High-resolution low-frequency probes of X-ray emitting knots in blazar jets

Clues on High-Energy Emission from Low-Frequency Radio Observations

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Etienne Bonnassieux , Matthias Kadler, Marcus Brüggen

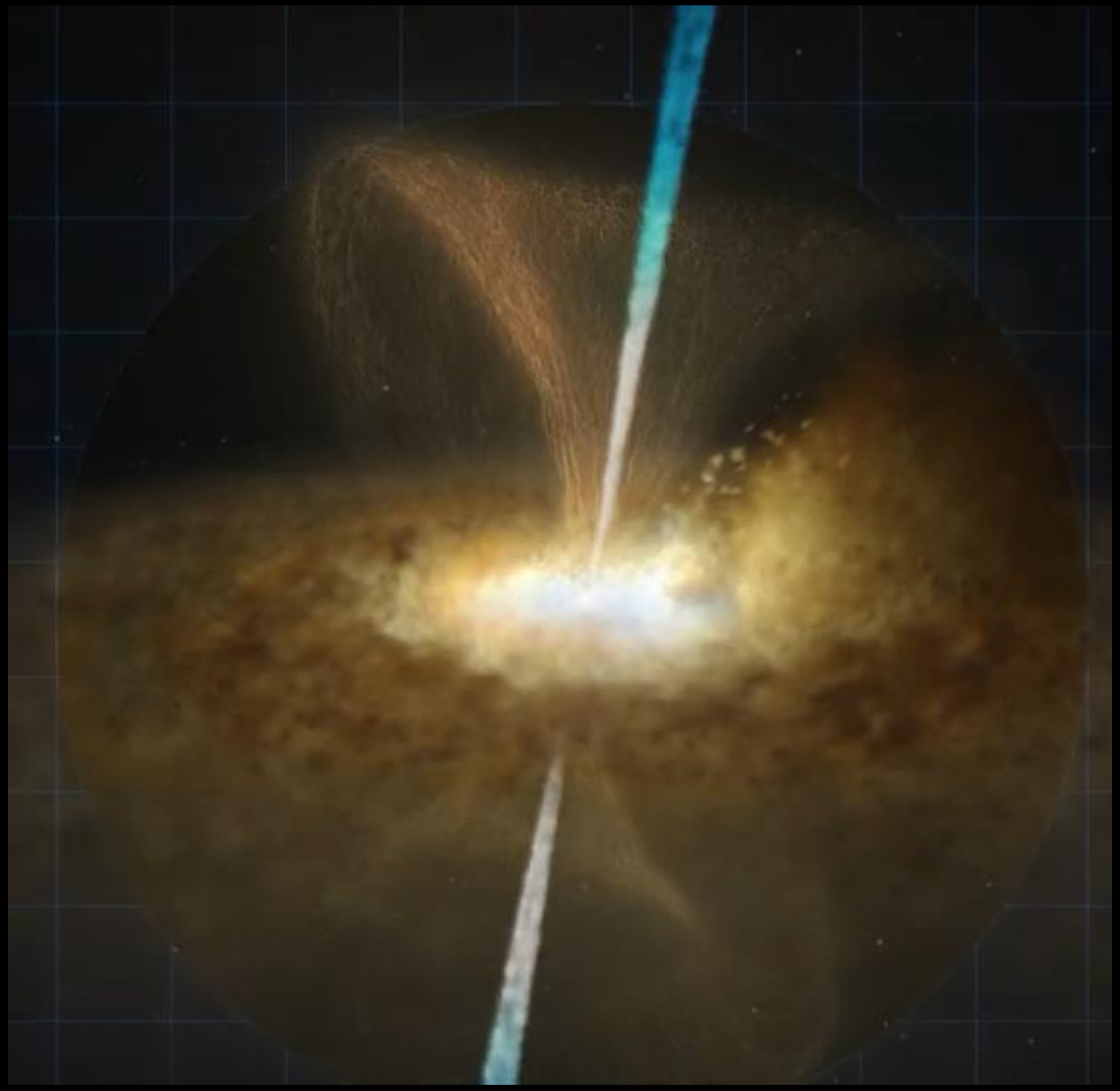
LOFAR Family

Olsztyn, Poland

14th June 2023

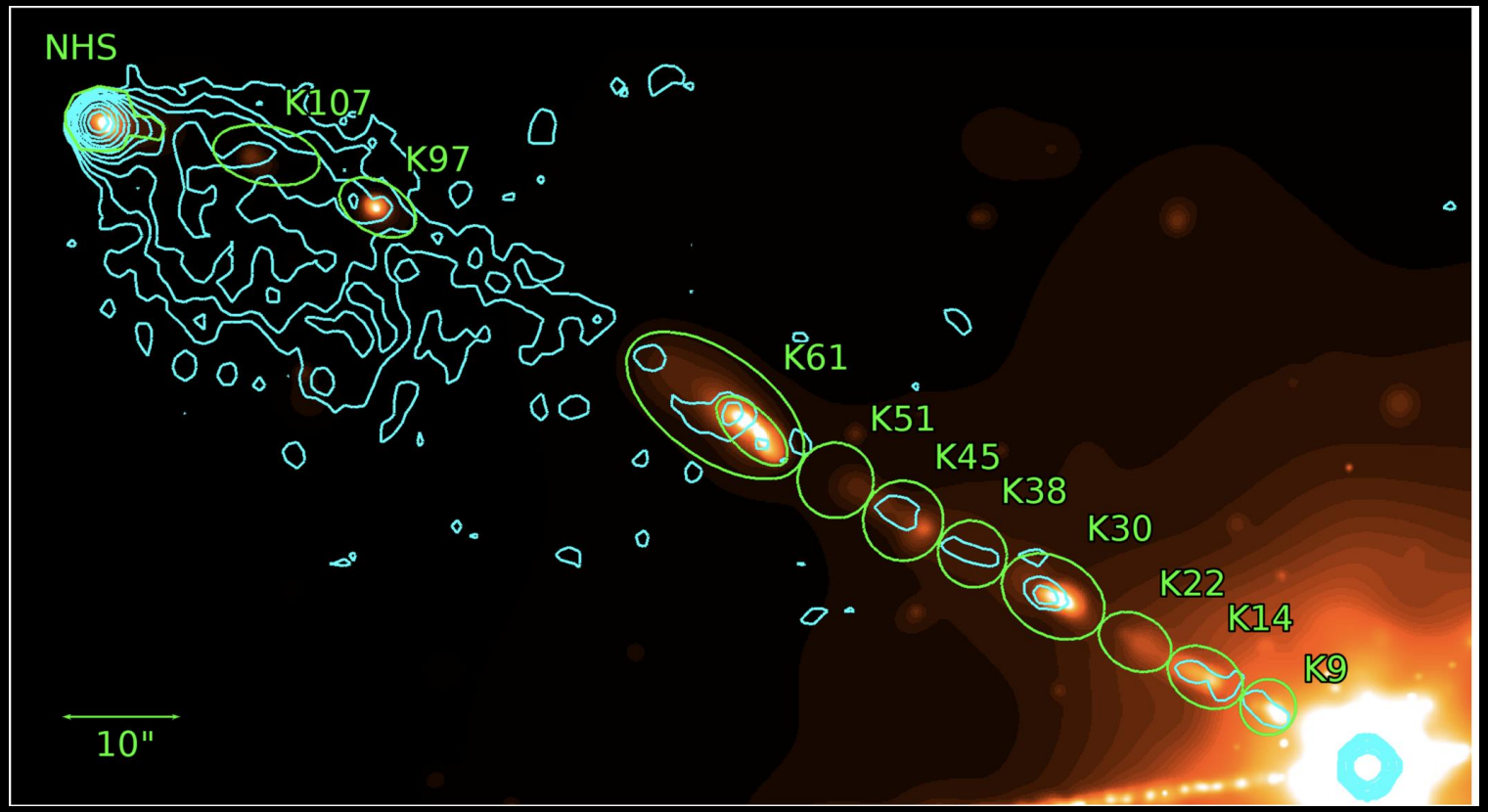
Blazars

- AGNs where jet is directed towards us
- Emit across the electromagnetic spectrum
- Relativistic beaming
- Particle accelerators
- Perfect laboratories for high-energy astrophysics!



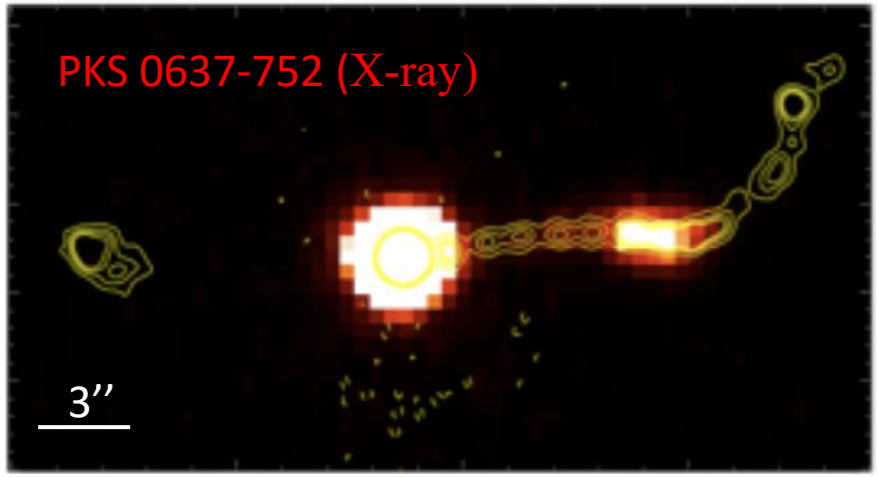
European Southern Observatory (ESO)

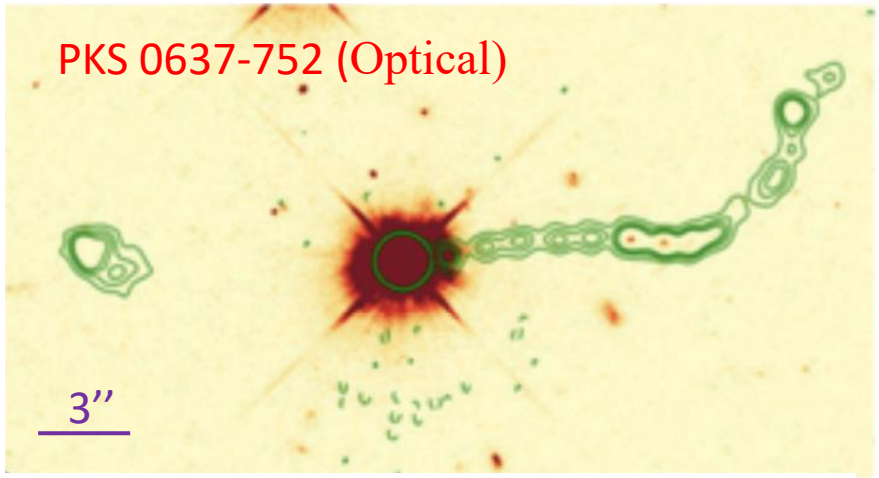
Knots in Jets

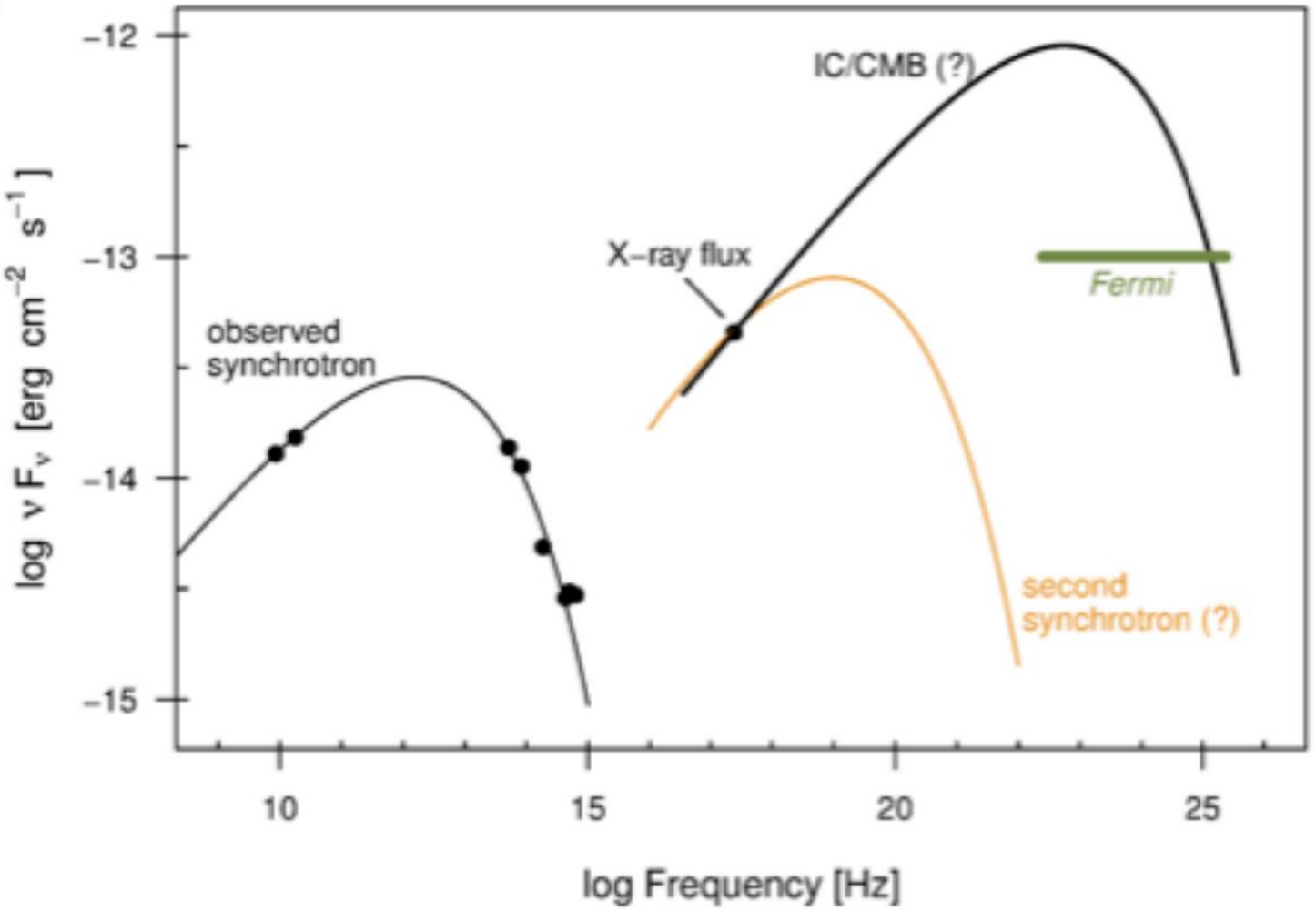


3C 111 in Chandra X-ray (heat scale), 8 GHz VLA (cyan contours)
Clautice et al., (2016)

- Compact bright regions in the jet
- Detection in X-rays -> emission processes?
- Re-acceleration mechanisms?
- Inverse scattering -> Photon field?
- High angular resolution necessary to separate the knots from core

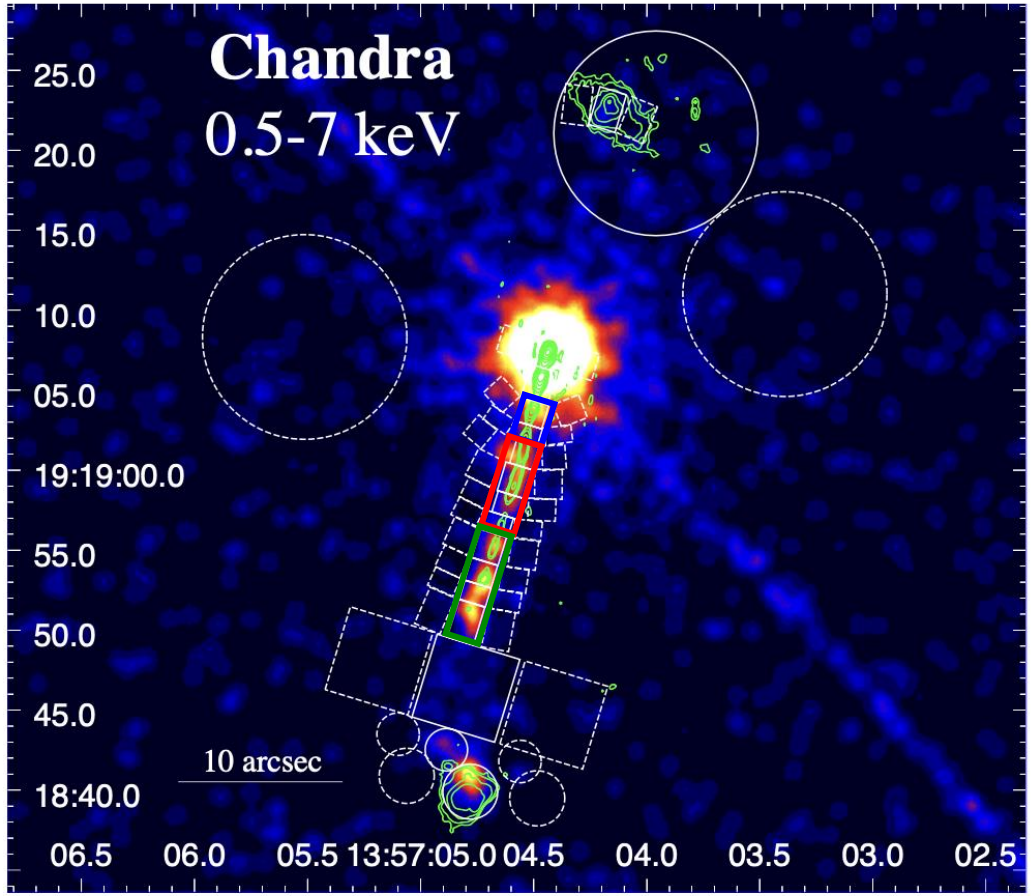


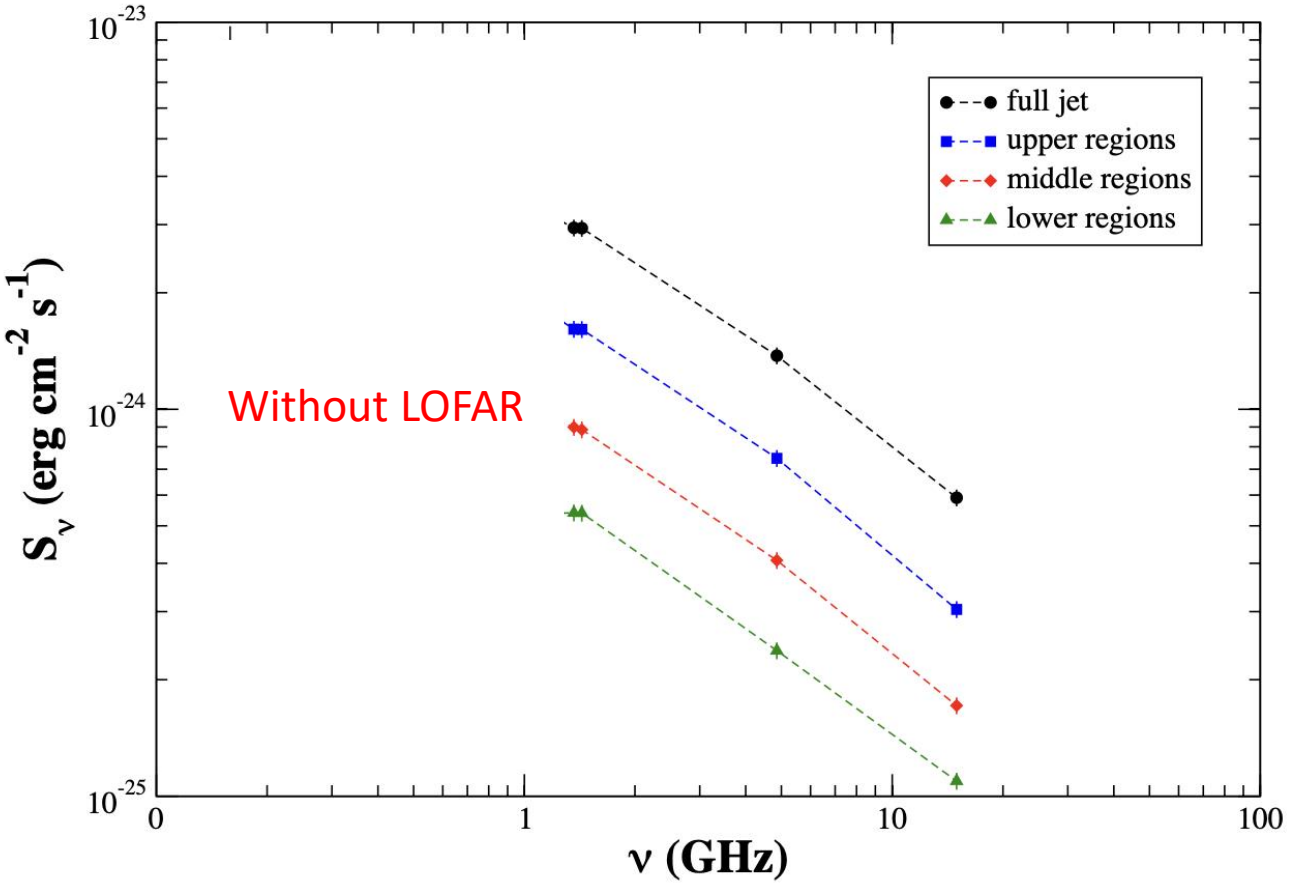




Left: PKS 0637-752 in X-ray (top), optical (bottom) with 17 GHz radio contours
Right: Radio to X-ray SED
Perlman et al. (2019)

Why LOFAR-VLBI?





