

From LOFAR to LOFAR 2.0

Current and future radio surveys
at the lowest frequencies

Francesco de Gasperin

SKA meeting - Catania

28/11/2023



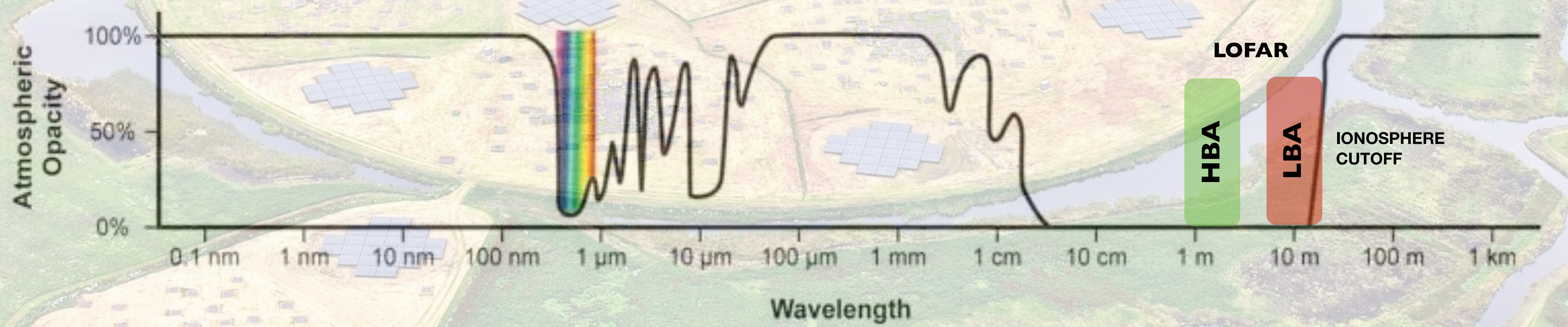
LOFAR HBA
Frequency: 120-240 MHz
Resolution: 5" (0.3")
Sensitivity: ~100 uJy/b
FWHM: 4 deg

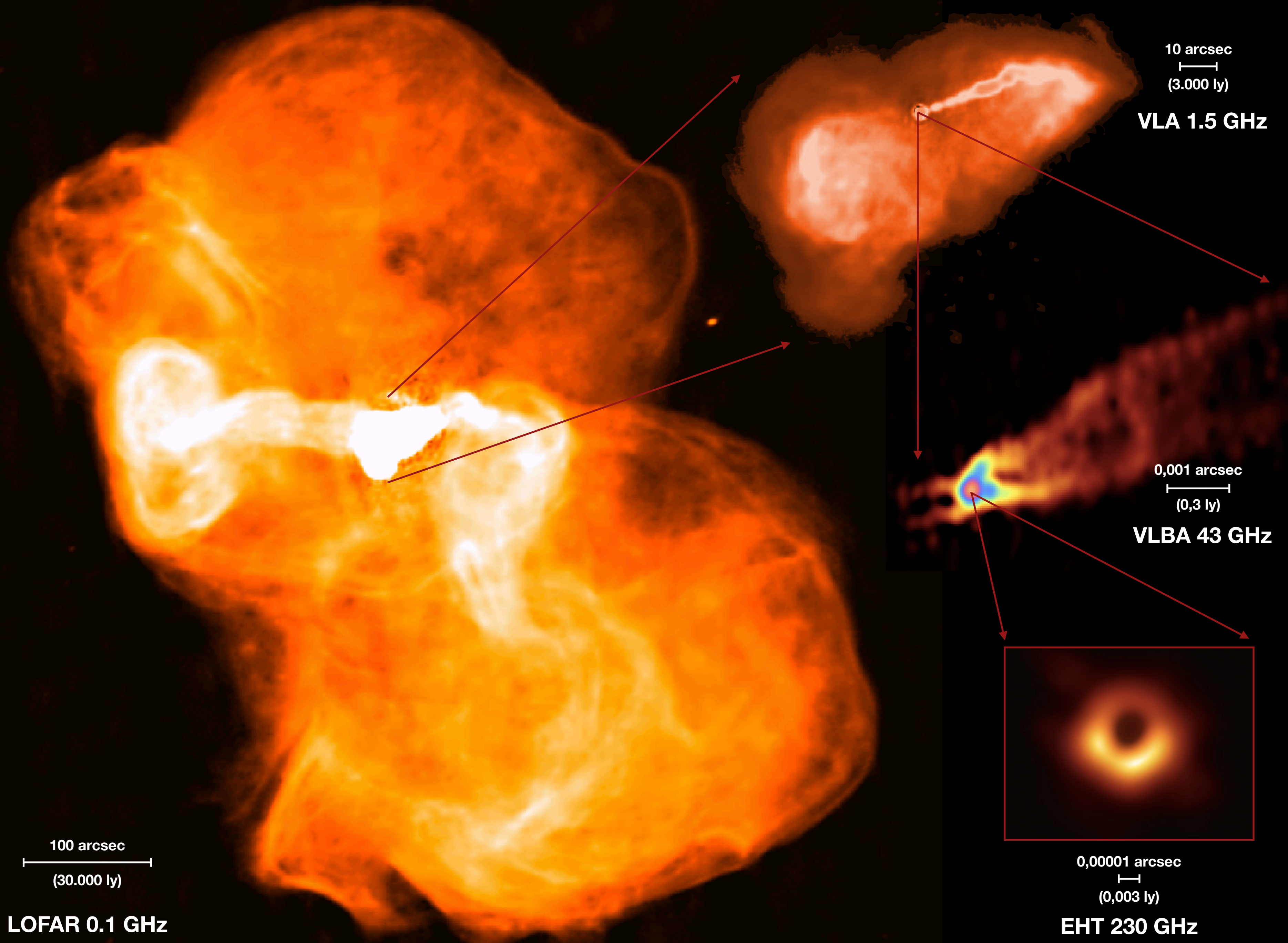
LOFAR LBA
Frequency: 10-90 MHz
Resolution: 15" (1")
Sensitivity: ~1 mJy/b
FWHM: 6 deg
Multi-beam



HBA

LBA

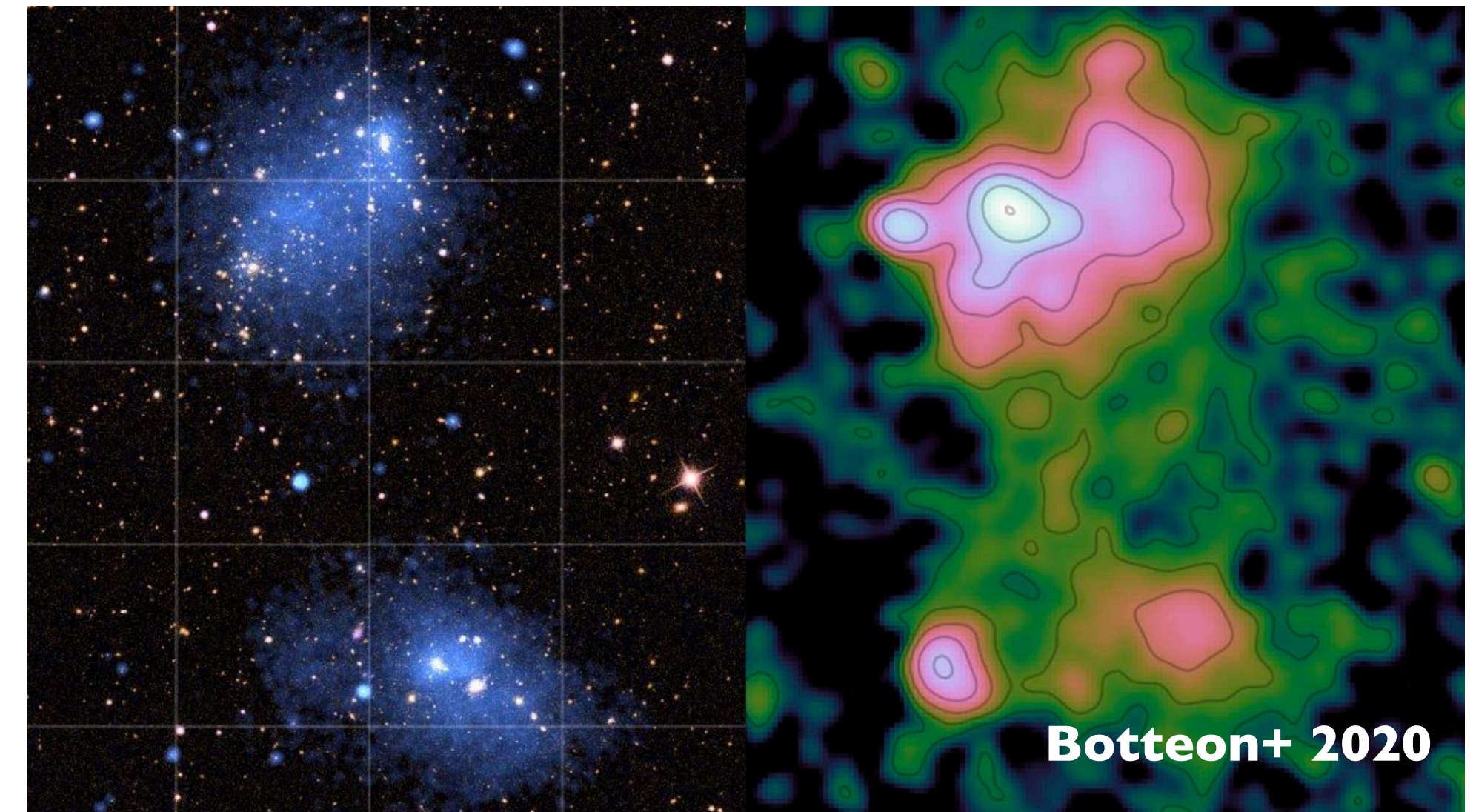
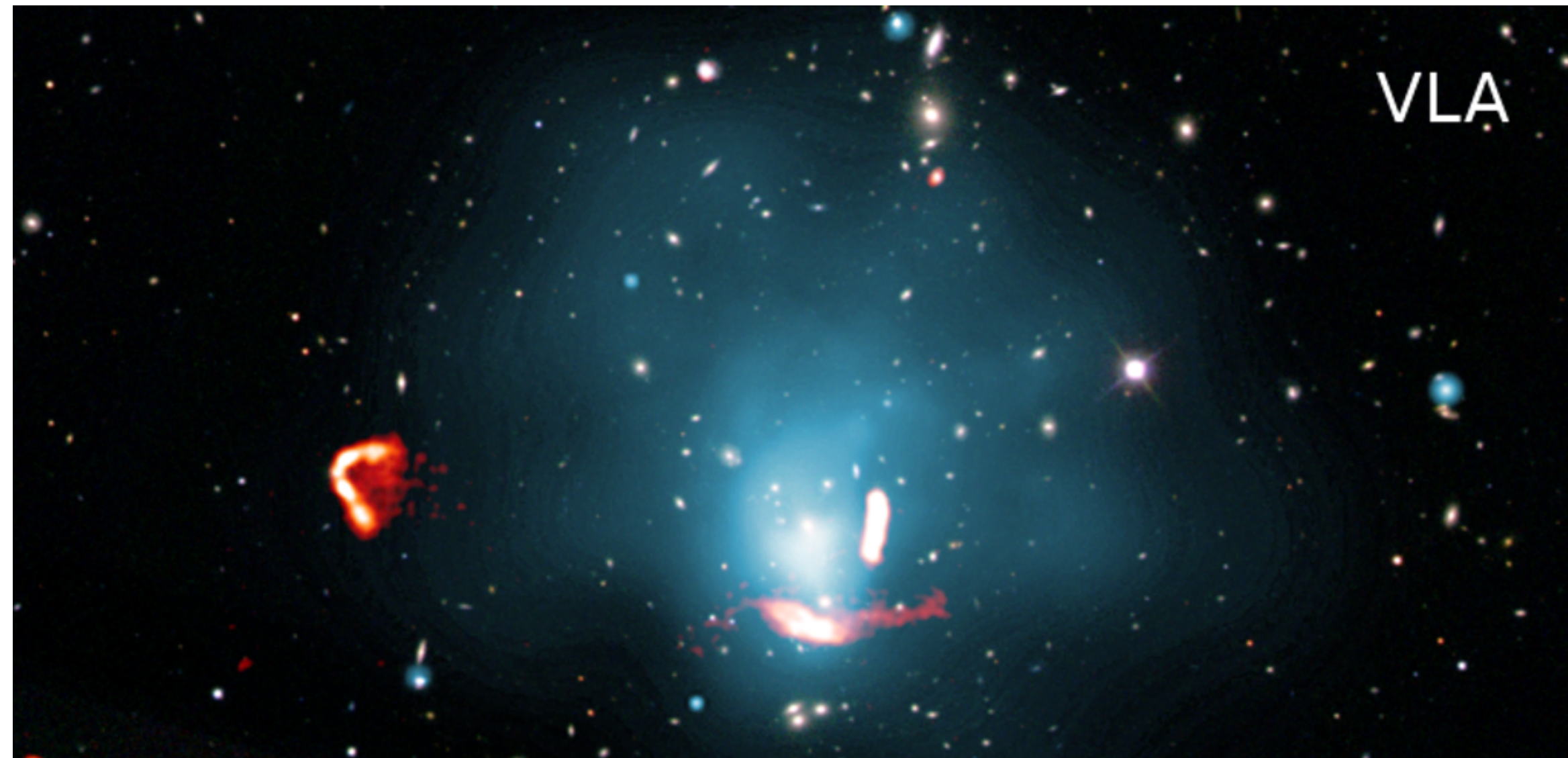




