

The Deep LBA View of the ELAIS-N1 Field

The Deepest Wide-field Observations at 50 MHz with LOFAR

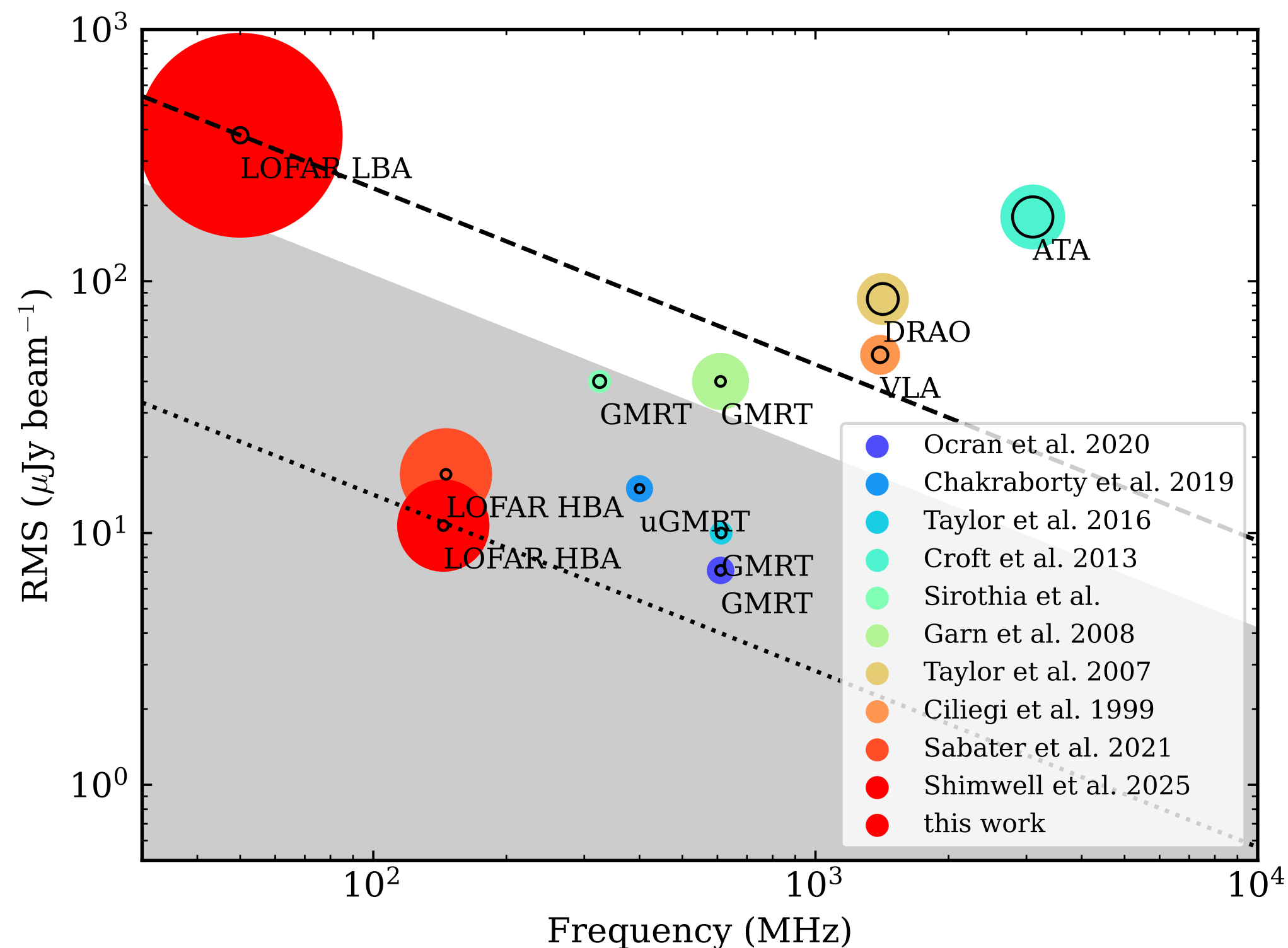
Jort Boxelaar

Università di Bologna
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The European Large Area /SO Survey N1

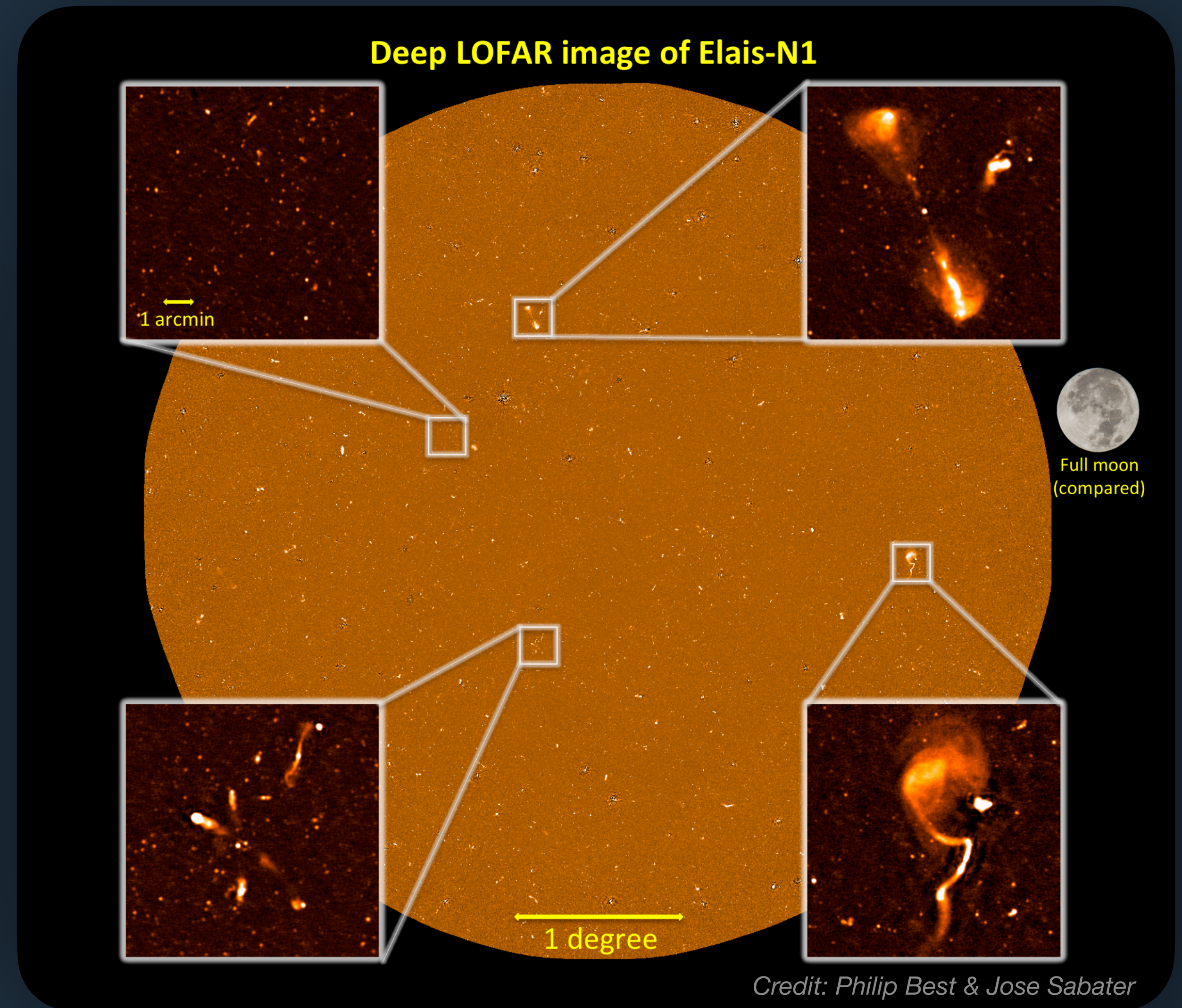
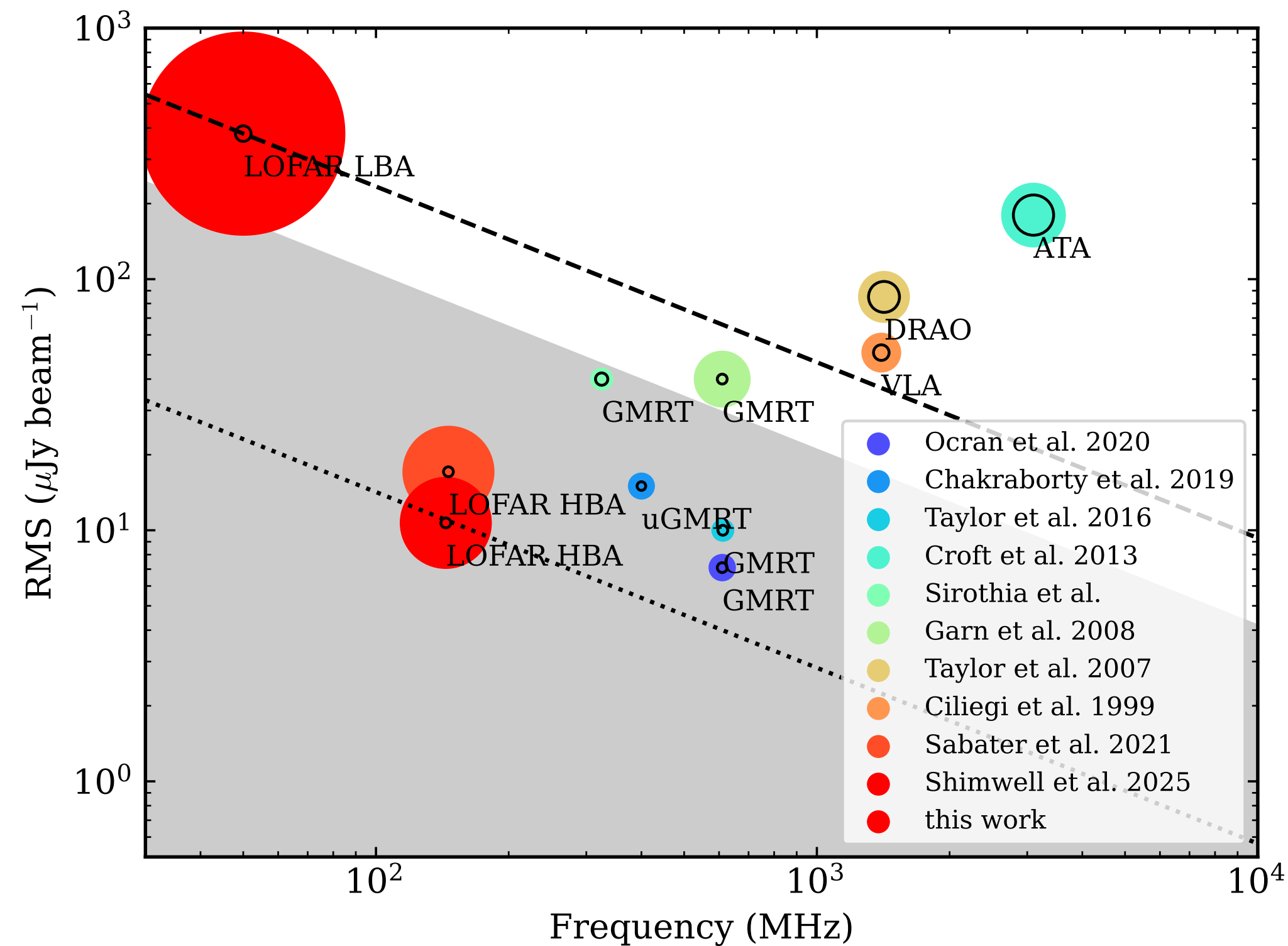
Existing radio observations of ELAIS-N1



- Extensively studied field in with some of the best multi-frequency coverage from radio to X-Ray.
- Radio observations from LOFAR HBA (144 MHz) to ATA (3 GHz)
- Optical to near-infrared from ground based telescopes
- Far-infrared from space based telescopes
- Photometric and spectroscopic redshift catalogues available

The European Large Area /SO Survey N1

Existing radio observations of ELAIS-N1



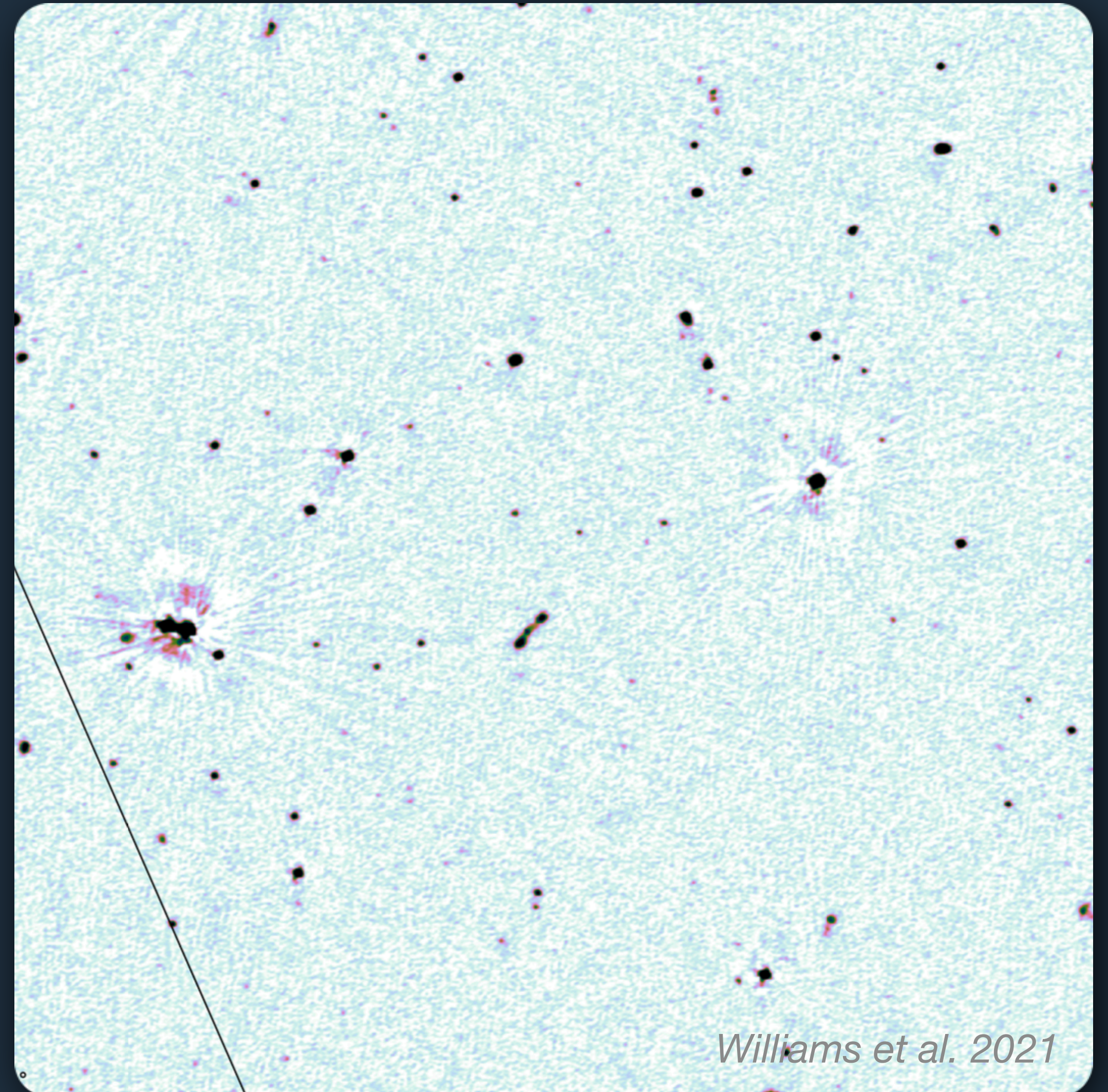
The European Large Area /SO Survey N1

Previous deep observations with LBA

- Not the first deep-field with LBA
- First deep-field by *Williams et al. 2021* of the Boötes field

