Imaging update: RSM zenith fields and the microquasars SS 433 + GRS 1915+105

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Adam Stewart, Antonia Rowlinson, Tim Staley,
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and the LOFAR Transients Key Science Project

UNIVERSITY OF OXFORD

LOFAR

four π sky

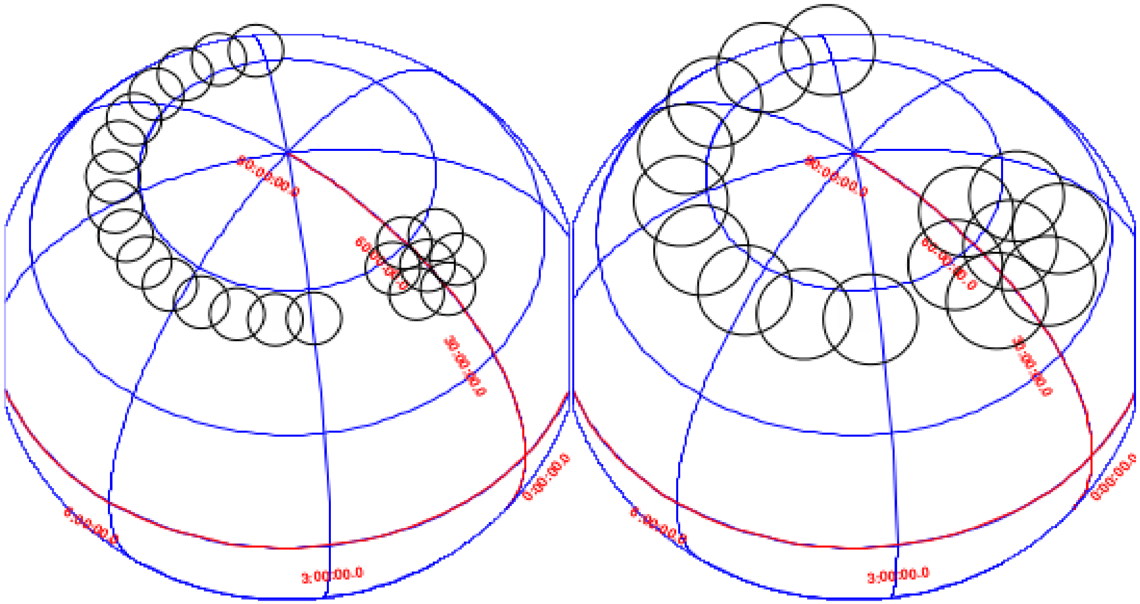
LOFAR Cycles 0, 1 and 2 – The Radio Sky Monitor (RSM)

Zenith strip monitoring (Dec +53º)

* 288 hours; 12 x 24 hr scans (8 with the HBA, 4 with the LBA).

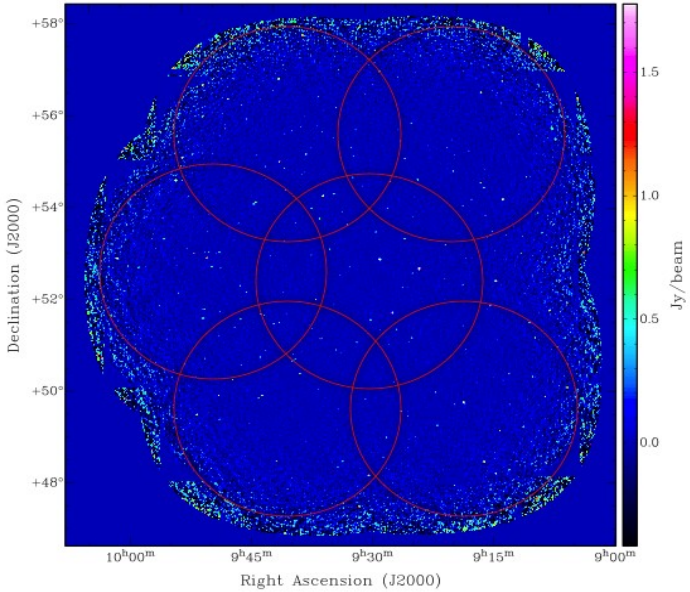
* ~1700 deg^2 sky coverage HBA (up to ~5000 deg^2 in LBA).

* Range of gaps between the observations: a few weeks up to ~6 months.



Fender et al. in prep.

RSM HBA observations



* Centre frequency ~150 MHz.

* 48 MHz bandwidth.

* Hexagonal mosaicking pattern used to cover the zenith strip; Nyquist spacing at ~150 MHz is 2.3 deg.

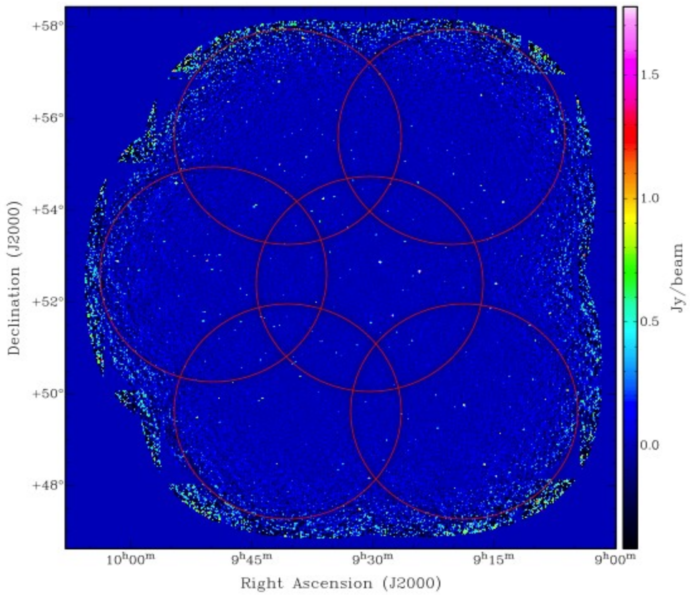
* 48 pointings, 6 beams per pointing (+ extra beam for additional targets within HBA tile beam). Total of 288 main fields.

* 30 mins per pointing including overheads; 2 x 11 min snapshots + observations of a calibrator.

* 4 bands per beam; centre frequencies 124, 149, 156 and 185 MHz. Bandwidth 2 MHz each.

Broderick, Stewart, Rowlinson

RSM HBA observations



* Runs 1-7 reduced.

* Use the TraP to search for transients/variables on a variety of timescales: ~minutes up to ~1 yr.

* Generate a source catalogue.

RSM - POINTINGS 34 to 18 - QC

Dataset ID	3
Description	RSM - POINTINGS 34 to 18 - QC
Reprocessing step	2
Processing started	Aug. 28, 2014, 1:56 p.m.
Processing Finished	Aug. 28, 2014, 3:11 p.m.
New Sources	242
Total image count	5120
Rejected image count	1103
running catalogs	5527
extracted sources	135856

Re-imaging the RSM data

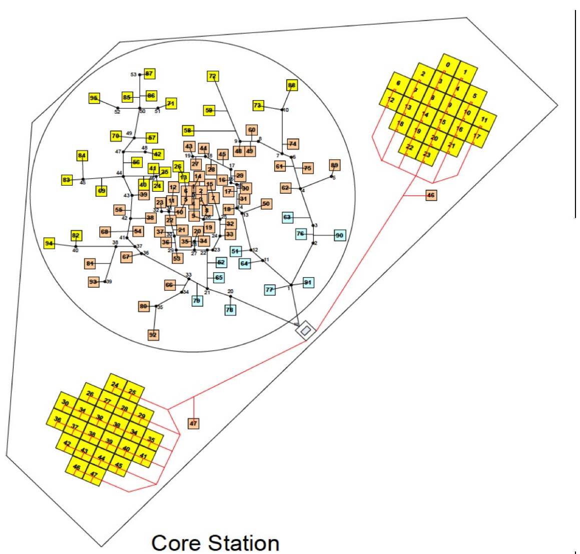
Two issues related to transient and variability searches:

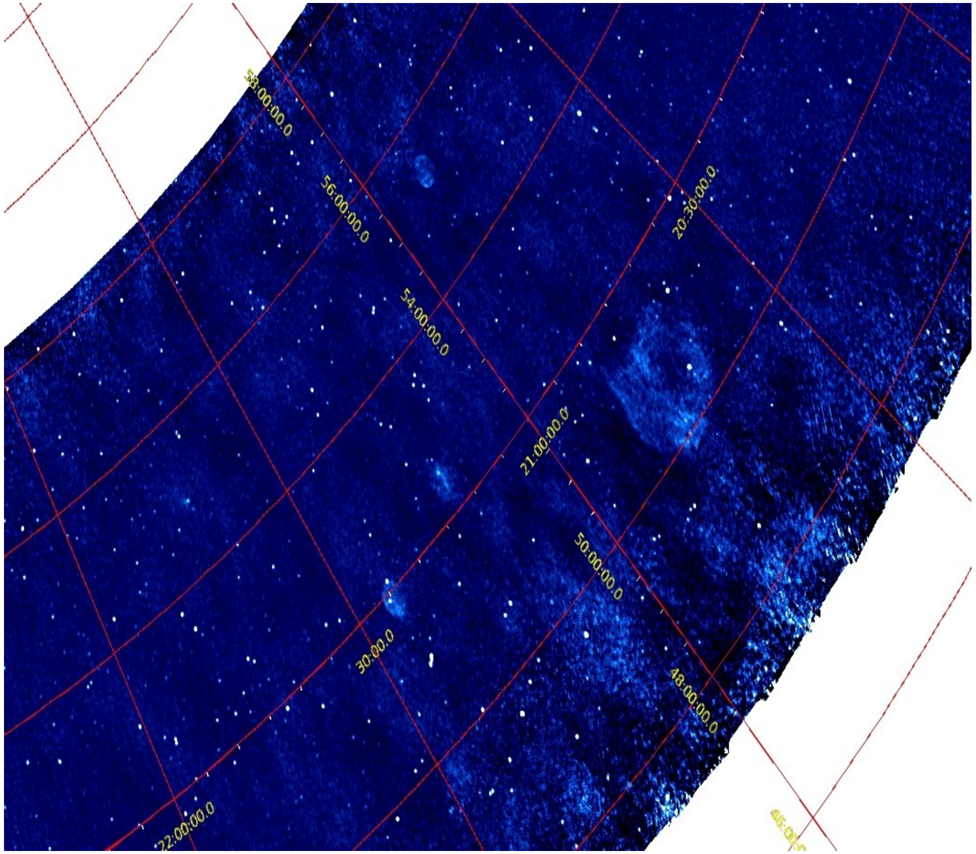
* Flux-elevation problem for 11 min snapshot images.

 - concatenate and make 22 min maps instead

* Short baselines between HBA 'ears' – sensitive to diffuse, extended emission. Image backgrounds sometimes 'patchy' (especially near Galactic Plane).

 - use a short baseline cut of 100 lambda
 (~200 m at 150 MHz)

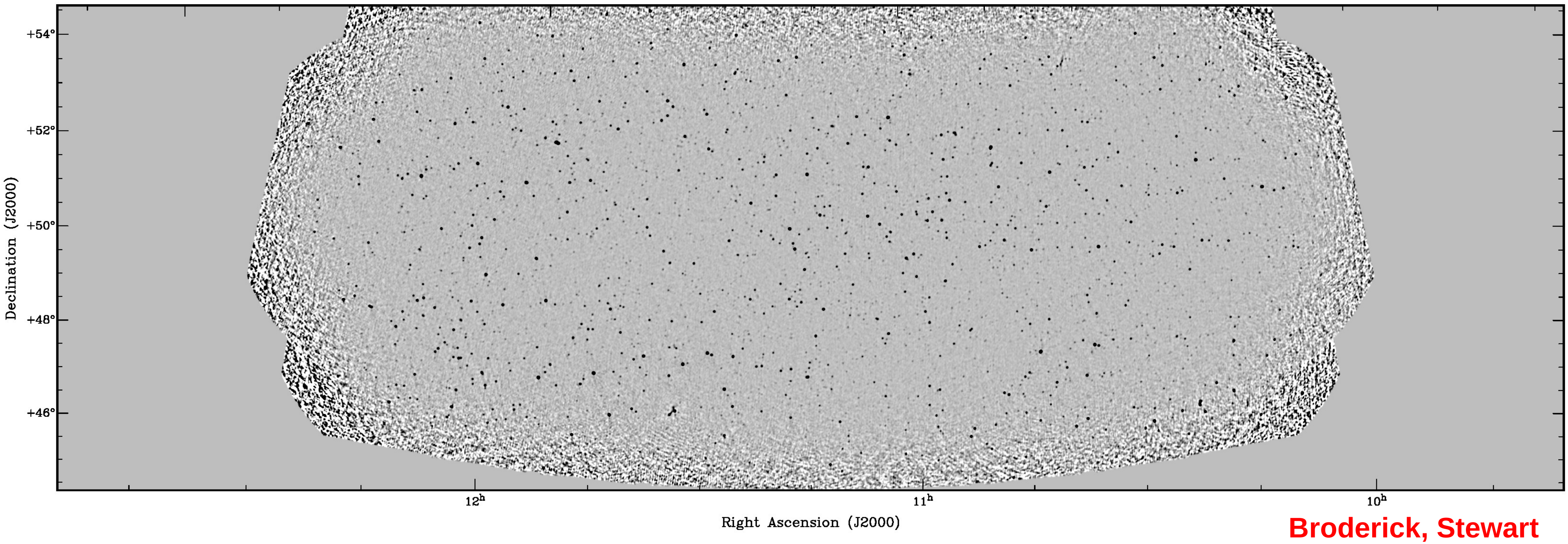




2013 Feb. 10, 149 MHz band, 1 snapshot

Mosaic - Rene Breton

RSM mosaics



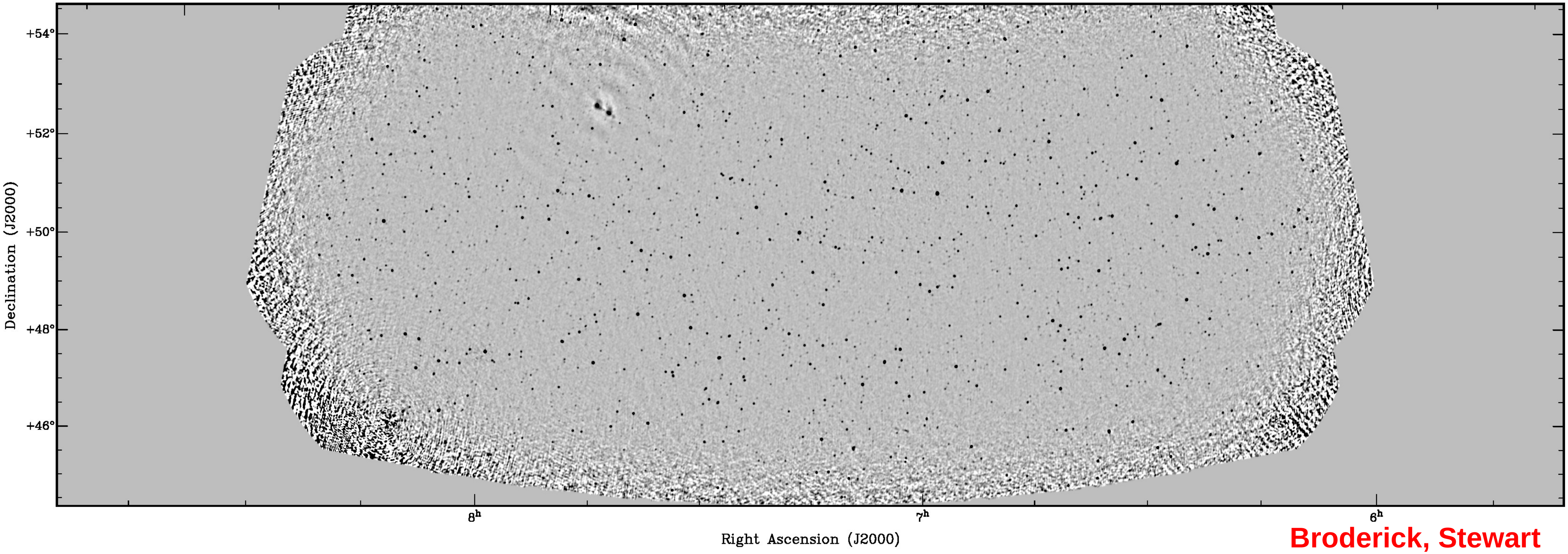
Broderick, Stewart

* Divide the zenith strip into 12 x ~140 deg^2 sectors.
* Generate a full-bandwidth, stacked mosaic for each sector in each run.
* Resolution ~120 arcsec (max. baseline ~6 km).
* Noise level ~10 mJy beam^{-1} (bands weighted equally for variability analysis).

