NenuFAR

New extension in Nançay upgrading LOFAR

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[1]LESIA-OP, [2]USN-OP, [3]LPC2E-Orléans, [4]AIM-P7/CEA-Saclay, [5]GEPI, LERMA, ONERA, ENS/IAP, OCA, ...

TS2020, 20-22/06/2017

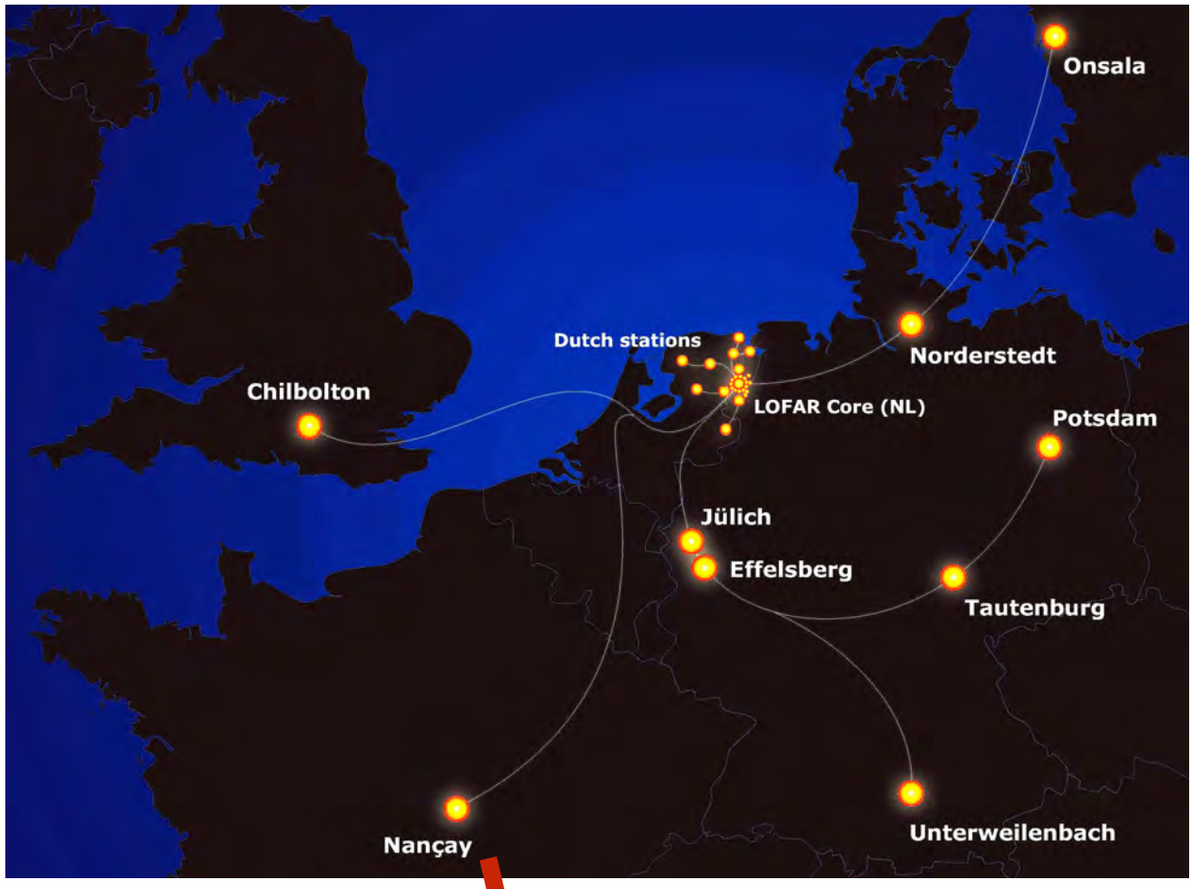
LAL, Orsay

Nouvel âge d'or de la radioastronomie

Interféromètres: VLA, ATCA, WSRT, …

LOFAR

F=30-250 MHz

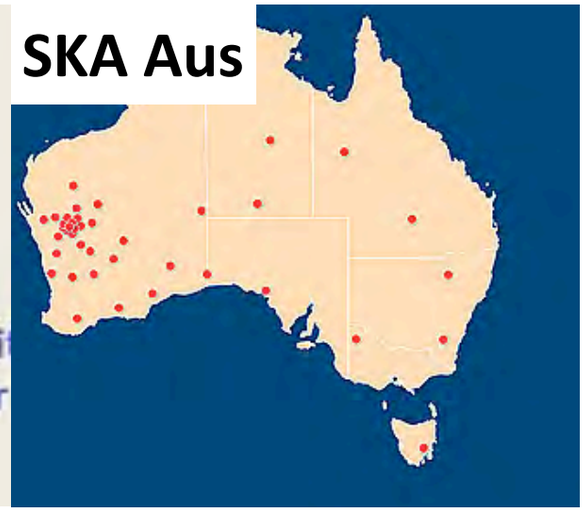


SKA
SQUARE KILOMETRE ARRAY

F=50 MHz - ~10 GHz

SKA SA

SKA Aus



~2020

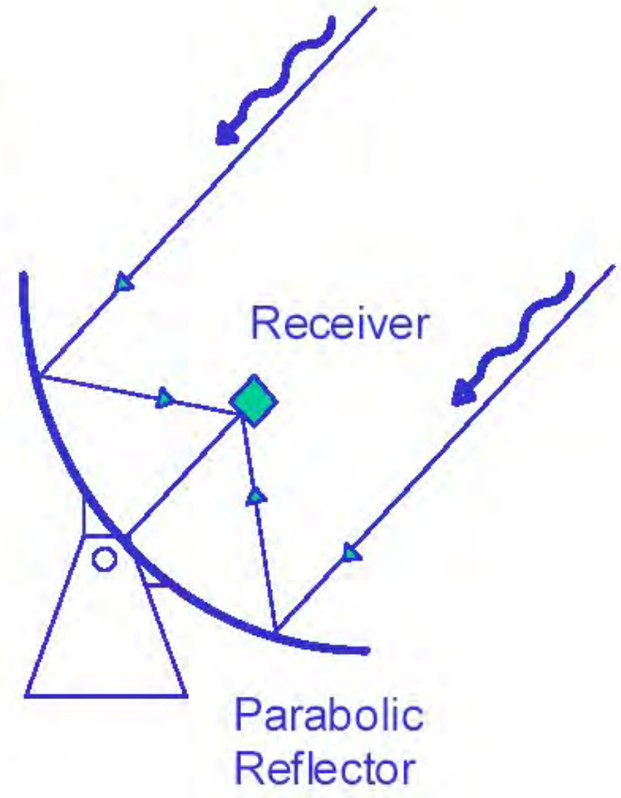
SKA-MID

SKA-MID

SKA-AA

SKA-LOW

Electronique vs. mecanique

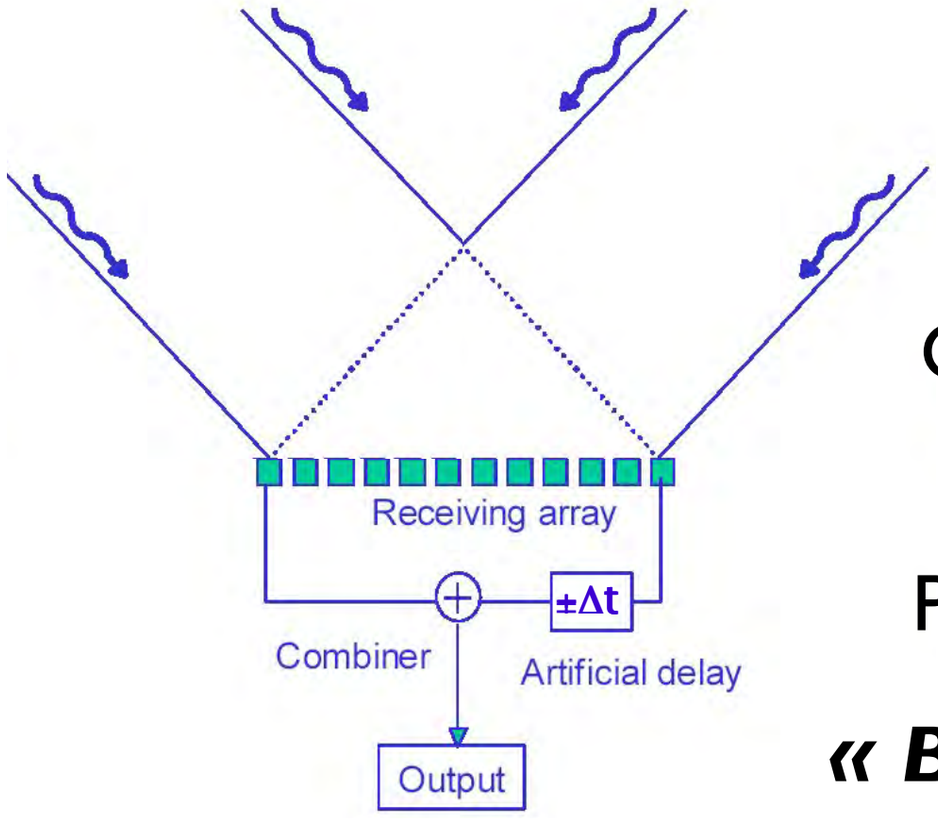


« Moyennes fréquences »
f~1-10 GHz

Petit champ de vue

Antenne orientable

Pointage mécanique



« Basses fréquences »
(HF, VHF)
f<200 MHz

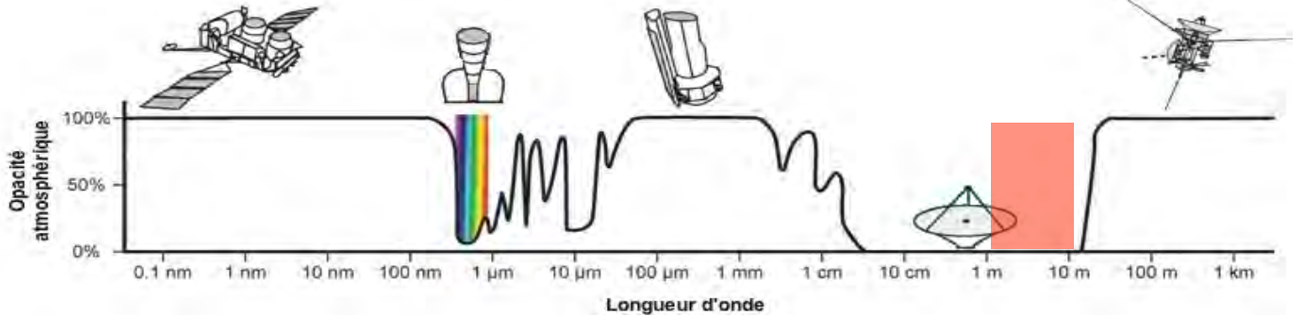
Grand champ de vue

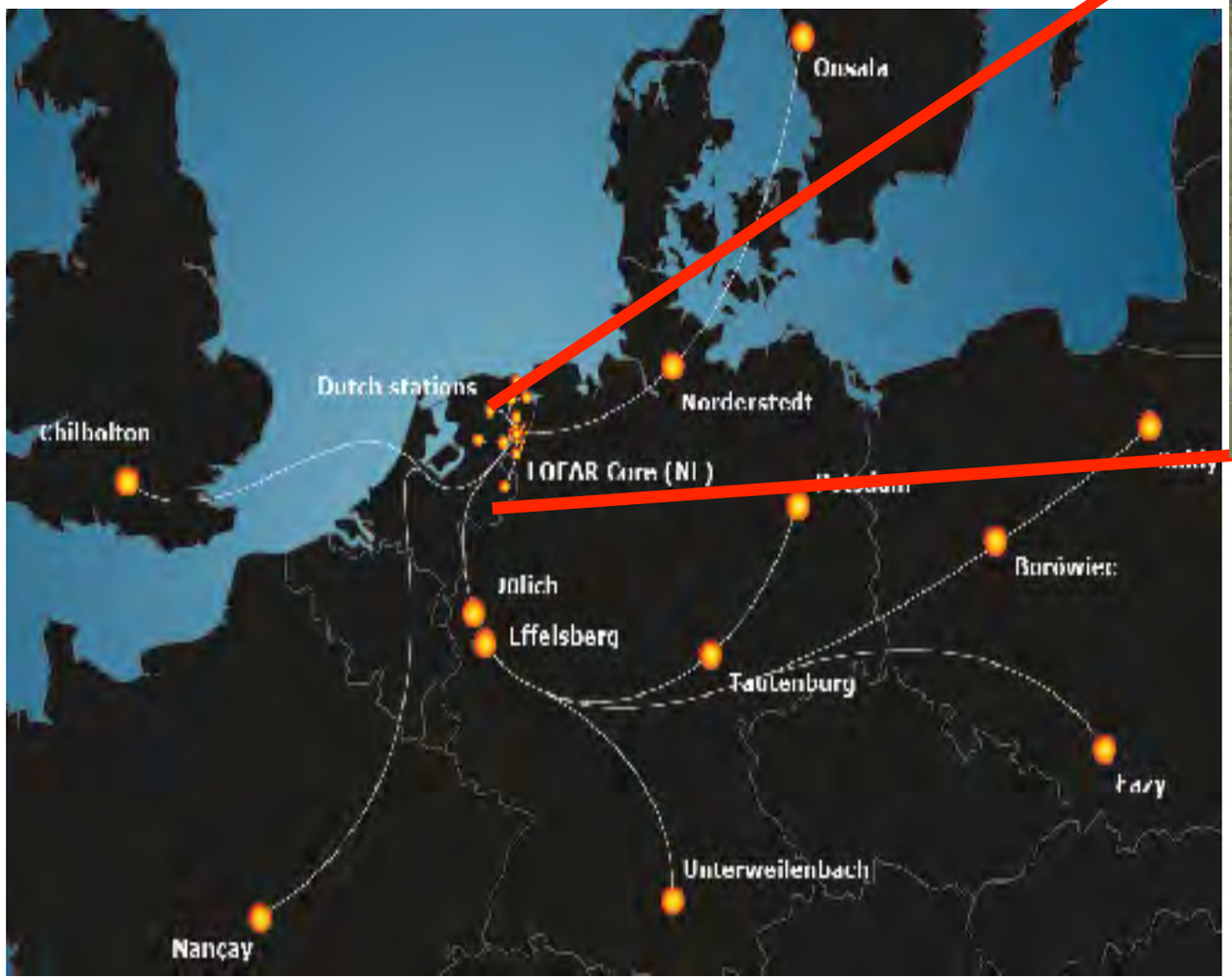
Antenne fixe

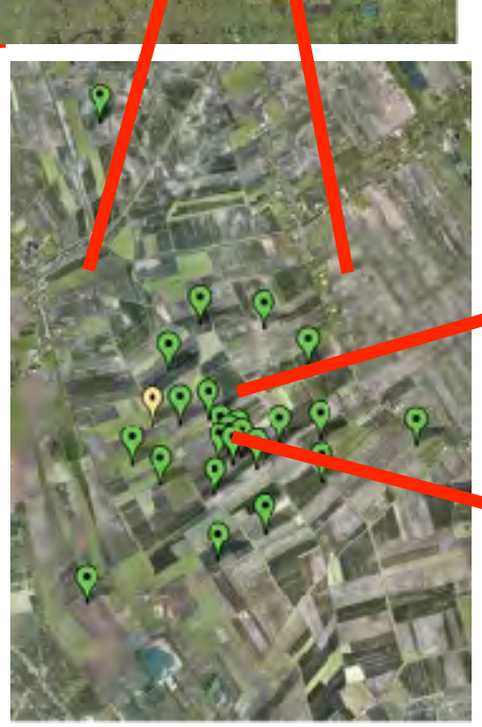
Pointage électronique

« Beamforming »

LOFAR
un réseau hiérarchique





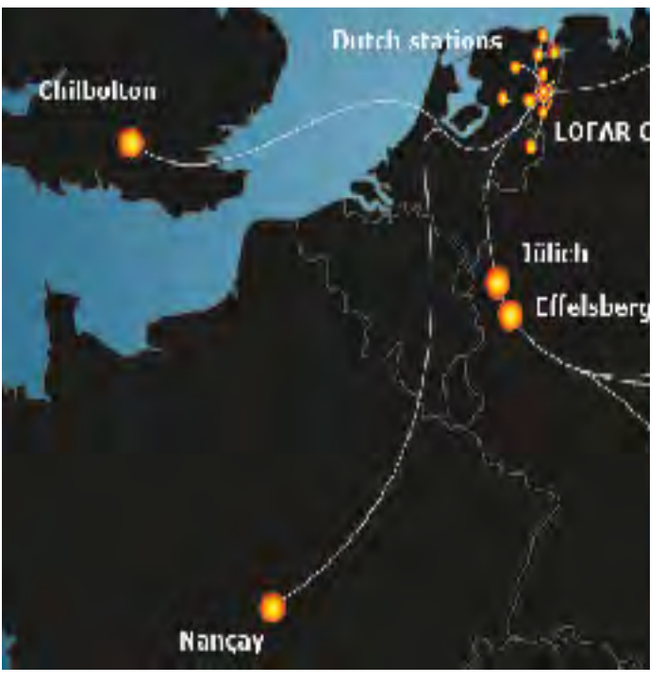


- 1824 antennes / tuiles NL + 1248 Internationales
- Imagerie, « Beamforming », Formes d'ondes

RDN

RH

LOFAR
FR606

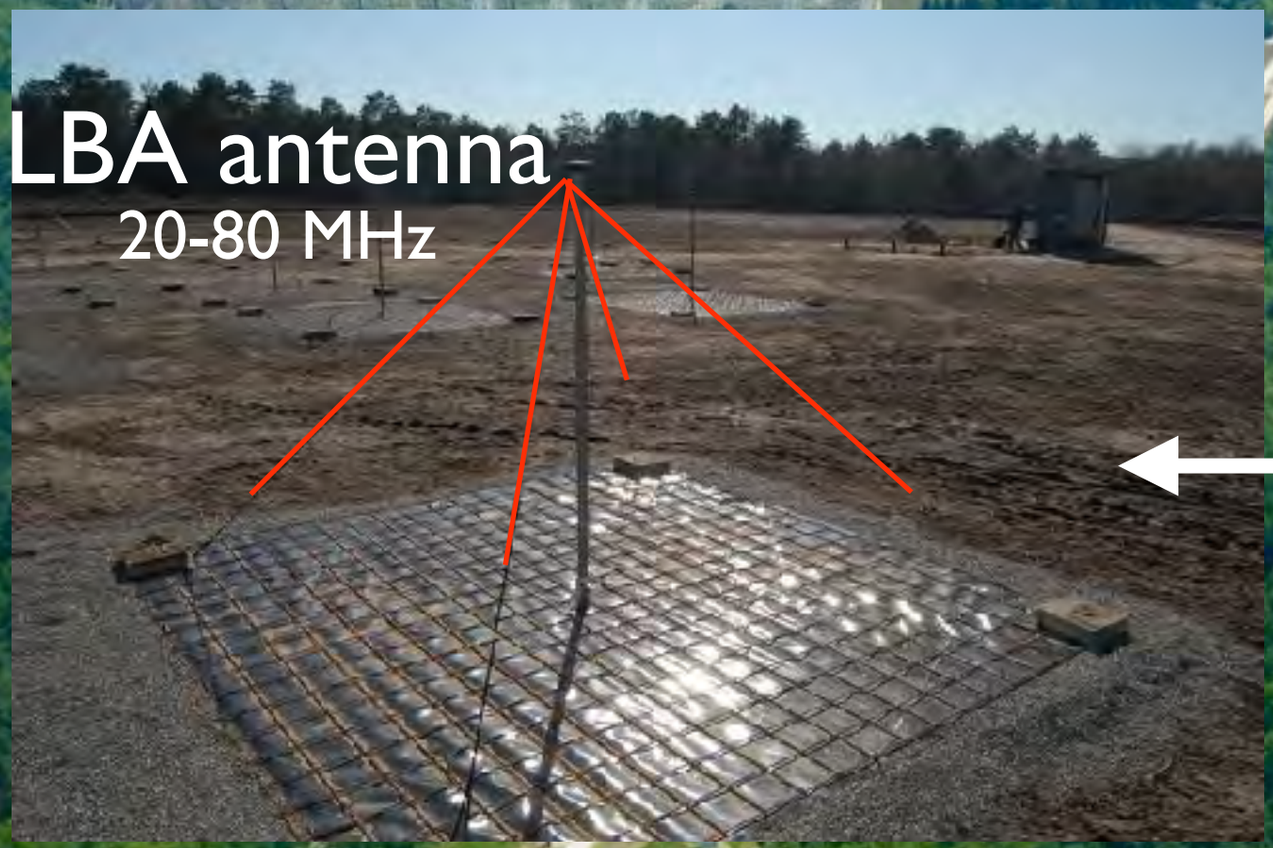


Bois Baunot

RT

Station de Radioastronomie de Nançay

LOFAR station in Nançay : FR606



LBA antenna
20-80 MHz

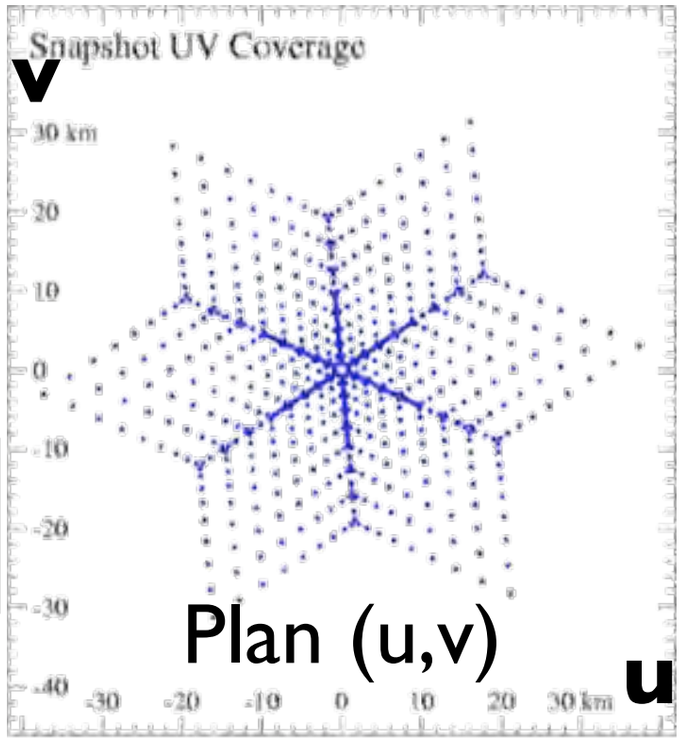
HBA tiles
110-250 MHz

LOFAR
un télescope numérique

Challenge: Complexité de l'étalonnage

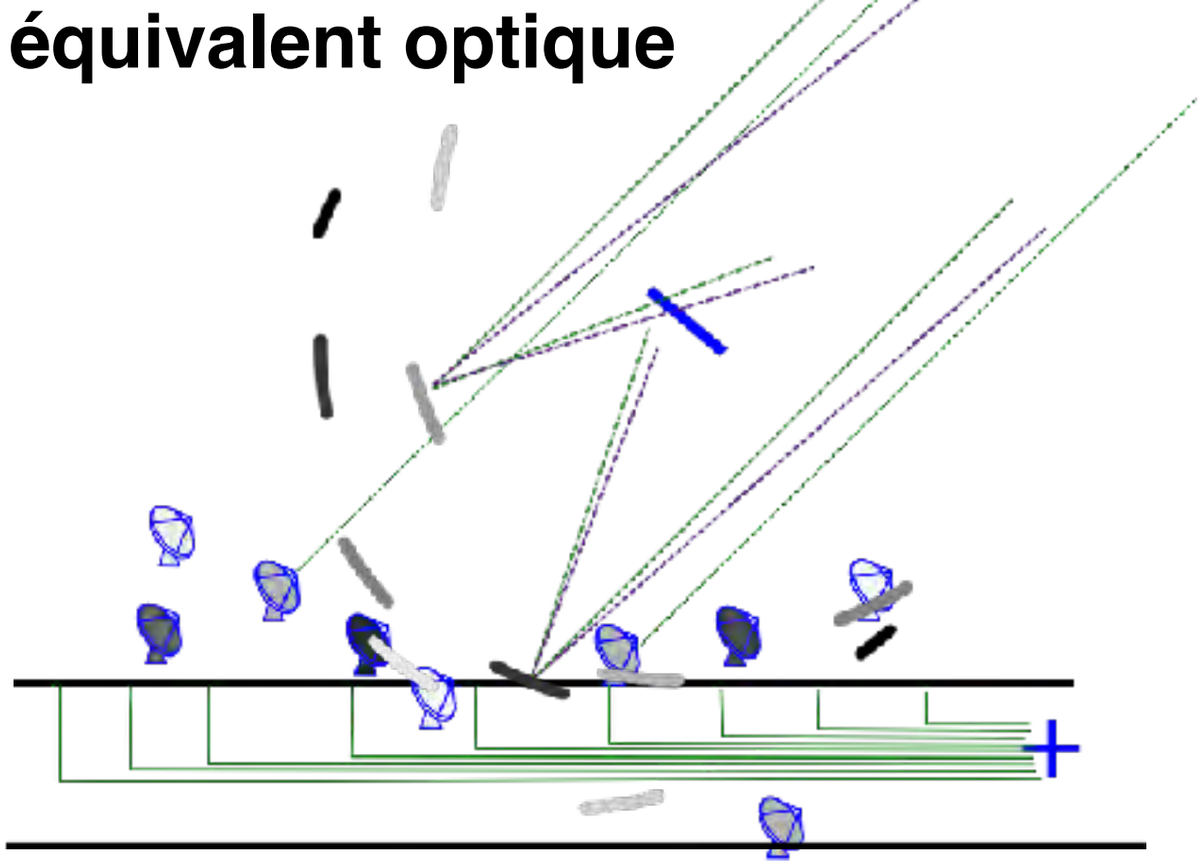
$$\sim \mathcal{F}$$

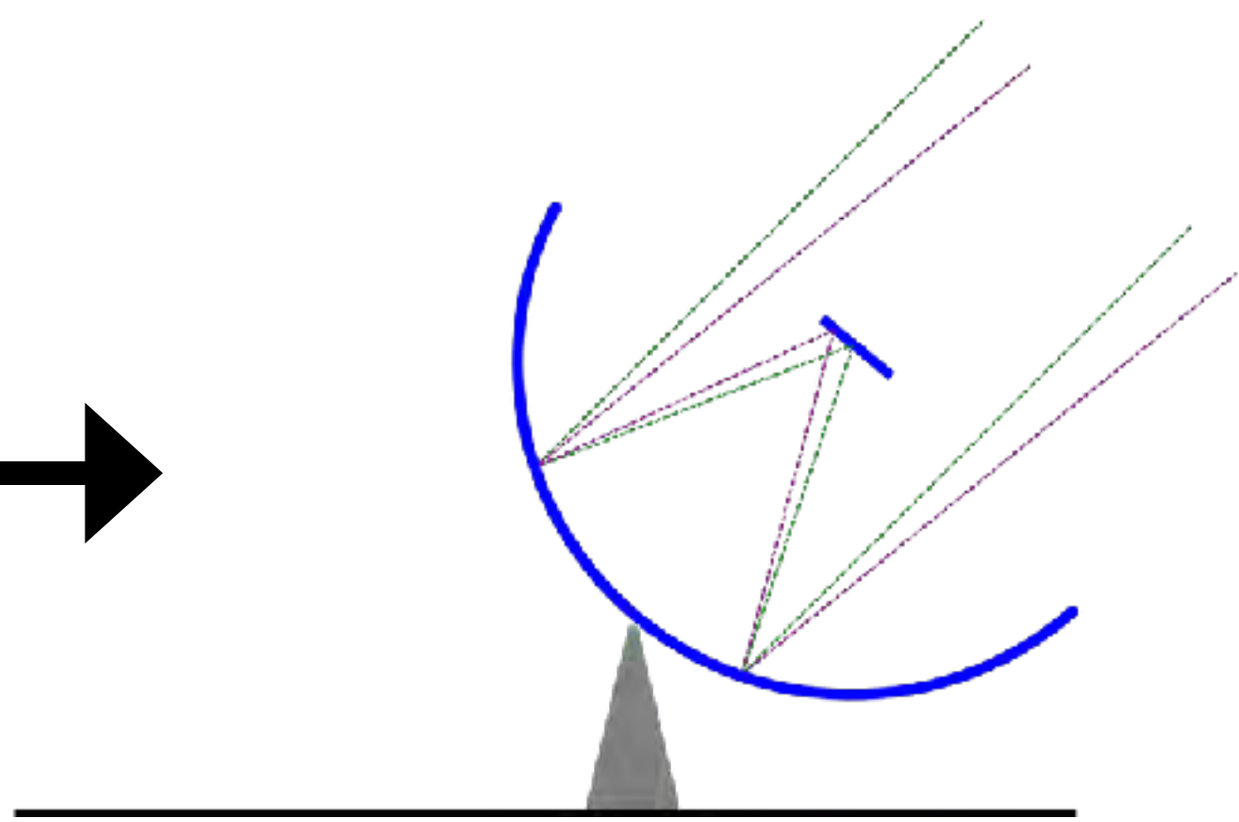
$$V(u,v) = \int\int T(l,m) e^{-i2\pi(ul+vm)} dl dm$$