56 hours
 $\sigma_{\text{rms}} = 0.7 \text{ mJy beam}^{-1}$

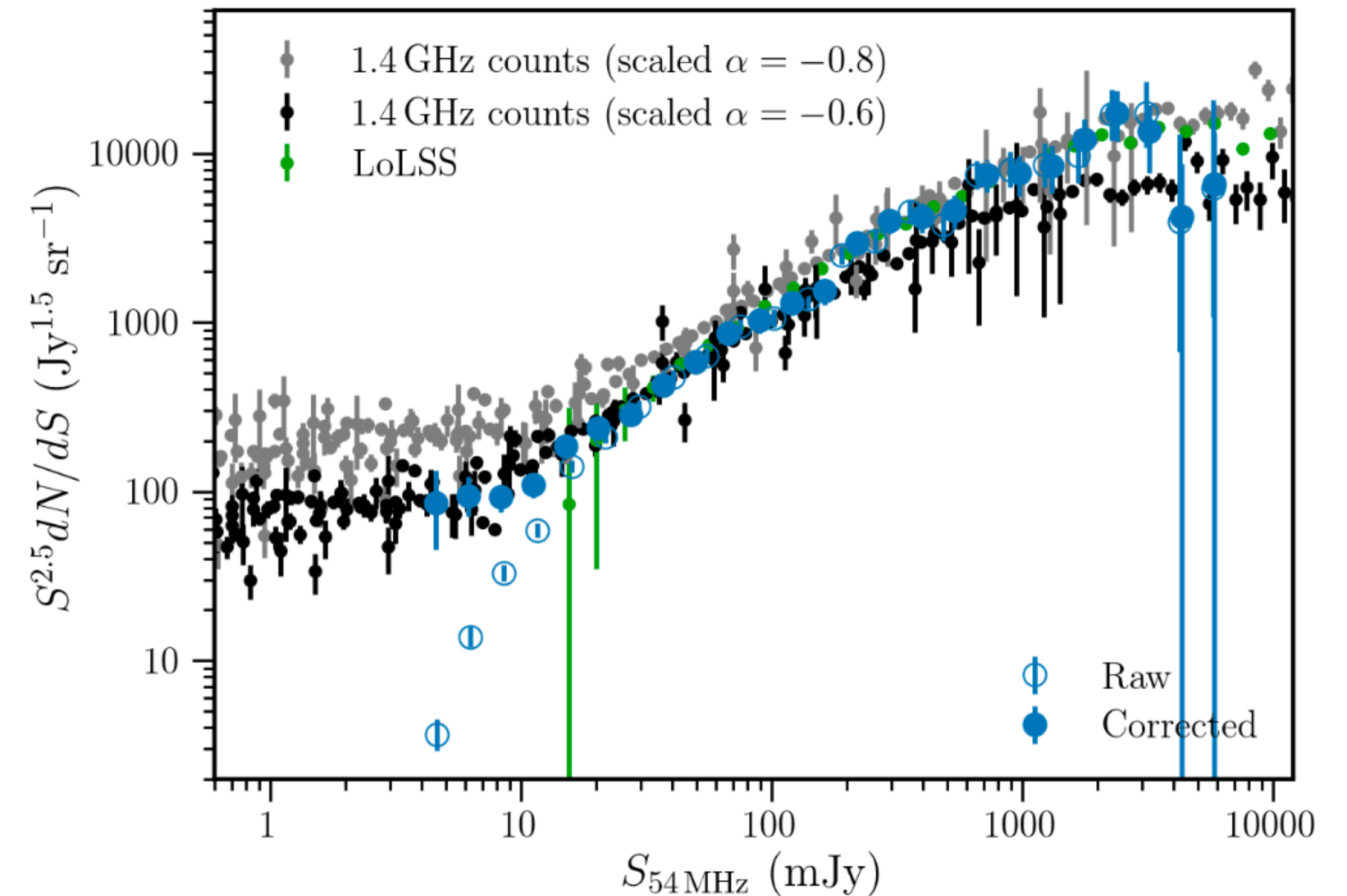
- Just deep enough to detect a few Star forming galaxies



The European Large Area ISO Survey N1

Why do we observe deep fields

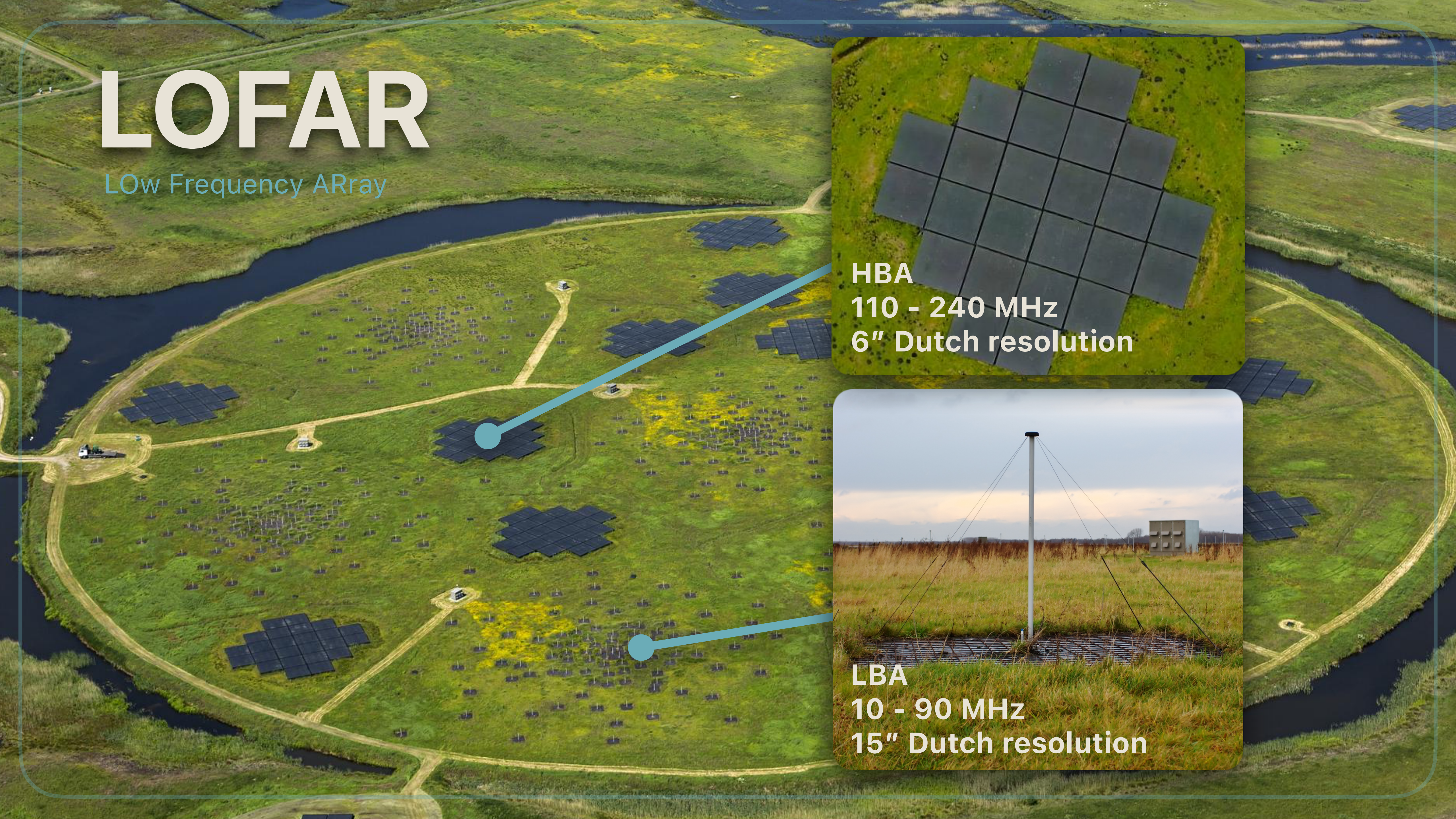
- Star forming galaxies (SFG) become the dominant population below $\sim 300 \mu\text{Jy}$
- Spectral properties at low frequencies unknown. Do they turn over due to absorption?
- Study galaxy evolution through high redshift galaxies
- Low frequency spectral properties of AGN



Williams et al. 2021

LOFAR

LOW Frequency ARray



HBA
110 - 240 MHz
6" Dutch resolution

This inset image shows a close-up of a hexagonal cluster of dark, rectangular antenna tiles. A light blue line originates from one of these clusters in the main aerial view and points to this inset.



LBA
10 - 90 MHz
15" Dutch resolution

This inset image shows a single antenna tile mounted on a metal frame. A tall vertical pole is supported by several guy wires. A light blue line originates from a single antenna tile in the main aerial view and points to this inset.

LOFAR

LOW Frequency ARray

HBA
110 - 240 MHz
6" Dutch resolution

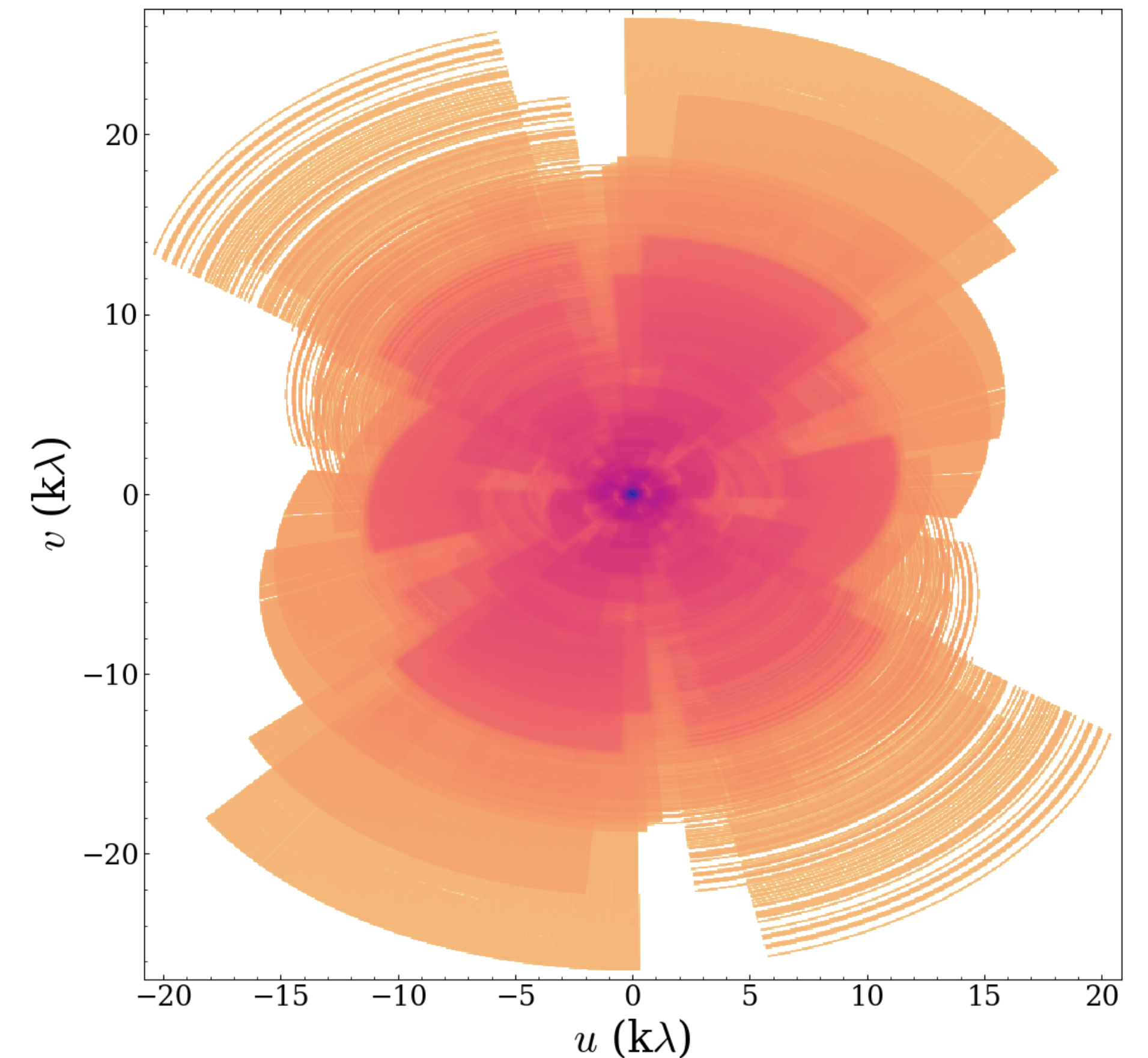
LBA
10 - 90 MHz
15" Dutch resolution



Observations

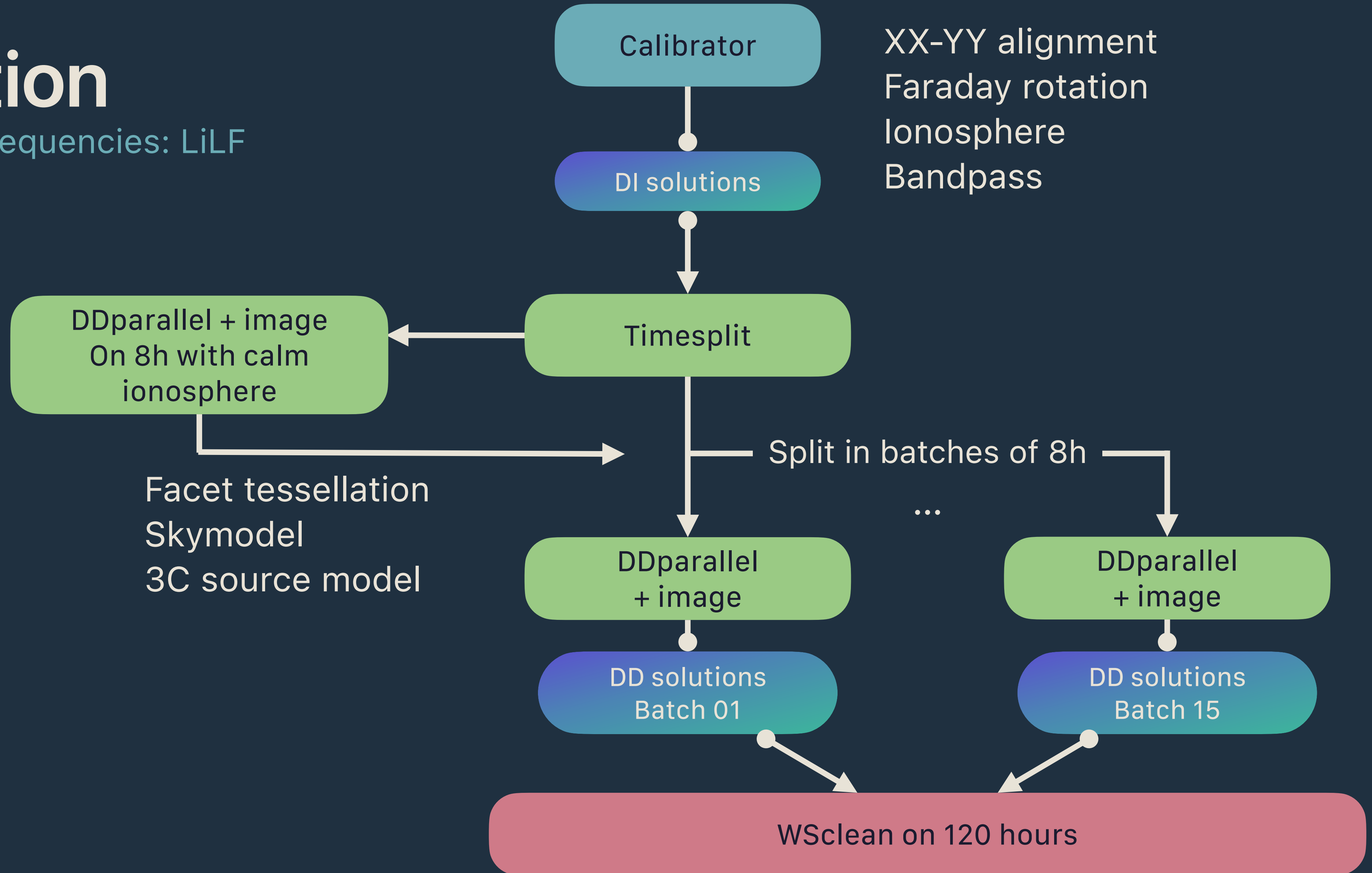
Fact sheet

- 160 hours of total observing time between November 2023 & April 2024
- Of which 40 hours were not retrievable or extremely bad ionosphere
- Central frequency: 50 MHz
- Total bandwidth: 32 MHz
- Primary beam size: ~ 5.3 deg
- Sky coverage: ~ 87.3 deg²