Low efficiency phenomena

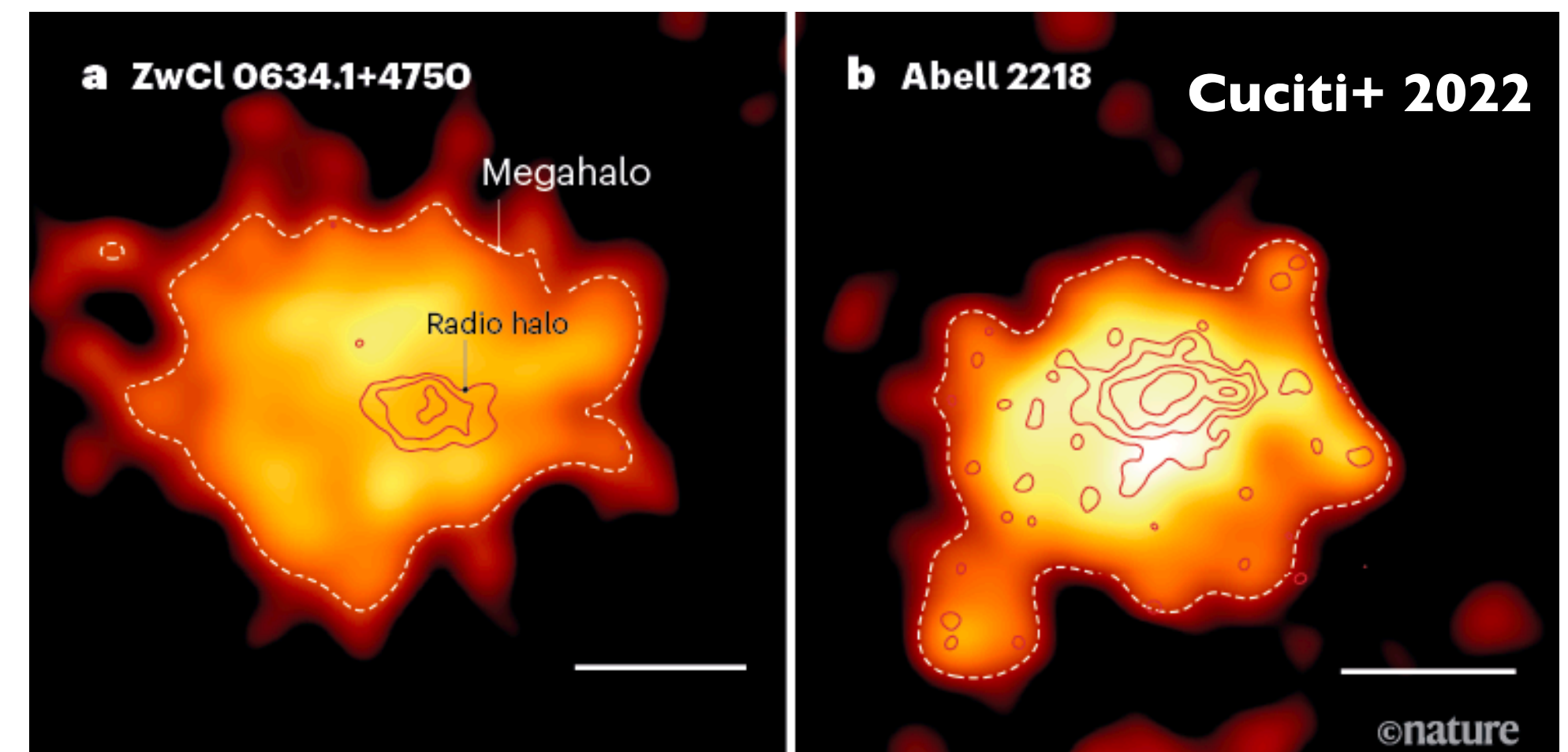
4

GReETs



Radio Bridges

Radio Megahalos



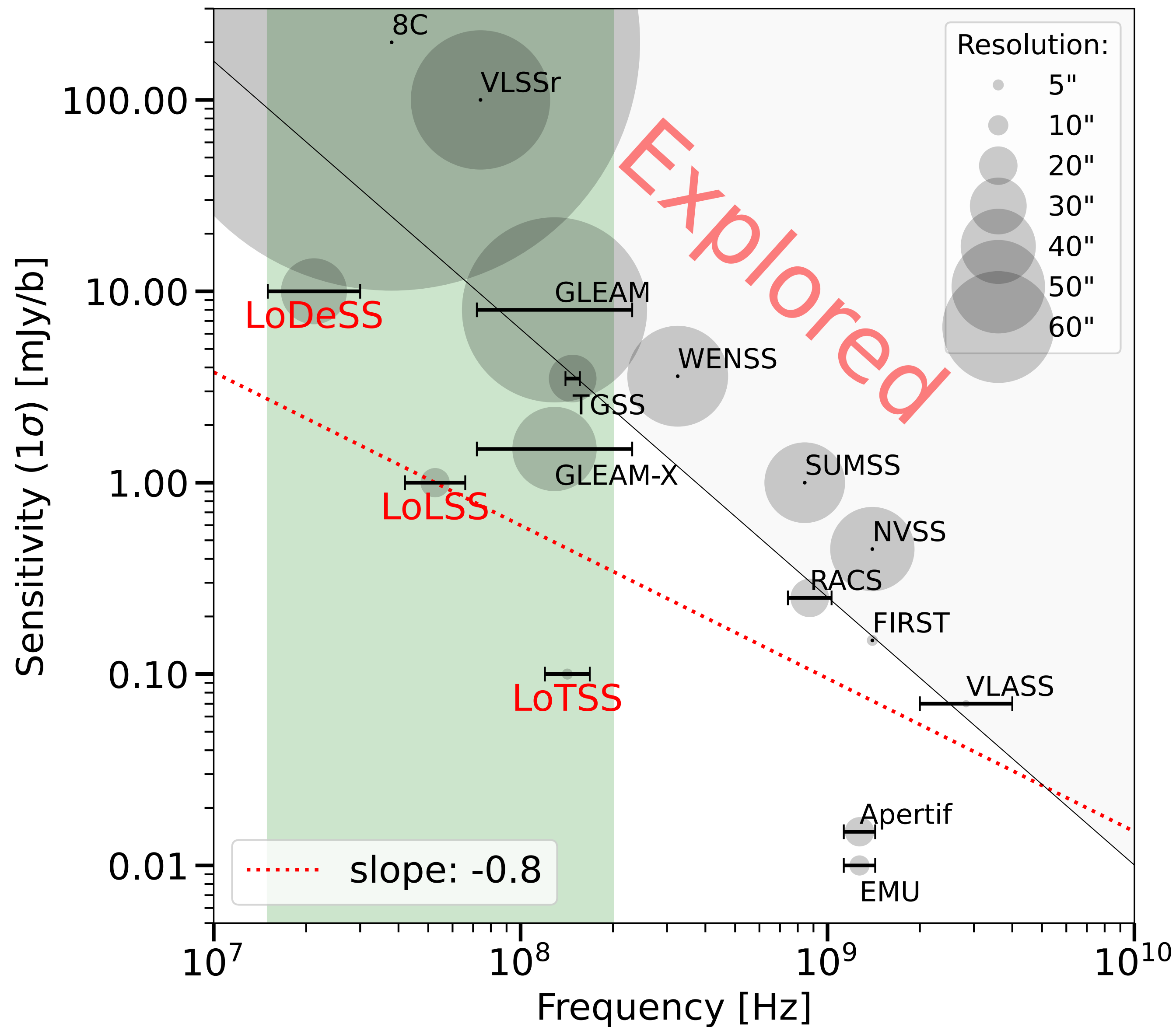
- **LOFAR Surveys**

- LOFAR upgrades

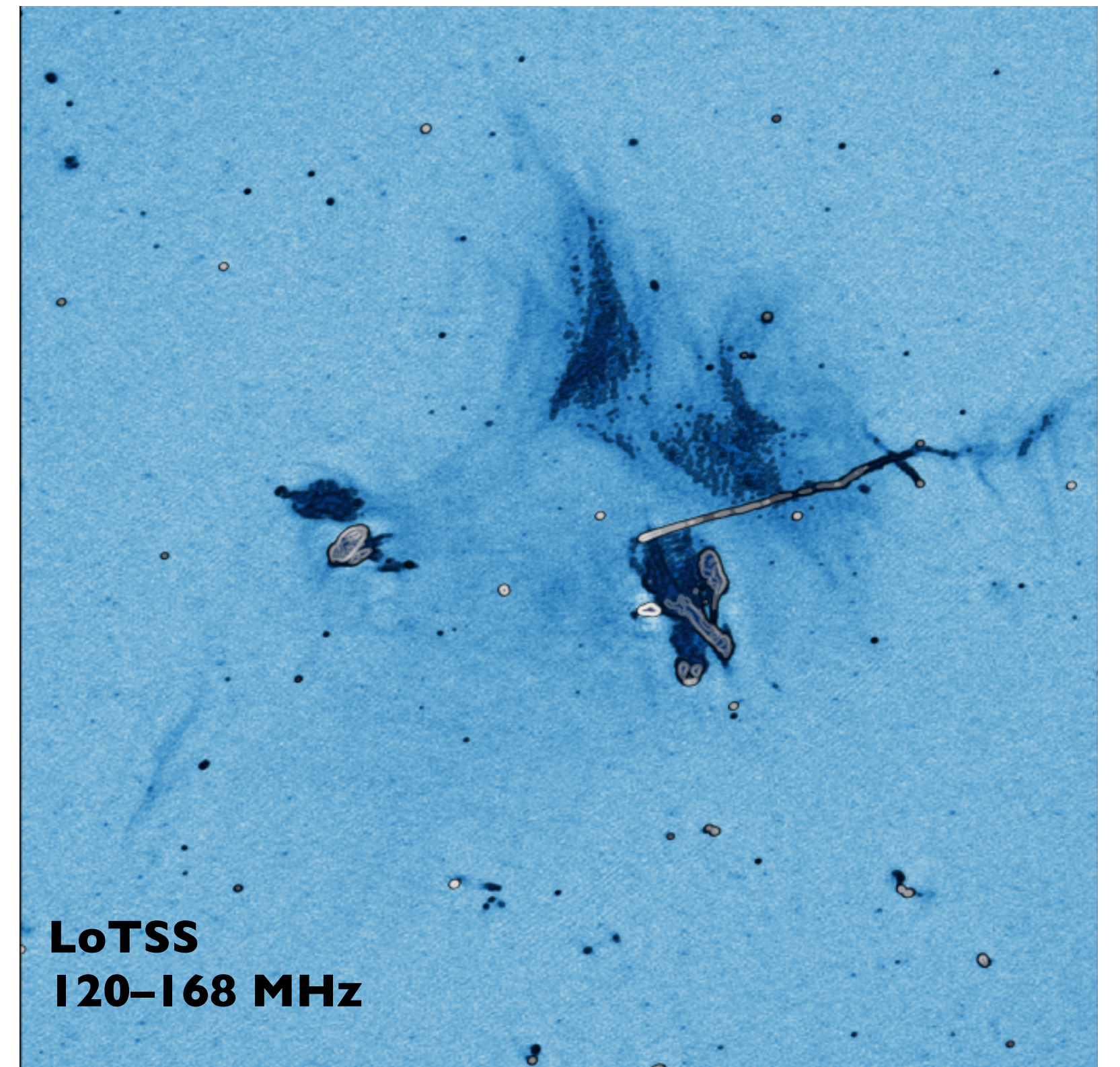
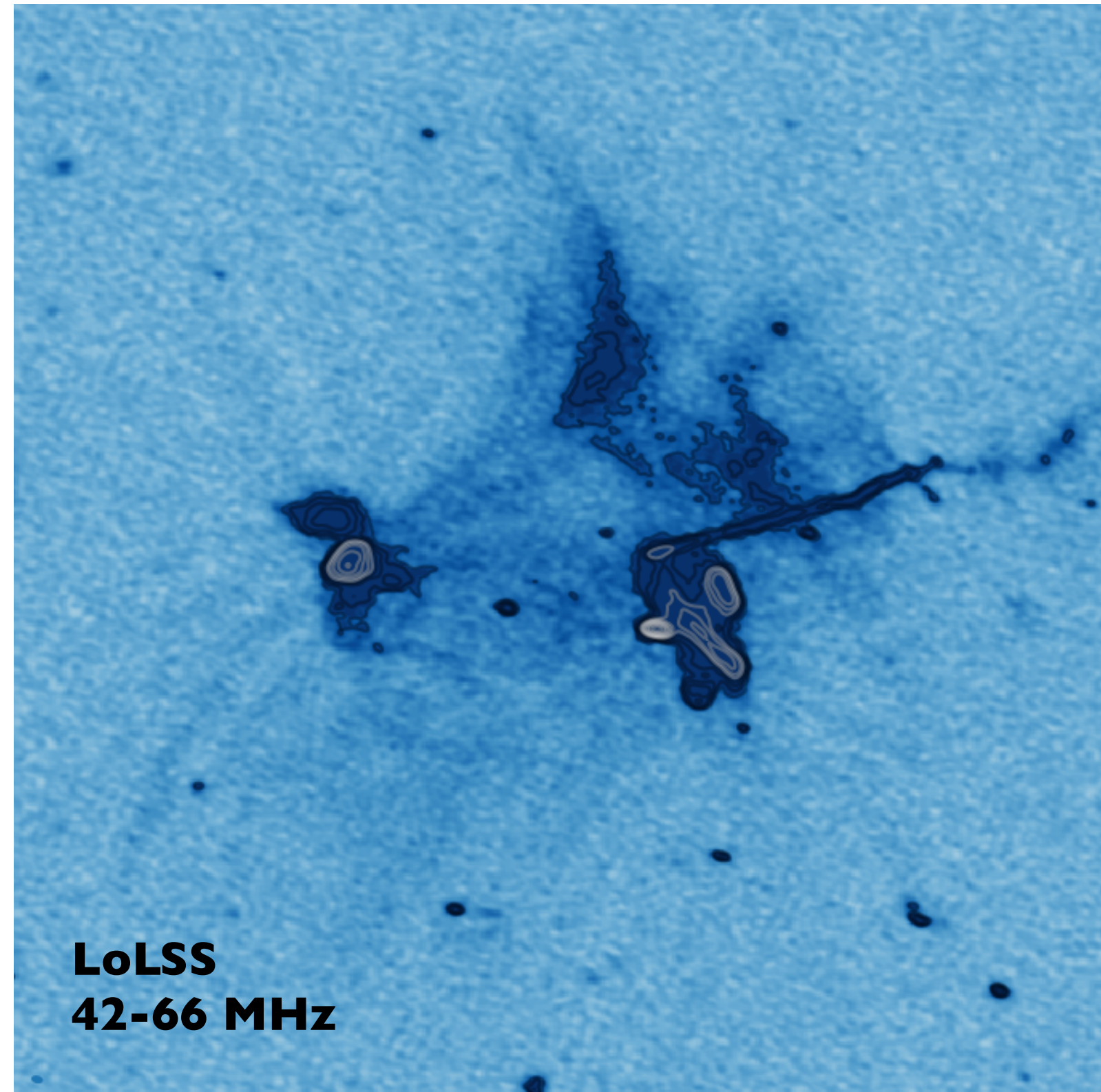
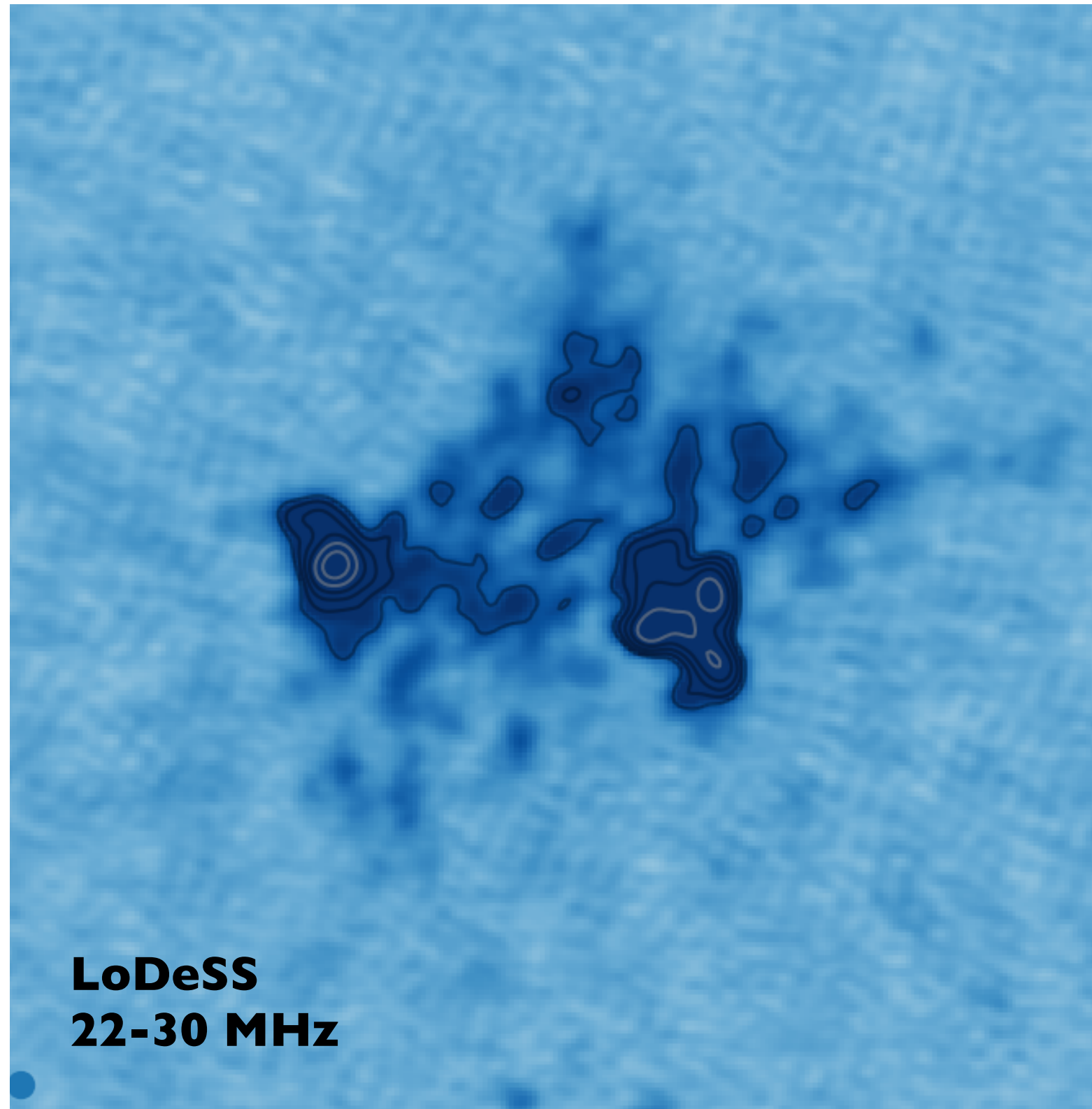
- LOFAR 2.0

- LOFAR Next Generation Surveys

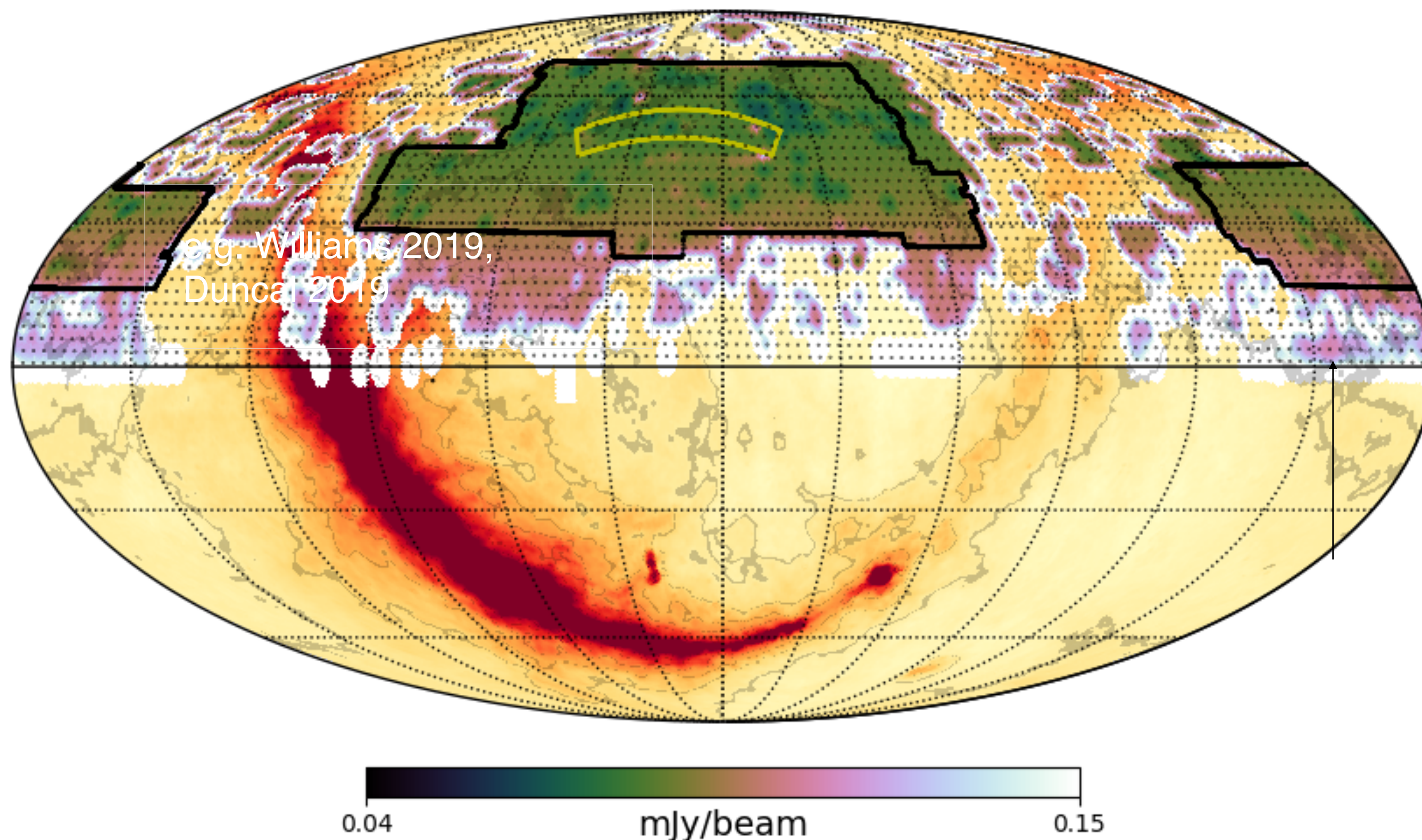
- LOFAR+MeeRKAT - ViCTORIA project



- **LOFAR Two Metre Sky Survey (LoTSS) 120 - 168 MHz**
- **LOFAR LBA Sky Survey (LoLSS) 42 - 66 MHz**
- **LOFAR Decametre Sky Survey (LoDeSS) 14 - 30 MHz**

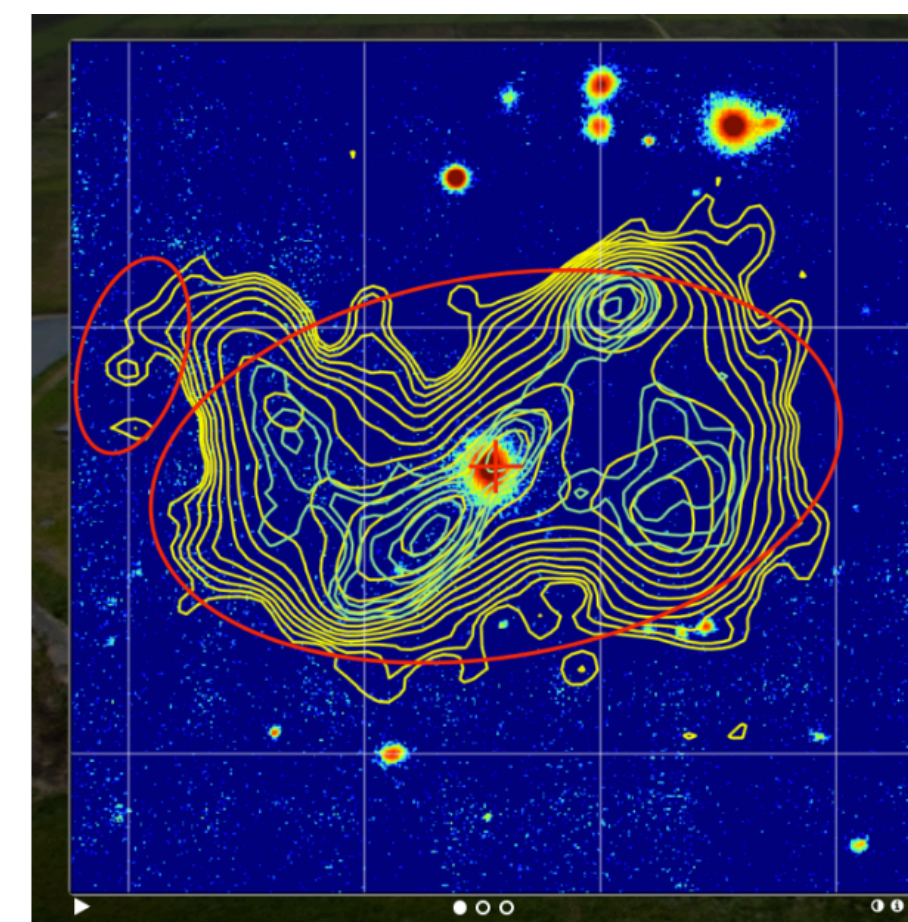


Abell 2256
Osinga+



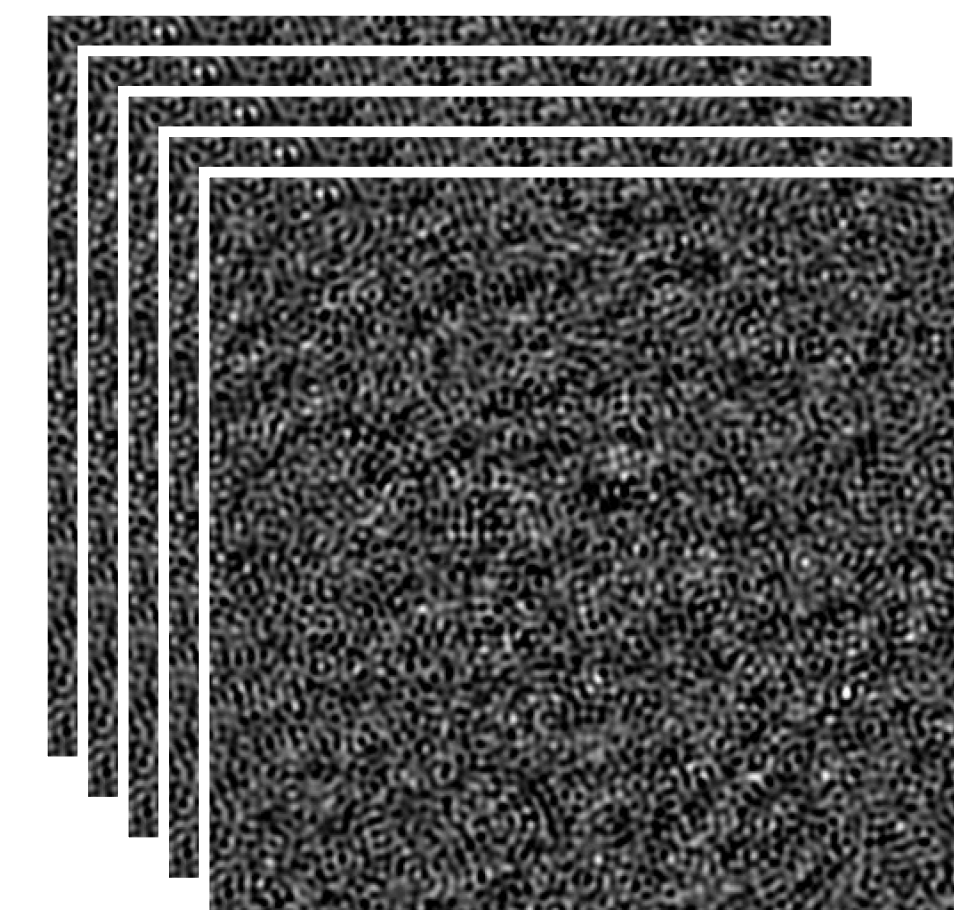
LoTSS-DR1 (outlined in yellow) and LoTSS-DR2 (outlined in black) are fully public
It consists of 7.6 PB of data processed using ~9 million cpu hours
LoTSS-DR2 is **26%** of the Northern sky at sensitivity of **80 μ Jy/b** and resolution of **6''**
The source catalogue contains 4,395,448 radio components

