The LOFAR EoR project:

VLBI and the flanking fields

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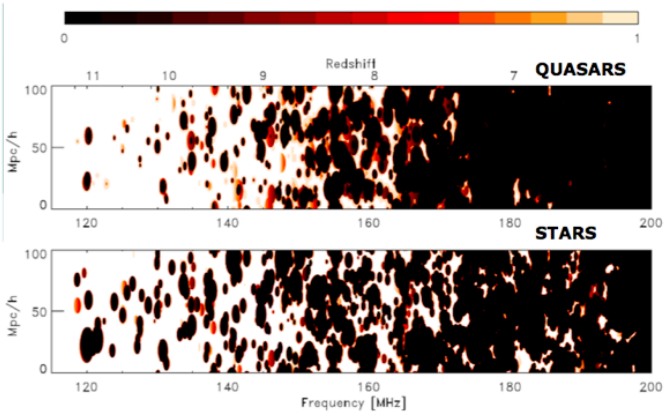
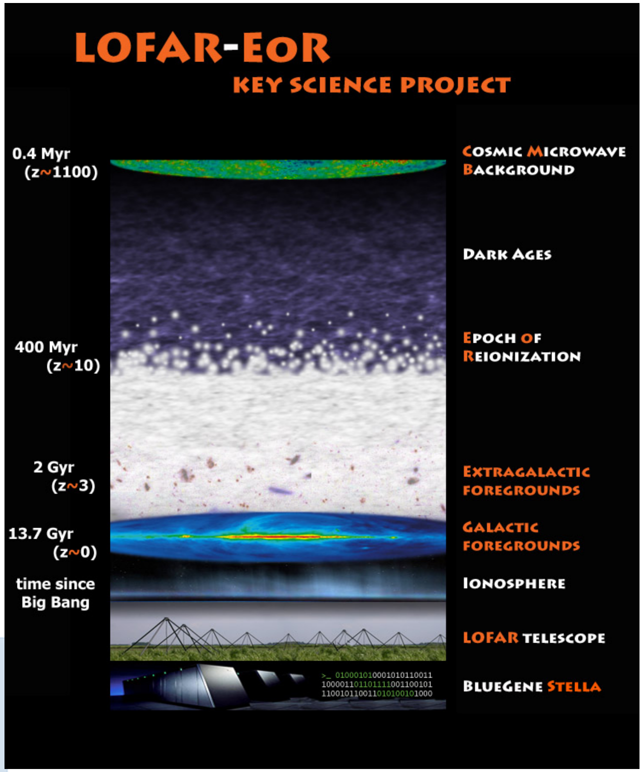
Main science goals of the LOFAR EoR project

- Statistical detection of global signal; z-evolution
- Measure underlying dark matter density spectrum
- Statistical characterization of ionization bubbles
- The environment of high z QSOs / SMBH
- Constrain the sources: stars, QSOs or …
- Study 21cm forest to high z radio sources (if any)
- Cross correlation with other probes: CMB, Ly-α, ….



Rajat Thomas (2009)

115 - 190 MHz
z = 11.4 – 6.4



Vibor Jelic (2010)

This will take ~ 3000h of LOFAR HBA observing (2-3 windows)

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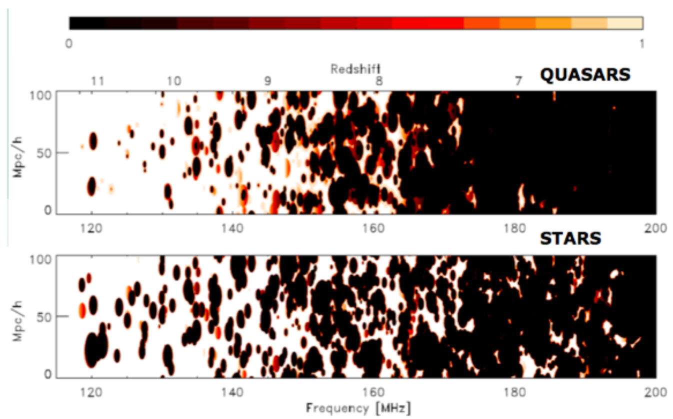
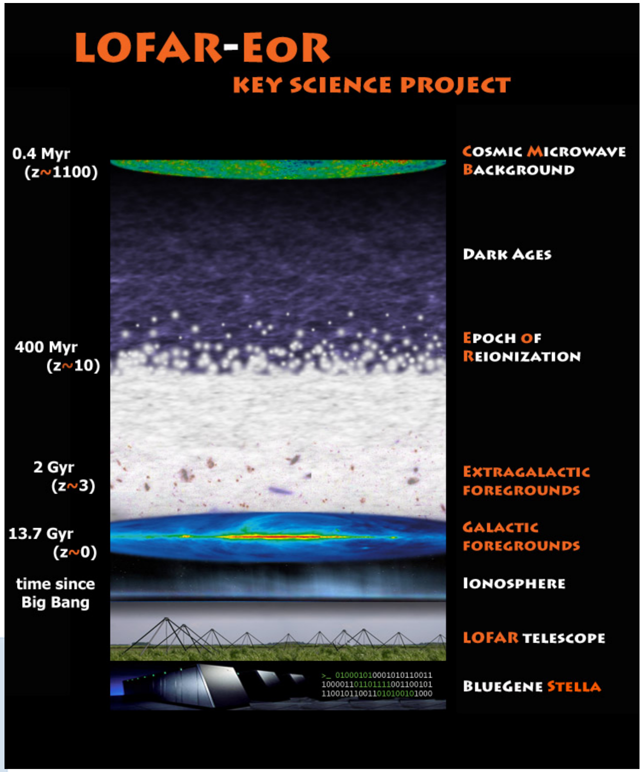


Rajat Thomas (2009)

115 - 177 MHz
z = 11.4 – 7.0



Vibor Jelic (2010)

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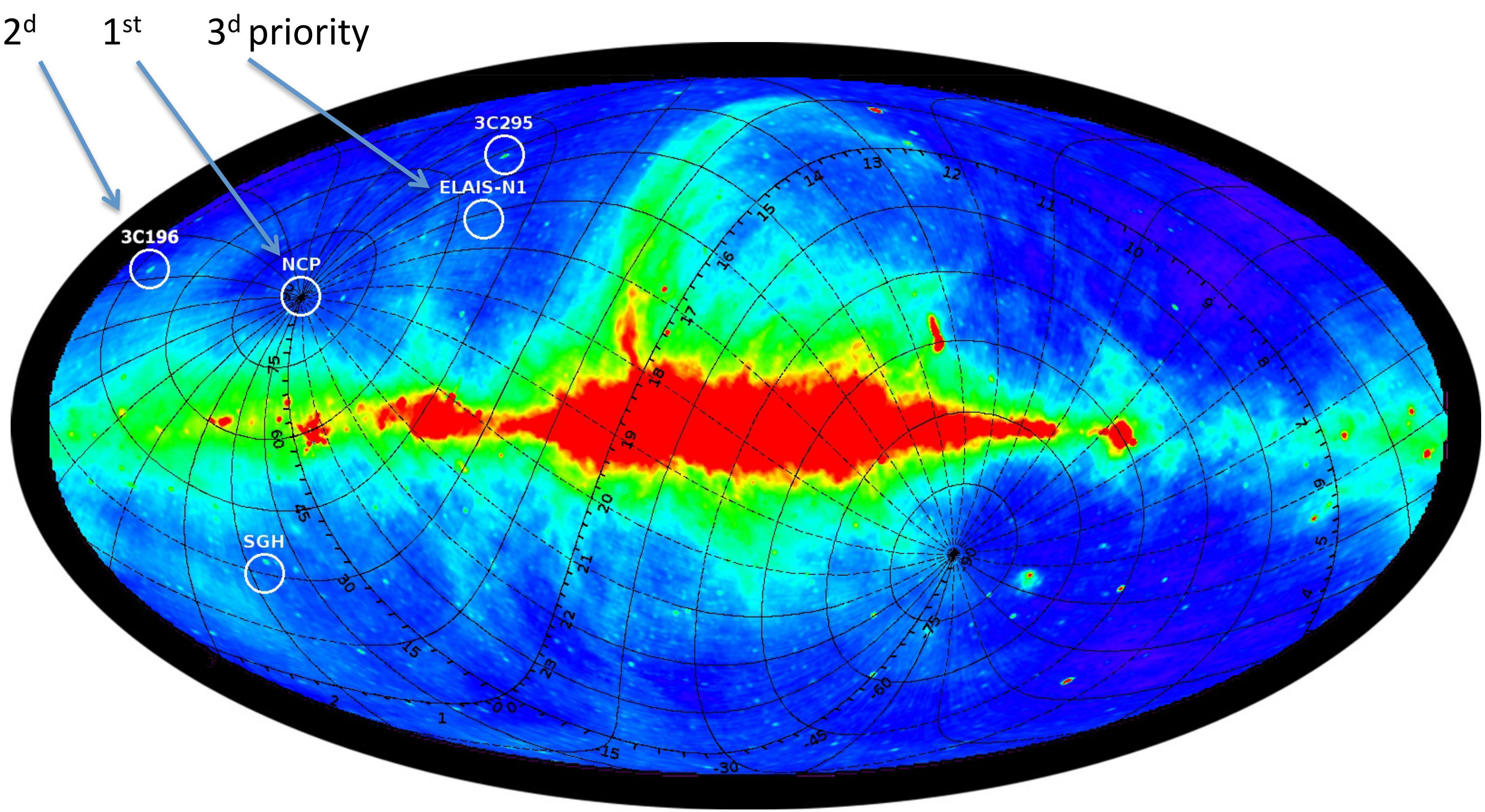
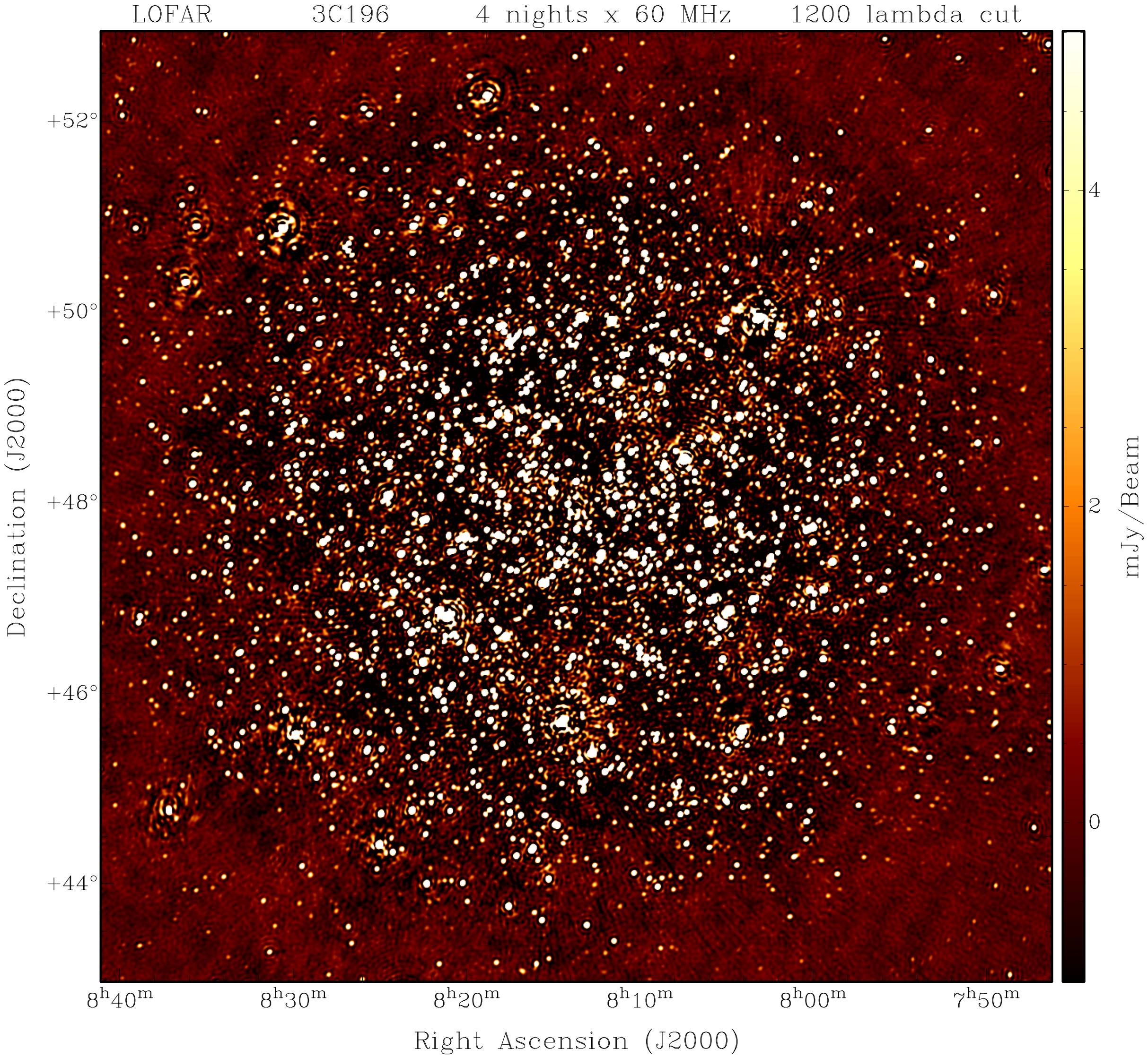
Location of our 3 EoR windows