* Run PyBDSM on each mosaic with thresh_isl=5.0, thresh_pix=10.0.

Ongoing work:
* Combine output (after some adjustments) to get a source catalogue for each run.
* Cross-match catalogues to obtain variability statistics.

RSM mosaics



Broderick, Stewart

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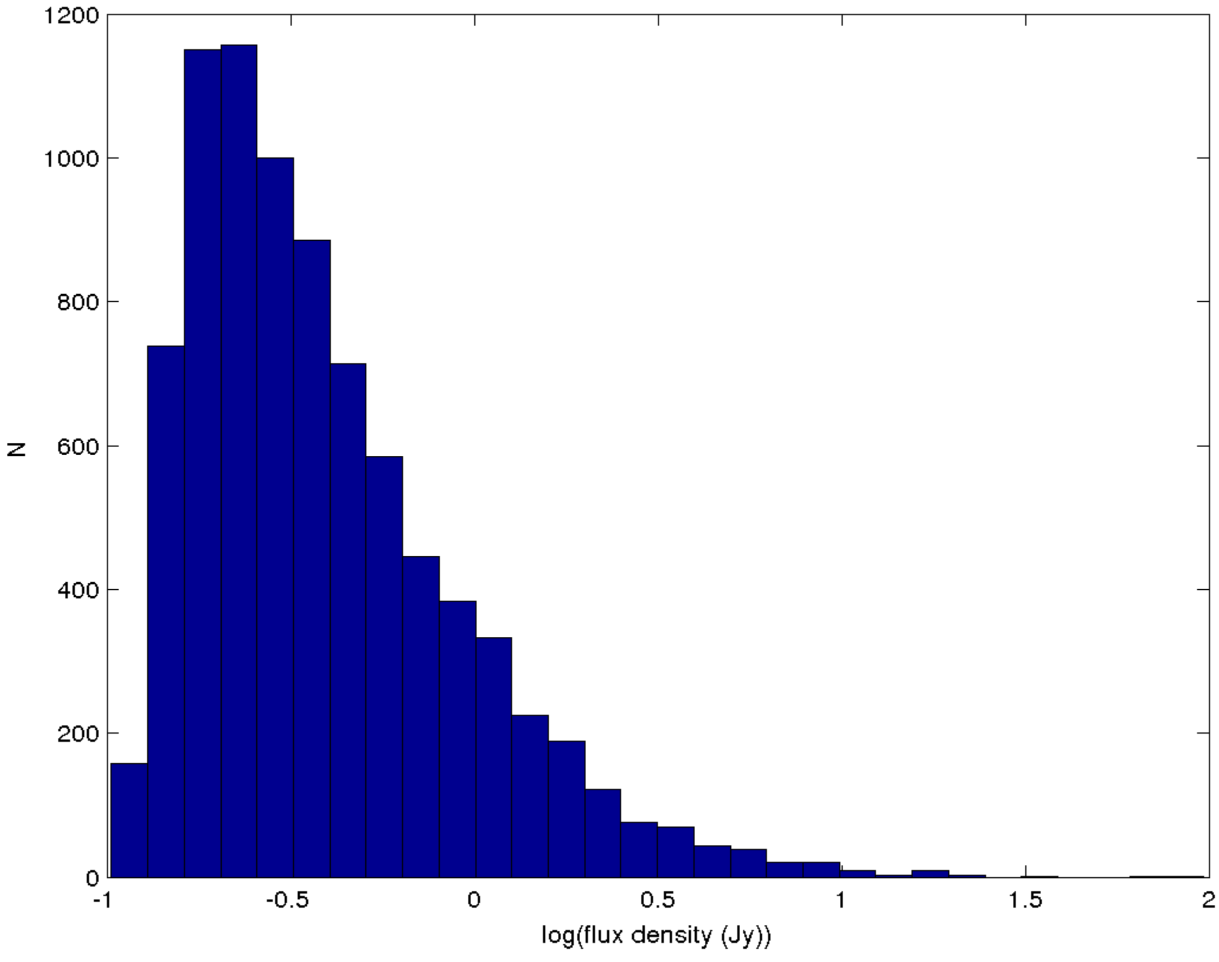
Zenith strip catalogue

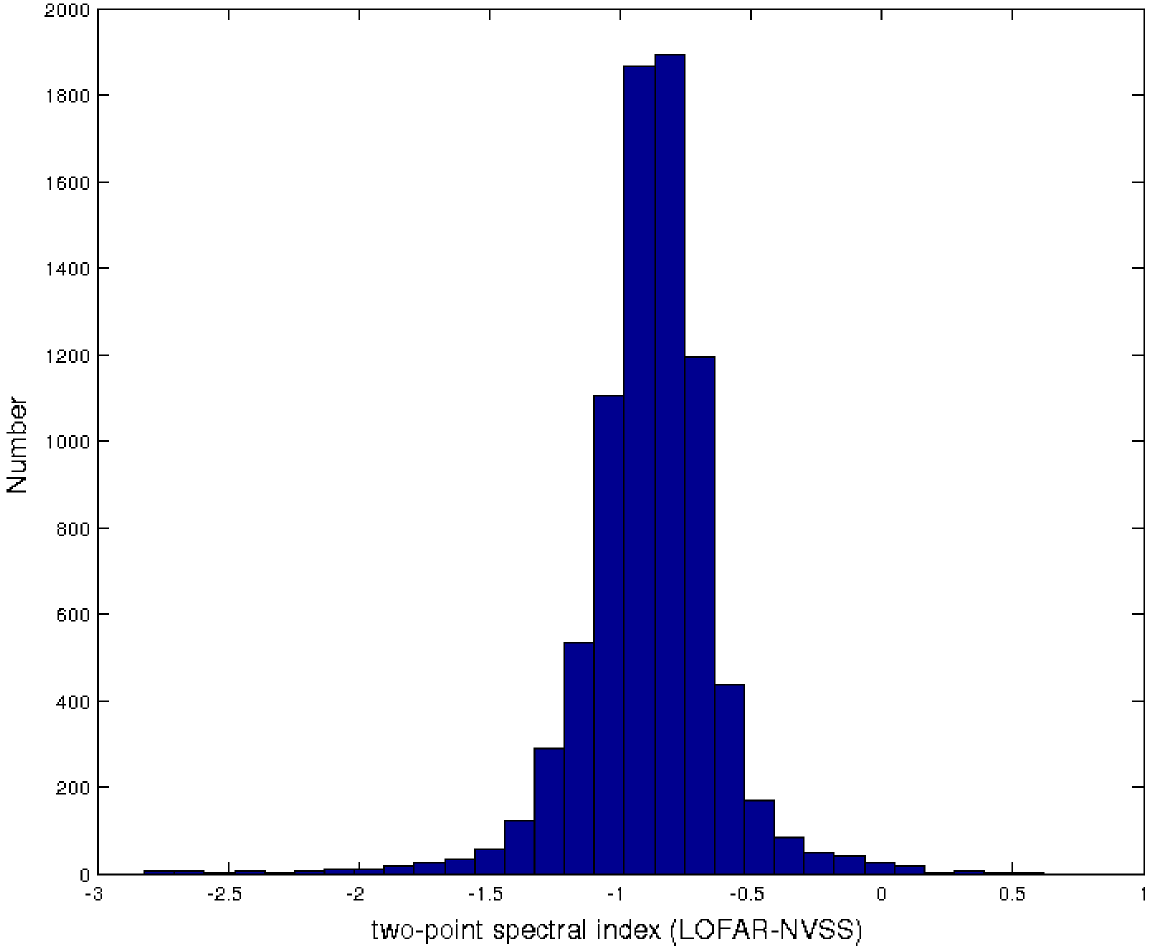


* ~7000 sources over ~1100 deg^2

* Median flux density ~320 mJy ; mode ~180 mJy

* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

Zenith strip catalogue



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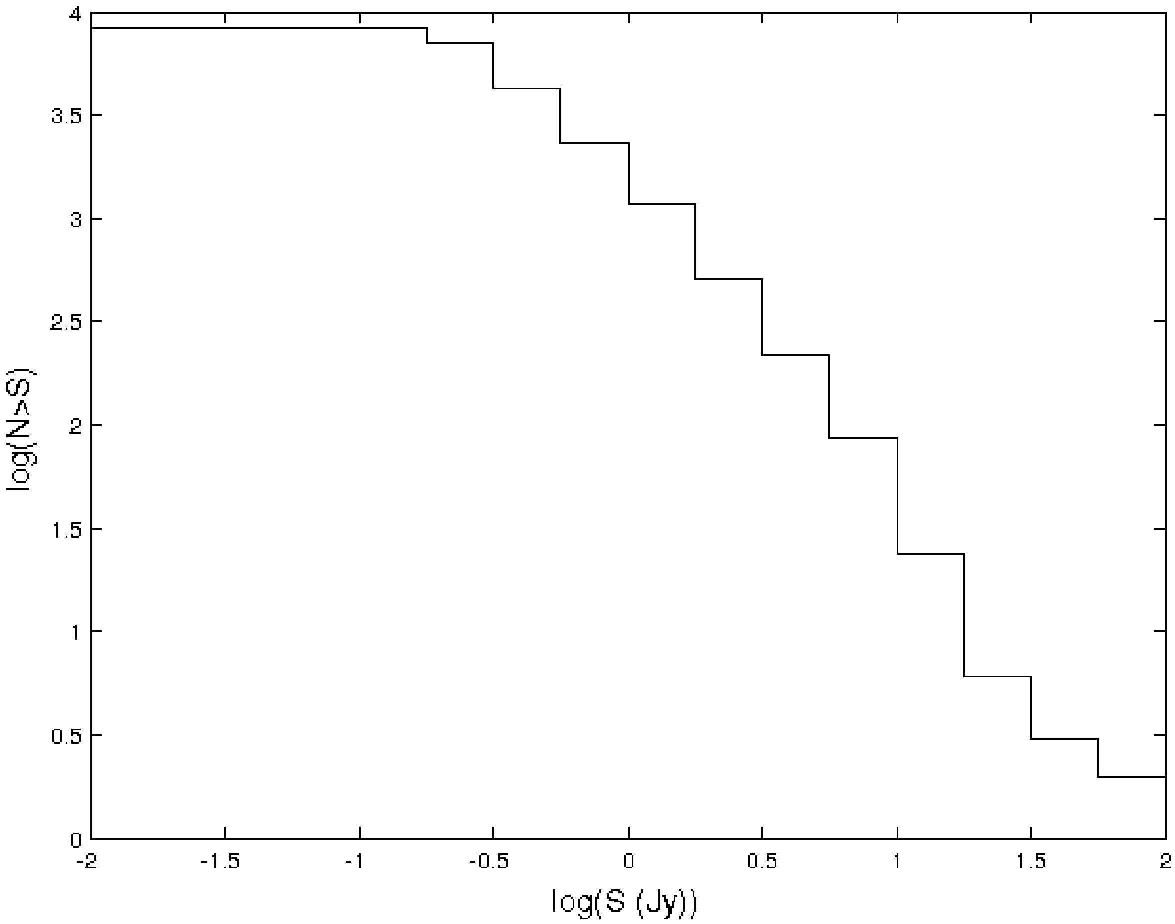
* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

* Median spectral index ~ -0.9 (cf. WENSS-NVSS = -0.8; De Breuck et al. 2000)
* Std. Dev. ~ 0.3 (~0.2 if tails excluded)
* Probably slightly steeper than expected due to resolution effect (~120 arcsec in LOFAR vs. 45 arcsec in NVSS).

Zenith strip catalogue



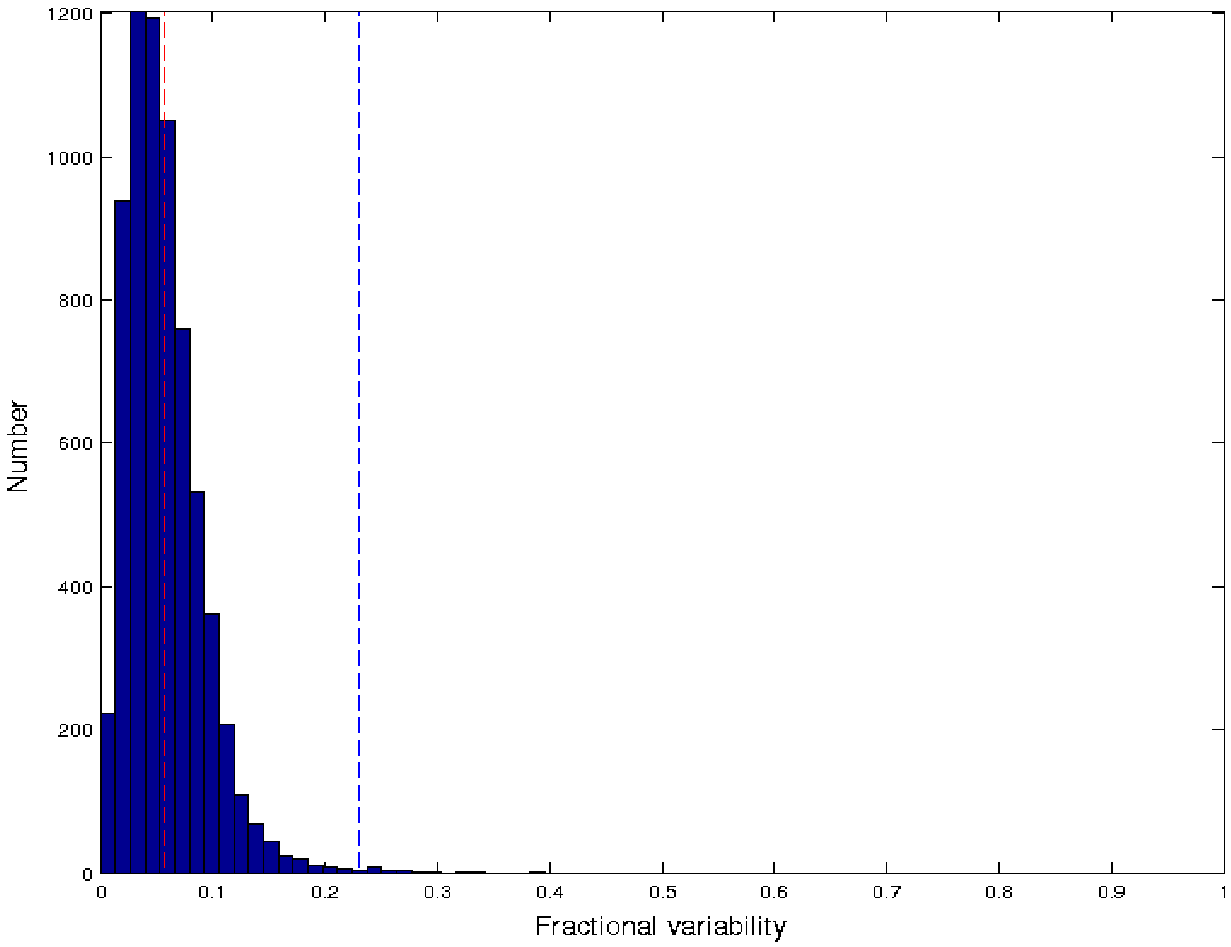
* ~7000 sources over ~1100 deg^2

* Median flux density ~320 mJy ; mode ~180 mJy

* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

* Slope about -1.3 – -1.4 (expect -1.5 for static population, Euclidean geometry)

