NenuFAR

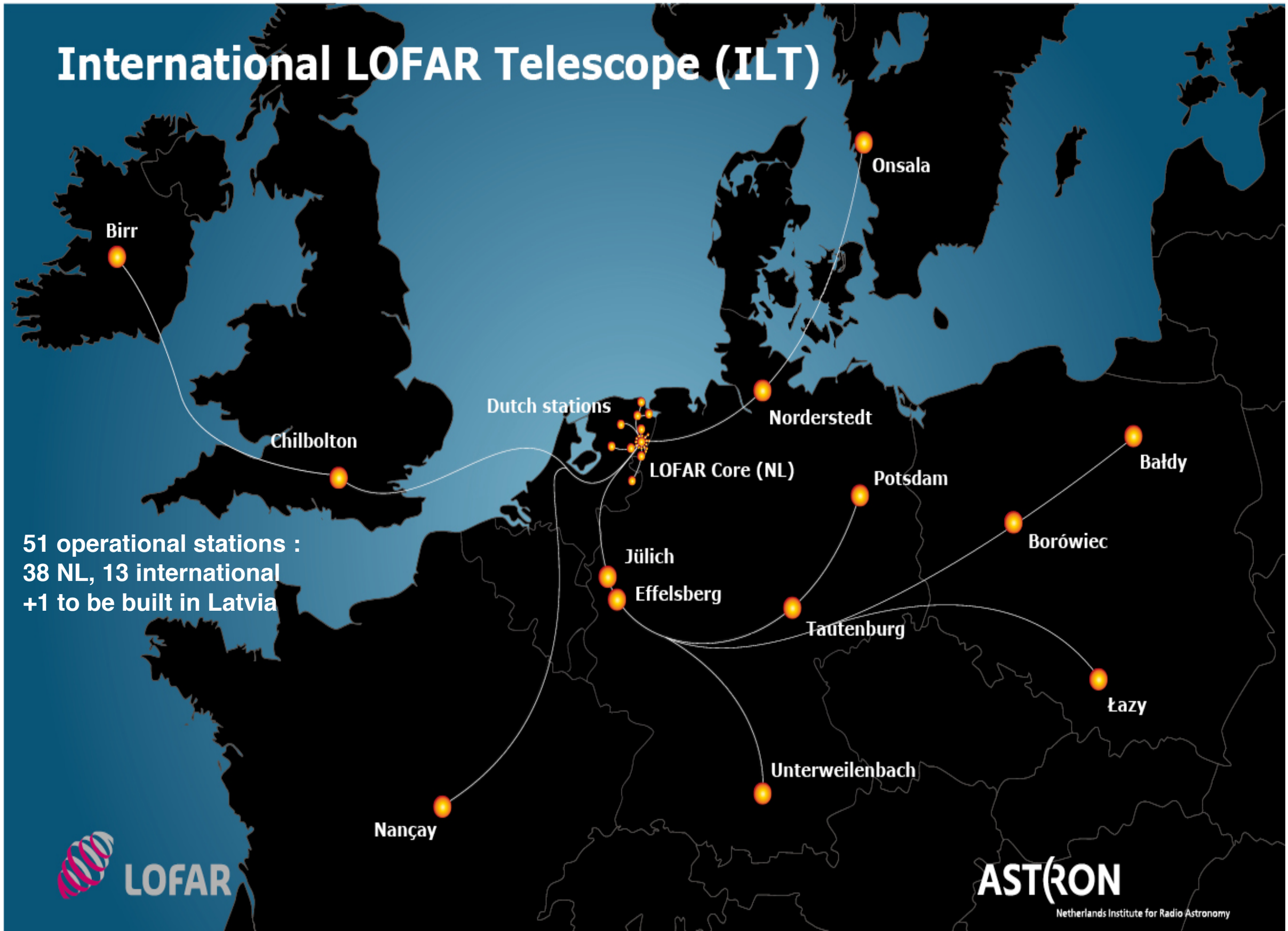
a SKA pathfinder

Philippe ZARKA
(LESIA & USN, Obs. Paris, CNRS, PSL, UO, Meudon, France)

Overview of the talk

- The LOFAR array
- LOFAR Science
- The NenuFAR project
- NenuFAR Concept, Design, Construction
- NenuFAR Science
- NenuFAR commissioning
- Status & closing remarks

LOFAR : the first new-generation radiotelescope



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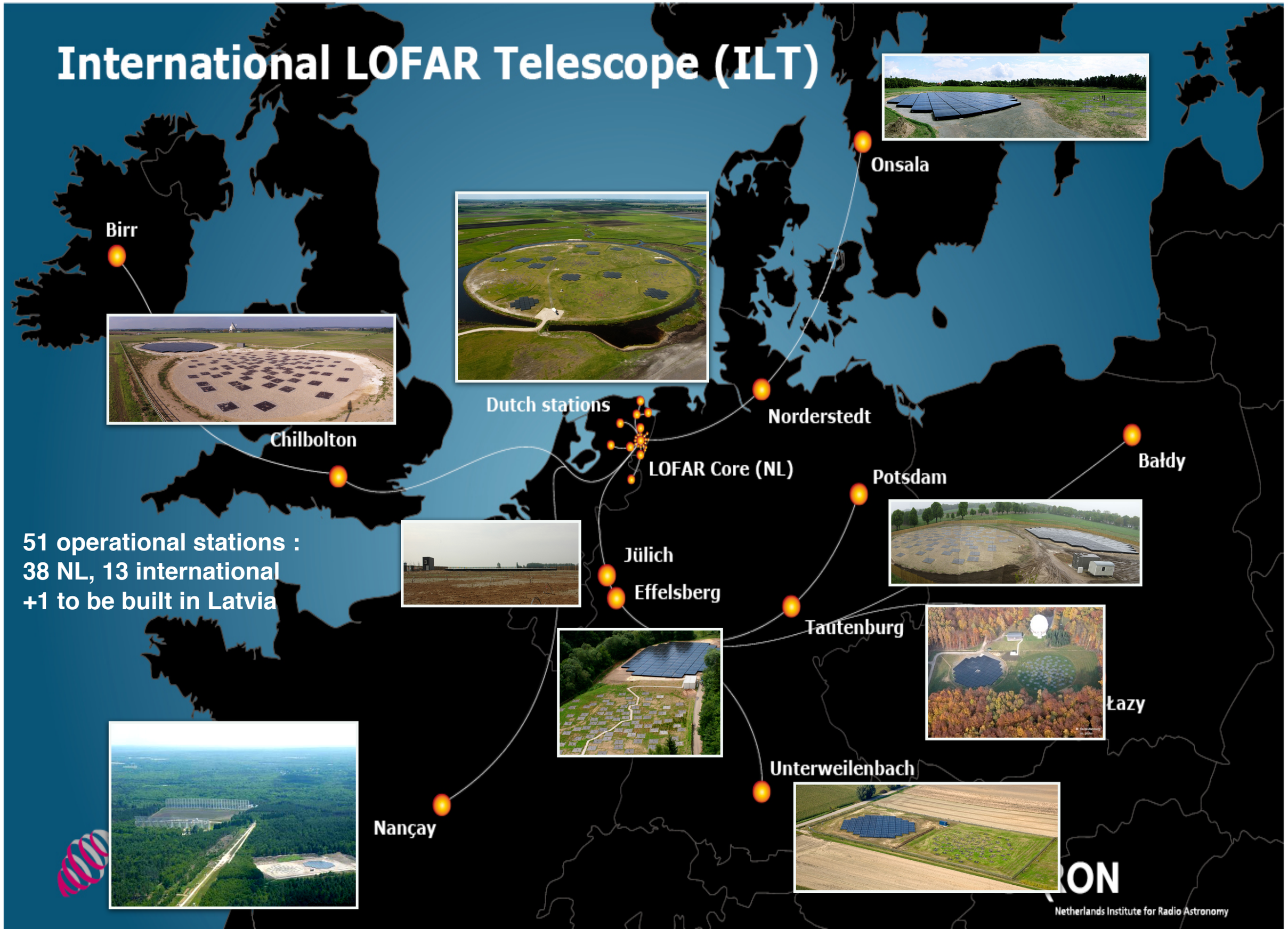
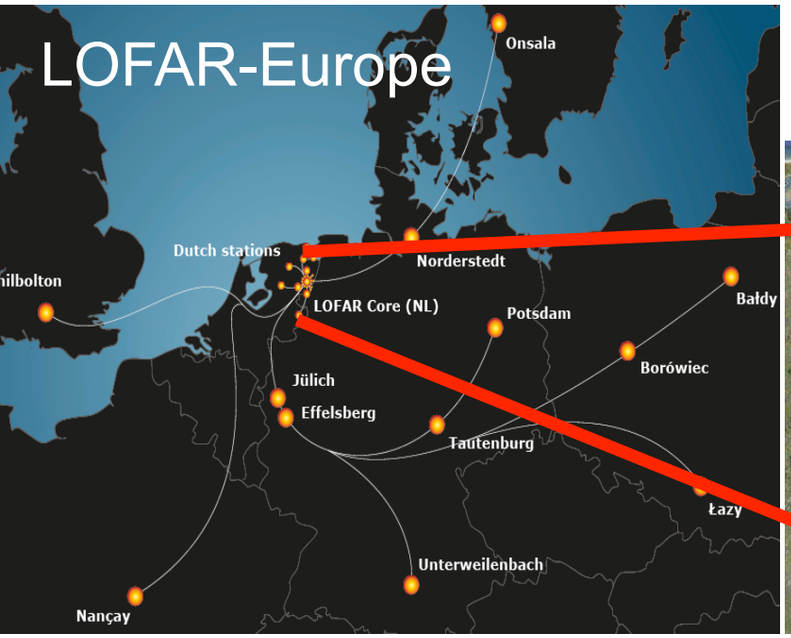
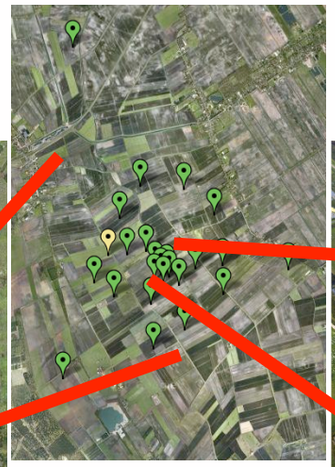


A multi-scale instrument : an European interferometer of phased arrays



LOFAR-NL

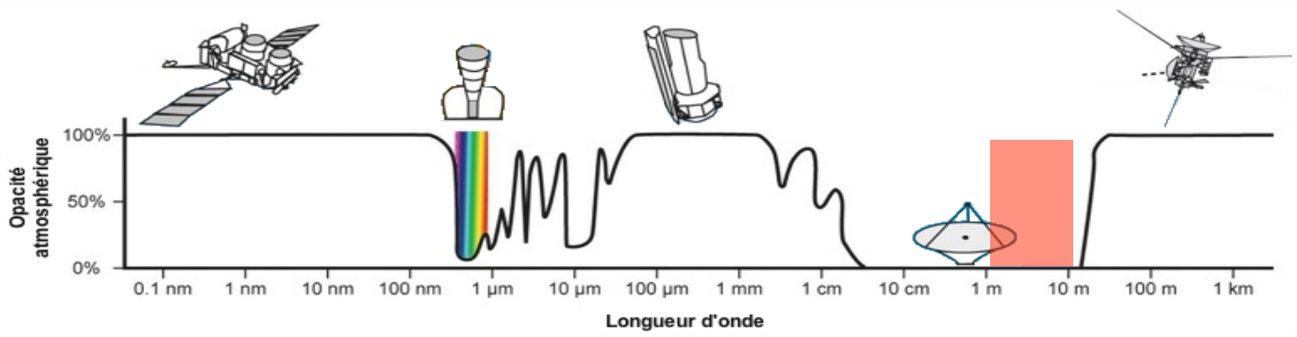


Core

Superterp

Station

- 1824 antennas / tiles NL
- 1248 " " international
- 30-80 & 110-250 MHz



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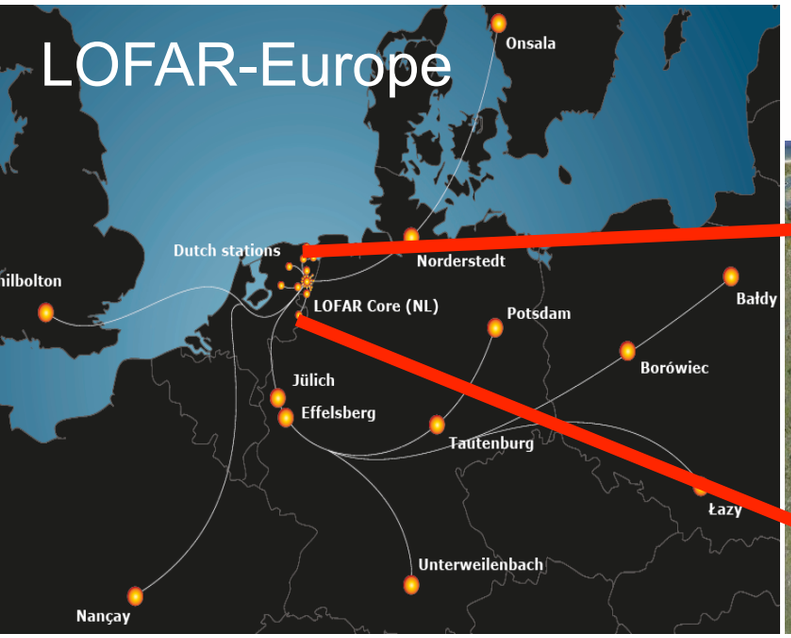

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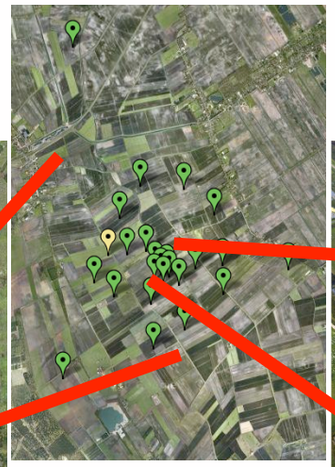

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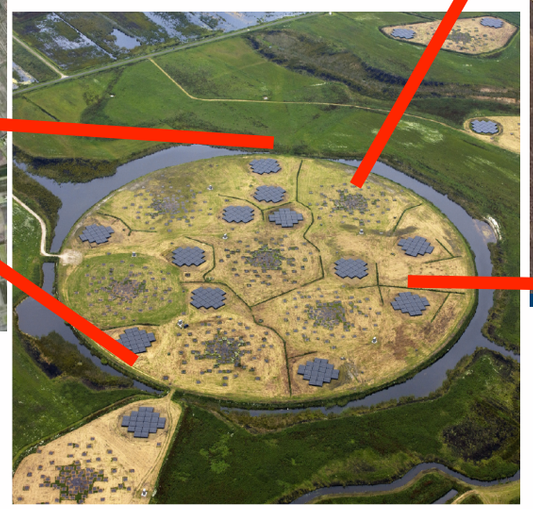

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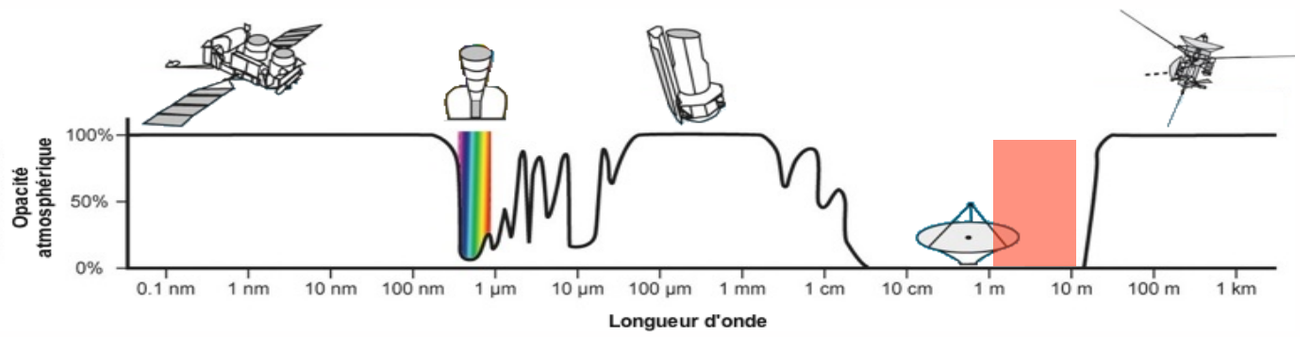

LOFAR station : 2 phased arrays + backends

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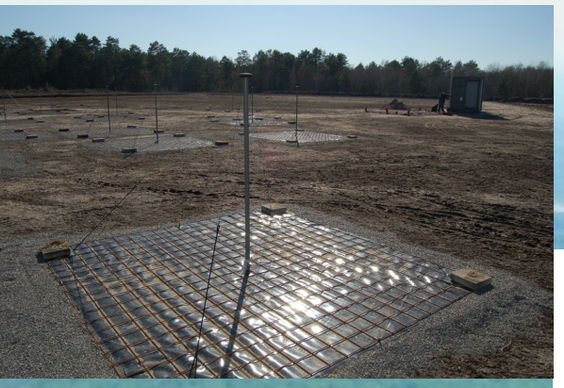
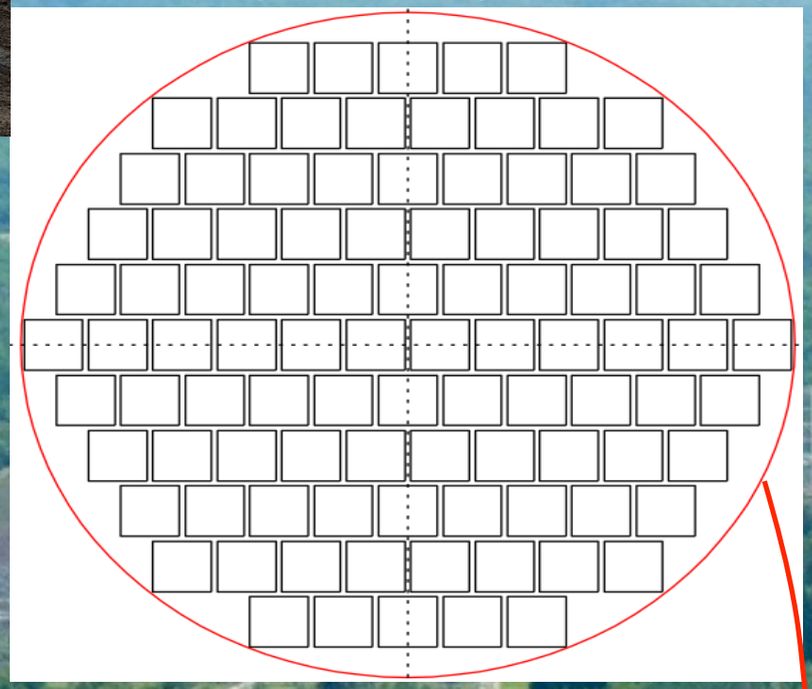
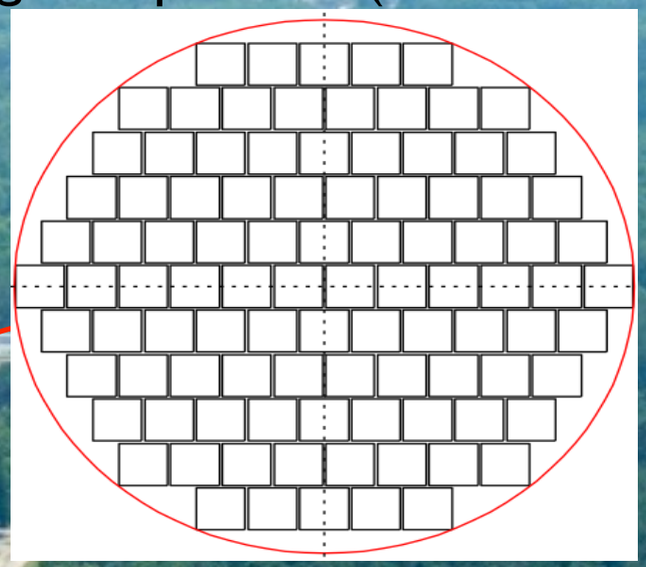


Low frequencies (30-80 MHz)

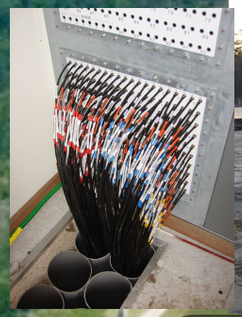


High frequencies (110-250 MHz)



60 m

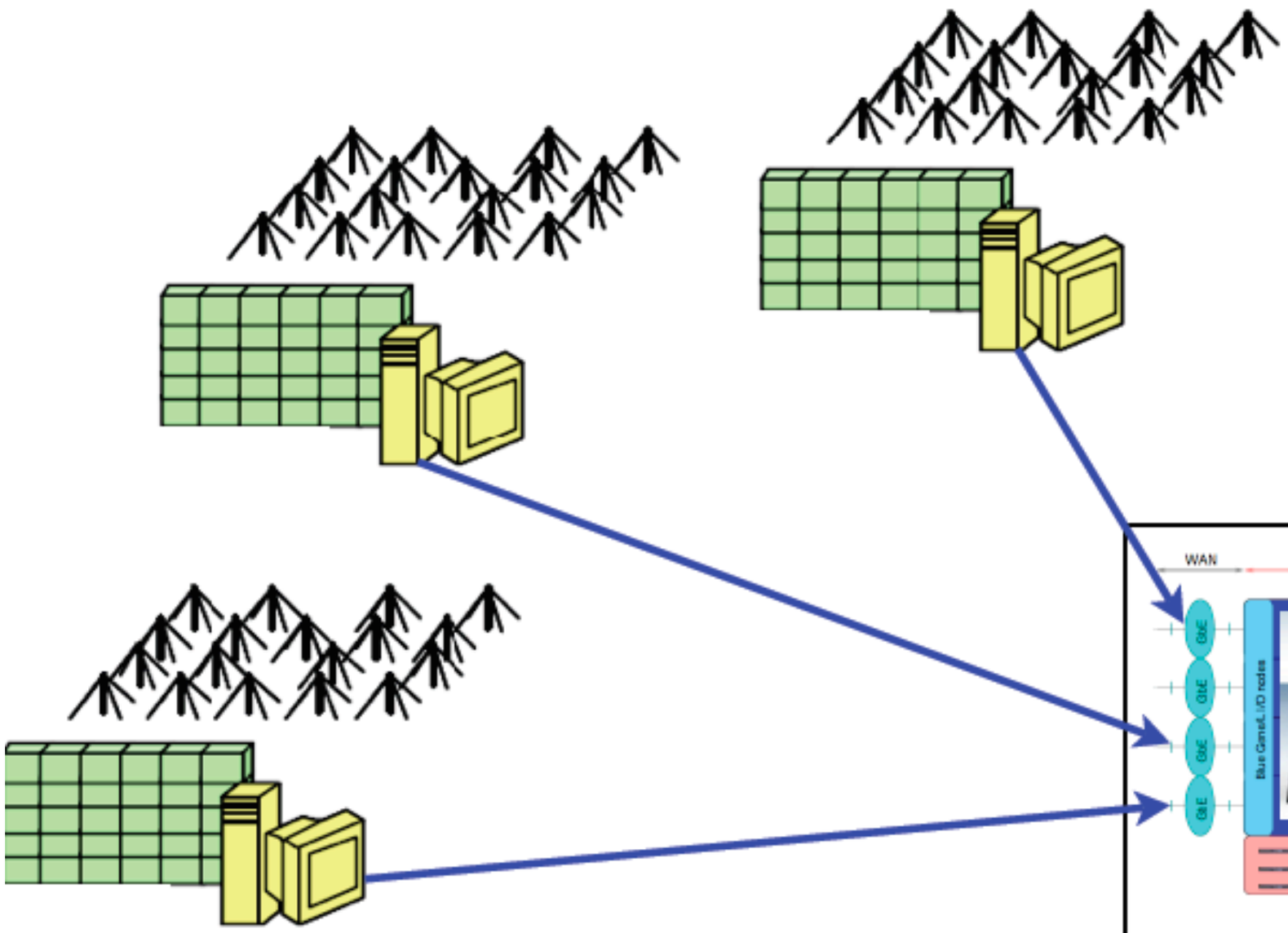
50 m

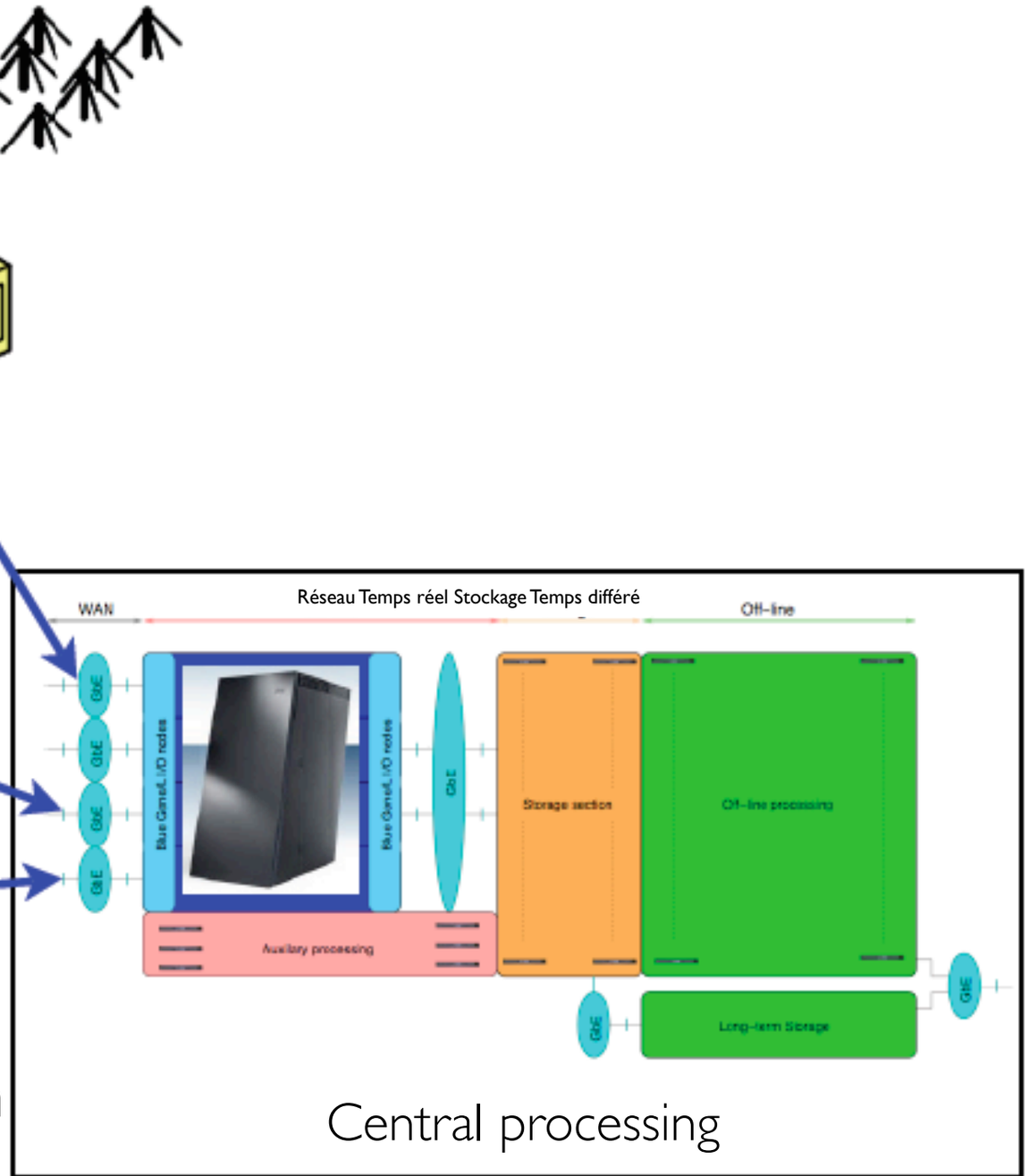


3+ Gbit/sec Link

Correlator : GPU cluster

The LOFAR array

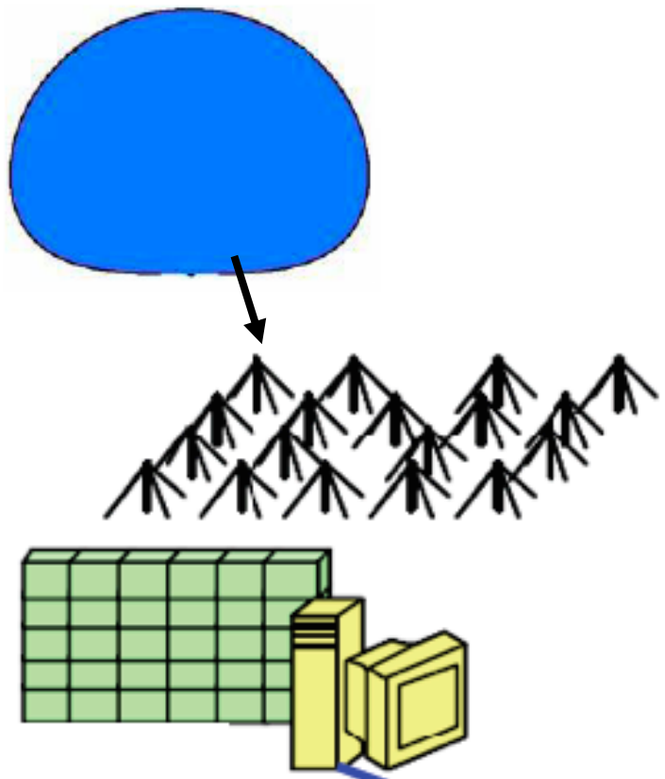


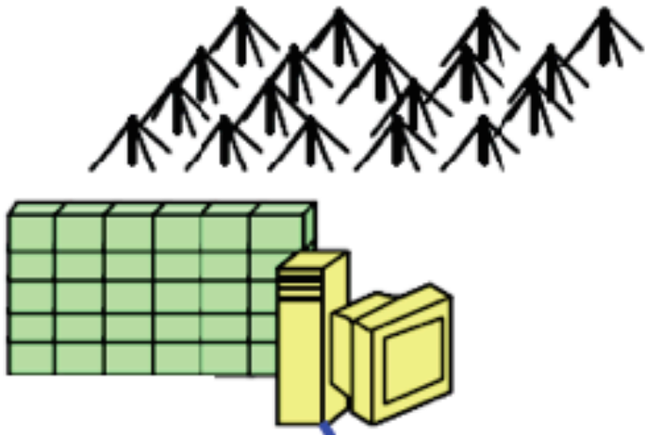


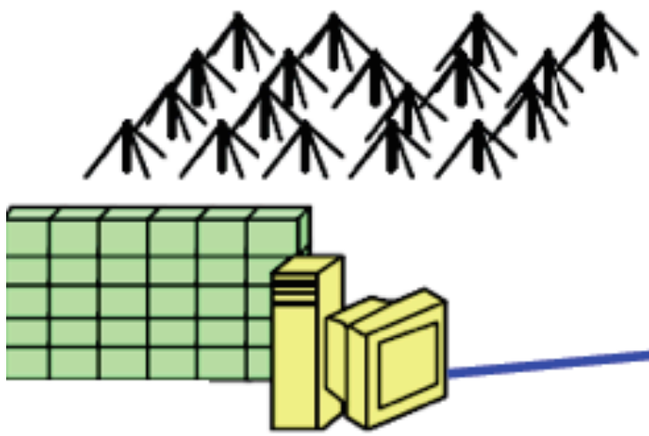
⇒ ~50 stations @ 3-10 Gbps/station

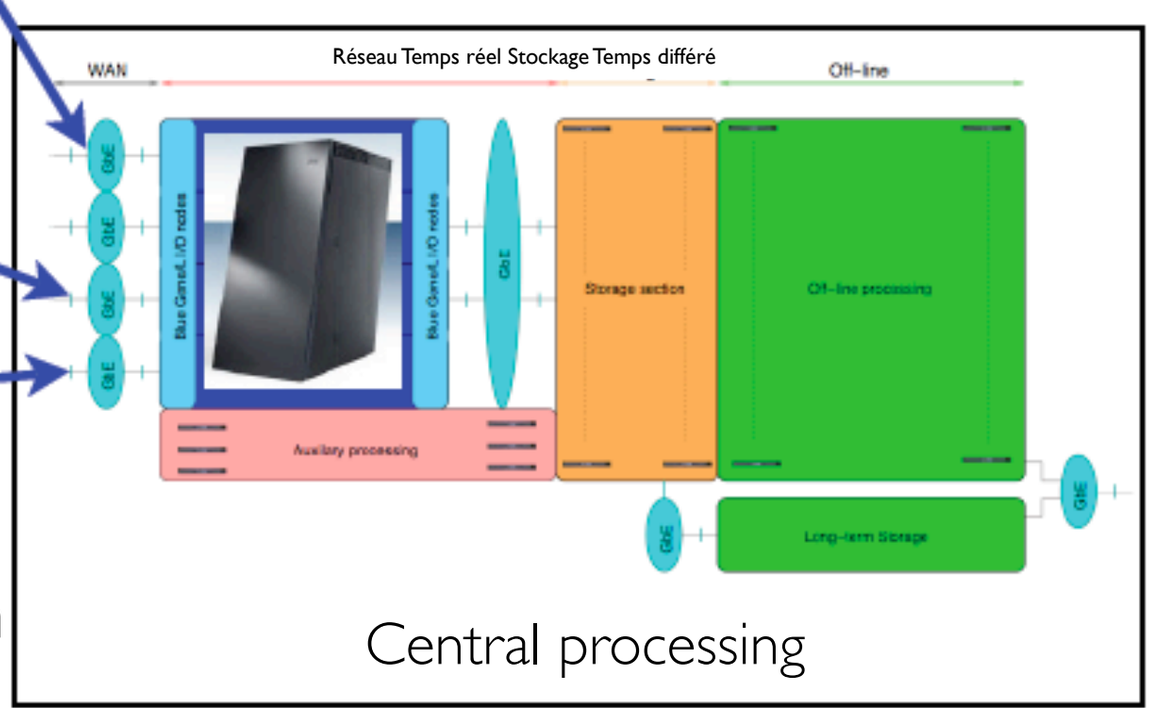
Central processing

The LOFAR array









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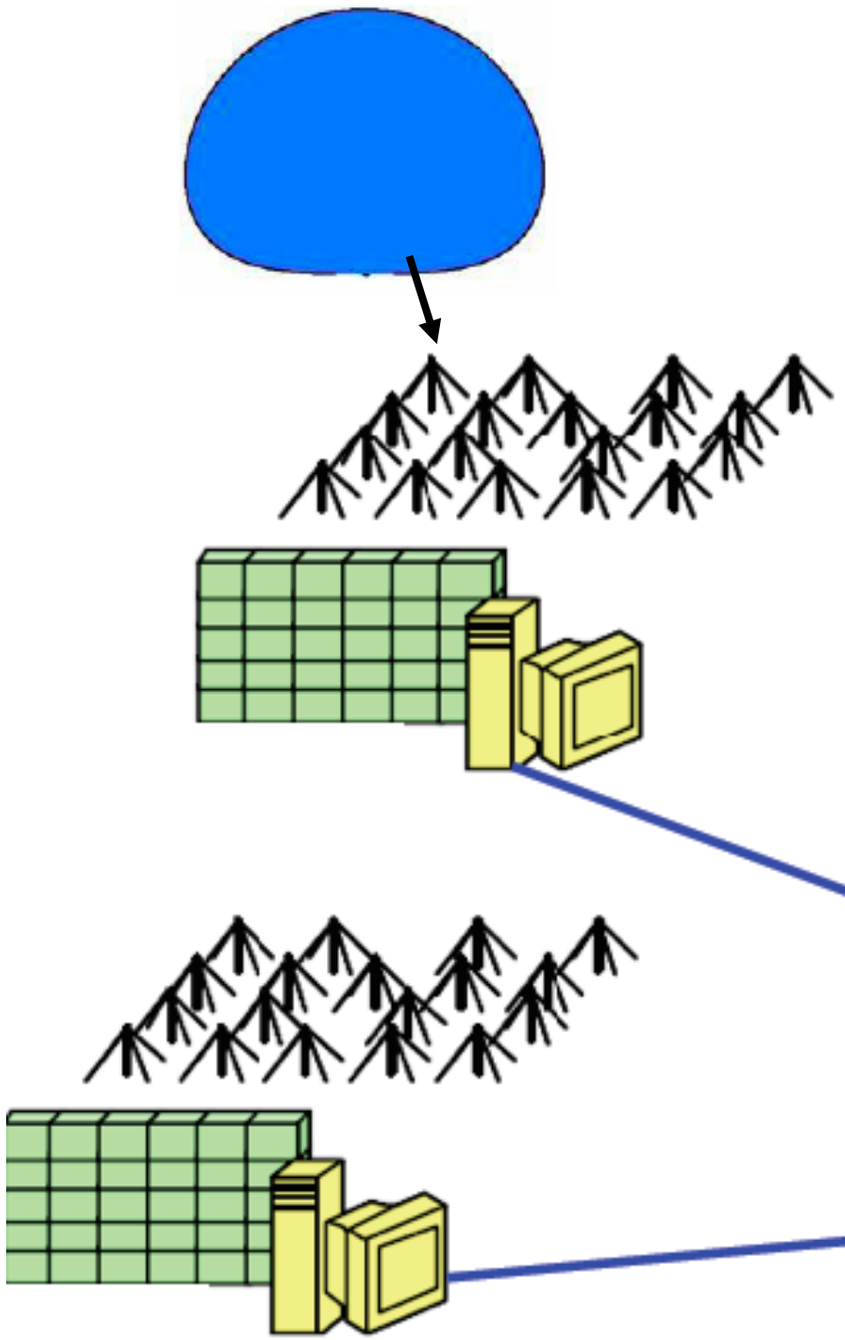

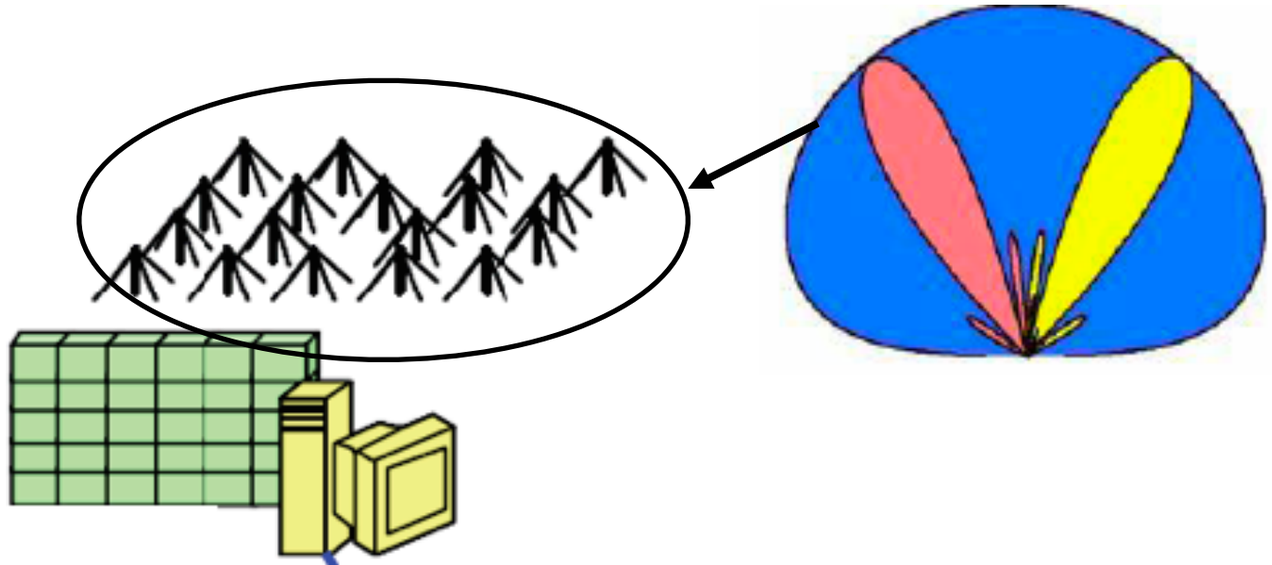

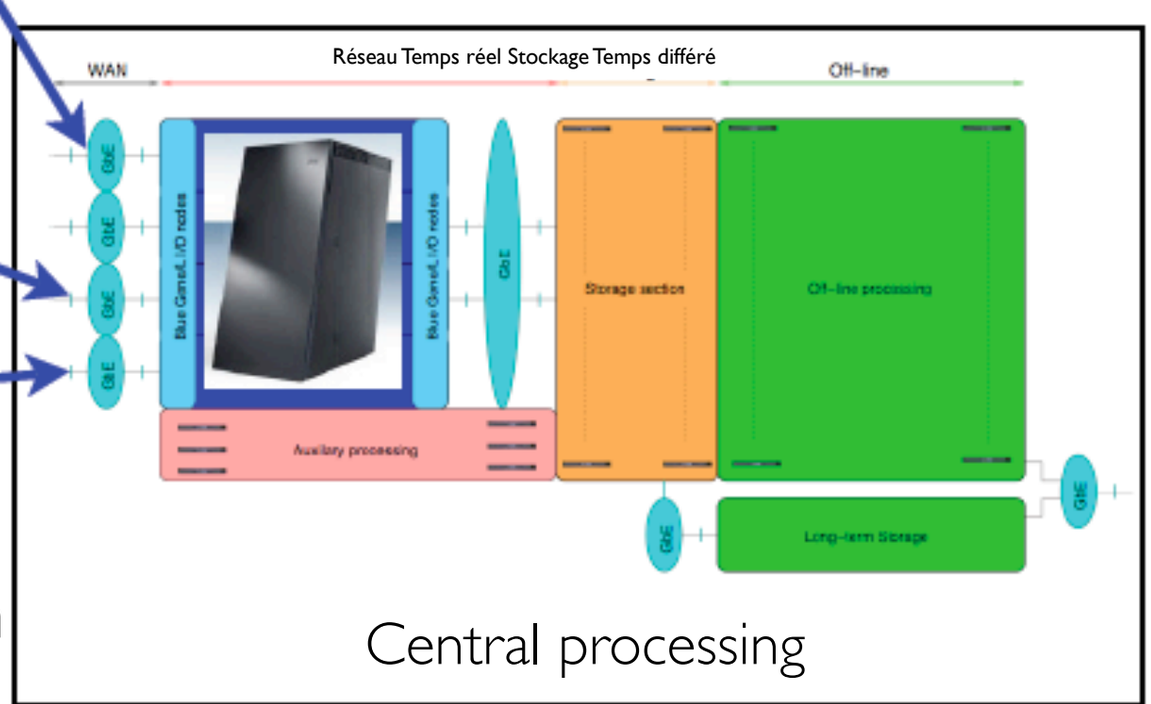

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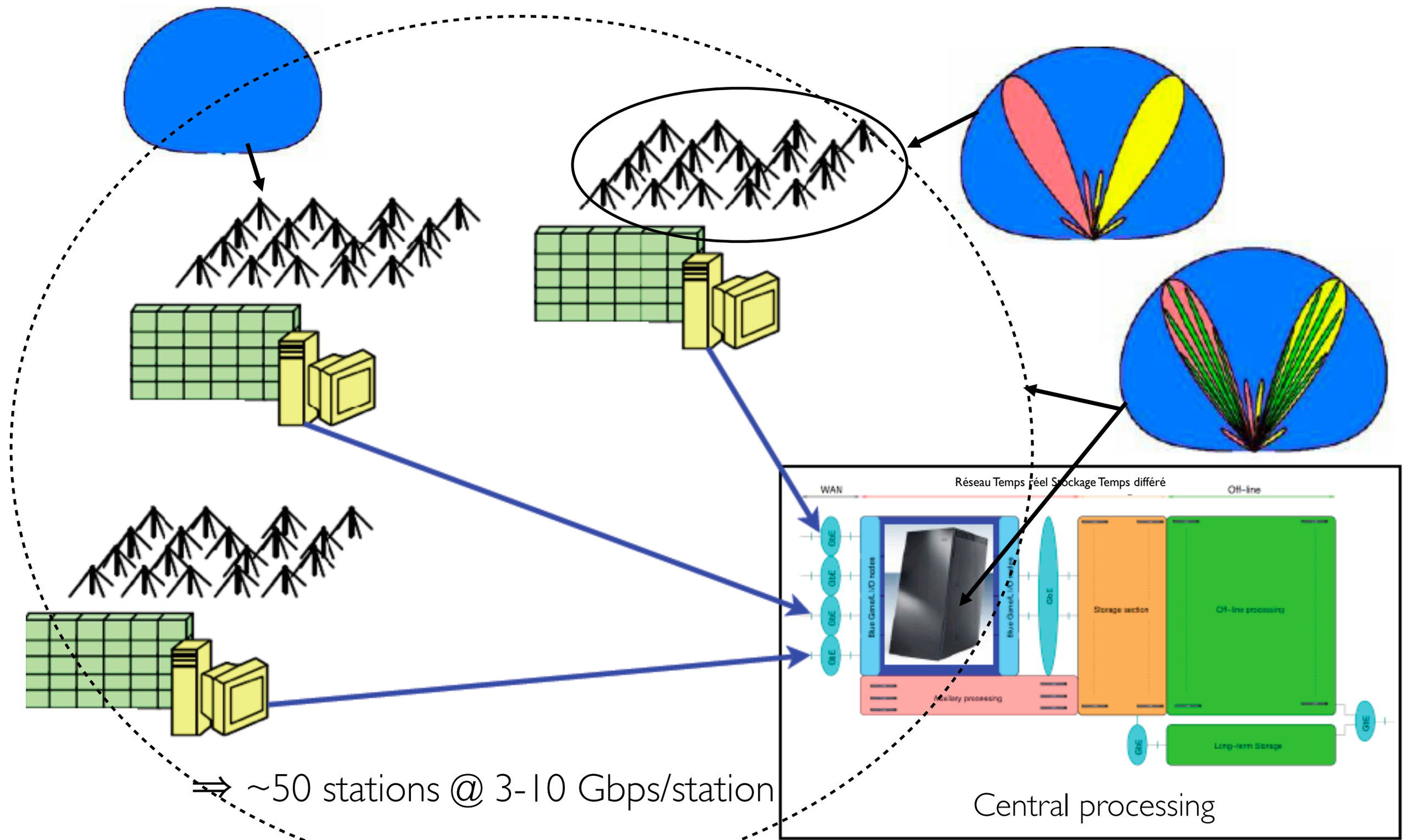

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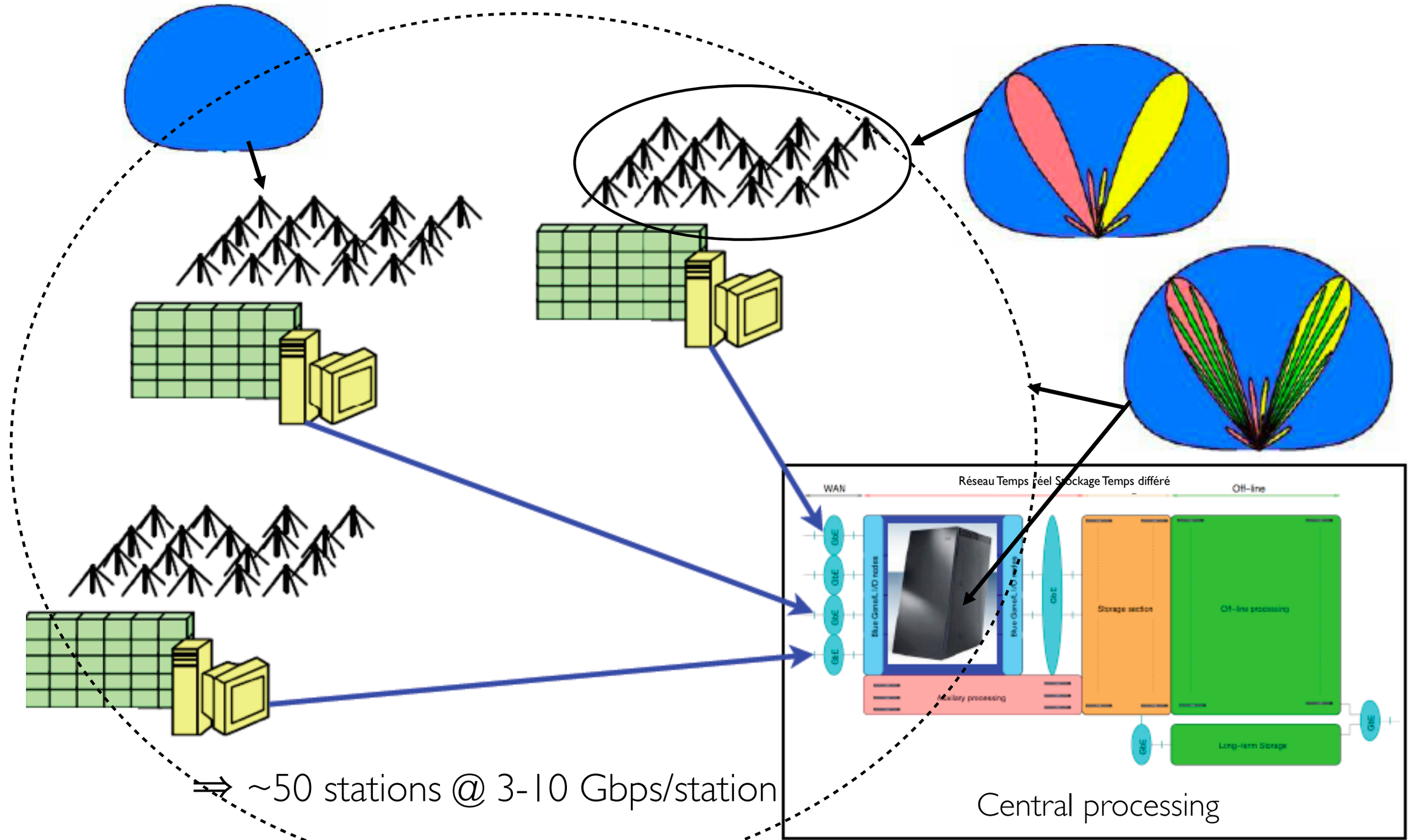
- Post-processing : calibration, imaging, science pipelines



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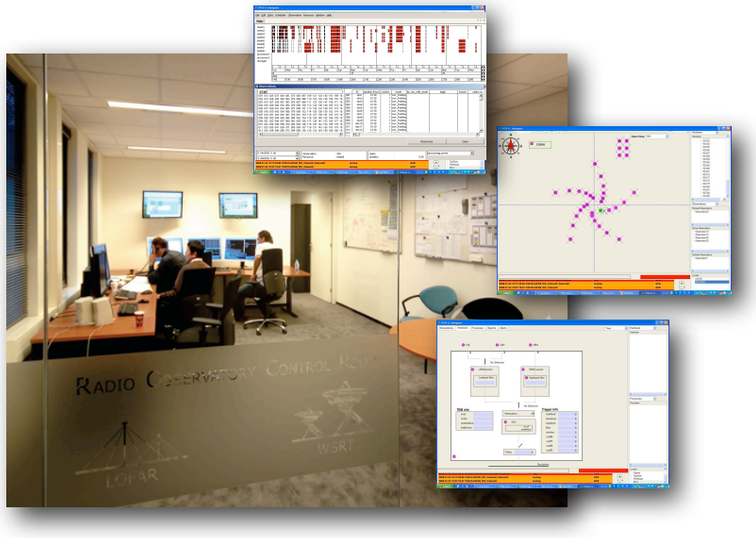
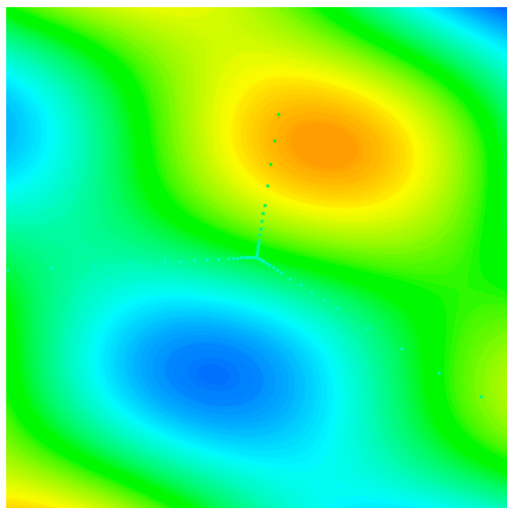
Central processing

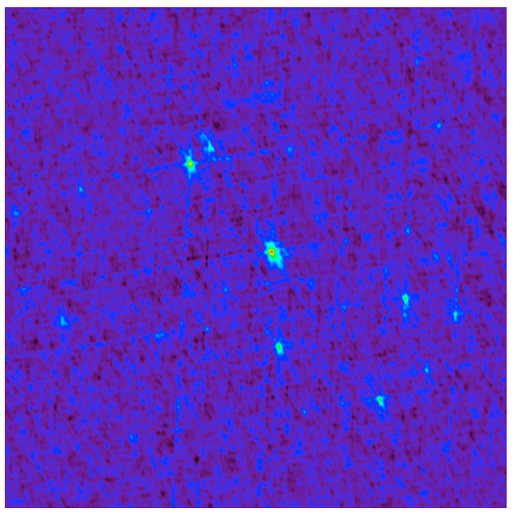
LOFAR main observing modes

- Interferometric Imaging
- Tied Array Beam(s) : incoherent & coherent
- Waveform snapshots



Modelling the ionosphere





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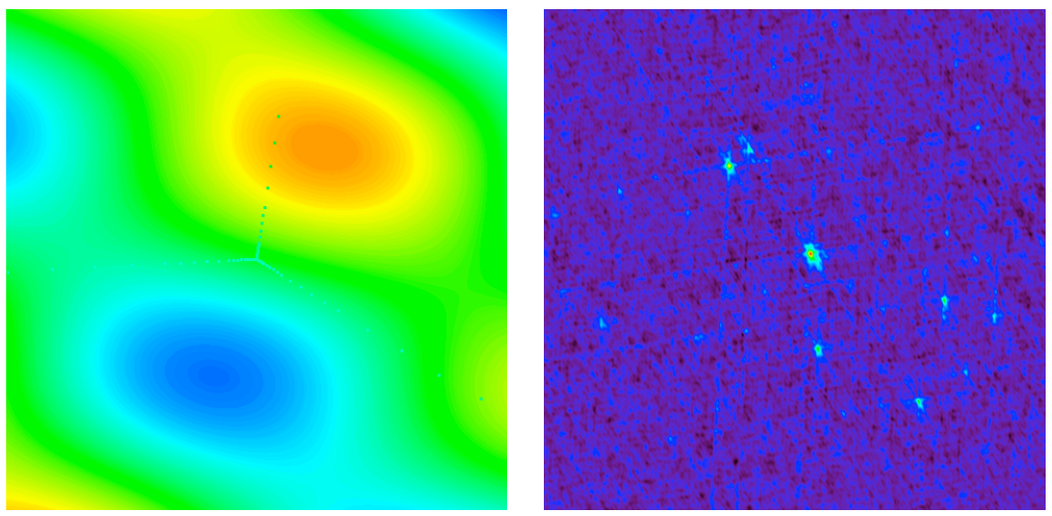