Haslam etal, 408 MHz (1981)

Challenge #7: Very high DR imaging   DR ~ 10^6 : 1



3C196

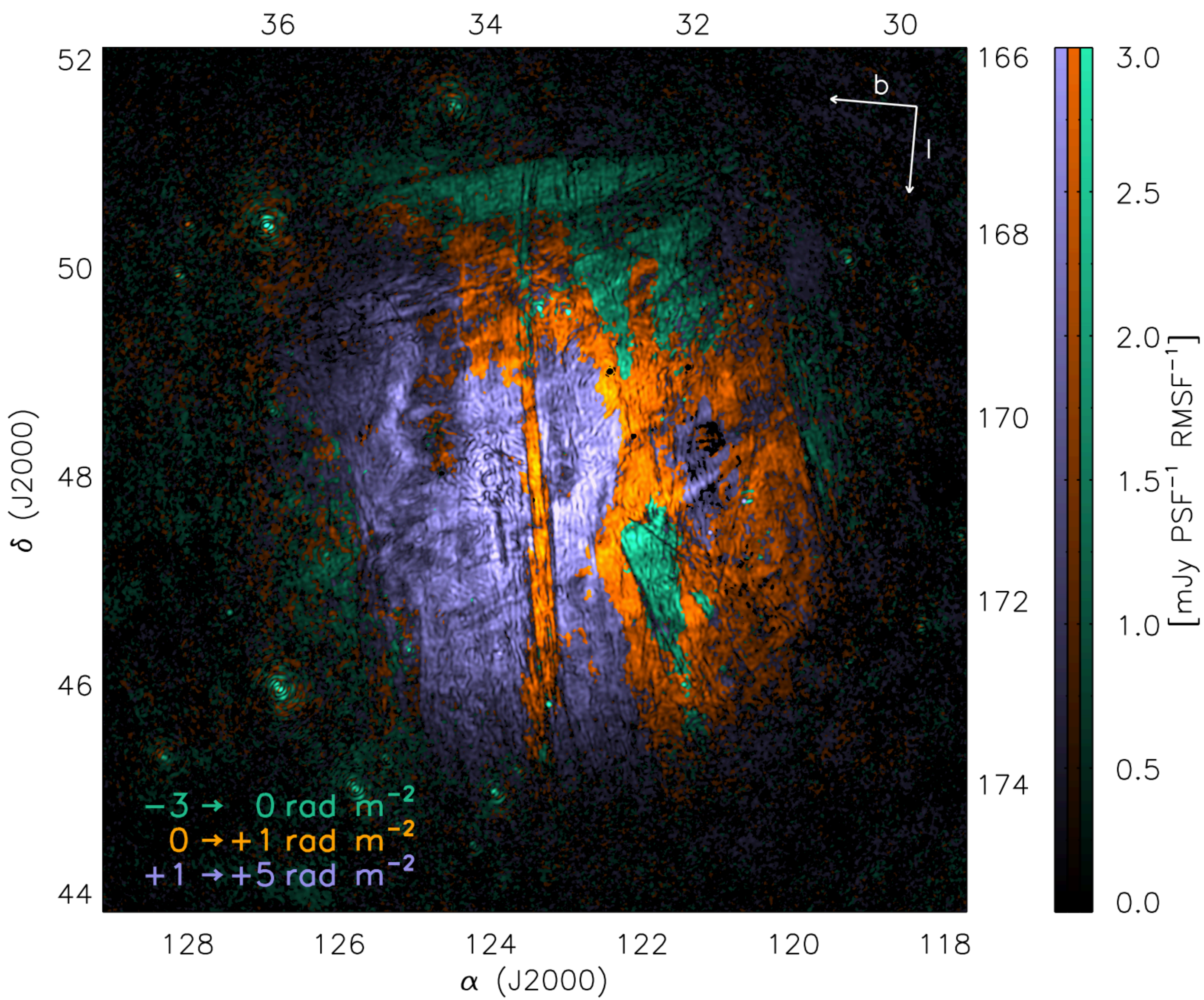
80 Jy source

80 µJy noise

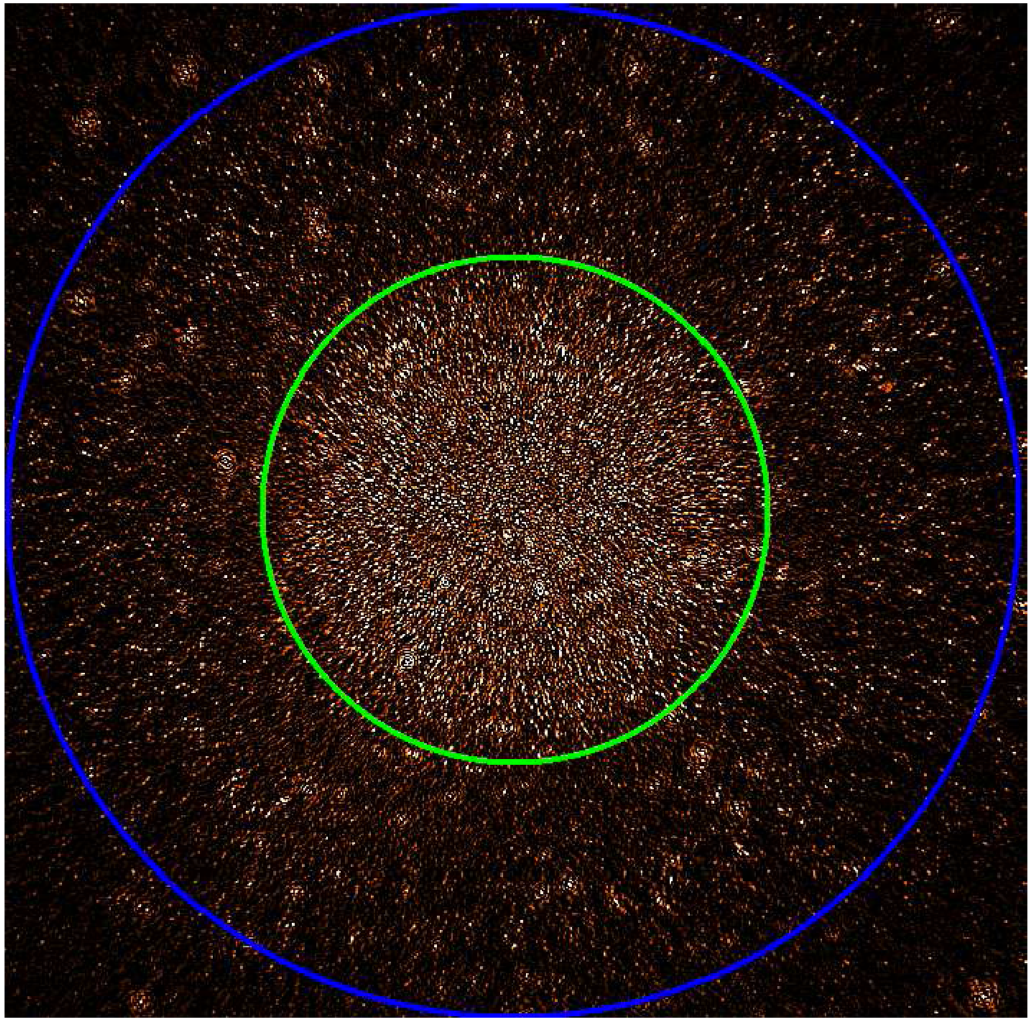
10 x 10°

#4 Galactic foreground polarization towards 3C196

Jelic etal, 2015



The NCP window: the deep and wide picture



First null 10 deg. diameter, second null 20 deg. diameter

EoR-group efforts in the last year(s)

- 'Known' unknowns: - sky-model, station-beams, ionosphere
- Unknown unknowns: - 'excess noise' (on large scales, Stokes V versus I)

(but also 3 'knowns' need much more work !)

Our main tools:

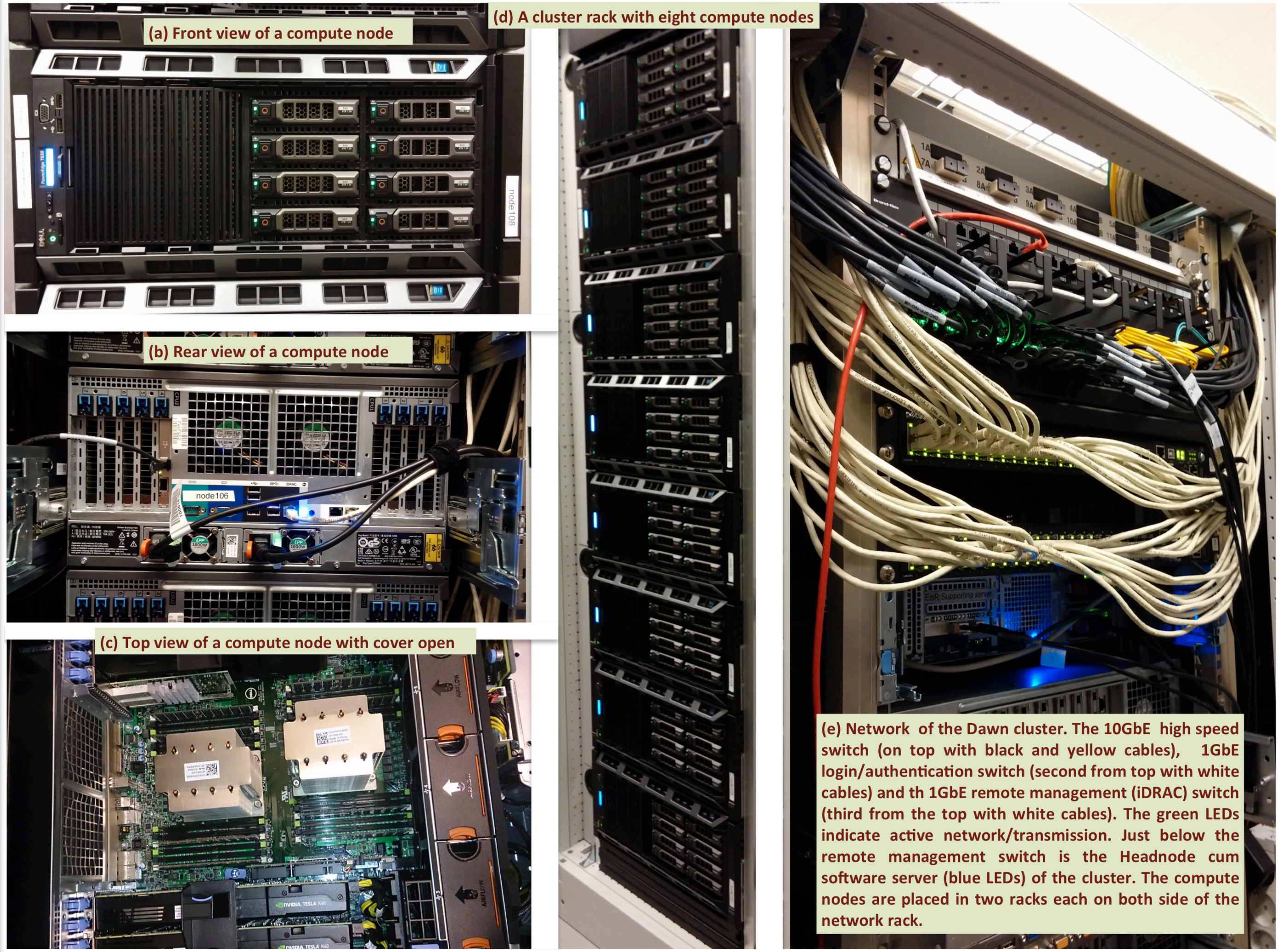
- NDPPP flagger (AO), averager, …
- BBS-NDPPP, SAGEcal calibration programs (now including LOFAR beam)
- ExCon, WSClean imager, deconvolution

