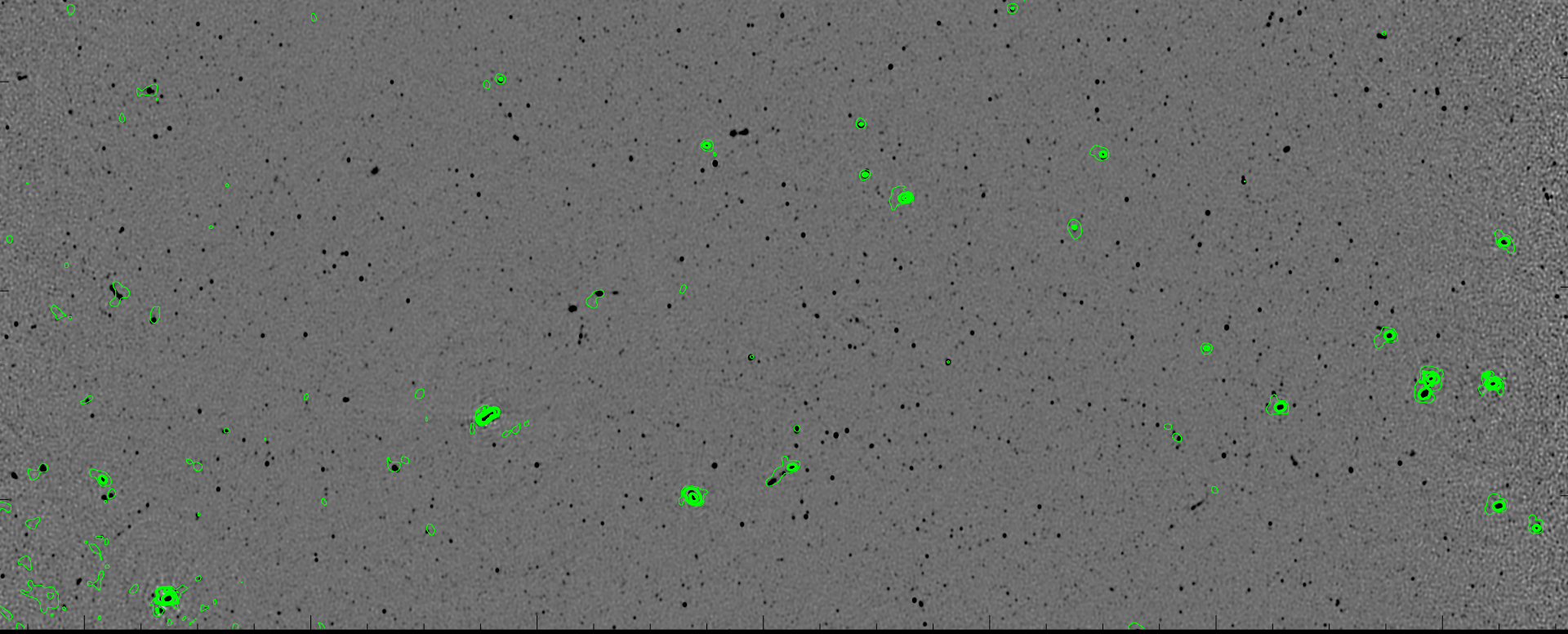

The Lockman Hole with LOFAR:

Searching for GPS and CSS sources at low frequencies

Elizabeth Mahony, Raffaella Morganti, Isabella Prandoni, Ilse van Bemmel
and many others in the LOFAR Surveys Key Science Project.

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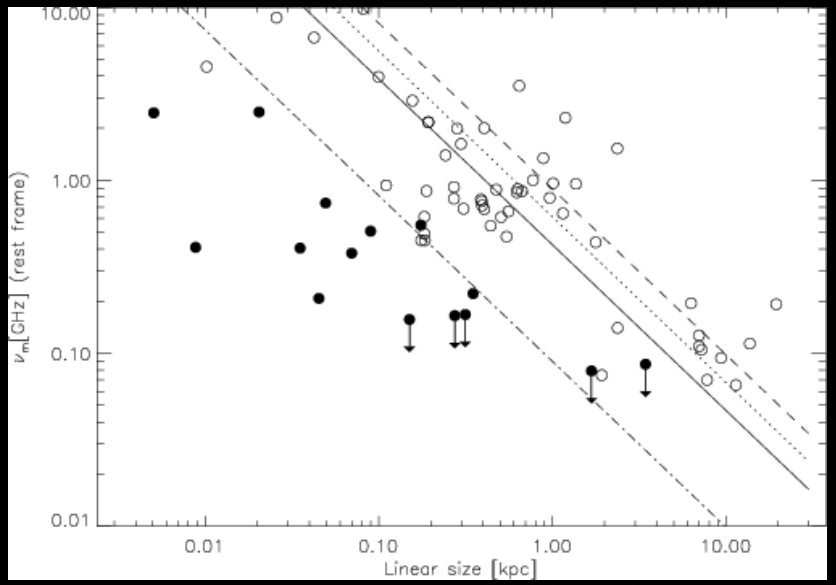
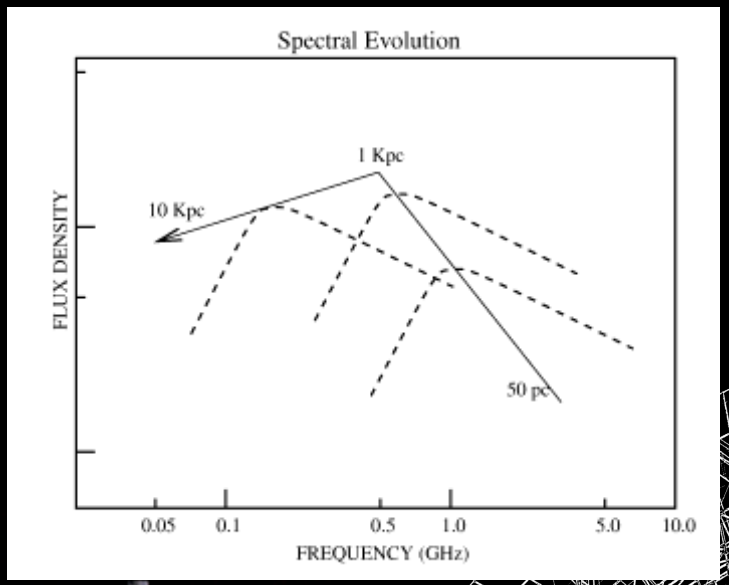
Why search for GPS and CSS sources at low frequencies?

- ‘nearby’ CSS sources
  - Correlation between spectral peak and linear size
- High-z GPS sources
  - Correlation between spectral peak and source age -> redshifted to low frequencies



de Vries et al., 2008



Snellen et al., 2000

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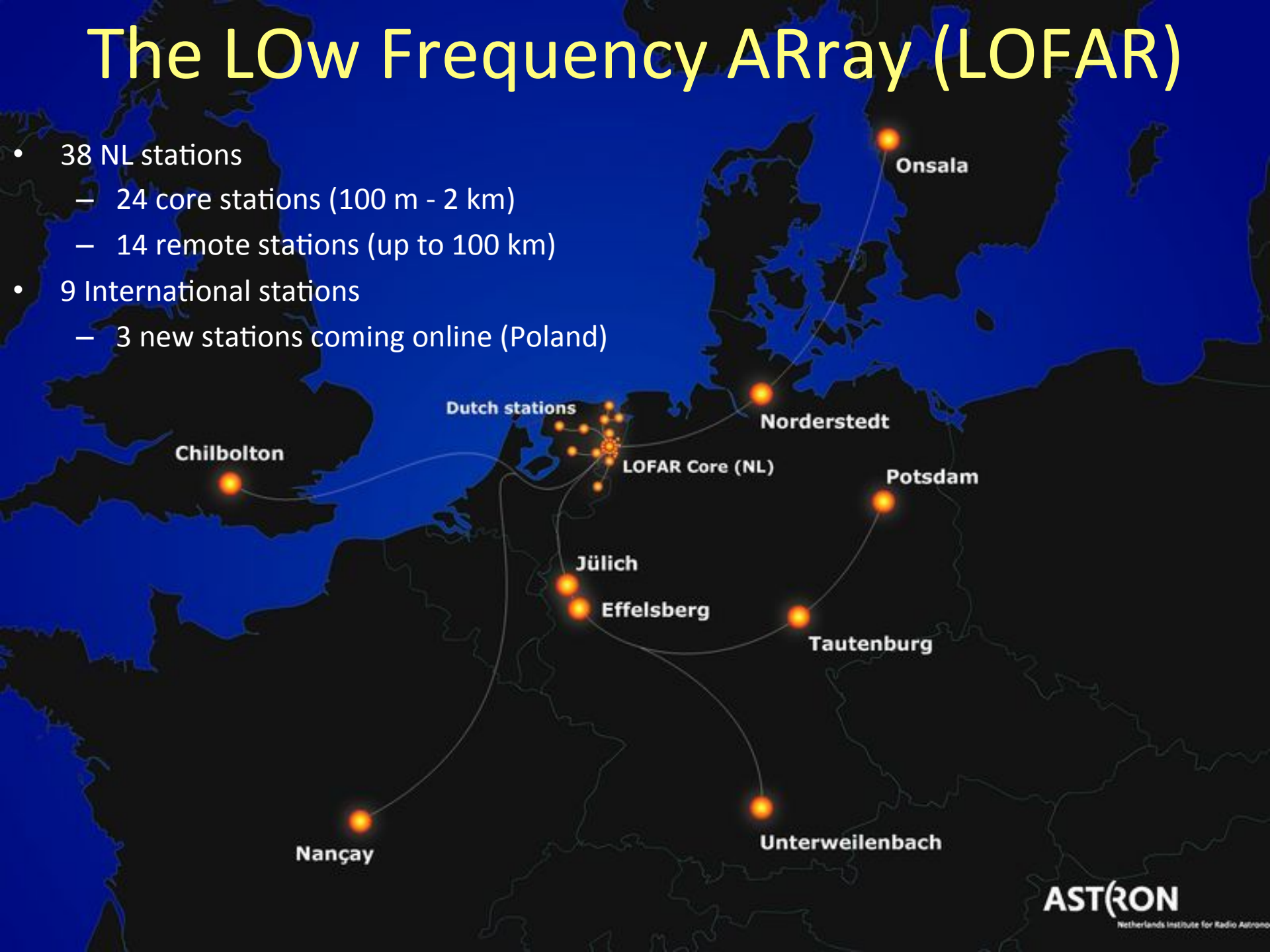
The LOw Frequency ARray (LOFAR)

