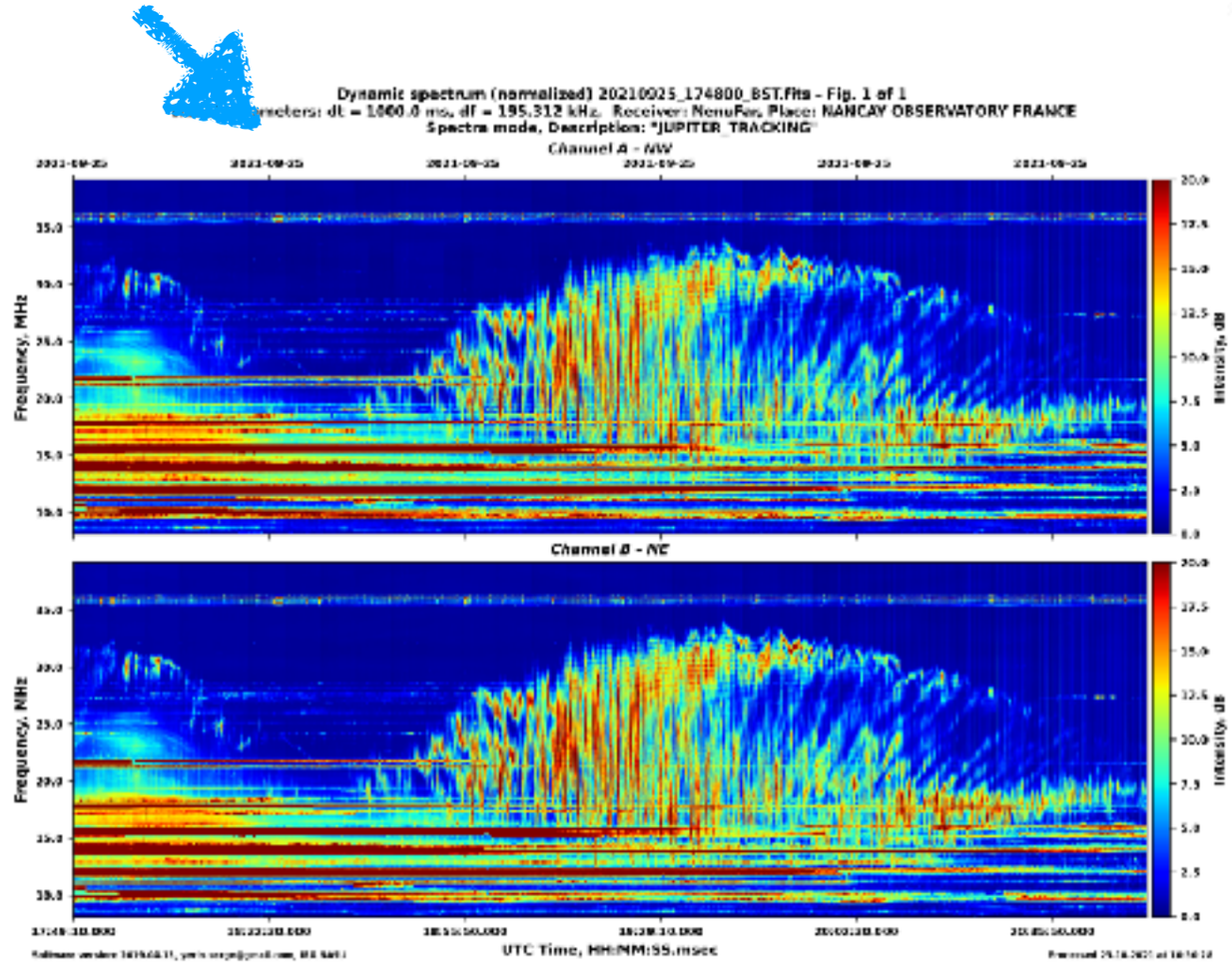
NenuFAR Key Project Jupiter



<u>* Team :</u> **L. Lamy & S. Yerin** (co-PIs), P. Zarka, B. Cecconi, J. Girard, C. Louis, J.-M. Griessmeier, V. Ryabov, V. Zakharenko, V. Yatsina, A. Konovalenko, O. Wucknitz + T. Kimura, H. Kita, C. Jackman, J. Waters

<u>* Early Science key project :</u> high sensitivity observations taken **in support to Juno**
(i) **survey** dynamic spectra (84 msec x 12 kHz) + (ii) **waveform** measurements

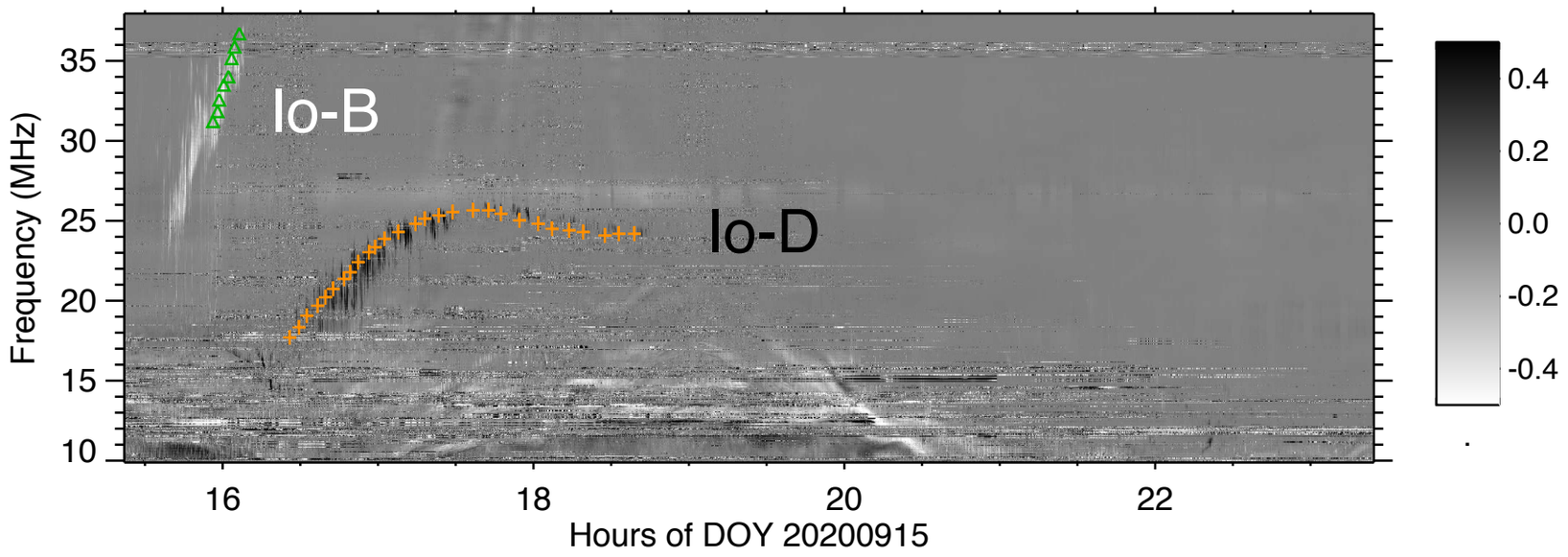


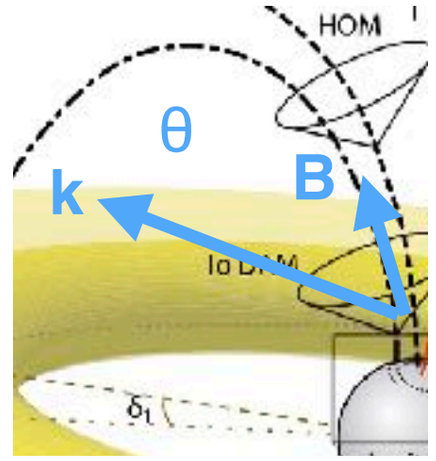


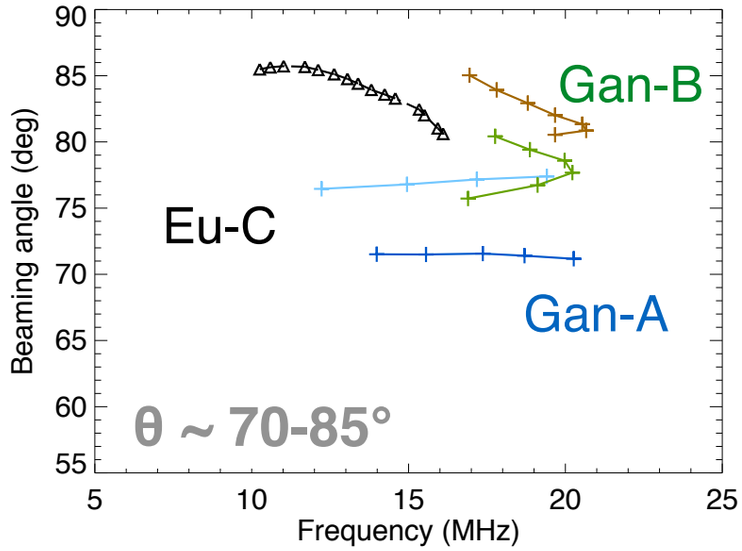
→ faint emissions, fine structures
use case to search highly circularly polarized extraterrestrial emissions

