Feeding the Monsters at Low Frequencies

LOFAR and the evolution of Radio-Loud AGN

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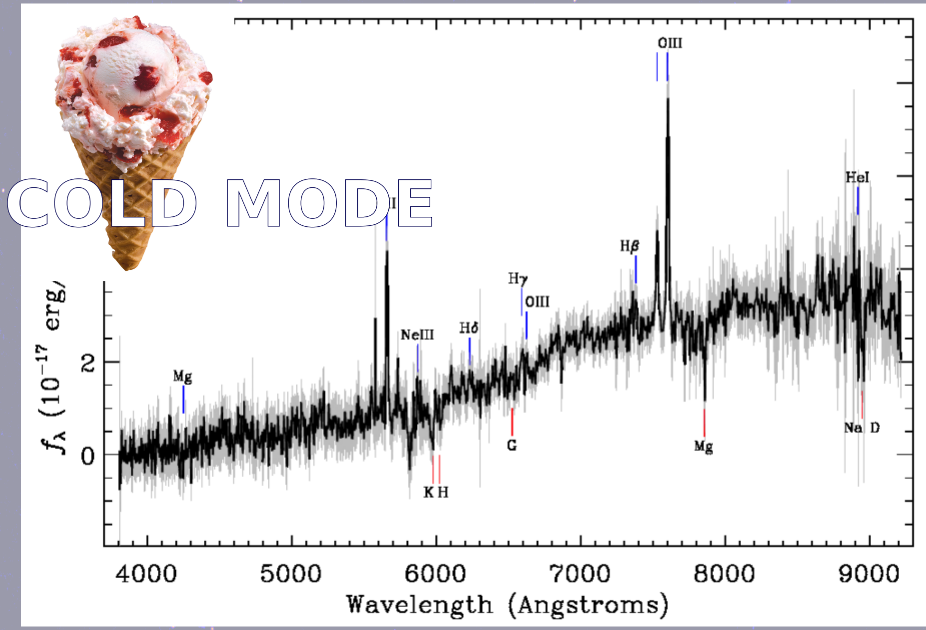
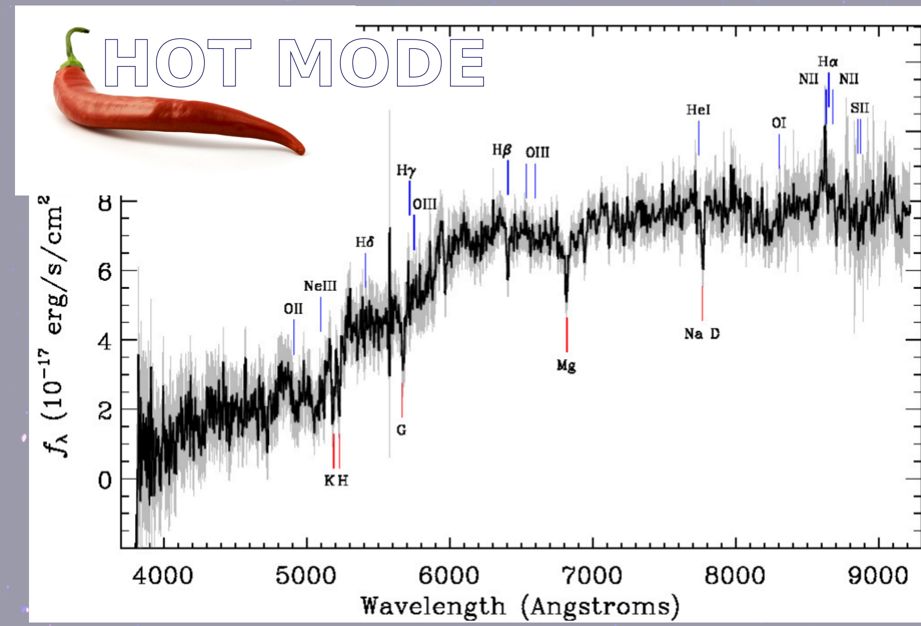
2 Types of Radio AGN





High Excitation (HERGs)

- Typical AGN
  - With an accretion disk
    - Strong emission lines
    - X-ray
    - IR/sub-mm dusty torus

Low Excitation (LERGs)

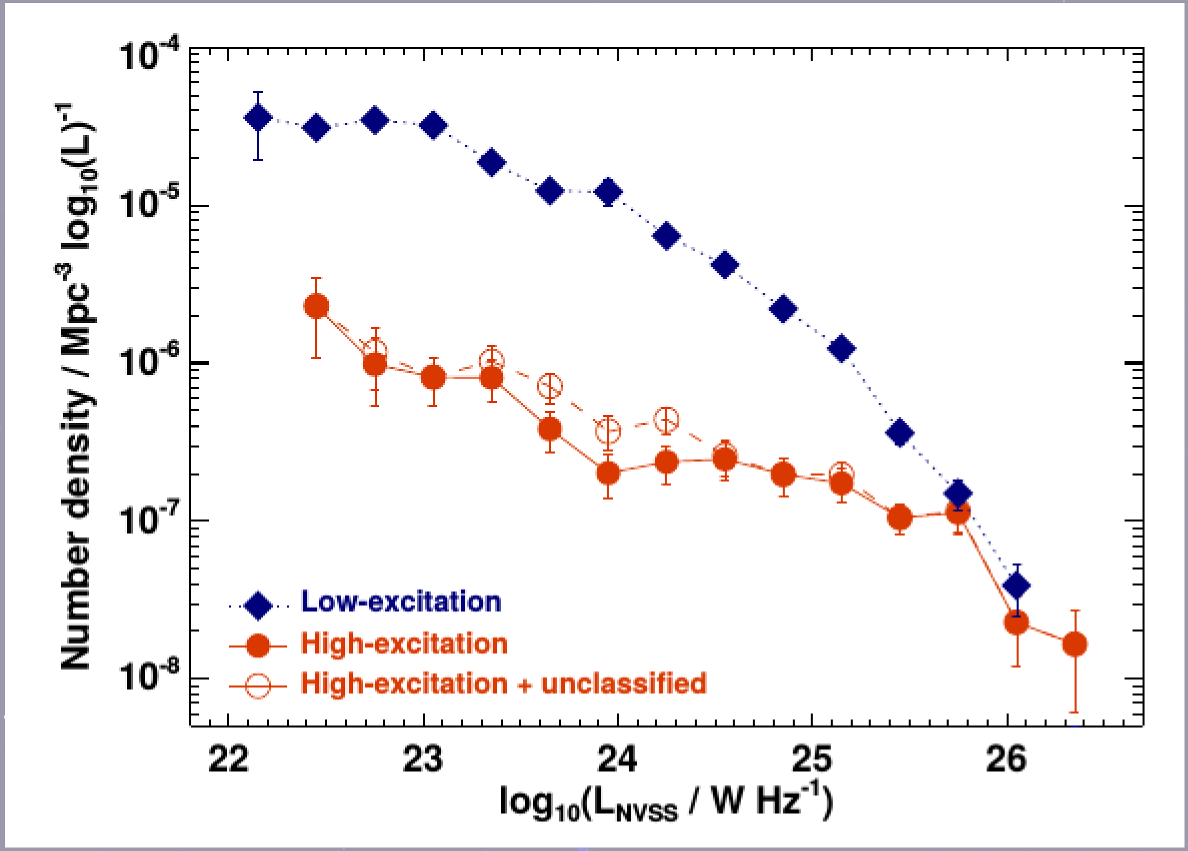
- Atypical
  - Missing all the emission associated with an accretion disk
  - Accretion of hot gas...

Laing+ 1994

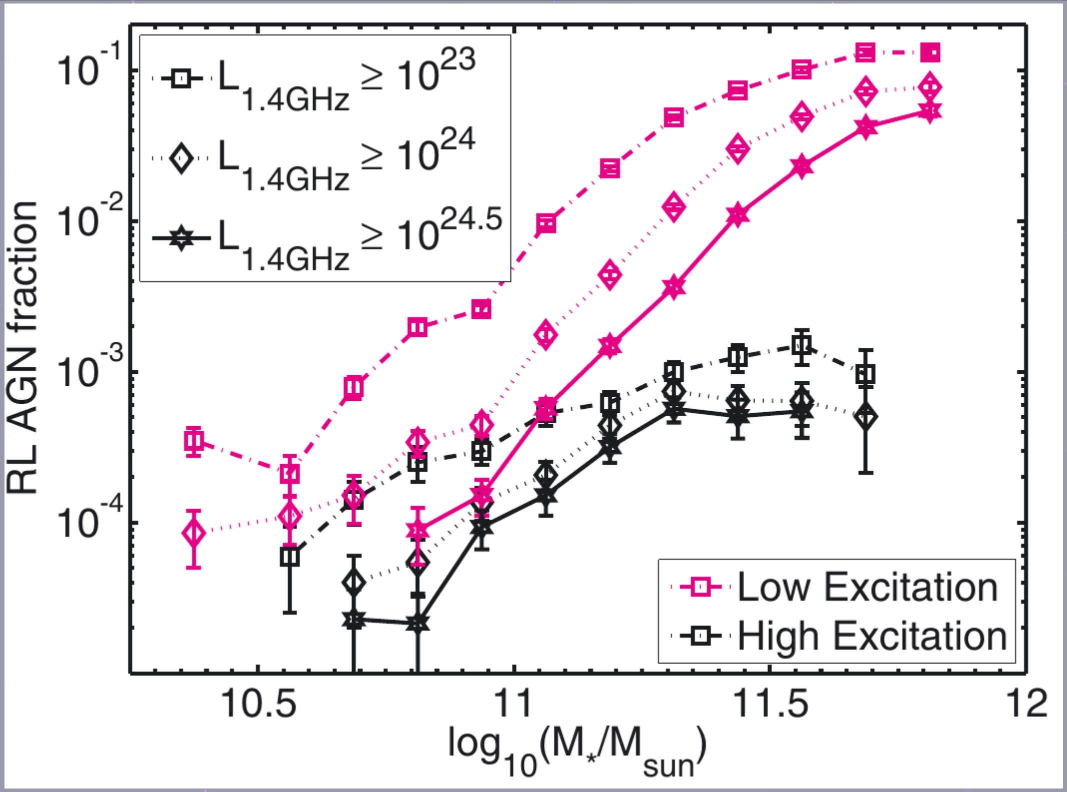
The local population

Best & Heckman 2012

- SDSS DR7 + NVSS/FIRST
  - sample of >18,000 radio sources
- Classify all radio galaxies as high- or low excitation
  - use SDSS emission line ratios (where possible)
  - use [OIII] 5007 line equivalent width
- Both classes are found over most of the range of luminosities
- LERGs dominate at low powers



Fuel source



$f_{LE} \sim M^{2.5}$

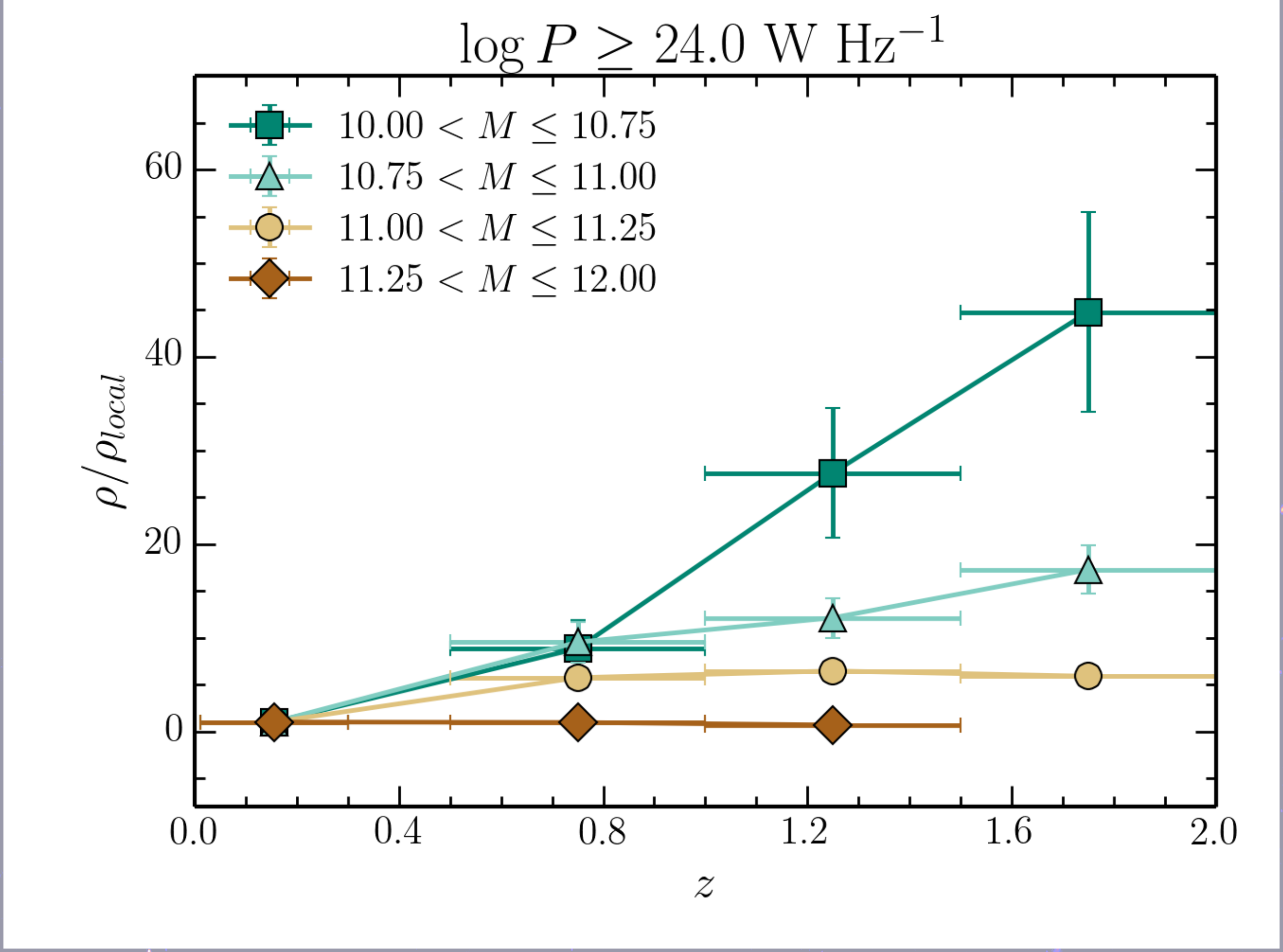
$f_{HE} \sim M^{1.5}$

- Radio-loud fraction for HERGs is weakly mass-dependent
  - Related to (minor)-merging? Supply of cold gas?
- For LERGs it is *strongly* mass dependent
  - Consistent with ADAF-like accretion of hot gas (Narayan & Yi 1994, 1995)

Best+ 2005, Janssen+ 2013

Mass-dependent Evolution

Williams+ 2015a



Low Mass

Low-mass (logM < 11 Msun) sources which are radio-loud (logP > 24 W/Hz) are ~40 times more prevalent at z~1.5-2

High Mass

The number density of high-mass (logM > 11 Msun) radio-loud (logP > 24 W/Hz) sources remains ~constant

What don't we know?