- 38 NL stations
  - 24 core stations (100 m - 2 km)
  - 14 remote stations (up to 100 km)
- 9 International stations
  - 3 new stations coming online (Poland)



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- Frequency coverage:
  - HBA (110-190 MHz)
  - LBA (10-90 MHz)
  - Bandwidth available: 95 MHz
    - Up to 488 subbands of 0.2 MHz each
- Primary beam:
  - HBA: ~5 degrees
  - LBA: ~7 degrees

LBA

HBA

Dutch stations

Chilbolton

LOFAR Core

Nançay

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  - LBA: ~7 degrees
- LOFAR Tier 1 survey:
  - 2π str, 0.1 mJy rms

LBA

HBA

Dutch stations

Chilbolton

LOFAR Core

Nançay

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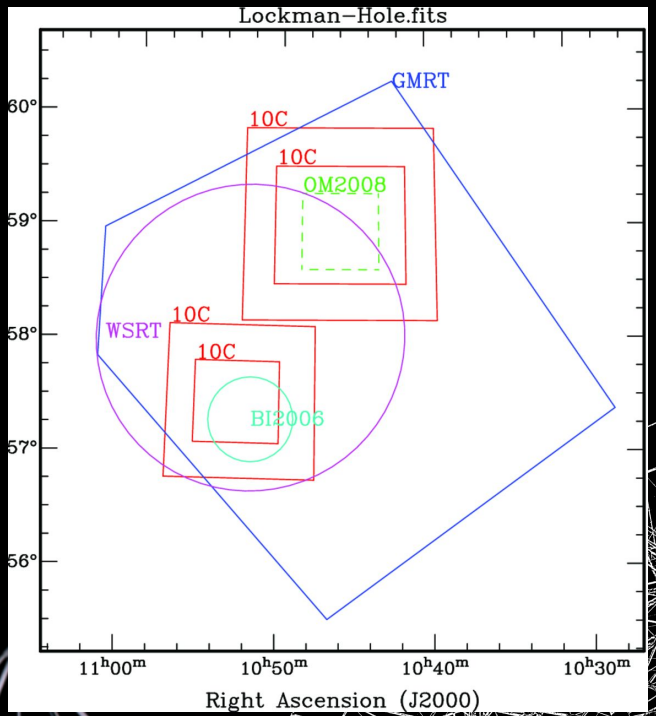
The Lockman Hole field

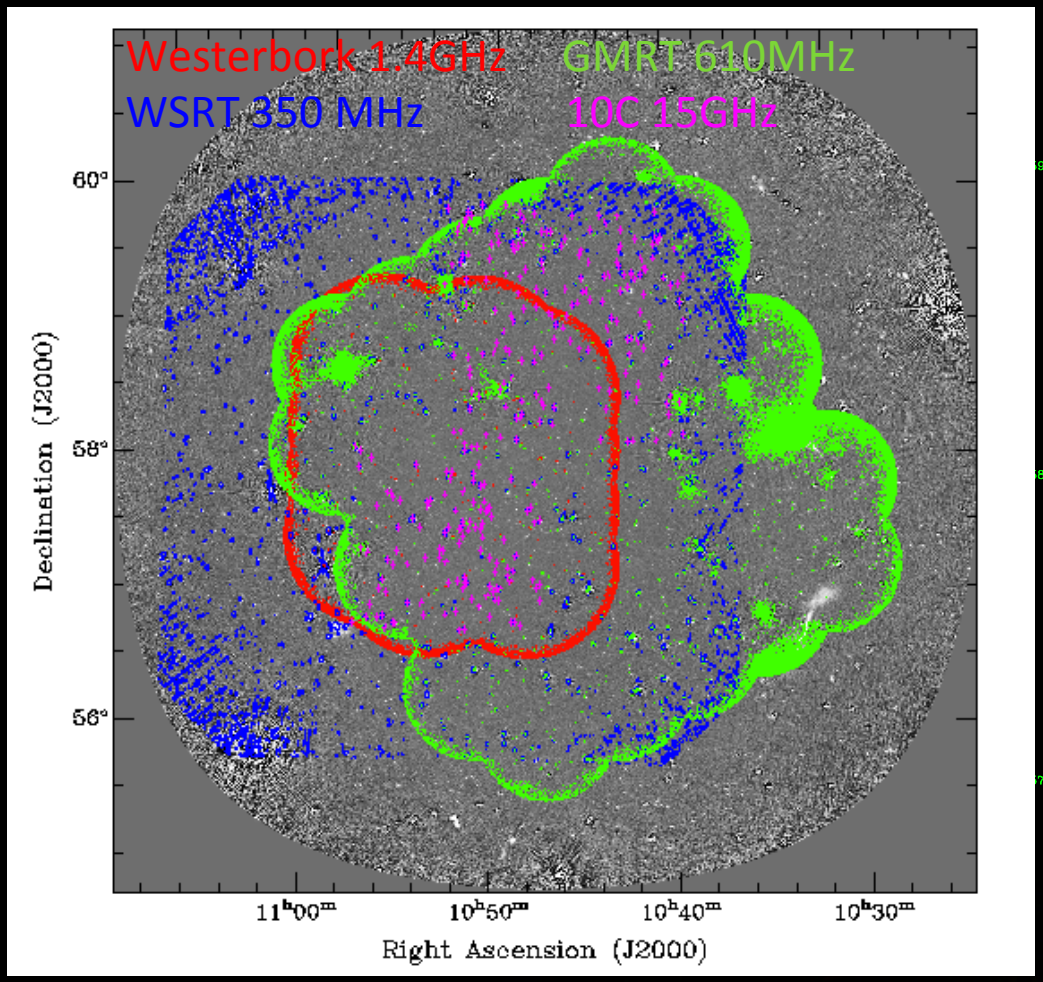
- Observed as part of the Surveys KSP (PI: Philip Best)
- Extensive multiwavelength data:
  - PanSTARRS, UKIDSS, SERVS, SWIRE, HerMES, VLA, GMRT, WSRT, Chandra, SCUBA, SCUBA-2, Galex