Left : 4C +19.44 in Chandra X-Ray with LOFAR radio contours overlaid

Right: MHz to GHz radio spectra of the jet.

Adapted from Harris et al., (2019)

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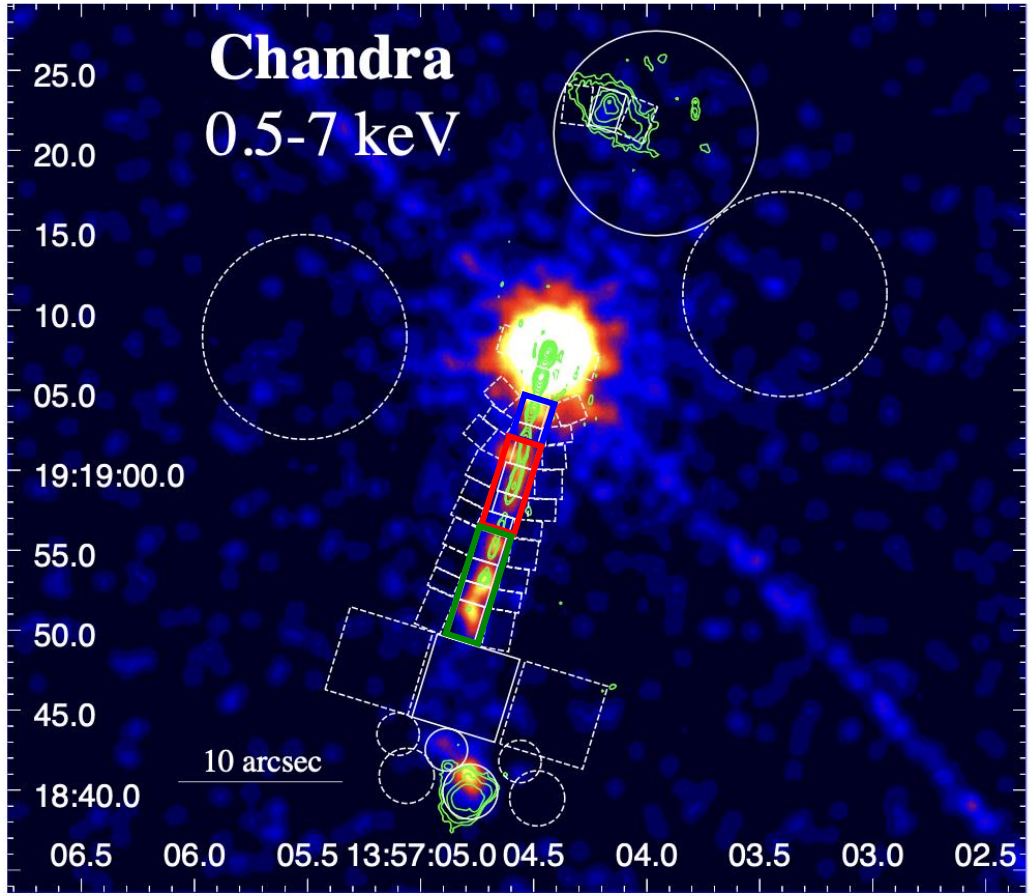

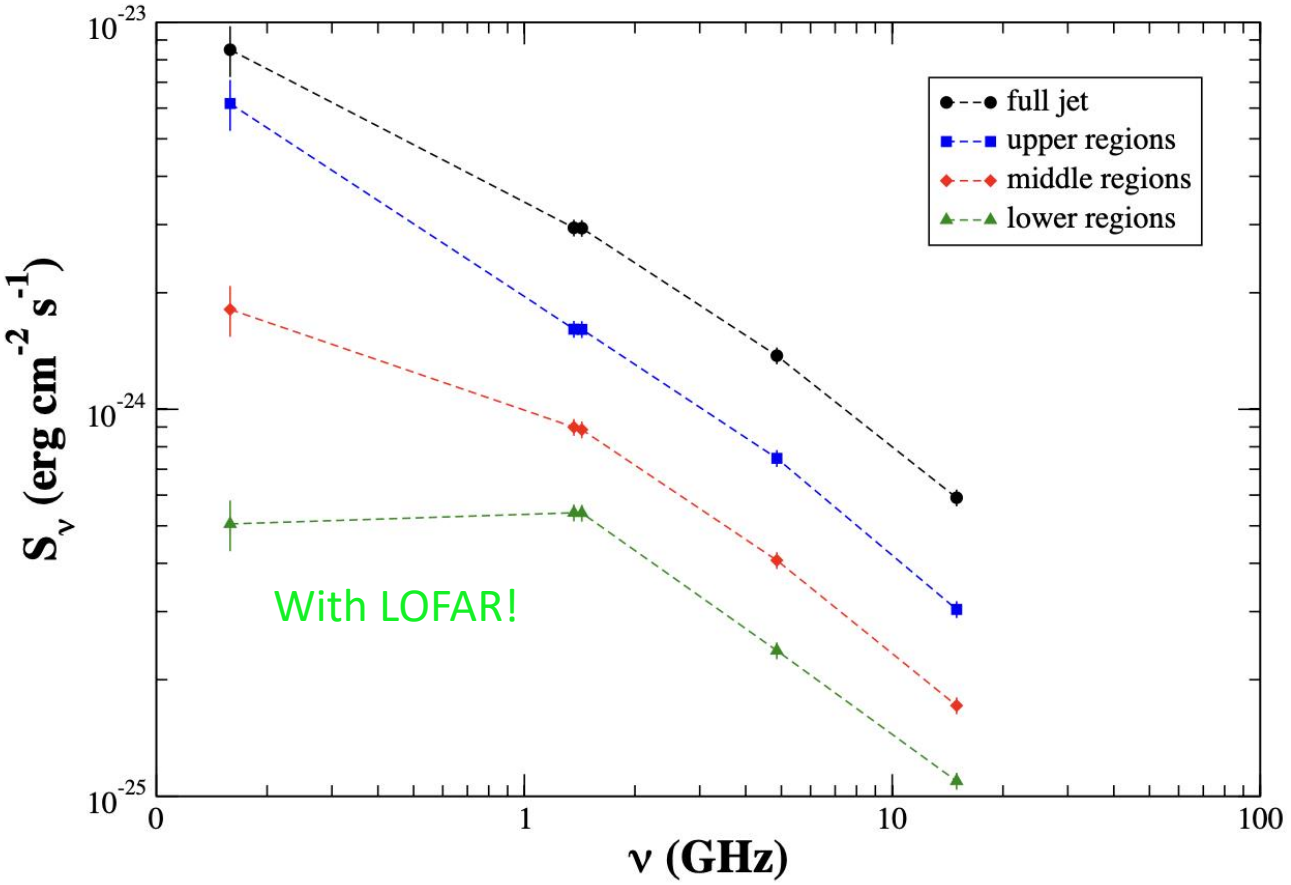

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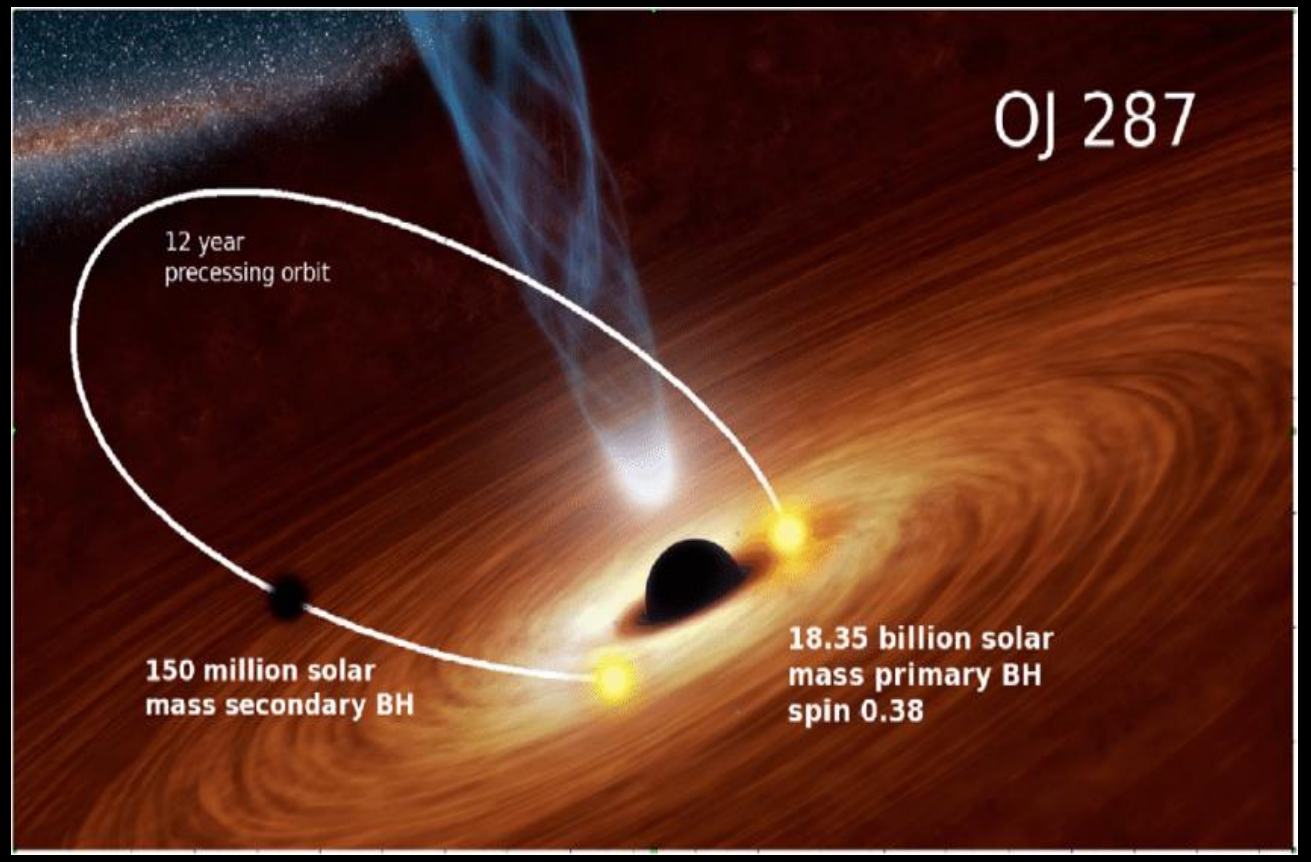
Pilot Dataset

- Target: OJ287
- 8 hour observation
  - 13 June 2019
  - 13 international stations
- 5 TB of data!
- PI: Sean Mooney



Artist impression
https://www.scientificeuropean.co.uk/sciences/space/flares-from-the-supermassive-binary-black-hole-oj-287-put-constraint-on-the-no-hair-theorem/

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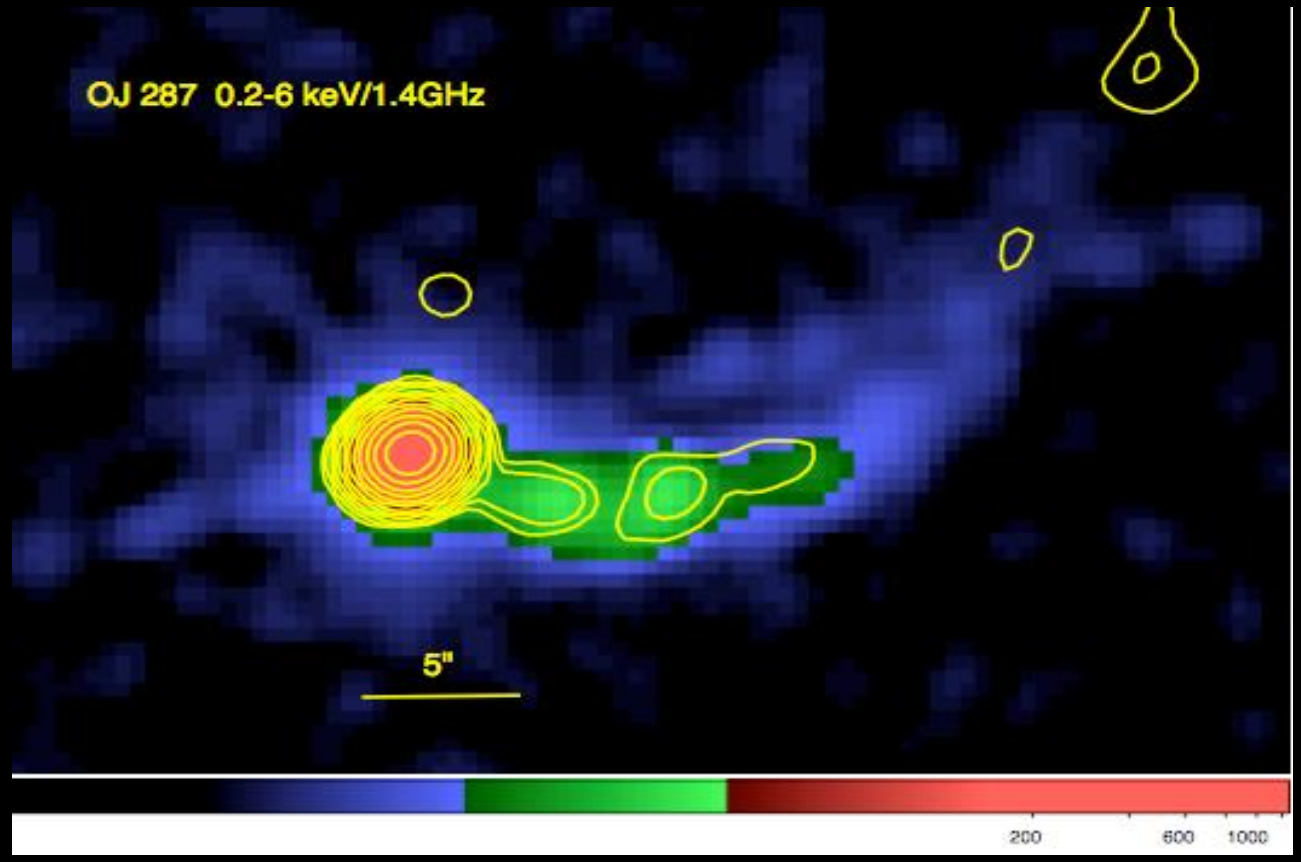


OJ287 in Chandra X-ray with VLA contours
Marscher, A.P., Jorstad, S.G. (2011)

LOFAR Initial Calibration (LINC) Pipeline

Calibrator and Target Pipeline

Self Calibration

Only Core and Remote stations
No International stations

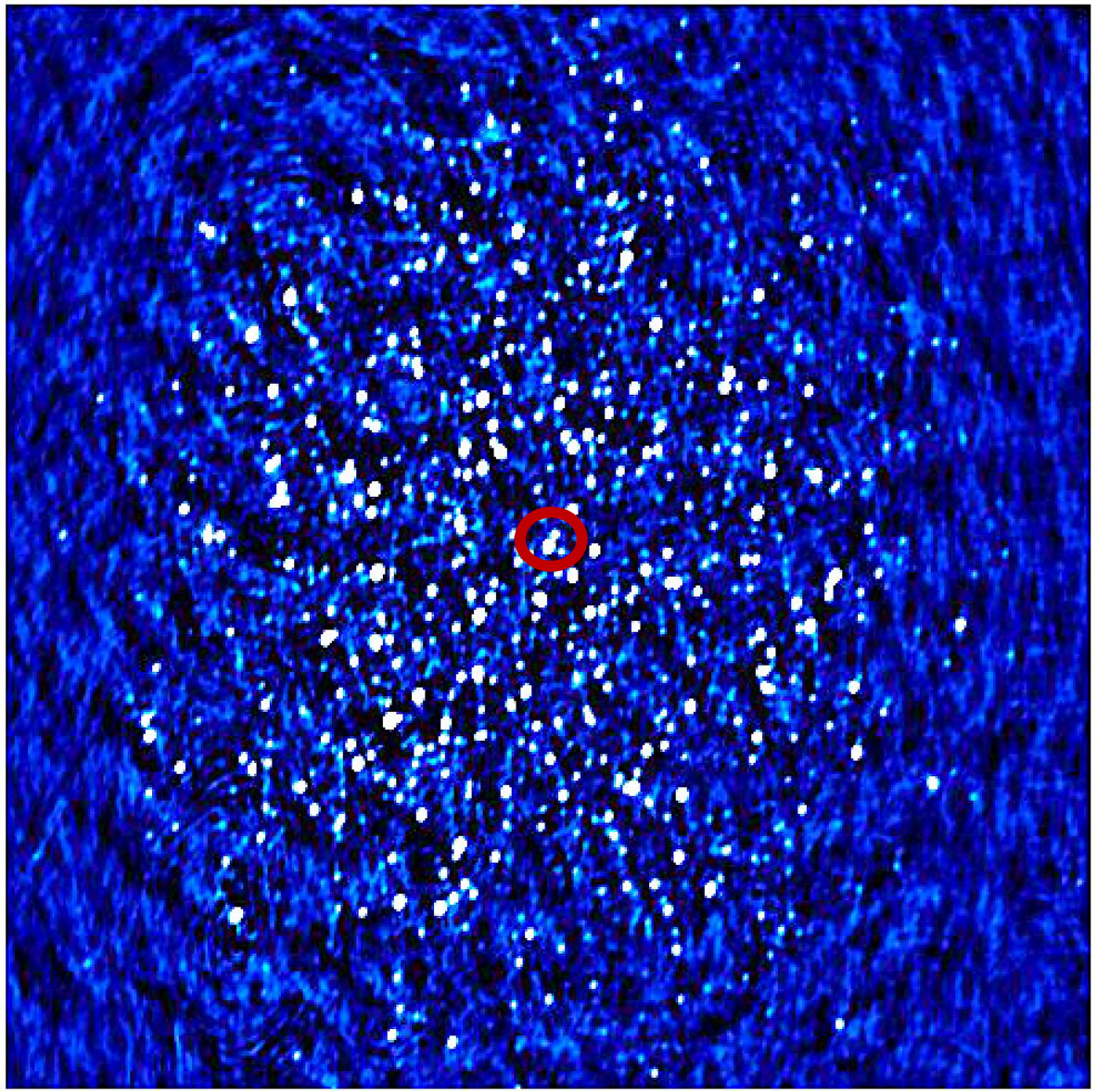
Field Subtraction

“Stay on target!”

