ASTRON

Netherlands Institute for Radio Astronomy

LOFAR MSSS

Multifrequency Snapshot Sky Survey

M*S*S*S

MULTIFREQUENCY SNAPSHOT SKY SURVEY

George Heald (MSSS Project Leader)
(on behalf of the MSSS Team)

LOFAR Data School, 20/11/2014

LOFAR

ASTRON is part of the Netherlands Organisation for Scientific Research (NWO)

Outline

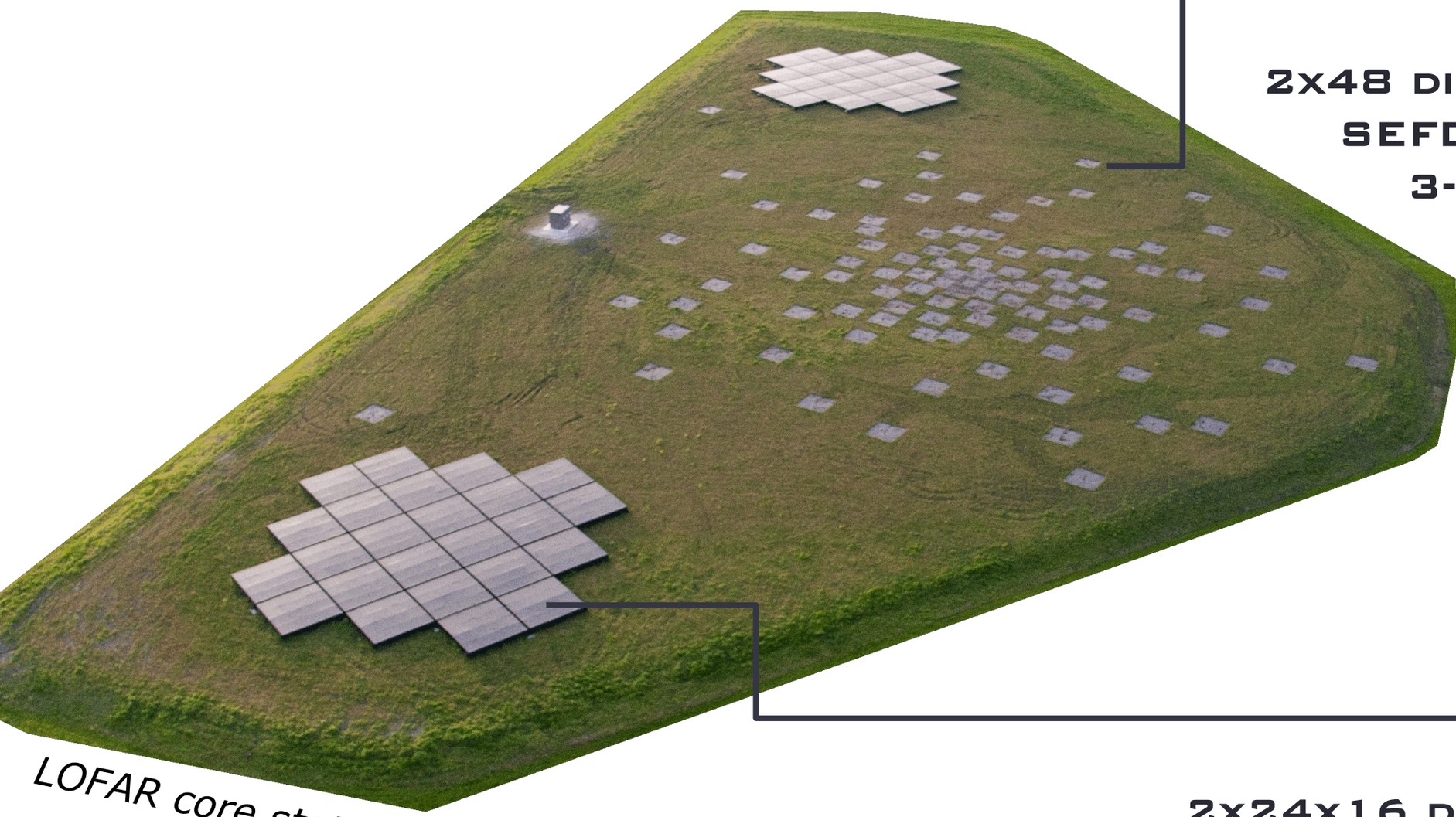
- Brief LOFAR overview
- MSSS motivation & setup
- MSSS science themes
- Initial MSSS results
- MSSS / GLEAM synergy

Thanks to the MSSS Team!

Björn Adebahr, Mike Bell, Laura Bîrzan, Annalisa Bonafede, Justin Bray, Rene Breton, Jess Broderick, Ger de Bruyn, Therese Cantwell, Dario Carbone, Patti Carroll, Yvette Cendes, Alex Clarke, Judith Croston, Soobash Daiboo, Francesco De Gasperin, Emilio Enriquez, Richard Fallows, Chiara Ferrari, Jon Gregson, Martin Hardcastle, Jeremy Harwood, Tom Hassall, Volker Heesen, Andreas Horneffer, Alexander van der Horst, Marco Iacobelli, Vibor Jelic, David Jones, Wojciech Jurusik, Georgi Kokotanekov, Giulia Macario, Poppy Martin, Carlos Martinez, John McKean, Leah Morabito, David Mulcahy, Ronald Nijboer, Błażej Nikiel-Wroczyński, Andre Offringa, Emanuela Orrú, V.N. Pandey, Gosia Pietka, Roberto Pizzo, Mamta Pommier, Peeyush Prasad, Luke Pratley, Chris Riseley, Huub Röttgering, Antonia Rowlinson, Pepe Sabater, Anna Scaife, Bart Scheers, Kati Sendlinger, Aleksandar Shulevski, Charlotte Sobey, Carlos Sotomayor, Adam Stewart, Andra Stroe, John Swinbank, Cyril Tasse, Bas van der Tol, Jonas Trüstedt, Sander ter Veen, Sjoert van Velzen, Reinout van Weeren, Wendy Williams, Michael Wise

LOFAR overview

- Highly flexible digital beamforming ("beams for bandwidth")

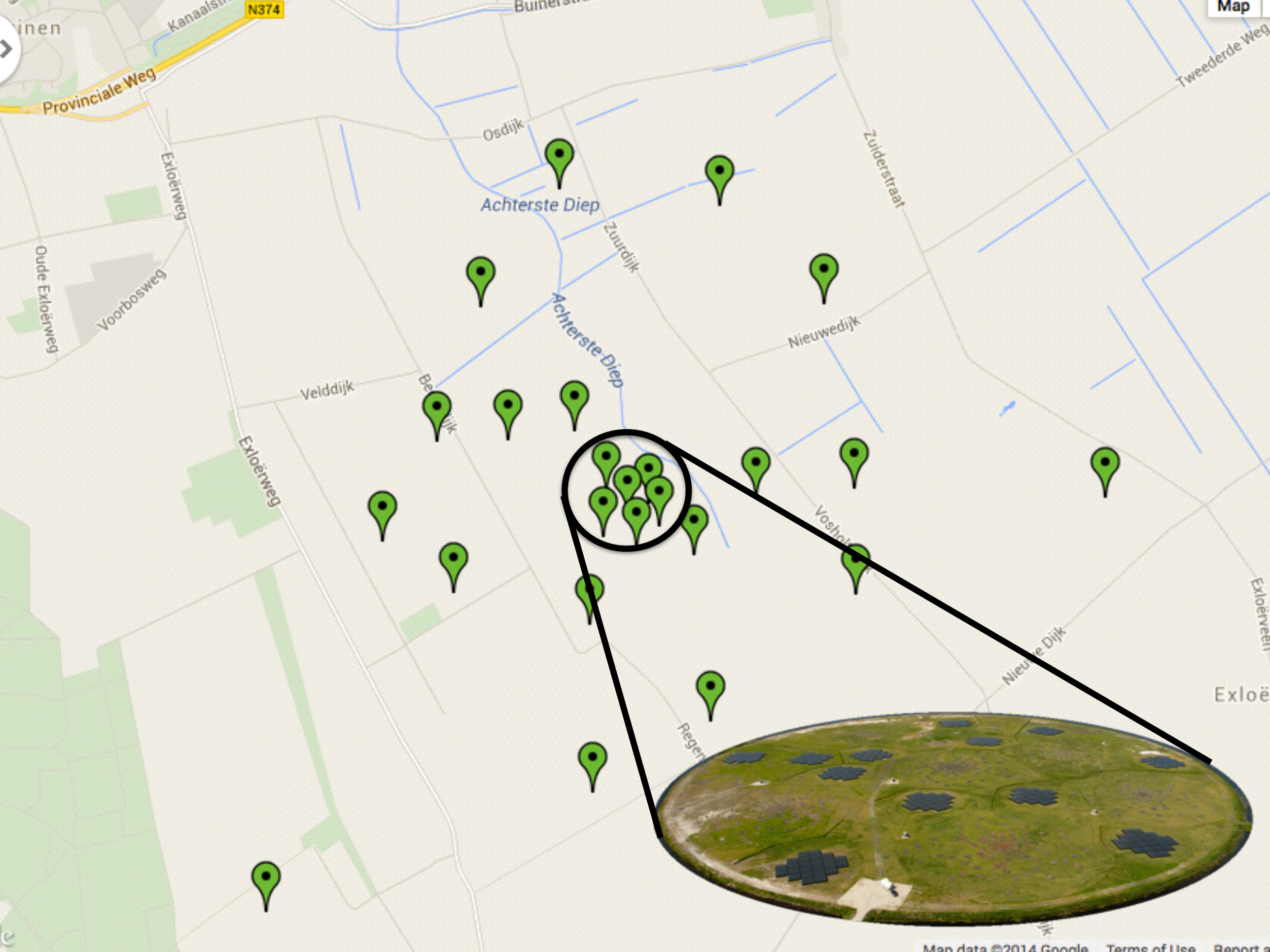


LOFAR LBA

10-80 MHz
2x48 dipole pairs / station
SEFD 25 kJy at 60 MHz
3-40 Deg FoV (FWHM)

LOFAR HBA

110-250 MHz
2x24x16 dipole pairs / station
SEFD 2 kJy at 150 MHz
1-5 Deg FoV (FWHM)


Map
N374
Kanaalstraat
Provinciale Weg
Buinerstraat
Tweederde Weg
Osdijk
Zuiderstraat
Exloërweg
Achterste Diep
Zuurdijk
Oude Exloërweg
Voorbosweg
Nieuwedijk
Velddijk
Voshol
Nieuwe Dijk
Regen
Exloë

bing exloo

Sign in

Road | Aerial | Traffic | Fullscreen | Print | Share

~120 km
Borkum
Norden
Esens
Wangerland
Wittmund
Wilhelmshaven
Bremen
Krummhörn
Aurich
Nordenham
Wiesmoor
Zetel
Varel
Emden
Ihlow
Moormerland
Delfzijl
Leer
Westerstede
Groningen
Leeuwarden
Weener
Bad Oldenburg
Zwischenahn
Harlingen
Roden
Drachten
Papenburg
Wardenburg
Sneek
Friesoythe
Assen
Heerenveen
Dörpen
Großenkneten
Den Helder
Wieringen
Wolvega
Cloppenburg
Schagen
IJsselmeer
Emmen
Haren
Enkhuizen
Emmeloord
Hoogeveen
Meppen
Löningen
Vechta
Bergen
Hoorn
Meppel
Lohne
Haselünne
Diepholz
Alkmaar
Hardenberg
Castricum
Purmerend
Lelystad
Kampen
Zwolle
Lingen
Damme
IJmuiden
Nordhorn
Amsterdam
Almere
Harderwijk
Heerde
Bramsche
Recke
Haarlem
Epe
Rijssen
Amstelveen
Deventer
Hengelo
Rheine
Osnabrück
Hoofddorp
Hilversum
Ermelo
Goor
Ibbenbüren
Melle
Leiden
Amersfoort
Apeldoorn
Enschede
Steinfurt
Lengerich
The Hague
Utrecht
Zutphen
Ahaus
Greven
Zoetermeer
Ede
Naaldwijk
Gouda
Arnhem
Houten
Doetinchem
Münster
Warendorf
Rotterdam
Coesfeld
Gütersloh
Tiel
Spijkenisse
Emmerich
Bocholt
Borken
Dordrecht
Nijmegen
Kleve
Dülmen
Rees
Rheda-Wiedenbrück
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MSSS: LOFAR's first imaging survey

Goals: obtain broadband sky model, shakedown LOFAR operations

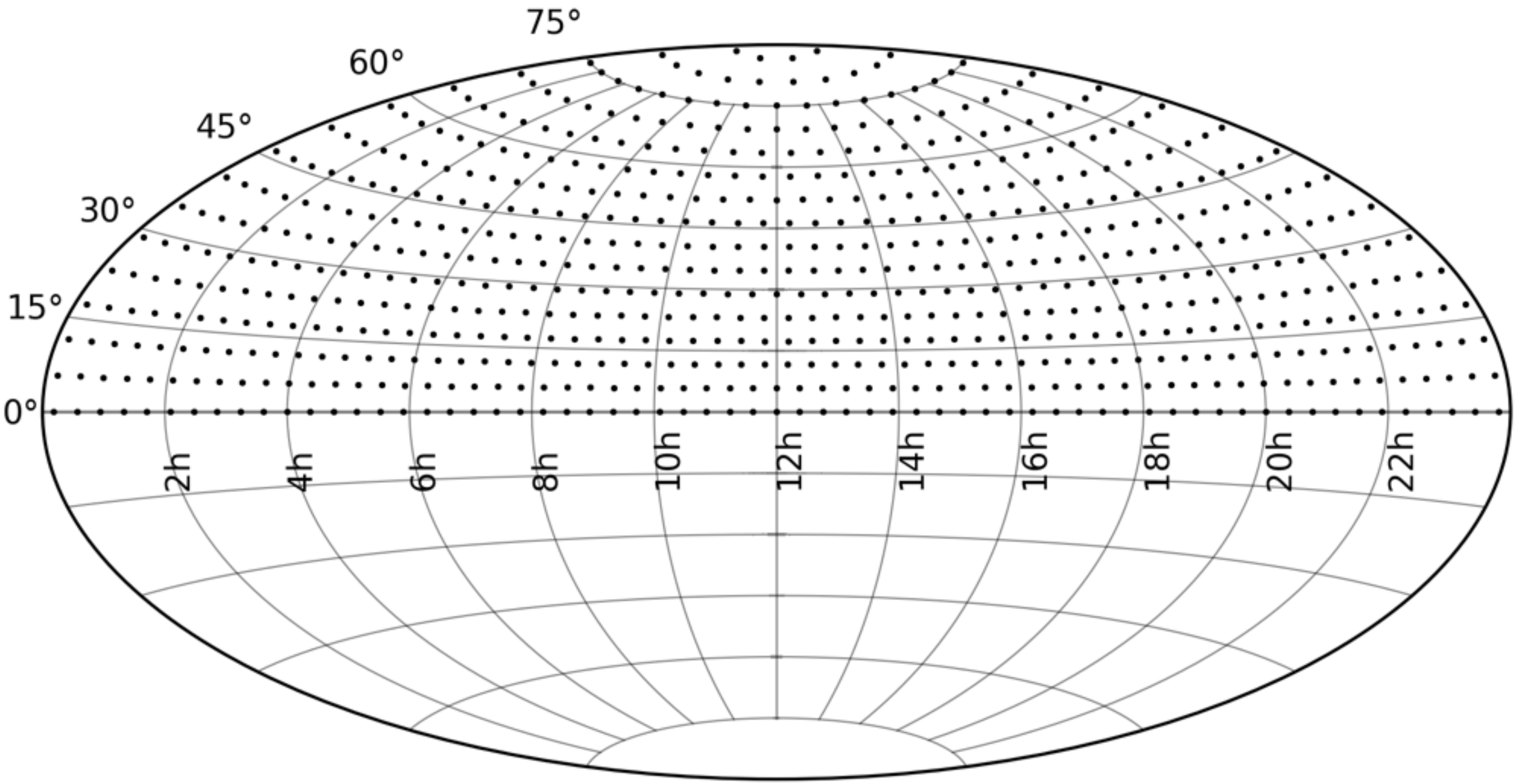
MSSS-LBA

Frequency: 30-75 MHz
(8 x 2 MHz bands)
Resolution: ≤100 arcsec
Sensitivity: ≤15 mJy/beam
Area: 20,000 square degrees
Number of Fields: 660
Simultaneous ~10° beams: 5
Test observations resuming

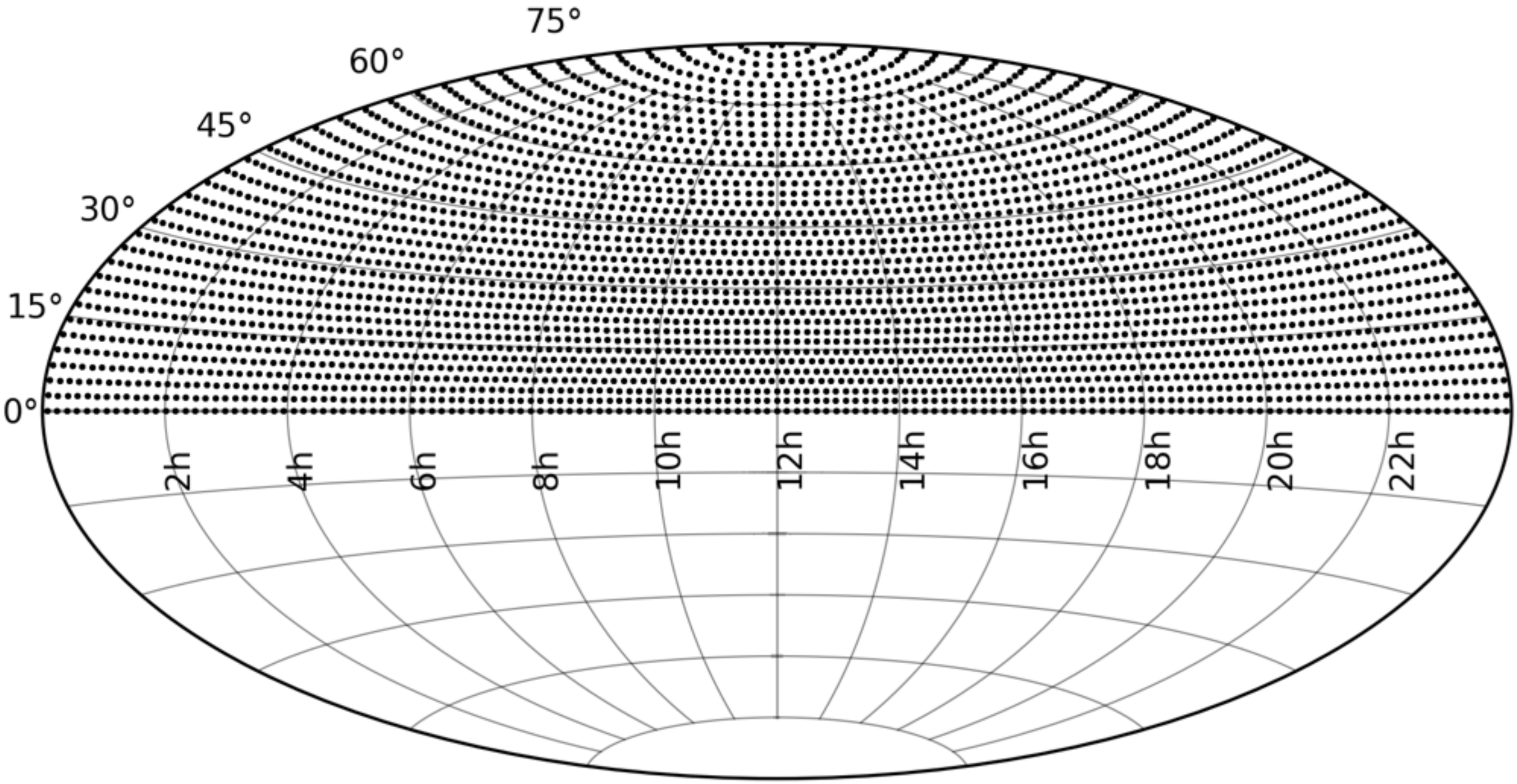
MSSS-HBA

Frequency: 120-160 MHz
(8 x 2 MHz bands)
Resolution: ≤120 arcsec
Sensitivity: ≤5 mJy/beam
Area: 20,000 square degrees
Number of Fields: 3616
Simultaneous ~4° beams: 6
Observations 100% complete

LBA Pointings

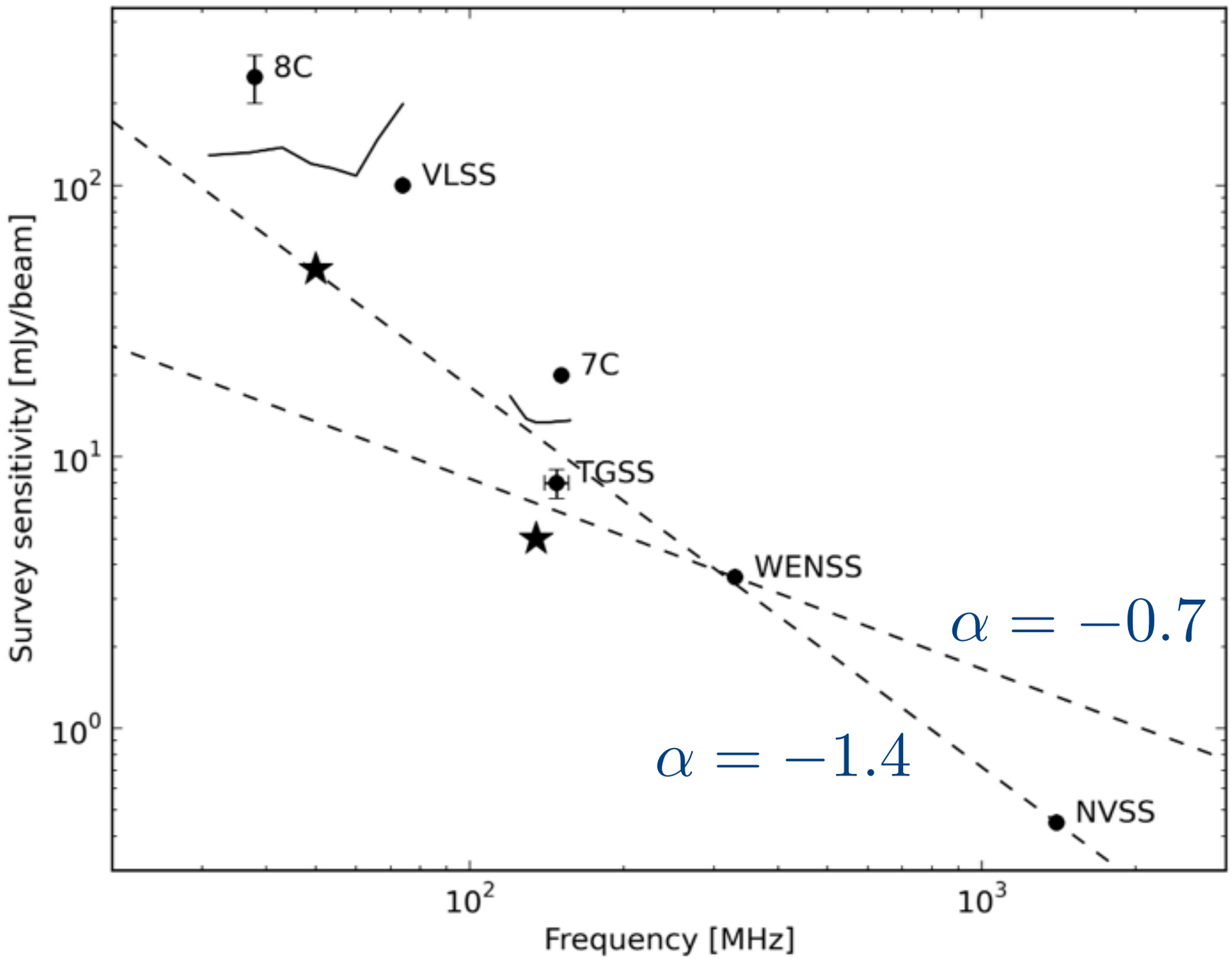


HBA Pointings



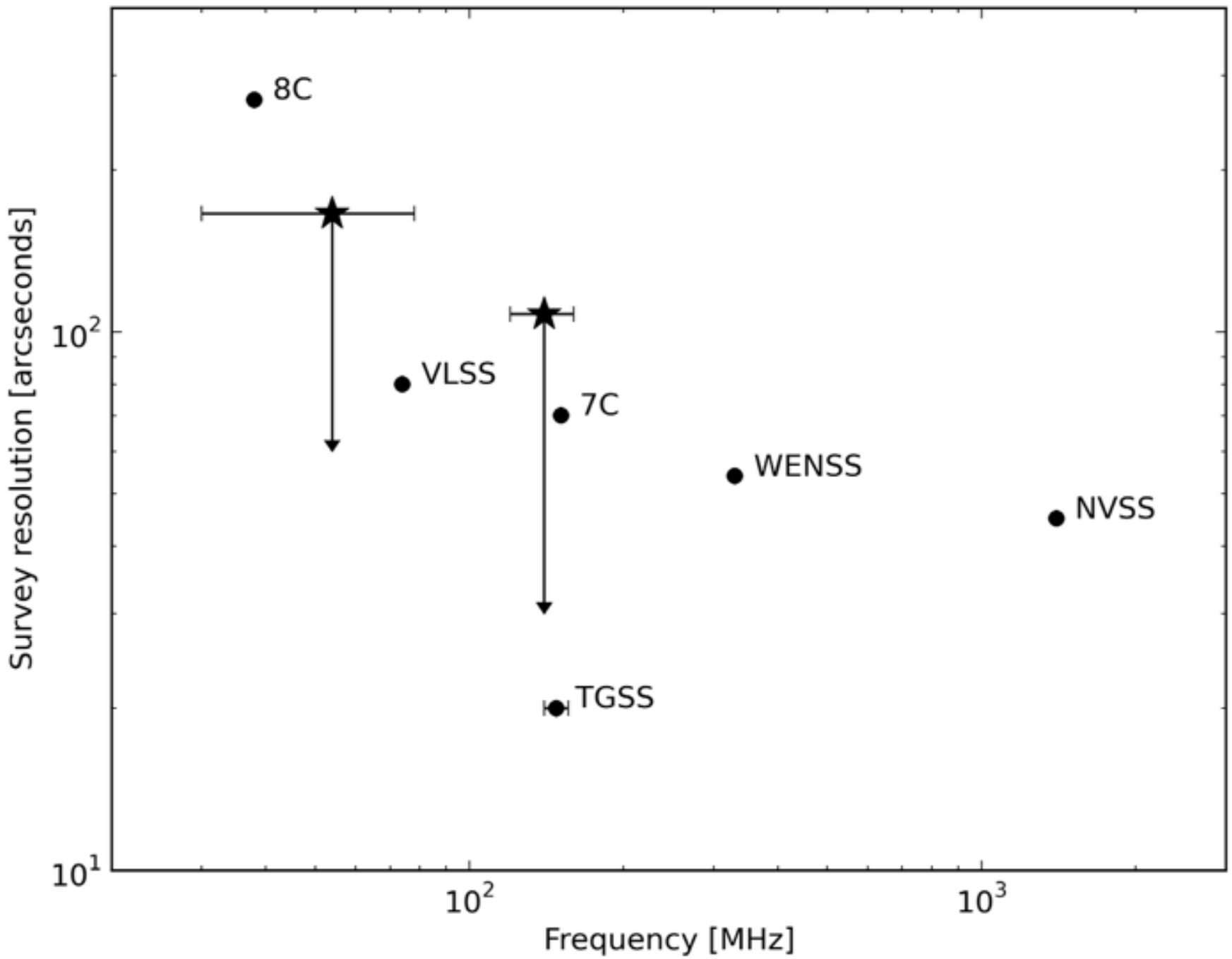
MSSS vital stats

- Highly complementary to GLEAM: together these surveys will provide a truly all-sky interferometric radio catalog!

