NenuFAR

Philippe Zarka*
and the NenuFAR-France team

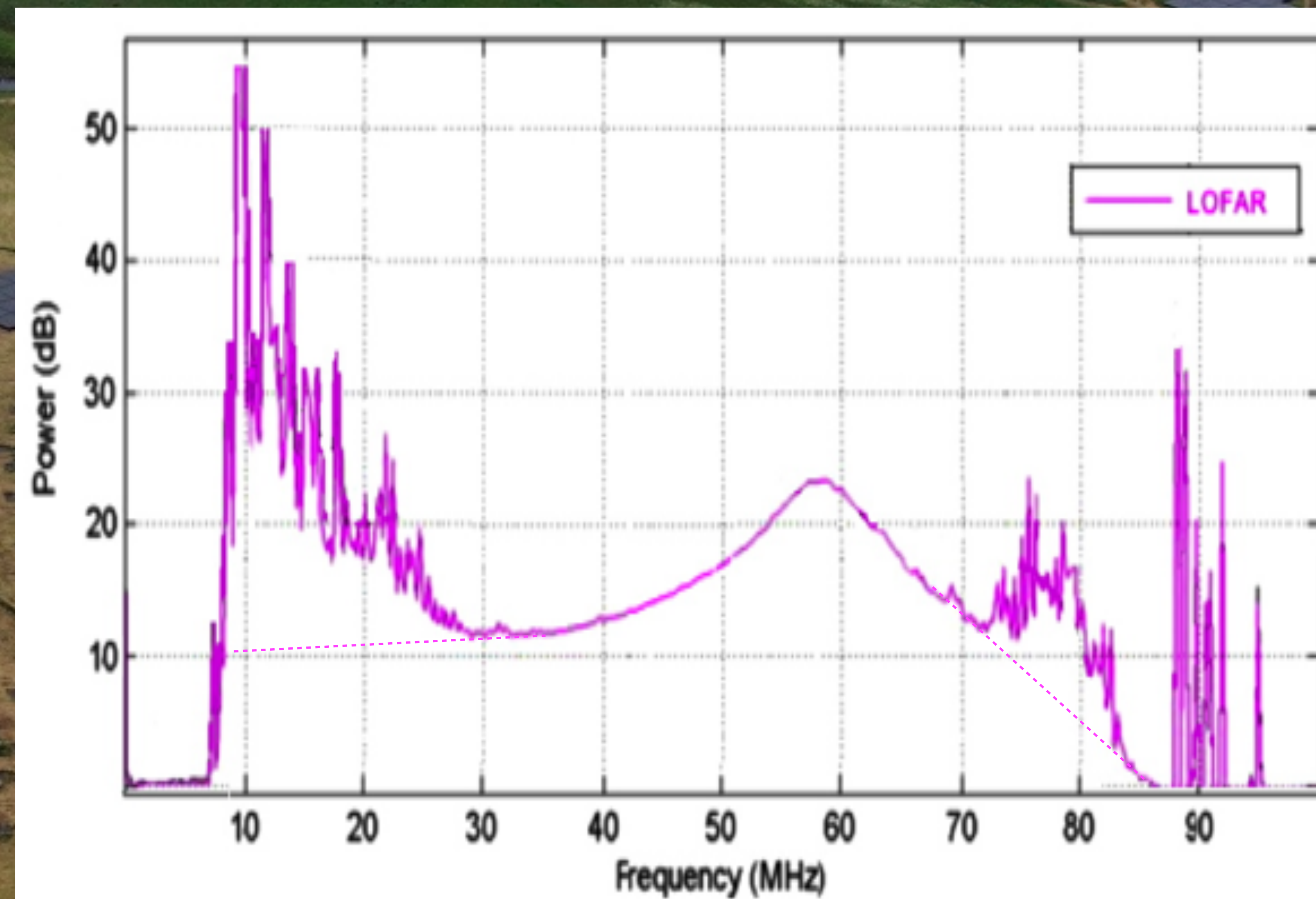
*LESIA & USN, Obs. Paris-CNRS-PSL

21cm Cosmology Workshop 2019
October 21-22-23 Orsay
Paris-Saclay University Campus
IPN auditorium, 21-22 Oct. Bldg 100
2019 Tianlai collaboration meeting
LAL auditorium, 23 Oct. Bldg 200

International LOFAR Telescope (ILT)

- LOFAR: 50000 HF antennas (110-250 MHz) + 3000 LF antennas (30-80 MHz)
  (2000 in NL, of which 1000 in core)

- At low frequencies, peaked response → non ideal



- Main idea of NenuFAR: maximum sensitivity at LF, down 10 MHz + compatibility with LOFAR

Motivations

- Interesting scientific «niches» for a large compact LF array :
  - more sensitivity at low / very low frequencies
  - more sensitivity to extended structures (short baselines)
  - compactness, large FoV, high sensitivity (multi-)beam formed mode

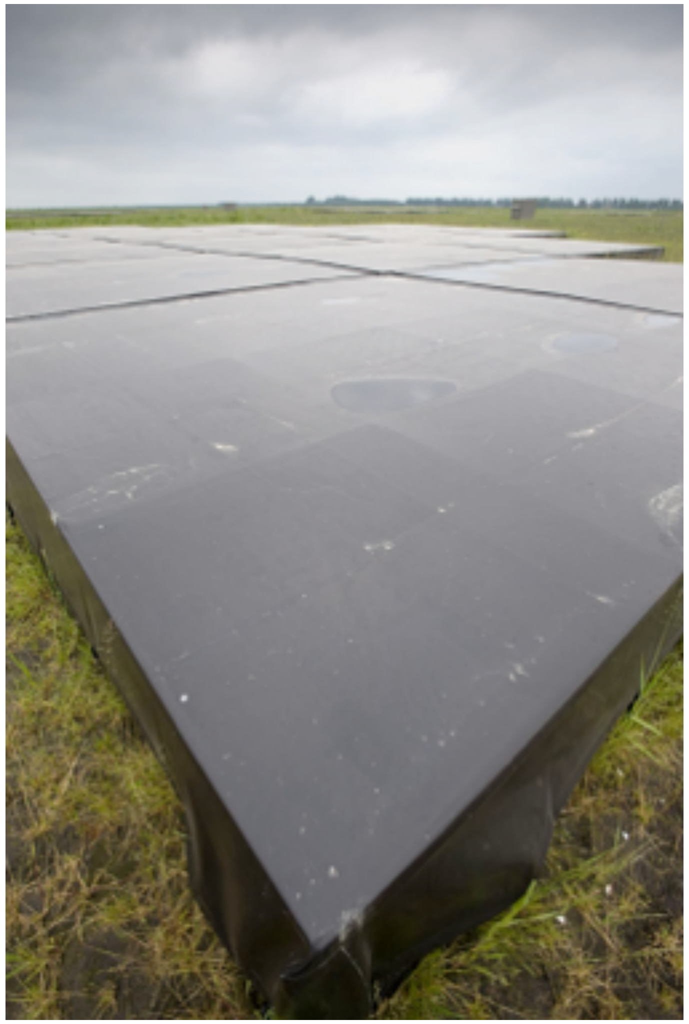
  ⇒ large programs : *pulsars & transients at LF, **cosmic dawn**, exoplanets, active/flaring stars*

- Complementarity with LOFAR
  - enabling very high resolution in LBA with sensitive international baselines

- Developing the French LF radio community

Basic Principle

x



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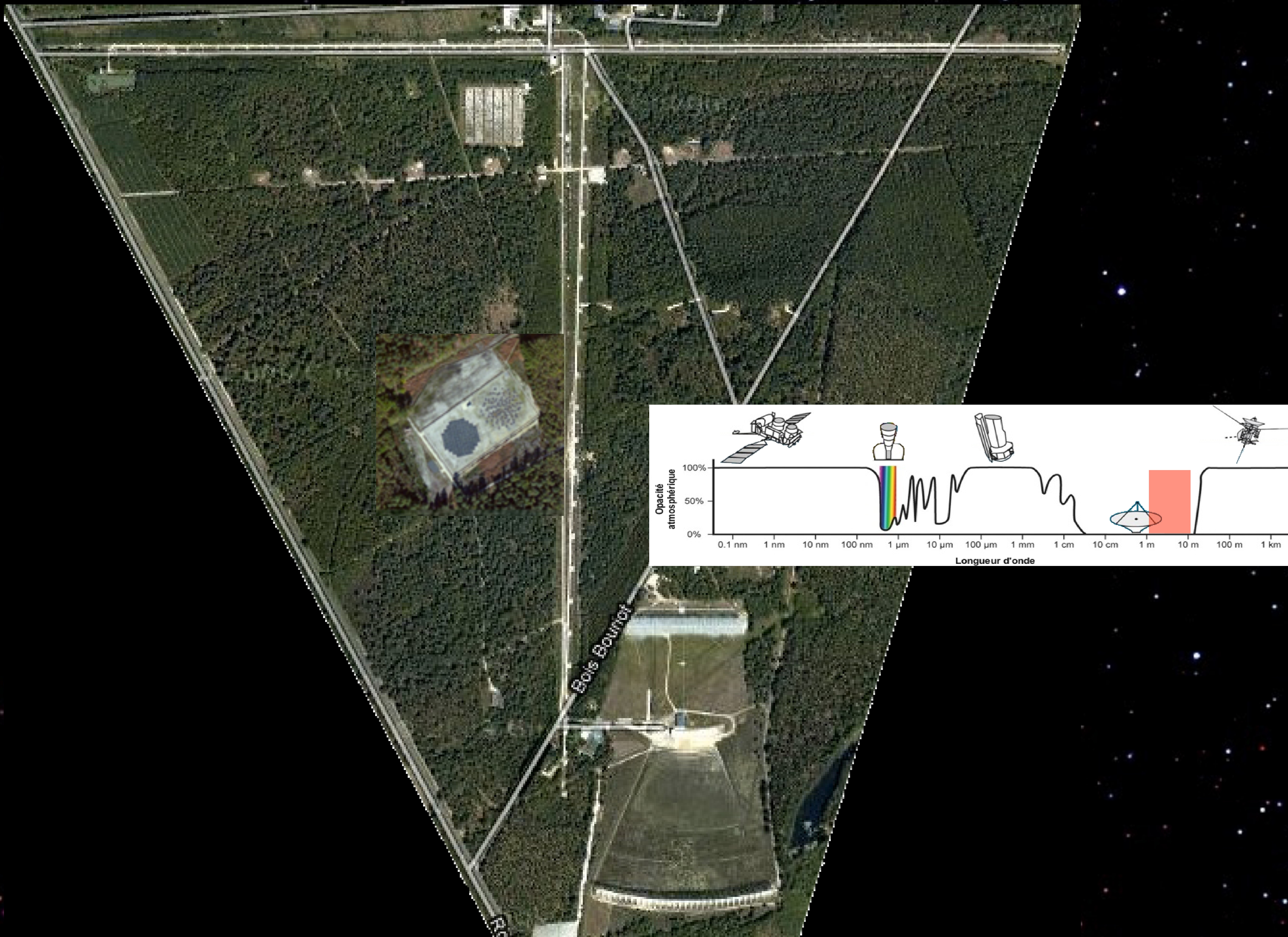
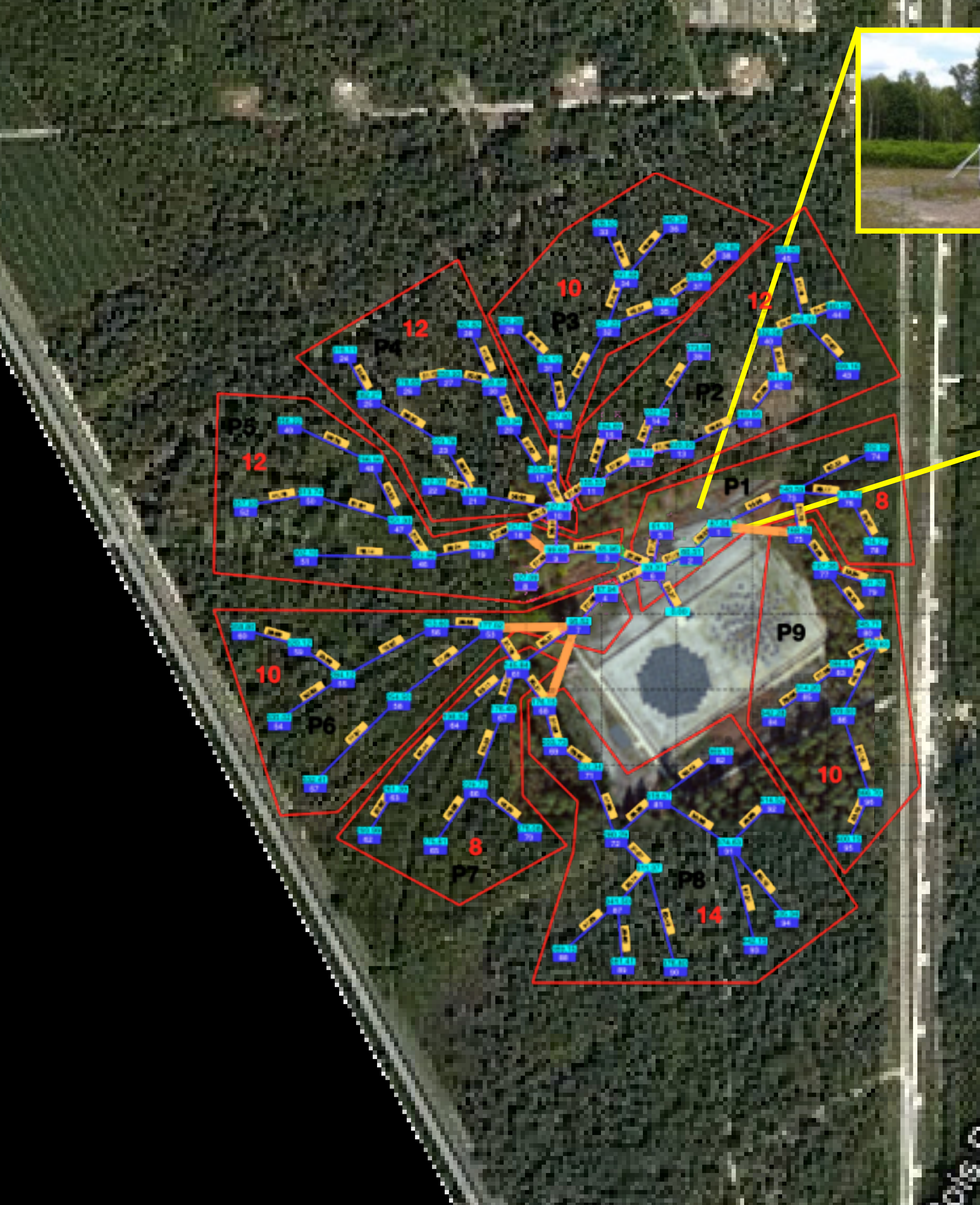
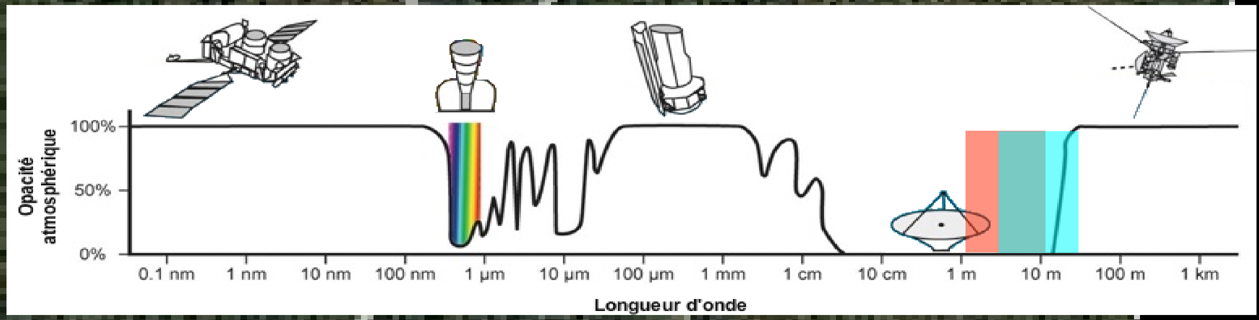
From LOFAR (FR606) to …



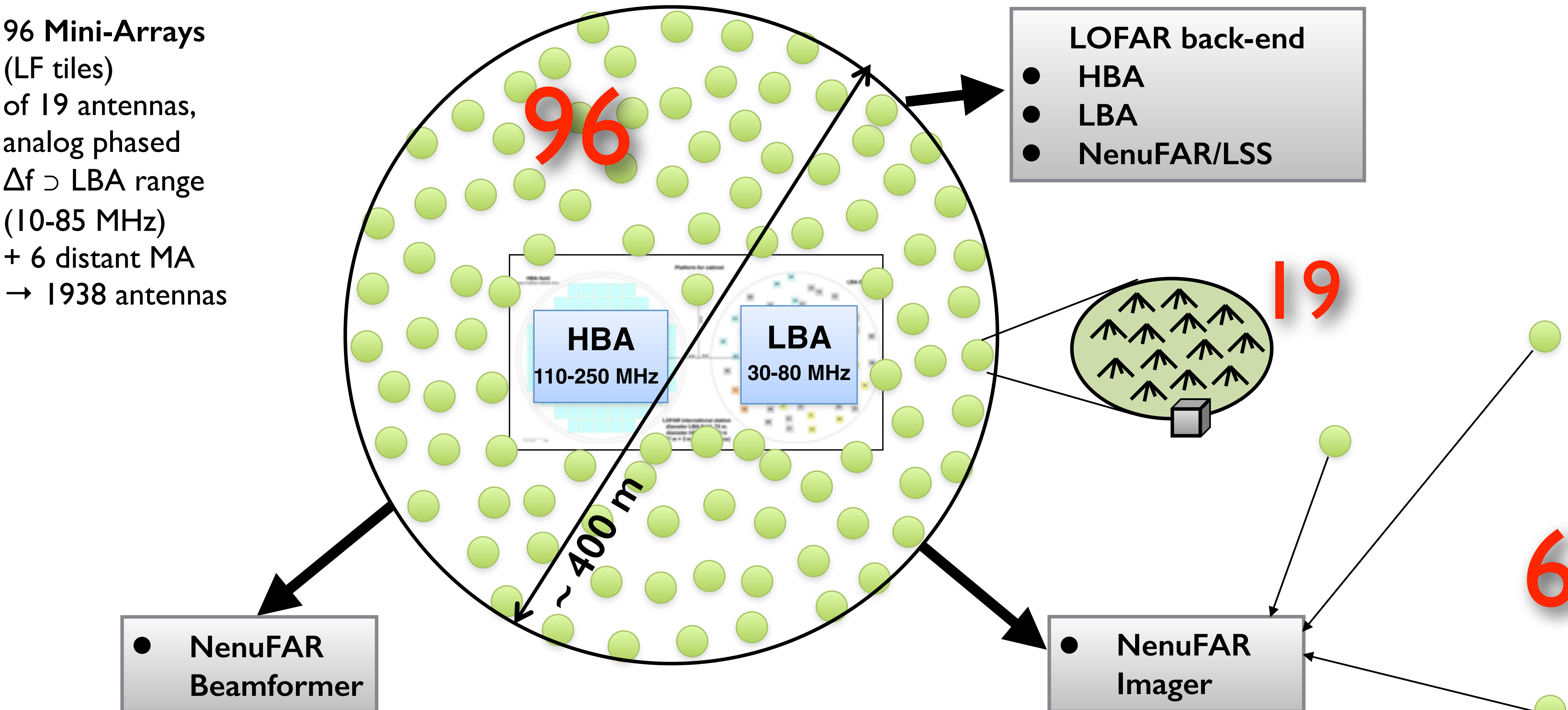
… NenuFAR

New extension in Nançay upgrading LOFAR





Concept



- Standalone Beamformer
- Standalone Transient Buffer
- Standalone Imager
- LOFAR Super Station

Sensitivity 2-8 x LOFAR

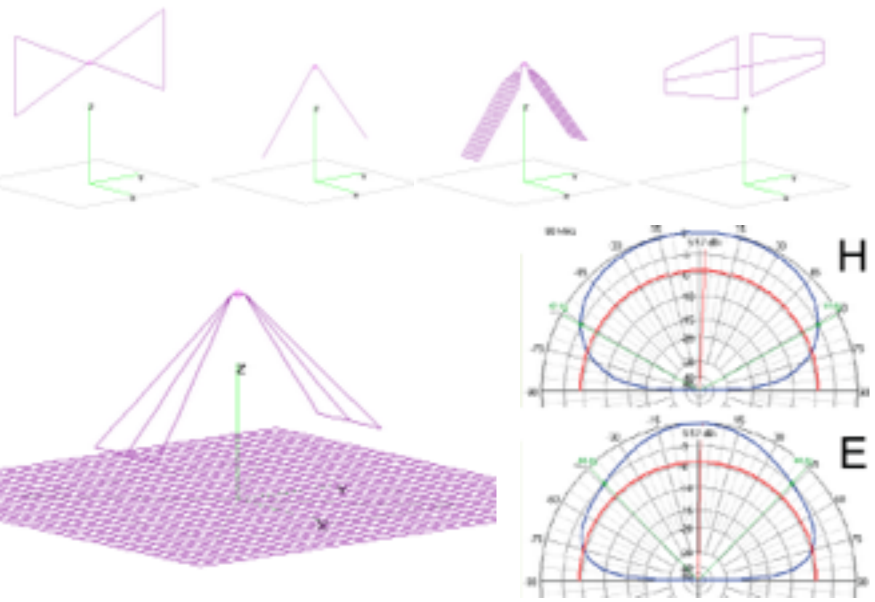
⇒ The world's most sensitive radiotelescope in the range 10-85 MHz

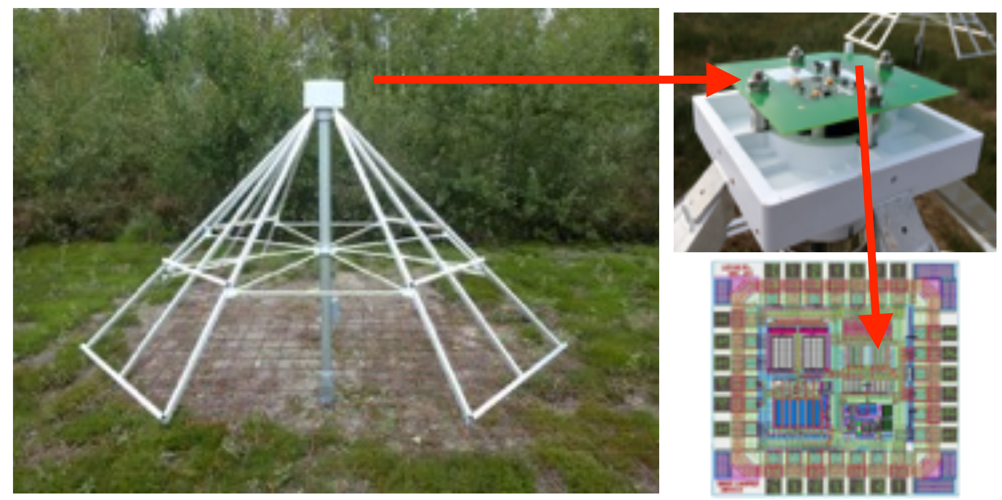
Technical developments

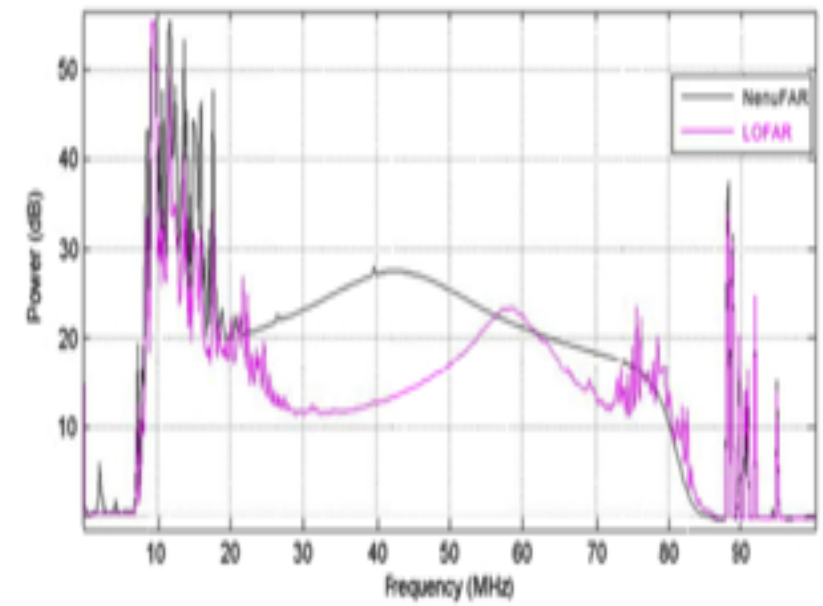
NenuFAR Design Study, 2009-2013 (ANR)

- Antenna (LWA) + preamplifier (France)
- Mini-Array of 19 antennas, hexagonal
- Optimization of the global 96 MA distribution + 6 distant MA
- Trenches/cables optimization [Vasko et al., 2016]
- Synchronization (White Rabbit)
- Flexible Pointing, Beam Squint, IMCCE Web-service for Solar system bodies
- Silent Control/Command system
- Advanced Control/Command GUI
- LaNewBa FPGA receiver
- Undysputed GPU calculators
- Correlator (under study)
- NenuFAR-LOFAR dialog

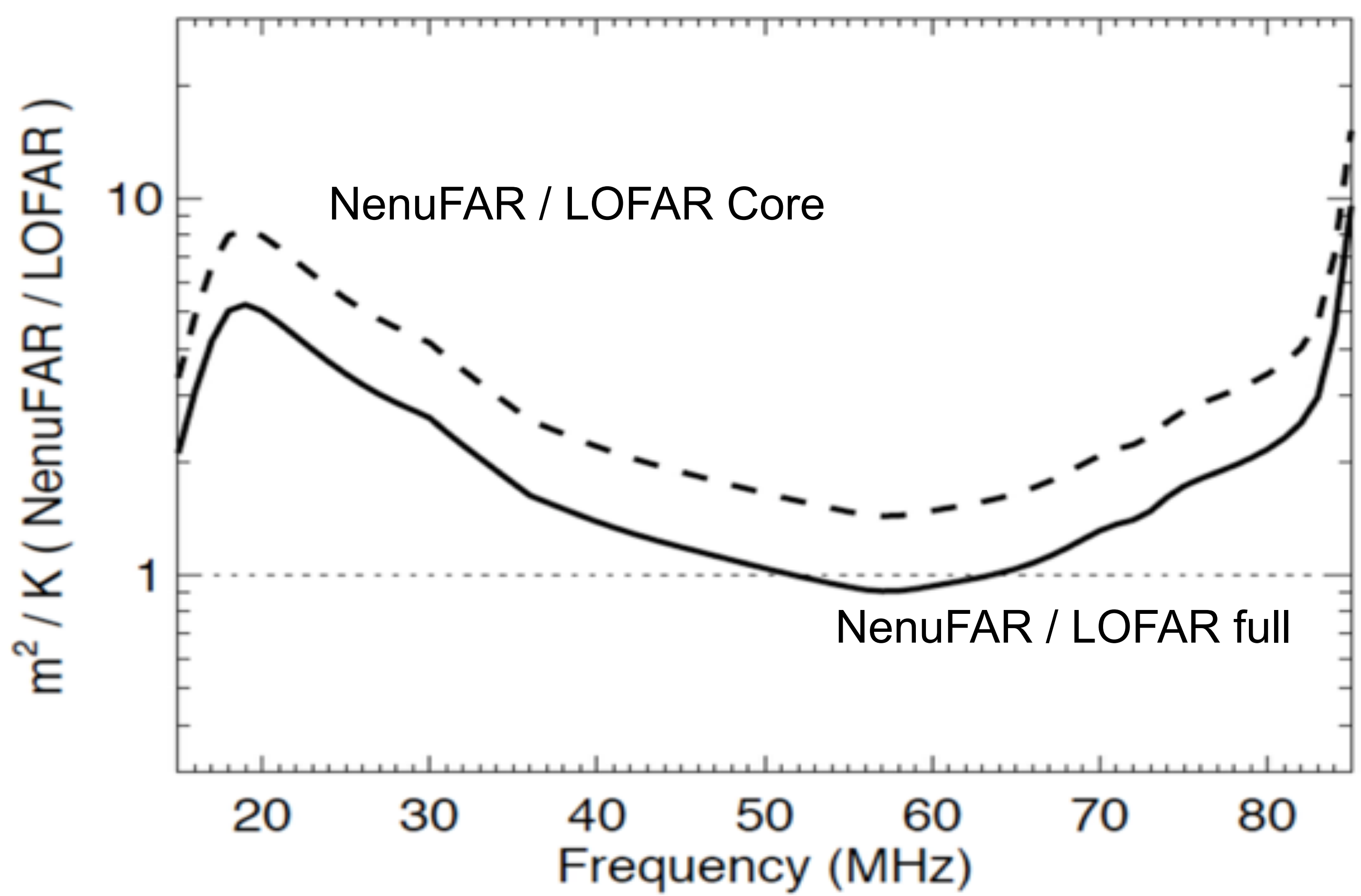
Antenna, Preamplifier, Sensitivity





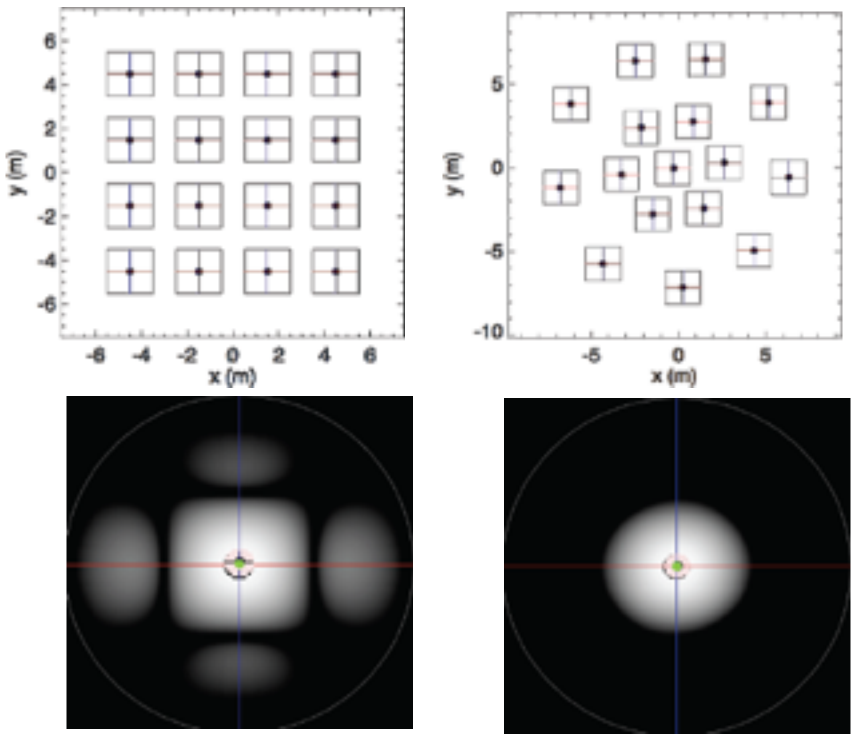


- Good LF antenna radiator + LNA [Hicks et al., 2012 ; Girard et al., 2012 ; Charrier et al., 2014]
- Ground plane improves antenna response and avoids variation / t of ground properties

