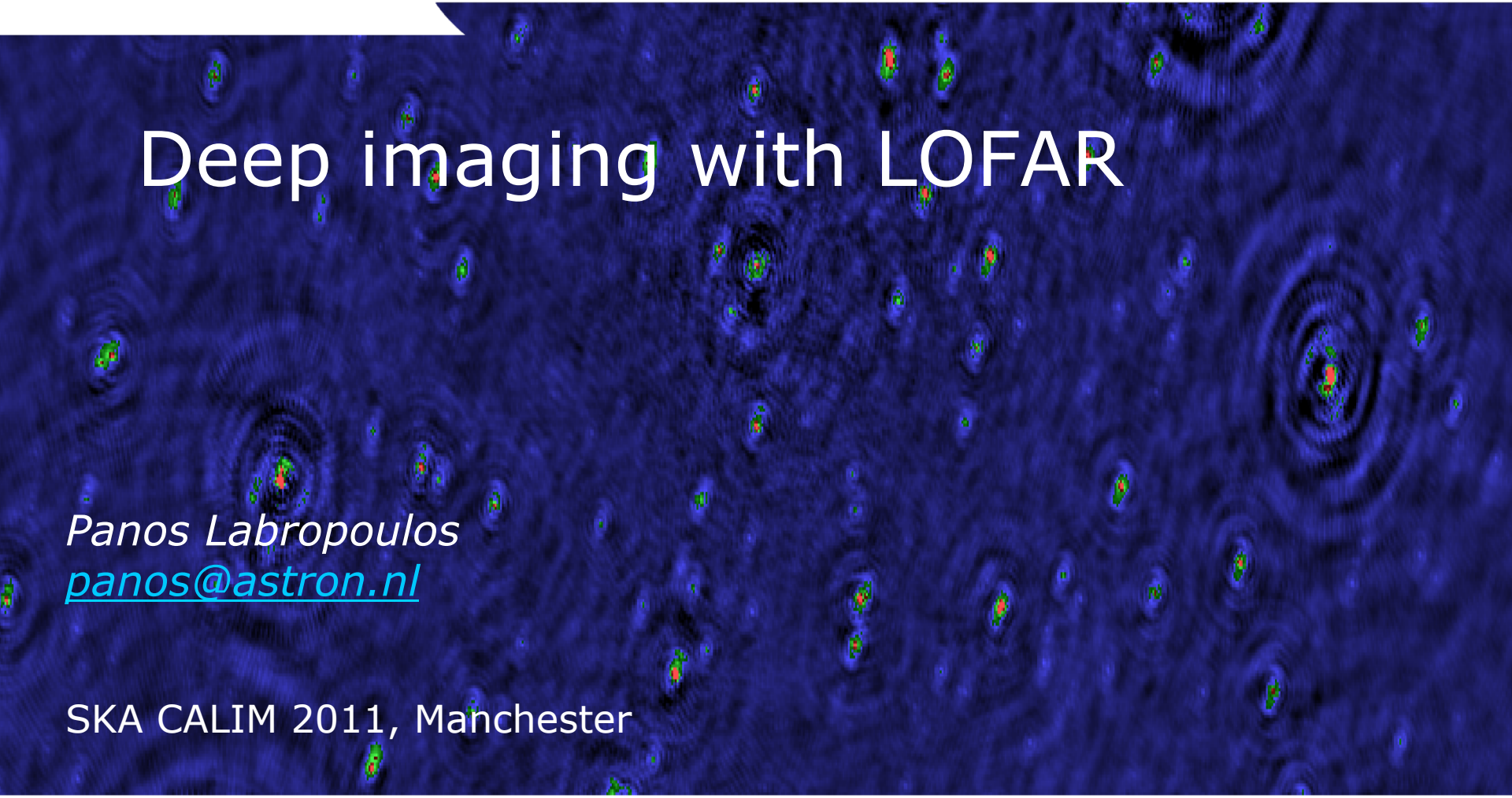
Deep imaging with LOFAR



Panos Labropoulos
panos@astron.nl

SKA CALIM 2011, Manchester

-0.0049 0.0095 0.024 0.038 0.053 0.067 0.081 0.096 0.11

Outline

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- Motivation
- EoR Cluster
- Calibration pipeline
- Directional dependent effects

Motivation

The Epoch of Reionization (EoR) Key Science Project (KSP) on the other hand requires beating down the thermal and systematic noise by continuously repeating the same observations on the same fields.

- Up what integration time can we reach the thermal noise?
- Does LOFAR have long term stability/systematic errors?
- What fraction of data is unusable due to RFI, ionosphere, bad calibration solutions?
- EoR strategy: day time vs night time, bright source in P.C., are foreground removal techniques adequate for sensitivities well below classical confusion?

LOFAR Early Access proposal 128: Weekly monitoring of the 3C196, J2000 NCP and a field with no bright sources (> 1 Jy)

EoR signal

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Effects on strategy – Strong Foregrounds

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Mild foregrounds

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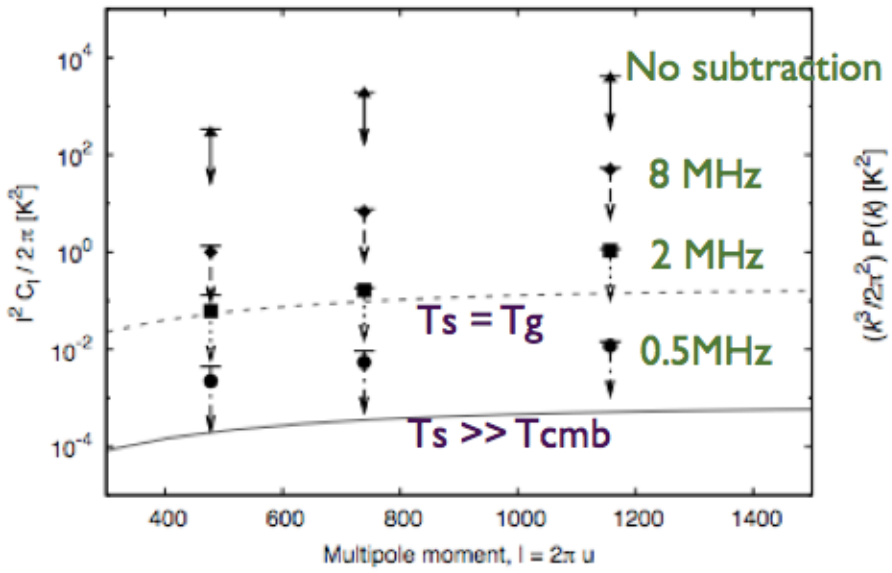
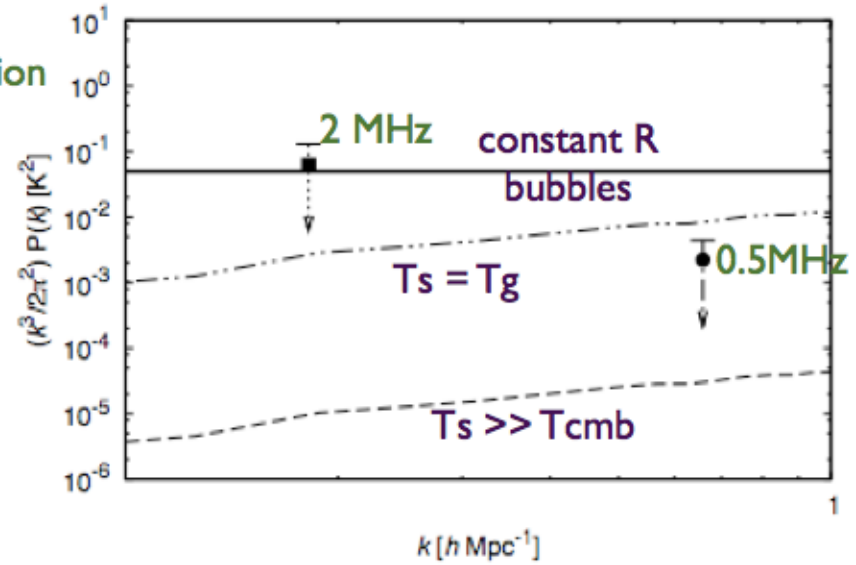
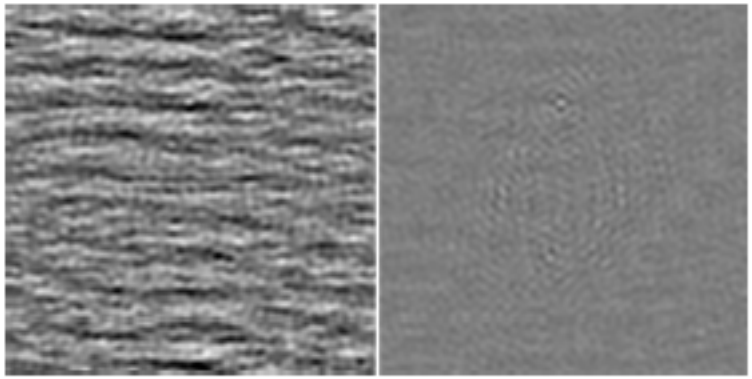
GMRT EoR



Jelic 08 models



Iliev 08 models



Paciga et al., 2010

3C196 vs NCP

3C196	NCP
high SNR for calibration	3C61.1 (5 Jy) off P.C. -> dynamic range
DEC 48 (Station Beam?)	**DEC 88**
Less noise due to the Galaxy	Stronger Galactic foregrounds
-	**RFI studies (0 fringe rate RFI)**
Observed with WSRT	Observed with WSRT

Observation specifications

- Phase center: 3C 196 (**76.8 Jy** at 150 MHz, α=0.64), NCP

3C196: R.A. = 08:13:36.00, δ= **+48.13.02.00** (l=171,b=33)

- NCP: R.A. = 04:00:00.00, δ= **+88.00.00.00** (l=124,b=25)
- Frequency range: **115-163 MHz**
- 248 sub-bands (0.183MHz)
- 15 x 12.2 kHz channels after compression
- **2 sec** avg. time, **6 hours** of synthesis
- **~8 arcsec** resolution

Available data

LEA128: Weakly monitor of the 3C196, NCP and an empty field using the HBAs (6h runs, 11 weeks) – also plan to observe other fields (Elias-N1, 3C 192, galactic cold spot,…)

LEA102: Using the Moon to measure the Moon to measure the global sky temperature and its spatial and spectral dependence at 60 and 150 MHz (4 nights, 3C 123 as calibrator)

24h RFI monitoring runs (+ raw LEA128 data sets)

MSSS: multi-beam A-team observation

A team observations

Total 240 TB of data

System stability

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Assume sky is mostly unpolarized and use XY,YX correlations to measure noise

7 Jan 2011	L22667	SB100	S/N = 18.6
28 Jan 2011	L23092	SB100	S/N = 17.0
11 Mar 2011	L23927	SB100	(S/N > 14.8)
19 Mar 2011	L24380	SB101	S/N = 24.1
1 Apr 2011	L24837	SB100	S/N = 28.3
15 Apr 2011	L25489	SB100	S/N = 20.0
29 Apr 2011	L24801	SB100	S/N = 27.7

Stability: Data

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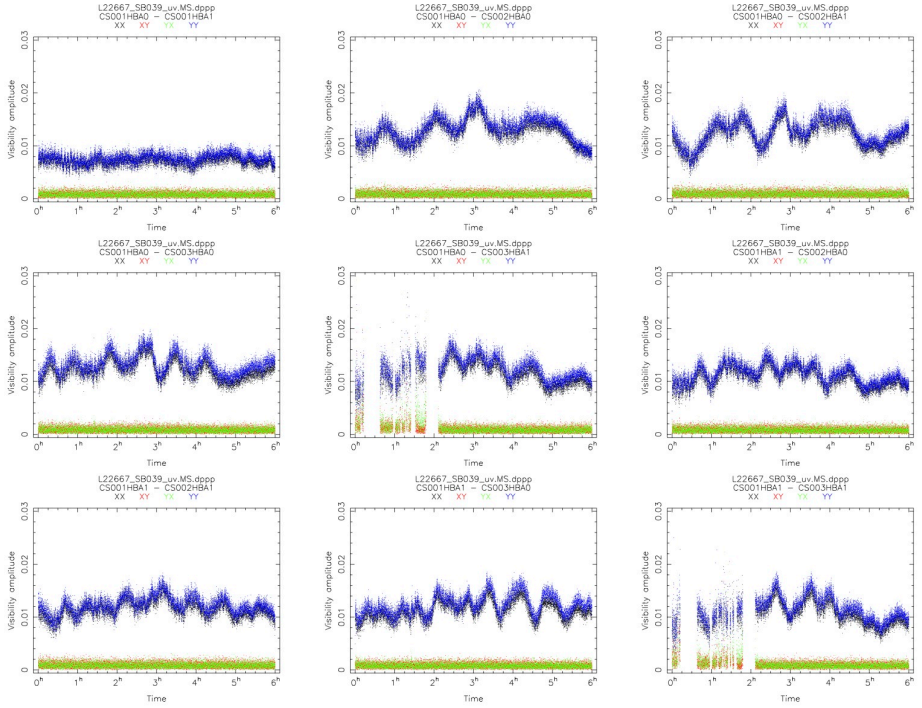
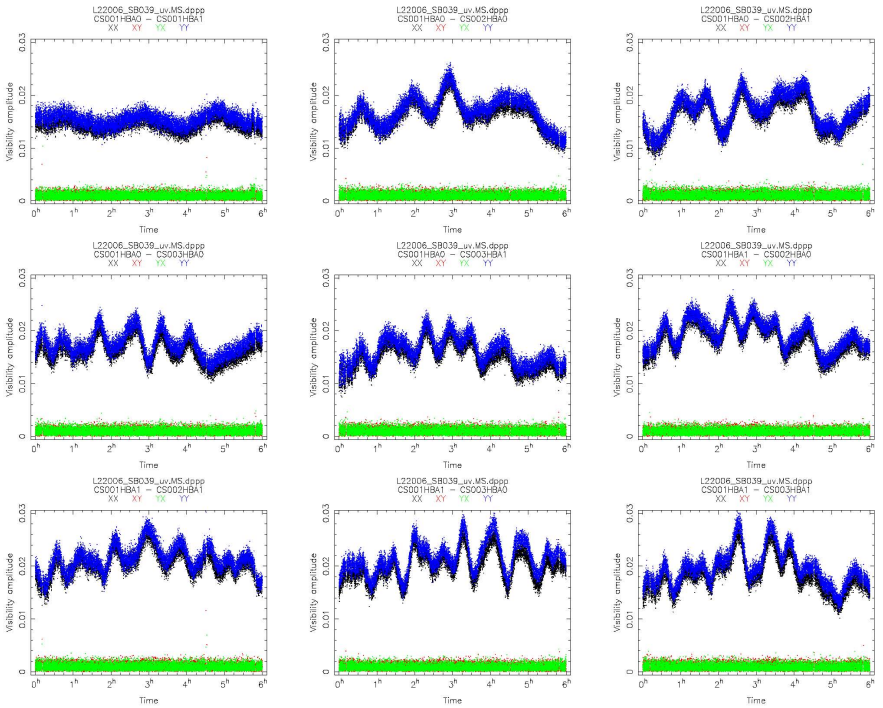
22006



22667



Motivation

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The EoR KSP will observe 5 windows with:

~6 beams in two bands (total 64MHz/10KHz=6400 channels)

Full stokes

1200 baselines

10 sec integration – 100 nights of 4 hours

It will accumulate **1.5 PB data**

Desired dynamic range is 10^6:1

After calibration: Maximum Likelihood inversion ($O(N^3)$ process) for map making (requires 10^{21} FLOPs or 140 days at a sustained 10 TFLOP computer)

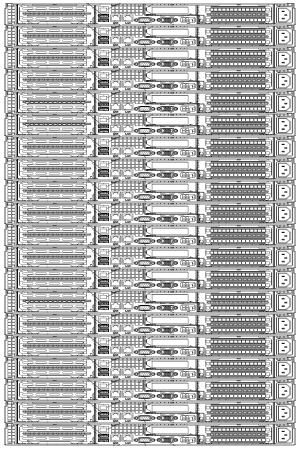
Cluster Layout

Lofareor01 inlog machine
Lofareor05 supporting machine
(alleen system administrators kunnen op deze machine inloggen)

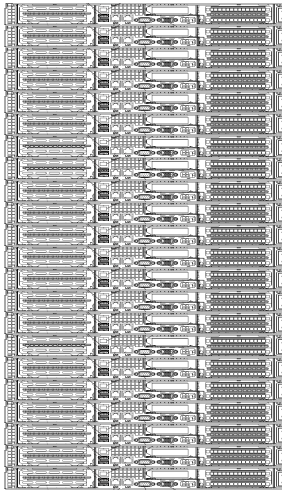
192.168.235.1 t/m 40
192.168.235.41 t/m 80
Impi 192.168.235.101 t/m 140
Impi 192.168.235.141 t/m 180

Netwerk switches worden ver bonden met 4 x 10 gb glas verbindingen. Totaal 40 gb

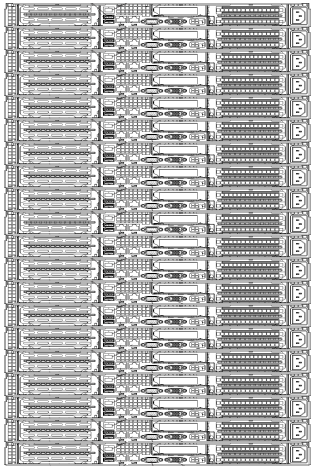
node001
node005
node009
node013
node017
node021
node025
node029
node033
node037
node041
node045
node049
node053
node057
node061
node065
node069
node073
node077



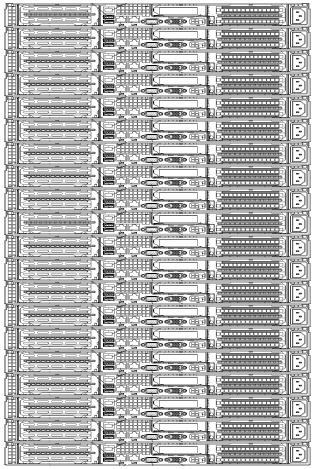
lofareor01
lofareor05
node002
node006
node010
node014
node018
node022
node026
node030
node034
node038
node042
node046
node050
node054
node058
node062
node066
node070
node074
node078



node003
node007
node011
node015
node019
node023
node027
node031
node035
node039
node043
node047
node051
node055
node059
node063
node067
node071
node075
node079



node004
node008
node012
node016
node020
node024
node028
node032
node036
node040
node044
node048
node052
node056
node060
node064
node068
node072
node076
node080



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Location

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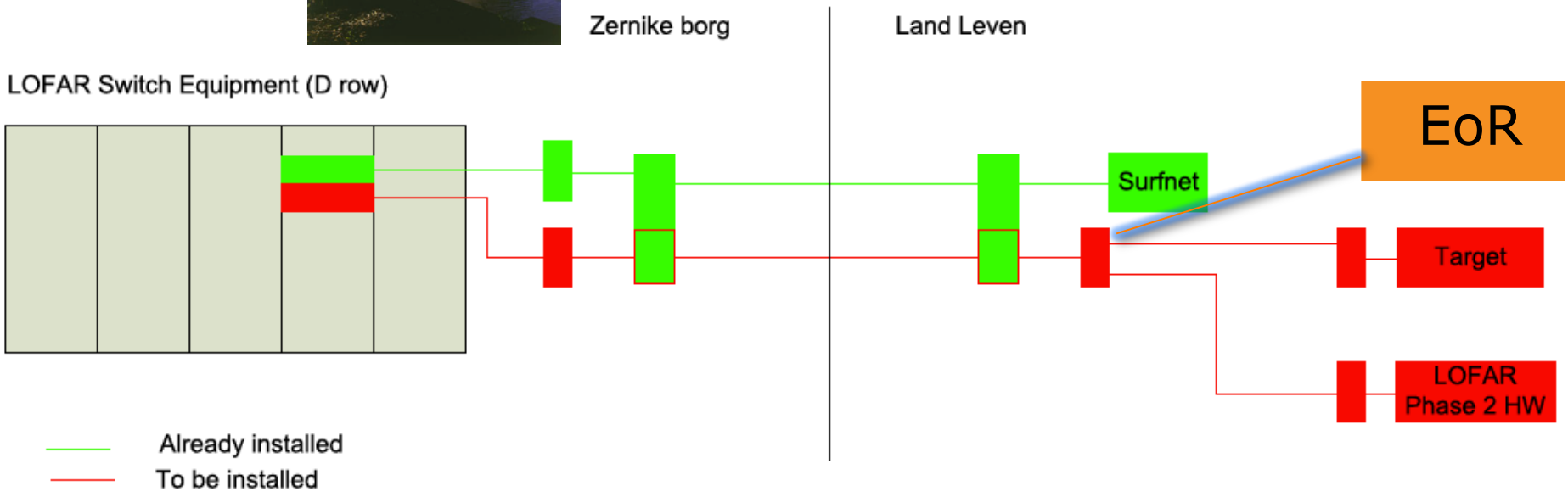