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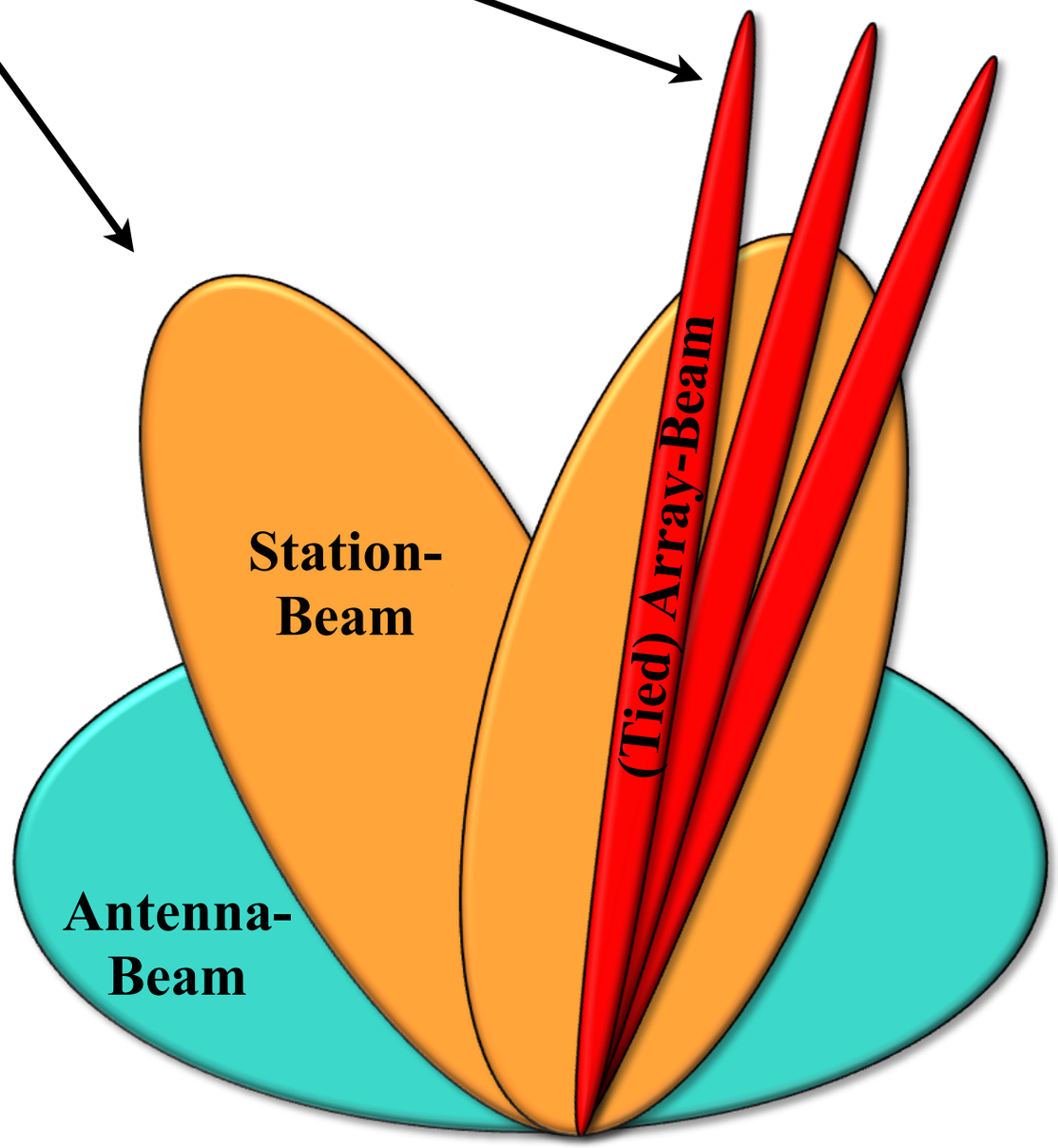
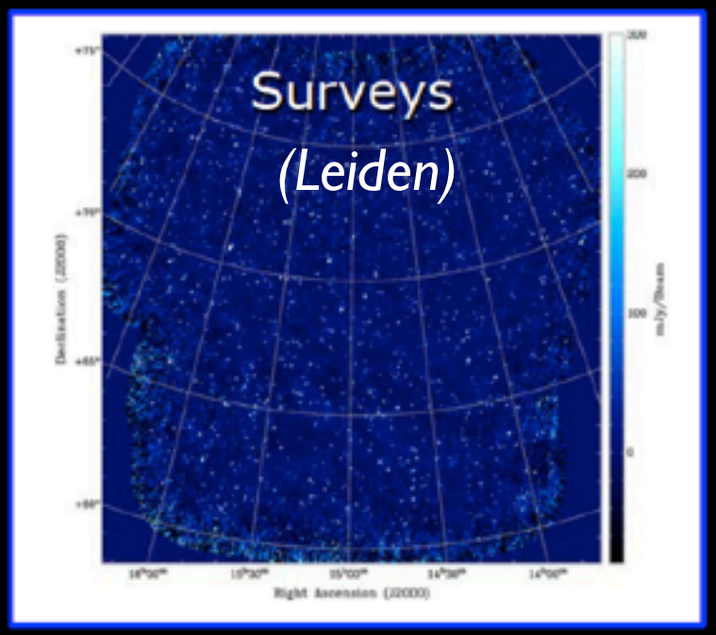


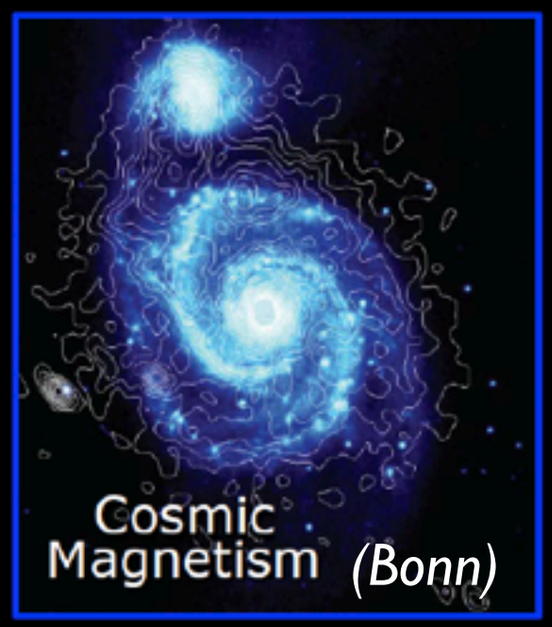
Summary of LOFAR technical characteristics

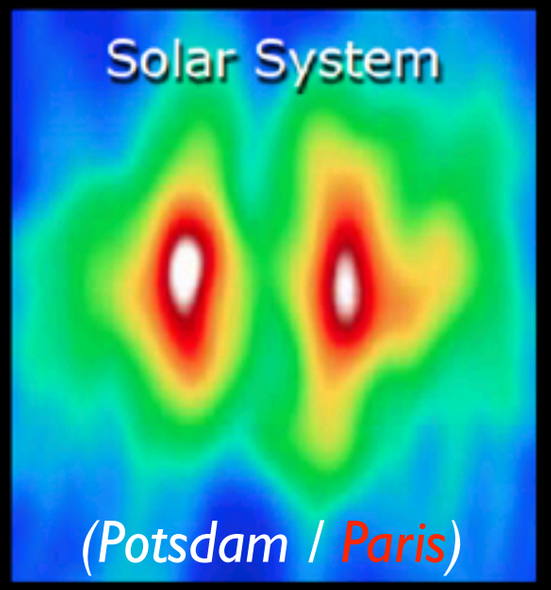
http://www.lofar.org/

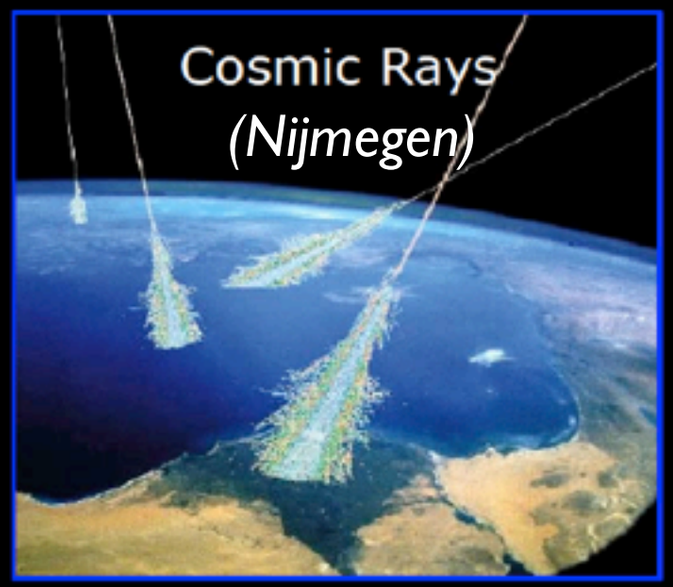
- European « Interferometer » of « Phased arrays »
- 24 stations «core» + 14 remote + 13 international
- Diameter ~90 km (NL) → 2000 km (Europe)
- Effective area ~ 100 000 m^2 ($\propto\lambda^2$)
- Frequency ranges = 30-80 & 110-250 MHz (λ=1.2-10m)
- Operation Modes = imaging, tied-array beams, waveform capture ...
- Resolution ~ 0.1 " - 10 ", large FoV (~10°)
- Sensitivity < mJy (10^{-29} $Wm^{-2}Hz^{-1}$)
- Resolutions → 1 msec × 1 kHz, Full polarization
- RFI mitigation, ionospheric « adaptive optics »
- First Low-Frequency « all-purpose » spectro-imager
- 1st SKA precursor

LOFAR KEY SCIENCE PROJECTS

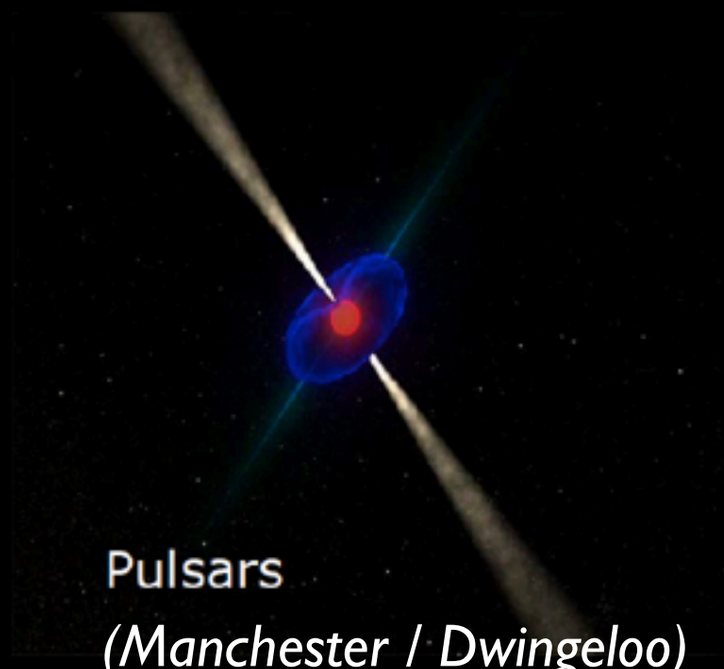


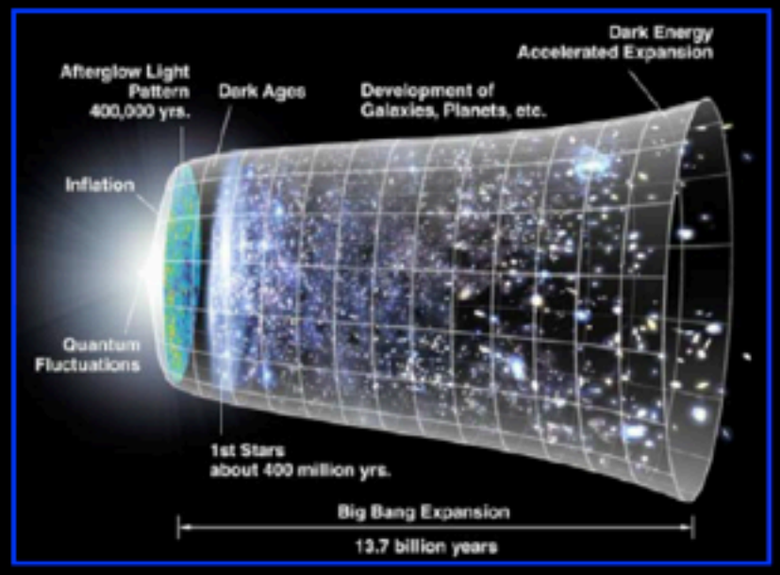






(Amsterdam)

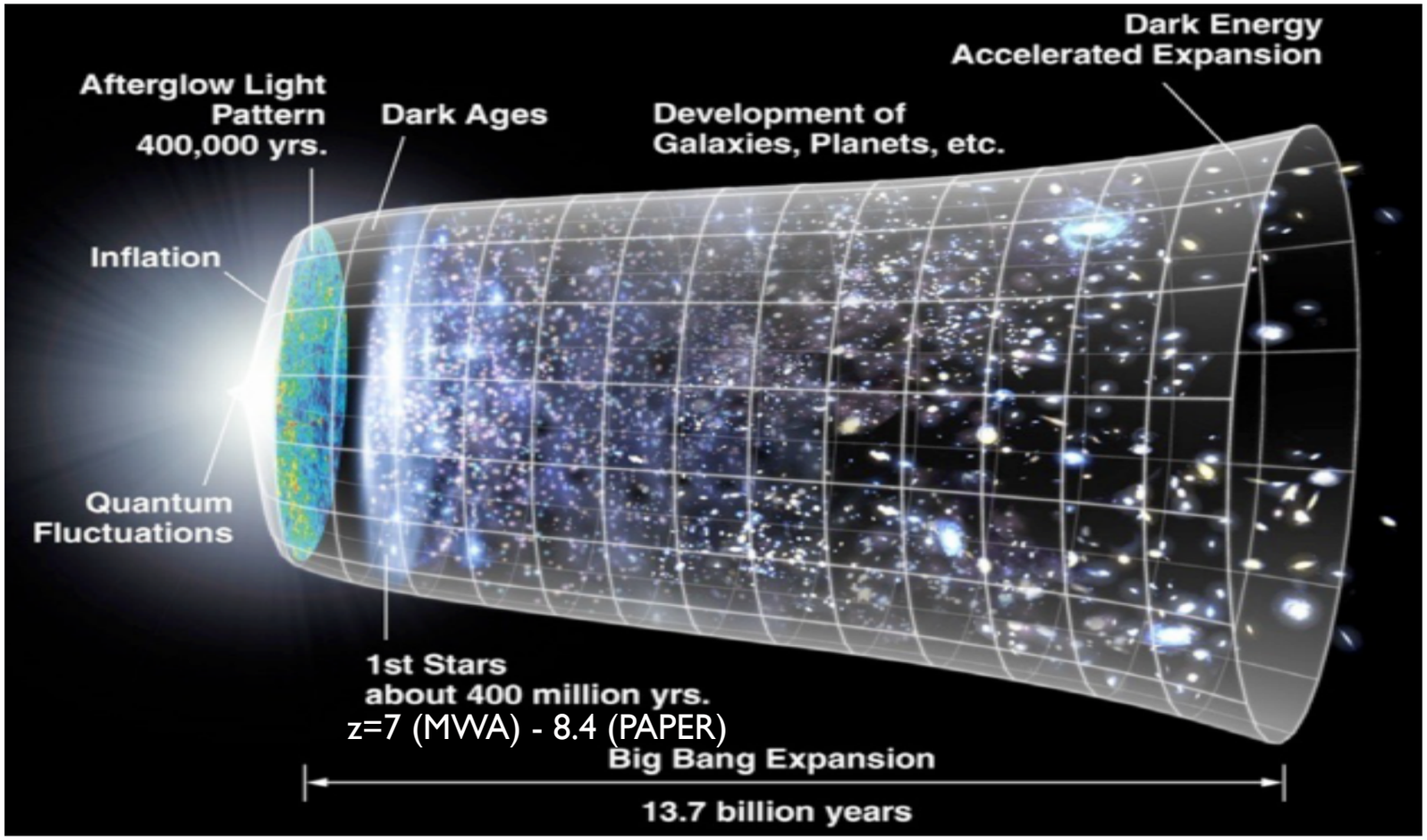




Epoch of Reionization

(Groningen)

The Epoch of Reionization



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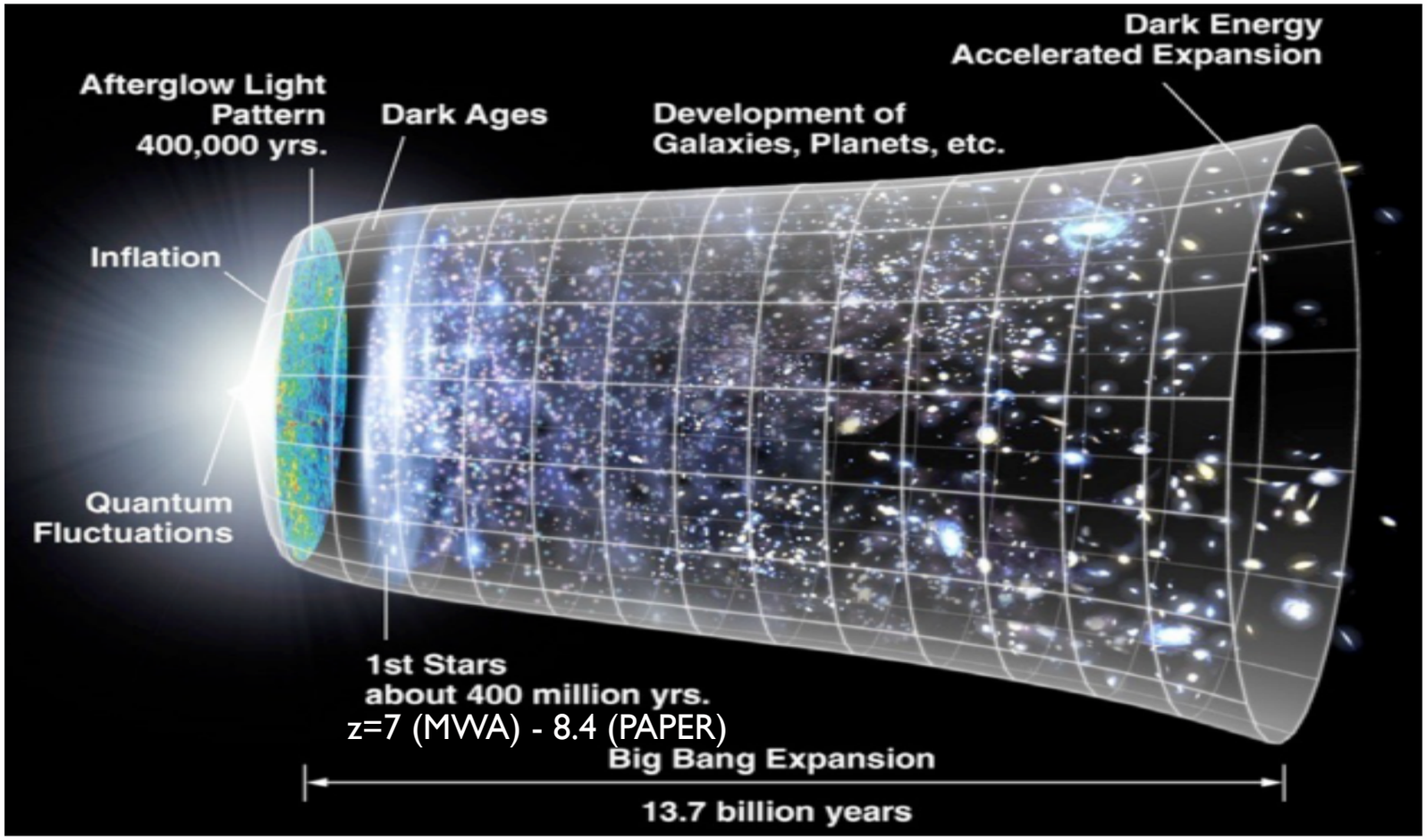

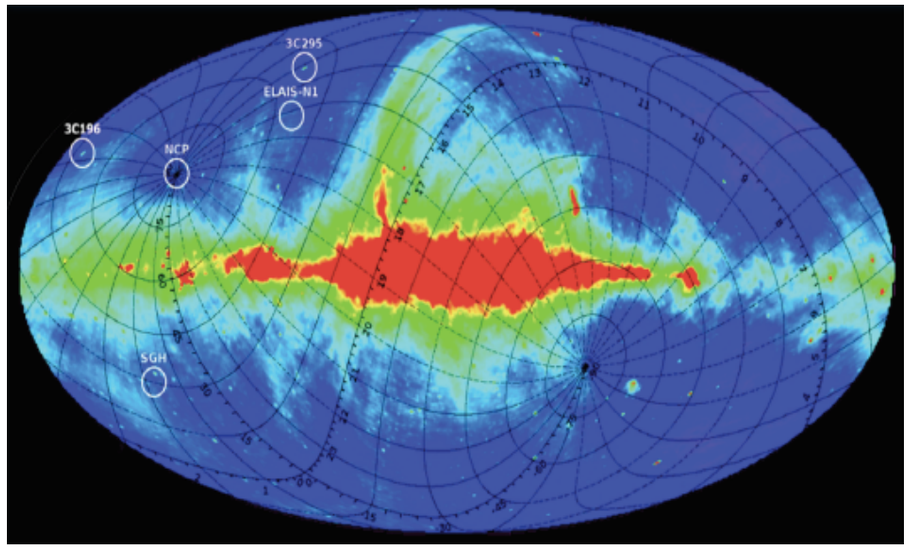

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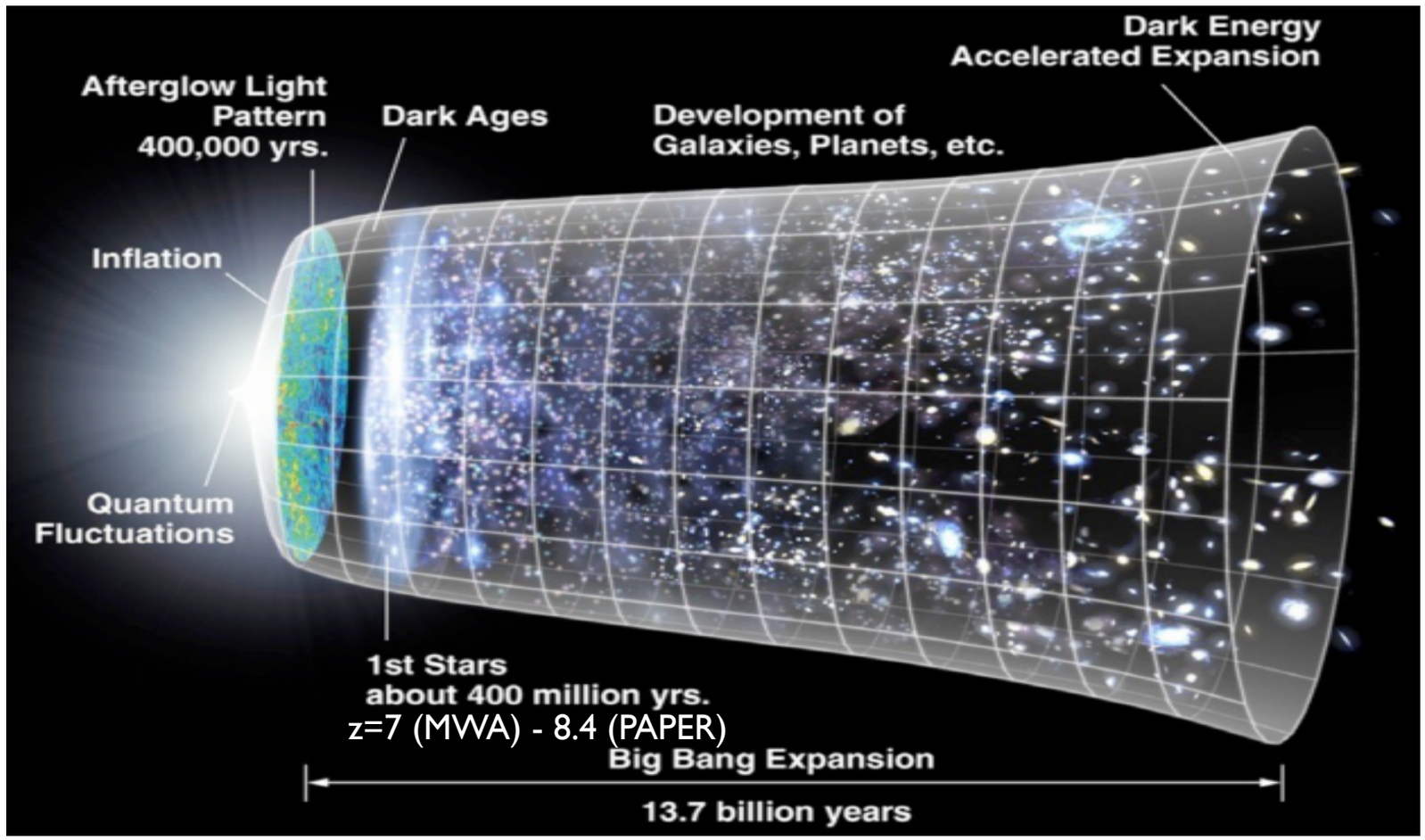

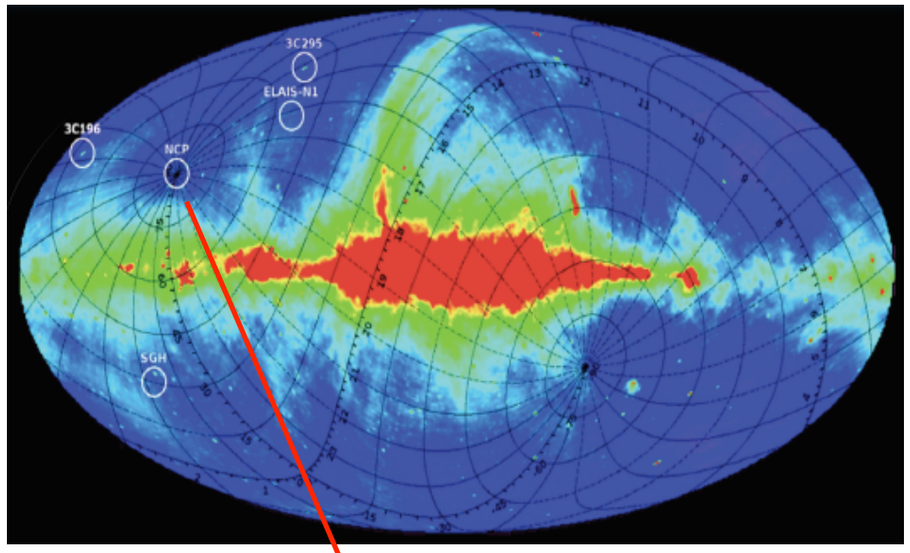

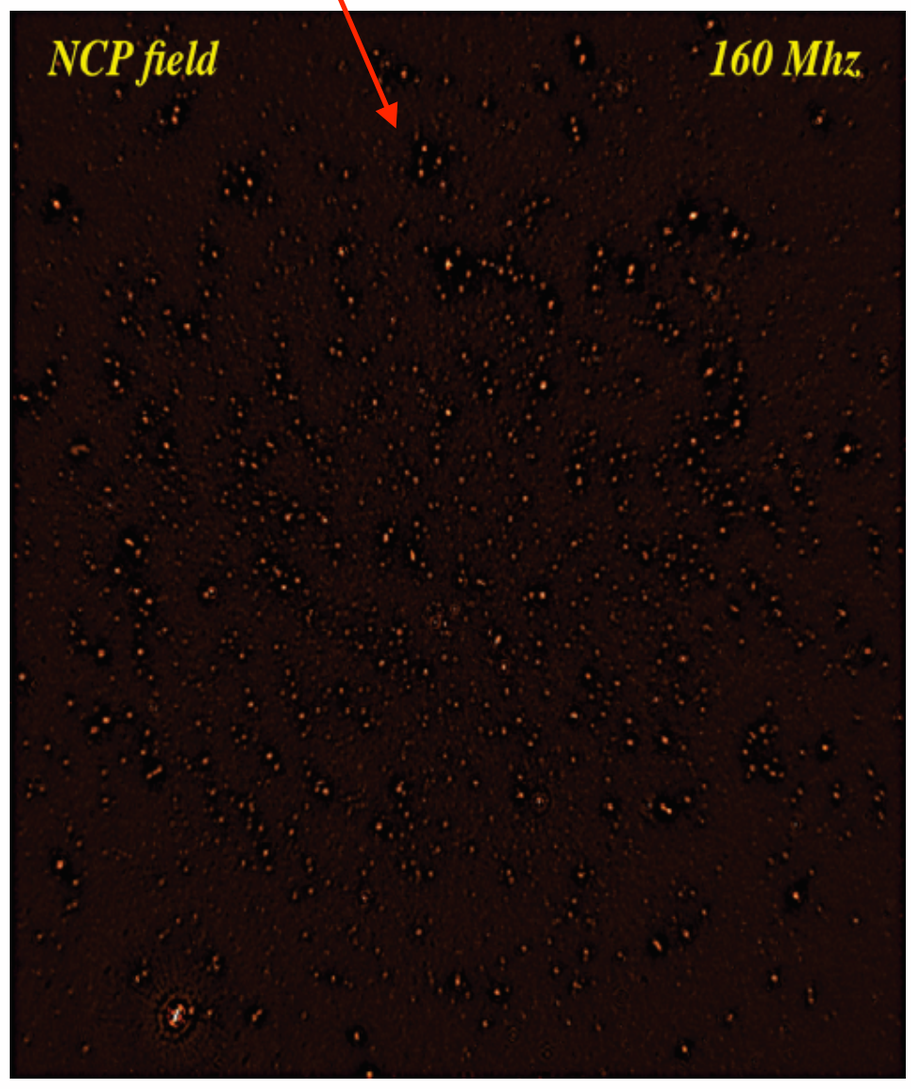

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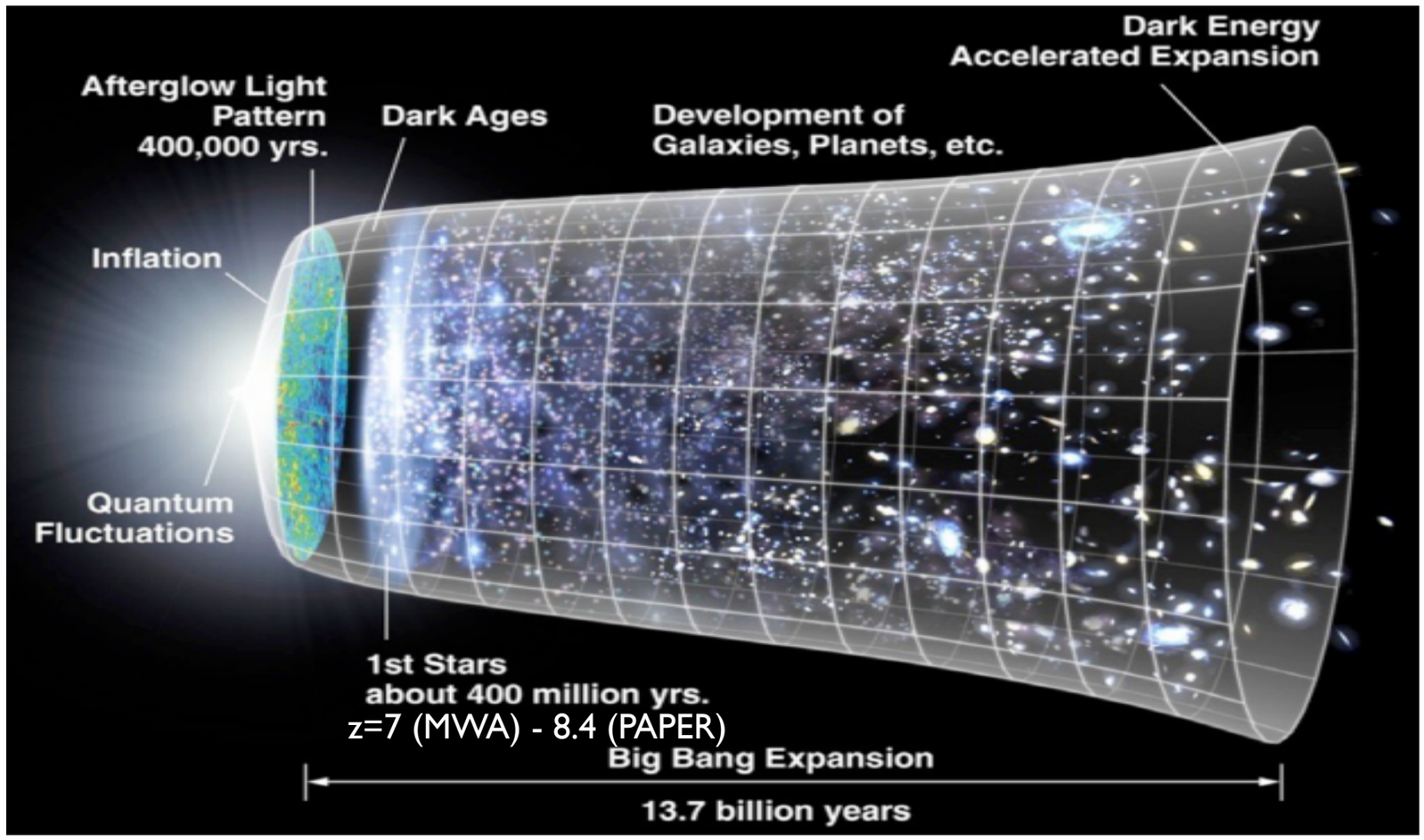
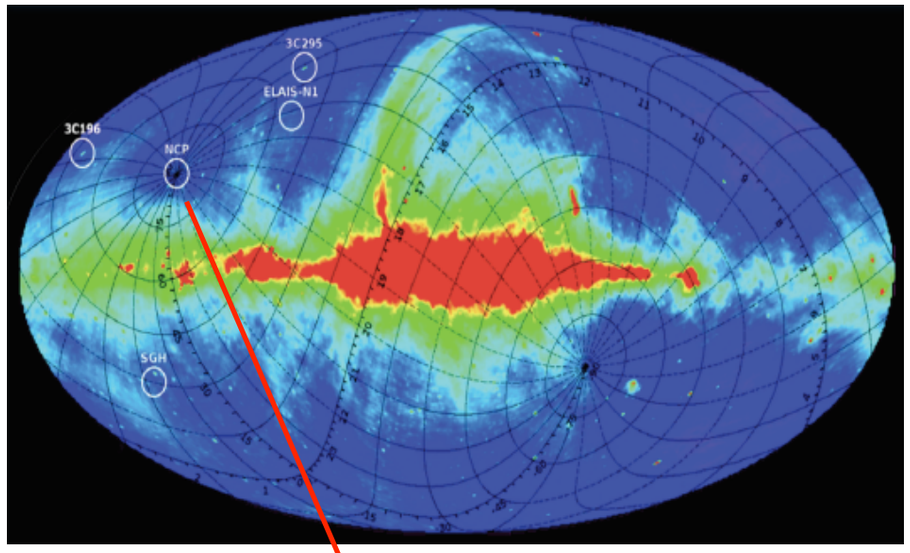
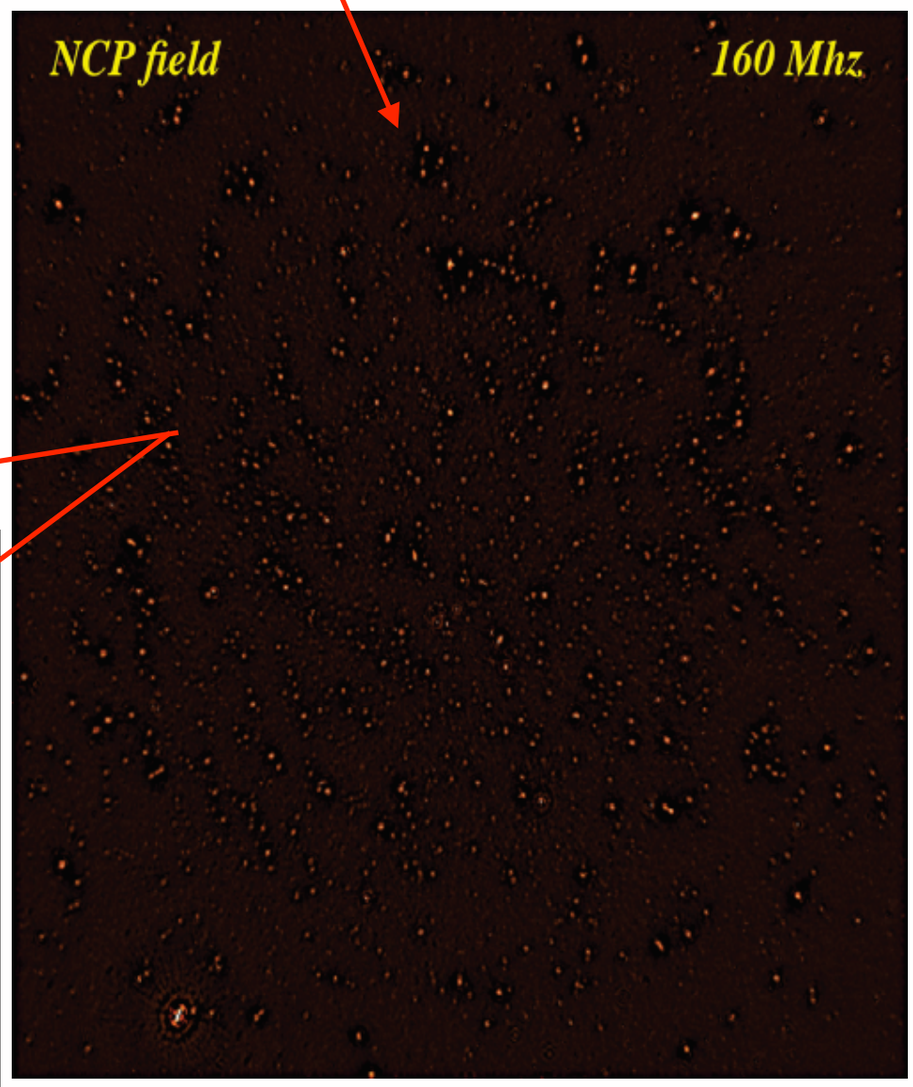
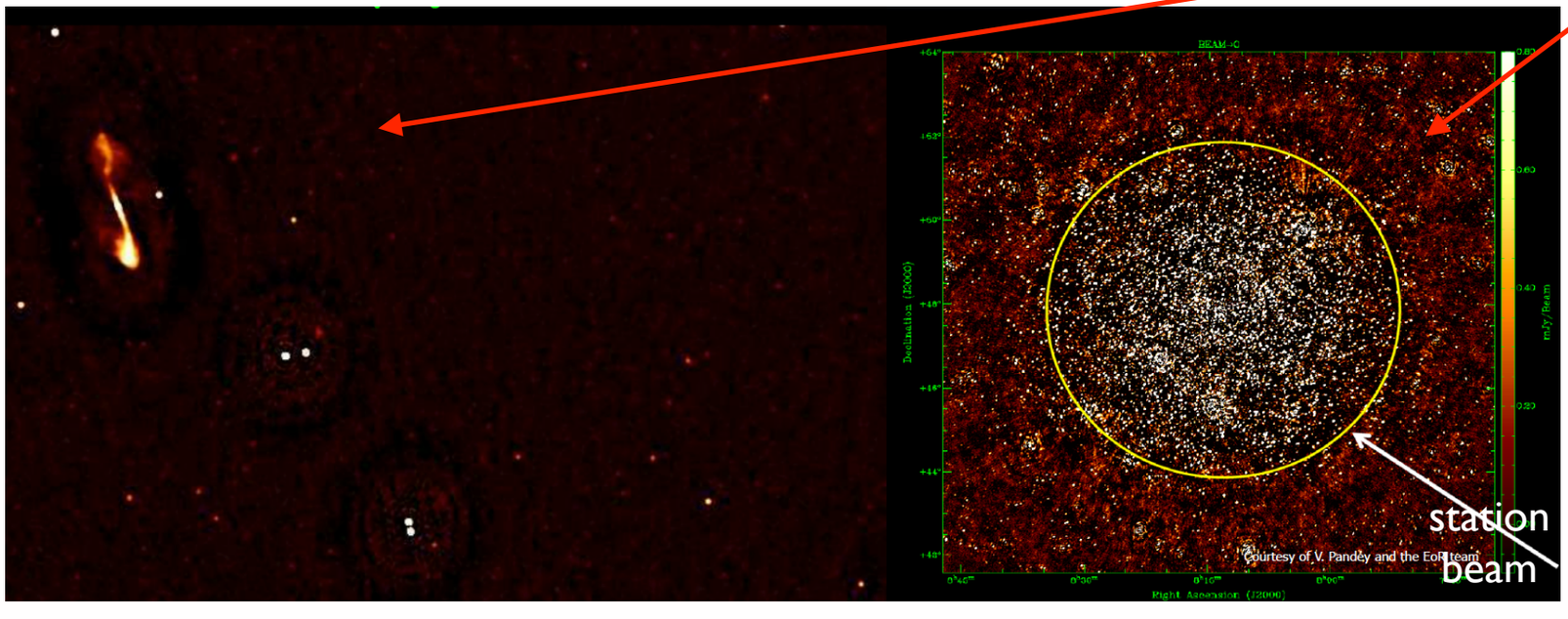


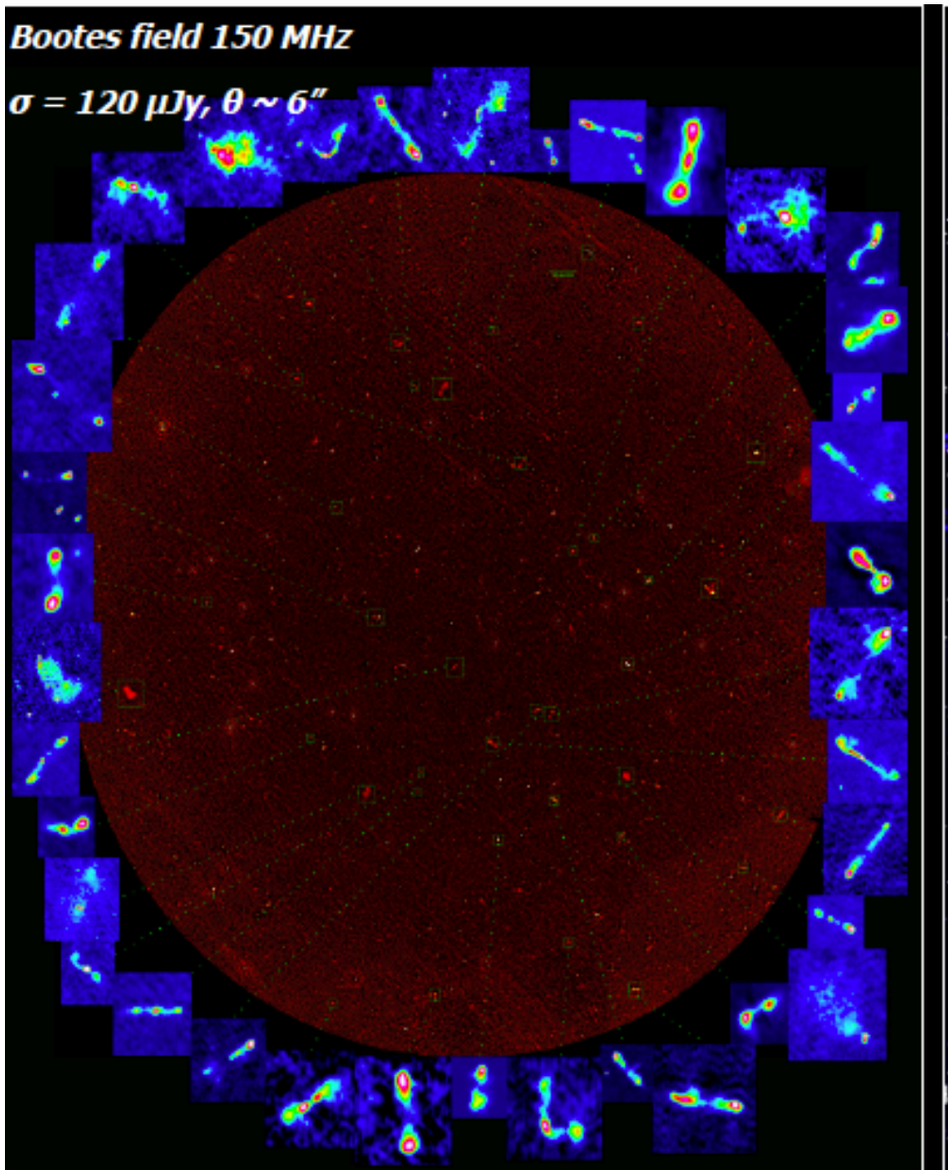




2000 h on 2 fields → σ = 25 μJy, DR = 10^6 @ scales 30'-60'

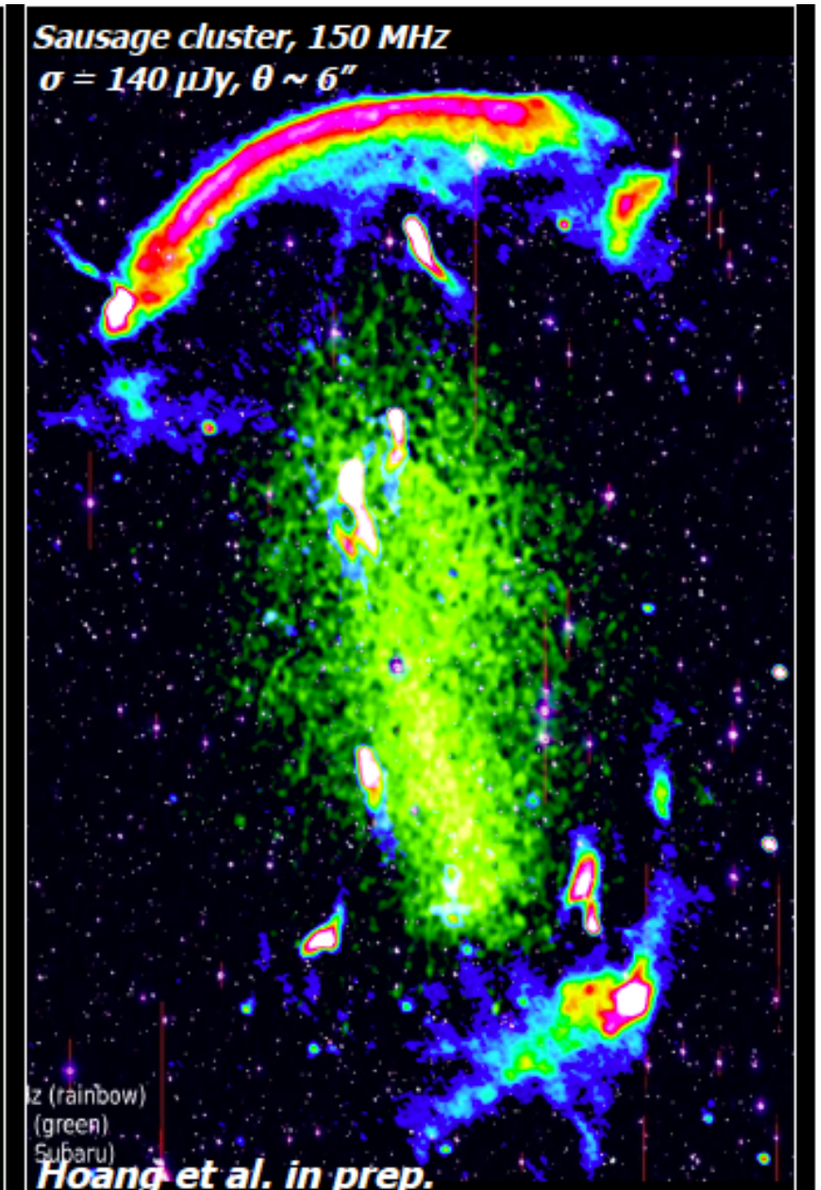


Surveys (galaxies)



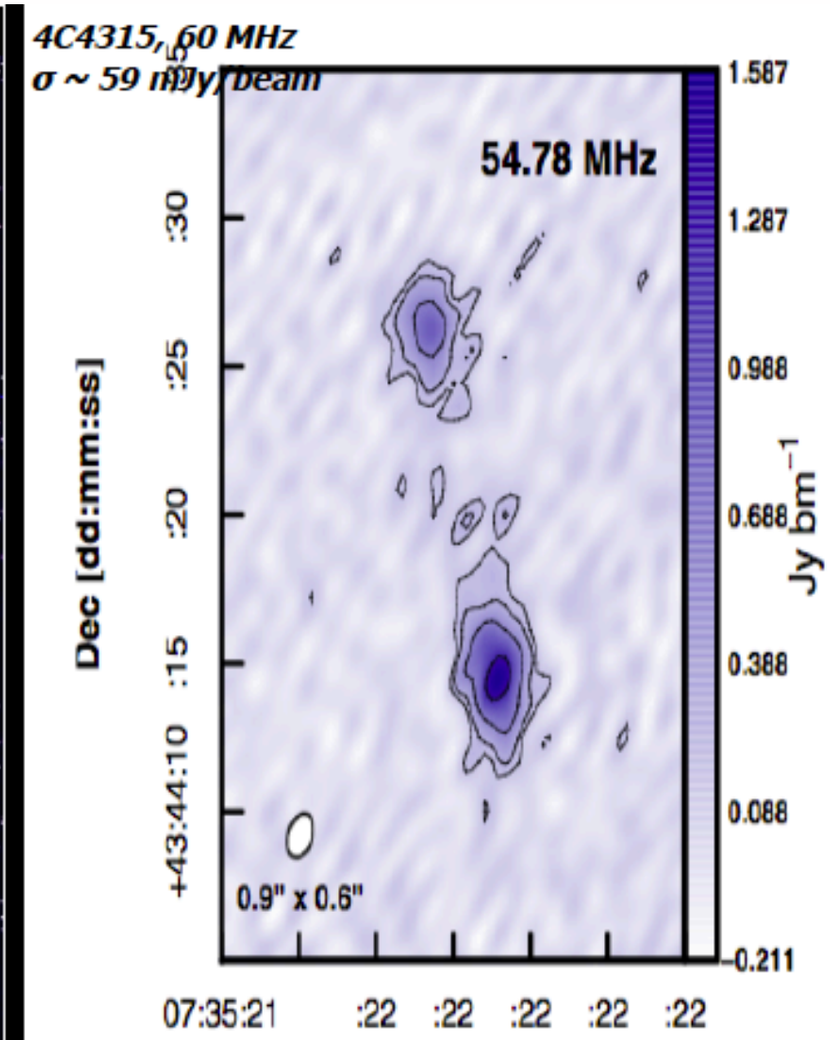
Williams et al. 2016

- *Differential source counts reaching an order of magnitude deeper in flux density than previous studies*



Hoang et al. in prep.

