Clusters of galaxies and AGNs NenuFAR Survey (CANS)- Key science project in Imaging mode

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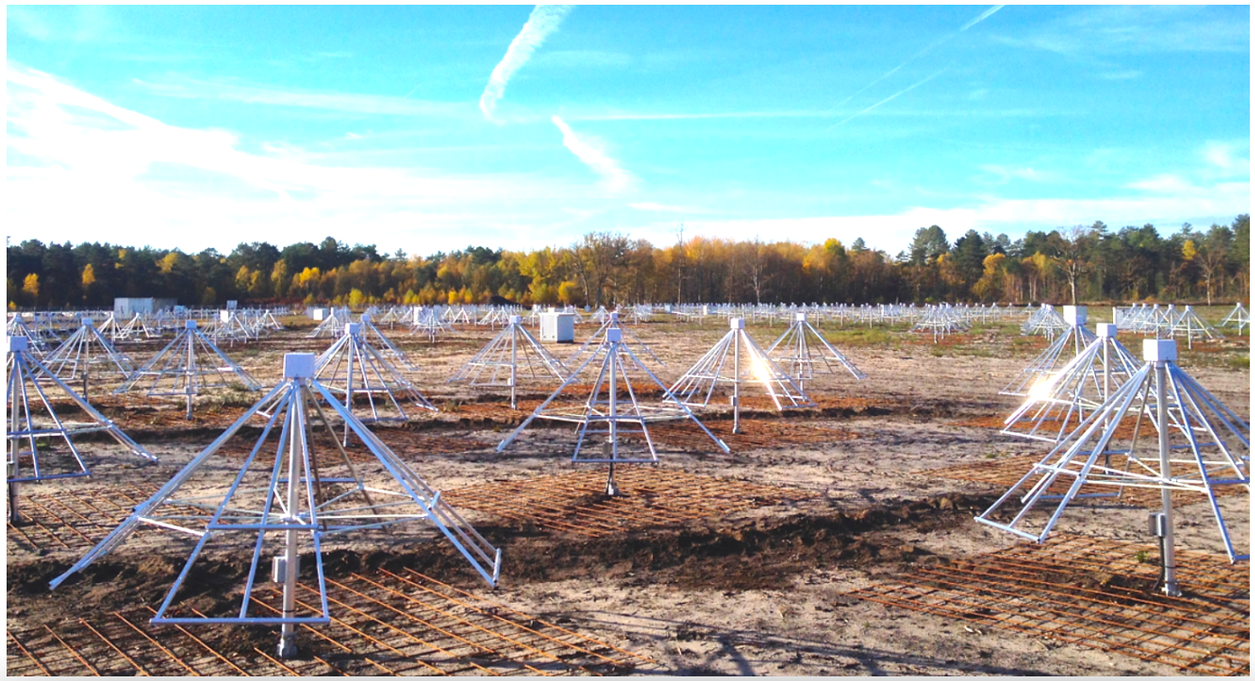
Plan

1. NenuFAR modes of operation
2. Clusters of galaxies and AGNs - Large scale structures in the Universe
3. LOFAR MSSS survey results and NenuFAR
4. Clusters of galaxies with NenuFAR in stand-alone imaging mode
5. AGNs with NenuFAR in stand-alone imaging mode
6. Faint galaxies with NenuFAR-LOFAR (International Long Baseline) combined mode observations
7. On-going Commissioning observations on radio galaxies with NenuFAR in Imaging mode
8. Conclusion

NenuFAR- French SKA-Low Pathfinder

Zarka et al. 2014

	NenuFAR system parameters		
Operation modes	Standalone Beam former	Standalone Interferometer Imaging mode	LOFAR International baselines + NenuFAR (high resolution)
Frequency	10-85 MHz	10-85 MHz	10-85 MHz
Mini-Array (MA)	96 (with 19 antenna per MA, dual polar)		
FoV	32° - 8°		
Array size	400m -3 km	400m -3 km	Long baseline 2000 km
Angular Resolution	2°- 0.5°	17'-4'	1 "
Sensitivity	2 – 0.5 Jy (5σ, 1 sec)	10 – 2 mJy (5σ, 6 hrs)	microJy level
Confusion at zenith	50 – 1 Jy (unpolarized, compact core)	1000 – 20 mJy (unpolarized, with distant MA)	



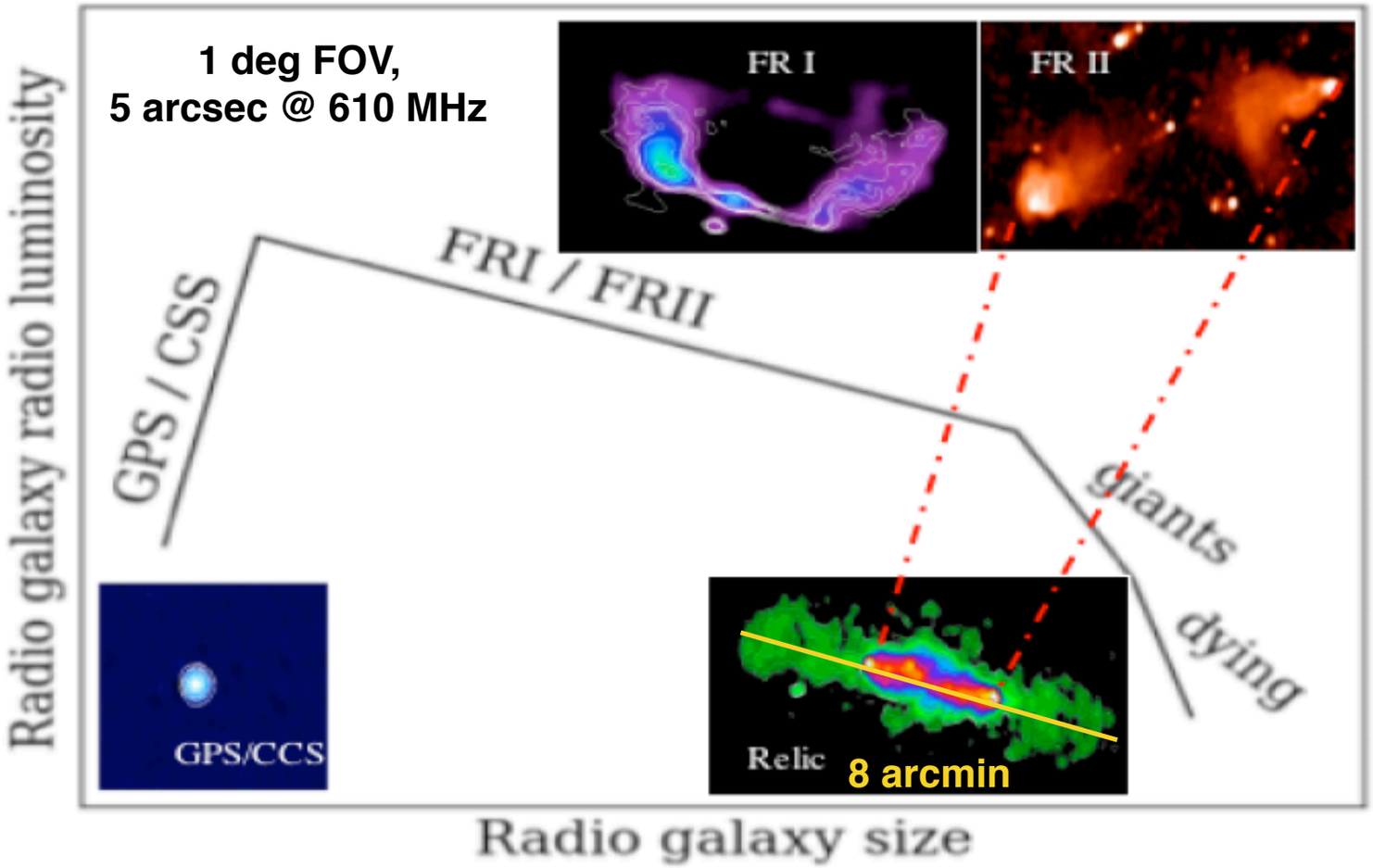
More sensitive than the LOFAR core in beam former mode

