



Netherlands Institute for Radio Astronomy

# LOFAR MSSS

*Multifrequency Snapshot Sky Survey*

## Status and results

George Heald (MSSS Project Leader)  
(on behalf of the MSSS Team)  
GerFeest, 04/11/2013



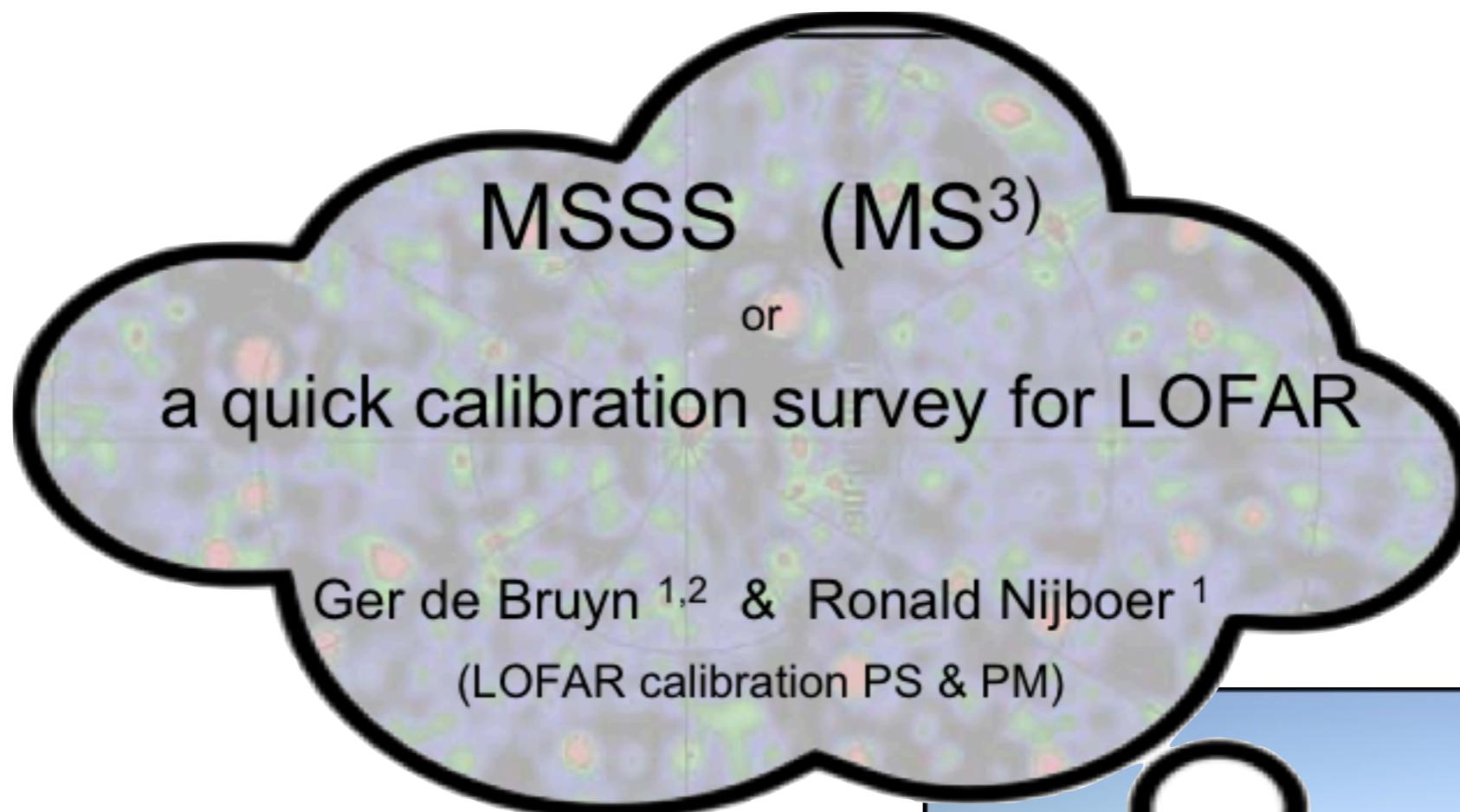
## Outline

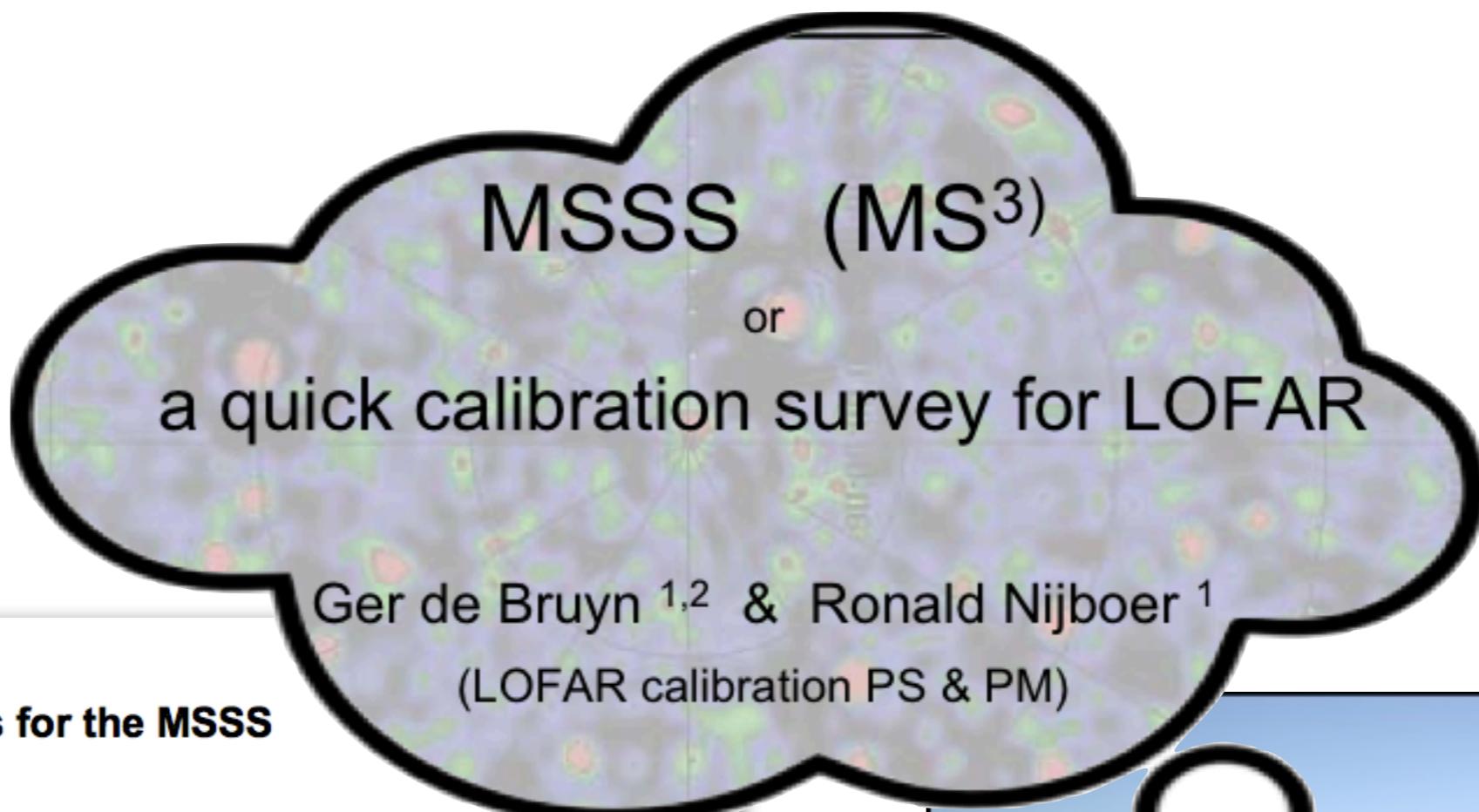
- MSSS: a brief history
- MSSS observational status
- Initial MSSS results
- MSSS in 2013/2014

- Roberto Pizzo
- Adebahr, Björn
- Bell, Michael
- Birzan, Laura
- Bonafede, Annalisa
- **Brentjens, Michiel**
- Breton, Rene
- Broderick, Jess
- Carbone, Dario
- Carroll, Patricia
- Cendes, Yvette
- Clarke, Alex
- Croston, Judith
- Daiboo, Soobash
- De Gasperin, Francesco
- **Fallows, Richard**
- Ferrari, Chiara
- Gregson, Jon
- Hardcastle, Martin
- Harwood, Jeremy
- Hassall, Tom
- Horneffer, Andreas
- Iacobelli, Marco
- Jelic, Vibor
- Jones, Dave
- Jurusik, Wojciech
- Macario, Giulia
- Martinez, Oscar
- McKean, John
- Montes, Pepe
- Mulcahy, David
- Nikiel-Wroczyński, Blazej
- Offringa, Andre
- **Orru, Emanuela**
- Pandey, V.N.
- Pietka, Gosia
- Pommier, Mamta
- Prasad, Peeyush
- Riseley, Chris
- Rowlinson, Antonia
- Sabater Montes, José
- Scaife, Anna
- Scheers, Bart
- Shulevski, Alexandar
- Sobey, Charlotte
- Sotomayor-Beltran, Carlos
- Stewart, Adam
- Stroe, Andra
- Swinbank, John
- Tasse, Cyril
- ter Veen, Sander
- van der Horst, Alexander
- van der Tol, Bas
- van Velzen, Sjoert
- van Weeren, Reinout
- Williams, Wendy

# The MSSS Team

- Roberto Pizzo
  - Adebahr, Björn
  - Bell, Michael
  - Birzan, Laura
  - Bonafede, Annalisa
  - **Brentjens, Michiel**
  - Breton, Rene
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  - Carroll, Patricia
  - Cendes, Yvette
  - Clarke, Alex
  - Croston, Judith
  - Daiboo, Soobash
  - De Gasperin, Fra
  - **Fallows, Richard**
  - Ferrari, Chiara
  - Gregson, Jon
- 
- A group photograph of seven people standing in a row, all wearing dark green t-shirts with the "M\*S\*S\*S" logo and "MULTIFREQUENCY SNAPSHOT SKY SURVEY 7991PD". They are indoors, with a large green plant visible behind them.
- Peeyush
  - Chris
  - Antonia
  - Montes, José
  - Anna
  - Bart
  - Alexander
- 
- A larger group photograph of ten people, including the previous group and several others, all wearing the same "M\*S\*S\*S" t-shirts. They are standing in two rows, with some people sitting in front. The background shows an indoor setting with a display board labeled "ASTRON".
- dam
  - ra
  - John
  - il
  - Sander
  - storst, Alexander
  - l, Bas
  - , Sjoert
  - n, Reinout
- Pommier, Mamta
  - Williams, Wendy





## Preliminary specifications for the MSSS

R.J. Nijboer & A.G. de Bruyn  
Version 5.0, 8-12-2008

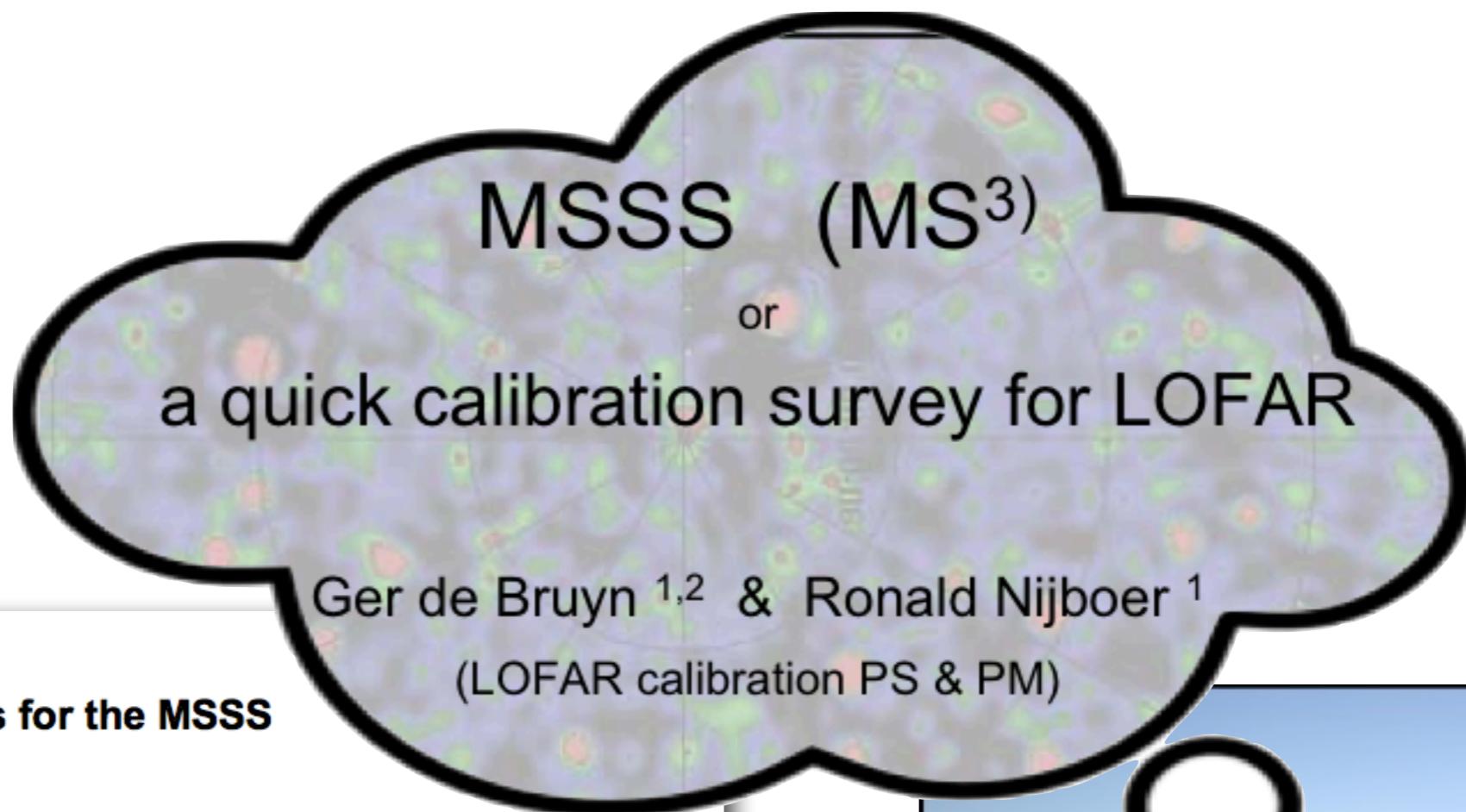
This document describes the preliminary specifications for the MSSS. These specifications are not final and we anticipate a final MSSS meeting in the spring of 2009 where we incorporate the results from the commissioning of LOFAR8-12 that will take place in the Nov08 - Mar09 period.

### Introduction

For MSSS there are 13 core stations and 7 remote stations. The HBA core stations are split in two half stations.

For the LBA stations 48 dipoles out of 96 are selected. The numbers below are based on an effective station diameter of 32 m. A reduction in sensitivity due to tapering is not taken into





## Preliminary specifications for the MSSS

R.J. Nijboer & A.G. de Bruyn  
Version 5.0, 8-12-2008

This document  
not final and  
results from

## A revised plan for MSSS

R. Nijboer, G. de Bruyn, G. Heald, M. Wise

Version 0.1; 30-07-2010

**Introduction**  
For MSSS to  
half stations

For the LBA  
effective sta-

### Introduction

Since we started thinking in early 2008 [1] about doing an initial all sky survey with LOFAR, i.e. the Million Source Shallow Survey, much has happened. The current situation of the available hardware and software is notably different from what we expected it would be. Most notably:

- The number of stations is significantly different from our initially expected 13 CS + 7 RS + 3 EU stations. As of 27 July 2010 we have 26 validated stations (18 CS + 6 RS + 2 EU). Around October we can expect to have 35 validated stations [TBC] (24 CS + 8 RS + 3 EU). Due to weather conditions it is not to be expected that there will be any additional stations available.



# Why do a MS<sup>3</sup> ?

LOFAR20 needs a ***Global Sky Model (GSM)*** for the northern sky ( $\sim 21,000 \square^\circ$ ) in an early phase and which:

- has a proper flux scale
- has validated (initial) source parameters (spectrum, structure, ..)
- is astrometrically correct to better than 0.5"
- interfaces efficiently to calibration & imaging pipeline (LSM)

It will create a ***joint focus for activities*** related to scheduling, monitoring, processing, calibration & imaging

It will provide realistic requirements for early storage and processing

# What's in a name....?

- Definition of MSSS acronym changed from pre-2010 to now:

# MILLION SOURCE SHALLOW SURVEY



# What's in a name....?

- Definition of MSSS acronym changed from pre-2010 to now:

# MULTIFREQUENCY SNAPSHOT SKY SURVEY



Goals: obtain broadband sky model, shakedown LOFAR operations

## MSSS-LBA



Frequency: 30-75 MHz  
(8 x 2 MHz bands)

Resolution:  $\leq 100$  arcsec

Sensitivity:  $\leq 15$  mJy/beam

Area: 20,000 square degrees

**Number of Fields: 660**

Simultaneous beams: 5

## MSSS-HBA



Frequency: 120-160 MHz  
(8 x 2 MHz bands)

Resolution:  $\leq 120$  arcsec

Sensitivity:  $\leq 5$  mJy/beam

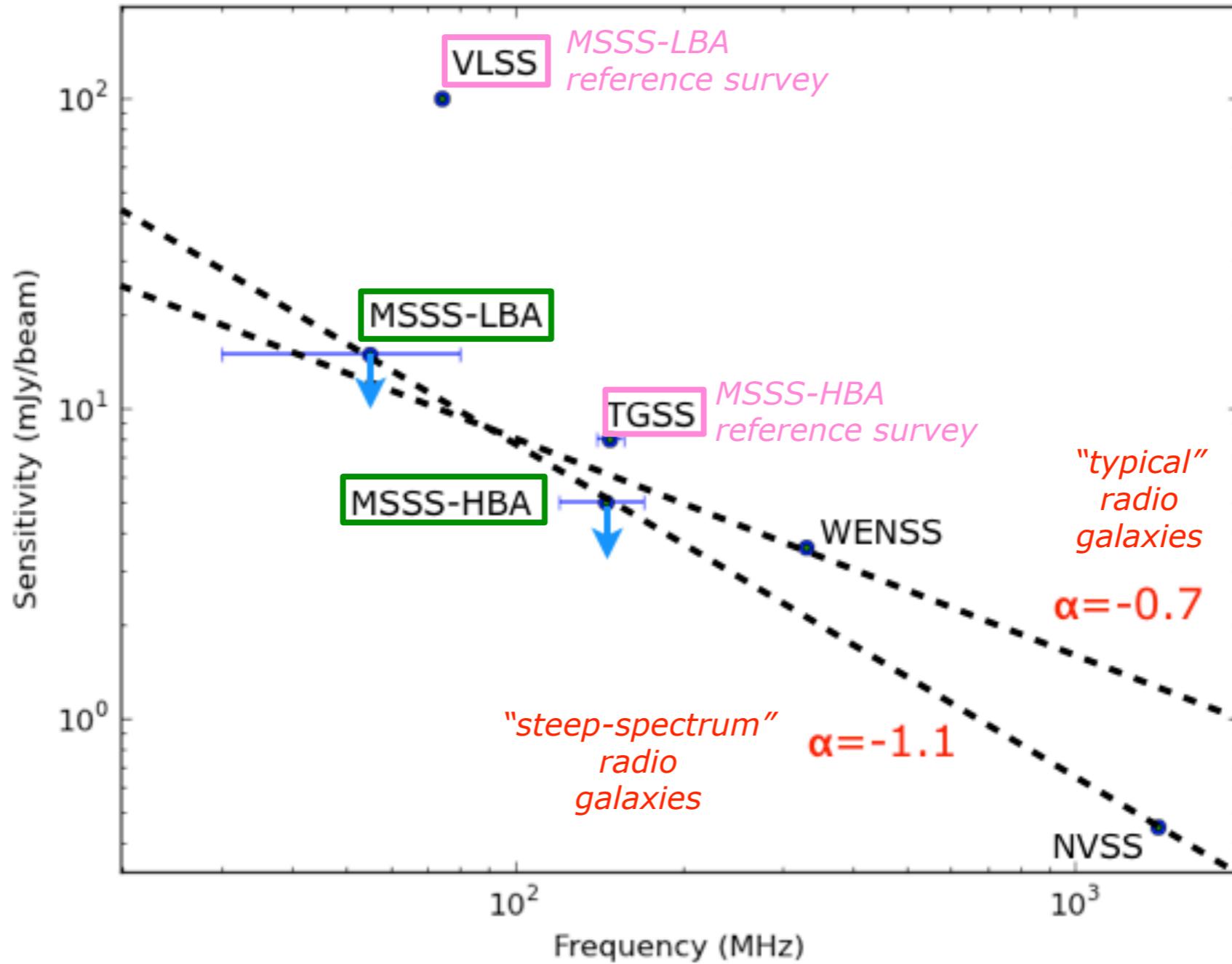
Area: 20,000 square degrees

**Number of Fields: 3616**

Simultaneous beams: 6

MSSS surveys the entire northern sky - **TWICE** - in 45 days

- MSSS covers a huge frequency span by itself, and matches well with existing radio surveys like WENSS and NVSS



- Highly complementary to other current surveys: TGSS and GLEAM

**MSSS observational status**

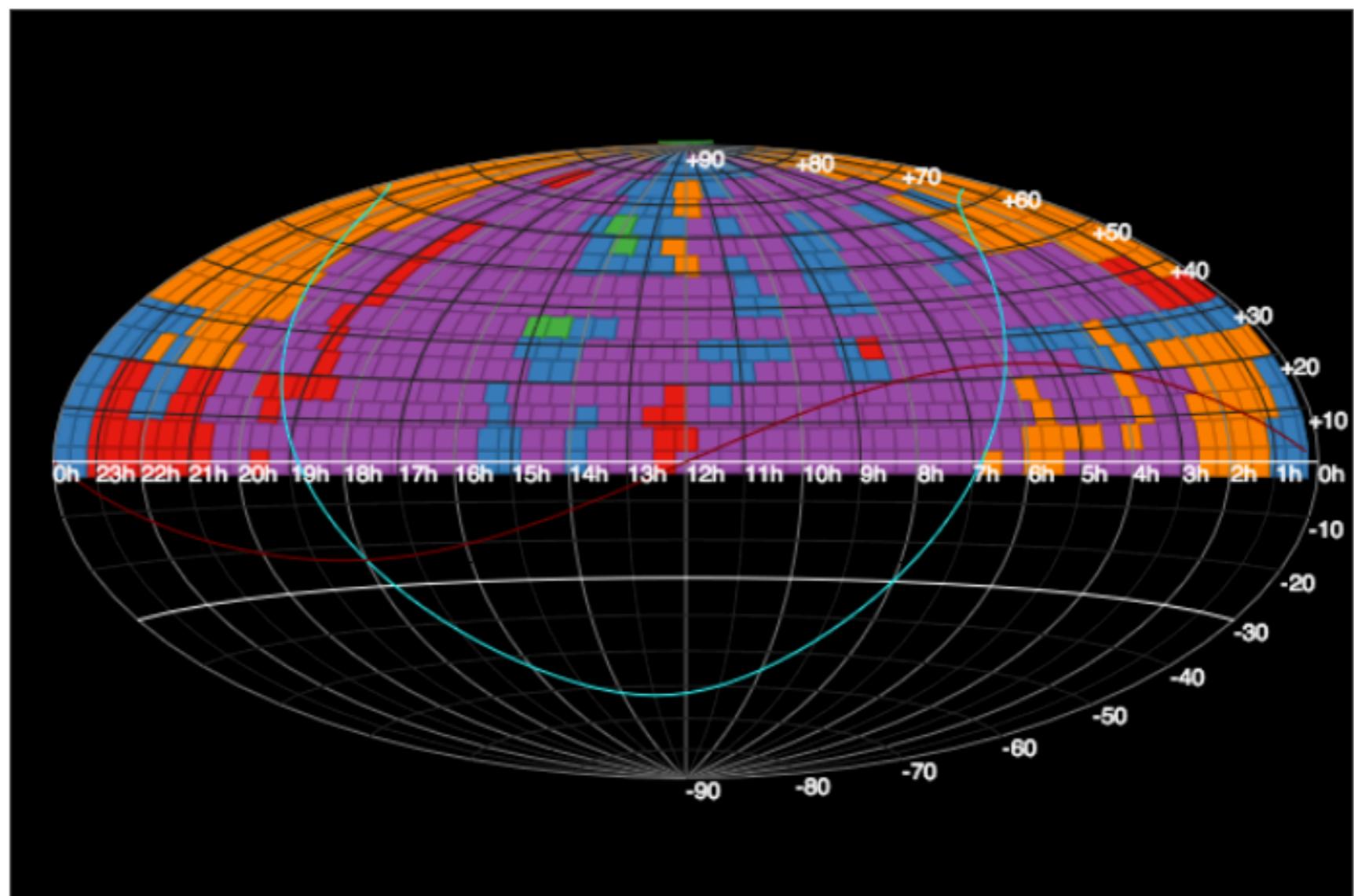
- About 80% observed in 2012; currently on hold

## LOFAR Observation Database

### MSSS LBA

Number of Targets	661
Number of Calibrators	8
Start Date	4 Nov. 2011
Stop Date	20 Jan. 2013
Completed Fields	382 (57.8%)
Information collected	18 March 2013

Show me the data »



**Swinbank**

Hammer Projection

Map based on code from [this project](#).

Data available on CEP (0.8%)  
Data archived (57.0%)  
Partial data available (16.3%)  
Data missing (7.4%)  
Not yet observed (18.5%)

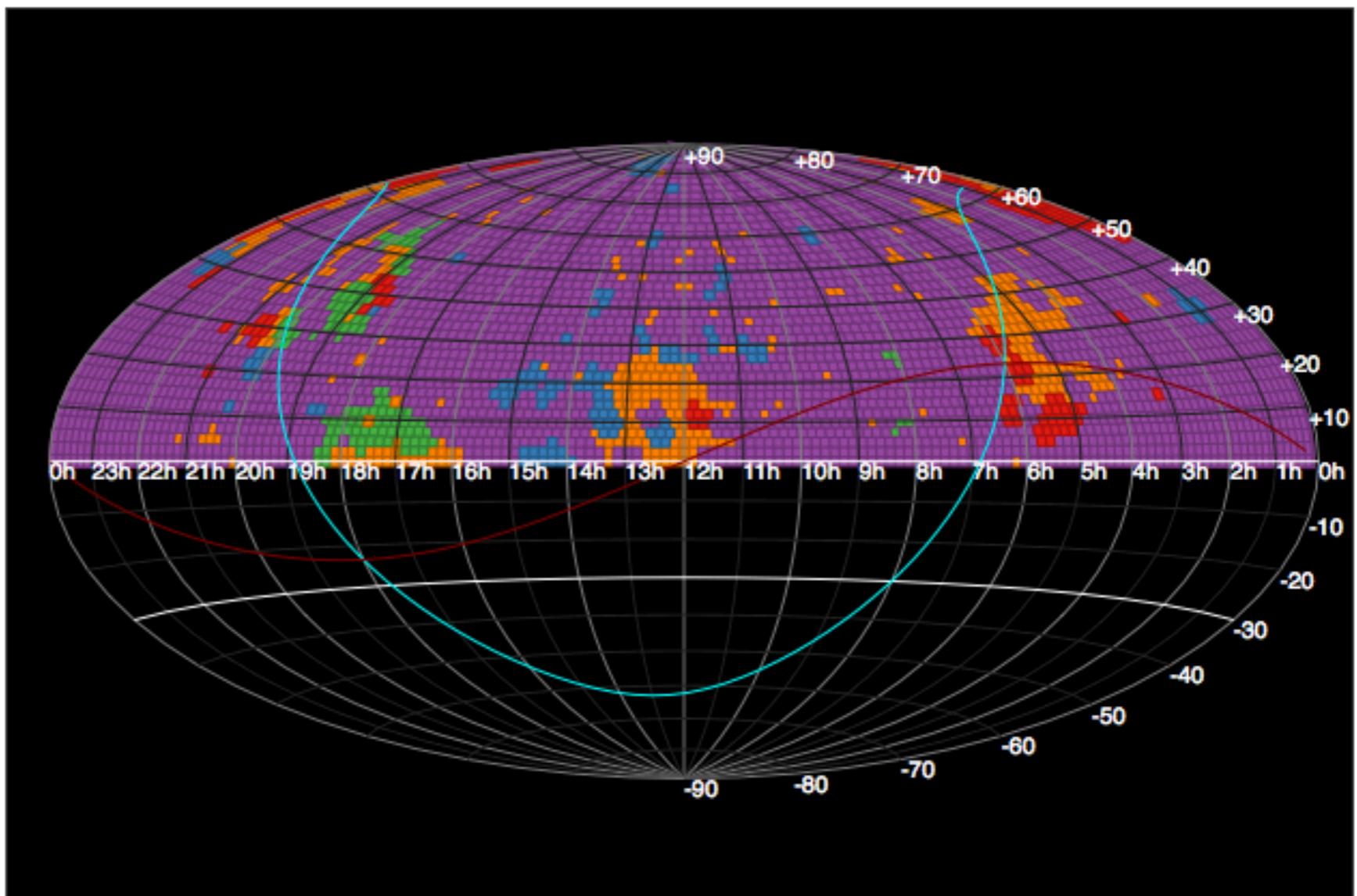
- MSSS-HBA is now almost 90% complete!

## LOFAR Observation Database

### MSSS HBA

Number of Targets	3616
Number of Calibrators	8
Start Date	8 Feb. 2013
Stop Date	4 Oct. 2013
Completed Fields	3063 (84.7%)
Information collected	29 Oct. 2013

Show me the data »



**Swinbank**

Hammer Projection

Map based on code from [this project](#).