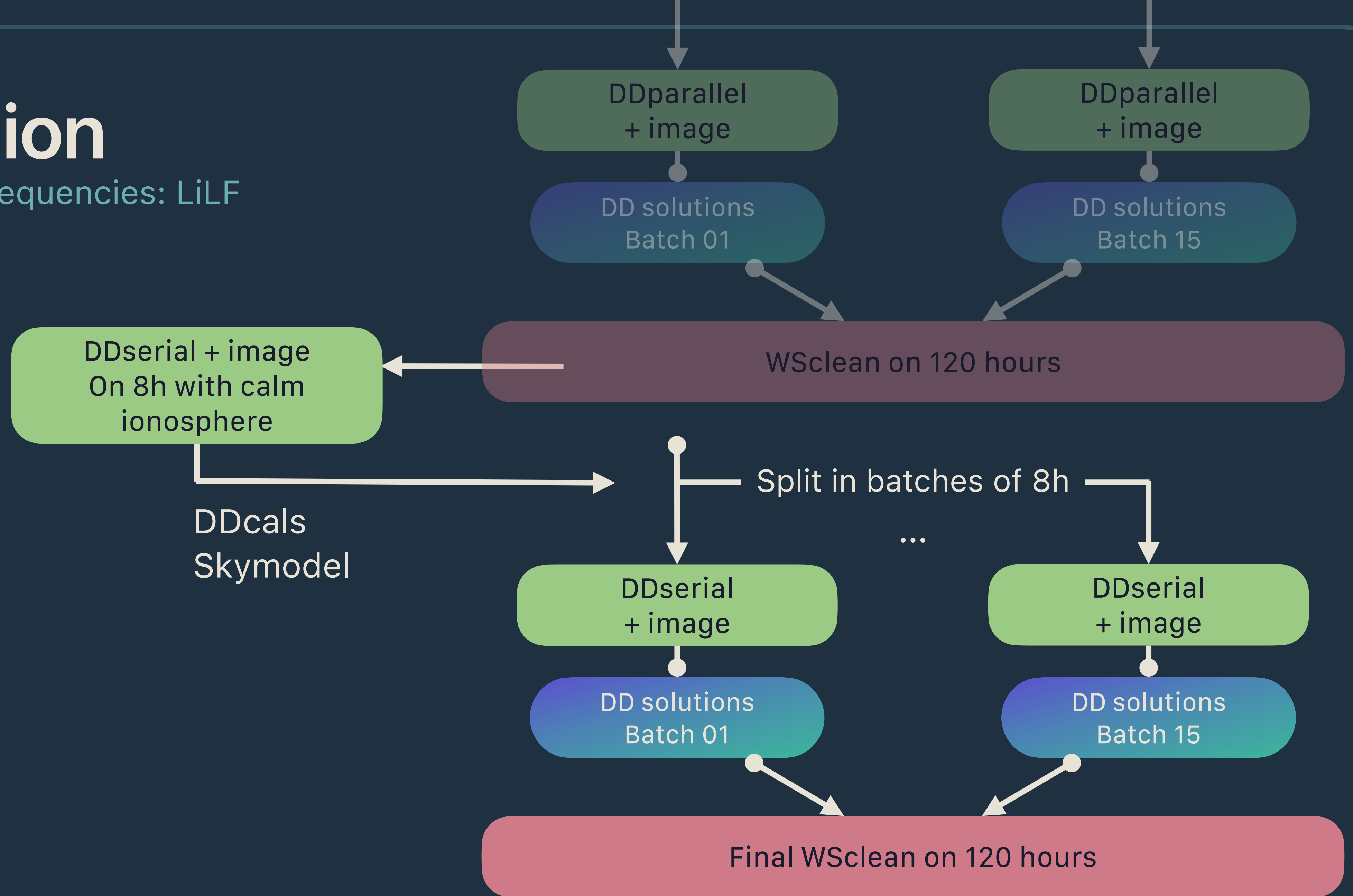
Calibration

Library for low frequencies: LiLF



Calibration

Library for low frequencies: LiLF



Calibration

DDparallel & DDserial

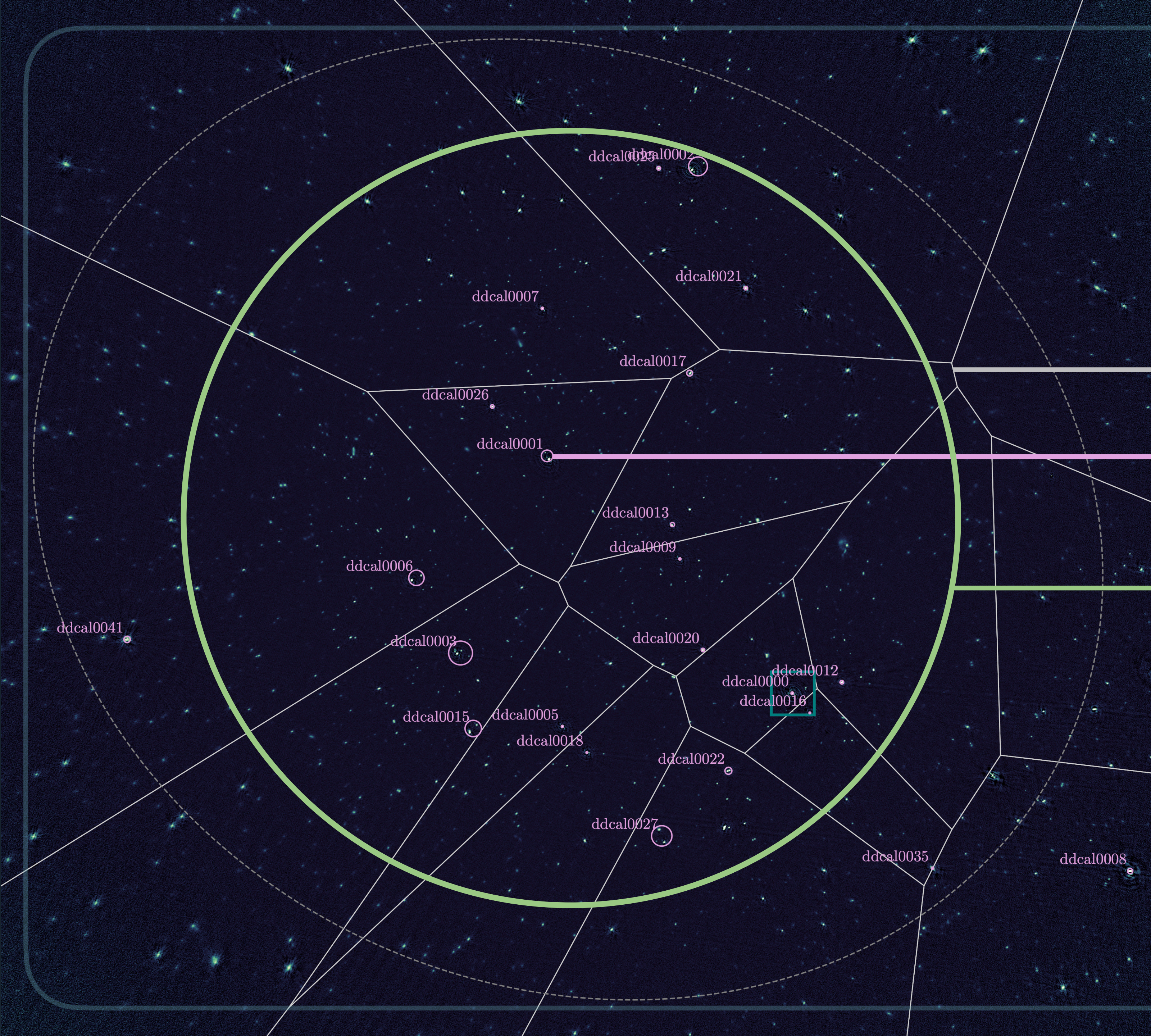
● DDparallel facets

● DDserial direction
dependent calibrators



Calibration

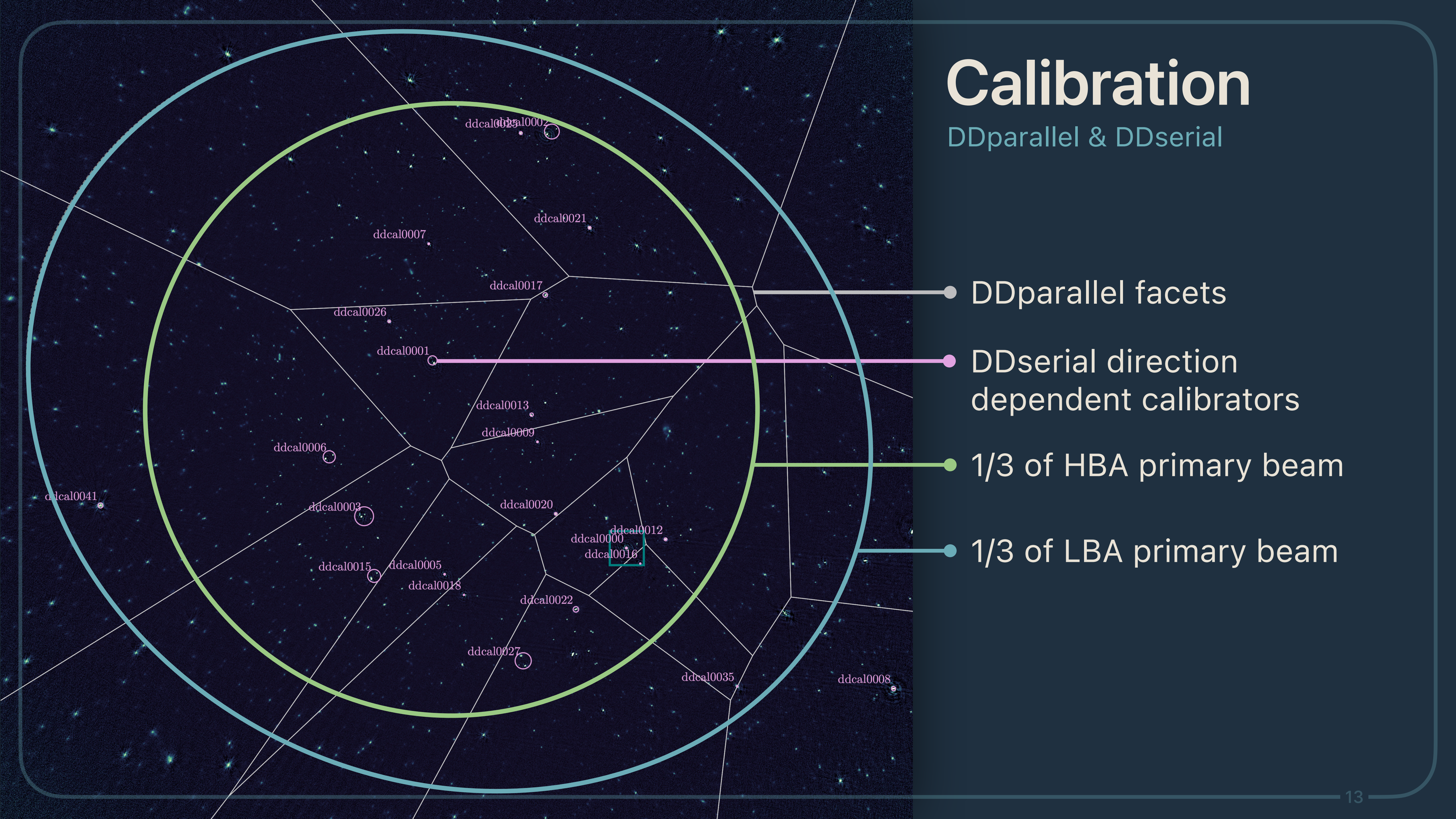
DDparallel & DDserial



- DDparallel facets
- DDserial direction dependent calibrators
- 1/3 of HBA primary beam