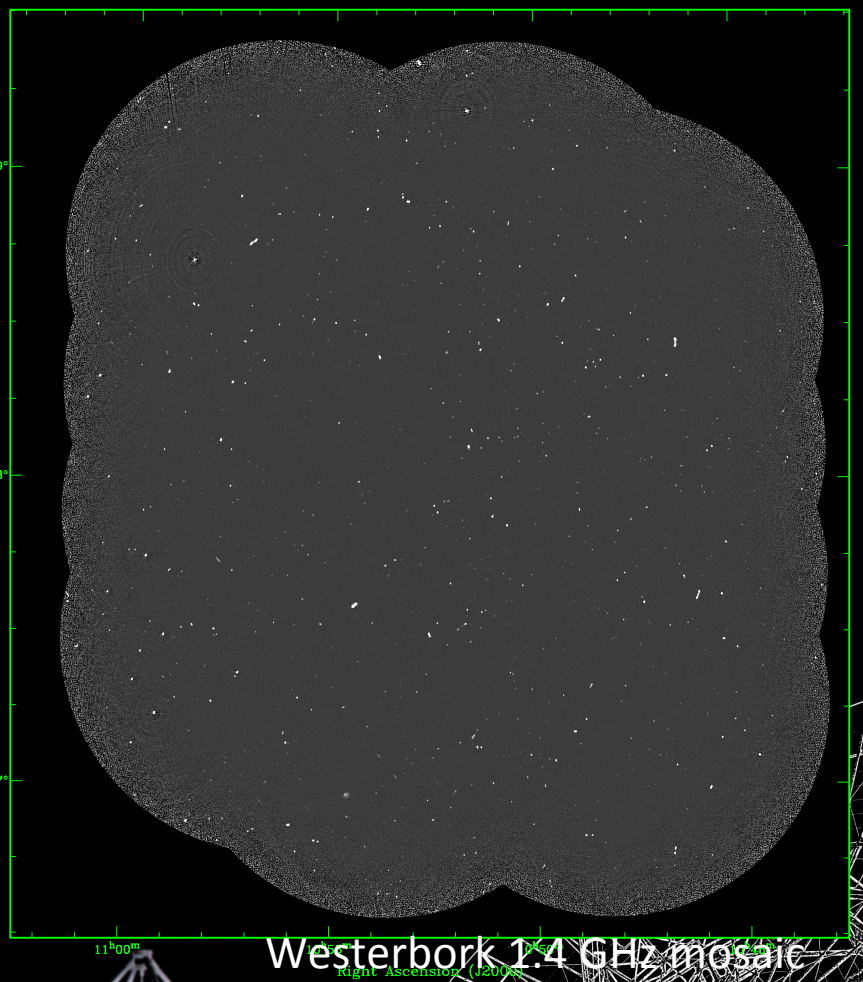
- Multiwavelength radio data covering a wide range in frequency:
  - WSRT: 1.4 GHz, 7 deg^2, 11 uJy
  - WSRT: 350 MHz, 0.7 mJy
  - GMRT: 610 MHz, 5 deg^2, 60 uJy
  - 10C: 15 GHz, 4.5 deg^2, 0.1 mJy



Whittam et al., 2013

The Lockman Hole





Westerbork 1.4 GHz mosaic
Guglielmino et al., 2012

HBA observations (110-180 MHz)

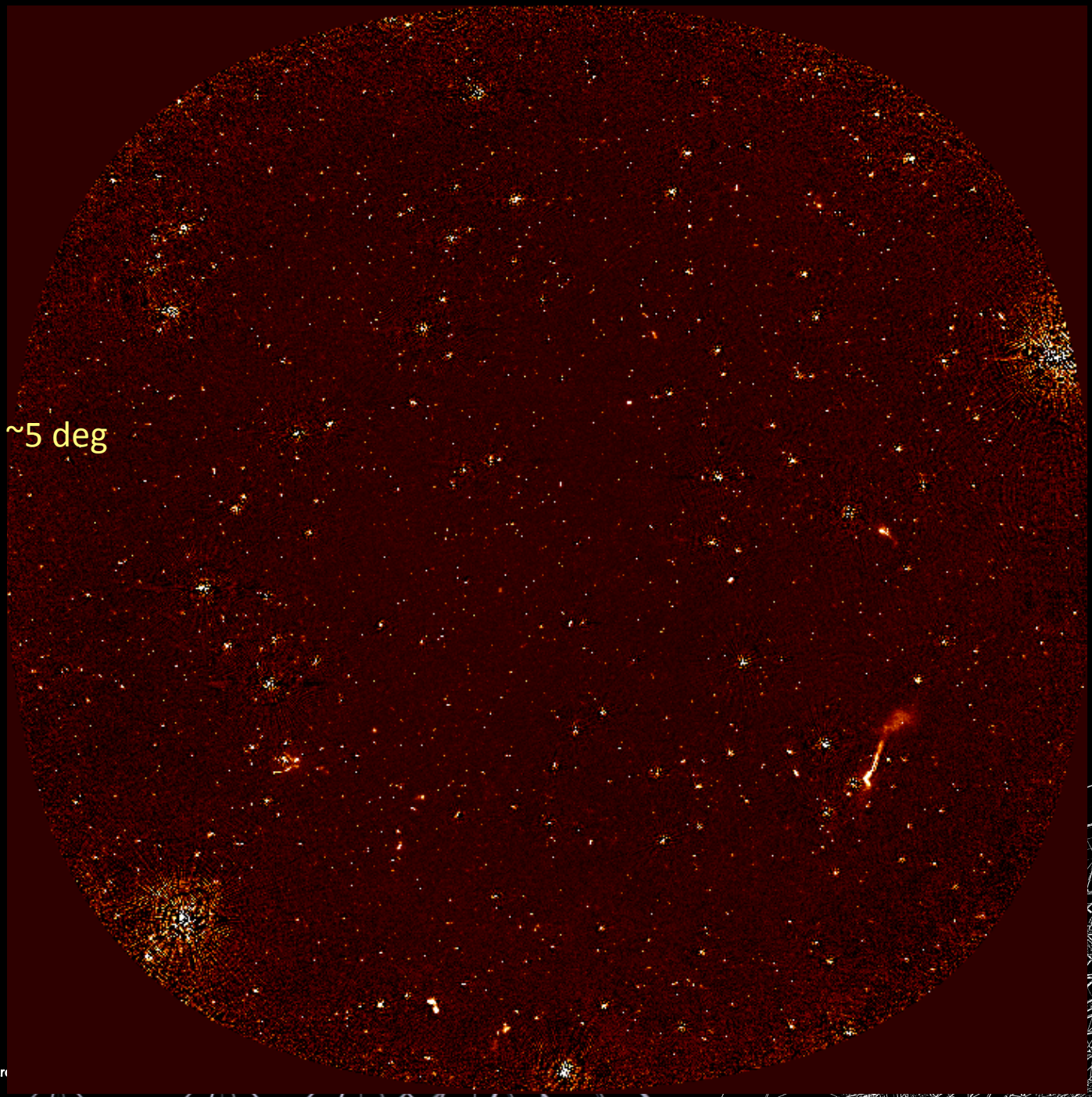
300 subbands (70 MHz bandwidth)

