



Les nouveaux radiotélescopes

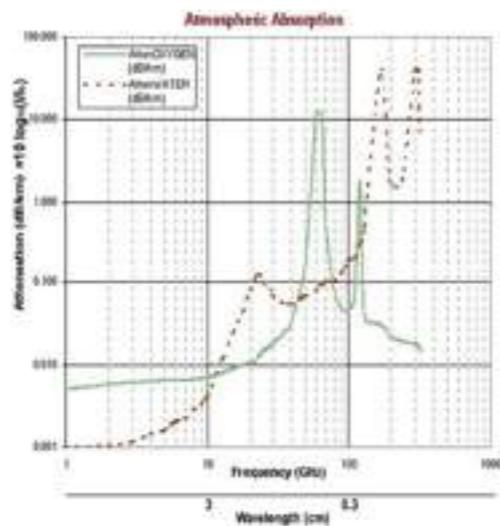
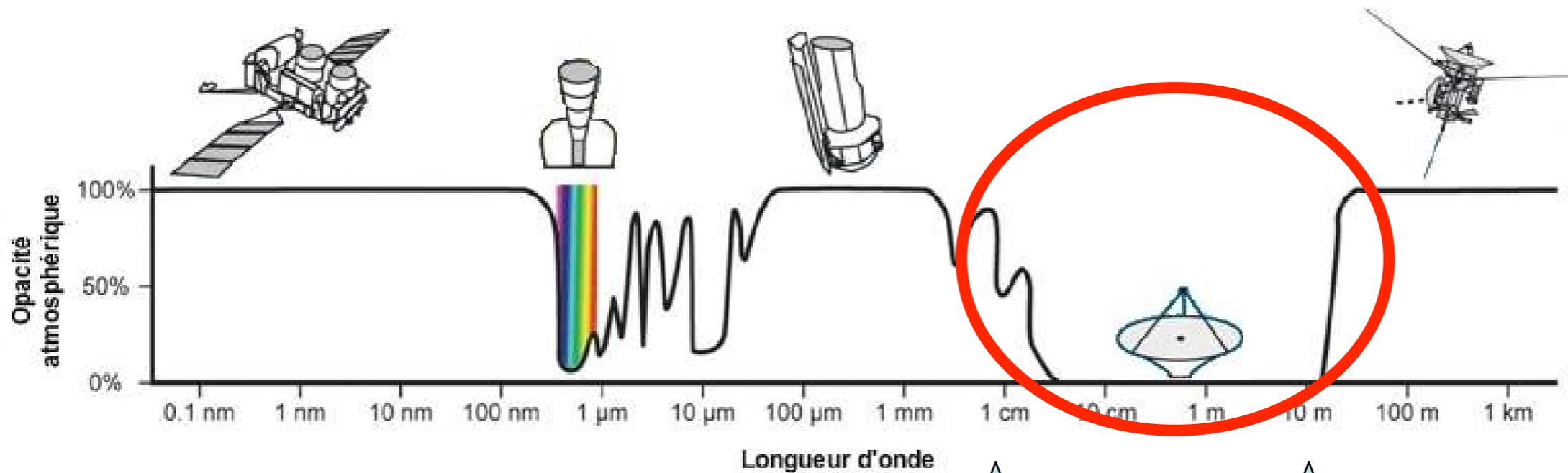
Philippe Zarka

LESIA, CNRS - Observatoire de Paris - PSL

Séminaire au Collège de France - 17/1/2022

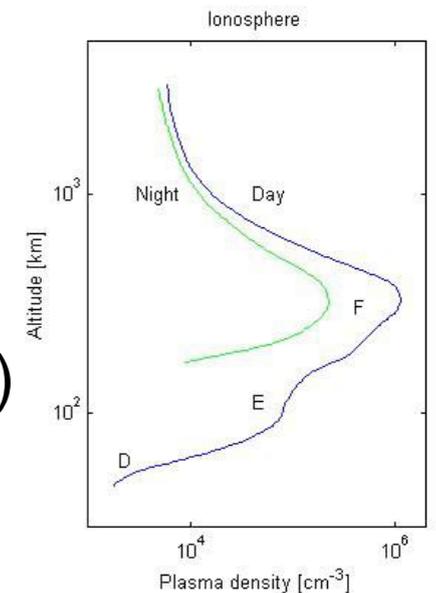
Domaine de la Radioastronomie

Transparence de l'atmosphère terrestre



↑
absorption
par O₂, H₂O ...
atmosphériques

↑
réflexion par
l'ionosphère
(z = 80 - 1000 km)

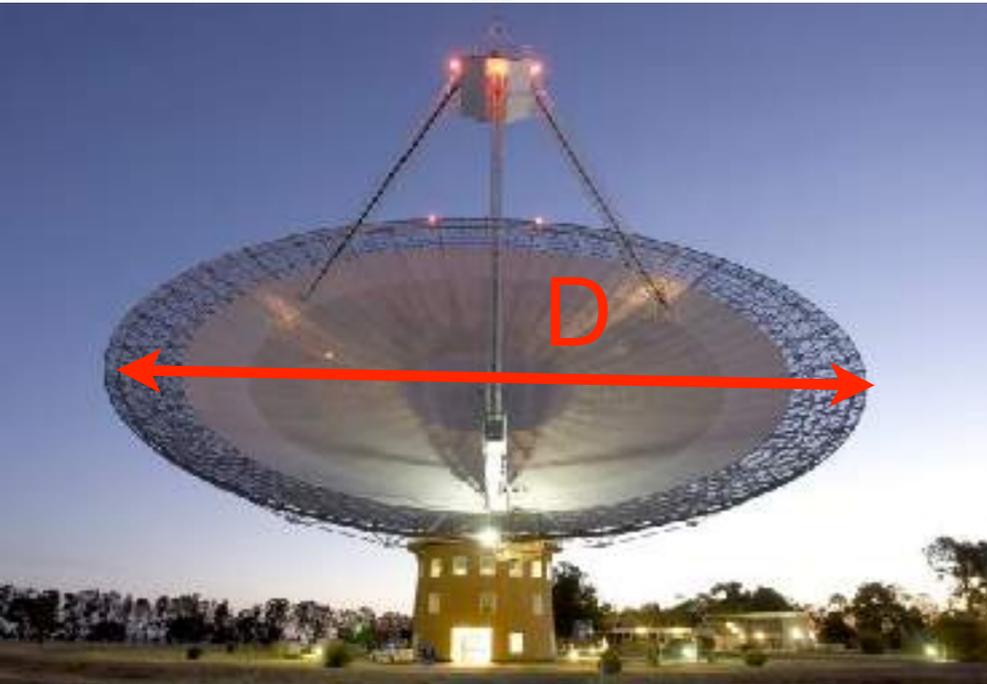
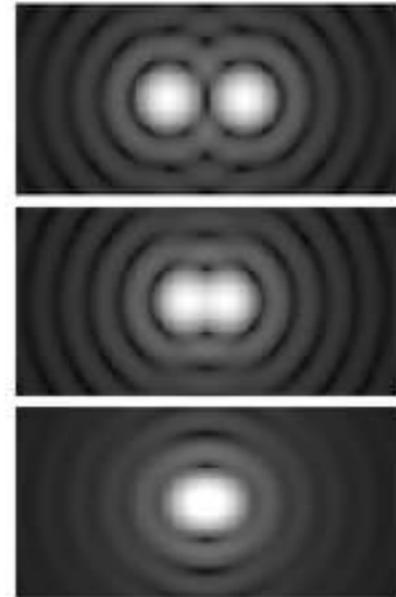
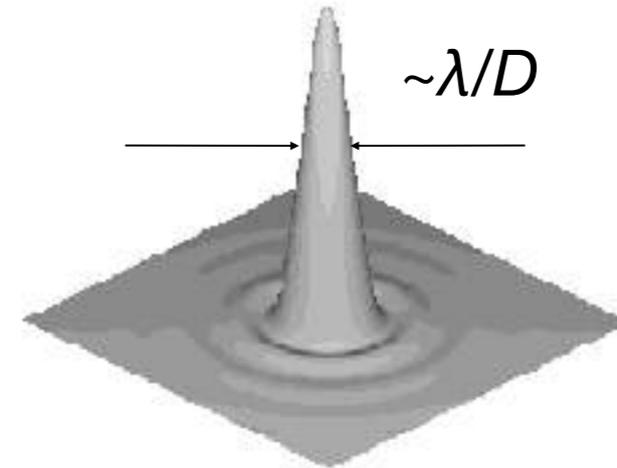
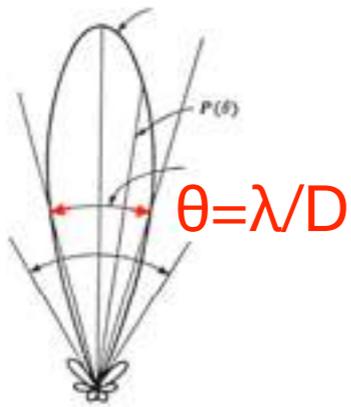


+ Détection cohérente ($|\mathbf{E}|$, φ)

Radiotélescope

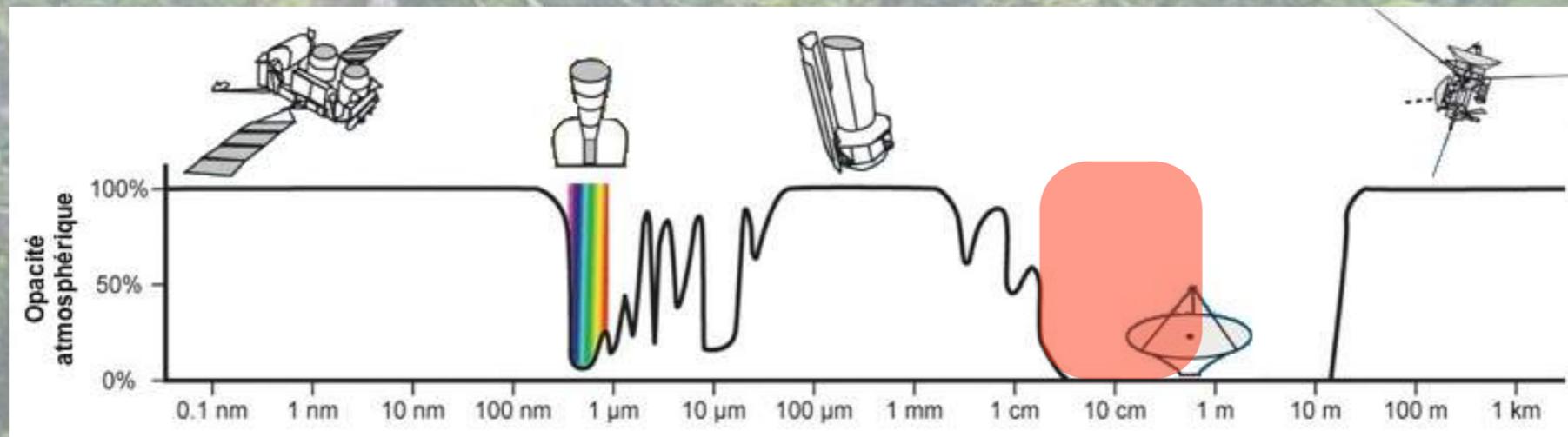
Sensibilité = surface collectrice

Résolution = diamètre



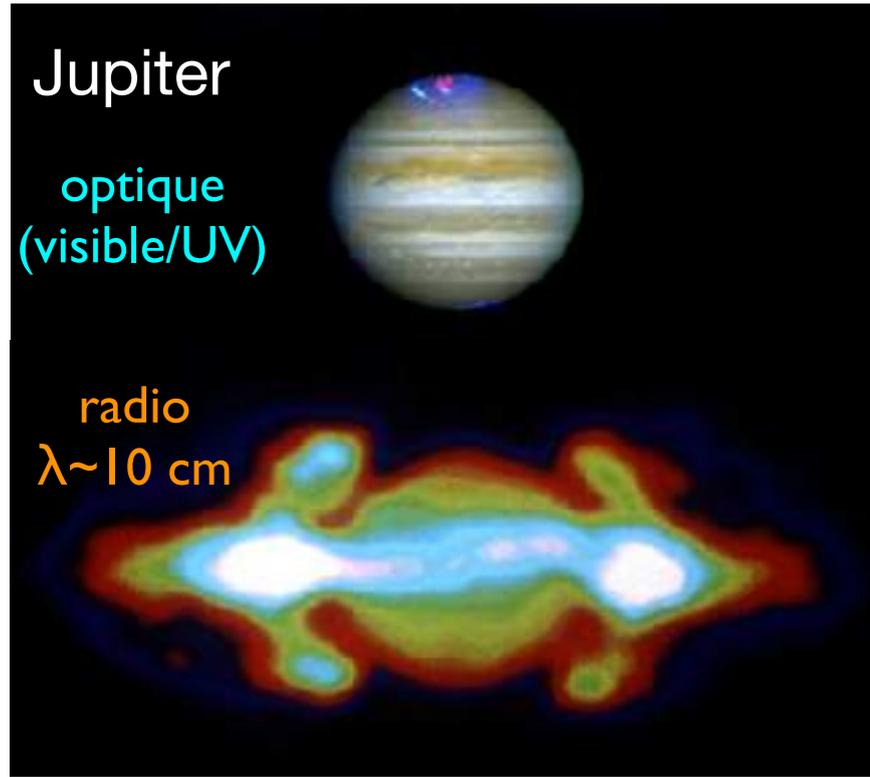
Radiotélescope

2^{ème} moitié du 20^{ème} siècle : âge d'or des grandes paraboles

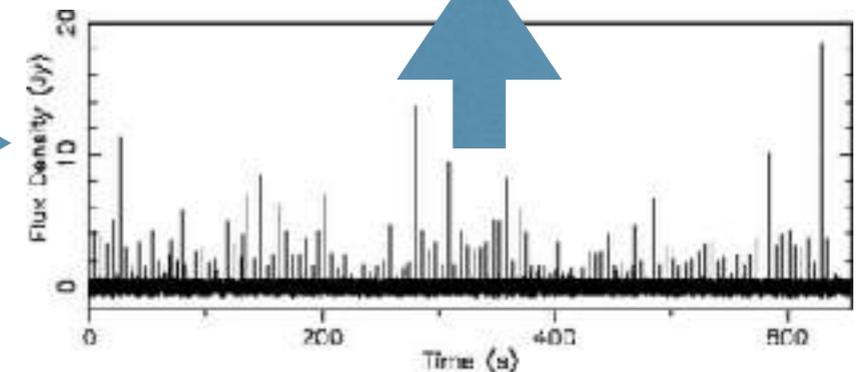
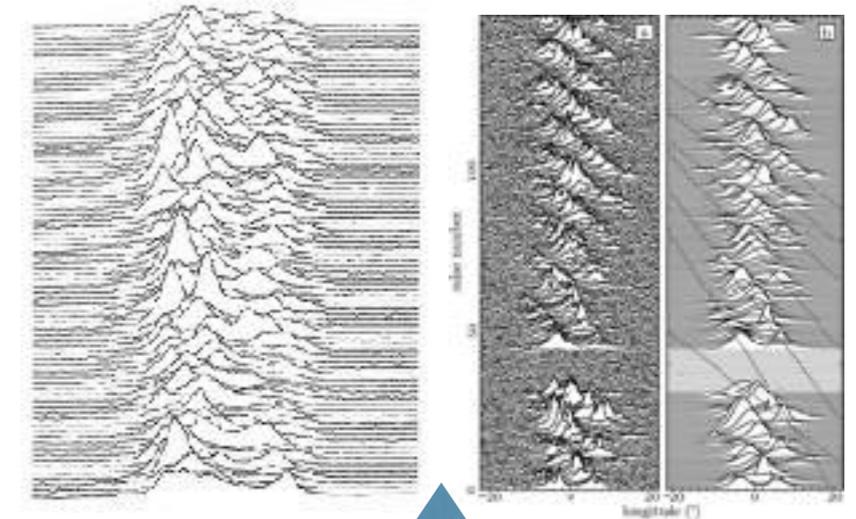
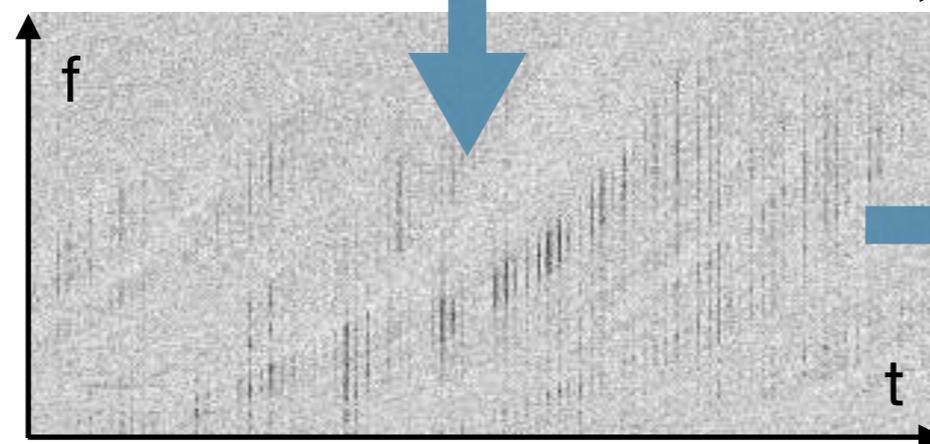
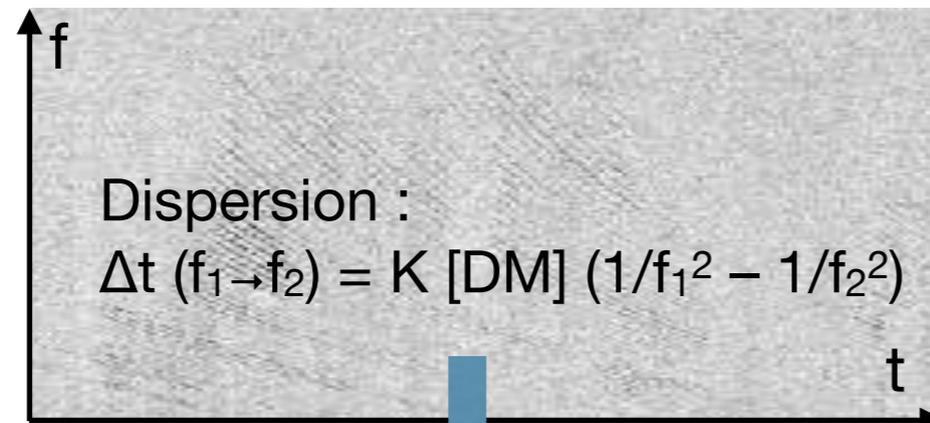
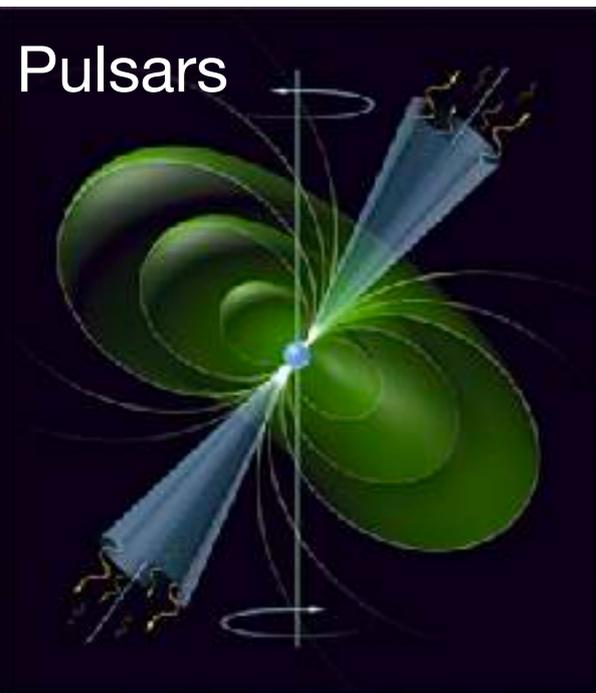
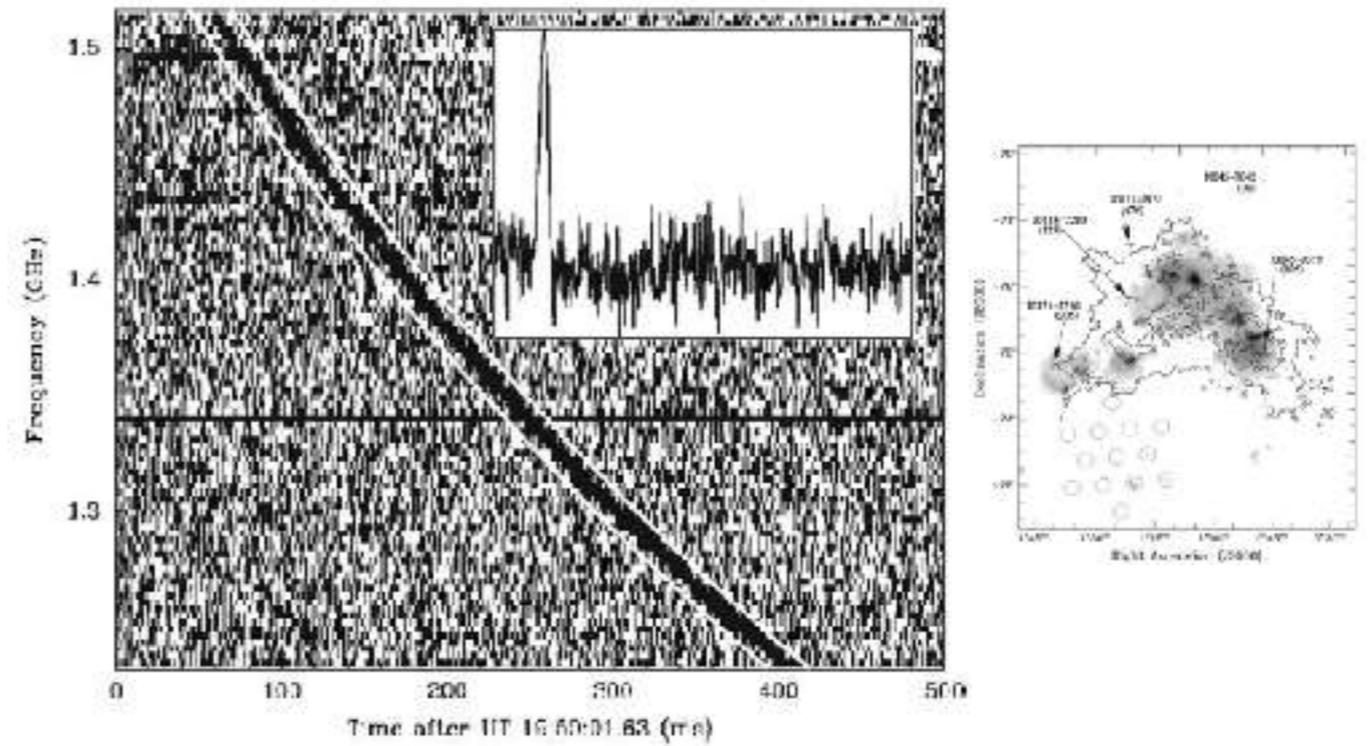


$f \geq \text{GHz}$, $A_{\text{eff}} \sim \text{quelques } 10^4 \text{ m}^2$, $\theta \sim 1'$

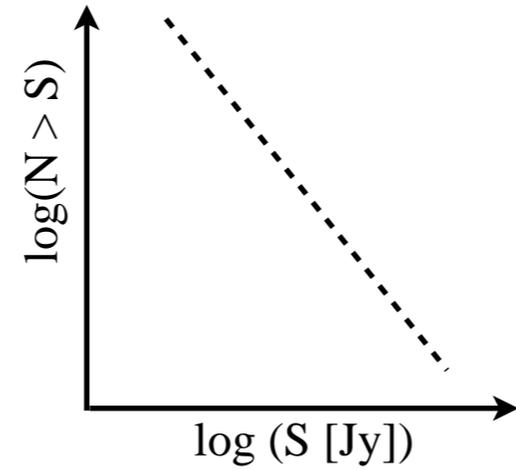
Quelques observations « single-dish »



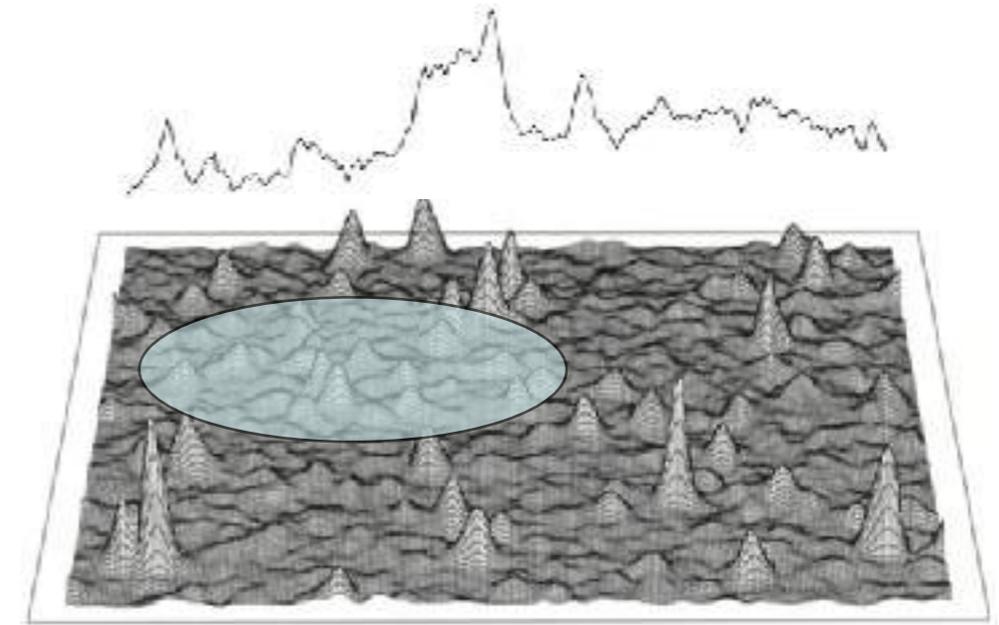
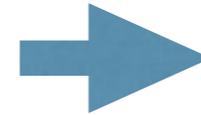
Fast Radio Bursts



Résolution, Confusion, Sensibilité, Imagerie



Distributions ~isotrope de sources
 Ex: NVSS (NRAO VLA Sky Survey)
 $\delta > 75^\circ$, $S > 2.5$ mJy

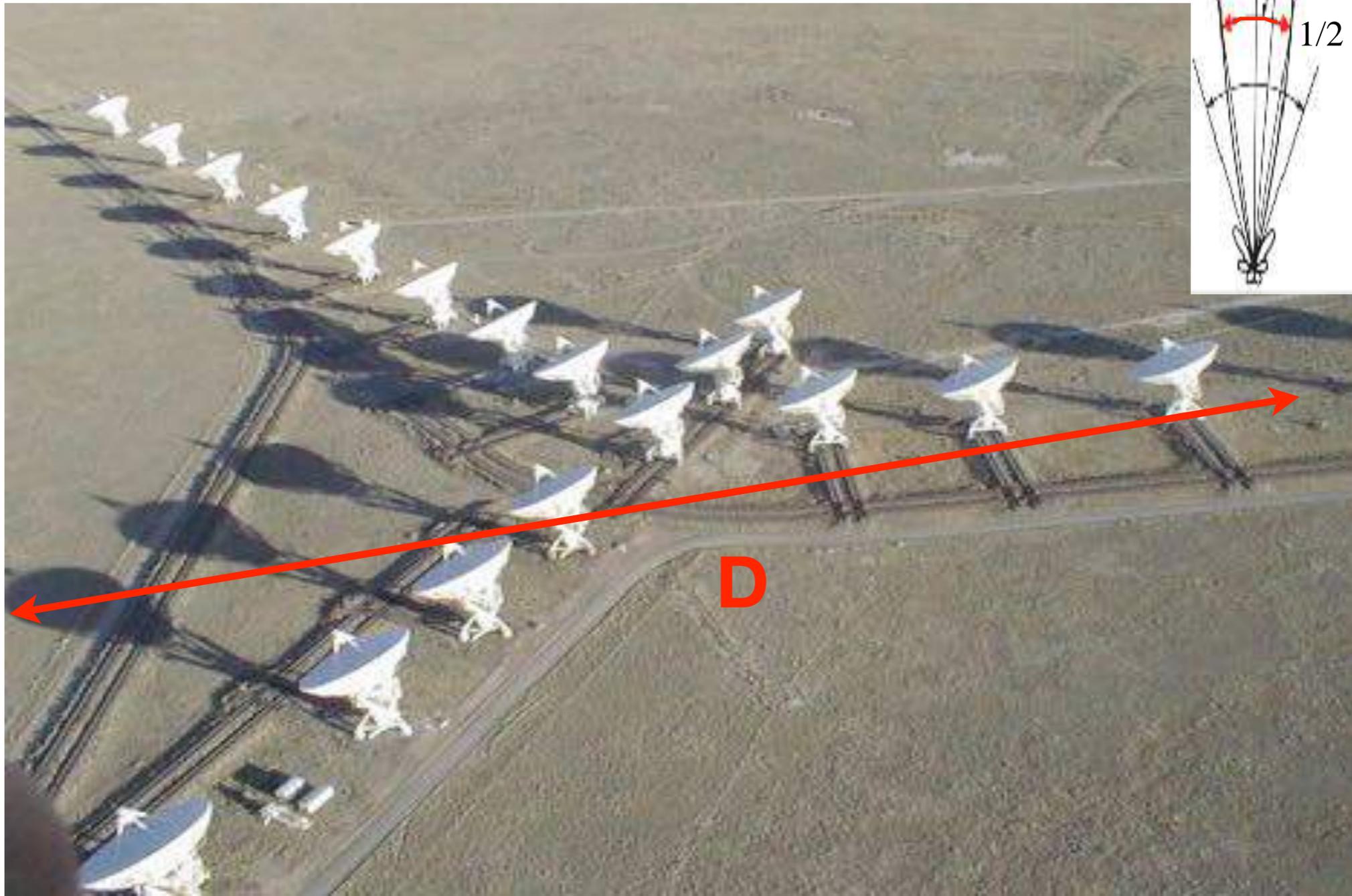
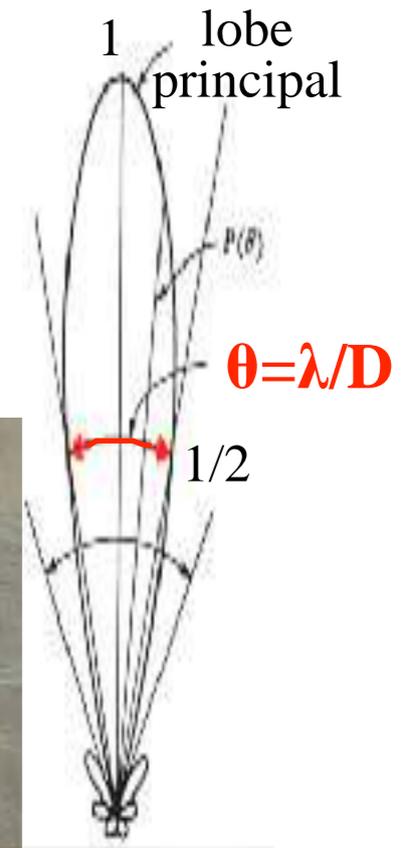


Confusion = bruit spatial (imagerie) :
 σ_c [mJy/beam] $\sim 0.2 (v / \text{GHz})^{-0.7} (\theta / \text{arcmin})^2$

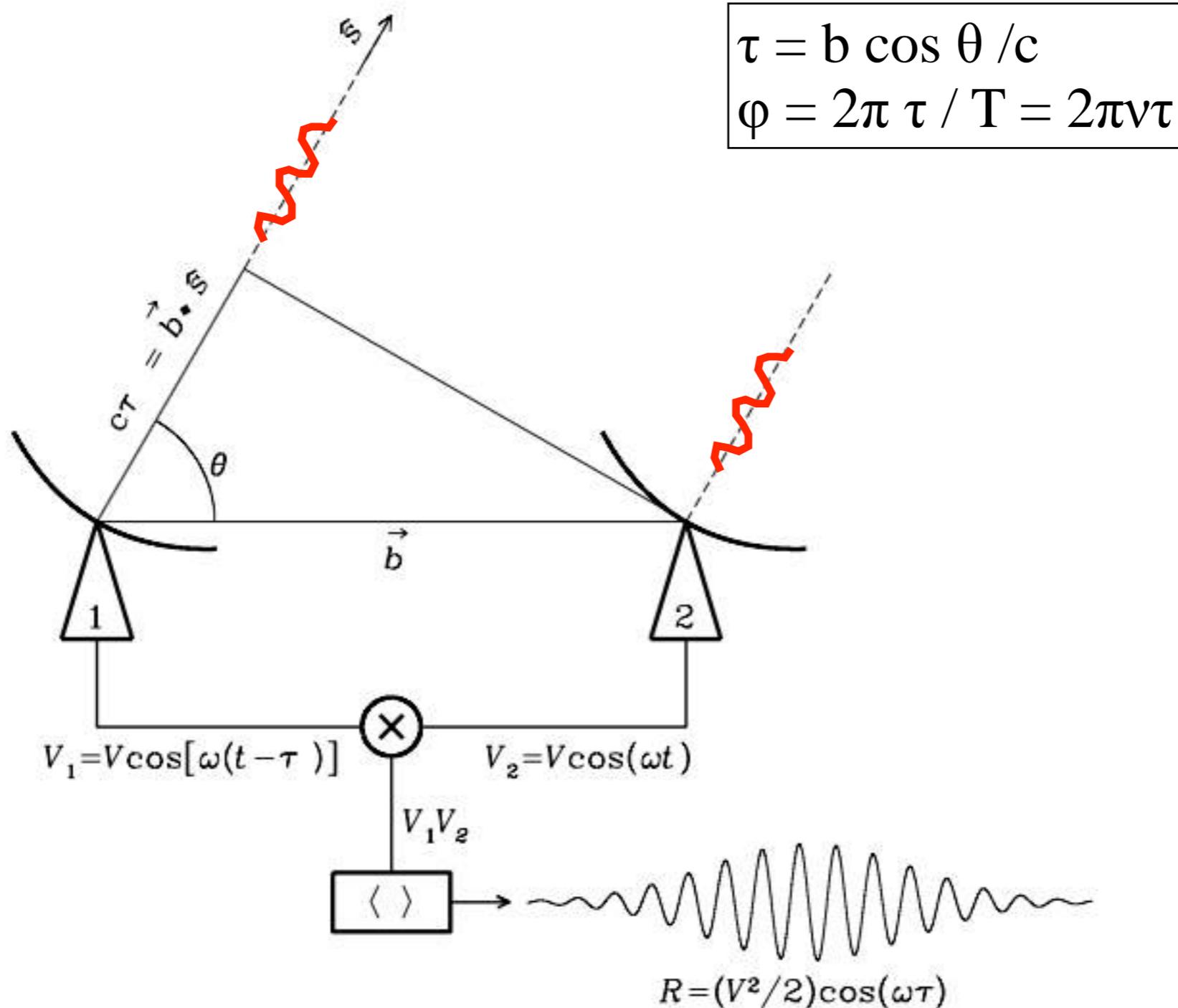


Détecteurs focaux : 1 à quelques pixels (FPA = Focal Plane Array) → imagerie difficile