'New concepts' /issues in ultradeep calibration/imaging at < noise

- 'suppression' of unmodelled structure a.k.a. scale-dependent 'bias'
- 'discontinuity' in intensity scale in residual data after SAGEcal (a.k.a. 'leverage')
- 'solver noise' => boosting of residual fluctuations
- polarization leakage from Q,U → I

++ Our new cluster: Dawn (see Pandey etal , ASTRON Newsletter Dec 2015)

EoR-group efforts in the last year(s)



(a) Front view of a compute node

(b) Rear view of a compute node

(c) Top view of a compute node with cover open

(d) A cluster rack with eight compute nodes

(e) Network of the Dawn cluster. The 10GbE high speed switch (on top with black and yellow cables), 1GbE login/authentication switch (second from top with white cables) and th 1GbE remote management (iDRAC) switch (third from the top with white cables). The green LEDs indicate active network/transmission. Just below the remote management switch is the Headnode cum software server (blue LEDs) of the cluster. The compute nodes are placed in two racks each on both side of the network rack.

phere

es V versus I)

LOFAR beam)

noise

ent 'bias'

(a.k.a. 'leverage')

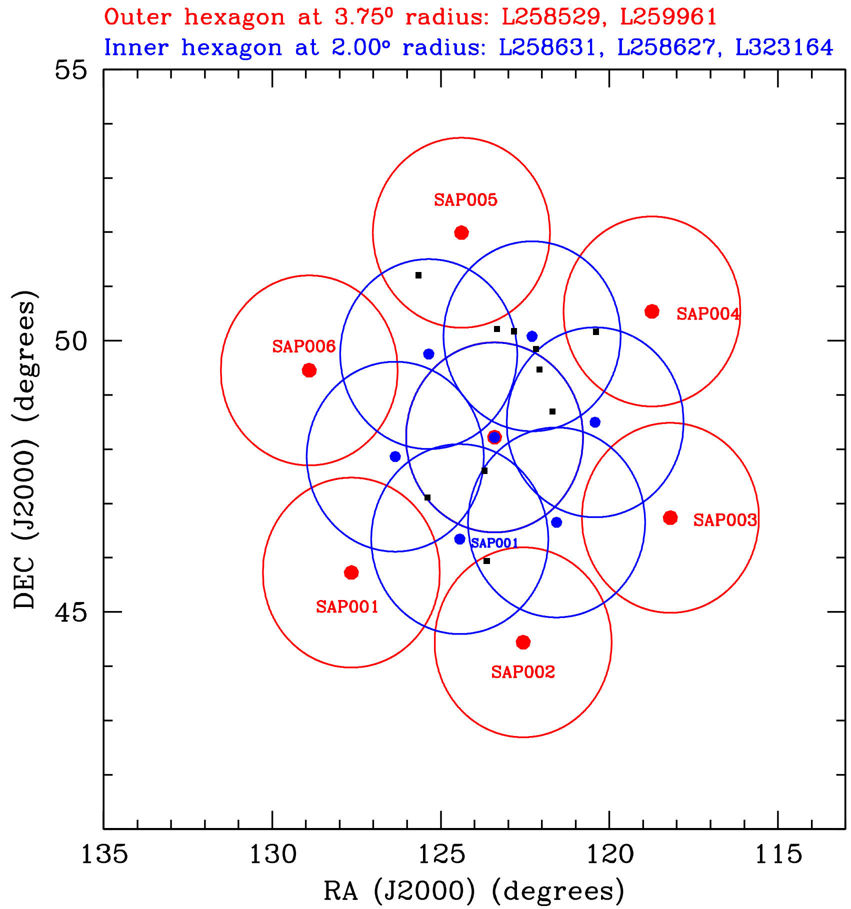
++ Our new cluster: Dawn (see Pandey etal , ASTRON Newsletter Dec 2015)

EoR observing configuration: 1 target + 6 flanking fields

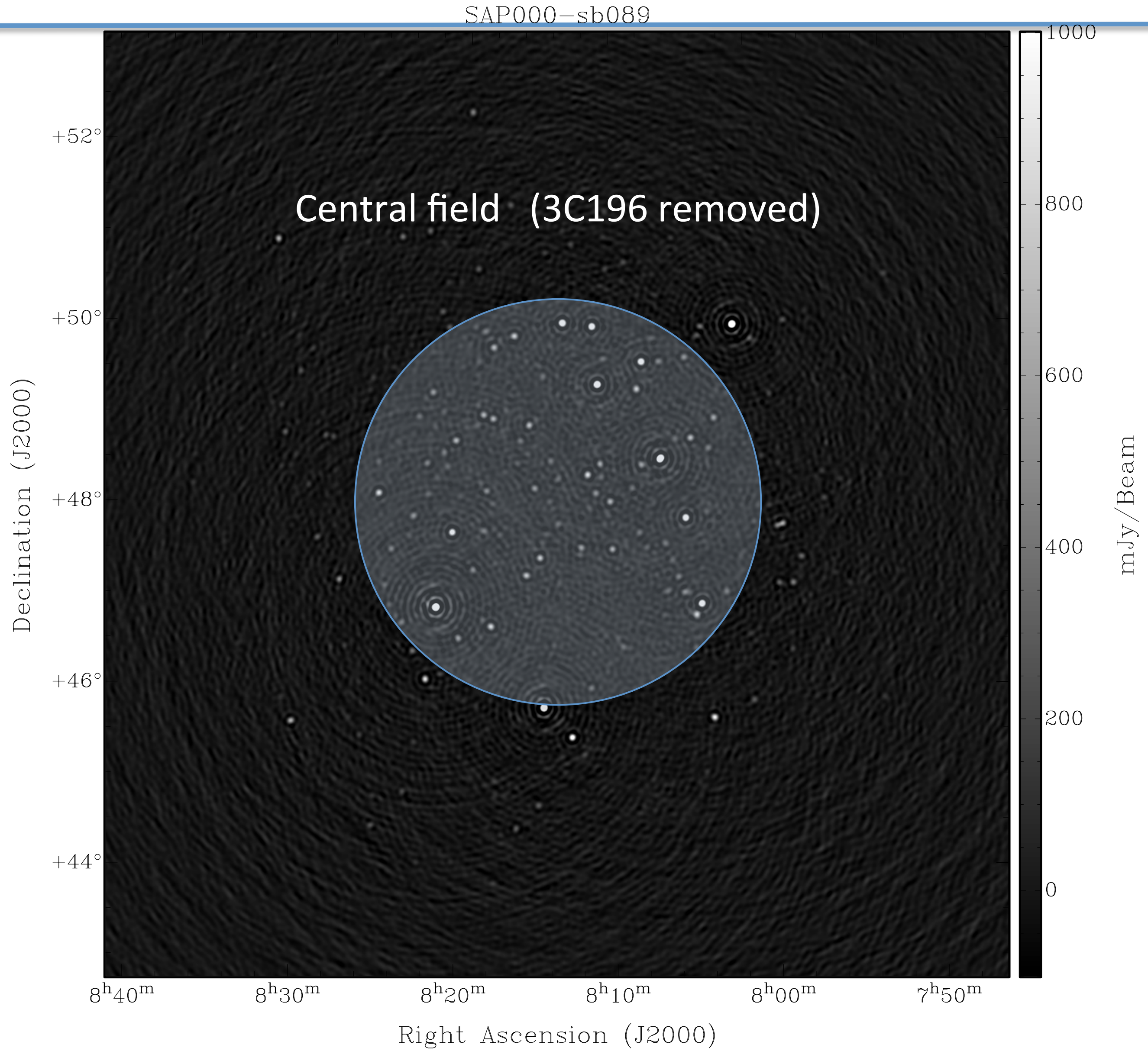
Normal observation

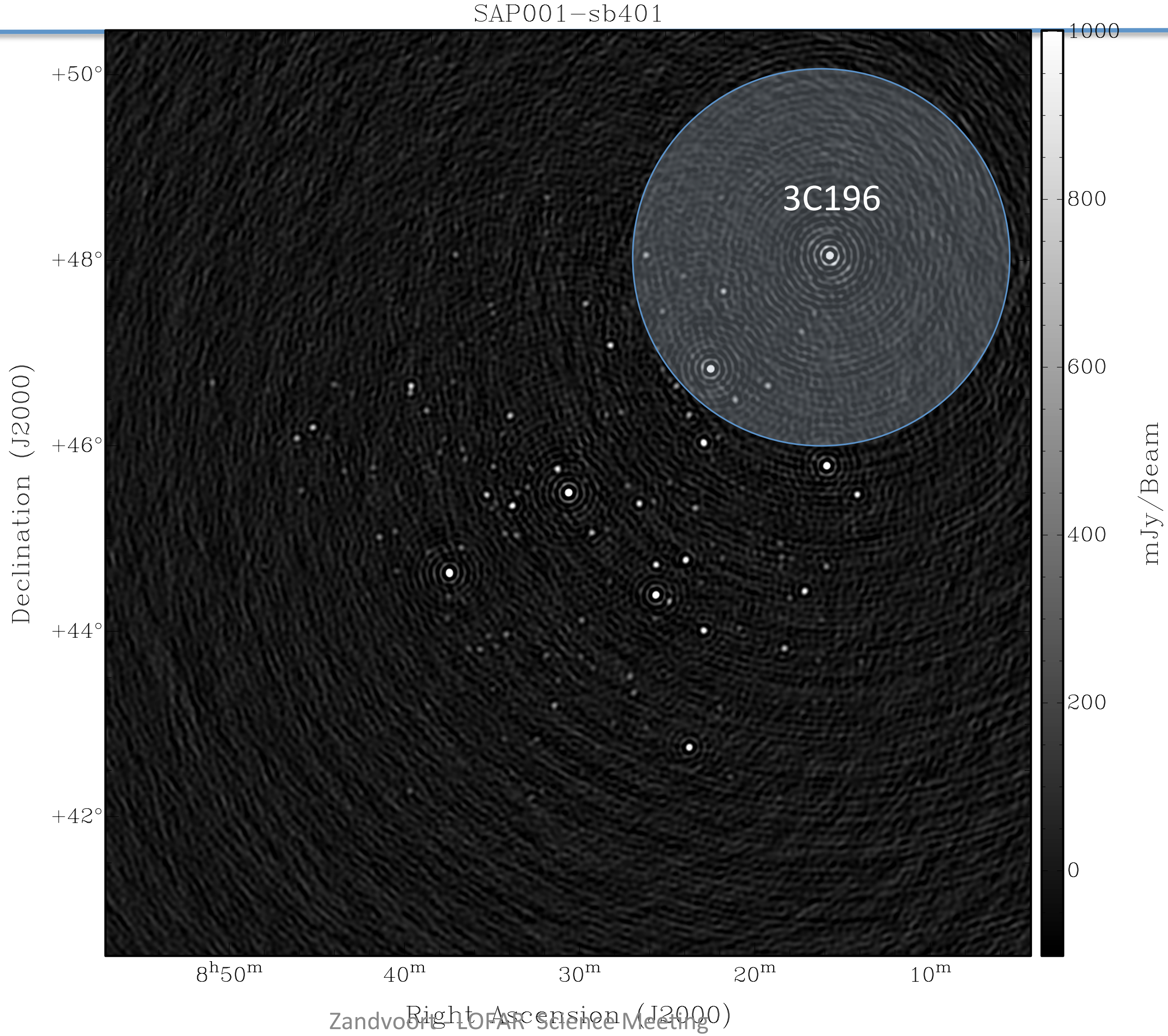
380 sb on target
+ 6x18 sb on flanking fields in two hexagon patterns (inner and outer)