Zenith strip catalogue



* ~7000 sources over ~1100 deg^2

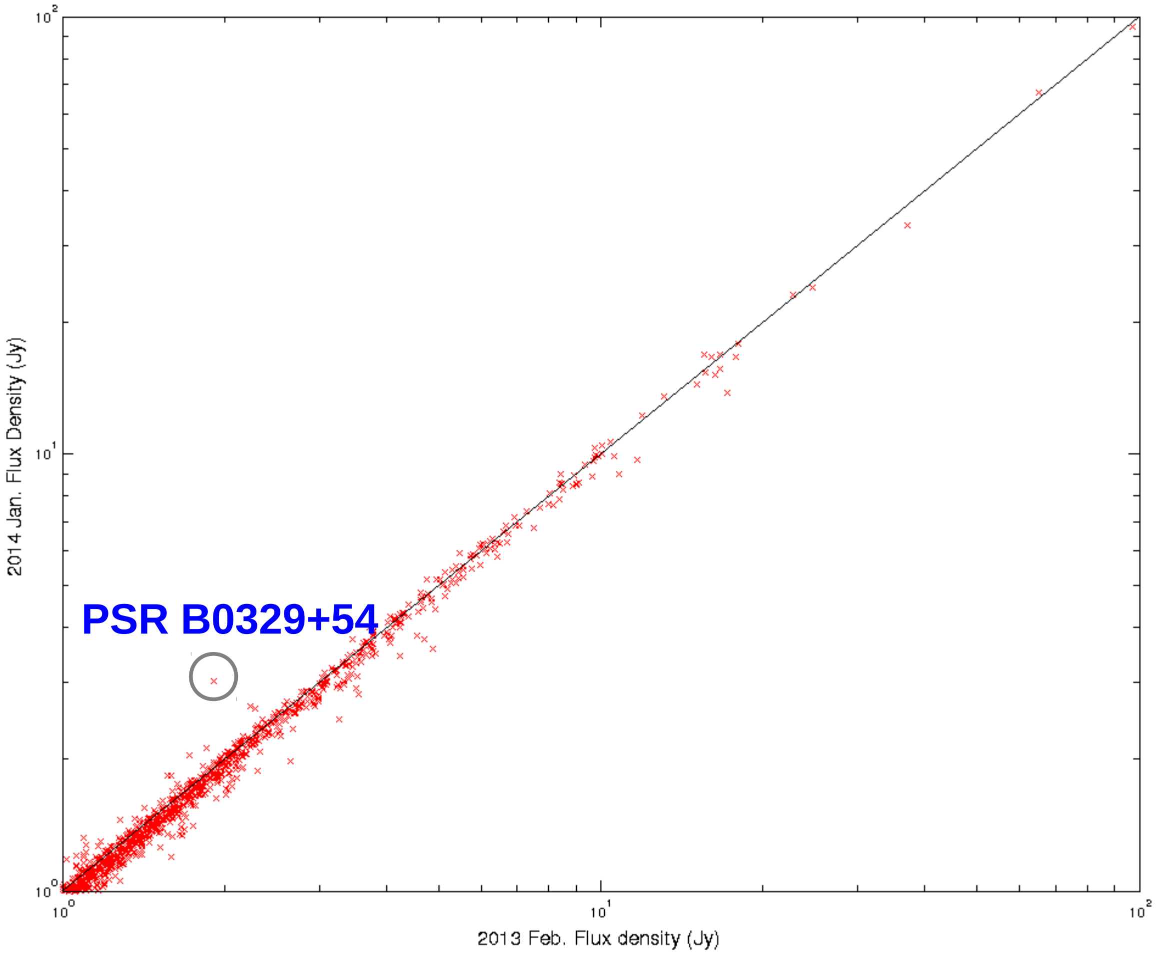
* Median flux density ~320 mJy ; mode ~180 mJy

* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

* Mean fractional variability ~6%, standard deviation ~3.5%.

* 25 sources 5σ above mean (manageable amount to look at by eye).

Zenith strip catalogue



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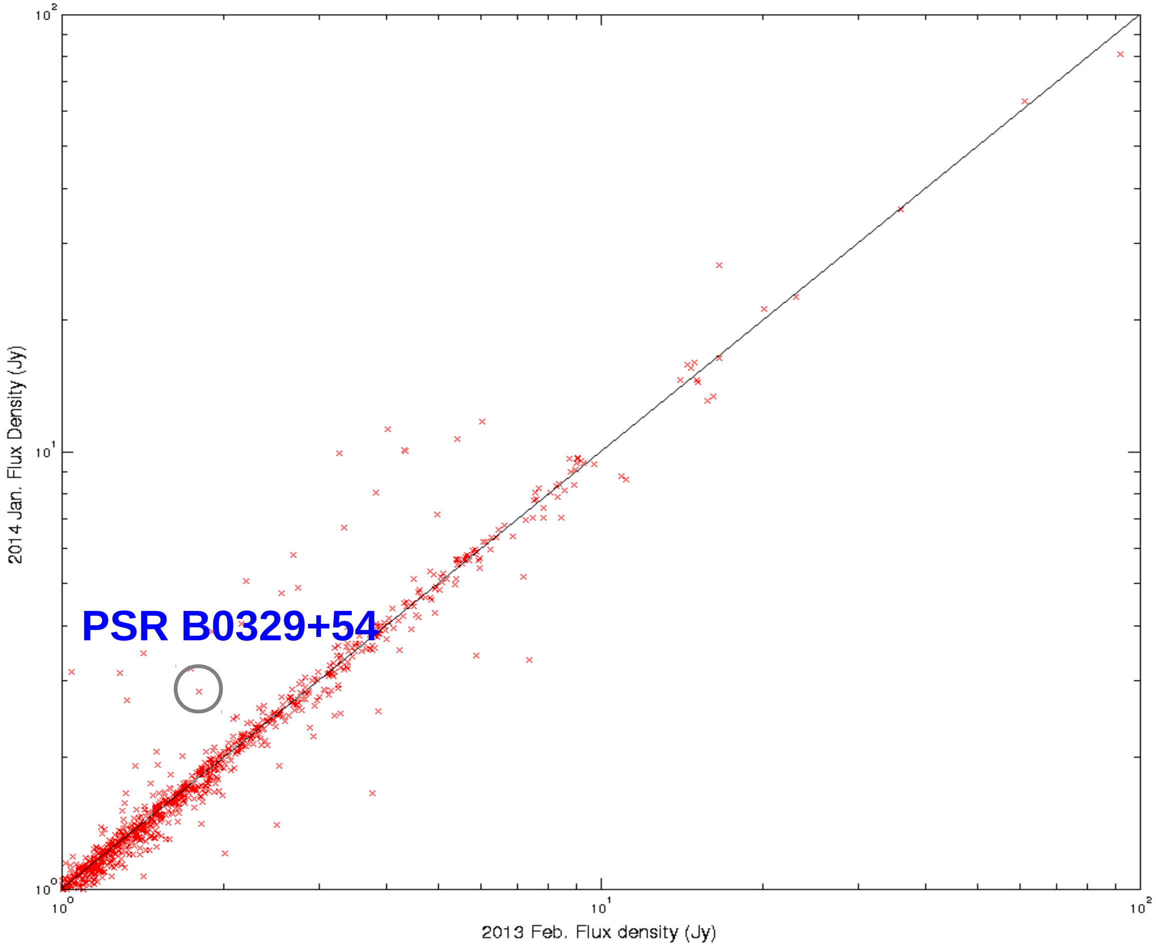
* Median flux density ~320 mJy ; mode ~180 mJy

* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

* Flux comparison on ~yr timescale.

* Possible systematic effect (~20%) for faint sources – general Gaussian fits not working well?

Zenith strip catalogue



* ~7000 sources over ~1100 deg^2

* Median flux density ~320 mJy ; mode ~180 mJy

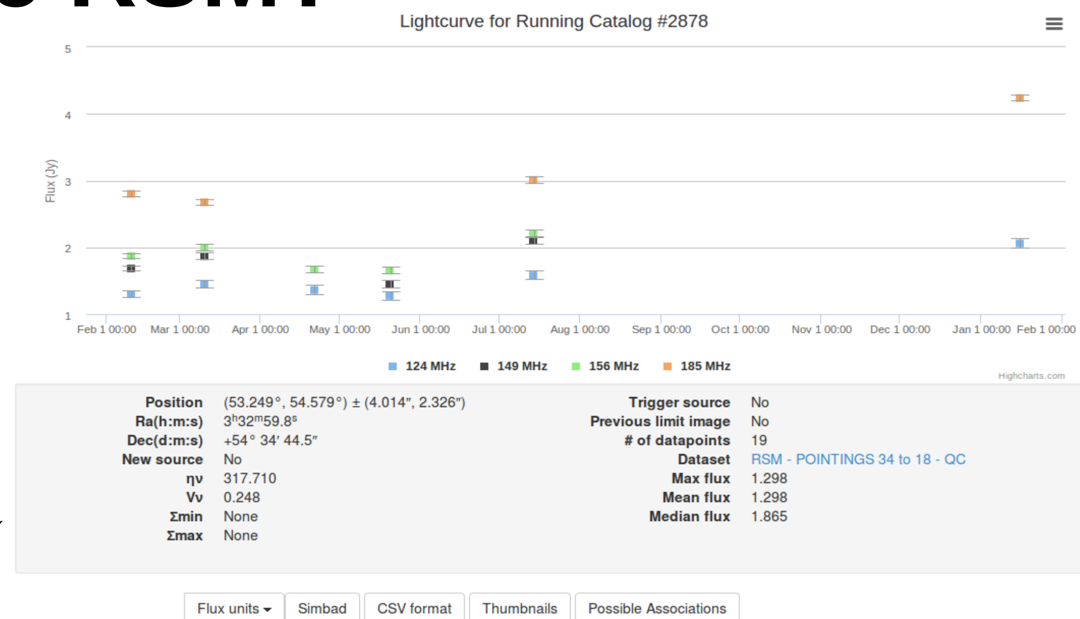
* Source density ~6 deg^{-2} (cf. 3 deg^{-2} for VLSS redux)

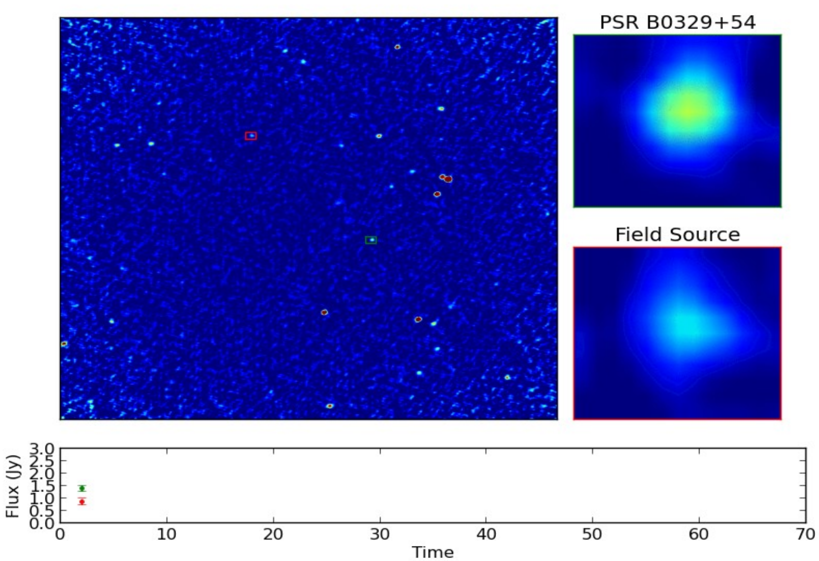
* Flux comparison on ~yr timescale (forced point-source fits in PyBDSM).
* Better agreement for the fainter sources.
* But...the resolution is not the same in both runs (2014 Jan. is ~20% worse). Cause of new scatter?
* General fits appear not to work properly all the time, but there are dangers in blindly using forced point-source fits too. Joint approach? More sourcefinder testing needed?

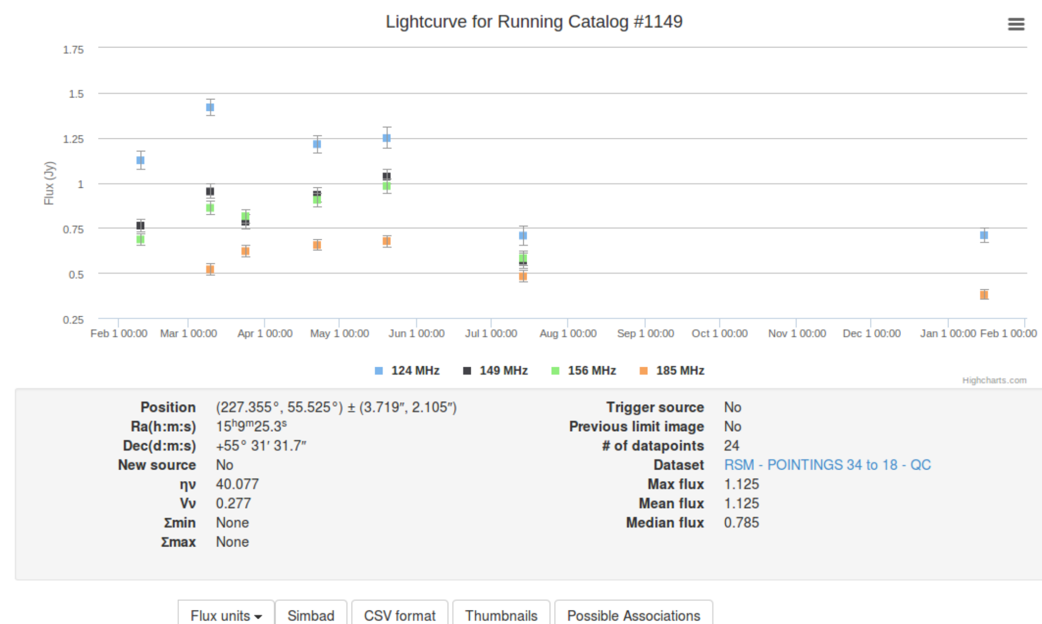
So is there anything interesting in the RSM?

* Yes! (thankfully)

* Low-hanging fruit - pulsars





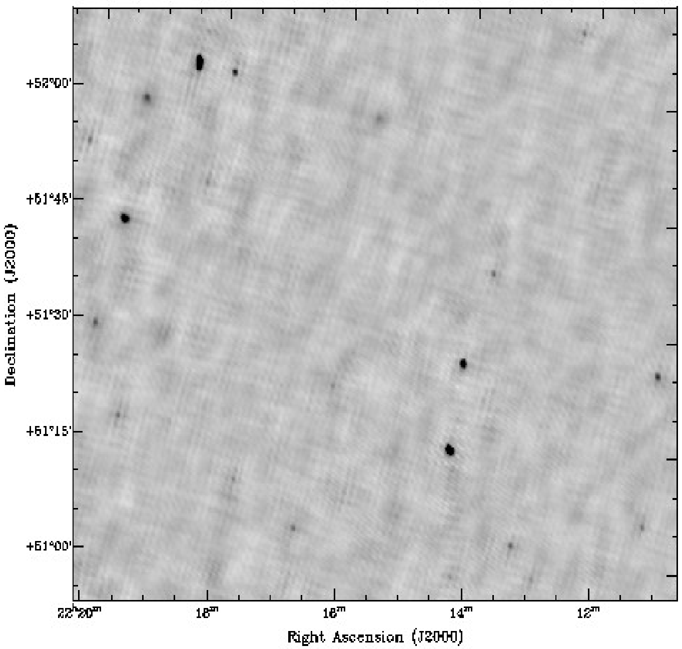


Hassall

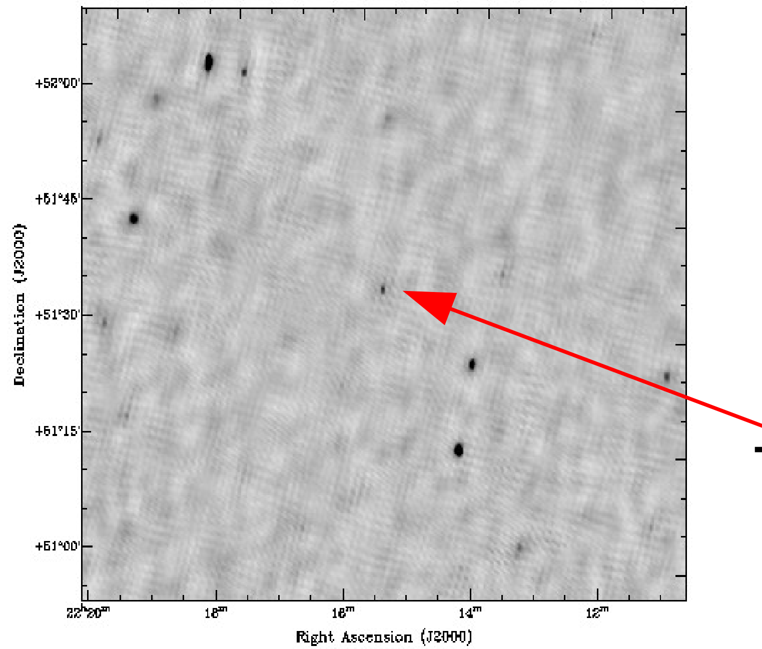
Rowlinson

Another interesting source...