Best suited for high sensitivity imaging at low frequencies in order to detect arc-min scale diffuse emission from extragalactic objects

Large-scale structures in the Universe- Galaxy clusters and AGNs Pommier et al. 2014 (NenuFAR white book)

- Non-thermal emission from extragalactic objects (like radio galaxies and clusters of galaxies) dominate the low frequency sky.

- Observations at MHz range- the life cycle of radio galaxies (from youngest compact objects to giant radio galaxies with relic emission at their decay phase and the origin of non-thermal diffuse emission in the form of relic, mini-halos and halos from galaxy clusters.



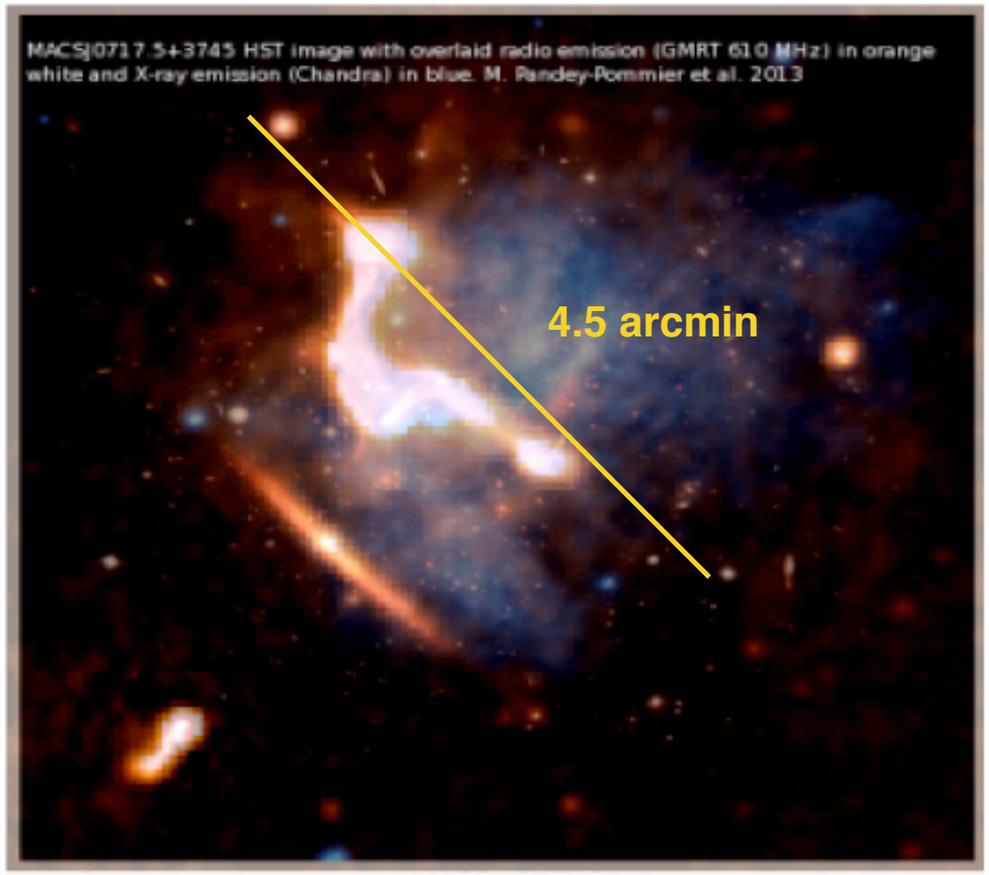


Figure 1. (*Panel I*) A schematic view of different stages (few kpc to Mpc-scale) of a radio galaxy life cycle. (*Panel II*) Galaxies in clusters with central Mpc-scale halo emission from GMRT (orange, refer observation parameters listed in table 1) overlaid on Chandra X-ray emission (blue) and HST optical emission (black-white) extracted from Pandey-Pommier et al. 2013.

LOFAR MSSS survey (Galaxy clusters and AGNs) & NenuFAR
Pommier et al. 2014 (NenuFAR white book)

-LOFAR MSSS (Multi Source Sky Survey at **2 arcmin resolution in roughly 1.5hrs on LBA fields and 14mins on HBA fields** discovered diffused Mpc-scale jet structure in giant radio galaxy UGC 9555 and diffuse radio halo in Abell 2256 clusters of galaxies