Data available on CEP (2.9%)

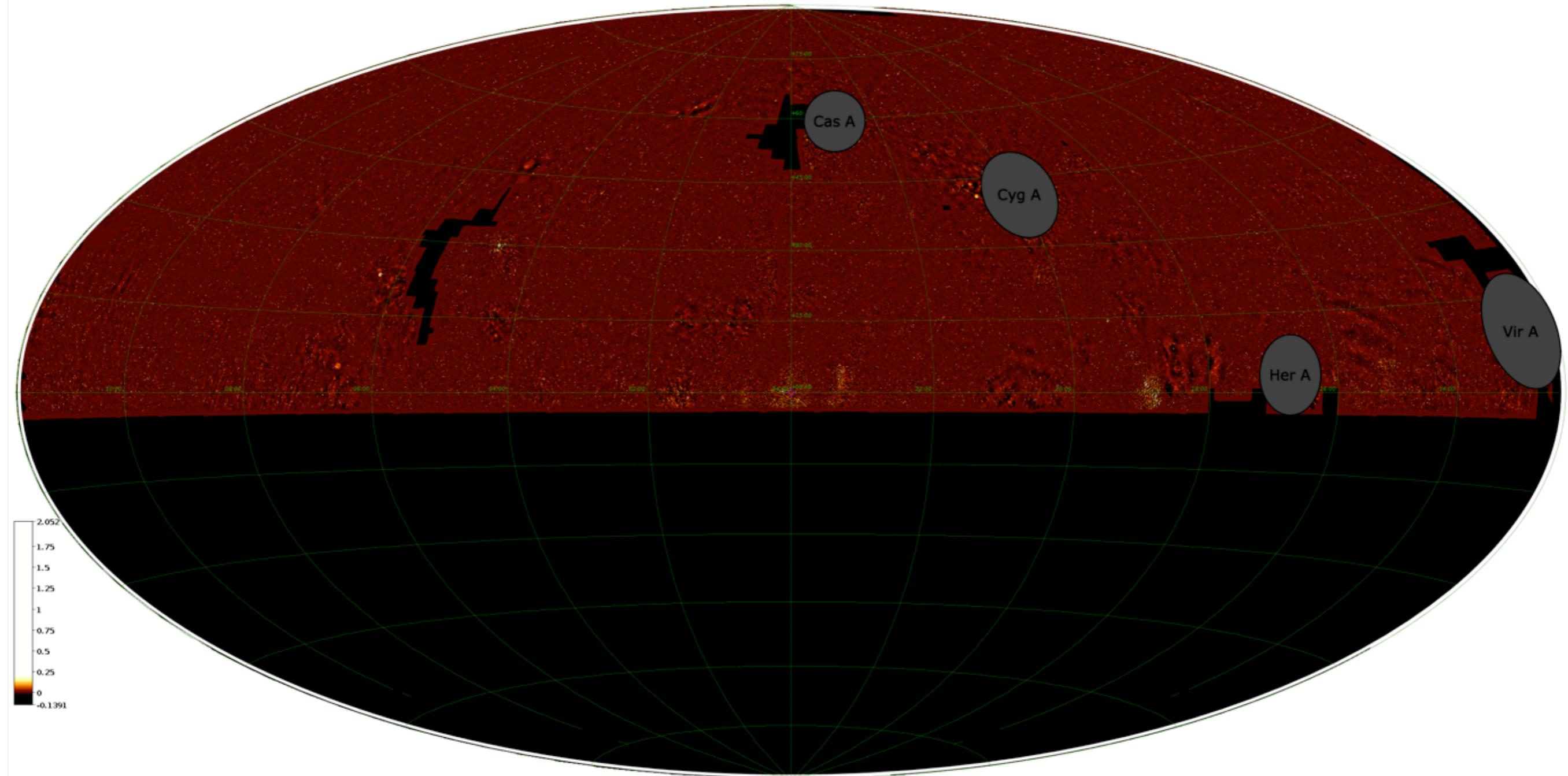
Data archived (81.3%)

Partial data available (3.2%)

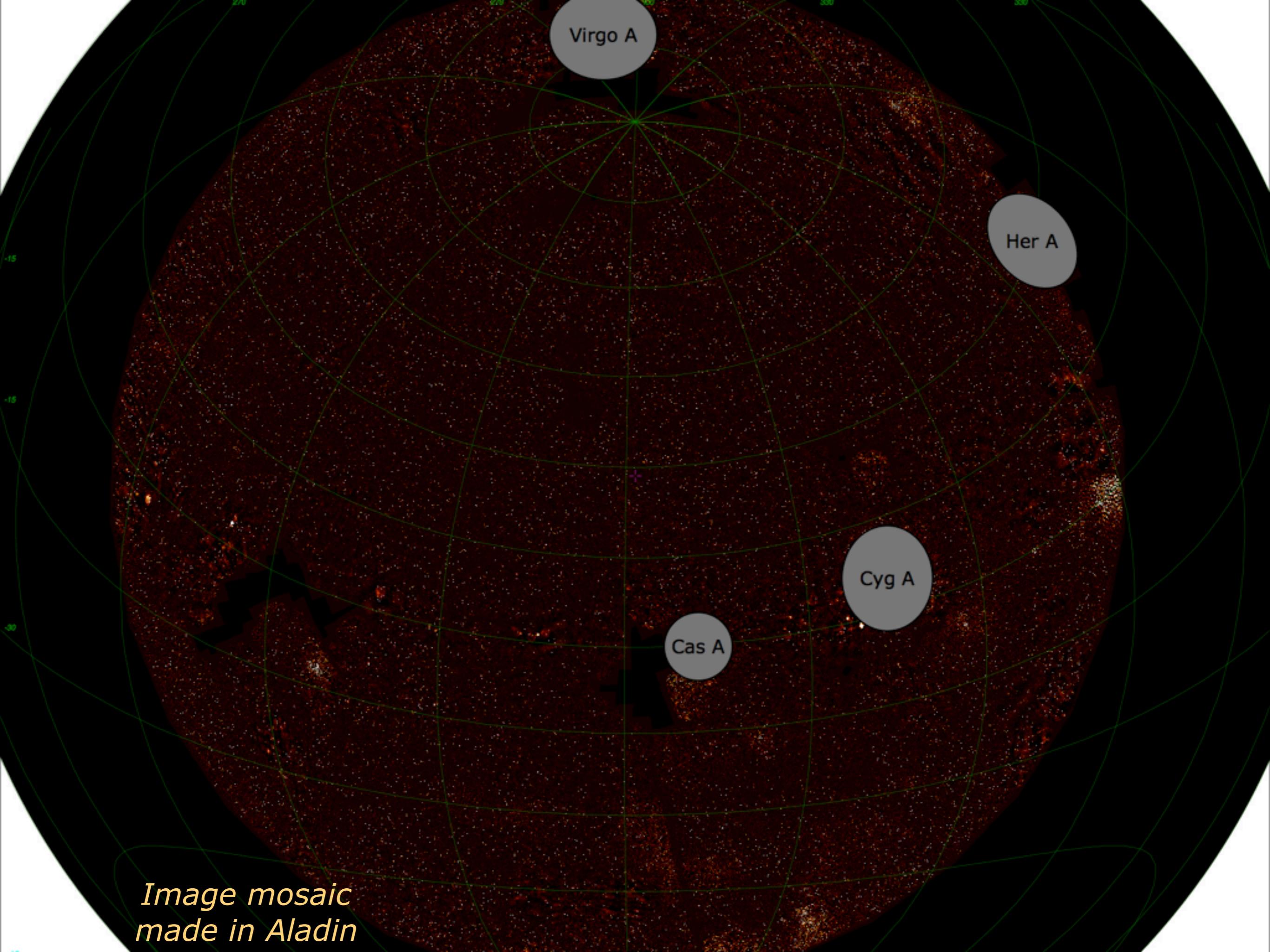
Data missing (3.0%)

Not yet observed (9.7%)

MEDIANALLSKY



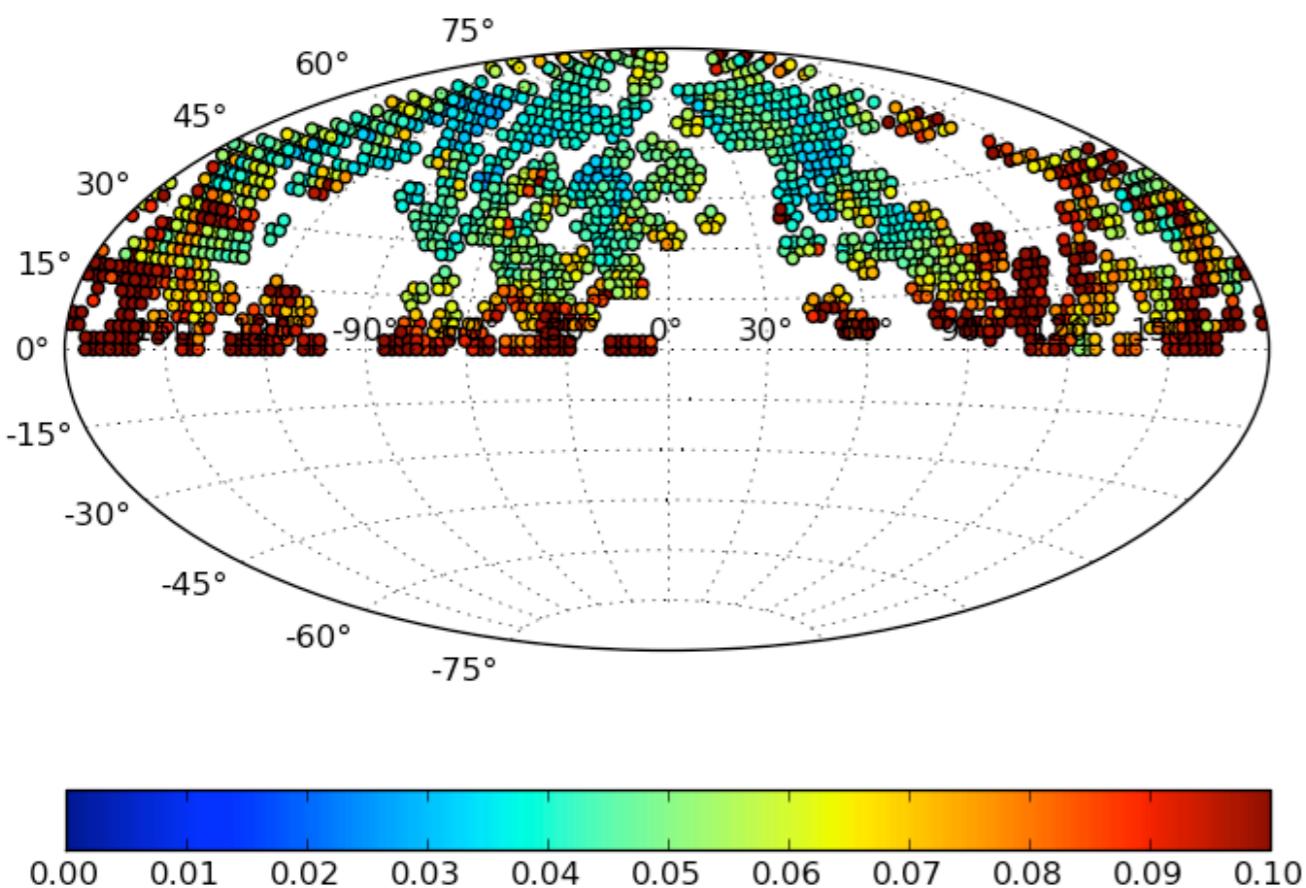
*Image mosaic  
made in Aladin*



*Image mosaic  
made in Aladin*

- Band 0 (120 MHz): 1767 fields

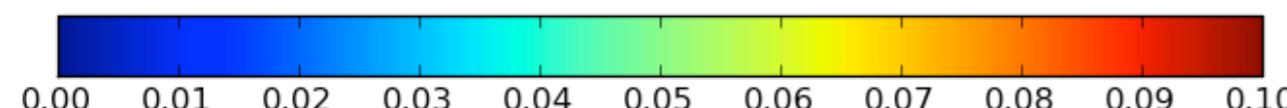
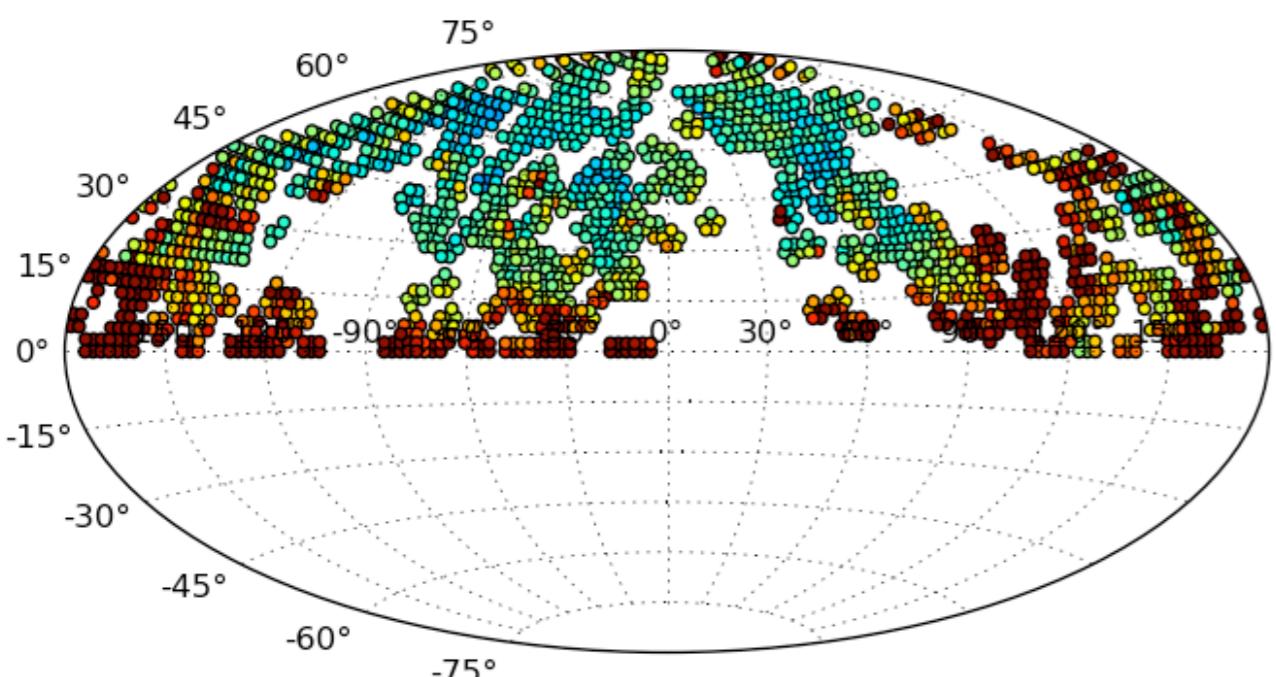
Equatorial J2000