Plan (u,v)

équivalent optique

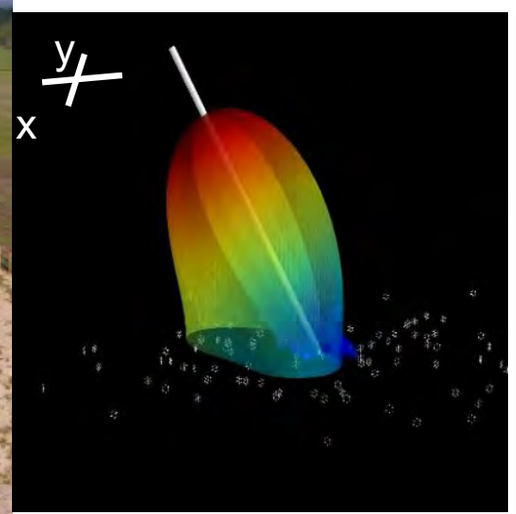


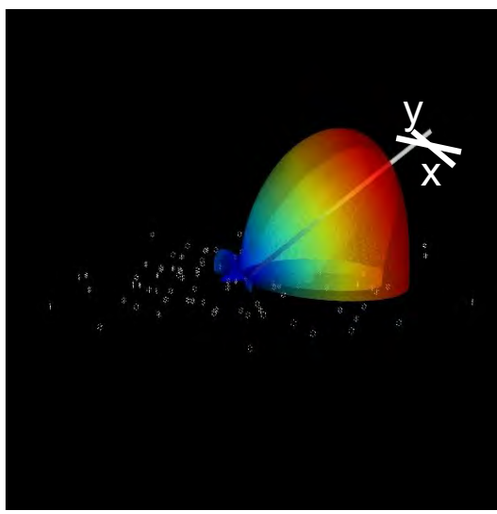


Étalonnage complexe = **« Optique adaptative » en post-traitement**

Challenge: Complexité de l'étalonnage

Effets dépendants de la direction (DDE)



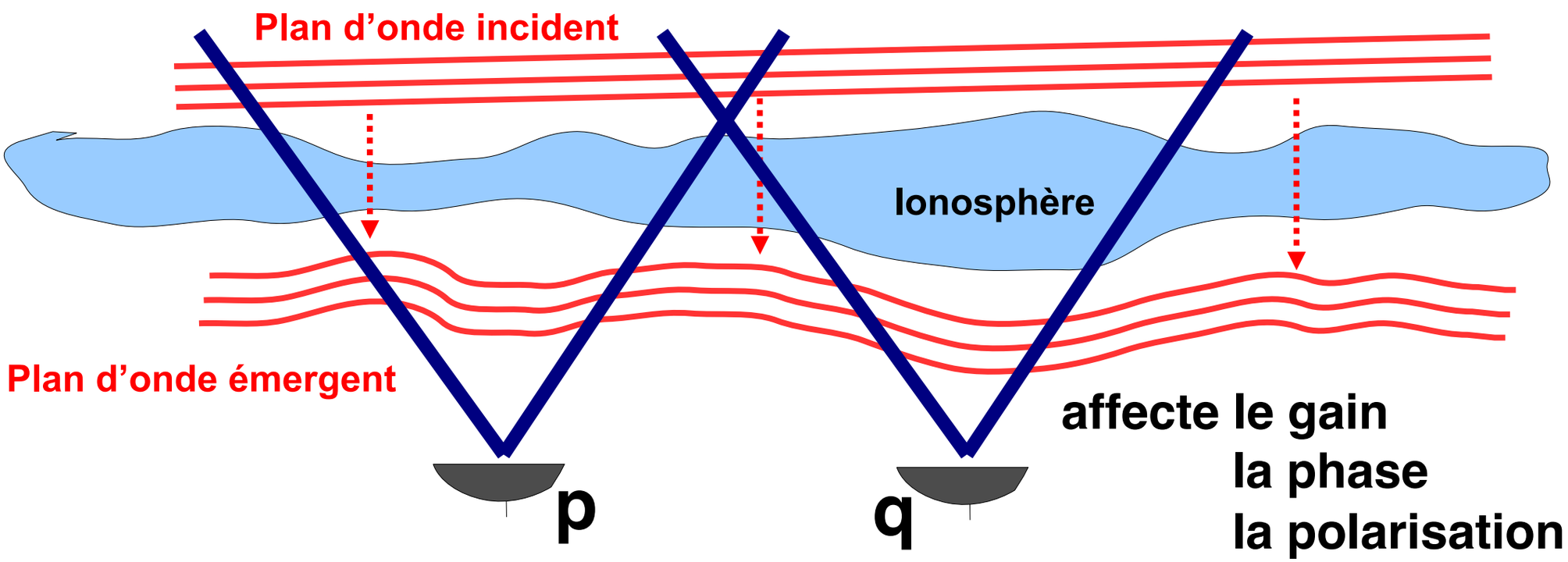


Direction 1
affecte le gain

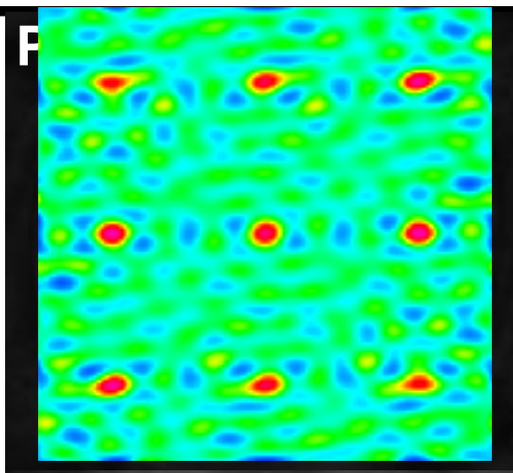
Direction 2
la polarisation

Diagramme d'antenne

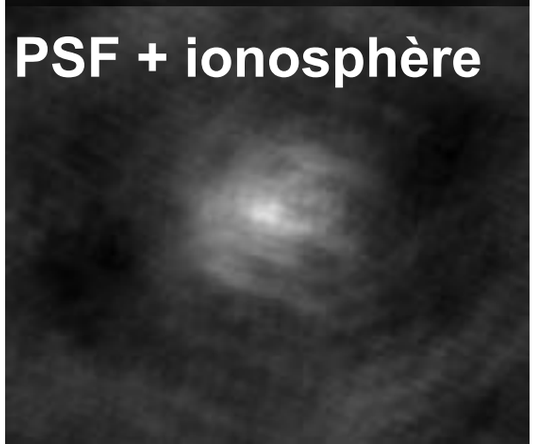
Fluctuations ionosphériques



affecte le gain
la phase
la polarisation



PSF + ionosphère

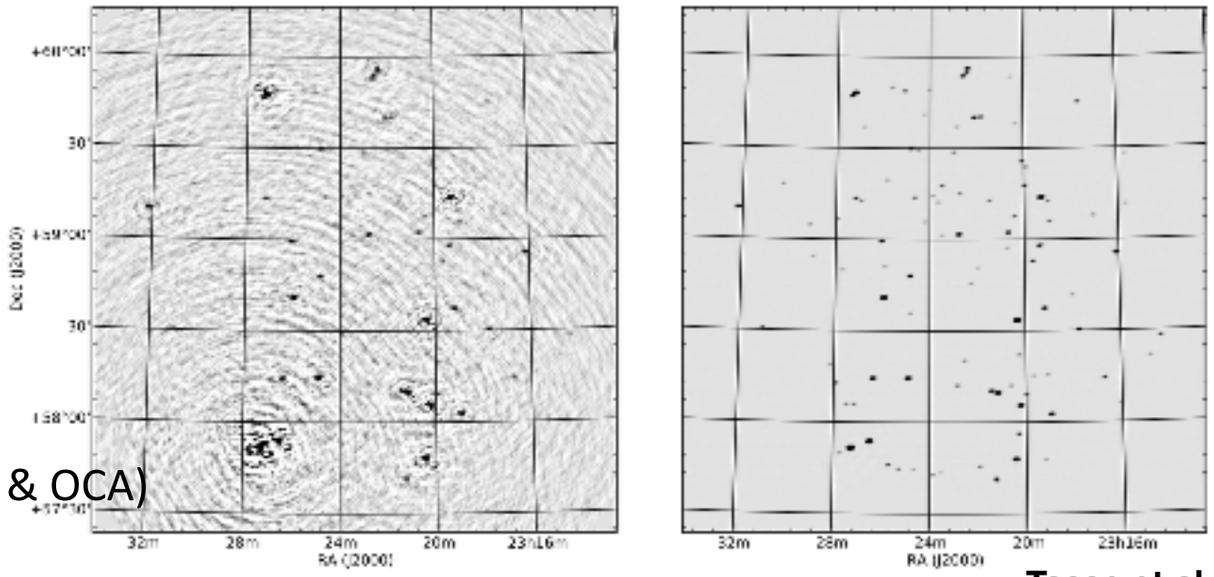


Forte expertise Française en imagerie et calibration BF

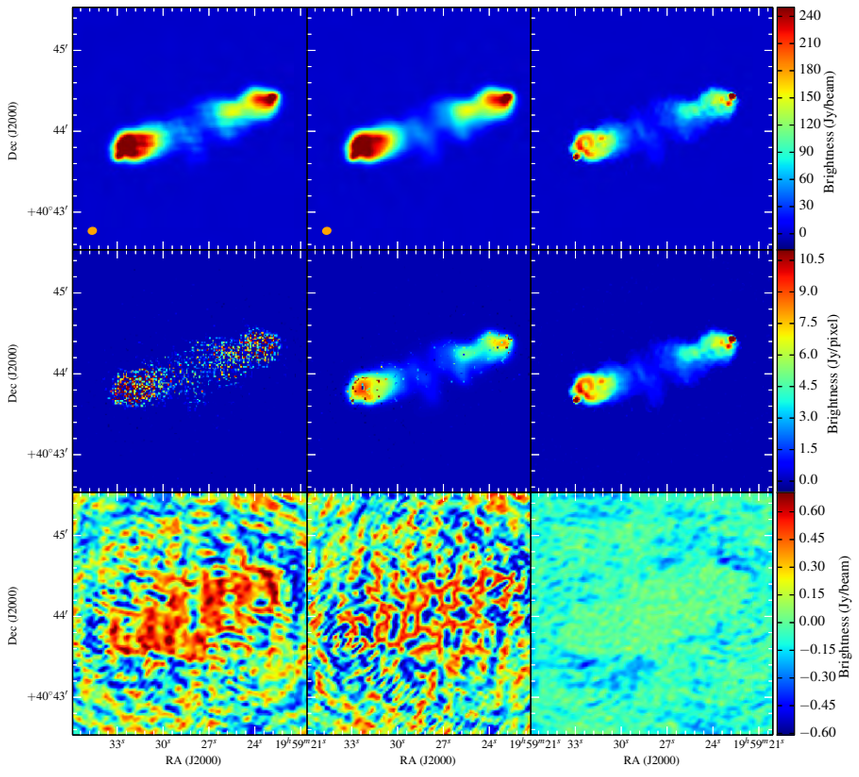
- **Imagerie « dépendante de la direction »**
  (AW-Imager, DDFacet, GEPI, OP)

- **Calibration** Non-linear Kalman filters (GEPI/OP)

- **Imagerie « Compressed sensing »** 2D et 3D (CEA/AIM & OCA)



Tasse et al., 2013



Garsden, Girard et al., 2014

- **DDFacet** (OP/SKA-SA) → MeerKAT 1st light image

Tasse, Smirnov et al., 2016

Programmes scientifiques

Interféromètres: VLA, ATCA, WSRT, …

LOFAR **F=30-250 MHz**

SKA SQUARE KILOMETRE ARRAY **F=50 MHz - ~10 GHz**

Projets-clefs		Projets-clefs
Cosmologie		Cosmologie
Sources transitoires		**Sources transitoires**
Rayons cosmiques	→	Tests RG en champ fort
Magnétisme cosmique	**~2020**	« Cradle of life »
Survey Extragalactiques		Magnétisme cosmique
Solaire & Météo spatiale		Evolution galactique HI < z~5 Structure grande échelle

Improving LOFAR ?

LOFAR provides already new science, thus why bother ?

- Radioastronomers ideally want: the whole sky
  at 1 ns x 1 Hz x 0.001" resolution
  all the time
  → necessity of compromises…

  → Building new facilities (e.g. SKA-low)

  → improving existing facilities (e.g. Nenufar !)

- **Improve LBA response**
  → more sensitivity at low frequencies (down to 10 MHz)
- **Large compact array + beamformer**, high instantaneous sensitivity, large FoV
  → pulsars & (fast) transients at LF
- **Large compact array + imager**
  → dark ages/cosmic dawn/(slow) transients
- **LOFAR compatible**
  → more sensitive international baselines (high resolution LBA imaging)
  → short baselines (extended structures)

- **Complementarity with LOFAR**
- **Large programs** (exoplanets, active/flaring stars, dark ages/cosmic dawn ...)
- **Training and development of the (French) community**, in preparation for SKA-1, SKA-LOW…
- **Preserve/develop instrumental expertise** through original developments

The NenuFAR concept

Low Frequency Antenna

LBA antenna
20-80 MHz

x

Analog phased array

HBA tiles
110-250 MHz

= « LBA » tiles → Increase instantaneous sensitivity

The NenuFAR concept

LOFAR Super Station & Large Standalone LF Radiotelescope (10-85 MHz)

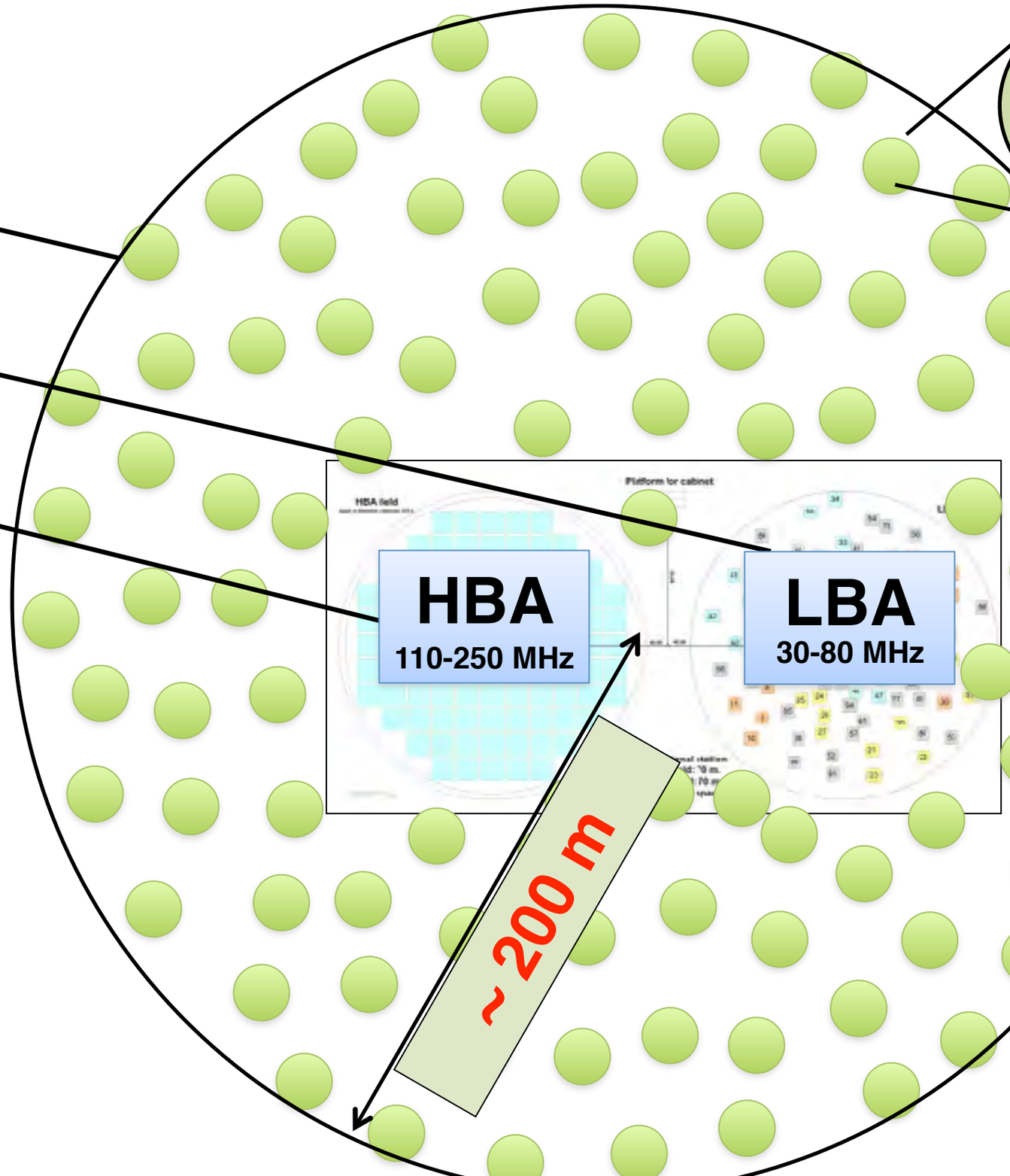
LOFAR Nançay back-end

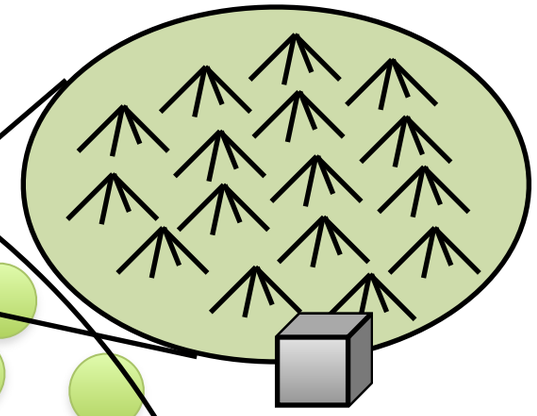
NenuFAR/ LSS

LBA

HBA

96 mini-arrays
(LF tiles)
of 19 antennas,
analog phased
$\Delta f \supset$ LBA range



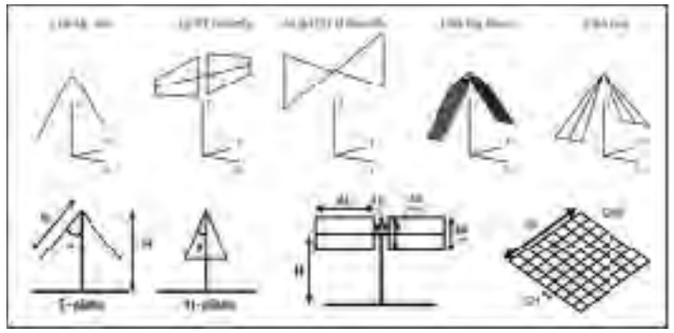


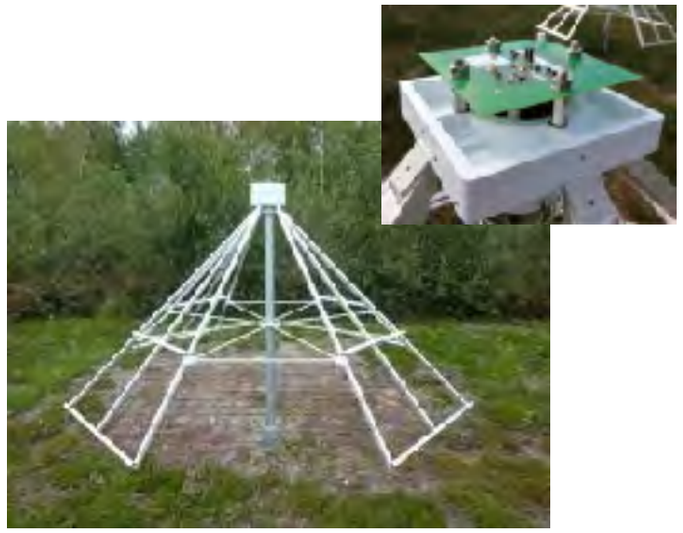
Phasing
+
Summation

Design studies

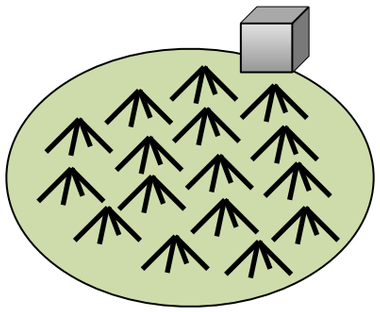
Simulations & optimisation multi-échelle

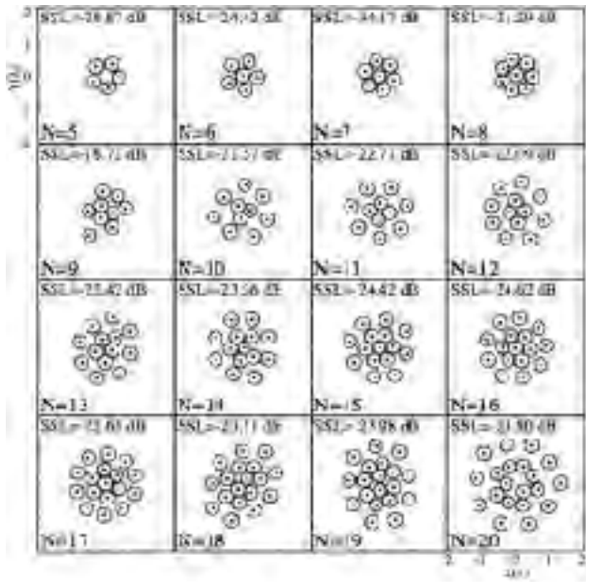
Antenne élémentaire



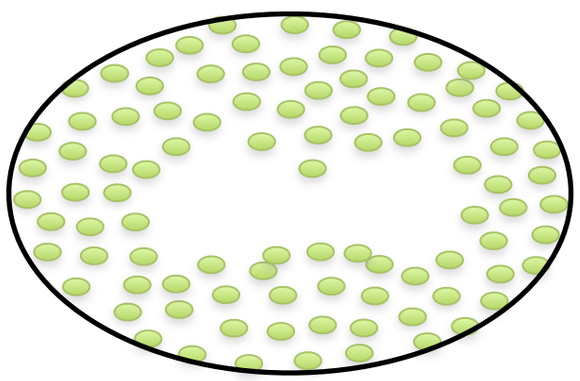


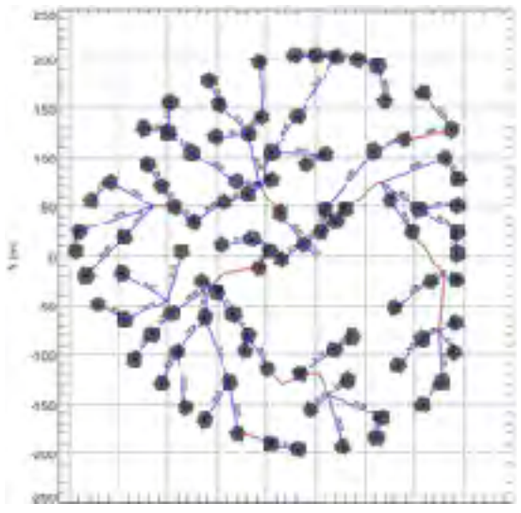
Mini-réseau





Interféromètre/Réseau phasé





Statut

En phase de recette

~28% réseaux construits

(15 à construire en 2017)