Calibration

DDparallel & DDserial



ELAIS-N1

8 hours

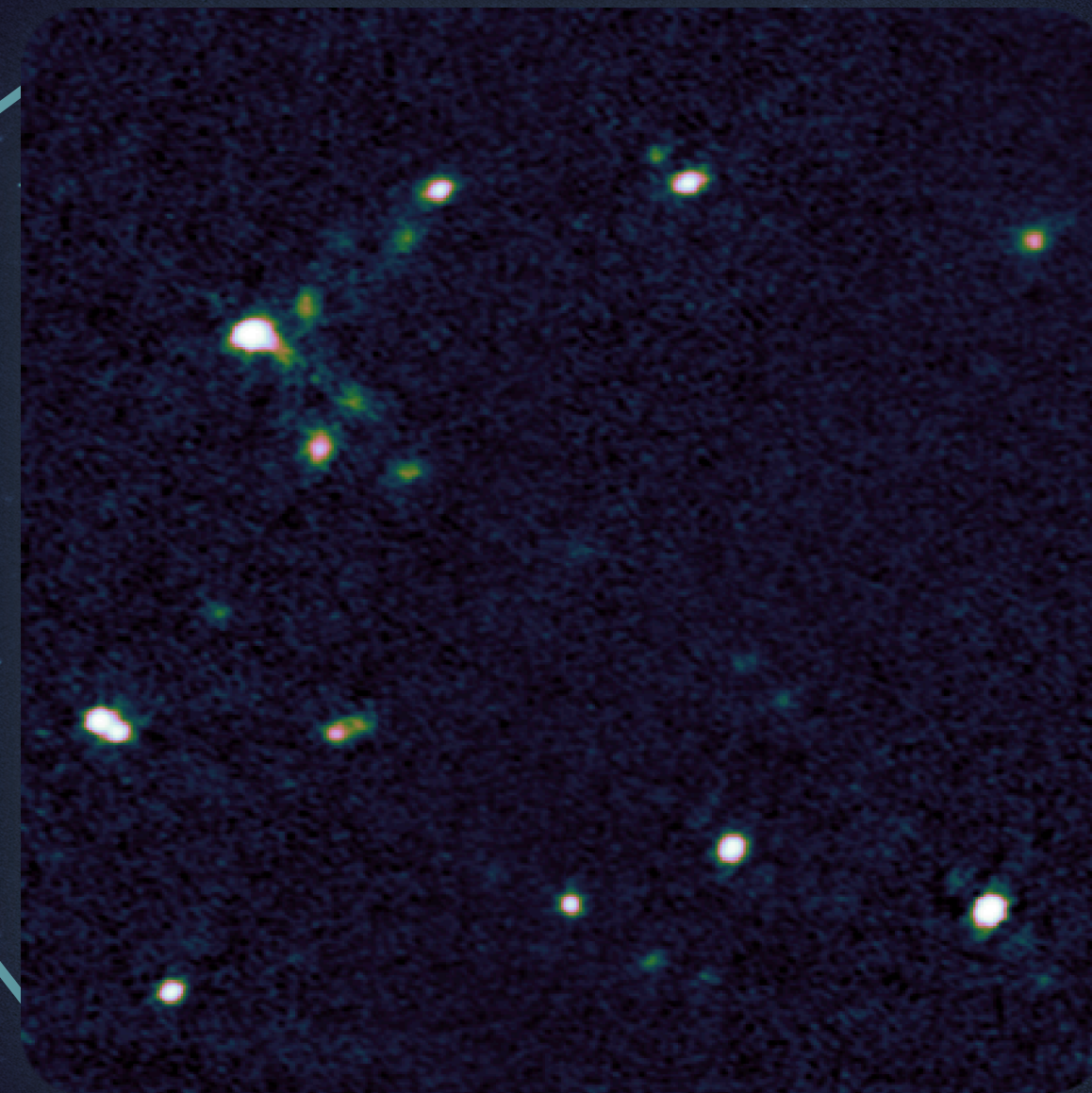
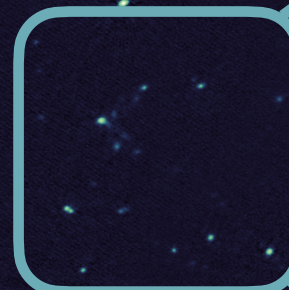
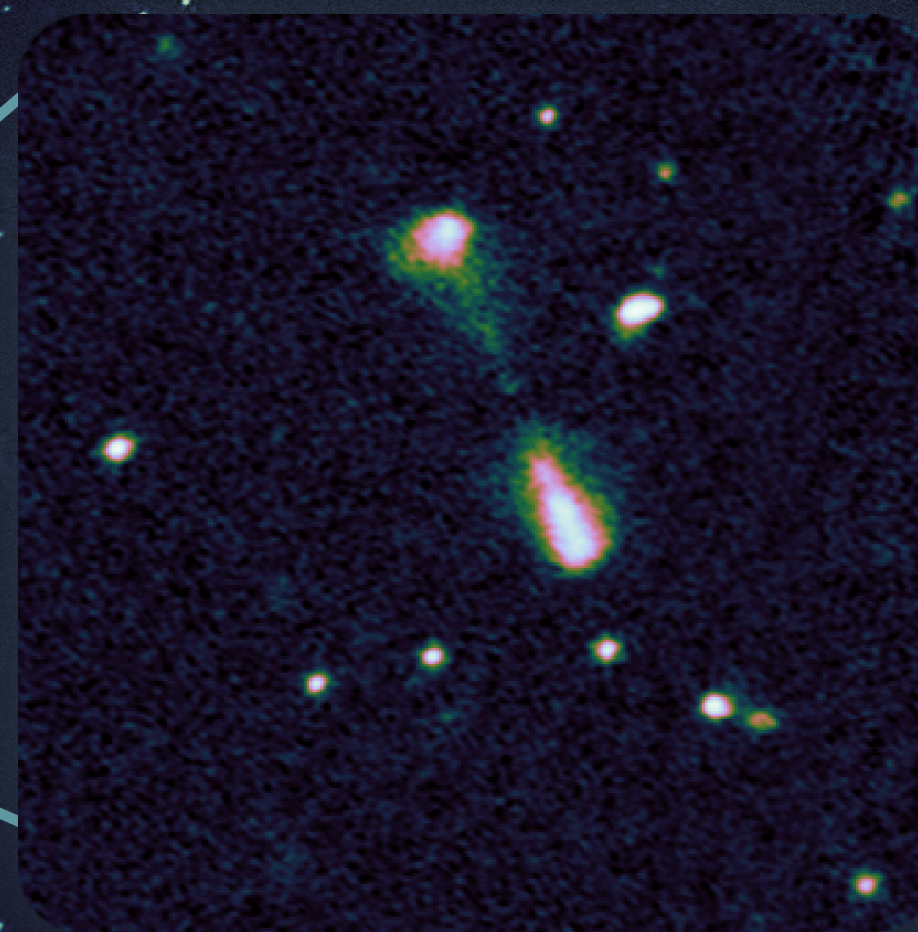
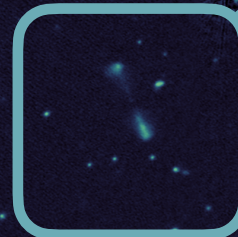
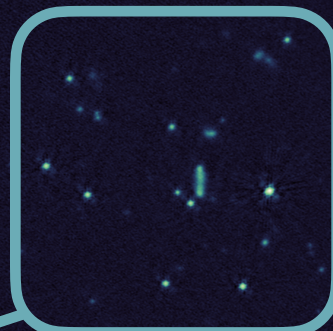
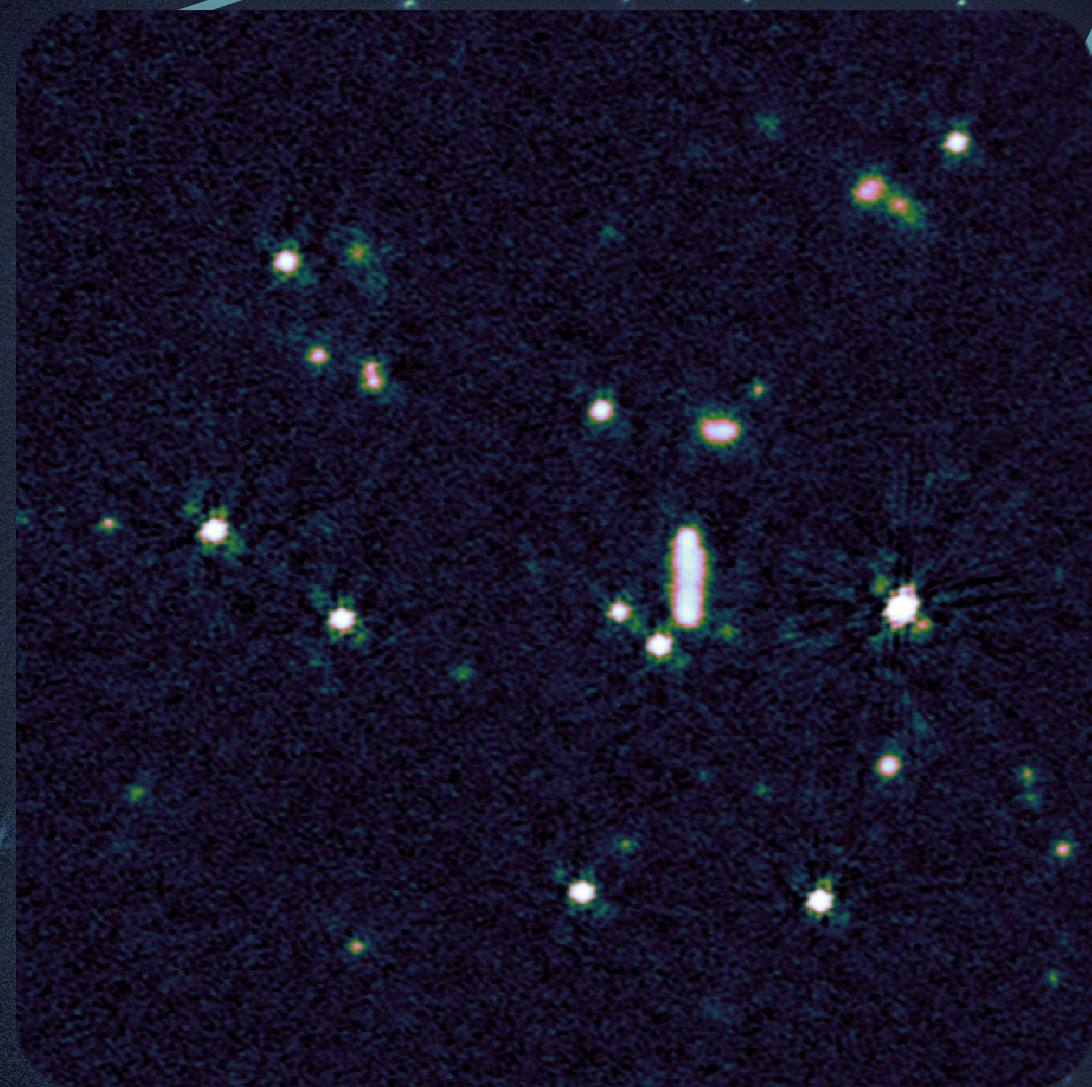
$\sigma_{\text{rms}} = 1.8 \text{ mJy beam}^{-1}$

ELAIS-N1

120 hours

$\sigma_{\text{rms}} = 500 \mu\text{Jy beam}^{-1}$

ELAIS-N1



8 hours

$\sigma_{\text{rms}} \sim 2 \text{ mJy beam}^{-1}$

$N * 8 \text{ hours: } \sigma_{\text{rms}} \sim \frac{2}{\sqrt{N}} \text{ mJy beam}^{-1}$

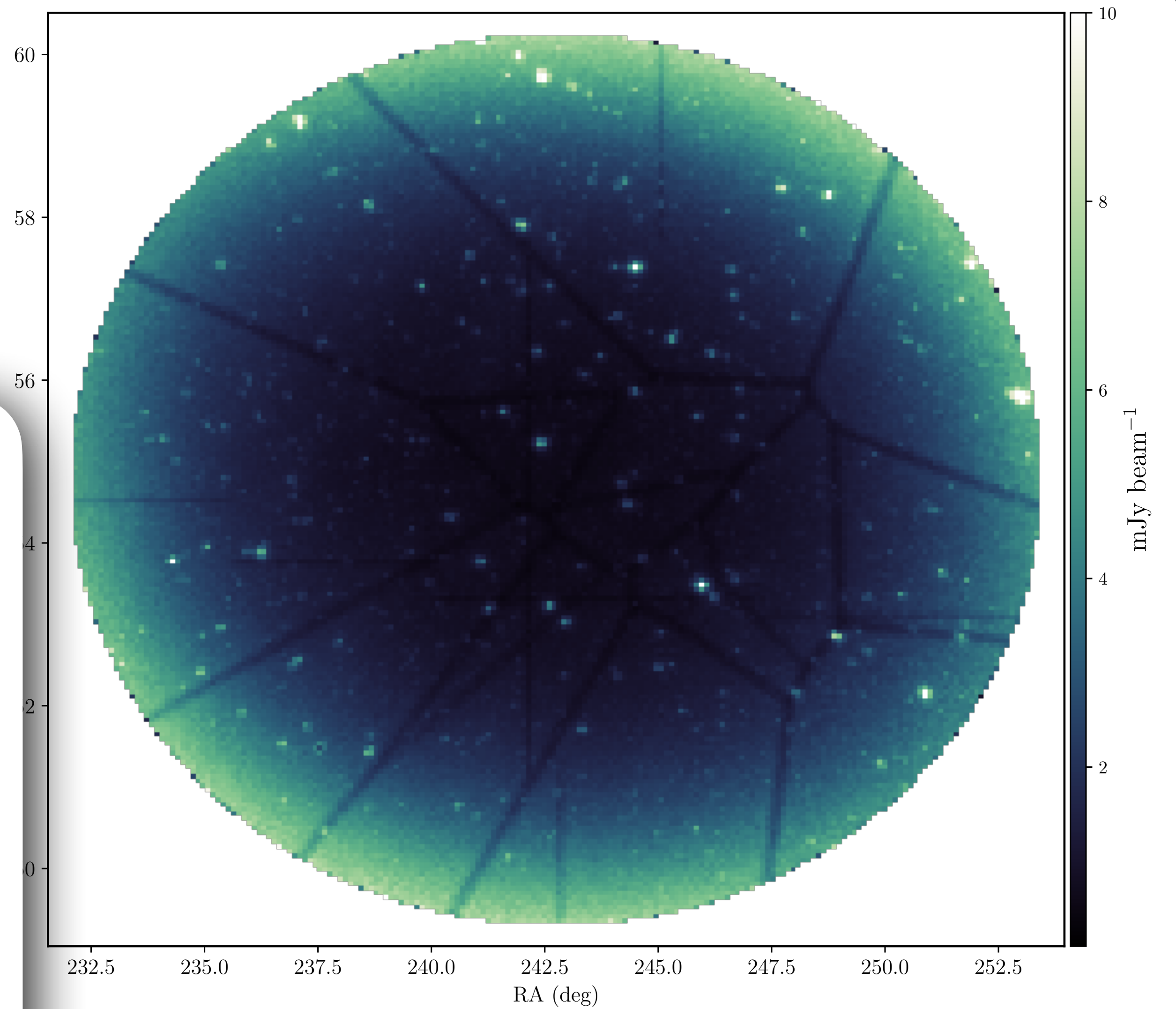
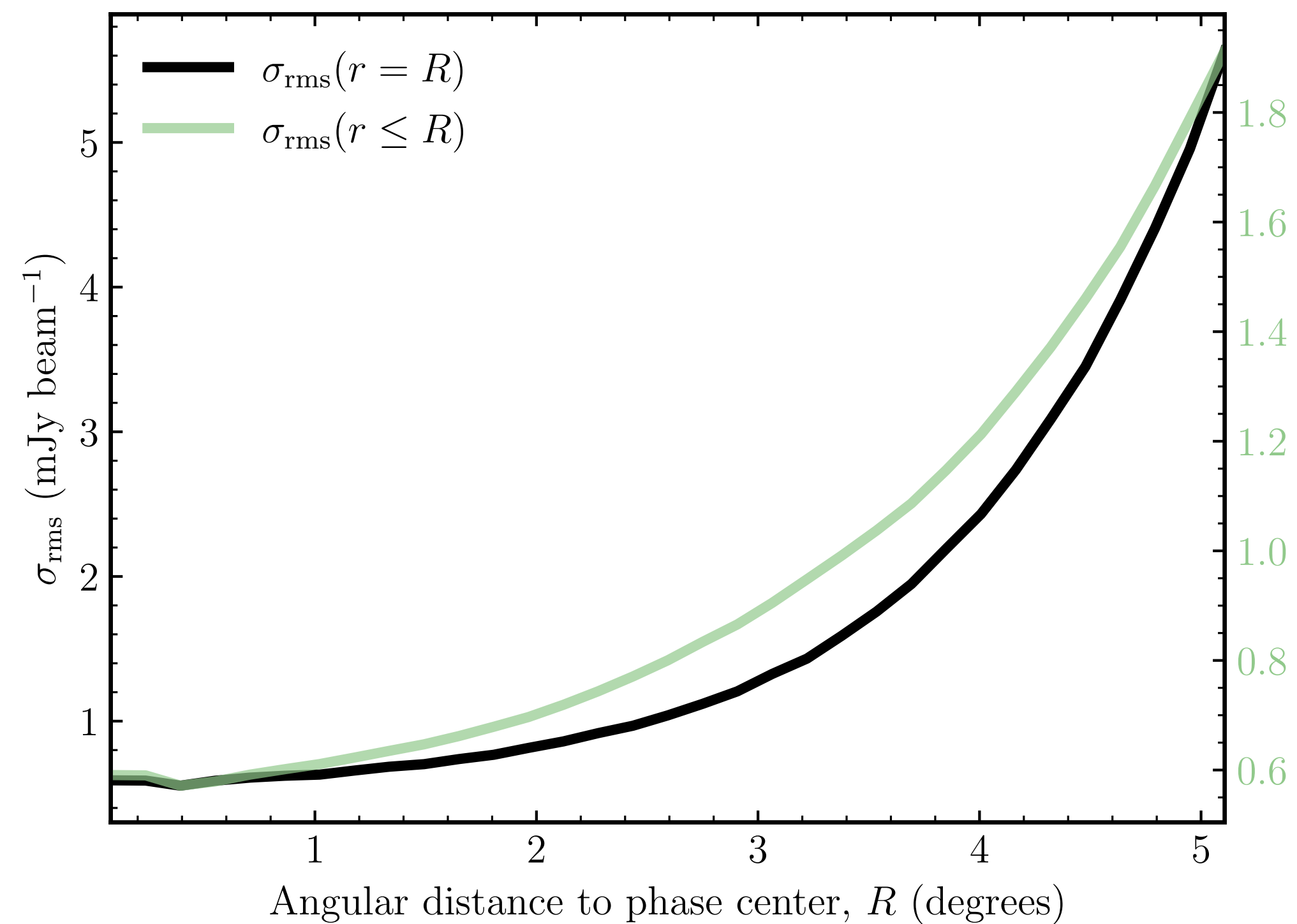
120 hours

