The LOFAR (zoom-)array and the EoR

(involving 500” - 50” - 5” - 0.5” imaging)

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Menu

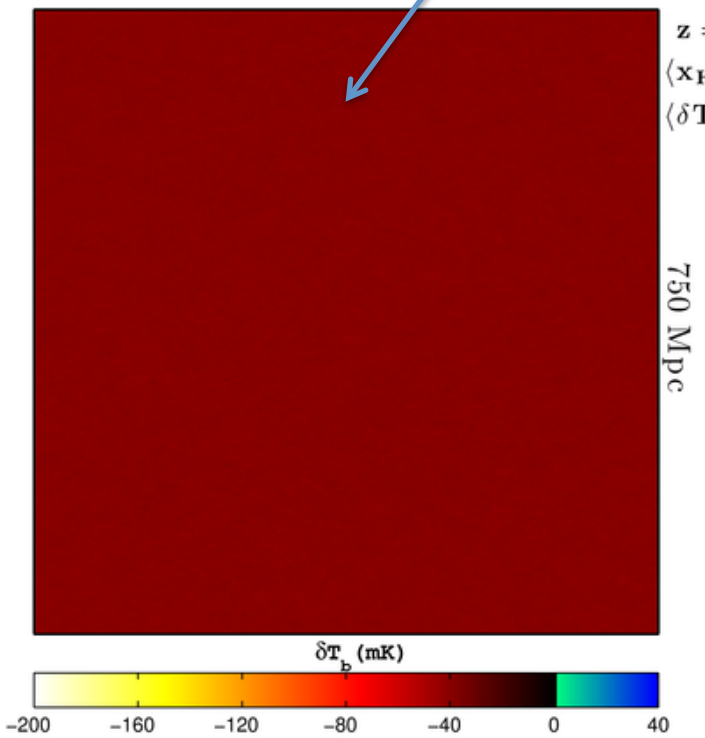
EoR science goals
EoR windows: NCP and 3C196: the BIG picture
Sensitivity and Scales ($k_{parallel}$ - $k_{perpendicular}$)
EoR observing strategy

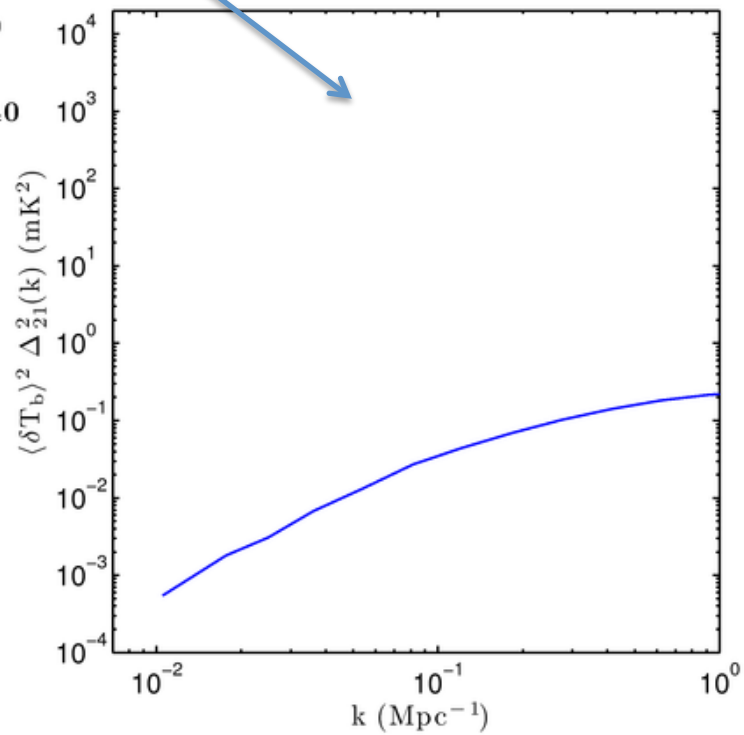
Challenges and Science
- Calibration → Yatawatta
- Ionosphere → Mevius
- Polarized foregrounds → Jelic

Sky modelling needs: from 500" → 50" → 5" → 0.5"
Ionospheric structure functions and LOFAR geometric models
Summary and Forward look

What are we looking for (or so we think) ?

Evolution of signal brightness and its power spectrum, with redshift z





Andrei Mesinger

NOTE: k = 0.1 Mpc^{-1} corresponds to 60 cMpc ≈ 24' ≈ 4 MHz

Main science goals of the LOFAR EoR project

— Statistical detection of global signal; z-evolution

— Measure underlying dark matter density spectrum

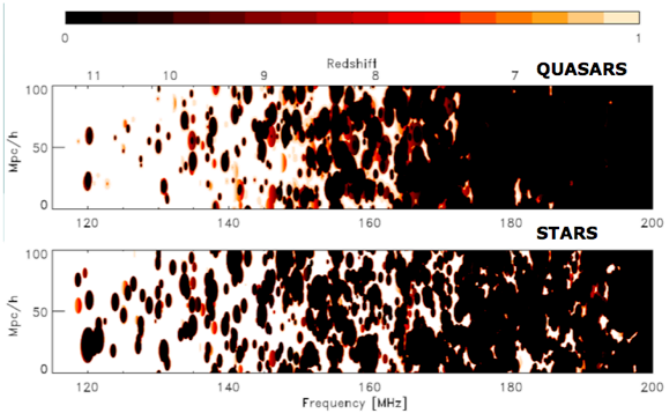
— Statistical characterization of ionization bubbles

— The environment of high z QSOs / SMBH

— Constrain the sources: stars, QSOs or …

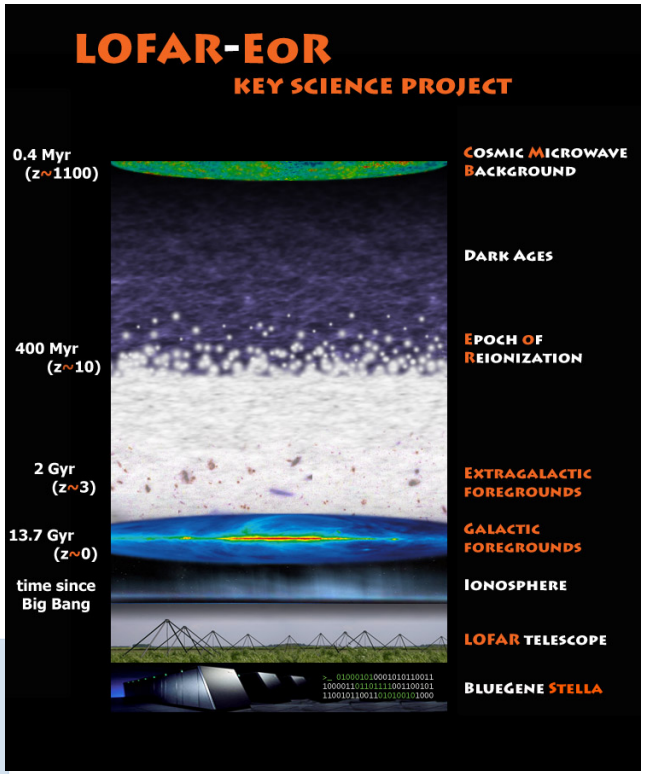
— Study 21cm forest to high z radio sources (if any)

— Cross correlation with other probes: CMB, Ly-α, ….



Rajat Thomas (2009)

115 - 190 MHz
z = 11.4 – 6.4



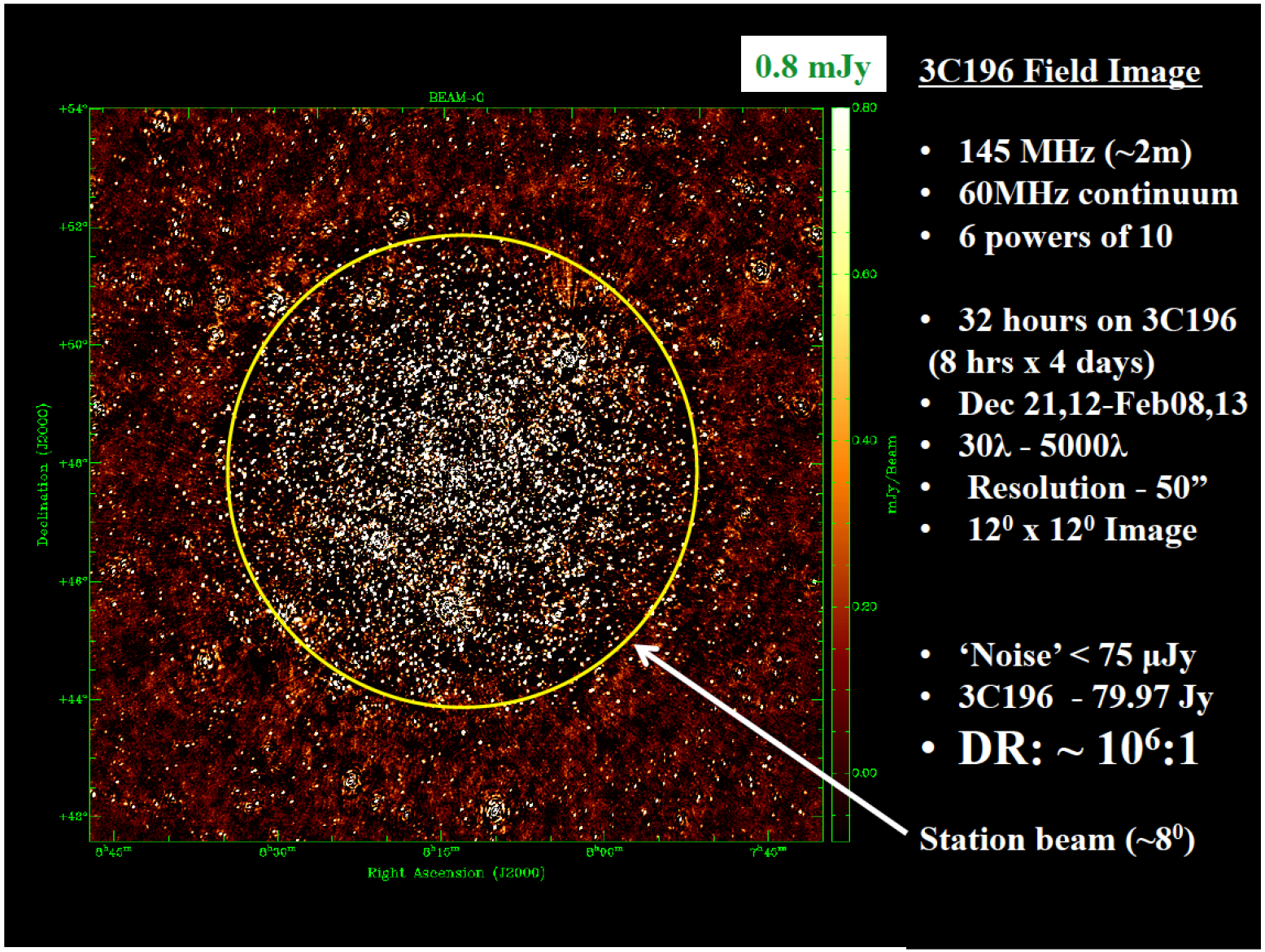
Vibor Jelic (2010)