- *Double radio relics*
- *Enables the most precise characterization of a cluster shock ever*

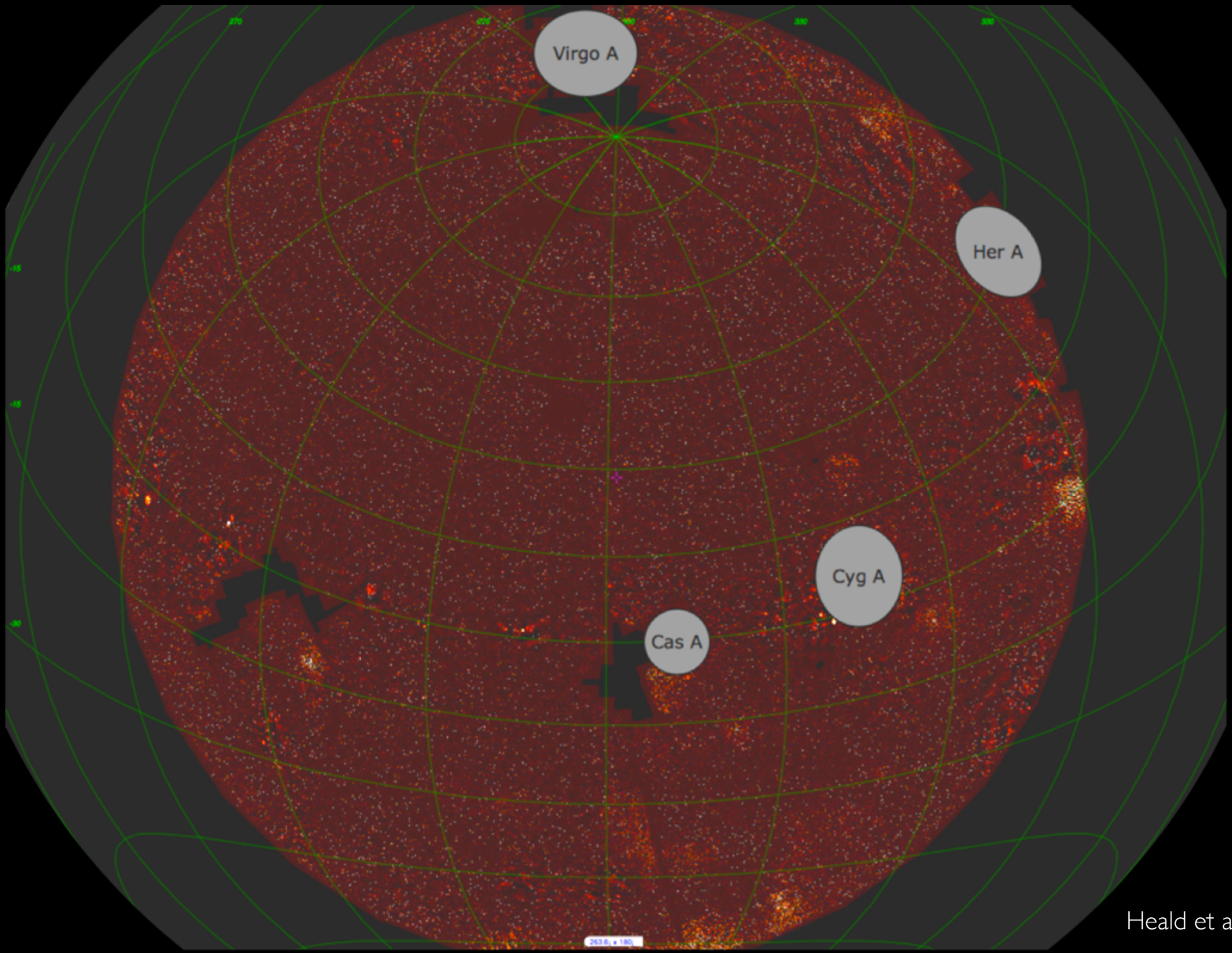


Morabito et al. 2016

- *First spatially resolved studies at frequencies below 100 MHz of high-z radiogalaxy 4C4315*

MSSS

The Multi Frequency Snapshot Sky Survey - LOFAR (150 MHz)

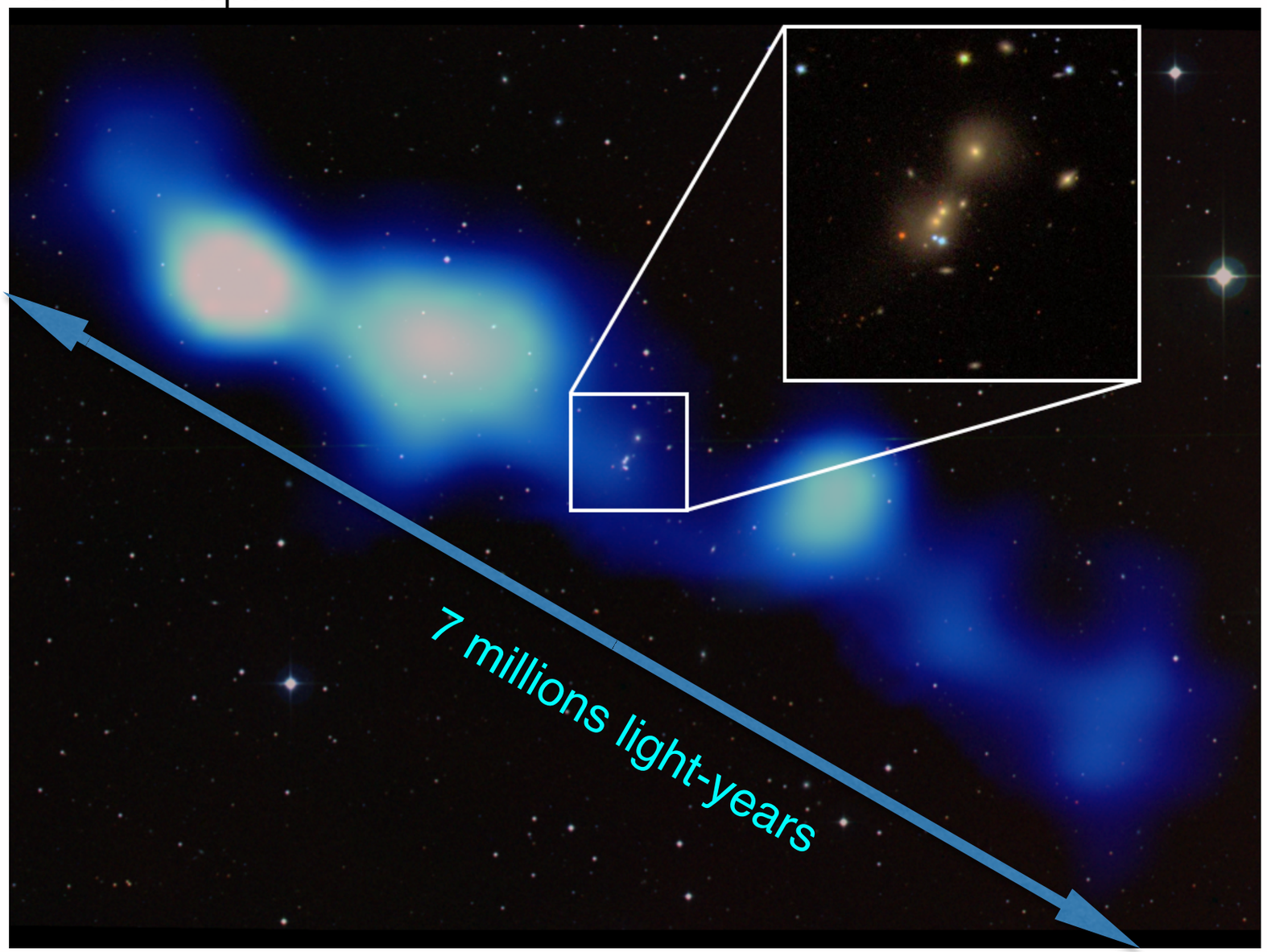


Heald et al., 2015

Discovery of giant radiogalaxies

around triplet UGC 09555

Clarke et al.



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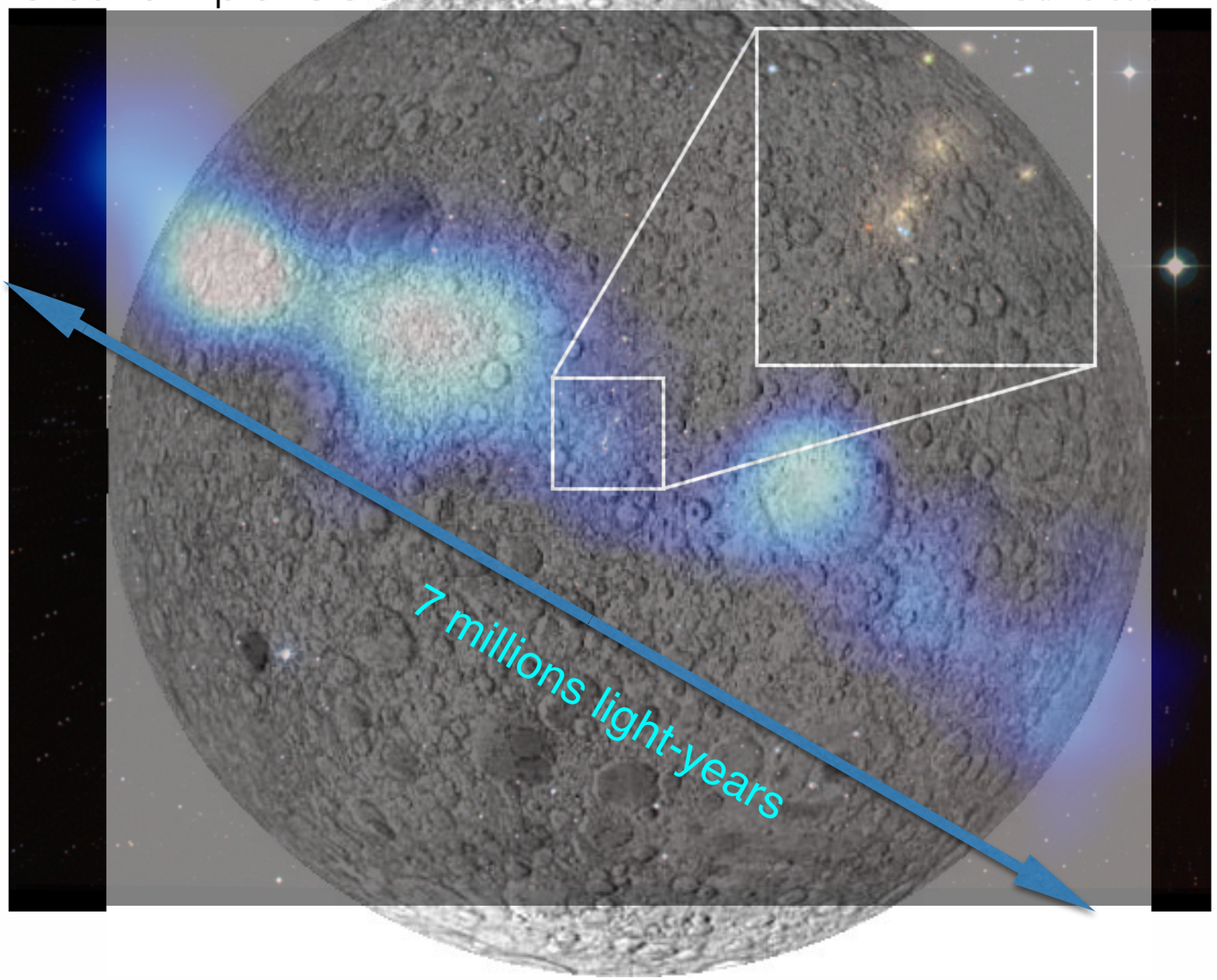

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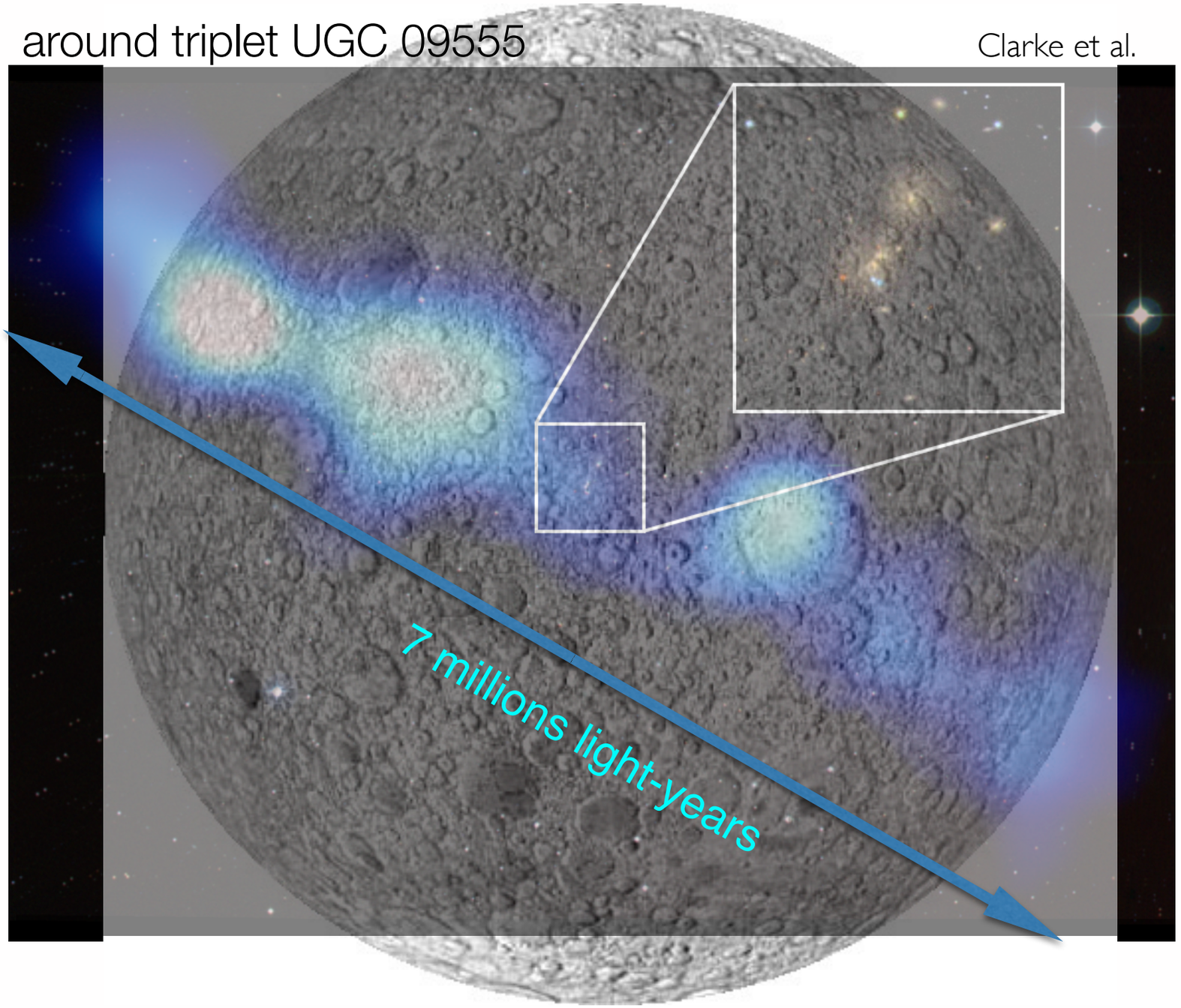
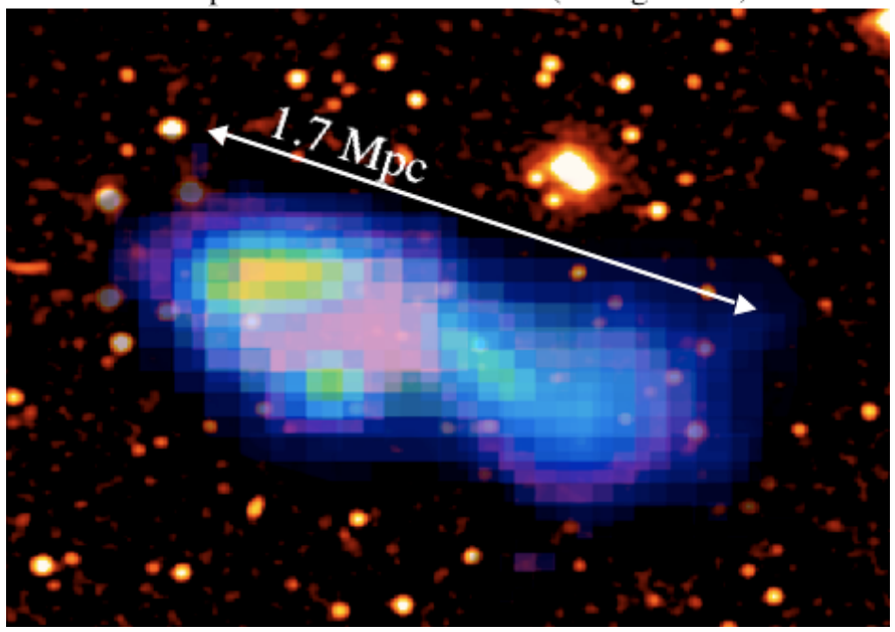
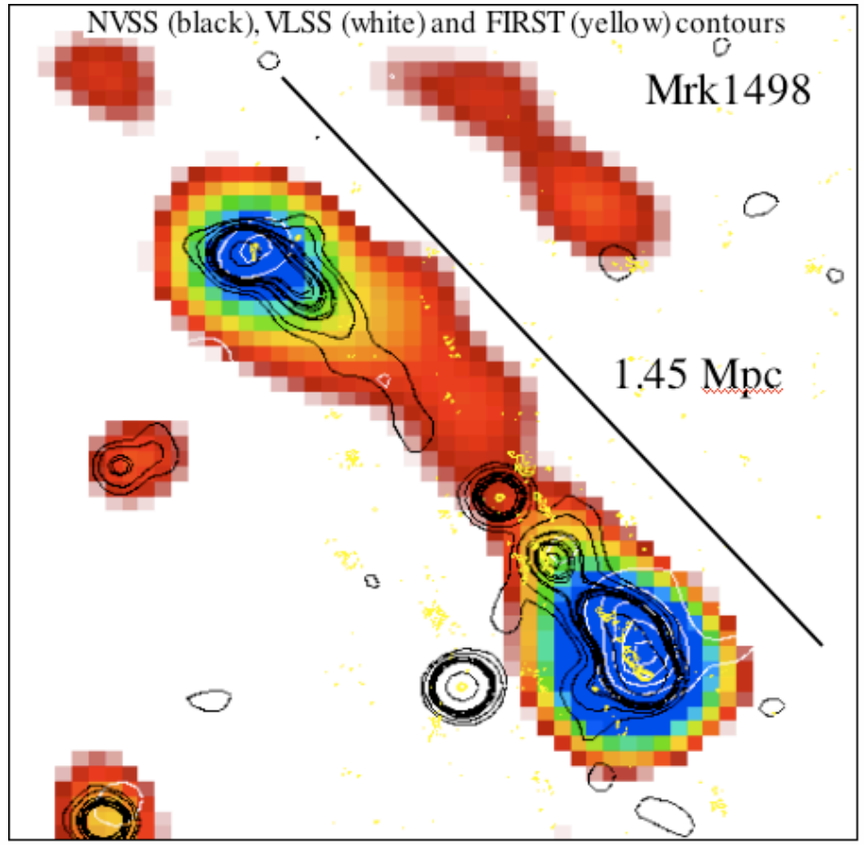


MSSS (blue) and NVSS (pink-yellow)
on optical data from SDSS (background)





Pommier et al.

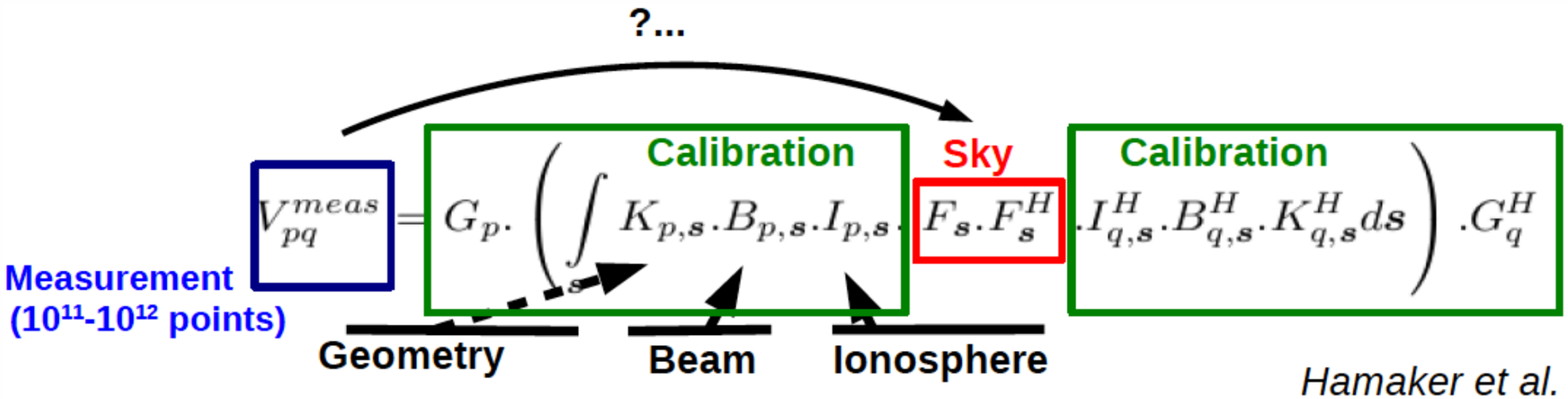
The Toothbrush galaxy cluster, LOFAR
(150 MHz)

Credits: R. van Weeren

Galaxy cluster Abell 2256,
LOFAR (150 MHz)

Credits: R. van Weeren

Calibration & Imaging algorithms



Hamaker et al. 1996abc

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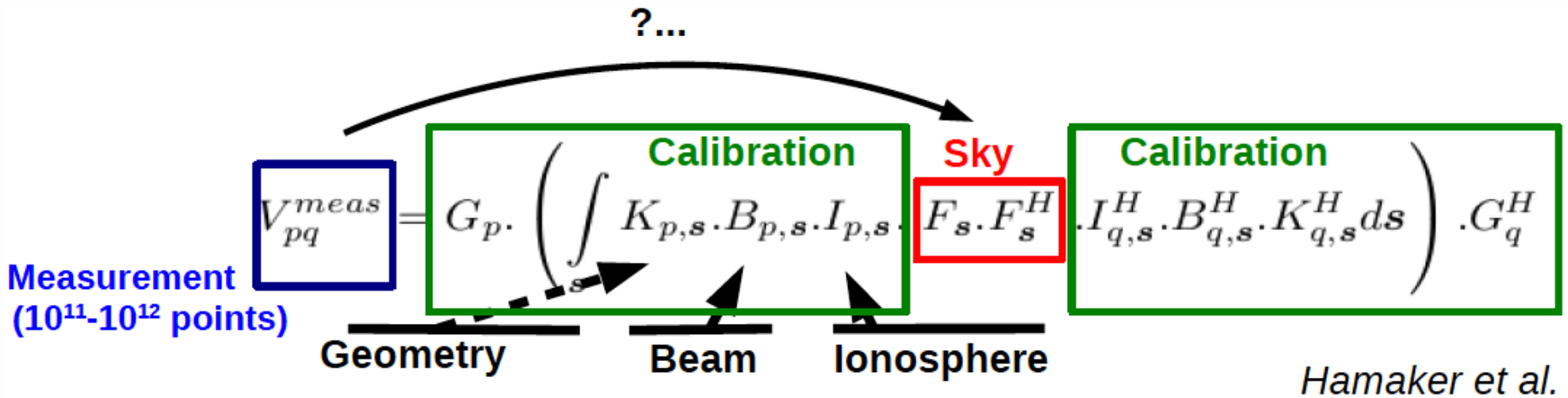

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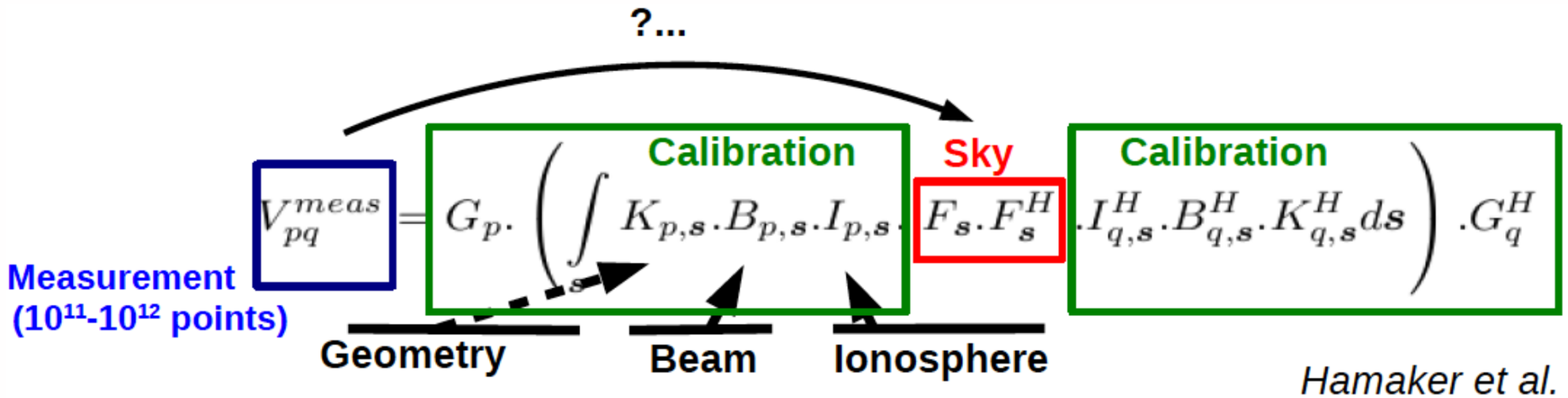

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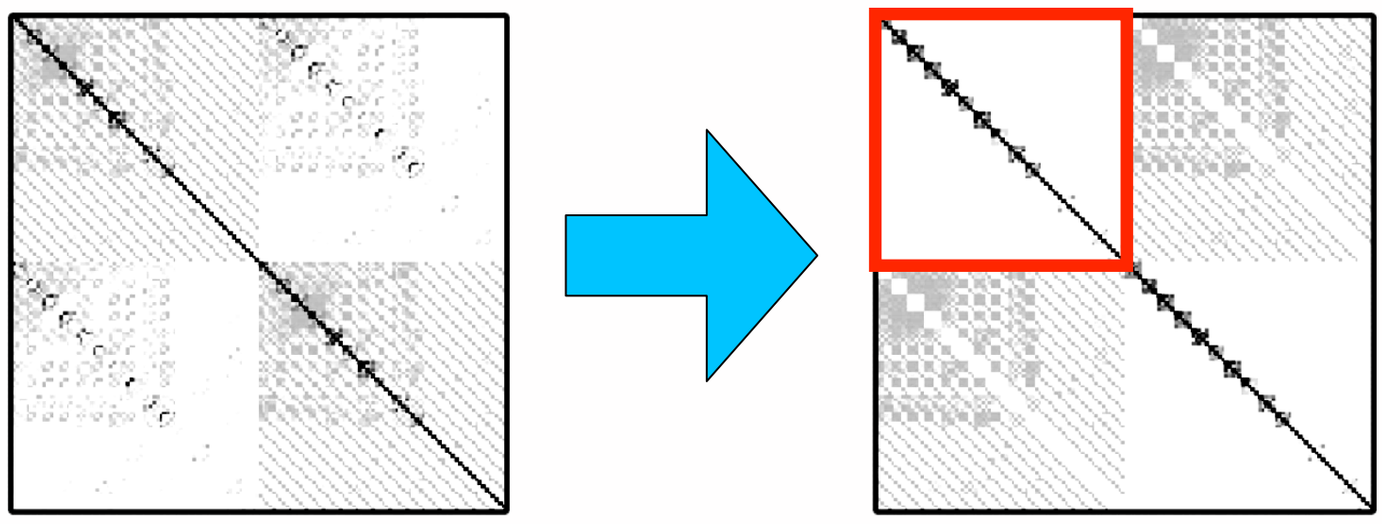

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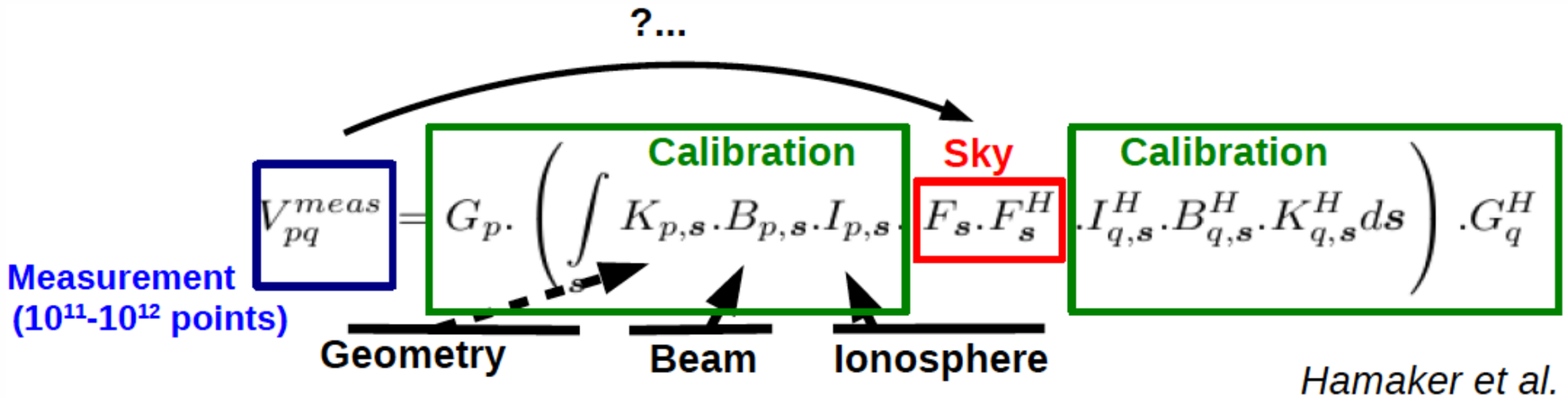

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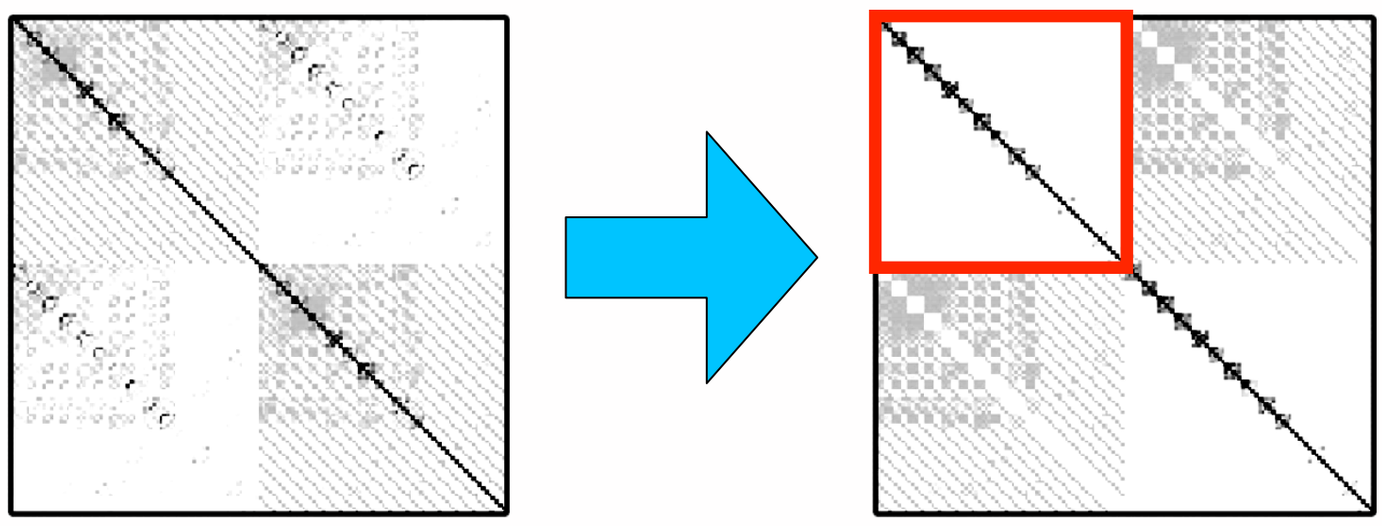
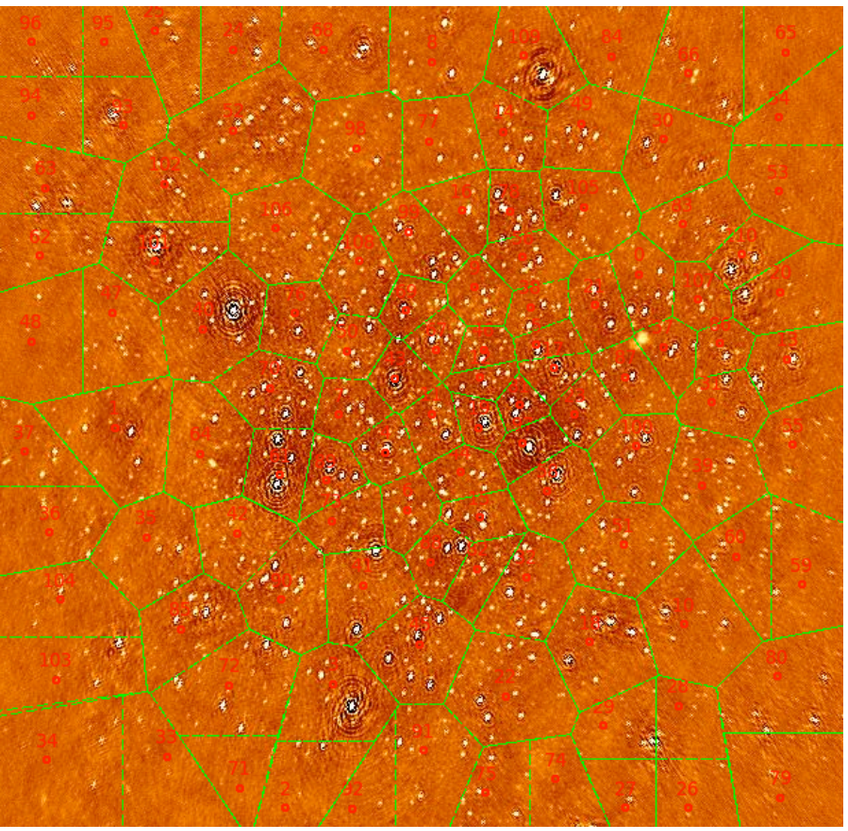


- **Lucky exposure : new weighting scheme to optimize SNR vs DR**

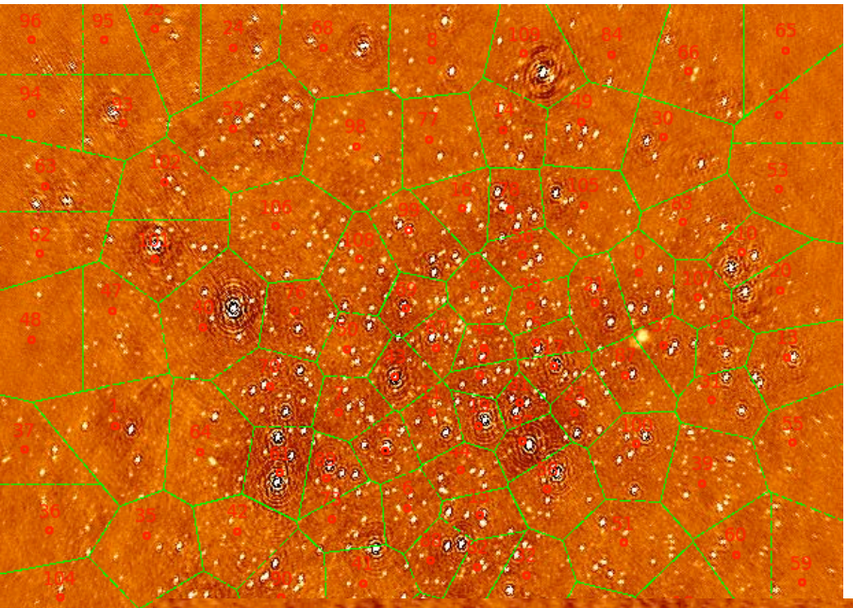
Bonnassieux et al., 2015

DDfacet



- Tesselated images, with continuity between facets
- Full polarisation DDE correction
- Variable t-f-uv variation of beam and PSF (smearing/decorrelation)
- Spectral + sub-spaces (of pixels) deconvolution, Mosaicing
- Works on LOFAR, VLA, ATCA, MeerKAT
- More sources detected, better detection of extended sources
- Flux scale fidelity

DDfacet



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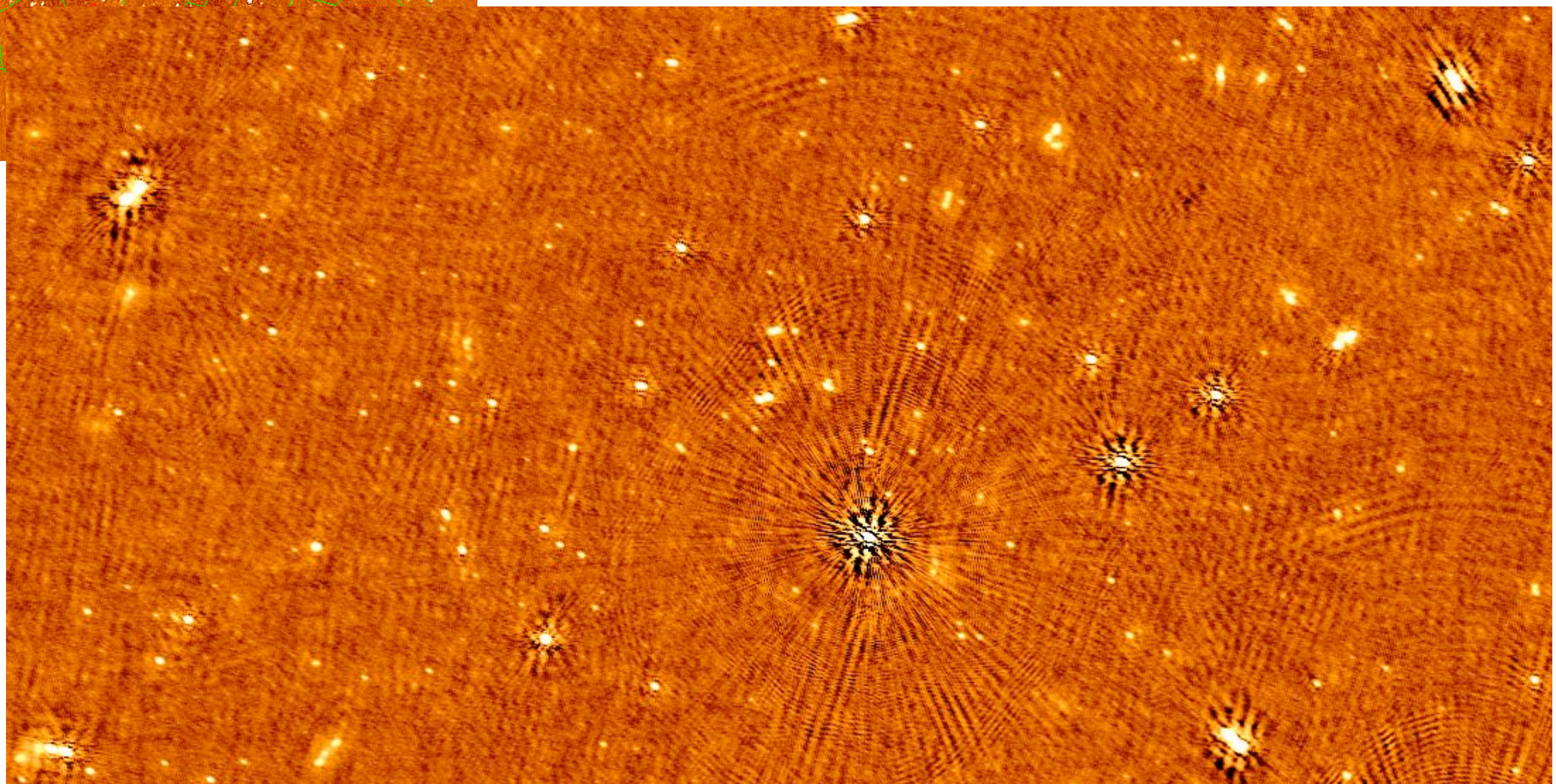

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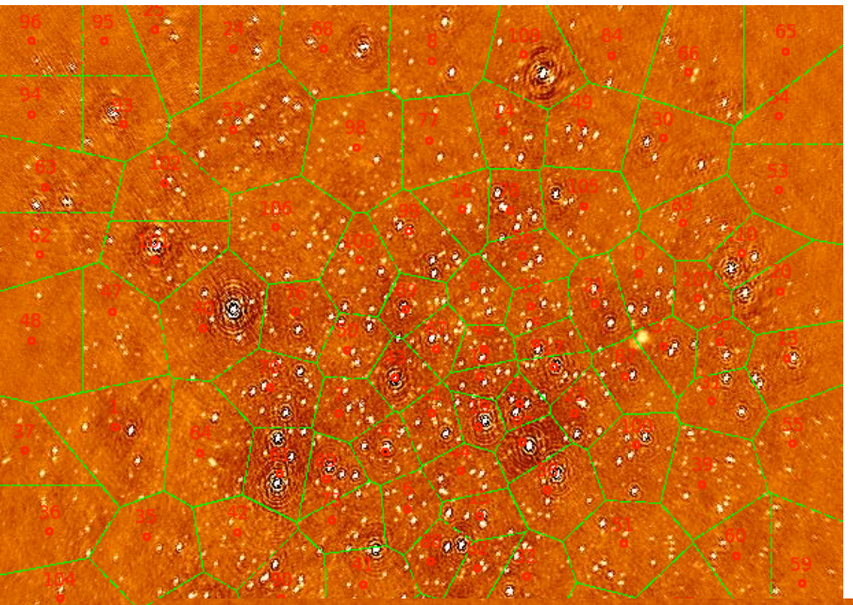

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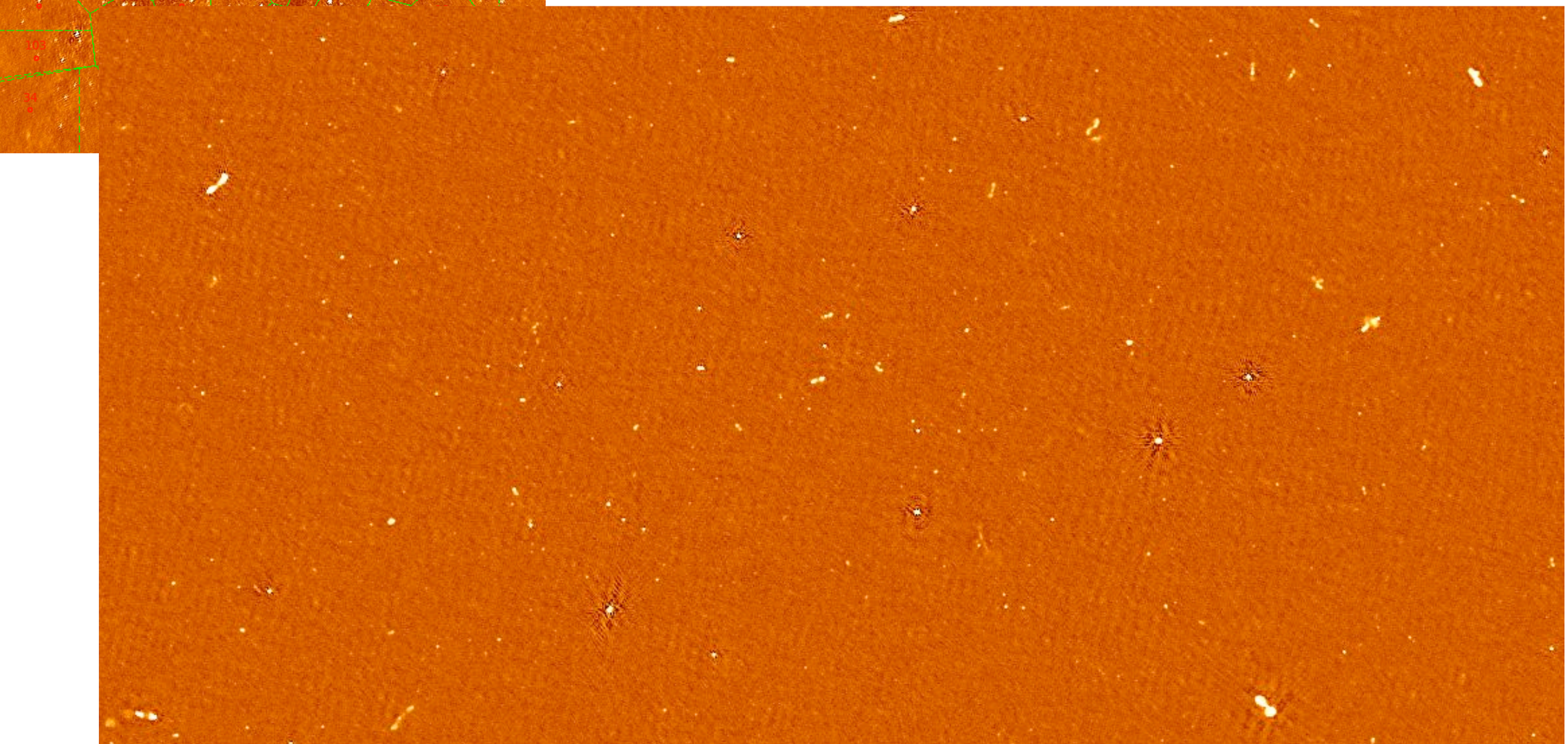

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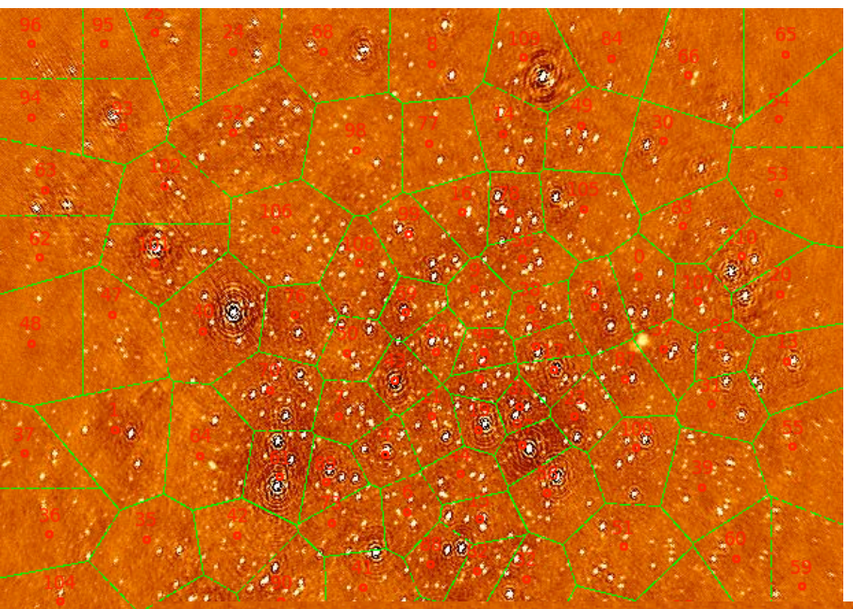

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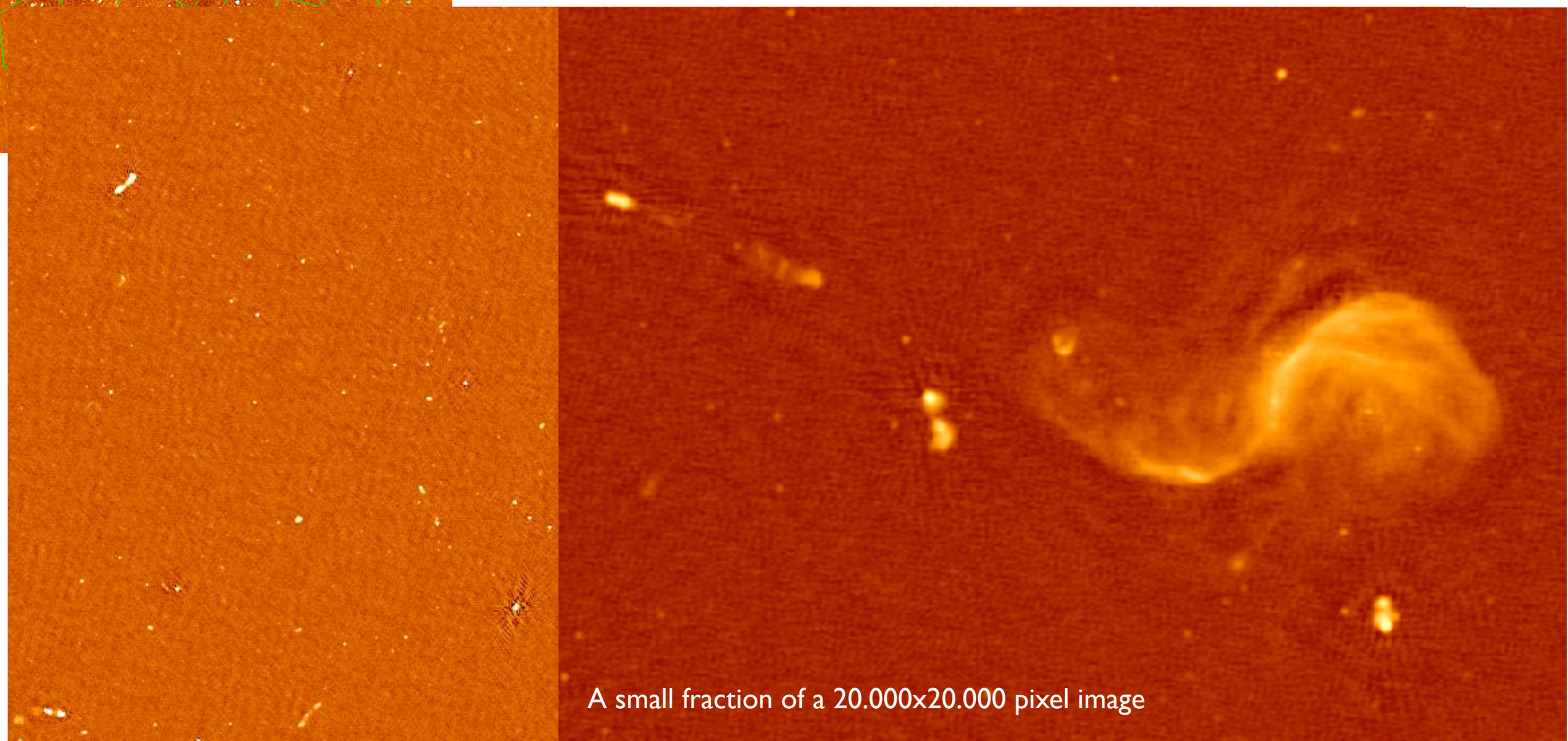


A small fraction of a 20.000x20.000 pixel image

NenuFAR

New Extension in Nançay Upgrading LOFAR

P. Zarka[1]

& the NenuFAR-France team[2]

[1]LESIA—USN, OP/CNRS/PSL
[2]GEPI, LPC2E, Subatech, CEA/AIM, OCA,
ONERA, LERMA, PRISME, APC …

Motivations

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

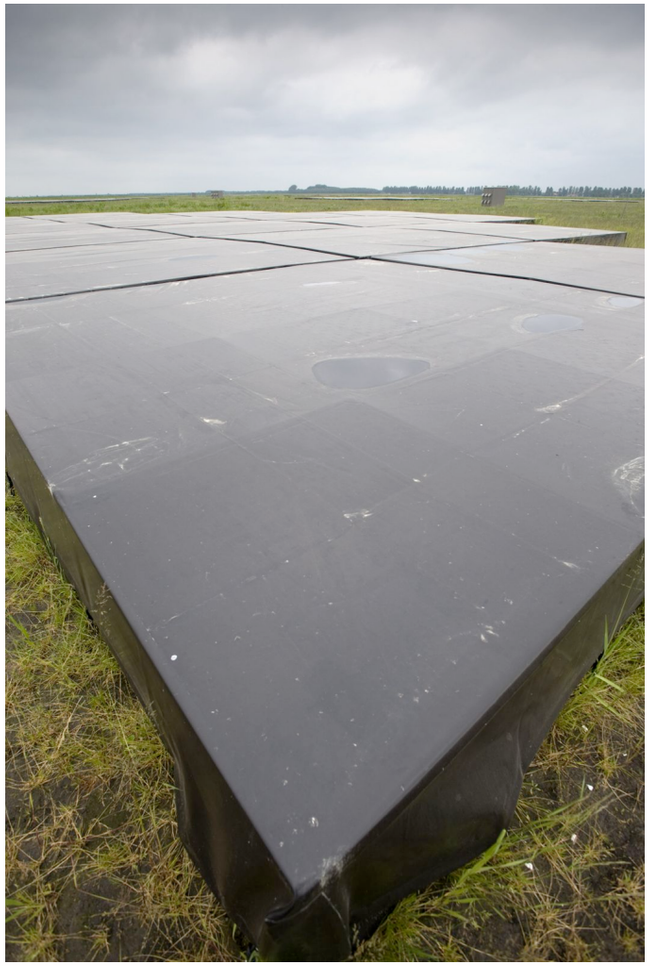
  ⇒ large programs : *pulsars & transients at LF, dark ages, exoplanets, active/flaring stars*