NenuFAR Key Project Jupiter

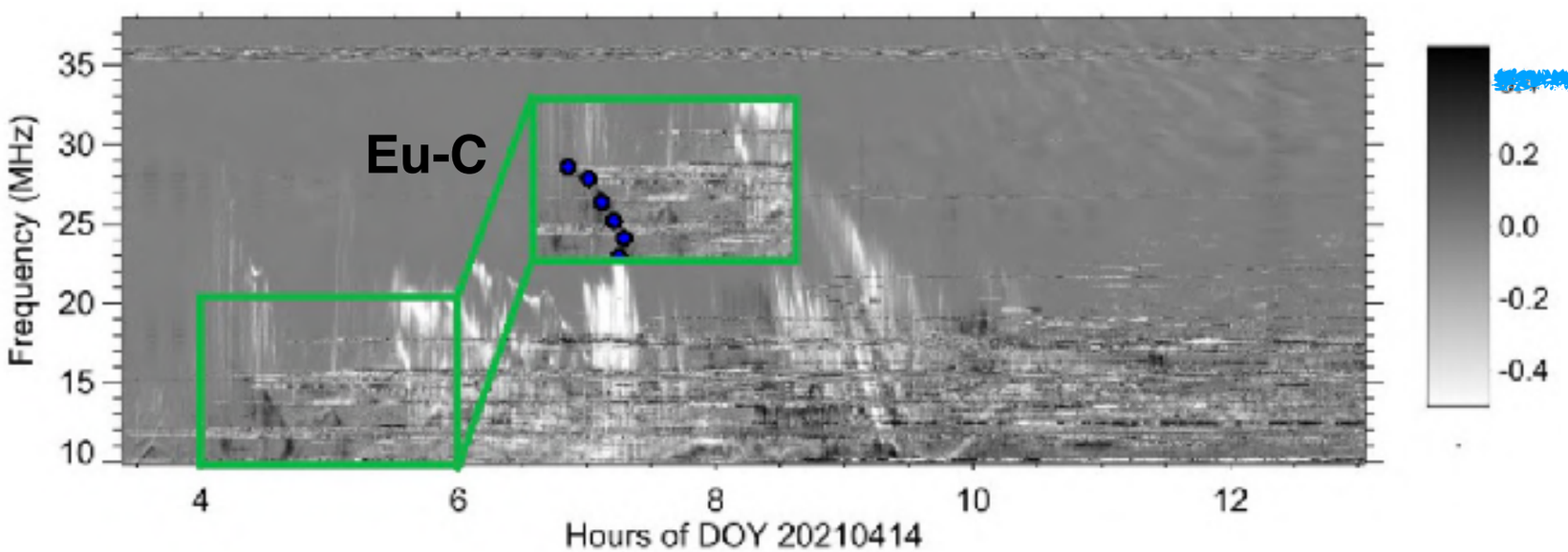
Recent study 1 : Tracking faint **Io-Jupiter** bursts + method to derive
→ the **emission beaming** + the source kinetic **electron energy**
[Lamy, Colomban et al., JGR, 2022a]

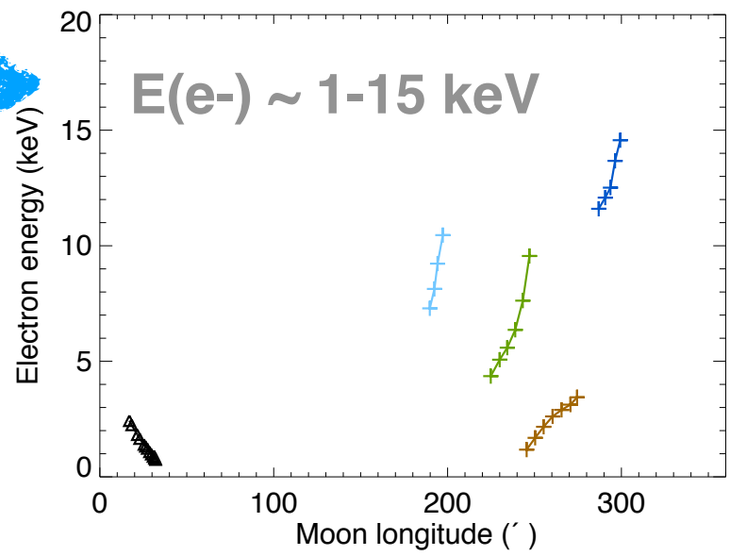






Recent study 2 : Similar study of **Europa- and Ganymede-Jupiter** bursts
[Lamy, Duchêne et al., PRE IX, 2022]