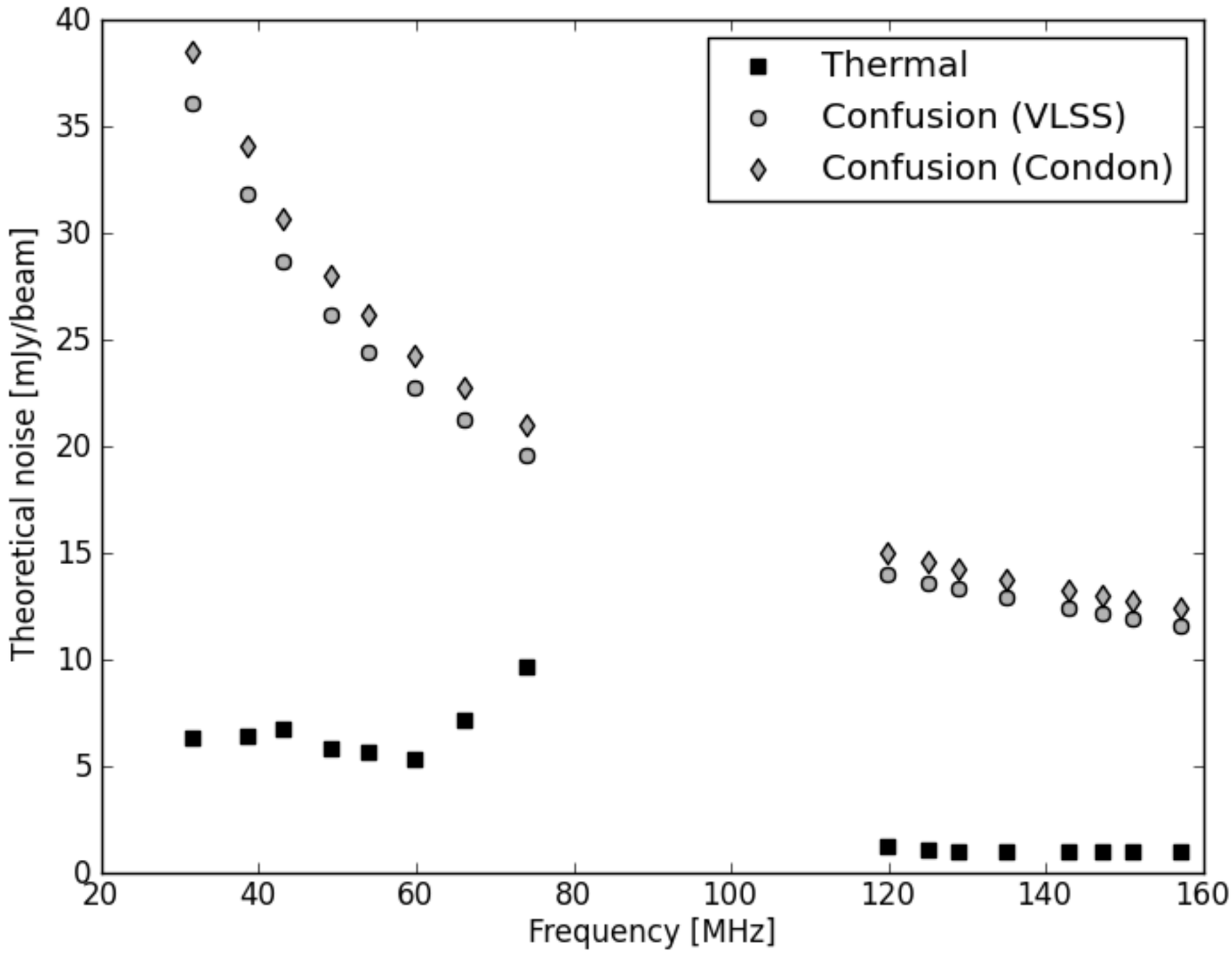


MSSS vital stats

- Highly complementary to GLEAM: together these surveys will provide a truly all-sky interferometric radio catalog!



Theoretical / confusion noise



MSSS pipeline ➤ LOFAR pipeline

- MSSS identifying proper strategies for early pipeline steps

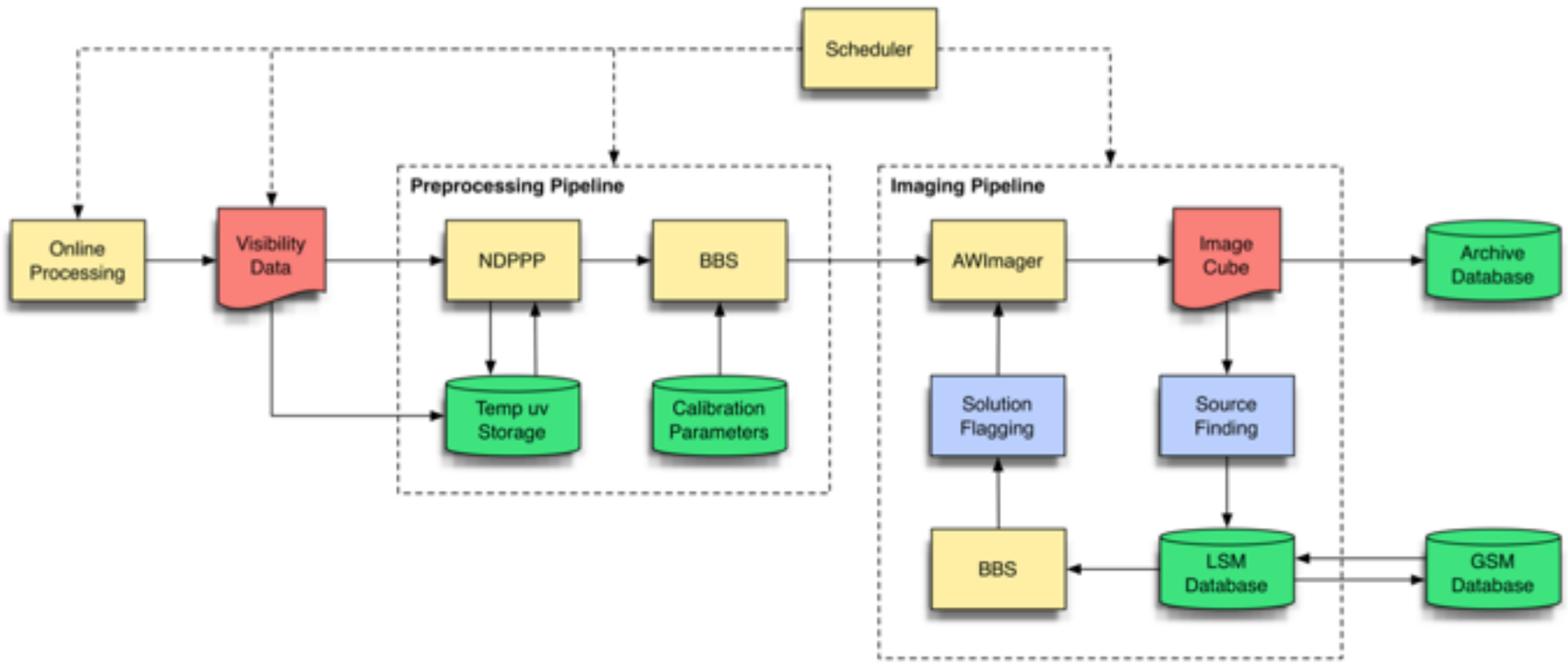
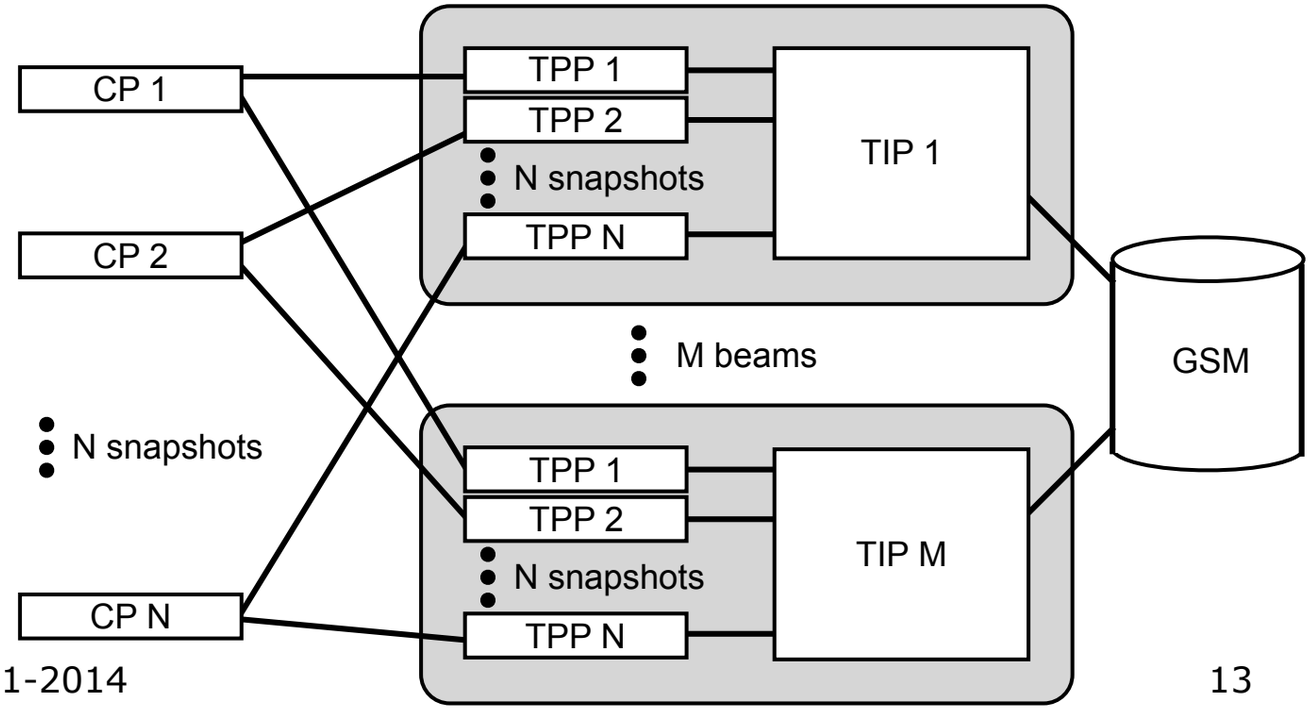
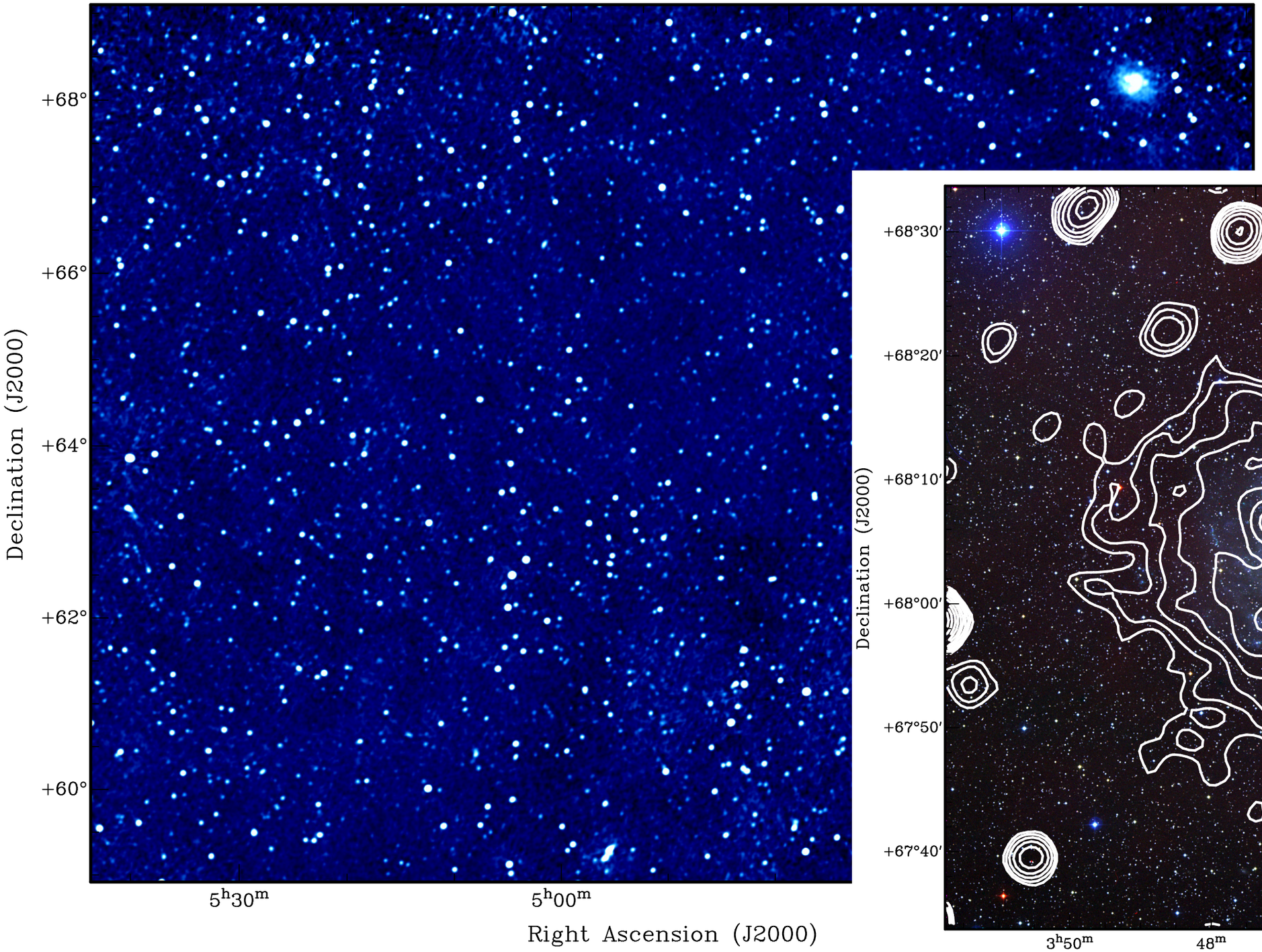


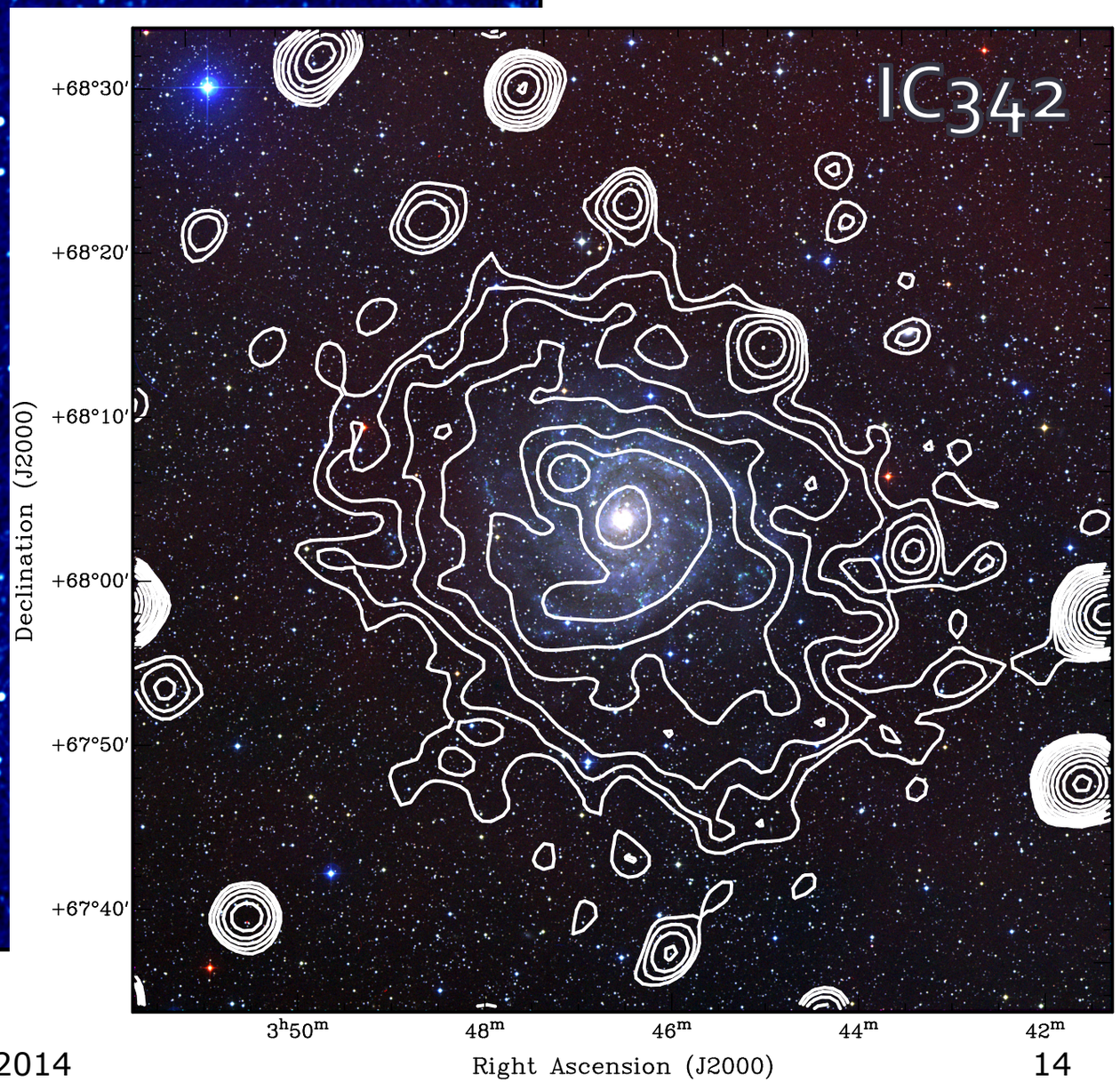
Fig. 12. The LOFAR imaging pipeline presented in schematic form (Heald et al. 2010). See the text for a description of the various software components and the data path.



MSSS mosaics

- Standard imaging product: 100 square degree mosaics, each composed of 10s of individual HBA fields





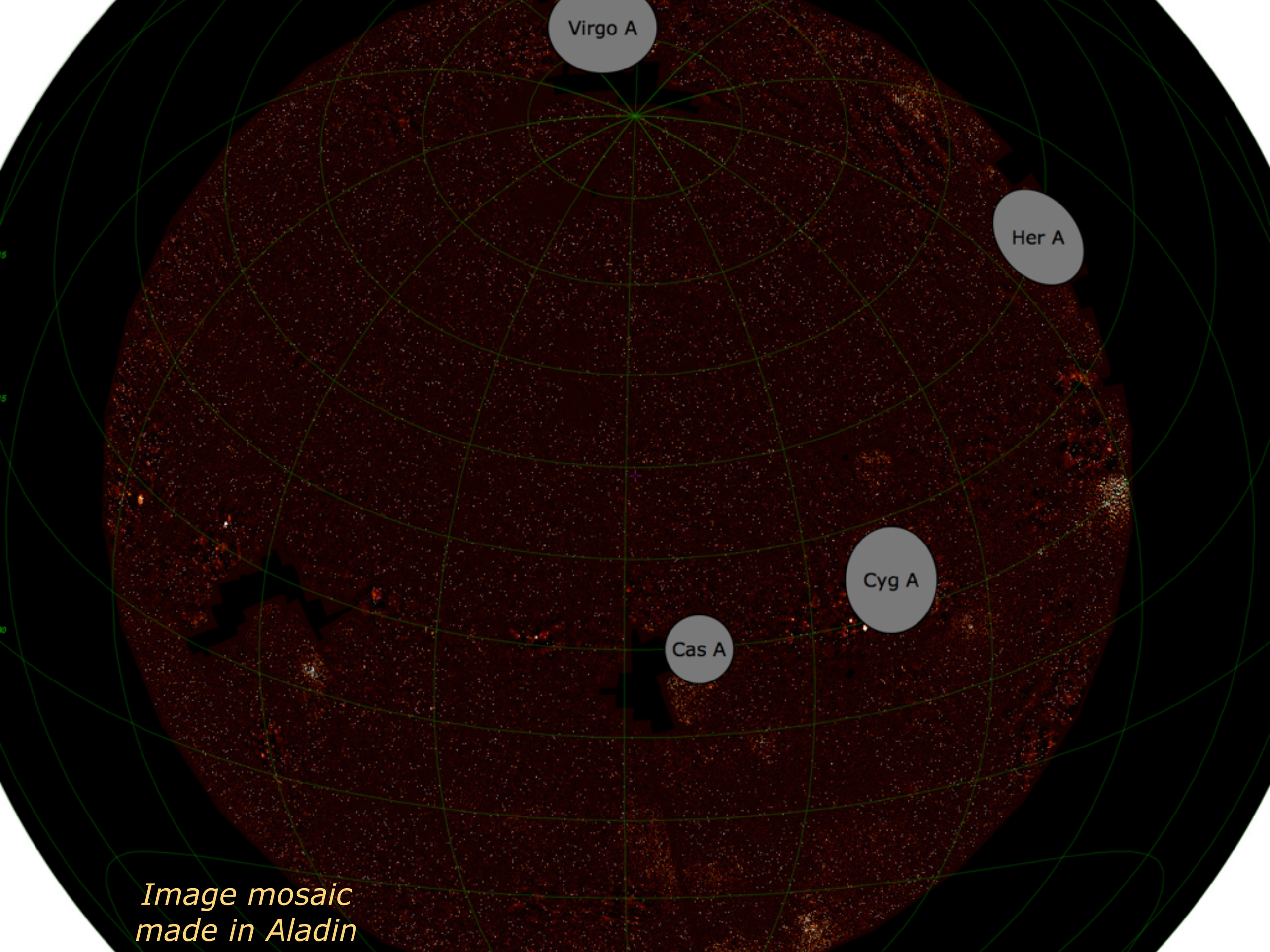
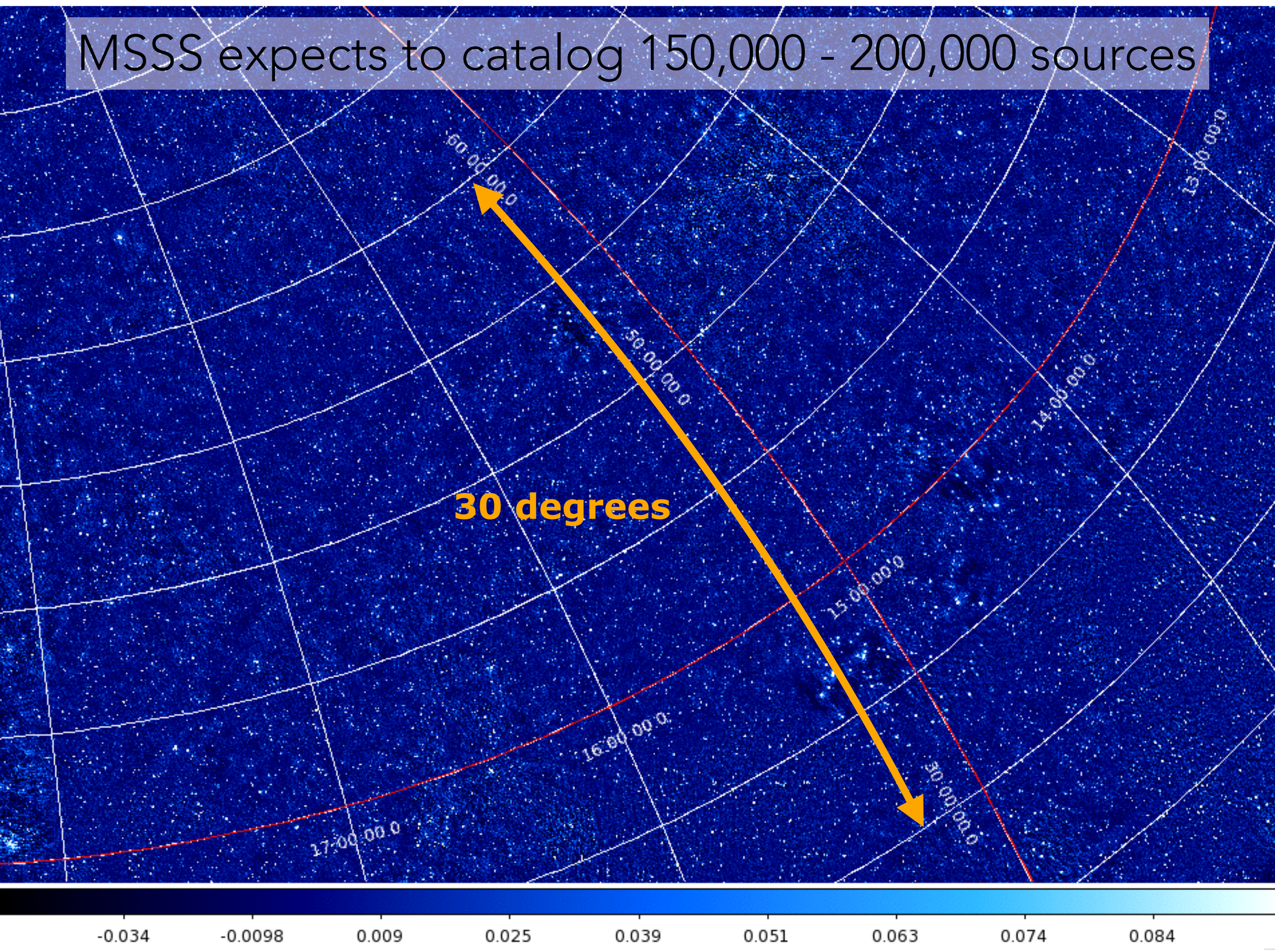


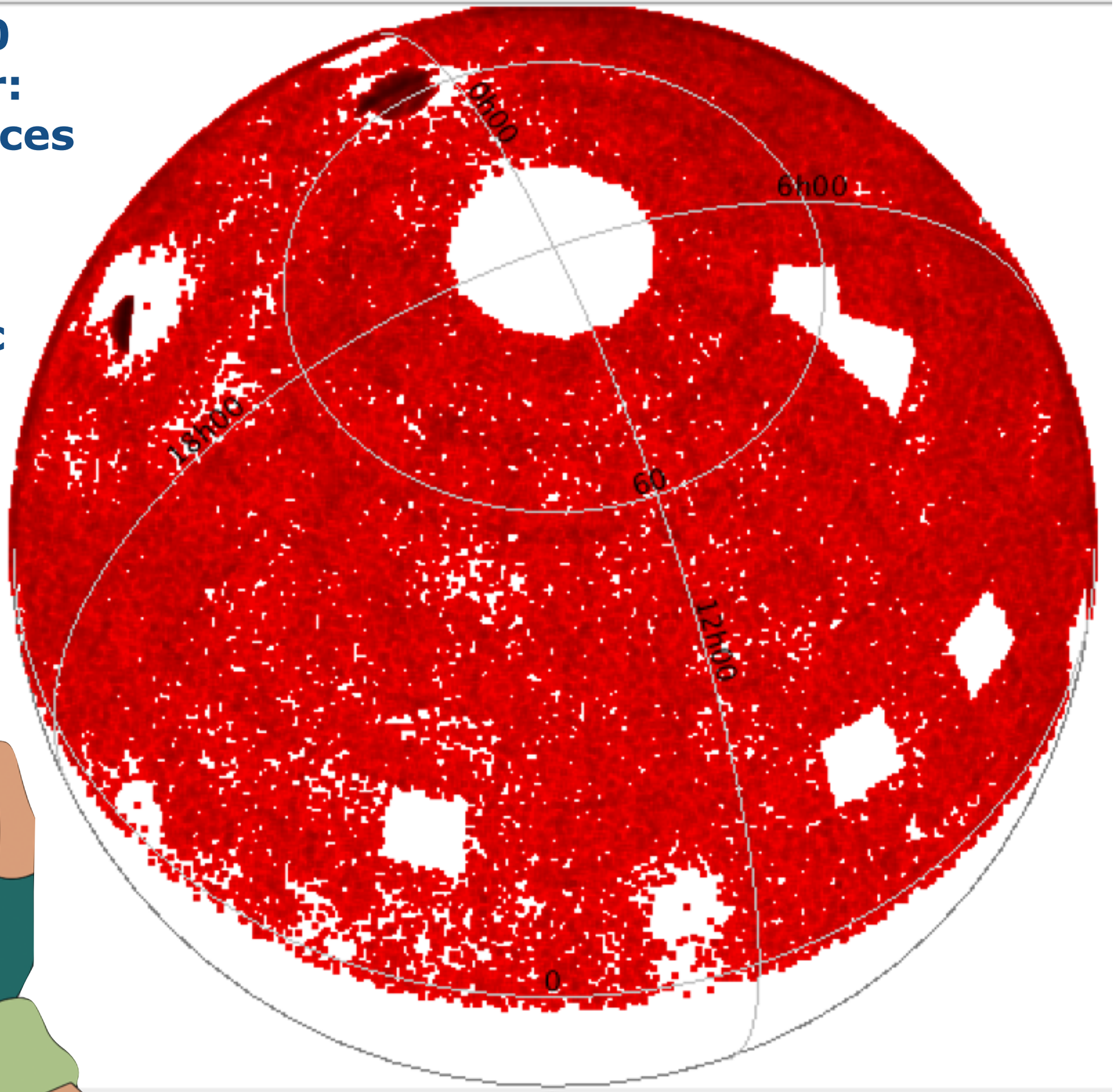
Image mosaic made in Aladin

MSSS expects to catalog 150,000 - 200,000 sources



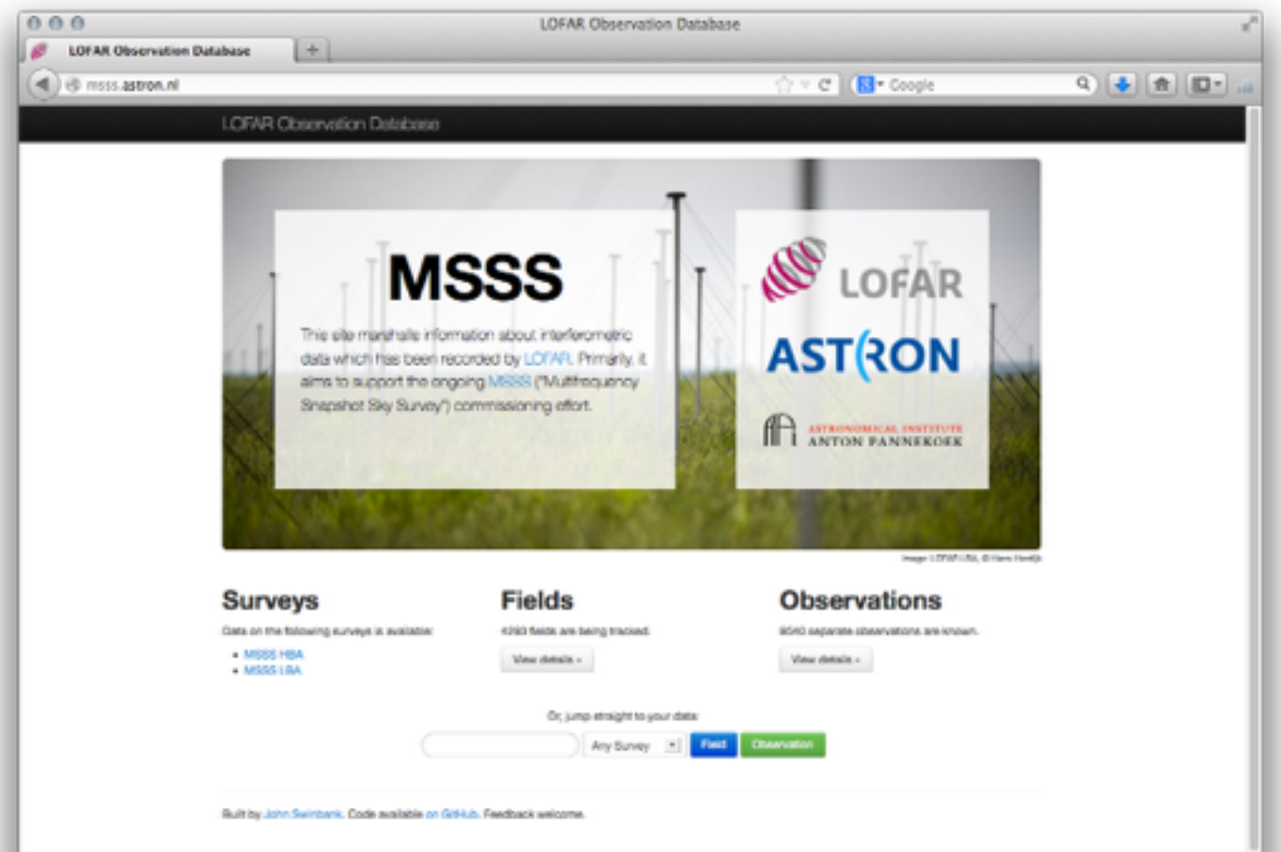
MSSS-HBA V0 catalog so far: 100,920 sources (Alex Clarke)