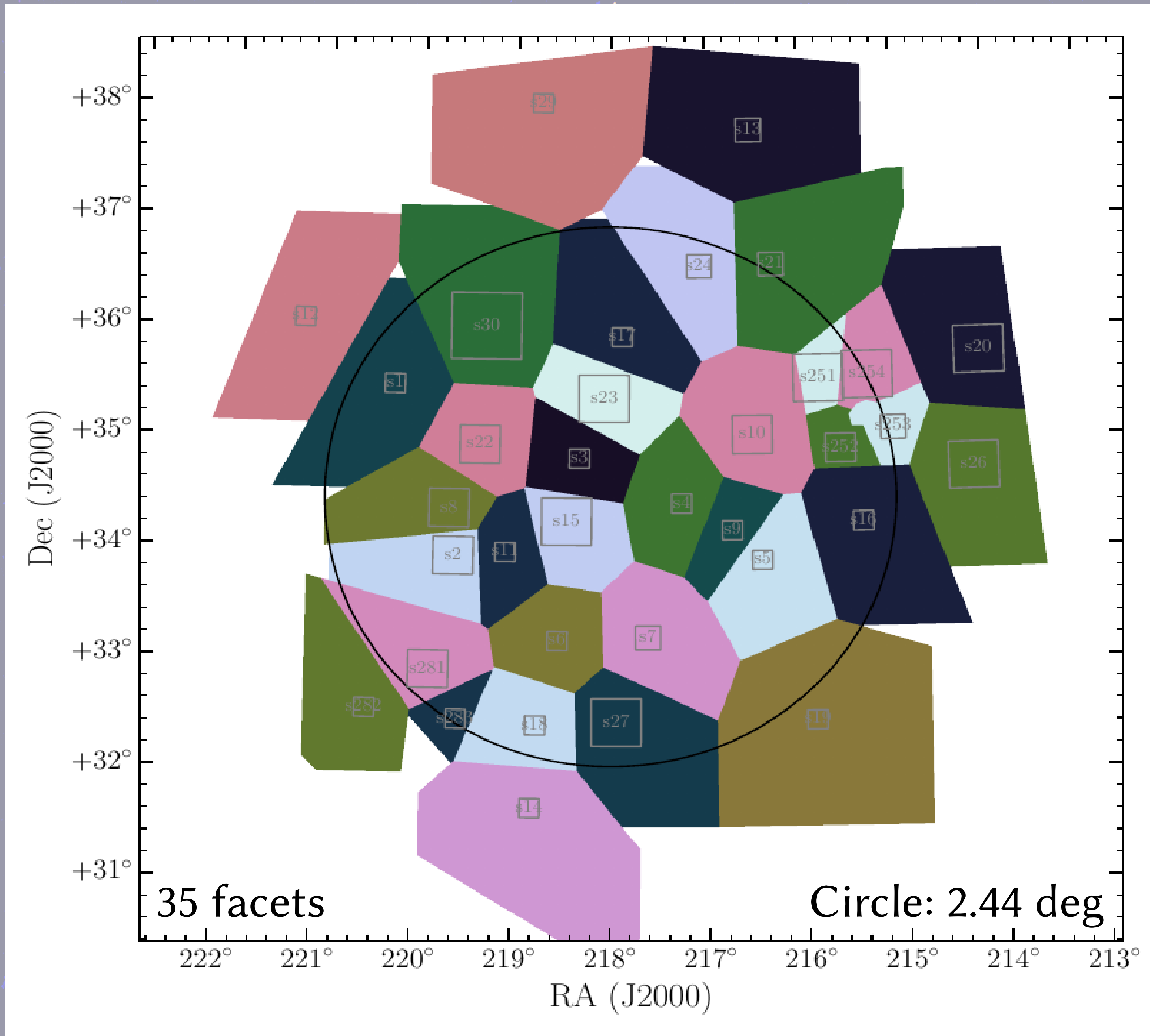
- How important are the different accretion modes in terms of galaxy evolution?
- How do they evolve with redshift?
- How efficient is the feedback?
- We can look at how the radio-loudness depends on:
  - Mass
  - Star formation
  - Galaxy type (e.g. colour)
  - Ionisation state

...All over cosmic time

Boötes Field Observations

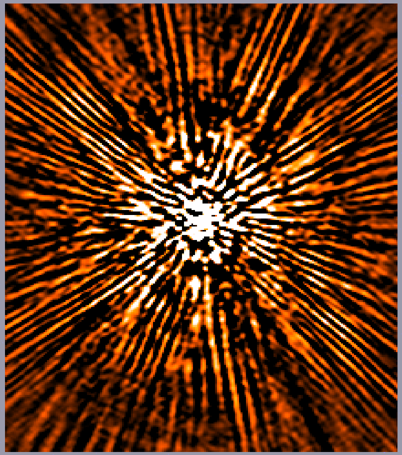
- Cycle 2 – 10 Aug 2014
  - 8 hrs
  - Dec is +34 deg
- 10 min Calibrator
  - Clock, Amplitude, Phase offset XX-YY
- Target
  - Basic flagging, Ateam clipping
  - Transfer of calibration (clock, amp, phase-offset)
  - Average (2ch 8s)
  - Merge subbands (10subbands – 2MHz bands)
  - Single Selfcal (A&P) against best model
- Run FACET calibration scheme

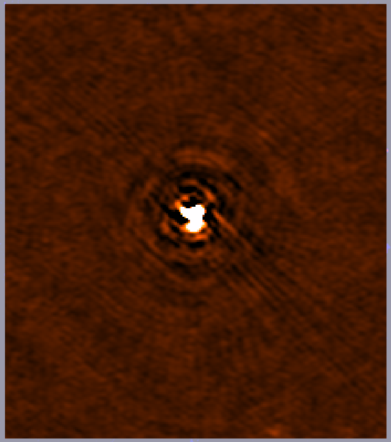
Facets



35 facets
Circle: 2.44 deg
Dec (J2000)
RA (J2000)
+38°
+37°
+36°
+35°
+34°
+33°
+32°
+31°
222°
221°
220°
219°
218°
217°
216°
215°
214°
213°
s30
s20
s23
s10
s22
s26
s15
s2
s8
s27
s251
s281
s24
s21
s17
s13
s3
s16
s7

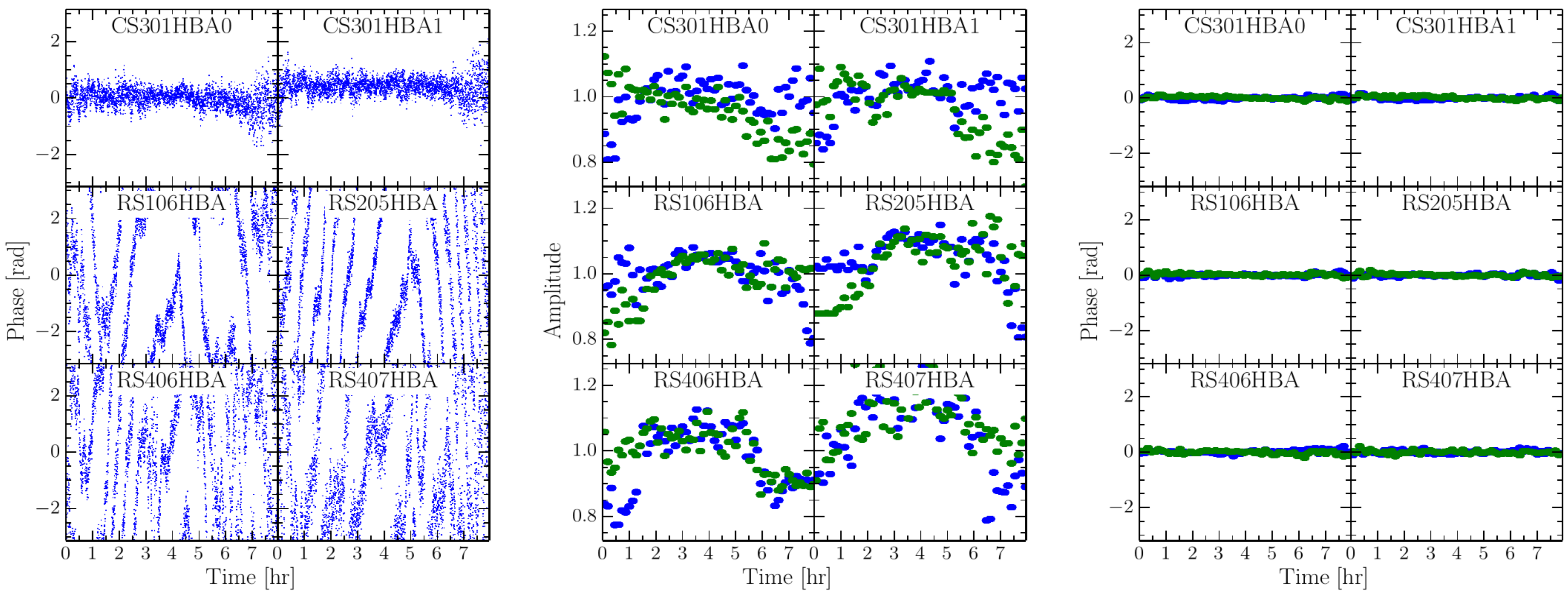
DDE Self-calibration





- Apply field selfcal solutions
  - Image
- Solve for scalarphase, TEC (in groups of 5-6 bands) using all bands x2
  - 10s timescales
  - Image & update CC model
- Solve for slow varying amplitudes in each band (10SB) x2
  - Pre-Apply “fast” phases
  - 5-20 min timescales
  - Image & update CC model