10 hrs int. time

14x18” resolution

rms ~0.15 mJy

> 5000 sources detected



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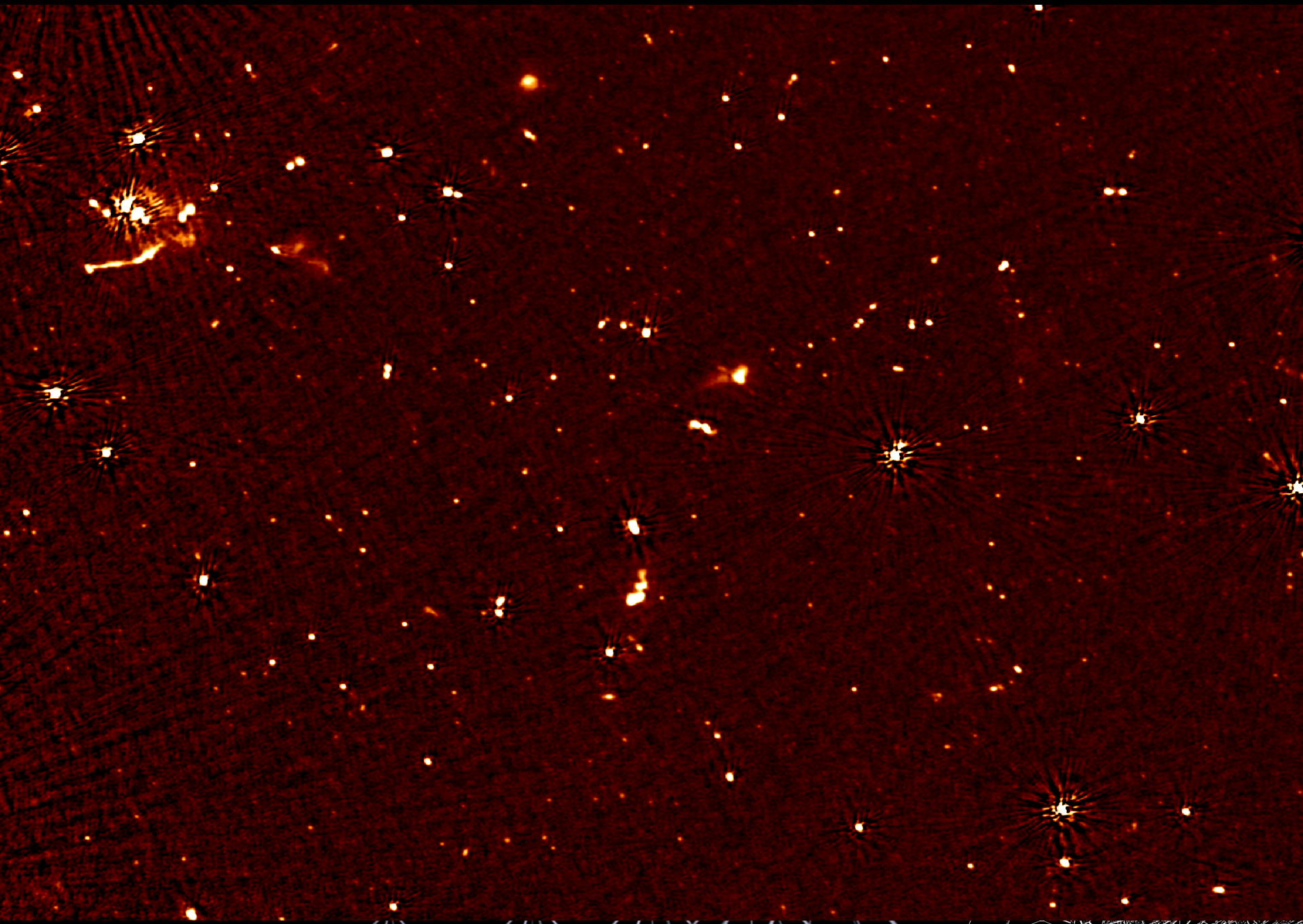
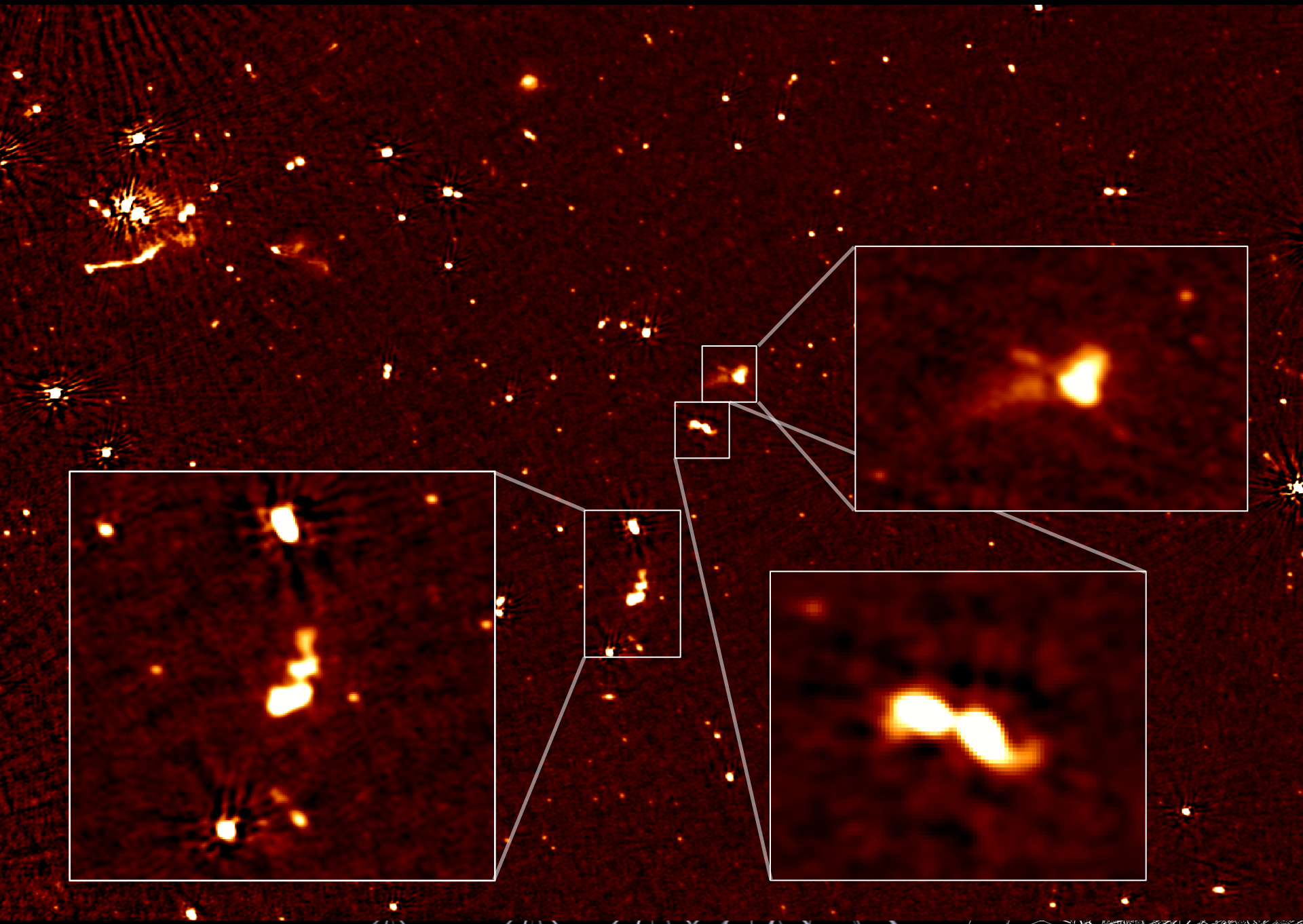
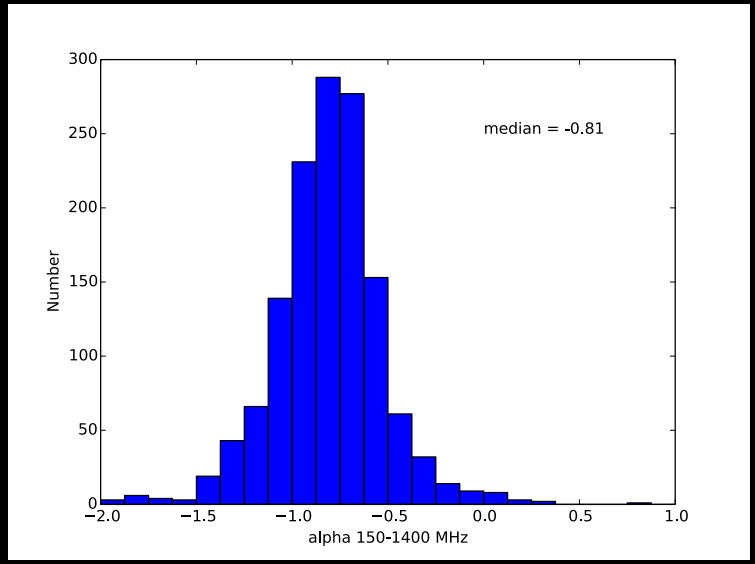