average ~400/mosaic

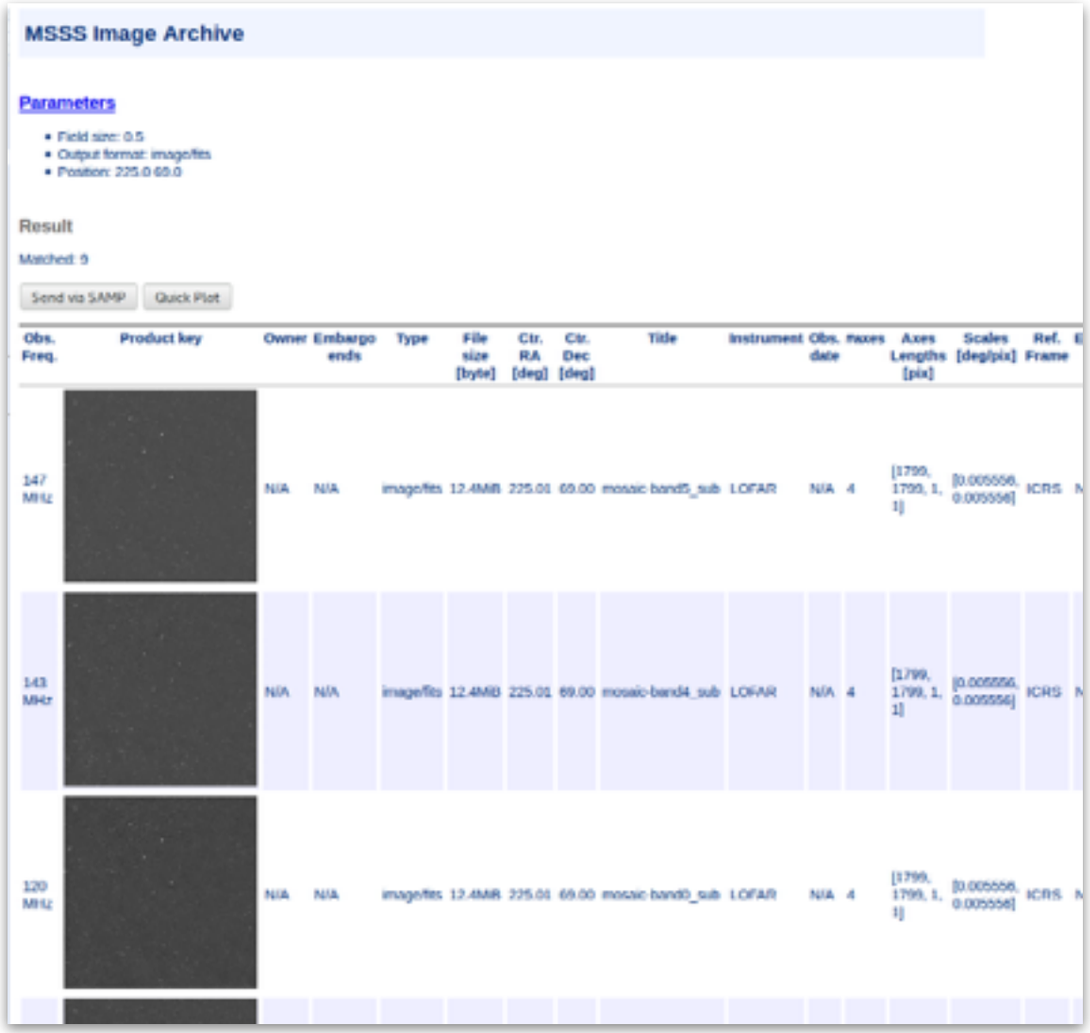


MSSS (VO) Data Portal

- MSSS data products to be available through VO and custom-built postage-stamp/catalog server



John Swinbank



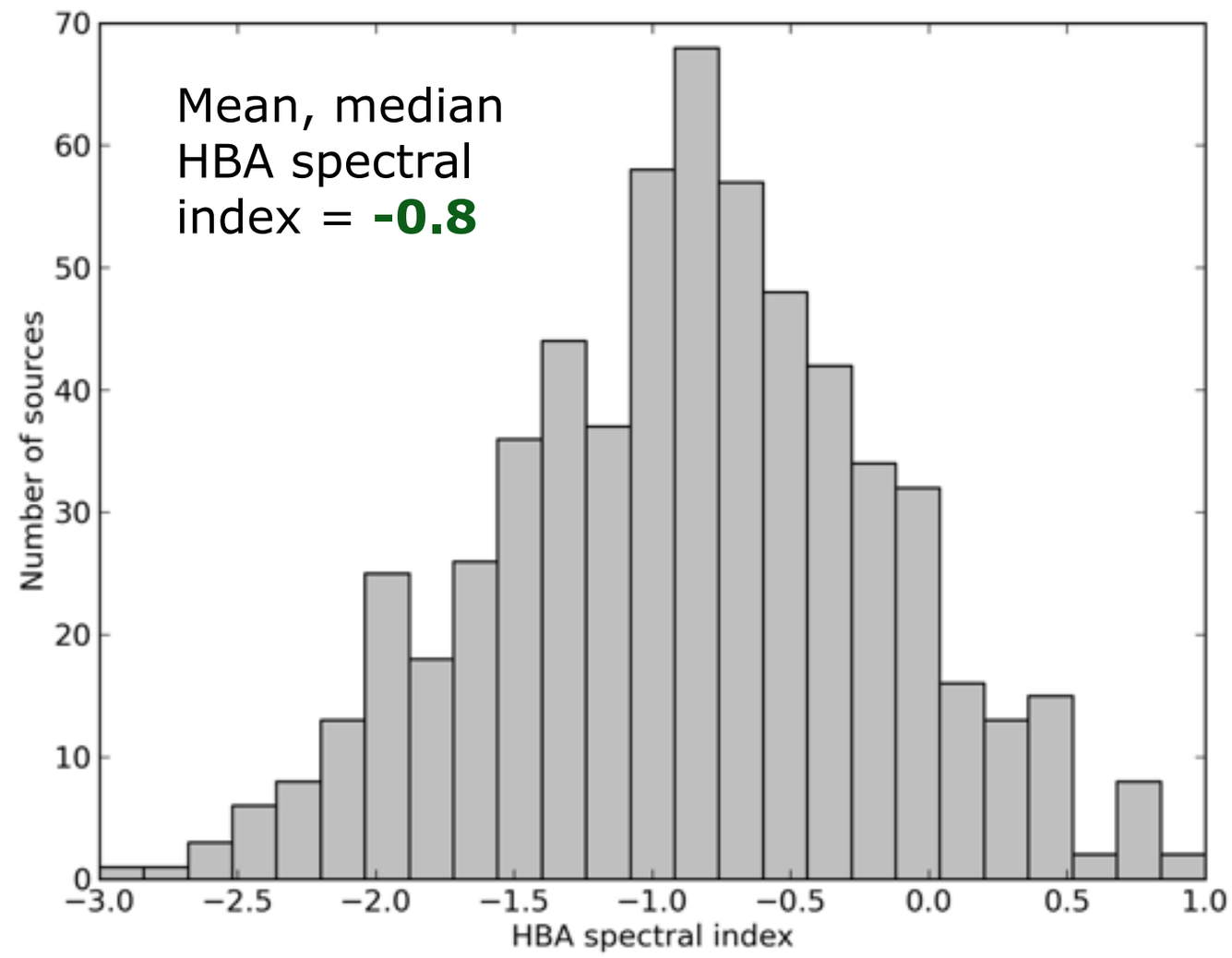
Mike Sipior

http://msss.astron.nl

MSSS spectral indices

- MSSS-HBA allows direct determination of local spectral curvature term (shown here using VO)

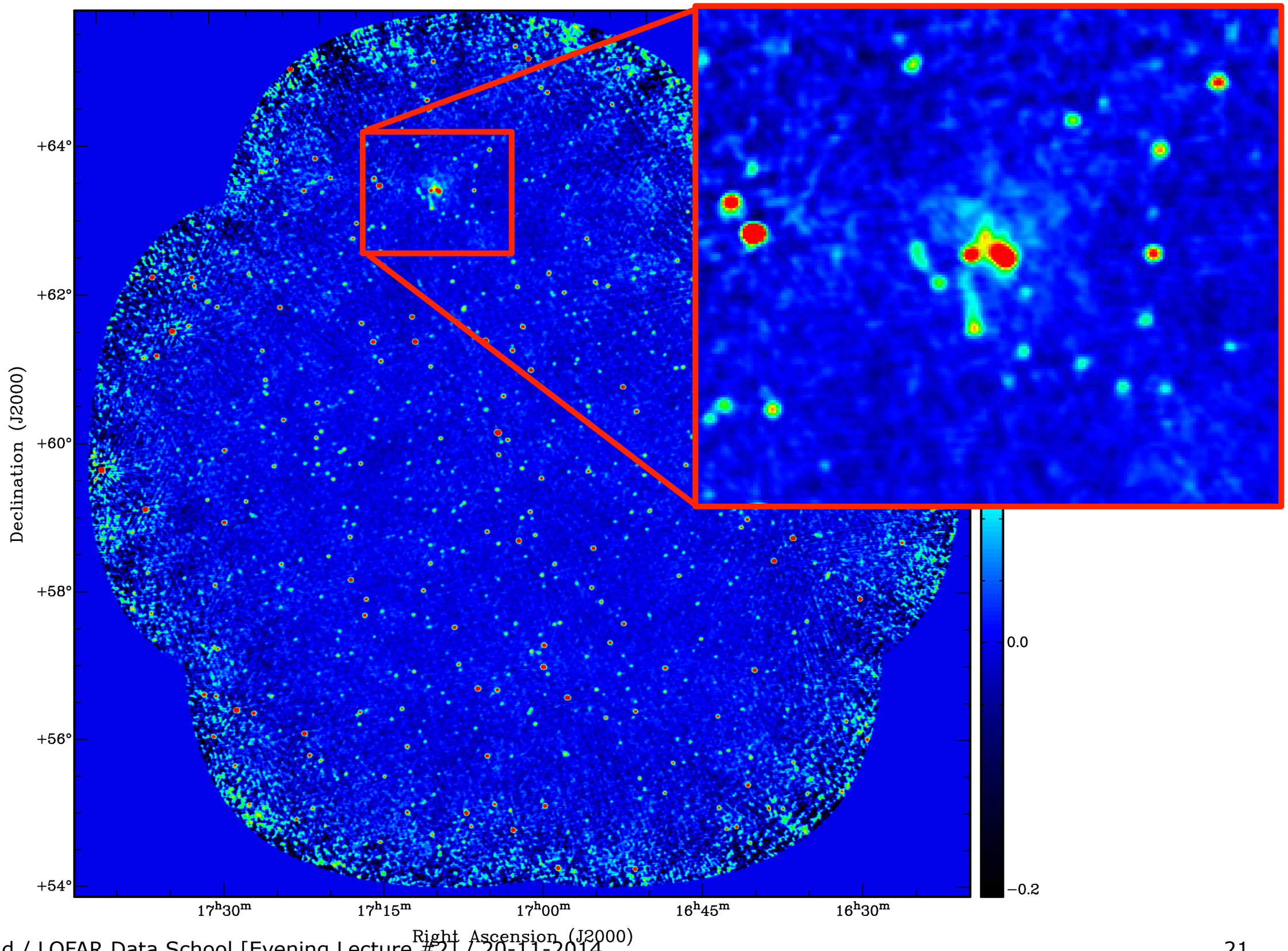
```
import pyvo as vo
import astropy.table as table

# get MSSS MVF
msssURL='http://PUBLIC.SOON'
query = vo.scs.SCSQuery(msssURL)
query.pos = (225.,69.)
query.radius = 10.
t = table.Table.read(query.execute_votable())

# now use the numbers
s120=t['Sint120']

# make plots etc ...
```



Selected MSSS science topics

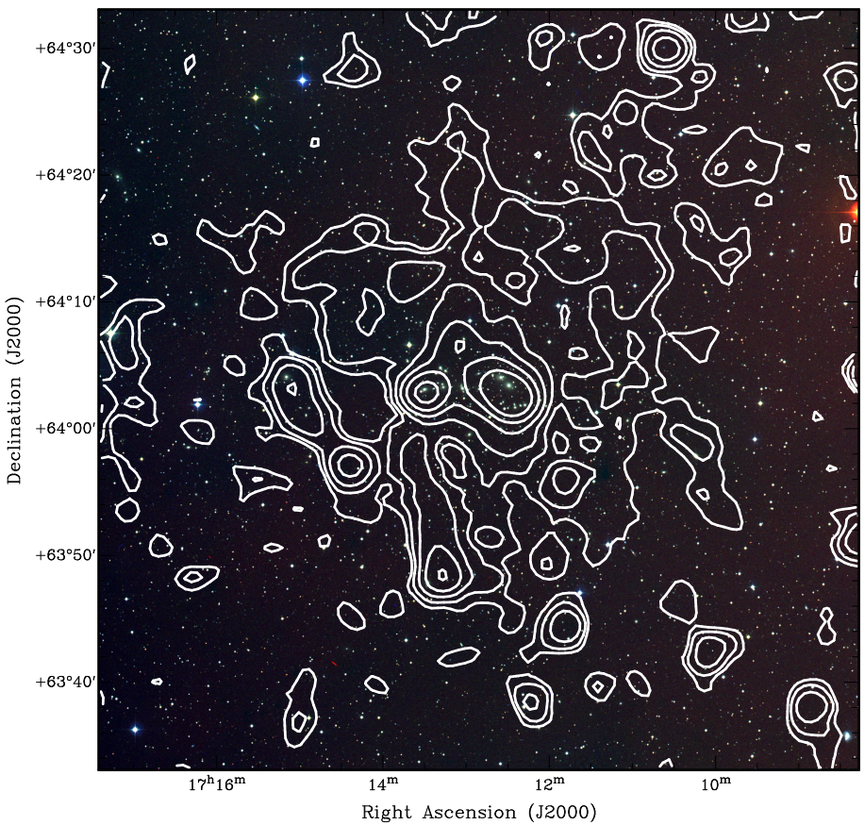
- Diffuse emission from galaxy cluster halos / relics
- Giant radio galaxies
- Supernova remnants
- Polarization and high angular resolution reprocessing
- Transients

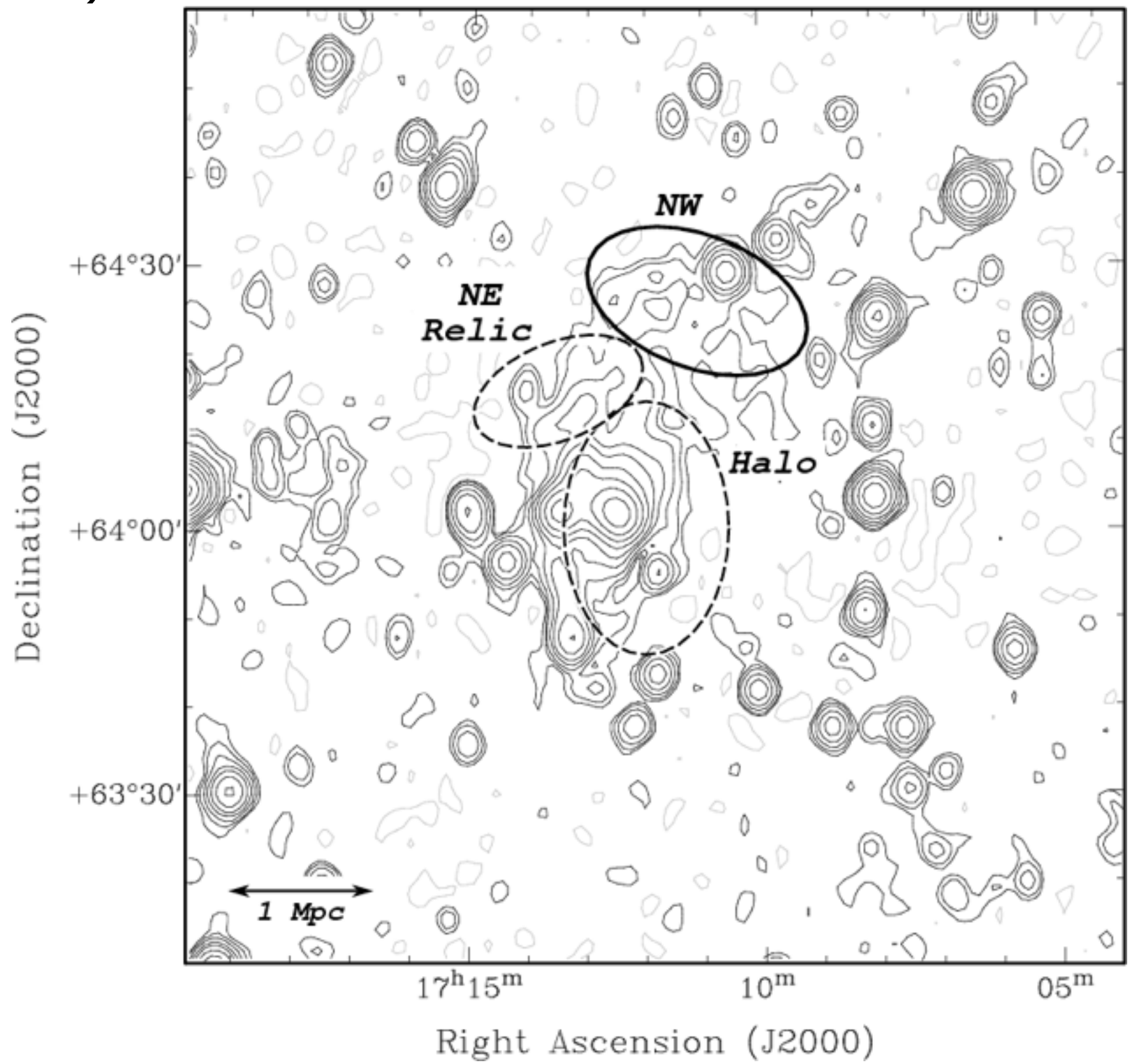
One of the first MSSS-HBA mosaics



MSSS-HBA: Abell 2255

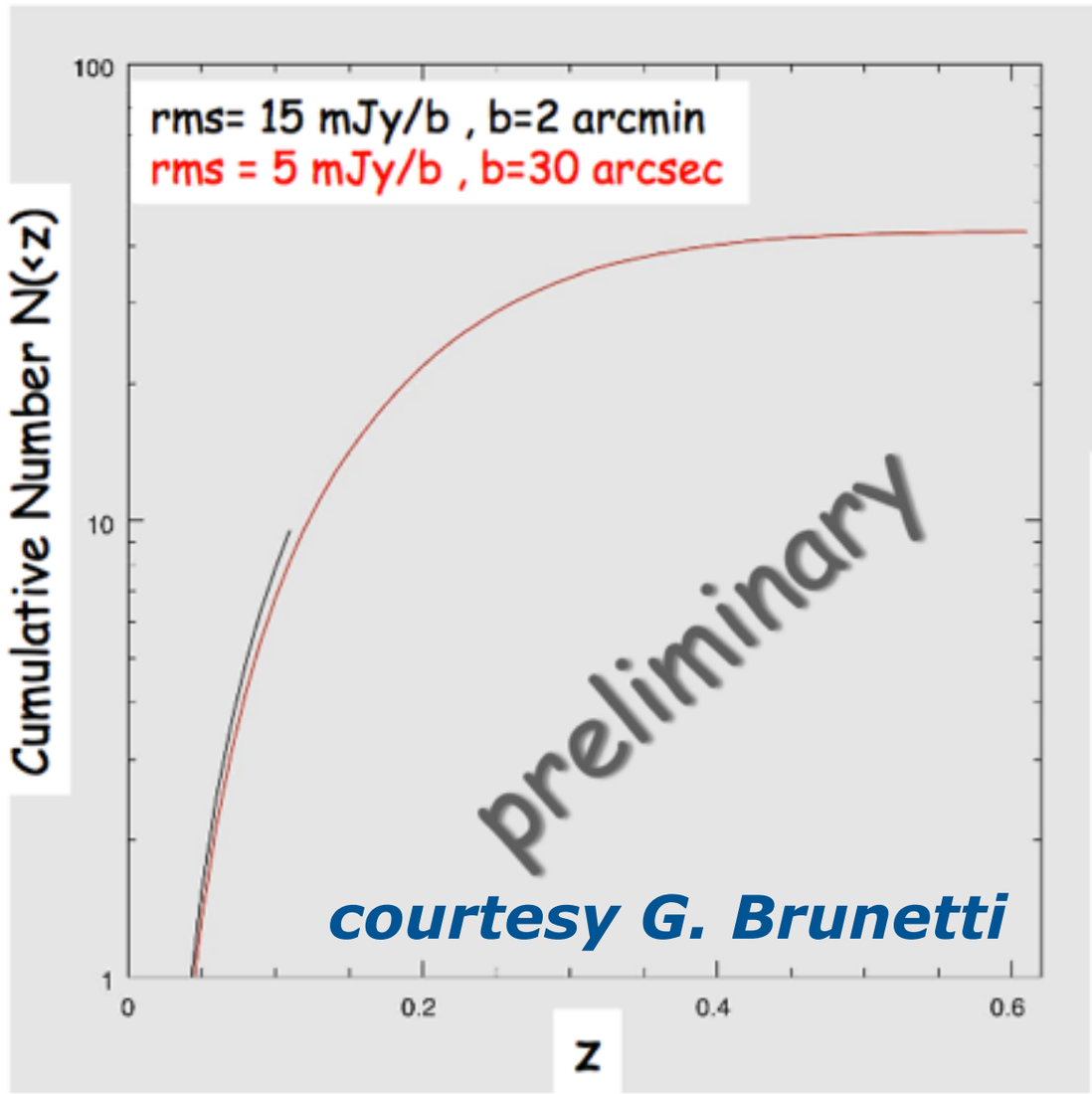
- cf Pizzo & de Bruyn (2009)
  WSRT, 150 MHz



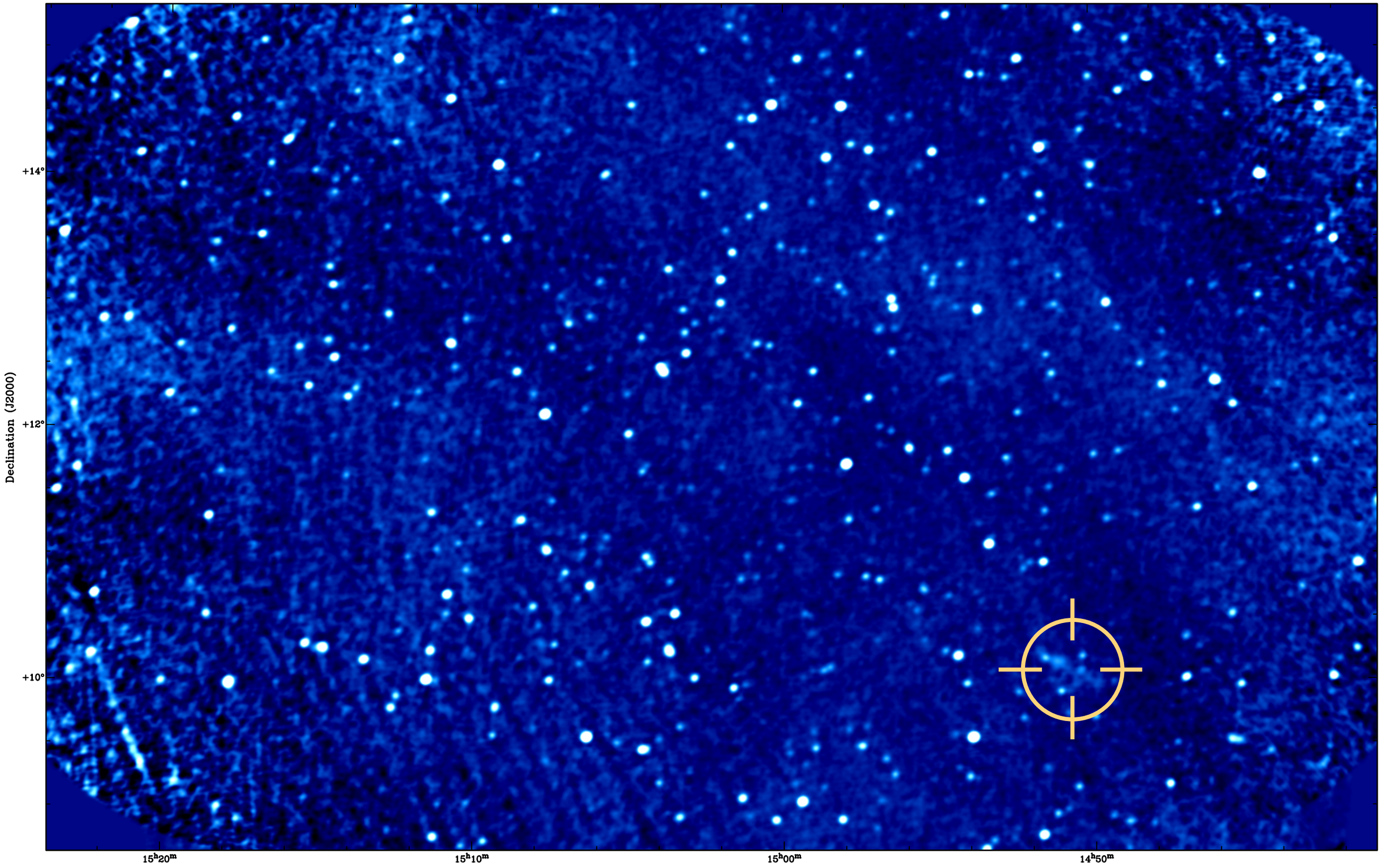


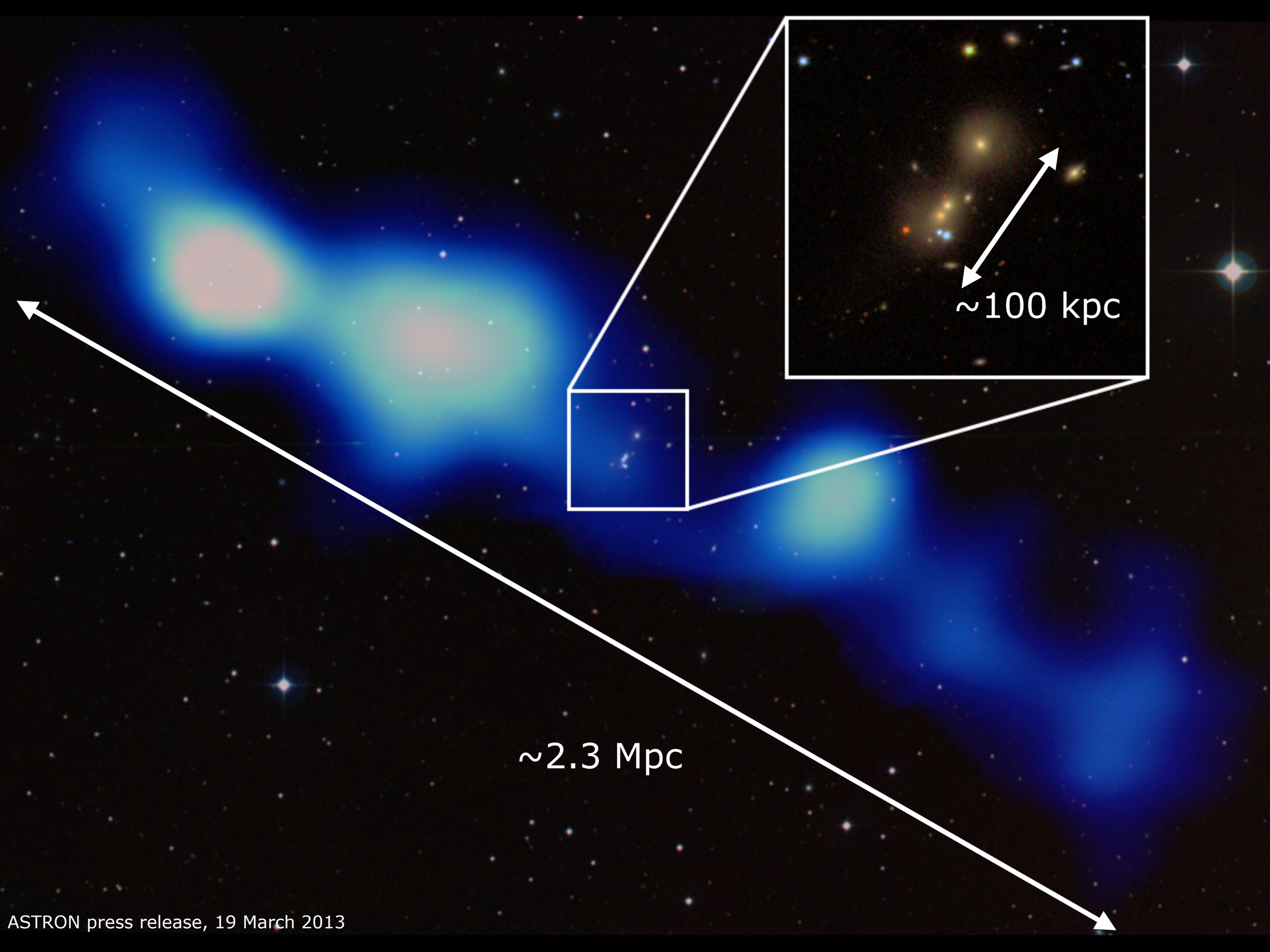
MSSS-HBA: prospects

- Higher resolution provides an interesting early view (before Tier 1)
  - Known systems (e.g. detected all strong AGN feedback systems in Bîrzan, Rafferty samples; Kokotanekov et al in prep)
  - New systems (effective search at higher resolution)