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

- Developing the French LF radio community

The NenuFAR concept

x

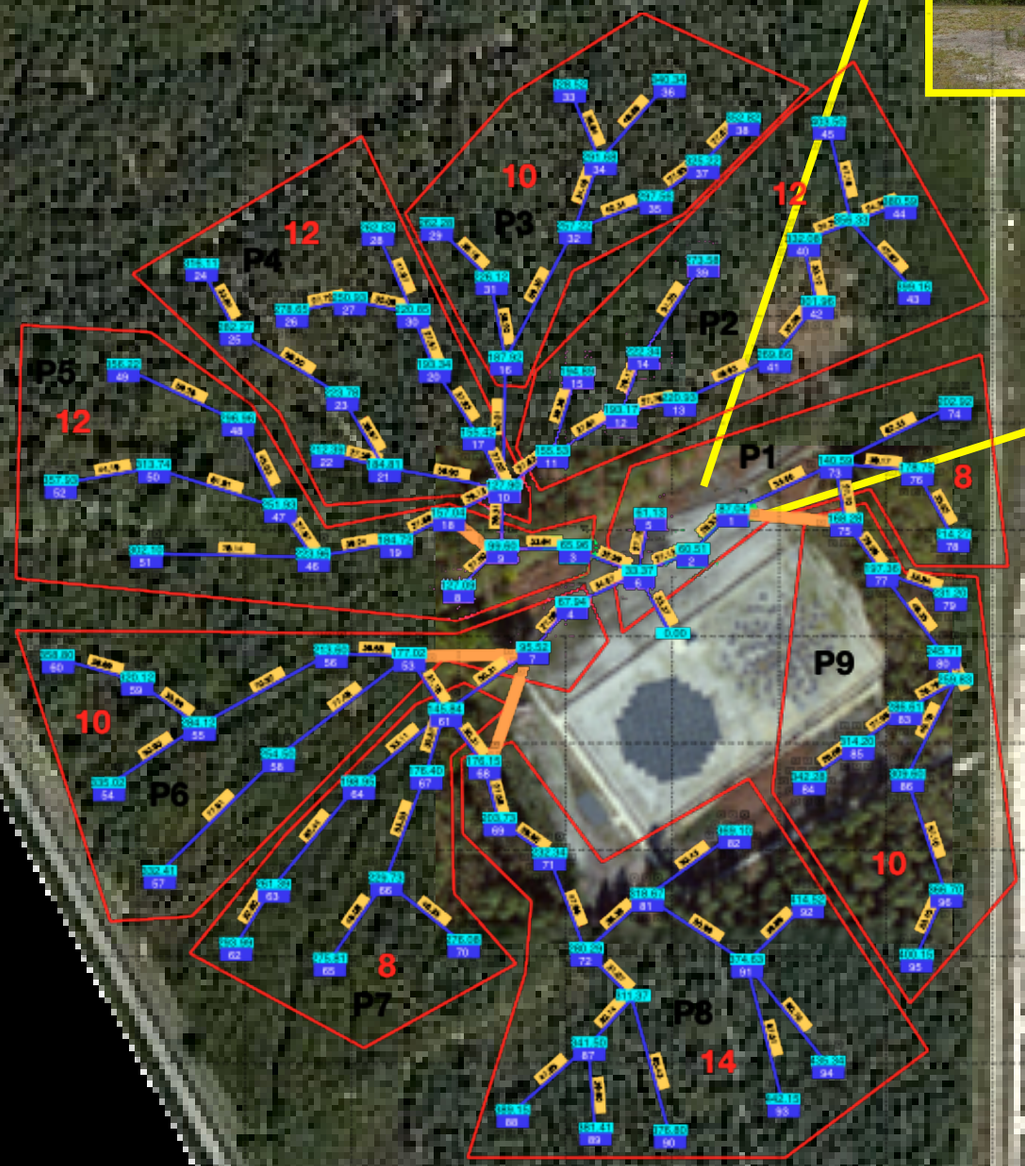


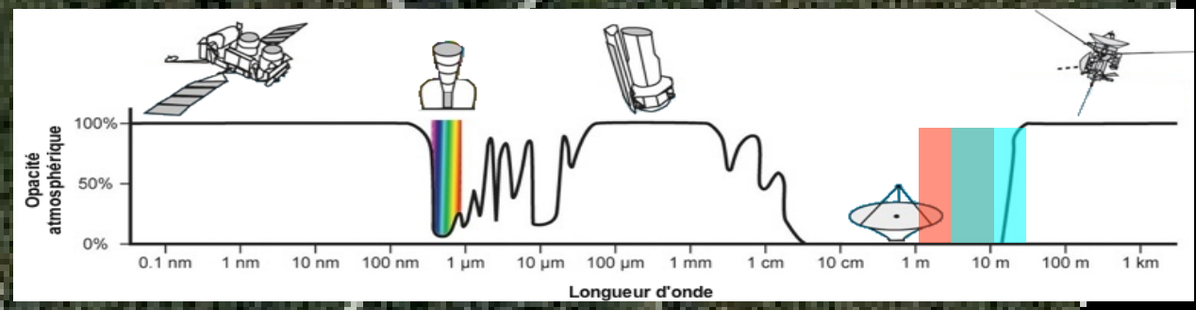
=

From LOFAR (FR606) to …

… NenuFAR

New extension in Nançay upgrading LOFAR





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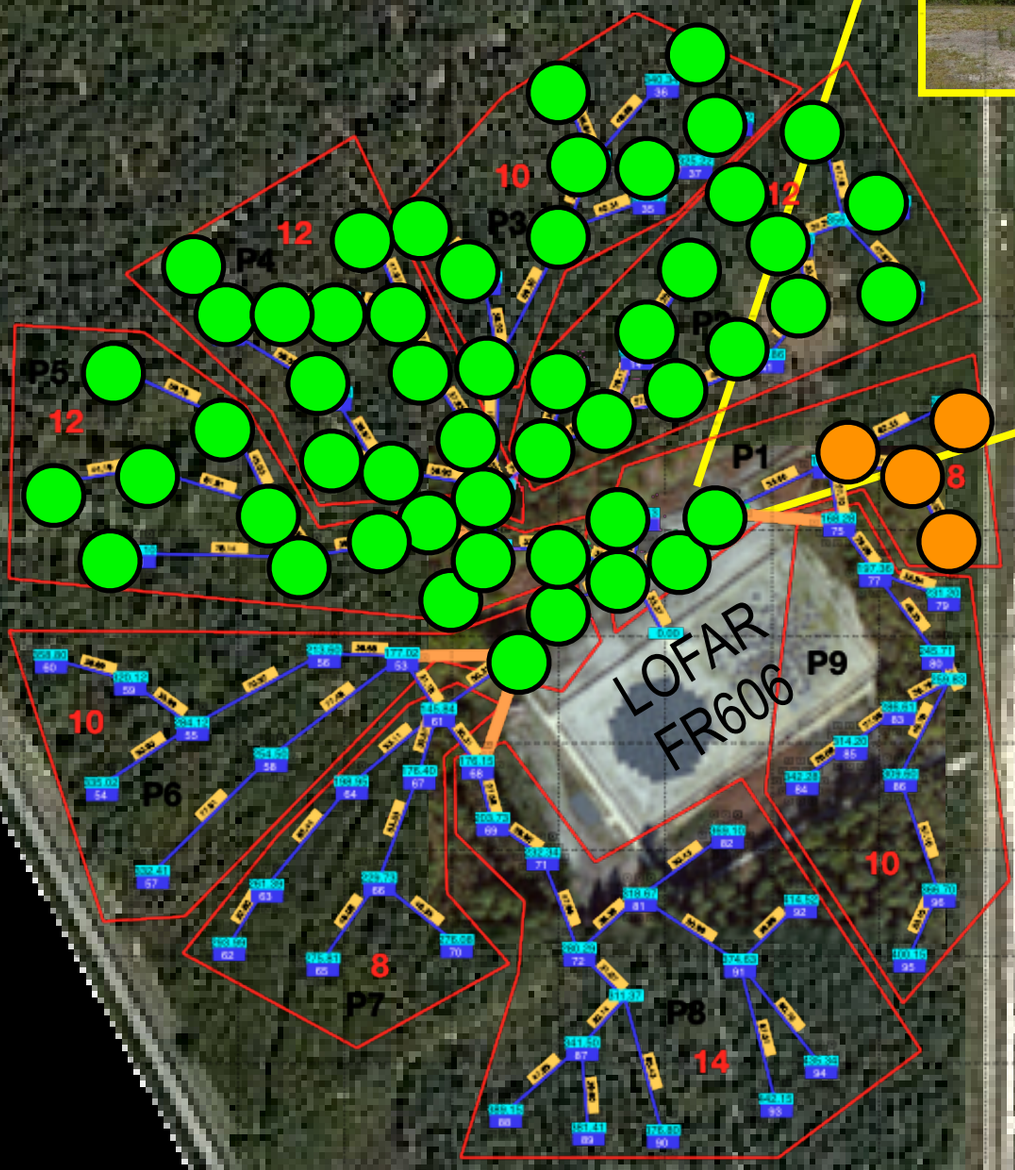
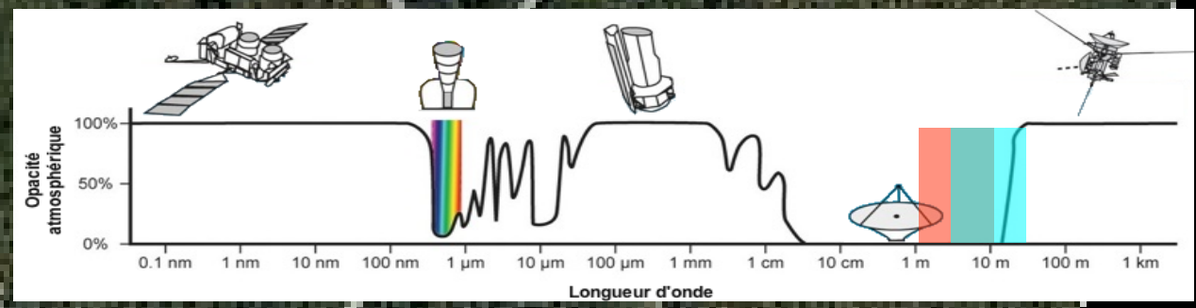




built today

to be built in 2018

NenuFAR in brief

NenuFAR, a LF instrument (10-85 MHz)

- triple: LOFAR Super Station, standalone Beamformer, standalone Imager

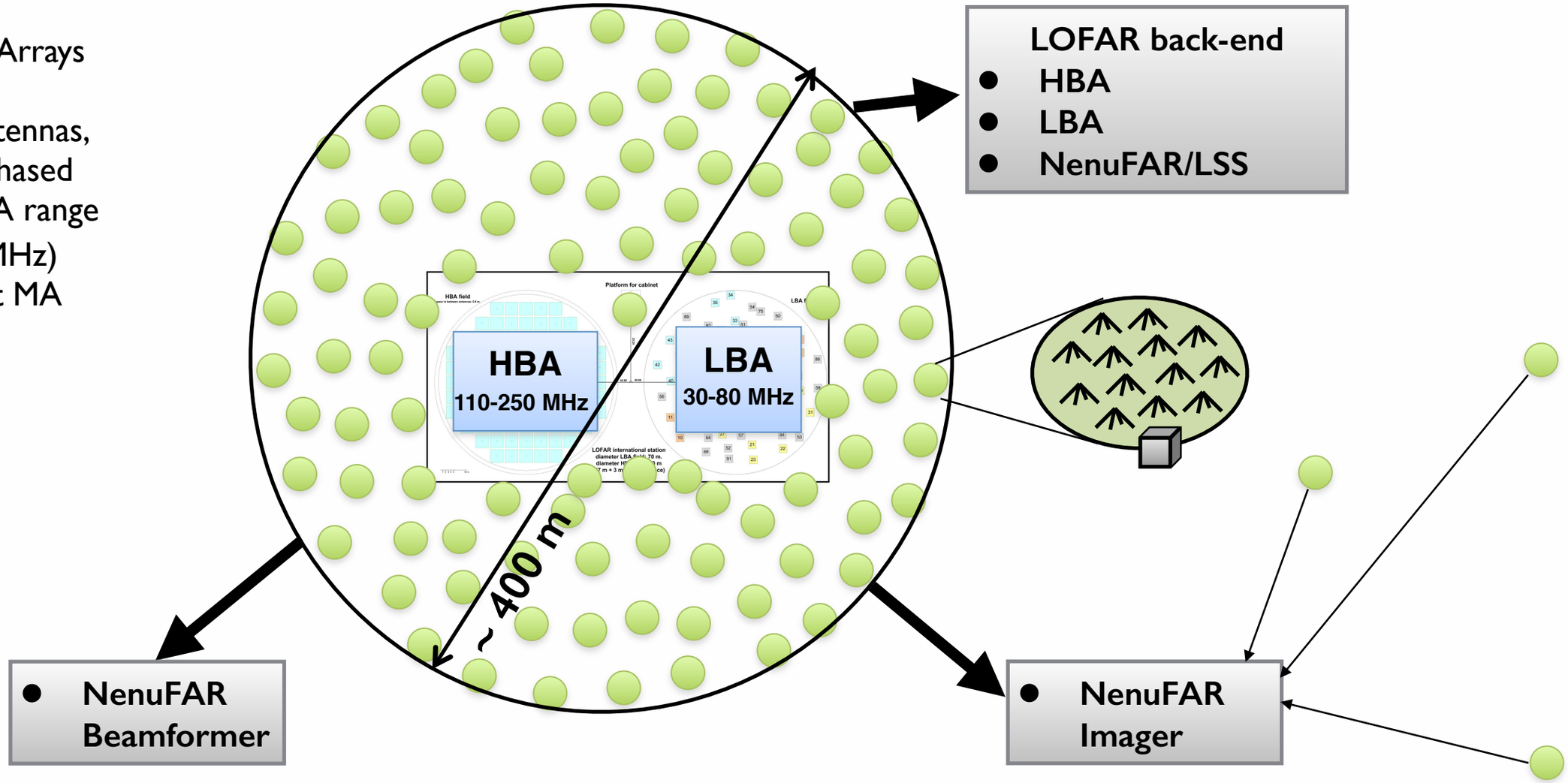
- complex: dialog with LOFAR / FR606 receivers, LaNewBa receiver +UnDySPuTeD, Correlator, SETI-machine ?

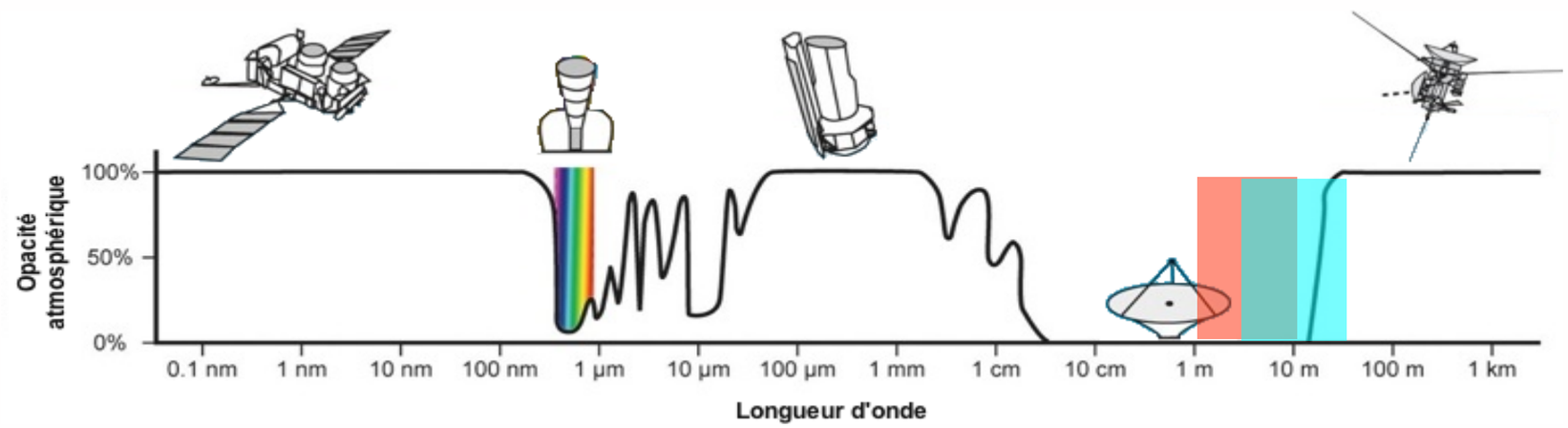
- ambitious: broad science expected (60-80 identified future users), SKA pathfinder (lessons, preparation of the community, complementarity)

→ build with limited money (≤6 M€) and manpower (Nançay radioastronomy station + commissioning team)

The NenuFAR concept (continued)

96 Mini-Arrays
(LF tiles)
of 19 antennas,
analog phased
Δf ⊃ LBA range
(10-85 MHz)
+ distant MA

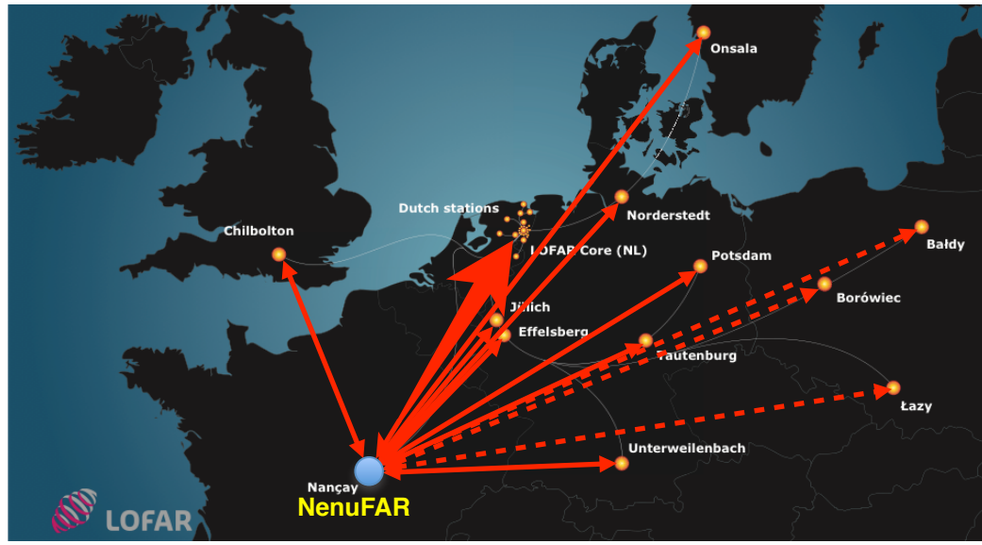




What NenuFAR brings

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 ?
- Short baselines intra-NenuFAR ⇒ large scale structures (>10°)



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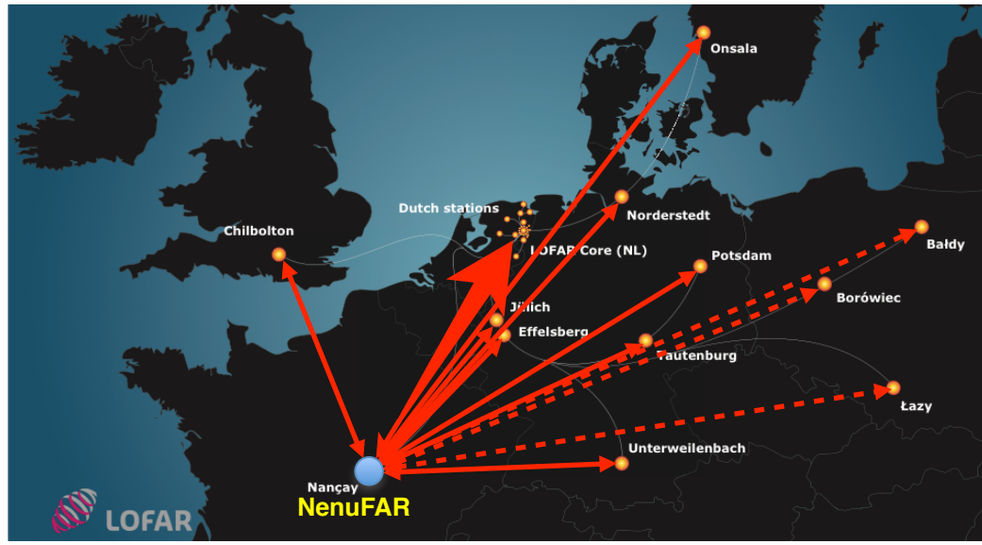
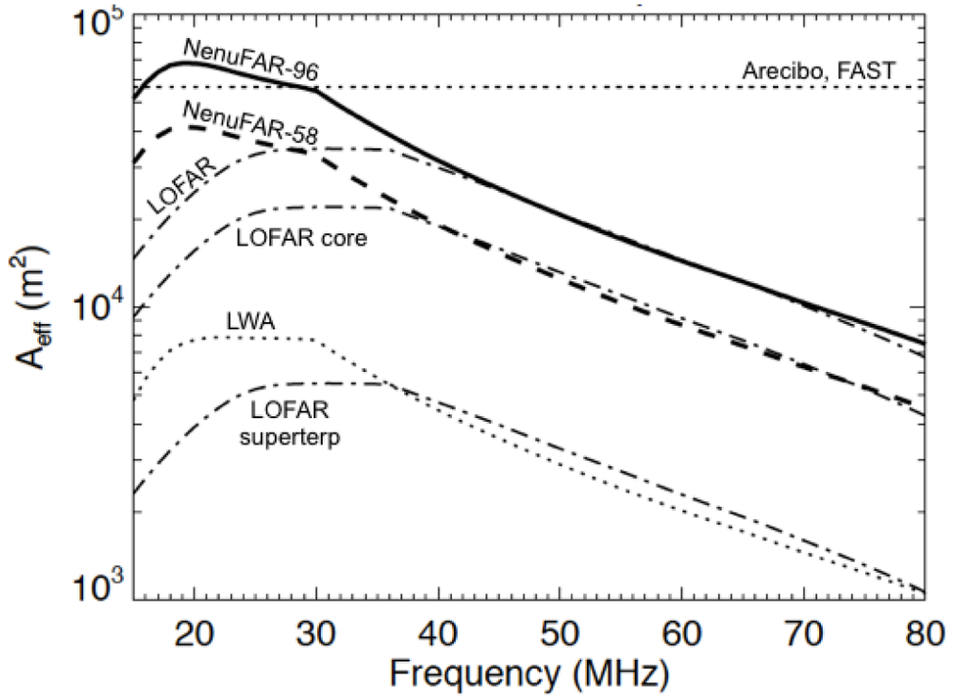


NenuFAR/Standalone Beamformer:

- 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 programs with high duty-cycle



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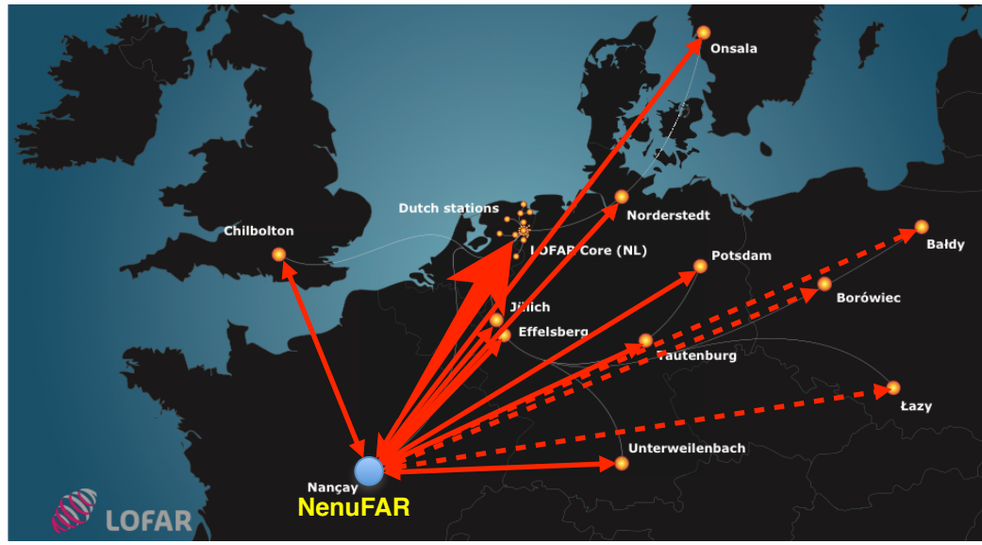

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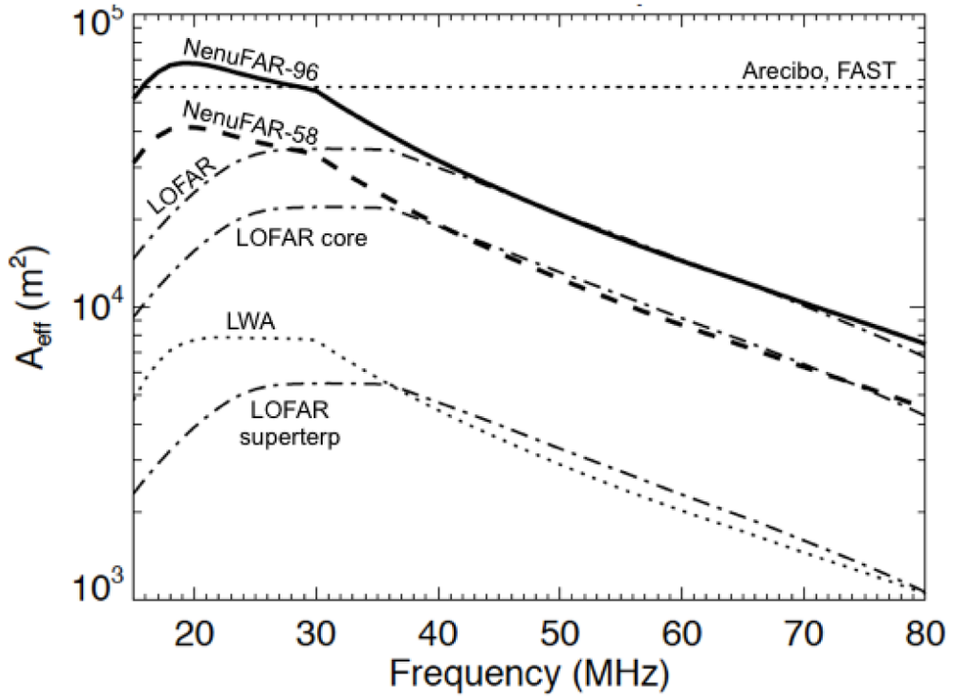
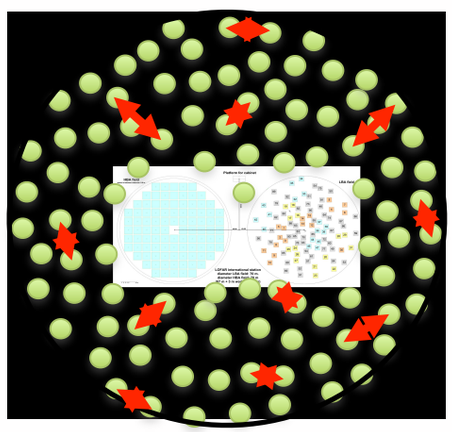


NenuFAR/Standalone Imager:

- Fast imager (1 sec., core only) → (40/f)° ~1°
- Slow imager (6-8 h, core + distant MA) → (340/f)' ~8'



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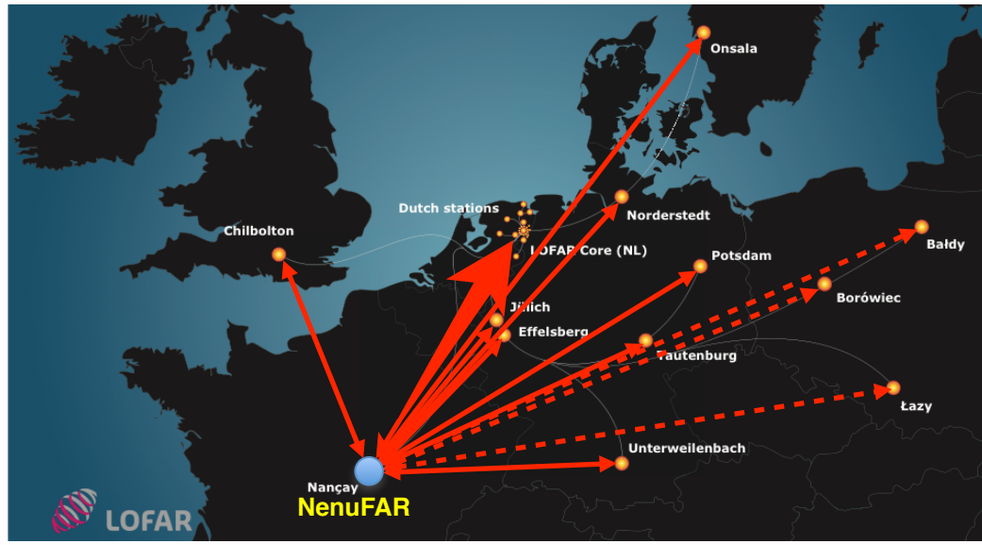

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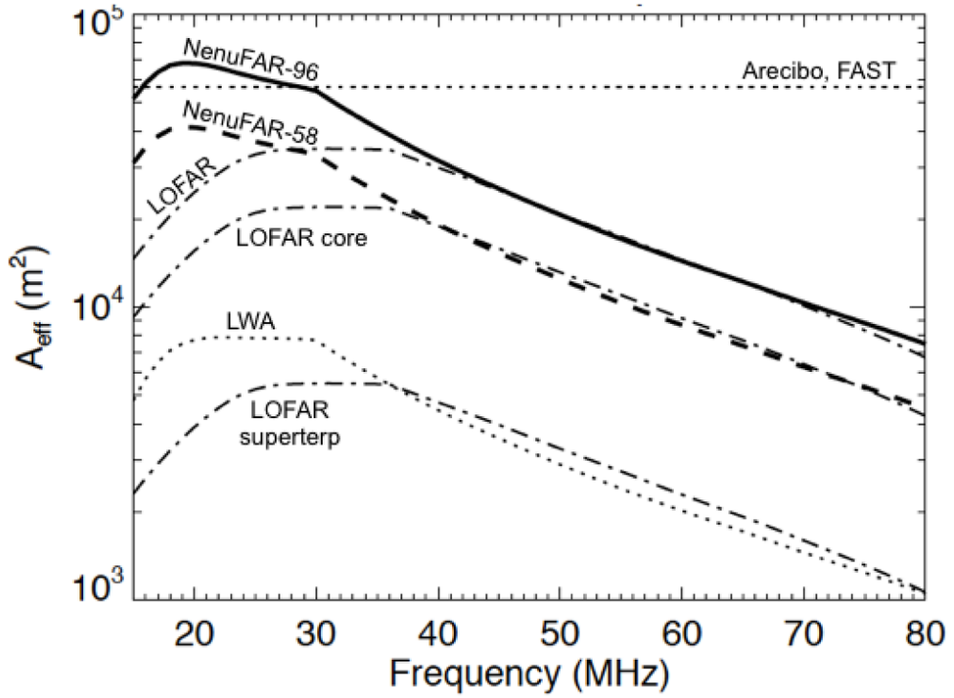

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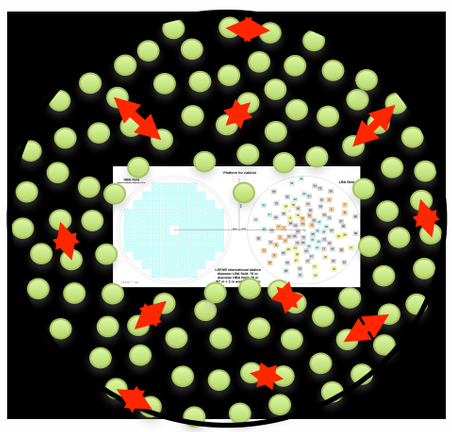

➡ All in parallel + Ongoing commissioning ...

Technical developments

ANR «Design» 2009-2013

- Antenna (LWA) + preamplifier (Subatech / Nançay)
- Mini-Array of 19 antennas, hexagonal
- Optimization of the global MA distribution
- Silent Control/Command system
- LANewBa receiver (FPGA, 768 beamlets x 200 kHz)
- NenuFAR-LOFAR dialog (Nançay / ASTRON)
- Pointing : fast, Beam Squint, IMCCE Web-service for planetary observations
- Control/Command GUI : programming observations (parsets), housekeeping, monitoring, data management

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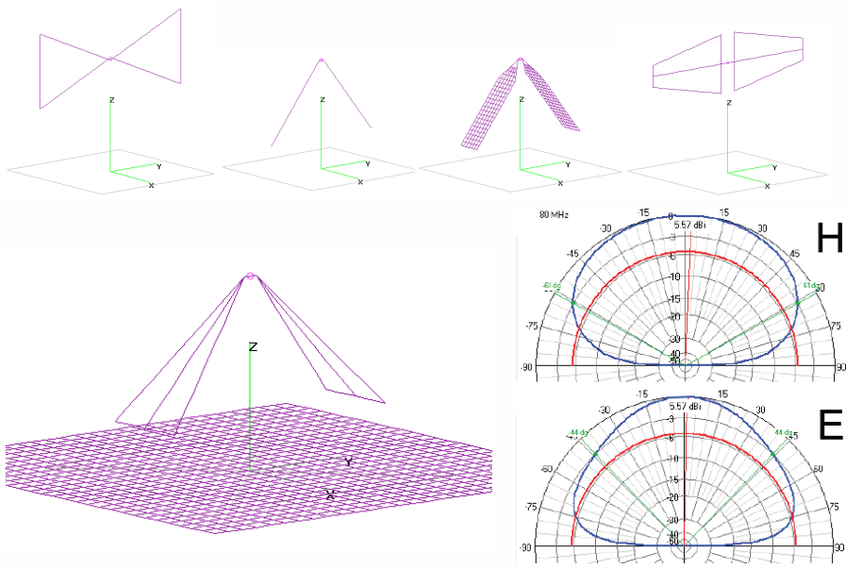
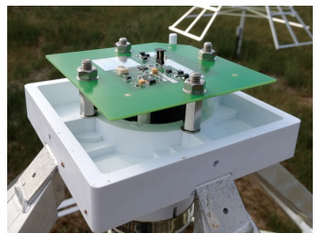
+ NenuFAR-Radio-imageur design (2015-2017) and construction (2018+)

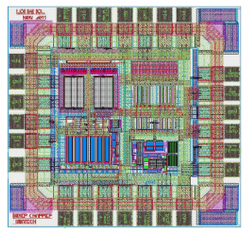
ANR «NRI» 2017-2019

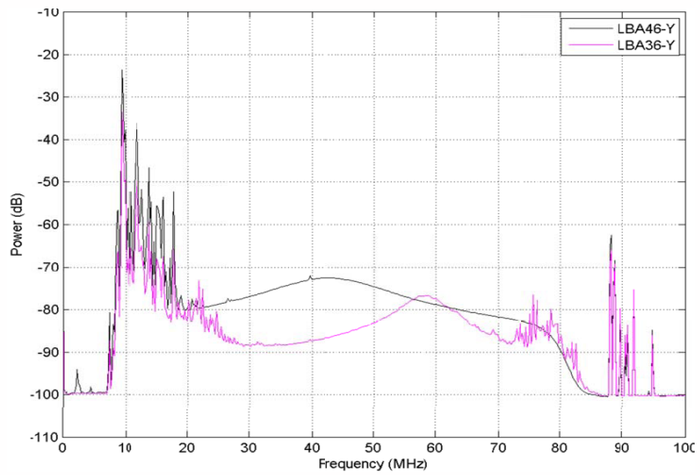
- Distant MA
- Infrastructure, Synchronization (White Rabbit)
- Correlator

Antenna, Preamplifier, Sensitivity









- Good LF antenna radiator + LNA [Hicks et al., 2012 ; Girard et al., 2012 ; Charrier et al., 2014]
- Ground plane <u>needed</u> <100 MHz, esp. to avoid time variation of ground properties

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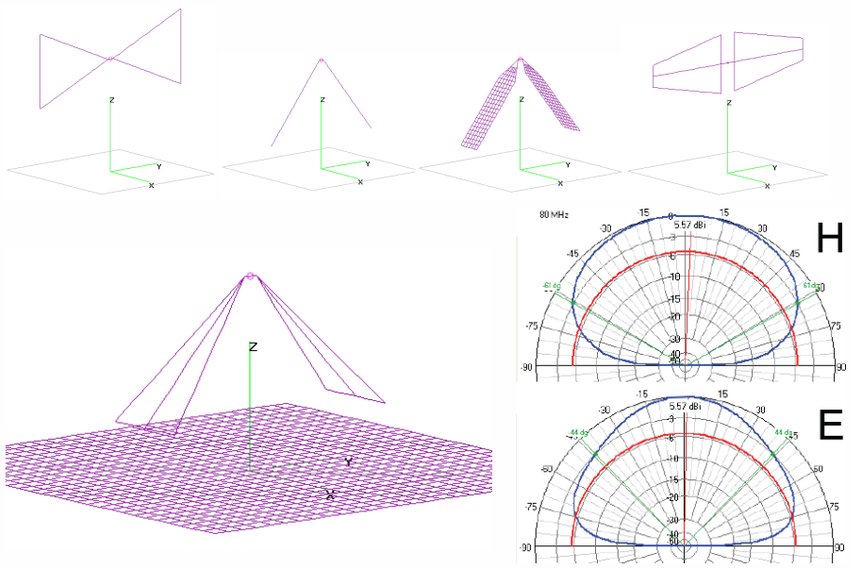

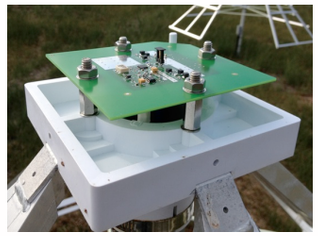

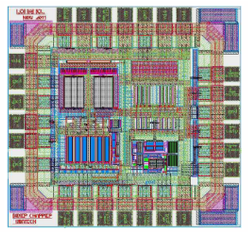

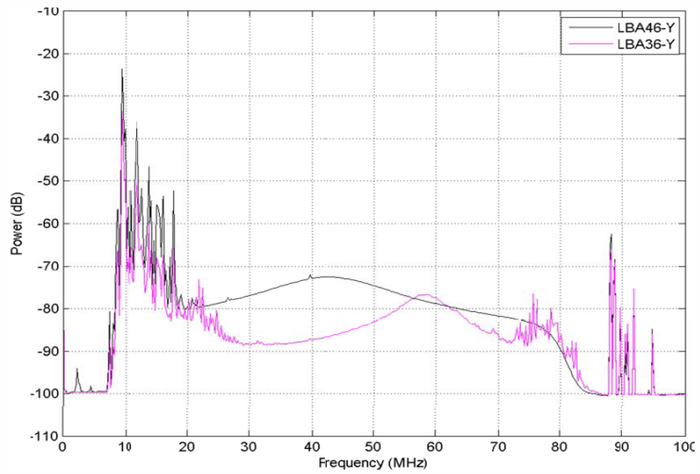

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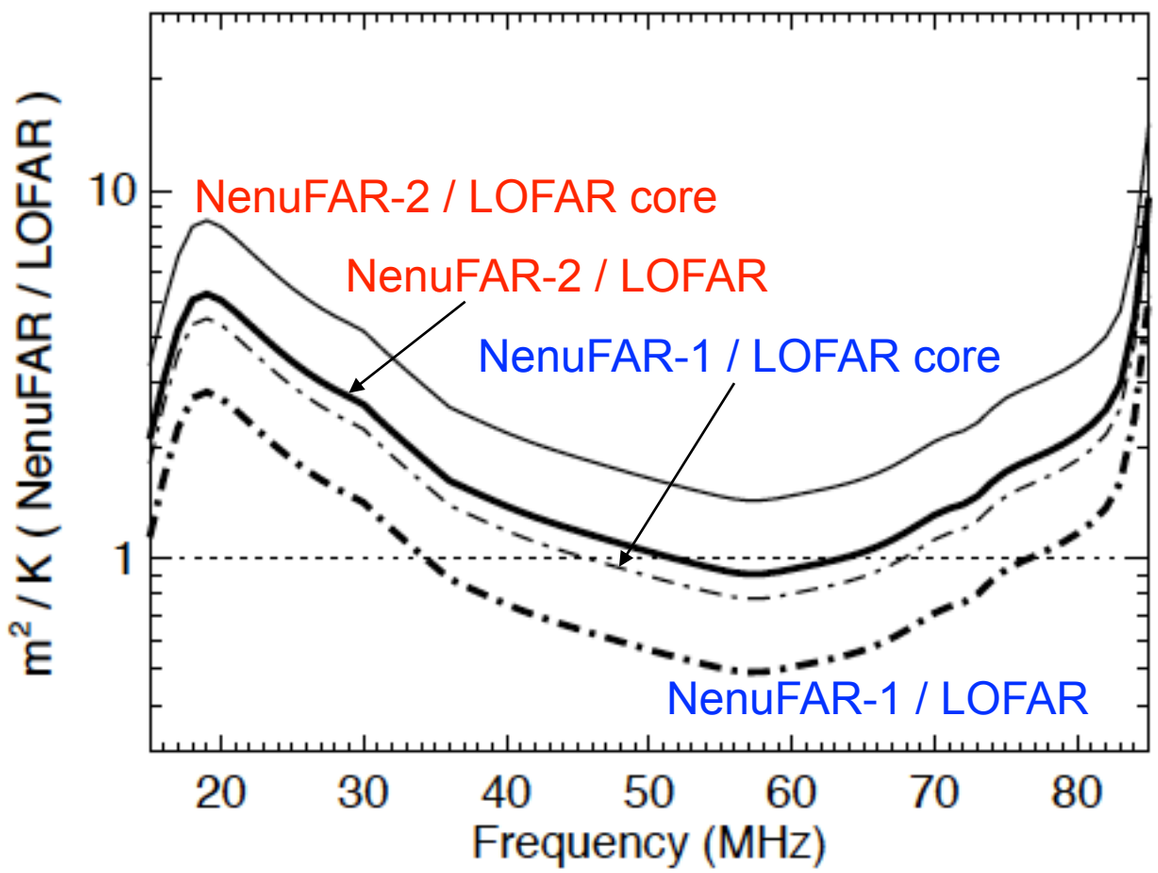
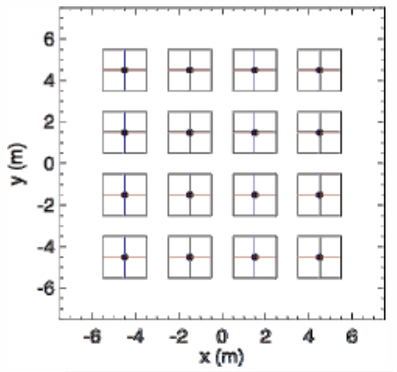
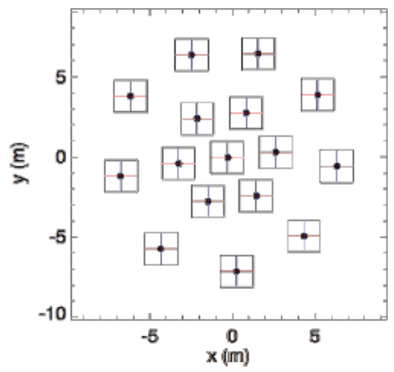
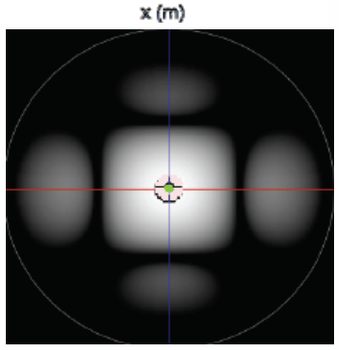


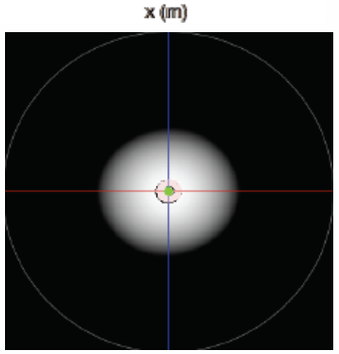
Mini-Array

40 MHz







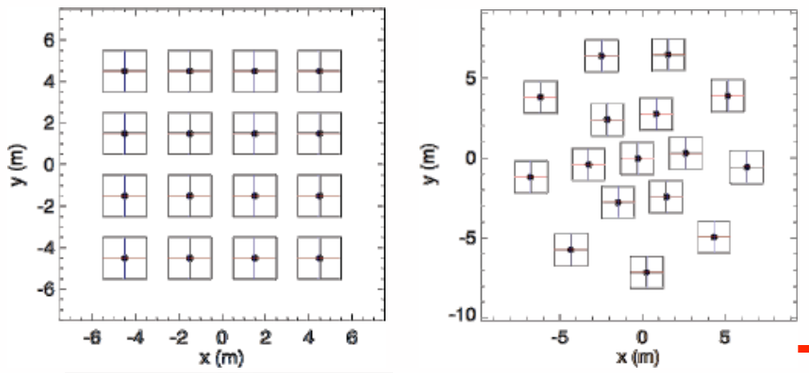


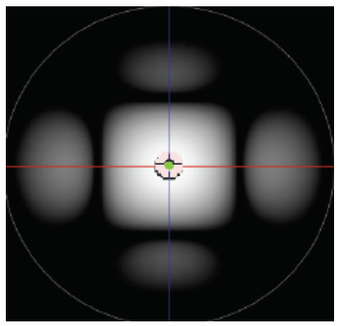
-15 dB sidelobes

-32 dB sidelobes

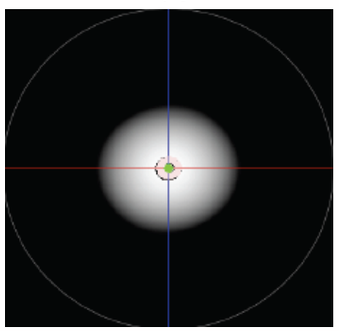
Mini-Array

40 MHz

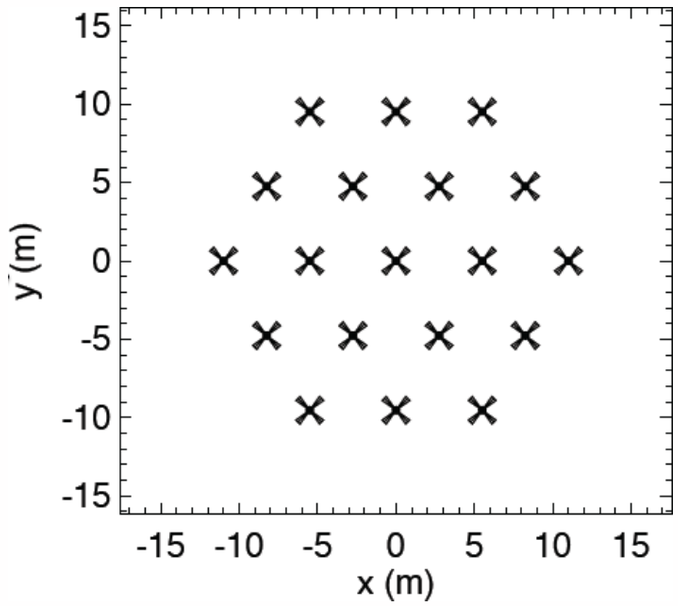




-15 dB sidelobes



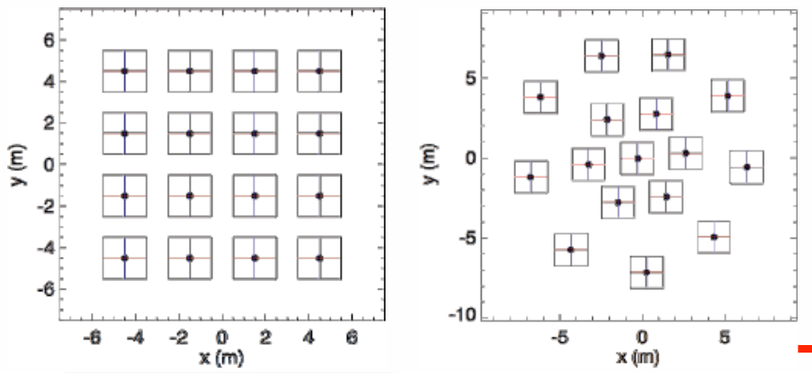
-32 dB sidelobes

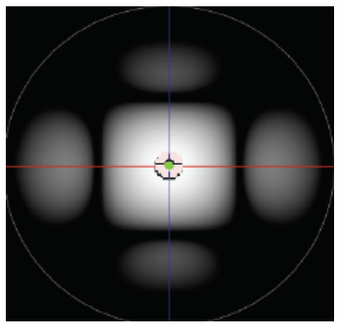


- Optimized 19-antenna distribution within Mini-Arrays

Mini-Array

40 MHz





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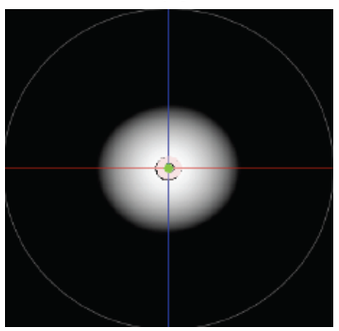

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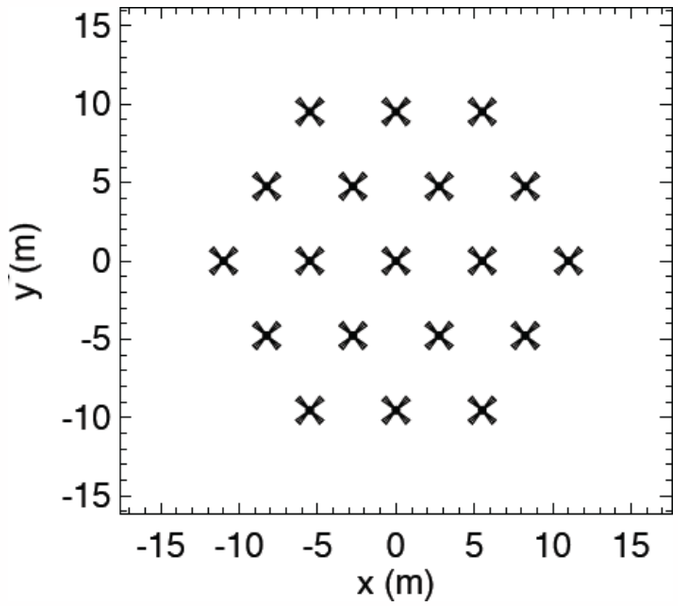

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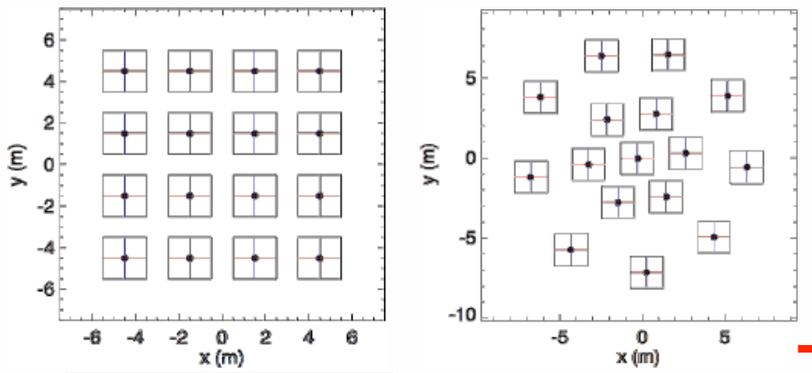

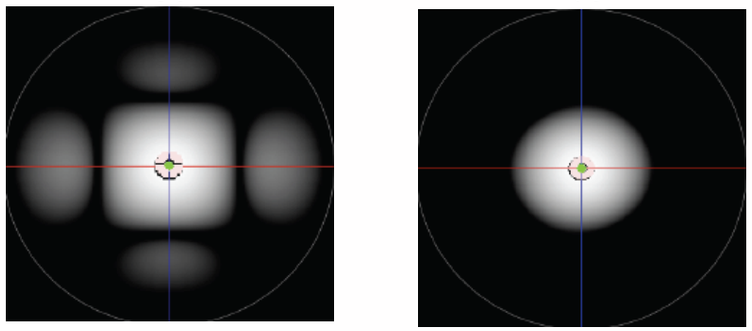

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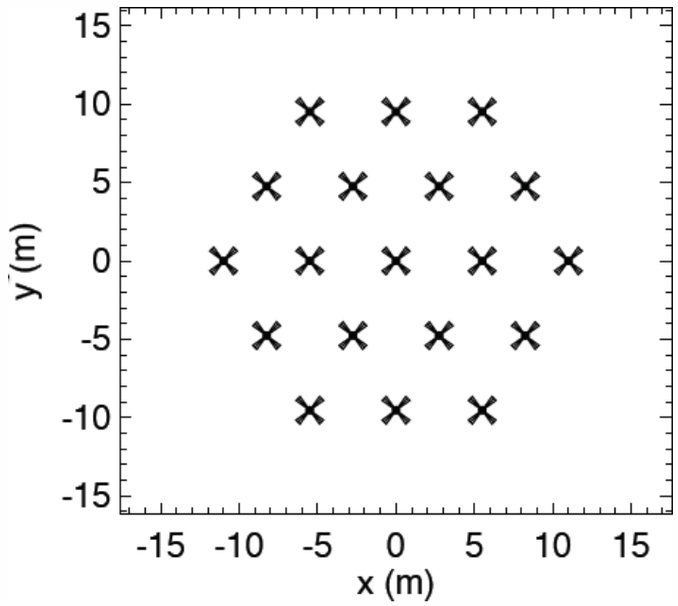
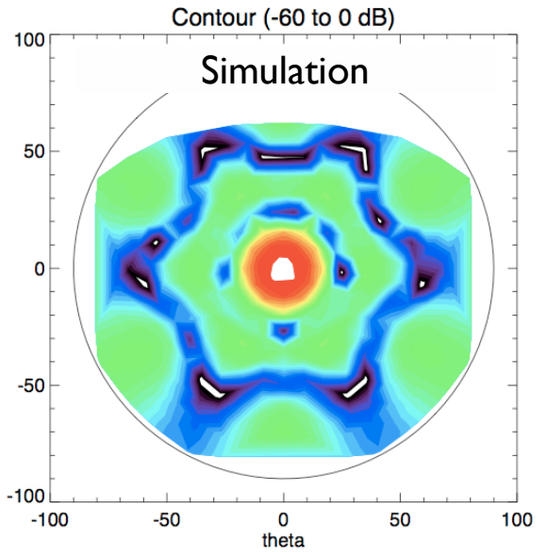
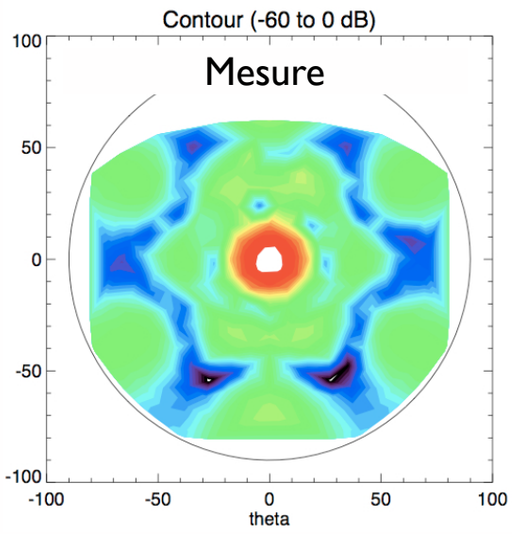
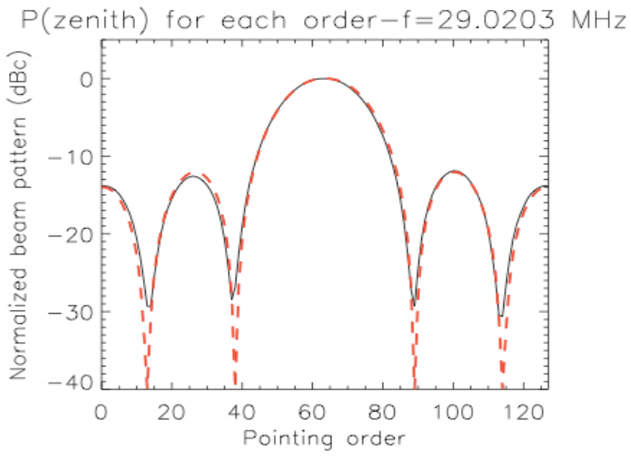