Solutions per direction

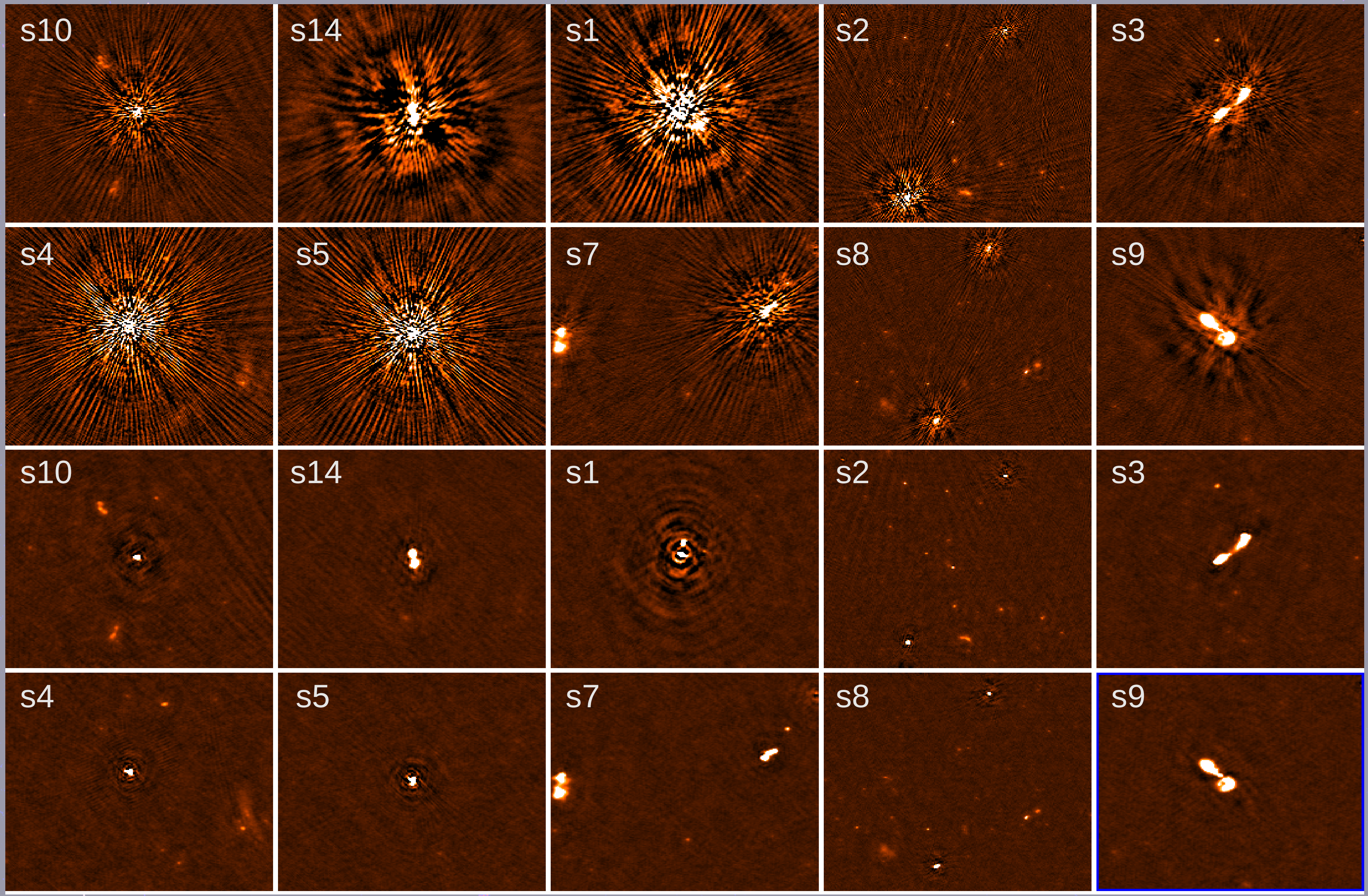


10s phases

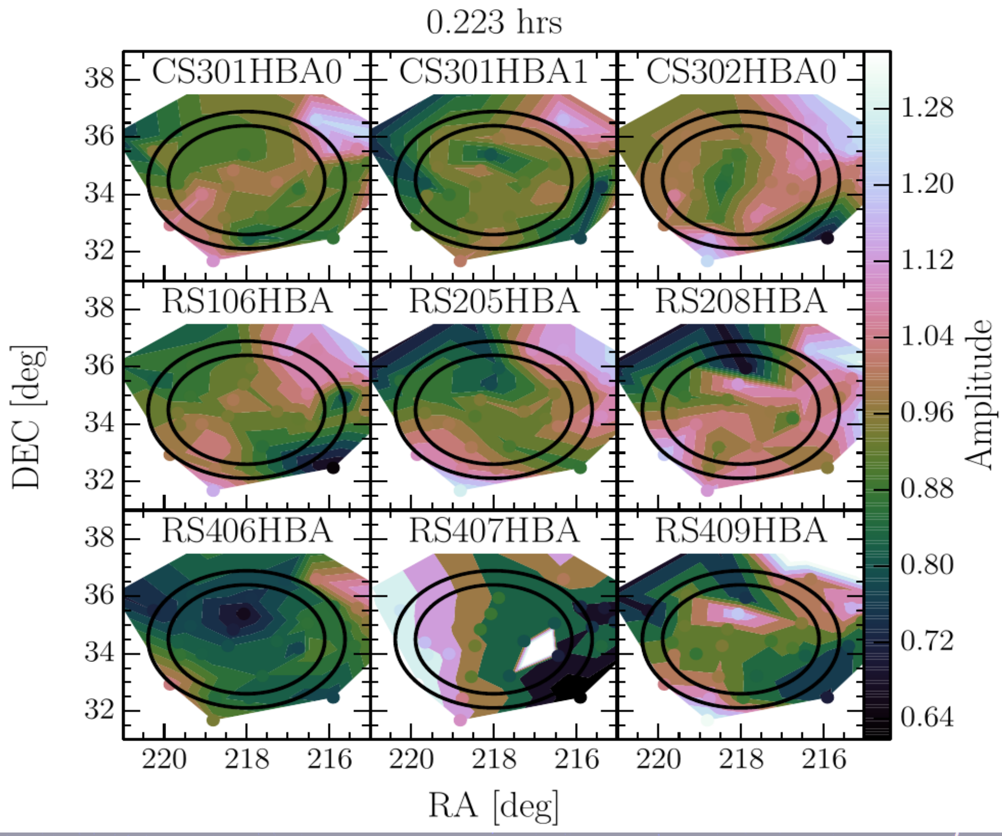
10min amps

10min phases

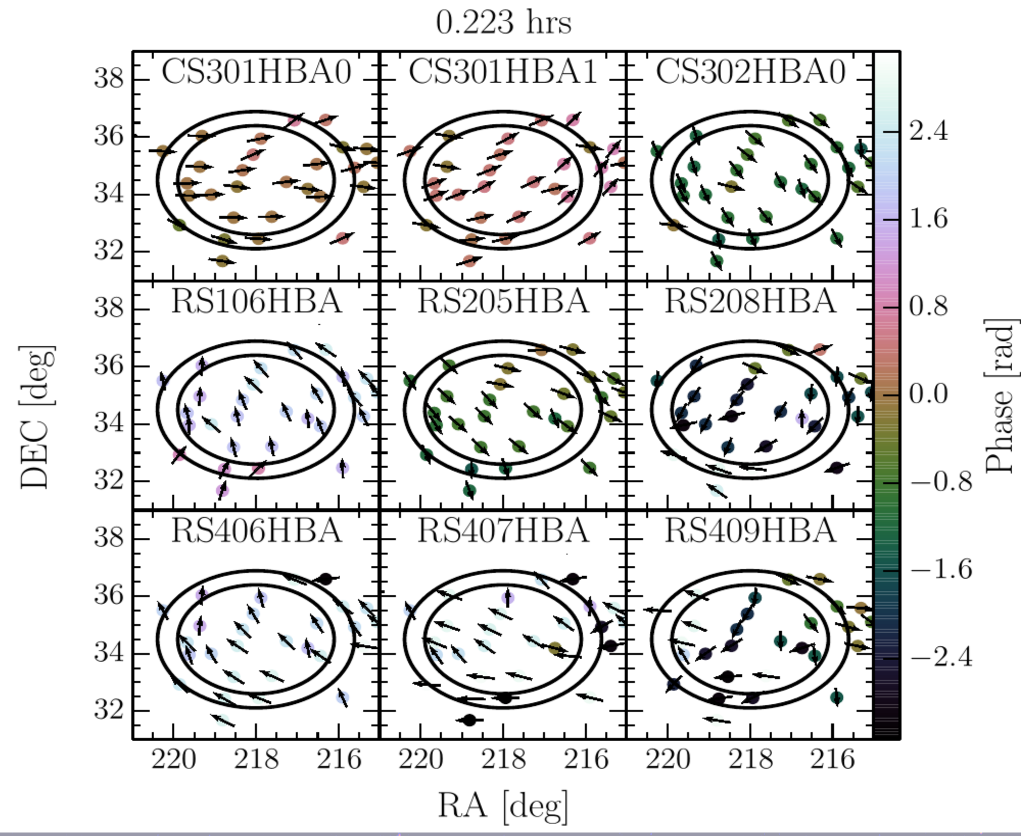
DDE Selfcal Gallery



Solutions per time step



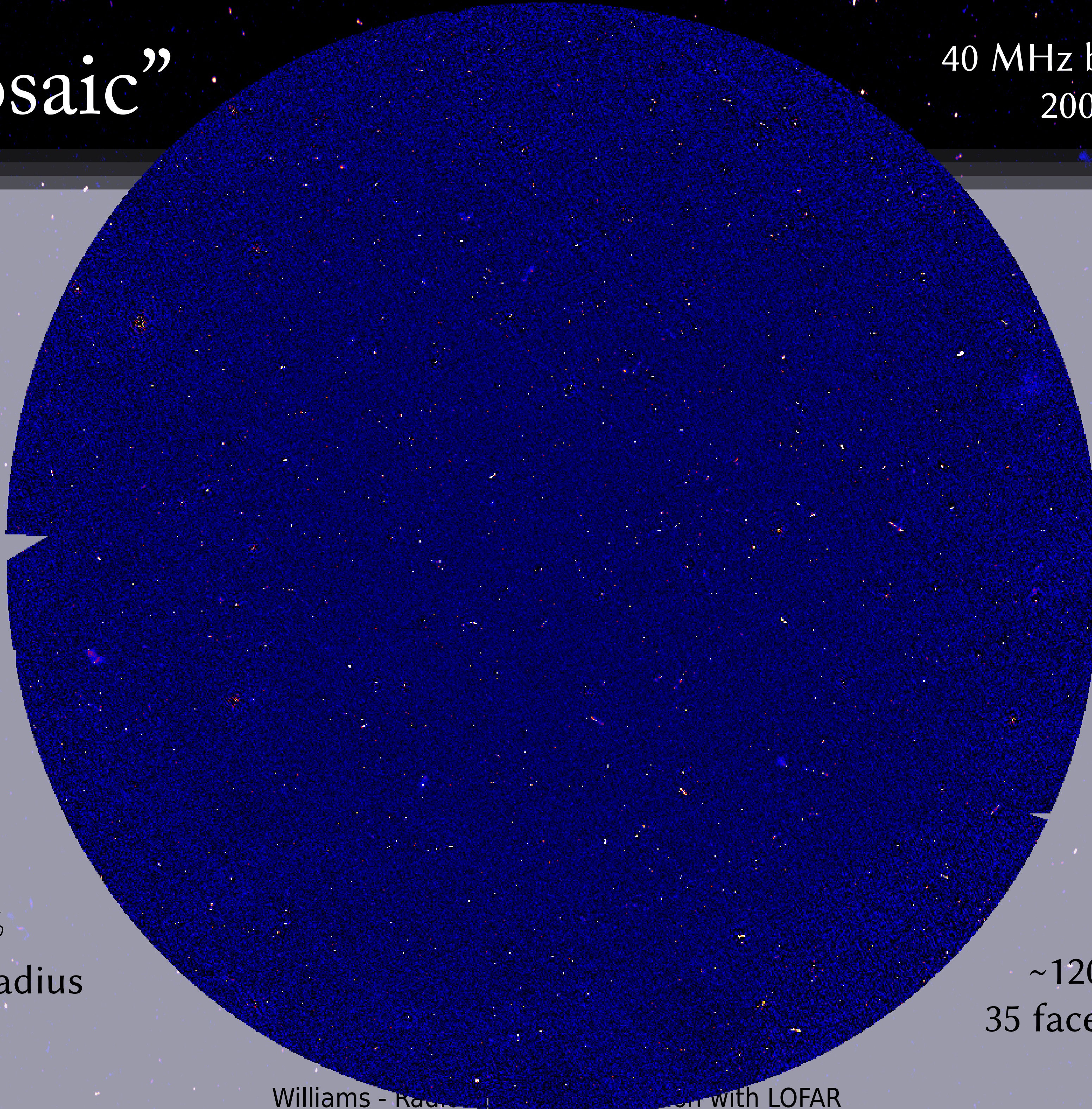
amplitude



phase

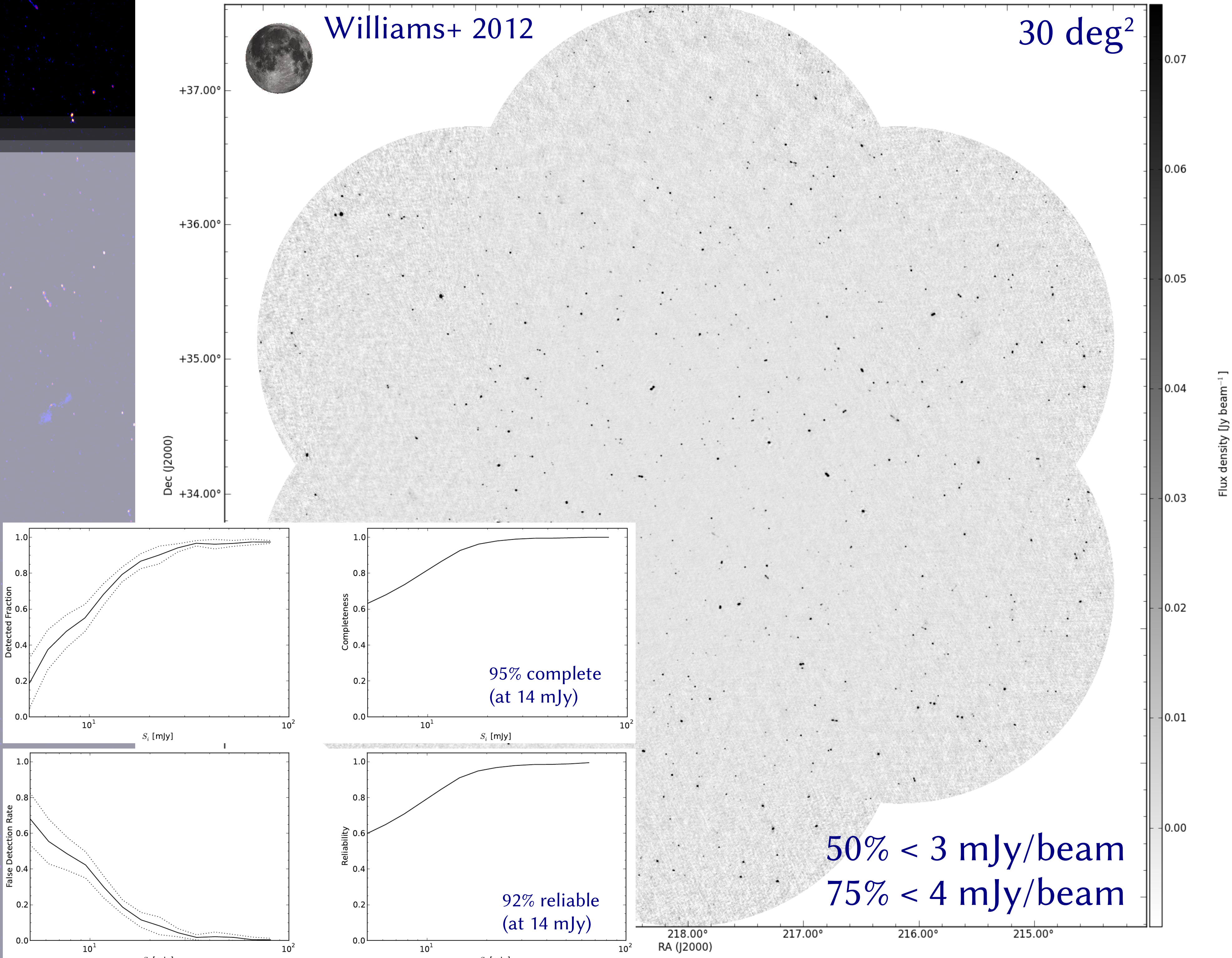
“Mosaic”

