

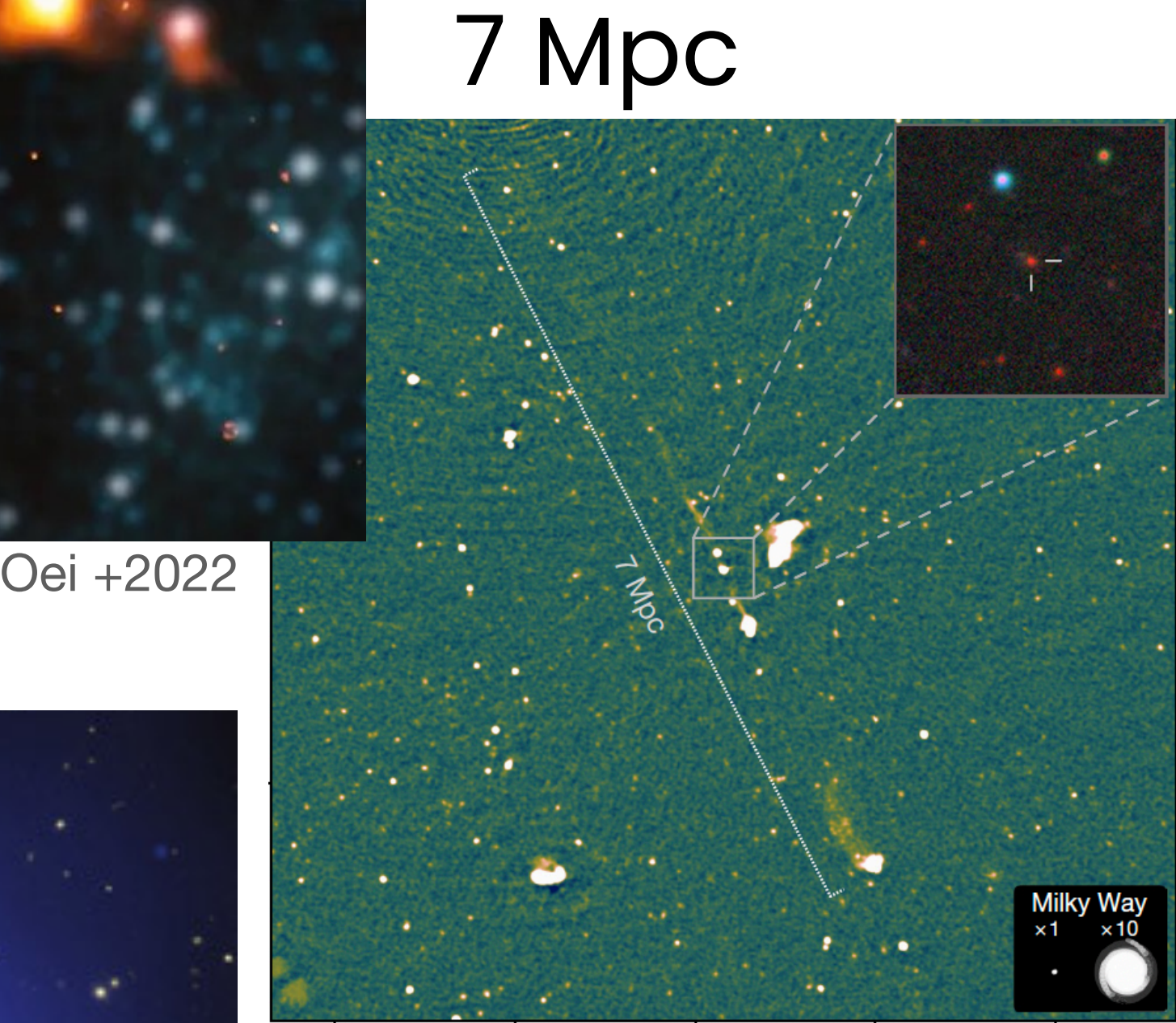
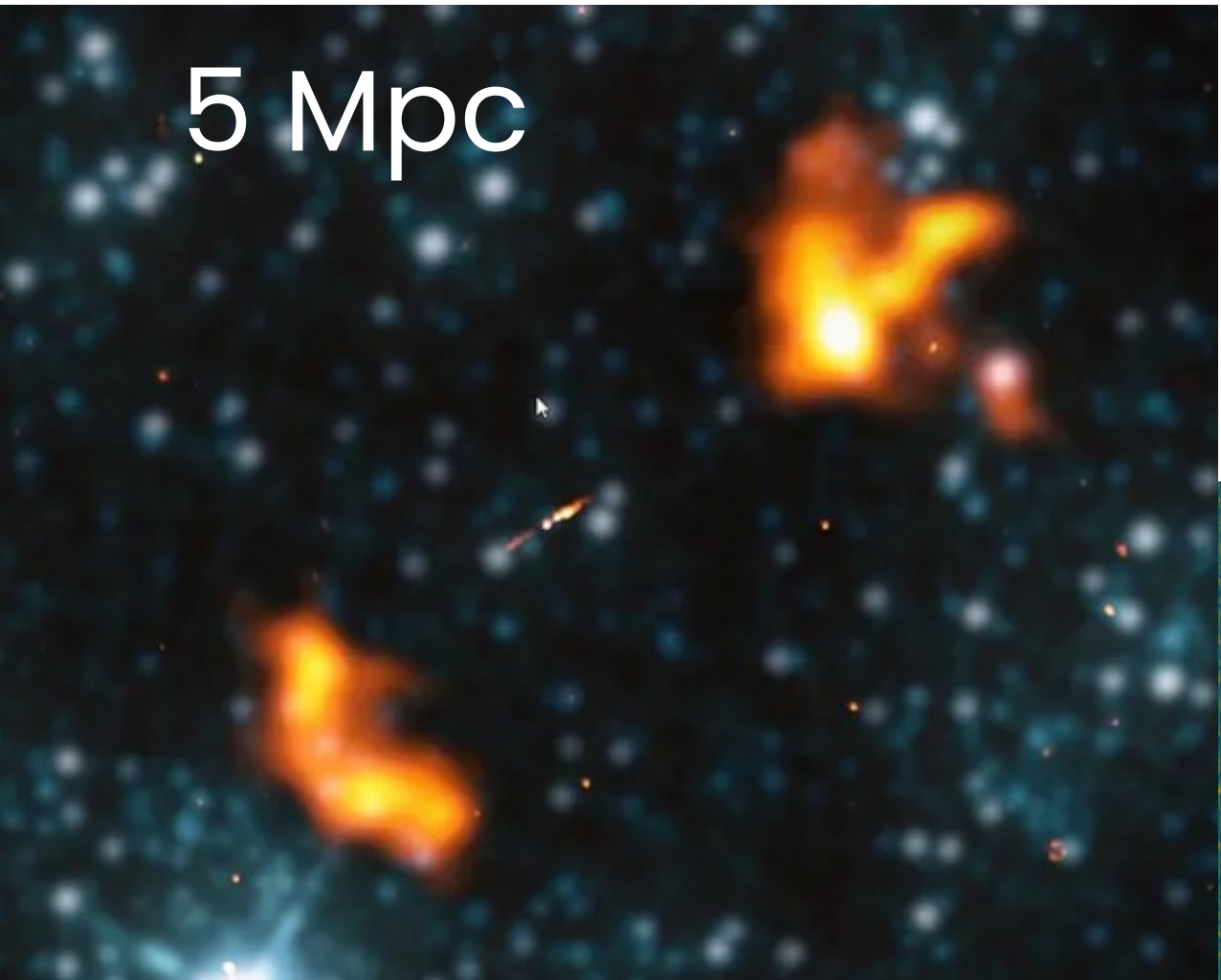
Galaxy-scale jets in the LOFAR-VLBI Deep Fields

Giulia Lusetti

PDRA at the Open University

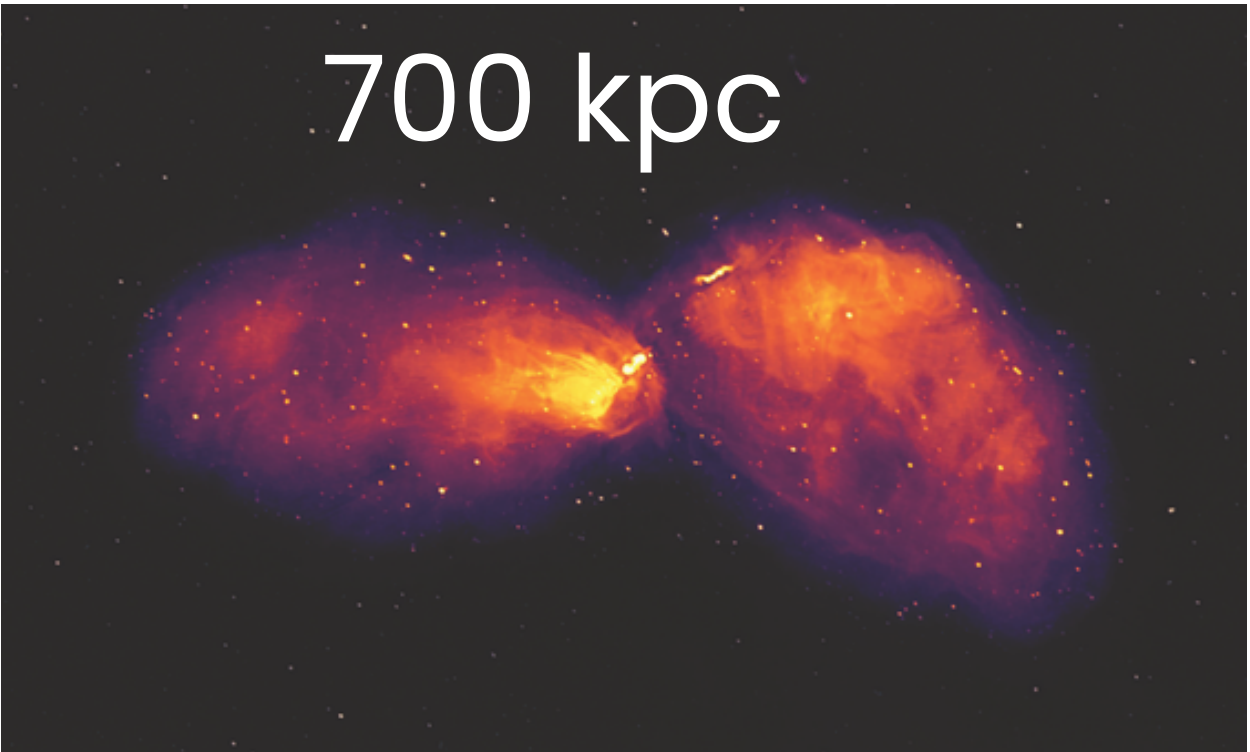
giulia.lusetti@open.ac.uk

AGN feedback is a multi-scale problem

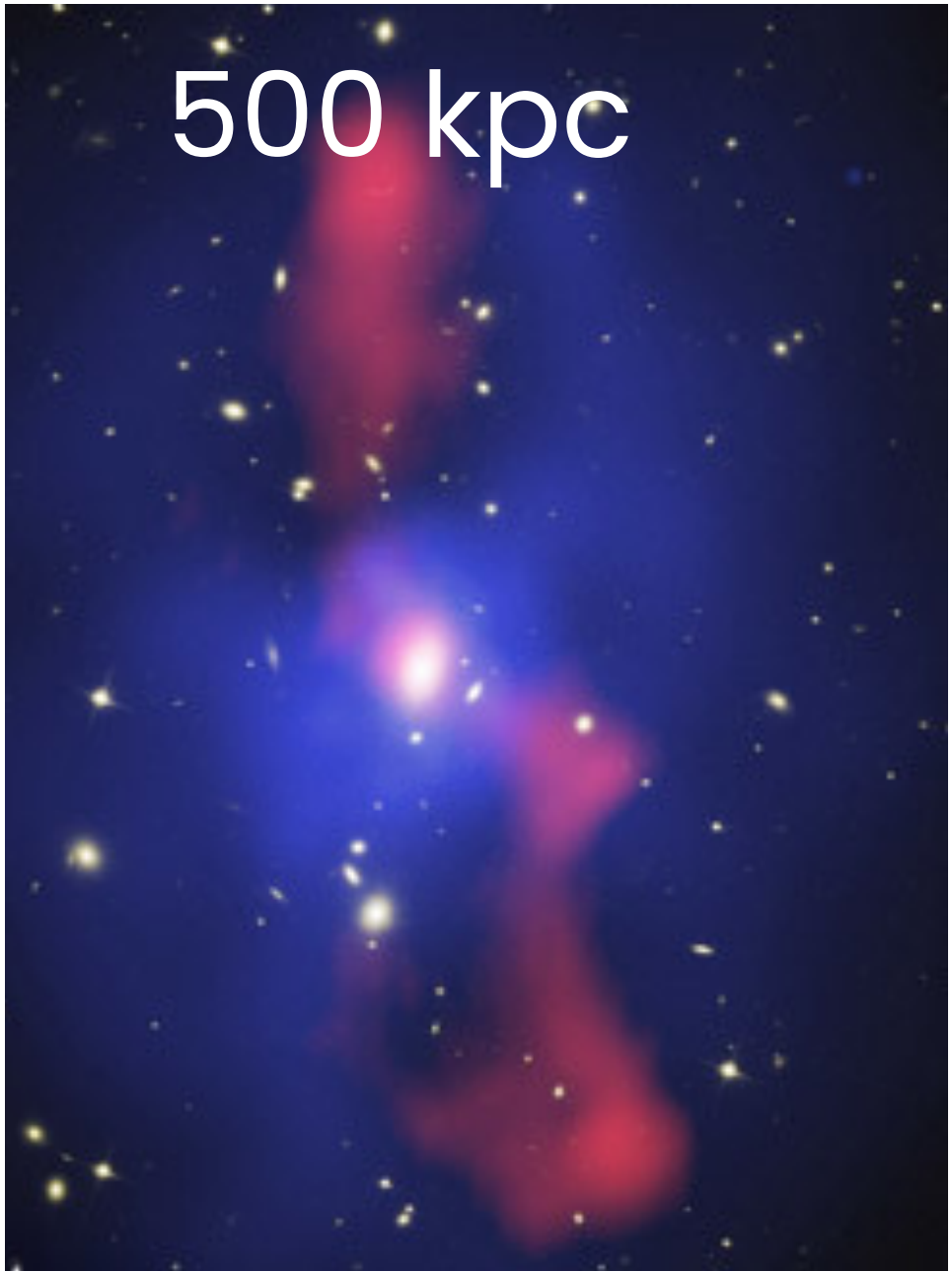


Oei +2022

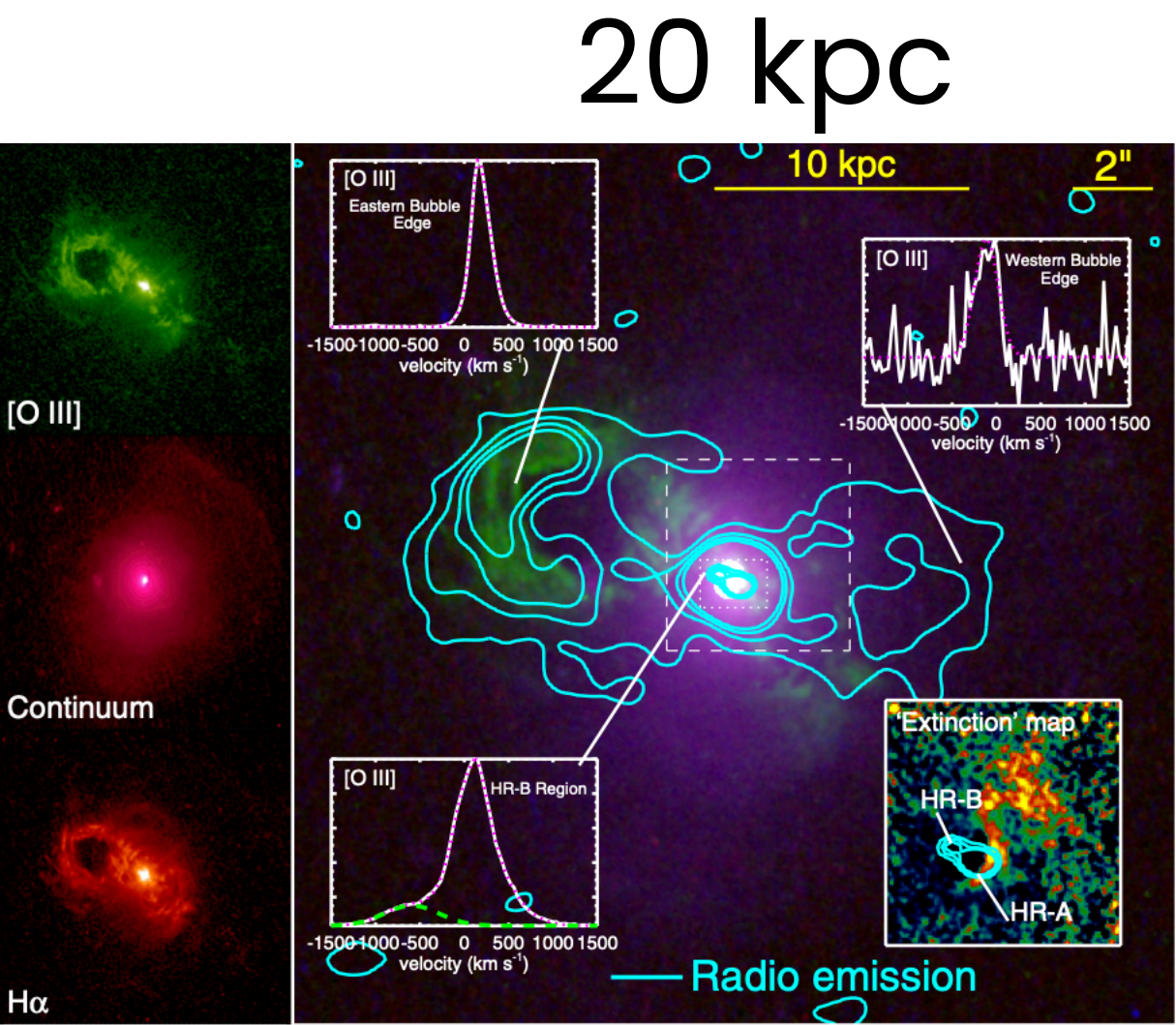
Oei+2024



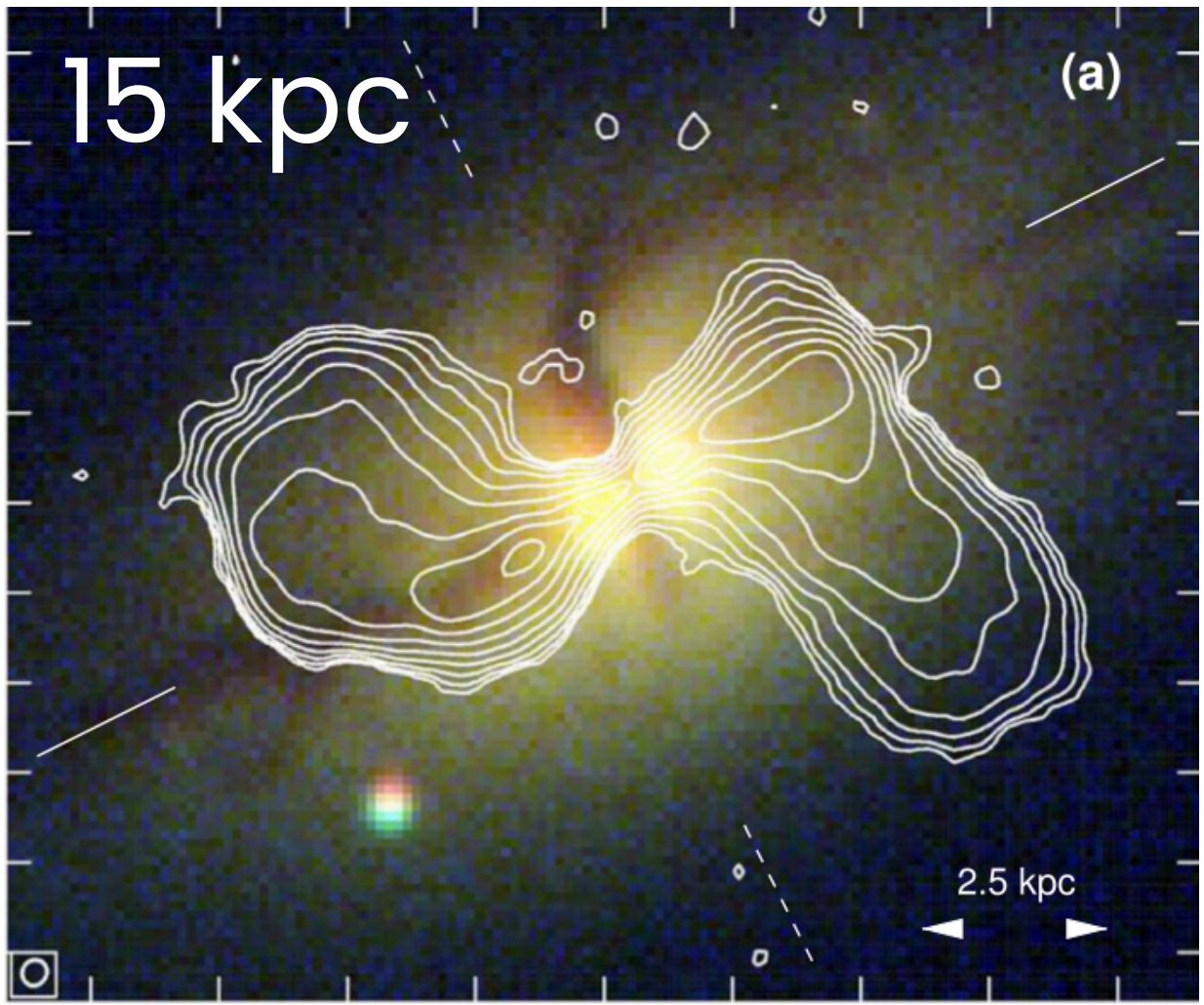
Credit: Ben McKinley



Credit: McNamara

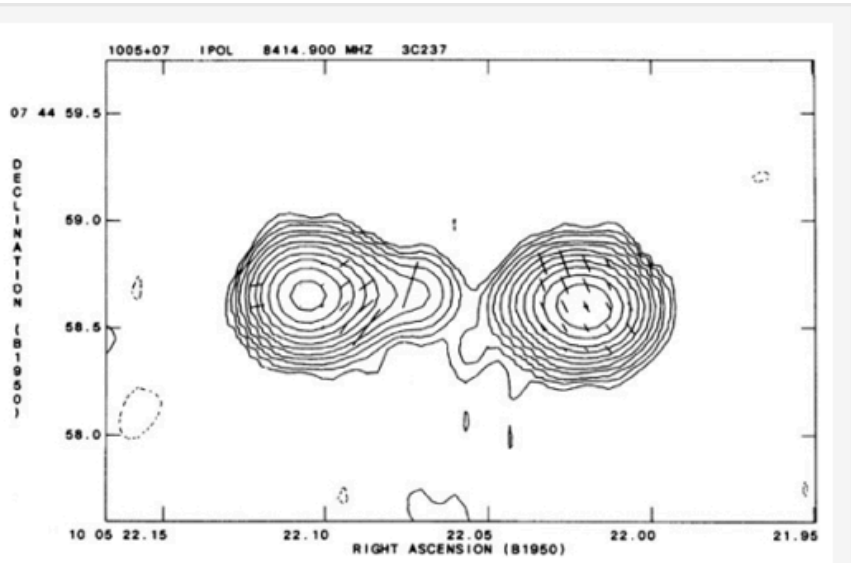
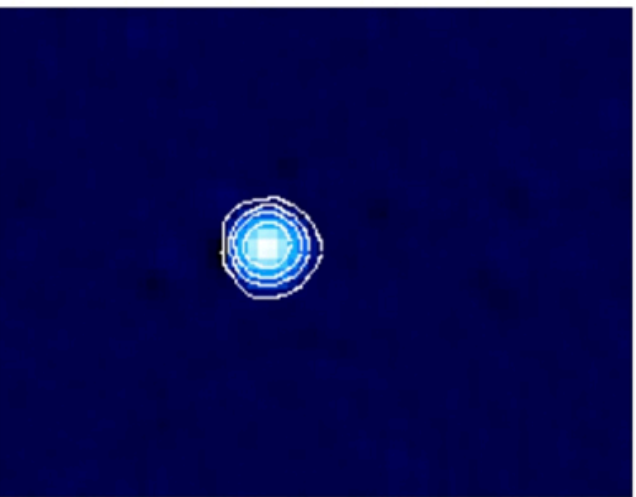