This will take 600 - 3000h of LOFAR HBA observing (2-3-5 windows)

The NCP window: the deep and wide picture

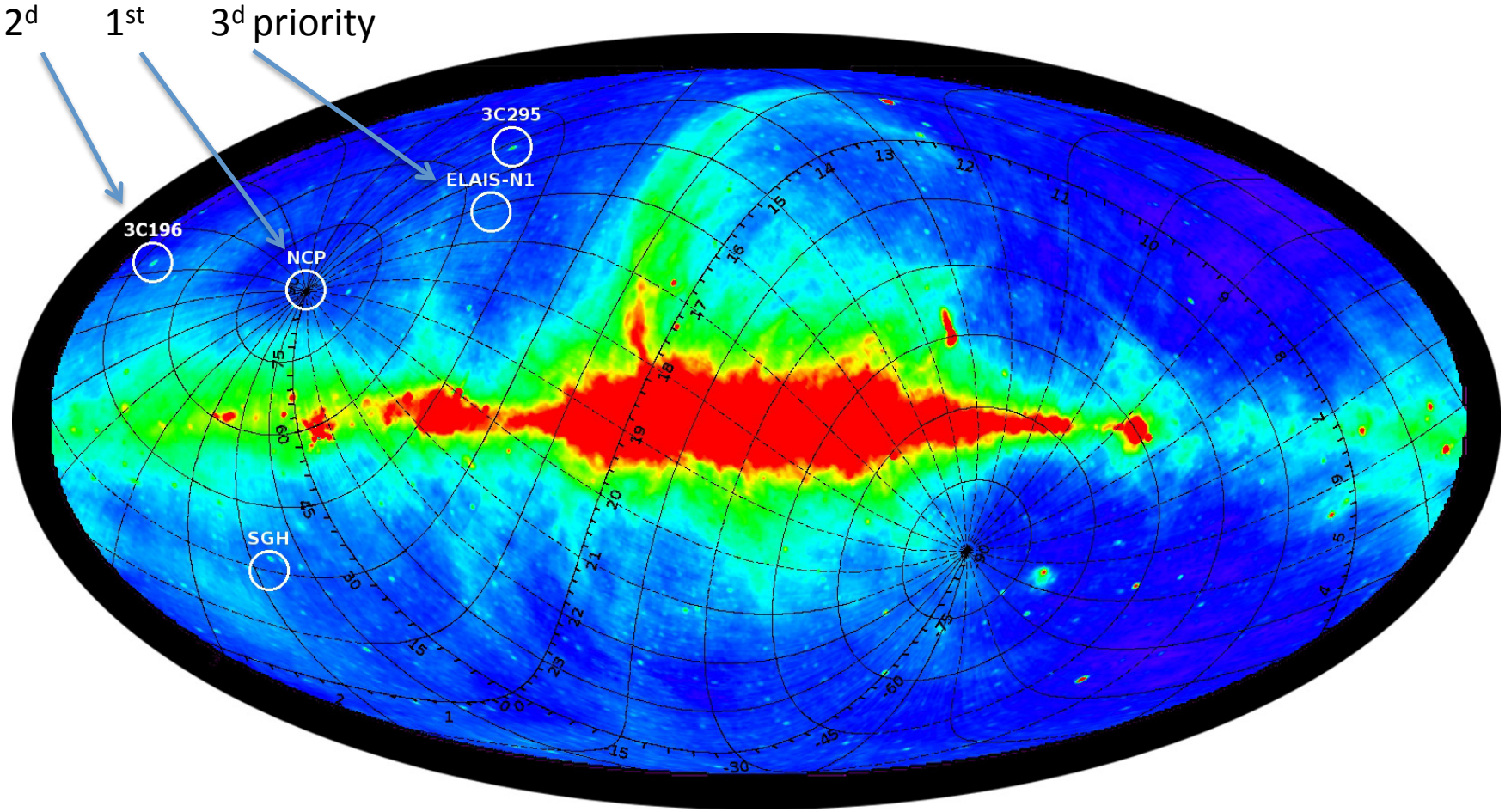
Sarod Yatawatta + Joeri van Leeuwen

Deep wide-field low-res image of 3C196 window



Pandey, Nov 2013

Location of our 3 EoR windows



Haslam etal, 408 MHz (1981)

EoR observing configuration: 1 target + 6 SAP's

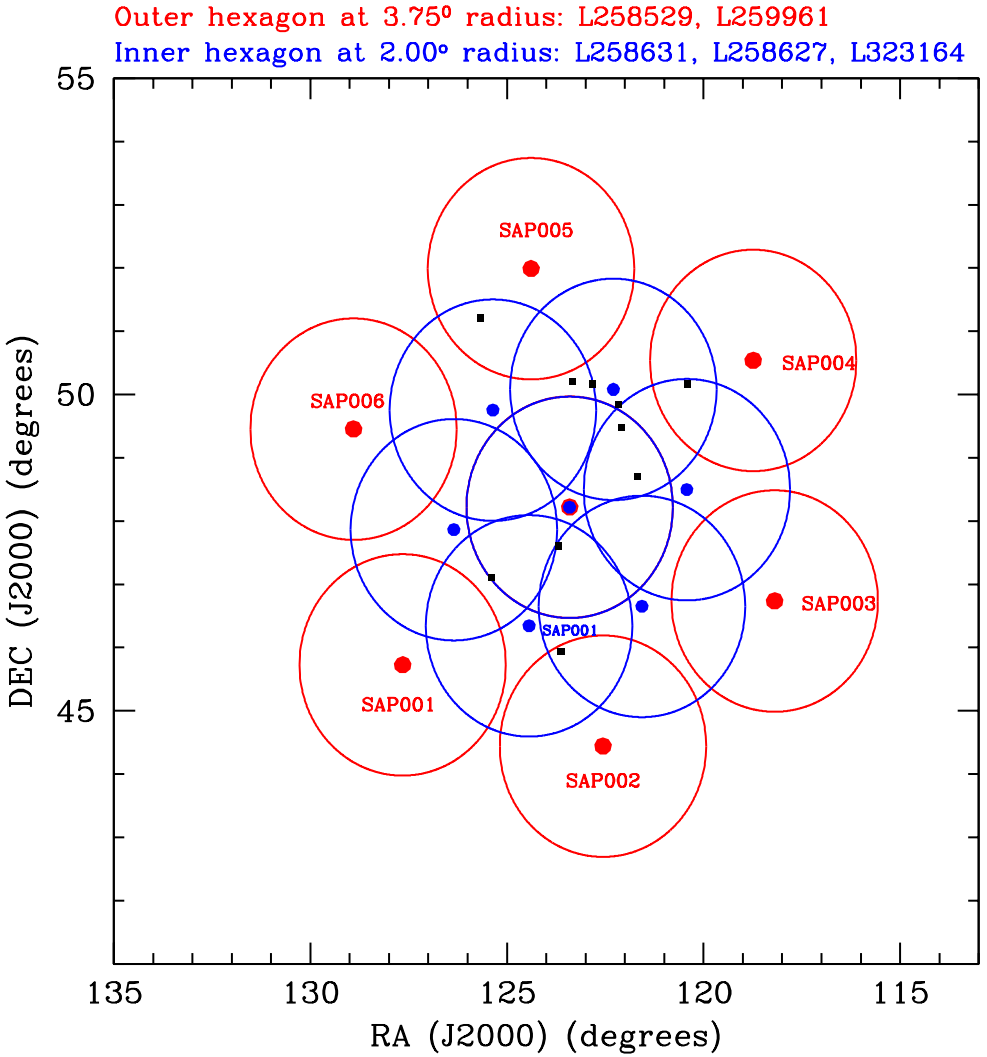
In Cycle 0,1,2

380 sb on target
+ 6x18 sb
outer hexagon

In Cycle 3:

added inner hexagon

Bright and flat spectrum sources indicated with small black squares



Why/How to use 4 orders of magnitude in resolution

EoR science on largest scales (core-superterp) - 400 λλ

Polarization signals best visible on ~ 1' - 4000 λλ

Calibration of core stations using NL baselines requires - 40000 λλ

Bright sources (3C196, NCP) at 5" do not subtract perfectly - 400000 λλ

Datasets used for 0.5” imaging

3C 196

L258627	28 Jan 2015	8IS, basic resolution:	64ch/sb - 2s	6h
L259961	11 Feb 2015	9IS,	64ch/sb - 2s	6h
L323614	1 April 2015	8IS,	32ch/sb - 0.5s	6h