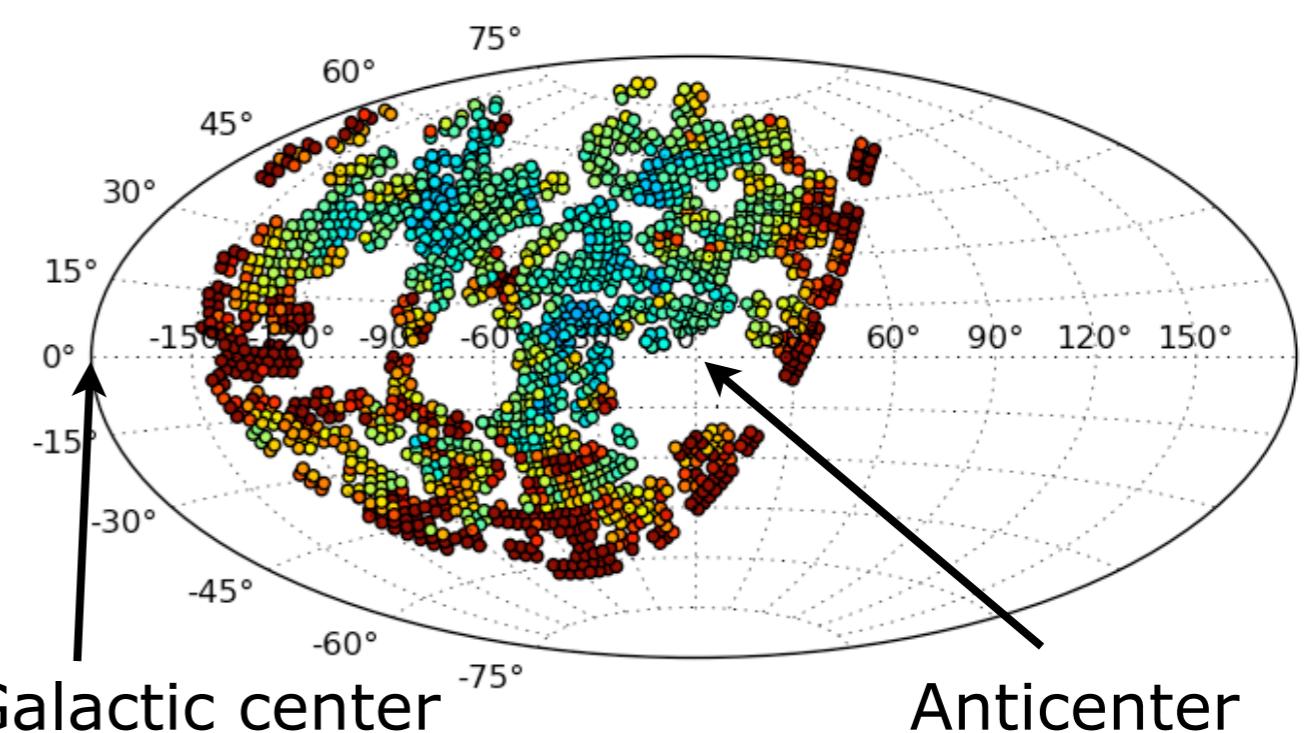
# Noise variation with sky position

- Band 0 (120 MHz): 1767 fields

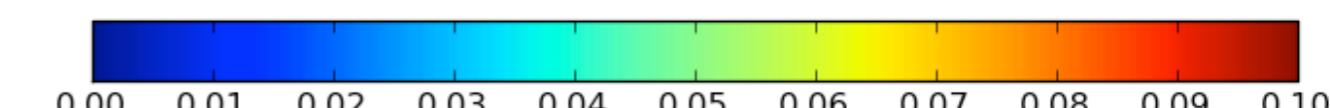
Equatorial J2000



Galactic



Galactic center

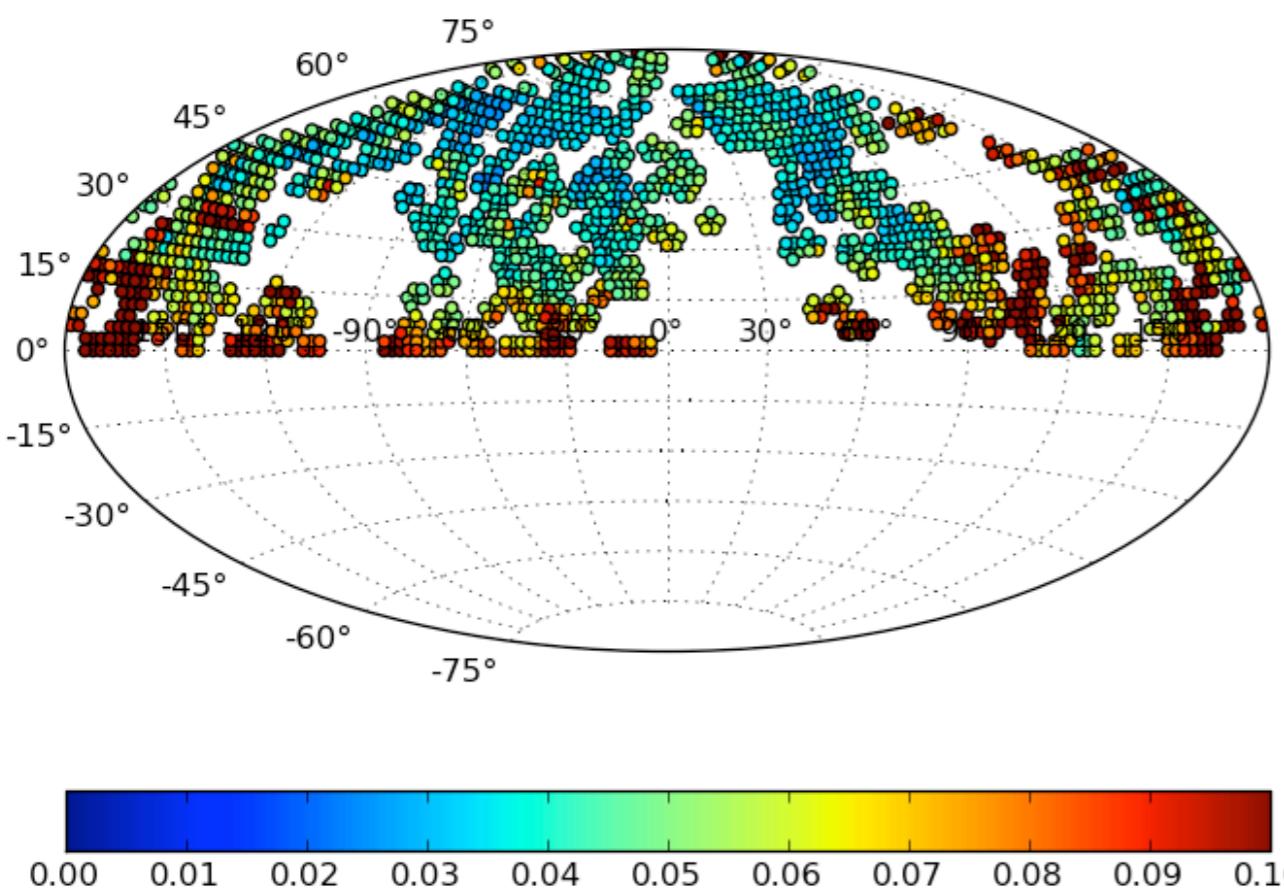


Anticenter

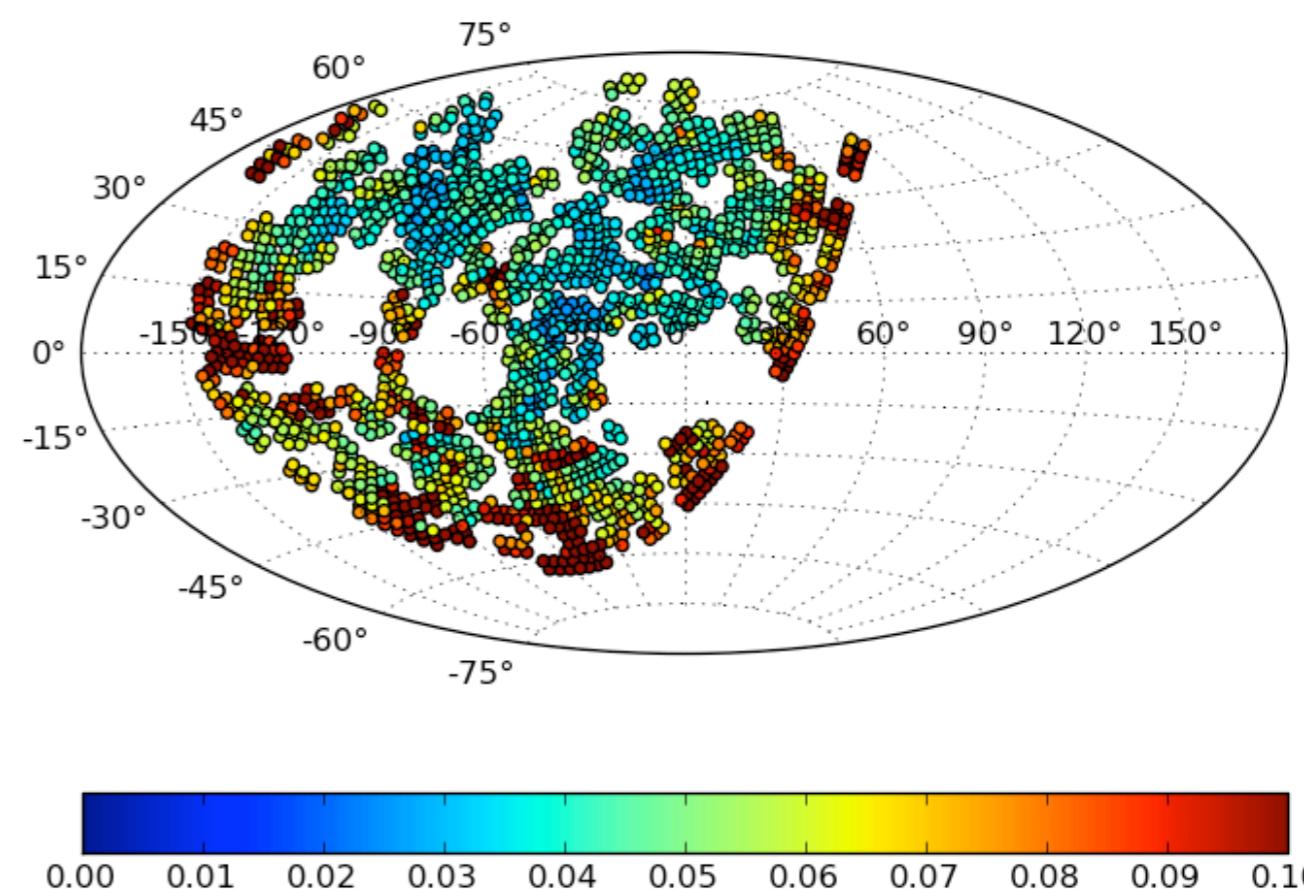
# Noise variation with sky position

- Band 1 (125 MHz): 1779 fields

Equatorial J2000



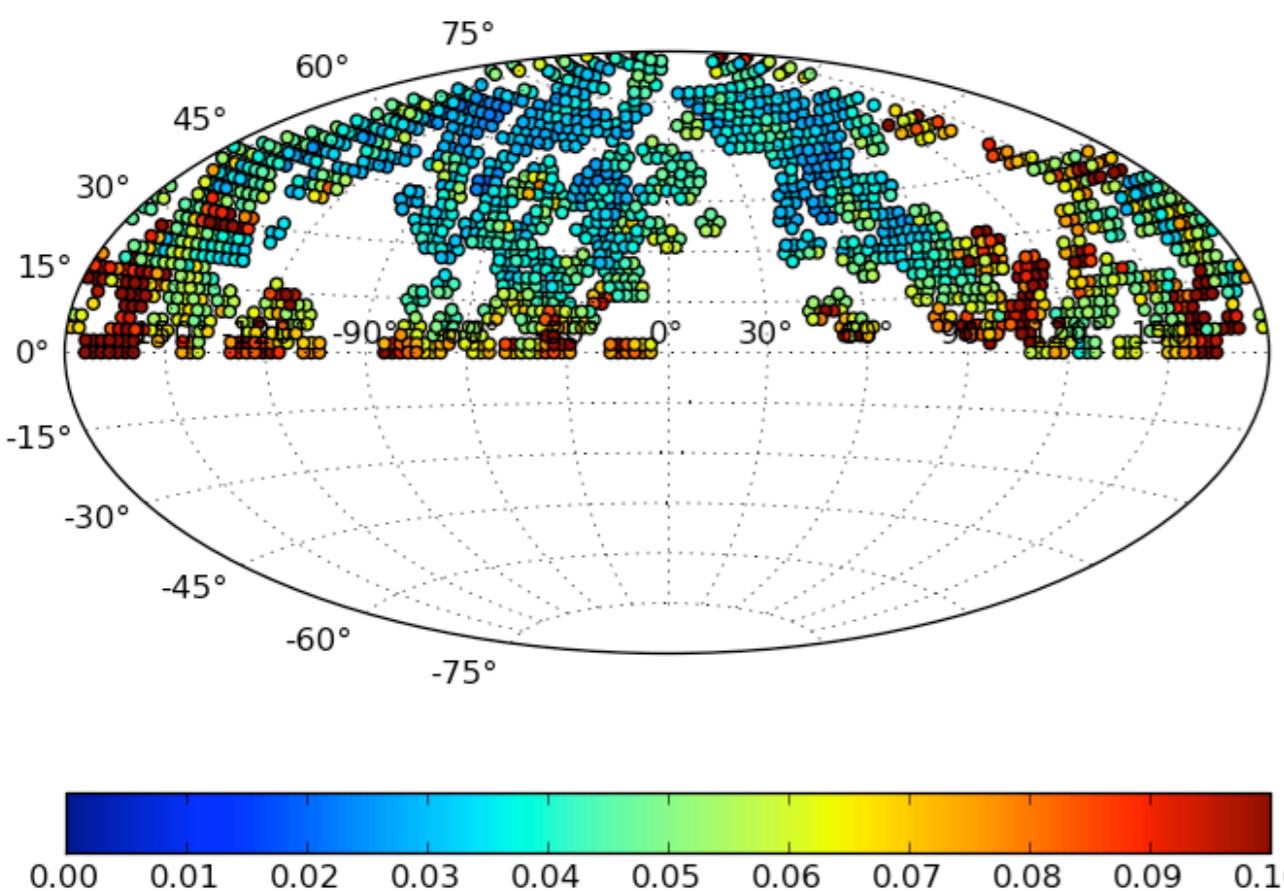
Galactic



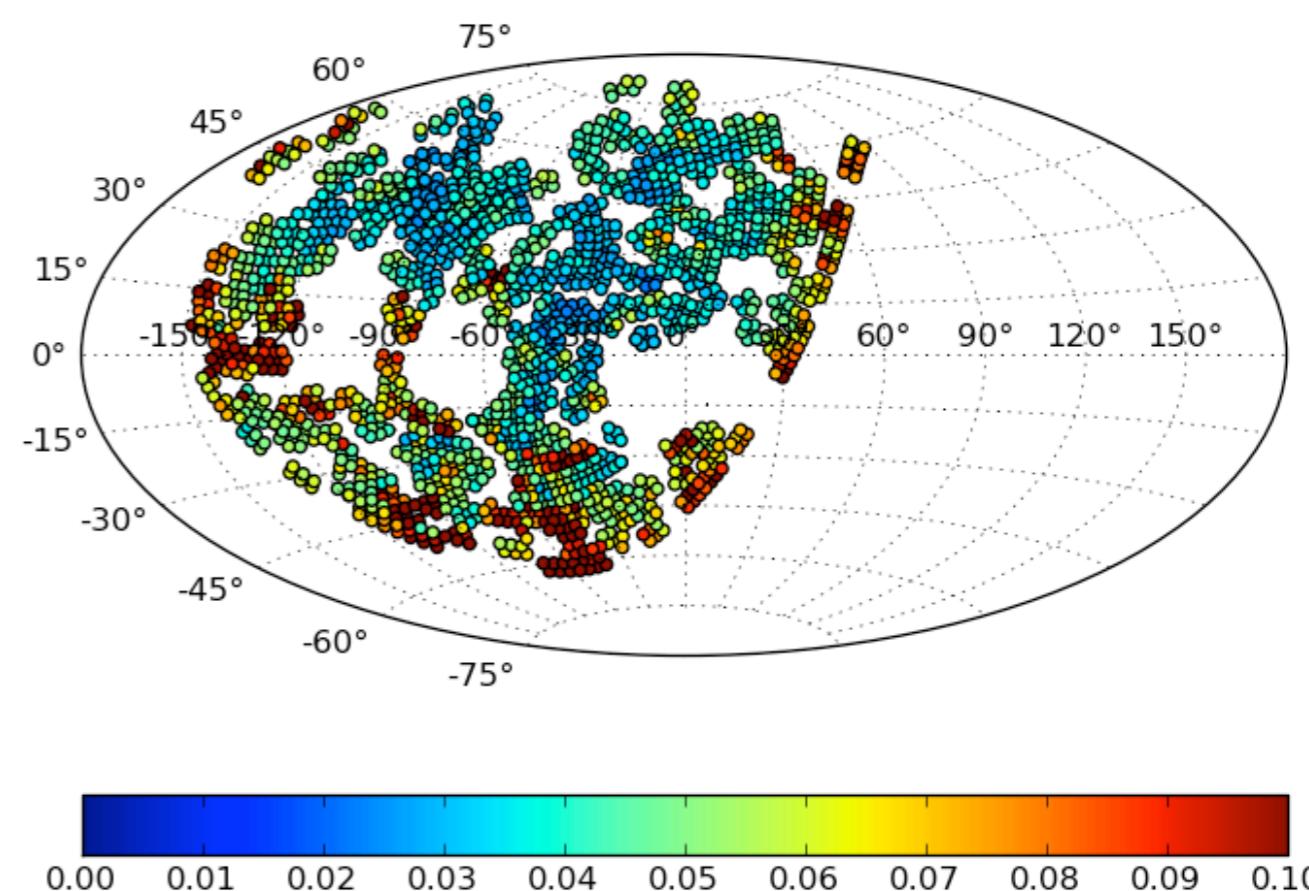
# Noise variation with sky position

- Band 2 (129 MHz): 1781 fields

Equatorial J2000



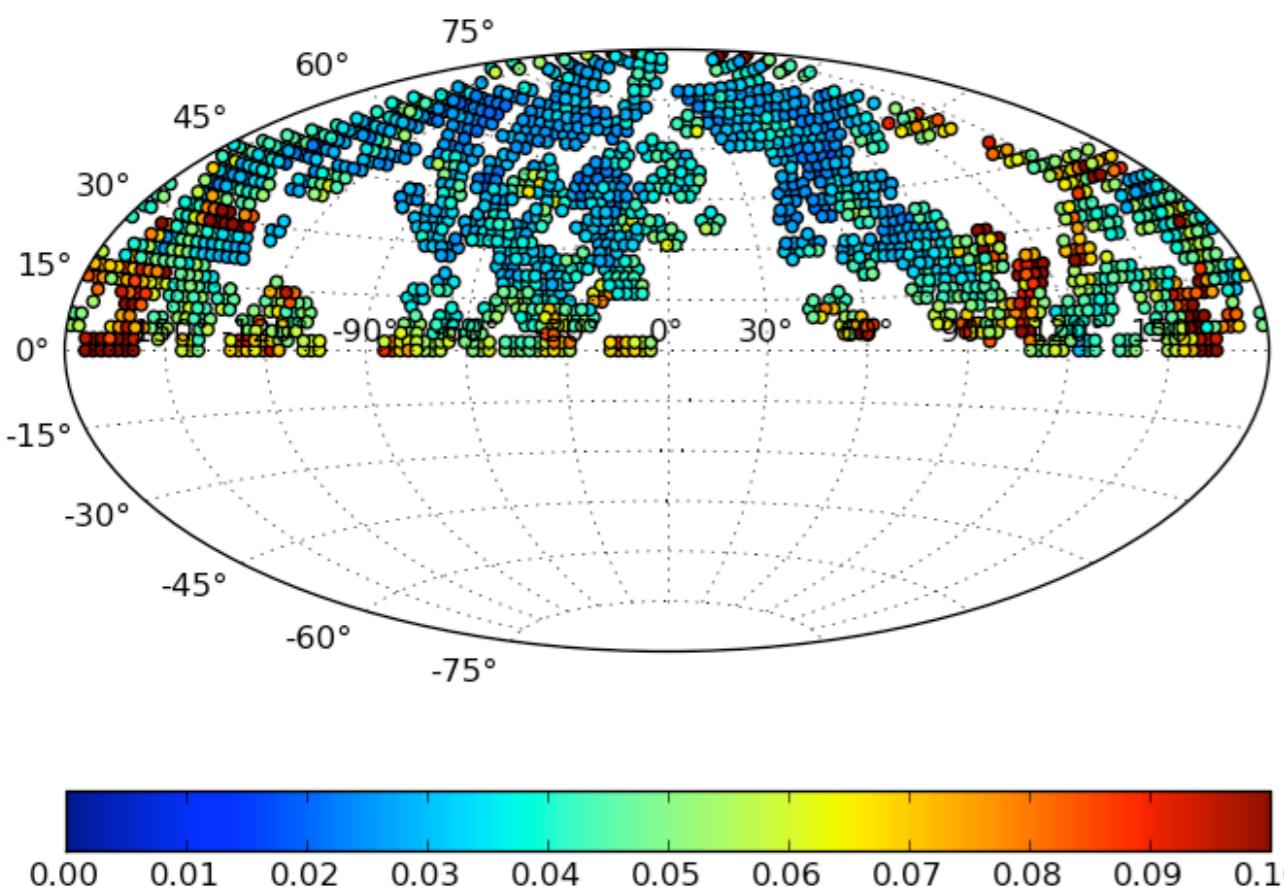
Galactic



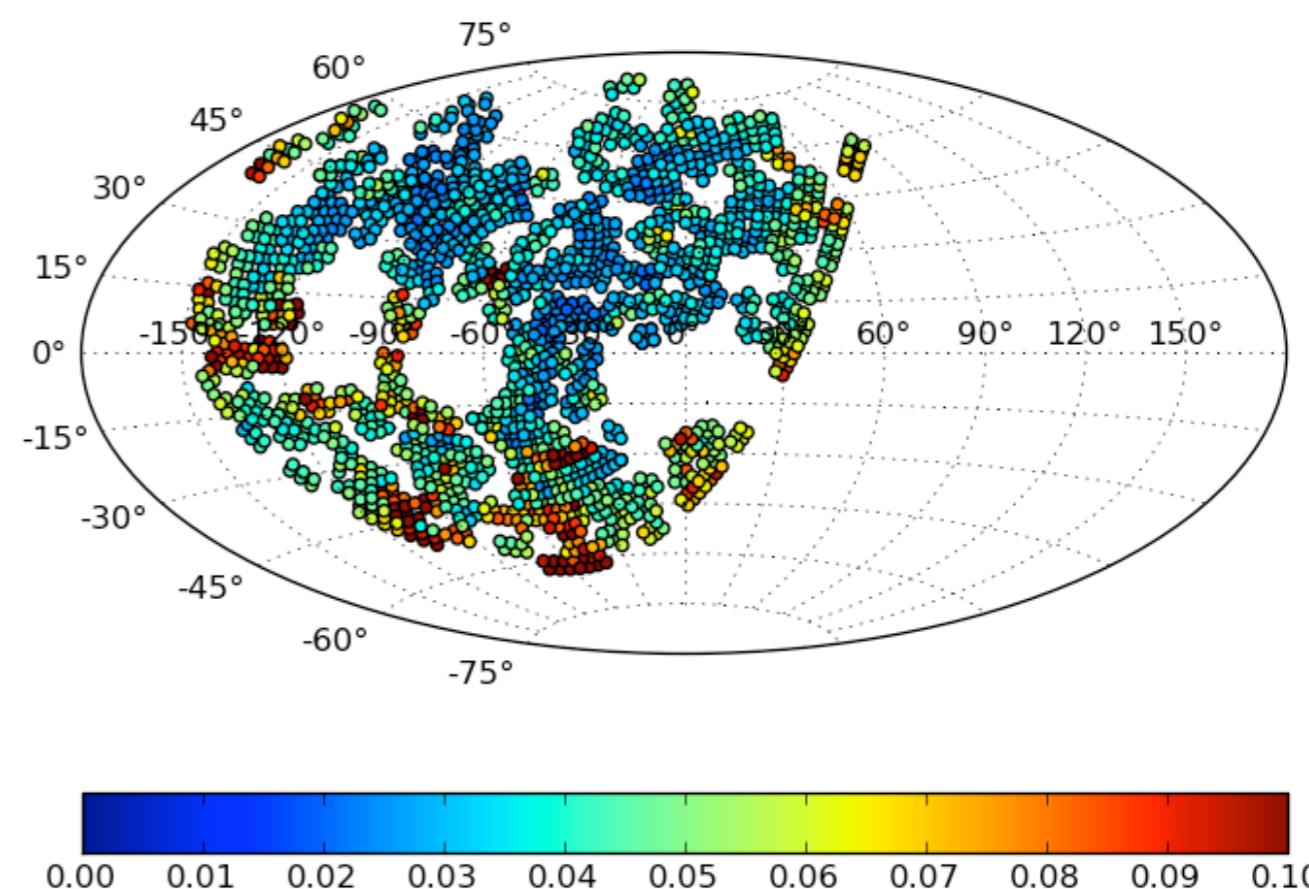
# Noise variation with sky position

- Band 3 (135 MHz): 1781 fields

Equatorial J2000



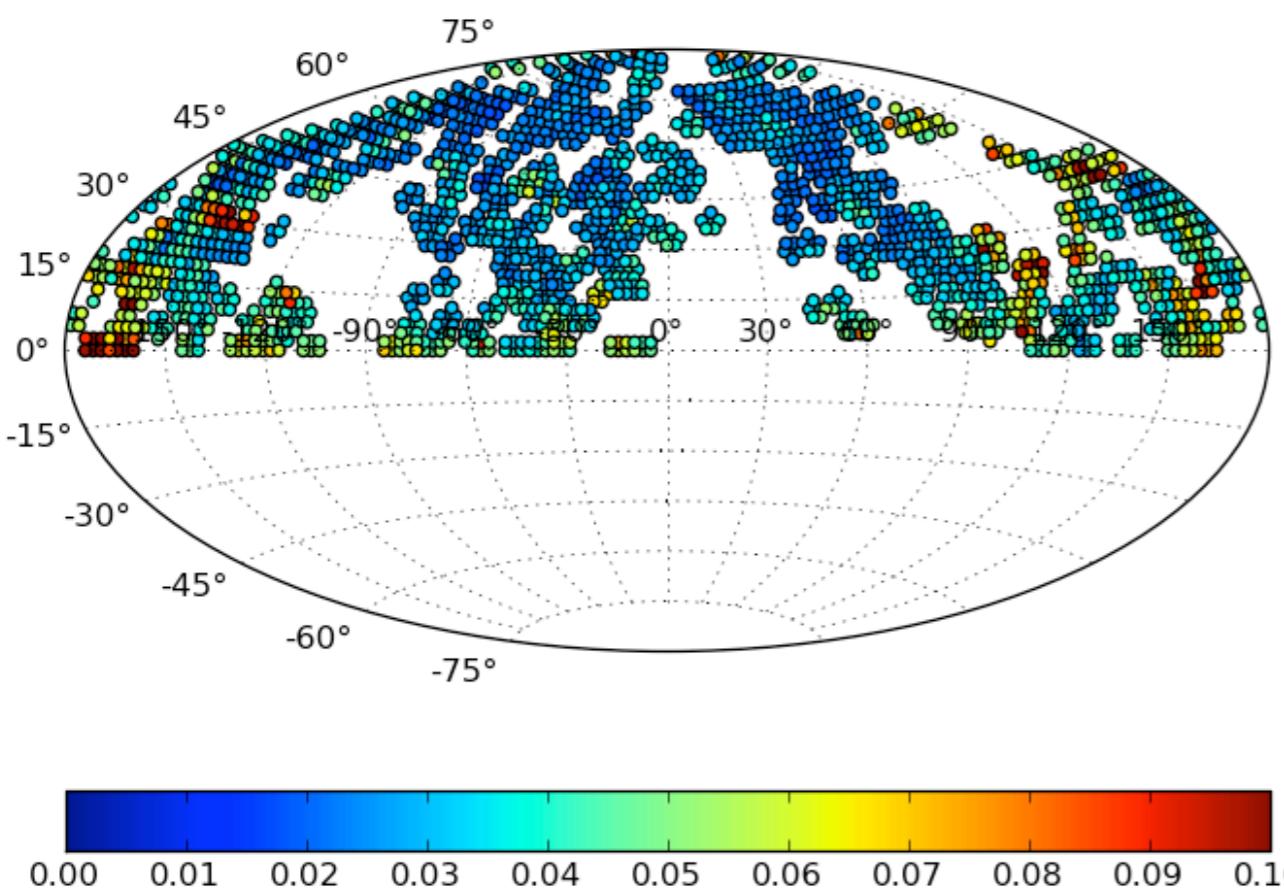
Galactic



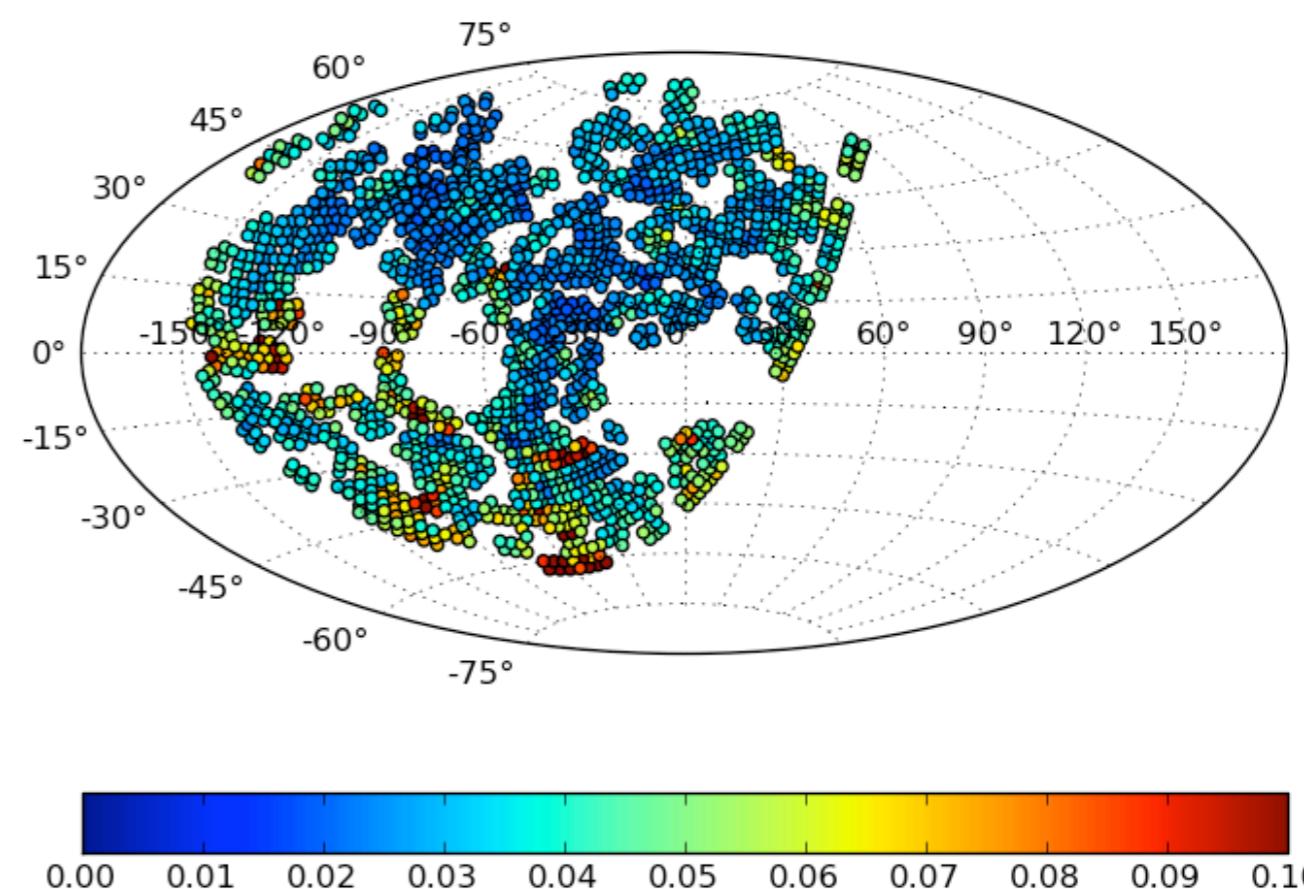
# Noise variation with sky position

- Band 4 (143 MHz): 1781 fields

Equatorial J2000



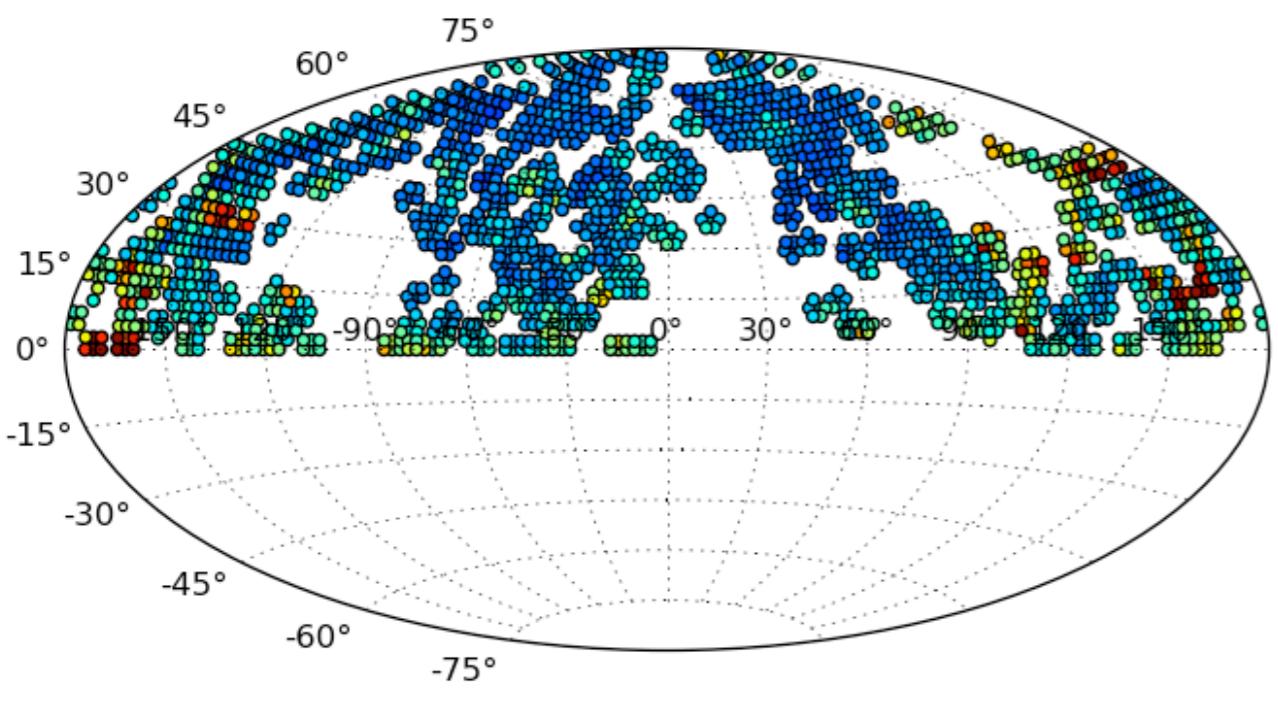
Galactic