Bright and flat spectrum sources are indicated with small black squares

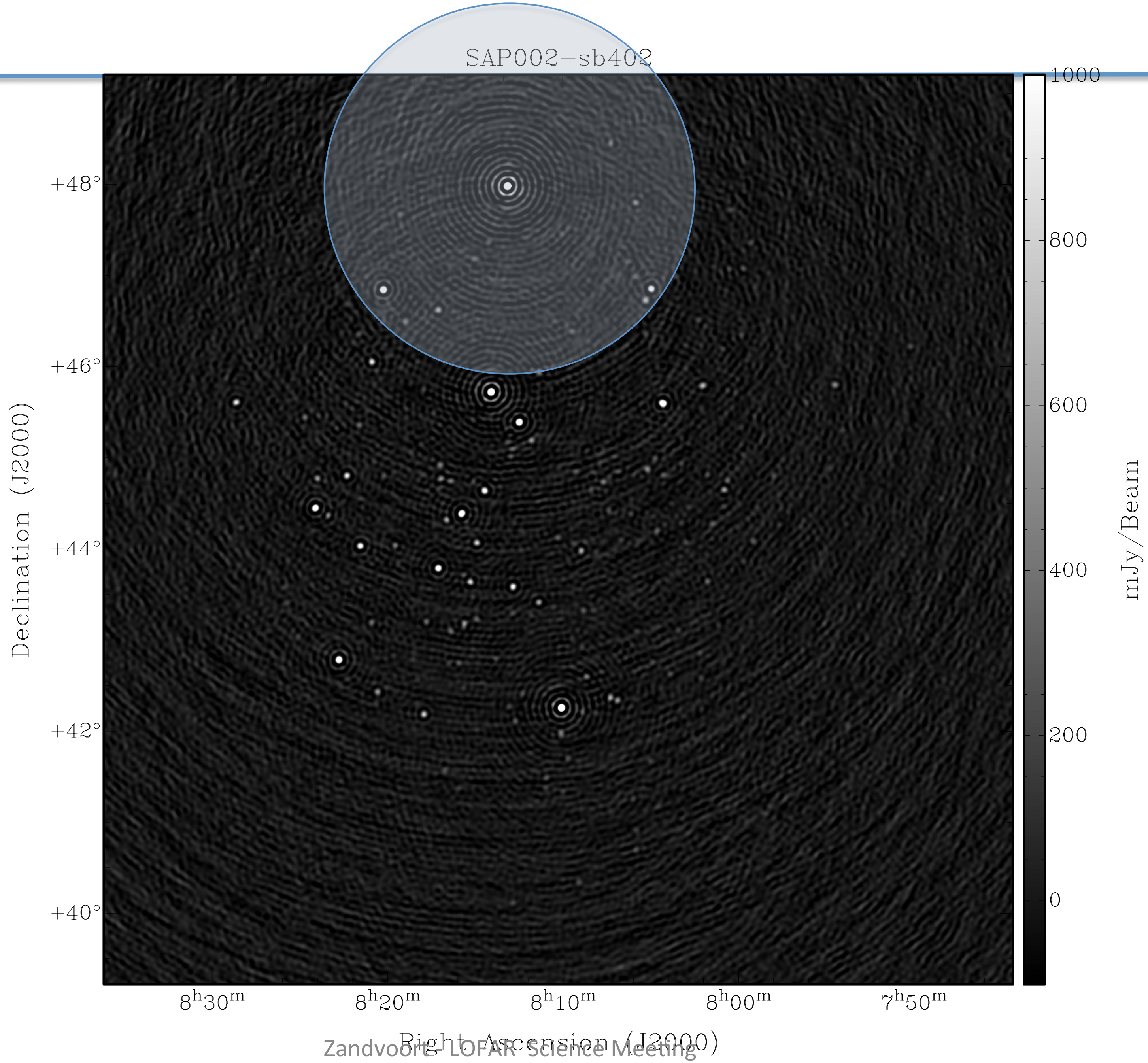


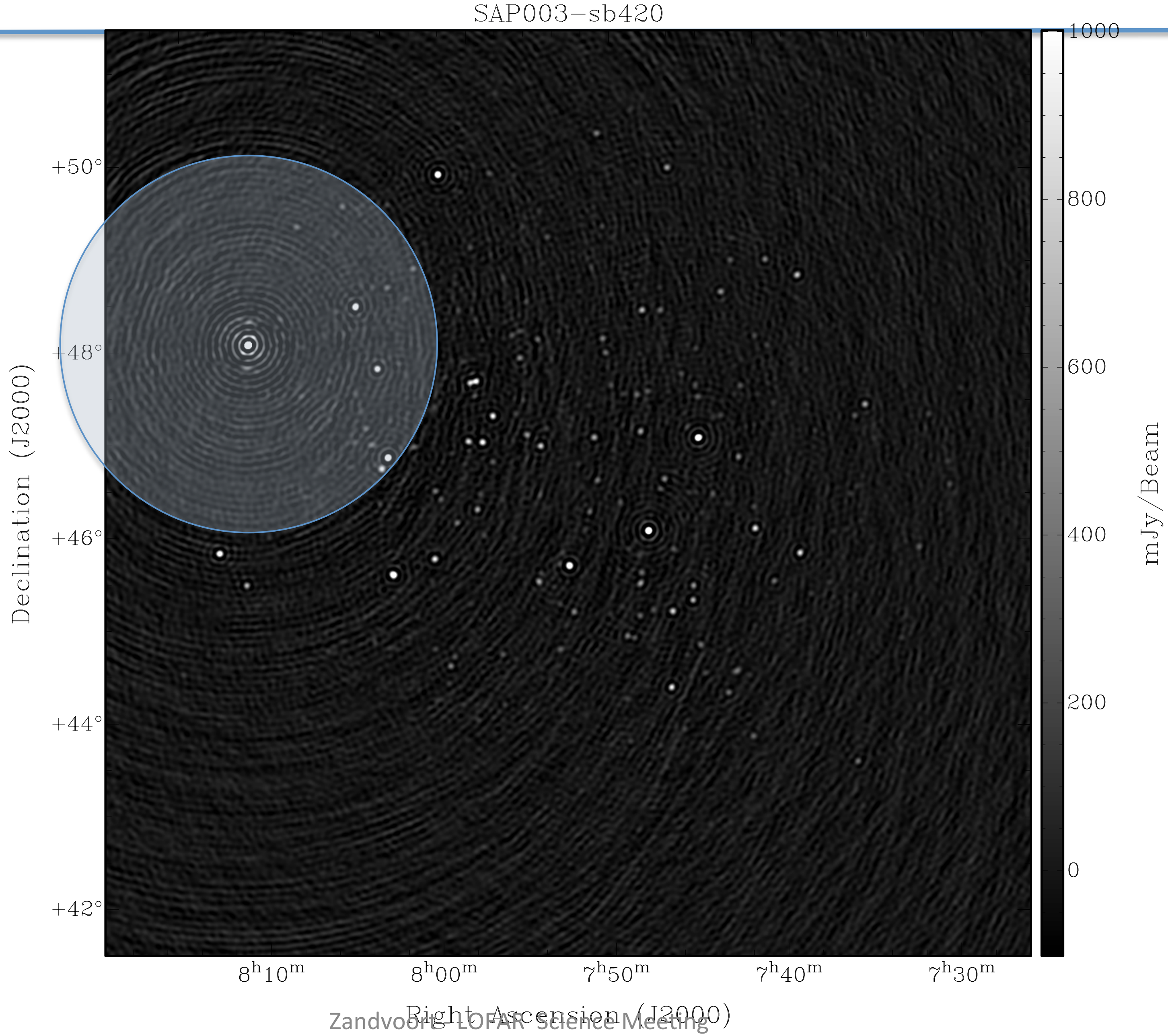
3C 196 situation

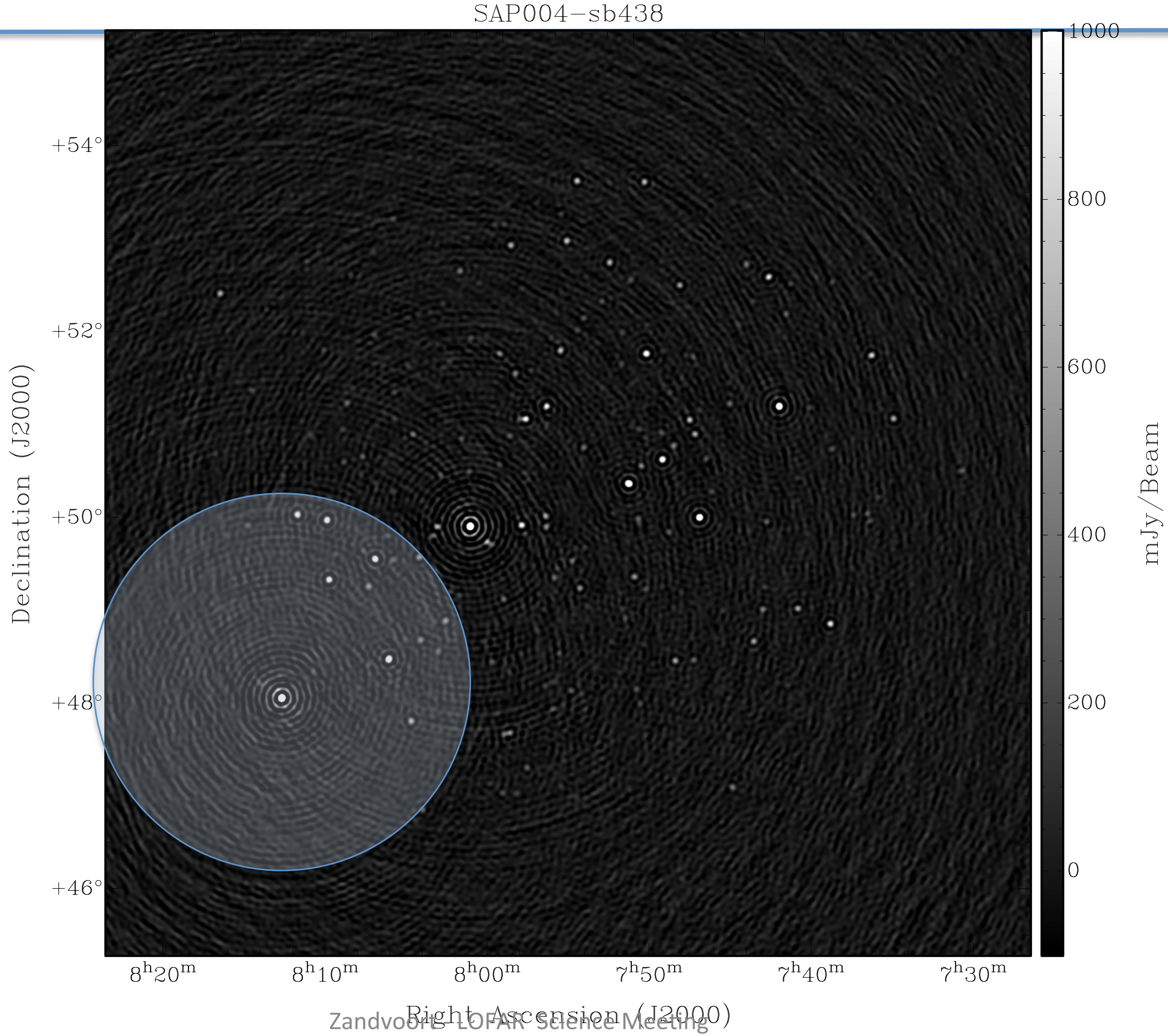

SAP000−sb089
Central field (3C196 removed)
+52°
+50°
+48°
+46°
+44°
Declination (J2000)
8h40m
8h30m
8h20m
8h10m
8h00m
7h50m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam

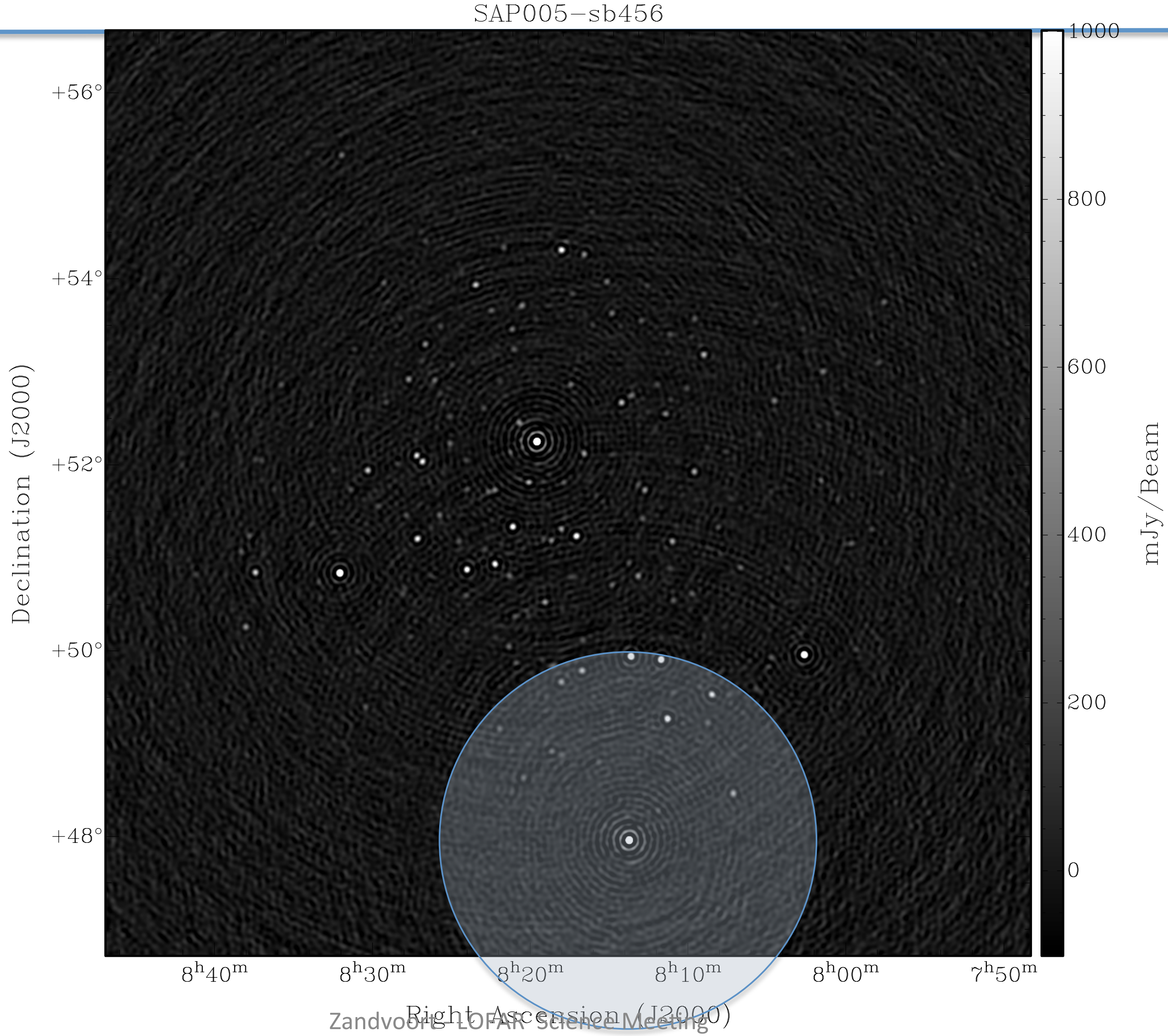


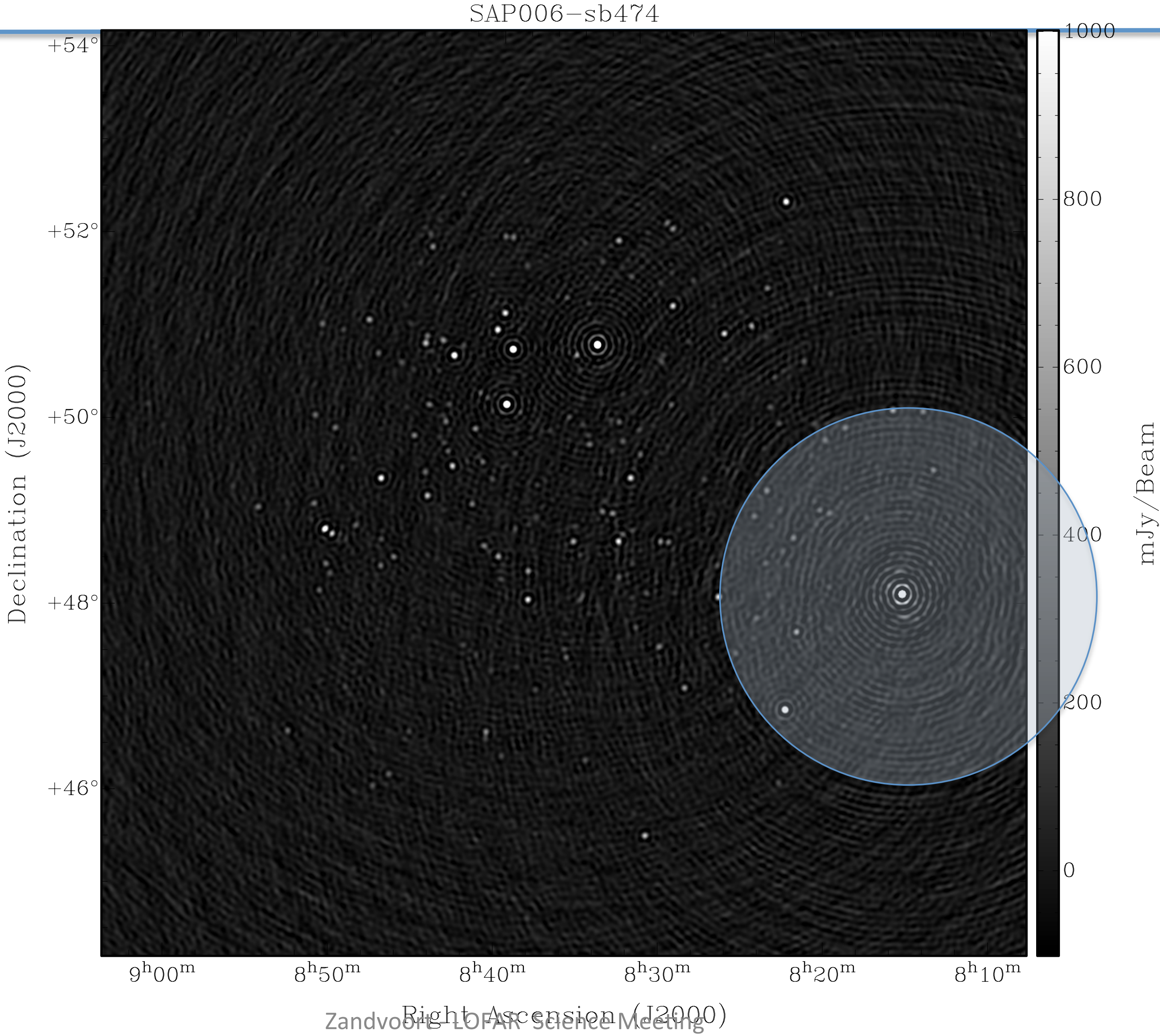
SAP001−sb401
3C196
+50°
+48°
+46°
+44°
+42°
Declination (J2000)
8h50m
40m
30m
20m
10m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam


SAP002-sb402
+48°
+46°
+44°
+42°
+40°
Declination (J2000)
8h30m
8h20m
8h10m
8h00m
7h50m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam


SAP003−sb420
+50°
+48°
+46°
+44°
+42°
Declination (J2000)
8h10m
8h00m
7h50m
7h40m
7h30m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam


SAP004−sb438
+54°
+52°
+50°
+48°
+46°
Declination (J2000)
8h20m
8h10m
8h00m
7h50m
7h40m
7h30m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam


SAP005−sb456
+56°
+54°
+52°
+50°
+48°
Declination (J2000)
8h40m
8h30m
8h20m
8h10m
8h00m
7h50m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam



SAP006−sb474
+54°
+52°
+50°
+48°
+46°
Declination (J2000)
9h00m
8h50m
8h40m
8h30m
8h20m
8h10m
Right Ascension (J2000)
1000
800
600
400
200
0
mJy/Beam

EoR and VLBI ? Why imaging at 4 resolutions ?

1st EoR detection probably will be on large scales (core-superterp) **10'**
→ exquisite calibration of stations between baselines to about 400 λλ

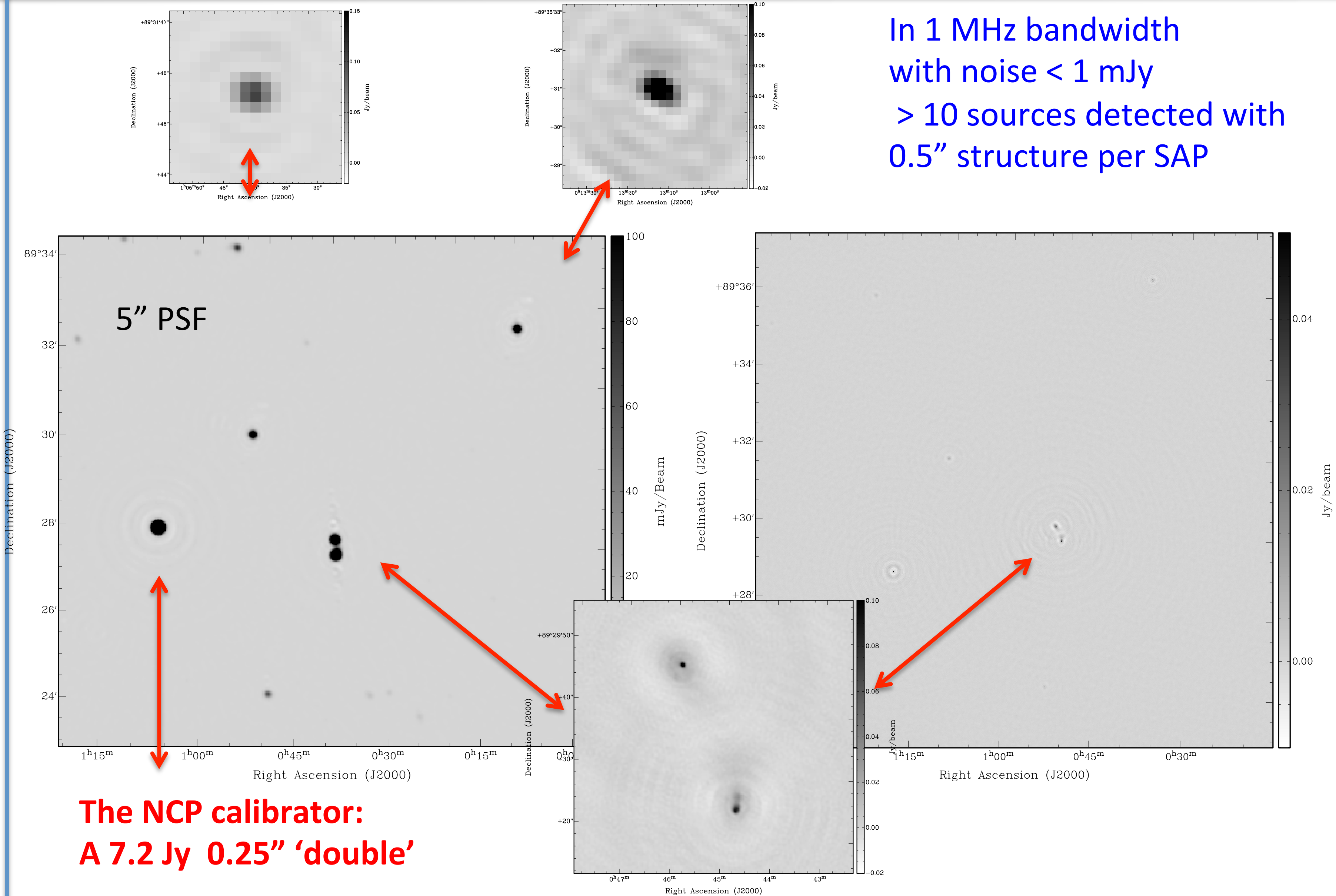
We also need to worry about polarization leakage (Q,U → I) .
Polarization signals are best seen at a resolution of about **1'**
This will require baselines out to about 4000 λλ