7 SAP’s with each 69 subbands (120-177 MHz)

NB 0.5s and 6 kHz limits smearing (time/freq) to about 0.15” at 1^{o} radius

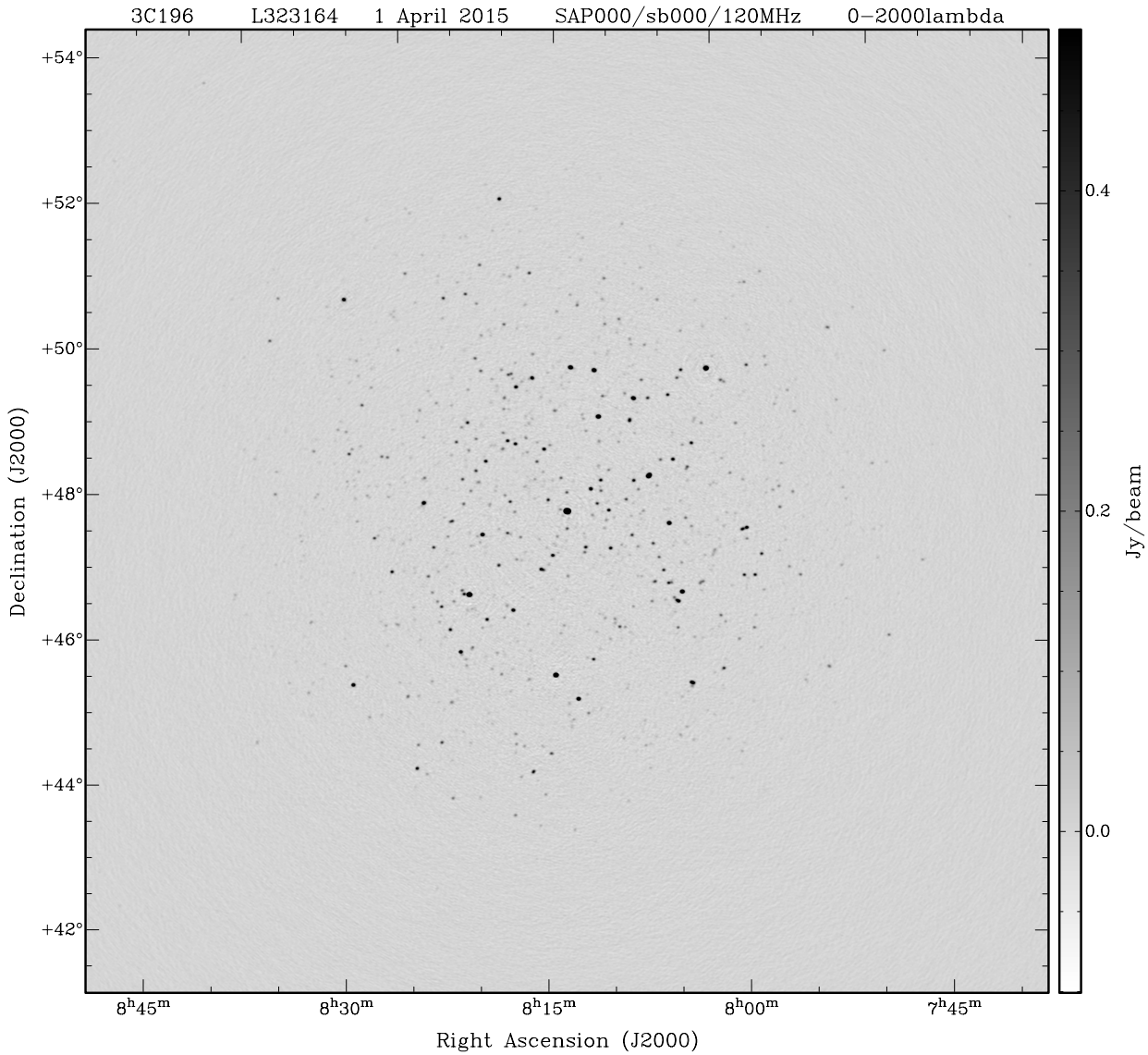
NCP

L246903	31 Oct 2014	6 IS, basic resolution:	64ch/sb - 2s	13.5h

3C196 120 MHz

30 - 2000 λλ
2’ PSF

13^{o} x 13^{o} FOV

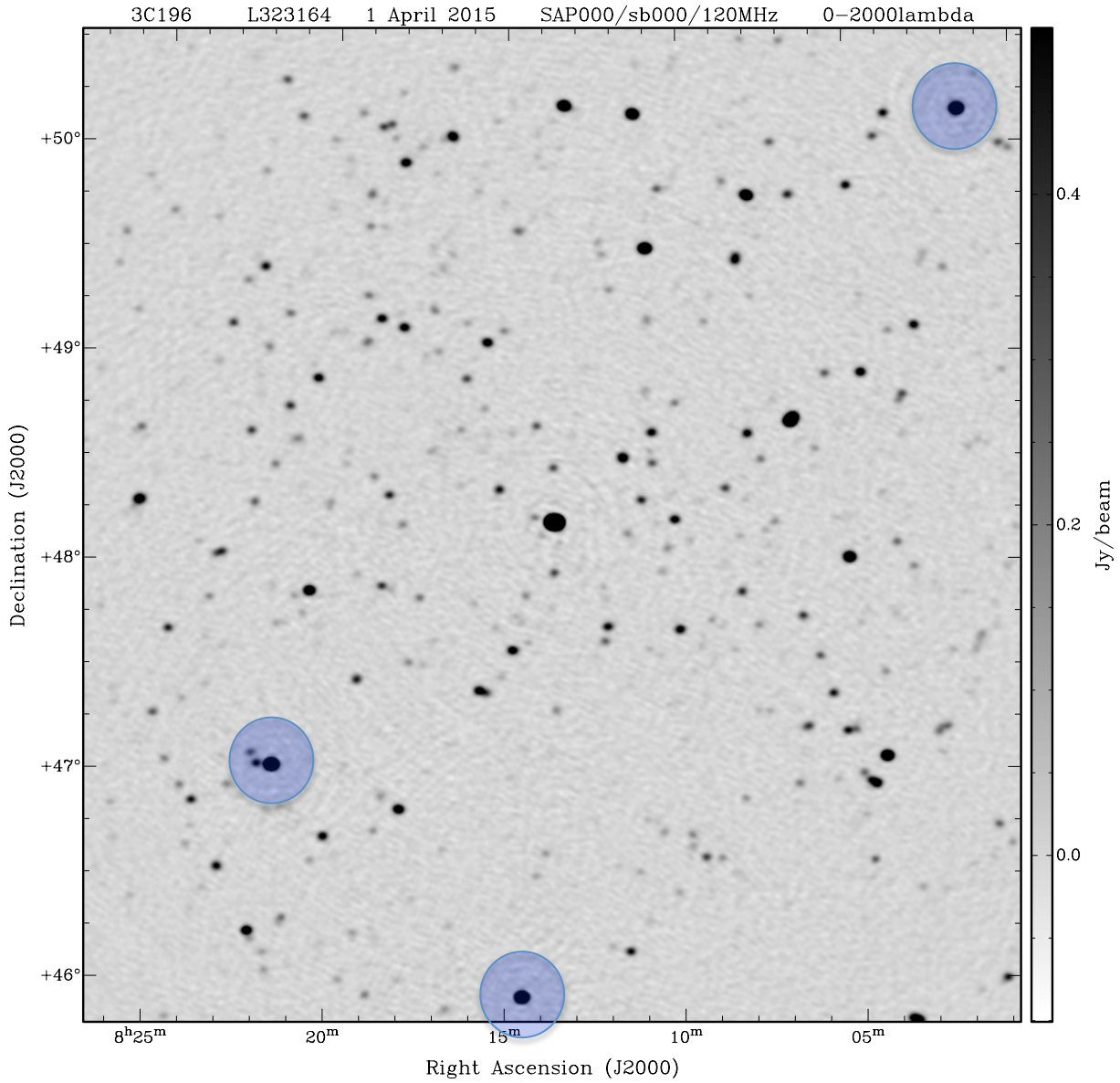


3C196 120 MHz

30 - 2000 λλ
2’ PSF

5º x 5º FOV

Bright (~ 5 Jy)
compact sources
(with arcsec structure)