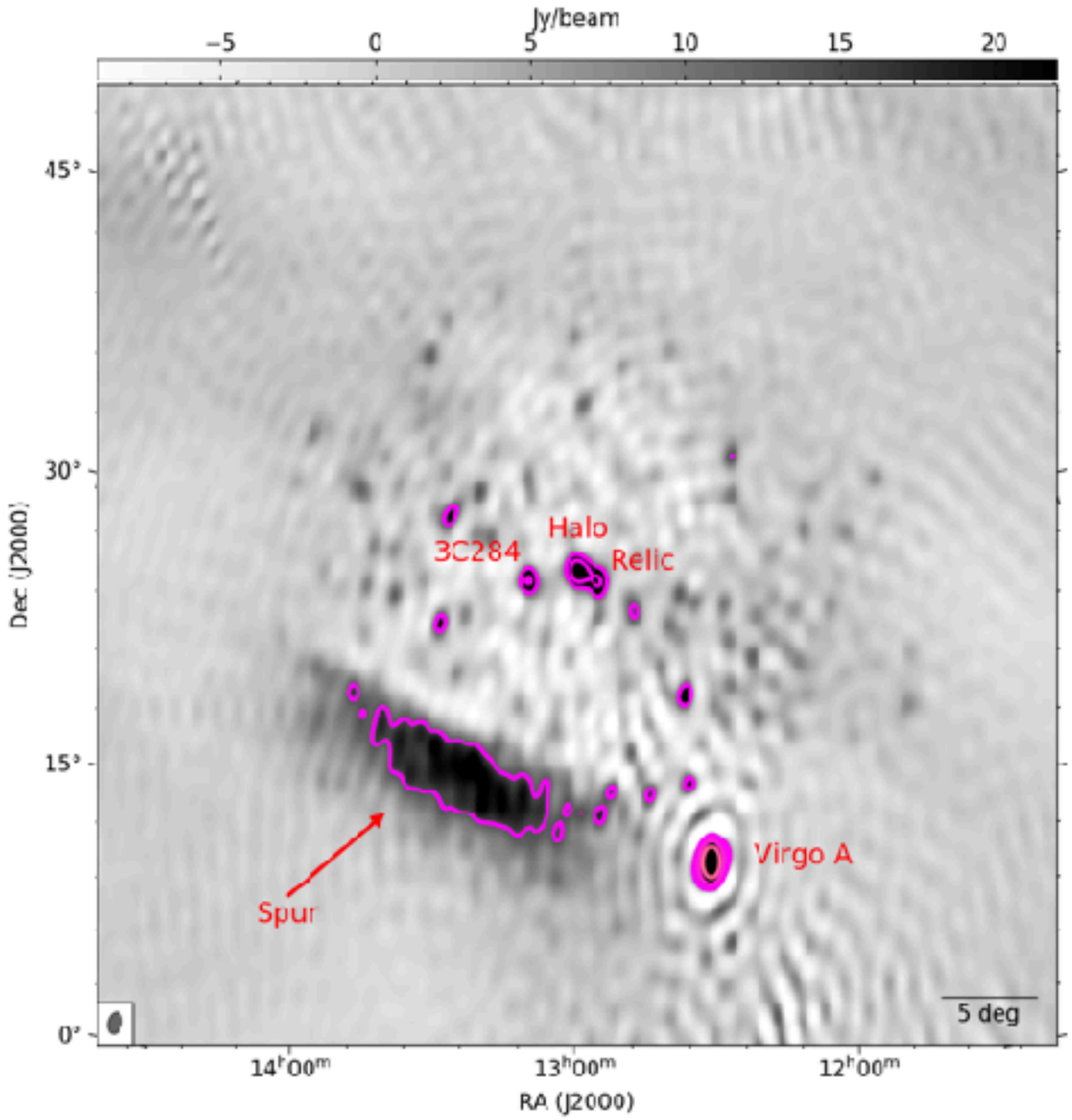


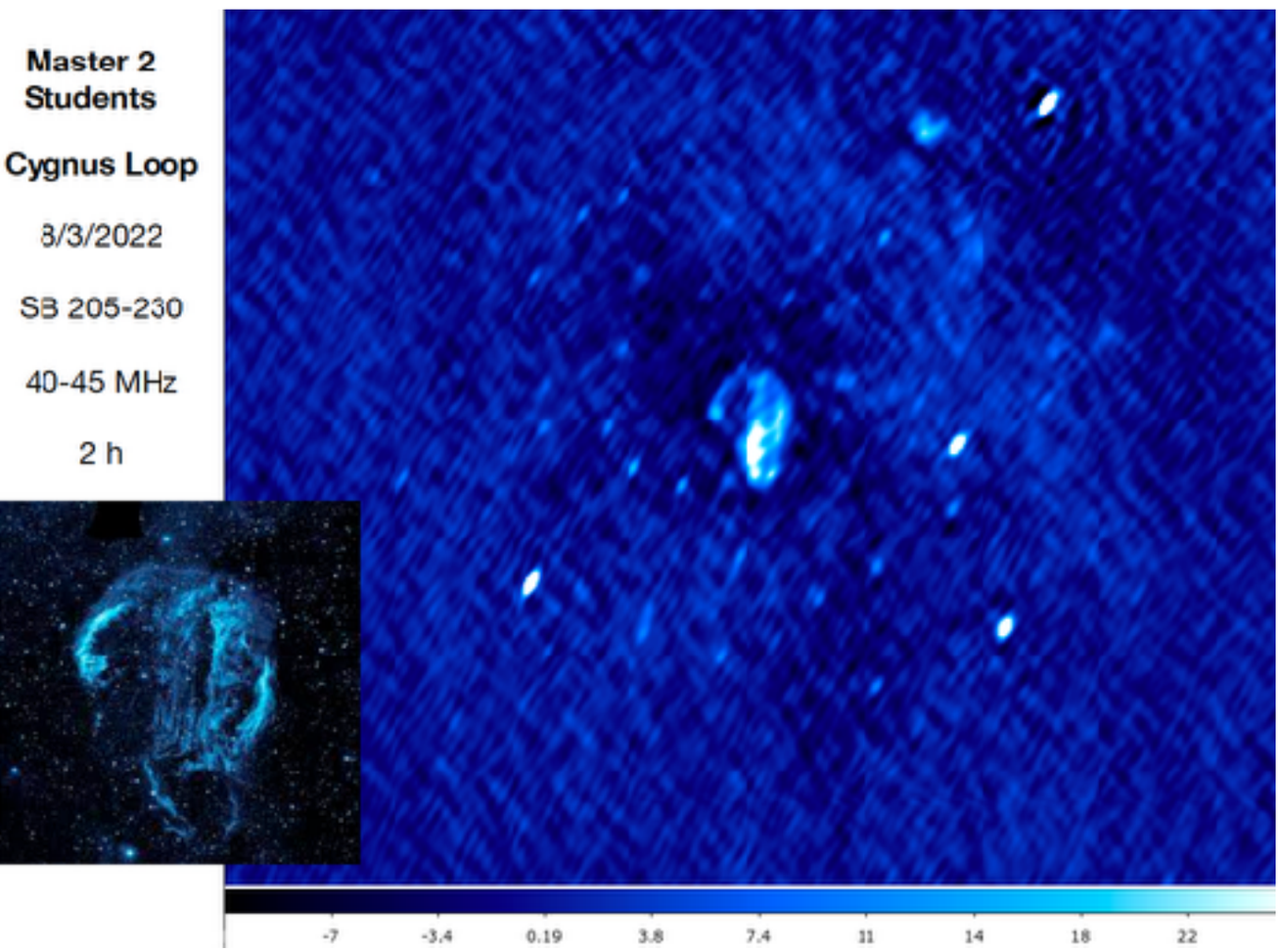


Imaging : extended structures

Coma cluster field

[Bonnassieux et al., 2021]