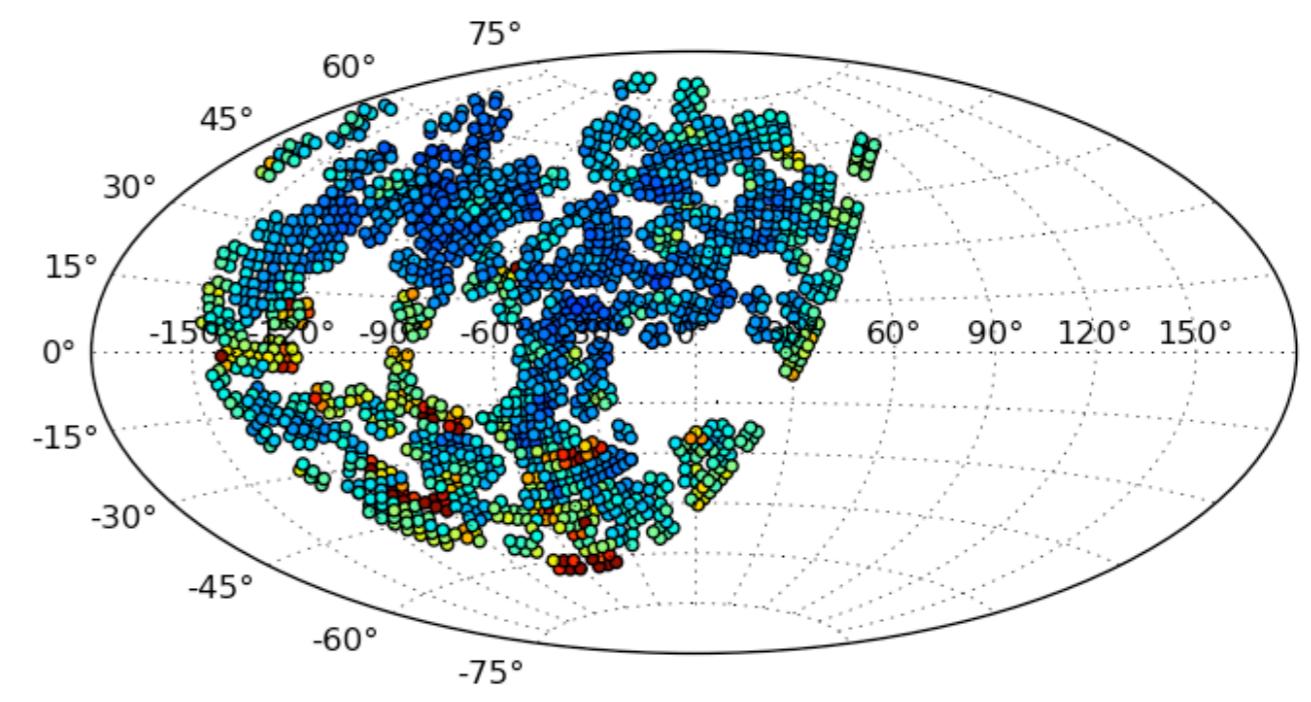
# Noise variation with sky position

- Band 5 (147 MHz): 1776 fields

Equatorial J2000



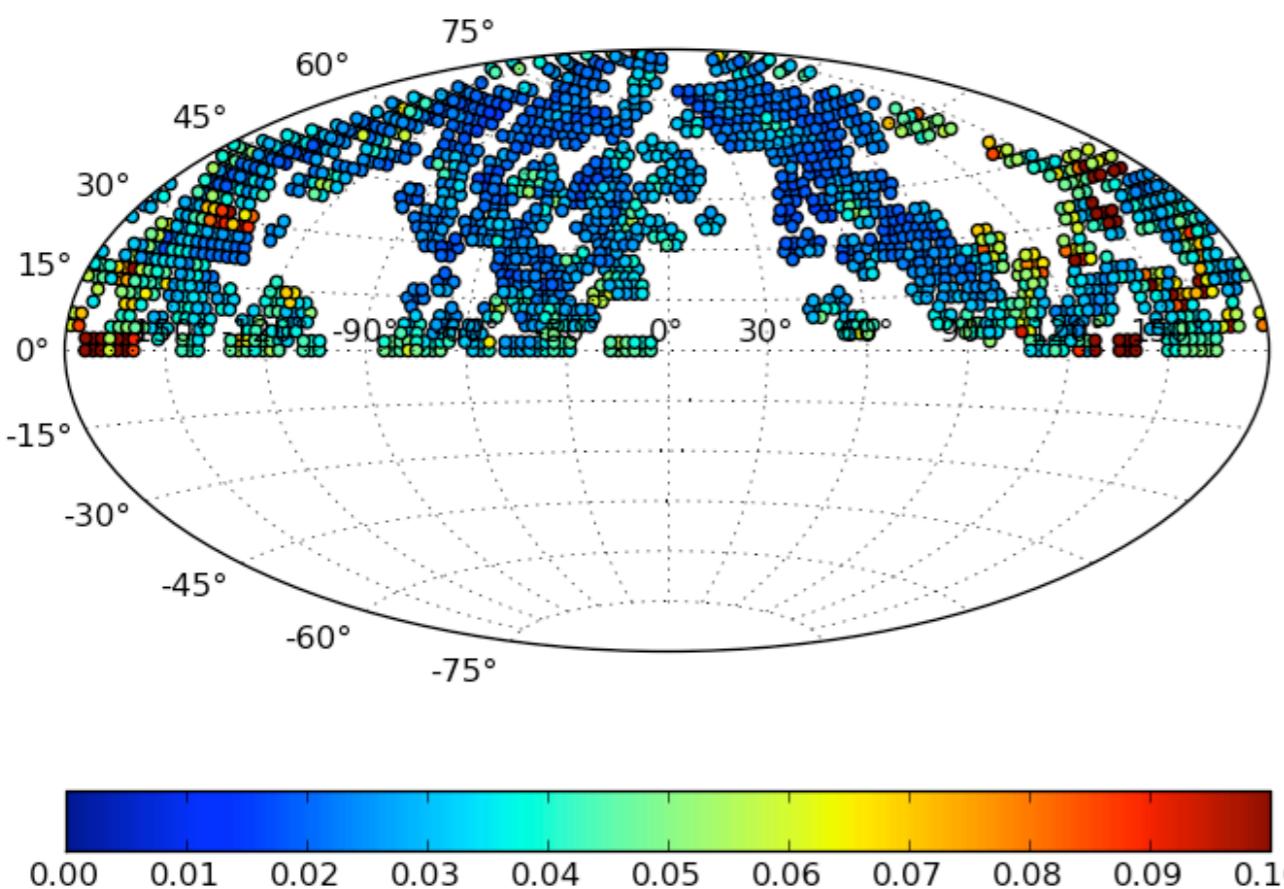
Galactic



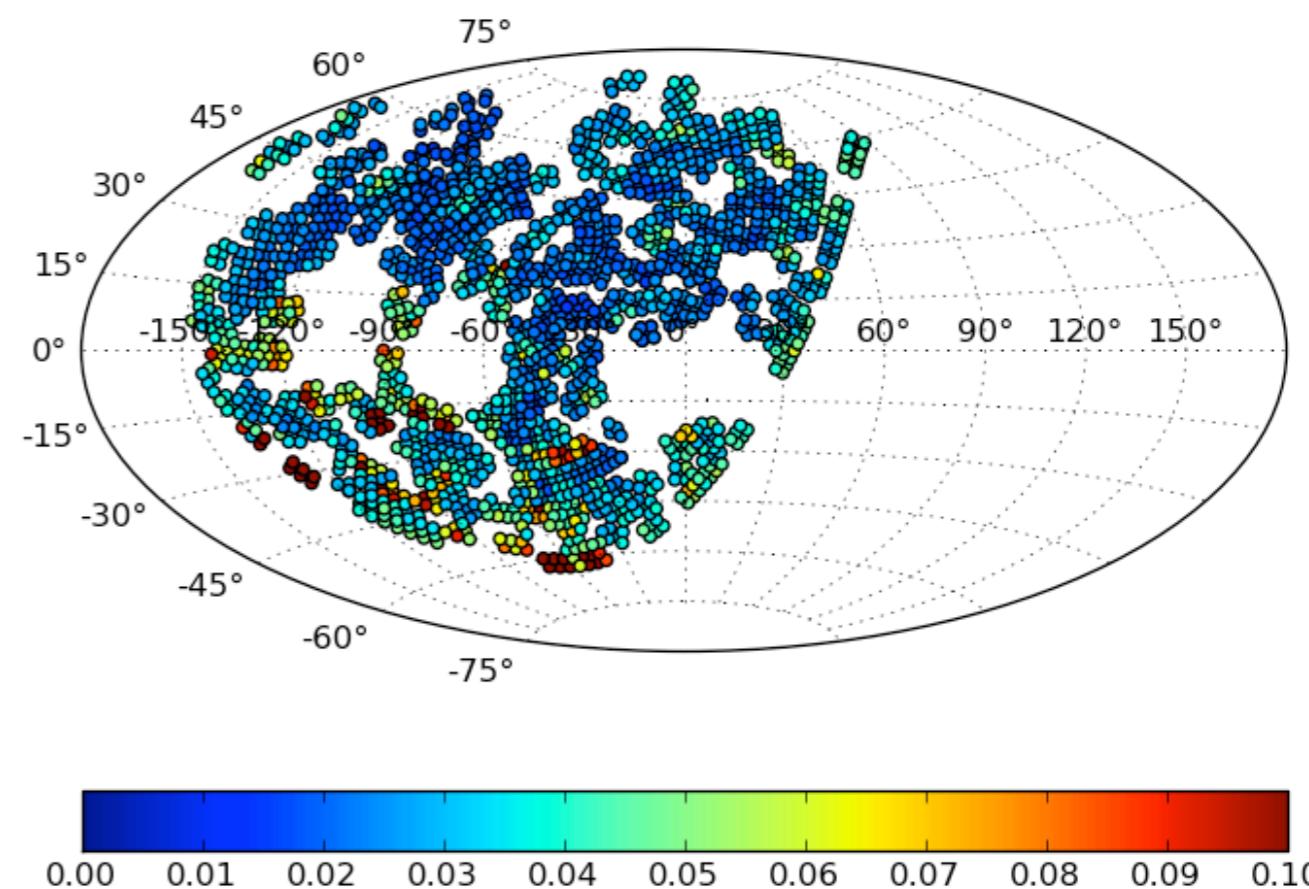
# Noise variation with sky position

- Band 6 (151 MHz): 1775 fields

Equatorial J2000



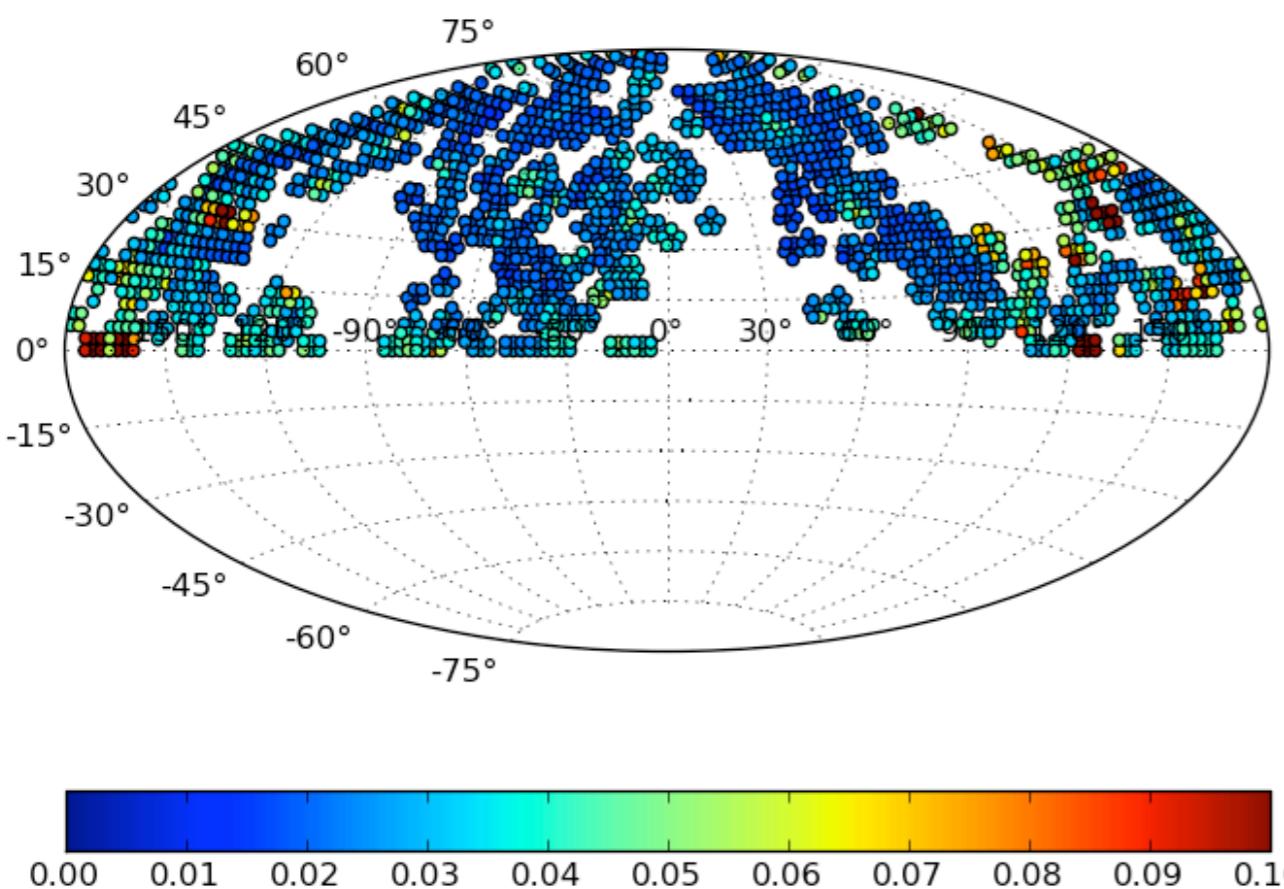
Galactic



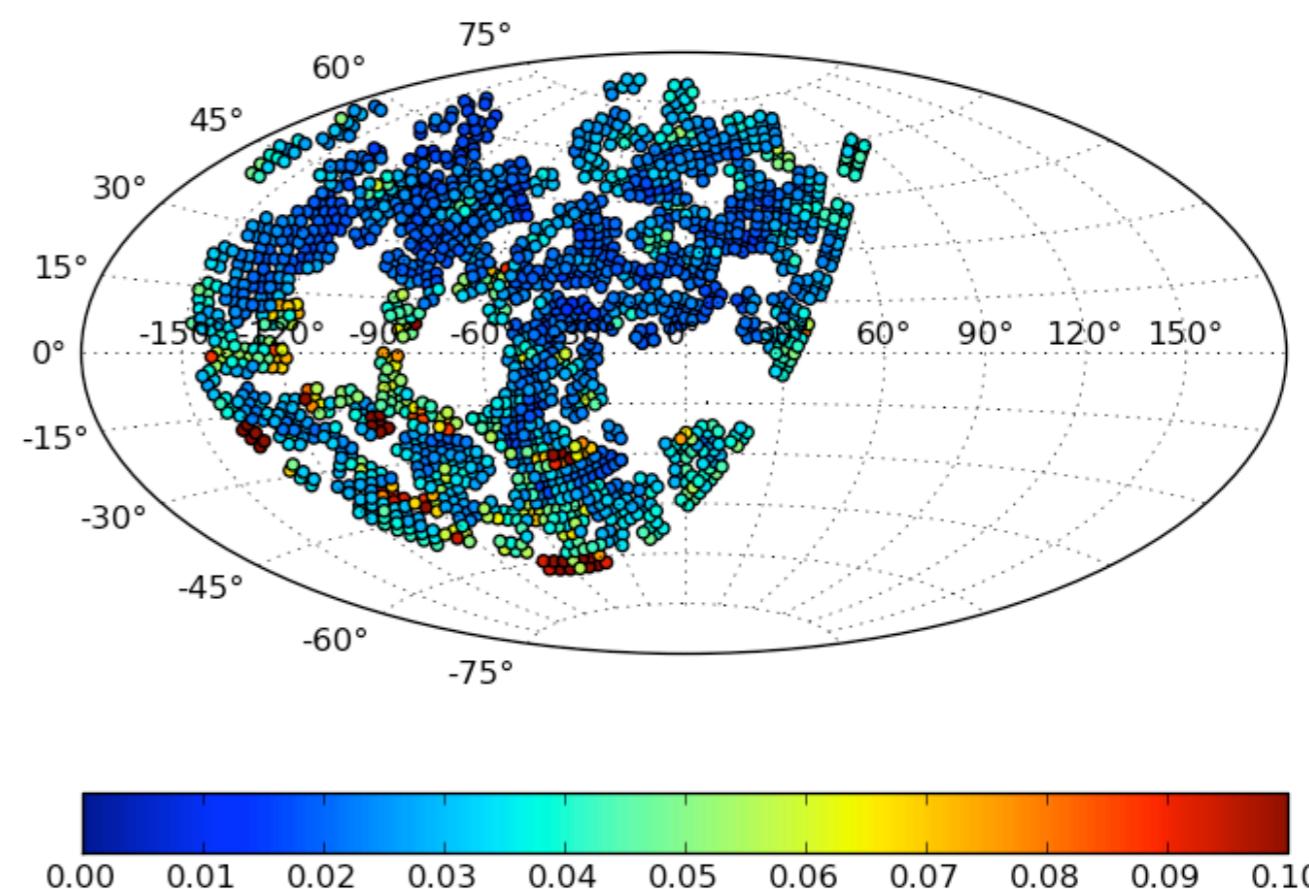
# Noise variation with sky position

- Band 7 (157 MHz): 1780 fields

Equatorial J2000

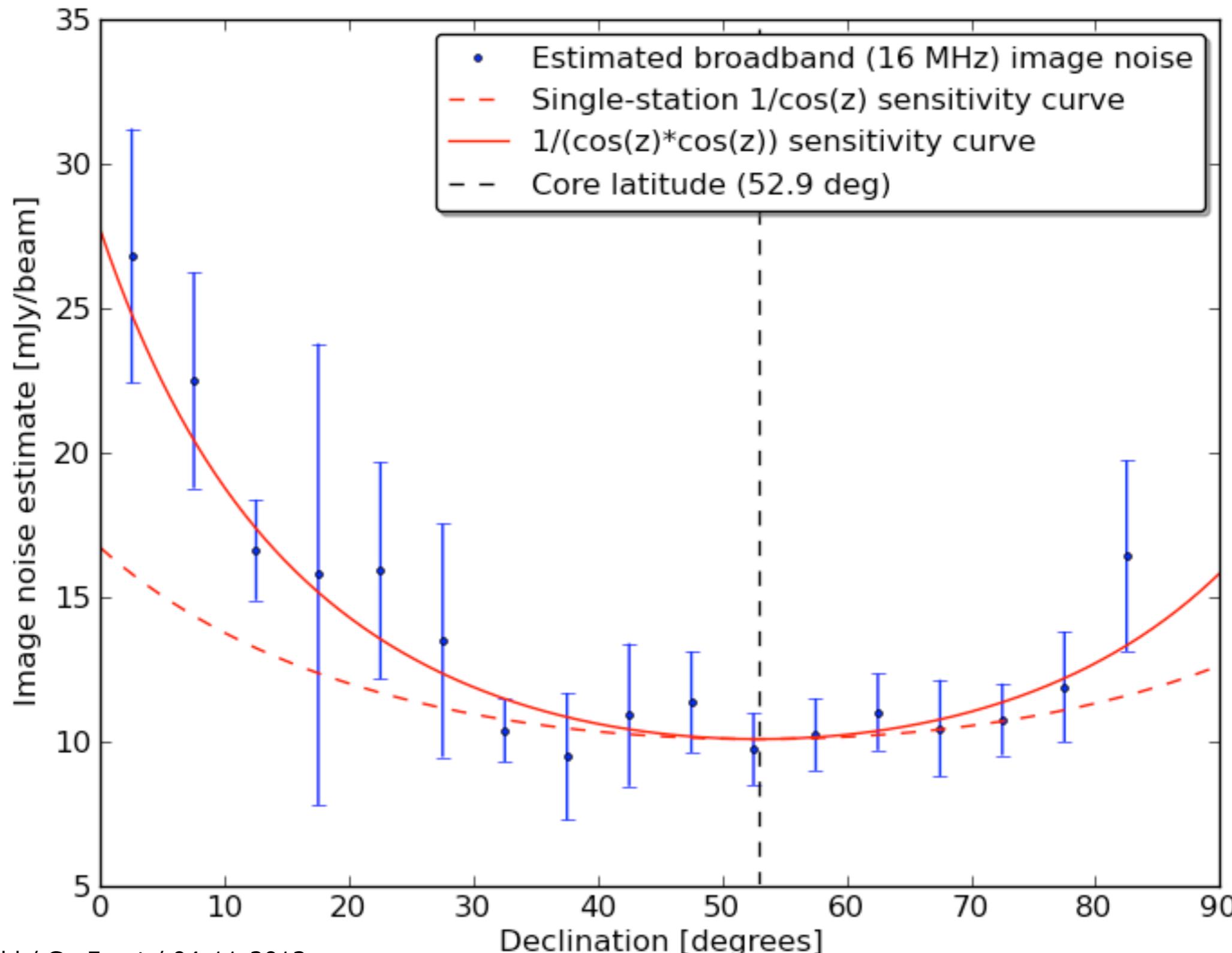


Galactic



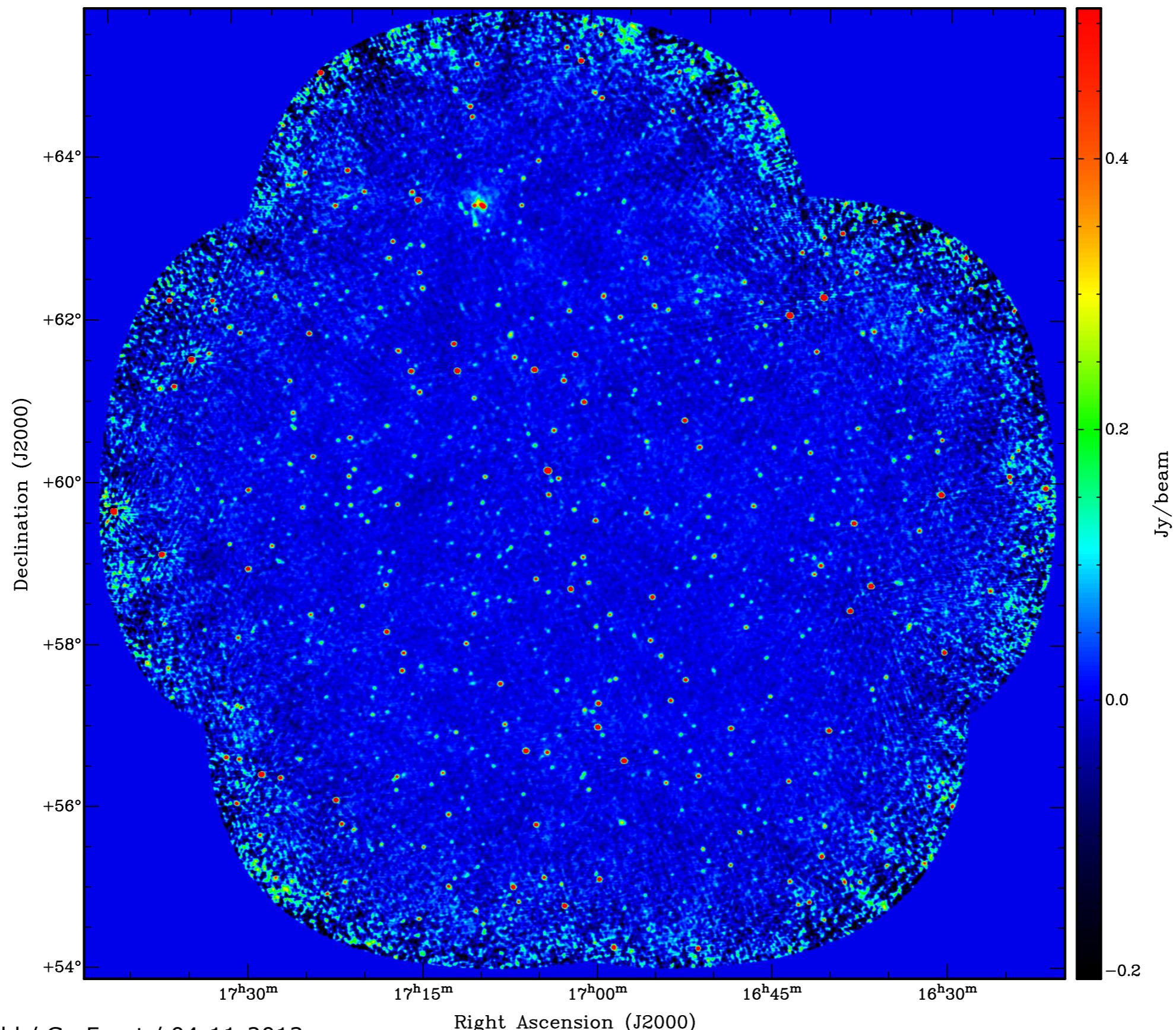
# Noise variation with sky position

- Measured rms noise in 2510 cleaned images

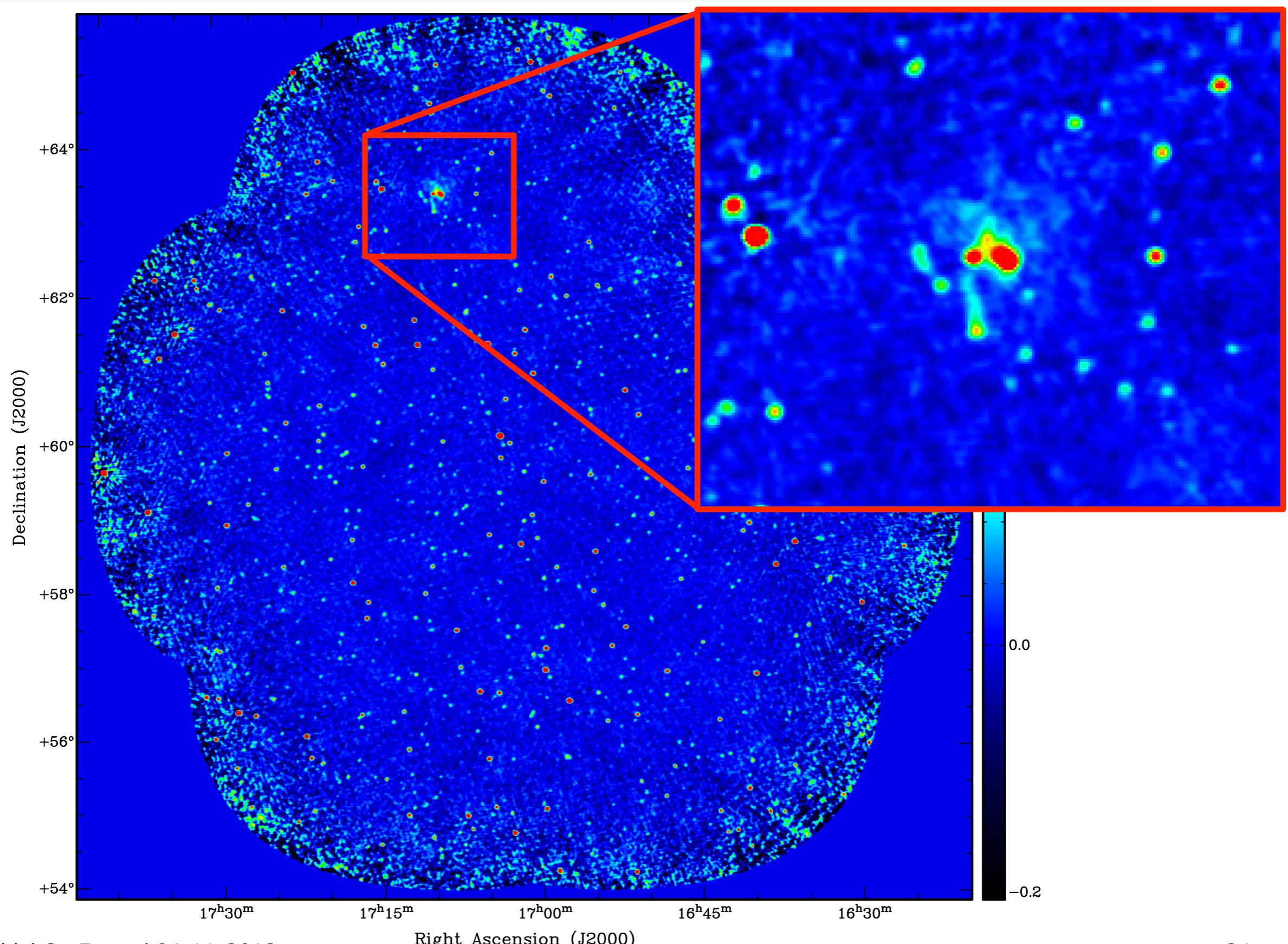


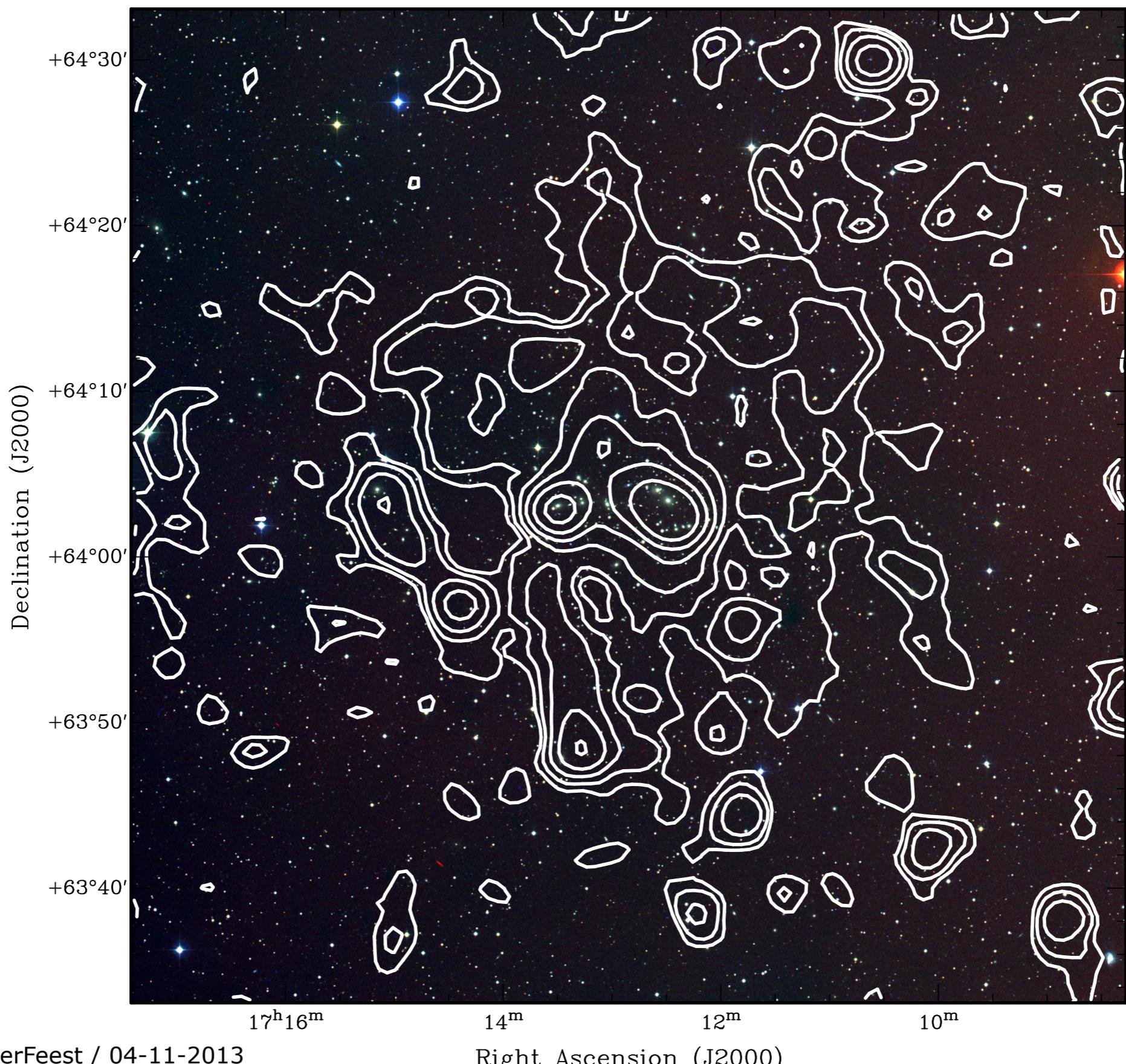
# MSSS early results (highlights)

# Mosaic using all 16 MHz bandwidth

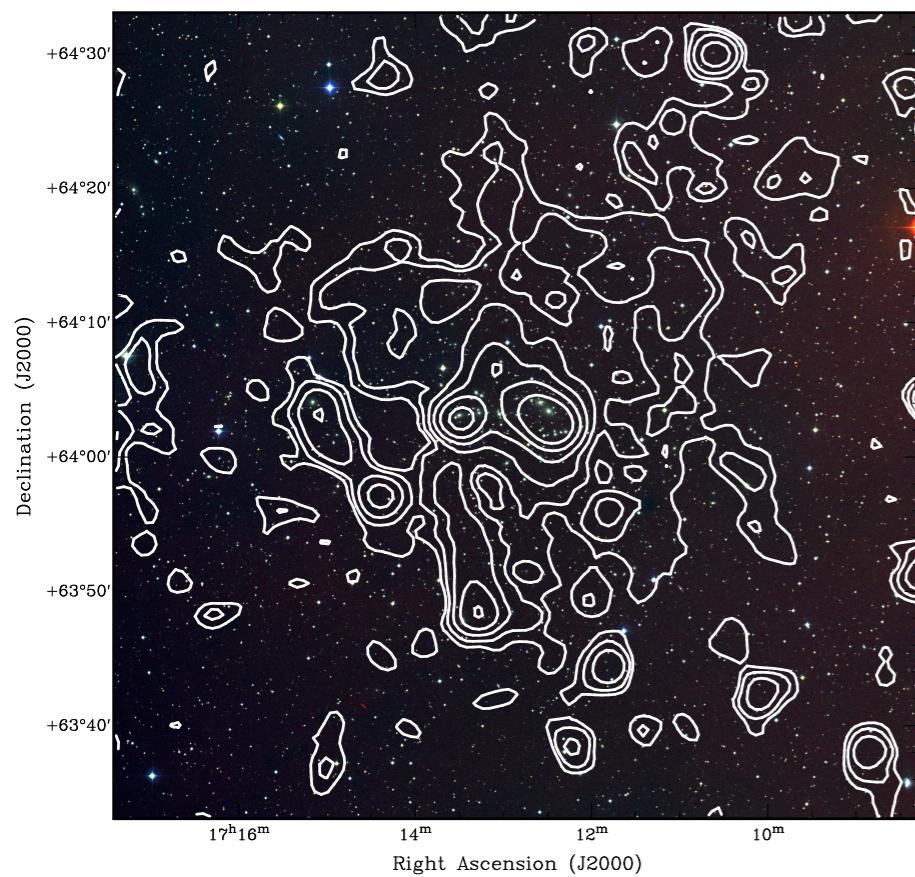


# Mosaic using all 16 MHz bandwidth





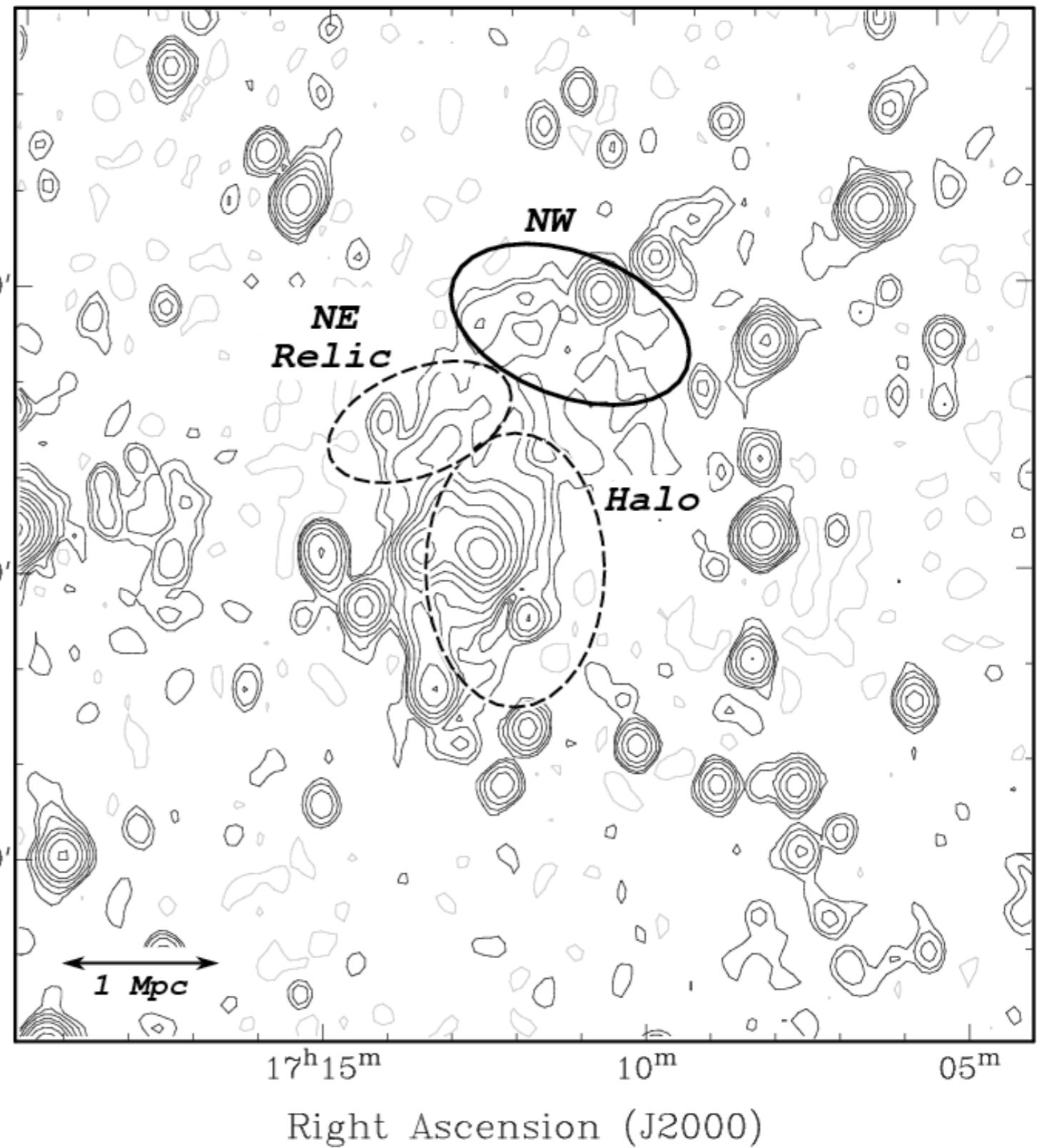
- cf Pizzo & de Bruyn (2009)  
WSRT, 150 MHz



Declination (J2000)