Harrison+2015



Heesen+2014

< 10 kpc

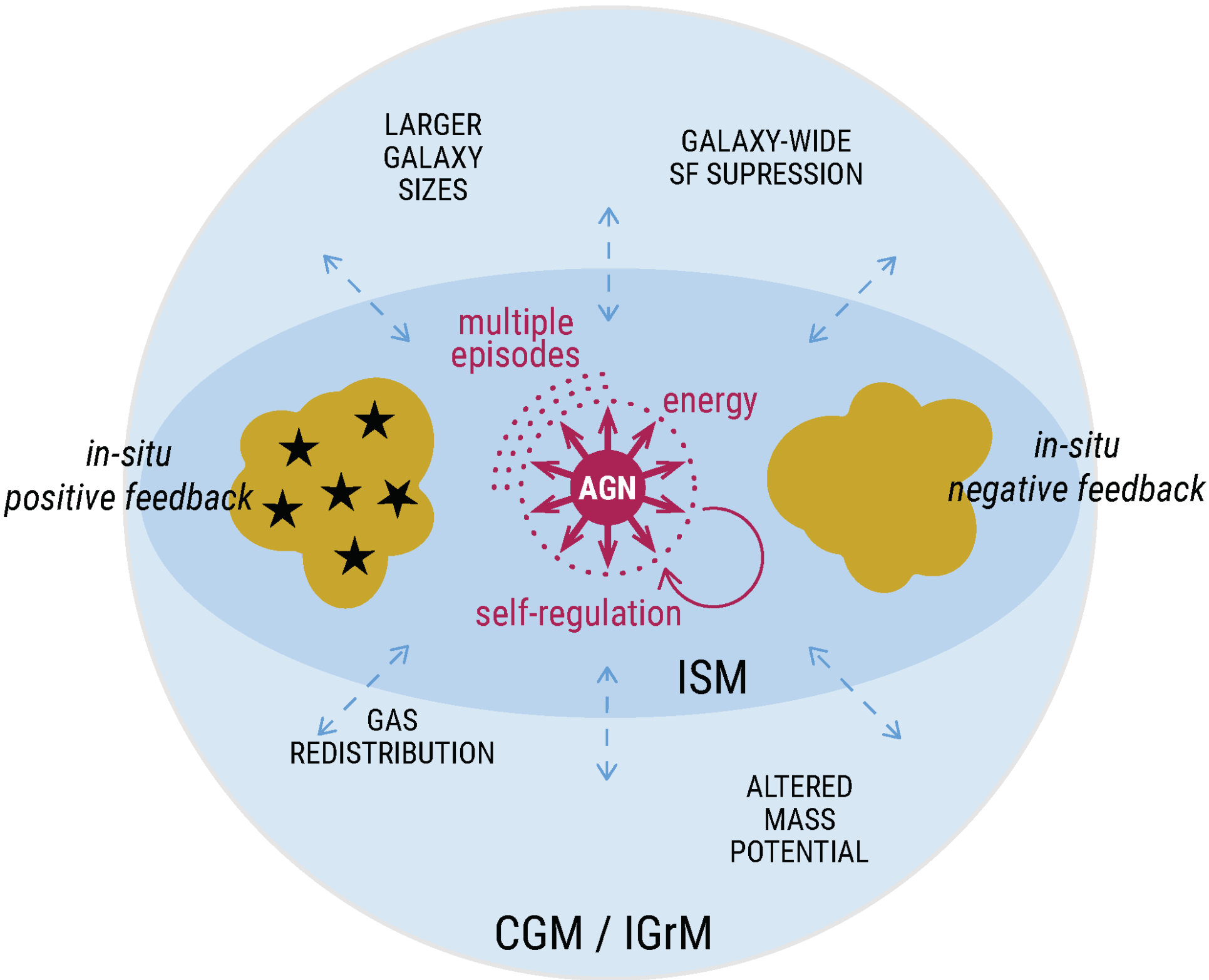
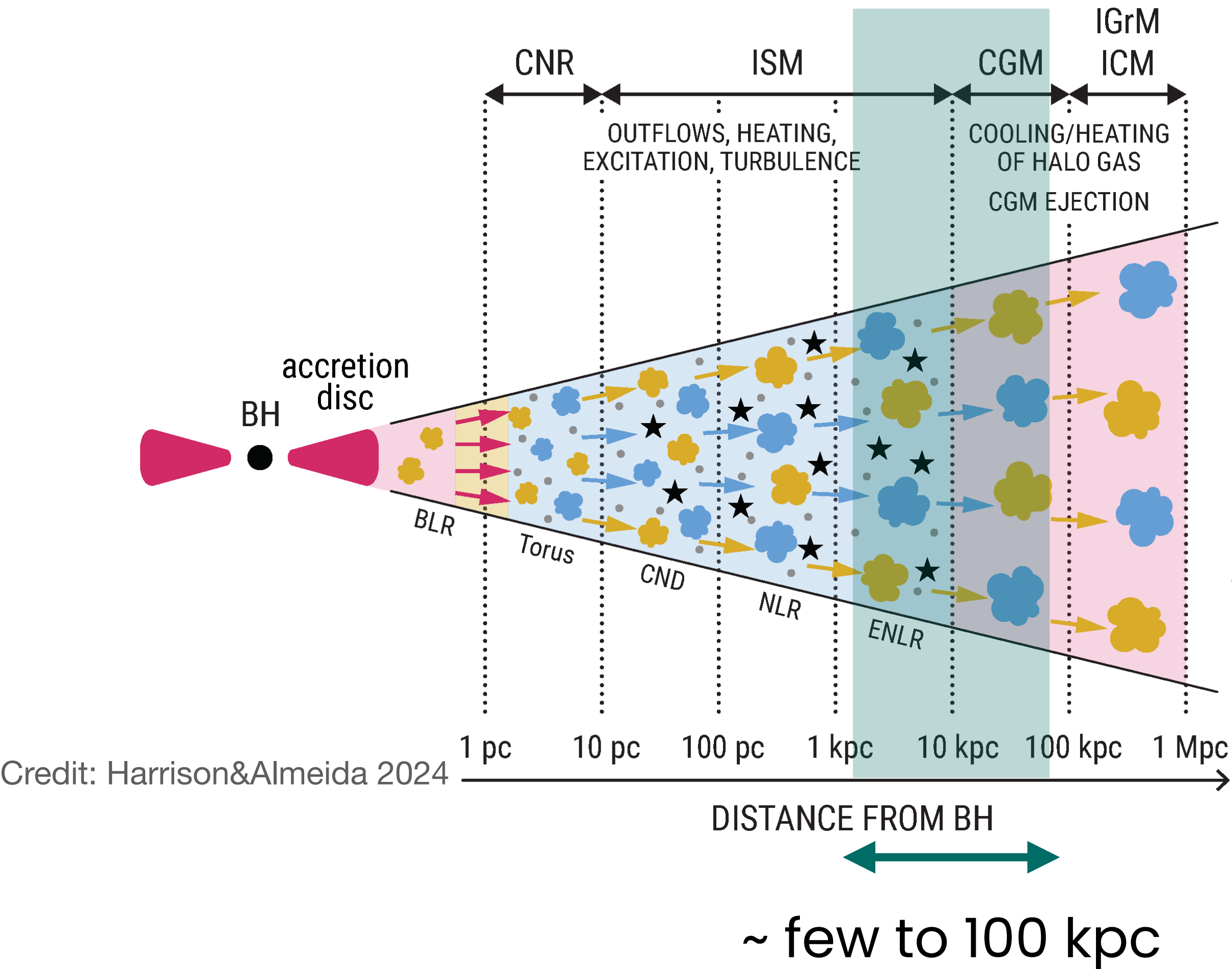


Akujor&Garrington+1995

The importance of small-scale jets

Galaxy-scale jets (GSJ):

radio jets extend $\sim$ host galaxy size (< 100 kpc)



Credit: Harrison&Almeida 2024

The importance of small-scale jets

- **Observations**

- Evidence of **shock/shock heating** on galactic scales (Croston+2009, Heesen+2014)
- Low-power, galaxy-scale radio sources can inject **energy comparable** to the thermal energy of the ISM (Webster+2021a, +2021b)
- Radio jets can interact with the ionized gas in the local ISM and driving **high-velocity outflows** (e.g., Harrison+2015)

- **Simulations**

- Young jets **efficiently couple** to the dense ISM, depositing up to 10–20% of jet energy into the ISM, and creating local outflows and gas heating (Mukherjee, 2025 review)

The importance of small-scale jets

Galaxy-scale jets (GSJ):

radio jets extend $\sim$ host galaxy size (< 100 kpc)

Galaxy-scale jets sample in order to study:

- The feedback impact on the host galaxy
- Radio galaxy duty-cycle

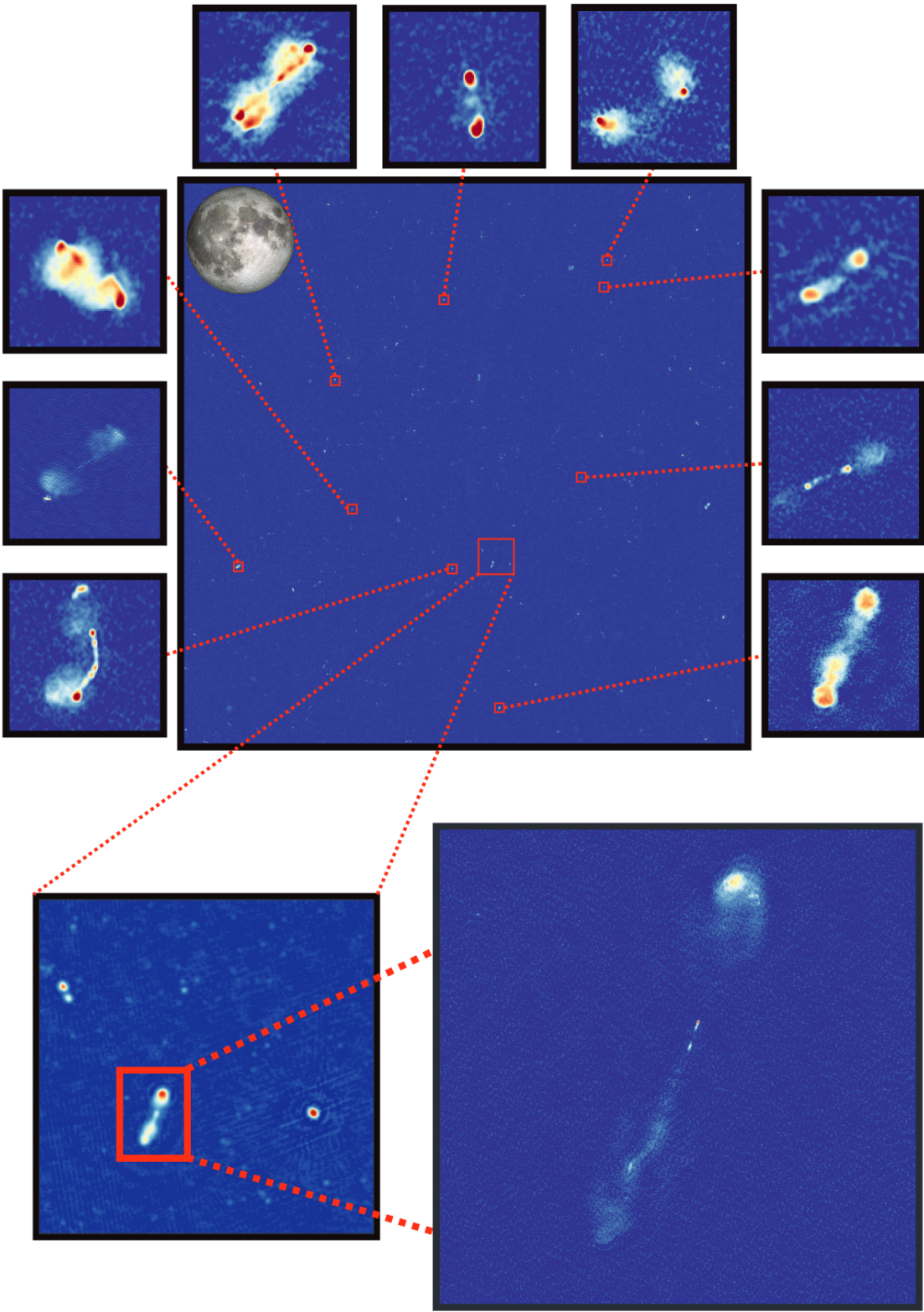
10–50 kpc sources up to $z \sim 3 \rightarrow 1\text{--}6$ arcsec size

High-sensitivity

High-resolution

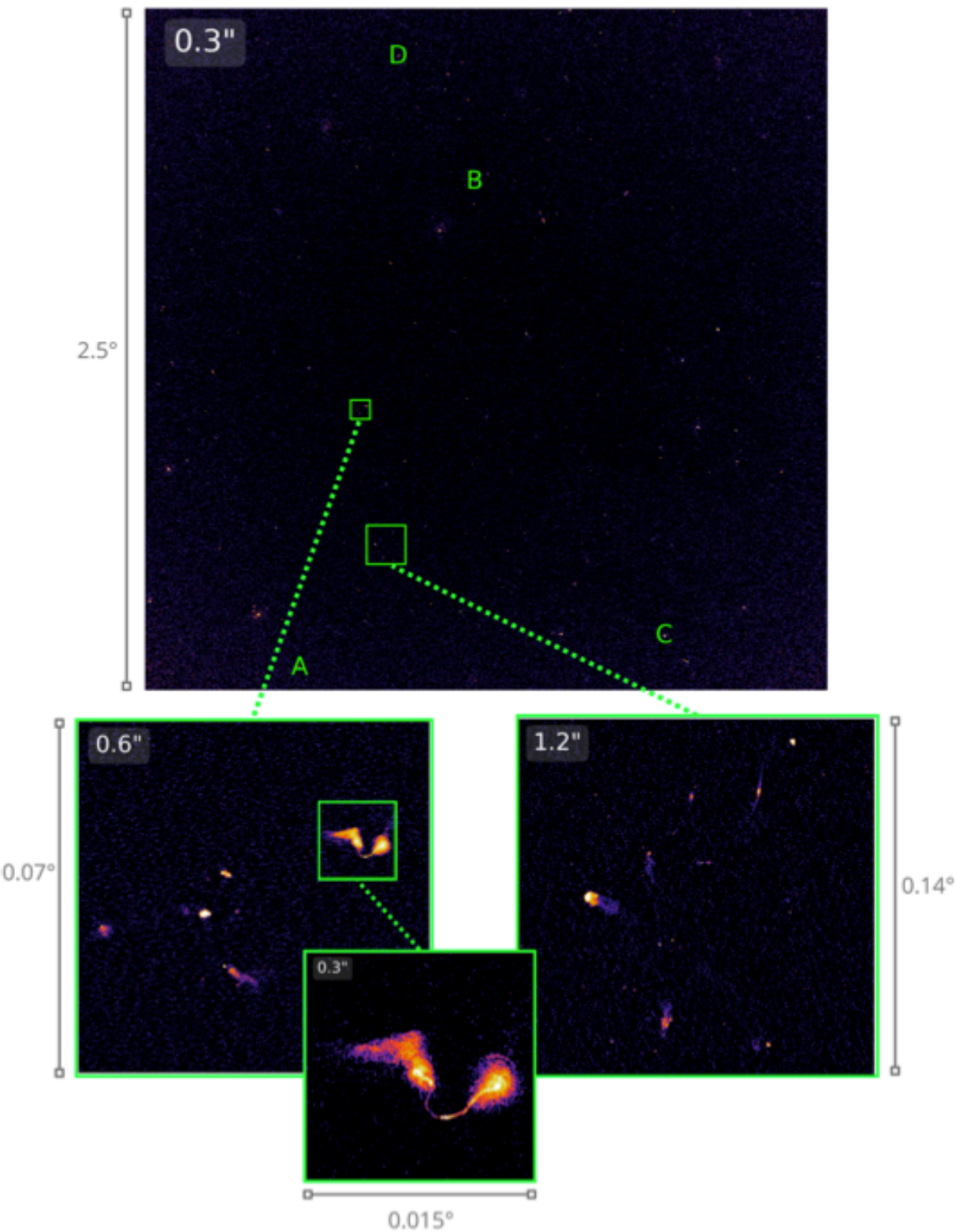
LOFAR-VLBI Deep Fields

Lockman Hole



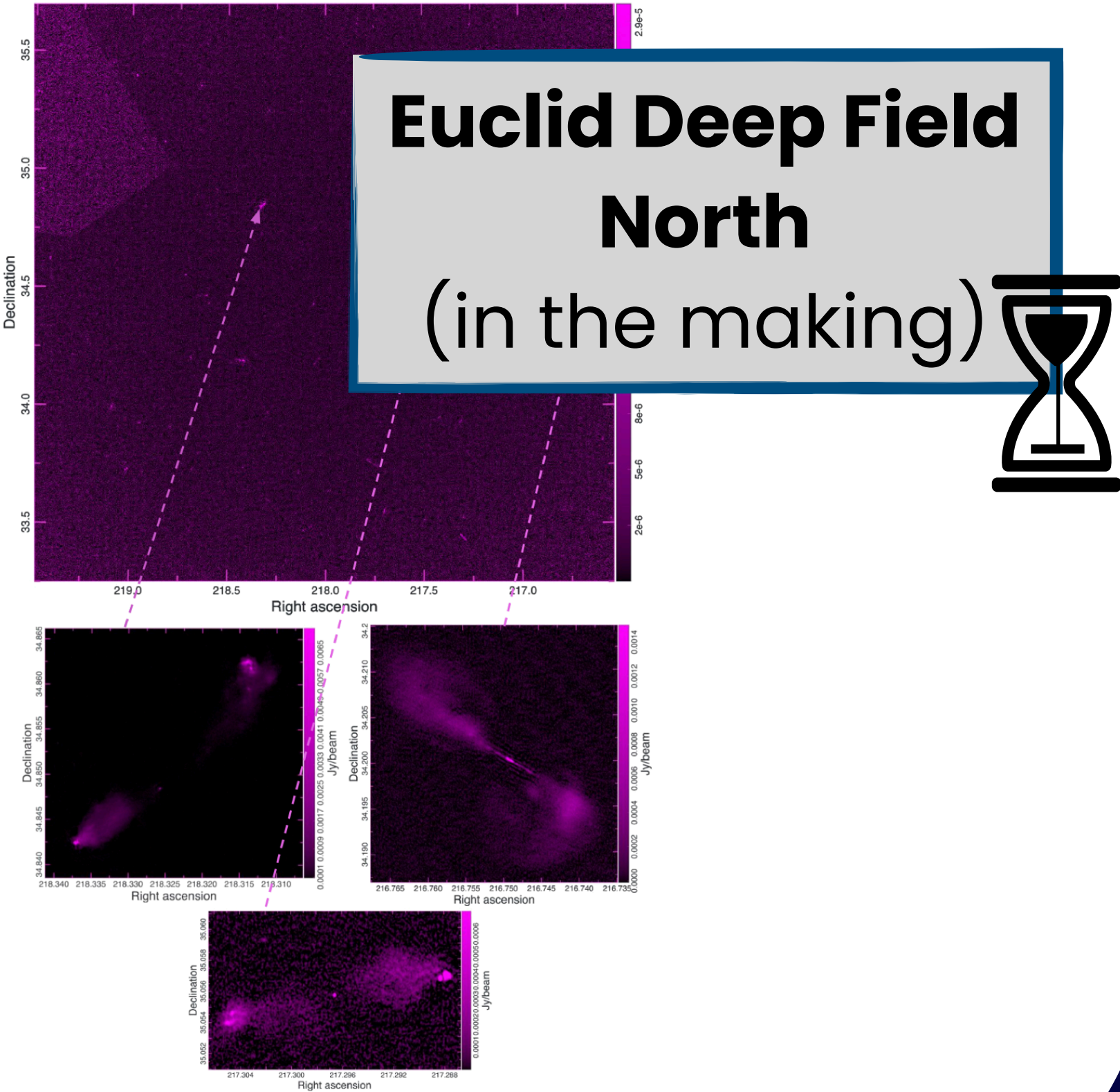
Sweijen+2022

ELIAS-N1



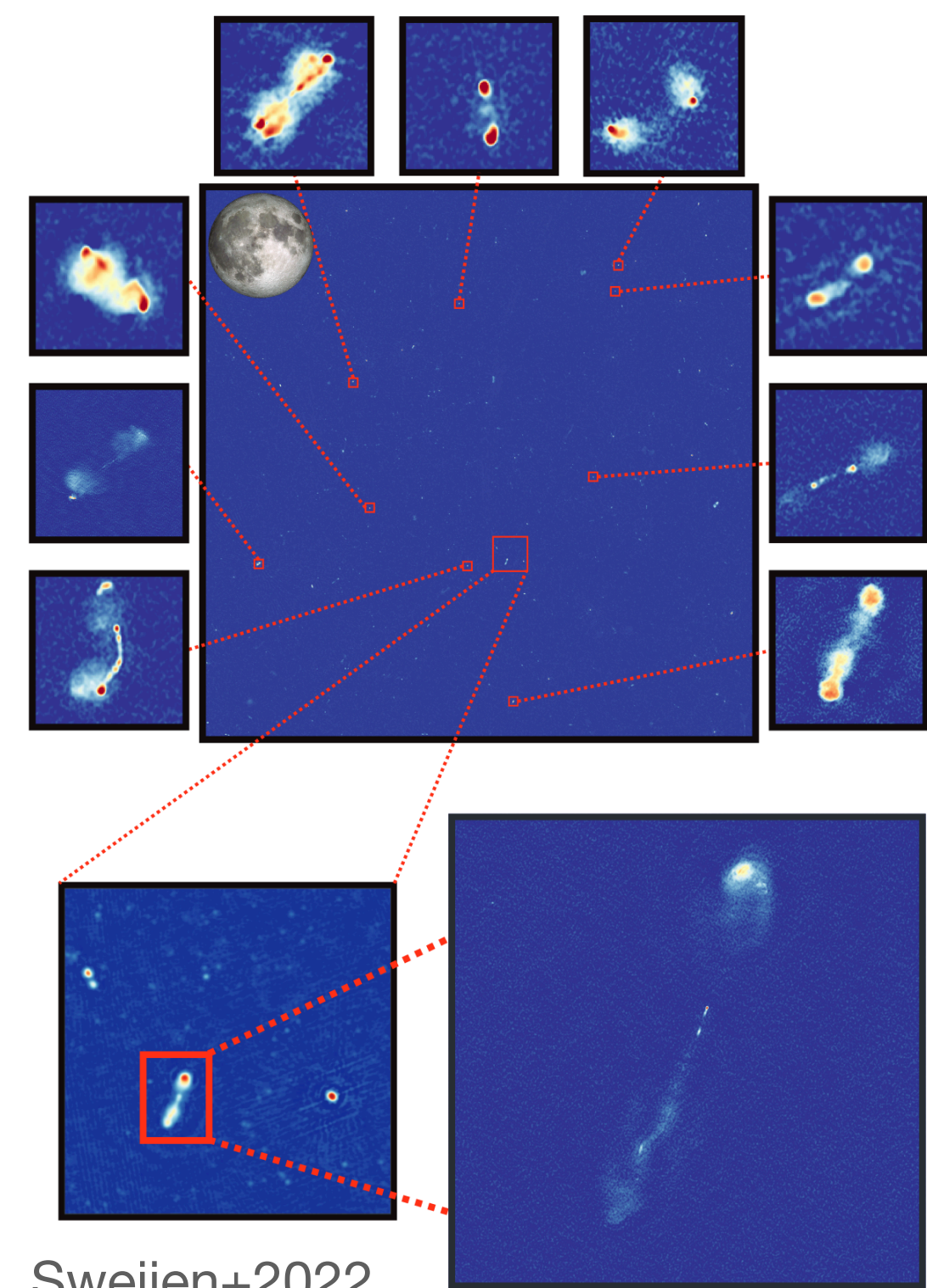
De Jong+2024

Boötes



Escott+2026

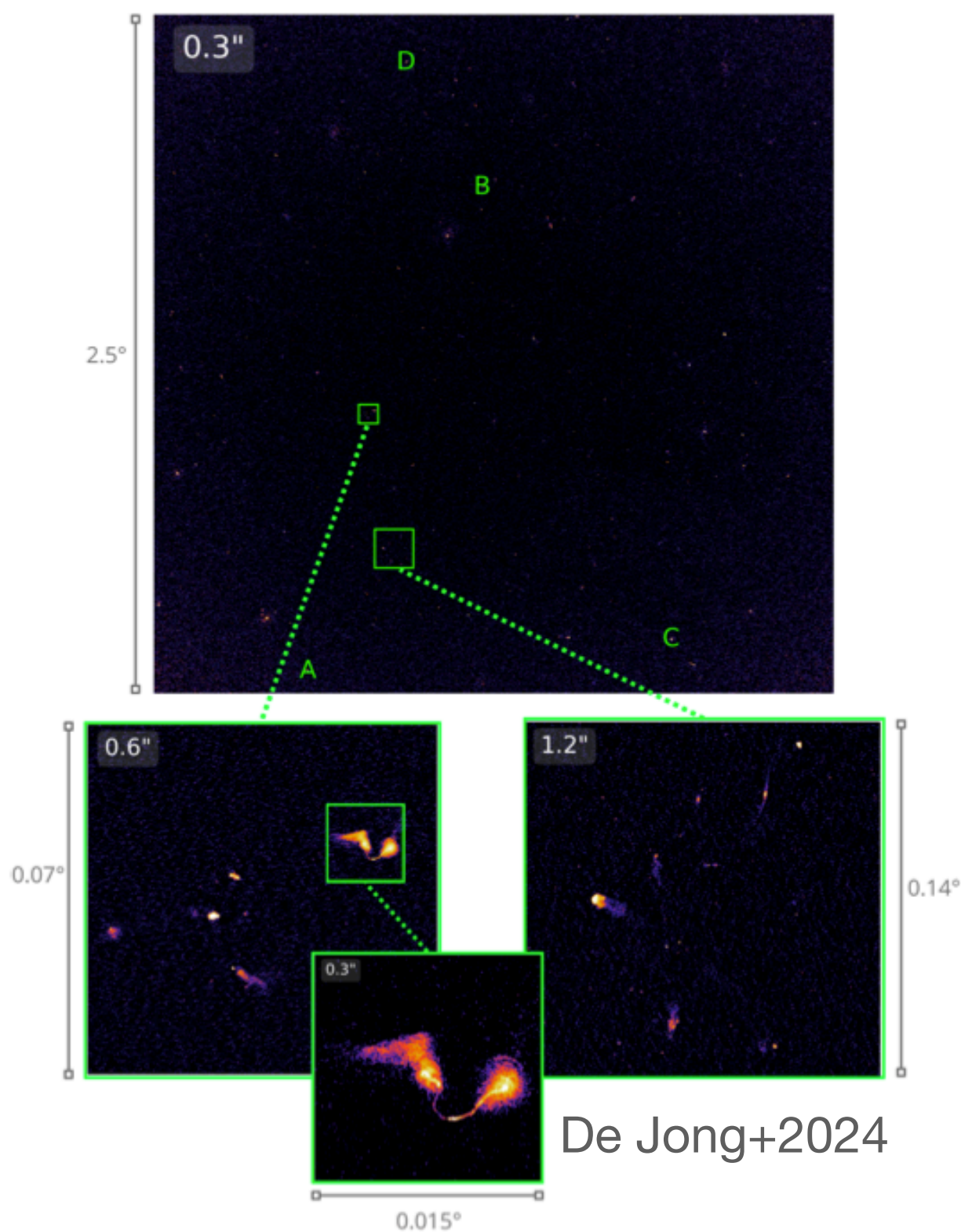
Lockman Hole



Sweijen+2022

LoTSS	6", 23 μ Jy/beam
VLBI	1.8", 50 μ Jy/beam
VLBI	0.4", 25 μ Jy/beam

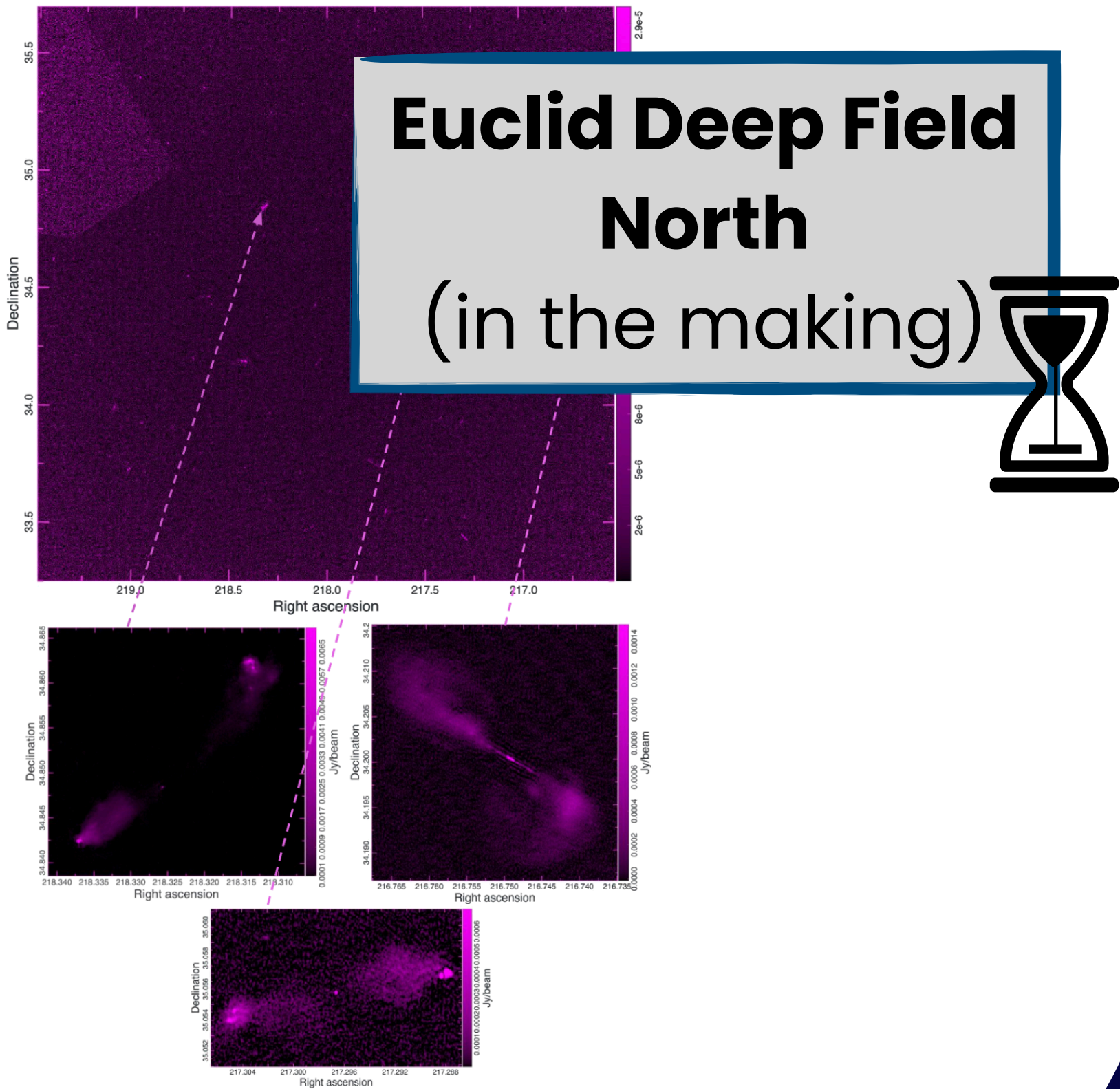
ELIAS-N1



De Jong+2024

LoTSS	6", ~20 μ Jy/beam
VLBI	1.2", 40 μ Jy/beam
VLBI	0.6", 21 μ Jy/beam
VLBI	0.3", 14 μ Jy/beam