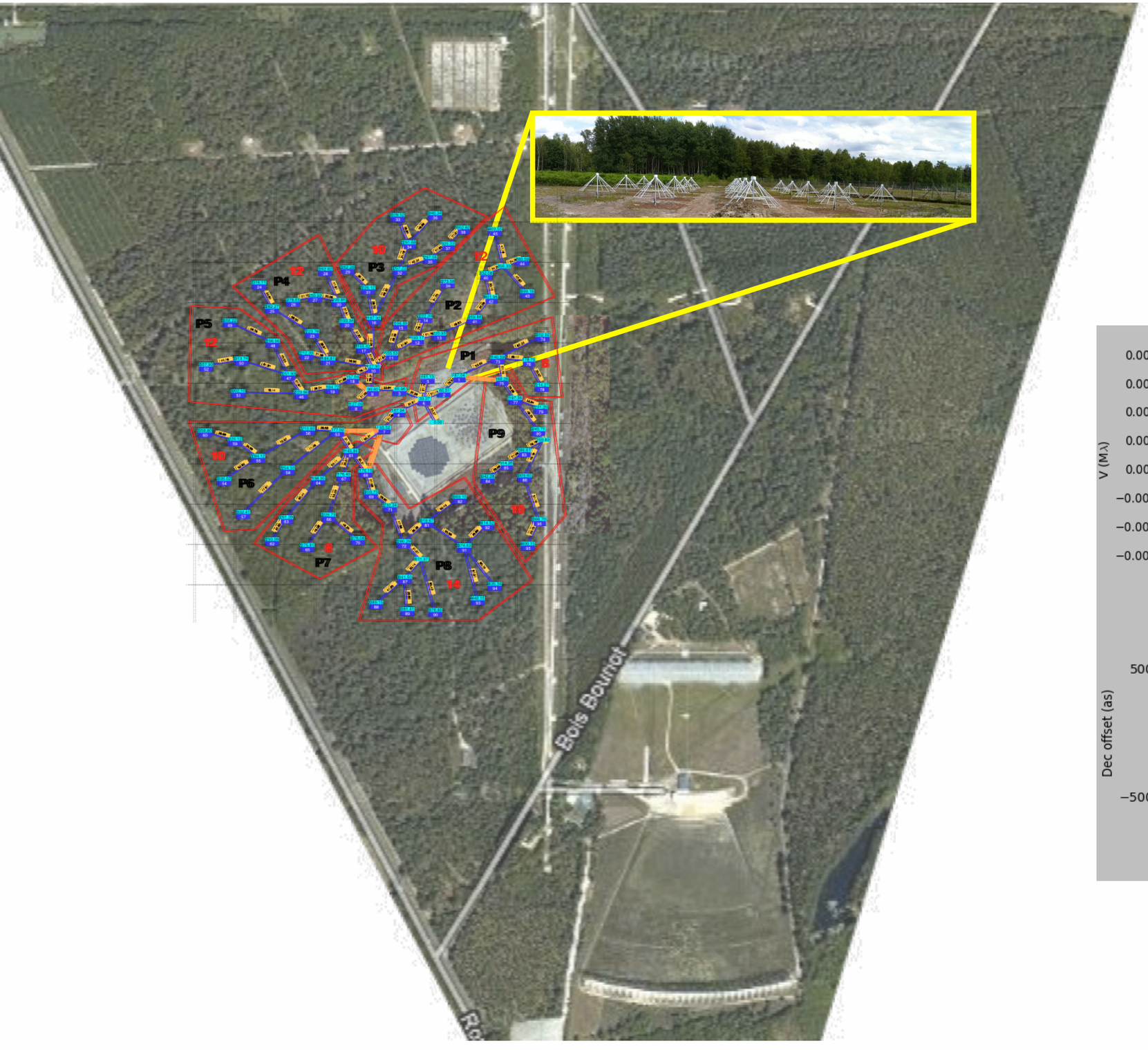


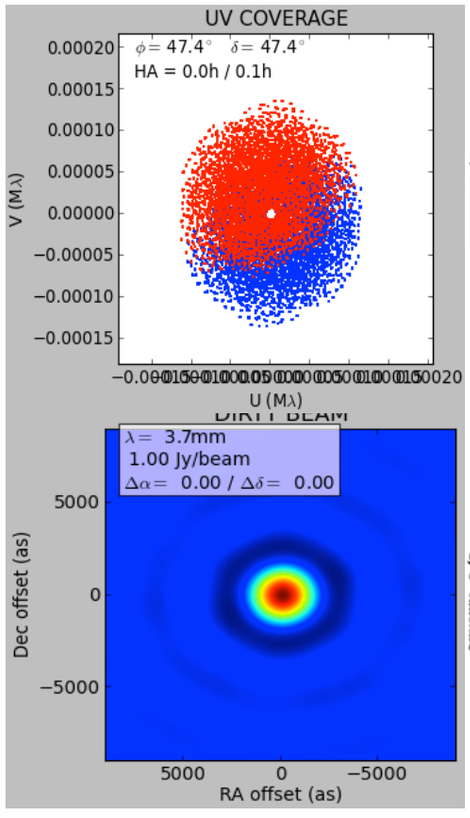


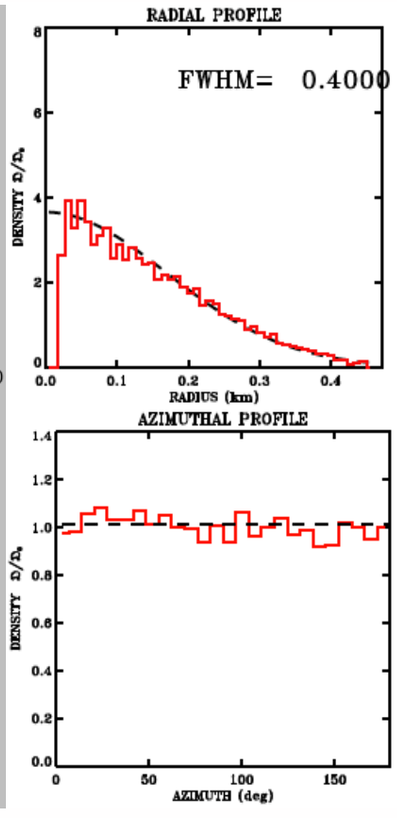


- Optimized 19-antenna distribution within Mini-Arrays

Global distribution

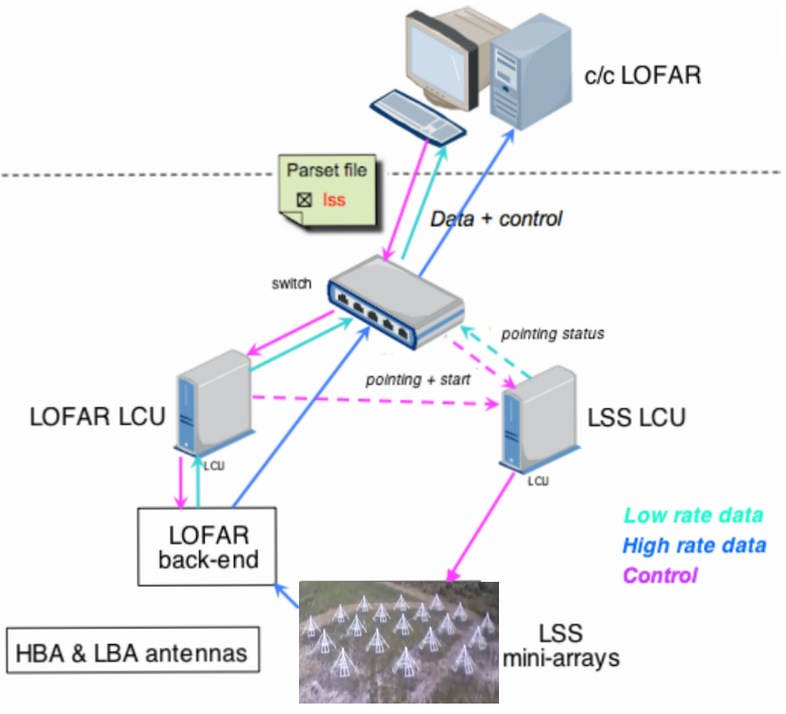






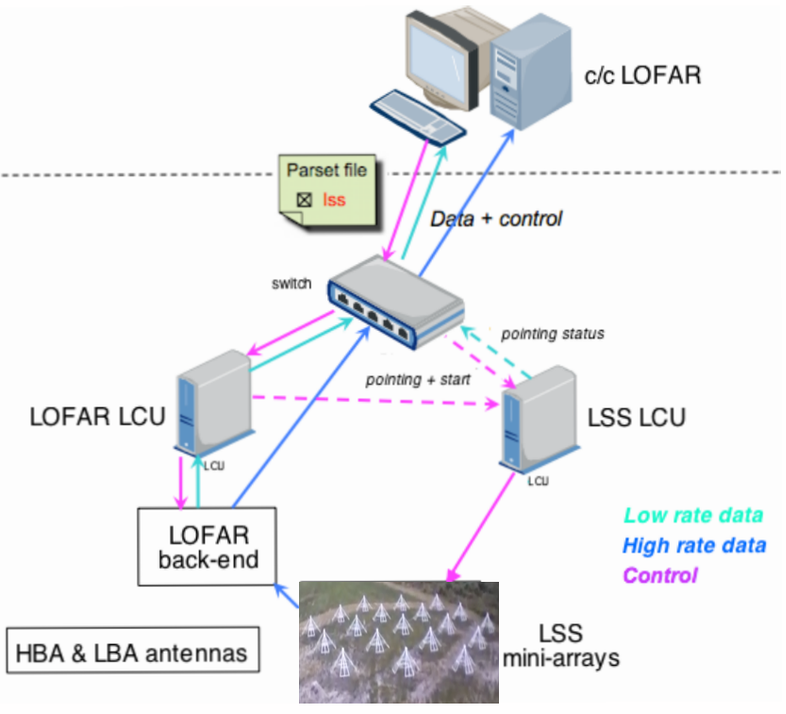
- Global design optimized for 96 MA (incl. MA rotations) + 6 distant MA
- Trenches/cables optimization [Vasko et al., 2016]
- Construction in 9 petals, consumption ~50 kW

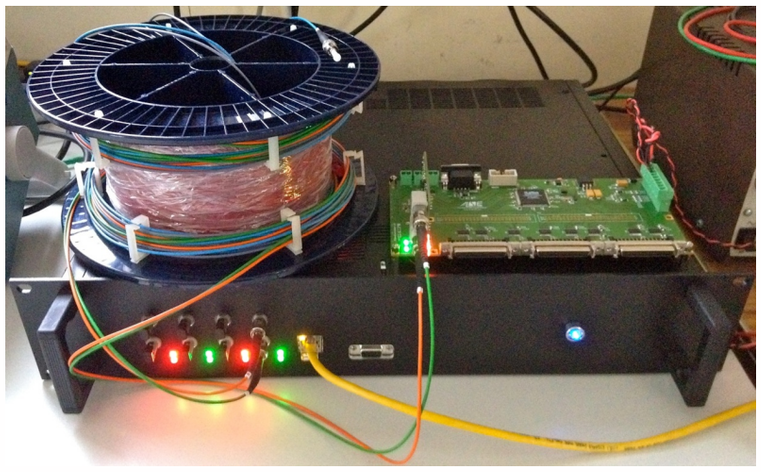
Operation & Control



- Dialog with LOFAR

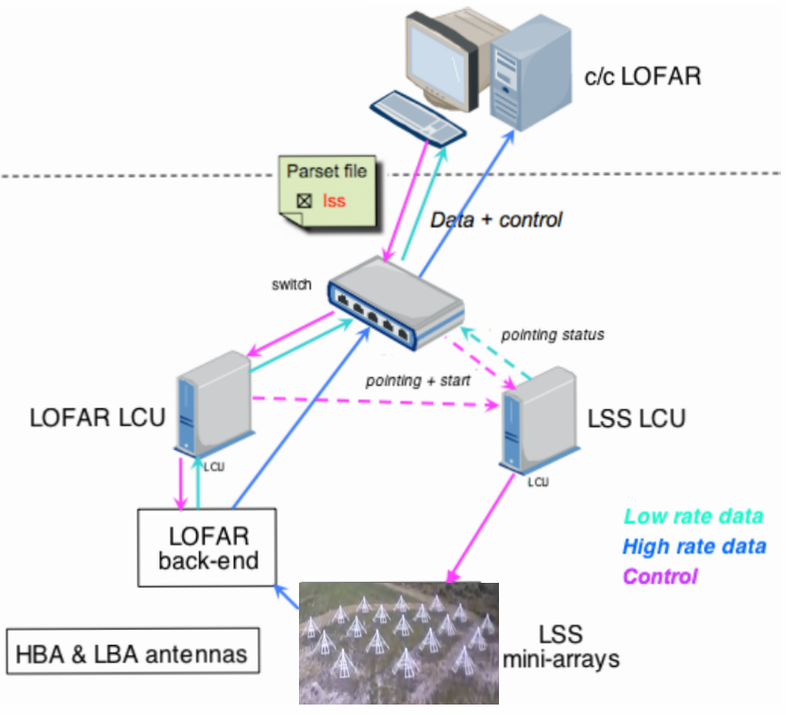
Operation & Control

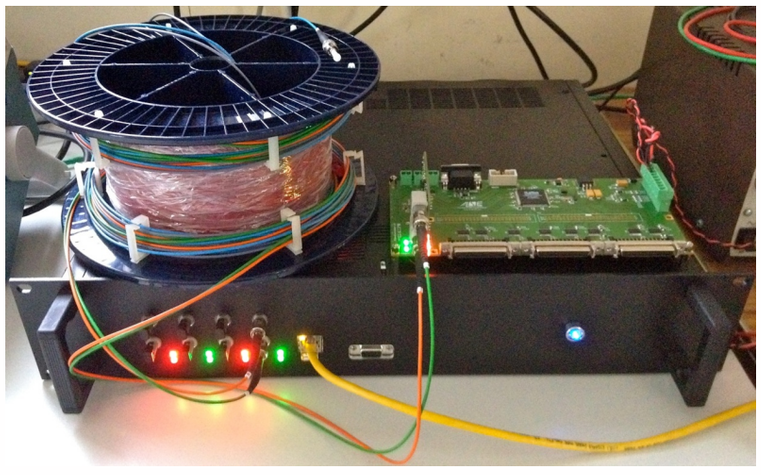




- Dialog with LOFAR
- Silent control/command system

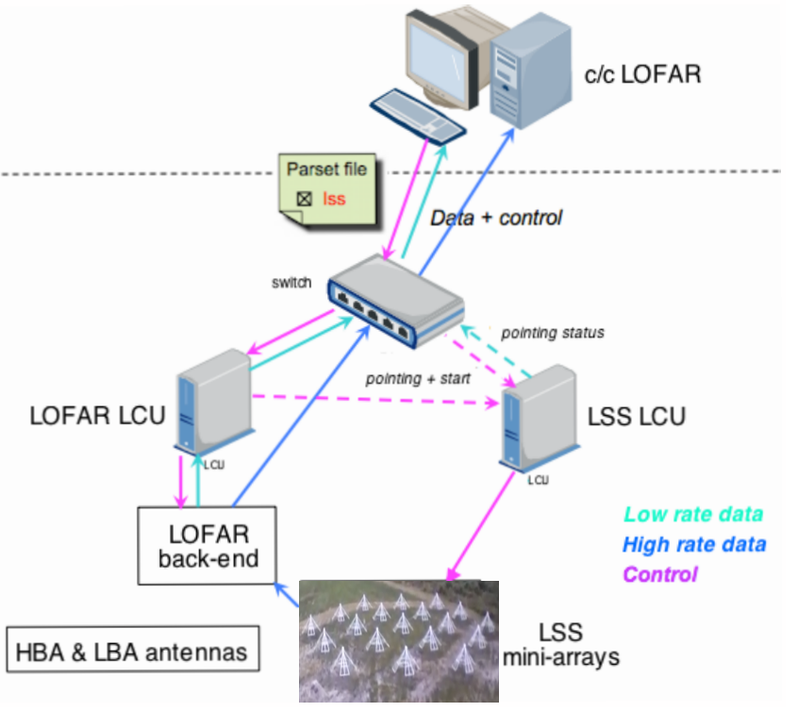
Operation & Control

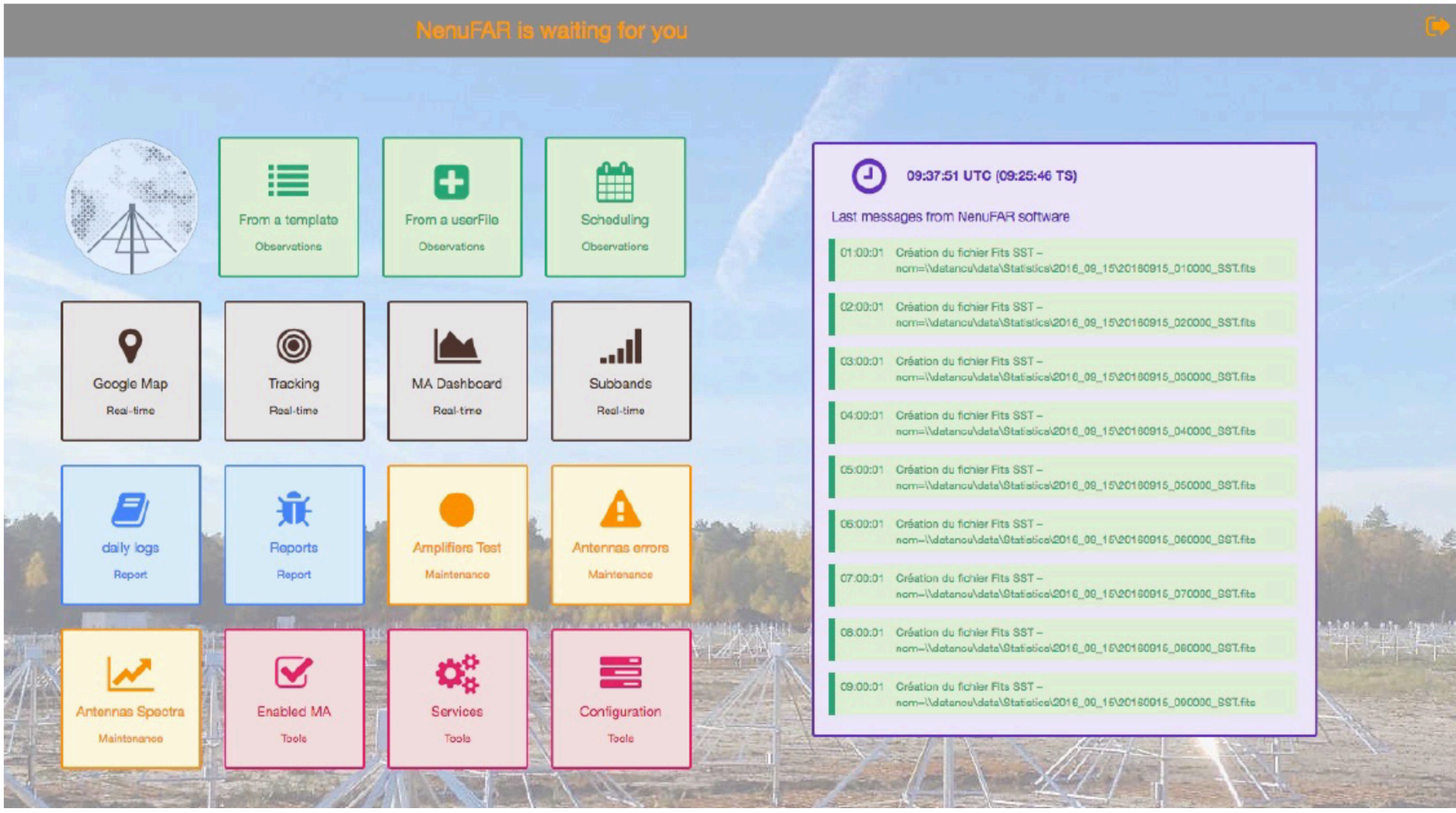


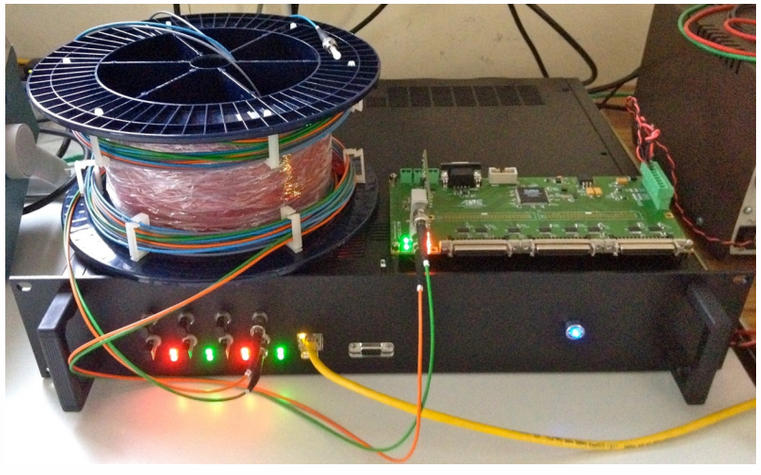


- Dialog with LOFAR
- Silent control/command system
- Pointing protocol : ramp of analog phasing switches over <10 msec at round multiples of 10 sec

Operation & Control







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- Online realtime system (antennas, preamps, ...) monitoring

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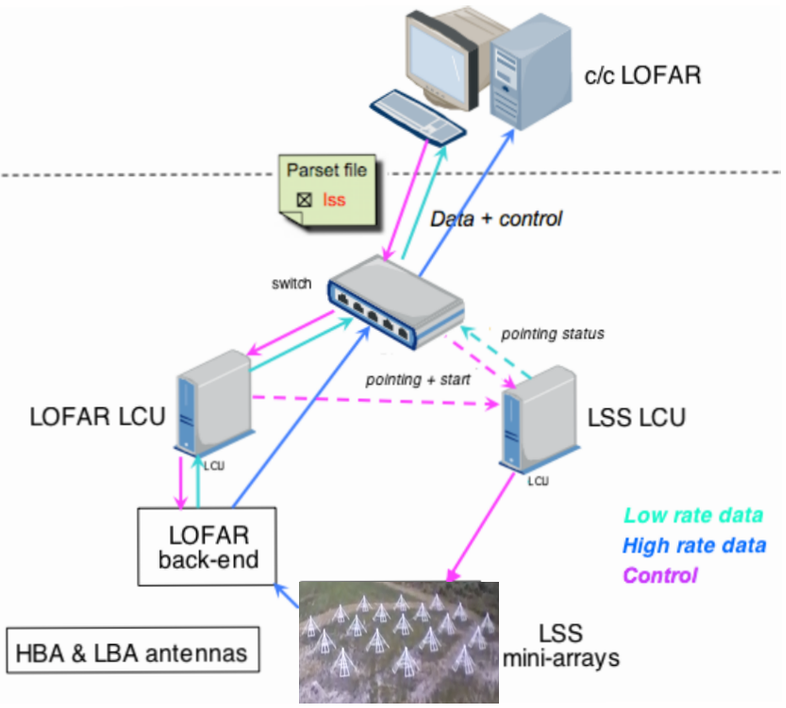

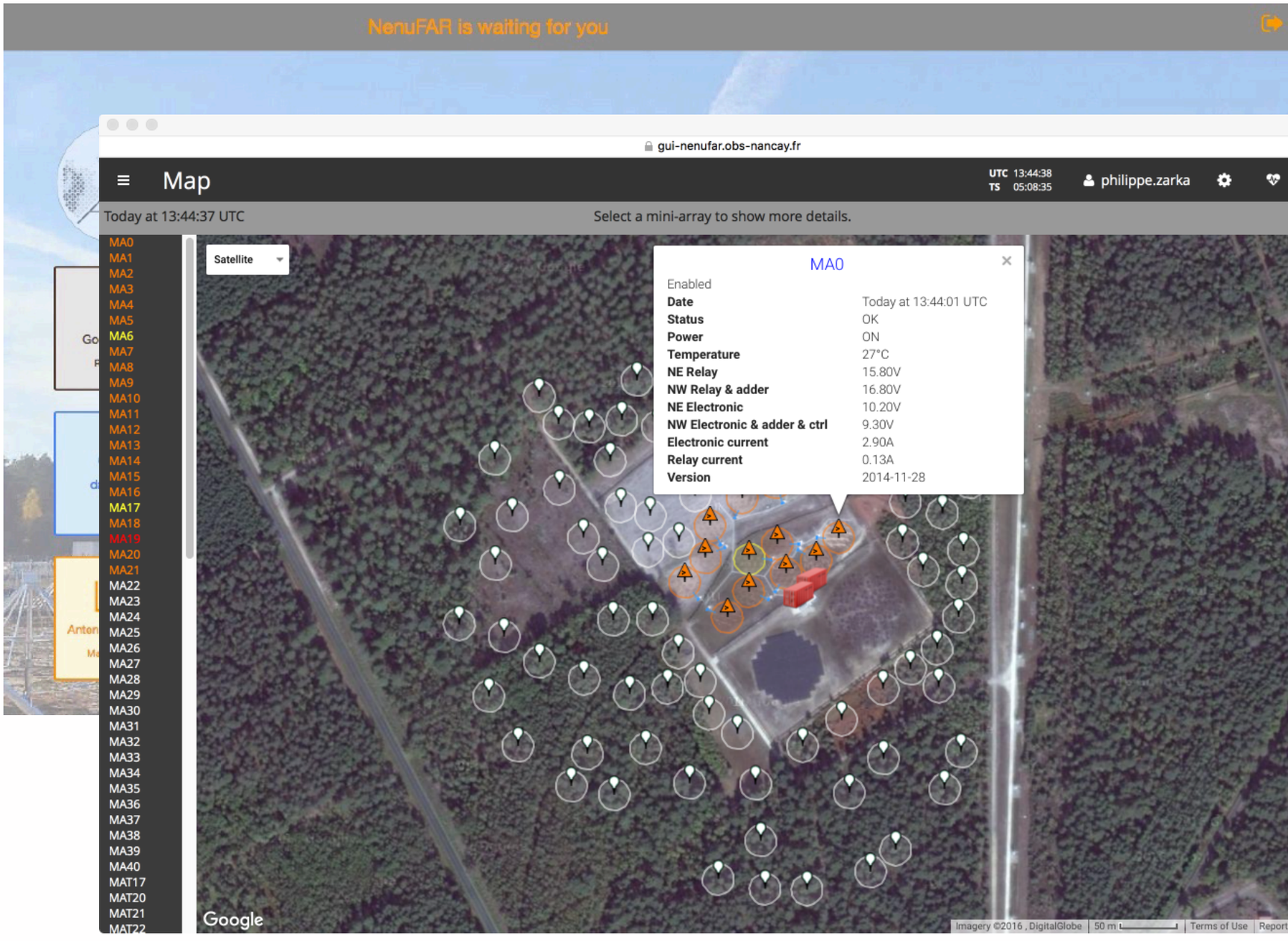

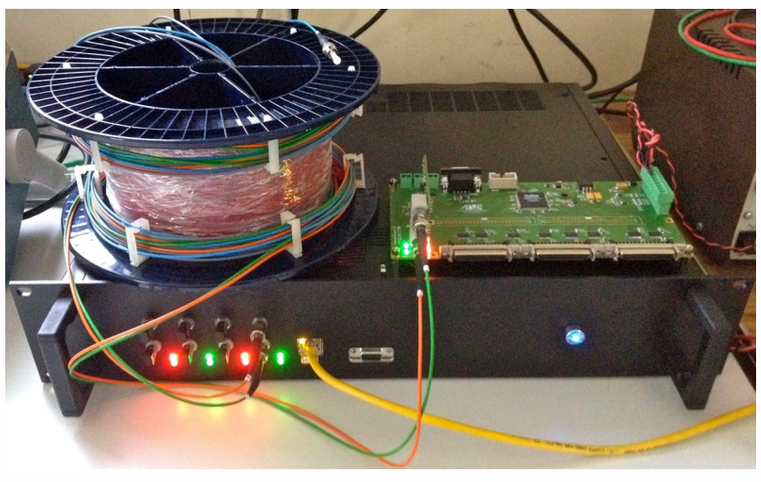

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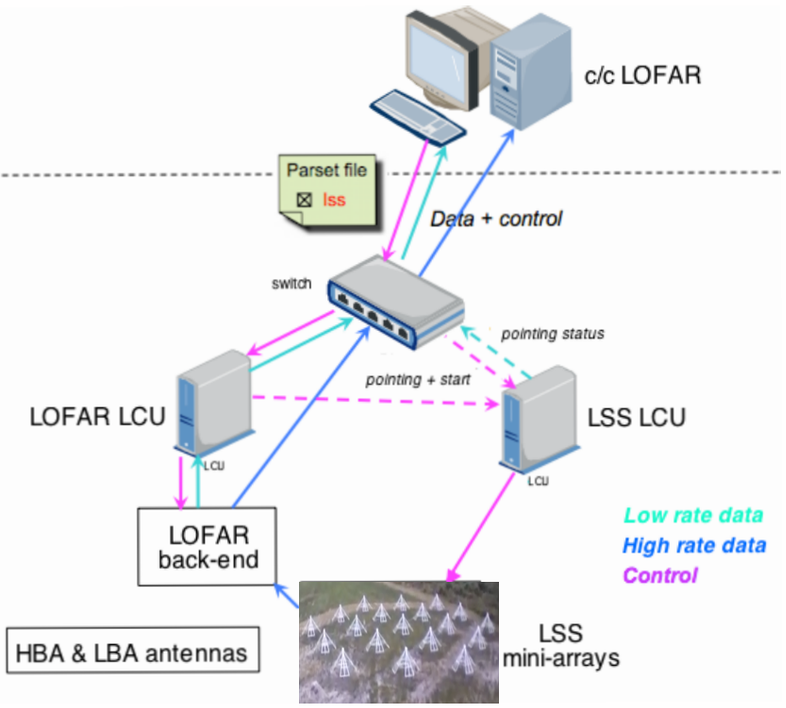

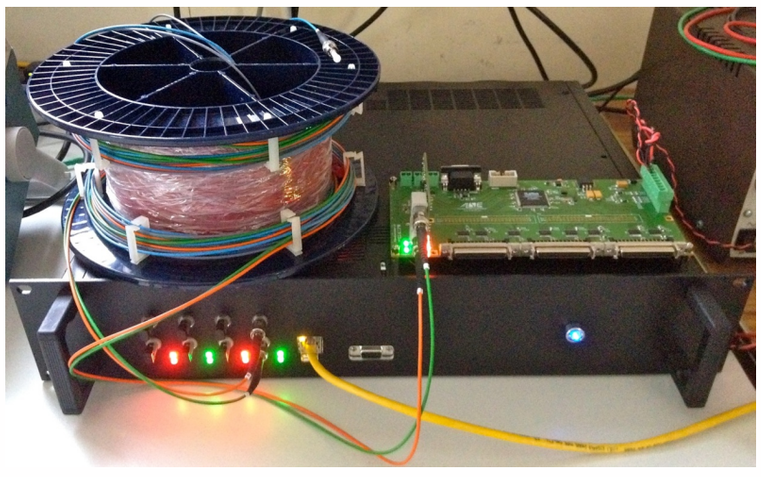

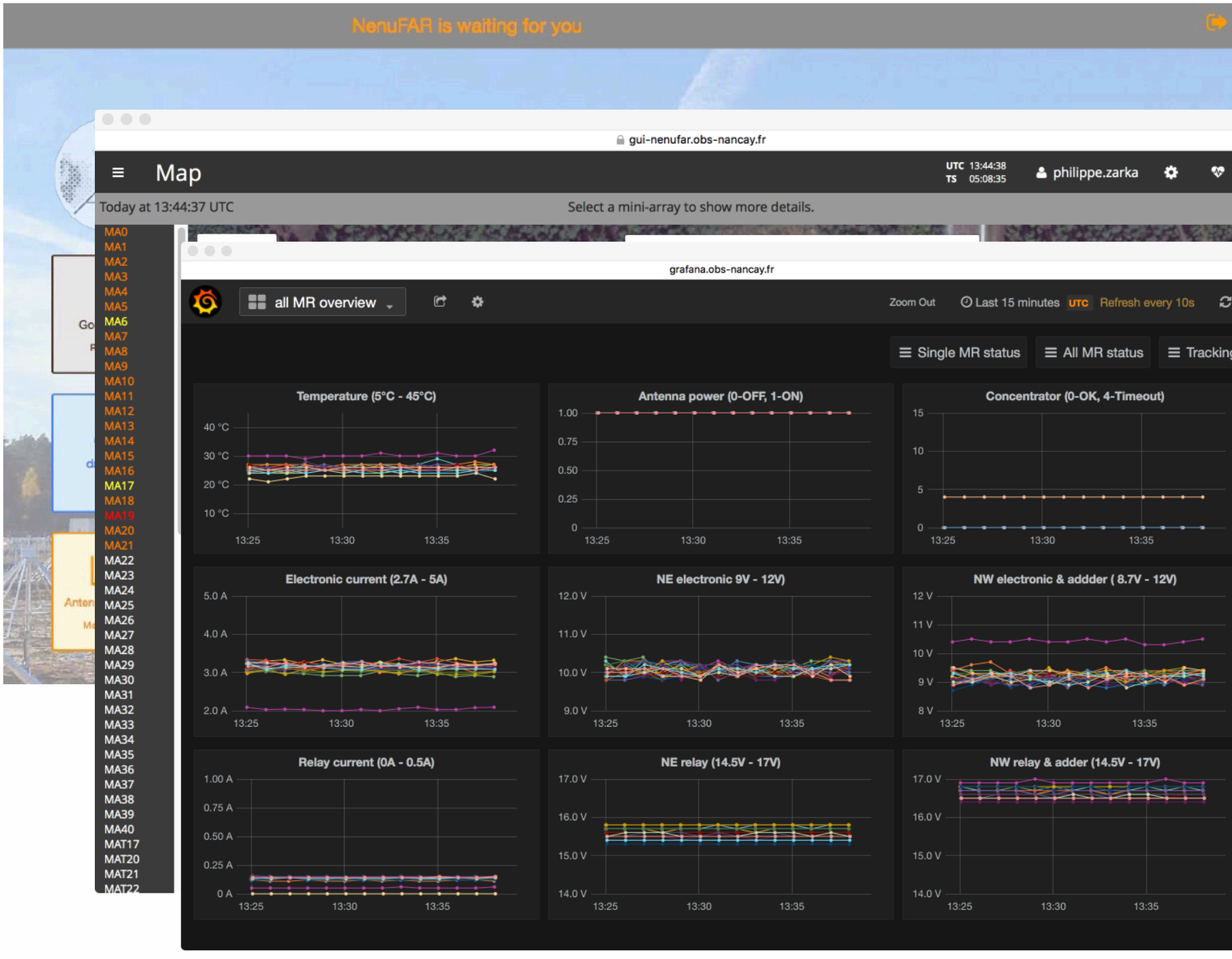

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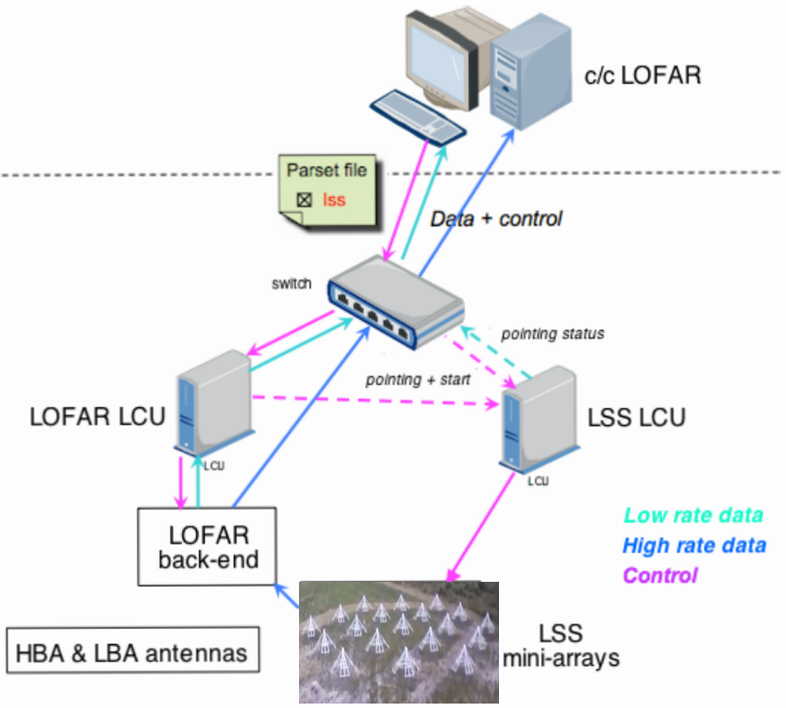

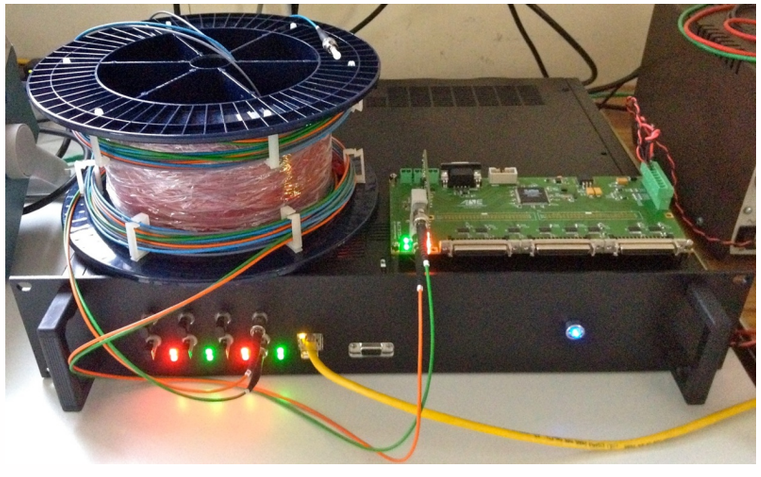

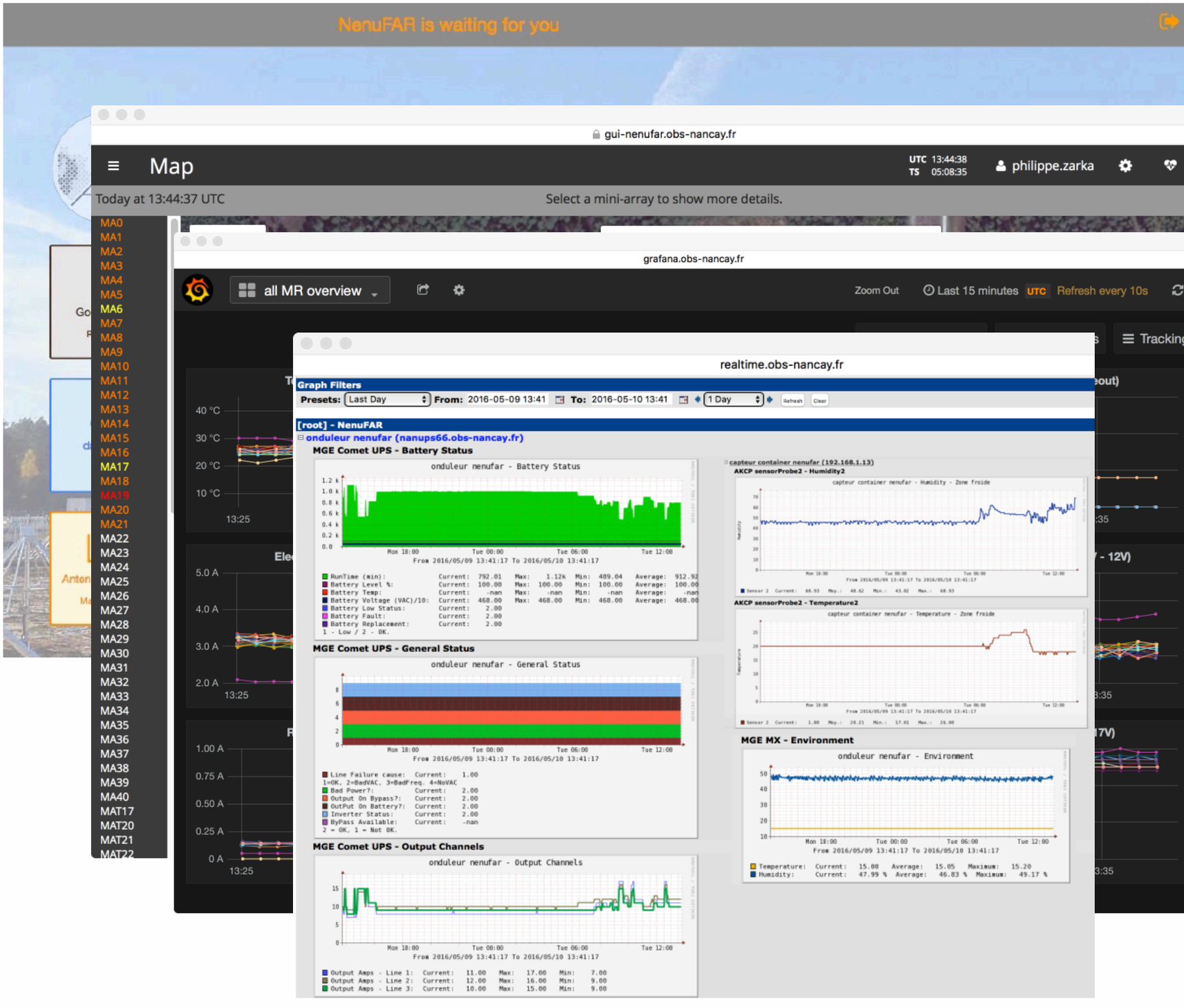

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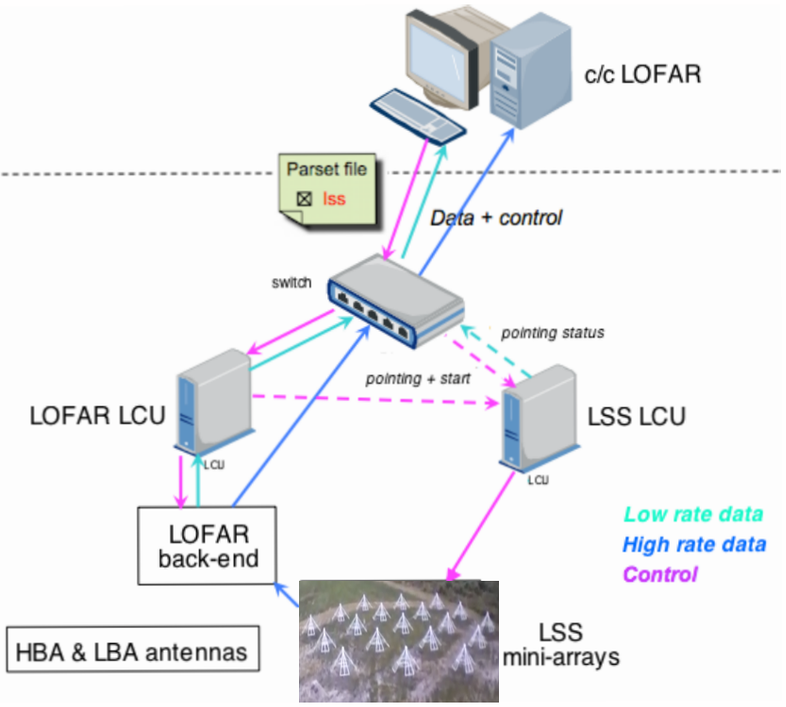

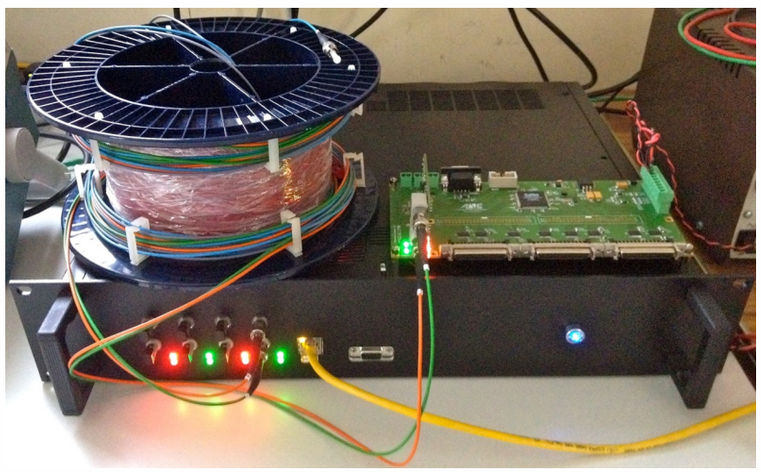

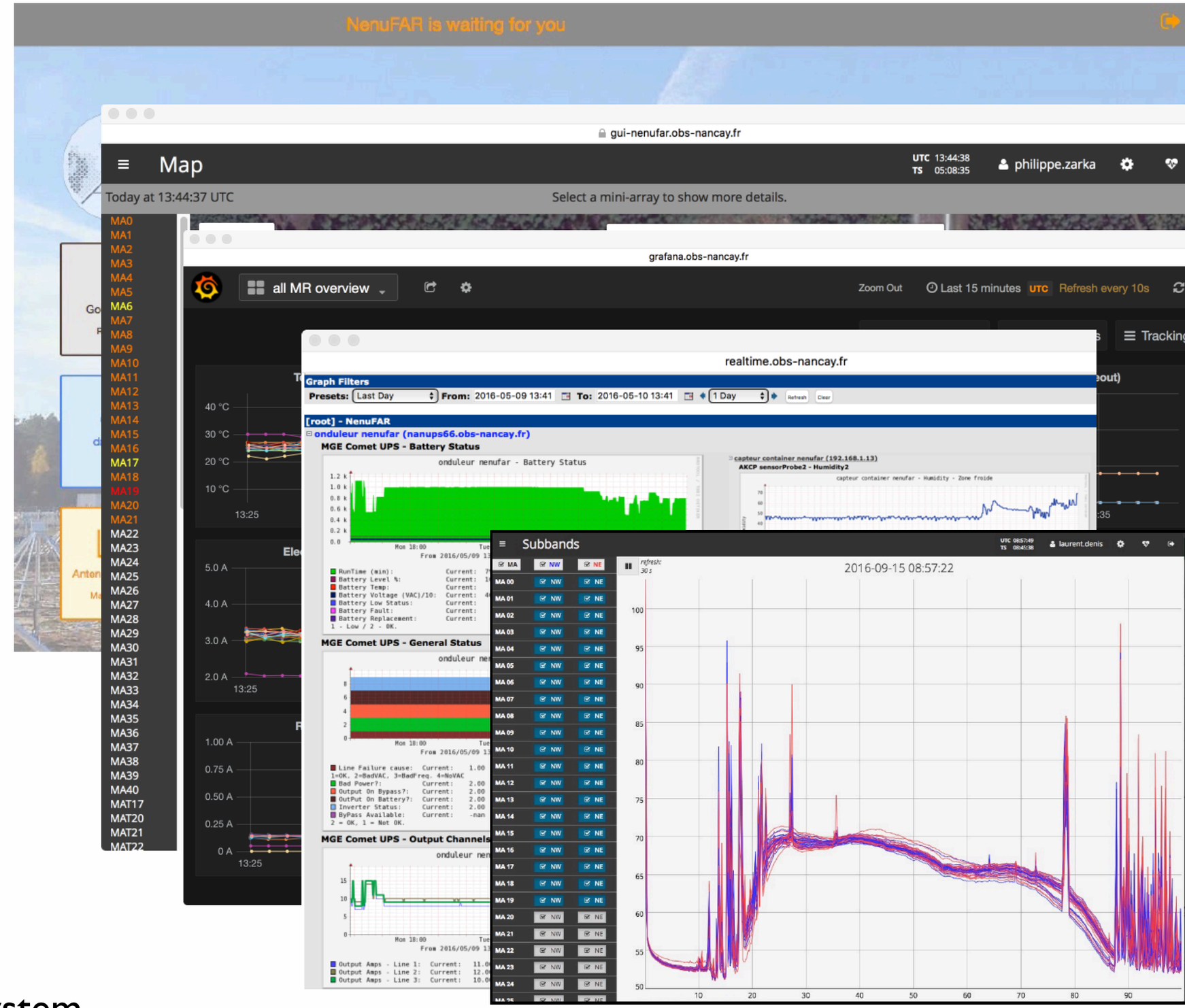

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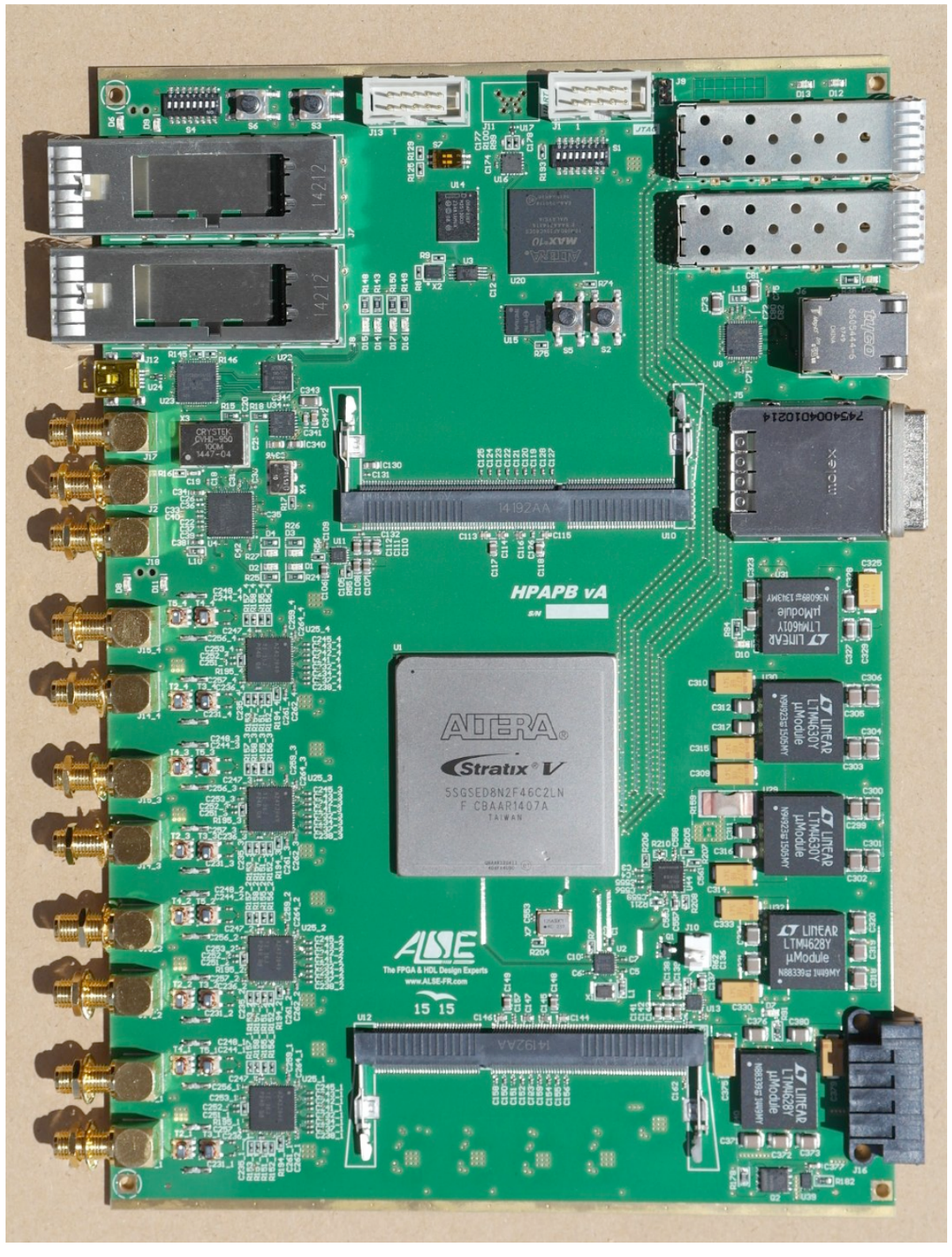
The LaNewBa receiver



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

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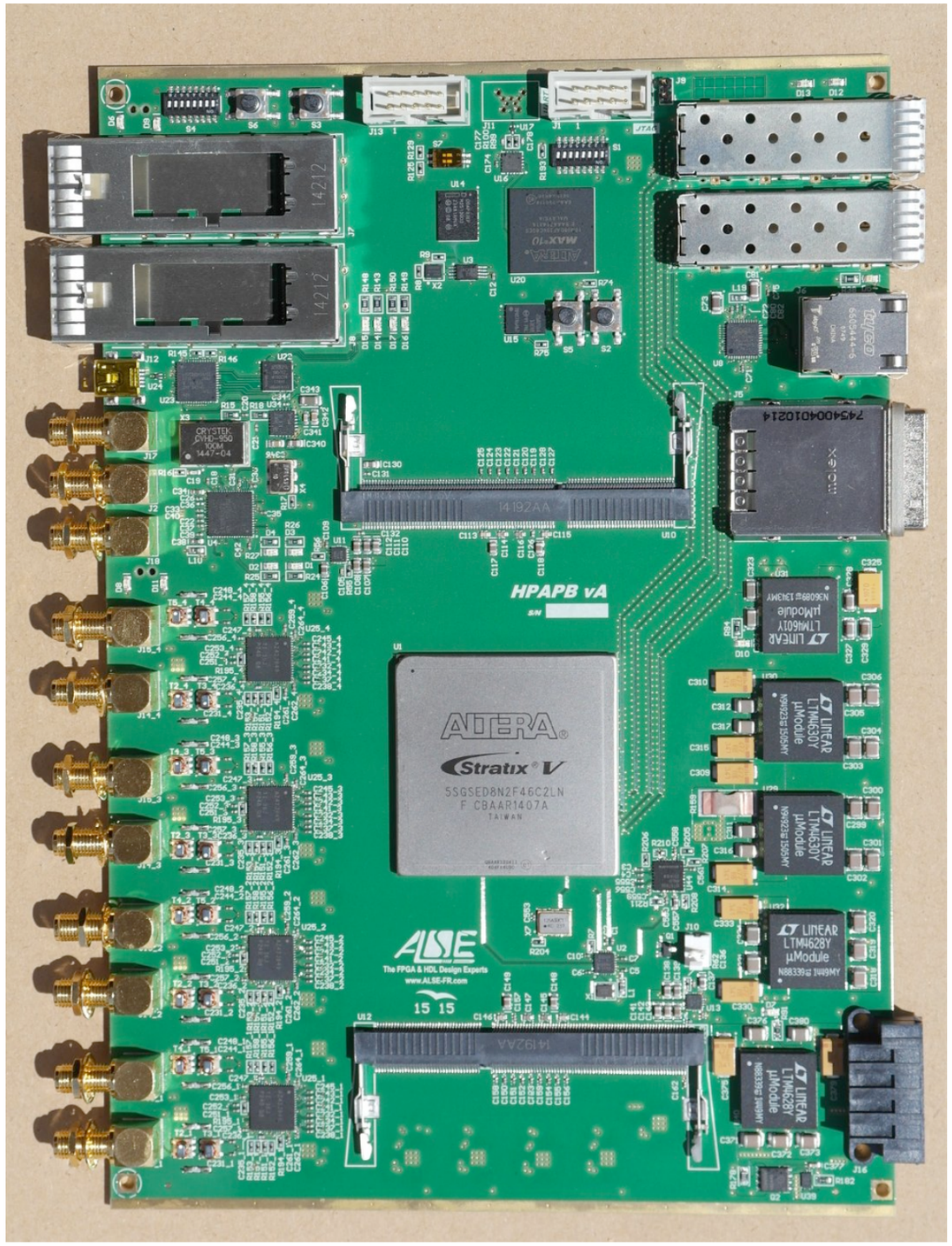

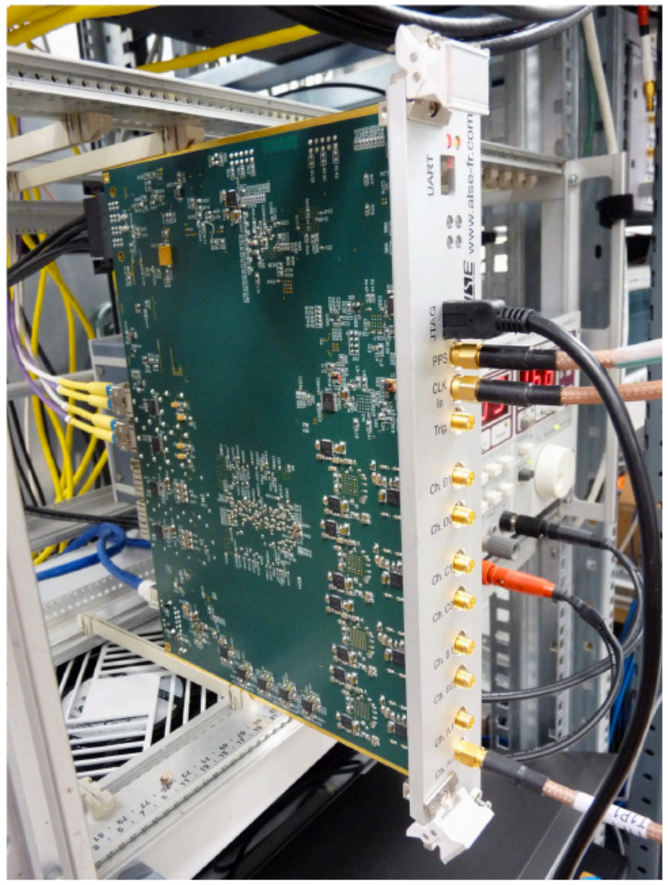

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The NenuFAR Radio Imager

- $\sigma_{confusion}$ [mJy/beam] ~ (ν / 100 MHz)$^{-0.7}$ (θ / ')^2 *[Condon, 2002, 2005]* → 1-50 Jy @ 20-80 MHz (unpolarized signal)