- Gold Five

VLBI Self Calibration

With International Stations



(9.7° x 9.7°)

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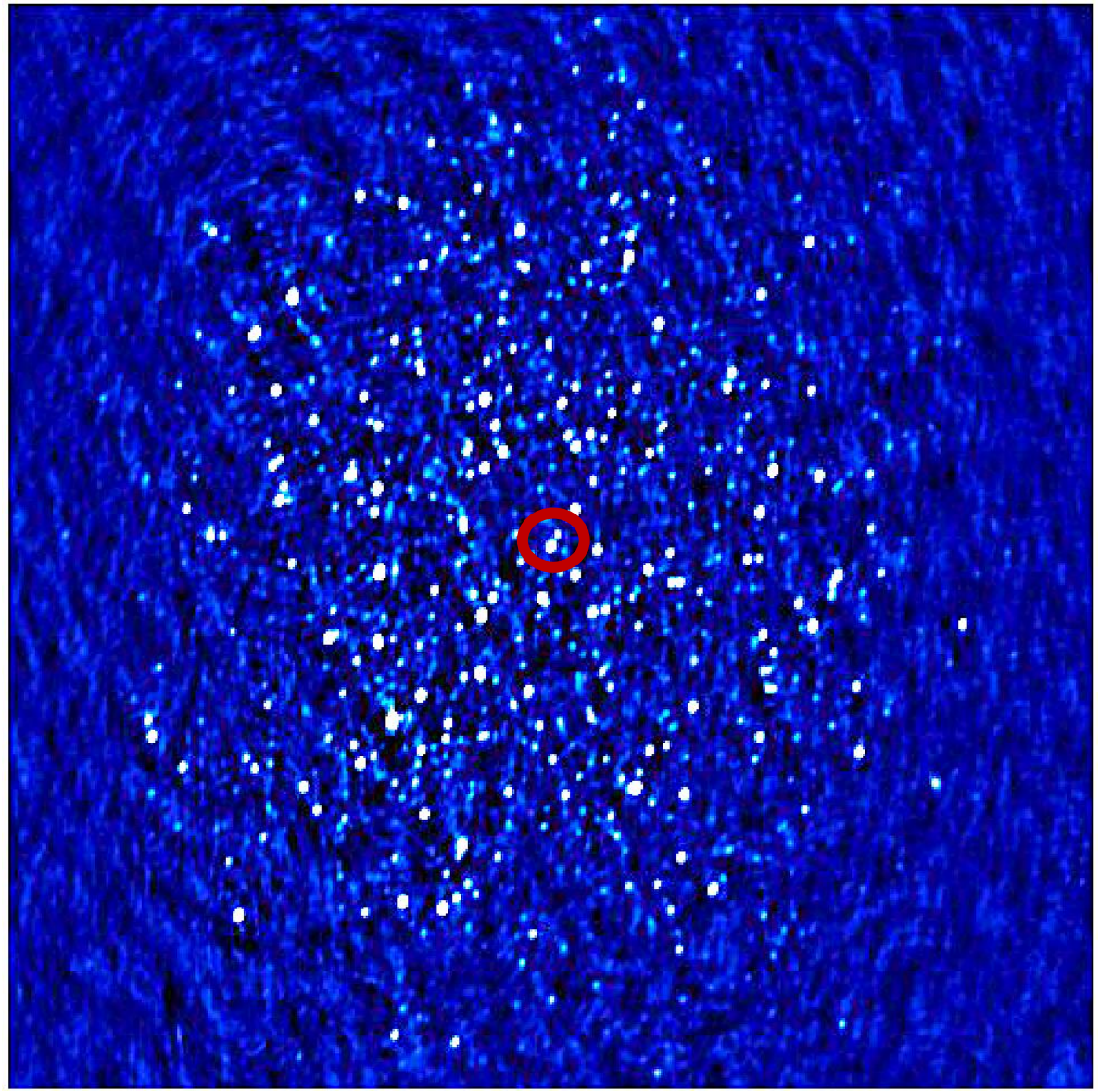

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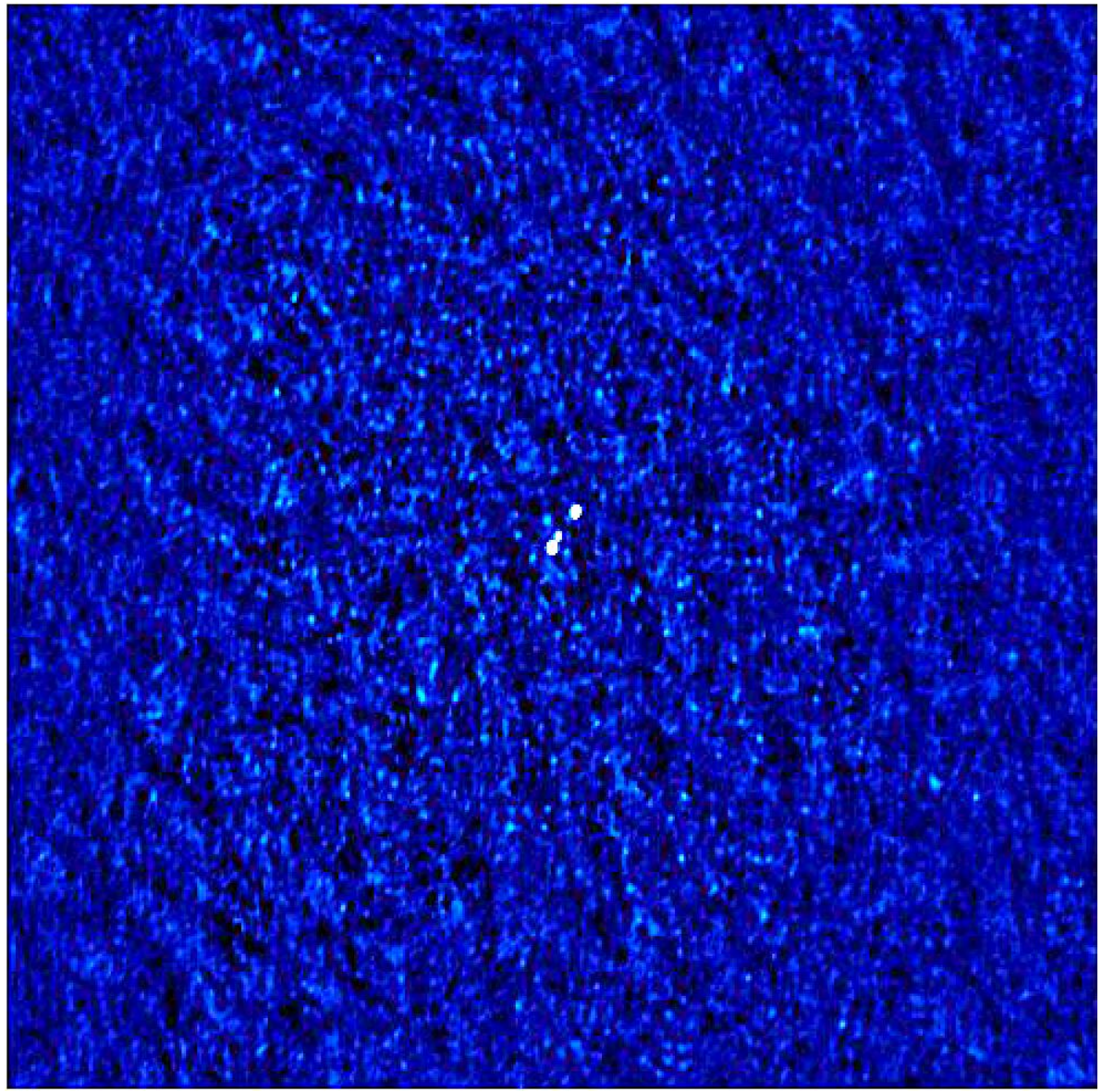

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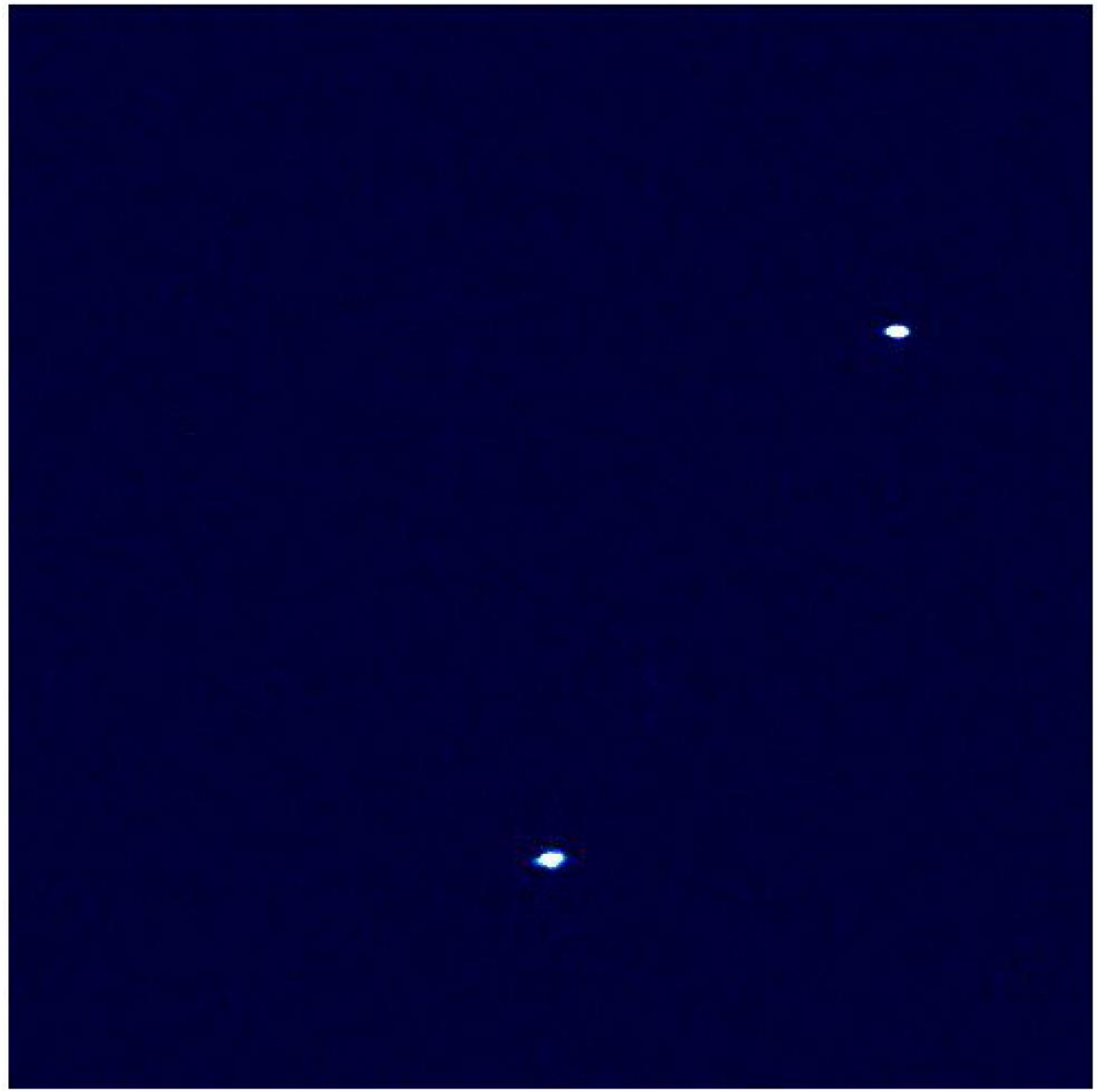

(0.66° x 0.66°)

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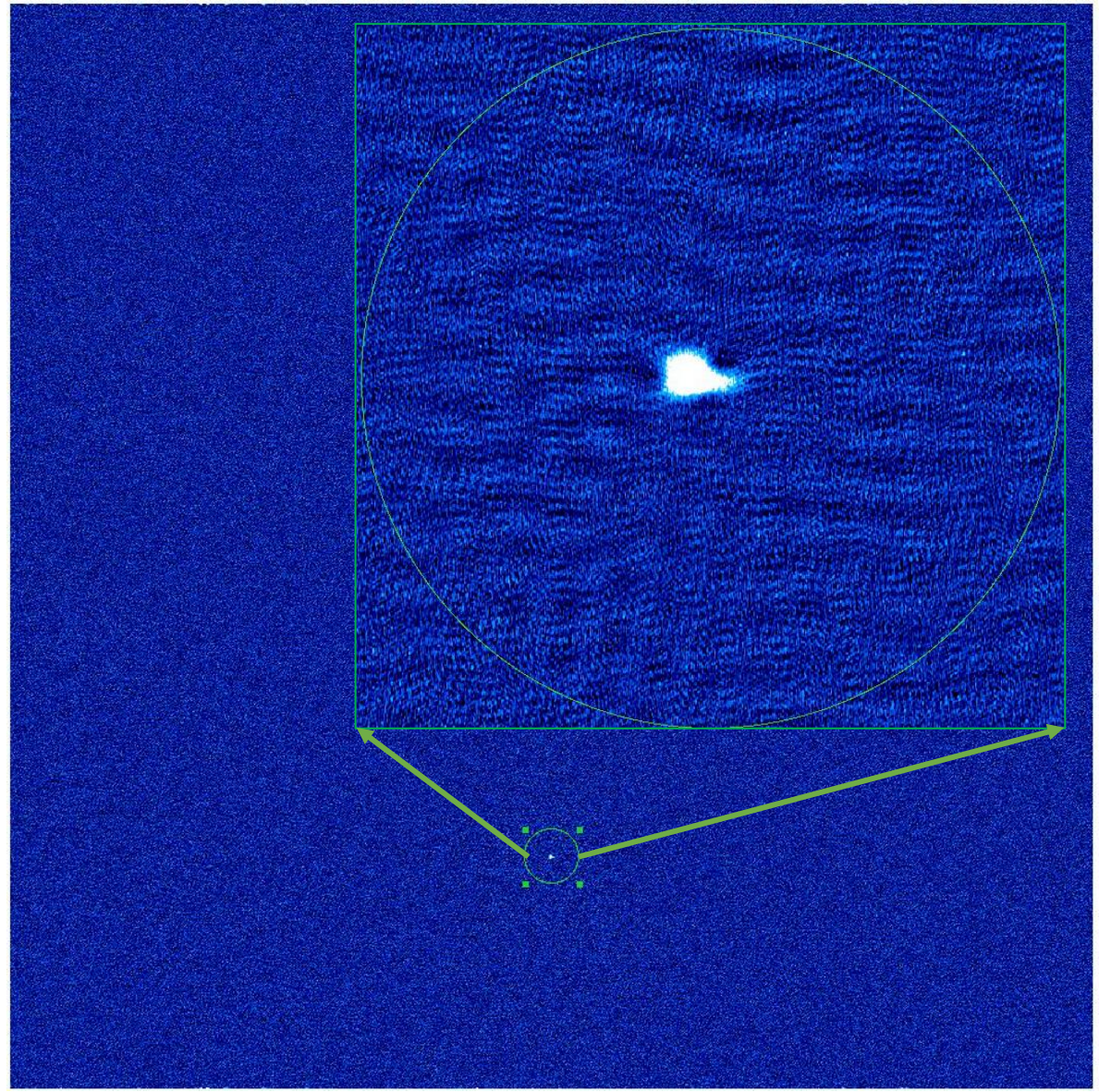

