

Études planétaires et exoplanétaires avec les grands radiotélescopes LOFAR, NenuFAR et SKA

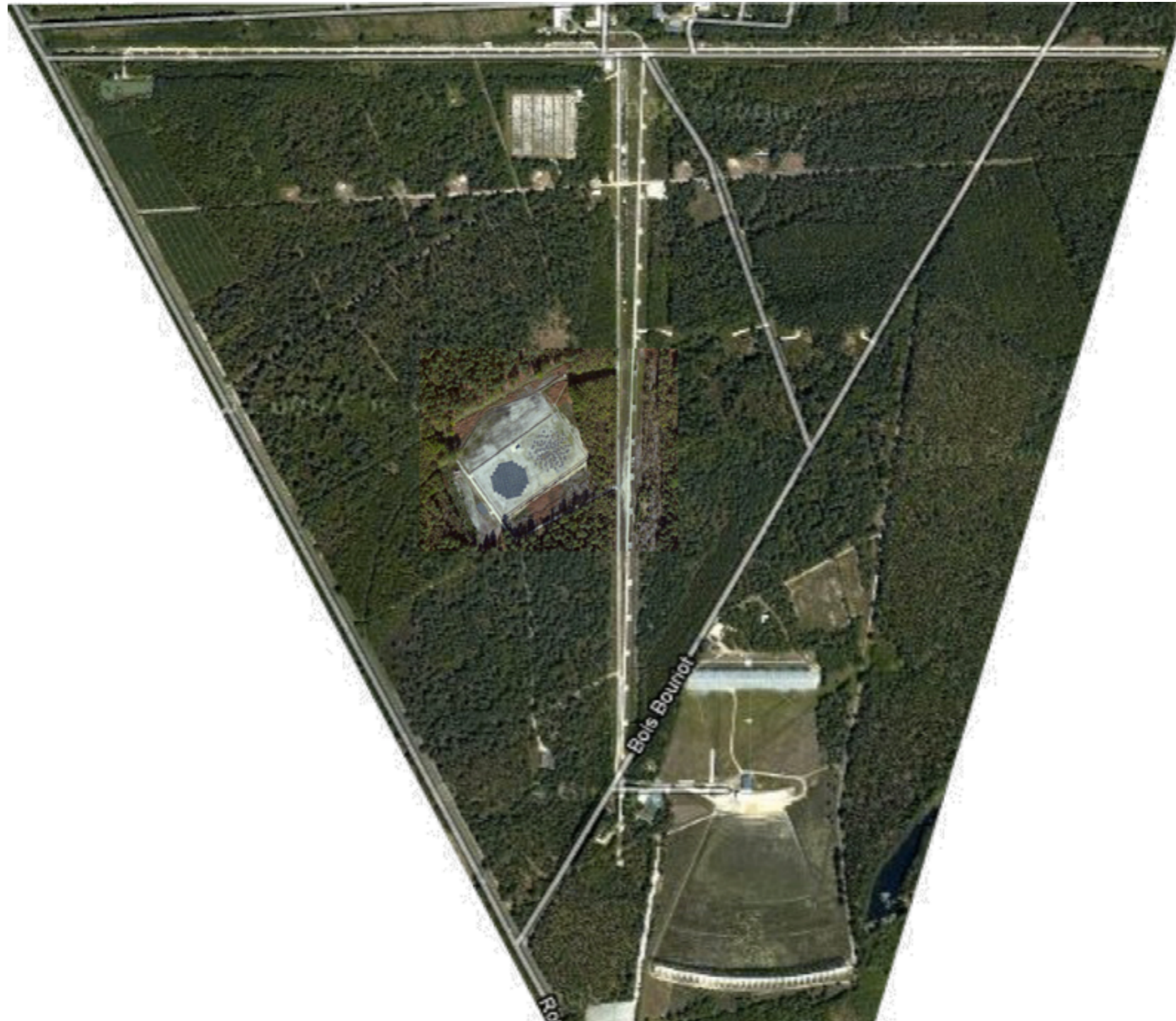
Philippe Zarka

LESIA & USN, Observatoire de Paris, CNRS, PSL, Meudon

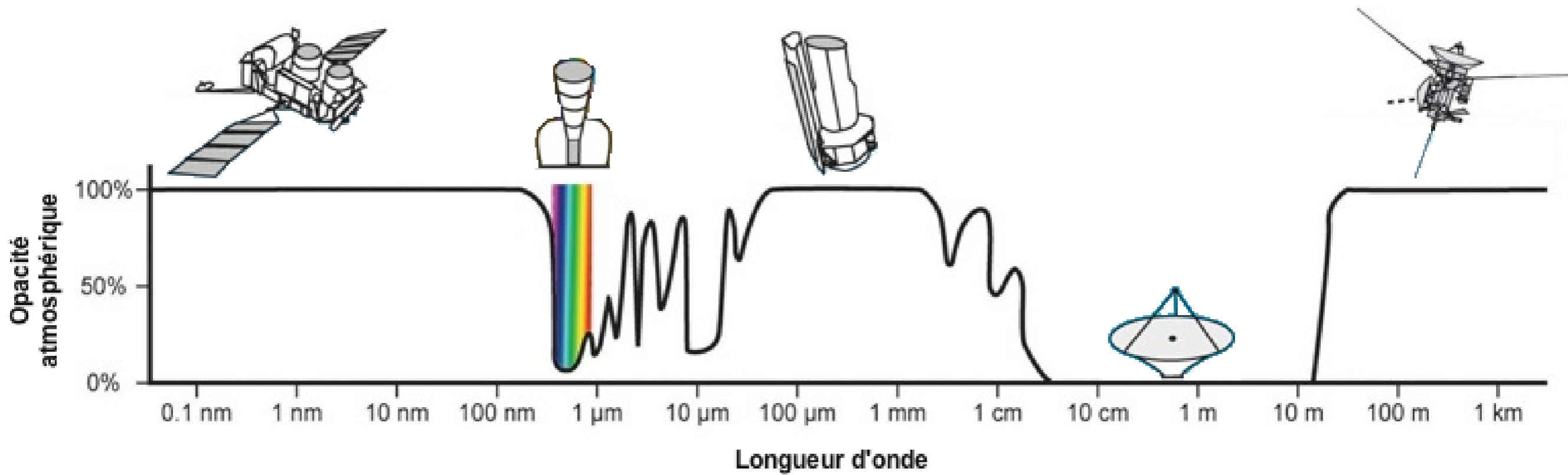
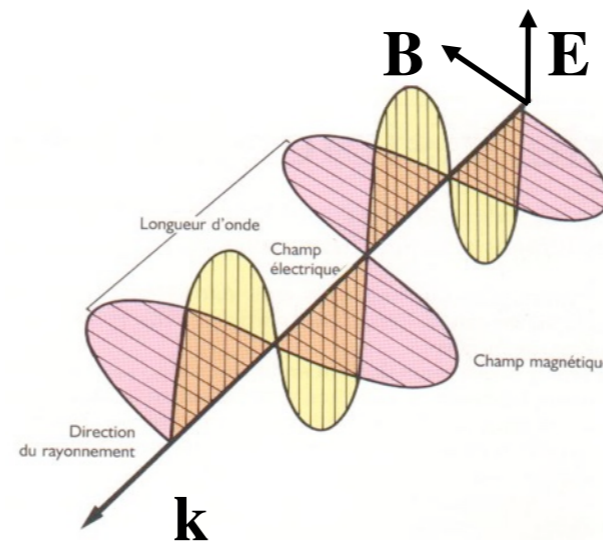
philippe.zarka@obspm.fr

- En Astronomie, comme dans d'autres domaines,
Démarche "Verticale" (objet) ou
"Horizontale" (méthode: théorie, labo, instru, obs $\neq \lambda$) ?
- Pavage de la discipline (redondances, gaps) ?
 - Programmes (ex: PNP, PNST...) $\Rightarrow V$
 - Actions Spécifiques (ex: ALMA, SKA-LOFAR) $\Rightarrow H$
- Ici, Radioastronomie Basses Fréquences $\Rightarrow H$
Essor récent \Rightarrow nouvelles possibilités & thématiques

- Nançay = site Français de Radioastronomie BF (Observations, R&D)

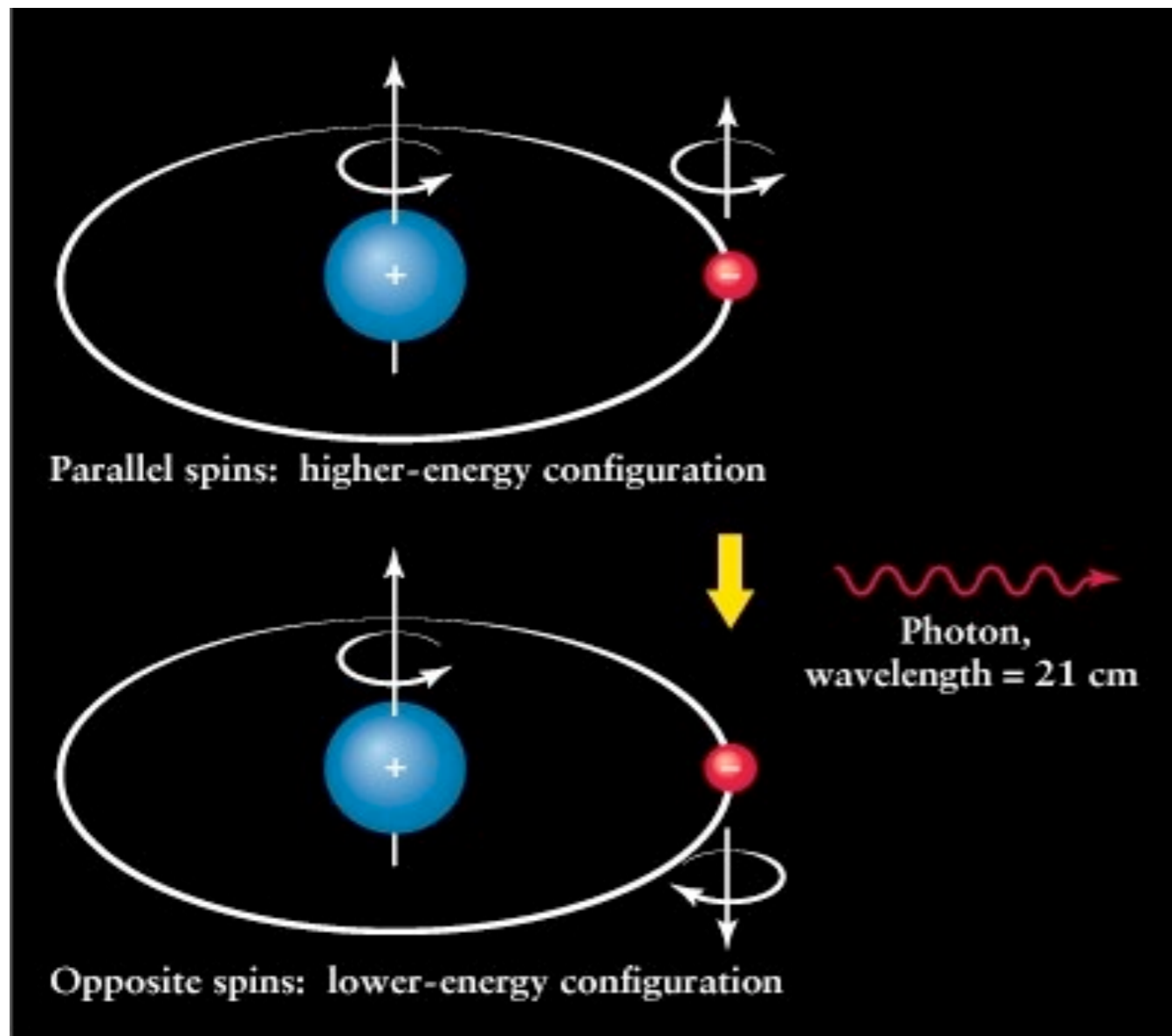


- Fenêtre radio

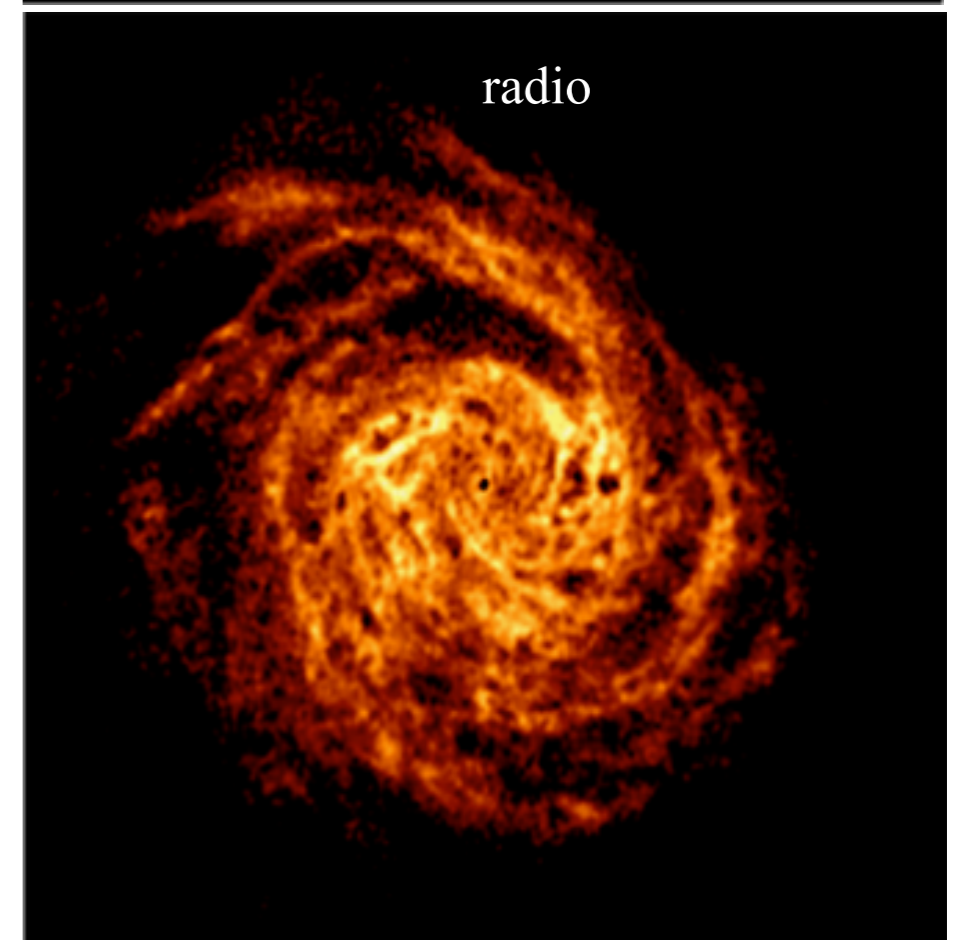
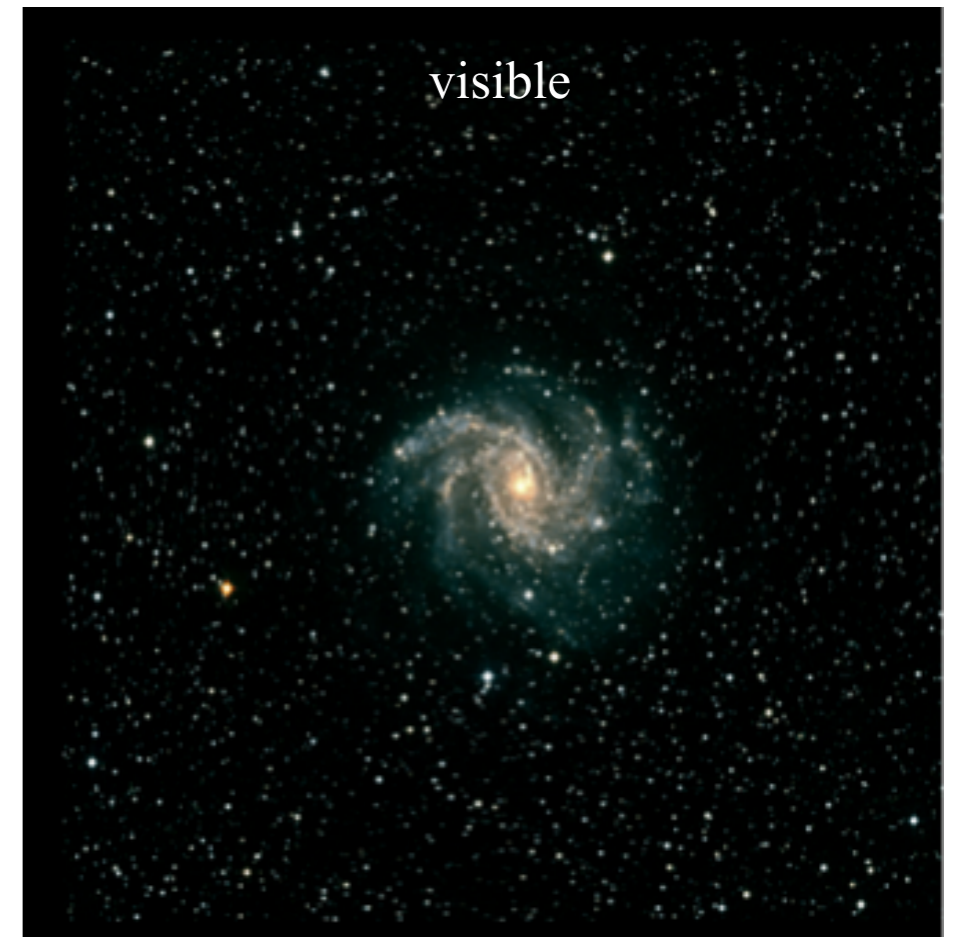


$$\nu \text{ (MHz)} = 300 / \lambda \text{ (m)}$$

- Intérêt BF : H_I ($\lambda=21$ cm)



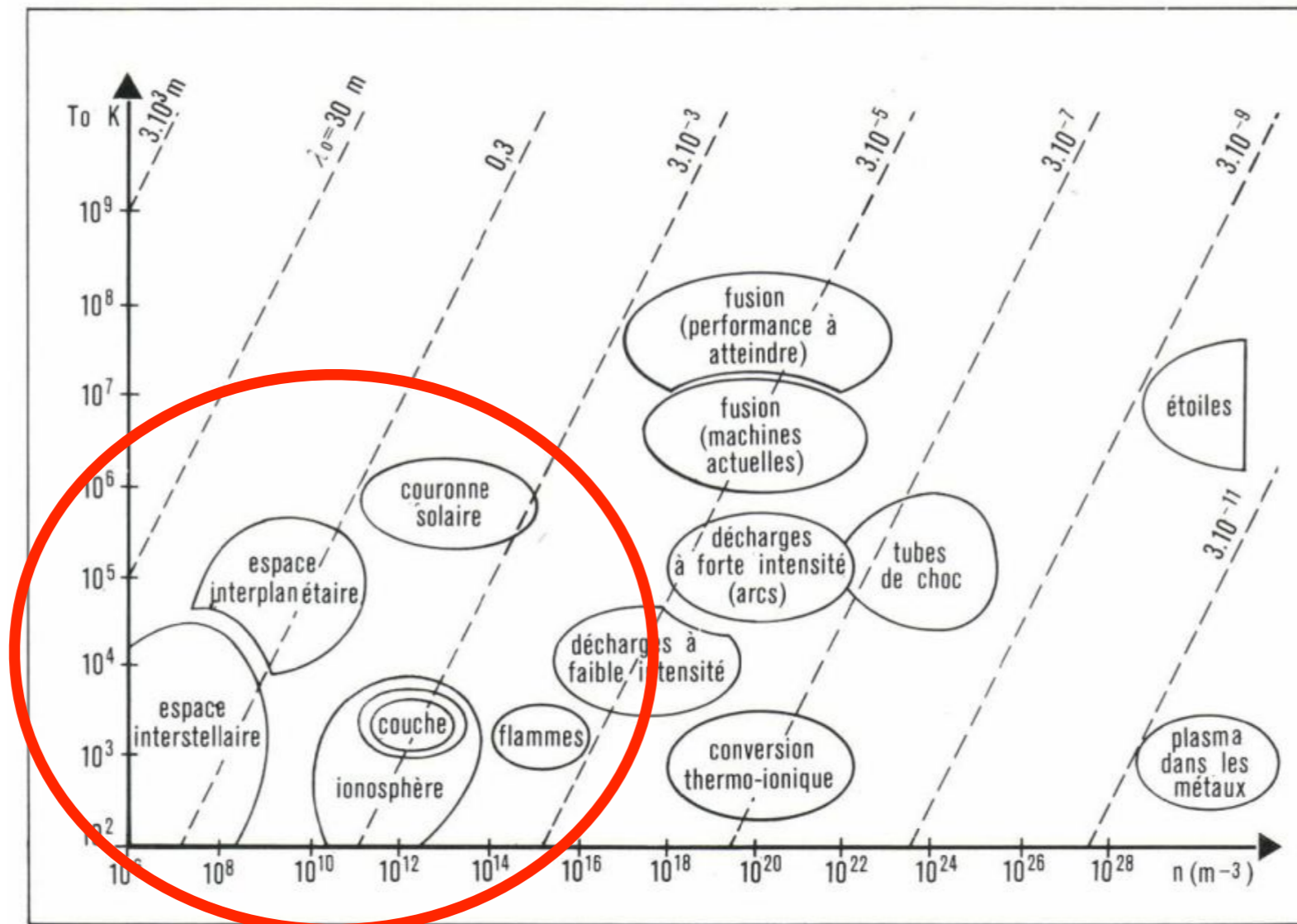
b



- Intérêt BF : plasmas astrophysiques

Fréquence plasma : $f_{pe} \text{ (Hz)} = 9 N_e^{1/2}$ avec N_e en m^{-3}

Fréquence cyclotron (électronique) : $f_{ce} \text{ (Hz)} = 2.8 \times 10^6 B$ avec B en Gauss ($10^{-4} T$)

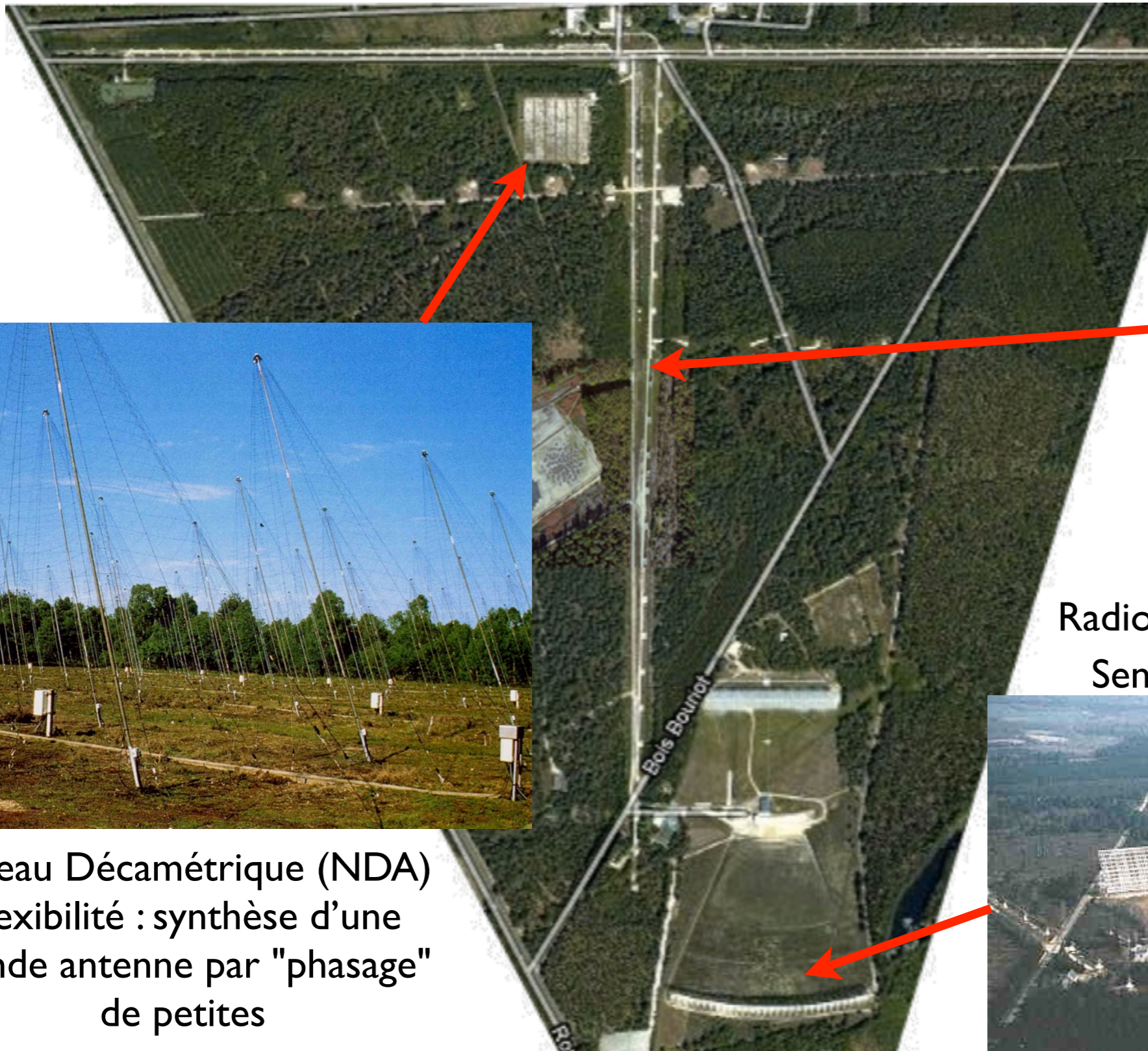


Domaines de densité (en abscisse) et de température (en ordonnée) pour différents types de plasmas.

→ $f_{pe}, f_{ce}, n \times f_{ce} =$ quelques kHz à centaines de MHz dans les environnements planétaires

- Radiotélescopes à Nançay

Radio-Héliographe (NRH)
Résolution angulaire $\sim \lambda/D$

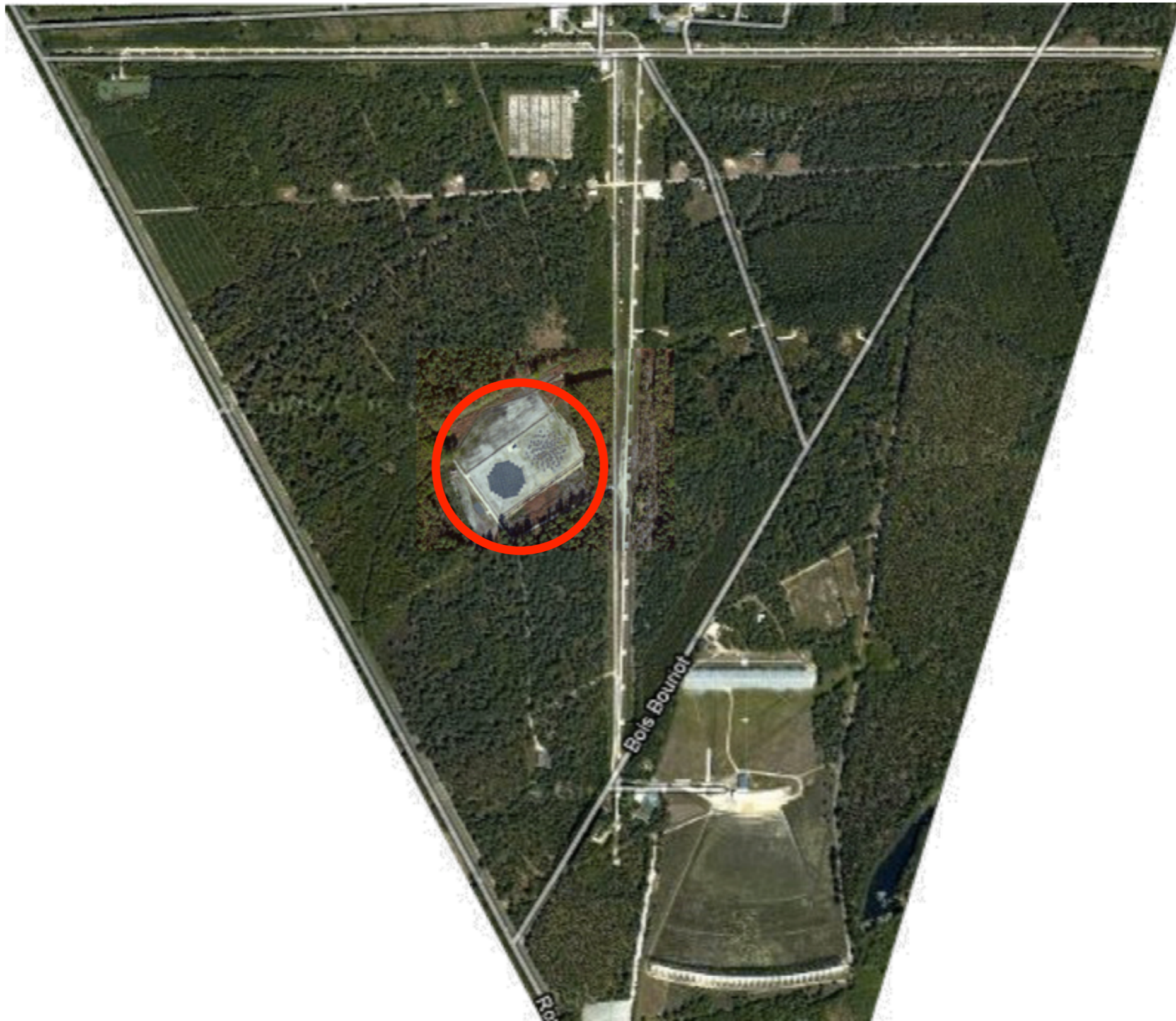


Radiotélescope décimétrique (NRT)
Sensibilité \propto surface collectrice



Réseau Décamétrique (NDA)
Flexibilité : synthèse d'une
grande antenne par "phasage"
de petites

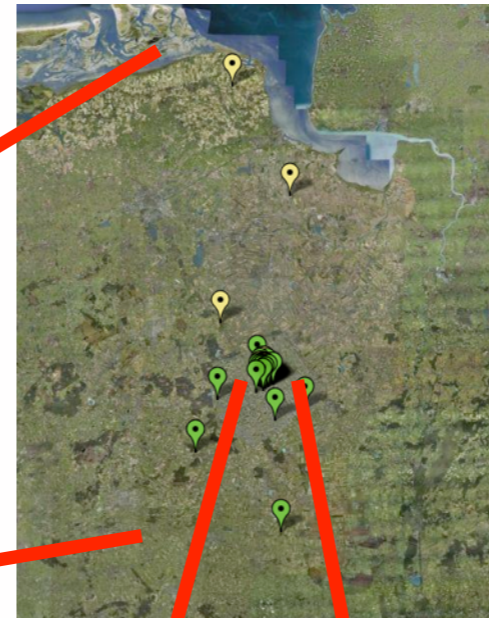
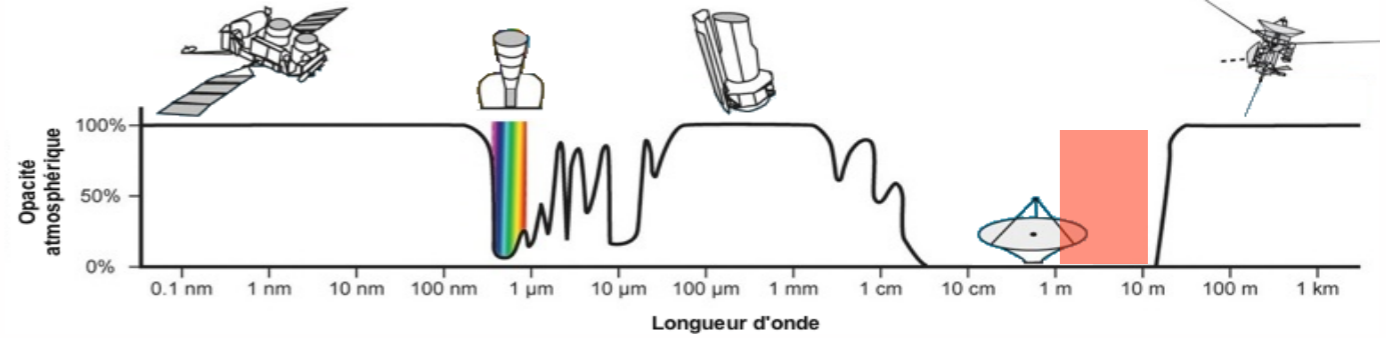
- Dernier né à Nançay : LOFAR



Radiotélescope Européen, numérique : grand réseau, très complexe, polyvalent ...

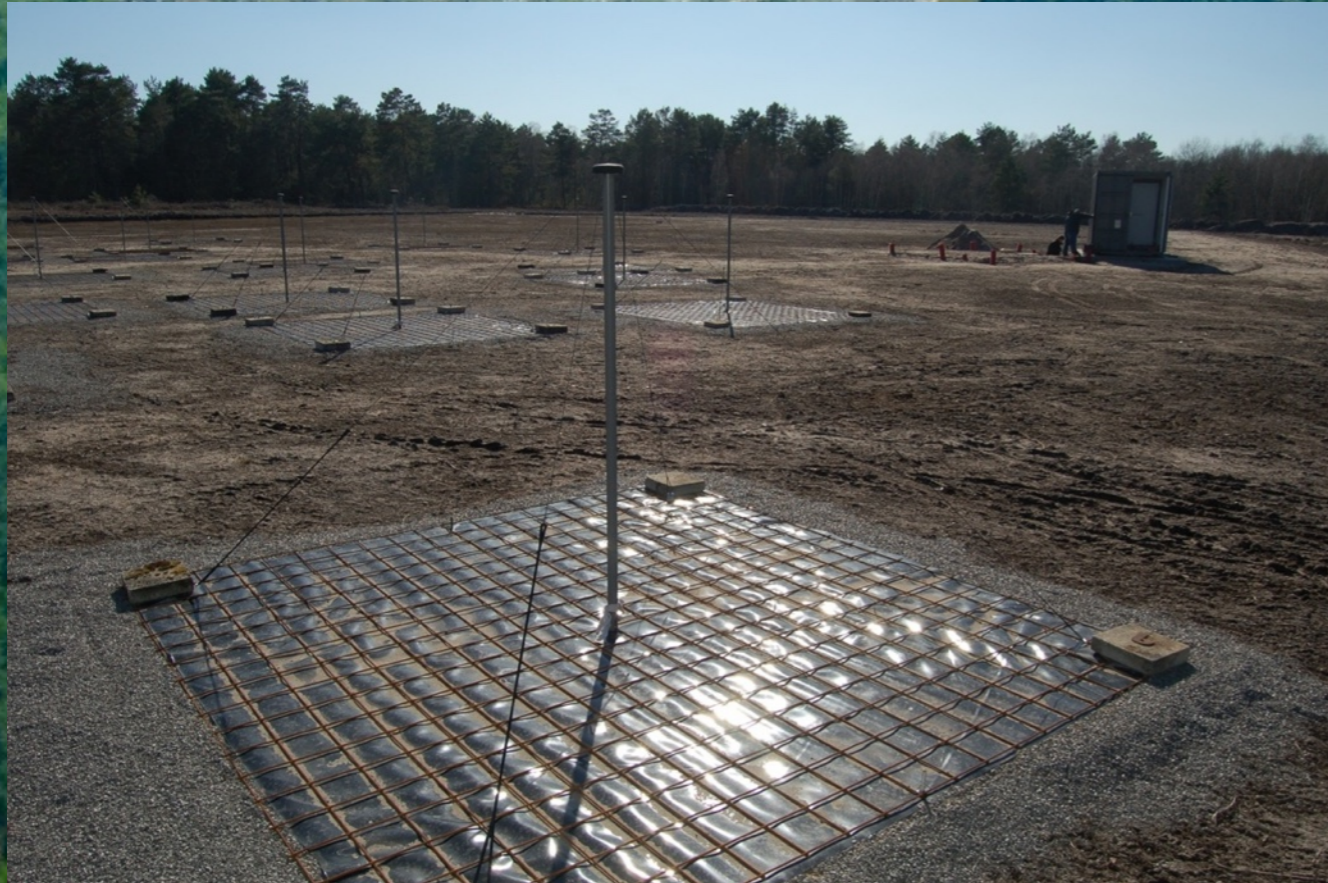
LOFAR

un réseau multi-échelles



- 1824 antennes (ou tuiles) NL + 1248 Internationales

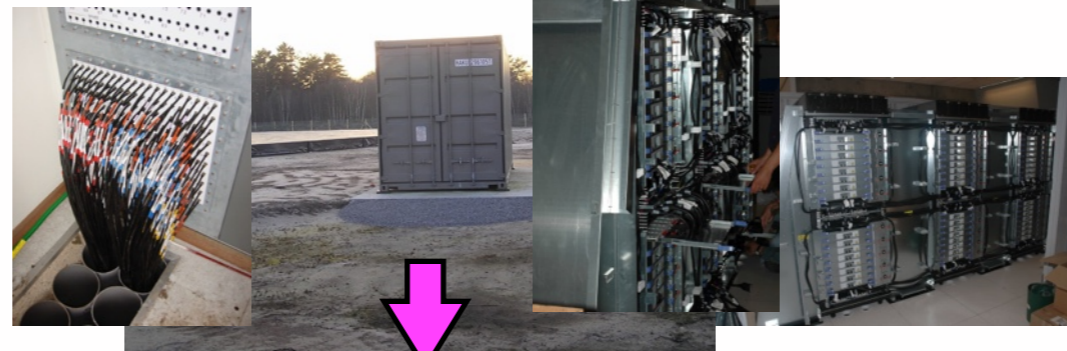
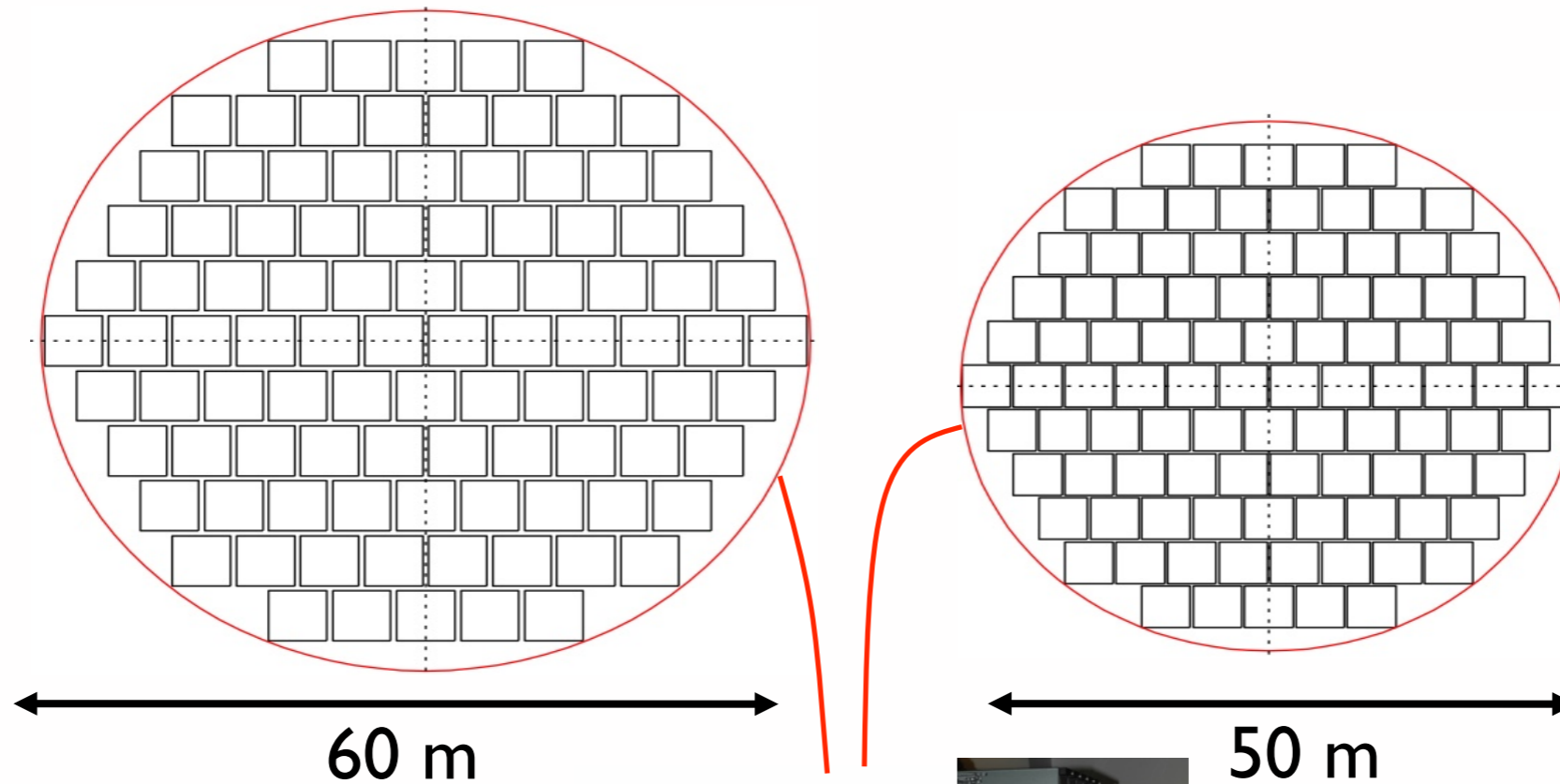
Station LOFAR à Nançay : FR606



Station LOFAR : 2 réseaux phasés + "backends"

Antennes "BF"
(30-80 MHz)

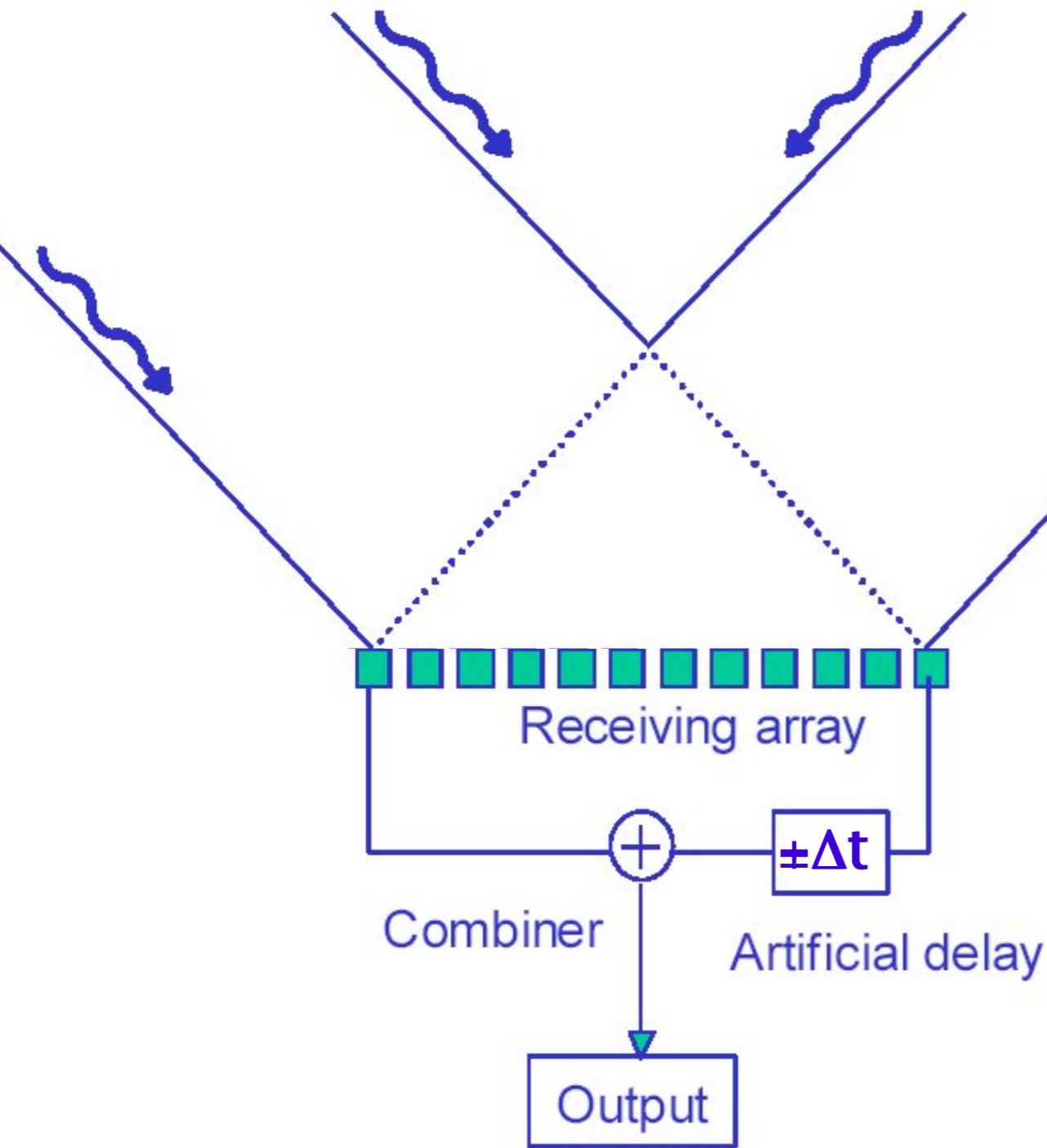
Antennes "HF"
(110-250 MHz)



3+ Gbit/sec

Corrélateur (grappe de calcul)

