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LOFAR

The LOFAR-View of Ram-Pressure Stripping in the Virgo Cluster

First insights from the ViCTORIA project

H. W. Edler, I. Roberts, F. de Gasperin, V. Heesen, A. Boselli ,T. Shimwell, M. Brüggen et al.

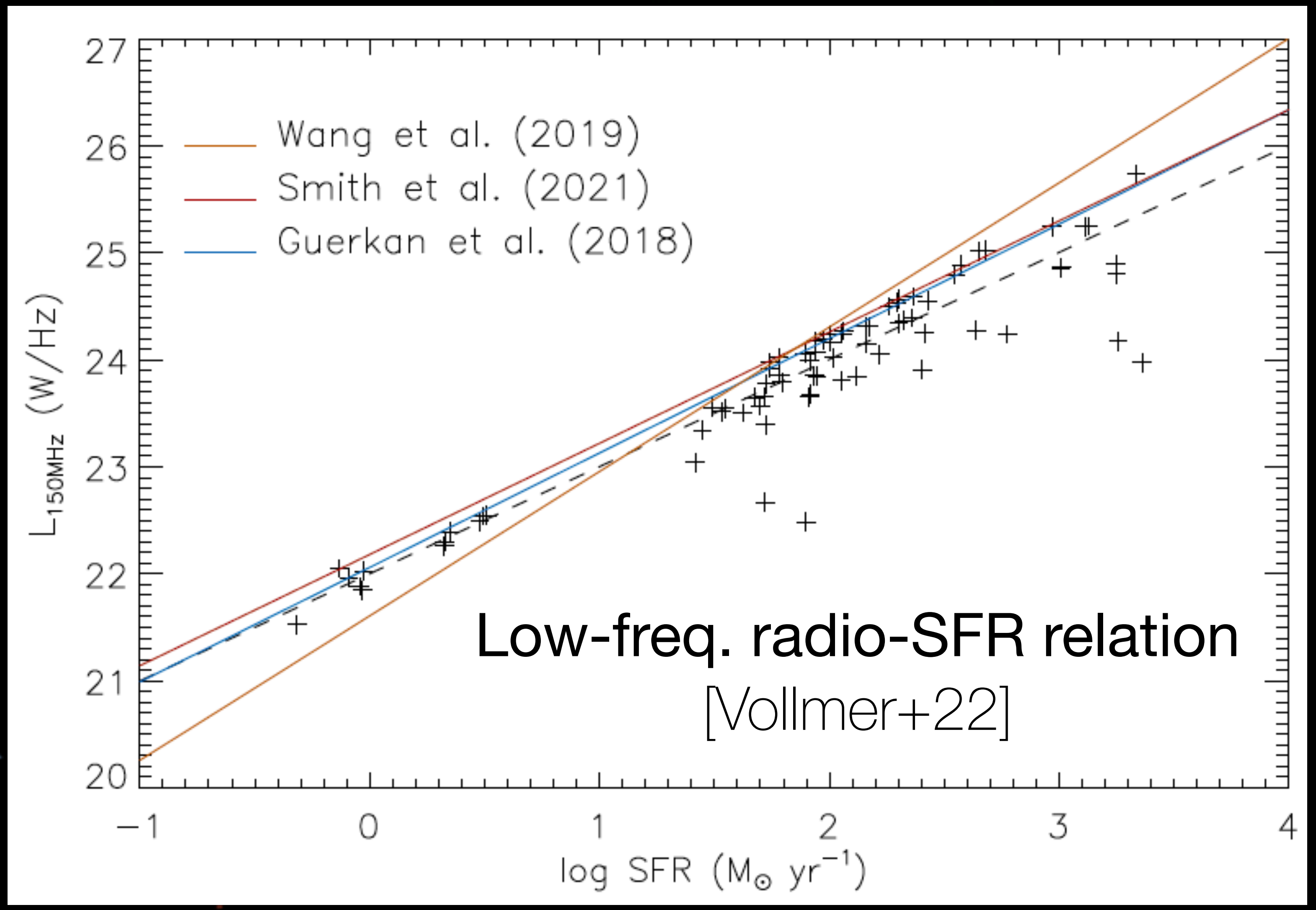
LOFAR Family Meeting 2023, UWM Olsztyn

Henrik Edler, Hamburg Observatory, 13 Juni 2023

Introduction

Galaxy evolution in different environments

- Cluster galaxies: less gas & star-formation rate (SFR)
- Significant contribution from ram-pressure stripping (RPS)
- Removes gas reservoir → quenching
- In the radio band
  - Identify RPS through non-thermal tails
  - Trace SFR → excess in RPS galaxies