Boötes



Euclid Deep Field
North
(in the making)

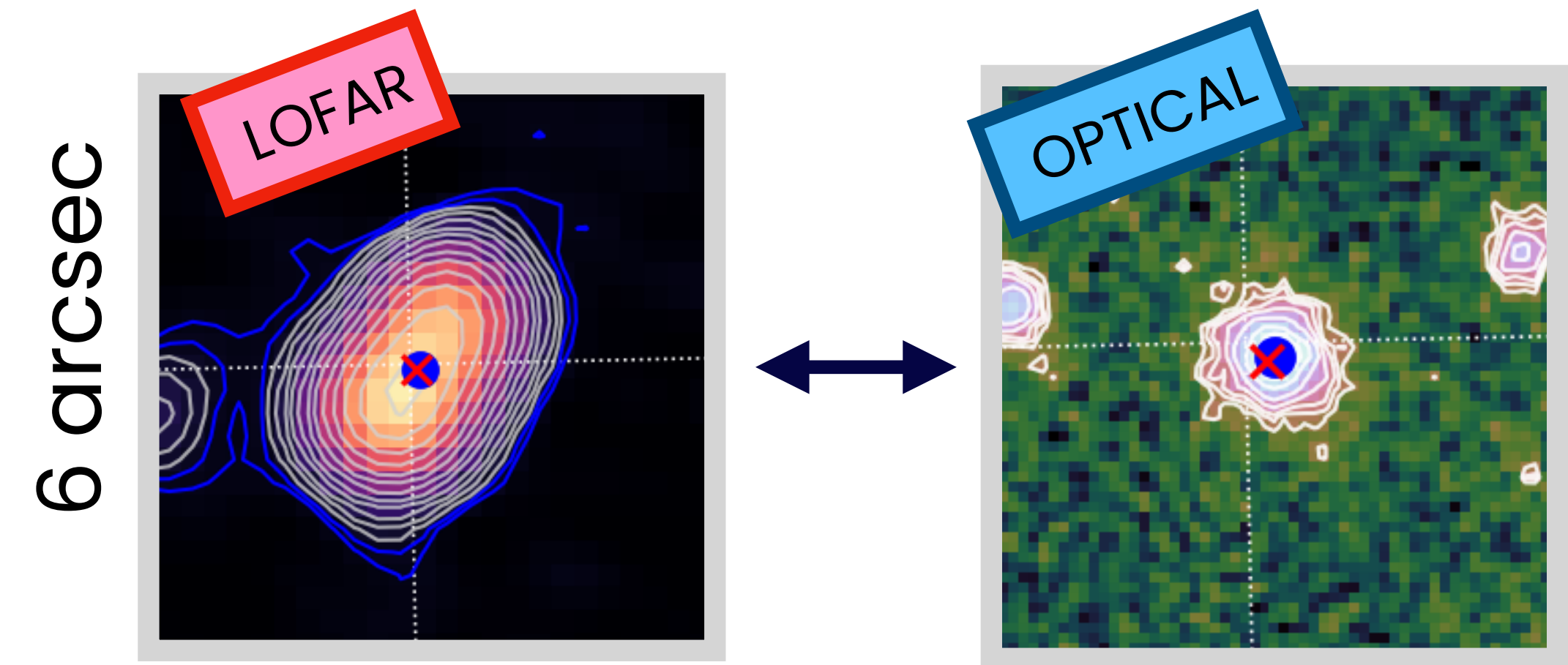


Escott+2026

Building the sample

A multi-step, collaborative effort

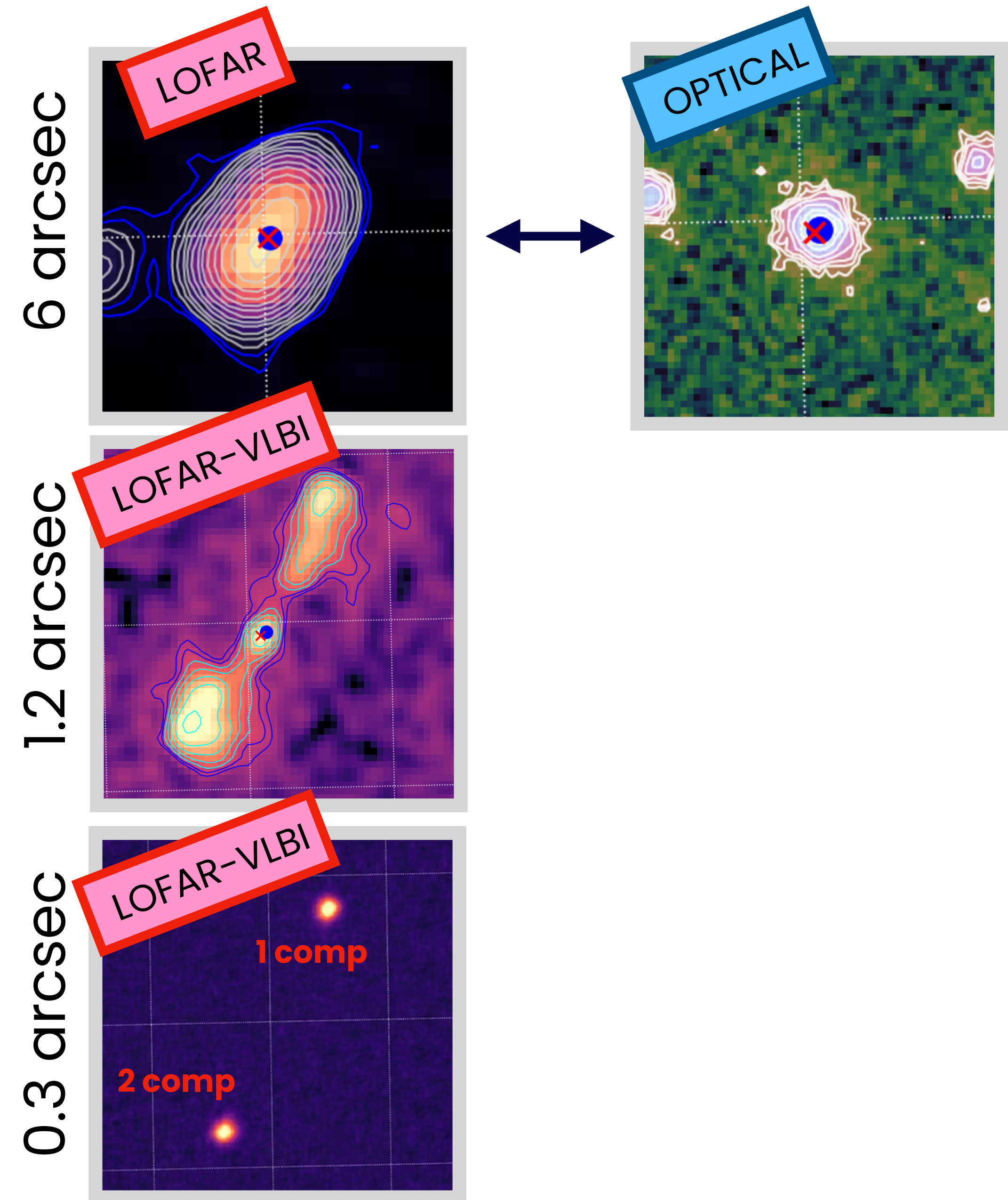
1. **Identification of radio sources (Sabater+2021) & optical crossmatching (Kondapally+2021)**
2. Multi-resolution association
3. Size & Flux density measurements (Sweijen+2025 and this work)
4. Morphological classification (helped by SED fitting classification from Best+2023)



Building the sample

A multi-step, collaborative effort

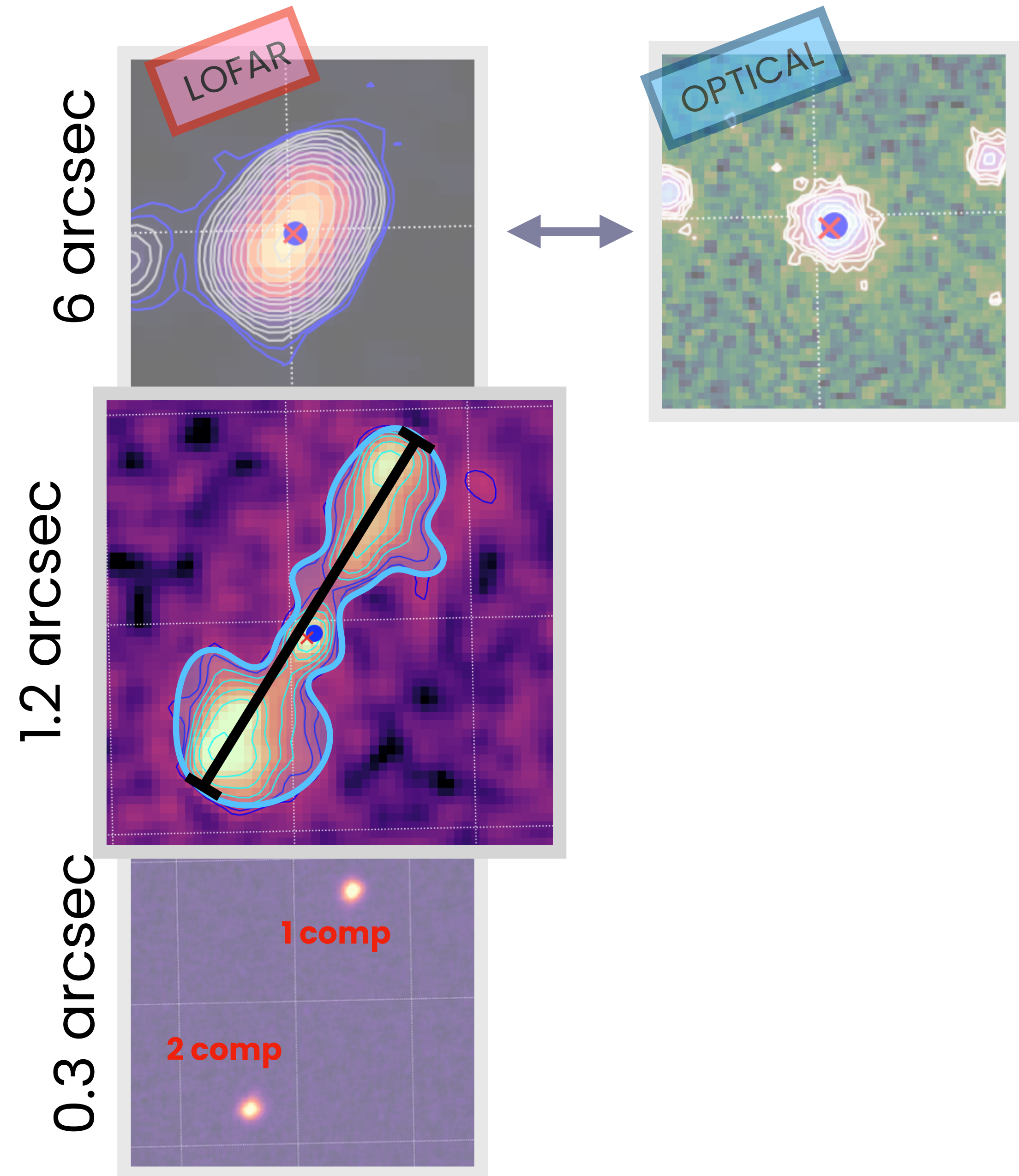
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Building the sample

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1. Identification of radio sources (Sabater+2021) & optical crossmatching (Kondapally+2021)
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4. Morphological classification (helped by SED fitting classification from Best+2023)

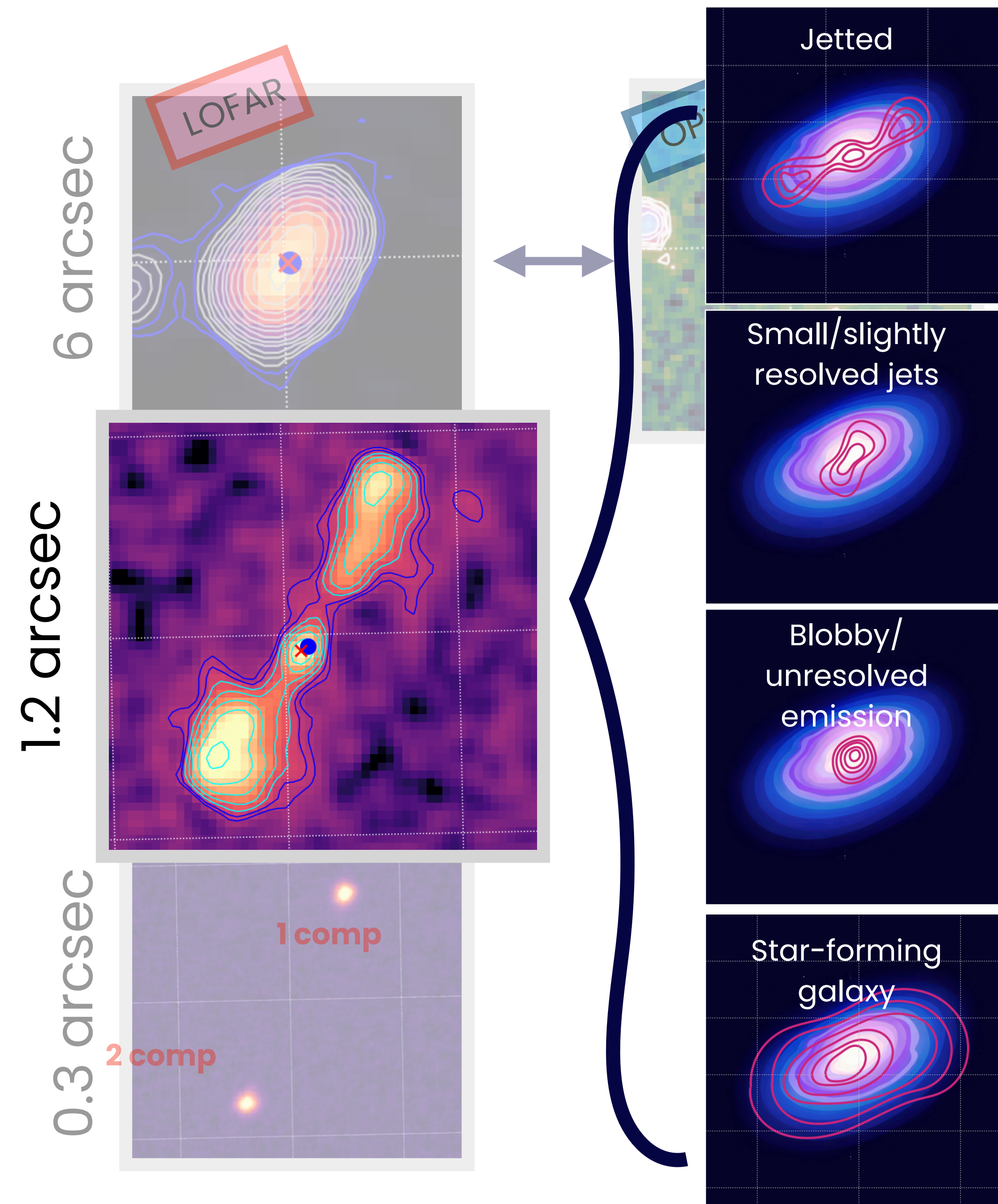


Building the sample

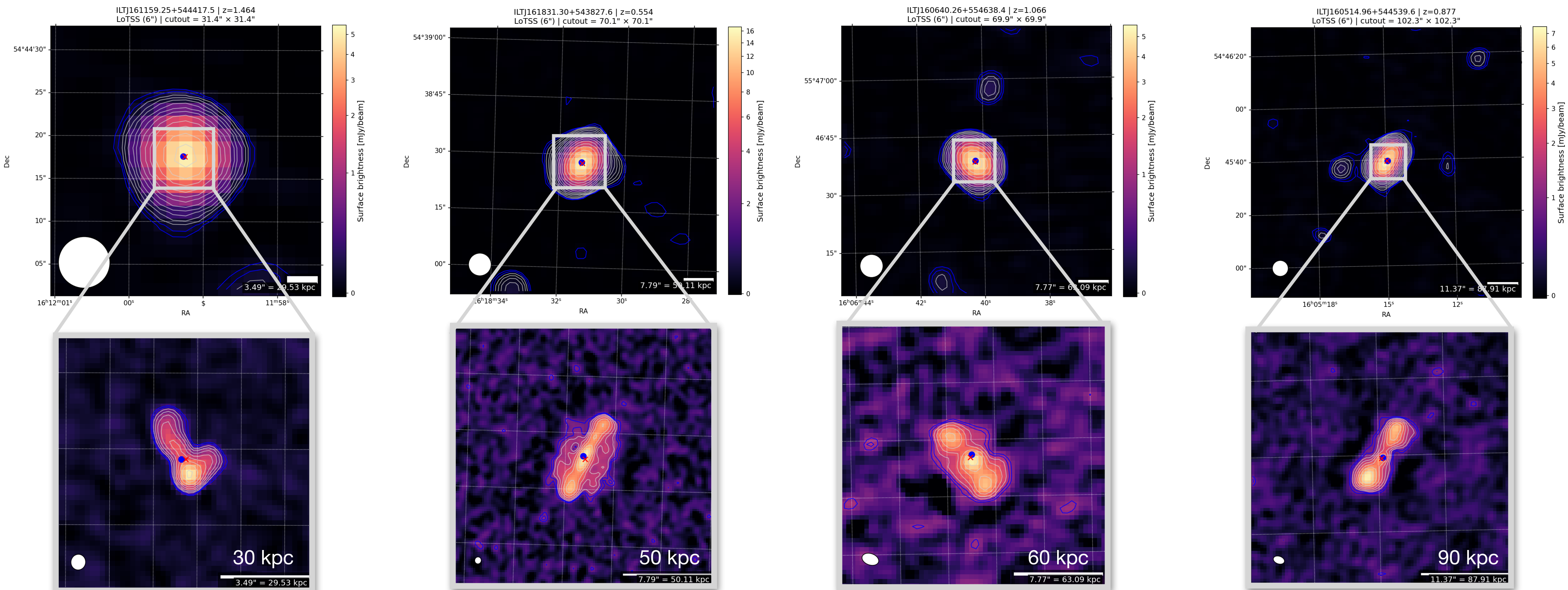
A multi-step, collaborative effort

1. Identification of radio sources (Sabater+2021) & optical crossmatching (Kondapally+2021)
2. Multi-resolution association
3. Size & Flux density measurements (Sweijen+2025 and this work)
4. **Morphological classification**
(helped by SED fitting classification from Best+2023)

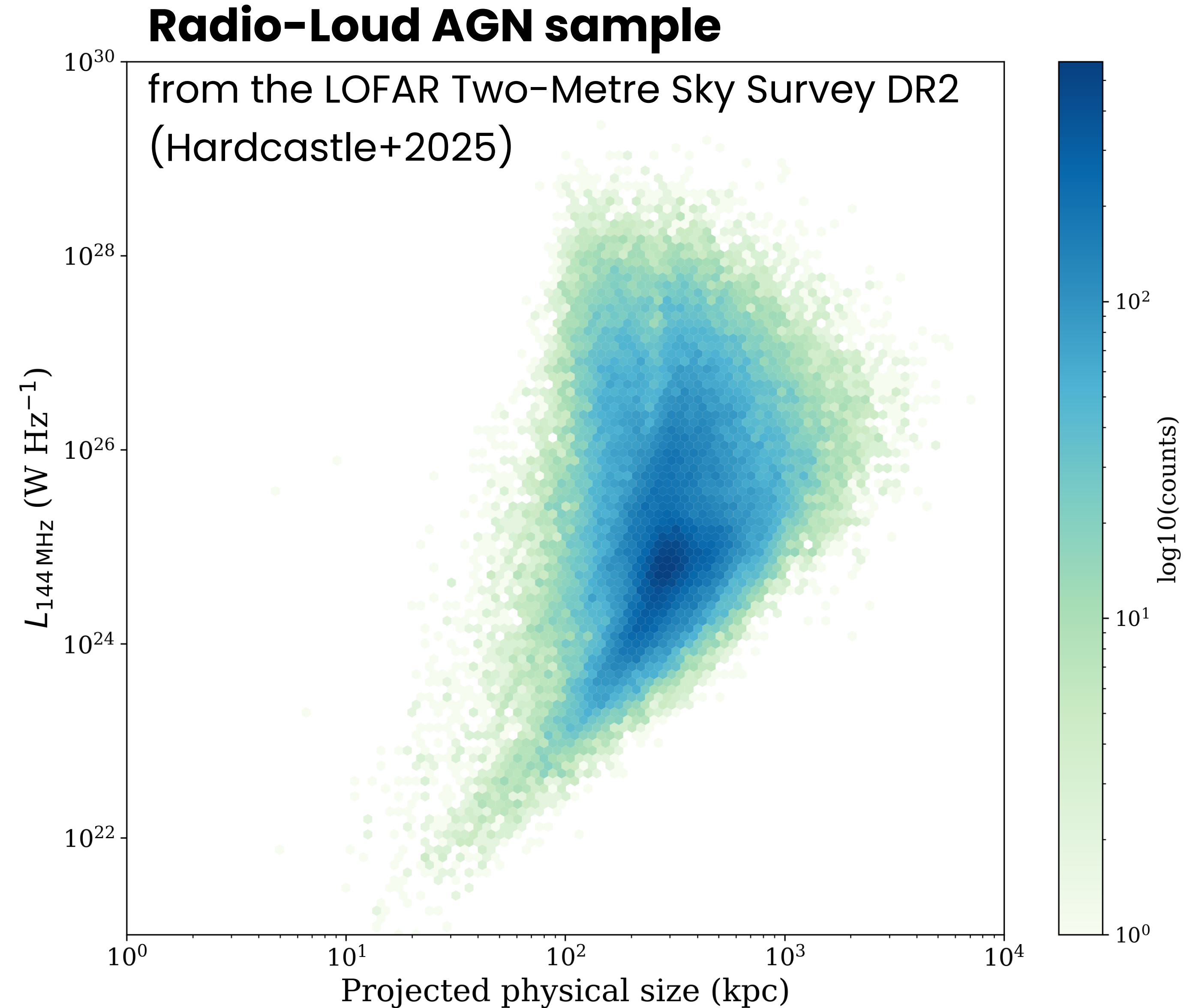
Repeat x each field!