Augmenter la résolution + Imagerie → Interférométrie



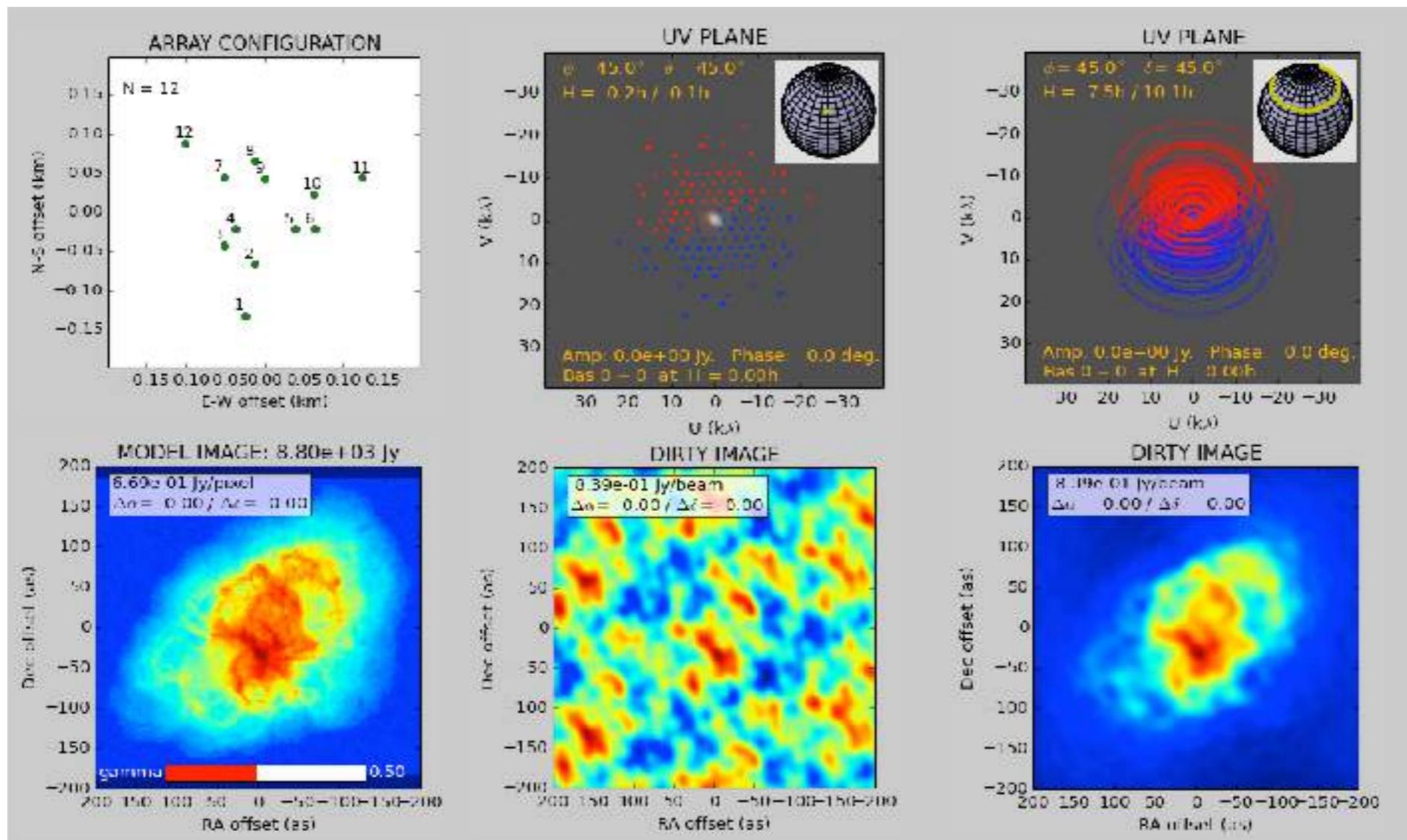
Imagerie Radio : Interférométrie



Combinaison (corrélation) des signaux radio détectés simultanément par 1 paire d'antennes (= 1 ligne de base)

Imagerie Radio : Interférométrie

- Principe : chaque ligne de base (u, v) correspond à un réseau de franges dans le ciel
- Combinaison des signaux pour toutes les lignes de base + opération mathématique
 → image du ciel : $V(u, v) = TF(T_{ciel}) * A(u, v) \Rightarrow TF^{-1}(V(u, v)) = T_{ciel} \otimes PSF$
 → la transformée de l'image du ciel est dans le plan des antennes (théorème ZVC)
- $N(N-1)/2$ bases pour N antennes → nécessité d'intégrer en temps et en fréquence pour une meilleure couverture du plan (u, v) + méthodes de déconvolution/reconstruction

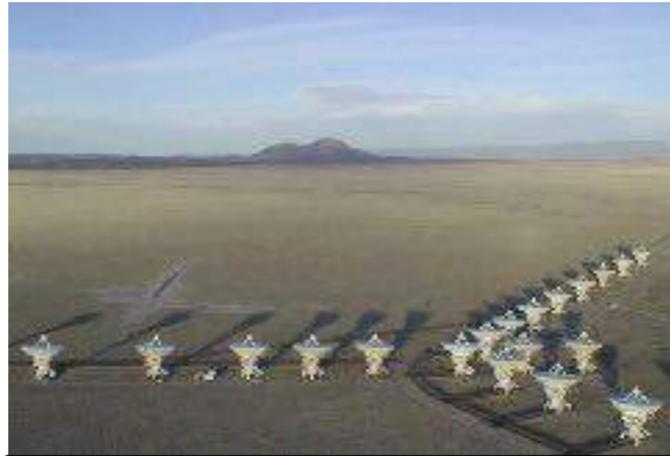


Demo ApSynSim

Interféromètres « classiques »

Quelques antennes (IRAM) à quelques dizaines d'antennes (VLA, GMRT, ALMA)

Westerbork
(ASTRON, NL)
14 paraboles de 6m
Base max: 2.7 km
 $\lambda \sim 10\text{cm} - 1\text{m}$
 $A \sim 400\text{ m}^2$



VLA (NRAO,
Nouveau Mexique)
27 paraboles de 25 m
Base max: 36 km
 $\lambda \sim 1\text{cm} - 1\text{m}$, $f_{\text{min}} = 74\text{ MHz}$
 $A \sim 14000\text{ m}^2$



SMA (USA – Taïwan) Hawaï
8 antennes de 6 m
Base max: 0.5 km
 $\lambda \sim 0.5\text{mm}$, $A \sim 220\text{ m}^2$



GMRT (Pune, Inde)
30 paraboles de 45 m
Base max: 25 km
 $\lambda \sim 1\text{m}$, $f_{\text{min}} = 153\text{ MHz}$
 $A \sim 50000\text{ m}^2$

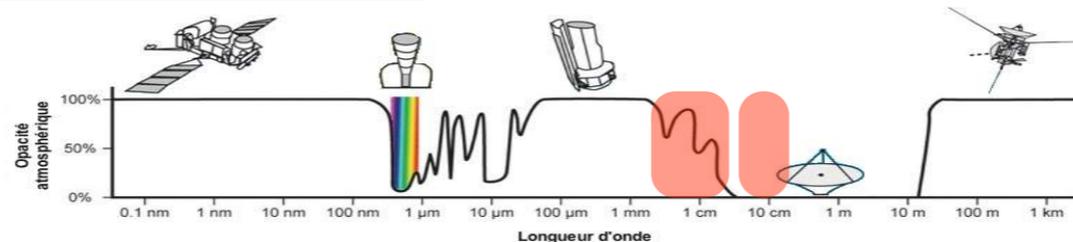
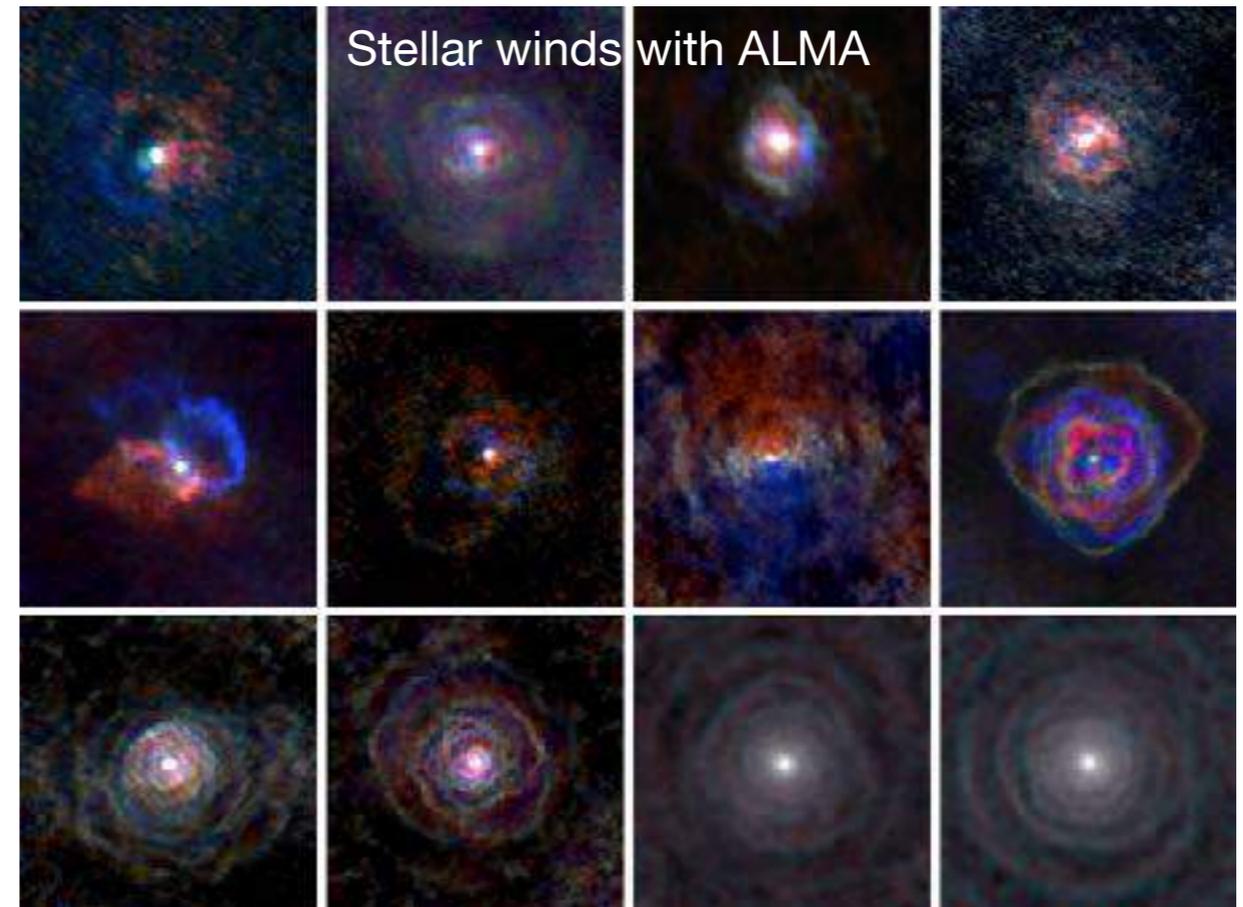
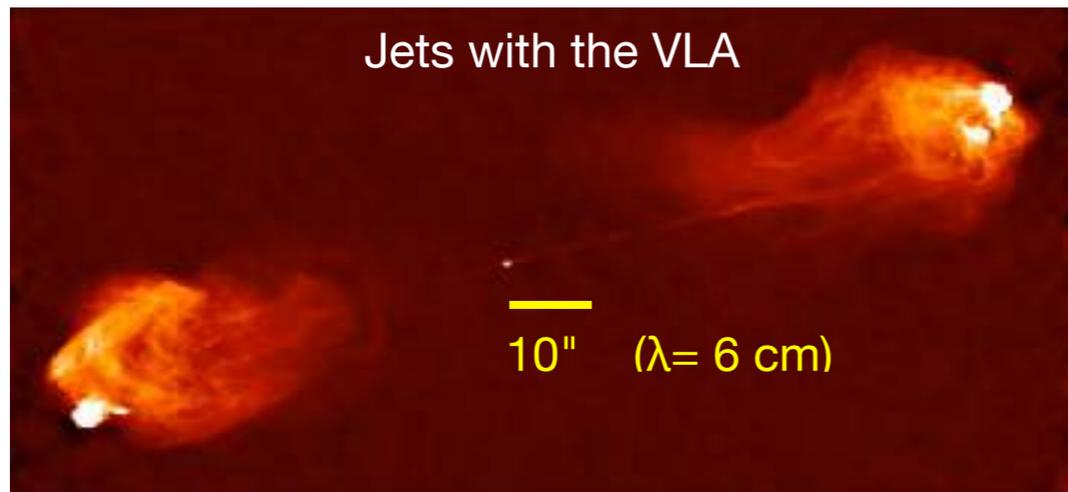
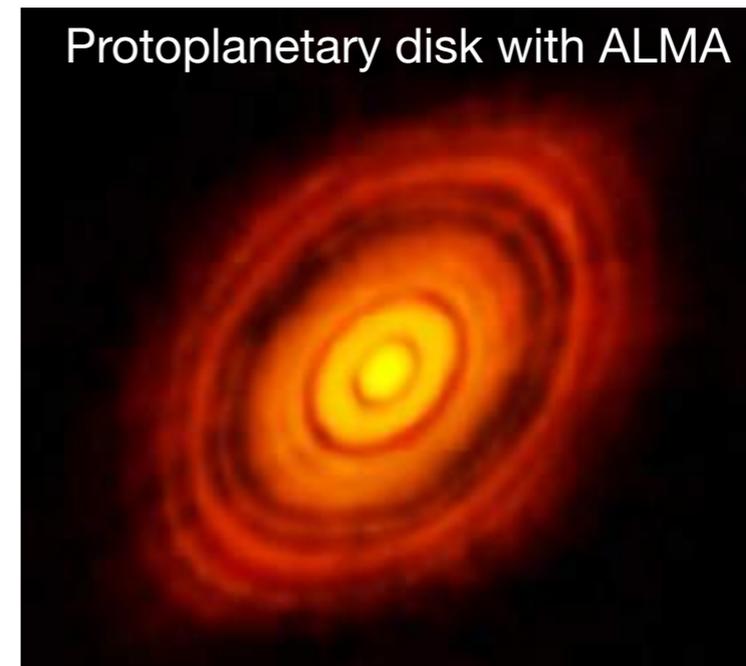
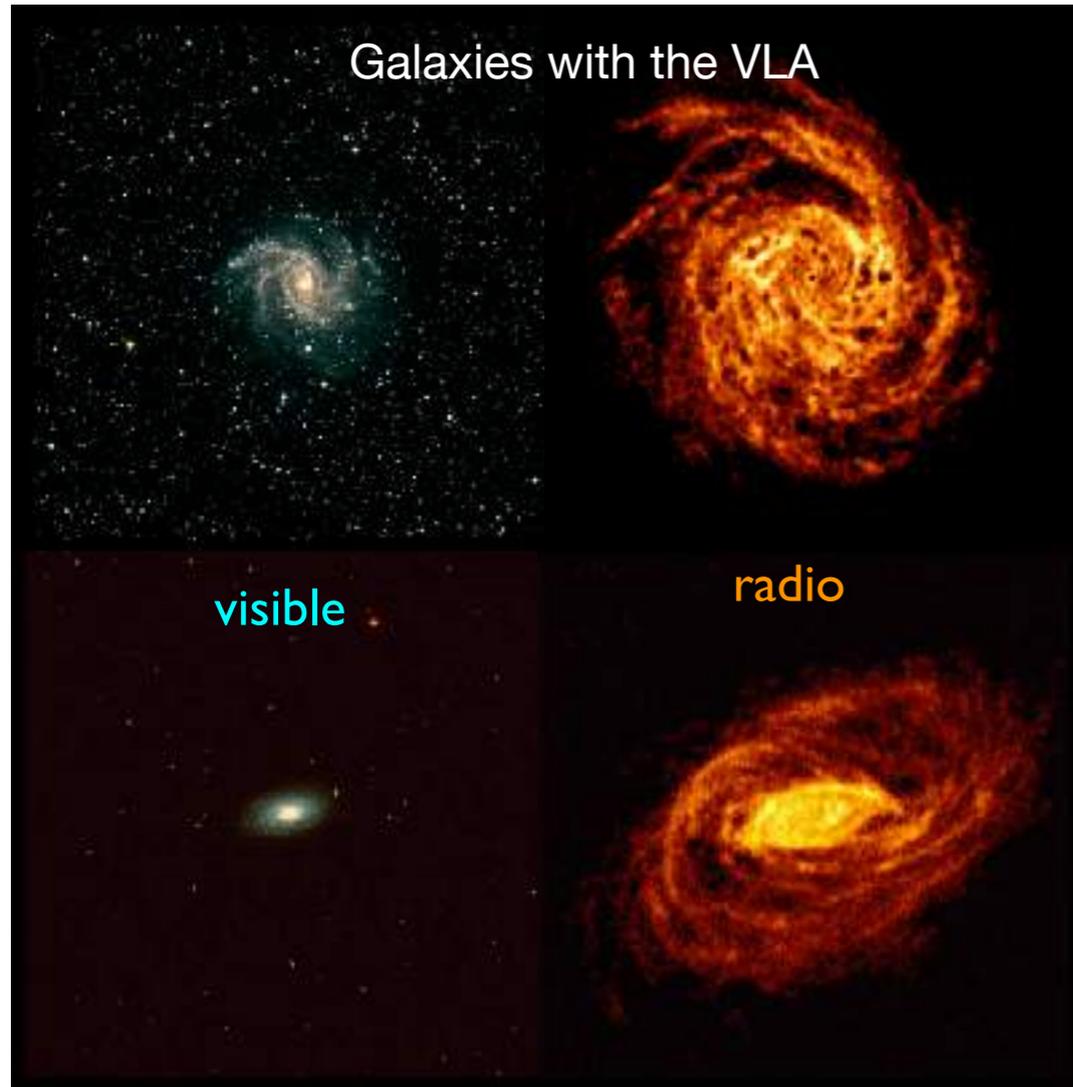


Plateau de Bure
(IRAM, France)
6 antennes de 15m
Base max: $\sim 1\text{ km}$
 $\lambda \sim 1\text{mm}$
 $A \sim 1000\text{ m}^2$



ALMA (Chili)
54 antennes de 12m
+ 12 de 7m
Base max: 16 km
 $\lambda = 1\text{ cm} - 0.3\text{ mm}$
 $f = 30 - 900\text{ GHz}$
 $A \sim 6000\text{ m}^2$

Quelques observations interférométriques

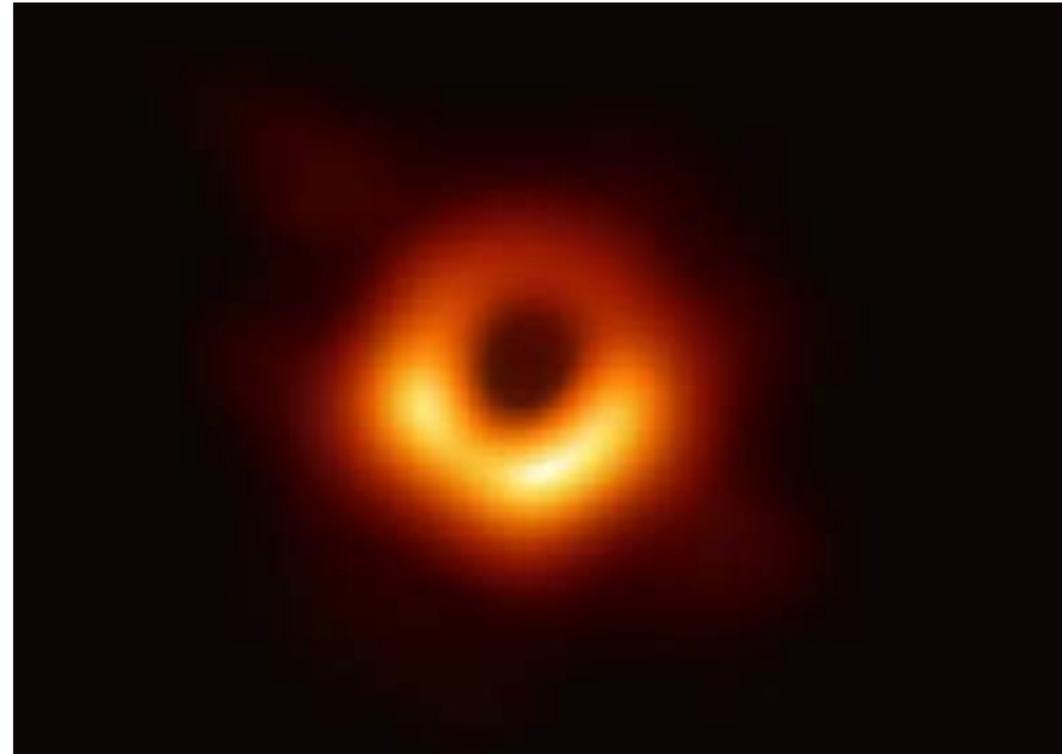
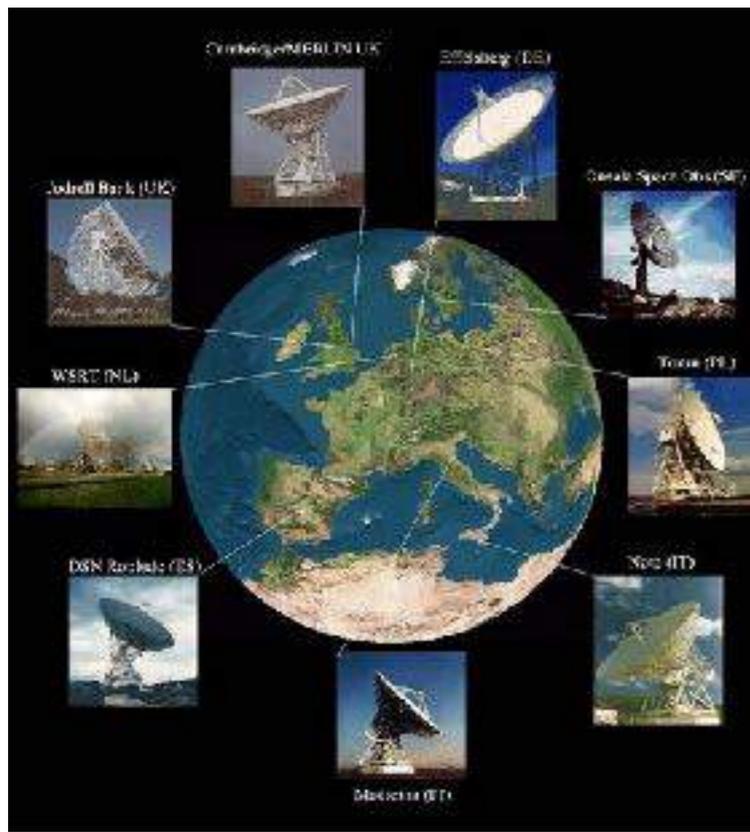


Polarisation → Champs magnétiques

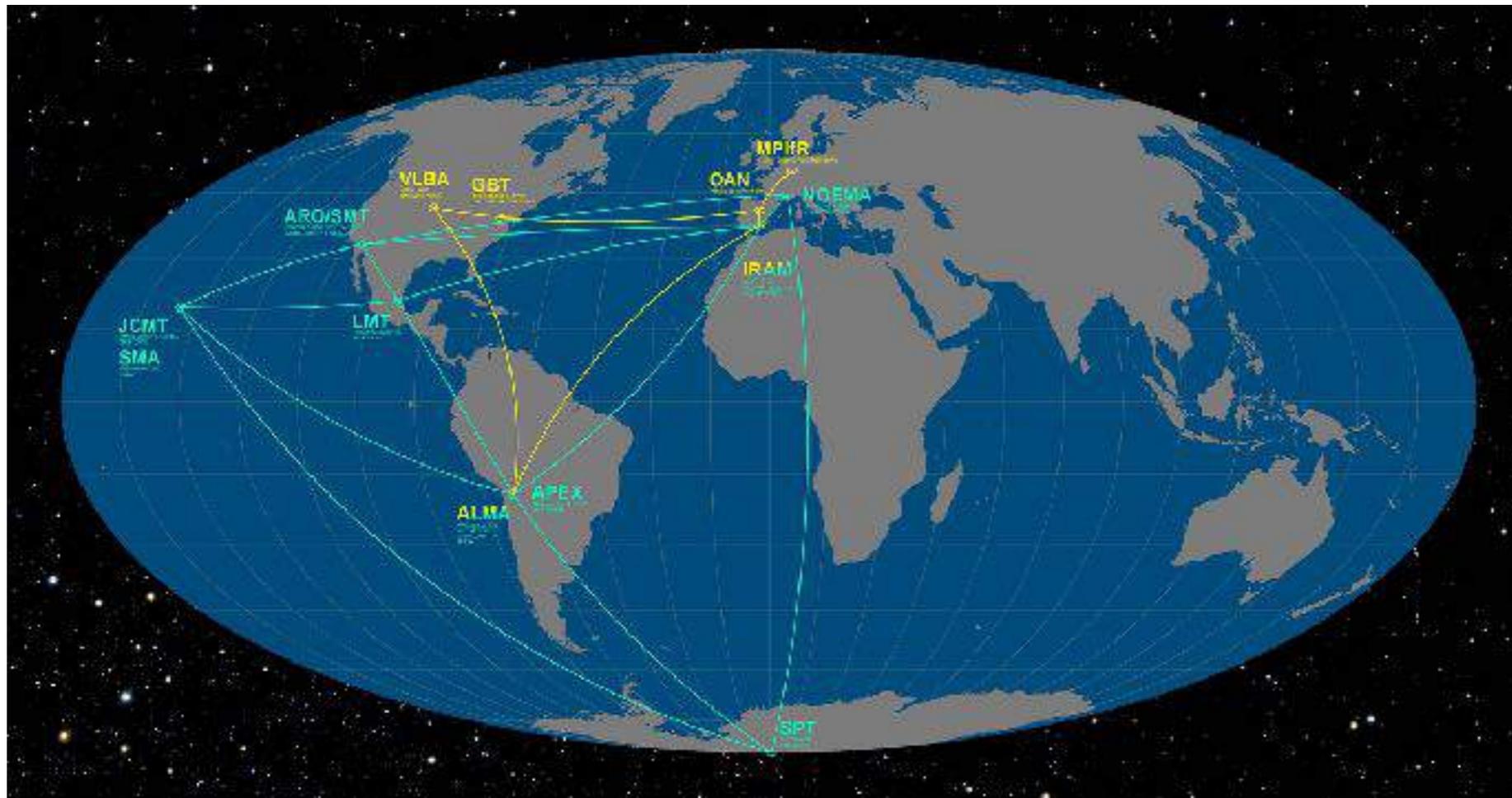
$$\text{Effet Faraday : } \Delta\theta (f_1 \rightarrow f_2) = K' [\text{DM}] B_{//} (1/f_1^2 - 1/f_2^2)$$



VLBI = interférométrie à très longues bases



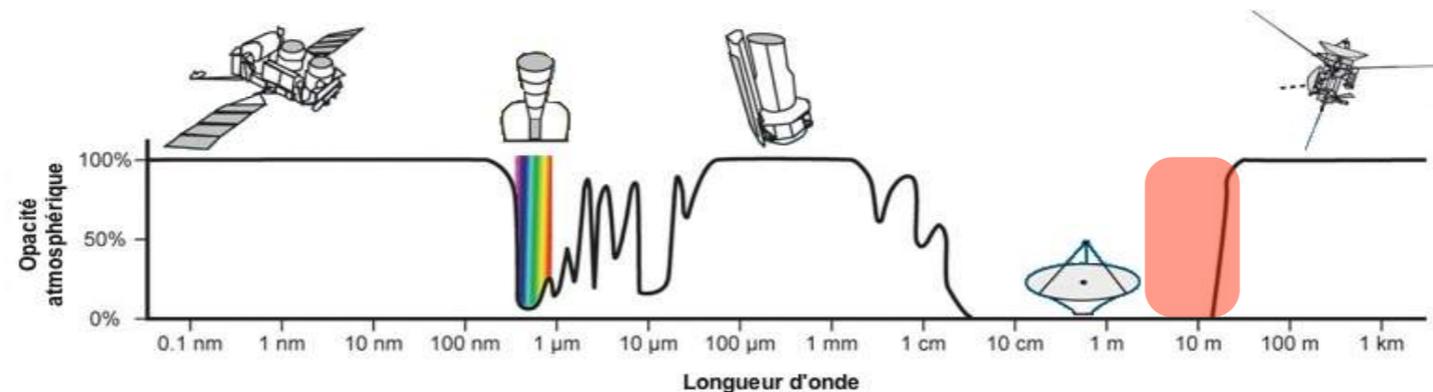
→ M87 en VLBI mm
par l'EHT telescope
10/4/2019



Très haute résolution,
très petits champs

Basses fréquences : réseaux phasés

Paraboles peu efficaces → réseaux d'antennes



UTR-2

(Kharkiv, Ukraine)

2040 « gros » dipôles (1 polar.)

2km x 50m (NS) + 1km x 50m (EW)

$f = 7 - 35$ MHz

$A = 60000 - 140000$ m²



Nançay Decameter Array

(Nançay, France)

144 antennes log-hélicoïdales

~100m x 100m

$f = 10 - 100$ MHz

$A = 2 \times 4000$ m² (2 polar.)



Long Wavelength Array

(New Mexico, USA)

256 dipôles croisés en Λ (2 polar.)