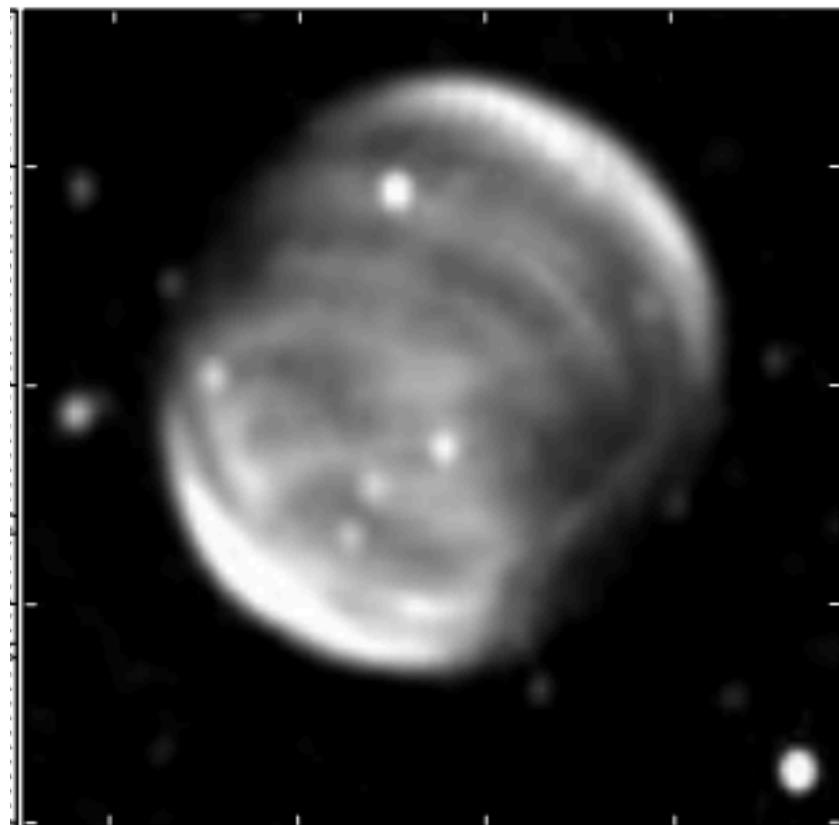
+64°30'  
+64°20'  
+64°10'  
+64°00'  
+63°50'  
+63°40'

17<sup>h</sup>16<sup>m</sup> 14<sup>m</sup> 12<sup>m</sup> 10<sup>m</sup>  
Right Ascension (J2000)

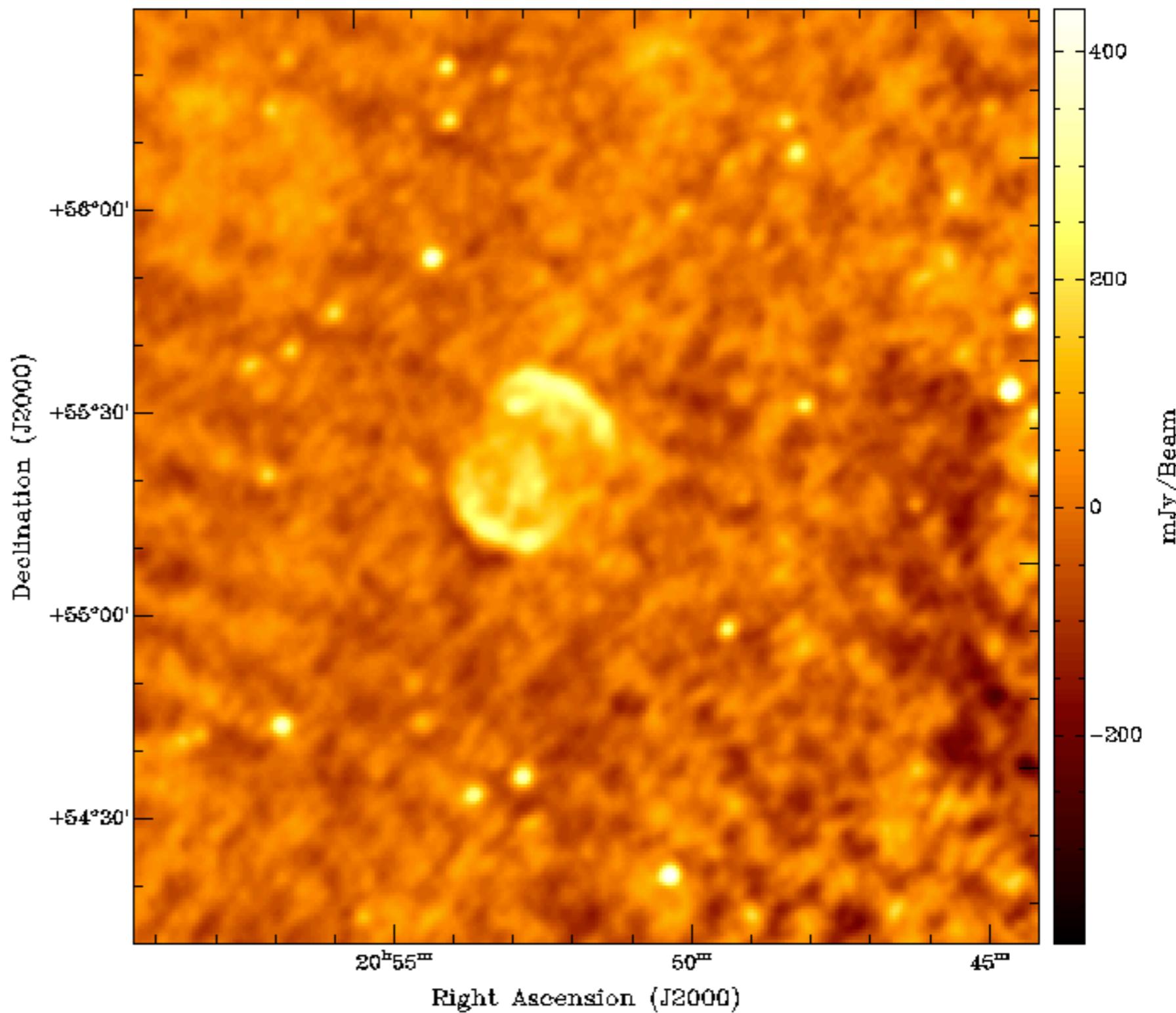


# Other well-known sources

- DA 530



Landecker+ (1999)

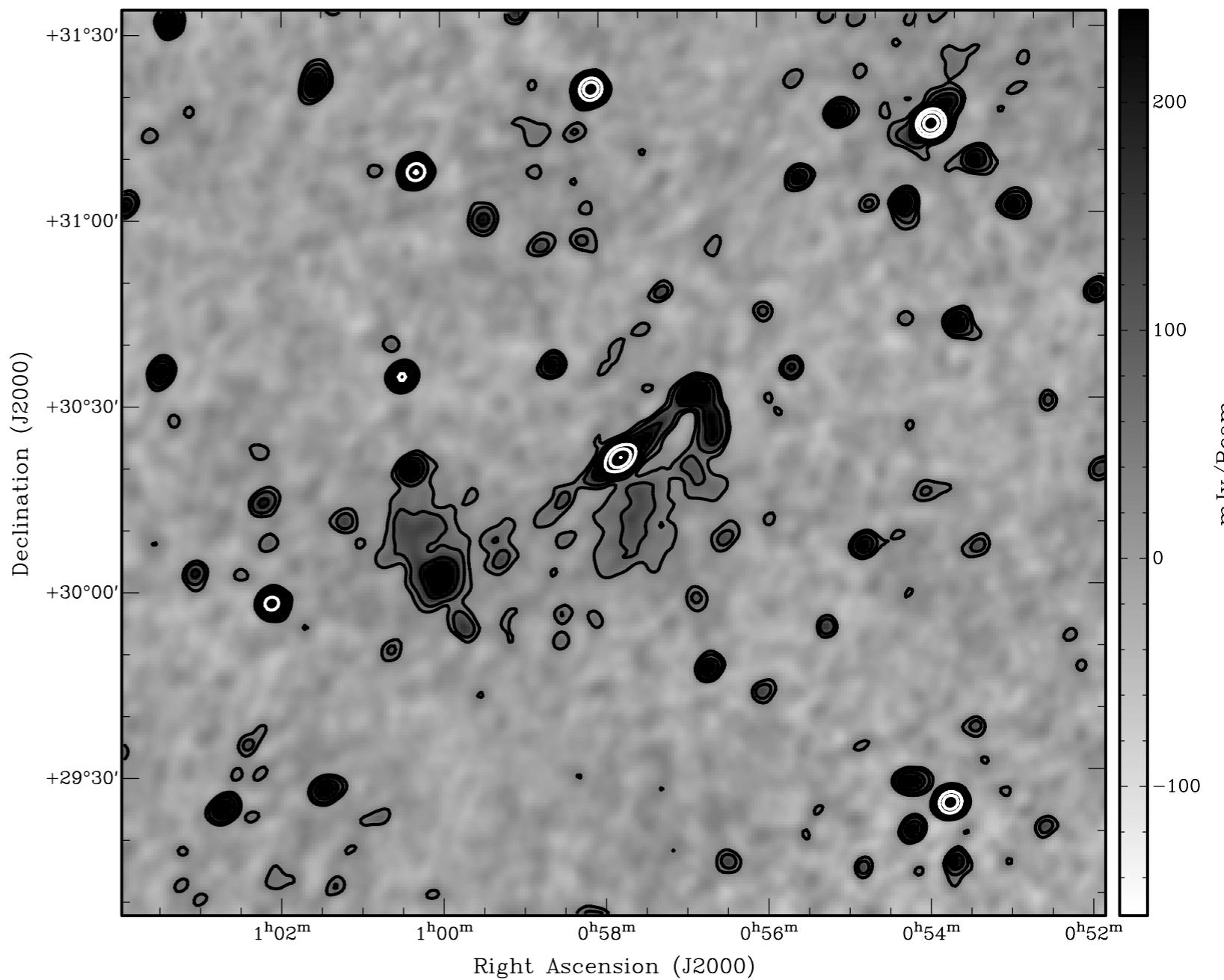


# Other well-known sources

- 3C31 and NGC 315 in same mosaic



Clarke



# N. de Kort, 1980/1981 Stichting Teleac

belangrijk geworden, nu men in staat is ook in het röntgengebied een hoog scheidend vermogen te behalen. De 'High Energy Ultraviolet Imaging Experiment' (HEAO-2) en de 'High Energy Ultraviolet Imaging Experiment' (HEAO-2).

## STERRENKUNDE

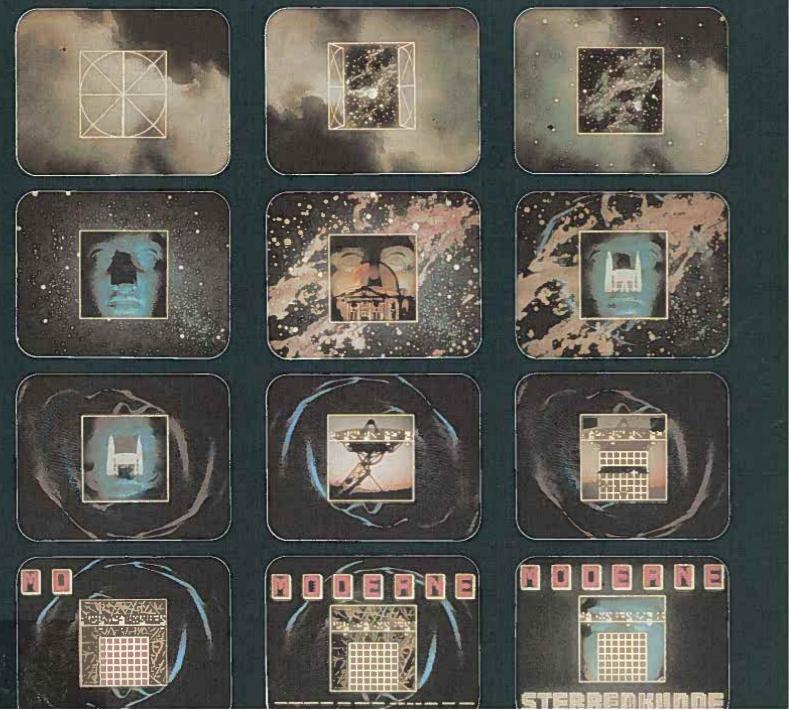
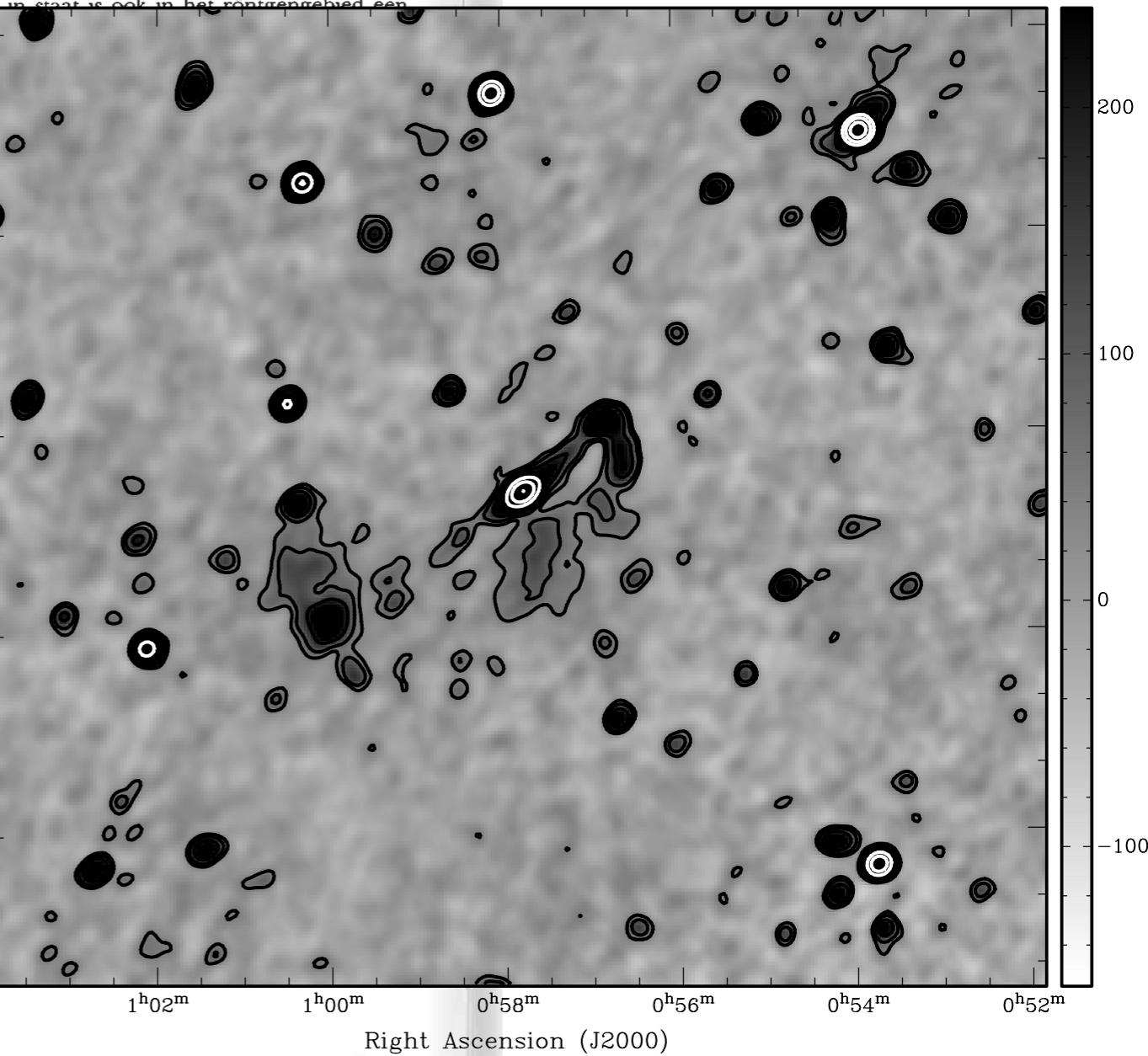


Fig. 16 Kaart van de radiobron die samenhangt met het stelsel NGC 315. De diameter van deze radiobron is 1 Mpc. NGC 315 bevindt zich op de met '+' gemerkte positie. Let op de rotatiesymmetrie en de radiojets.

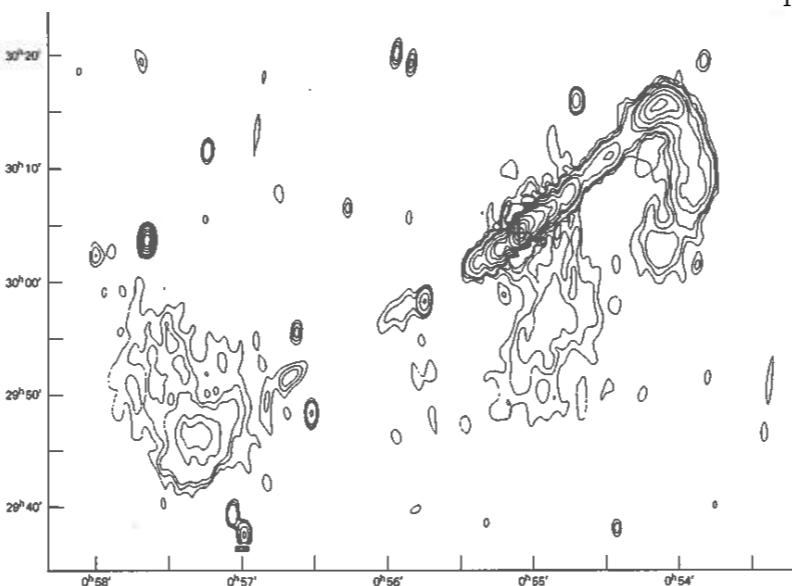
### 10.2.4. Jets

In 1918 vond men dat het resultaat (aangeduid) een uitstulping was van een vrij korte belichtingstijd. Het werd begrensd en wordt een 'jet' genoemd. De met M 87 gerelateerde radiobronnen 15 en 25. Het fenomeen is niet bekend. Zowel uit het spectrum van het licht als uit het stralingsmechanisme van sterren. Het is een synchrotron-gelijk vreemd object ook in de radiostraling. Daarover in hoofdstuk 11. Onderstaande kaart werd gevonden, beschouwd en verder onderzocht.

Deze situatie veranderde in de jaren die ontstonden in de jaren die ontsprongen in of bestaan. Ze eindigen honderden tot duizenden parsecs van de centrale bron. Het is moeilijk te maken hebben met het stralingsmechanisme naar de radiostraling. Leidse astronomen nu ook 3C 273 zijn nabije exemplare voorbeeld. Men kent er nu (oktober 1980) maar 100 radiojetbronnen. Ook de radiostelsels die zich in de nabijheid van de centrale bron bevatten dergelijke jets bevatte. Aan de andere kant is de momenteel verschijnsel is in radiostraling van radiojets in NGC 315. Onderstaande kaart toont de positie van een dubbele radiobron.



Right Ascension (J2000)





*N. de Kort, 1980/1981 Stichting Teleac*

belangrijk geworden, nu men in staat is ook in het röntgengebied een oog scheidend vermogen te halen. Figuur 14 toont een resultaat van 'Ein-stein Observatory' (HEAO-2).



Fig. 16 Kaart van de radiobron die samenhangt met het stelsel NGC 315. De diameter van deze radiobron is 1 Mpc. NGC 315 bevindt zich op de met '4' gemerkte positie. Let op de rotatiesymmetrie en de radiojets

#### 0.2.4. Jets

1918 vond men dat het reuzenstelsel M 87 (toen nog slechts als 'nevel' aangeduid) een uitstulping vertoonde op fotografische opnamen die met een vrij korte belichtingstijd waren gemaakt. Dit uitsteeksel is vrij scherp begrensd en wordt een 'jet' genoemd. Ruim vijftig jaar later vond men in de met M 87 gerelateerde radiobron Virgo A eveneens de jet (zie de figuren 15 en 25). Het fenomeen heeft een aantal bijzondere eigenschappen. Onder uit het spectrum van het zichtbare licht als van de radiostraling blijkt dat het stralingsmechanisme niet thermisch is; de uitstulping bestaat niet uit sterren. Het is een synchrotron-bron. Enige tijd later vond men een dergelijk vreemd object ook in de optische tegenhanger van 3C 273 (meer daarover in hoofdstuk 11). Omdat jarenlang verder geen enkele jet meer werd gevonden, beschouwde men beide bronnen als vreemde uitzonderingen.

Deze situatie veranderde in de zeventiger jaren. Lange, dunne radiostructuren die ontspringen in of bij de centrale bron van een radiostelsel, werden ontdekt. Ze eindigen honderdduizenden lichtjaren verder in de uitgebreide radiolobben. Het is niet onredelijk om te veronderstellen dat ze iets maken hebben met het transport van de energie vanuit het centrale mechanisme naar de radiolobben. In enkele stelsels met radiojets hebben Duitse astronomen nu ook optische tegenhangers gevonden. M 87 en C 273 zijn nabije exemplaren van een kennelijk vrij algemeen verschijnsel. Men kent er nu (oktober 1980) ruim twintig.

Ook de radiostelsels die zich manifesteren als kop/staart-stelsels, kunnen vergelijkbare jets bevatten. Alles wijst erop dat een dergelijke jet een fundamenteel verschijnsel is in radiostelsels. In figuur 16 zien we een voorbeeld van radiojets in NGC 315. Ook 3C 449 in figuur 9 is een goed voorbeeld van een dubbele radiobron met jets.

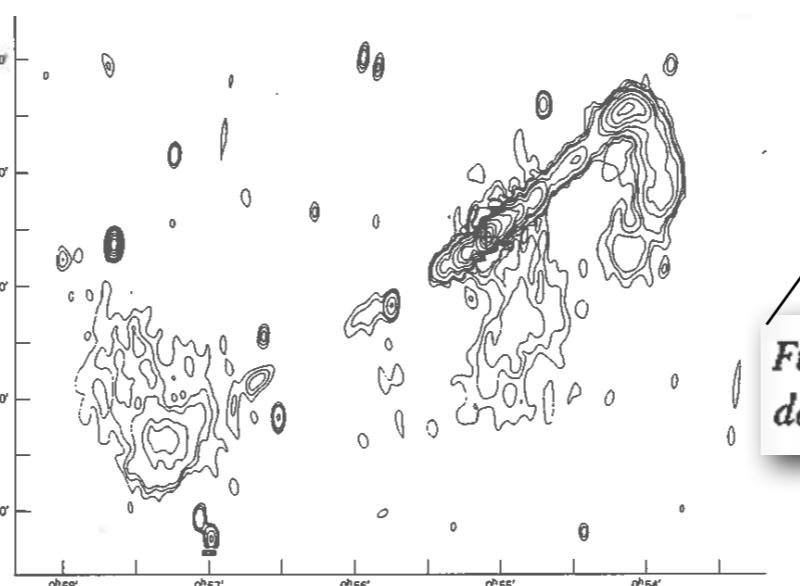


Fig. 17 Dr. A. G. de Bruyn was de gast-astronoom in deze televisiesessies



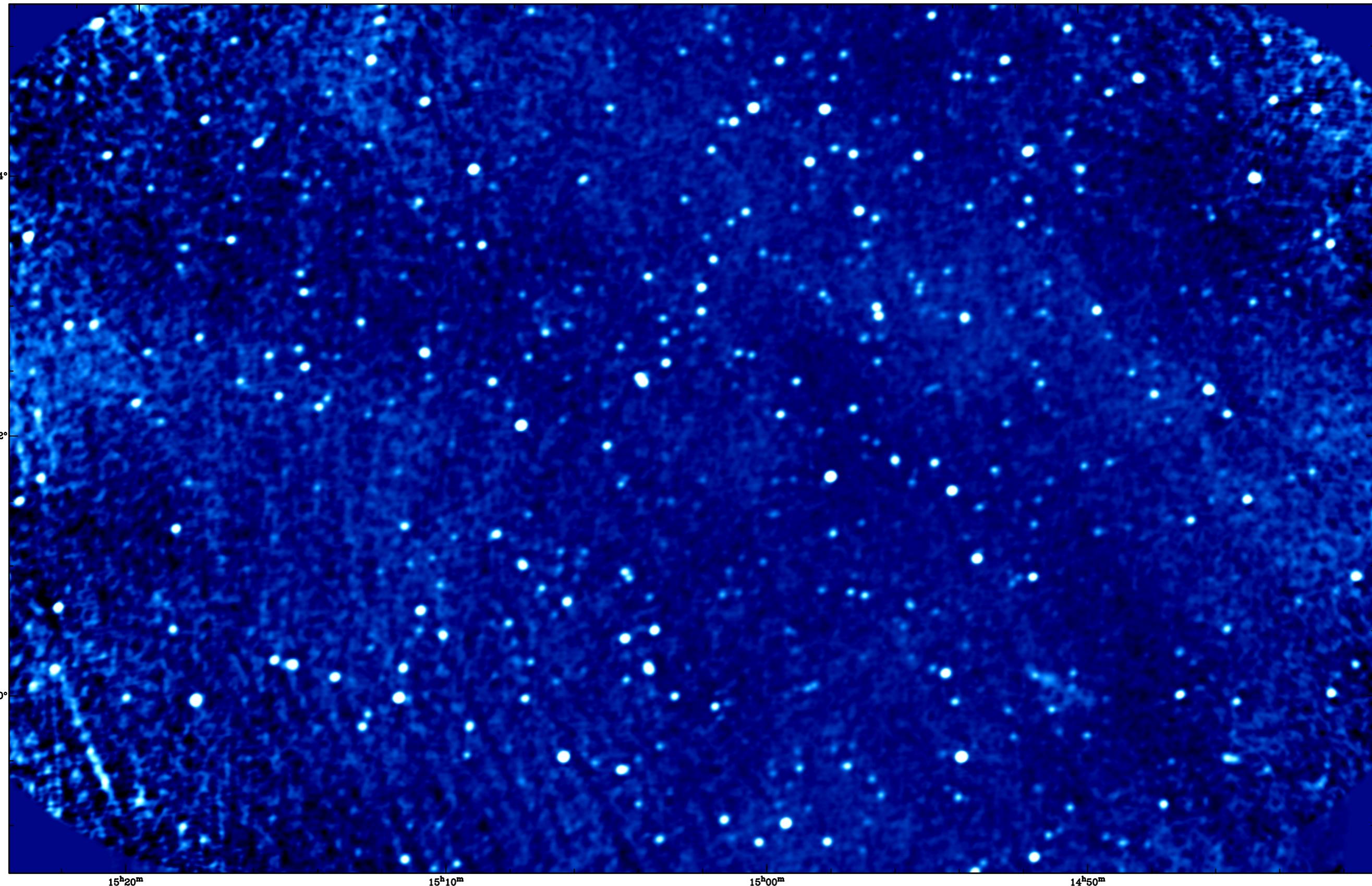
Fig. 17 Dr. A. G. de Bruyn was de gast-astronoom in deze televisiesessie.

#### 10.2.5. Recapitulatie

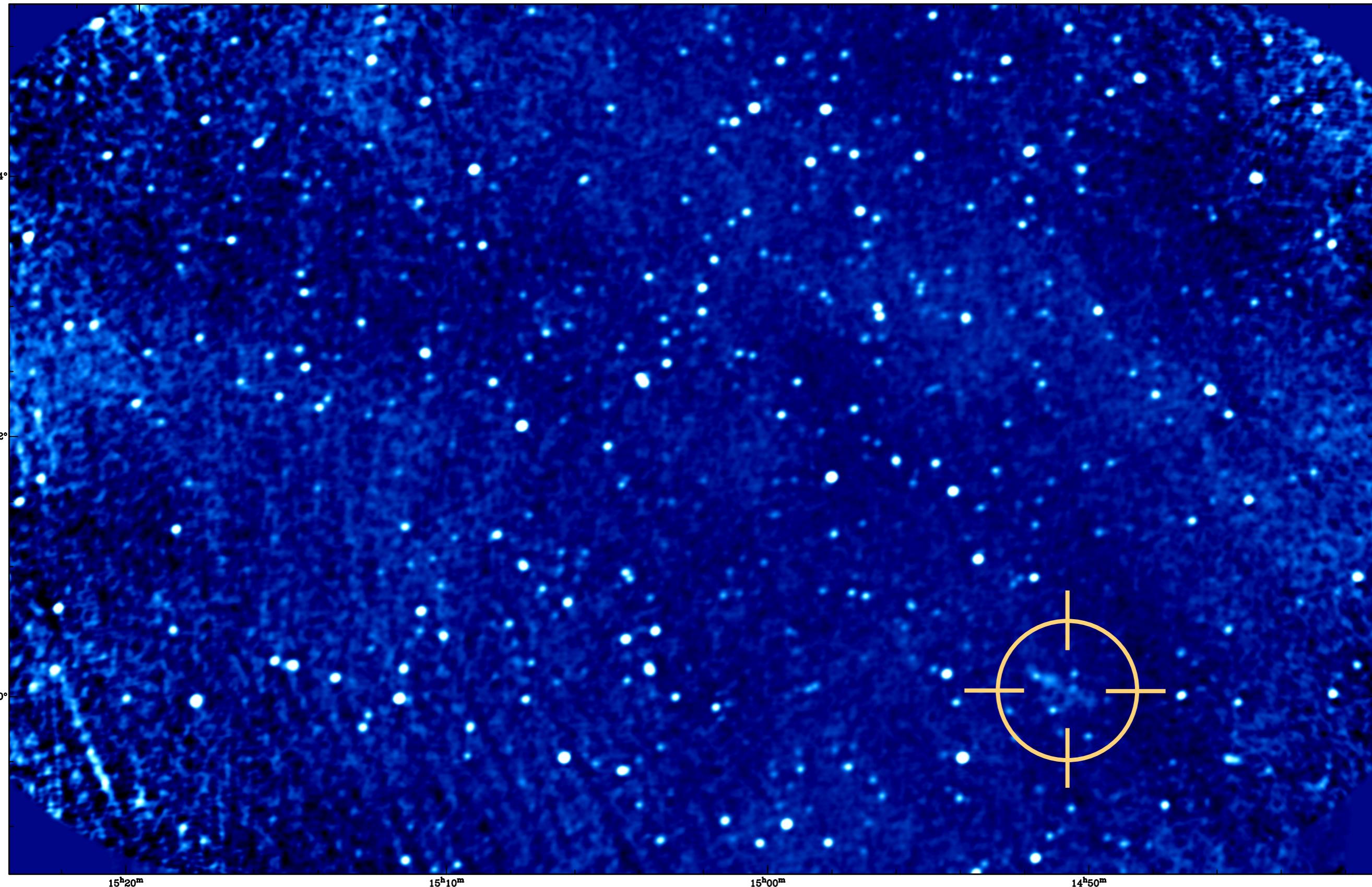
### **10.3. Naar een verklaring**

Eaten we nog eens harder staat; we kunnen daarbij de lichtsnelheid voortbewerken – zenden radiostraling uit en op een spiraalbaan worden gedwongen.