Phasage d'antennes et pointage



Pointage électronique

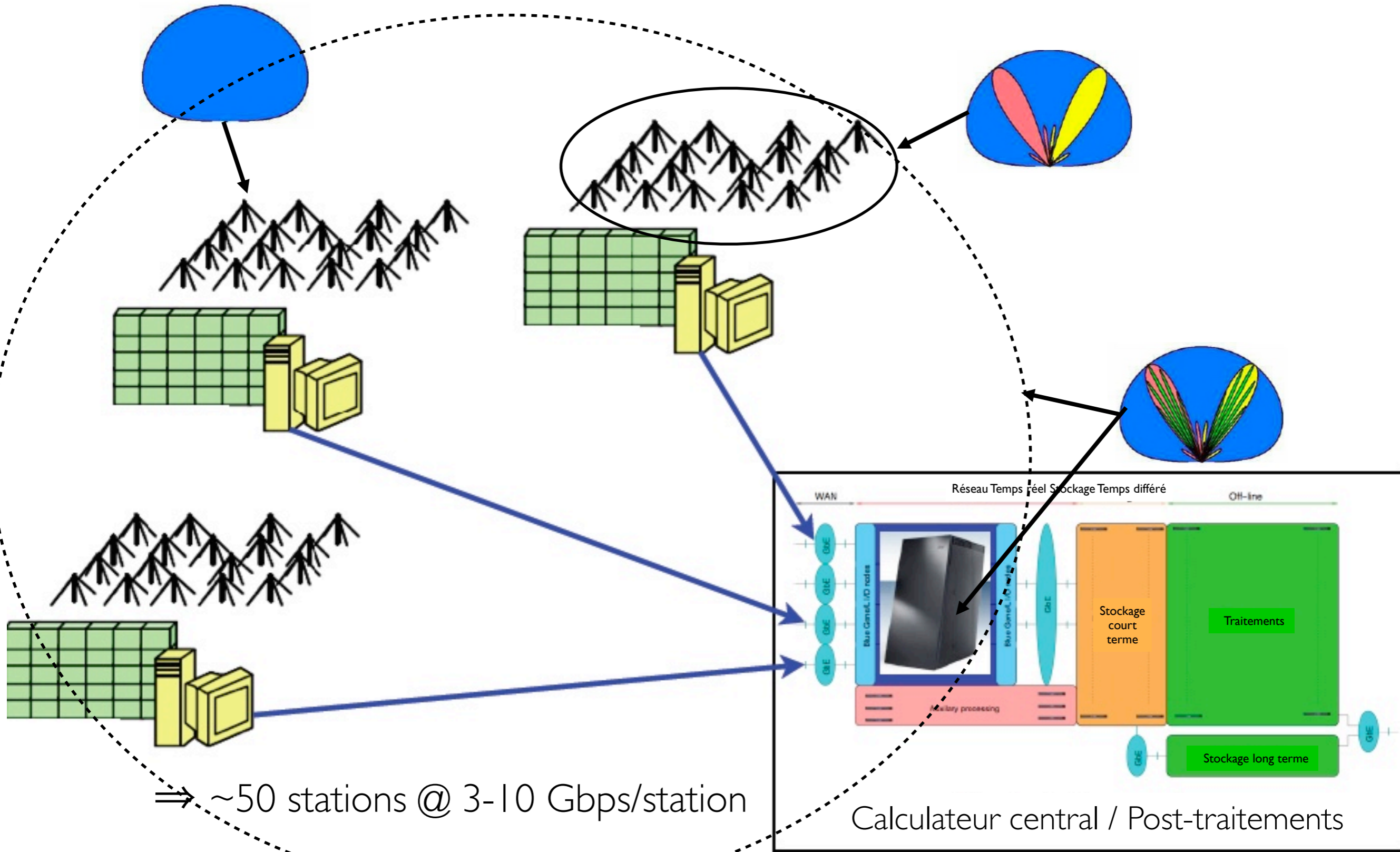


Parabolic Reflector

Pointage mécanique

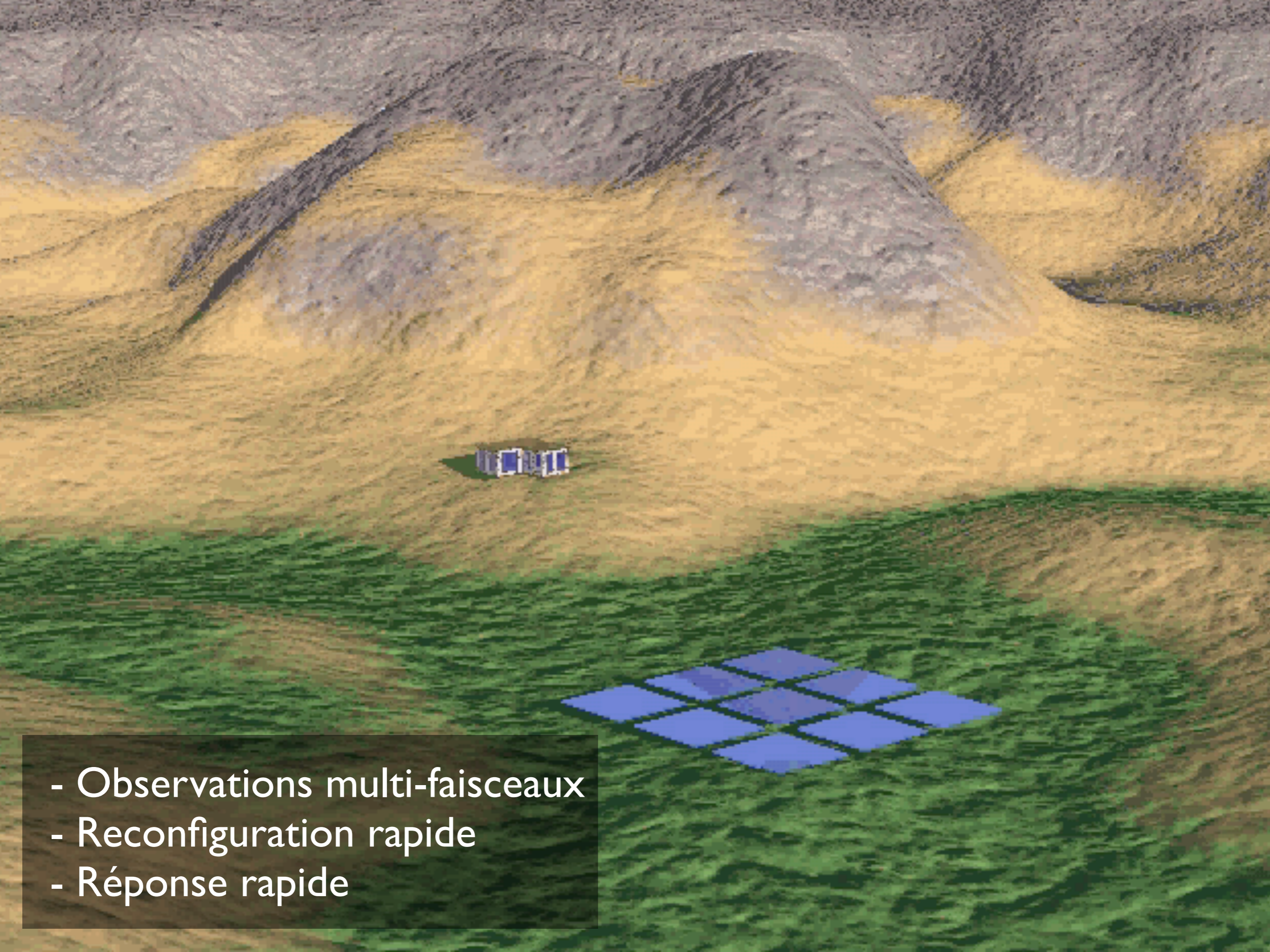
Le réseau LOFAR

- Traitements «station» : amplification, numérisation, filtrage, beam-forming, buffers «transitoires» (TBB)
- Calculateur central : compensation des délais, corrélation / sommation
- Post-traitements : étalonnage, traitements scientifiques, archive long terme



Un radiotélescope "logiciel"



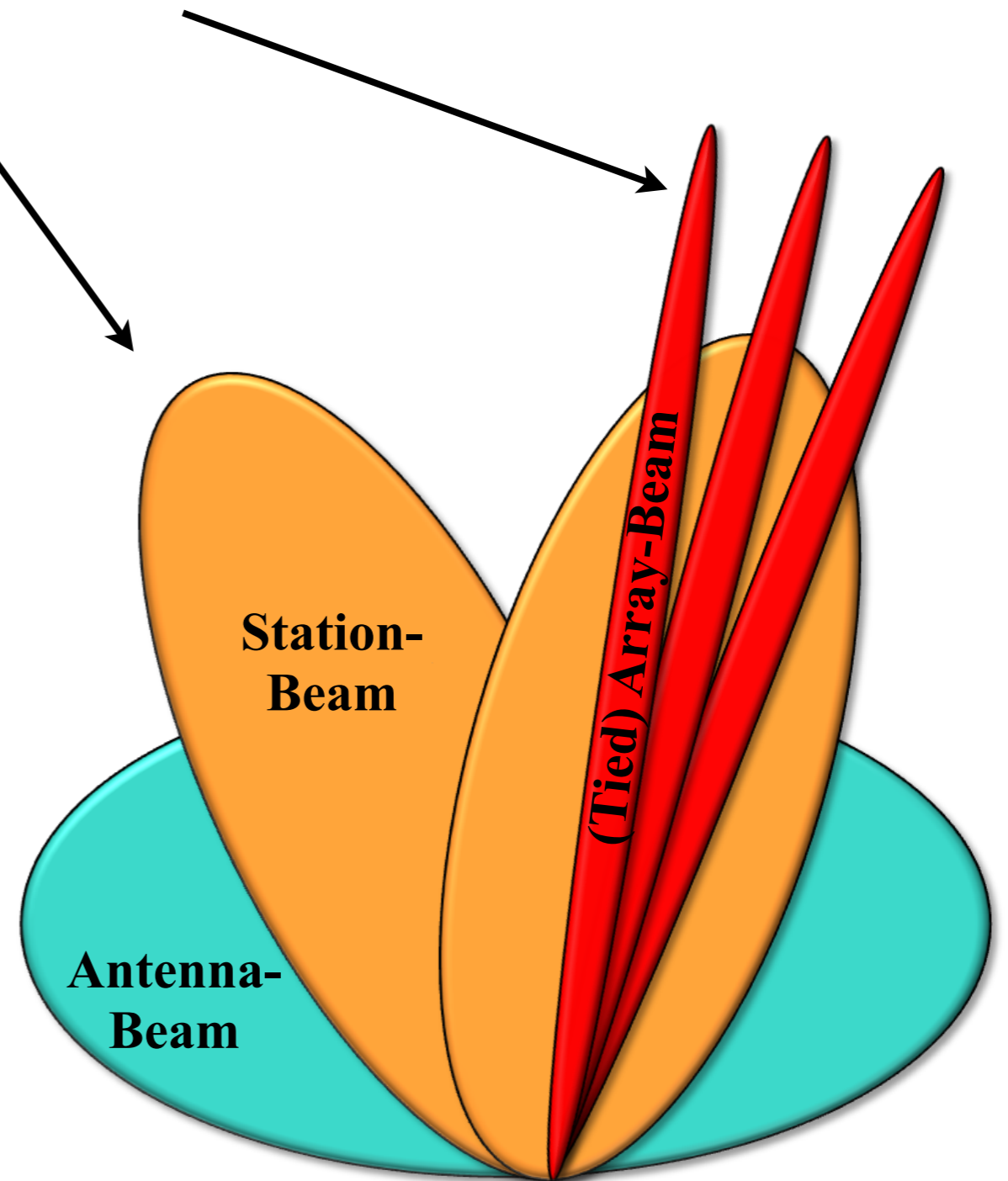


- Observations multi-faisceaux
- Reconfiguration rapide
- Réponse rapide

Modes d'Observation

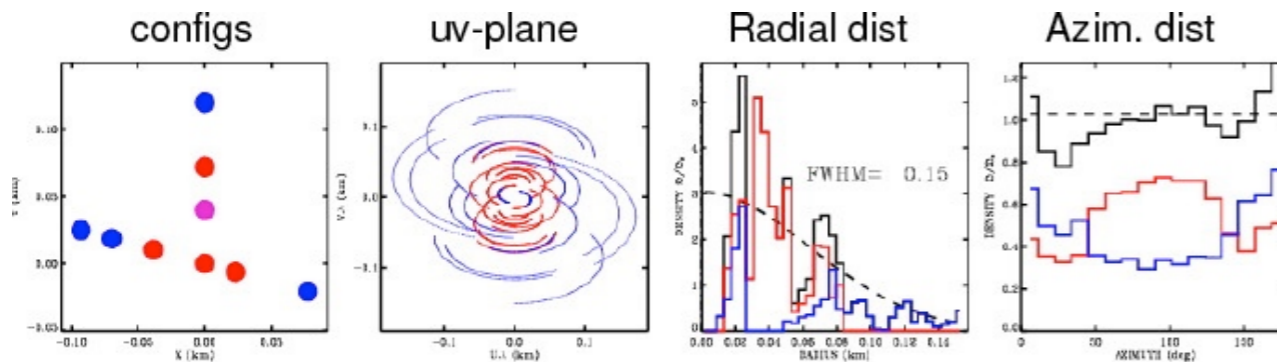
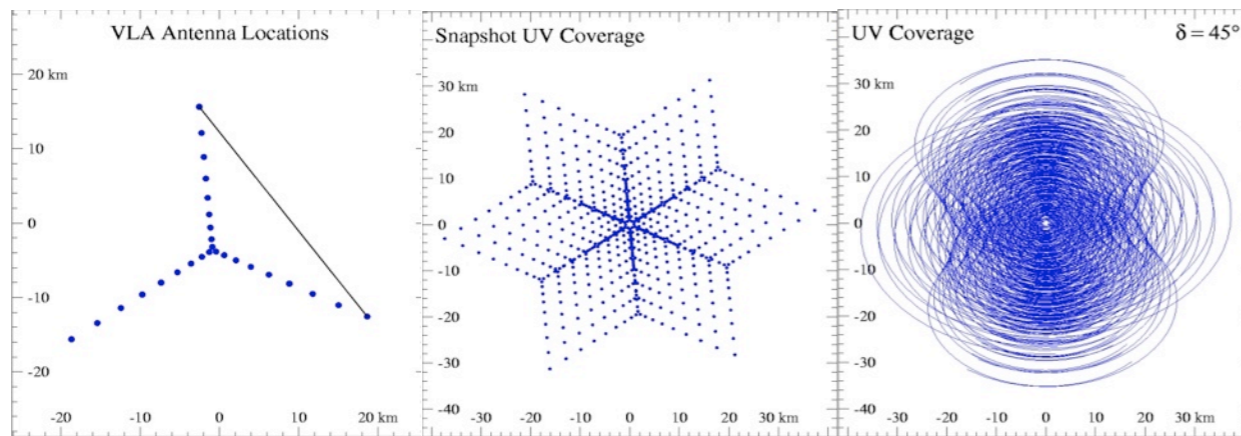
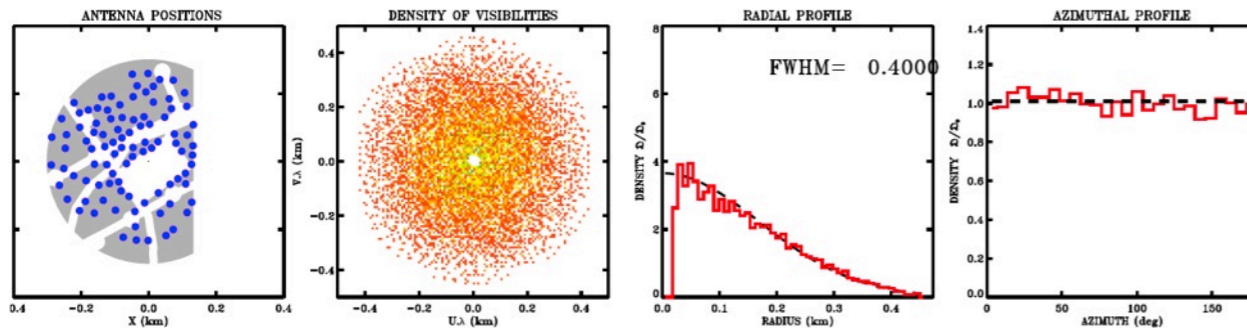
- Faisceaux phasés : incohérents & cohérents

- Capture de forme d'onde (instantanés)



Modes d'Observation

- Imagerie Interférométrique



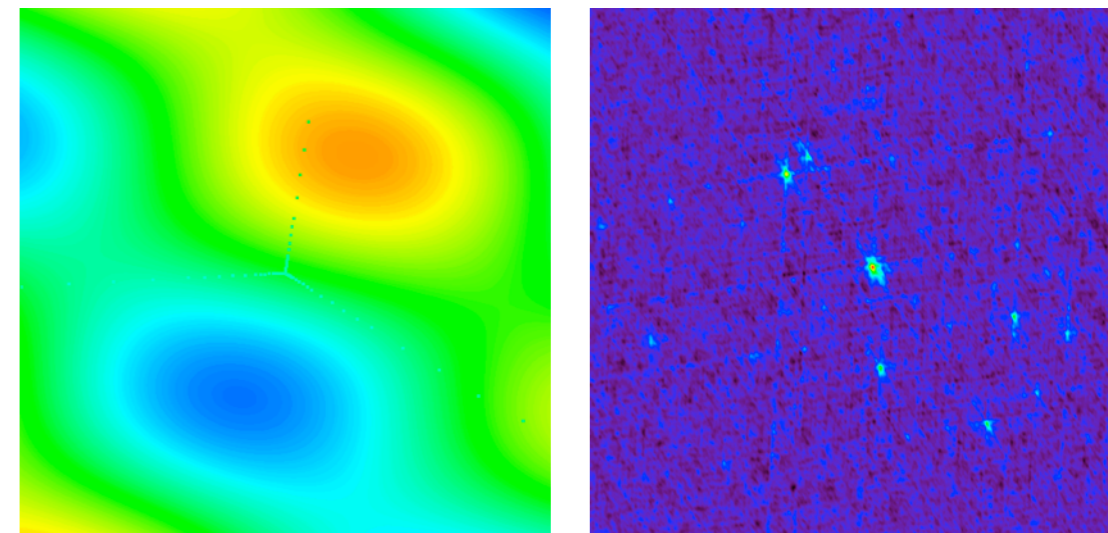
Plateau de Bure observations, supersynthesis + multiconfiguration

Cartes des visibilités
(corrélations 2 à 2)
complexes

$$= \text{TF}(\text{image du ciel}) \times \text{Couverture } (u,v)$$

$$= \text{TF}(\text{image du ciel} \otimes \text{PSF})$$

+ Nécessité de corriger
des effets de l'ionosphère



Caractéristiques techniques de LOFAR

- « Interféromètre » de « Réseaux phasés » Européen
- 24 stations «coeur» + 14 distantes + 12 internationales
- Diamètre ~90 km (NL) → >2000 km (Europe)
- Aire collectrice ~ 10^{4-5} m^2 ($\propto \lambda^2$)
- Gamme de fréquences = (10)30-80 et 110-250 MHz ($\lambda=1.2-10\text{m}$)
- Modes Imagerie + Faisceaux cohérents + Forme d'onde
- Résolution ~ 0.1 " à 10 ", grand champs ($\sim 10^\circ$)
- Sensibilité $\leq 1 \text{ mJy}$ ($= 10^{-29} \text{ Wm}^{-2}\text{Hz}^{-1}$)
- Résolutions → 1 msec × 1 kHz, Polarisation complète
- Élimination des parasites, « optique adaptative » ionosphérique
- Premier spectro-imageur Basses Fréquences « généraliste »
- 1^{er} « pathfinder » de SKA

Un instrument puissant mais complexe

Télescope multi-programmes

Project Code	PI	Title	CYCLE 7		CYCLE 8		
			Awarded observing hours	Awarded processing hours	Awarded observing hours	Awarded processing hours	
LC7_001*	R. Fallows	Monitoring Scintillation above LOFAR	0,0	5,0			
LC7_002	A. Bilous	A Full Census of the Known Pulsar Population: Expanding Sky Coverage	24,0	17,0			
LC7_003	L. Gu	Radio Structures in a Newly-Discovered Early-Stage Major Merger	8,7	15,0			
LC7_004	F. Savini	STUDY OF NON-MERGING MASSIVE CLUSTERS AT LOW FREQUENCY	8,3	8,3			
LC7_006	S. Koenig	Disentangling the central kpc of the Medusa merger	8,3	16,3			
LC7_007***	G. Mann	Interferometric imaging observations of the Sun with LOFAR	41,2	75,1			
LC7_008	M. Chernyakova	PSRJ2032+4127 toward					
LC7_009	D. Santos-Costa	Coordinated multi-frequency and in-situ study of Jupiter					
LC7_010	U. Pajdosz	Duty cycle of the active galactic nuclei: deep low-frequency					
LC7_012	A. Scaife	Deep Polarization Observations of the					
LC7_013	J.-M. Griessmeier	Radio observations of the planets					
LC7_014**	J. Hessels	Simultaneous Radio/X-ray Observations					
LC7_015	L. Lamy	Search for variable radio emissions from the V830					
LC7_016	S. Seethapuram Sridhar	Magnetizing the universe with					
LC7_017	S. Mooney	Probing the Jets of Blazars with					
LC7_018	C. Bassa	A LOFAR survey for millisecond pulsars in unexplored					
LC7_019	R. Oonk	The physical conditions of the cold neutral					
LC7_020	B. Nikiel-Wroczyński	The curious case of HCG15: a little closer					
LC7_022	A. G. de Bruyn	The LOFAR EoR project					
LC7_023	V. Jelic	Faraday tomography of the local ISM, and					
LC7_024	T. Shimwell	The LOFAR Two-metre Sky Survey: Opening a					
LC7_025	D. Hoang	Intergalactic shock-fronts and their					
LC7_026***	J. Broderick	Low-frequency follow-up of					
LC7_027	K. Emig	Carbon radio recombination					
LC7_029	M.A. Krishnakumar	A LOFAR survey of low Dispersion measure pulsars to study frequency evolution of scatter broadening	20,0	7,0			
LC7_030***	M. Kuiack	Triggered follow-up for AARTFAAC Transient Sources	8,0	16,0			
LC7_031	M. Geyer	Pulsar scattering analysis using LOFAR and the GBT	7,6	2,4			
LC7_032	S. Straal	Confirmation and timing of pulsar candidates from a targeted LOFAR search towards PWNe and SNRs.	12,0	4,9			
LT5_001**	M. Serylak	Studying Pulsars and the Interstellar Medium using International LOFAR Stations	0,0	0,0	0,0	0,0	
LT5_002***	J.-M. Griessmeier	Measuring the energy of Saturn's lightning	28,0	28,0	28,0	28,0	
LT5_003	J. Verbiest	Pulsar Timing with LOFAR	141,4	57,0	141,4	57,0	
LT5_004	J. Hessels	LOTAAS: the LOFAR Tied-Array All-Sky Survey	260,0	364,0	260,0	364,0	
LT5_009	A. G. de Bruyn	The LOFAR EoR project	200,0	0,0	200,0	0,0	
LT5_010*	S. Buitink	Precision Measurements of Cosmic Rays with LOFAR	0,0	0,0	0,0	0,0	
			TOTAL	1751,4	1478,2	629,4	449,0

Week number	week day	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
21, 20th May	Mon	LC0_003 - Zenith fields - 24 hrs											Stress system runs + TBB runs	LC0_031 - MS0735.6 - 6hrs				LC0_019 (EoR)							
	Tue	LC0_019 (EoR)				Investigation week-end failures; Stress system runs; TBB runs			LC0_002 - Jupiter - 10:20 to 13:20 UT		Commissioning OH test				Stress system runs + TBB runs		LC0_005 - Saturn - 5hrs								
	Wed	Pulsars								DE601, DE602, DE603, DE605, FR606, SE607, UK608 switched to local mode at 9 UTC; FE monitoring runs; beam tests								Pulsars				LC0_005 - Saturn - 5hrs			
	Thu	Stress system runs + TBB runs		LC0_039 - SS433		Stress system runs + TBB runs			Station test runs; Stress system runs; TBB runs				LC0_012 - 3C223 - 10hrs								Stress system runs + TBB runs				
	Fri	MSSS - HBA - 16 hrs																Stress system runs + TBB runs		LC0_019 (EoR)					
	Sat	LC0_019 (EoR)				Pulsars												Stress system runs + TBB runs		LC0_012 - VLSS1431 - 8hrs					
	Sun	LC0_012 - VLSS1431 - 8hrs		Observations for system characterization + TBB runs																		LC0_019 (EoR)			

* = pyggybacking mode
 ** = stand alone mode
 *** = trigger

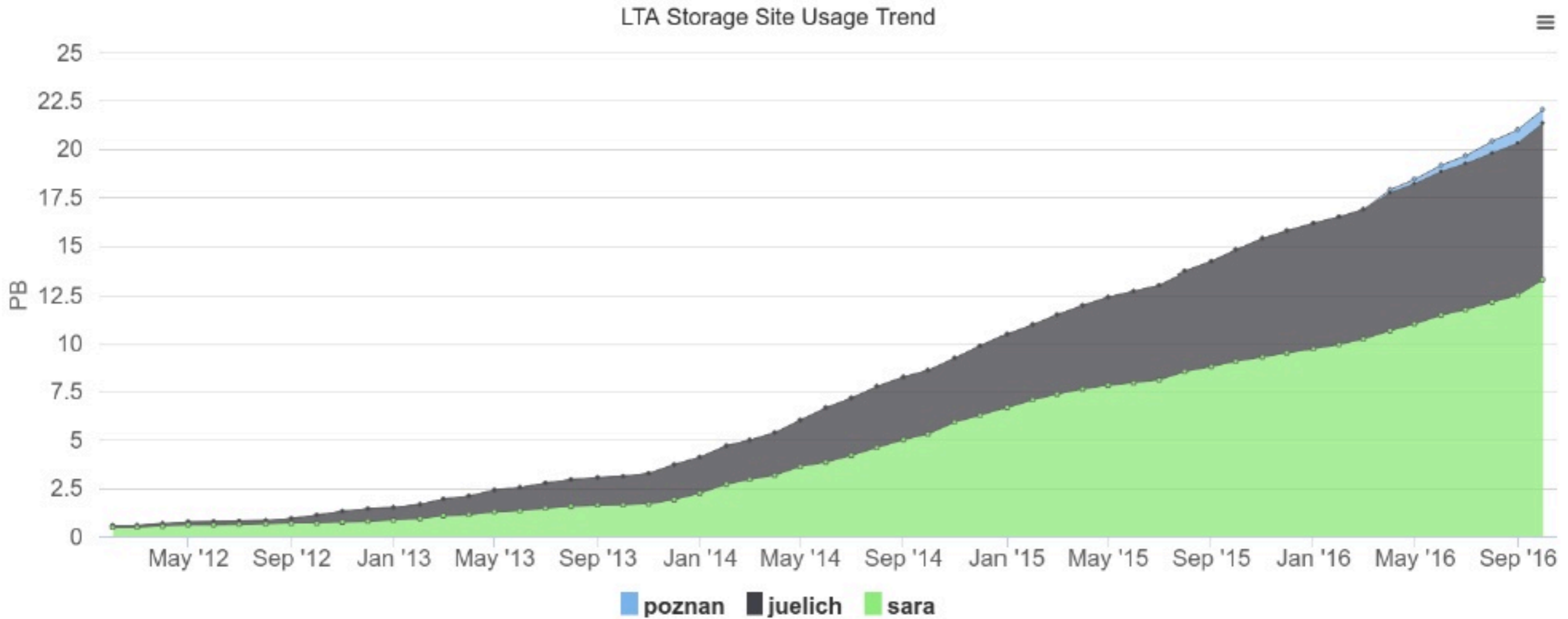
• Cycle 0 : 1/12/2012 → 14/11/2013

• Cycle 10 : 15/5/2018 → 14/11/2018

...

Archive long-terme de LOFAR

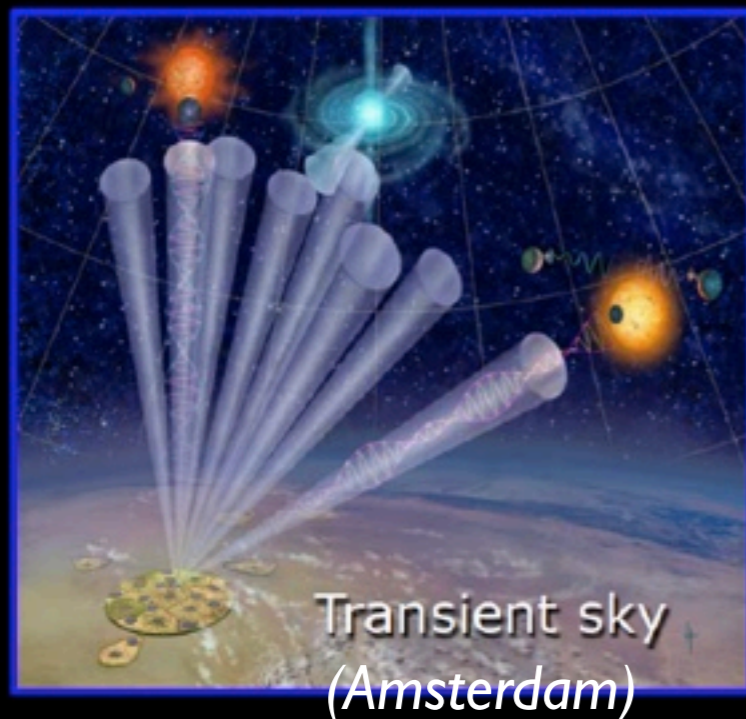
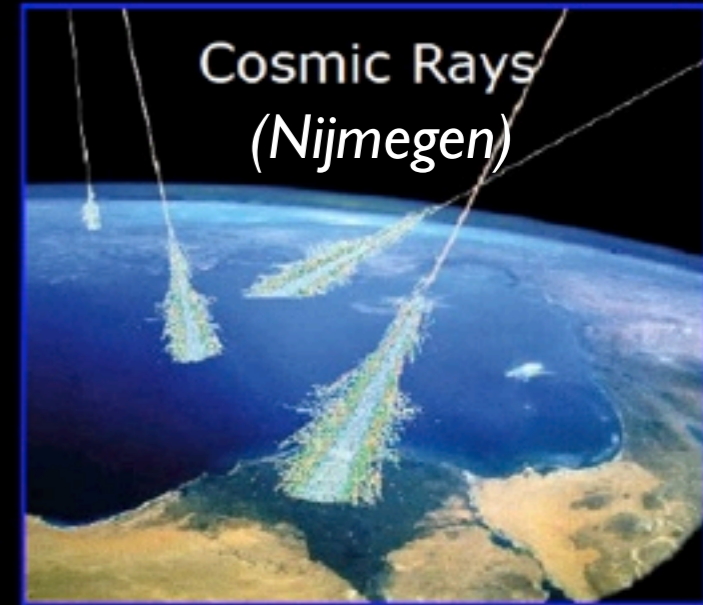
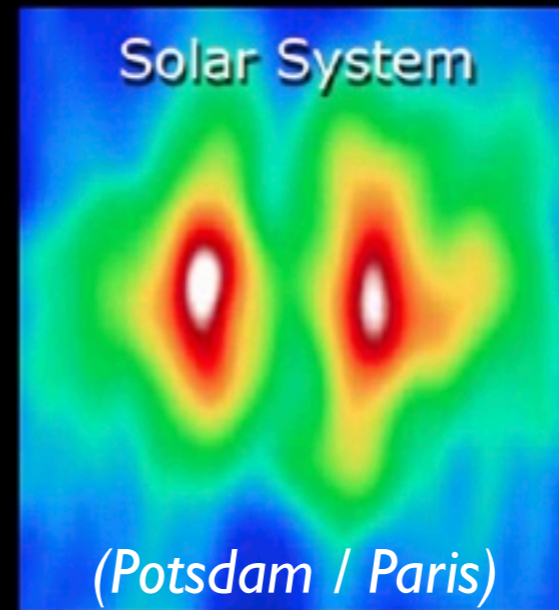
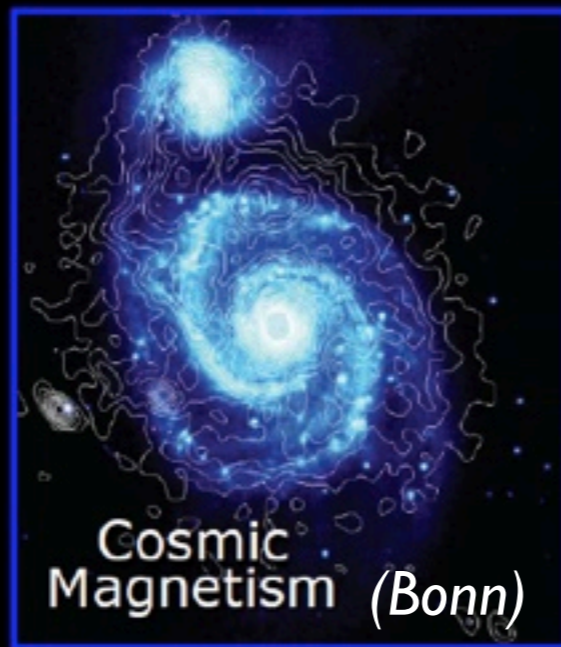
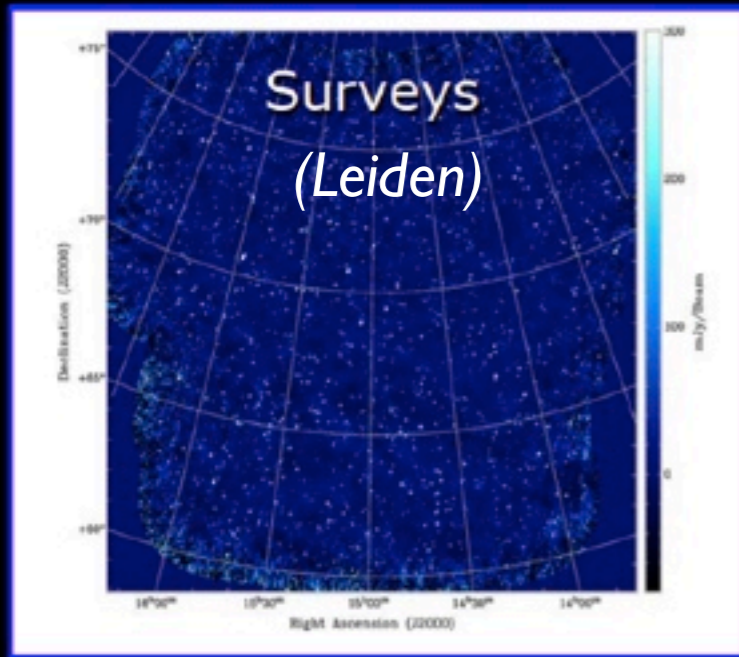
<http://lofar.target.rug.nl>



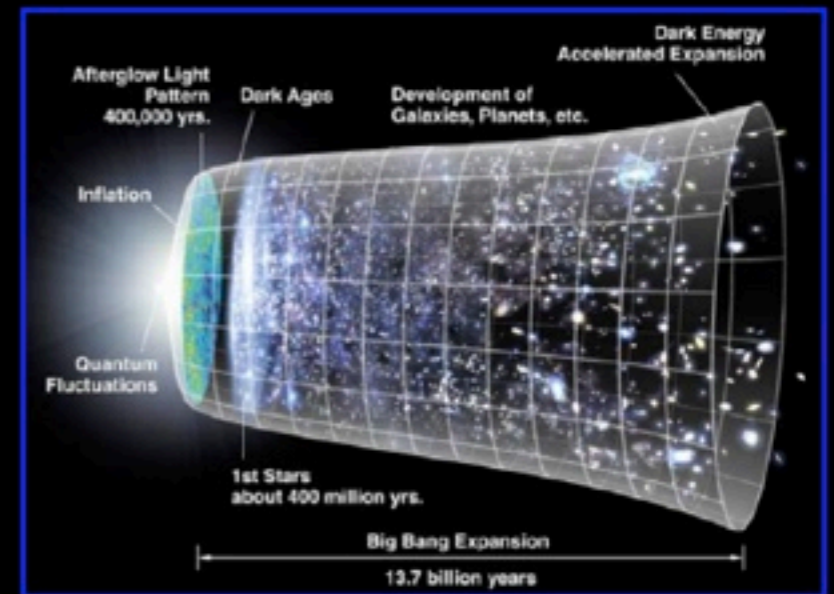
LTA Storage Site Usage
Total: 22.1PB #dataproducs: 7.8M

Taux de croissance estimé ~ 2.5 Péta-Octet/an

LOFAR KEY SCIENCE PROJECTS

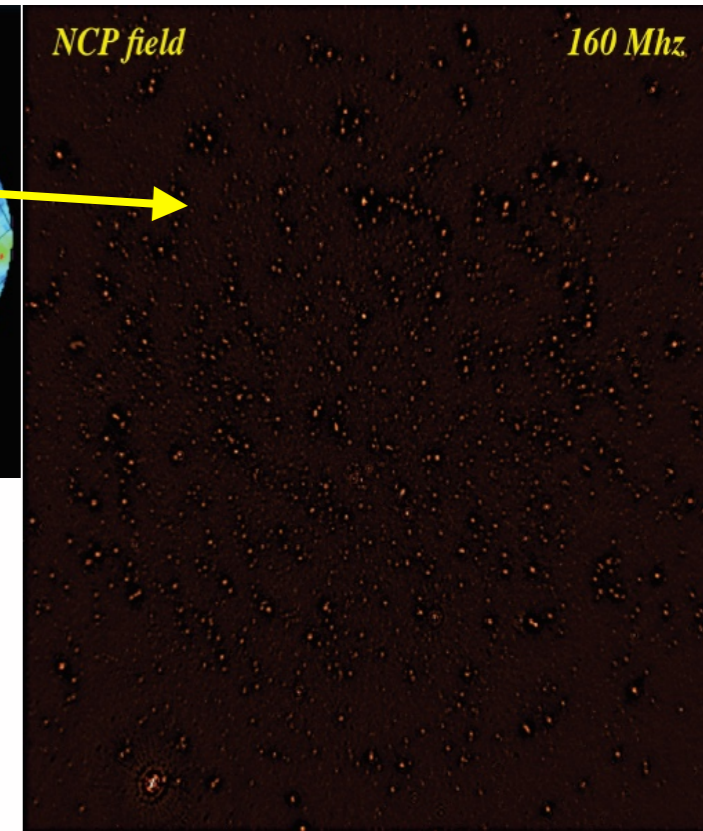
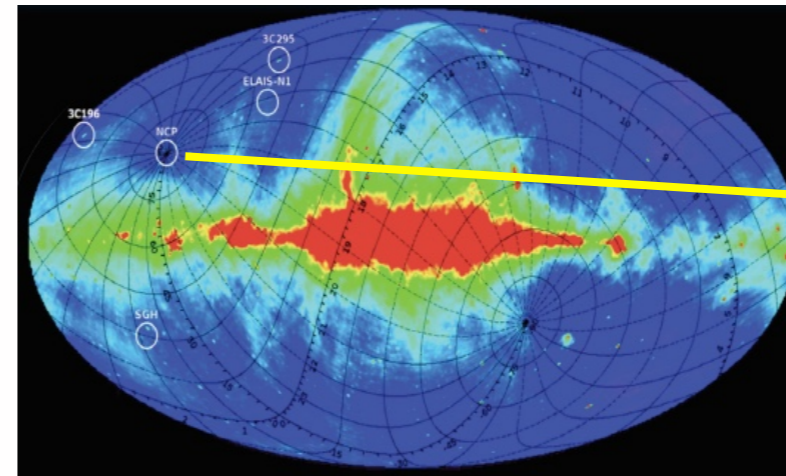
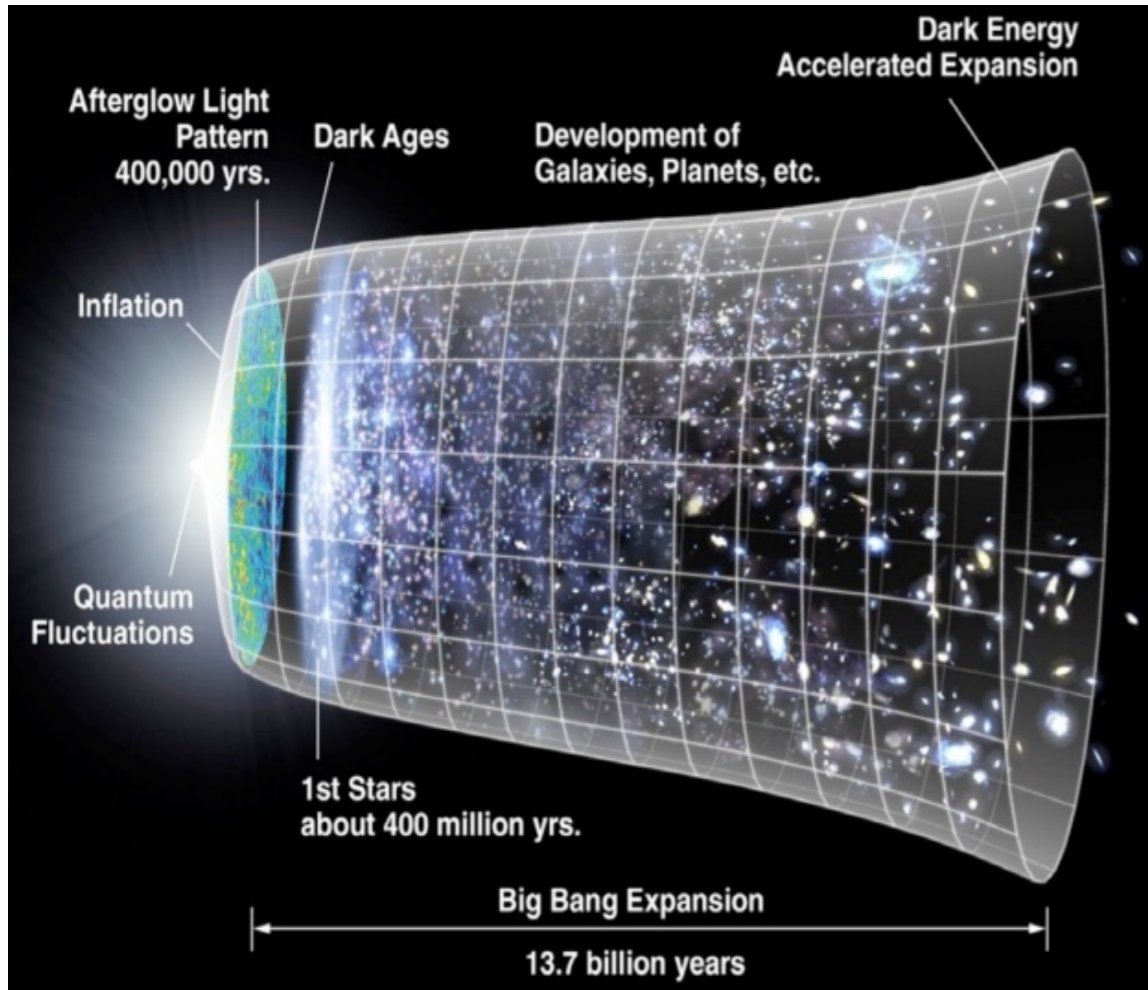


▷ (Exo)Planets : Obs. Paris

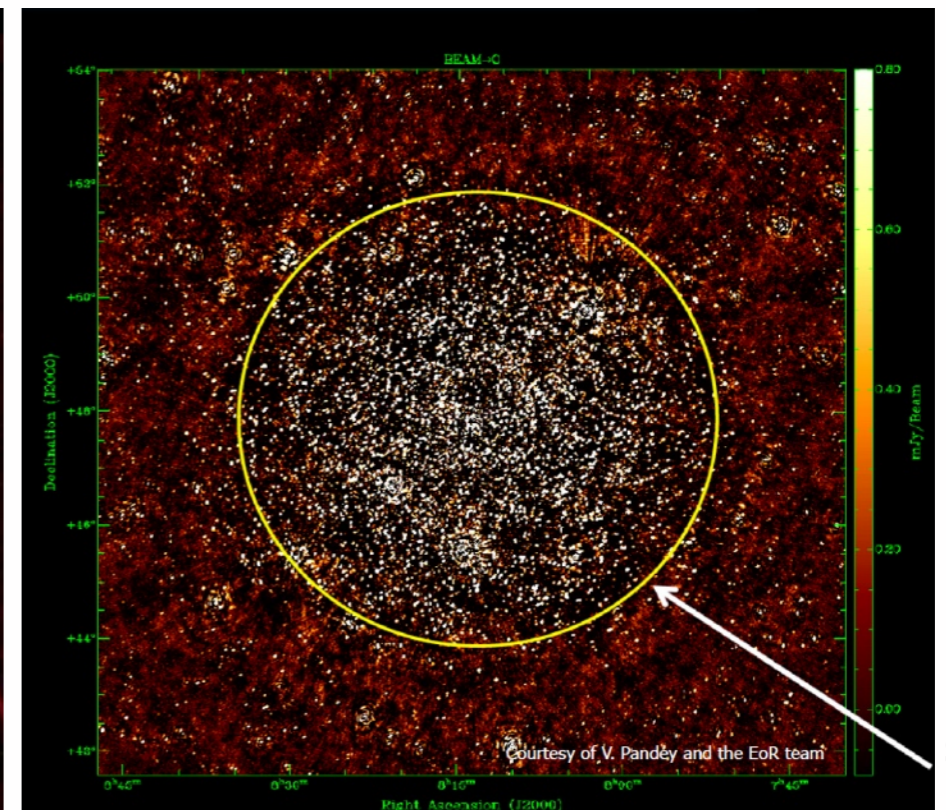
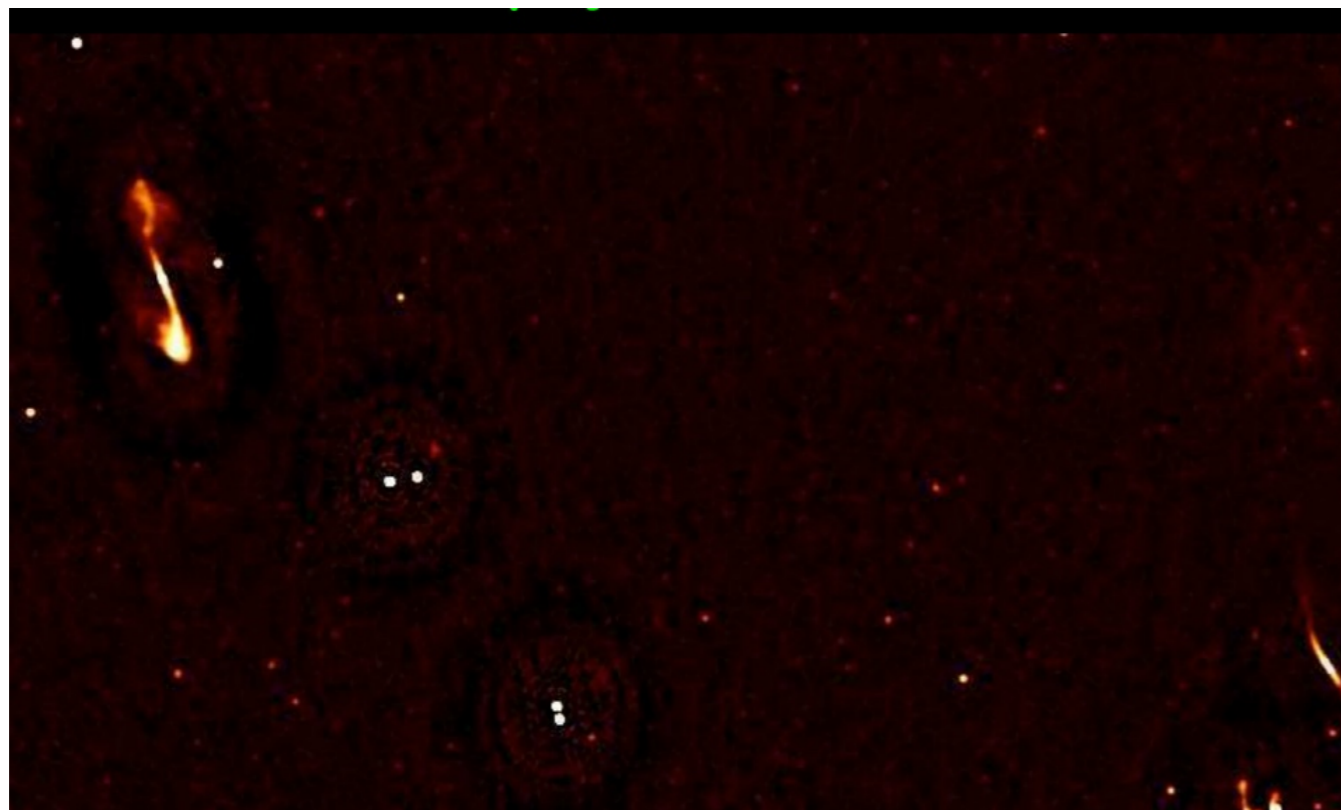


Epoch of Reionization
(Groningen)