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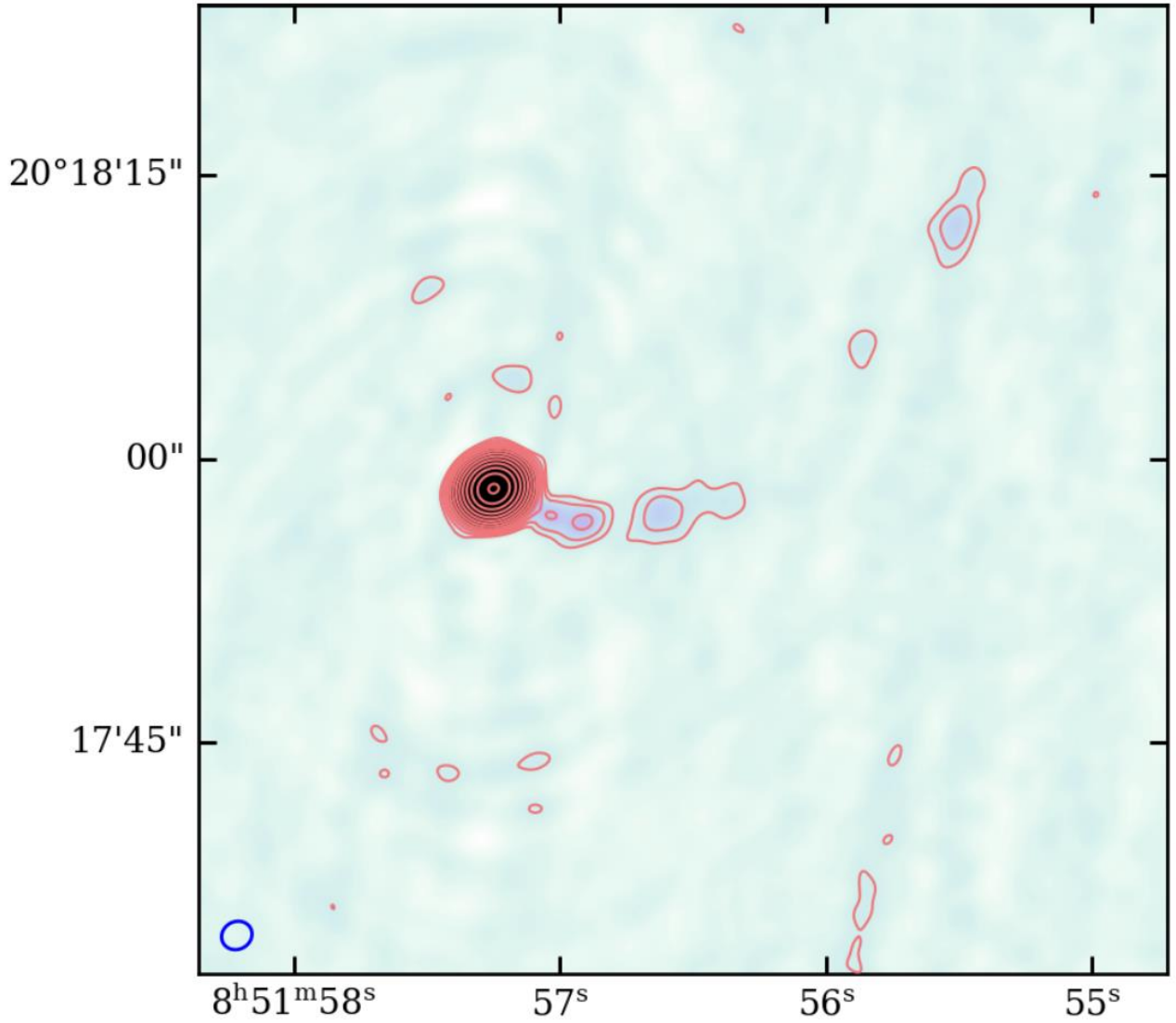
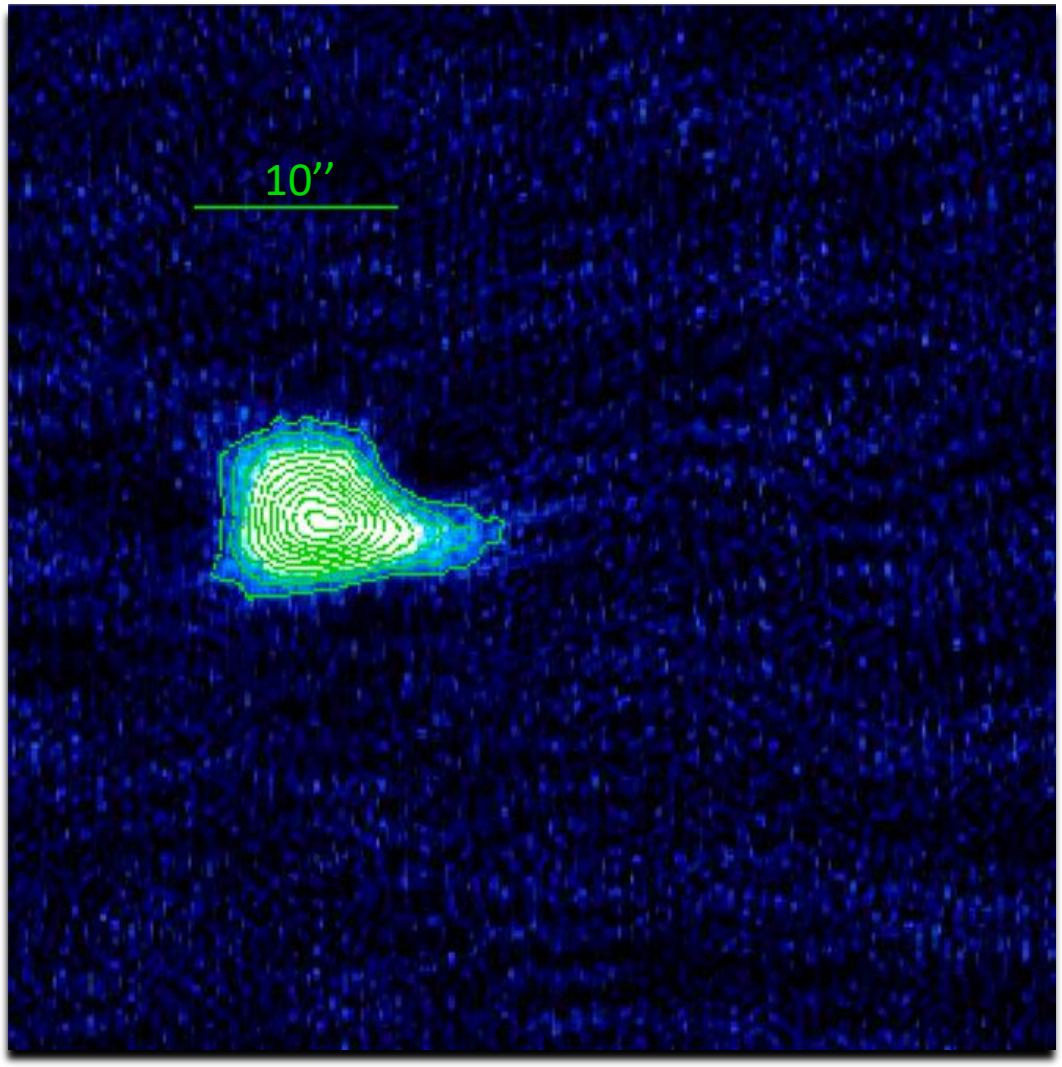
VLA



OJ 287 at 1.424 GHz
Mooney S. PhD Thesis (2020)

LOFAR

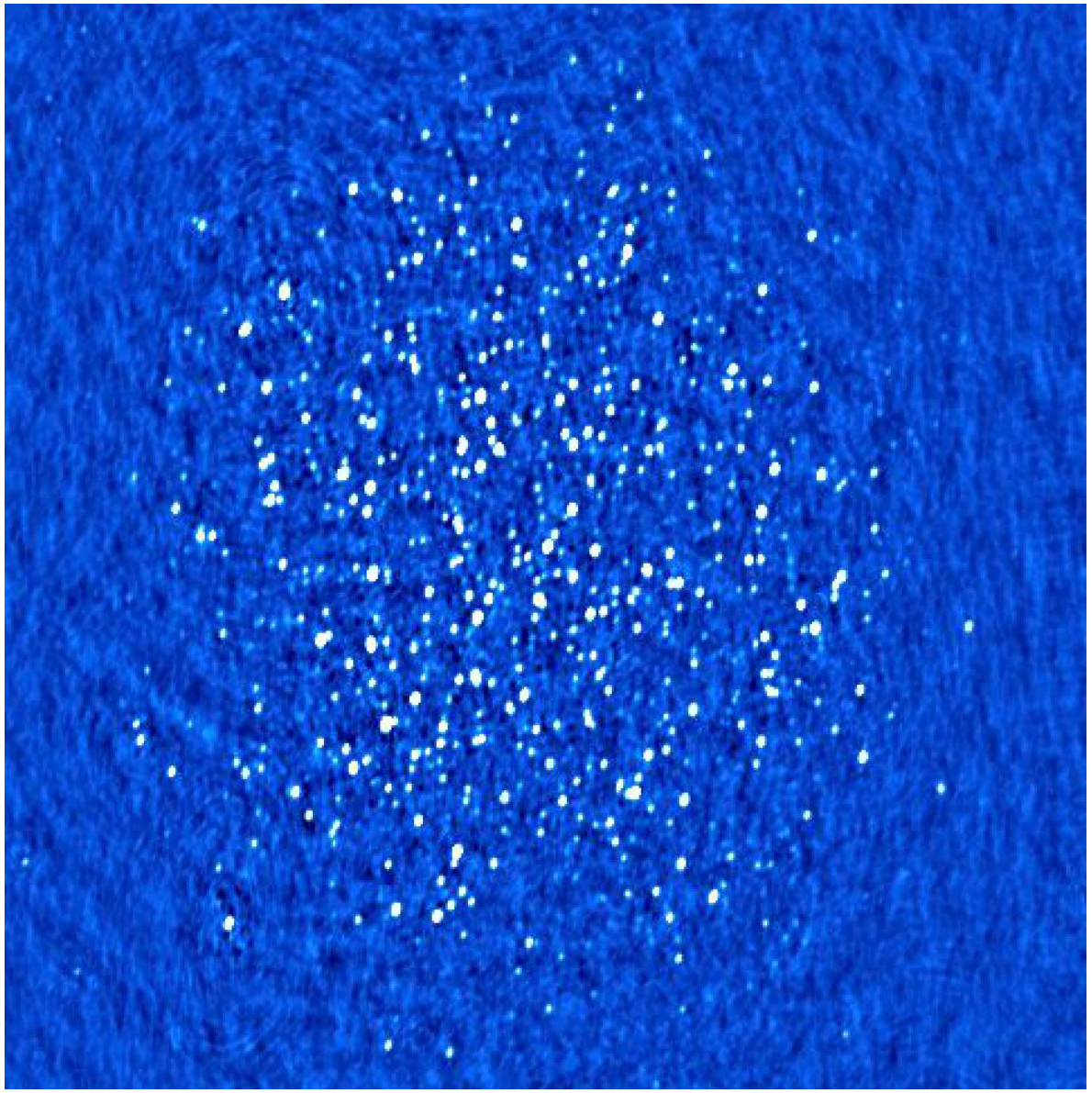


After one self-calibration pass,
With International Stations

10 Sub-bands

Low Sensitivity

Full Band



(9.7° x 9.7°)

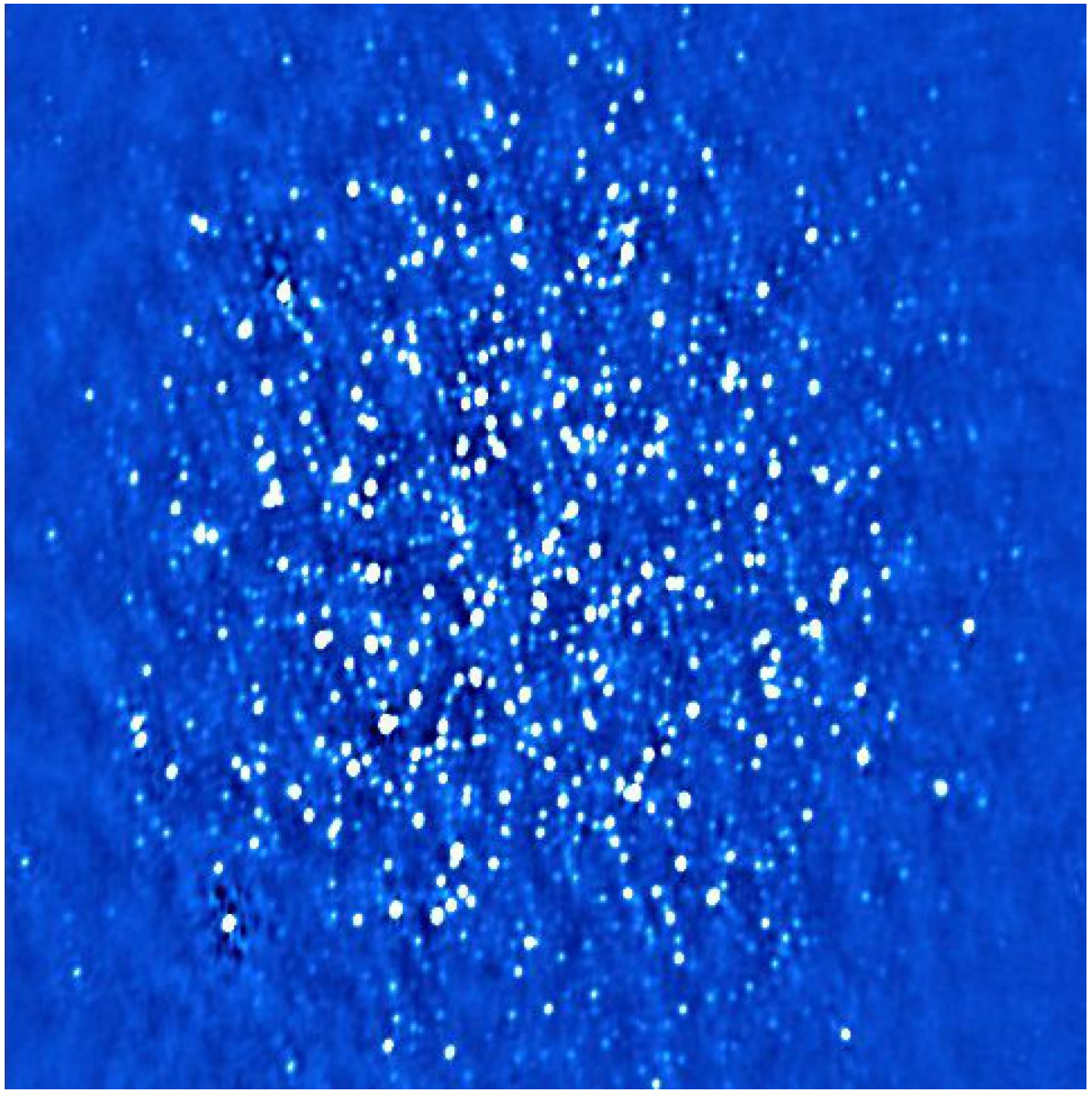
10 Sub-bands

Low Sensitivity

Full Band

Higher Sensitivity

"More Data, More Problems"



(9.7° x 9.7°)

Widefield Subtracted

Uncalibrated International Stations

Calibrating International Stations

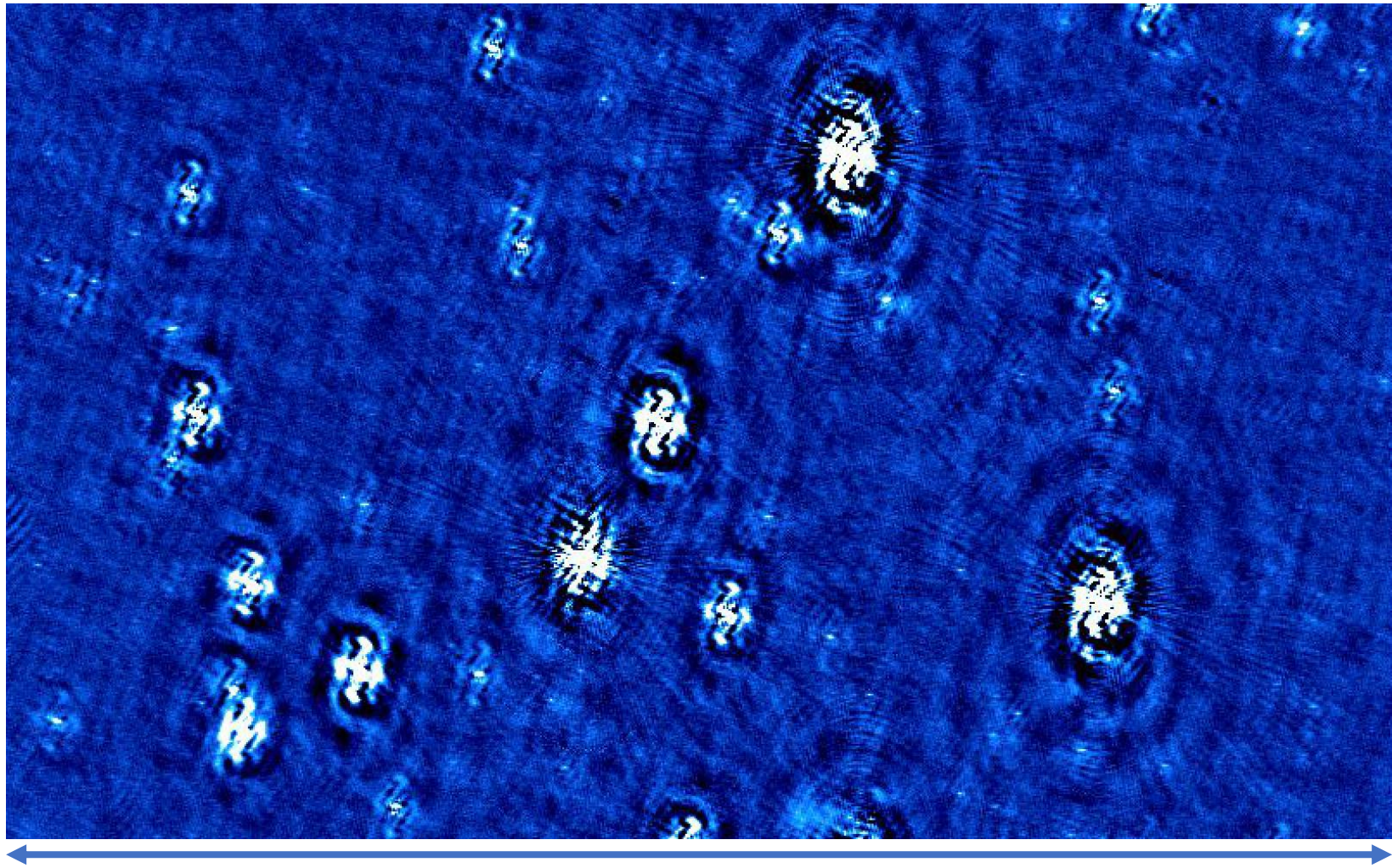
Getting rid of artifacts

More Field Subtraction

Selecting only OJ287

Calibration International Stations

Fine tuning to bring out the jet structure



(4000’’)