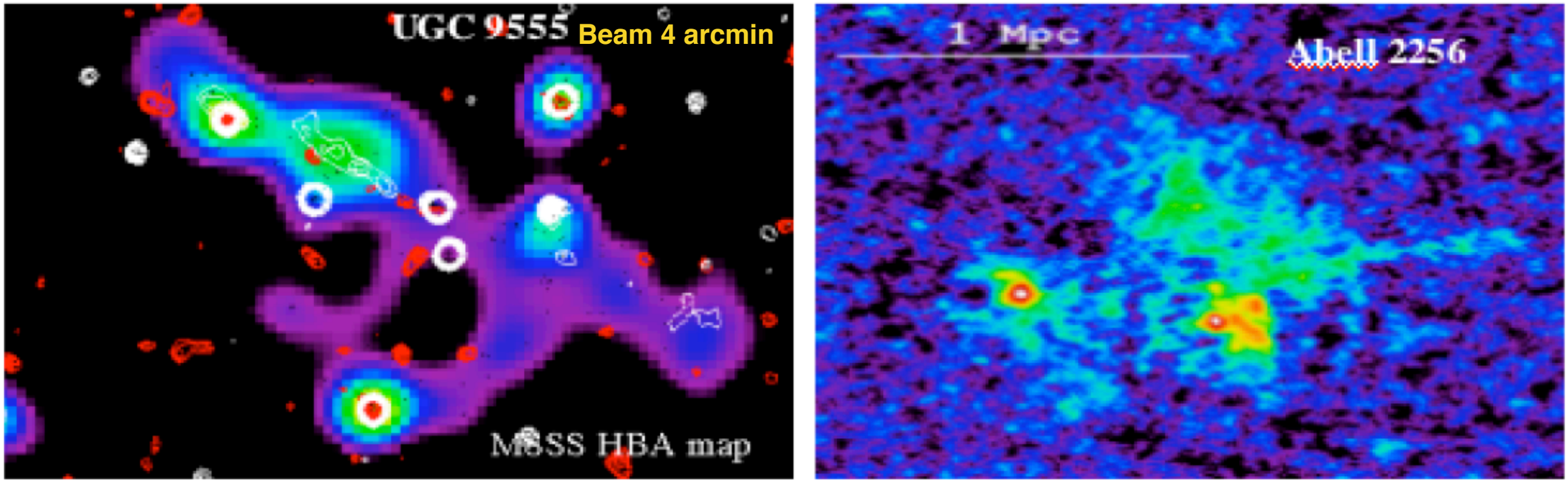


Figure 2. (*Panel 1*) Giant radio galaxy UGC 9555 discovered in MSSS data. (*Panel 2*) Abell 2256 halo emission imaged in LOFAR LBA and MSSS data (extracted from Pandey-Pommier et al. 2014, Heald et al. 2013, van Weeren et al. 2012)

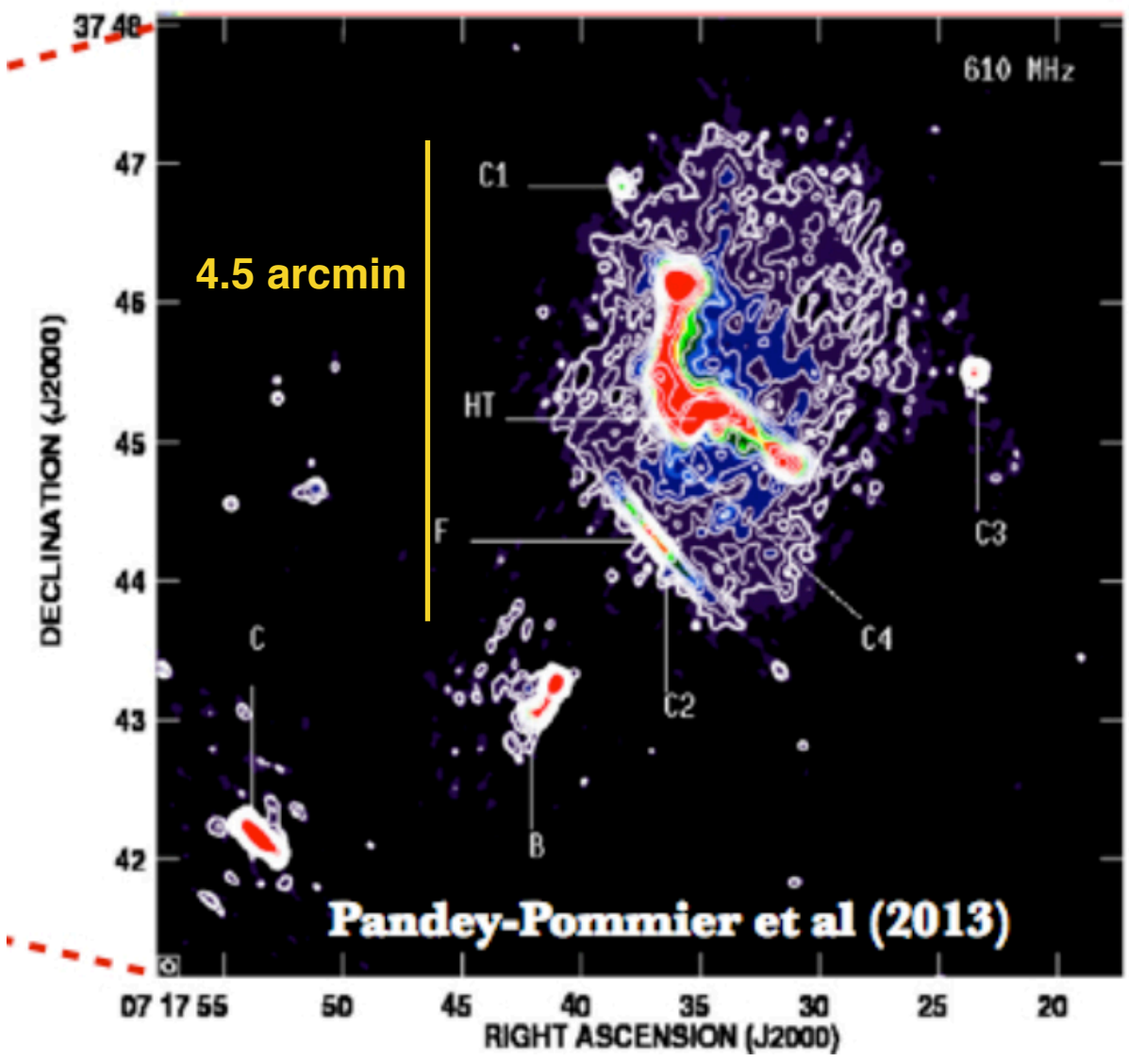
NenuFAR can play a significant role in the study of bright non-thermal (> 10 mJy) emission from the large-scale structures in the Universe as it offers wide field imaging (10s of deg. FOV) in stand-alone mode with 4 arcmin-scale resolution and above.

- discover extended diffuse emission in such extragalactic objects.
- study the MHz range emission from AGNs and clusters (with flux density > few 10s of mJy) to derive their spectral information (flat, steep) via wide frequency coverage offered with NenuFAR in standalone imager mode.
- multi-wavelength data (radio data at GHz-range, X-ray, Gamma-ray, optical, IR) allows us to identify their redshift, correlation between radio power at MHz-range and high energy luminosity over cosmic time scale

NenuFAR (Stand alone mode)- Galaxy clusters and AGNs Science case

Pommier et al. 2013, A&A

Galaxy clusters host a variety of diffuse and extended (arcmin-scale) radio sources: tailed radio galaxies (Feretti & Venturi 2002); radio bubbles (de Gasperin et al. 2012); diffuse giant radio sources, "halos" and "relics" (Pommier et al. 2013,2014.2015).