Epoch of Reionization

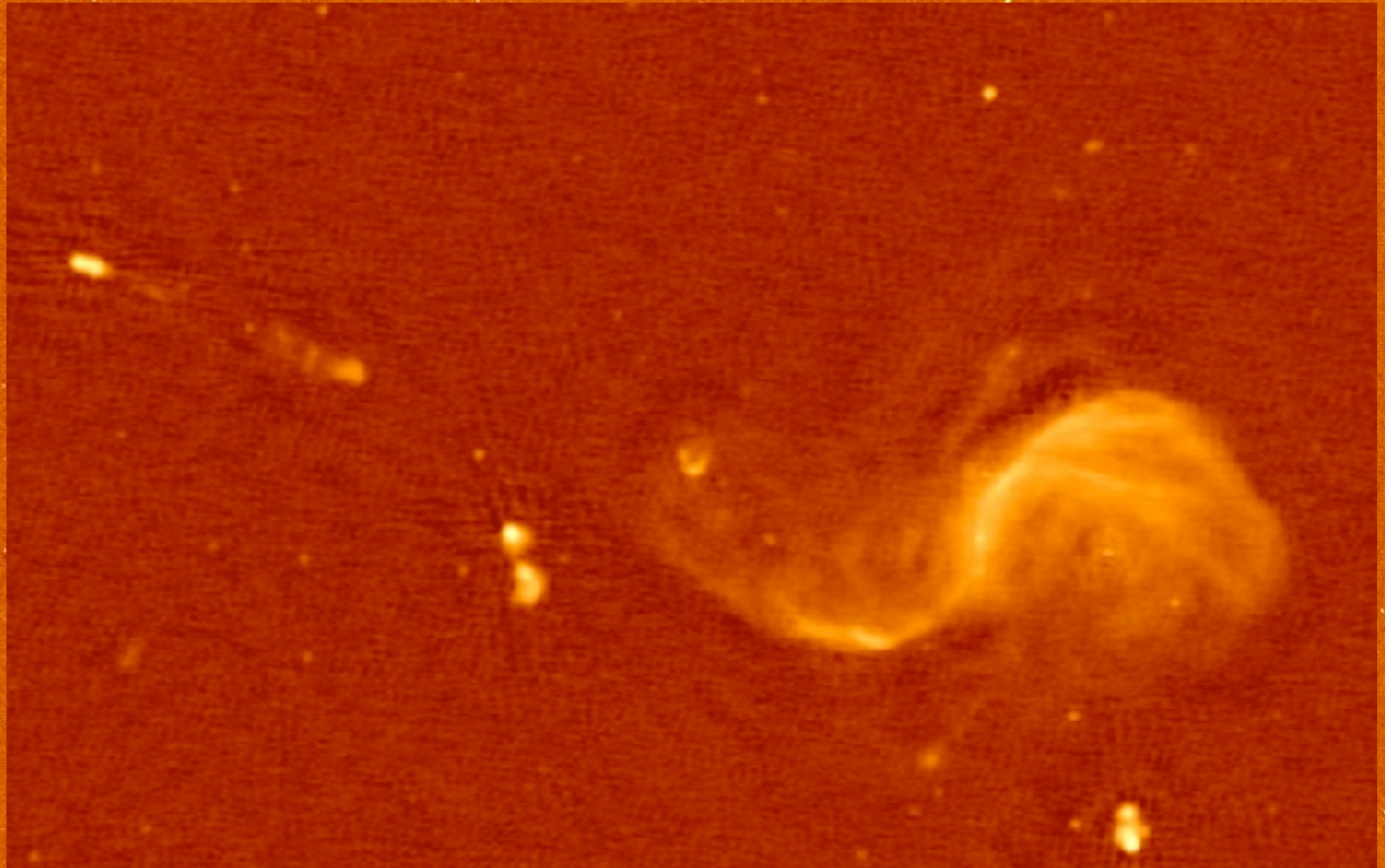


- $\sigma = 25 \mu\text{Jy}$
- $\text{DR} = 10^6$



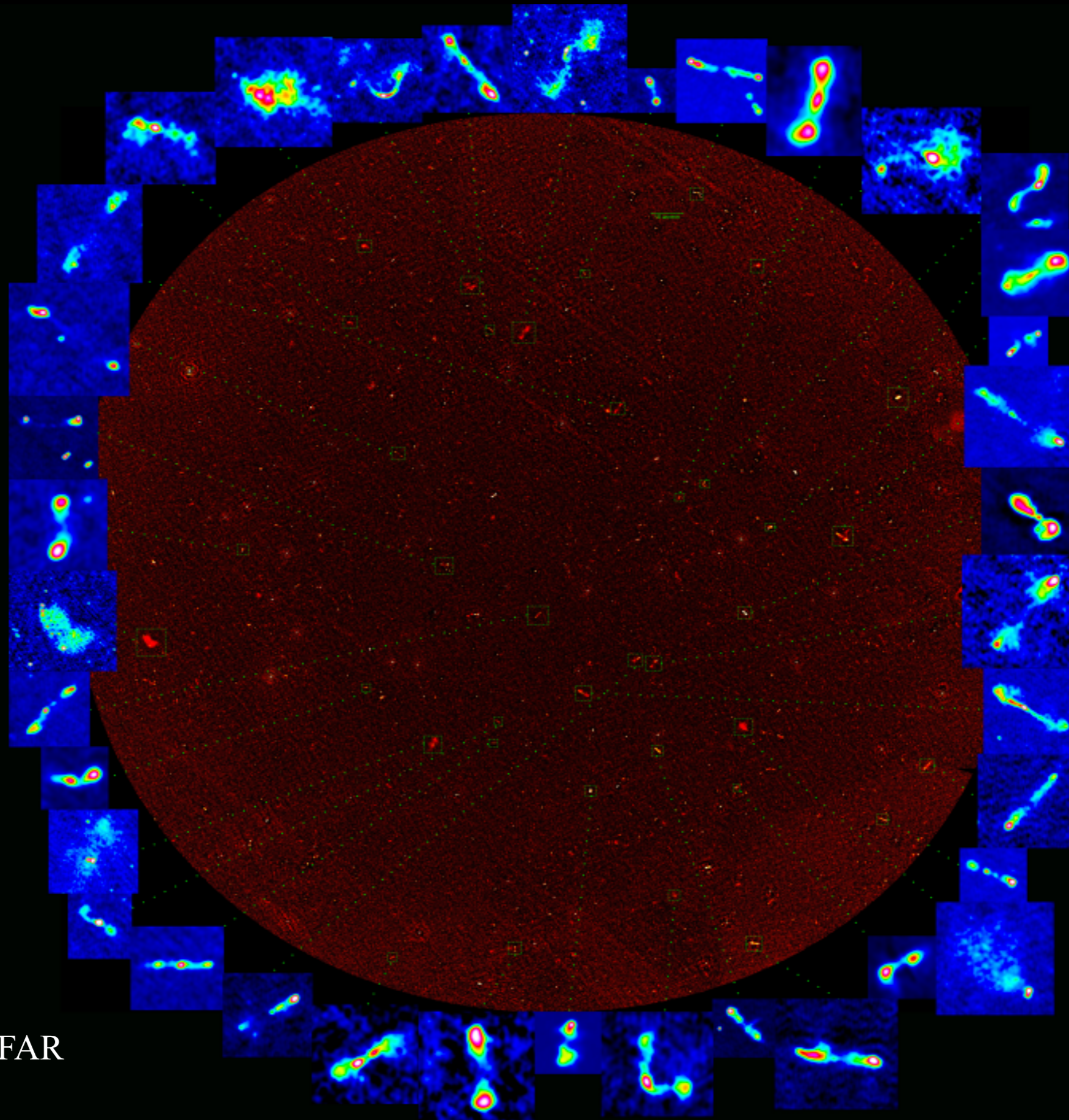
station beam

Surveys



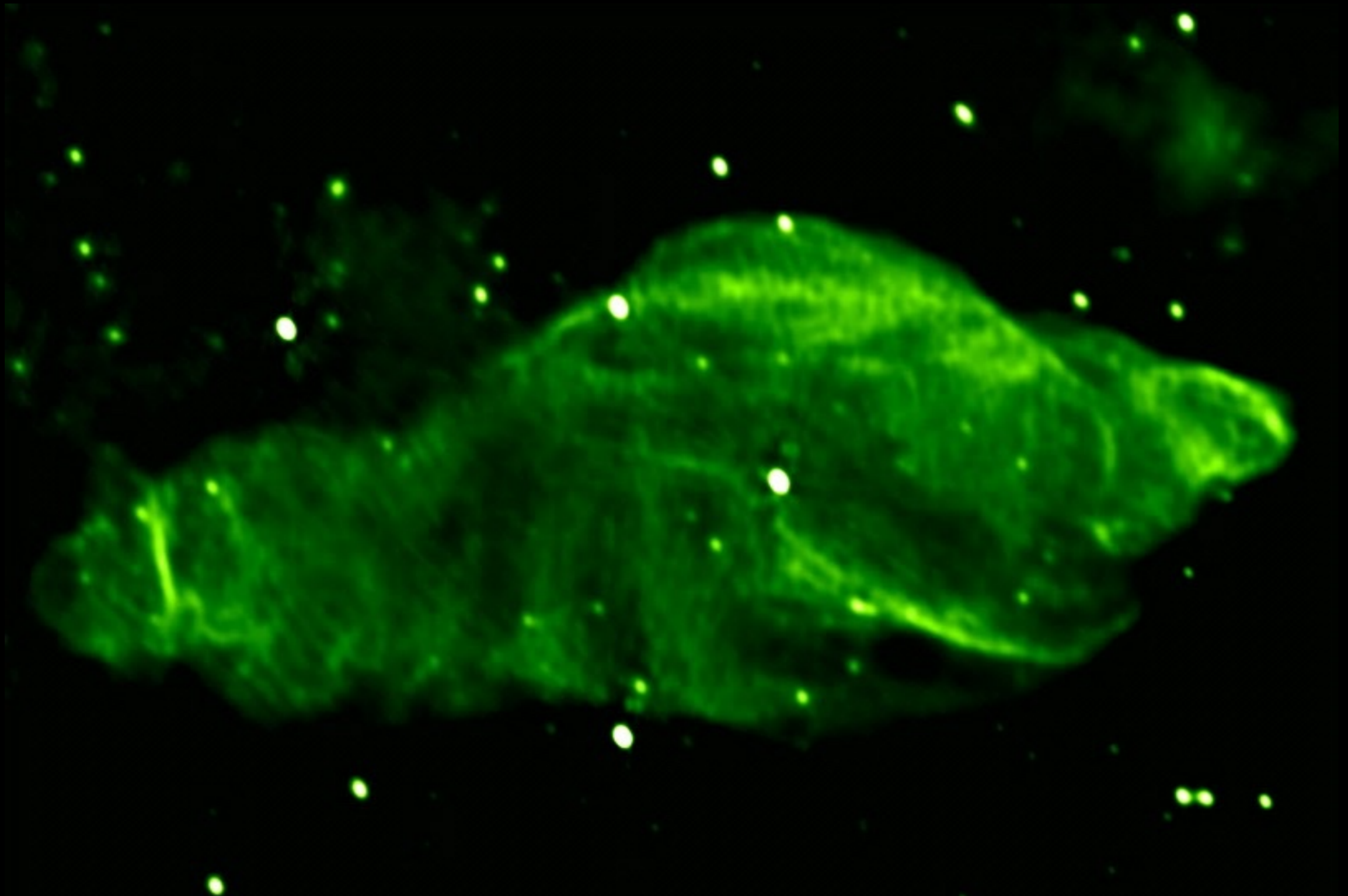
A small fraction of a 20.000x20.000 pixel image

Surveys



Bootes field, LOFAR
(150 MHz)

SS 433 microquasar

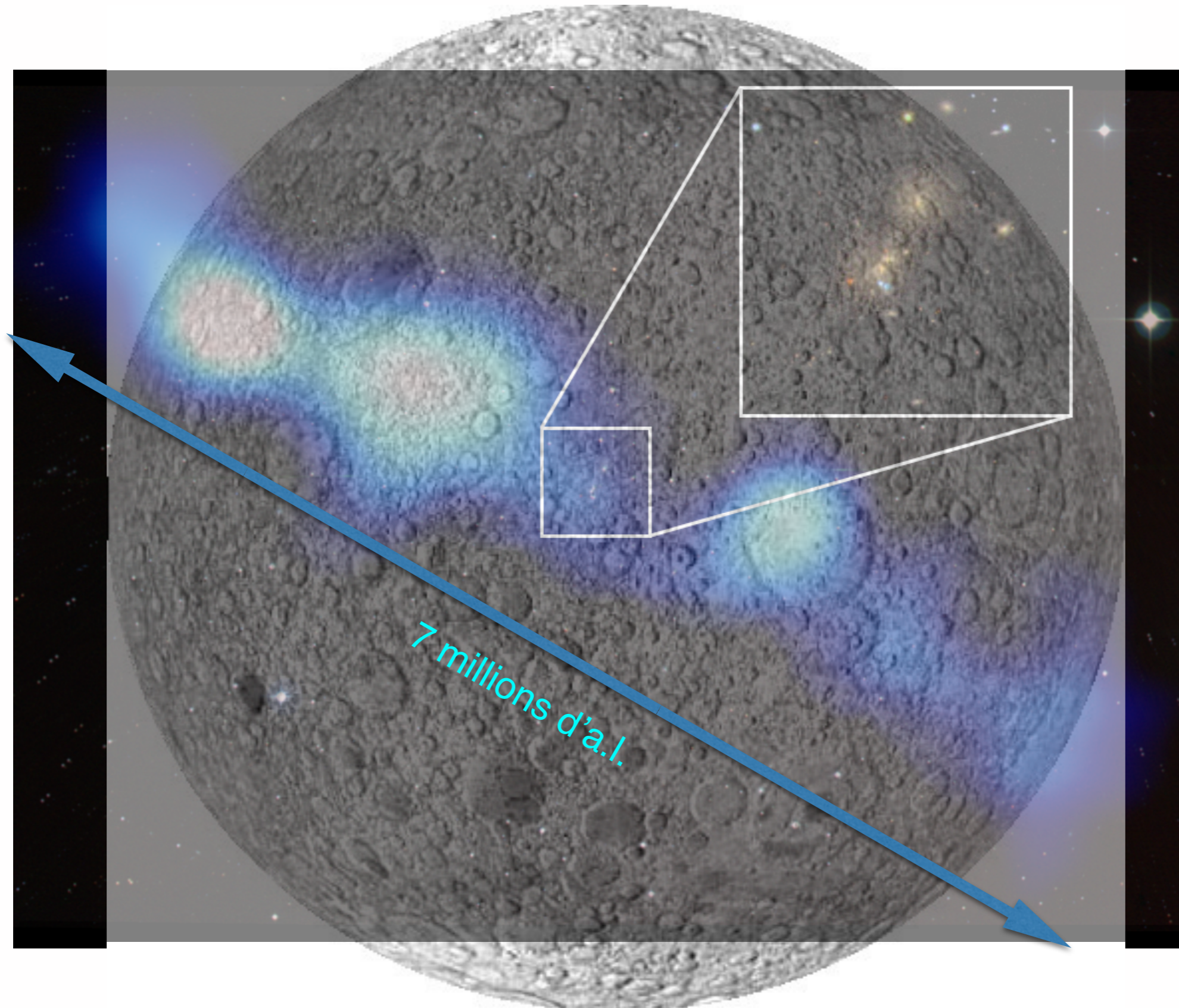


Microquasar SS433,
LOFAR (150 MHz)

Broderick et al., 2017

Discovery of a giant radiogalaxy

around triplet UGC 09555

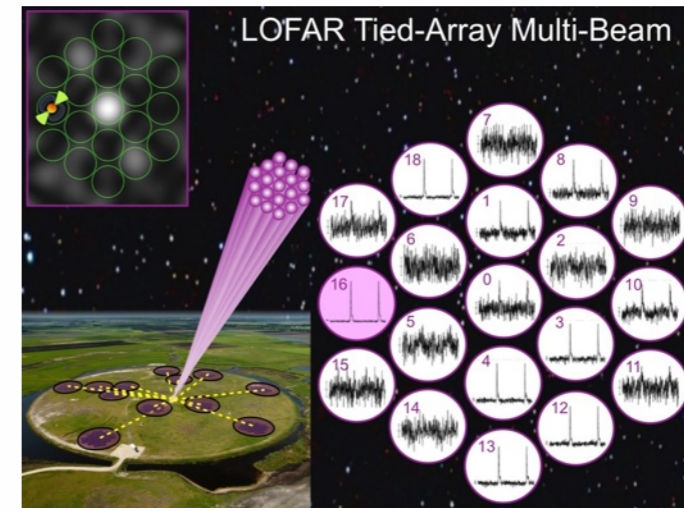


Credits: G. Heald and
the MSSS team
(150 MHz)

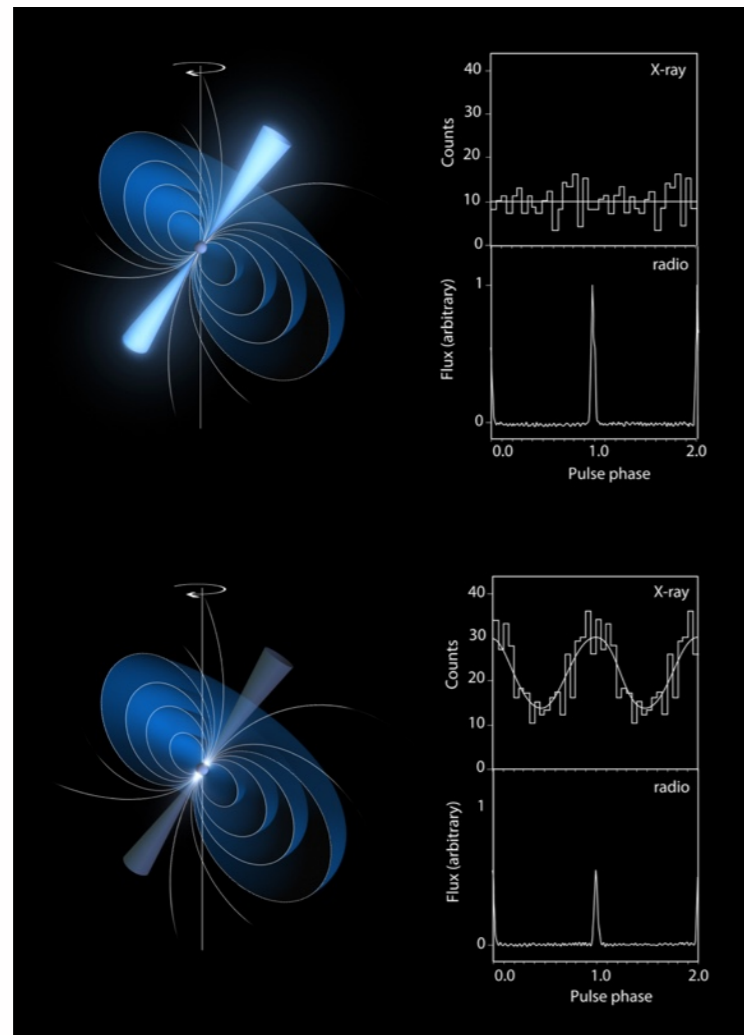
Pulsars



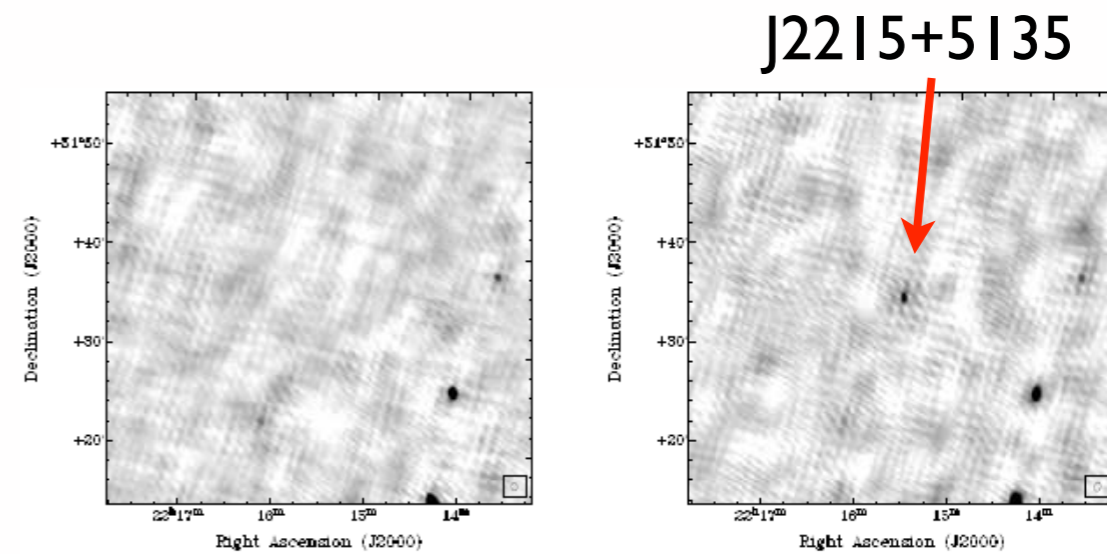
Stappers et al. 2011



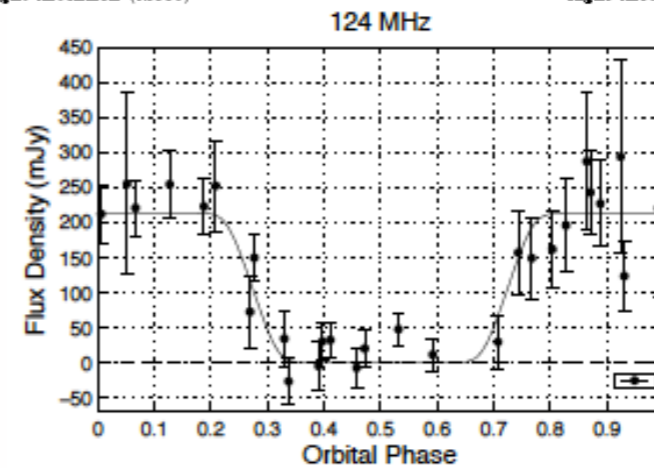
Hessels et al., Coenen et al. 2014, Kondratiev et al. 2015



Hermsen et al., 2012

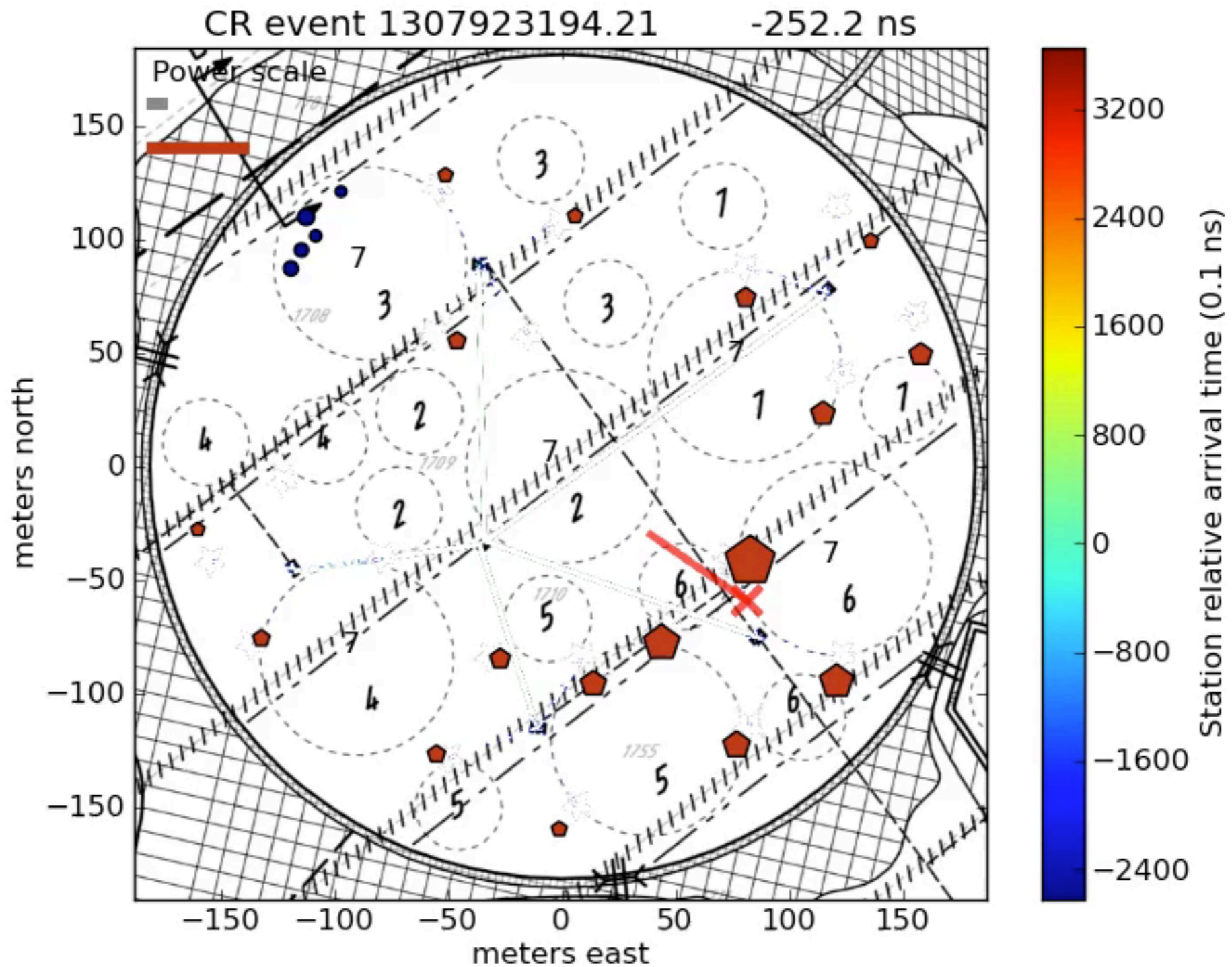


J2215+5135



Broderick et al. 2015

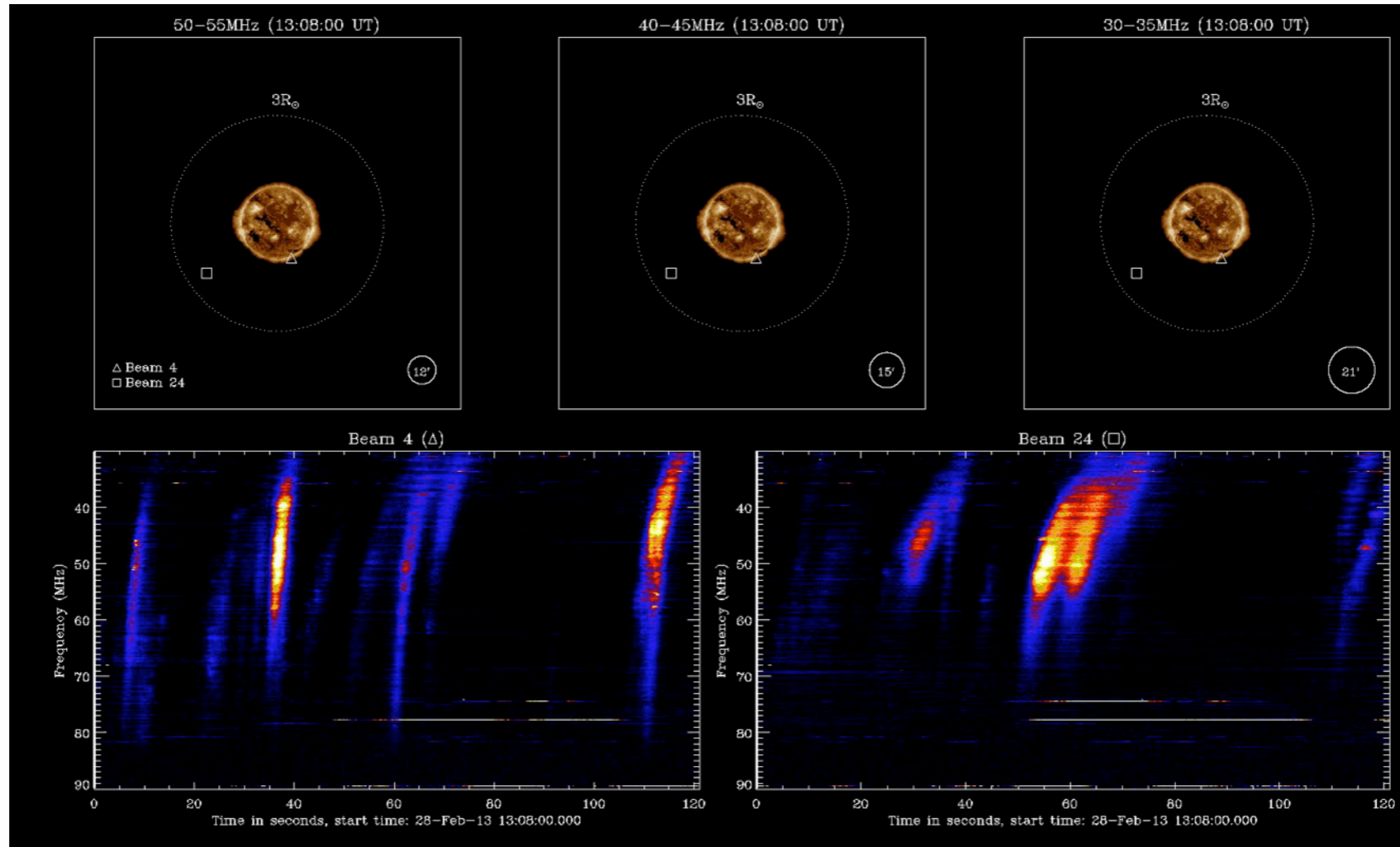
Cosmic Rays



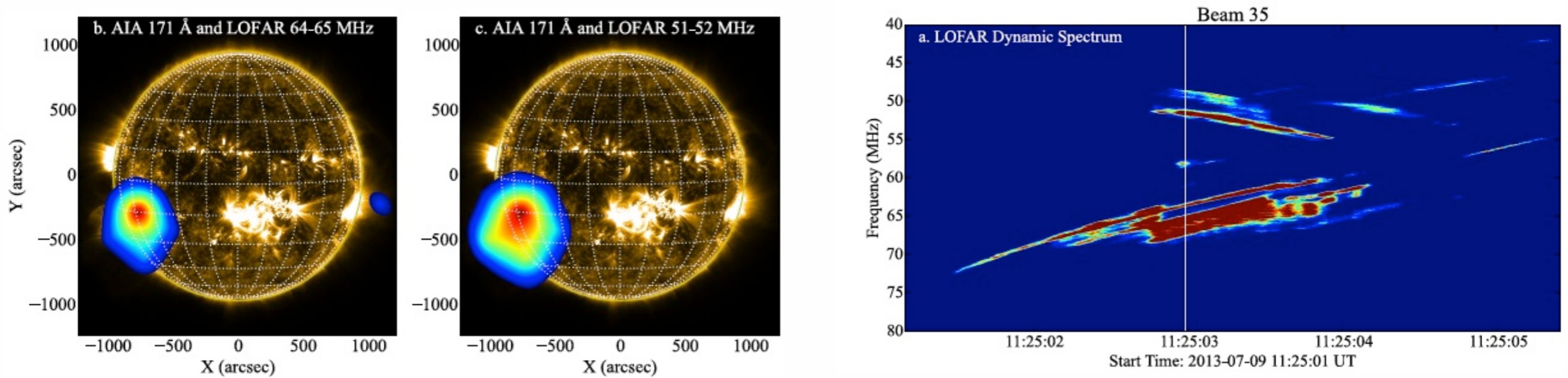
Circles: LOFAR antennas, Pentagons: LORA particle detectors, size denotes signal strength

- Accurate Direction-of-Arrival, energy, composition ...

Solar bursts



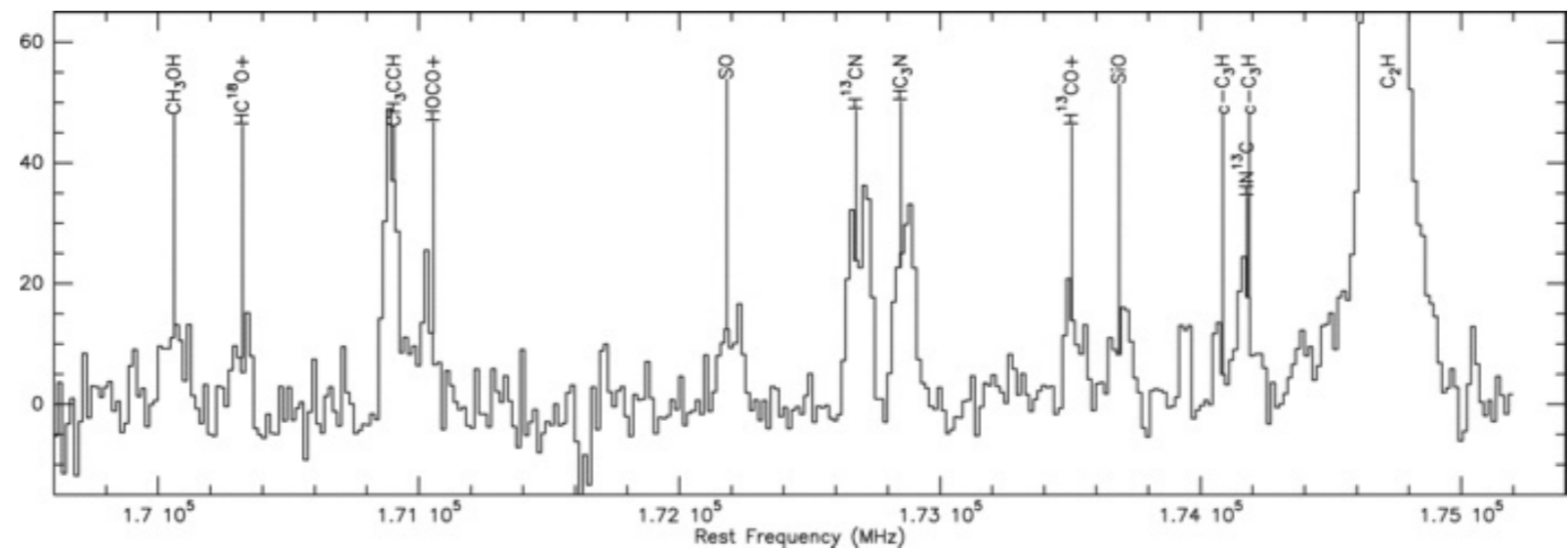
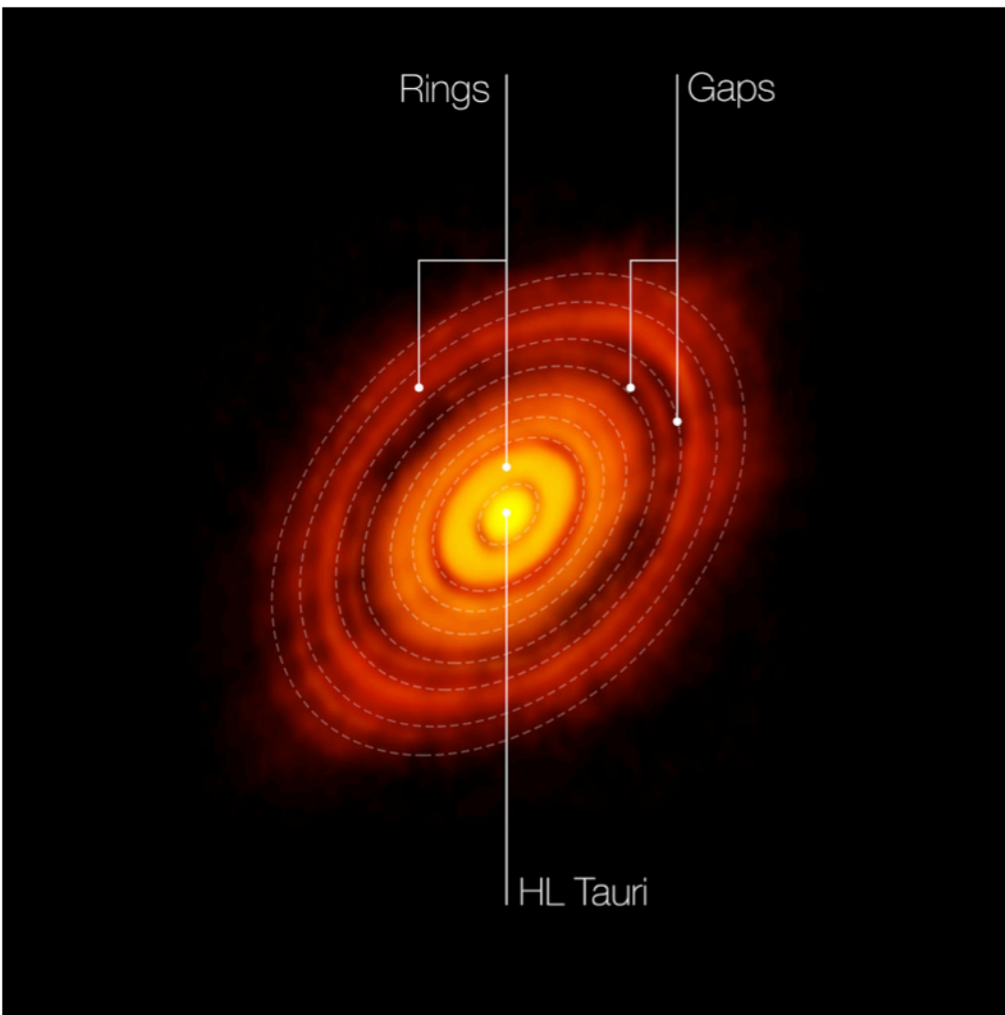
Morosan et al., 2014



Morosan et al., 2015

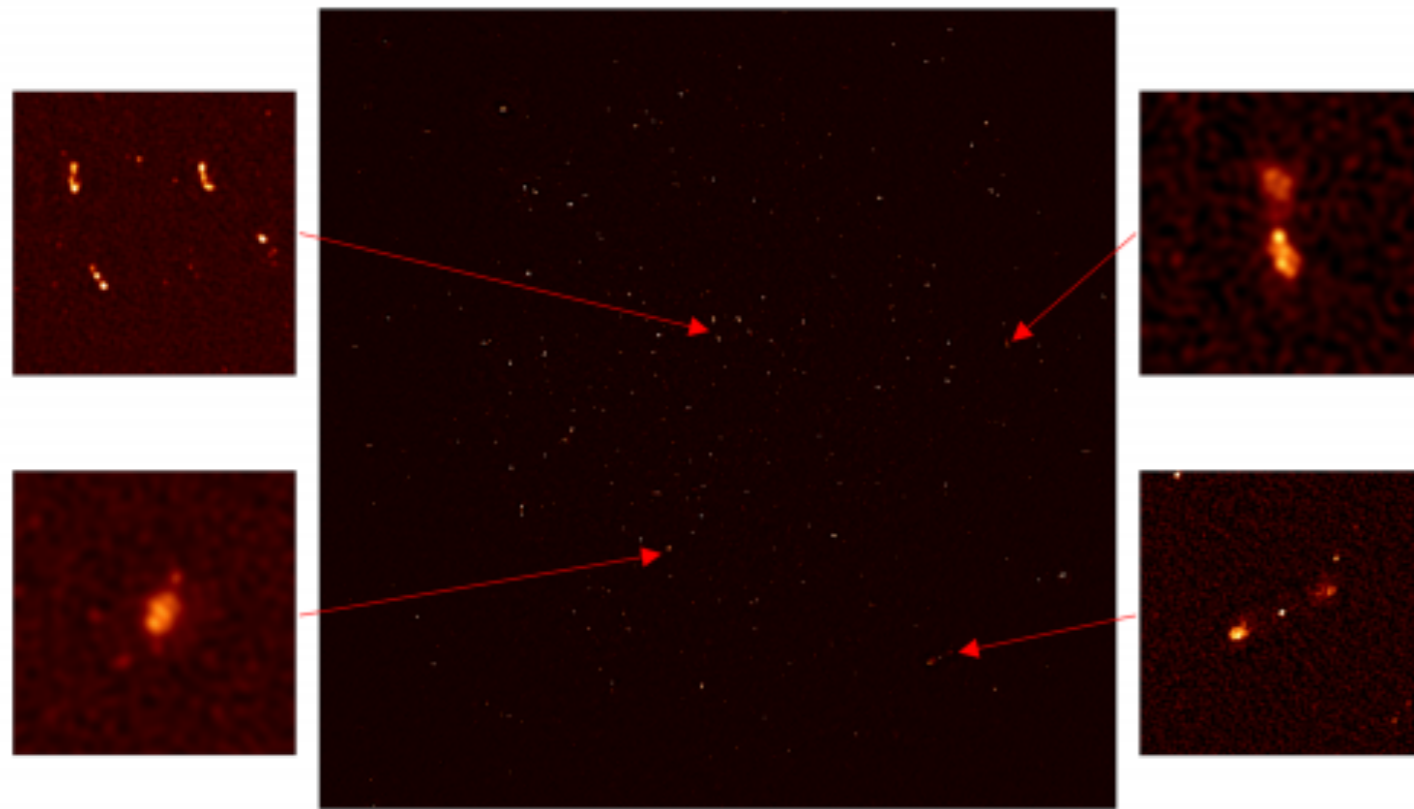
Science Planétaire en Radio

- Hautes Fréquences (e.g. ALMA) : images & spectres

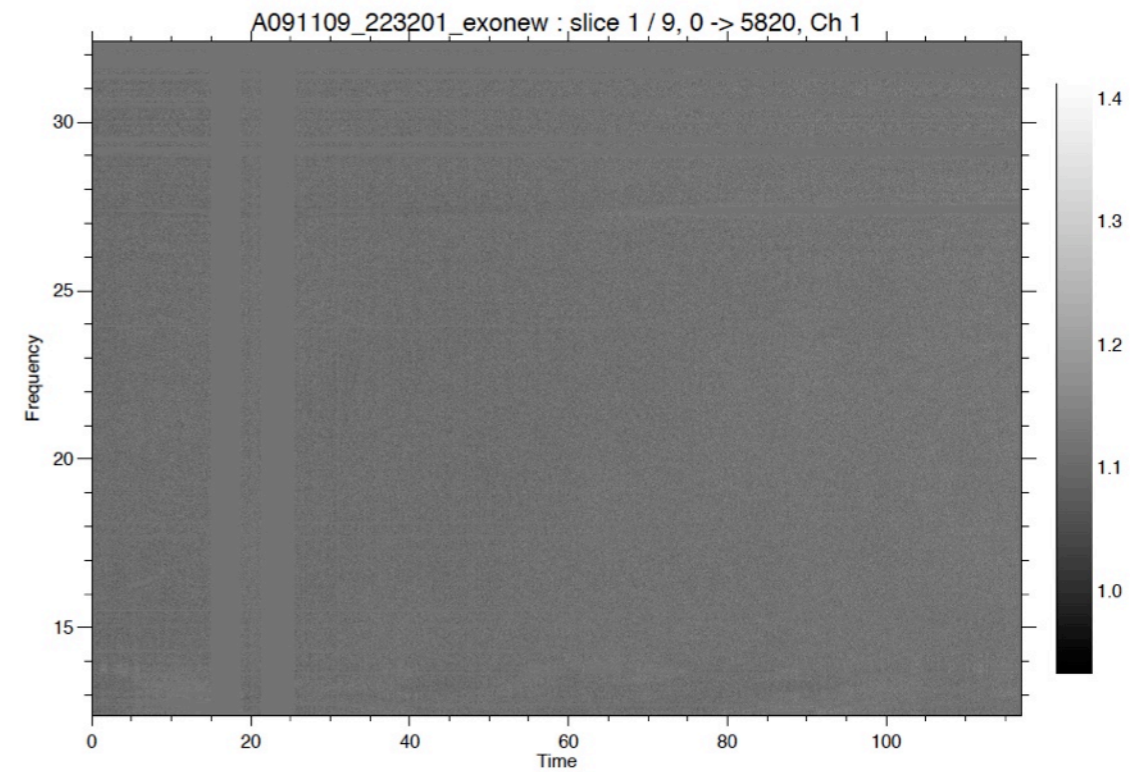


Science Planétaire en Radio

- Basses Fréquences : images & spectres dynamiques



(LOFAR, MeerKAT, C. Tasse)

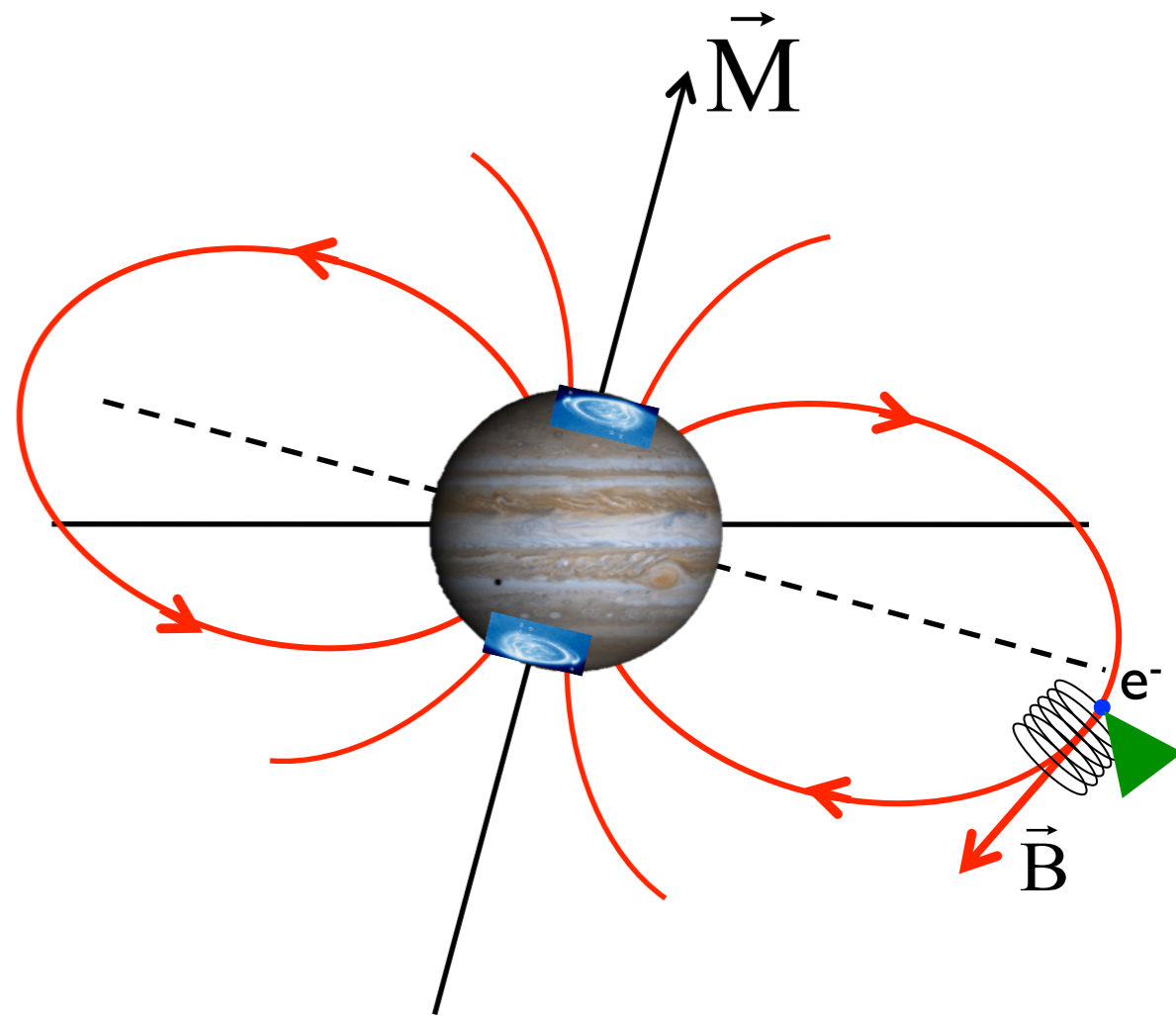
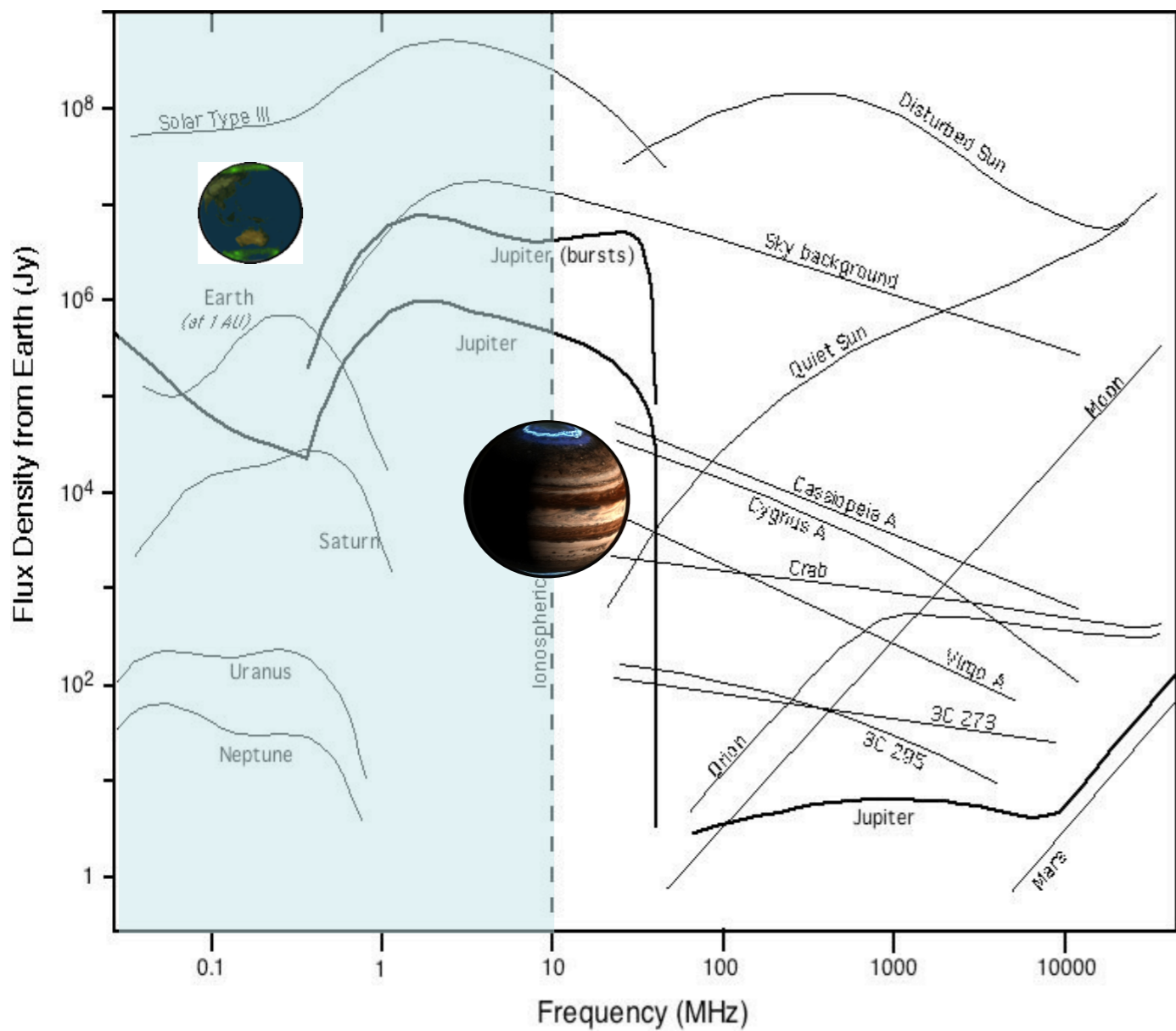