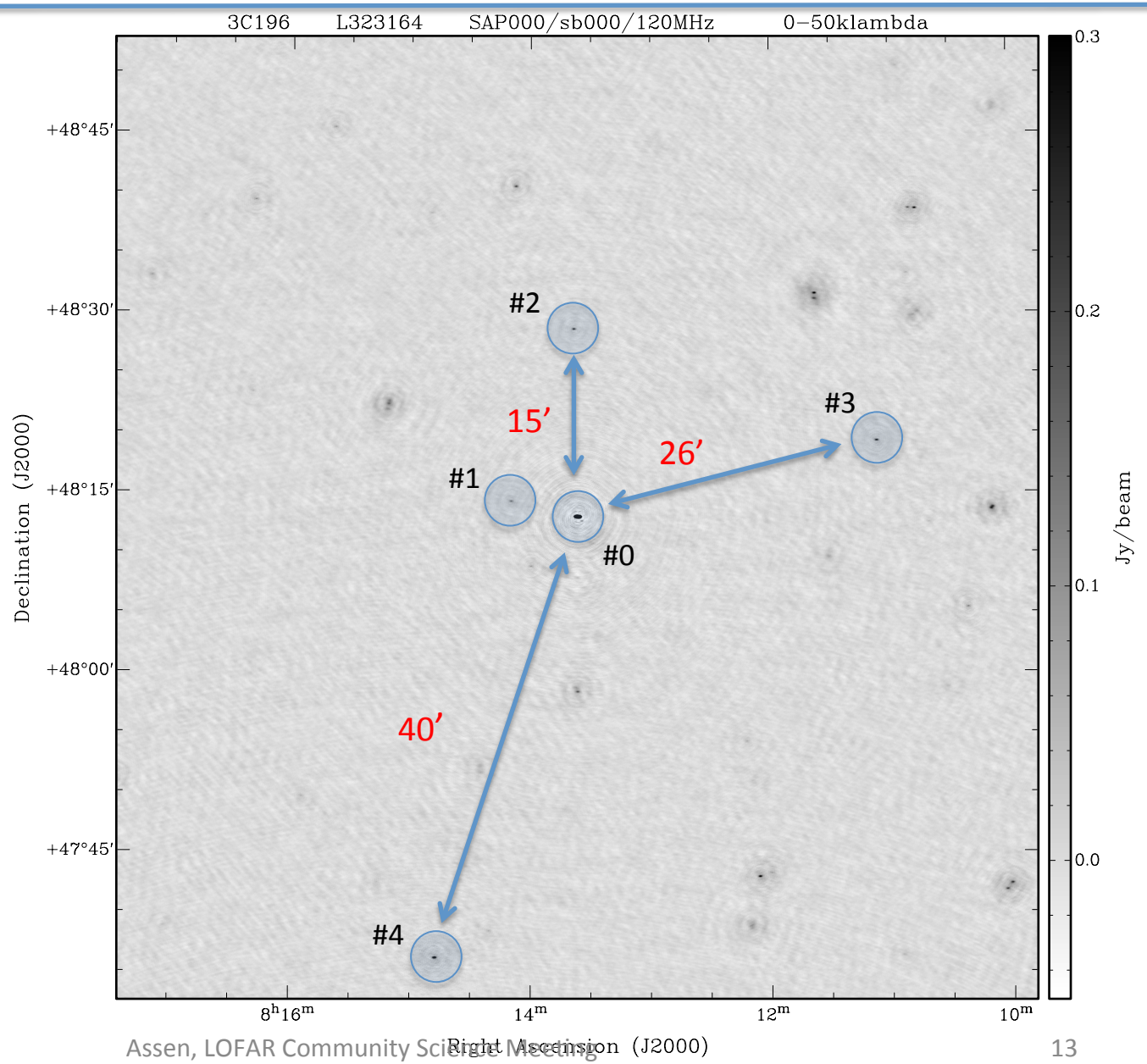
3C196 120 MHz

30 – 50000 λλ
4x7” PSF

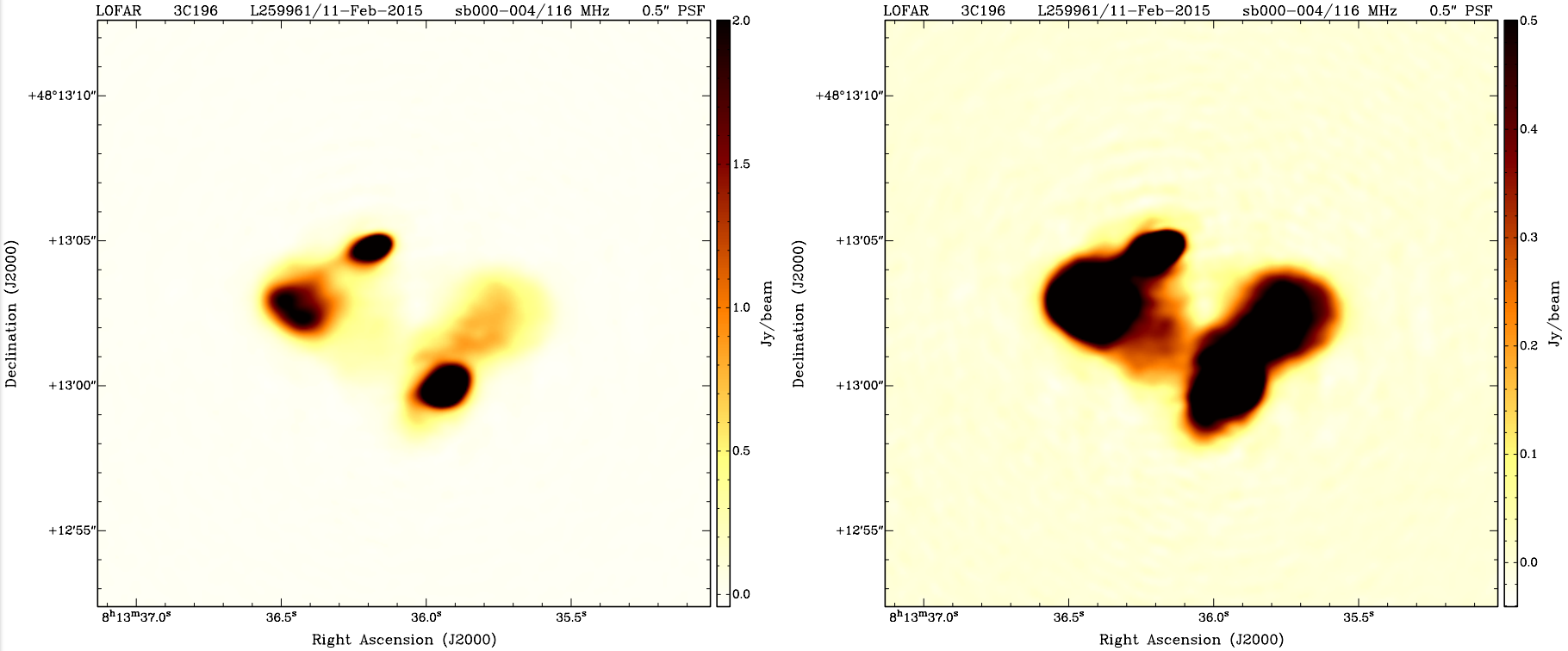
1.3º x 1.3º FOV

Source #0 = 3C196

Sources #1,#2,#3,#4 are compact and ~ 200 - 300 mJy



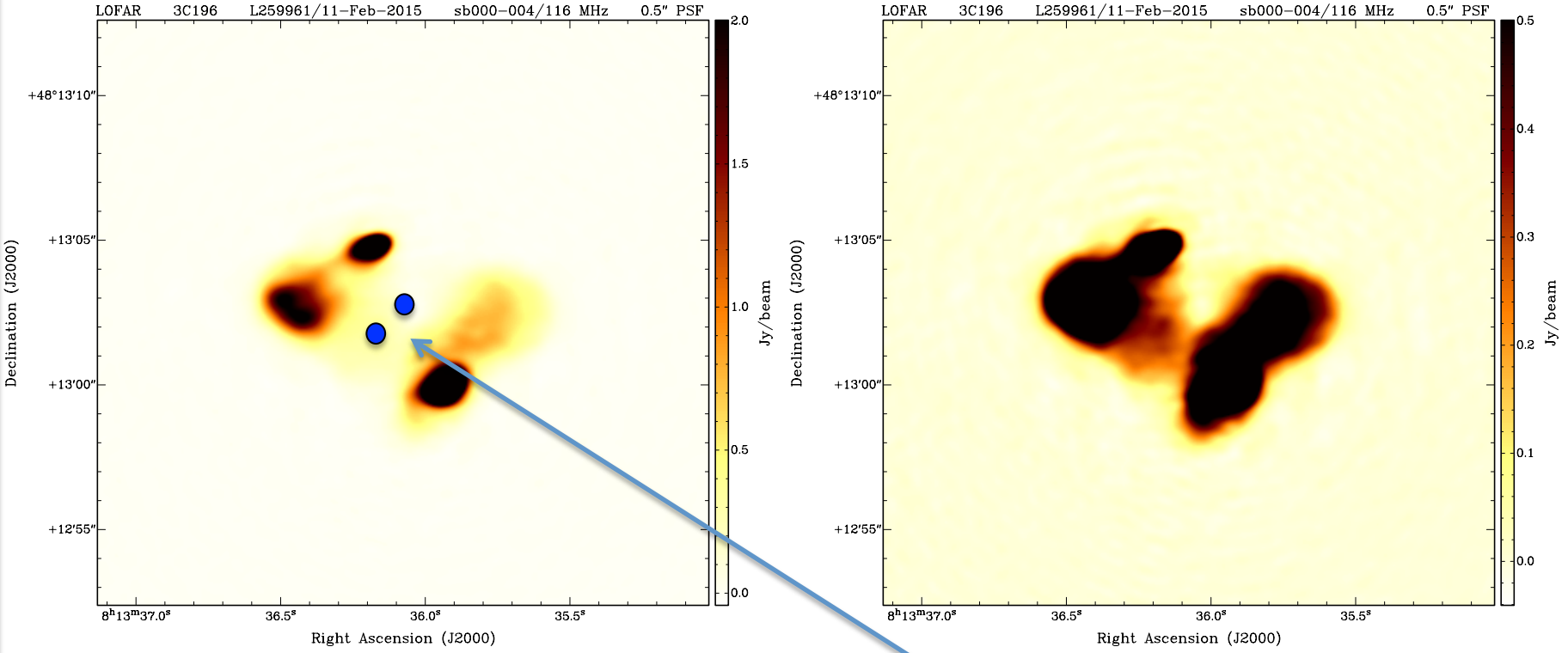
3C 196: imaged with a 0.5” PSF



115-116 MHz DR ~ 1000:1

Still working on broad-band multi spectral modelling

3C 196: imaged with a 0.5” PSF



115-116 MHz DR ~ 1000:1

Still working on broad-band multi spectral modelling