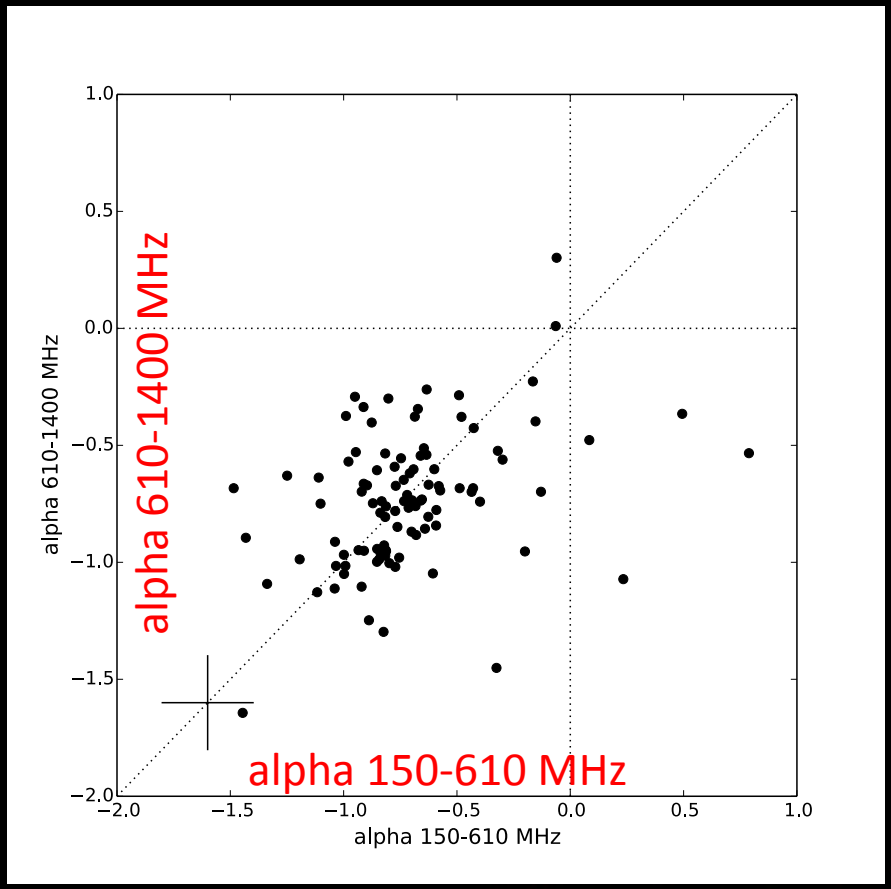


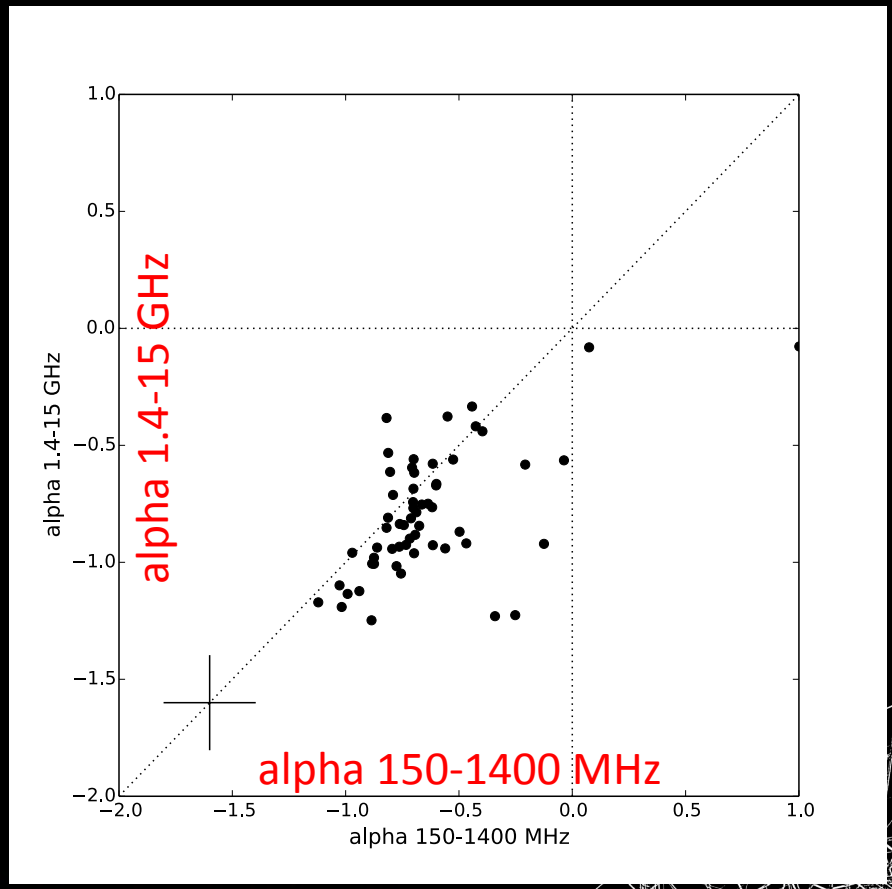
Spectral indices of low-freq. sources

- Crossmatched with deep WSRT mosaic
  - 1366 matches.
  - All LOFAR sources have a 1.4 GHz counterpart
- Counterparts at other frequencies:
  - GMRT (610 MHz): 125 matches
  - WSRT (345 MHz): 222 matches
  - LOFAR LBA (60 MHz): 43 matches
  - 10C (15 GHz): 119 matches
- Required at least 4 points in radio SED
  - Leaves us with a sample of 117 sources to search for peaked spectra



alpha-alpha plots





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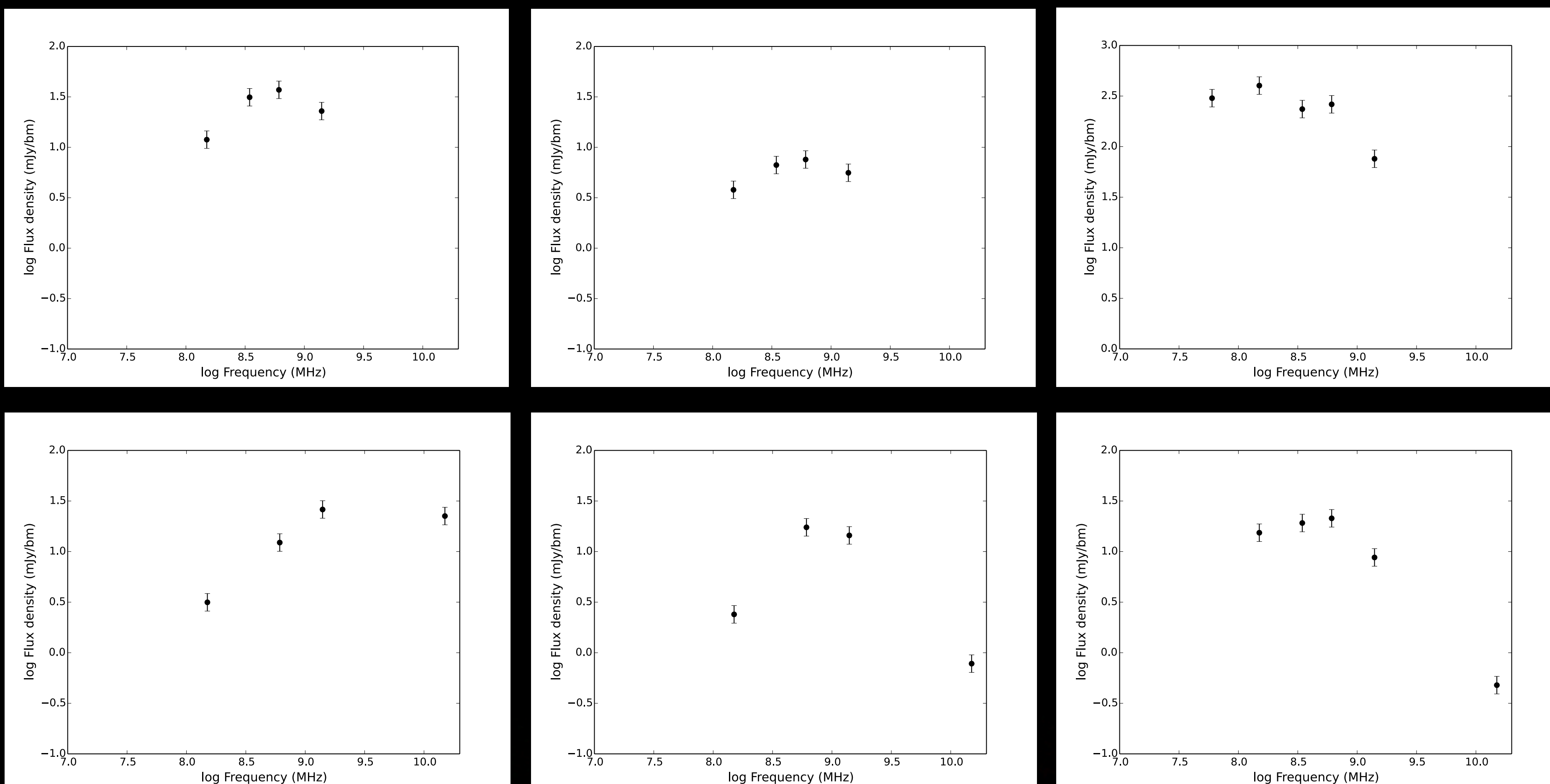
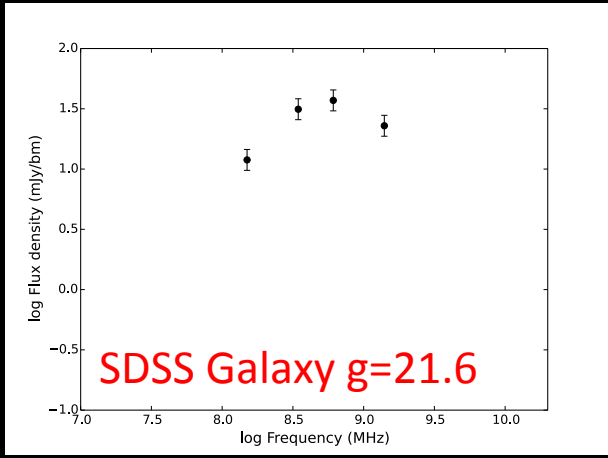
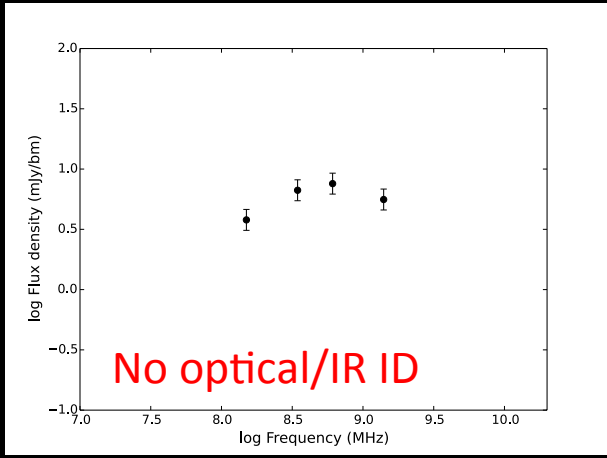
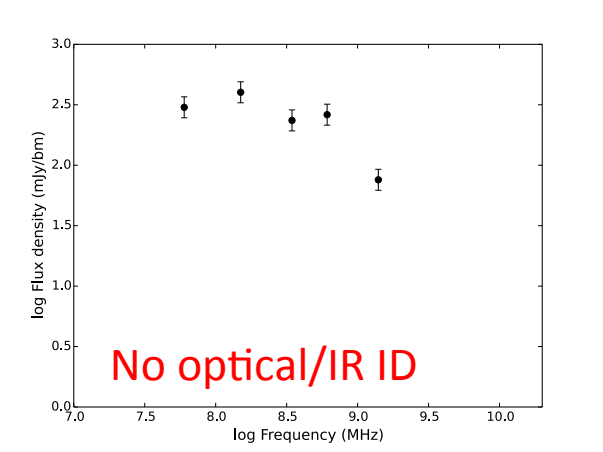
MHz-peaked spectrum sources in the Lockman Hole field