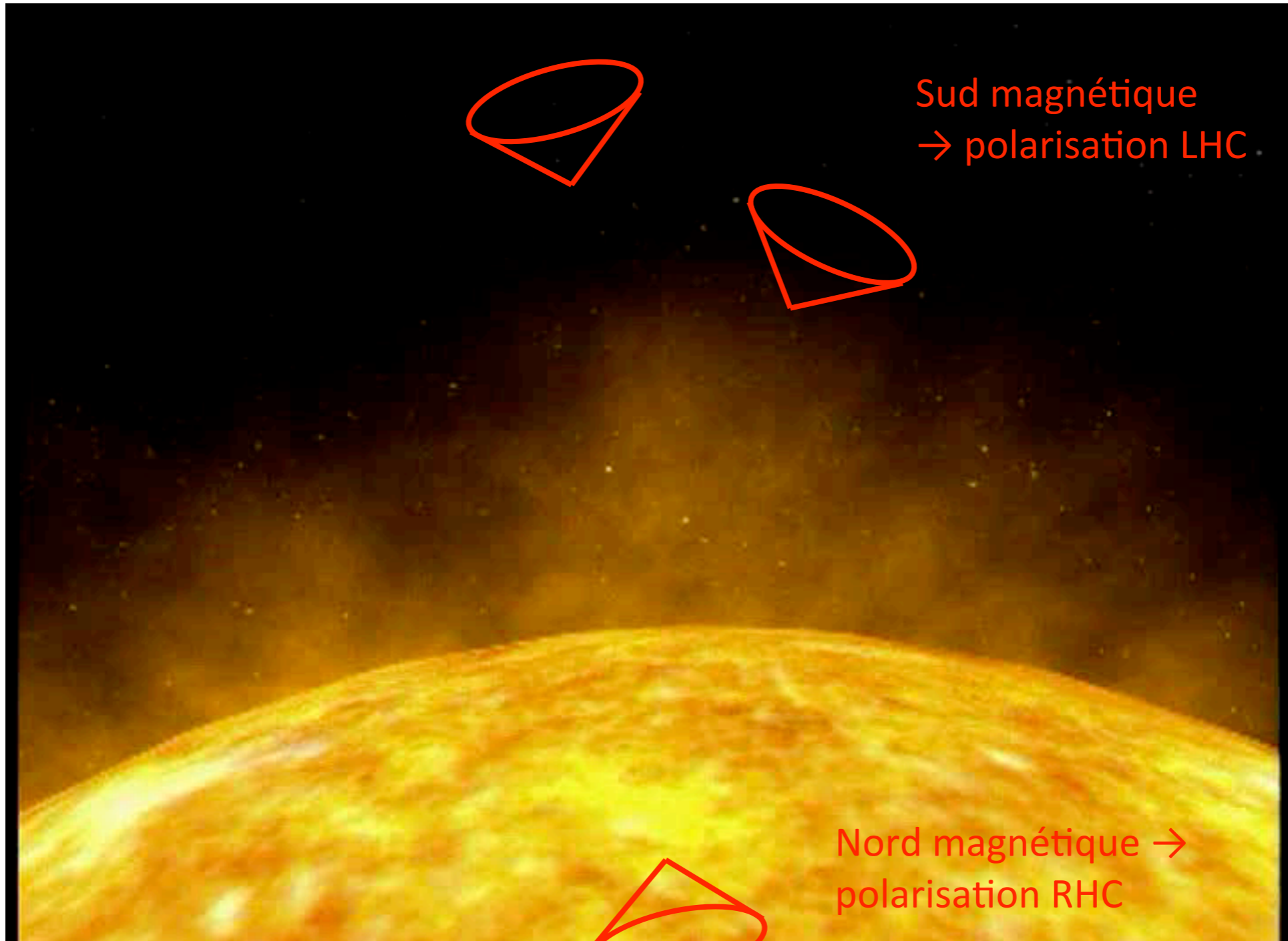
(UTR-2, P. Zarka)

Observations Planétaires avec LOFAR

- (1) magnétosphères planétaires (aurores et satellites)
et *exoplanétaires* ?
 - émission cyclotron (f_{ce})
- (2) magnétosphères : ceintures de radiations,
 - émission synchrotron ($n \times f_{ce}$)
- (3) atmosphères : éclairs d'orages
 - rayonnement d'antenne
- (4) autres :
 - spectre thermique de l'atmosphère Saturne
 - occultation de radiosources par les petits corps

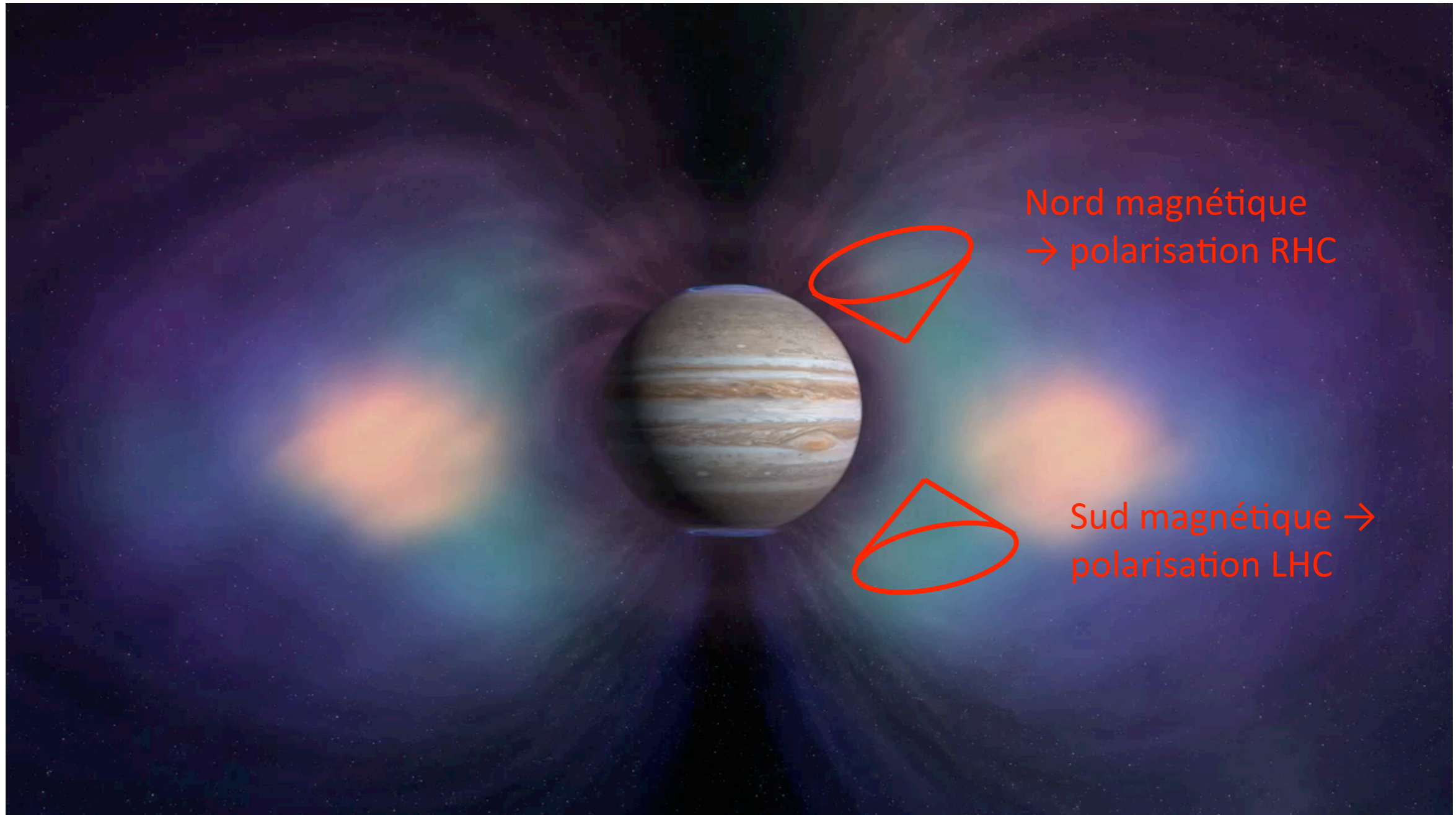
(I) magnétosphères : aurores et satellites → émission cyclotron ($\sim f_{ce}$)





Sud magnétique
-> polarisation LHC

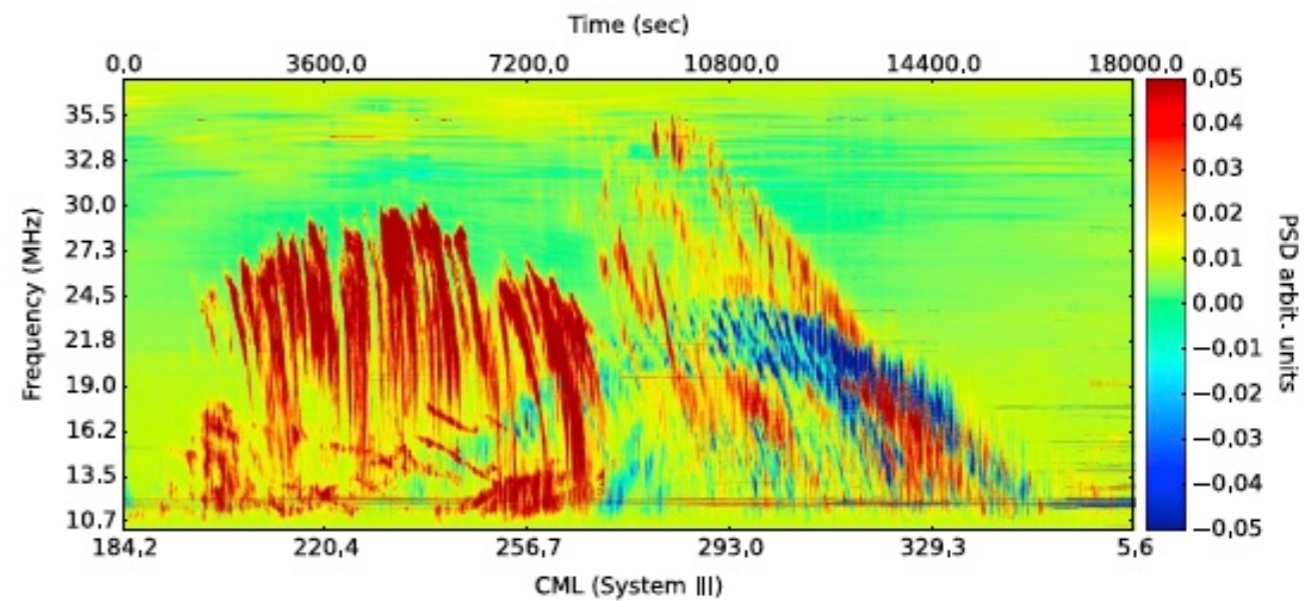
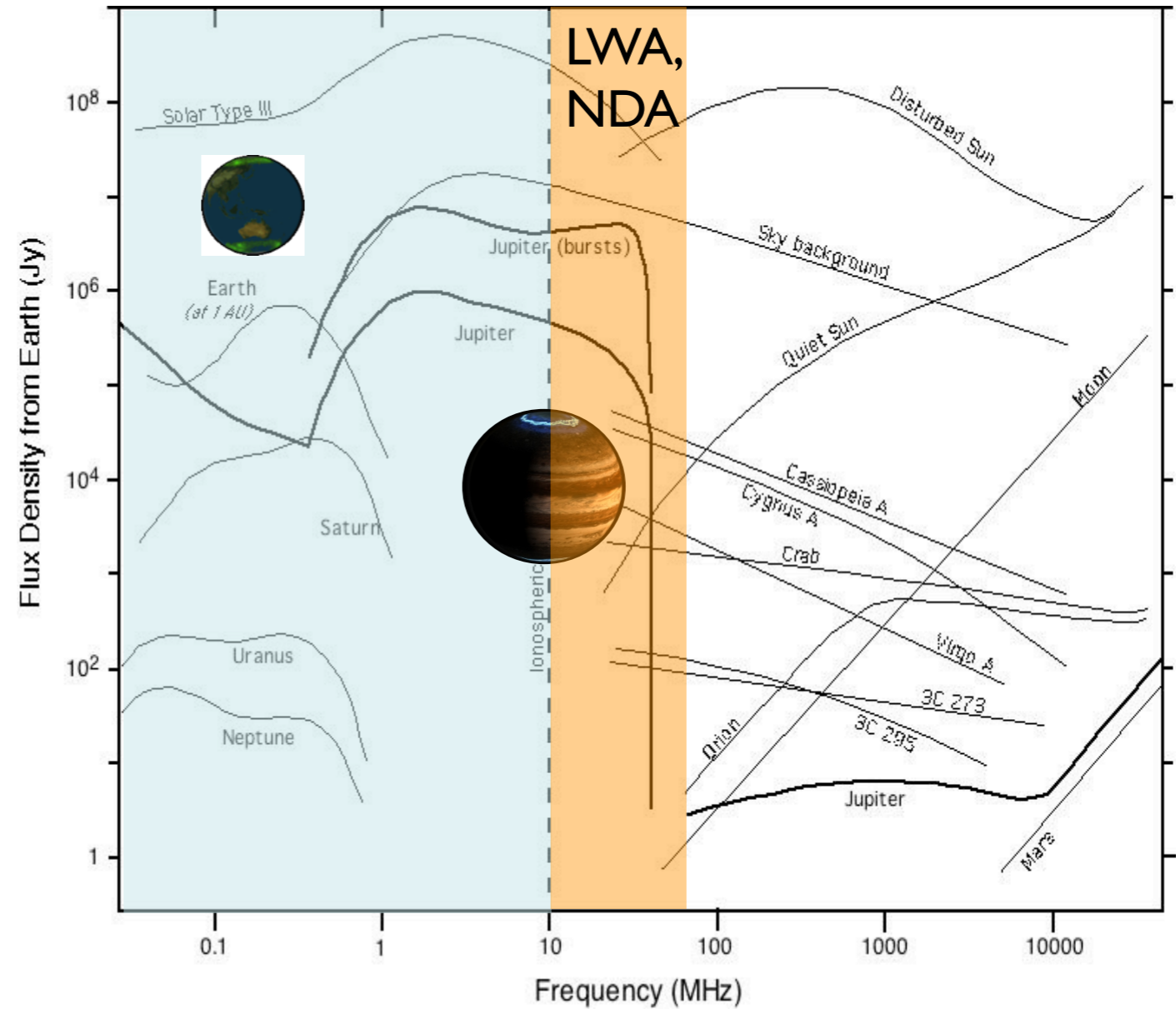
Nord magnétique ->
polarisation RHC



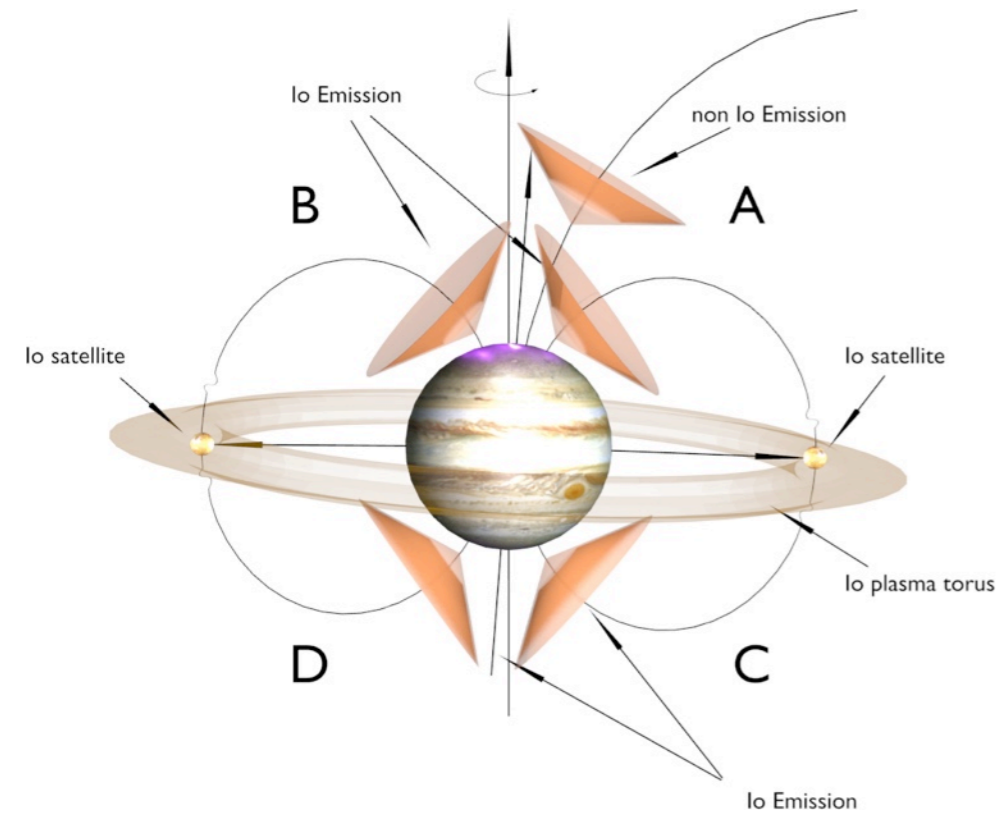
Nord magnétique
→ polarisation RHC

Sud magnétique →
polarisation LHC

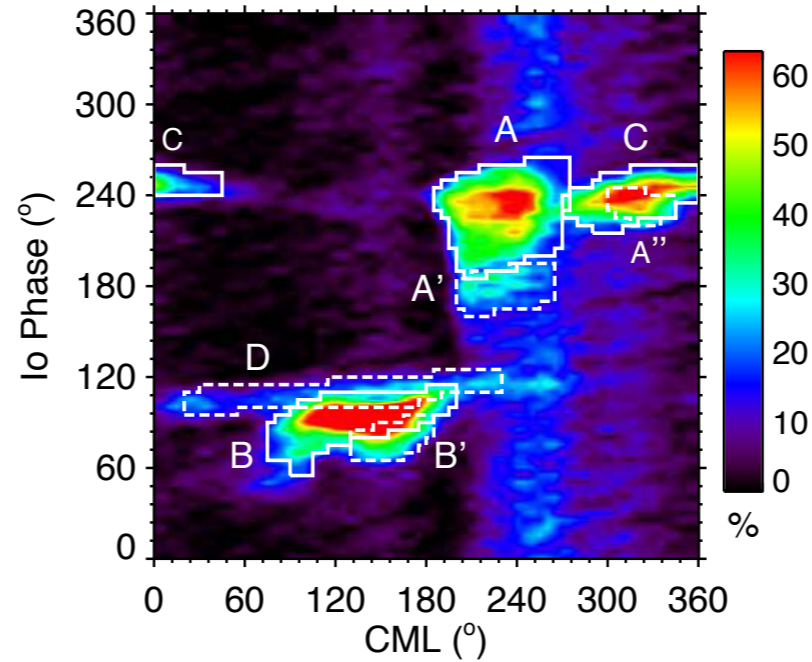
- Pour les planètes du système solaire, NDA, LWA assez sensibles



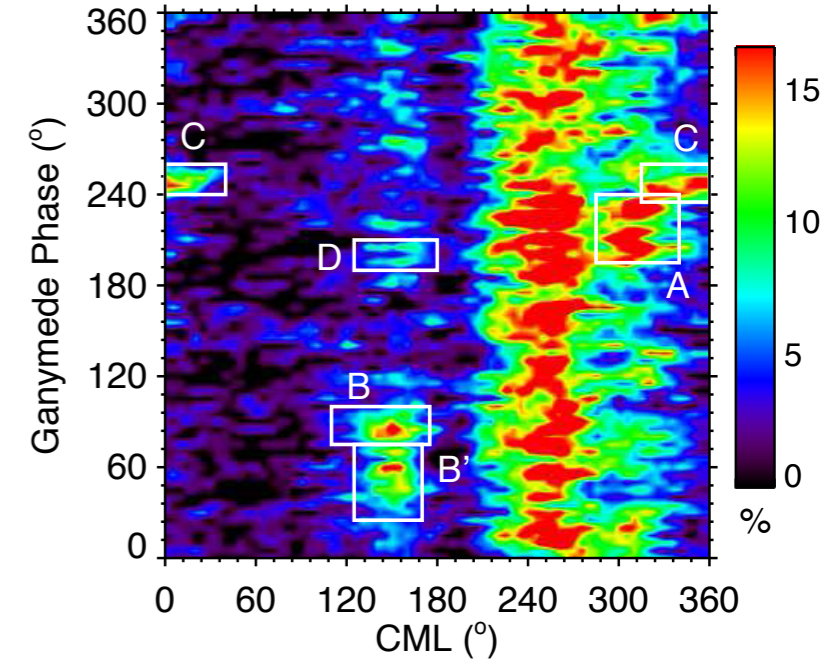
- Pour les planètes du système solaire, NDA, LWA assez sensibles



Io-Jupiter

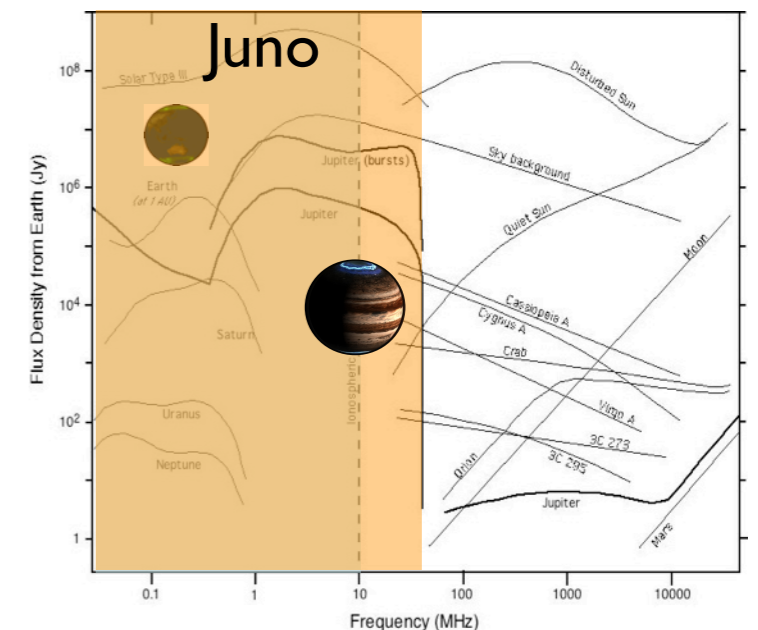


Ganymede-Jupiter

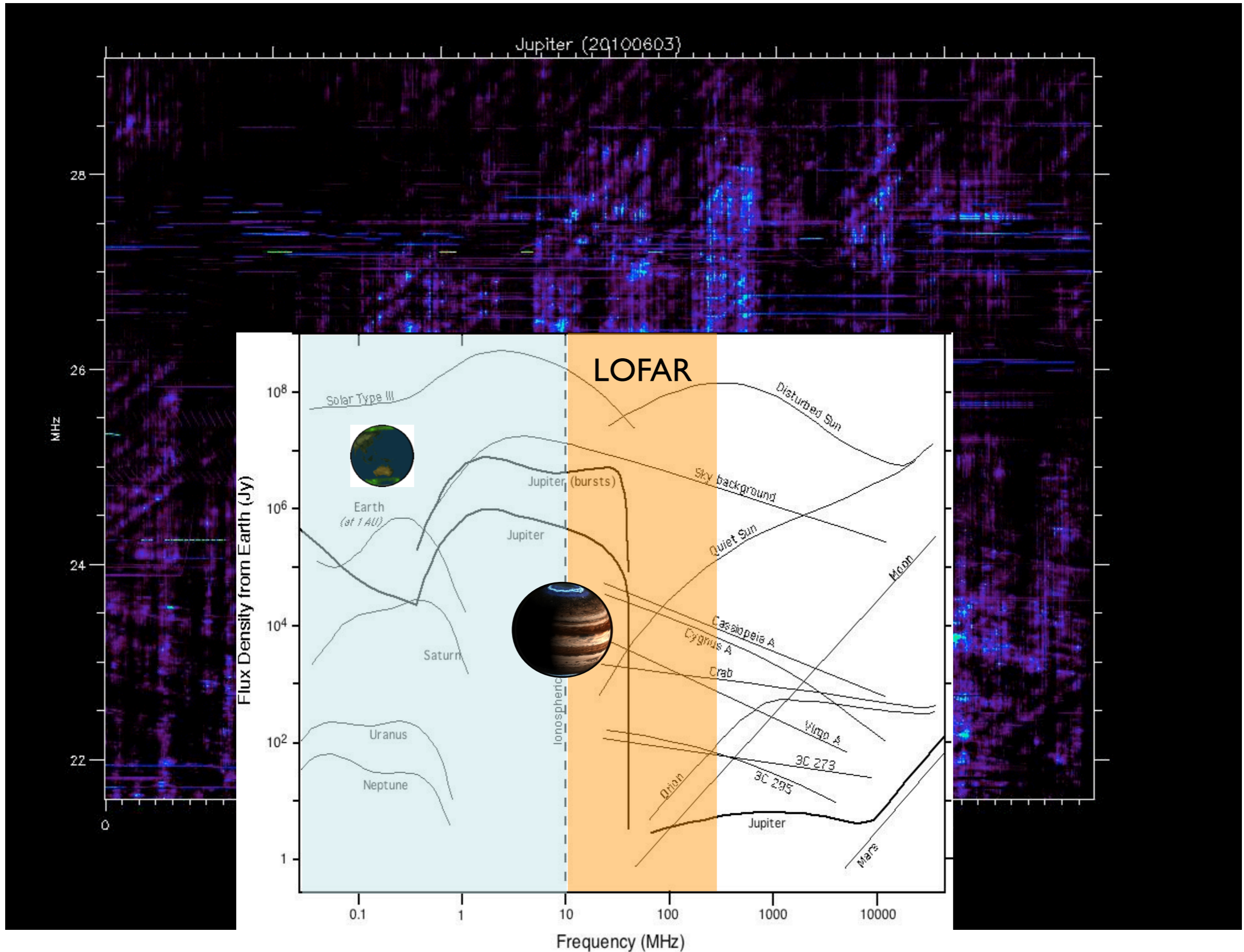


[Zarka et al., 2018]

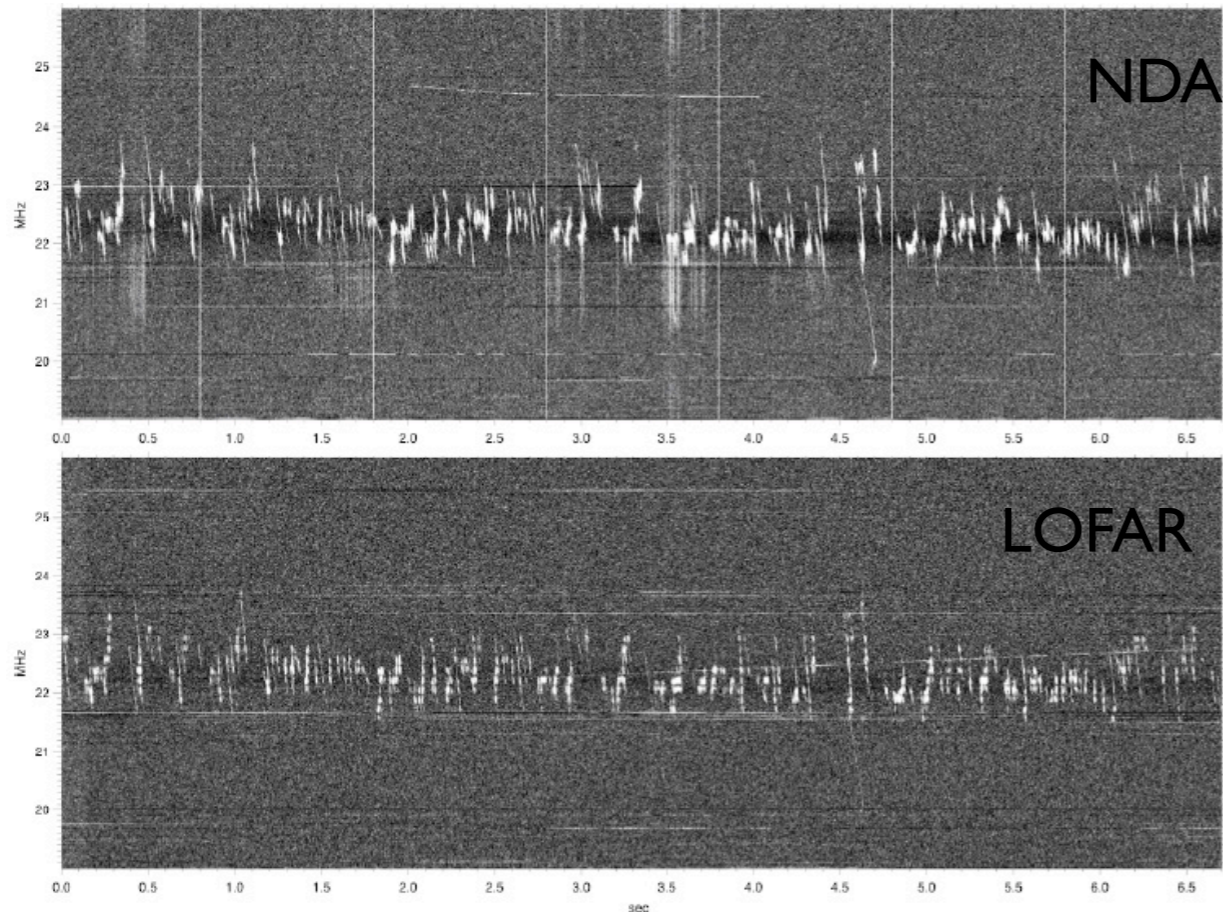
(+ spatial: JUNO, Cassini)



- LOFAR : imagerie (difficile) des "structures fines"

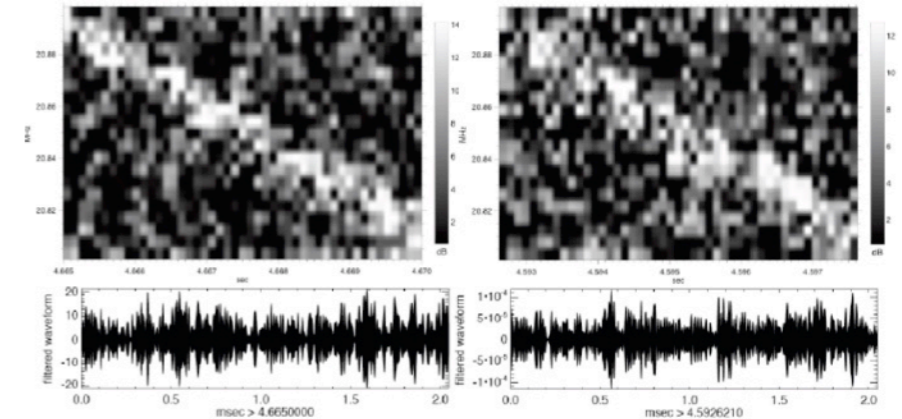
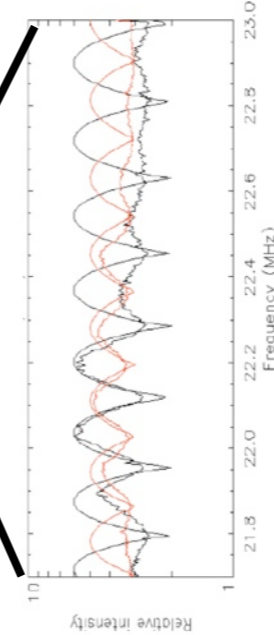


- LOFAR : imagerie (difficile) des "structures fines"

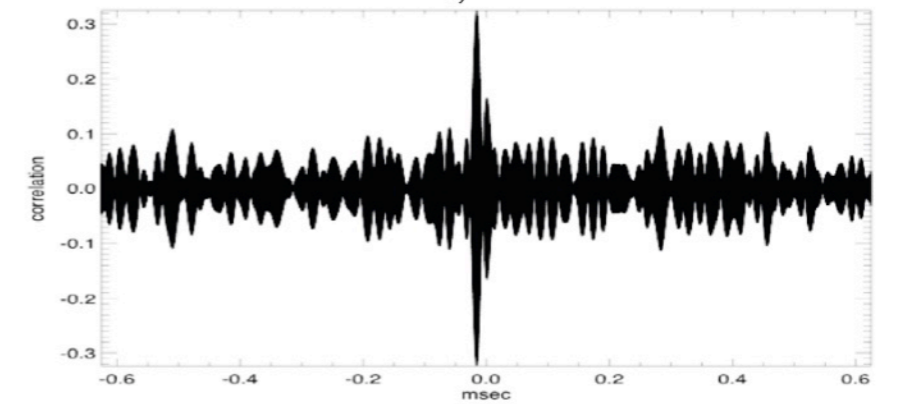


6.7 sec of Sburst observations at the 2 sites

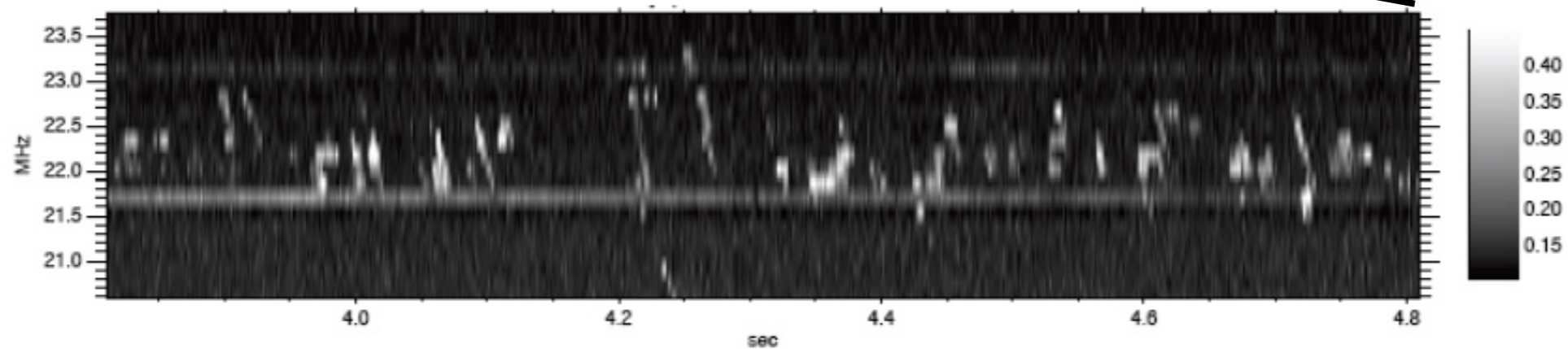
Faraday fringes seen by ITS (linear pol.)



c)

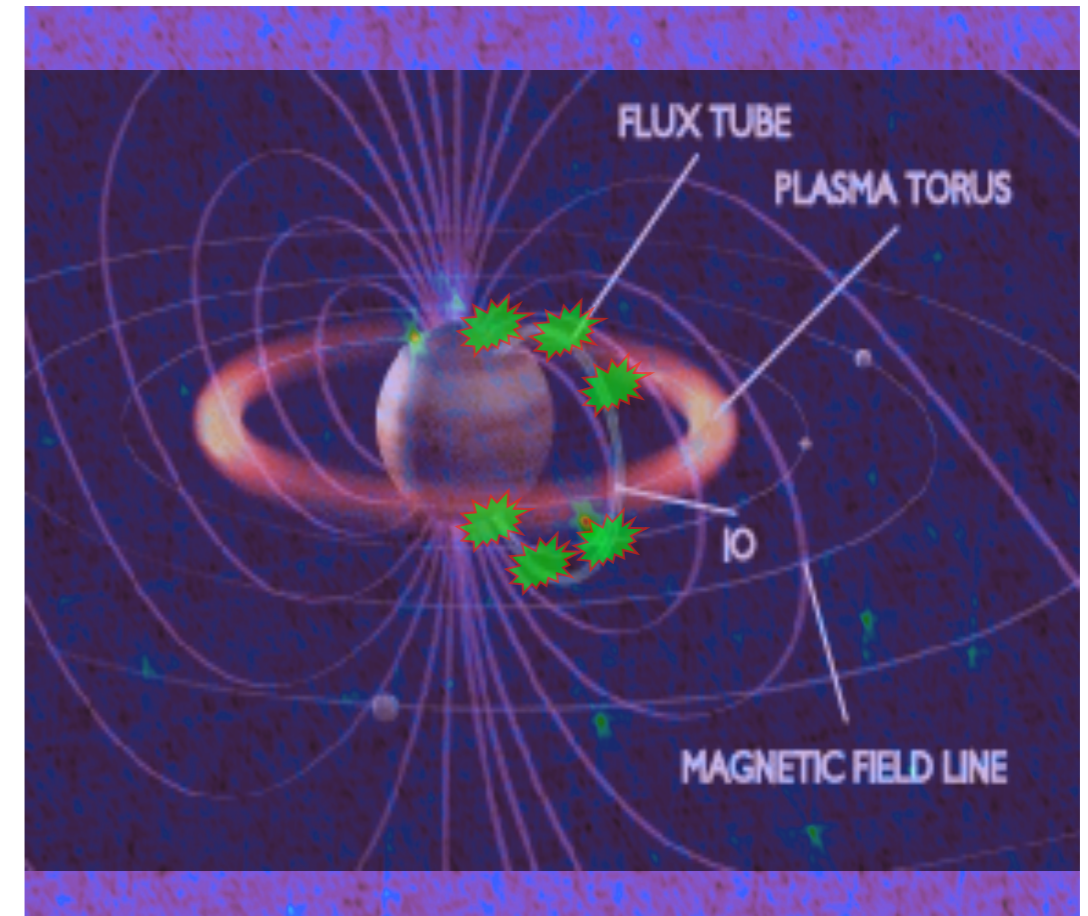
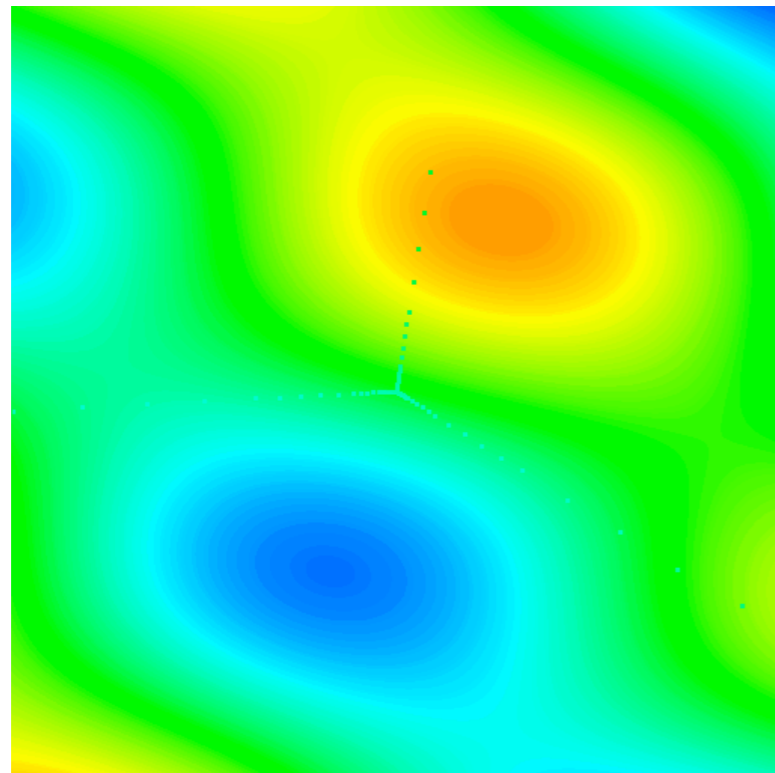
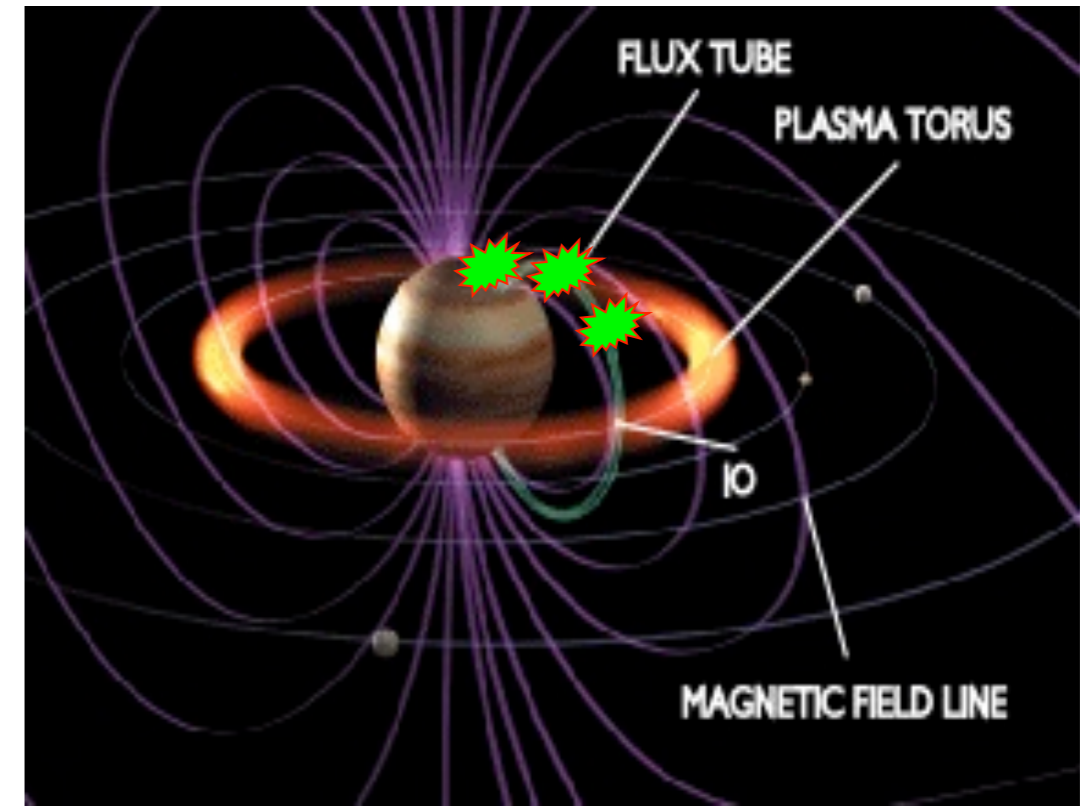
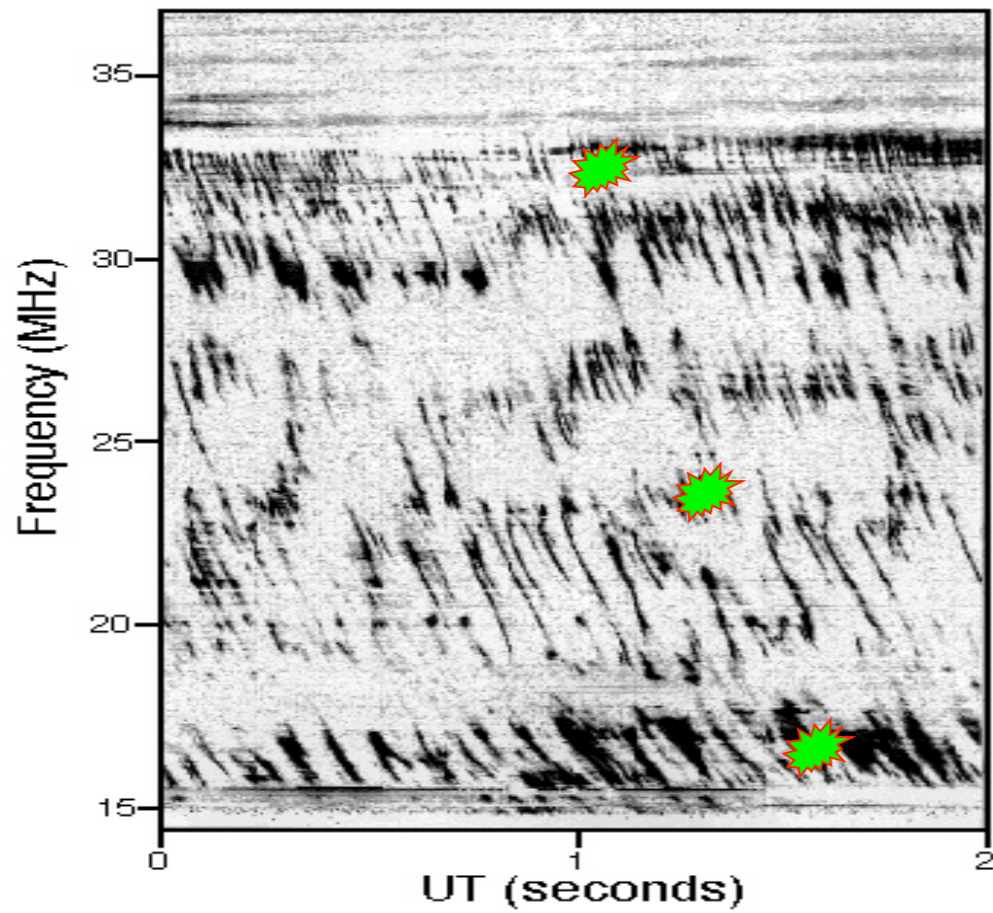