www.LOFAR-surveys.org

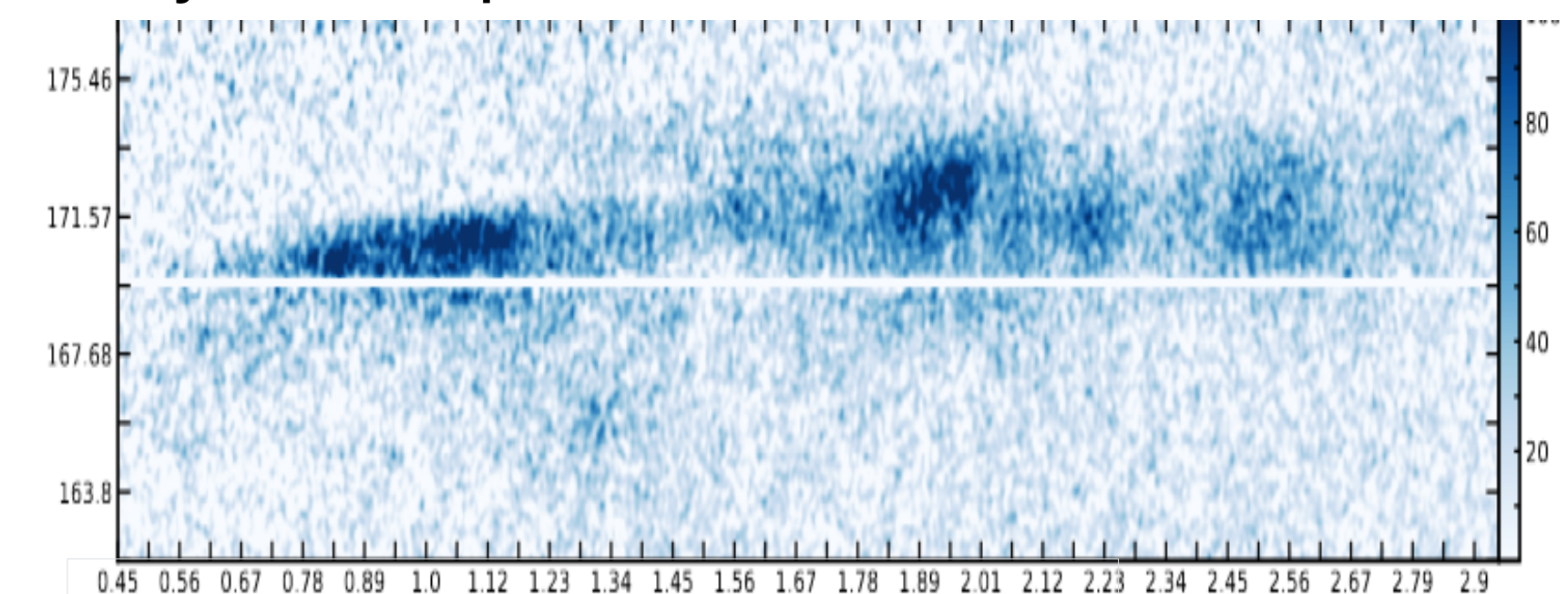


Cross matching
<http://lofargalaxyzoo.nl/>

Polarisation cubes



Dynamic spectra

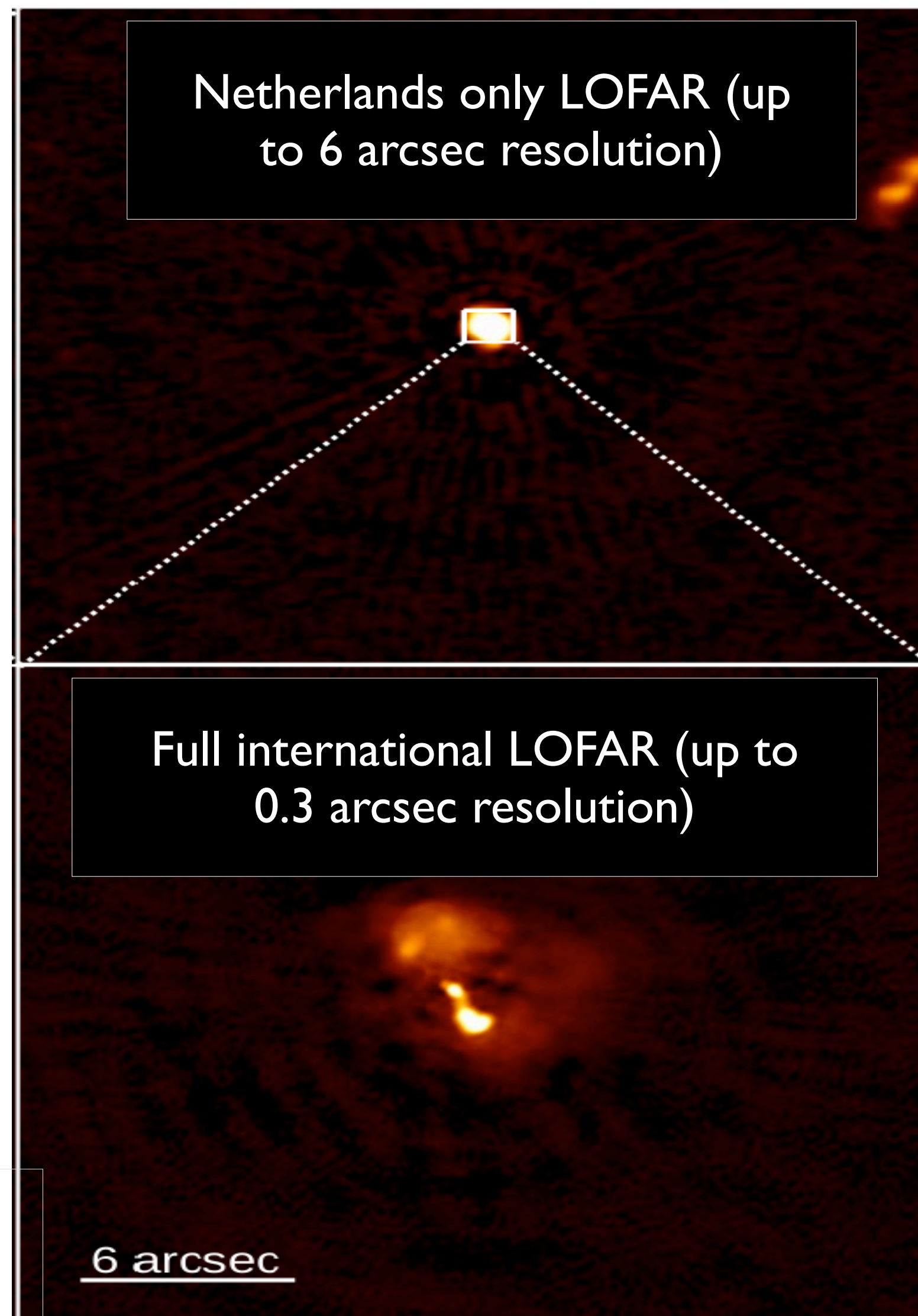


Example from Callingham+ 2021

LOFAR Two Metre Sky Survey

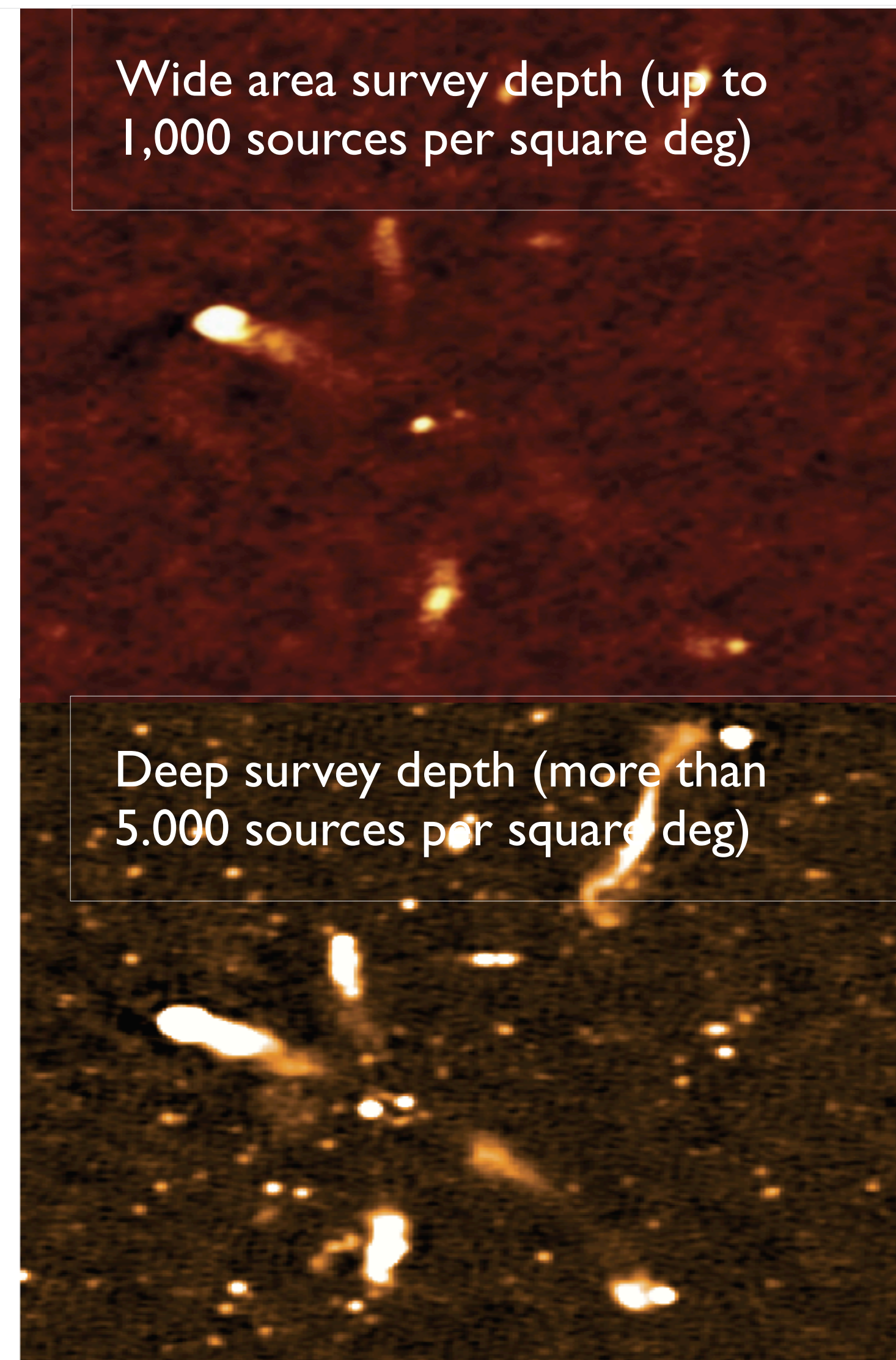
9

Images at up to 0.3 arcsec resolution

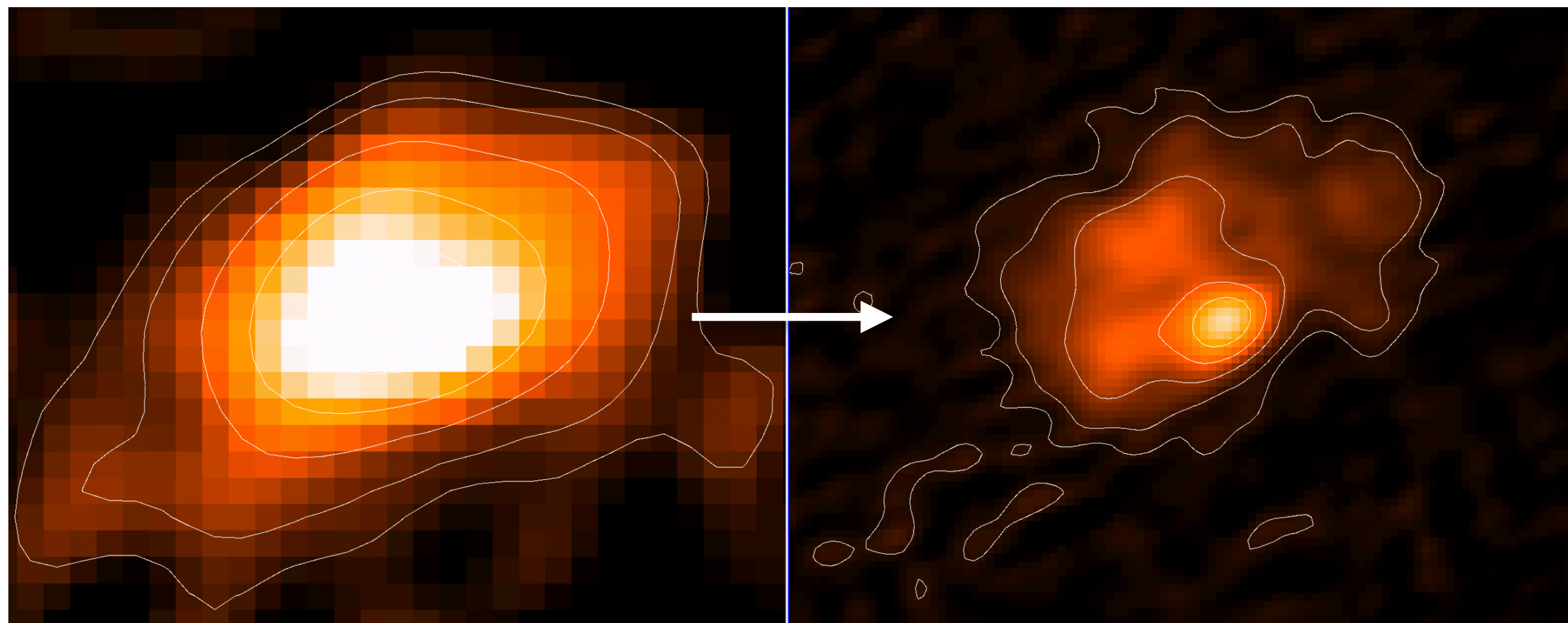


Morabito, et al. 2021
Sweijen et al. 2022

Images as sensitivity as $\sim 12 \mu\text{Jy/b}$



Sabater et al. 2021

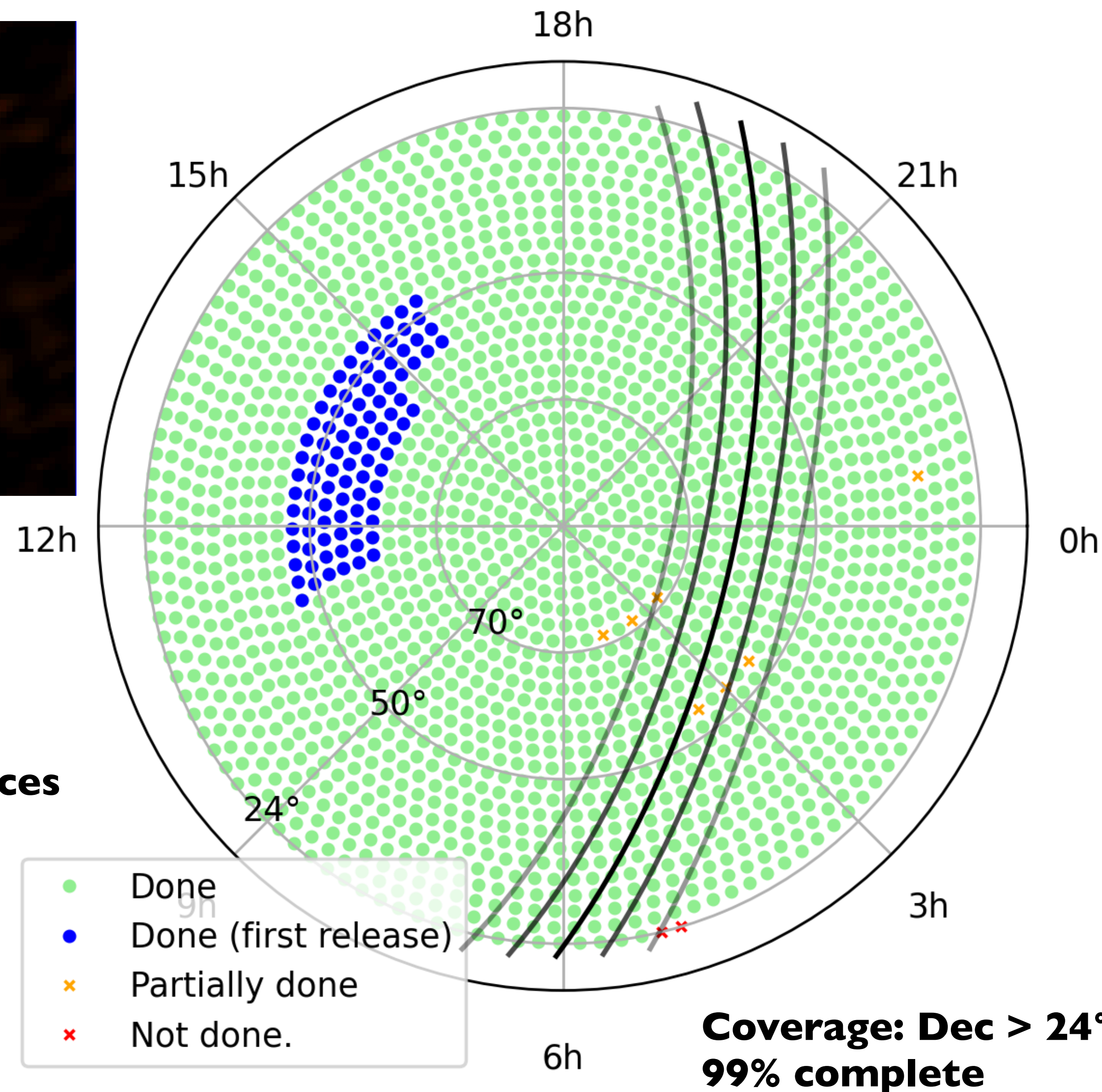


2021:
LoLSS Pr. release
• res.: 45''
• sens.: 5 mJy/b

2023:
LoLSS I release
• res.: 15''
• sens.: 1 mJy/b

Catalogue of 42,463 sources

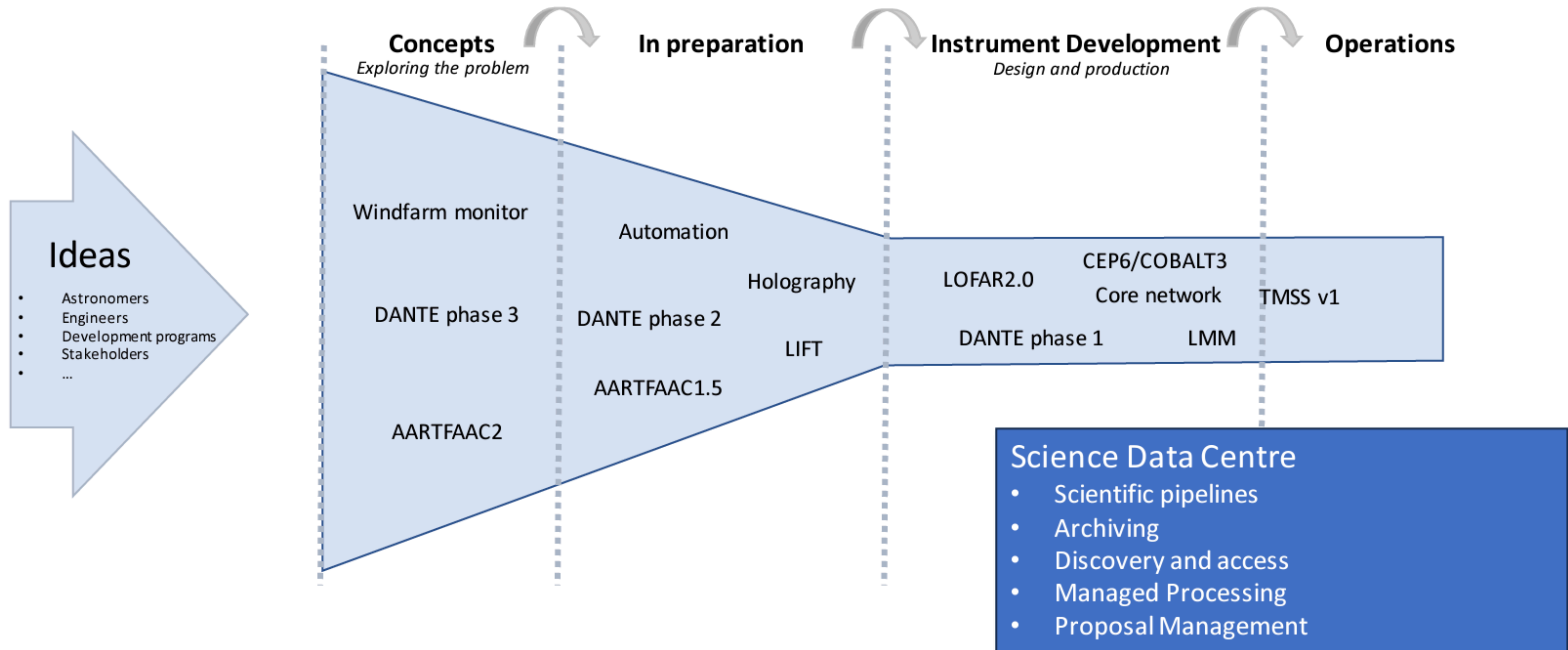
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- LOFAR Surveys
- **LOFAR upgrades**
 - **LOFAR 2.0**
 - **LOFAR Next Generation Surveys**
- LOFAR+MeeRKAT - ViCTORIA project

LOFAR Development overview

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- Almost every bit of LOFAR will be upgraded in the next 2-3 years
- LOFAR2.0 upgrade period: June 2024 – End of 2025.