Statut de pathfinder de SKA

Priorité P1 pour l'INSU

Girard et al., CRAS, 2012

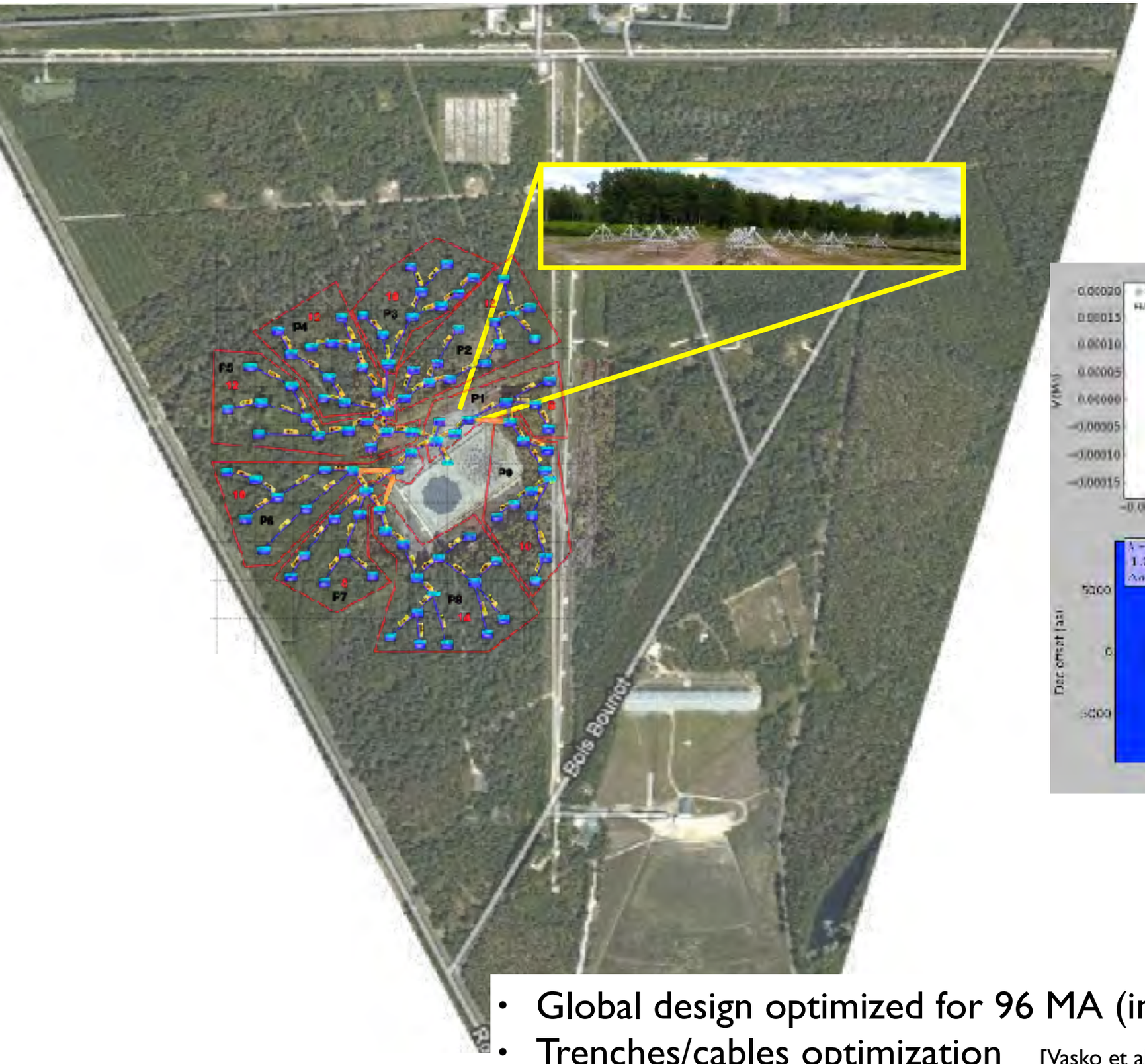
Girard et al., SF2A, 2012

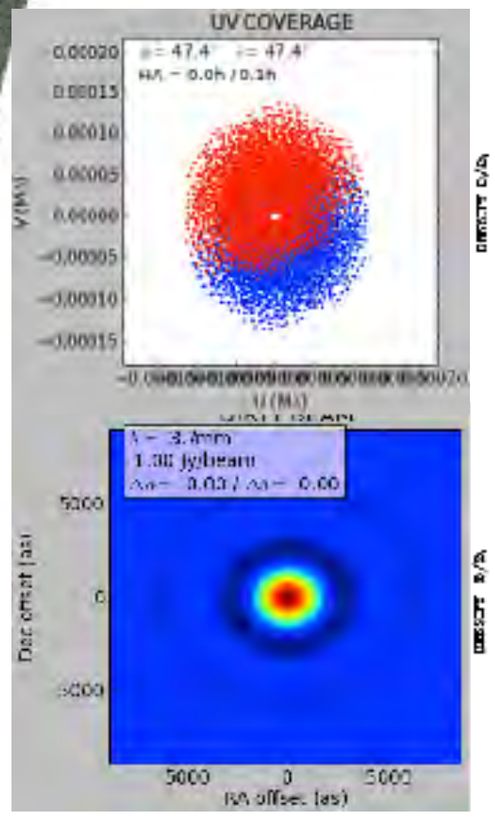
Zyma, Girard, Vasko et al., 2016

Zarka, Tagger, Denis, Girard et al., in prep

Design studies

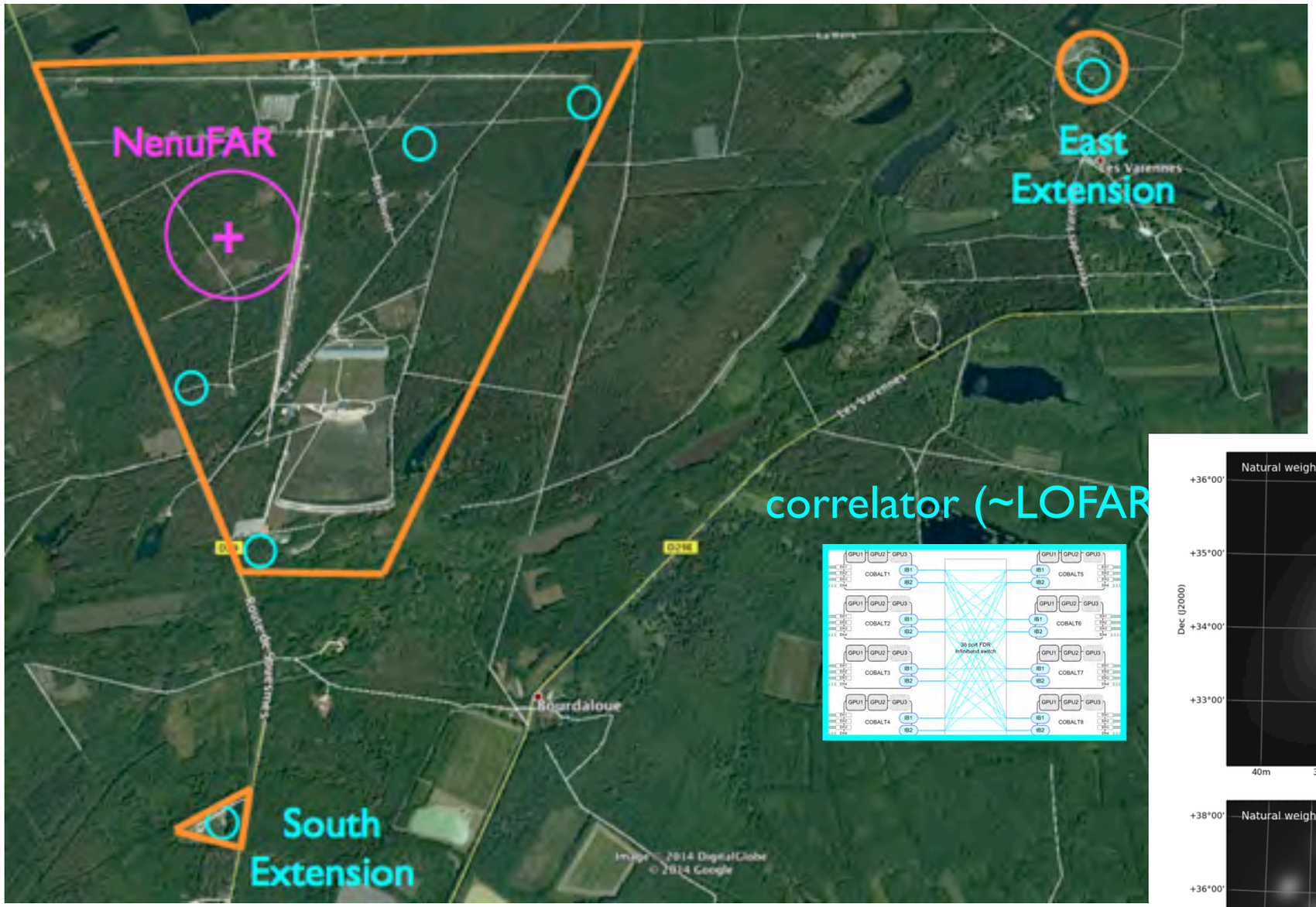
Distribution sur le terrain

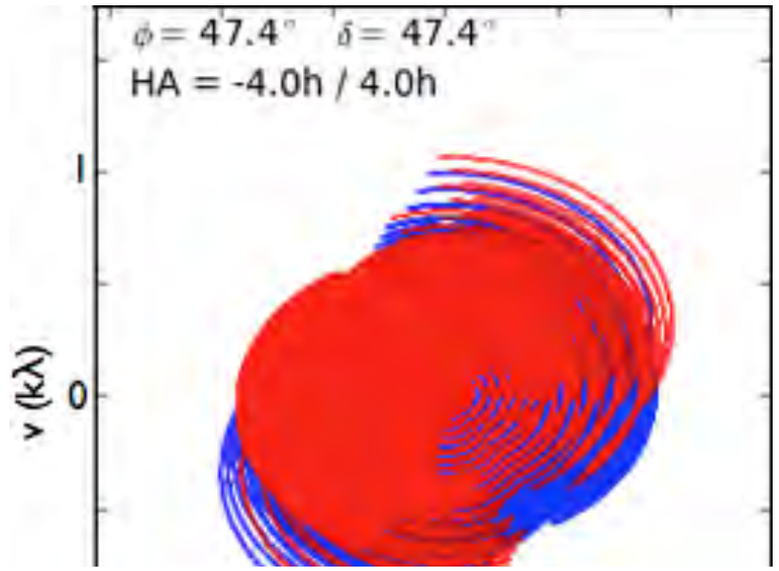


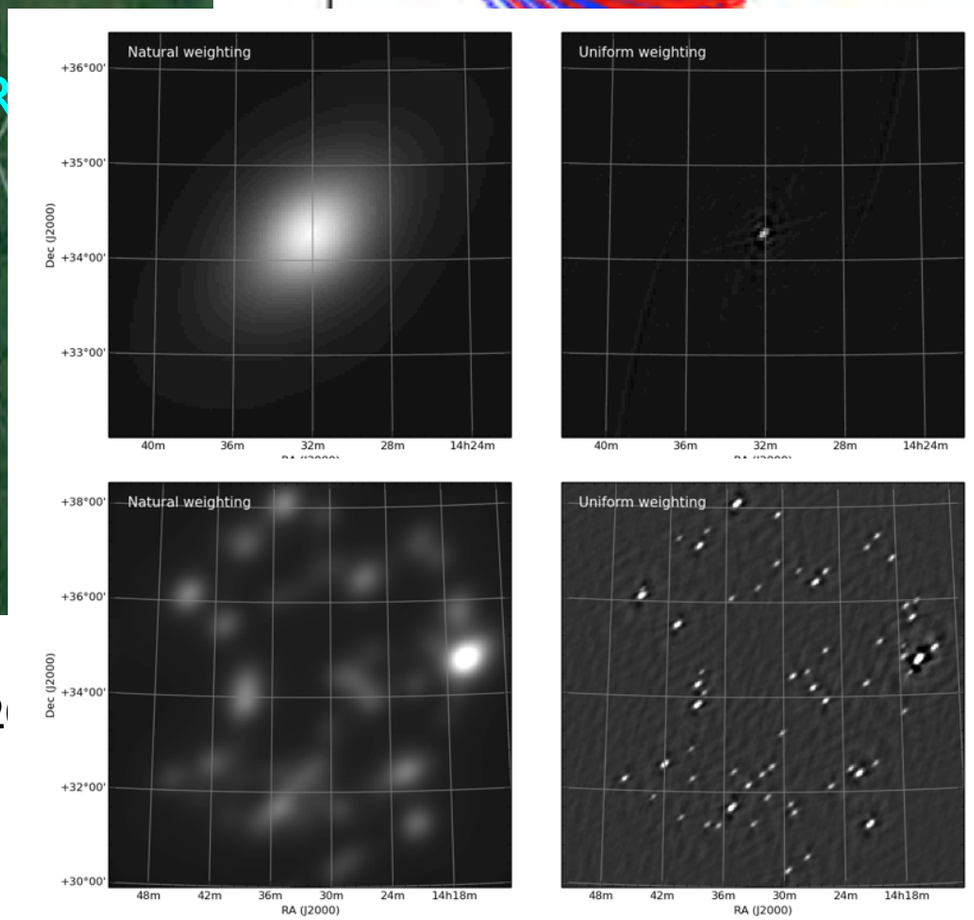


- Global design optimized for 96 MA (incl. MA rotations) + 6 distant MA
- Trenches/cables optimization [Vasko et al., 2016]
- Construction in 9 petals, consumption ~50 kW

Design studies: the extended NenuFAR







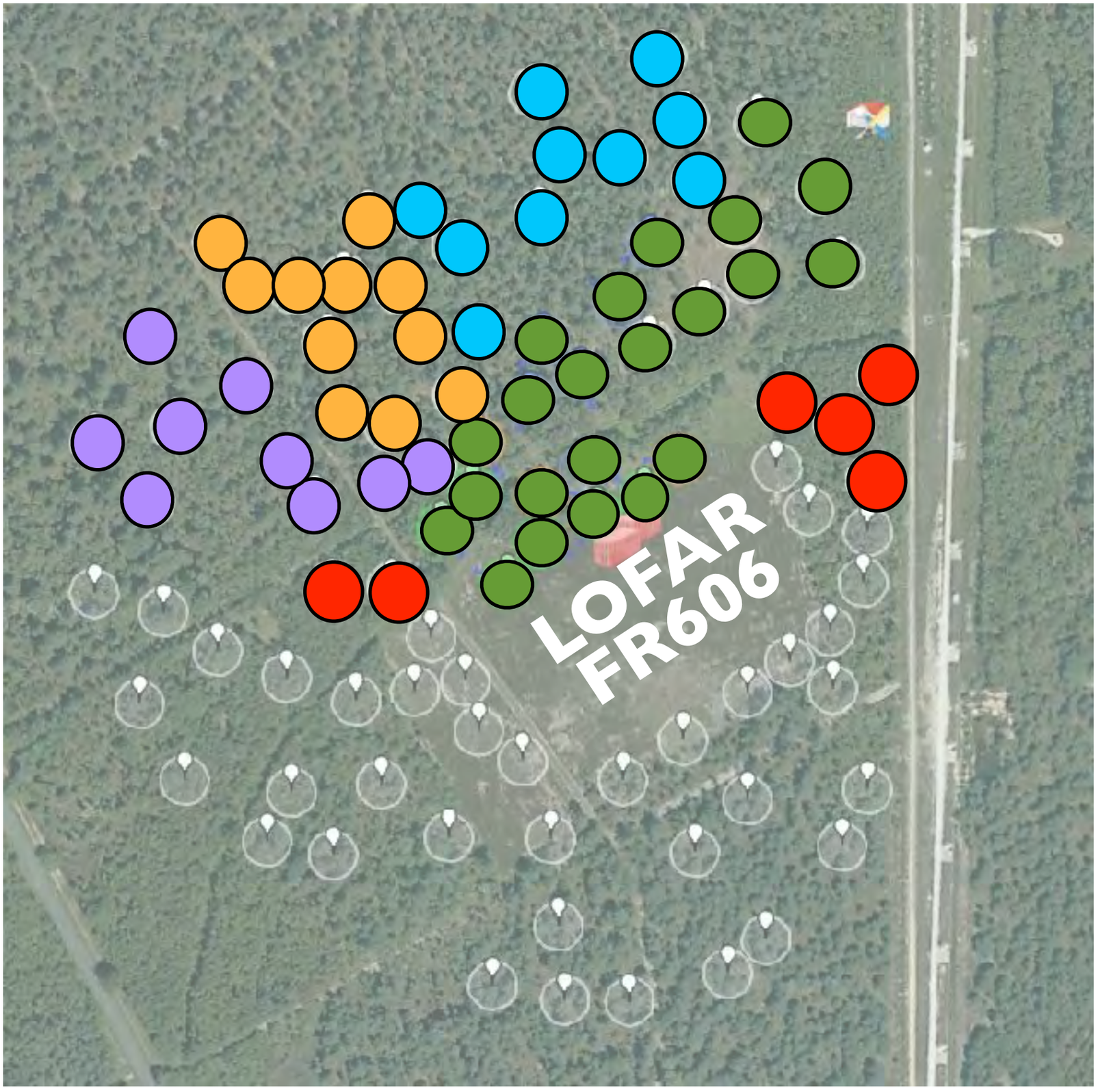
- $\sigma_{confusion}$ [mJy/beam] ~ $(\nu / 100\ MHz)^{-0.7}$ $(\theta / ')^2$ [Condon, 2
  → 1-50 Jy @ 20-80 MHz (unpolarized signal)

- correlator + 6 distant MA + multi-λ synthesis
  → angular res. x7 for stationary broadband sources → $\sigma_{confusion}$ / 50

- Relative sensitivity beyond compact core = $(N_{distant}/N_{core})^{1/2}$ ~ 25%

Construction

Construction



Coût total non consolidé

~4,5 M€

(96 x 41 k€ +

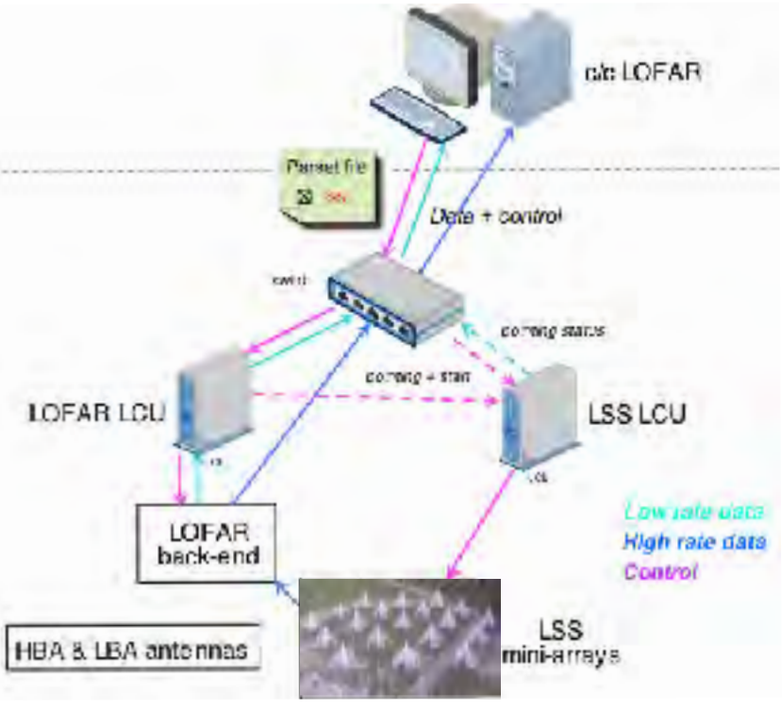
infrastructures)

+ manpower + centre de

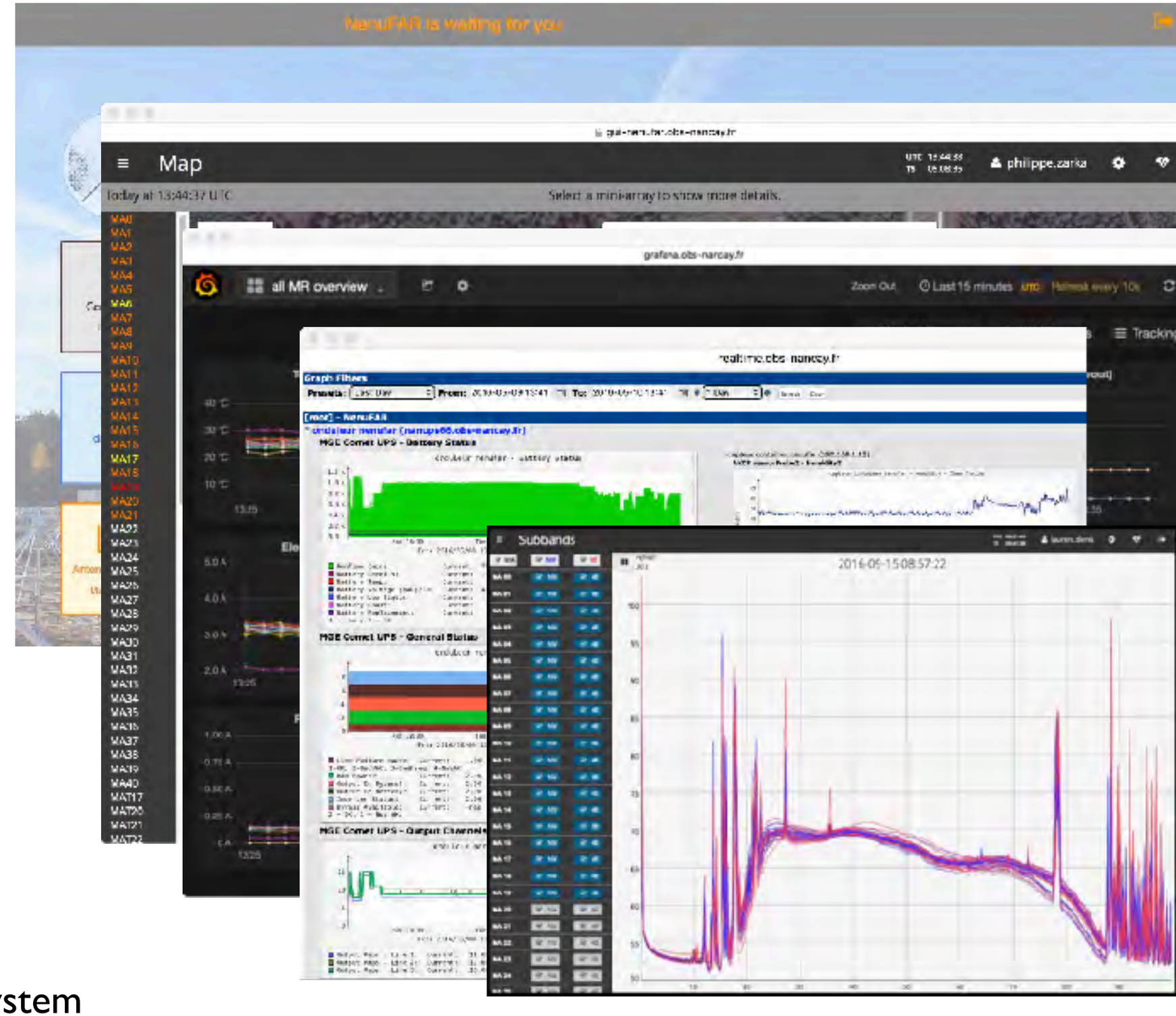
données

- Octobre 2015 - 22MR
- Décembre 2016 - 32 MR
- Printemps 2016 - 41 MR
- Juillet 2017 - 52 MR
- Novembre 2017 - ≥58 MR

Design studies

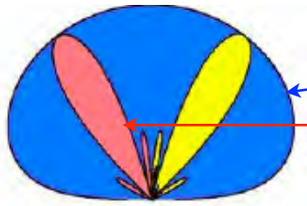


Operation, control & monitoring



- Dialog with LOFAR
- Silent control/command system
- Pointing protocol : ramp of analog phasing switches over <10 msec at round multiples of 10 sec
- Online realtime monitoring

NenuFAR : 3 instruments in 1
signal path/data flow/receivers/data products



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

Distant MA (≤3 km) : 6 MA x 2 polar.

analog signals

analog signals

analog signals

Recepteur Station LOFAR FR606

LOFAR Super Station NenuFAR

40 kB /s /channel

High-resolution imaging
(~0.1" , IQUV) [+TBB]

Recepteur NenuFAR Dédié

Post-backend Spectroscopie dynamique + dedispersion

16/δt bytes /s /channel

- Dynamic spectra (δt x δf)
- Time series (δt)

(IQUV, multibeam) [+TBB]

150 MB /s /SB

Correlateur Dédié Imagerie

NenuFAR Standalone Radio Imager

40 kB /s /channel

- Instantaneous (~1 s) coarse imaging (~1°)
- Slow (6-8h) multi-λ mid-resolution (8') imaging → confusion ~ thermal noise (IQUV)

1.6 MB /s /SB

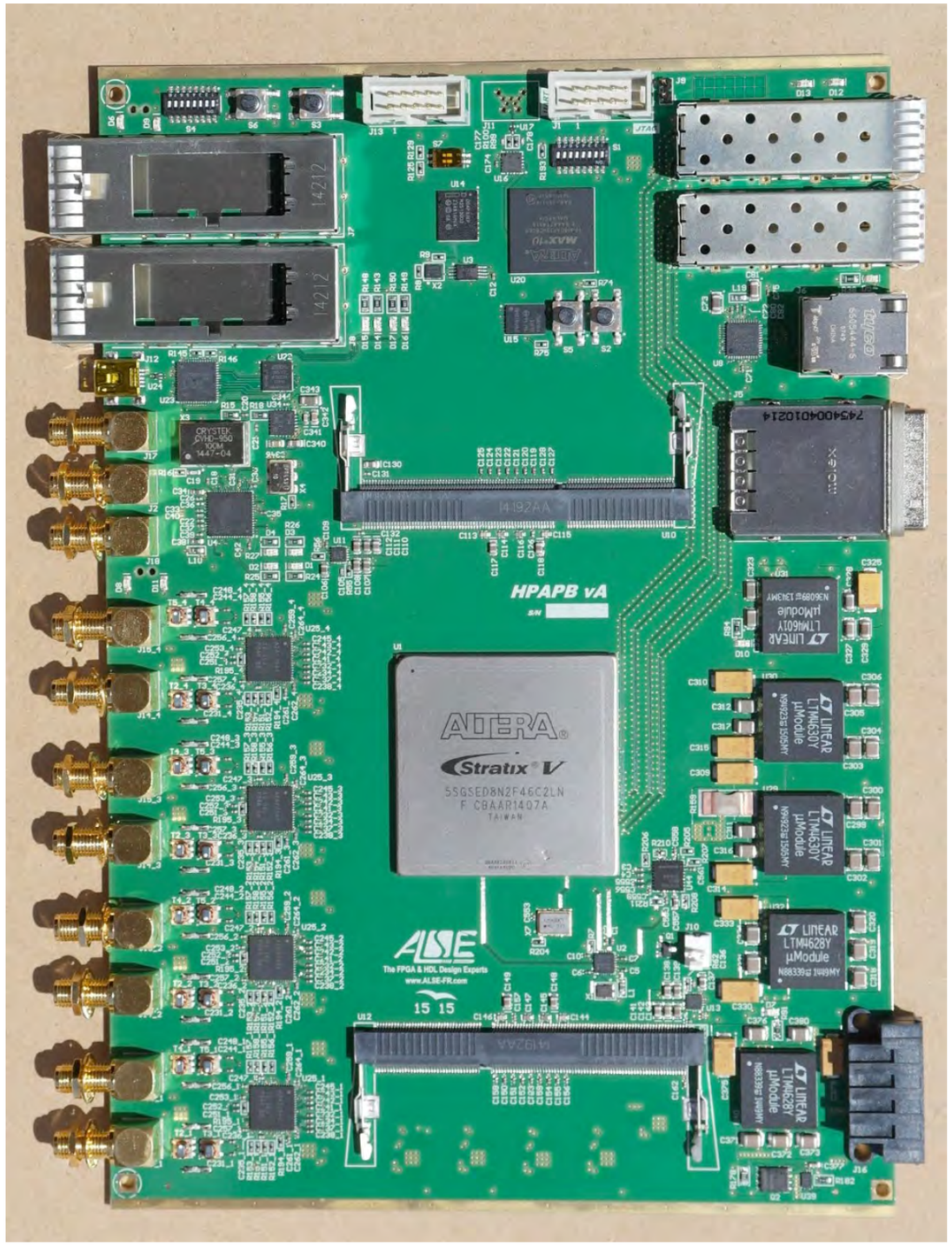
NenuFAR-Backend-0
(= UnDySPuTeD offline on <<768 SB)

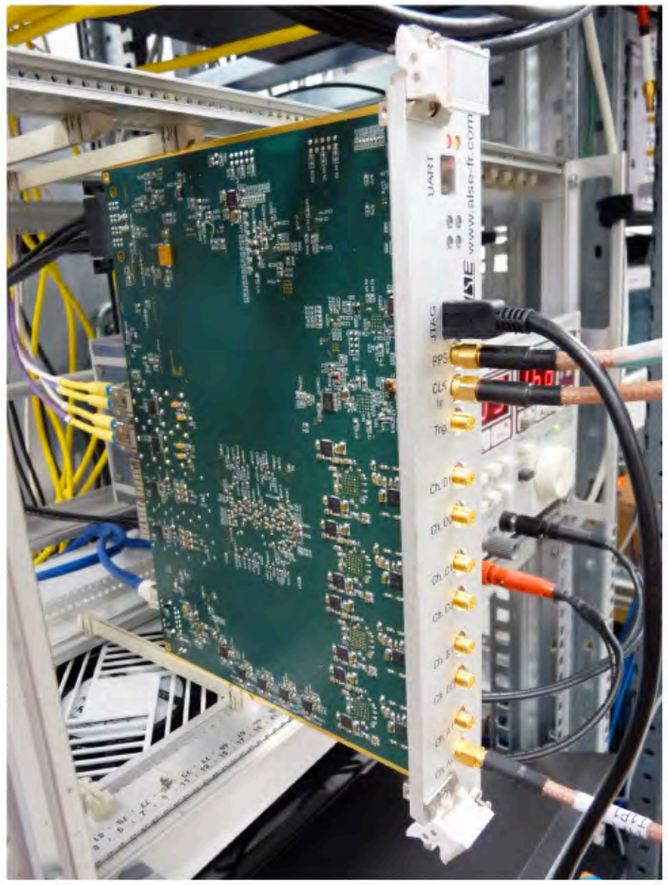
- Channelization down to δf<1 kHz
- Dedispersion (predefined, parametric)
- Integration over δt ≥5 µs

MA = 19 antennas mini-array
SB = ~200 kHz sub-band
PFB = polyphase filter bank
TBB = Transient Buffer Boards
SST/BST/XST = Subband/Beamlet/Crosslet STatistics

Design studies

Digital Beamformer: LaNewBa





96 x 2 ADC @ 200 MHz

FPGA polyphase filtering + beamforming

→ 768 beamlets, 200-kHz wide, 200 k-complex/s

No correlation, statistics data:

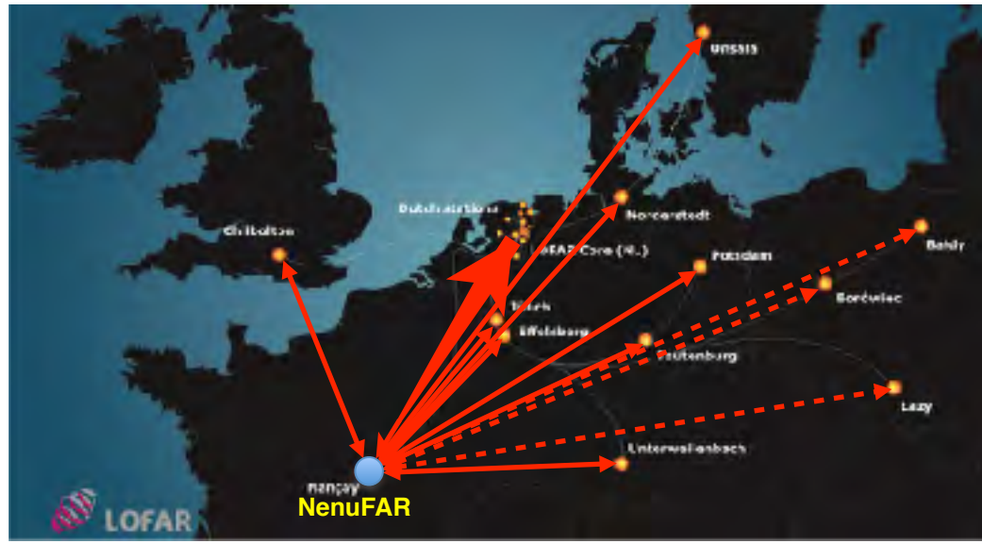
SST, BST : 1 / sec / subband

XST : 32 SB / sec

What NenuFAR will bring

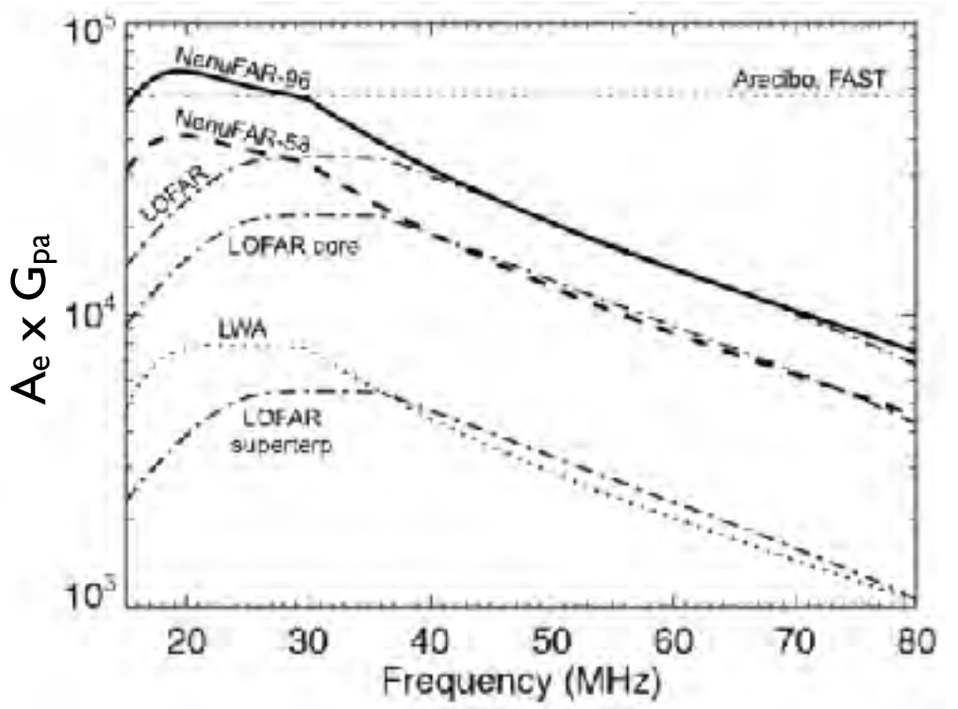
NenuFAR/Lofar Super Station (LSS): *[MoU LOFAR-NenuFAR]*

- ~4x more sensitive long baselines
  → ~10x more calibrators, better high res. (0.1") imaging
- Global LOFAR LBA sensitivity x 2
- NenuFAR as 2nd LOFAR core ?