-2 x 1GBs to the world
-4 x 10GBps connections to the TARGET cluster

Hardware

- 4x Intel Xeon E5520 @ 2.27 GHz
- 12 GB RAM

  2x 2TB SATA HDDs

  2x 1GBps NICs
- **2x NVIDA TESLA C1060 GPUs (4G DDR3 RAM)**

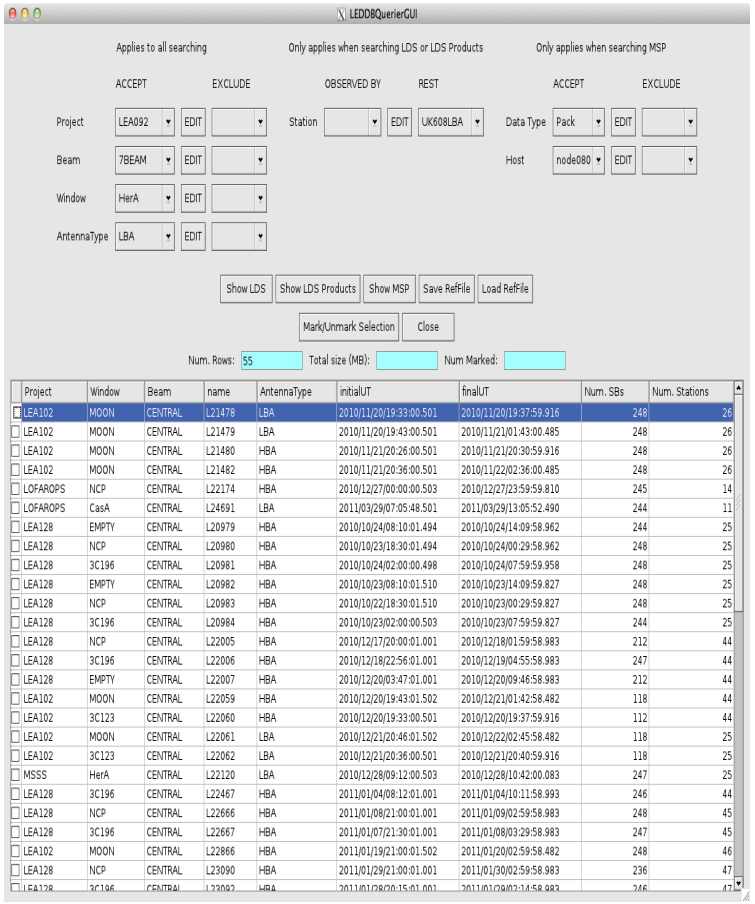
  Centos LINUX 5.5

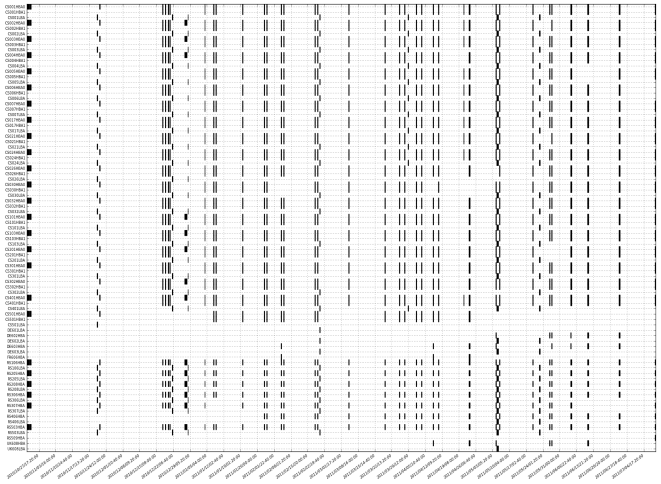
  LOFAR software installed

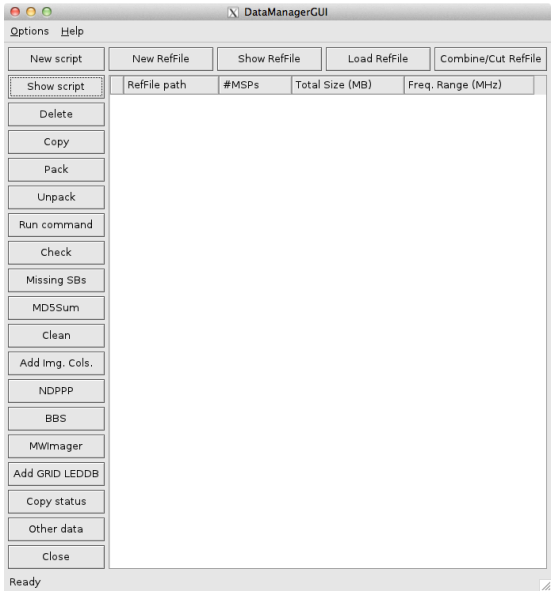
  Grid software for transfers to LTA (160MB/s ~ 80% 2Gbps)

Diagnostic database

Contains metadata about observations and data quality (RFI, failing tiles, noise, solutions etc)

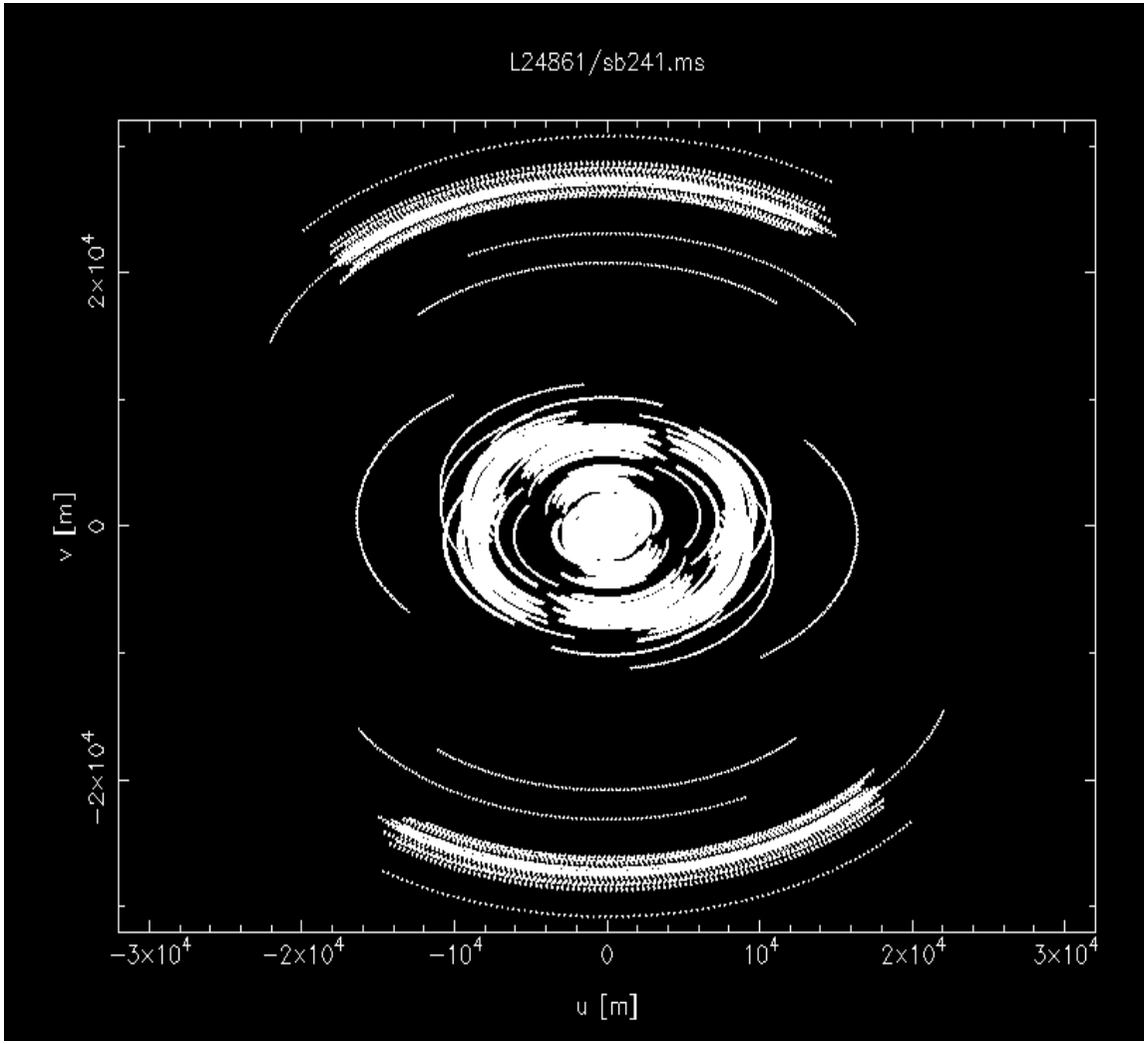







ClusterMonitorGUI
STORAGE
CPU
MEM
NET
GPU
GPU MEM
AutoUpdate [s]: None
Select user: lofardat
Select command: None
Kill
Close
lofardat CPU
ALL CPU
lofareor01 0.0 0.0
node001 1133.8 1133.8
node002 1029.5 1029.5
node003 804.0 804.0
node004 3.9 3.9
node005 Error Error
node006 1390.4 1390.4
node007 17.7 17.7
node008 1399.0 1461.0
node009 809.3 811.3
node010 1575.7 1581.6
node011 2.0 1476.1
node012 7.9 1507.1
node013 2.0 1472.4
node014 15.8 1486.1
node015 0.0 102.4
node016 0.0 102.8
node017 23.6 1498.9
node018 2.0 453.7
node019 2.0 1103.3
node020 11.8 1474.1
node021 27.7 521.6
node022 2.0 483.1
node023 13.7 1506.0
node024 2.0 100.3
node025 13.8 1480.5
node026 2.0 1492.9
node027 13.8 112.6
node028 0.0 1484.9
node029 39.2 139.1
node030 0.0 570.4
node031 13.8 511.0
node032 2.0 102.3
node033 11.8 1490.6
node034 1.9 1397.0
node035 15.8 114.6
node036 4.0 688.0
node037 1.9 592.1
node038 21.6 476.7
node039 1047.4 1047.4
node040 997.0 999.0
node041 1336.7 1338.4
node042 1017.2 1019.1
node043 808.2 808.2
node044 964.7 966.6
node045 974.7 974.7
node046 1362.7 1362.7
node047 1494.3 1506.1
node048 1260.0 1269.9
node049 1256.8 1256.8
node050 1428.7 1428.7
node051 778.5 812.1
node052 1498.2 1506.1
node053 1133.9 1133.9
node054 803.1 803.1
node055 803.7 803.7
node056 805.8 821.5
node057 846.3 852.2
node058 1049.4 1049.4
node059 805.0 807.0
node060 898.4 936.0
node061 1092.3 1101.9
node062 1195.2 1195.2
node063 1049.1 1049.1
node064 1045.1 1047.1
node065 1316.2 1325.9
node066 1049.3 1049.3
node067 793.3 812.6
node068 803.9 817.7
node069 1425.4 1436.7
node070 1185.1 1185.1
node071 Error Error
node072 1319.4 1326.1
node073 1084.5 1085.9
node074 1047.7 1051.7
node075 Error Error
node076 Error Error
node077 1494.9 1508.7
node078 2.0 106.6
node079 3.9 3.9
node080 4.0 6.0
Finished update: Thu Jul 7 16:21:39 2011

uv coverage



21 (42) Core stations

5 remote stations

Baselines ~130m up to 27 km

3C 196 Field

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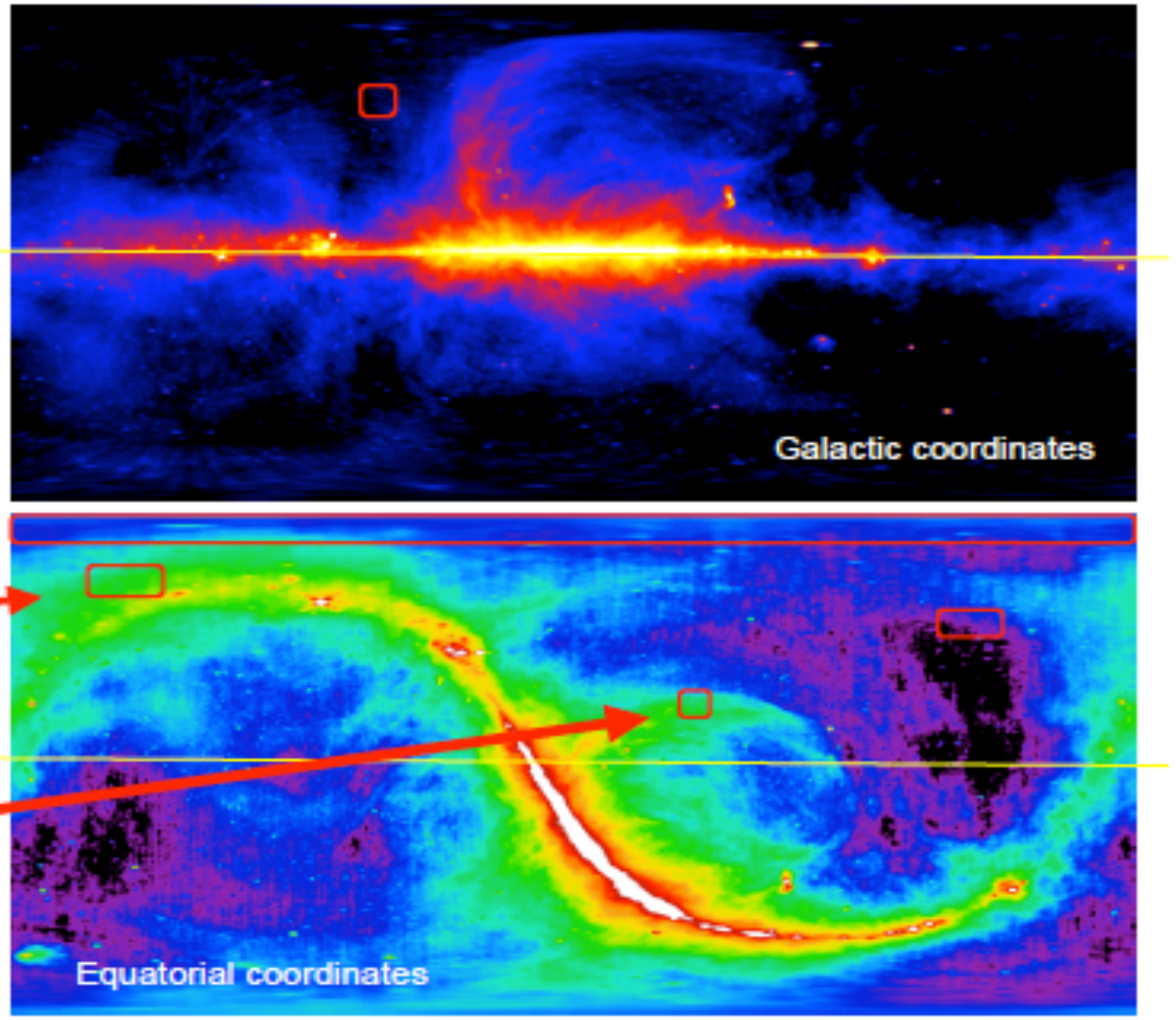


Location of 3 WSRT LFFE-fields (Nov07)

From left-to-right

— NCP

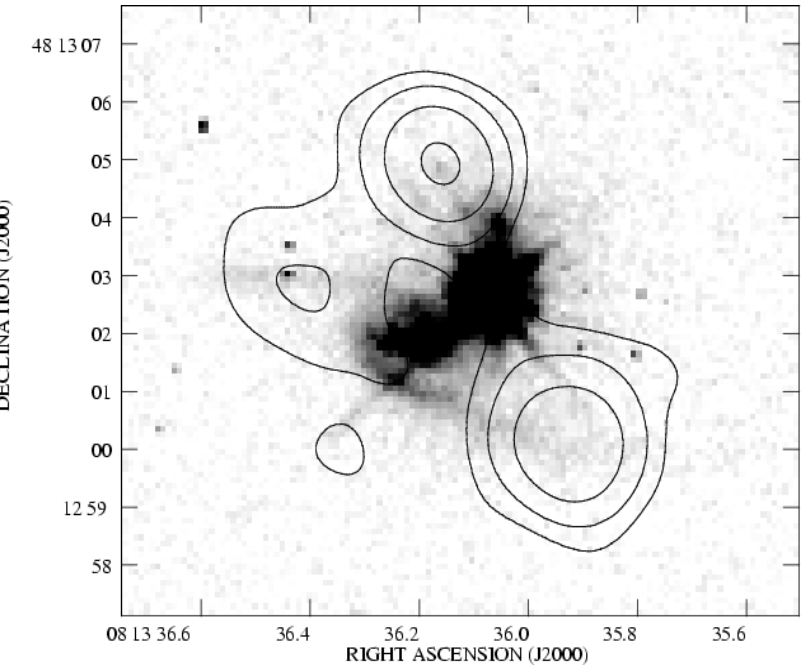
— 'FAN'

— 3C196

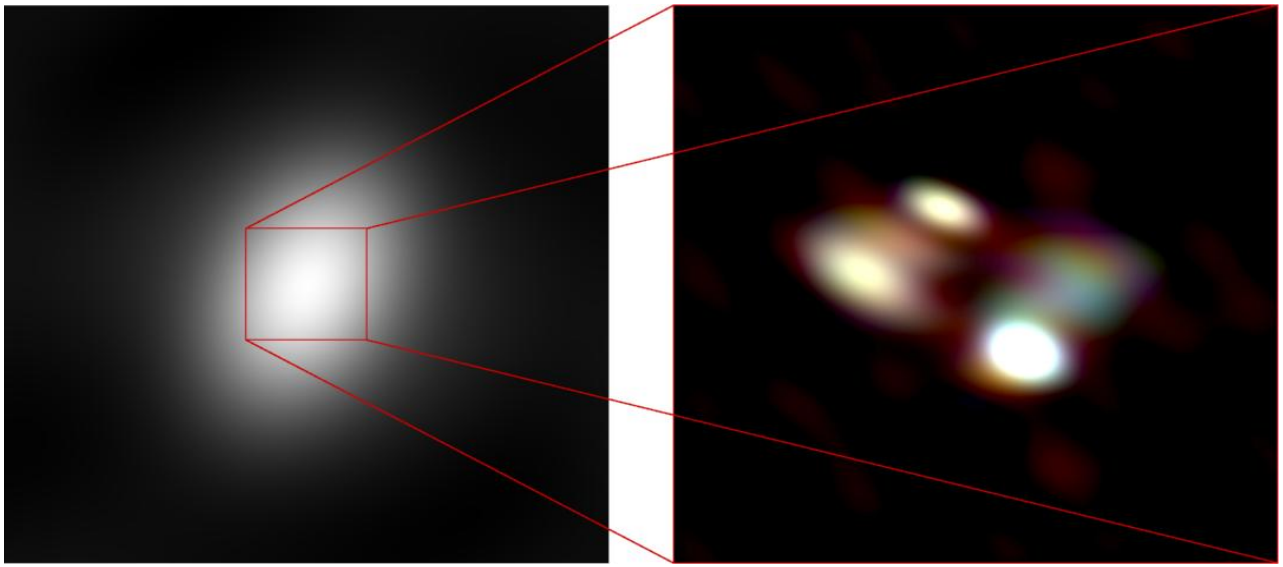
May 2009: NPS field !!