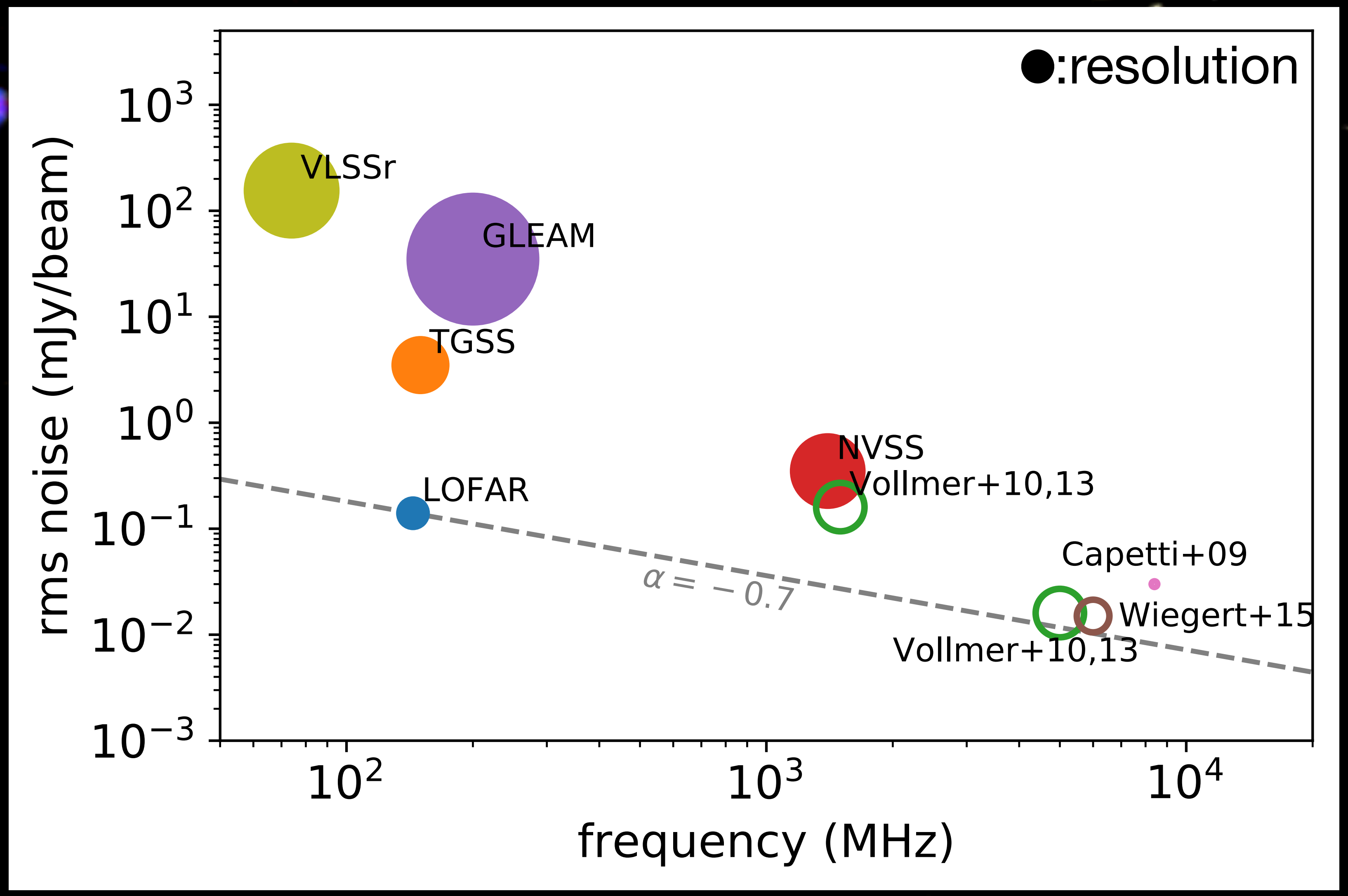


ViCTORIA project

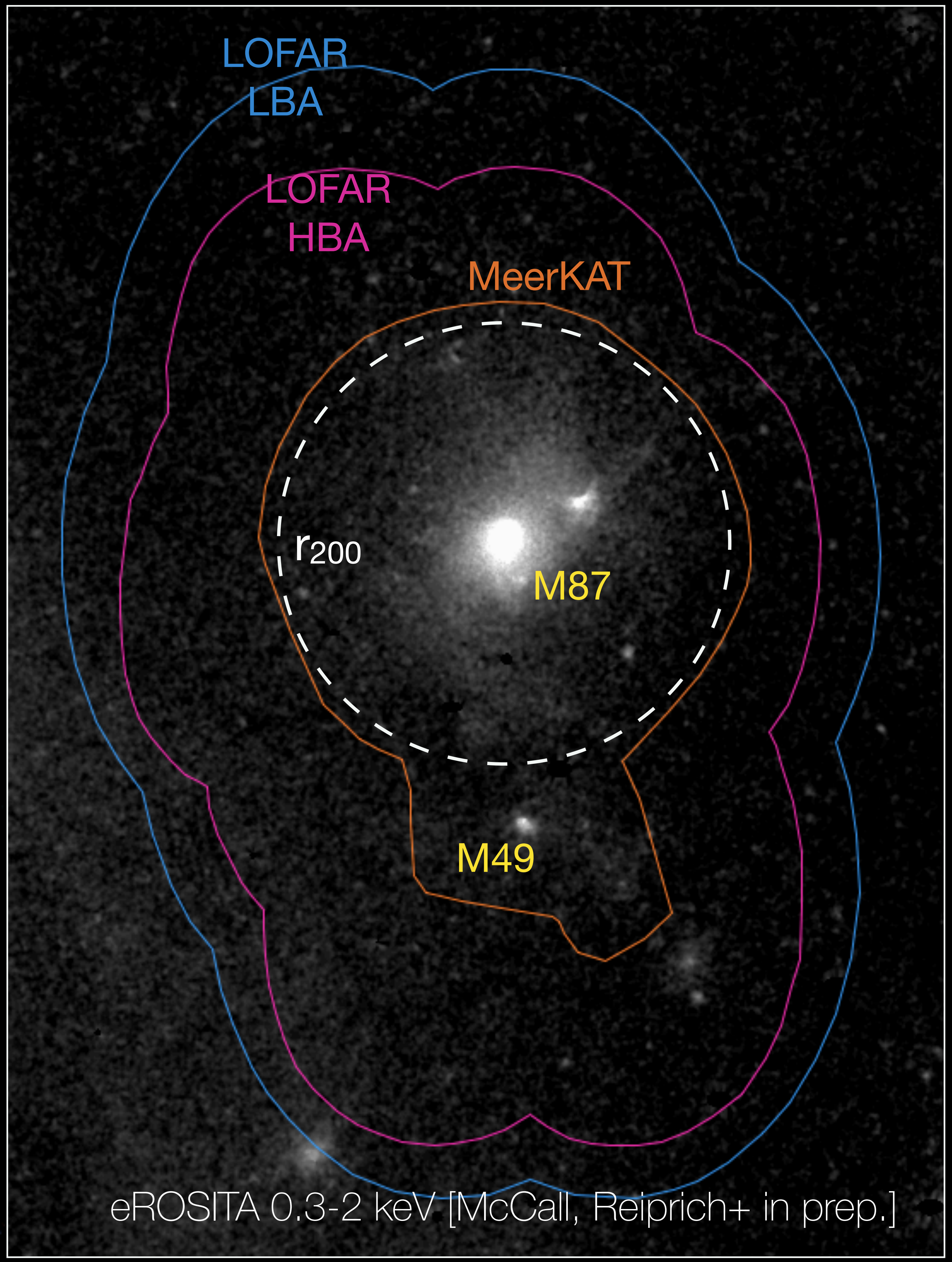
Virgo Cluster multi-Telescope Observations in Radio of Interacting galaxies and AGN

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

1. LOFAR HBA: 144 MHz
2. LOFAR LBA: 54 MHz
3. MeerKAT: 1.3 GHz



with F. de Gasperin, A. Boselli, P. Serra et al.



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1. LOFAR HBA: 144 MHz → arXiv:2306.04513 lofar-surveys.org/virgo_data.html
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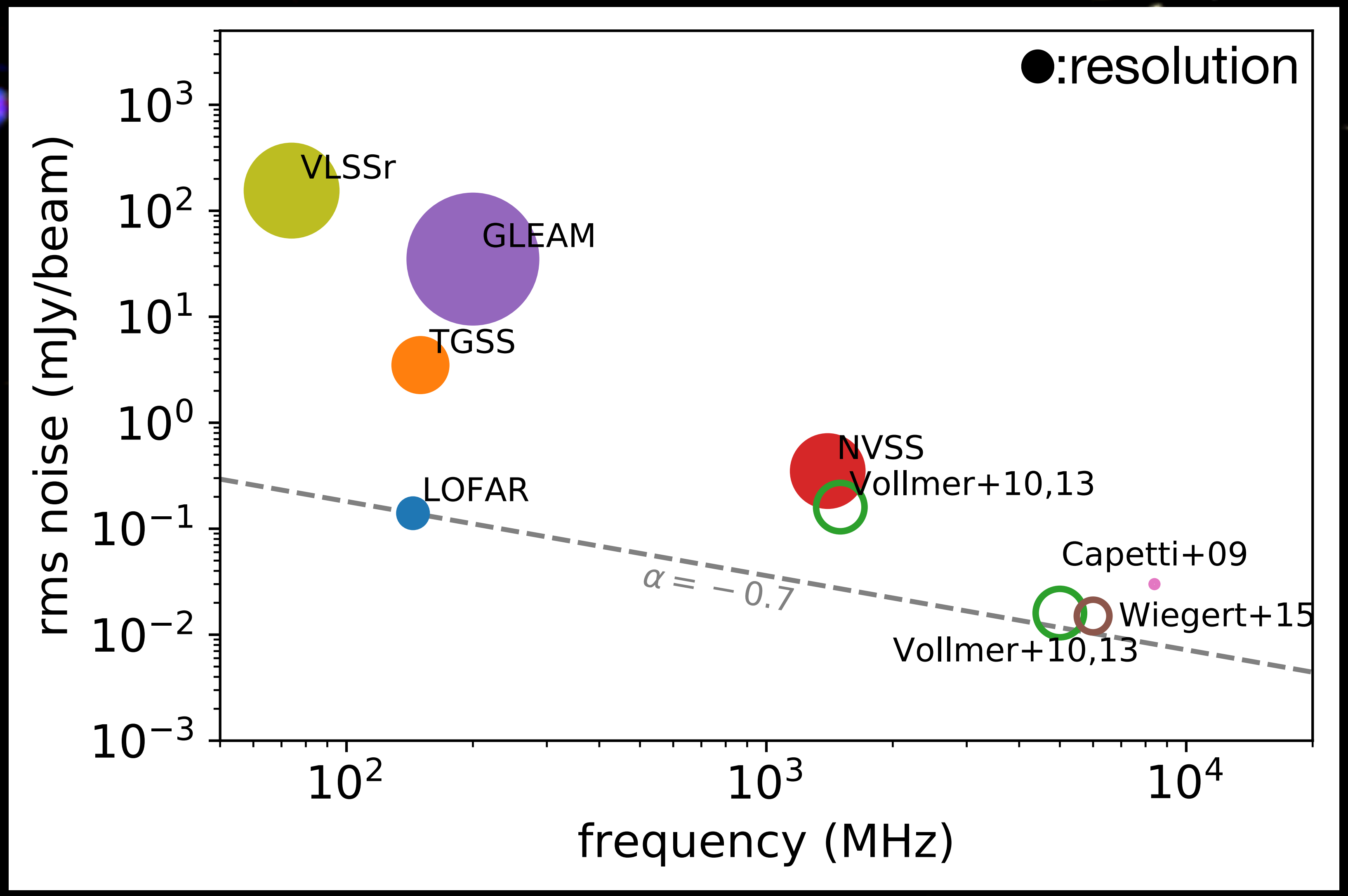
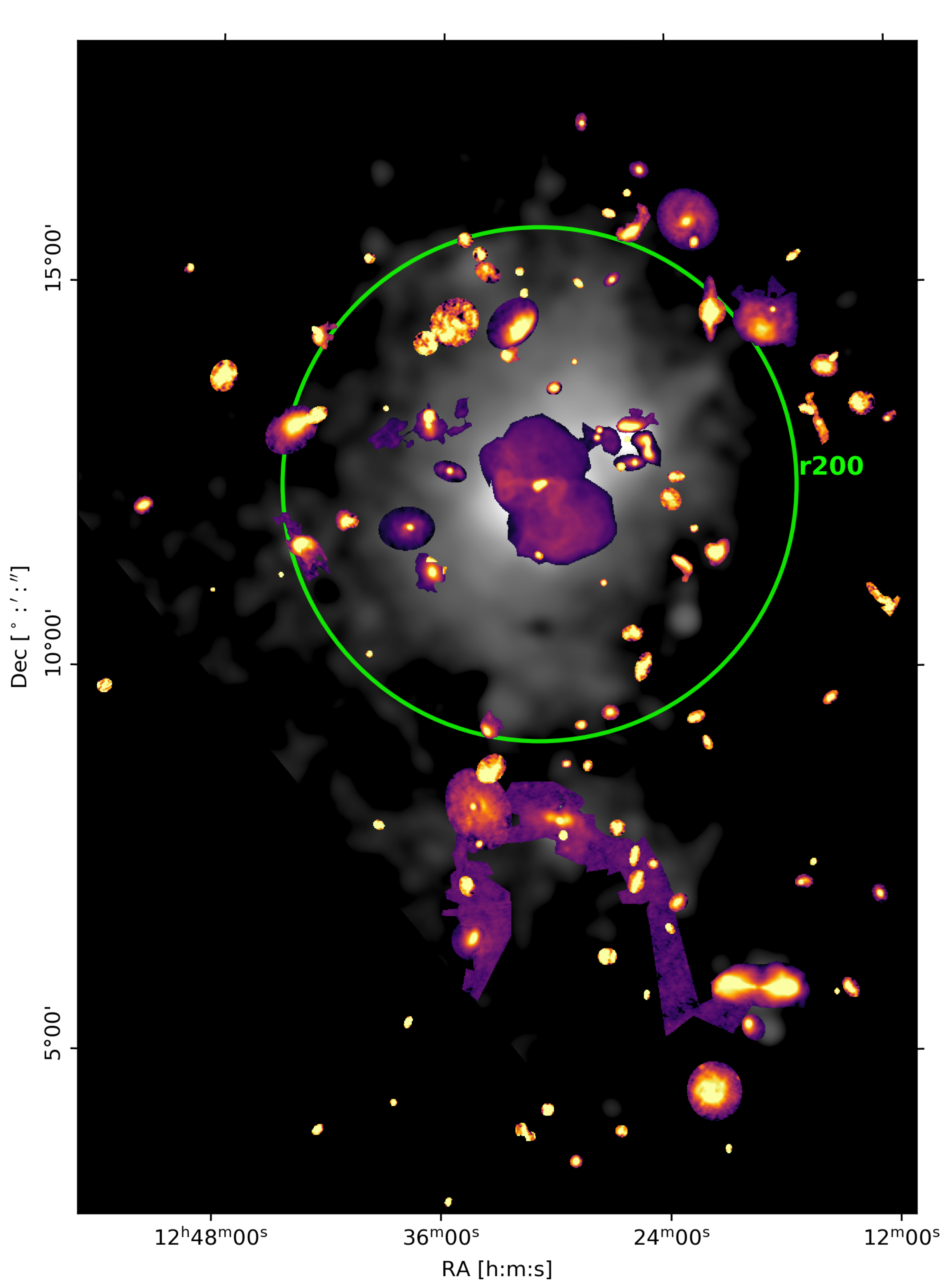