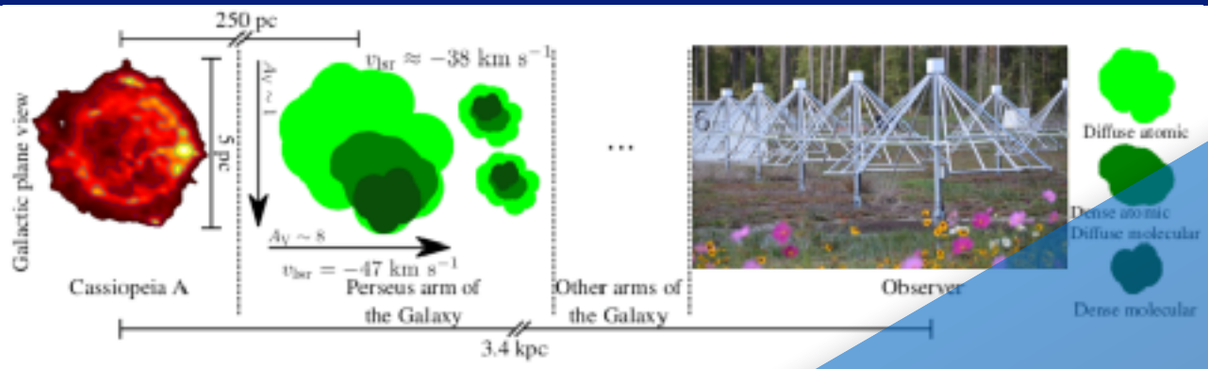




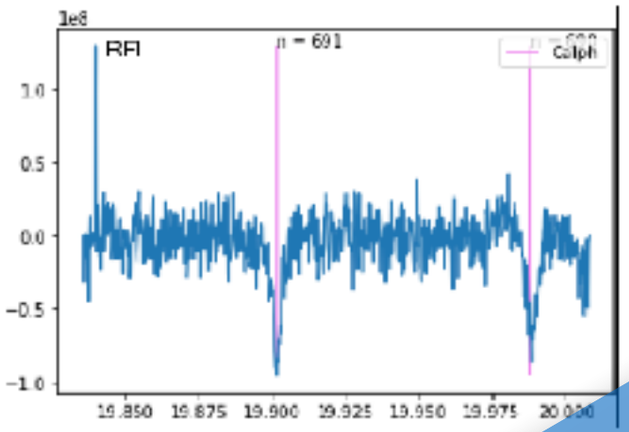
Cygnus loop field

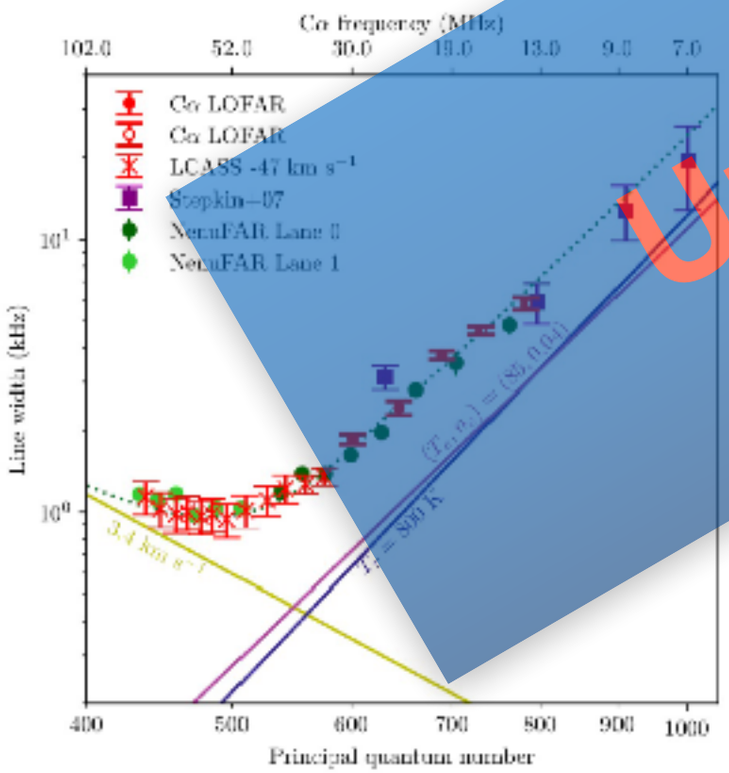
[Girard + M2 students, 2022]

Radio recombination lines in the ISM



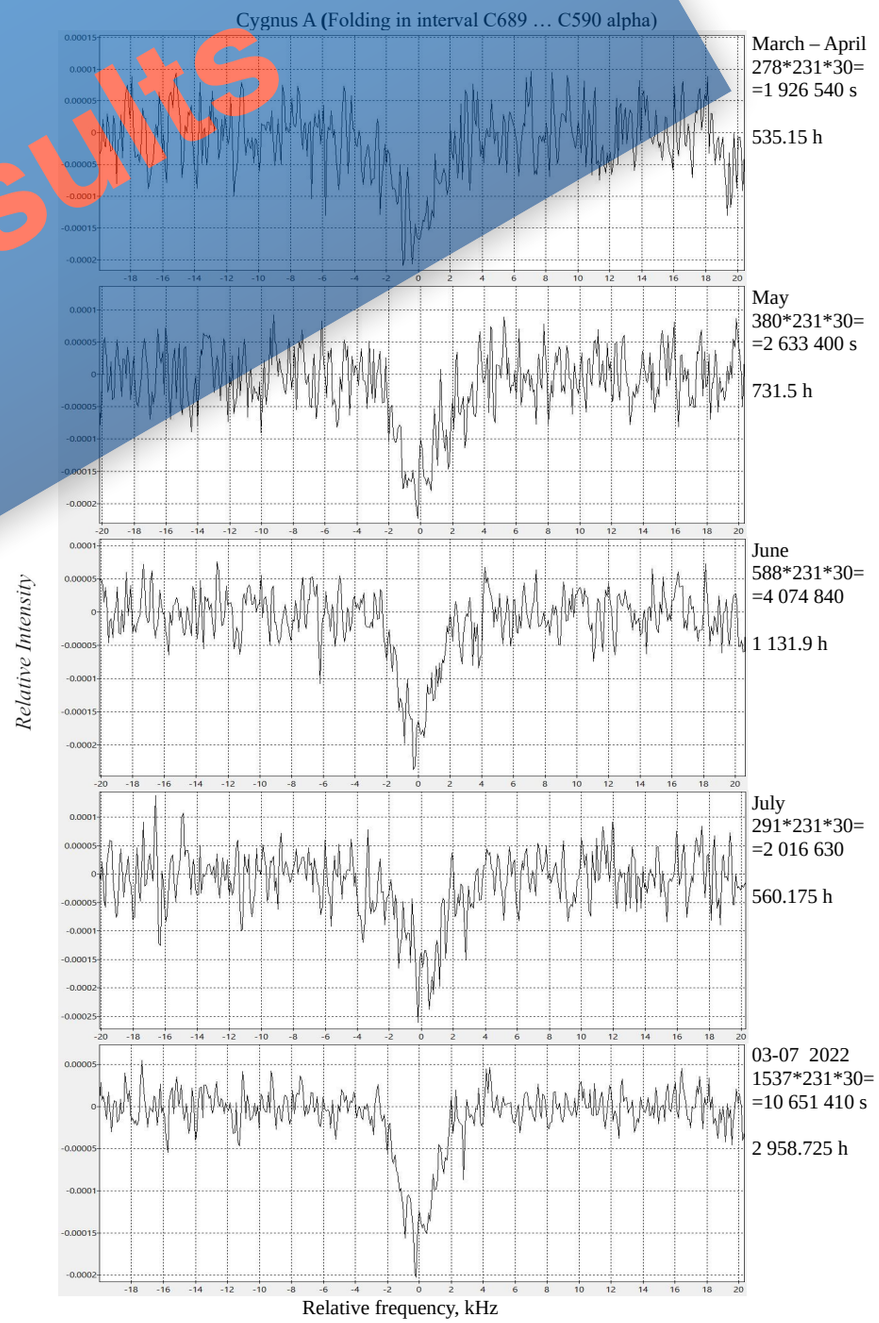
- High SNR detection



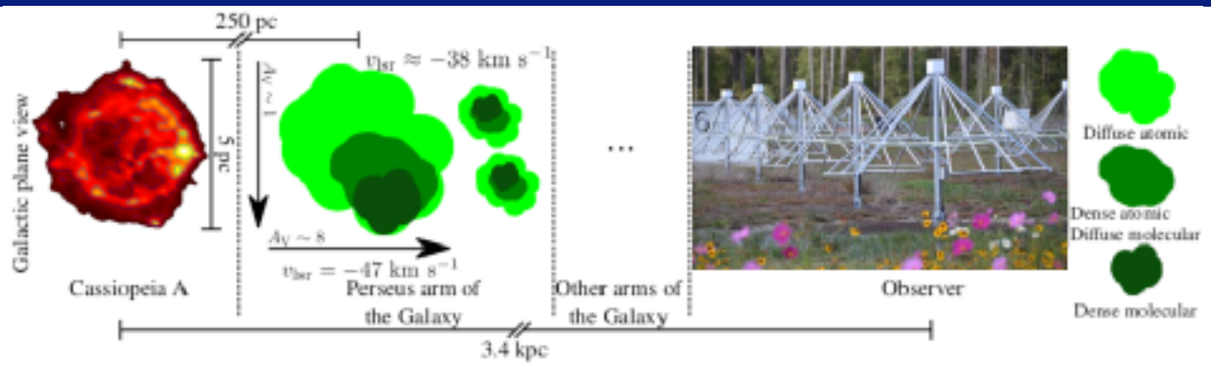


[Cros, Gusdorf, Salome et al., in prep.]