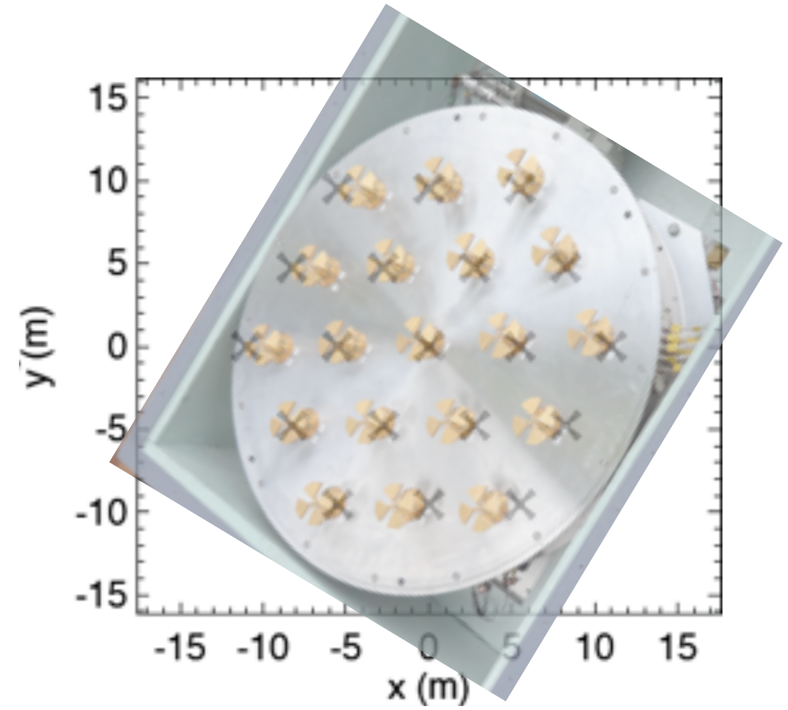


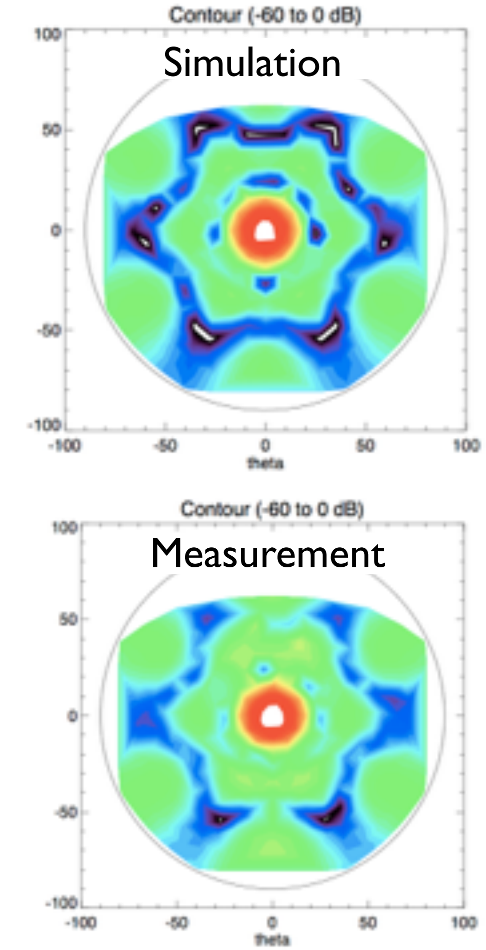
Mini-Array

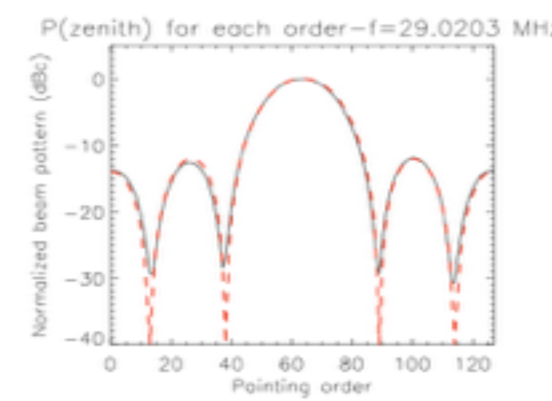
40 MHz



-15 dB sidelobes   -32 dB sidelobes

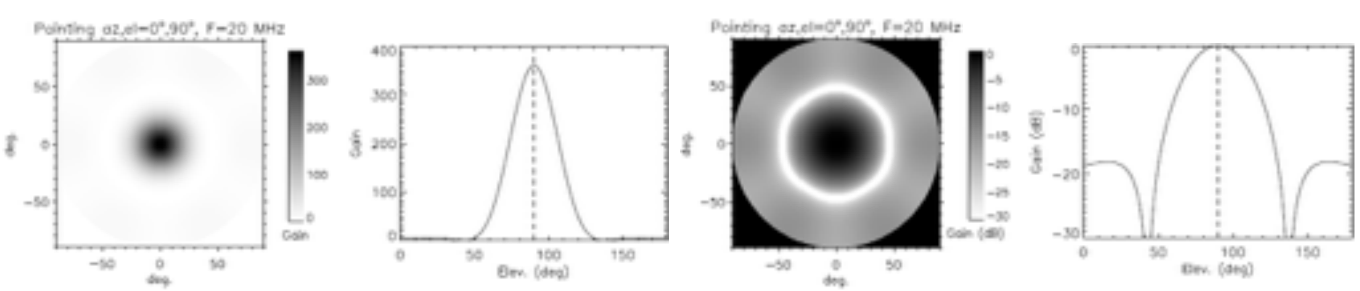




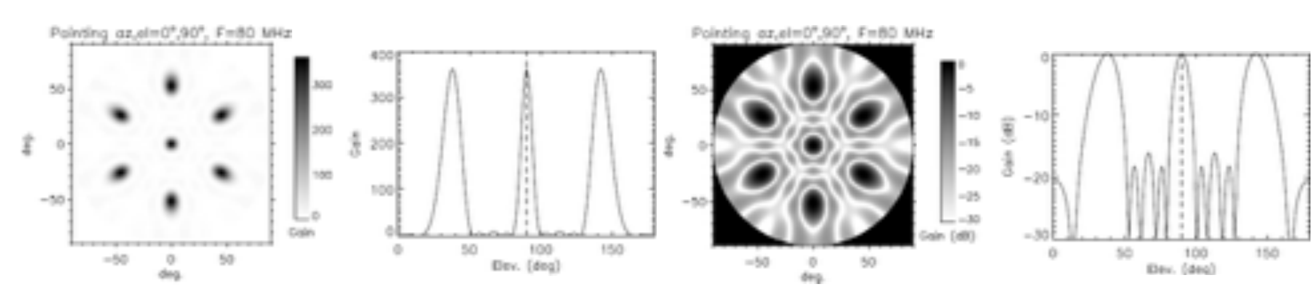


- Optimized 19-antenna distribution within Mini-Arrays

20 MHz

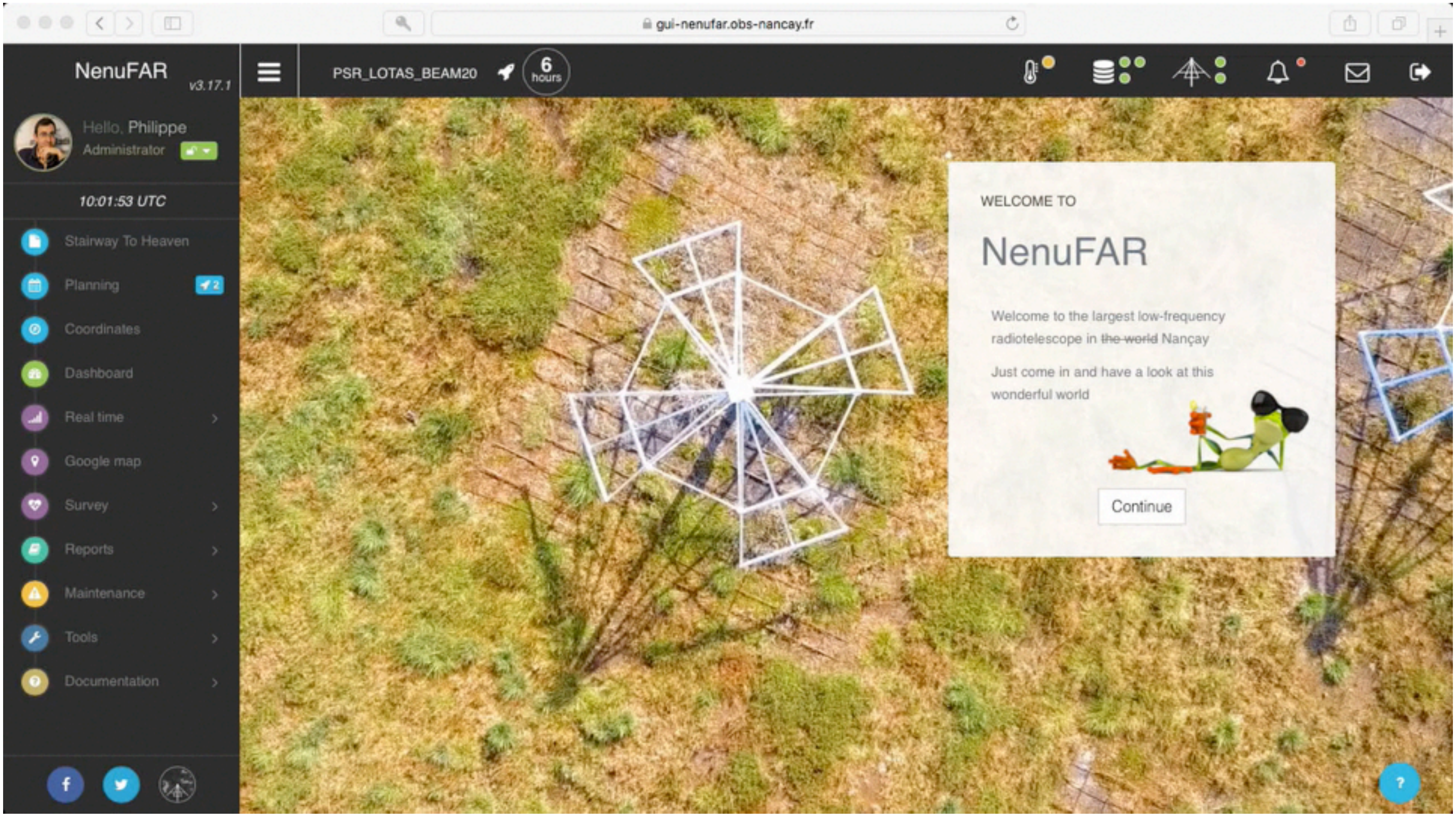


80 MHz

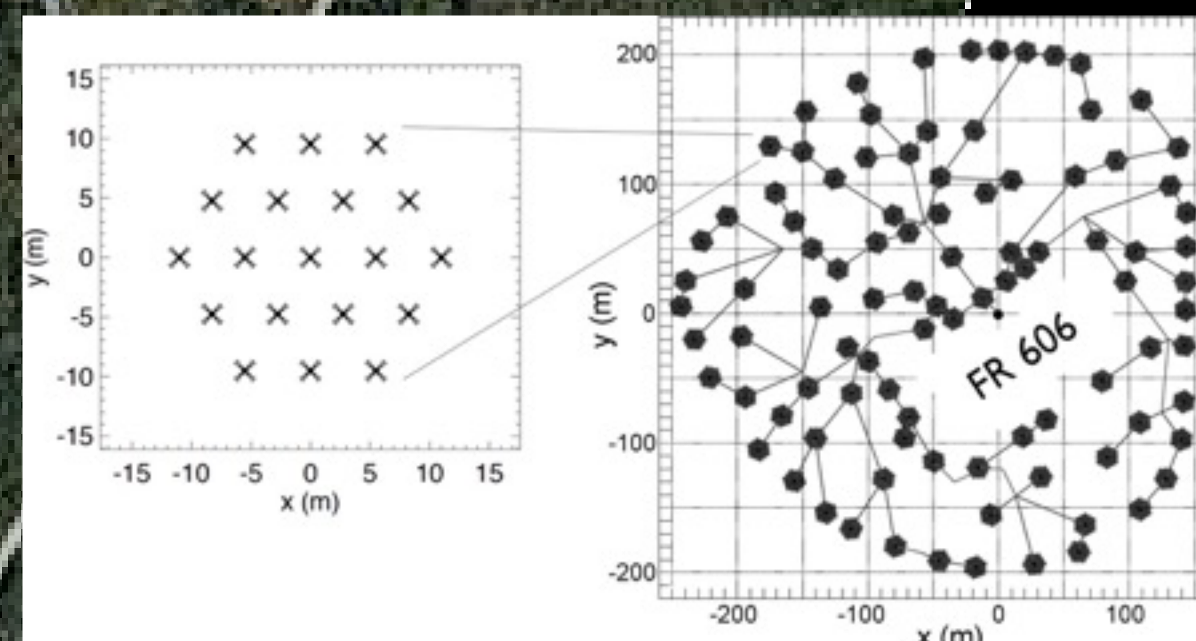


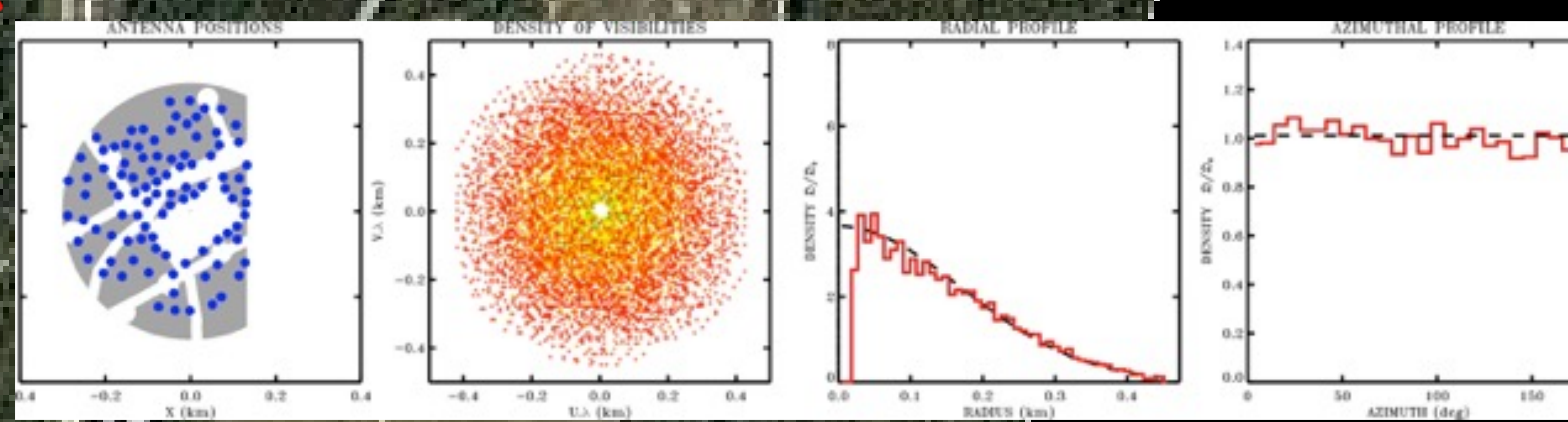
Operation & Control

- Virtual Control Room : telescope web interface → programming / managing the telescope & observations

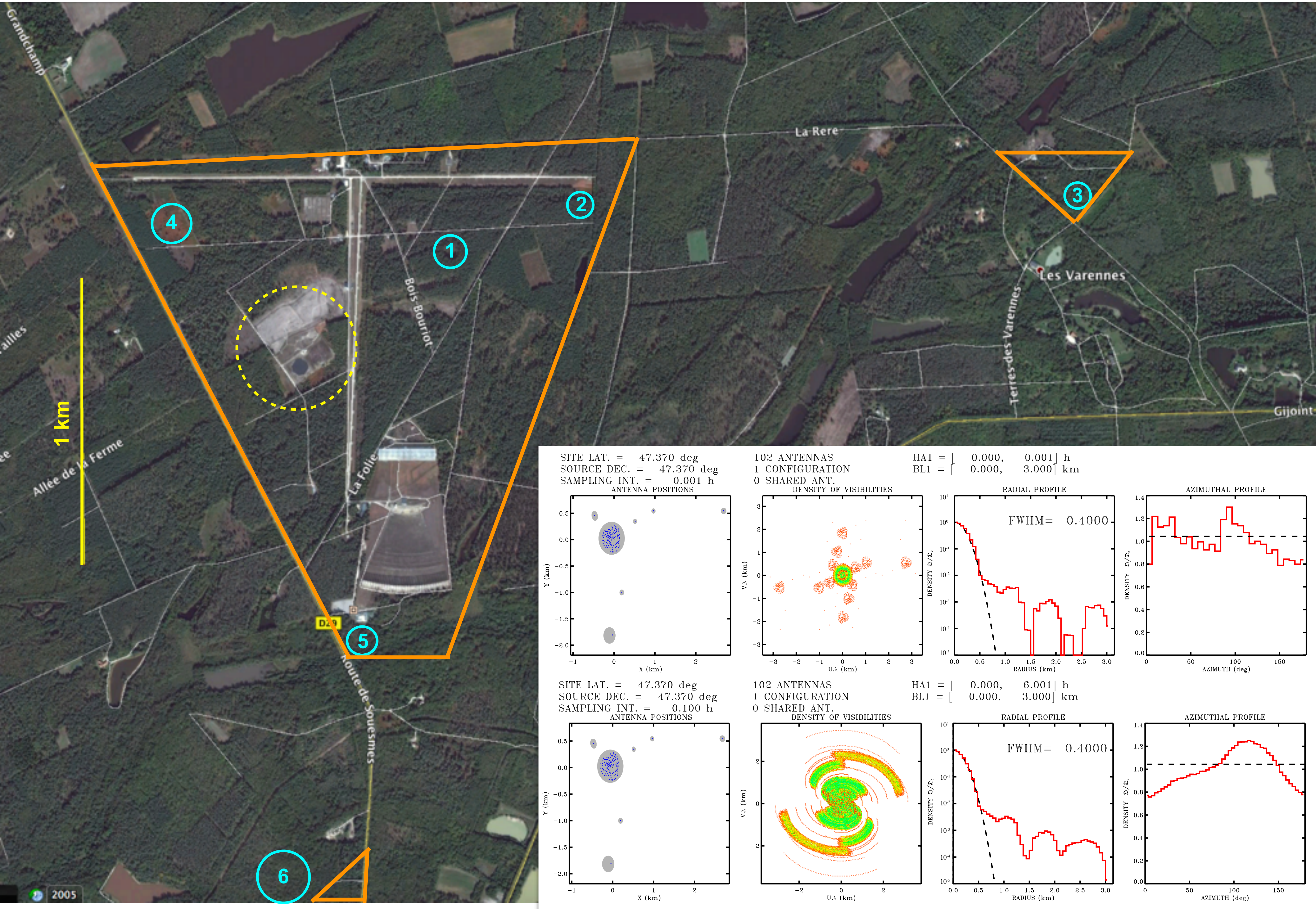


NenuFAR core distribution



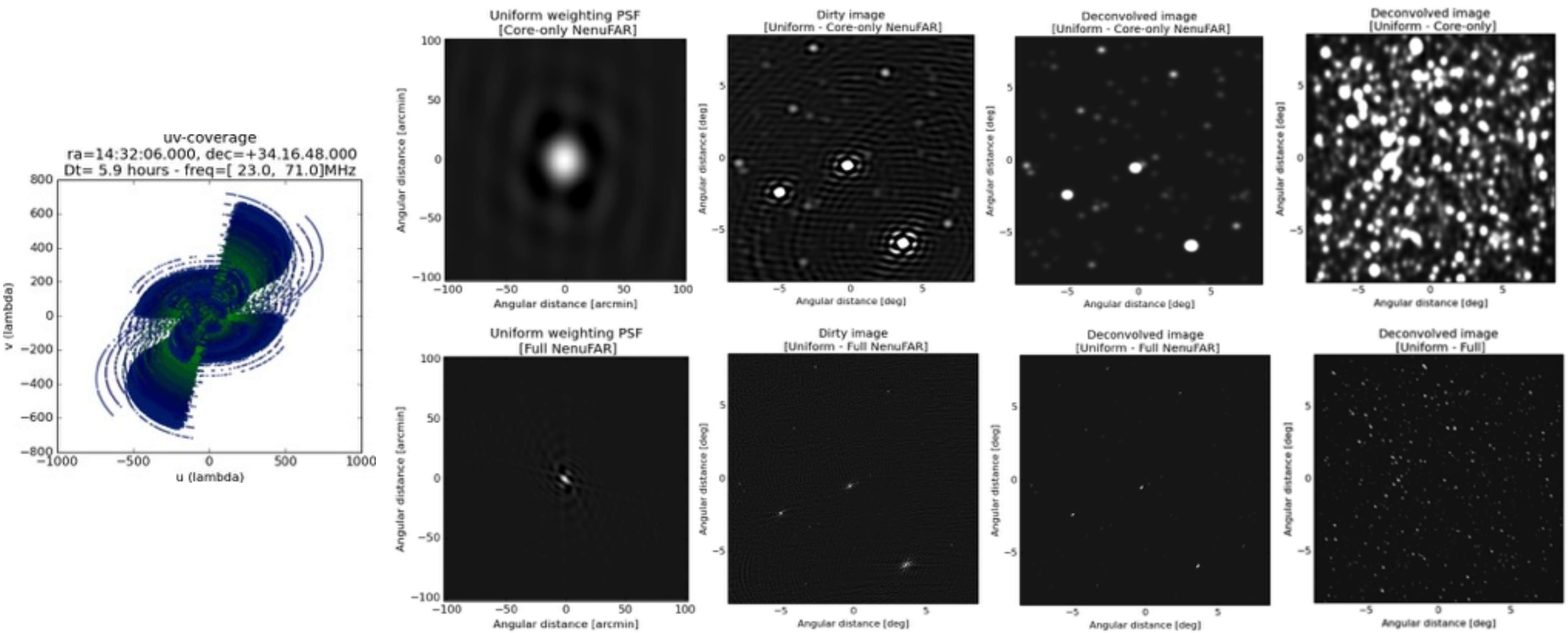


NenuFAR array (core + remote MA)



NenuFAR imager mode

- $\sigma_{confusion}$ [mJy/beam] ~ $(\nu$ / 100 MHz$)^{-0.7}$ $(\theta$ / ' $)^2$ [Condon, 2002, 2005] → 1-50 Jy @ 20-80 MHz (unpolarized signal)
- 6 distant MA + multi-λ synthesis → angular res. x 7 for stationnary broadband sources → $\sigma_{confusion}$ / 50
- Relative sensitivity beyond compact core = $(N_{distant}/N_{core})^{1/2}$ ~ 25%
- Synchronization via White Rabbit
- Correlator LOFAR/Cobalt-2 being deployed/adapted



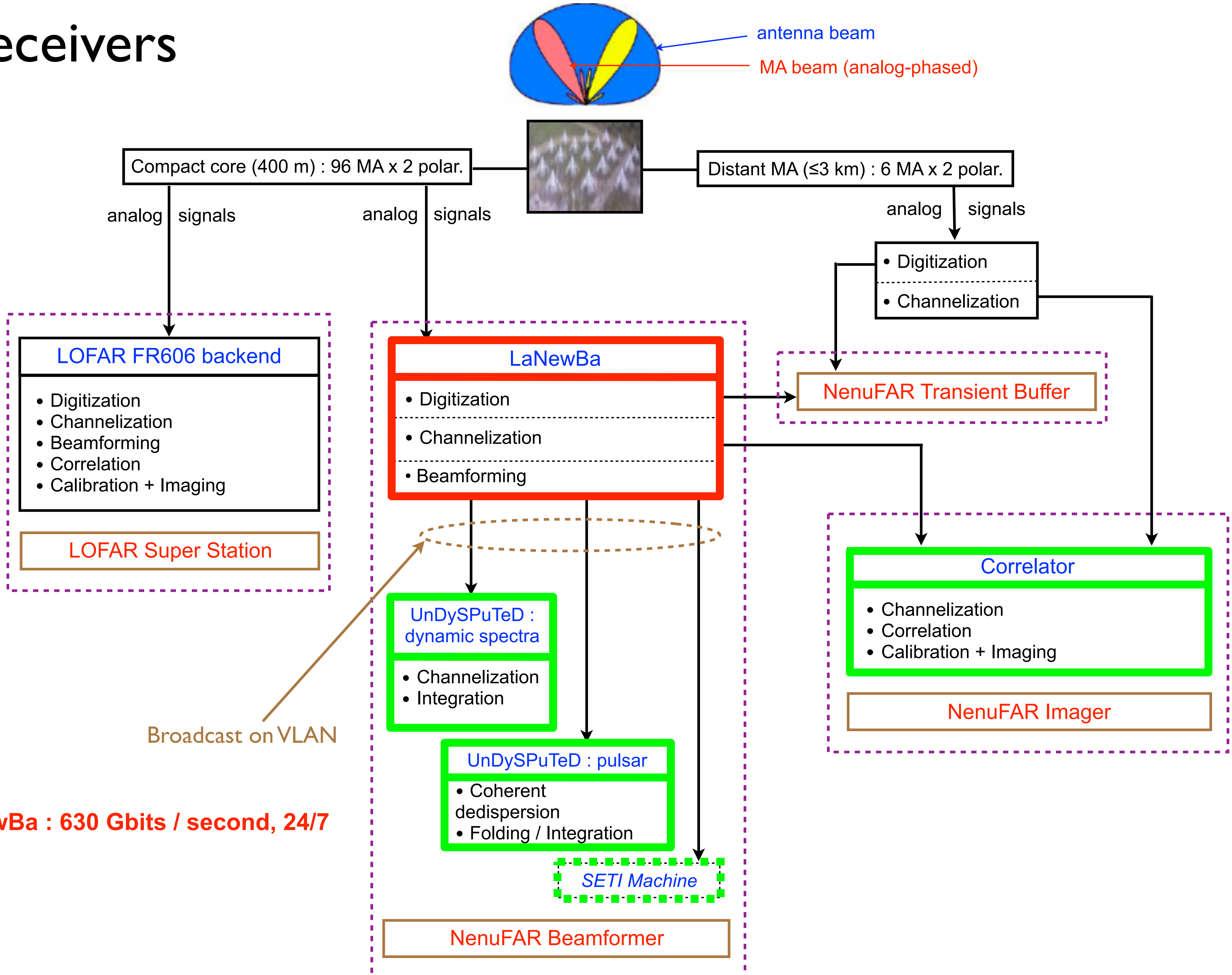
NenuFAR array

https://nenufar.obs-nancay.fr/en/astronomer/

Frequency (MHz)	Wavelength (m)	$A_{e\text{-}dipole}$ (m^2)	$A_{e\text{-}MA}$ (m^2)	$A_{e\text{-}core}$ (m^2)	$A_{e\text{-}all}$ (m^2)
15	20.	133	864	83001	88189
27	11.1	41	568	54612	58025
48	6.2	13	247	23750	25234
85	3.5	4	78	7574	8047