124 MHz maps



2013 February



Transient?!

2014 January

* First spotted by eye, but also picked up by TraP.

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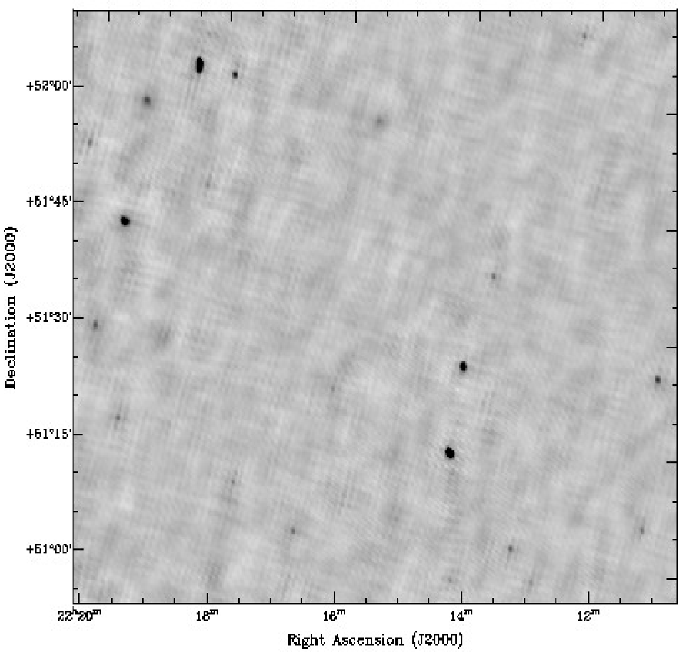

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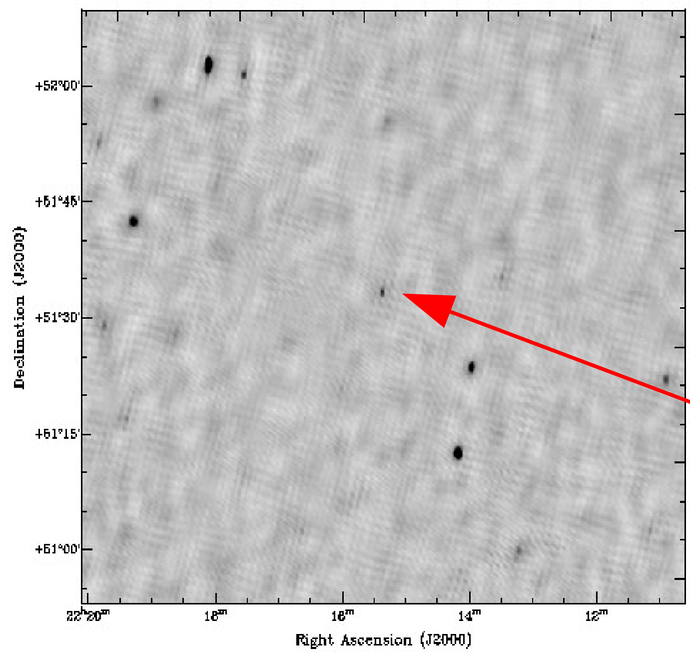

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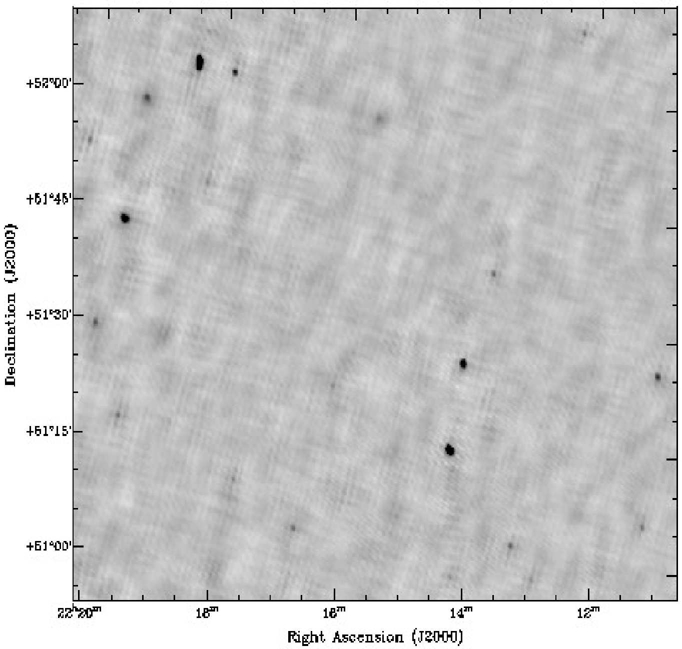

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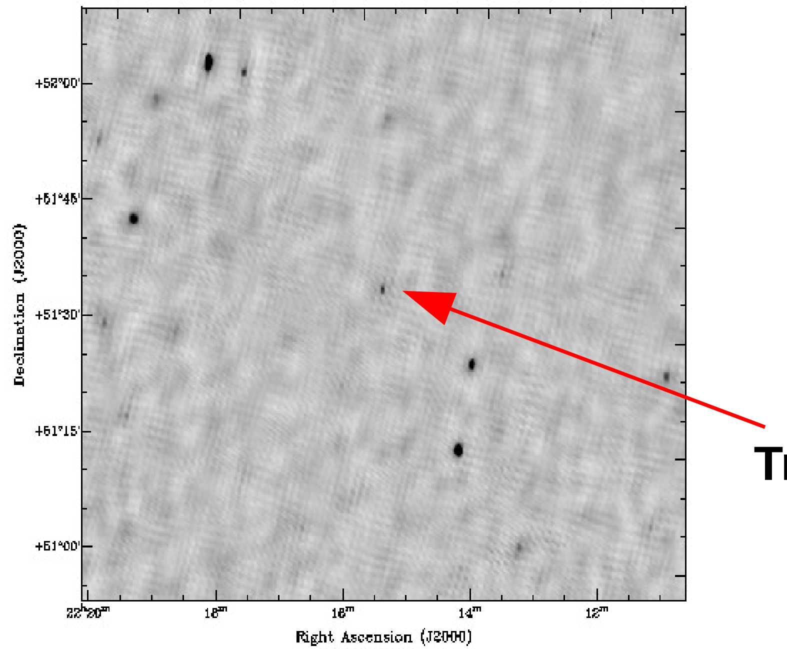

2014 January

Transient?!

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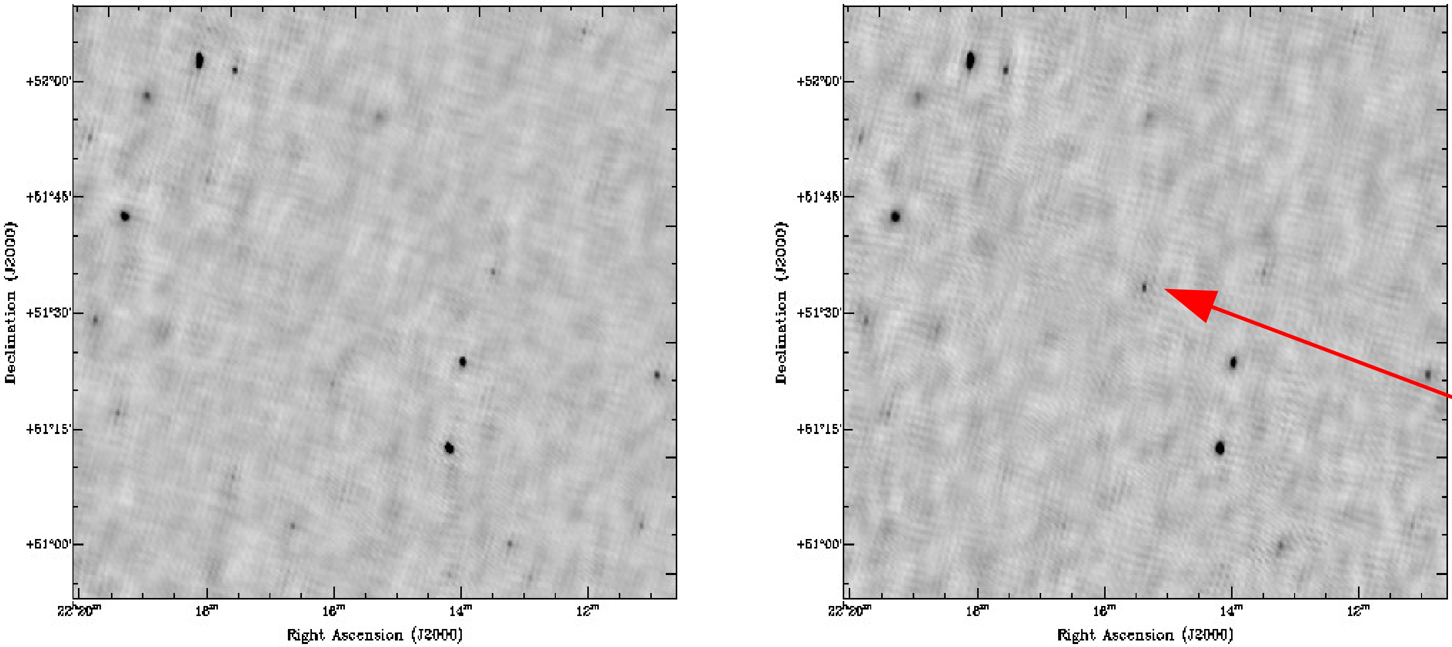
Finding spiders in the dark - an eclipsing redback pulsar in the RSM

124 MHz maps

Broderick et al. in prep.



2013 February

2014 January

* First spotted by eye, but also picked up by TraP.
* Position coincident with PSR J2215+5135 (Hessels et al. 2011).
* Discovered at 350 MHz with the GBT (survey of faint *Fermi* gamma-ray sources, looking for radio millisecond pulsars).
* Period 2.61 ms, $S_{350\ \mathrm{MHz}}$ ~ 5 mJy
* 'Redback' pulsar. The source is eclipsed for ~half of its ~4 hr orbit at 350 MHz, and probably a bit more at LOFAR frequencies.
* **Of particular interest here is that we have blindly detected this source in the image plane (as opposed to time series data).**

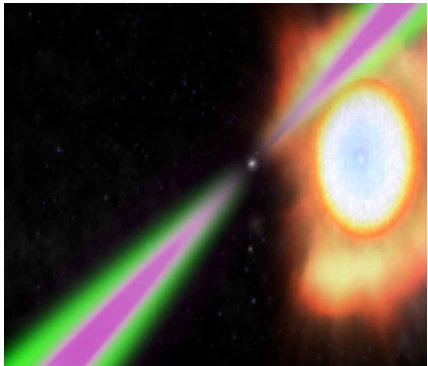


Table 1. HBA image-plane observations of PSR J2215+5135. MJD is the Modified Julian Date at the halfway point of each observation, and ϕ the unitless orbital phase (we state the range). Spectral indices across the high-band were determined from linear least-squares fits in $\ln(S)$–$\ln(\nu)$ space with inverse-variance weighting. All uncertainties are 1σ.

(22 min mosaics)

Date	MJD (days)	ϕ	$S_{124\,\mathrm{MHz}}$	$S_{149\,\mathrm{MHz}}$ (mJy)	$S_{156\,\mathrm{MHz}}$	$S_{185\,\mathrm{MHz}}$	α_{HBA}
2013 February 10	56333.509	0.14–0.24	16 ± 14	-9 ± 9	1 ± 8	-4 ± 9	
	56333.530	0.26–0.36	3 ± 12	-1 ± 9	5 ± 10	8 ± 12	
2013 March 10	56361.431	0.01–0.11	52 ± 17	55 ± 12	45 ± 11	48 ± 11	-0.3 ± 1.0
	56361.452	0.13–0.23	6 ± 15	3 ± 10	6 ± 11	13 ± 12	
2013 March 24	56375.392	0.94–0.04	153 ± 46	125 ± 31	116 ± 30	103 ± 30	-1.0 ± 1.0
	56375.413	0.06–0.16	1 ± 19	8 ± 17	12 ± 20	-14 ± 50	
2013 April 22	56404.314	0.60–0.70	184 ± 38	118 ± 36	103 ± 32	104 ± 30	-1.6 ± 0.9
	56404.335	0.72–0.82	189 ± 63	168 ± 40	113 ± 41	91 ± 45	-1.8 ± 1.4
2013 May 20	56432.238	0.47–0.58	155 ± 33	110 ± 39	89 ± 34	99 ± 31	-1.3 ± 0.9
	56432.258	0.59–0.70	233 ± 68	154 ± 34	134 ± 35	73 ± 47	-2.6 ± 1.4
2013 July 14	56487.087	0.44–0.54	106 ± 33	65 ± 35	36 ± 30	39 ± 32	-2.9 ± 1.9
	56487.108	0.56–0.66	166 ± 32	156 ± 54	78 ± 47	91 ± 47	-1.5 ± 1.2
2014 January 15	56672.578	0.74–0.84	207 ± 25	123 ± 16	126 ± 16	89 ± 13	-2.1 ± 0.5
	56672.599	0.86–0.96	215 ± 26	141 ± 18	120 ± 17	86 ± 15	-2.3 ± 0.5

(magenta – 'good' demixing)

* Note: source appears in two overlapping RSM pointings

* Calibration uncertainty ~10-20%.

* Some significant differences within individual runs!