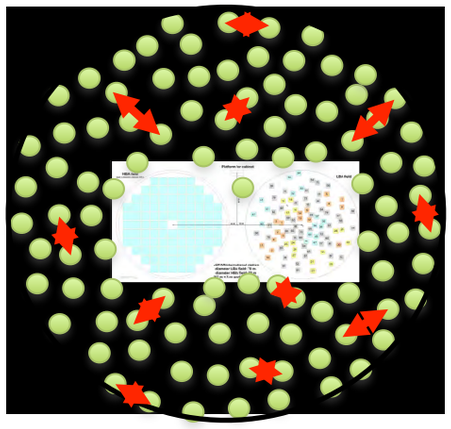
NenuFAR/Standalone Beamformer:

- High sensitivity in LBA range, down to ~10 MHz (>LOFAR)
- Broad instantaneous bandwidth (150 MHz, full polar.)
- Multi coherent tied-array beams (768 200kHz-beamlets)
- Broad FoV (10's°)
- Large duty-cycle programs



NenuFAR/Standalone Imager:

- Short baselines intra-NenuFAR ⇒ large scale structures (>10°)
- Fast imager (1 sec., core only) → (40/f)° ~1°
- Slow imager (6-8 h, core + distant MA) → (340/f)' ~8'



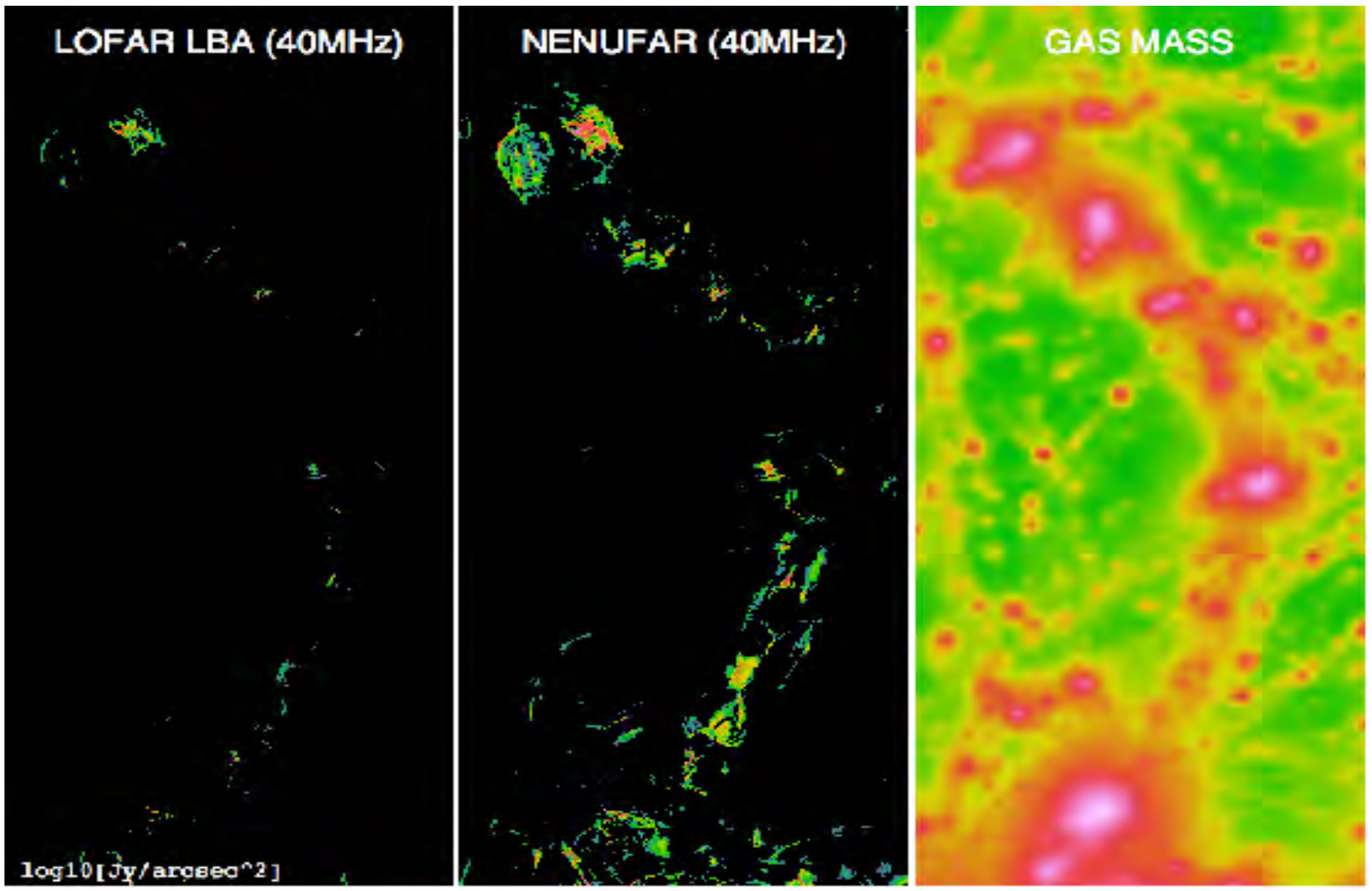
Caractéristiques techniques de NenuFAR

- Réseau phasé et interféromètre géant compatible avec LOFAR
- 1938 antennes : 96+6 mini-réseaux de 19 antennes chacun (25 m ∅)
- Diamètre : ~400 m + extensions → 3 km
- 5151 lignes de base
- Gamme de fréquences = 10-85 MHz (λ=3.5-30m)
- Resolutions : δf = 200 kHz → 1 kHz, δt = 5 µsec, Waveform @ 5 nsec
- Polarisation complète (4 Stokes)
- Champ de vue (FoV) : 32° - 8° @ 20-80 MHz ; pointage (δ) -23° → +90°
- Résolution Angulaire : 2°-0.5° (Standalone instantanée),
  17'-4' (Imageur standalone), 0.1 " (dans LOFAR)
- Surface collectrice : ~650λ^2 ≤ 65 000 m^2
- Sensibilité : 2 - 0.5 Jy @ 20-80 MHz (5σ, 1 sec x 10 MHz, signal polarisé)
  10 – 2 mJy '' (5σ, 6 h x 40 MHz)
- Confusion au zénith : 50 – 1 Jy @ 20 – 80 MHz (non pol)
  1 Jy - 20mJy @ 20 – 80 MHz (non pol avec extens.)

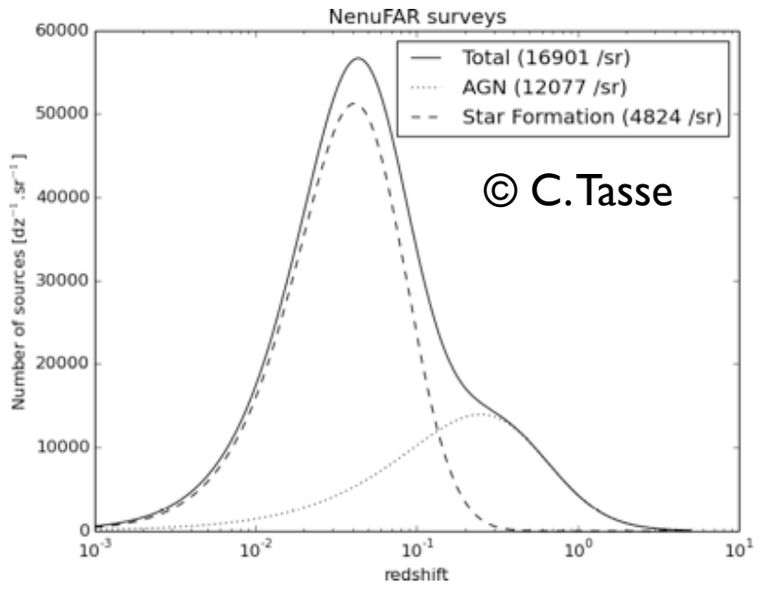
Science with NenuFAR

- **NenuFAR in LOFAR** : very high resolution wide-field LBA imaging, more sensitivity to extended structures

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



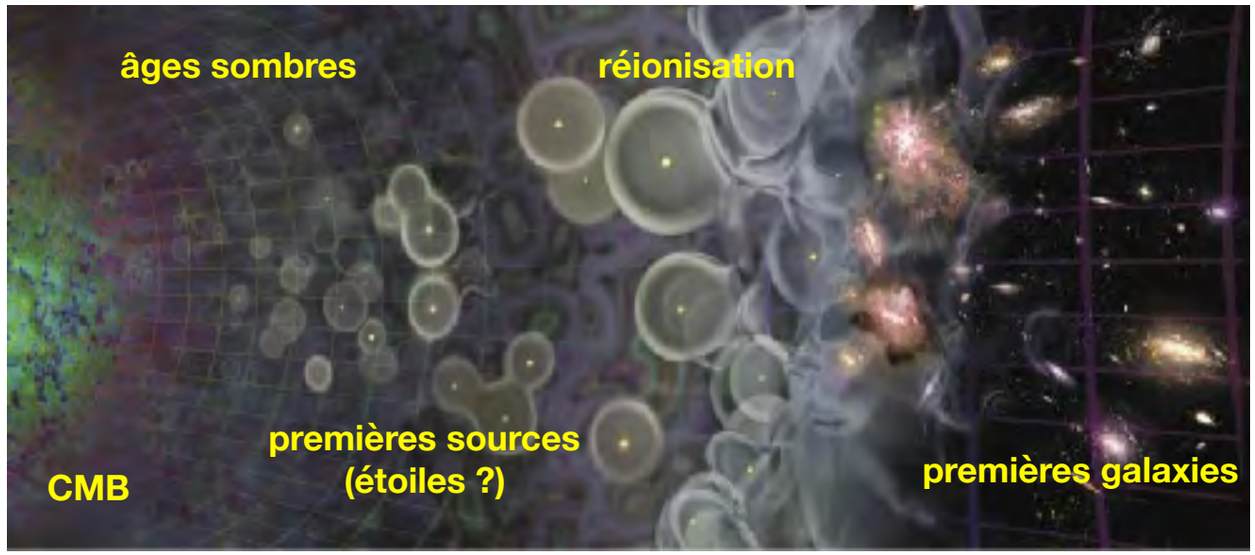
© F. Vazza

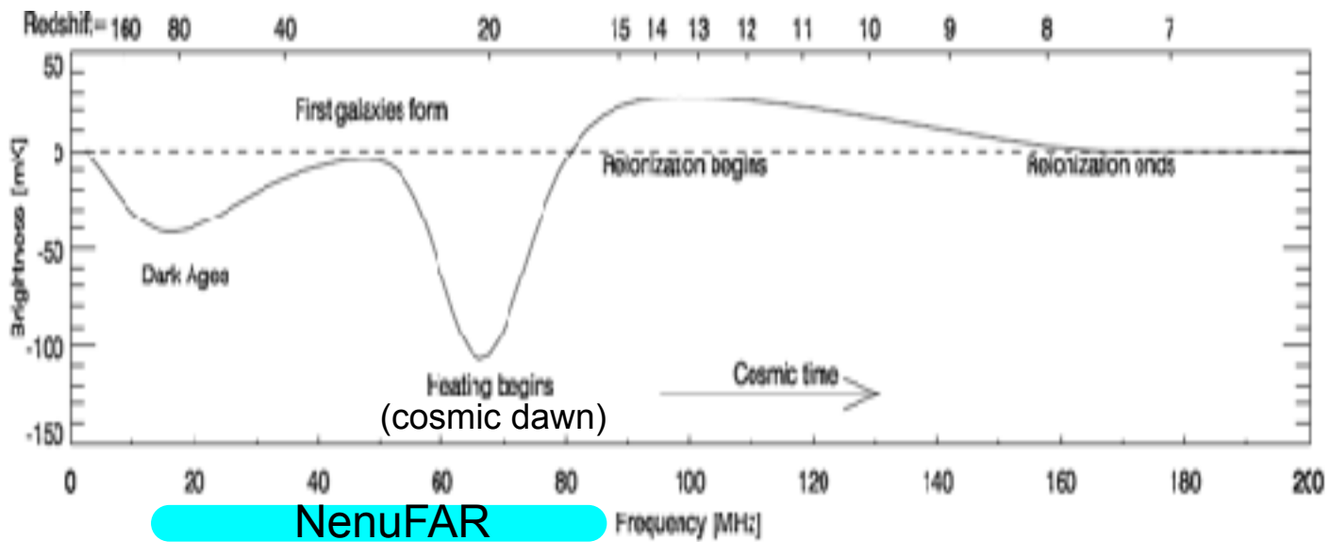


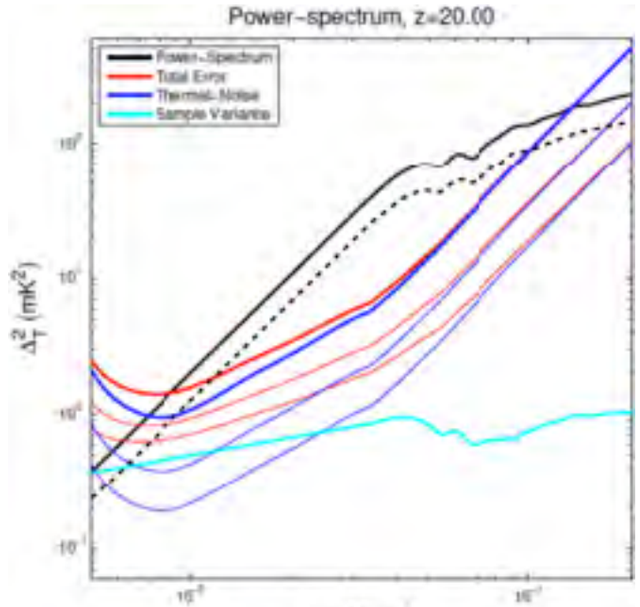
© C. Tasse

Science with NenuFAR

- **Standalone imaging** (multi-frequency rotational synthesis): Dark Ages/Cosmic Dawn

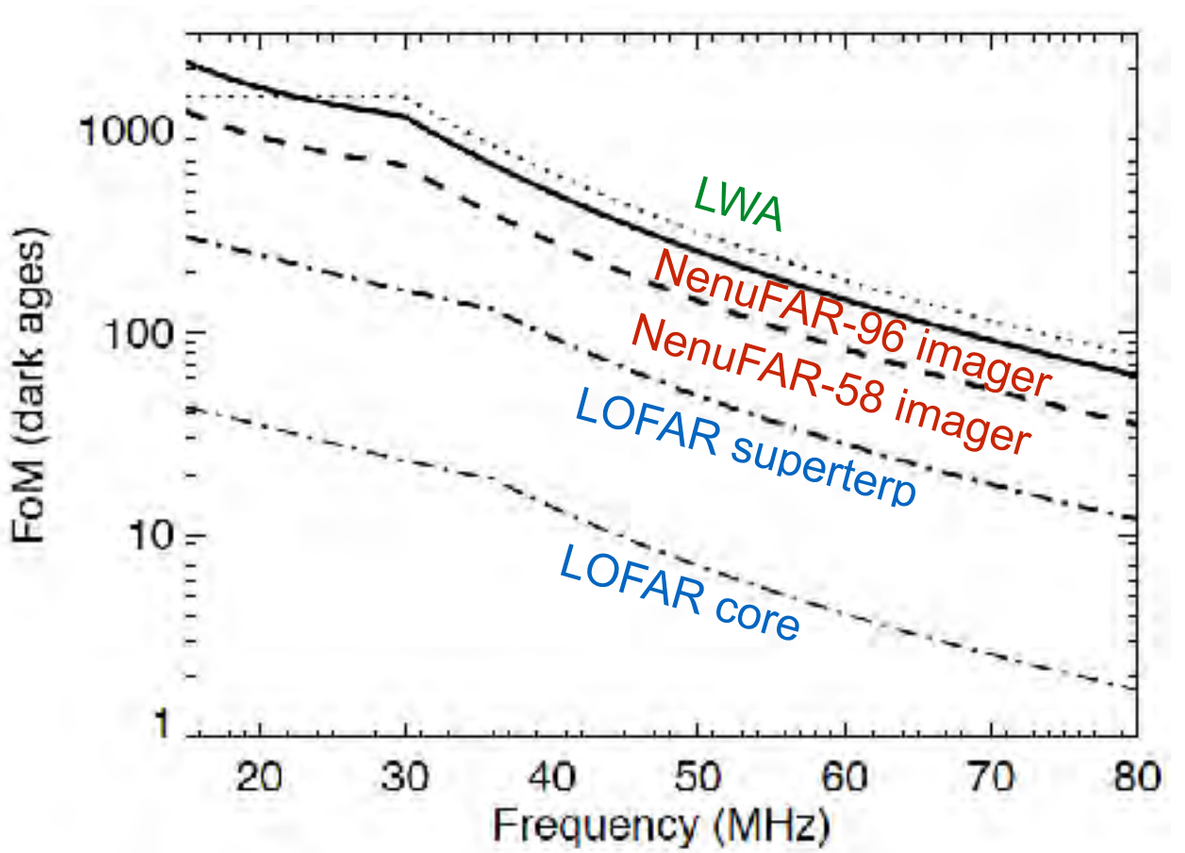






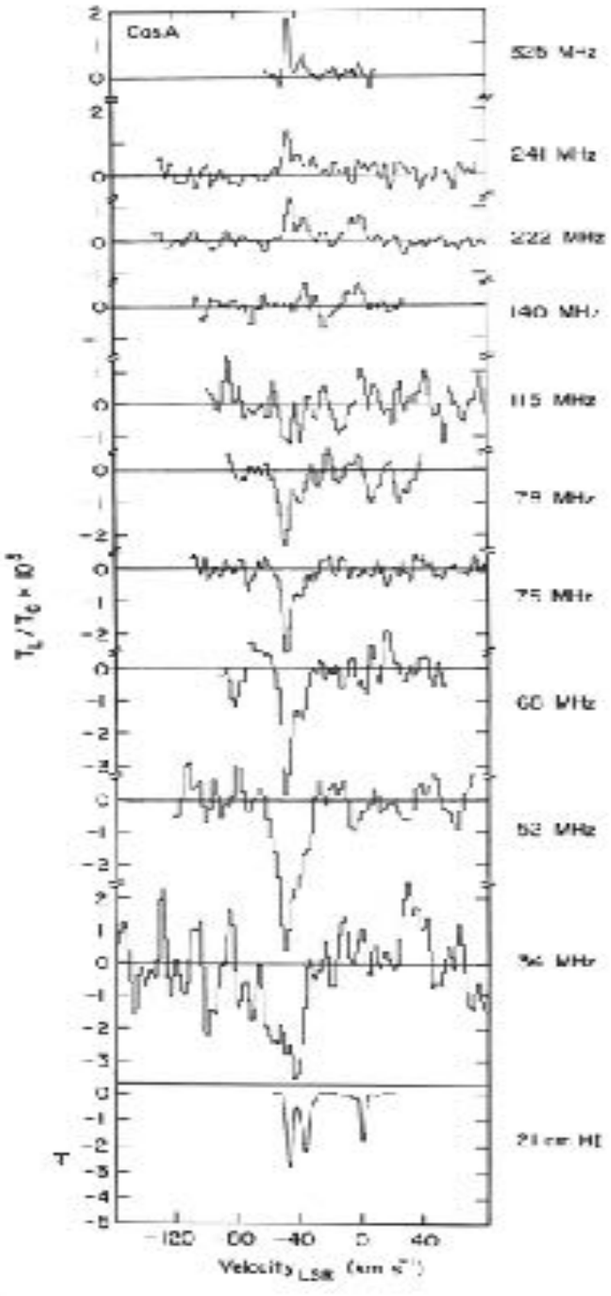
Koopmans et al., 2015

fréquence spatiale

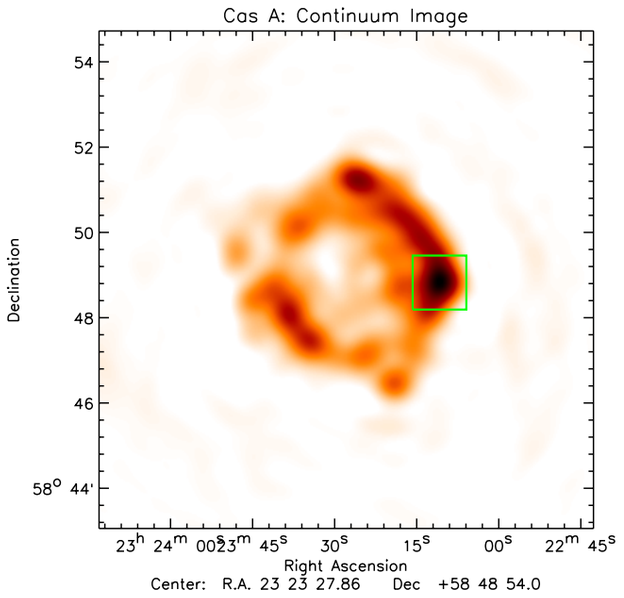


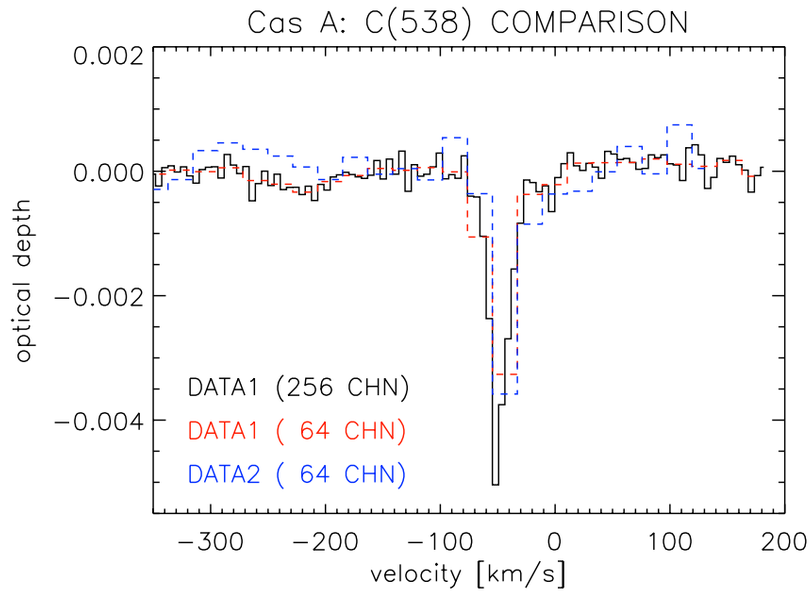
Science with NenuFAR

- **Stand-alone beamforming/Slow Imaging** : Radio Recombination Lines

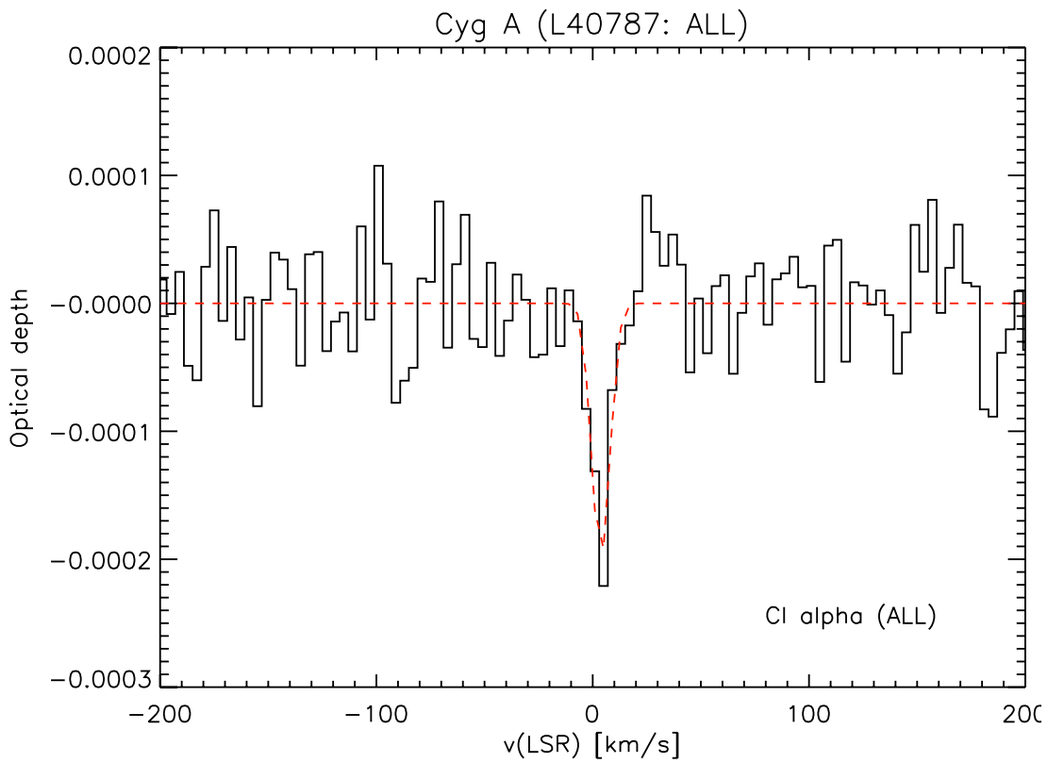


Carbon RRL's towards Cas A
[Gordon & Sorochenko, 2002]