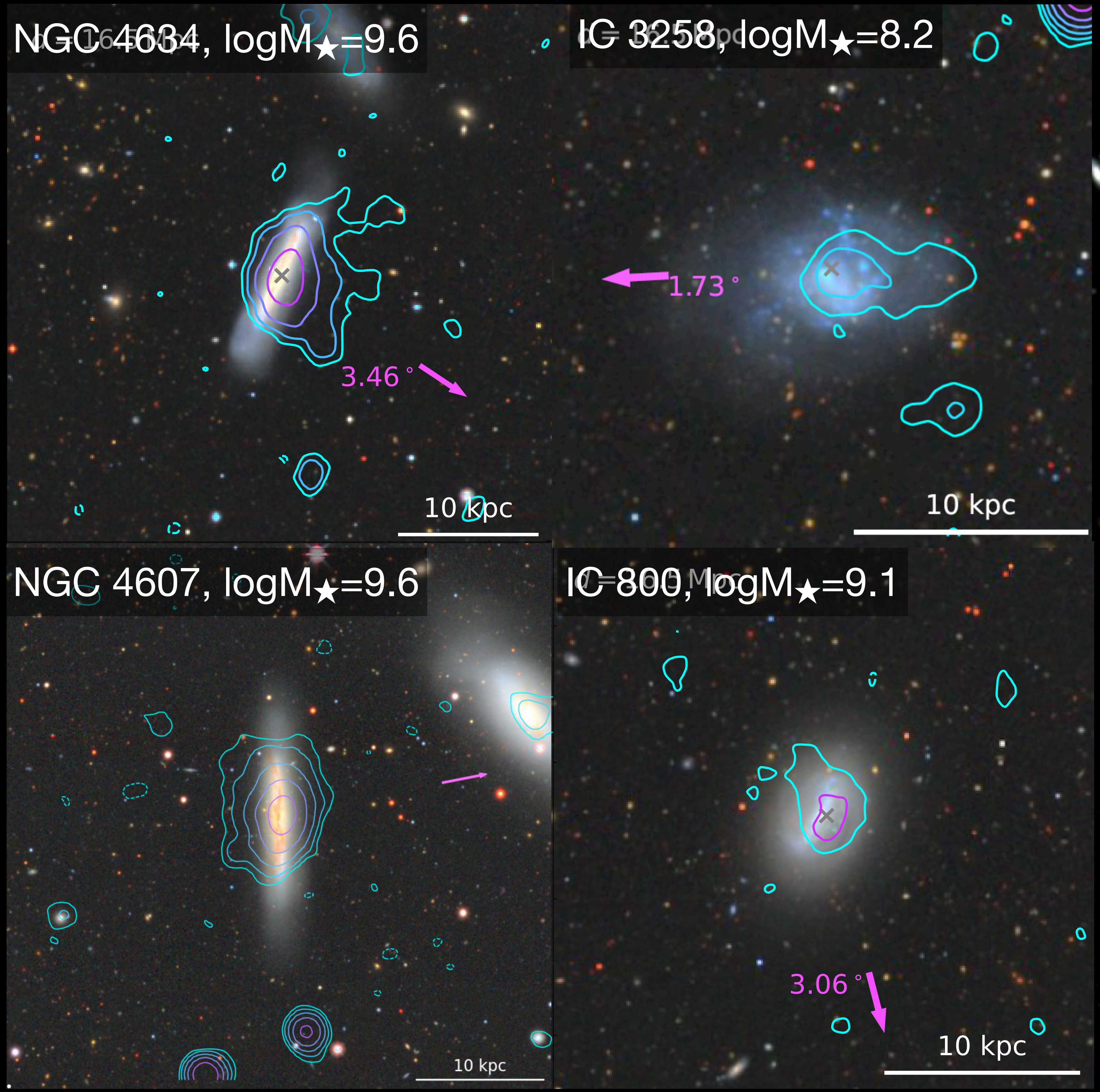


with F. de Gasperin, A. Boselli, P. Serra et al.