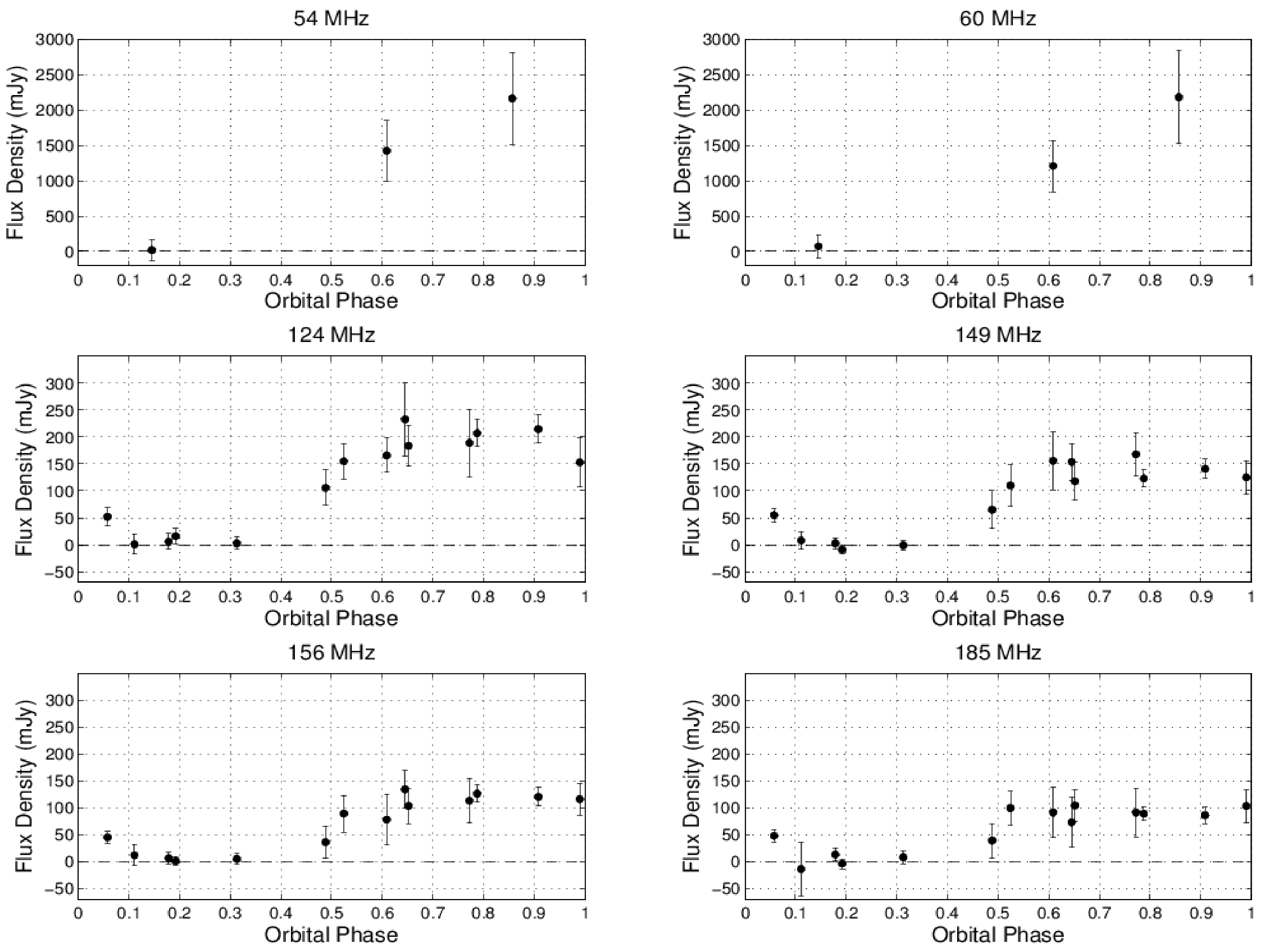
Table 2. LBA image-plane observations of PSR J2215+5135. The flux densities are the averages from the two beams used in this study (see Table A1). See Table 1 for a description of the acronyms/symbols used and conventions followed.

Date	MJD (days)	ϕ	$S_{54\,\mathrm{MHz}}$ (mJy)	$S_{60\,\mathrm{MHz}}$
2013 August 11/12	56516.0	0.03–0.26	20 ± 150	70 ± 170
2013 October 29	56594.8	0.74–0.98	2160 ± 650	2180 ± 650
2014 March 30	56746.4	0.49–0.73	1420 ± 430	1210 ± 360

(1 hr maps)

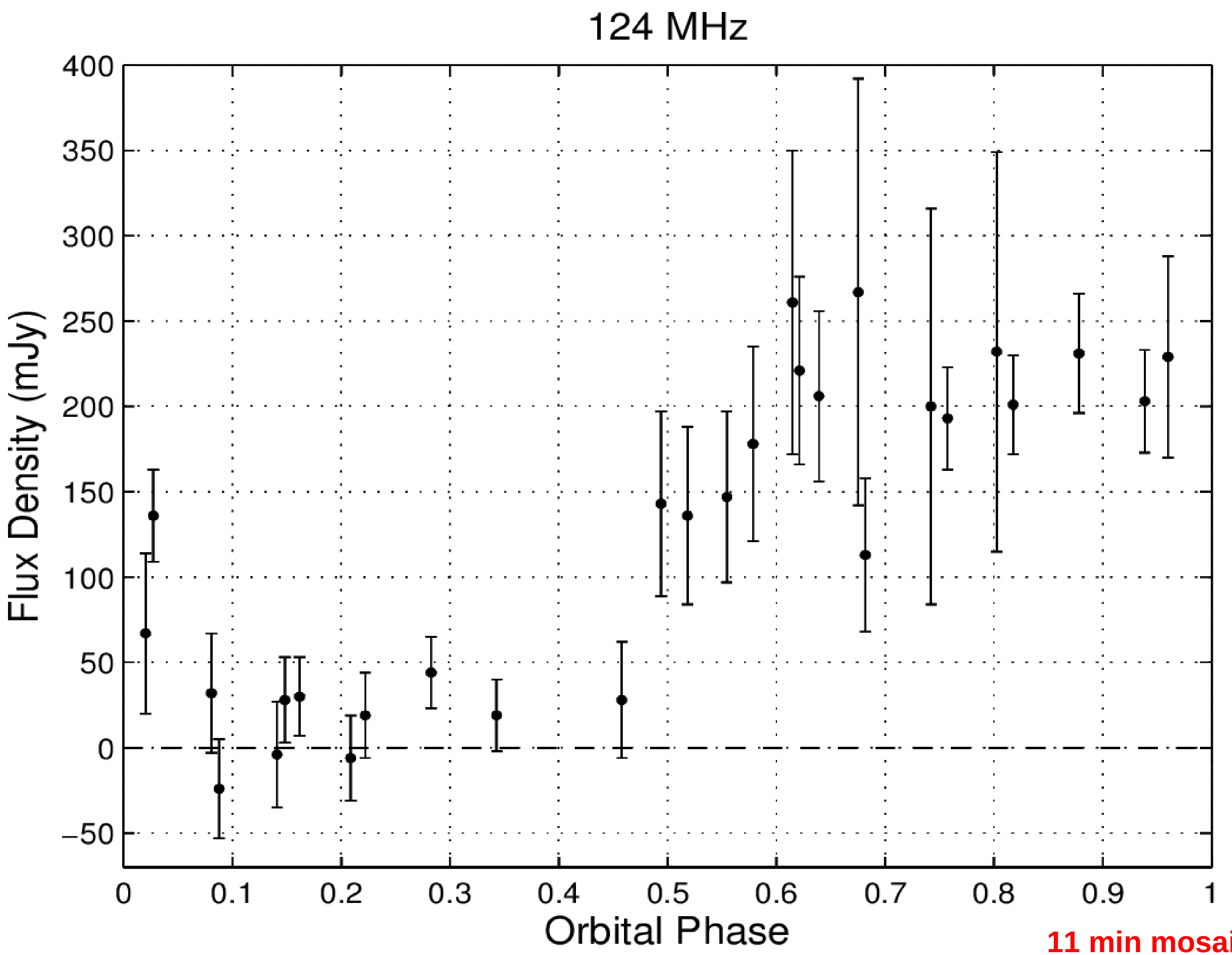
Flux density vs. orbital phase

Orbital phase timing solution – Hessels (priv. comm.)



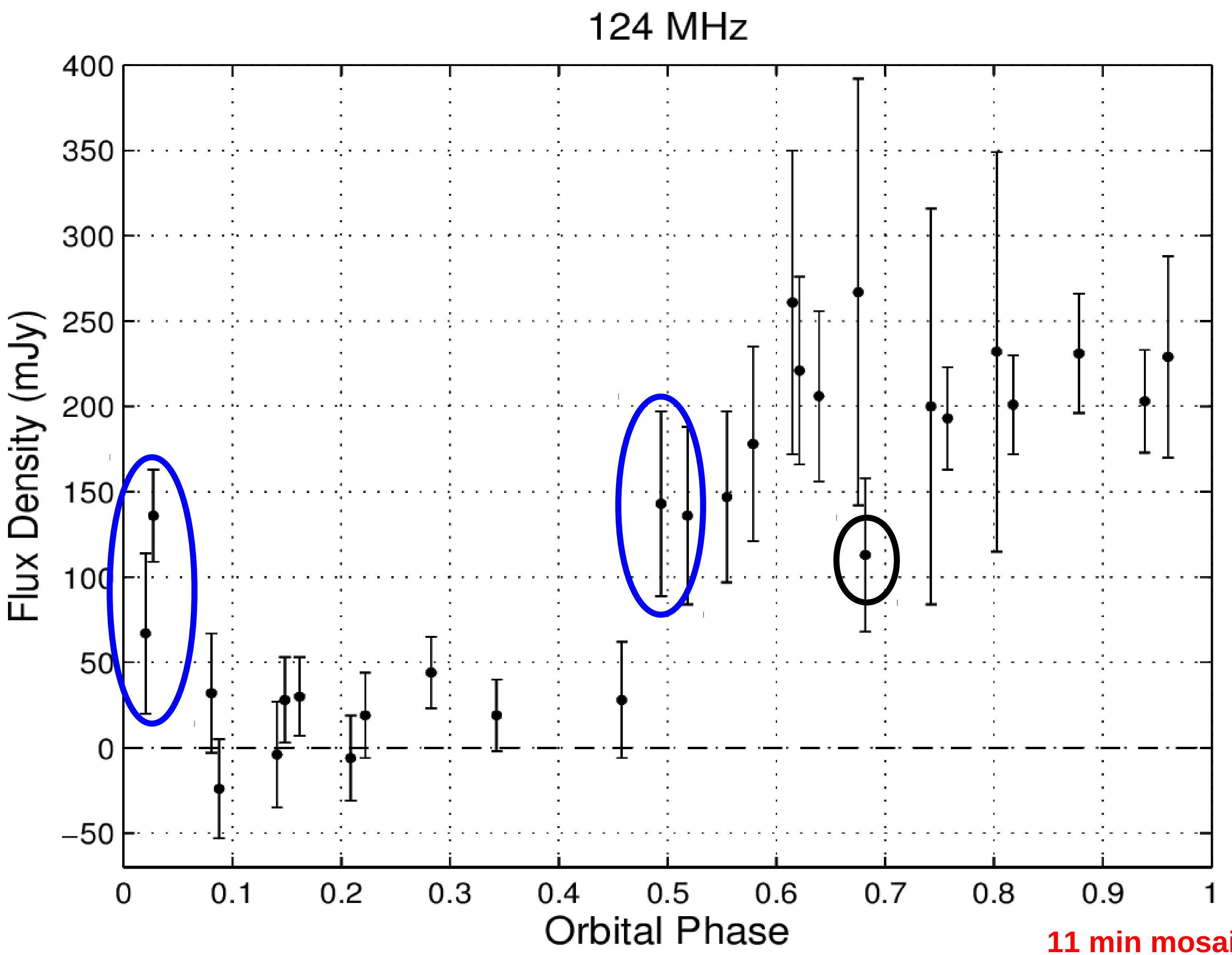
Expect eclipse for orbital phase ~0-0.5

Flux density vs. orbital phase



11 min mosaics; finer resolution in orbital phase space

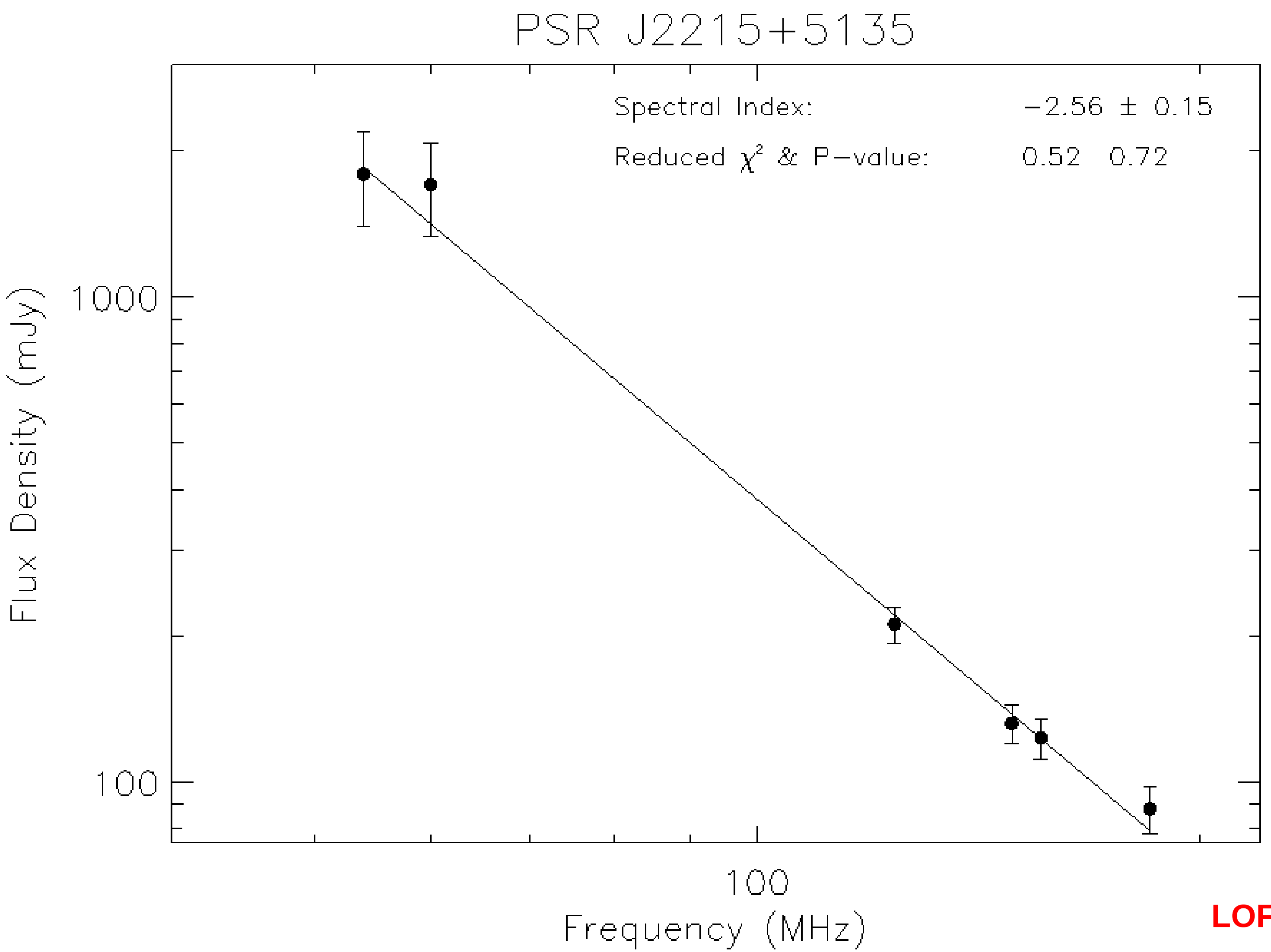
Flux density vs. orbital phase



11 min mosaics; finer resolution in orbital phase space

* During eclipse ingress (~0.0-0.1) and egress (~0.4-0.5), sometimes the pulsar is seen in time series, but partially absorbed (so flux should be lower).

* Mini eclipses can possibly drag average flux down.



LOFAR SED

* Extrapolate SED to 350 MHz -> predicted flux 3x higher than value reported in Hessels et al. (2011).
* Pulse profile known to evolve significantly, though, as a function of frequency (multiple components).

* Blind image-plane searches at low frequency useful for finding such sources?
* Simultaneous image-plane and time-domain observations would help to verify new candidates.

Summary and future work (RSM)

* Ongoing zenith strip monitoring campaign: deep, multi-epoch, large-volume search for transients at low frequency.

* Lots of time spent trying to optimise the reduction settings, and understand the data.

* Preliminary source catalogue + several interesting variables (pulsars).

* Cycle 3 request: two more 24 hr runs (1 HBA, 1 LBA).

Lots of testing still needed! For example:

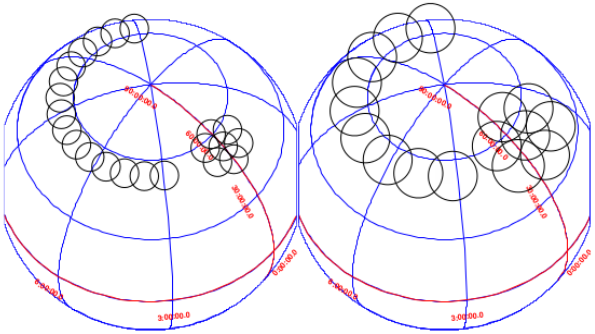
* Higher-resolution imaging strategy.

* Self-calibration and direction-dependent calibration.