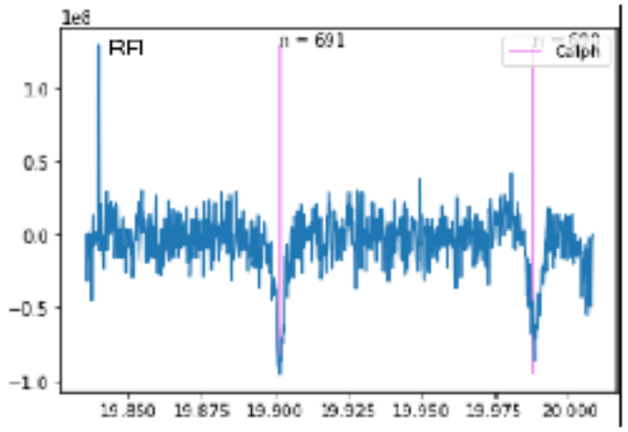
- Cyg A studies

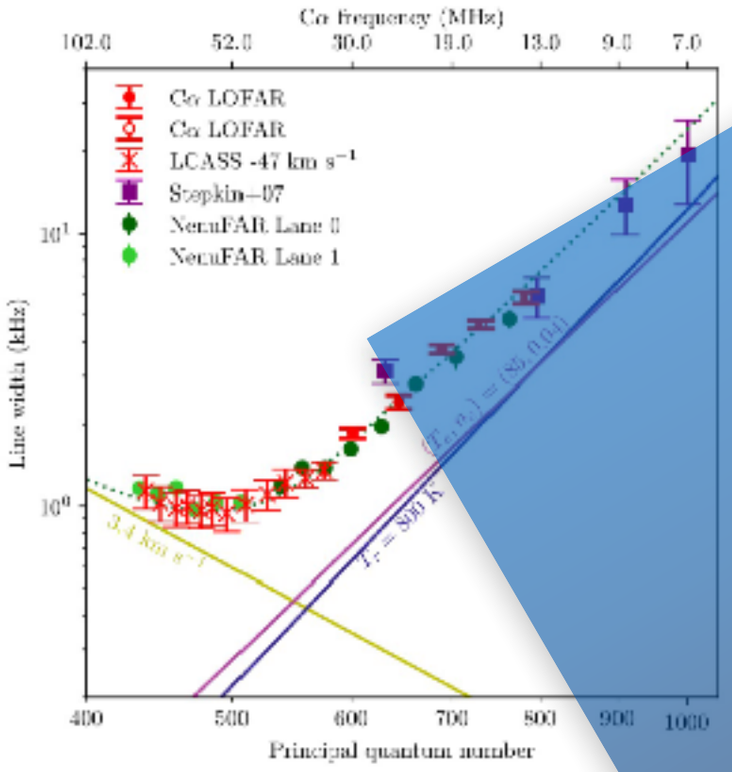


Radio recombination lines in the ISM



- High SNR detection





[Cros, Gusdorf, Salome et al., in prep.]

- Tau A : first detection of RRLs

Sensitivity : 8 x 10^{-5}

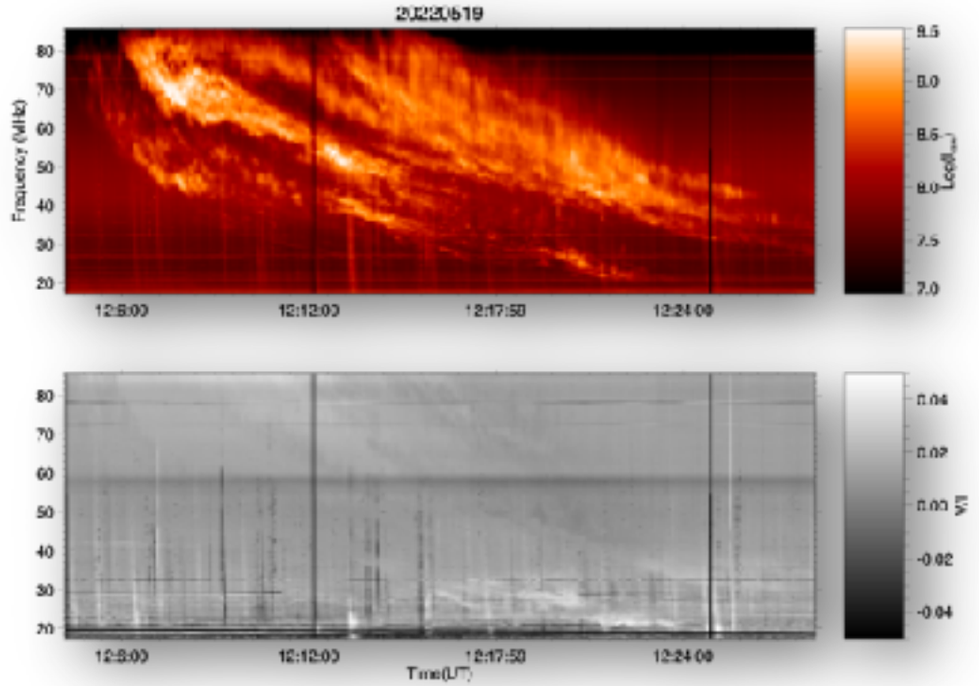
Line amplitude : 3.3 x 10^{-4} (4σ)

[Stepkin, Gusdorf, et al., in prep.]

Solar Key project

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	

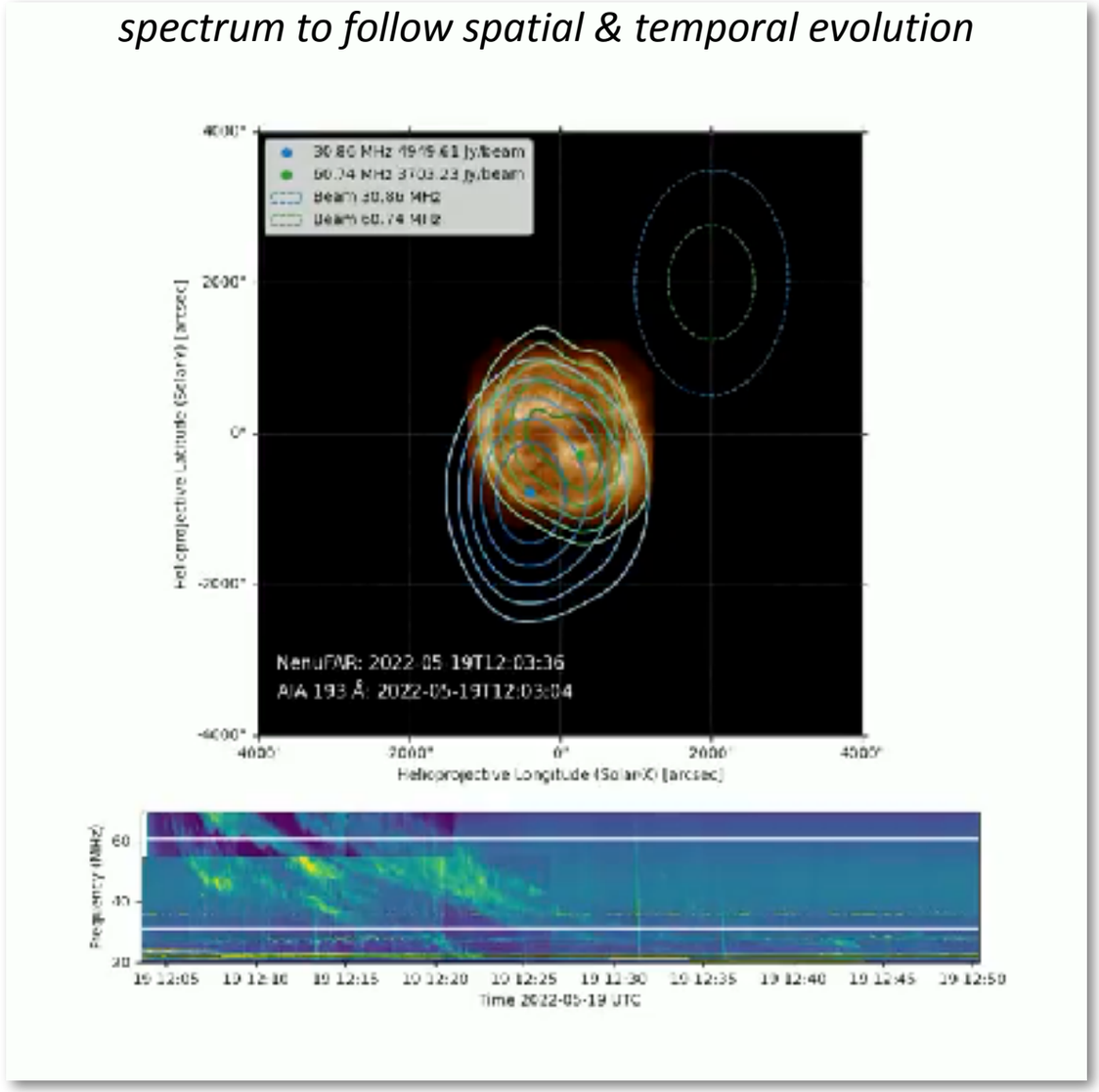
NenuFAR high sensitivity, polarization, dynamic spectra + imaging