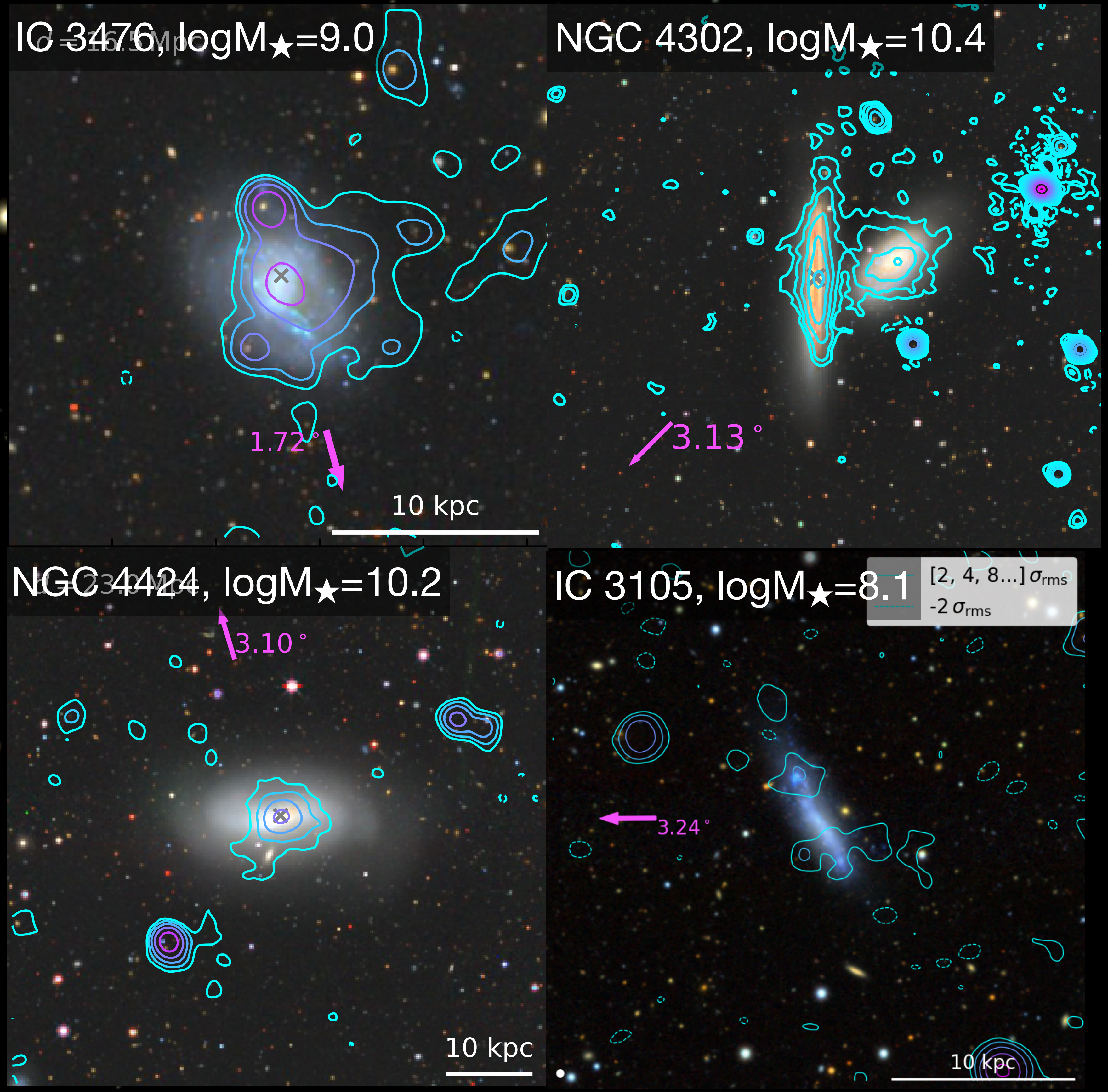
Census of Ram-Pressure Stripping in Virgo