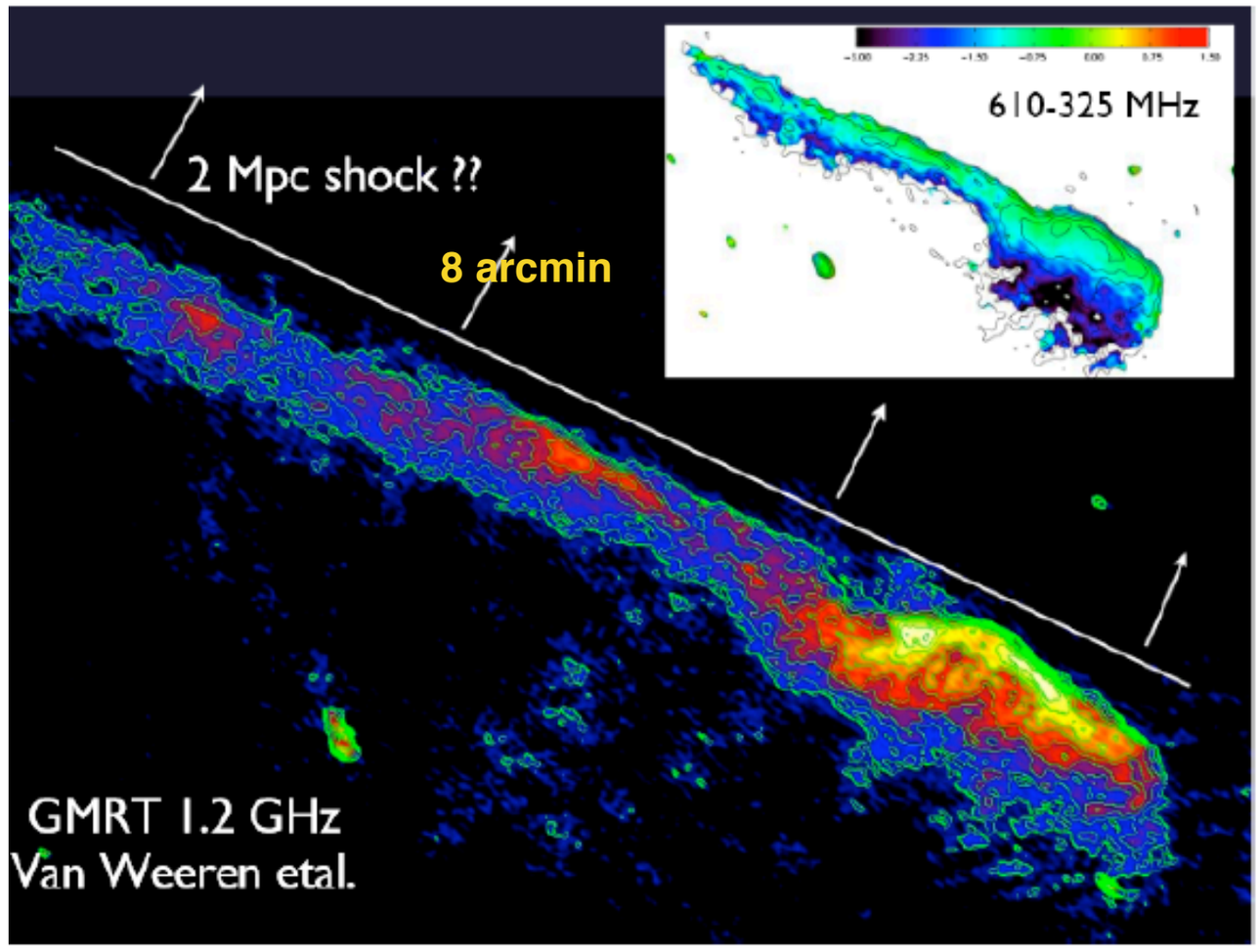


Figure 3- Observation on galaxy clusters show diffuse halo (left) and shocked relic (right) regions. Spectral index map shows aging plasma

NenuFAR (Stand alone mode)- Galaxy clusters and AGNs Science case

Combes …Pommier et al. 2014, NenuFAR White Book

AGNs- survey at z=0 and at low frequencies to study radio jets in Giant Radio Galaxies, FR1/FR11 radio galaxies, lobes and relics to understand the evolution of radio emitting plasma at lower frequencies

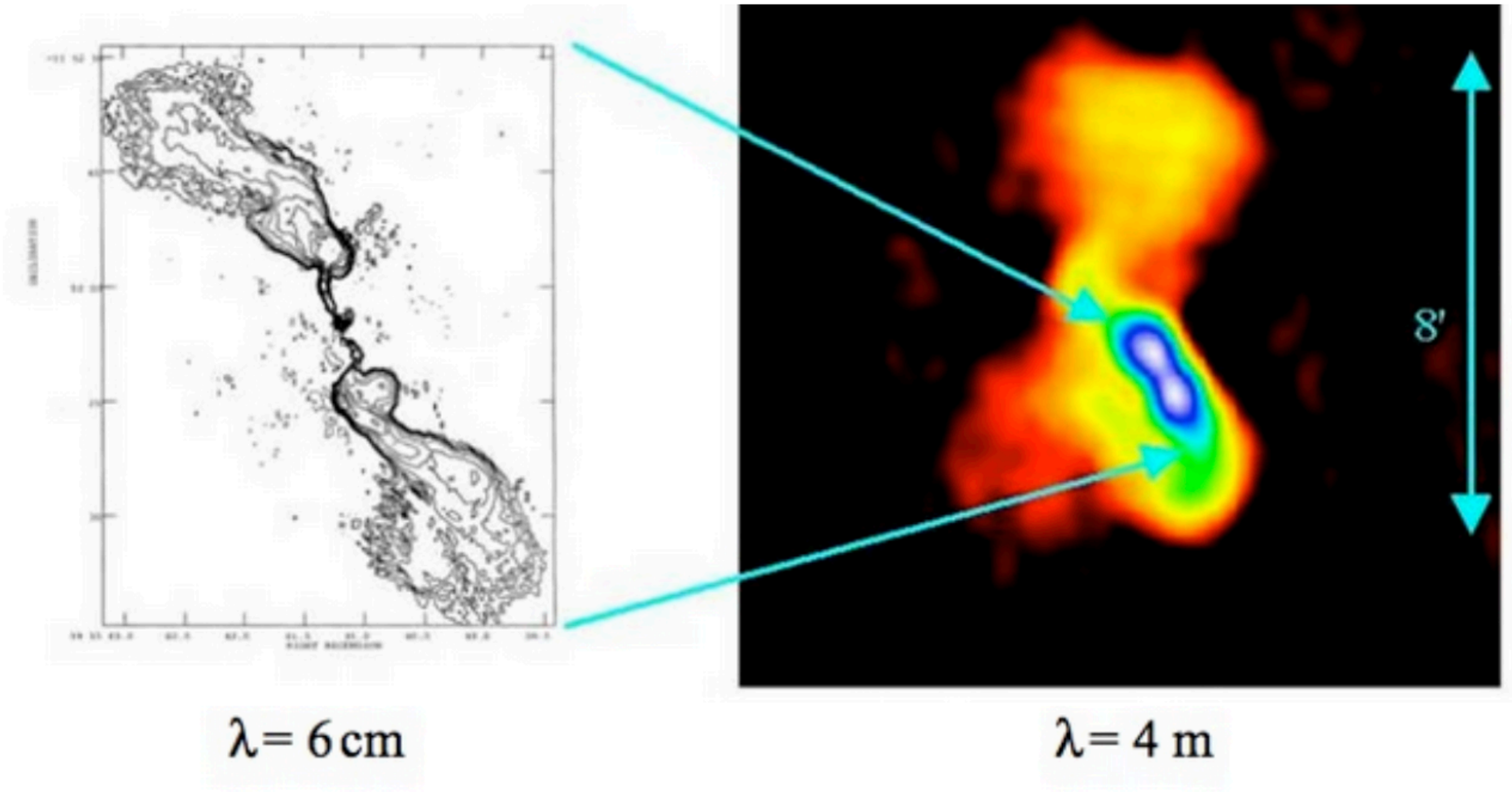


Figure 4 Hydra-A, at 74MHz (λ=4m), compared to at 5GHz (λ=6cm), from Lane et al. (2004). The observations have been done with the VLA, with 20'' resolution. At low frequency, the source appears much more complex and extended, over about 8' (530 kpc) in a north-south direction. The spectral slope is steeper in the South, where the source appears more confined. Aging of relativistic jets with time steepens their spectral slope.