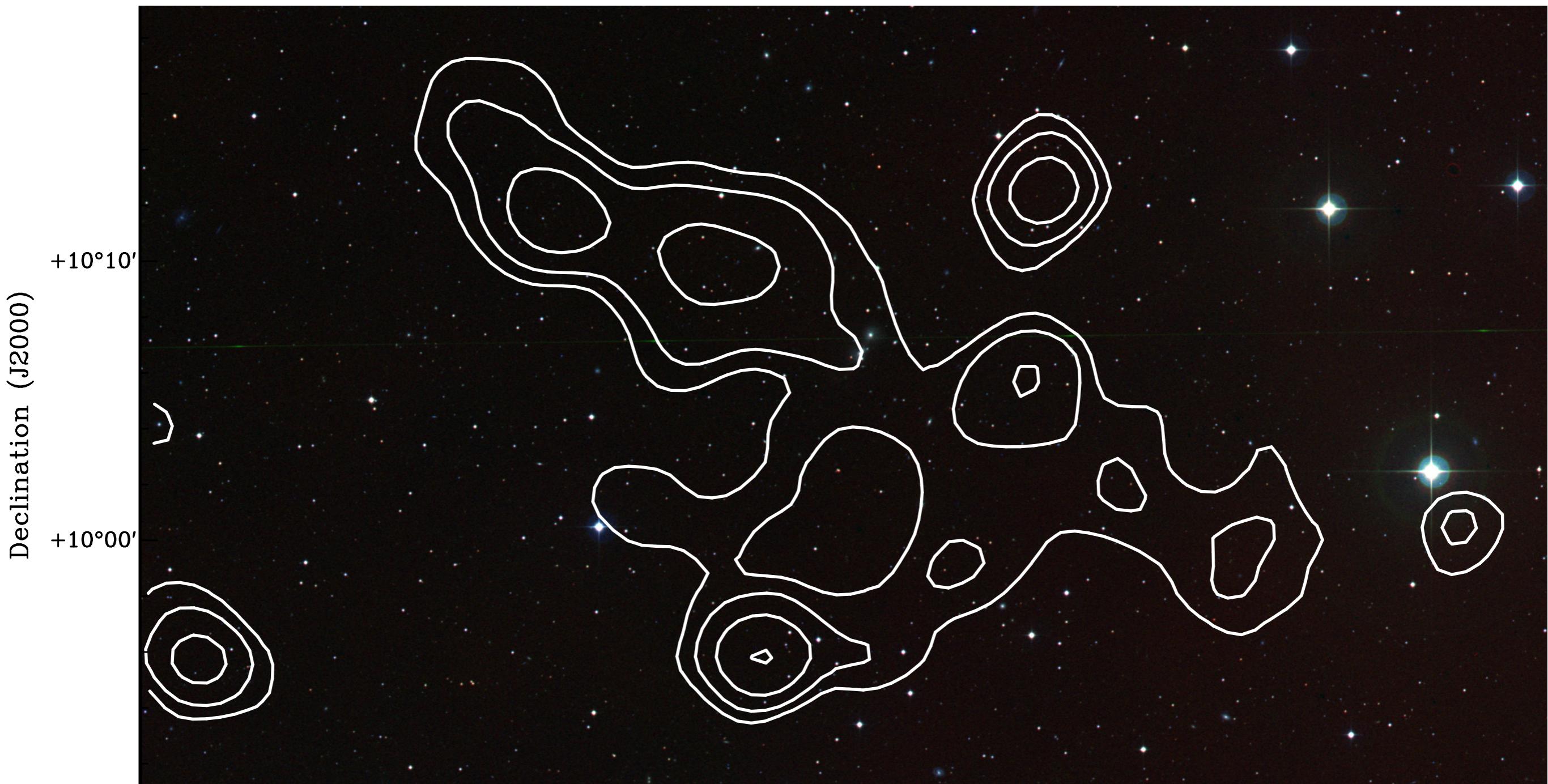
# Not all MSSS sources are known...



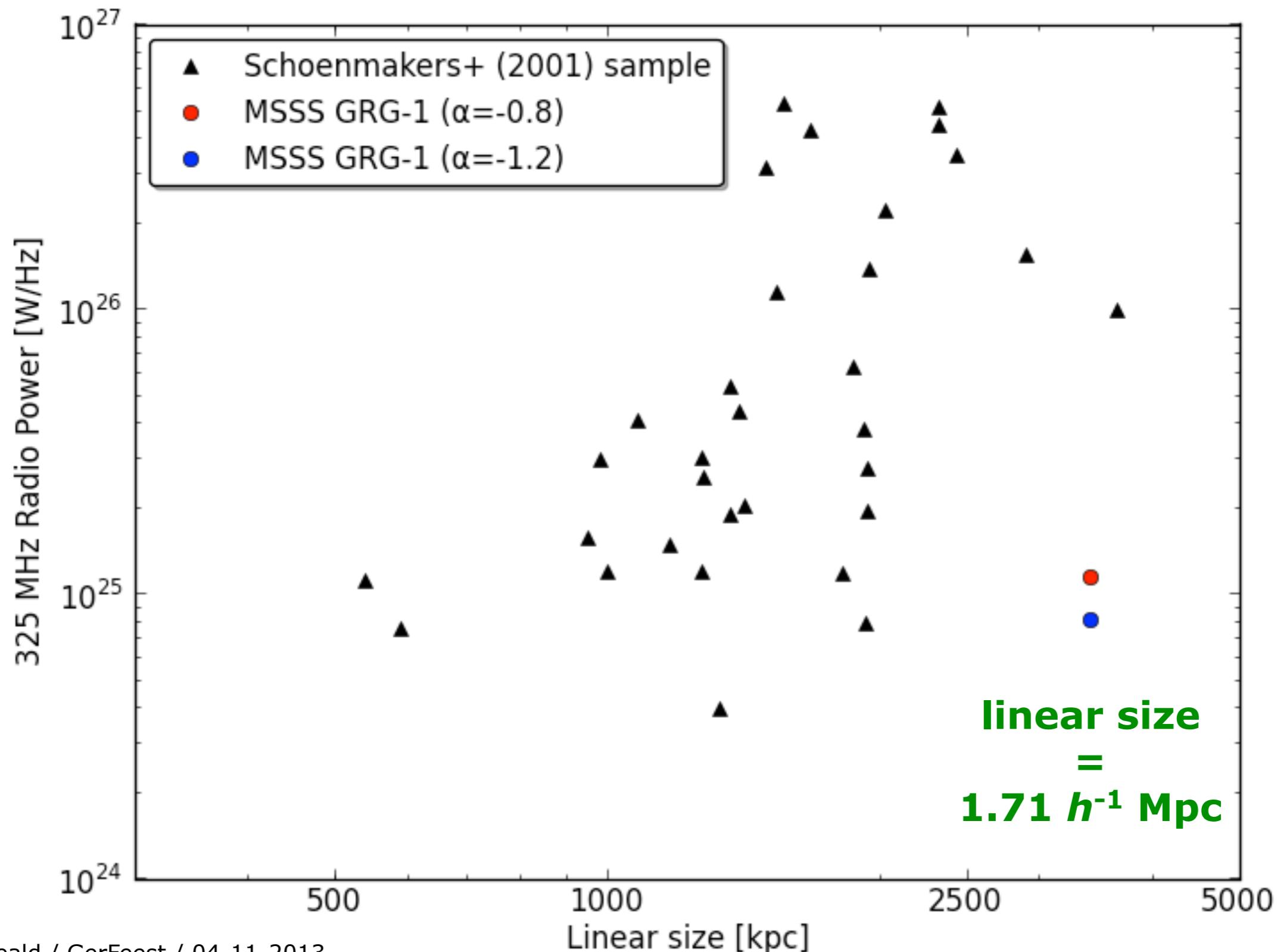
# Not all MSSS sources are known...



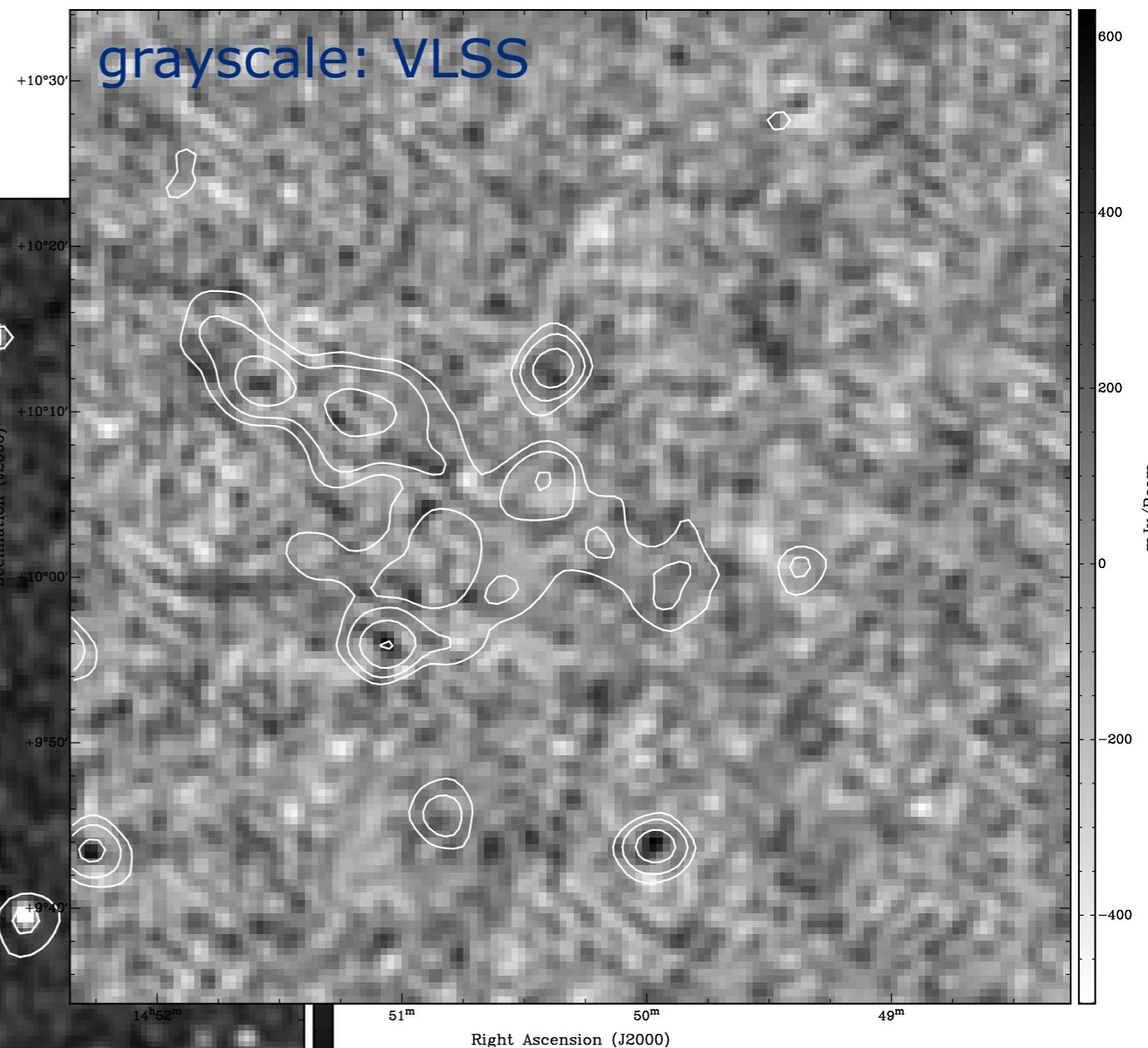
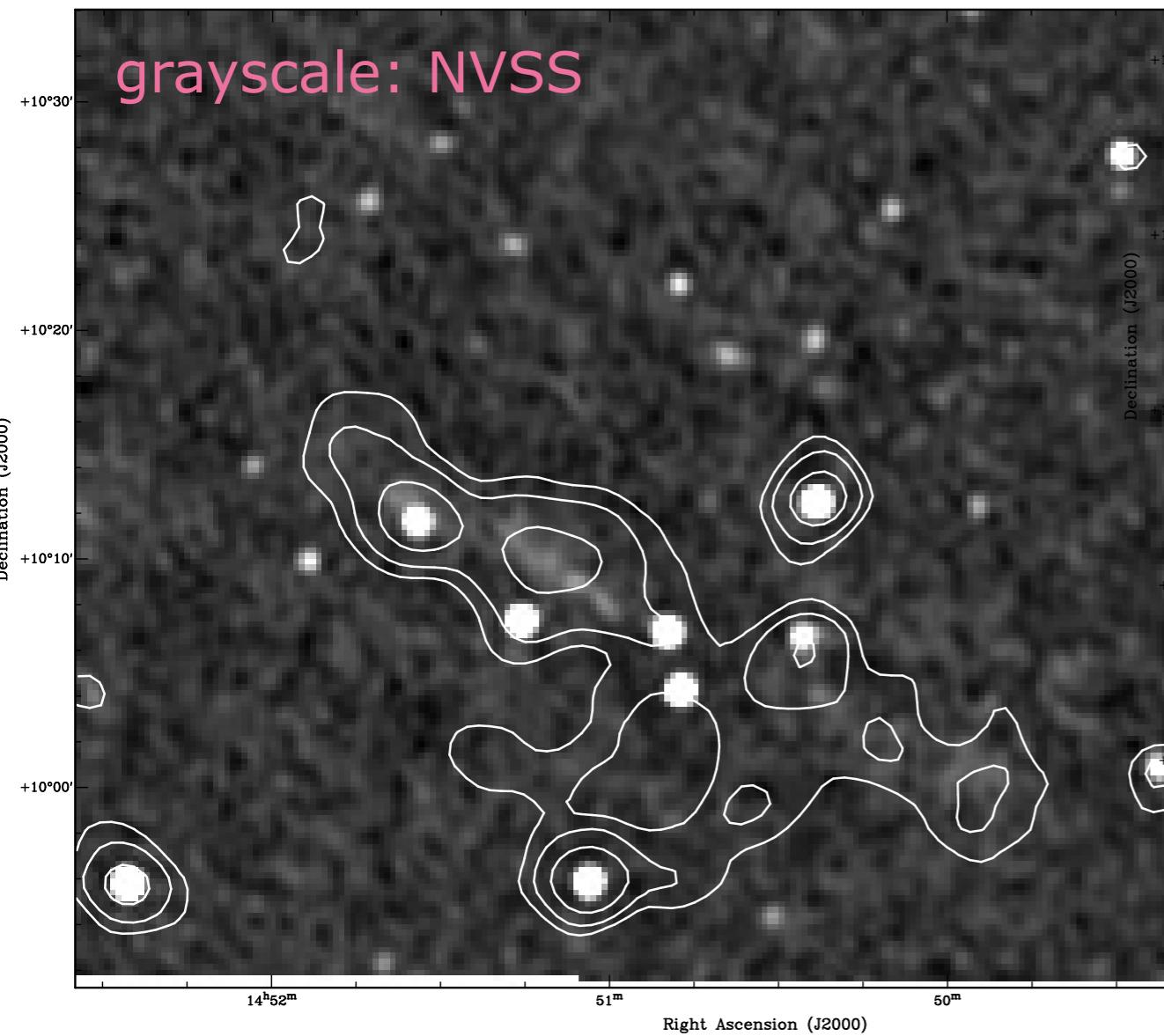
- Extended ( $\sim 36'$ ) source centered on flat-spectrum radio source coincident with one member ( $z=0.054536$ ) of a galaxy triplet

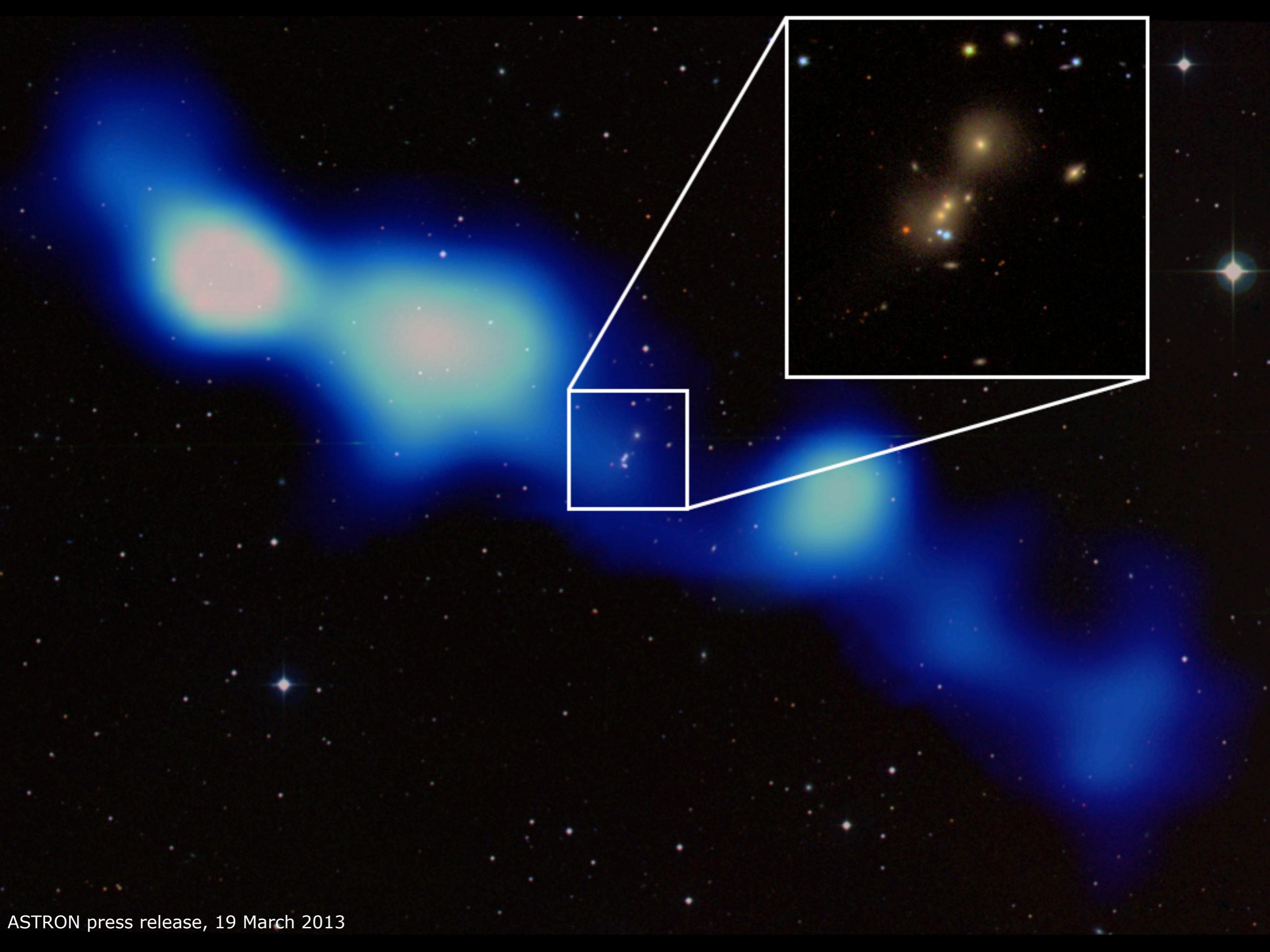


- Identified as a GRG associated with the flat-spectrum NVSS source

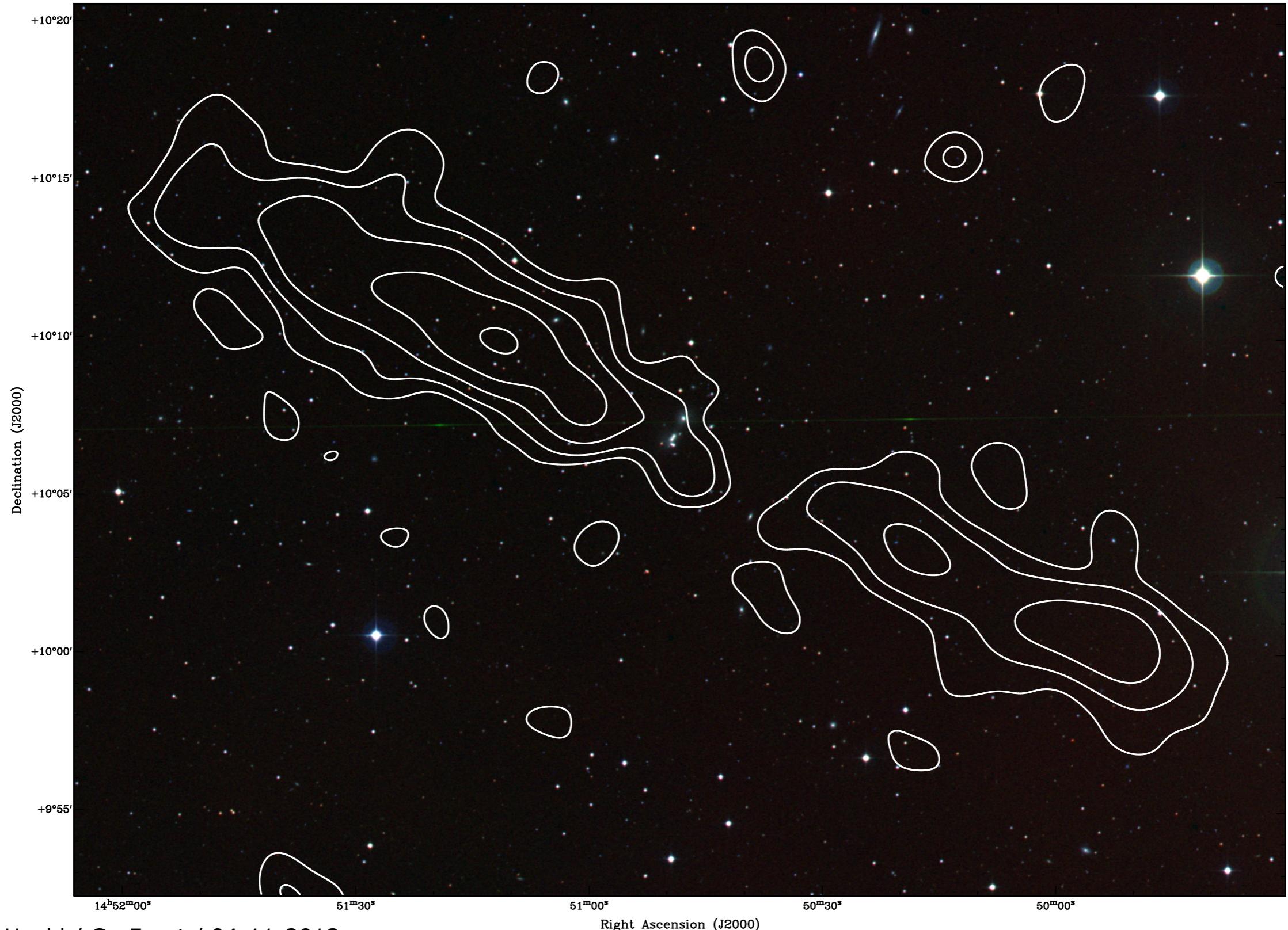


- Faint flux visible in NVSS postage stamp - brightest emission has a steep spectral index between 140 and 1400 MHz ( $\alpha \sim -1.2$ )  
but it is not visible in VLSS



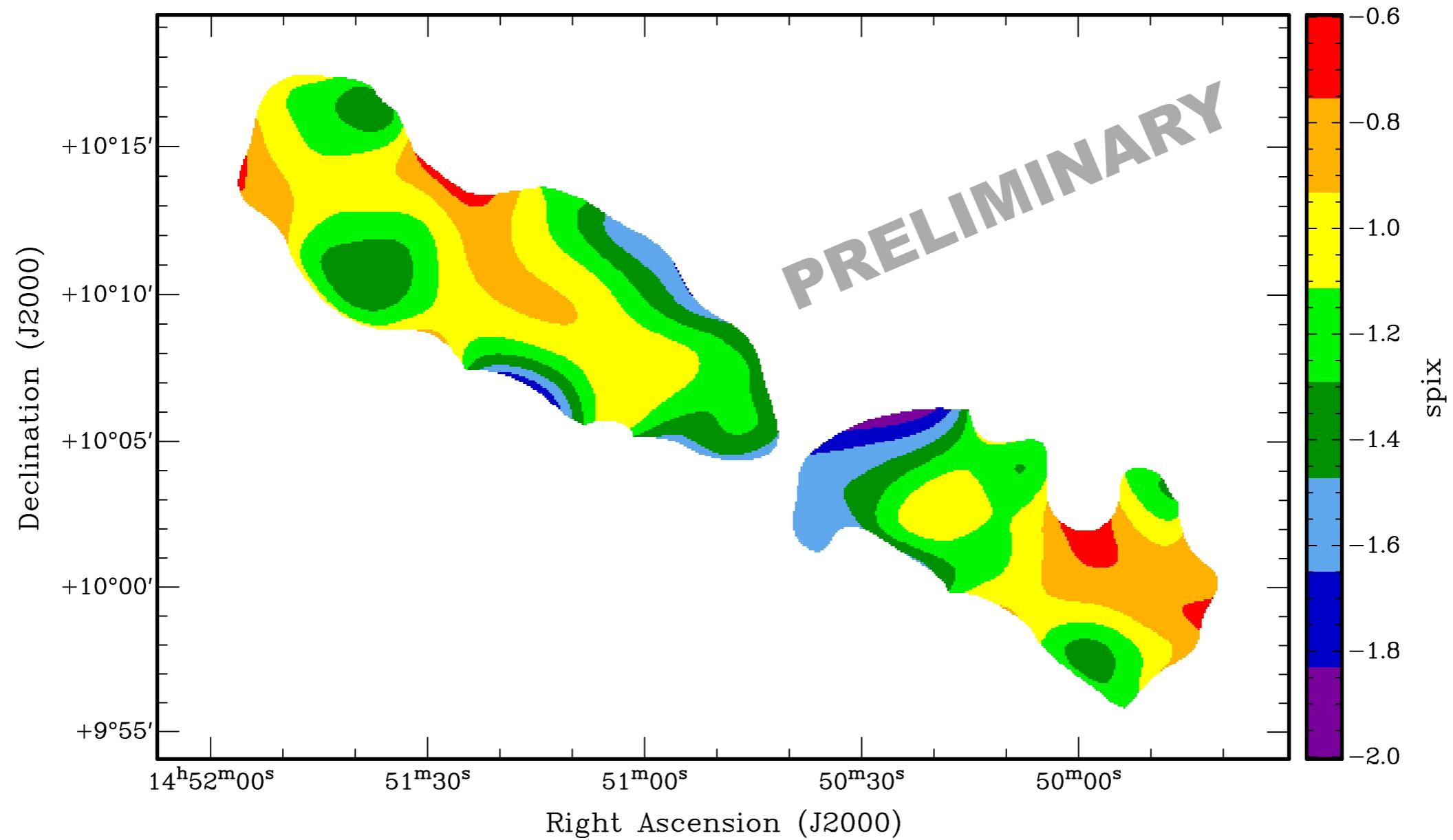


- After point source subtraction and at MSSS-image resolution (2.5')