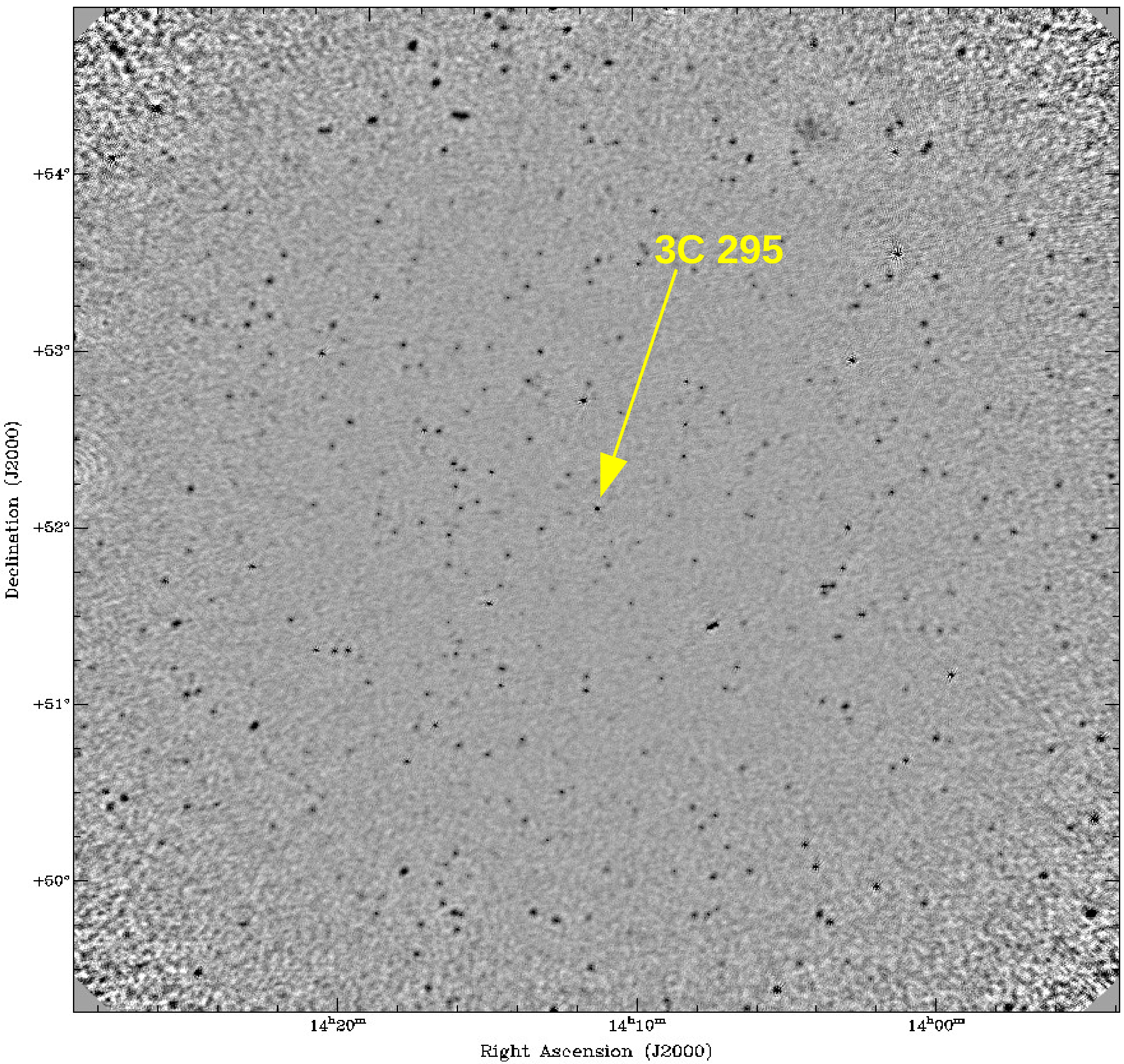
* Detailed investigation of artefacts in the maps (e.g. flashing sources).

* Demixing problems near Cas A.

* New tools being developed by imaging tiger team.



Future work - going to higher resolution....



* 3C 295 calibrator data

* Each run:
  12 pointings *
  2 snapshots *
  2 min integrations

* Very good initial calibration.

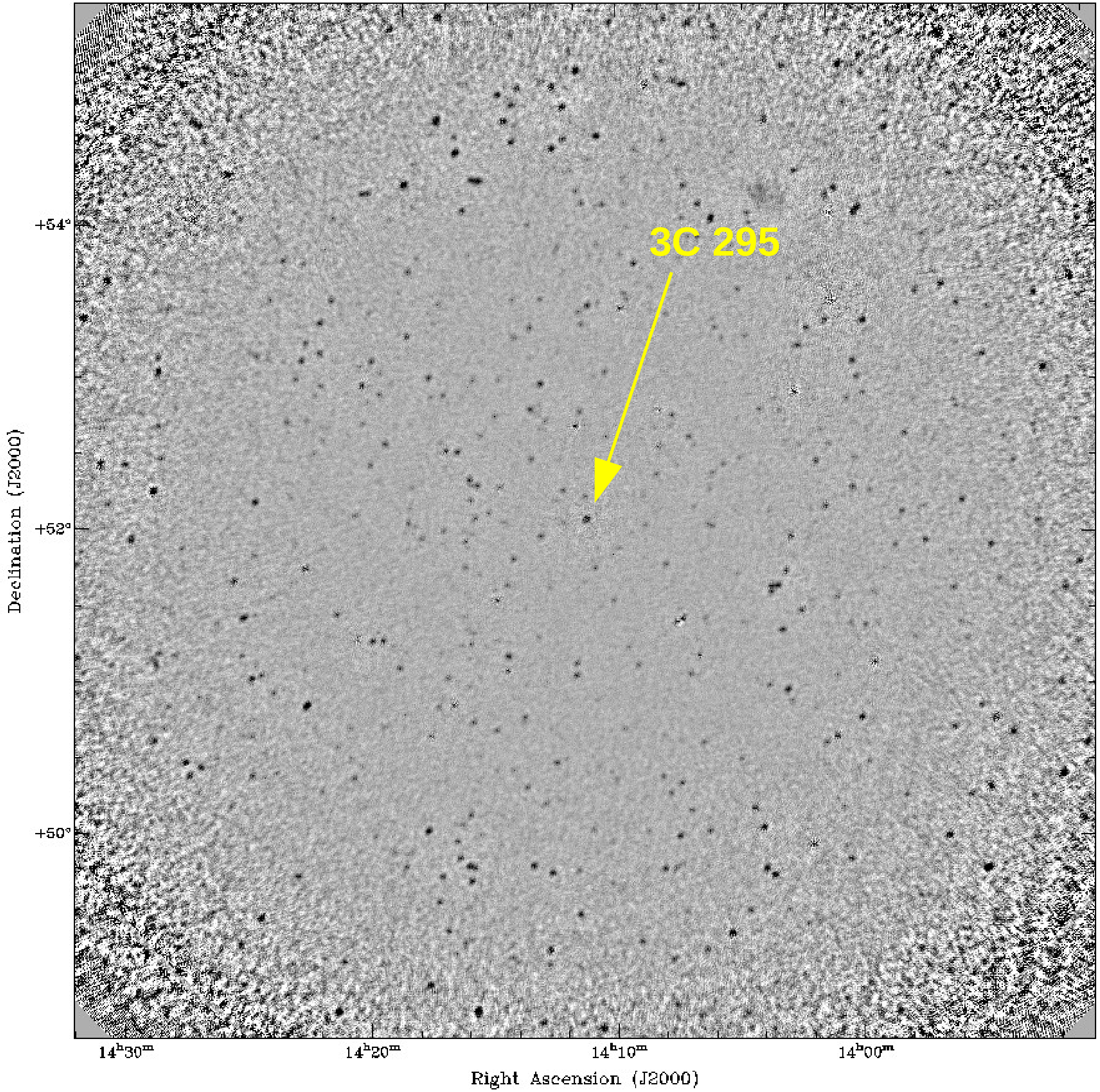
* Reduce confusion noise
  by increasing max. baseline.

* Lots of sources (including some
  previously uncatalogued).

* Transient search – nothing
  significant.

*** 2013 Feb. 10 run, bands 1-3 stacked (bandwidth 6 MHz)**
*** Resolution 27 arcsec * 23 arcsec (BPA 80 deg)**
*** Max. baseline 20 km**
*** rms noise level ~4 mJy beam^{-1}**

Future work - going to higher resolution....



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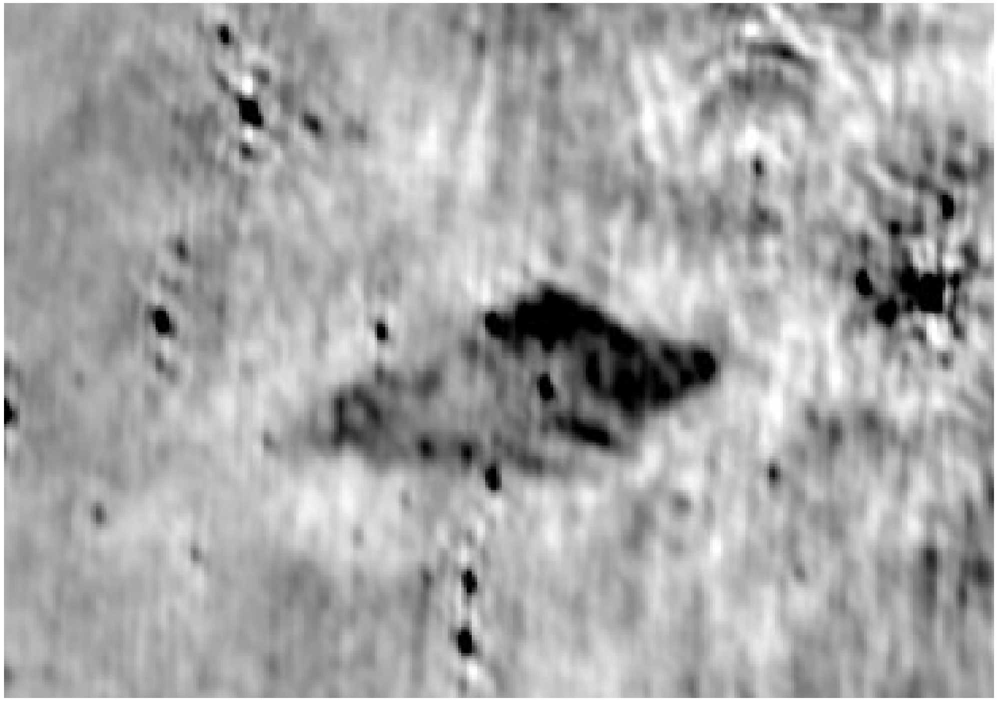
*** 2013 Feb. 10 run, bands 1-3 stacked (bandwidth 6 MHz)**
*** Resolution 15 arcsec * 8 arcsec (BPA 84 deg)**
*** Max. baseline 50 km**
*** rms noise level ~3 mJy beam^{-1}**

SS433/W50 update

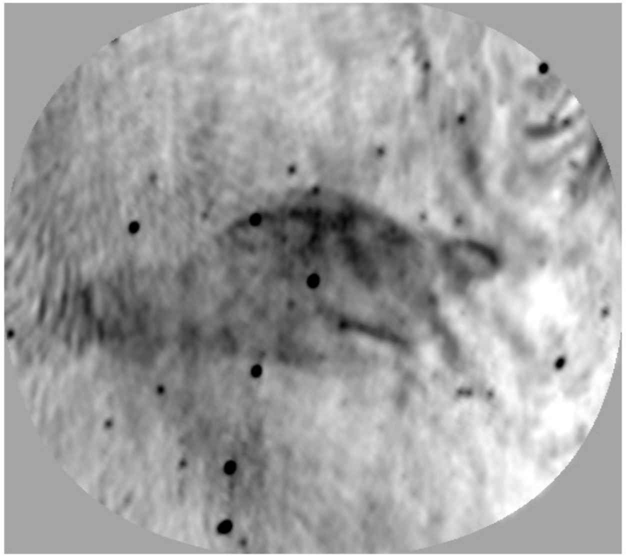


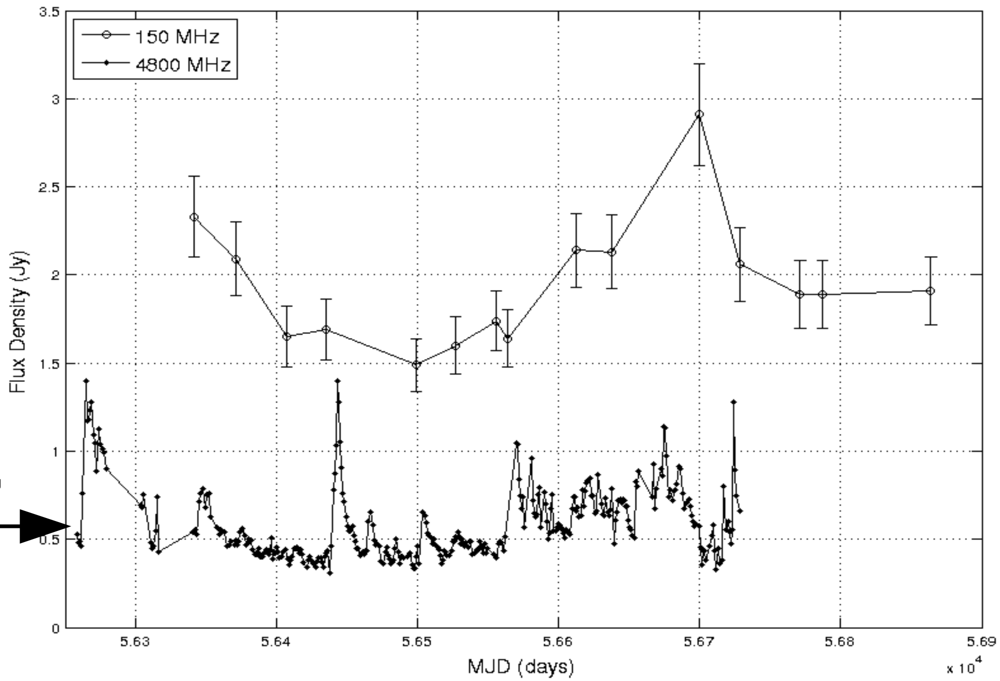
2010-11

*** Broderick et al. in prep. - hopefully finished very soon!**

*** Search conducted for new SNR candidates in field (in collaboration with Gemma Anderson and Anton Lizancos).**

HBA monitoring Feb 2013 – Mar 2014



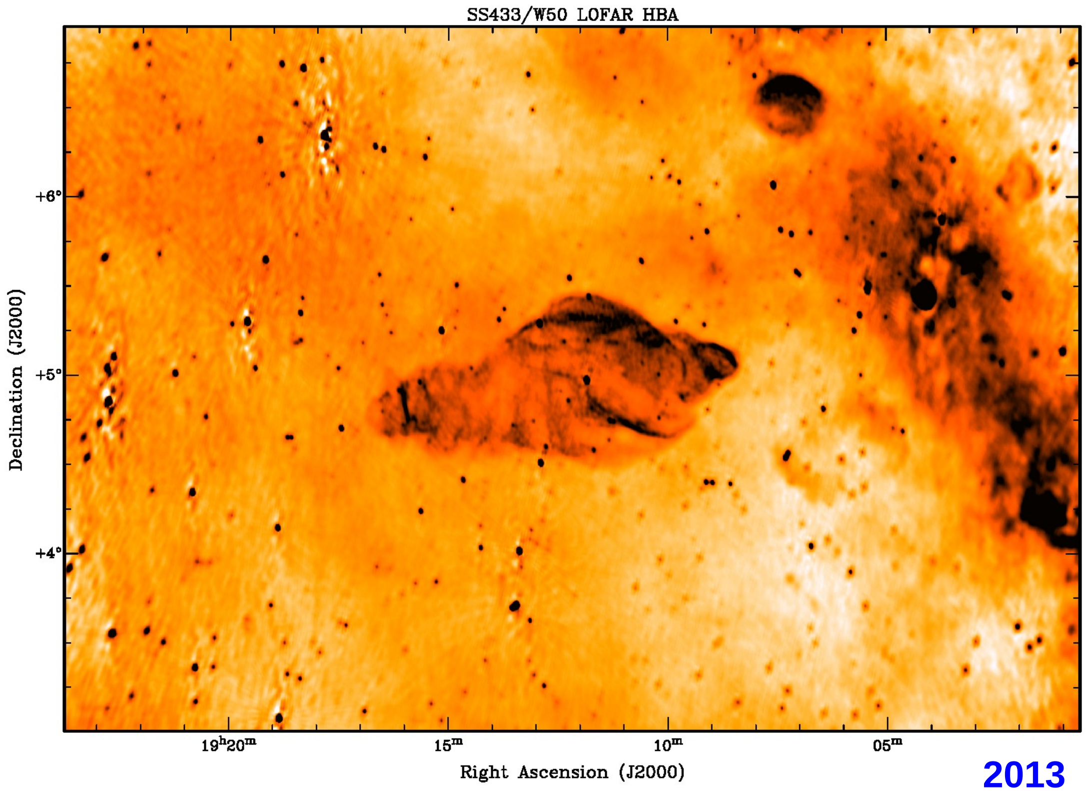


(RATAN-600 data; courtesy S. Trushkin)