- Leverage existing investments
 - hardware (stations, networks, data centres)
 - algorithms, software, pipelines
- Remain unique and scientifically impactful (in SKA era):
 - lowest frequencies
 - highest resolution
- Financially, technically feasible on a 3-10 year timescale

LOFAR 2.0 Vs SKA-low (ph. I)

LOFAR 2.0:

- Reaches 2x lower frequencies
- 10x higher resolution
- not confusion limited

SKA-low (ph. I)

- Reaches 2x higher frequencies
- 10x greater collecting area



LOFAR



SKA Low

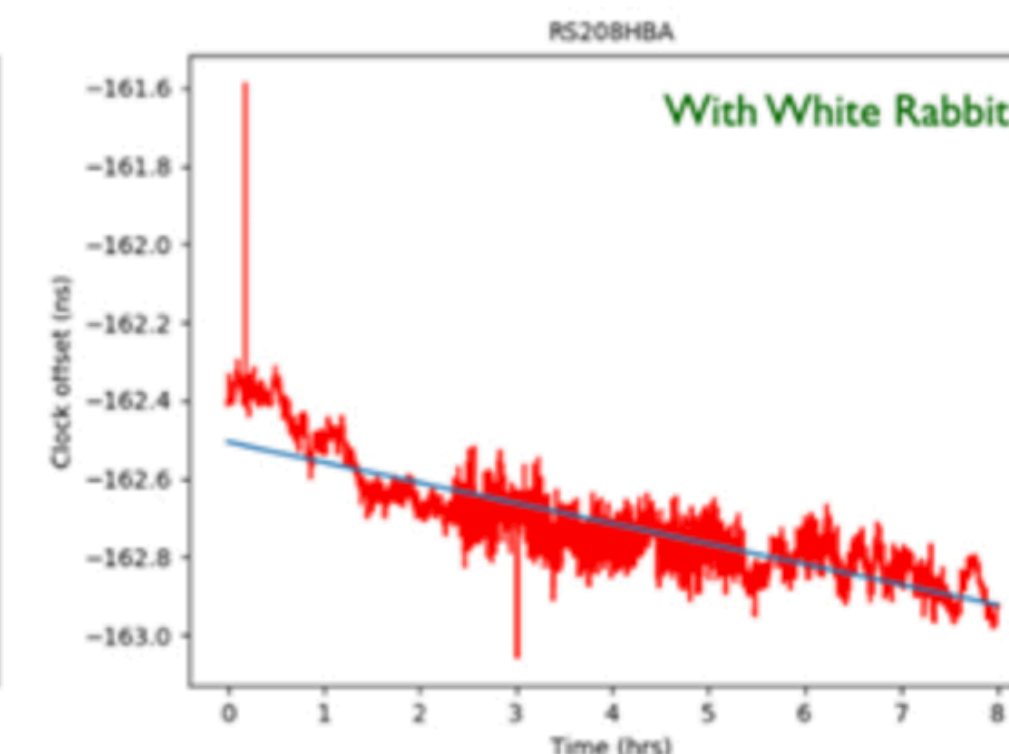
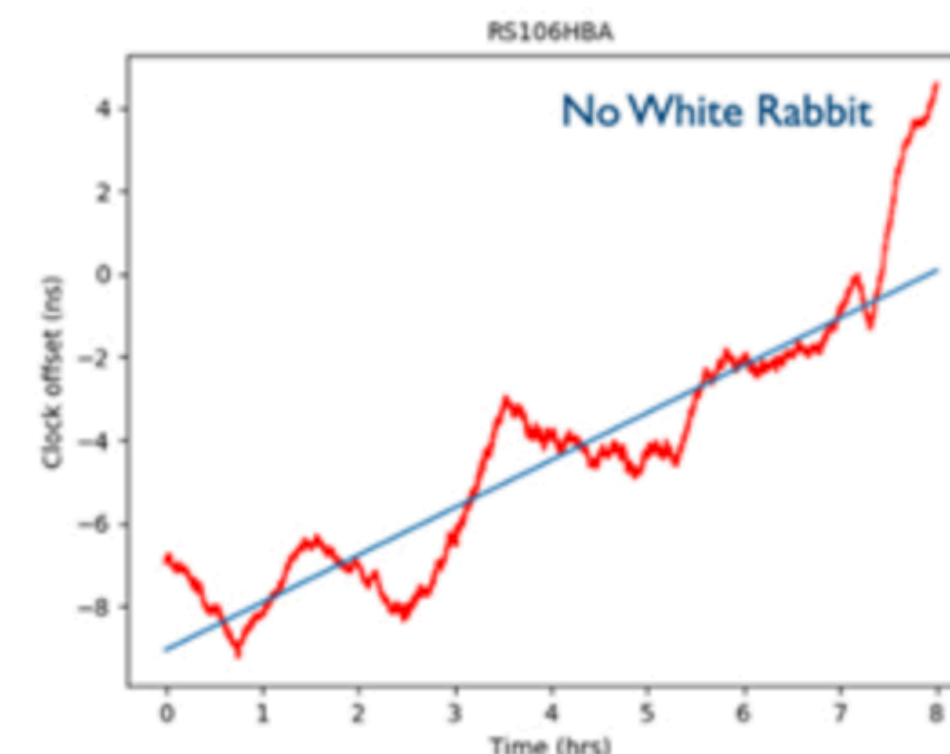
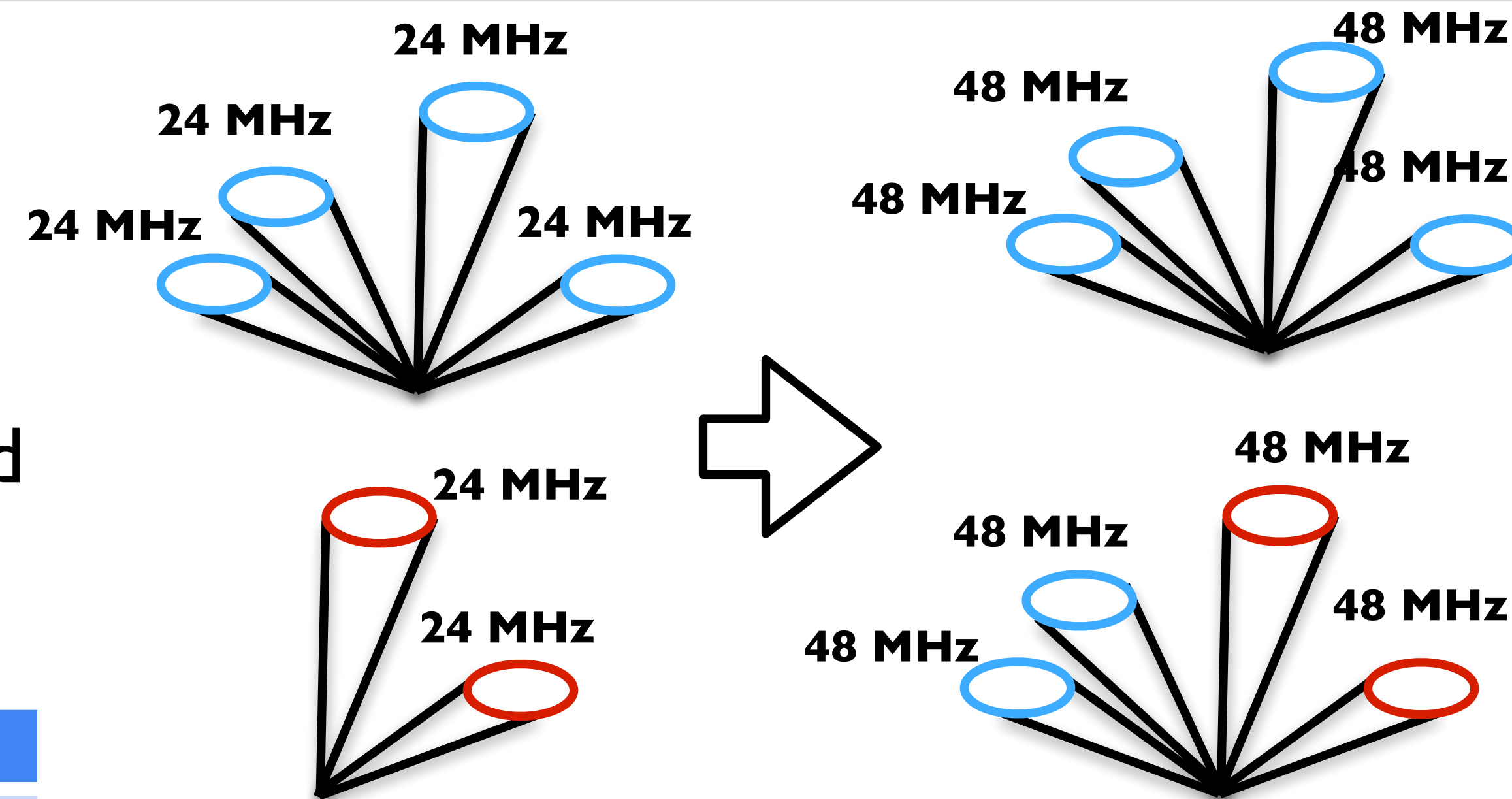
LOFAR 2.0 station upgrade includes:

- **Dual band** (2x96 MHz): enabling simultaneous observation capability for **Low Band Antennas** and **High Band Antennas**

- **Receivers:**

	LOFAR	LOFAR 2.0
Dutch Array	48 LBA or 48 HBA	96 LBA and 48 HBA
International	96 LBA or 96 HBA	96 LBA and 96 HBA

- **Clock:** distribution of a central clock to all NL stations (White Rabbit)
- **Filters:** exclude 180-190 MHz in HBA-LOW
- **Hardware:** redesigning and replacing of station electronics, including digital processing systems and receiver units; LOFAR Mega Mode (Cobalt 2.0, simultaneous observations for several science cases)



LOFAR Family Meeting June 2022 in Köln

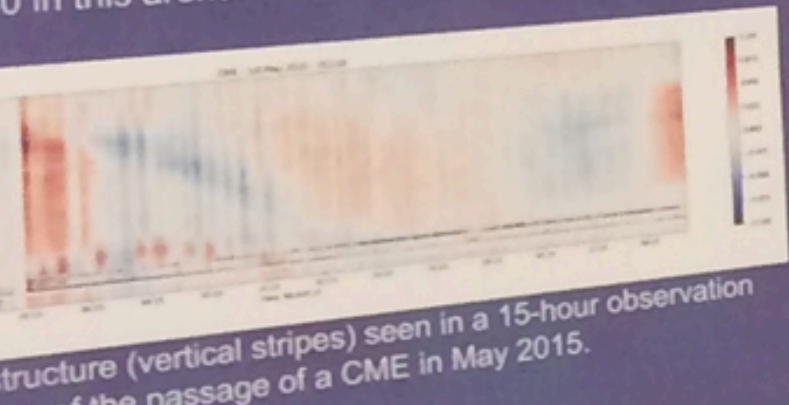
Atmosphere and Space LOFAR 2.0.

Prof. Dr. Anja Klein, Nataliya Porayko, Mario M. Bisi, Frankowski, Gottfried Mann, Jasmina Tiburzi, and Christian Vocks

Acceleration of particles, the expulsion of plasma into the magnetosphere, and the conditions of the ionosphere. However, the study of the conditions of the ionosphere. However, the study of the conditions of the ionosphere. However, the study of the conditions of the ionosphere.

Ionosphere

Scintillation (IPS) is caused by the refraction of radio waves by irregularities in the ionosphere. The combination of ground-based and remote sensing instrumentation available to the LOFAR community is unprecedented over the next few years. Significant progress in the analysis of IPS measurements, playing to the strengths of LOFAR, have been made recently, paving the way for a more fundamental understanding of the solar wind turbulence, and how that may be related to the larger-scale density structure seen in solar wind light imagery. In addition, solar activity is expected to increase in the coming years, paving the way for an evolution of the global solar wind structure and an enormous opportunity to exploit the capabilities of LOFAR in this arena.



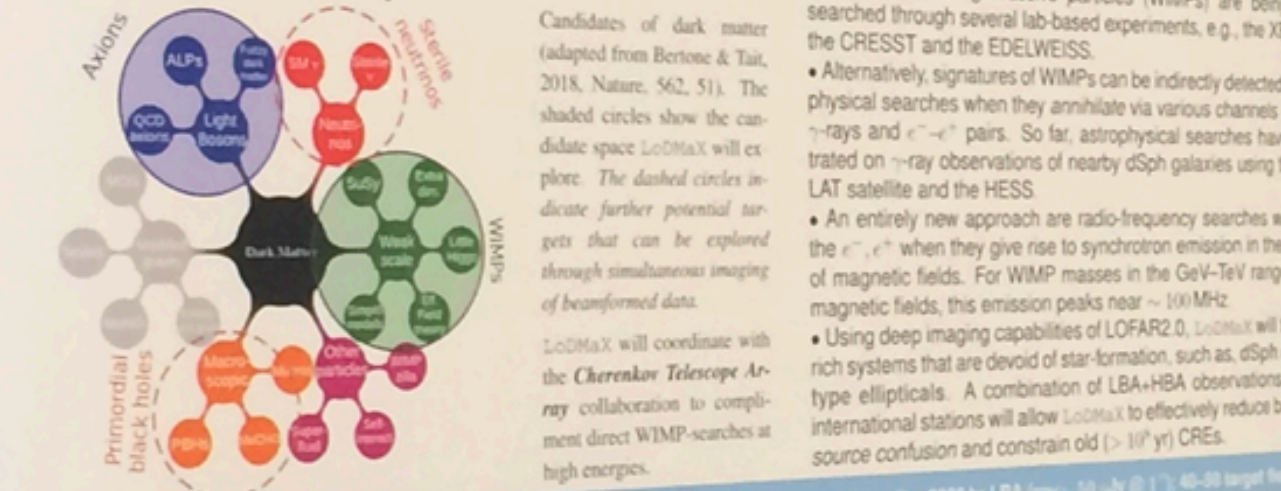
Dispersion Measure and Rotation Measure are key parameters for studying the ionosphere. Dispersion is modified by the action of the traversed plasma, that can induce four kinds of effect: Faraday rotation, scattering, scintillation. The study of these effects can lead to the inference of parameters such as the electron column density, Faraday rotation, and the turbulence of the plasma and its magnetic field of the plasma, while scattering and Faraday rotation depend on the turbulence of the plasma and its frequency. With LOFAR2.0 we can further pursue the study of the frequency-dependent dispersion measure, with an increased sensitivity of simultaneously observing DM with an increased

LOFAR 2.0 Expression of Interest LOFAR2.0 Dark Matter eXperiment (LoDMaX)

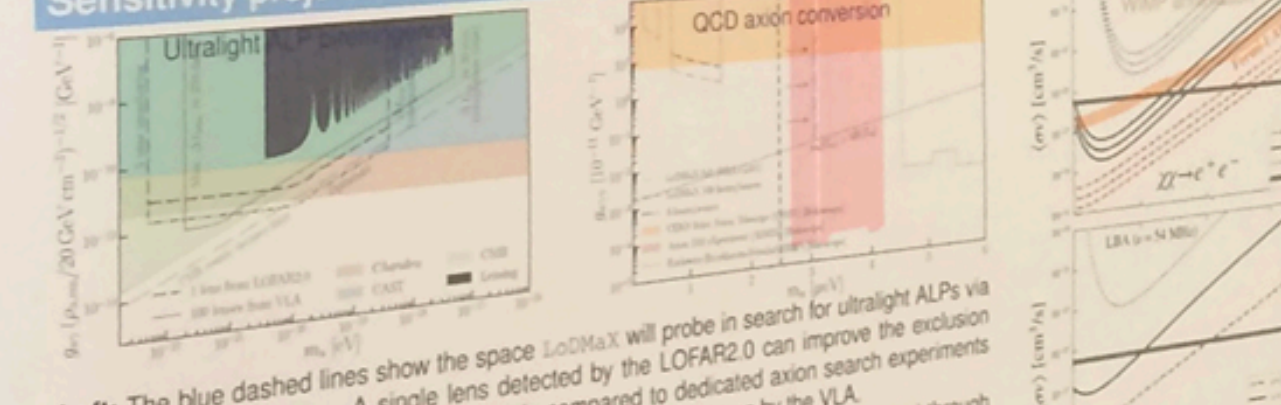
Aritra Basu¹ (abasu@t1s-lautenburg.de), Dominik J. Schwarz² (dschwarz@physik.uni-bielefeld.de) [on behalf of the LoDMaX team]
¹Thüringer Landessternwarte, Sternwarte 5, 07778 Tautenburg, Germany; ²Fakultät für Physik, Universität Bielefeld, Postfach 100131, 33501 Bielefeld, Germany

Introduction
The nature of dark matter (DM) remains elusive, and various types of matter including particles beyond the Standard Model and massive objects have been put forward as its candidate. Although DM are not visible directly, depending on their nature, they can manifest through indirect processes or via the effects they have on electromagnetic radiation. Many of these processes leave measurable imprints on astrophysical scales, and radio continuum observations using LOFAR2.0 can play a crucial role in our quest of detecting DM.

- The LoDMaX large programme will systematically hunt for dark matter using LOFAR2.0's state-of-the-art capabilities.
- LoDMaX will focus on detecting **ultralight axion-like particles (ALPs)** and **QCD axions** through signatures of birefringence, stimulated decay and axion-photon conversion, and decay products of annihilating **weakly-interacting massive particles (WIMPs)**.
- LoDMaX will also foster imaging-synergy with beamformed-based EoLs to search for exotic **sterile neutrinos** and **primordial black holes**.
- The parameter space that LoDMaX will probe can not only compete with dedicated DM search experiments, but potentially improve the search dramatically.



Candidates of dark matter (adapted from Bertone & Tan, 2018, Nature, 562, 51). The shaded circles show the candidate space LoDMaX will explore. The dashed circles indicate further potential targets that can be explored through simultaneous imaging of beamformed data.

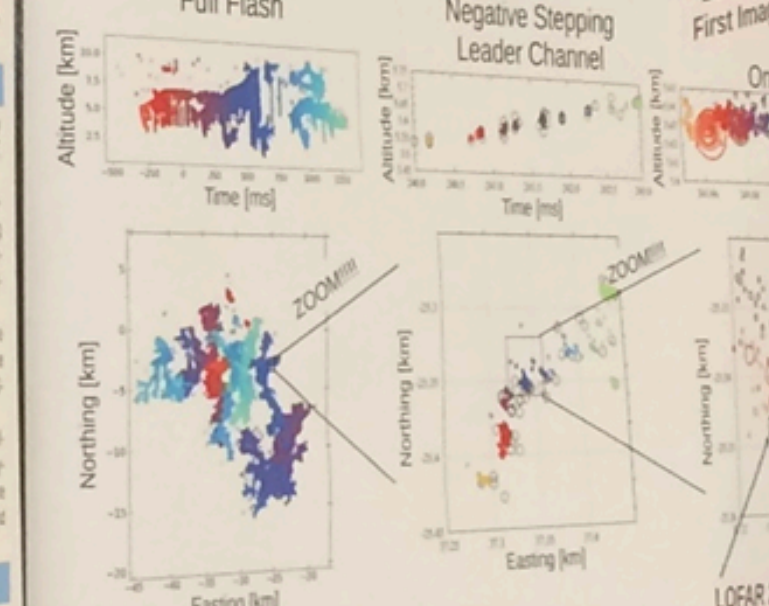


Left: The blue dashed lines show the space LoDMaX will probe in search for ultralight ALPs via differential birefringence. A single lens detected by the LOFAR2.0 can improve the exclusion bounds by more than an order of magnitude compared to dedicated axion search experiments. **Middle:** Parameter space expected to be probed by LOFAR2.0 HBAs and LBAs (in gray) through deep observations of about 40 DM-rich systems to search for spectral-line emission due to Primakoff effect. LoDMaX will probe a complementary parameter space towards lower m_{ax} compared to the current and future efforts of lab-based QCD axion searches and improve the exclusion bounds by more than an order of magnitude. **Right:** Sensitivity of LoDMaX towards WIMP annihilation signal through deep observations (~ 15 - 30 $\mu\text{Jy beam}^{-1}$ at 6° ; 100 hr per target) of about 40 DM-rich systems. LoDMaX will complement direct WIMP searches, extending to lower masses and improve the constraints by up to 100x.