Correlation of waveform excerpt

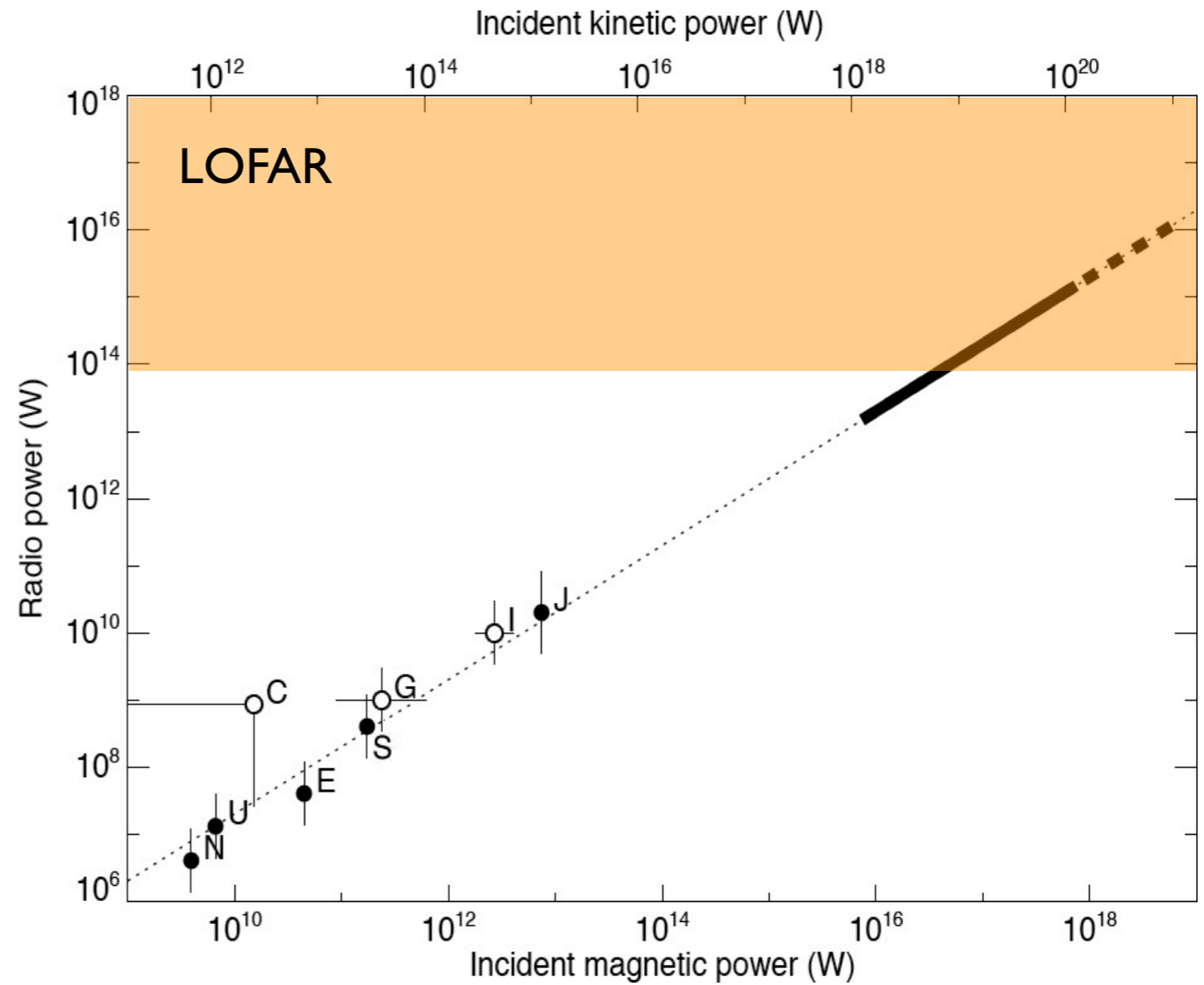


Dynamic spectrum of waveform correlation coefficient

- LOFAR : imagerie (difficile) des "structures fines"



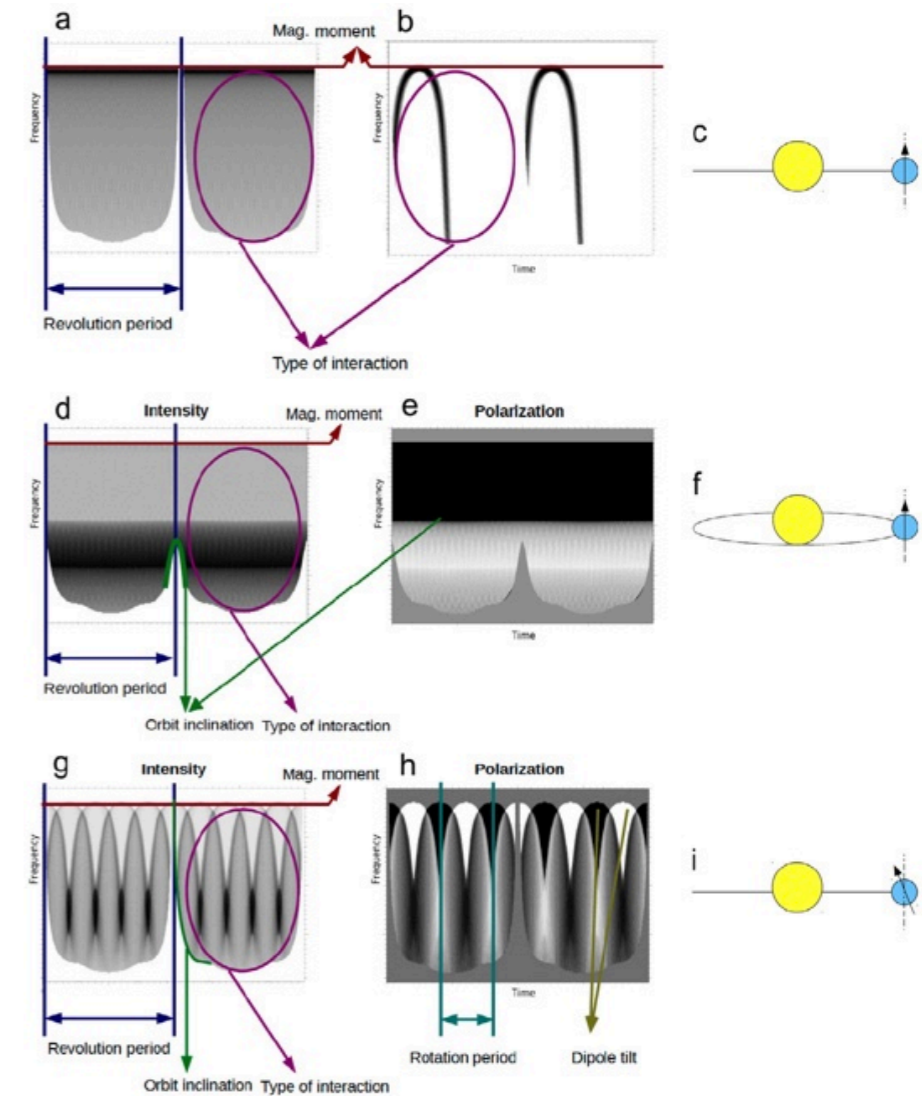
- LOFAR : recherche de l'émission radio des exoplanètes



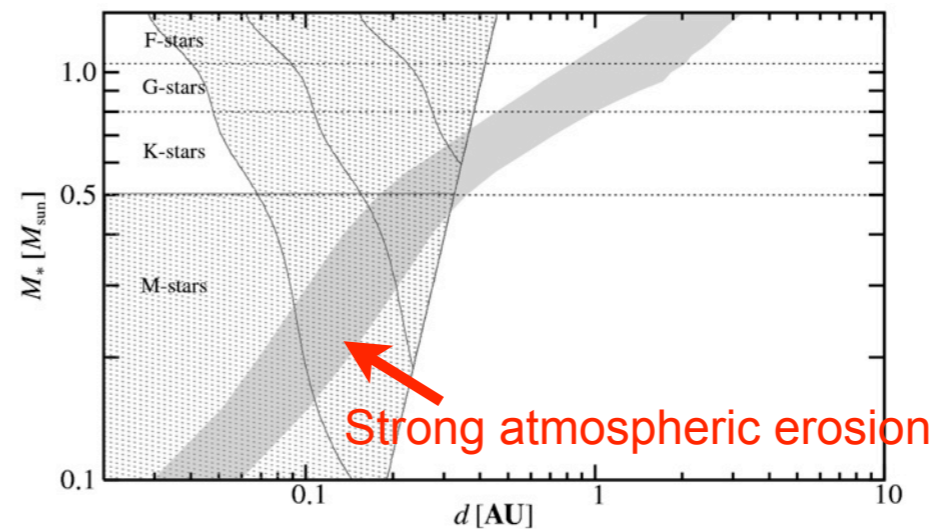
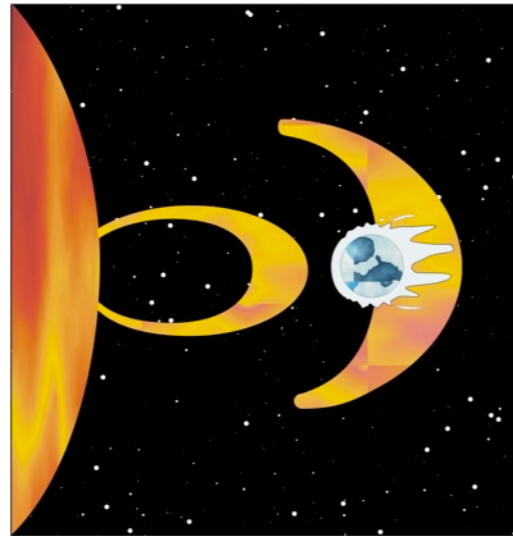
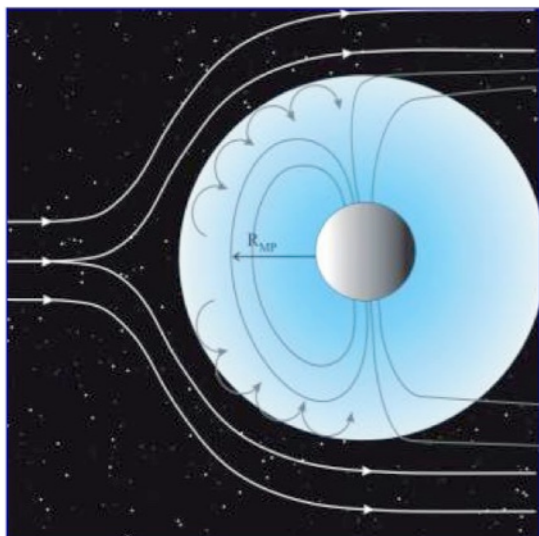
[Zarka, 2001, 2007]

• Motivations

- B ? \Rightarrow dynamo \Rightarrow structure interne
 - Rotation planétaire \Rightarrow couplage spin-orbite ?
 - Présence de satellites (e.g. Io)
 - Energie de l'interaction étoile-planète
 - Physique magnétosphérique comparée
 - Inclinaison orbitale
-
- Conditions favorables pour la vie ? (bouclier magnétique / destruction de O_3 par vent stellaire, CME, rayons cosmiques, réduction de l'érosion/échappement atmosphérique)

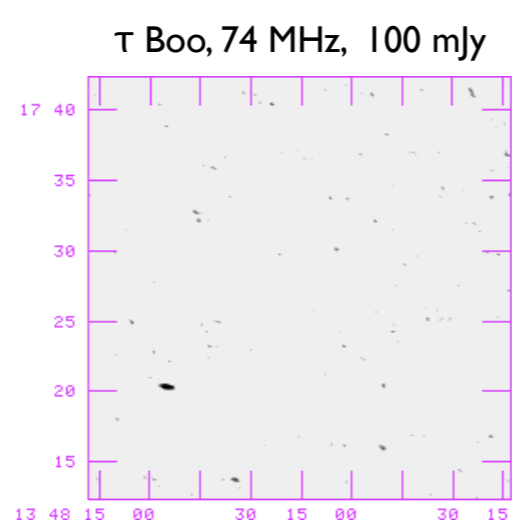


[Hess & Zarka 2011]

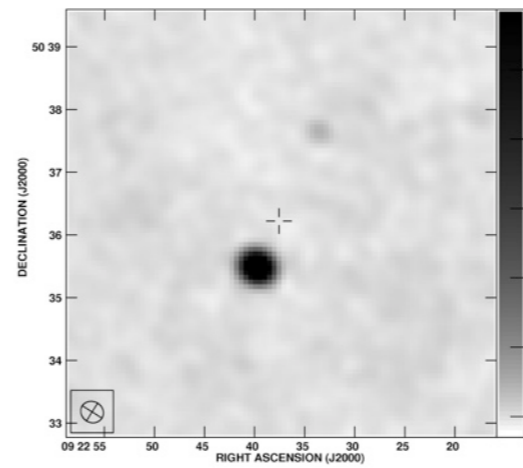


• Observations récentes

VLA 74 MHz

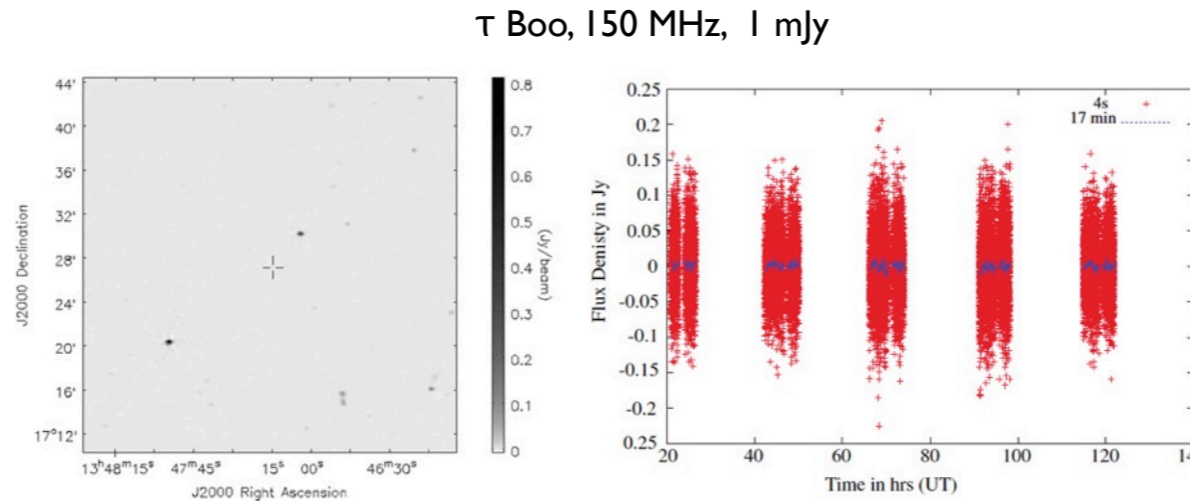


HD80606, 330 MHz, 1.7 mJy

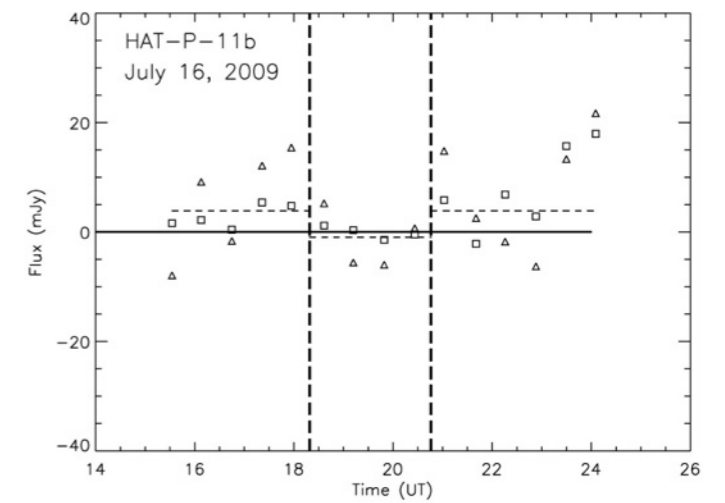


[Farrell et al., 2003, 2004 ;
Lazio & Farrell, 2007]

GMRT 150 MHz



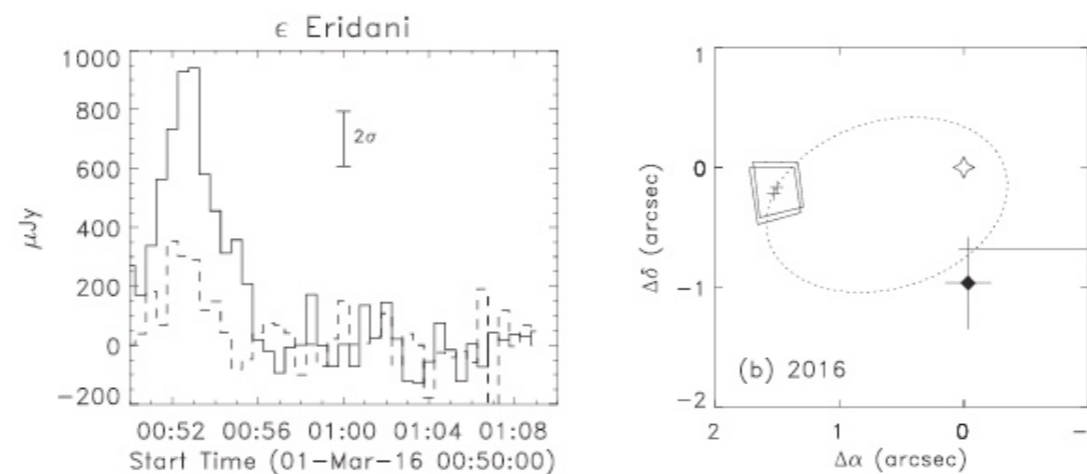
Hat-P-11, 150 MHz, 3.9 mJy



[Hallinan et al., 2013]

[Lecavelier et al., 2013]

VLA 2-4 GHz

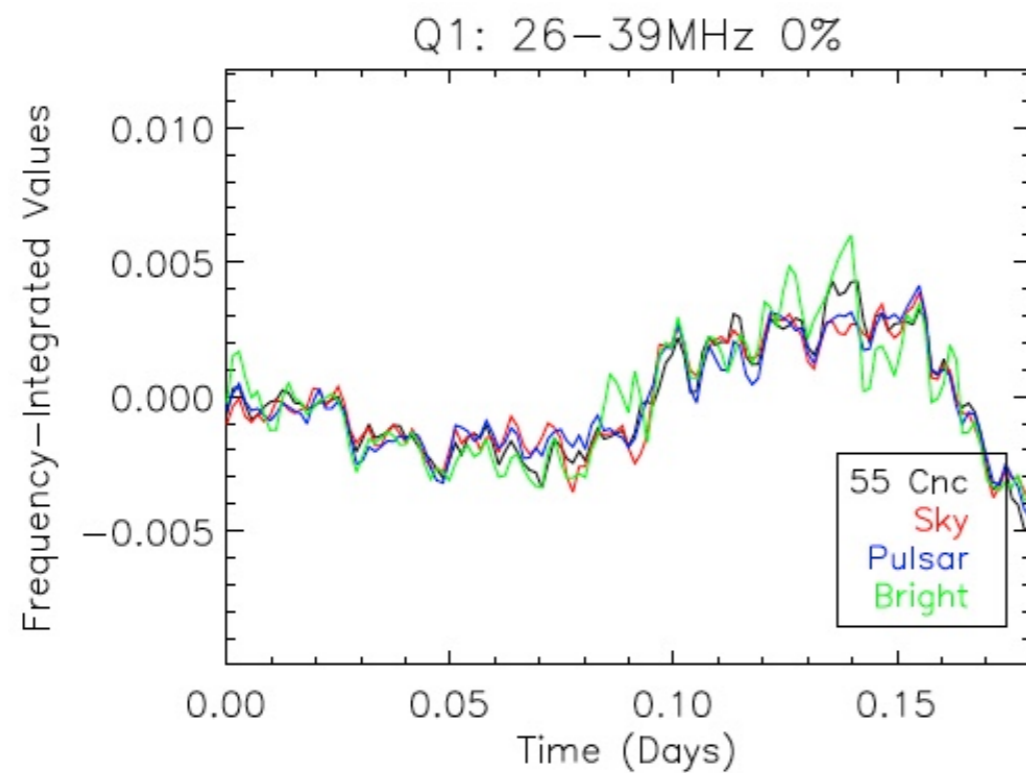
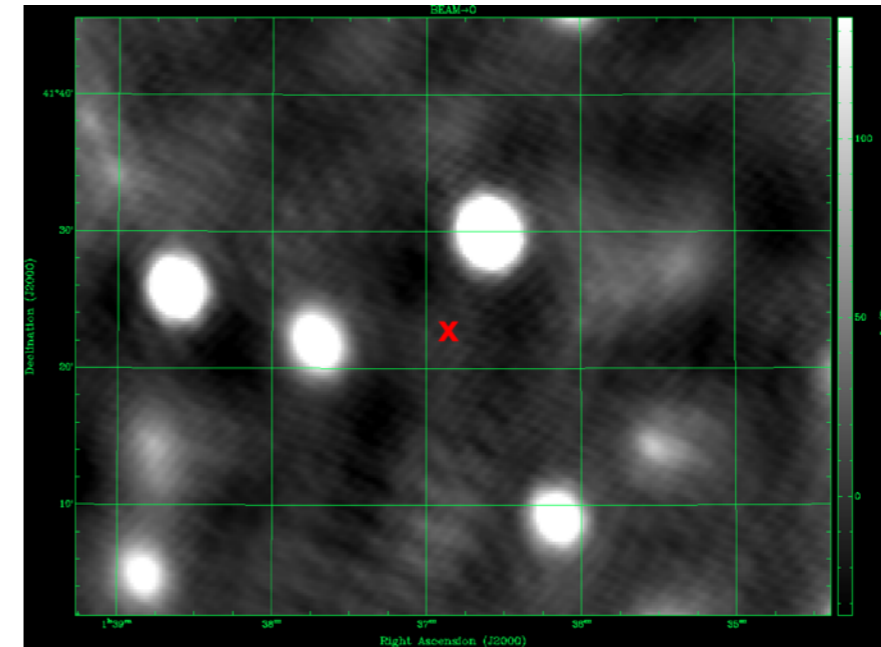
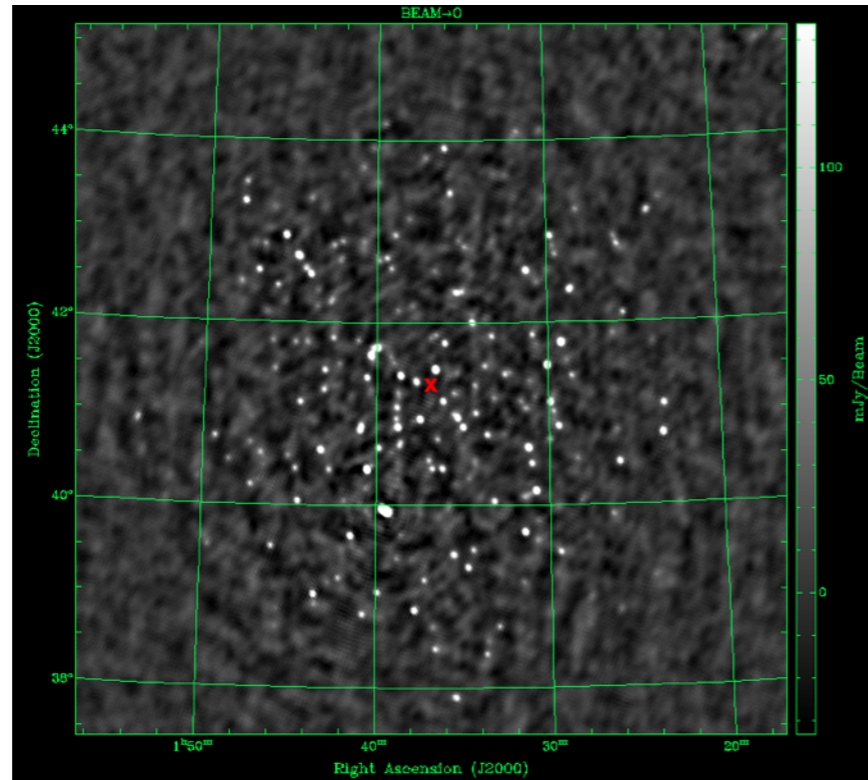


[Bastian et al., 2018]

→ aucune détection confirmée (HAT-P-11 @ GMRT ? ϵ Eri @ VLA ?)

- Observations de LOFAR (26-74 MHz)

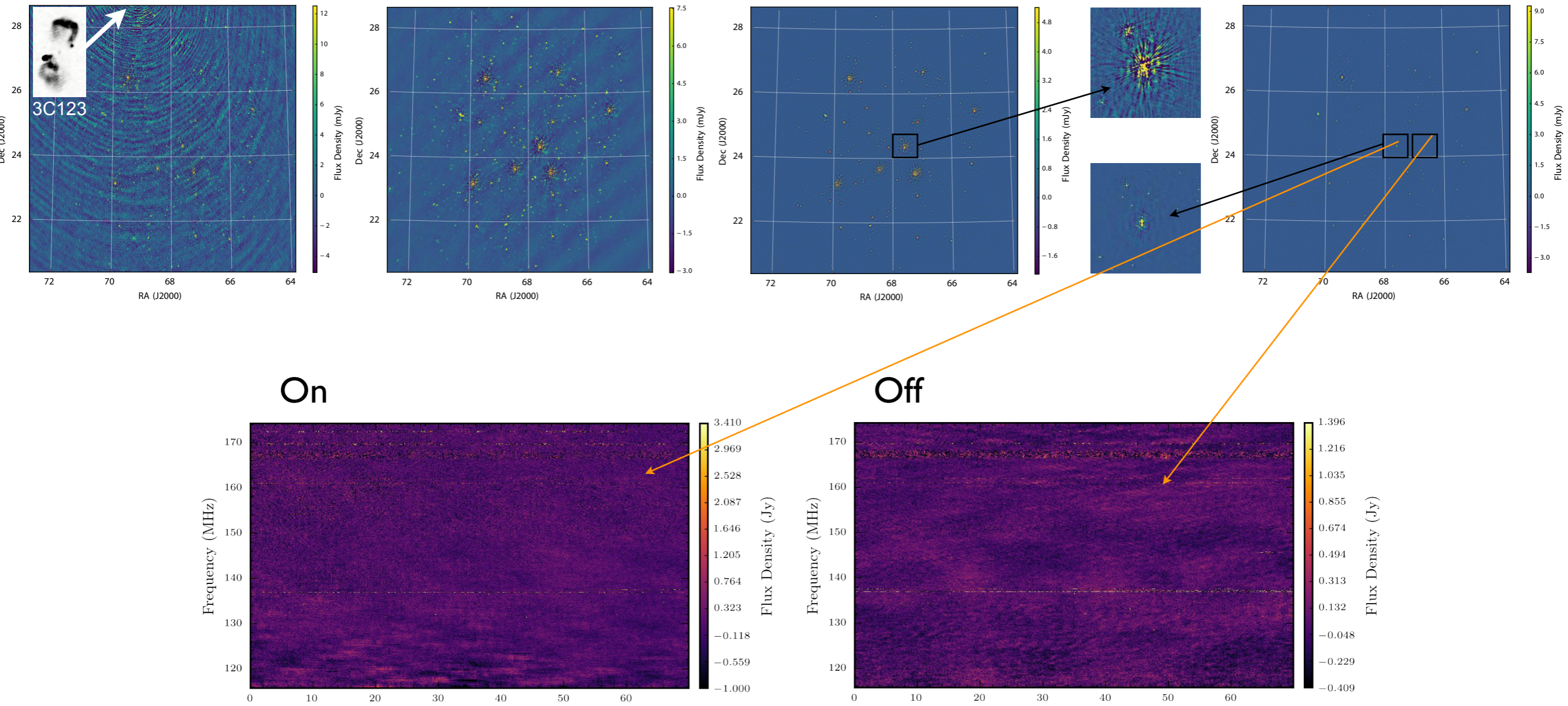
Ups And en mode imagerie (Daiboo & Zarka)



55 Cnc, Ups And, Corot 7b
en mode multi-faisceaux
[Turner et al., 2017]

• Observations de LOFAR (120-168 MHz)

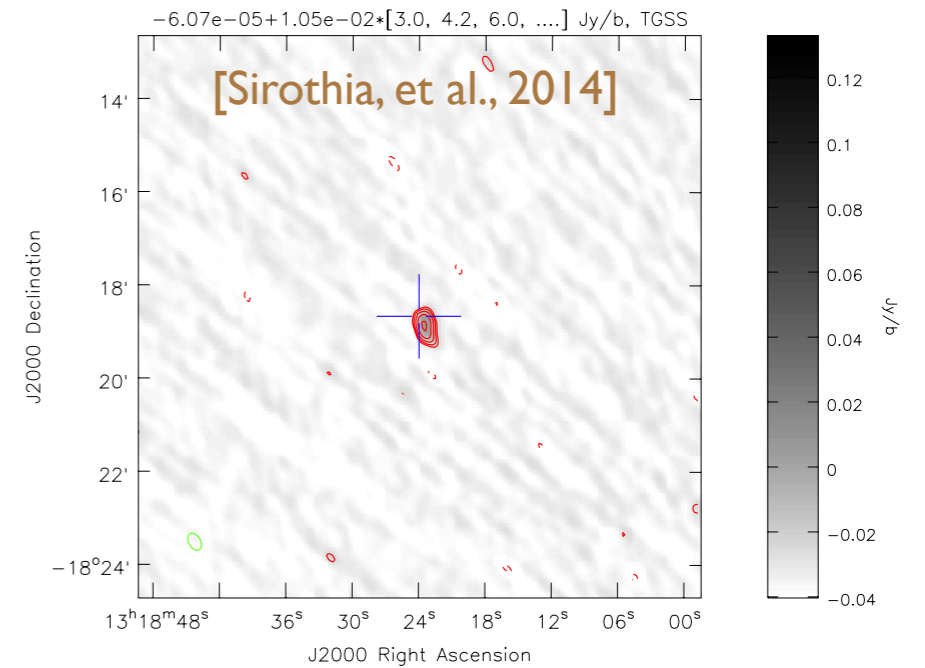
V830 τ en mode spectrographie intégrale de champ [Loh et al., 2018]



- **Corrélations surveys - catalogues**

- **TGSS 150 MHz**

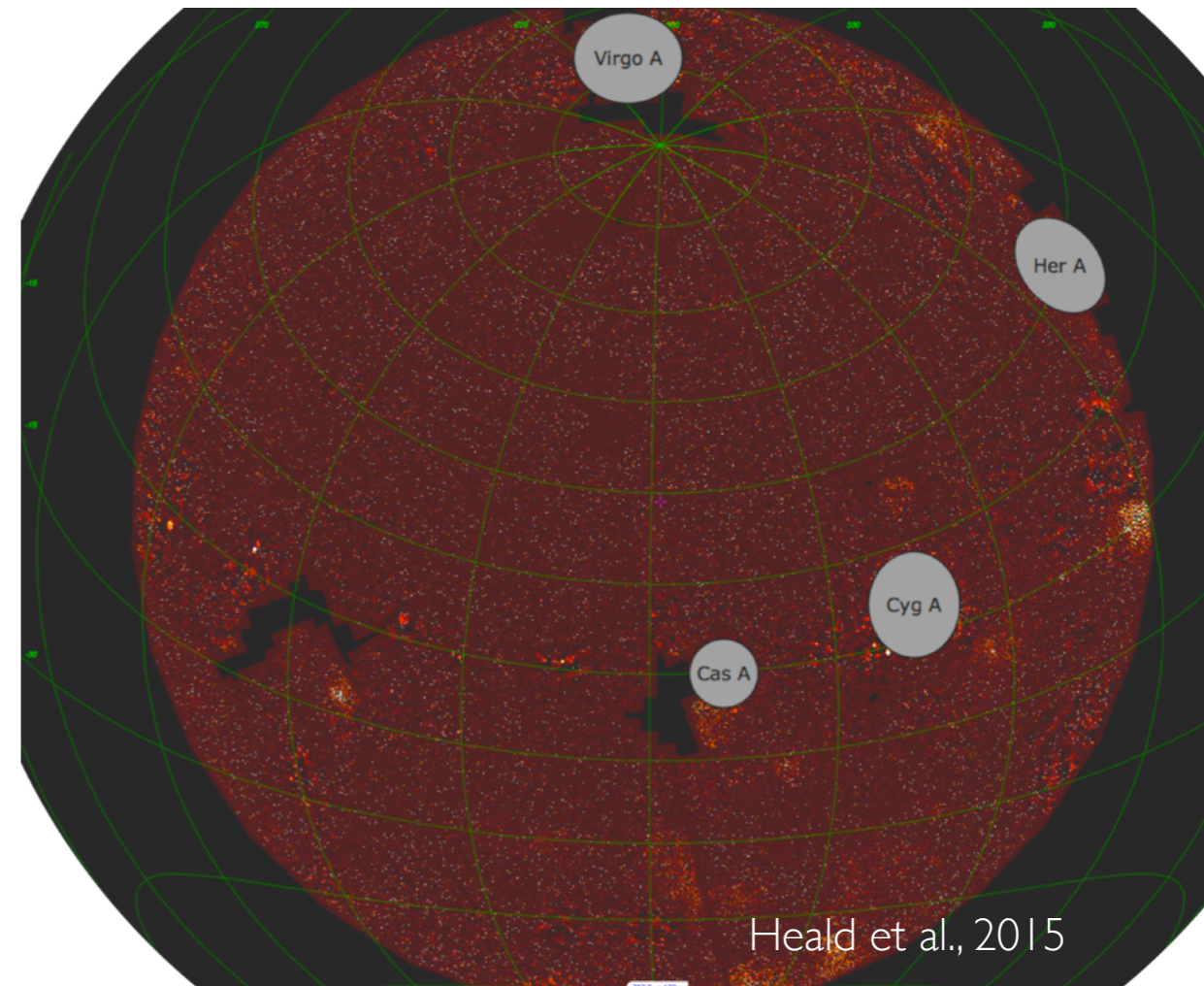
- 4 candidates out of 175 exoplanetary systems, flux \sim 18-120 mJy



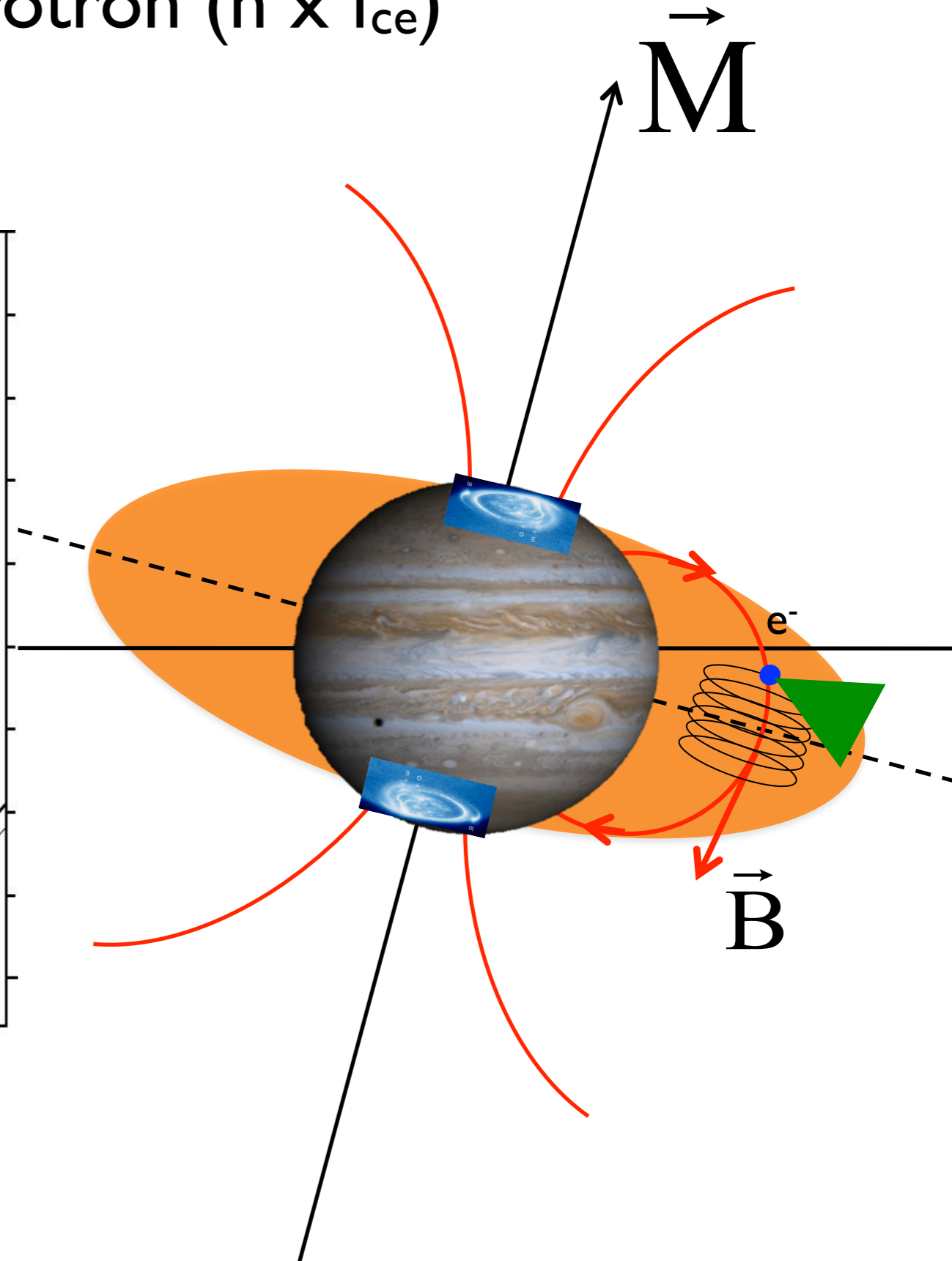
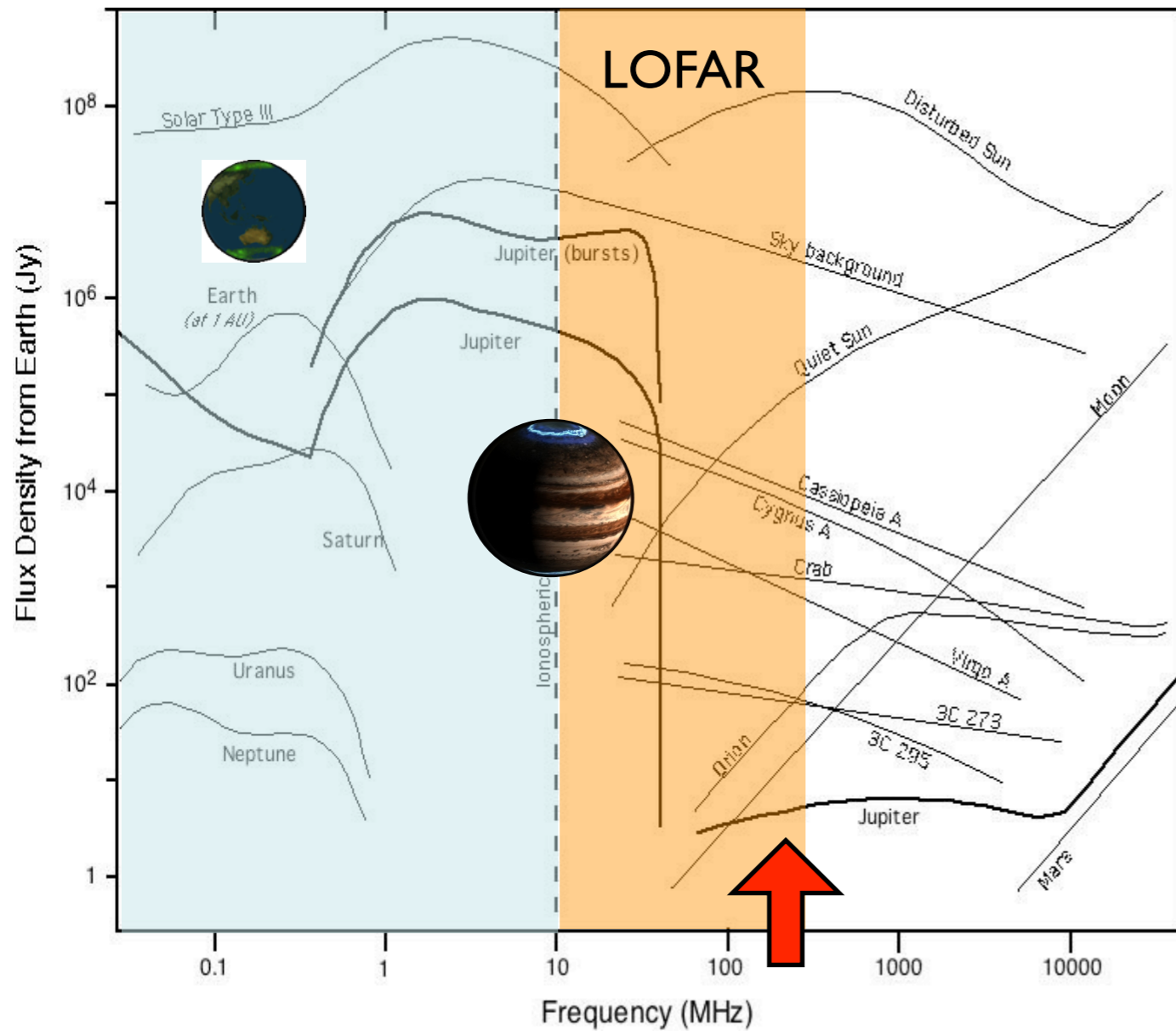
- **LOFAR MSSS**

- HBA : 120-160 MHz ($\leq 120''$, ≤ 5 mJy/b)

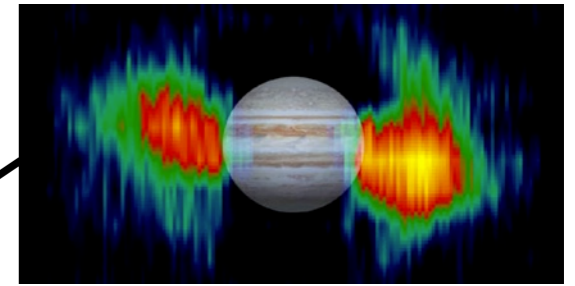
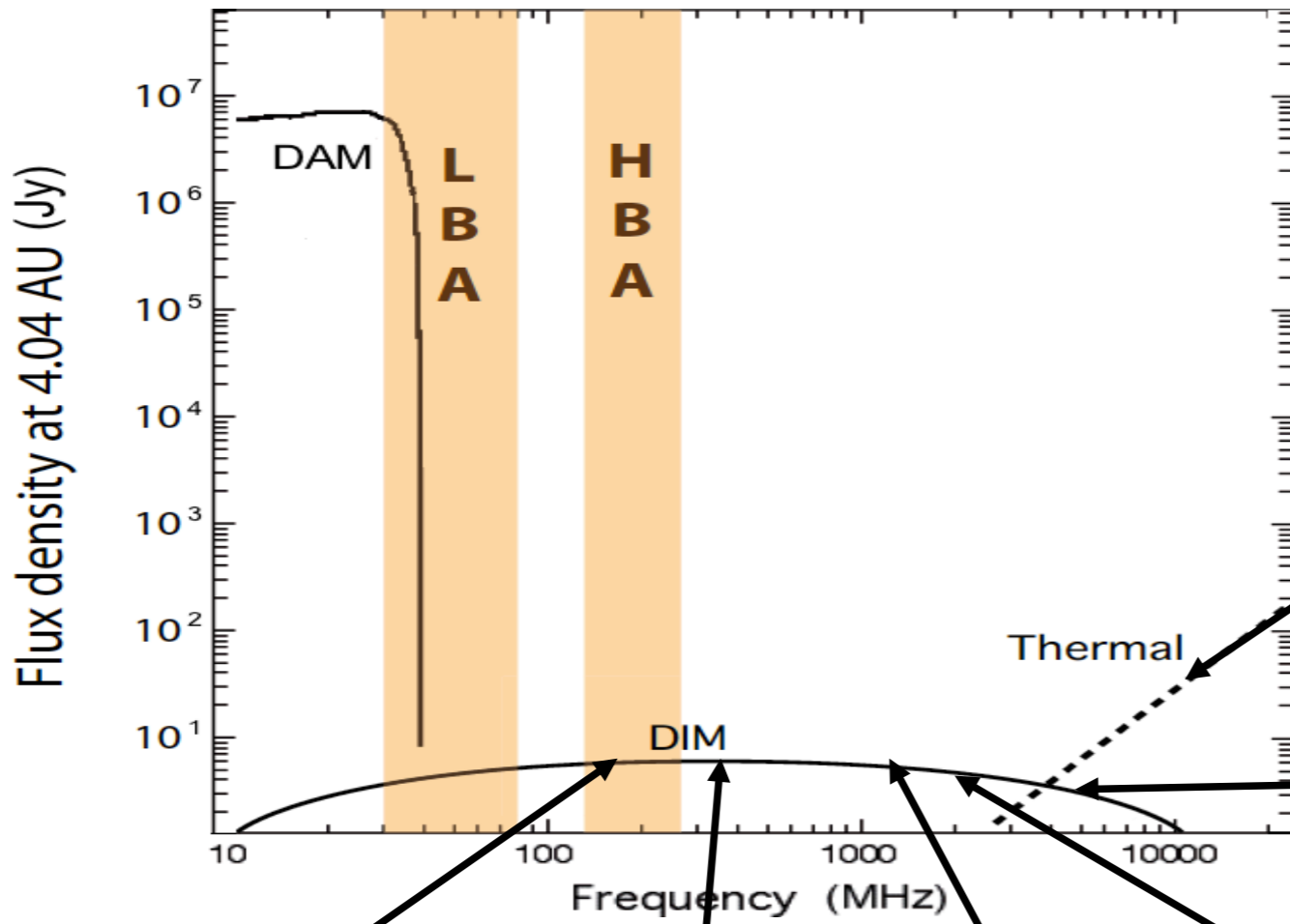
- LBA : 30-75 MHz ($\leq 100''$, ≤ 15 mJy/b)



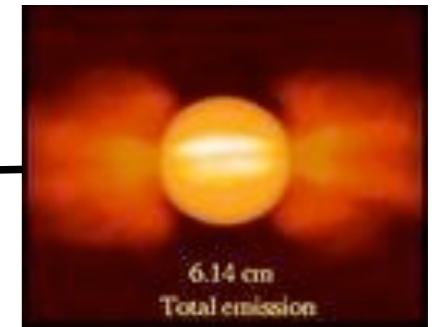
(2) magnétosphères : ceintures de radiations, → émission synchrotron ($n \times f_{ce}$)