Another (early) MSSS-HBA mosaic

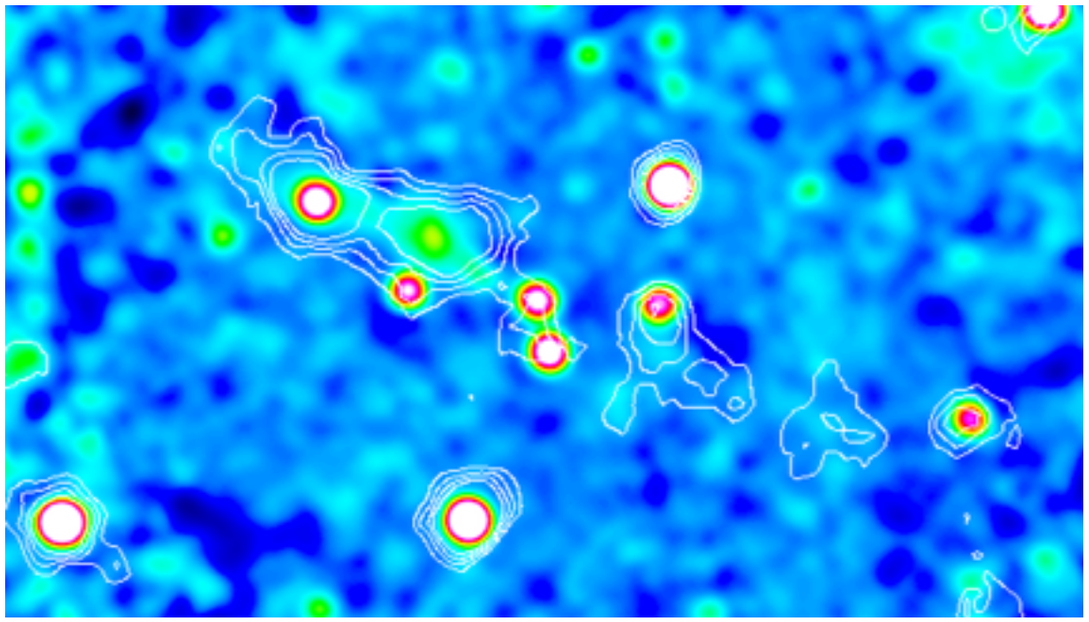


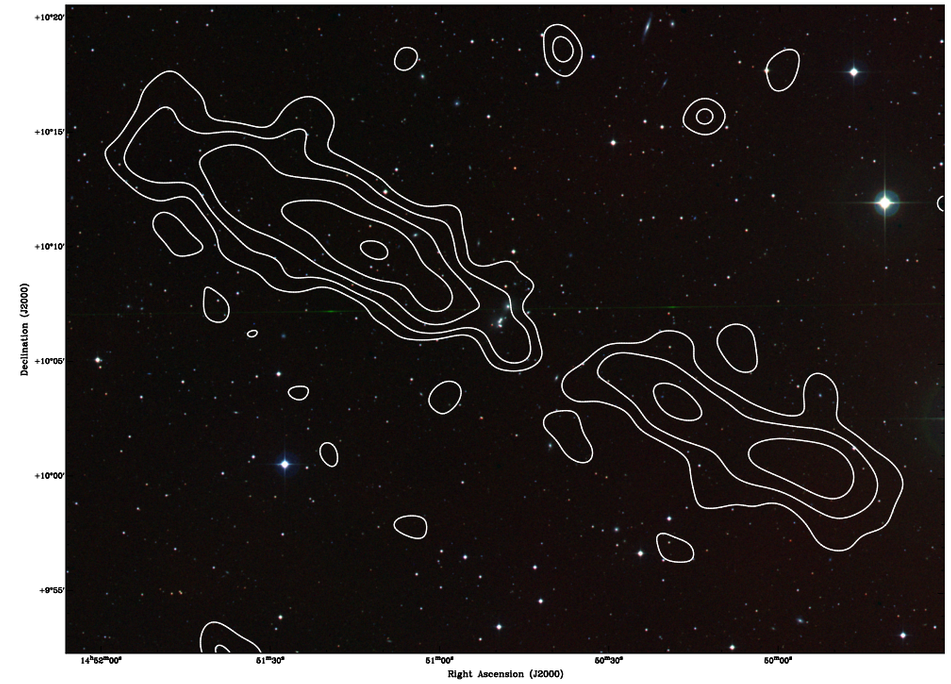


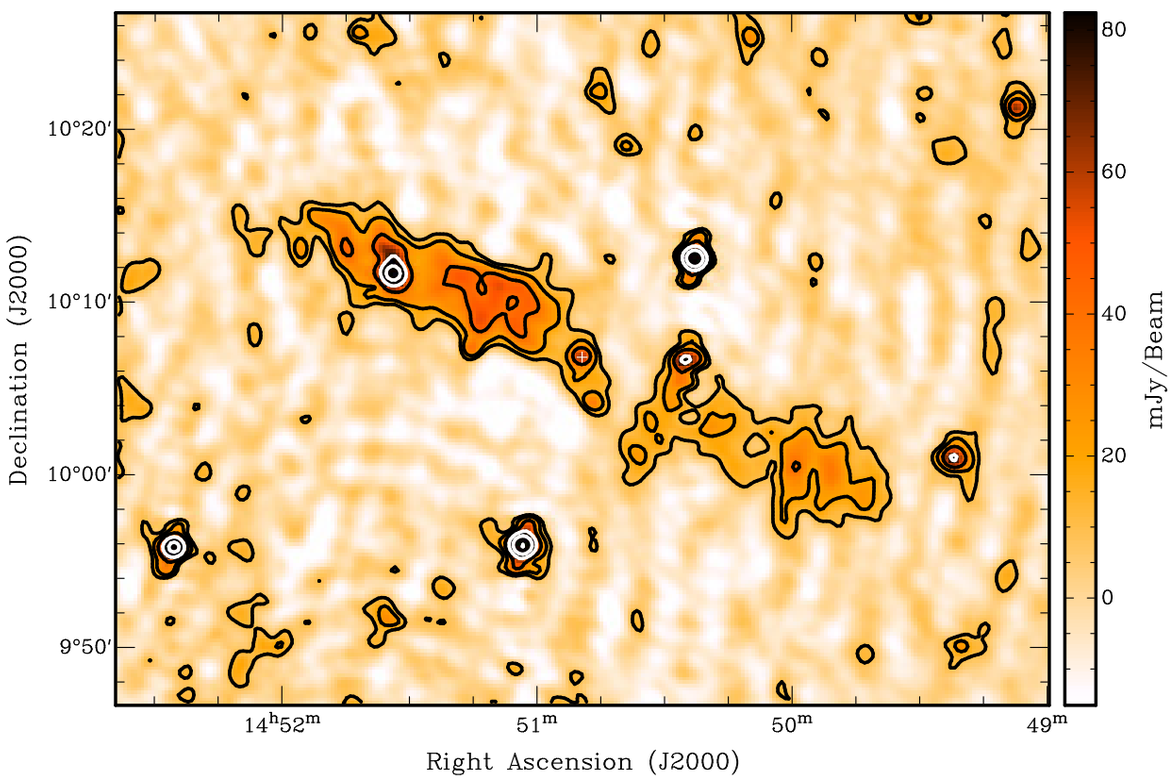
ASTRON press release, 19 March 2013

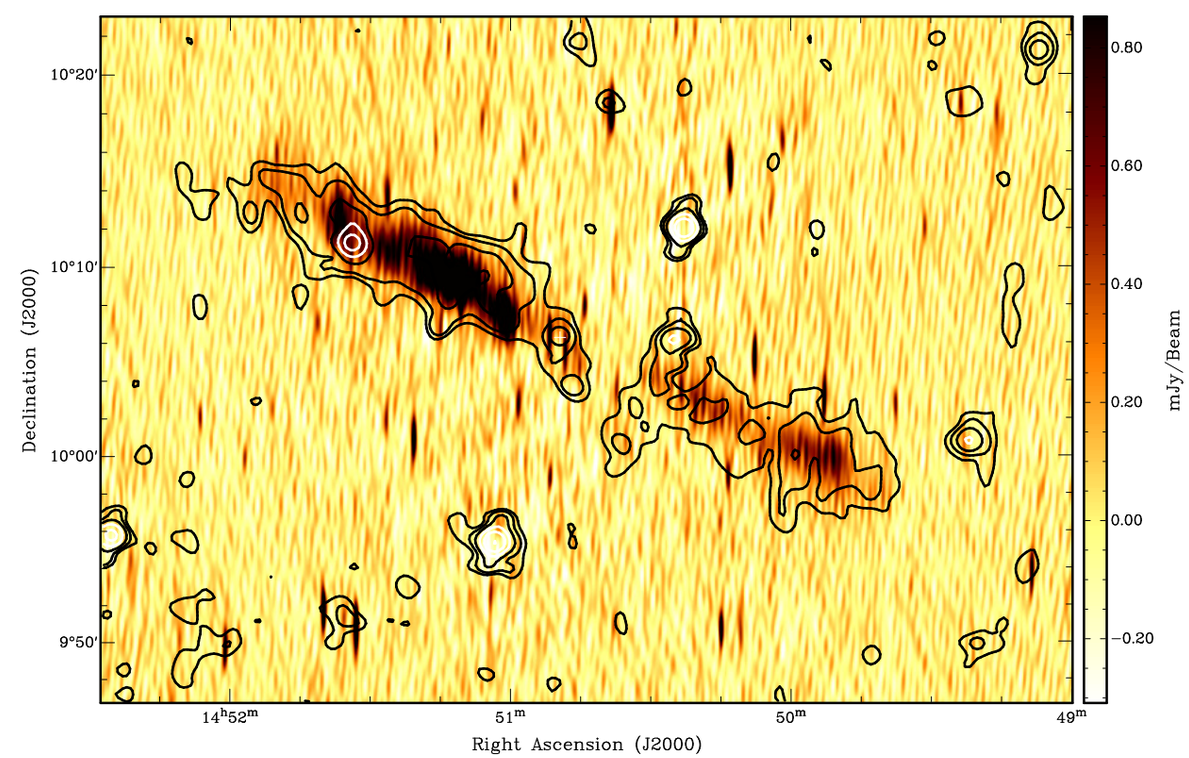
MSSS-discovered GRG

- Followup observations with WSRT, GMRT, LOFAR





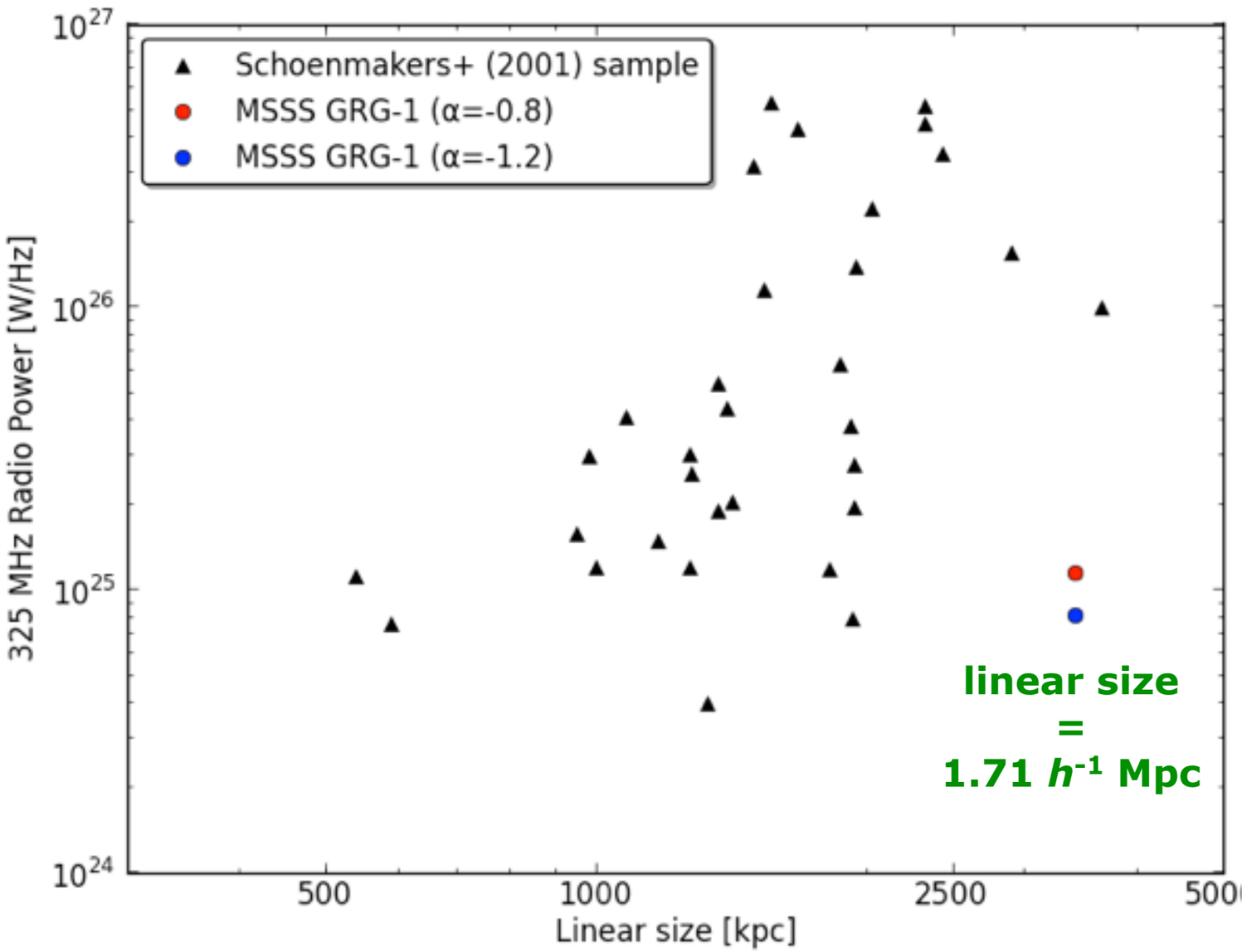




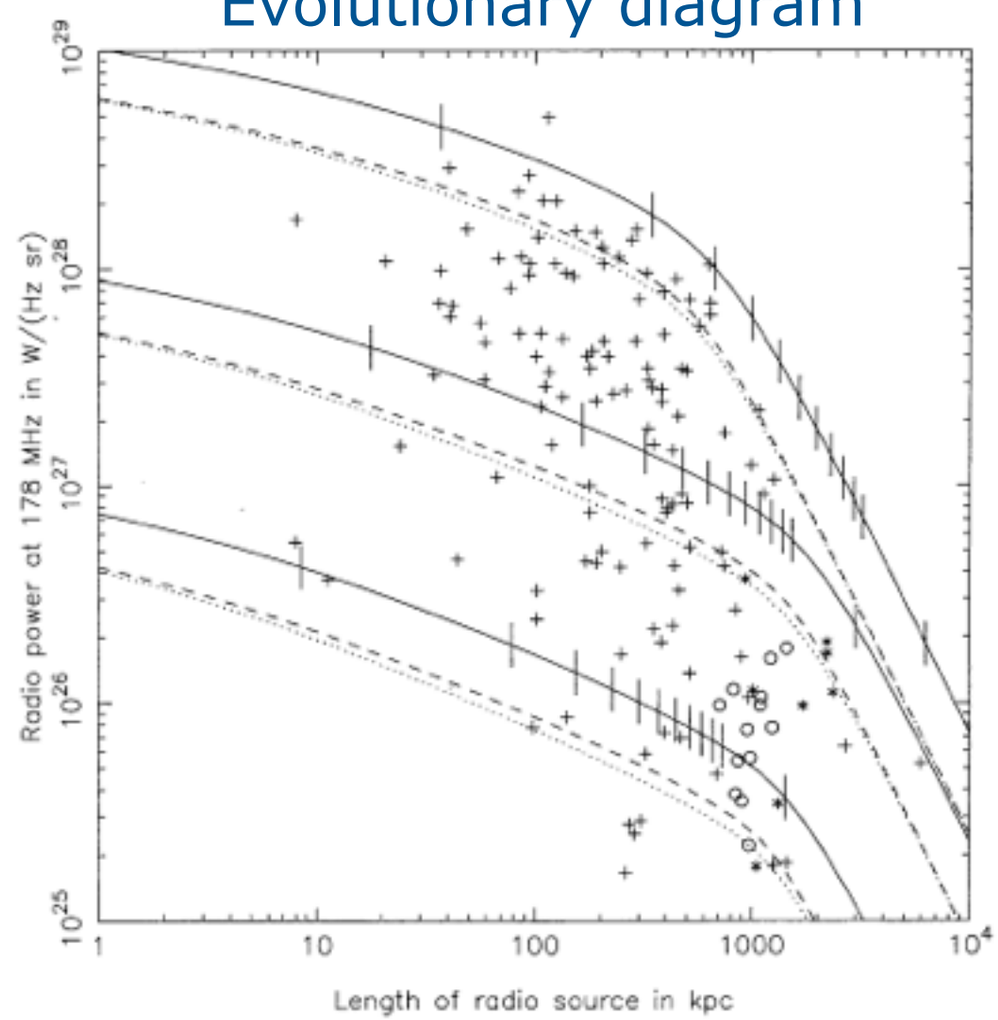
Clarke et al (in prep)

MSSS-discovered GRG

- Identified as a GRG associated with the central flat-spectrum NVSS source
- Large size for its radio power - particularly old GRG? First of a new population to be revealed by LOFAR?



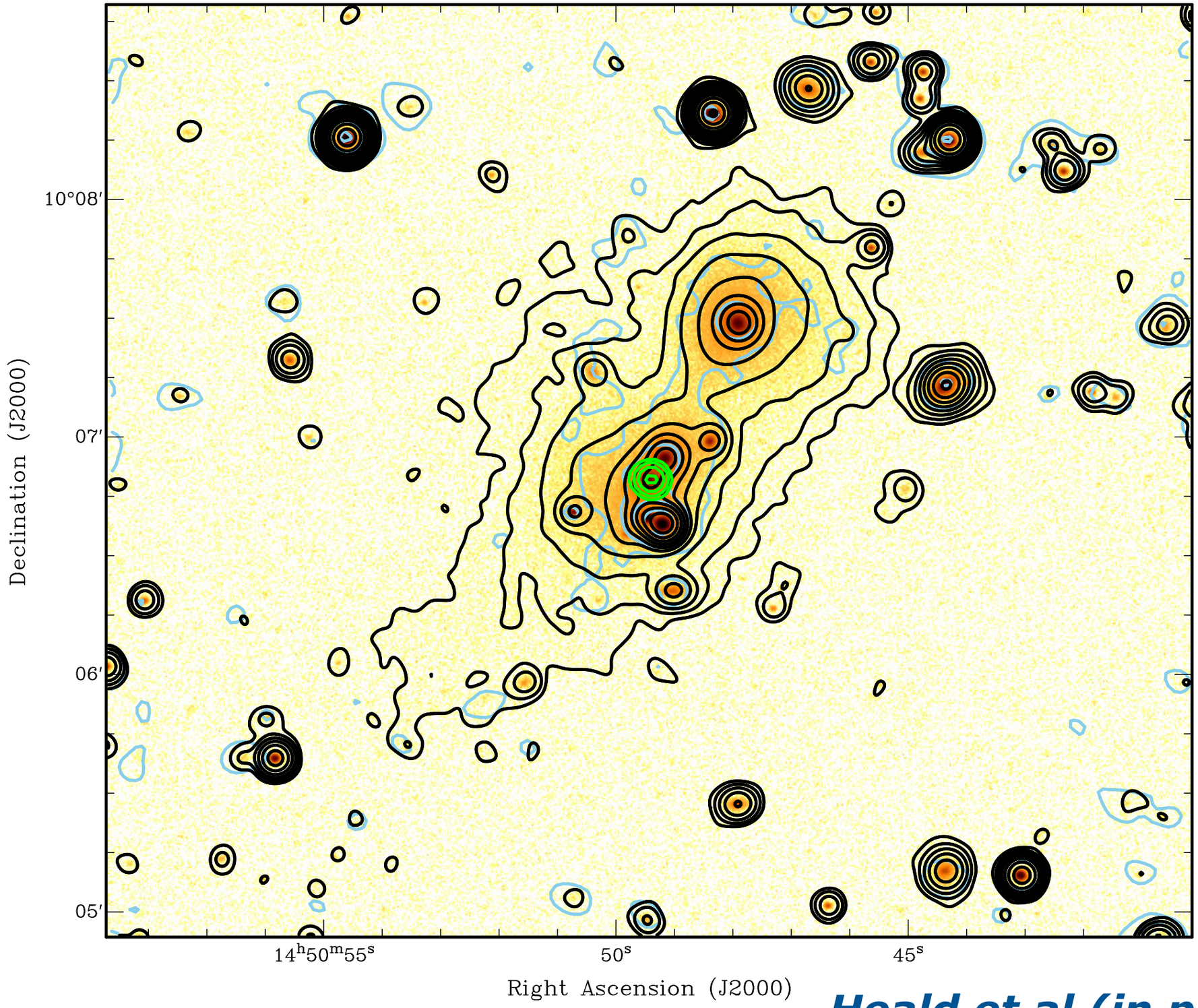
Evolutionary diagram



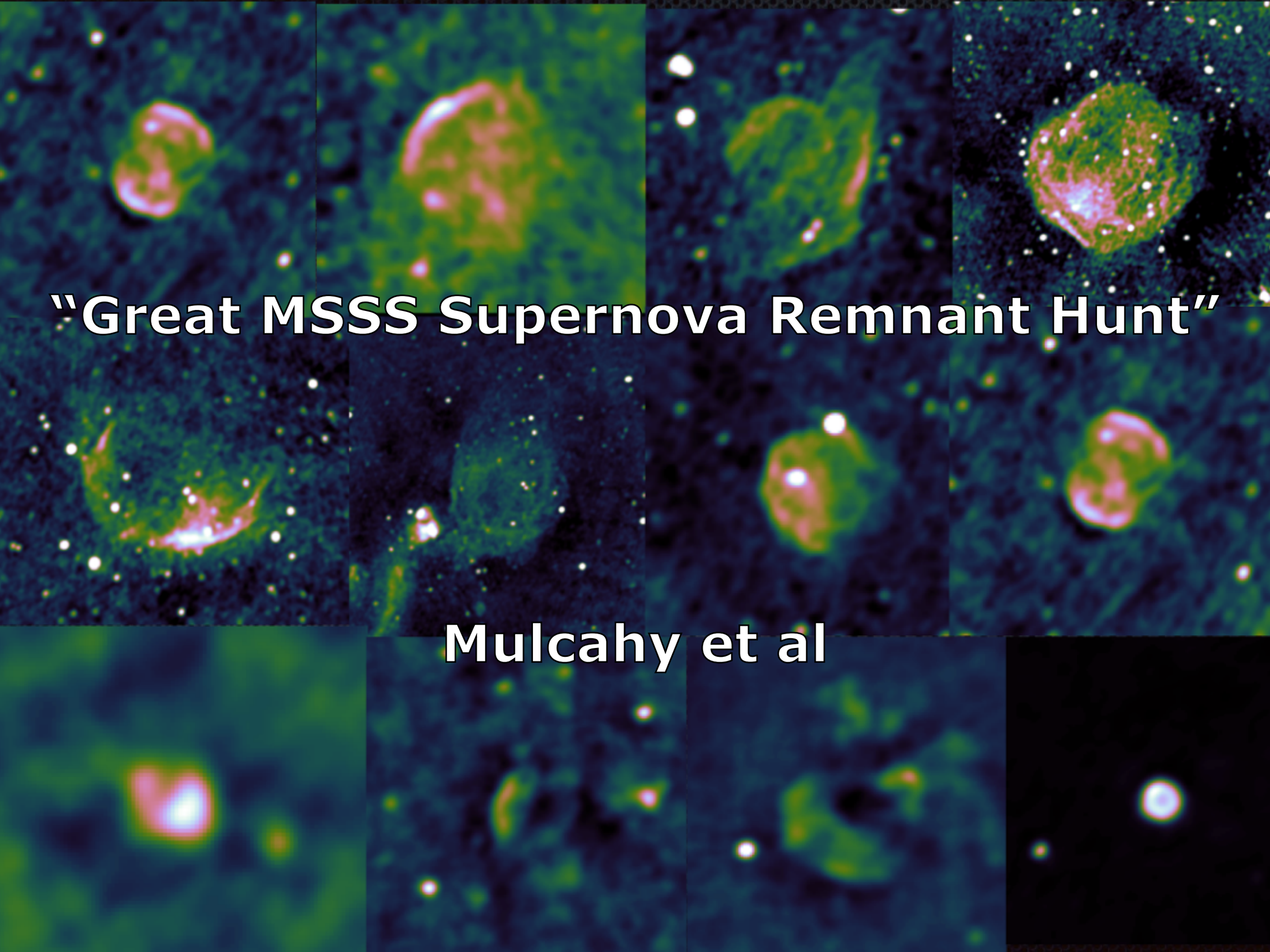
Kaiser et al (1997)

MSSS-discovered GRG

- Host system interesting in its own right!