NenuFAR (+LOFAR long baseline mode)- Galaxy clusters and AGNs Science case

Pommier et al. 2018 LOFAR LB busy week report

NenuFAR+LOFAR:

-combined LOFAR and NenuFAR array, it will be possible to achieve sub-arcsec scale resolution < 80 MHz at MHz-range, comparable to GMRT/VLA at 1.4 GHz, but better in sensitivity (mJy-level).

-NenuFAR data in combined mode and at arcsec scale resolution will not only help us to identify the source morphology and detect more diffuse emission due twice more sensitive at short baselines than the LOFAR core, but will also provide highly sensitive long baselines to detect faint objects.

-possible to study fainter AGNs population, SF galaxies, lensed galaxies

Faint (mJy-level) source at 150 MHz with LOFAR long baselines using FR606

Long Baseline pipeline is compatible at LBA frequencies !

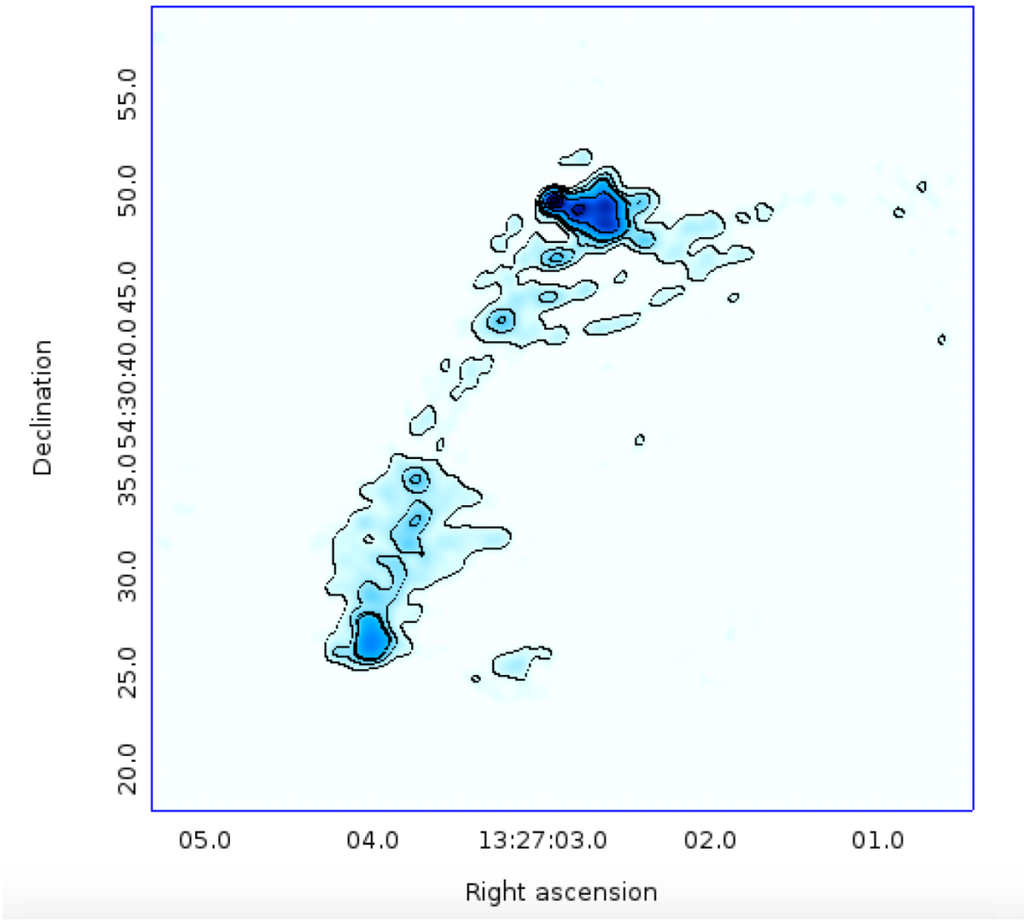
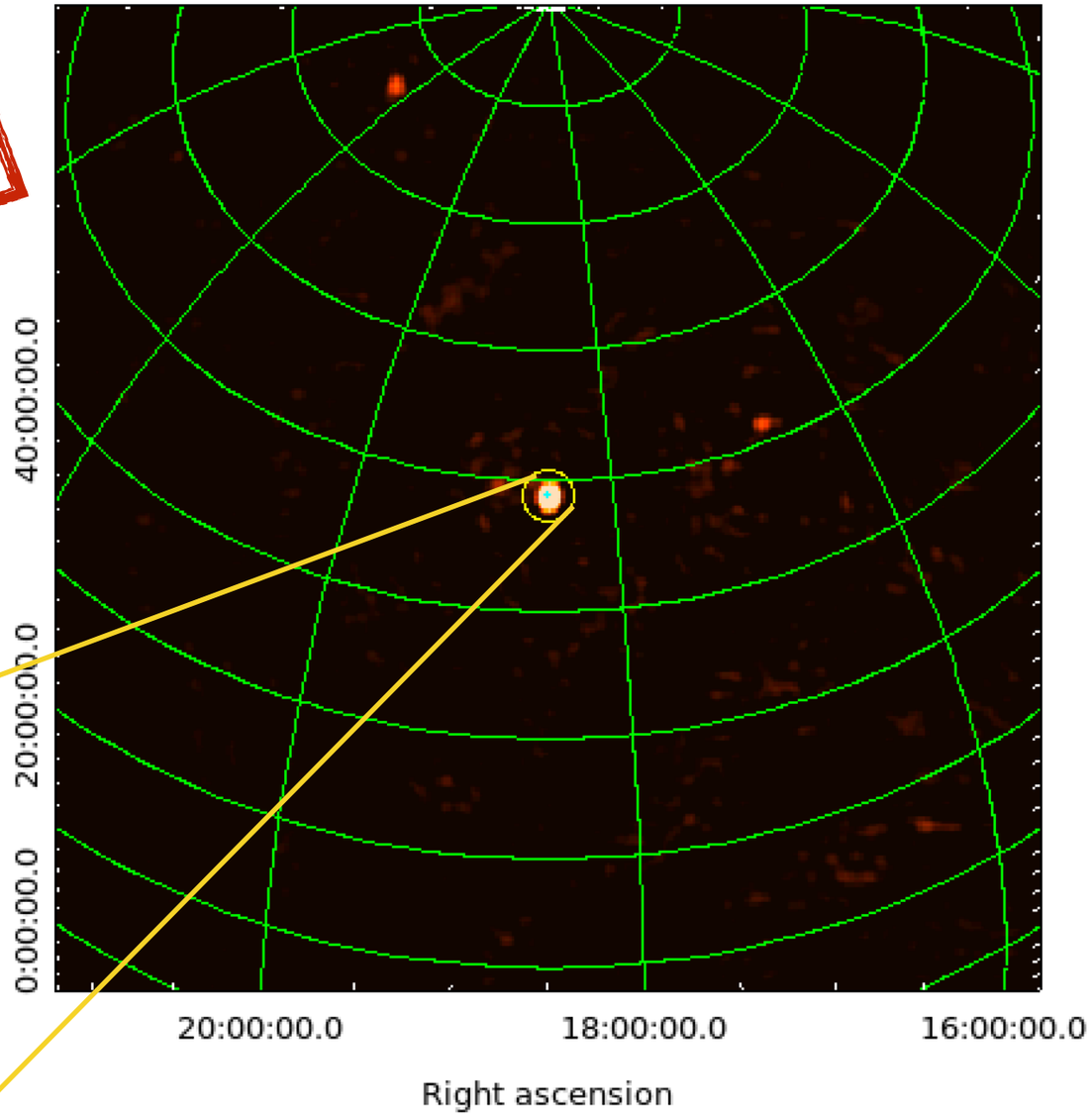