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

Short-lived, narrow-banded, highly polarized emissions

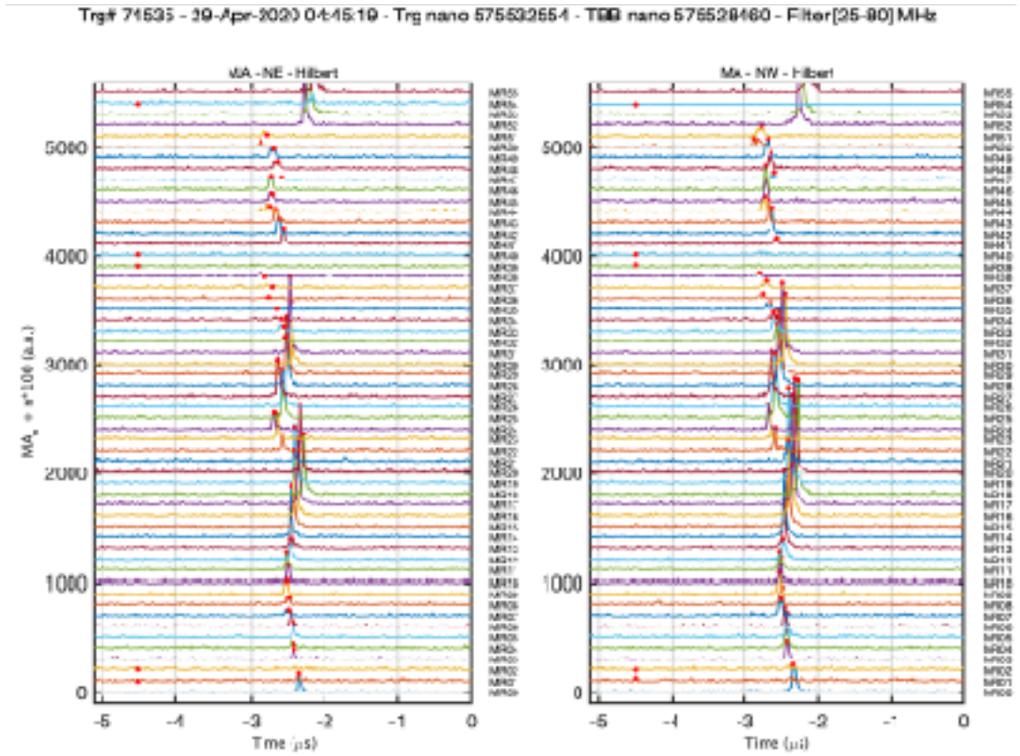
Highly dynamical phenomena: imaging + dynamic spectrum to follow spatial & temporal evolution

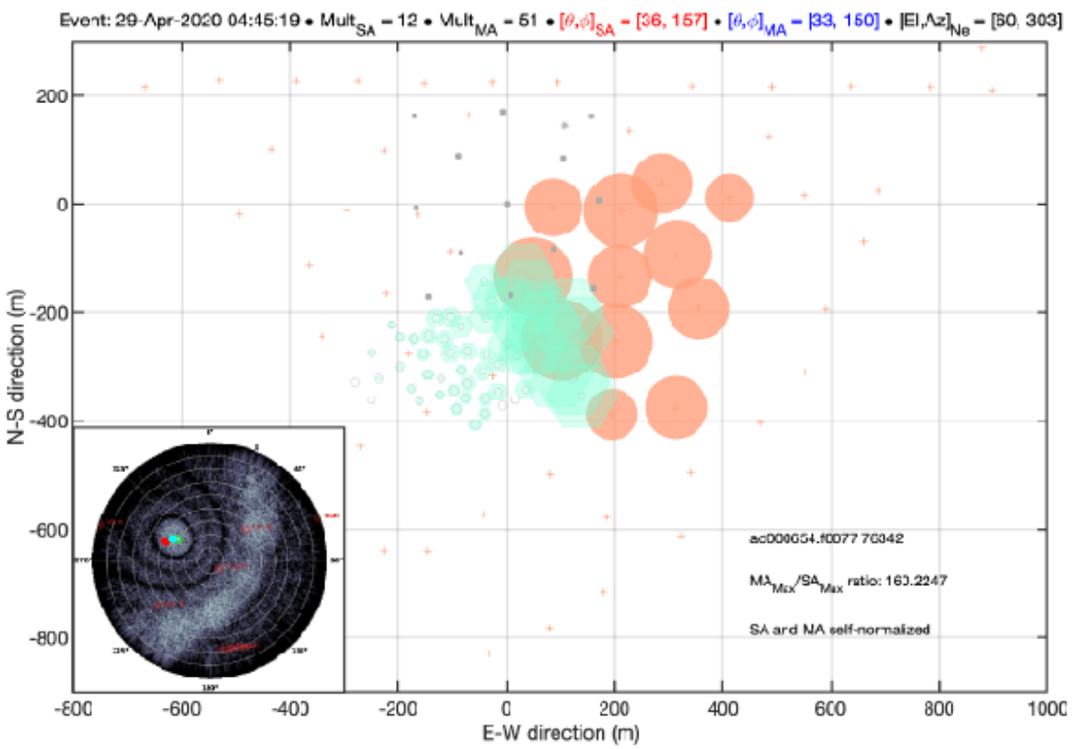


[Briand et al., 2022 ; Murphy et al., in prep.]

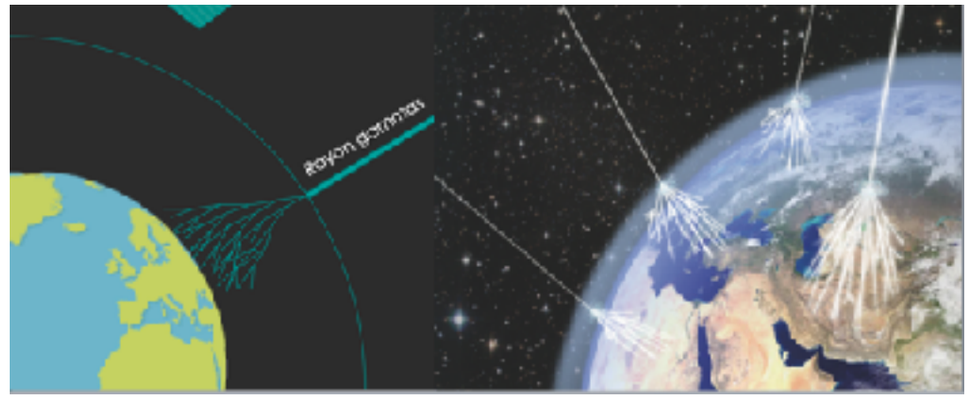
Radio Gamma Key Project

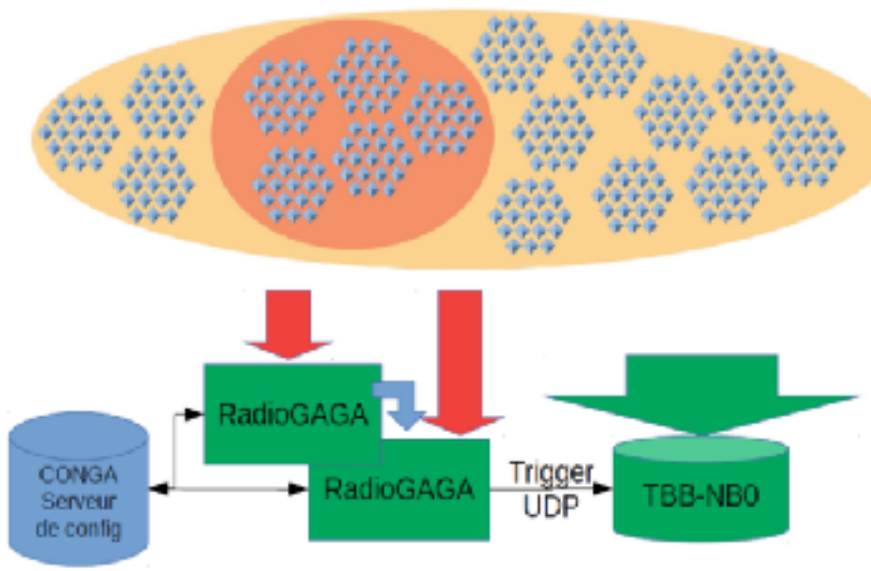
- Regular detection of Cosmic ray showers (TBB)