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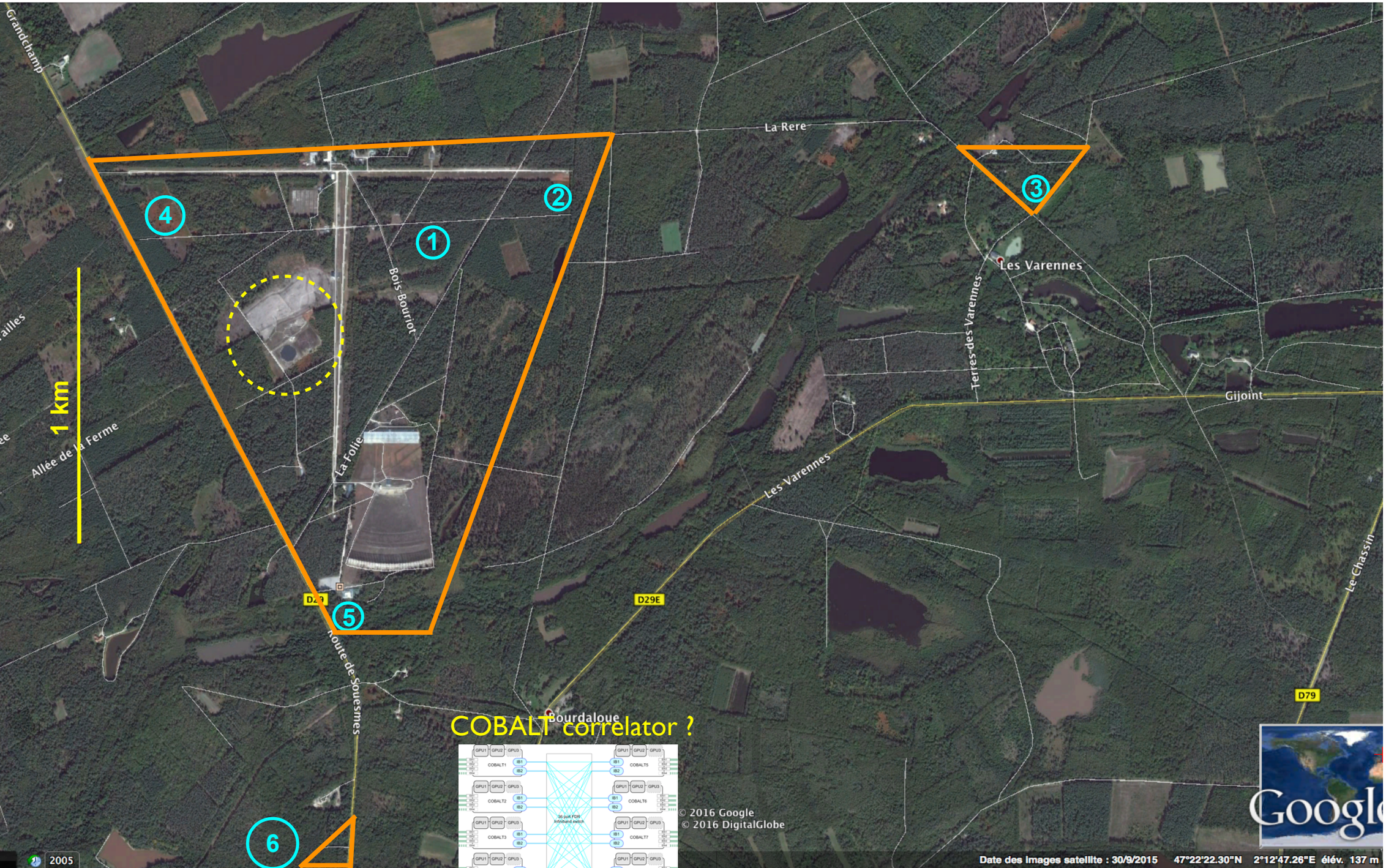
- correlator + 6 distant MA + multi-λ synthesis → angular res. x7 for stationnary broadband sources → $\sigma_{confusion}$ / 50



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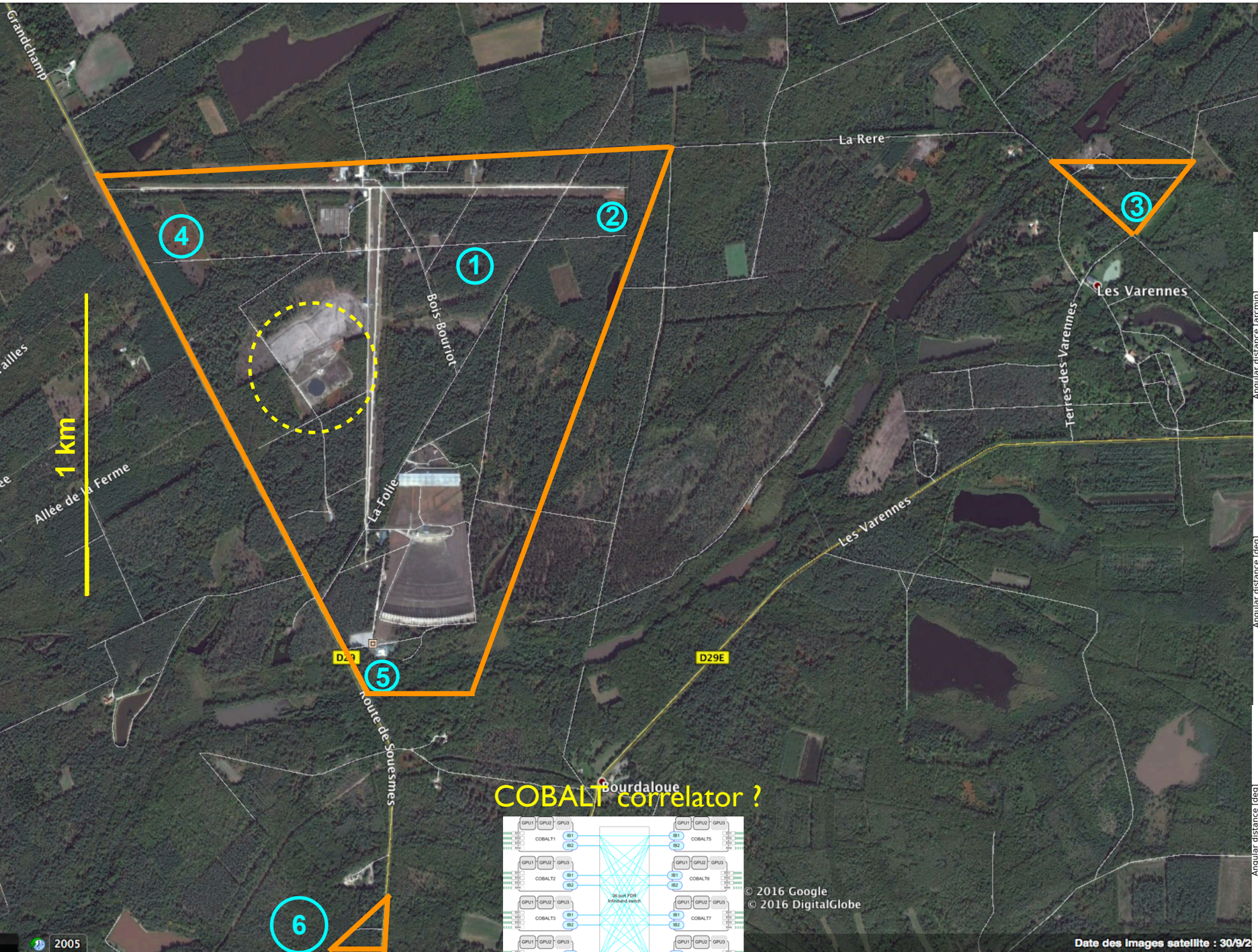
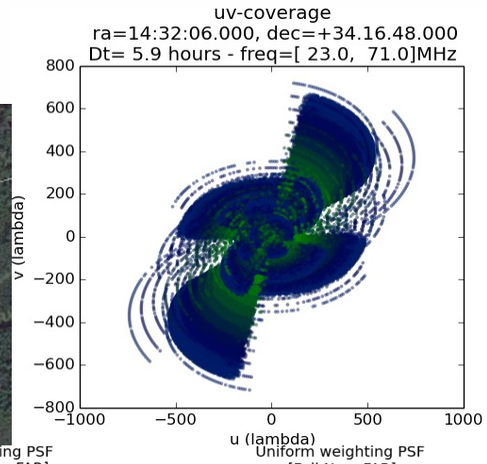
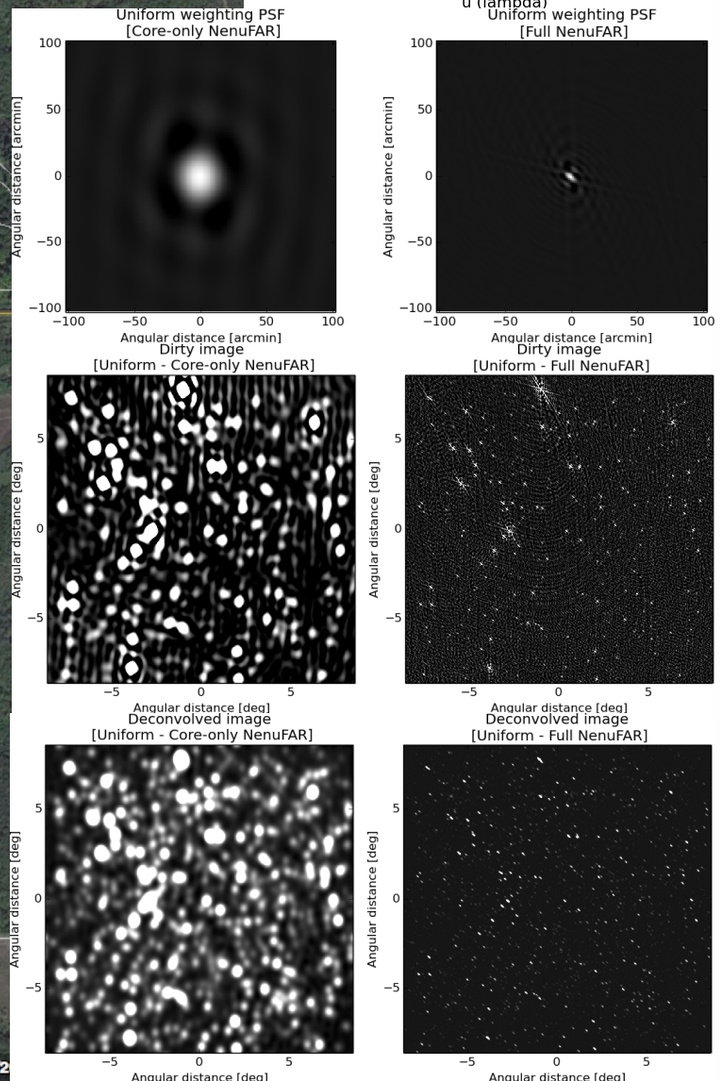
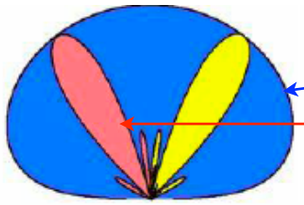
- Relative sensitivity beyond compact core = $(N_{distant}/N_{core})^{1/2}$ ~ 25%







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 (~7') imaging → confusion ~ thermal noise (IQUV)

1.6 MB /s /SB

SETI Machine (BL)

- Channelization down to δf=3 Hz or δt=300 µs
- Classified narrowband signals map

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

Technical characteristics of NenuFAR

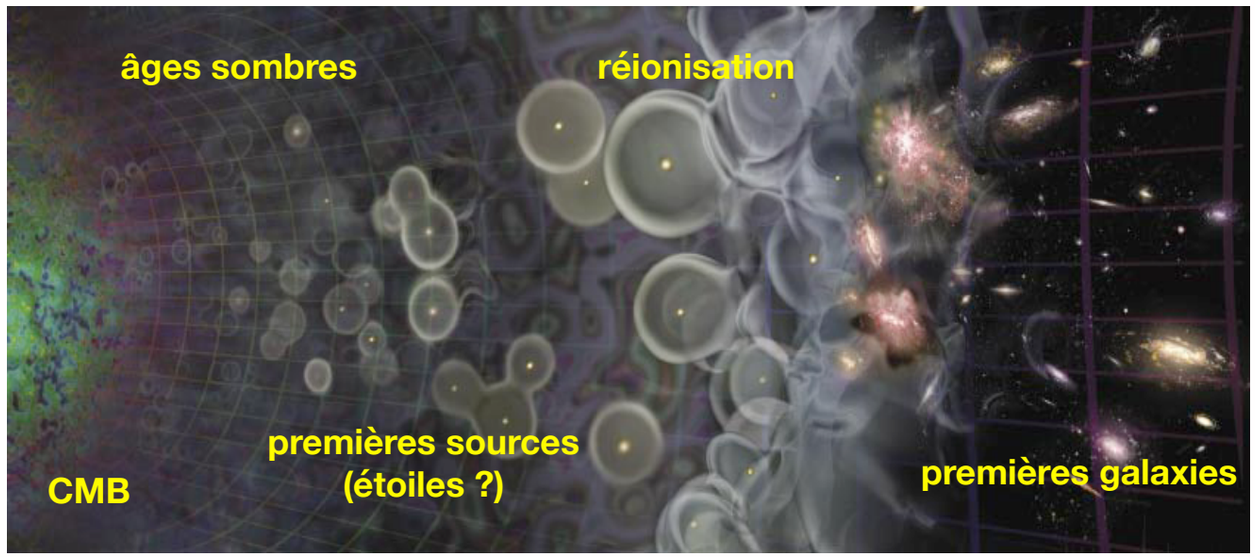
- Giant LOFAR-compatible phased array & interferometer
- 1938 antennes : 96+6 mini-arrays of 19 antennas each (25 m ∅)
- Diameter ~400 m + extensions → 3 km
- 5151 baselines
- Frequency range = 10-85 MHz (λ=3.5-30m)
- Resolutions: δf = 200 kHz → 1 kHz, δt = 5 μsec, Waveform @ 5 nsec
- Full polarization (4 Stokes)
- Collective area ~650λ^2 ≤ 65 000 m^2
- FoV = 32° - 8° @ 20-80 MHz ; pointing (δ) -23° → +90°
- Angular Resolution: 2°-0.5° (Standalone instantaneous Beamformer/Imager)
  17'-4' (Slow Imager), 0.1 " (LSS)
- Sensitivity : 2 – 0.5 Jy @ 20-80 MHz (5σ, 1 sec x 10 MHz, polarized signal)
  10 – 2 mJy ‘‘ (5σ, 6 h x 40 MHz)
- Confusion at zenith: 50 – 1 Jy @ 20 – 80 MHz (unpolarized, compact core)
  1000 – 20 mJy " (unpolarized, with distant MA)

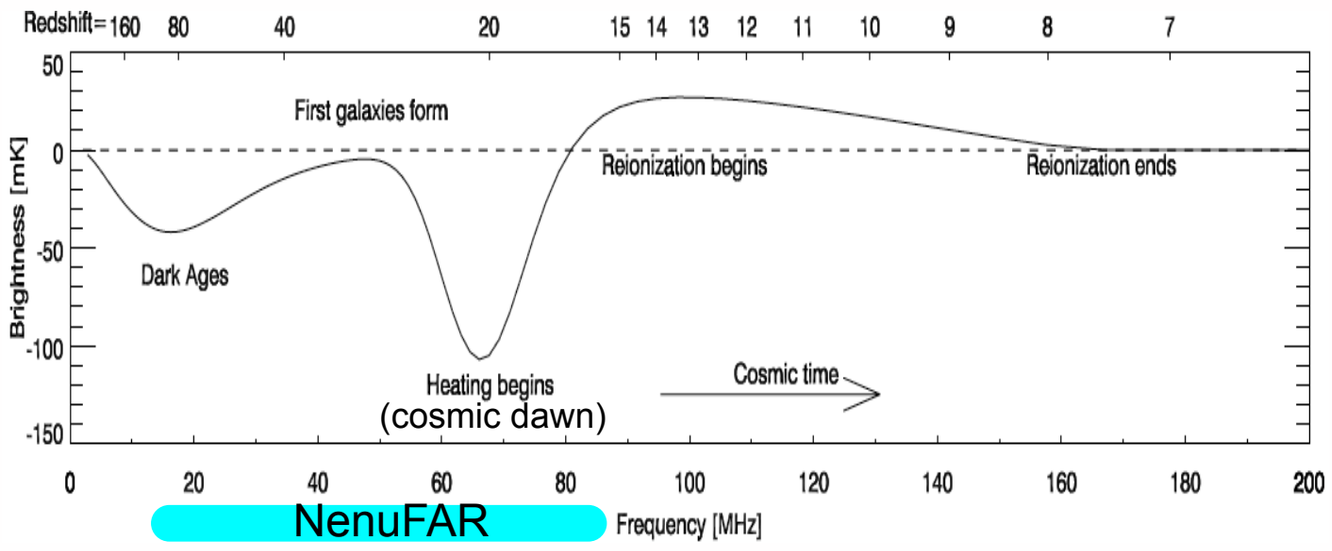
NenuFAR today

988 antennas built, 190 to come, 760 yet to be funded

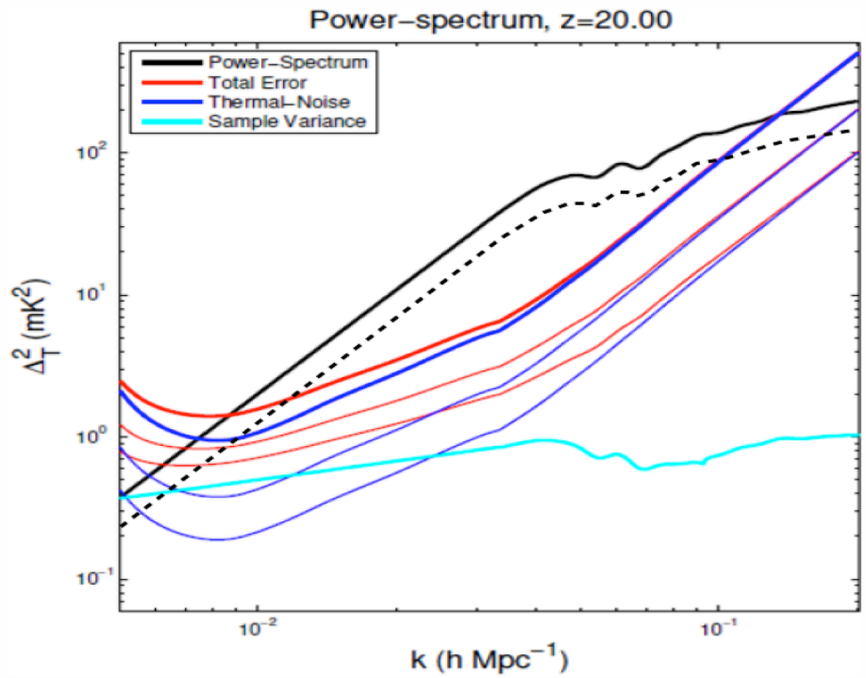
The Science

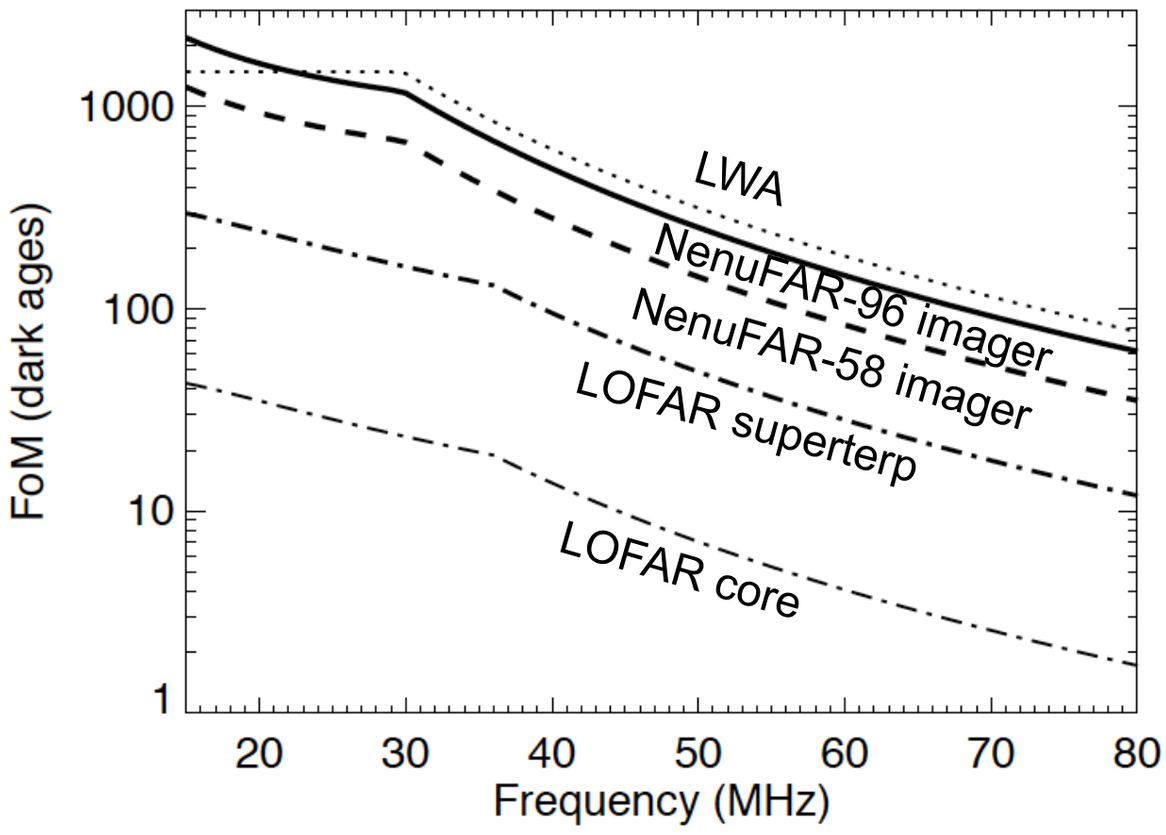
- *Standalone Slow Imaging (multi-λ rotational synthesis) :* Dark Ages/Cosmic Dawn





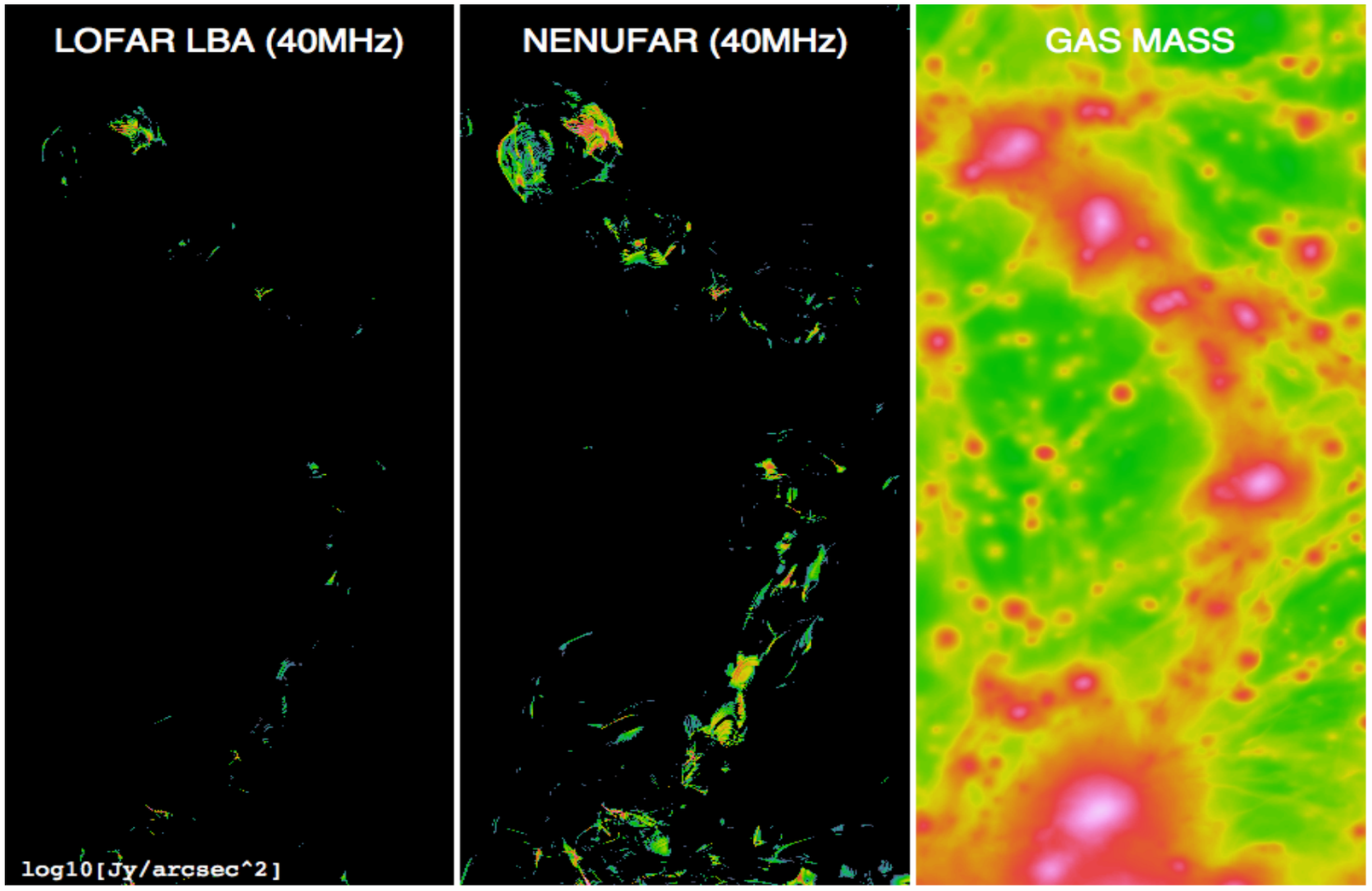
Koopmans et al. [2015]
Semelin et al. [2015]



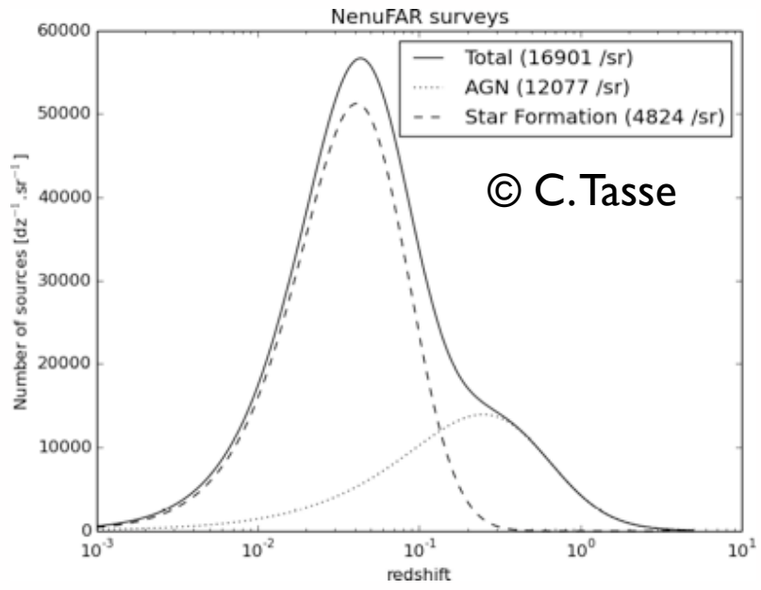


The Science

- *NenuFAR / LSS* : very high resolution wide-field LBA imaging,
  more sensitivity to extended structures
  (BH, AGN, star formation, IGM, clusters, haloes, relics, IGM, ISM, B fields)
- + *Standalone Slow Imaging* : short baselines, diffuse emission



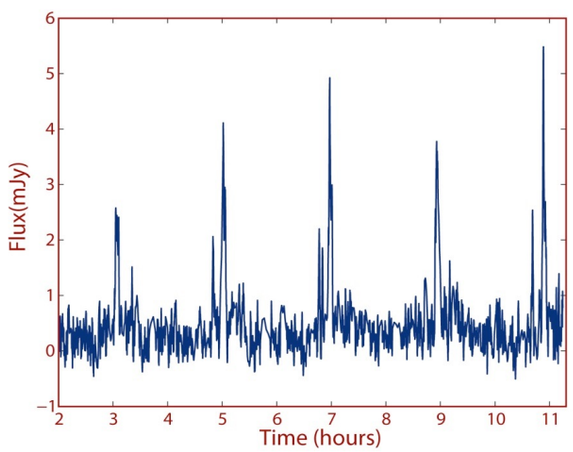
© F. Vazza



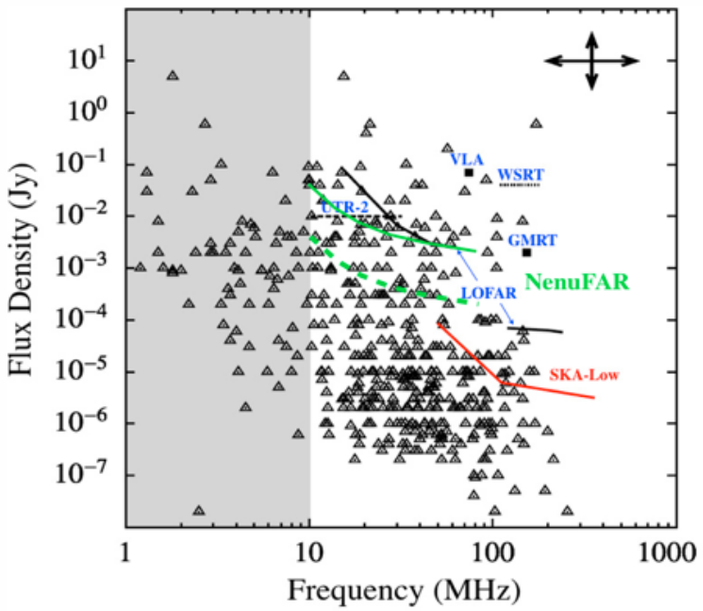
© C. Tasse

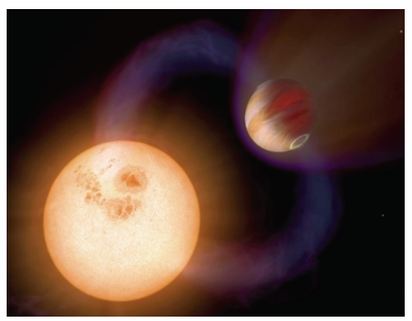
The Science

- *Standalone Slow & Fast Imaging* : Stars (Flaring/Dwarf/Cool), Planets, Star-Planet plasma Interactions

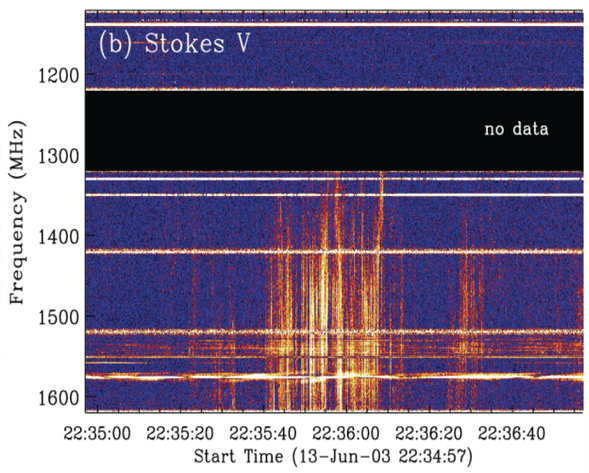


Hallinan et al., 2007, 2008, 2015





Zarka et al., 2015



Osten et al., 2006, 2008

The Science

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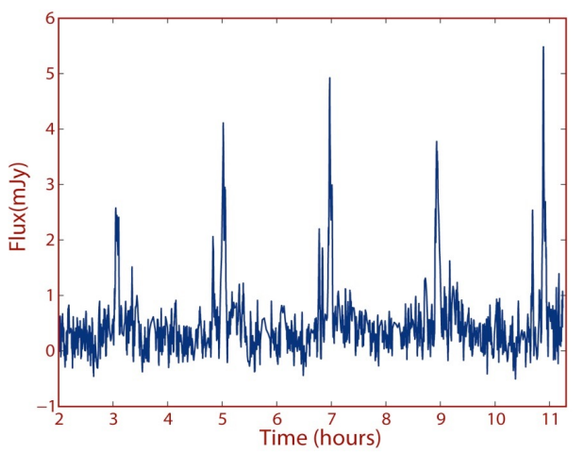

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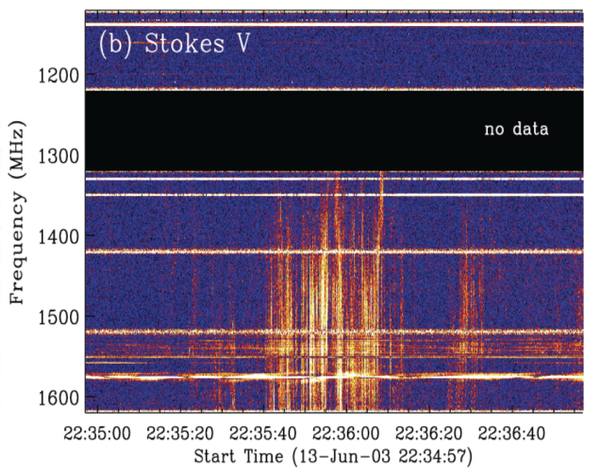

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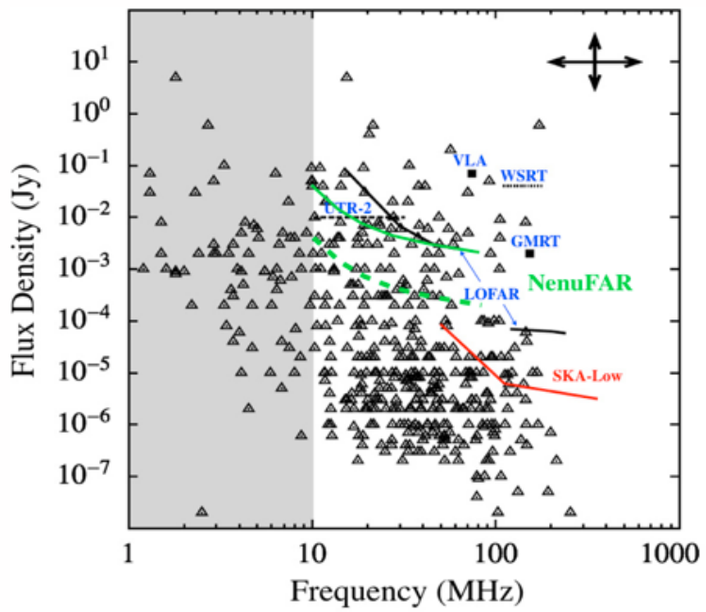
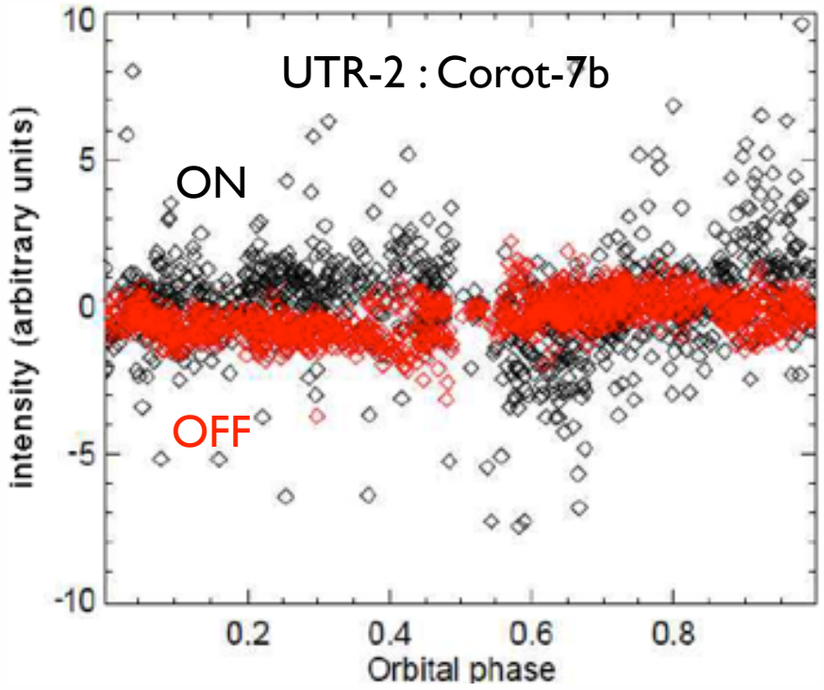
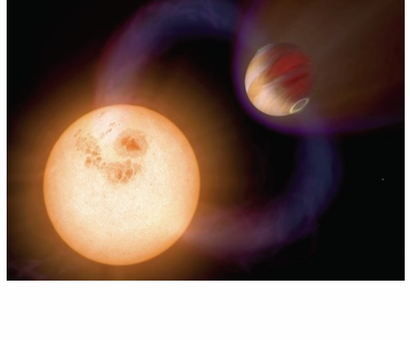
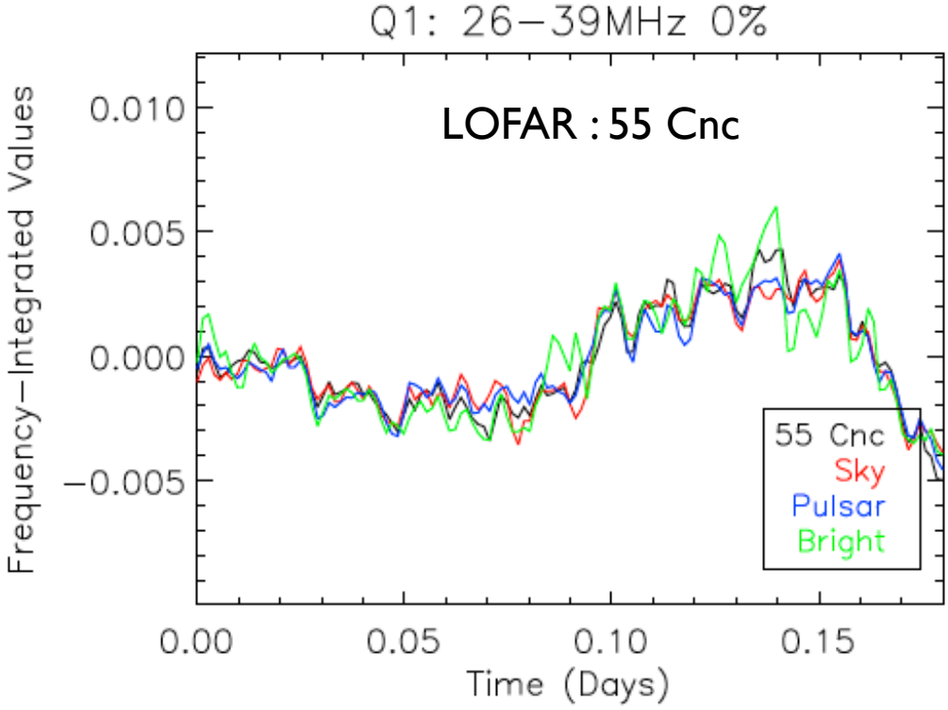




Vasylieva et al., 2016



Zarka et al., 2015

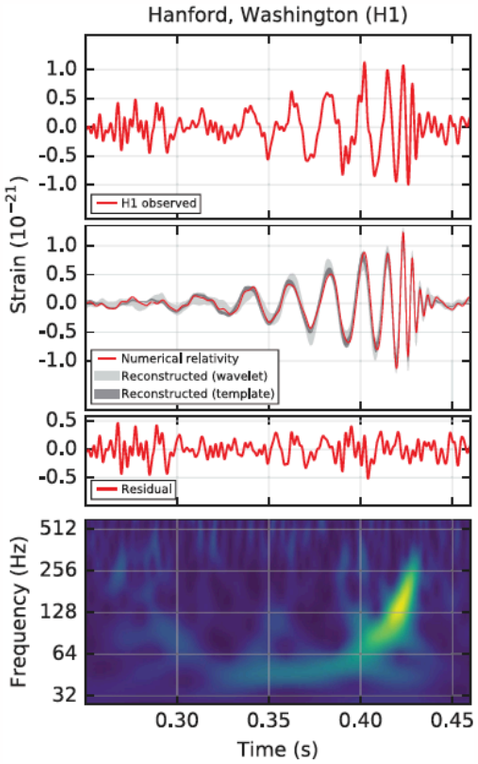


Turner et al., 2016

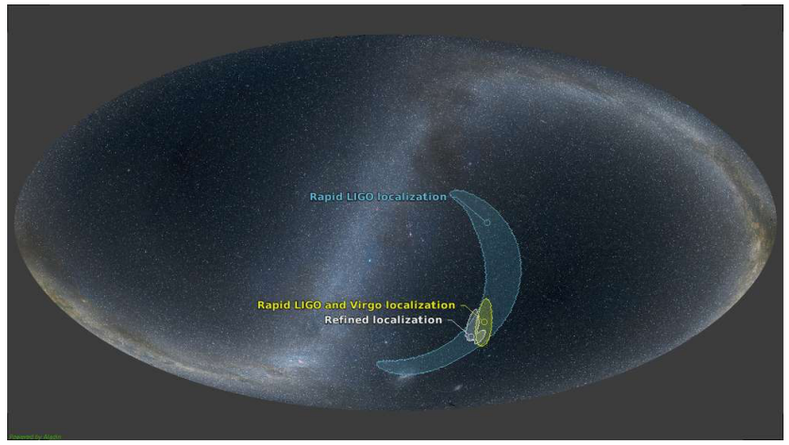
The Science

- *Standalone Slow Imaging (multi-λ rotational synthesis) :* GW/GRB afterglows ?
- *Standalone Beamforming/Fast imaging* : Prompt GW emission ?

[MoU LIGO-Virgo / NenuFAR → broad FoV, upper limits]



LIGO coll., 2016



LIGO + VIRGO coll., 2017

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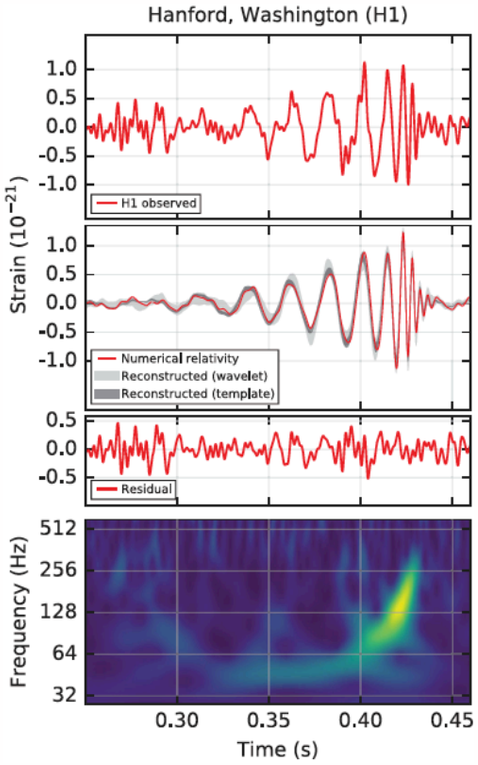
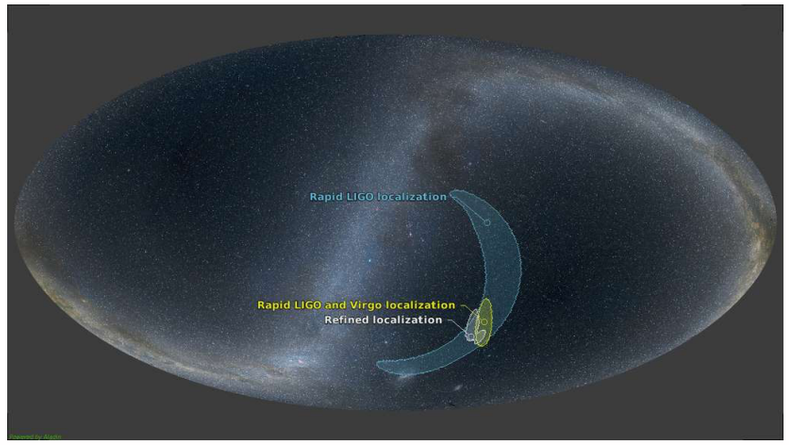
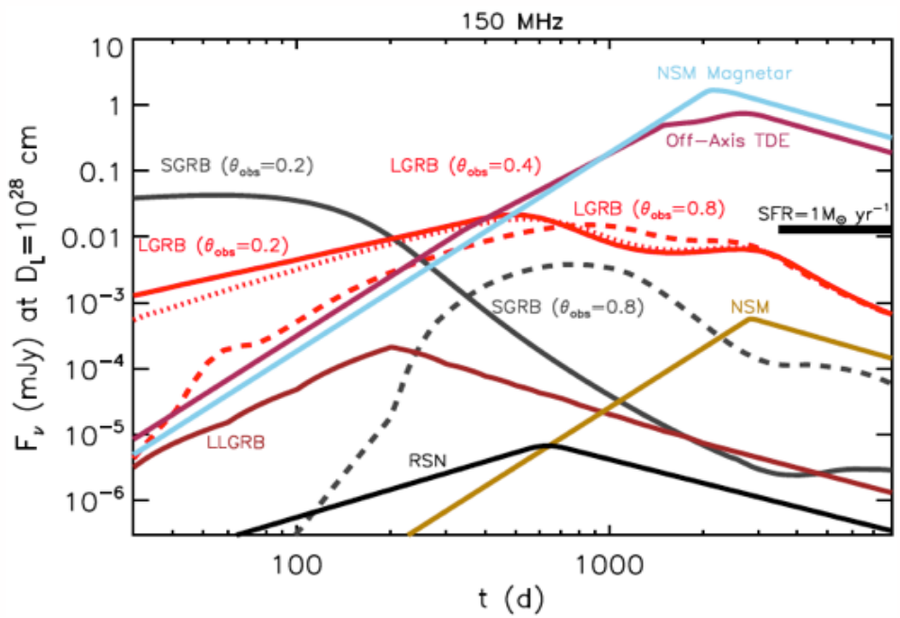


LIGO coll., 2016



LIGO + VIRGO coll., 2017



[Metzger et al., 2015]

The Science

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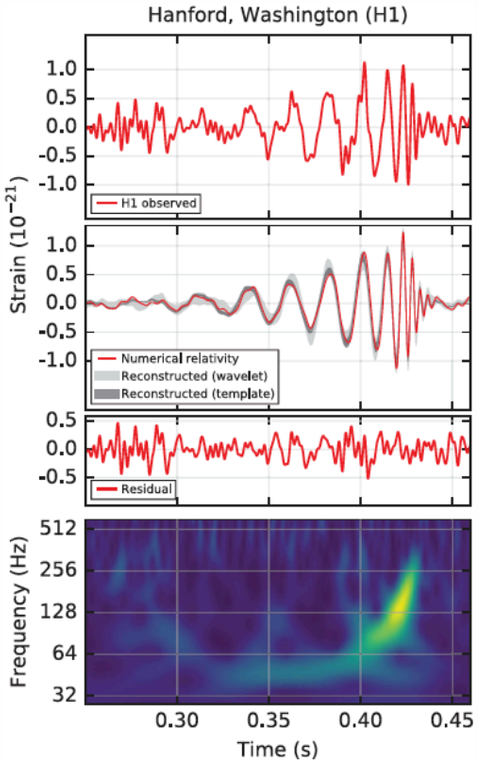
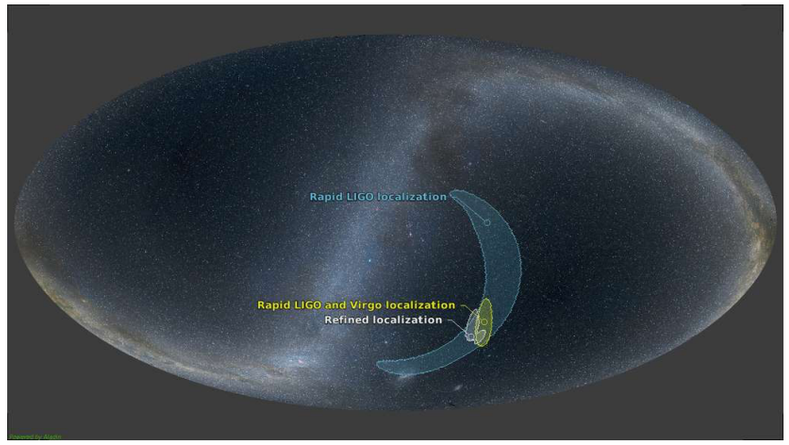
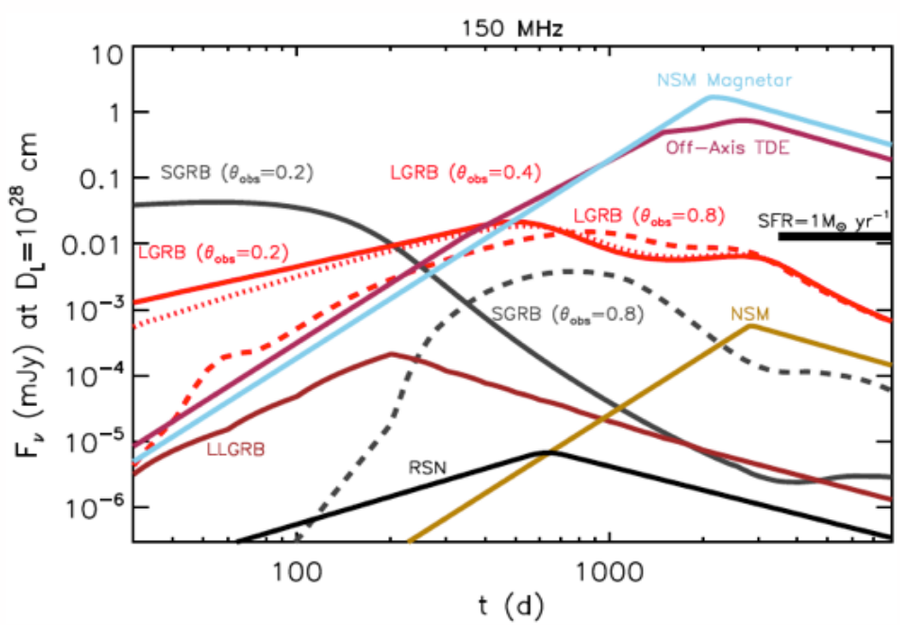


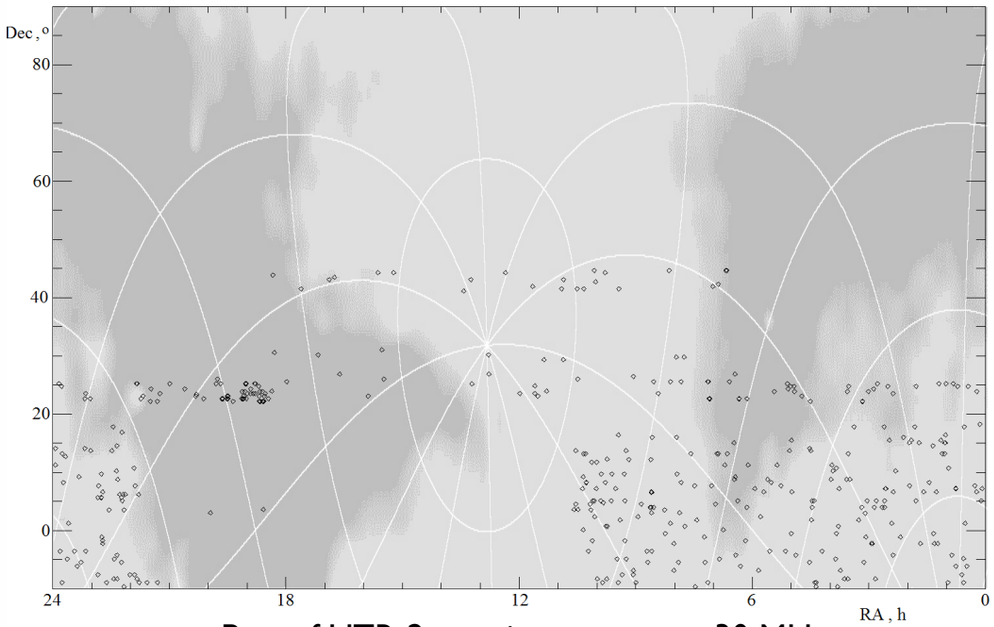
LIGO coll., 2016



LIGO + VIRGO coll., 2017



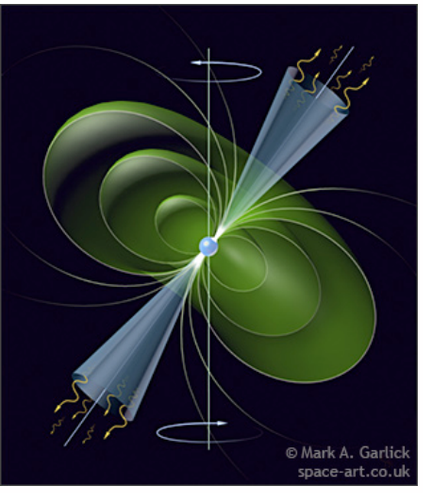
[Metzger et al., 2015]

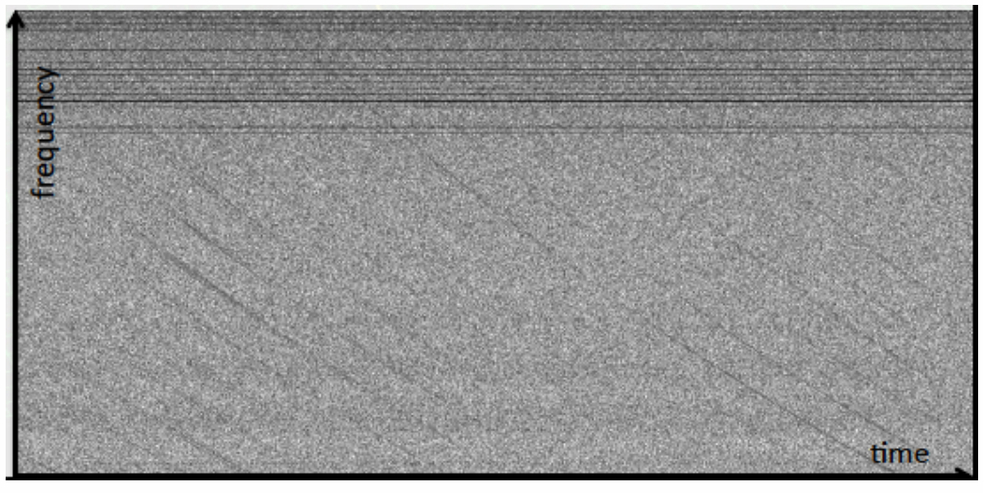


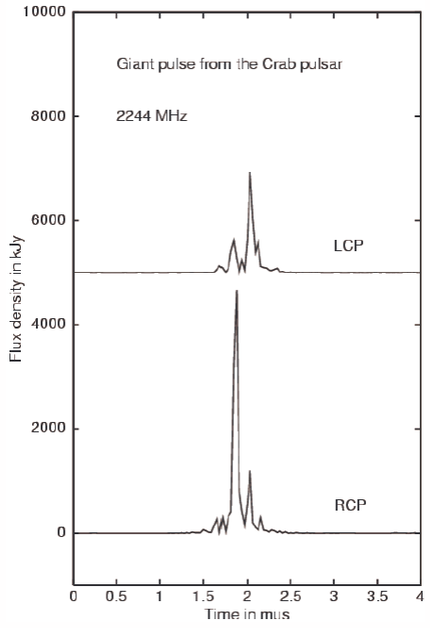
Part of UTR-2 transients survey ≤30 MHz
[Zakharenko, Vasylieva et al., 2015]

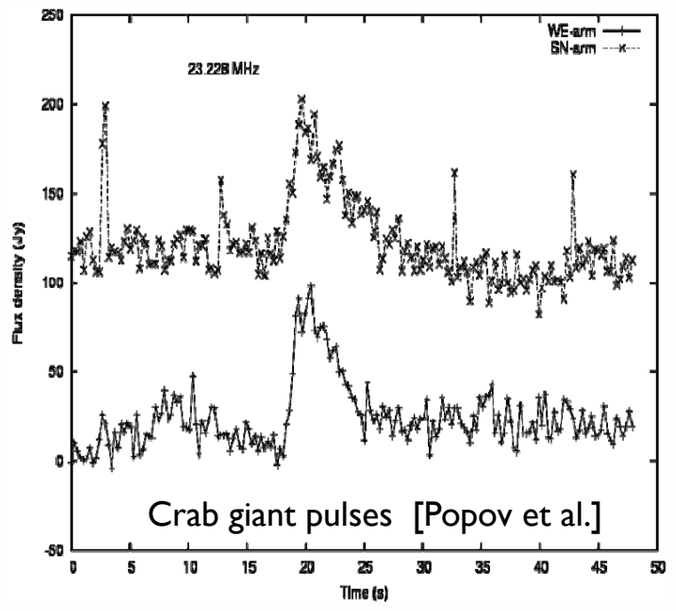
The Science

- *Standalone Beamforming/Fast imaging* : Pulsars (detection with FoM ≥ LOFAR), Giant pulses ...