~100 m de diamètre

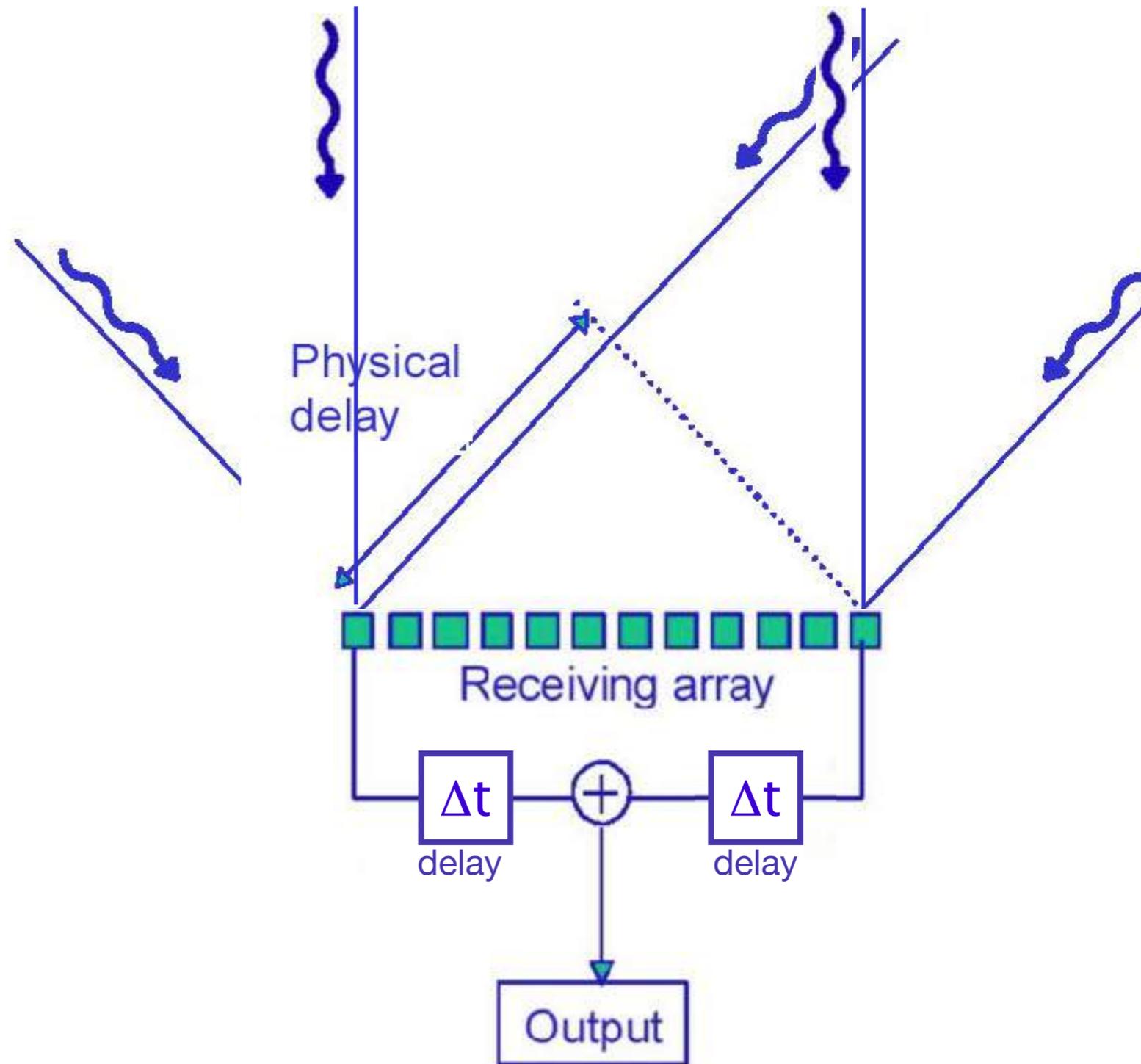
$f = 10 - 188$ MHz

$A = \leq 8000$ m²

Réseaux phasés : principe du pointage

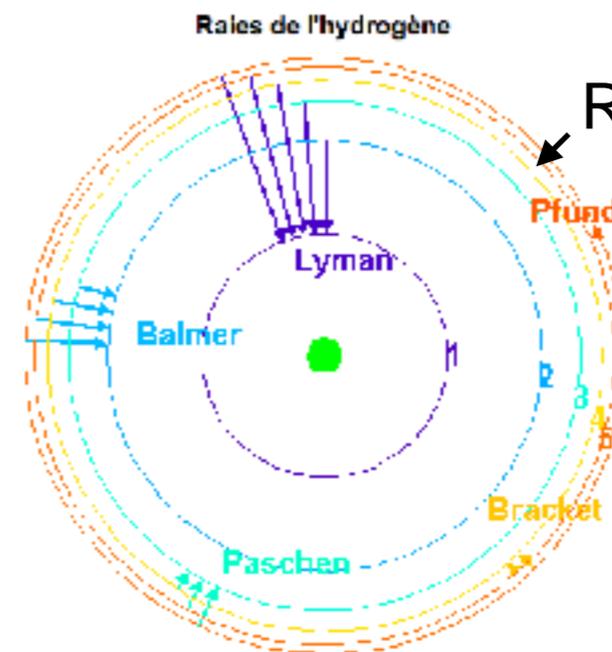
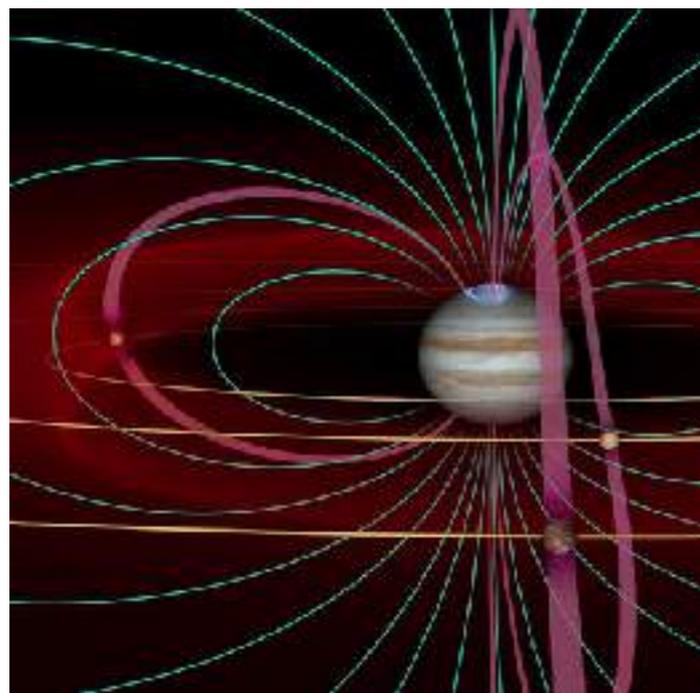
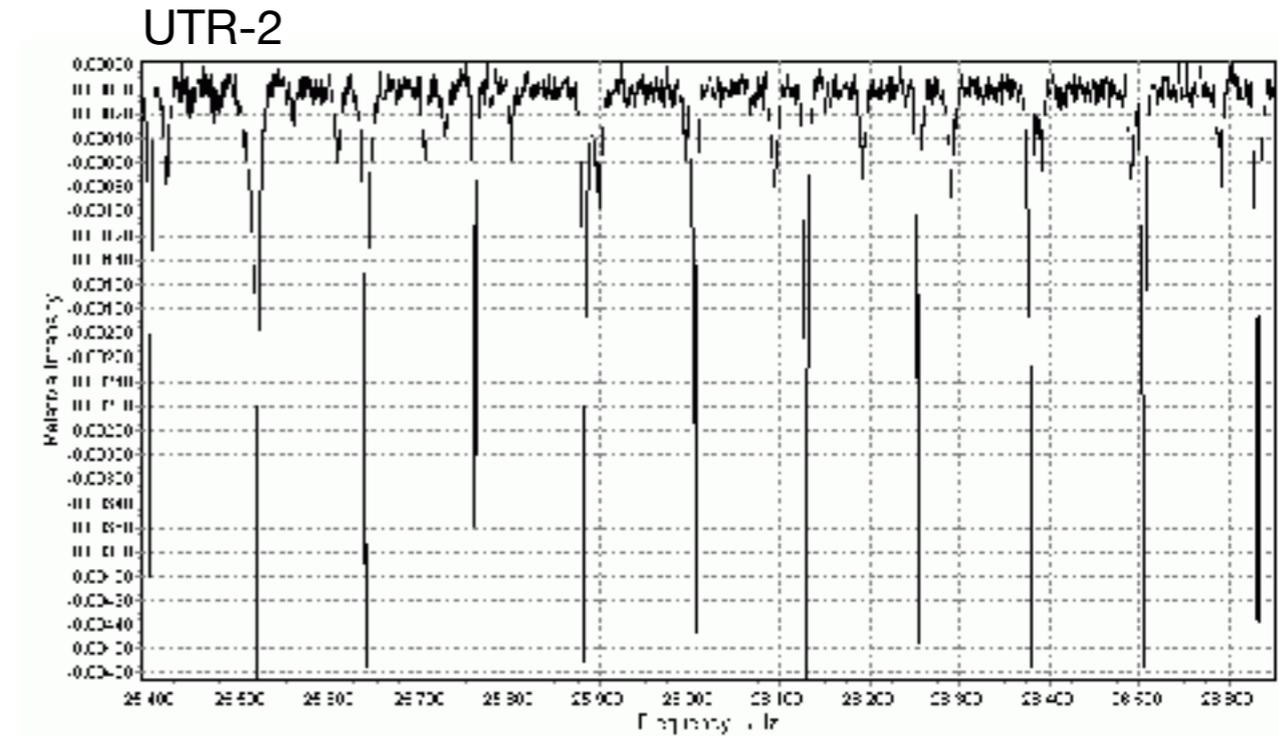
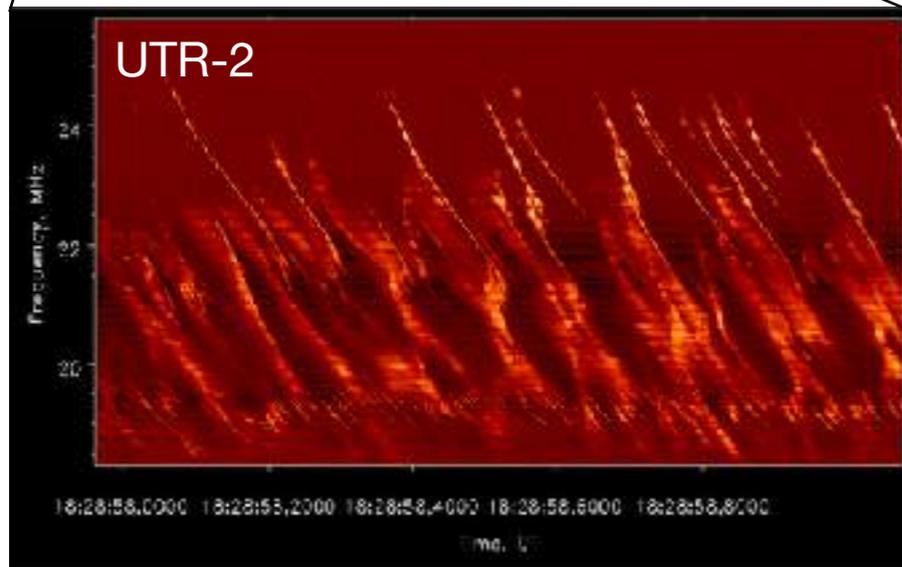
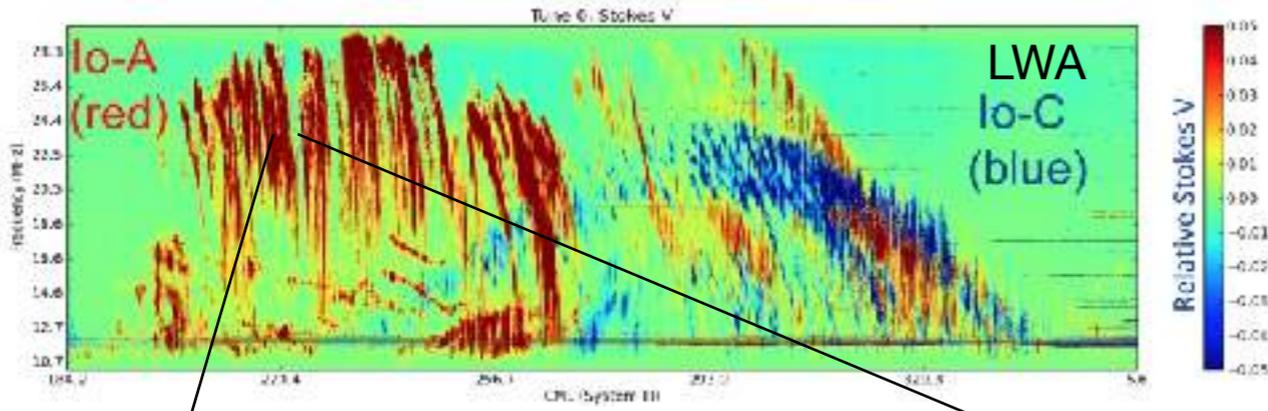


Pointage mécanique



Pointage électronique

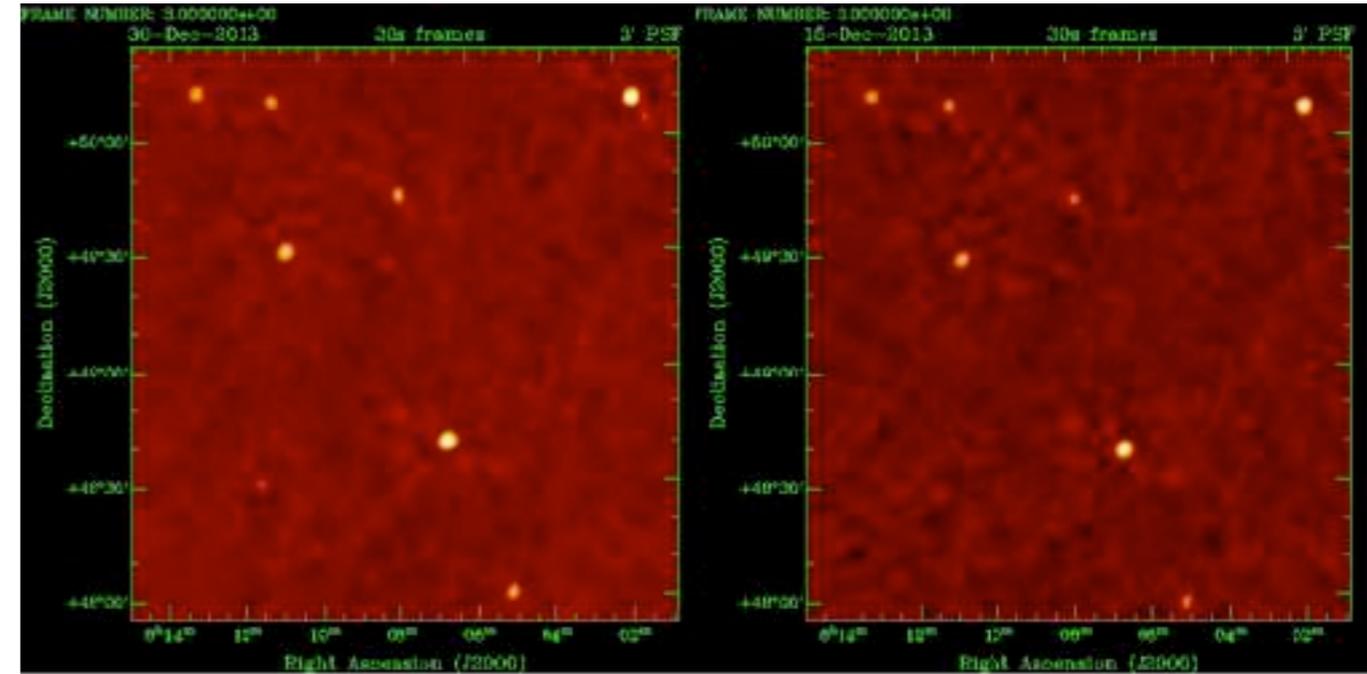
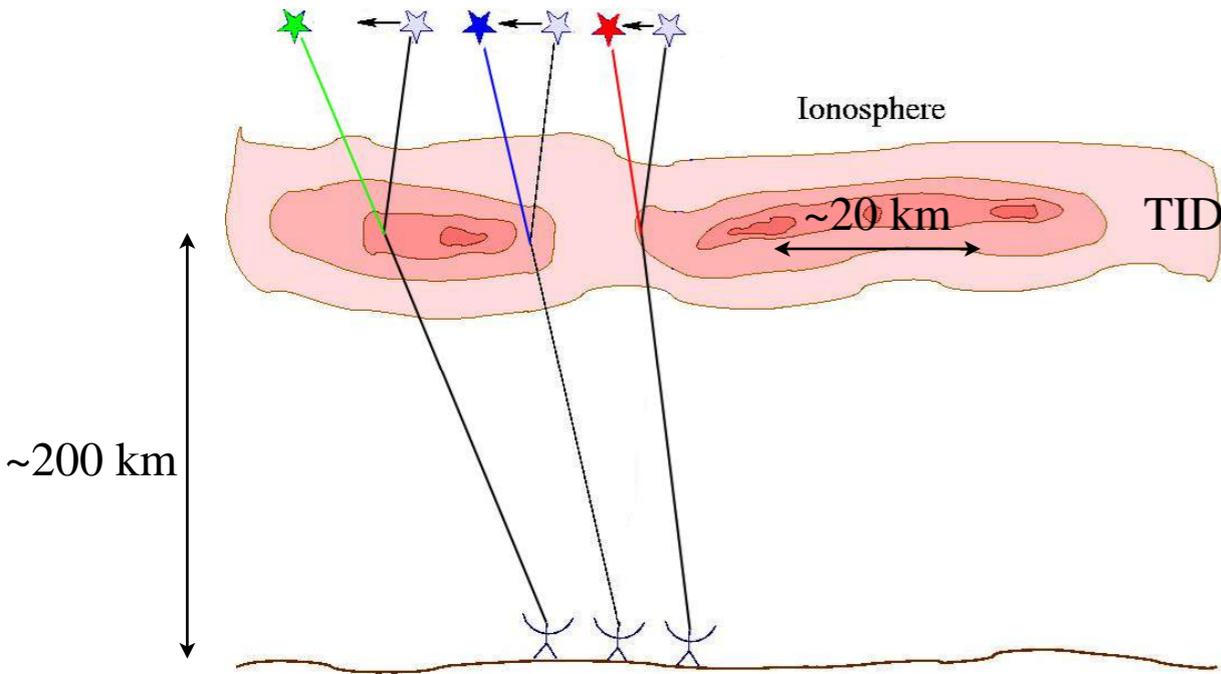
Quelques observations en réseau phasé BF



RRLs = Radio Recombination Lines
= raies de recombinaison atomiques

Difficultés de l'observation radio BF

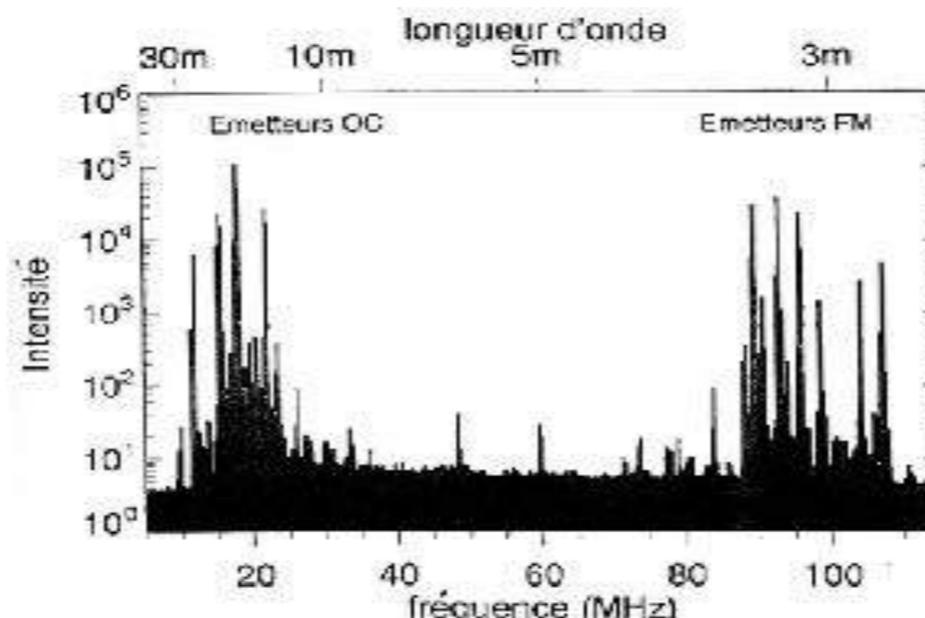
☹️ Ionosphère perturbatrice aux BF



☹️ Ciel basses fréquences brillant : $T(K) \sim 60 \times \lambda^{2.55}$

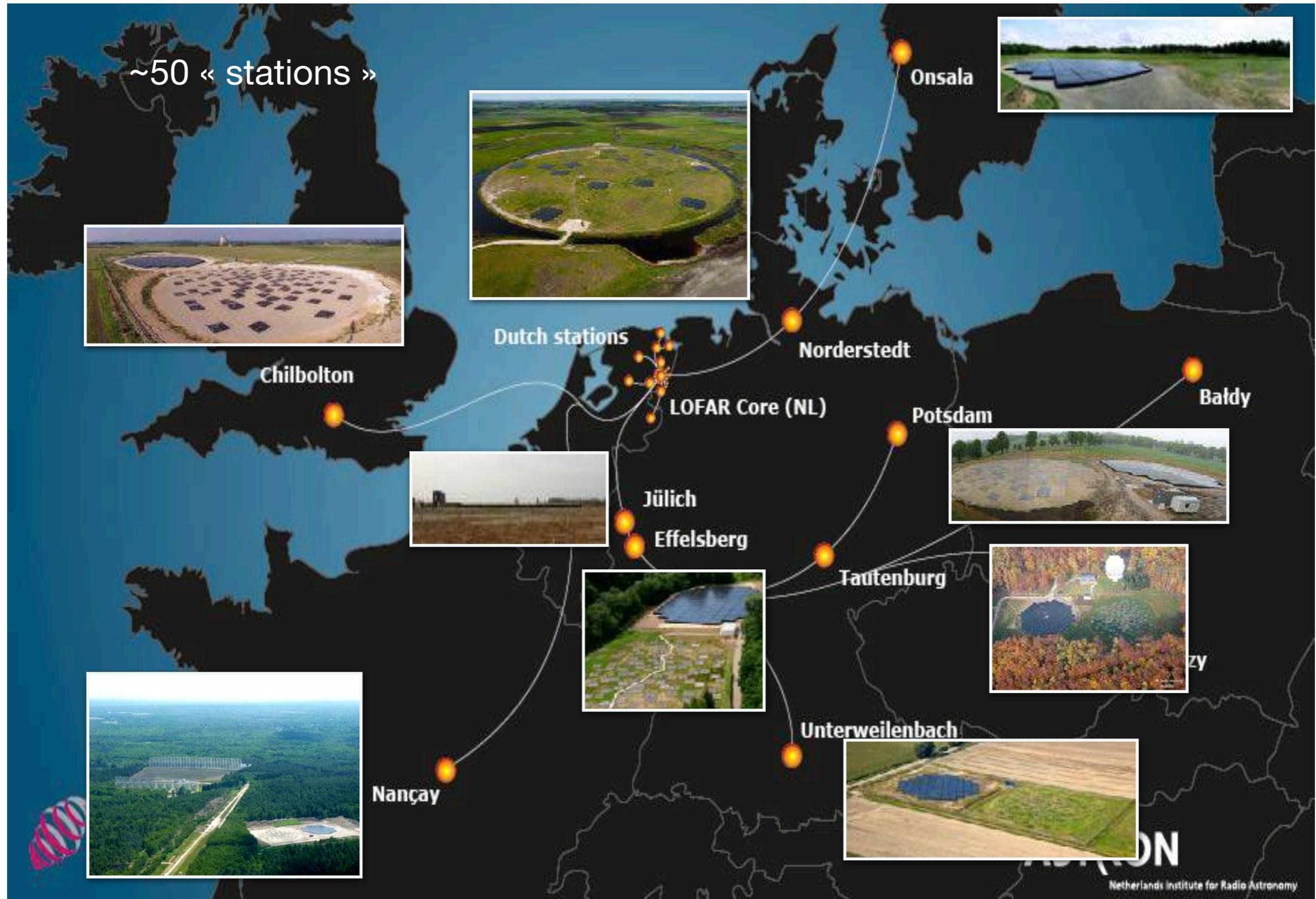
f (MHz)	λ (m)	T (K)
1	300	$>10^7$
10	30	$\sim 3 \times 10^5$
100	3	$\sim 10^3$
1000	0.3	~ 5

☹️ Parasites radio (RFI)

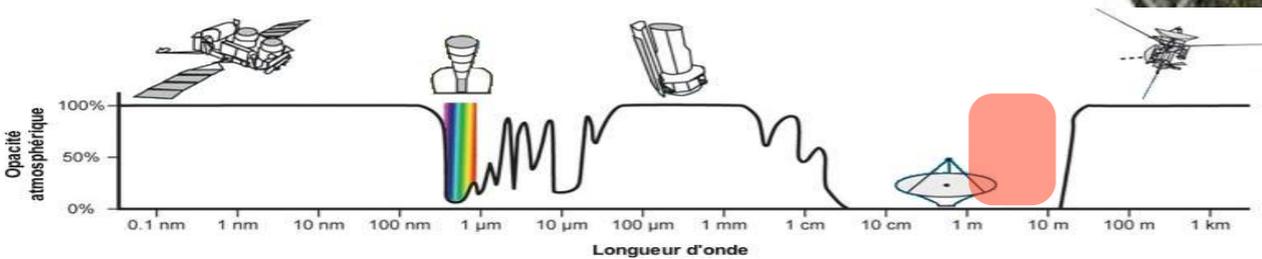
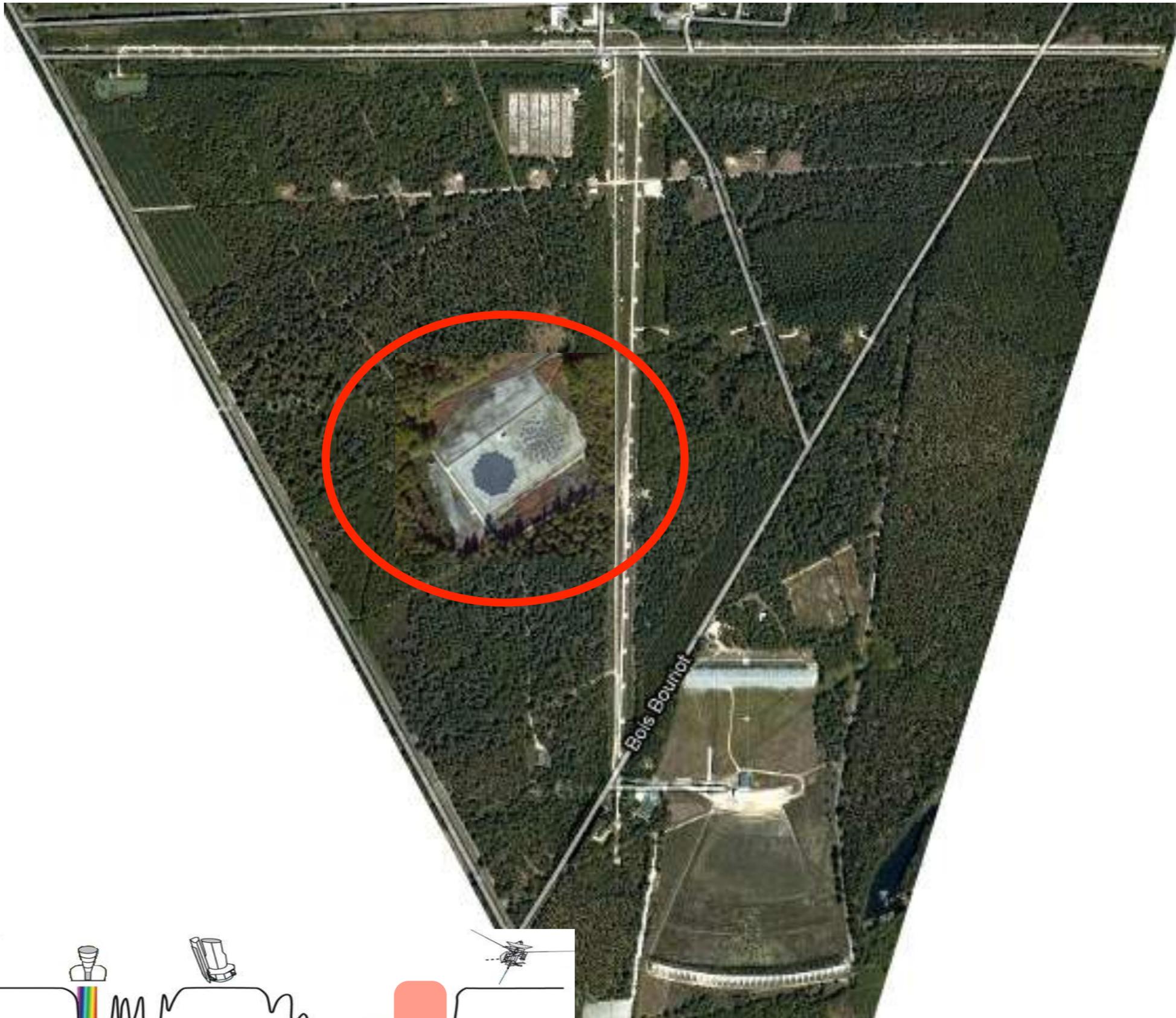


**Une révolution en route :
les nouveaux radiotélescopes
numériques**

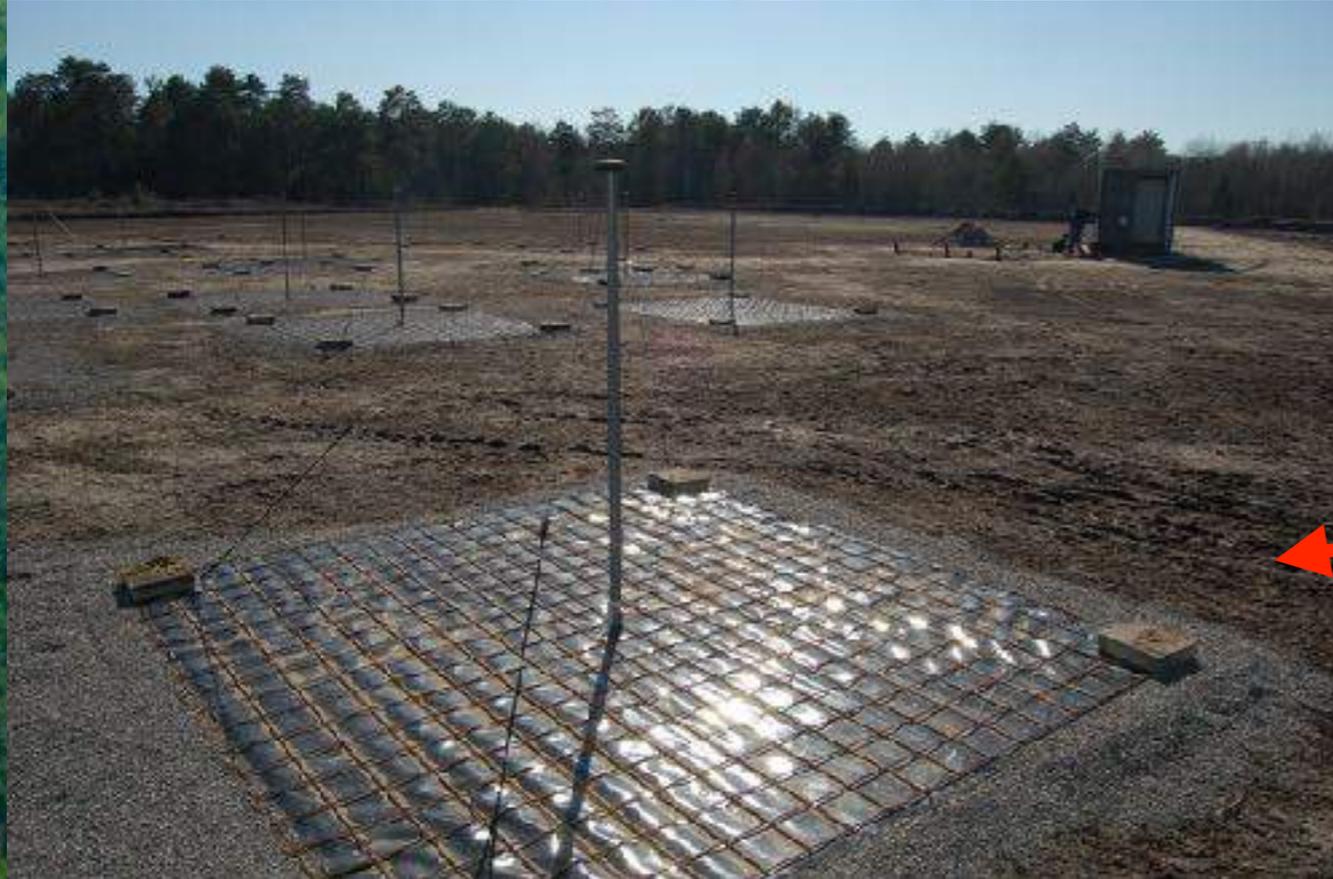
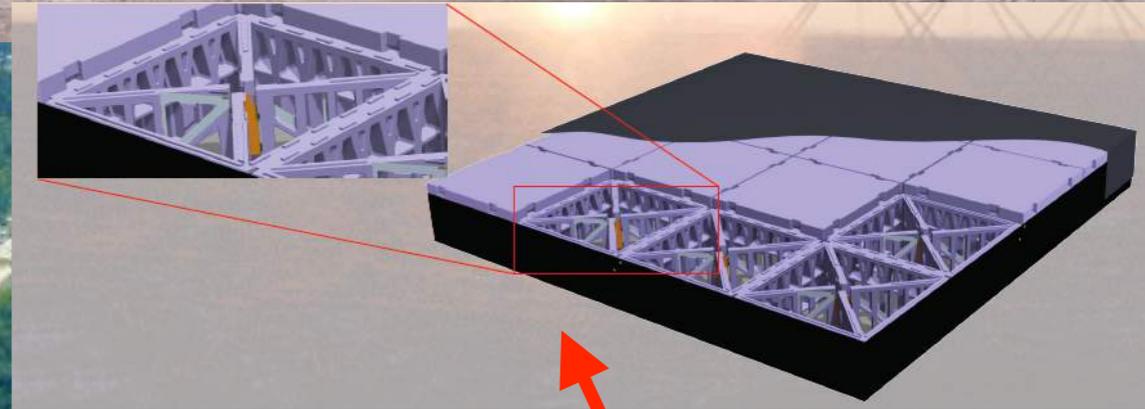
LOFAR, interféromètre radio Européen de nouvelle génération (≥ 2012)