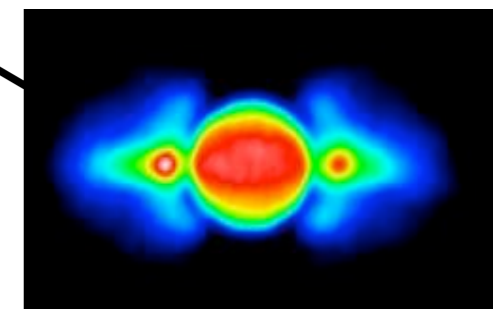
- Observations résolues



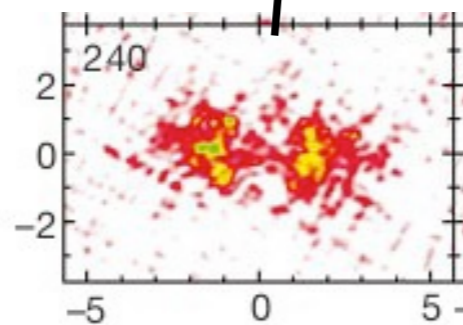
14 GHz / 2 cm
Cassini



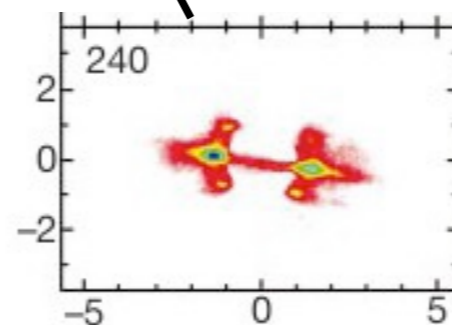
5 GHz / 6 cm
ATCA



2.3 GHz / 13 cm
ATCA



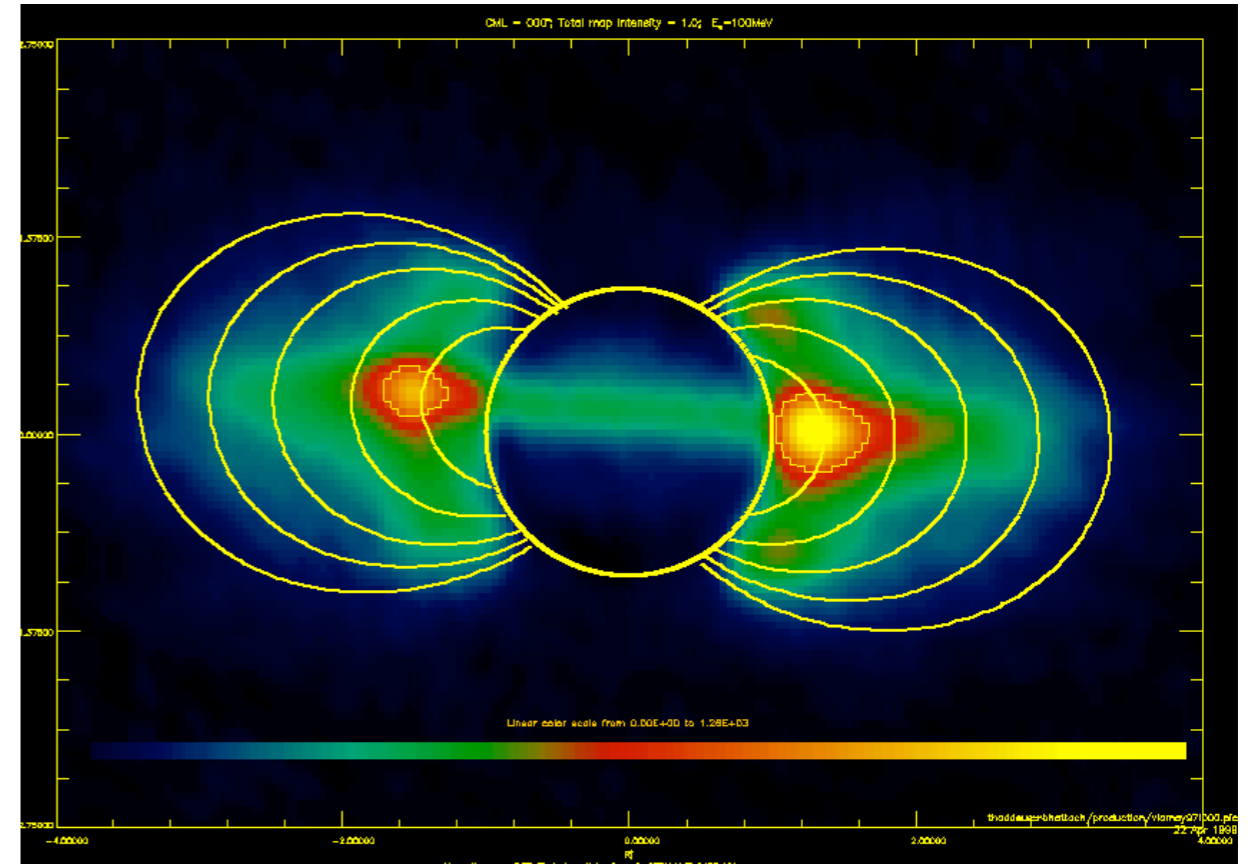
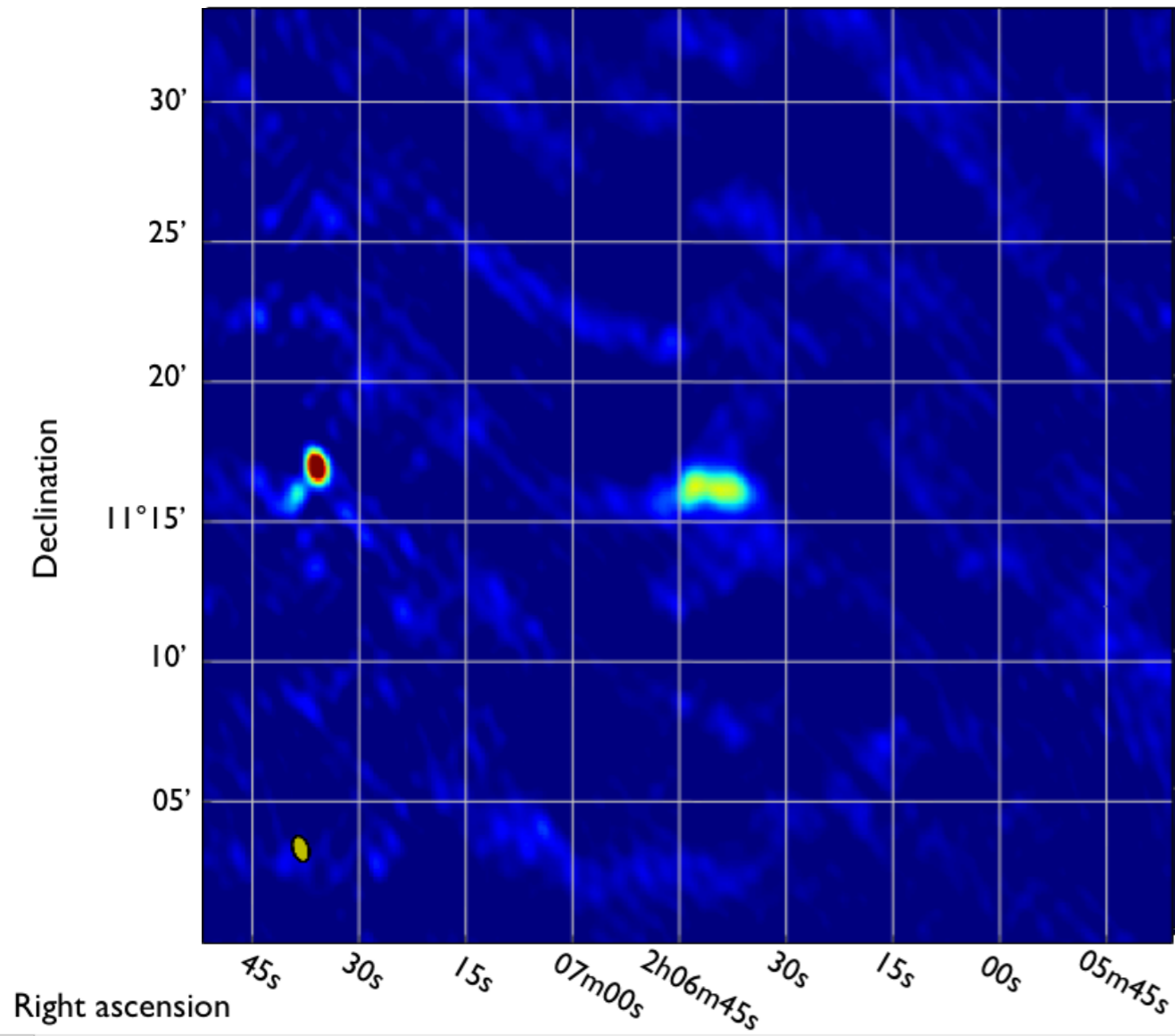
333 MHz / 90 cm
VLA



1.4 GHz / 20 cm
VLA

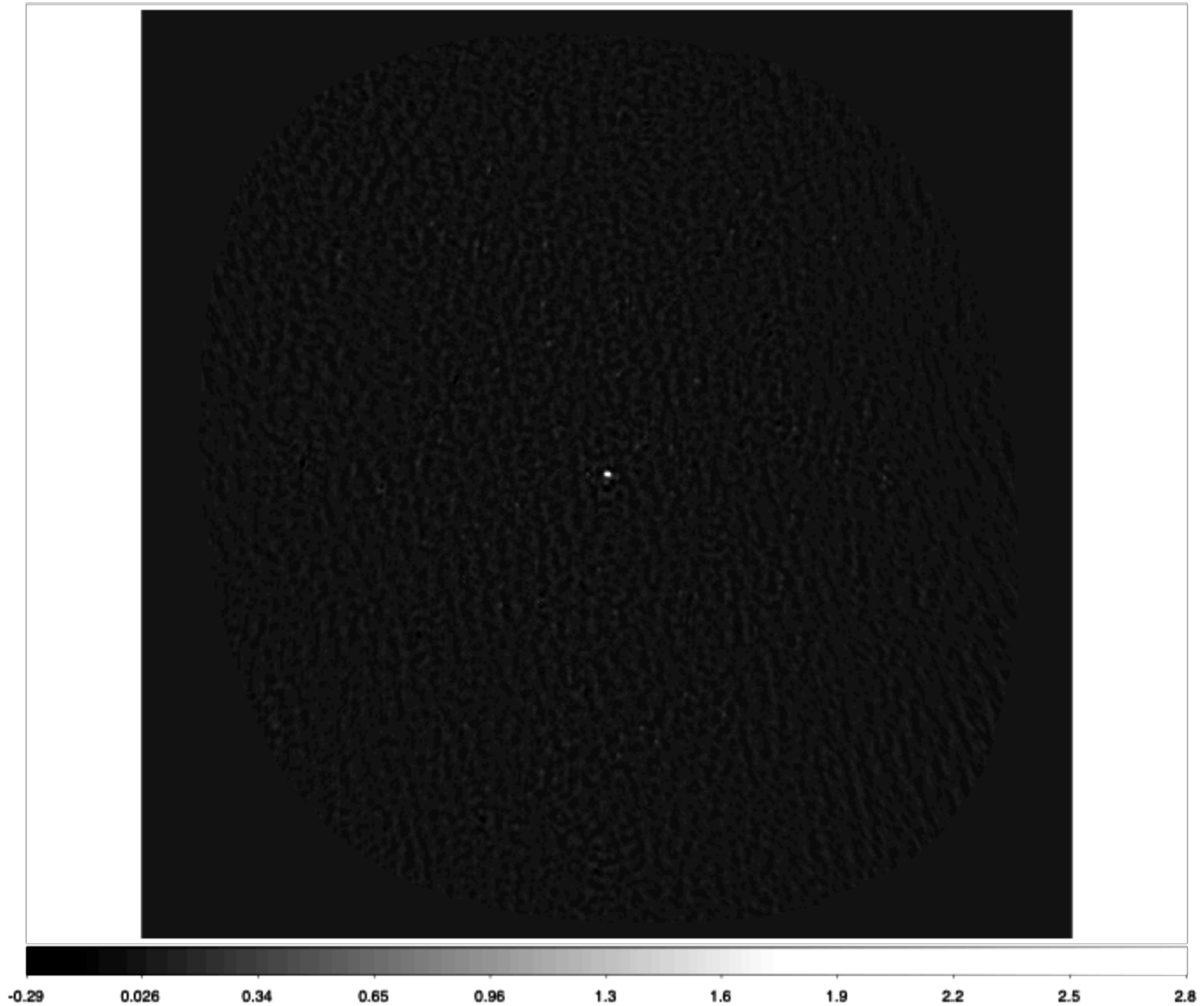
$$\nu_{max} \propto E^2 |B| \Rightarrow \text{accès aux électrons de plus basse énergie dans B plus faible}$$

- Mouvements propres rapides de la source



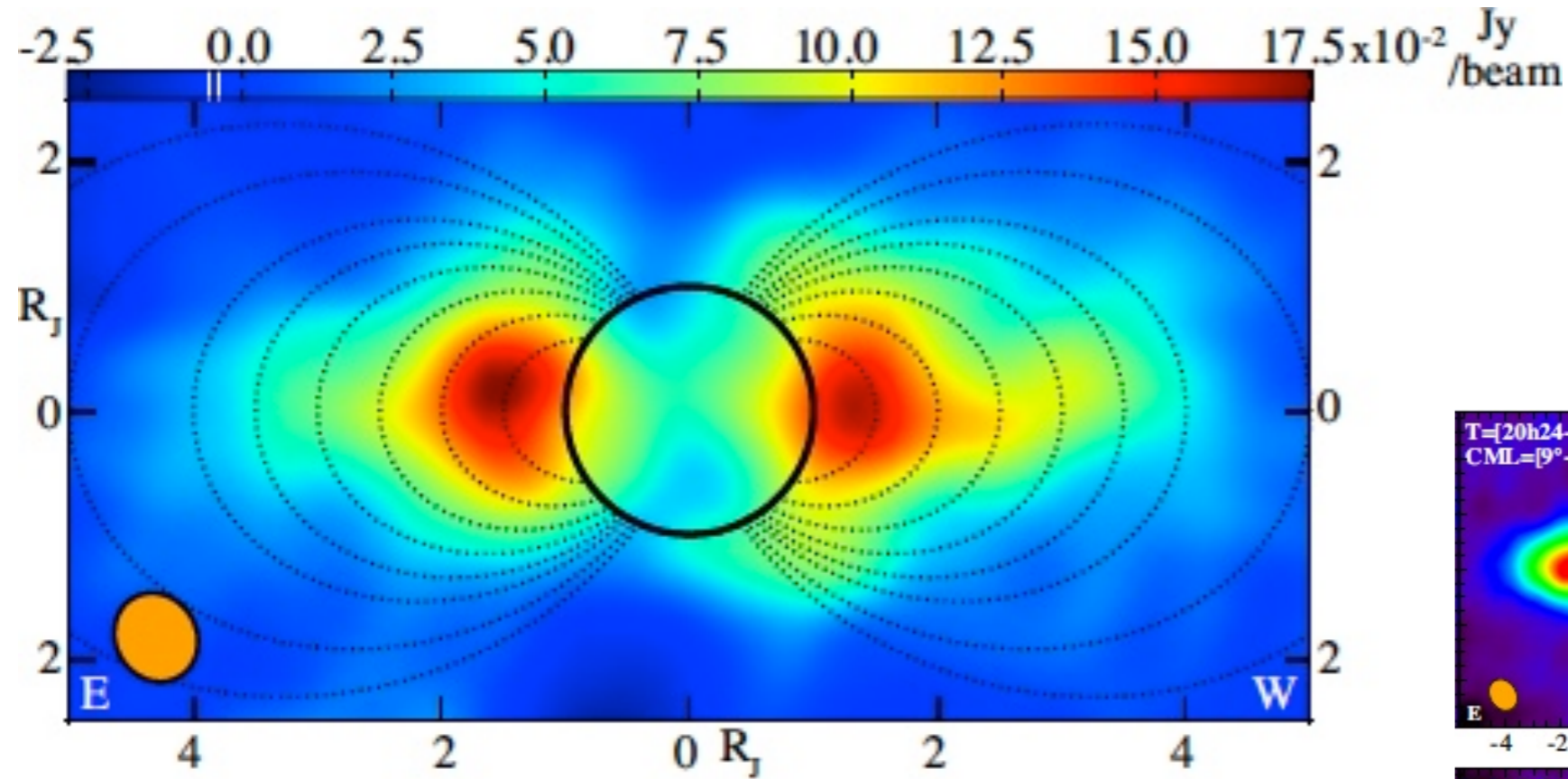
- "Peeling" des autres sources

$10^\circ \times 10^\circ$

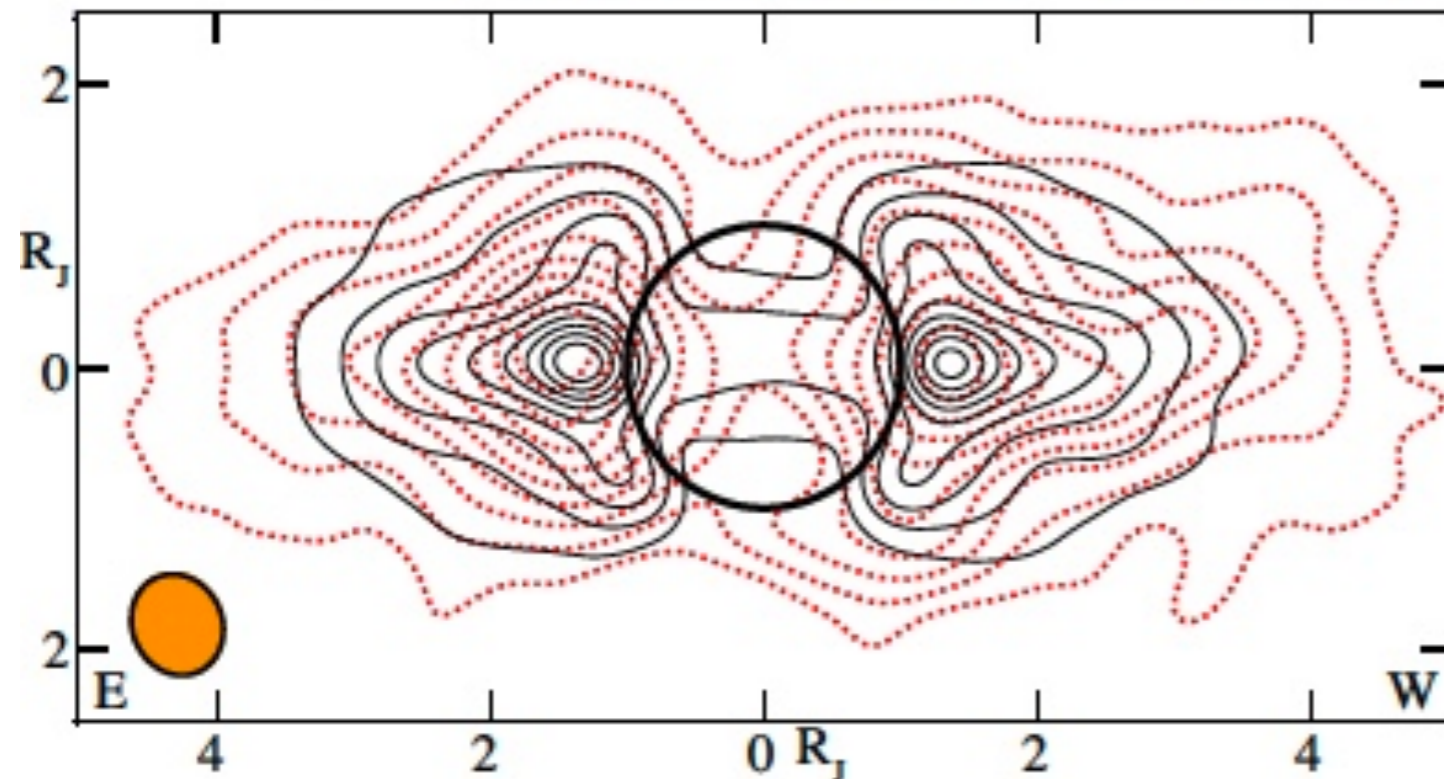


- Image LOFAR (127-170 MHz)

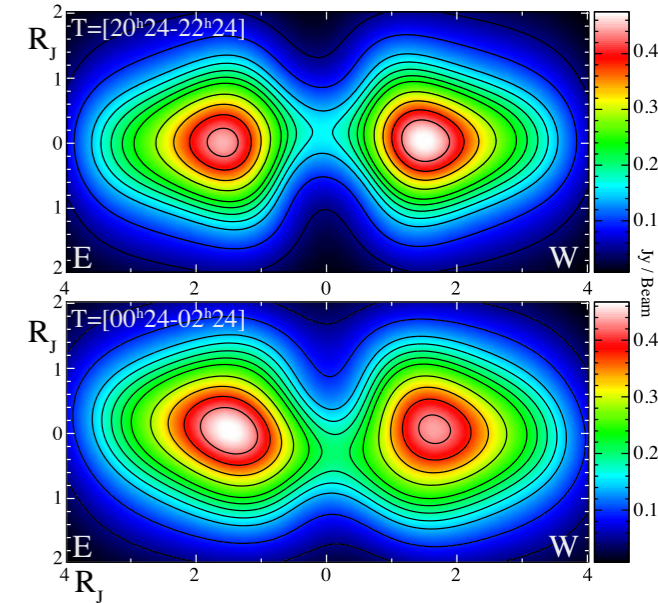
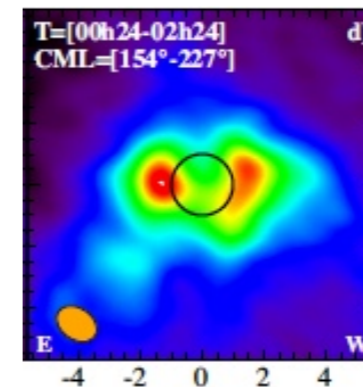
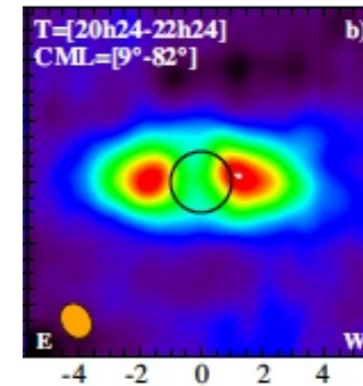
[Girard et al., 2016]



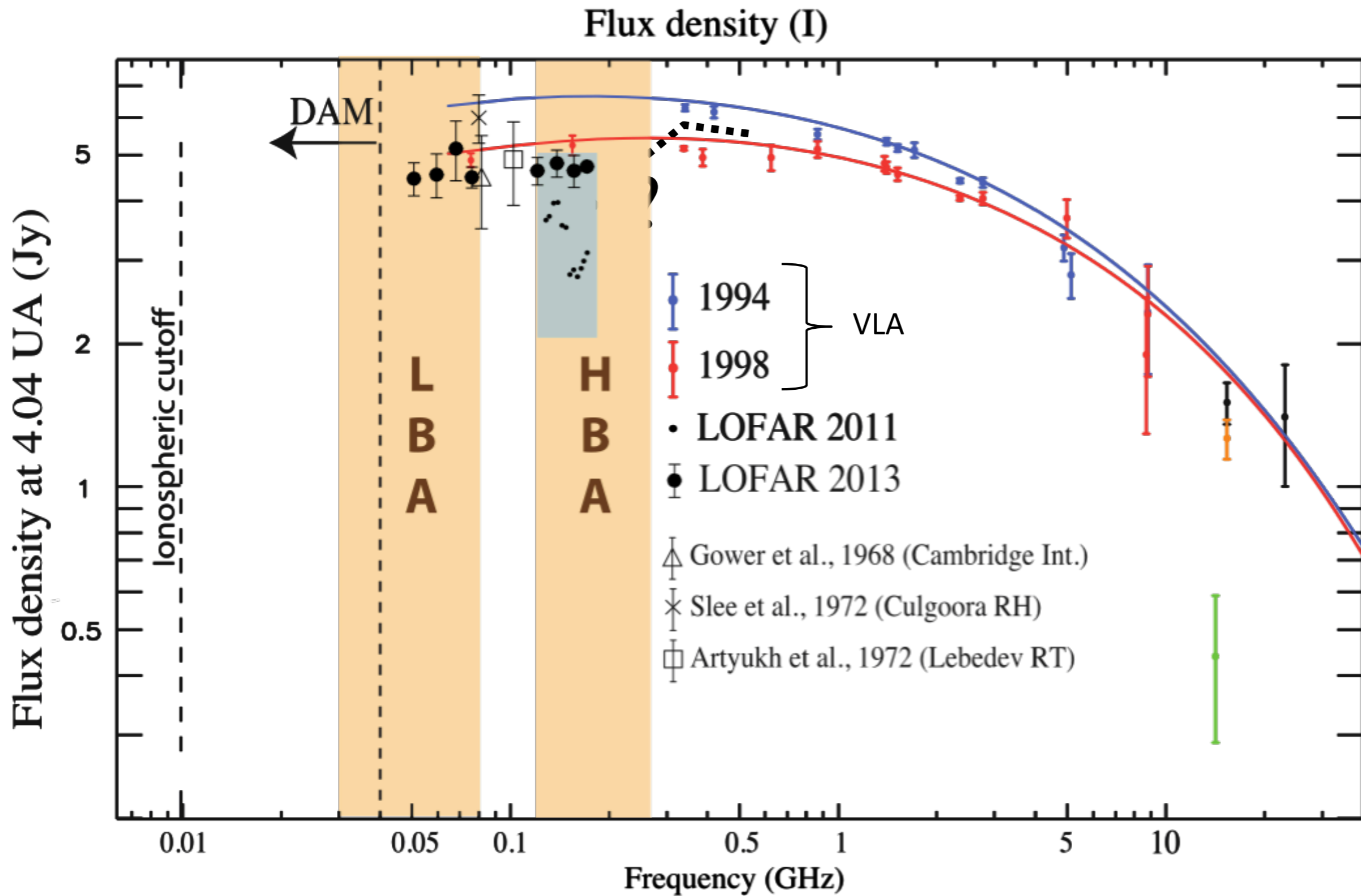
— Convolved VLA data LOFAR data



Simulations (ONERA)

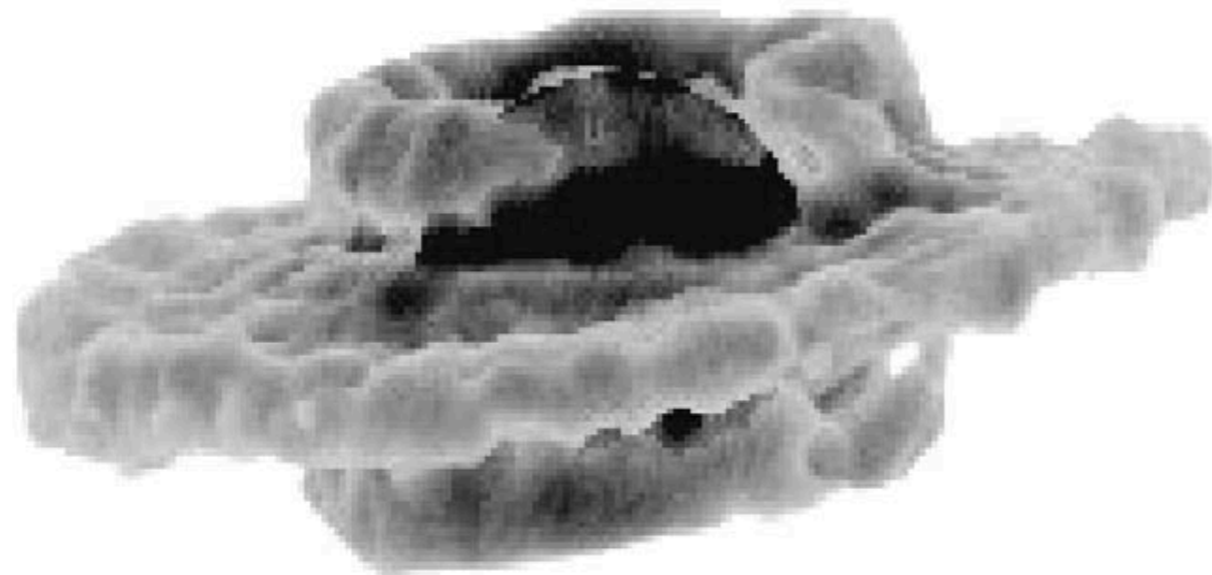


- Spectre



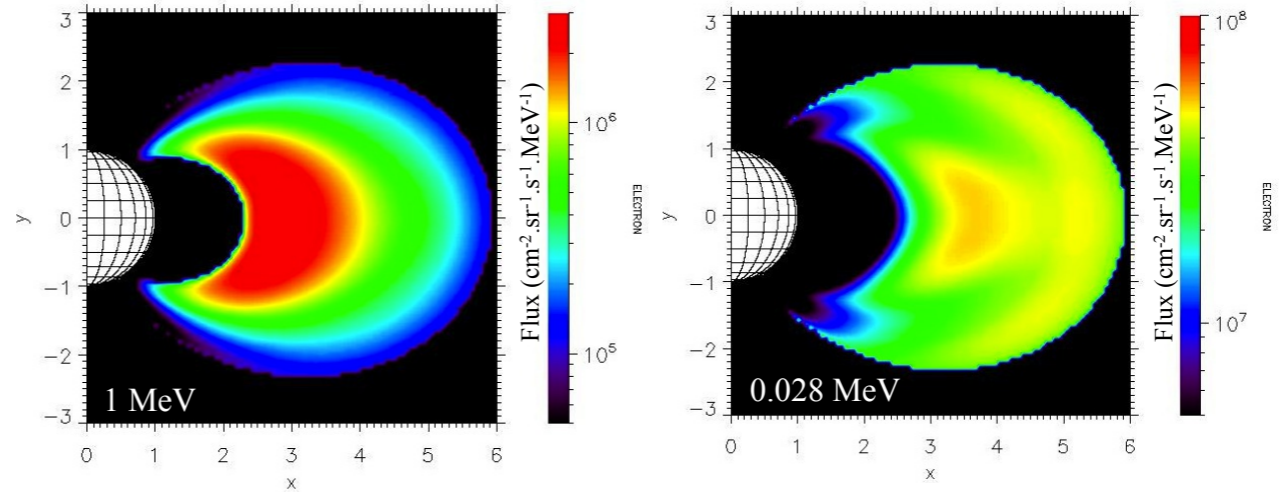
• Perspectives

- Propriétés morphologiques, extension, variations temporelles (→ dynamique magnétosphérique)
- Spectre instantané complet (LOFAR + VLA/WSRT)
- Polarisation
- Reconstruction 3D tomographique du champ magnétique
- Interprétation via simulations détaillées
 - Processus de source / transport / pertes des électrons de 100s keV
 - Topologie de B interne (termes multipolaires ?) à basses latitudes

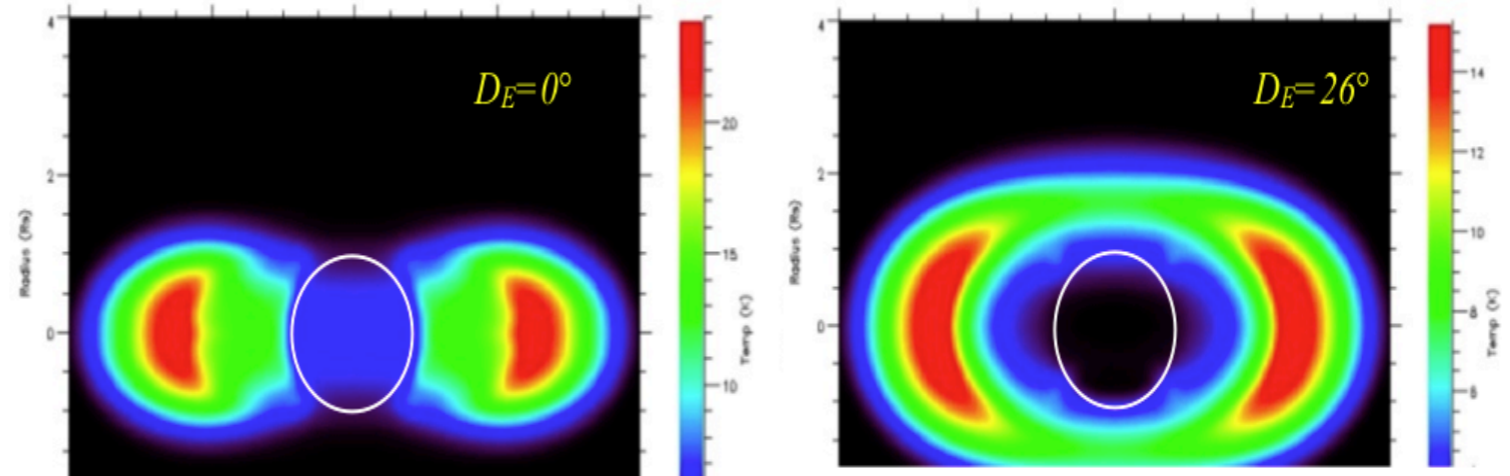


- Ceintures de radiations de Saturne ?

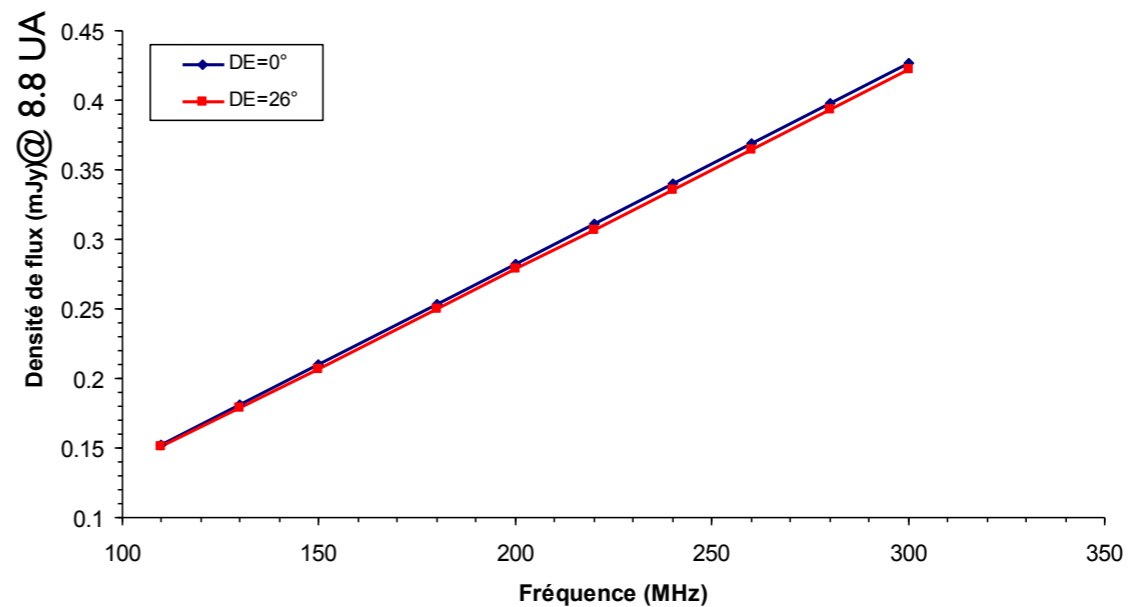
Modelled electrons fluxes
(Salammbô-3D)



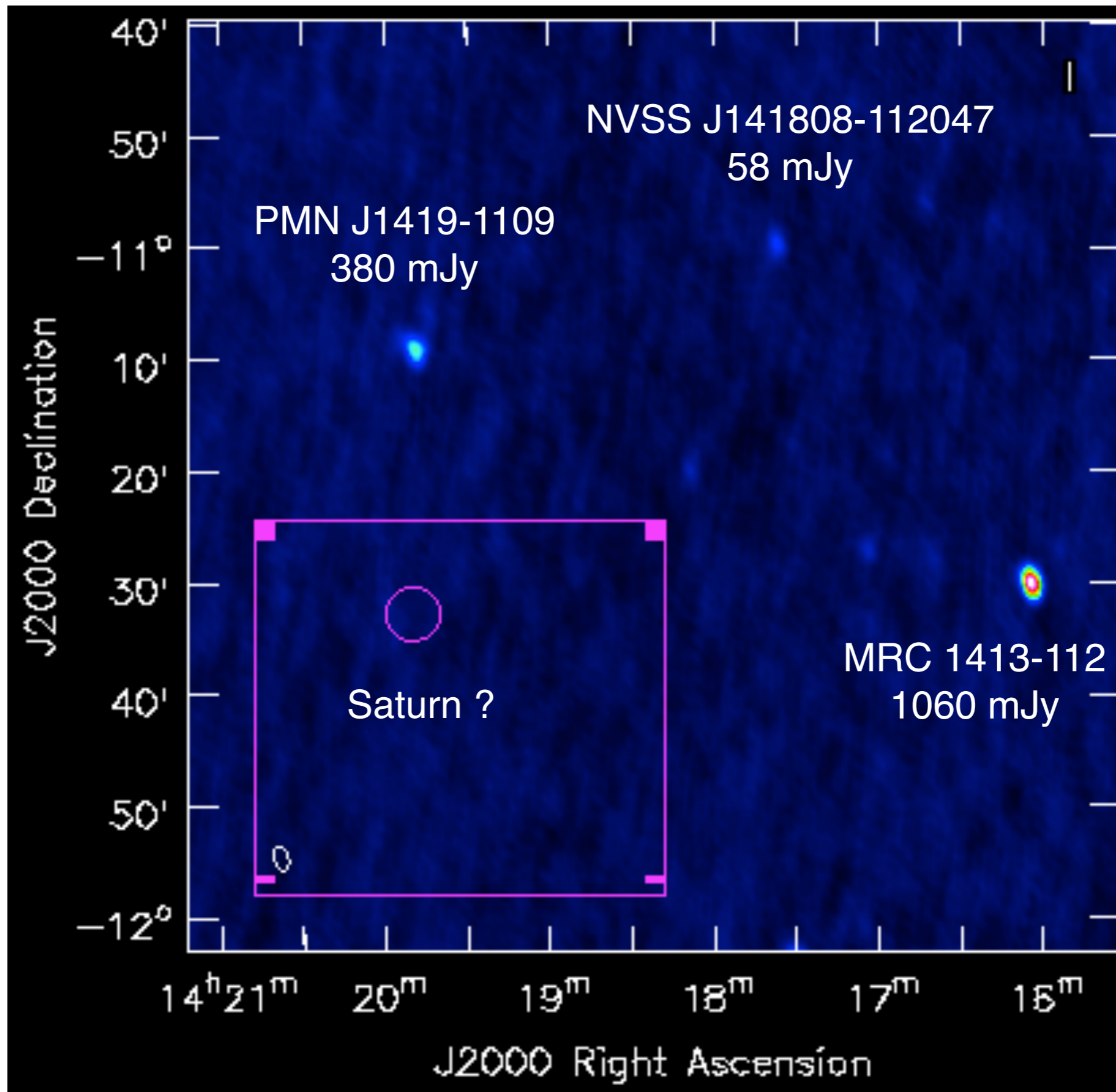
Modelled 2-D maps at
110-300 MHz



Computed disk-integrated spectrum



- Observation LOFAR (8/2013)

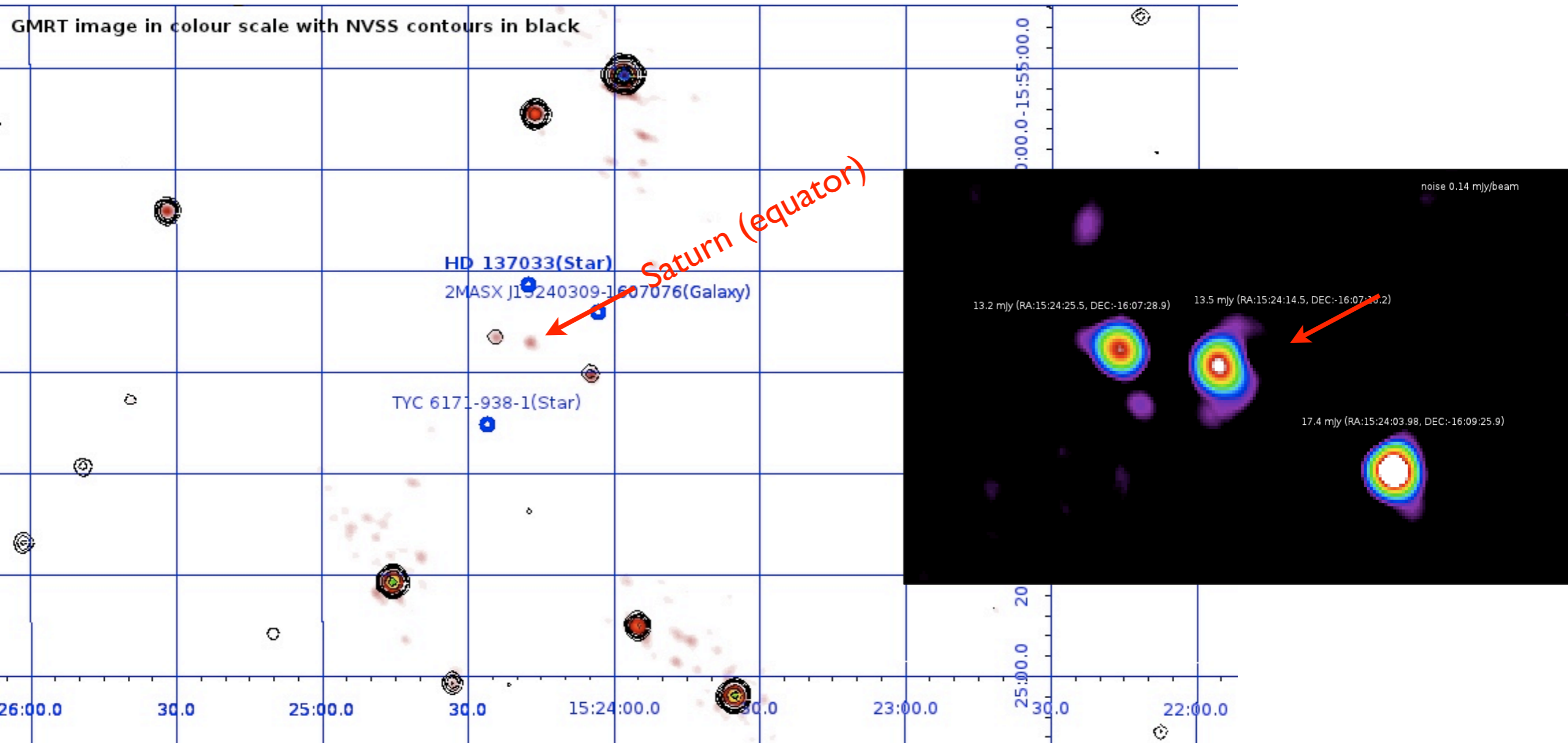


$f = 160 \text{ MHz}$
 $\Delta f = 4 \text{ MHz}$

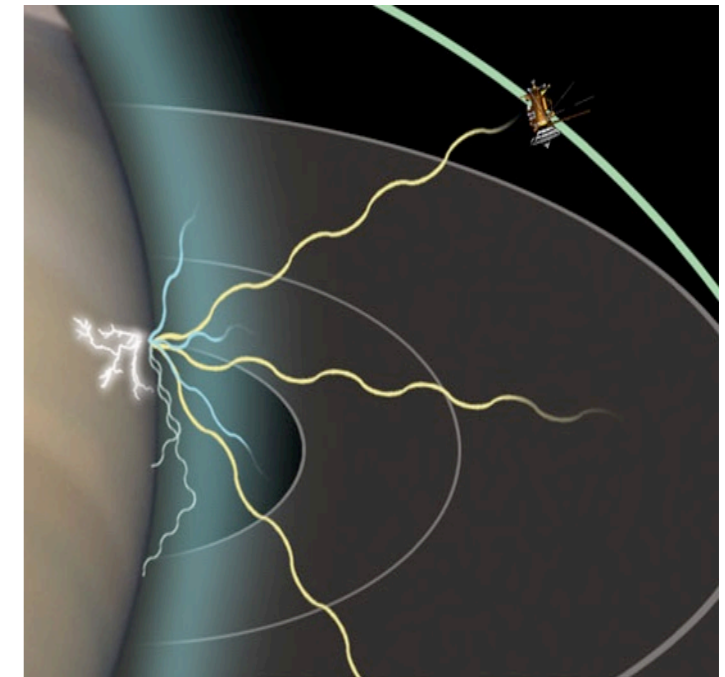
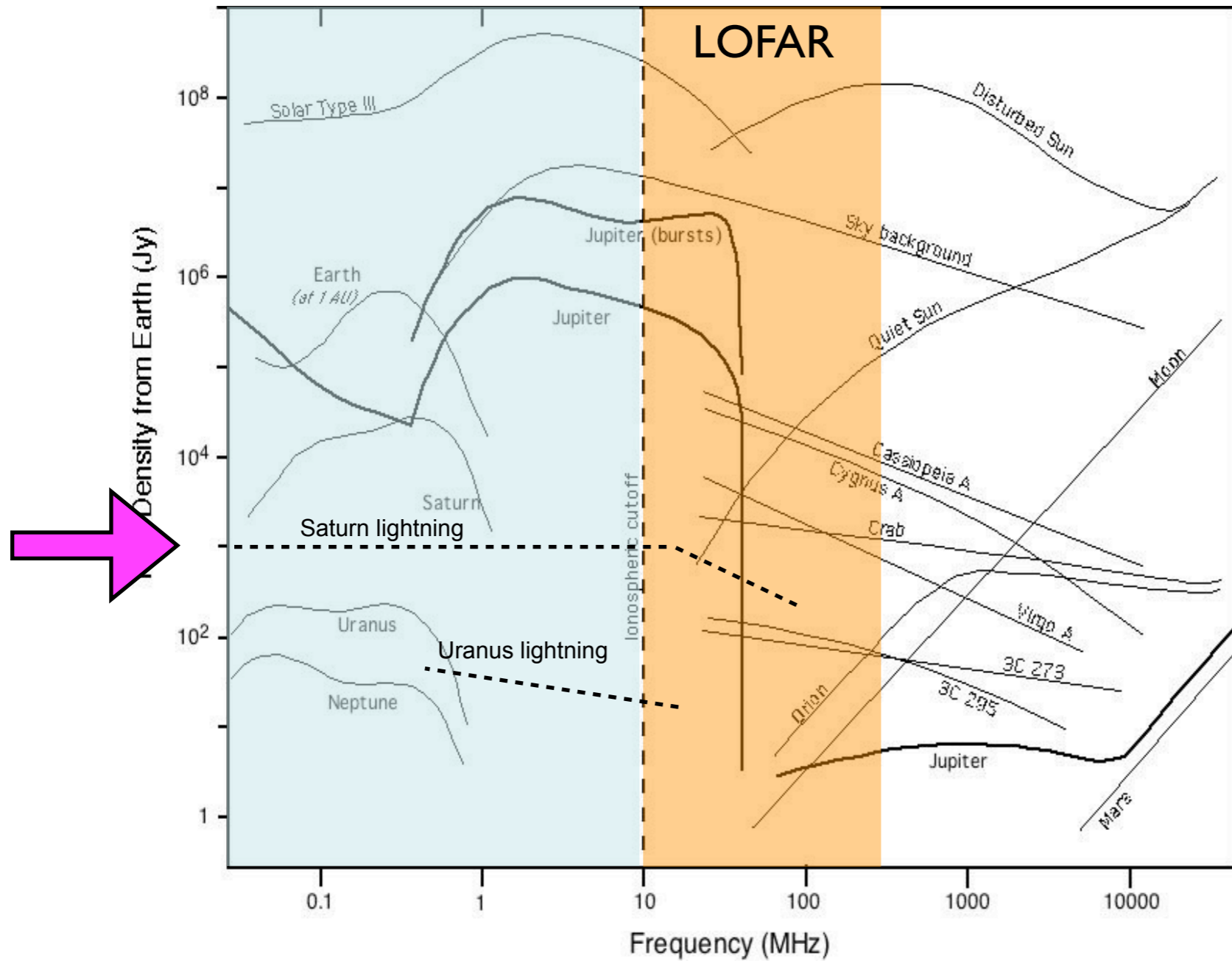
Noise =
14 mJy/beam

- Observation GMRT (3 & 8/2014)