$\sigma_{\text{rms}} = 0.5 \text{ mJy beam}^{-1}$

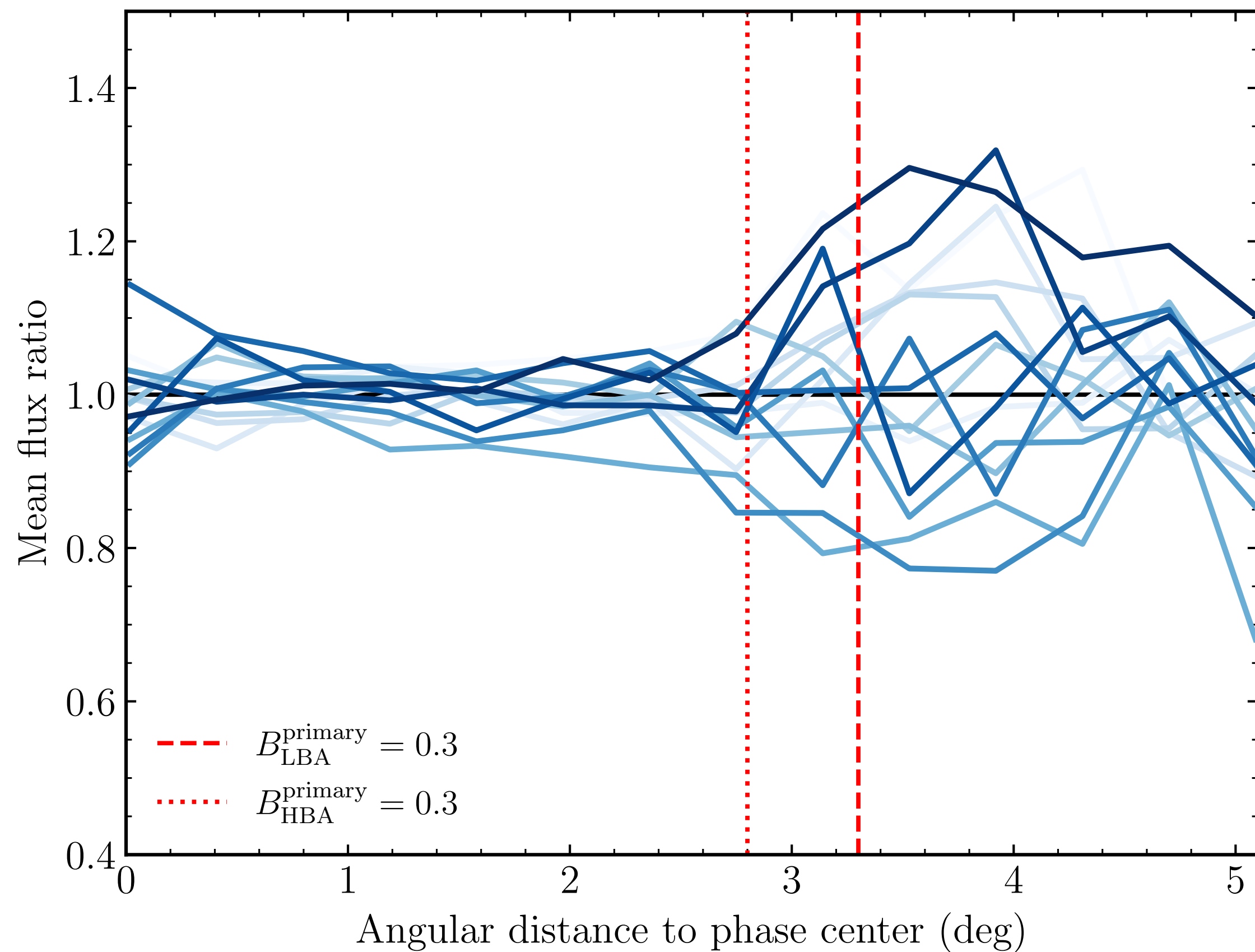
Image statistics

RMS noise distribution

$$\sigma_{\text{rms}} \Big|_{r=0} = 0.5 \text{ mJy beam}^{-1}$$

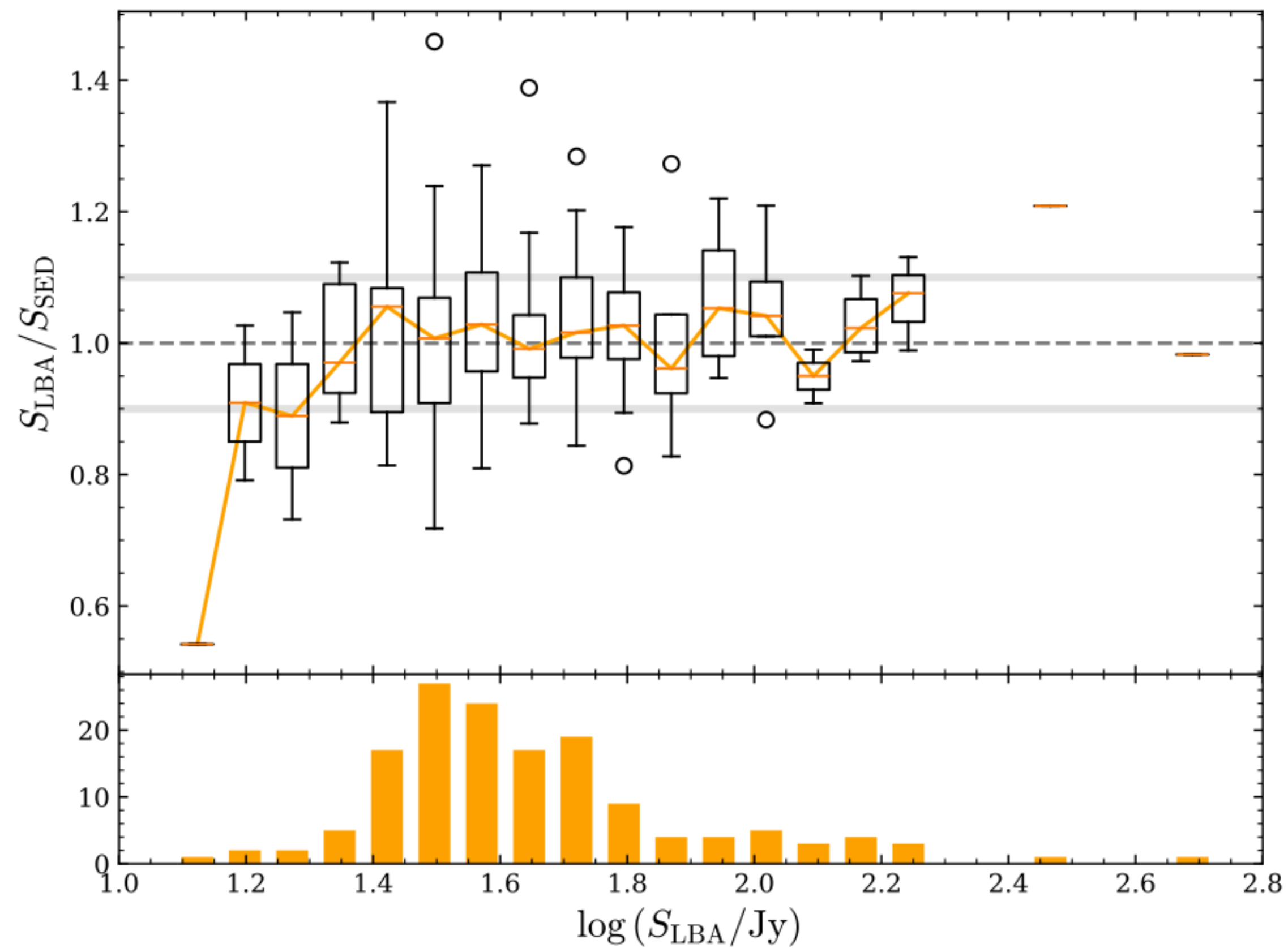
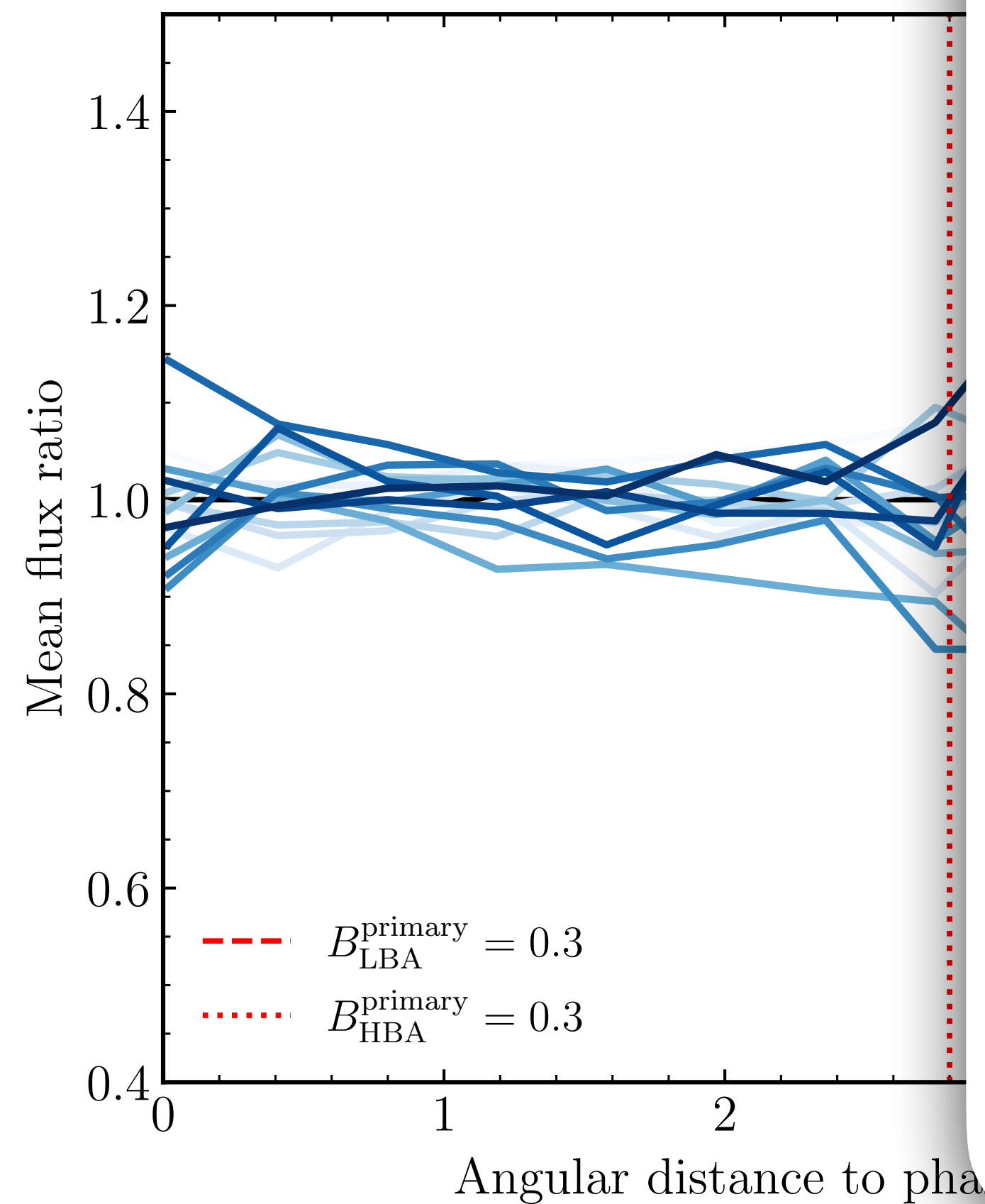


LBA Flux scale



- Is the flux scale self-consistent over time?
- Is the flux scale self-consistent everywhere in the field?
- Is the flux scale globally correct?

LBA Flux scale



Boxelaar et al. 2025

istent over time?