La station LOFAR de Nançay



La station LOFAR de Nançay

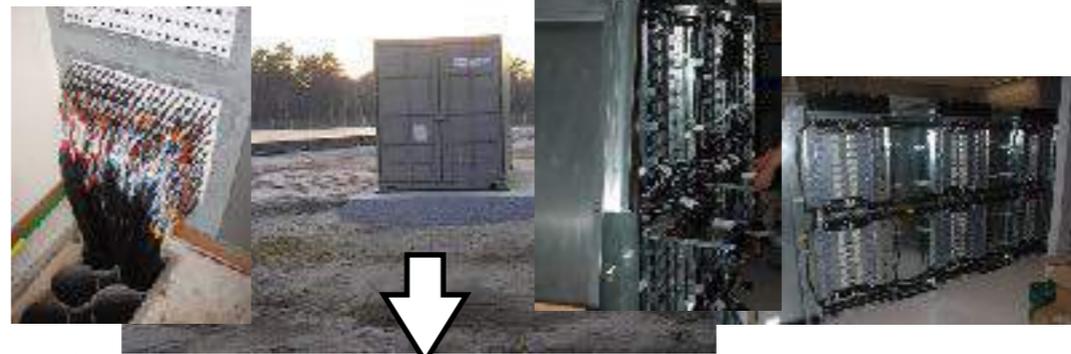
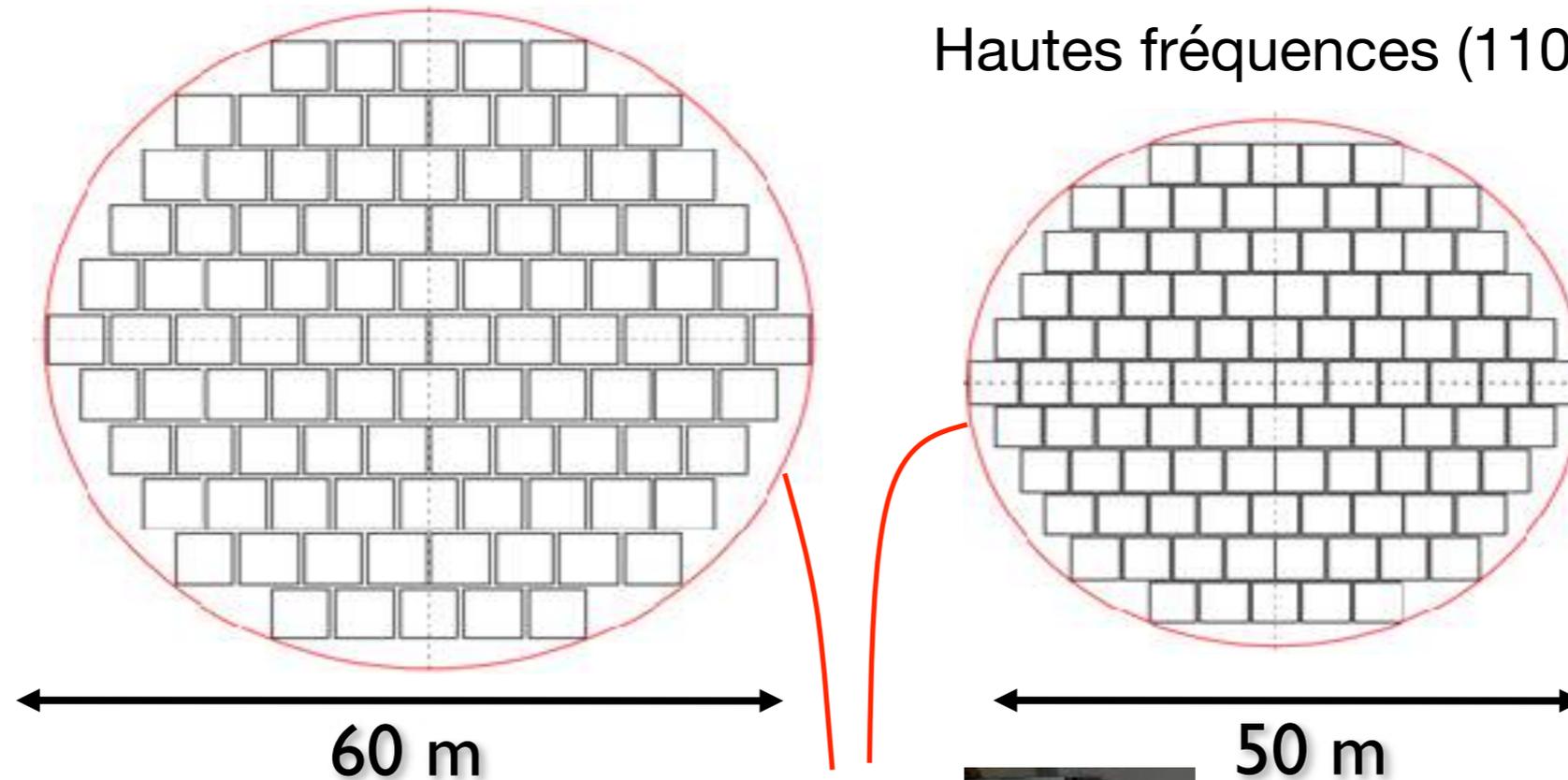


Station LOFAR :

2 réseaux d'antennes + électronique + lien haut débit

Basses fréquences (30-80 MHz)

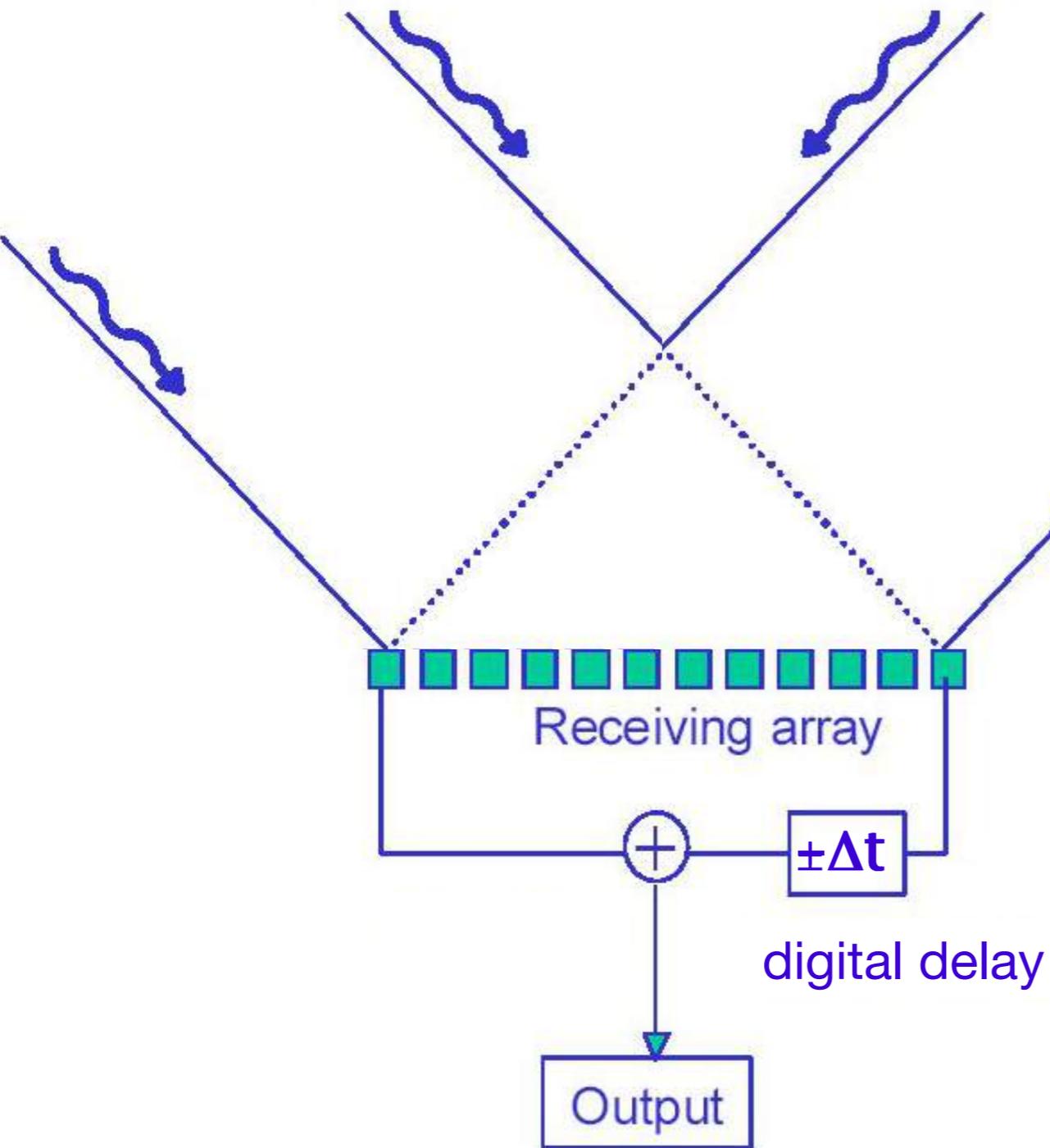
Hautes fréquences (110-250 MHz)



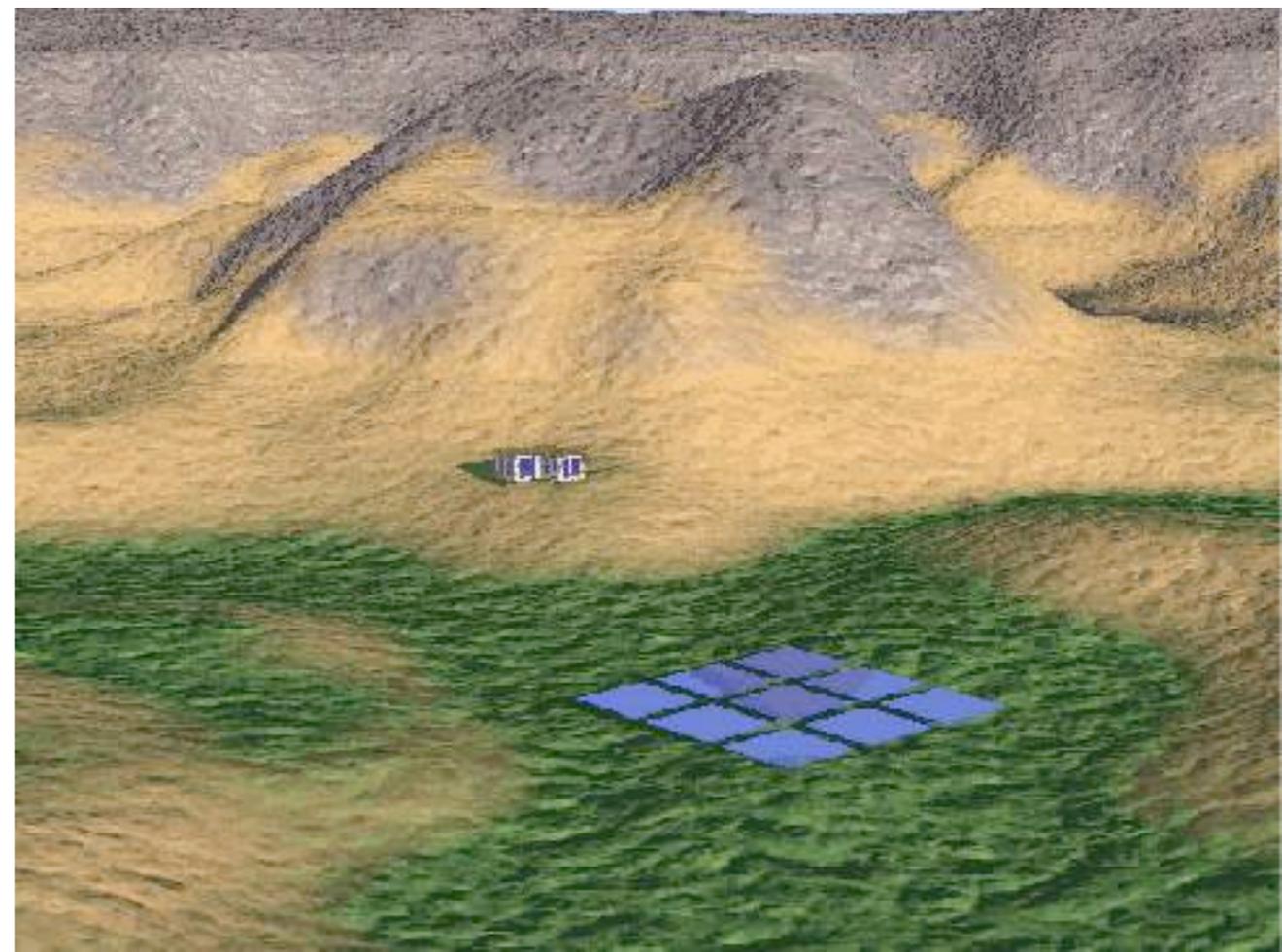
Lien à 3 Gbit/sec

Corrélateur : grappe de calcul

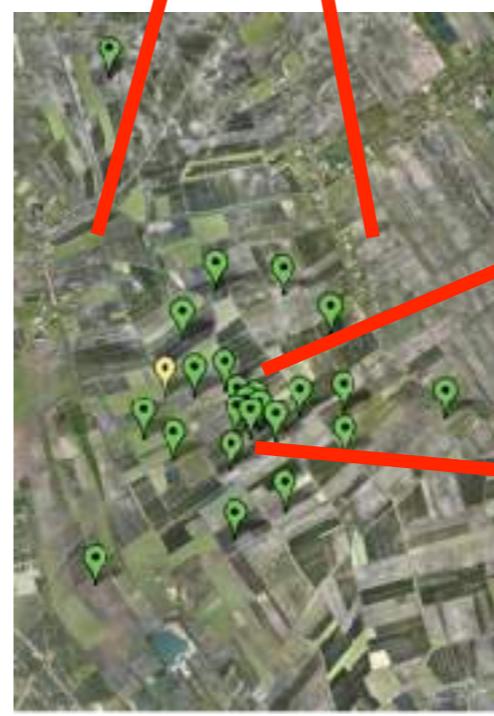
Principe du pointage numérique



- Observations multi-faisceaux
- Reconfiguration rapide
- Réponse rapide

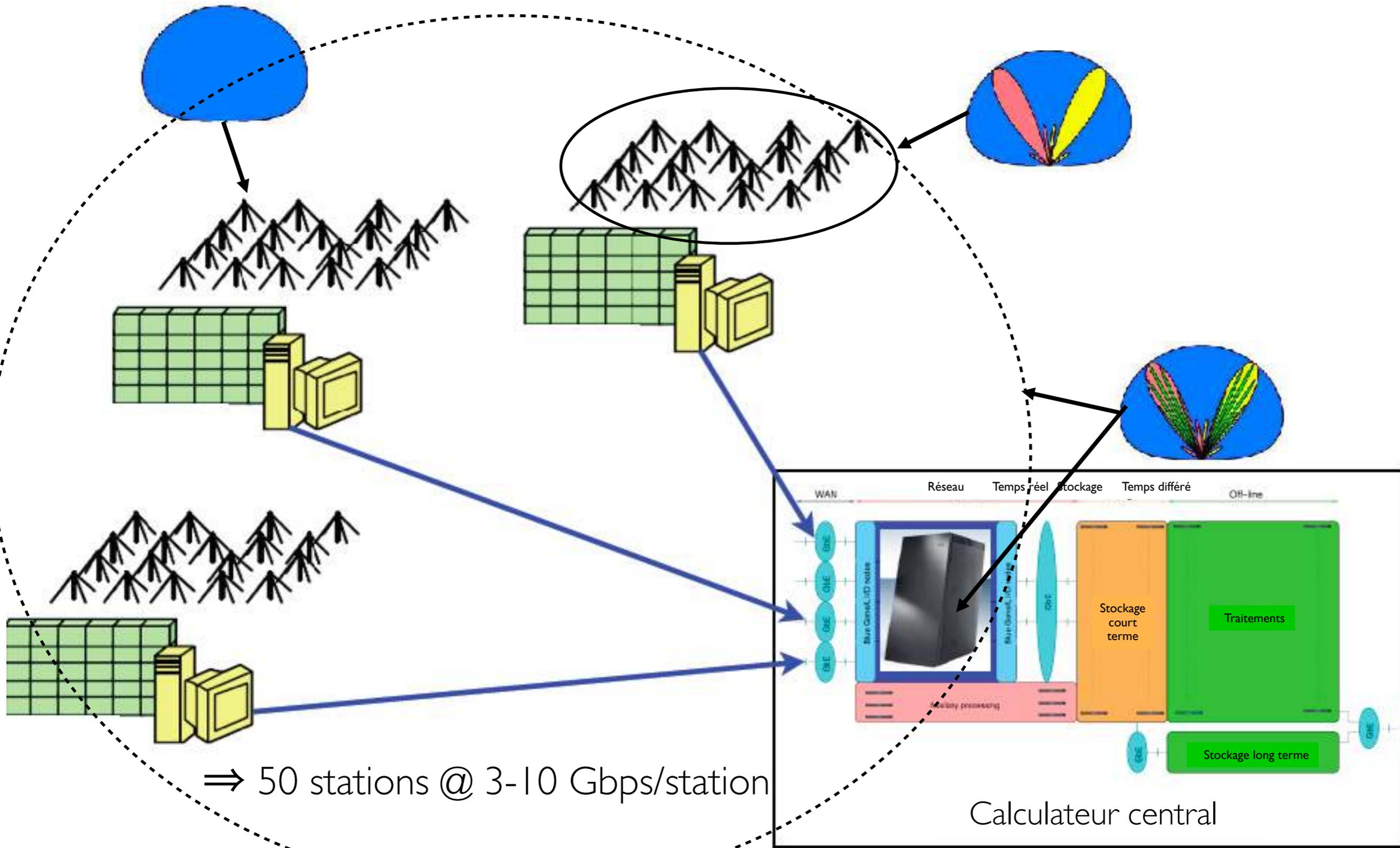


LOFAR : réseau phasé + interféromètre multi-échelles



Le réseau LOFAR

- Traitements «station» : amplification, numérisation, filtrage, beam-forming, buffers «transitoires» (TBB)
- Calculateur central : compensation des délais, corrélation / sommation, étalonnage, trait^s scientifiques



Un radiotélescope "logiciel"



flexibilité, nombreux modes d'observation
mais faisceau phasé dépend de la
direction de pointage \neq paraboles

Calibration & Imagerie

- 1960's : équation explicite reliant les mesures interférométriques au paramètres de Stokes S,Q,U,V [Morris et al., 1964]
- 1996 : nouveau cadre mathématique = Radio Interferometer Measurement Equation = RIME [Hamaker et al., 1996abc]

$$V_{pq}^{meas} = G_p \cdot \left(\int K_{p,s} \cdot B_{p,s} \cdot I_{p,s} \cdot F_s \cdot F_s^H \cdot I_{q,s}^H \cdot B_{q,s}^H \cdot K_{q,s}^H ds \right) \cdot G_q^H$$

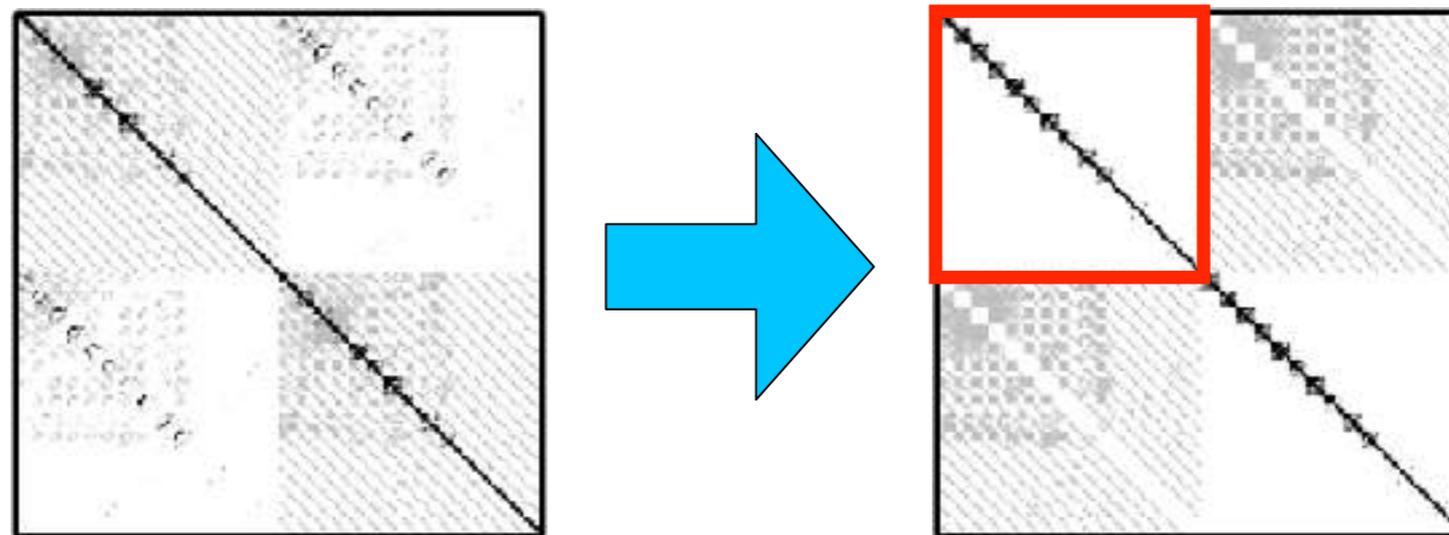
Measurement (10¹¹-10¹² points)

Geometry Beam Ionosphere

Calibration Sky Calibration

?...

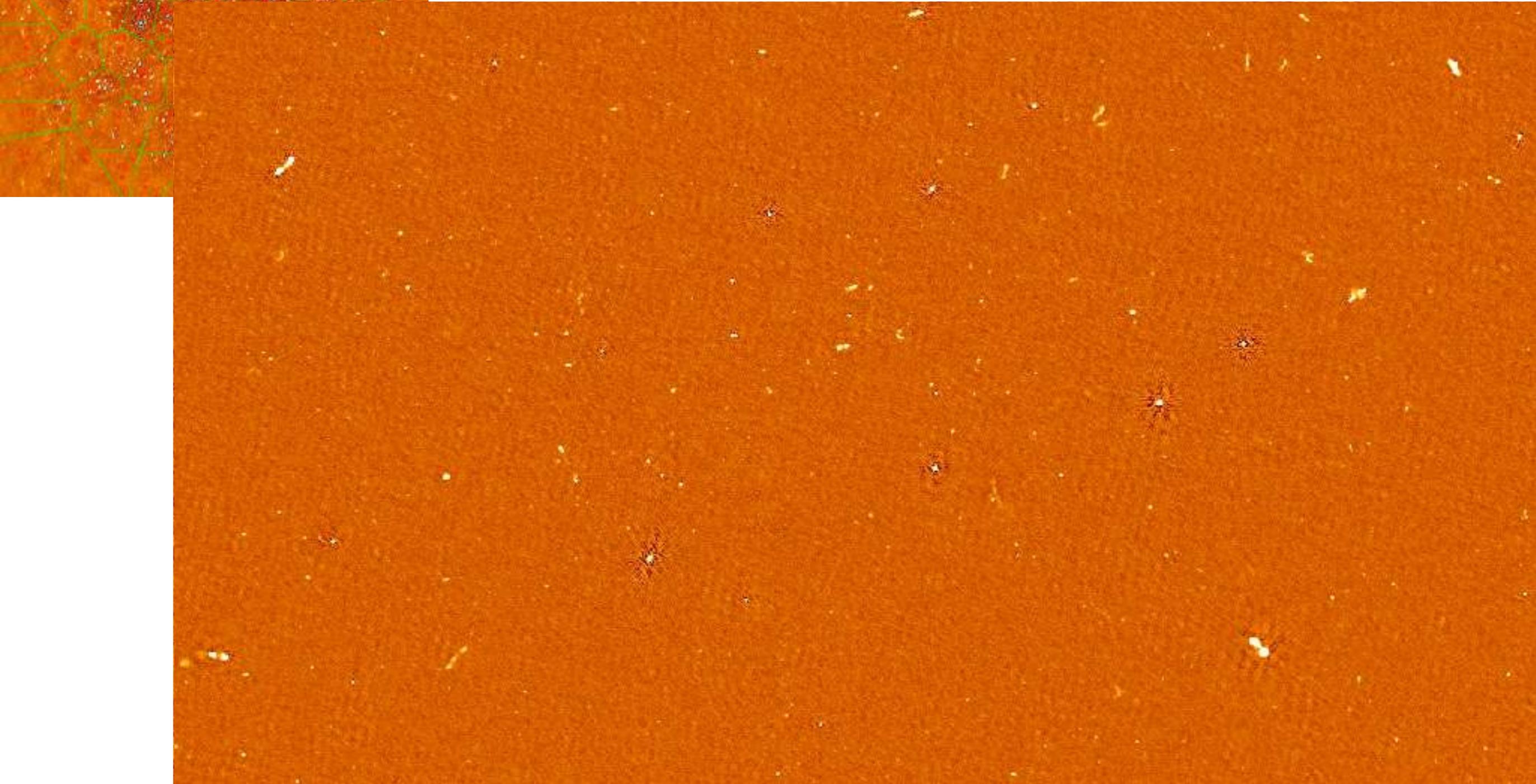
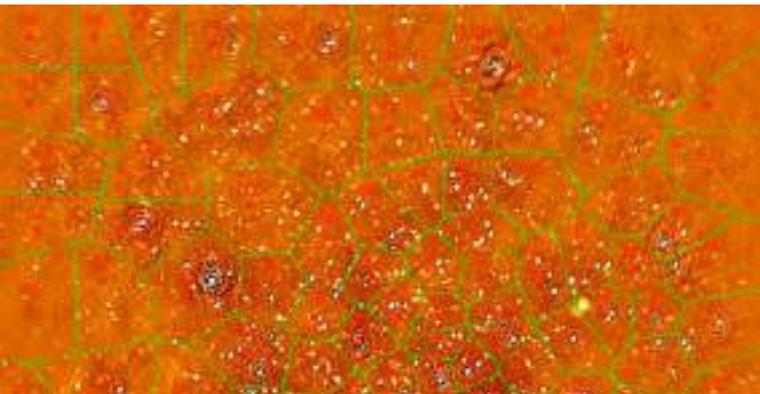
- 2014-2018 : nouvel algorithme de résolution kMS/DDf [Tasse et al. 2014-2018]



Calibration & Imagerie

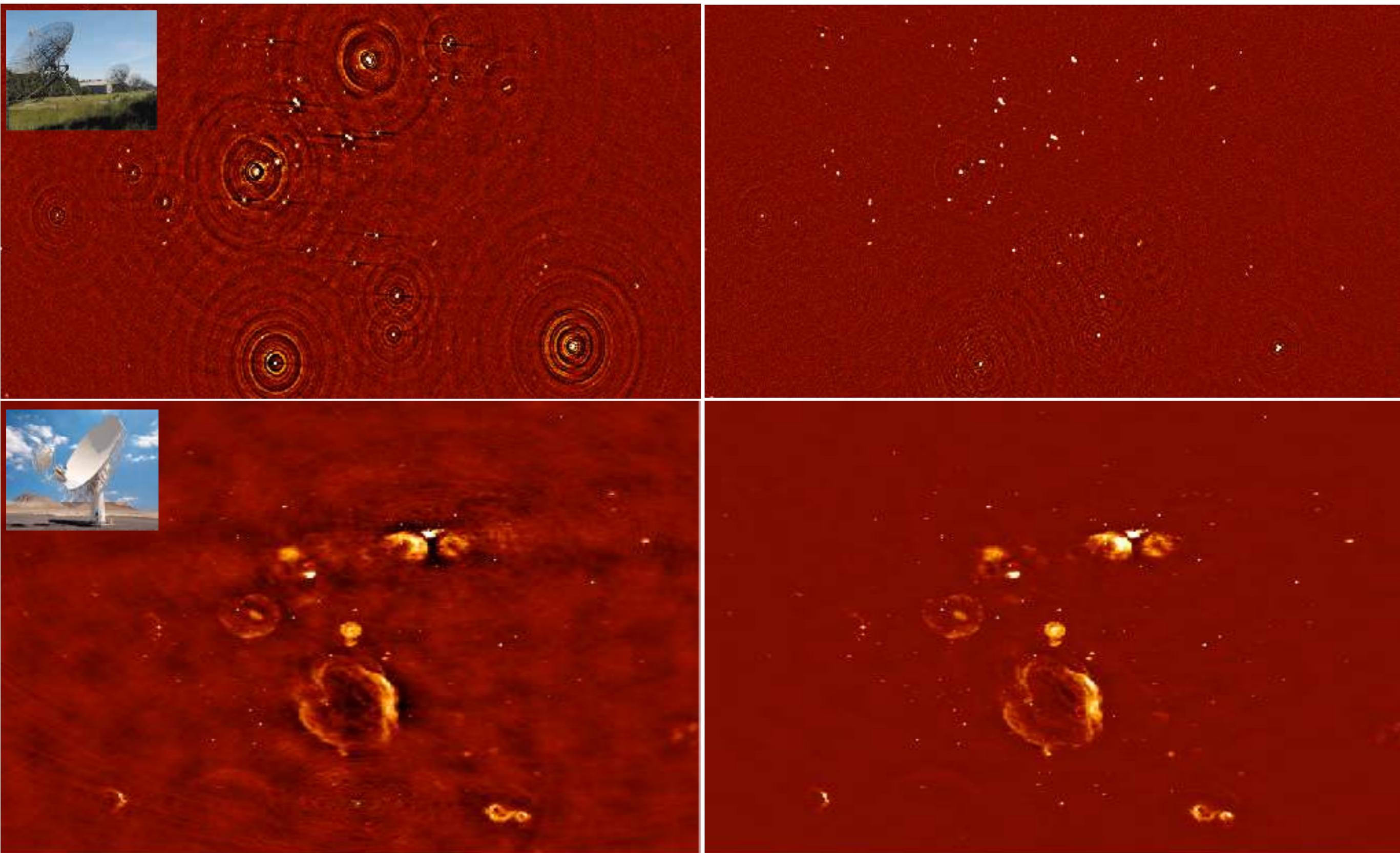
kMS/DDf sur LOFAR

→ polar, effets instrumentaux, Optique Adaptative numérique

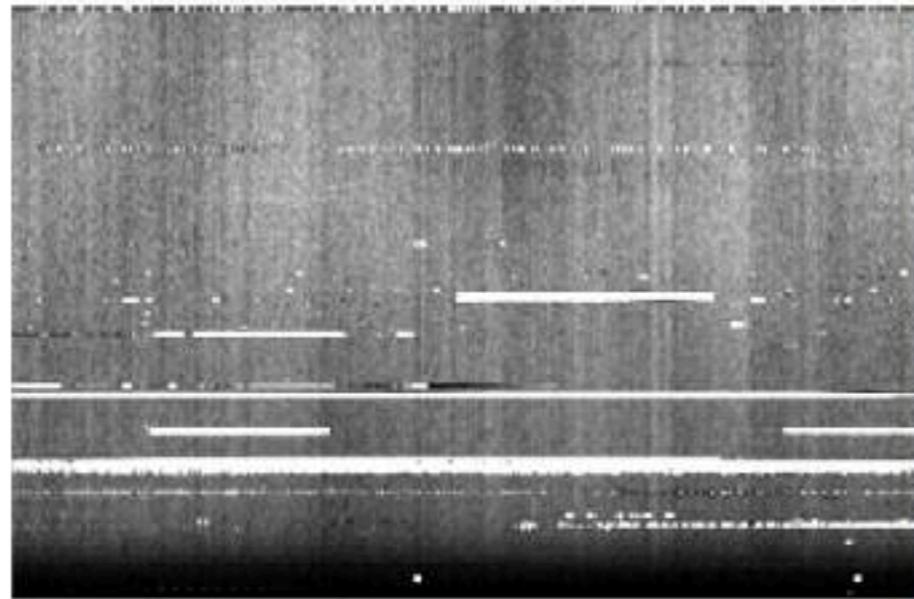
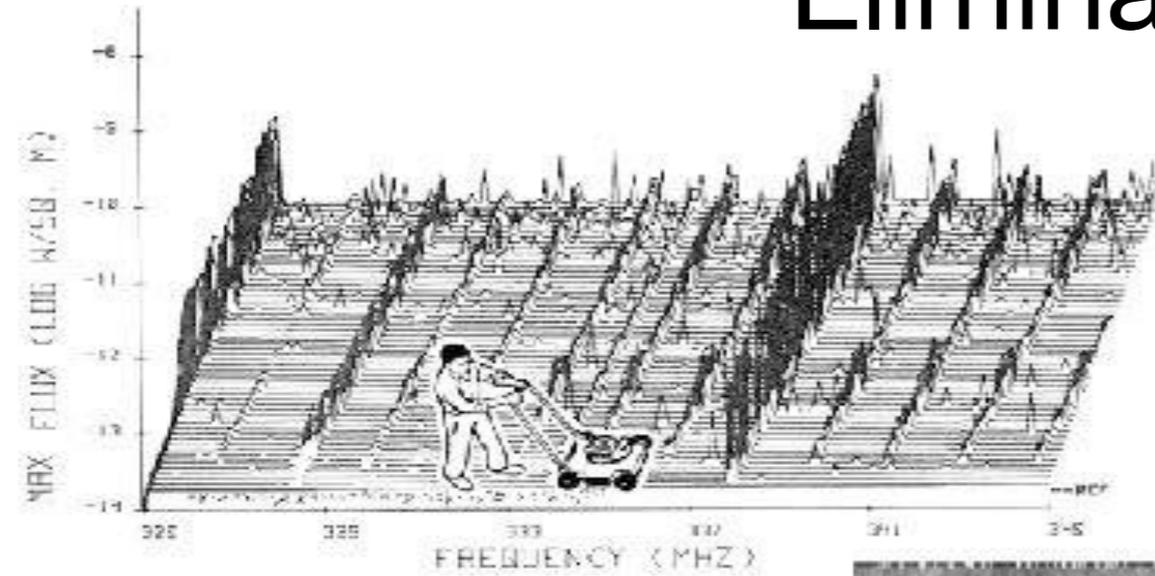


Calibration & Imagerie

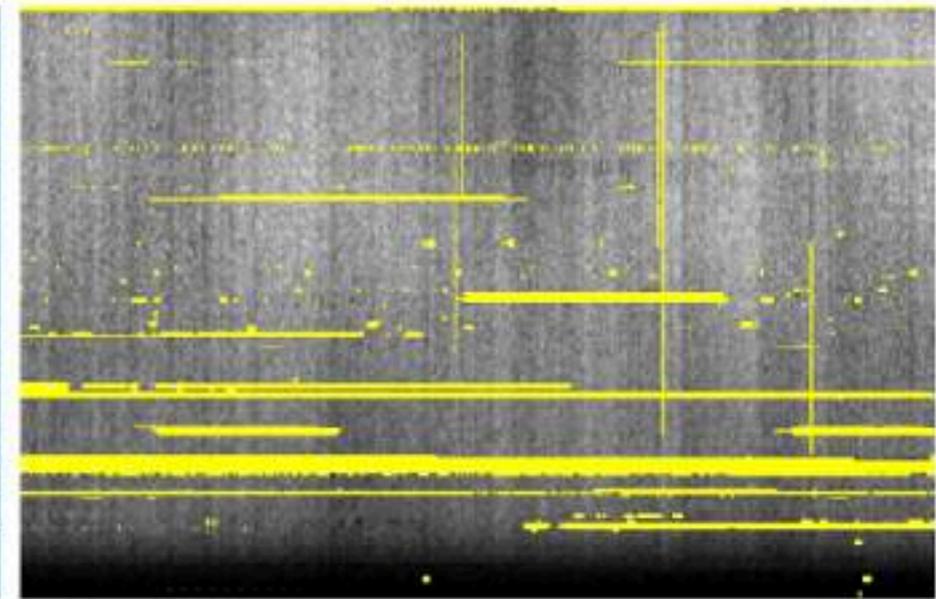
kMS/DDf sur VLA, ATCA, WSRT, GMRT, MeerKAT)