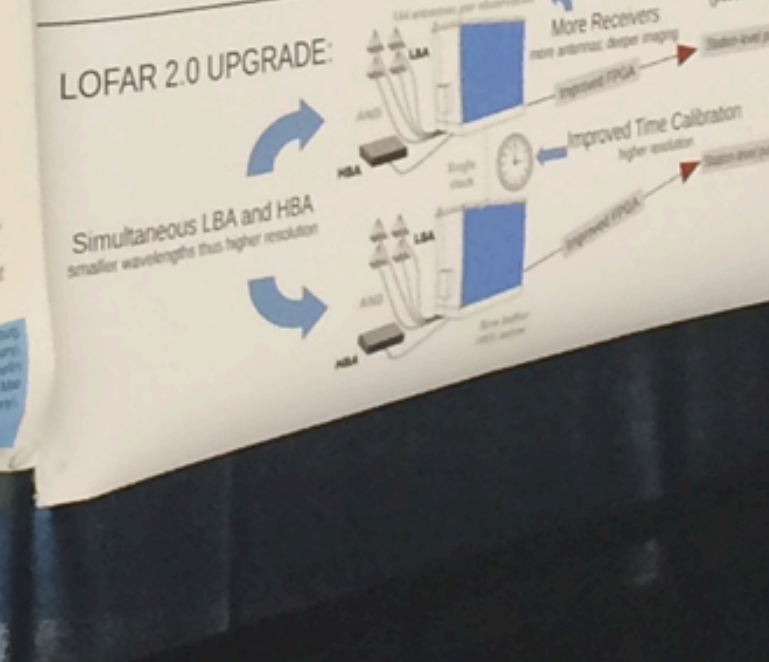
LOFAR 2.0 Expression of Interest Lightning Imaging with LOFAR 2.0

Brian M. Hare^{*}, Stijn Buitink, Joseph Dwyer, Ningyu Liu, Olaf Scholten, and Sander ter Veen
^{*}b.h.hare@rug.nl

- Axions were predicted as a solution of the strong CP-problem. Axion-like particles (ALPs) are a generalization of that idea.
- A tiny interaction between the electromagnetic and the ALP fields gives rise to observable phenomenon, such as, **achromatic birefringence** and conversion of ALPs into photons. The **Primakoff effect** and conversion of ALPs into photons. The **Primakoff effect** gives rise to observable phenomenon, such as, **achromatic birefringence** and conversion of ALPs into photons. The **Primakoff effect** gives rise to observable phenomenon, such as, **achromatic birefringence** and conversion of ALPs into photons.

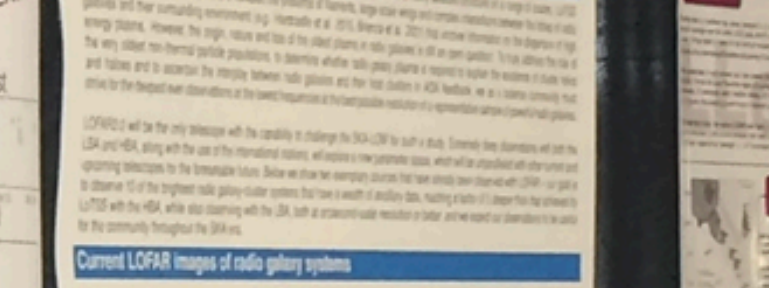


SCIENCE: Lightning plasma modeling works at sub-meter level. Measurements are at 10 m resolution. Thus, large gap between the two. Goal is to close gap and measure plasma at meter-level scale. Figures above show LOFAR 1.0 has reduced this gap significantly. LOFAR 2.0 will let us push to higher resolution than ever before.



LOFAR 2.0 Expression of Interest LOFAR's deepest view of radio Plasma in AGN lobes and Clusters (LoDePAC)

Open questions: Recent observations of radio plasma with 500 patches show a plasma with a complex structure. The plasma is observed in the form of filaments, loops, and other structures. The plasma is observed in the form of filaments, loops, and other structures.



Proposed observations: We will target large and high-redshift galaxies that have been well studied in the past at higher frequencies. We will target large and high-redshift galaxies that have been well studied in the past at higher frequencies.

Benefits to the community: High-resolution radio images of AGN lobes and clusters will provide a new window into the physical processes that shape these structures. The images will provide a new window into the physical processes that shape these structures.

LOFAR 2.0 Expression of Interest LBA LOFAR Community Sky Survey

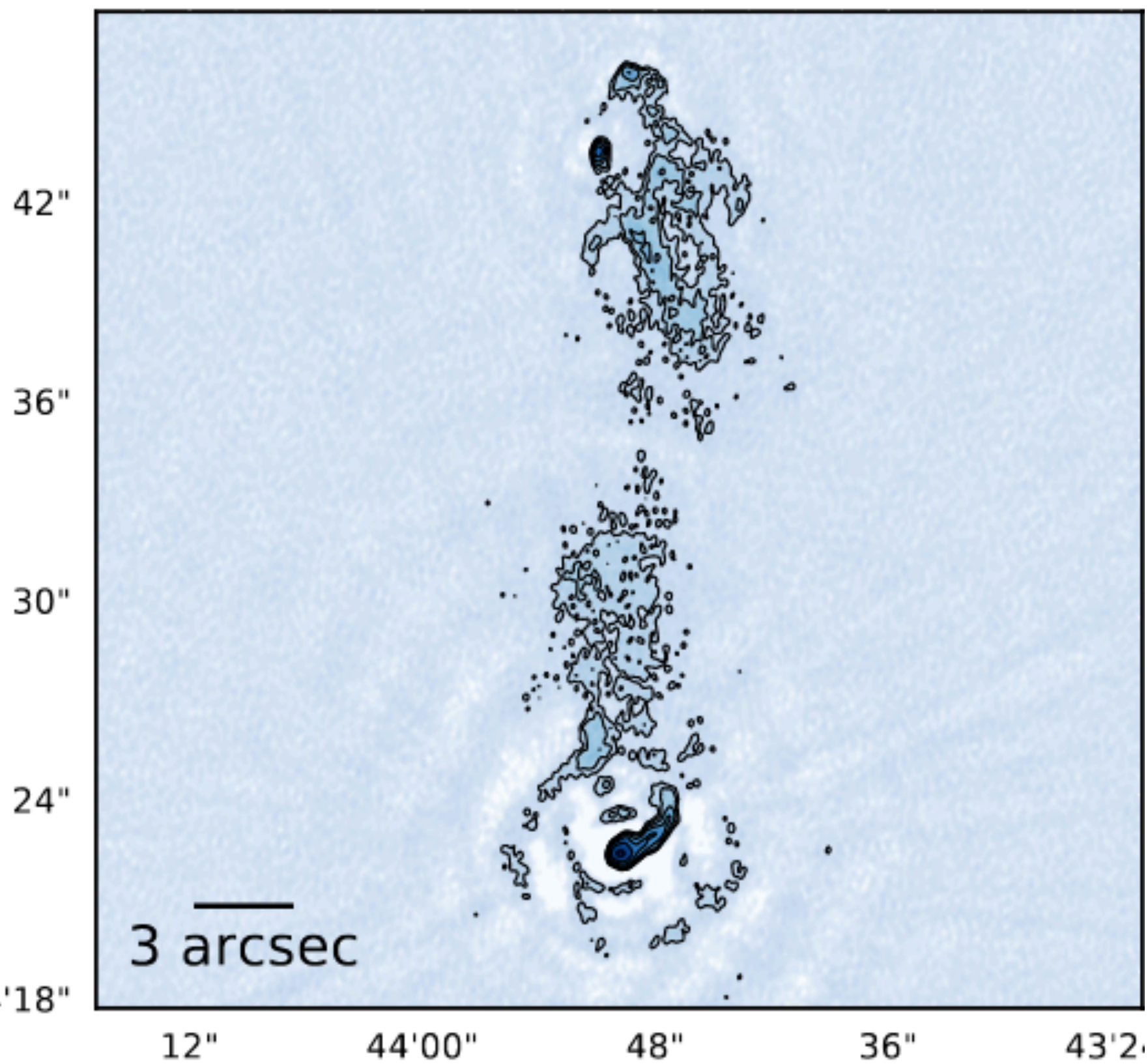
Information about the LBA LOFAR Community Sky Survey, including details on data access, survey progress, and community involvement.

Additional LOFAR 2.0 posters and information, including details on the AARTFAAC Relocalization Survey (ARES) and other community projects.

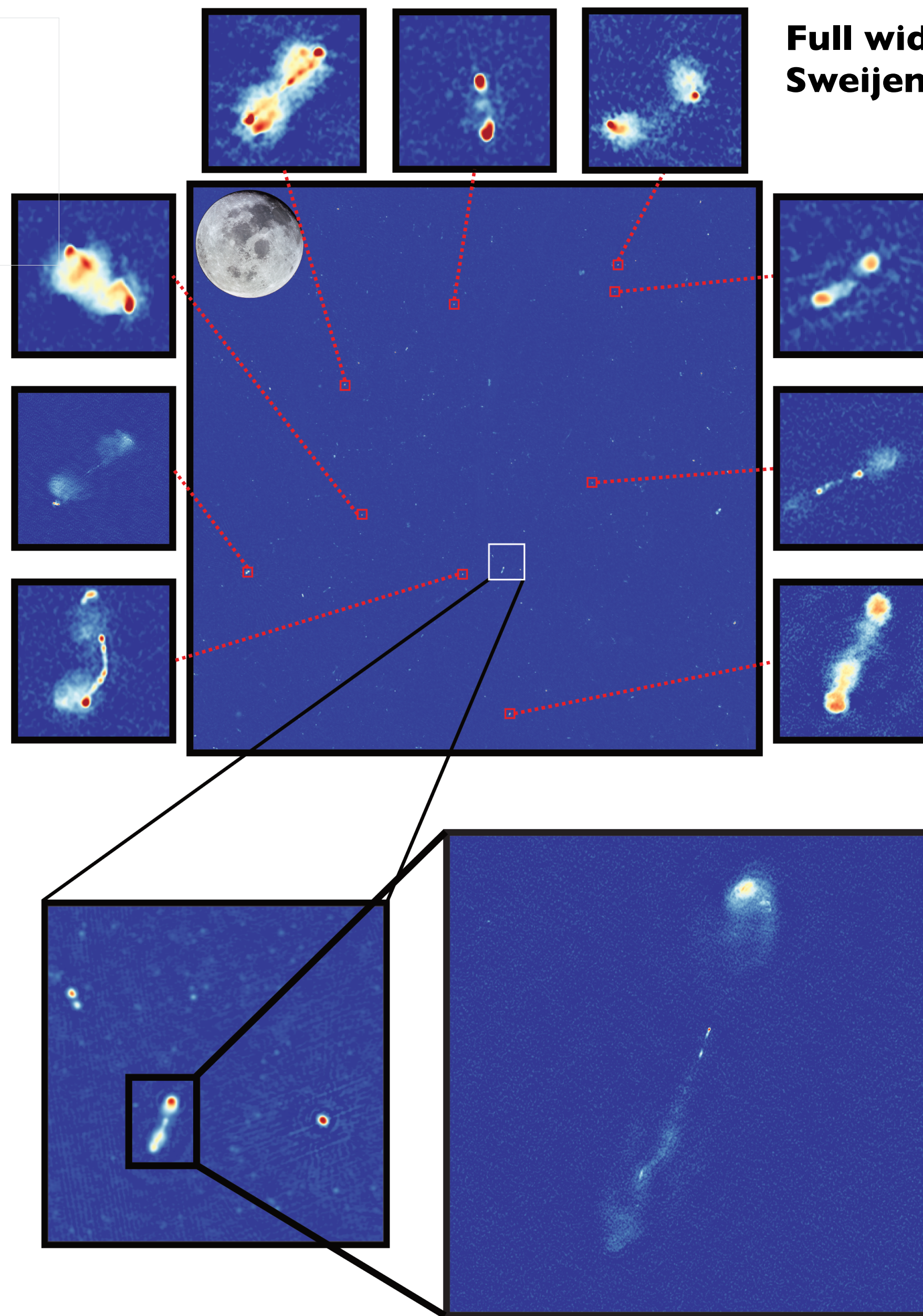
International LOFAR Telescope

Almost all LoTSS data contains the LOFAR international stations (up to 1600km)

134255.151+541432.752

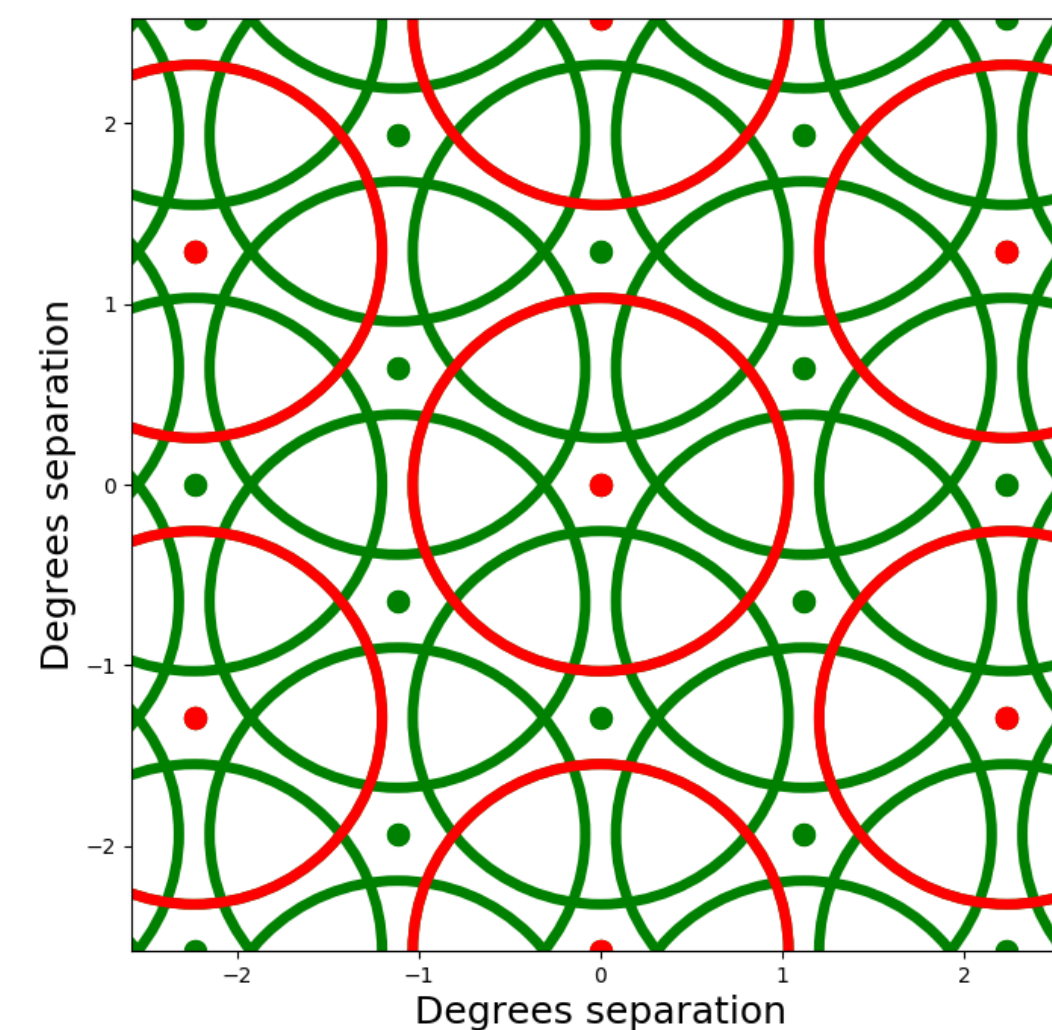


Selected source imaging: Morabito+ 2021

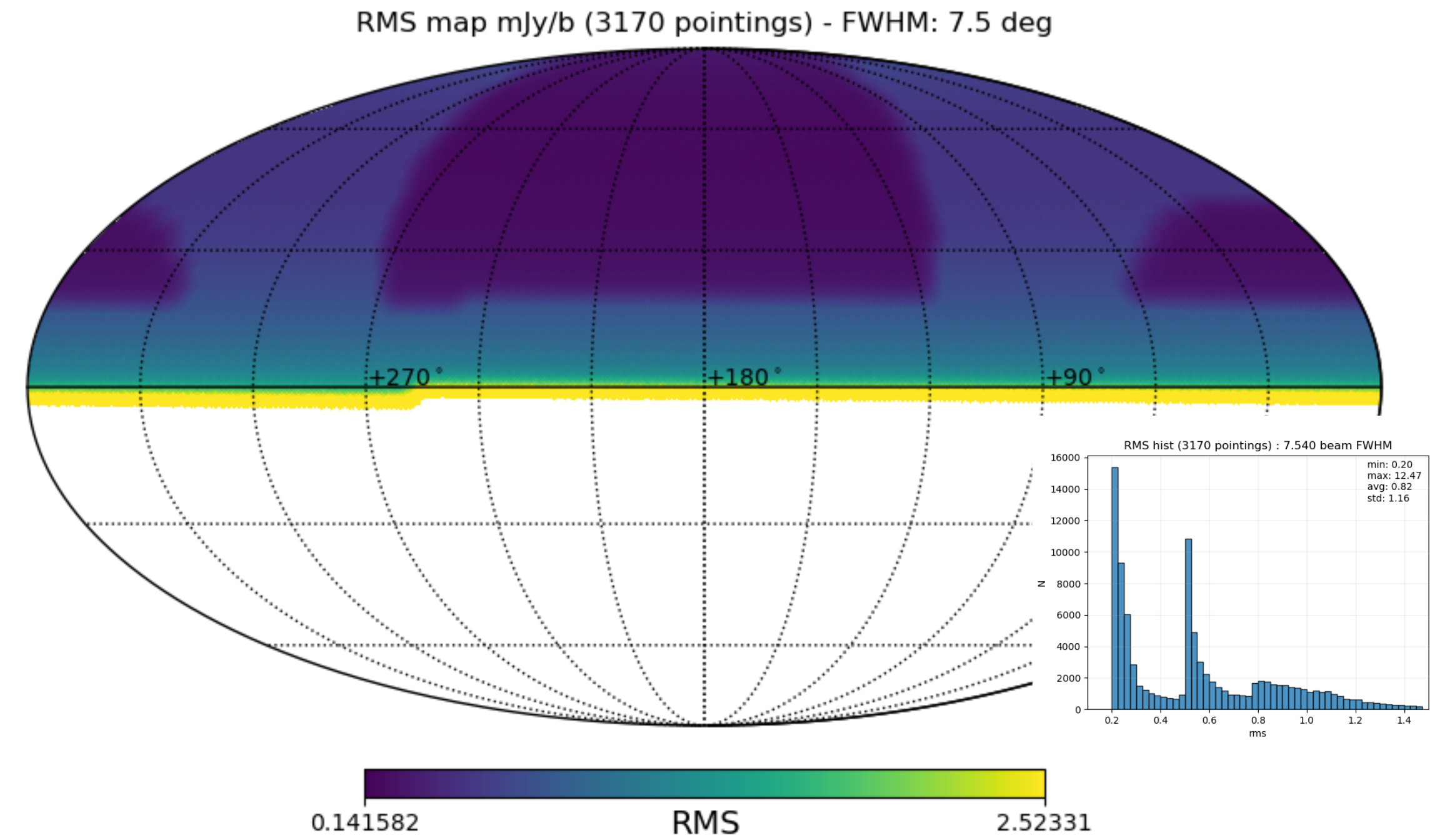
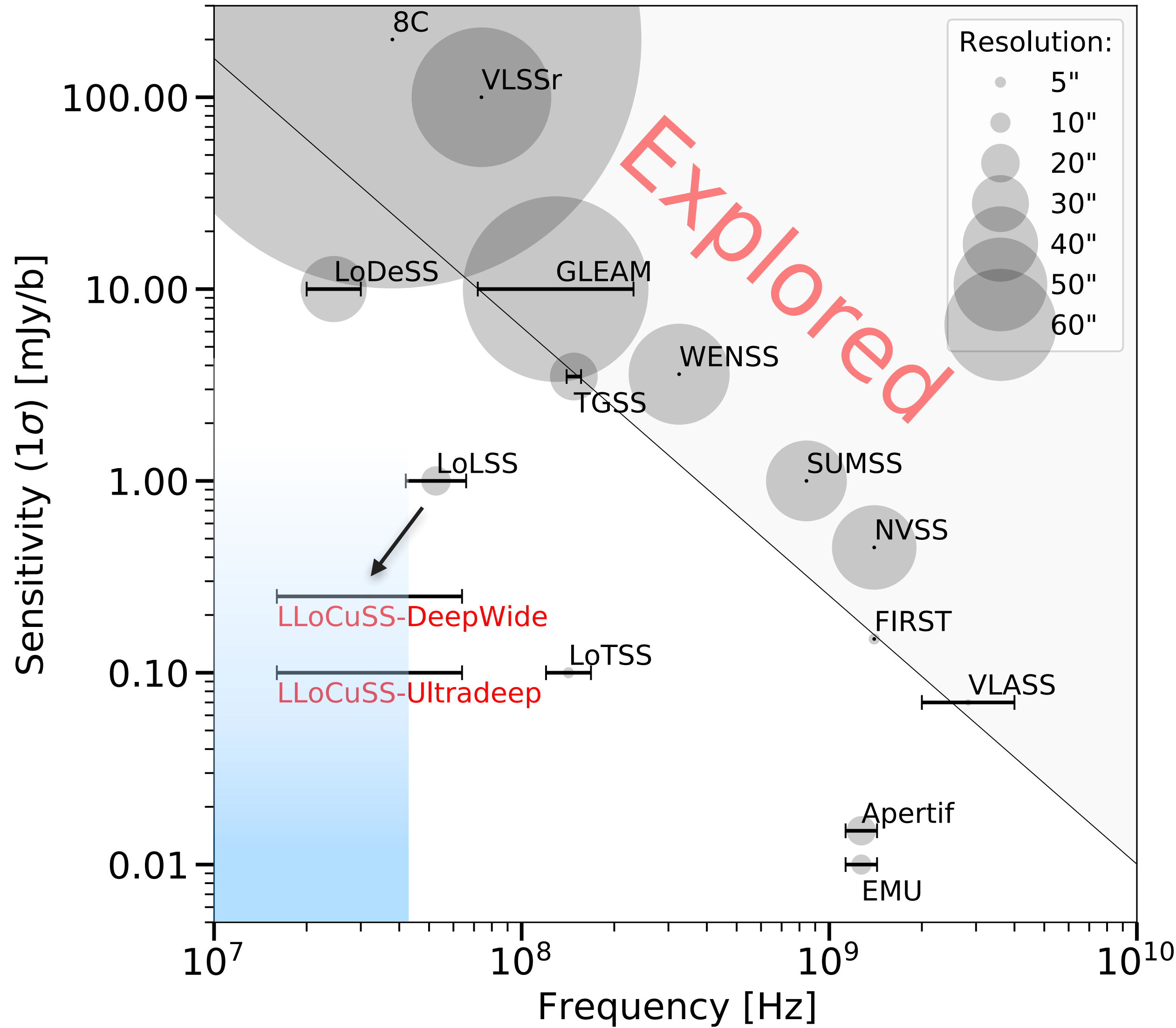