Heald et al (in prep)

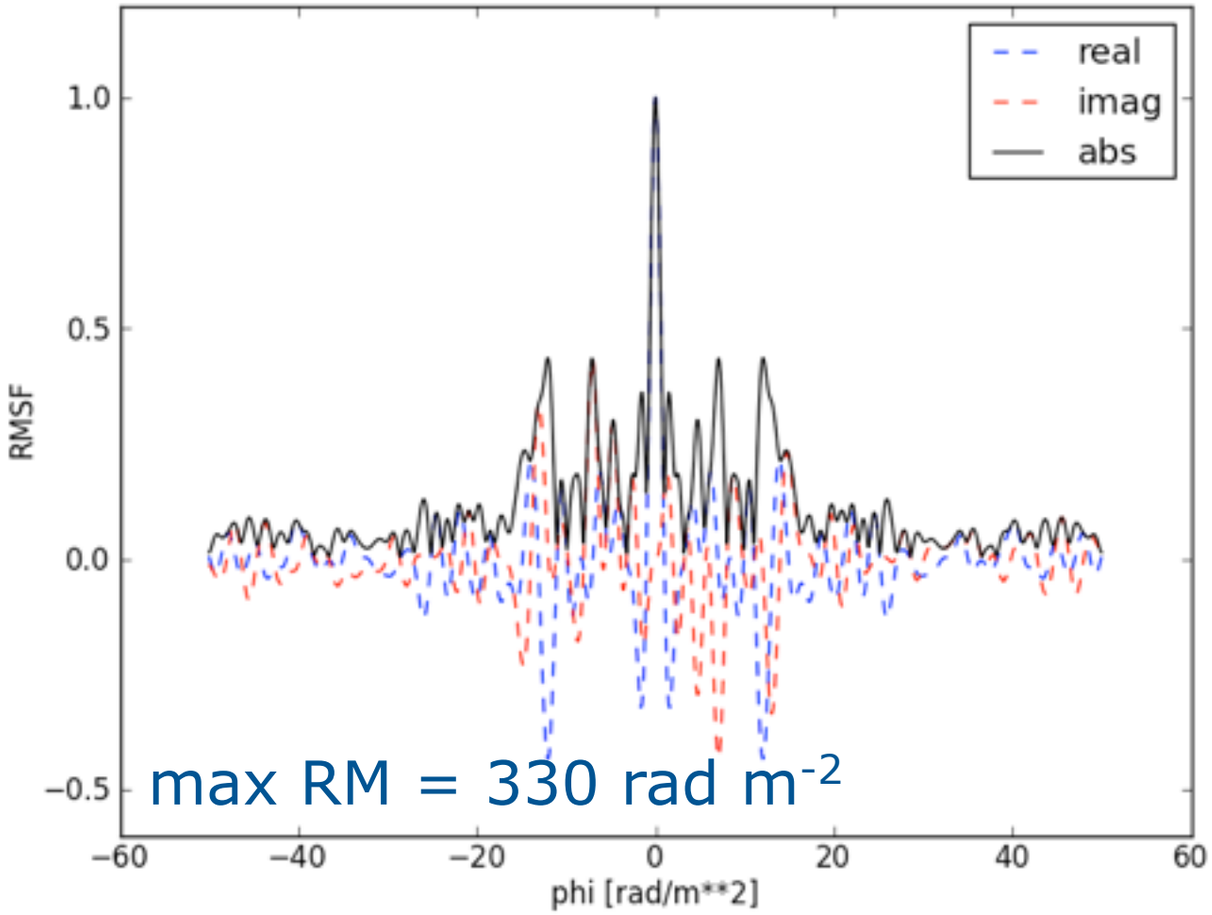


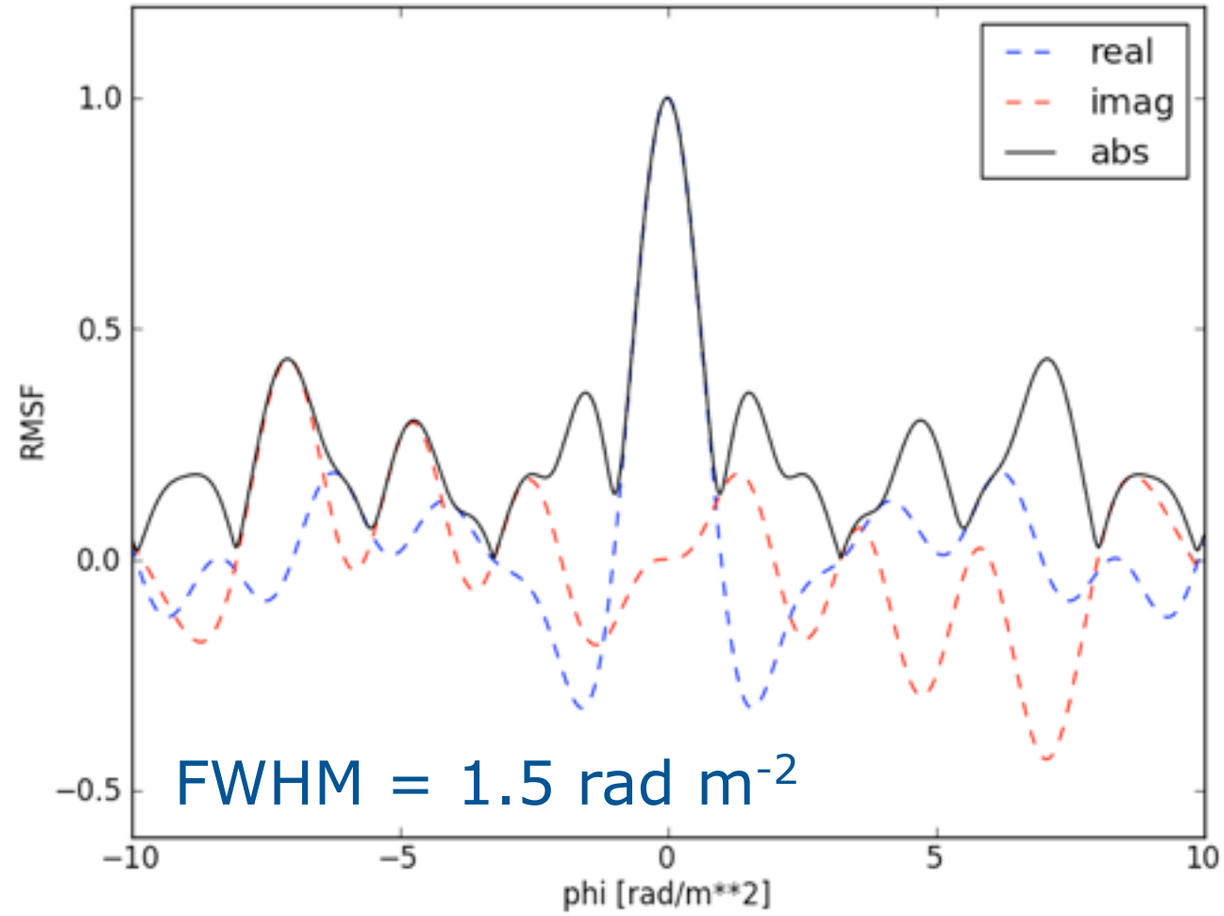
“Great MSSS Supernova Remnant Hunt”

Mulcahy et al

RM Synthesis with MSSS data

- Frequency coverage in HBA allows for shallow polarization search

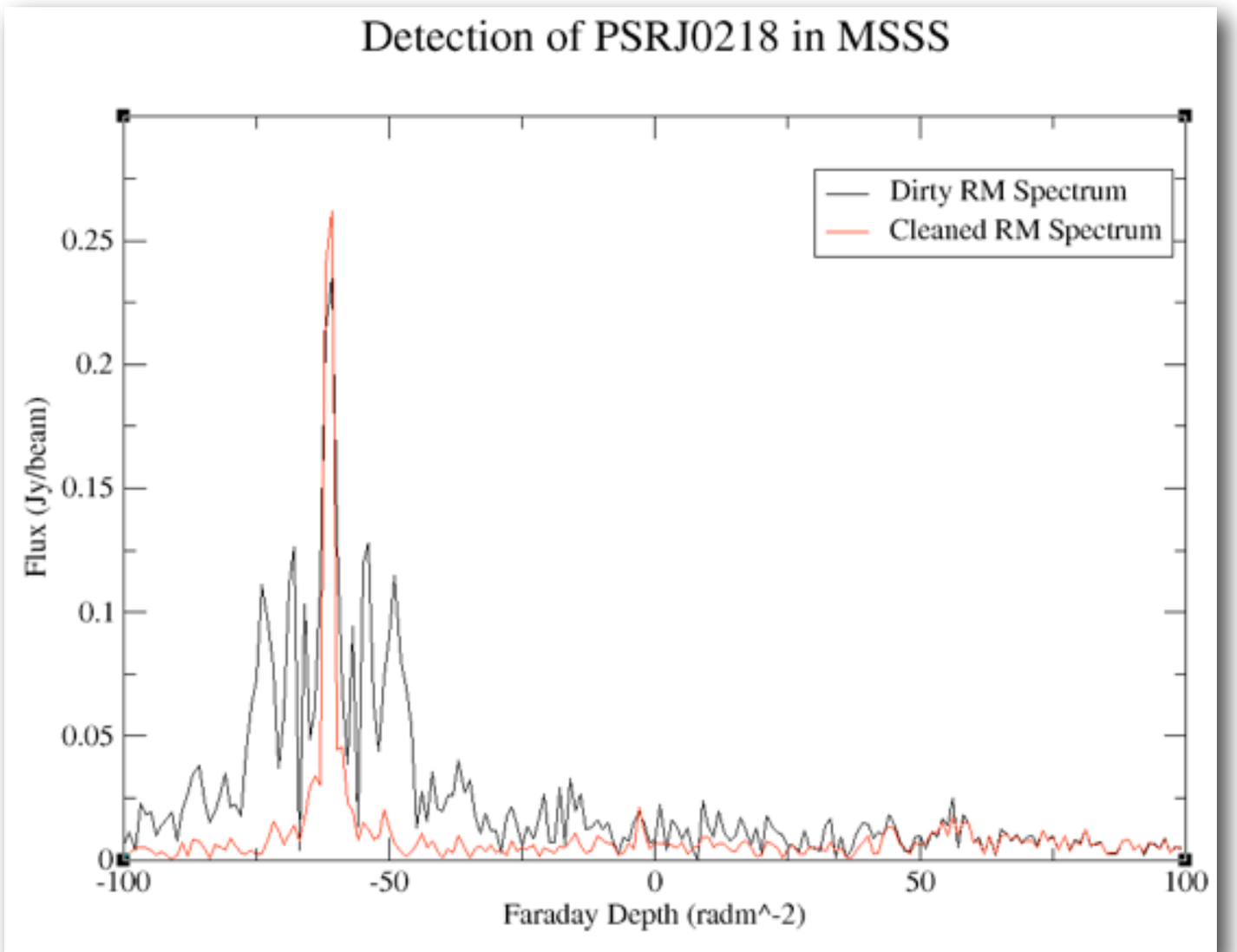


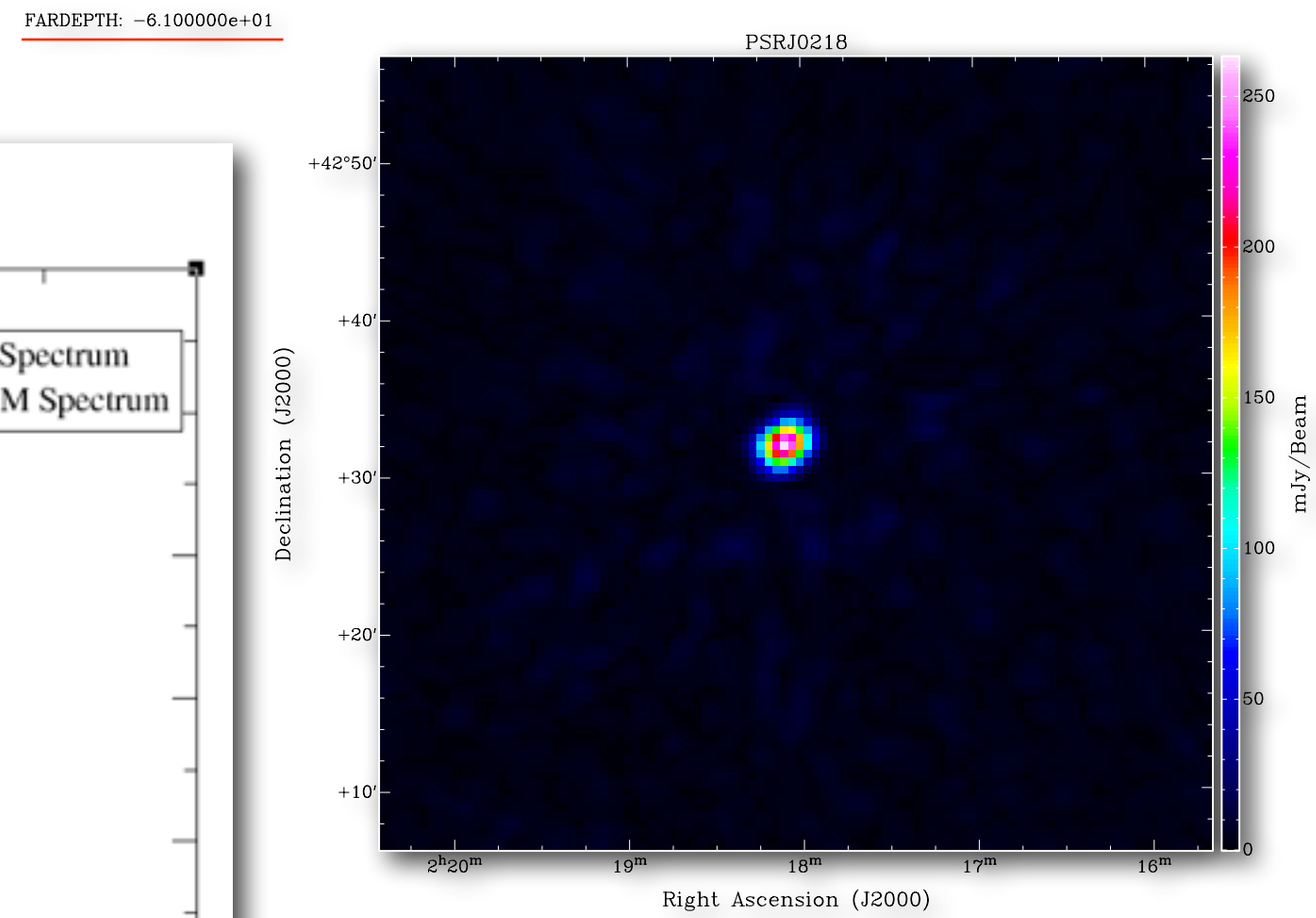


- Calibration and imaging needs a bit of work but no show stoppers:
  - ionospheric RM (predictions) can be applied
  - imaging step is a bit awkward for non-MFS use
- Fields with bright polarization (Fan region and some polarized pulsars) have been observed

MSSS-HBA polarization

- Polarized pulsar (PSRJ0218) detected with MSSS image data!
- 51% polarized, and with correct RM of -61 rad m^2 (ionospheric RM correction was applied to the data)

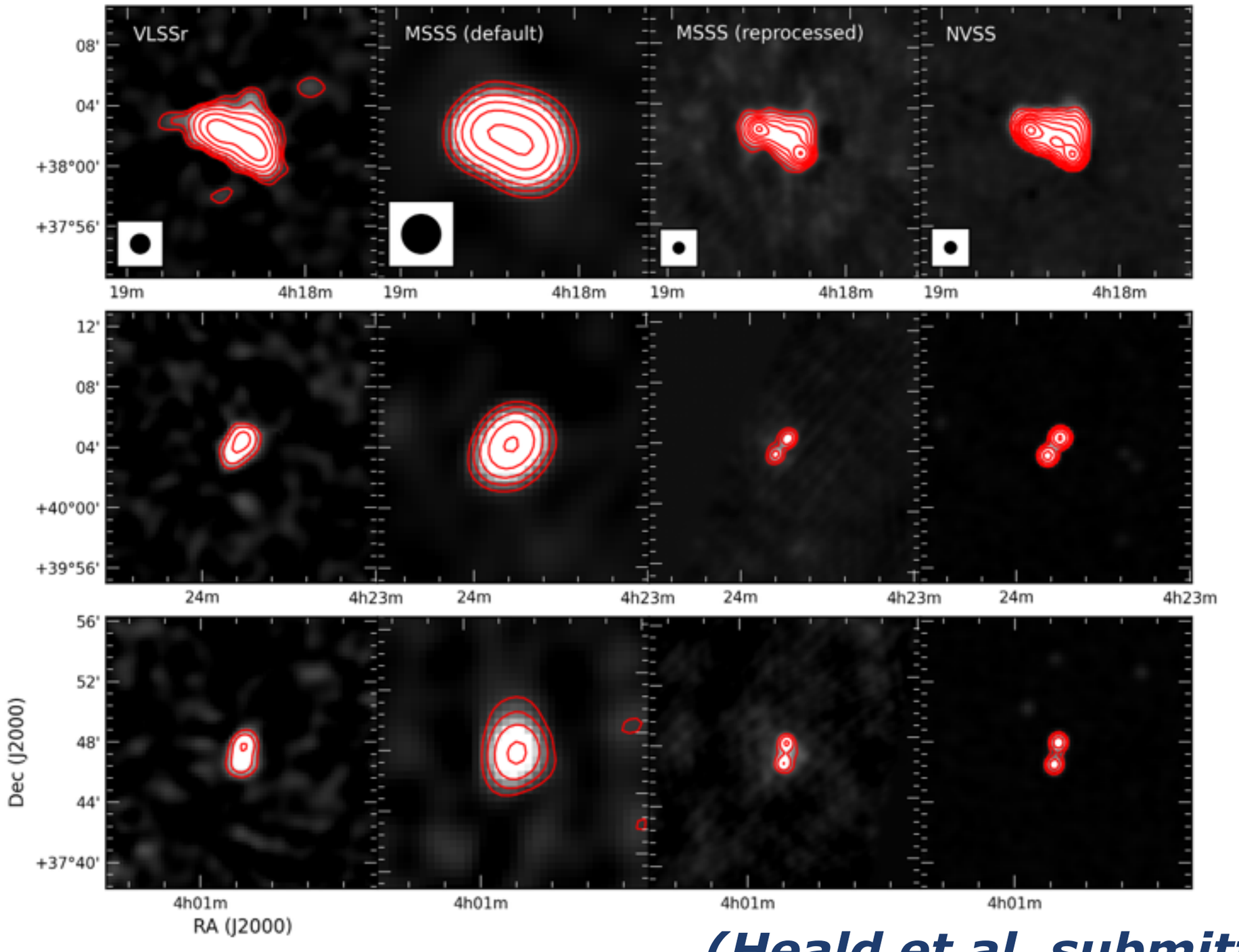




David Mulcahy

Reprocessing MSSS data

- Initial MSSS data product is ~2′ resolution, but visibility data allows for better angular resolution. Plan is to provide v2 catalog.

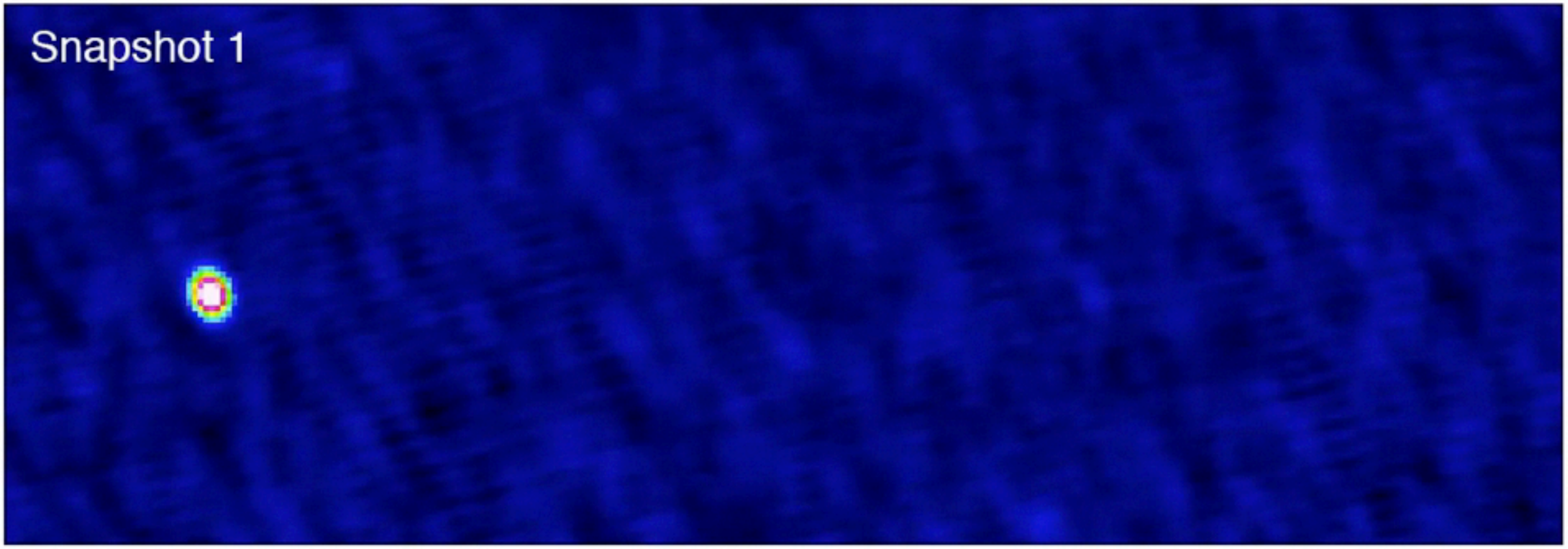


(Heald et al, submitted)

Transients with MSSS

- In MSSS-LBA, 1 subband always on NCP (200 kHz bw at 60 MHz)
- In both MSSS-LBA and MSSS-HBA, multiple epochs (9,2 resp)

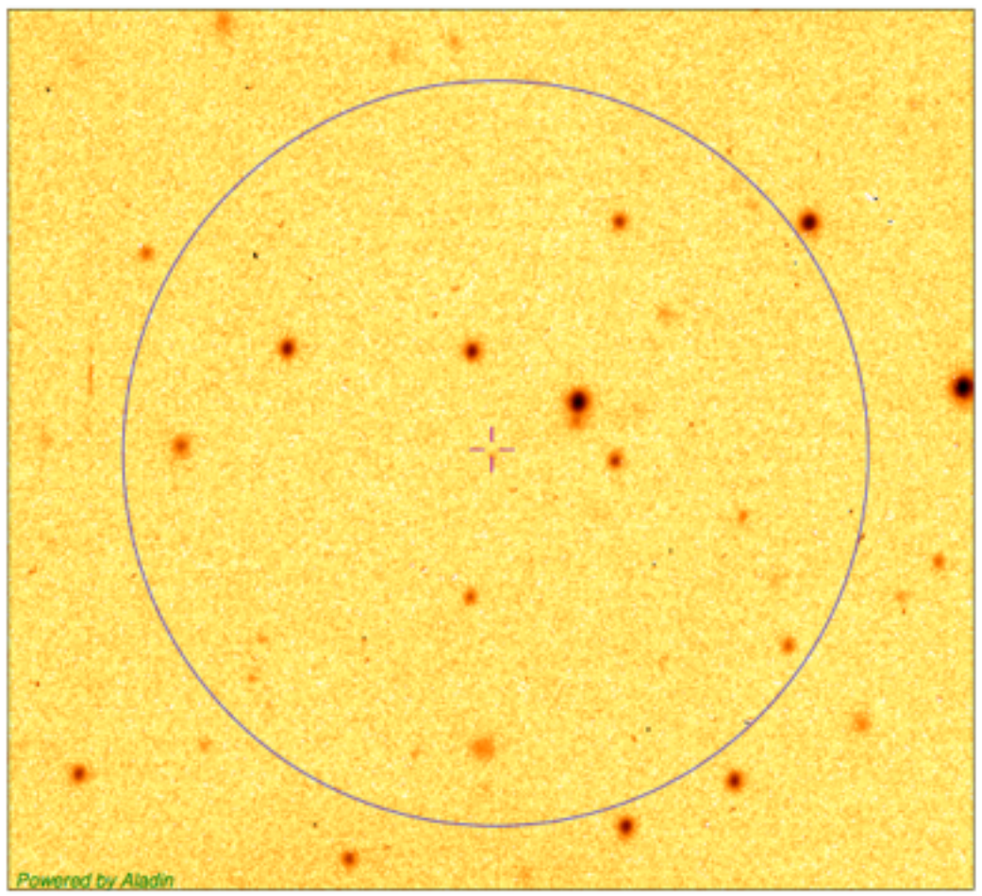
Transient Candidate #1

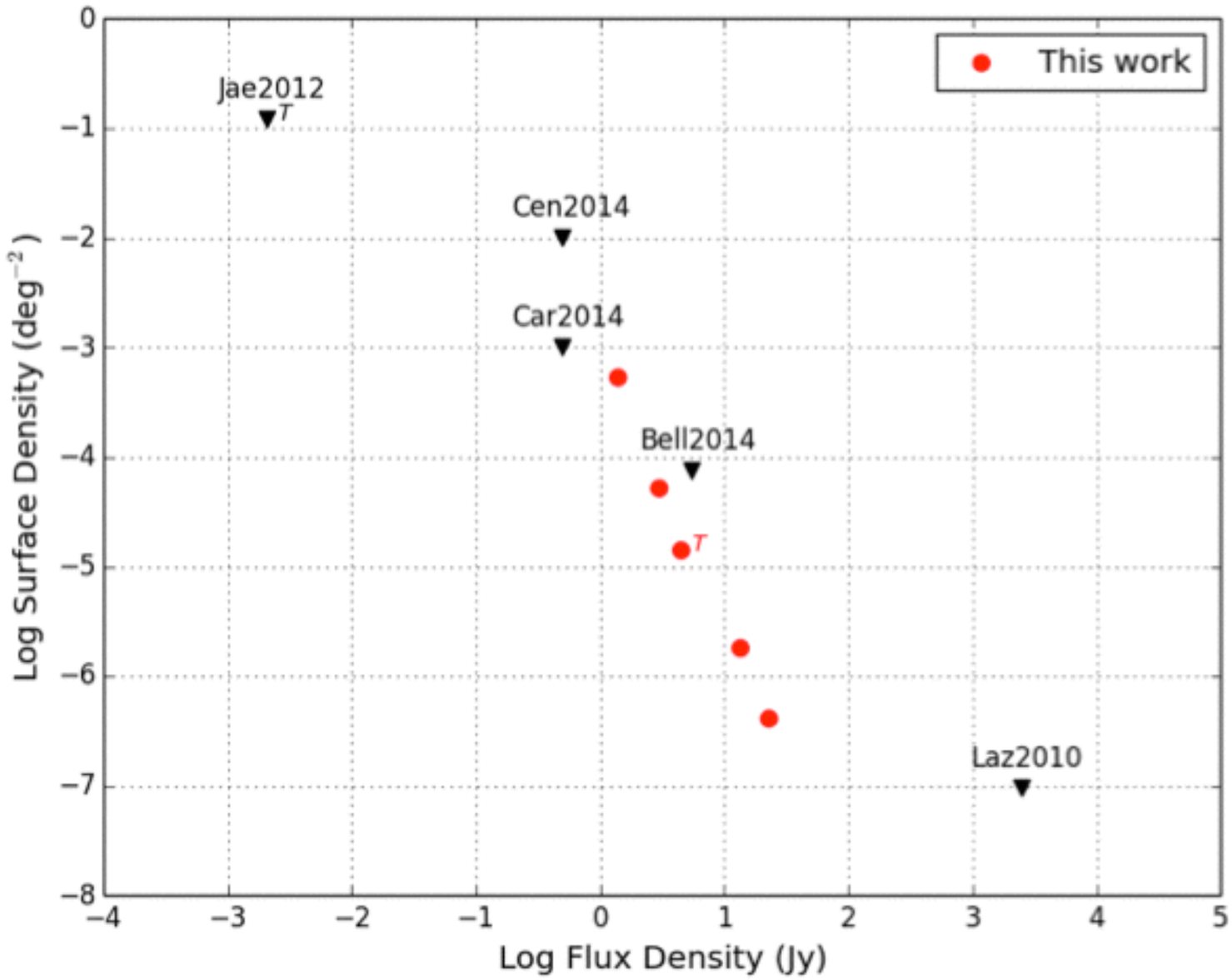


- First MSSS(-LBA) transient candidate (***Stewart et al, in prep***)
  - Appears in one 11-min snapshot, flux density 15-25 Jy beam^{-1}
  - Implied rate for Δt=11min is 1±1/2538 transients day^{-1} deg^{-2} (~1 transient per square degree per 7 years!)

Transients with MSSS

- Possible origins: flare star? highly dispersed FRB?