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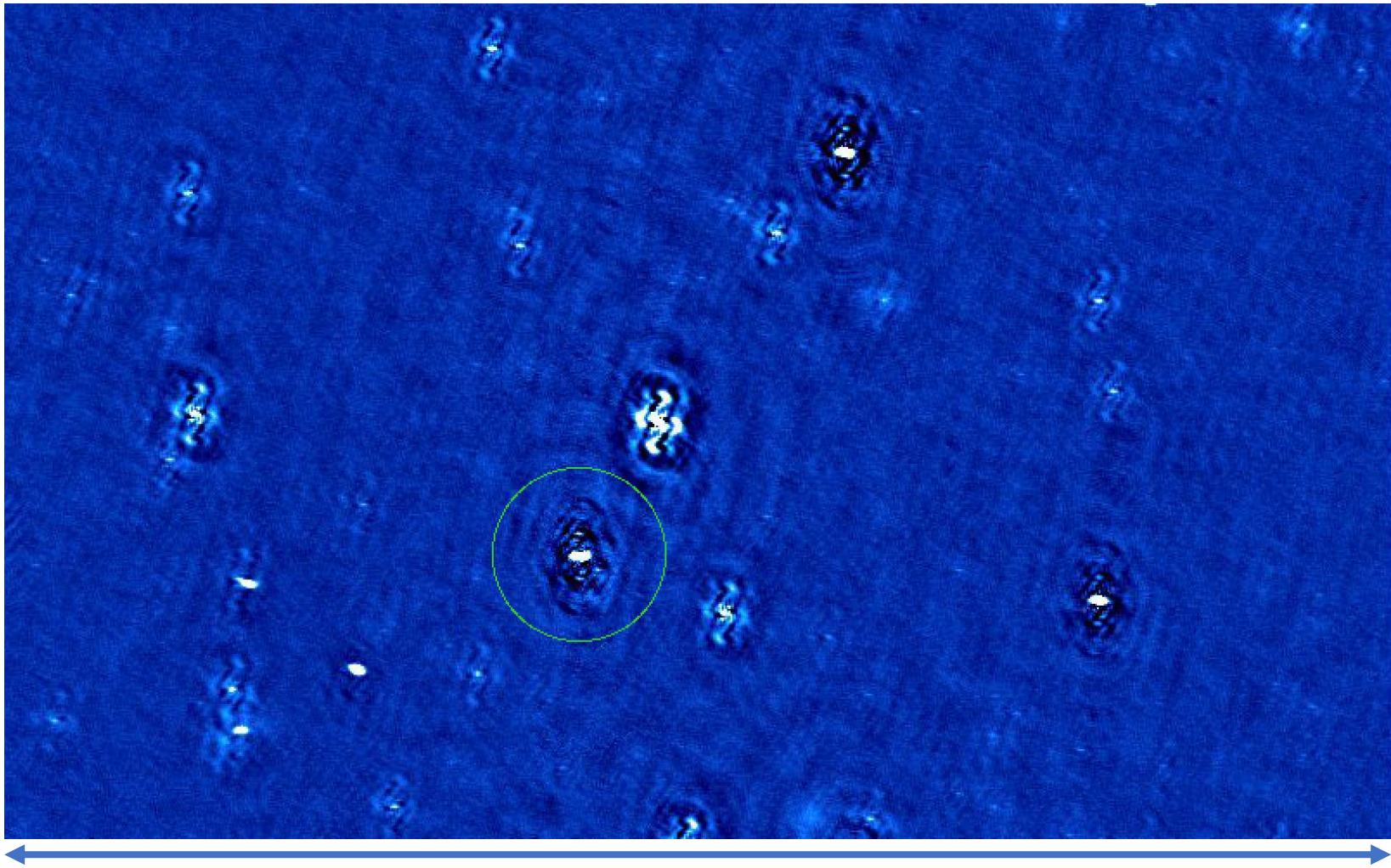

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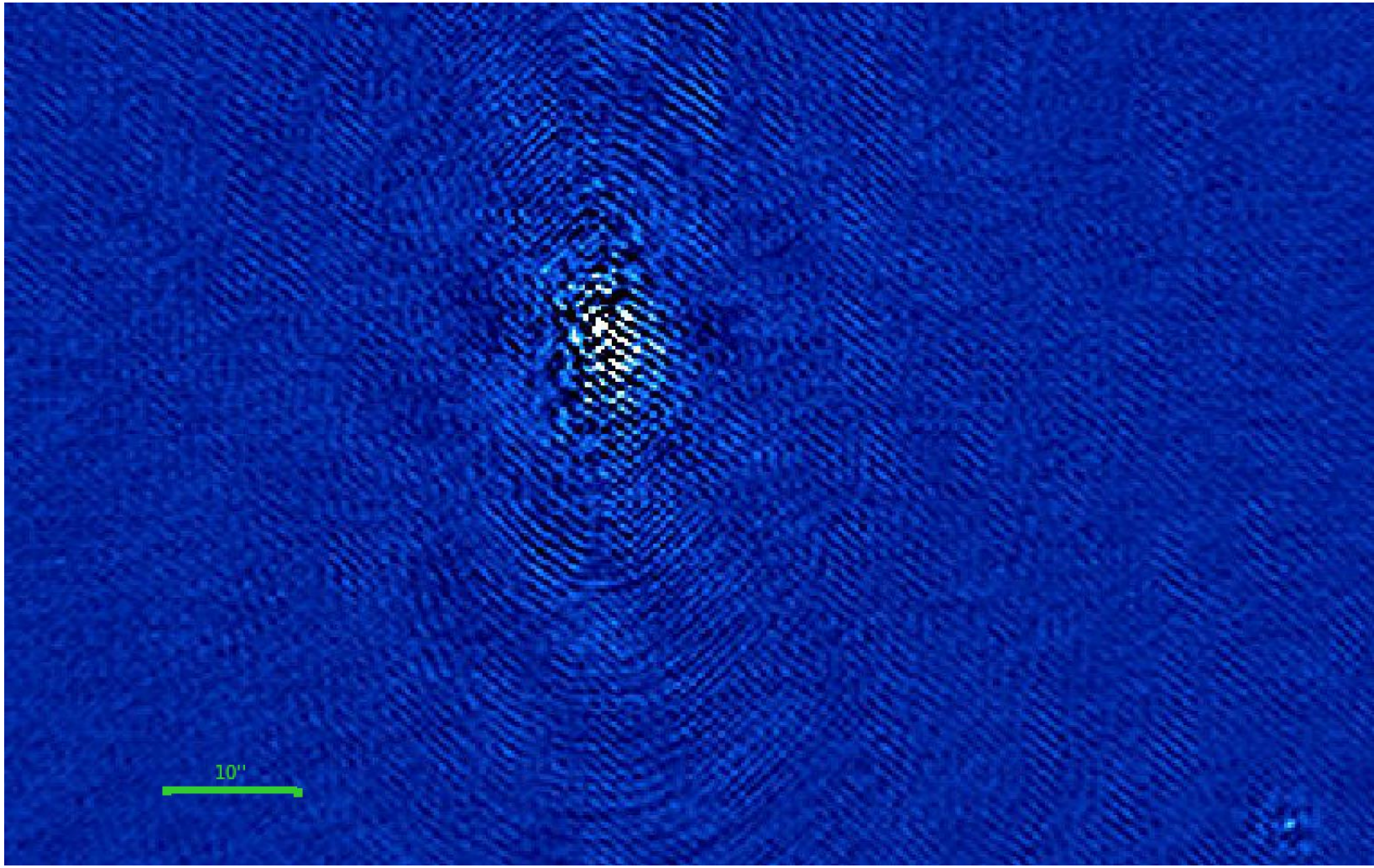

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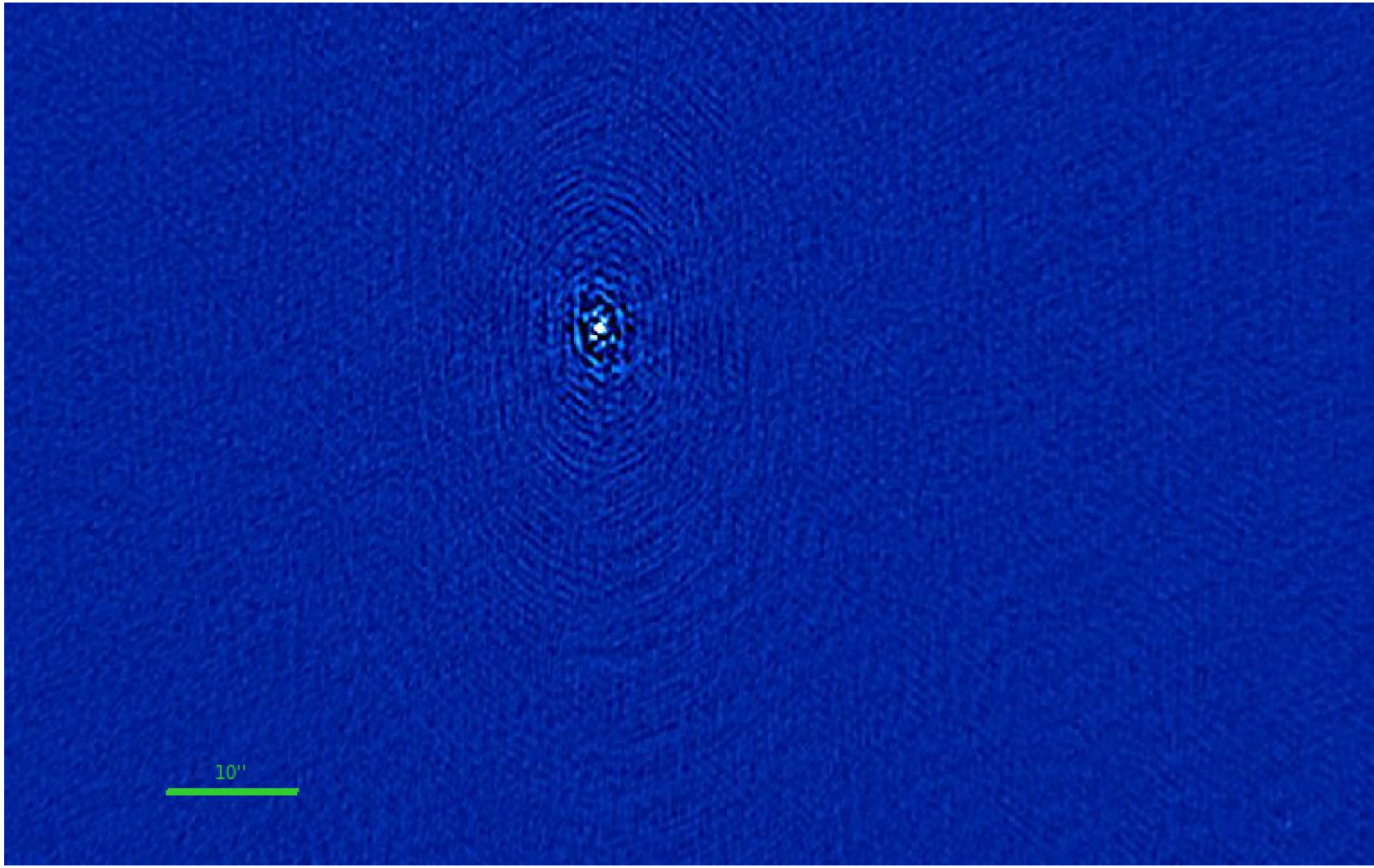
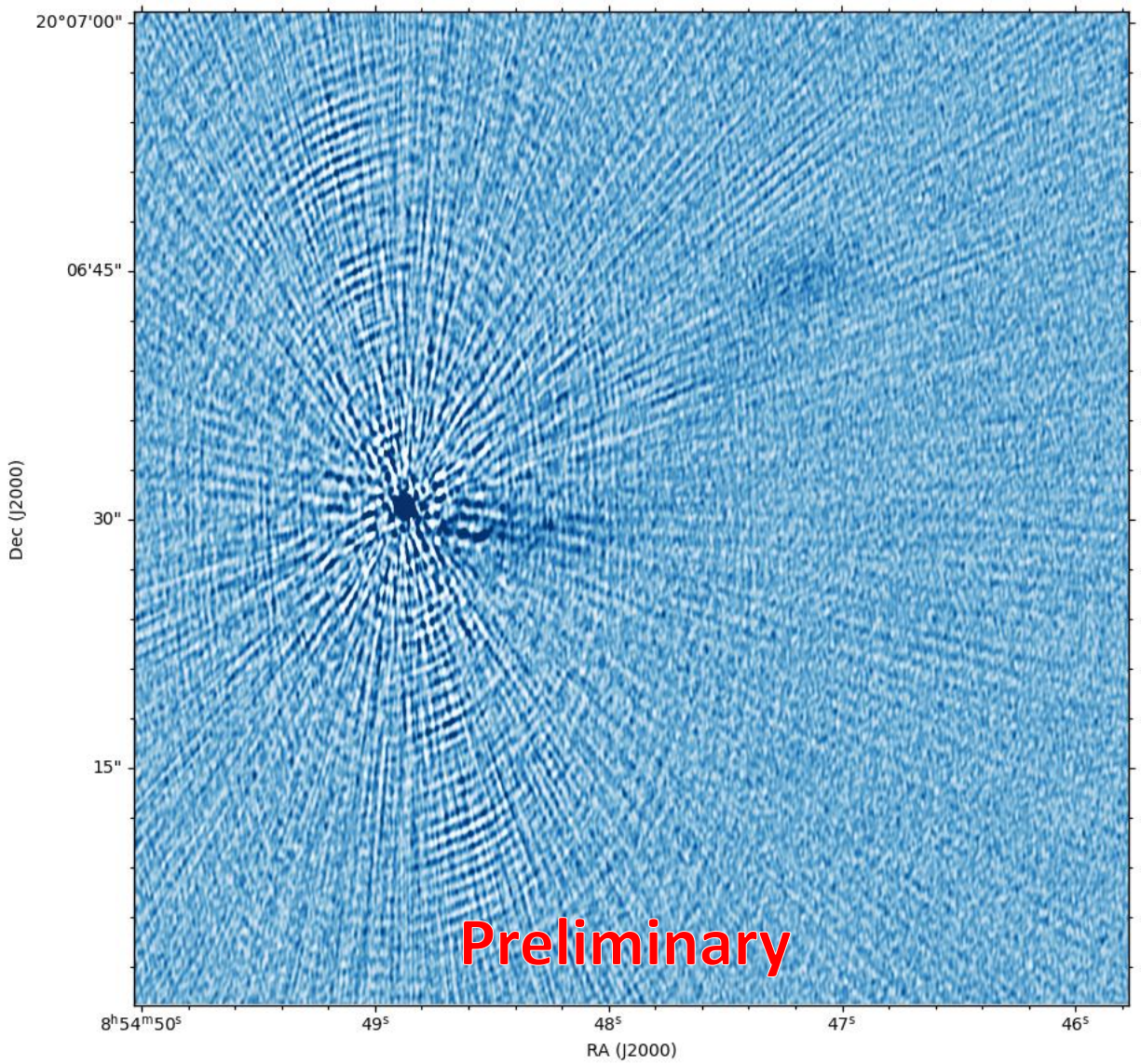


The journey so far…

- ‘Artisian’ self calibration with DDF and kMS
  - Pro: Deep understanding of imaging
  - Con: Takes too long!
- Downloaded LOFAR cycle 4 project 26 data for 6 blazars
- Setting up LOFAR-VLBI pipeline on local architecture in Würzburg
  - https://github.com/lmorabit/lofar-vlbi



Fullband LOFAR-VLBI image of OJ287

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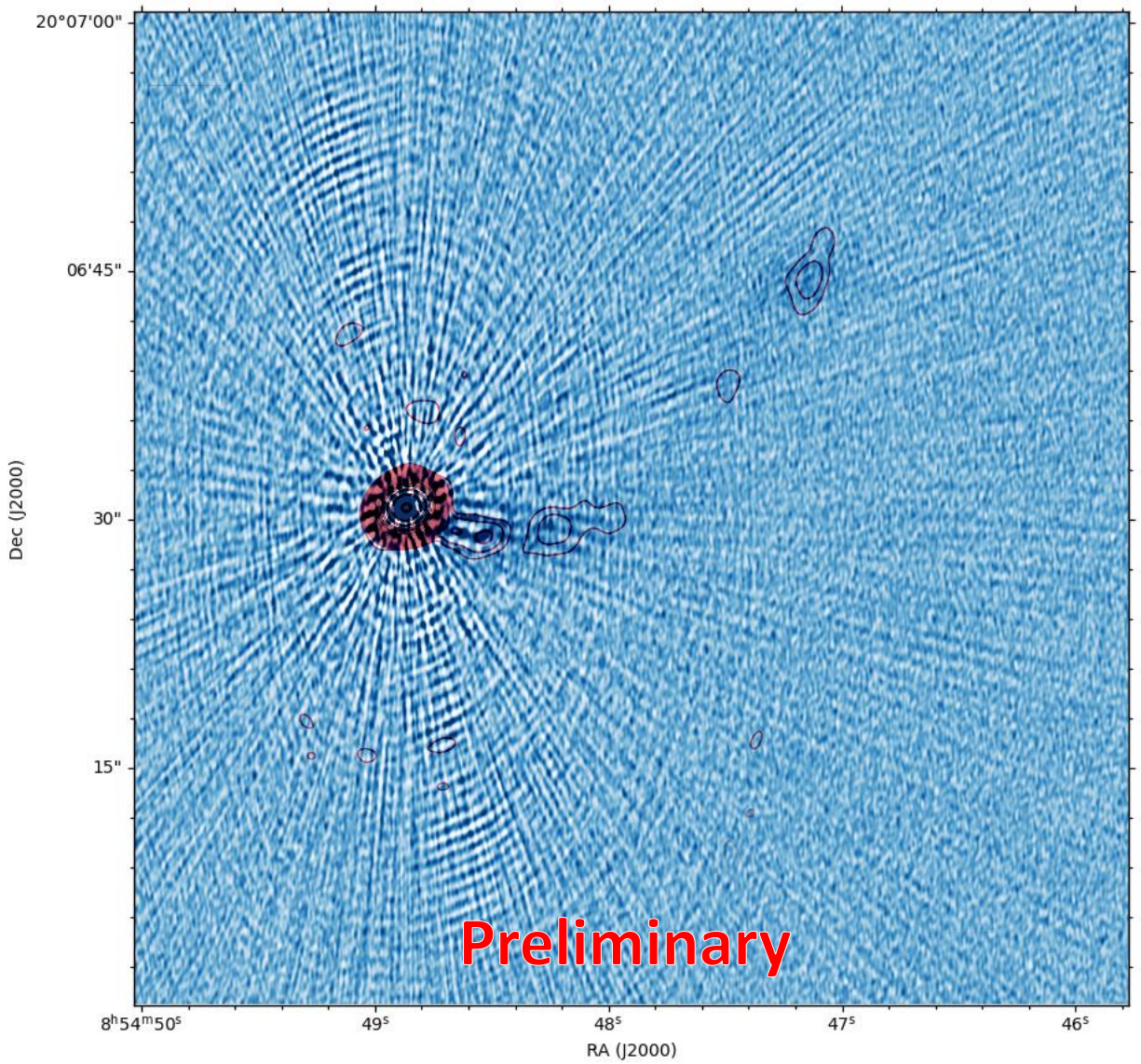
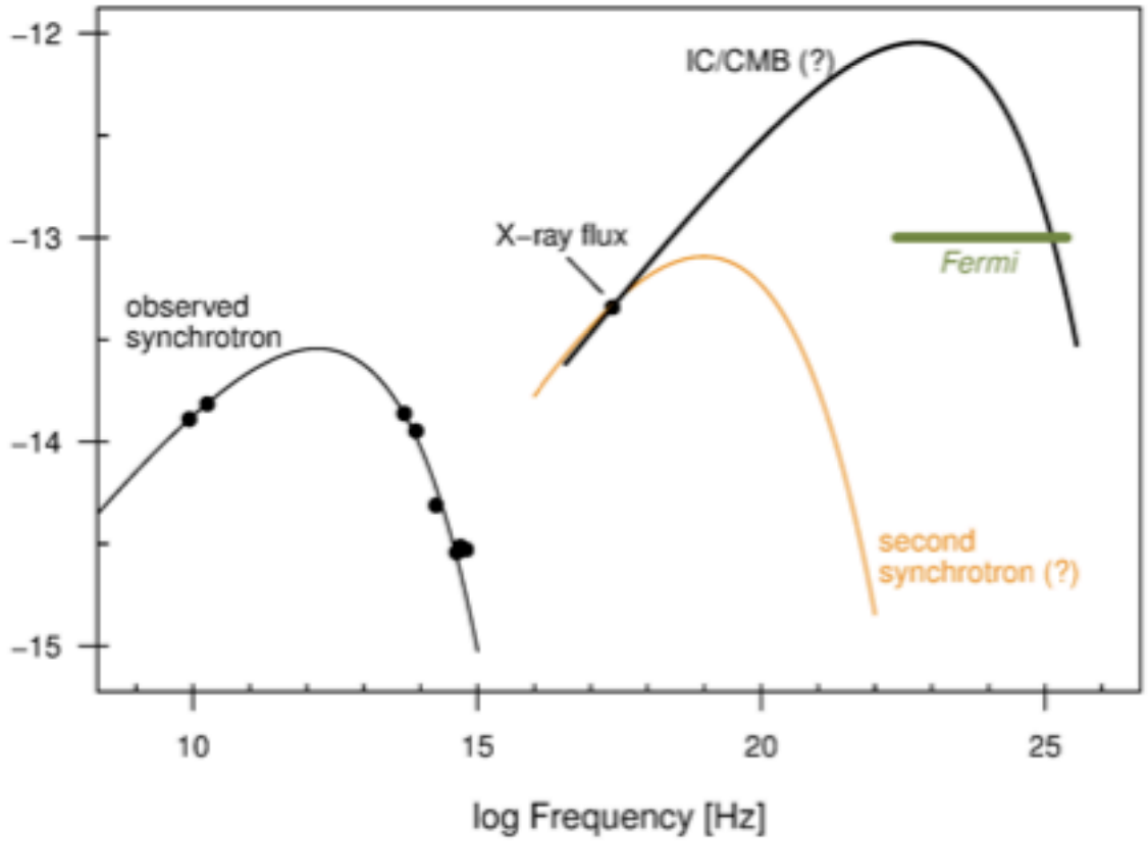