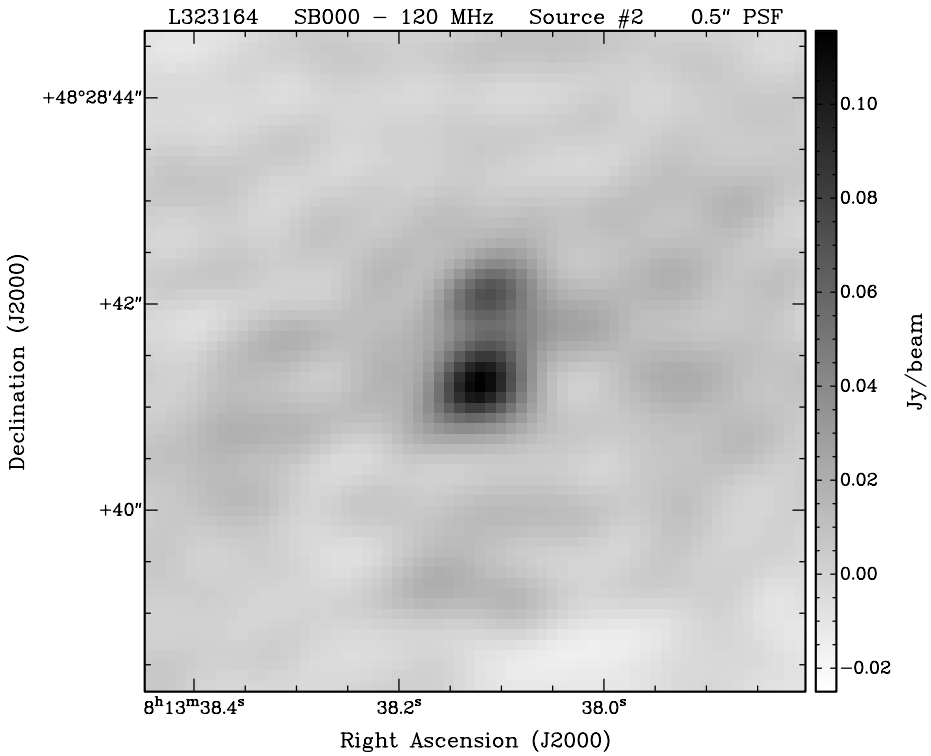
Interesting detail
3C196 quasar at z=0.87
Massive SB at z=0.43

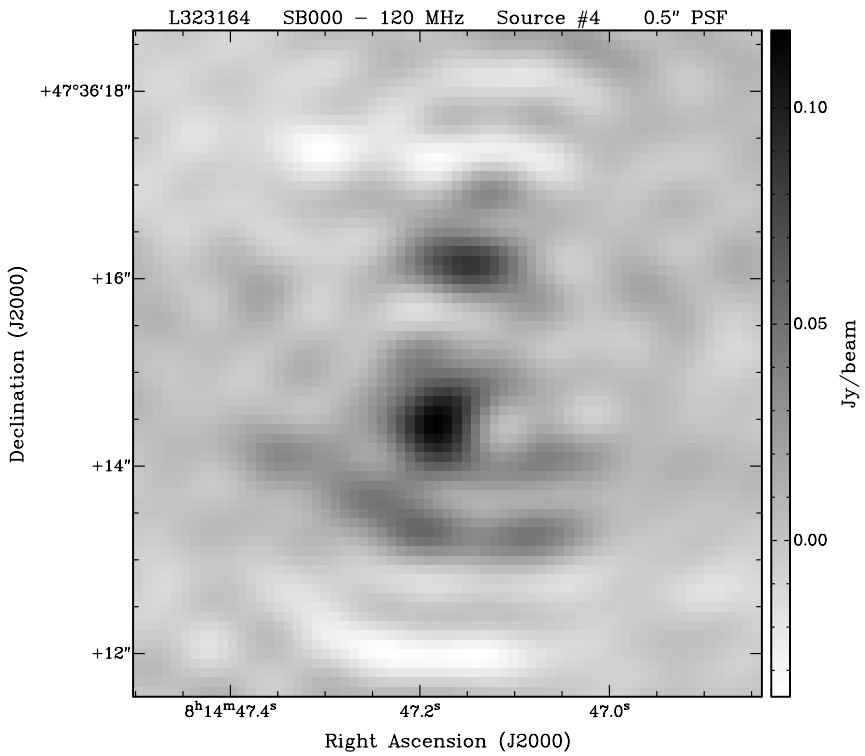
Briggs, deBruyn, Vermeulen, 2001

3C196 field observed with 8 Int Stations (10-400 kλ)

Source #2 at 15’

Source #4 at 40’

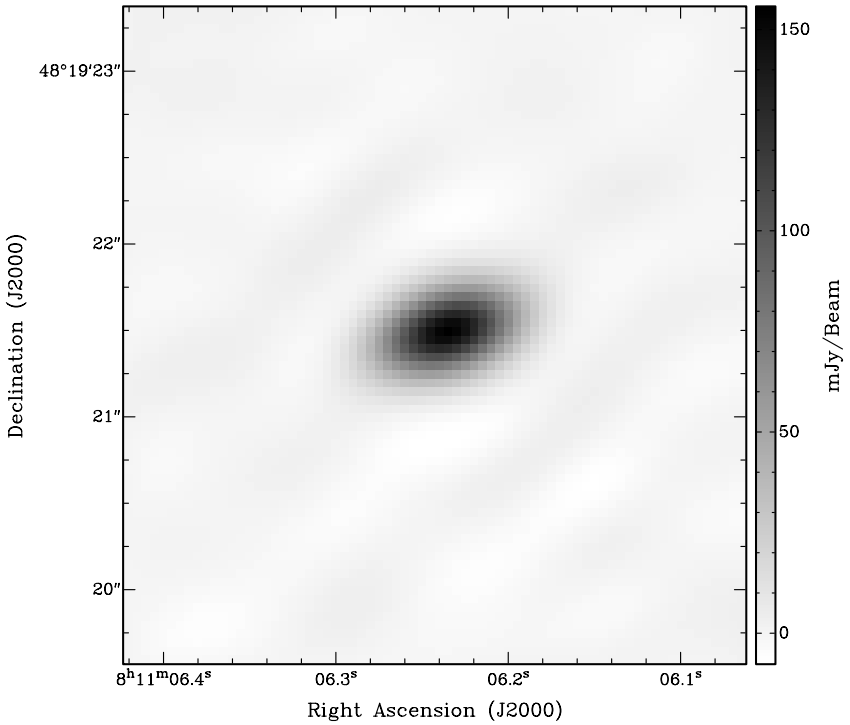




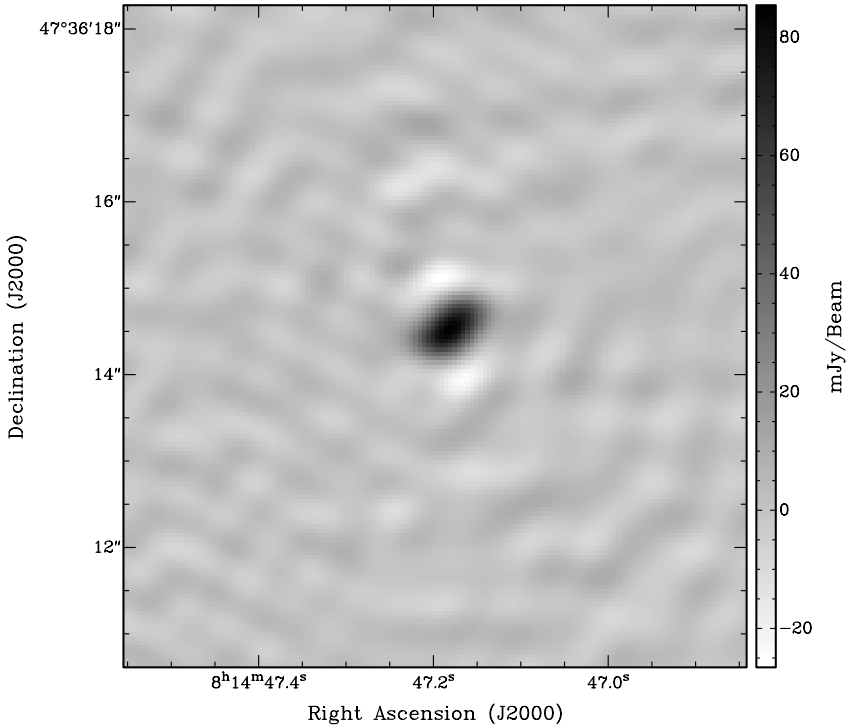
Noise in 1 subband ~ 2 mJy 0.5” PSF NO SELFCAL

Sources after selfcalibration

Source #3 at 26’