Frequency (MHz)	Wavelength (m)	θ_{MA} (°)	FoV_{MA} (°^{2})	θ_{core} (°)	θ_{all} (’)
15	20.	46	1650	2.9	23
27	11.1	26	509	1.6	13
48	6.2	15	161	0.9	8
85	3.5	8	51	0.5	4

Receivers



LANewBa : 630 Gbits / second, 24/7

Data products (see details on Astronomers page)

- **Beamformer mode :**
  - BST (Beamlet STatisics) data (FITS format): systematically recorded in //, 200 kHz x 1 s resolution, X & Y, include full setup info *(+ SST per Mini-Array)*
  - Pulsar (PSRFITS format → Presto, DSPSR...) : coherently dedispersed at known DM + folded, or filterbank/search mode, full polar
  - DynSpec (proprietary format): down to 0.2 kHz & 1 msec, full polar
  - Waveform (proprietary format): 200 k-complex/s X & Y signals written to disk
  - SETI data

- **Transient Buffer mode :**
  - TBB (Transient Buffer Board) data (proprietary format) :last 5 seconds of 200 MHz waveform per MA (or selected antenna), X & Y, written to disk

- **Imager mode :** (2-hour files max)
  - XST (Cross-Correlation STatistics) data (Fits → MS format *v.0*) : 16 SB / s ~ 3 MHz bandwidth, 1 MS / SB, phased to zenith ; tracking computed at conversion to MS → calibration
  - Visibilities data (LOFAR MS format) : 75 MHz, 384 SB, down to 3 kHz, 0.5-2 s, 1 MS / SB, phased to RA,δ (incl. fringe stopping + delay tracking)
  - LOFAR Super Station mode : Visibilities data (LOFAR MS format) : 48+ MHz, 244+ SB, produced by LOFAR

Summary of NenuFAR characteristics at completion

- **Number of antennas :** 1938 = 96 core + 6 remote MA of 19 antennas each
- **Dimensions :** MA diameter = 25 m, core diameter ~400 m, remote MA up to ~3 km
- **Number of baselines :** 5151

  = 4560 baselines from 25 m to 400 m + 591 baselines from 400 m to 3 km
- **Frequency range :** 10-85 MHz (λ = 3.5 – 30 m)
- **Time-Frequency resolutions :** δf = 195.3125 kHz x δt = 5.12 µs

  Channelization down to 0.2 kHz x time integration down to 1 ms

  Waveform at 5 ns time resolution
- **Full polarization** (4 Stokes)
- **Collecting area :** from ~220 λ^2 to ~ 650 λ^2 (function of effective area overlap within MA)

  from ~83000 m^2 at 15 MHz to ~7500 m^2 at 85 MHz for the core

  from ~88000 m^2 at 15 MHz to ~8000 m^2 at 85 MHz for core+remote MA
- **Pointing :** from declination δ = -23° to δ = +90°
- **Field of View :** ~46° (1650°^{2}) at 15 MHz to ~8° (51°^{2}) at 85 MHz
- **Angular Resolution :** from 2.9° at 15 MHz to 0.5° at 85 MHz for the core

  from 23' at 15 MHz to 4' at 85 MHz for the core+remote MA (down to 0.4″ in LSS mode)
- **Sensitivity** (thermal noise) :

  from ~130 mJy at 15 MHz to ~9 mJy at 85 MHz with Δf=10 MHz x Δt=1 h

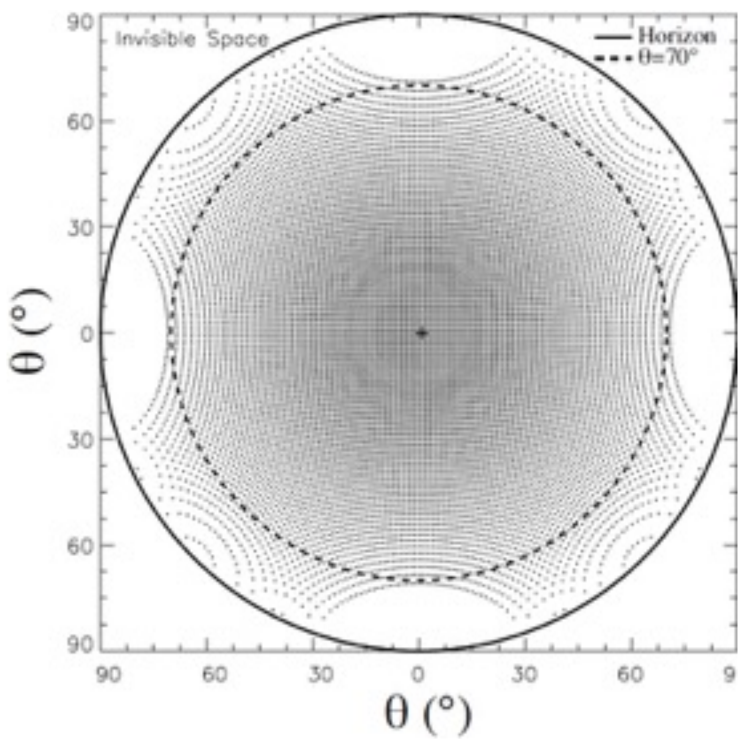
  (similar values for the core & core+remote MA)
- **Confusion at zenith :**

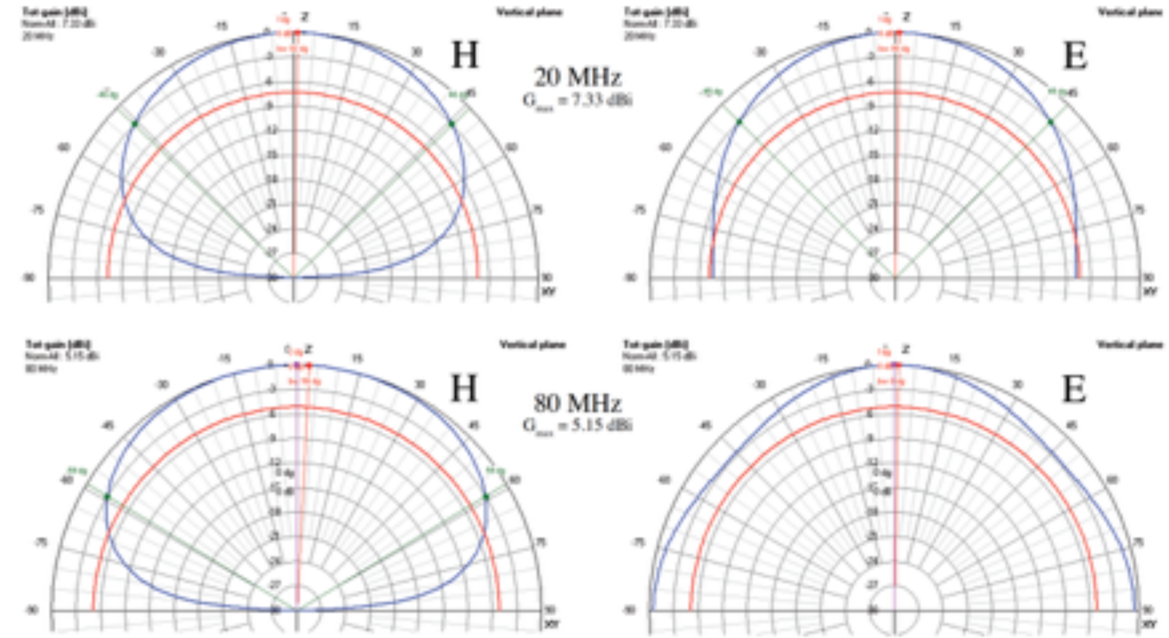
  from ~120 Jy at 15 MHz to ~2 Jy at 85 MHz for the core

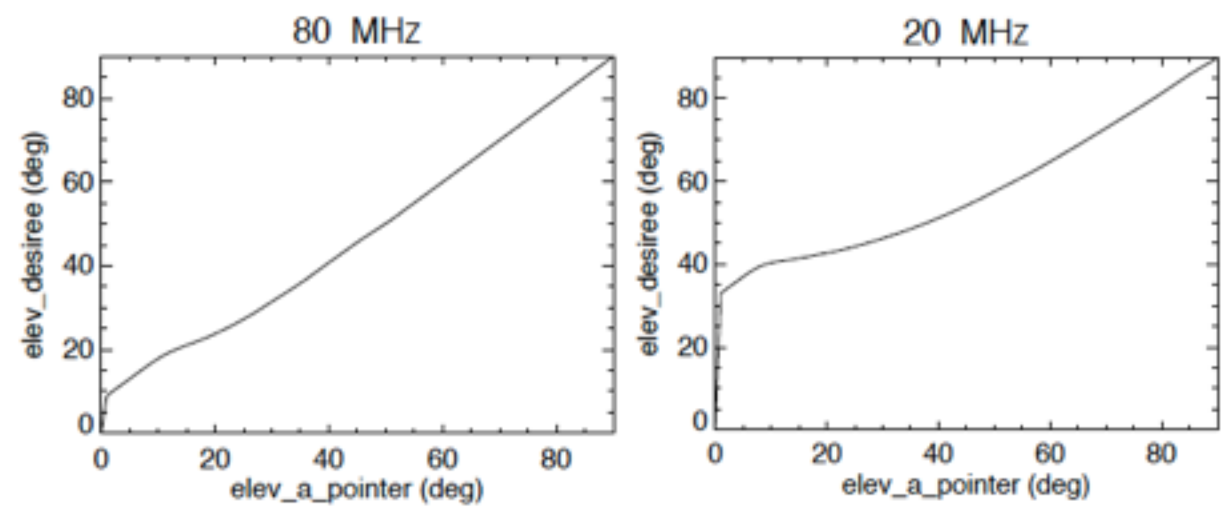
  from ~5 Jy at 15 MHz to ~100 mJy at 85 MHz for the core+remote MA

Pointing

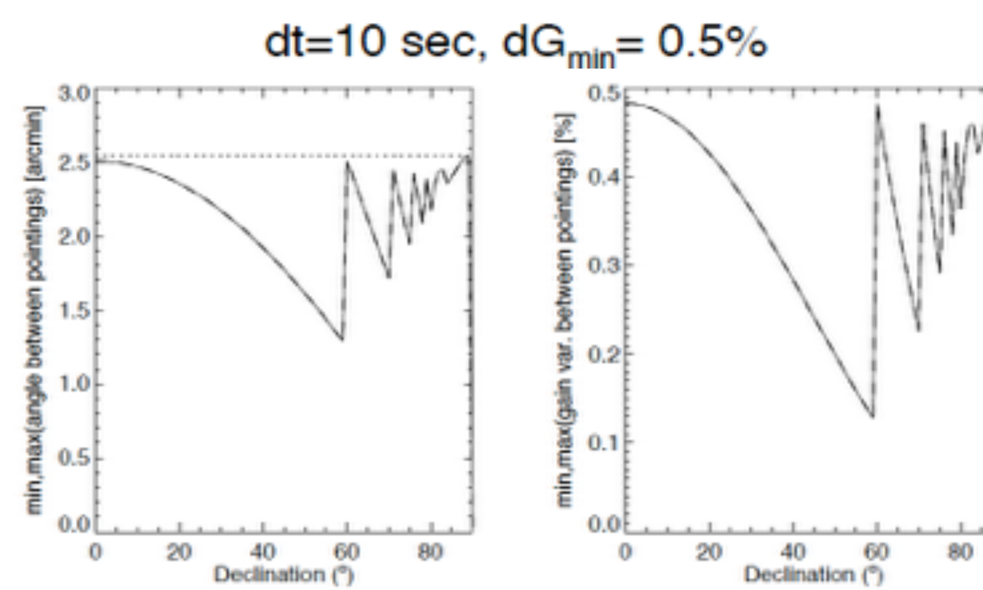
- **Analog** pointing of Mini-Arrays :
  - 128 x 128 pointable positions > 20° elevation
  - from declination δ = -23° to δ = +90°
  - beam squint (elevation >20° !)
  - silent pointing system, 10 sec-6 min. scheme





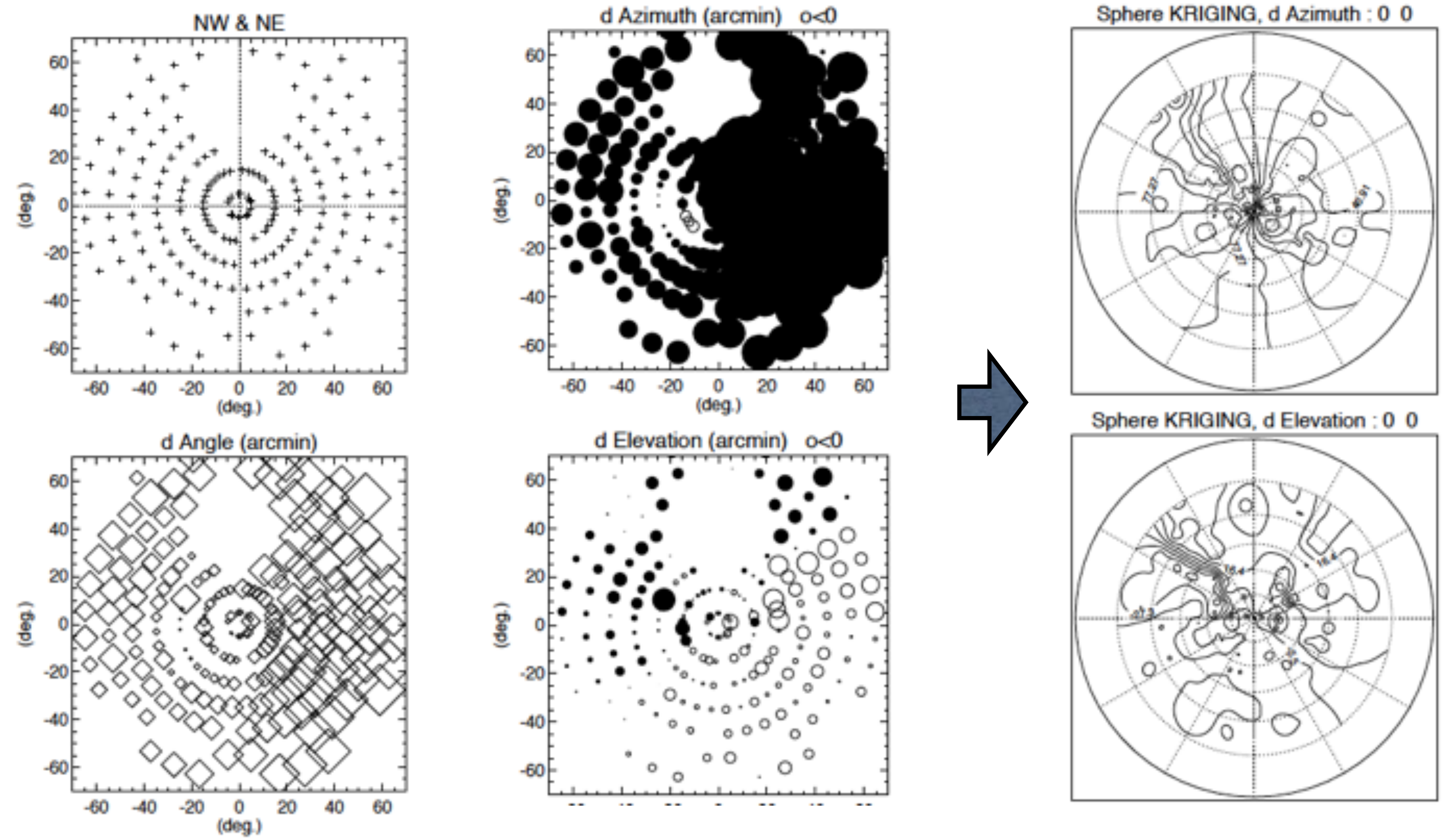


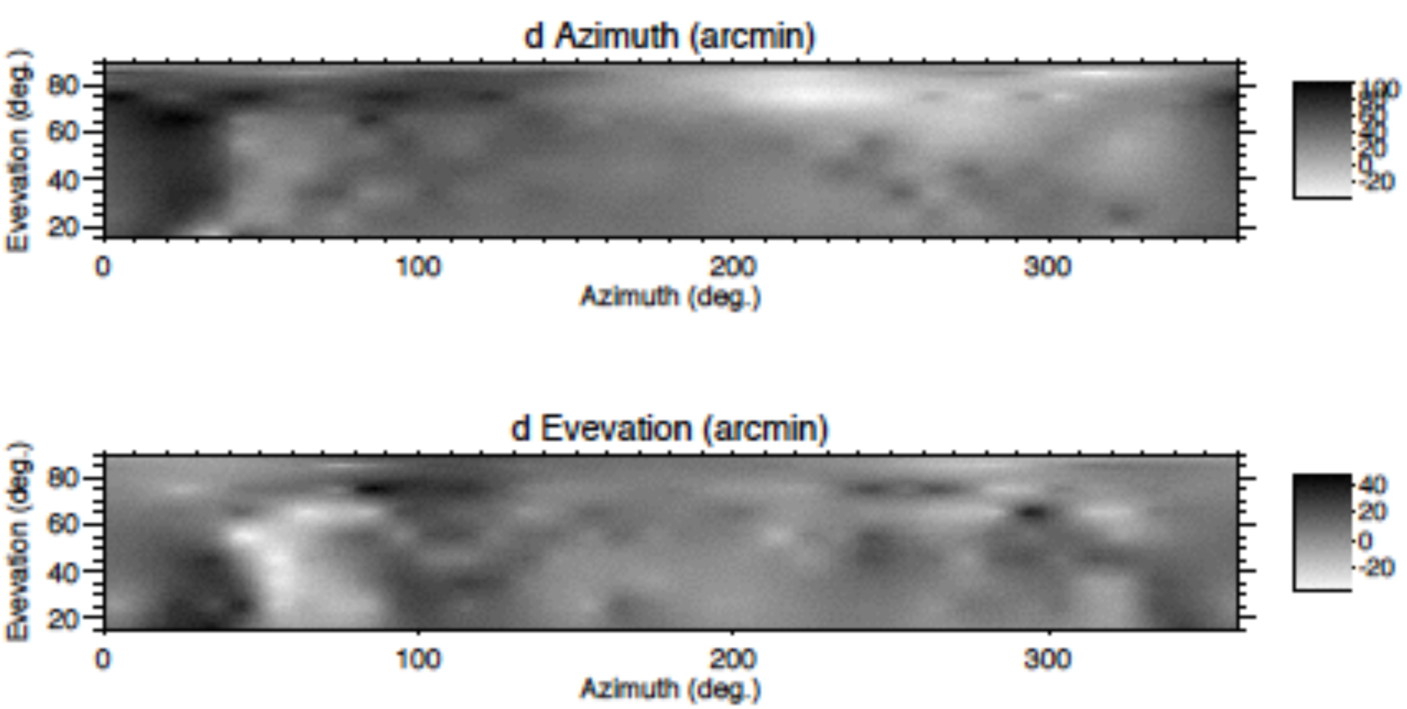
- **Digital** pointing of NenuFAR :
  - real, computed : tracking (RA,δ), fixed pointing or table (az,el)
    IMCCE Web-service for Solar system bodies
  - 10 sec scheme (±5 sec) → <0.5% gain variations
  - effective pointing accuracy ~5' (1 σ)

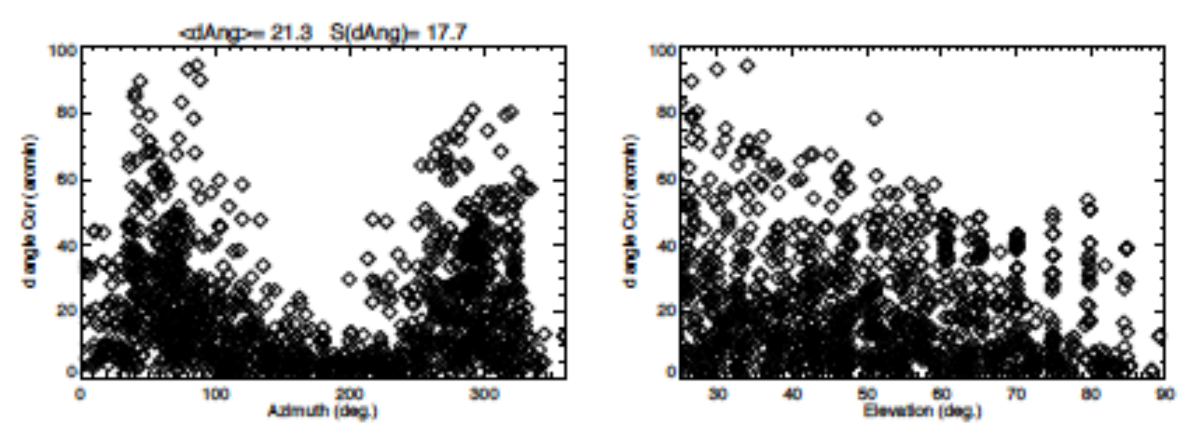


Pointing

- Pointing **errors**
  ~30'   ~LWA
  → ~10' after 1st correction
  → to be improved

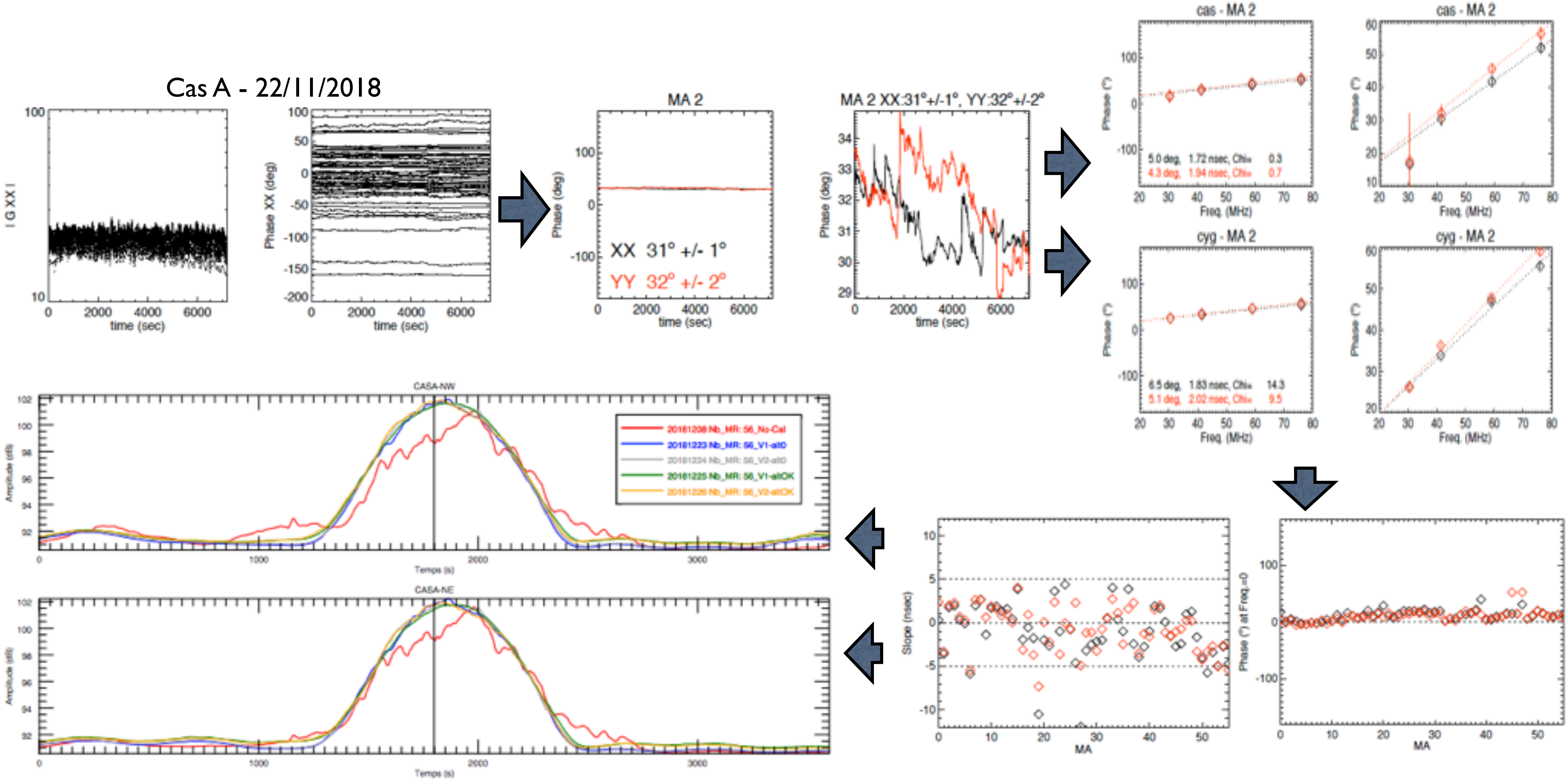






Calibration

- **Phase calibration** of beamformer mode **done**
  - XST (rephased) tracking A-team sources, NDPPP with 1 source sky model → complex gains of each MA, X & Y → delays → calibration table in LANewBa



- **Phase calibration** of imaging mode **through LOFAR pipeline**

Calibration

- **Flux calibration** of beamformer mode
  - from A-team sources + Galaxy (LFmap, GSM)

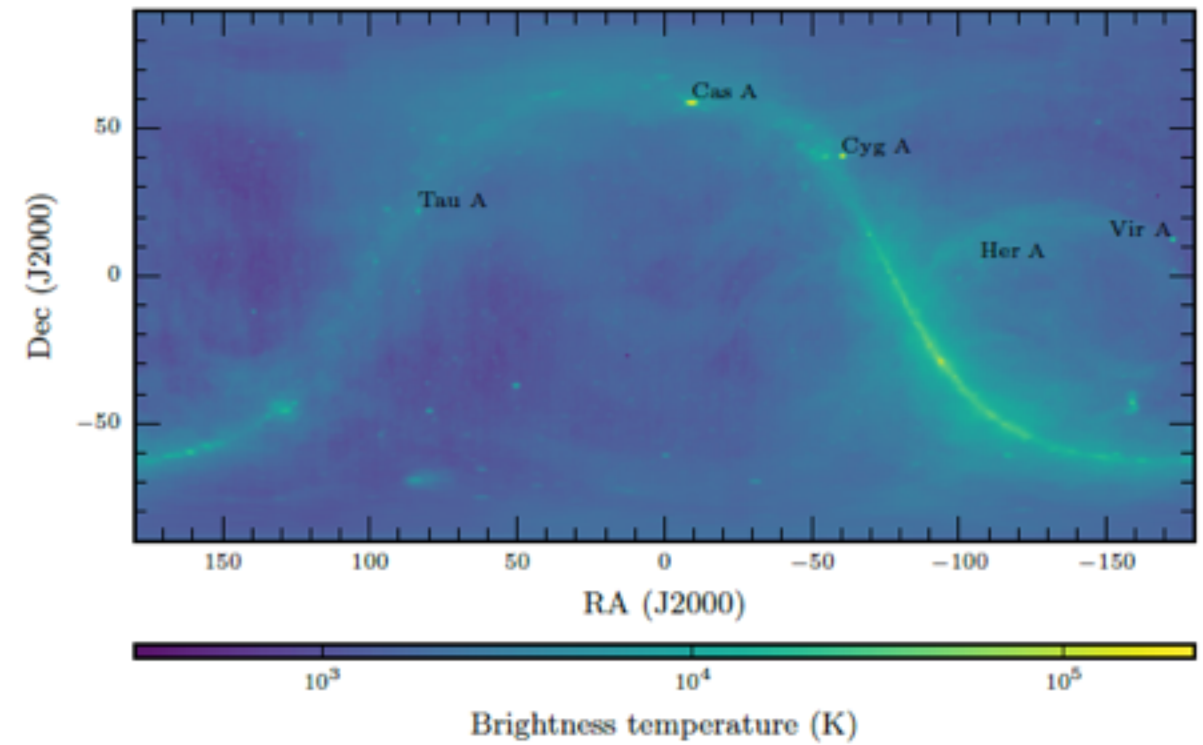
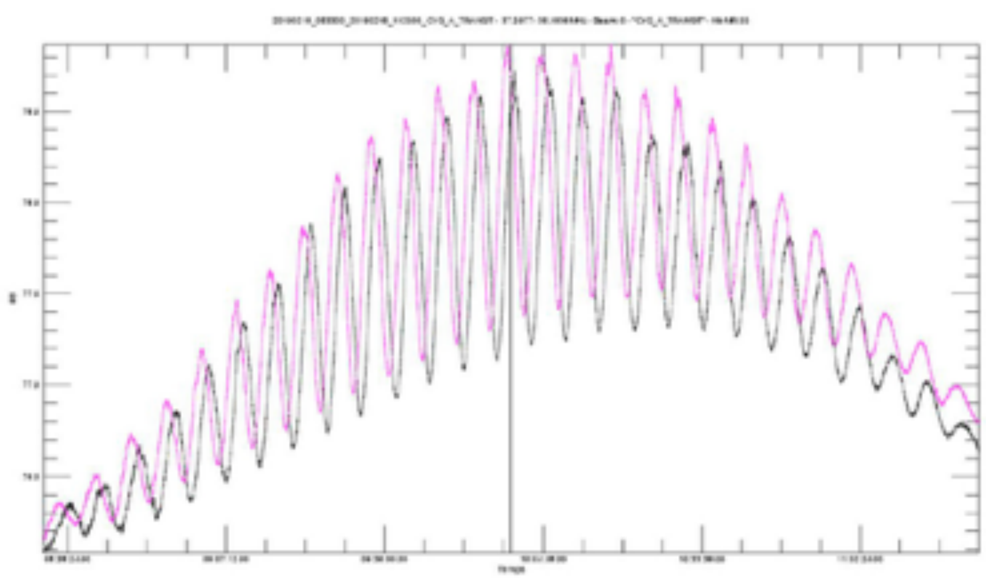
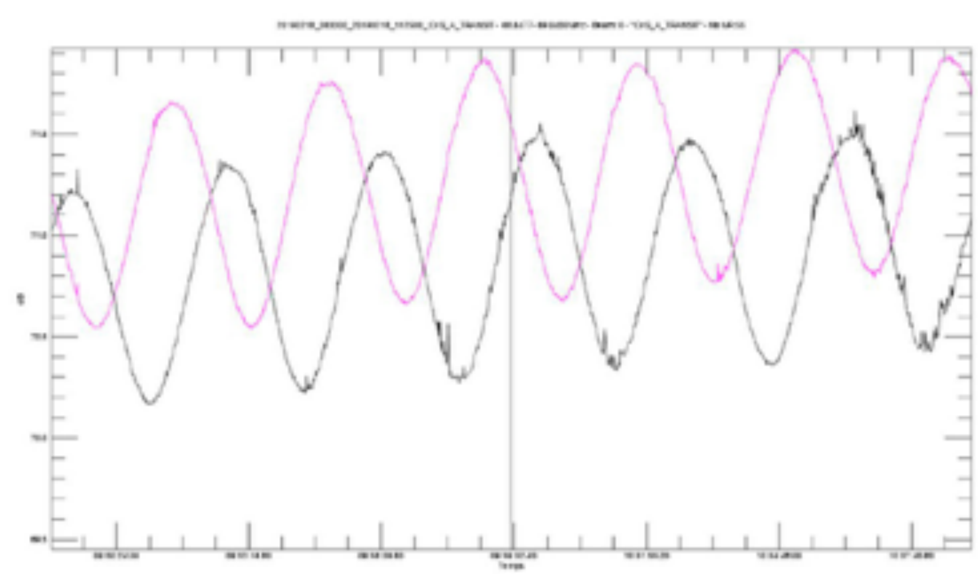


Figure 1: GSM low-frequency sky model at 72 MHz.