*** Indications of low-frequency variability → illustration of how LOFAR can become a key trigger for other facilities.**

Ongoing testing with the new AWimager

SS433/W50 update



2013

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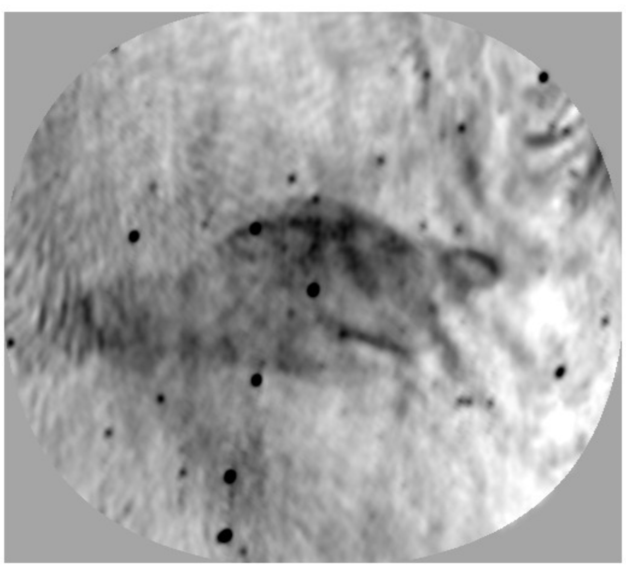
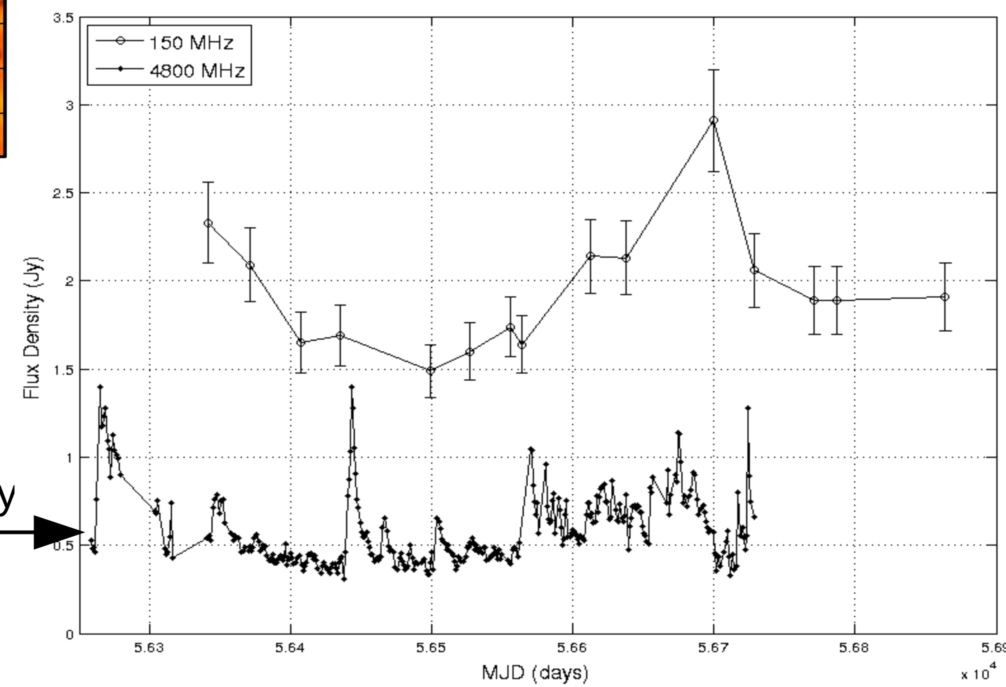


Ongoing testing with the new AWimager

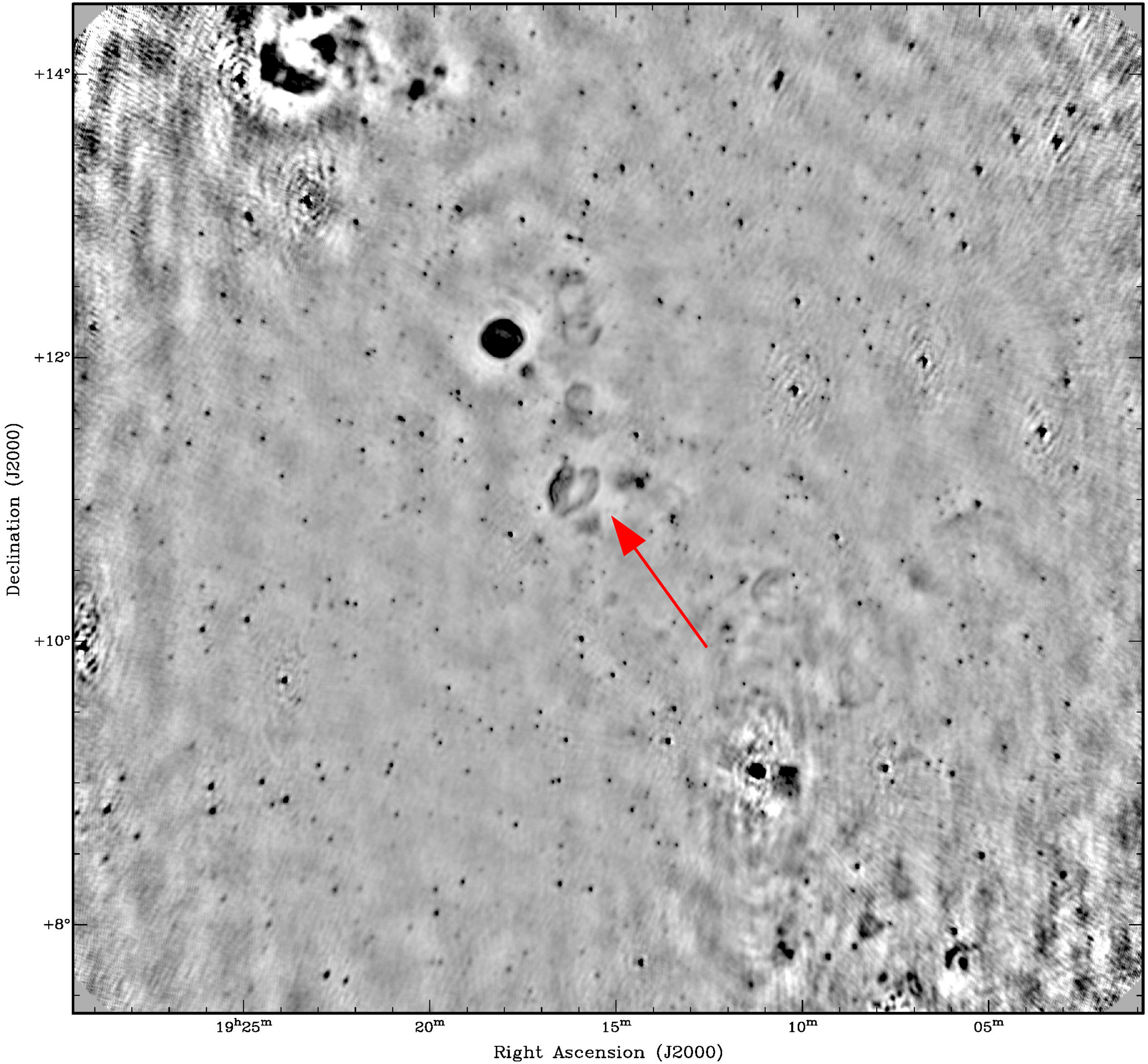
HBA monitoring Feb 2013 – Mar 2014

(RATAN-600 data; courtesy S. Trushkin)



* Indications of low-frequency variability → illustration of how LOFAR can become a key trigger for other facilities.

GRS 1915+105 update



Broderick et al. in prep.

* HBA_DUAL_INNER map from Cycle 1

* 10.5h over 4 runs in 2013 November

* 20 MHz bandwidth; 140-160 MHz

* Observations of 3C380 every ~20 min

* Baselines 0.1-6kλ (~0.2-12 km) for imaging

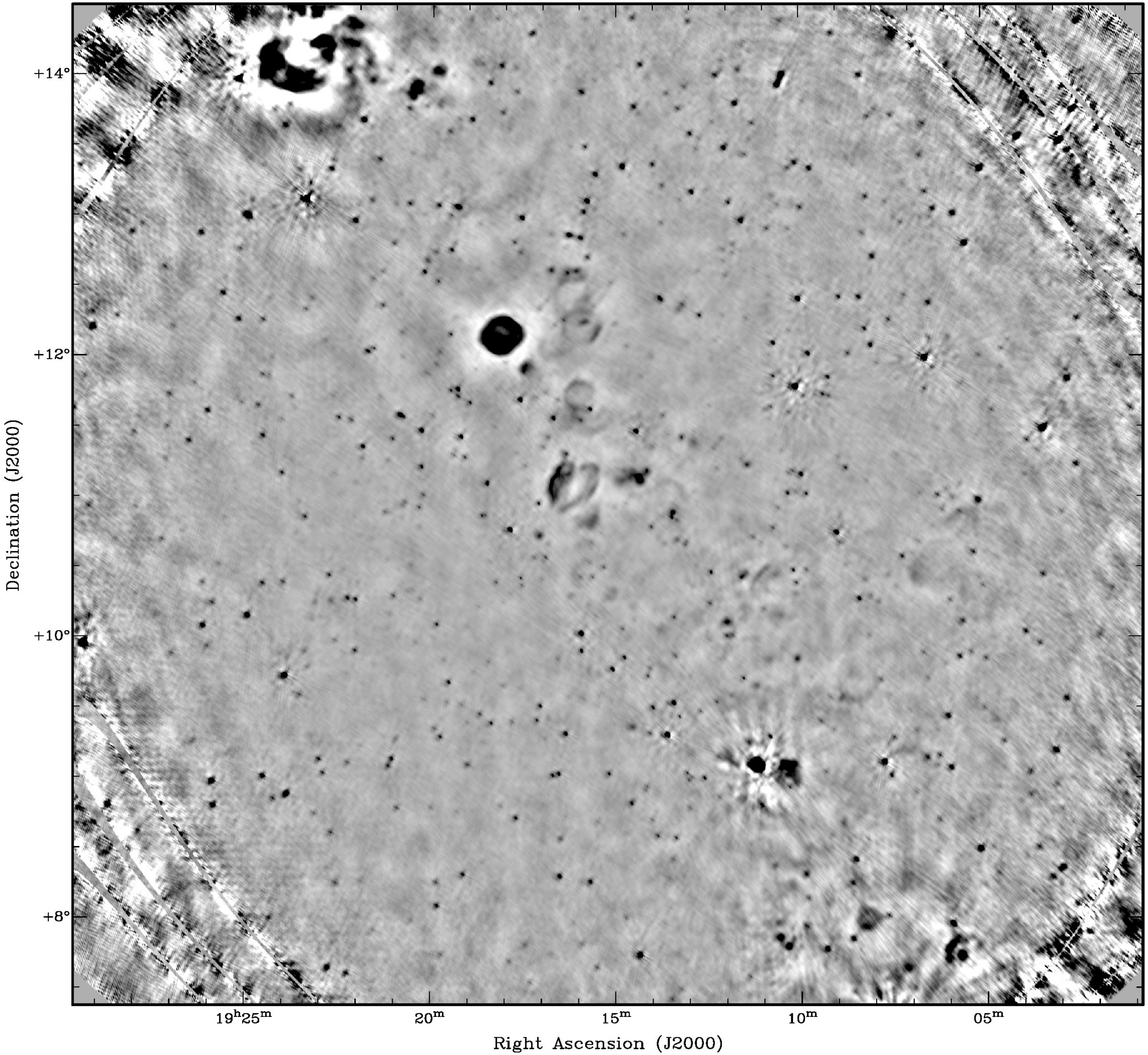
* Robust=0

* Resolution 60 arcsec x 40 arcsec (beam PA 14 deg)

* Noise ~6 mJy/beam

* GRS 1915 flux ~30 mJy

(cf. 750 mJy at 244 MHz; Ishwara-Chandra et al. 2005)



* HBA_DUAL_INNER map from Cycle 2

* 2h in 2014 July

* 74 MHz bandwidth; 115-189 MHz

* Observations of 3C380 every ~20 min

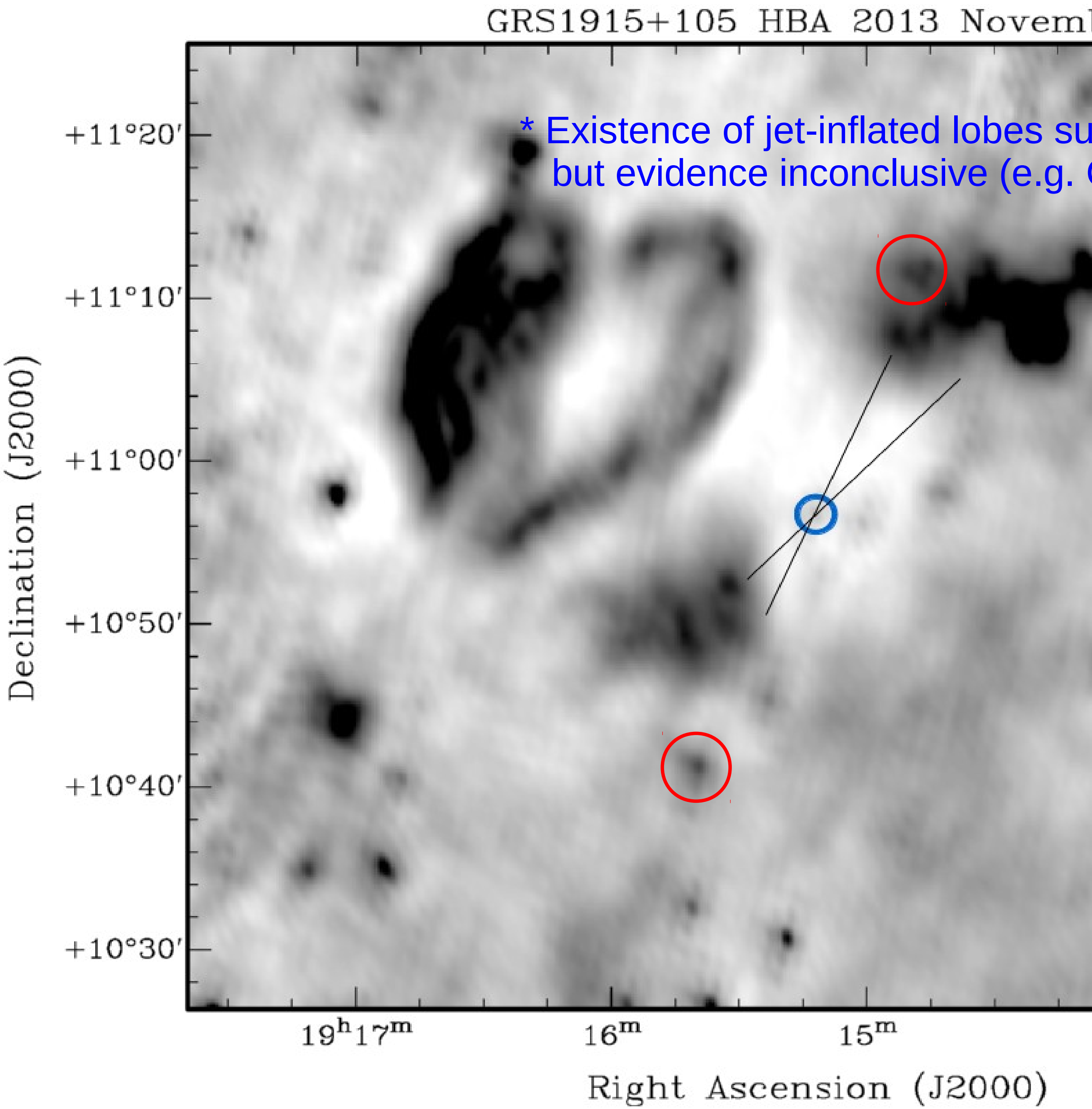
* Baselines 0.1-6kλ (~0.2-12 km) for imaging