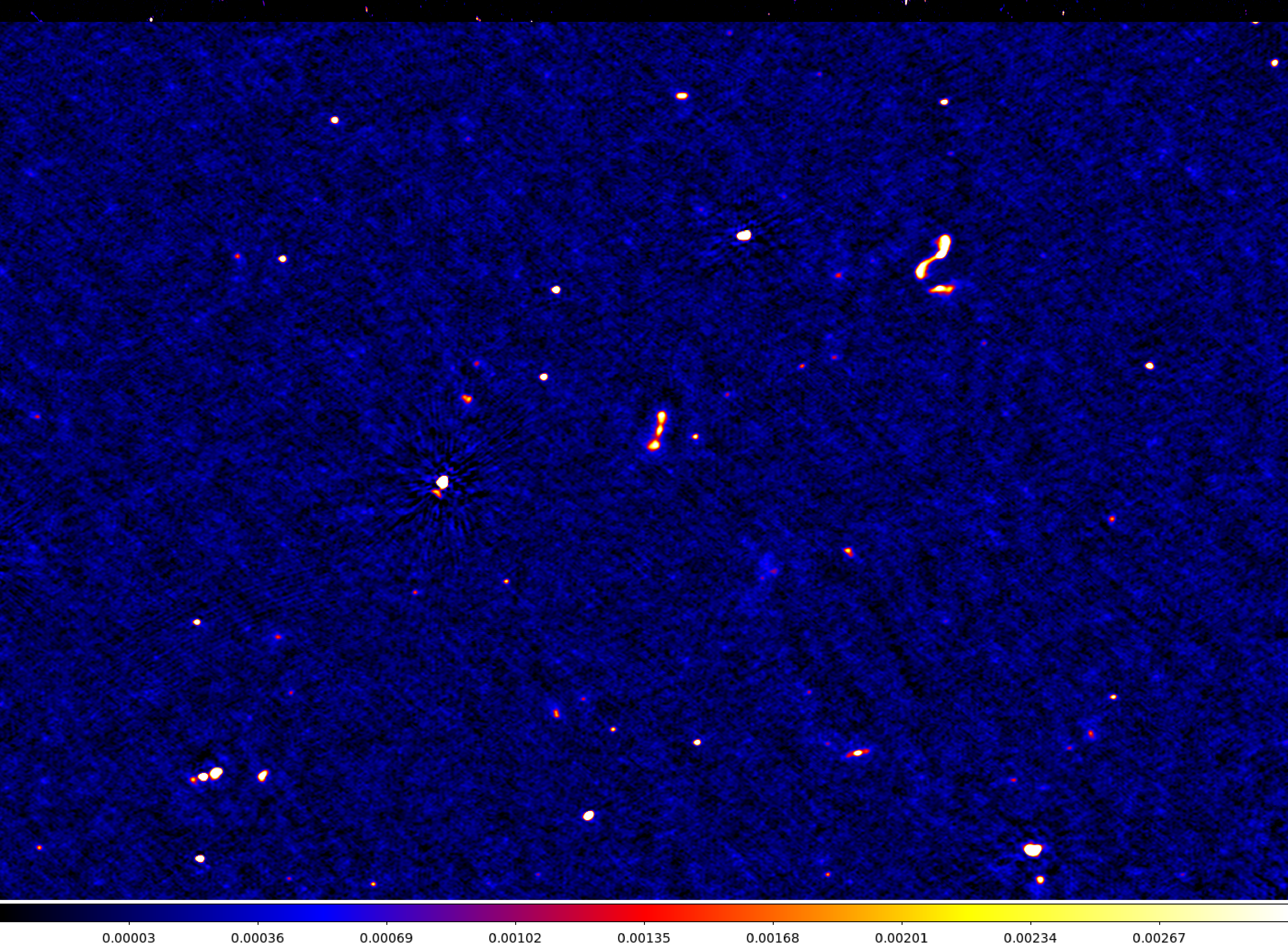
40 MHz bandwidth
200 subbands

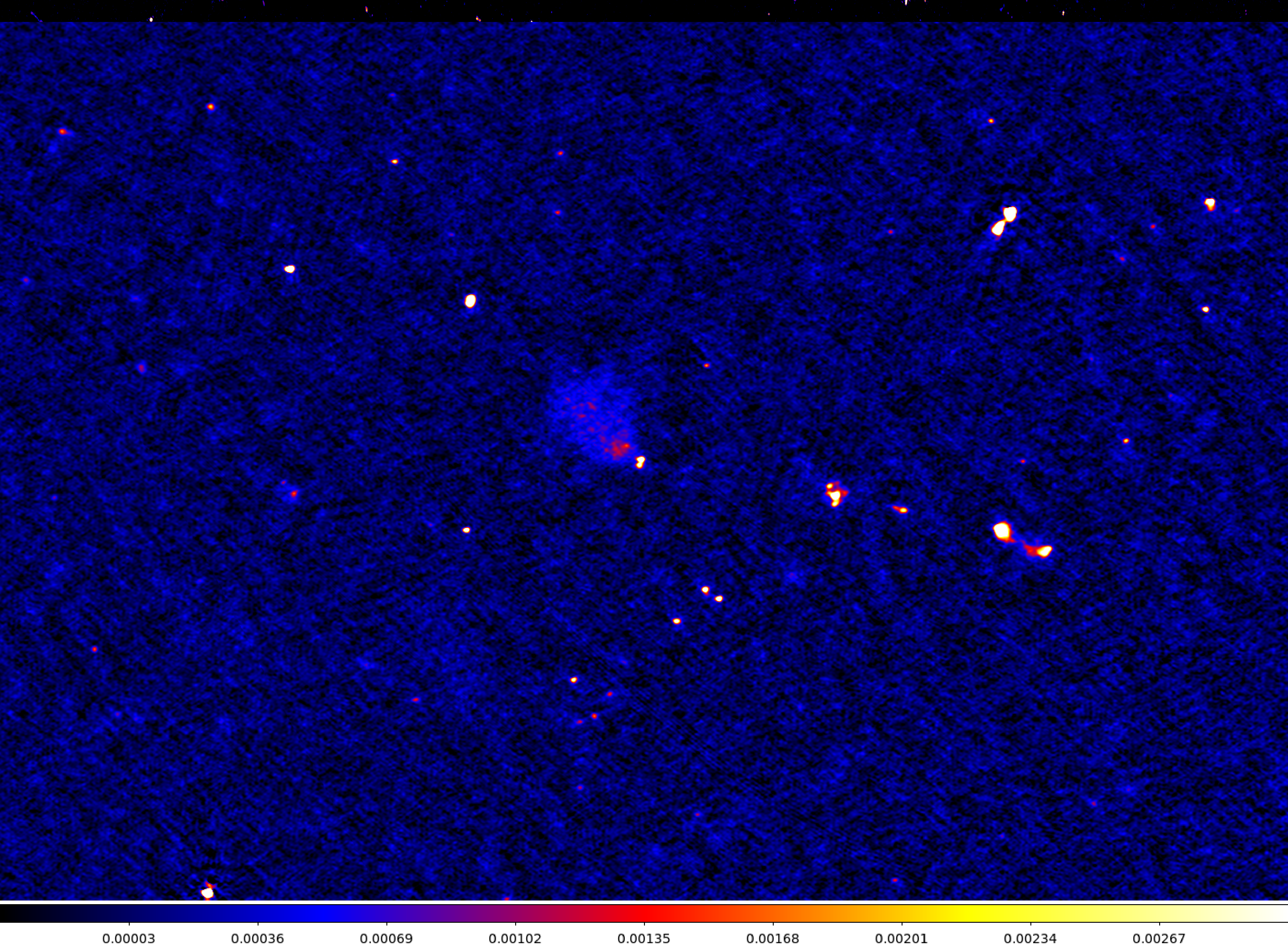


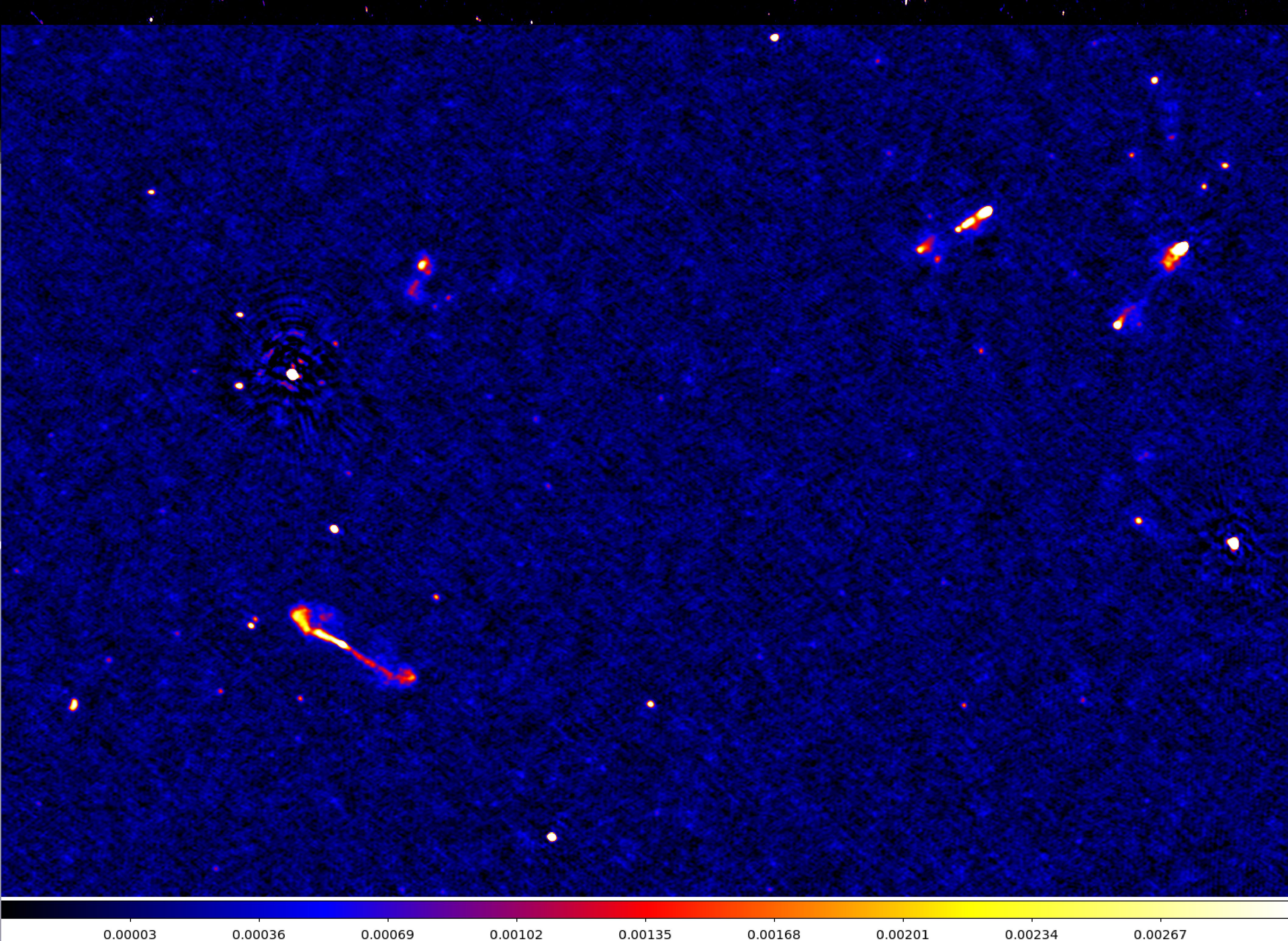
P_{cut} at 40%
2.44 deg radius
~19 deg^2

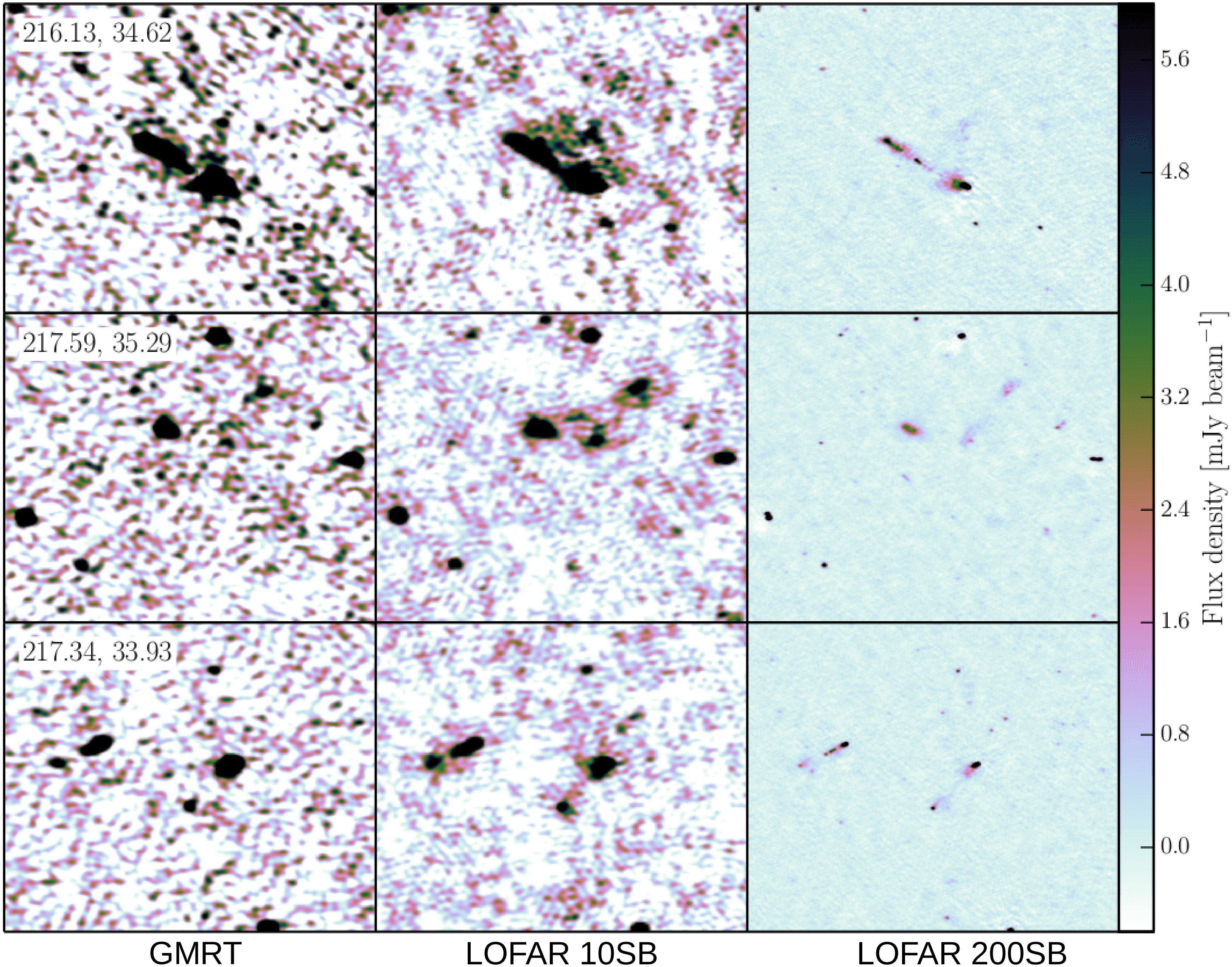
5.6"x7.4"
~120μJy/beam
35 facets imaged


Williams+ 2012
30 deg²
+37.00°
+36.00°
+35.00°
+34.00°
Dec (J2000)
218.00°
217.00°
216.00°
215.00°
RA (J2000)
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
Flux density [Jy beam⁻¹]
50% < 3 mJy/beam
75% < 4 mJy/beam
Detected Fraction
Completeness
95% complete
(at 14 mJy)
False Detection Rate
Reliability
92% reliable
(at 14 mJy)
S_i [mJy]


0.00003
0.00036
0.00069
0.00102
0.00135
0.00168
0.00201
0.00234
0.00267

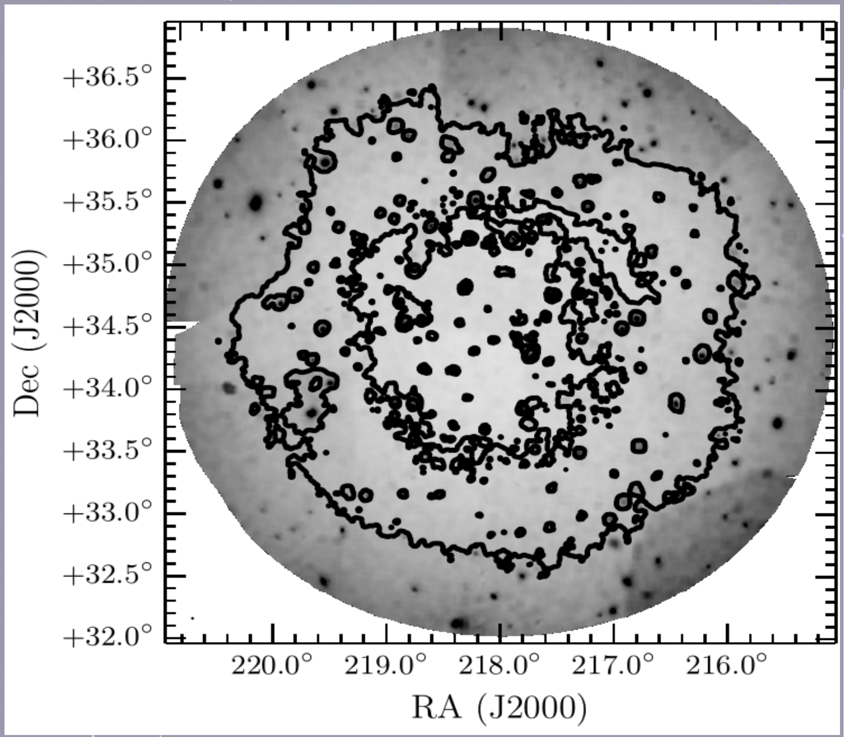

0.00003
0.00036
0.00069
0.00102
0.00135
0.00168
0.00201
0.00234
0.00267


0.00003
0.00036
0.00069
0.00102
0.00135
0.00168
0.00201
0.00234
0.00267

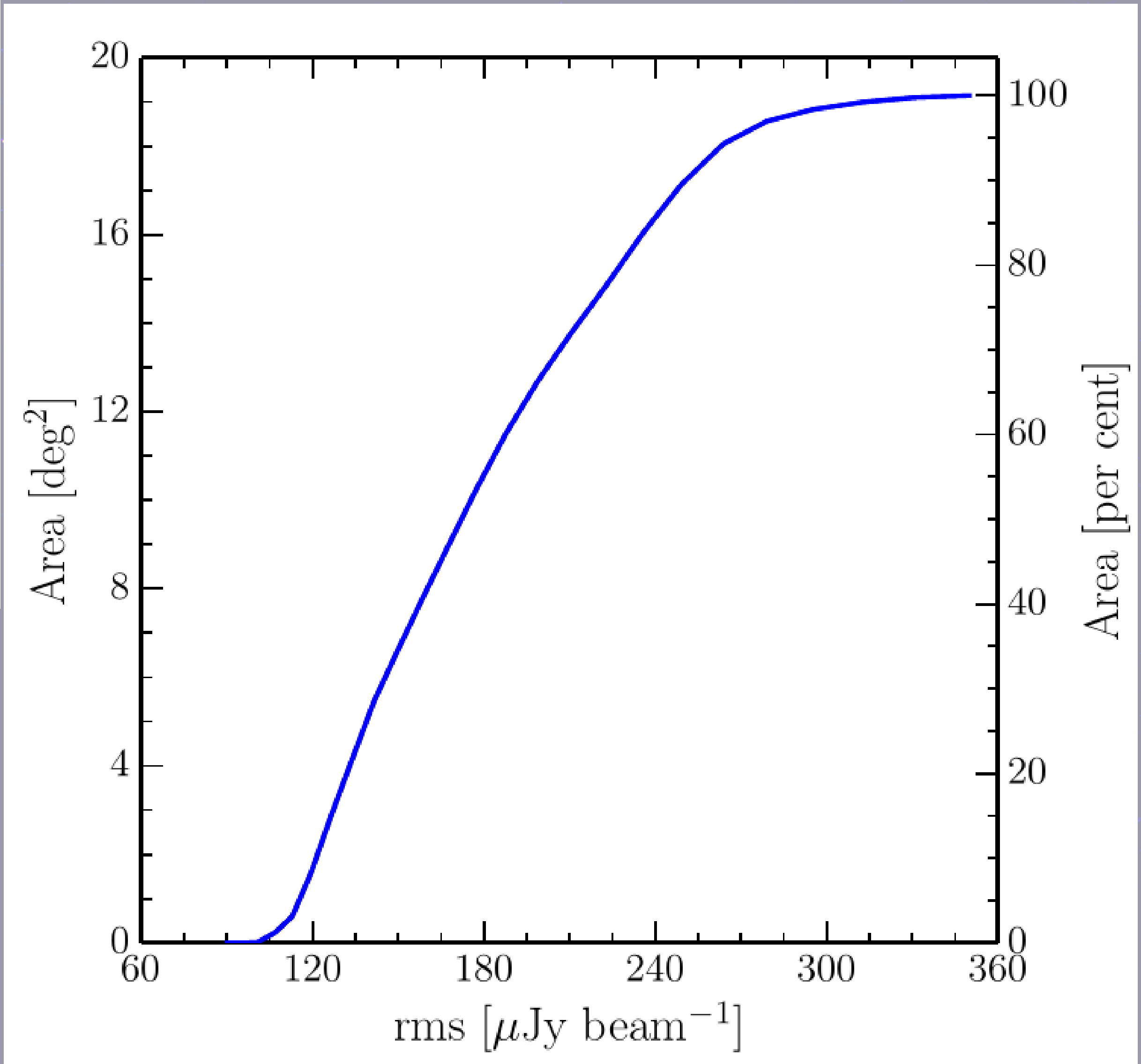


216.13, 34.62
217.59, 35.29
217.34, 33.93
5.6
4.8
4.0
3.2
2.4
1.6
0.8
0.0
Flux density [mJy beam^{-1}]
GMRT
LOFAR 10SB
LOFAR 200SB