(red box=12°x12° but HPBW ~5°-7° and 'tile' beam ~ 22°)

3C 196



Hardcastle (2001)
HST WFC2

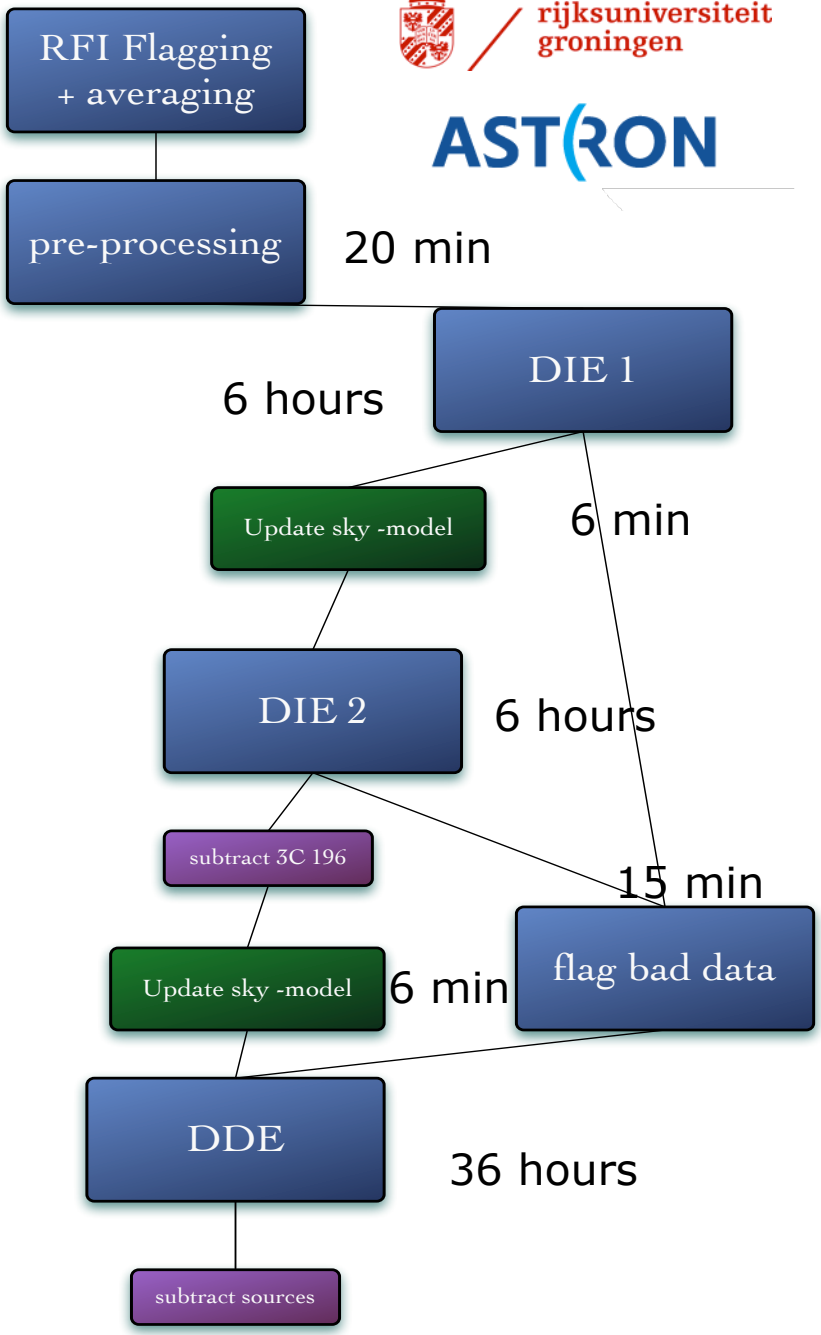


O. Wucknitz
LOFAR Long Baselines

Processing Pipeline

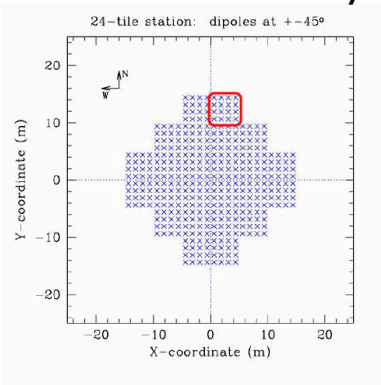
6 hours

- Need a good sky model to begin with. (difference between 5 and 15 mJy rms noise/sbb)
- Beam attenuation complicates the sky model construction.
- Using all baseline combinations, ST-ST,ST-CS,ST-RS, CS-CS, CS-RS, RS-RS -> Different beam sizes
- Flux scale sensitive to initial sky model and use of station beam.
- 70 model component

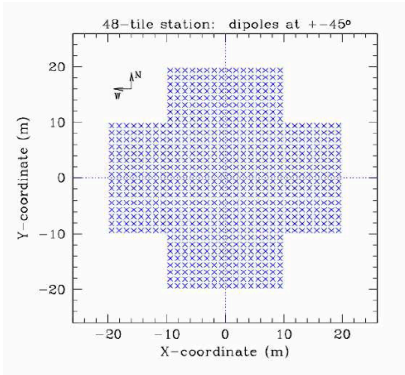


Total: 62.3 hours

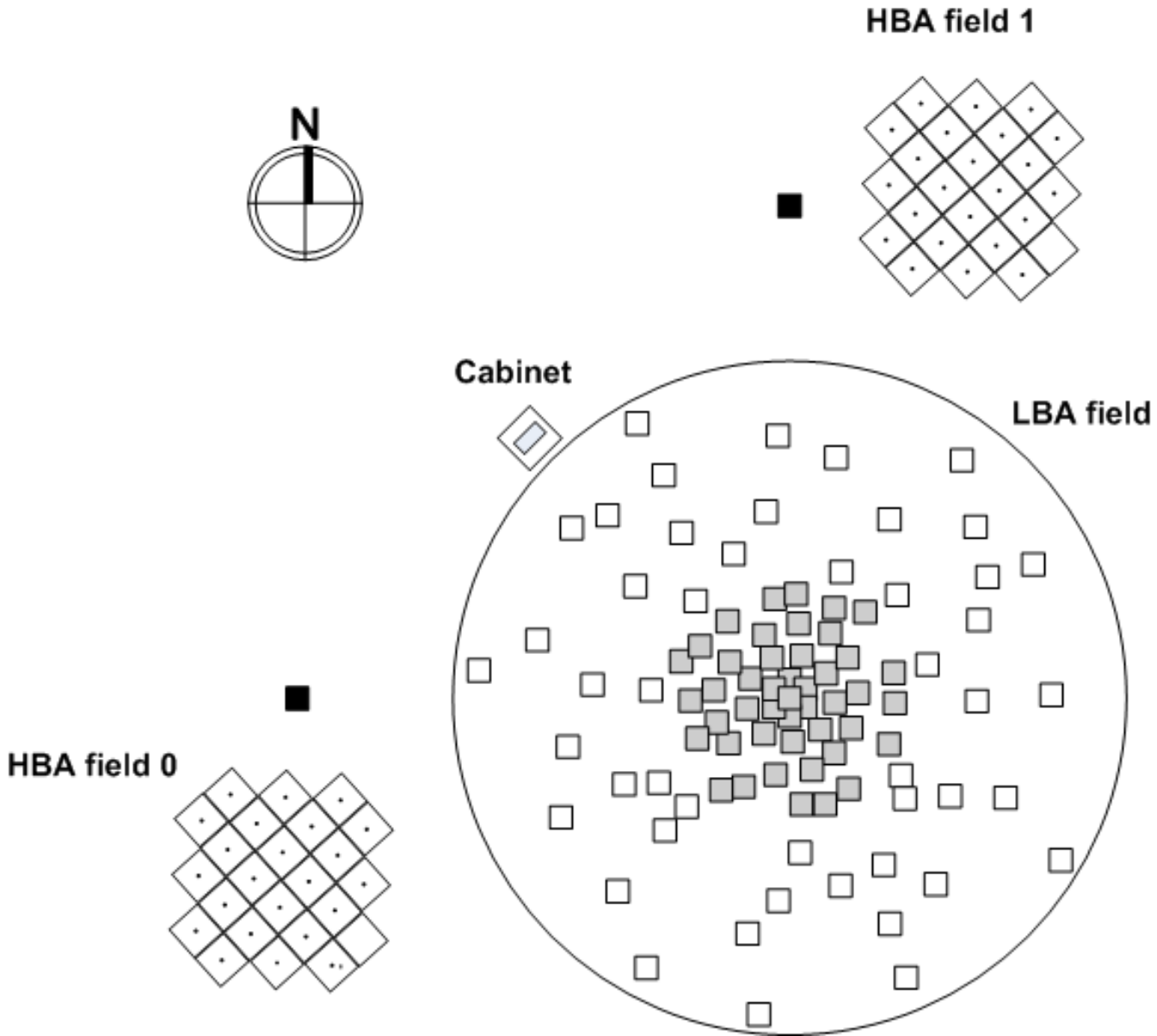
SEFD ~2000 Jy



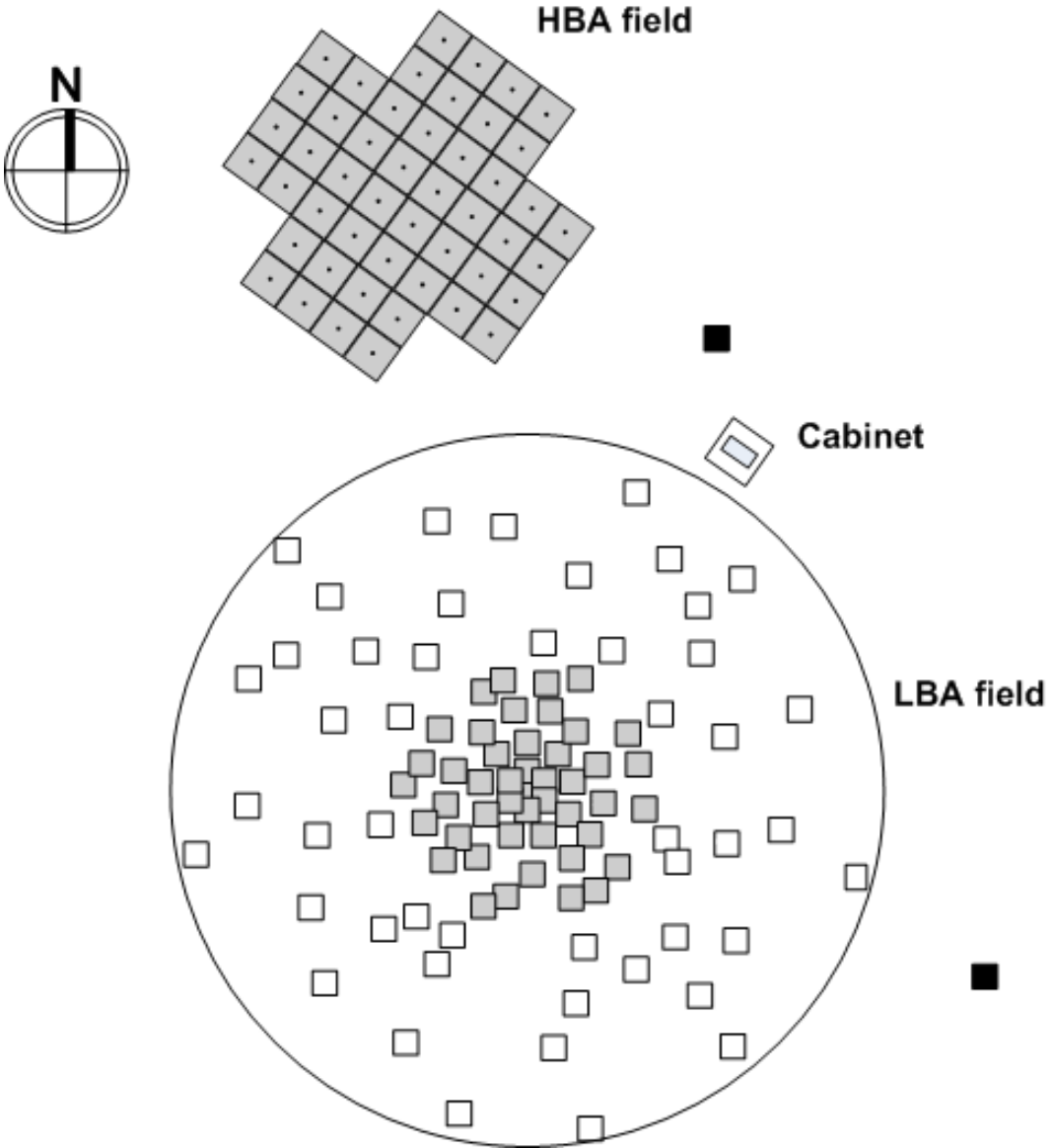
SEFD ~1000 Jy



Core Stations (24)



Remote Stations (16)



International Stations (≥ 8)

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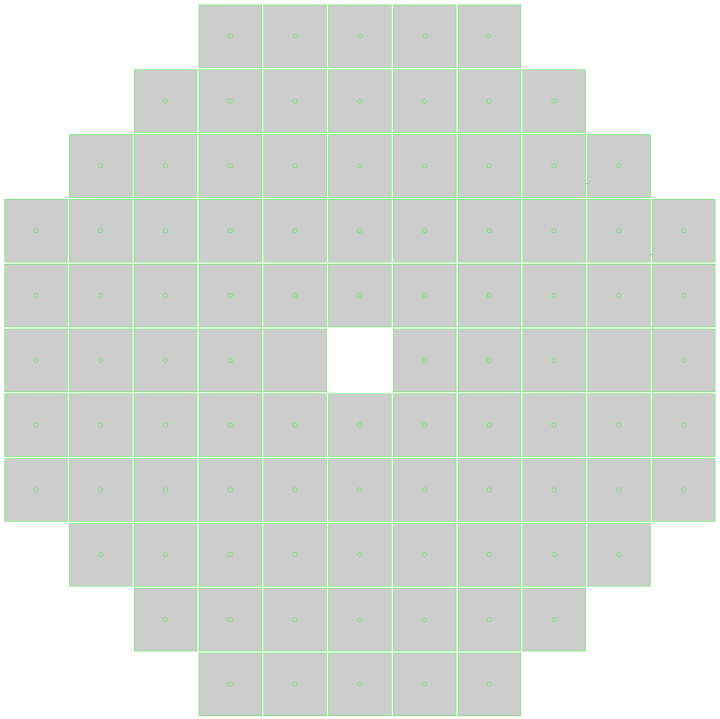
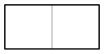
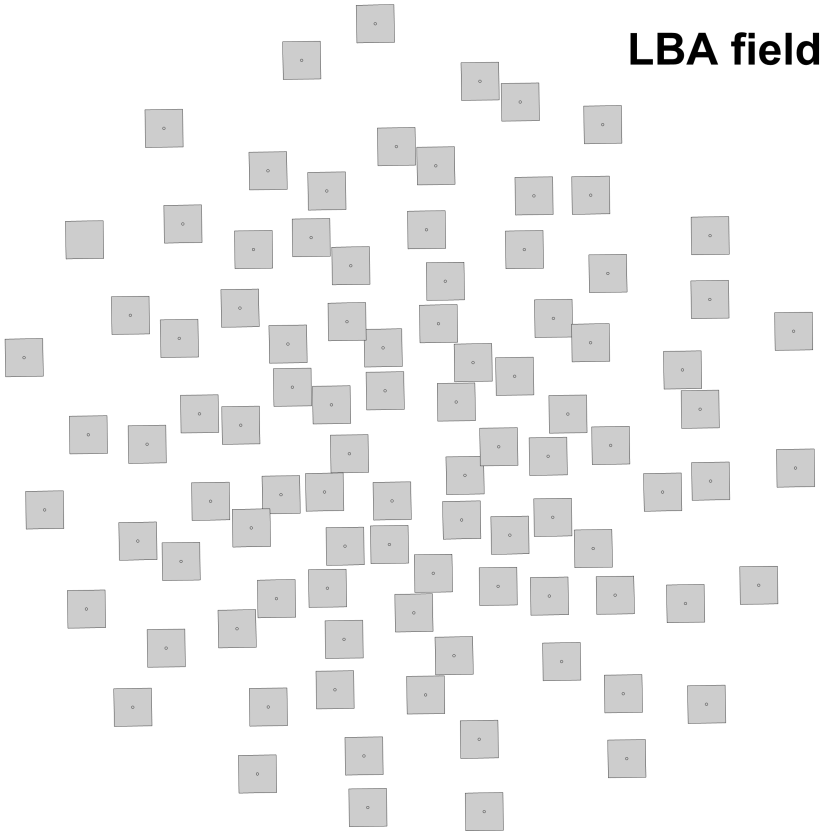
HBA field



Cabinet



LBA field



Results

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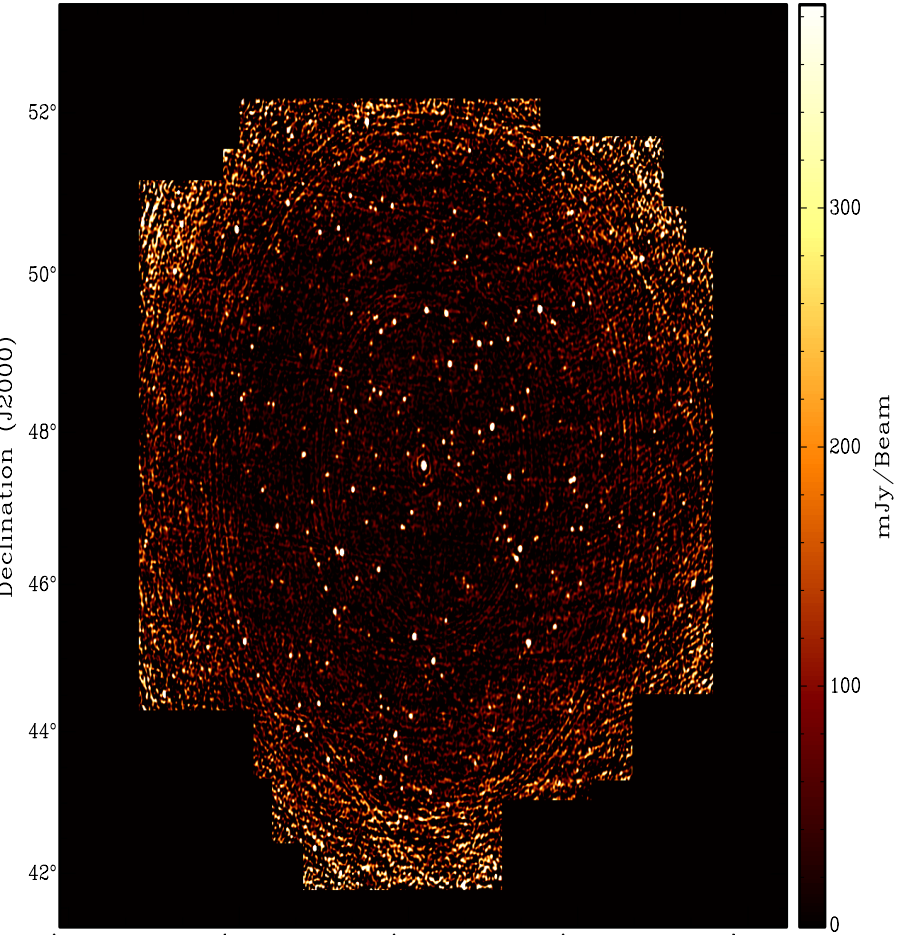
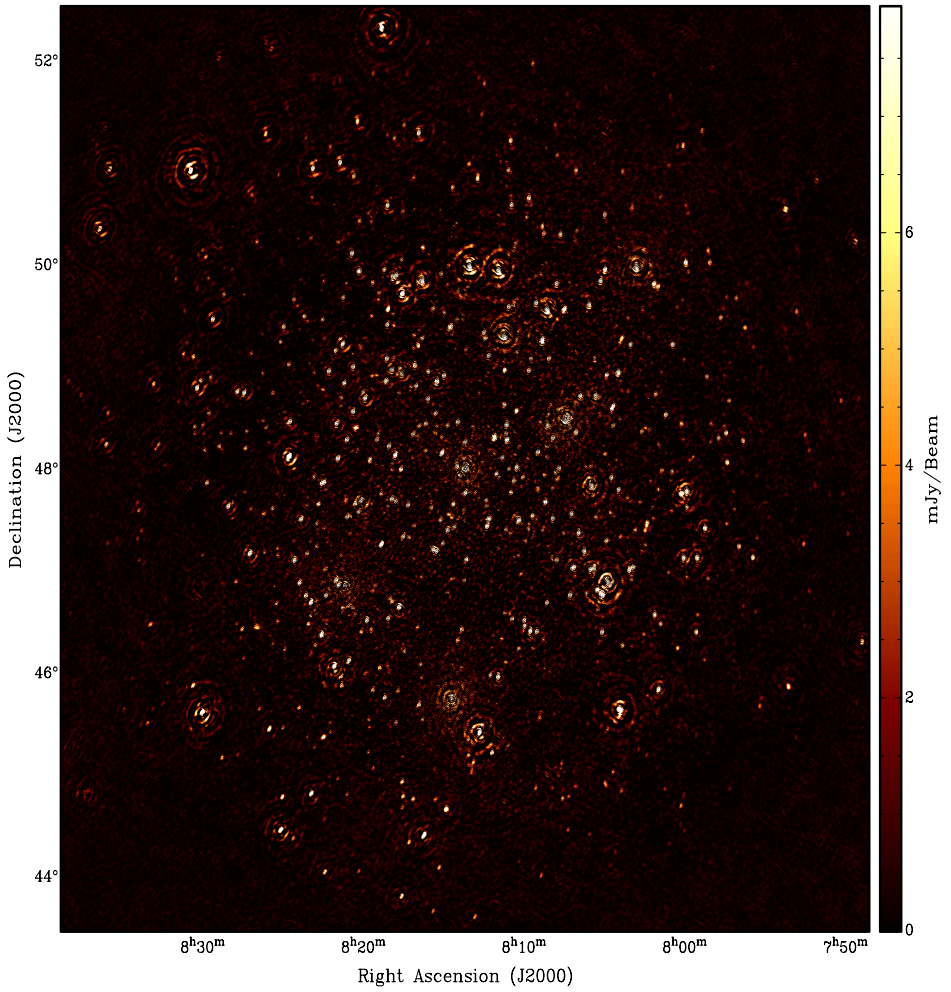
Labropoulos et a al., in prep