- **Polarization calibration** of beamformer mode
  - from XST using NDPPP in full polarization (full Jones matrix)





- **Flux / polar. calibration** of imaging mode **through LOFAR pipeline**

Simulations

- Instrument (MA or NenuFAR) + GSM, necessary for proper use/interpretation of BF mode

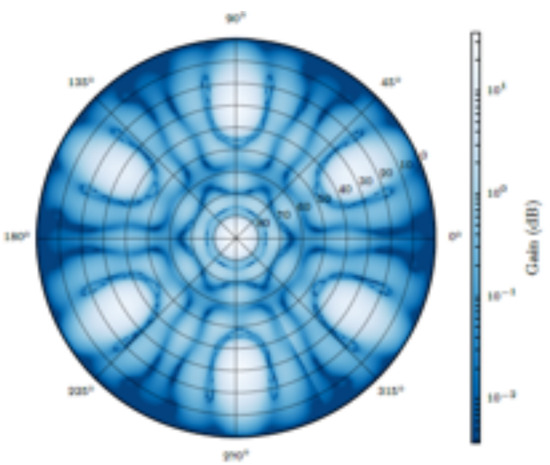


Figure 3: Gain pattern of the Mini-Array 0 (with the 88° offset angle). North is at 0°, East at 90° in azimuth.

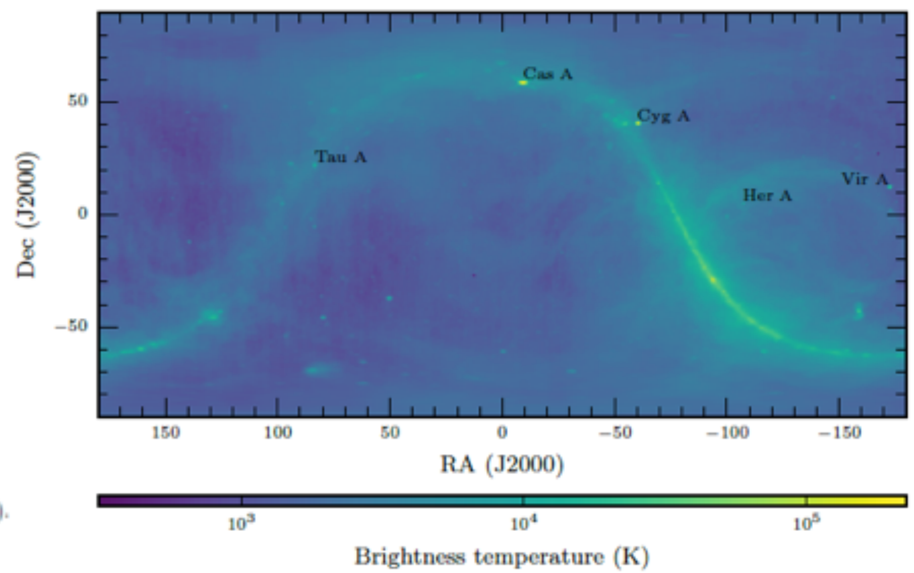
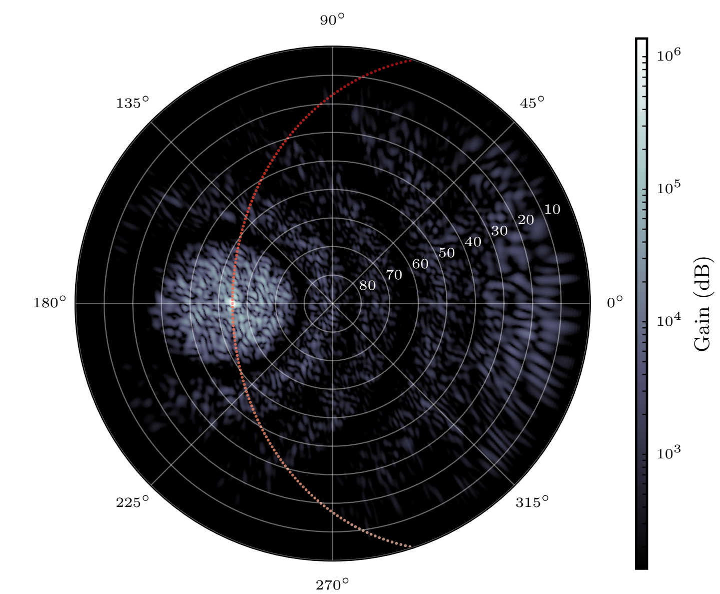


Figure 1: GSM low-frequency sky model at 72 MHz.



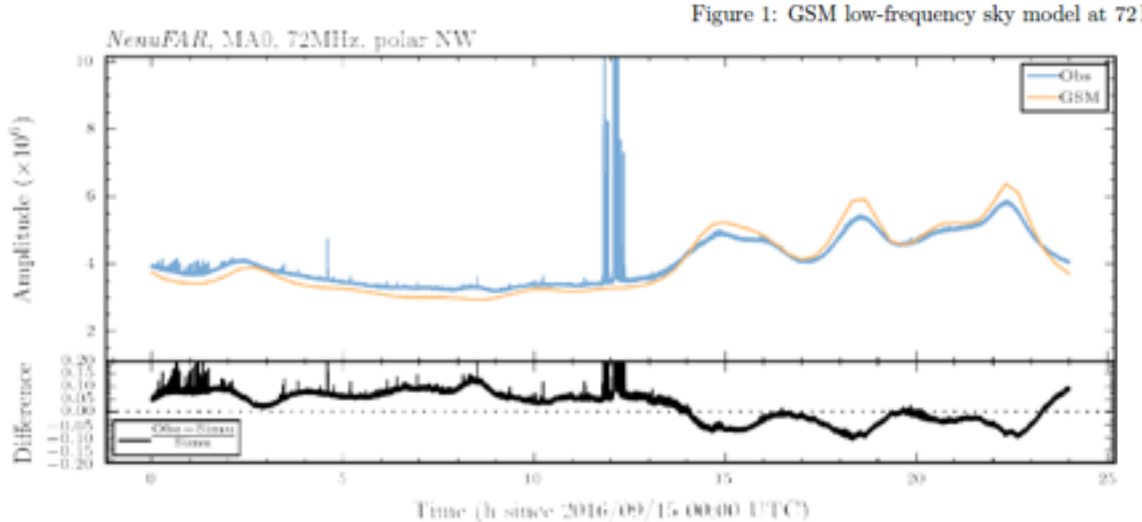
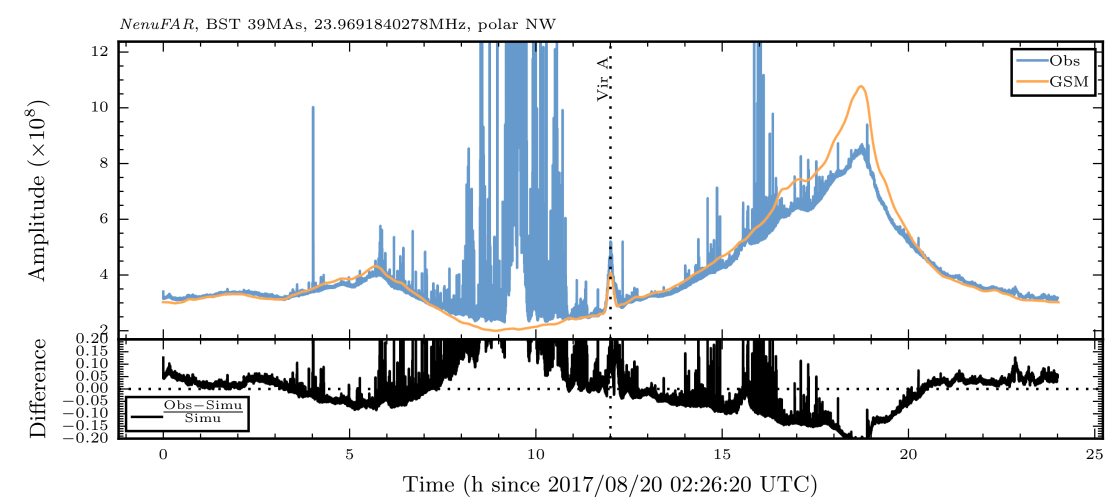
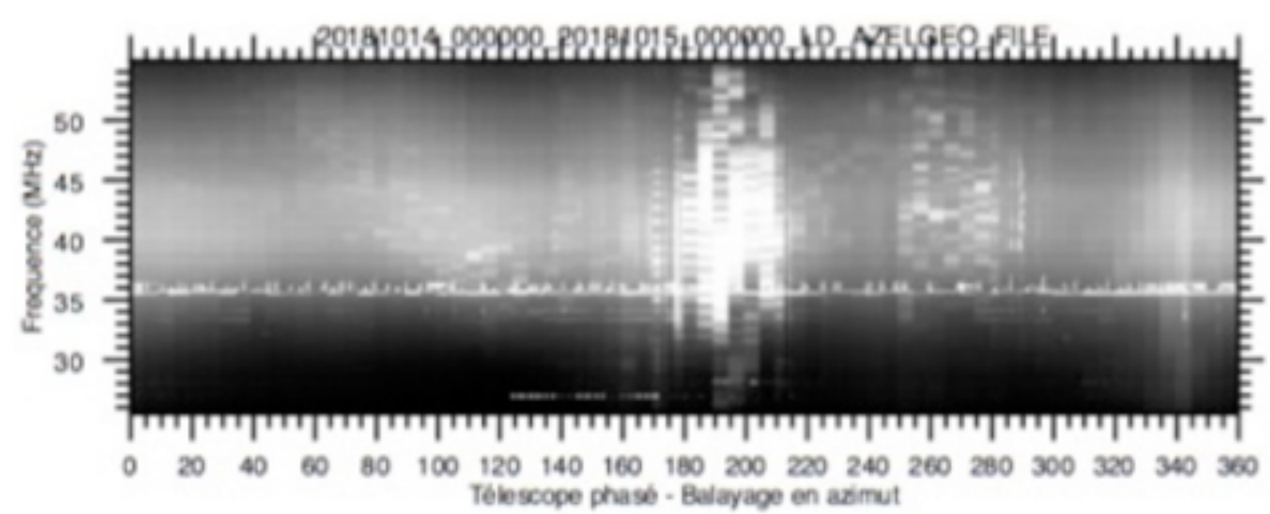


Figure 4: Time profile at 72 MHz of the Mini-Array 0 during the zenith observation on 2016 October 15 and simulation using a 88° offset angle.

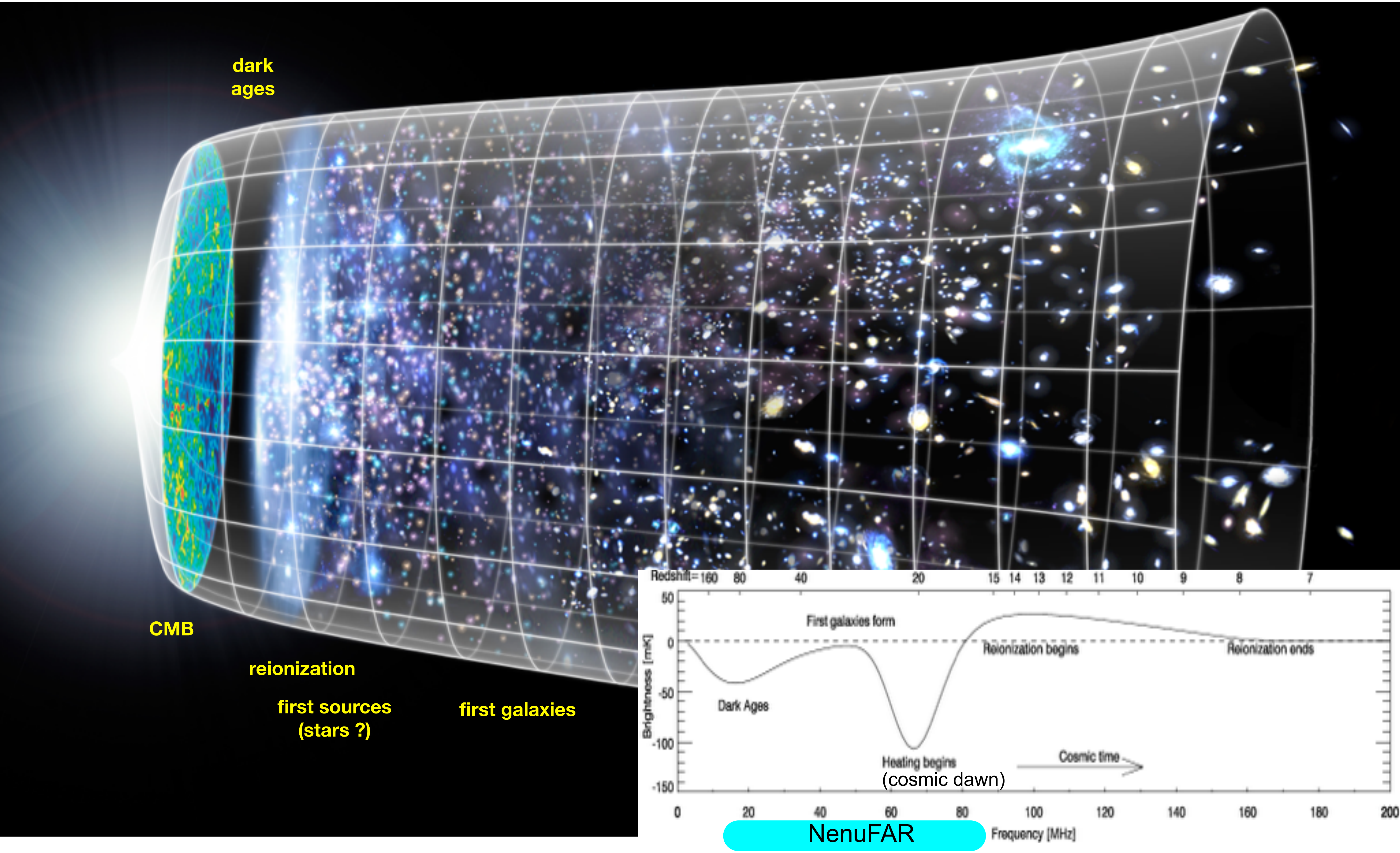


- RFI localization
  - rotating phased beam 0°-360° by 5° steps, elev. = 20°



The Science

- Cosmic Dawn signal (fluctuations spectrum)



The Science

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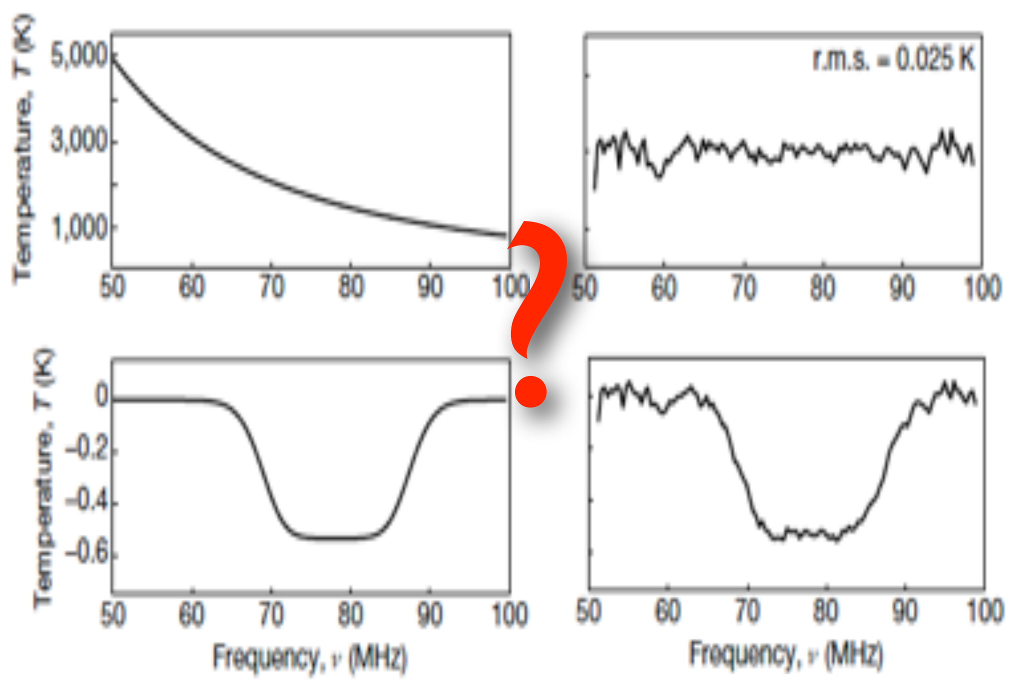
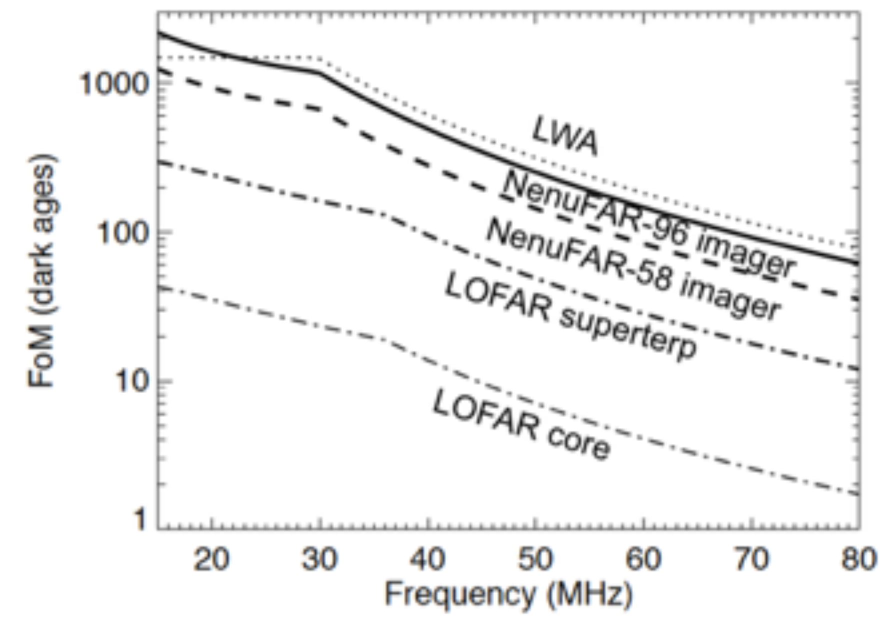
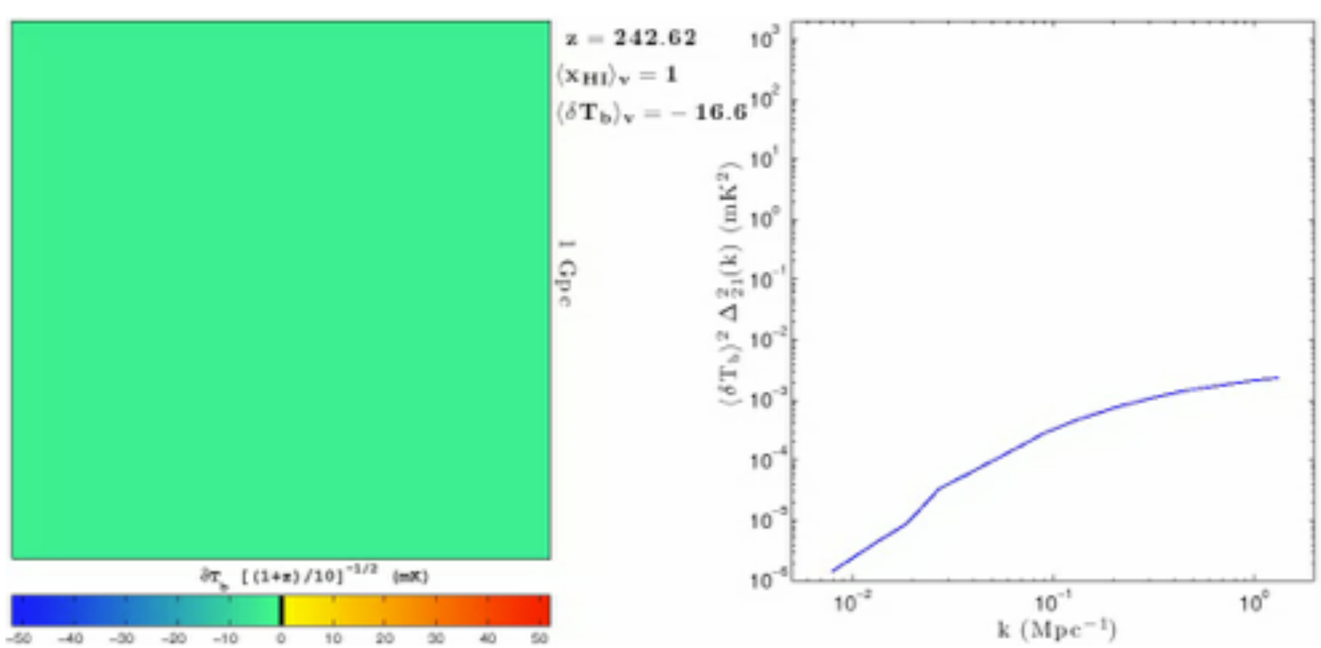
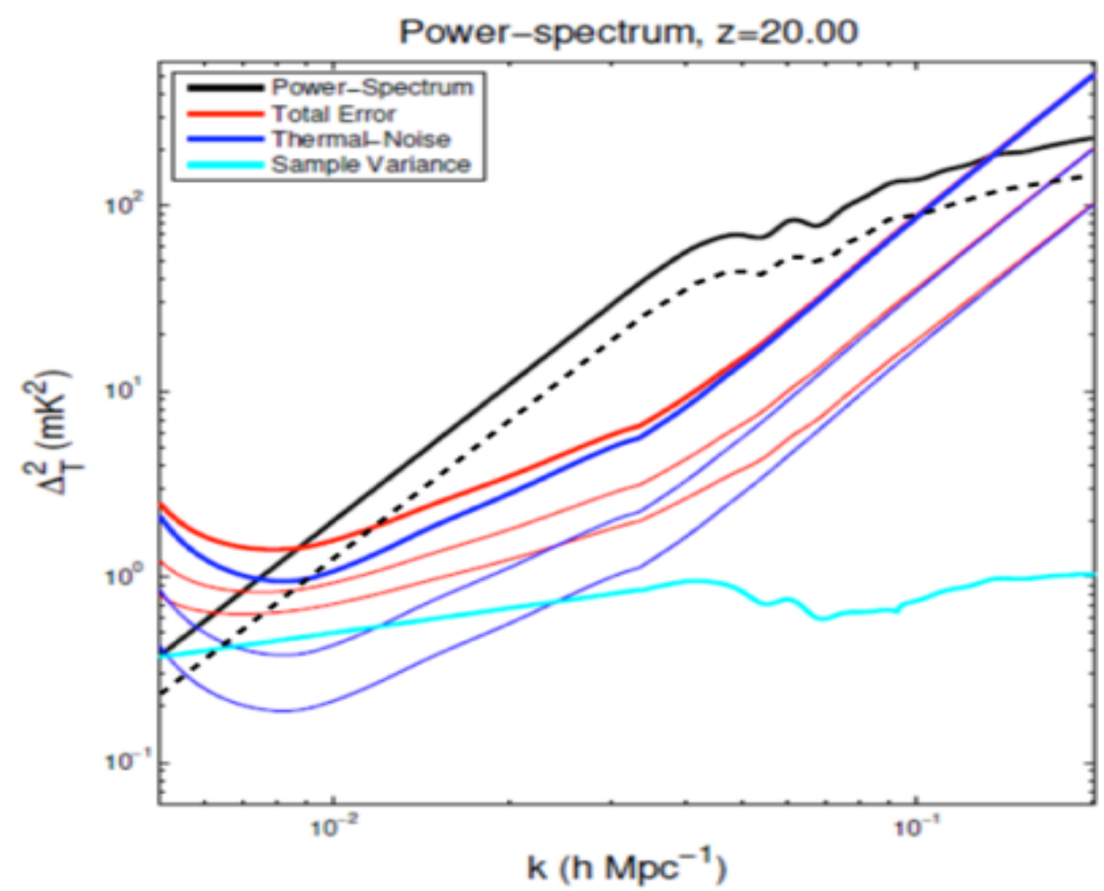


[Bowman et al. , Nature 2018]



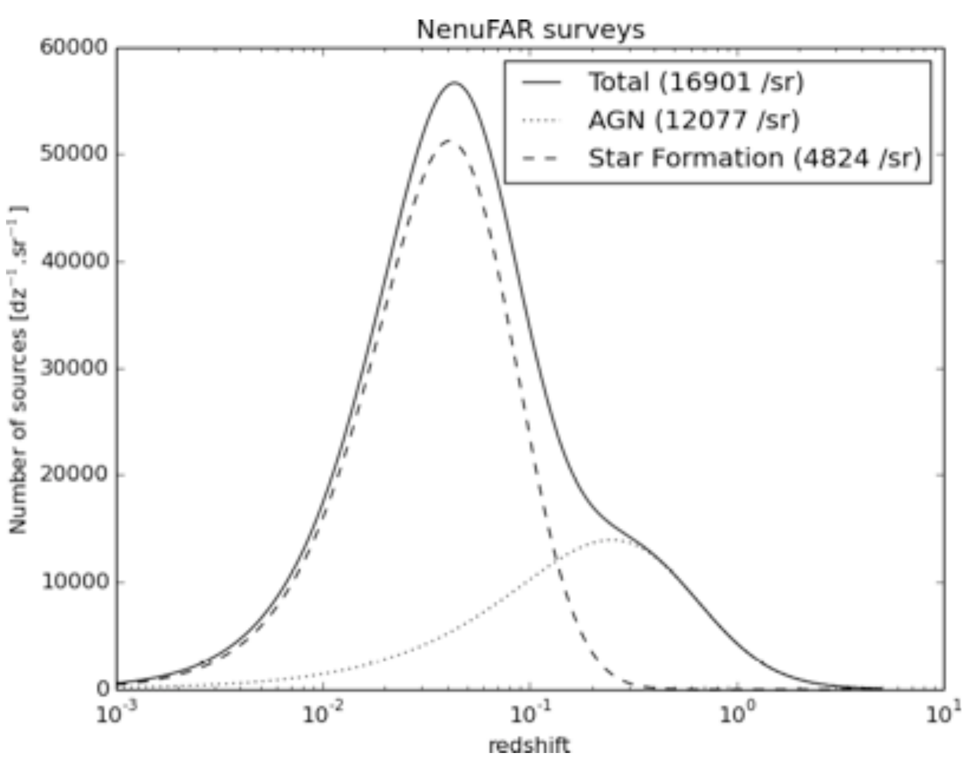




[Koopmans et al. 2015 ; Semelin et al., 2015]