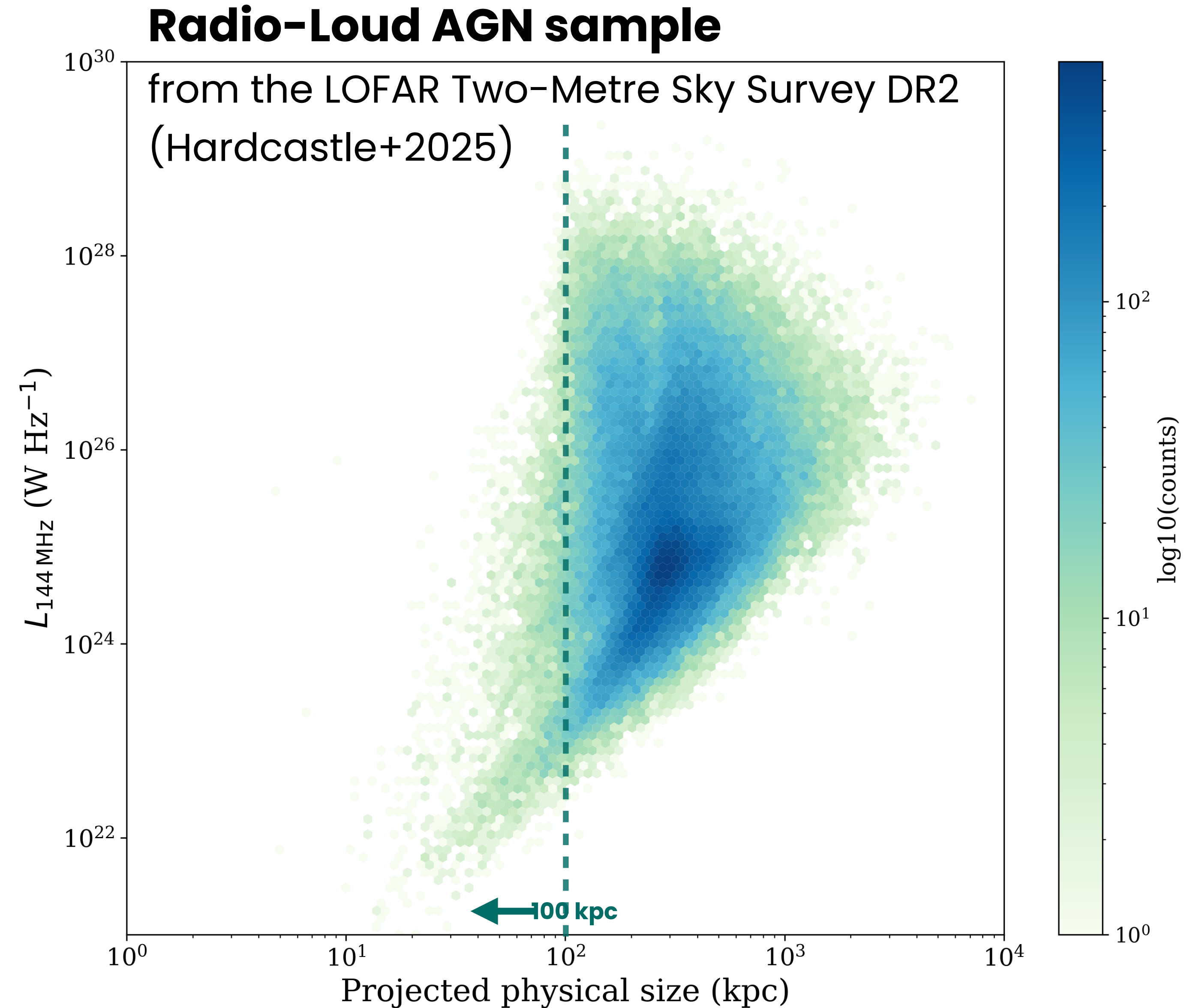
Resolving kpc-scale radio jets with LOFAR-VLBI



Luminosity-Size Diagram



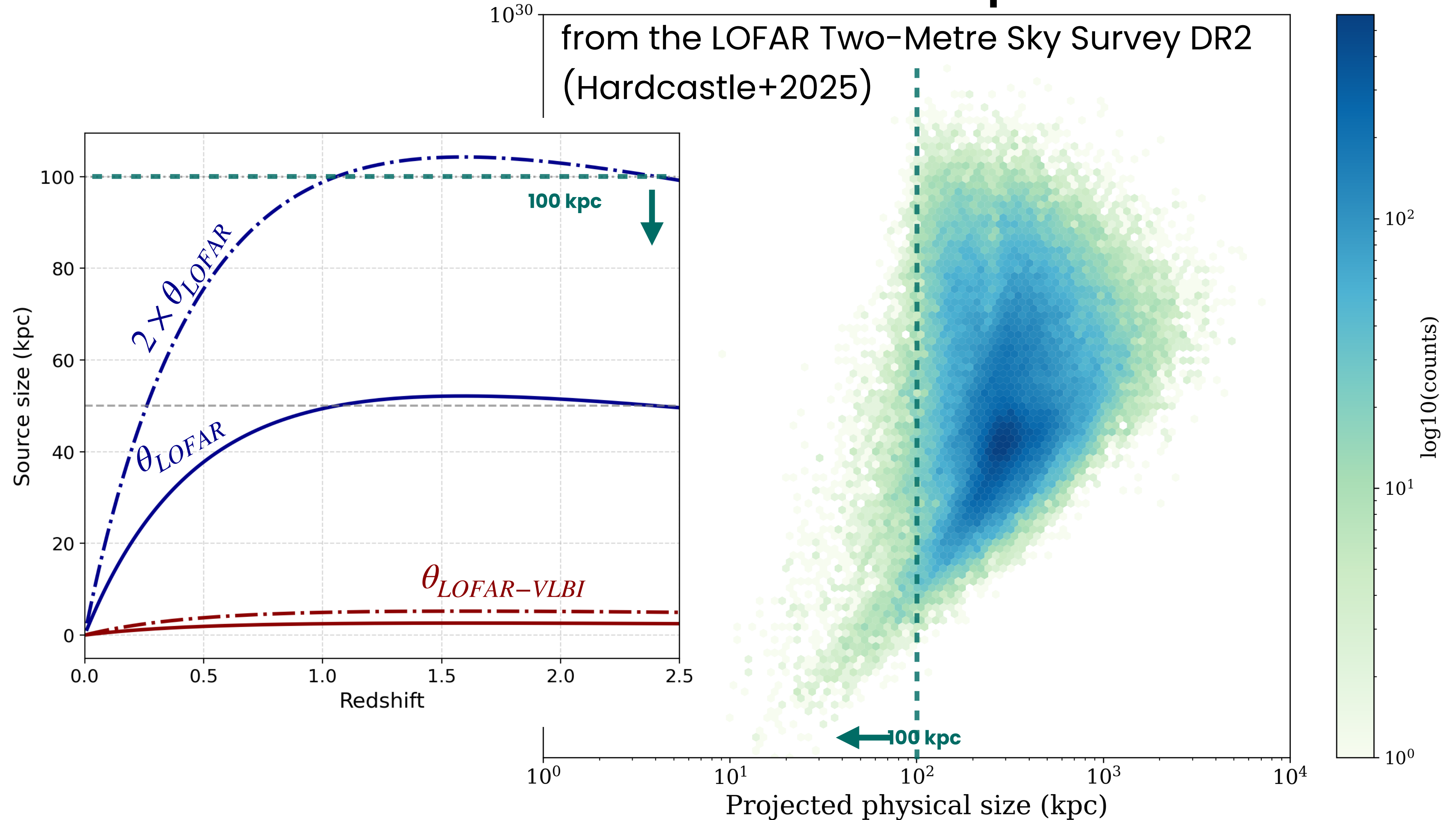
Luminosity-Size Diagram



Luminosity-Size Diagram

Radio-Loud AGN sample

from the LOFAR Two-Metre Sky Survey DR2
(Hardcastle+2025)



Luminosity-Size Diagram

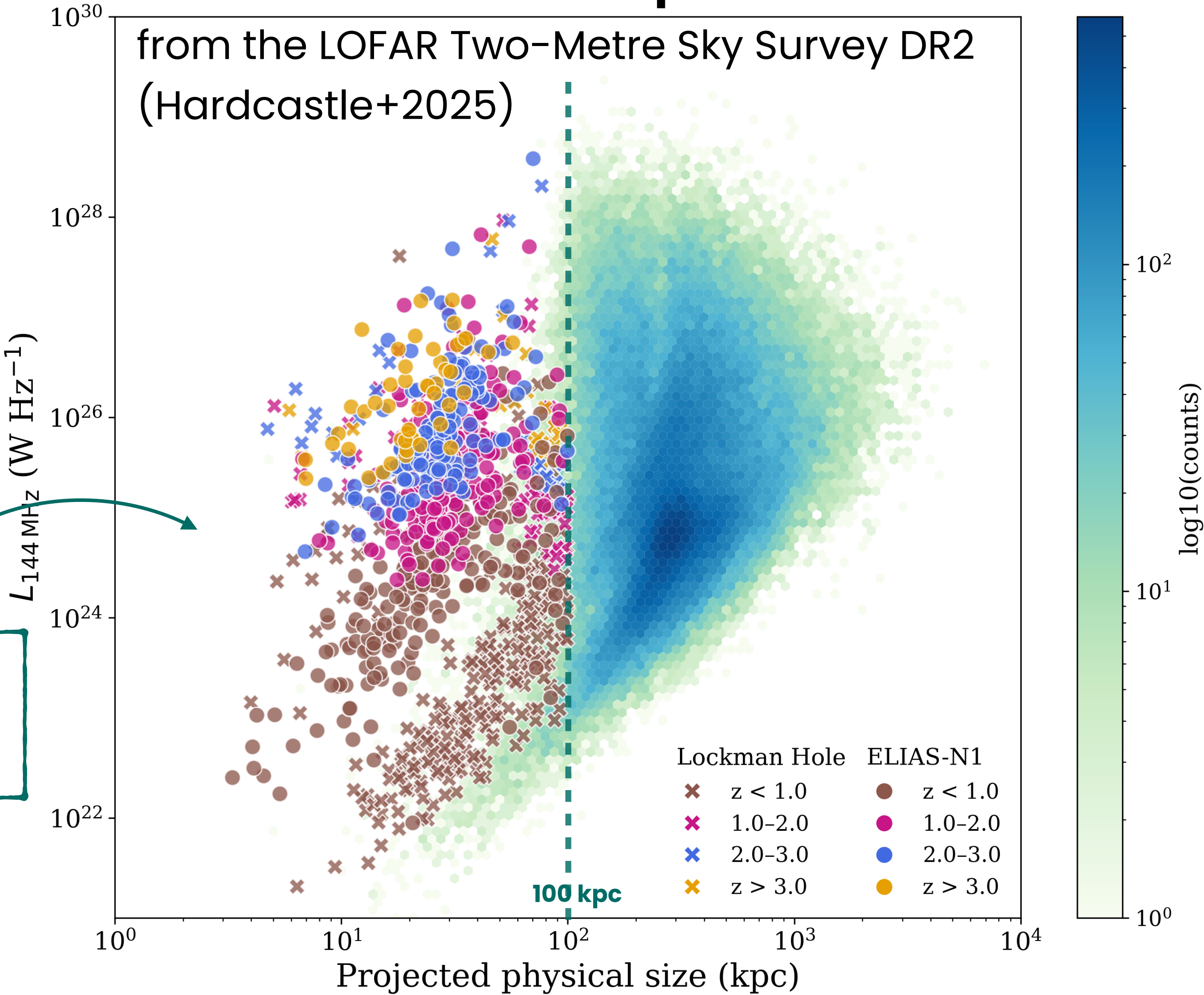
LOFAR-VLBI is able to detect and resolve a previously under-explored population of radio galaxies with physical size below ~100 kpc

LOFAR-VLBI based galaxy-scale jet sample

Lusetti+ in prep.

Radio-Loud AGN sample

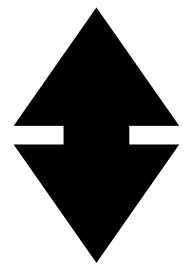
from the LOFAR Two-Metre Sky Survey DR2 (Hardcastle+2025)



Luminosity-Size Diagram

LOFAR-VLBI is able to detect and resolve a previously under-explored population of radio galaxies with physical size below ~100 kpc

$$L_{144 \text{ MHz}} \in [10^{22}, 10^{28}] \text{ W Hz}^{-1}$$



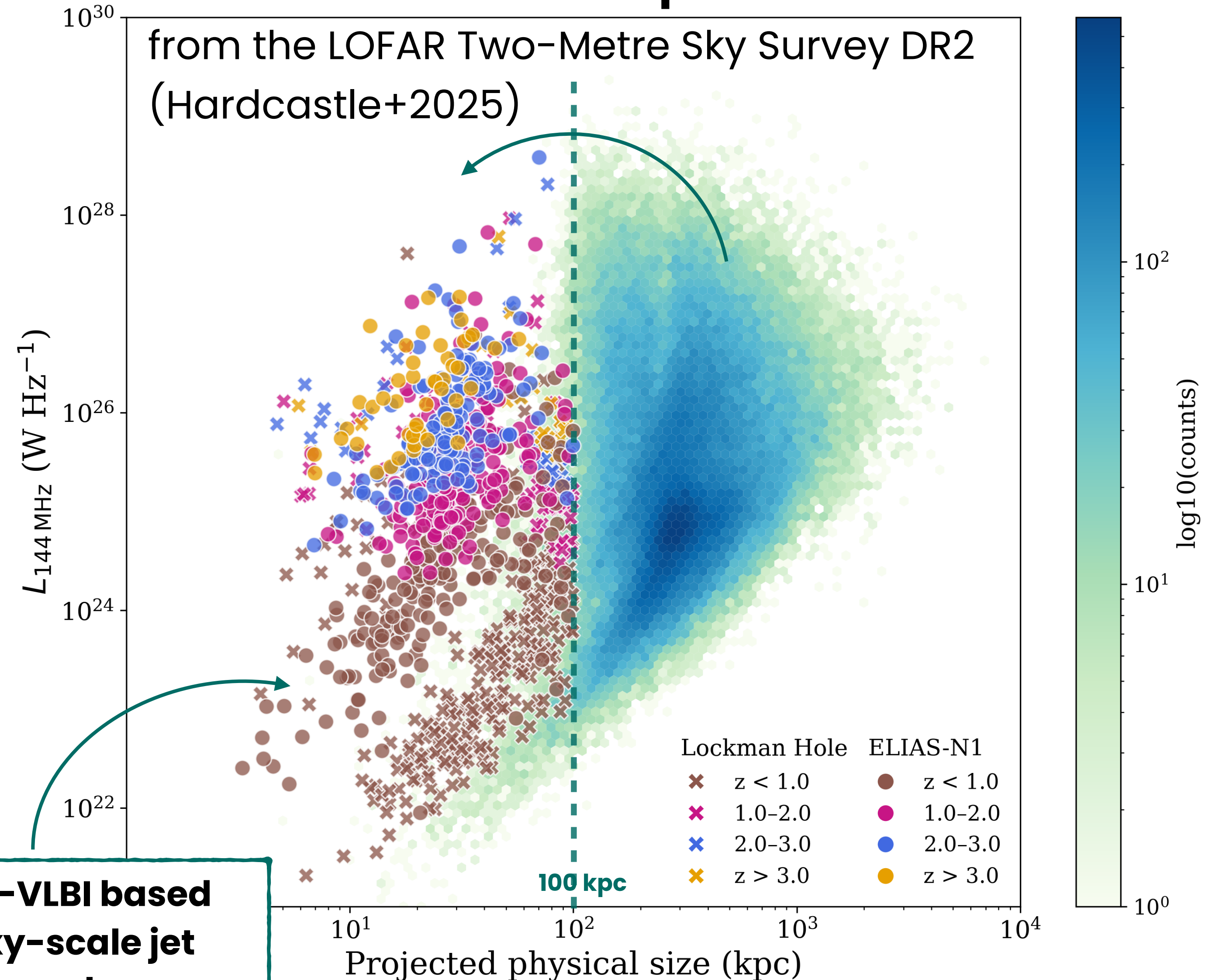
$$L_{150 \text{ MHz}} \in [3 \times 10^{22}, 1.5 \times 10^{25}] \text{ W Hz}^{-1}$$

Webster+2021, GJS in LoTSS

**LOFAR-VLBI based
galaxy-scale jet
sample**

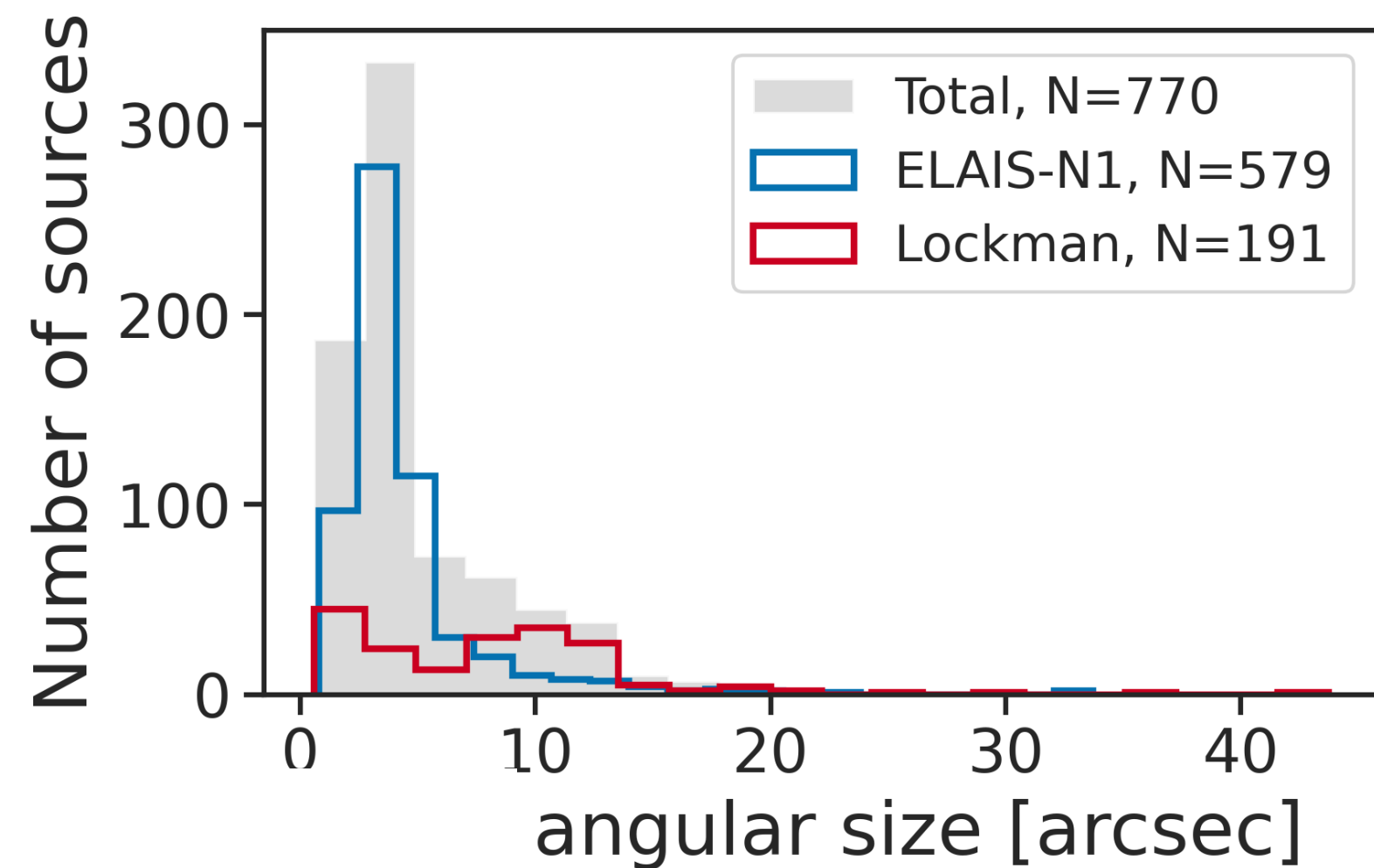
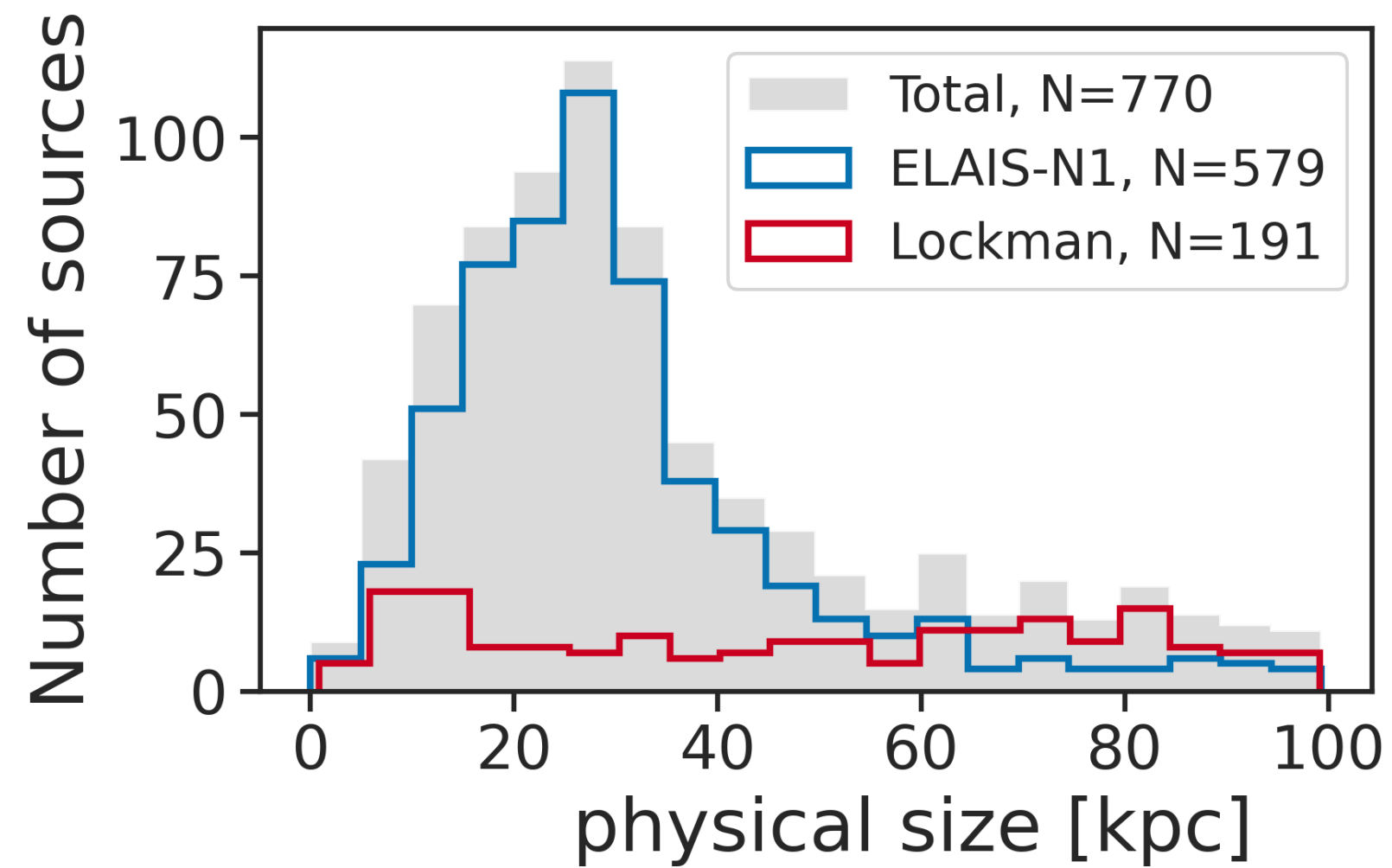
Radio-Loud AGN sample

from the LOFAR Two-Metre Sky Survey DR2
(Hardcastle+2025)

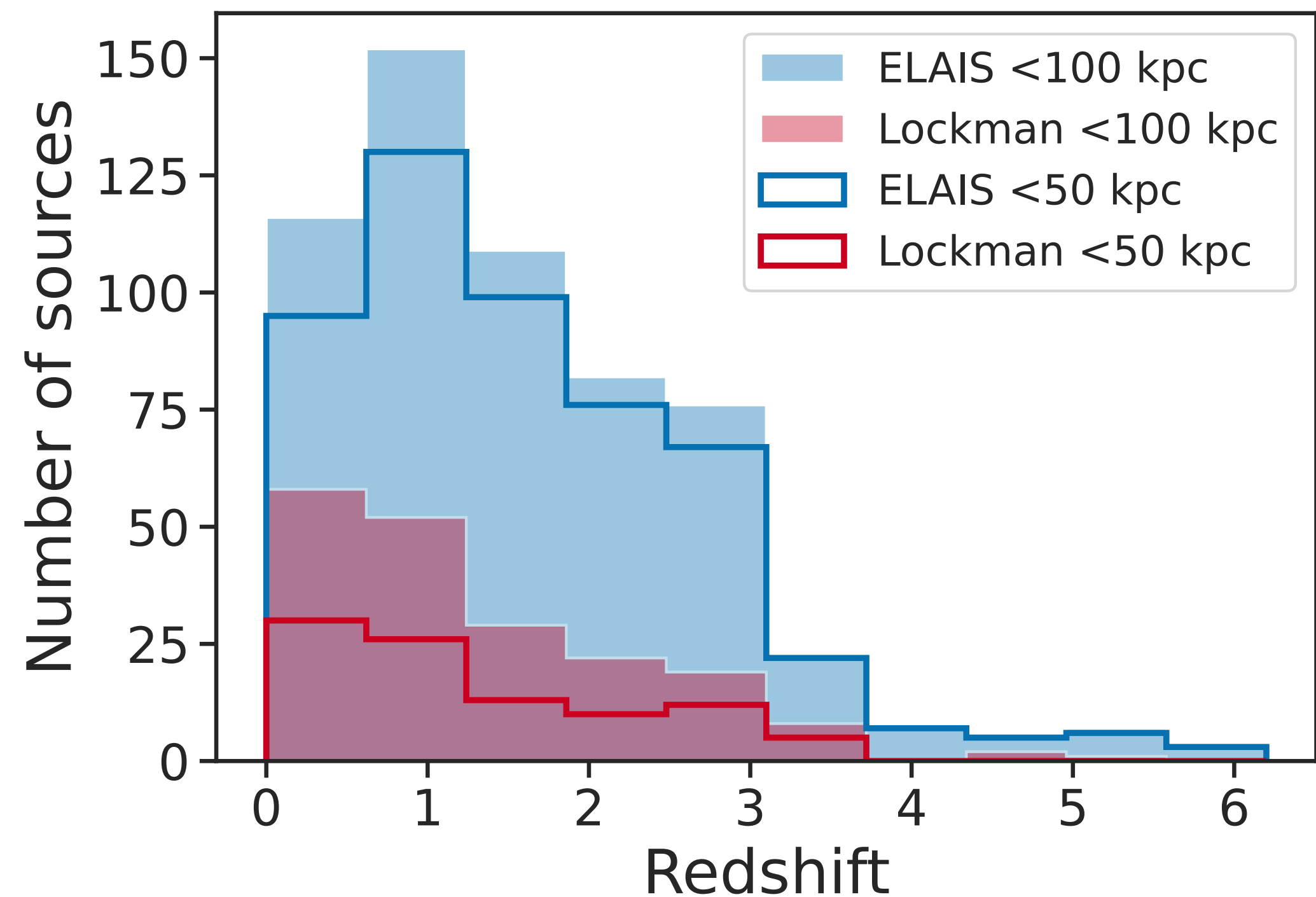


GSJ final sample

Size distribution and redshift range



Final sample
(Lockman Hole + ELAIS-N1):
770 GSJ-objects



Open questions

How common are galaxy-scale jets (GSJ), and is there a **distinct population** that fails to evolve into classical, large-scale radio galaxies?