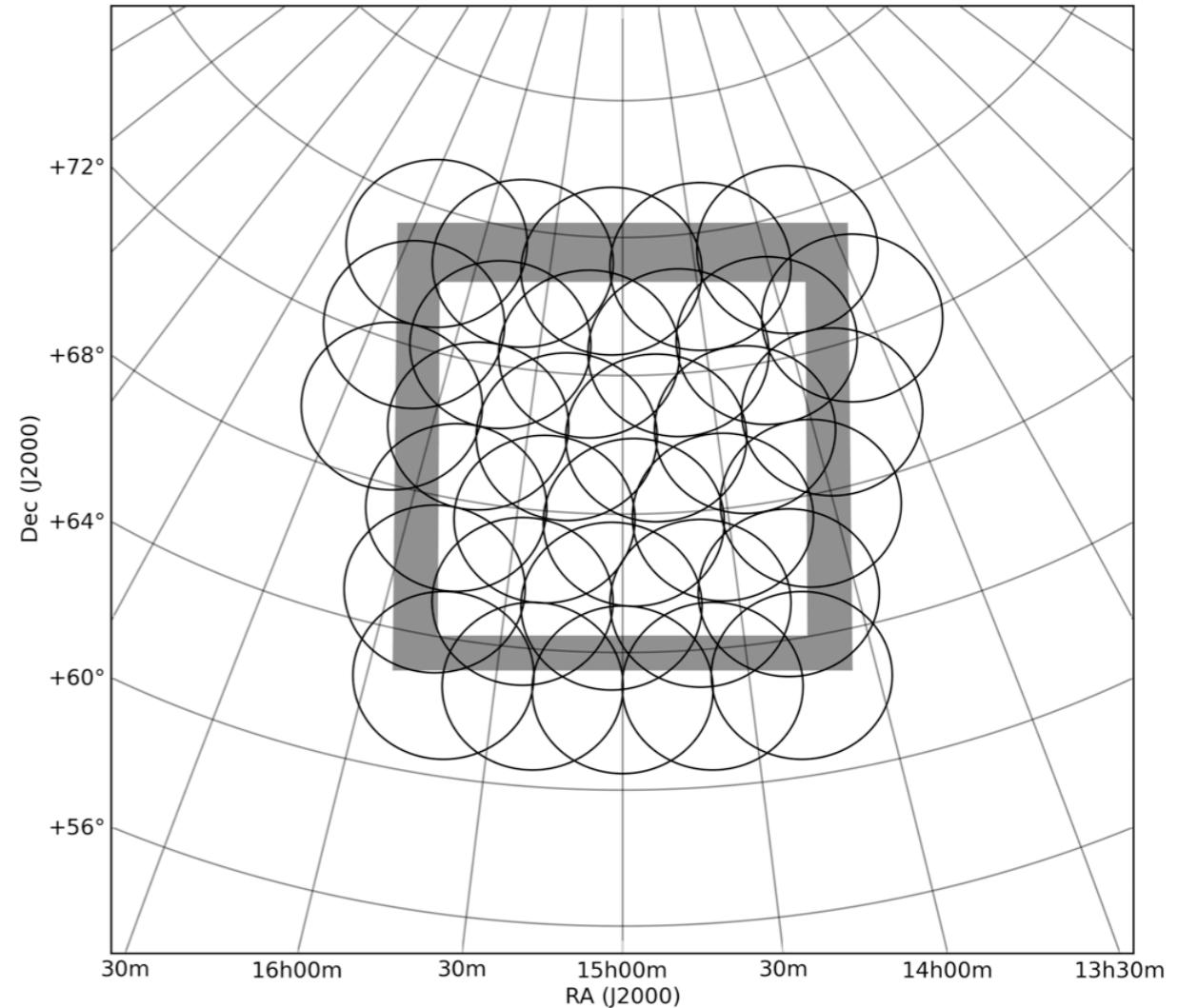
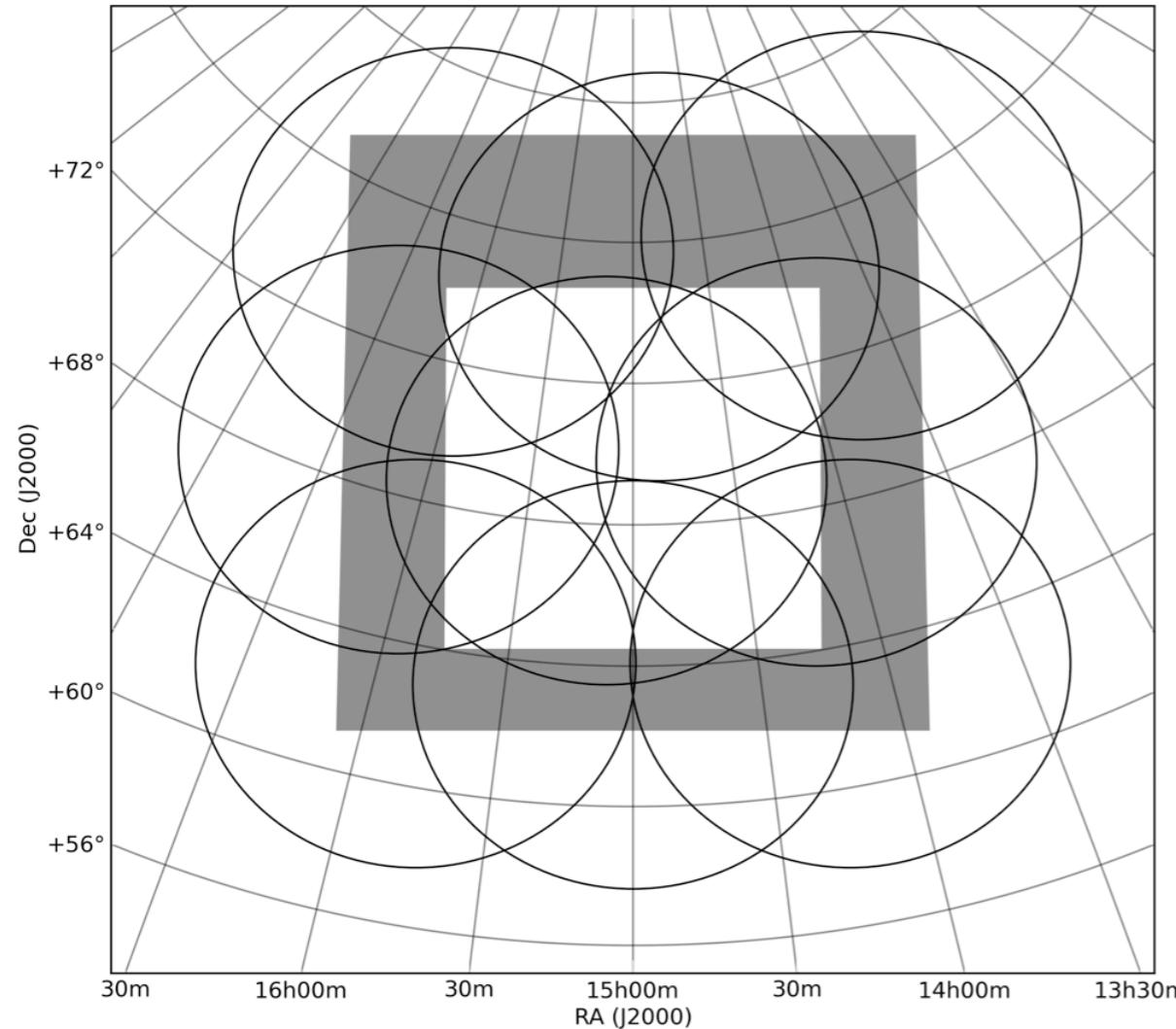
# Spectral index distribution

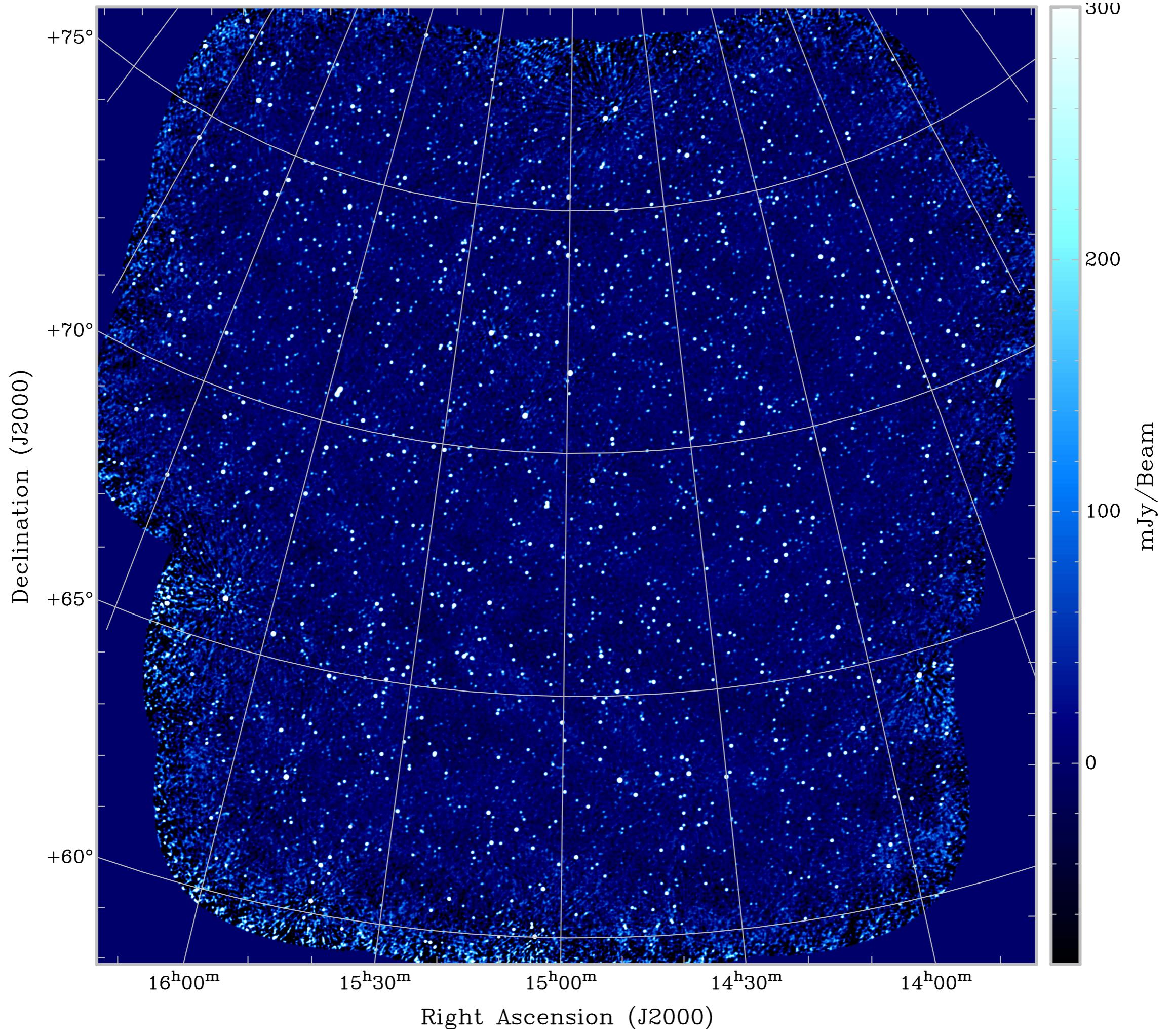
- NB, MSSS image not pointsource-subtracted

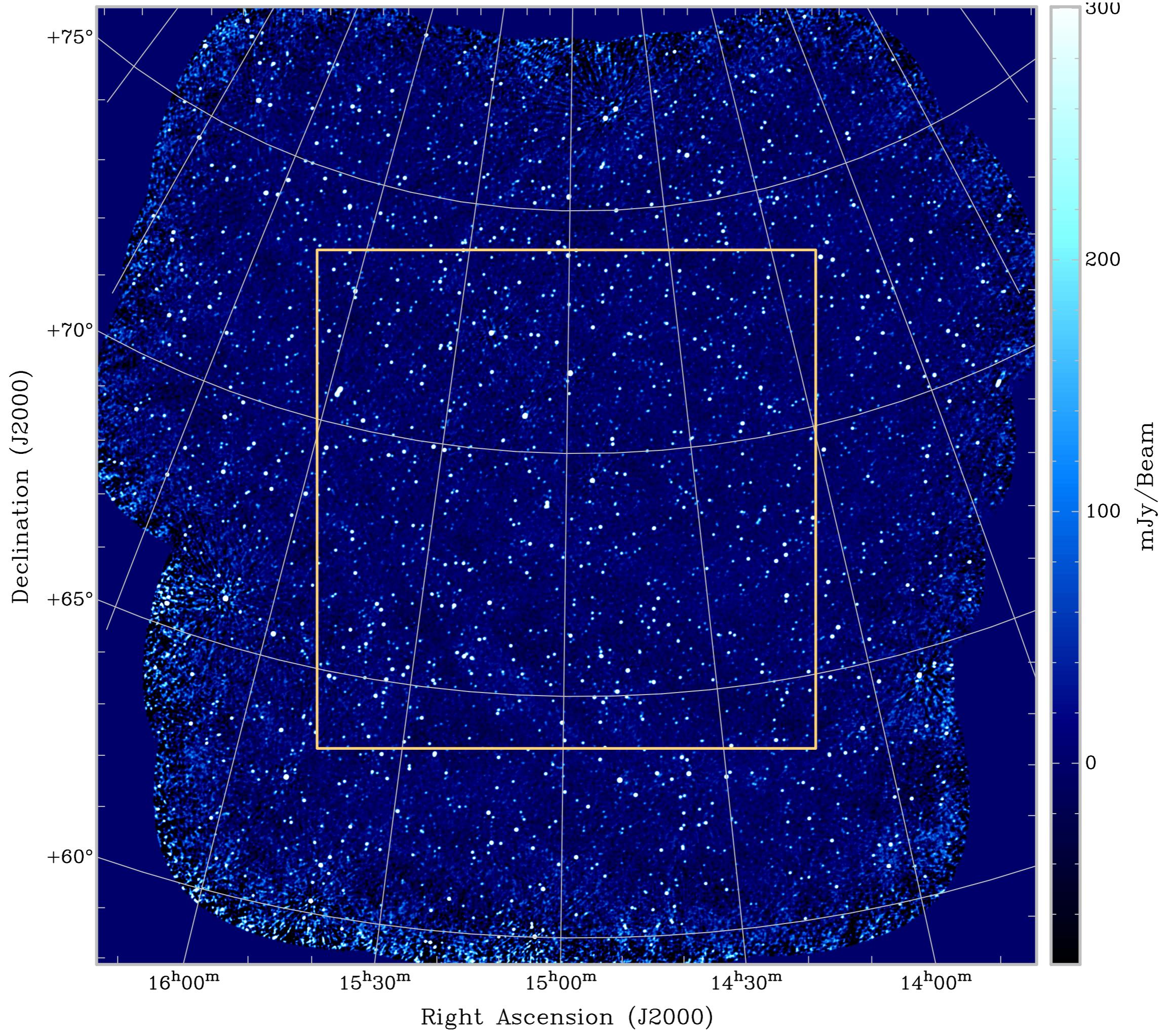


**MSSS ongoing work**

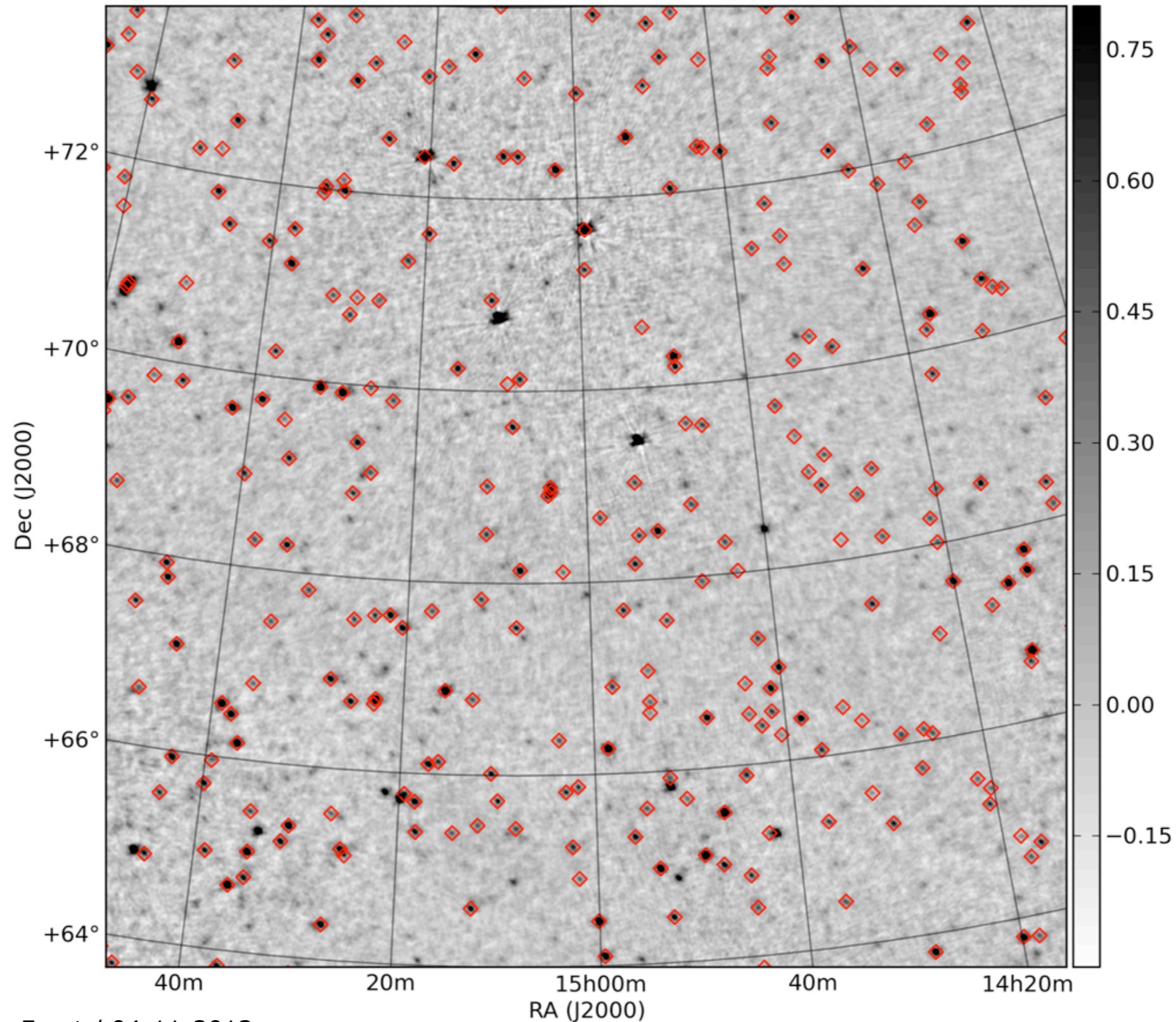
- Mosaics formed from 9 LBA fields and 32 HBA fields



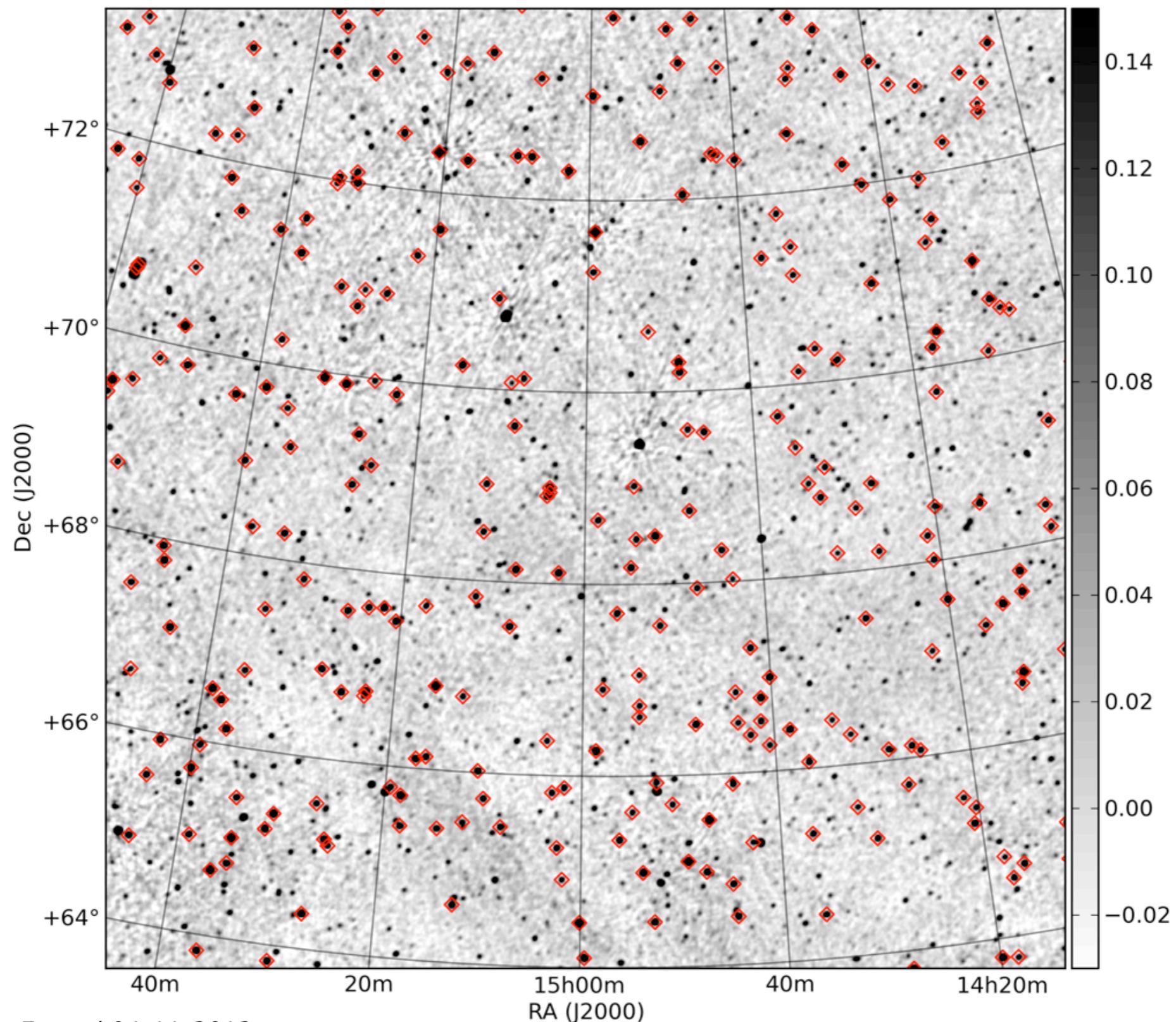




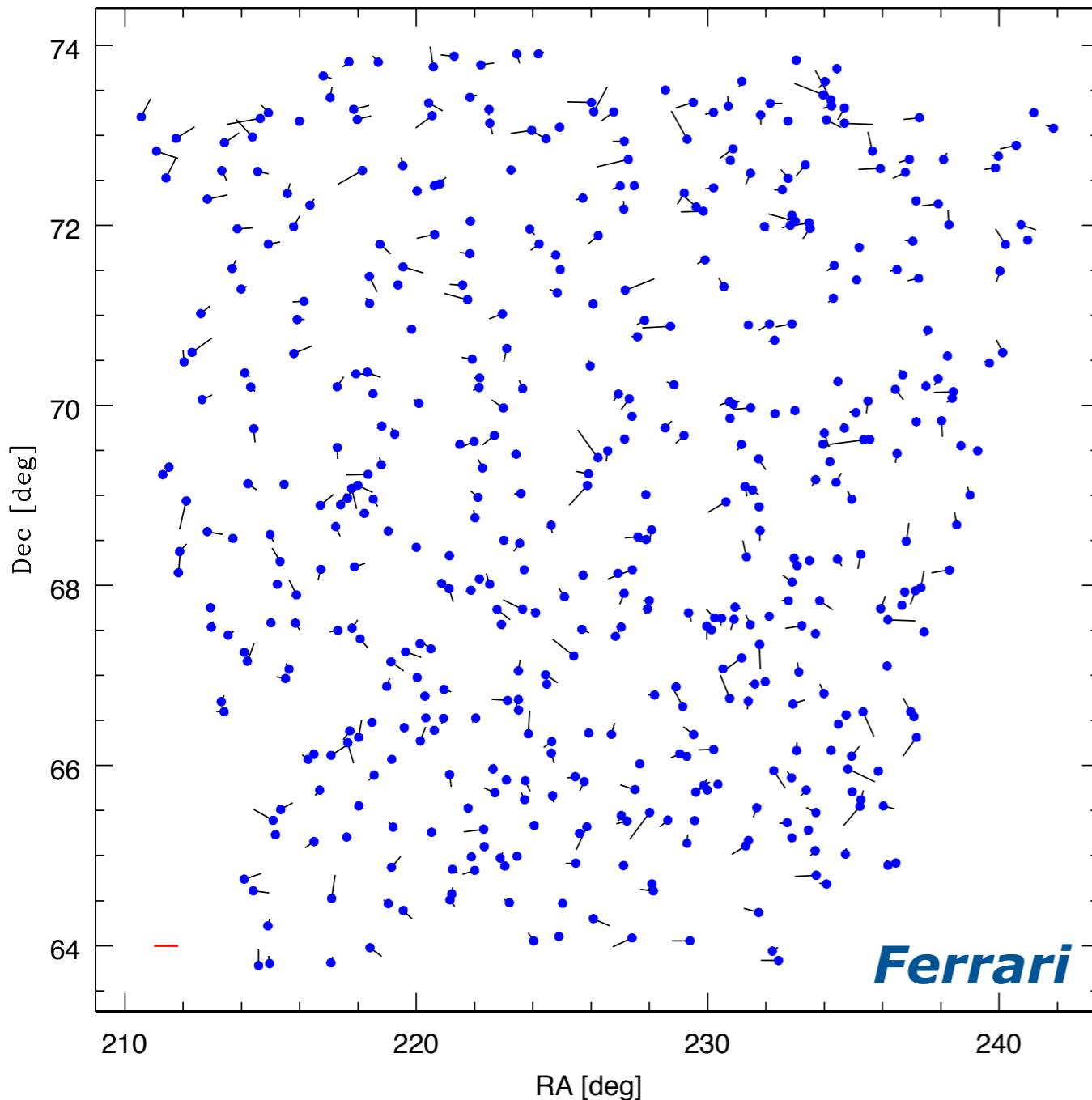
- LBA 46 mJy/beam, 2' resolution



- HBA 11 mJy/beam, 2' resolution - 630 sources detected in all 8 bands!