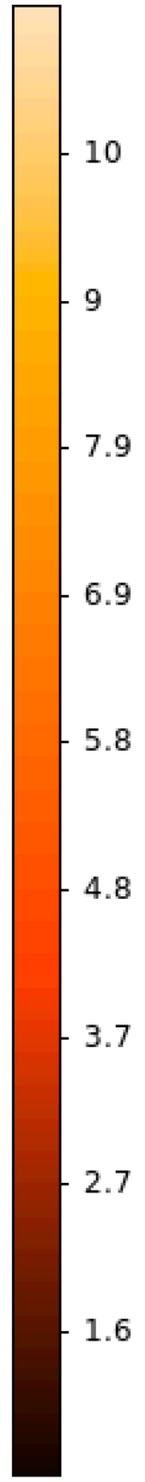
Figure 5 *FRII Radio galaxy 1327+5430 of size 23 arcsec imaged with LOFAR long baseline (rms 100.5 microJy, resolution 0.3 arcsec) in at 150 MHz*

3C380

3C380 field imaged with NenuFAR at 50 MHz yellow circle marks the position of 3C380

Multiple sources detected in the NenuFAR data with faint field sources. Results are promising but resolution is coarse and noise is high!





VLA 1.4 GHz

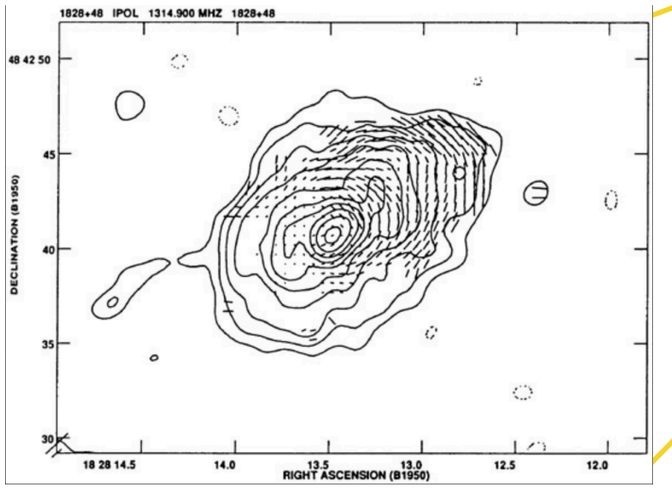


Figure 7- Observation on 3C380 (LOFAR Calibrator and a radio galaxy at z=0.69) in the center at 0.7 Jy/beam rms noise and 1 degrees resolution @ 50 MHz

3C380

Detection of the target source is not enough !

Multiple field sources flux contribution along with the central target source - limitation in resolution !