Providing enough constraints to model the stationbeams and the ionosphere, in more than 100 directions requires sky models at **6"**
This requires all Dutch baselines going up to 40000 λλ

Our EoR windows are dominated by very bright, compact, sources.
Removal to a DR of 1,000,000:1 requires knowledge at scales of **0.5"**
This corresponds to baselines on a European scale of 400000 λλ

NCP imaging at 5" and 0.5" *PSF* *(deBruyn, Assen 2015)*

In 1 MHz bandwidth
with noise < 1 mJy
> 10 sources detected with
0.5" structure per SAP



The NCP calibrator:
A 7.2 Jy 0.25" 'double'

Recent (Cycle 5) datasets used for 0.25-0.50” imaging

3C 196

L432696 26 Feb 2016, 12 IS, resolution: 32ch/sb - 1s 8h

20 SAP’s with each 24 subbands (115-172 MHz)

NCP

L426512 14 Jan 2016, 9 IS, resolution: 32ch/sb - 1s 15 h

9 SAP’s with each 54 subbands (115 - 172 MHz)

SAP = Sub Array Pointing (‘digital array beam’)

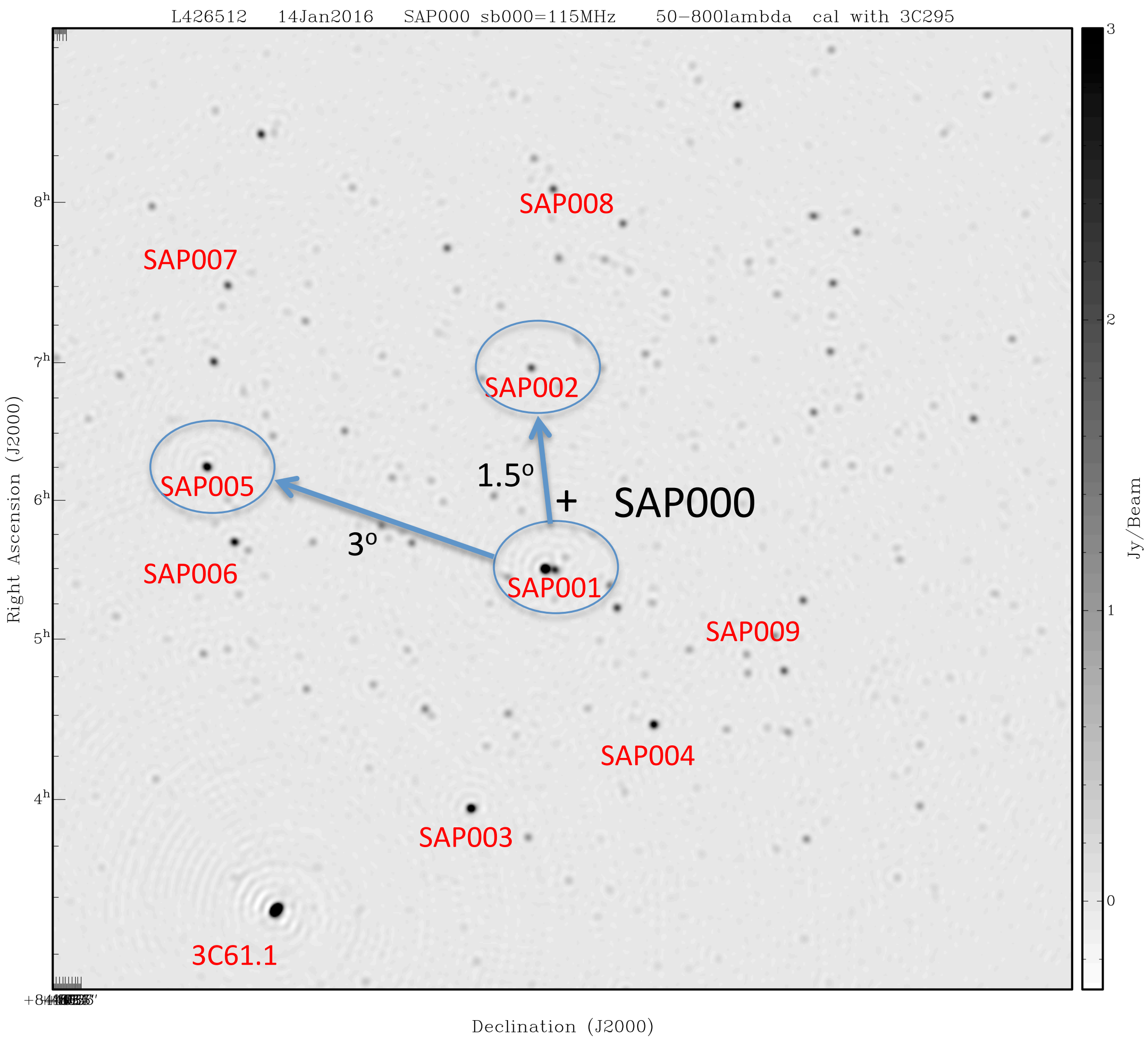
NB: 1s and 6 kHz limits time/freq smearing to about 0.3” at 1^o distance from phase tracking centre.

Bright (> 1 Jy) , compact, sources in the NCP window

NCP
115 MHz
8º x 8º
PSF 3'

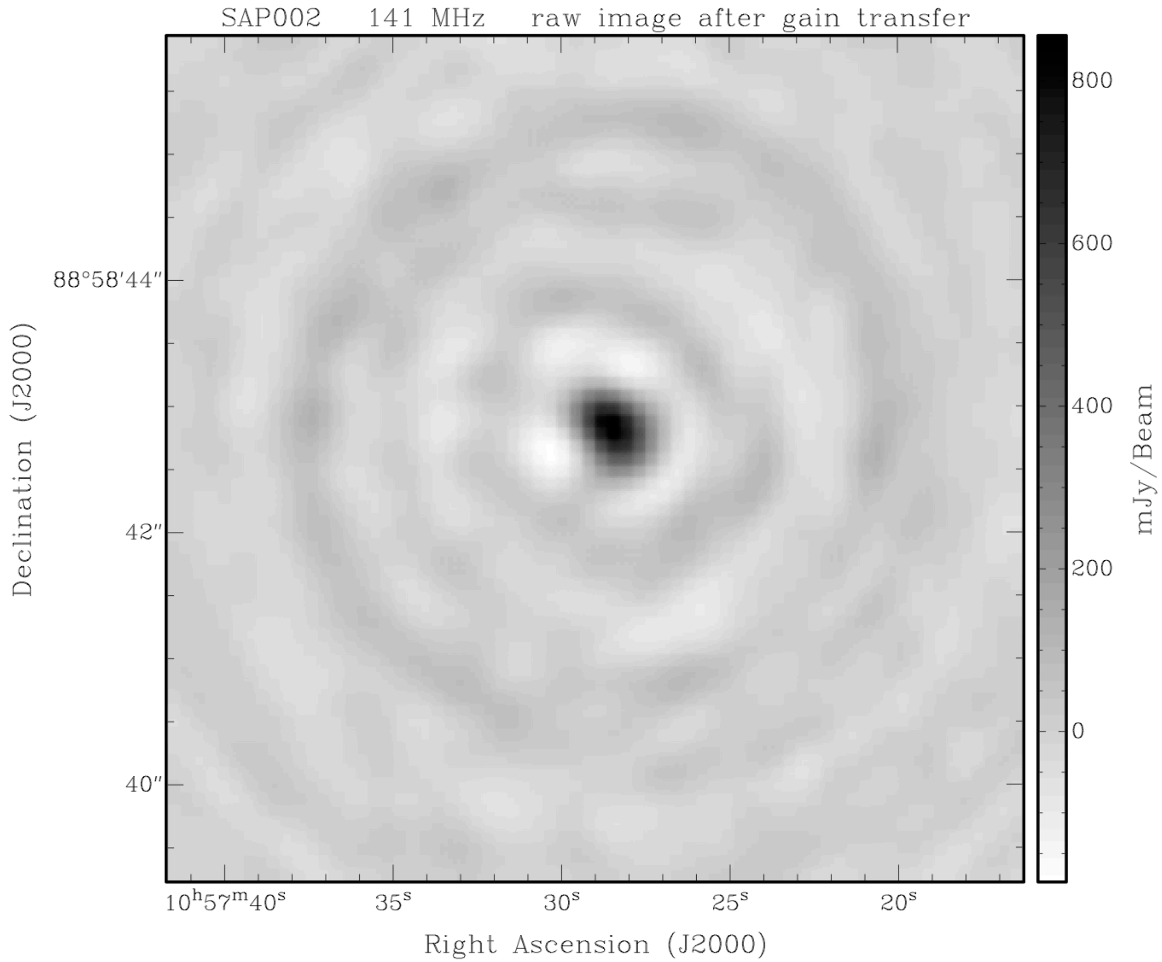
SAP000 is centered at (00h+90º, + sign)

The bright source in SAP001 is 7.2 Jy and ~ 0.3" size



VLBI Imaging in SAP002 (1.5° away from SAP001)