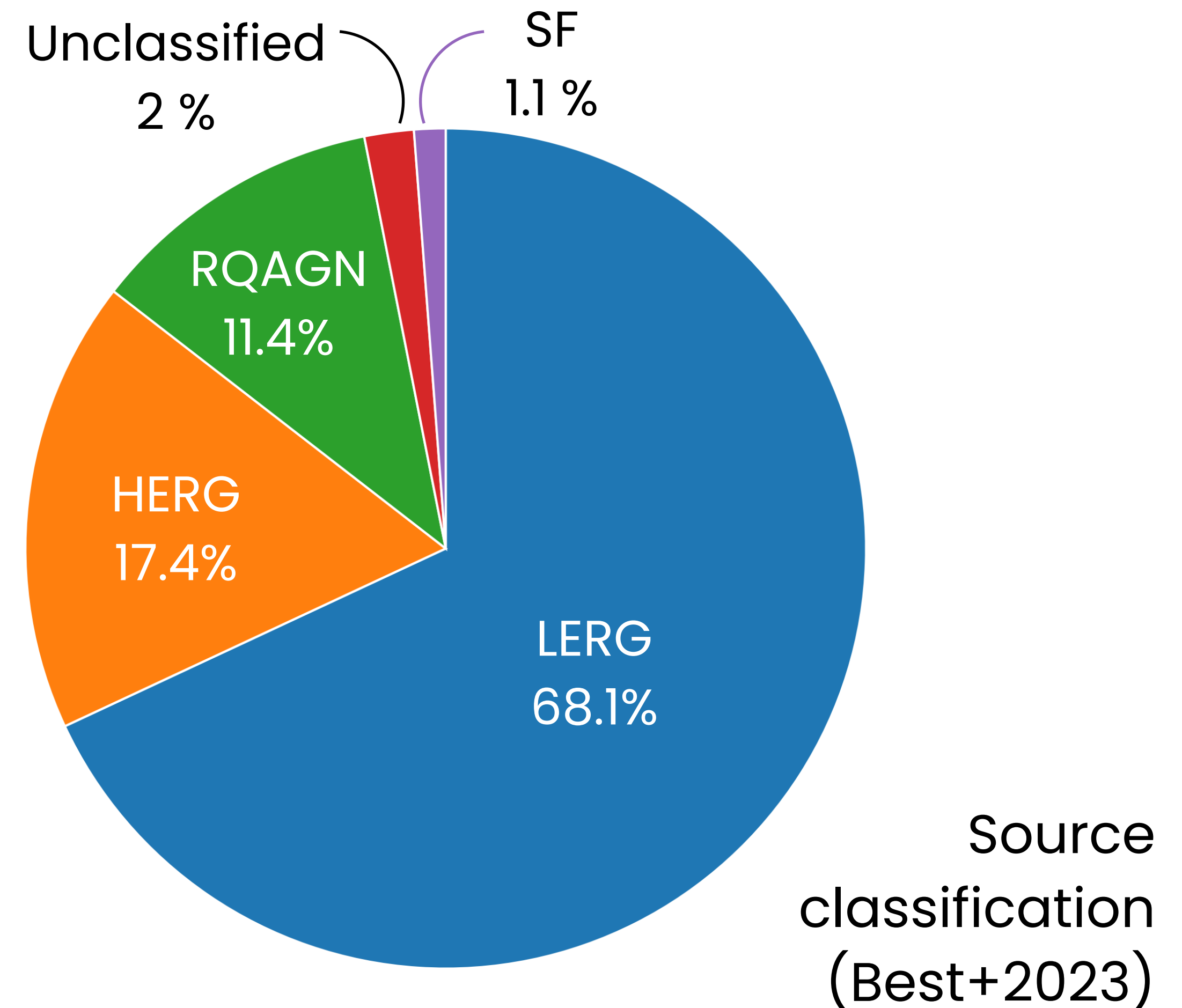
What are the **typical life stages of GSJ** — are they predominantly young, fading, or recurrent—and how does this distribution evolve with redshift?

How do host galaxy properties (e.g. stellar mass, morphology) **influence** the occurrence, evolution and feedback impact of GSJ?

The nature of the GSJ population

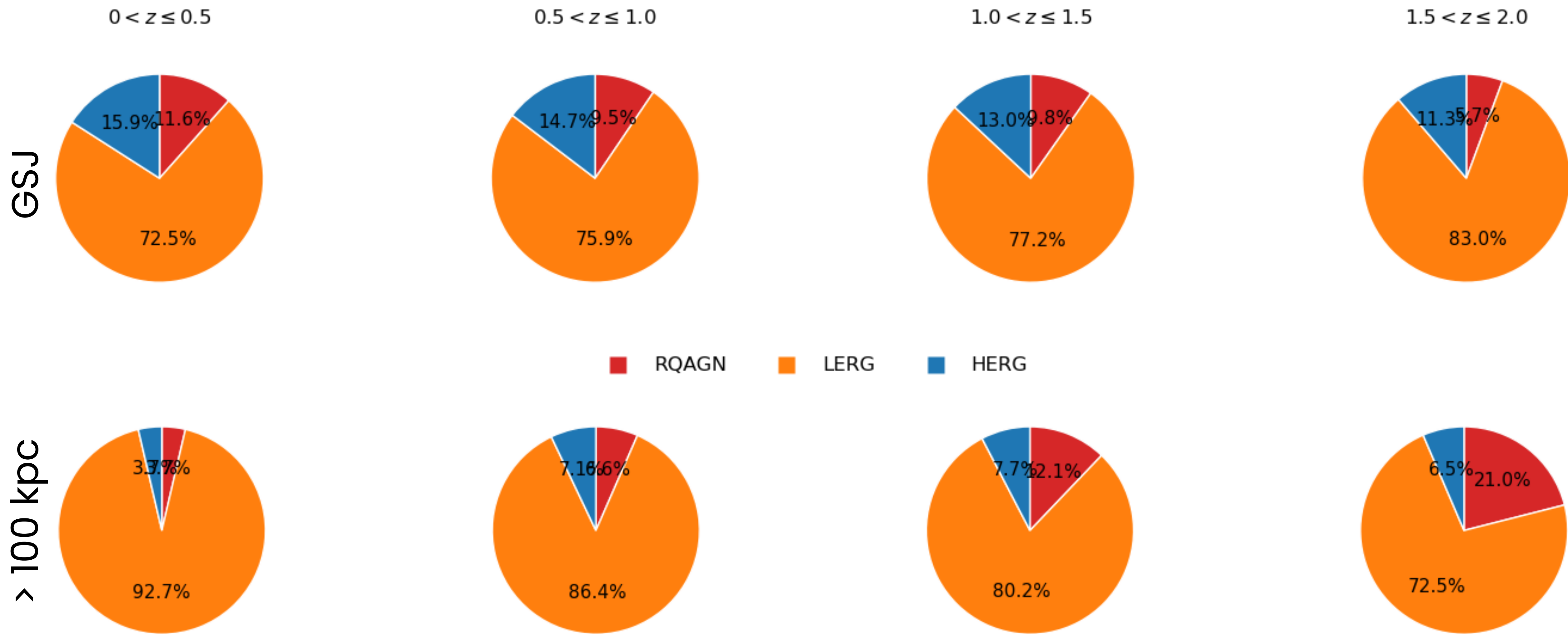
Do galaxy-scale jets correspond to a particular type of AGN?

- Majority (~68%) are LERGs
- Significant contribution from HERGs (~18%) and radio-quiet AGN (~11%)
- Small percentage (1.1%) of sources classified as Star-Forming galaxies presents kpc-scale jets



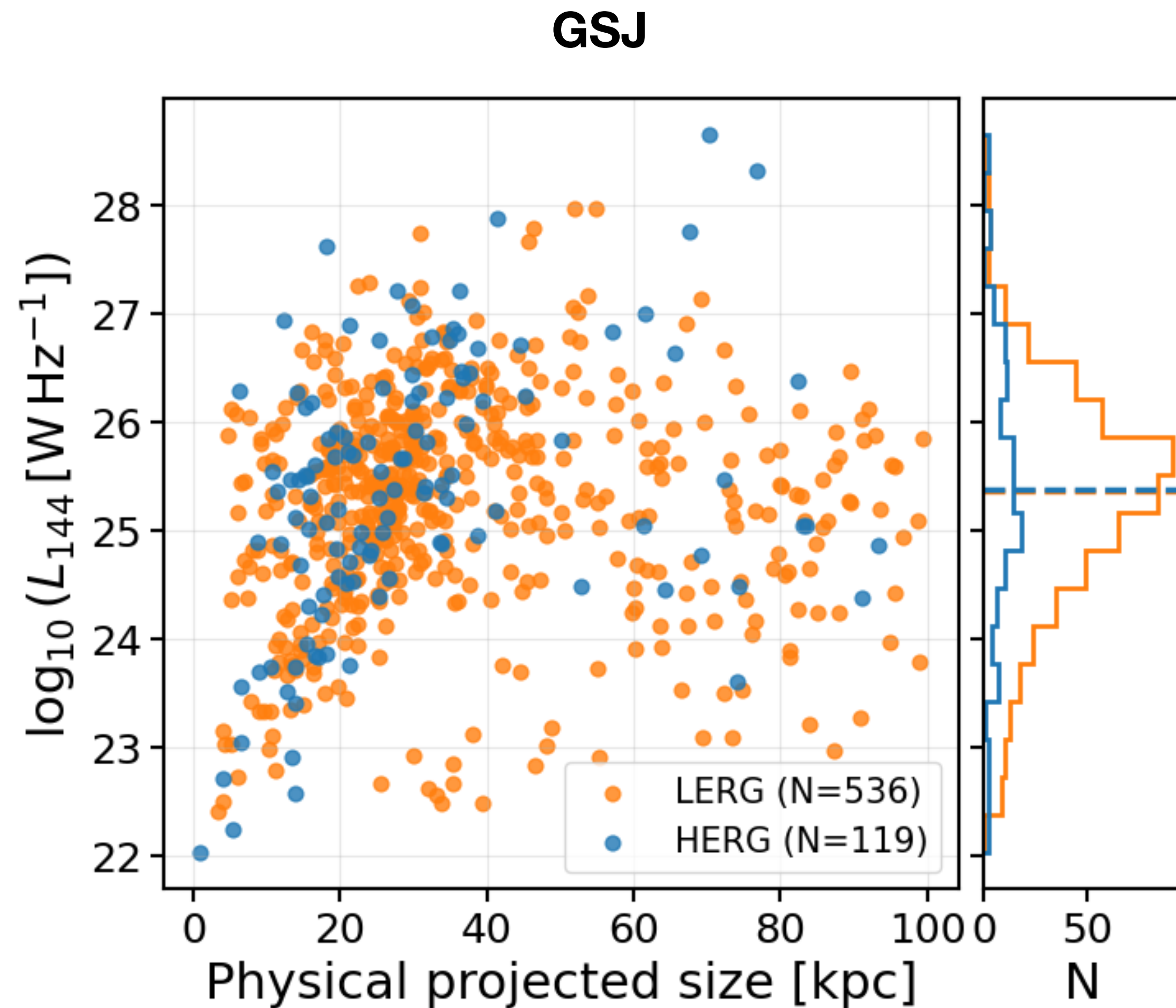
Population Composition: GSJs vs. >100 kpc Radio Galaxies

Are GSJs a Distinct Population?

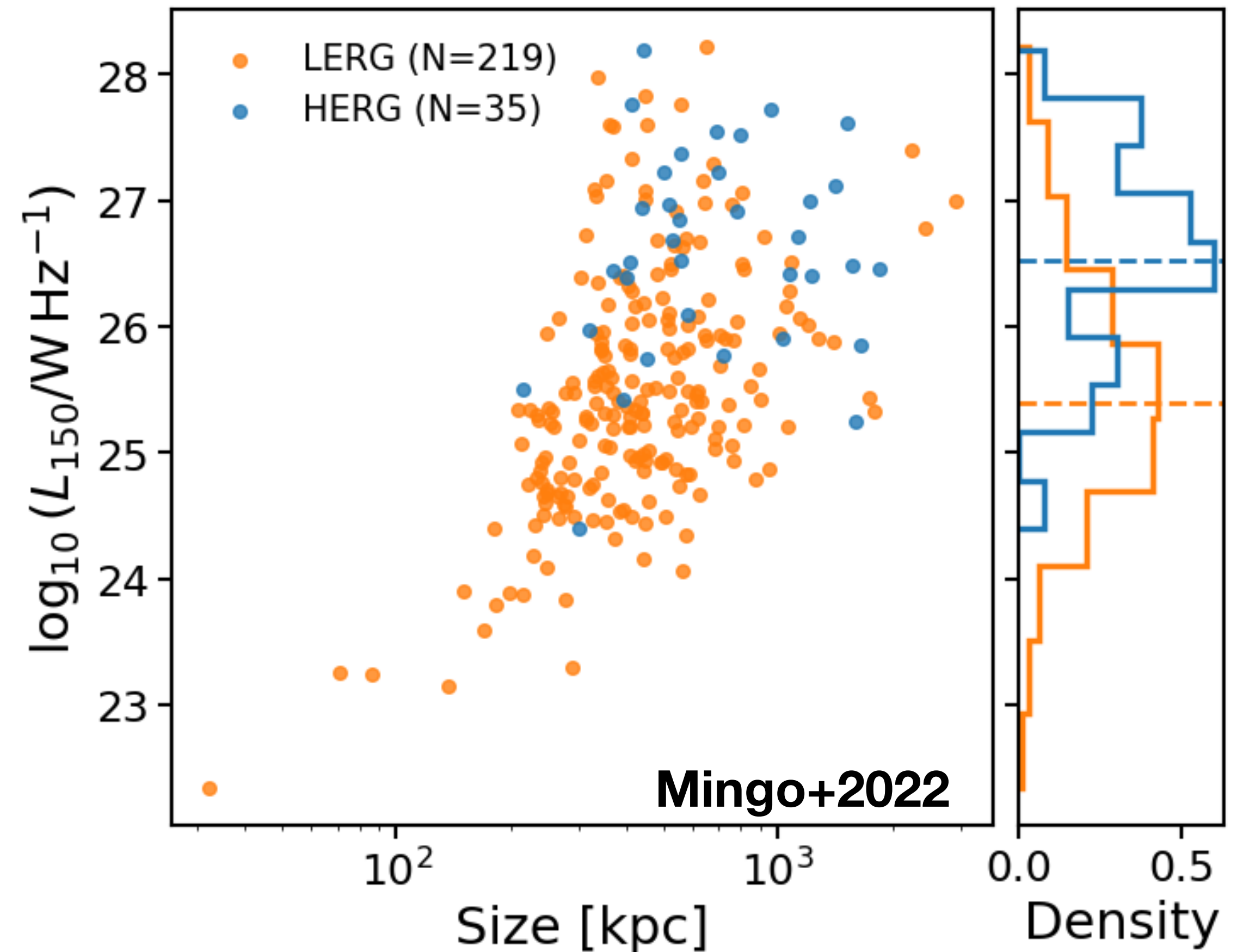


GSJ final sample

Luminosity distribution



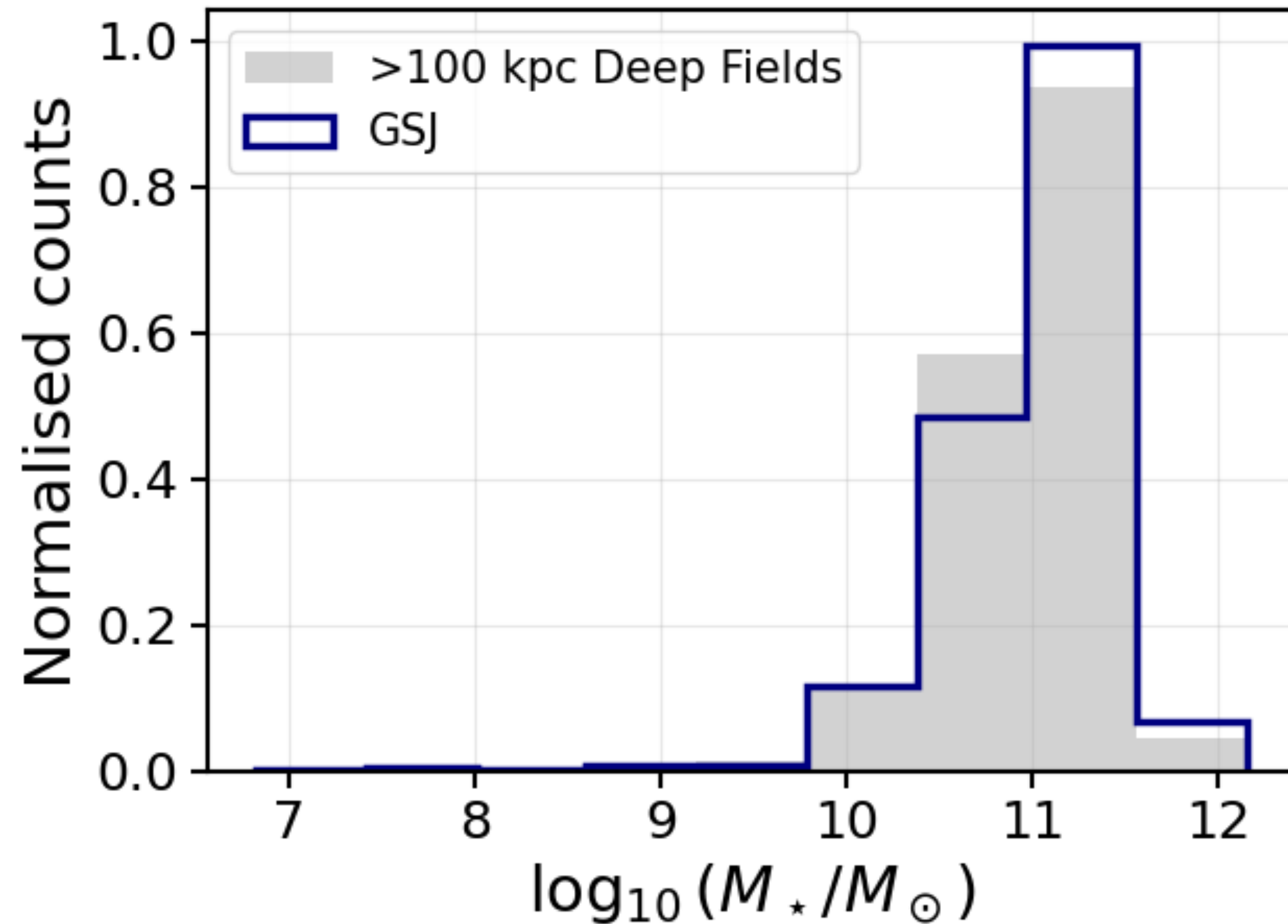
Radio-loud AGN in the LOFAR Deep Fields with a robust FRI-FRII morphological classification



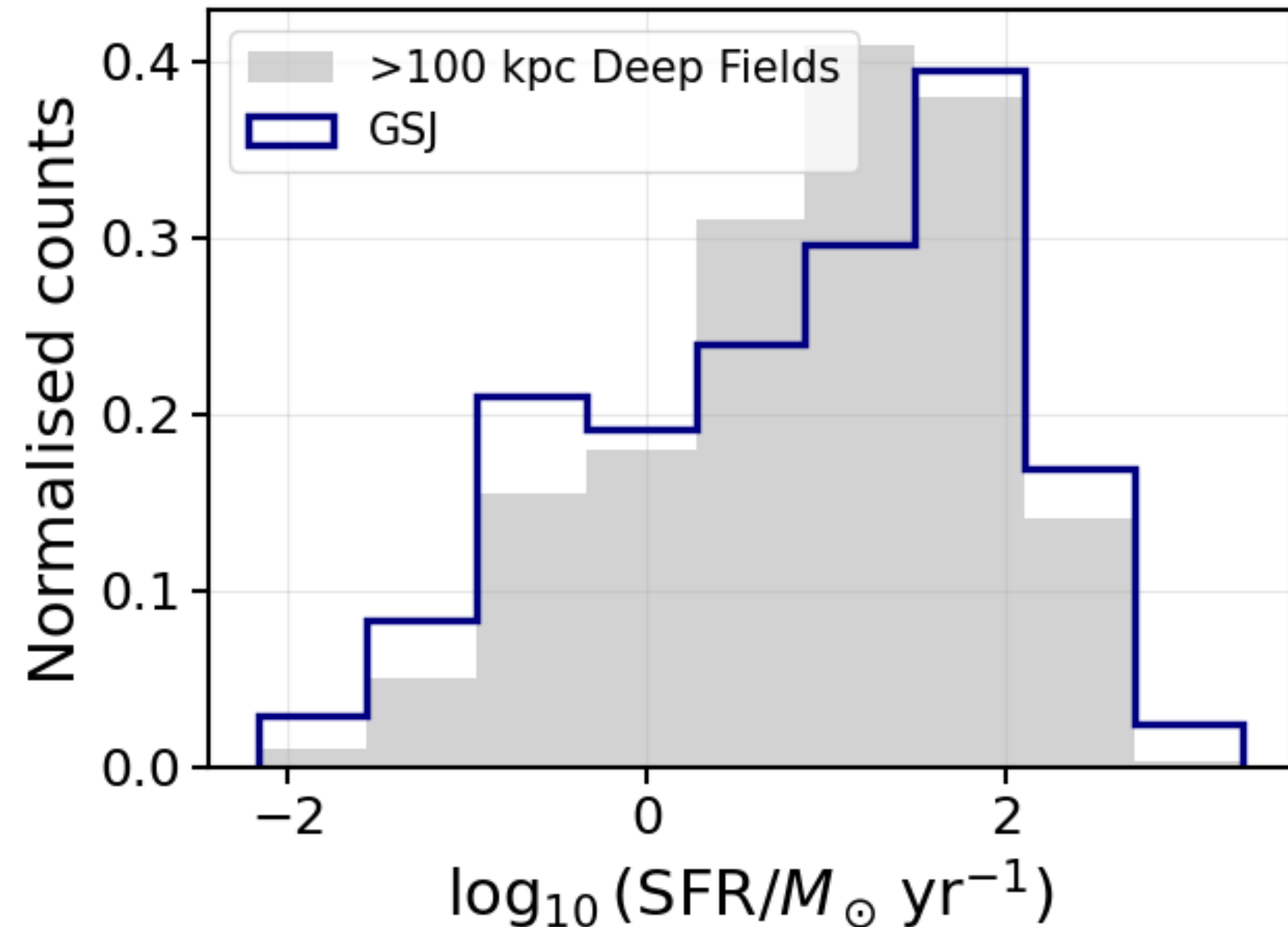
GSJ – host galaxy properties

GSJ vs Parent sample of radio galaxies > 100 kpc from LOFAR Deep Fields

Stellar Mass



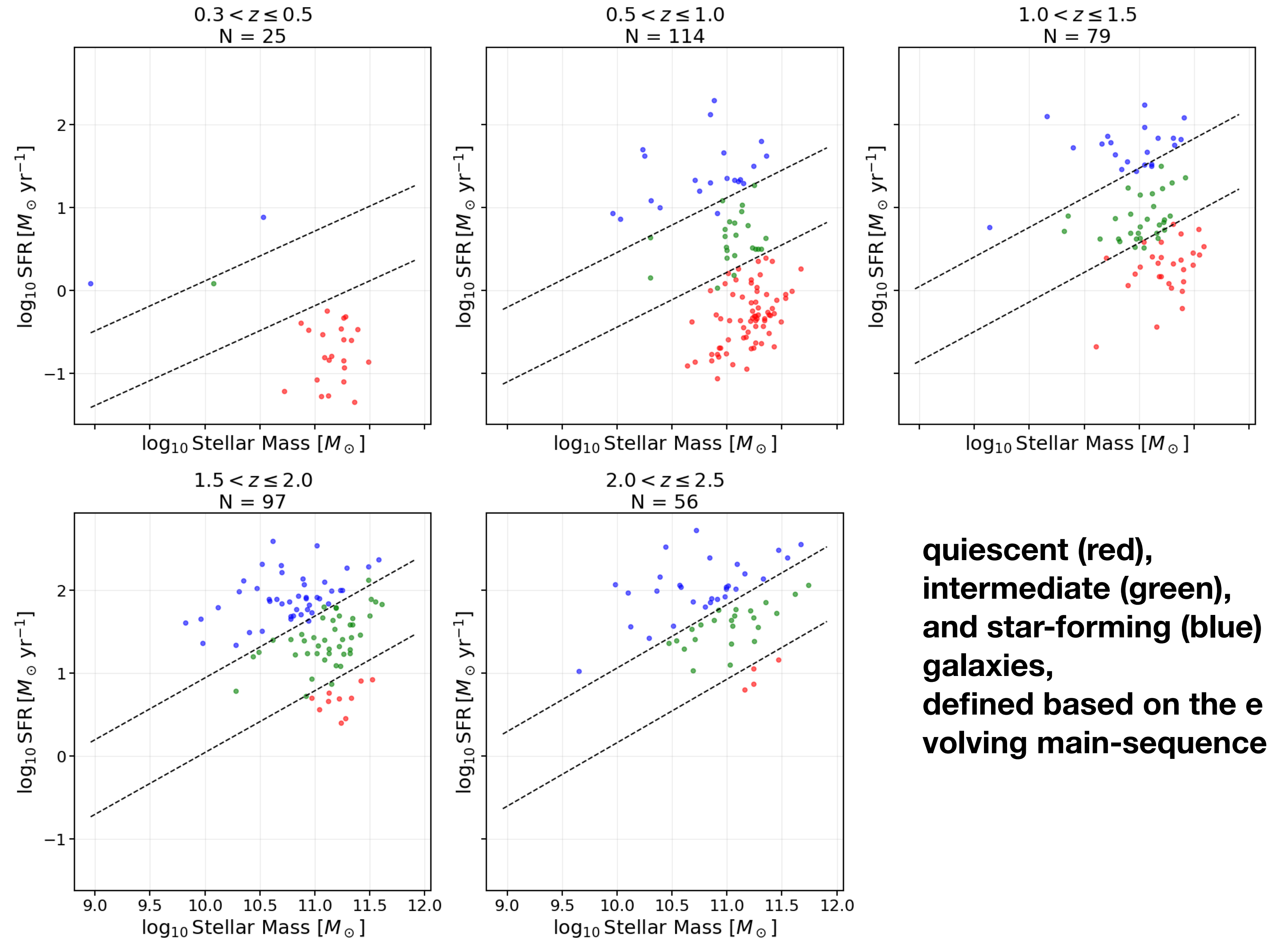
SFR



GSJ hosts basic properties resemble those of the parent larger-scale radio galaxy population

Host activity

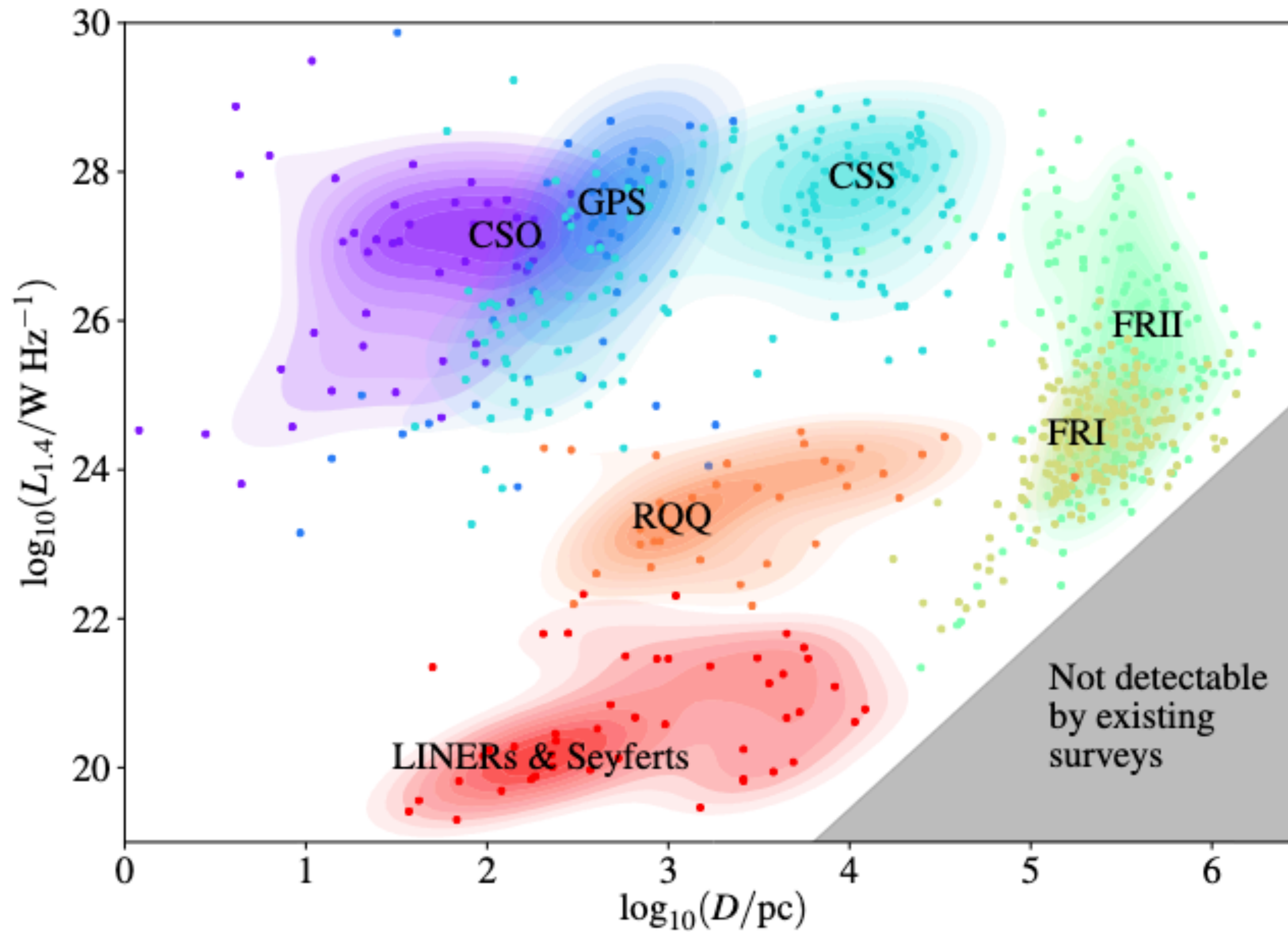
The host-galaxy activity of GSJ-LERGs is broadly consistent with the general LERG population in the LOFAR Deep Fields reported by Kondapally et al. (2025)