Noise



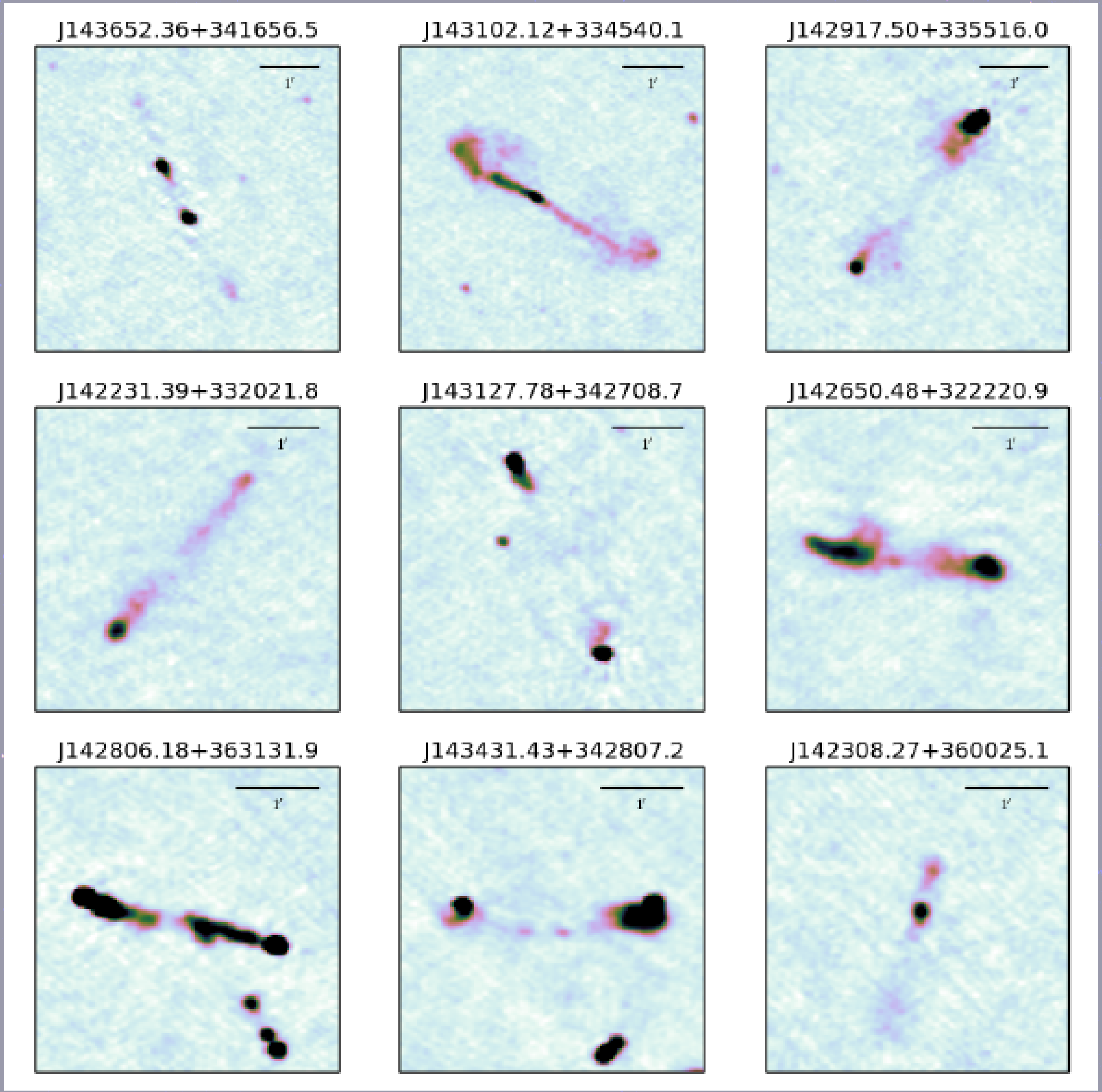
Contours:
125 & 175 μJy/beam



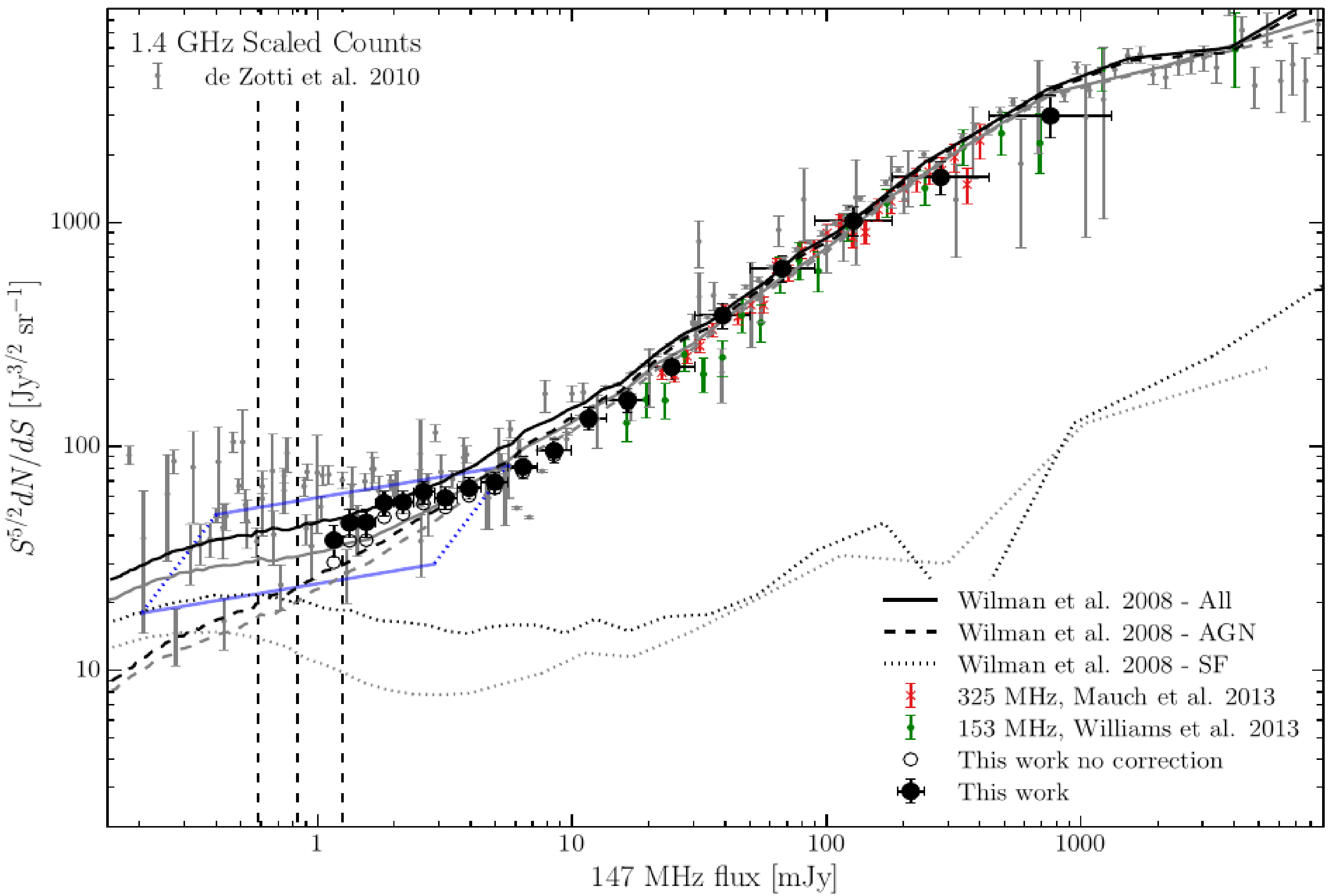
50% below 180 μJy/beam
>95% below 300 μJy/beam

Sources

- PyBDSM
  - 5σ Peak threshold
  - 3σ Island threshold
- 5652 sources
  - Over 19 deg^2
  - 10771 Gaussian Components
  - 3010 Single Gaussian Sources

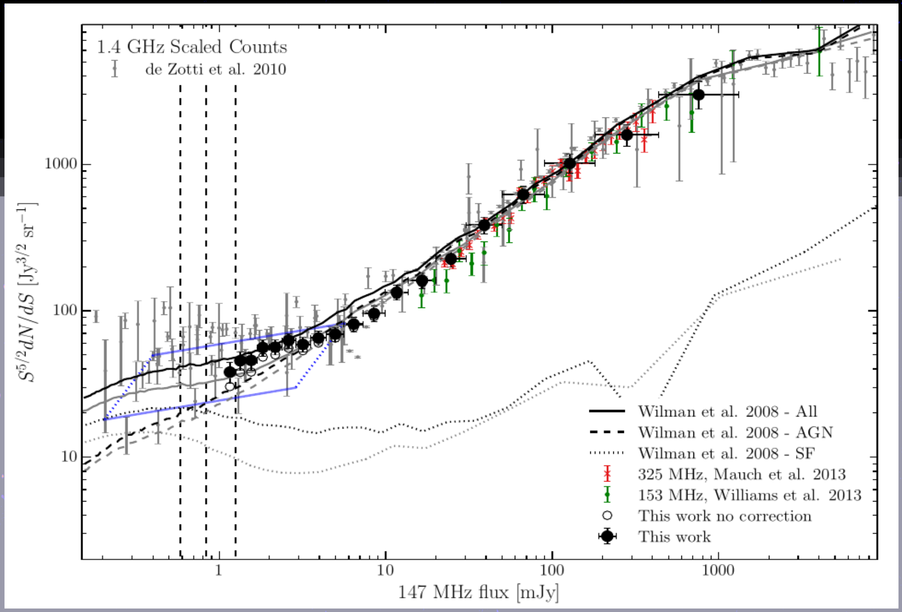


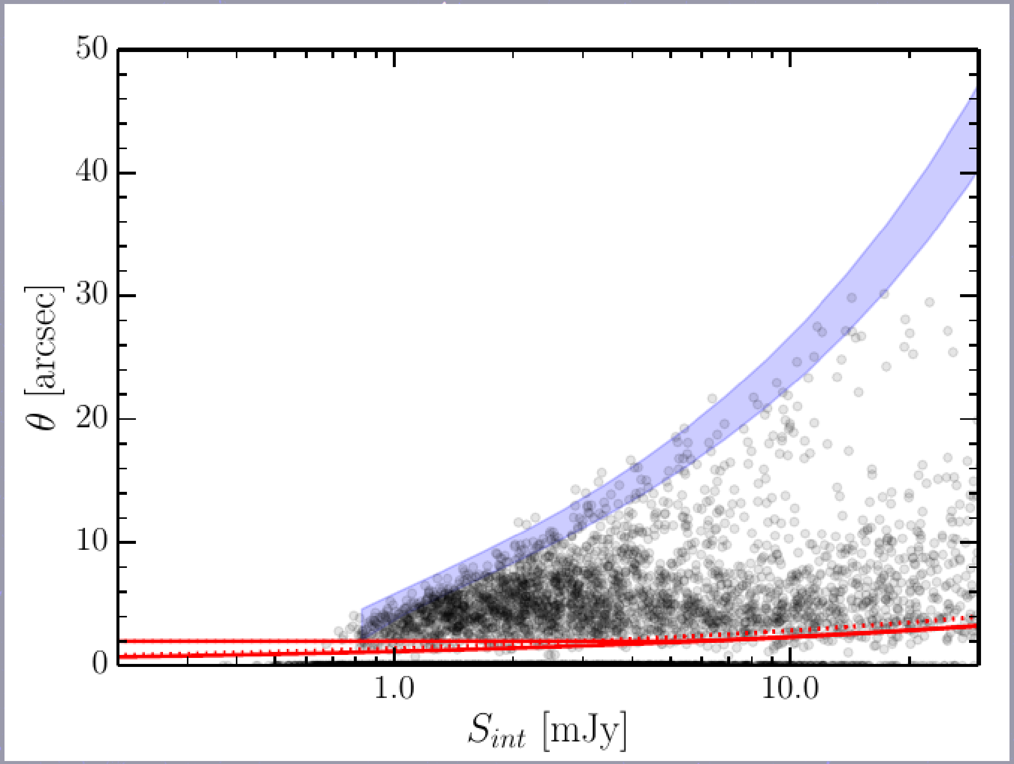
Source Counts

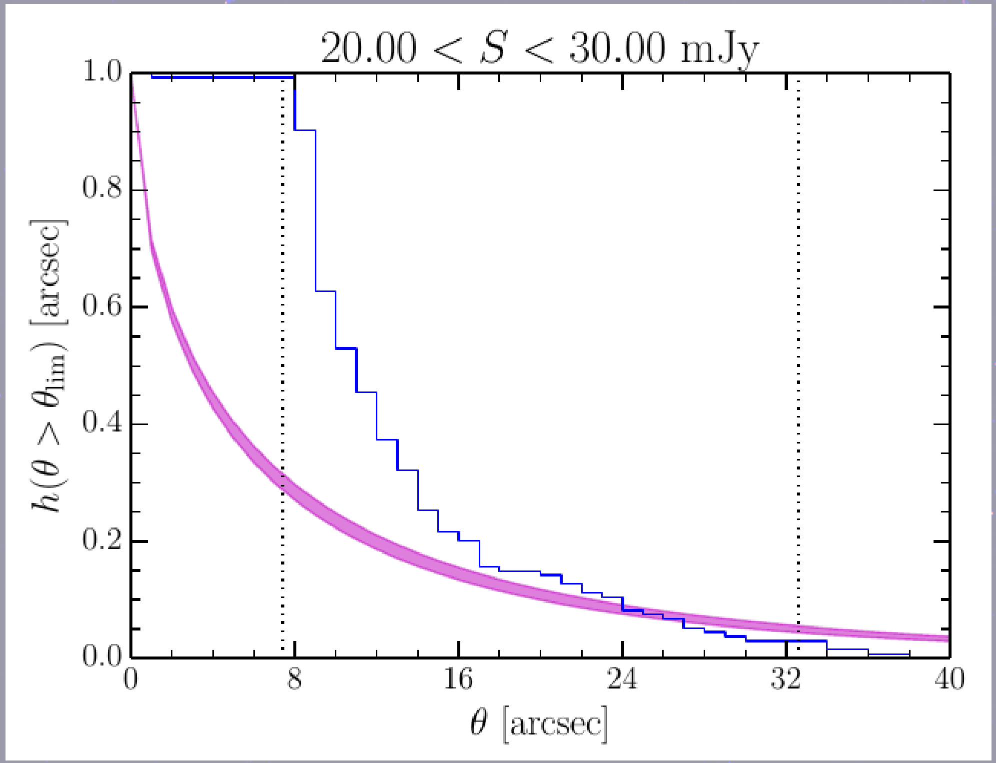


Source Counts

- Resolution bias
- Assumed source size distribution







Boötes Field

NDWFS – B_W,R,I – 9.3 deg^2

zBootes – z'