Bernardi et al. (2010)
0.6 mJy/beam



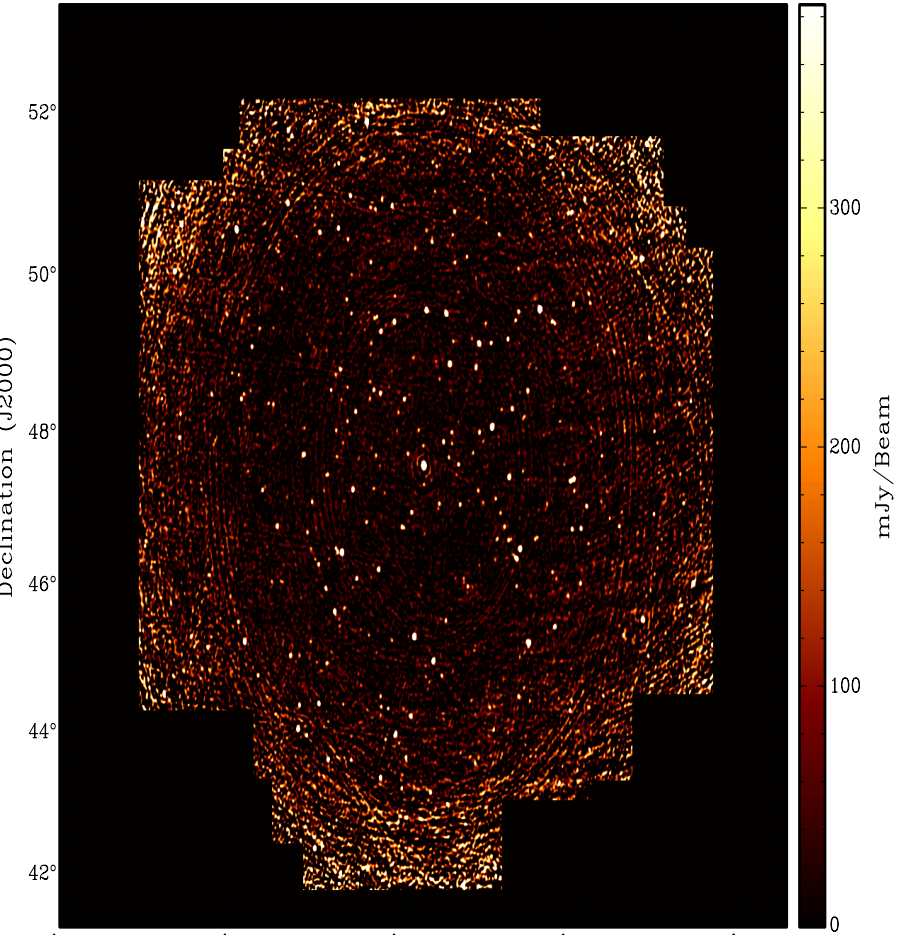
LOFAR (2011)
0.3 mJy/beam

Results

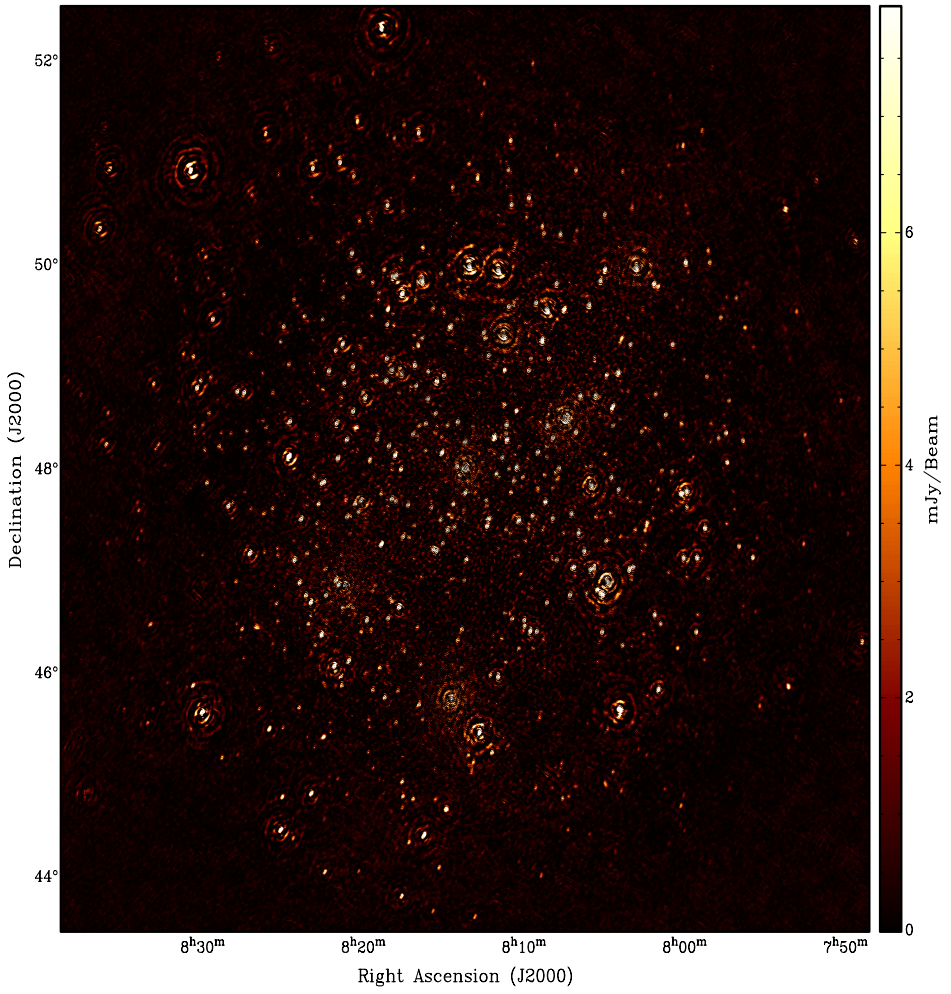
rijksuniversiteit groningen

ASTRON

Labropoulos et a al., in prep

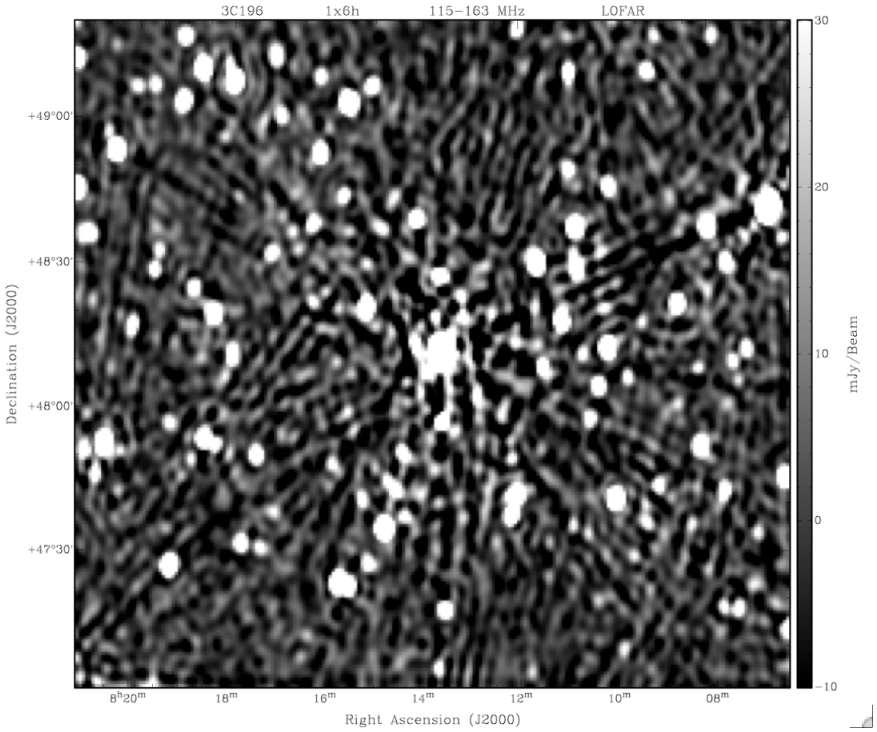


Bernardi et al. (2010)
250 sources



LOFAR (2011)
1662 sources

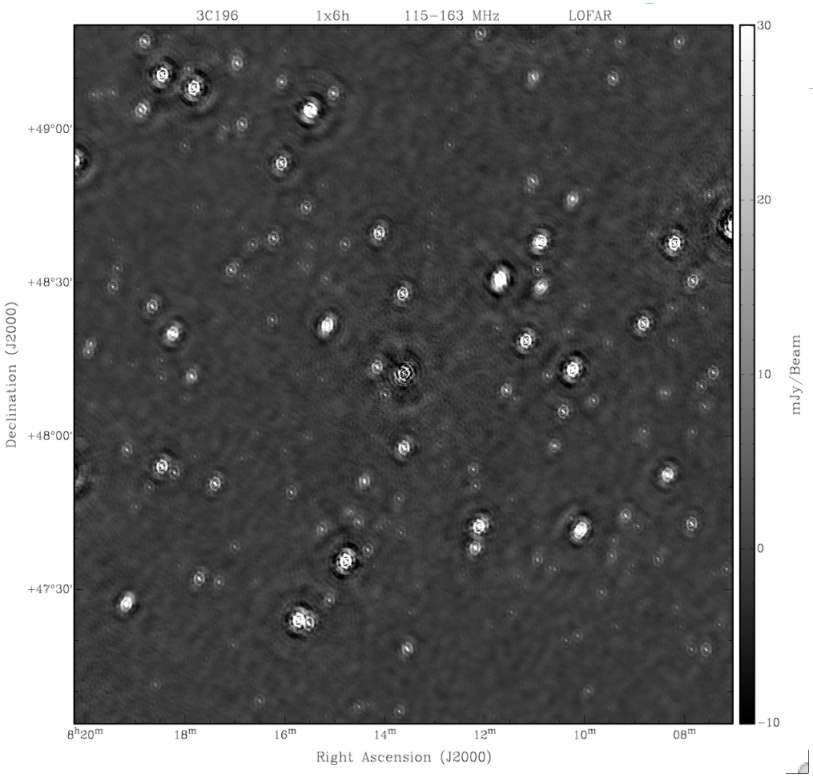
3C196: WSRT versus LOFAR 115-163 MHz



WSRT 72h thermal noise 0.6 mJy

confusion noise 3 mJy

Gianni Bernardi et al (2010)