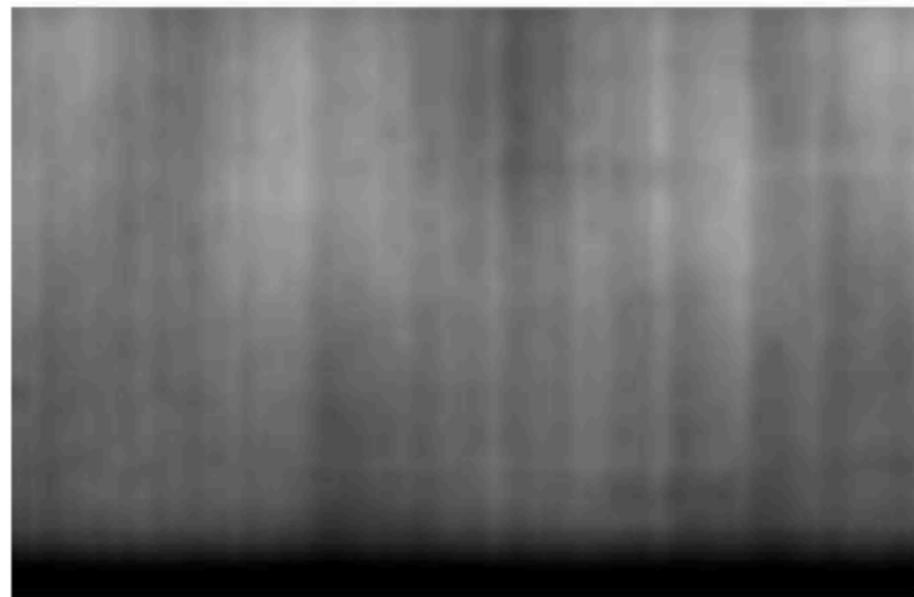
Elimination des parasites



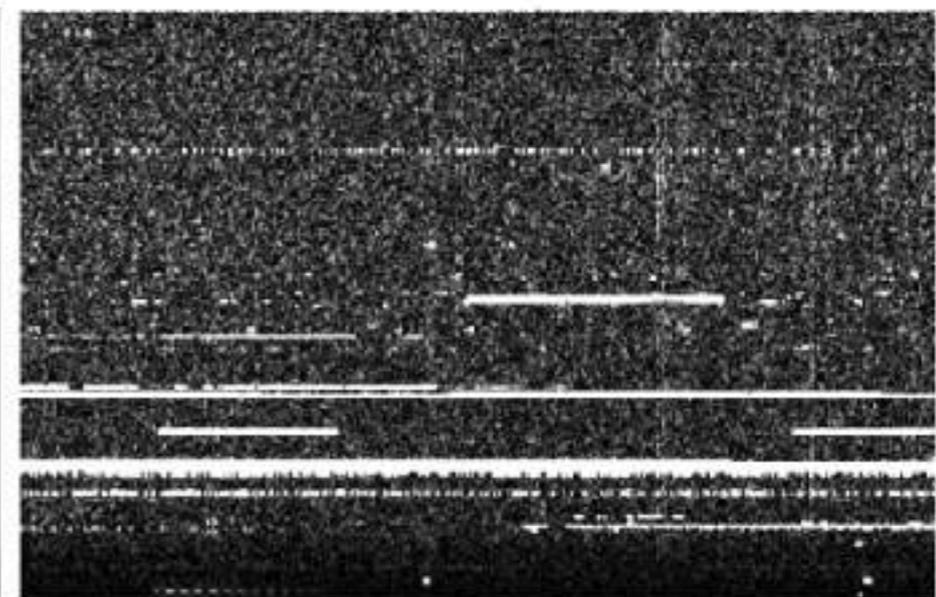
(a) Original



(b) Automated flagging result



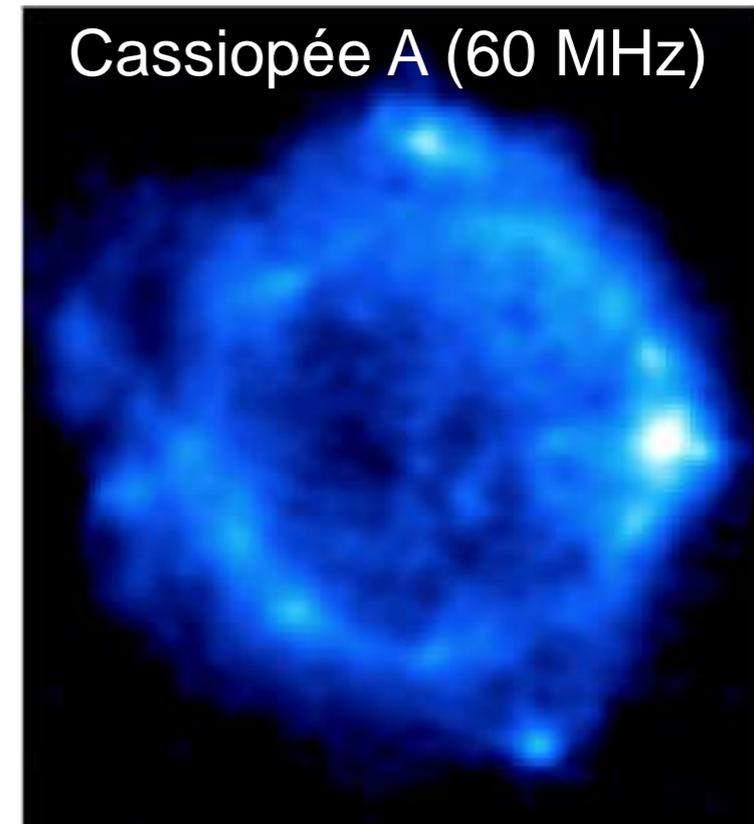
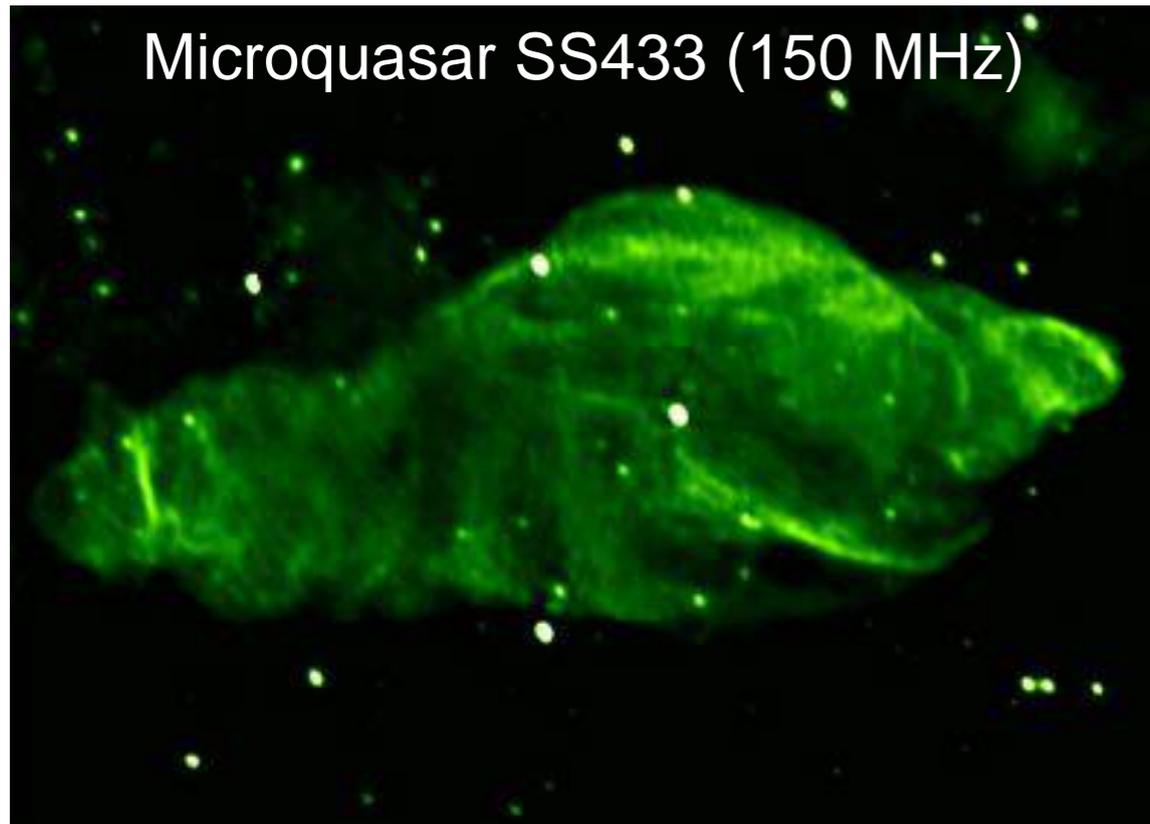
(c) Smoothed



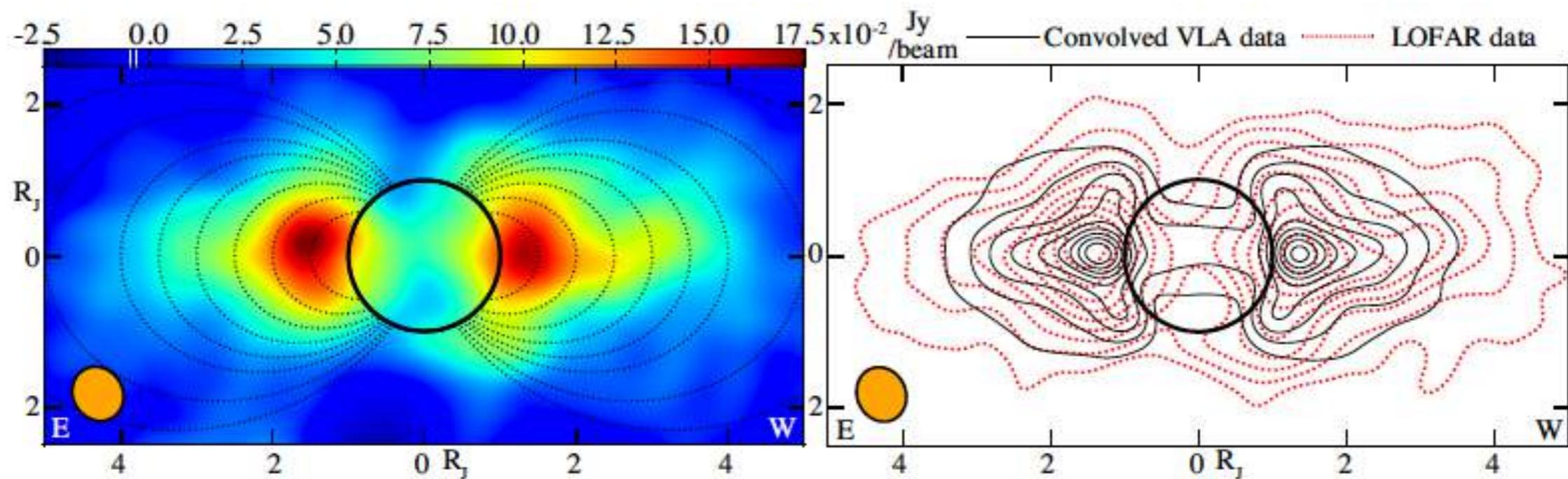
(d) Difference

[Offringa, 2012]

Quelques observations de LOFAR en imagerie

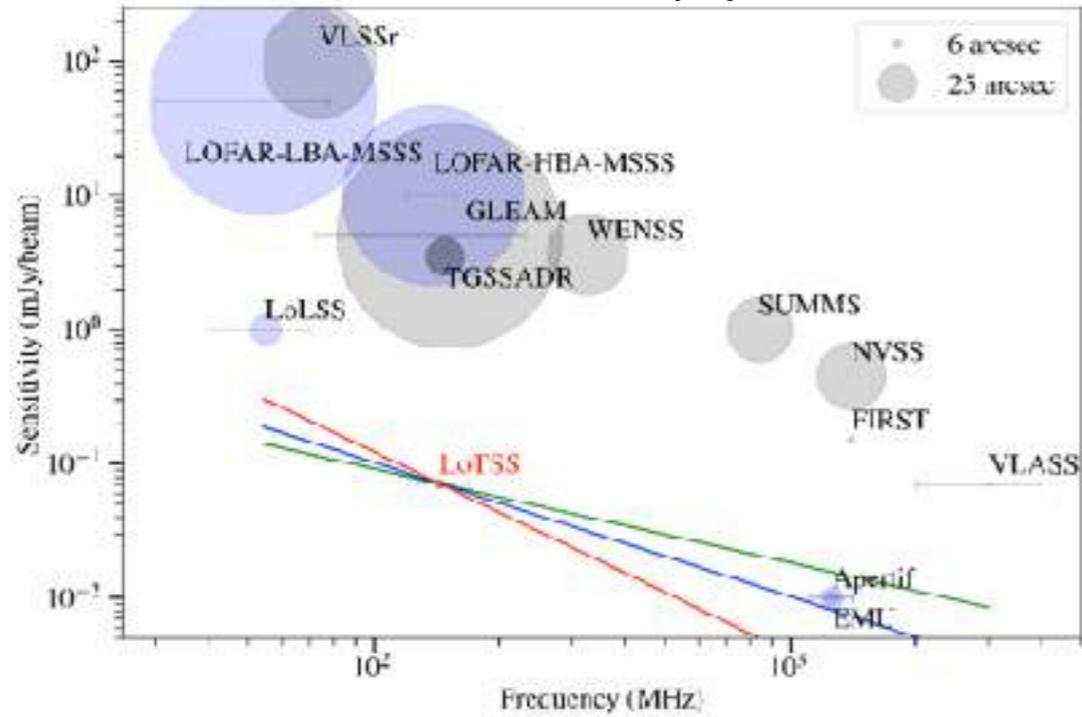


Jupiter (120-170 MHz)

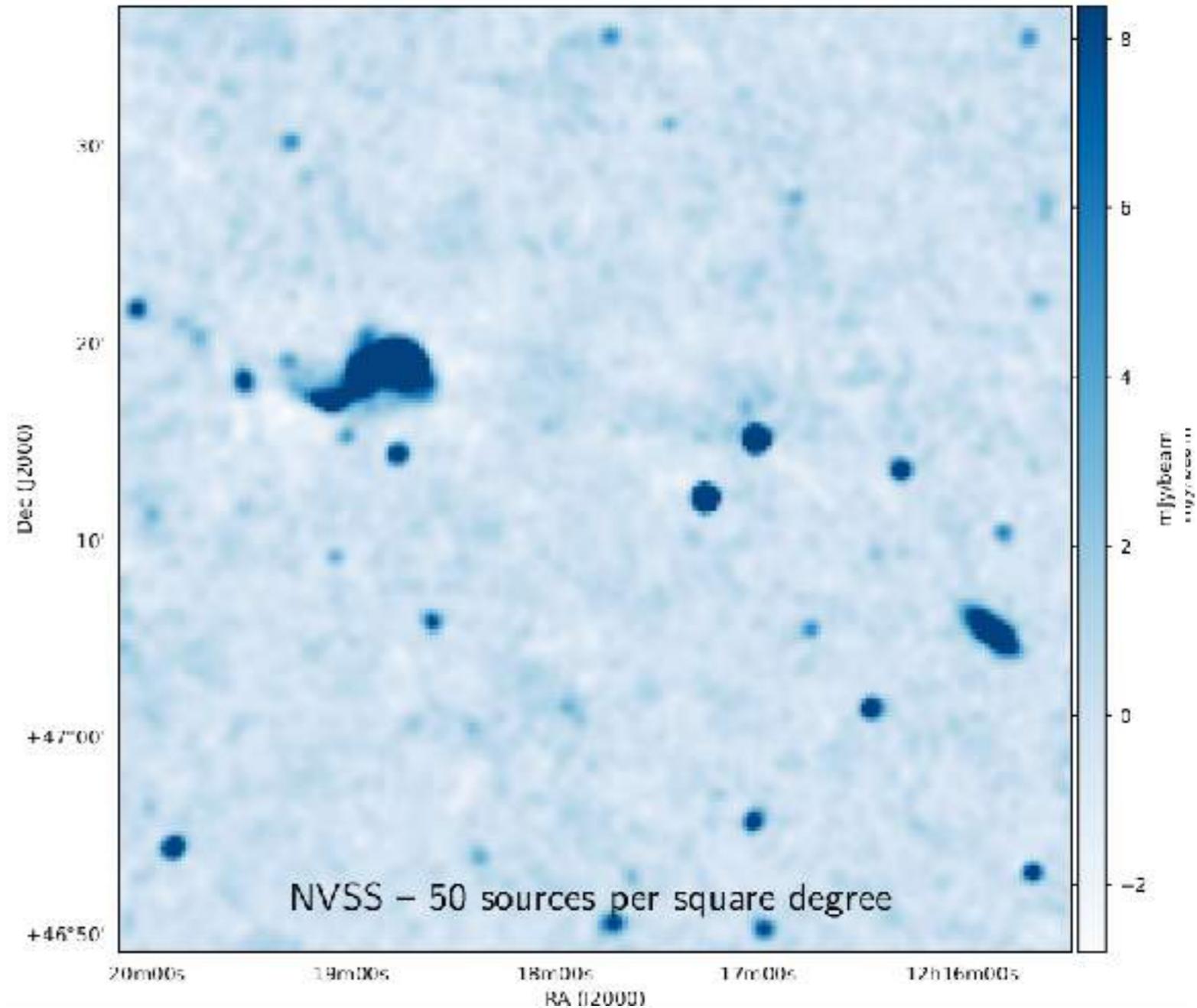


LOFAR Two-meter Sky Survey : LOTSS

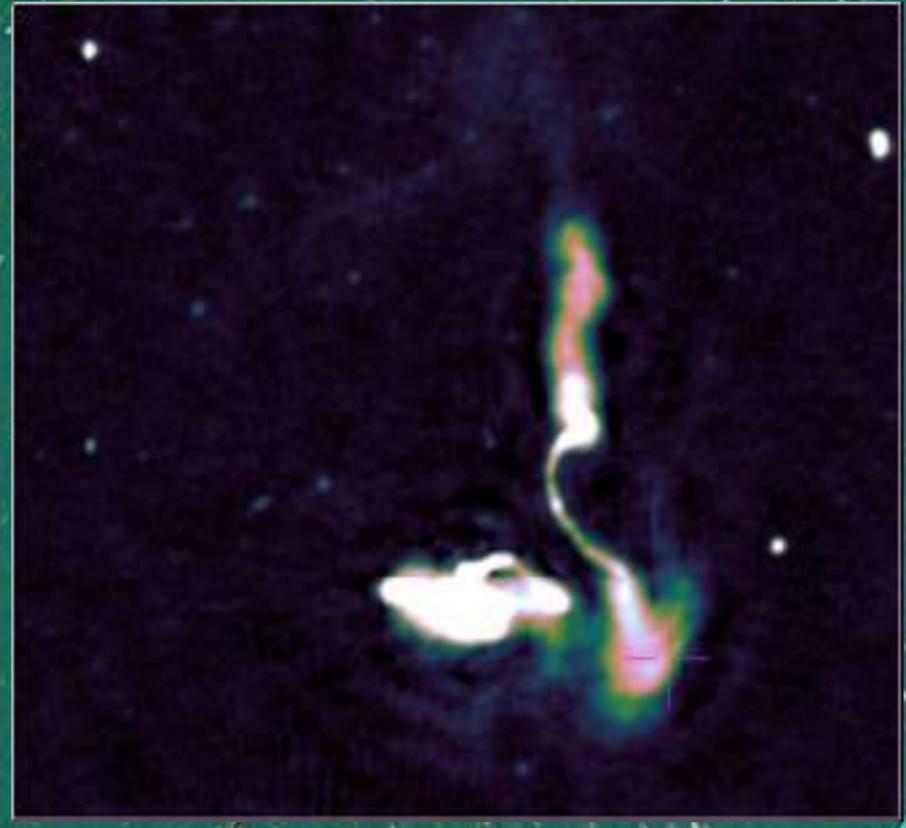
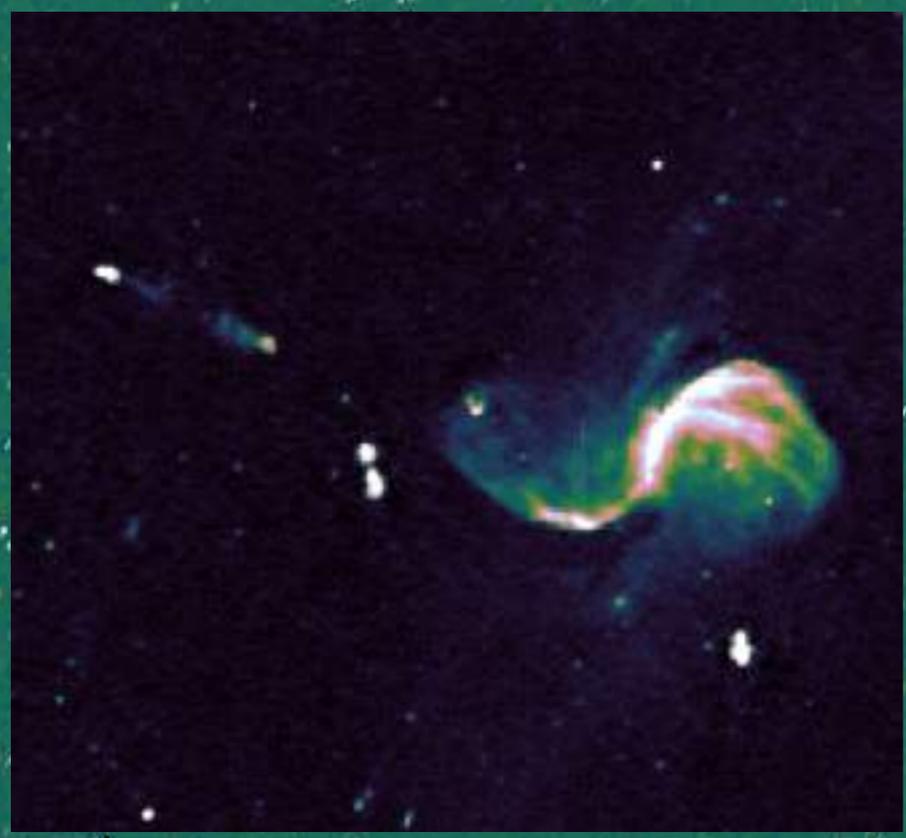
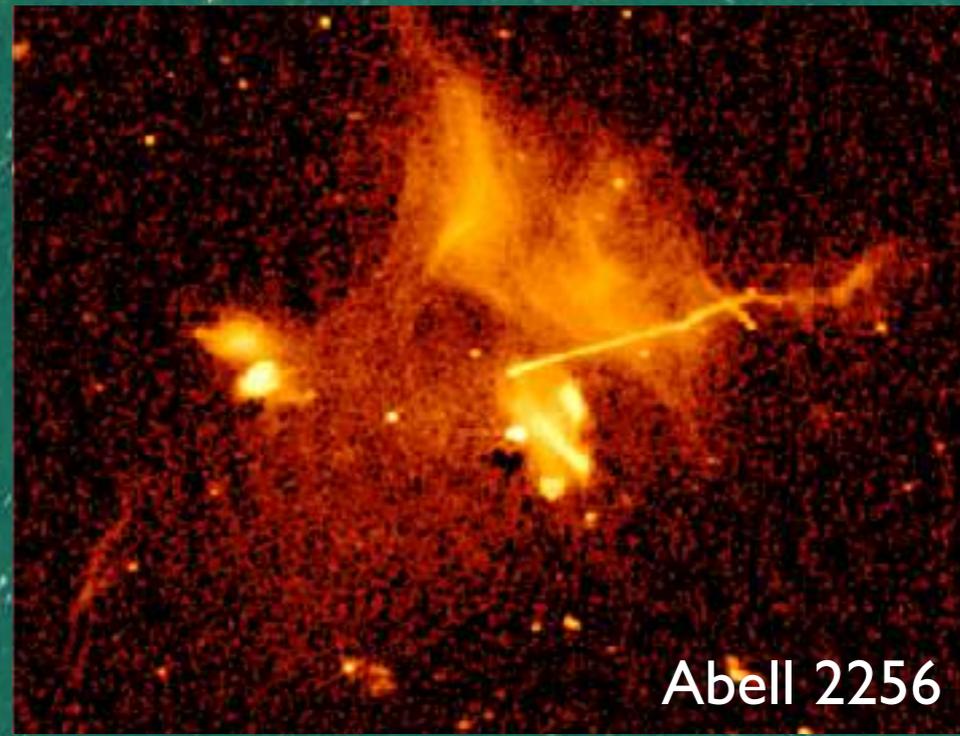
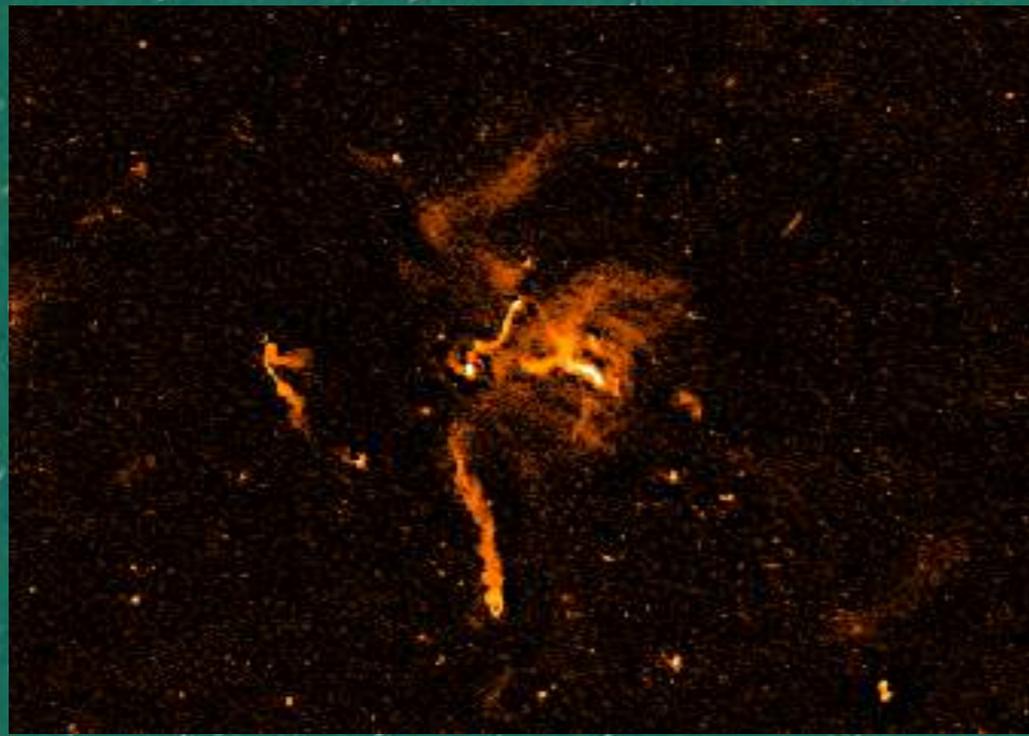
>3000 pointés, hémisphère Nord, Résolution $\approx 5''$
Sensibilité $\approx 100 \mu\text{Jy}/\text{beam}$



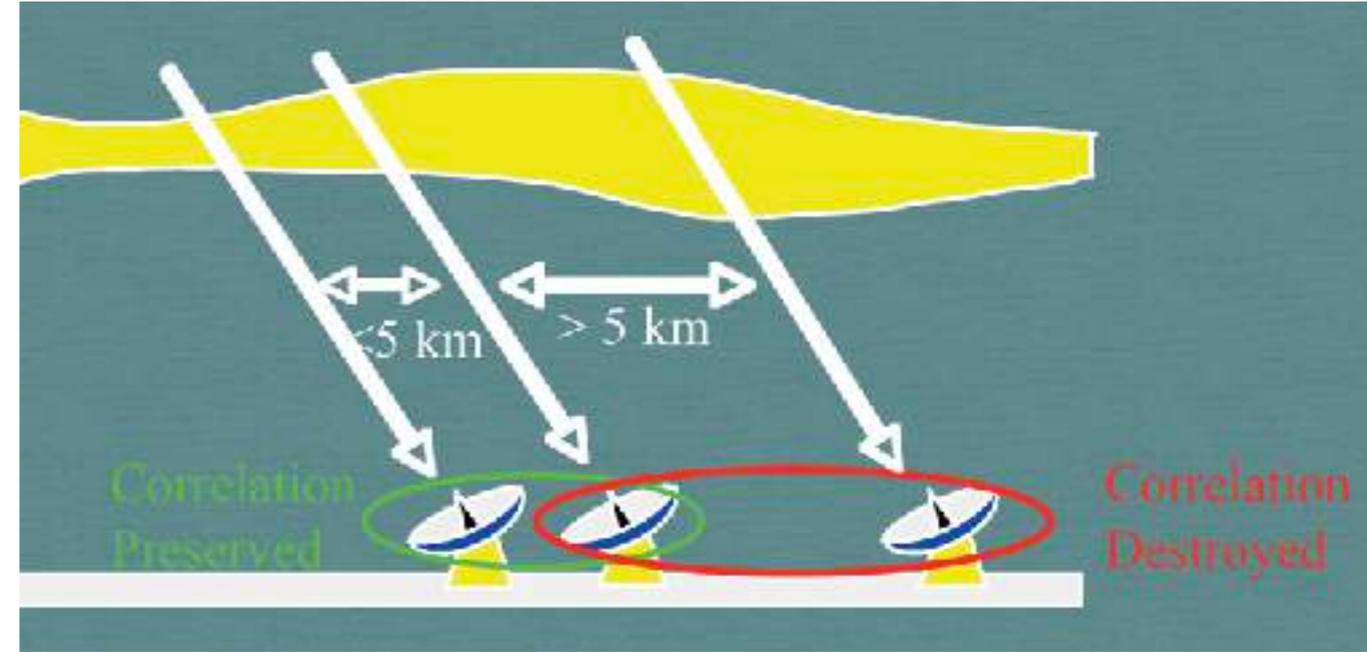
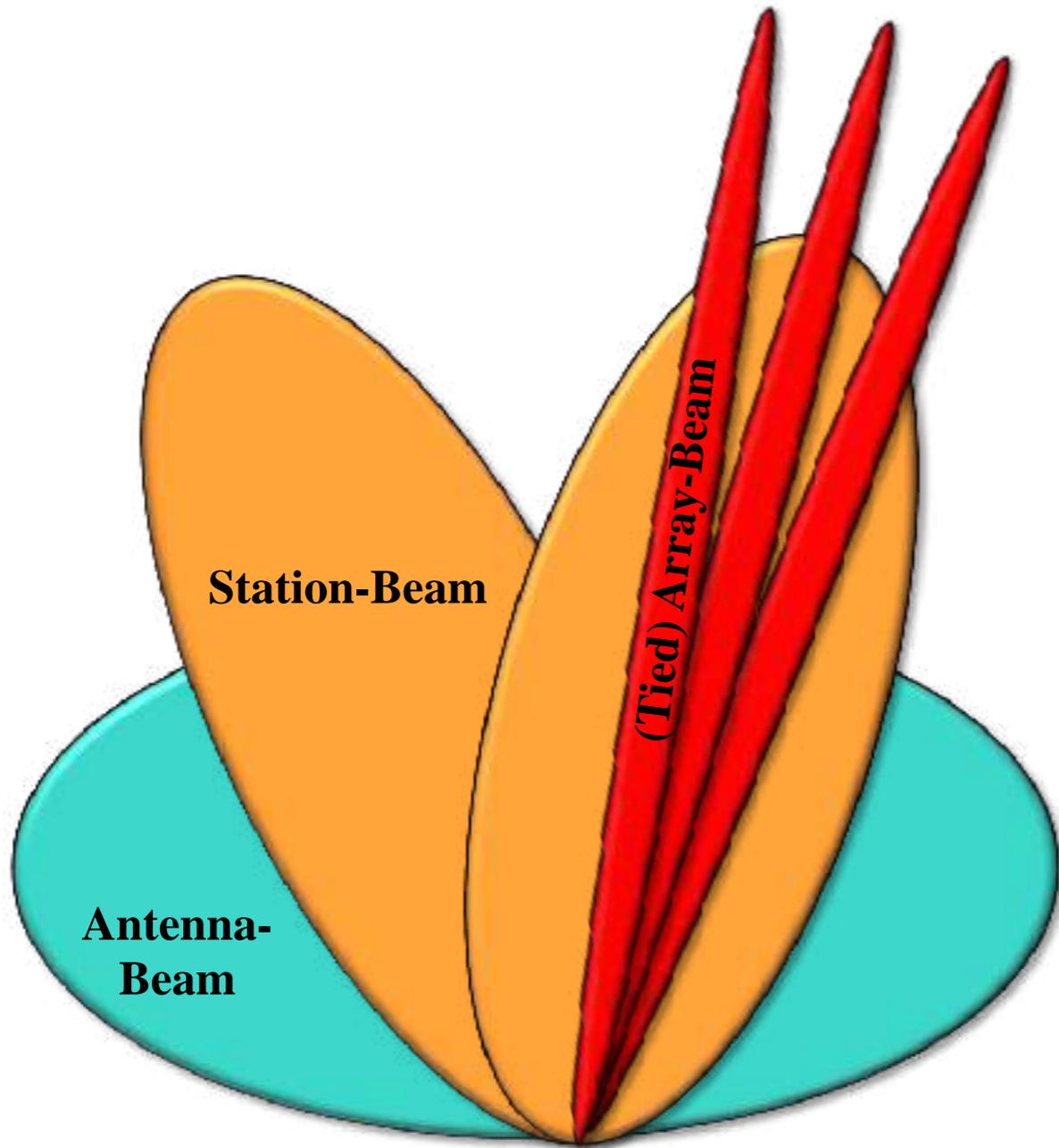
VLA compact, 1.4 GHz