1.5 Jy peaked spectrum source



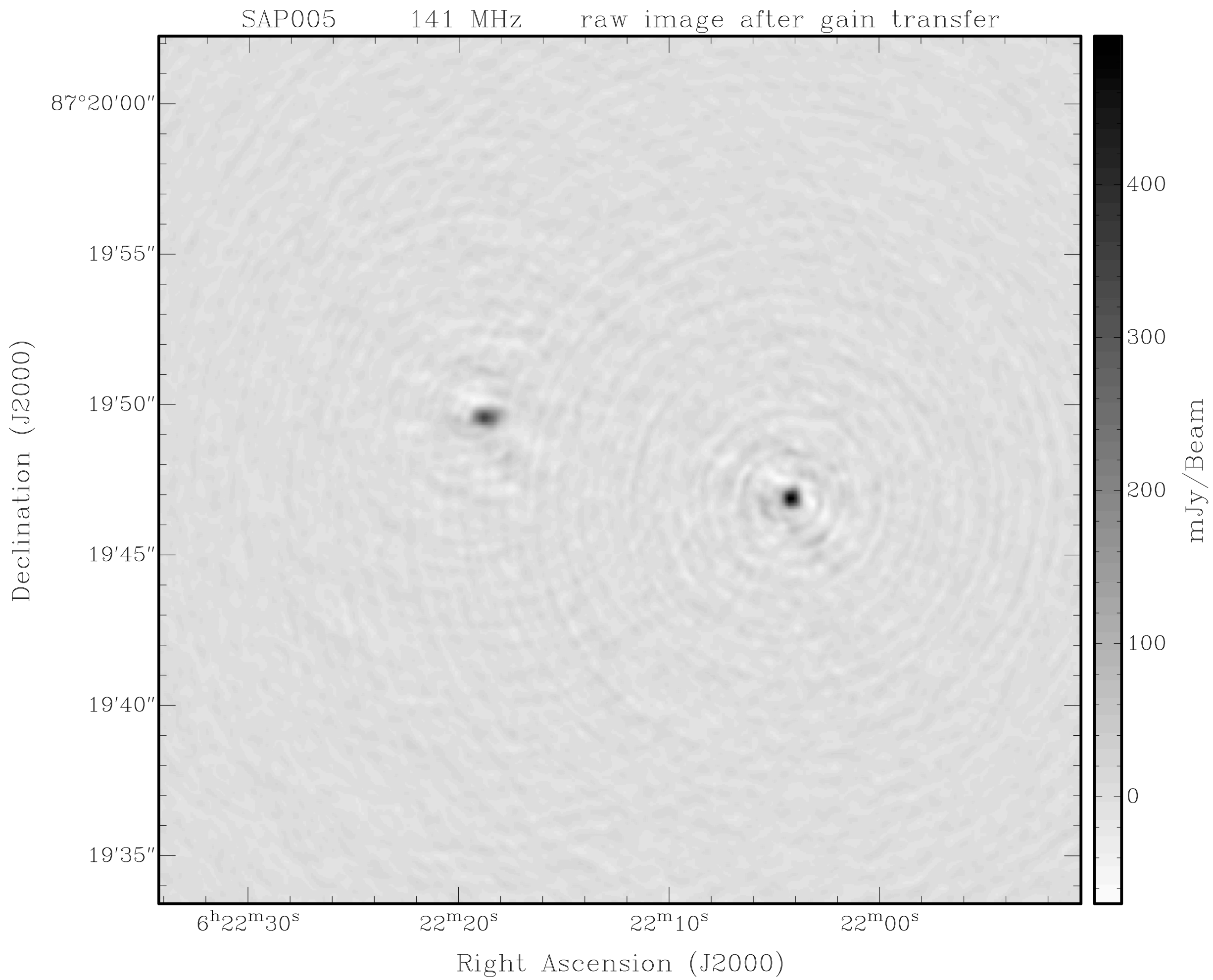
VLBI Imaging in SAP005 (3° away from SAP001)

10" double source

0.5 Jy peaks in hotptspotsts

1 subband

No (self-)calibration as yet !!



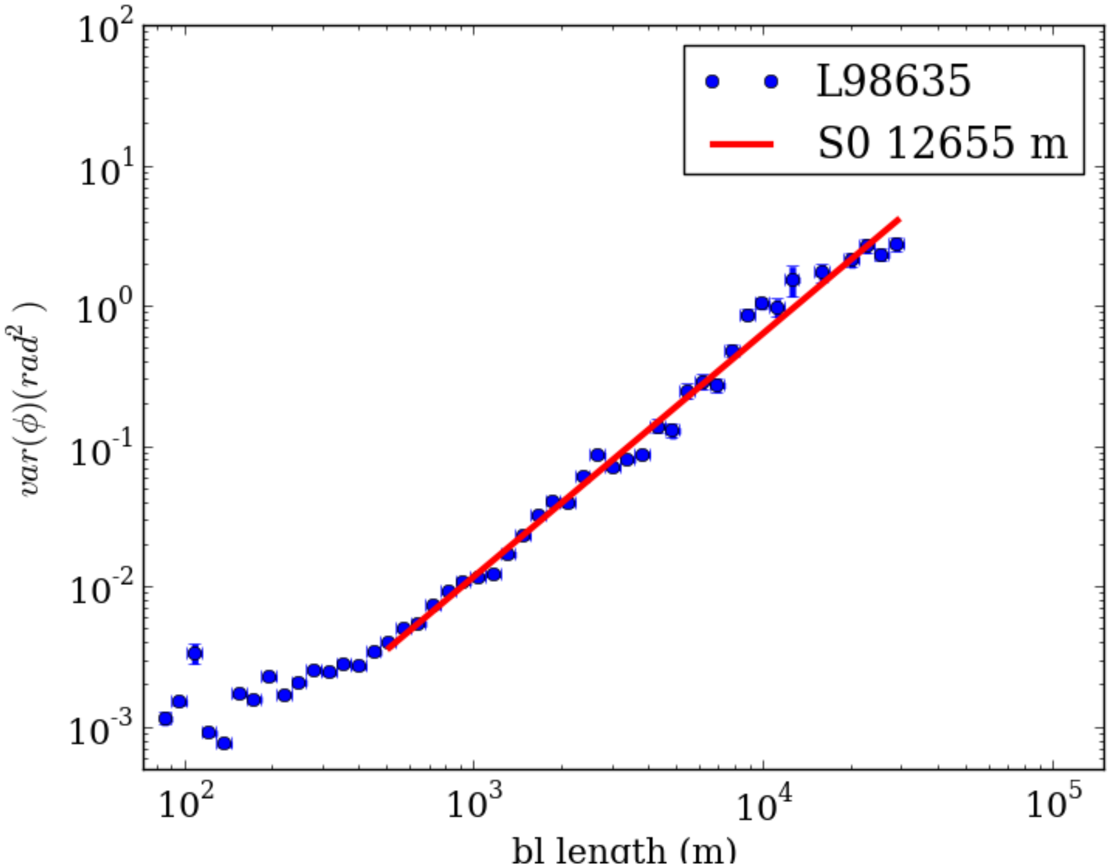
The ionospheric phase structure function

3C196

3/4 Mar 2013 (8h)

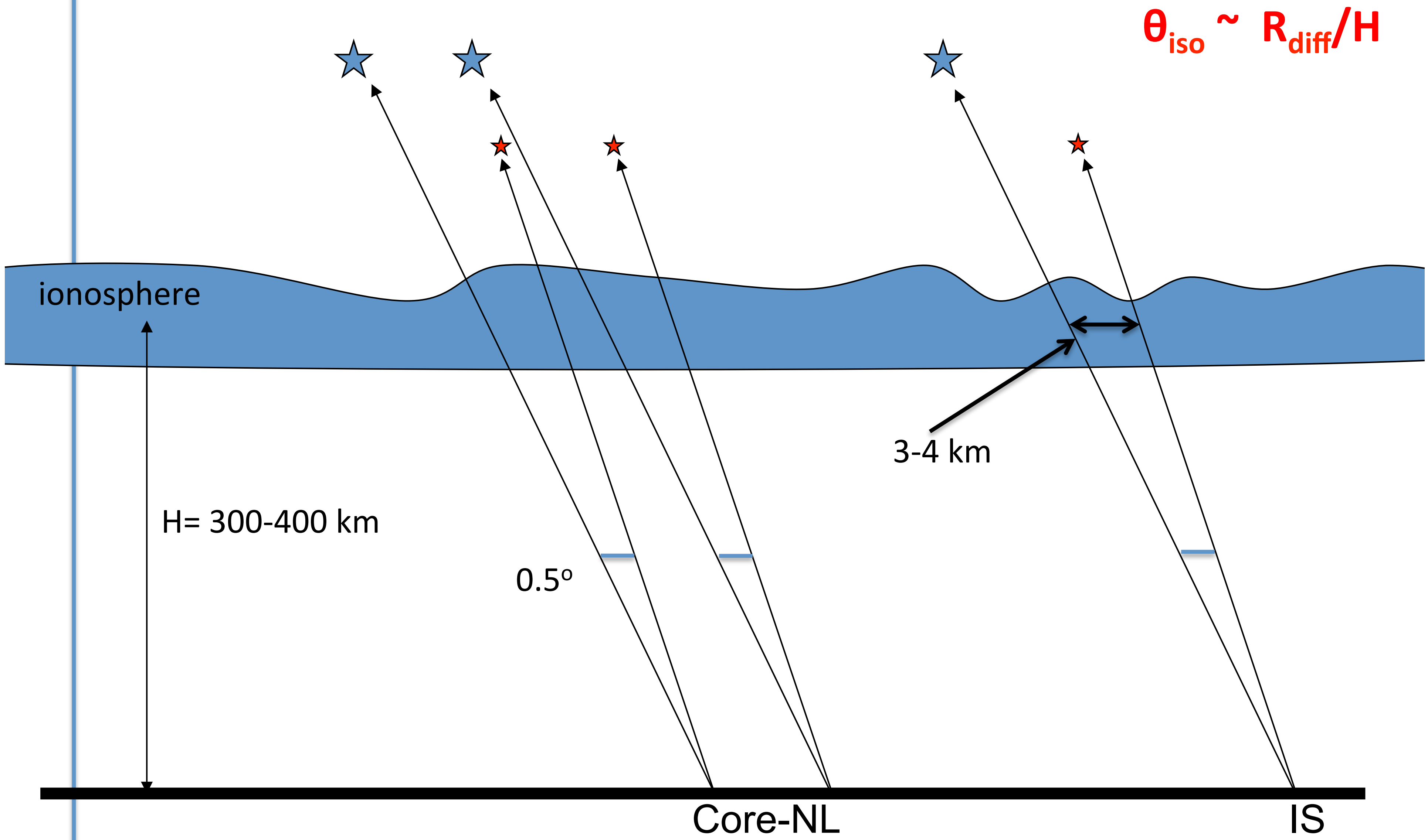
HBA 115-177 MHz

S_o is also known as the diffractive scale r_{diff}, the baseline scale over which we have 1 radian rms phase fluctuation.



Mevius etal 2015

‘Differential’ phase structure functions & isoplanatic angle



0.5" PSF imaging over 1° wide fields should be possible !

For a good ionospheric night (say $r_{diff} > 8$ km) and with similar ionospheres over all LOFAR stations in Europe the isoplanatic angle appears to be >1°

Transfer of the complex instrument gains for a VLBI-compact central source generally should be straightforward over a > 1° FOV or more !!

Note that the HPBW of an International Station (96 tiles) is ≈ 2° at 150 MHz

If you are only interested in compact structure in a small area use only IS-IS baselines augmented with baselines between some remote NL stations (say > 20 klambda).

The main issue faced when making multi-scale images of the VLBI sources is that you need to combine data from three different interferometer–beams (NL24-NL24, NL24-IS96, IS96-IS96) which have different FOV and different sensitivity to extended structure.