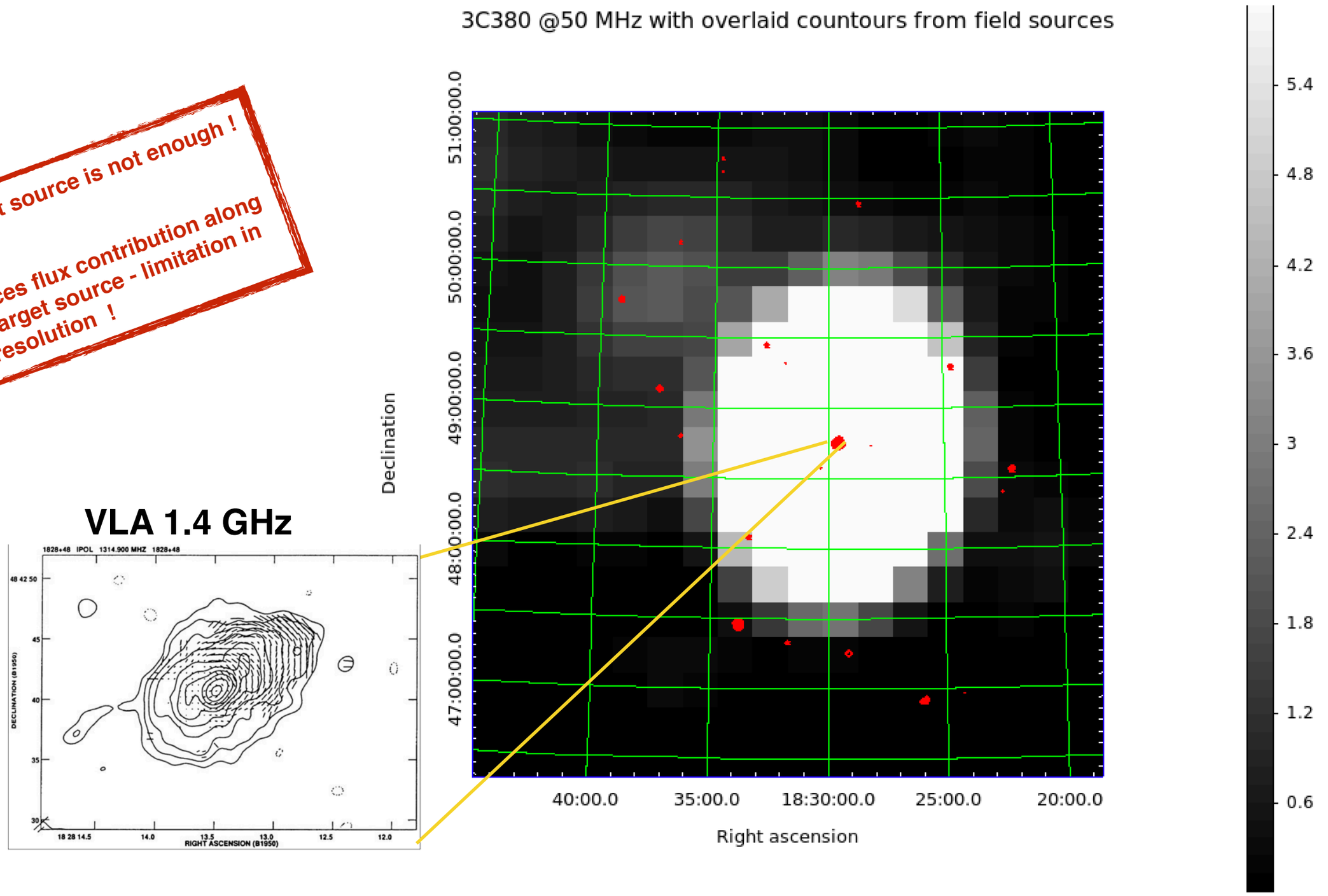
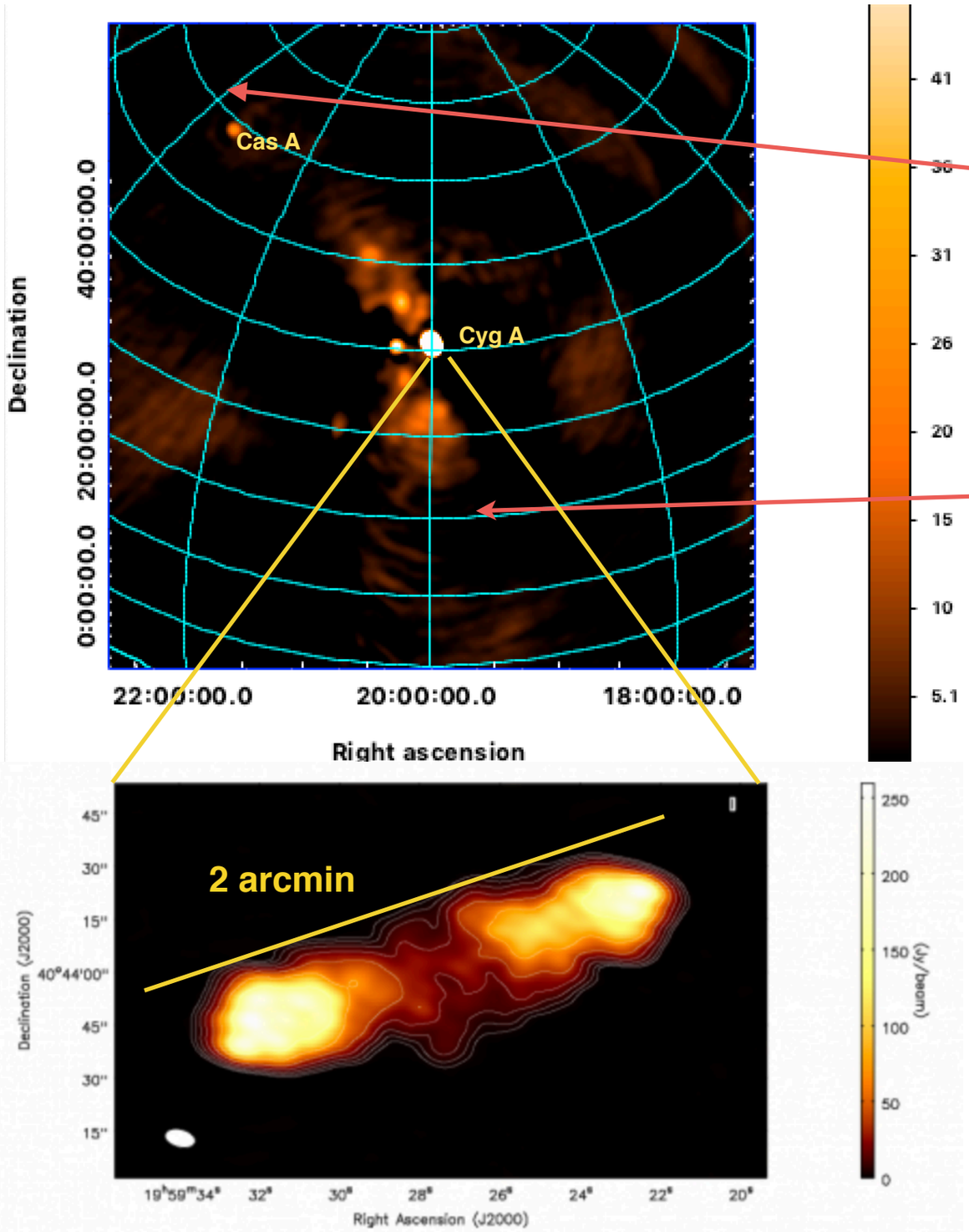
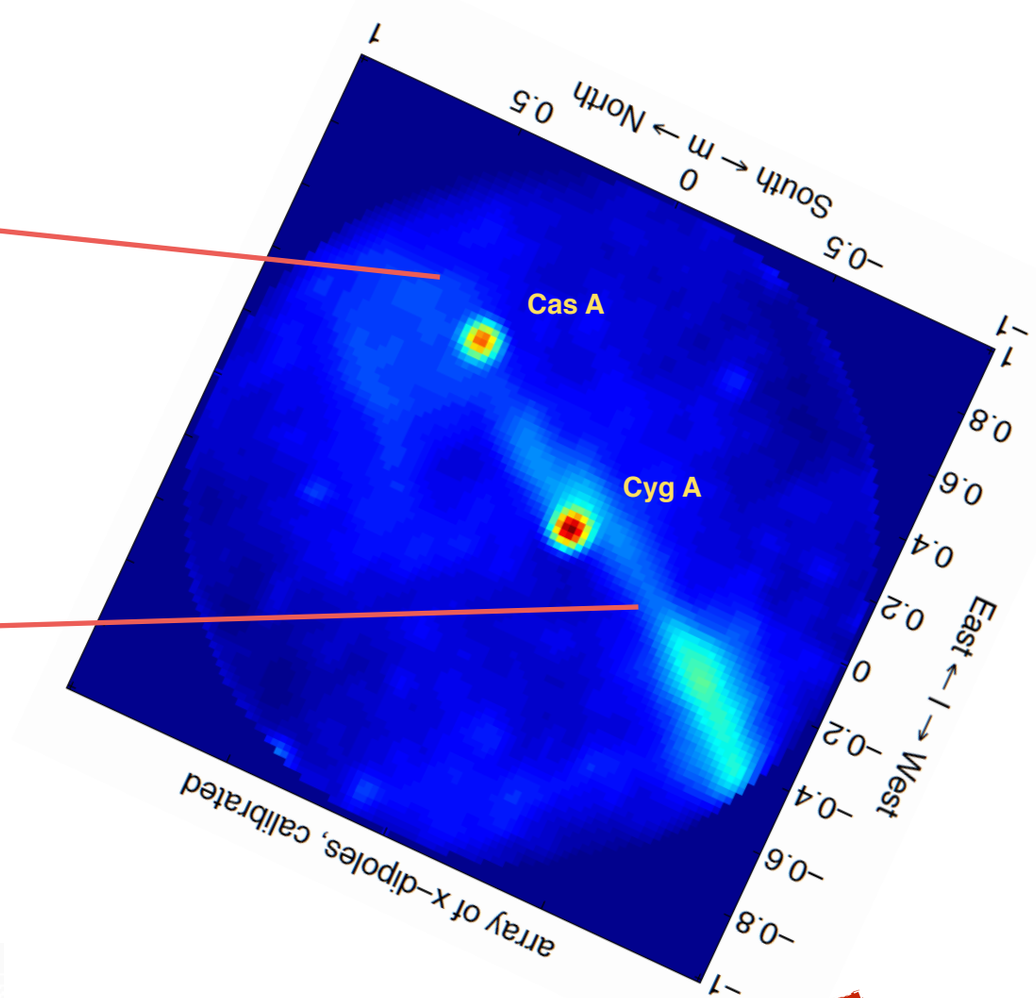