Galaxies & Amas



Mode faisceaux (réseau phasé global)

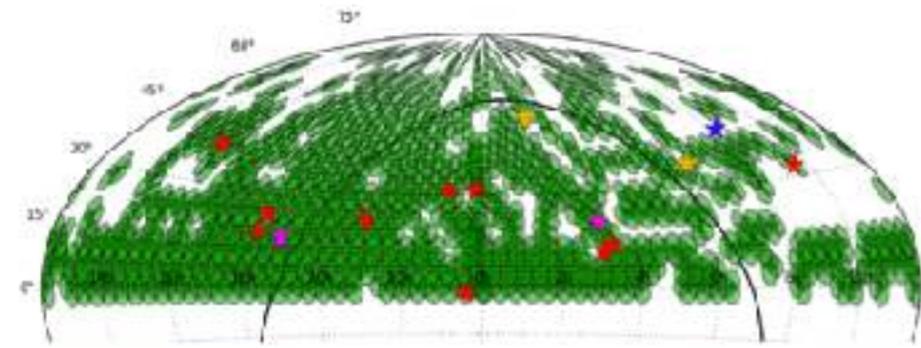


Quelques observations de LOFAR en mode réseau phasé global

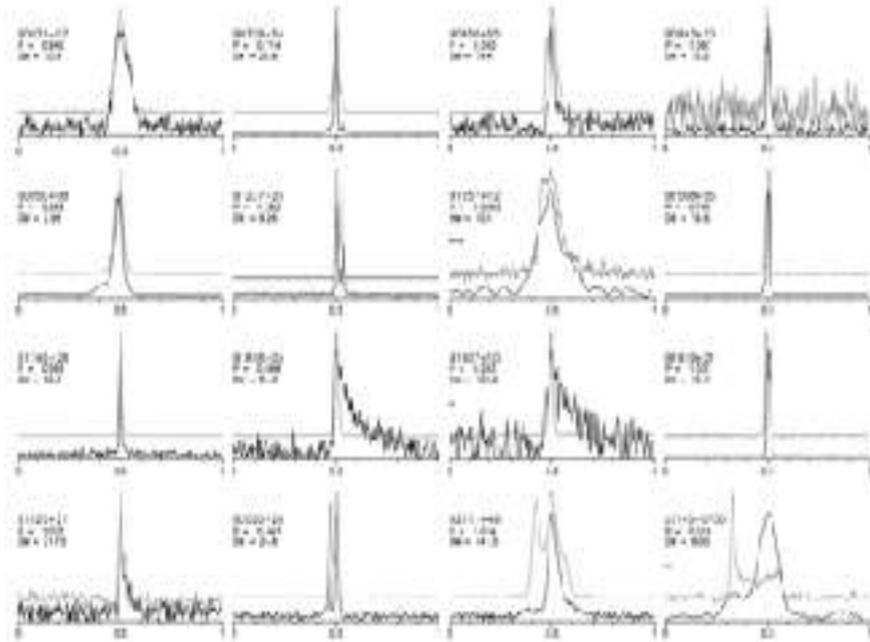
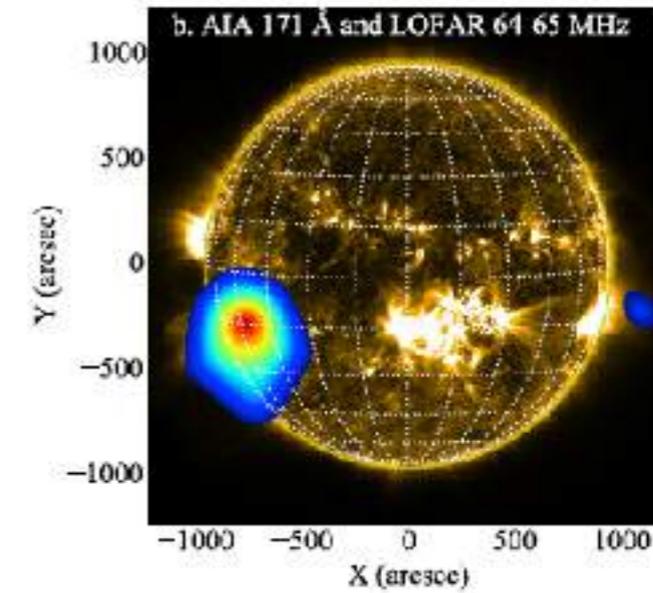
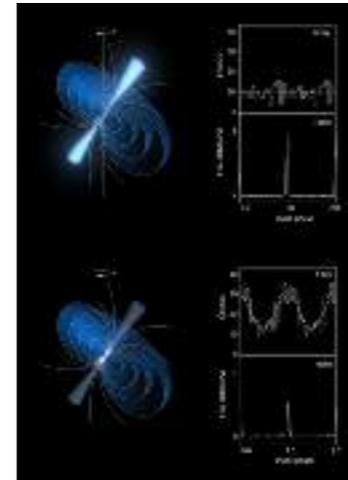
Pulsars

Pulsar bimodal X/radio

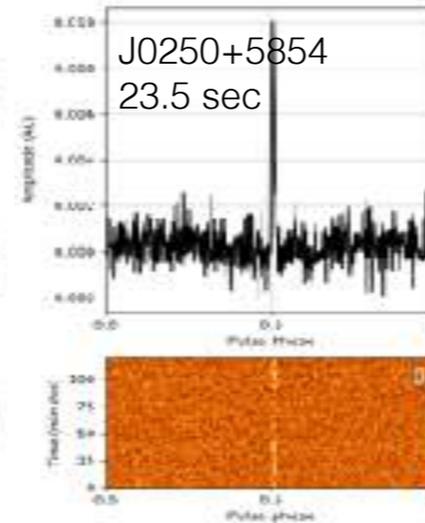
Soleil



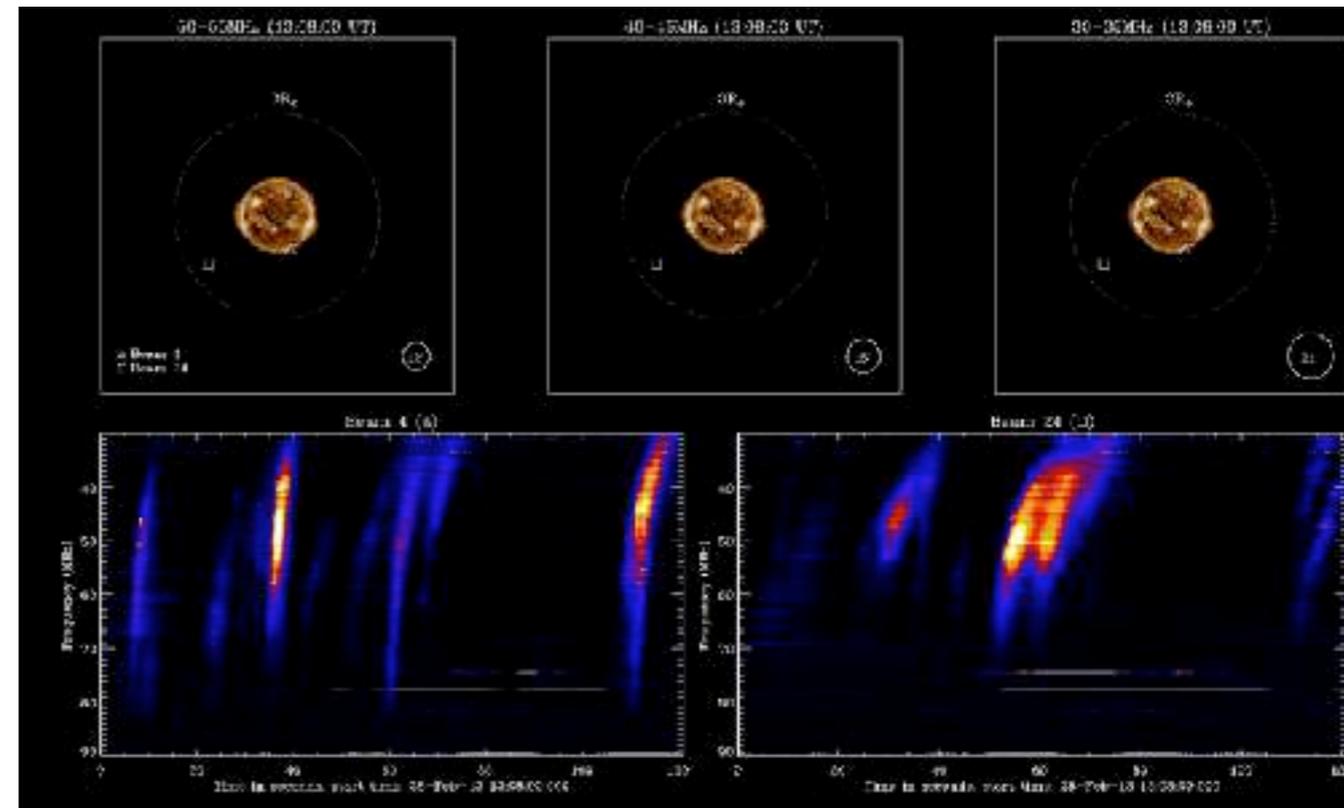
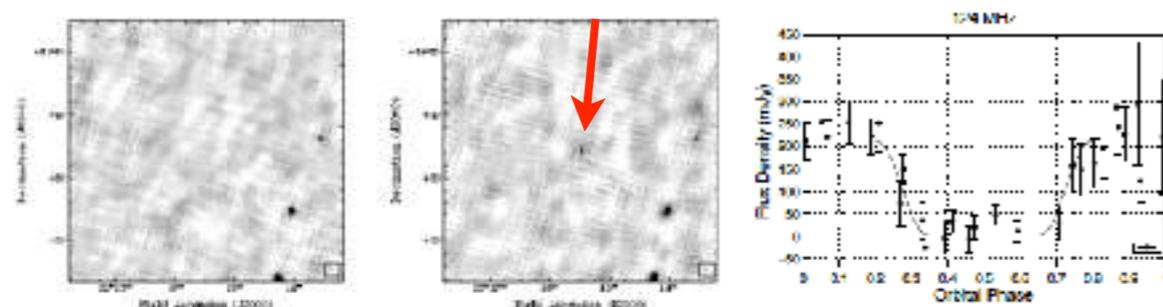
> 100 pulsars découverts



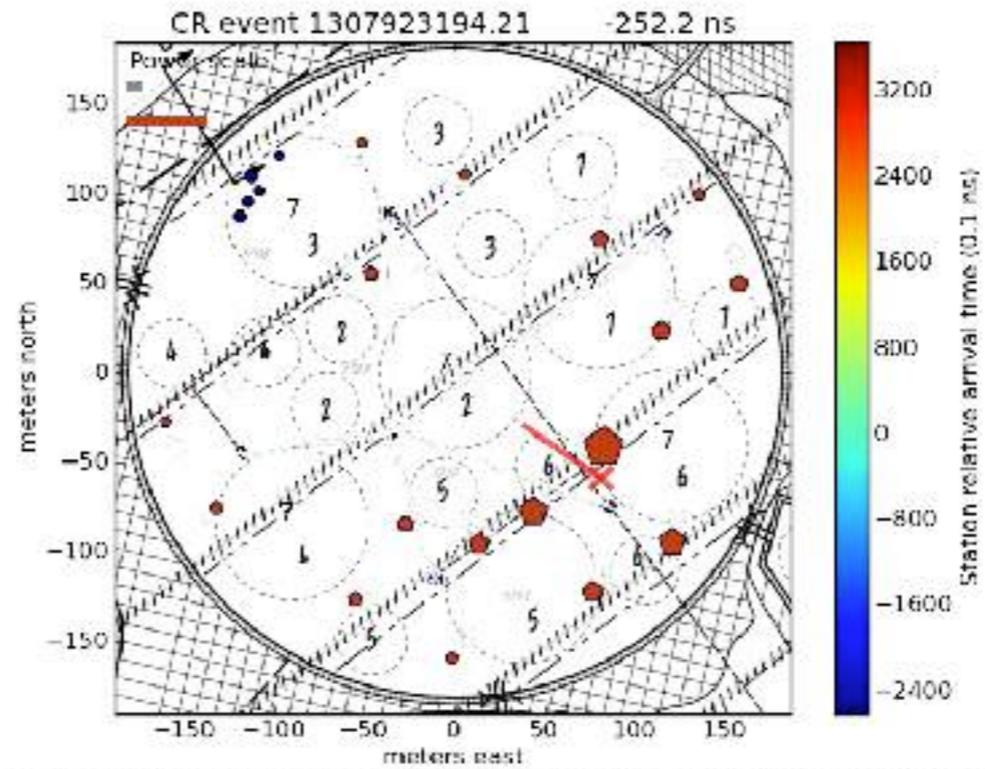
Le pulsar le + lent



J2215+5135 (« redback » à éclipses)



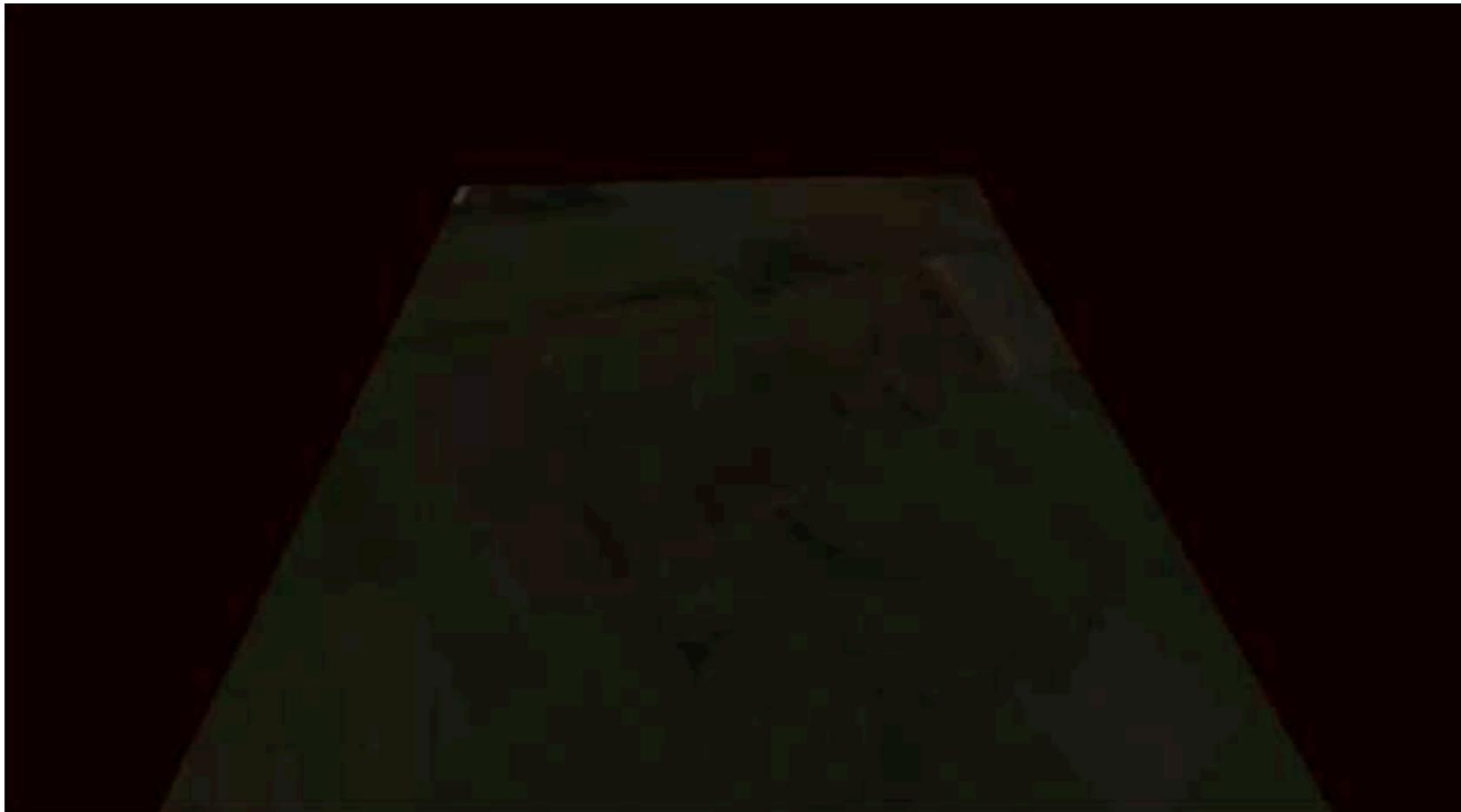
Mode forme d'onde (par station)



Rayons cosmiques

- Direction d'arrivée
- Énergie,
- Profondeur de pénétration
- Composition

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



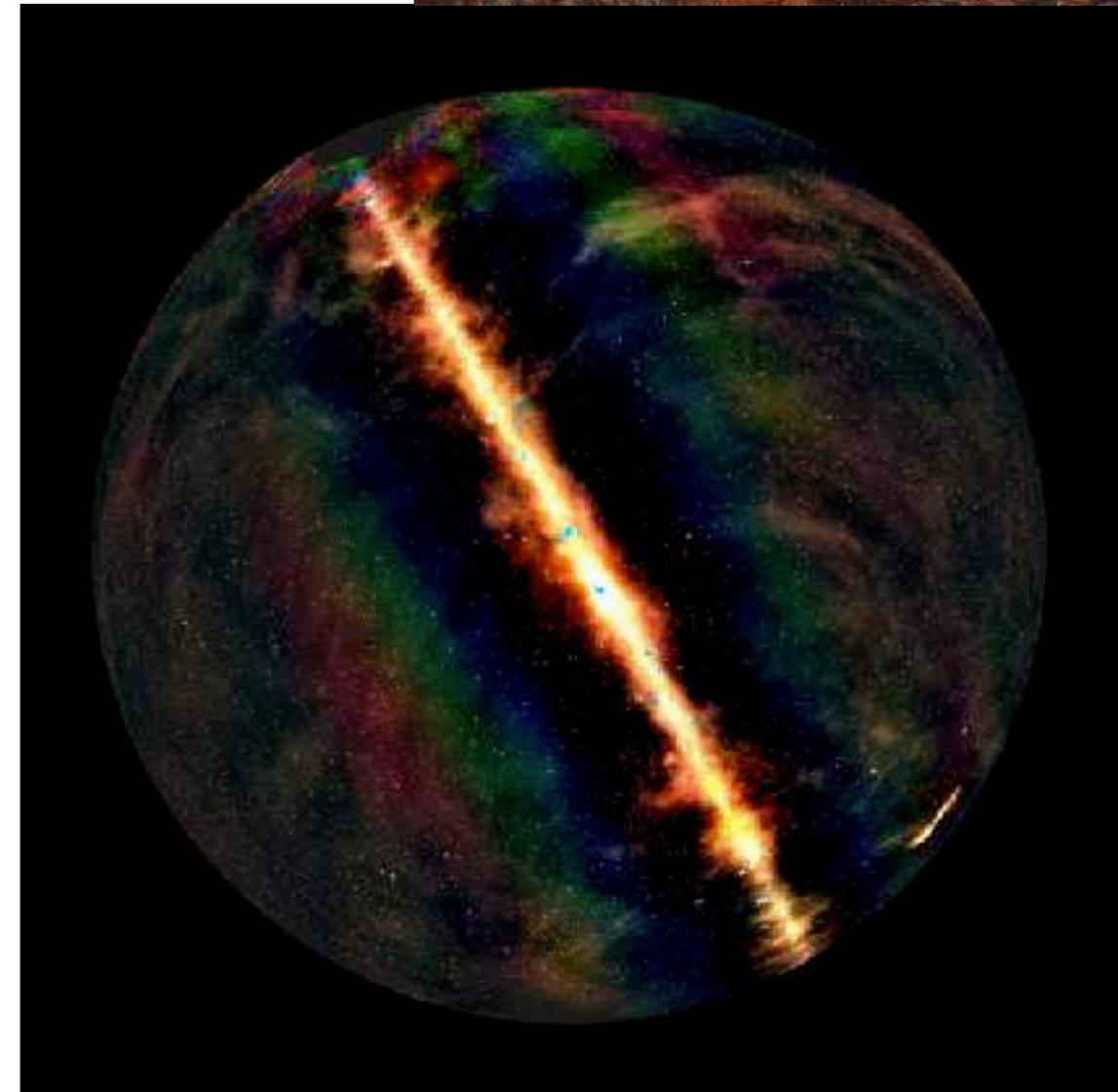
Eclairs d'orages Terrestres

Autres nouveaux radiotélescopes

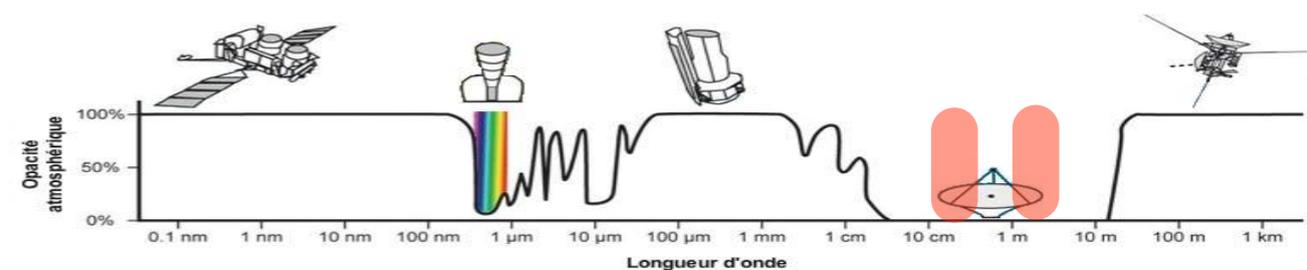


MeerKAT
Centre Galactique
Galaxy Cluster Legacy
~1.4 GHz

MWA
GLEAM
70-230 MHz



Images extracted from the MeerKAT Galaxy Cluster Legacy Survey (Credit: SARAO, 2022)



Autres nouveaux radiotélescopes

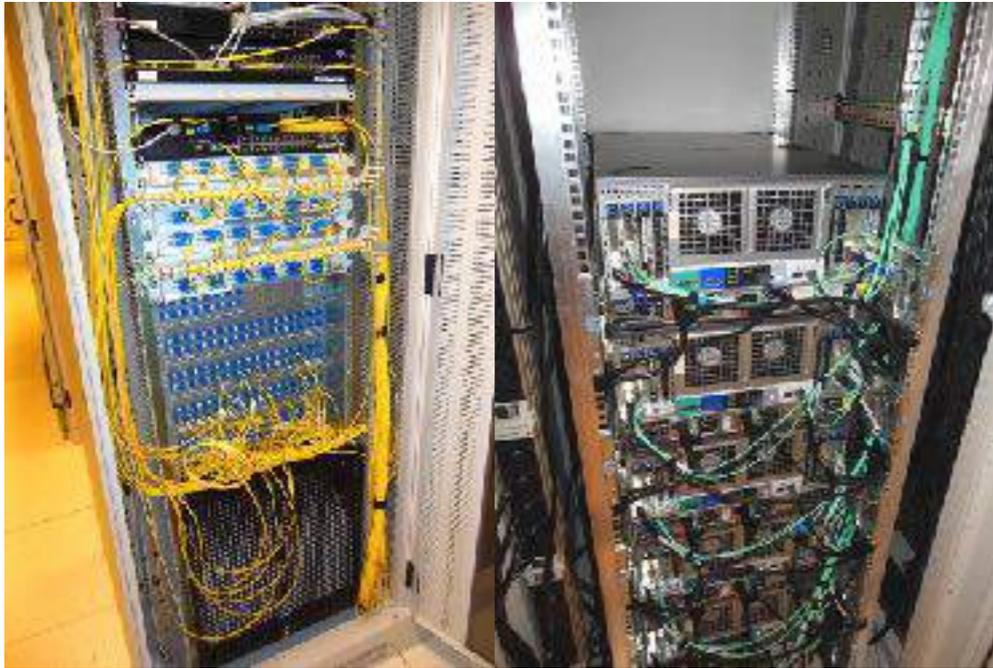
FAST : le géant Chinois



Le coût de la révolution numérique : débit, stockage, traitement des données

LOFAR / COBALT

(grappe de PC CPU/GPU)



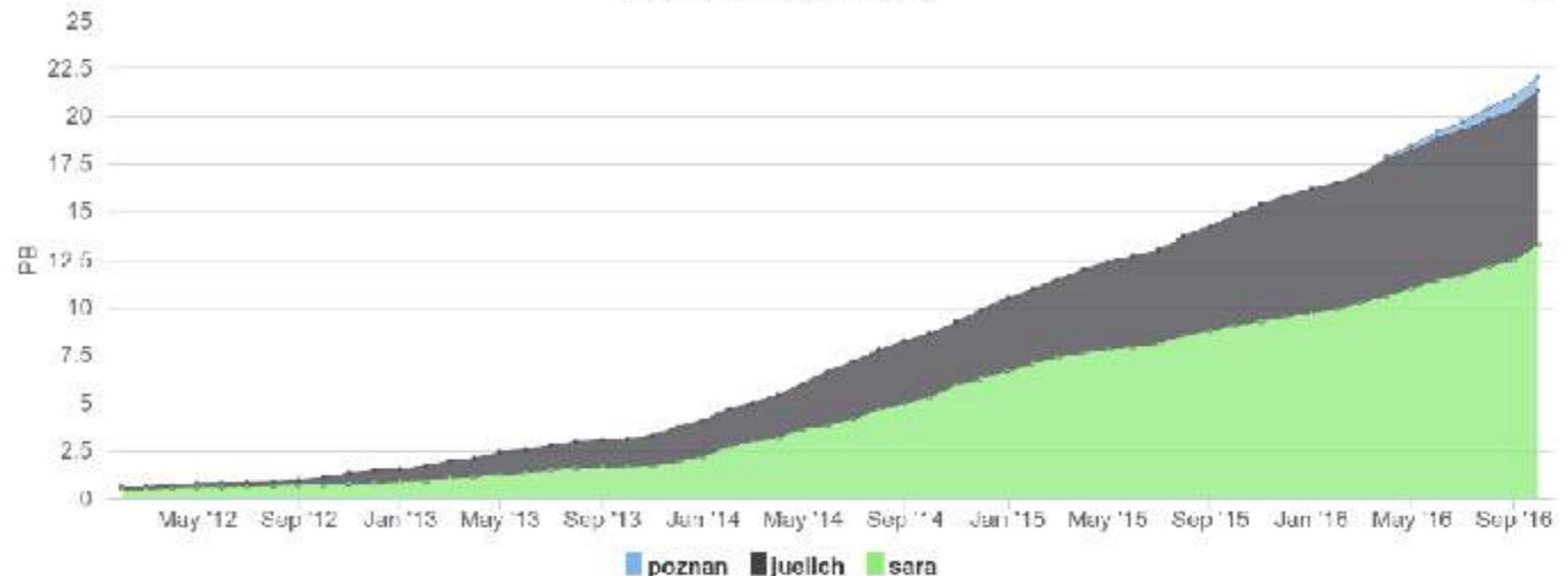
Post-Traitement

(grappe de PC CPU/GPU)



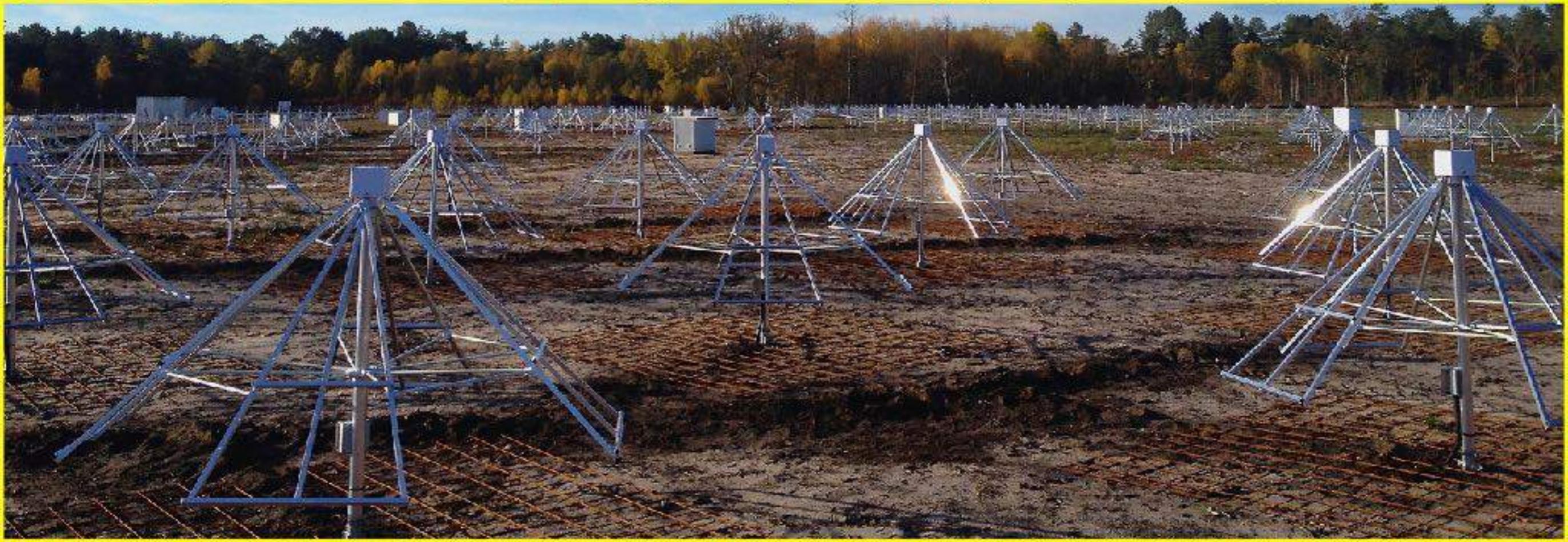
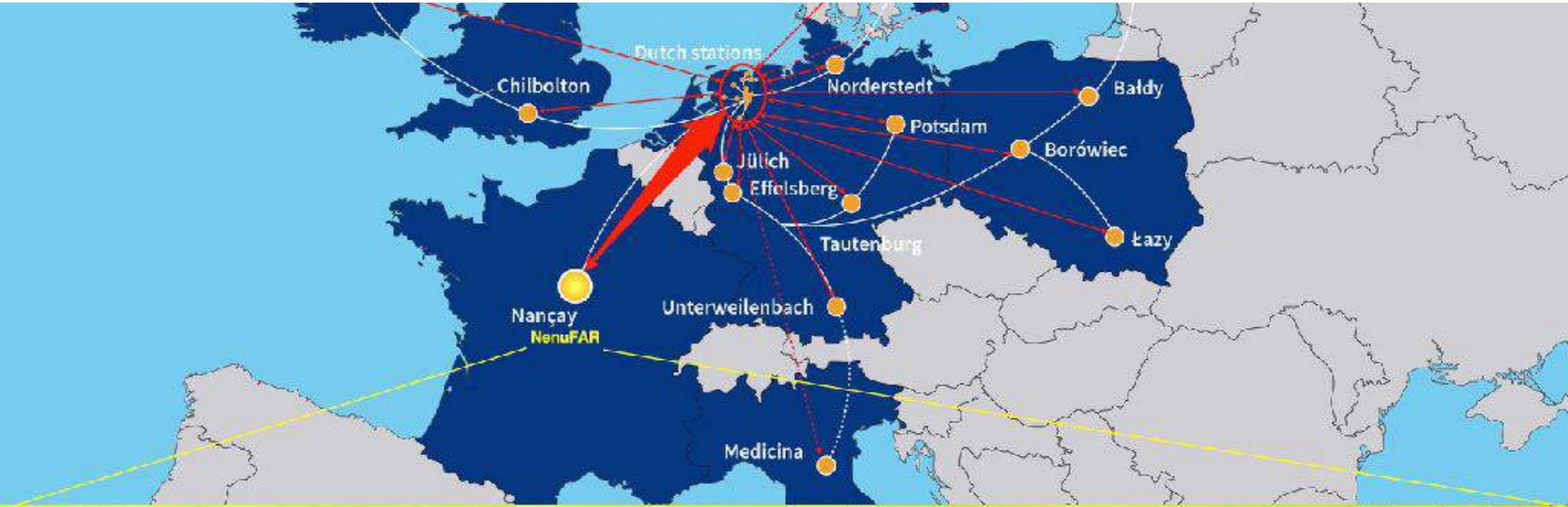
Long Term Archive

>30 Po, 3 sites, 10 M jeux
de données, > 1 Go/s



Vers les très basses fréquences : NenuFAR

New extension in Nançay upgrading LOFAR



NenuFAR

en chiffres...