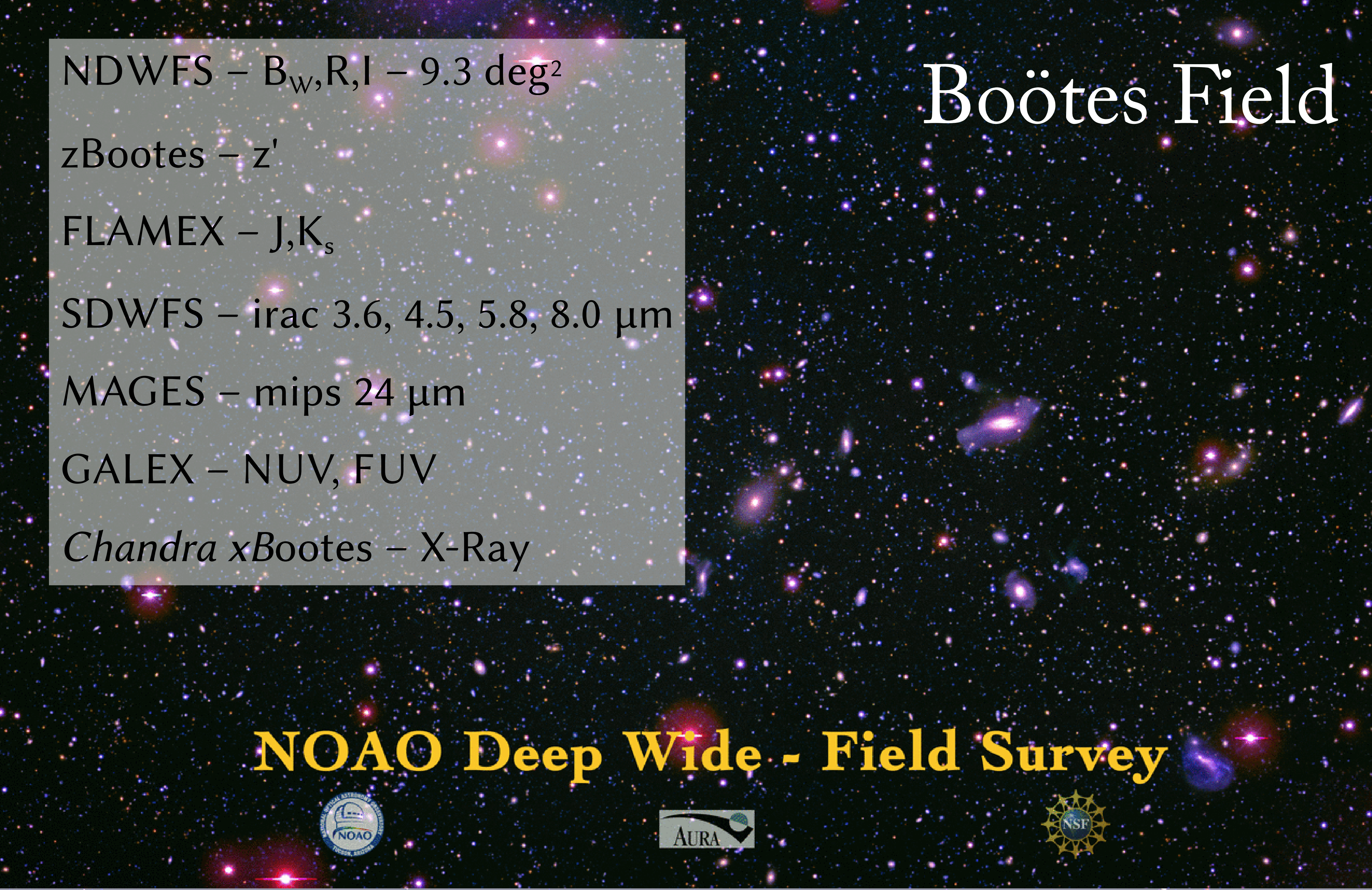
FLAMEX – J,K_s

SDWFS – irac 3.6, 4.5, 5.8, 8.0 μm

MAGES – mips 24 μm

GALEX – NUV, FUV

Chandra xBootes – X-Ray

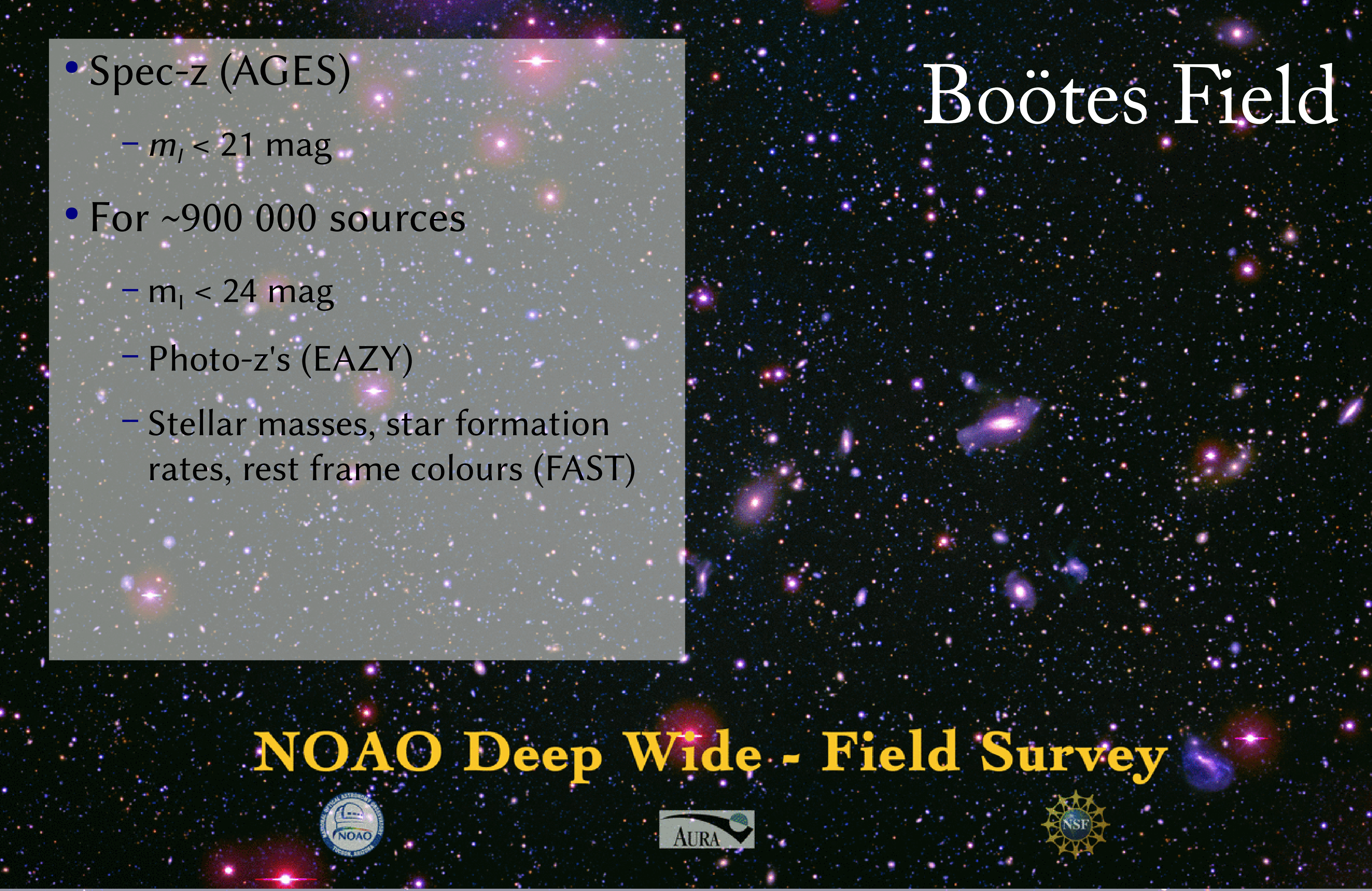


9.3 deg^2

NOAO/AURA/NSF

Boötes Field

- Spec-z (AGES)
  - $m_I < 21$ mag
- For ~900 000 sources
  - $m_I < 24$ mag
  - Photo-z's (EAZY)
  - Stellar masses, star formation rates, rest frame colours (FAST)

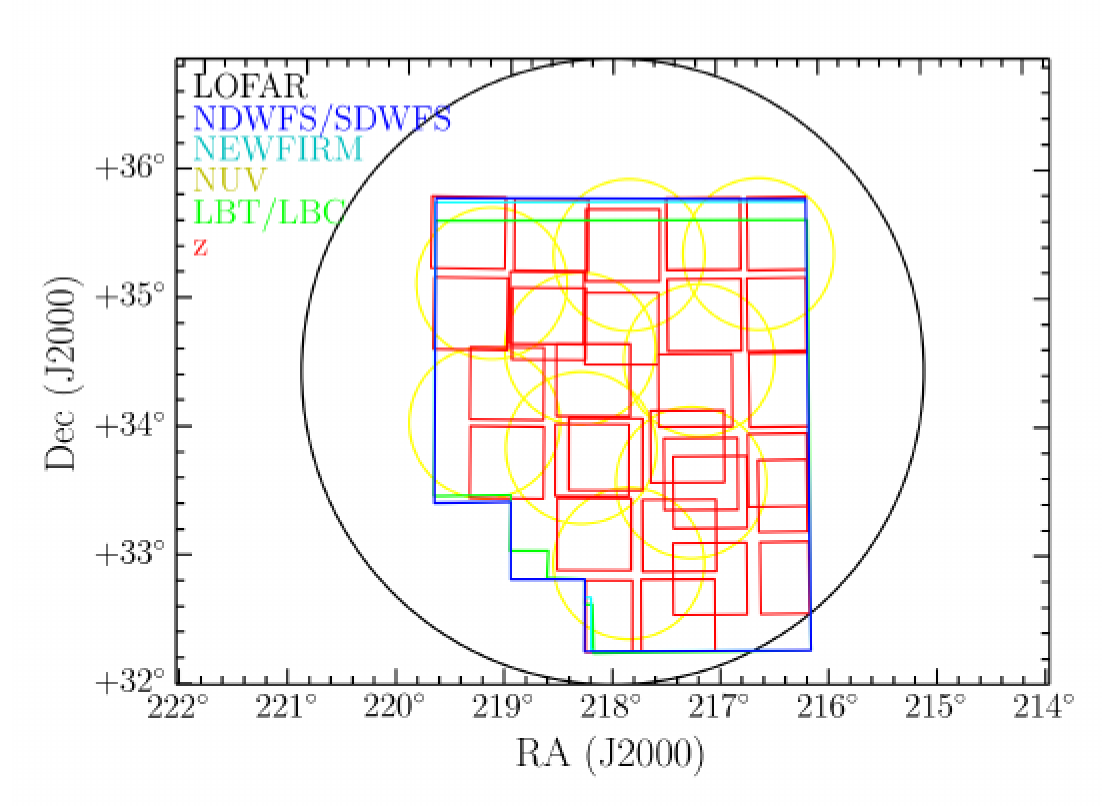


9.3 deg^2

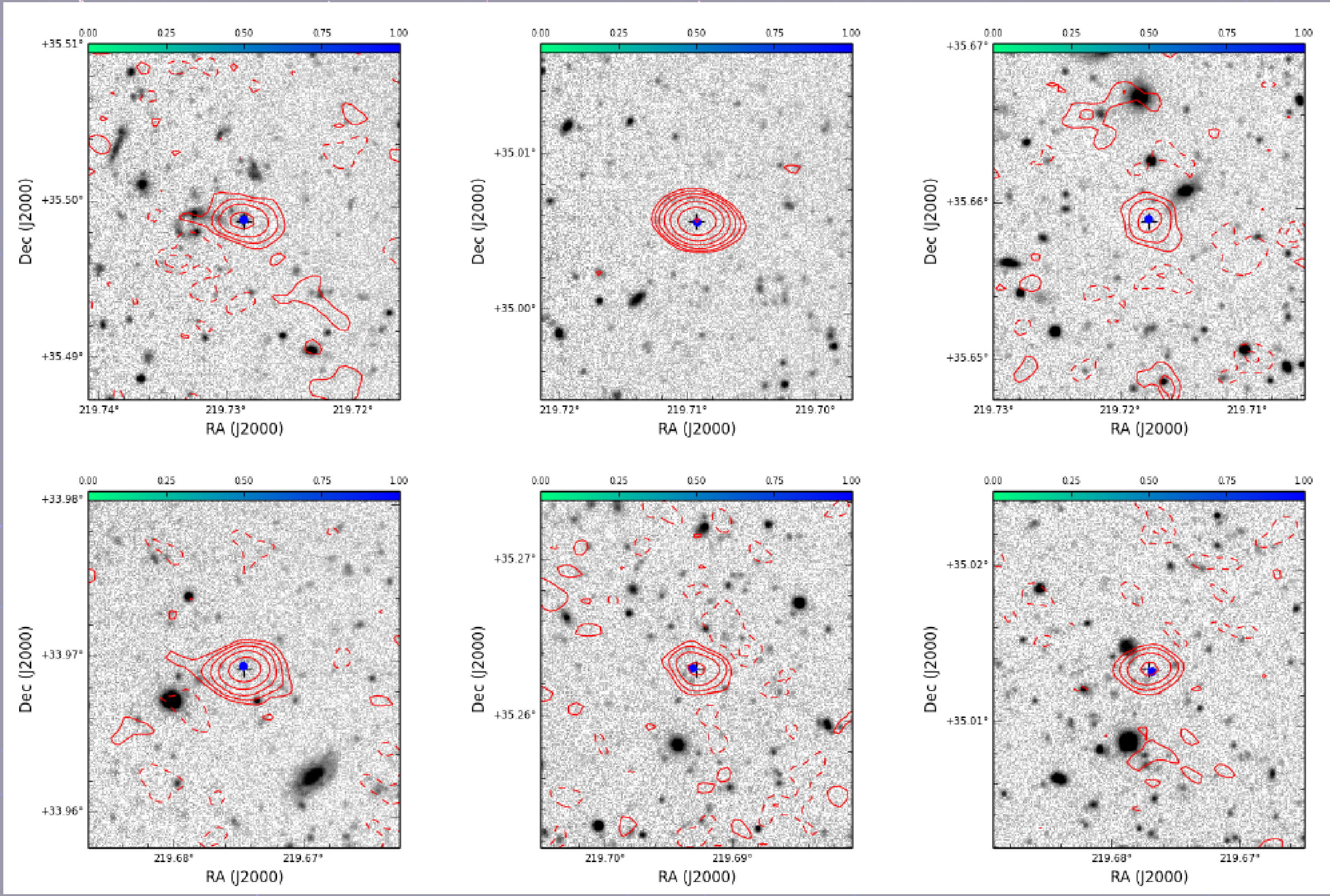
NOAO/AURA/NSF

Radio-Optical Matching

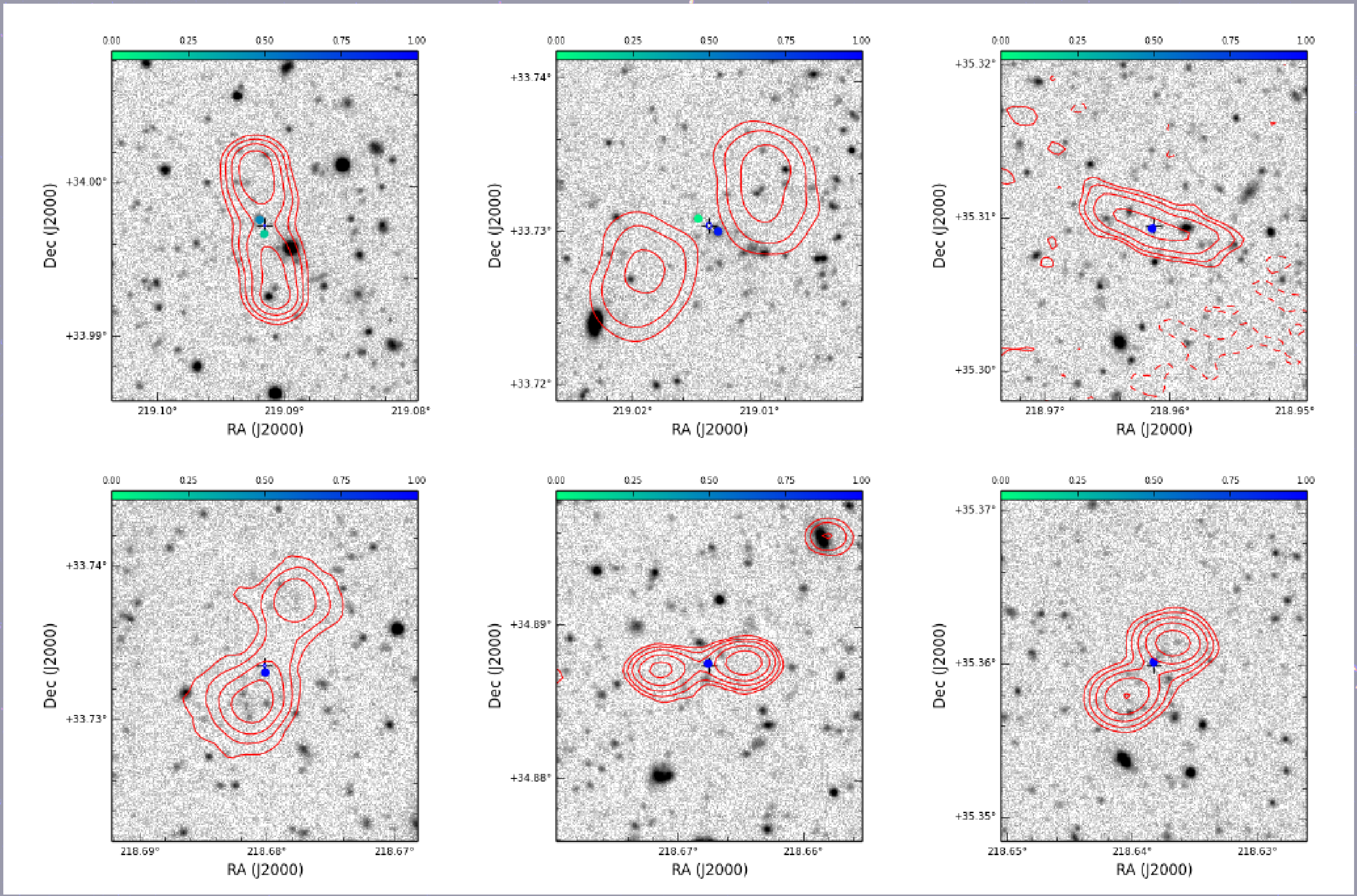
- Likelihood Ratio
  - Visually id extended/multi-component sources
- 3317 of 5652 LOFAR sources lie within the optical coverage
- 2326 with optical ID
  - 70% identified fraction