Full wide area imaging: Sweijen+ 2022

LOFAR 2.0: complete LoTSS-IS survey grid doubling the pointings
Aim: entire extragalactic northern sky at 0.3"



LBA LOFAR Community Sky Survey (LLoCuSS)



- **Band:** 16 – 64 MHz
- **Resolution:**
 - 1" (upper half of the band)
 - 15" (lower half of the band)

- Wide Survey (2004 hrs):**
- Coverage: Dec > 0°
 - Sensitivity: 500–800 $\mu\text{Jy beam}^{-1}$

- Deep-Wide Survey (5830 hrs):**
- Coverage: Dec > 20°, |b| > 23°
 - Sensitivity: 350 $\mu\text{Jy beam}^{-1}$

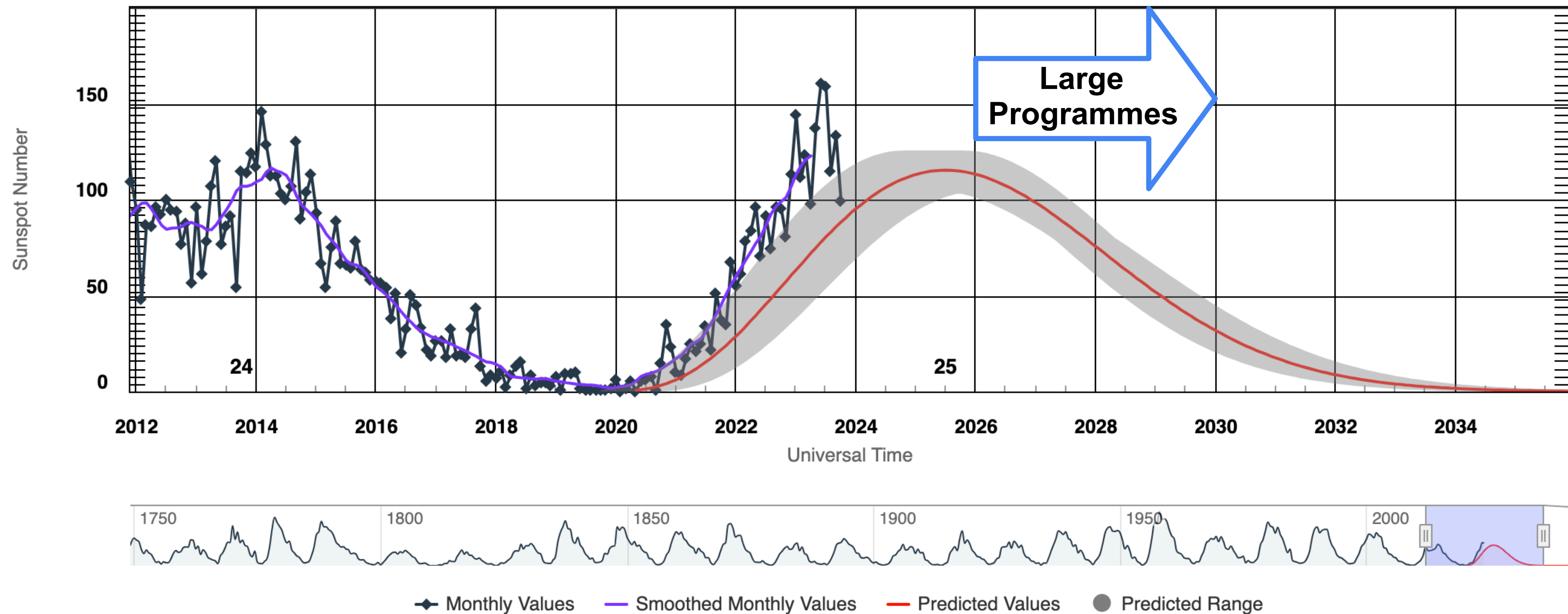
- Ultra-deep Fields (100 hrs per field):**
- Sensitivity: 130 $\mu\text{Jy beam}^{-1}$

LOFAR 2.0 upgrade:

- 2023: 1 LOFAR 2.0 station (L2TS) fully working
- 2024-1q: 3 LOFAR 2.0 stations
- 2024-2q; 2025-1q: roll out of all LOFAR stations
- 2025-2q: data flow

Science programmes:

- 2022: Eol for Large Programme
- 2023: Proposal submission
- 2024: Proposal evaluation
- 2025 - commissioning
- 2026-2030 - observations

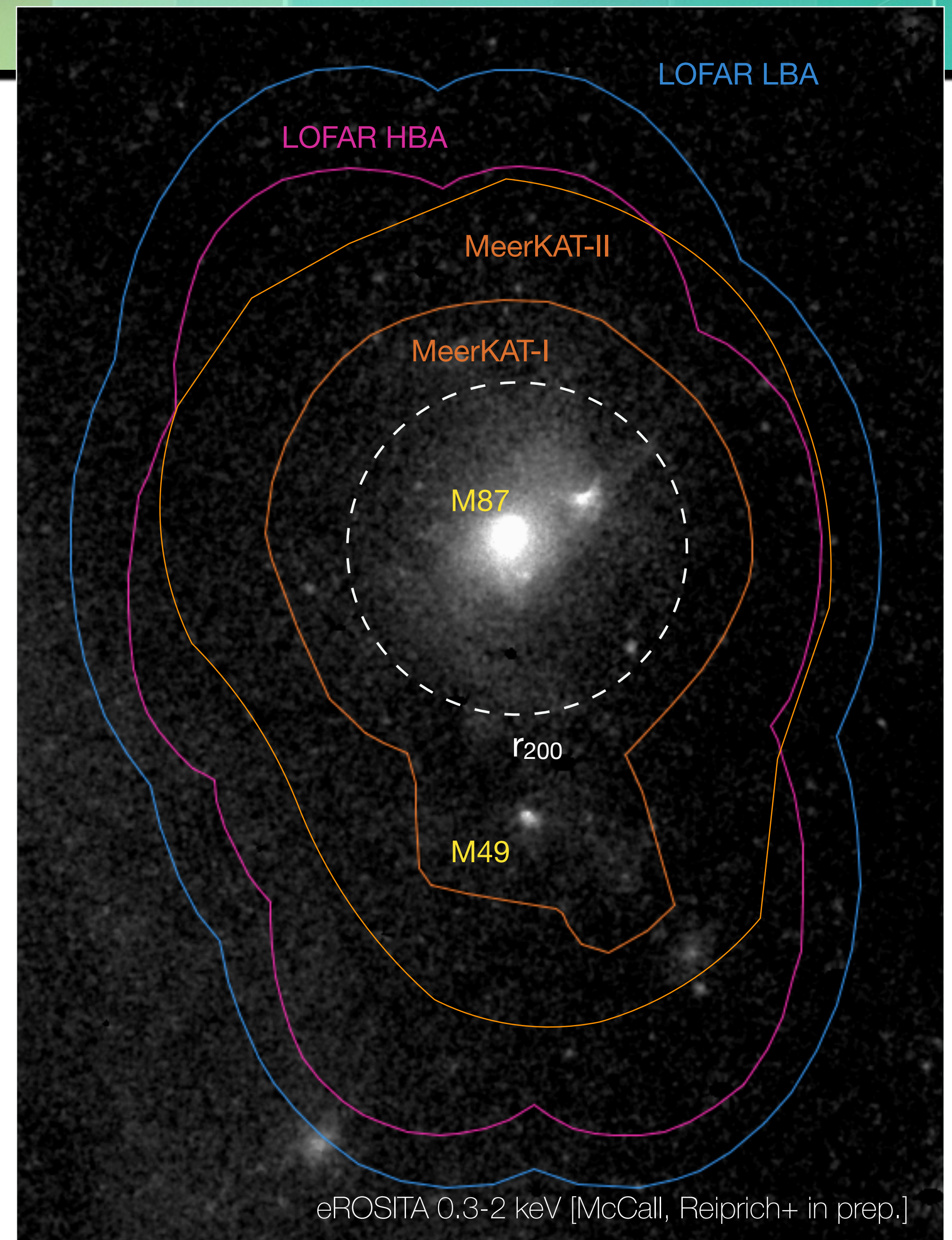
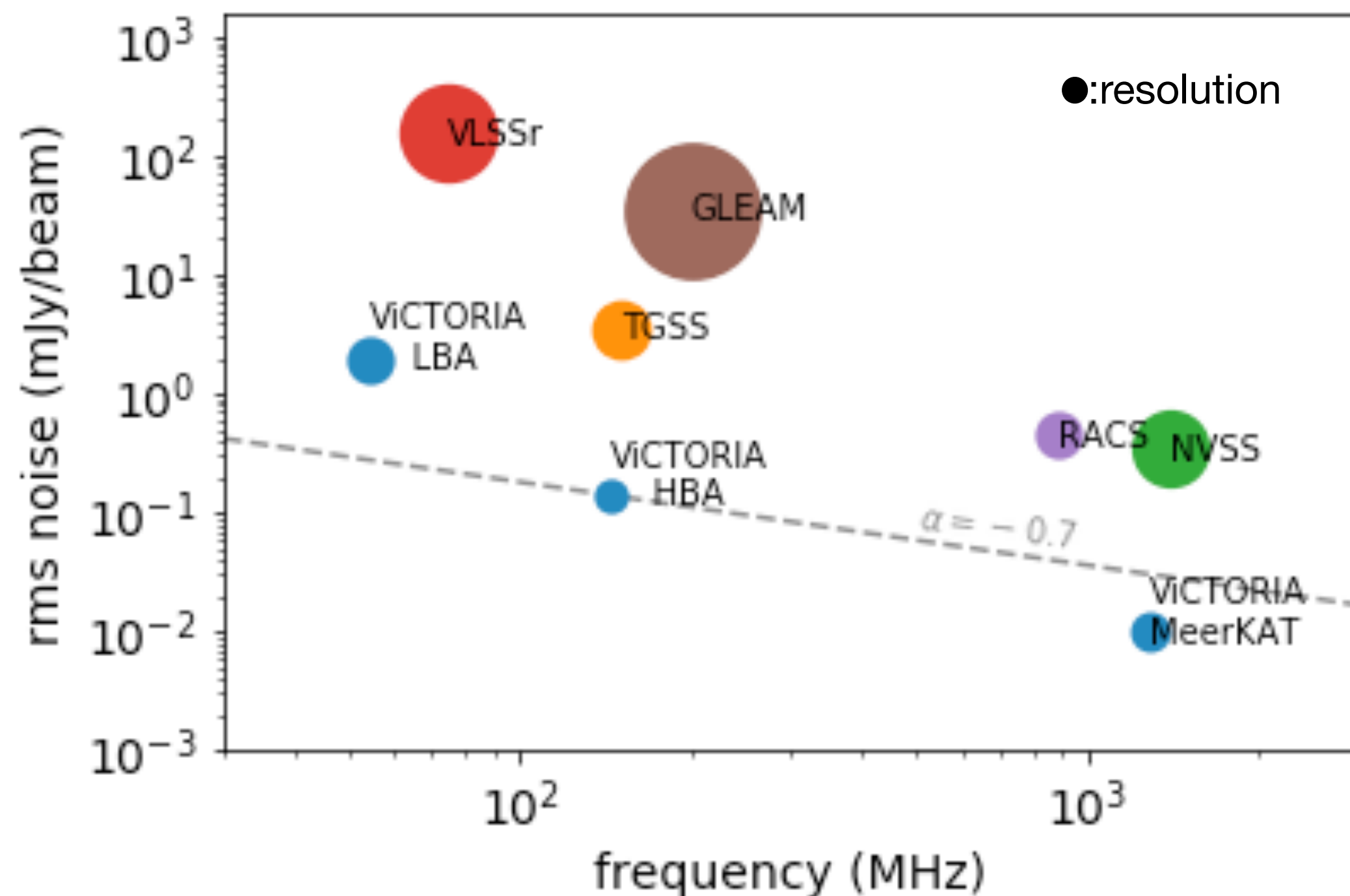


- LOFAR Surveys
- LOFAR upgrades
 - ➔ LOFAR 2.0
 - ➔ LOFAR Next Generation Surveys
- **LOFAR+MeeRKAT - ViCTORIA project**

Virgo Cluster multi-Telescope Observations in Radio of Interacting galaxies and AGN

Aim: Drastically improve the multi-frequency radio-coverage of the Virgo cluster
→ Enable studies of the **environmental effects** in galaxies and AGN

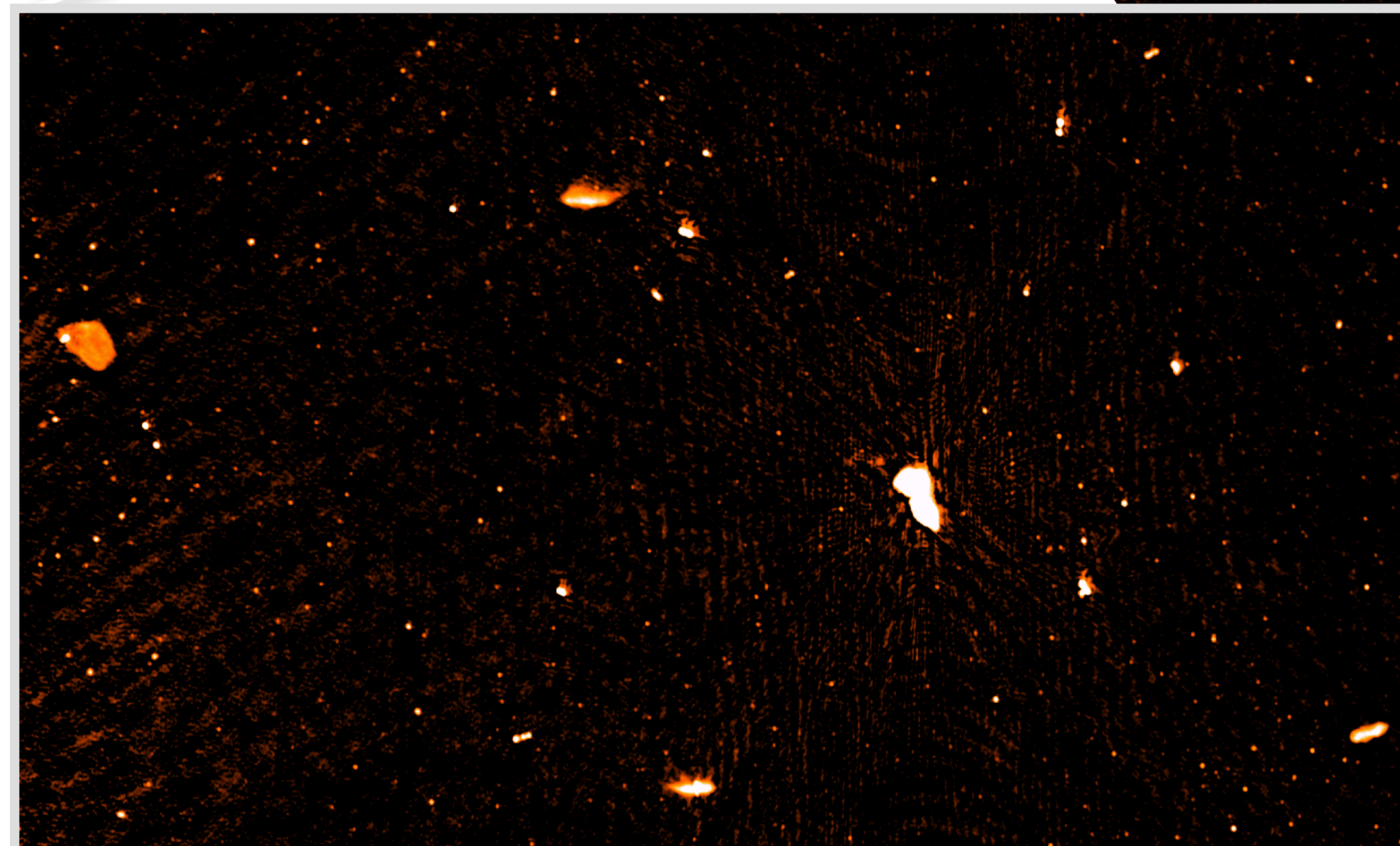
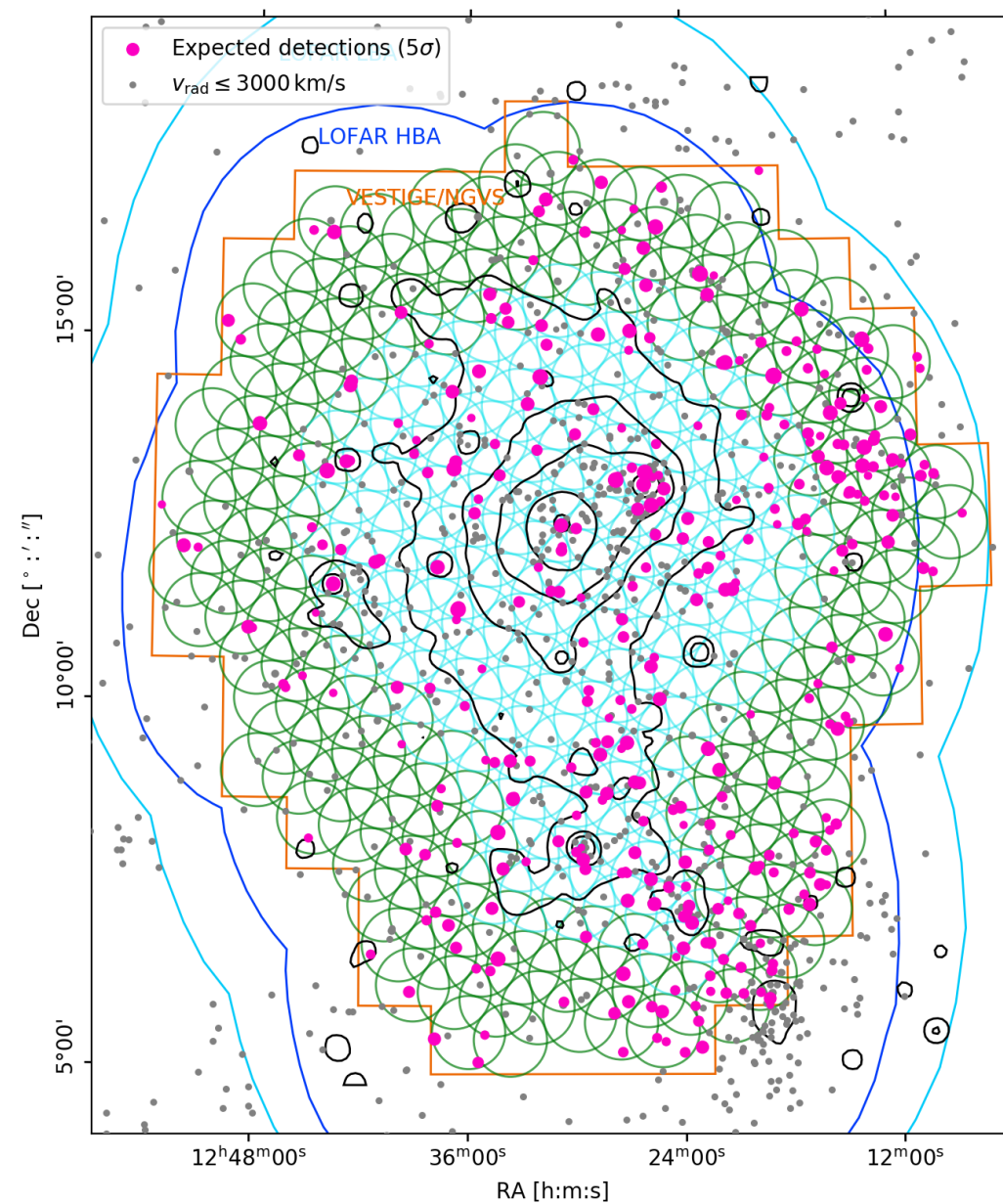
1. LOFAR LBA: 54 MHz (56 hrs)
2. LOFAR HBA: 144 MHz (64 hrs)
3. MeerKAT: 1.3 GHz (125 hrs + 158 hrs)



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2. LOFAR HBA: 144 MHz
3. **MeerKAT: 1.3 GHz (including HI)**
(+ expansion to twice the coverage)



- **LoTSS**

reference person: Tim Shimwell

- for deep fields: Philip Best
- for long baselines: Leah Morabito
- data at www.lofar-surveys.org/dr2.html

- **LoLSS**

reference person: Francesco de Gasperin

- for deep fields: Wendy Williams
- data at www.lofar-surveys.org/lolss.html

- **LOFAR 2.0** upgrade is ongoing with very positive results from the test station. Data flow is expected from 2025.