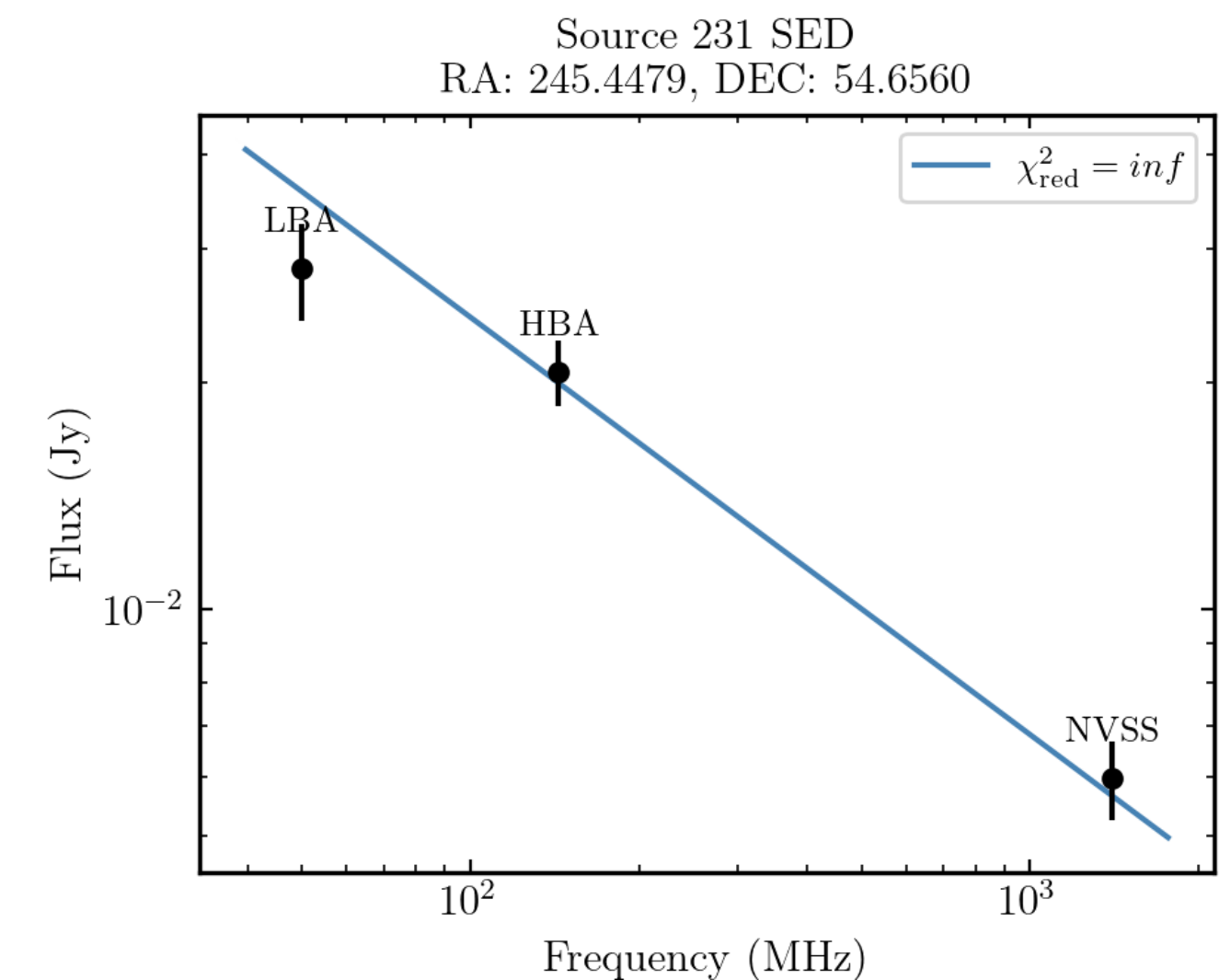
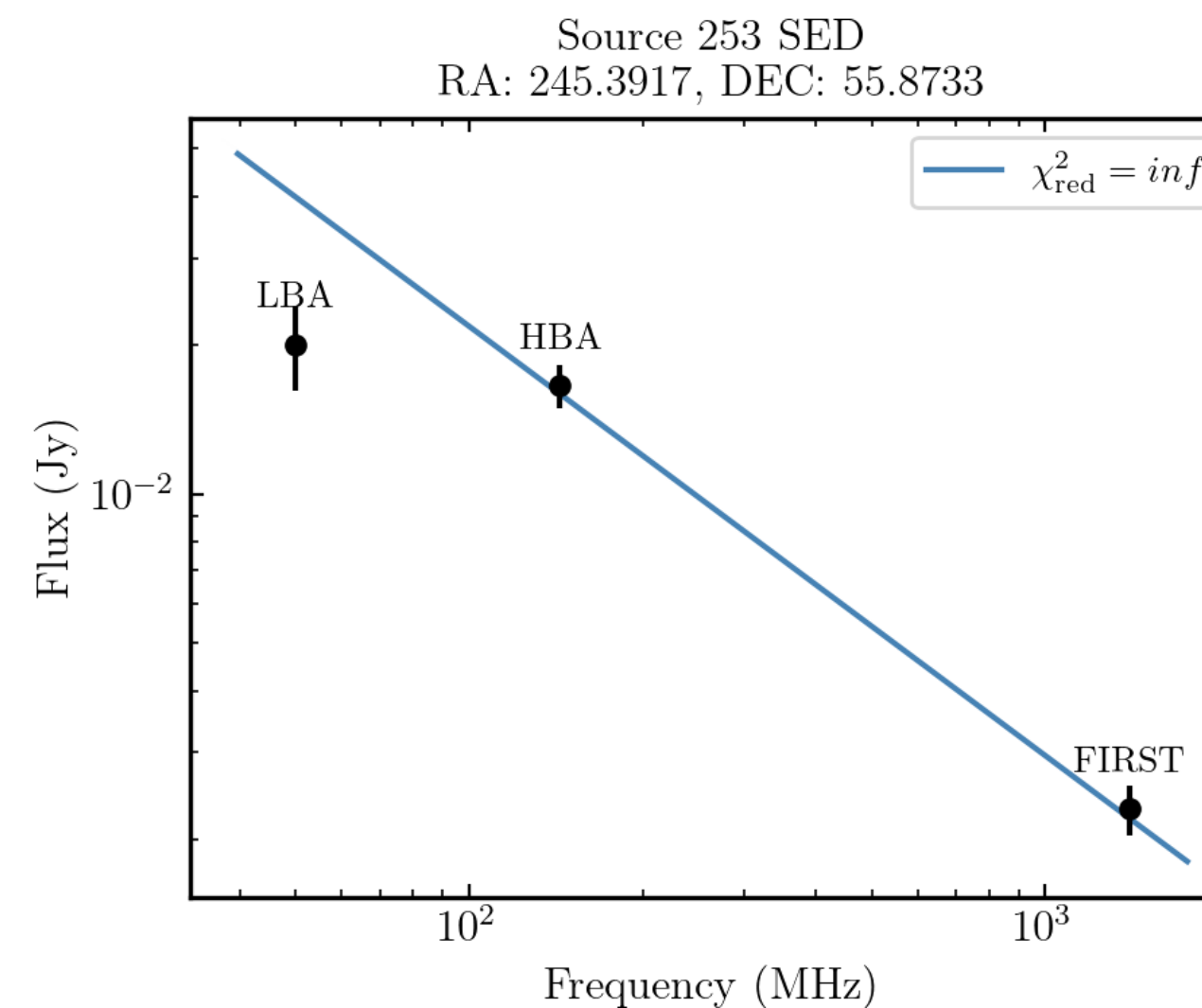
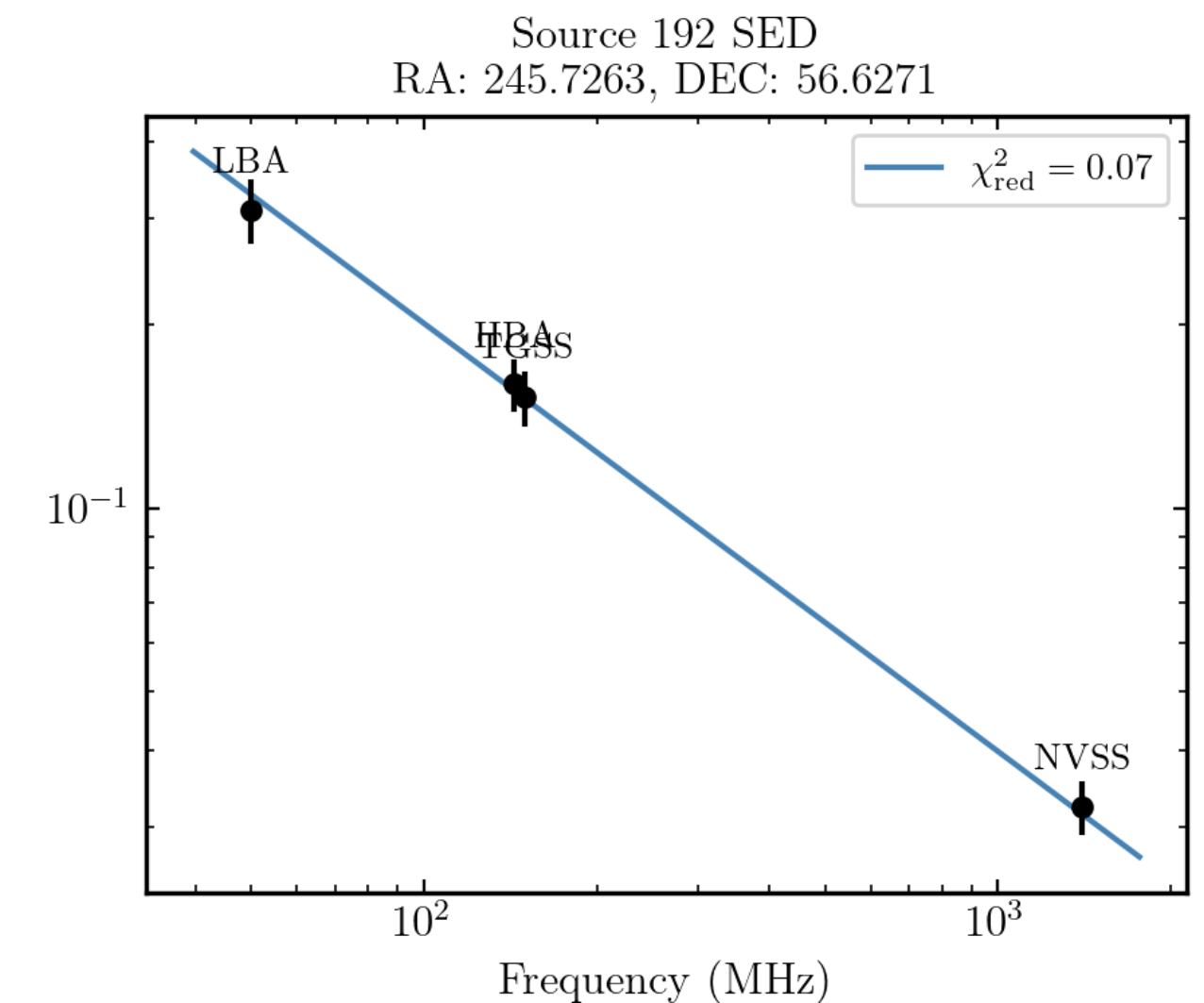
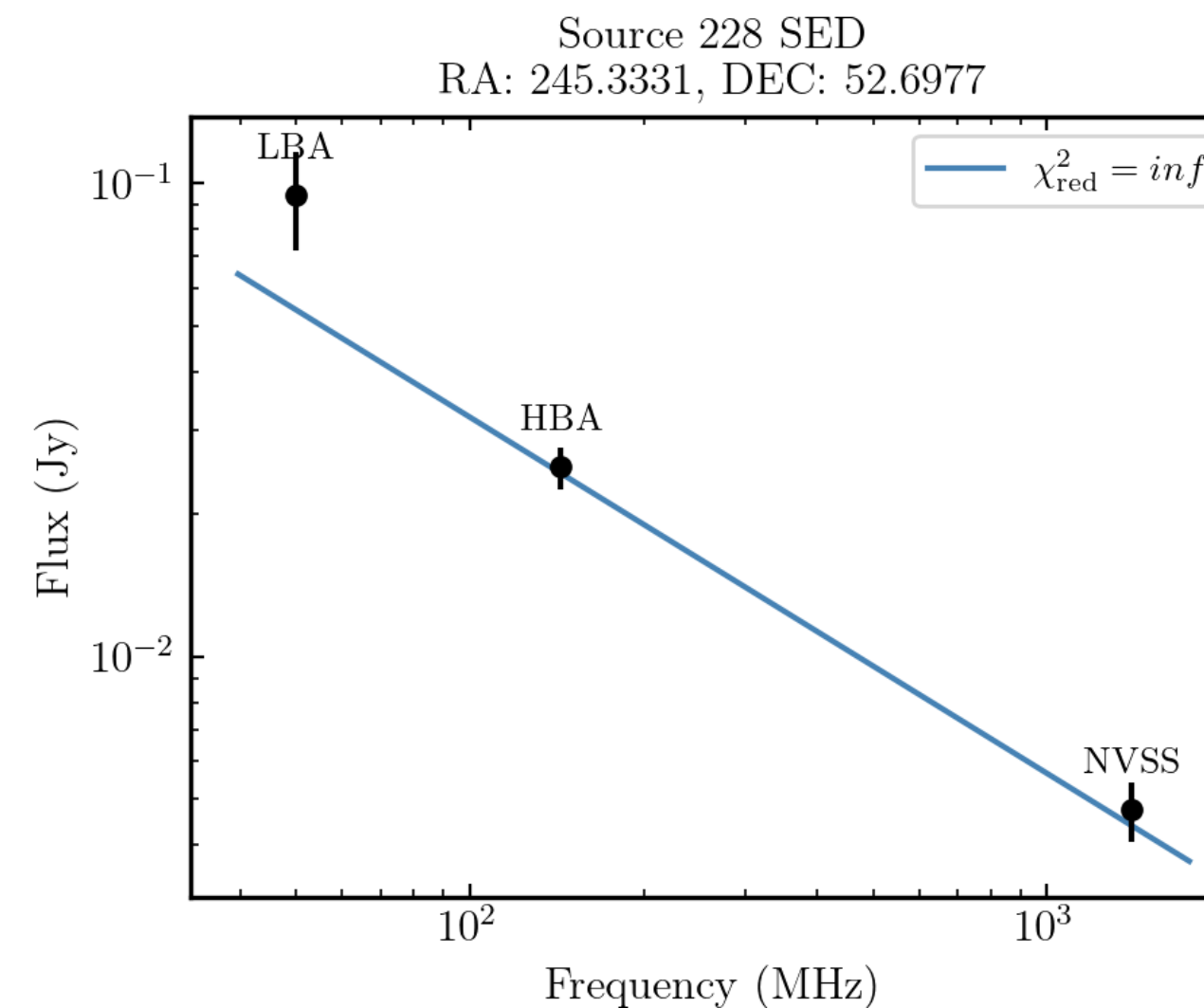
istent

correct?

LBA Flux scale

Match with higher frequency catalogues

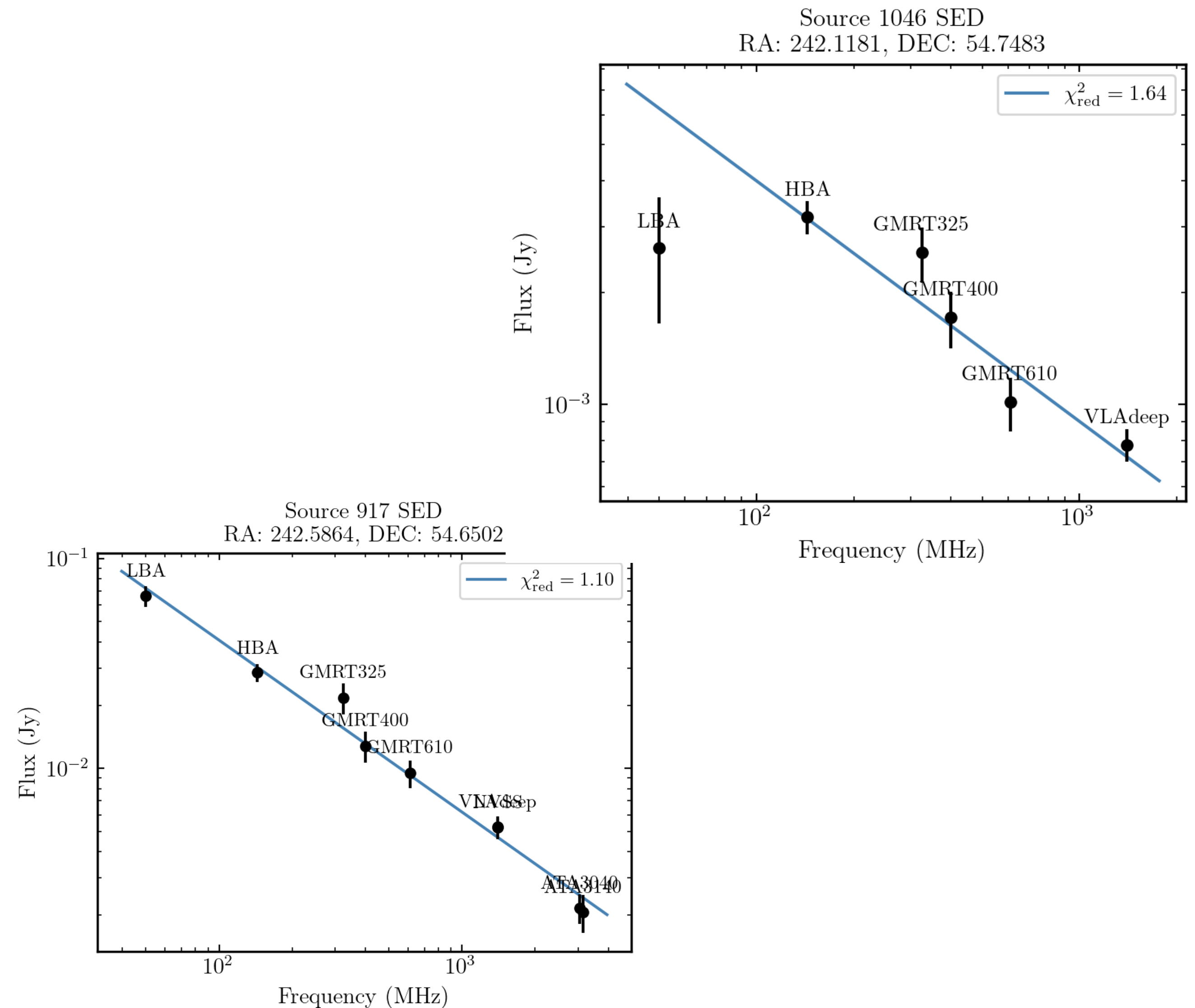
LOFAR HBA	144 MHz
VLSSr	74 MHz
6C	151 MHz
TGSS	150 MHz
GMRT	325, 400, 610 MHz
VLA deep	1.4 GHz
WENSS	325 MHz
FIRST/NVSS	1.4 GHz
ATA	3.04, 3.14 GHz