New candidates of RPS in radio

New candidates

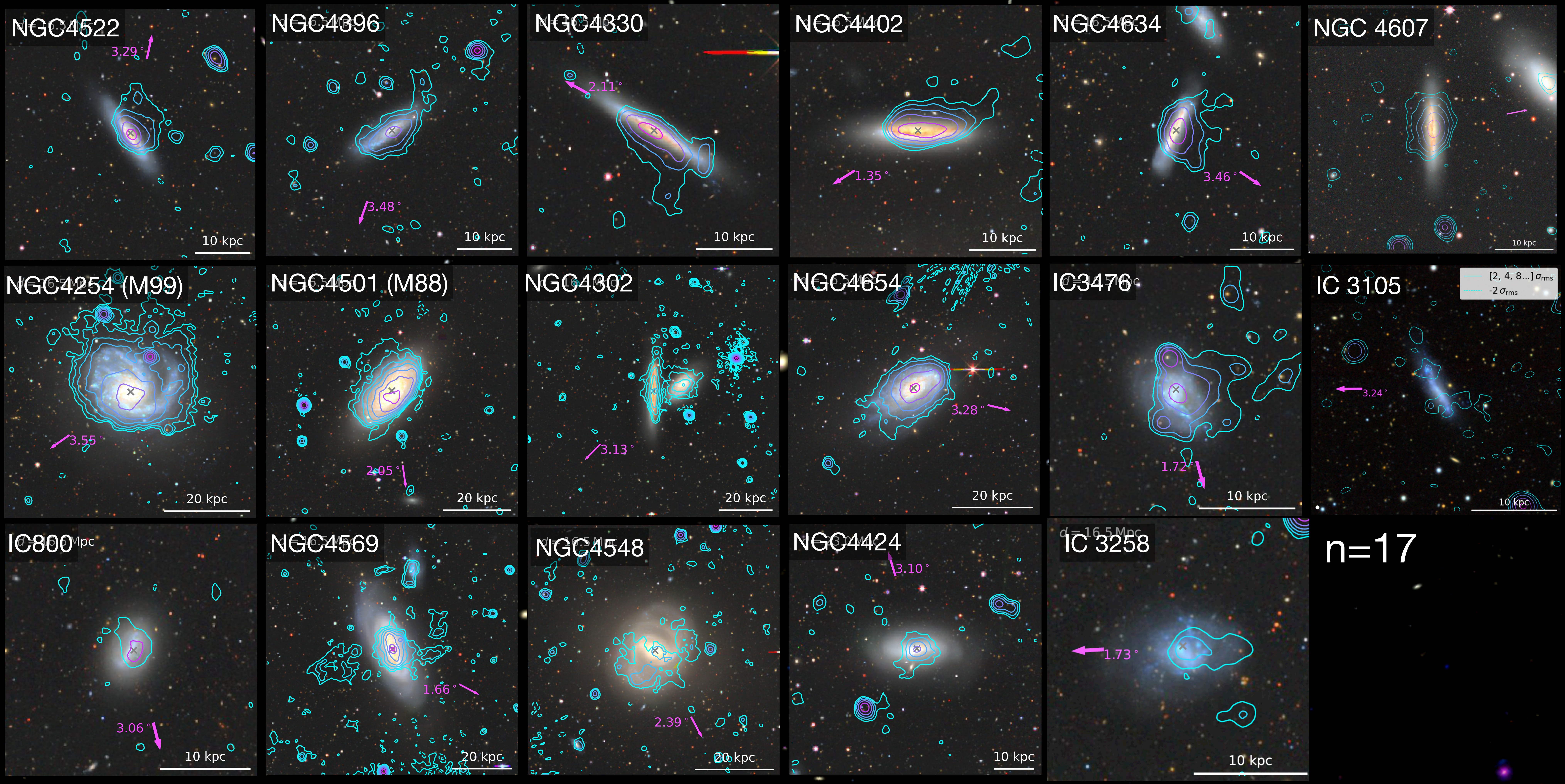


Newly reported in radio



Starting to probe **lower-mass systems** and less extreme cases of RPS

LOFAR Sample of Virgo cluster RPS galaxies



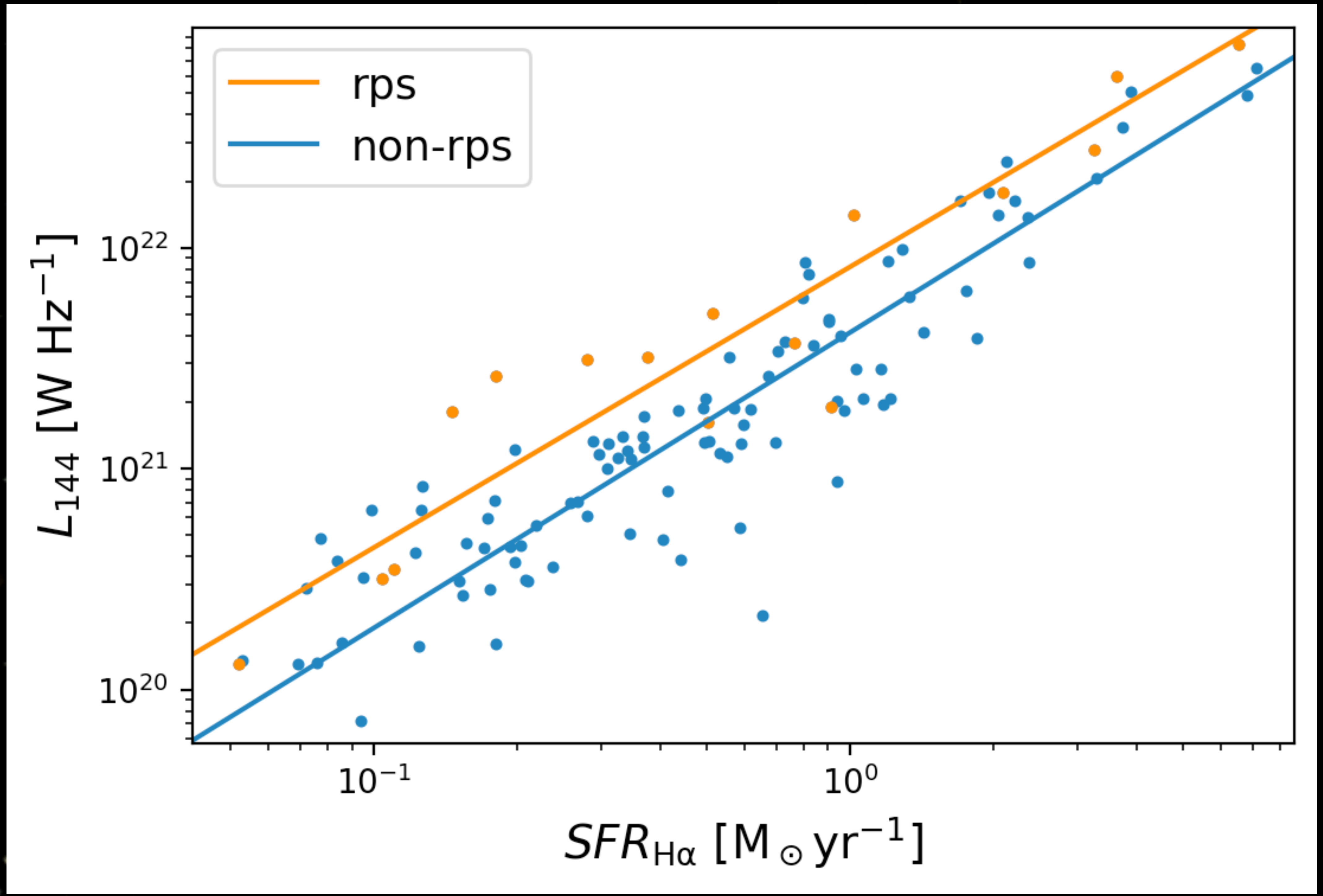
➡Compare RPS sample with statistical sample of 135 LOFAR-detected star-forming galaxies in the Herschel Reference Survey

Radio-SFR relation

Normal vs. stripped galaxies

- $L_{144} = N_0 \mathrm{SFR}^{\delta}, \delta = 1.33$
- 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 SI + enhanced SB at location of shock
3. Rapid decline in SFR [Ignesti+22]
    - Steeper spectral index

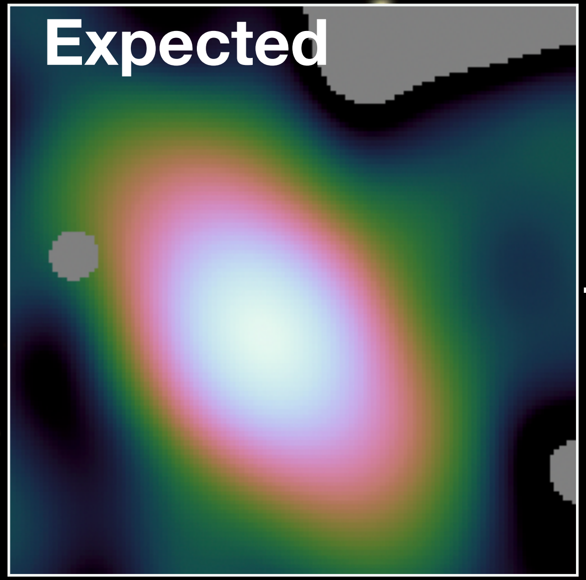


Nature of the Radio-Excess

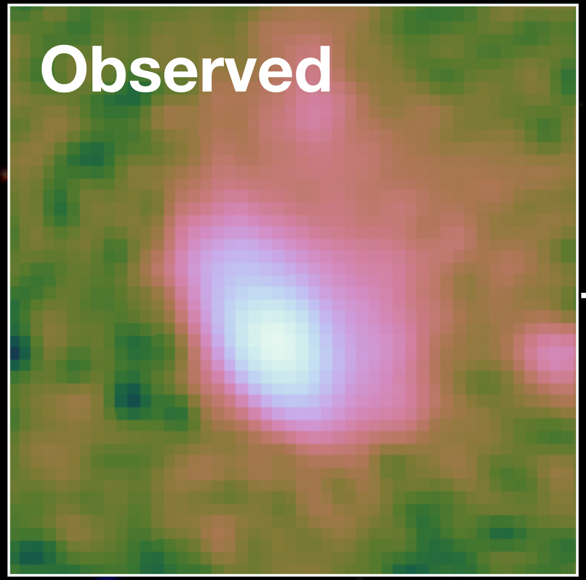
Compare expected and observed radio emission

- SFR surface density from GALEX UV + Herschel IR
- Assume isotropic diffusion (Gaussian kernel)
- Convert to radio surface brightness using global radio-SFR relation

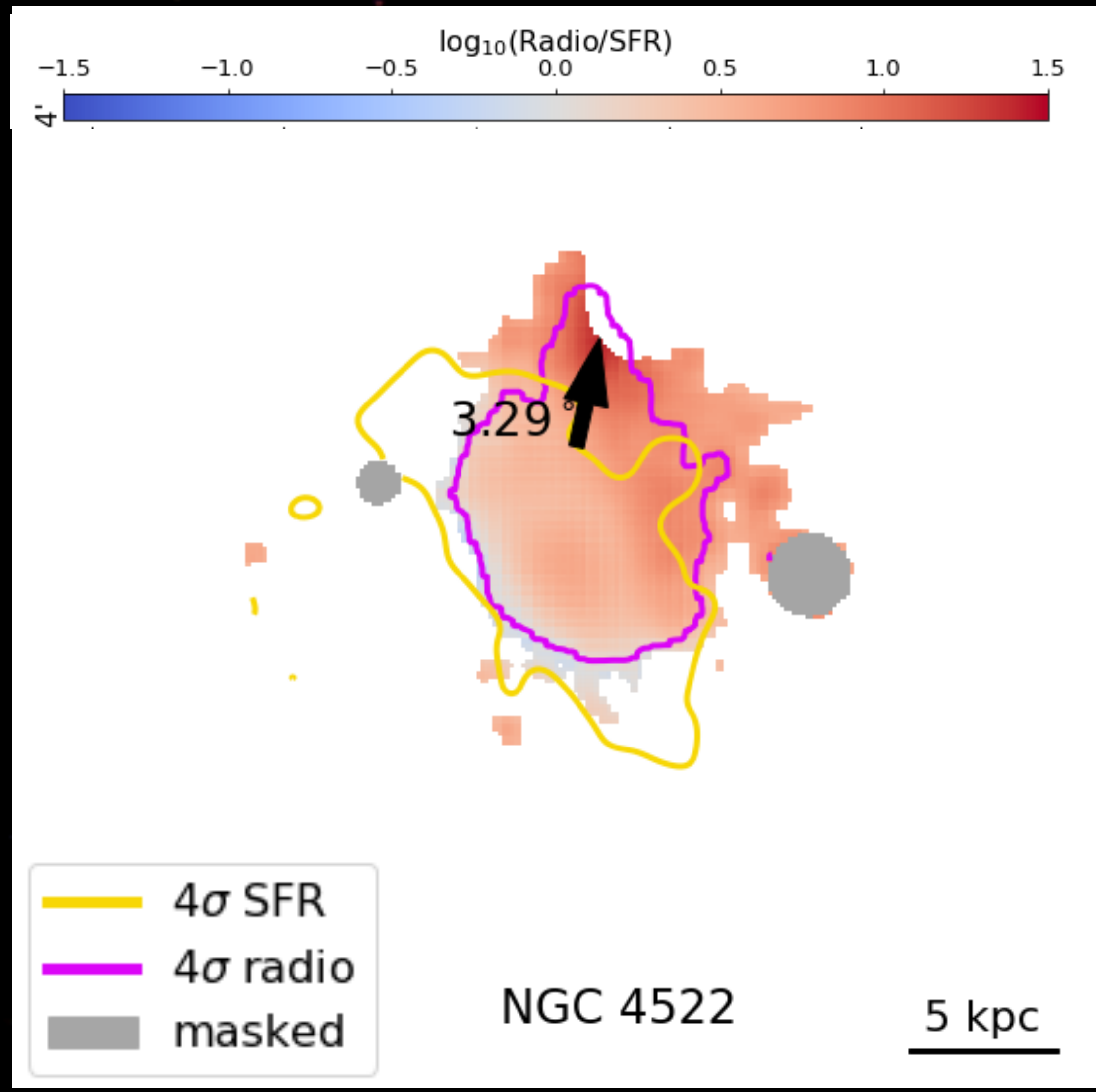
UV + IR
Gaussian convolution
radio-SFR-relation