- **Large Programmes** will be selected in 2024, the community is very open: get involved!

- **LLoCuSS (LOFAR 2.0 LBA survey)**

reference persons: Francesco de Gasperin / Reinout van Weeren

**Interested in working with
LOFAR surveys / LOFAR 2.0?
Postdoc positions open in
Bologna, contact me!**

- **ViCTORIA Project**

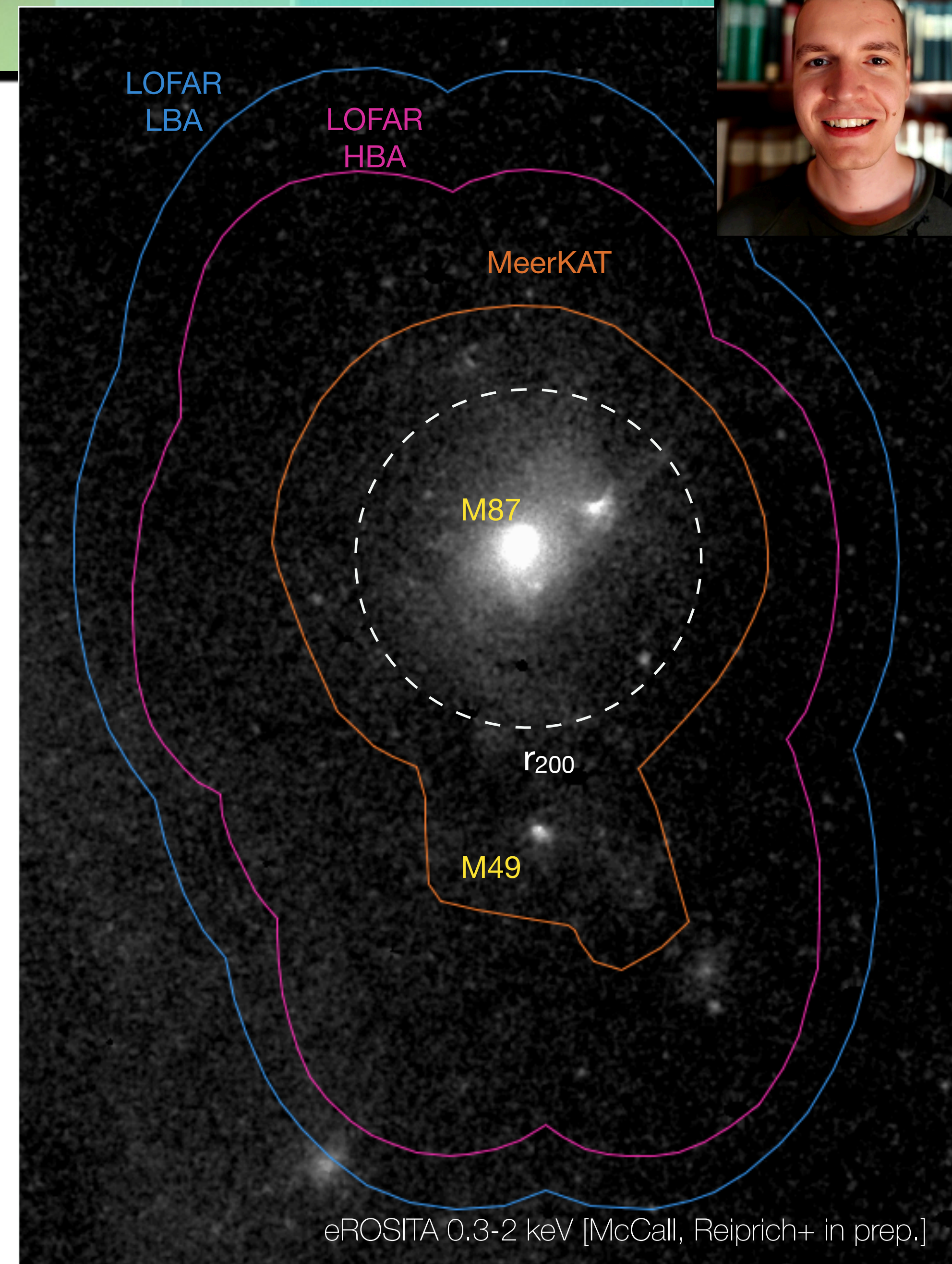
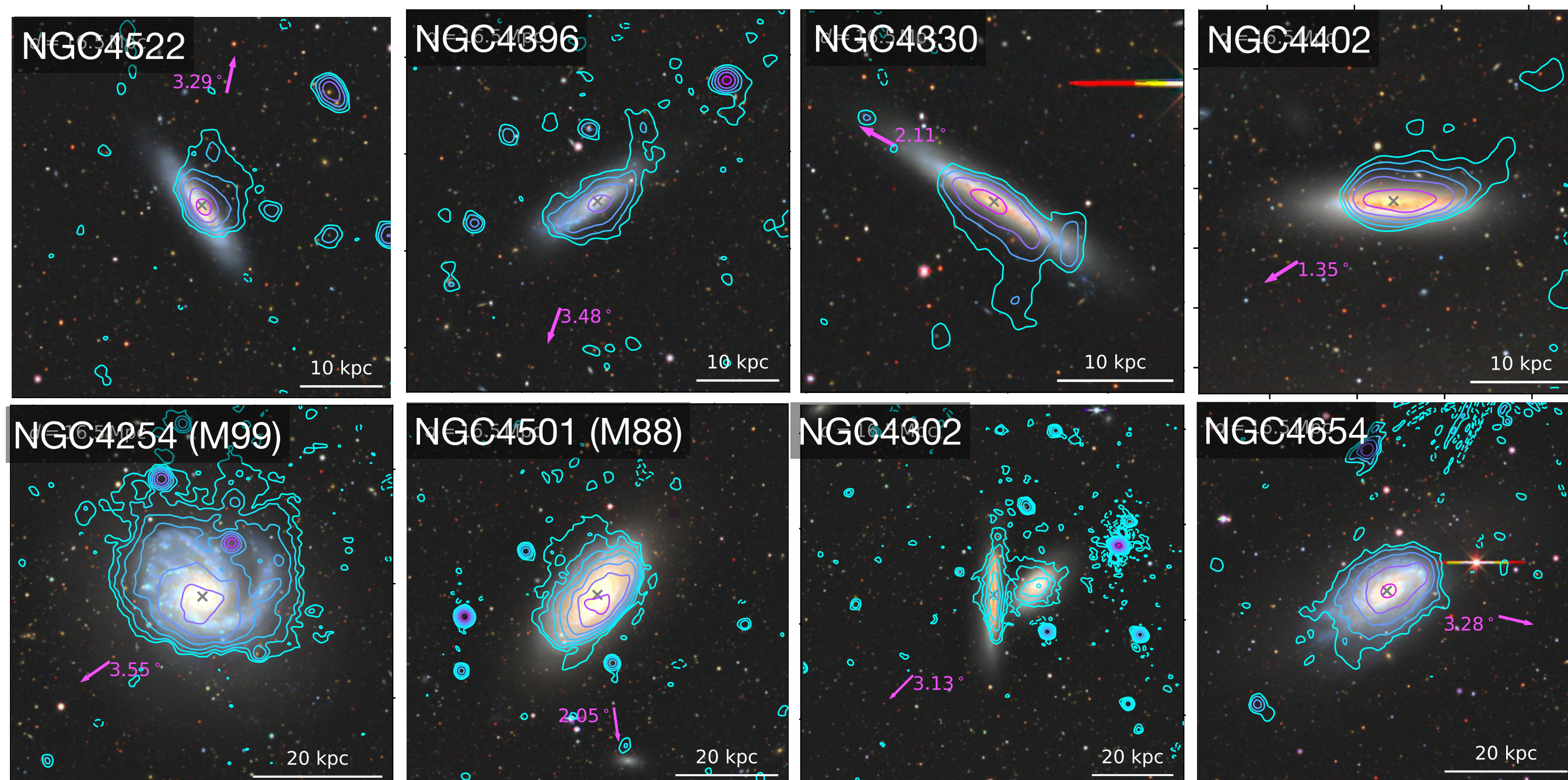
reference persons: Francesco de Gasperin / Henrik Edler / Paolo Serra / Alessandro Boselli

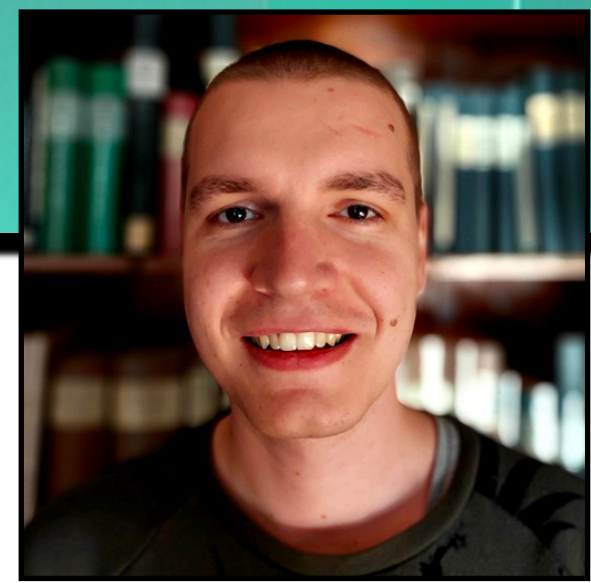


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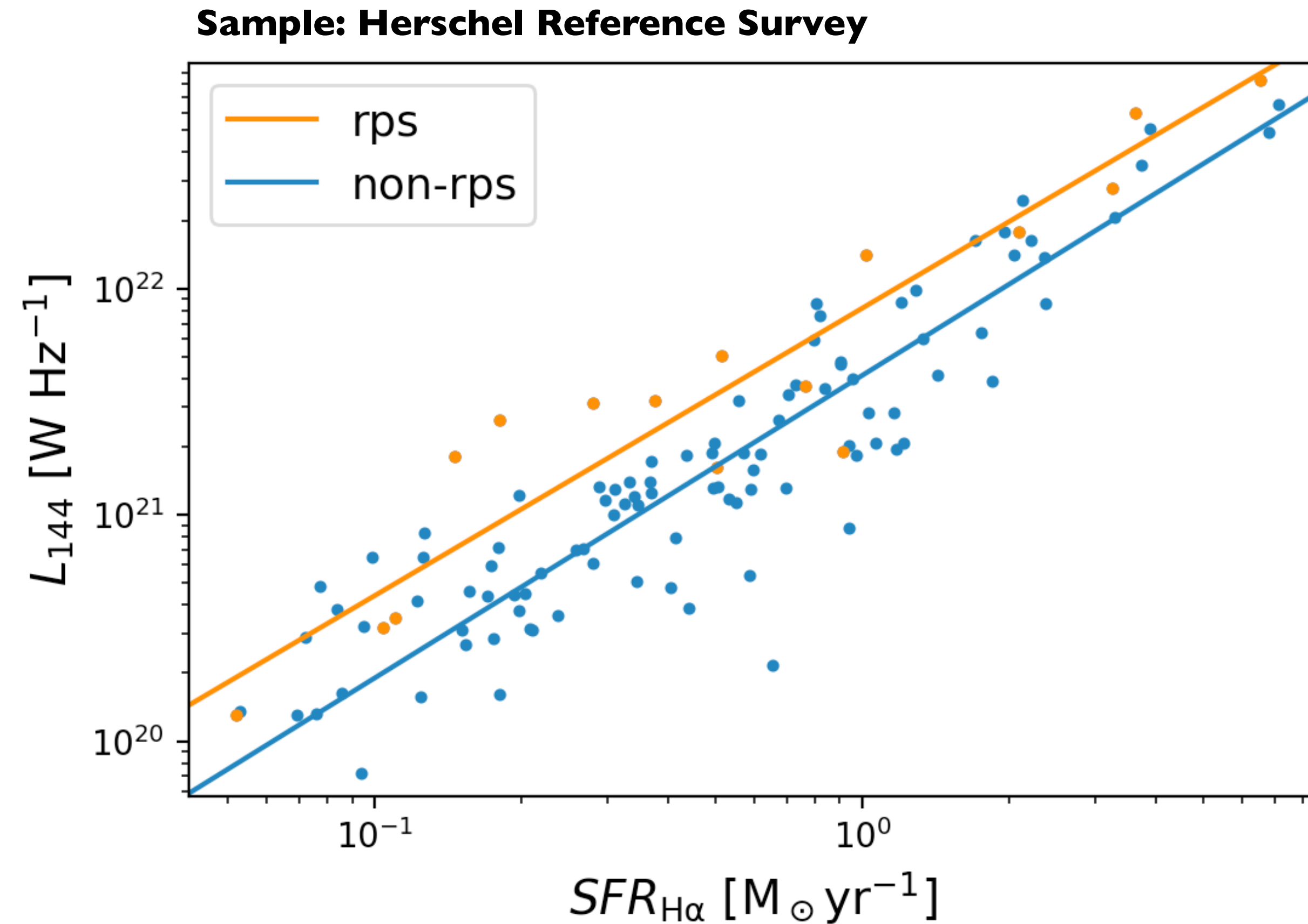
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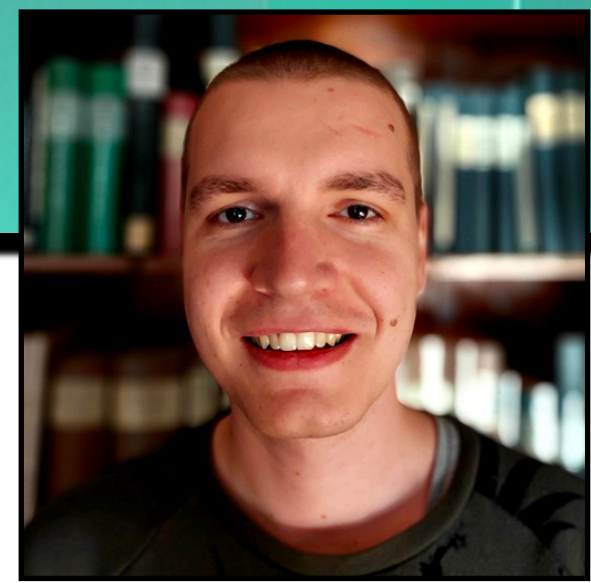




Normal vs. stripped galaxies

- $L_{144} = N_0 \text{SFR}^\delta, \delta = 1.33$
- Most of RPS galaxies show radio-excess!
 1. Enhanced magnetic field due to compression [Gavazzi+99]
 2. Re-acceleration at shocks [Völk+94, Murphy+09]
 - Flatter spectral index + enhanced surf. brightness at location of shock
 3. Rapid decline in SFR [Ignești+22]
 - Steeper spectral index

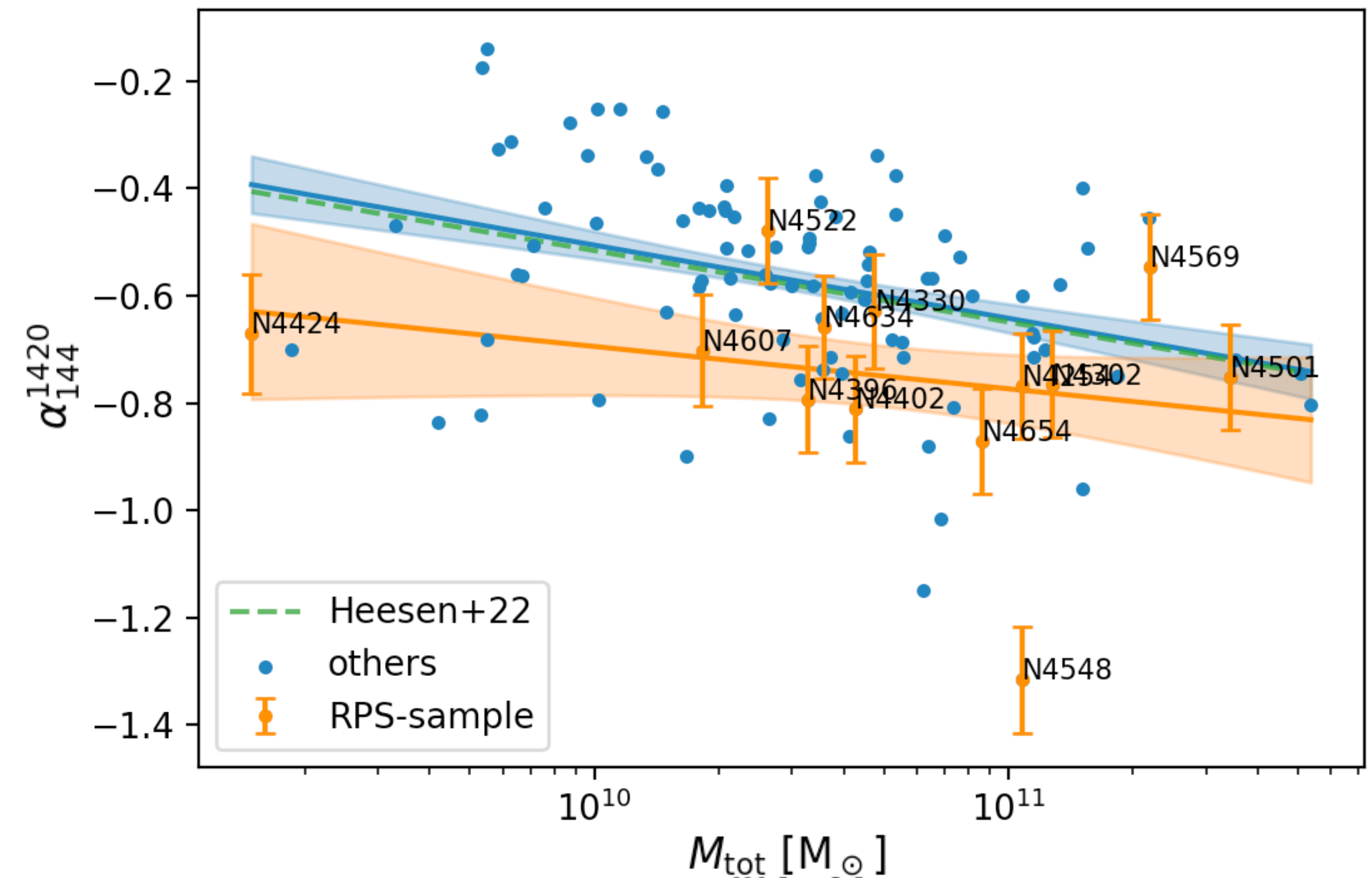




Spectral index-mass relation

- Relation due to mass-dependent CR escape
- Non-stripped sample: good agreement with literature [Heesen+22]
- For RPS galaxies - spectral indices steeper, even though CR-escape likely more efficient
- RPS galaxies host older cosmic ray-populations!
➔ recent quenching of star-formation [e.g. Ignesti+22]