Radio-Optical Matching

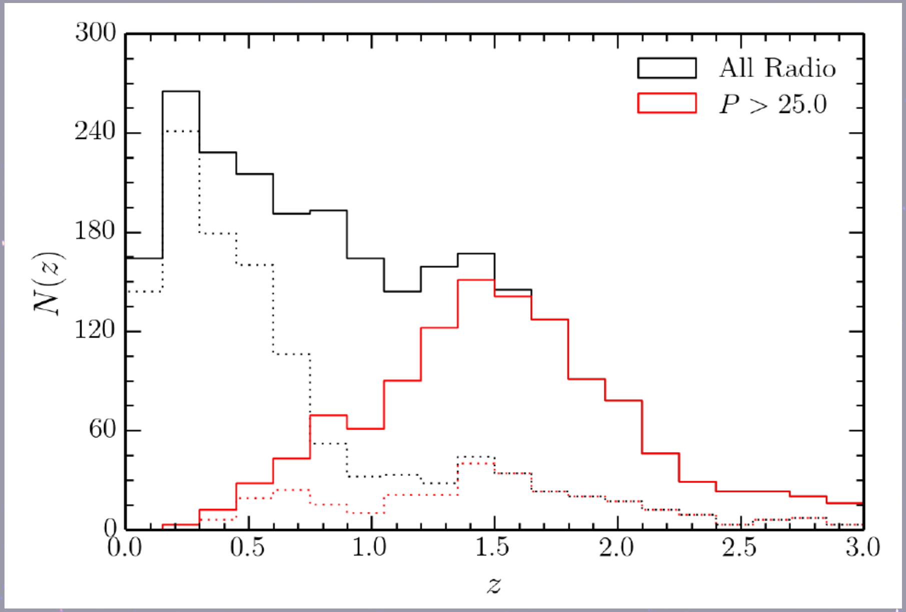


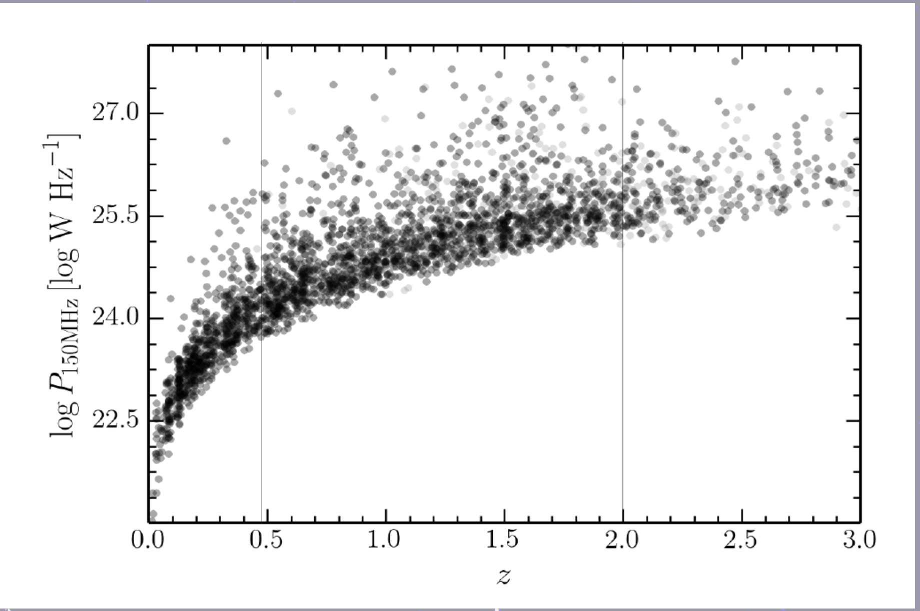
Radio-Optical Matching



At moderate redshift?

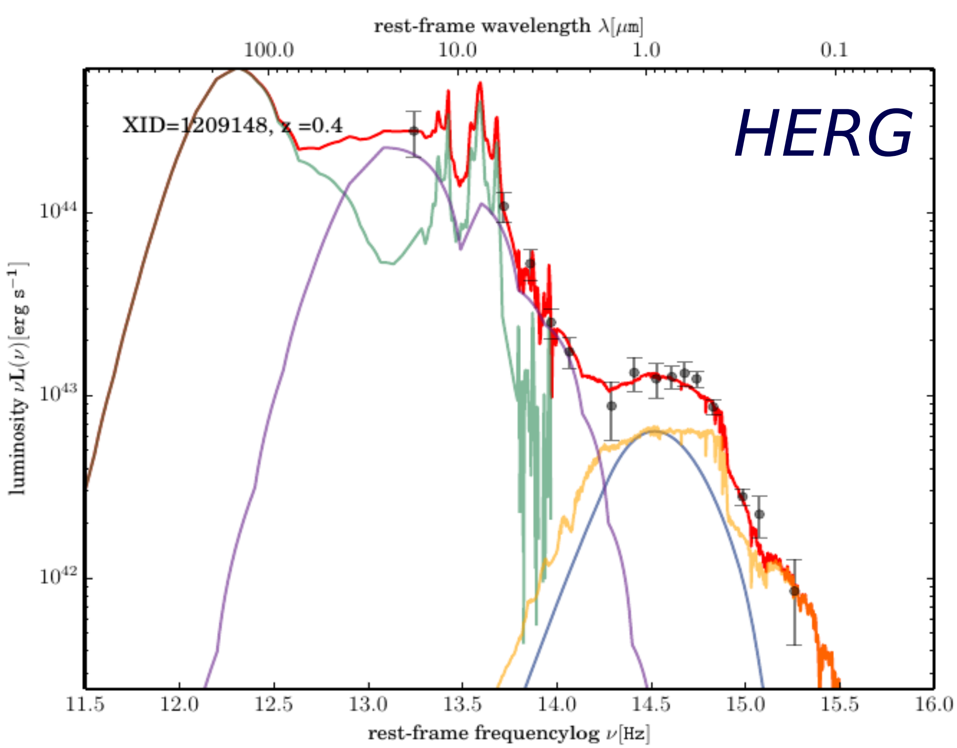
- Select LOFAR sample
  - $0.5 < z < 2.0$
  - $P_{150\,MHz} > 10^{25}$ W/Hz
  - 974 sources

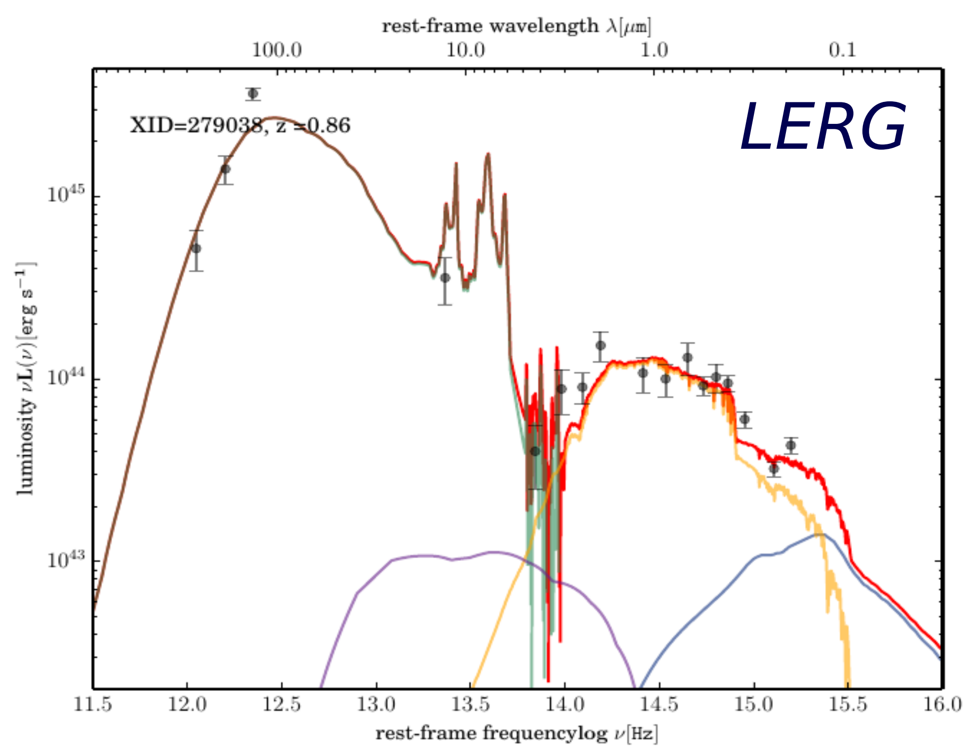




AGN modes from SED fitting?

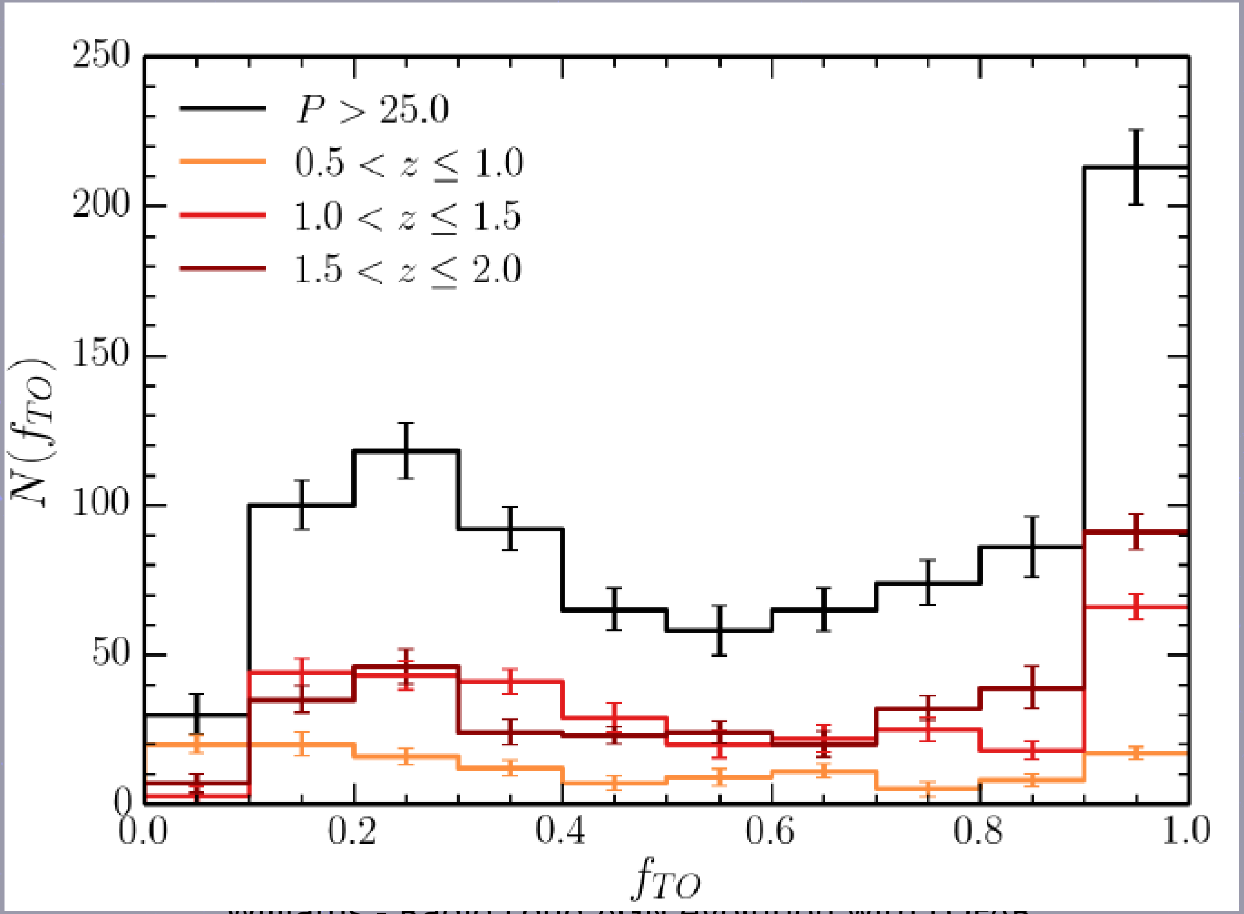
- AGNfitter (Calistro-Rivera)
  - *Including* FIR Herschel data from HERMES
  - Components
    - Galaxy & Starburst
    - IR torus and accretion disk





AGN modes from SED fitting?

- AGN Torus fraction
  - Fraction of IR light from torus relative to Galaxy
- Classify cold- vs hot-mode (HERG vs LERG)



The hosts of moderate-z radio AGN

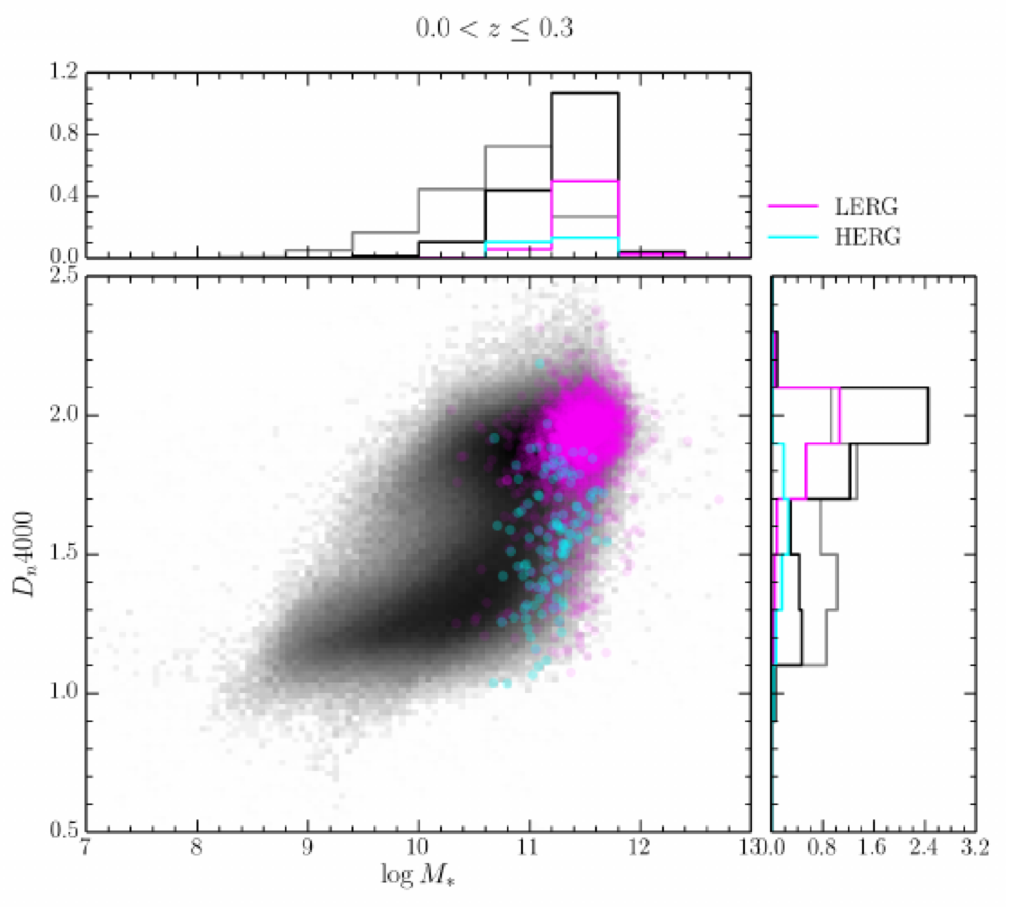
HERG/LERG fraction

z	N	LERGs (%)	HERGs (%)
0.01–0.3	3736	3066 (96%)	121 (4%)
0.5–1.0	173	52 (30%)	121 (69%)
1.0–1.5	384	72 (18%)	312 (81%)
1.5–2.0	390	67 (17%)	321 (82%)

By colour: Red vs Blue

z	N	BLERGs (%)	RLERGs (%)	BHERGs (%)	RHERGs (%)
0.01–0.3	3736	148 (3.9%)	2918 (78%)	61 (1.6%)	60 (1.6%)
0.5–1.0	173	17 (9%)	32 (18%)	89 (51%)	28 (16%)
1.0–1.5	384	52 (13%)	20 (5%)	248 (64%)	57 (14%)
1.5–2.0	390	55 (14%)	12 (3%)	301 (77%)	10 (2%)