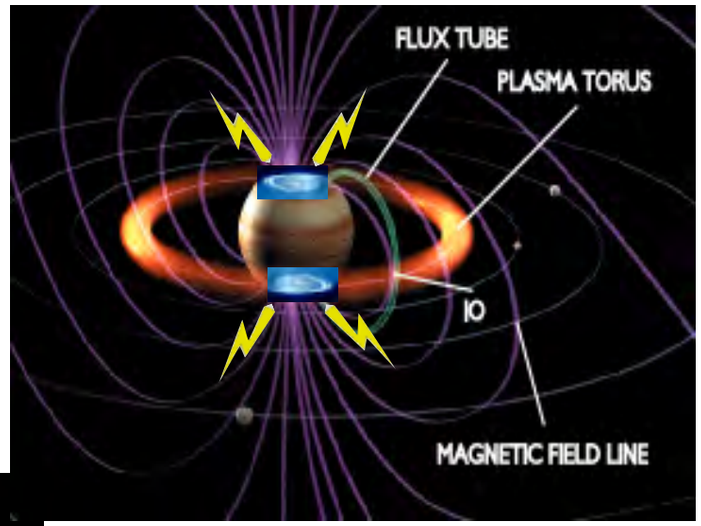


[Asgekar et al., 2013]



Carbon RRL's towards Cyg A (discovery with LOFAR)
[Oonk et al., 2014]

Transitoires radio



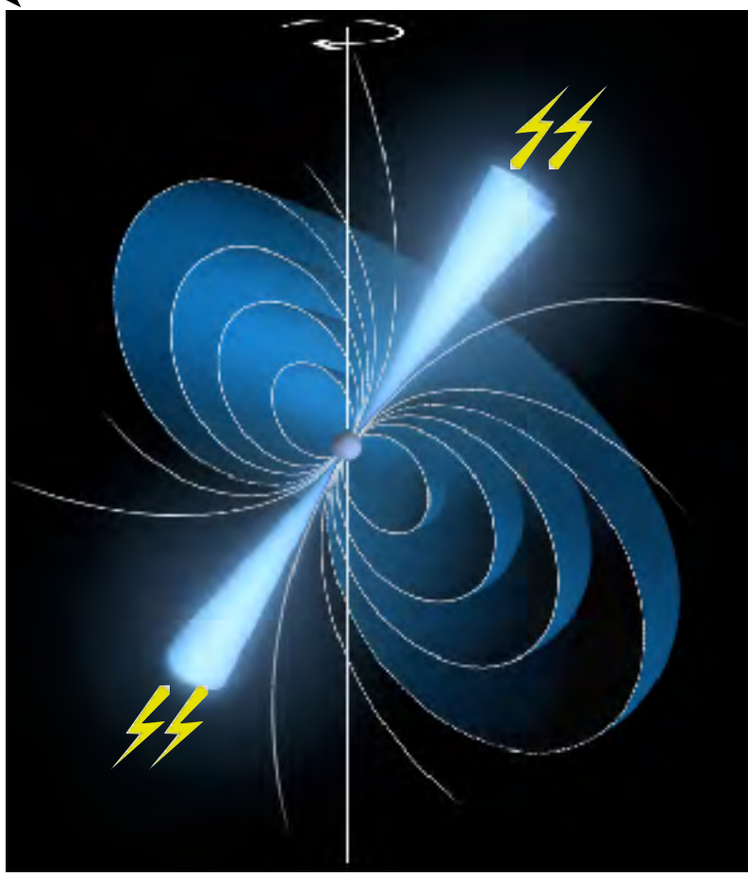
Phénomènes fortuits, non prévisibles

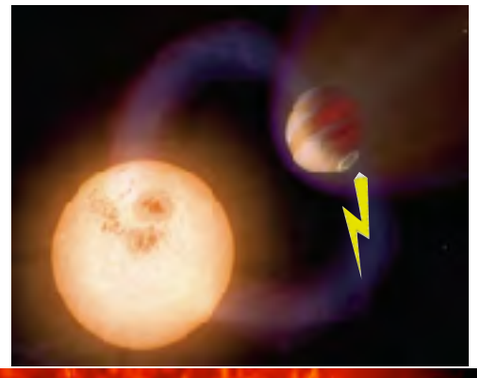
En radio

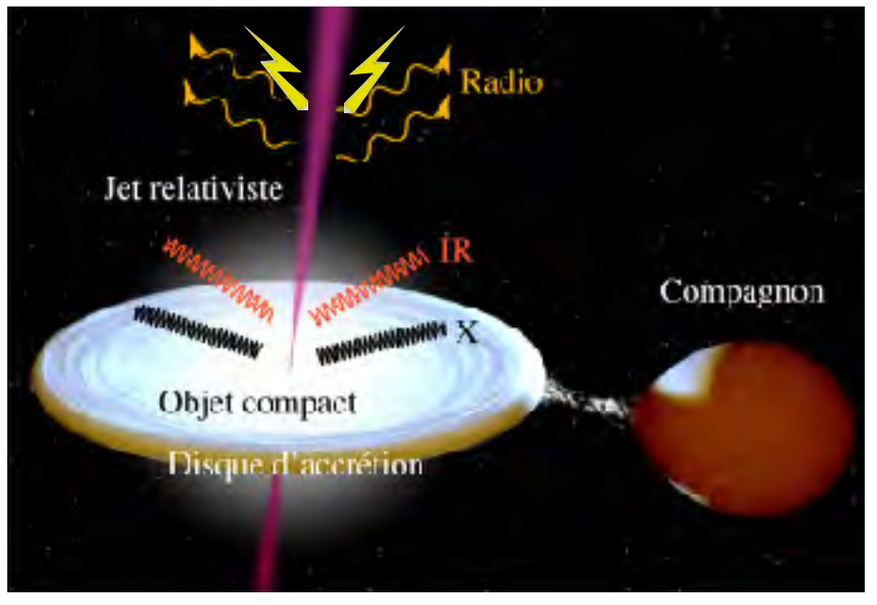
- généralement associés à des plasmas
- dans des champs magnétiques intenses
- contreparties d'évènements catastrophiques

à toutes échelles d'énergie, de distance, de durée…

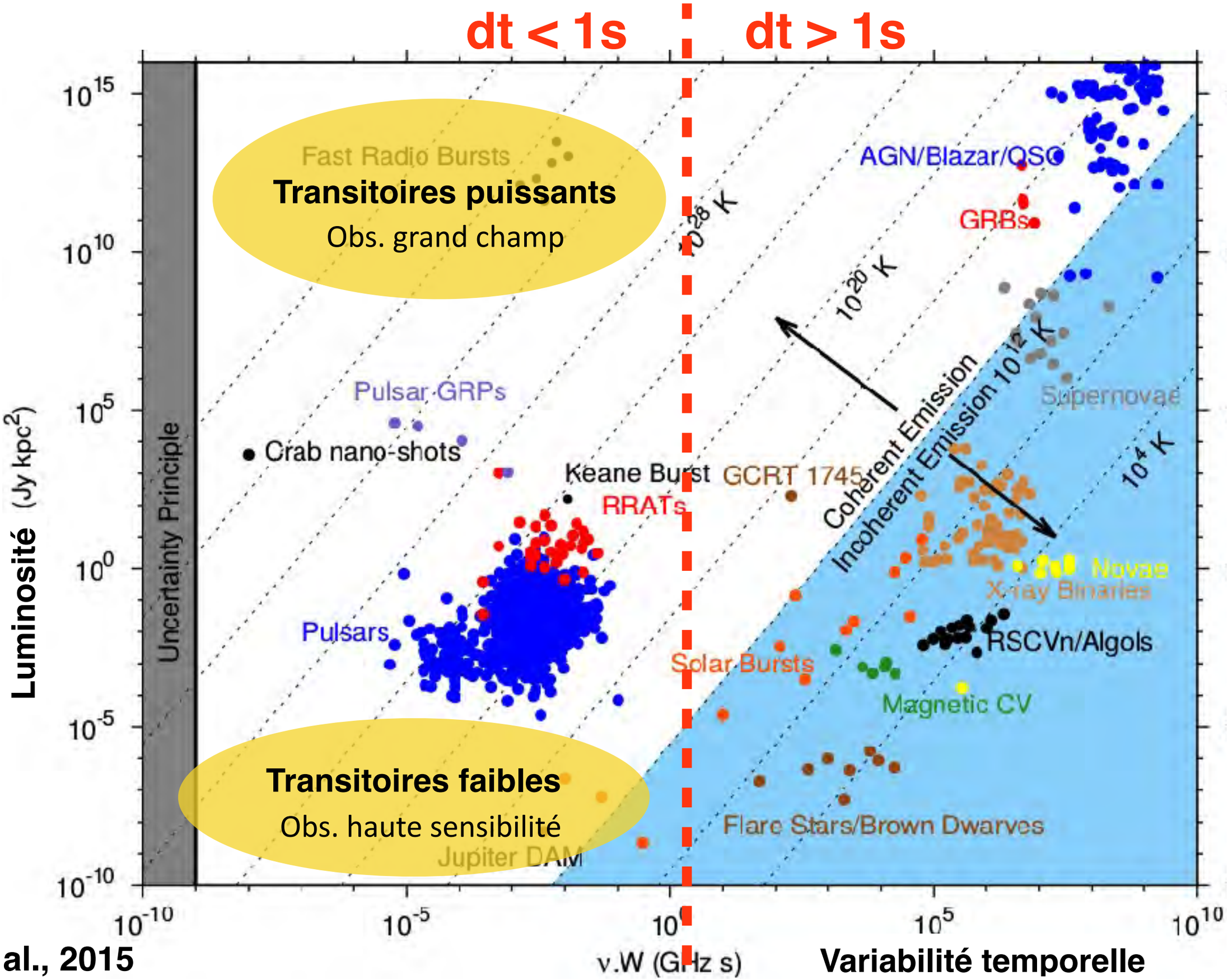
<< 1ms 1s 10s 1m 10m 1h 1j 1 sem 1 mois t







Transitoires radio



Pietka et al., 2015

Science with NenuFAR

- **Standalone Beamforming** == fast astrophysical transients (pulsars, giant pulses, RRATs, FRBs, perytons), surveys

$FoM_1 = N_{beams} * FoV * (A/T)^2 \propto N_{beams} * A^2 / D^2$

$FoM_2 = N_{beams} * A^2 * FoV/Beamwidth \propto N_{beams} * A^2 / D$

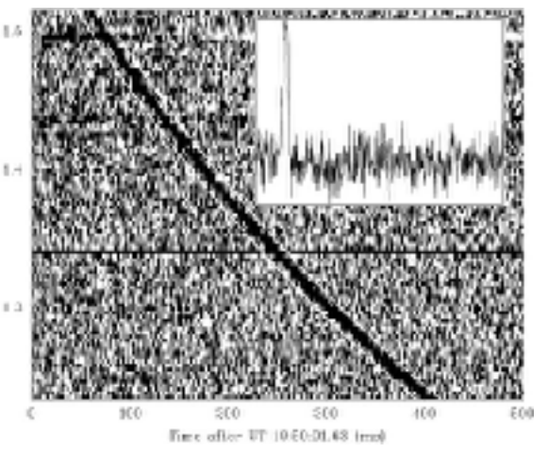
[Smits et al. 2009, Stappers et al. 2010, 2011]

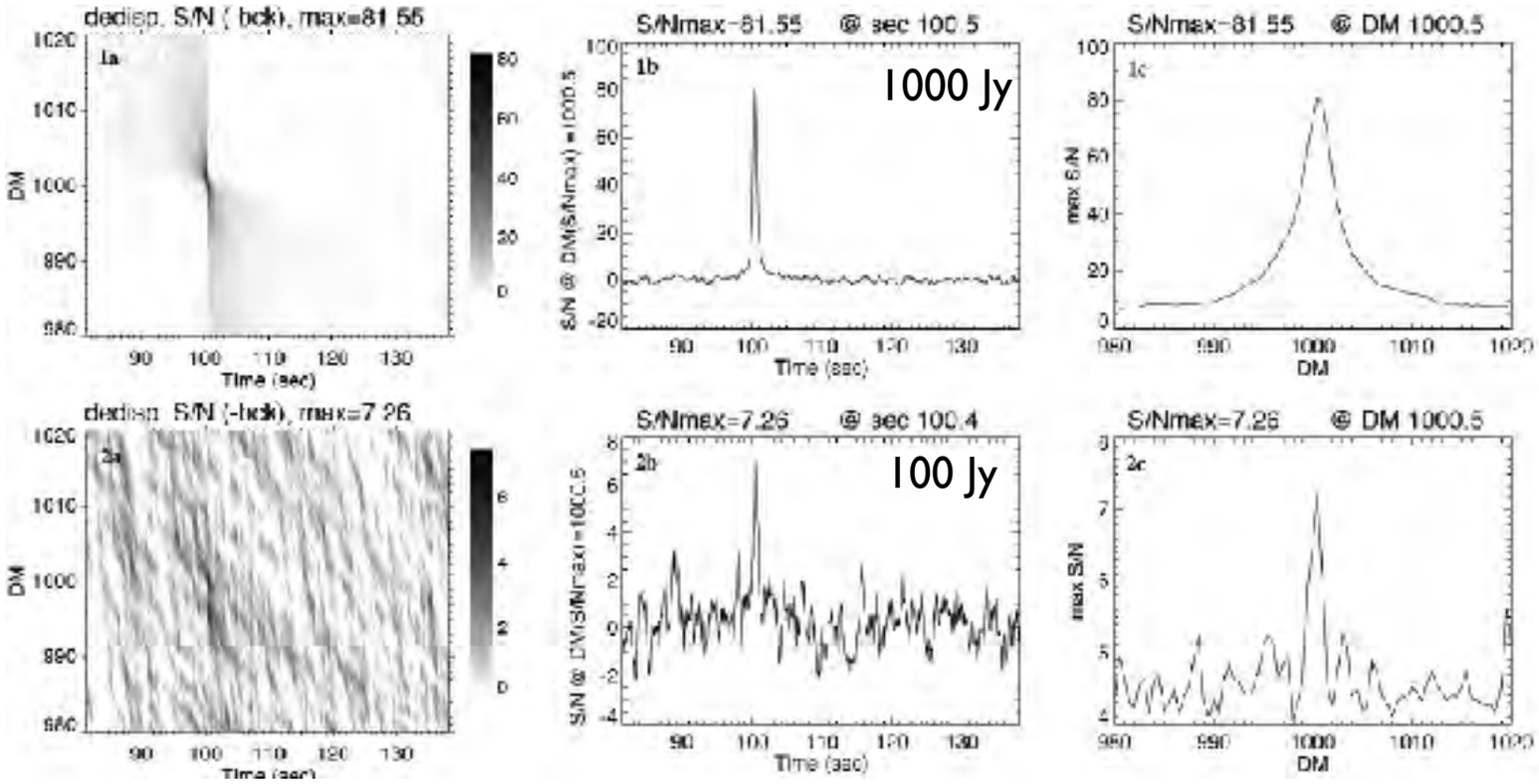
setup	# beams	d [m]	# stations	# dipoles/ MPA	# MPA/ station	norm. FOM_1	norm. FOM_2
single LBA station (LBA_OUTER)	1	32.25	1	1	48	1	1
Incoherent sum of superterp (LBA_INNER)	1	32.25	6	1	48	39	15
Coherent sum of superterp (LBA_INNER)	100	300	6	1	48	270	980
Incoherent sum of **LOFAR** core (LBA_INNER)	1	32.25	22	1	48	140	56
Coherent sum of **LOFAR** core (LBA_INNER)	100	2000	22	1	48	81	2000
LOFAR INT station	1	65	1	1	96	6	5
incoherent sum of INT stations	1	65	8	1	96	51	40
Coherent sum for **LSS**	10	300	1	19	96	1100	3900
Incoherent sum for **LSS**	1	300	1	19	96	6	21
NLLOFAR Fly's Eye (LBA_INNER)	1	32.25	40	1	48	260	102
NL **incoherent** sum (LBA_INNER)	1	32.25	40	1	48	260	102
NL **coherent** sum (LBA_INNER)	100	1e5	40	1	48	0.1	131

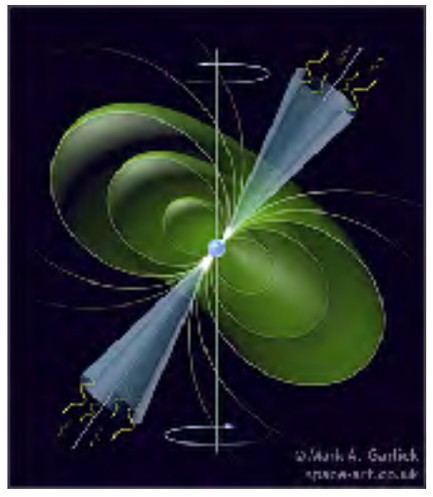
nenuFAR →

Science with NenuFAR

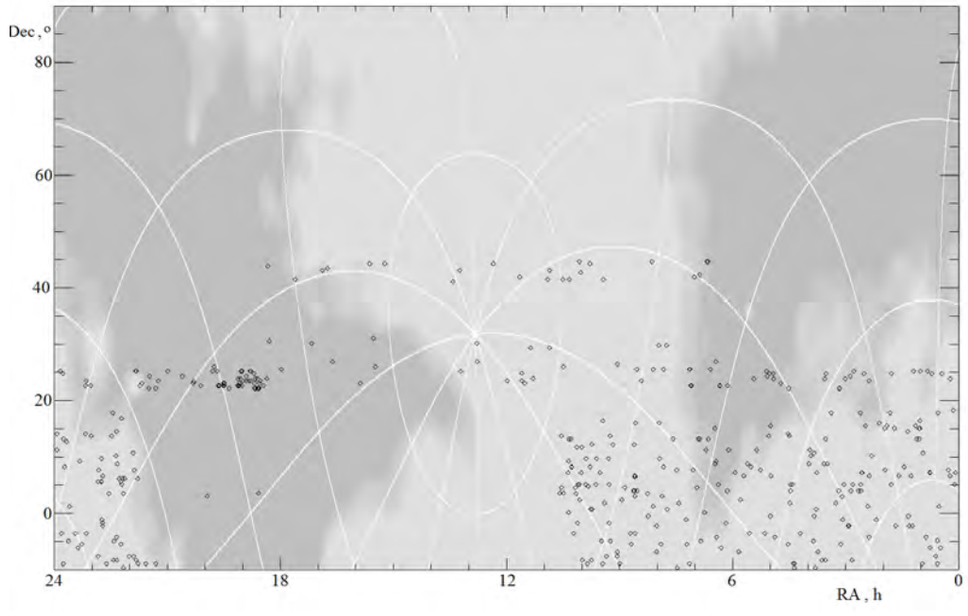
- **Standalone Beamforming / Fast imaging** : FRB, giant pulses, prompt GW?, in large FoV *[MoU LIGO/VIRGO]*, other transients ...



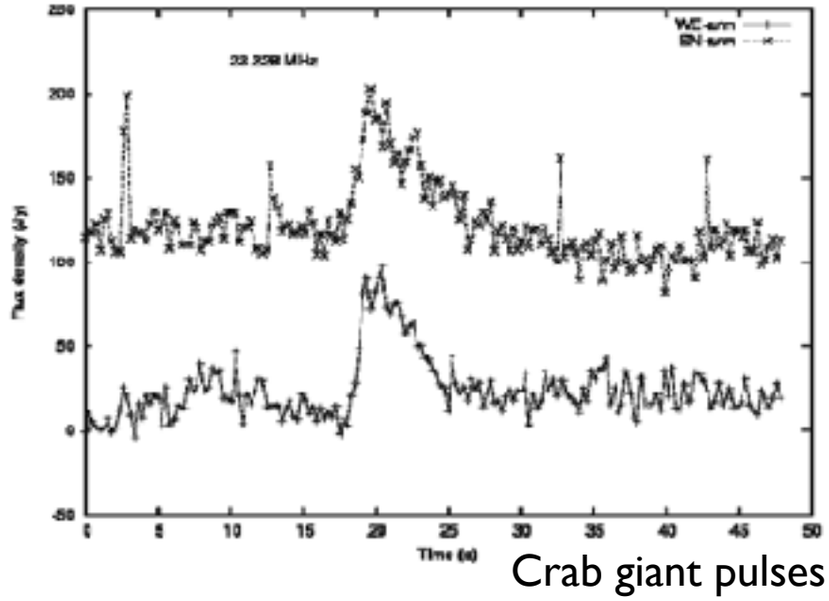




FRB LF simulations [Zarka & Mottez, 2016]



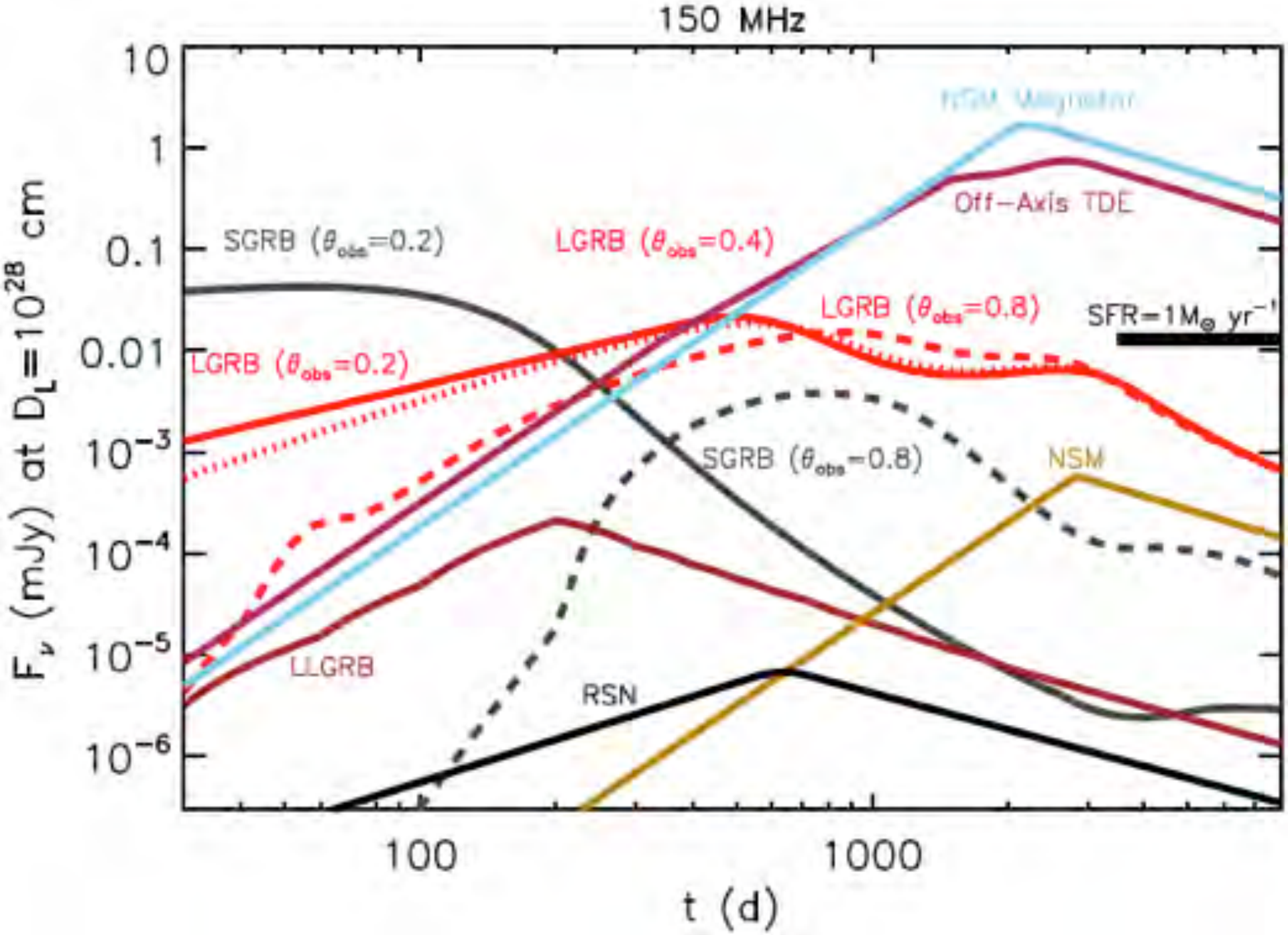
UTR-2 transients survey [Zakharenko et al., 2015]



Crab giant pulses [Popov et al.]