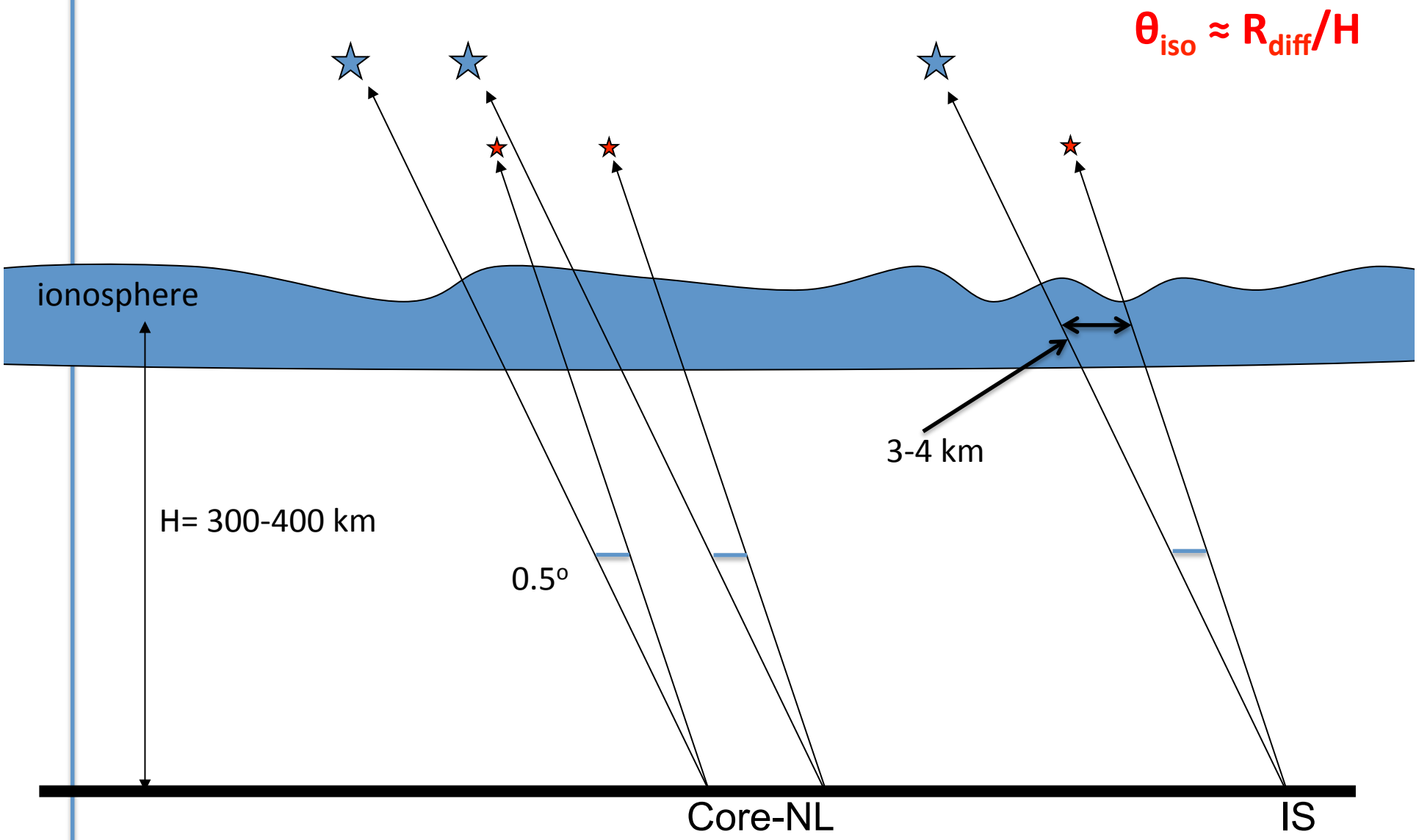


Source #4 at 40’



Significant phase effects removed !!??

‘Differential’ phase structure functions & isoplanatic angle



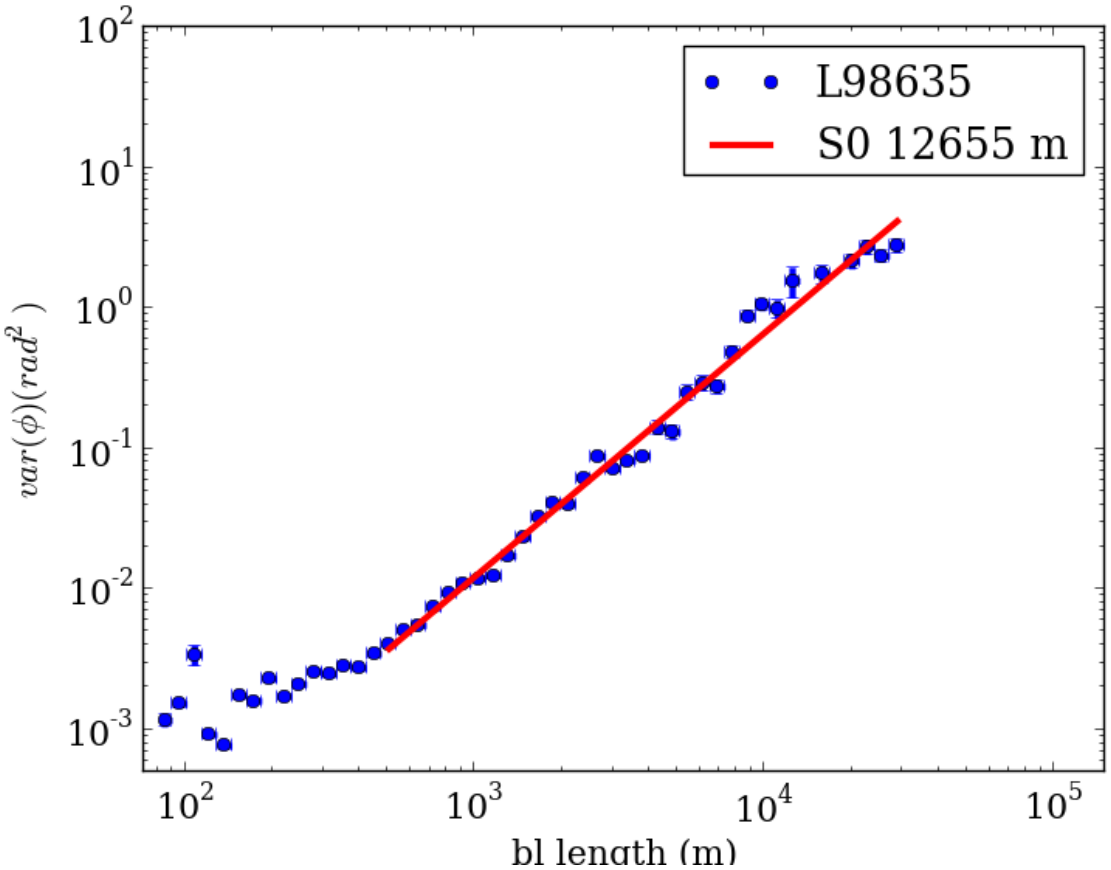
The ionospheric phase structure function

3C196

3/4 Mar 2013 (8h)

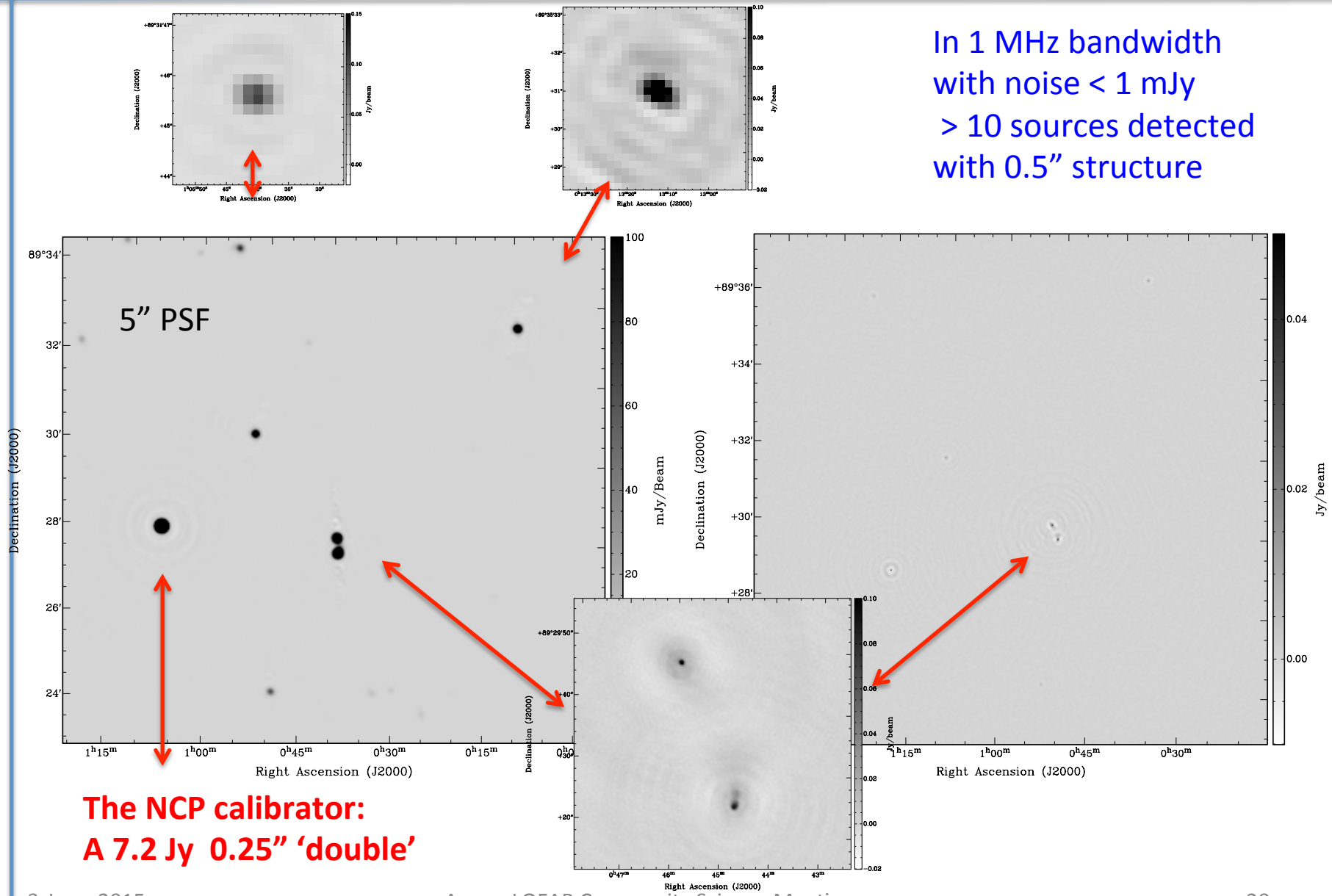
HBA 115-177 MHz

S_0 is also known as the diffractive scale, the baseline scale over which we have 1 radian rms phase fluctuation.



Mevius etal 2015

NCP imaging at 5” and 0.5” PSF



In 1 MHz bandwidth
with noise < 1 mJy
> 10 sources detected
with 0.5” structure

The NCP calibrator:
A 7.2 Jy 0.25” ‘double’

0.5” PSF imaging over 1^o wide fields should be possible !

For a good ionospheric night (say S_o > 8 km)
and with similar ionospheres over all LOFAR stations in Europe:

Imaging using the complex instrument gains for a central source
should be relatively easy over a > 1^o FOV or more !!