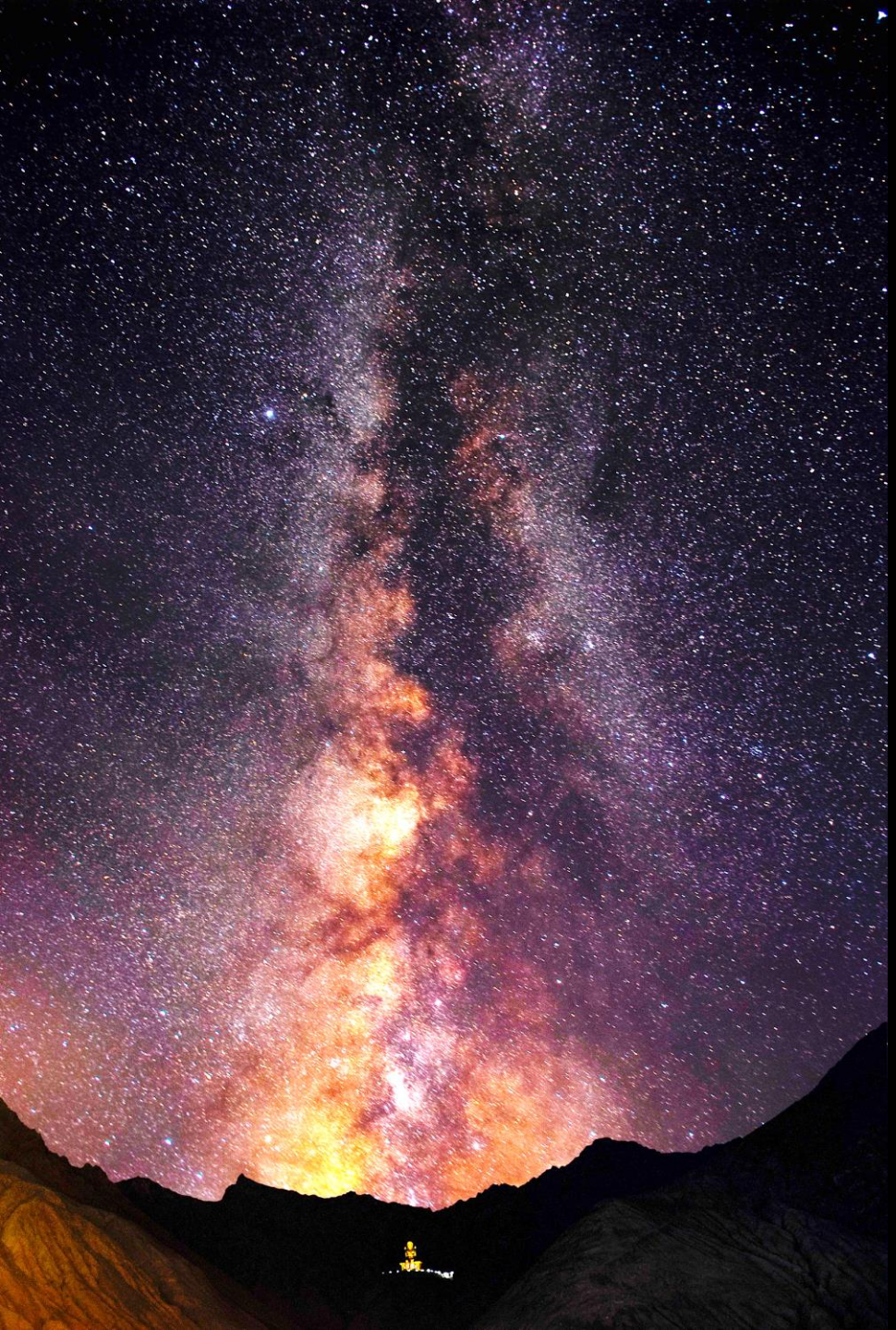
Fullband LOFAR-VLBI image of OJ287

The road ahead…

- Run LOFAR-VLBI pipeline and some more ‘artisian’ self calibration
- Complement with high-frequency radio, optical and X-ray data
- Spectral Energy Distribution (SED) modelling to test models
  - IC/CMB, SSC, second synchrotron
- Repeat the analysis for other X-ray selected blazars!



Radio-X-ray SED
Perlman et al. (2019)

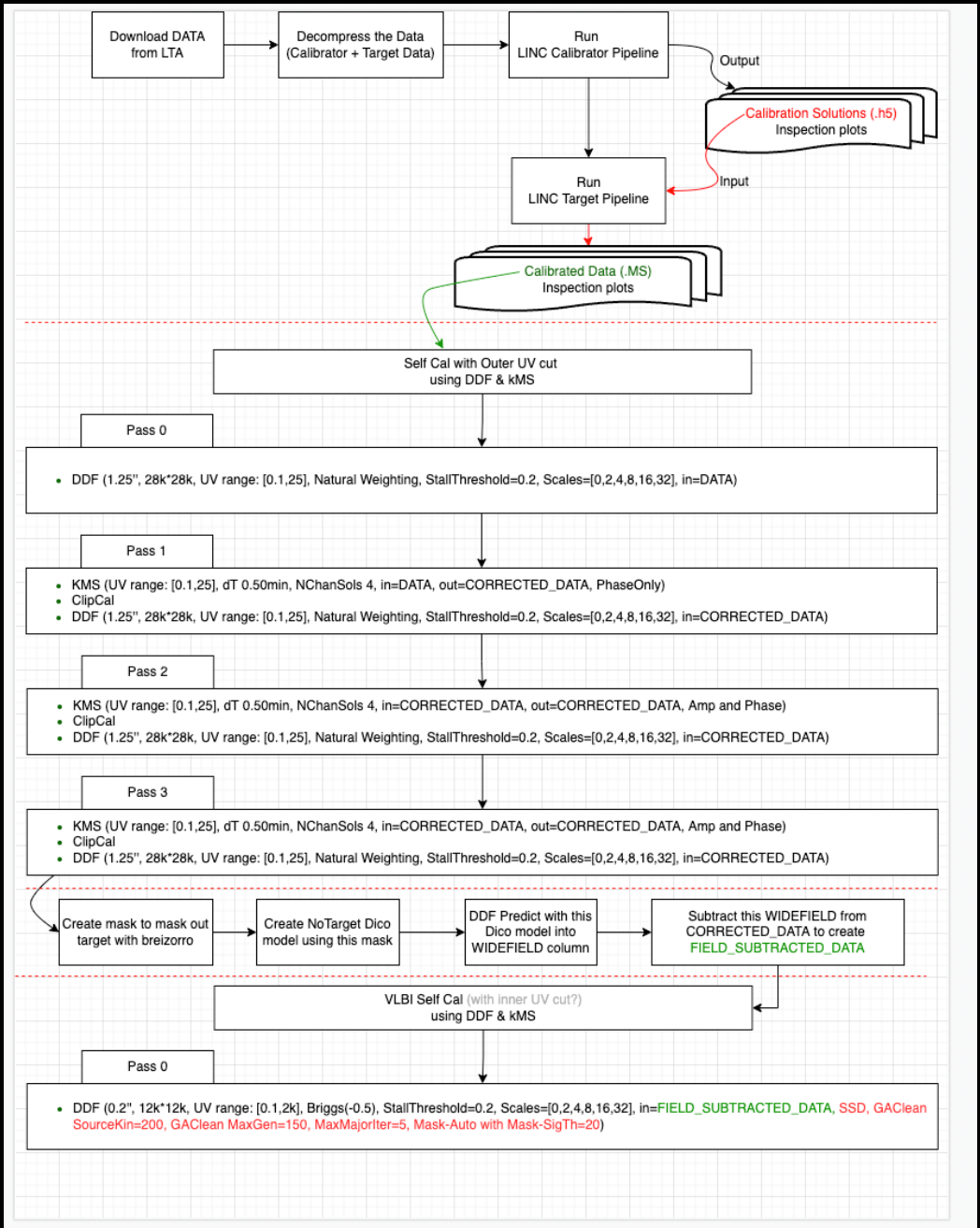


Thank You!

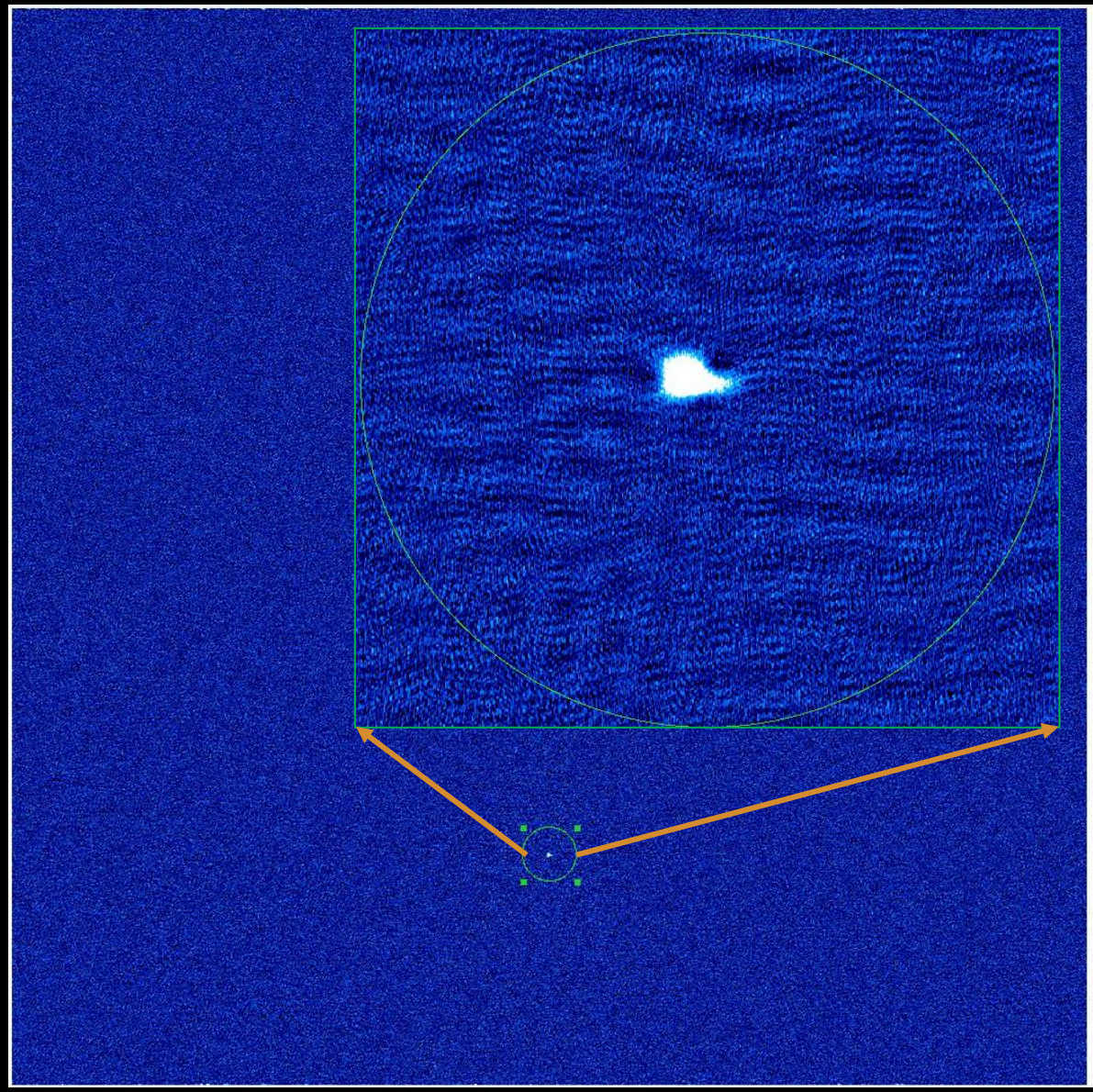
Question?

Comments and suggestions?

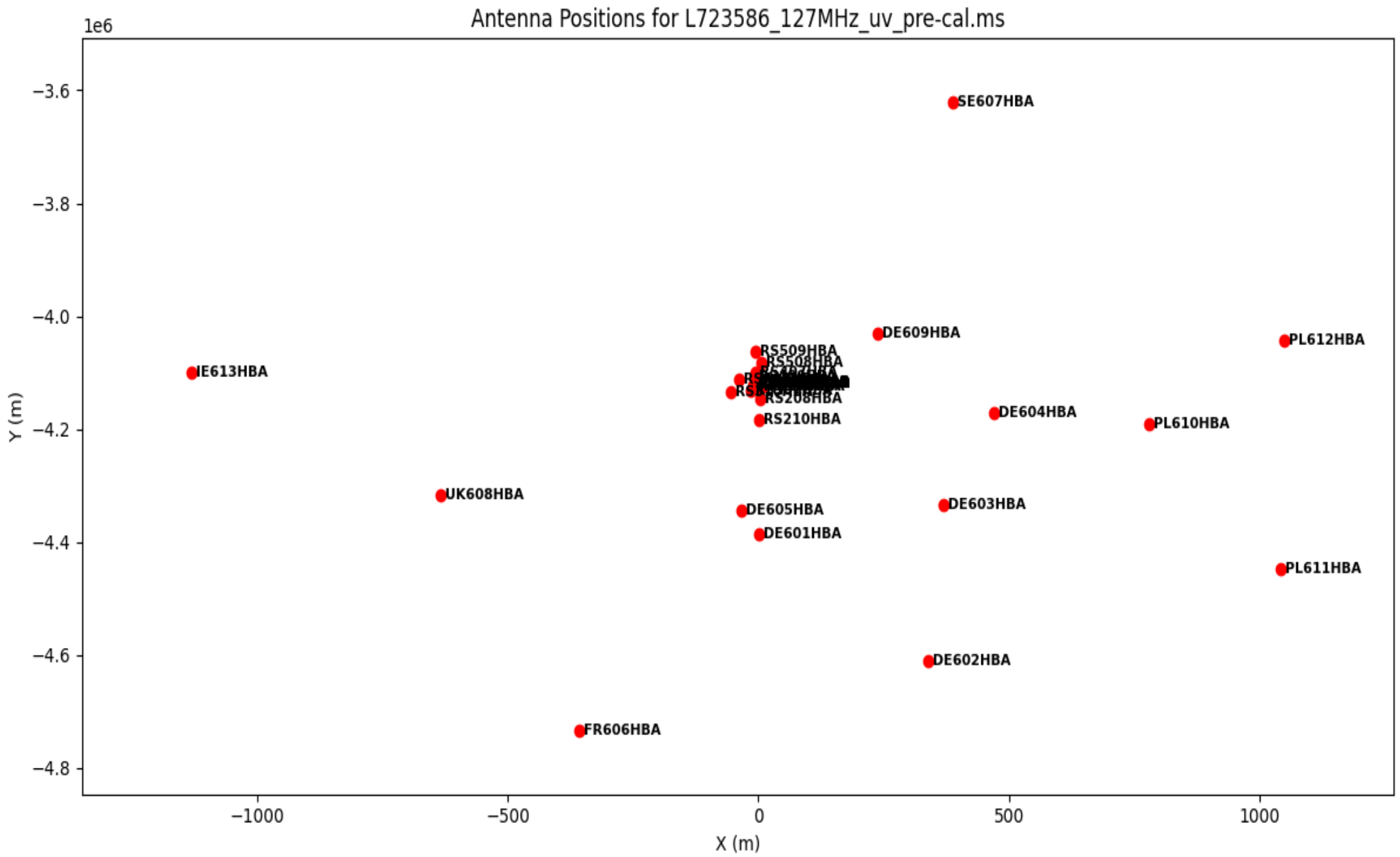
Email:
hrishikesh.shetgaonkar@uni-wuerzburg.de
LinkedIn:
https://www.linkedin.com/in/hrishikesh-shetgaonkar/



VLBI SelfCal, Pass 1, Target, Restored



(0.66° x 0.66°)