The Science

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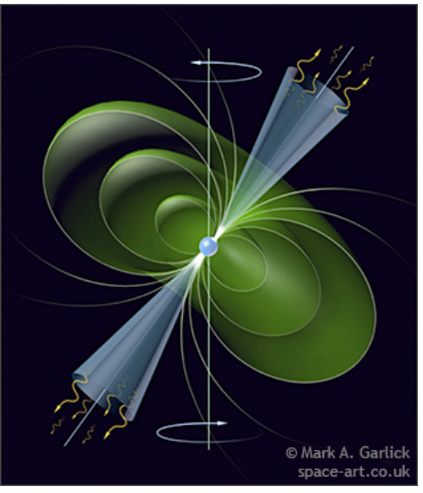
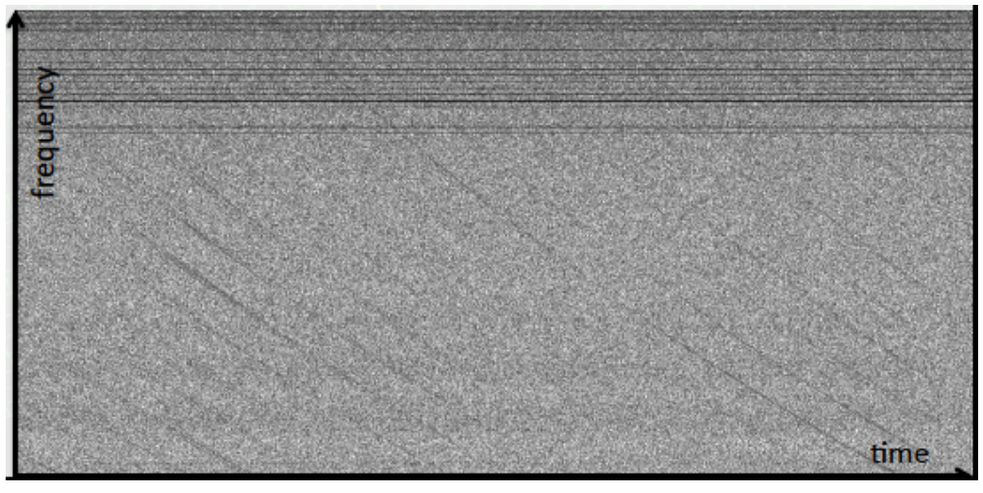
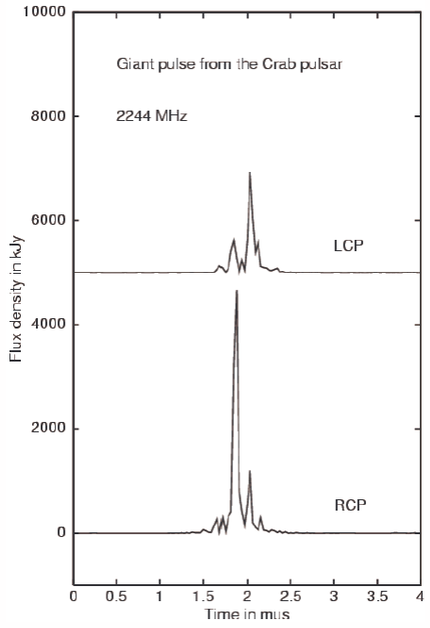
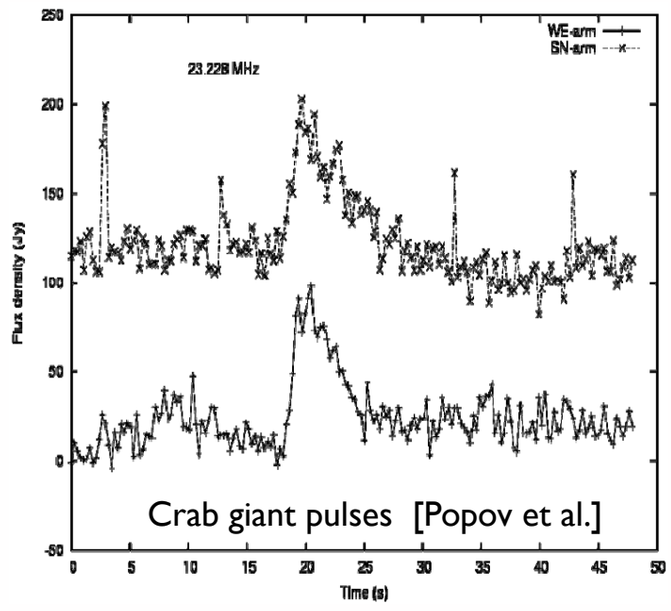
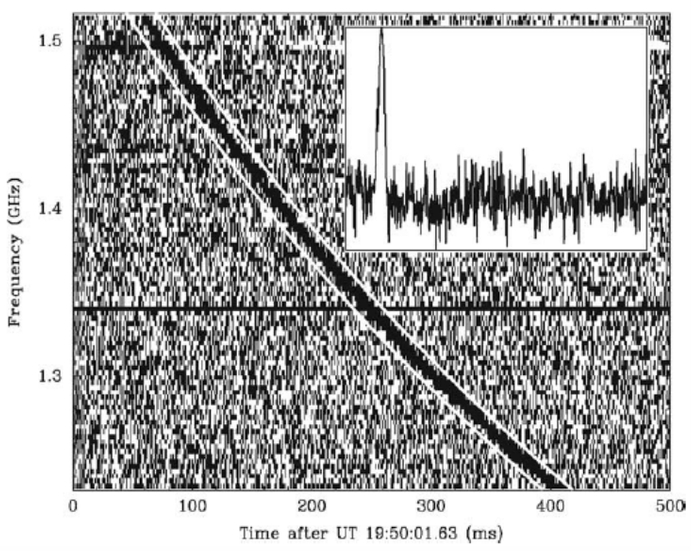




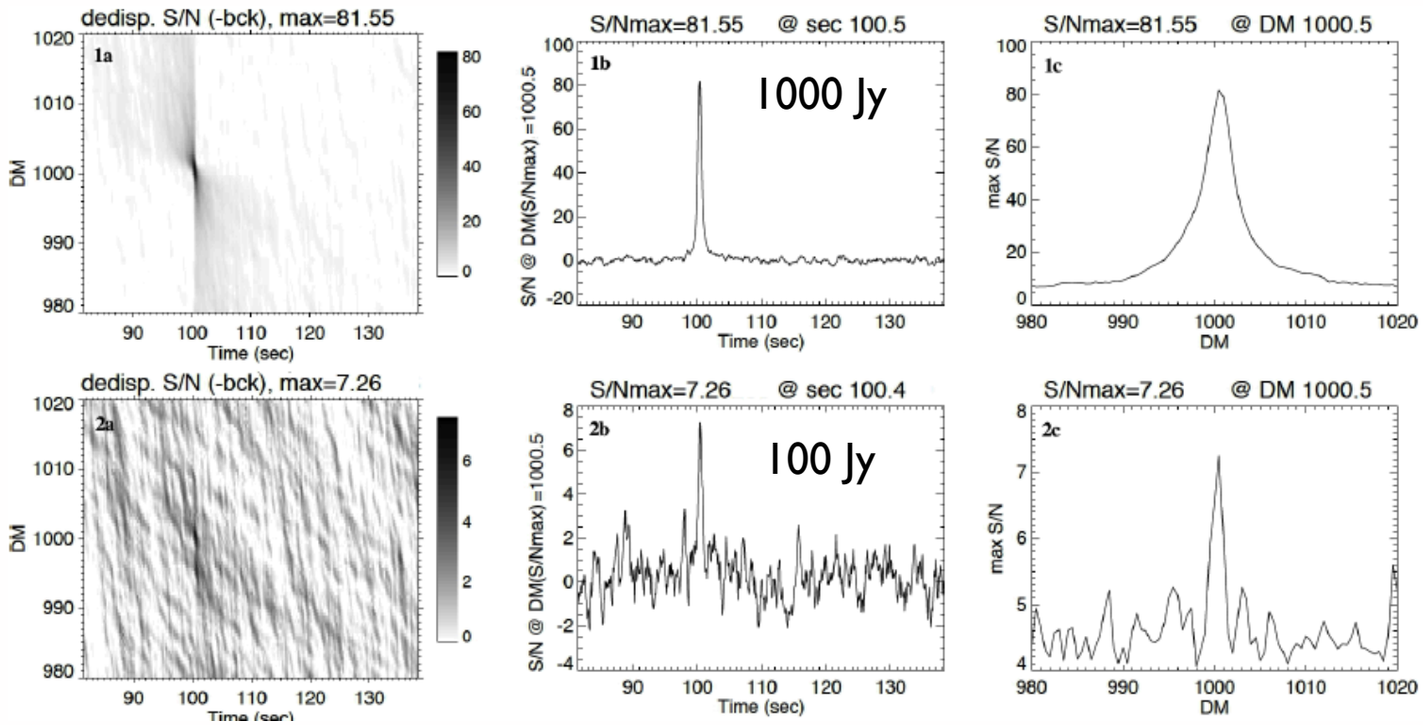




- *Standalone Beamforming/Fast imaging* : FRB, blind transient search in large FoV ...



FRB discovery
[Lorimer et al., 2007]



FRB LF simulations [Zarka & Mottez, 2016]

The Science

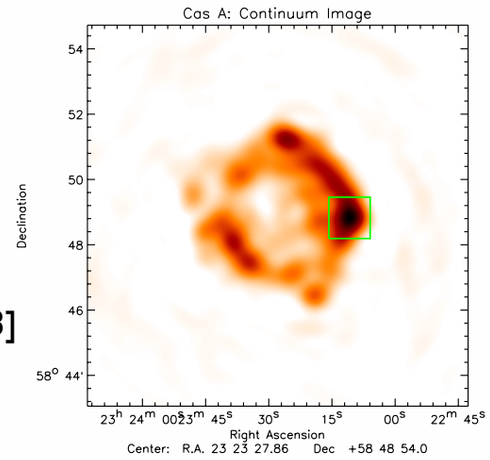
Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

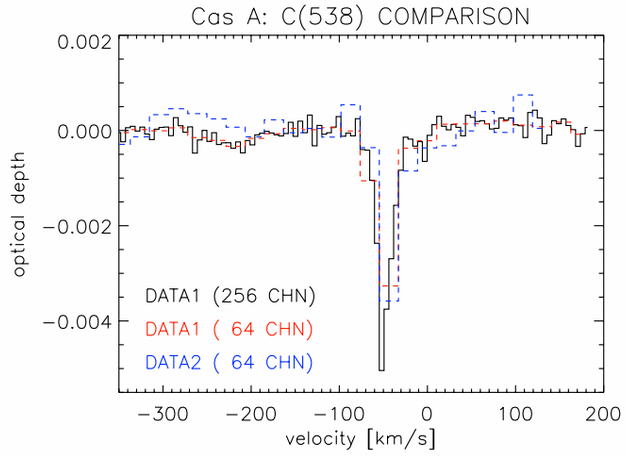
The Science

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

- Radio Recombination Lines, Grains ? *(SB, SI)*

[Asgekar et al., 2013]





The Science

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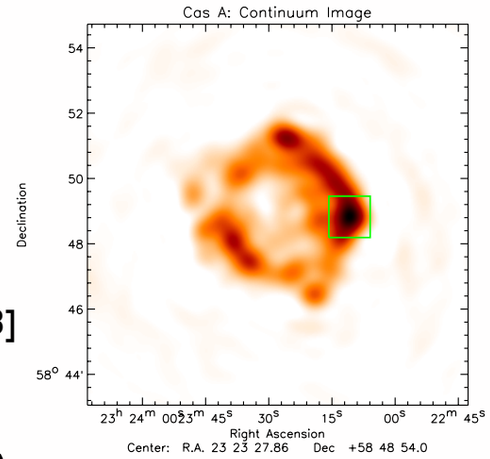
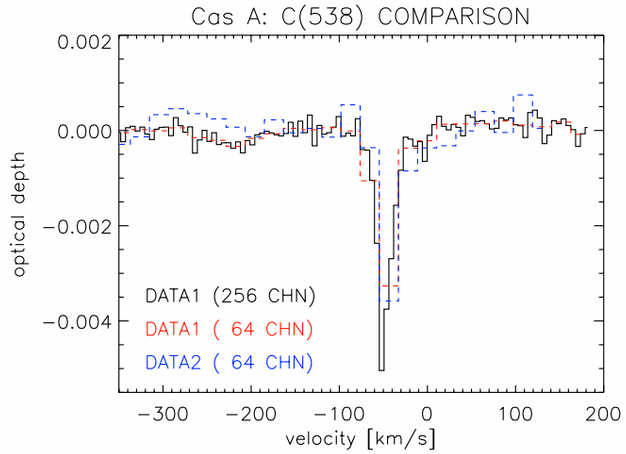
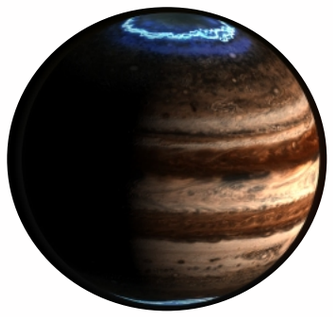
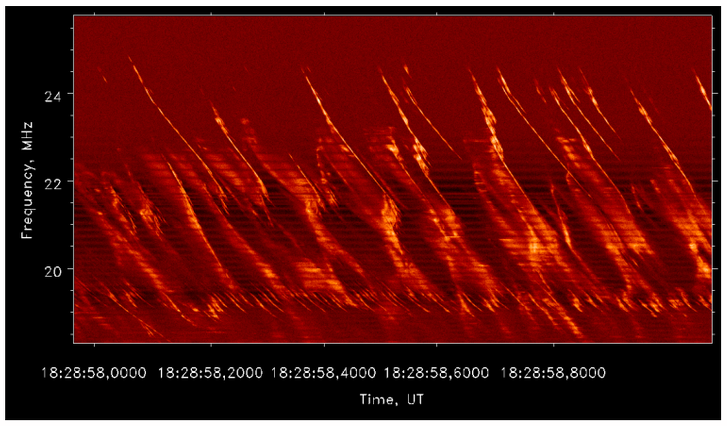




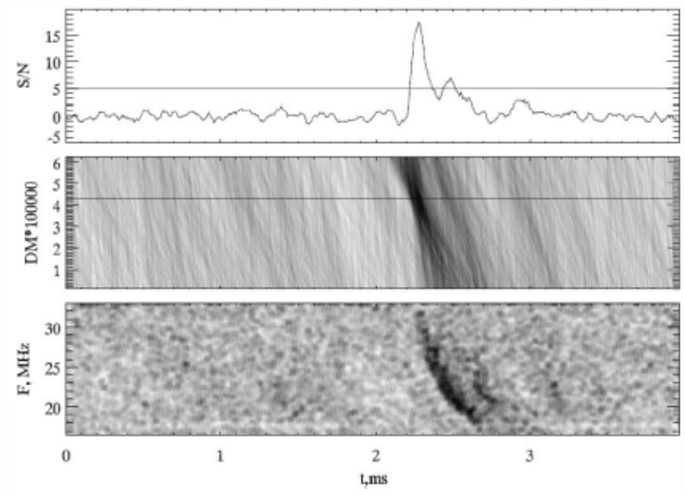
[Asgekar et al., 2013]

- Héliosphère: Soleil, Jupiter, Éclairs *(SFI, SB)*





[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]

The Science

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

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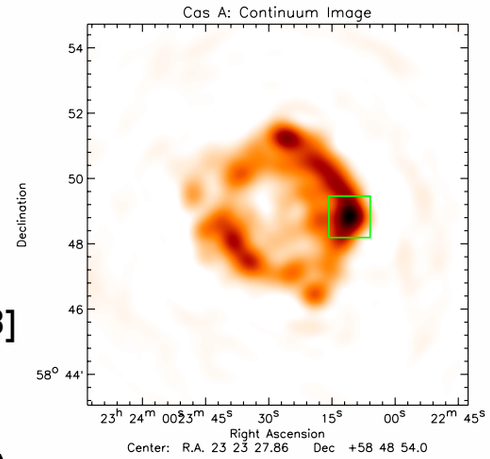

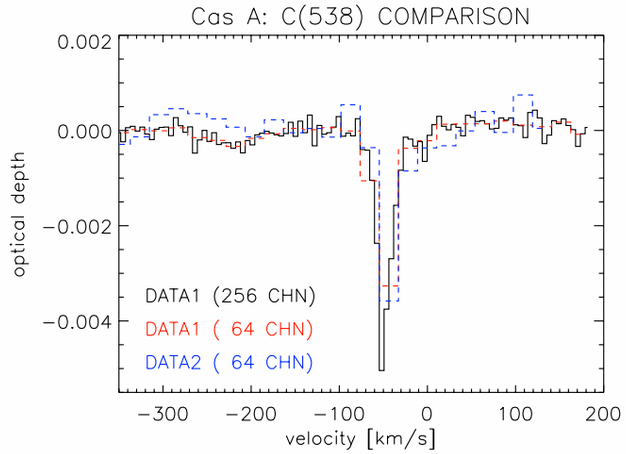

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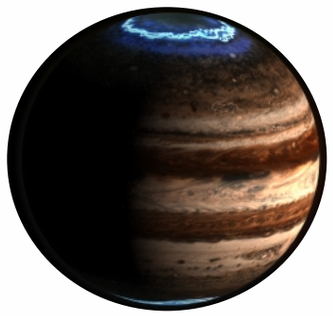
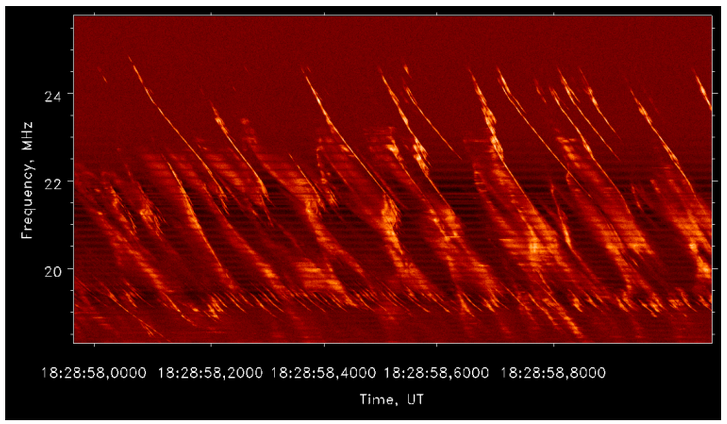
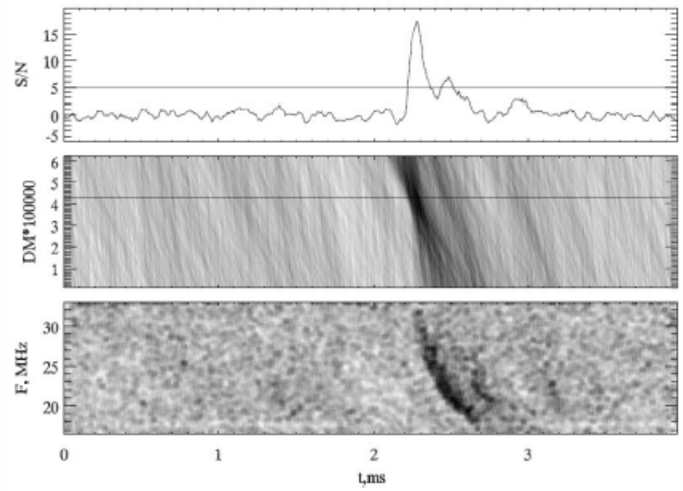




[Ryabov et al., 2014]



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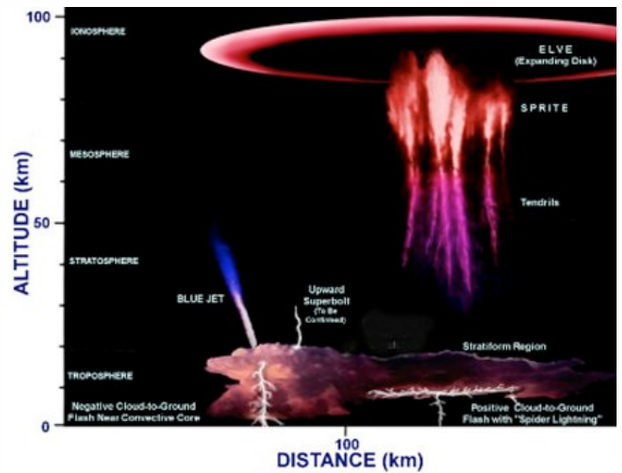
→ Solar Wind probing up to 10 AU [Zakharenko,et al., 2012]

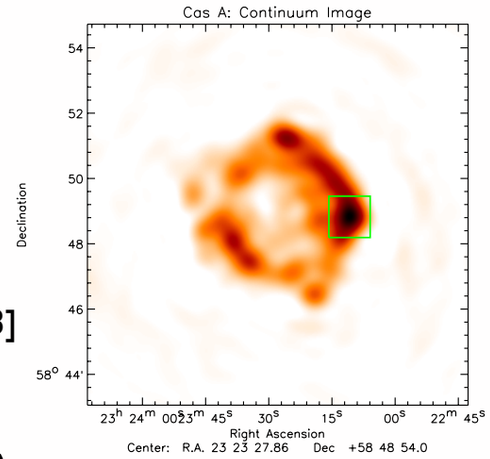
- Terre: Éclairs/Sprites, TLEs *(SFI, SB)*

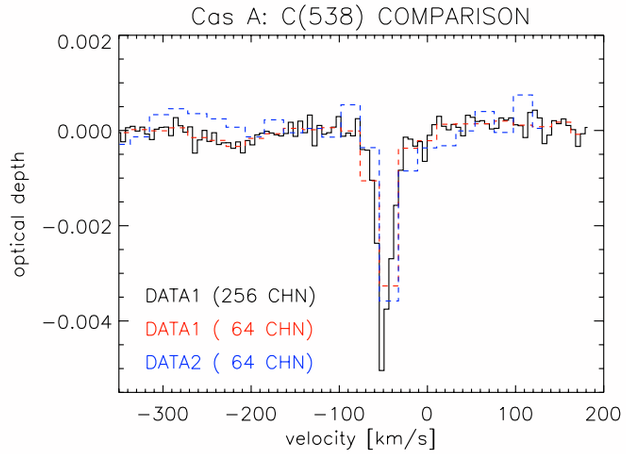


The Science

Standalone Slow/Fast Imaging, Standalone Beamforming, LOFAR Super Station)

- Radio Recombination Lines, Grains ? *(SB, SI)*





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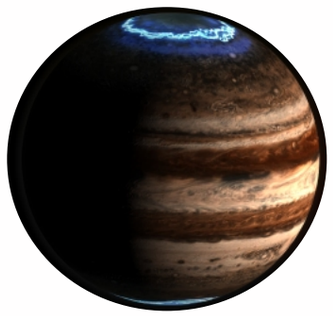
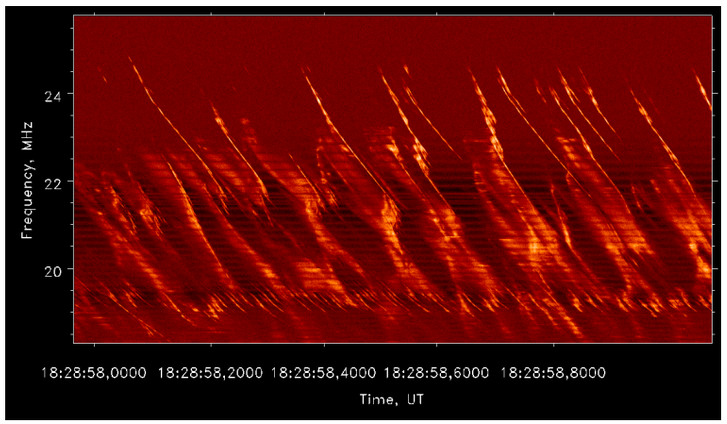
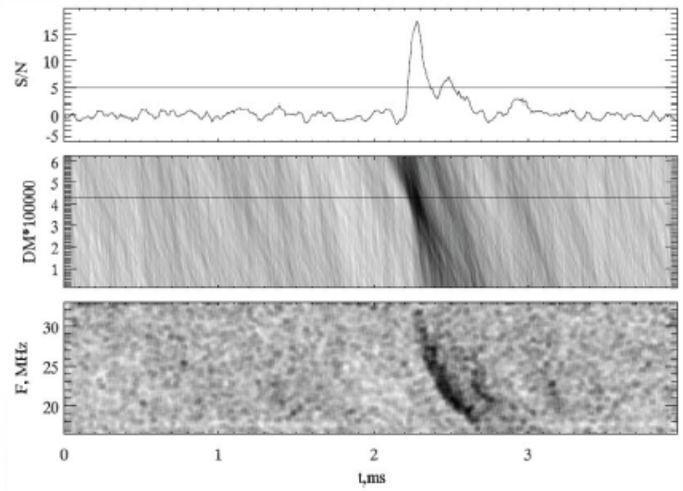


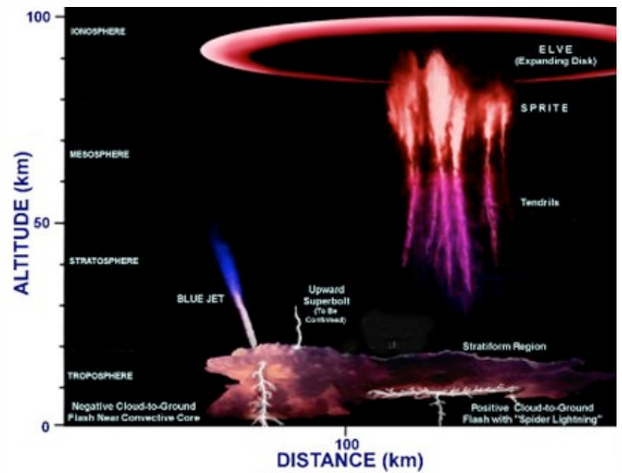


[Ryabov et al., 2014]



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

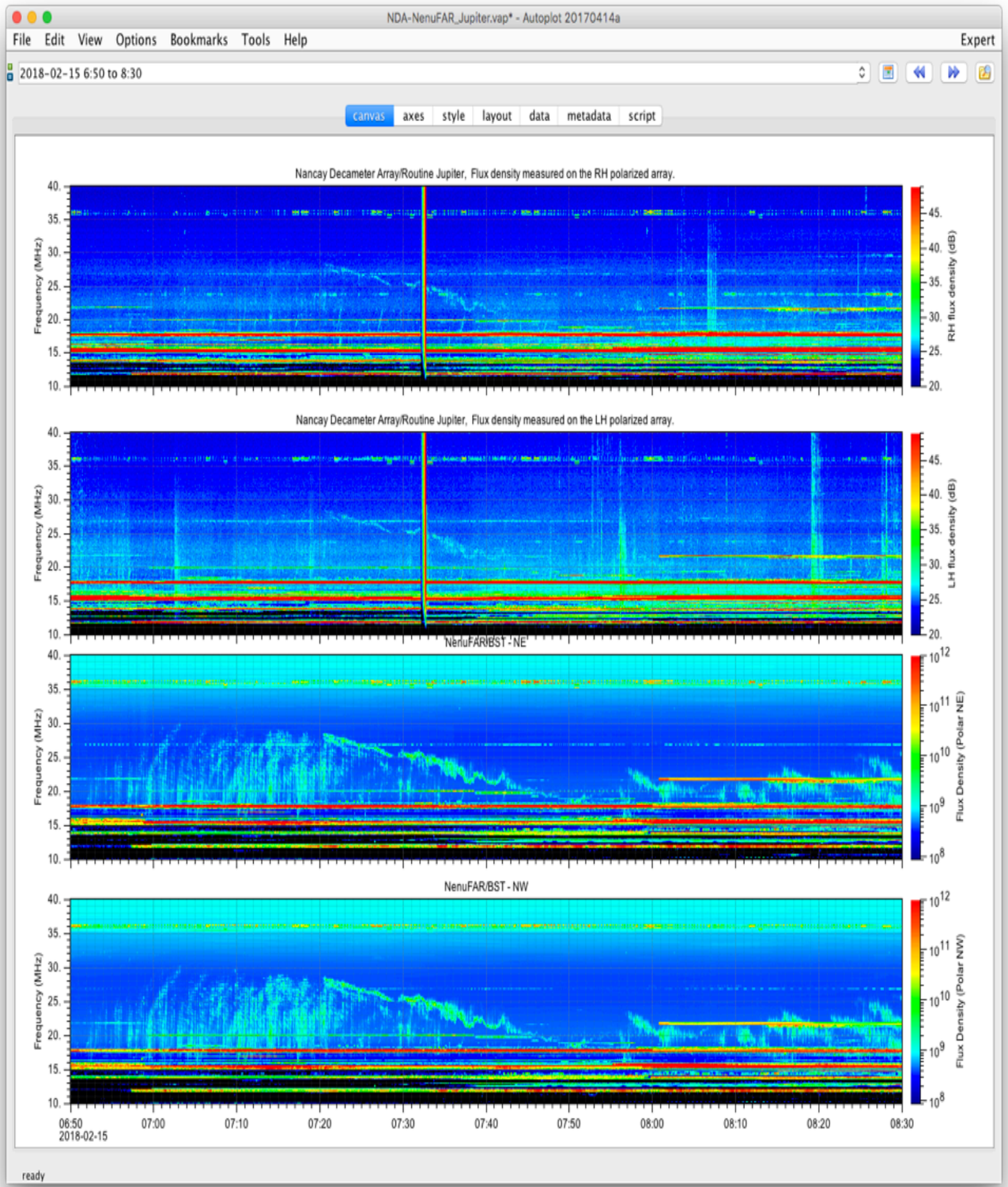
- Terre: Éclairs/Sprites, TLEs *(SFI, SB)*



- SETI *(SB)*

Commissioning, Calibration

- Quantifiying the sensitivity : Jovian & Solar bursts



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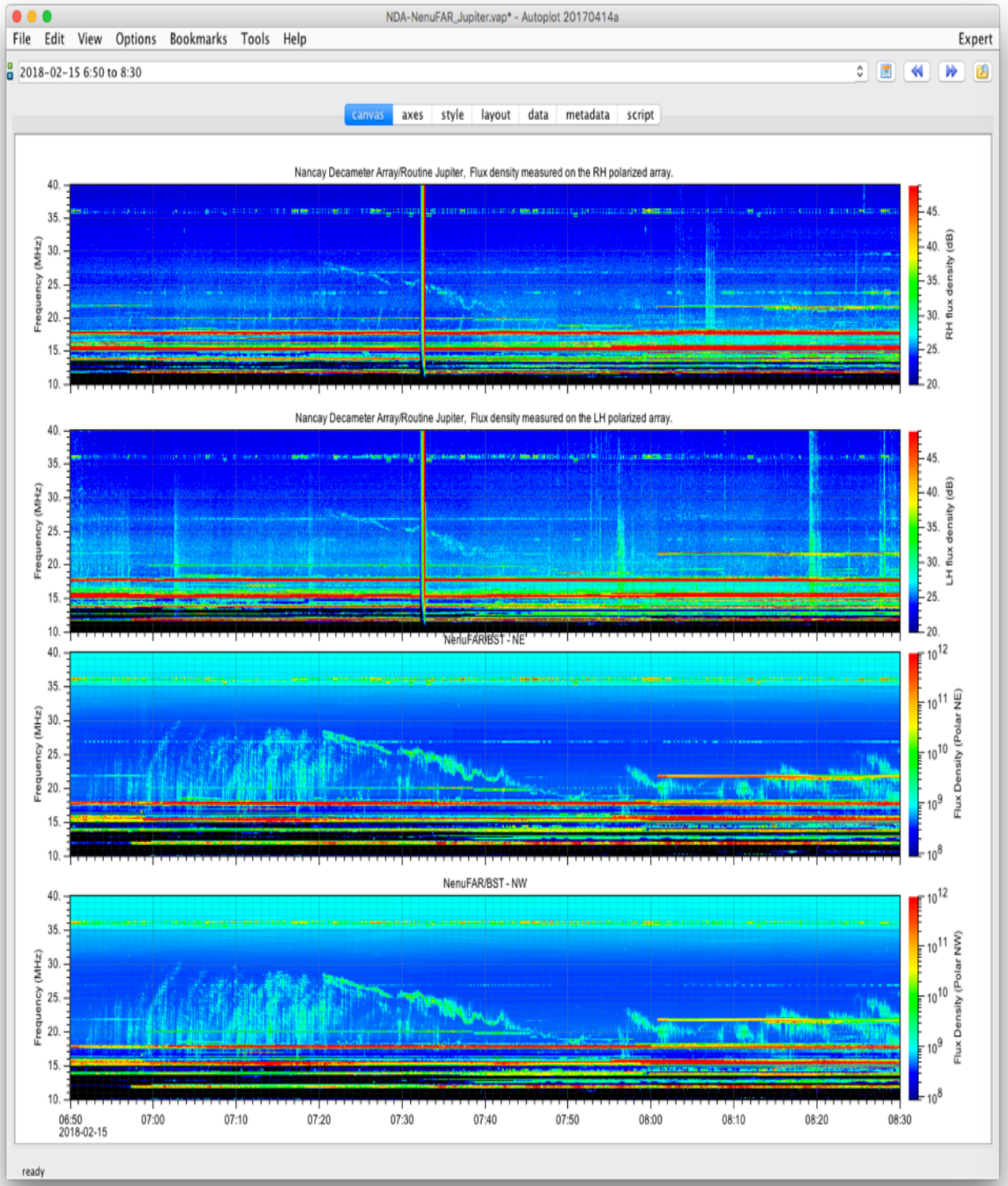

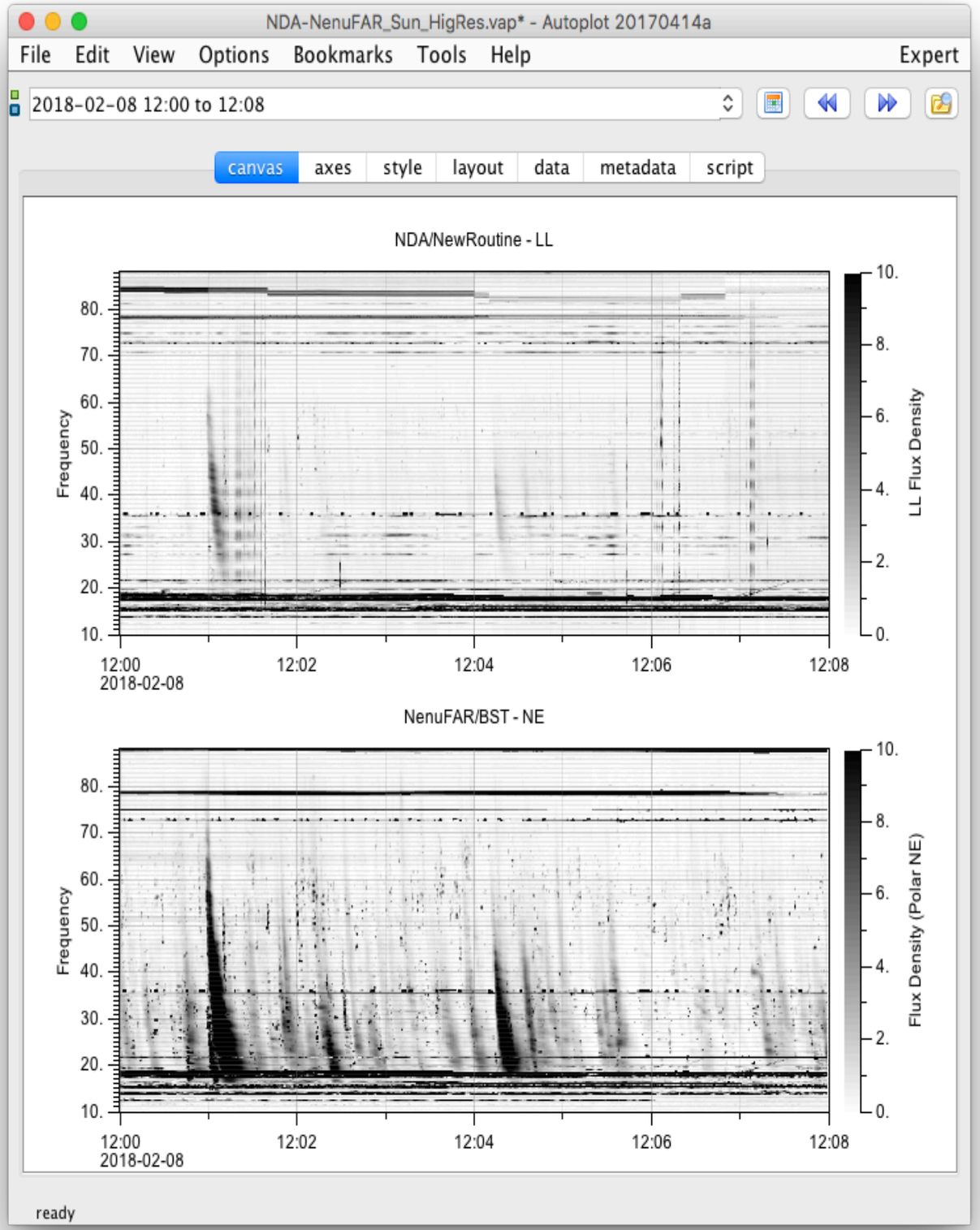

Commissioning, Calibration

- Quantifiying the sensitivity : Jovian & Solar bursts
- Instrument simulations + GSM

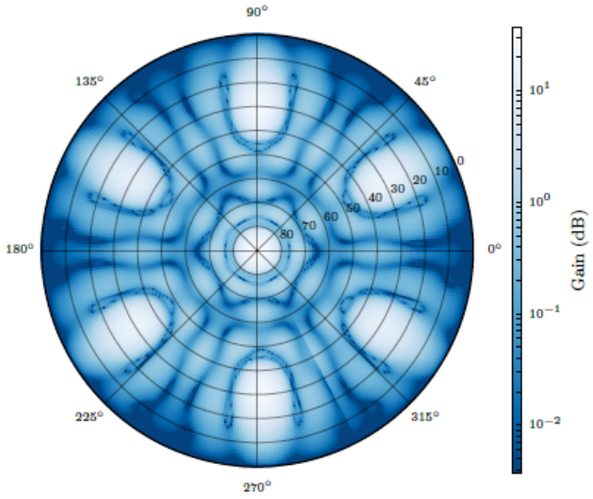

Figure 3: Gain pattern of the Mini-Array 0 (with the 88° offset angle). North is at 0°, East at 90° in azimuth.

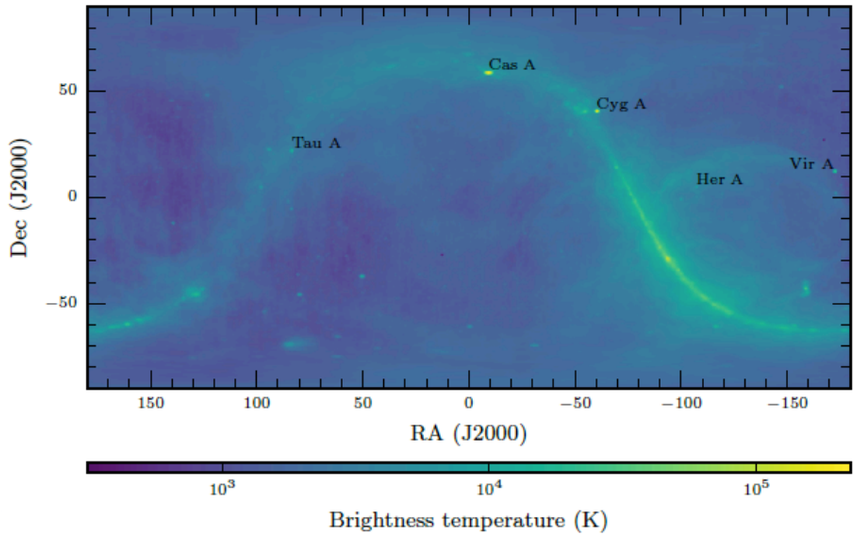

Figure 1: GSM low-frequency sky model at 72 MHz.

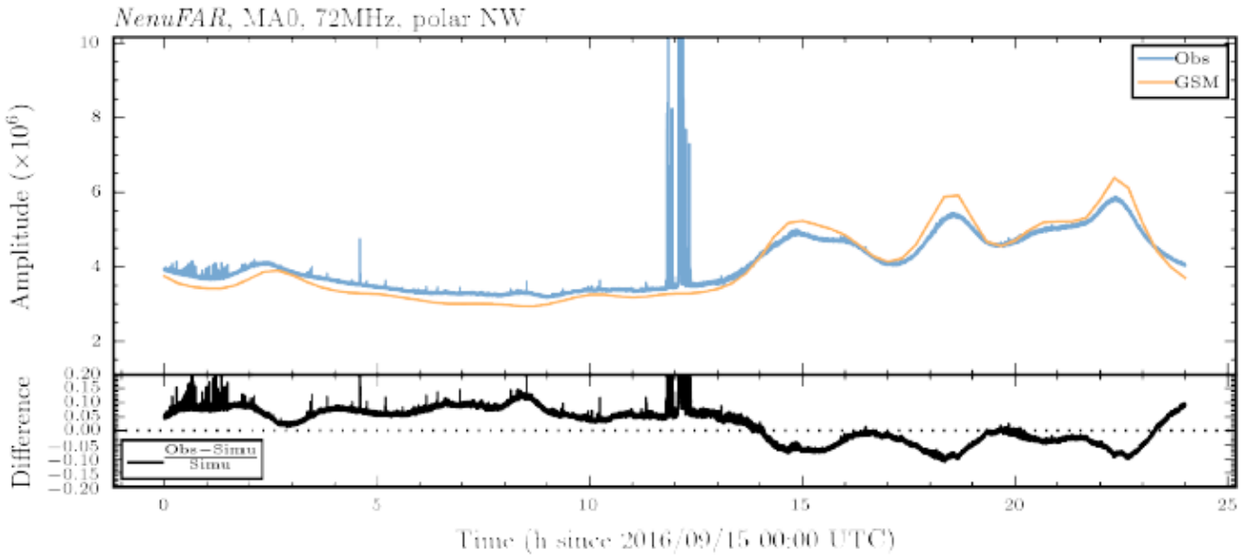

Figure 4: Time profile at 72 MHz of the Mini-Array 0 during the zenith observation on 2016 October 15 and simulation using a 88° offset angle.

Commissioning, Calibration

- Quantifiying the sensitivity : Jovian & Solar bursts
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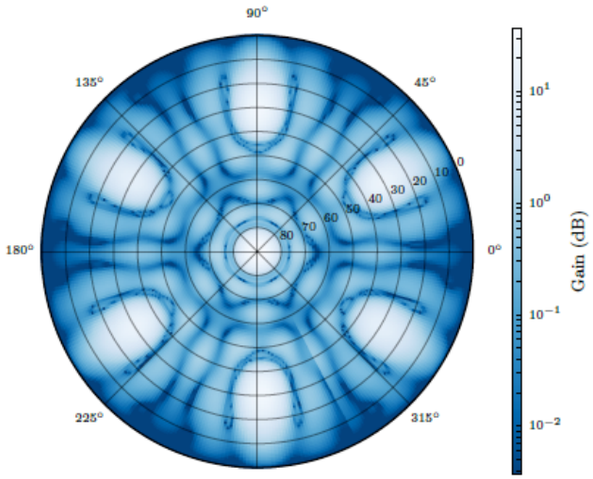

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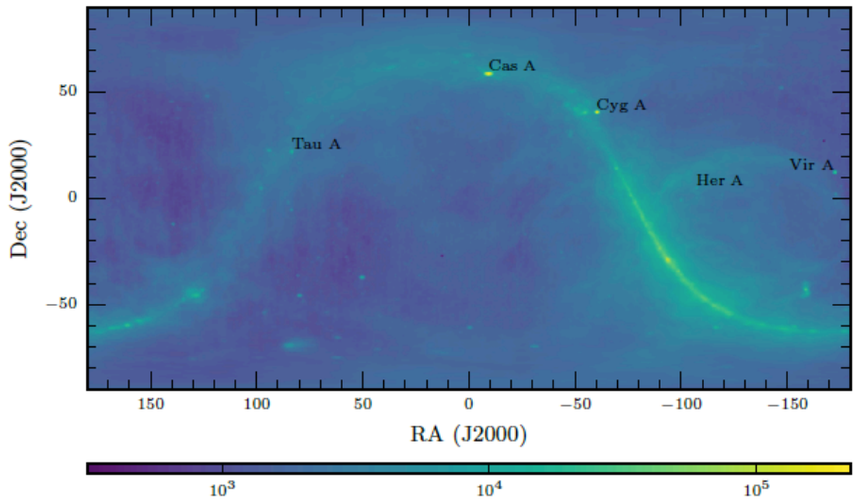

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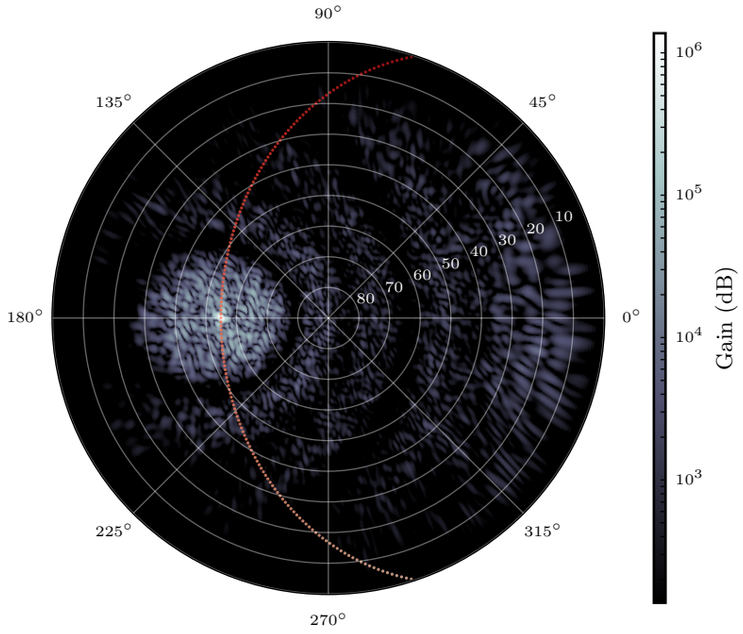

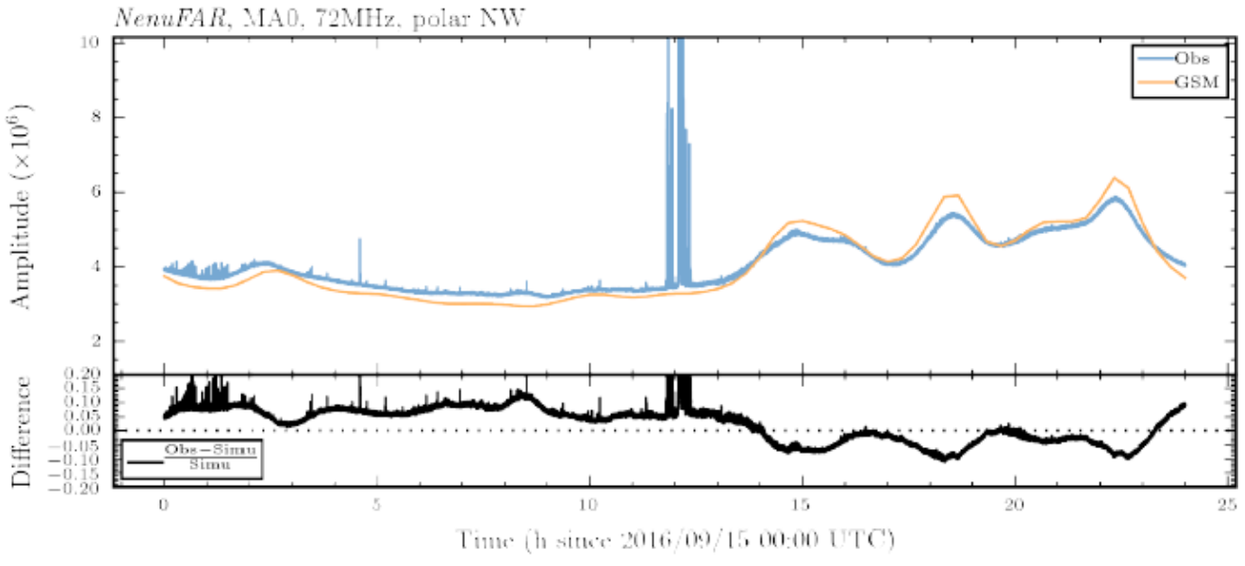

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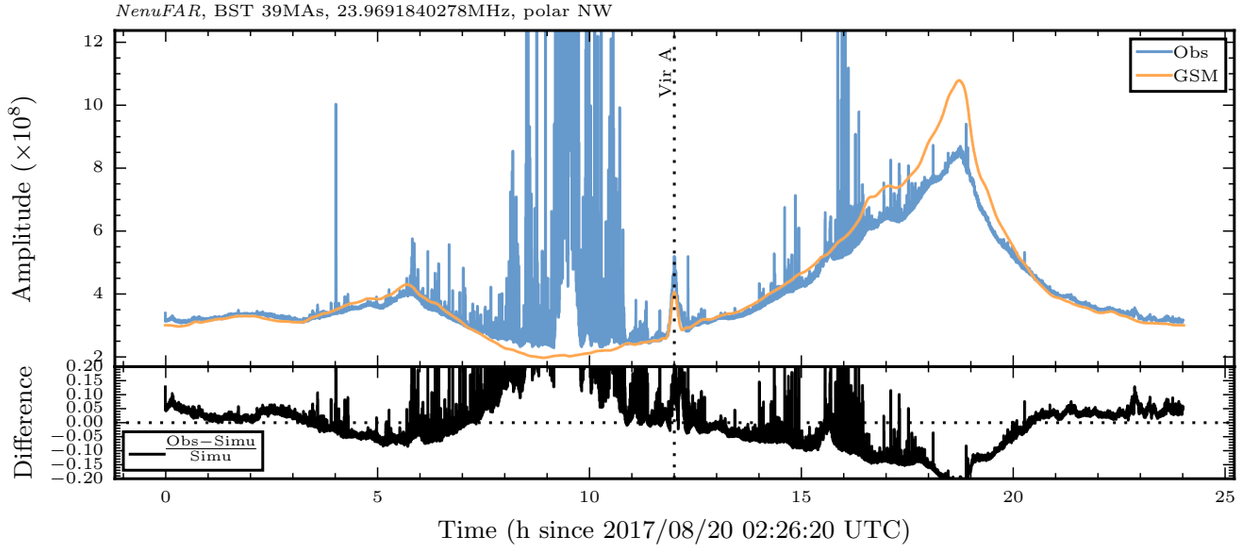

Commissioning, Calibration

- Quantifiying the sensitivity : Jovian & Solar bursts
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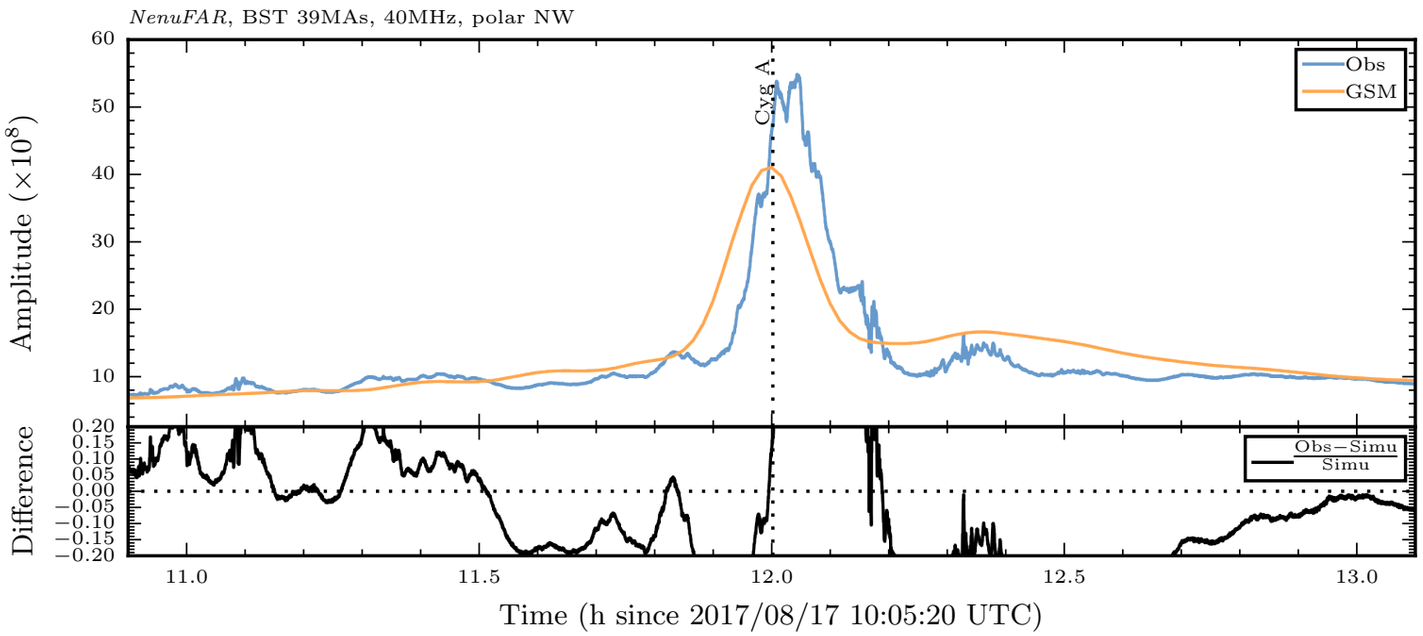