LOFAR 6h thermal noise ~ 0.1 mJy

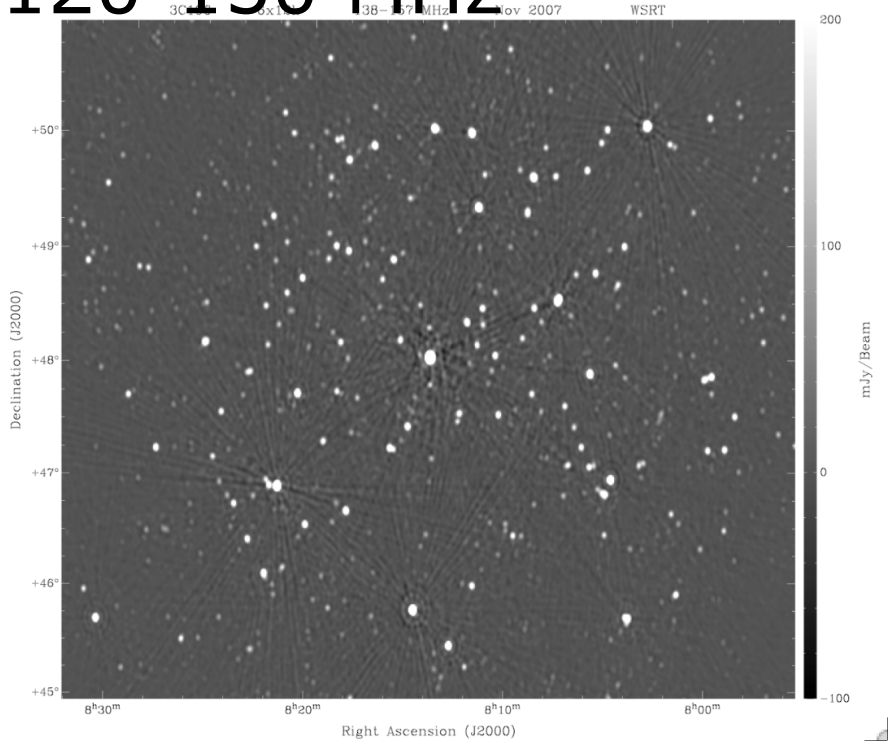
image noise ~ 0.3-0.7 mJy

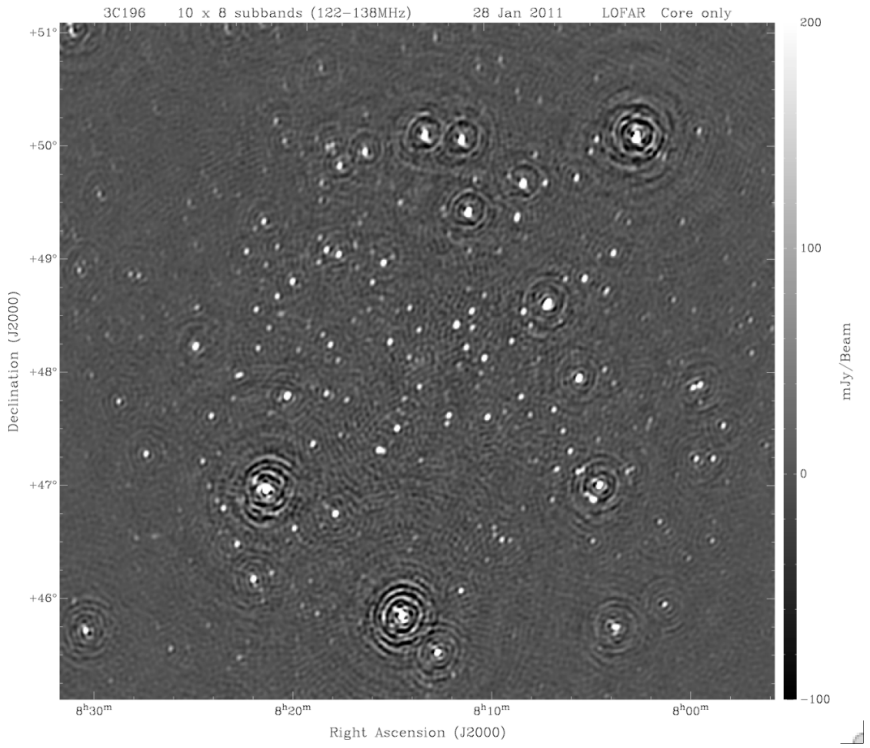
CS +RS, ~ 30 km ! 244 subbands

DR ~ 83 Jy/0.5 mJy ~ 200,000:1

Panos Labropoulos et al

3C196: WSRT versus LOFAR 120-150 MHz





WSRT 72h thermal noise 0.6 mJy

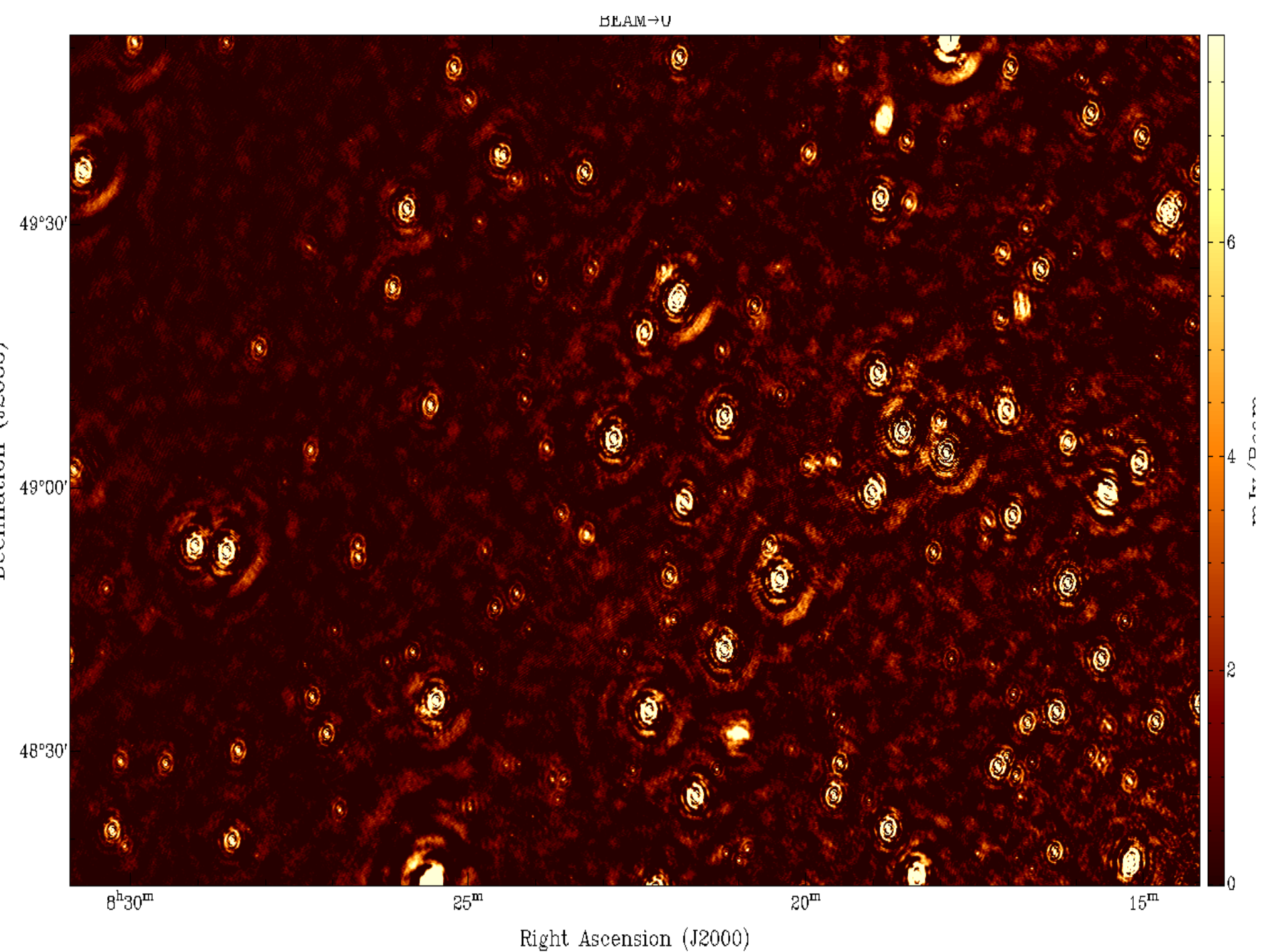
confusion noise 3 mJy

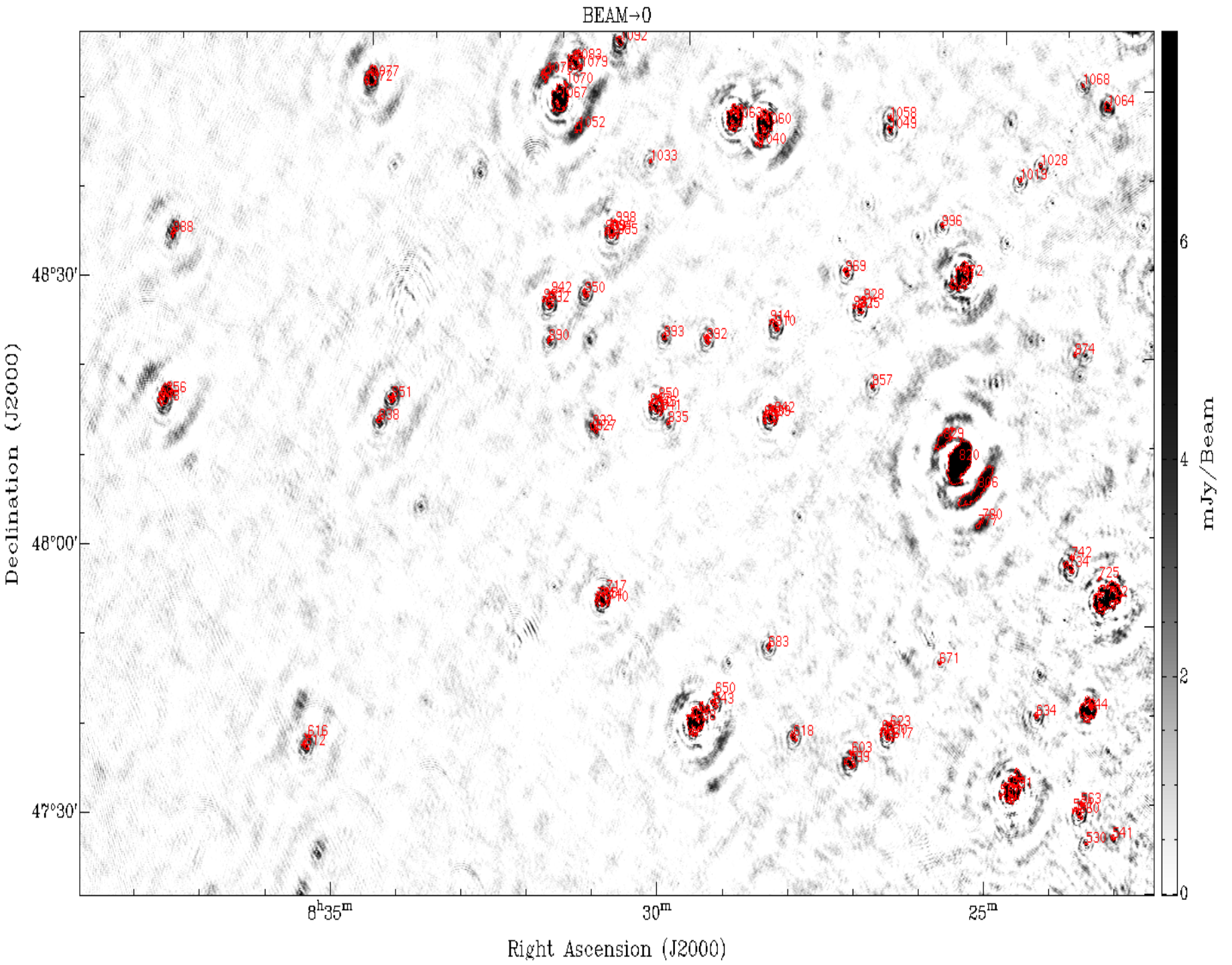
LOFAR 6h thermal noise ~0.2 mJy

(conf+sidelobe noise) ~ 4 mJy

CS only , ~ 2.5 km ! 80 subbands:

BBS with only 3C196 (subtracted) !


BEAM→0
49°30′
49°00′
48°30′
8h30m
25m
20m
15m
Right Ascension (J2000)
6
4
2
0


BEAM→0
Declination (J2000)
48°30′
48°00′
47°30′
8h35m
30m
25m
Right Ascension (J2000)
mJy/Beam
0
2
4
6

Results

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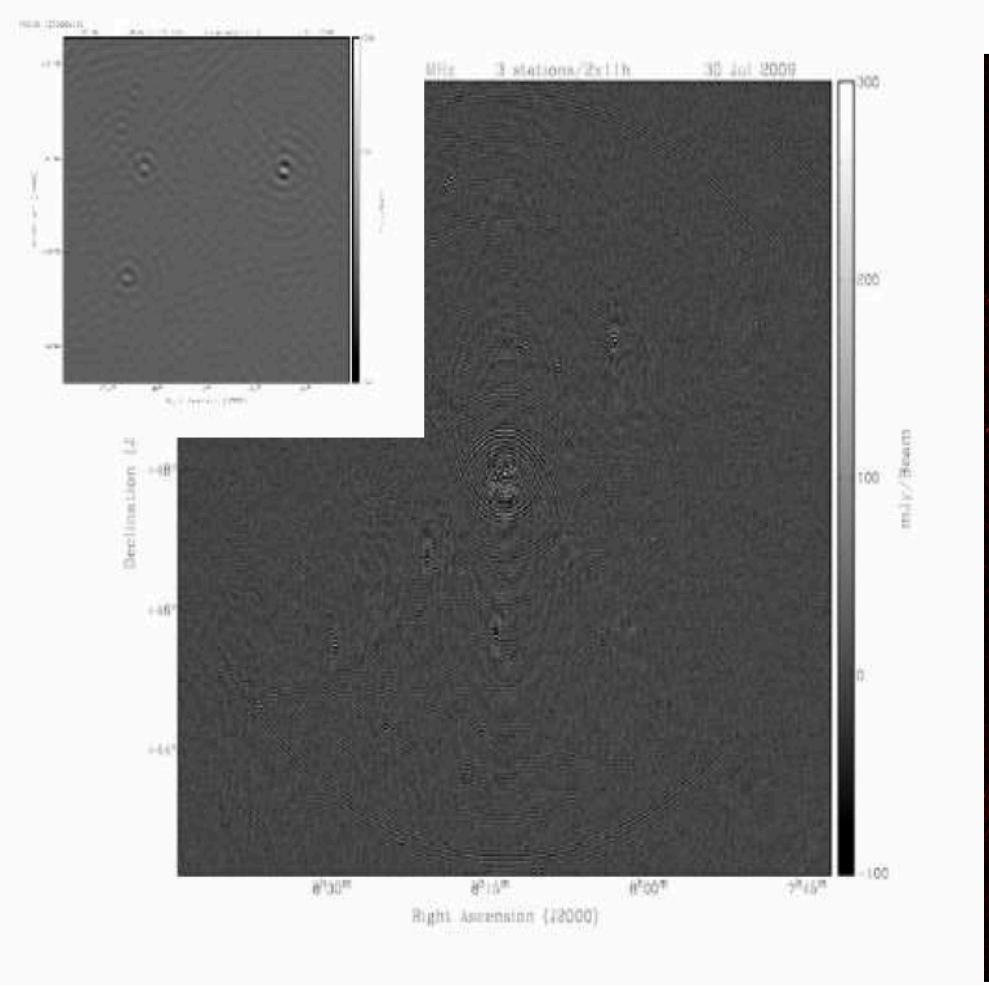
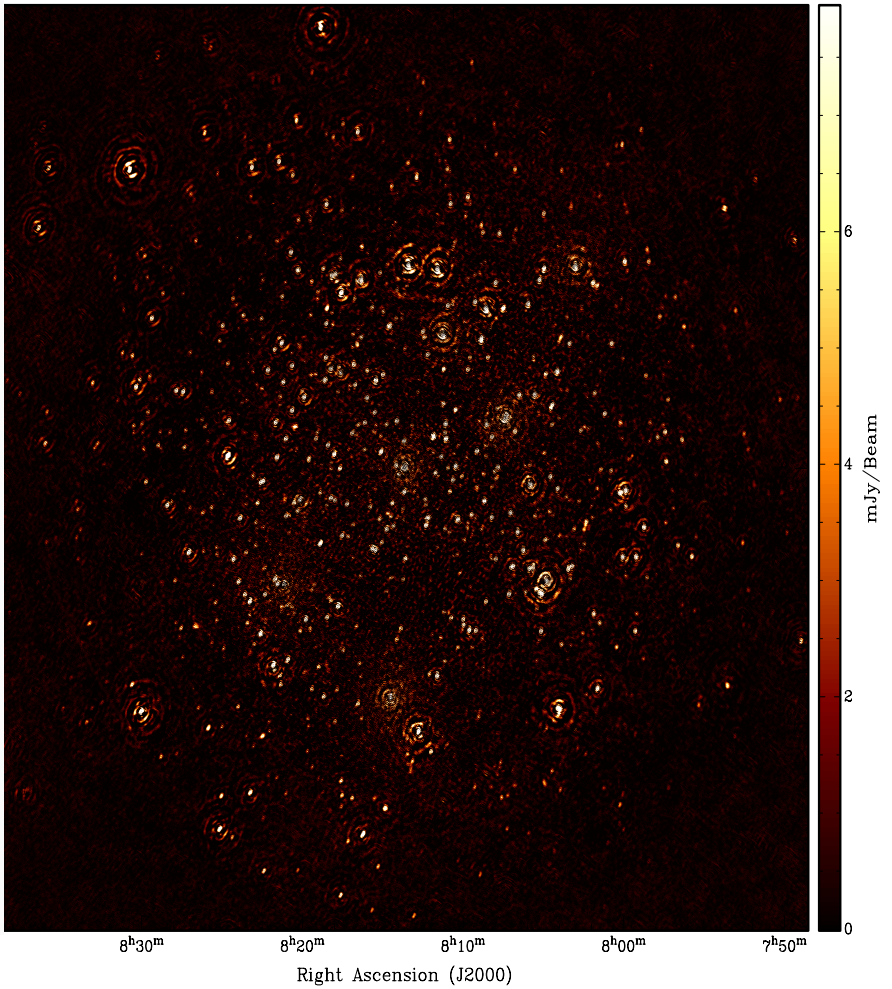


S. Yatawatta (2009)
3 stations, DR 1000:1



LOFAR (2011)
47 stations, DR 250000:1

North Celestial Pole (NCP) Yatawatta/Brentjens

~ 6h synthesis

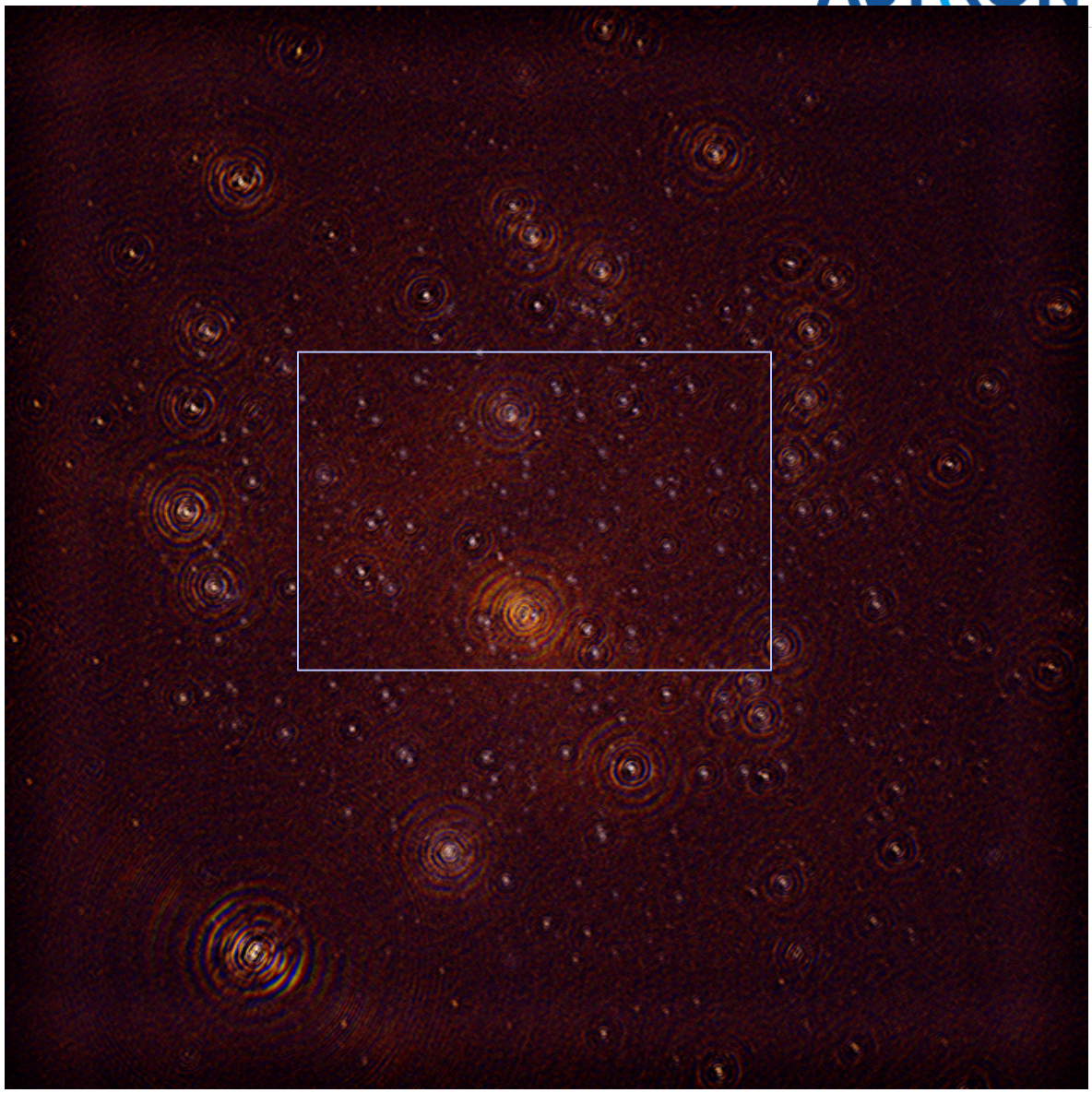
244 subbands (115-163 MHz)

~ 30 km baselines

8” PSF

8192x8192 pixels
4” grid

9º x 9º FOV



North Celestial Pole LOFAR
115-163 MHz σ ~ 0.5 mJy

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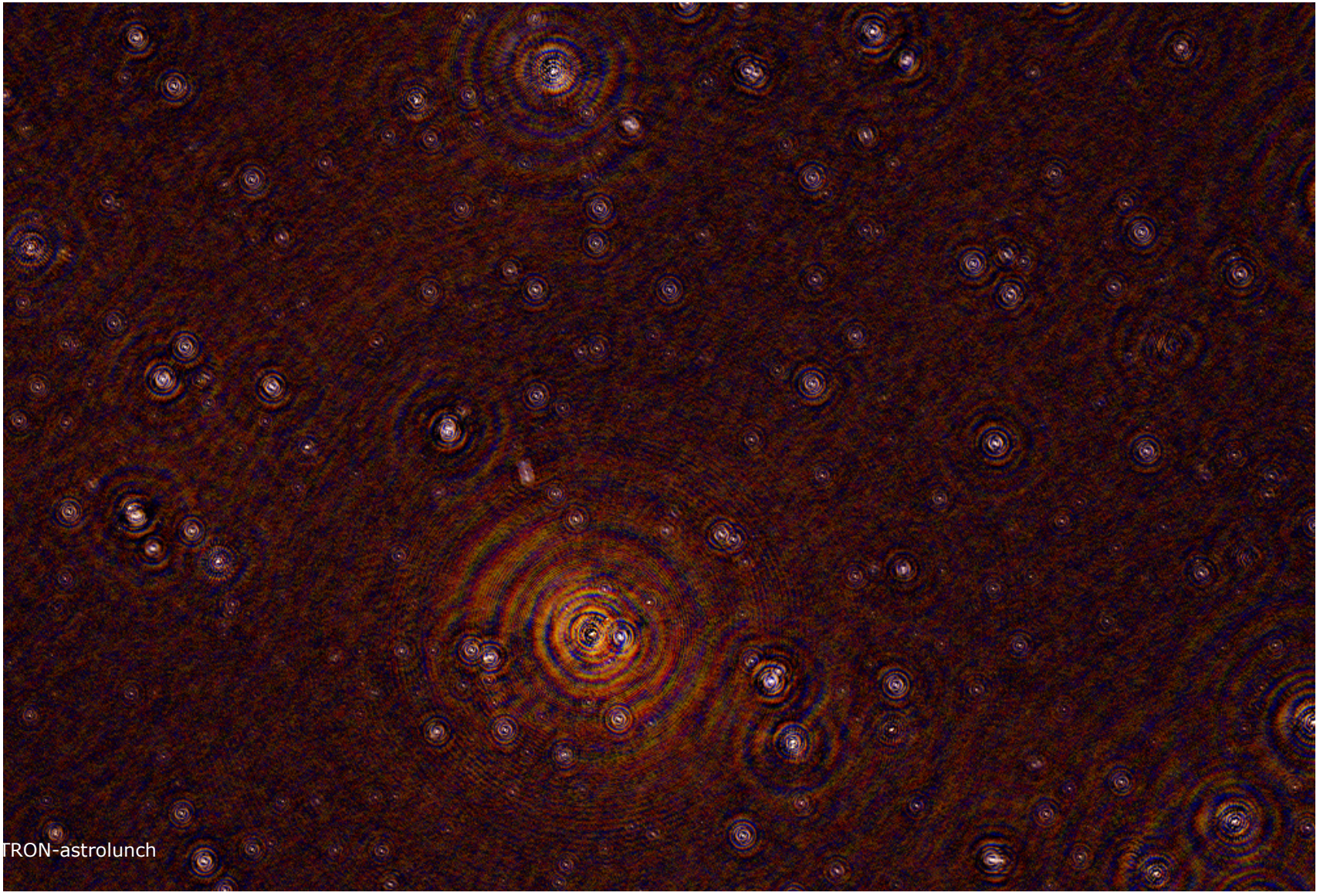

North Celestial Pole WENSS (1995) - 350 MHz σ ~ 2 mJy

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Closing the Major loop

Sarod's **buildsky** model fits models to sources taking into account the PSF and noise.

Uses LM or EM to fit the components and also AIC to decide on the correct model.