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

But remember that imaging with three different interferometer–beams is introducing problems (NL24-NL24, NL24-IS96, IS96-IS96)

The fact that this is not yet possible, without direction dependent calibration,
→ geometric model probably not correct

Update on status EoR project

EoR-group efforts in the last year

- 'Known' unknowns: - sky-model, station-beams, ionosphere
- Unknown unknowns: - 'excess noise'

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

Our tools:

- NDPPP flagger (AO), averager, …
- BBS, SAGEcal calibration programs
- ExCon imager
- AWimager

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

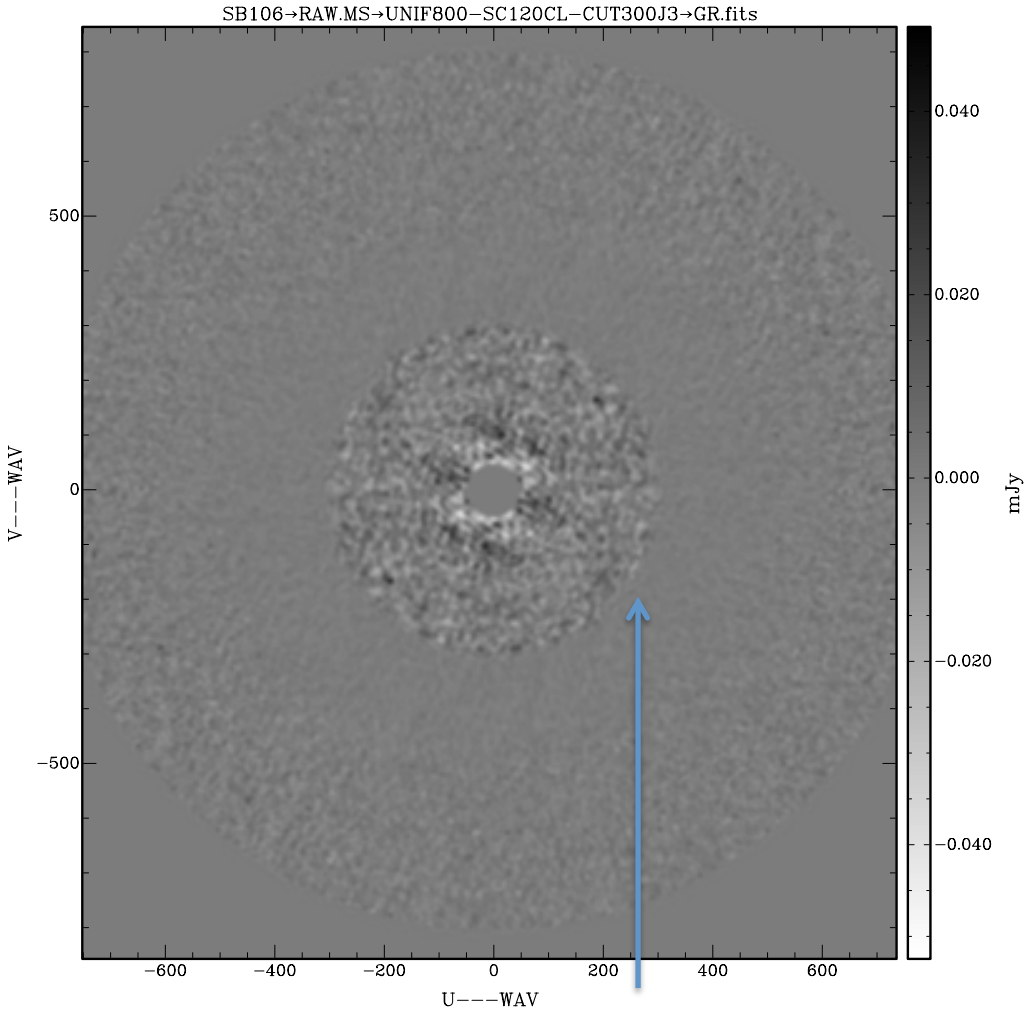
- 'suppression' of unmodelled structure a.k.a. scale dependent 'bias'
- 'discontinuity' in intensity scale in residual data after SAGEcal (a.k.a. 'leverage')
- 'solver noise' => boosting of residual fluctuations
- polarization leakage from Q,U → I

Constrain-limited selfcal processing effects (early 2014)

Stokes I Gridded data image

SAGEcal
120 clusters/directions
300λ cut in uv-plane

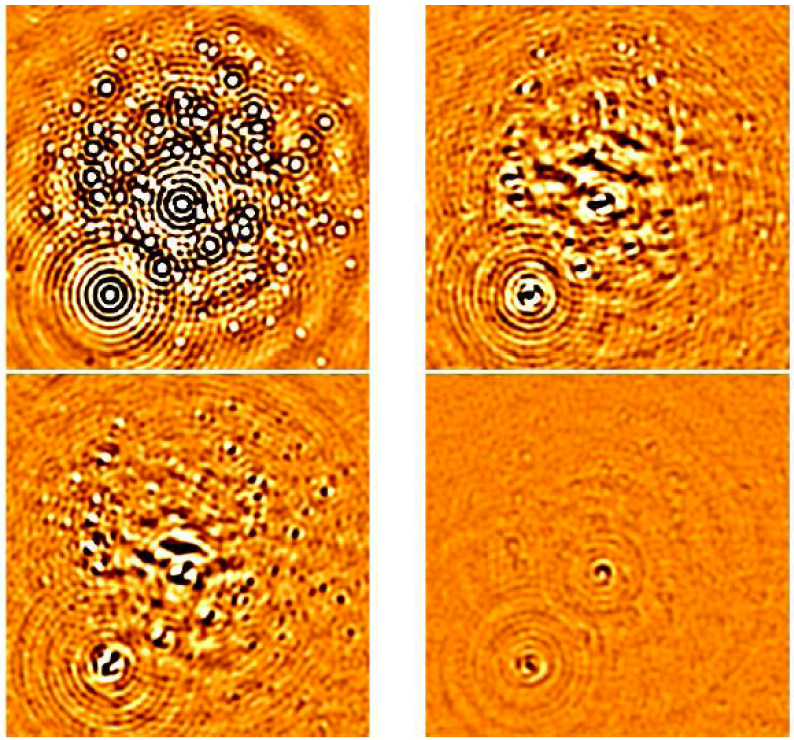
ExCon
50-800λ
1200x30”
Uniform weights



Discontinuity
(leverage)

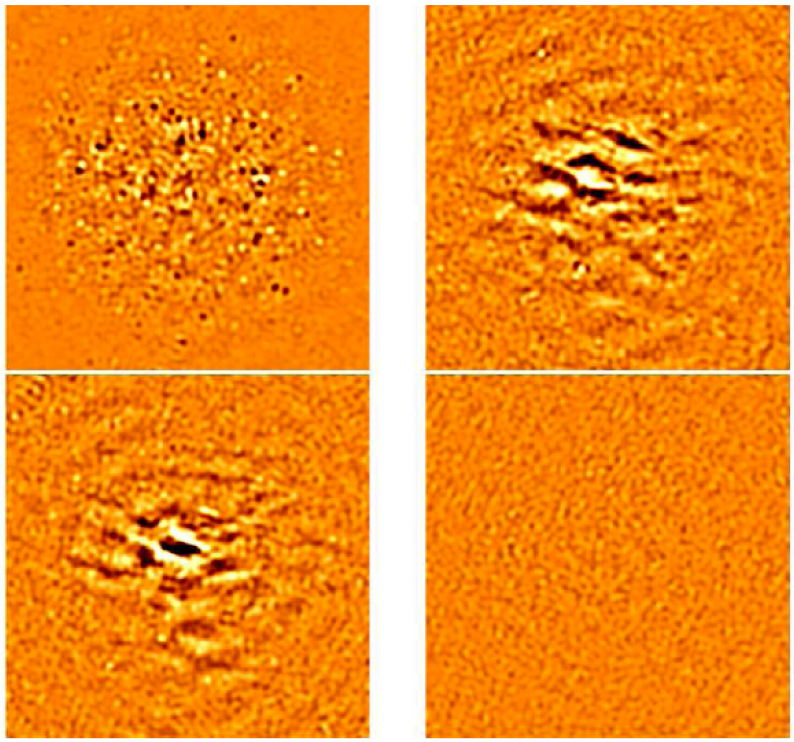
New SAGEcal CO processing, single night NCP

Image before calibration



I,Q,U,V images baselines $<=$ 250 wavelengths

Image after calibration



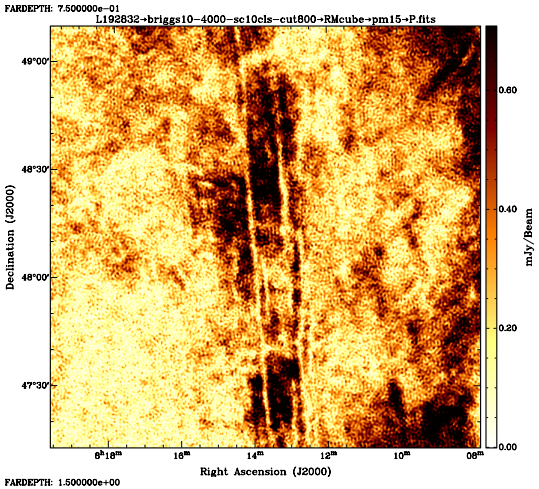
I,Q,U,V calibration using baselines $>$ 250 wavelengths

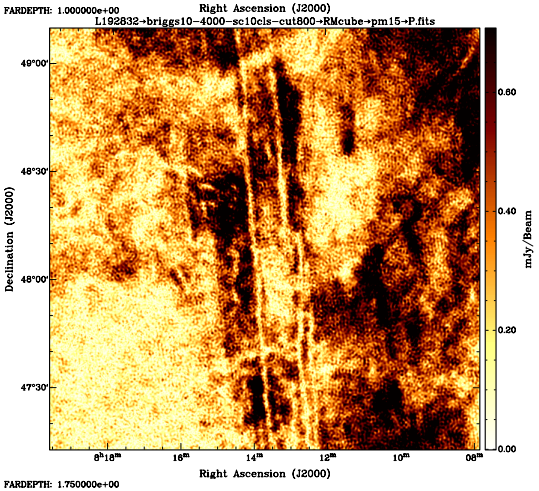
Note that these are 12' PSF images
Diffuse polarization is preserved !