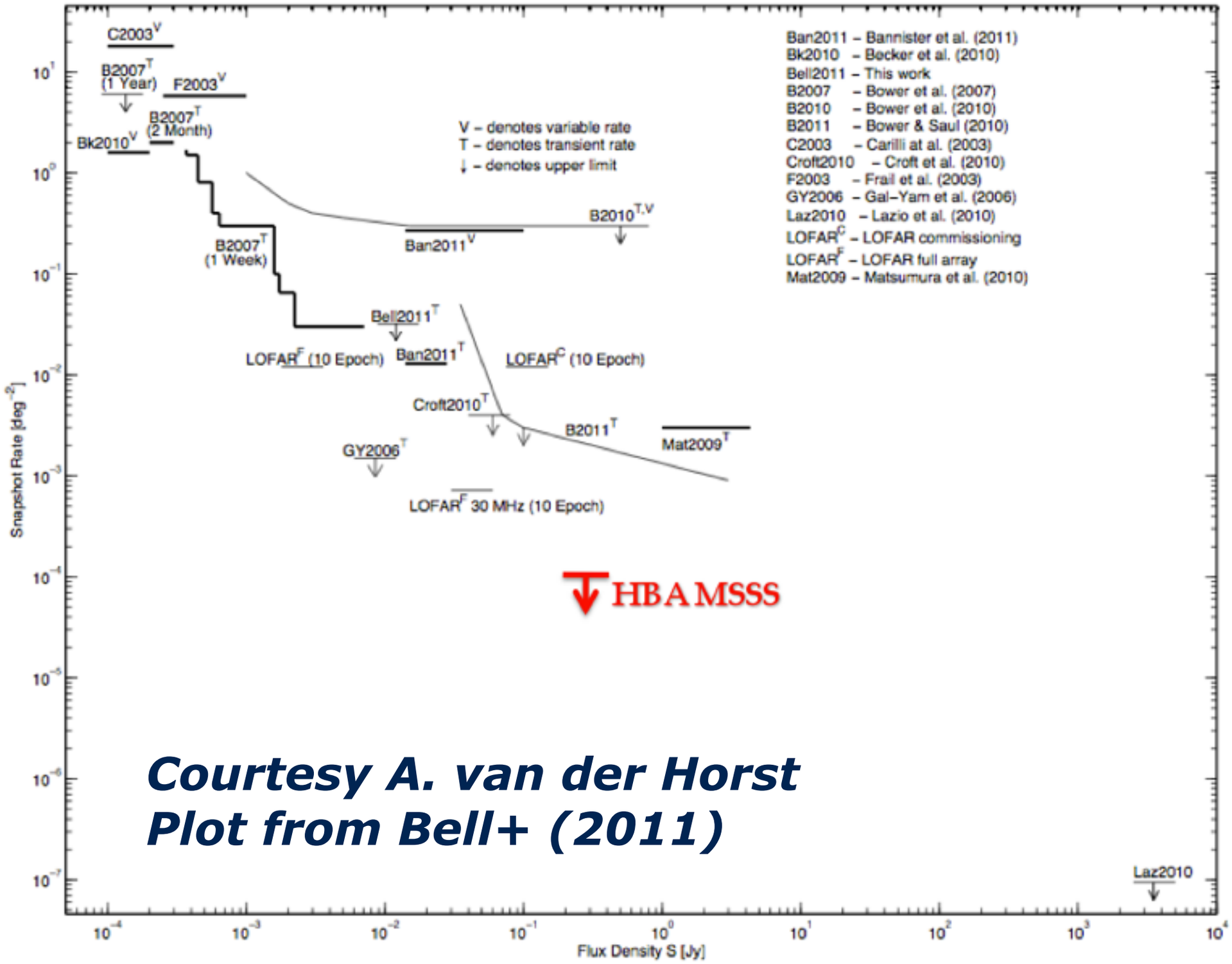




(Stewart et al, in prep)

Additional MSSS transient searches

- MSSS HBA: overlapping fields, 2 snapshots each



Courtesy A. van der Horst
Plot from Bell+ (2011)

MSSS overview & VF paper

- Heald et al 2014 (submitted to A&A)

The LOFAR Multifrequency Snapshot Sky Survey (MSSS)

I. Survey description and first results

G. H. Heald[1,2], R. F. Pizzo[1], E. Orrú[1], R. P. Breton[3], D. Carbone[4], C. Ferrari[5], M. J. Hardcastle[6], W. Jurusik[7], G. Macario[5], D. Mulcahy[8,3], D. Rafferty[9], A. Asgekar[1⋆], M. Brentjens[1], R. A. Fallows[1], W. Frieswijk[1], M. C. Toribio[1], B. Adebahr[8], M. Arts[1], M. R. Bell[10], A. Bonafede[9], J. Bray[3], J. Broderick[3,11], T. Cantwell[3], P. Carroll[12], Y. Cendes[4], A. O. Clarke[3], J. Croston[3], S. Daiboo[13], F. de Gasperin[9], J. Gregson[14], J. Harwood[1,6], T. Hassall[3], V. Heesen[3], A. Horneffer[8], A. J. van der Horst[4], M. Iacobelli[15,1], V. Jelić[2,1], D. Jones[16], D. Kant[1], P. Martin[3], J. P. McKean[1,2], L. K. Morabito[15], B. Nikiel-Wroczyński[7], A. Offringa[1], V. N. Pandey[1], M. Pandey-Pommier[17], M. Pietka[3,11], L. Pratley[18], C. Riseley[3], A. Rowlinson[19], J. Sabater[20], A. M. M. Scaife[3], L. H. A. Scheers[21], K. Sendlinger[22], A. Shulevski[2], C. Sobey[8,1], A. J. Stewart[11,3], A. Stroe[15], J. Swinbank[4], C. Tasse[23,24,25], J. Trüstedt[26,27], E. Varenius[28], S. van Velzen[29], N. Vilchez[1], R. J. van Weeren[30], S. Wijnholds[1], W. L. Williams[15,1], A. G. de Bruyn[1,2], R. Nijboer[1], M. Wise[1], A. Alexov[31], J. Anderson[32], I. M. Avruch[33,2], R. Beck[8], M. E. Bell[19], I. van Bemmel[1,34], M. J. Bentum[1,35], G. Bernardi[30], P. Best[20], F. Breitling[36], W. N. Brouw[1,2], M. Brüggen[9], H. R. Butcher[37], B. Ciardi[10], J. E. Conway[28], E. de Geus[1,38], A. de Jong[1], M. de Vos[1], A. Deller[1], S. Duscha[1], J. Eislöffel[39], D. Engels[40], H. Falcke[16,1], R. Fender[11], M. A. Garrett[1,15], J. Grießmeier[41,42], A. W. Gunst[1], J. P. Hamaker[1], J. W. T. Hessels[1,4], M. Hoeft[39], J. Hörandel[16], H. A. Holties[1], H. Intema[15,43], N. J. Jackson[44], E. Jütte[22], A. Karastergiou[11], W. F. A. Klijn[1], V. I. Kondratiev[1,45], L. V. E. Koopmans[2], M. Kuniyoshi[46,8], G. Kuper[1], C. Law[47], J. van Leeuwen[1,4], M. Loose[1], P. Maat[1], S. Markoff[4], R. McFadden[1], D. McKay-Bukowski[48,49], M. Mevius[1,2], J. C. A. Miller-Jones[50,4], R. Morganti[1,2], H. Munk[1], A. Nelles[16], J. E. Noordam[1], M. J. Norden[1], H. Paas[51], A. G. Polatidis[1], W. Reich[8], A. Renting[1], H. Röttgering[15], A. Schoenmakers[1], D. Schwarz[52], J. Sluman[1], O. Smirnov[25,24], B. W. Stappers[44], M. Steinmetz[36], M. Tagger[41], Y. Tang[1], S. ter Veen[16], S. Thoudam[16], R. Vermeulen[1], C. Vocks[36], C. Vogt[1], R. A. M. J. Wijers[4], O. Wucknitz[8], S. Yatawatta[1], and P. Zarka[13]

(Affiliations can be found after the references)

Received date / Accepted date

ABSTRACT

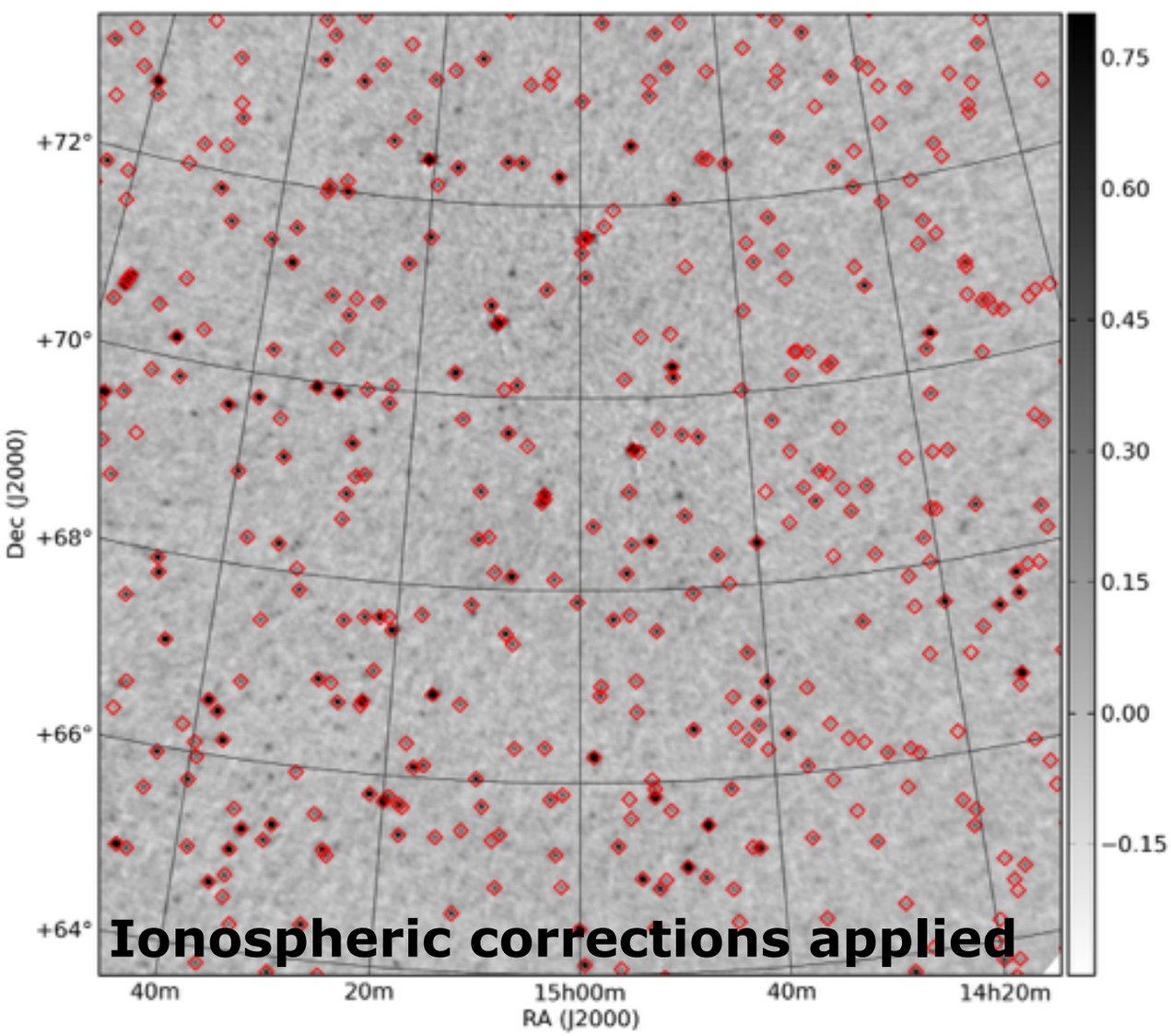
We present the Multifrequency Snapshot Sky Survey (MSSS), the first northern-sky LOFAR imaging survey. In this introductory paper, we first describe in detail the motivation and design of the survey. Compared to previous radio surveys, MSSS is exceptional due to its intrinsic multi-frequency nature providing information about the spectral properties of the detected sources over more than two octaves (from 30 to 160 MHz). The broadband frequency coverage, together with the fast survey speed generated by LOFAR's multibeaming capabilities, make MSSS the first survey of the sort anticipated to be carried out with the forthcoming Square Kilometre Array (SKA). Two of the sixteen frequency bands included in the survey were chosen to exactly overlap the frequency coverage of large-area Very Large Array (VLA) and Giant Metrewave Radio Telescope (GMRT) surveys at 74 MHz and 151 MHz respectively. The survey performance is illustrated within the "MSSS Verification Field" (MVF), a region of 100 square degrees centered at $(\alpha, \delta)_{J2000} = (15^h, 69°)$. The MSSS results from the MVF are compared with previous radio survey catalogs. We assess the flux and astrometric uncertainties in the catalog, as well as the completeness and reliability considering our source finding strategy. We determine the 90% completeness levels within the MVF to be 100 mJy at 135 MHz with 108″ resolution, and 550 mJy at 50 MHz with 166″ resolution. Images and catalogs for the full survey, expected to contain 150 000–200 000 sources, will be released to a public web server. We outline the plans for the ongoing production of the final survey products, and the ultimate public release of images and source catalogs.

Key words. Surveys — Radio continuum: general

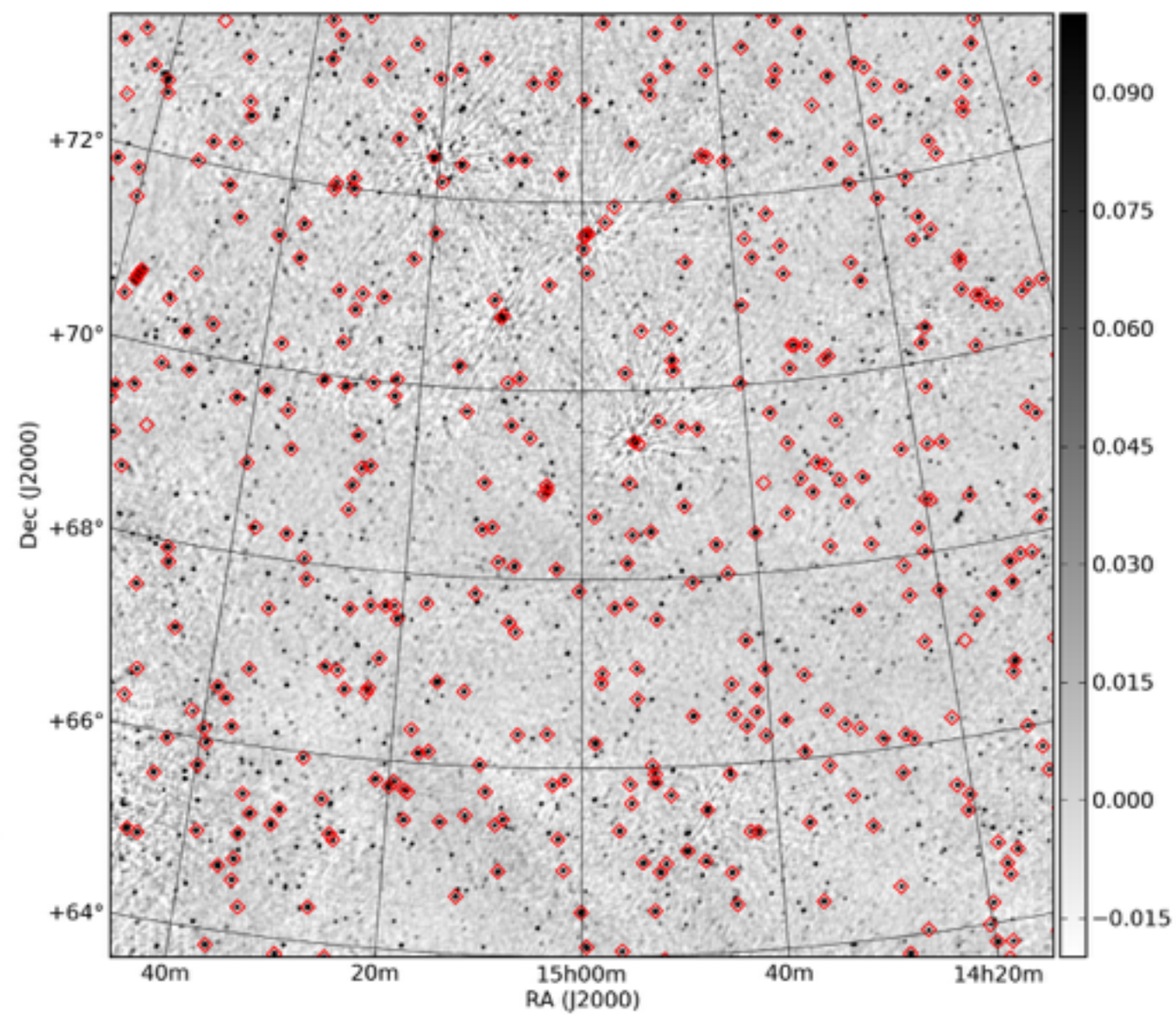
MVF

- 100 sq deg test region at (ra,dec) = 15h, 69d
- 307 sources in LBA, 1234 in HBA

LBA (30-74 MHz)

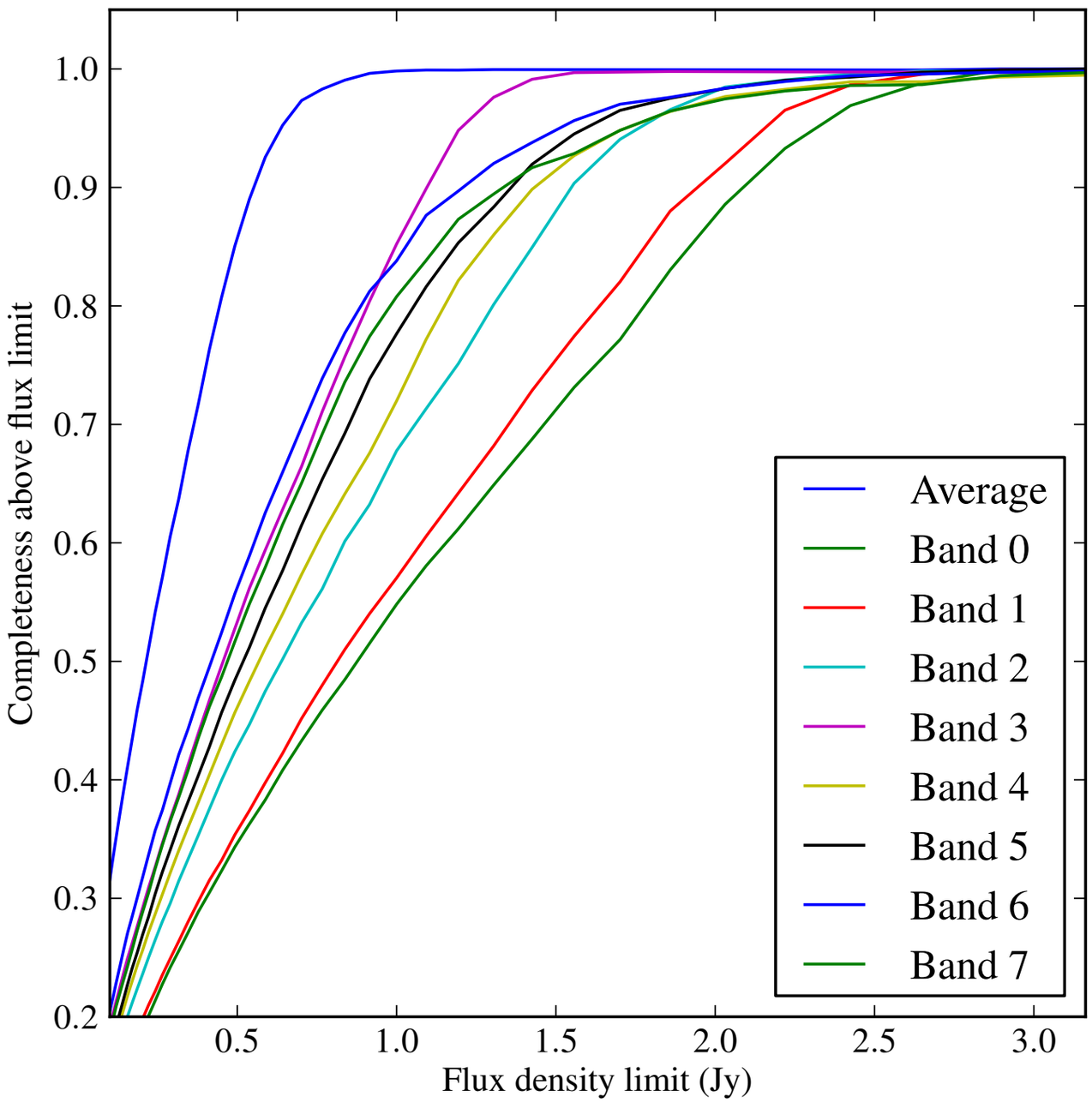


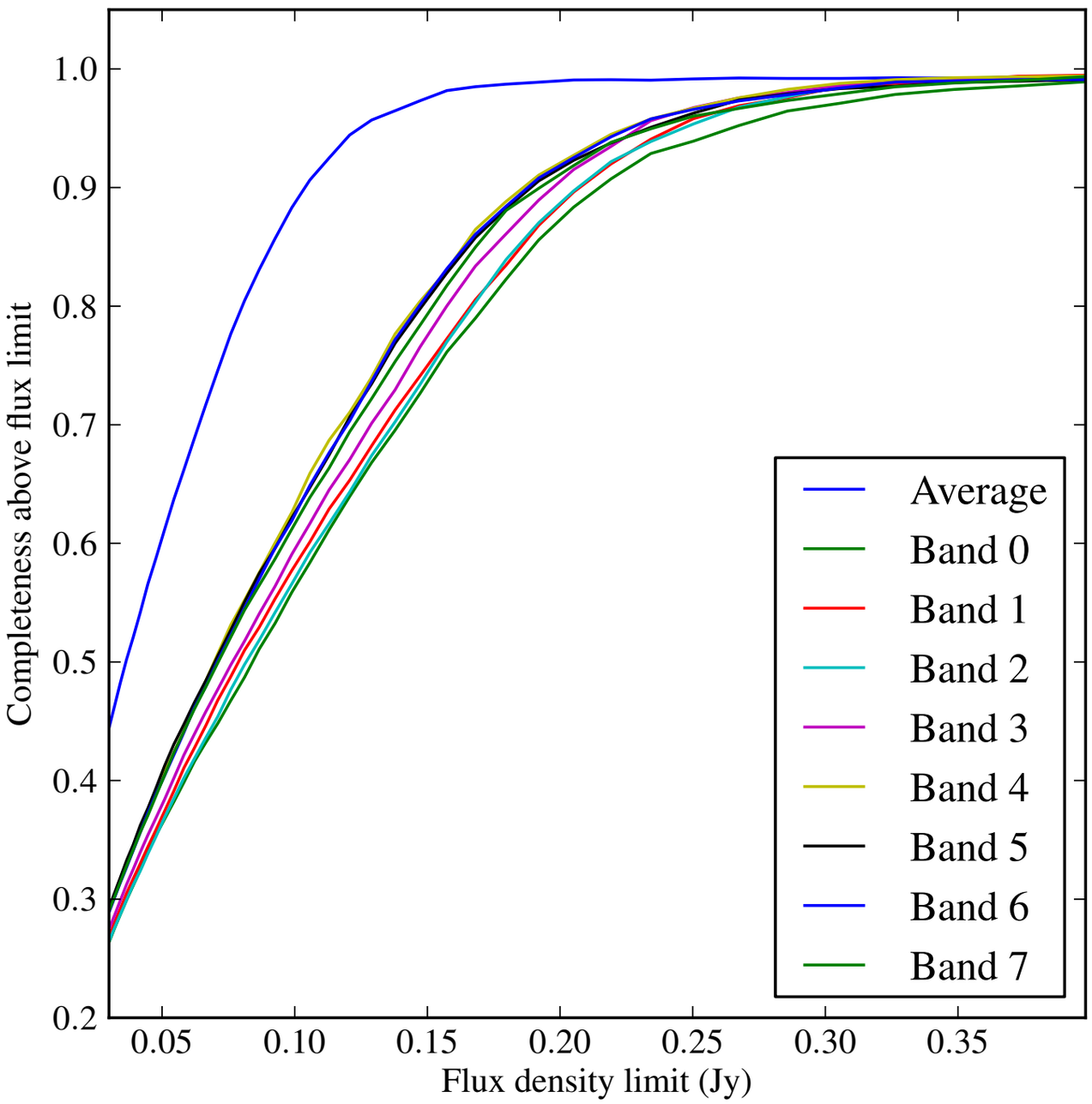
HBA (120-160 MHz)



Completeness (from MVF only)

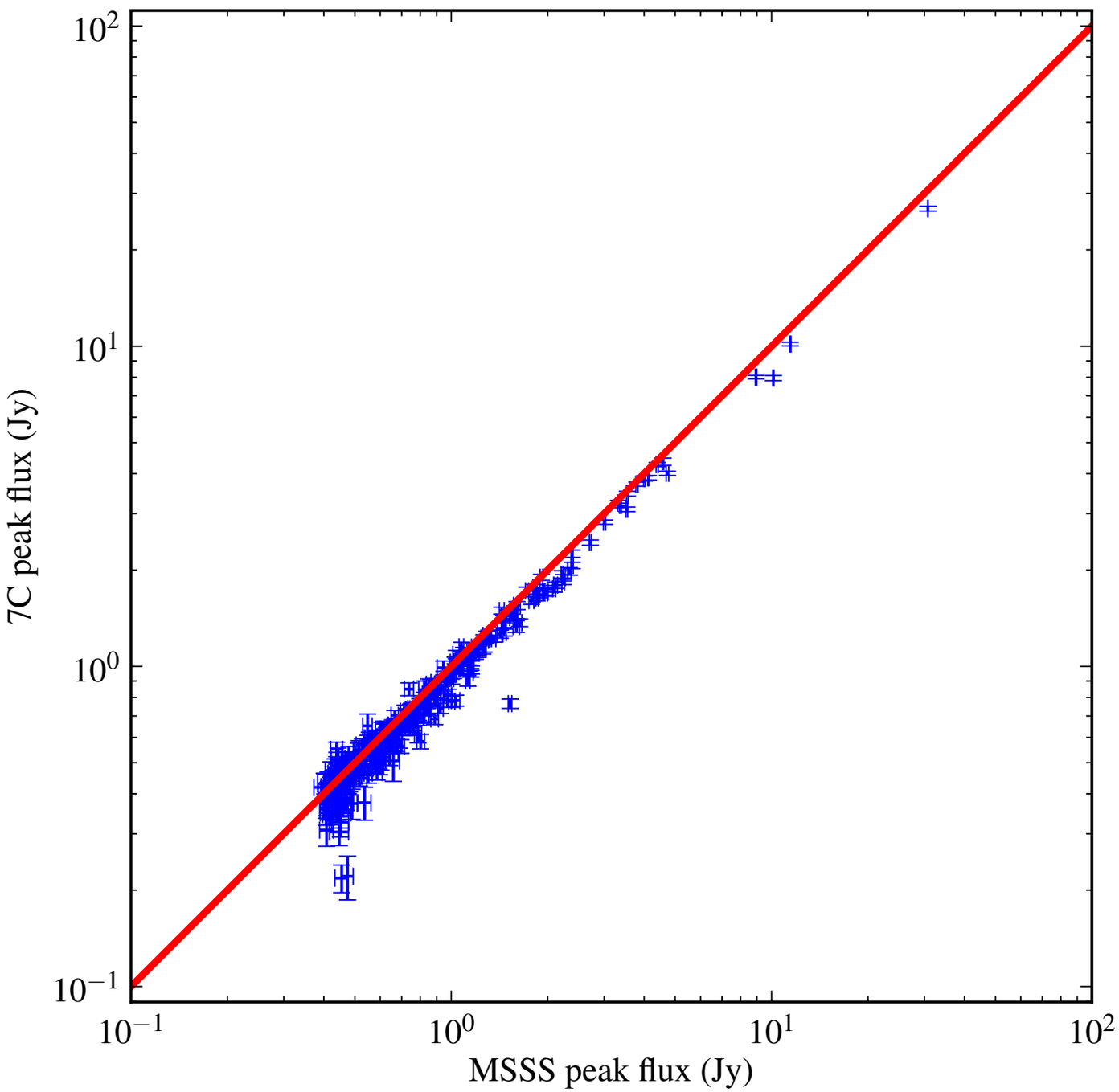
- 90% completeness: 100 mJy at 135 MHz (108”),
  550 mJy at 50 MHz (166”)

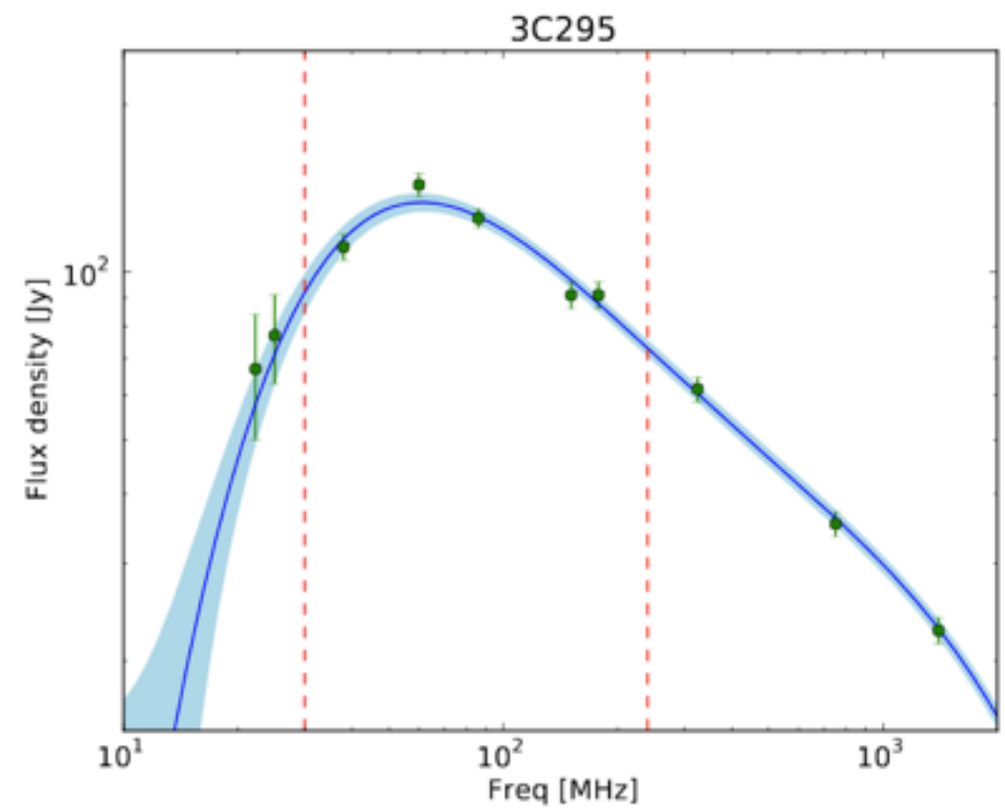




MVF fluxes vs 7C catalog

- Agreement excellent but MSSS-HBA has ~9% higher fluxes, originating from different assumptions about flux of 3C295 (see Rick's talk)

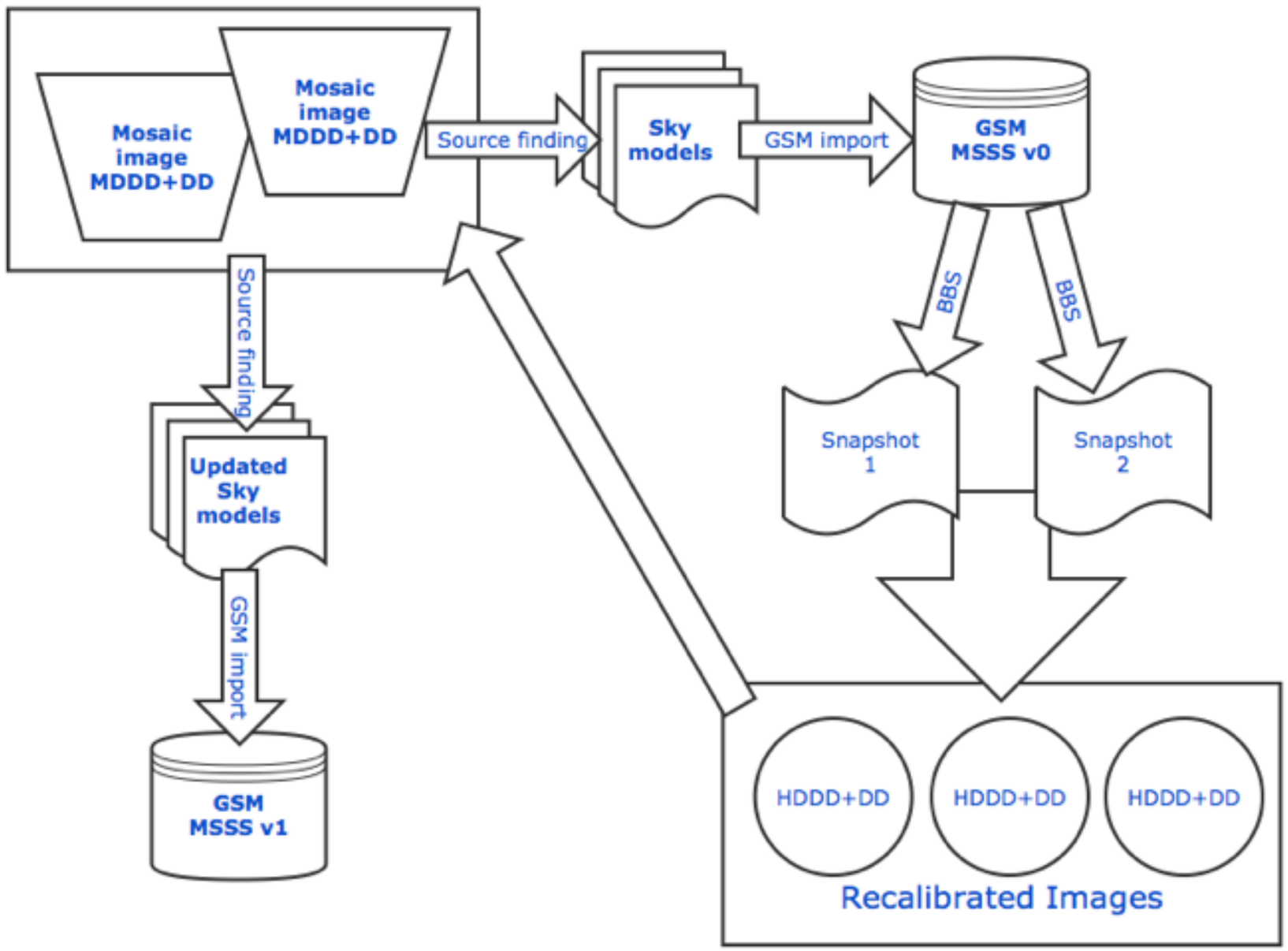




Scaife & Heald (2012)