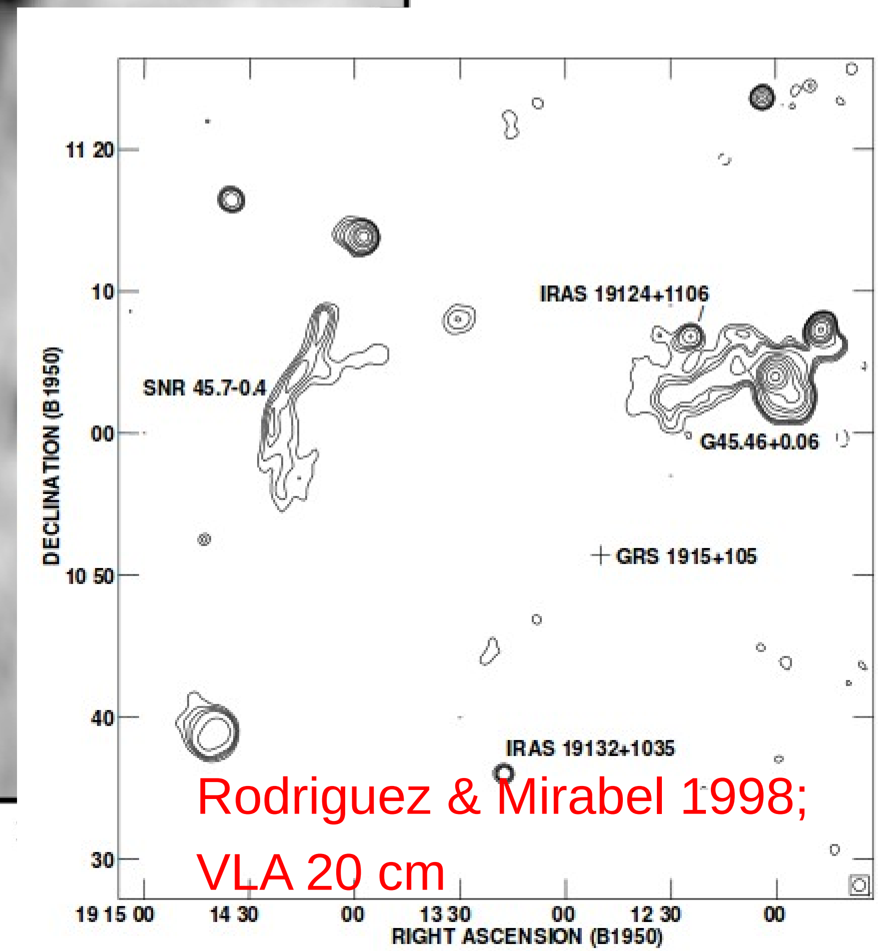
* Robust=0

* Resolution 69 arcsec x 38 arcsec (beam PA 19 deg)

* Noise ~5 mJy/beam

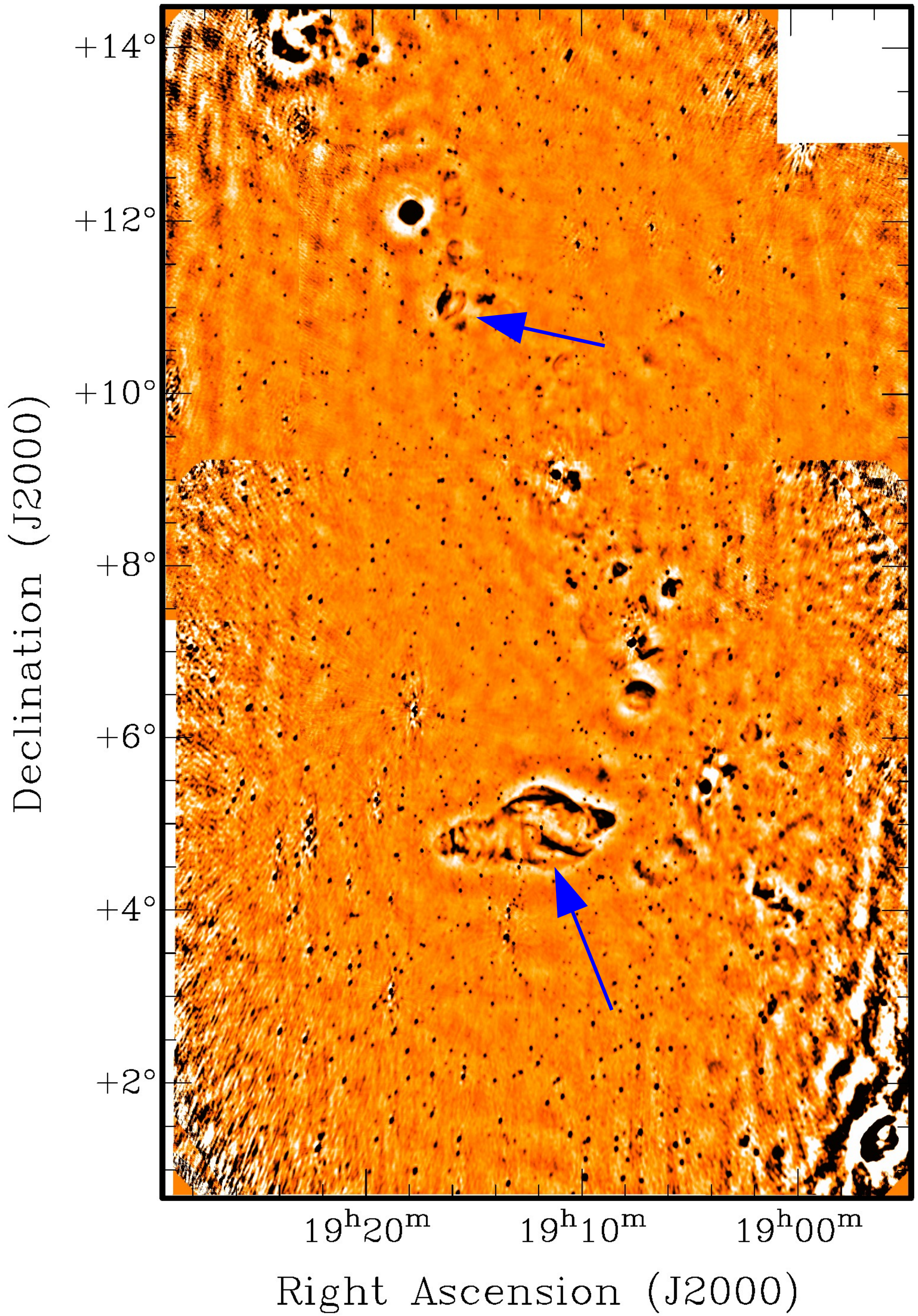
* GRS 1915 not detected





* Measurement of the low-frequency morphology and spectra of the extended emission would help resolve debate. Should they be associated with the jets, could determine time-averaged jet power.

Summary and future work (microquasars)



HBA mosaic of SS433/GRS1915 fields

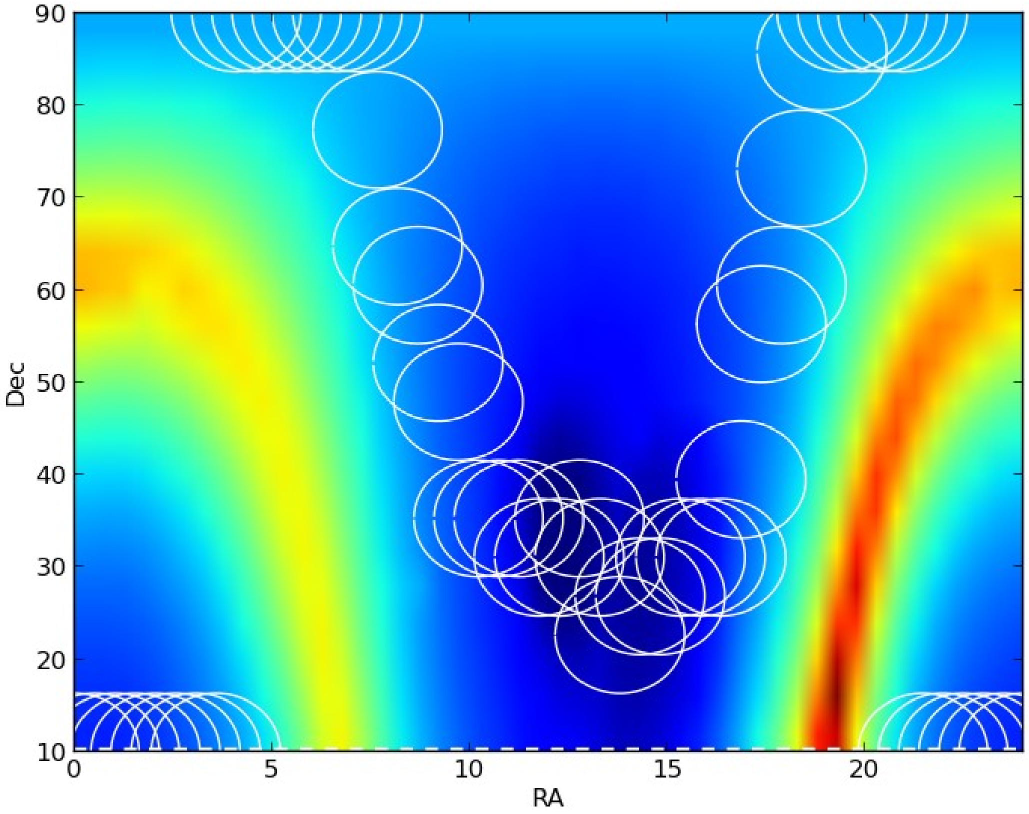
* High-quality SS433/W50 data – paper in preparation.
* Variability detected for SS433 in high band.
* SS433 LBA observations to be fully reduced.
* Spectral index map between HBA and LBA.
* International station data for one HBA monitoring run.
* Multi-scale, wide-band deconvolution in updated AWImager.
* Higher-resolution HBA maps.
* GRS 1915+105 detection; variability, lobes?

RSM HBA Short Timescale Transient Search

* Concentrate search to pointings with a low DM (14/48 ~ 440 deg^2)

* 6 zenith scans
* 2 x 10 min snapshots per scan
* 2 min mosaic images for each of the 14 pointings
* Using two bands (149 & 156 MHz)
* 6 Zenith scans
  x 2 snapshots
  x 5 (2min) epochs
  x 2 bands
  = 120 x 2 min epochs

* No strong transient candidates
* Some source association problems; centroids can shift slightly due to ionosphere etc.

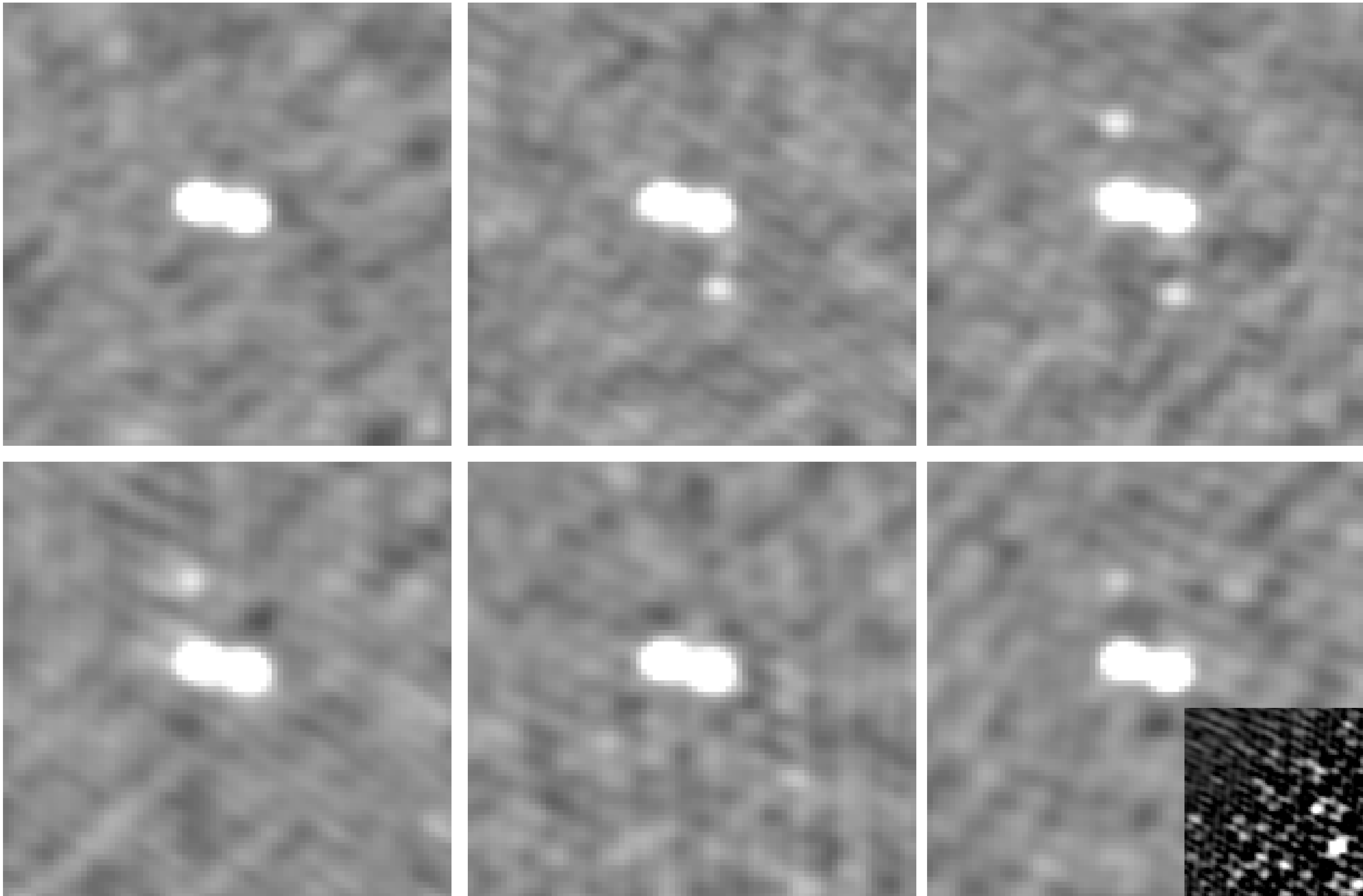


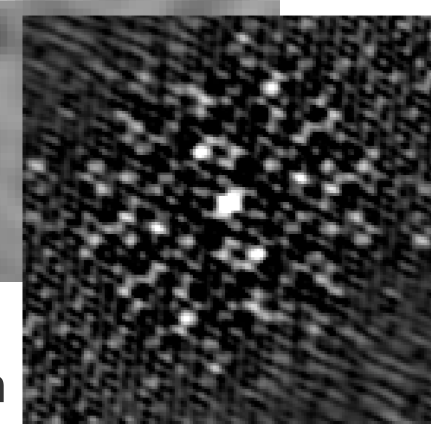
An ideal low DM strip

Pietka

Artefacts...

Pietka





Synthesized beam