LBA Flux scale

Match with higher frequency catalogues

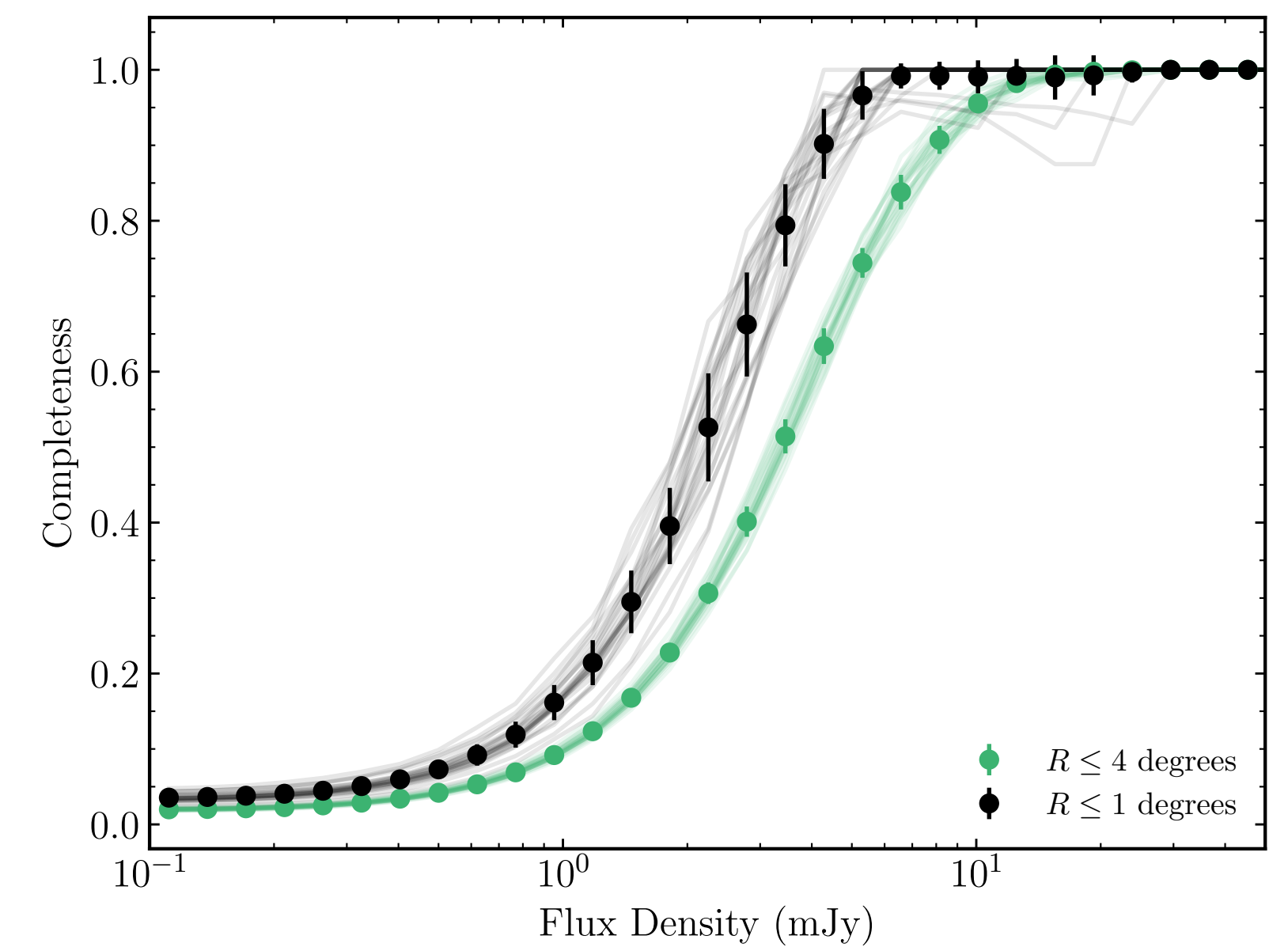
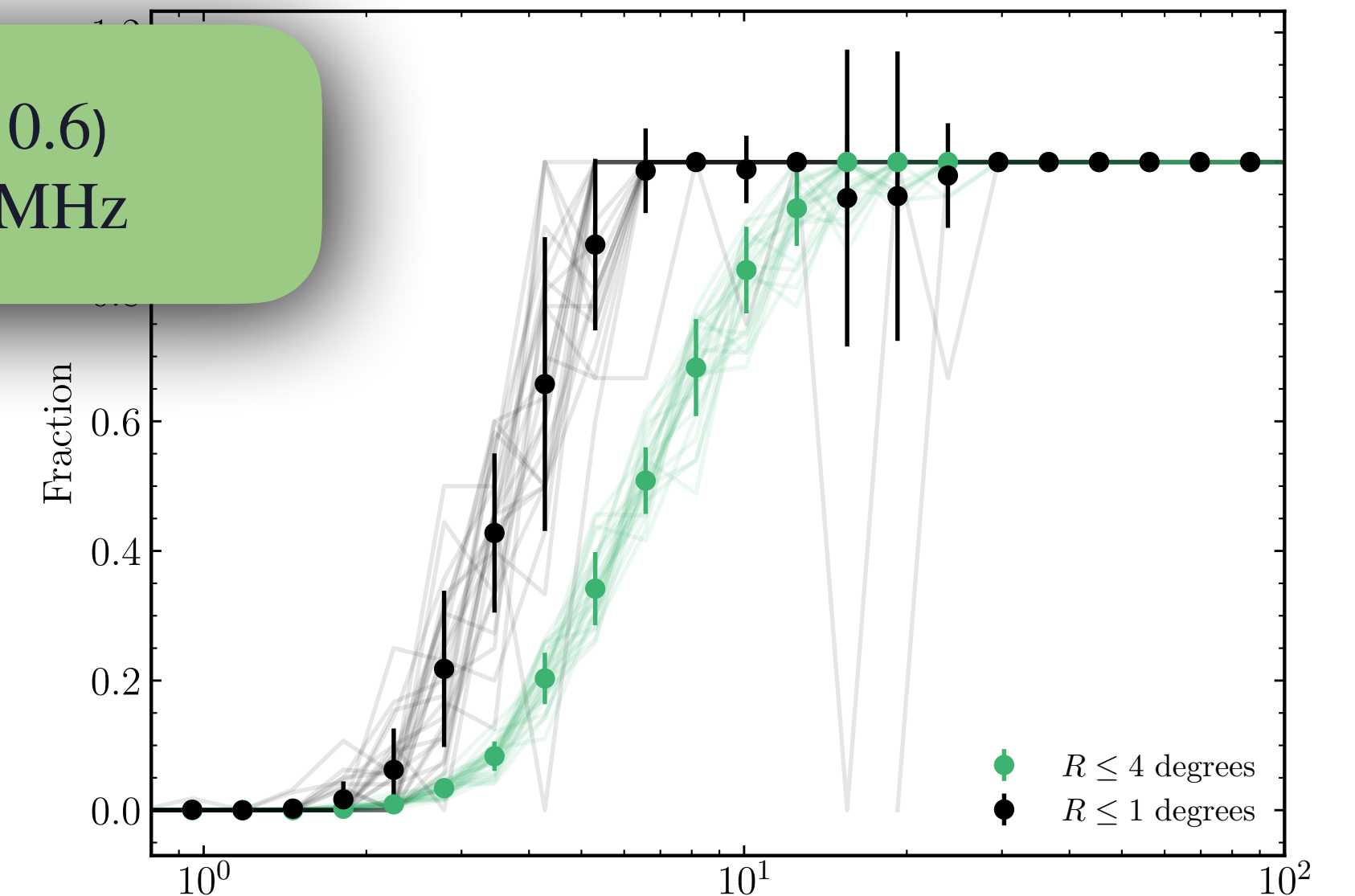
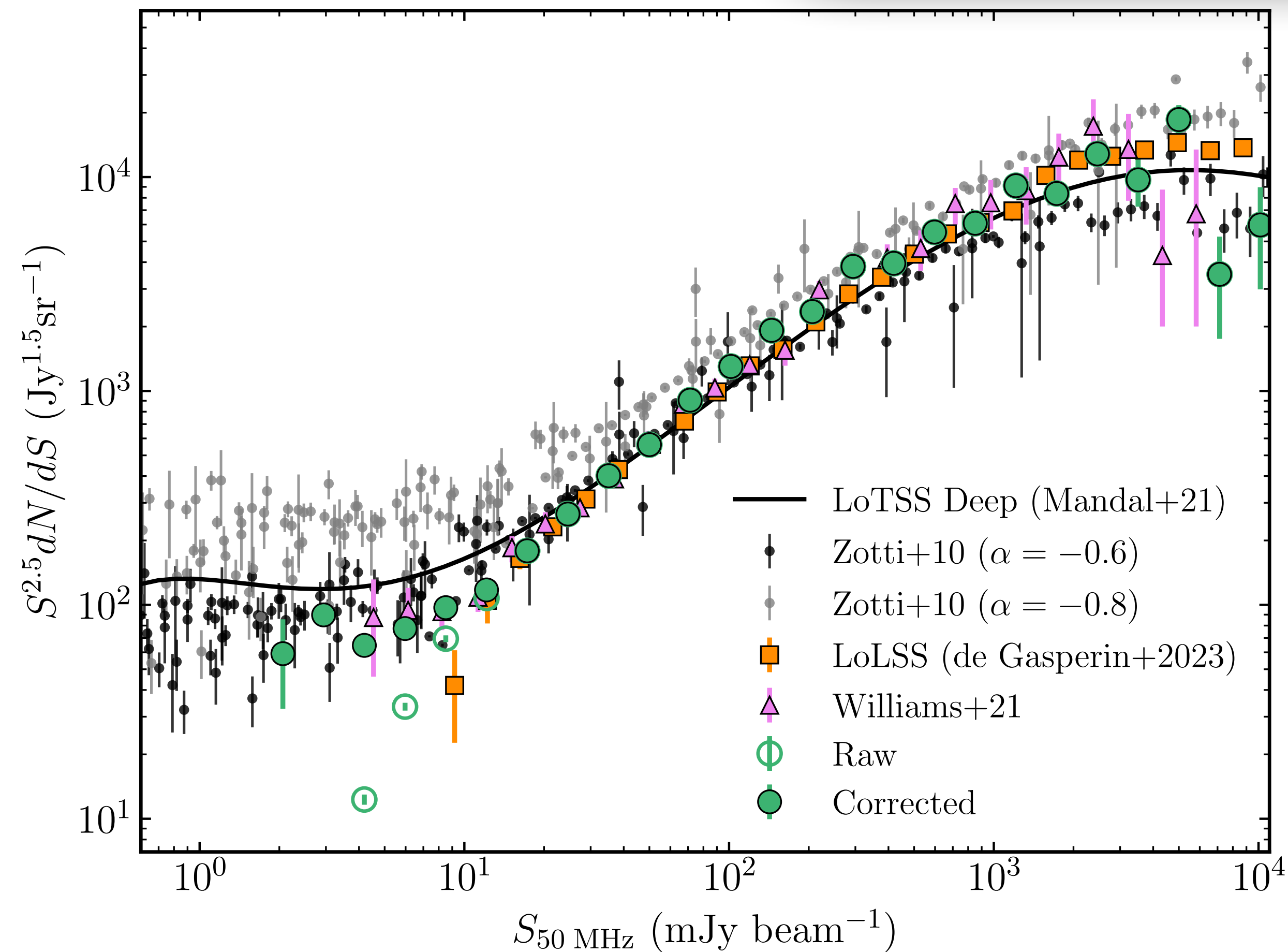
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FIRST/NVSS	1.4 GHz
ATA	3.04, 3.14 GHz



Results

Source counts

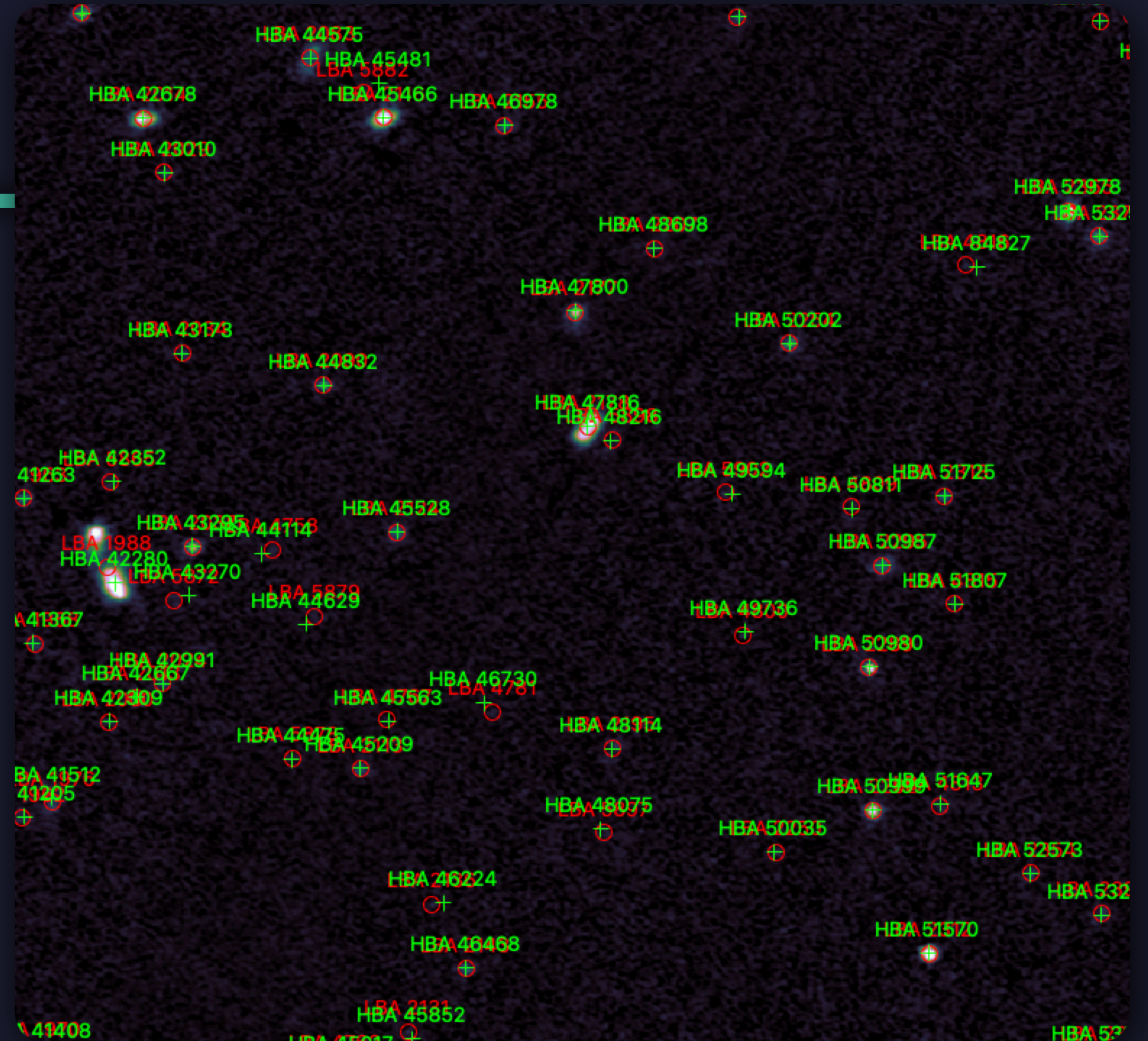
LoTSS deep-fields at 150 MHz ($\alpha = -0.6$)
Williams+21 and de Gasperin+23 at 54 MHz



Results

Source matching with HBA & Classification

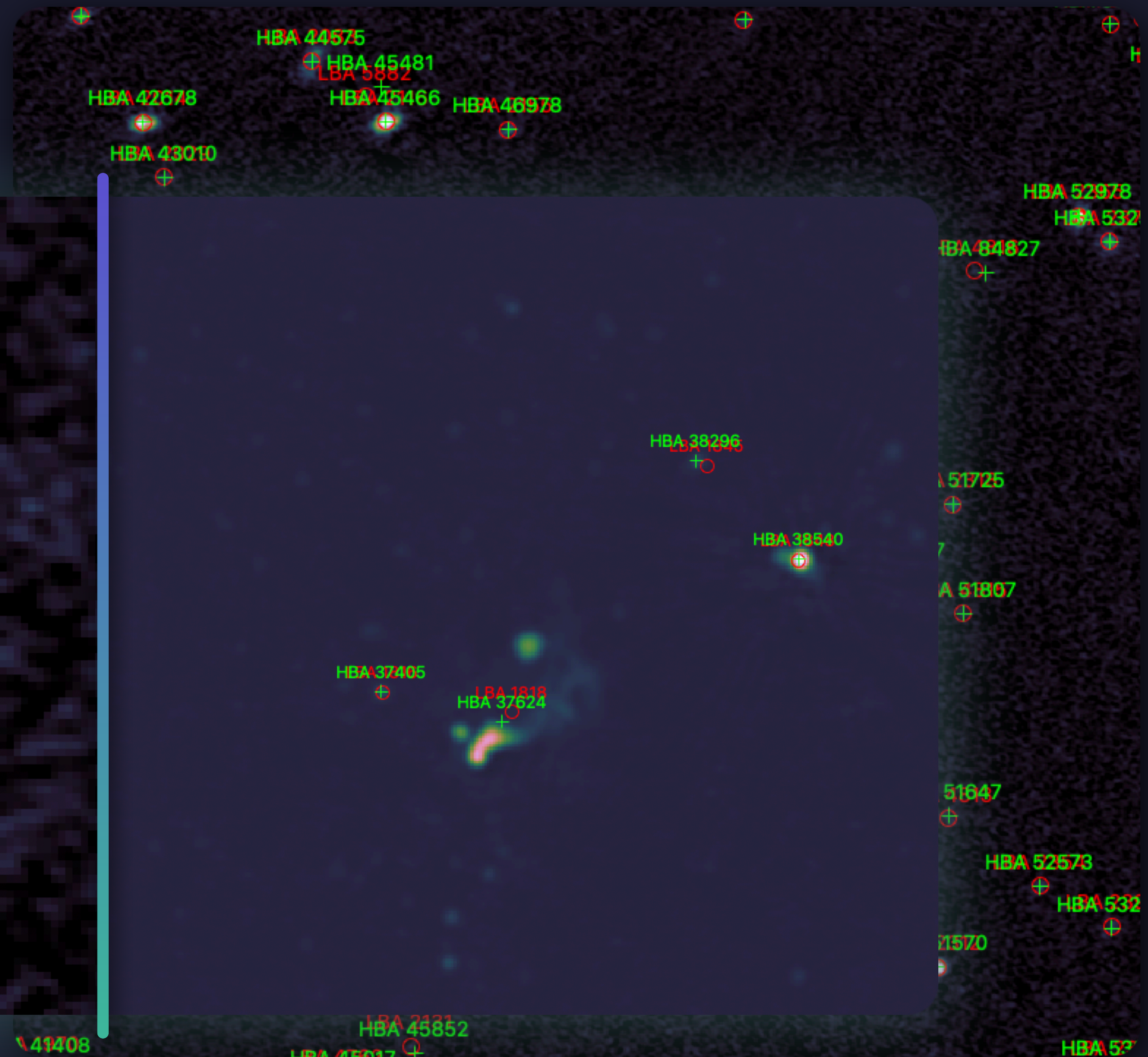
- Cross match LBA source catalog with HBA catalog from *Sabater et al. 2021*
- 2292 sources matched
- Leverage earlier work with HBA to obtain:
 - Source classification (*Best et al. 2023, Das et al. 2024, Arnaudova et al. 2025*)
 - Optical and IR cross match with phot. redshift. (*Kondapally et al. 2021, Duncan et al. 2020*)
 - Spectroscopic redshifts from DESI