Science with NenuFAR

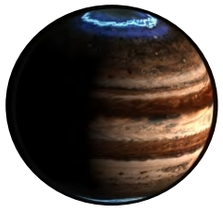
- **Standalone « slow » imaging** (multi-frequency rotational synthesis): GW/GRB afterglows ? (if EM emission mechanism) (MoU LIGO-Virgo / NenuFAR)



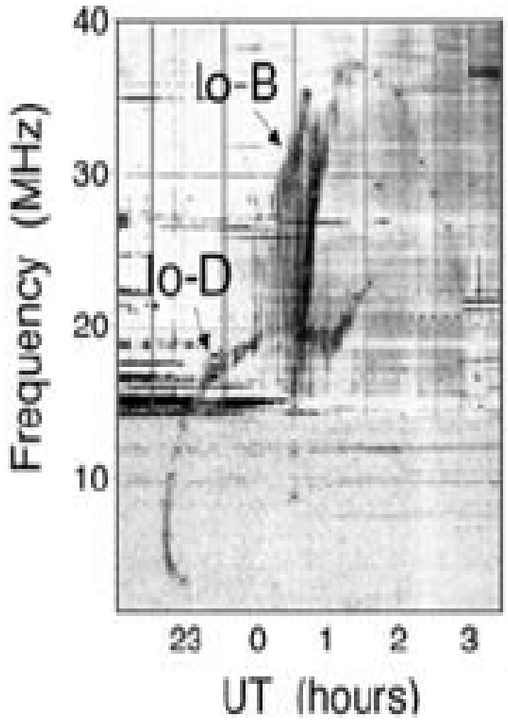
Metzger et al., 2015

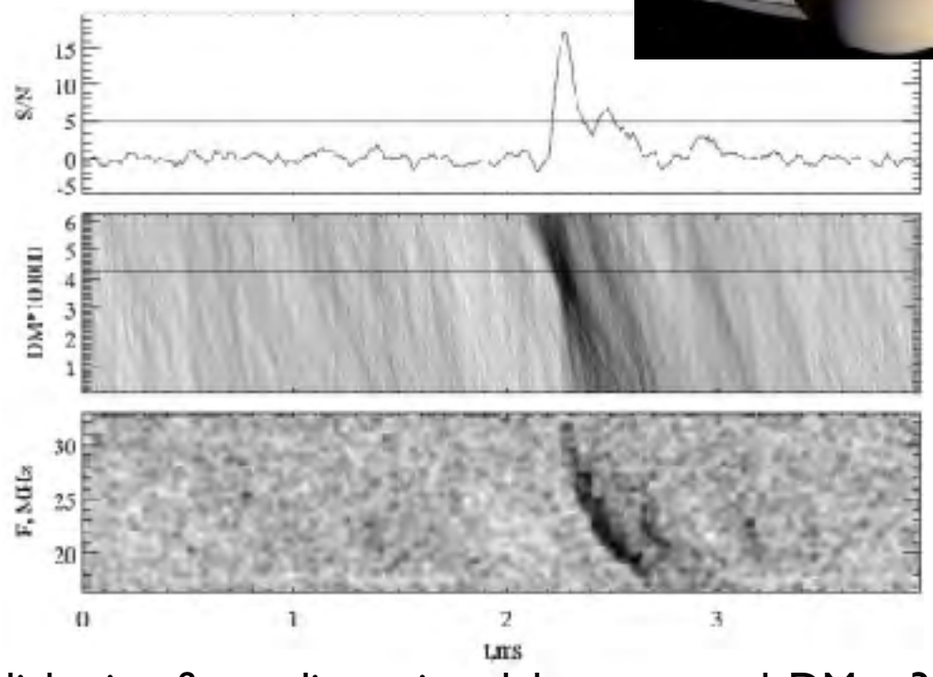
Science with NenuFAR

- **Stand-alone beamforming** : fast heliospheric transients
  (Solar System magnetospheres, Terrestrial & Planetary Lightning and Transient Luminous Events, Solar bursts)

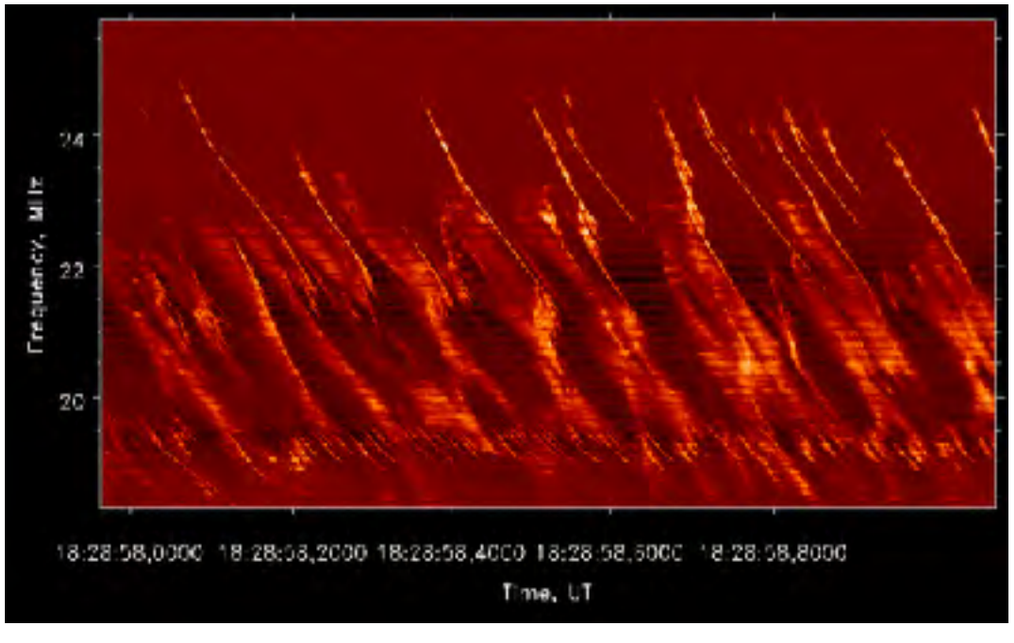


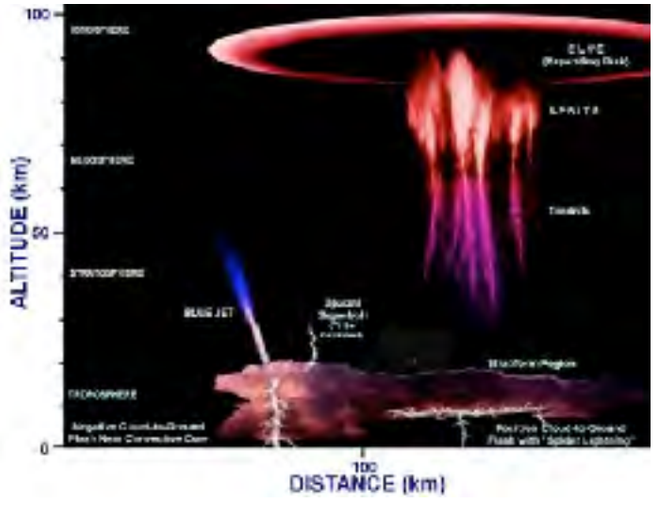
Jupiter
[Queinnec & Zarka, 1998,
Ryabov et al., 2014]





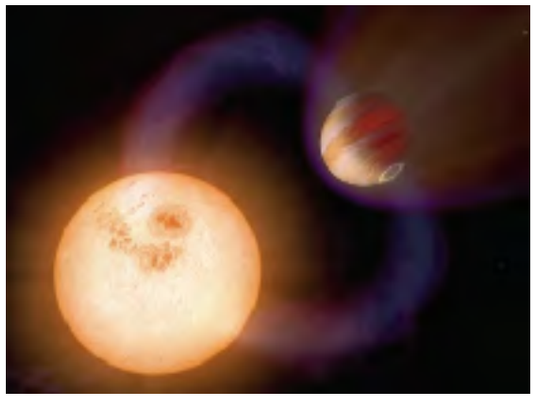
Saturn lightning: finest dispersion delay measured: DM ~ 3×10^{-5} pc.cm^{-3}
→ Solar Wind probing up to 10 AU [Zakharenko,et al., 2012]

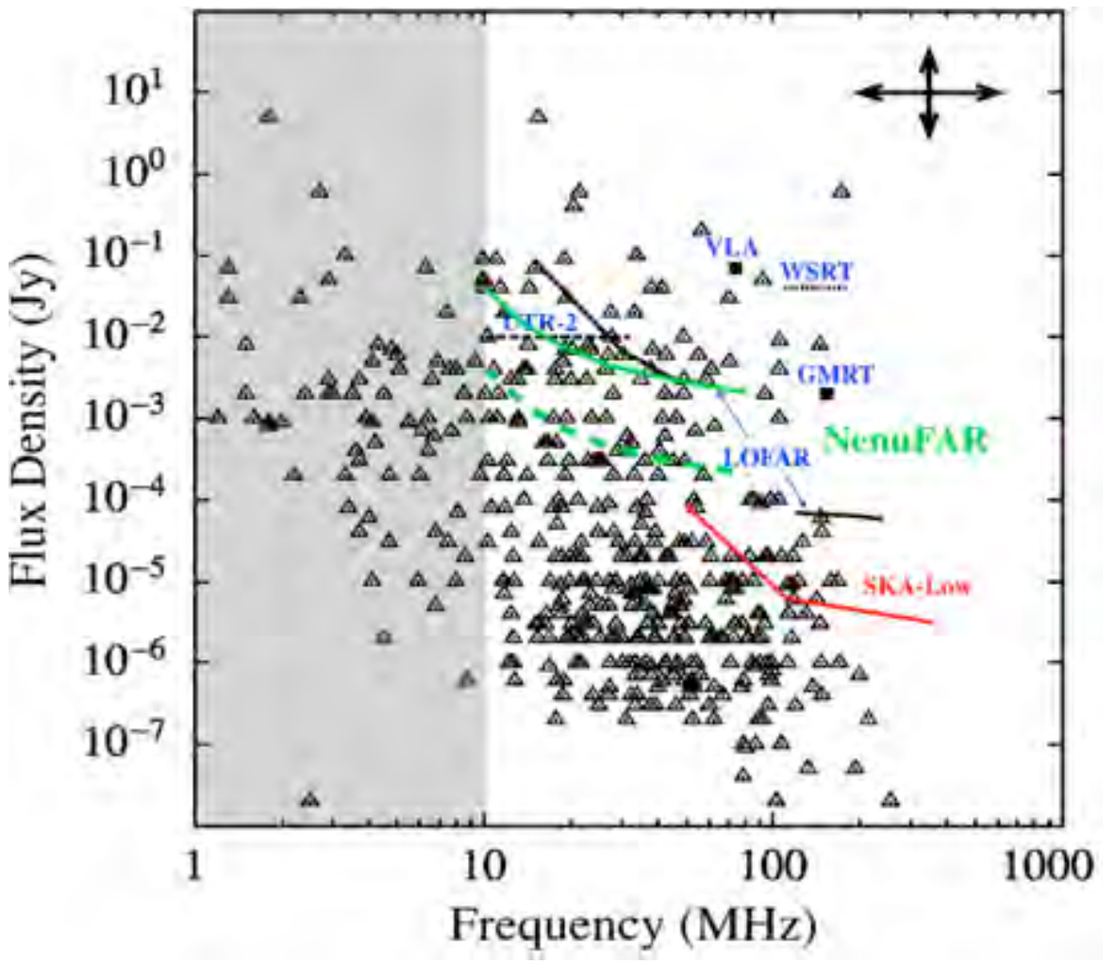




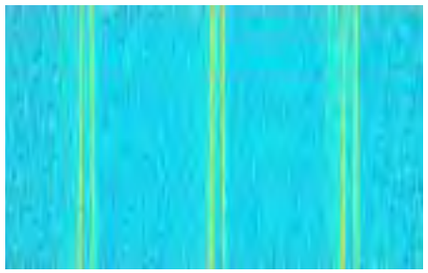
Science with NenuFAR

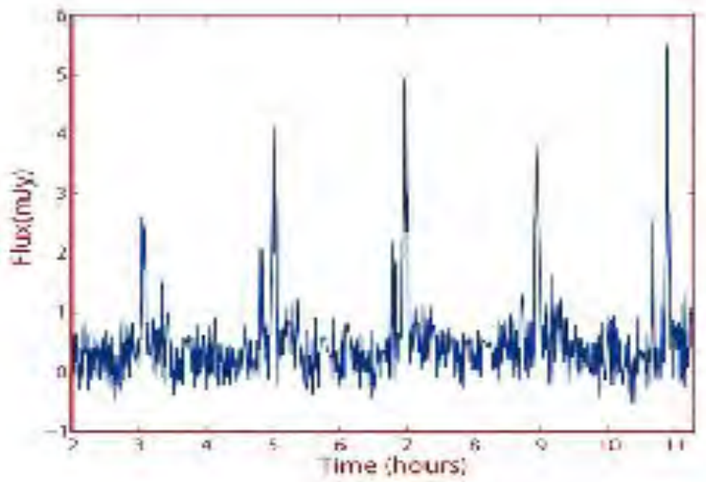
- **Standalone Beamforming / Fast imaging** : Exoplanets, Star-Planet interactions, Flaring/Dwarf/Cool stars (with large duty-cycle)



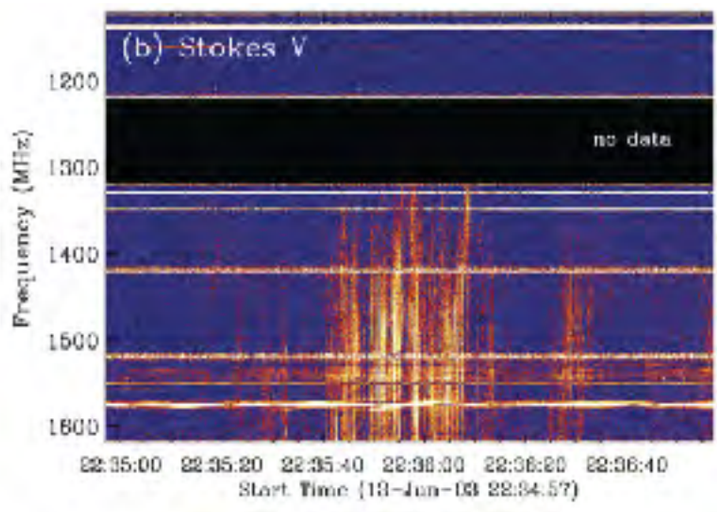


Zarka et al., 2015





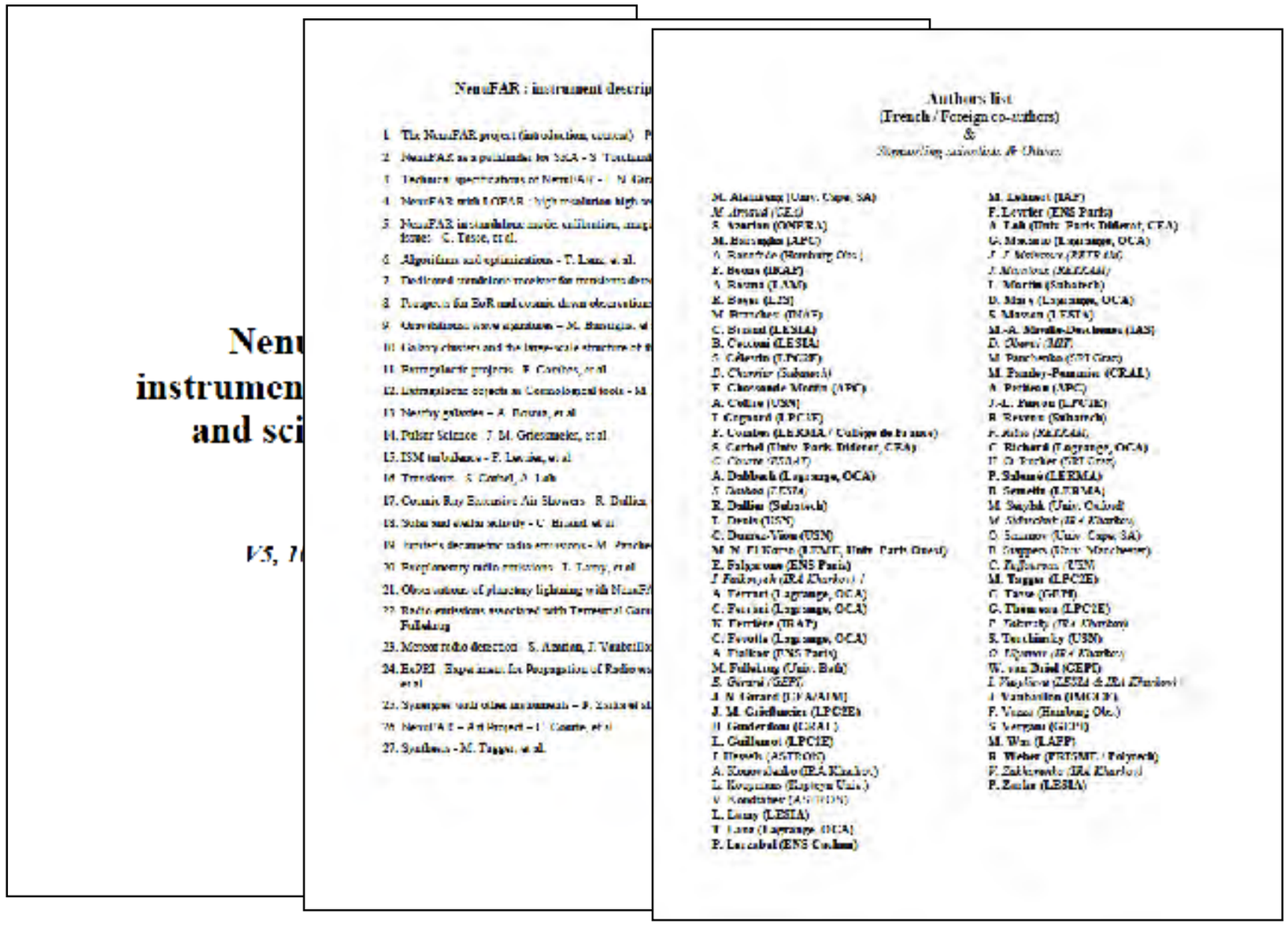
© G. Hallinan



© R. Osten

Science with NenuFAR

- NenuFAR workshop & science case ⇒ Science groups (**open!**)



NenuFAR Operating modes & Data policy

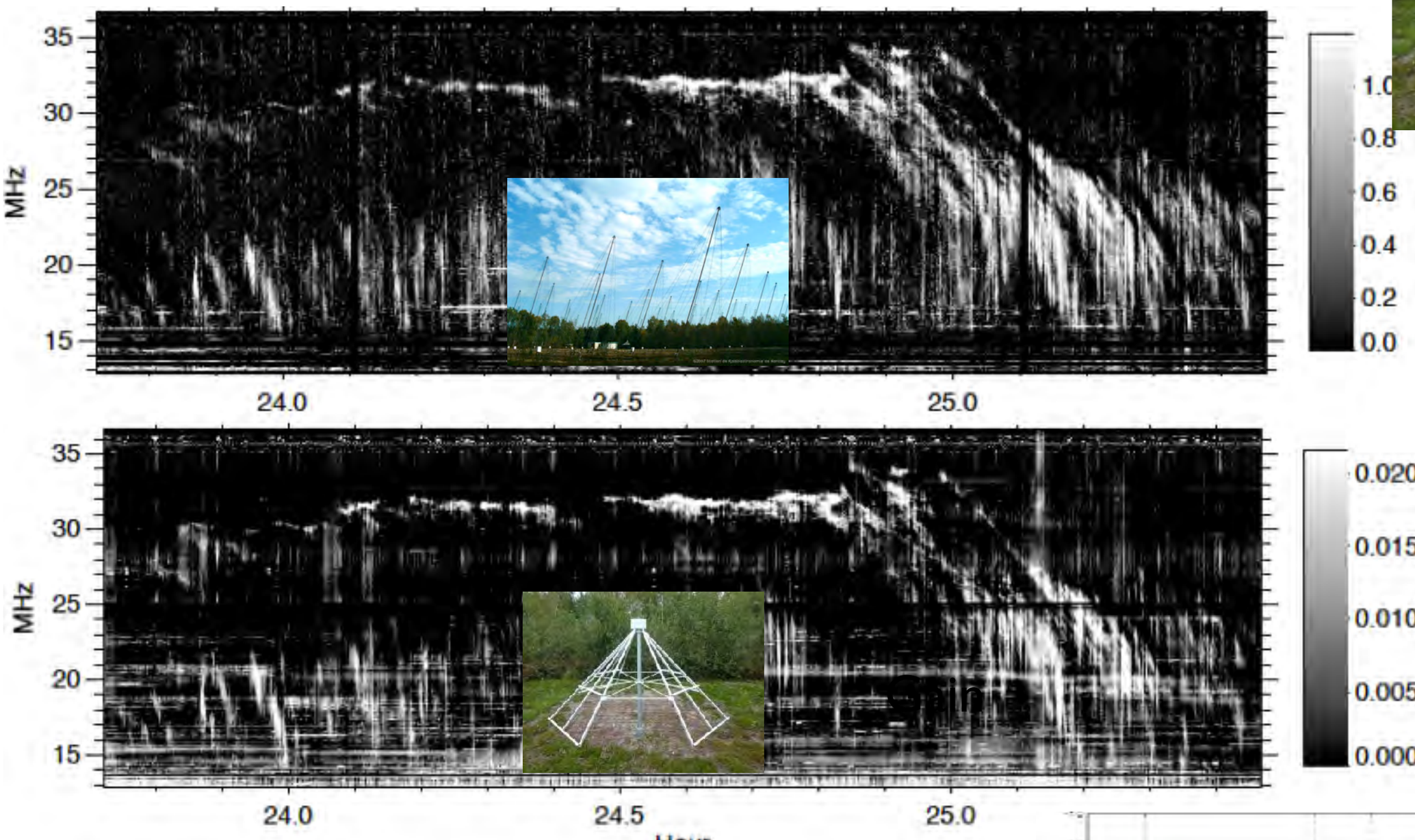
- **NenuFAR/LSS mode via ILT (MoU)**
- **NenuFAR/Standalone mode via FLOW PC**

Open discussion about
Public data access
Alerts

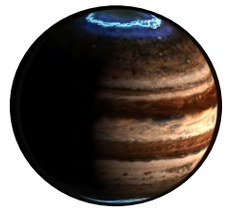
Commissioning

The antenna

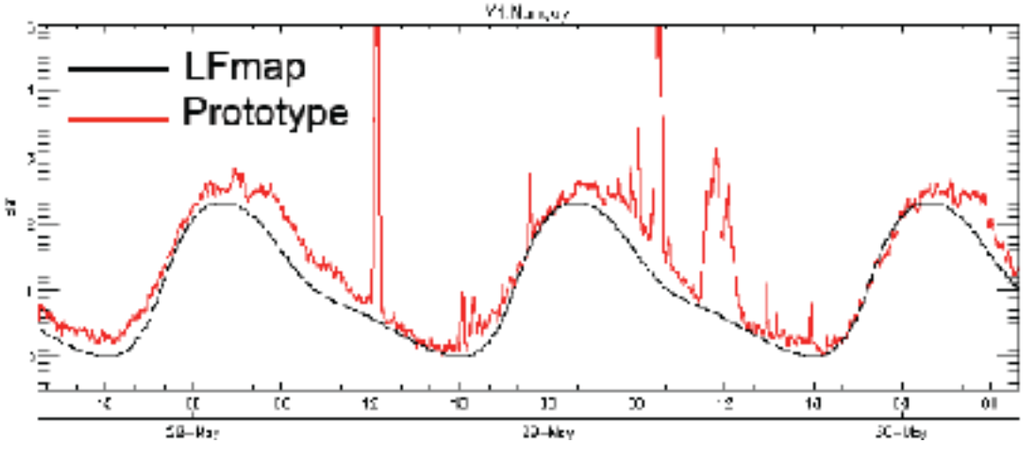
- Antenna + amplifier tested with dedicated test receiver

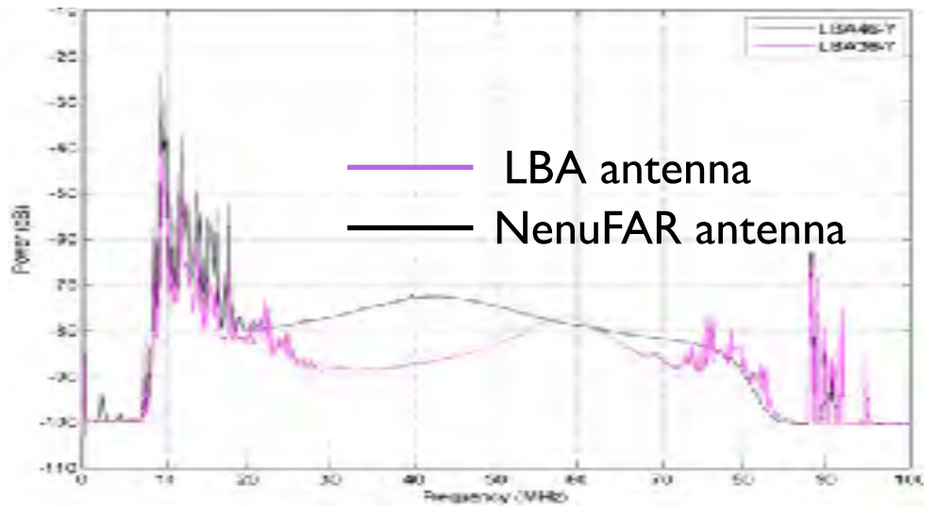


Jupiter



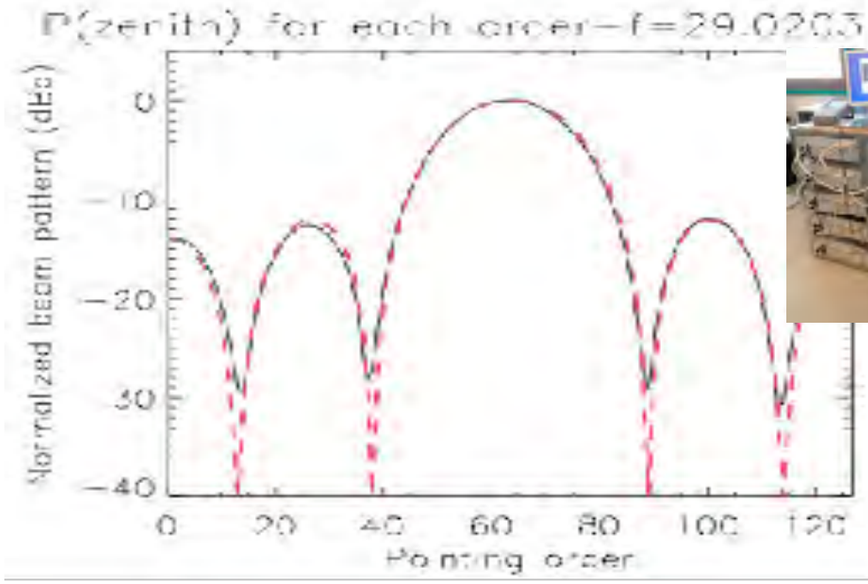
Galaxy

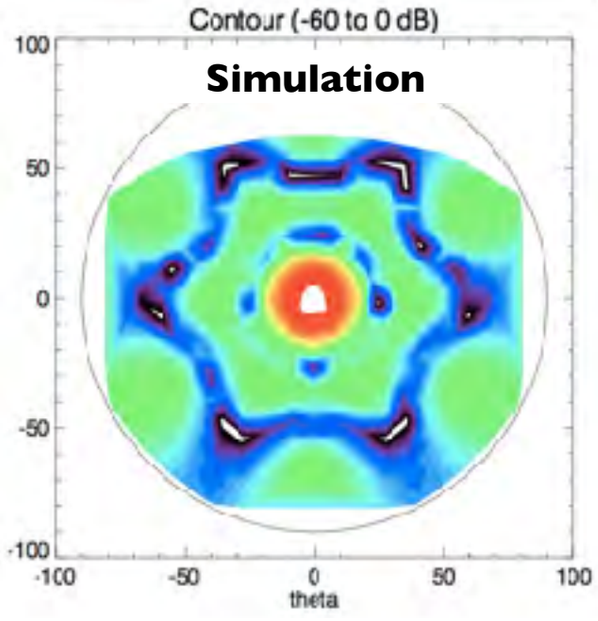


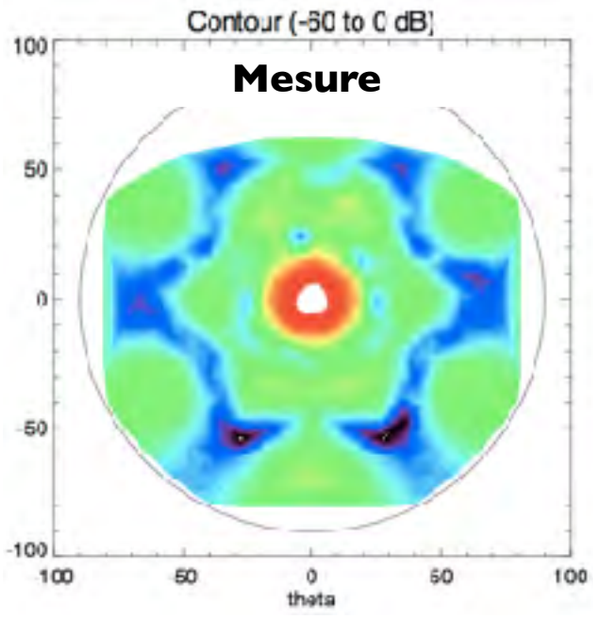


Commissioning

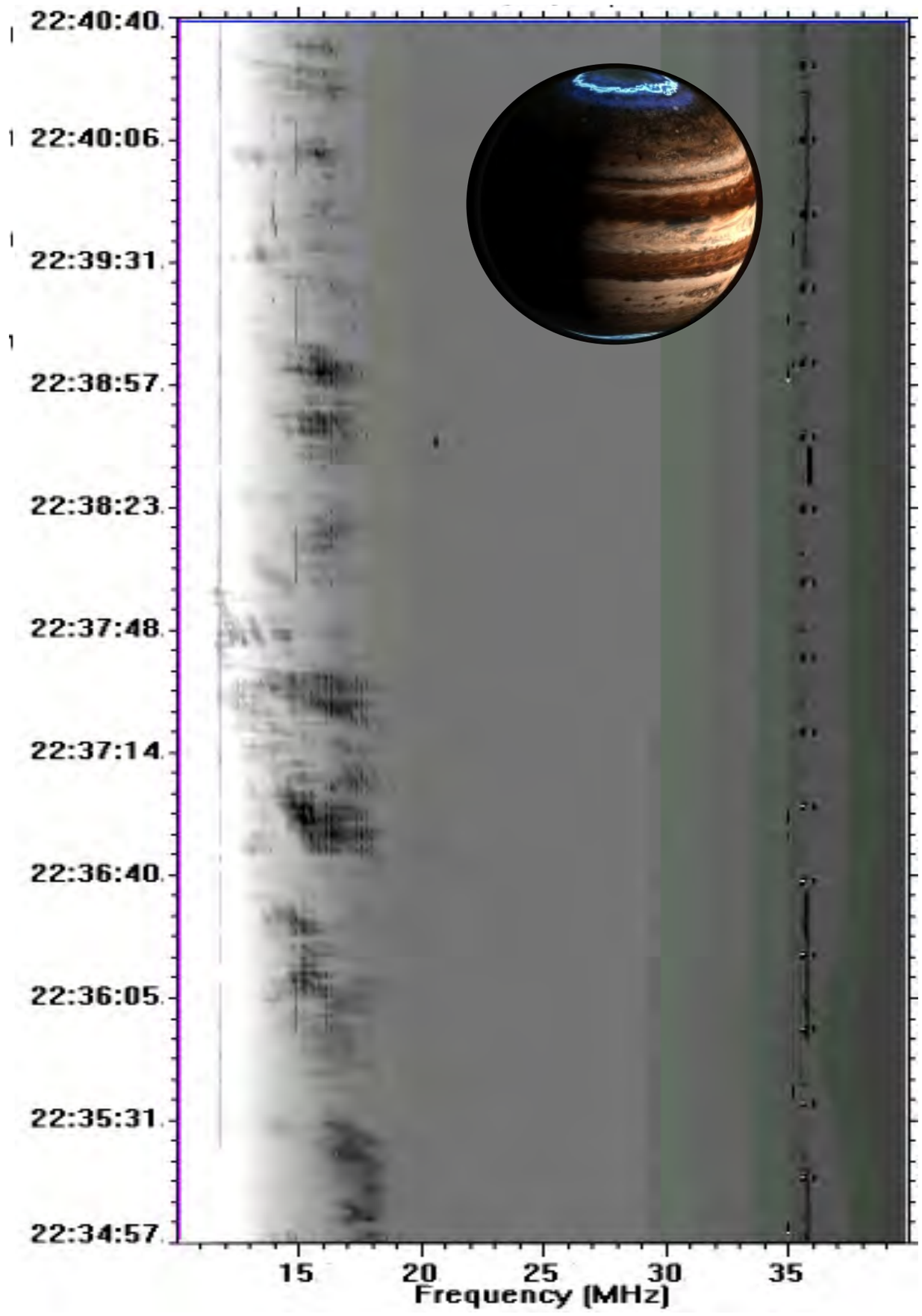
- Phasing system : simulation + laboratory
- Mini-array analog beamforming on sky