**quiescent (red),
intermediate (green),
and star-forming (blue)
galaxies,
defined based on the e
volving main-sequence**

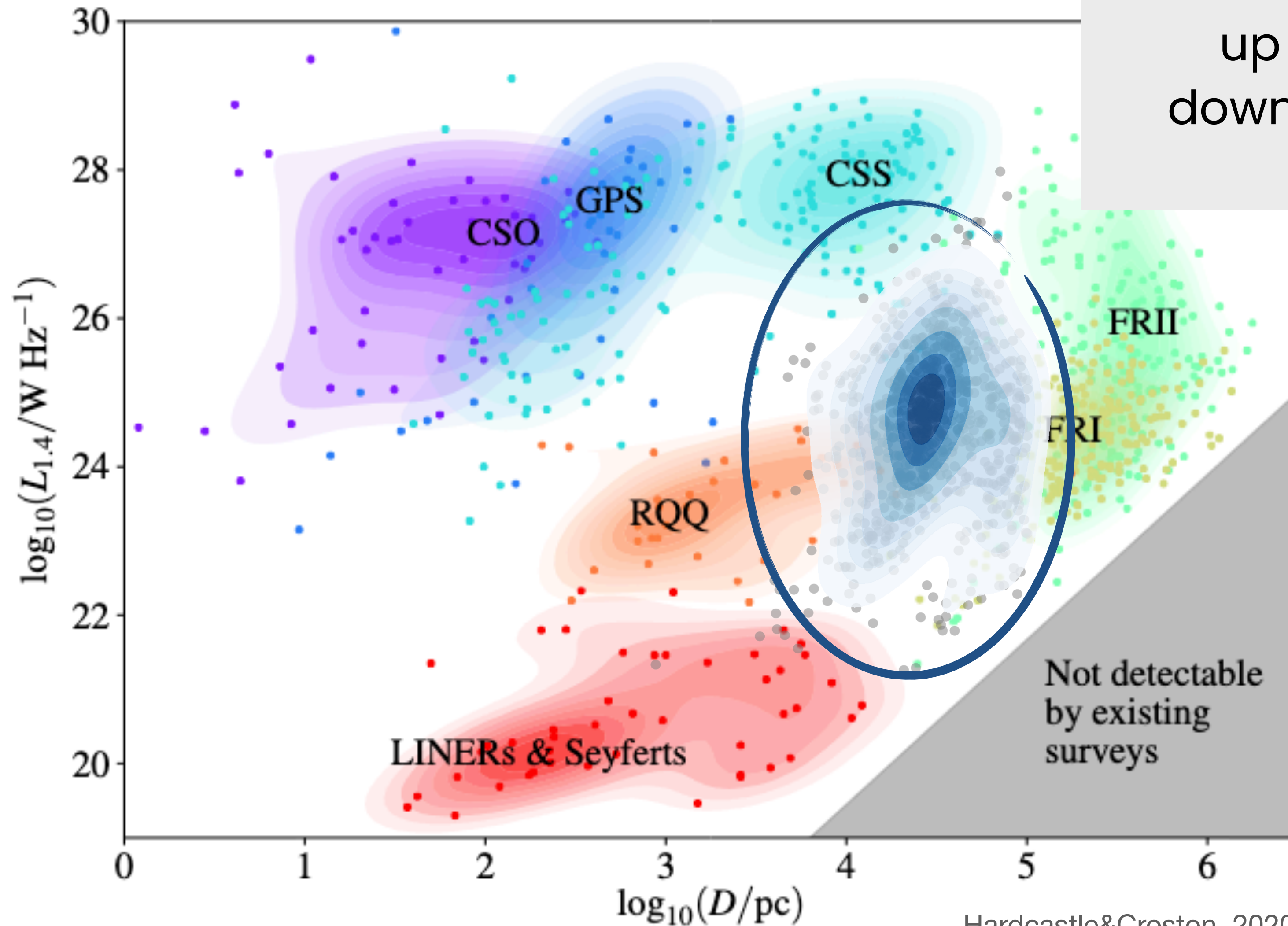
● Quiescent ● Intermediate ● Star-forming ----- $\log_{10}(\text{SFR}/\text{SFR}_{MS}) = -0.4$ $\log_{10}(\text{SFR}/\text{SFR}_{MS}) = -1.3$

Conclusions



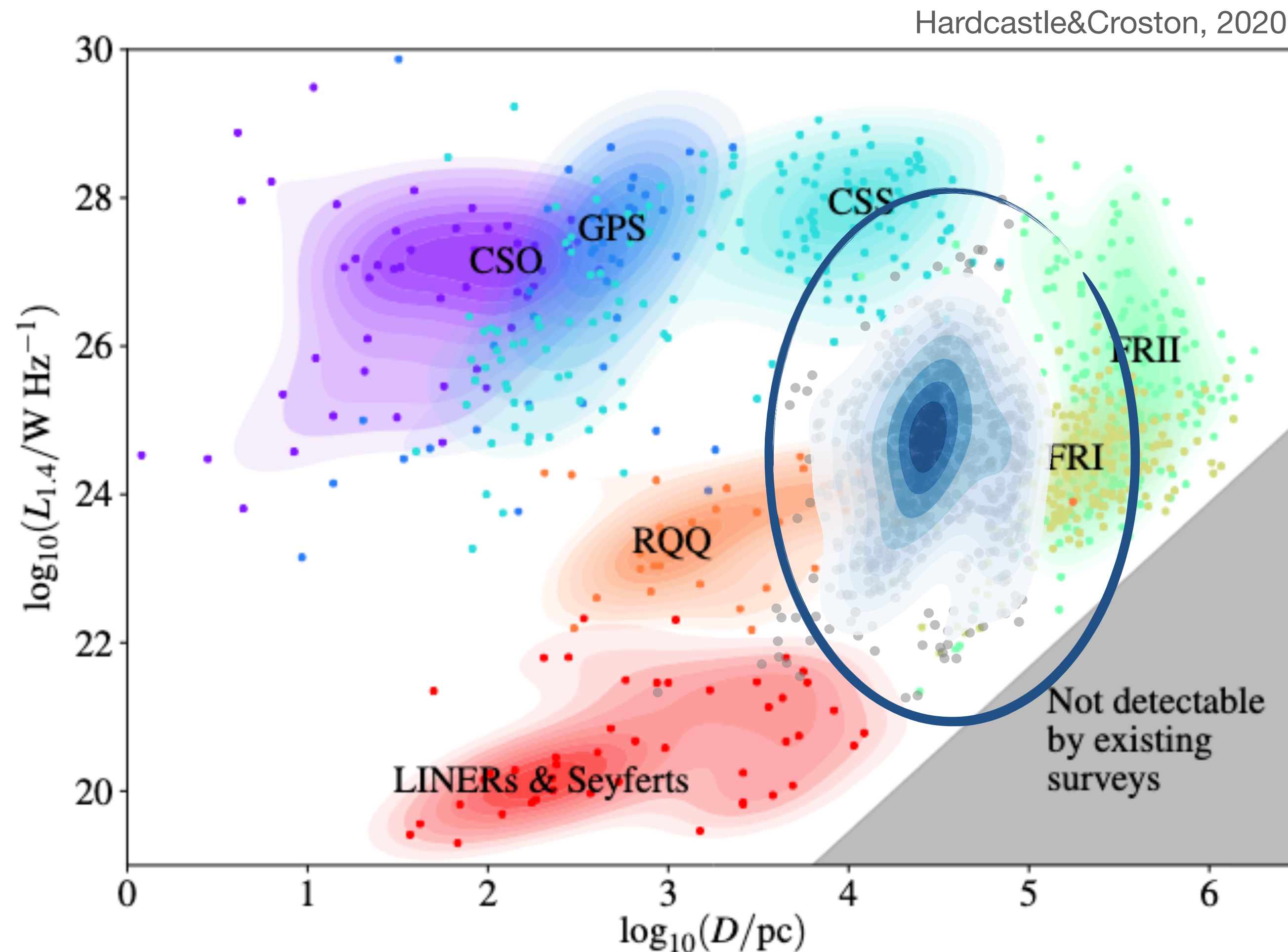
Conclusions

GSJ sample of **~770 objects**
(x4 times previous
LoTSS-based studies,
Webster+2021)
up to **redshift ~3** and
down to **~20 kpc** physical
projected size



Hardcastle&Croston, 2020

Conclusions



- GSJ appear across a **broad range of AGN populations** (HERGs, LERGs, RQAGN), supporting the idea that galaxy-scale jet activity may represent a **common phase** in the life cycle of radio galaxies
- **HERGs** are **systematically more common** among GSJs than among larger radio galaxies larger counter part, suggesting suggesting that radiatively efficient AGN may be preferentially observed during the galaxy-scale phase, possibly reflecting differences in source lifetimes, duty cycles, or fuelling histories
- Host properties of our GSJ (such as stellar mass or SFR) **do not show deviation** from the parent LOFAR Deep Fields sample, suggesting that GSJs are not associated with a distinct host-galaxy population

Future steps

- Complete the full Deep Fields GSJ sample (**Booties, EDFN**)
- Incorporating/Developing **ML-techniques** to assist (or replace?) morphological classification via visual inspection
- **Spectral Analysis** to constrain GJS spectral ages
- Follow-up studies of rarer **high-redshift ($z > 2$)** GSJ systems

Back-up

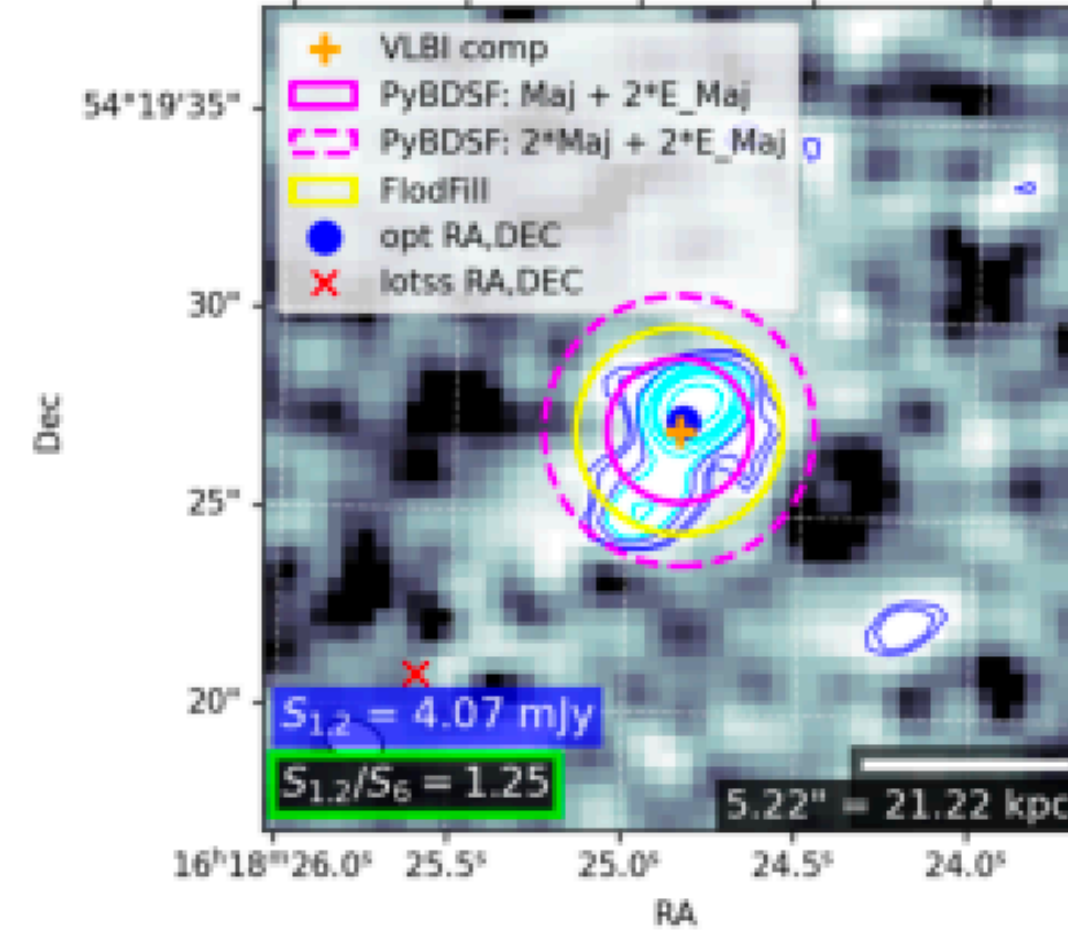
Association successful

ILTJ161824.85+541927.0 2255_2177_ILTJ161824.85+541927.0.png

ILTJ161824.85+541927.0 | $z=0.264$ | class=HERG | opt_RA=244.604, opt_DEC=54.324

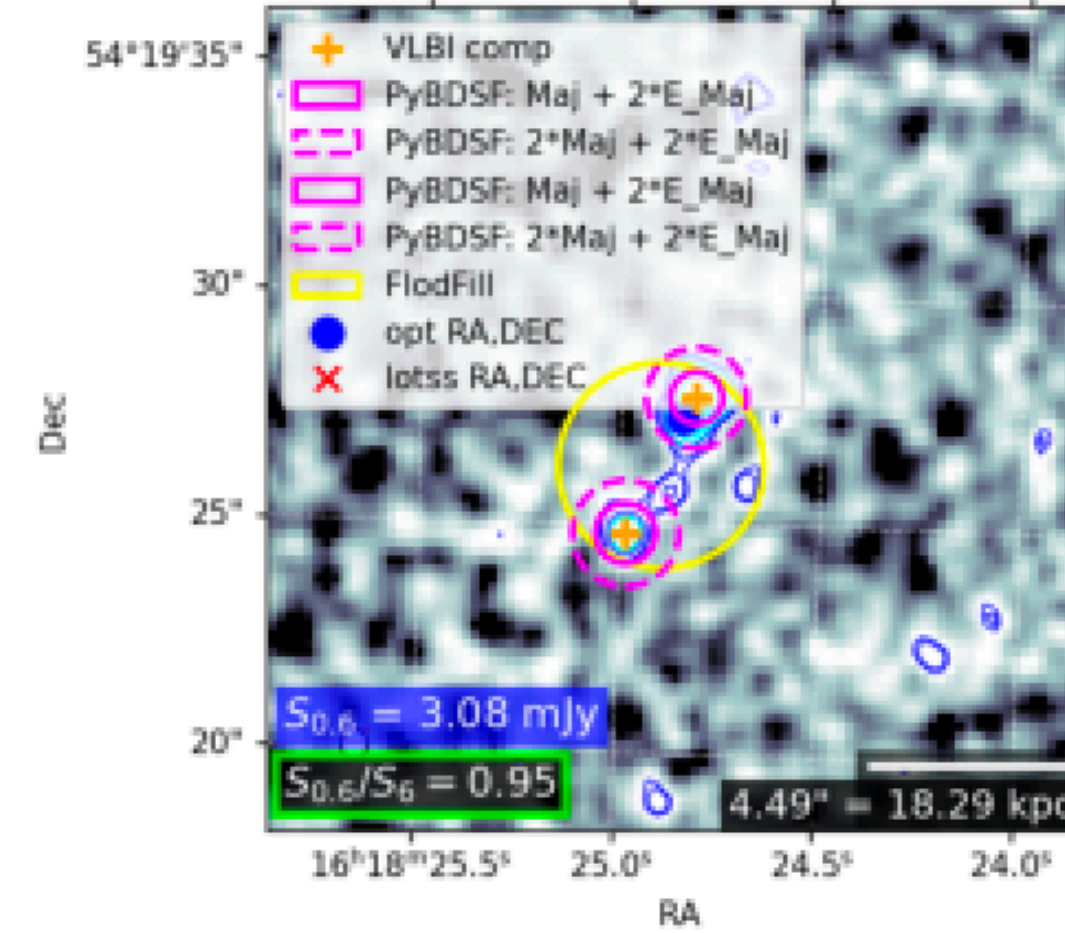
LOFAR-VLBI 1.2"

VLBI 1.2" + contours
cutout size = 20.9" x 20.9"