Results

Source matching with HBA & Classification

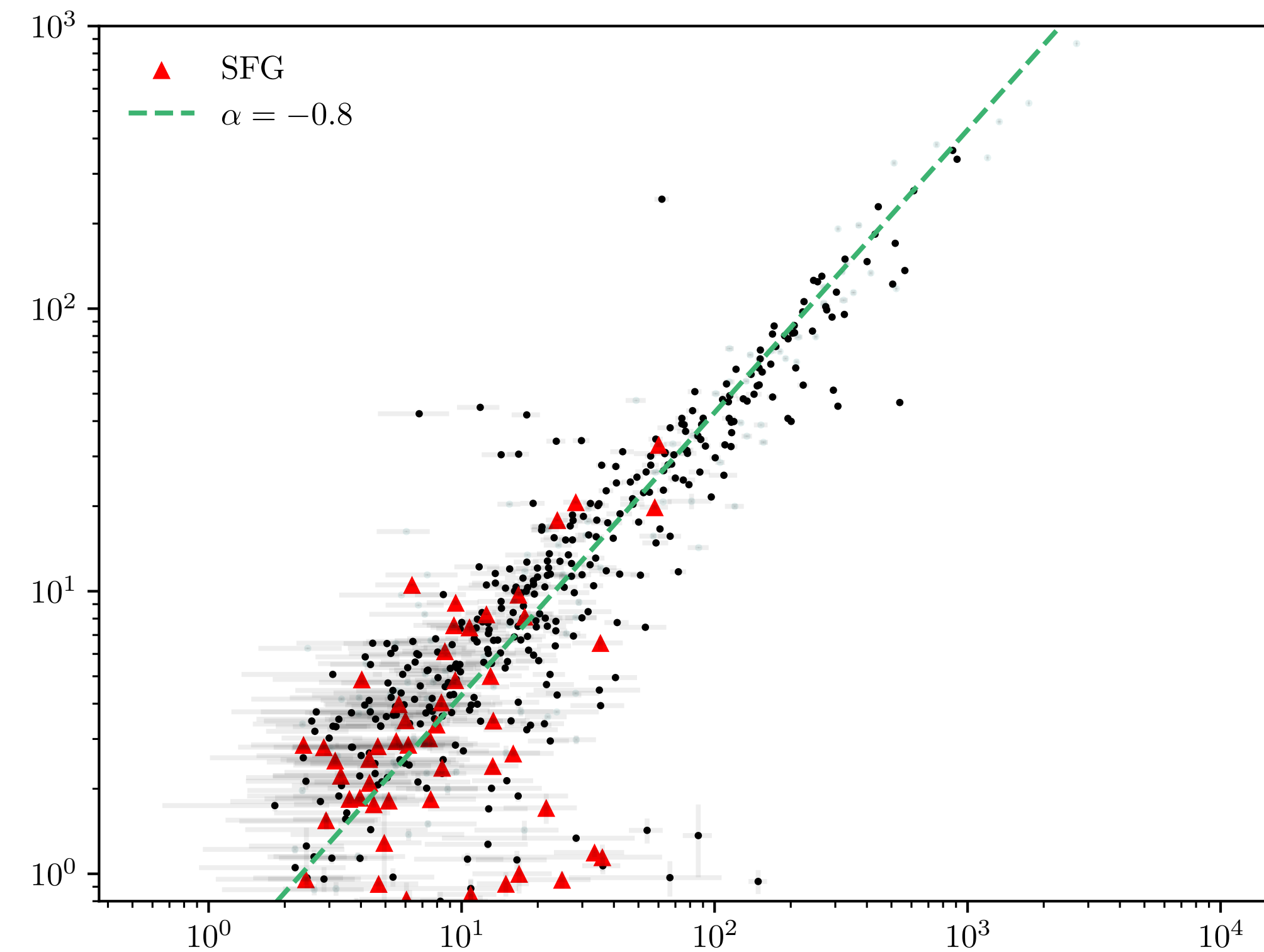
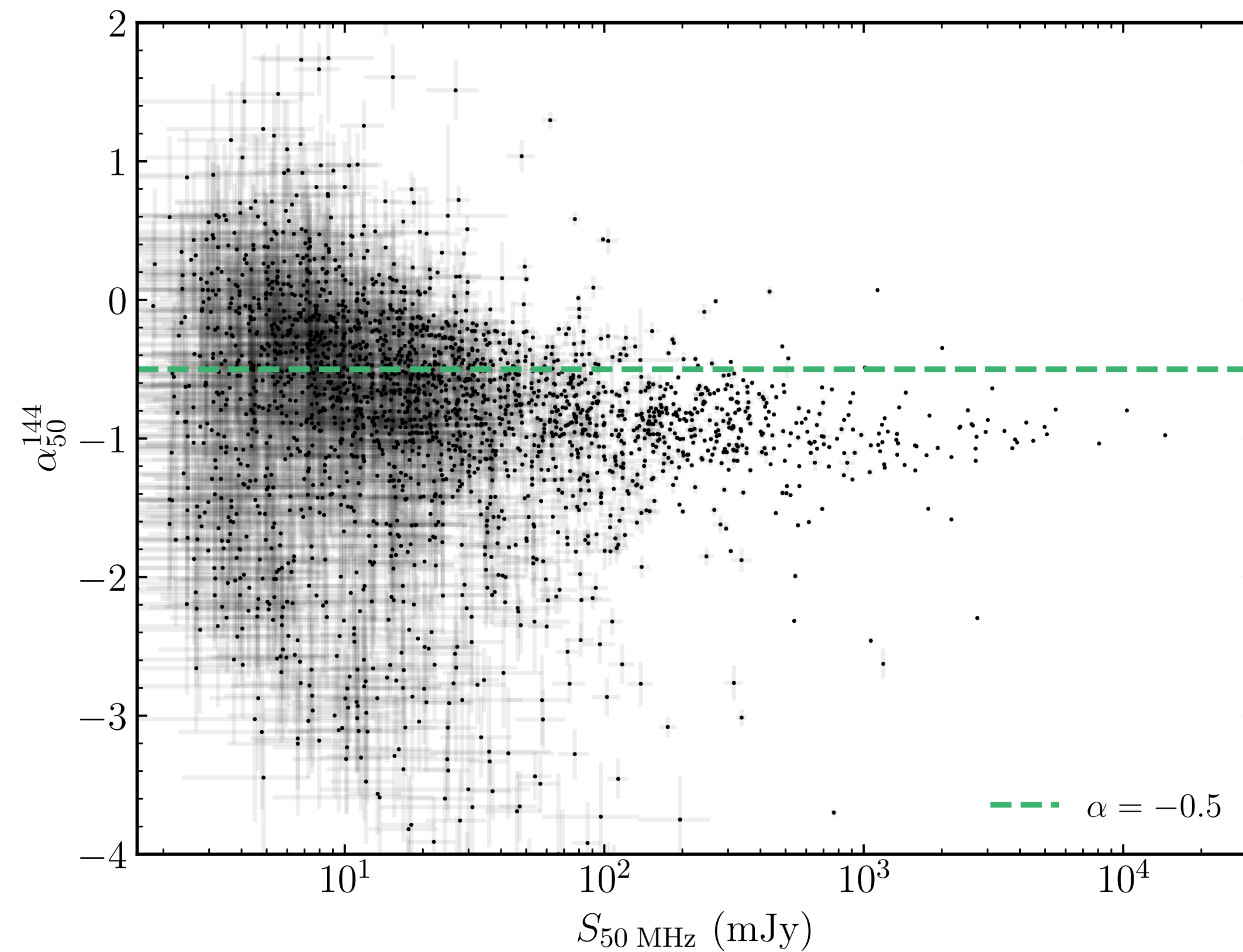
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Results

Source matching with HBA & Classification

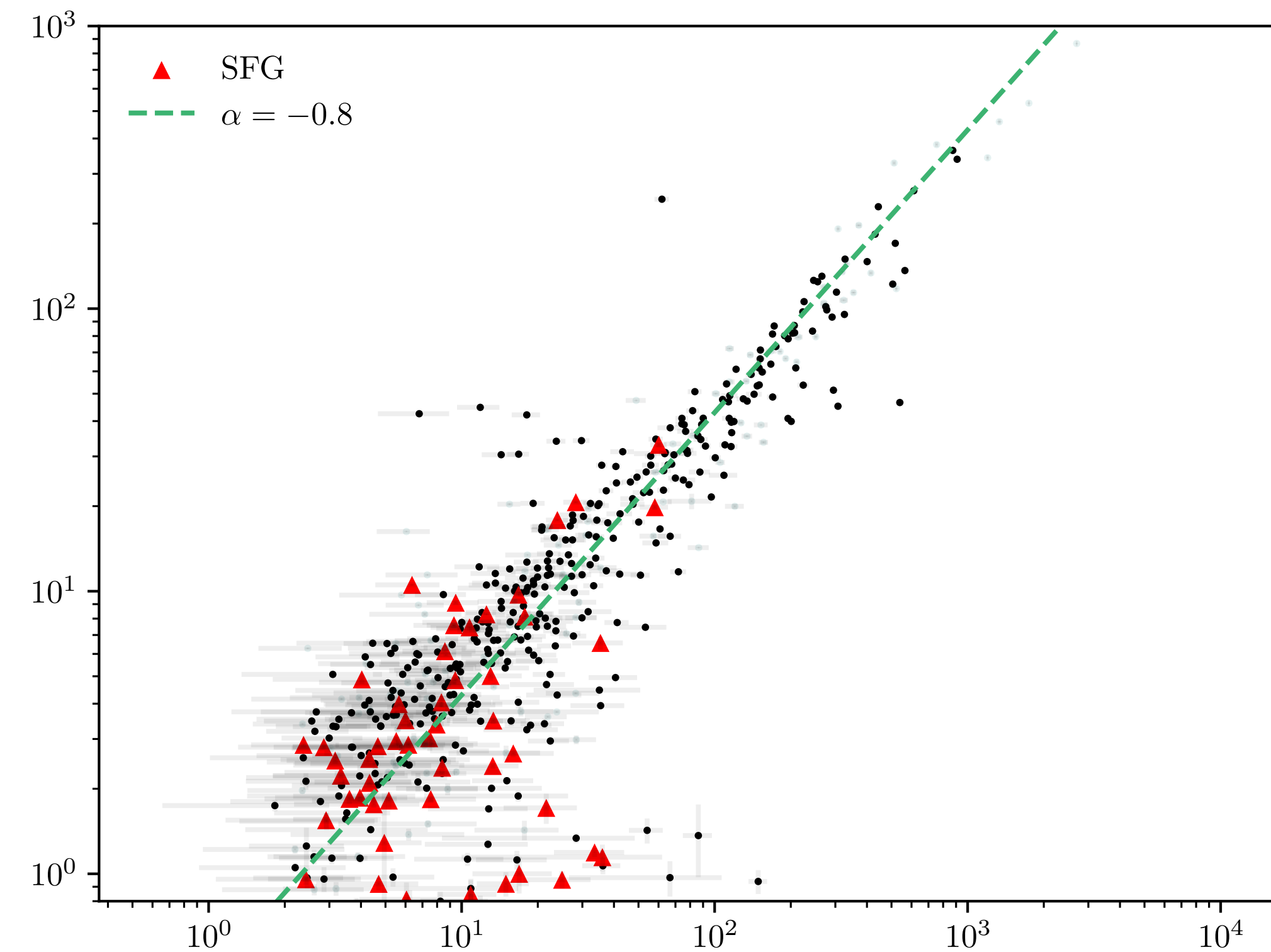
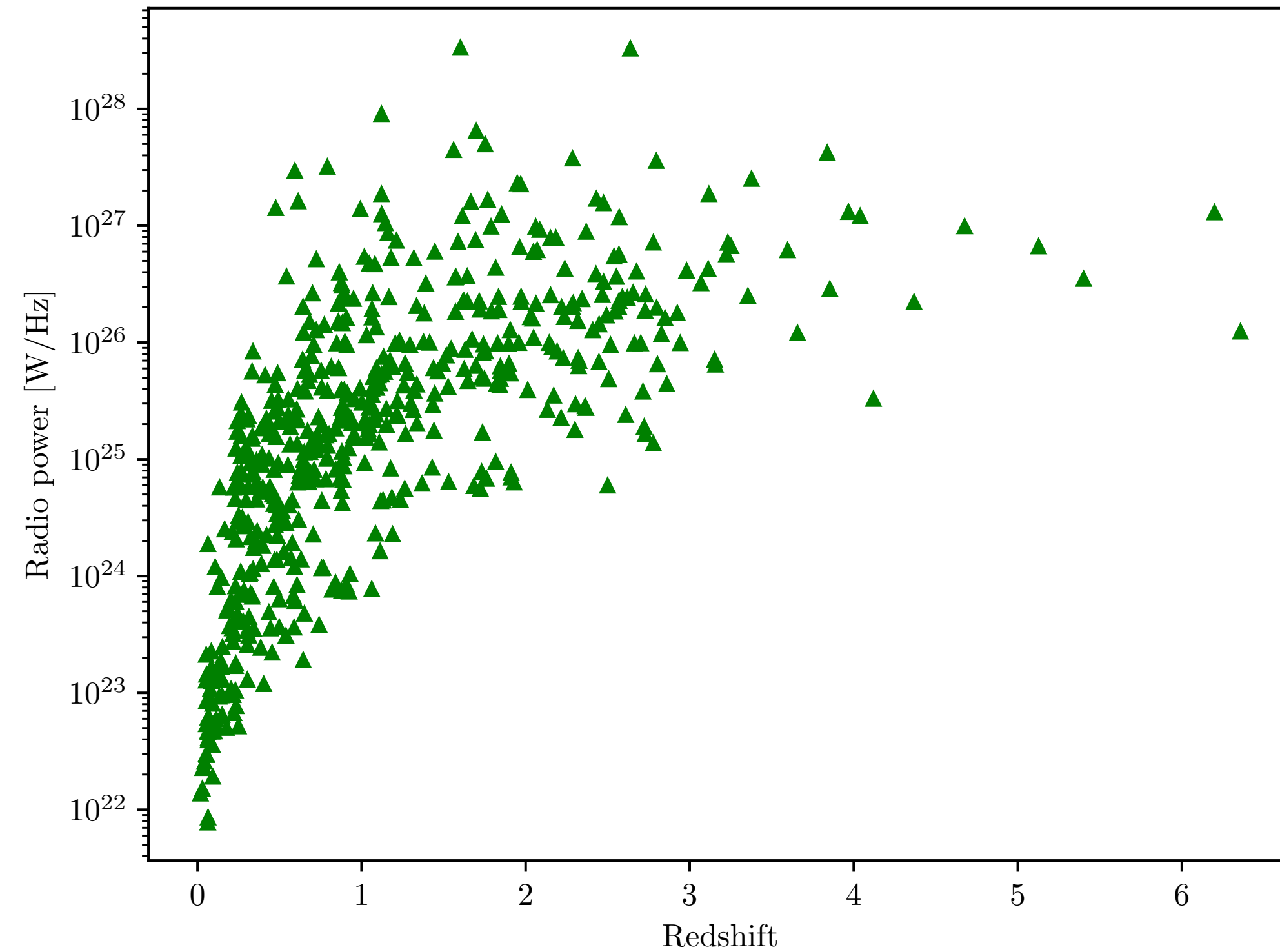
52 SFG and 376 AGN
Using classification from *Das et al. 2024*



Results

Source matching with HBA & Classification

52 SFG and 376 AGN
Using classification from *Das et al. 2024*



ELAIS-N1

Summary

- Deepest radio image < 100 MHz with RMS noise of 0.5 mJy
- More than 2200 radio sources matched to HBA ELAIS-1N catalogues
- 52 SFG

Next steps

- Produce final image (less artifacts around brightest sources & astrometry correction)
- Statistical study of low frequency spectra of SFG
- Complete the LBA Deep-field collection with Lockman Hole and Boötes (more hrs than Williams+21)

LOFAR 2.0

- With the LOFAR2.0 upgrade, the same depth can be reached with less observing time
- We will observe more SFG and high redshift galaxies at 50 MHz
- VLBI probably possible with calmer ionosphere

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VLBI