The mini-array

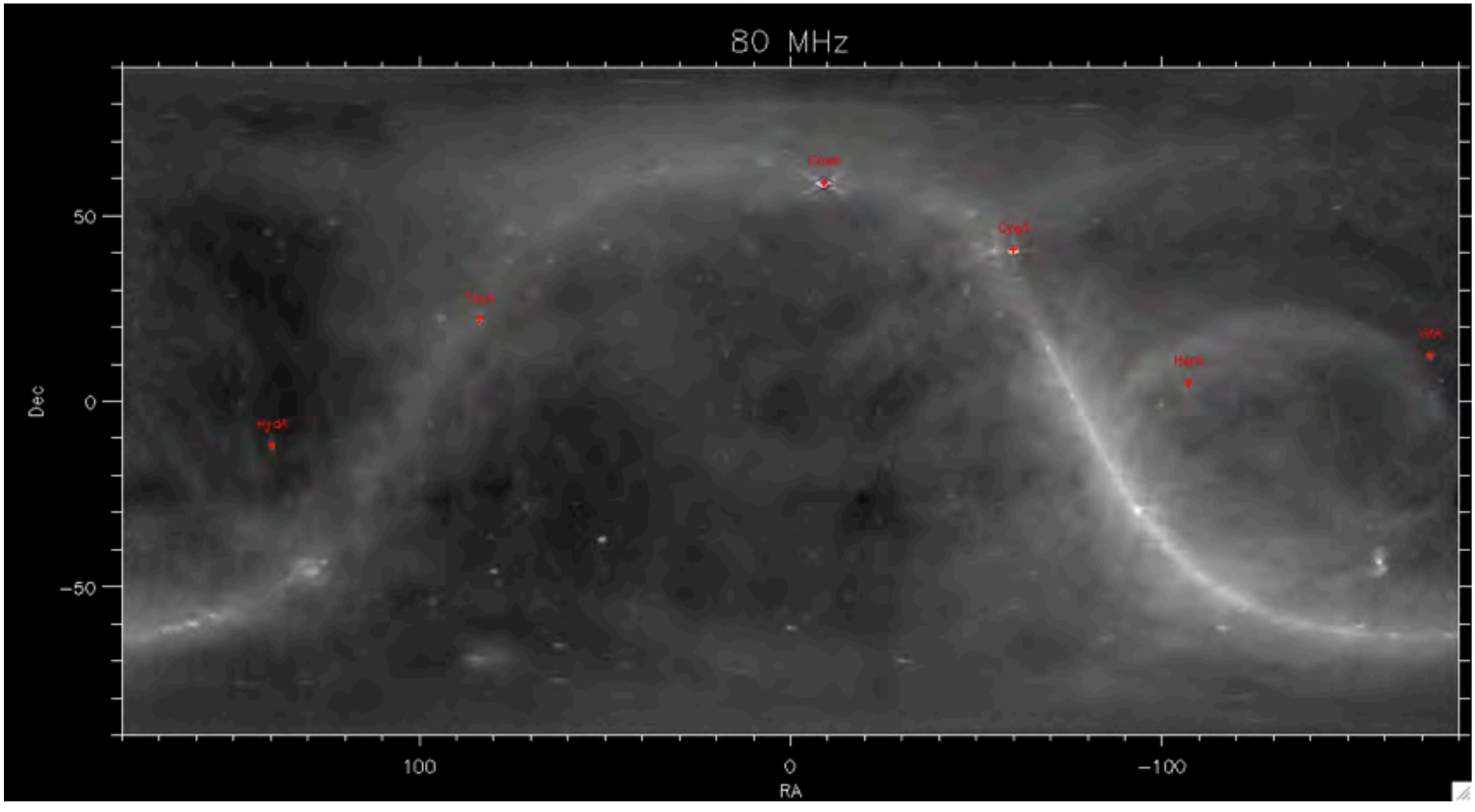


Commissioning

- Phasing system : simulation + laboratory
- Mini-array analog beamforming on sky

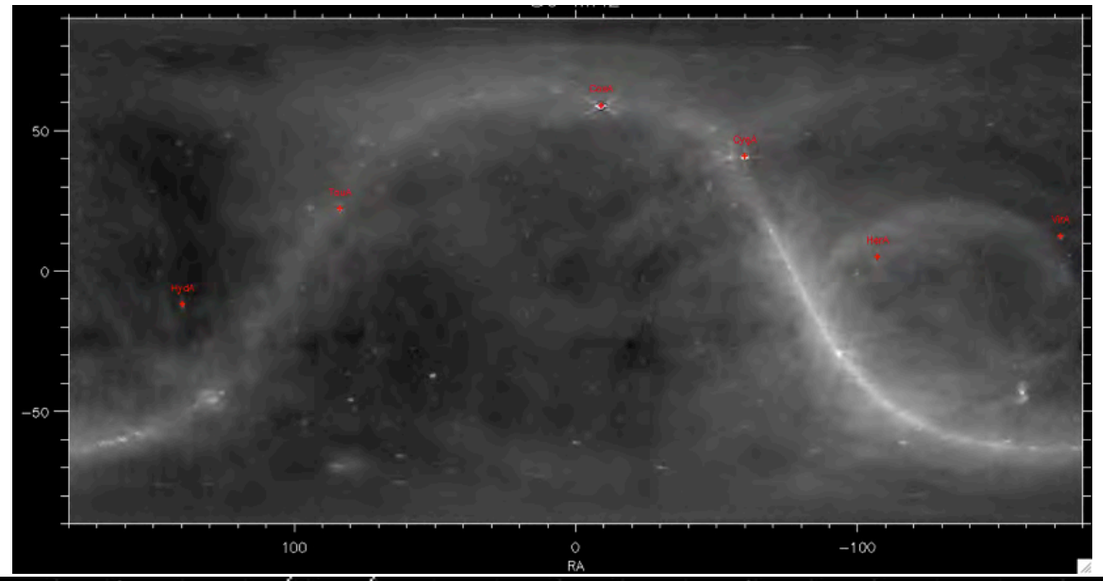
The mini-array

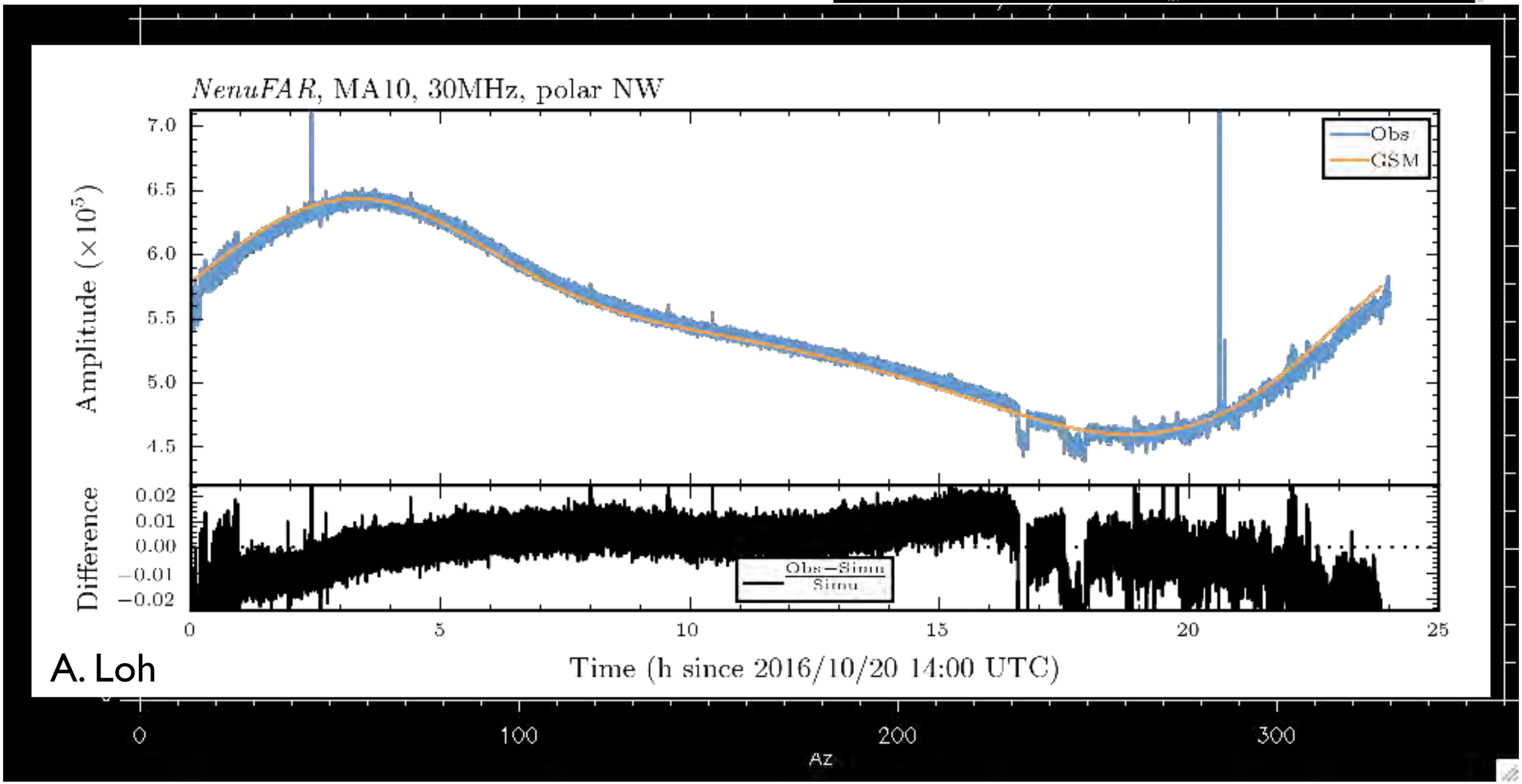
Model of the galaxy at LF



Commissioning

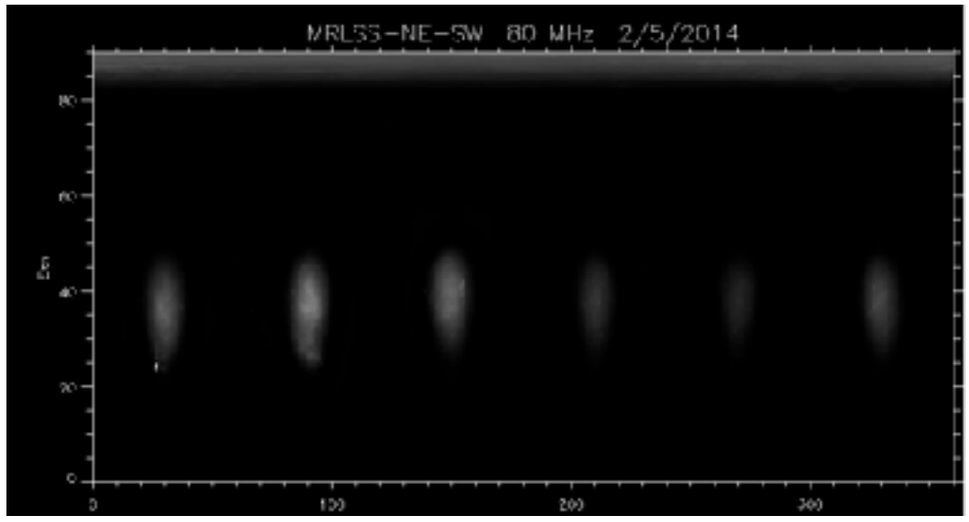
- Phasing system : simulation + laboratory
- Mini-array analog beamforming on sky