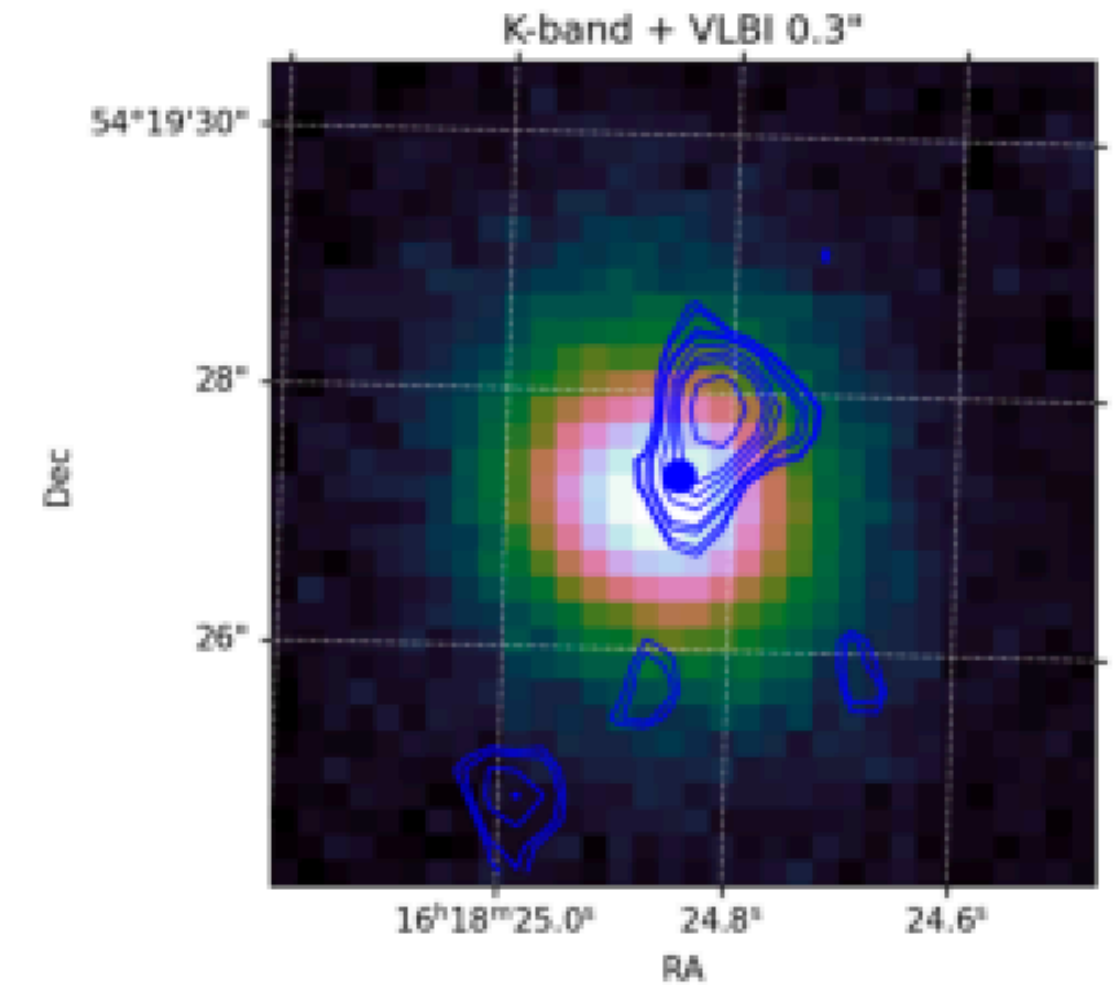
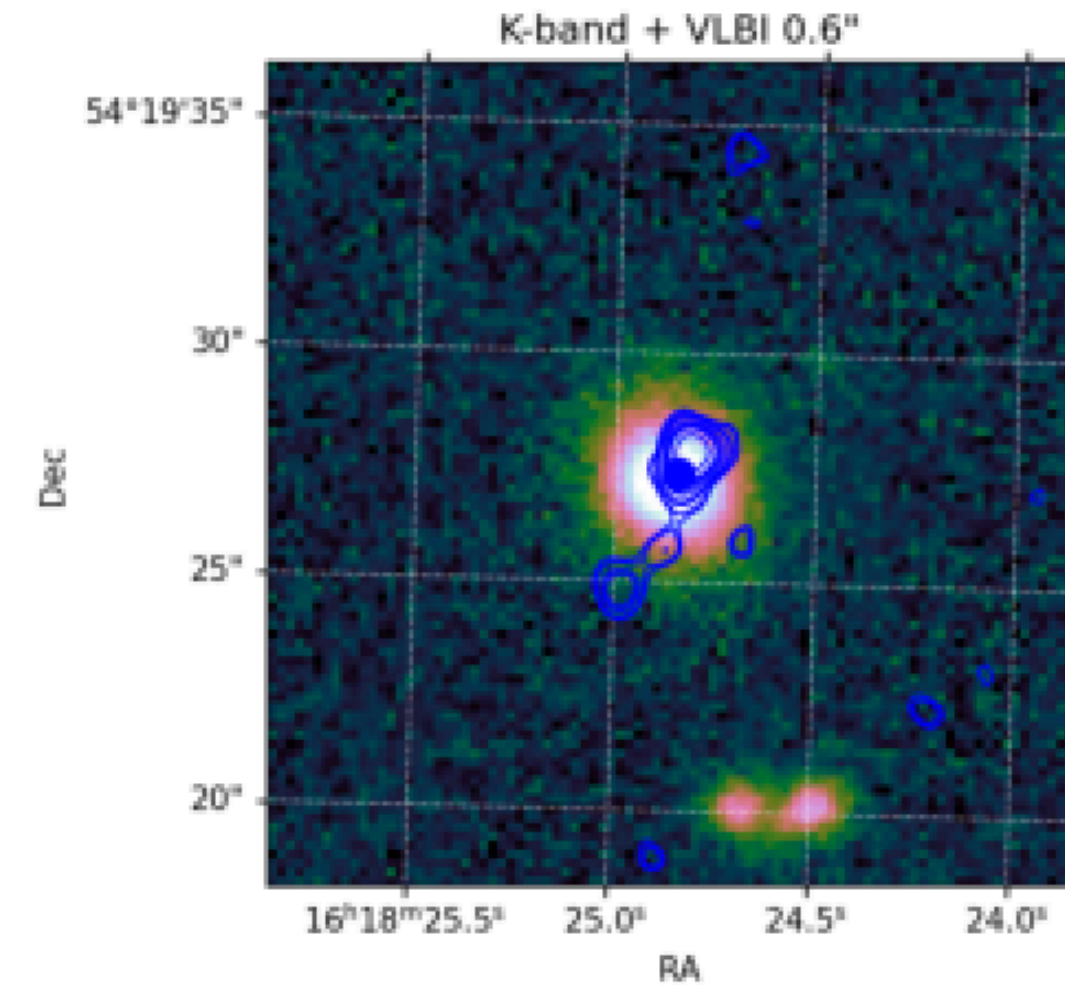
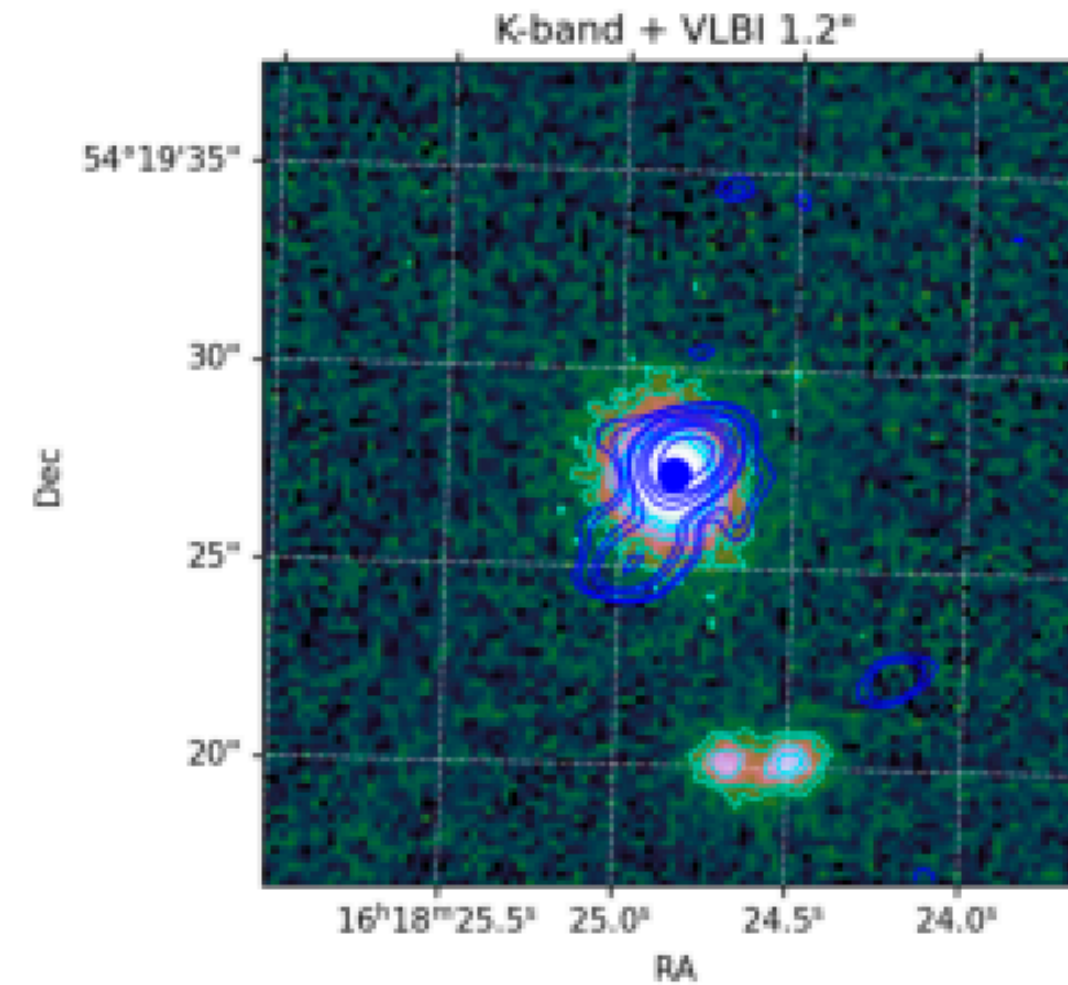
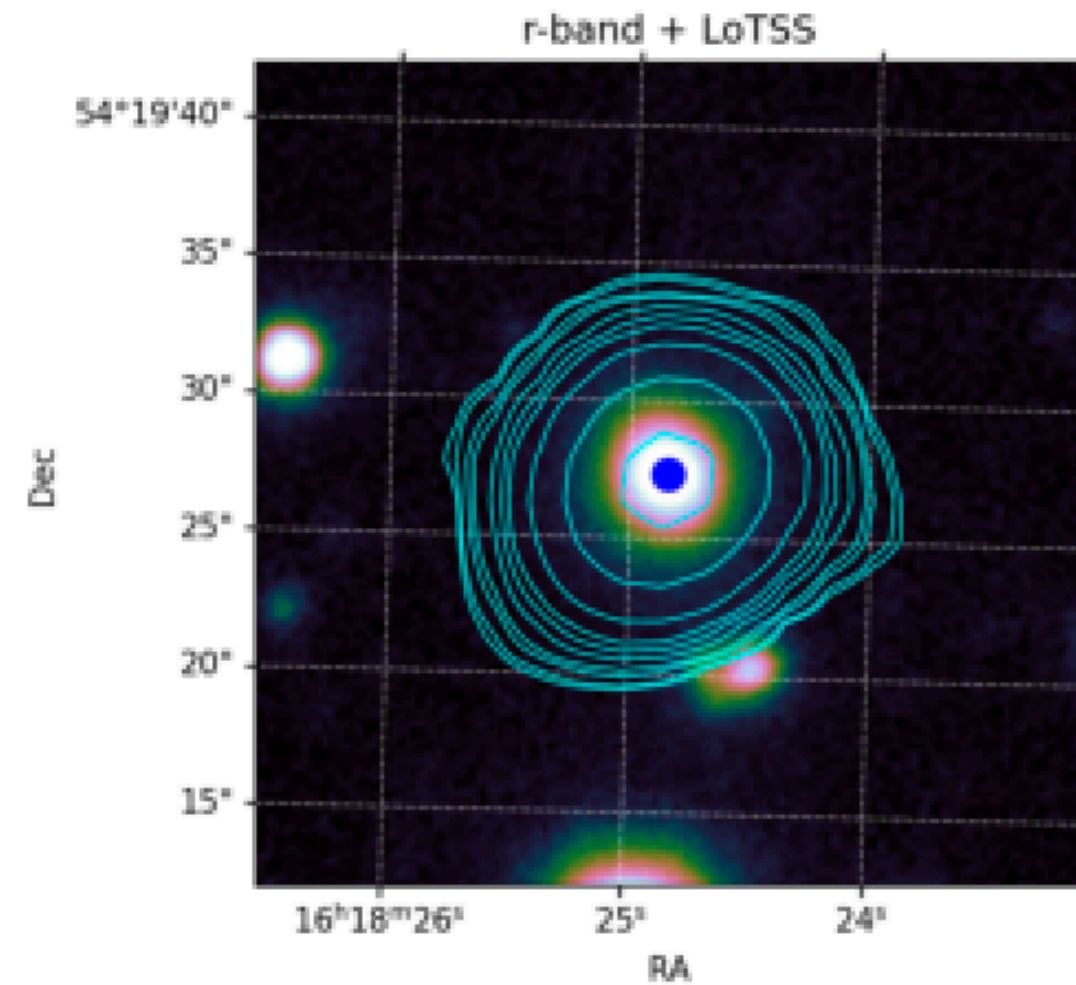
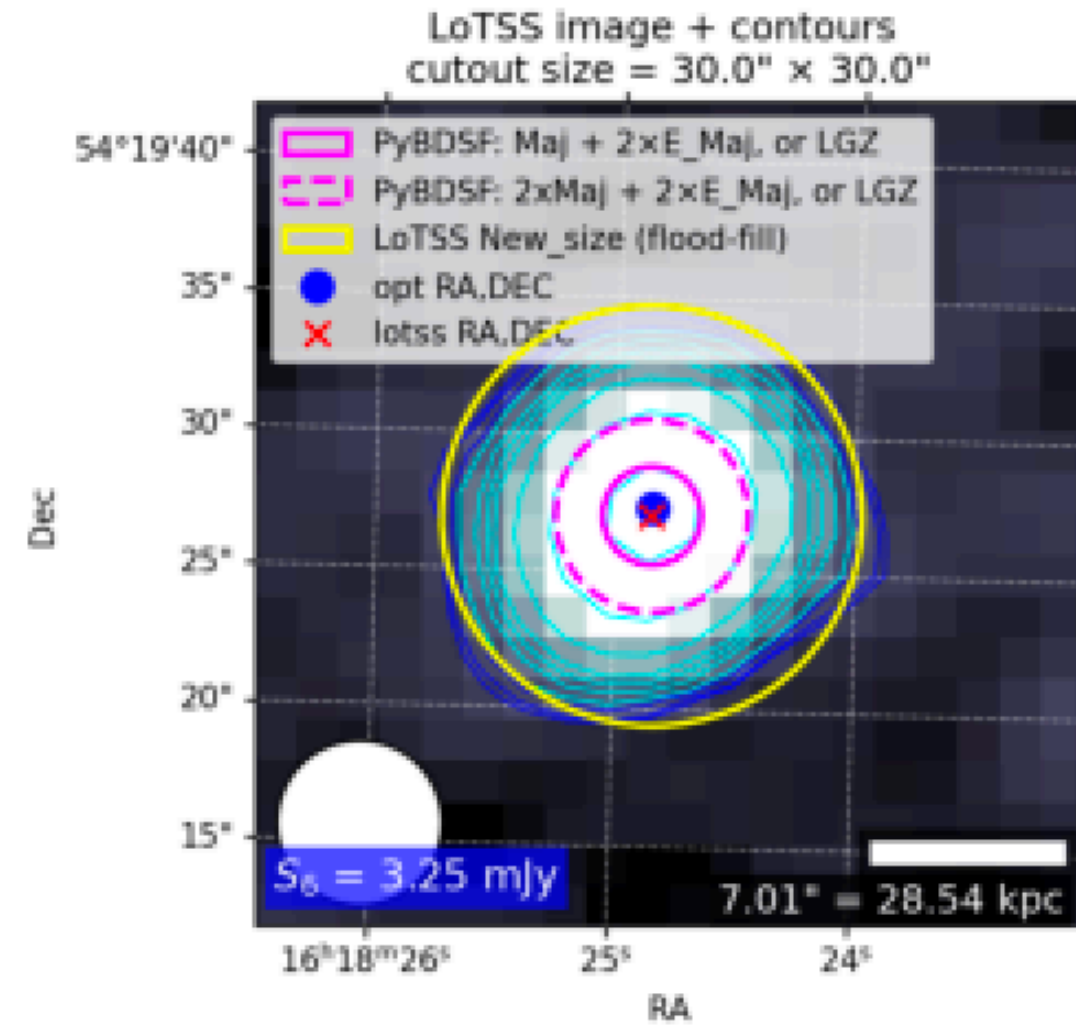
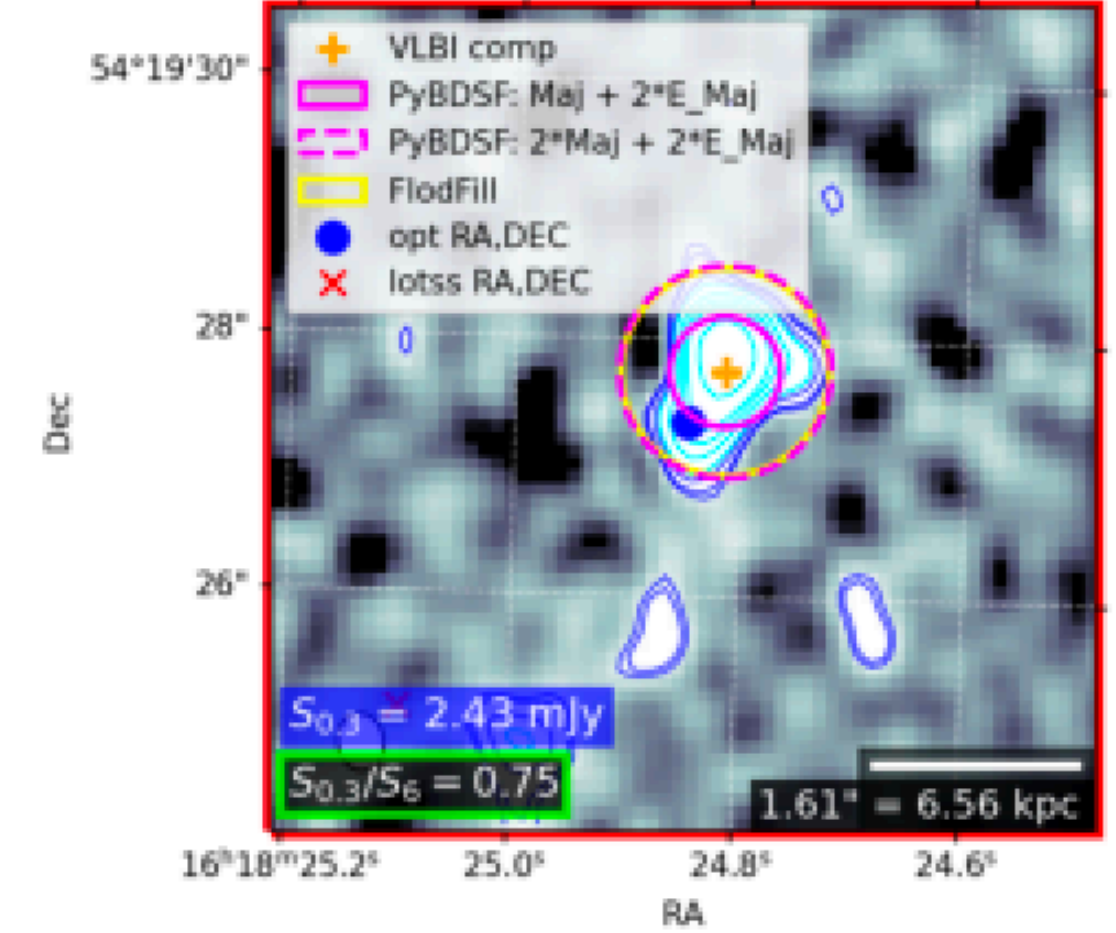
LOFAR-VLBI 0.6"

VLBI 0.6" + contours
cutout size = 18.0" x 18.0"



LOFAR-VLBI 0.3"

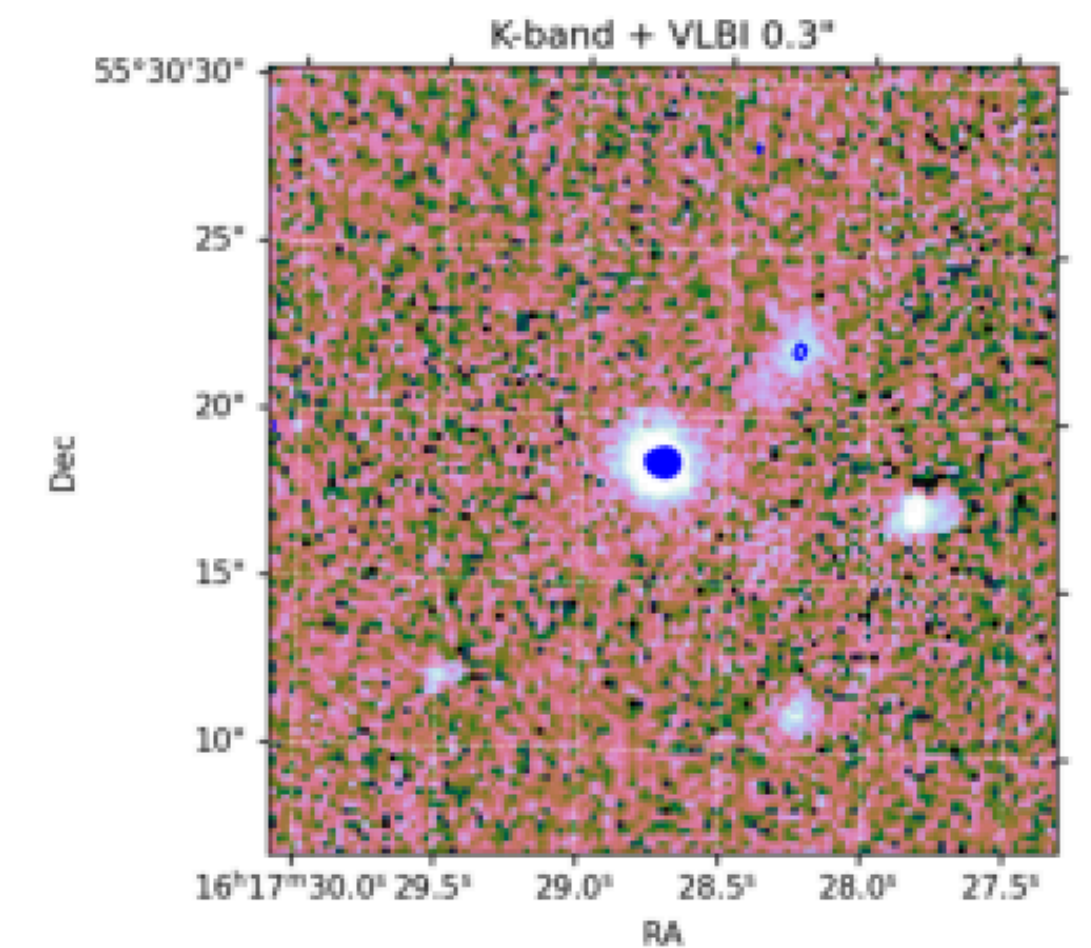
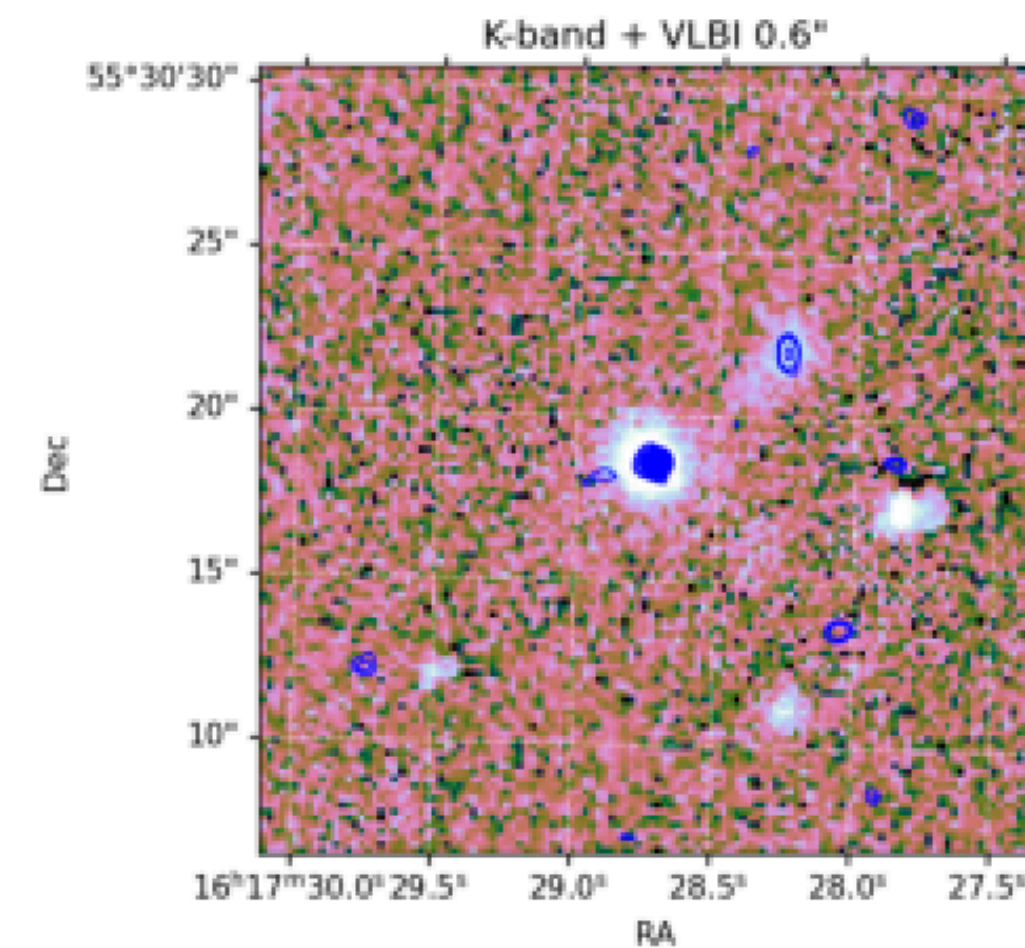
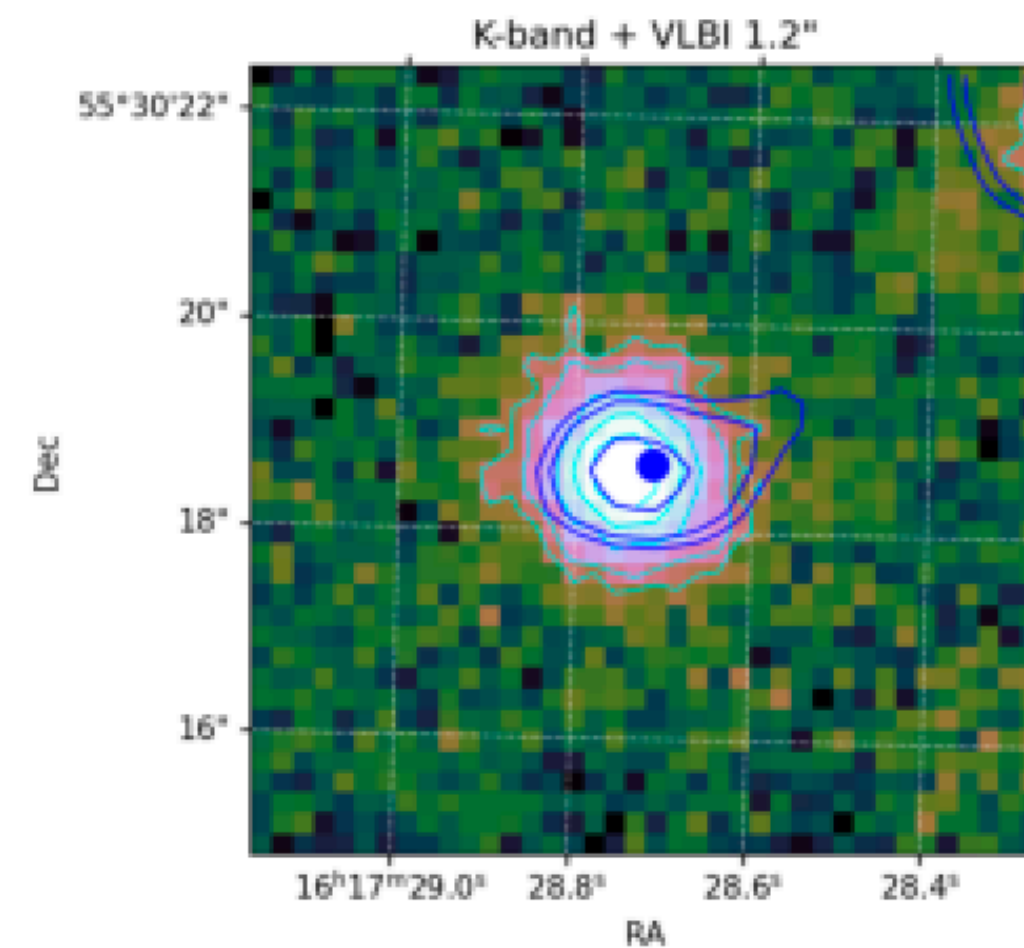
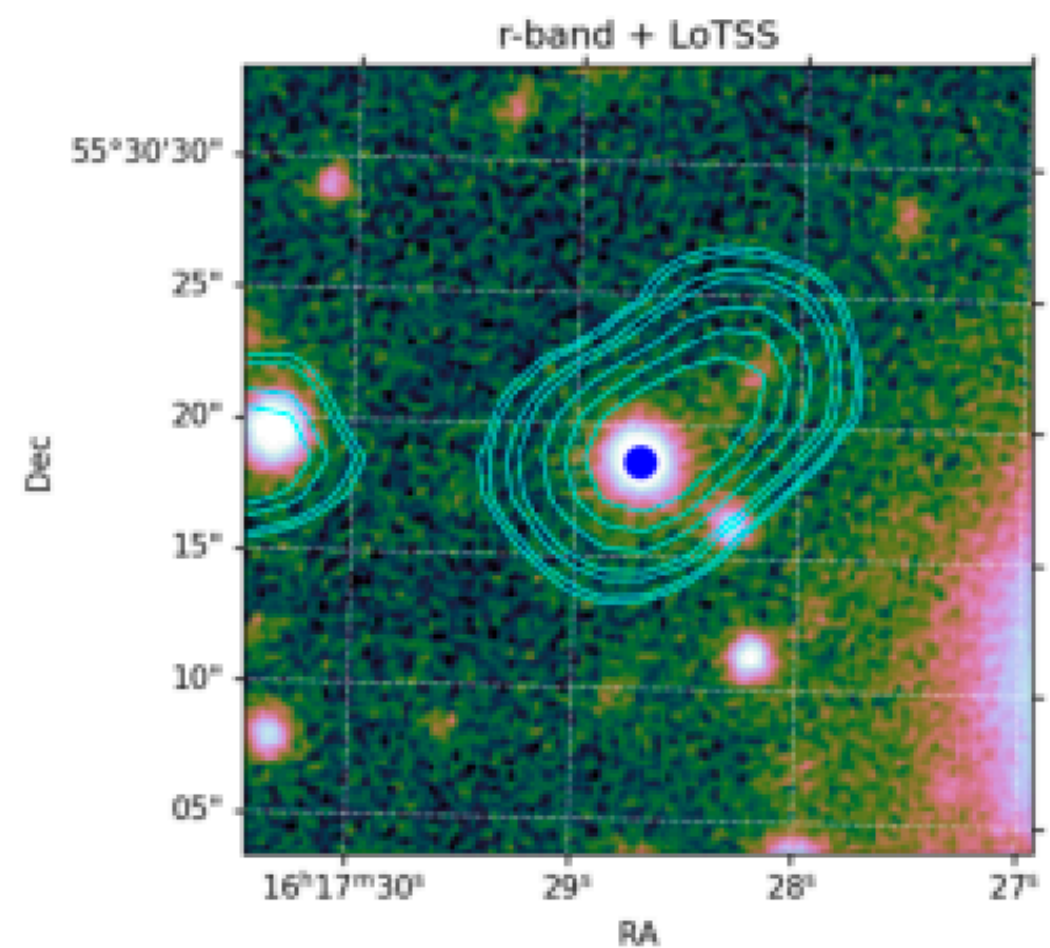
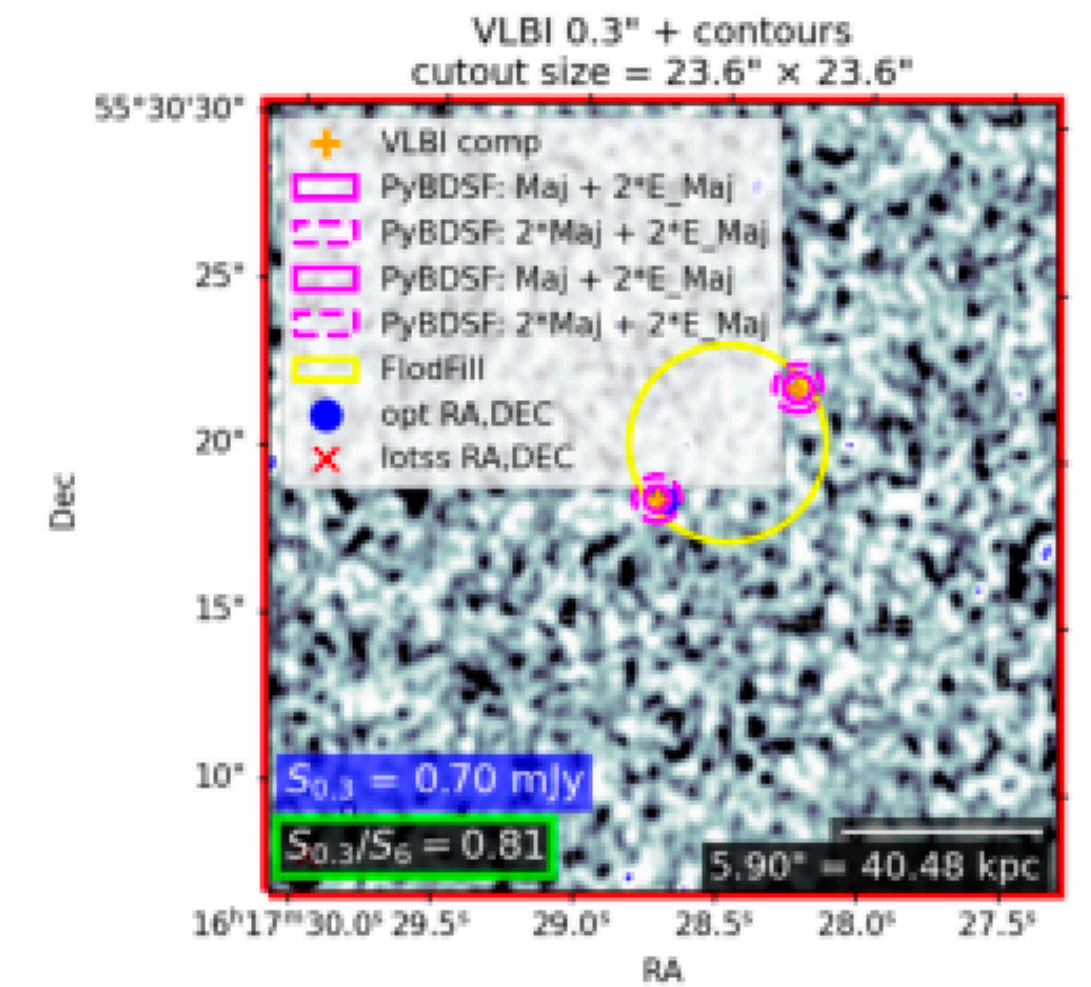
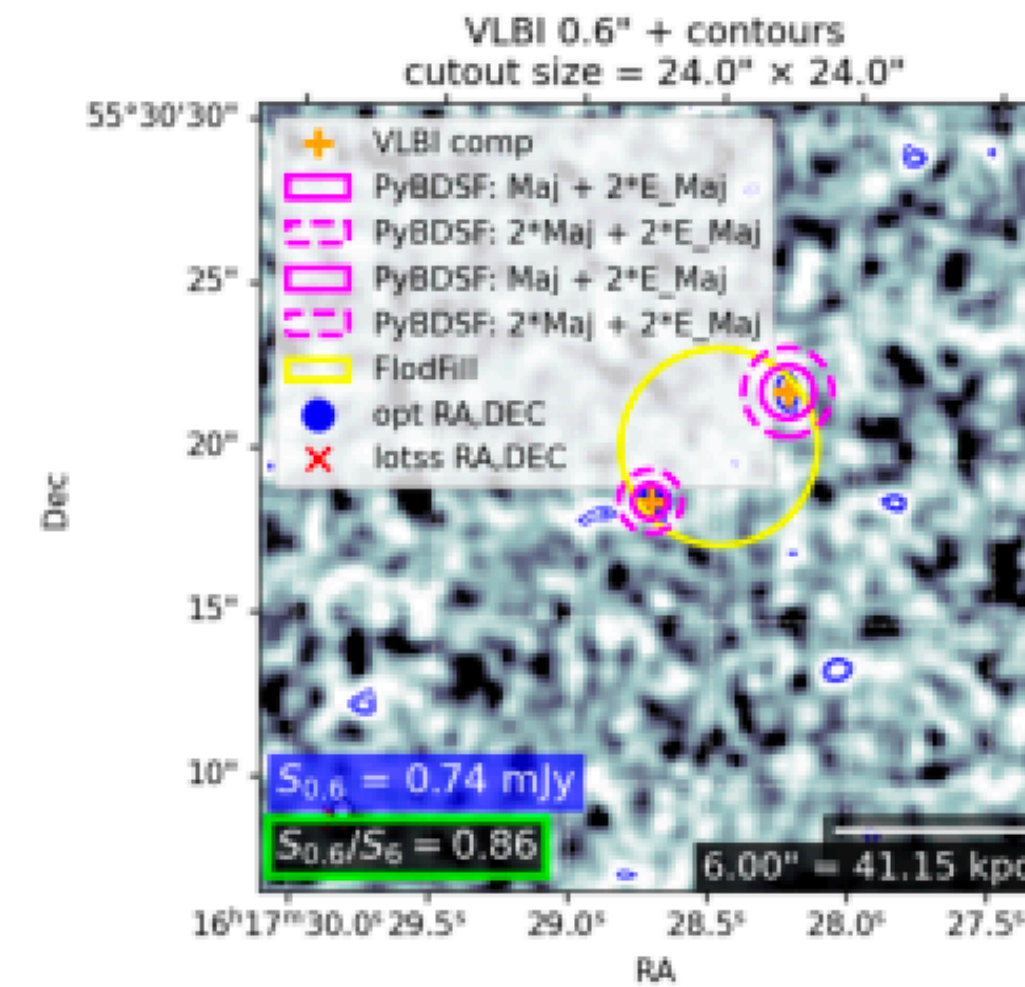
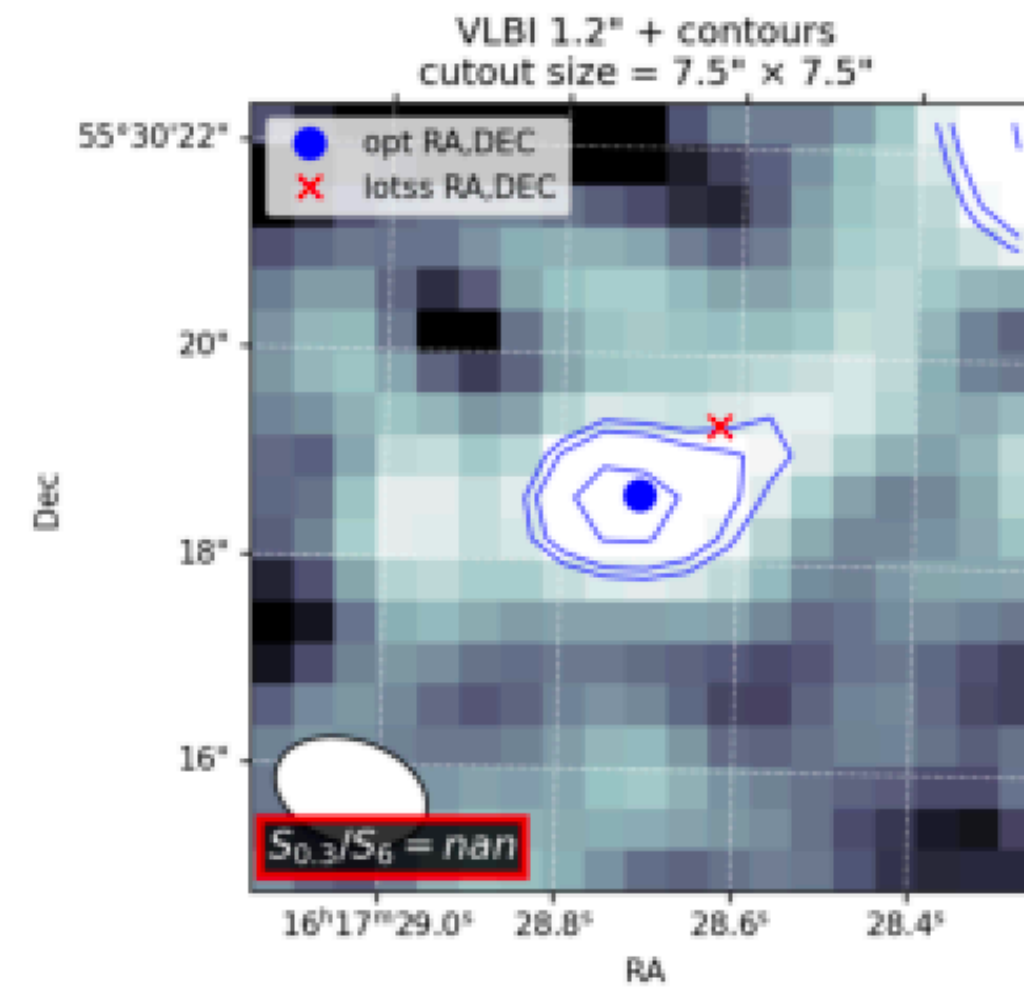
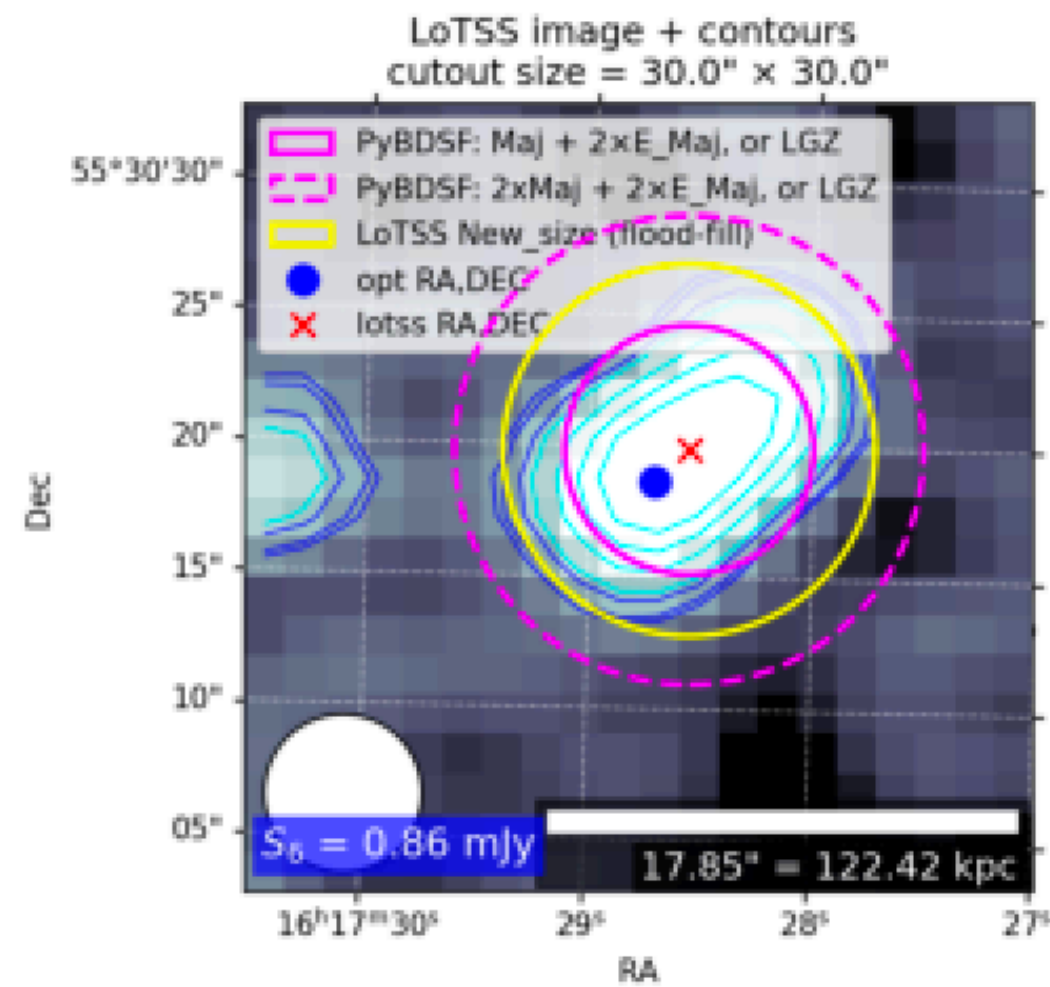
VLBI 0.3" + contours
cutout size = 6.4" x 6.4"