The Science

- Galaxies & halos



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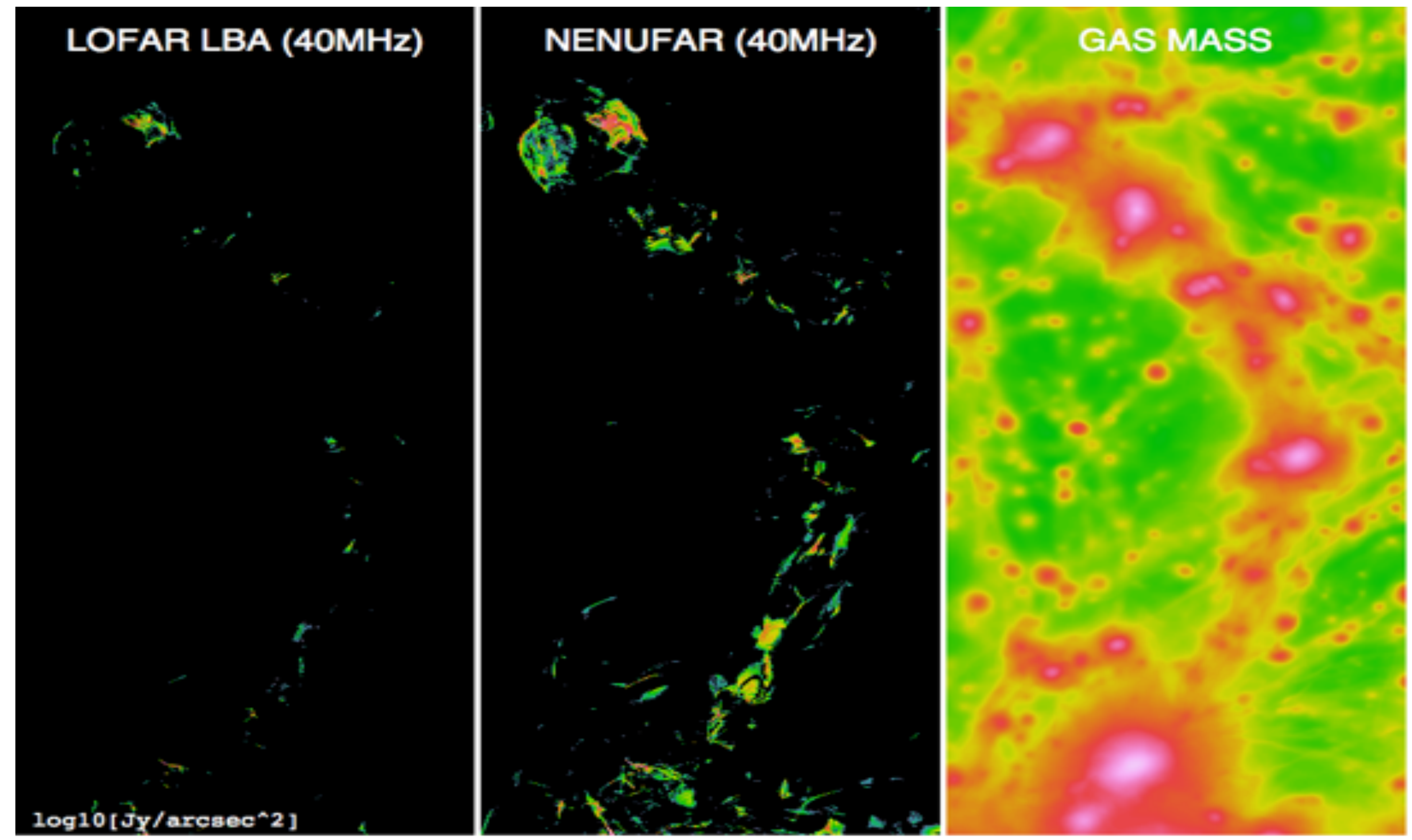

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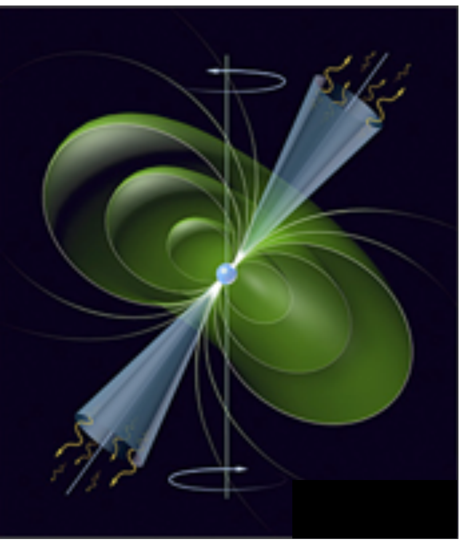
→ *NenuFAR / LSS* : very high resolution Low-Frequency imaging :

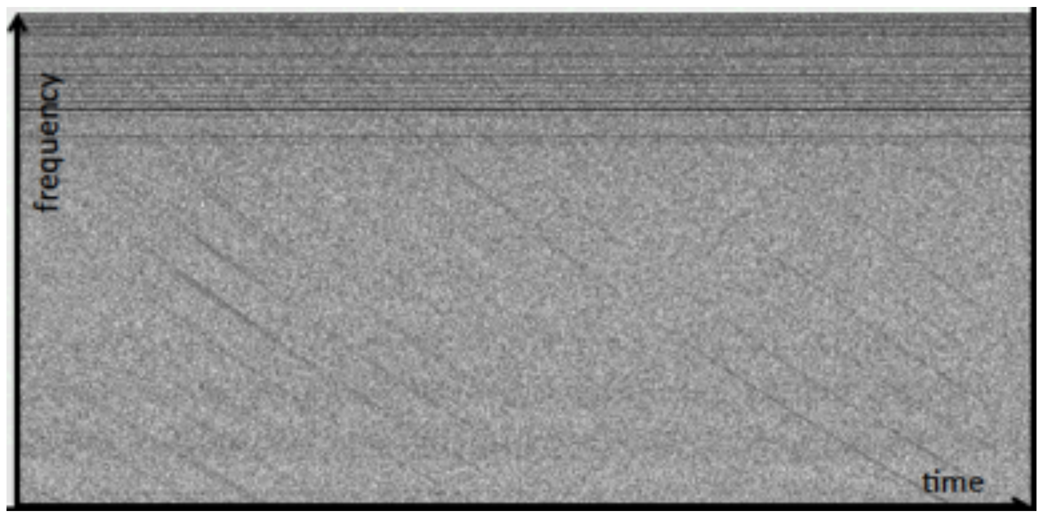
BH, AGN, star formation, clusters, haloes, relics, IGM, ISM, B fields

→ *Standalone Imaging* : short baselines, diffuse emission

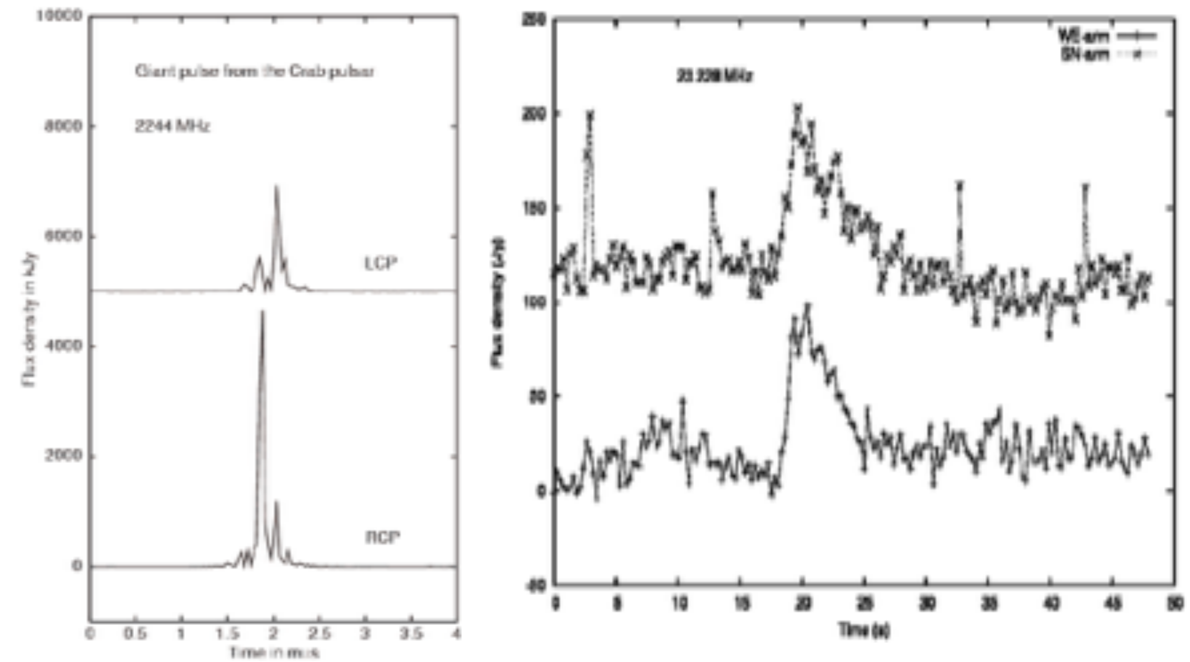
The Science

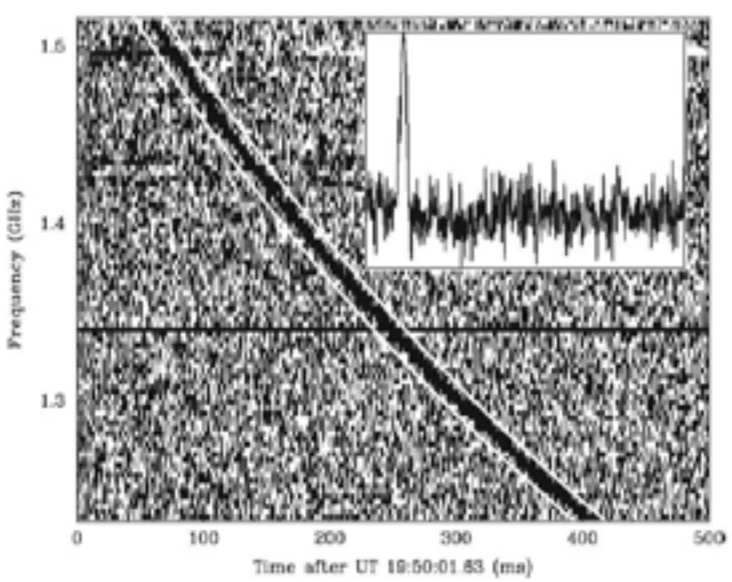
- Pulsars, RRATs, Giant pulses, FRB



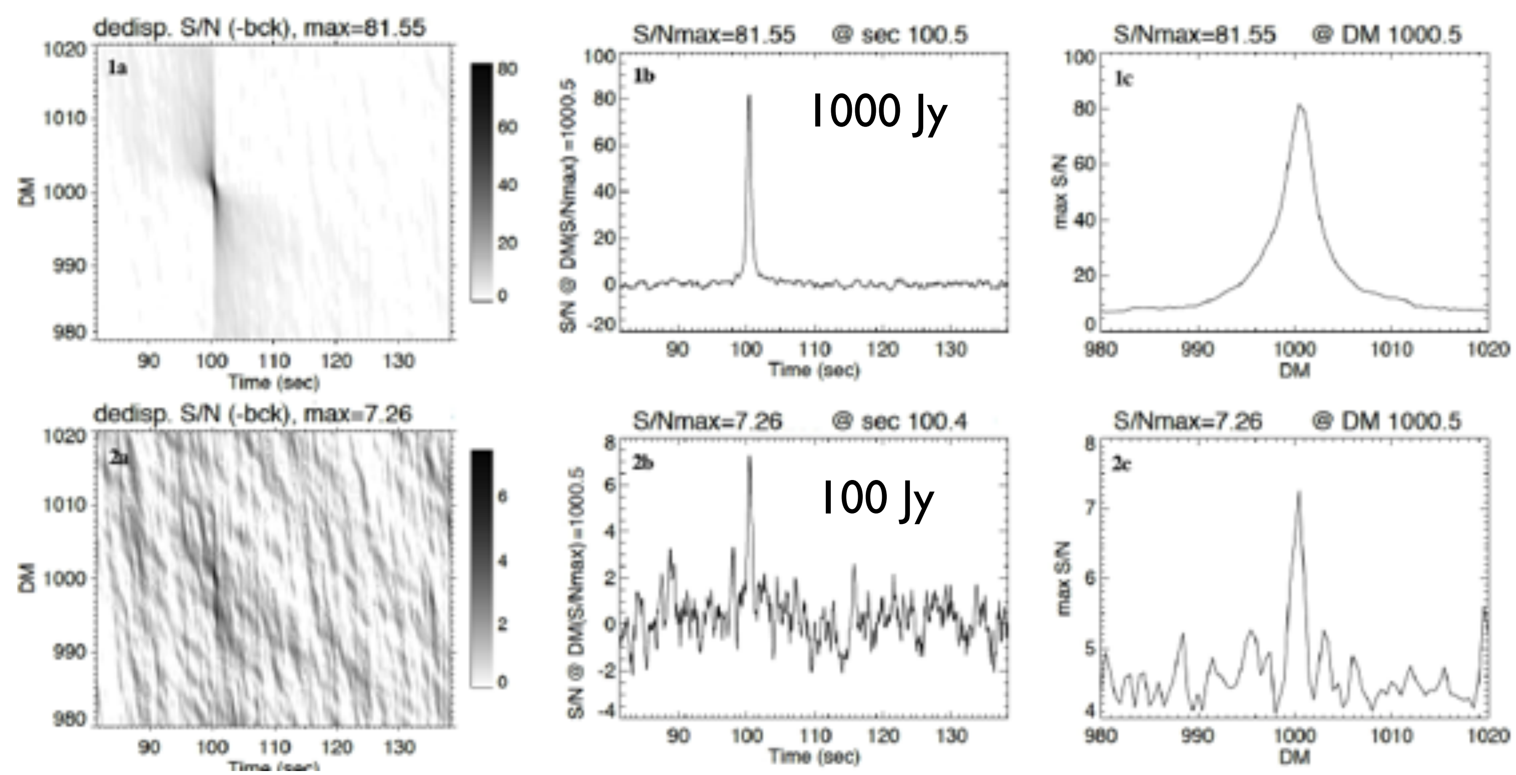


Crab giant pulses [Popov et al.]





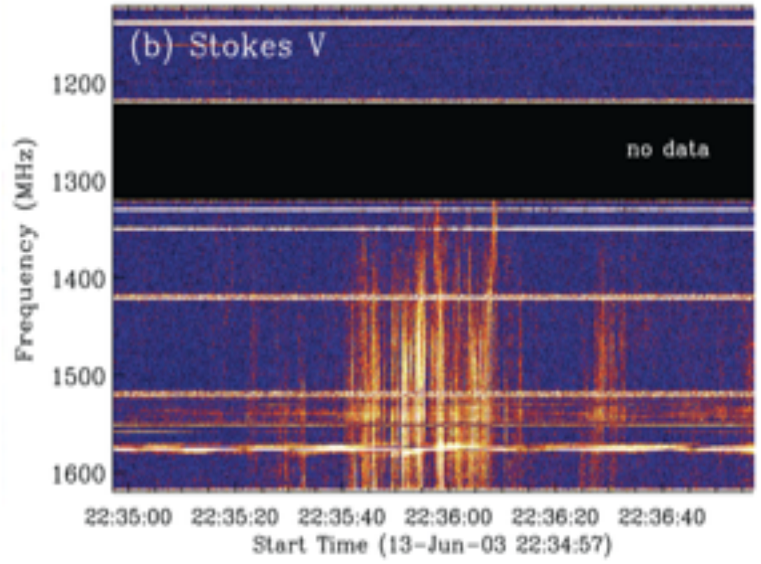
FRB discovery
[Lorimer et al., 2007]

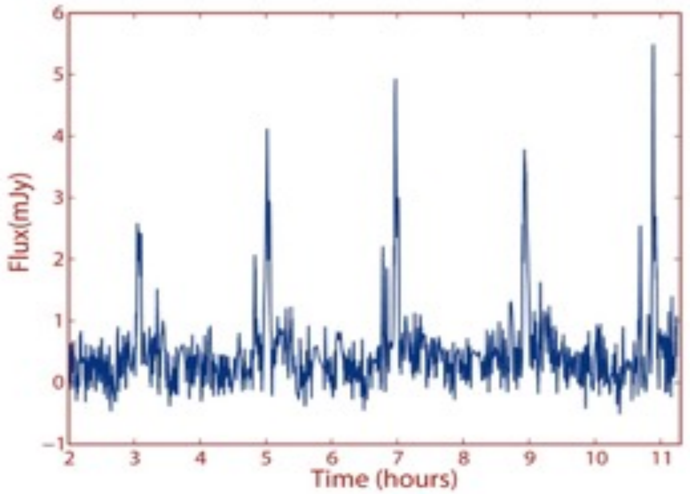


FRB LF simulations [Zarka & Mottez, 2016]

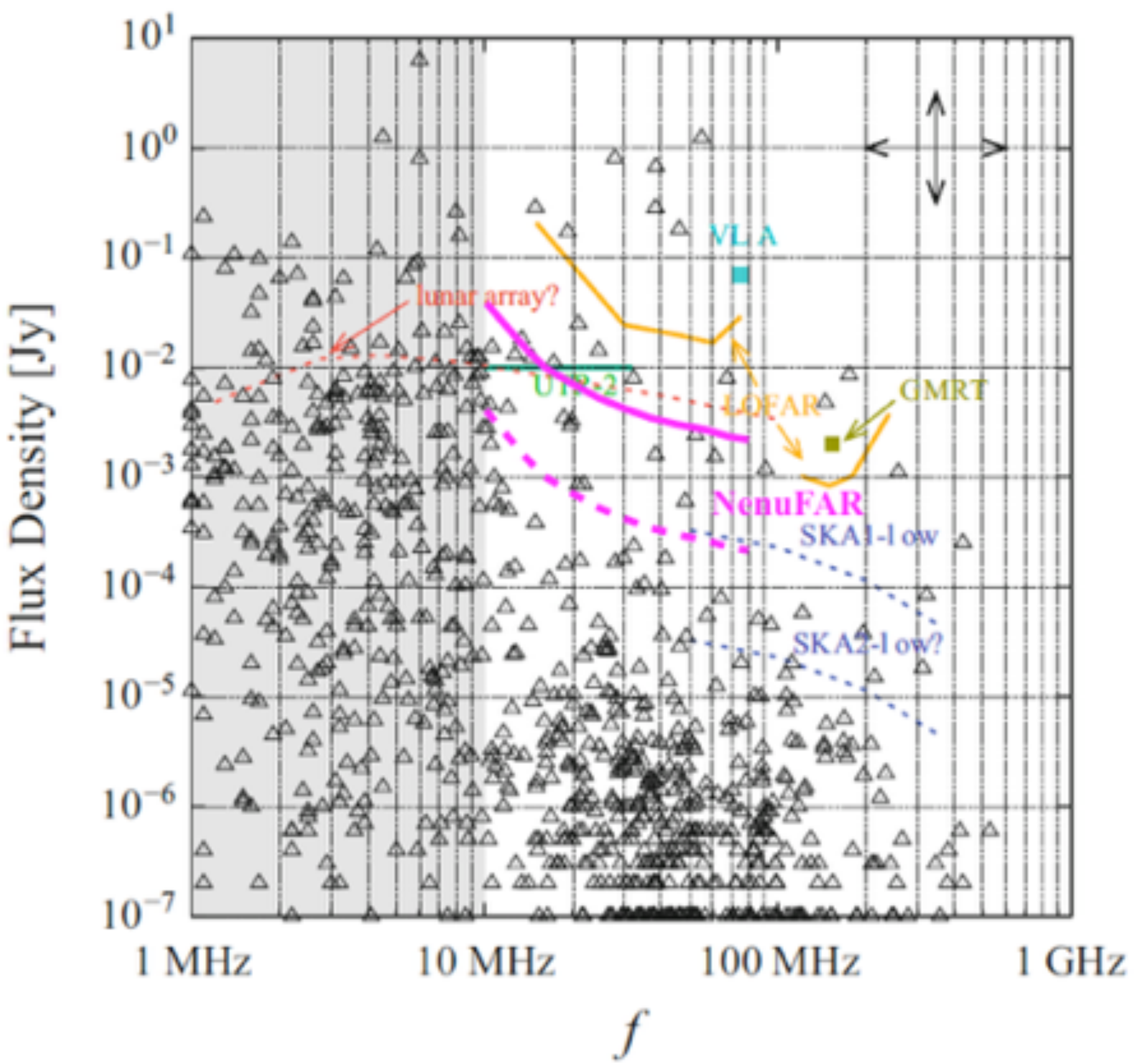
The Science

- Stars, exoplanets, interactions :
  (comparative exo-magnetospheric physics & stellar activity)





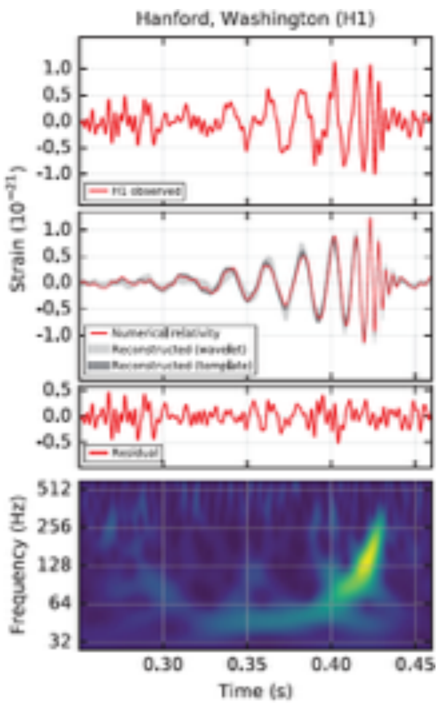
[Osten et al., 2006, 2008 ; Hallinan et al., 2007, 2008, 2015]

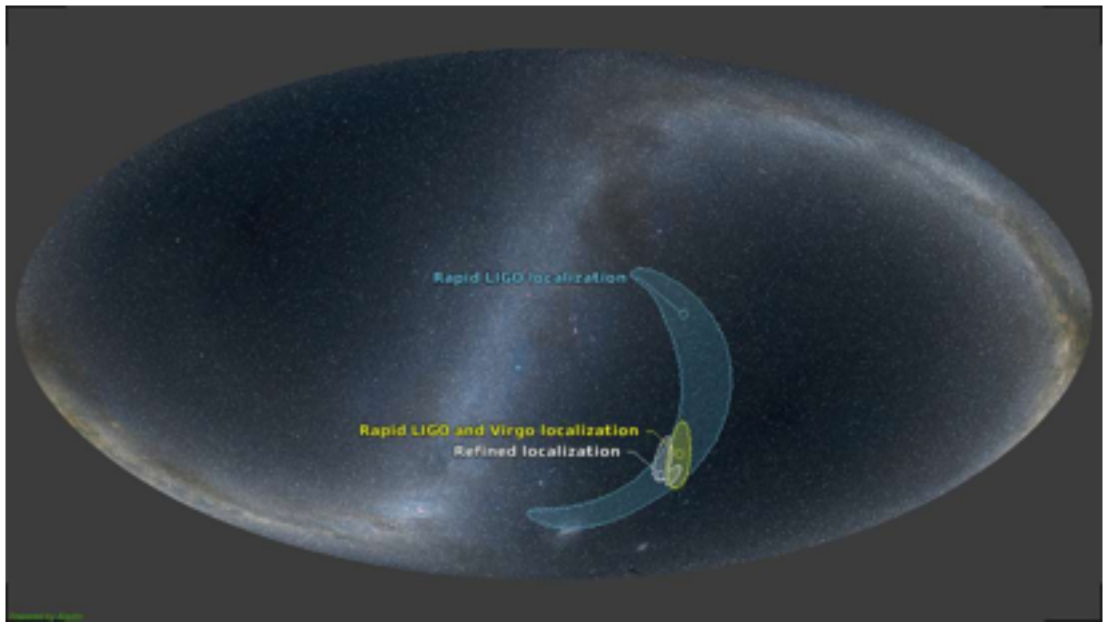


[Zarka et al., 2007, 2015; Grießmeier et al., 2007, 2011; Turner et al., 2017]

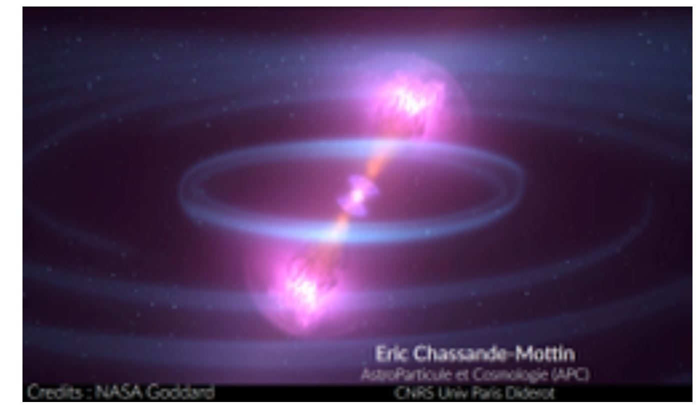
The Science

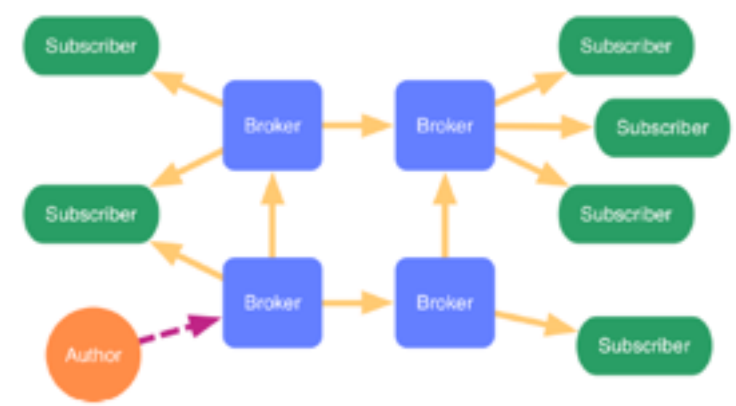
- Prompt GW emission ? GW/GRB afterglows ?