Sample: Herschel Reference Survey

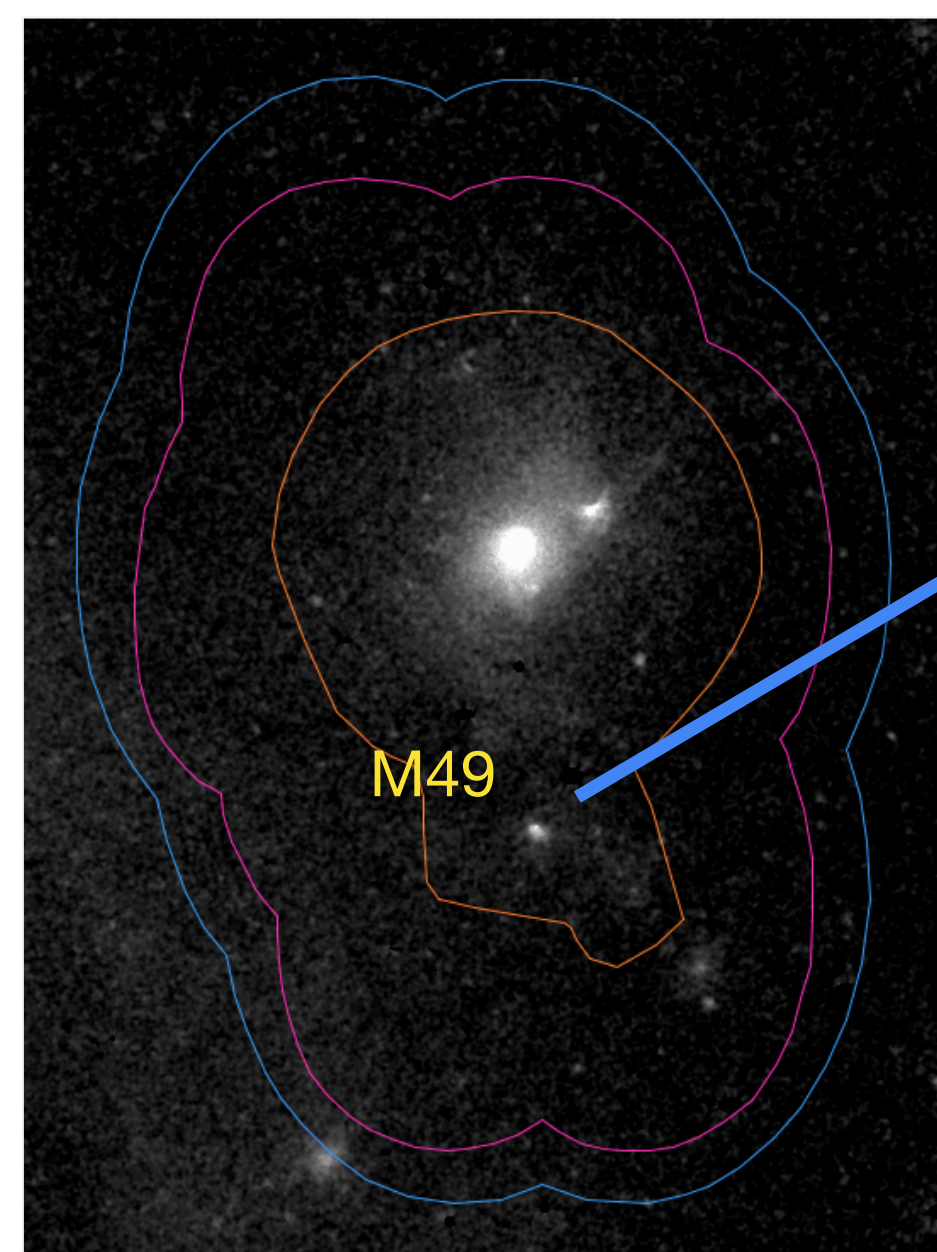




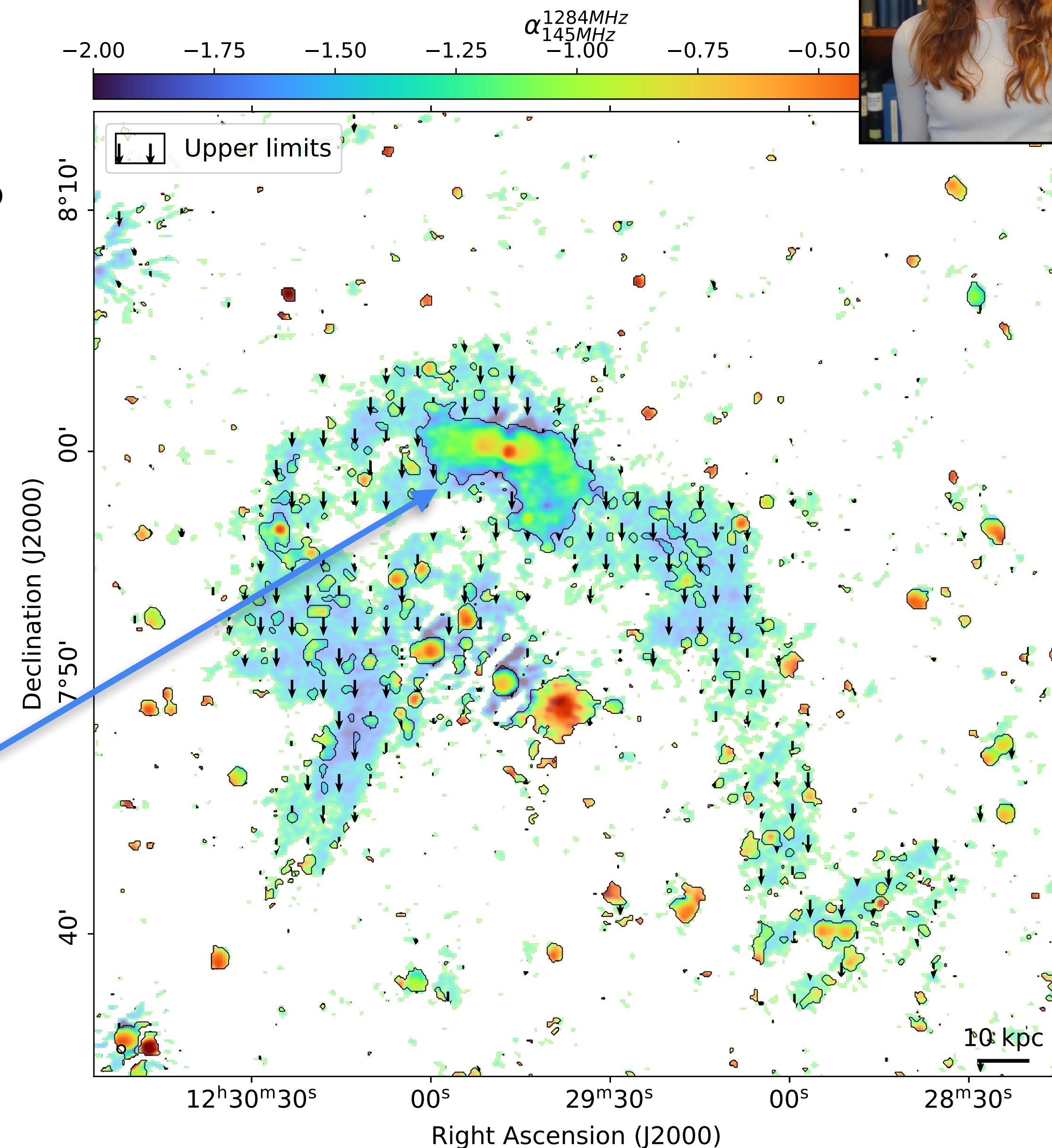
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M49: 100 kpc + 100 kpc long radio lobes from past AGN activity co-spatial with X-ray cavities



M51: the whirlpool galaxy

Lovorka Gajovic



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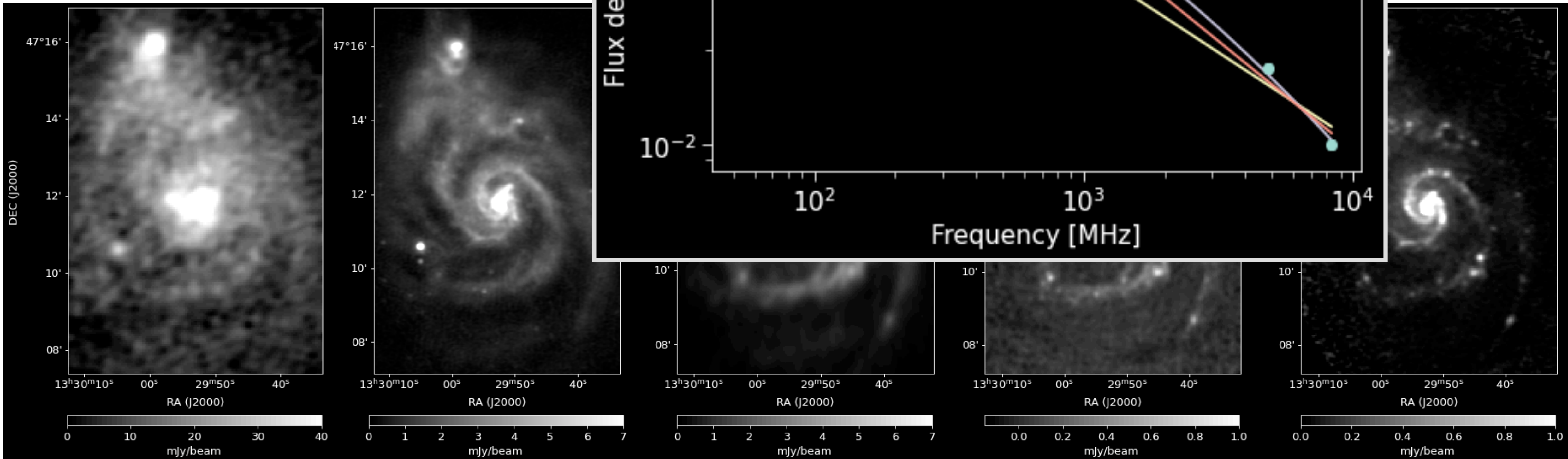
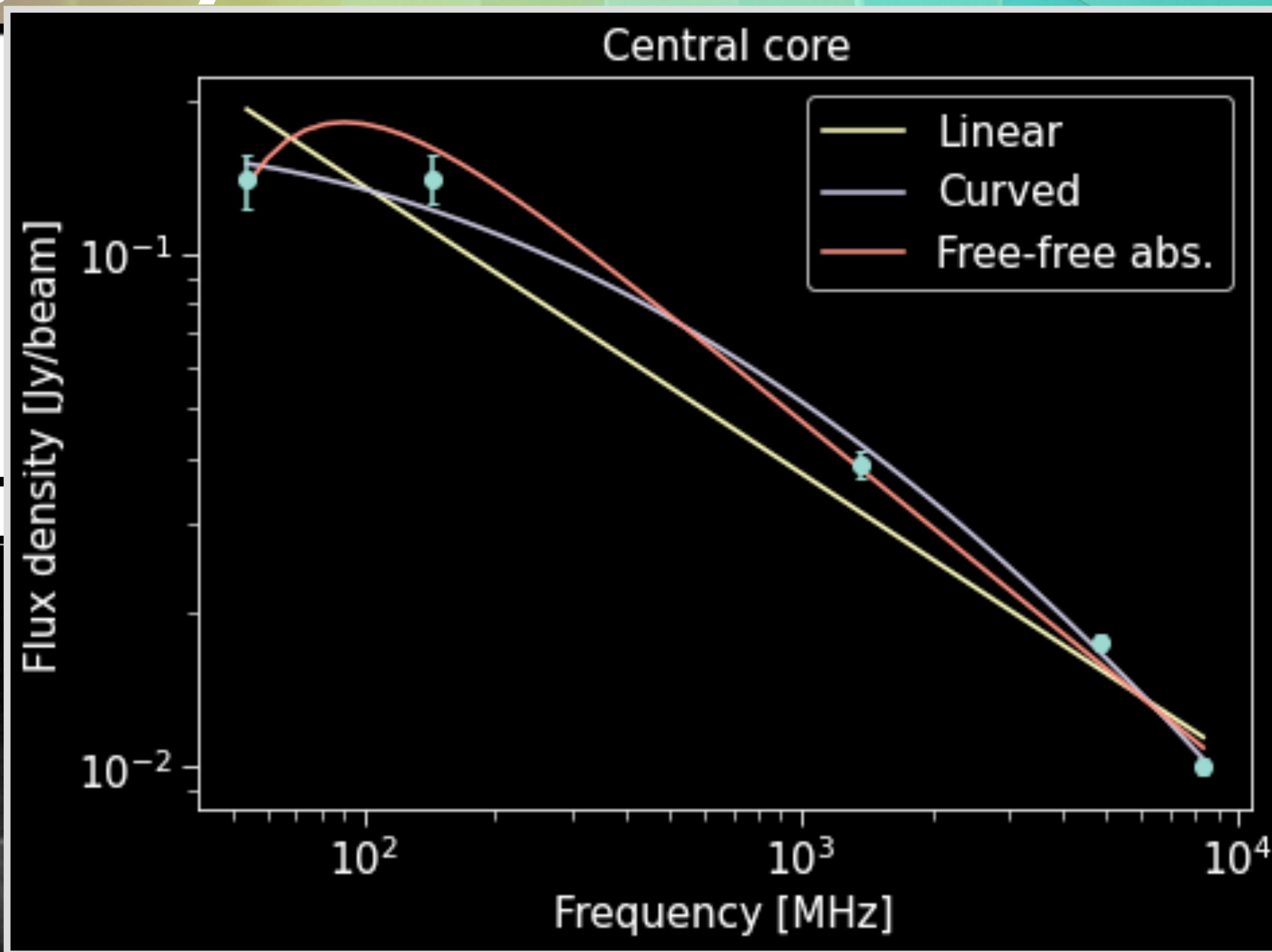
We can fit the free-free absorption model to find the emission measure in HII regions

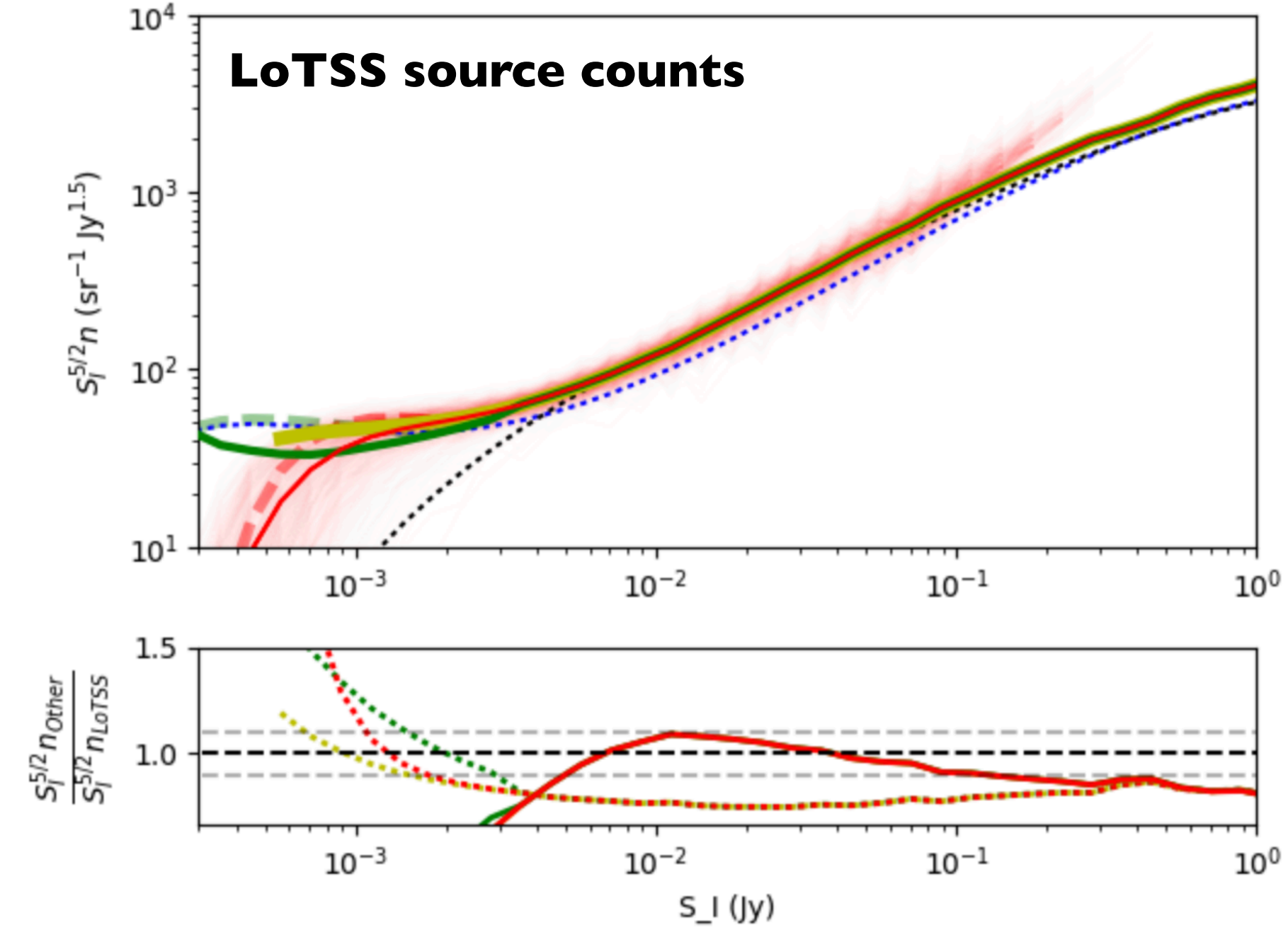
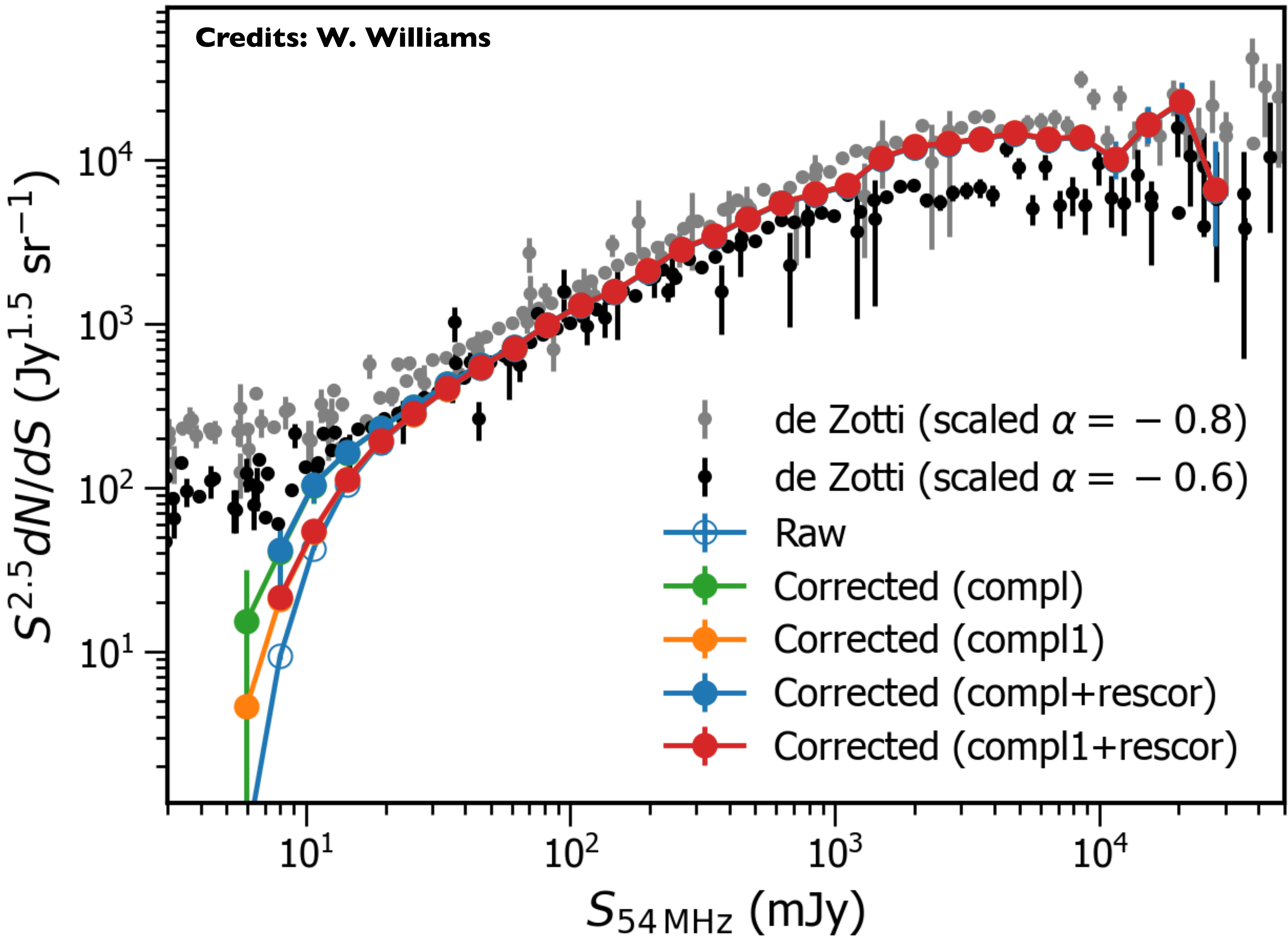
54 MHz

144 MHz

8.35 GHz

Frequency





LoLSS not deep enough to see SF galaxy turnover: need deep fields

High flux sources: steep (-0.8)
Low flux sources: flat (-0.6)