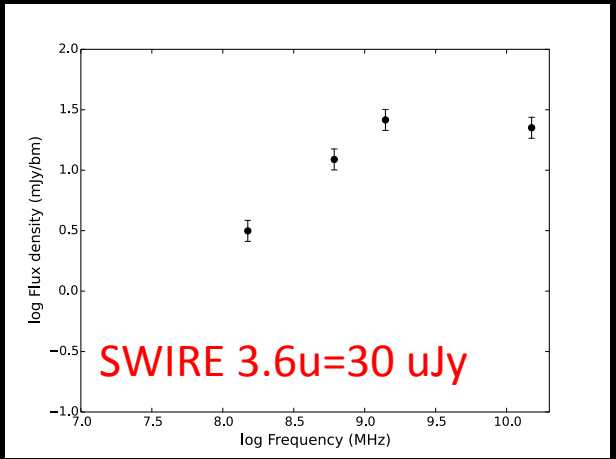


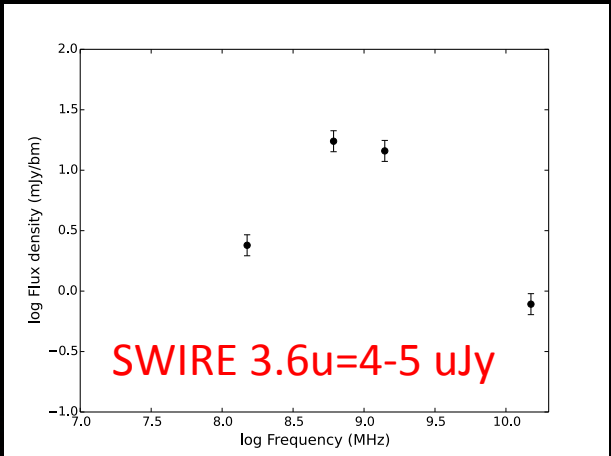
MHz-peaked spectrum sources in the Lockman Hole field

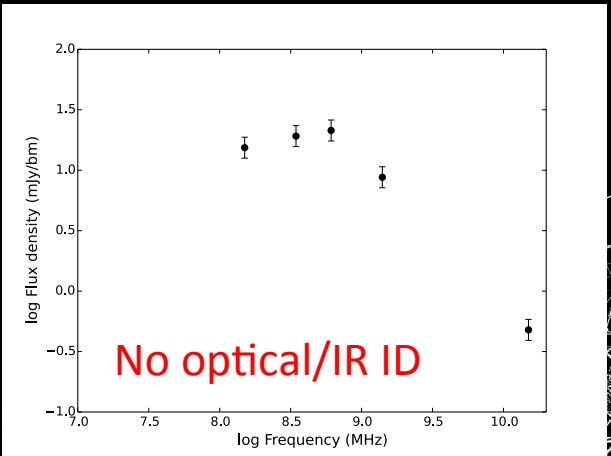












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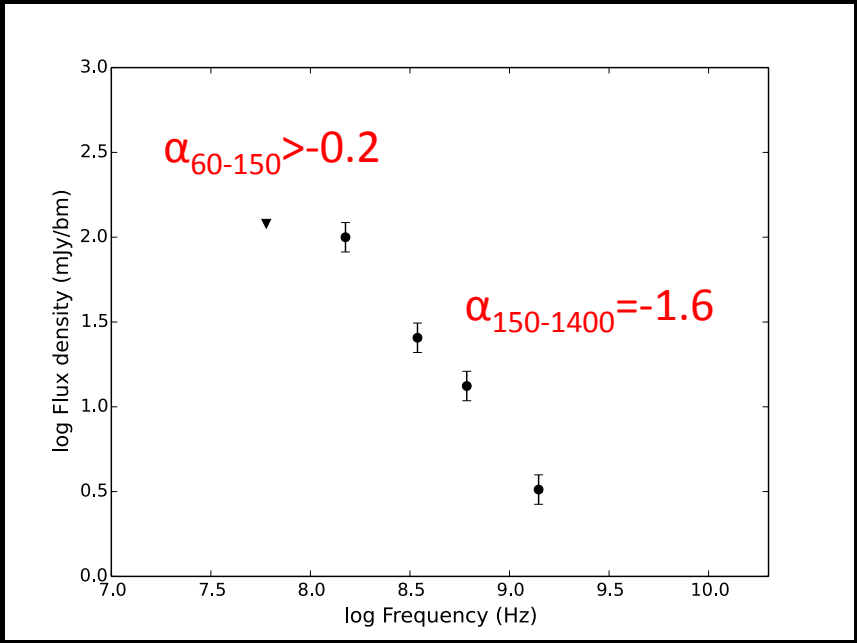
MHz-peaked spectrum sources in the Lockman Hole field



- Ultra Steep Spectrum (USS) source
  - 100 mJy at 150 MHz, very steep (α=-1.6) up to 1.4 GHz
  - No detection at 60 MHz (< 120 mJy)
  - Possible spectral peak @ 100 MHz?
  - No SDSS counterpart, 3.6um dectection at 10 uJy.

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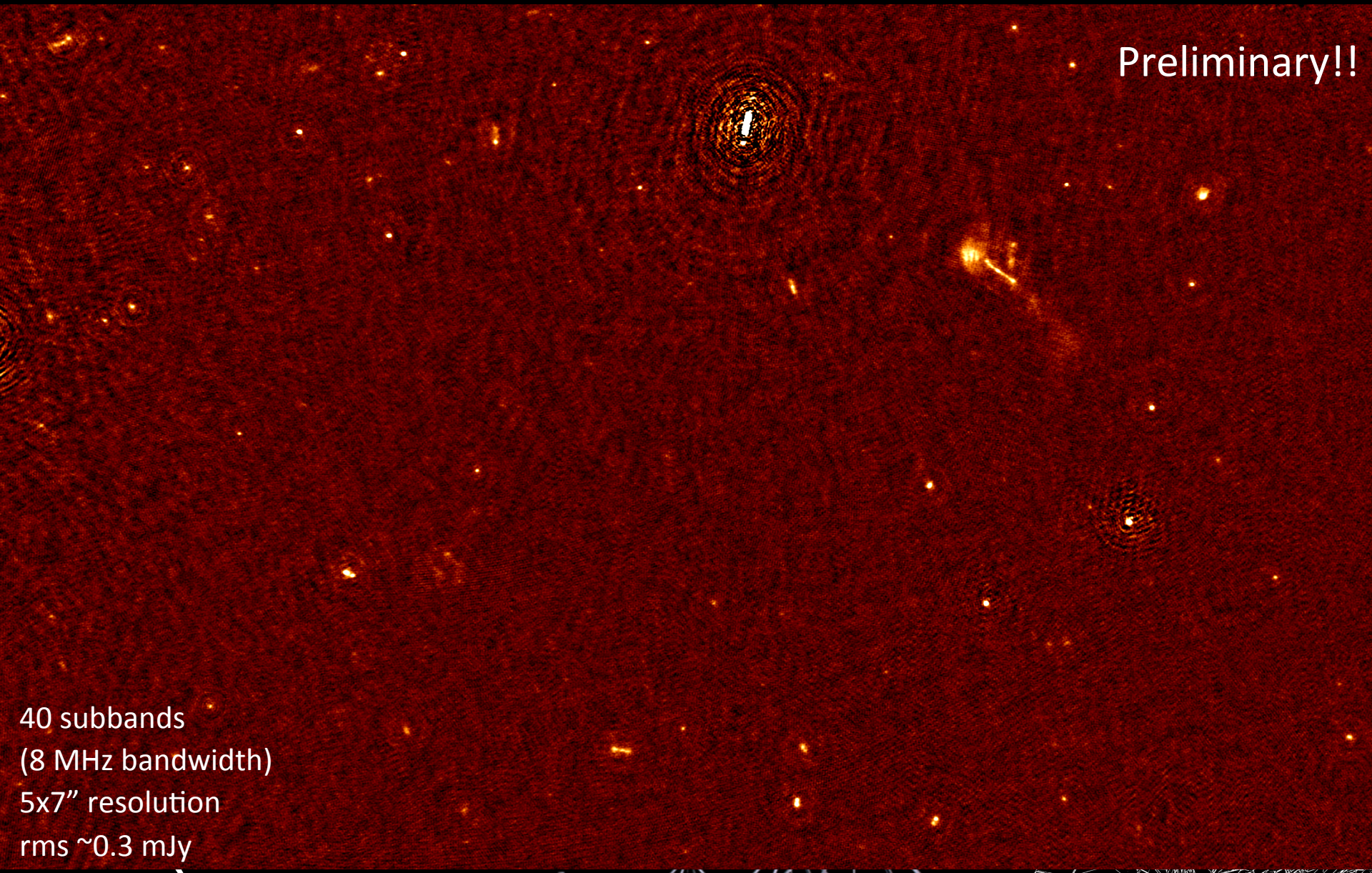
Preparing for LOFAR surveys

- We detect 7/117 (6%) GPS/CSS sources in the Lockman Hole field
- Extrapolating this to the full LOFAR sky survey (2π str): can expect to detect more than 20,000 MHz-peaked sources
  - However, strongly dependent on the multiwavelength data available!