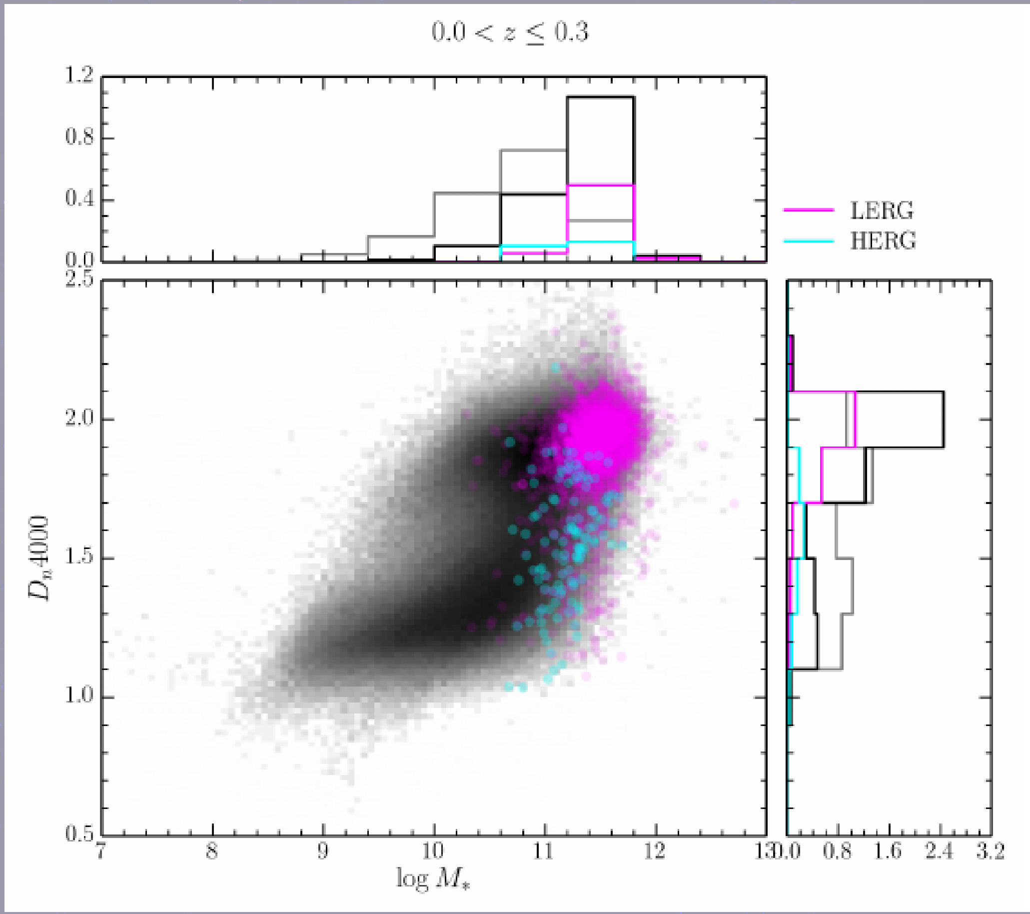
The hosts of moderate-z radio AGN



Local sample

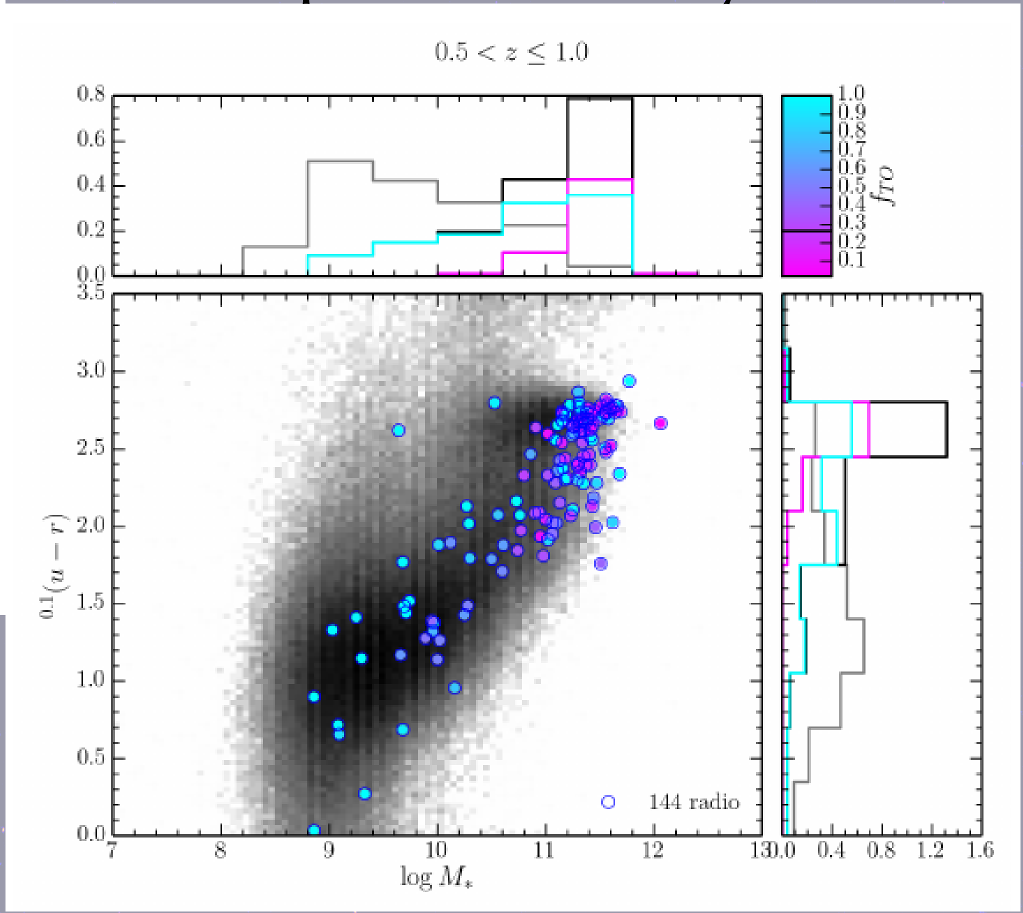
- Colour vs mass
- HERGs/LERGs classified spectroscopically

The hosts of moderate-z radio AGN



LOFAR sample

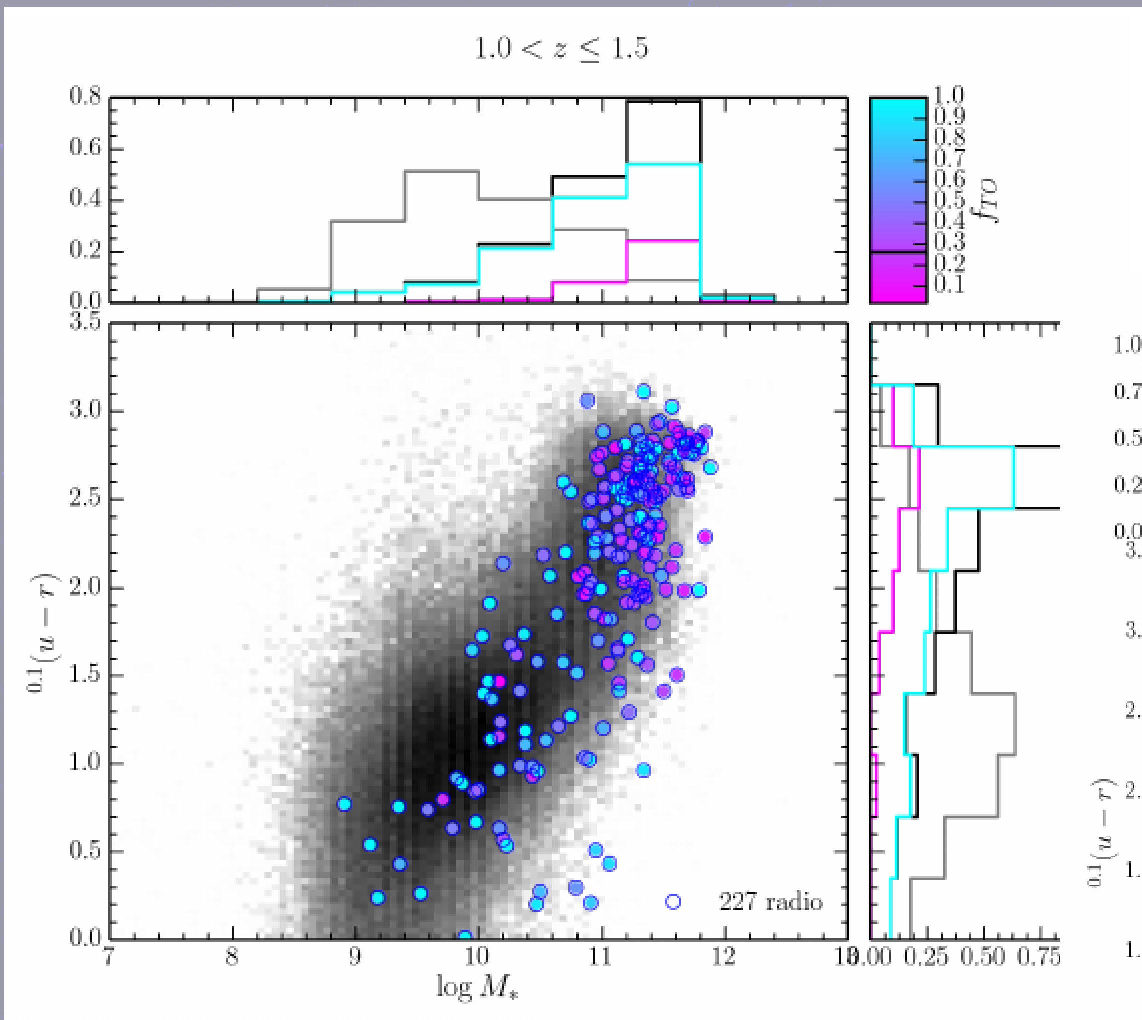
- Colour vs mass
- HERGs/LERGs classified photometrically

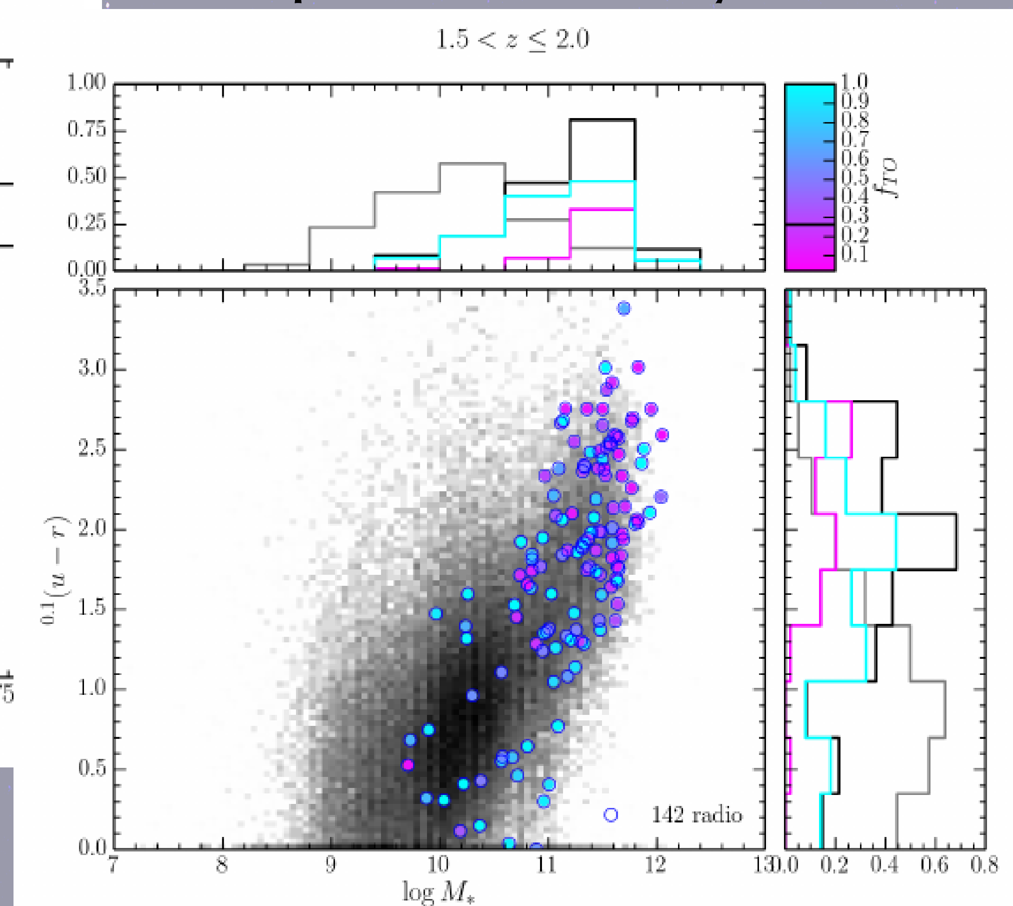


The hosts of moderate-z radio AGN

LOFAR sample

- Colour vs mass
- HERGs/LERGs classified photometrically





Summary

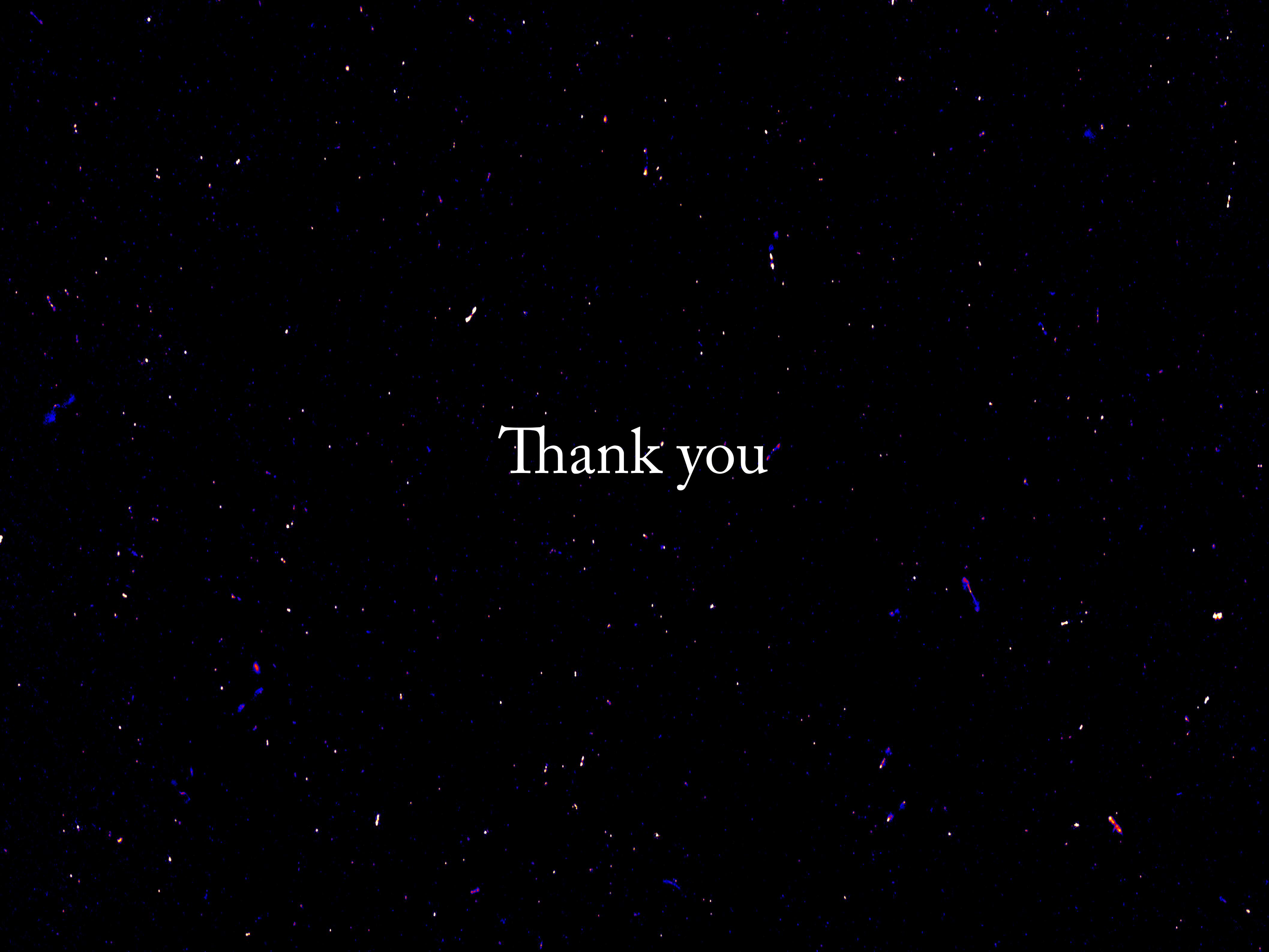
Combined with excellent multiwavelength data, (LOFAR) Radio Surveys are important for understanding the radio AGN population

The LOFAR Bootes sample shows

- Radio AGN are hosted by bluer, less massive galaxies
- Cold-mode accretion becomes dominant at z>~1

LOFAR is a great tool for studying AGN and is producing nice images

- Low frequency imaging capability is steadily improving
- Cutting edge calibration & imaging techniques required


Thank you