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

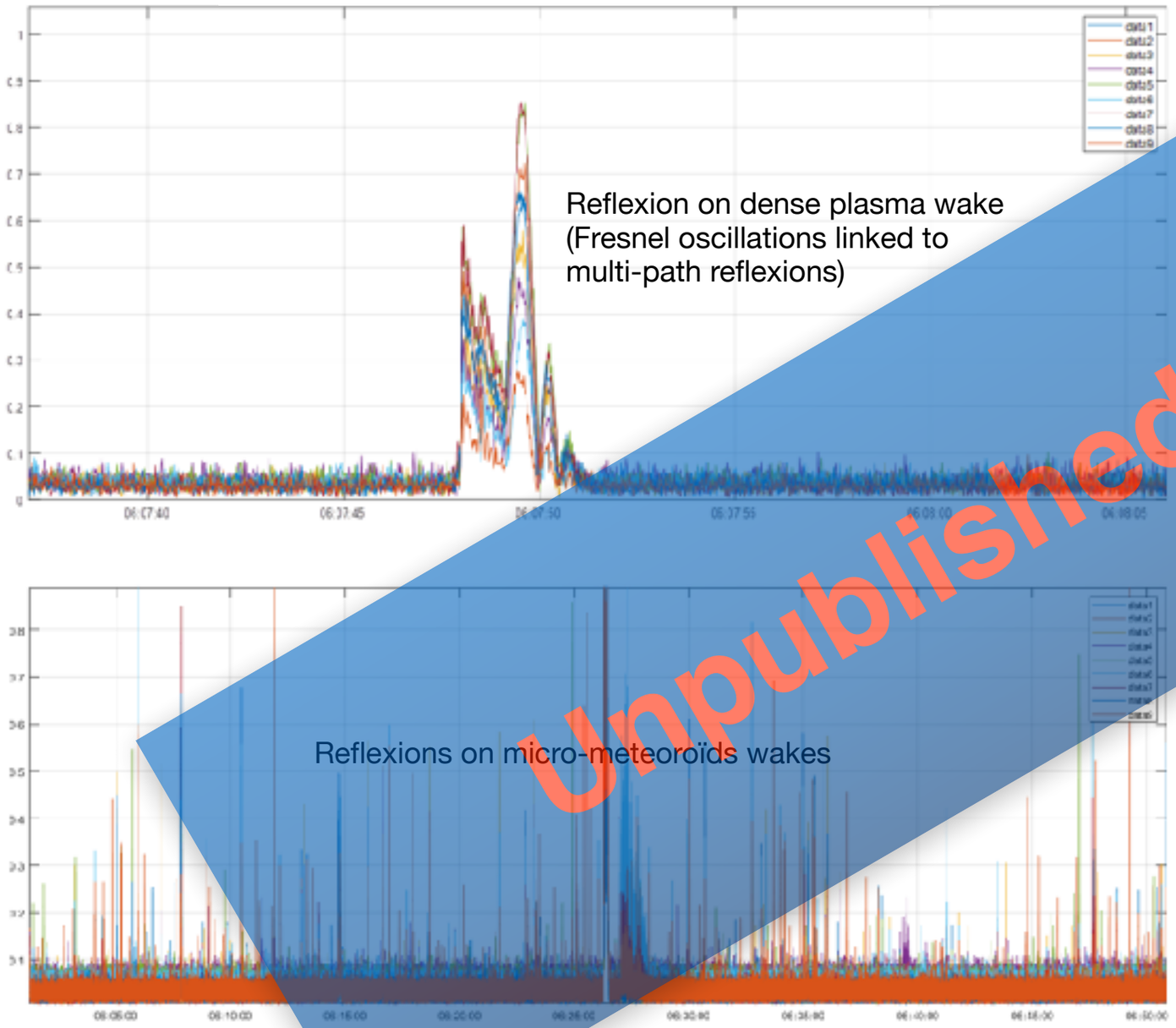




[Berthet, Viou, Dallier, Martin, et al.]

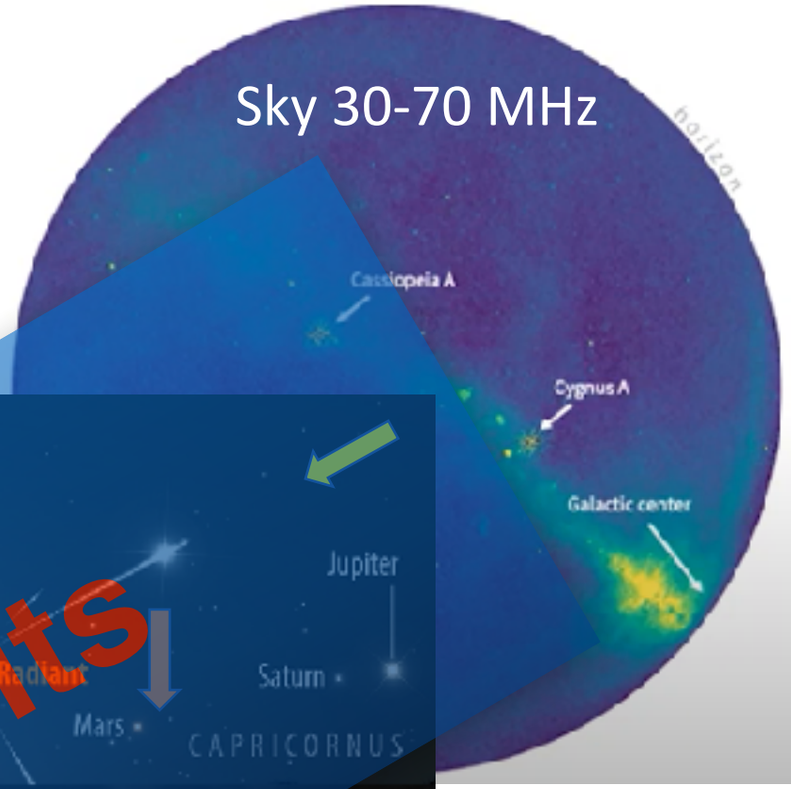
Radio Amateurs group

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



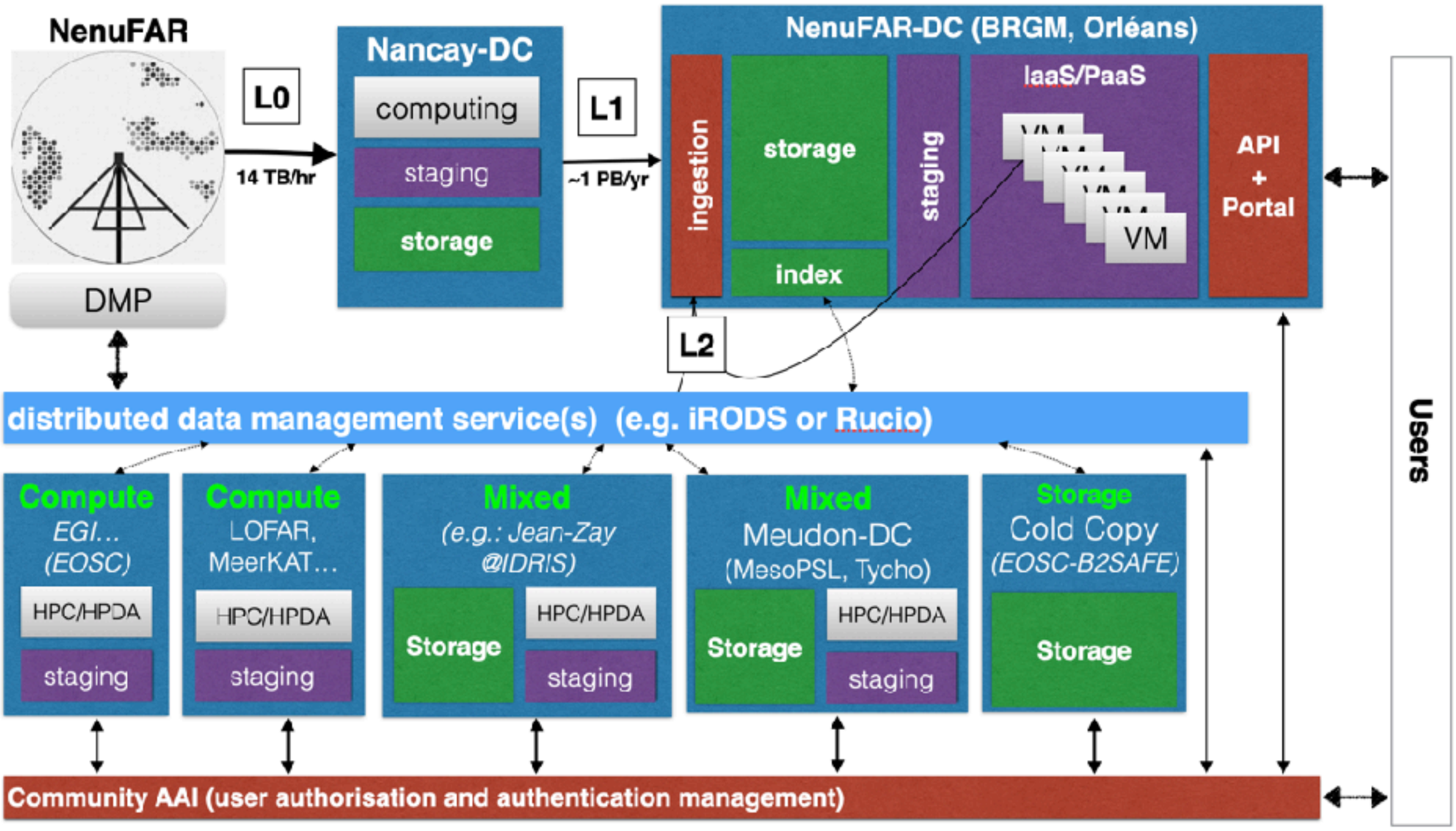
Incident radio flux
Reflected radio flux