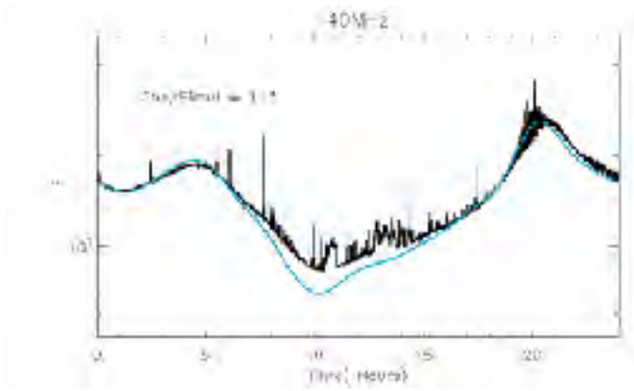
Commissioning

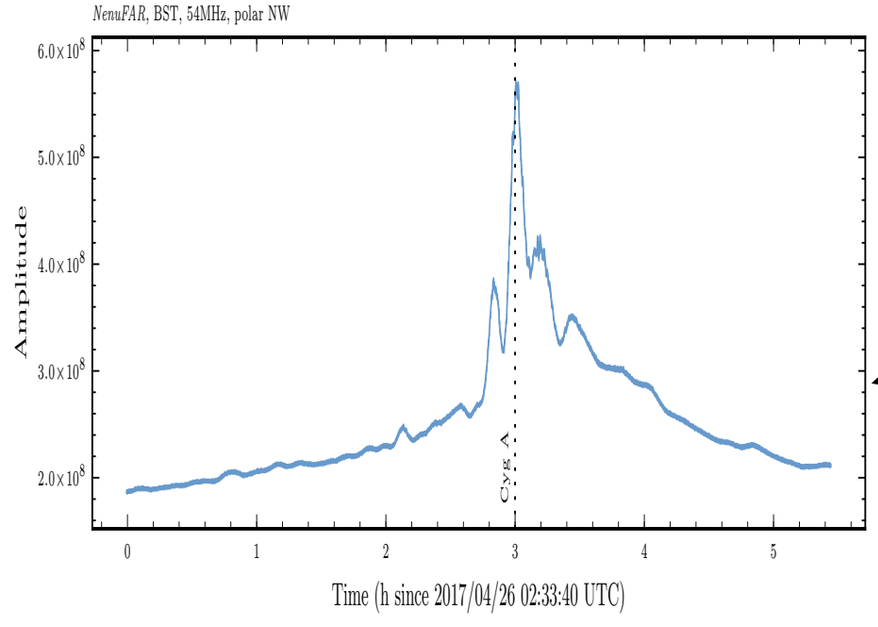
Gain MR x Ciel



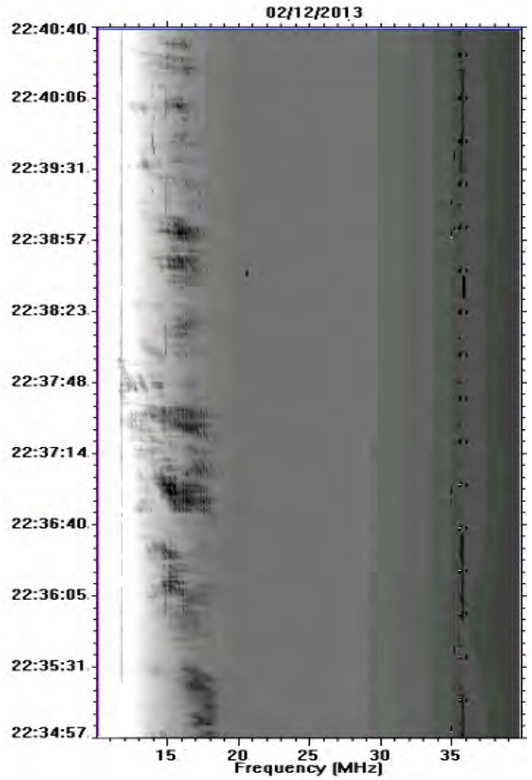
Z

H





Validation on strong LF sources

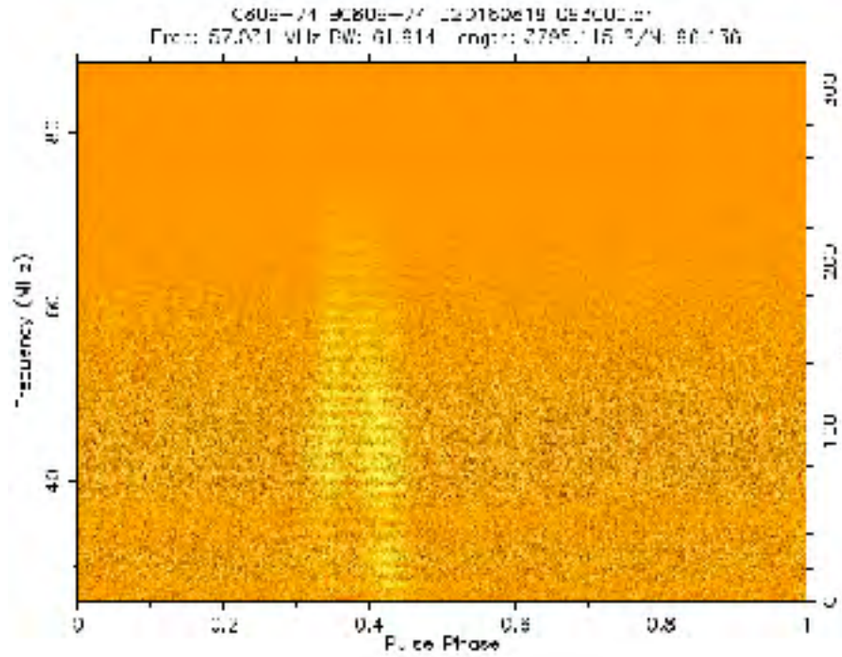


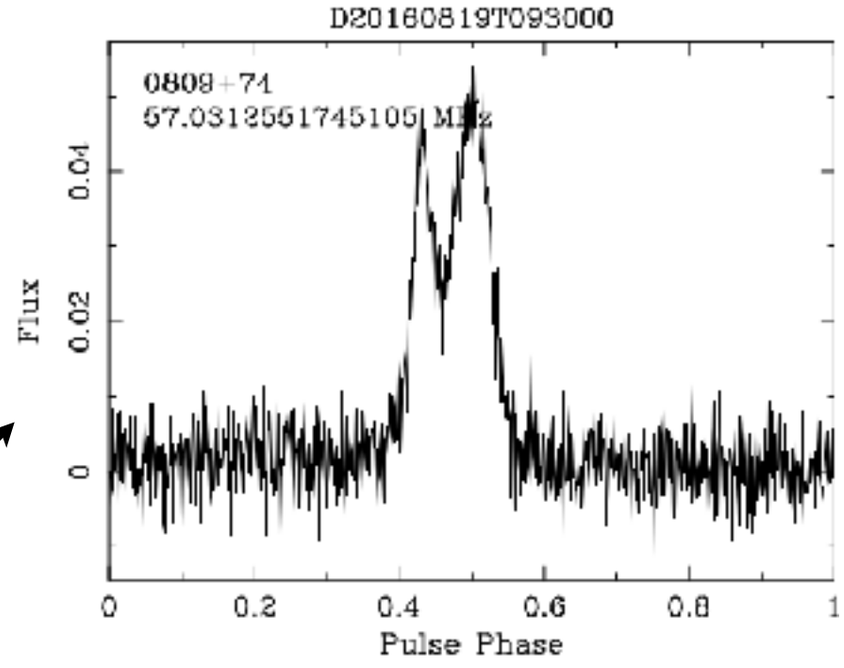
Jupiter

Galaxie

Pulsars

Radio sources

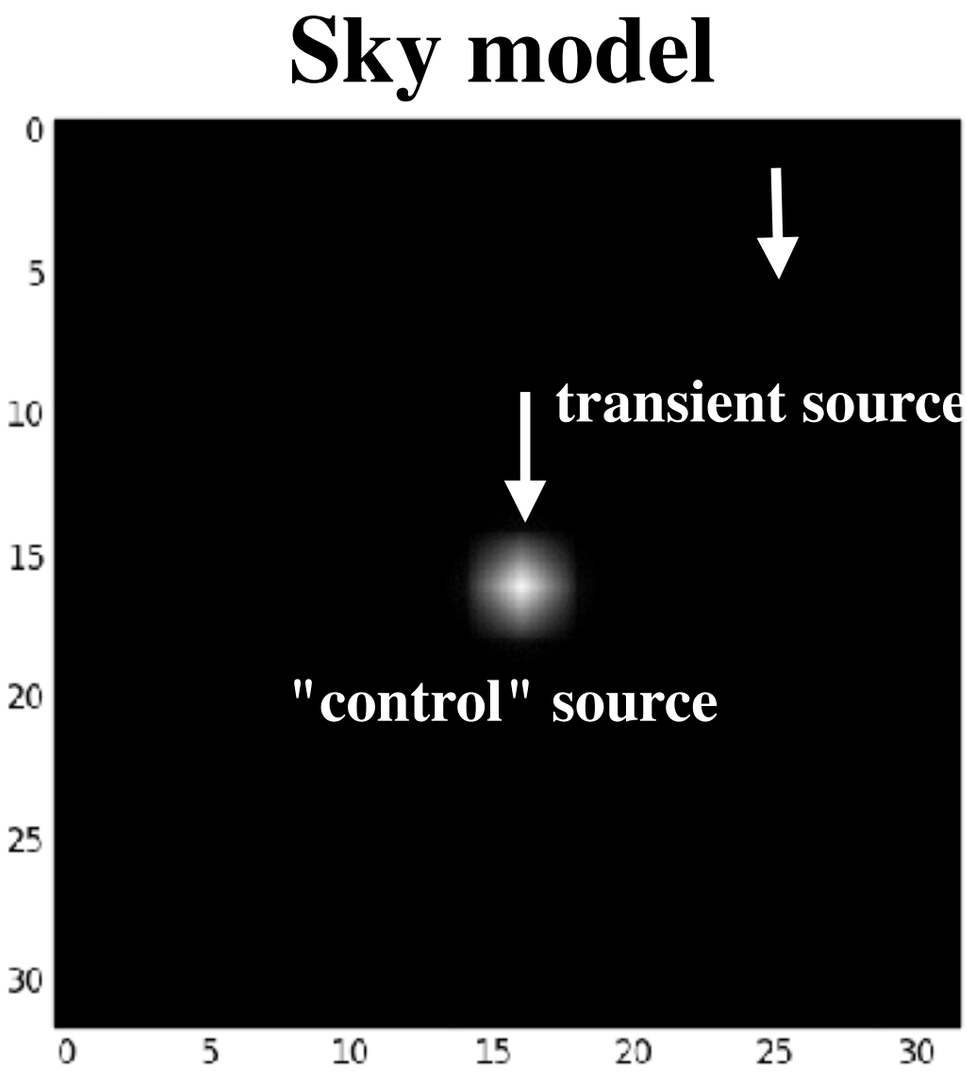


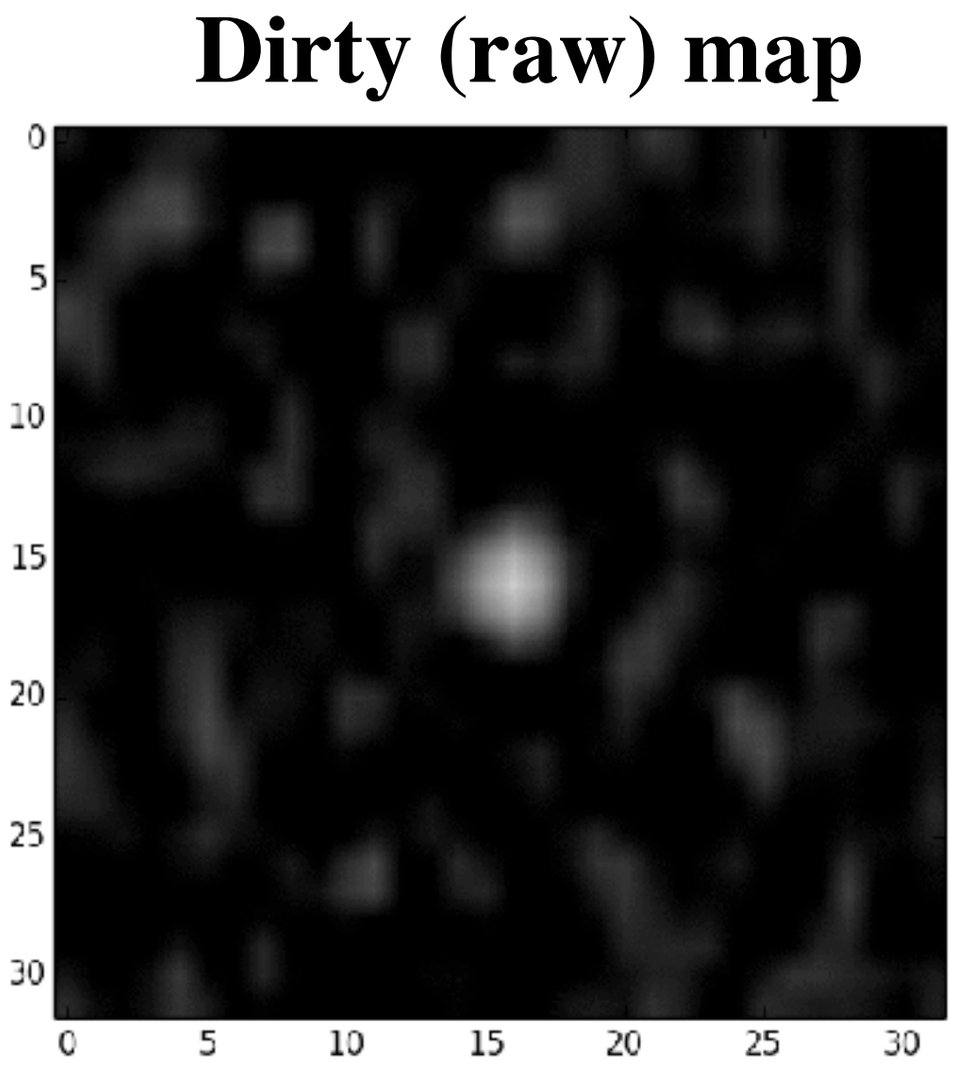


C. Briand, J.-M. Grießmeier, M. Serylak, B. Censier, L. Denis, P. Zarka
+ A. Loh, J. Girard, L. Bondonneau ...

Reconstruction de profils de transitoire

2D+temporel Sparse reconstruction





- **"control" steady source**
- **transient gaussian source**

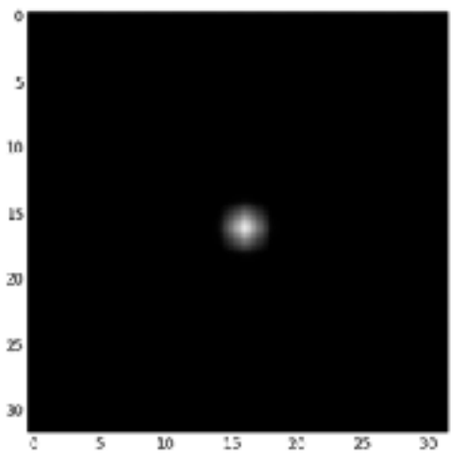
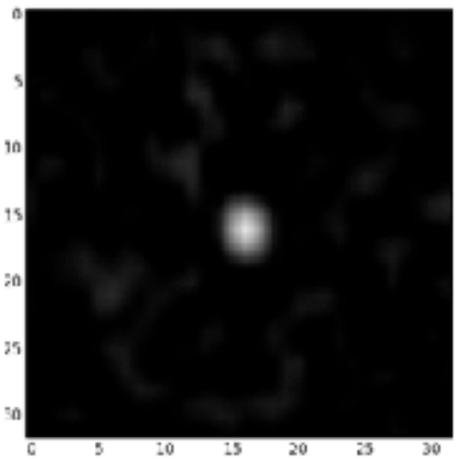
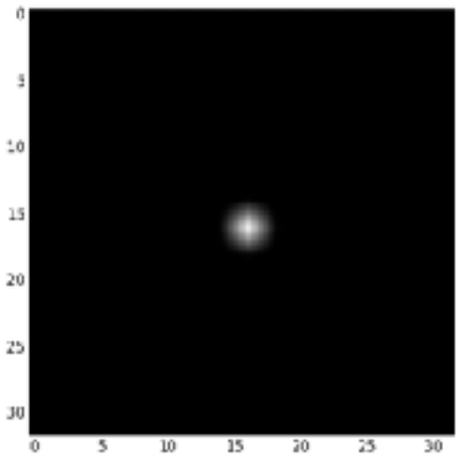
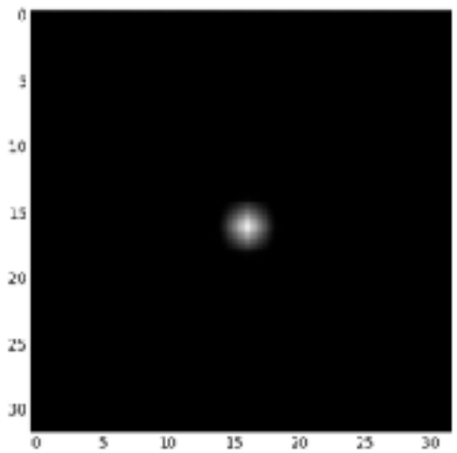
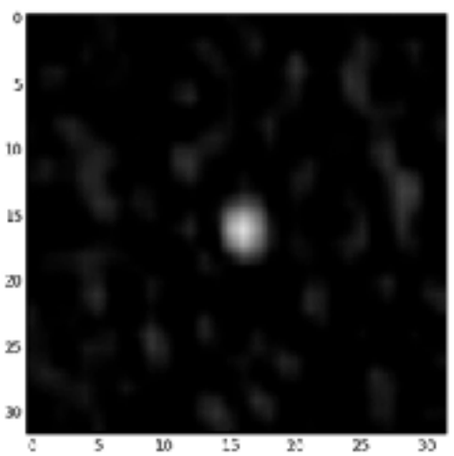
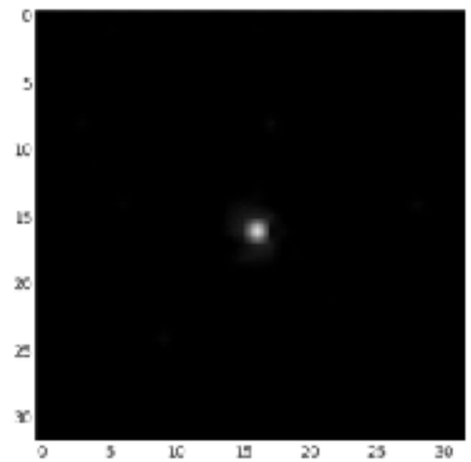
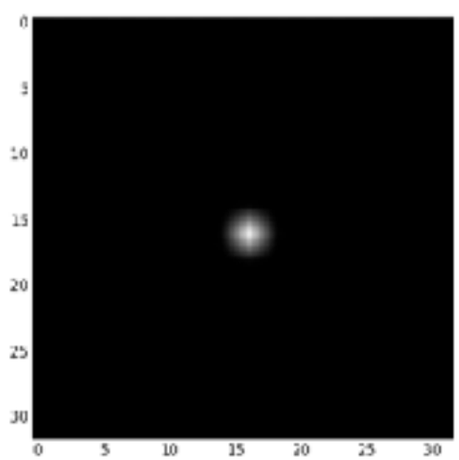
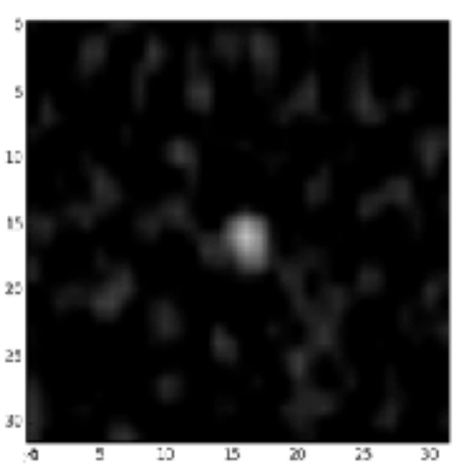
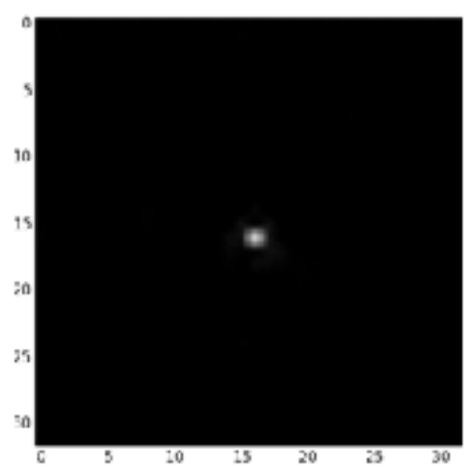
A new source appeared but side lobes as well !

Need a time-agile deconvolution algorithm

Girard et al., submitted

Reconstruction de profils de transitoire

2D+temporel

	Sky model	Dirty map	Reconstruction
σ=0.5			
σ =1.0			
σ =1.5			

Girard et al., submitted

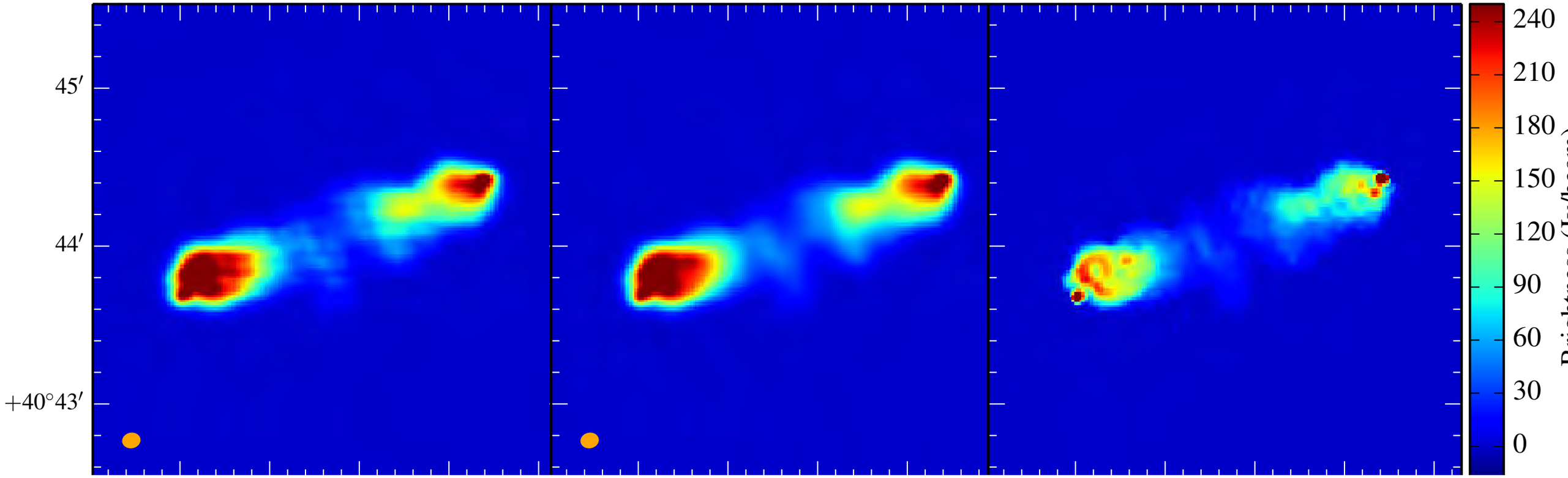
Challenge #2: Reconstruction d'image grand champ

Imagerie classique radio $Y = HX + N$ → CLEAN (1974)

échantillons de Fourier — réponse instrumentale — vrai ciel — bruit

Résultats sur des données réelles de LOFAR (150 MHz) sur Cygnus A

CLEAN | **CLEAN multi-échelle** | **Parcimonie**



Gain d'un facteur 4 en résolution angulaire

Garsden, Girard, Starck et al., A&A, 2015 & Girard et al., JINST, 2015

NENUFAR: A VERY LOW FREQUENCY TRANSIENT DETECTION MACHINE

- Wide FOV
- Currently under commissionning (—>2018)
- Implication of french laboratories: Observatoire de Paris, LPC2E/OSUC, Station de radioastronomie de Nançay.

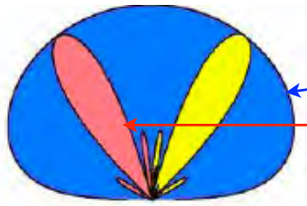
Ground	Instrument 1	Band sensitivity (Gamma/X-ray …)	Description of the instruments
	NenuFAR Array	VHF: ~mJy (1 Crab at 6 keV)	Electronically steerable phased array: - Time series (ns) - Dynamic spectroscopy (X MSample/s) - Interferometric imaging (~1° instantaneous angres)

SCIENCE CASE IN TIME ASTRONOMY

- Target transients sources (Pulsars)
  - Expected scientific return (ex: afterglow of XRFs, ultra-long GRBs, …)

- Target transients sources (ex GRBs)
  - Expected scientific return (ex: afterglow of XRFs, ultra-long GRBs, …)

NenuFAR : 3 instruments in 1
signal path/data flow/receivers/data products



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

Distant MA (≤3 km) : 6 MA x 2 polar.

analog signals

analog signals

analog signals

LOFAR FR606 backend

- ADC 200 MHz (x 96 x 2)
- PFB → 200 kHz SB [+TBB]

- Phasing+Summation per SB = beamlet (244 simultaneous ~ 48 MHz total bandwidth)
- *SST, BST, XST → Calibration*

1.6 MB /s /SB

- 3 Gbit/s link to LOFAR correlator
- Channelization down to <1 kHz
- Correlation with signals from LBA stations (~1 s)

LOFAR Super Station NenuFAR

40 kB /s /channel

High-resolution imaging
(~0.1" , IQUV) [+TBB]

LaNewBa

- ADC 200 MHz (x 96 x 2)
- PFB → 200 kHz SB [+TBB]

- Phasing+Summation per SB = beamlet (768 simultaneous ~ 150 MHz total bandwidth)
- Incoherent summation
- *SST, BST, XST → Calibration*

1.6 MB /s /SB

UnDySPuTeD

- Channelization down to δf<1 kHz
- Dedispersion (predefined, parametric)
- Integration over δt ≥5 μs

NenuFAR Standalone Beamformer

16/δt bytes /s /channel

- Dynamic spectra (δt x δf)
- Time series (δt)
(IQUV, multibeam) [+TBB]

150 MB /s /SB

- ADC 200 MHz (x 6 x 2, at MA foot)
- PFB → 200 kHz subbands

9.6 MB /s /SB

Local correlator

- Channelization down to <1 kHz
- MA coherent sum (by 1, 2, 4)
- MA (or MA sum) correlation (~1 s)

NenuFAR Standalone Radio Imager

40 kB /s /channel

- Instantaneous (~1 s) coarse imaging (~1°)
- Slow (6-8h) multi-λ mid-resolution (8')
imaging → confusion ~ thermal noise
(IQUV)

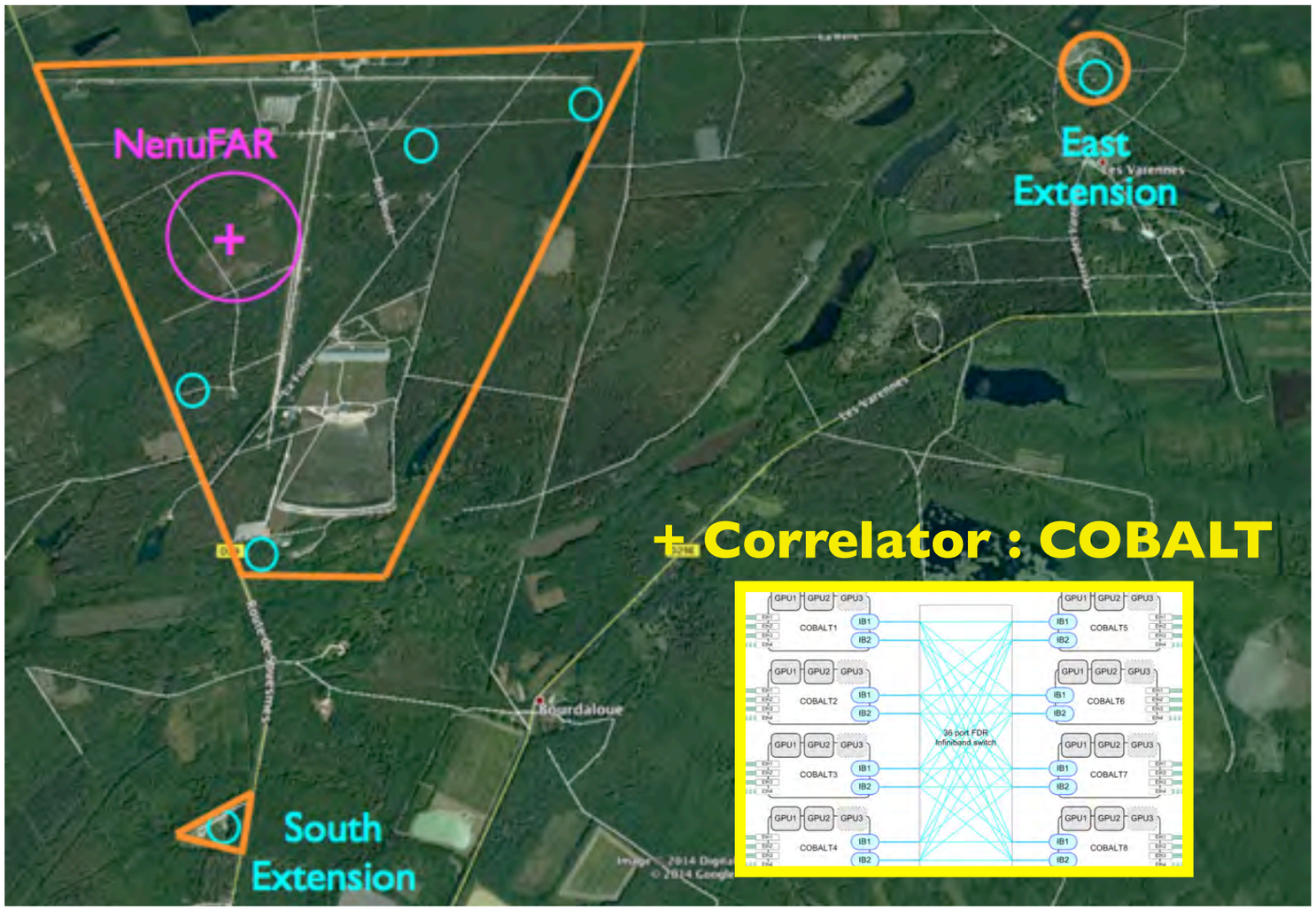
1.6 MB /s /SB

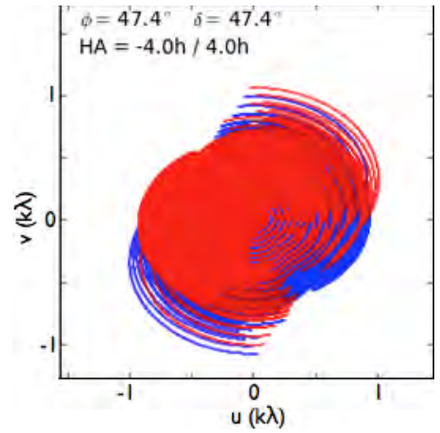
NenuFAR-Backend-0
(= UnDySPuTeD offline on <<768 SB)

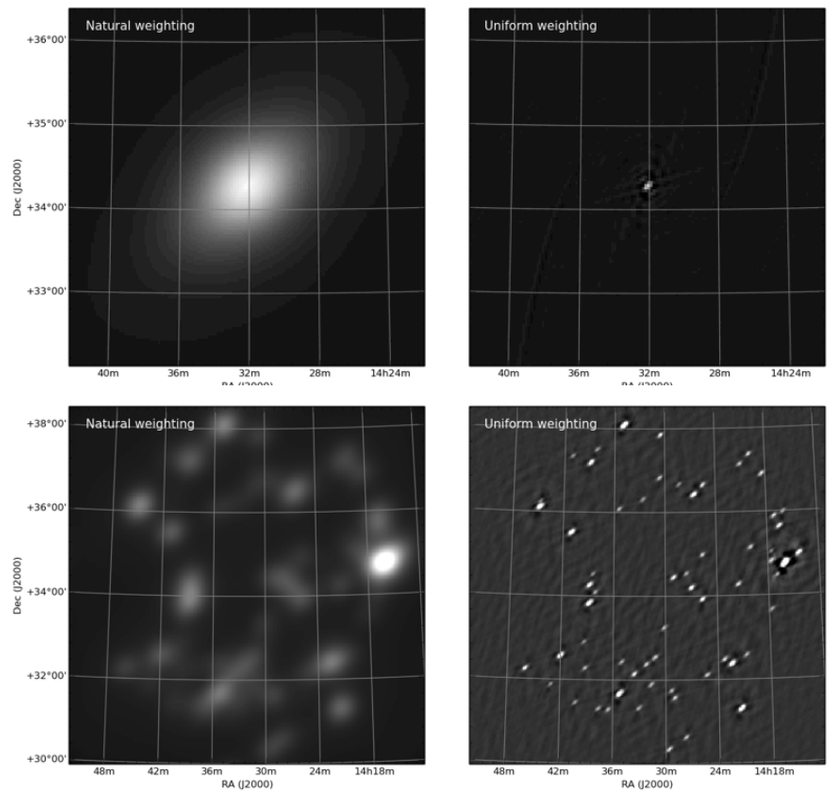
- Channelization down to δf<1 kHz
- Dedispersion (predefined, parametric)
- Integration over δt ≥5 μs

MA = 19 antennas mini-array
SB = ~200 kHz sub-band
PFB = polyphase filter bank
TBB = Transient Buffer Boards
SST/BST/XST = Subband/Beamlet/Crosslet STatistics

- Mode Imagerie autonome
  - Corrélateur (=LOFAR-Cobalt) + 6 MR distants synchronisés + synthèse multi-λ
    ⇒ résolution angulaire x7 pour les sources stationnaires large-bande
  - σ(confusion) ∝ θ^2 ⇒ réduite 50x
  - Sensibilité au-delà du coeur = $(N_{distant}/N_{core})^{1/2}$ ~ 25%



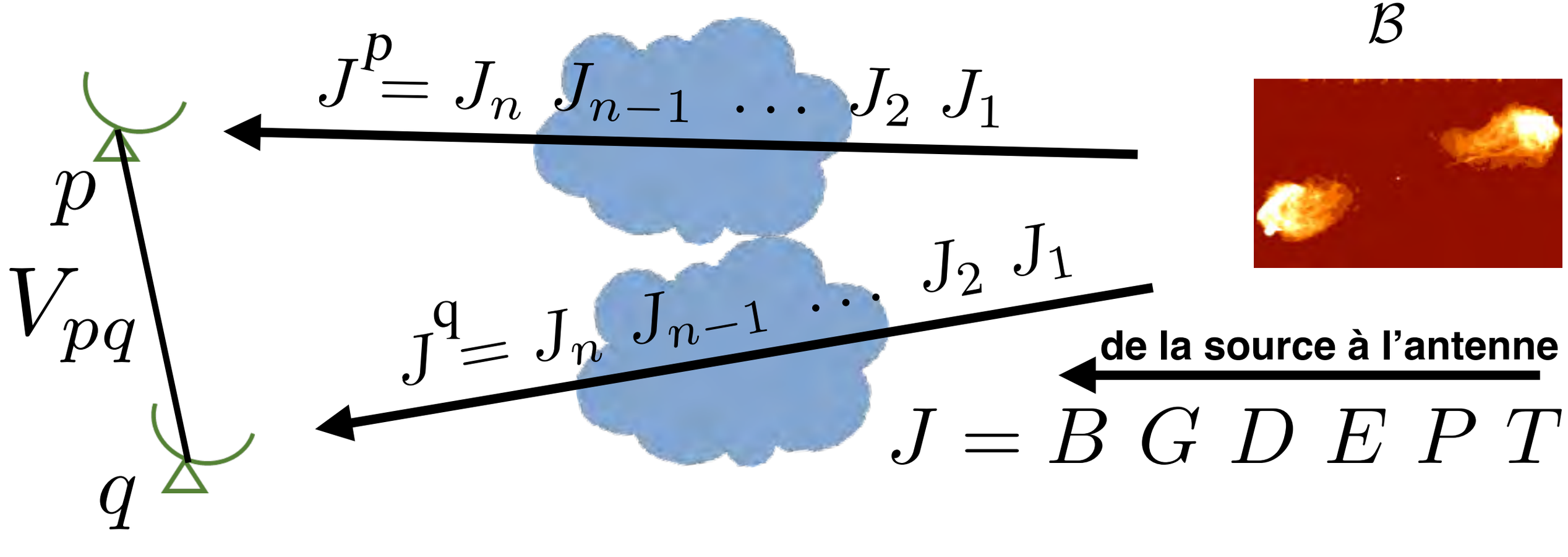




- Coût ~ 720 k€
- Demande ANR (re)soumise 2017 (600 k€)

Sans correction des DDE

Mesure par un interféromètre



Radio Interferometer Measurement Equation

$$V_{pq} = J_p \mathcal{B} J_q^H$$

[Hamaker, Bregman, Sault, 96]
[Smirnov, 11]

- V_{pq} : **Visibilité interférométrique**
- J_p : **Effets de la source jusqu'à l'antenne p**
- $\mathcal{B}$: **Brillance**
- J_q^H : **Effets de la source jusqu'à l'antenne q**

Représentation **compacte**, **intuitive** et **matricielle** des effets de propagation
Maintenant **indispensable** pour l'étalonnage des grand interféromètres

Préparation du NenuFAR-Radio-Imageur (NRI)

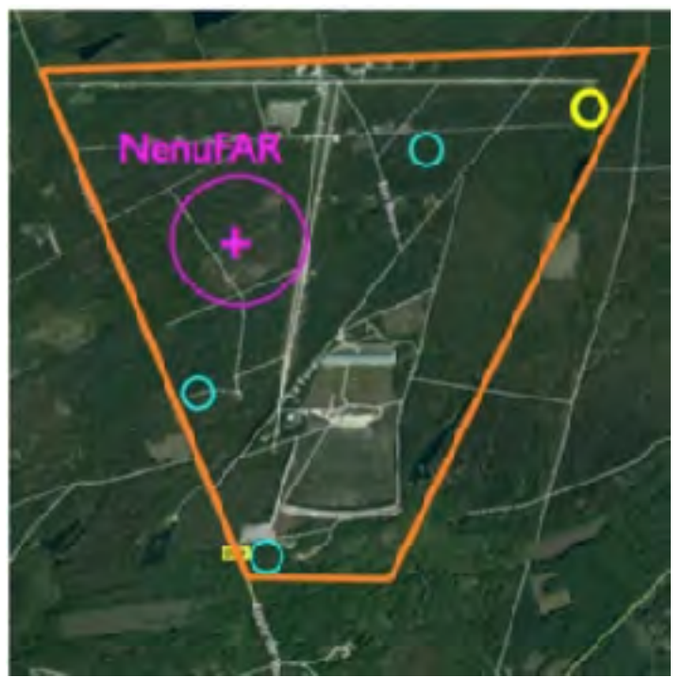
- *Coût total NRI : 720 k€*

- *Demande ANR 2016 rejetée en 2ème étape, mais rapports de referees majoritairement favorables*

- Réalisation d'un démonstrateur en 2017 : 127,23 k€
  - corrélateur = 1/4 Cobalt
  - 1 MR distant, numérisation, synchro, fibre, infrastructure ...

  (+ étude d'optimisation positionnement)

  → imageur rapide, calibration



- Devis, soutiens ASTRON (Cobalt) + Univ. Kapteyn (calibration, post-traitement aube cosmique/âges sombres)

- Manpower + expertise technique à Nançay :

  priorité clairement établie / fin construction coeur

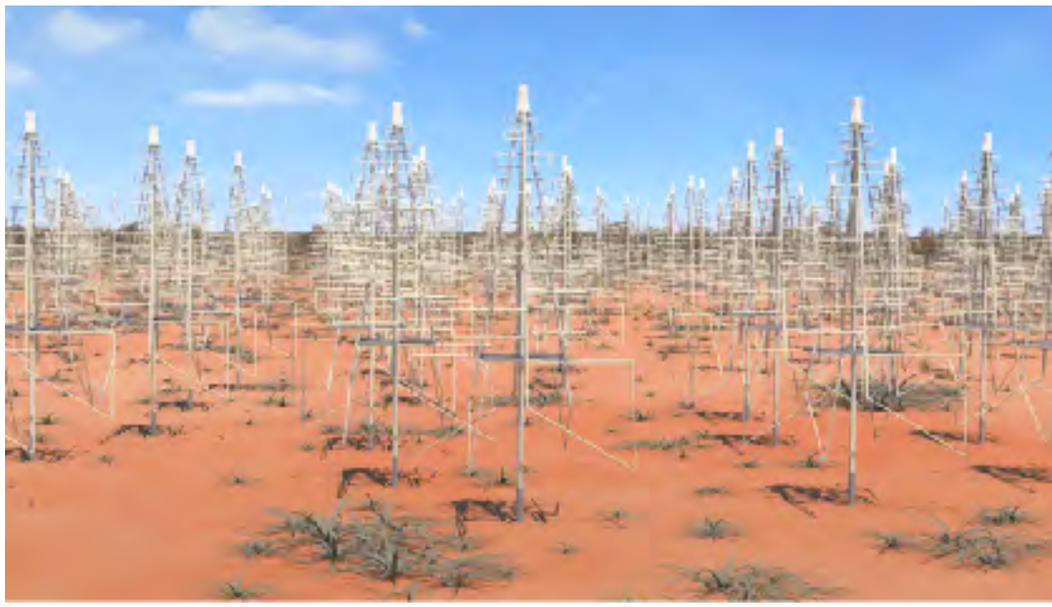
- NenuFAR >> LWA, complémentaire à LOFAR, IR MESR,
  pathfinder officiel de SKA, complémentaire (fréquence & hémisphère)
  ouverture internationale (PC)

- Mission : préparation de la communauté Française pour SKA
  → Beamformer et Imageur

- Développement original, Soutenu par prospective INSU 2014,
  OP, CSD Nançay, SKA-France ...

- Communauté scientifique intéressée
  ~70 chercheurs (cf. Science Case)

- Équipe de commissioners en expansion



SKA-Low