Can get image cubes to provide source spectra, spectral indices etc

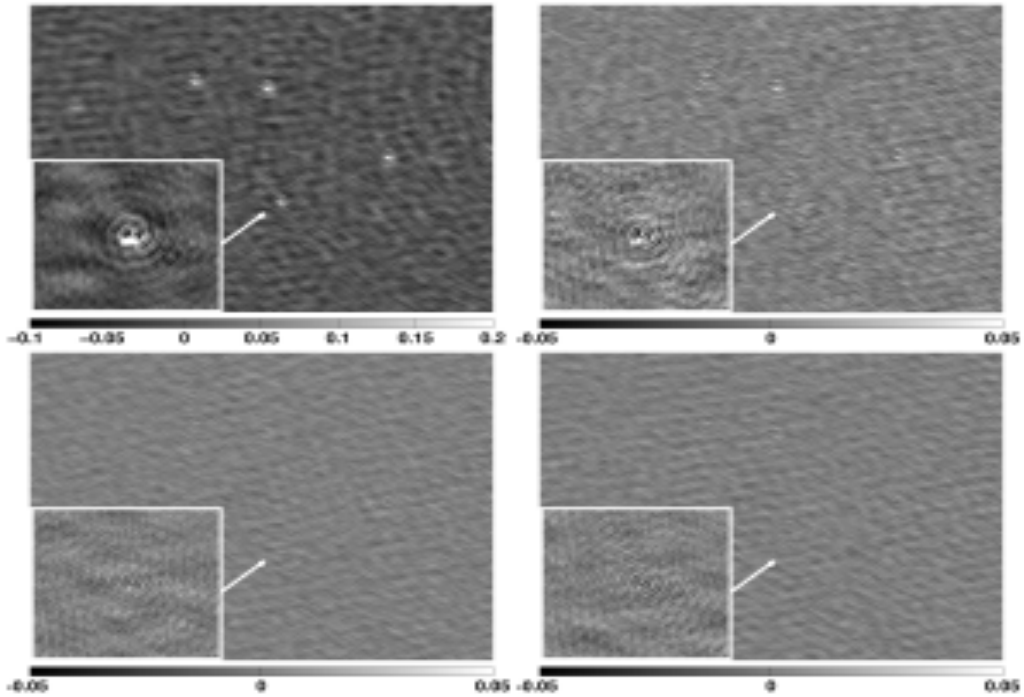
Can use a mask created using other software to avoid unnecessary searches.

Soon to include support for shapelets

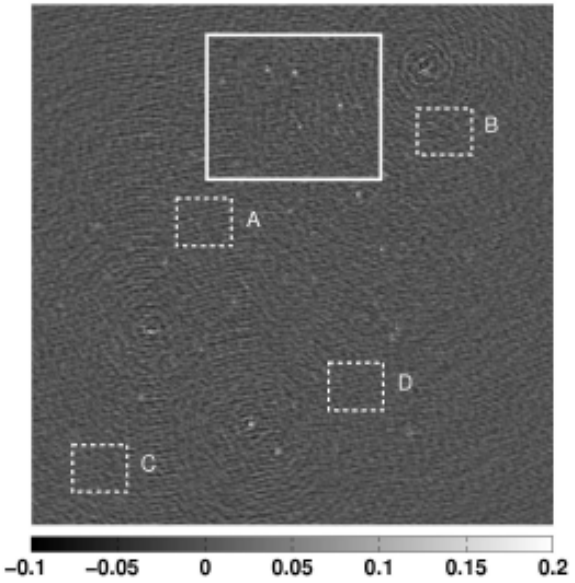
Clustered calibration

Use spatial proximity to assign sources to clusters

Different schemes available: K-means, EM, Hierarchical clustering, fuzzy clustering (Kazemi et al, 2011)



RMS (mJy)	A	B	C	D	Full image
Classical	6.5	6.0	5.6	6.5	6.8
HC	5.2	5.3	5.4	5.5	5.4
WKC	5.5	5.4	5.5	5.3	5.9



Directional calibration: Expensive and problematic! Program X

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Program Y

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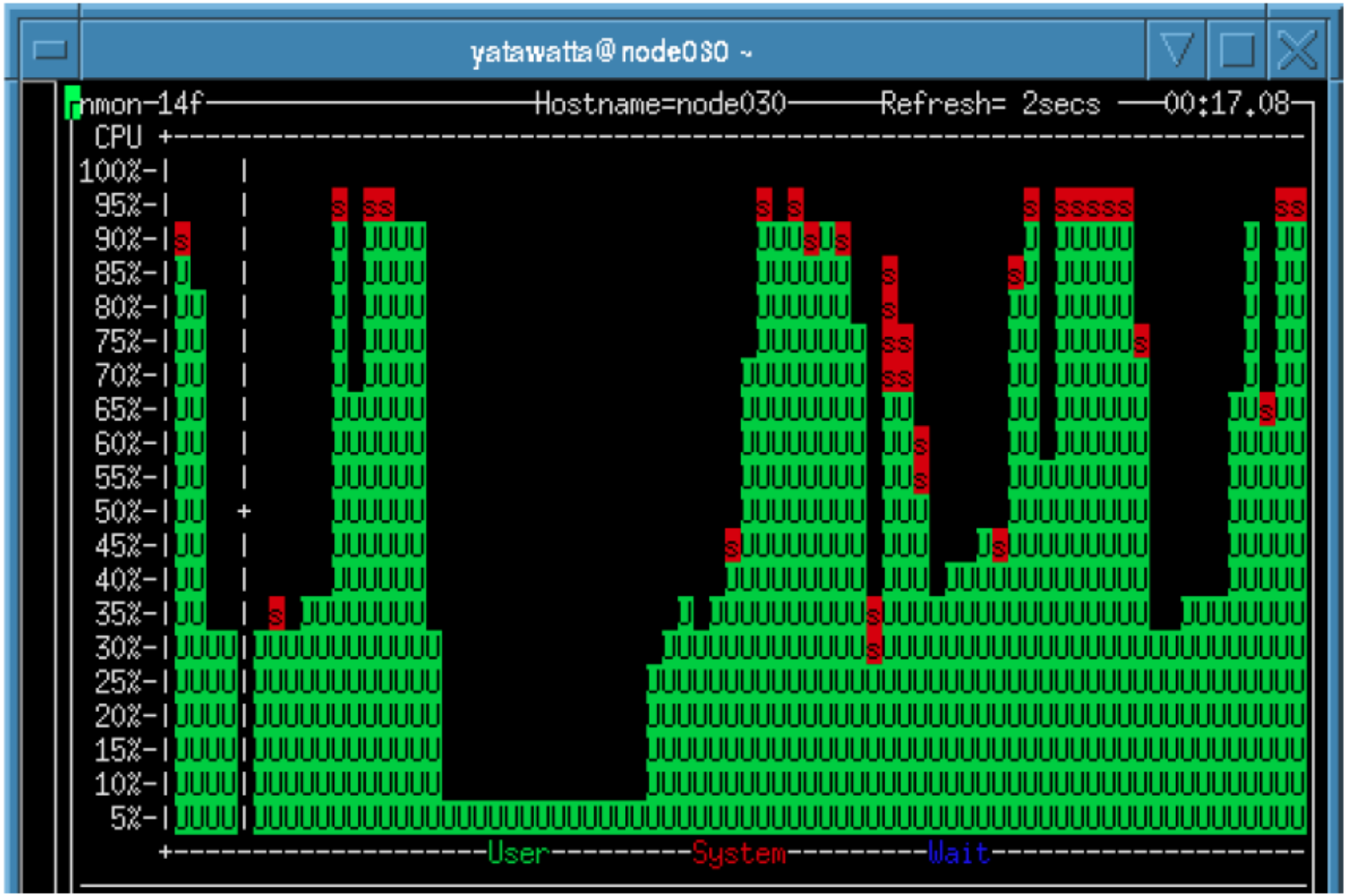

Ideal case!

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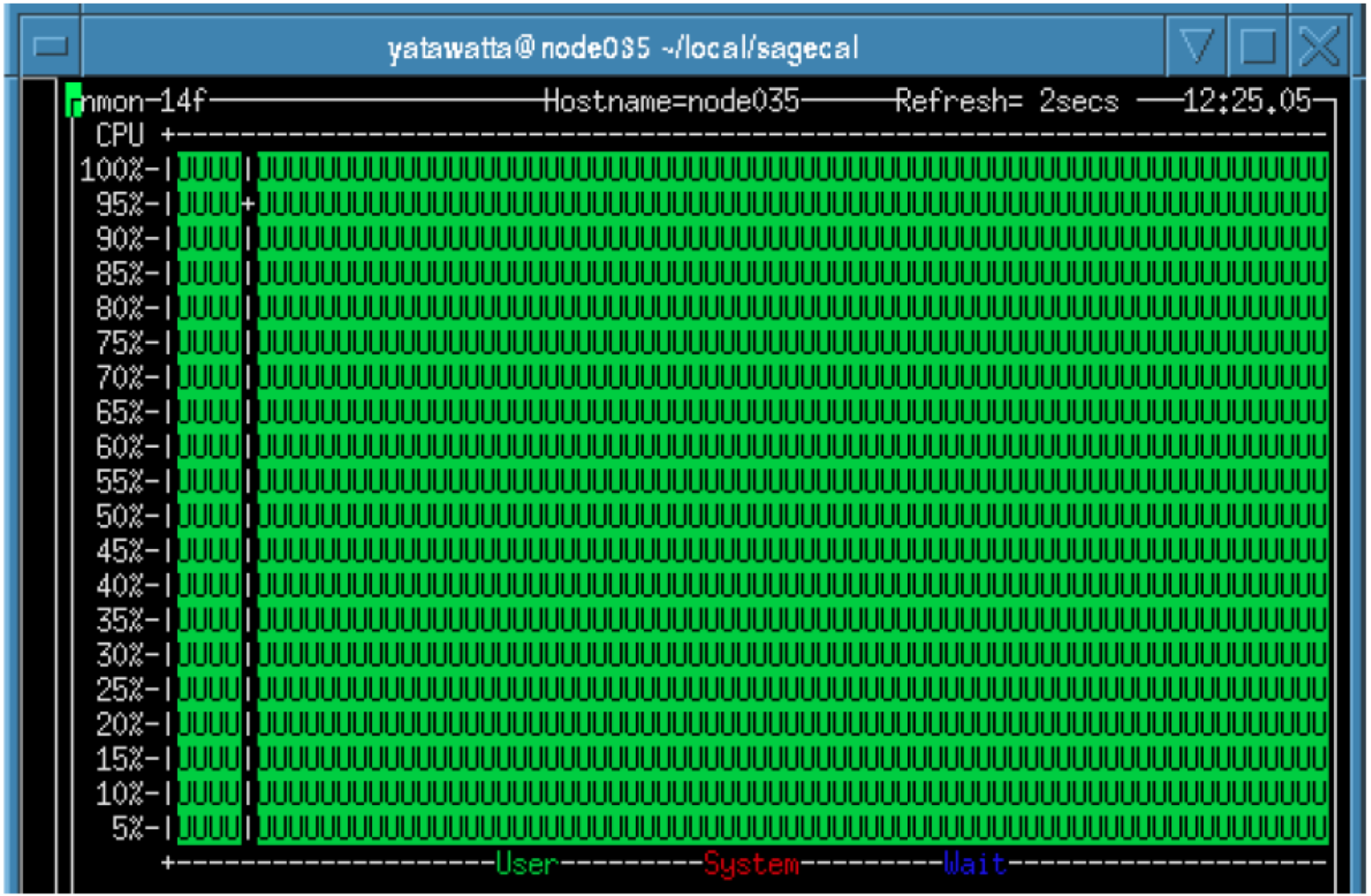

MVDR Imager

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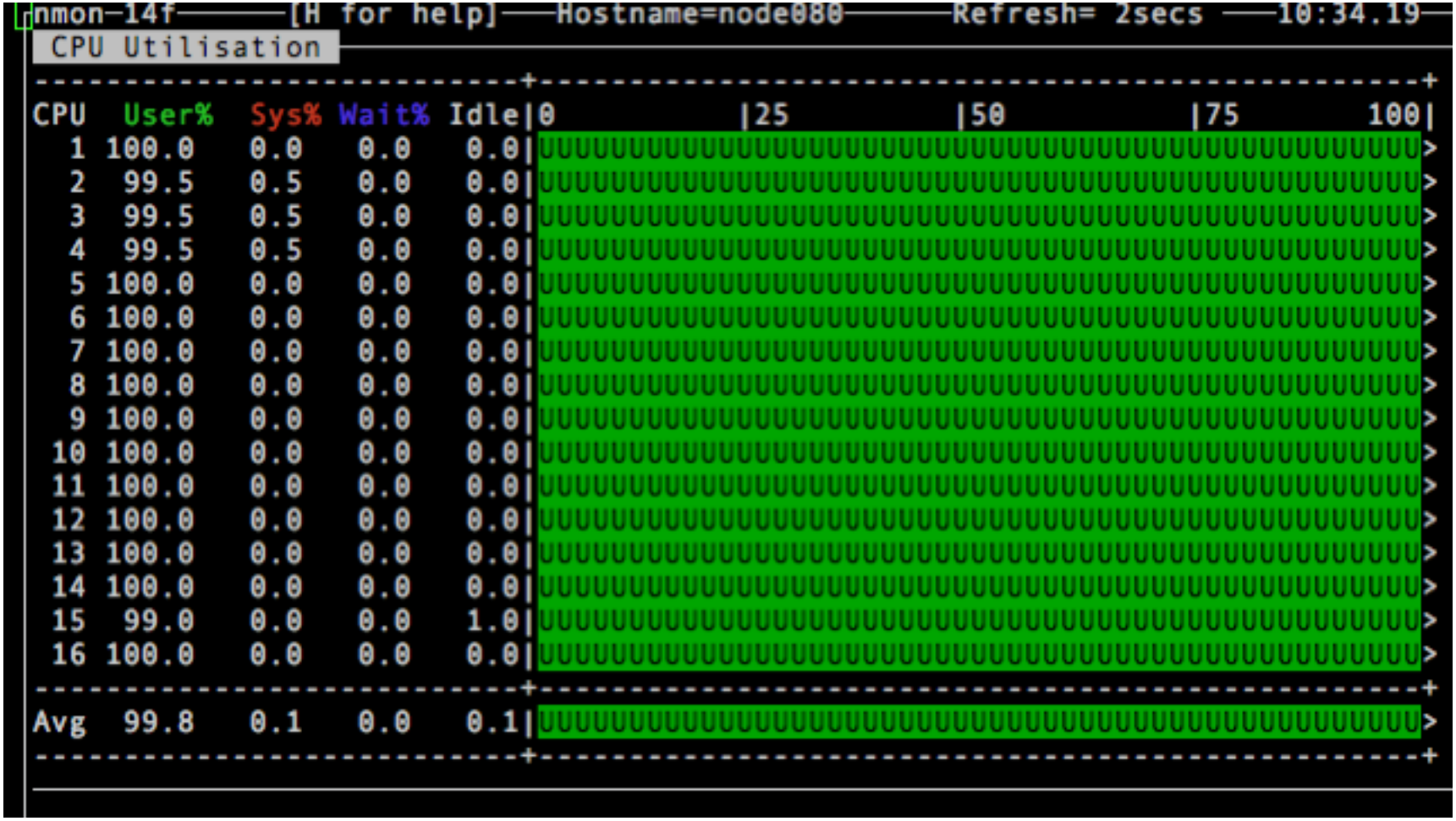

Sagecal

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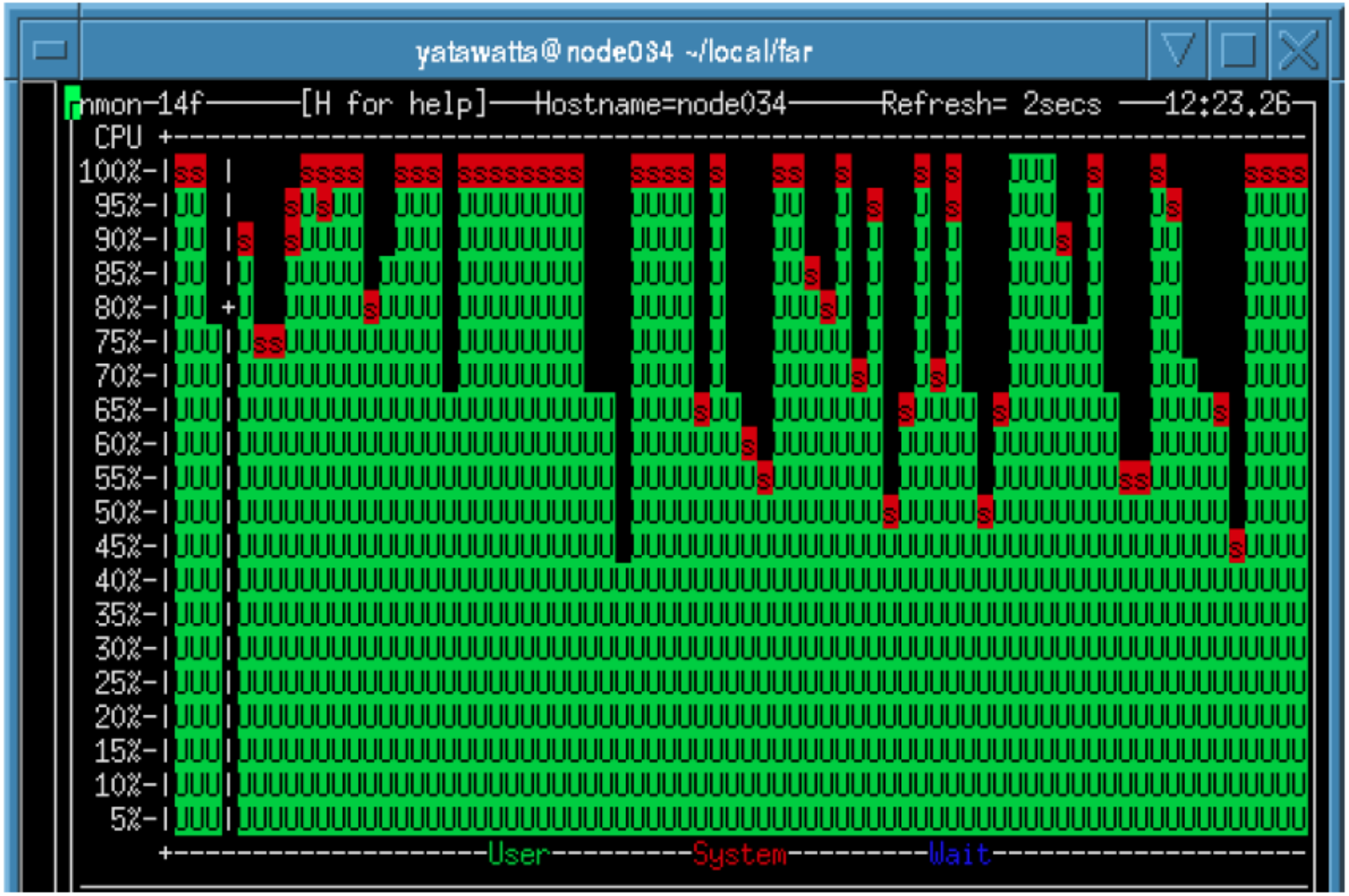

Sagecal

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Yatawatta et al. 2009, Kazemi et al. in prep.

$$\mathbf{x}^i = \mathbf{s}_i(\boldsymbol{\theta}_i) + \mathbf{n} \longrightarrow \boxed{\mathbf{y} = \mathbf{x}^i + \sum_{\substack{l=1 \\ l \neq i}}^{K} \mathbf{s}_l(\boldsymbol{\theta}_l)} \longrightarrow$$

E- Step: $\hat{\mathbf{x}}_i^k = E\{\mathbf{x}_i | \mathbf{y}, \boldsymbol{\theta}^k\}$

M- Step: $\min_{\boldsymbol{\theta}_i} \phi_i(\boldsymbol{\theta}_i) = \|[\hat{\mathbf{x}}^{i\,k} - \mathbf{s}_i(\boldsymbol{\theta}_i)](\boldsymbol{\Pi})^{-\frac{1}{2}}\|^2$

Advantages of the EM algorithm over the Normal algorithm:

- Breaking the likelihood maximization into smaller computational steps
- Computational cost equal to $KO(N^2)$

$$\boldsymbol{\theta}_i^{k+1} = \boldsymbol{\theta}_i^k - (\nabla_{\boldsymbol{\theta}_i} \nabla_{\boldsymbol{\theta}_i}^T \phi_i(\boldsymbol{\theta}_i) + \lambda \mathbf{H}_i)^{-1} \nabla_{\boldsymbol{\theta}_i} \phi_i(\boldsymbol{\theta}_i)|_{\boldsymbol{\theta}_i^k} \quad \text{for } i \in \{1, 2, \ldots, K\}$$

- Increasing the likelihood at each iteration step
- Improving the speed of convergence compared with LS calibration

But still,

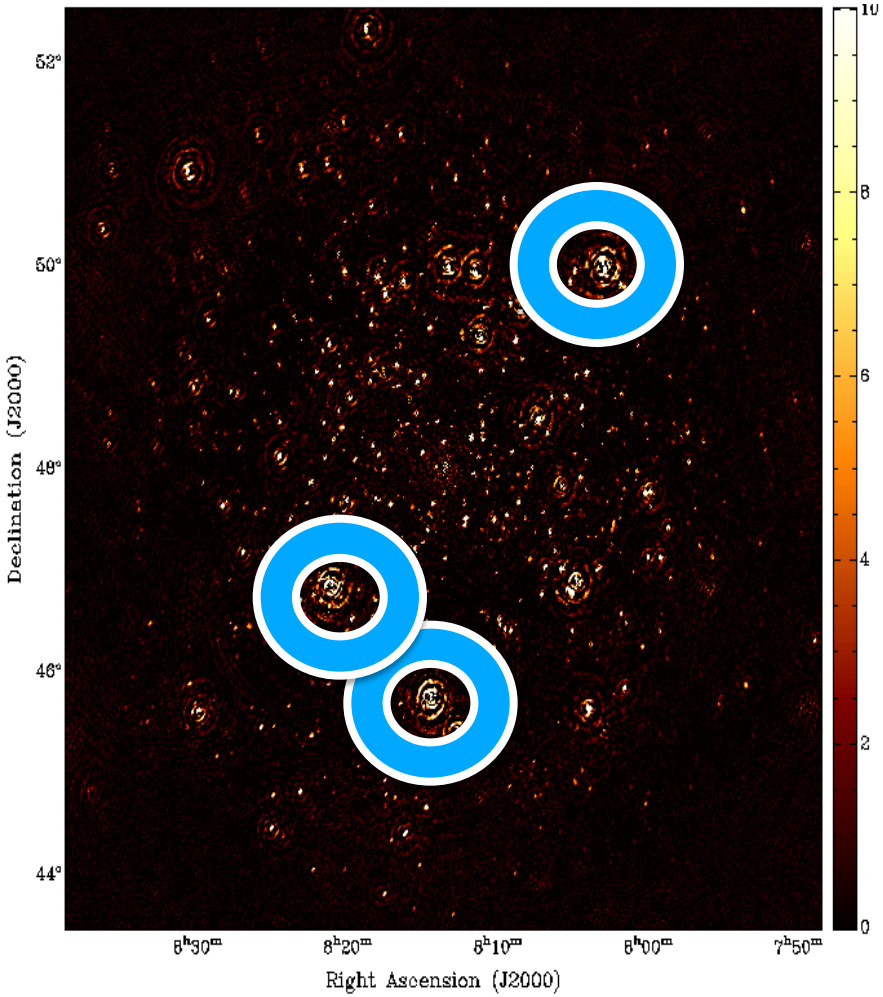
- Possibility of converging to a local optimum
- Implementation of the algorithm is complicated compared with LS method

Additional advantages of using the SAGE algorithm:

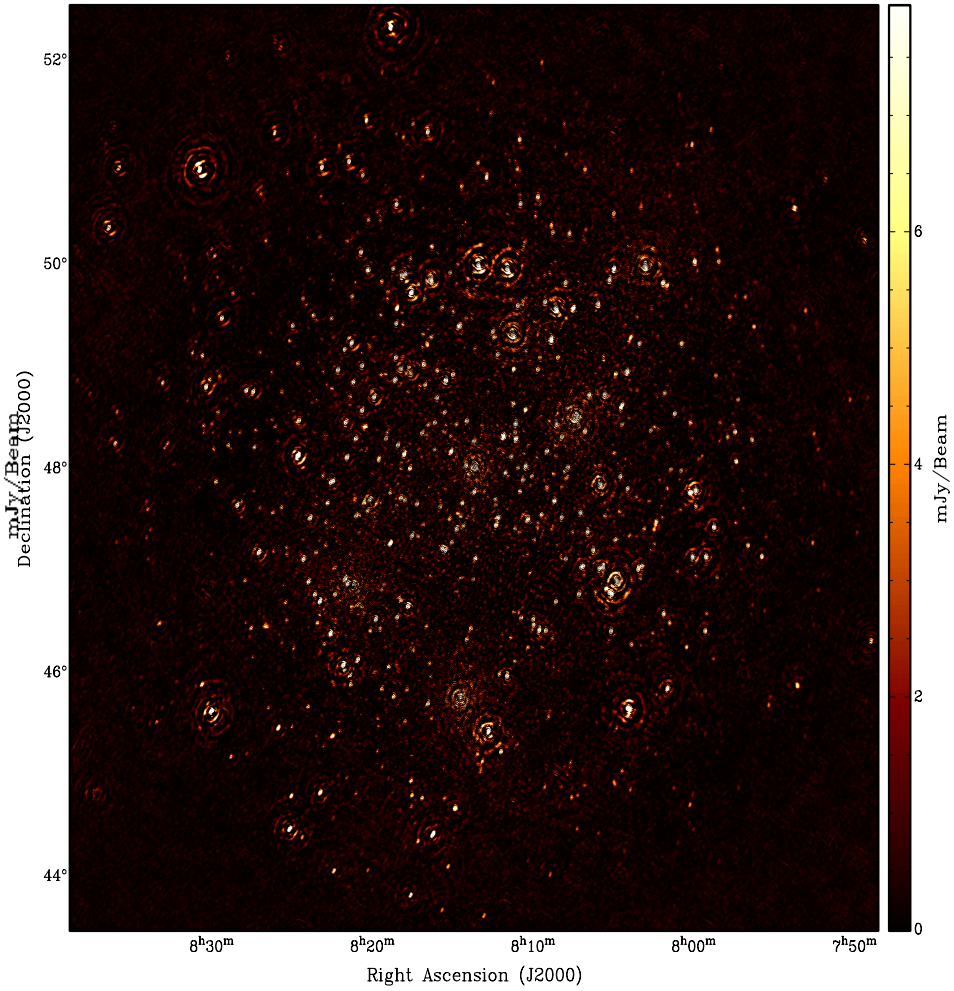
- Improving the speed of convergence
- Improving the accuracy of calibration results

Use L-BFGS to limit memory
(can do Hessian update on GPU)

Results: 4 directions



No DDE calibration



DDE along 3 directions

VLA FIRST Survey - LOFAR

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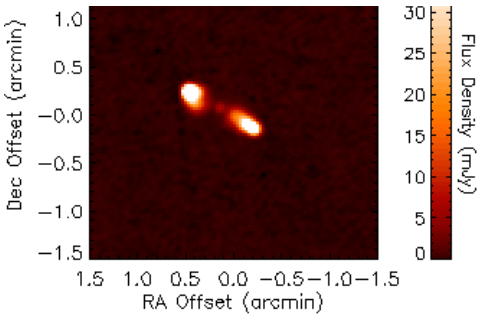
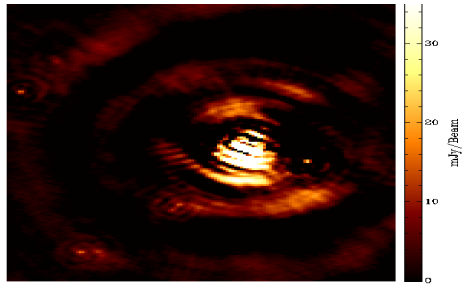
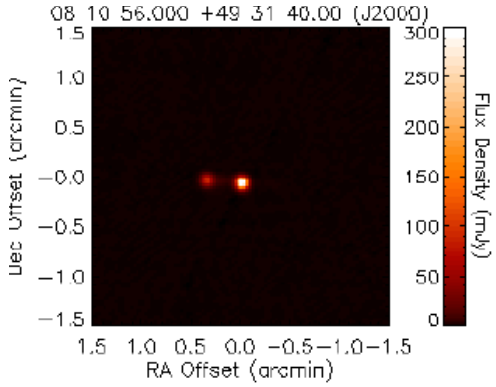
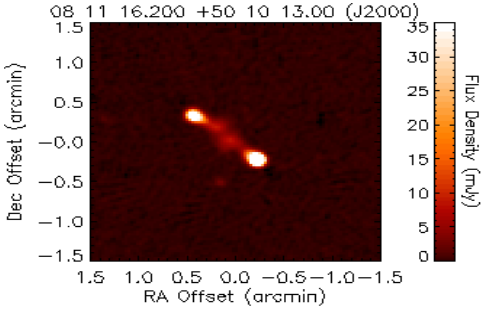


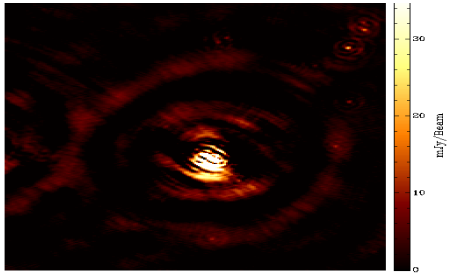
100 x 100 pixels extracted from FIRST image 08120+50218F
Brightest pixel is 176.24 mJy/beam at

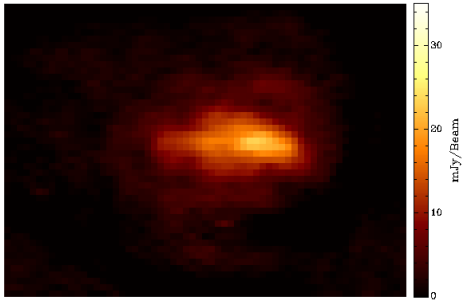


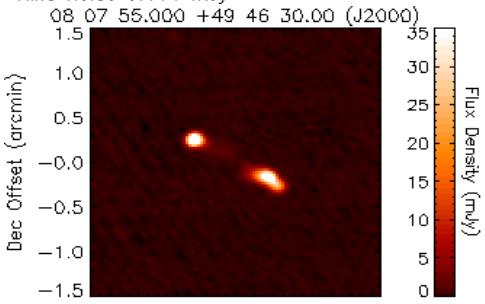




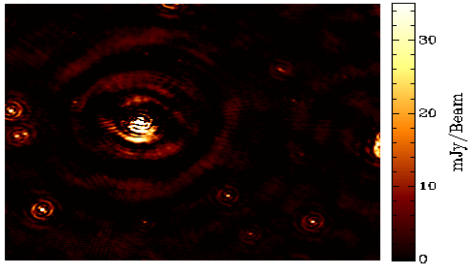
100 x 100 pixels extracted from FIRST image 08120+50218F
Brightest pixel is 222.82 mJy/beam at
X, Y = 58, 43 pixels
RA, Dec = 08 11 14.973 +50 09 58.25 (J2000)
RMS noise 0.164 mJy



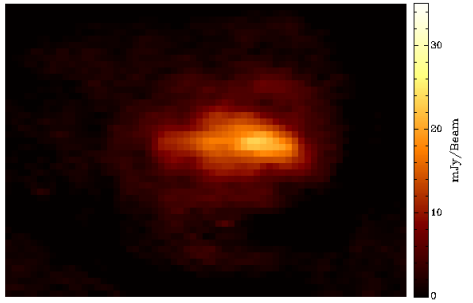


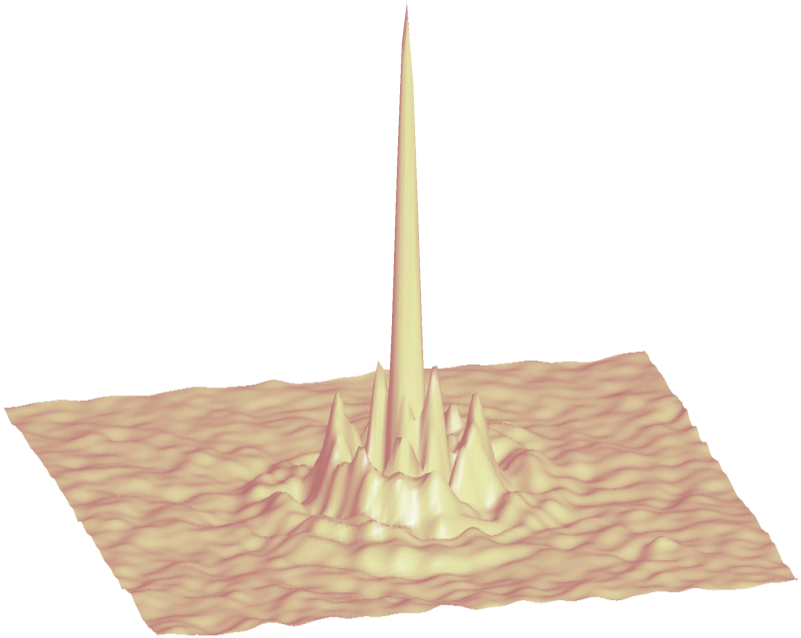


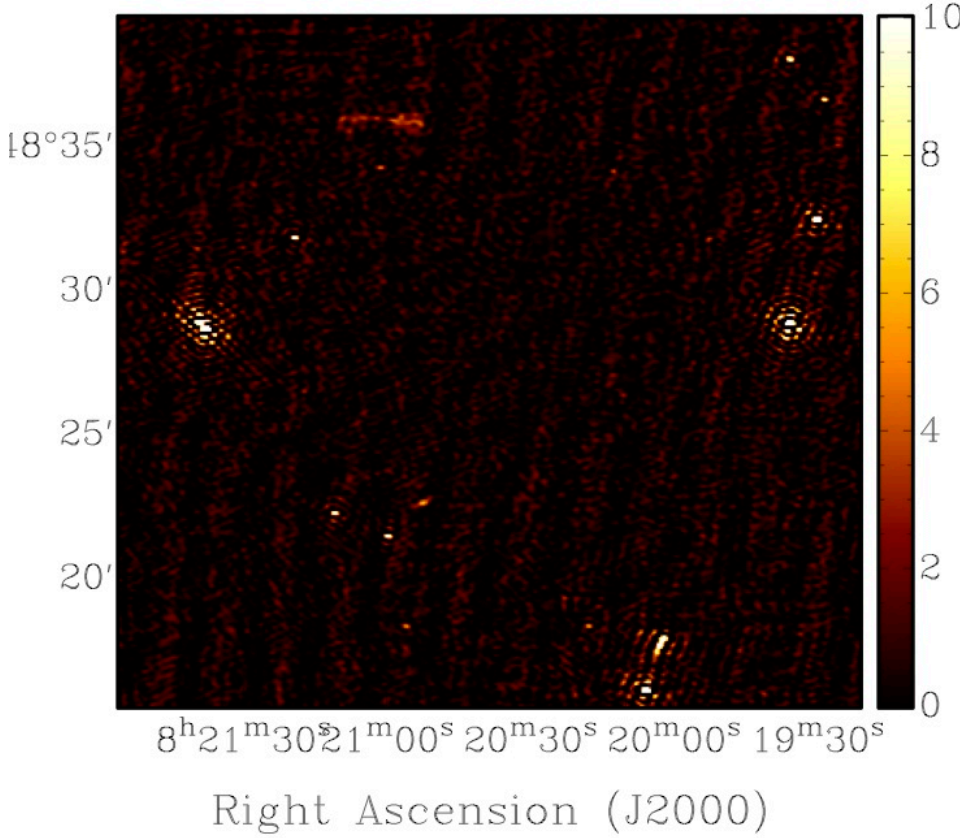
100 x 100 pixels extracted from FIRST image 08090+49440F
Brightest pixel is 85.78 mJy/beam at
X, Y = 36, 59 pixels
RA, Dec = 08 07 57.865 +49 46 44.56 (J2000)
RMS noise 0.196 mJy