Antenna Positions for L723586_127MHz_uv_pre-cal.ms
1e6
−3.6
−3.8
−4.0
−4.2
−4.4
−4.6
−4.8
Y (m)
−1000
−500
0
500
1000
X (m)
SE607HBA
DE609HBA
PL612HBA
IE613HBA
RS509HBA
RS208HBA
RS210HBA
DE604HBA
PL610HBA
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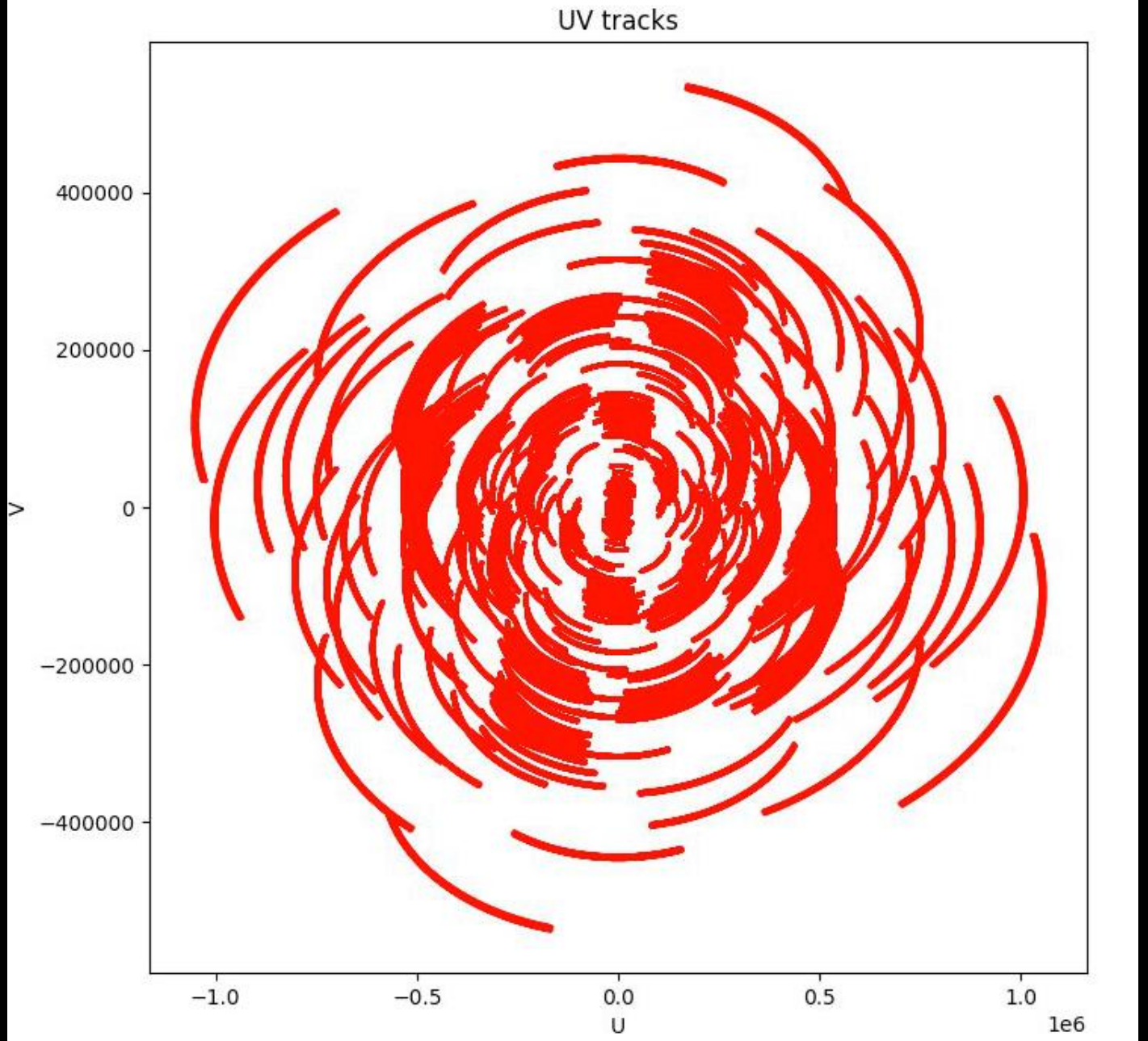
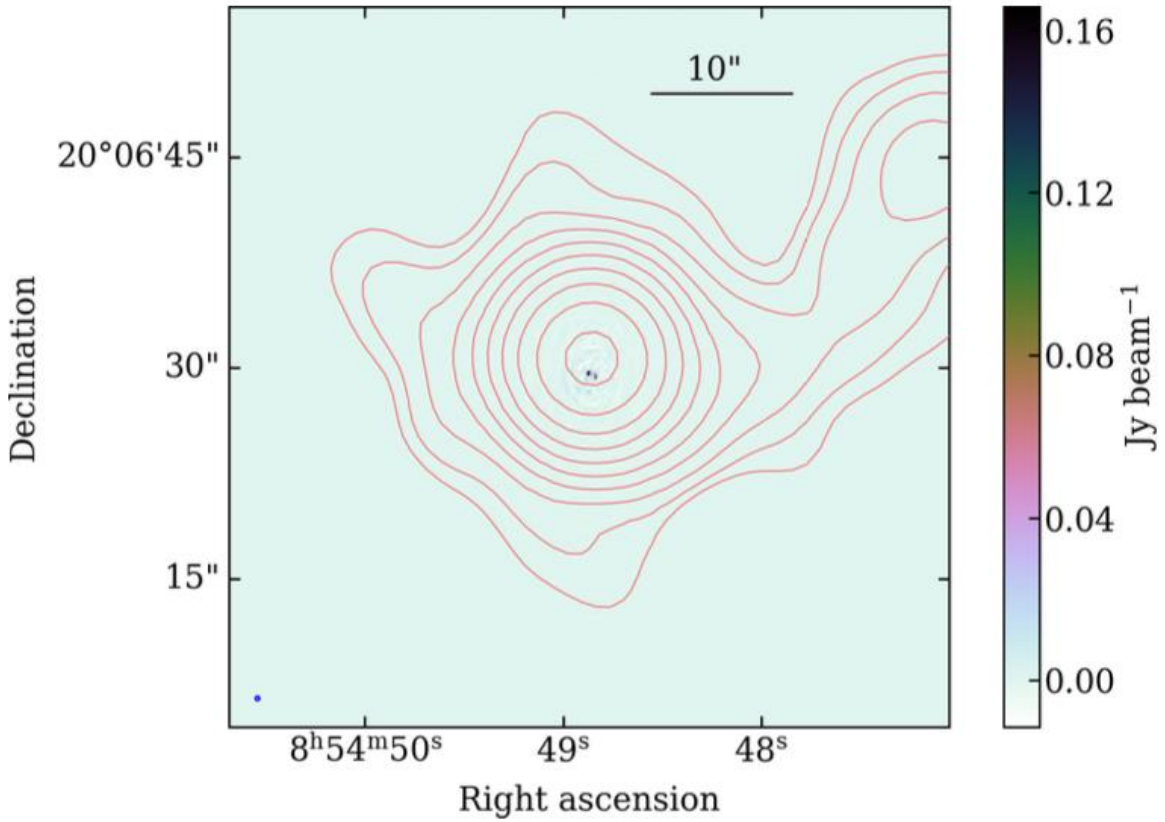
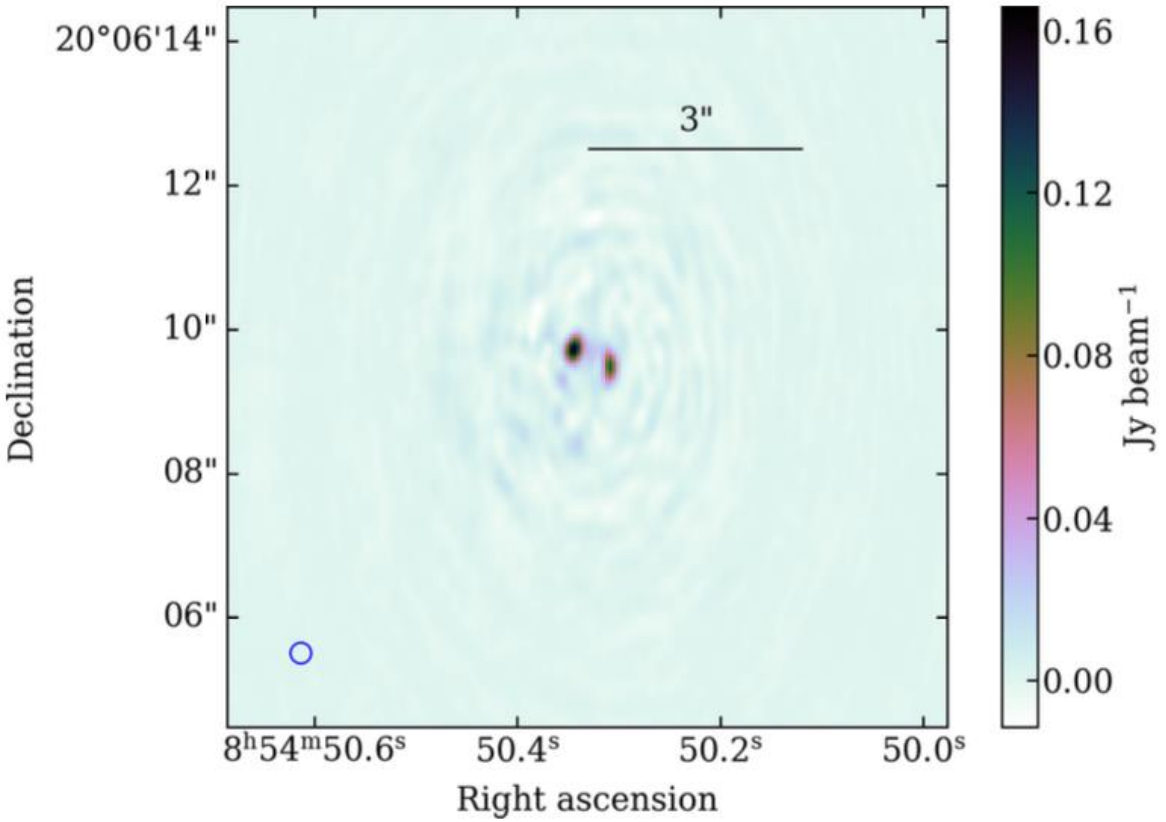
DE601HBA
DE603HBA
PL611HBA
DE602HBA
FR606HBA

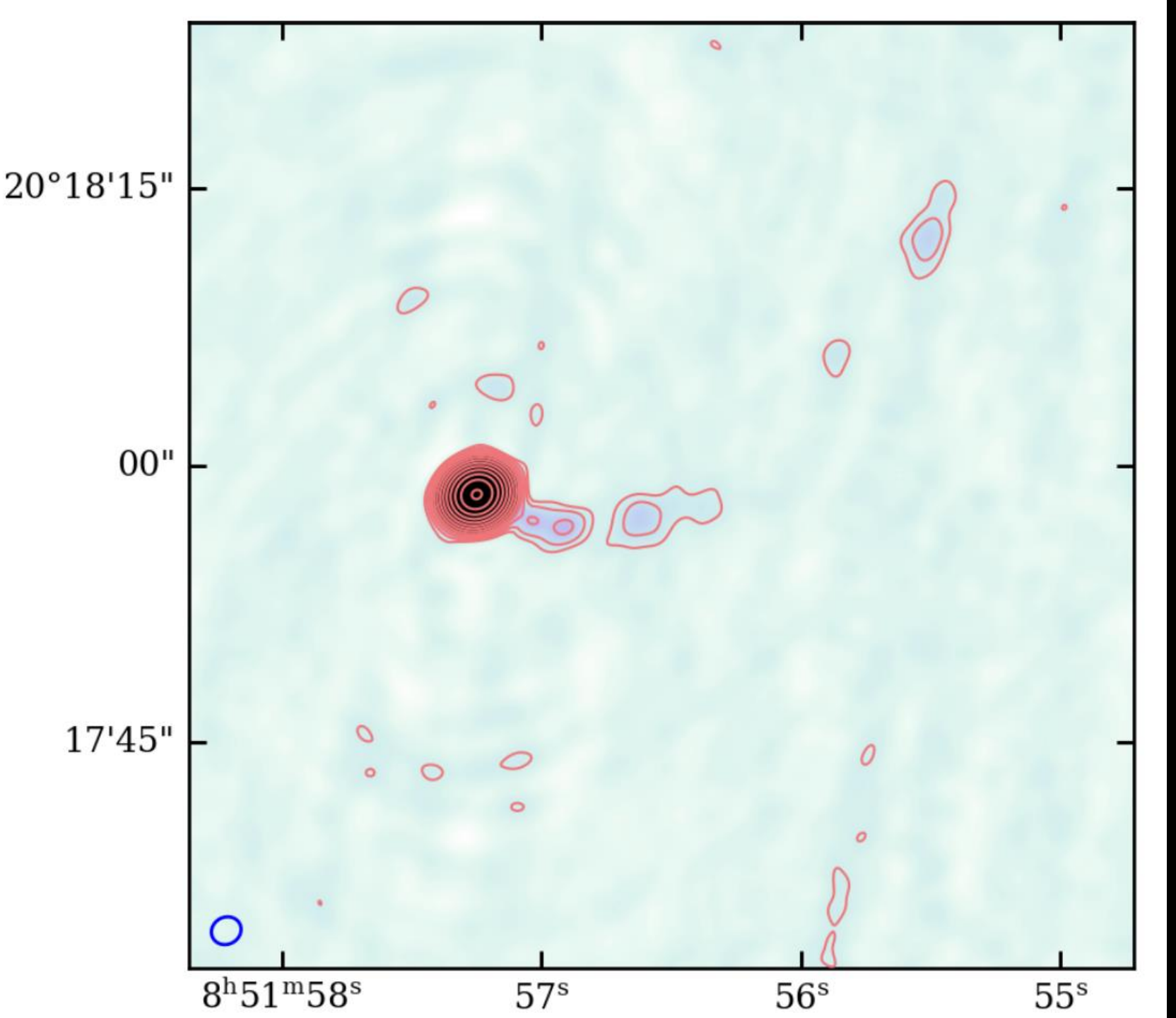

UV tracks
400000
200000
0
−200000
−400000
V
−1.0
−0.5
0.0
0.5
1.0
U
1e6

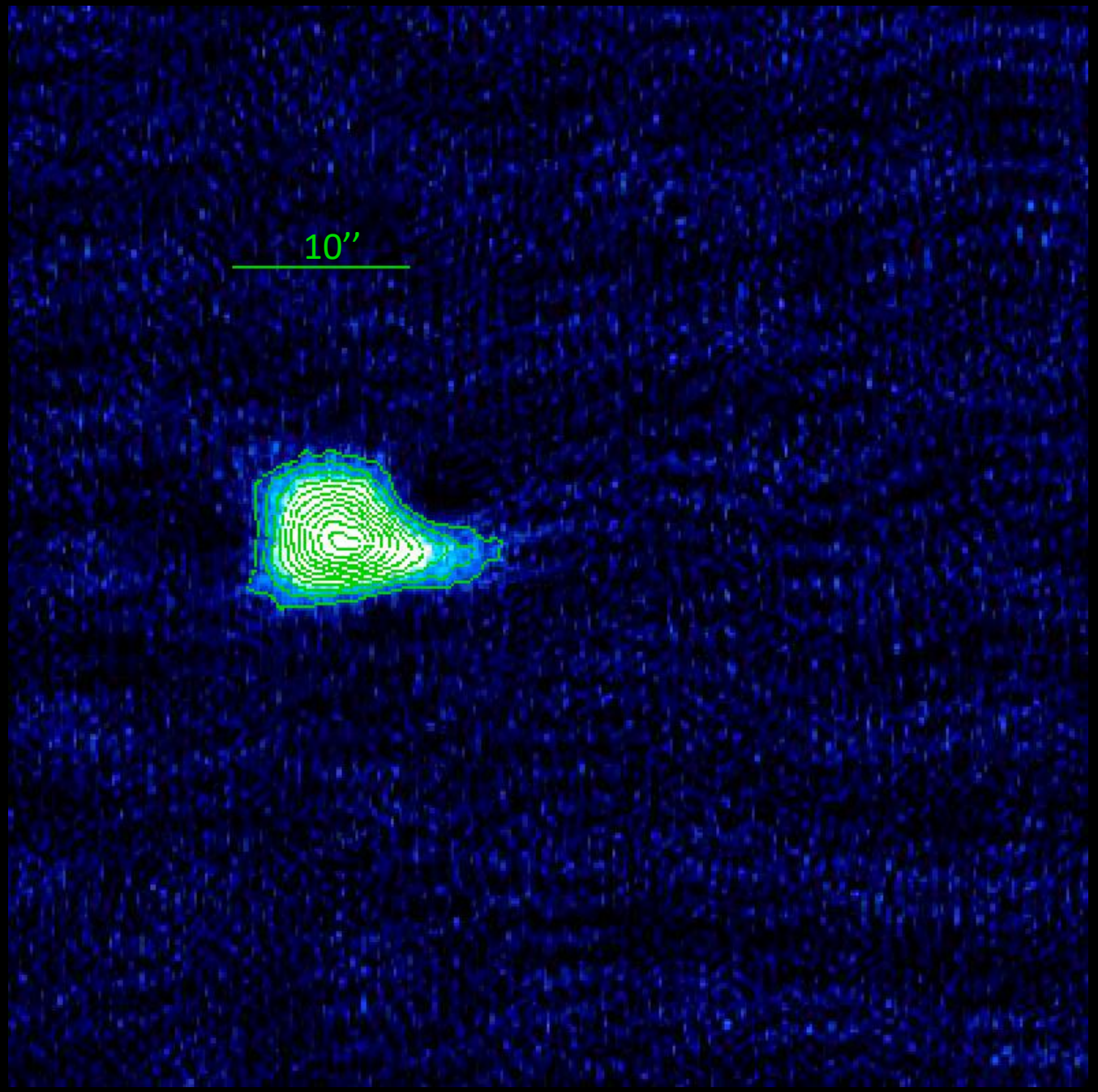


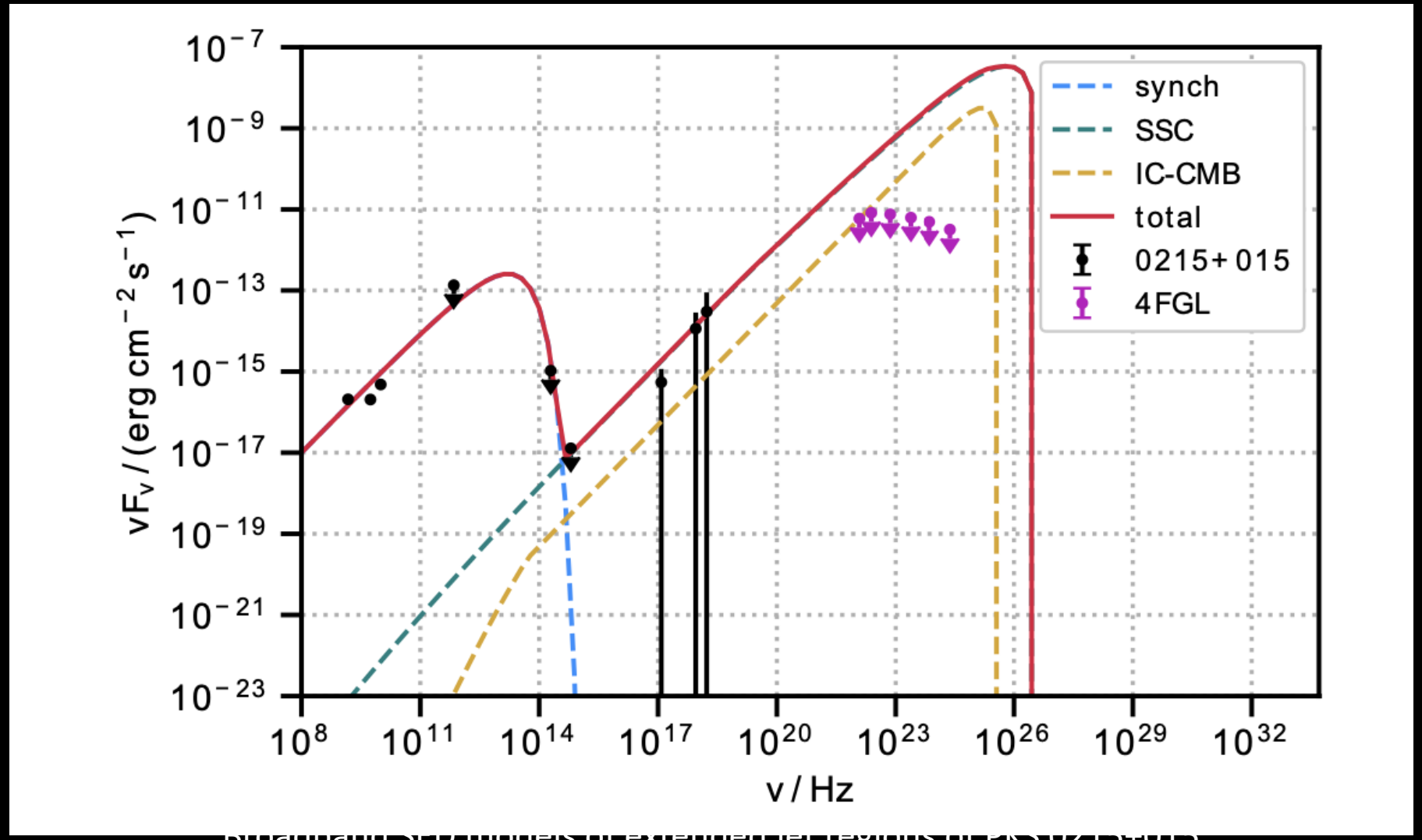
(a) Image that includes the international stations (colour map) overlaid with data from just the core and remote stations (contours).