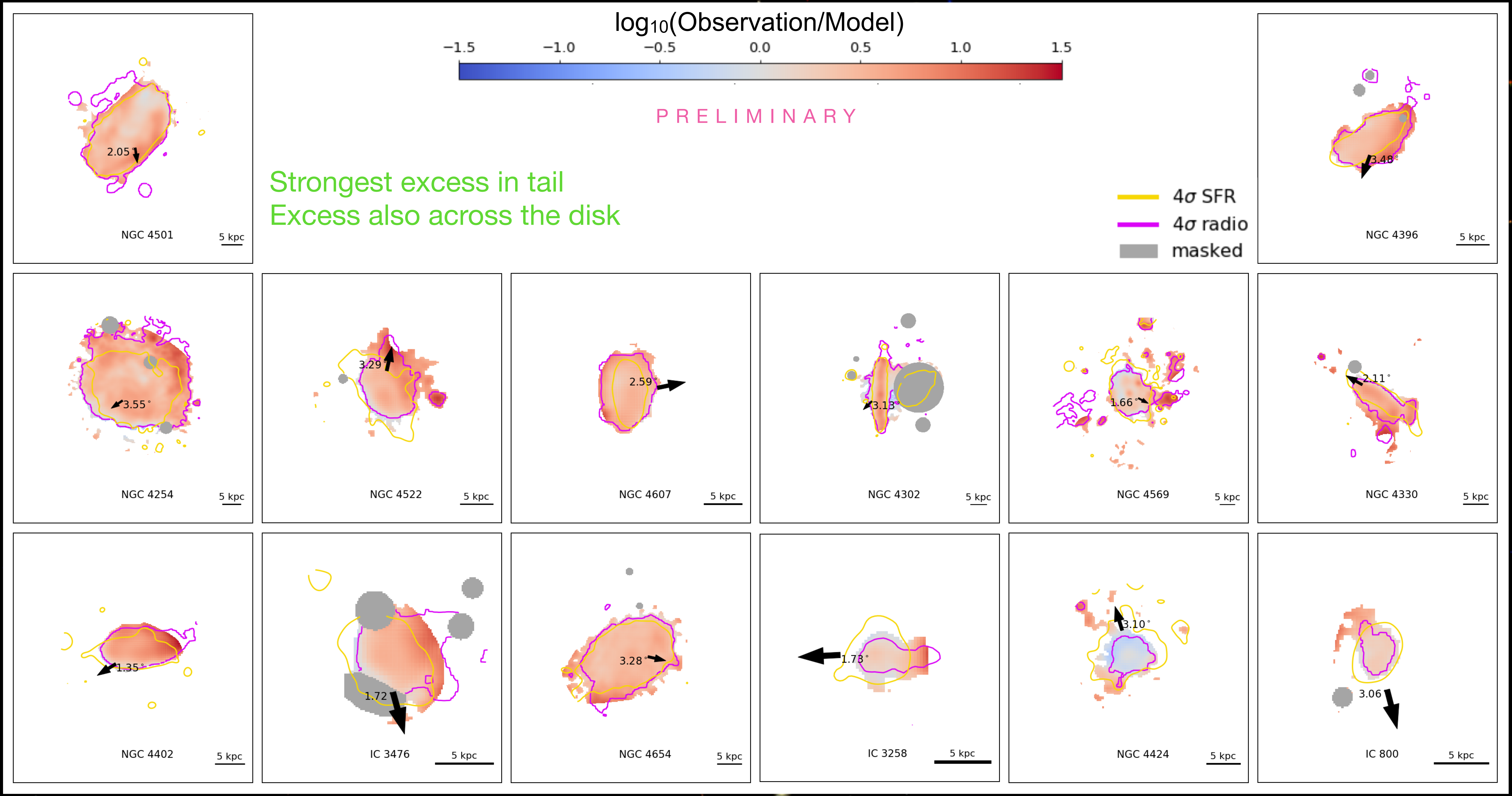


LOFAR HBA 20”

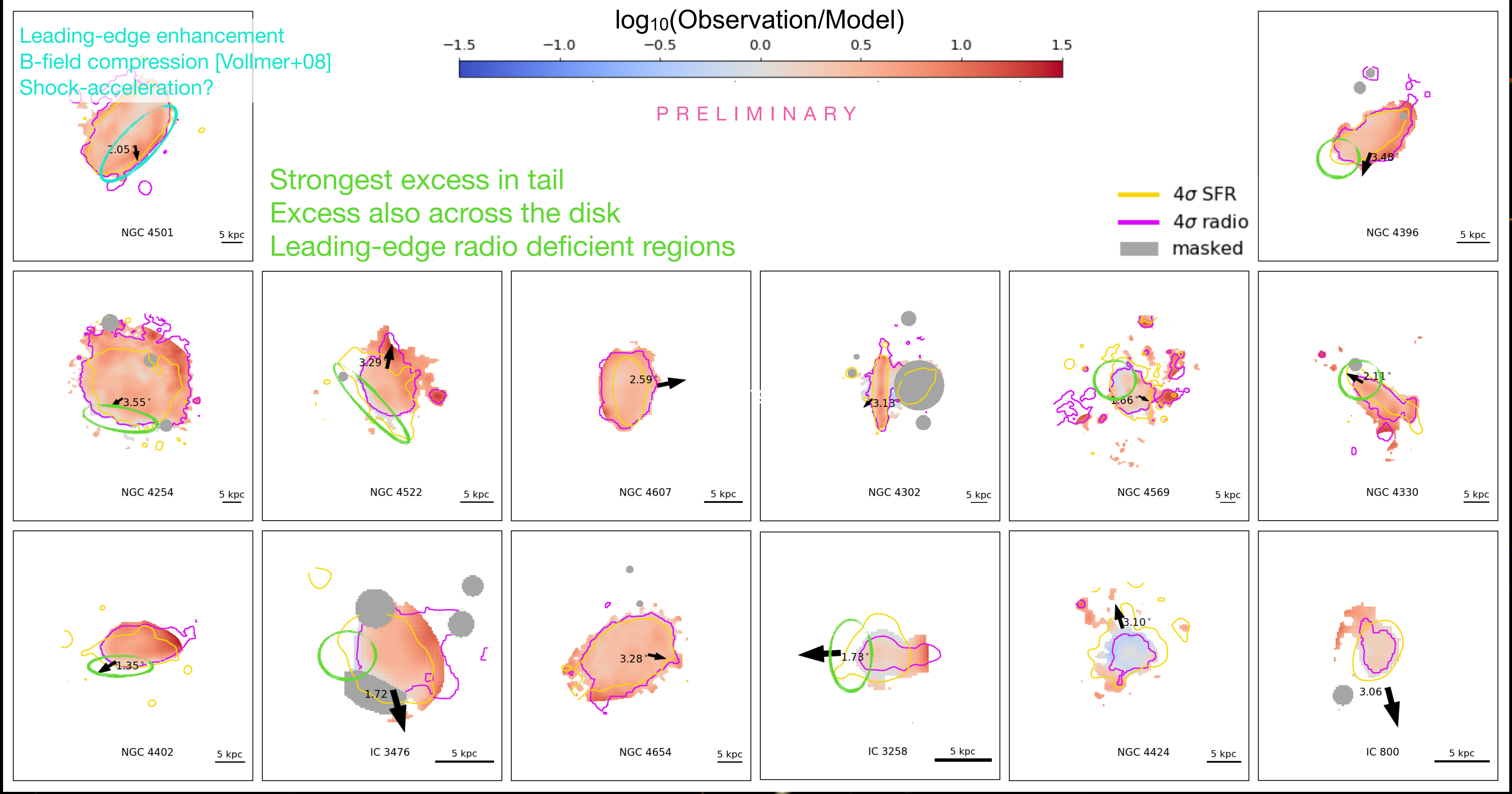


log(ratio)





see also [Murphy+09]