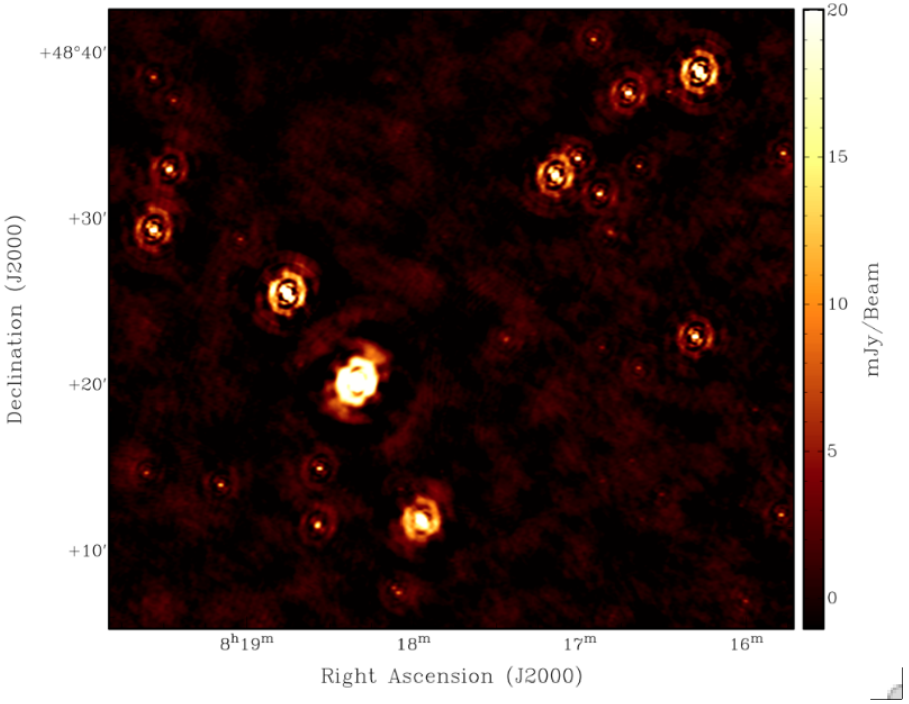
Deconvolution: quick and dirty approach

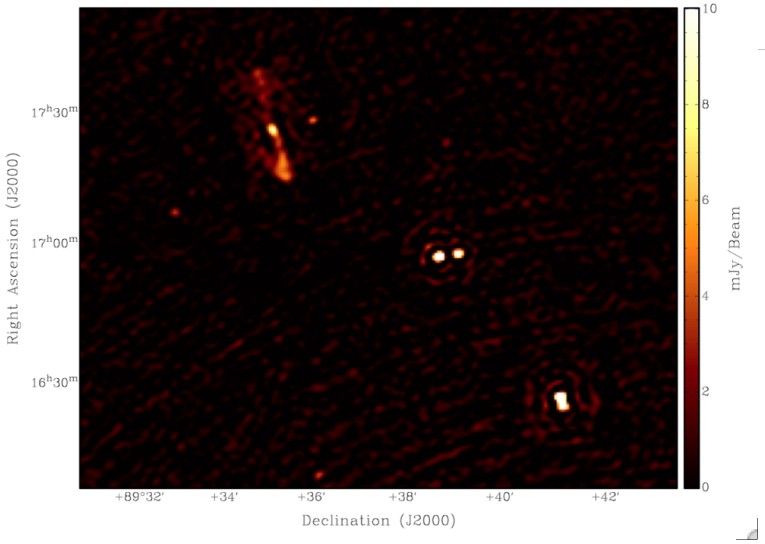


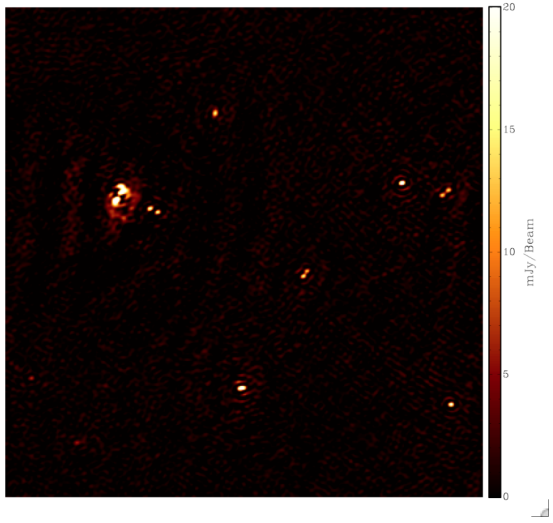




Images from the press release



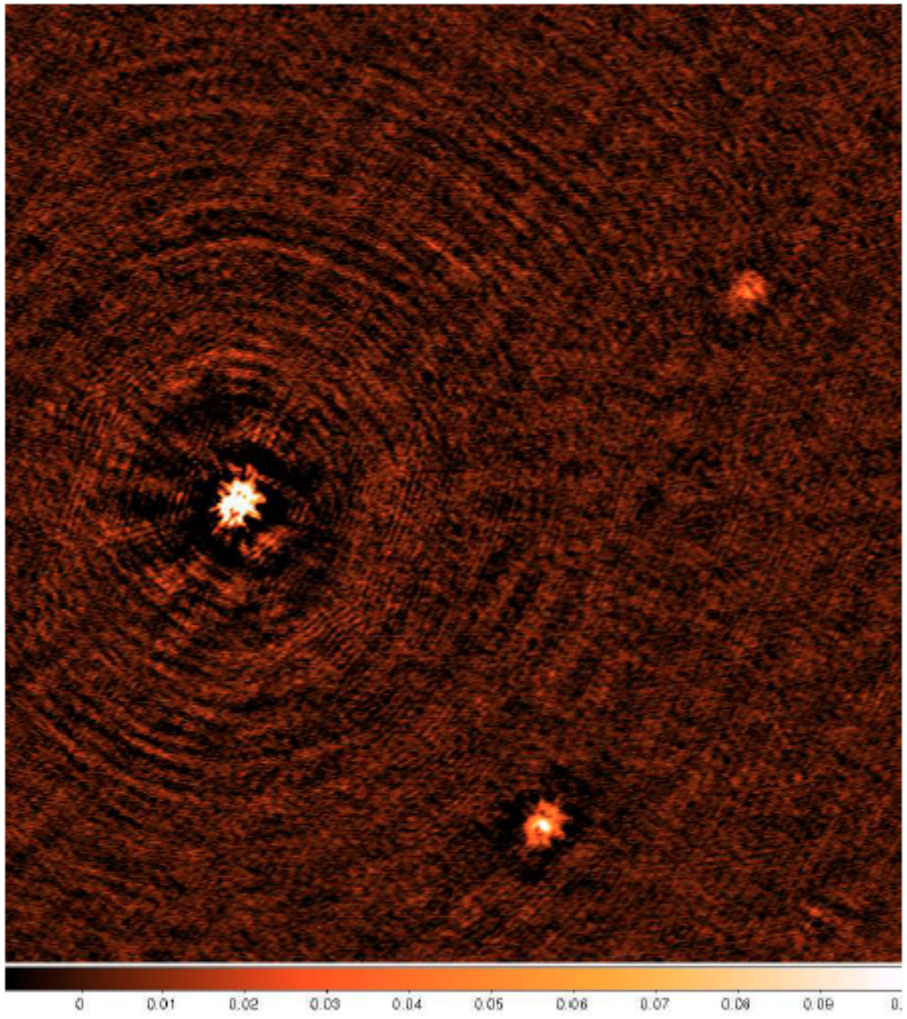


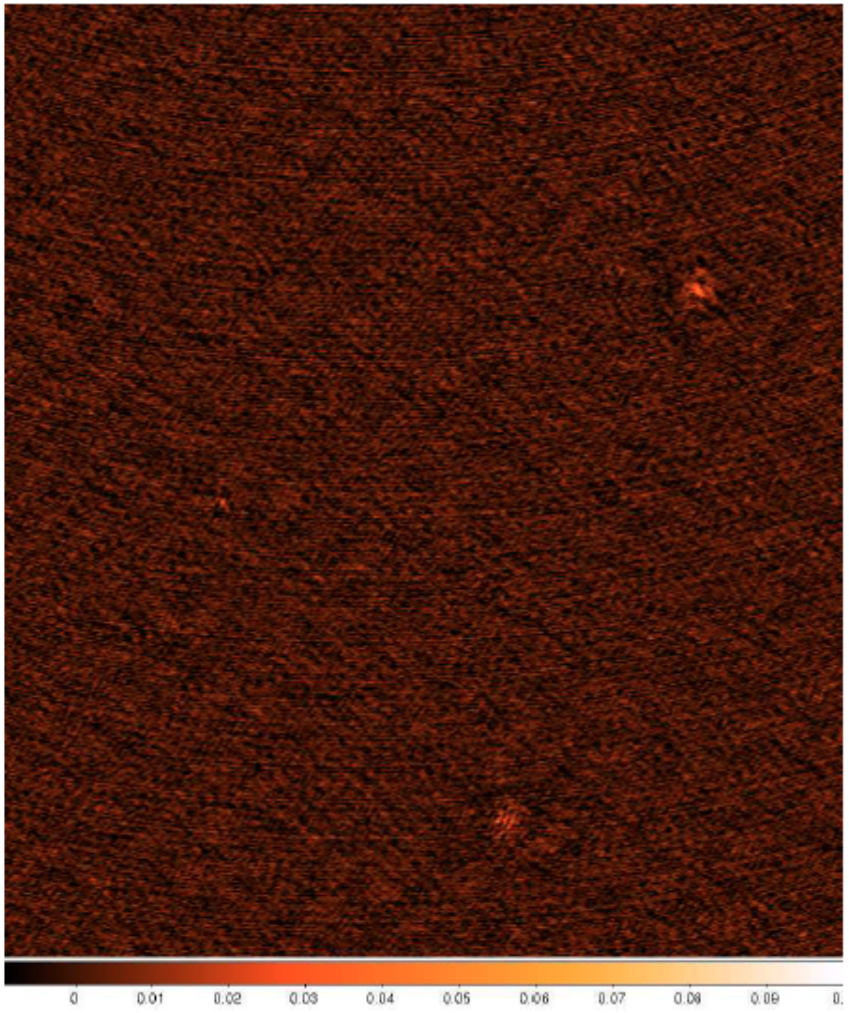


Zoom images from the 3C196 and NCP fields. NOT or only partly deconvolved

Noise at edges ~ 0.3 -0.5 mJy / PSF

Proper approach





Proper approach

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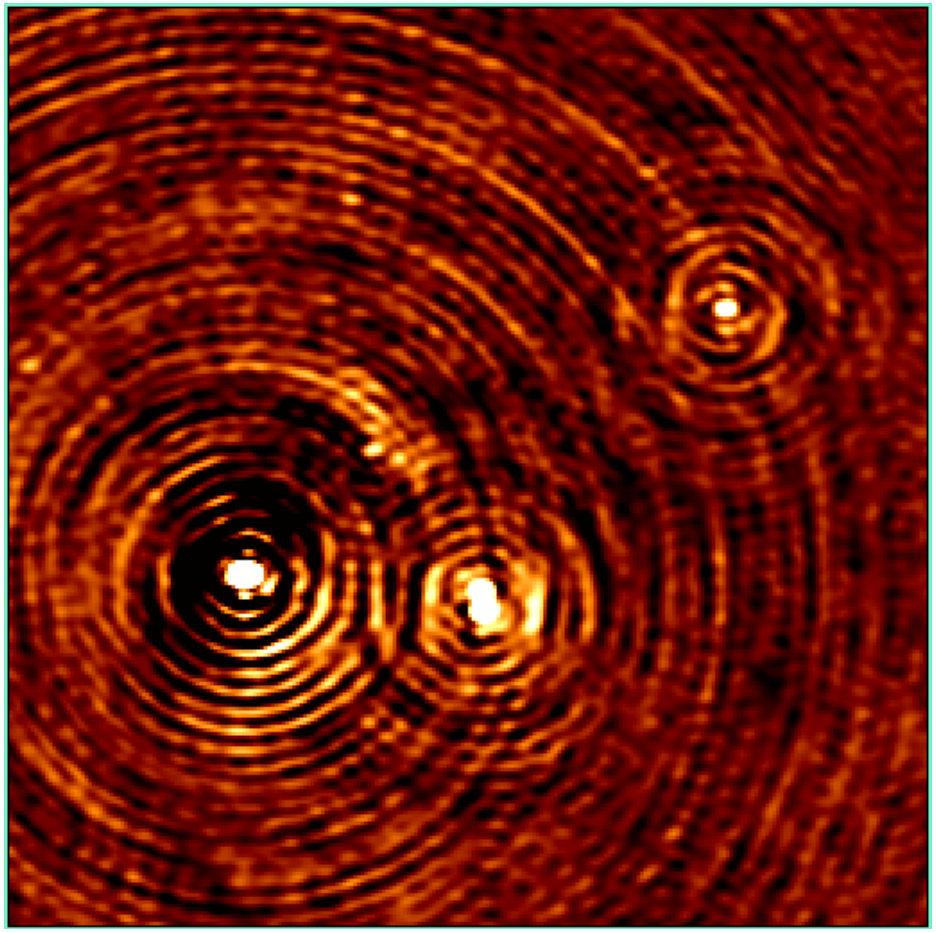
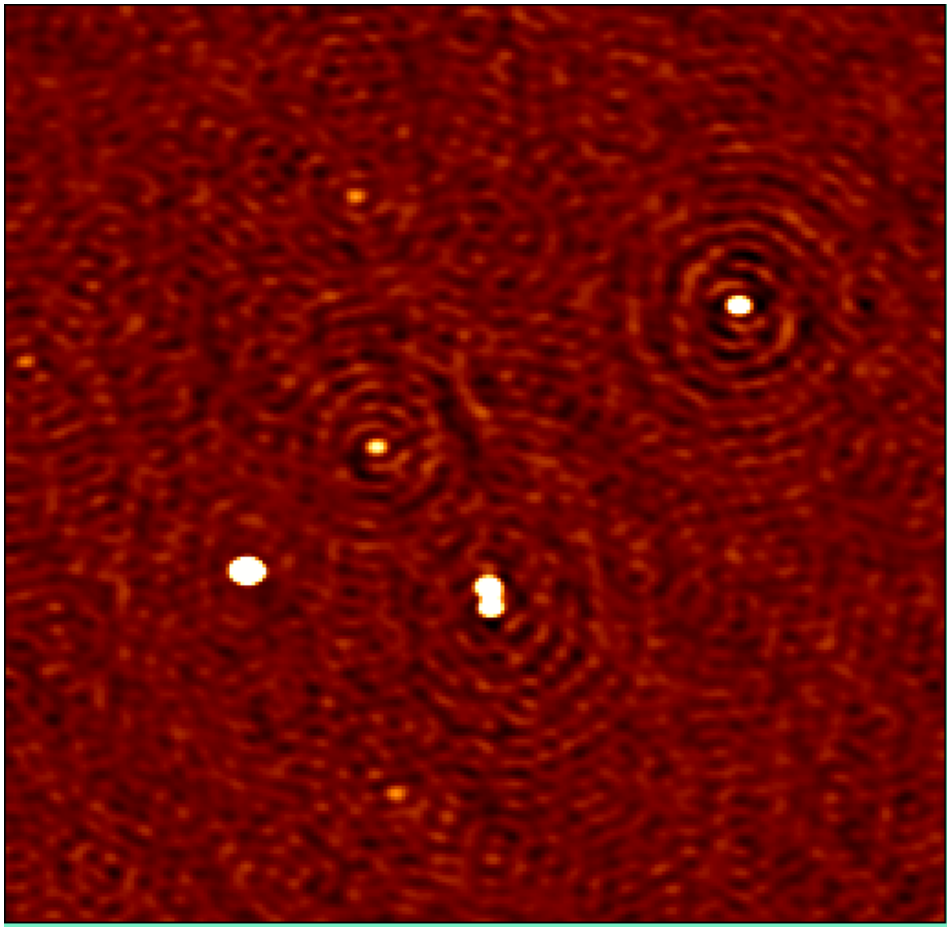
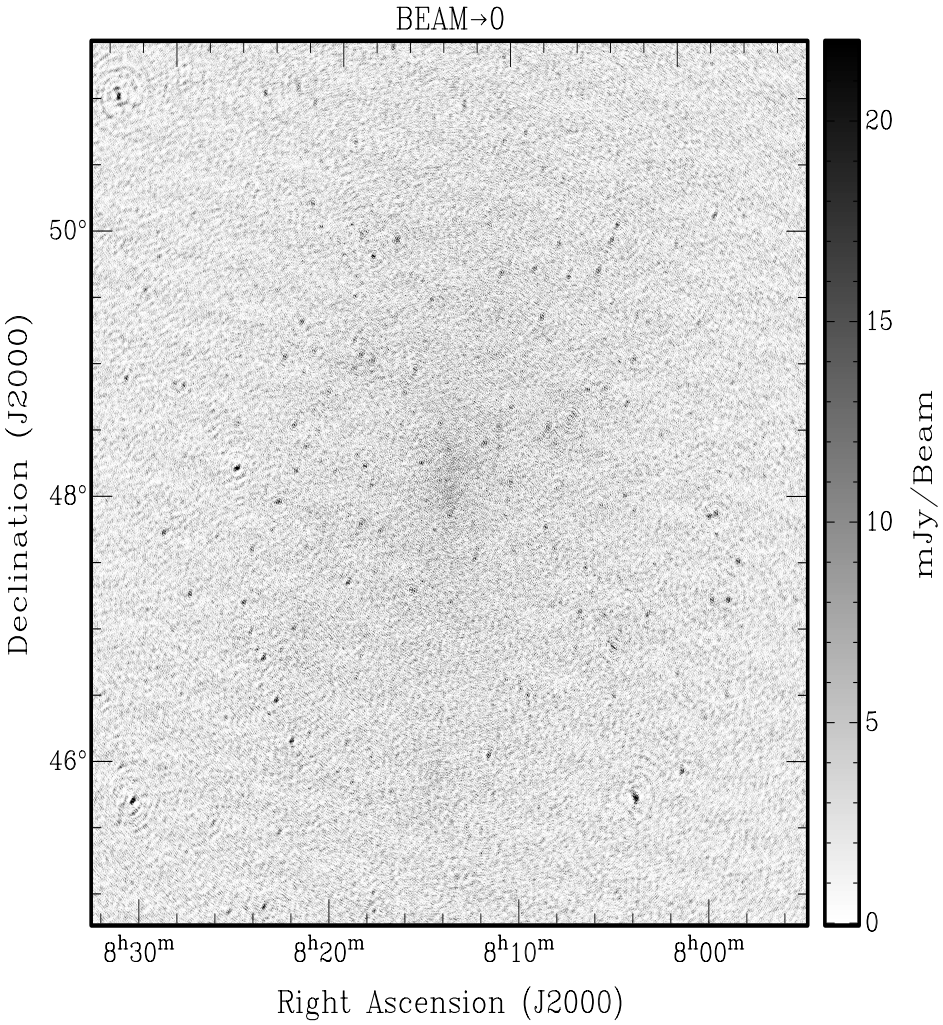




3C196: 50 directions



50 sources removed

30.000: 1 DR – single sub-band

3 mJy rms noise

Less than 24 hours

Caveats?

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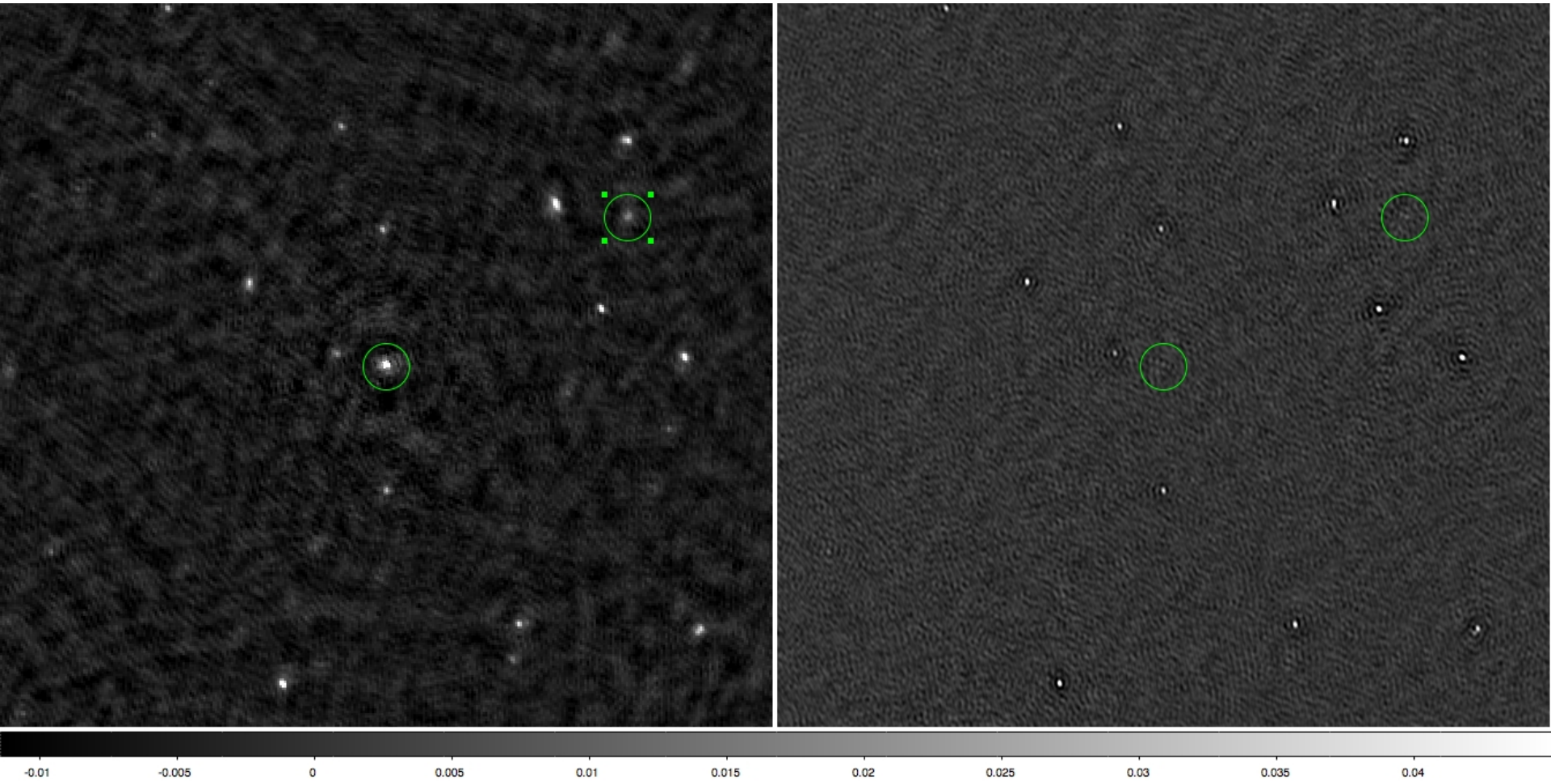

Next steps

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Significant milestone but still need to correct for directional effects to achieve higher sensitivity

Computational speed is an issue

- ✧Set improved limit on the level of the foregrounds and the detectability of the EoR
- ✧Study spectral properties and statistics of radio sources at those frequencies
- ✧New sources?

Labropoulos et al., Yatawatta et al., Khrachmalnikoff et al. in preparation

Conclusions

- Significant and accelerating progress has been made in the last two years

- LOFAR has made an important step: starts producing scientific quality results

- Several steps remain but we will soon be able to **begin EoR observations**

Ger de Bruyn, S. B. Yatawatta, M. Brentjens
A. R. Offringa, O. Martinez, V. N. Pandey
E. Tiesinga, V.-K. Veligatla and the
LOFAR builders and commissioners

ASTRON

Netherlands Institute for Radio Astronomy

LOFAR NWO

THANK YOU FOR YOUR ATTENTION !

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