Figure 7- Observation on 3C380 (LOFAR Calibrator and a radio galaxy at z=0.69) in the center at 0.7 Jy/beam rms noise and 1 degrees resolution @ 50 MHz

Cyg A





Multiple sources detected with diffuse emission but limited in resolution !

Figure 6- Observation on Cyg A (A-Team source and a FRII type radio galaxy at z=0.056) in the center with **diffuse extended emission of 36 degrees from the Galactic plane** at 1.7 Jy/beam rms noise and 1 degrees resolution@ 45 MHz

NenuFAR- commissioning results on **extended galactic sources** (SNR)
Pommier et al. 2018 NenuFAR commissioning report

Cas A

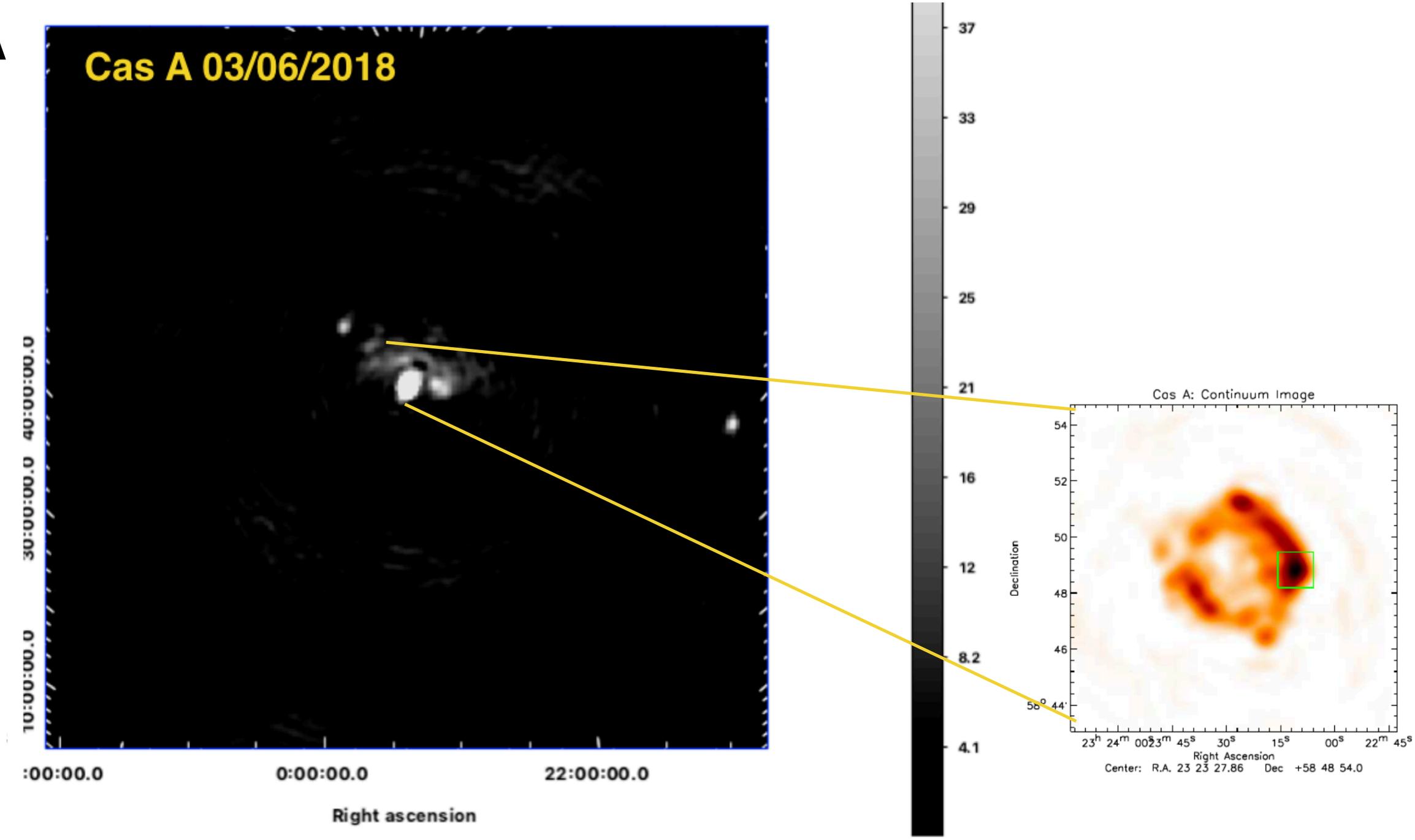


Figure 8- Observation on Cas A (A-Team source and a SNR) in the center (left) at 3.2 Jy/beam rms noise and 1.5 degrees resolution. Right panel- Cas A image at 52 MHz at 40 arcsec resolution with LOFAR (Asgekar et al. 2013)

Conclusion

1- Direction dependent Self-calibrated images are regularly being produced on radio galaxies (A-Team sources, LOFAR Calibrators) with NenuFAR in the current imaging mode with 56 Mini Arrays, 1 degrees resolution@50 MHz, 0.7 Jy/beam rms noise level (M. Pommier et al. 2018, 2019). **Images are limited in resolution and sensitivity but results are promising !**

2- Need careful analysis of the image and the field sources to do science

3- A NenuFAR commissioning survey on faint radio galaxies (few 10-100 Jy) is being carried out to show the imaging capability of the NenuFAR array (M. Pommier, L. Denis, P. Zarka)

4- With the **NenuFAR complete array in the imaging mode**, at 80 MHz with 4 arcmin resolution and a noise level of a few 10s of mJy/beam, we will be able to better resolve the structure of diffuse emission in AGNs and clusters of galaxies and do interesting science

5- ***Clusters of galaxies and AGNs NenuFAR Survey (CANS)*** KSP proposes to carry out the first ever study at low frequencies < 80 MHz of the spectral properties of bright diffuse emission (aging plasma, shocked regions, jets, lobes) in extragalactic objects.