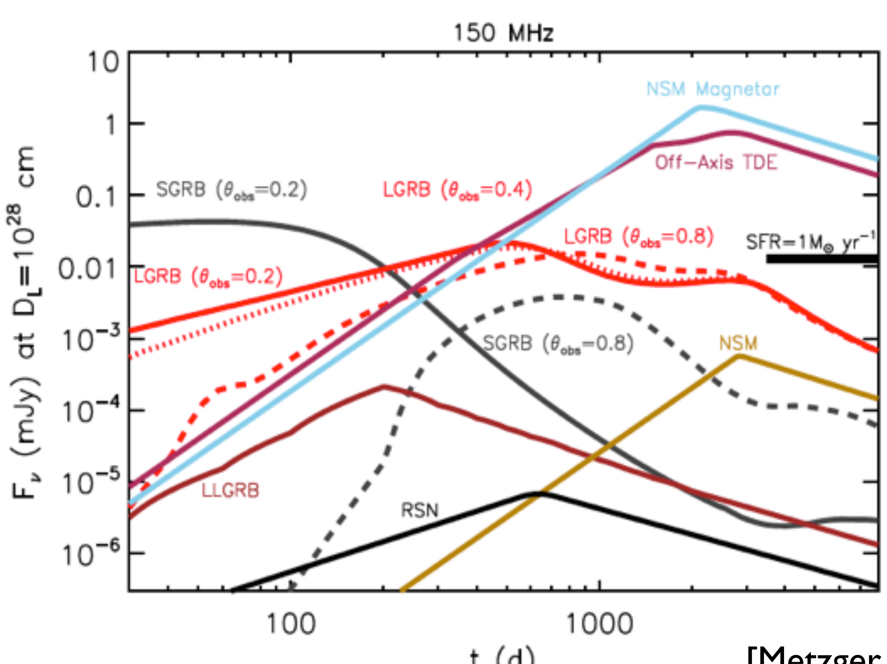


[LIGO-VIRGO coll., 2016, 2017]

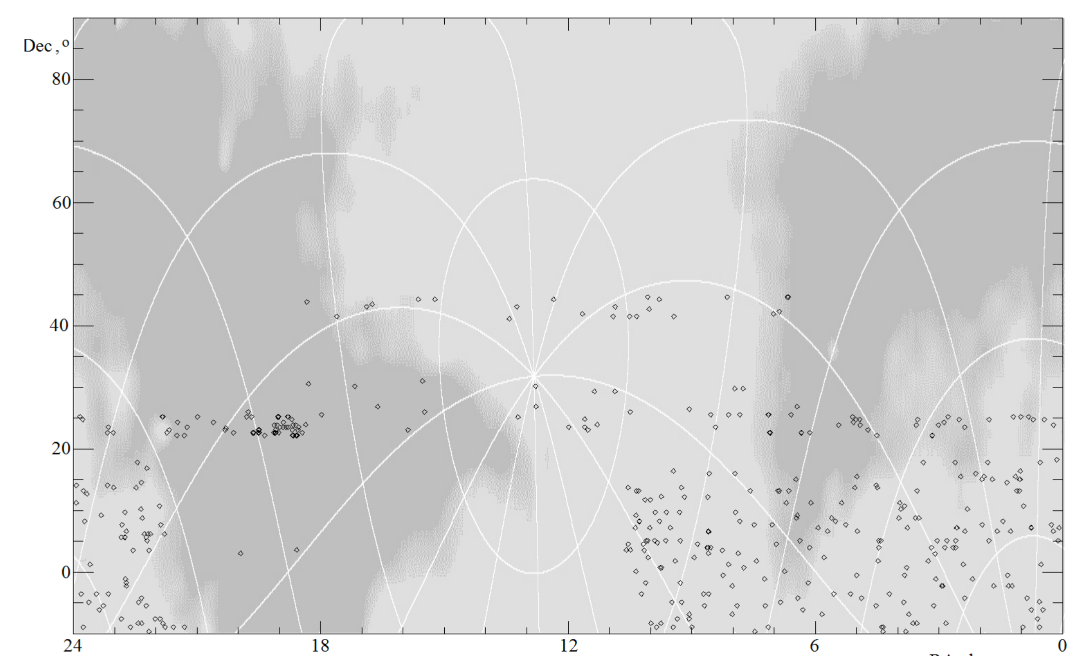




- Slow / Fast transients



[Metzger et al., 2015]

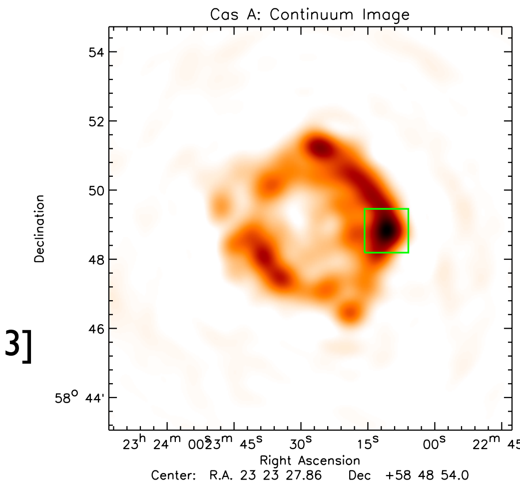


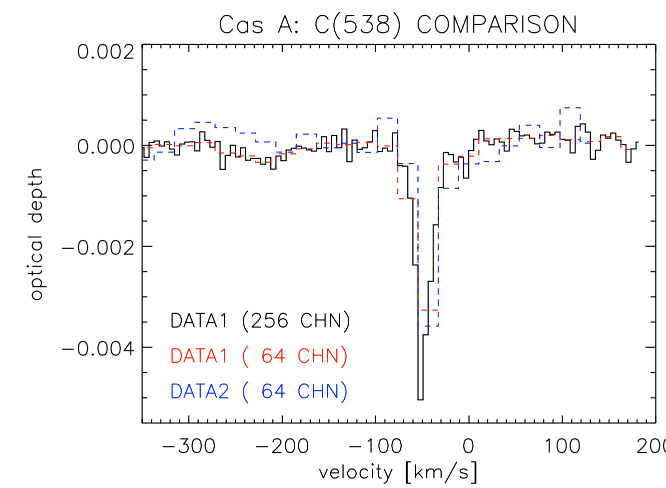
Part of UTR-2 transients survey ≤30 MHz
[Zakharenko, Vasylieva et al., 2015]

The Science

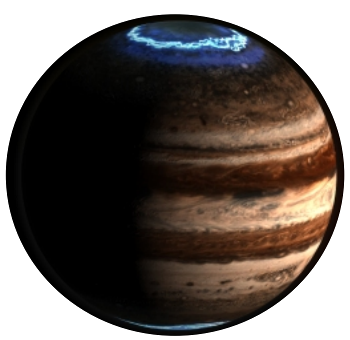
- Radio Recombination Lines, Grains ?

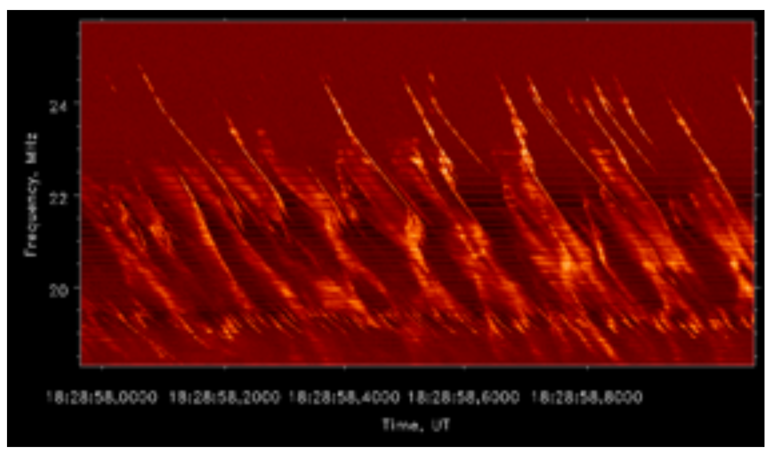
[Asgekar et al., 2013]



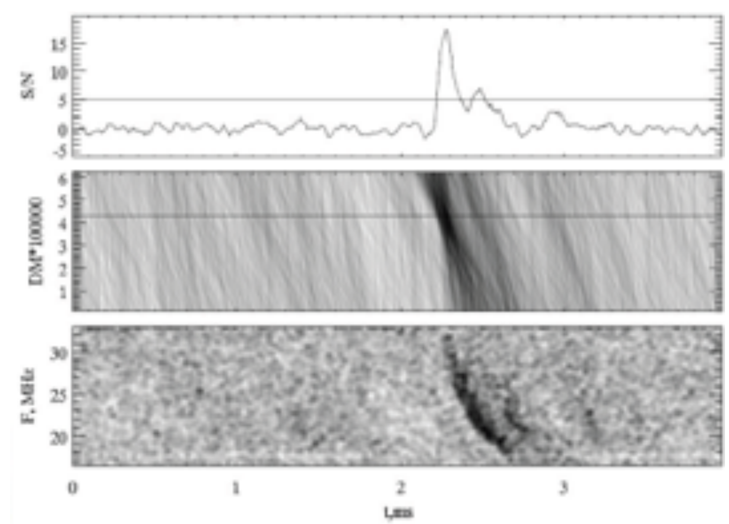


- Heliosphere: Solar bursts, Jupiter, Planetary lightning





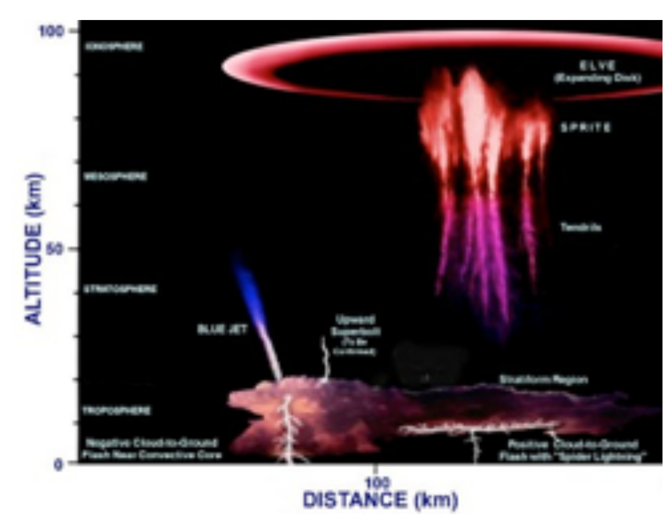
[Ryabov et al., 2014]



Saturn lightning: finest dispersion delay measured: DM ~ 3×10^{-5} pc.cm^{-3}

→ Solar Wind probing up to 10 AU [Zakharenko,et al., 2012]

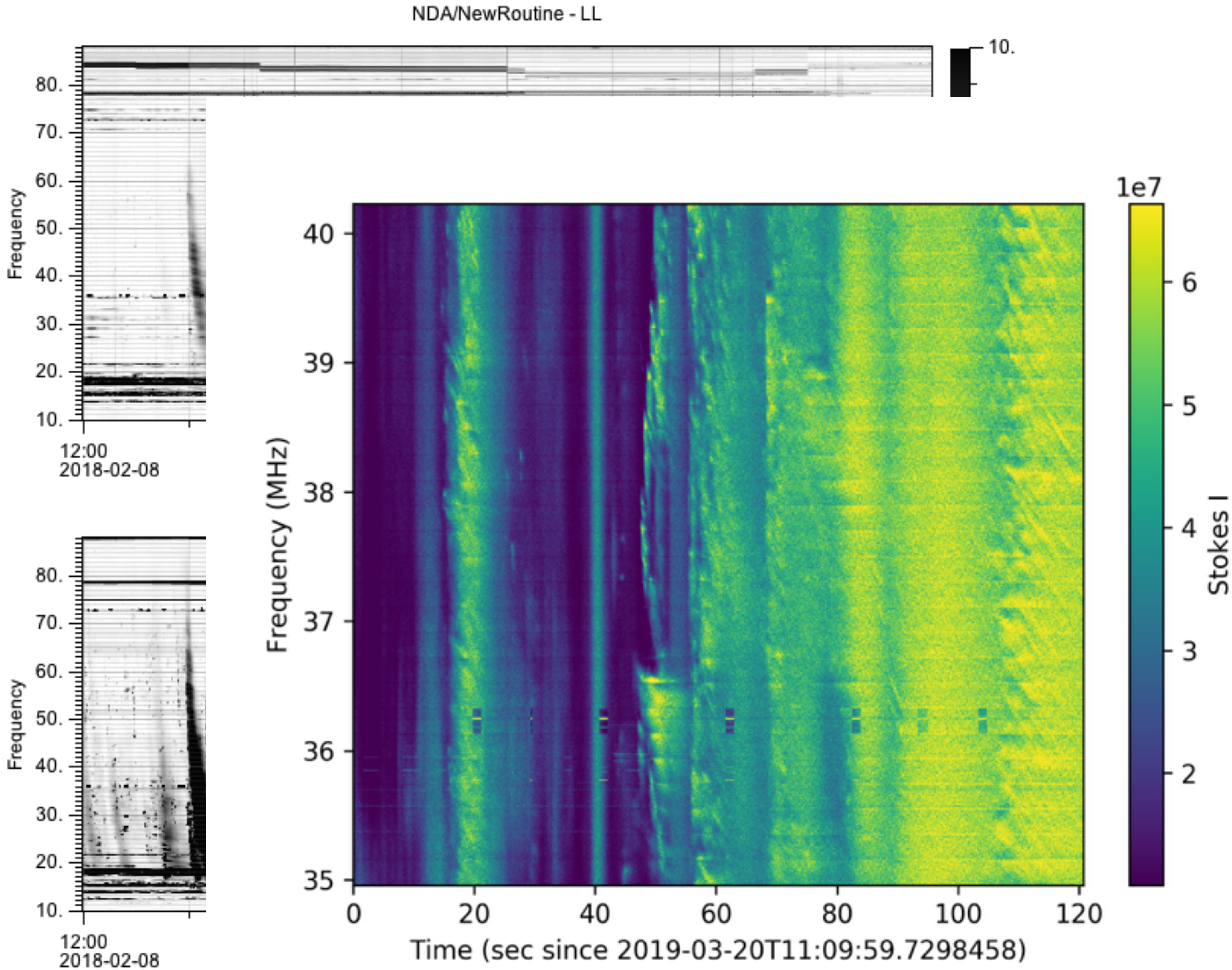
- Earth lightning, Sprites, TLEs



- SETI

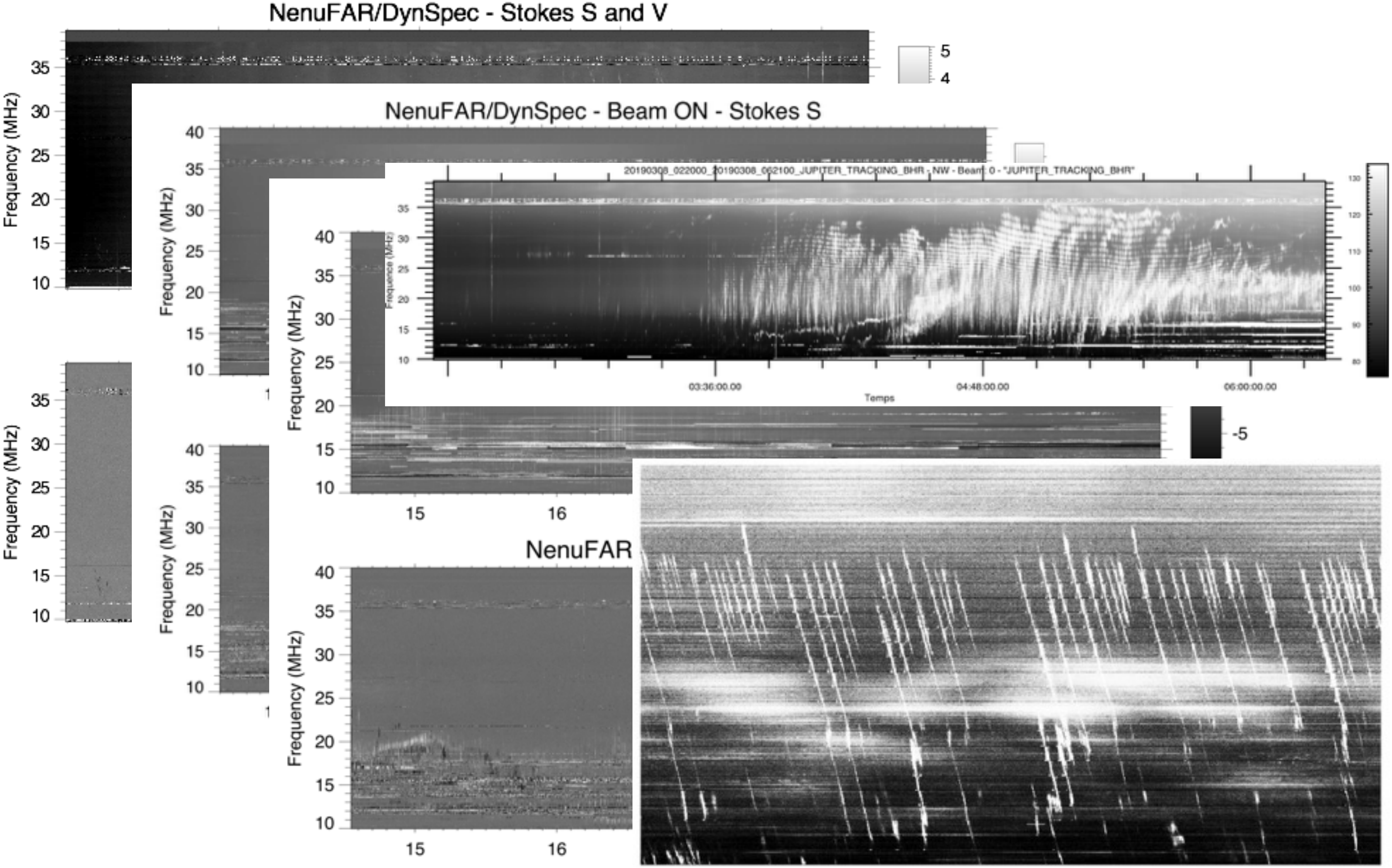
Commissioning / Early Science

- Sun



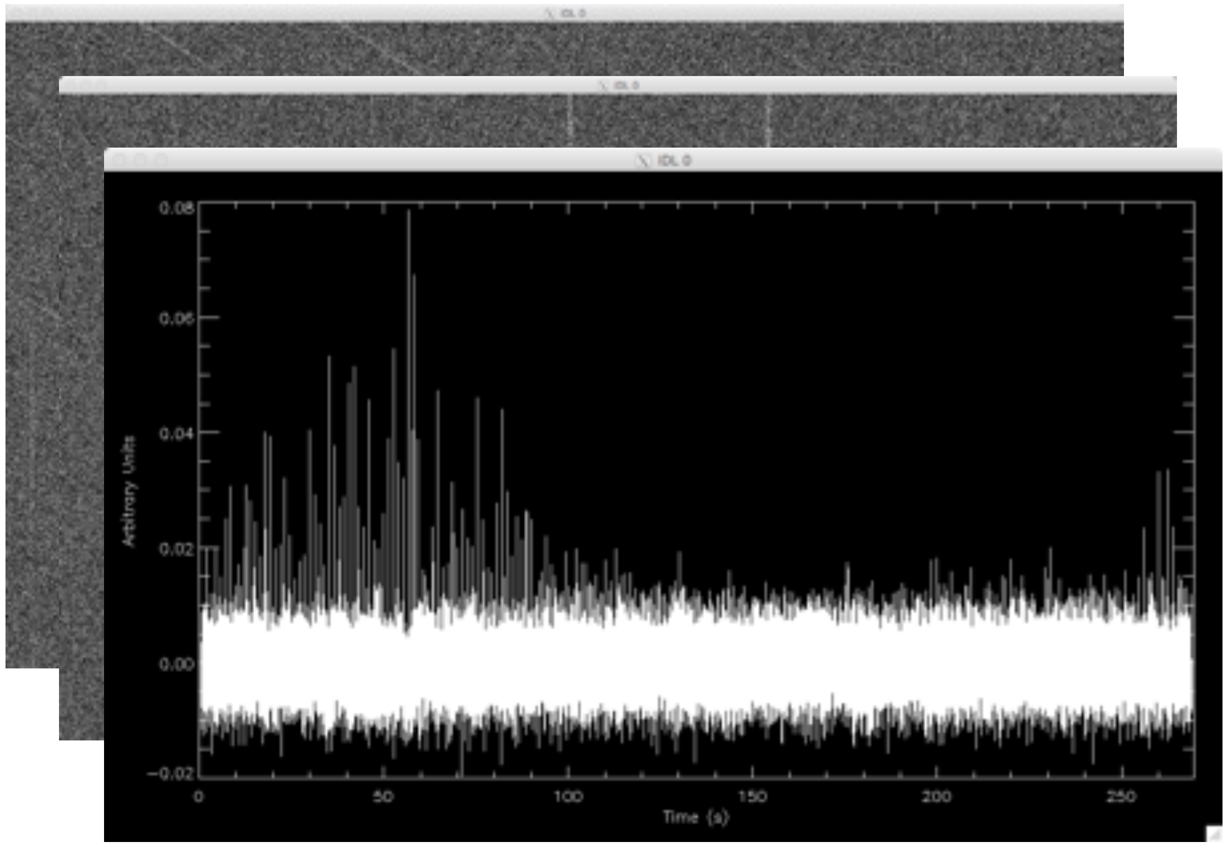
Commissioning / Early Science

- Jupiter

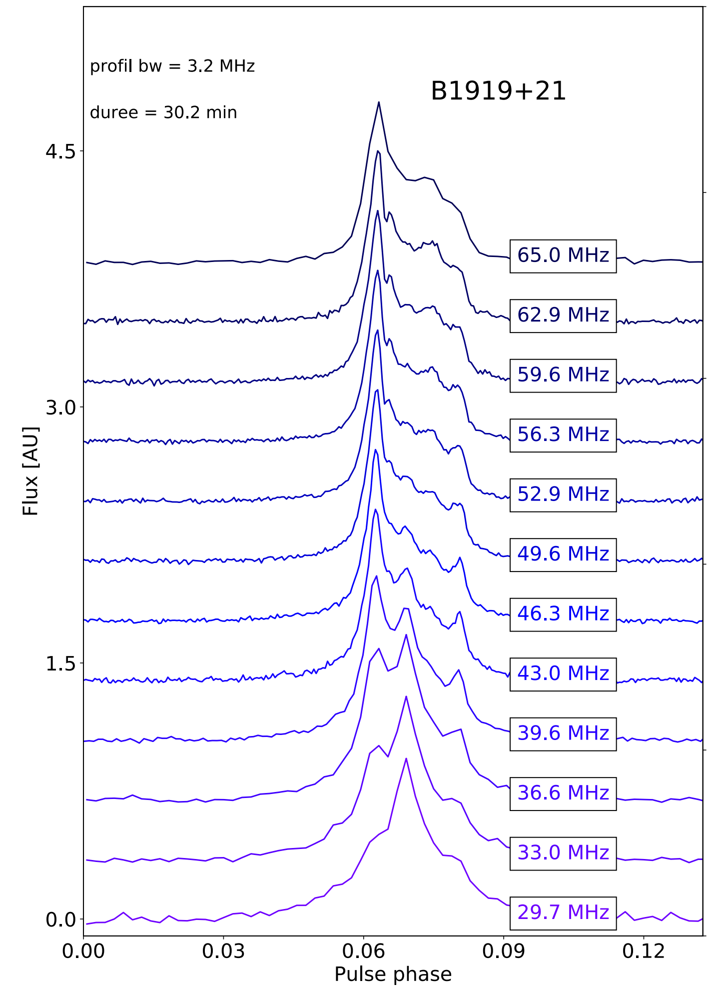


Commissioning / Early Science

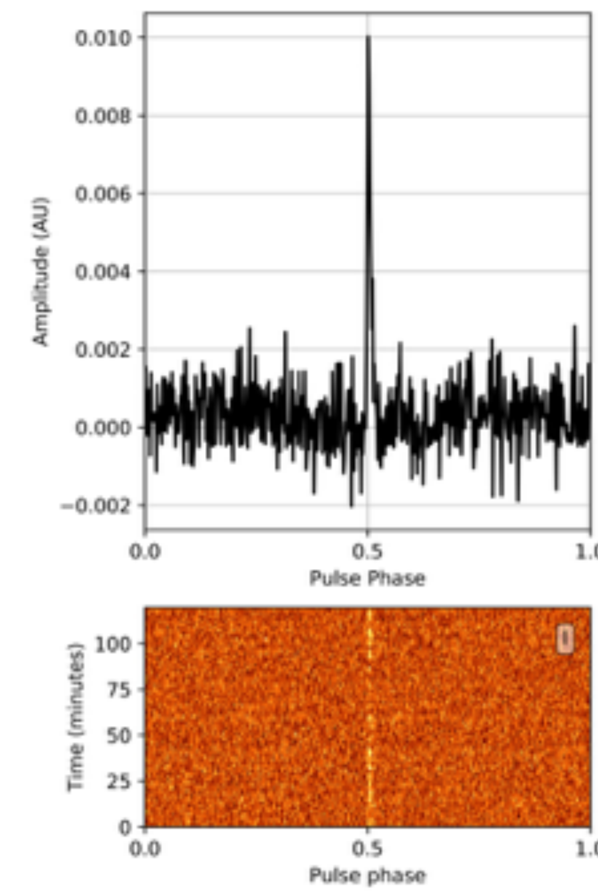
- Pulsars



Broadband detection / polar.

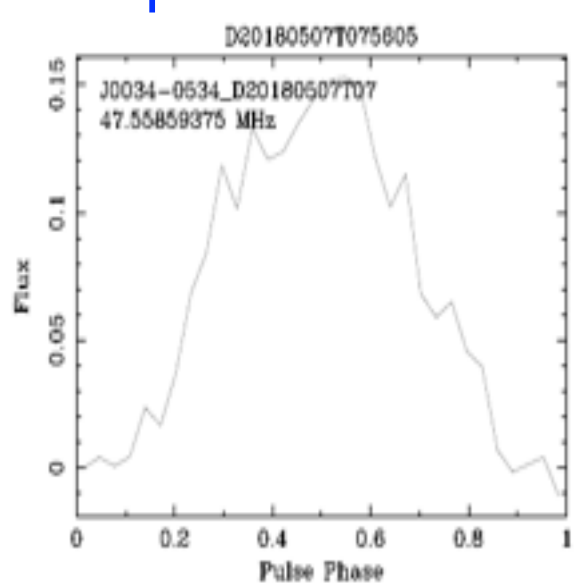


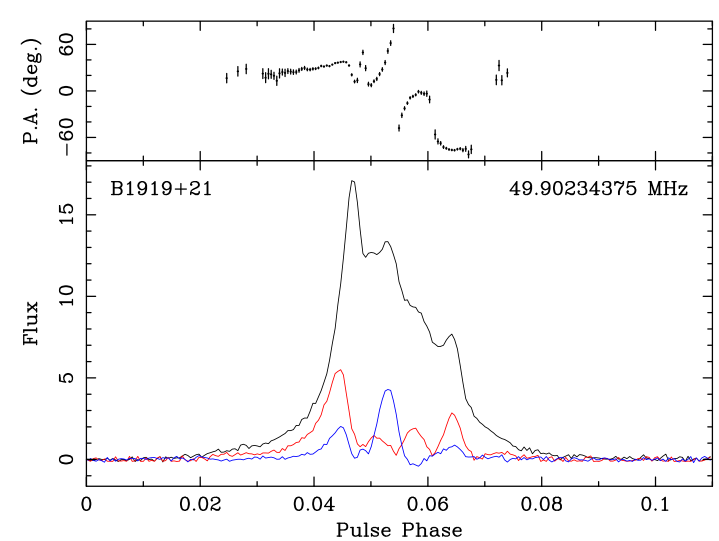
LOFAR's slow pulsar



Millisecond pulsar

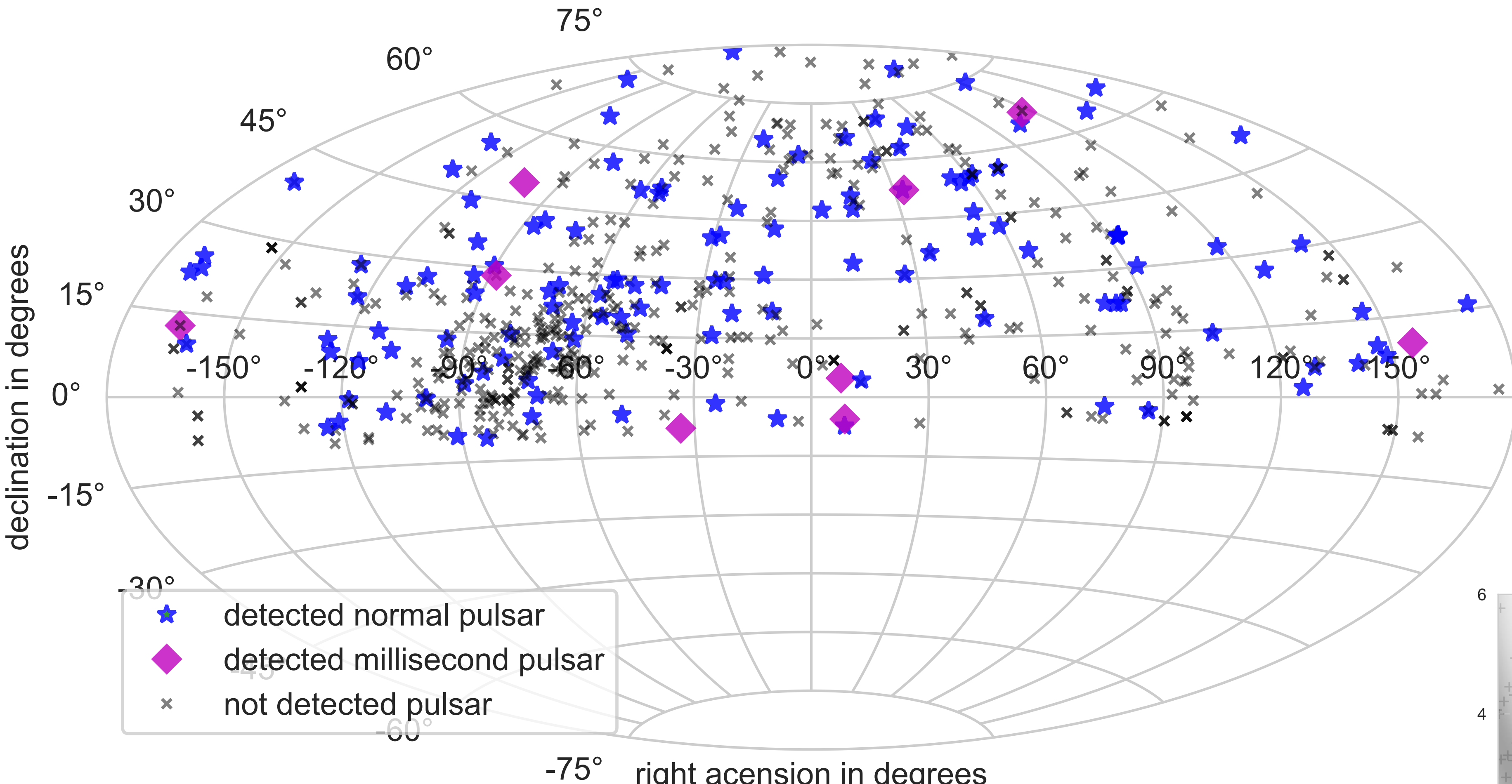
observatory	nenufar
obs.id	J0034-0534_D20180507T075605_010072
PSRNAME	J0034-0534
JNAME	J0034-0534 bhl+94
P0	0.0018770921083743
DM	13.7662
length	7247.00540000001
nsubint	150
center freq.	47.55859375
BW	50
S/N	9.71
%RFI	2.42
quicklook created	May 7, 2018
by	quicklook.sh (version 1.11.00, 08.11.2017)