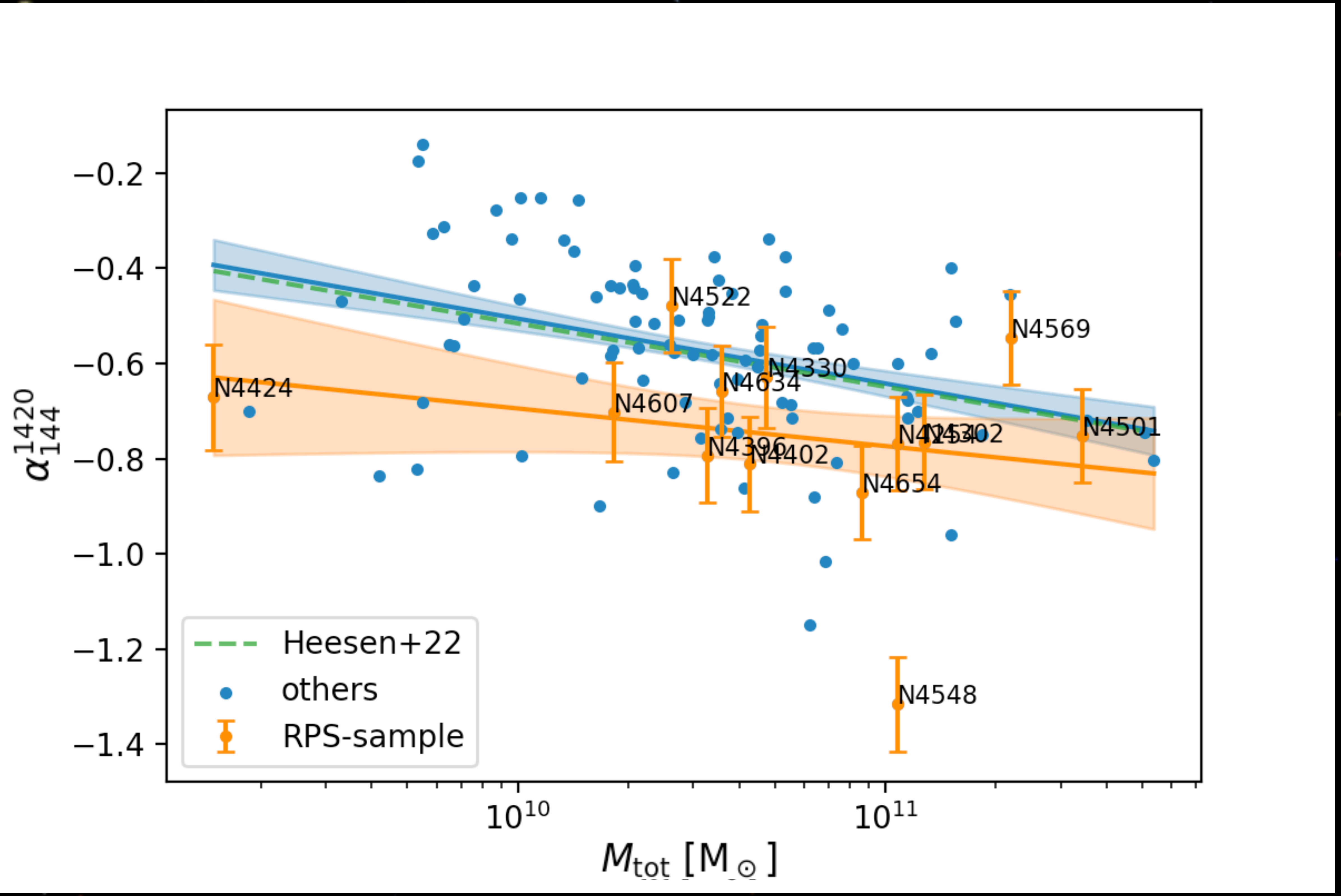
see also [Murphy+09]

Spectral Properties of RPS Galaxies

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]