Feb 2016: LOFAR goes East: → 1300km baseline

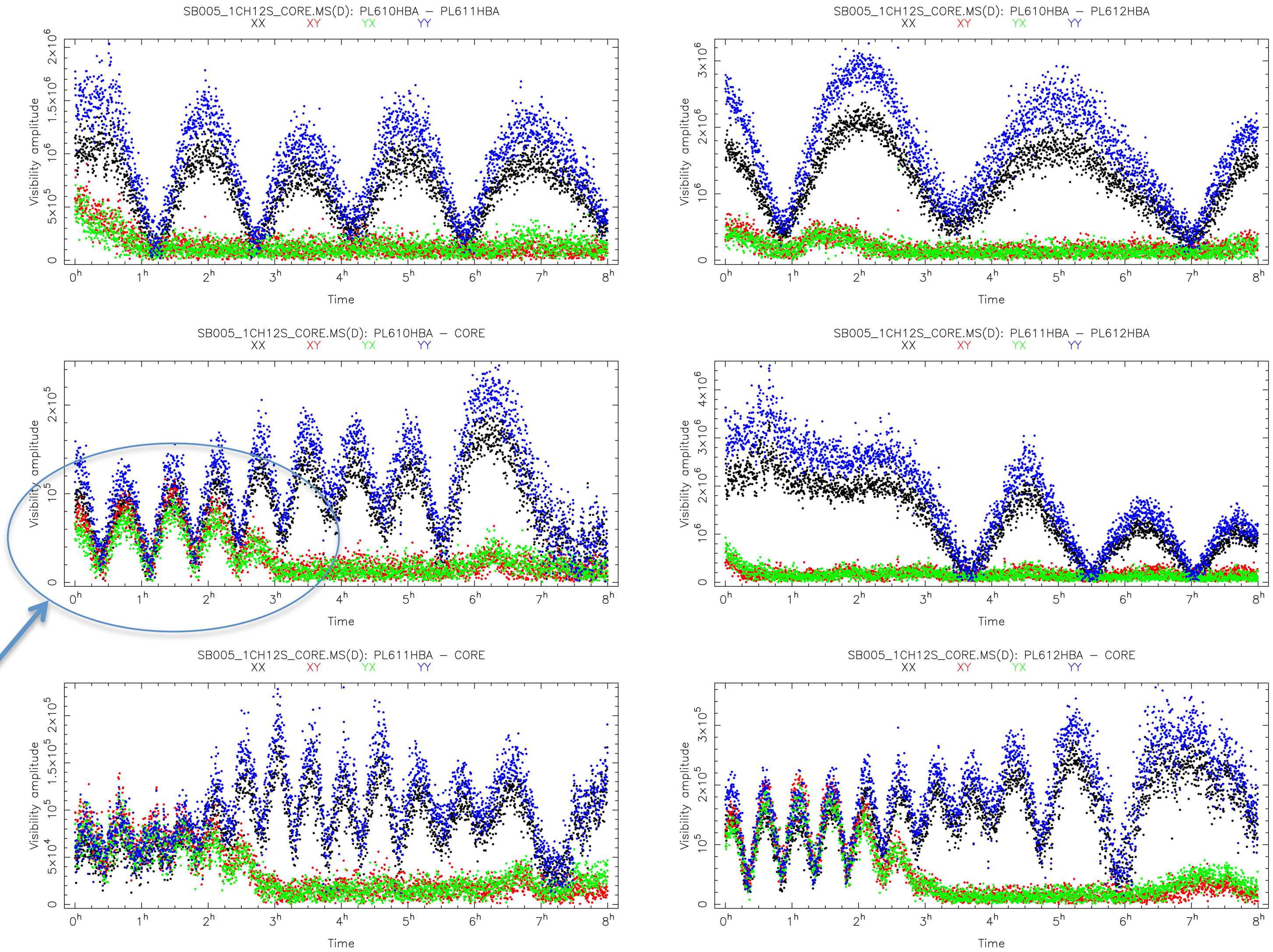
Raw visibilities : ‘CORE’ - Stations PL610,PL611,PL612

26 Feb 2016

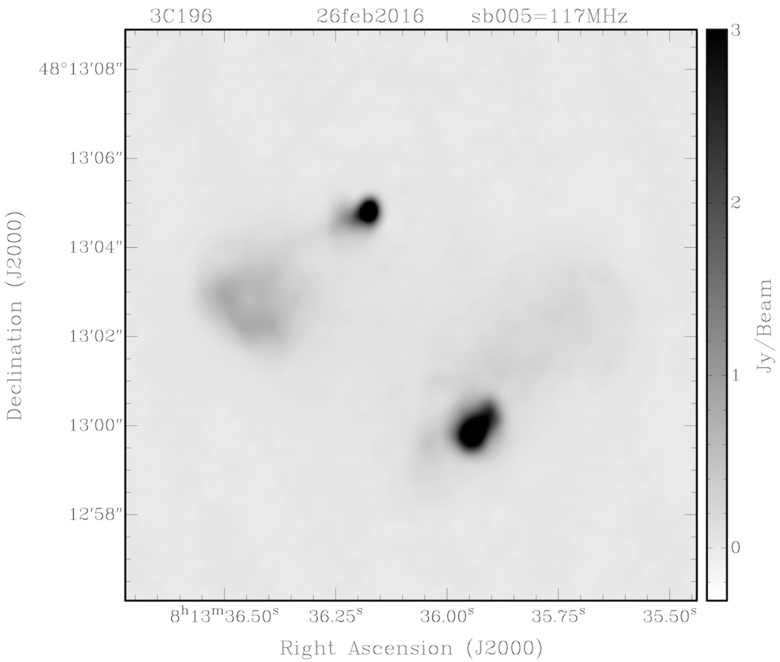
117 MHz

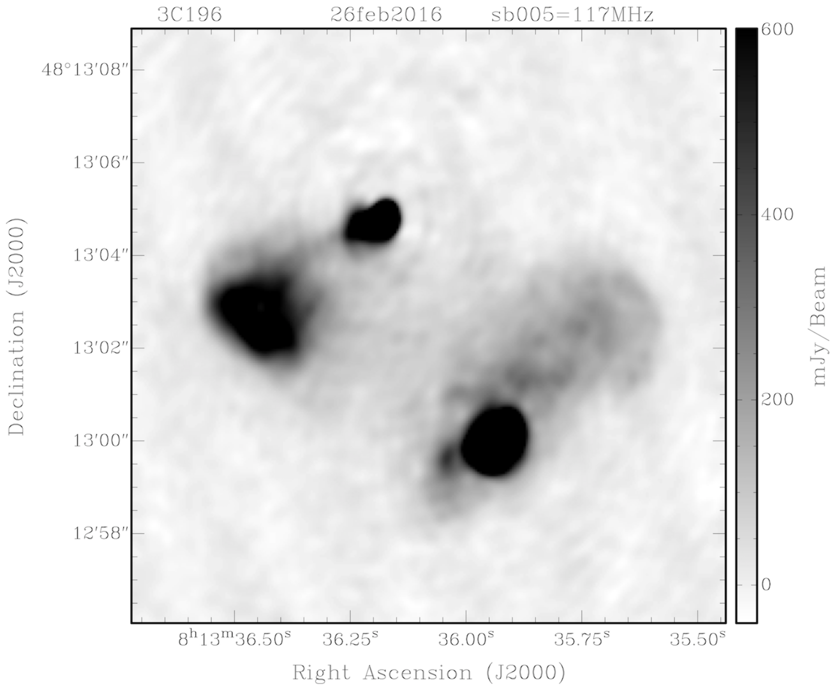
48 CS added to create superstation called CORE

Note strong differential Faraday rotation in first few hours (after sunset)



New images of 3C196 using PL610,PL611,PL612

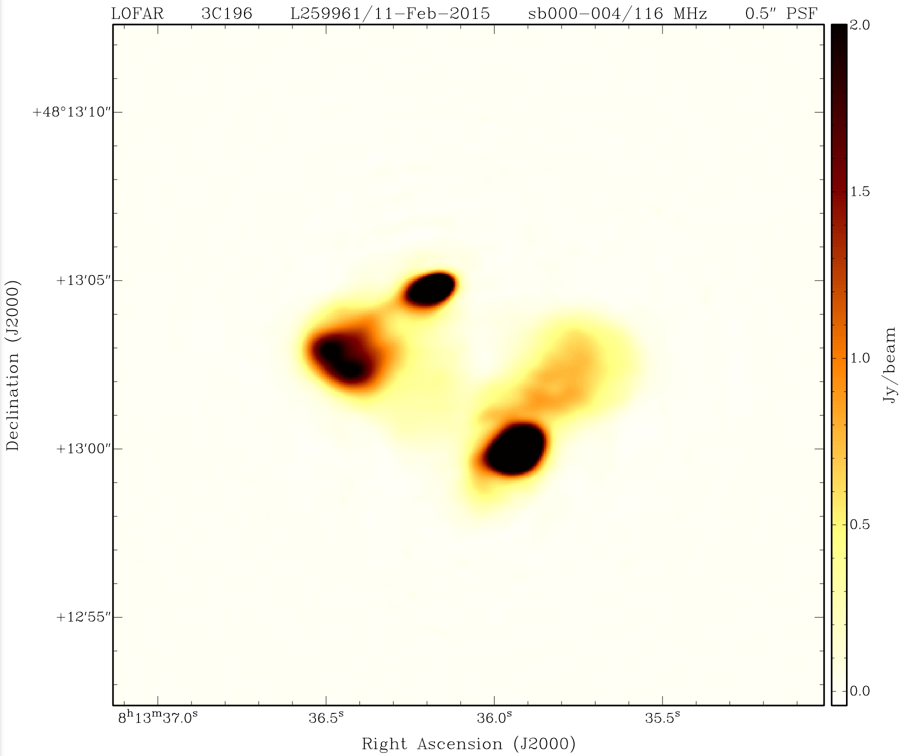


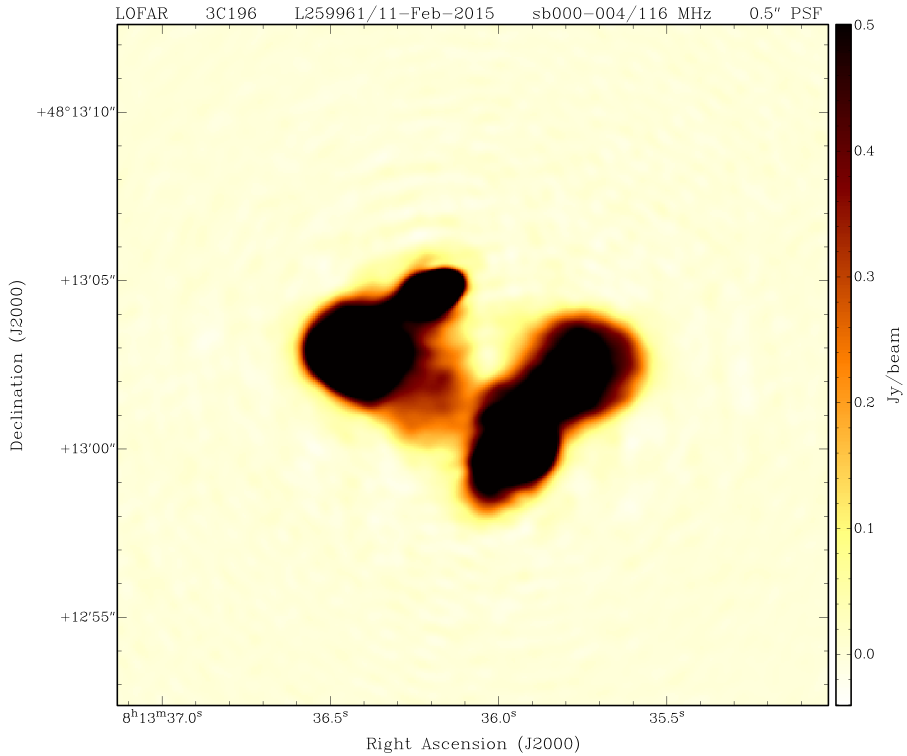


117 MHz   PSF is about 0.40x0.50”

173 MHz → PSF   0.25x0.35”
imaging still continuing, as well as multi-frequency fitting

3C 196: imaged with a 0.5" PSF *(de Bruyn, Assen 2015)*





115-116 MHz DR ~ 1000:1

Still working on broad-band multi spectral modelling

Summary and Forward look

Imaging and calibration challenges on a wide range of scales: 0.5” - 5” – 50” – 500”

- EoR science mostly in inner uv-plane:	30 - 400 λλ
- but bright polarized foregrounds at up to	4000 λλ
- Calibrating with baselines up to	40000 λλ
- Requiring models (of bright sources) up to	400000 λλ

Depending on ionospheric ‘stability’ the complex gains can be transferred over a distance of up to 3^{o} from calibrator. Then selfcal can improve images further
→ < 0.5” PSF in reach over a very wide field

Working on complete spectral models for all bright sources in the two EoR windows.

Using data from 3C196 flanking fields

The flanking field data will be used to construct better sky models, enlarge the FOV for polarization images and improve ionospheric modelling

72 MHz (380 subbands) are allocated to the target field (115-189 MHz)

24 MHz (108 subbands) form 6 beams, each 18 subbands also covering 115-189 MHz

These socalled flanking fields are in a hexagon pattern at a radius of 3.75°.

As of Jan 2015 the 6 flanking fields were moved inwards to a radius of 2° (and rotated)

We also created 4 staggered frequency combs to combine data (from 4 nights) to provide better frequency coverage with lower RMSF sidelobes.

Hereafter we show 7 images of the flanking fields (still at 3.75° from 3C196)

- SAP000 (the central beam) was calibrated with only the 3C196 4-comp model
- SAP001-006 data were calibrated using the gain transferred from SAP000

NB: SAP = Sub Array Pointing