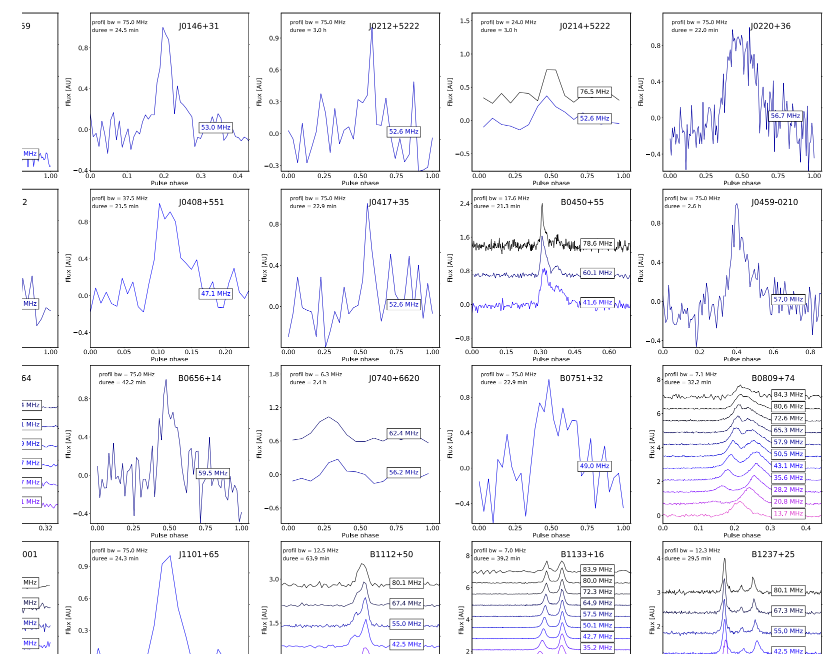


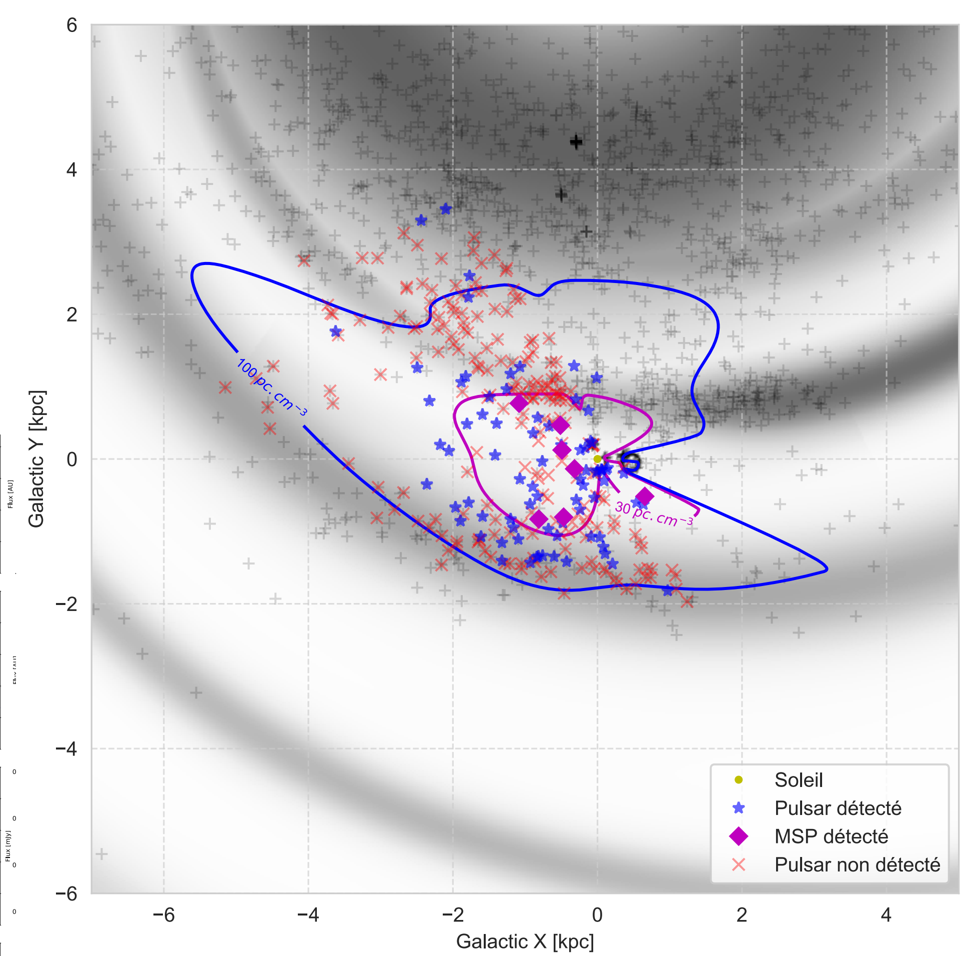


Commissioning / Early Science

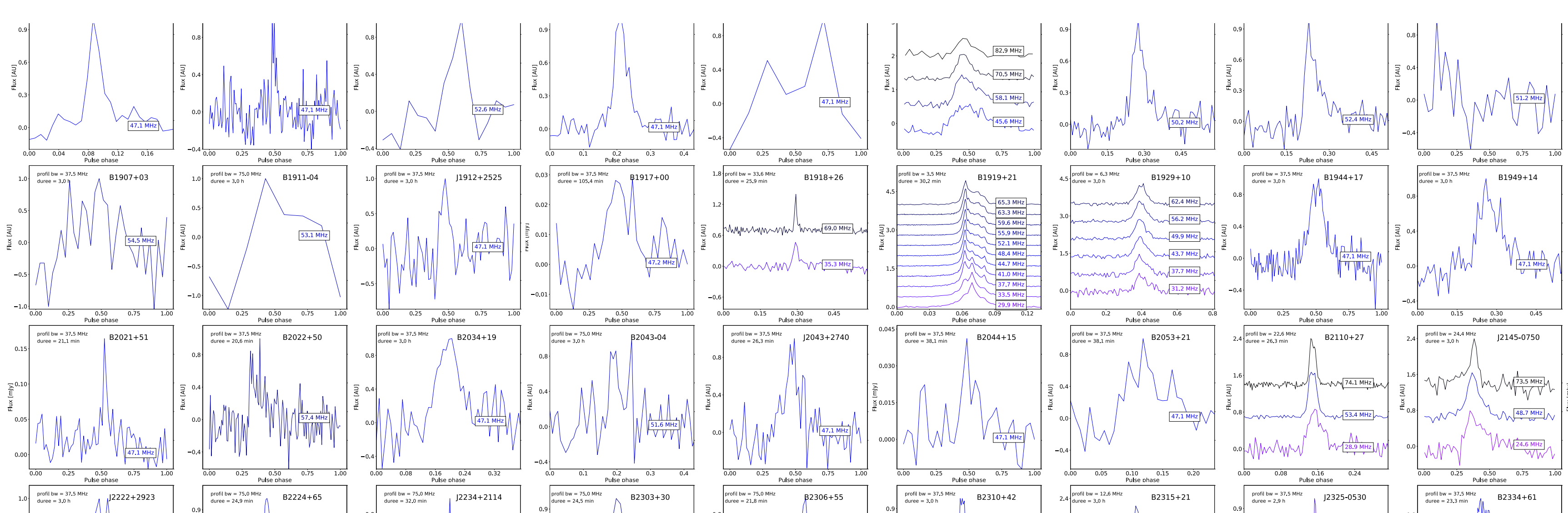
- Pulsars





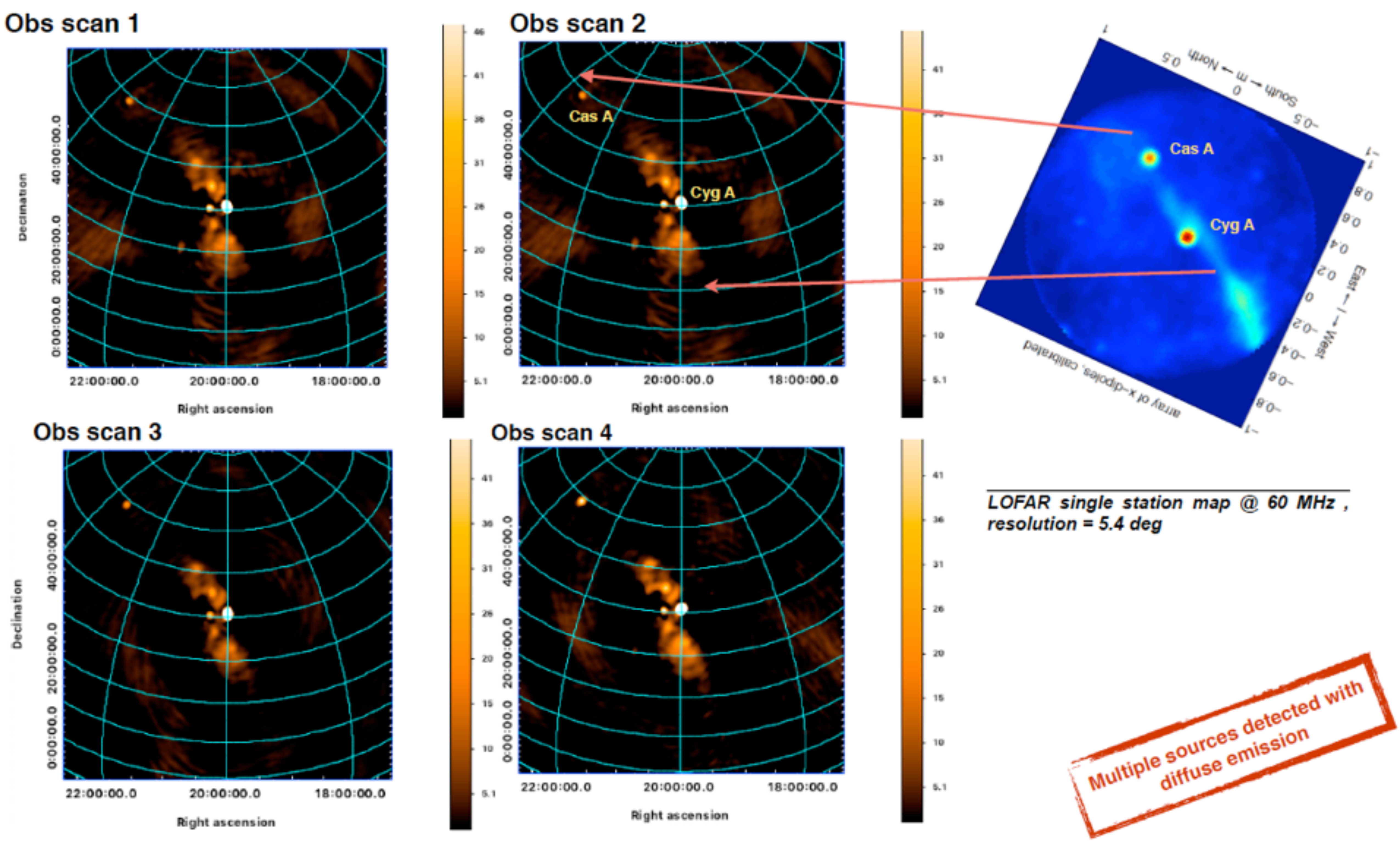


50% new detections



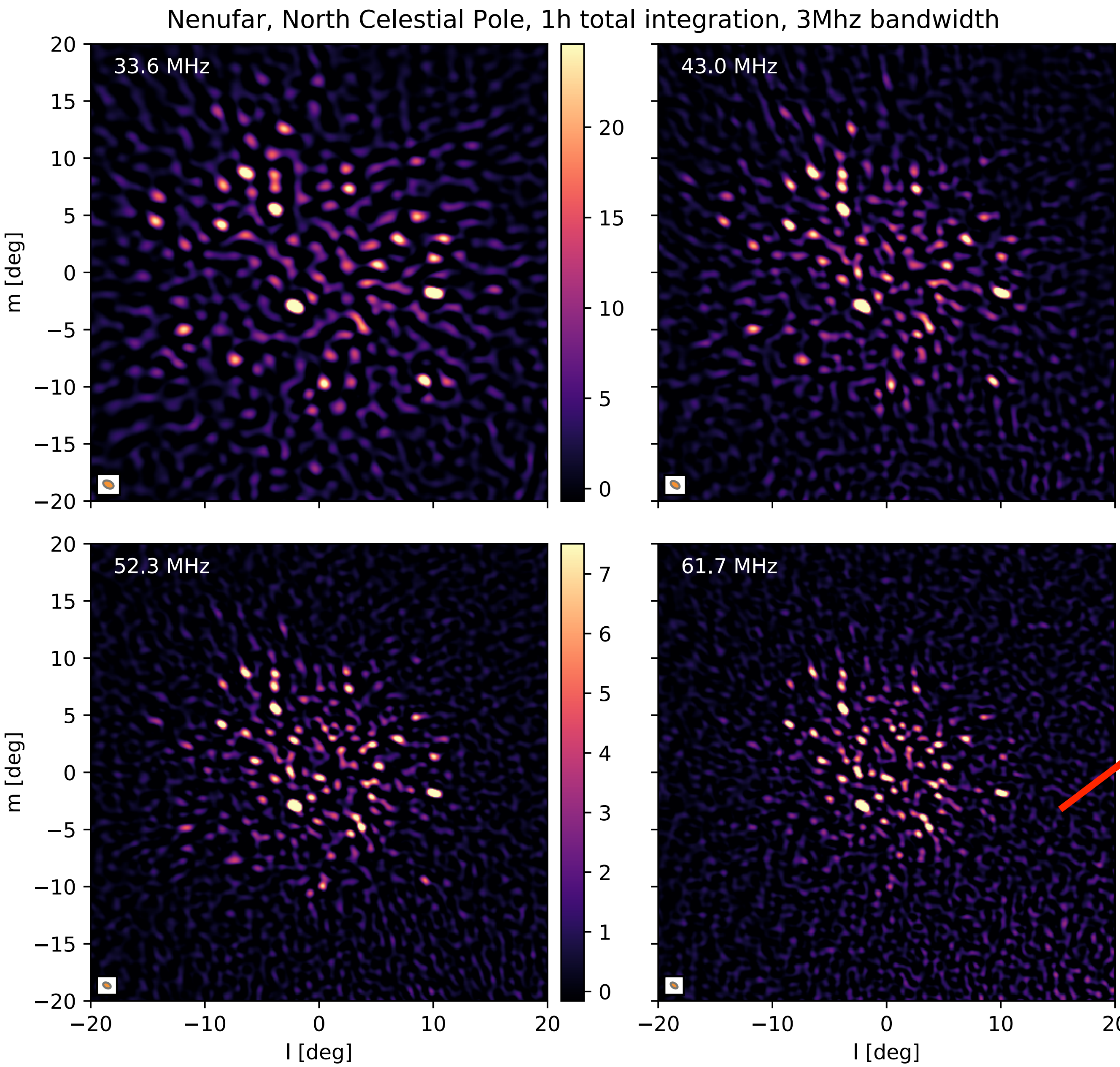
Commissioning / Early Science

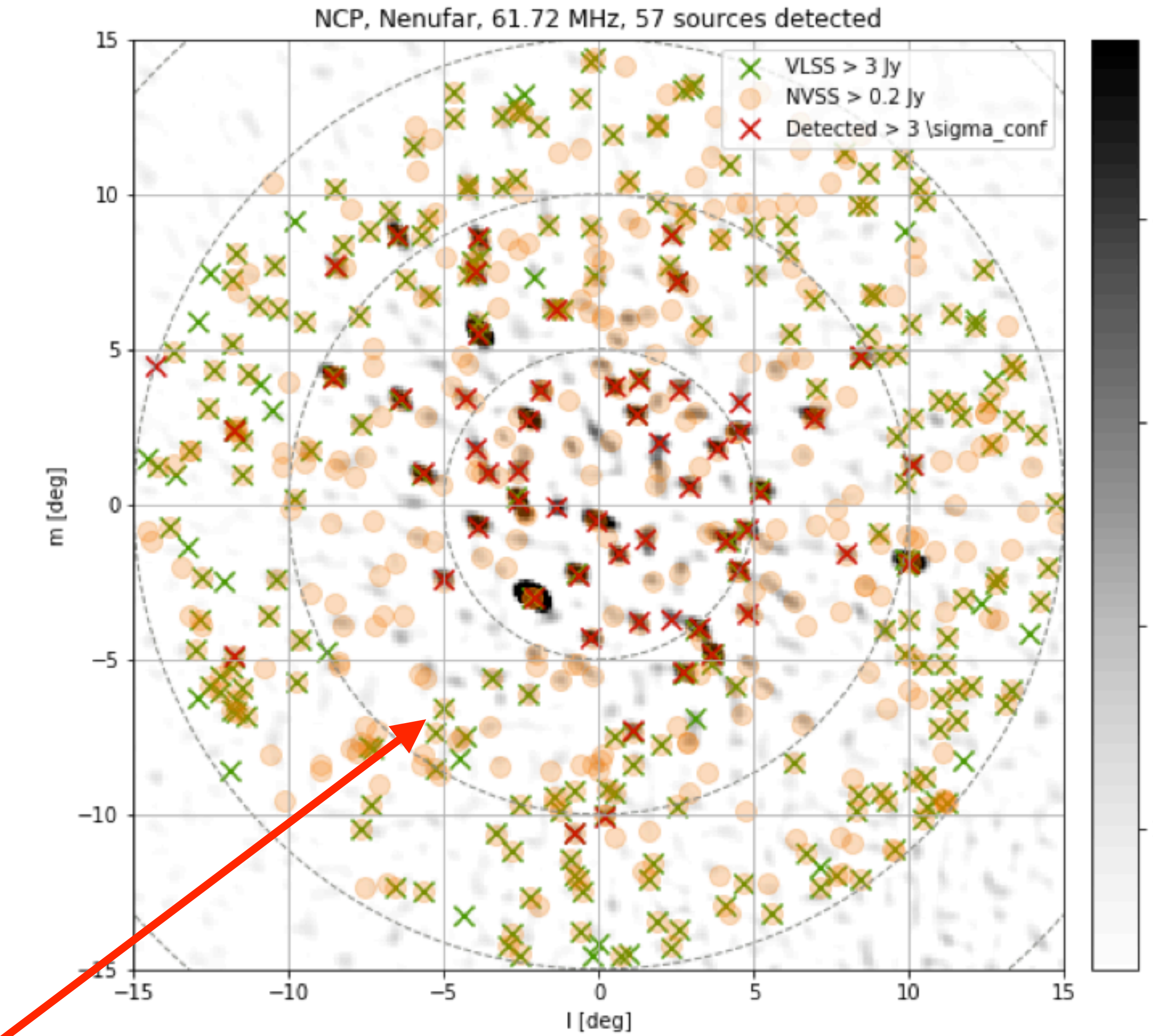
- Imaging : A-team

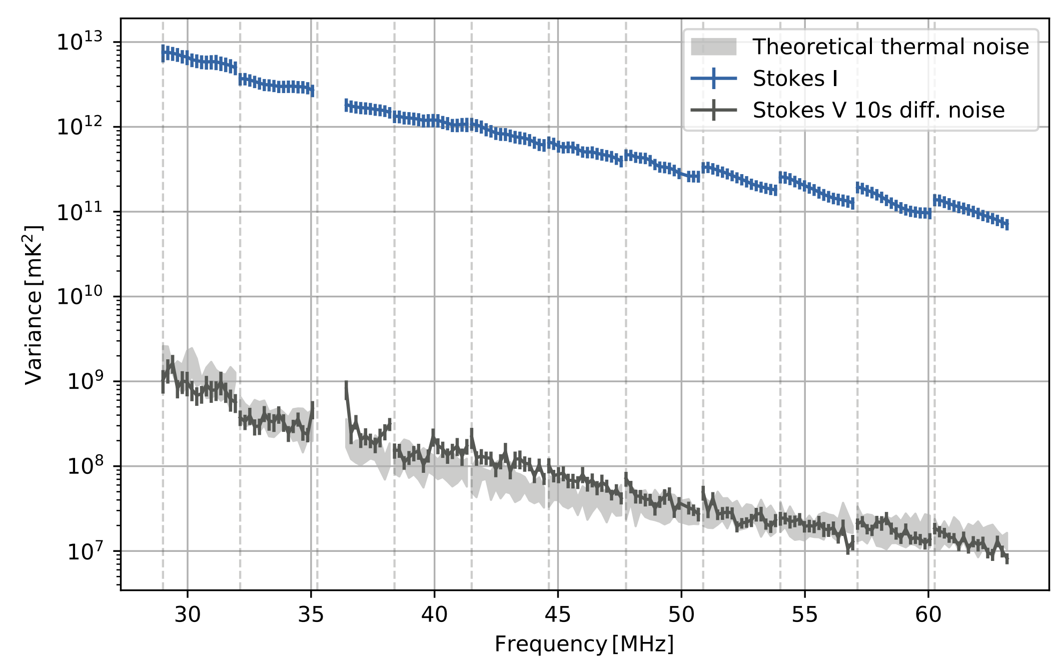


Commissioning / Early Science

- Imaging : NCP

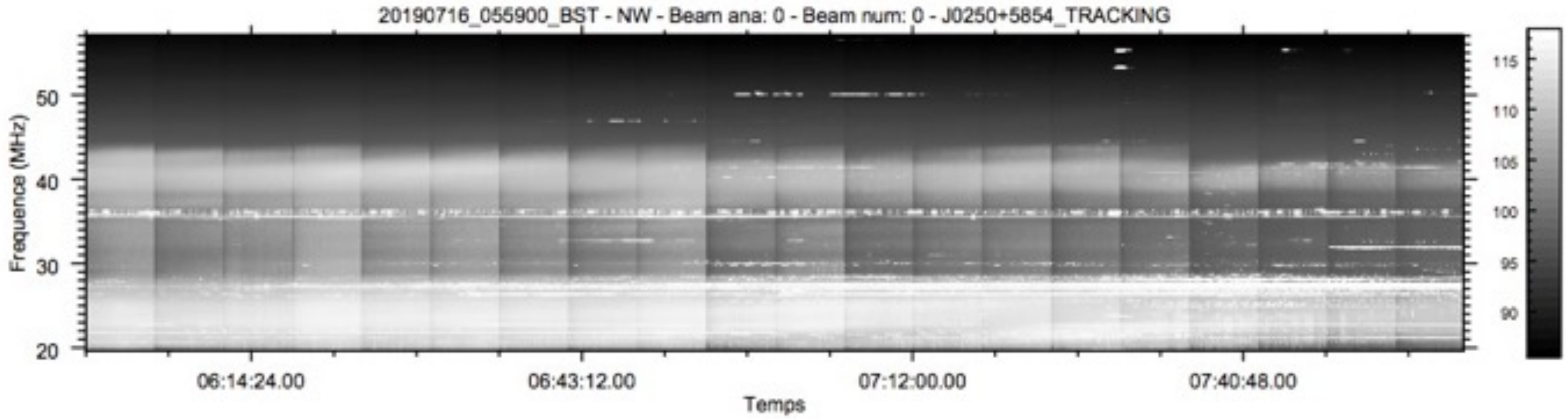


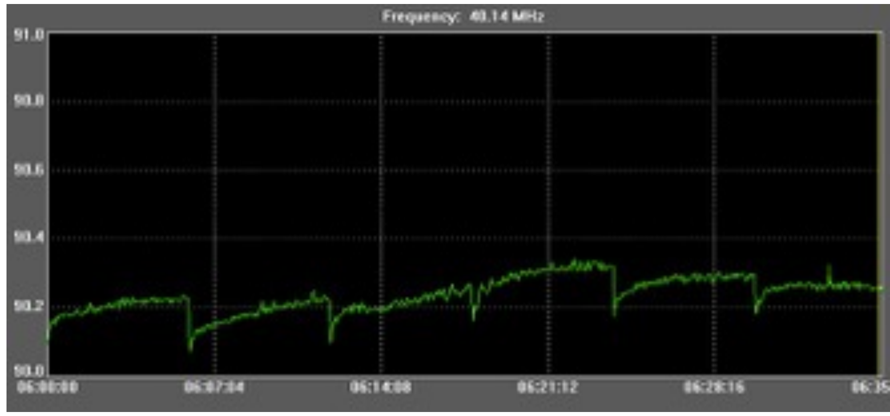


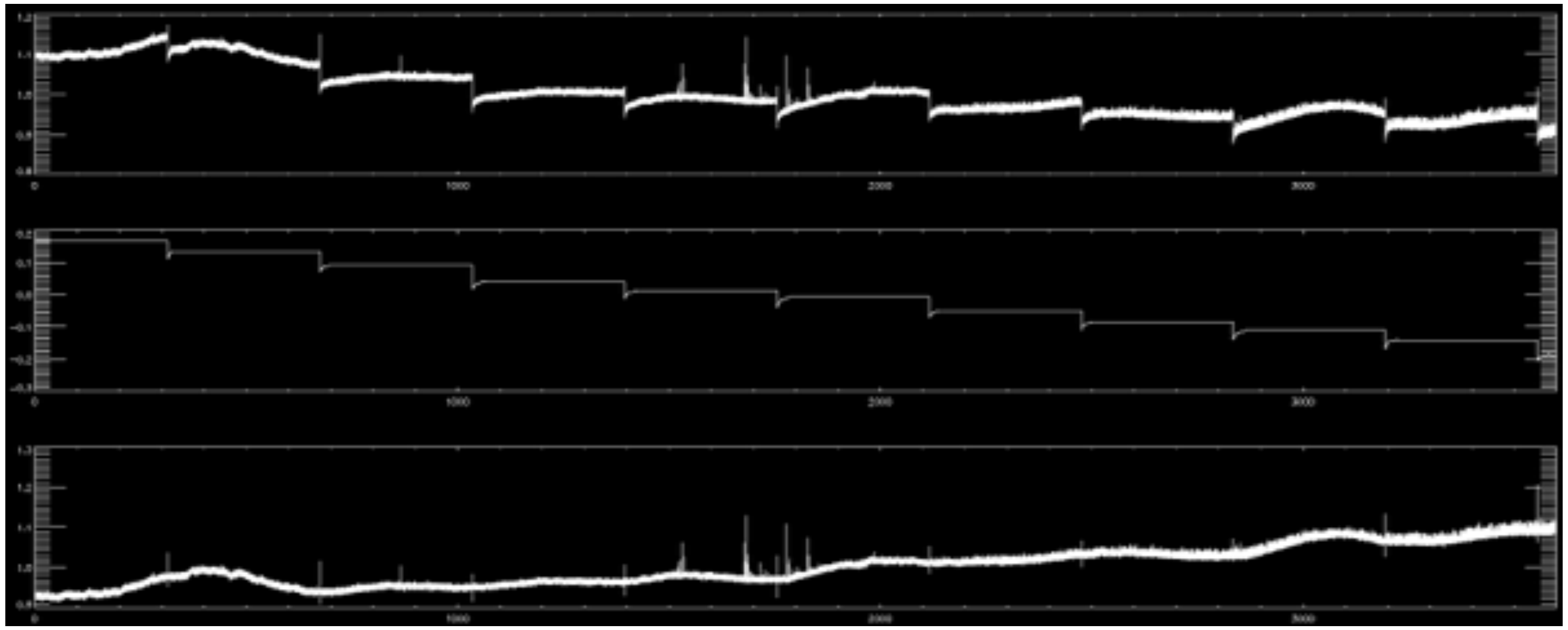


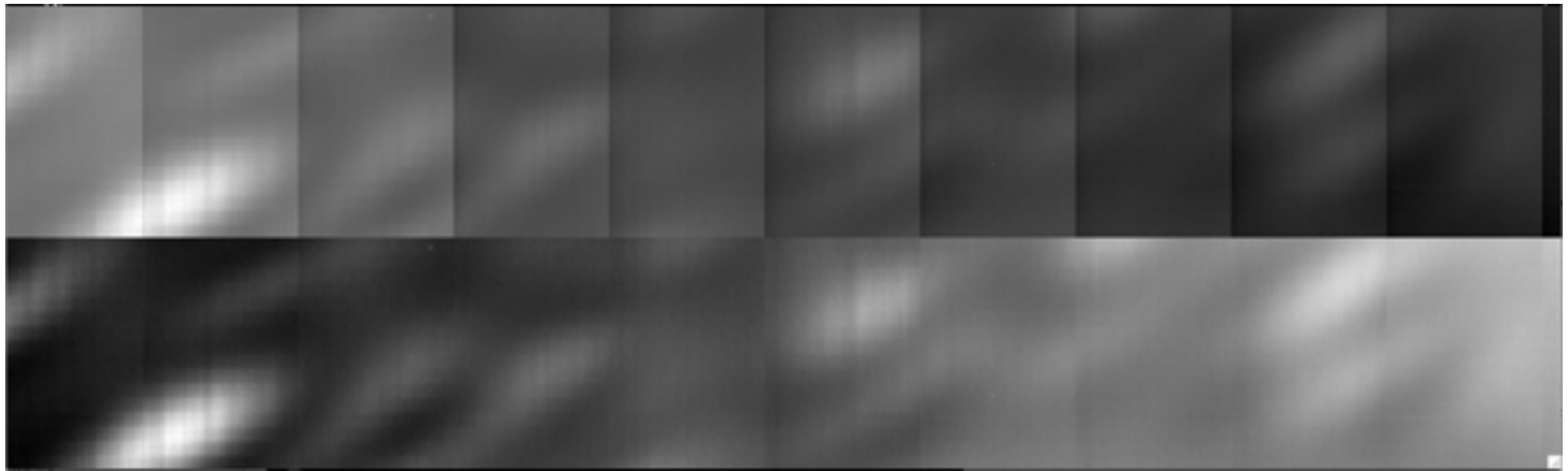
Open problems

- Gain jumps



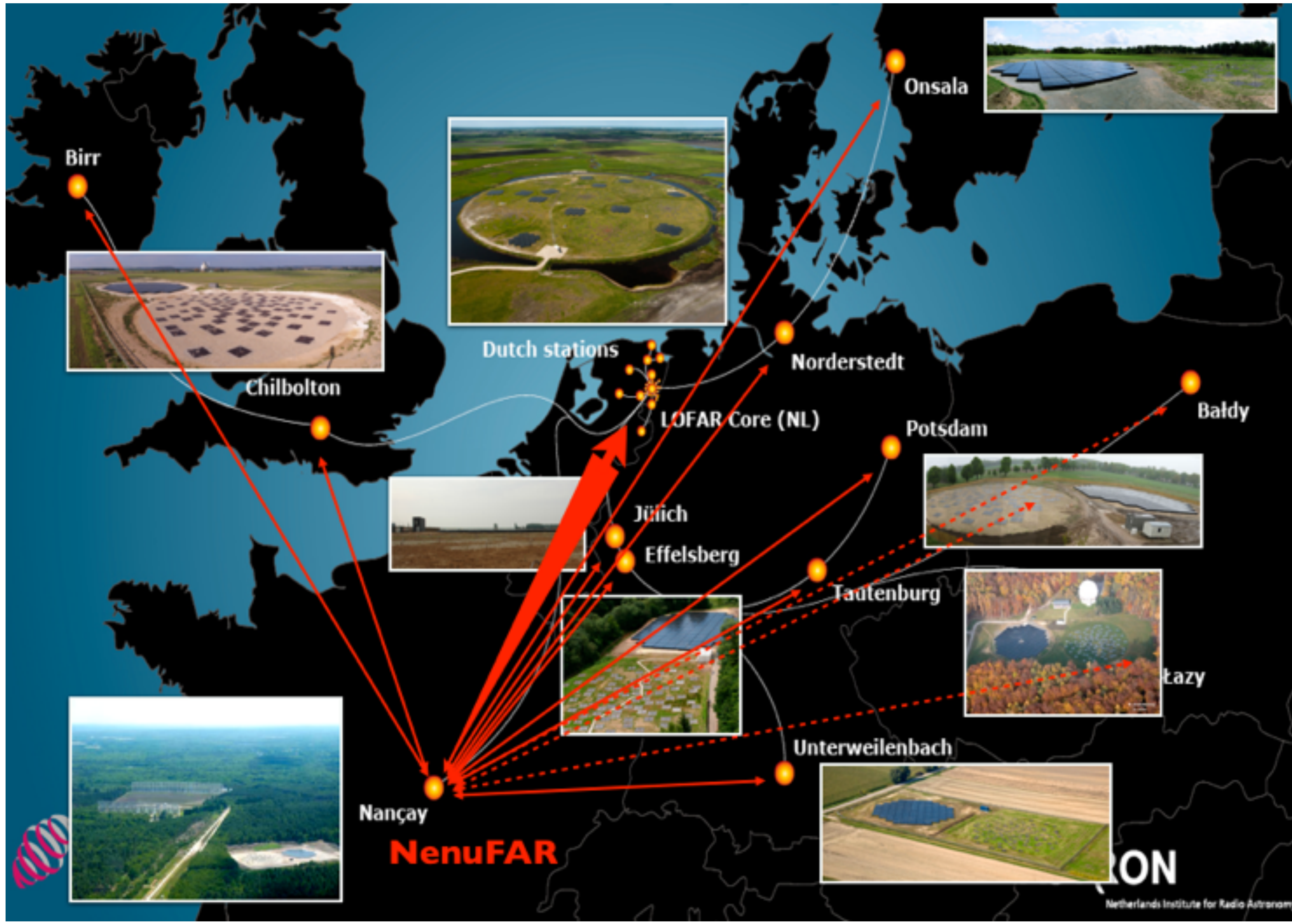






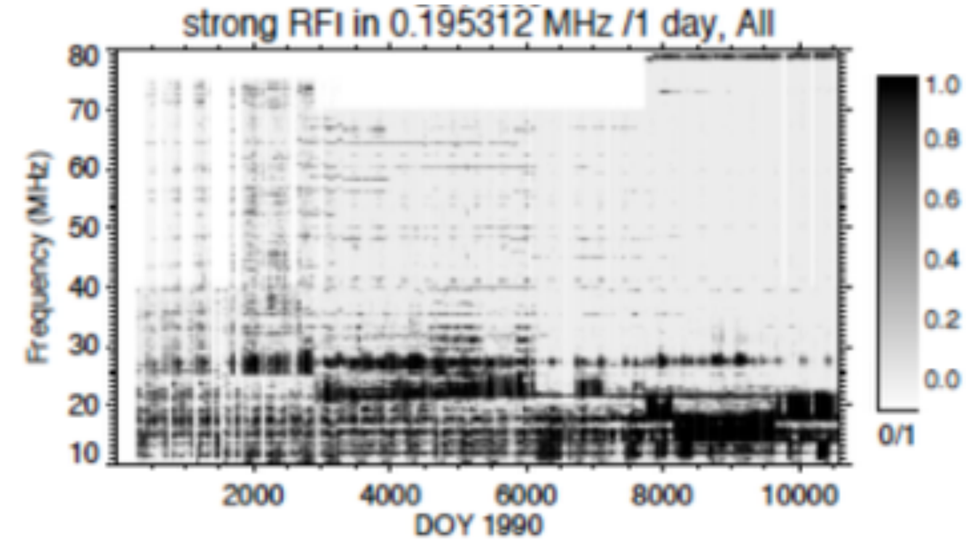
LOFAR Super Station mode

- Exploitation via LOFAR (ILT plan 23/9/2018, need ASTRON manpower for full integration)
- Tests in progress

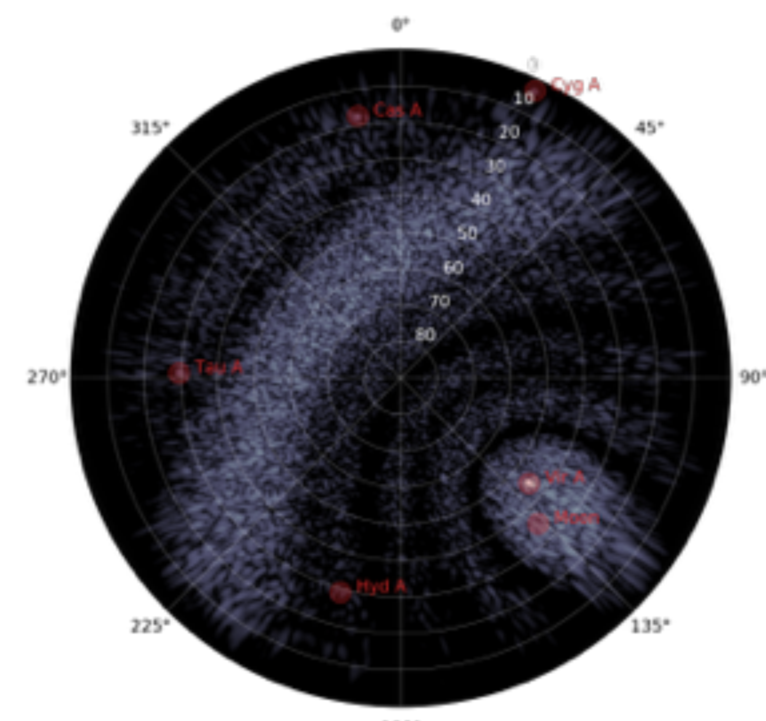


- Integration in LOFAR 2.0 in discussion

In development (see details on Astronomers page)



- **Preparation of observations**
  - Smart SB selection / RFI occupancy statistics
  - VOevents for GW follow-up observations
- **Data analysis**
  - Develop the NenuFAR pre-processing pipeline: Flagging, rebinning, demixing/DD subtraction, …
  - Develop the NenuFAR Calibration & Imaging pipeline : DDFacet/KillMS for DI and DD calibration (A-team subtraction, beam model, wide-field imaging, polarization…)
  - NenuFAR TV (Near Real-time "all-sky" imager in I and |V|)
  - Simulation tools
- **Hardware**
  - Implementation of correlator
  - End of core & imager construction
- ...

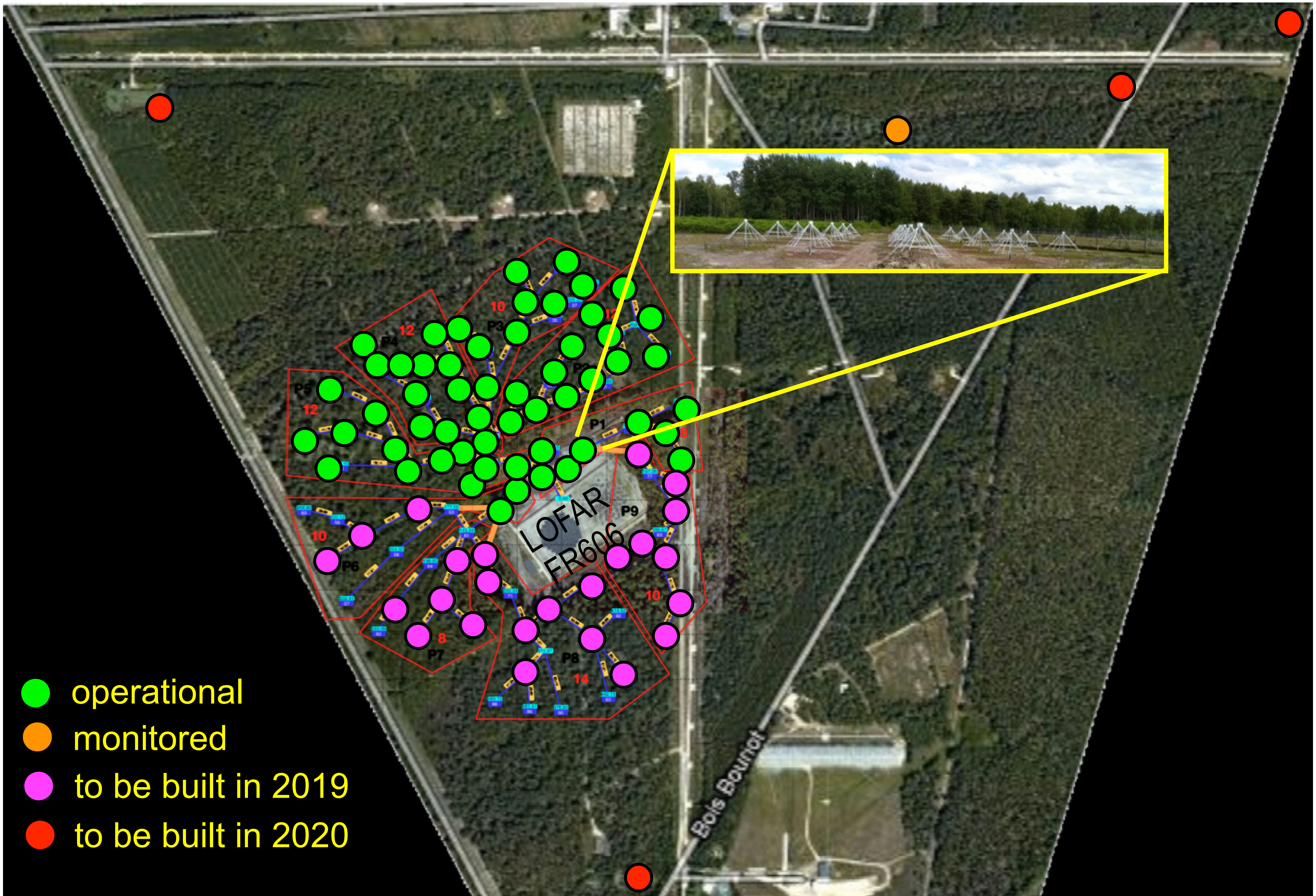


NenuFAR today

1083 antennas built, 532 being installed, 323 yet to be funded

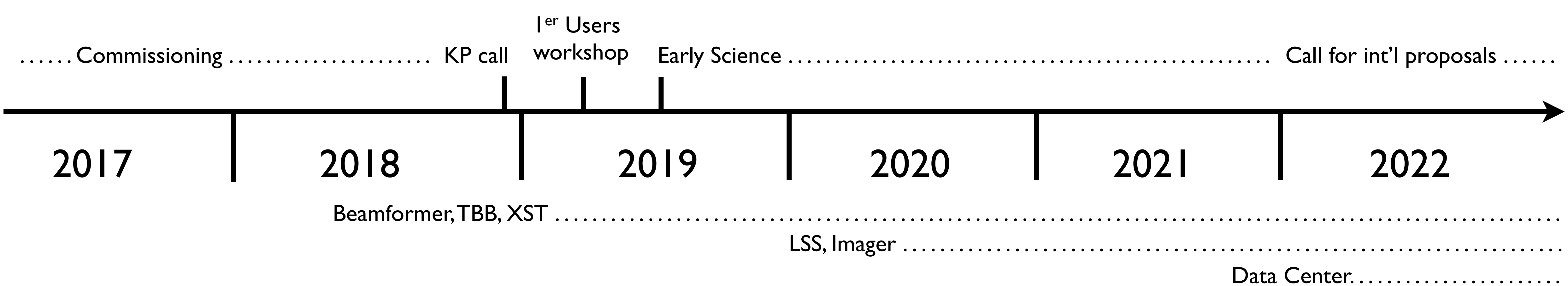
Construction

56 MA core built & operational (1064 antennas) + 1 remote MA built & monitored
24 (core) +3 (remote) additional MA funded (total =80+4)



Timeline

- 2008 : Initial idea & workshop :
- 2009-2013 : Design study
- 2014-2019 : Construction (75%)
- 2016-2019 : Tests, Qualification, Commissioning
- 2019/03 : 1st Users Workshop (https://nenufar2019.sciencesconf.org) & LF meeting (Fr,NL,Ukr,D)
- 2019/7/1 : Early science begins
- 2019/10/03 : Inauguration of NenuFAR (https://www.obspm.fr/inauguration-de-nenufar-un.html)



- 2022/1/1 : Early science (and construction?) ends ; start of nominal exploitation
  => gradual increase of open time from ~10-30% to ~100% in 5-10 years

Proposed Key Programs / Pilot Programs

- Formation of KP : Call to the French community + ~30 foreign colleagues (+ teams) involved in NenuFAR since 1st proposal
- Outcome : 15 KP/PP, 140 participants, 50% French, 50% Foreign (mostly Western Europe + Ukraine)

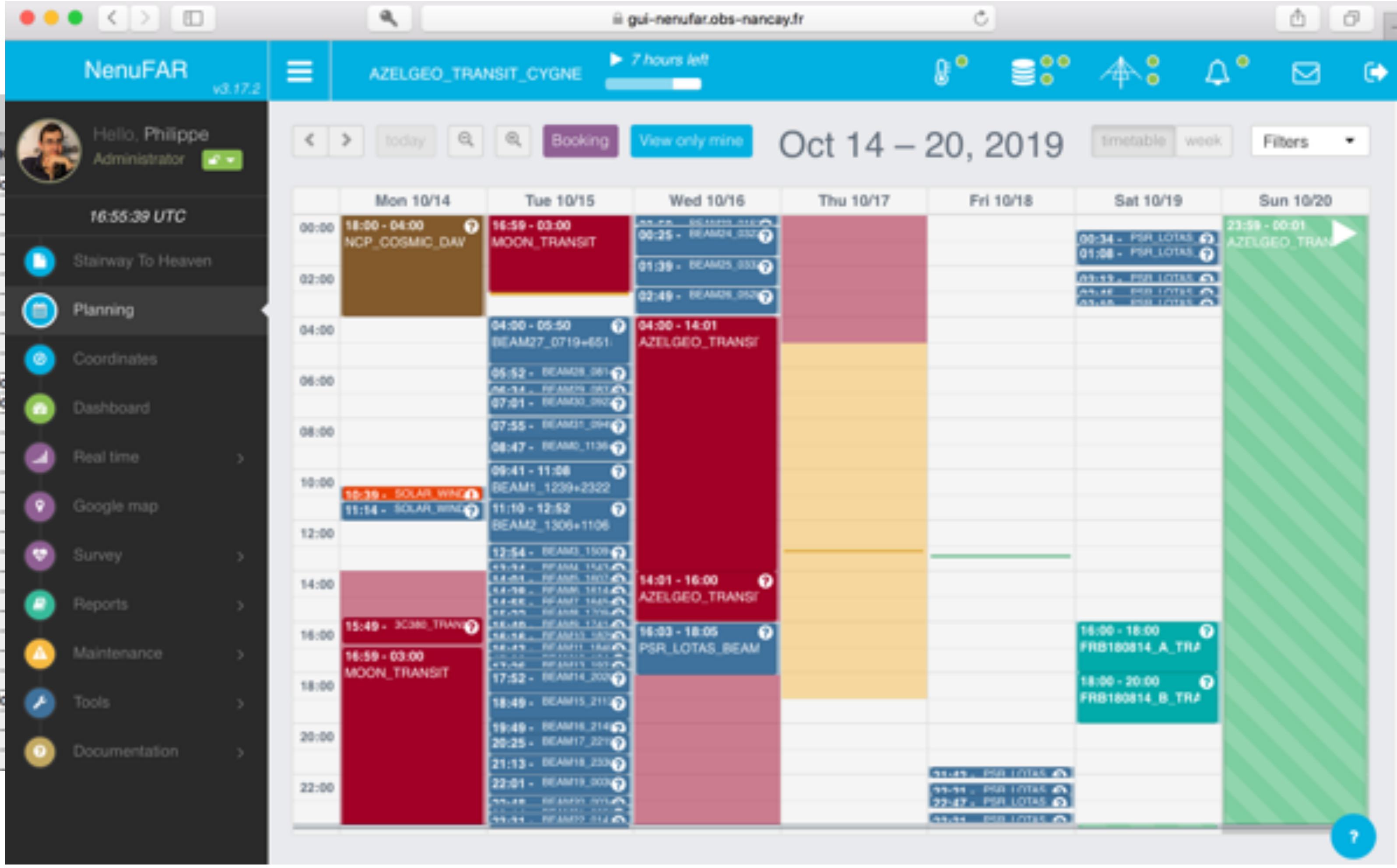
  - **ES1 Cosmic Dawn KP (Koopmans, Semelin et al.)**
  - ES2 Exoplanets & Stars KP (Zarka, Lamy et al.)
  - ES3 Pulsars KP (Grießmeier et al.)
  - ES4 Transients KP (Corbel, Girard et al.)
  - ES5 Fast Radio Bursts PP (Decoene, Zarka et al.)
  - ES6 Planetary Lightning KP (Grießmeier et al.)
  - ES7 Joint Jupiter studies KP (Yerin, Lamy et al.)
  - ES8 Cluster of galaxies & AGNs KP (Pommier et al.)
  - ES9 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.)

Observations & Data *(in ES phase)*

- Initial proposals by KP/PP + semester updates