- Currently focused on producing MVF mini-catalog for public release



*Ferrari*

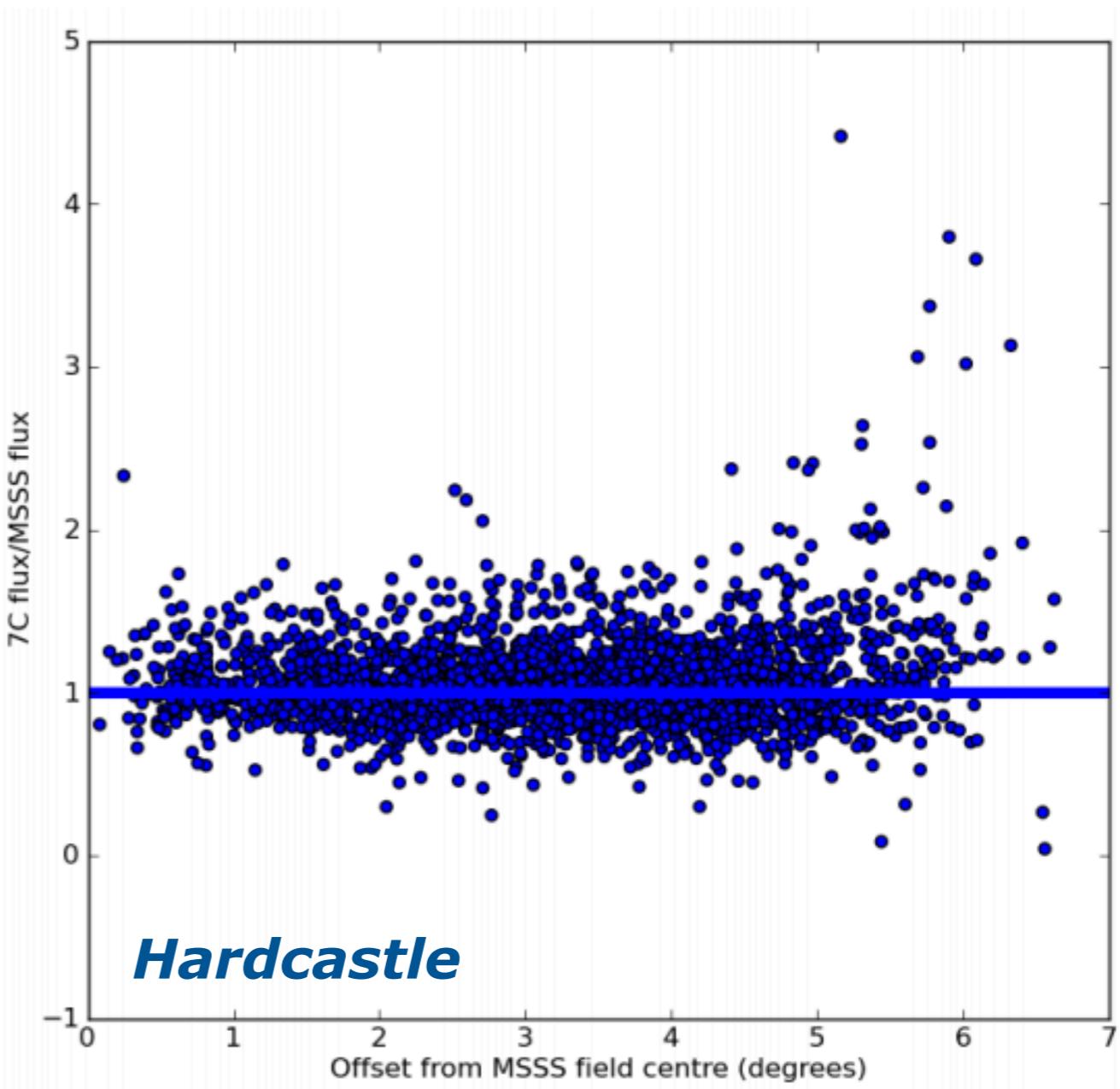


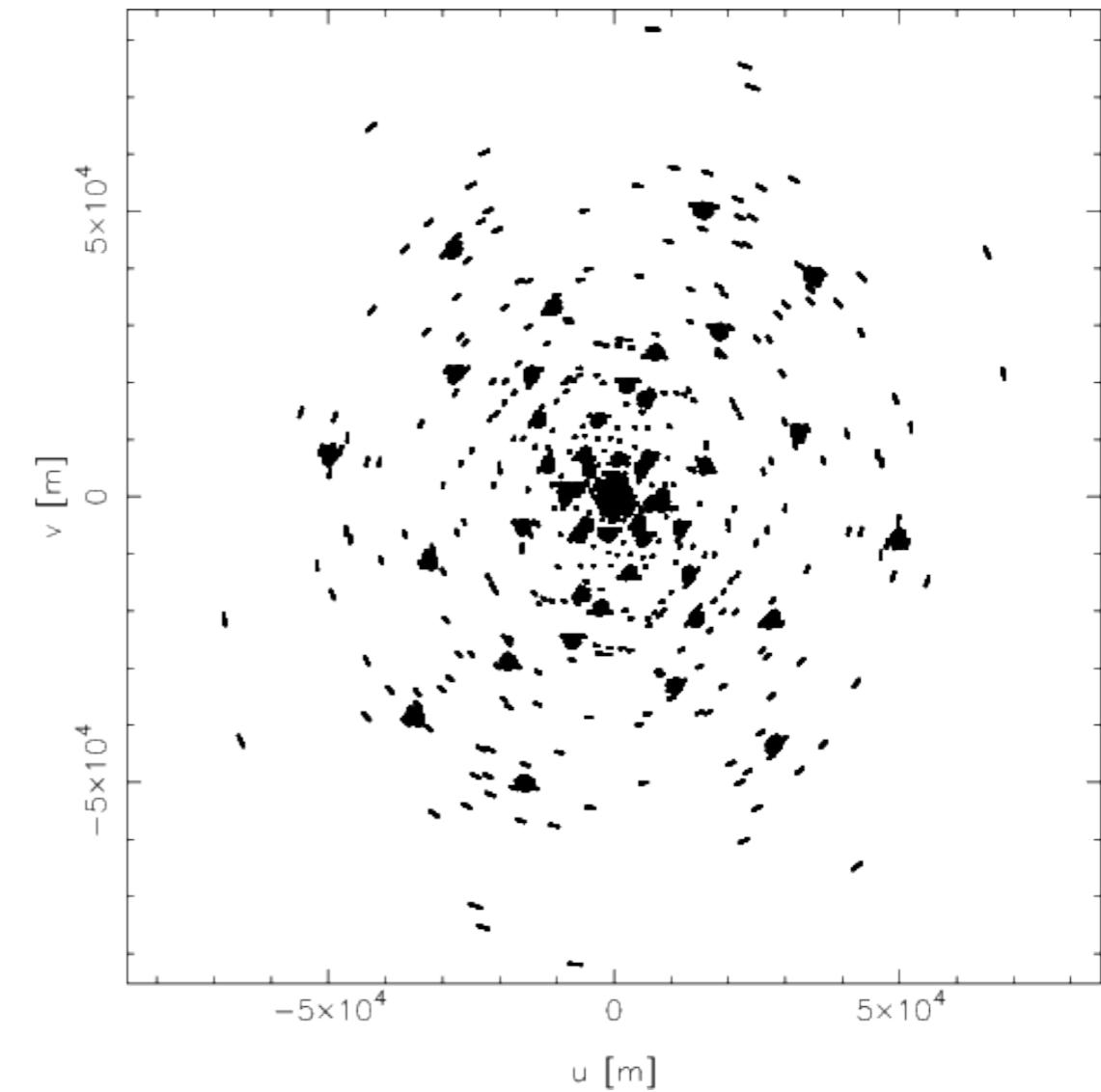
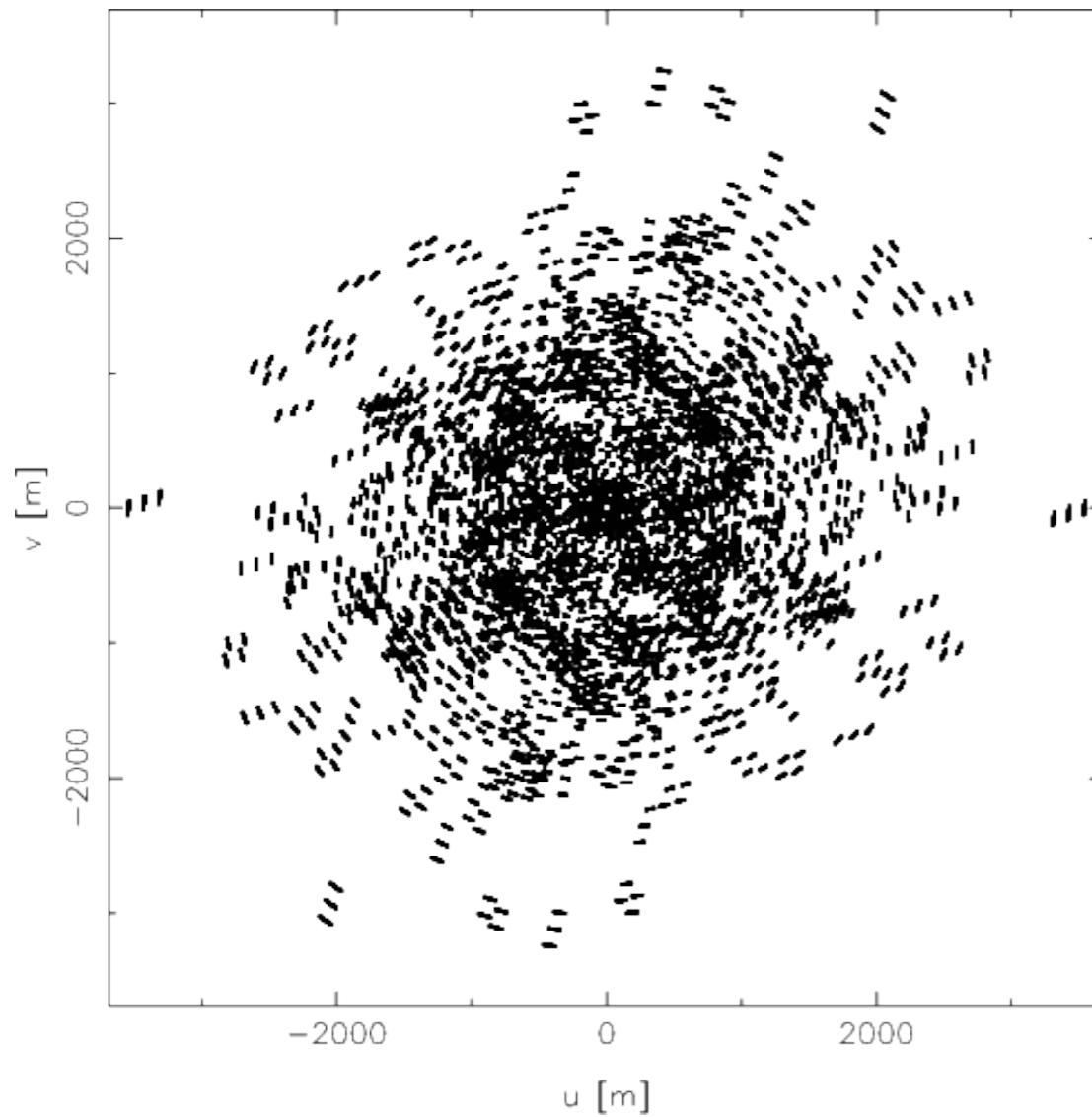
Figure 5: Flux ratio against offset from the field centre, in degrees.



**MSSS future plans**

# High-resolution imaging

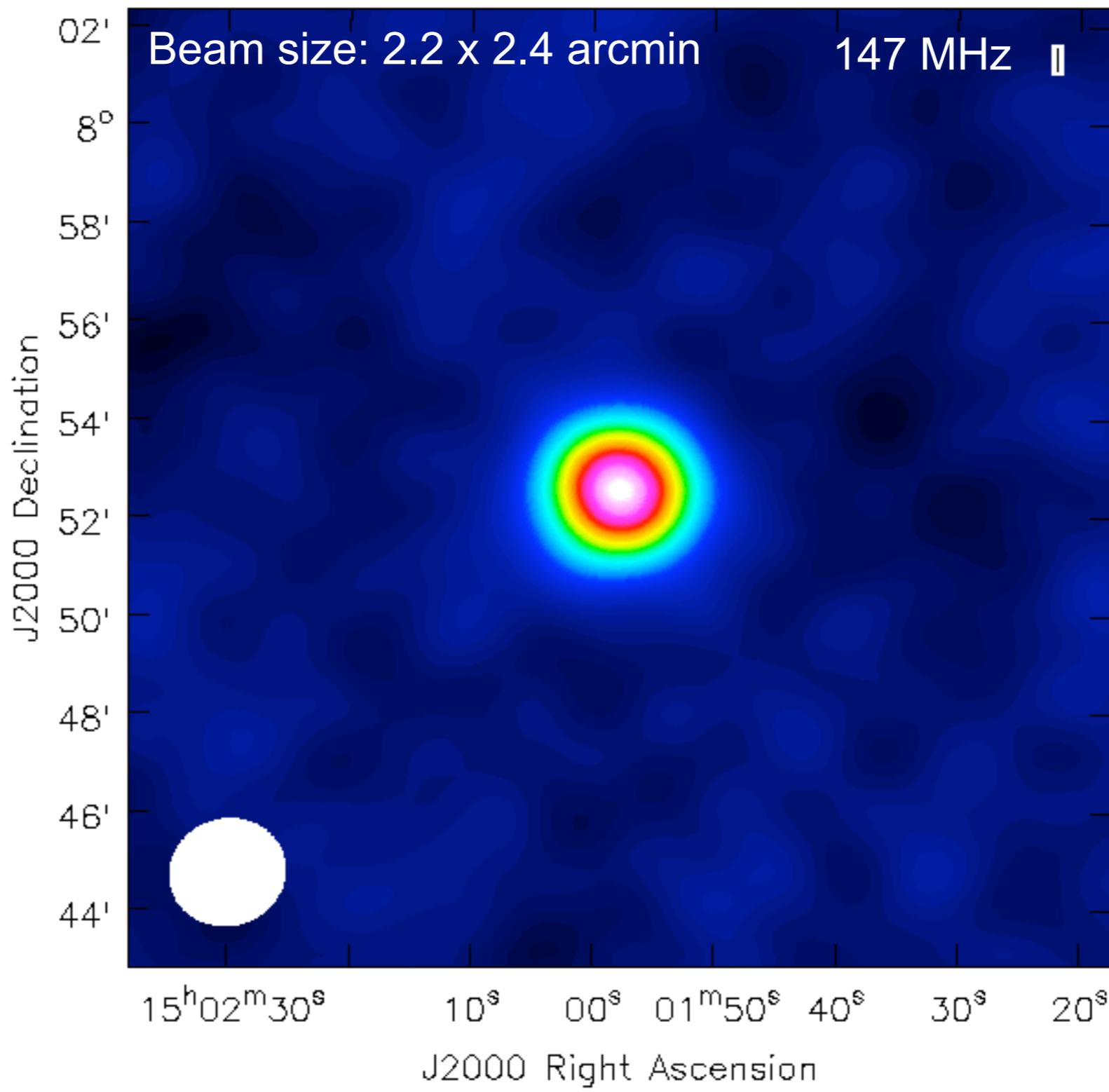
- Longer baselines are present in the data and are calibrated
- Higher resolution images of selected sources/fields can be produced if compute time available for the imaging (and should lead to an updated MSSS after the first data release)



# Cranking up the resolution of MSSS



4C +08.43

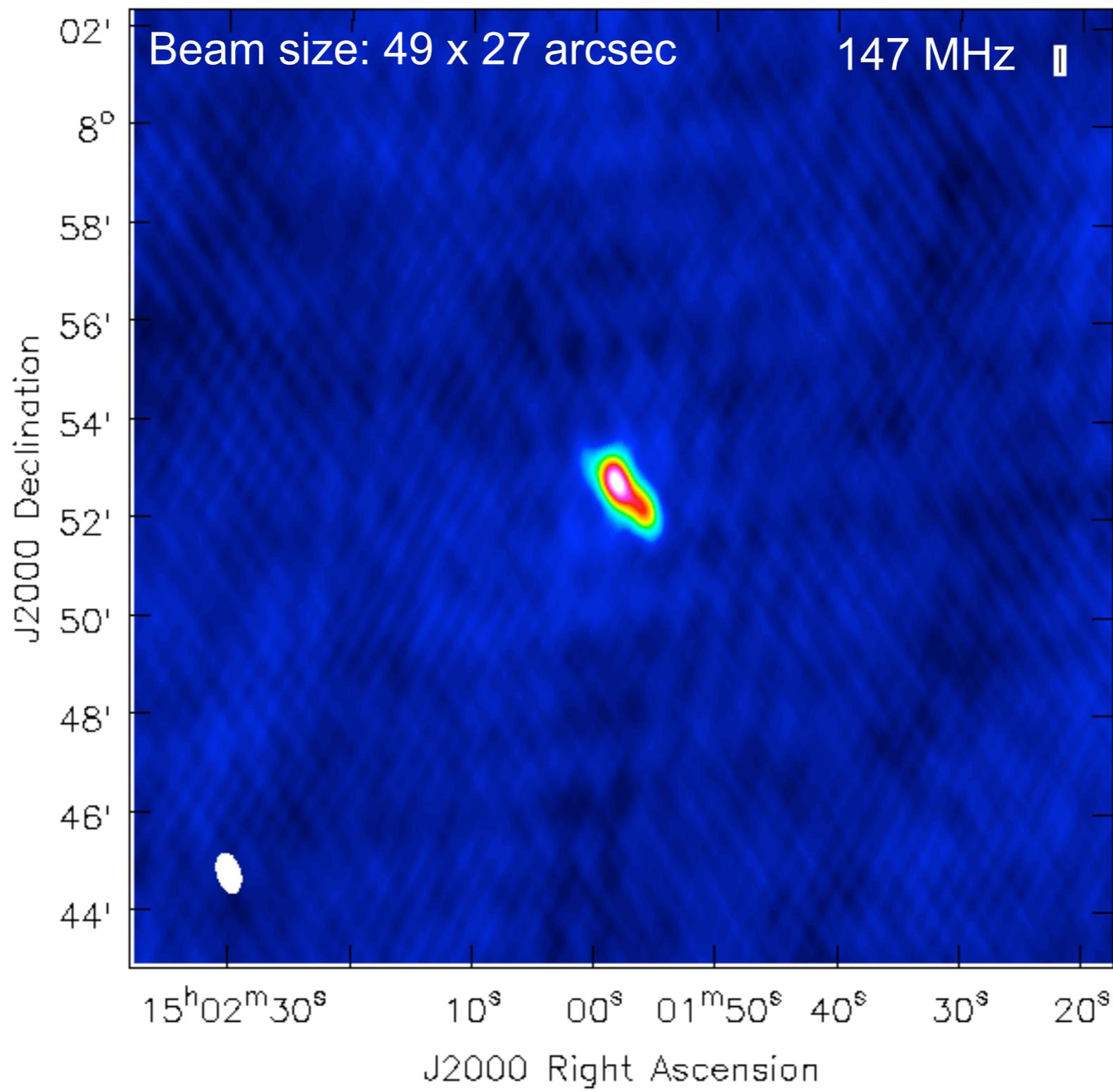


**McKean**

# Cranking up the resolution of MSSS



4C +08.43

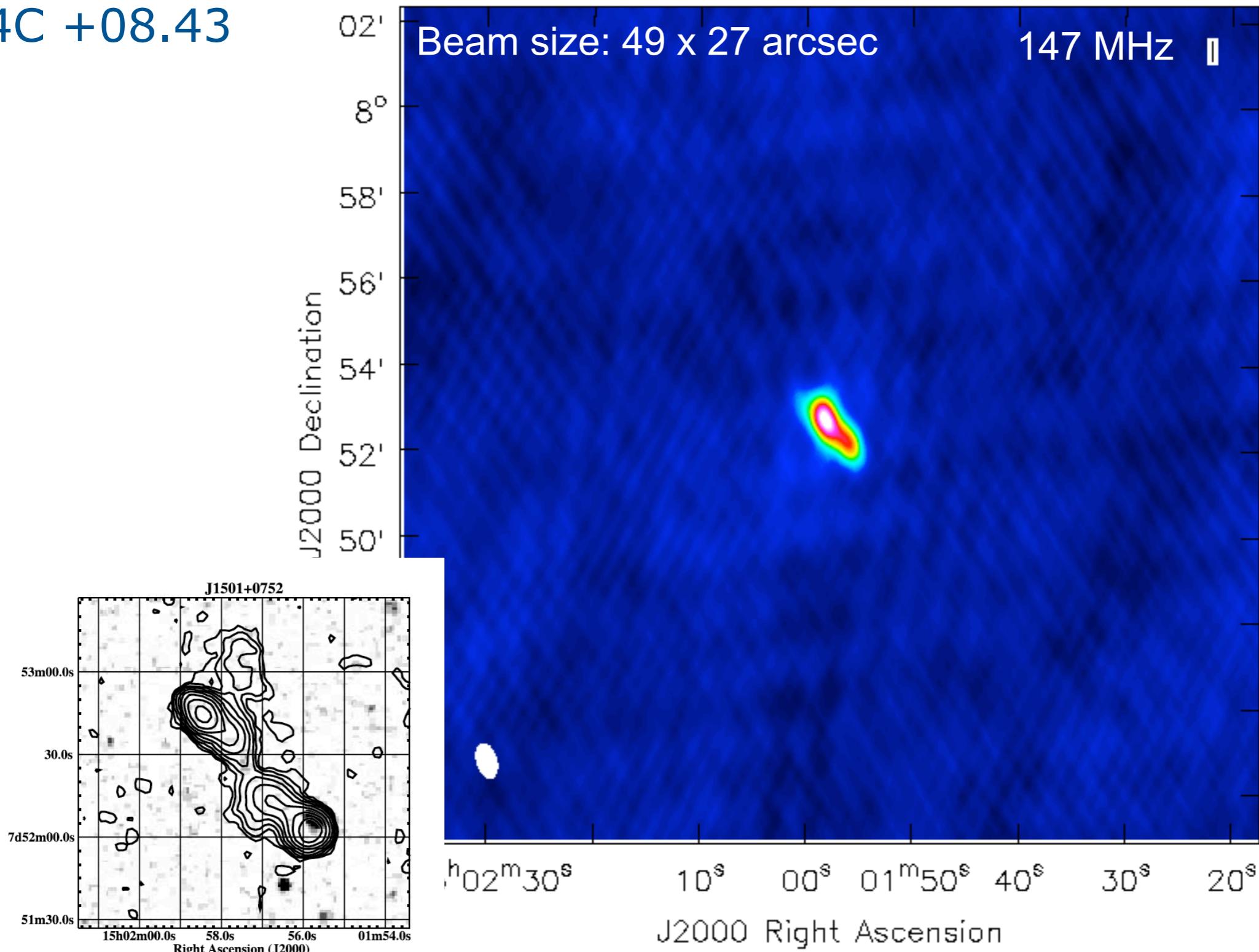


**McKean**

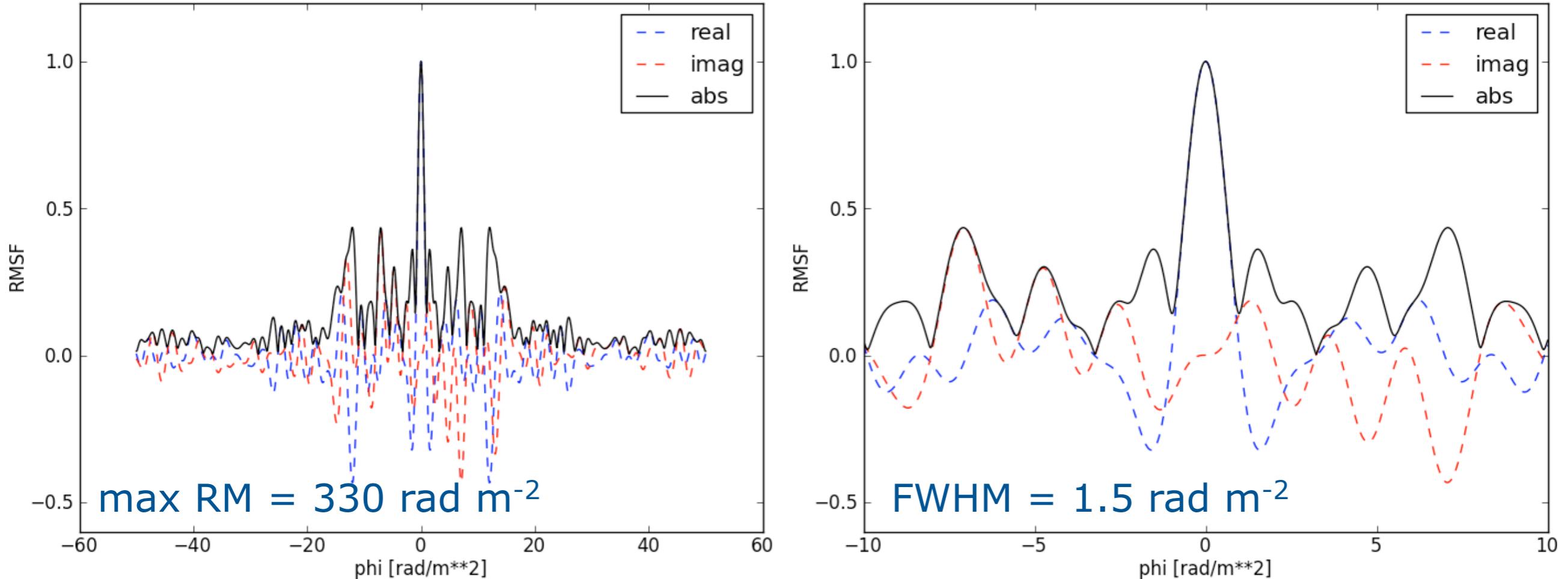
# Cranking up the resolution of MSSS



4C +08.43



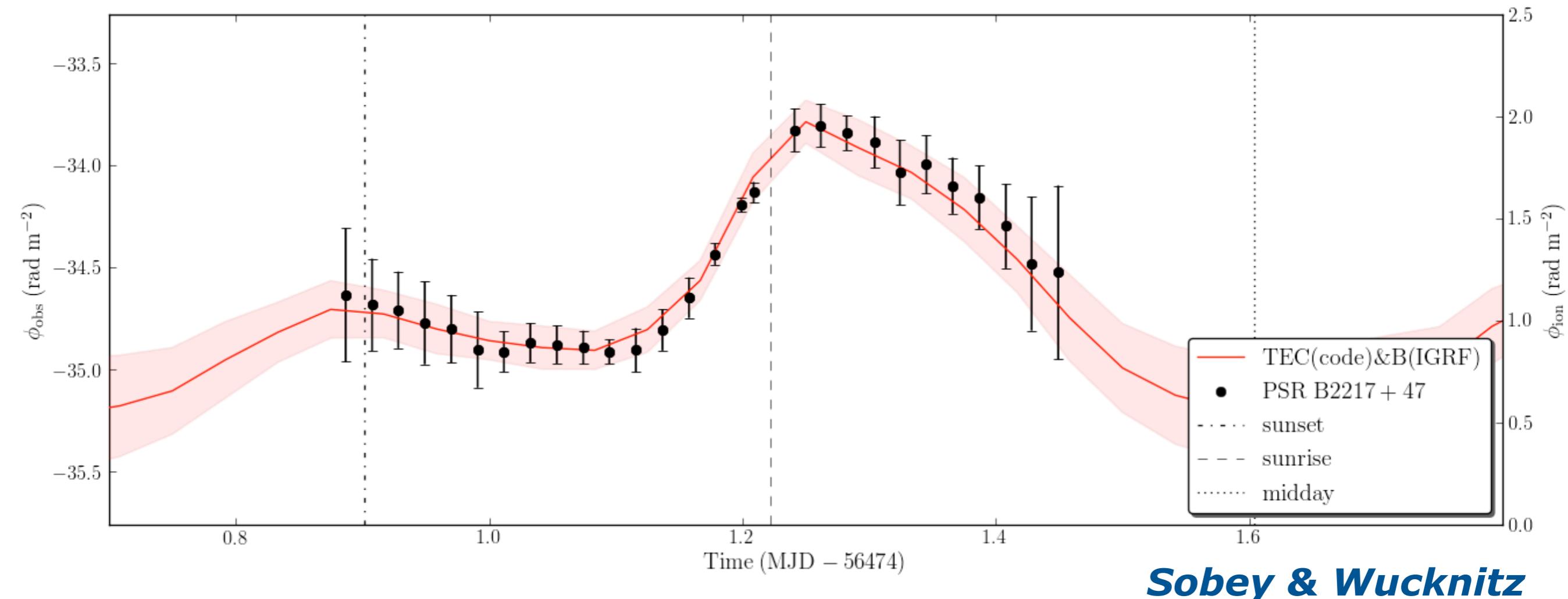
- Frequency coverage in HBA allows for shallow polarization search



- 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

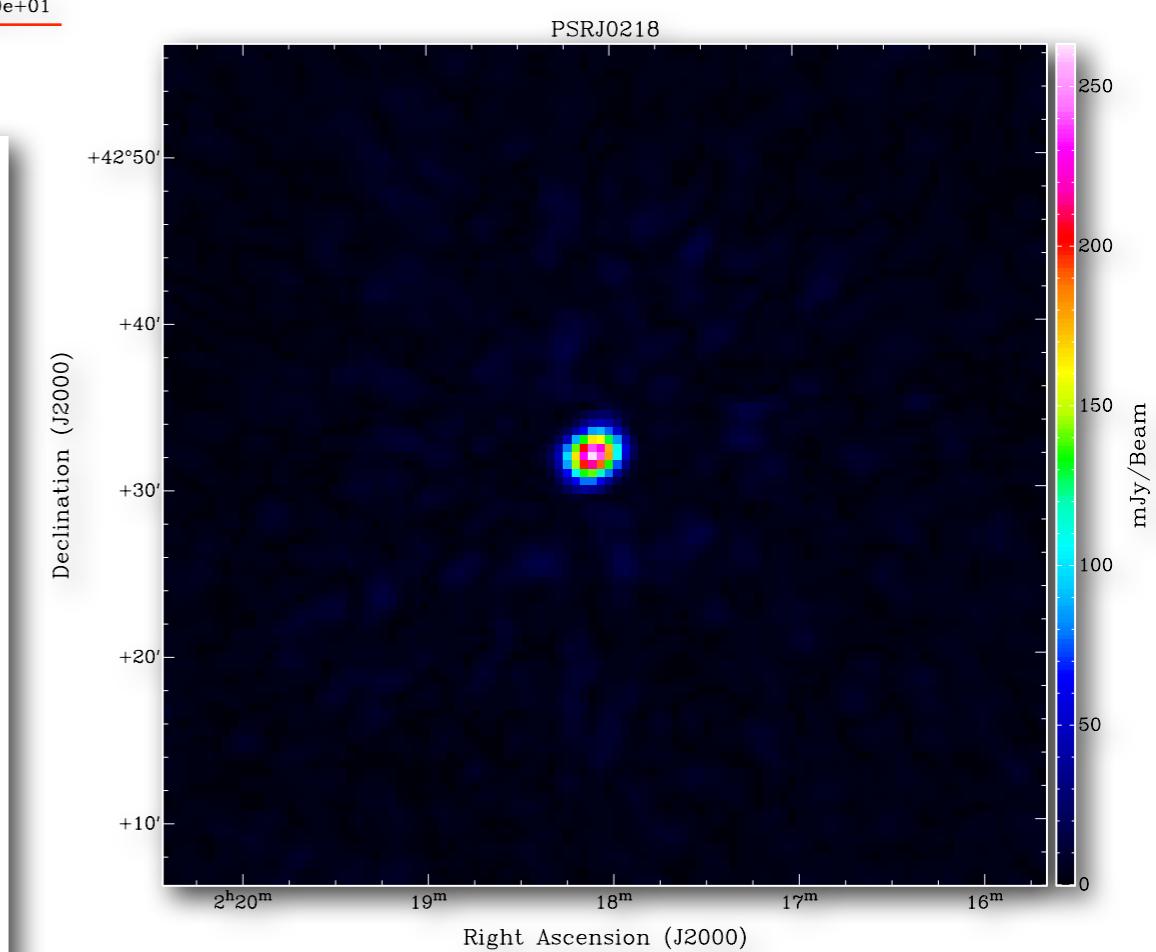
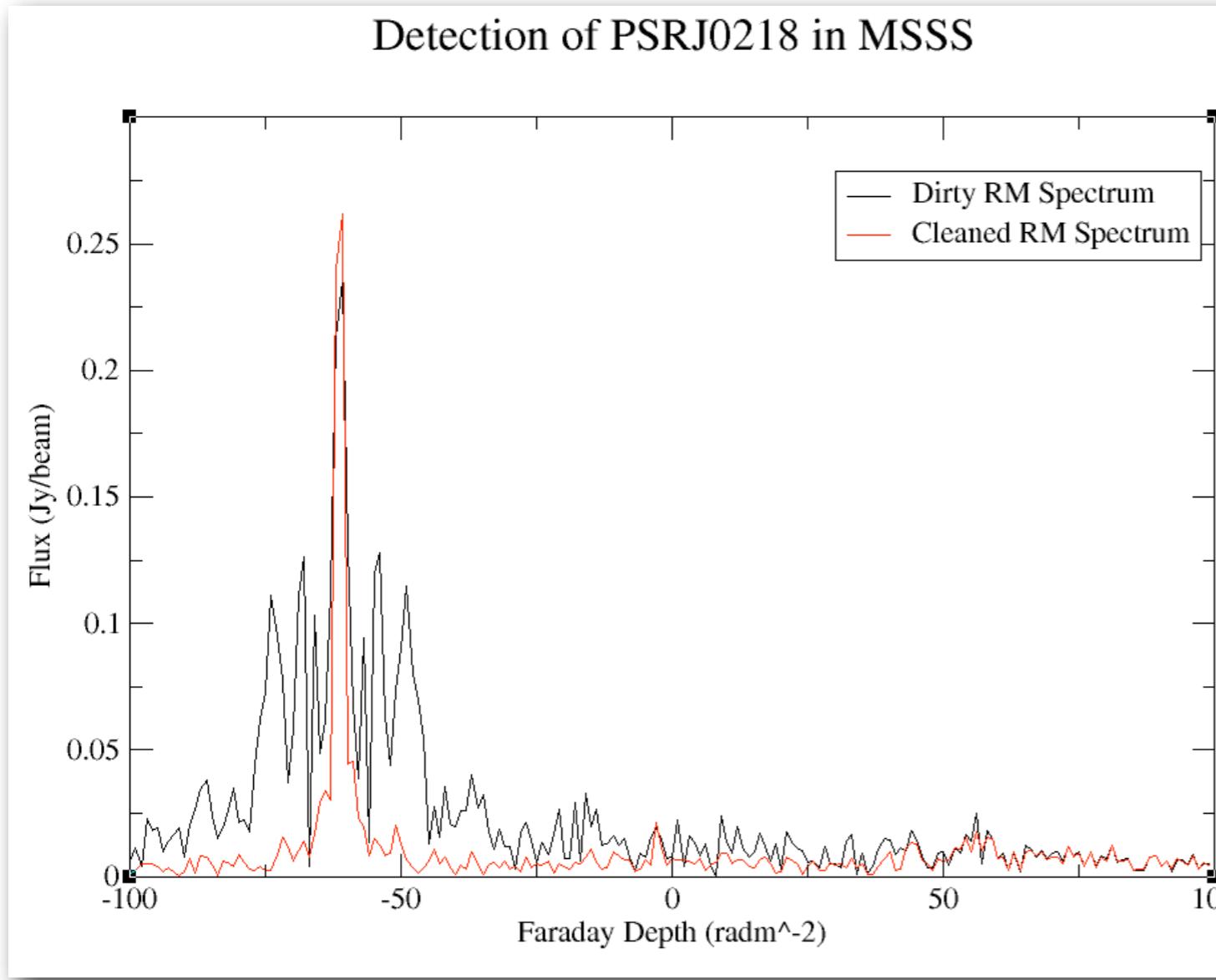
# Ionospheric RM prediction

- See Sotomayor-Beltran et al (2013)



# MSSS-HBA polarization

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



**David Mulcahy**

- Release MVF mini-catalog in 2013 (together with publication of MSSS overview journal article)
- Complete MSSS-HBA observations (projected end 2013)
  - Processing & imaging keeps up with observations
  - Selfcal round to follow completion of observations
  - Production of HBA catalog and QC phase
  - Release of HBA catalog projected mid-2014
- Resume MSSS-LBA observations
  - Ionospheric situation needs additional effort
  - Release of LBA catalog likely late 2014 or after
- As (computing) time allows, re-processing and imaging to allow higher angular resolution / polarization survey products

**<http://msss.astron.nl>**