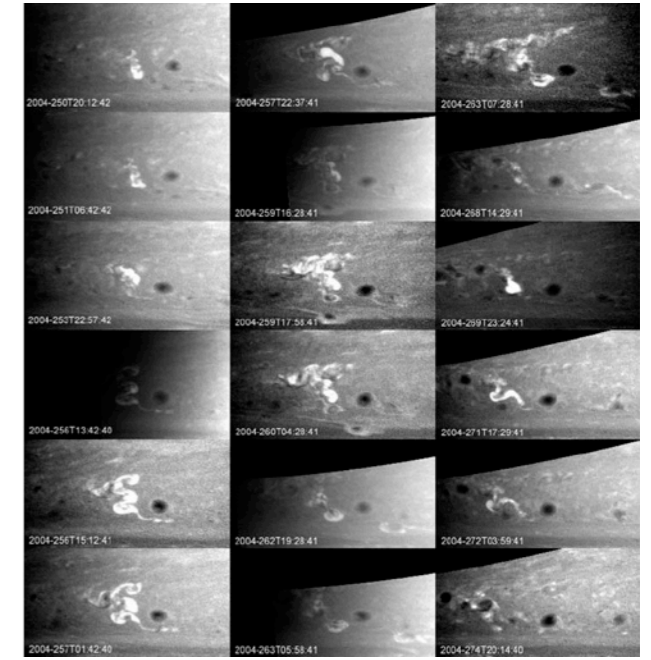
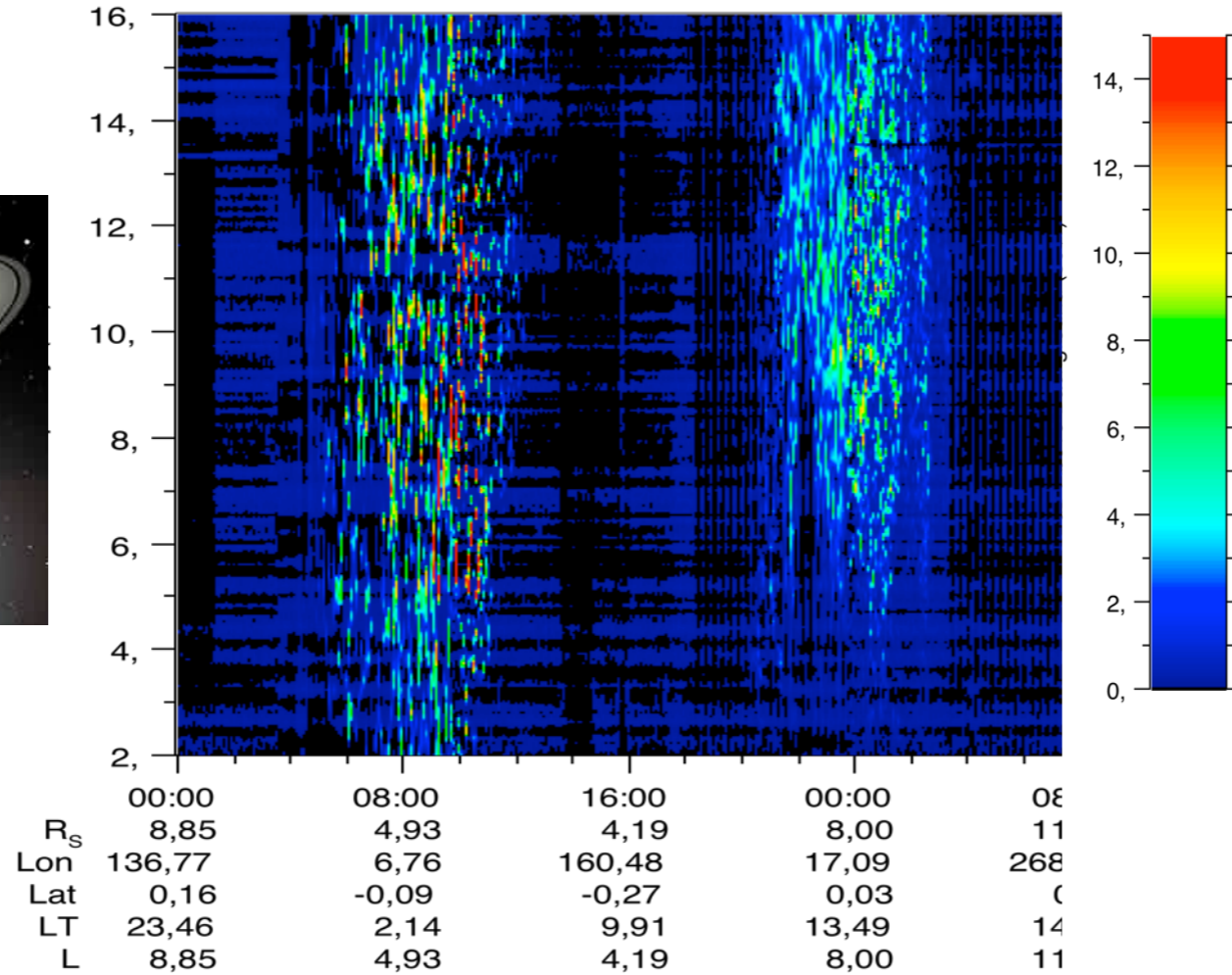
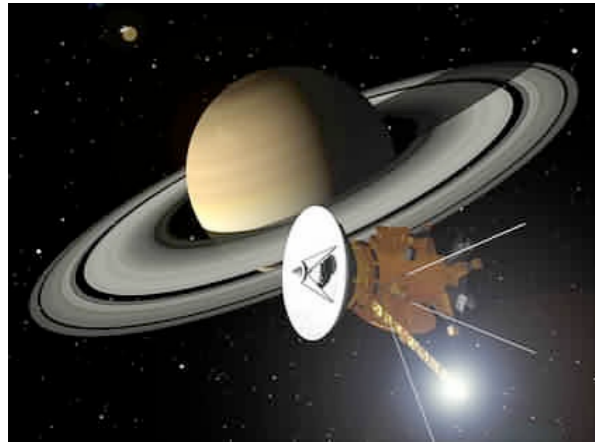
f = 610 MHz



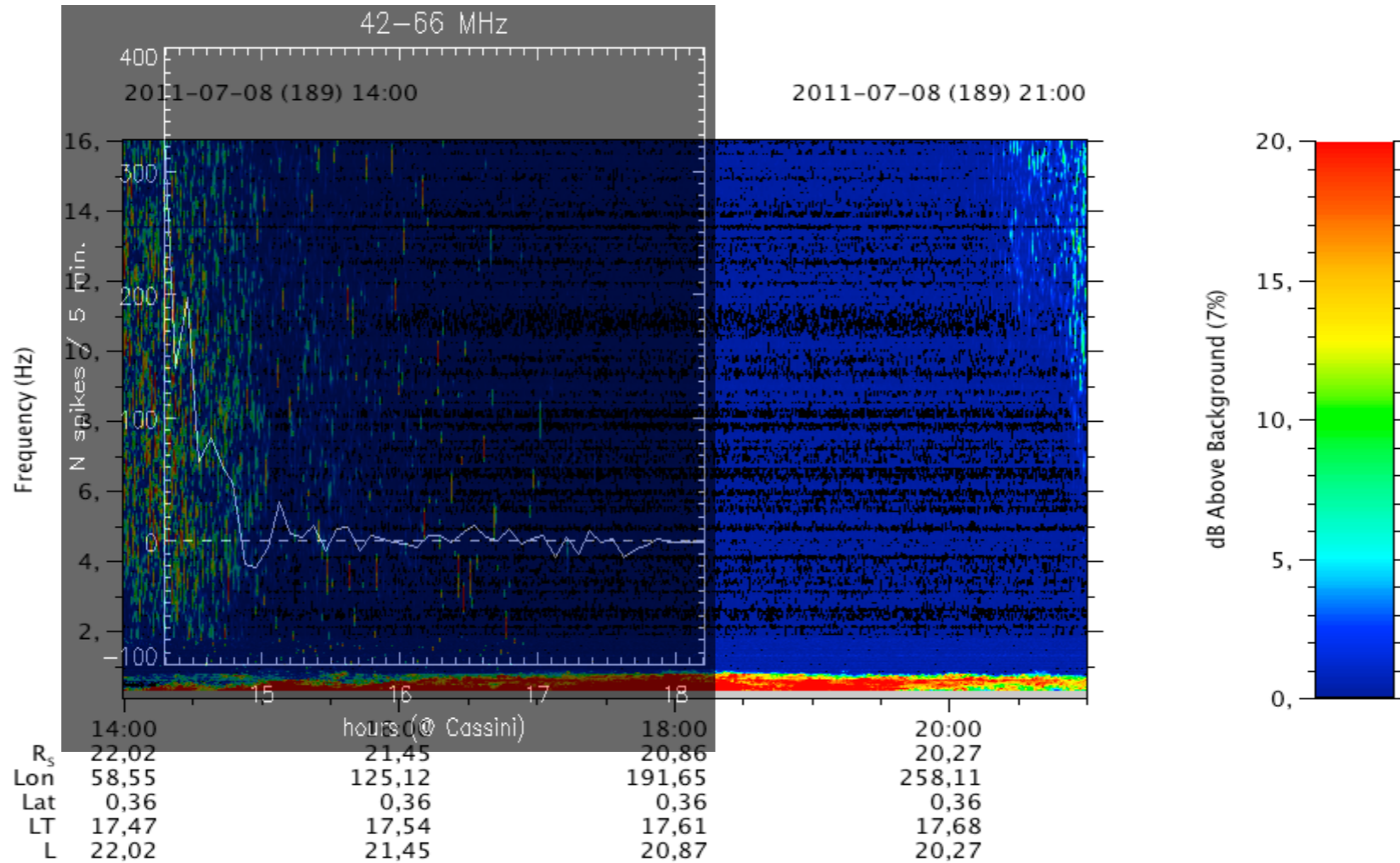
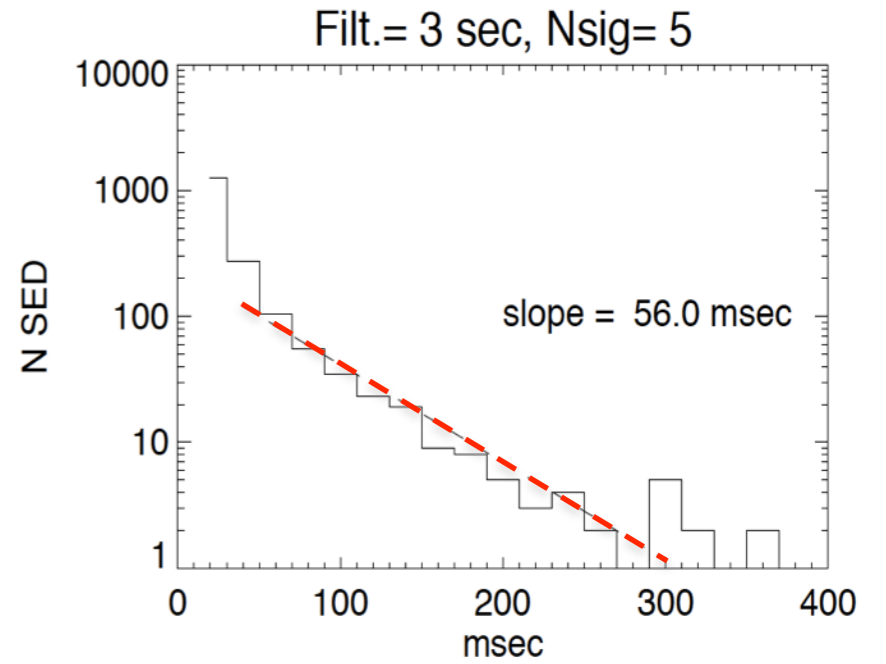
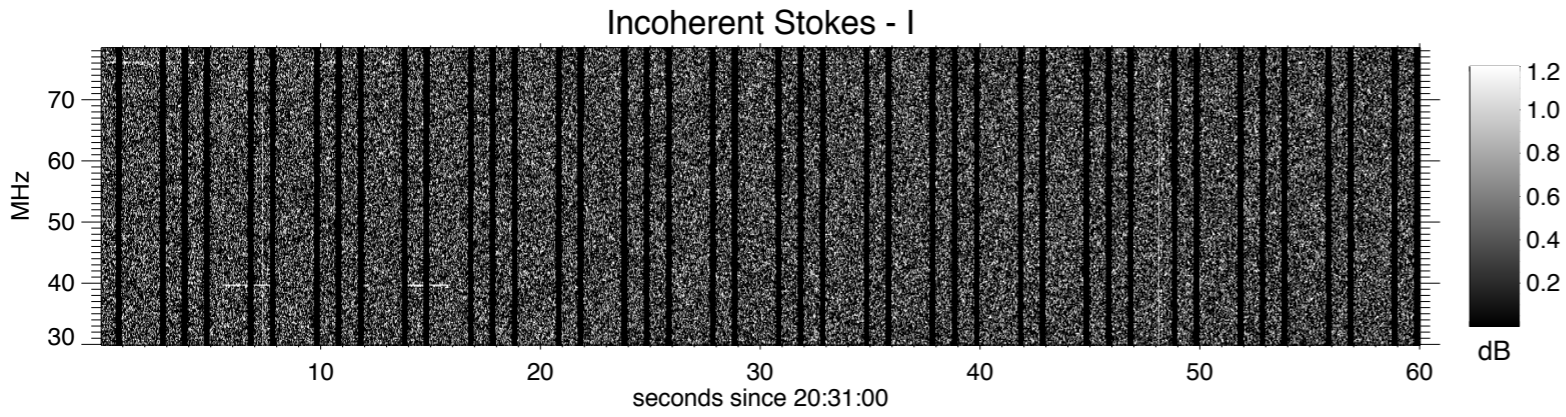
(3) atmosphères : éclairs d'orages → rayonnement d'antenne



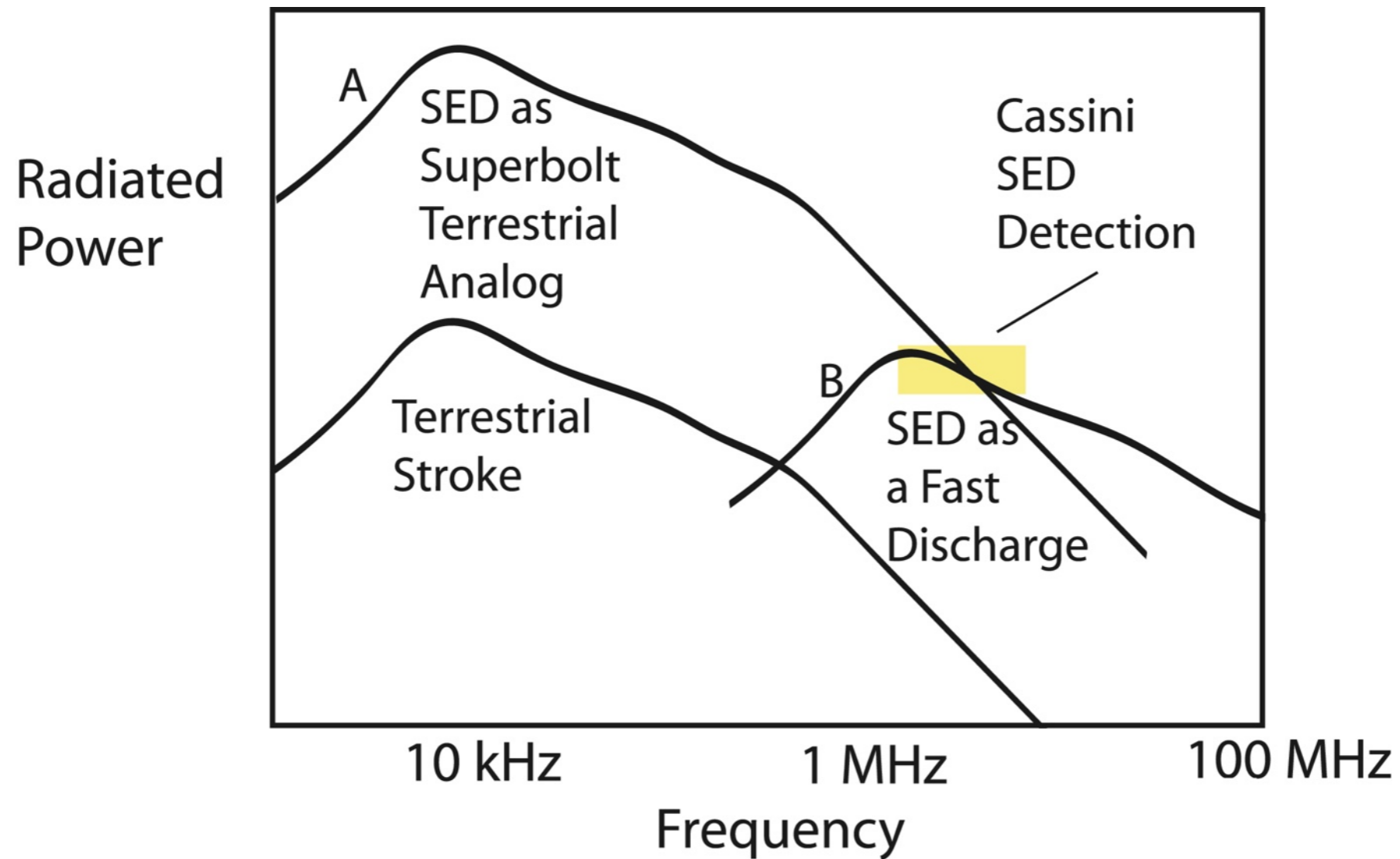
- Découverte par Voyager I & 2, réobservation par Cassini



• Observations LOFAR



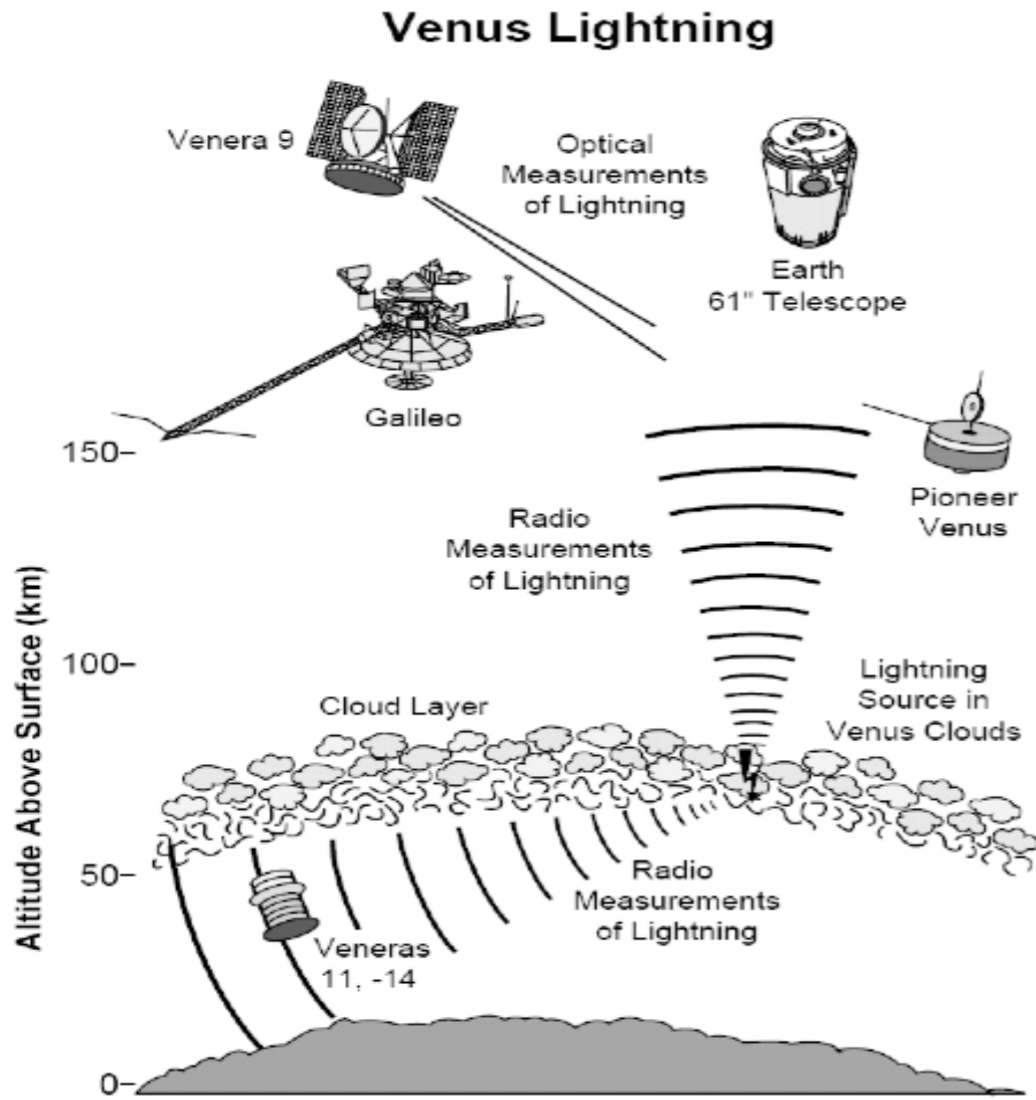
- Intérêt



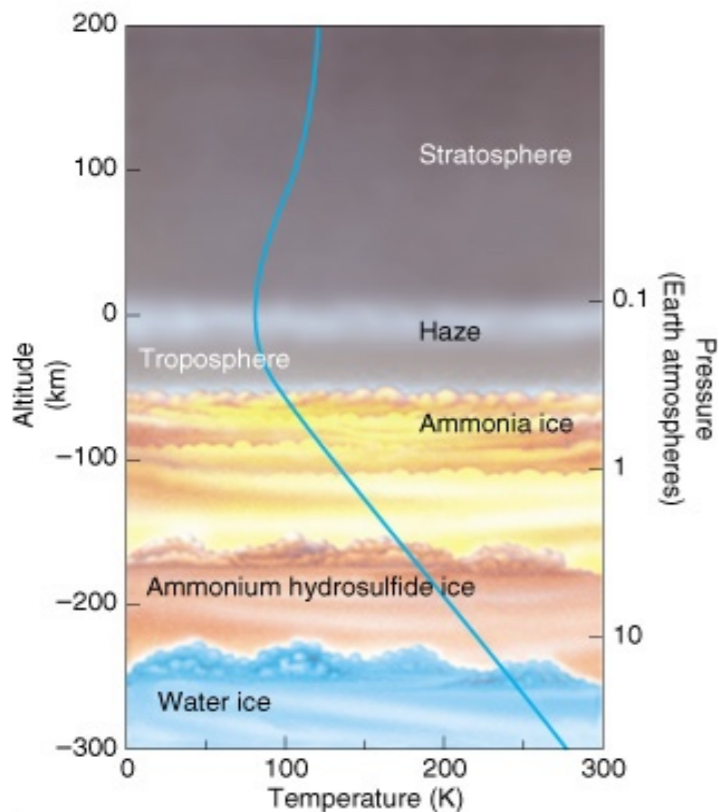
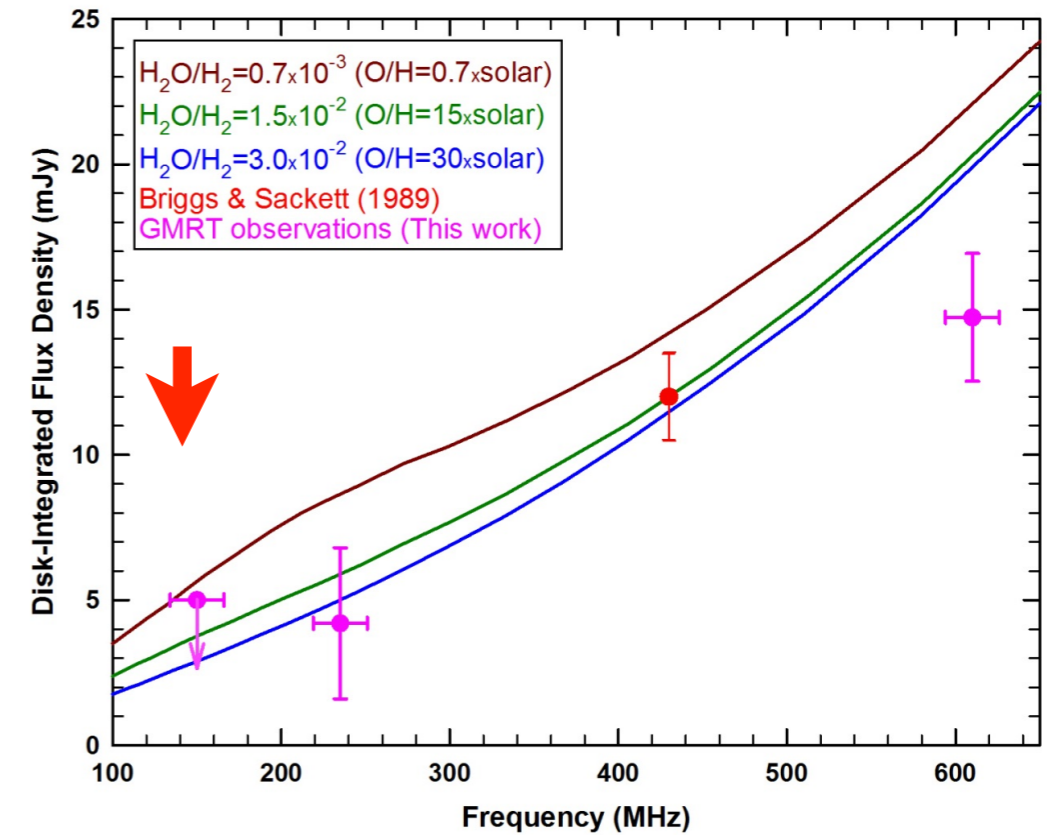
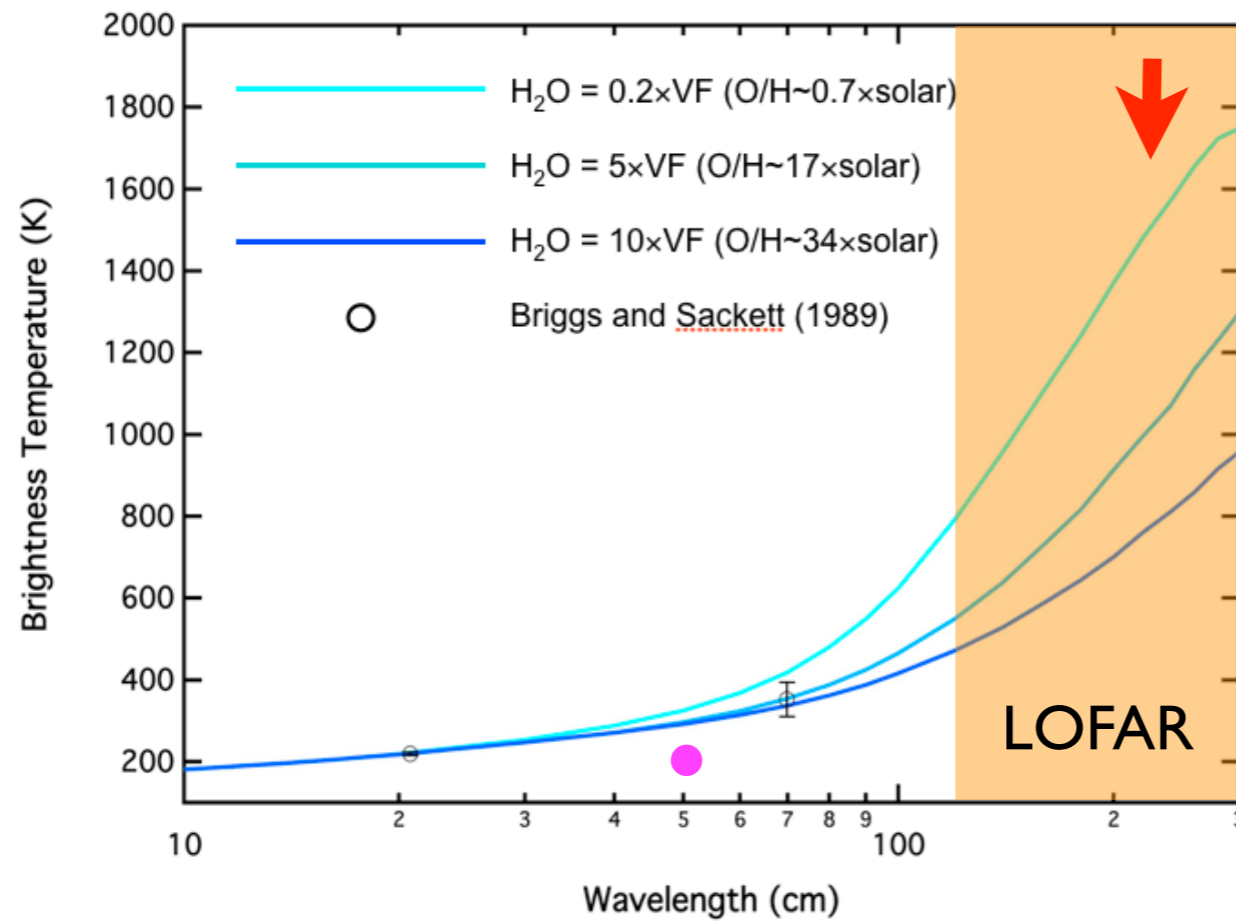
Structure fine temporelle & spectre

→ énergie des flashes comparée au cas Terrestre

Venus ? Mars ? Jupiter ? Titan ?

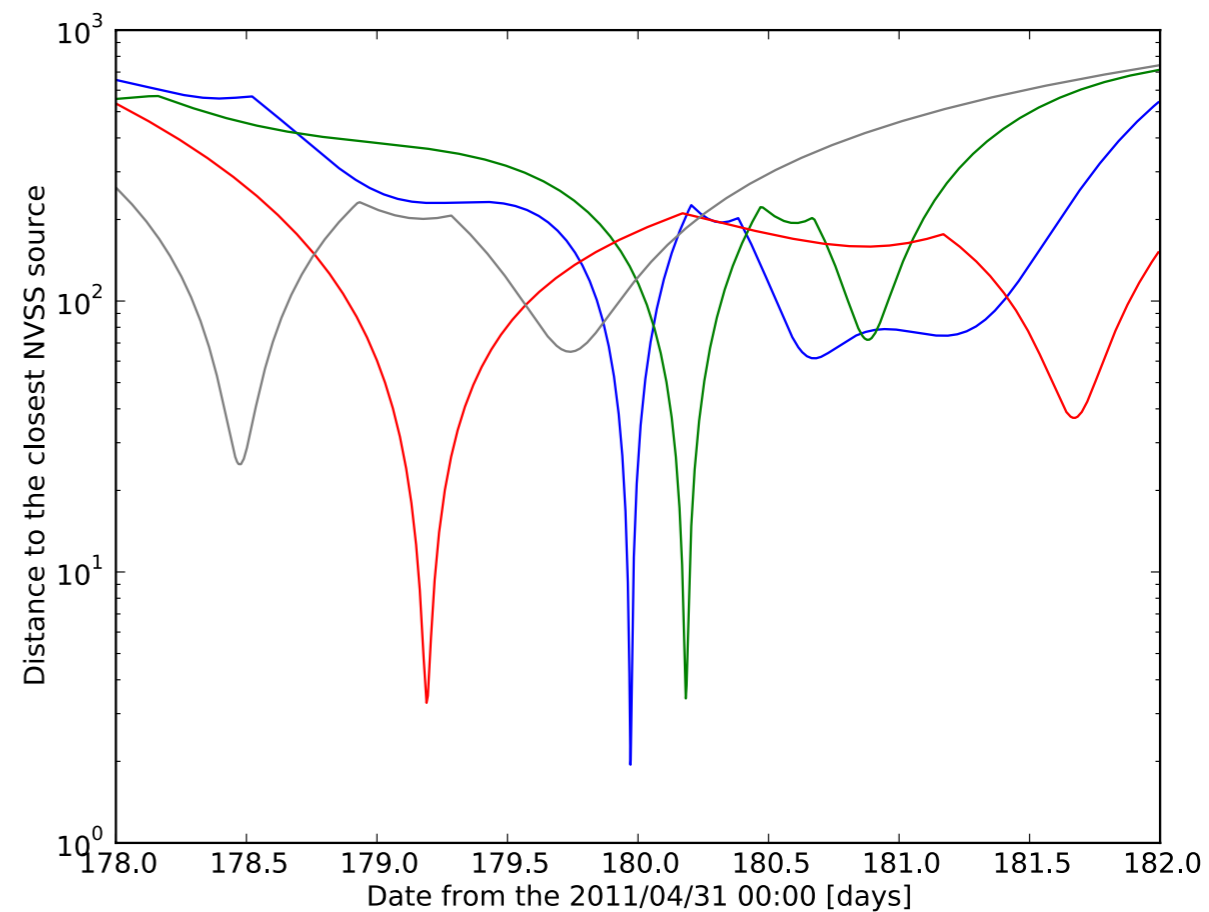
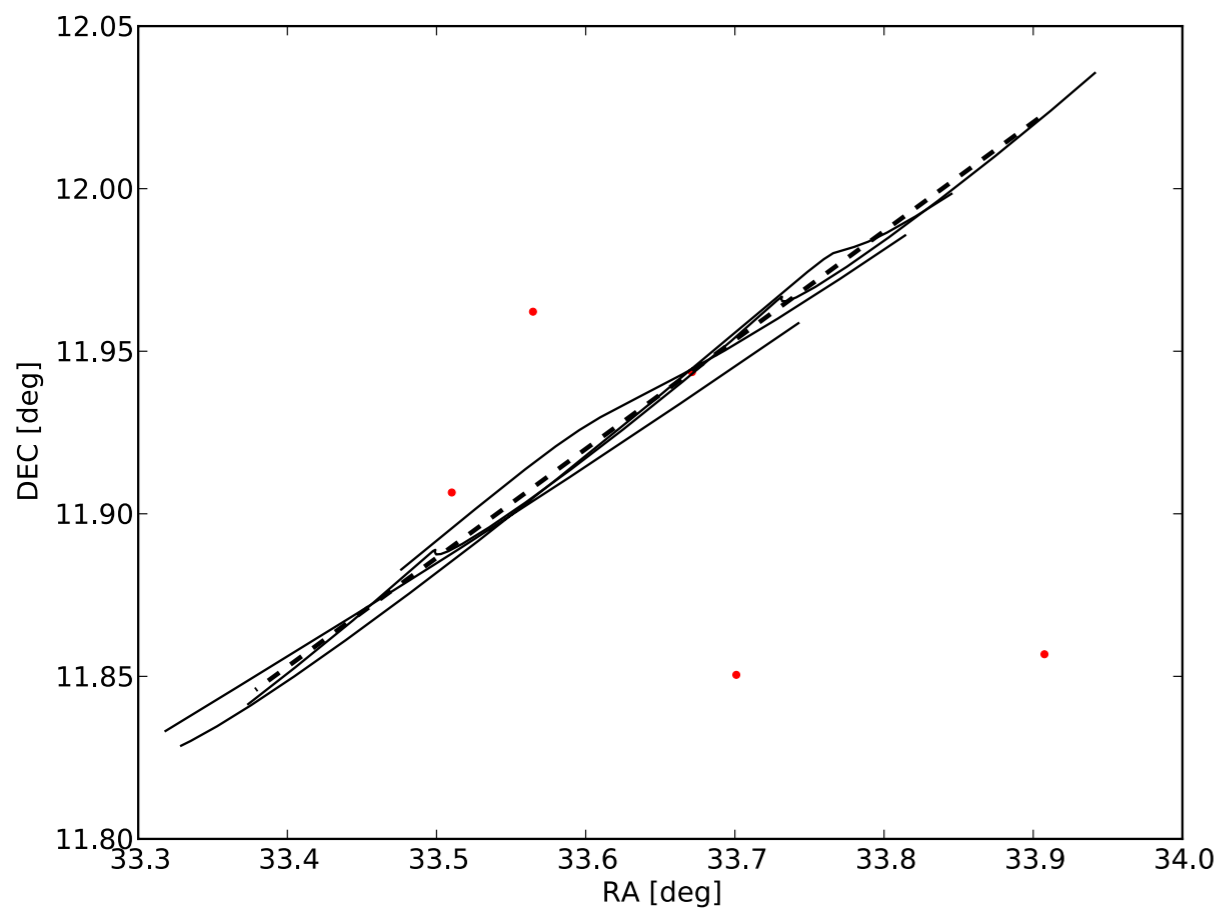


(4) autres : spectre thermique de l'atmosphère Saturne

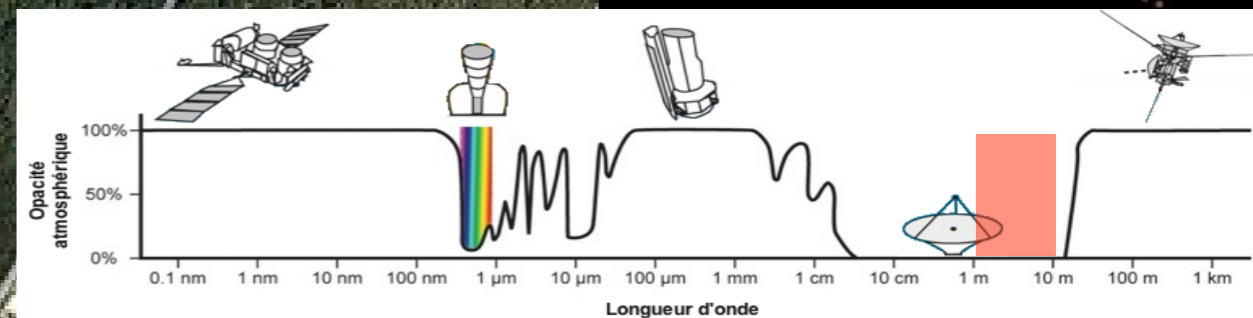


- Sondage profond (quelques kbar)
- Spectre thermique fonction de la concentration profonde d'H₂O
- Applicable seulement à Saturne (J trop "bruyant", U & N trop loin)

(4) autres : occultation de radiosources par les petits corps (du système solaire)

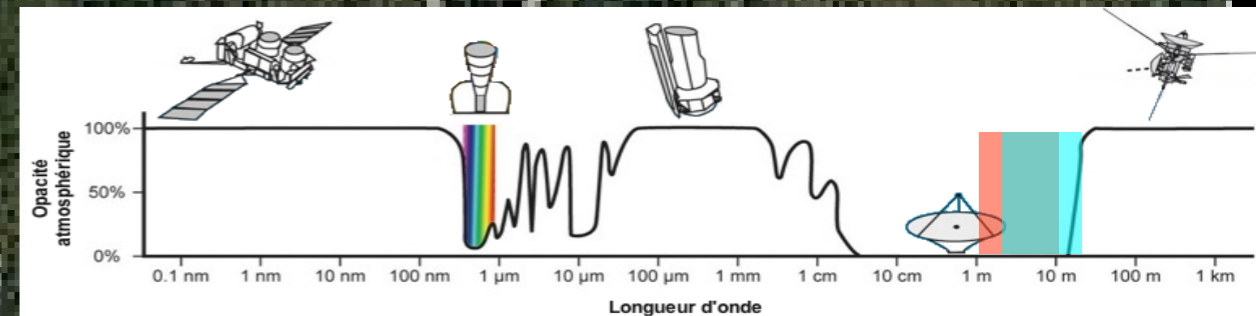
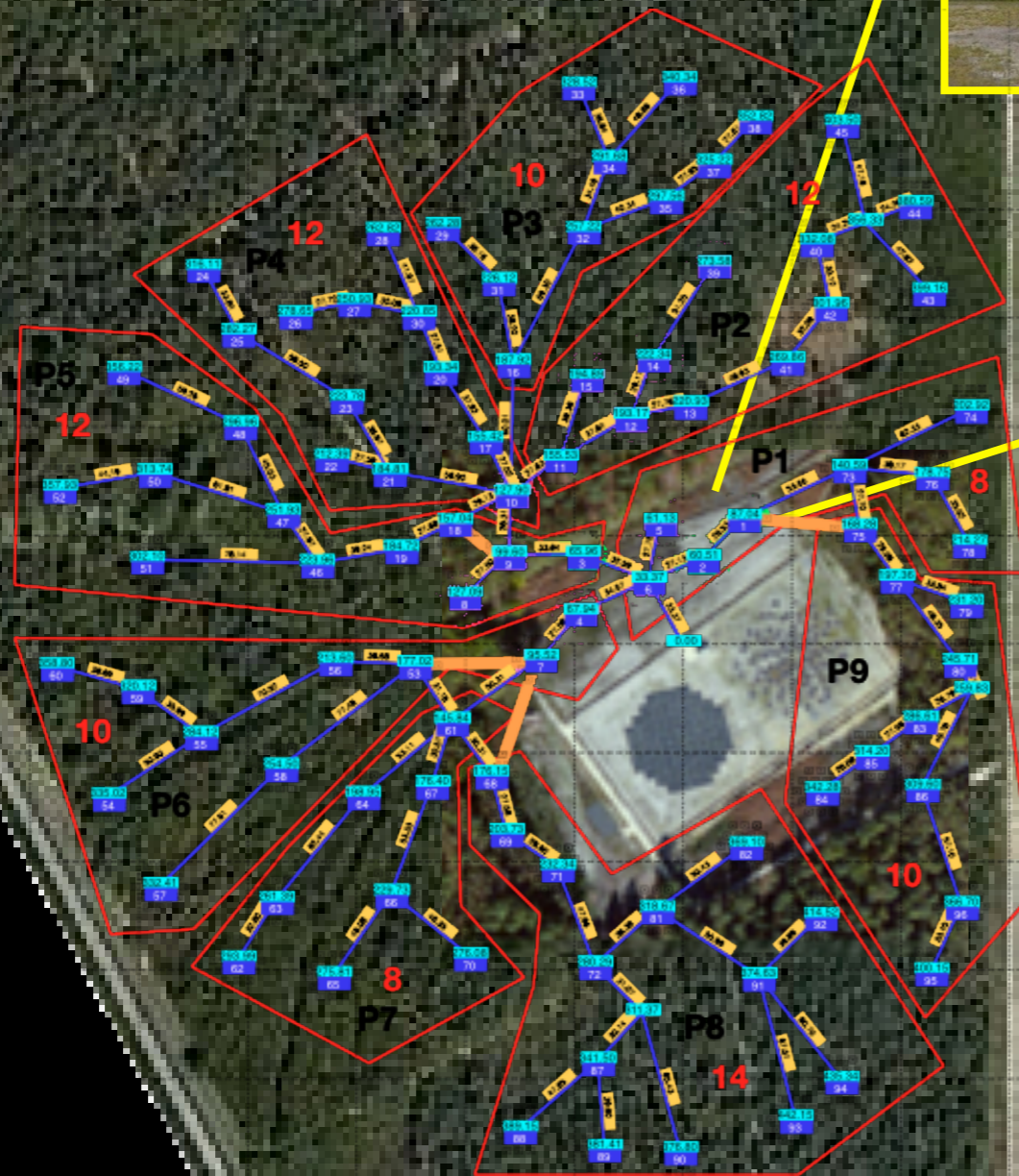


De LOFAR FR 606 à ...