(b) A $10'' \times 10''$ cutout of the image that includes the international stations.


20°18'15"
00"
17'45"
8h51m58s
57s
56s
55s

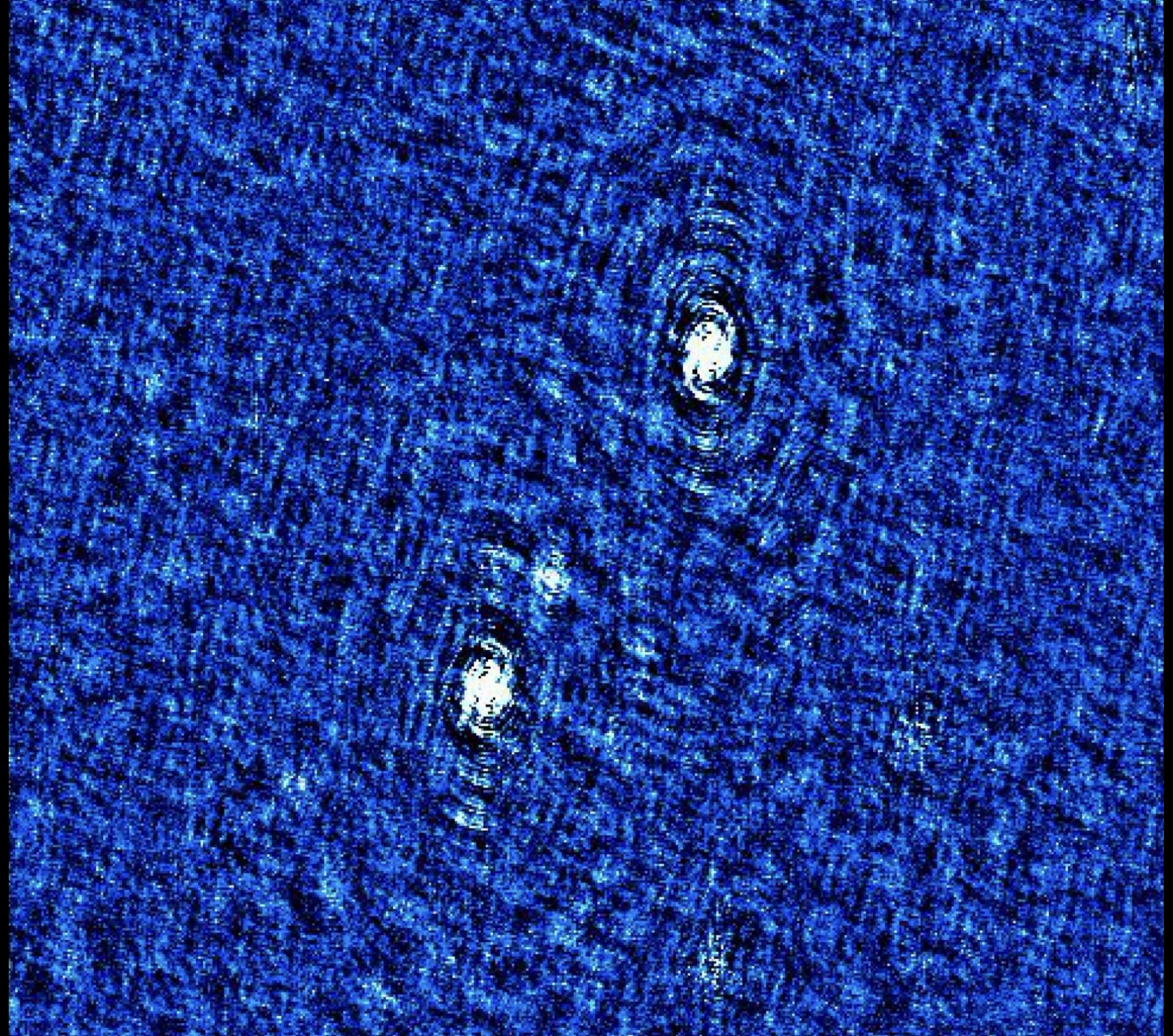

10’’

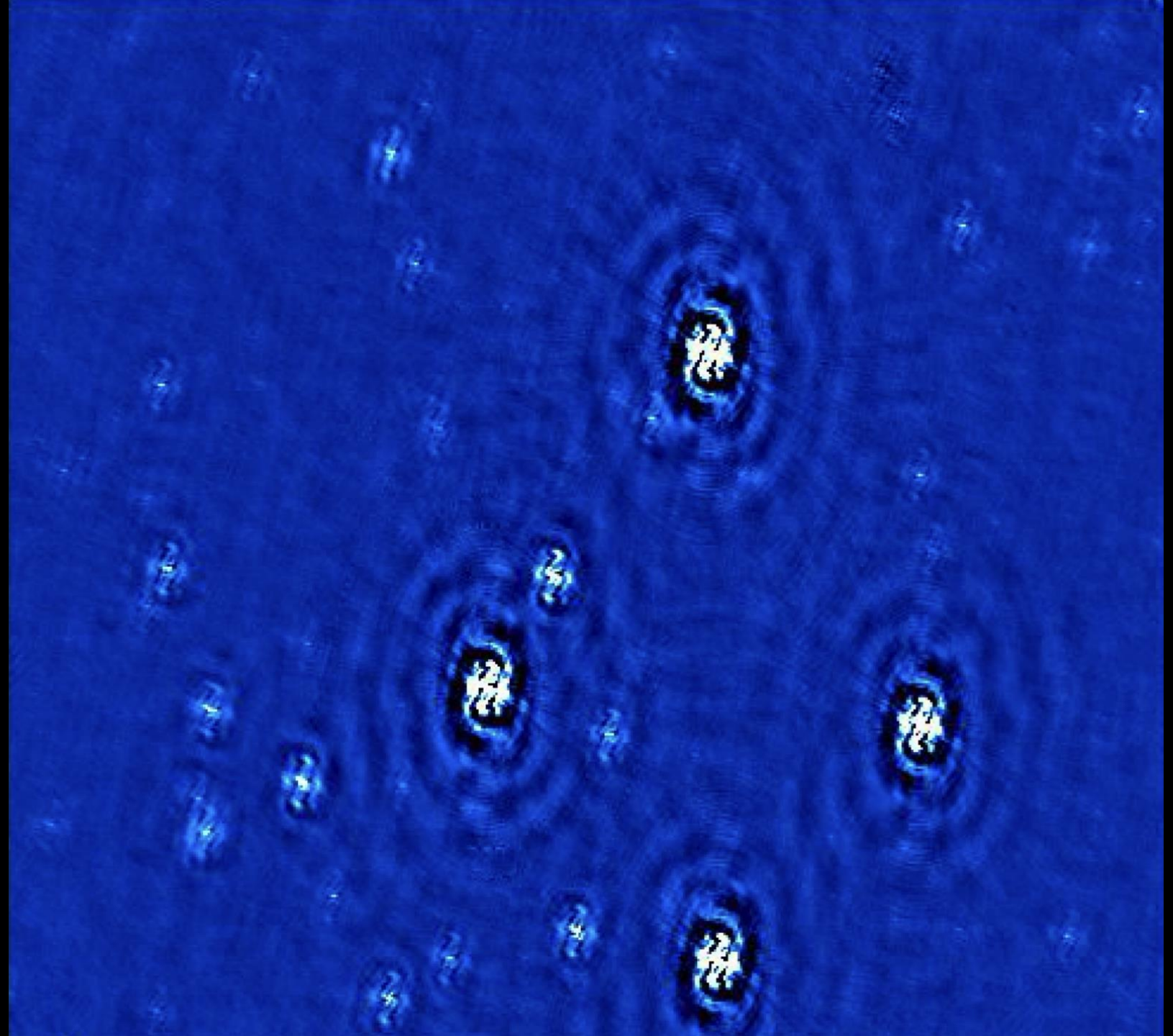


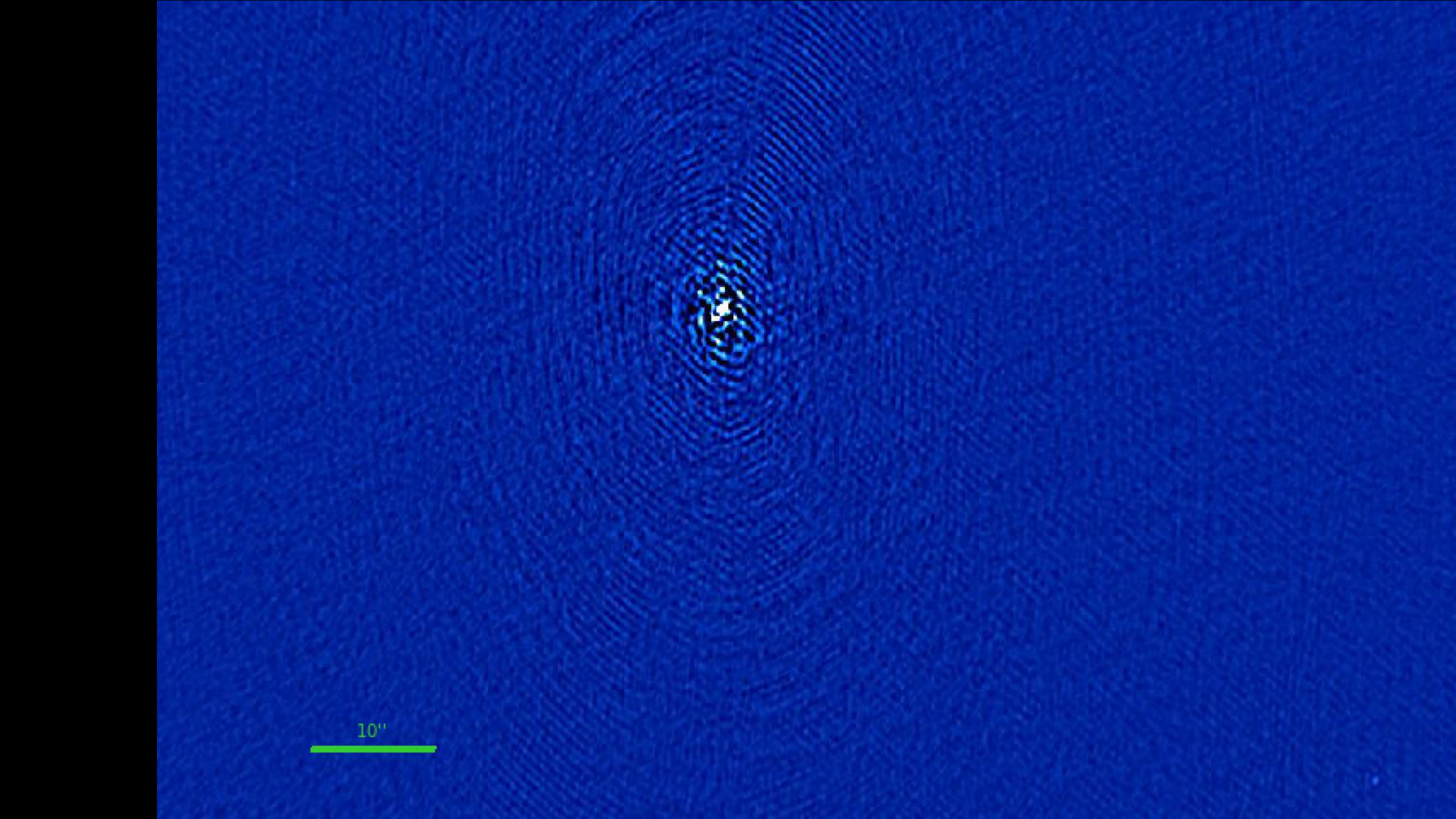
Broadband SED models of extended jet regions of PKS 0215+015

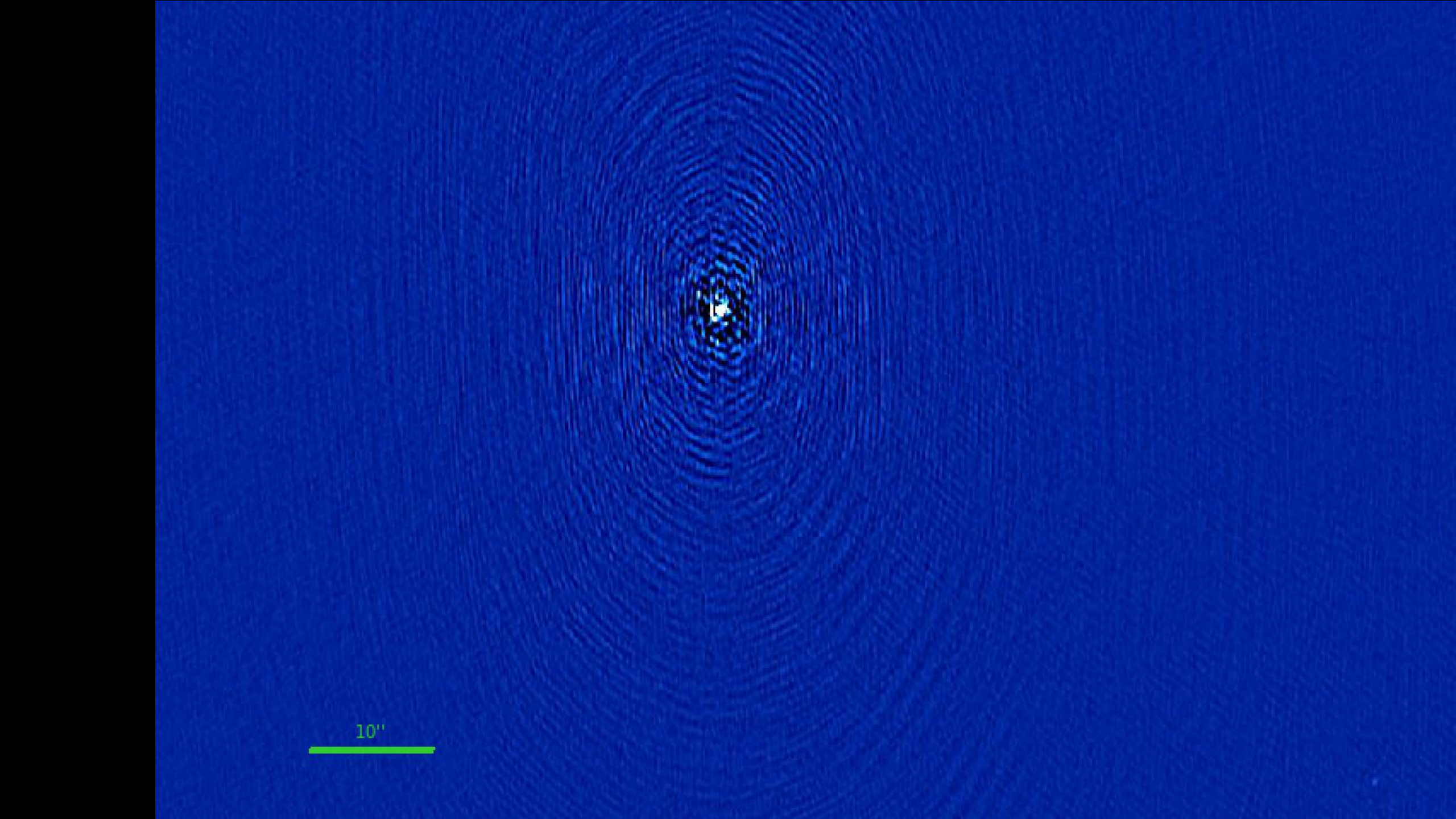
Sebastian B., Kharb P., et al (2020)

```
center=133.72709 20.109456
fk5
1 pixel = 0.2 arcsec

reg     sum            error   area           surf_bri        surf_err
                               (arcsec**2)    (sum/arcsec**2) (sum/arcsec**2)
---     ---            -----   -----------    --------------- ---------------
1       -0.28891329    0.537507 1477.8        -0.000195502    0.000363721

reg     sum     npix    mean    median  min     max     var     stddev  rms
---     ---     ----    ----    ------  ---     ---     ---     ------  ---
1       -0.28891329 36945 -7.82009e-06 -2.4712e-05 -0.016241 0.0152849 1.55683e-05 0.00394567 0.00394568
```






10''


10''

Observation Description	A S
1641+399/1/TO (Target Observation)	
3C196/1/CO (Calibration Observation)	
1803+784/1/TO (Target Observation)	
3C48/1/CO (Calibration Observation)	
2230+114/1/TO (Target Observation)	
3C48/1/CO (Calibration Observation)	
1226+023/1/TO (Target Observation)	
3C196/1/CO (Calibration Observation)	
1823+568/1/TO (Target Observation)	
3C48/1/CO (Calibration Observation)	
0838+133/1/TO (Target Observation)	
3C196/1/CO (Calibration Observation)	


Stay on target