- Proposed schedule by CSN + iteration
- Reserved time blocks in Virtual Control Room
- Programmation of observation setups ≤7 days before obs. date
- Observation …

NenuFAR booking

2019-09	KP - day	KP – night	KP – h
2019-09-01			ES7 J
2019-09-02		ES3 Pulsars	
2019-09-03		ES3 Pulsars	
2019-09-04		ES3 Pulsars	
2019-09-05			
2019-09-06			
2019-09-07	ES3 Pulsars (2h)		
2019-09-08	ES2 Exoplanets & Stars	ES2 Exoplanets & Stars	
2019-09-09	ES2 Exoplanets & Stars	ES2 Exoplanets & Stars	
2019-09-10		ES2 Exoplanets & Stars	
2019-09-11			ES7 J
2019-09-12			ES7 J
2019-09-13			
2019-09-14	ES3 Pulsars (2h)		
2019-09-15		ES10 Radio recombination lines	
2019-09-16	ES3 Pulsars	ES3 Pulsars	
2019-09-17	ES9 Cluster Filament & Cosmic Magnetism	ES9 Cluster Filament & Cosmic Magnetism	
2019-09-18		ES1 Cosmic Dawn	
2019-09-19		ES1 Cosmic Dawn	
2019-09-20		ES1 Cosmic Dawn	
2019-09-21	ES3 Pulsars (2h)		
2019-09-22			
2019-09-23		ES13 SETI	
2019-09-24			
2019-09-25			
2019-09-26		ES1 Cosmic Dawn	
2019-09-27		ES1 Cosmic Dawn	ES7 J
2019-09-28	ES3 Pulsars (2h)	ES1 Cosmic Dawn	
2019-09-29		ES1 Cosmic Dawn	
2019-09-30			



- Data to Nançay Data Center (databf storage + nancep computing nodes) : L0 → L1
- L1+ stored at DIO/OP (Active Circle robot tape)
- Archive under study (National/European cloud)
- Data use policy in discussion

The team

- **PI** : P. Zarka, M. Tagger **Project Manager** : L. Denis
- **Comité Scientifique NenuFAR** : the above 3 + F. Casoli, S. Corbel, G. Theureau
- **Commissioning team** : J. Girard, L. Denis, P. Zarka, A. Loh, L. Bondonneau, M. Pommier, J.-M. Grießmeier, C. Tasse, C. Briand, E. Bonnassieux, C. Viou, B. Censier

  → support for Early Science observations
- **Development team** :
  - Nançay : L. Denis, A. Coffre, C. Viou, C. Taffoureau, E. Thetas, A. Le Gall, F. Guilbeau, S. Garnier, B. Gond, L. Alsac, P. Cottet, J.-B. Vimon, F. Floquet, S. Joly + *support*
  - Other : D. Charrier, J. Girard, A. Loh, L. Bondonneau, I. Cognard, B. Cecconi, P. Zarka
- **NenuFAR-France consortium** : incl. B. Semelin, E. Chassande-Mottin, G. Hellbourg, R. Dallier, L. Martin, L. Lamy, E. Tremou, et al.
- **Artist** : C. Courte

Status, Governance, Cost

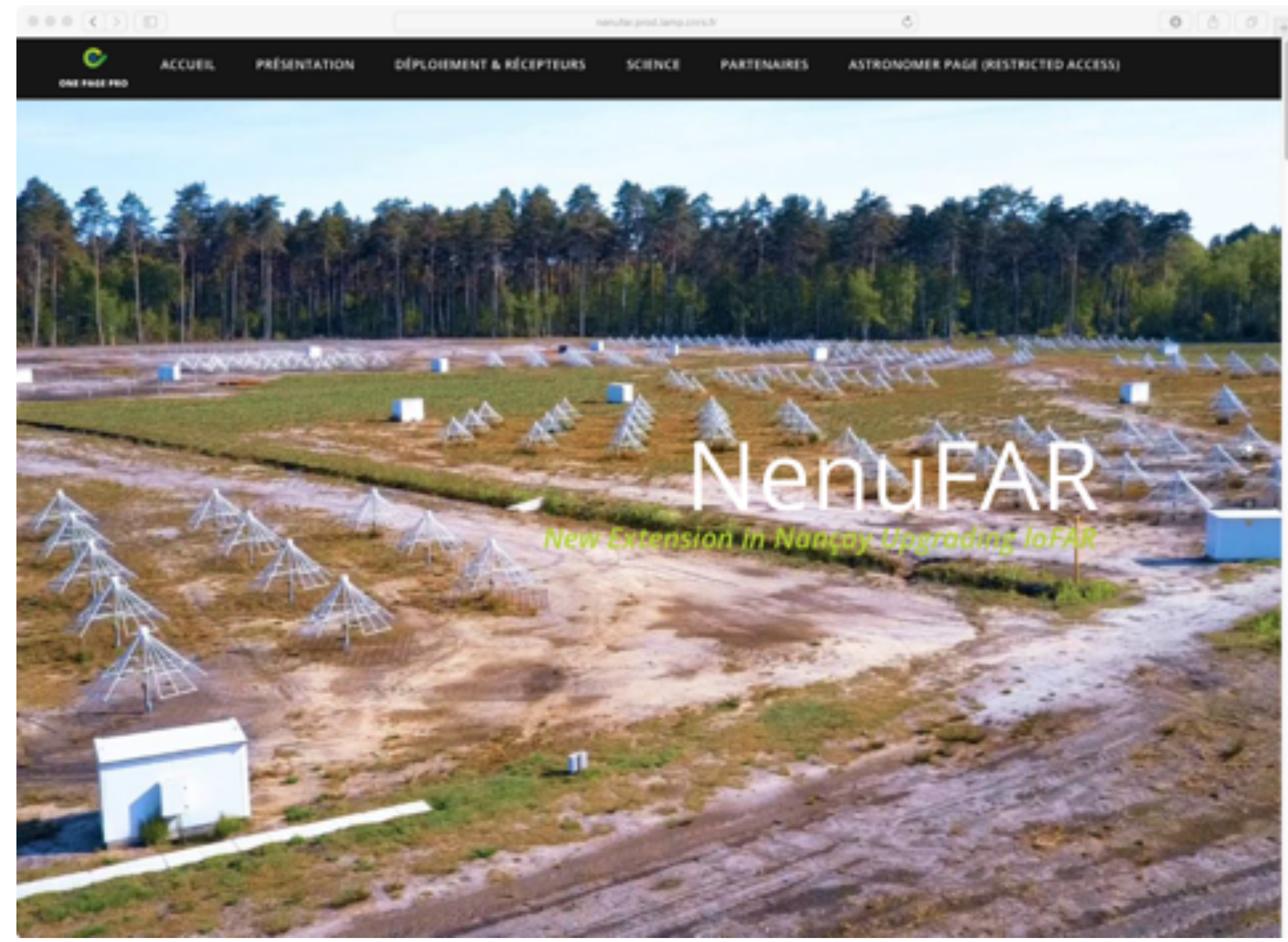
- NenuFAR is an official SKA precursor since 2015
- NenuFAR+LOFAR are a Research Infrastructure from MESRI

- Project : P. Zarka (P.I.), L. Denis (Project Manager)
- NenuFAR Scientific Committee : F. Casoli, S. Corbel, L. Denis, M. Tagger, G. Theureau, P. Zarka
- ≥2022 : International Program Committee (to be set up in 2021)
- NenuFAR Scientific Committee → Board (including foreign partners ?)
- Report to CS OP, Nançay CSD, CNRS/AA, OSUC/UO, Regions …

- Hardware construction cost : ~6 M€
- ~5 M€ secured from Region Ile-de-France, Region Centre, ANR, CNRS, OP…
- Manpower USN, LESIA + 3 post-docs & 2 CDD (OP, CNRS)
- ~1 M€ hardware still necessary to obtain → CPER, international collaboration, ERC…
- Data center : ~3 M€
- Exploitation costs : ~200 k€ / year + ~5 ETP

Web site

- https://nenufar.obs-nancay.fr/en/homepage-en/
  - Art project : "Le Dôme de NenuFAR"



- Astronomers page : https://nenufar.obs-nancay.fr/en/astronomer/
  - Identified features
  - "Contact NenuFAR team" form for feedback / questions


NENUFAR
Le projet dans les temps