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



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



96
mini-réseaux



6
mini-réseaux
distants



400 m
de diamètre au
cœur du réseau



180 km
de câbles
coaxiaux



60 000 m²
d'aire effective
à 25 MHz



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



19
antennes dans
1 mini réseau



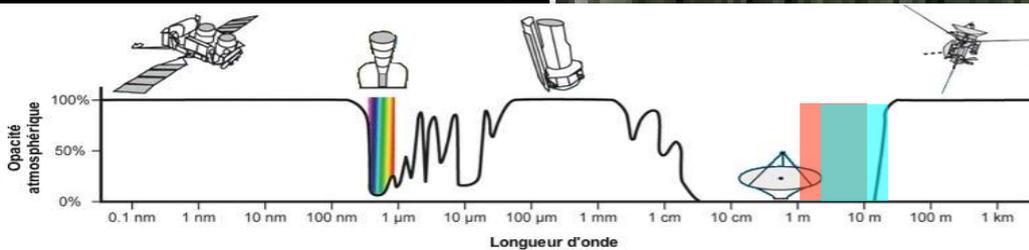
3 km
de distance
au mini-réseau
le plus éloigné



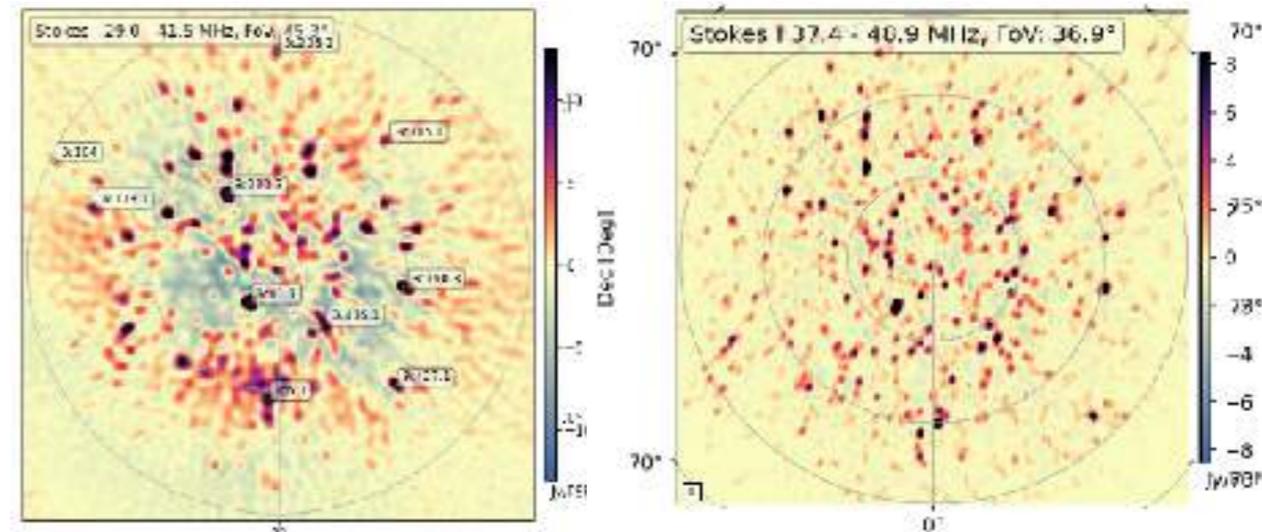
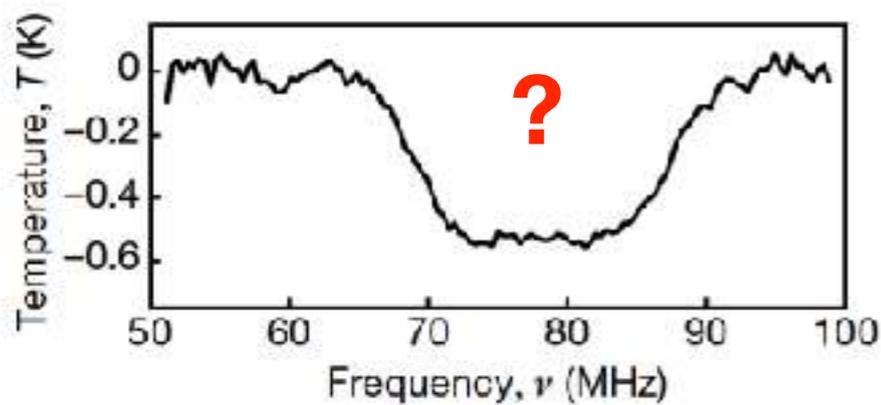
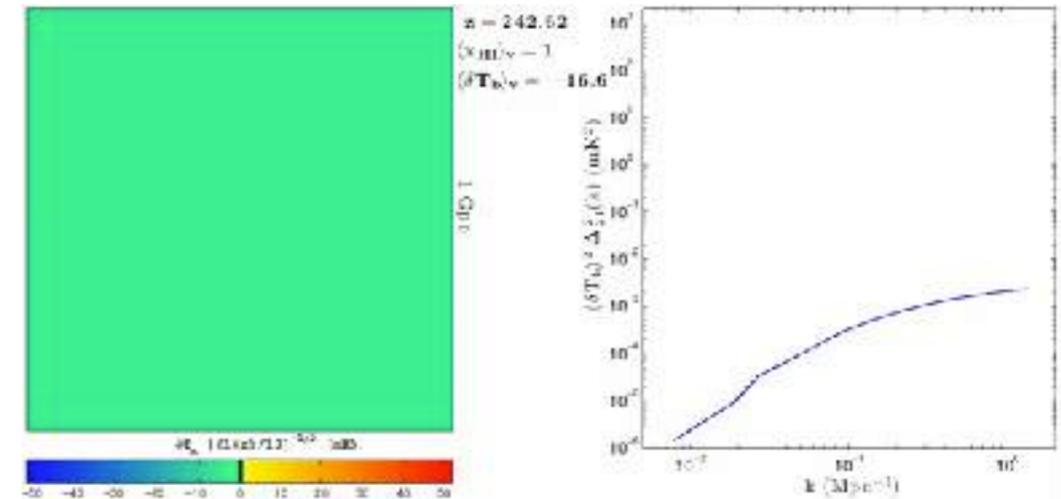
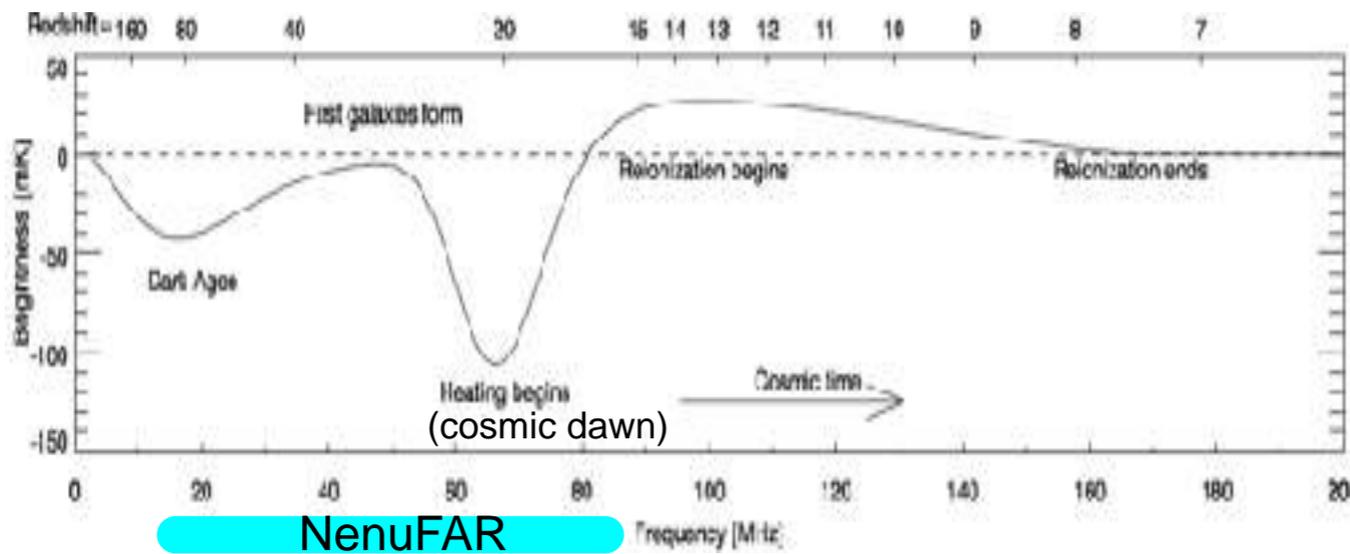
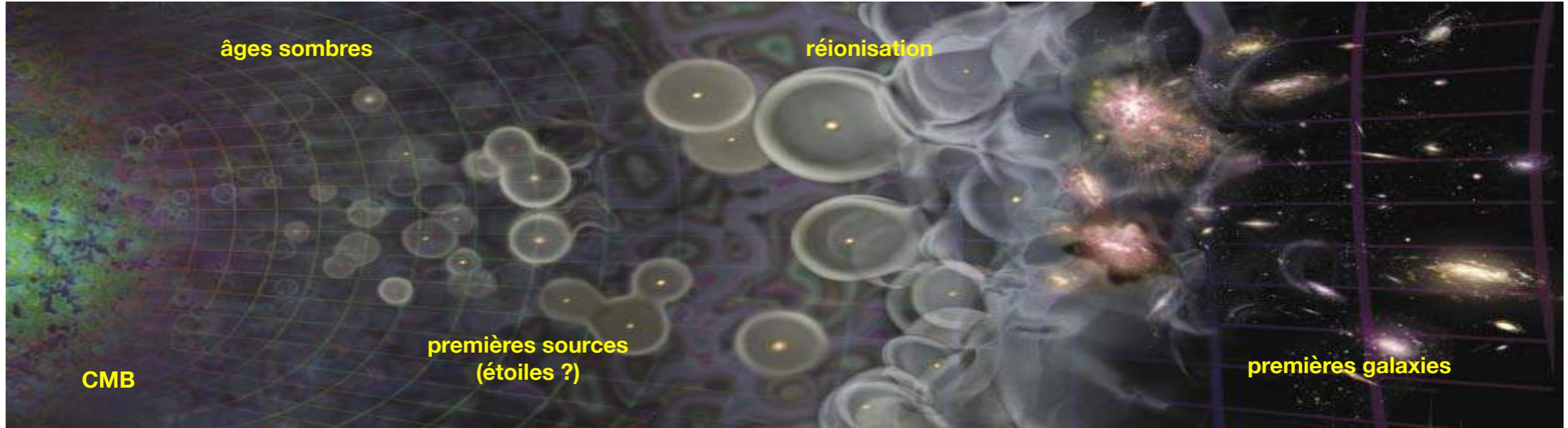
600 Gbits/s
de volume de données
traitées en temps réel
24/7



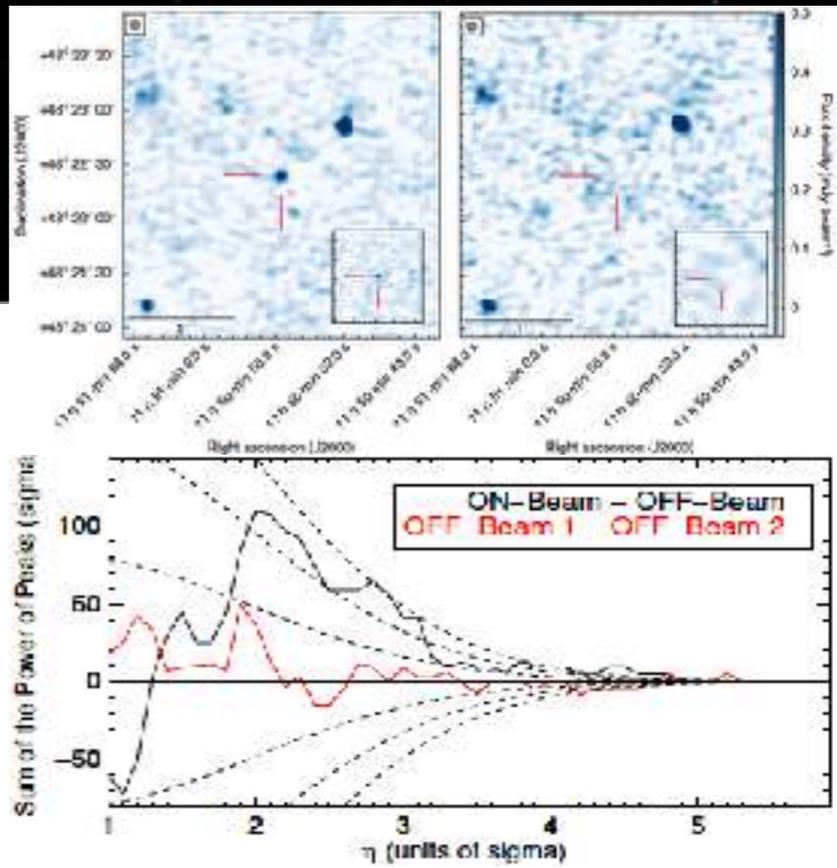
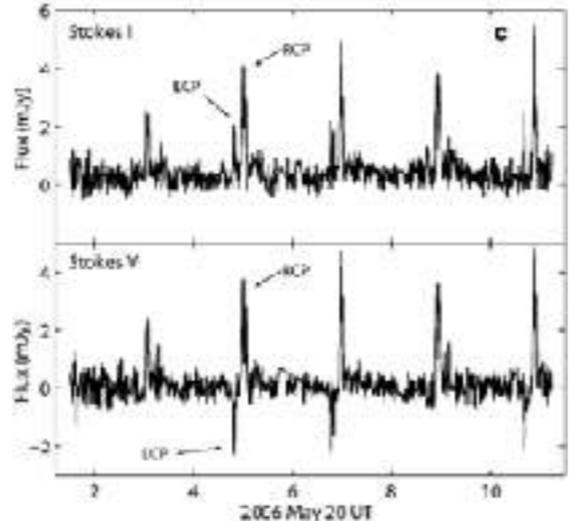
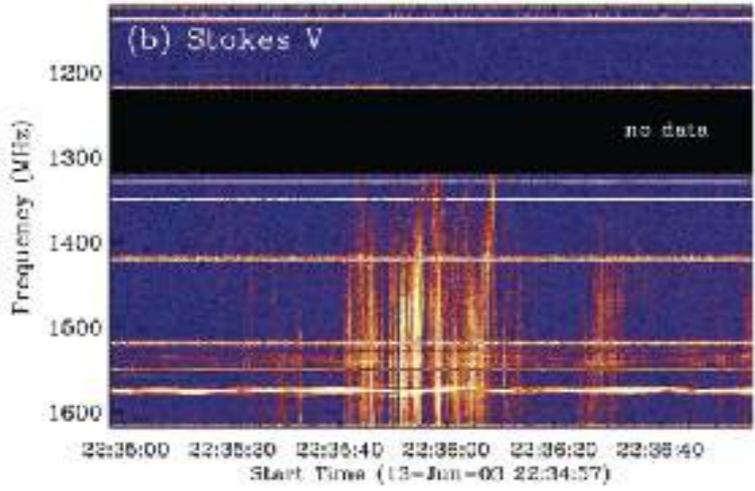
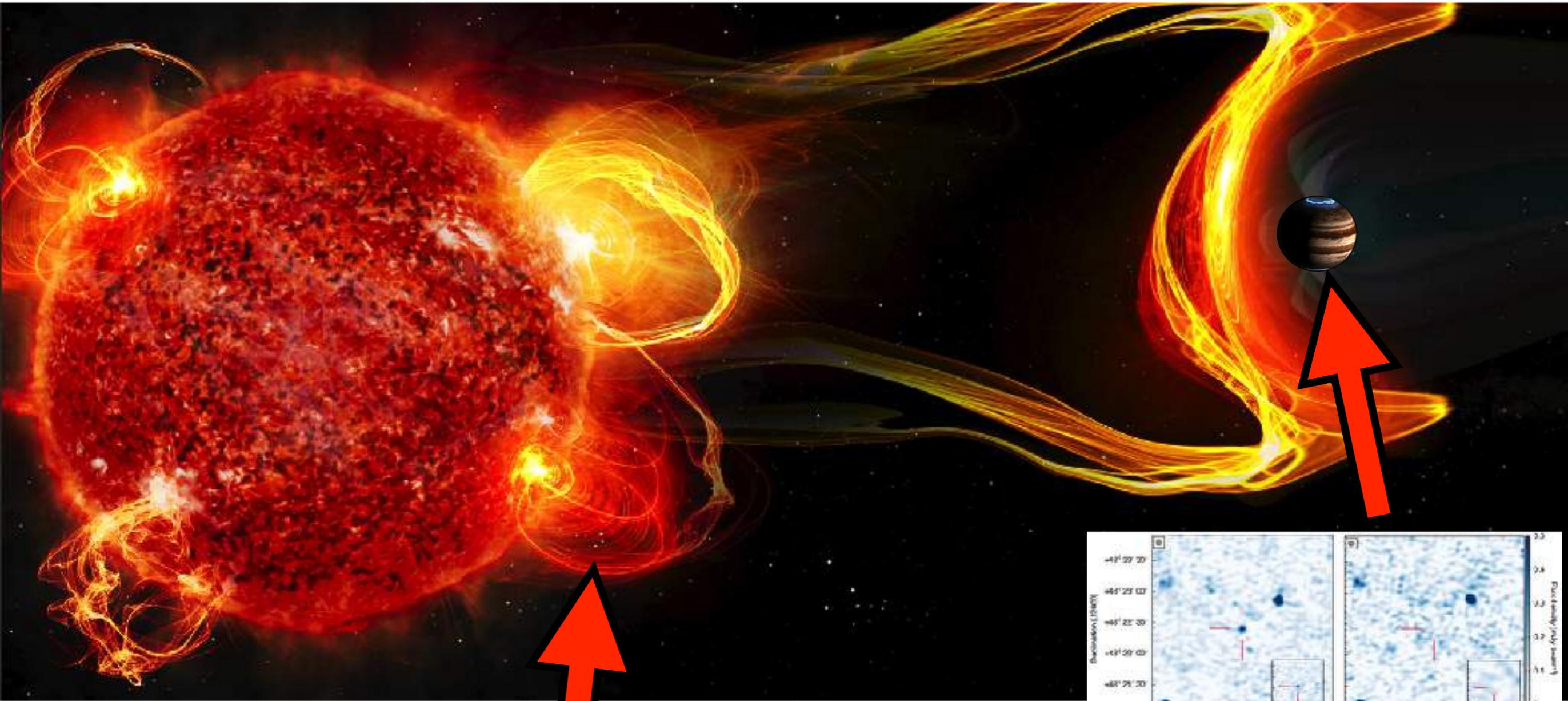
10 Po
de données brutes
traitées par an



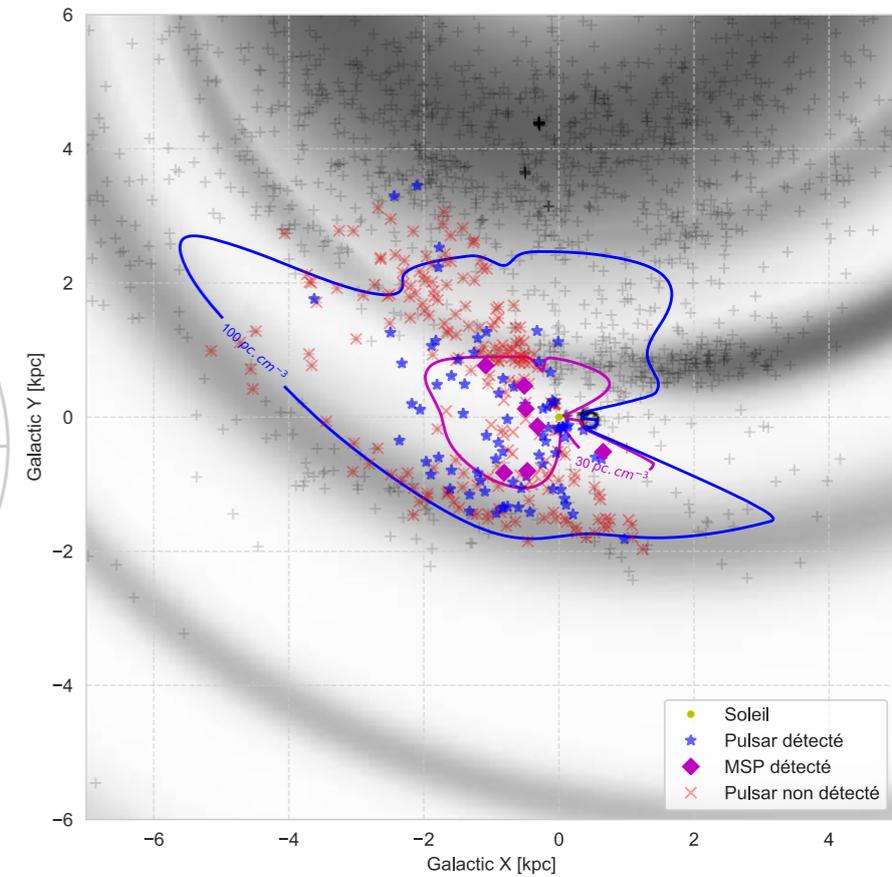
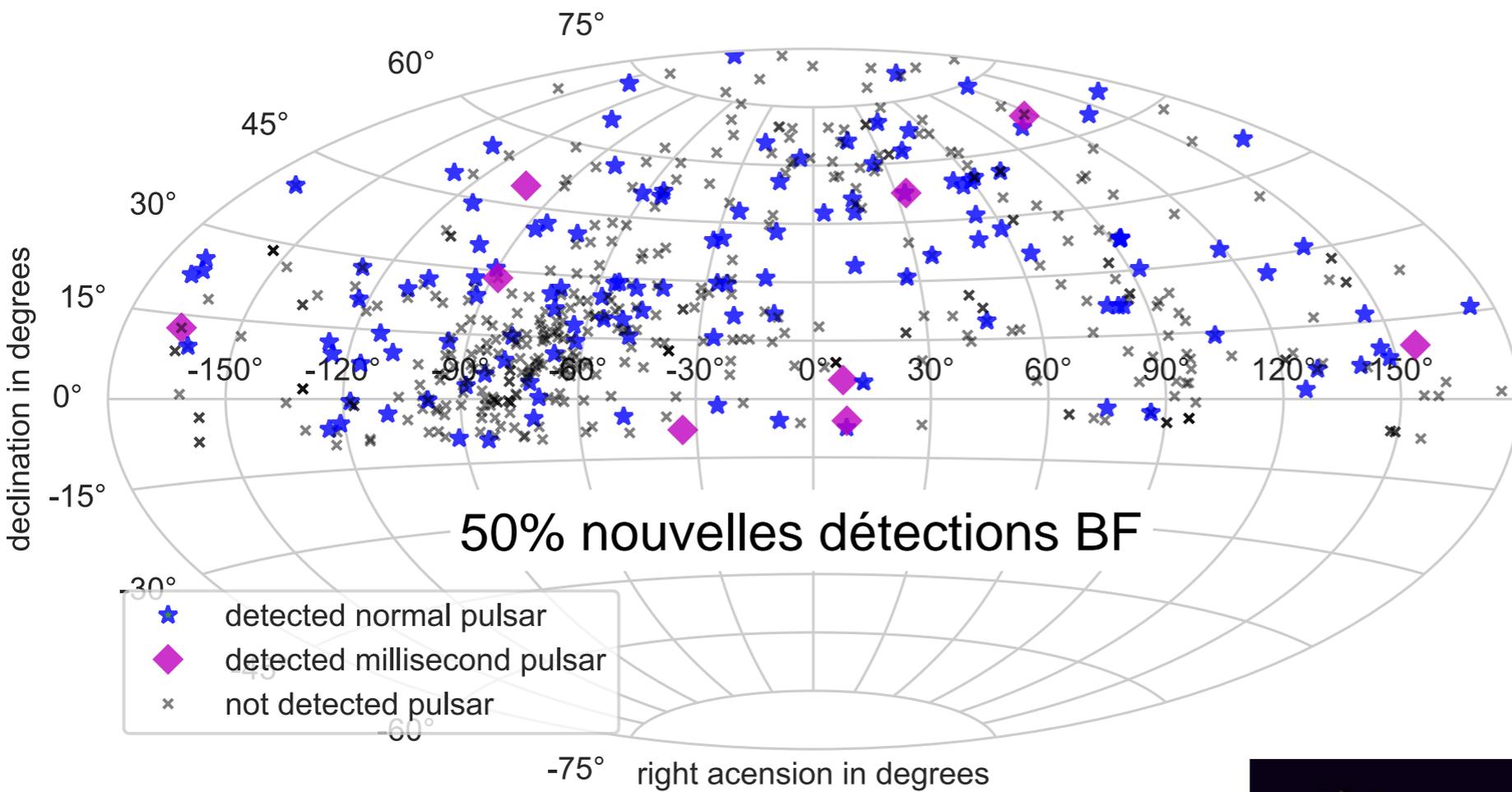
La science de NenuFAR : Aube Cosmique



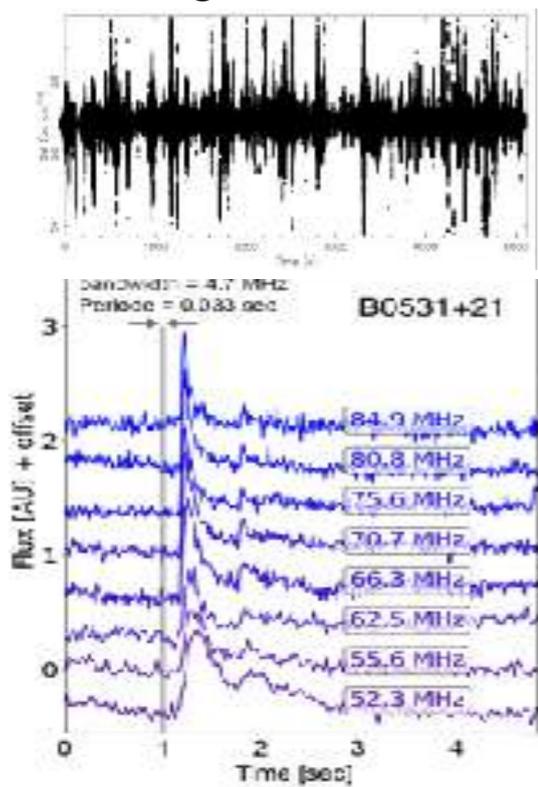
La science de NenuFAR : Étoiles & Exoplanètes



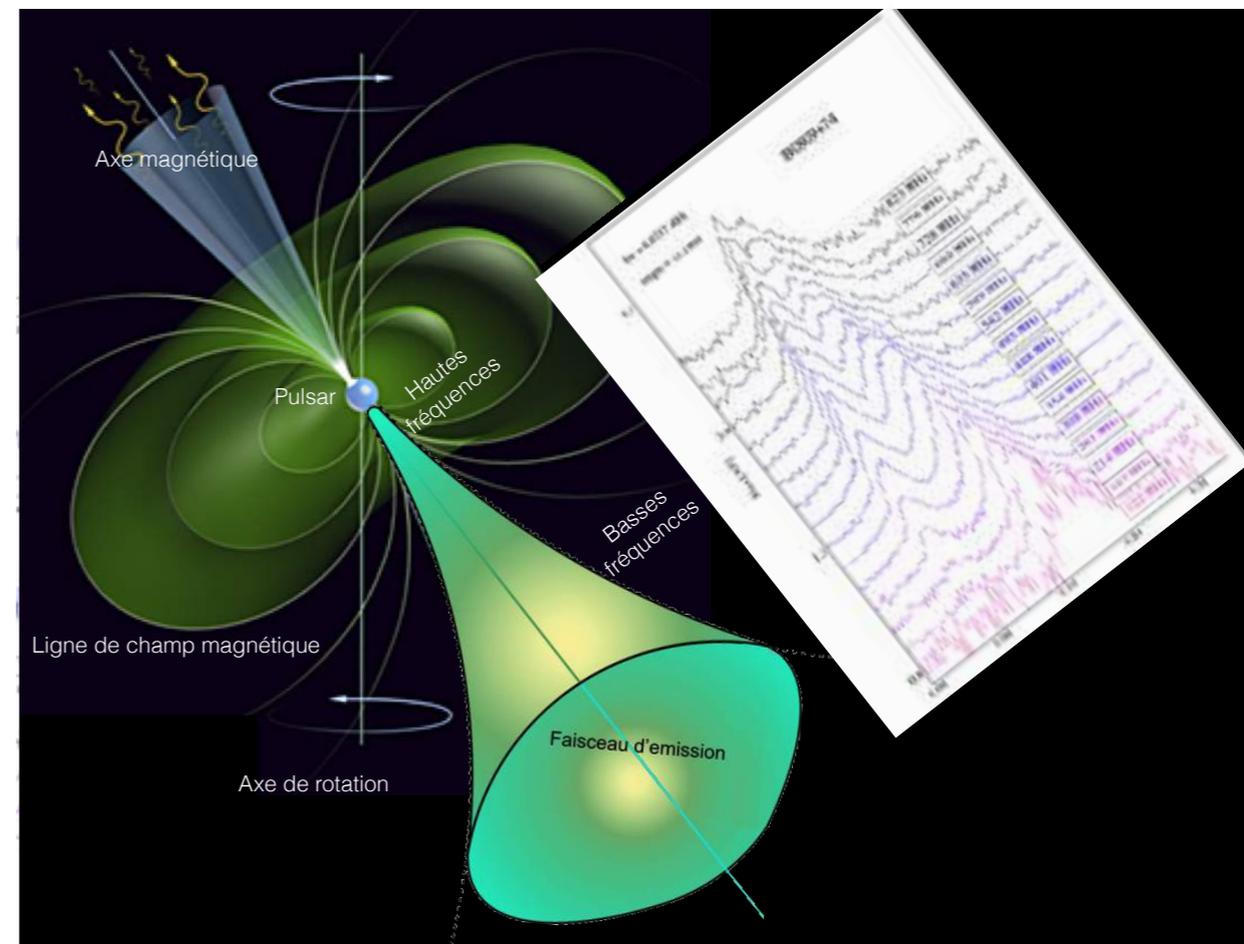
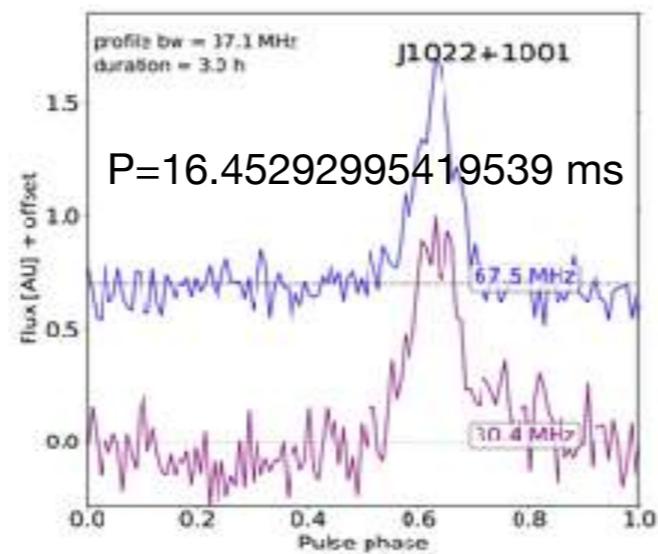
La science de NenuFAR : Pulsars



Pulsars géants du Crabe



Pulsars milliseconde

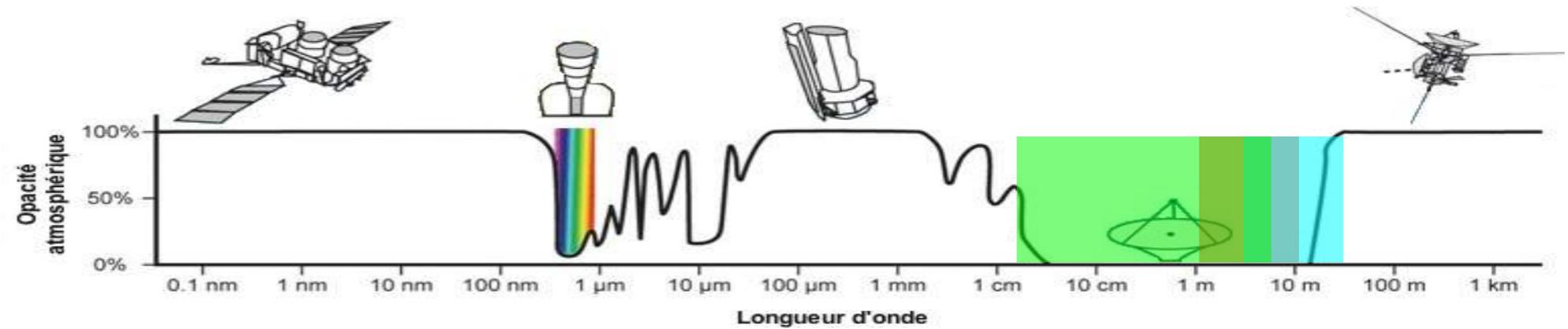


NenuFAR : salle de contrôle virtuelle

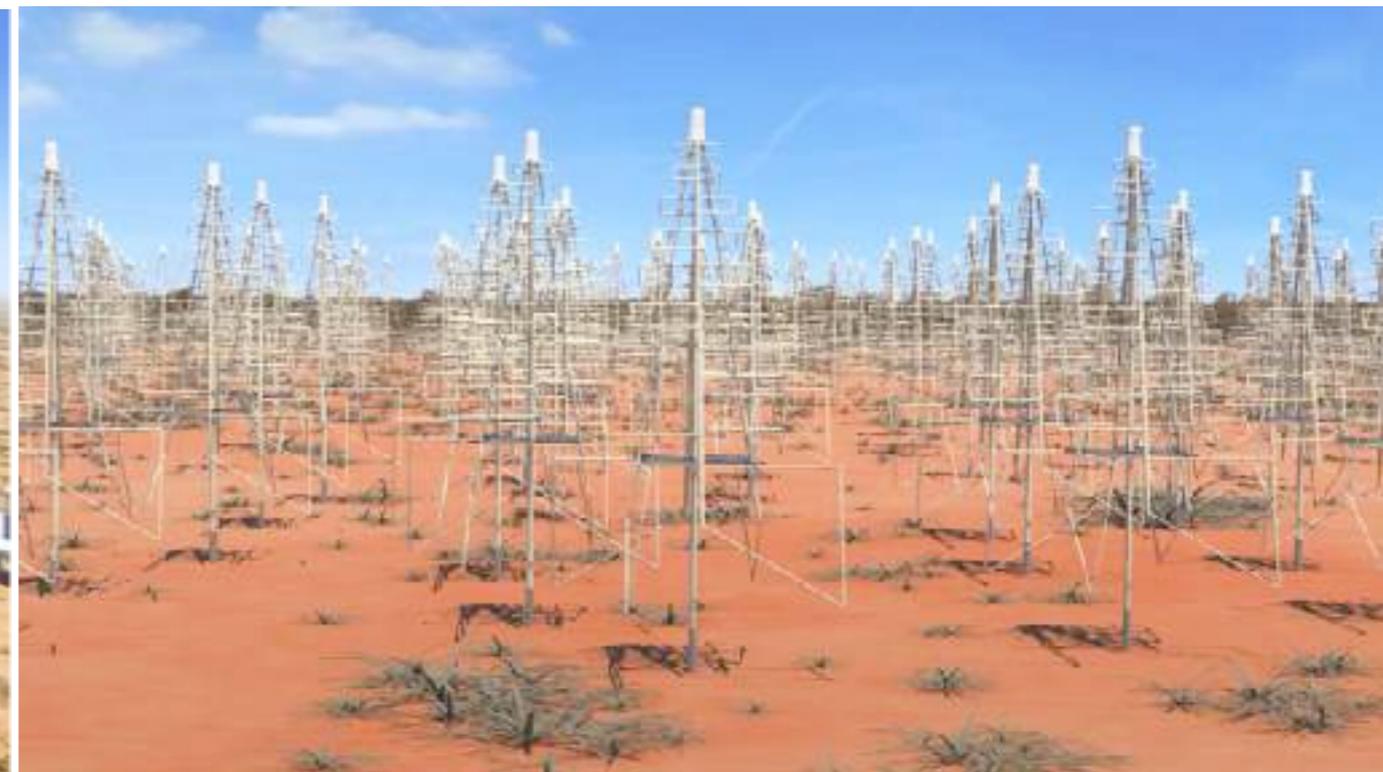
The image shows a web browser window displaying the NenuFAR virtual control room interface. The browser's address bar shows the URL `gui-nenufar.obs-nancay.fr`. The interface features a dark sidebar on the left with the title "NenuFAR v3.17.1" and a user profile for "Philippe Administrator". Below the profile is a clock showing "10:01:53 UTC" and a list of menu items: "Stairway To Heaven", "Planning", "Coordinates", "Dashboard", "Real time", "Google map", "Survey", "Reports", "Maintenance", "Tools", and "Documentation". At the bottom of the sidebar are social media icons for Facebook, Twitter, and a globe. The main content area displays an aerial satellite view of a grassy field with a white wireframe model of the NenuFAR radio telescope structure. A white welcome dialog box is overlaid on the right side of the view, containing the text "WELCOME TO NenuFAR", "Welcome to the largest low-frequency radiotelescope in the world Nancay", and "Just come in and have a look at this wonderful world". Below the text is a small illustration of a person sitting on the ground with a telescope, and a "Continue" button.