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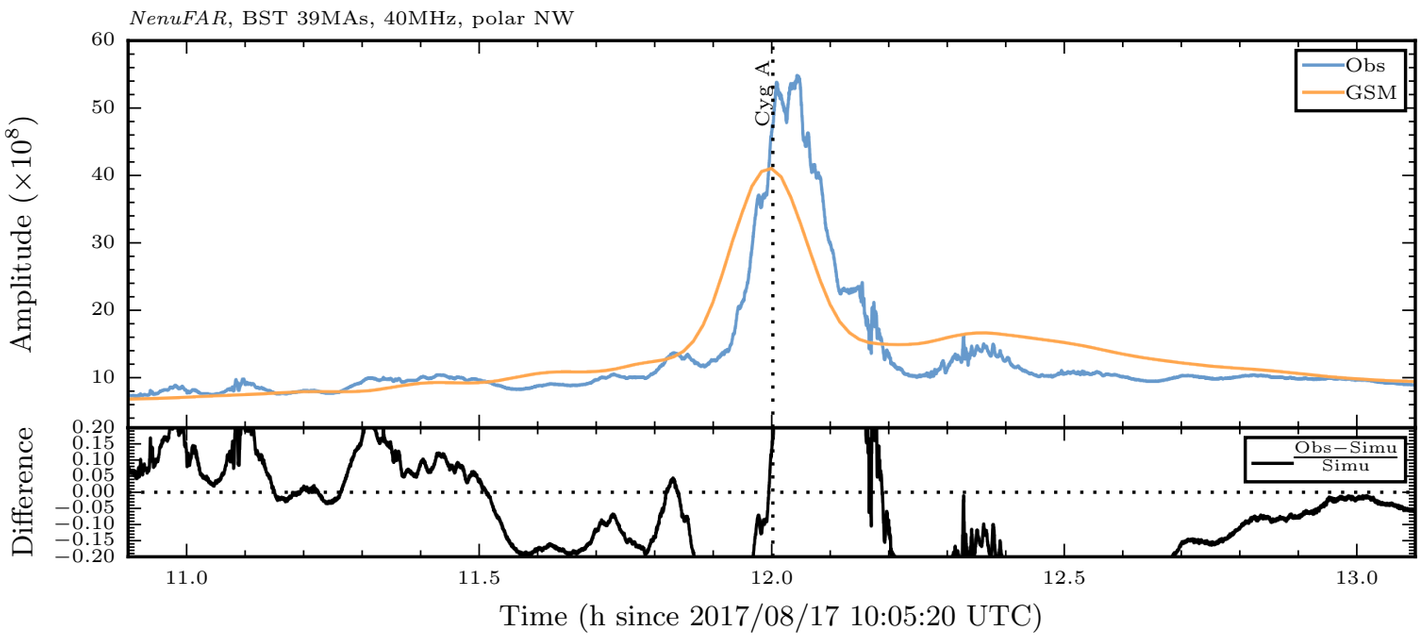

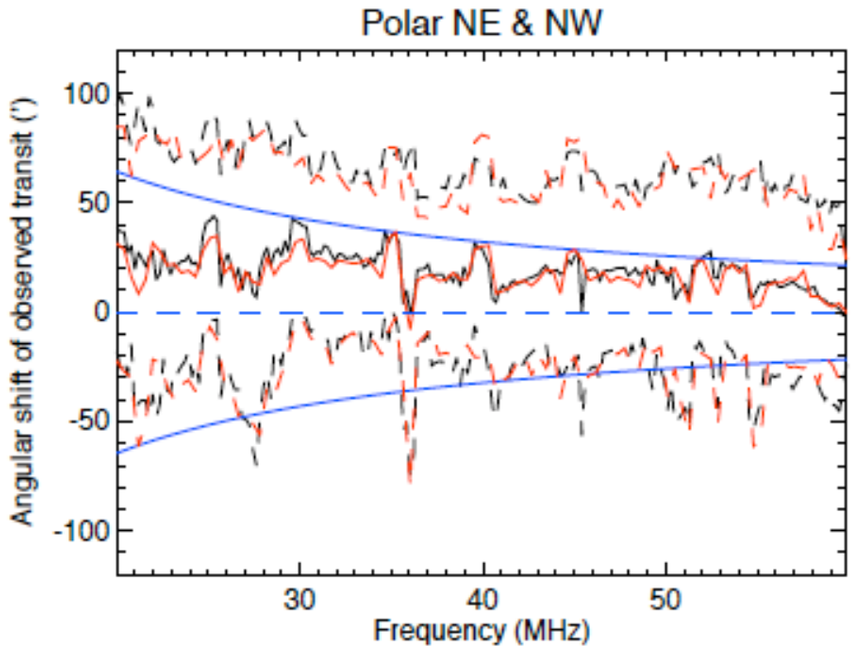

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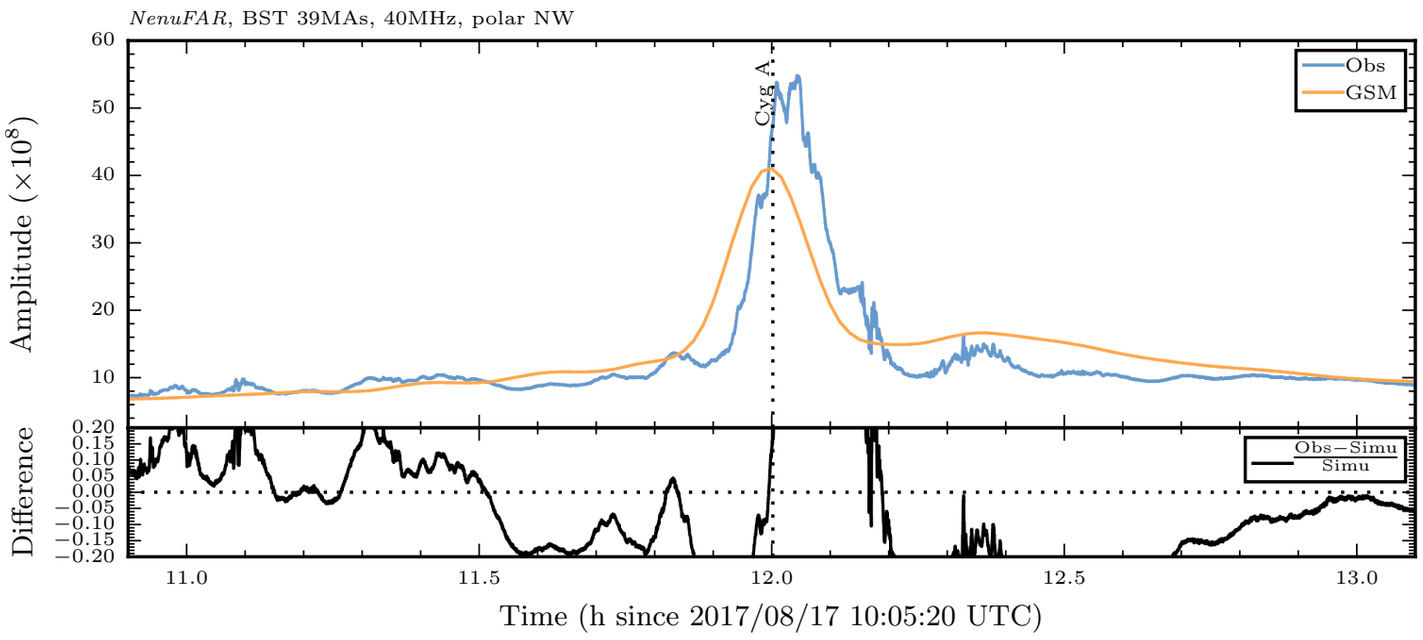

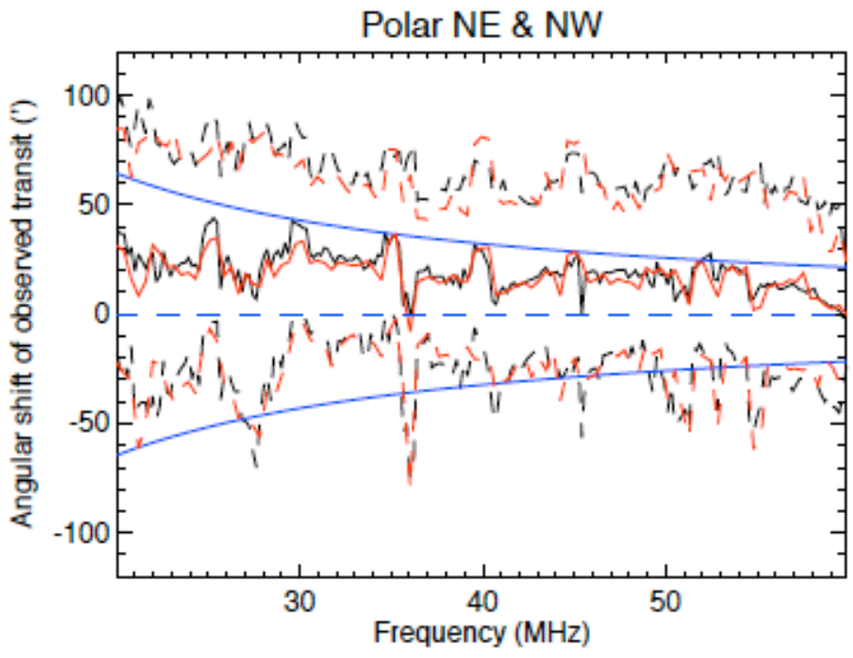

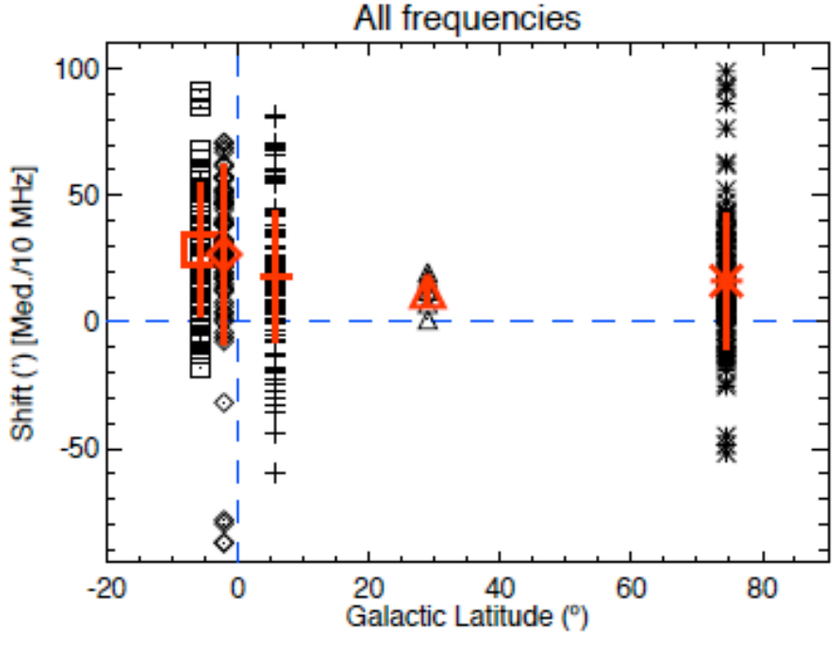

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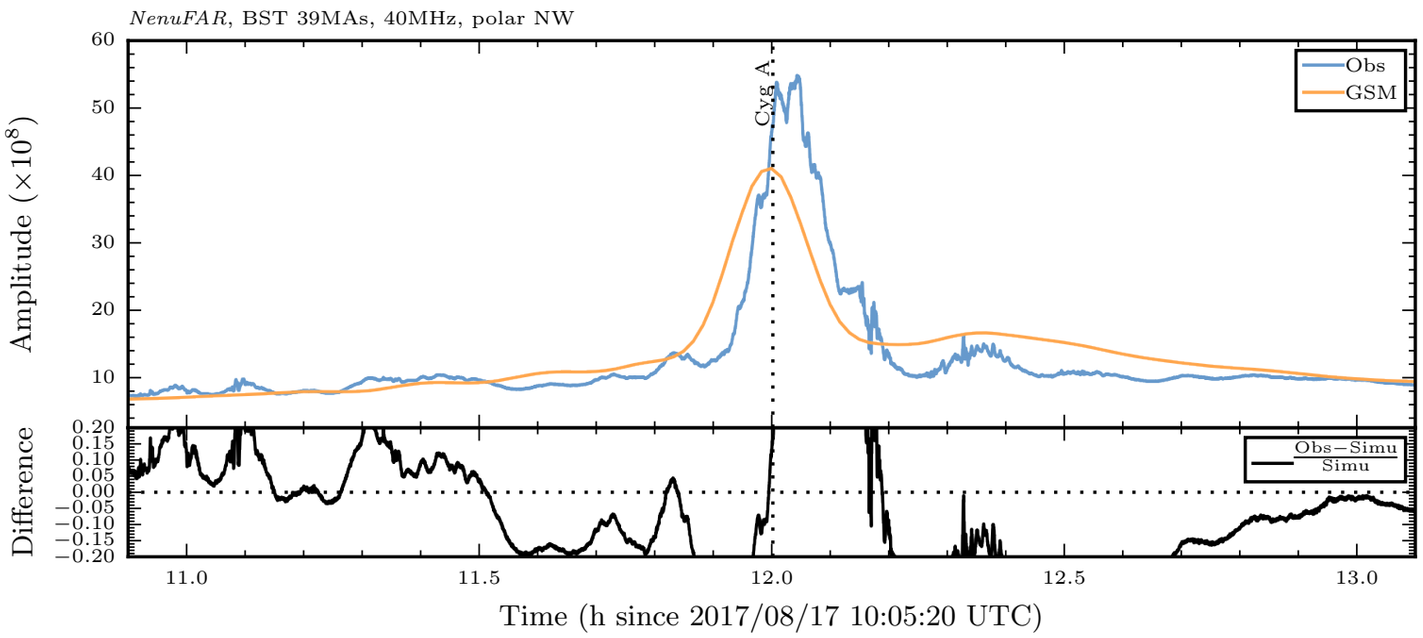

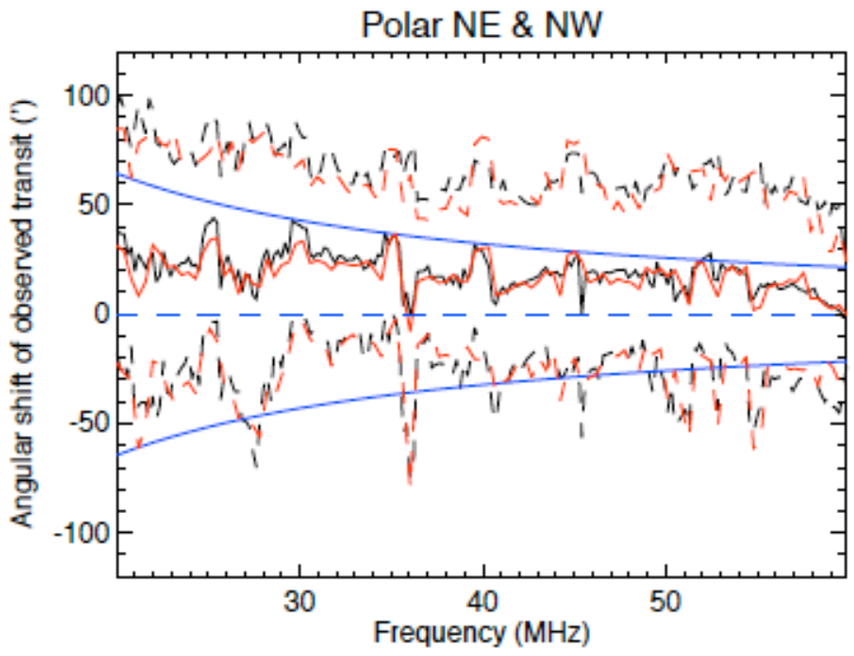

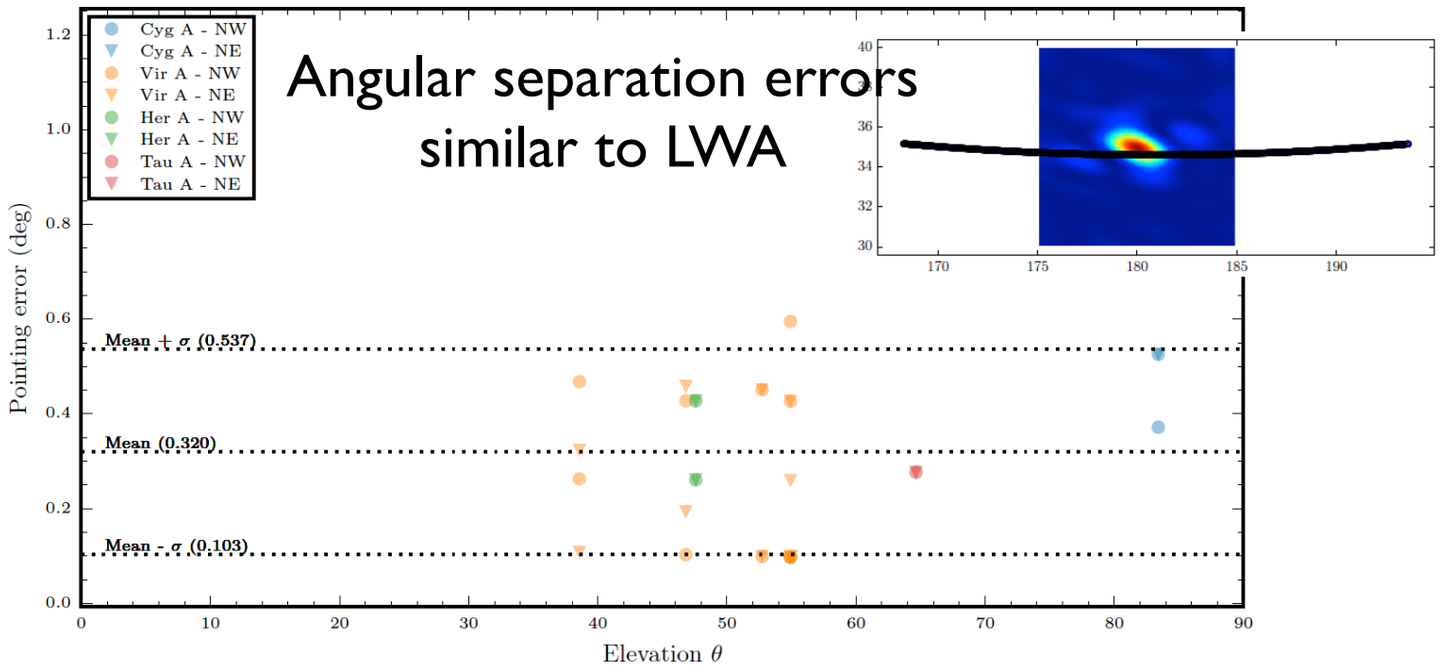

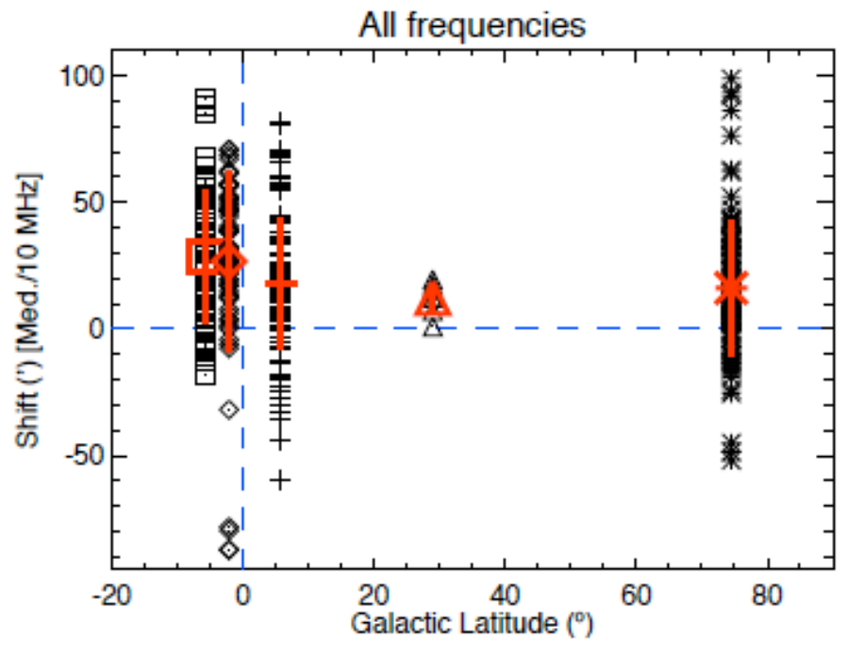

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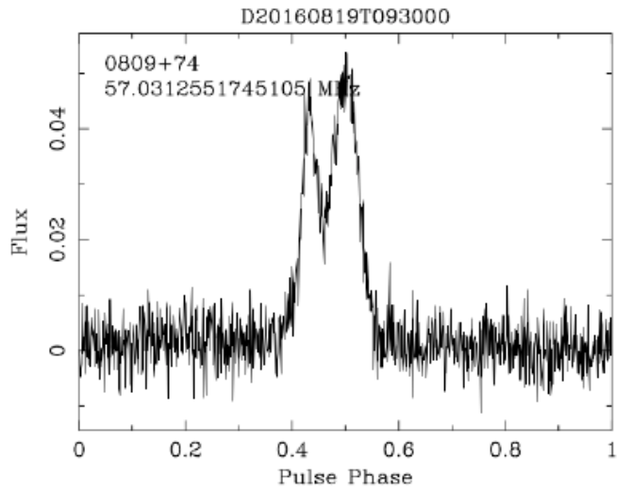
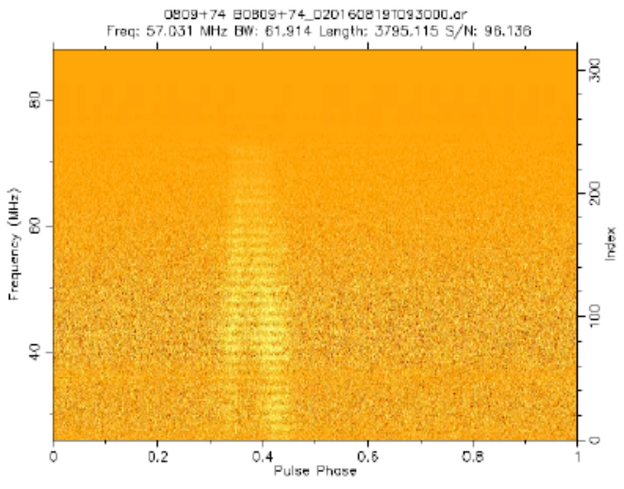
FR606 + 15 MR





Commissioning, Calibration

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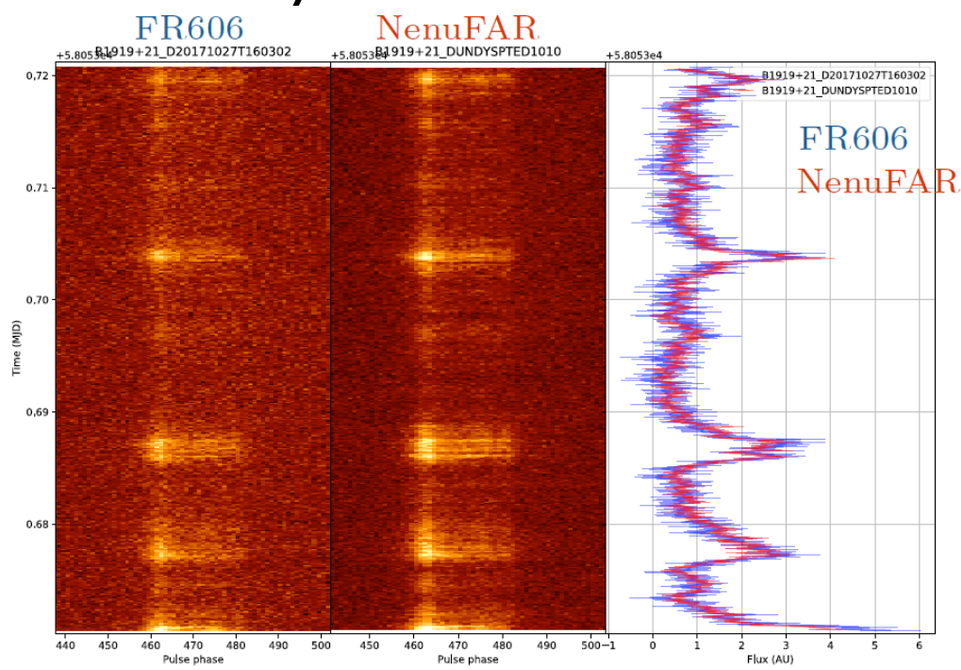
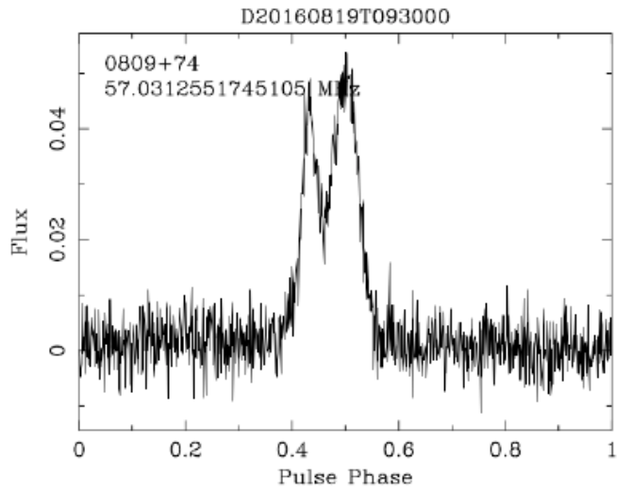
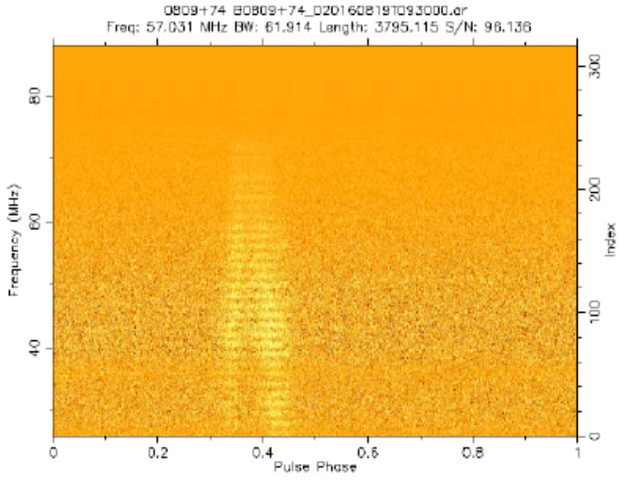
UnDySPuTeD + 41 MR



FR606 + 15 MR





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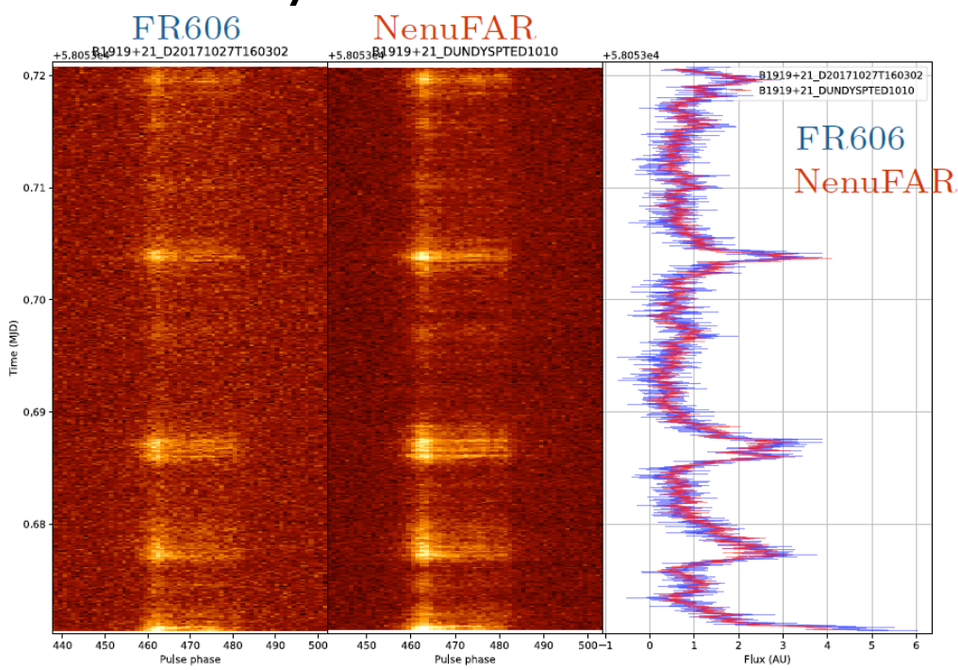

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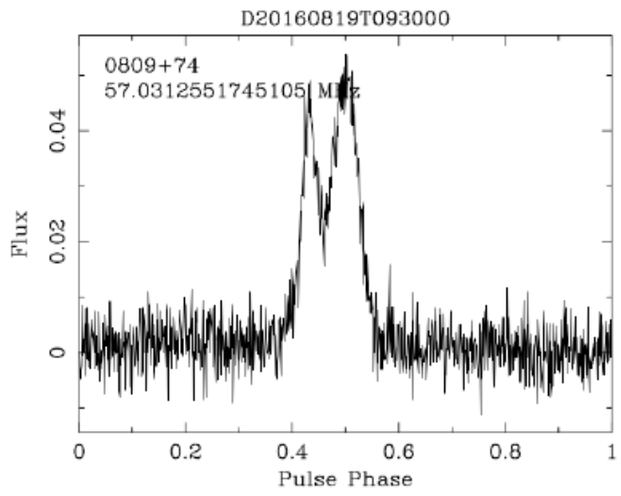
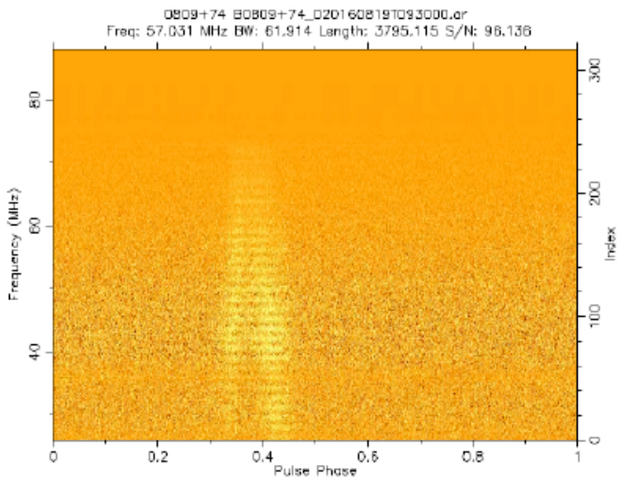
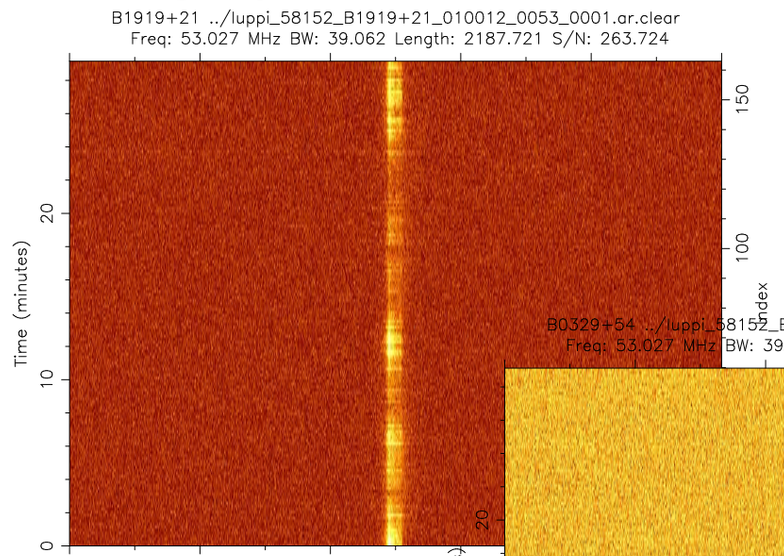
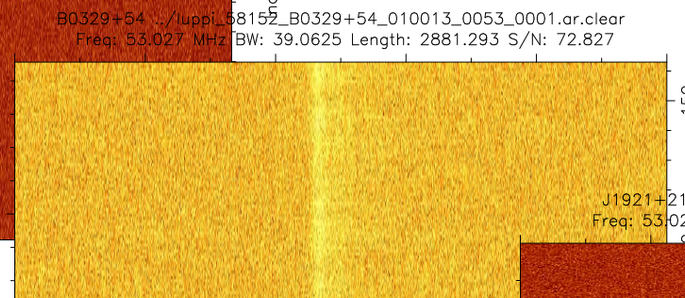
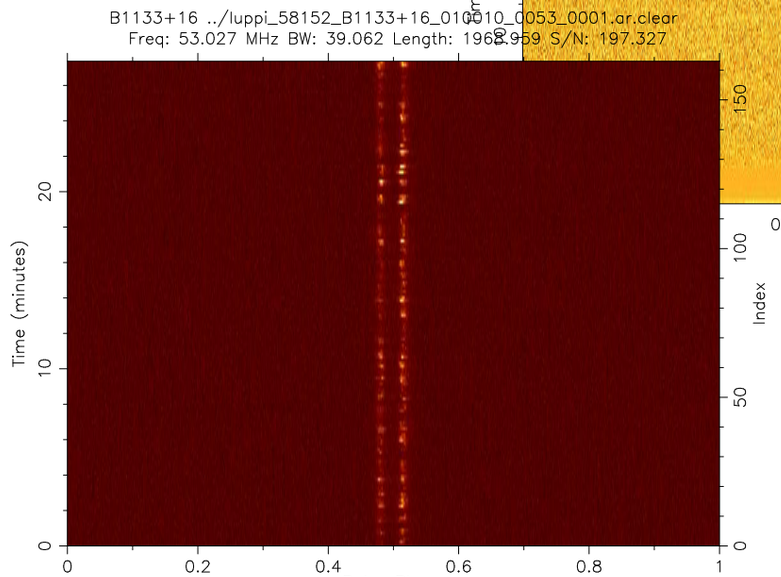


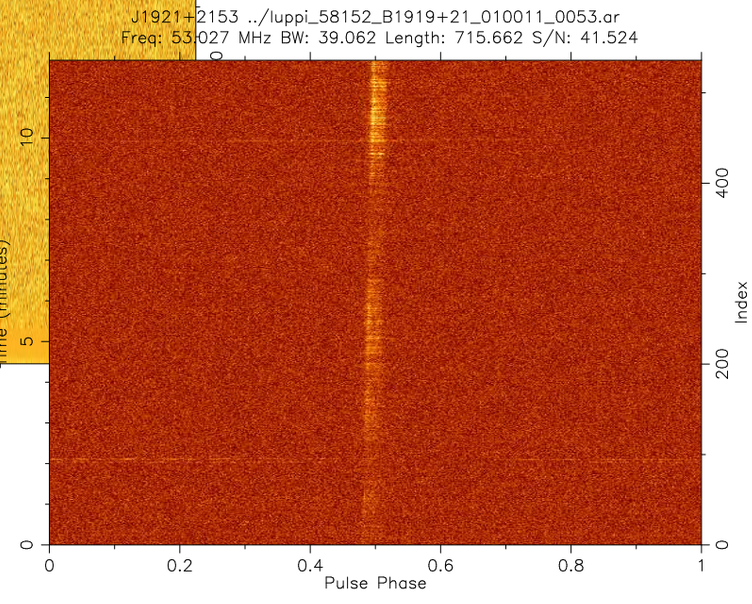


Single pulse detections



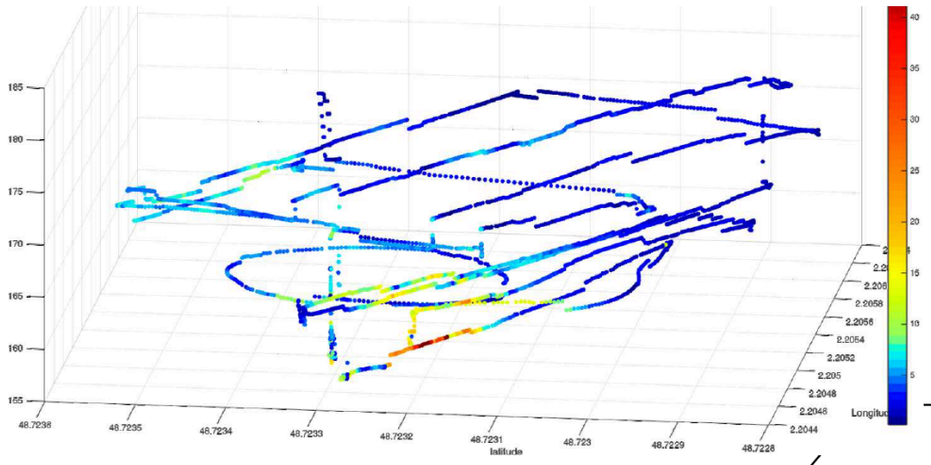


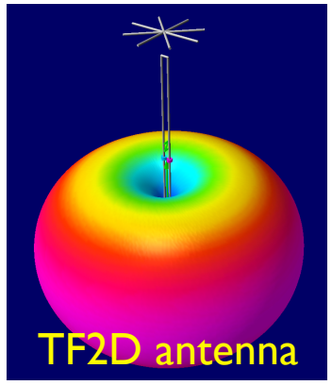




Commissioning, Calibration

- Quantifiying the sensitivity : Jovian & Solar bursts
- Instrument simulations + GSM
- Pointing Offset ~15' => tests, correction matrix
- Observations UnDySPuTeD
- Antenna / MA measurements from helicopter *(ongoing ...)*





- Measurements of antenna (far-field ≥10's m) and mini-array (far-field >500 m) patterns

Organization

- NenuFAR workshop & science case (2014) http://nenufar.sciencesconf.org/

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  - *Transients*
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- Cosmic Dawn/Dark Ages (LERMA, Kapteyn ...) https://indico.in2p3.fr/event/11207/overview

- GW counterparts (MoU LIGO-Virgo), VOevents
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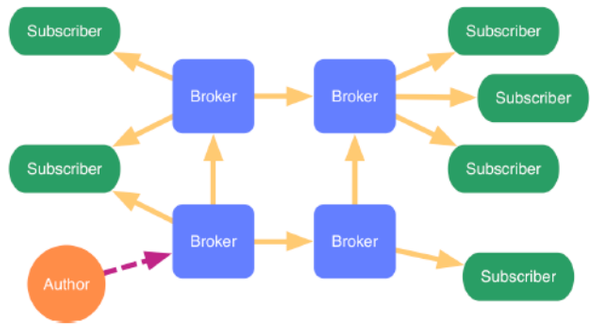

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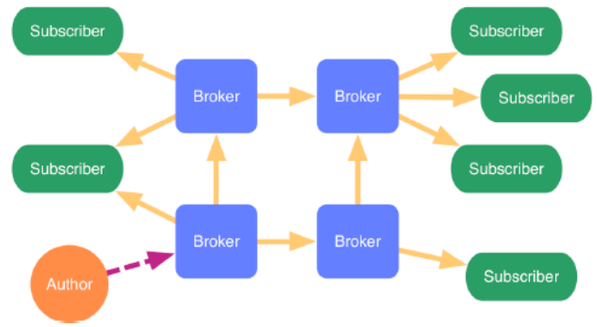


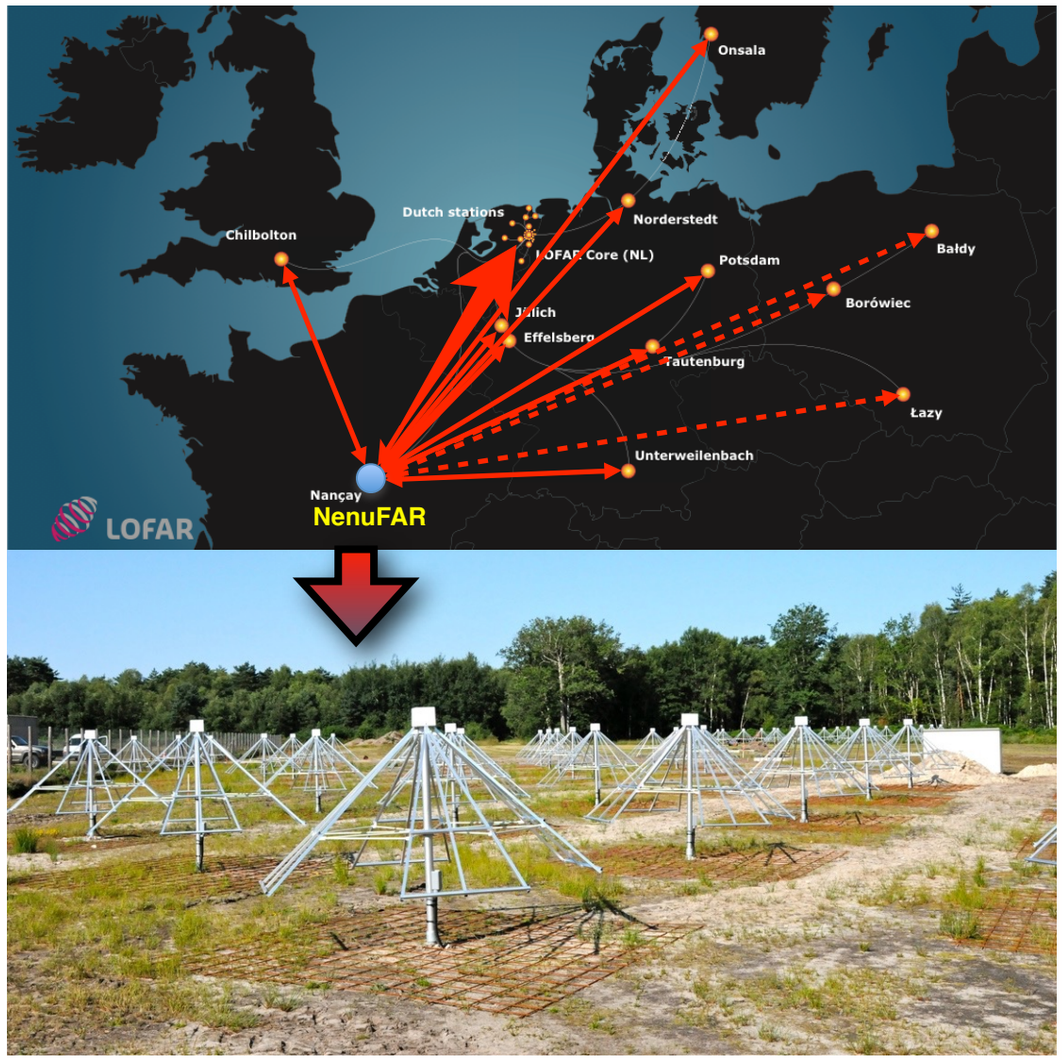
- SETI-Machine @ NenuFAR (MoU Obs. Paris / Breakthrough Listen SETI Lab. Berkeley)

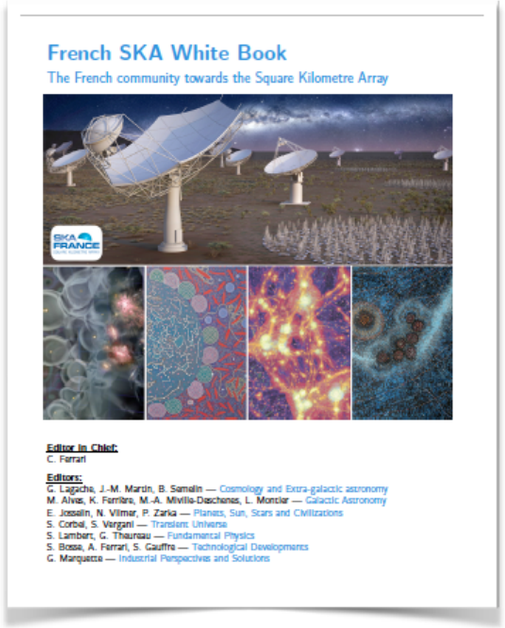
- Mou LOFAR-NenuFAR (FLOW/INSU - ILT): NenuFAR Operating modes & Data policy
  - NenuFAR/LSS mode via ILT (MoU)
  - NenuFAR/Standalone mode via FLOW PC

- NenuFAR workshop in 2018

Status

- SKA(-Low) pathfinder (2014)
- Synergy/complementarity with LOFAR (AARTFAAC), LWA, MWA, SKA, UTR-2
- Coordination with SKA-France activities (white book 2017)
- French "Research Infrastructure"
- Inauguration 2018-2019 (NRI 2020)





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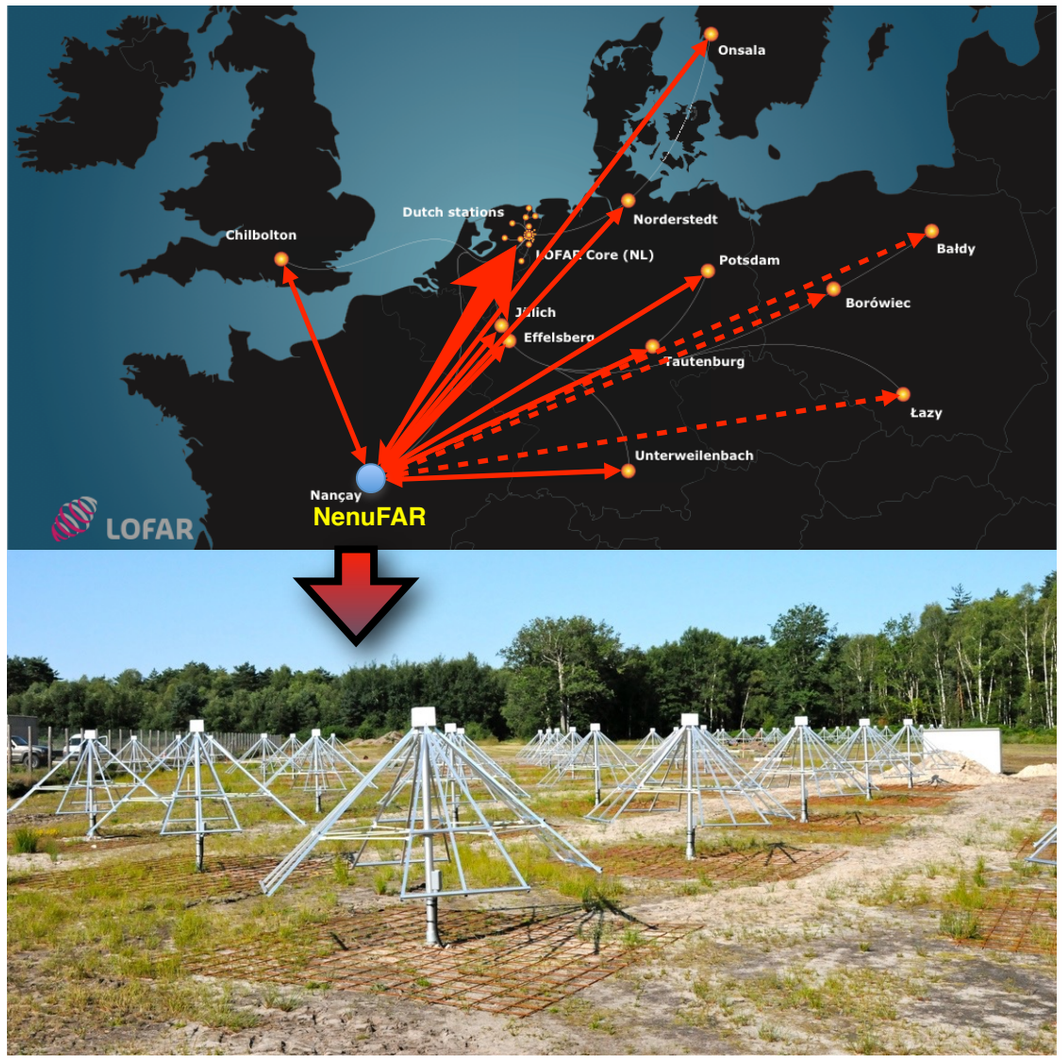

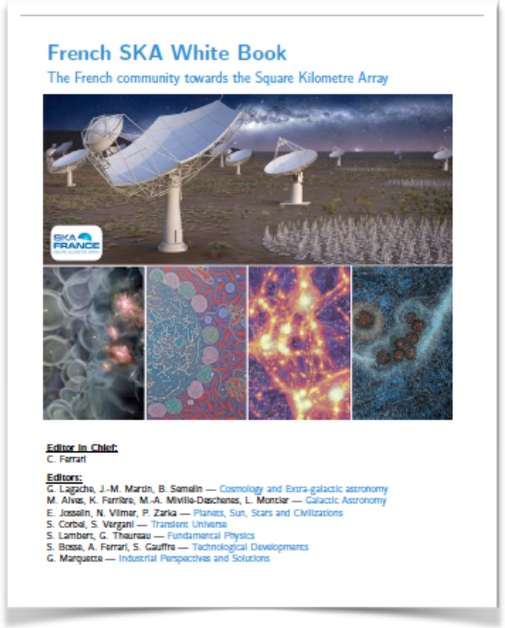

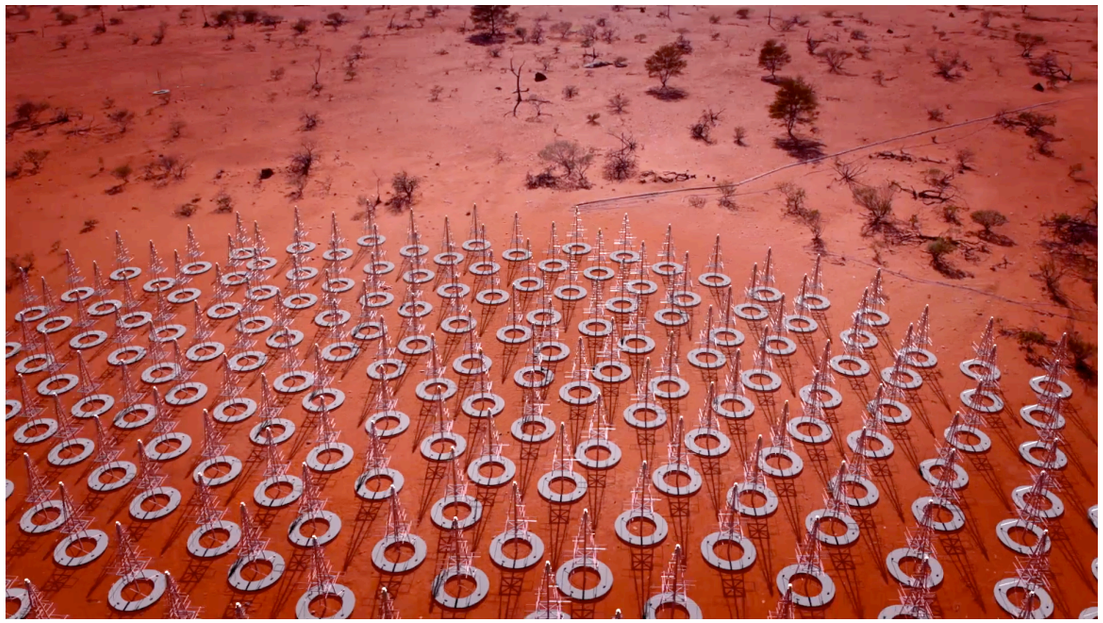

Site

- http://nenufar.obs-nancay.fr/
- https://twitter.com/SSL_Nancay
- https://www.skatelescope.org/precursors-pathfinders-design-studies/

Publications

Published / in press :

- Girard et al., *Antenna design and distribution of the LOFAR Super Station*, C.R. Phys. 13, « Les radiotélescopes du futur », p. 33-37, **2012**.
- Zarka et al., *LSS/NenuFAR: The LOFAR Super Station project in Nançay*, SF2A-2012: Proc. Annual meeting of the French Society of Astronomy and Astrophysics, Eds.: Boissier et al., pp.687-694, **2012**.
- Vasylieva et al., *Data Processing Pipeline for Decameter Pulsar/Transient Survey*, Odessa Astronomical Publications, vol. 26, p. 159, **2013**.
- Zakharenko et al., *Decameter Pulsars and Transients Survey of the Northern Sky. Status, First Results, Multiparametric Pipeline for Candidate Selection*, Odessa Astron. Pub., vol. 28, p. 252, **2015**.
- Zarka et al., *NenuFAR: Instrument Description and Science Case*, International Conference on Antenna Theory and Techniques (ICATT), Kharkiv, Ukraine, pp. 13-18, 4/**2015**.
- *SKA book, 2015* (Hoare et al., Zarka et al., Koopmans et al., Semelin & Iliev, ...), Proc. AASKA14. Giardini Naxos, Italy. Online at http://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215, id.115, **2015**.
- Turner, J.D., J.–M. Grießmeier, P. Zarka, and I. Vasylieva, *The search for radio emission from exoplanets using LOFAR low-frequency beam-formed observations: Data pipeline and preliminary results for the 55 Cnc system*, in Planetary Radio Emissions VIII, edited by G. Fischer, G. Mann, M. Panchenko, and P. Zarka, Austrian Acad. Sci. Press, Vienna, 301–313, **2017**.
- Zarka & Mottez, *Observations of Fast Radio Bursts and perspectives at low frequencies*, Proc. SF2A-2016, Eds.: Cambrésy et al., 343-347, **2016**.
- Zyma et al., *Formulating and solving a radio astronomy antenna connection problem as a generalized cable-trench problem: an empirical study*, Int. Trans Op. Res., 1-15, **2016**.

Submitted / in preparation :

- Tasse et al., Faceting for direction-dependent spectral deconvolution, A&A, submitted, **2017.**
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