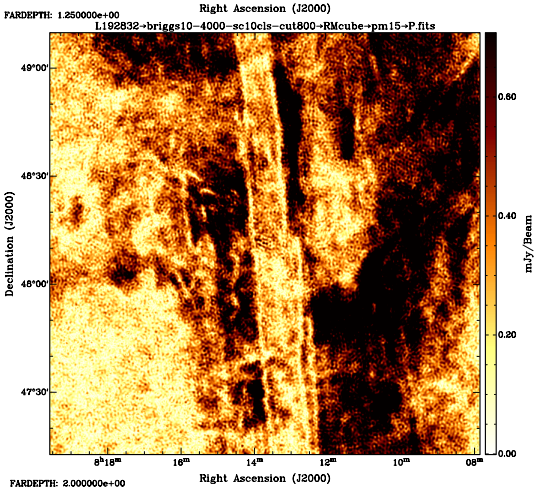
Sarod Y. talk

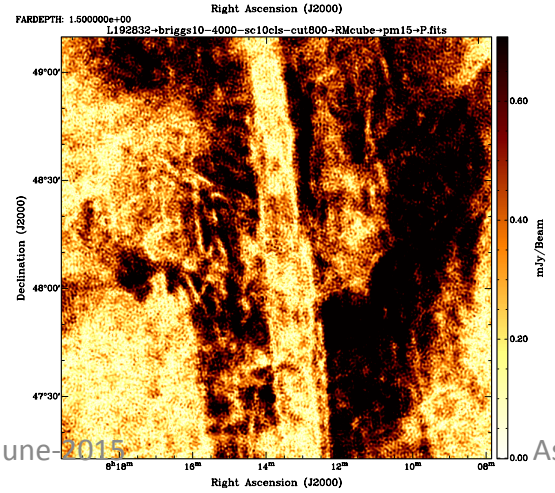
3C196 pol. 50” PSF

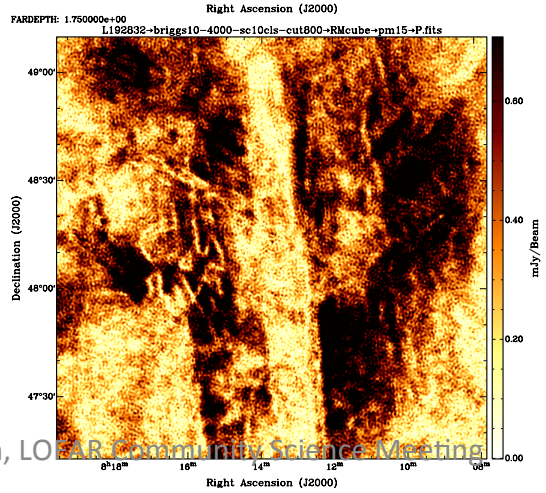
Only 10 cluster SAGEcal
8 Faraday-depth frames
at 0.25 (0.25) 2.00 rad/m^2

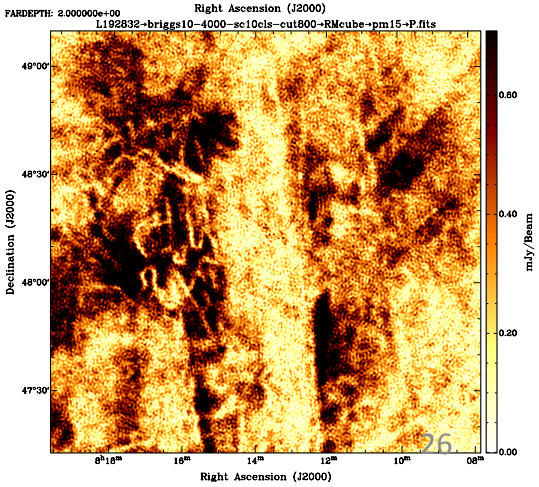


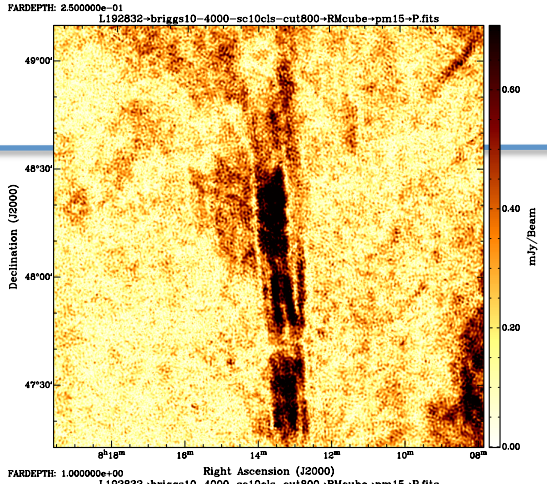


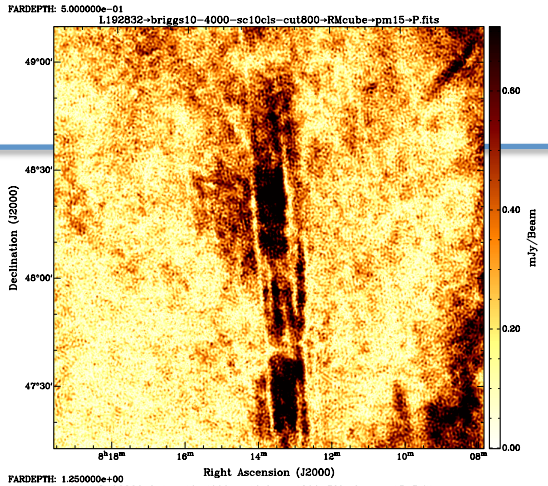












Noise after new SAGEcal processing (May 2015)

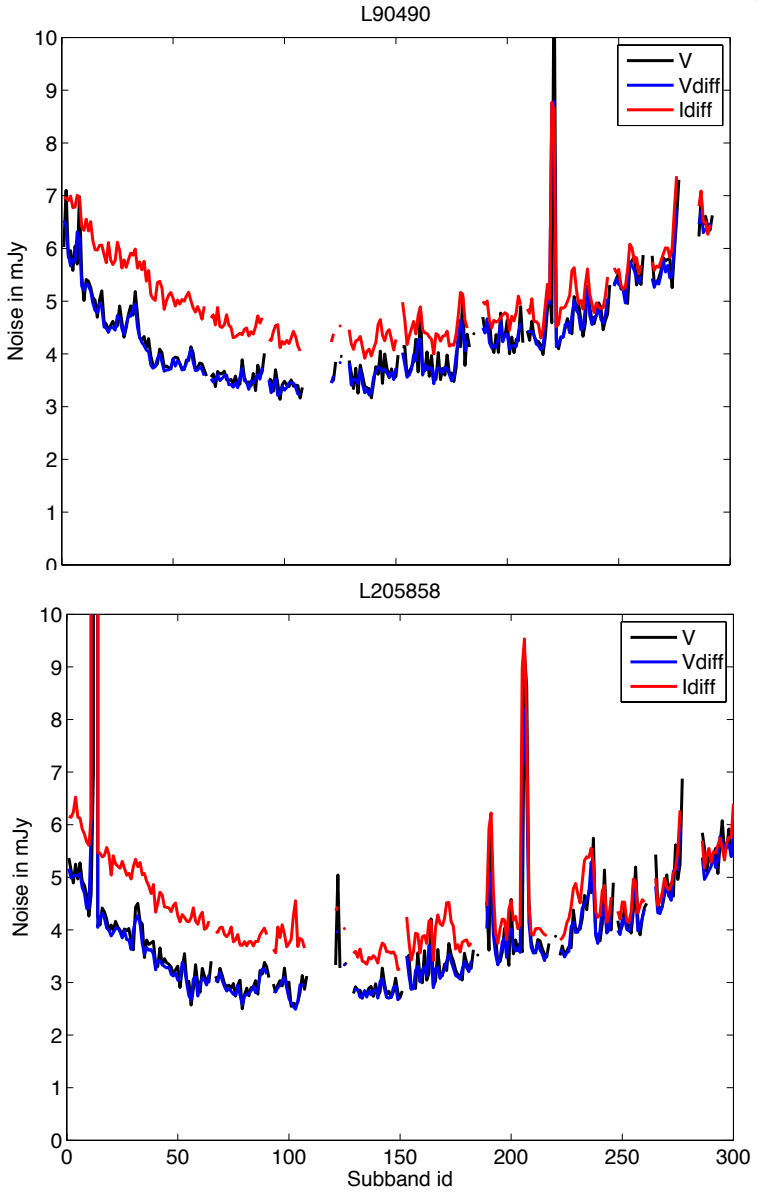
Noise per subband
V, ΔV and ΔI

sb000= 115 MHz
sb300= 173 MHz

Images made with uvrange 50-250 λλ (only 20% of core visibilities)

→ PSF ~ 12'

Stokes I noise only 5-30% higher than Stokes V noise !!



Summary and Forward look

1500 hours of data (NCP, 3C196) accumulated: > 1000 h of good quality

Challenges and science at scales from 0.5" - 5" – 50" – 500"

The LOFAR zoom array:
- 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

0.5" PSF over a wide field (1^o – 2^o) possible around a bright calibrator

2014: a 'difficult' learning year: systematics → new calibration (SAGEcal CO)
working on sky models, polarization and ionospheric effects ('scintillation' noise)

Now processing about one 13h NCP night /week
Soon (August 2015) new ERC-funded cluster operational (→ > 5 x speed improvement)

2015 and 2016: years to harvest