Le futur radiotélescope SKA

(Square Kilometer Array = réseau d'1 km²)

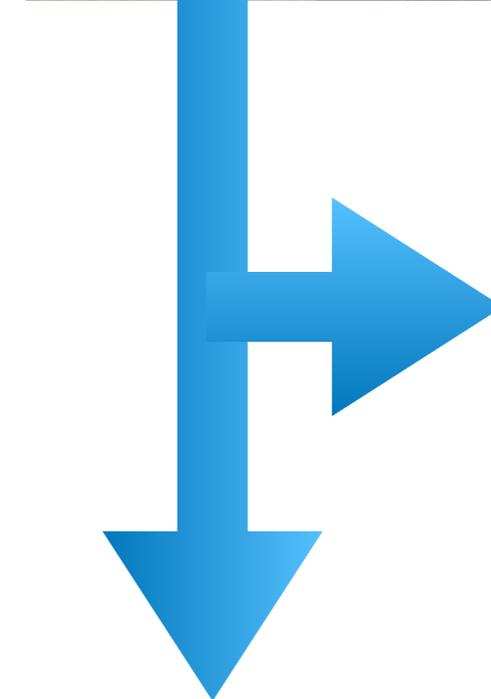
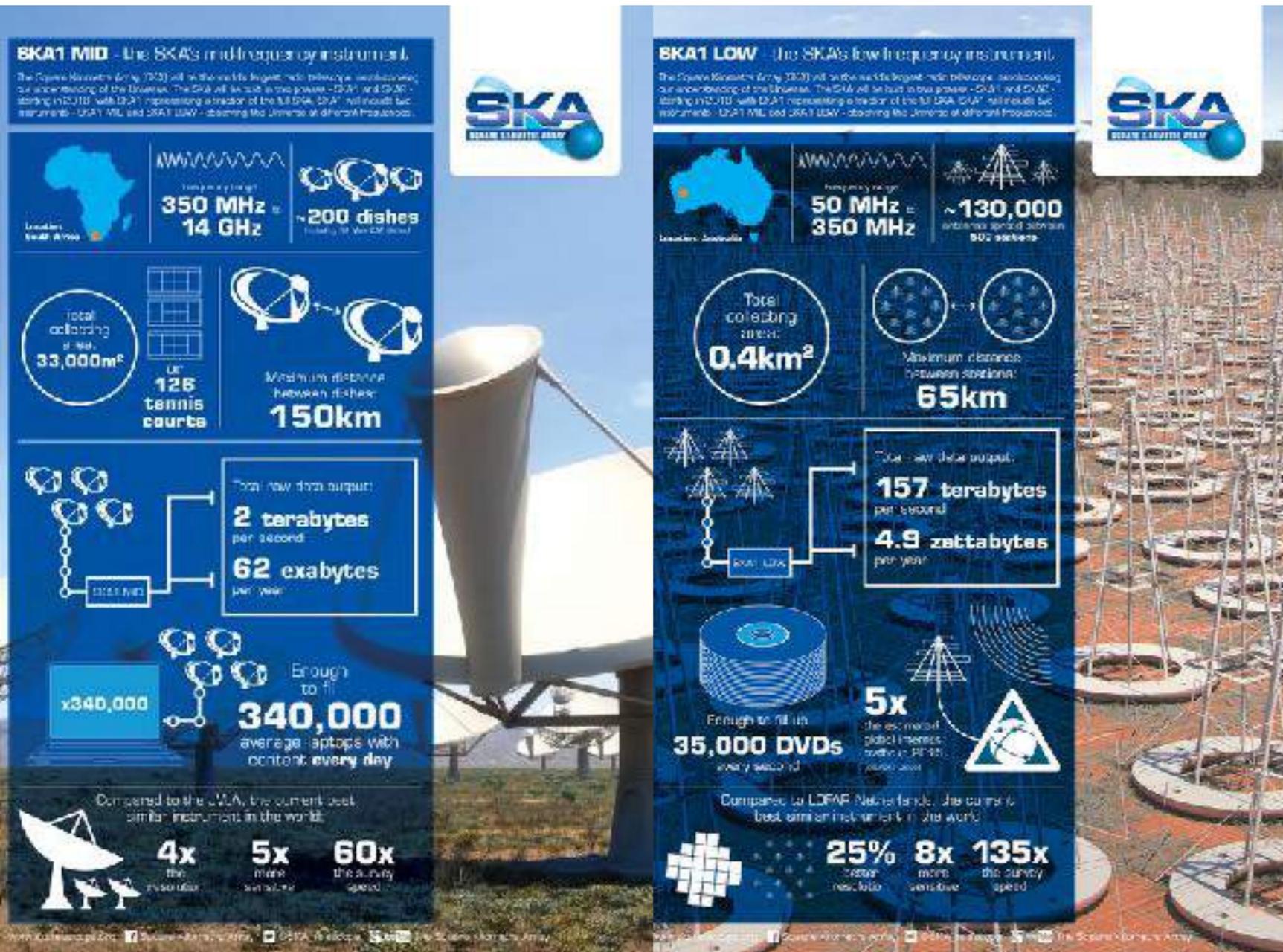


Moyennes fréquences :
200 paraboles, Afrique du Sud



Basses fréquences :
250000 antennes, Australie

SKA : un débit de données colossal



- ~500 Po / heure ~ 10 Eo / jour ~ 5 Zo / an (1 Zo = 1 MPo)
- (> trafic internet mondial aujourd'hui)
- stockage des données brutes impossible
- calibration (étalonnage) & imagerie temps réel = indispensable

SKA : organisation et groupes scientifiques

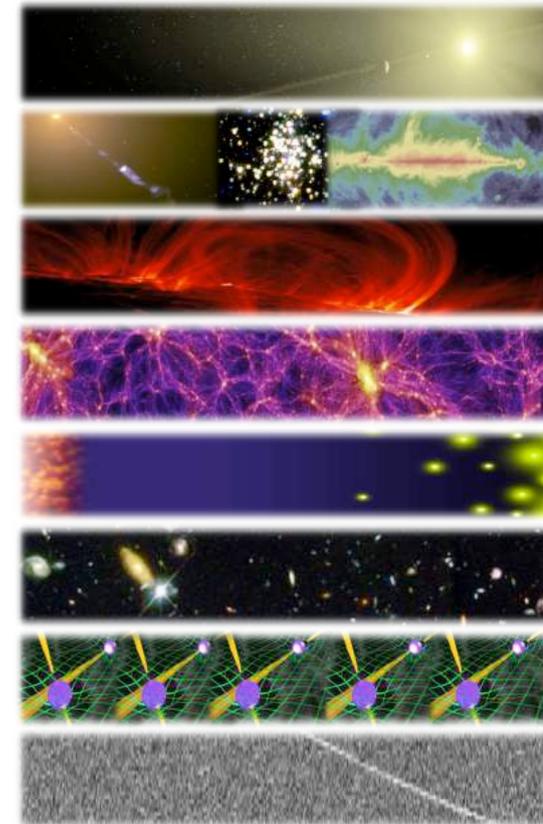


SKAO map June 2021

The Science Working Groups

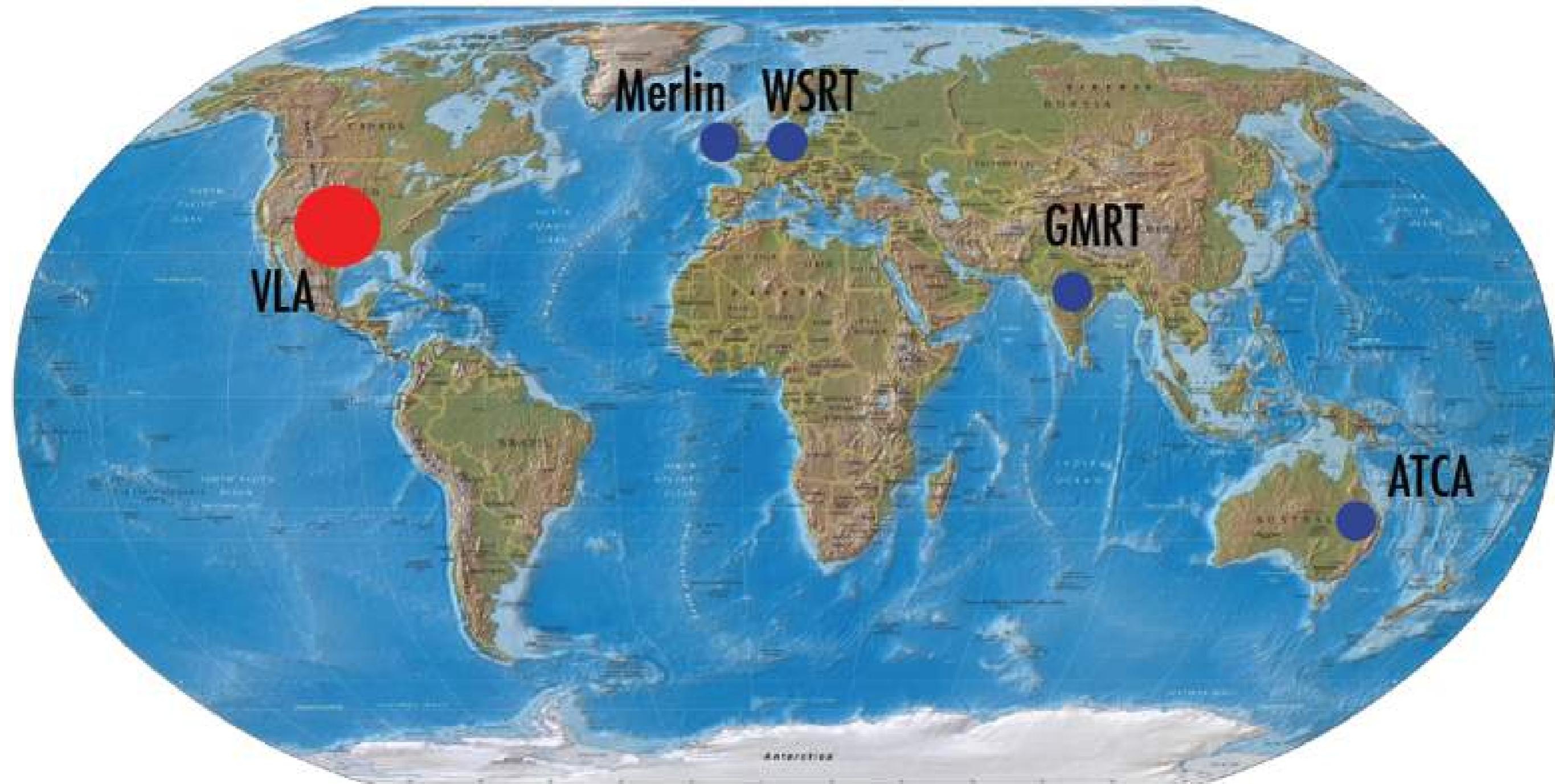


- **Astrobiology (“The Cradle of Life”)**
 - *Project Scientist:* Tyler Bourke
 - *Working Group Chair:* Melvin Hoare
- **Galaxy Evolution – Continuum**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chairs:* Nick Seymour & Isabella Prandoni
- **Cosmic Magnetism**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Melanie Johnston-Hollitt & Federica Govoni
- **Cosmology**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chair:* Roy Maartens
- **Epoch of Reionisation & the Cosmic Dawn**
 - *Project Scientist:* Jeff Wagg
 - *Working Group Chair:* Leon Koopmans
- **Galaxy Evolution – HI**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Lister Staveley-Smith & Tom Osterloo
- **Pulsars (“Strong field tests of gravity”)**
 - *Project Scientist:* Jimi Green
 - *Working Group Chairs:* Ben Stappers & Michael Kramer
- **Transients**
 - *Project Scientist:* Tyler Bourke
 - *Working Group Chair:* Rob Fender

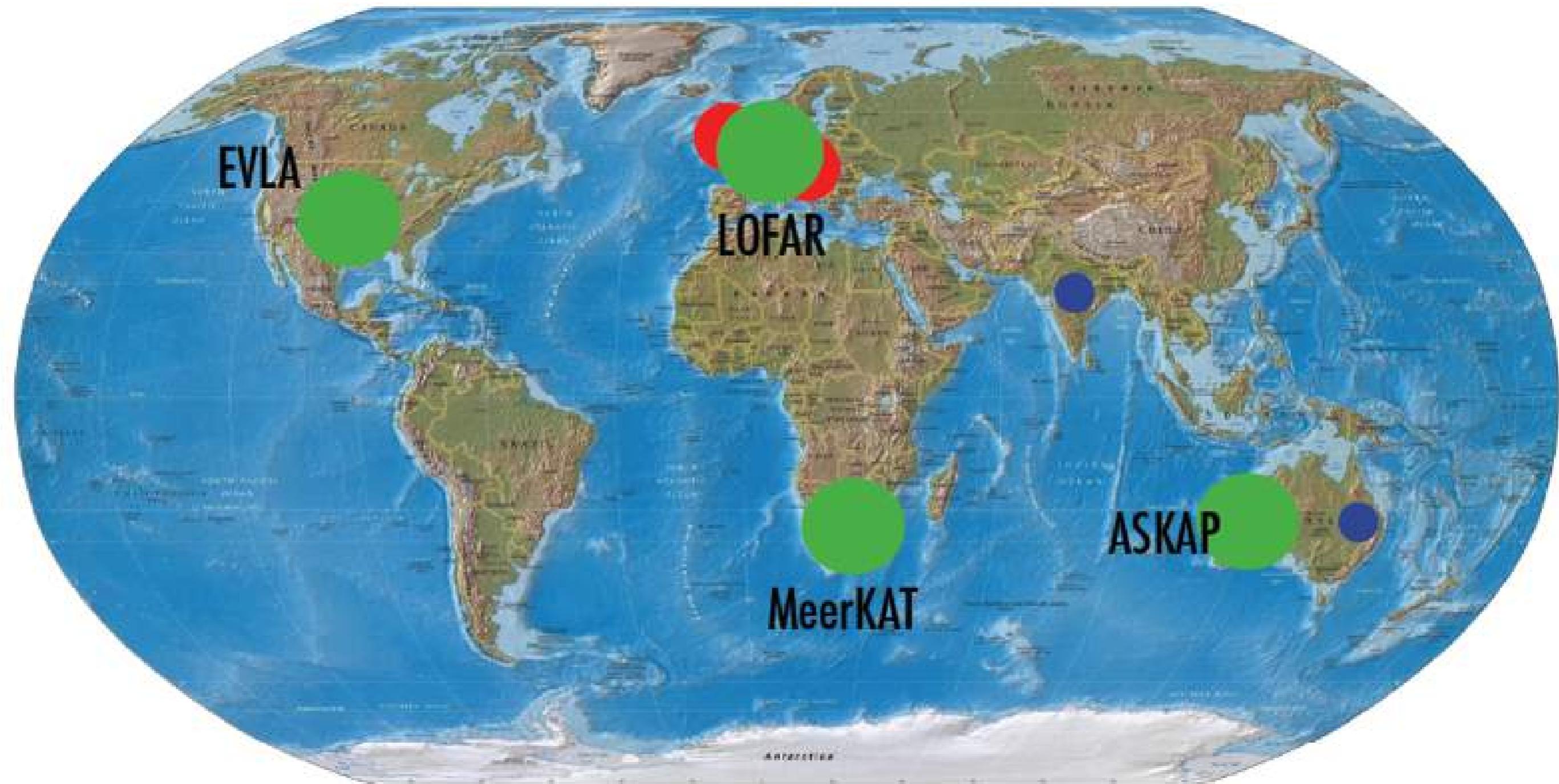


Exploring the Universe with the world's largest radio telescope

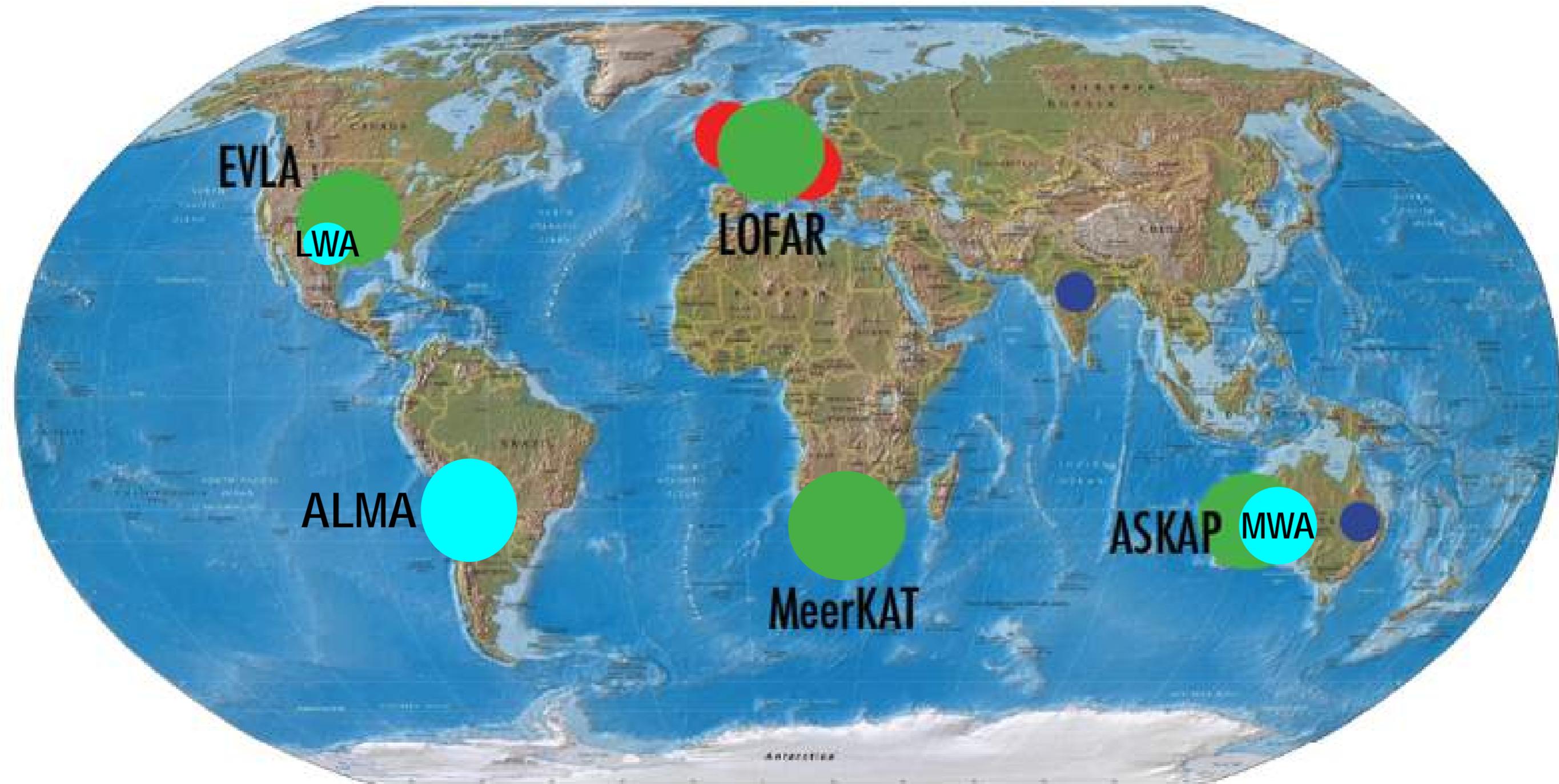
La radioastronomie en ~2005



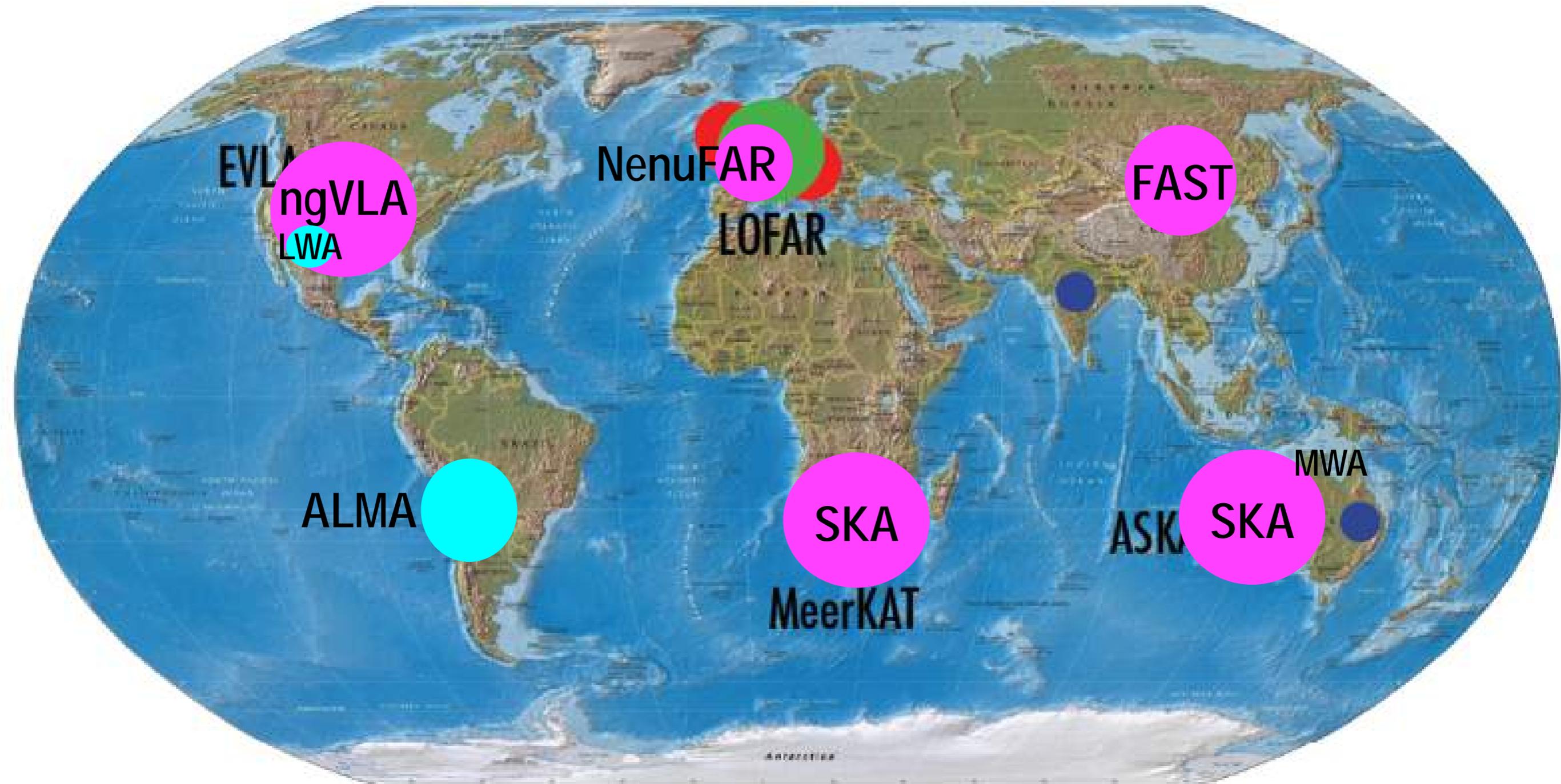
La radioastronomie en ~2010



La radioastronomie en ~2015



La radioastronomie en 2020+

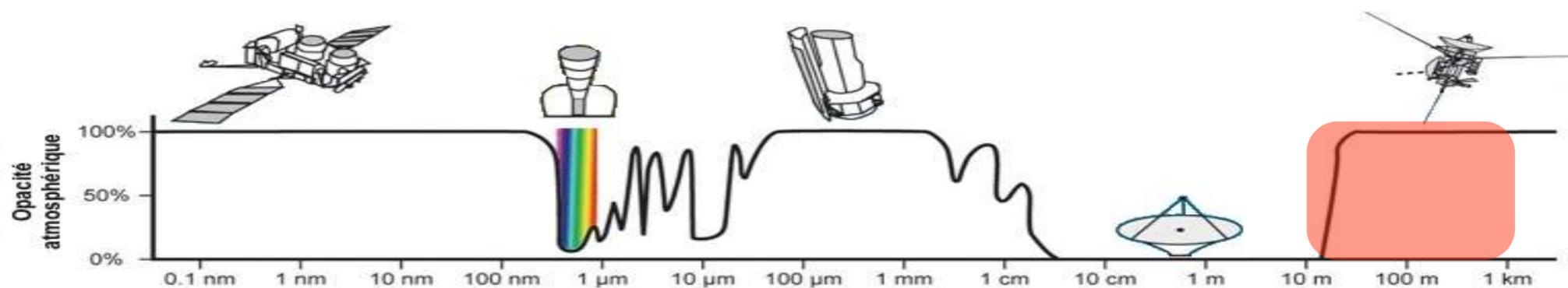
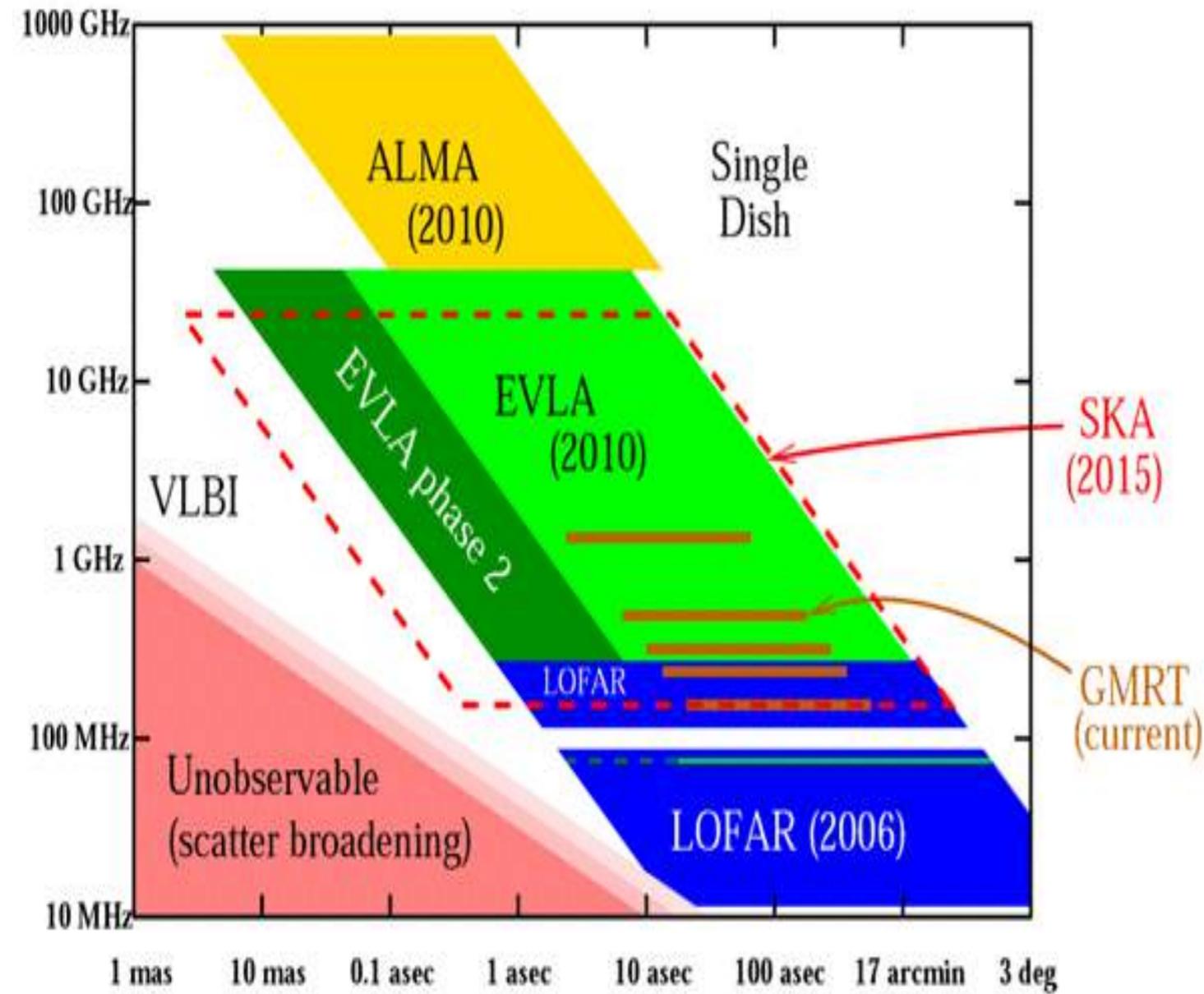
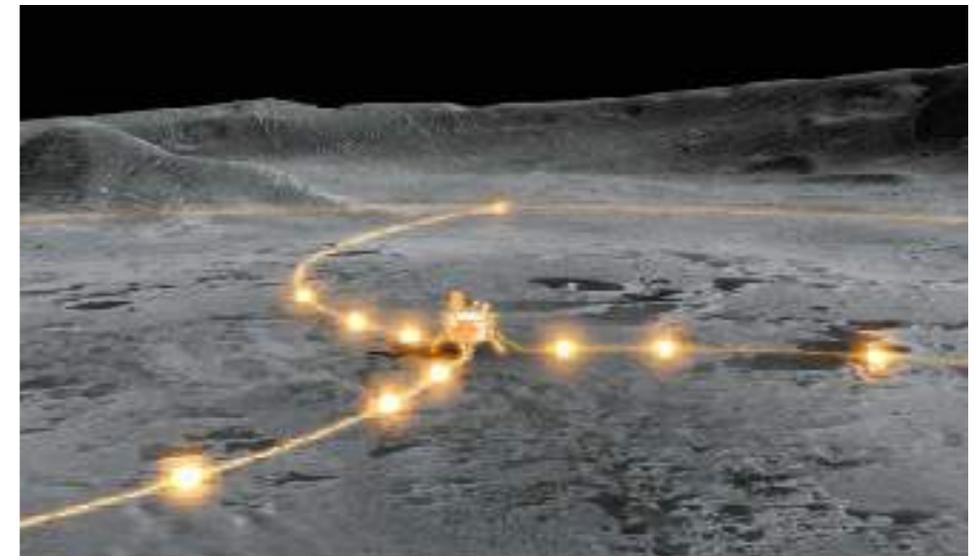


Et ensuite ?

Interférométrie radio TBF dans l'espace



Grand réseau d'antennes sur la Lune



Pour aller plus loin ...

- IRAM <https://www.iram-institute.org/>
- LWA <https://leo.phys.unm.edu/~lwa/>
- MWA <https://www.mwatelescope.org/>
- ALMA <https://www.almaobservatory.org/>
- LOFAR <https://www.lofar.org>
- MeerKAT <https://www.sarao.ac.za/gallery/meerkat/>
- NenuFAR <https://nenufar.obs-nancay.fr/>
- SKA <https://www.skatelescope.org/>
- SKA-France <https://ska-france.oca.eu/>
- ngVLA <https://ngvla.nrao.edu/>
- Nançay <https://www.obs-nancay.fr/>
- ApSynSim <https://launchpad.net/apsynsim>
- SALF <https://salfconference.org/>
- IYAS2015 <https://tinyurl.com/3de3zw6r>

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