Reprocessing scheme

- Large-scale self-calibration loop to suppress false detections that may be present in initial sky model (VLSSr based)
- Beginning this month, running until ~ end of 2014

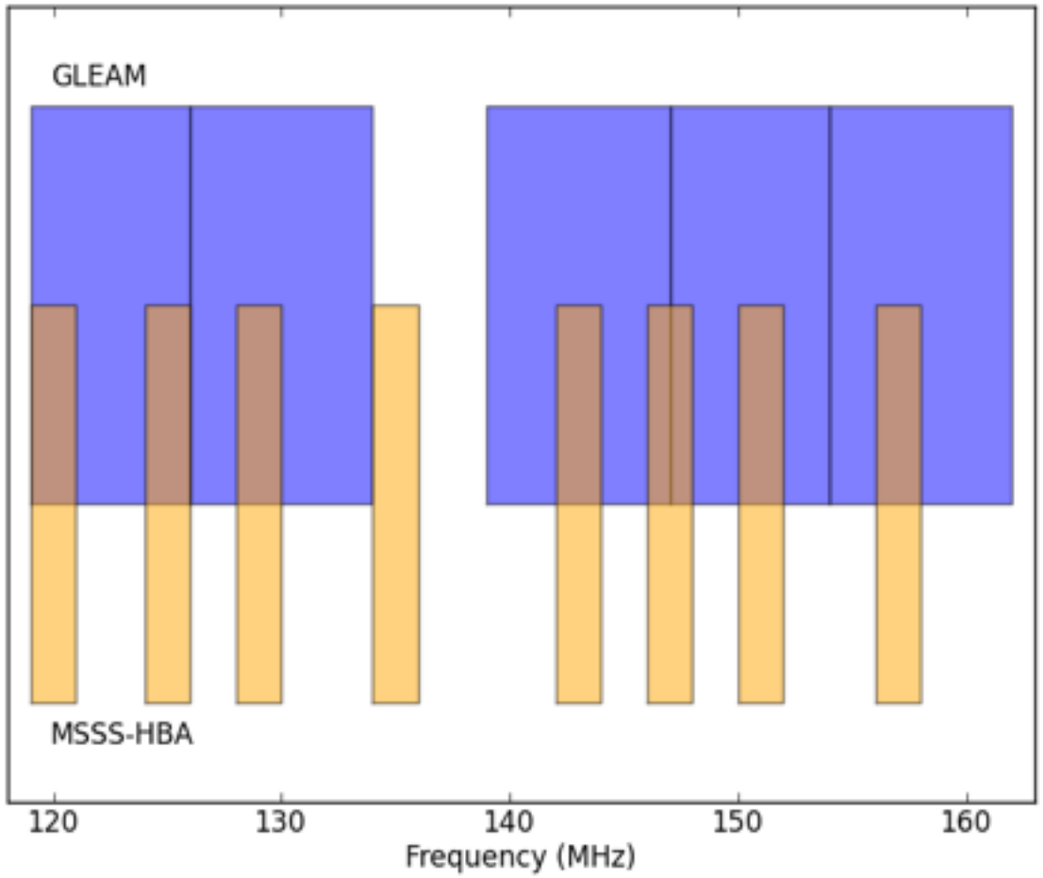


Comparing MSSS & GLEAM

	Full Instrument
Number of 16-dipole tiles	128
Number of receivers	16
Observing frequencies	75—220 MHz
Frequency resolution	40 kHz
Longest baseline	2800m
Angular resolution	4'—1.2'
Polarisation	I, Q, U, V
Primary beam FHWM	25º—10º
Confusion limit/mJy	60mJy—5mJy

Comparing MSSS and GLEAM

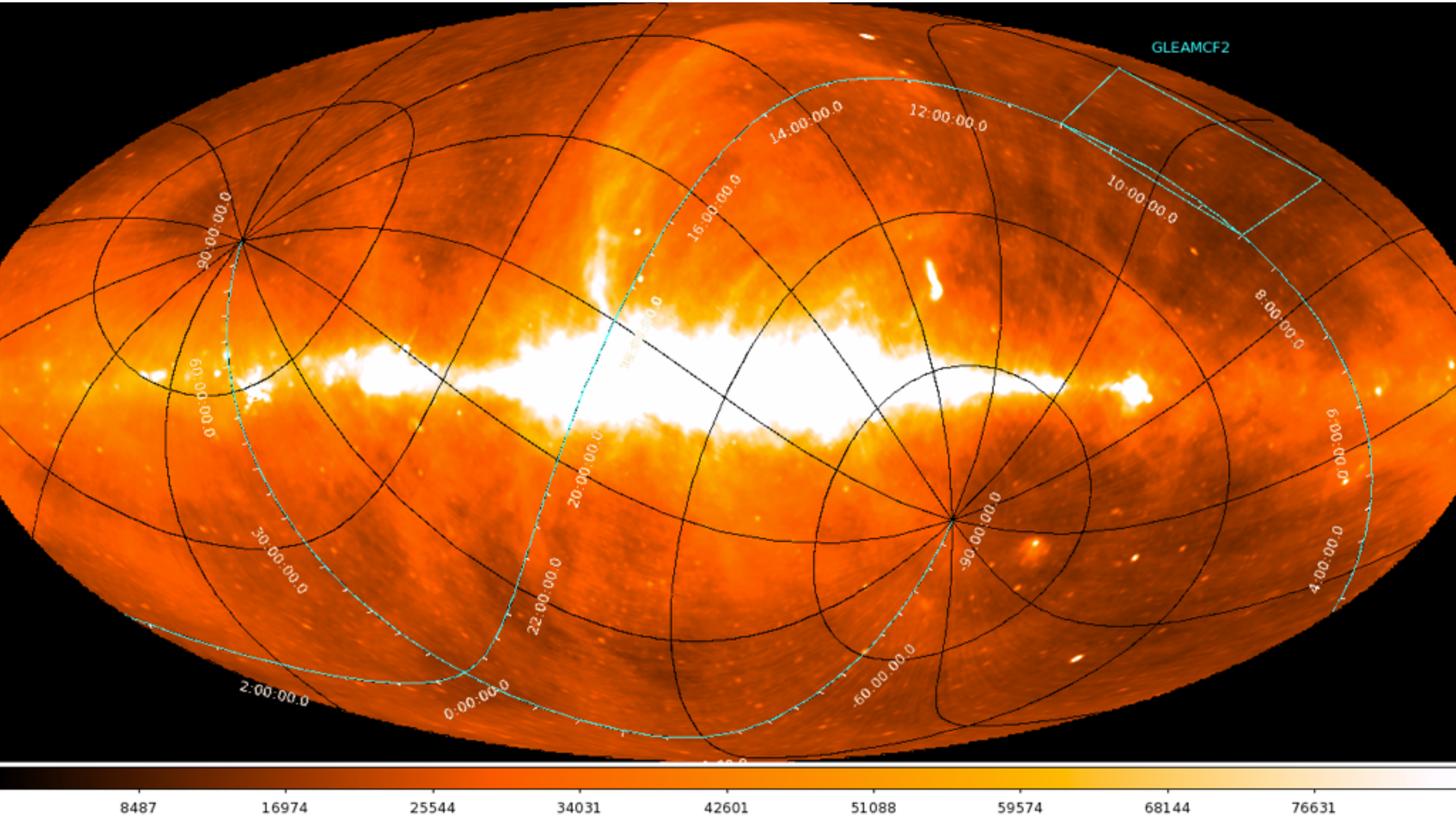
- Substantial overlap in frequency (subset with overlap shown)



- Compatible beam size, (confusion) noise level
- Large overlap in declination coverage (GLEAM goes up to +30°, MSSS down to 0°)
- Both have systematics to address, but they are different (and often orthogonal!)

Comparing MSSS and GLEAM

- Region picked between RA=9-11h, Dec=0-30d

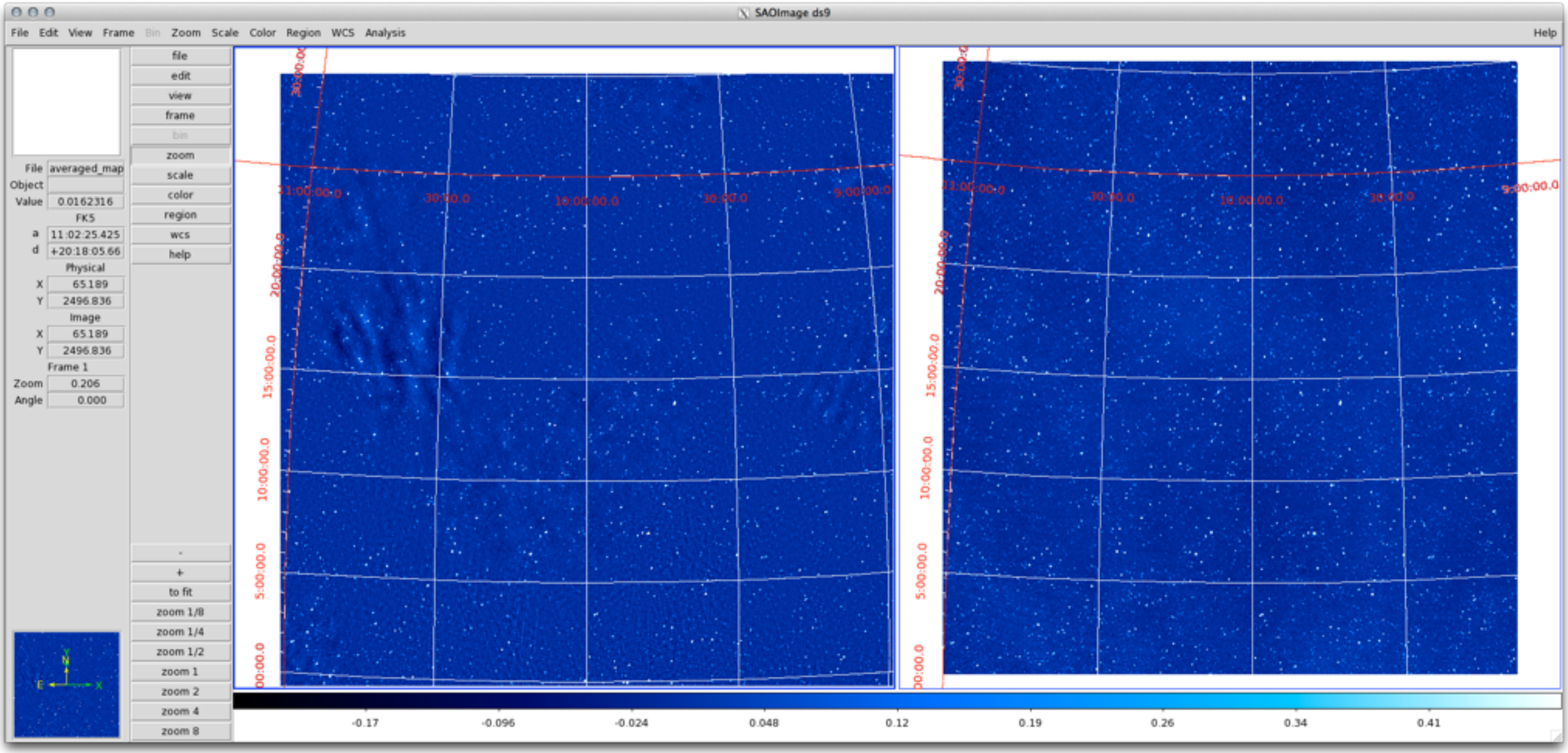


Colormap: Haslam 408 MHz

Comparing MSSS and GLEAM

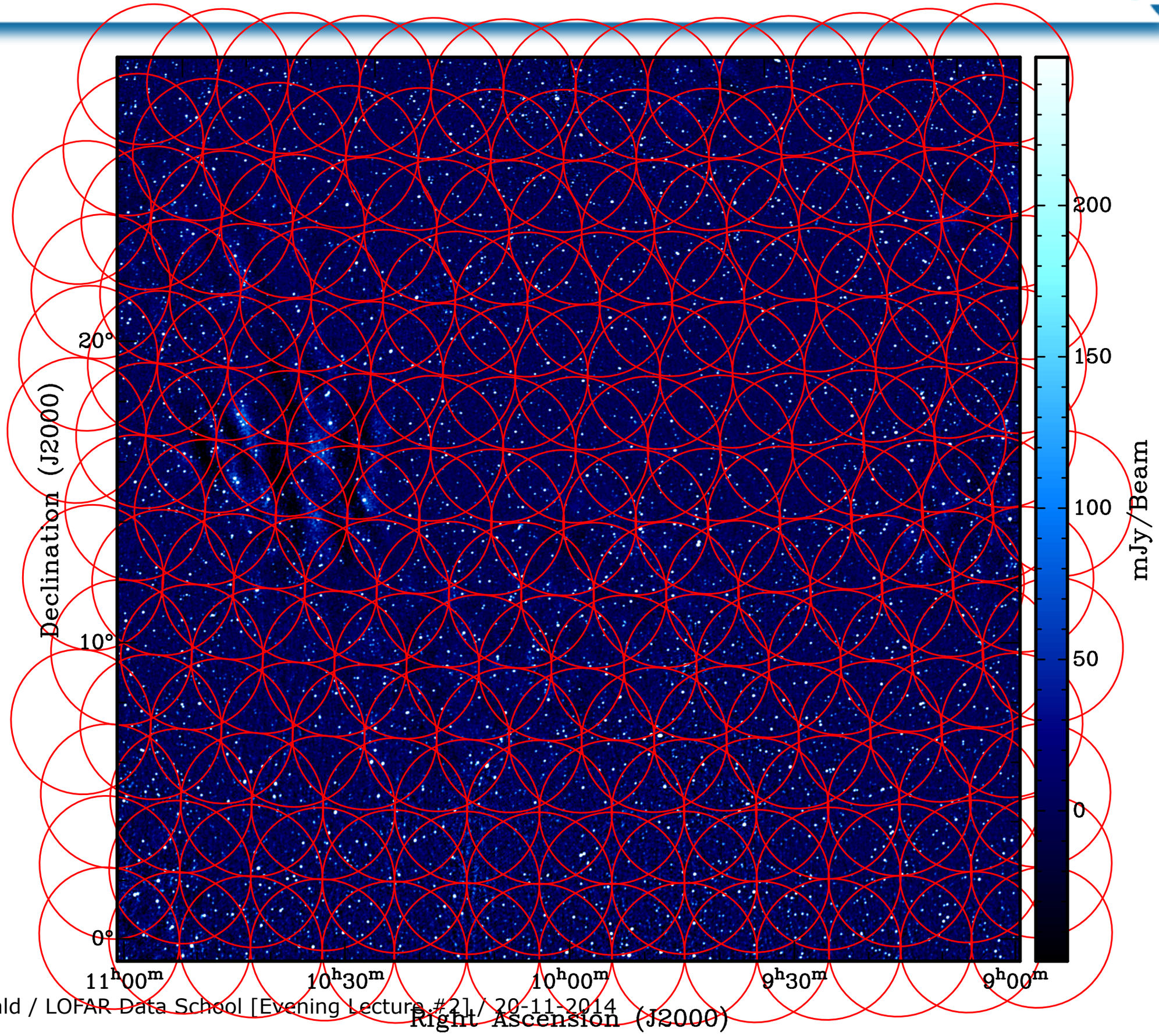
- Ongoing comparison between MSSS and GLEAM

  GLEAM image courtesy Natasha Hurley-Walker

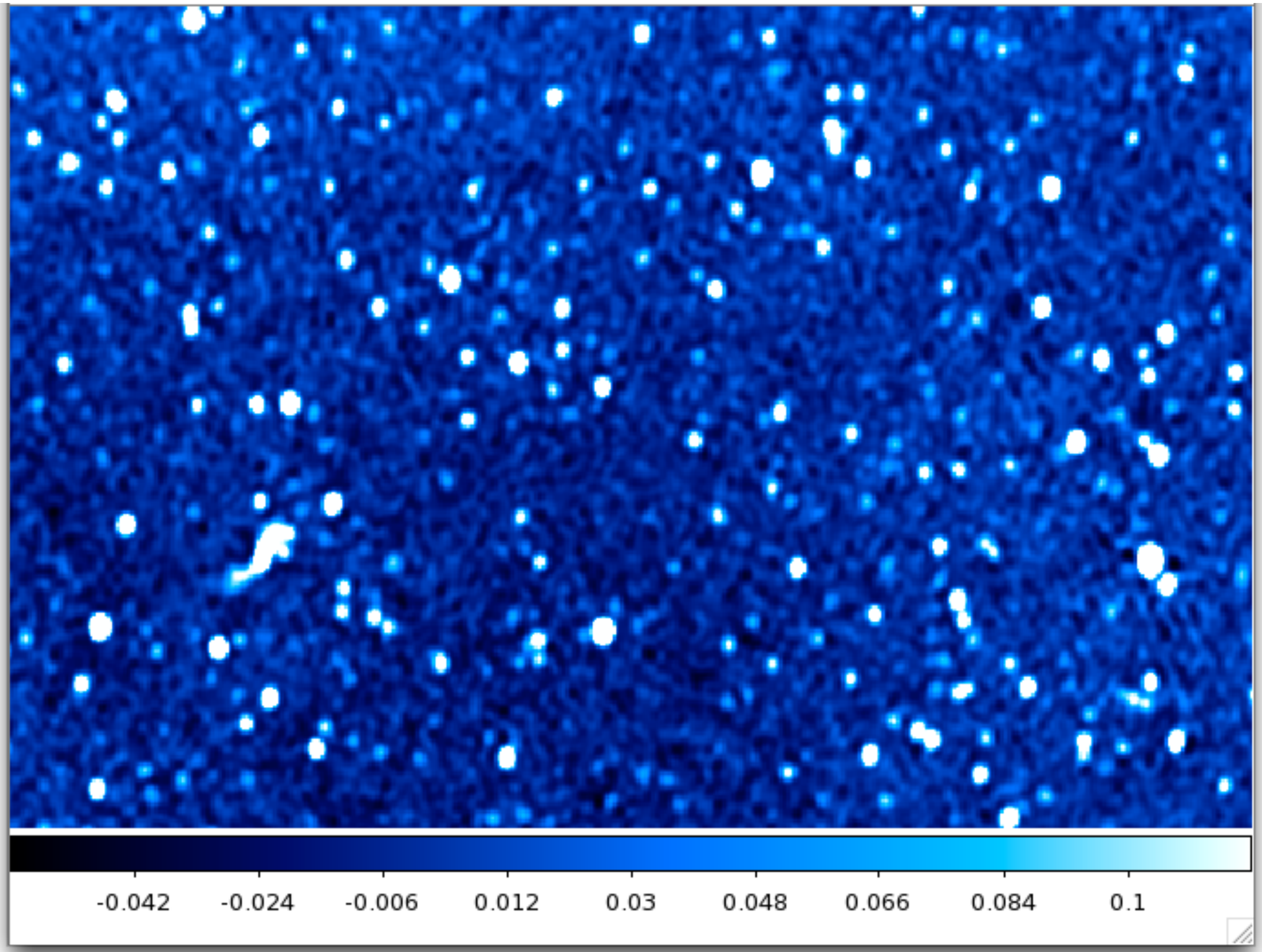


MSSS (v0) GLEAM

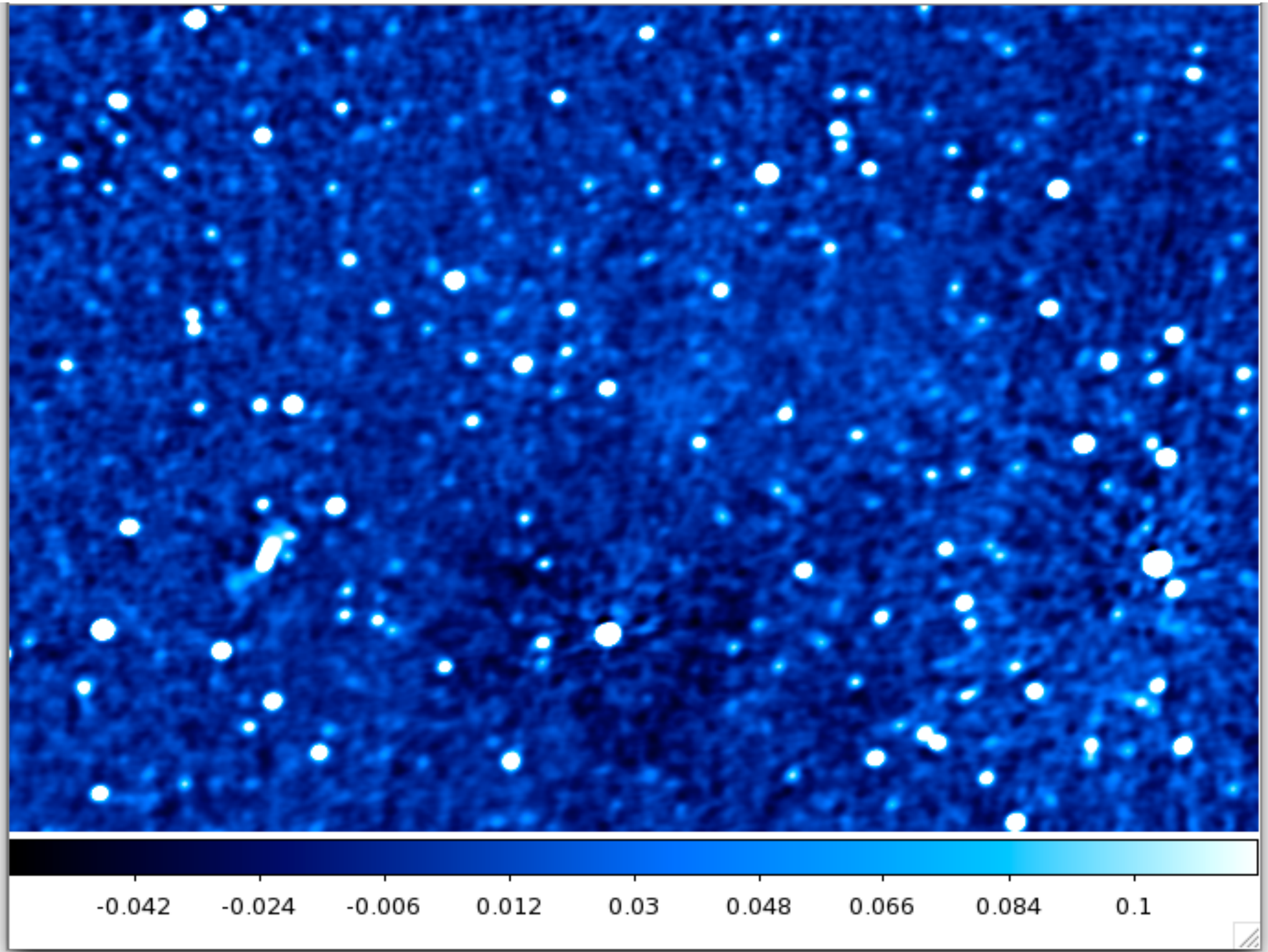
Mosaicing MSSS



Zoomin comparison - GLEAM



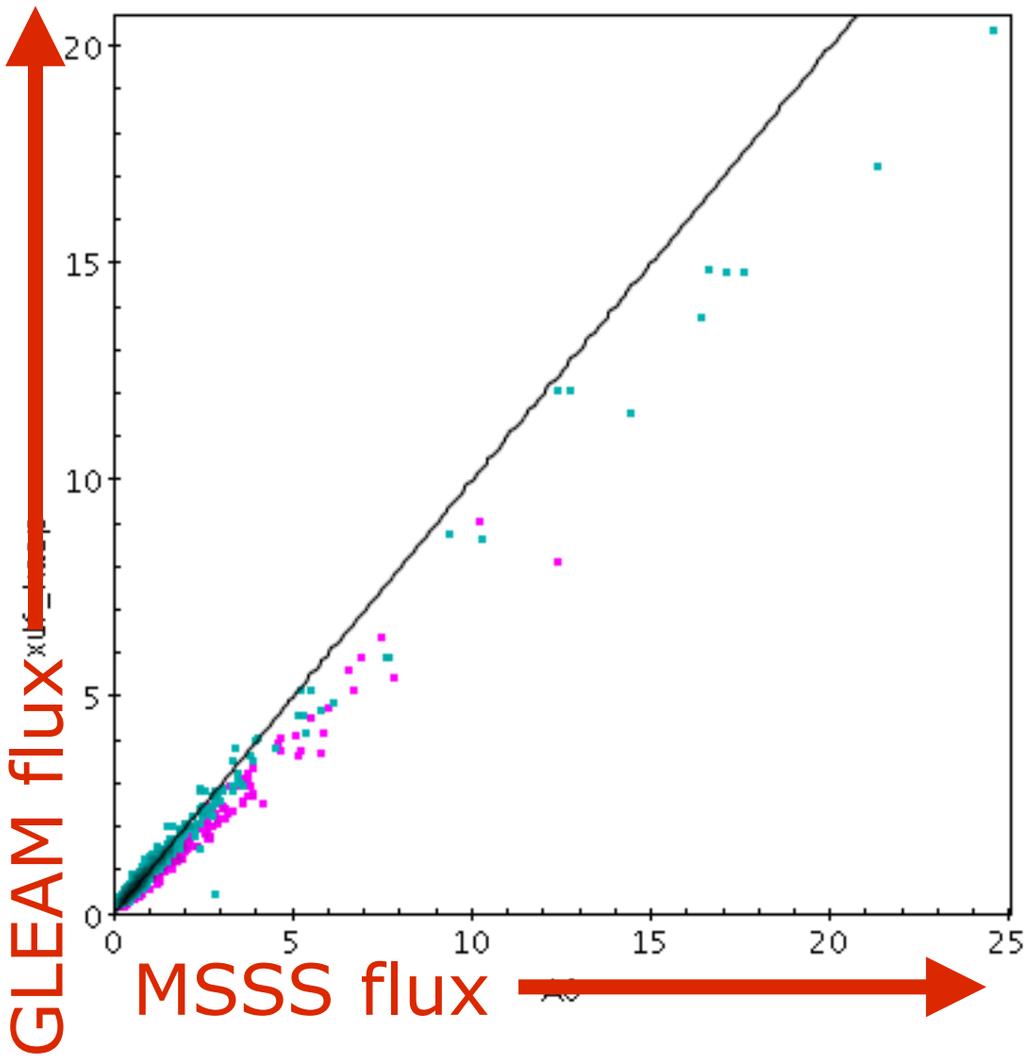
Zoomin comparison - MSSS

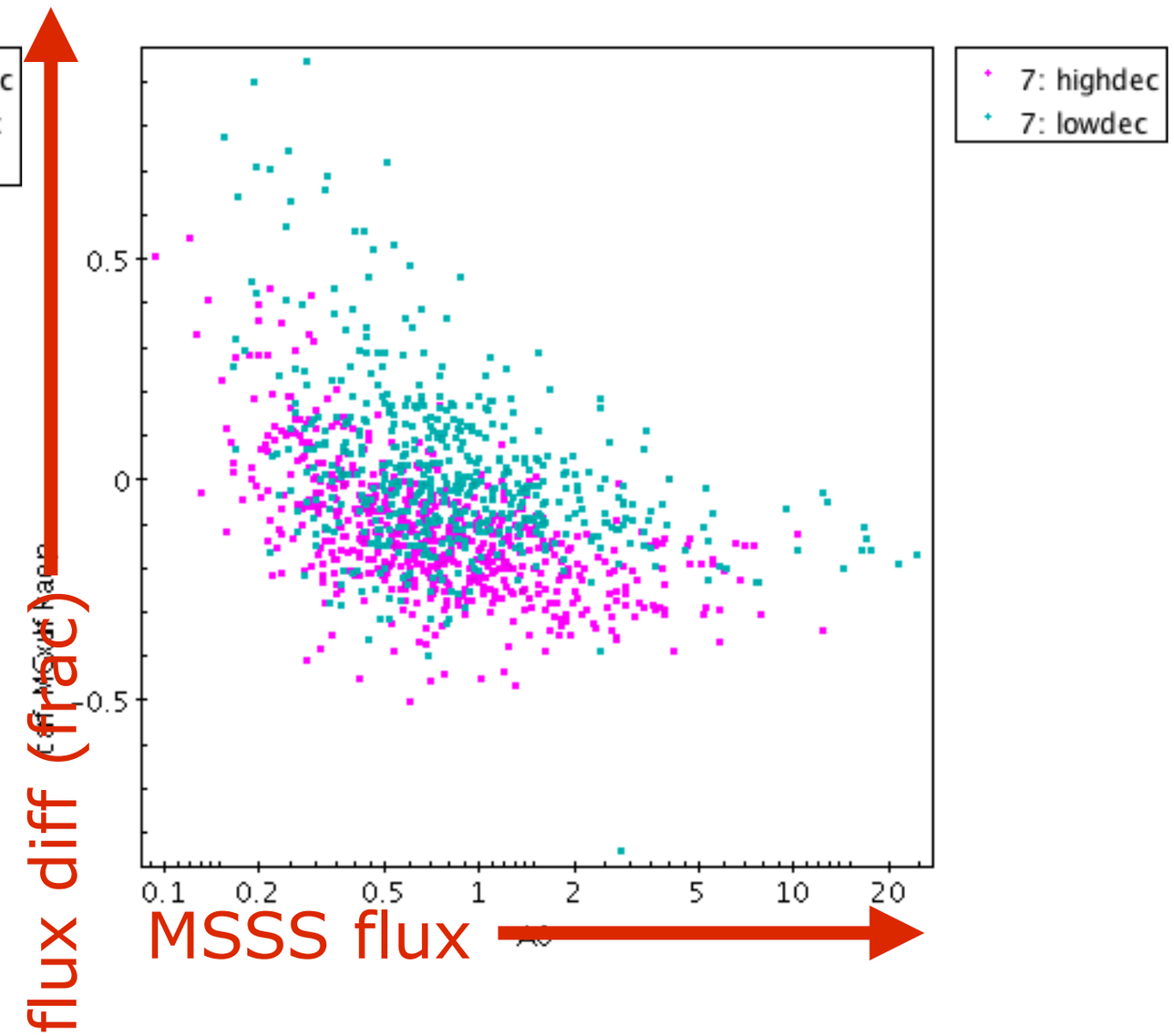


Comparing MSSS and GLEAM

- Initial flux density and position comparison:

  Dec dependent flux scale mismatch

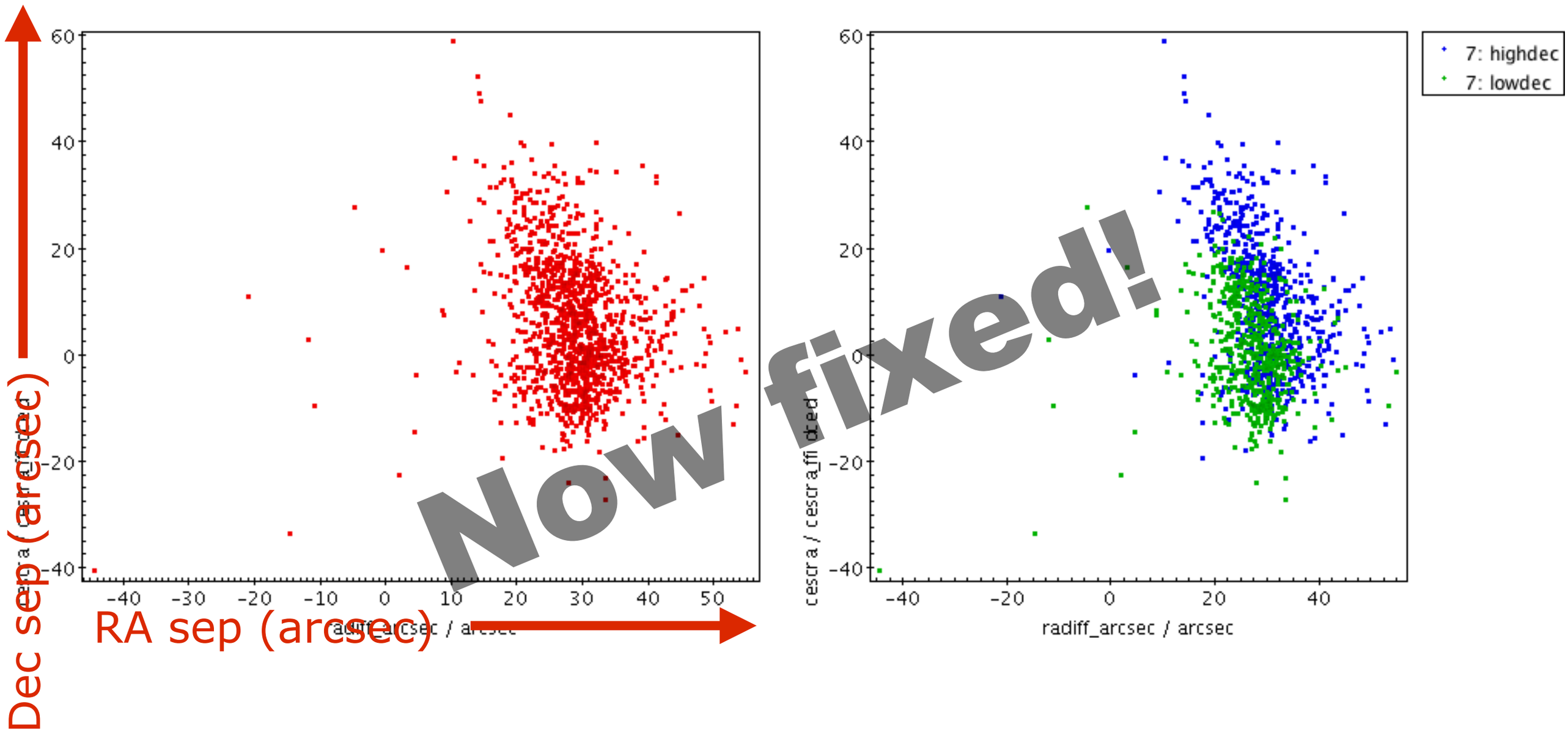




Comparing MSSS and GLEAM

- Initial flux density and position comparison:

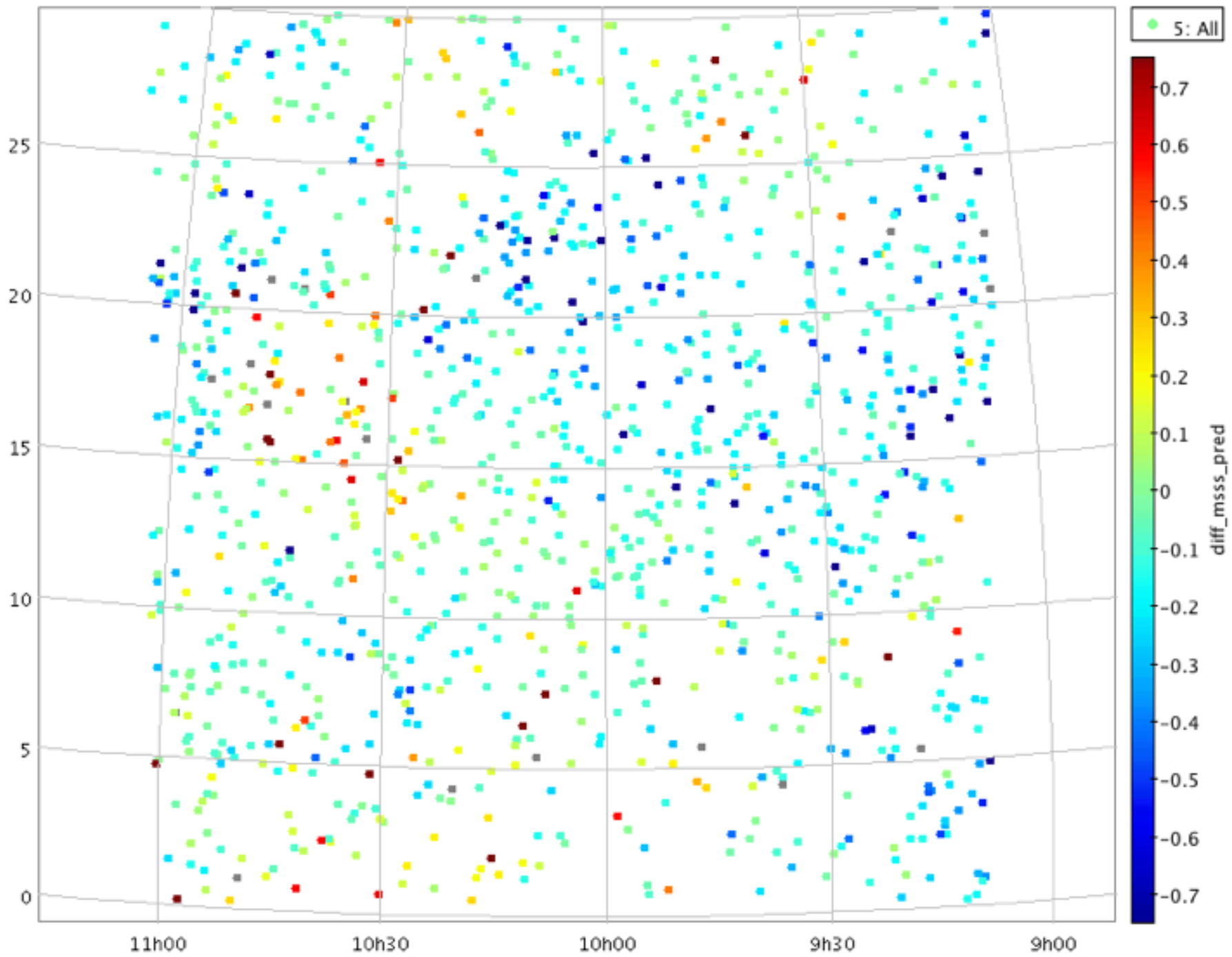
  Dec dependent positional offset



Comparing MSSS+GLEAM+others

- Comparison of MSSS and GLEAM fluxes with extrapolation from VLSSr and NVSS catalog values

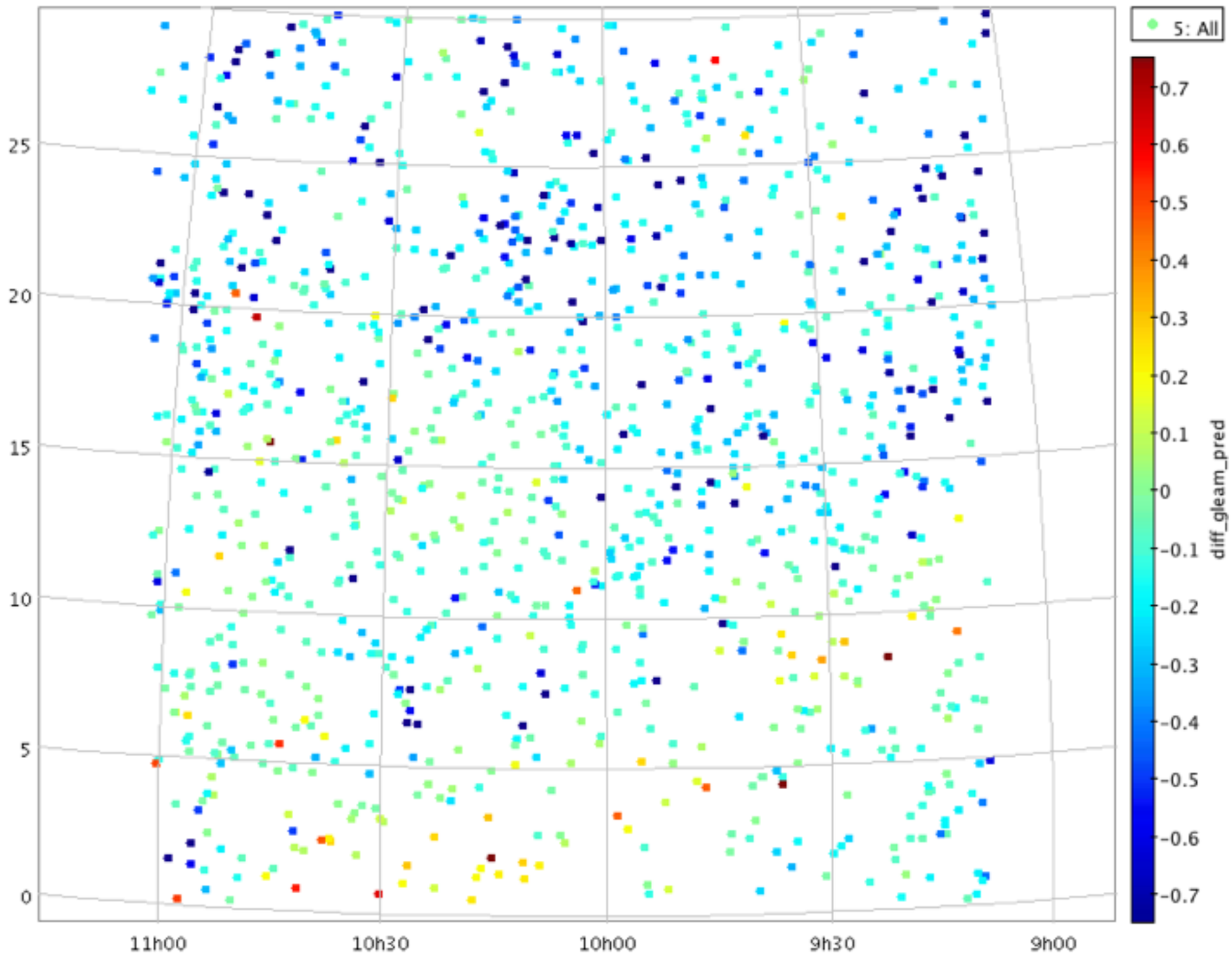
MSSS



Comparing MSSS+GLEAM+others

- Comparison of MSSS and GLEAM fluxes with extrapolation from VLSSr and NVSS catalog values

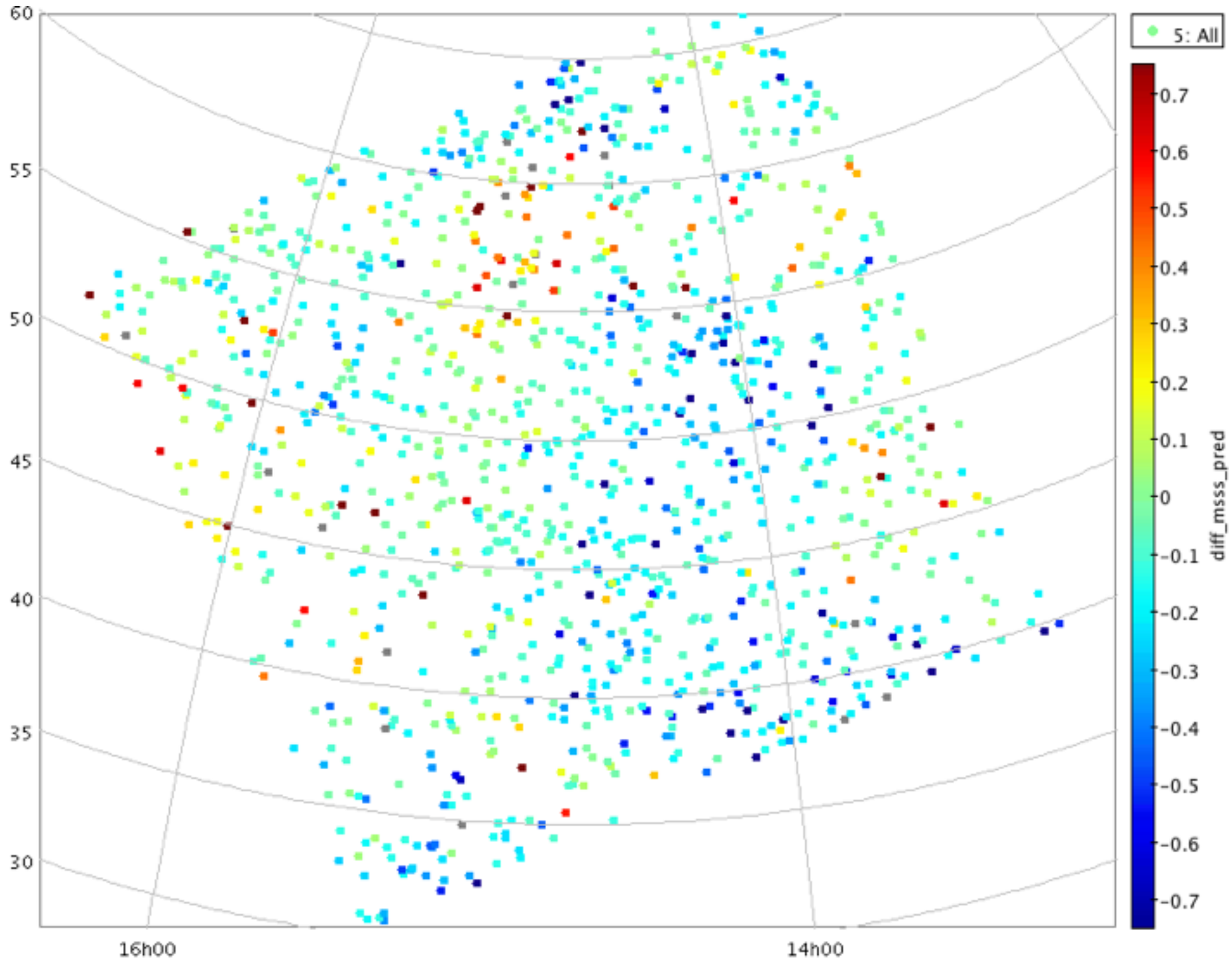
GLEAM



Comparing MSSS+GLEAM+others

- Comparison of MSSS and GLEAM fluxes with extrapolation from VLSSr and NVSS catalog values

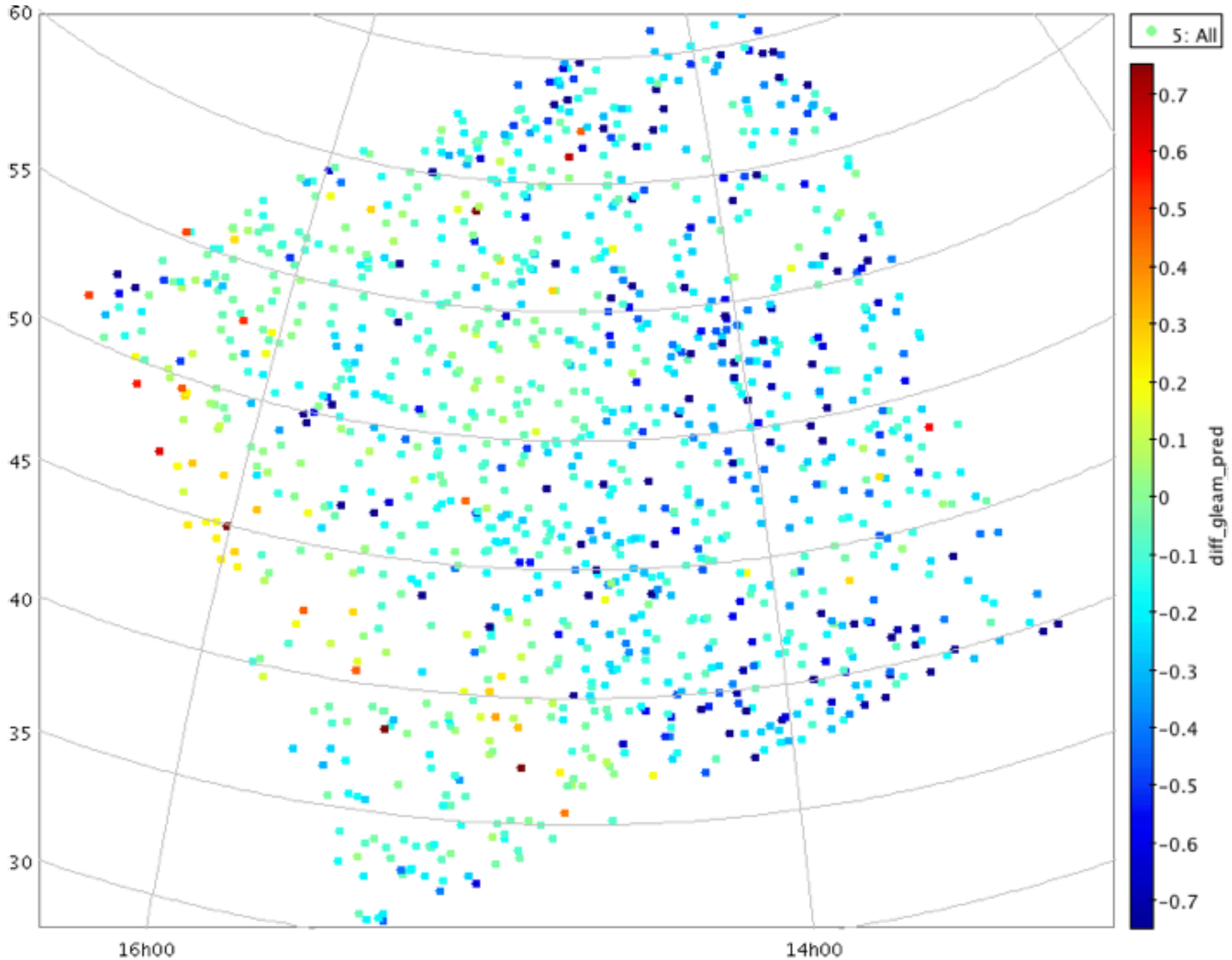
MSSS



Comparing MSSS+GLEAM+others

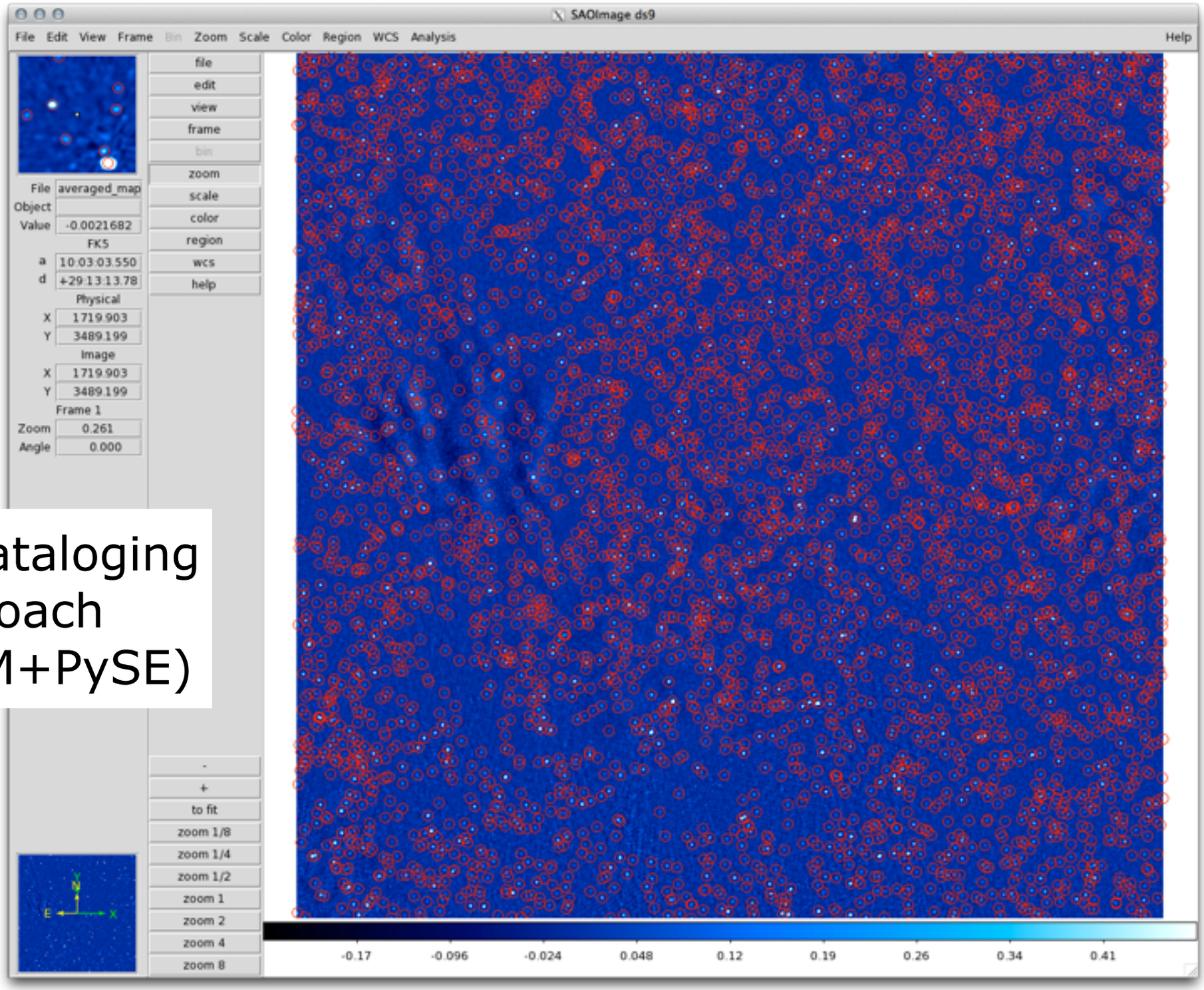
- Comparison of MSSS and GLEAM fluxes with extrapolation from VLSSr and NVSS catalog values

GLEAM



Comparing MSSS and GLEAM

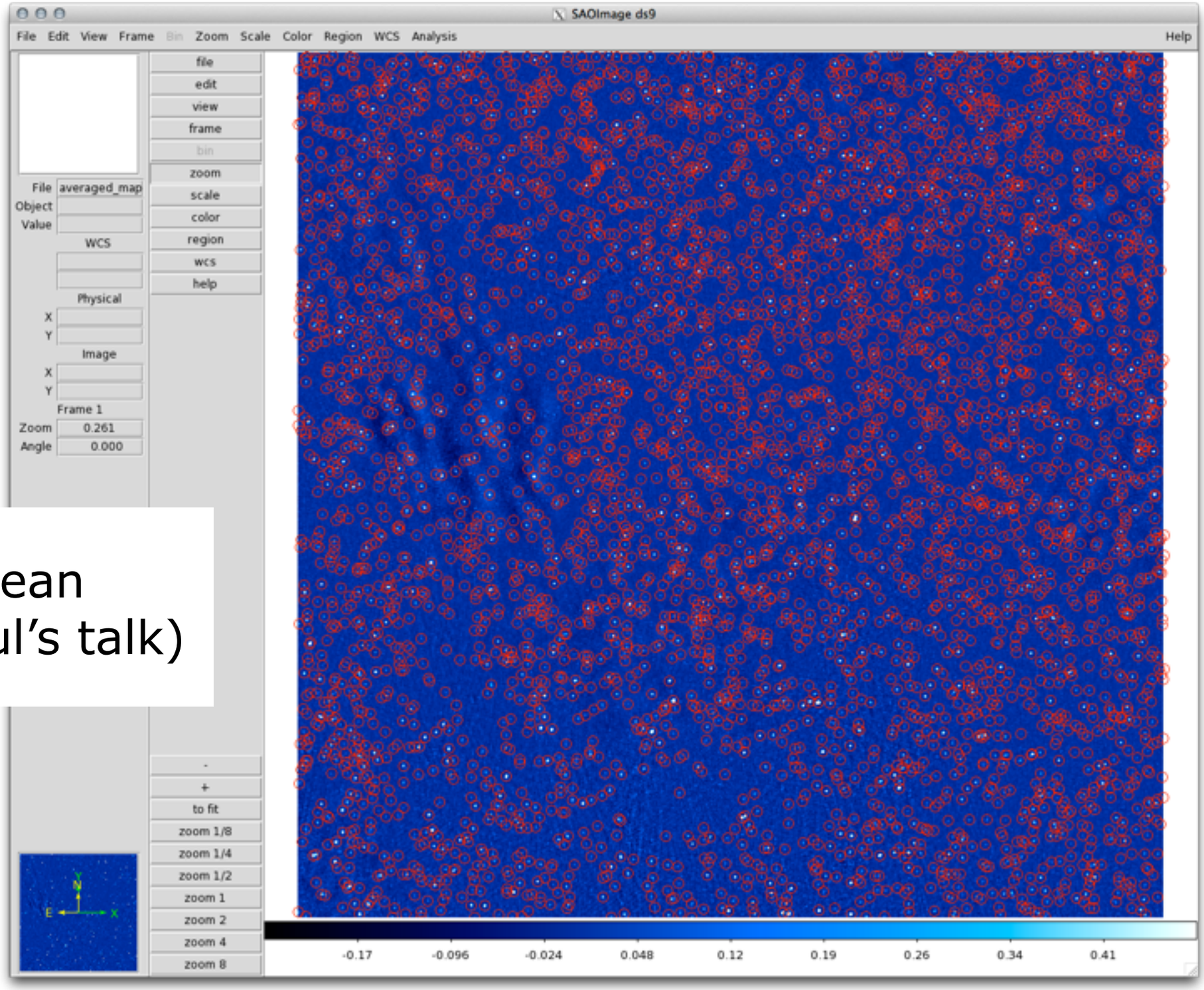
- Source finding / catalog creation also under study



LOFAR cataloging approach (PyBDSM+PySE)

Comparing MSSS and GLEAM

- Source finding / catalog creation also under study



Aegean
(see Paul's talk)

Summary

- MSSS has made excellent progress in the HBA segment, work on LBA continuing soon
- Stay tuned for description paper with Verification Field results, coming soon
- "Version 0" data products in hand and being used to pursue early science projects
  - Broad range of science topics e.g. transients, clusters, GRGs,…
- "Version 1" data products to be wrapped up soon, to be public next year
- "Version 2" (high resolution ~20-30", polarization) in the works
- MSSS-GLEAM overlap region very interesting both technically and scientifically (transient search?)
  - May immediately provide crucial flux scale information
  - Prospect of a truly **ALL**-sky interferometric radio survey!