- How to separate high-z GPS sources from nearby CSS sources?
  - Follow-up in Optical/NIR
  - Need higher resolution data -> aim is to get to 5 arcsec resolution

Higher resolution LOFAR images…



Summary

- LOFAR is an ideal instrument for searching for high-z GPS or nearby CSS sources (where the spectral peak occurs at MHz frequencies).

- In the Lockman Hole field we discover 7 new GPS/CSS sources peaking at MHz frequencies
  - Corresponds to 6% of the sample studied
  - Can expect to find > 20,000 in full LOFAR sky survey

- BUT…
  - Only possible with multi-frequency radio data, in particular need deep 1.4 GHz data!

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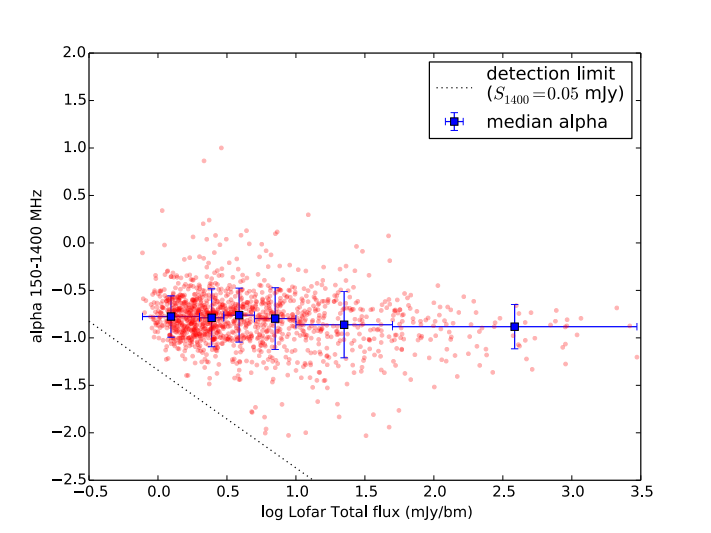
Observations + data reduction

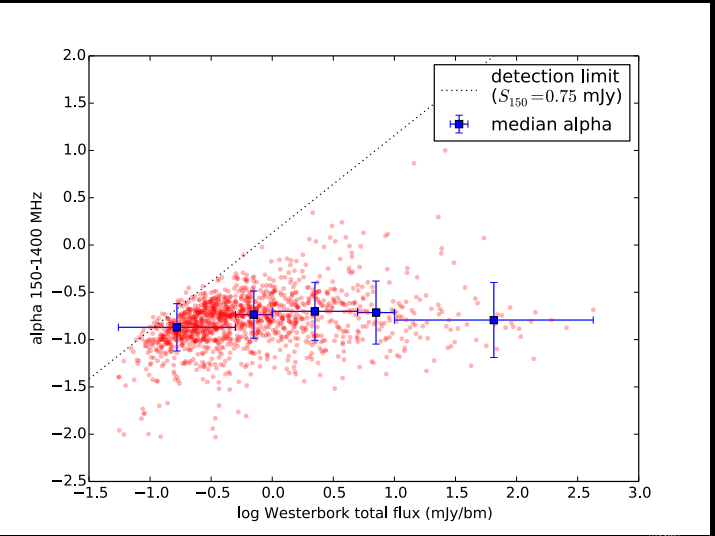
- HBA observations (110-180 MHz)
  - Cycle 0 observations, 10 hrs, 366 subbands
  - 3C196 + 3C295 observed for 10 mins at beginning and end

- Data reduction:
  - Preprocessing (RFI flagging/averaging – 5sec, 4 channel per SB)
  - Solve for amplitude solns on primary calibrator (3C295)
  - Transfer solutions (both amp and phase) to Lockman Hole
  - Combine SBs into groups of 10 (2 MHz bandwidth)
  - Solve for phase-only solutions on Lockman Hole field
  - Peel 3C244.1 (~30 Jy source in the field)
  - Phase cal again
  - Image

Do we see any spectral flattening?

- Previous studies have found a flattening of the spectral indices towards fainter flux density limits (Prandoni+ 2006, Whittam+ 2013)

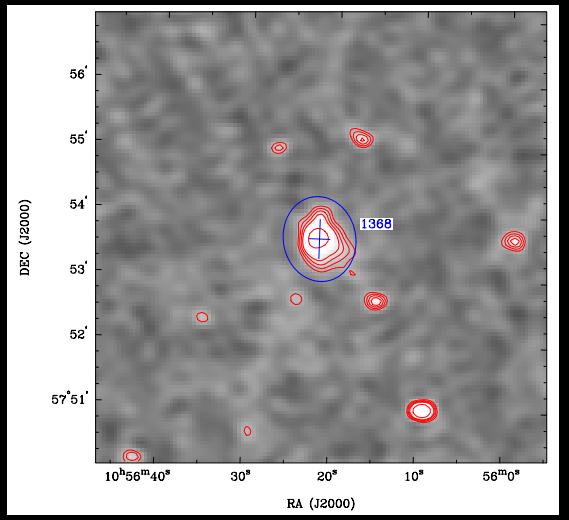




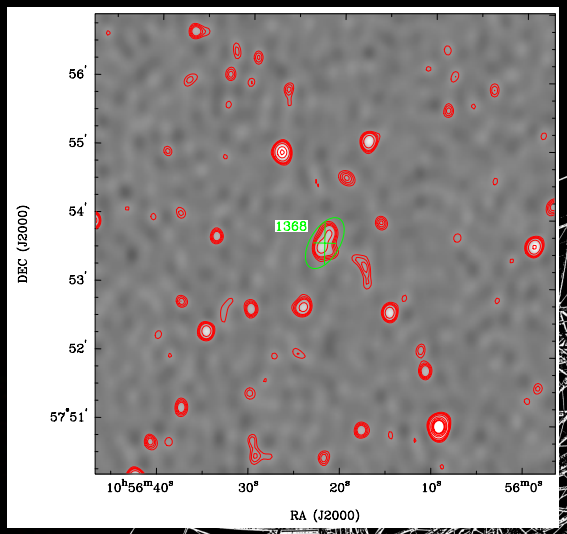
- No strong evidence that we're seeing any flattening at these frequencies
  - Although note that we don't detect flat spectrum sources fainter than ~1 mJy

Searching for ultra-steep spectrum sources

- 51 sources with alpha<-1.3
  - 18 compact
    - -> candidate USS sources
    - None of these are known high-z USS sources
  - 10 resolved/diffuse emission
    - -> candidate relics?
  - 23 multi-component radio galaxies



LOFAR



WSRT

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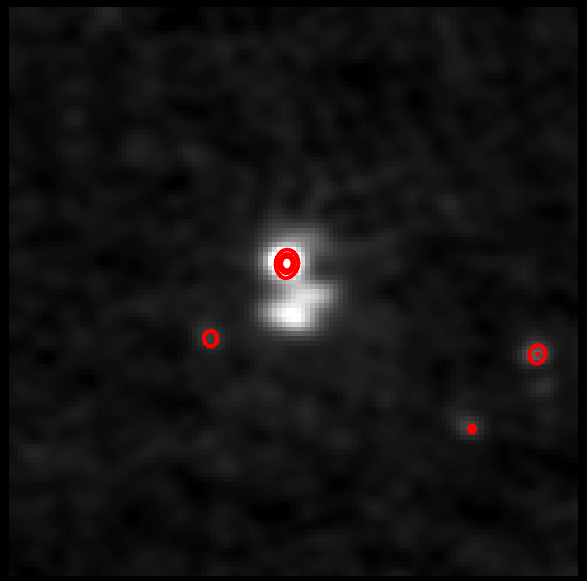
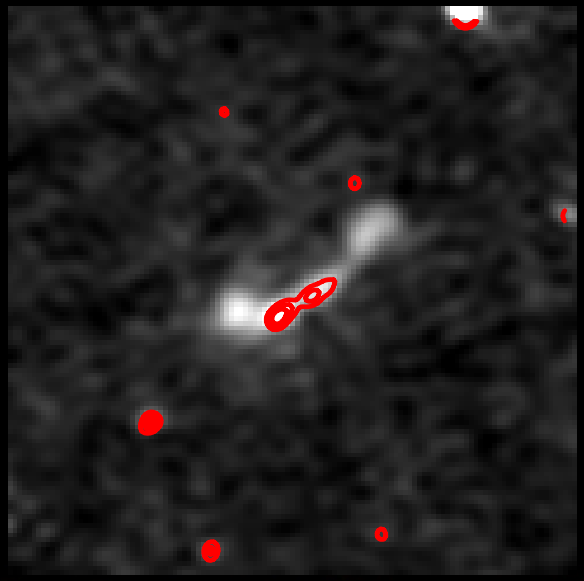
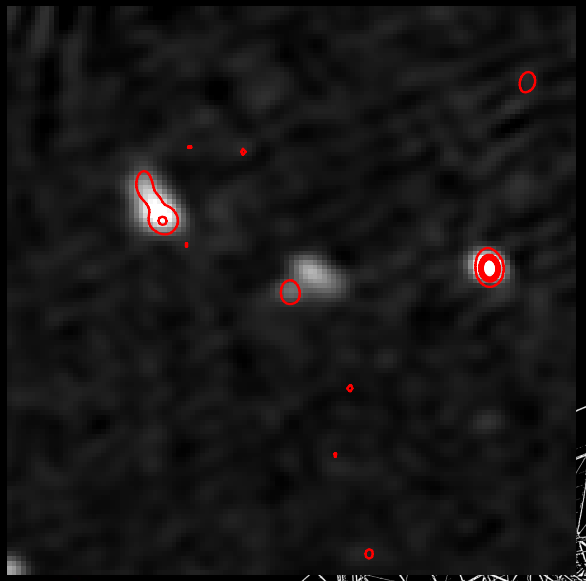
Searching for ultra-steep spectrum sources