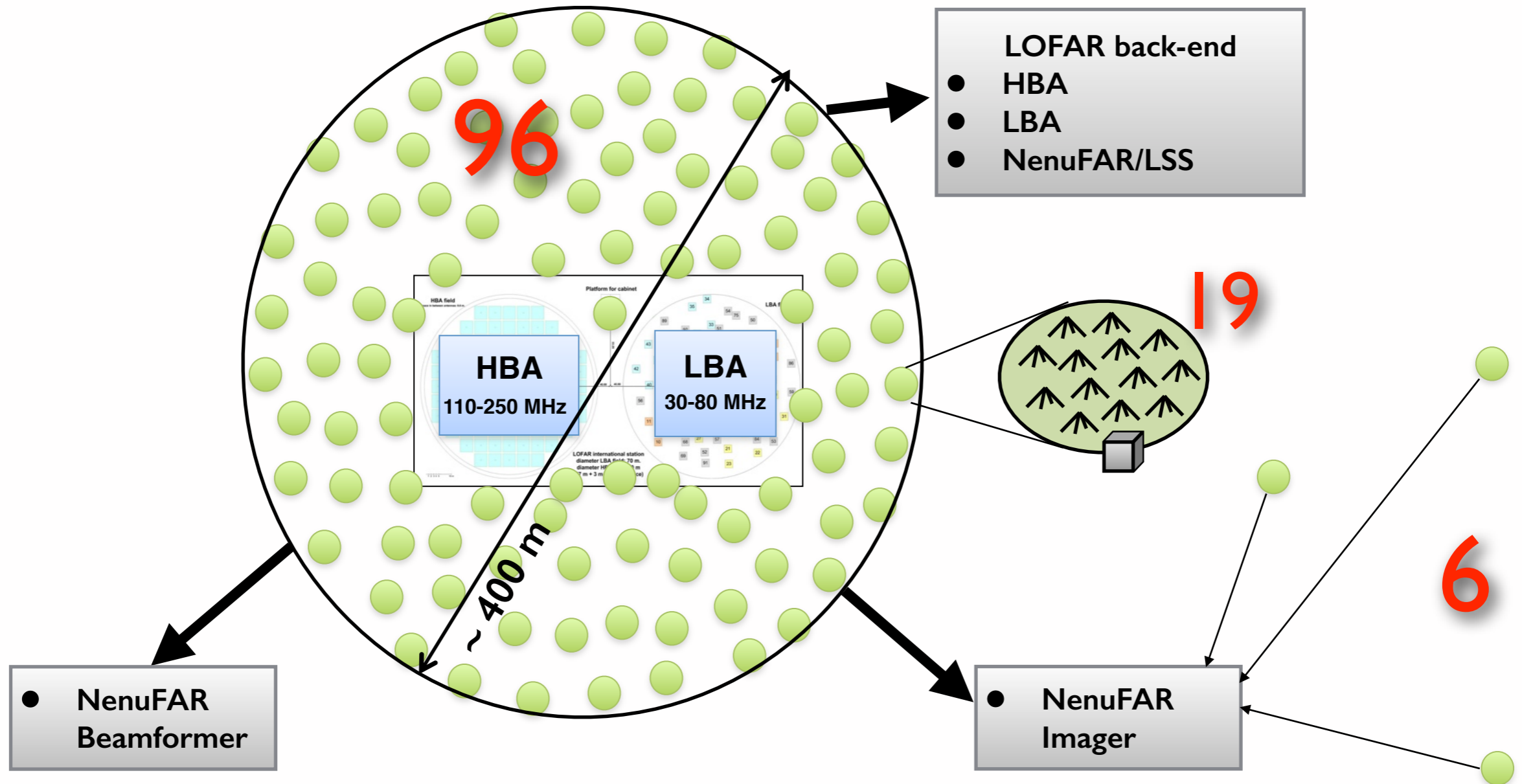
... NenuFAR

New extension in Nançay upgrading LOFAR



de Gauron

Le concept de NenuFAR

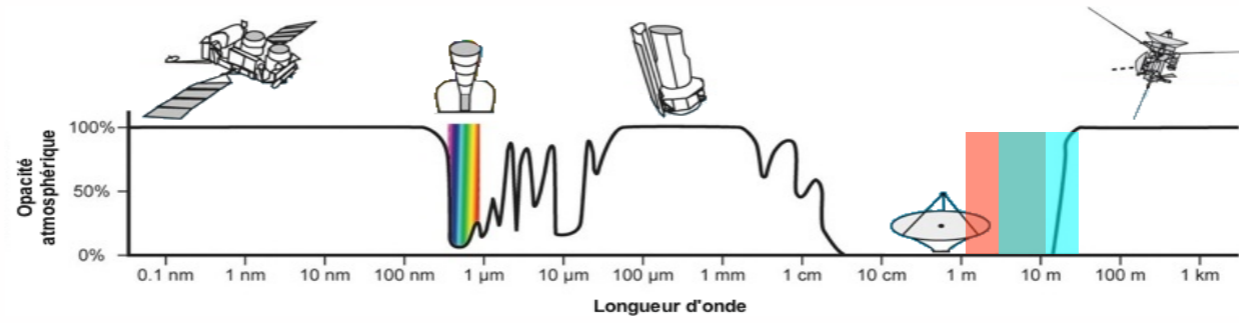


Beamformer, Imageur, Station géante LOFAR (Pulsar machine, SETI machine)

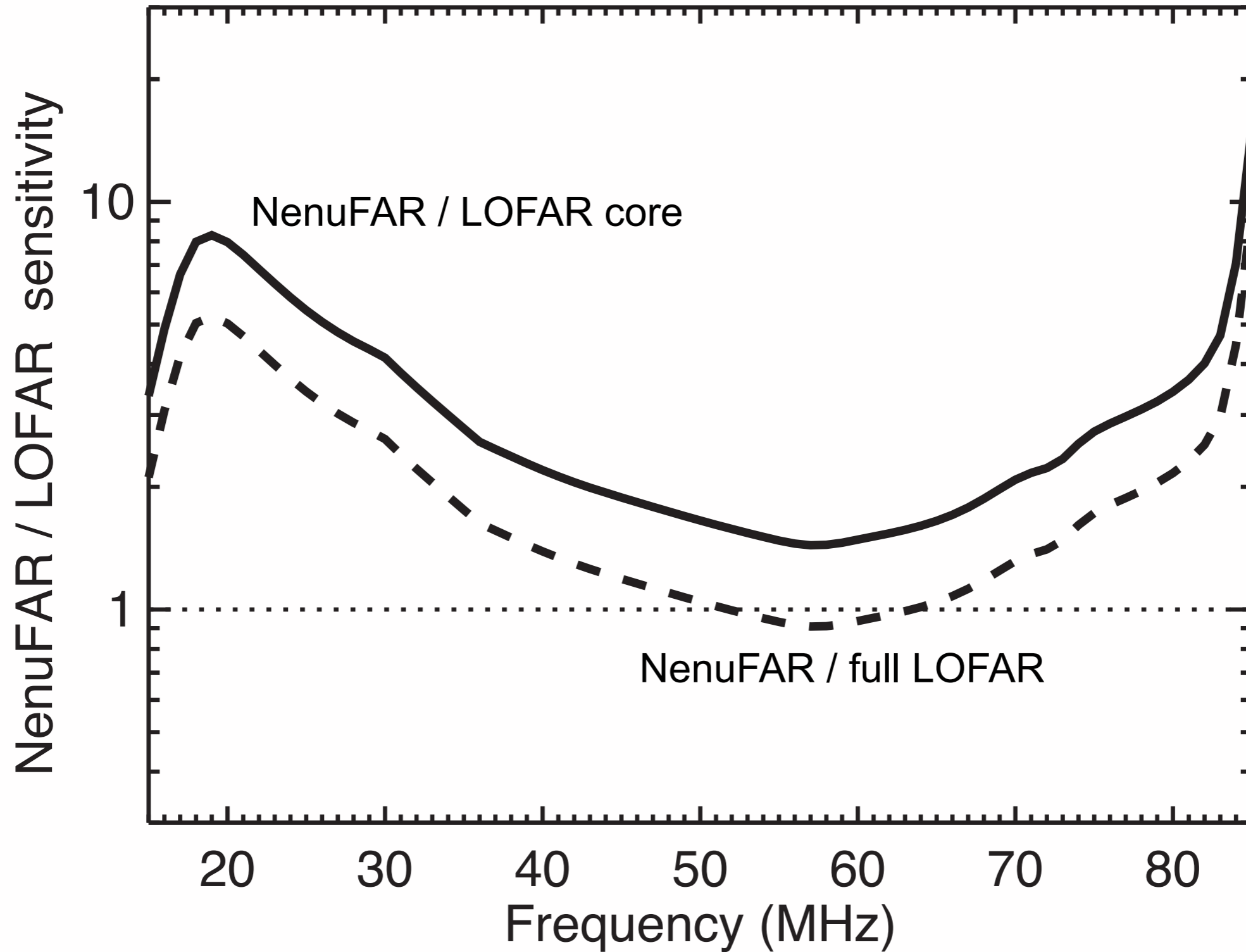
(96+6) Mini-Réseaux x 19 antennes = 1938 antennes++
(> LOFAR), Sensibilité 2-8 x LOFAR, 10-85 MHz,

NenuFAR

10-85 MHz



Sensibilités comparées



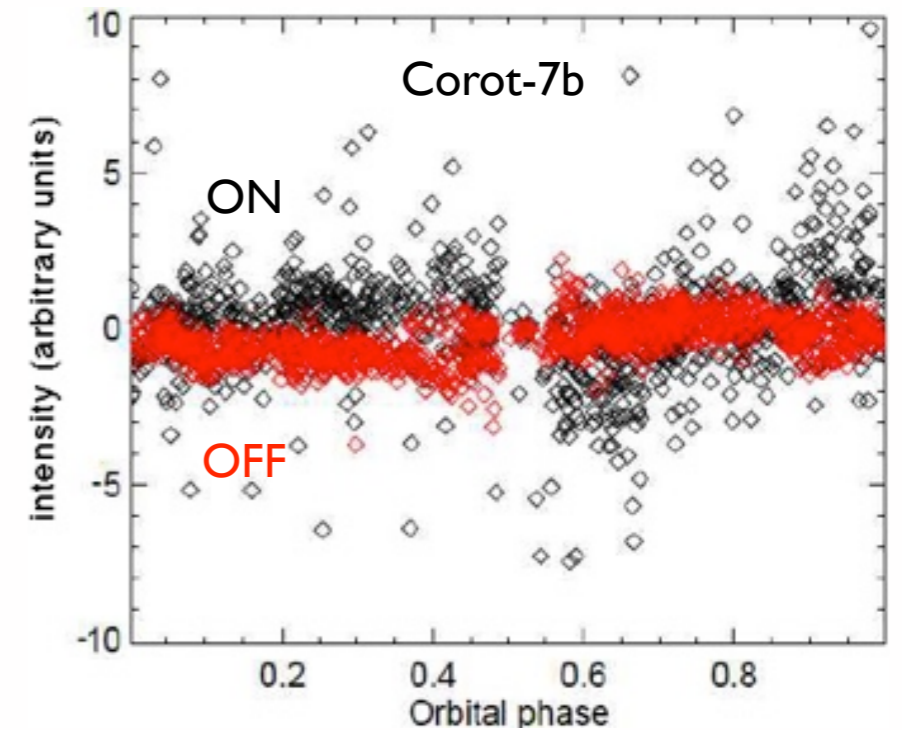
Apports de NenuFAR

- Super Station LOFAR (LSS)
 - ➔ Bases longues + sensibles → imagerie à haute résolution (0.1")
 - ➔ Sensibilité globale x 2
 - ➔ 2^{ème} coeur
 - ➔ Bases courtes (NRI) → grandes structures ($>10^\circ$)
- Beamformer (réseau phasé) autonome
 - ➔ Sensibilité $\geq 1.6x$ LOFAR core ($\geq 5x$ au-dessous de 30 MHz), 8x LWA
 - ➔ Δf instantanée = 150 MHz, multi-beams (768 beamlets de 200-kHz)
 - ➔ Polarization complète
 - ➔ Grand champ de vue (10's $^\circ$)
 - ➔ Grands programmes avec duty-cycle élevé
- Imageur (interféromètre) autonome
 - ➔ Mode rapide (coeur, 1 sec) → $(40/f)^\circ \sim 1^\circ$
 - ➔ Mode lent (NRI, 6-8 h), multifréquences → $(340/f)' \sim 8'$

➔ Les 3 en //

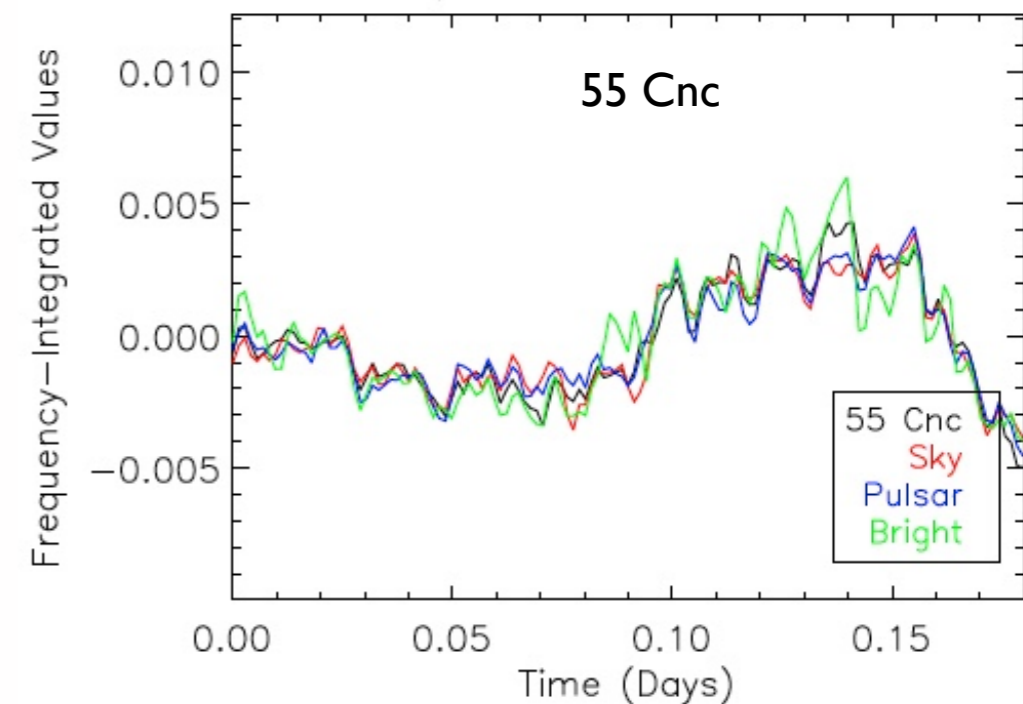
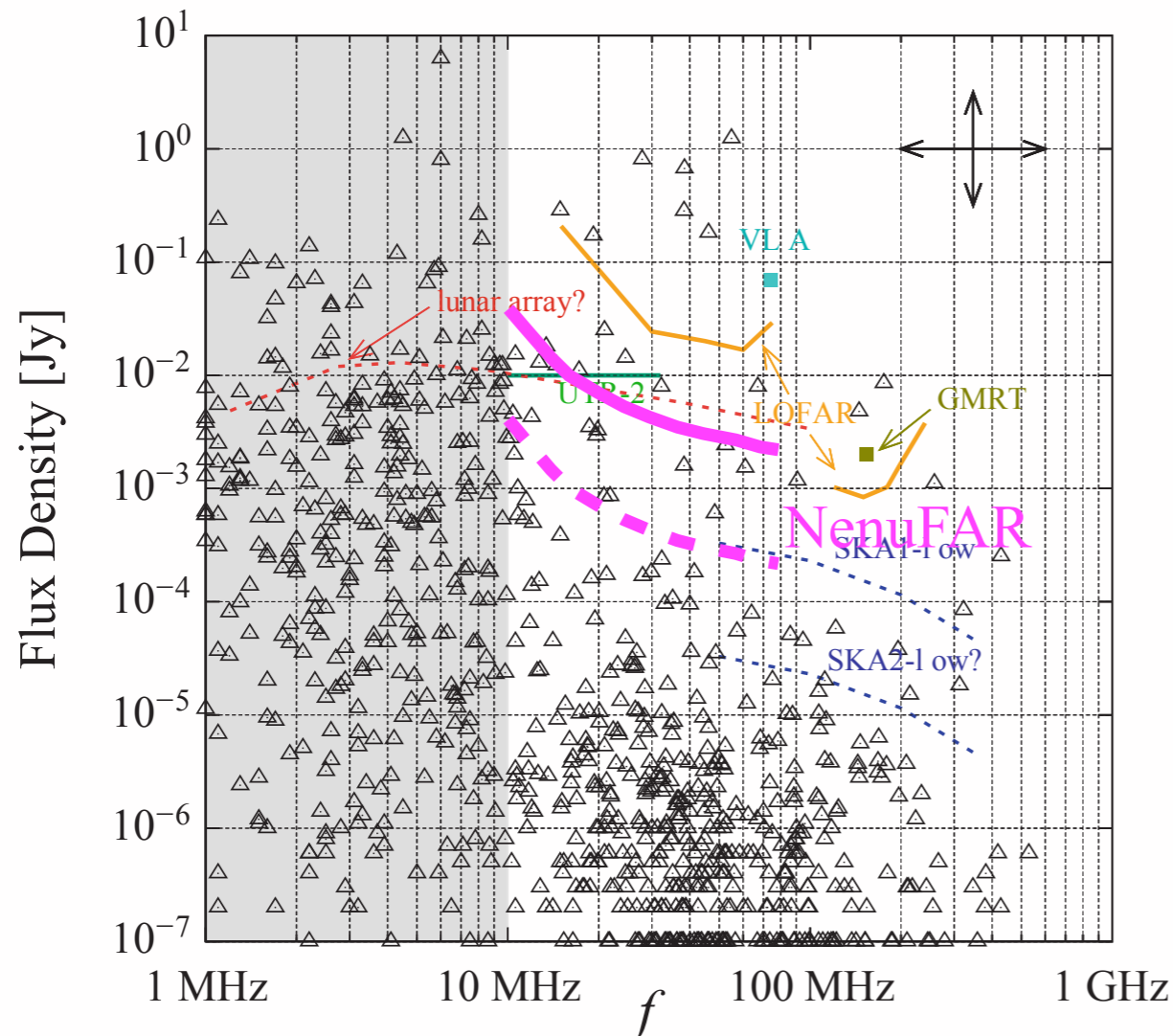
The Science of NenuFAR

- *Standalone Slow & Fast Imaging* : Planets, Star-Planet plasma Interactions



[Vasylieva et al., 2016]

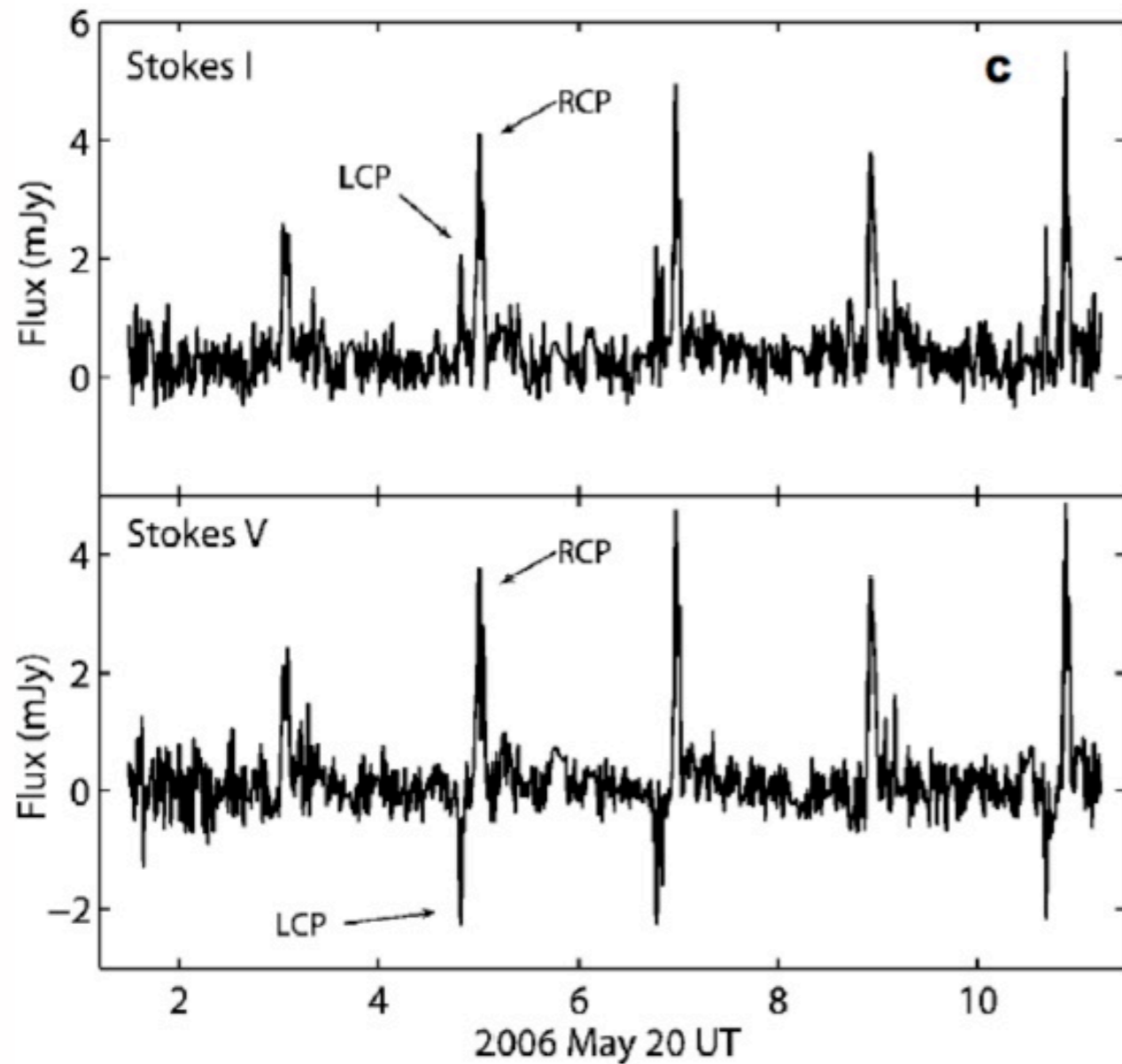
Q1: 26–39MHz 0%



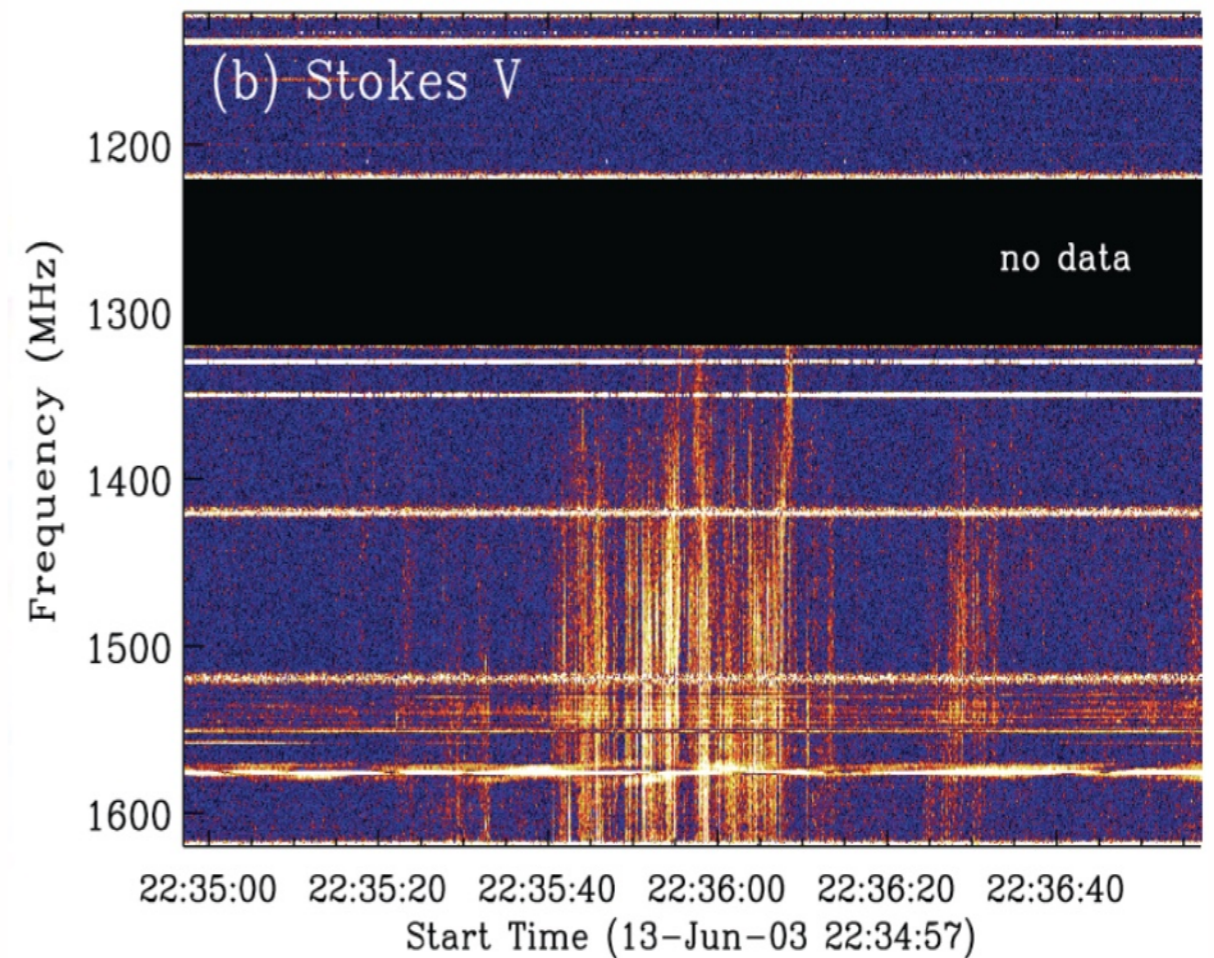
[Turner et al., 2017,2018]

The Science of NenuFAR

- *Standalone Slow & Fast Imaging : Stars (Flaring/Dwarf/Cool)*



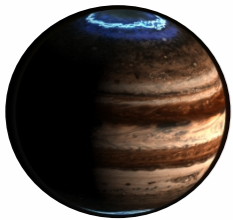
[Hallinan et al., 2007, 2008, 2015]



[Osten et al., 2006, 2008]

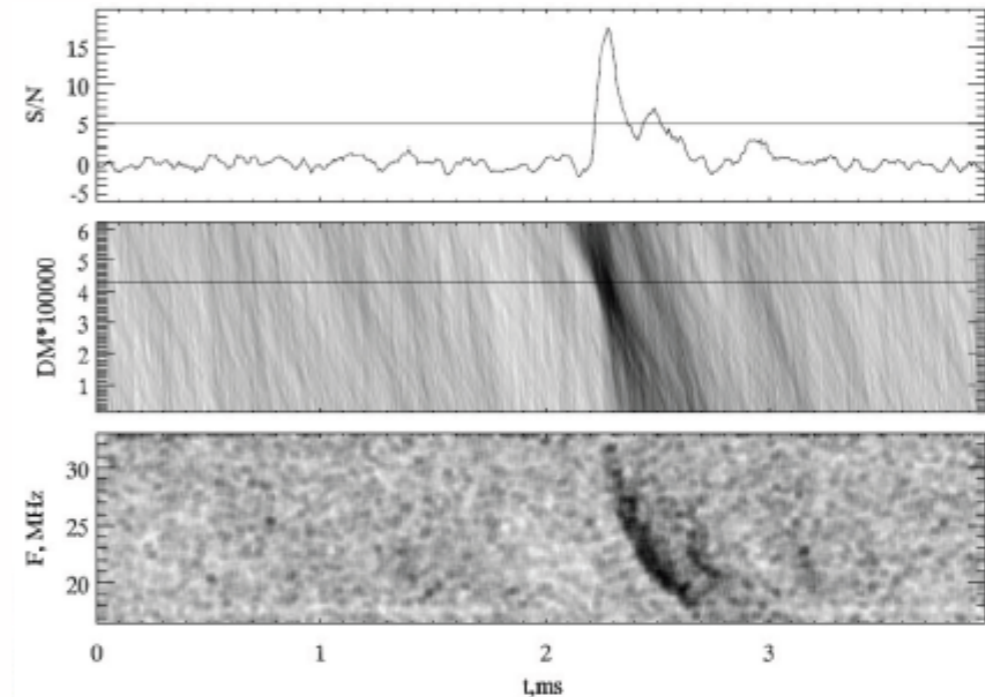
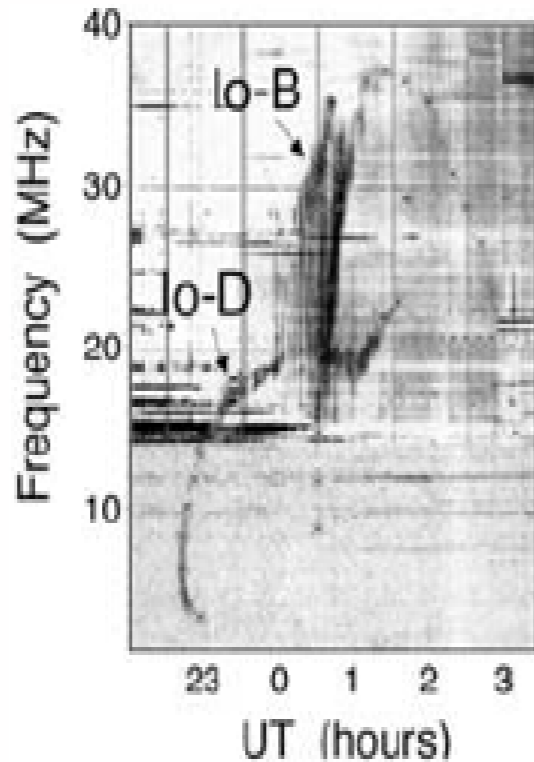
The Science of NenuFAR

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

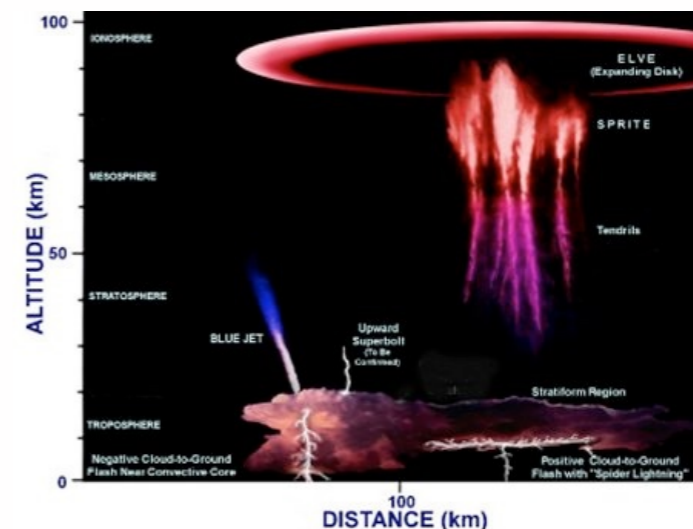
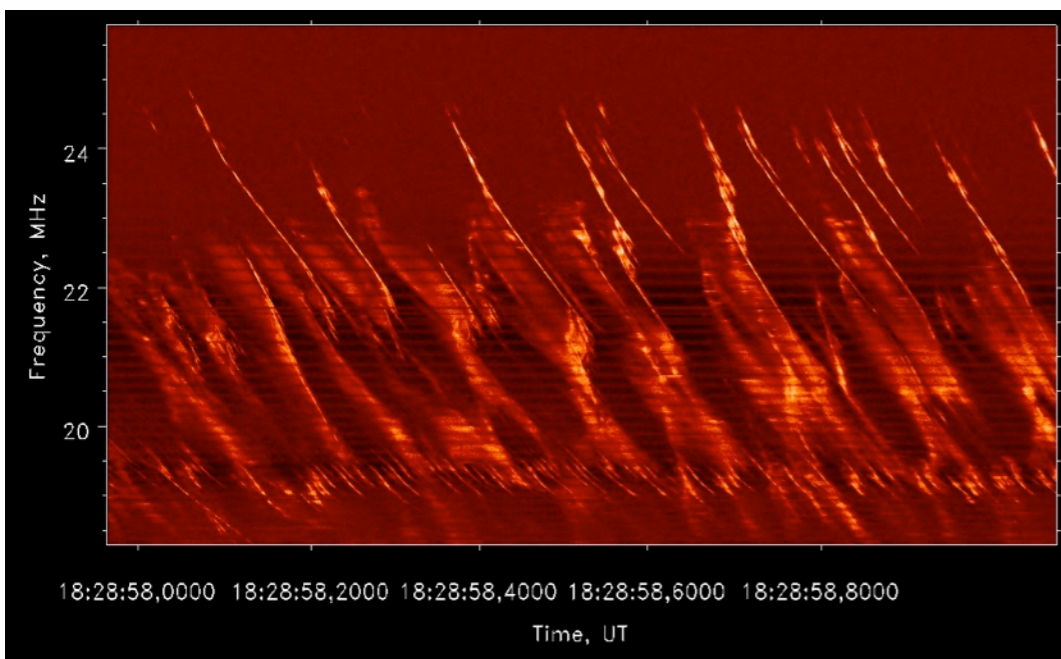


Jupiter

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

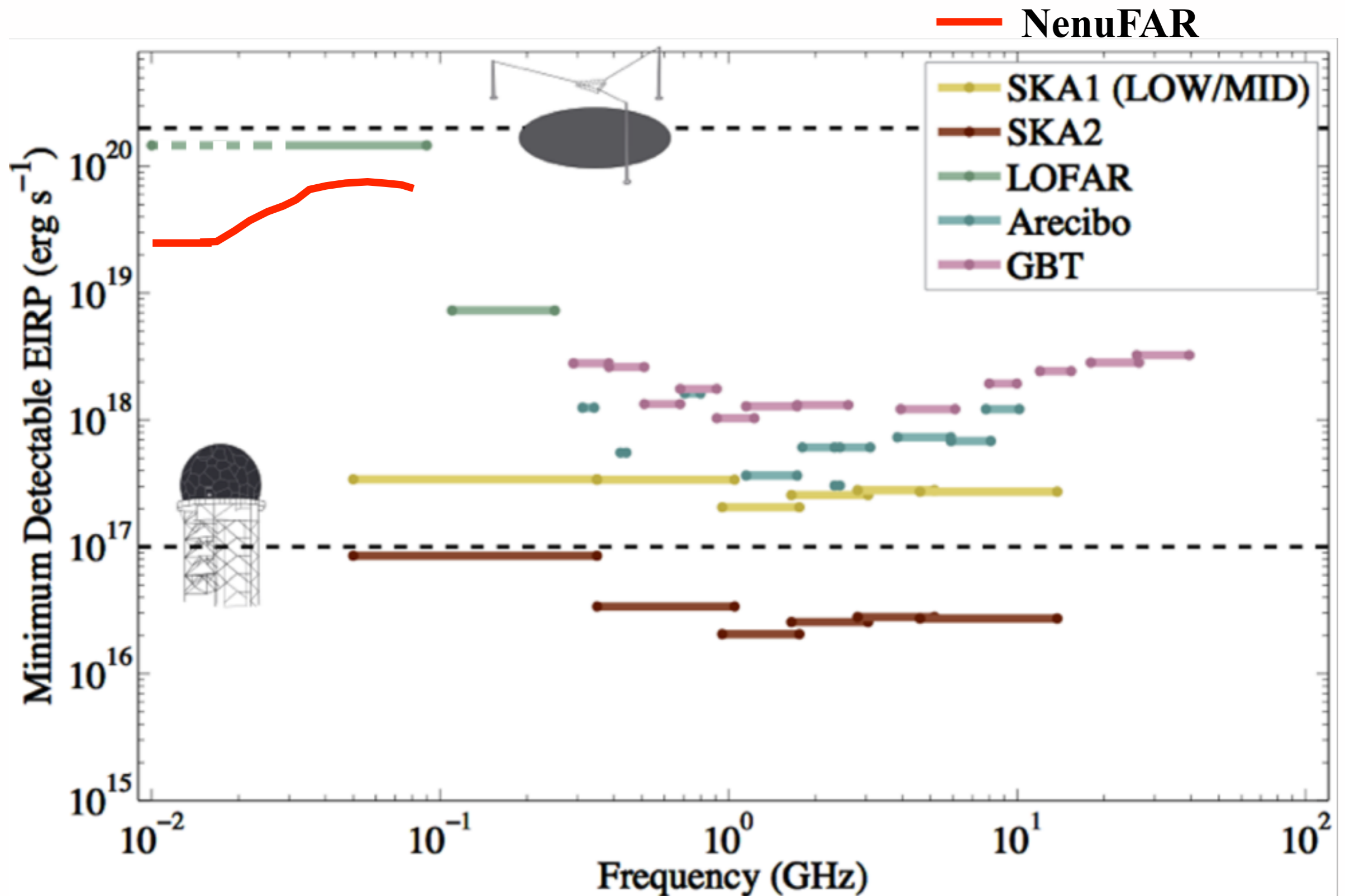


Saturn lightning: finest dispersion delay measured: $DM \sim 3 \times 10^{-5} \text{ pc.cm}^{-3}$
→ Solar Wind probing up to 10 AU [Zakharenko, et al., 2012]

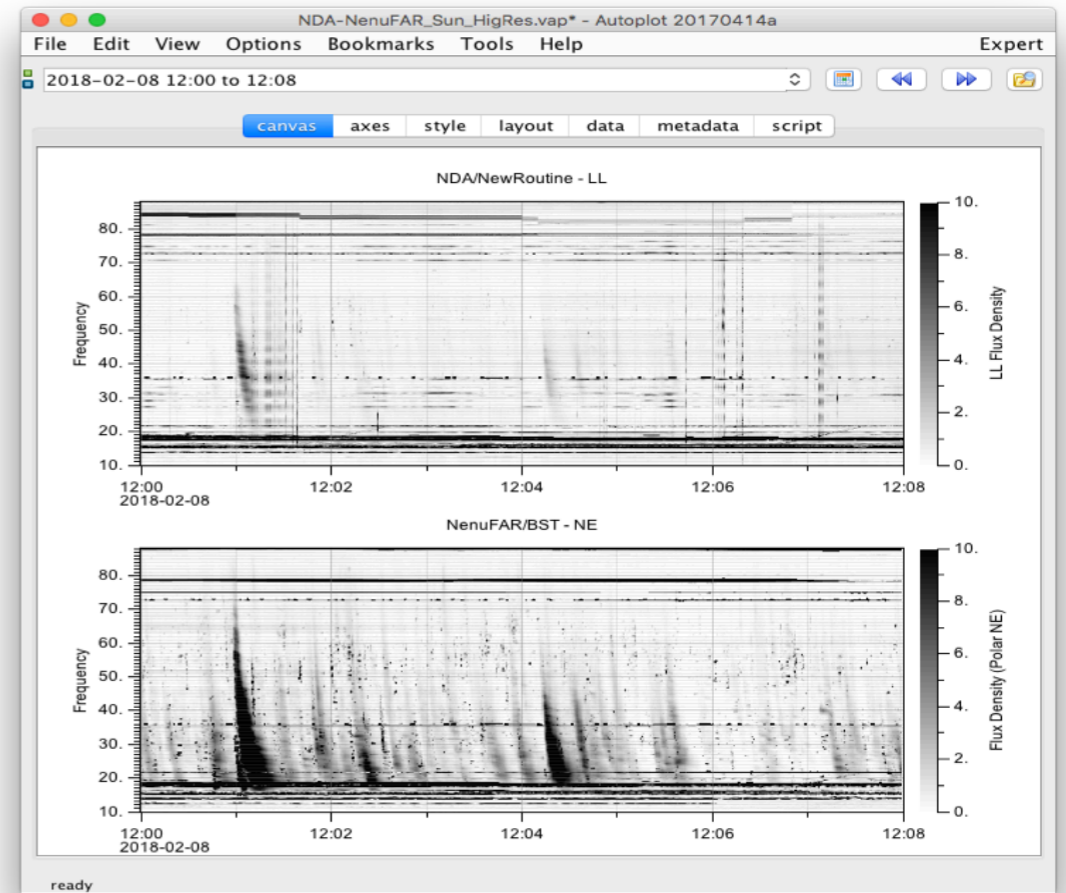
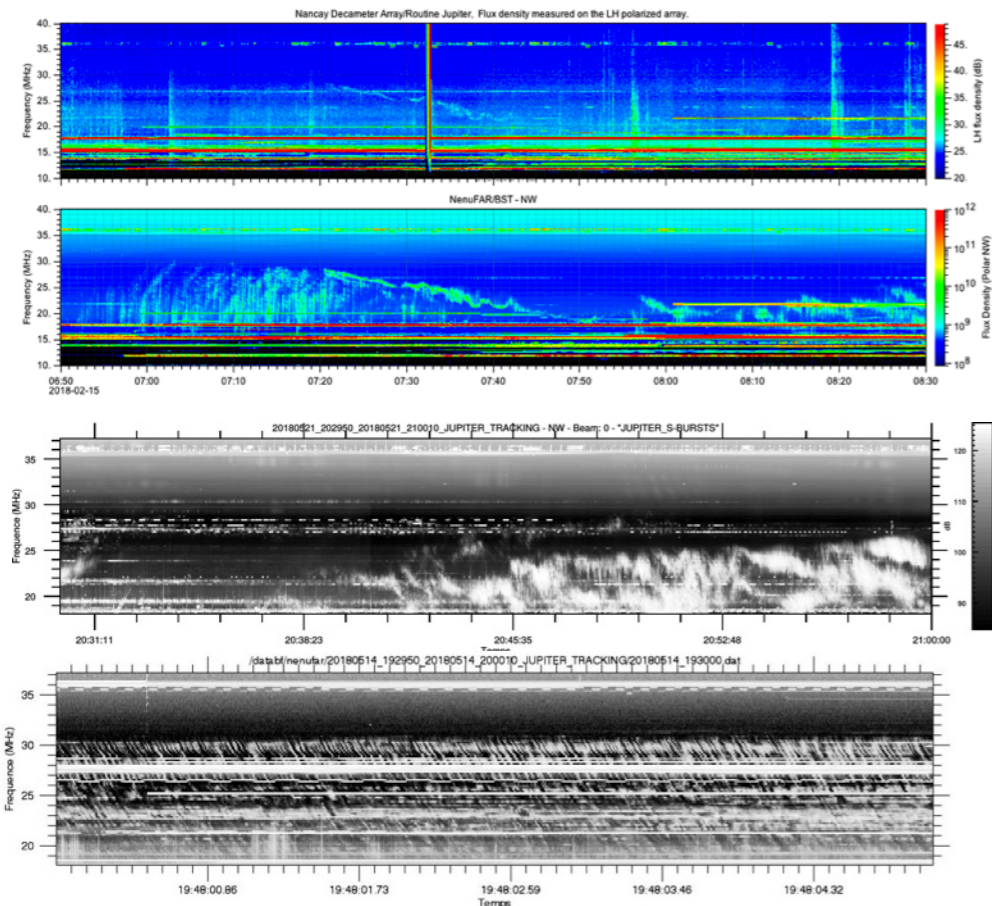
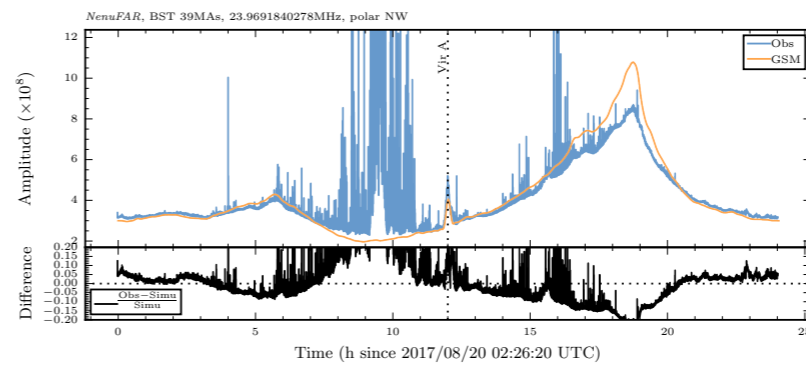
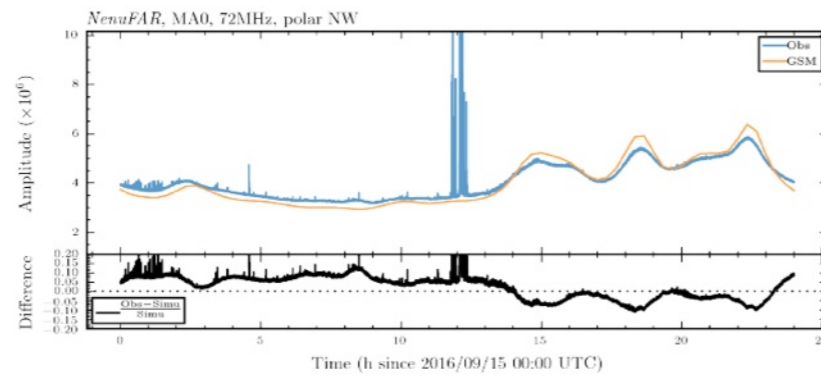
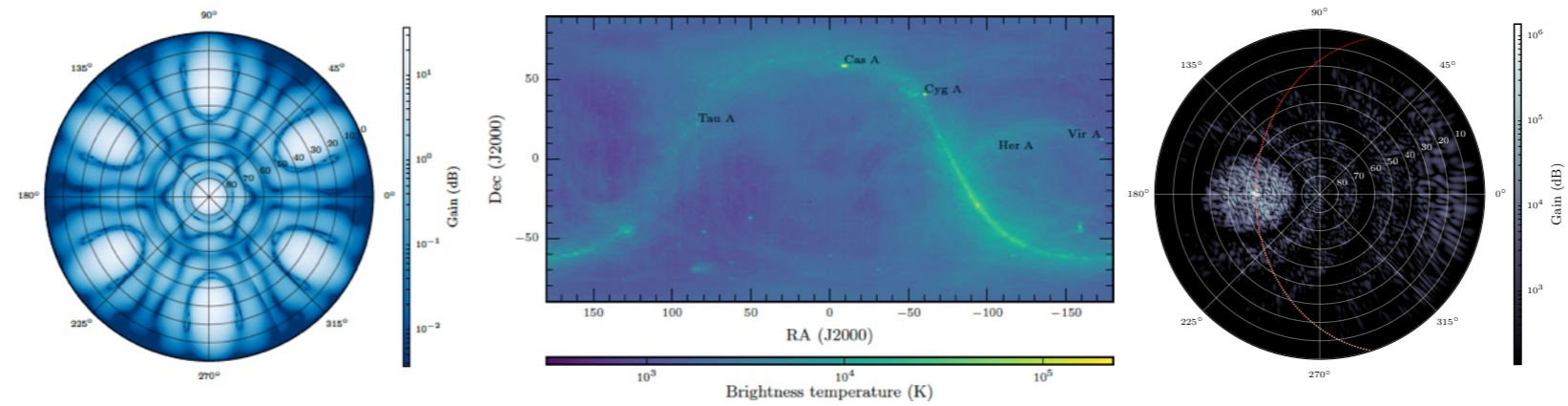


The Science of NenuFAR

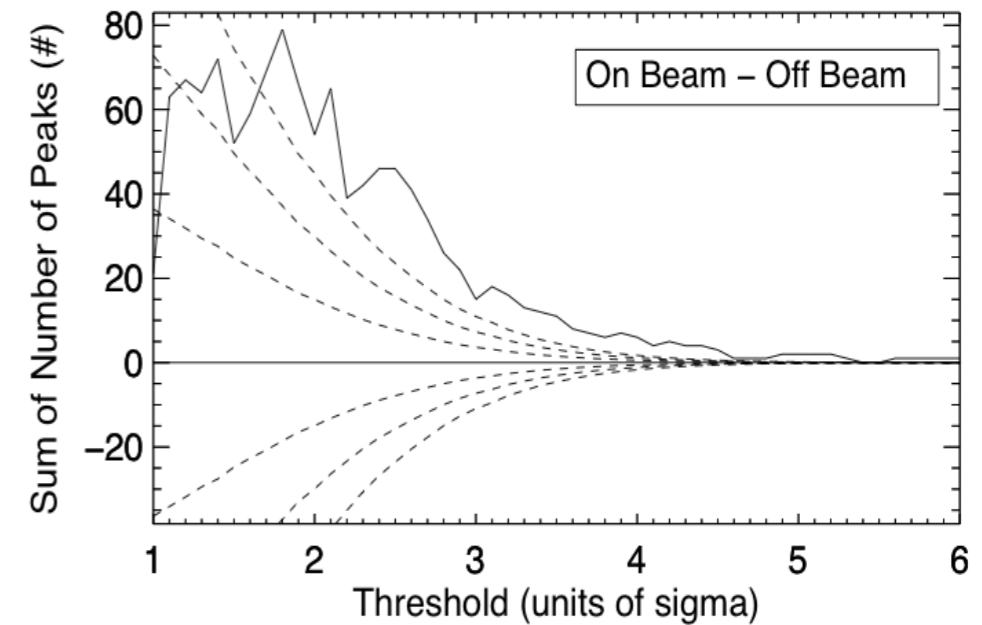
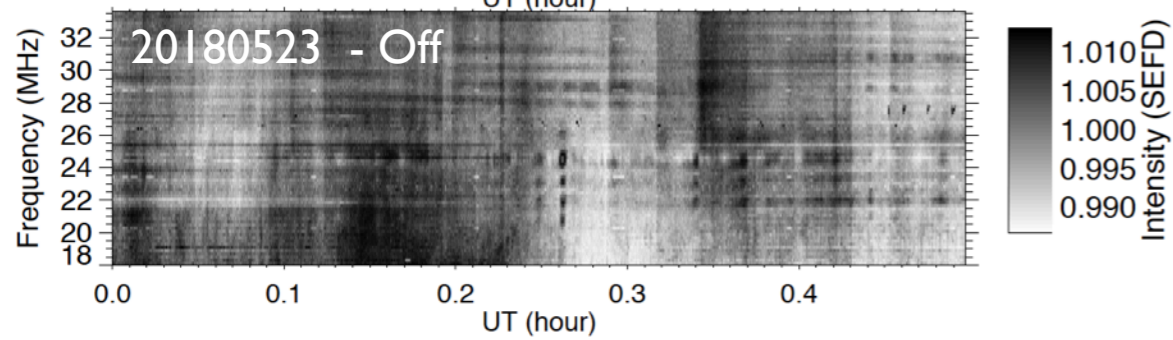
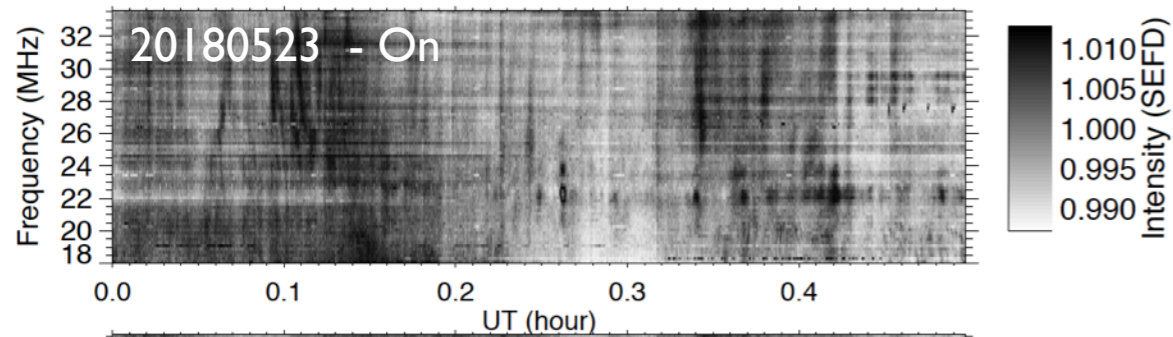
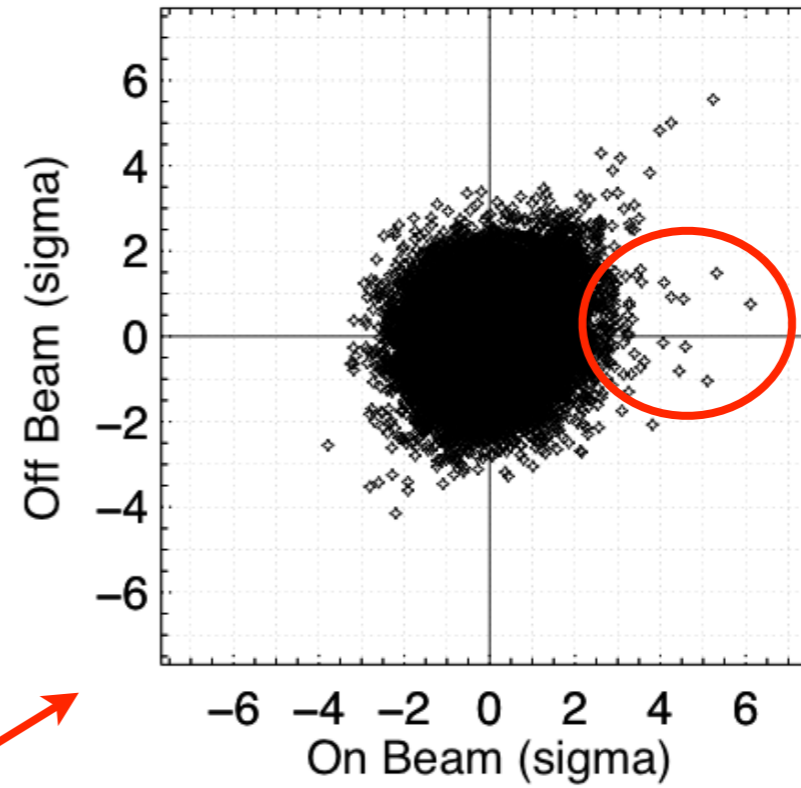
- *Standalone Beamforming* : SETI searches (in piggyback)



Commissioning (Recette, en cours)



Commissioning (Recette, en cours)



Le Futur ...

SKA-Low (Australie)



SKA-Mid (Afrique du Sud)



LOFAR sur la Lune



Quelques liens

- <http://www.lesia.obspm.fr/perso/philippe-zarka/CoursPZ.html>
- <http://www.lofar.org/>
- <http://www.astron.nl/radio-observatory/astronomers/lofar-astronomers>
- <http://www.transientskp.org/>
- <http://www.transientskp.org/science/planets/>
- <https://www.obs-nancay.fr/lofar/>
- <https://nenufar.obs-nancay.fr>
- <http://www.skatelescope.org/>

Un conseil

UE I2 !