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

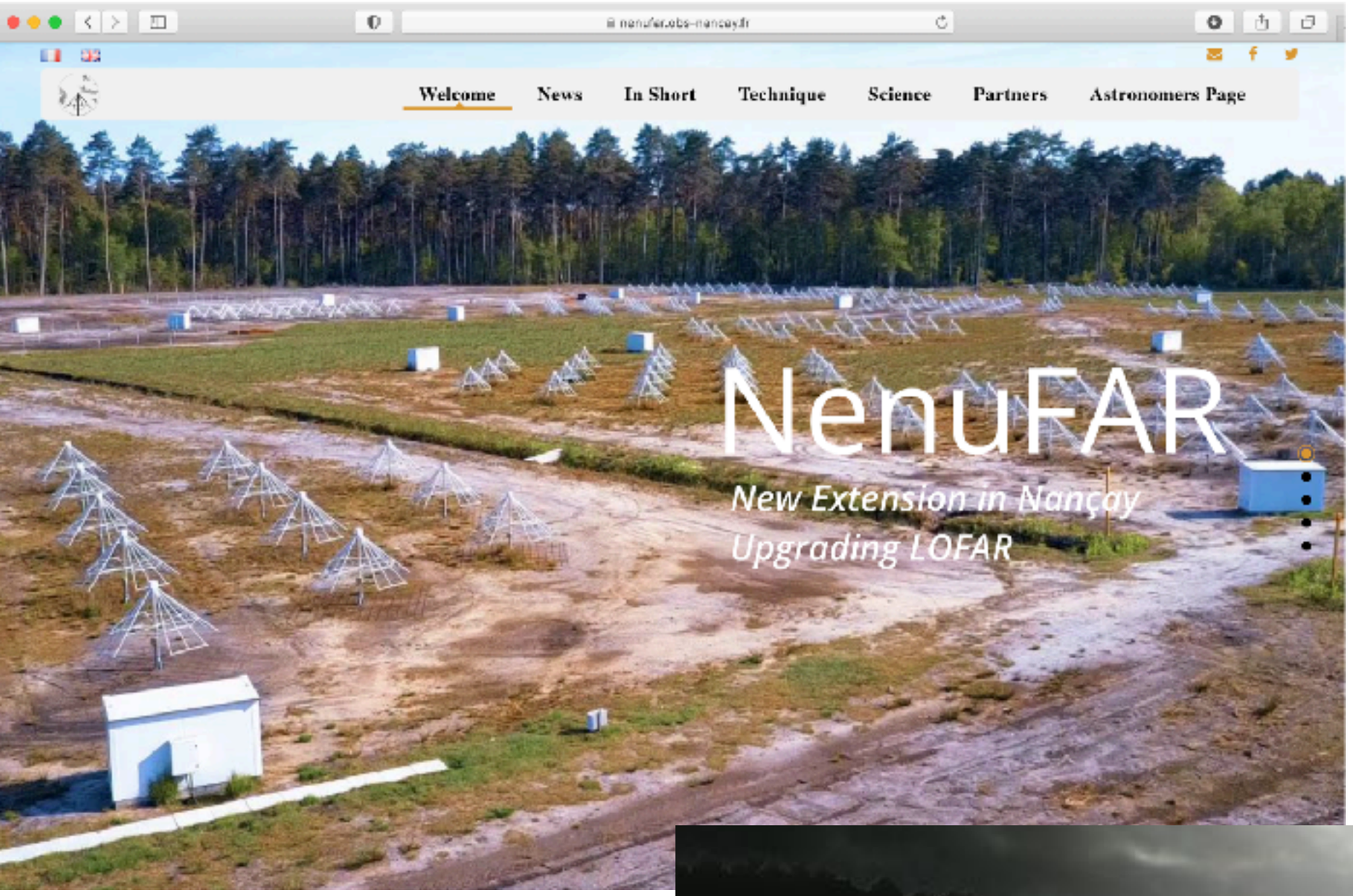
[Maintoux, Boureille et al.]

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



Web site, Art project (Le Dôme)



[Y. Bertho, C. Taffoureau]

[C. Courte, S. Lorillard]

NenuFAR

- Small project, key Nançay manpower, funding ≠ national
- Gain expertise (technical & scientific), develop the French LF radio community, prepare SKA(-Low)

Lessons

- VCR & scheduling
- NenuFAR-TV (monitoring, outreach)
- Full instrument simulations (nenupy on github)
- Many parallel receivers and modes, SETI piggyback
- Phased trigger
- Limits on analog beamforming (→ ASIC dual beam)
- NenuFAR-DC
- Sky is clean >50 MHz
- MODS / DynSpecMS for variable emission
- Polar. calibration of beamformed data

Synergies

- Complementary frequency ranges
- Different hemispheres
- Scientific exploration & feasibility (CD, Exoplanets...)

NenuFAR publications

Refereed / published or in press : 10

- 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. https://doi.org/10.1029/2021JA030160
- Girard, J. & P. Zarka, Toward optimal phased array tile configurations for large new generation radiotelescopes and application to NenuFAR, A&A, in press.

Non-refereed or Proceedings / published or in press : 18 (+ 5 PRE IX)

Submitted : 3
- Ziwei Wu,et al., Pulsar Scintillation Studies with LOFAR: II. Dual-frequency scattering study of PSR J0826+2637 with LOFAR and NenuFAR, MNRAS, sumitted.
- Semelin, B., et al., Accurate modelling of the Lyman-coupling for the 21-cm signal, observability with NenuFAR and SKA, A&A, submitted.
- Tiburzi, C., et al., Frequency-dependent dispersion measure detected during the Solar approach of PSR J1022+1001, Astron. Astrophys., submitted.

In preparation : 3 + 5 (pulsars)
- Tasse, C., et al., Multi-Object Dynamic Spectro-Polarimetry : a new way to study radio transients, A&A, to be submitted.
- Mertens, F., NenuFAR Cosmic Dawn team, NenuFAR builders list, Cosmic Dawn observations with NenuFAR, to be submitted.
- NenuFAR collaboration, The LF radiotelescope NenuFAR, Exp. Ast., to be submitted.

Theses : 2 + 2
- 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.
- 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.
- Brionne,, M. Thèse de Doctorat, Université d'Orléans, 2019-2022, NenuFAR blind pulsar survey.
- 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).

Outreach : 3

Web / press releases : 10