- Nearby radio galaxies with very steep spectra
  - Extra extended, diffuse emission only detected by LOFAR

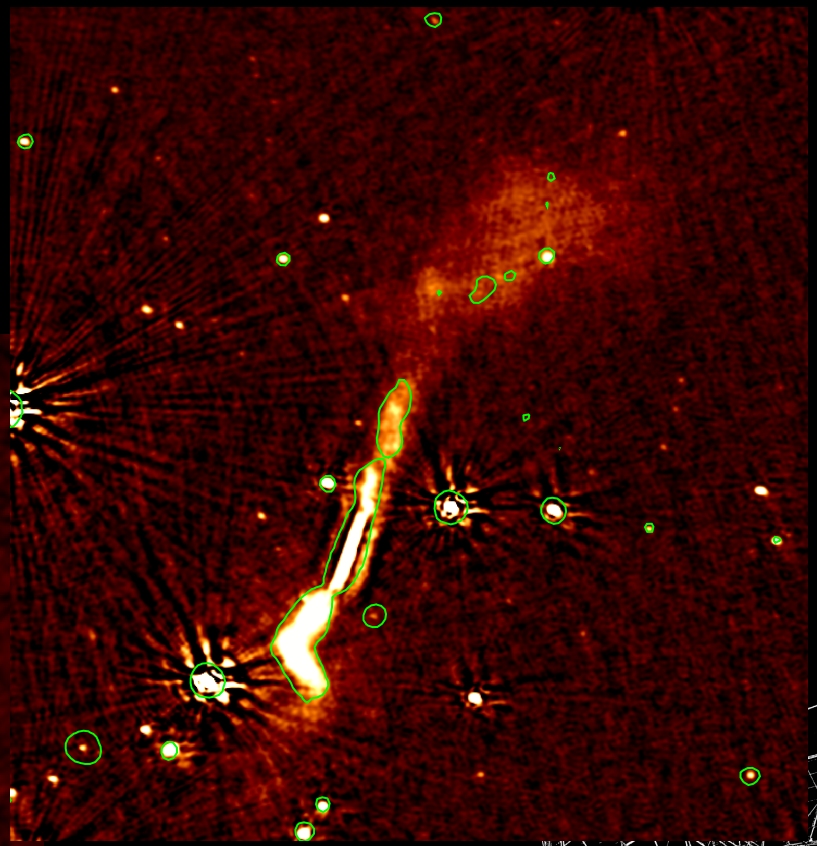






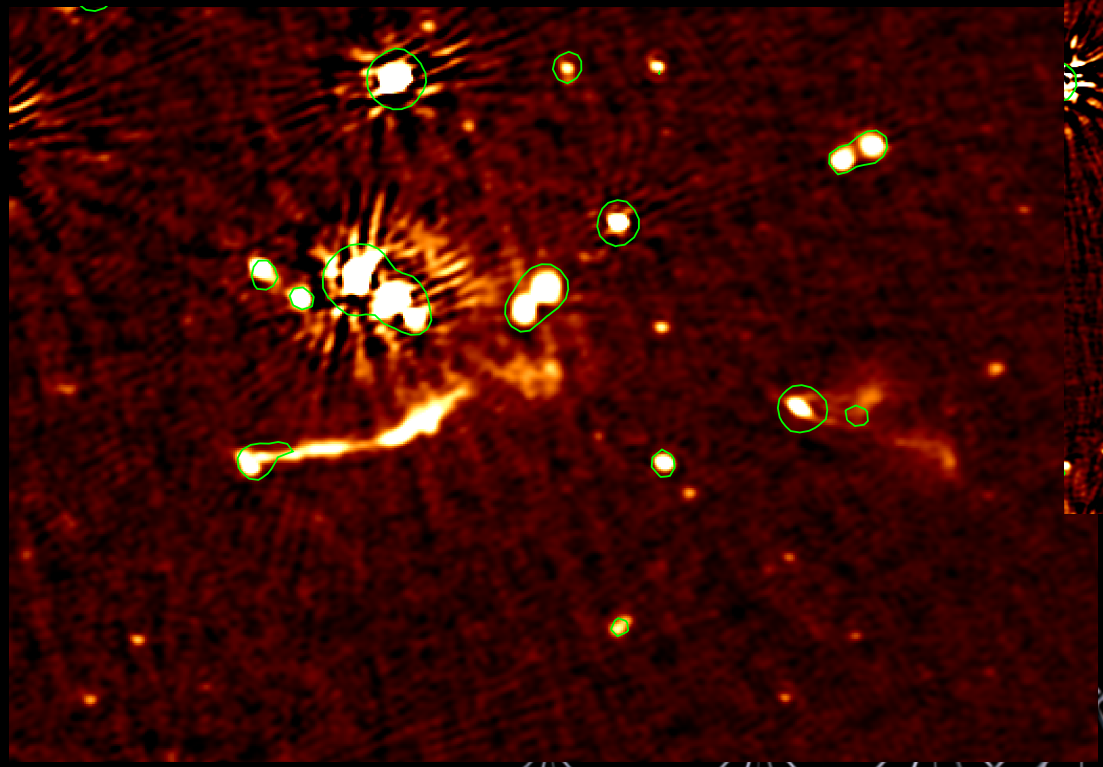
Interesting sources

1029+5702



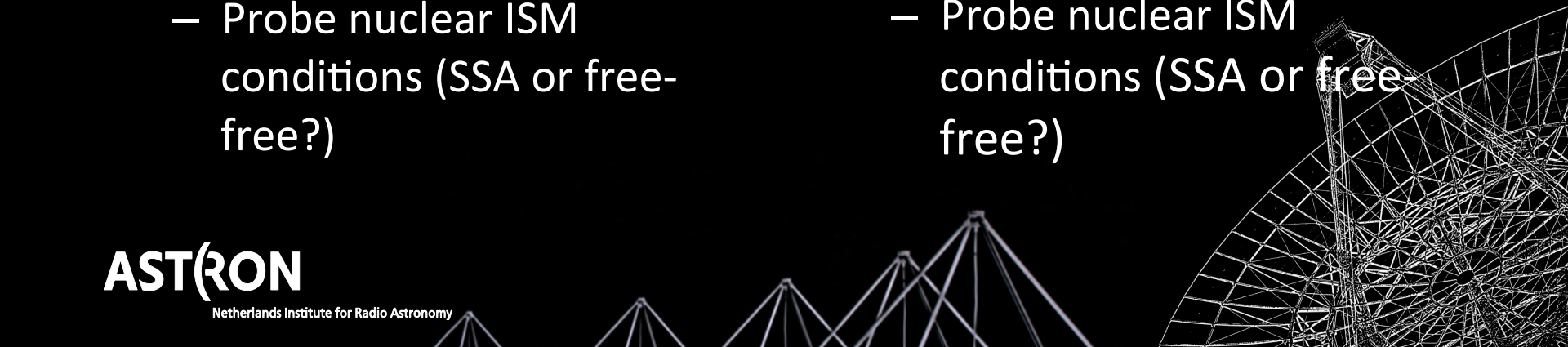
Abell 1132

NVSS contours @ 2.5mJy



Why search for GPS and CSS sources at low frequencies?

- ‘nearby’ CSS sources
  - Track intermediate stages of radio galaxy evolution
  - With large samples - possibly provide key to understanding the FRI/II dichotomy
  - Probe nuclear ISM conditions (SSA or free-free?)
- High-z GPS sources
  - Find first radio galaxies: do high-z GPS sources differ from nearby GPS sources?
  - With large samples - possibly identify trigger conditions for AGN activity
  - Probe nuclear ISM conditions (SSA or free-free?)



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