Association went “wrong” → Visual inspection crucial

ILTJ161728.56+553019.8 2149_2076_ILTJ161728.56+553019.8.png

ILTJ161728.56+553019.8 | $z=0.635$ | class=LERG | opt_RA=244.370, opt_DEC=55.505



Best+2023 – classification

4 primary classes based on the presence or absence of these two features:

- **Star-Forming Galaxies (SFGs)**: Sources that show neither evidence of a radiative-mode AGN in their optical/IR SED nor a significant radio excess.
- **Radio-Quiet AGN (RQAGN)**: Sources identified as radiative-mode AGN through their SED but which do not exhibit a radio excess (their radio emission is consistent with their star-formation rate).
- **Low-Excitation Radio Galaxies (LERGs)**: Also known as jet-mode AGN, these sources show a significant radio excess but no signatures of a radiative-mode AGN in their optical/IR SED.
- **High-Excitation Radio Galaxies (HERGs)**: Sources that exhibit both radiative-mode AGN signatures in their SED and a significant radio excess (e.g., radio-loud quasars).
- **Unclassified**: A small fraction of sources (less than 5%) where reliable classification for either criterion was not possible

Duncan+2021 – redshift estimates

In the catalogue, the column `Z_BEST`, prioritizes literature spectroscopic redshifts if they are of high quality; otherwise, it uses the median of the primary peak from its photo-z estimation

The proportion of radio sources with spectroscopic information in each field is:

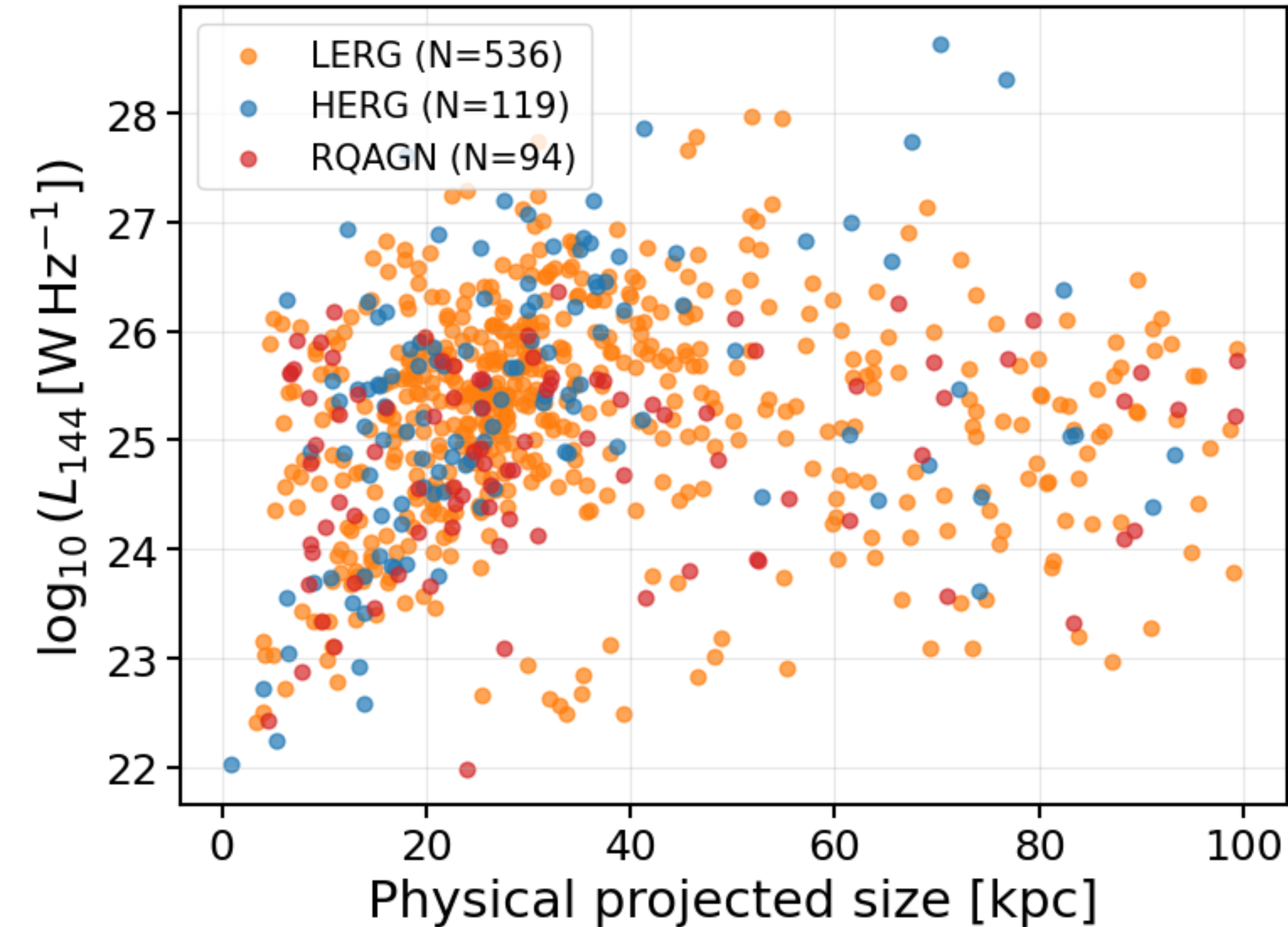
- Boötes: 21.1%
- ELAIS-N1: 5.1%
- Lockman Hole: 4.7%

For the final source classifications and SED fitting (Best et al., 2023), the spectroscopic redshifts was used for

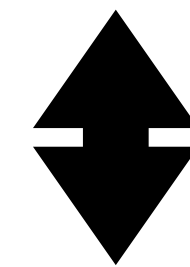
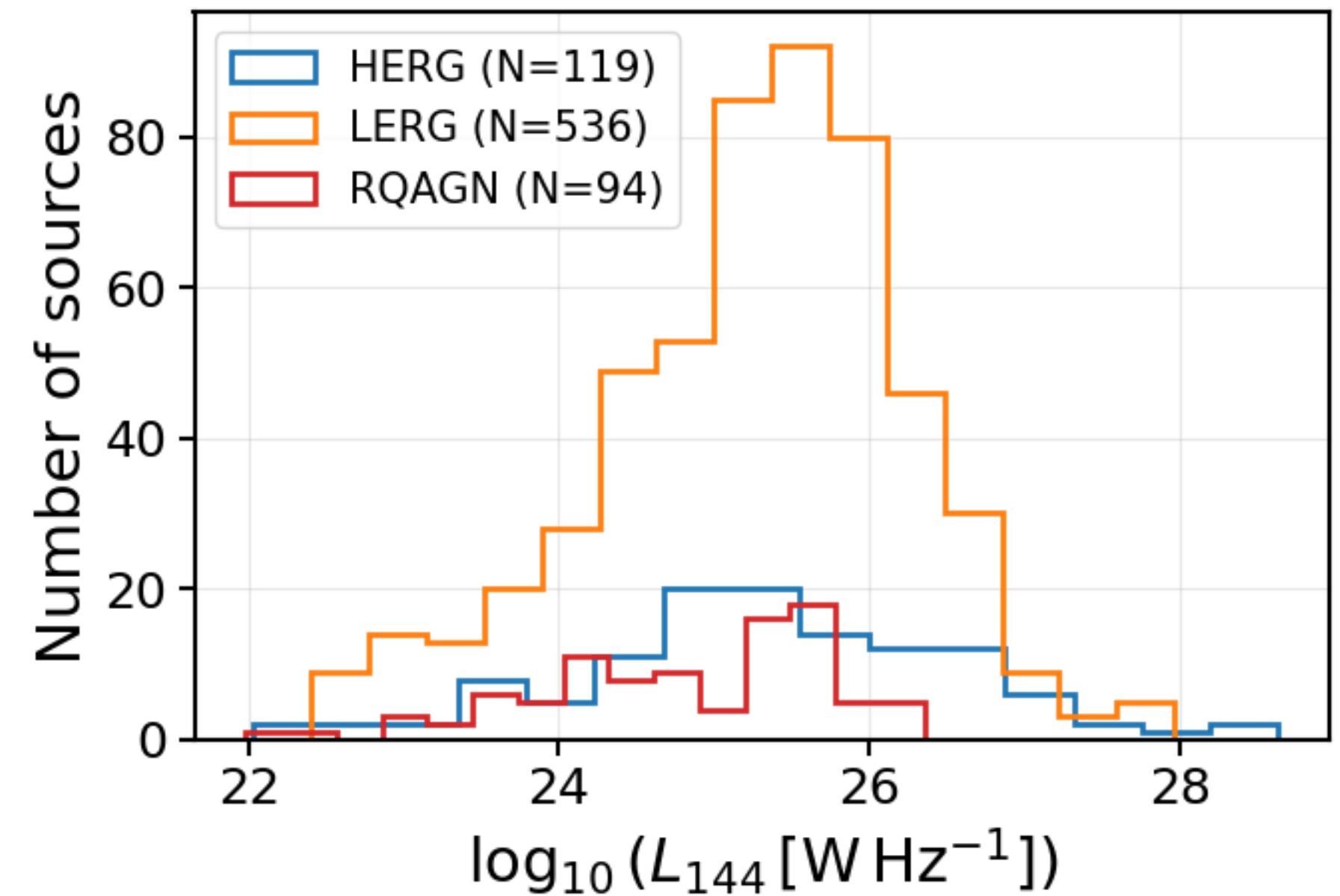
- Boötes: 4,039 sources
- ELAIS-N1: 1,602 sources
- Lockman Hole: 1,466 sources

GSJ final sample

Luminosity distribution



$$L_{144 \text{ MHz}} \in [10^{22}, 10^{28}] \text{ W Hz}^{-1}$$



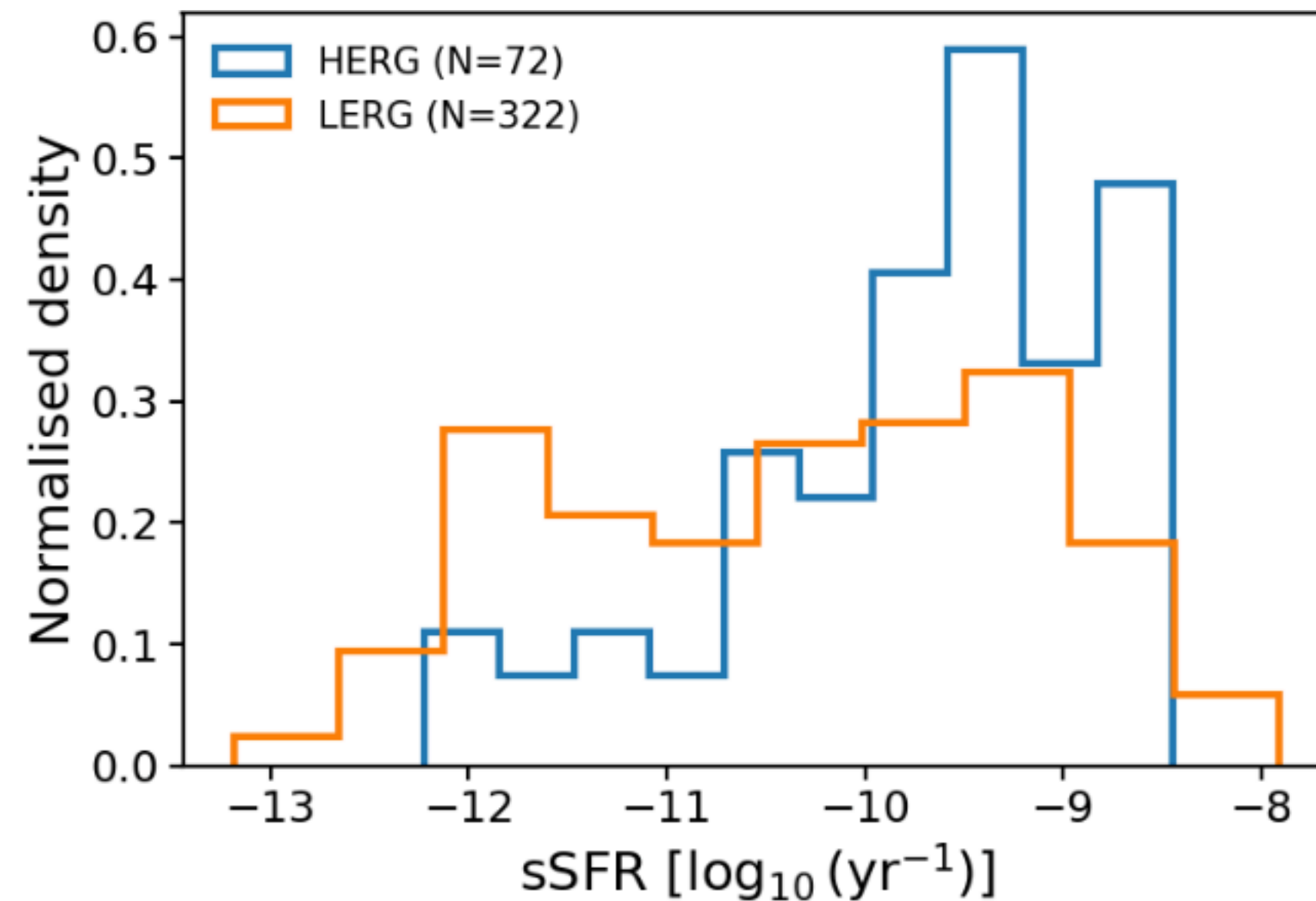
$$L_{150 \text{ MHz}} \in [3 \times 10^{22}, 1.5 \times 10^{25}] \text{ W Hz}^{-1}$$

Webster+2021, GJS in LoTSS

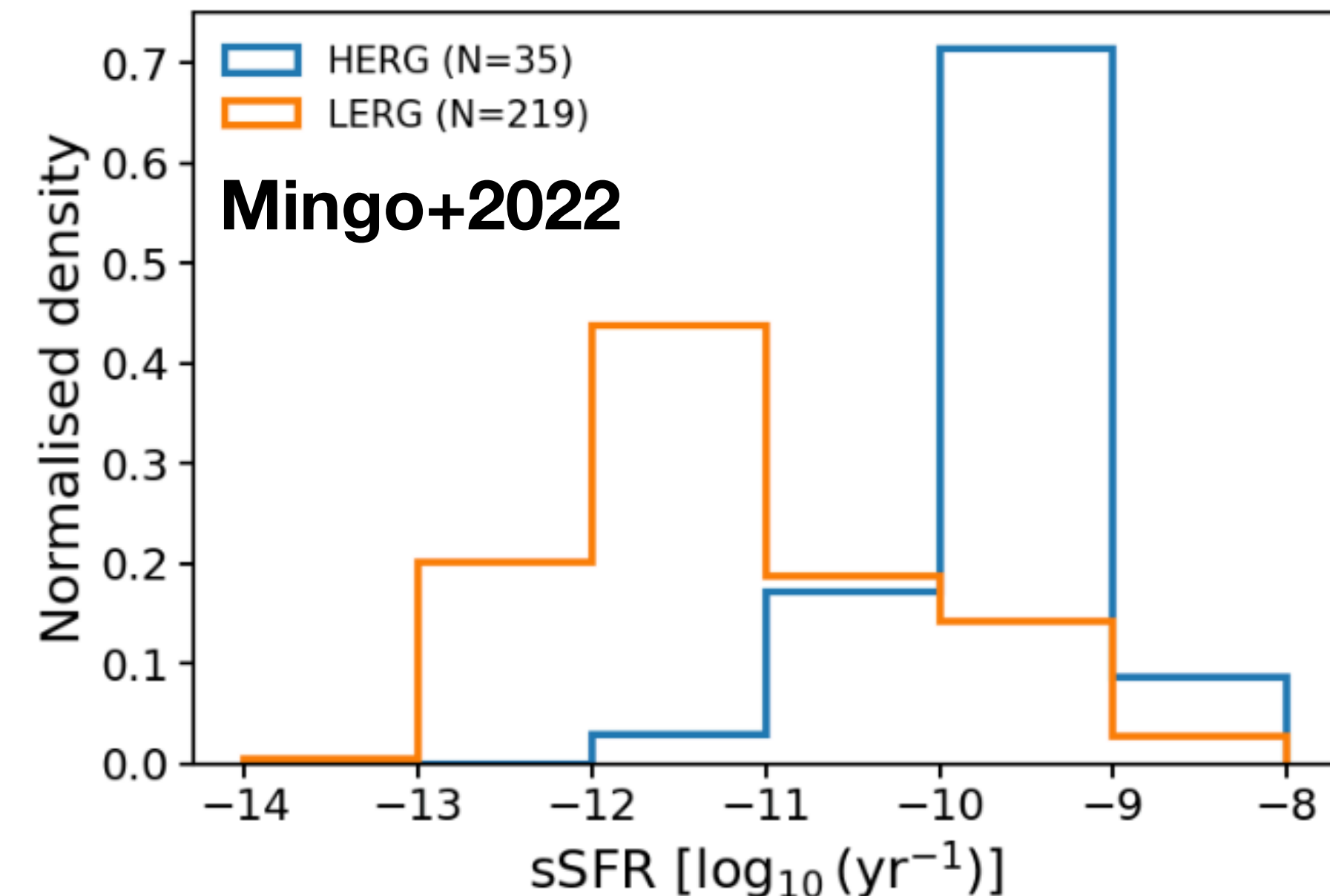
GSJ – host galaxy properties

Specific SFR

GSJ



Radio-loud AGN in the LOFAR Deep Fields with a robust FRI-FRII morphological classification



- Strong preference for GSJ-HERGs to be in star-forming systems (consistent with other studies of larger scales RLAGN in the LOFAR Deep Fields, Mingo+2022)
- No bimodal sSFR distribution between LERGs and HERGs: significant population of LERGs in high-forming systems ($\sim 40\%$ LERGs with $\text{sSFR} > -10/\text{yr}$)

sSFR in GSJ – from redshift 0.5 to 2.5