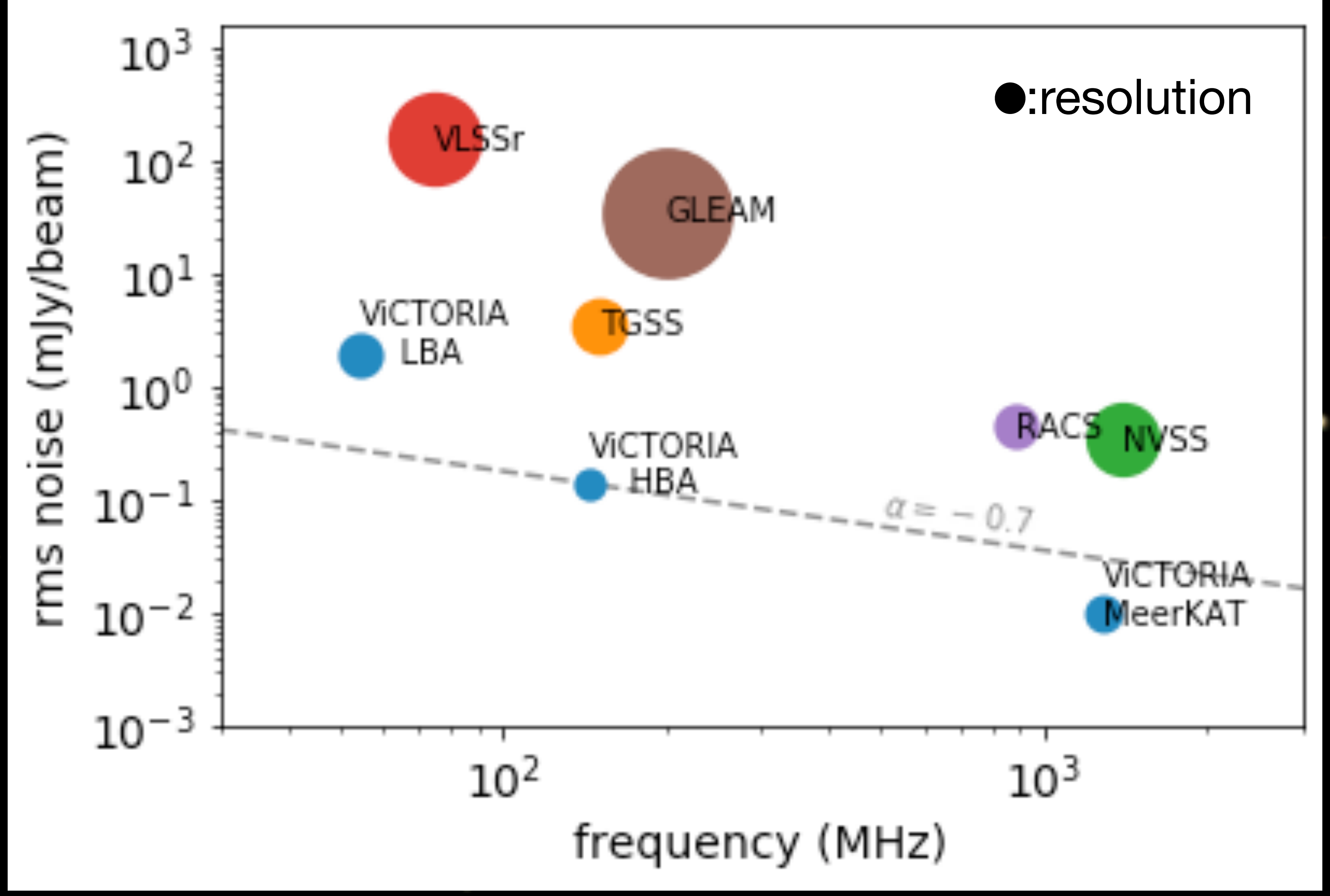


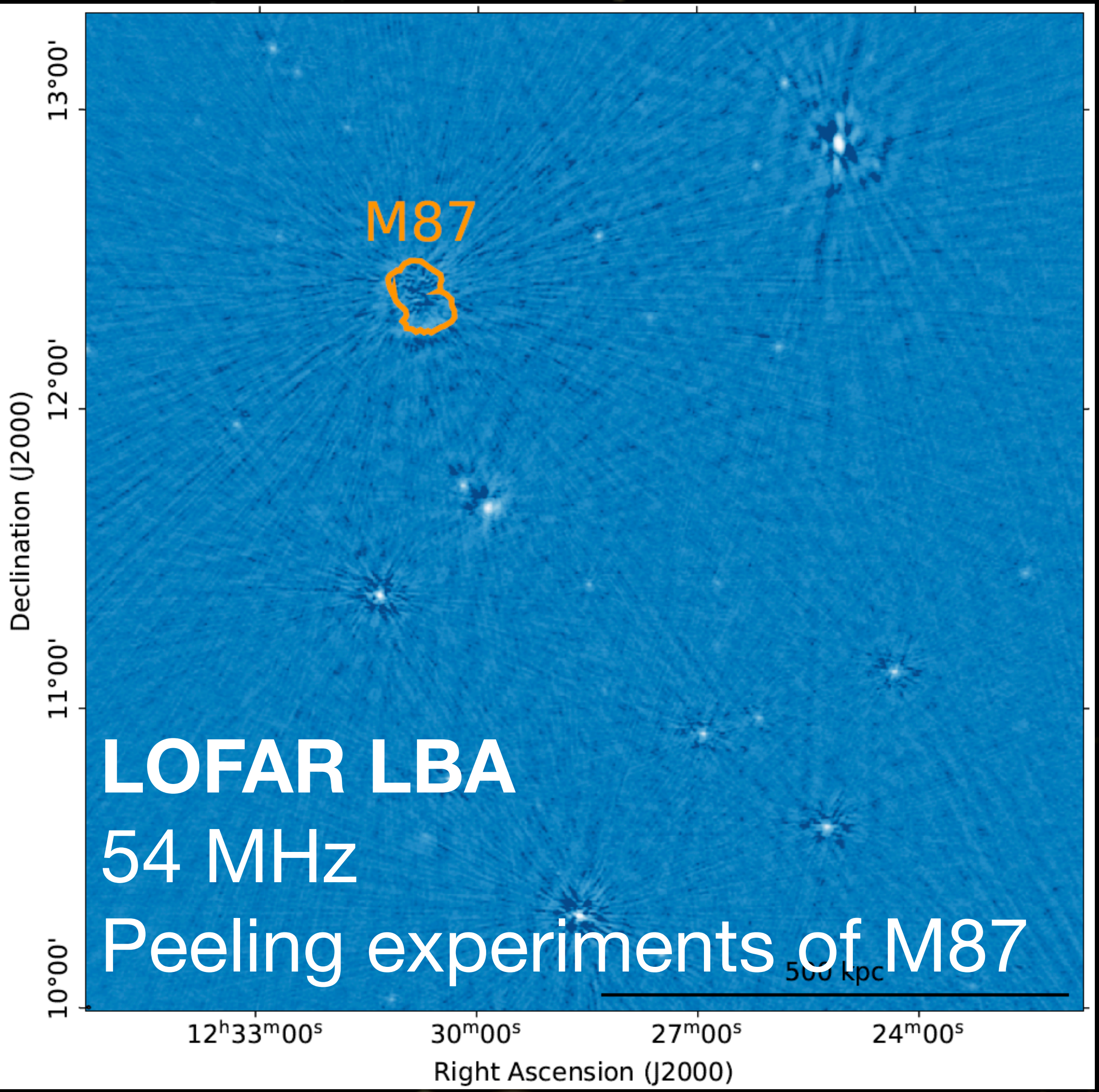
1.4 GHz from [Murphy+09, Chung+09, Vollmer+10, Boselli+15]

Outlook

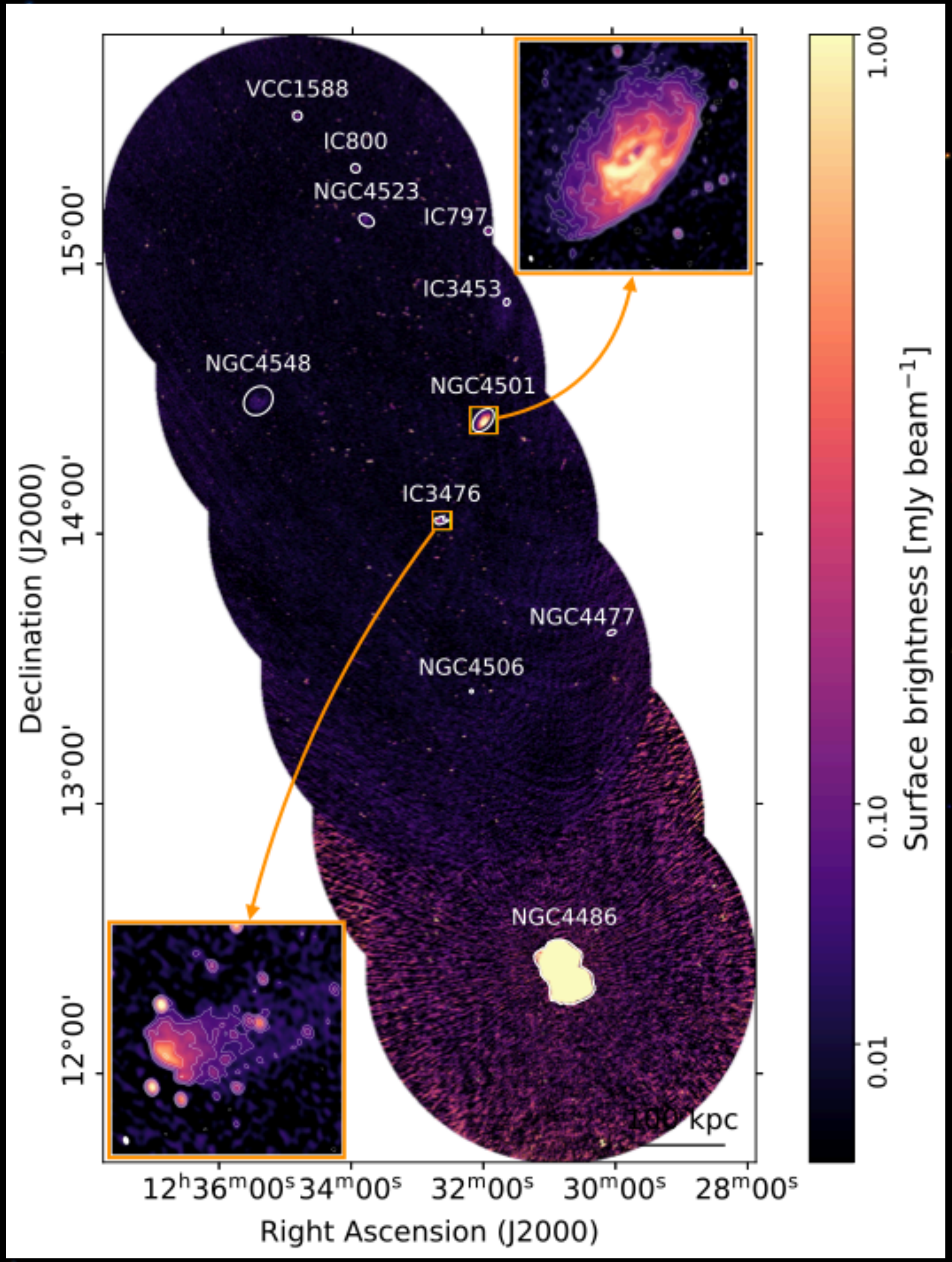
ViCTORIA MeerKAT and LBA

- **MeerKAT** and **LOFAR LBA** Virgo Cluster surveys for HI and spectral studies!





MeerKAT pilot, σ≥10μJy/beam



Conclusion

- **LOFAR HBA** Virgo Cluster Survey
  - Catalog of 112 cluster member galaxies
  - ~18 cases with **RPS morphology** in radio
- LOFAR-HRS-sample
  - Confirm low-frequency radio-SFR-relation
  - Clear radio-excess in galaxies that suffer from RPS
  - Excess usually in tail, also across the disk, leading edge deficit
  - RPS galaxies show steeper spectral index -> decline in SF-activity?
- Outlook
  - **MeerKAT** Survey - all data taken + first study on the way
  - **LOFAR LBA** Survey- first cycle of data taken

Data paper: "*ViCTORIA Project: The LOFAR HBA Virgo Cluster Survey*"
arXiv:2306.04513
lofar-surveys.org/virgo_data.html

Backup section

Cosmic ray diffusion lengths at 144 MHz

Results from linearizing SFR-surface density-radio relation.

Some objects (NGC4254, NGC4302) show fast CR-transport -> imprint of advection/ram pressure?

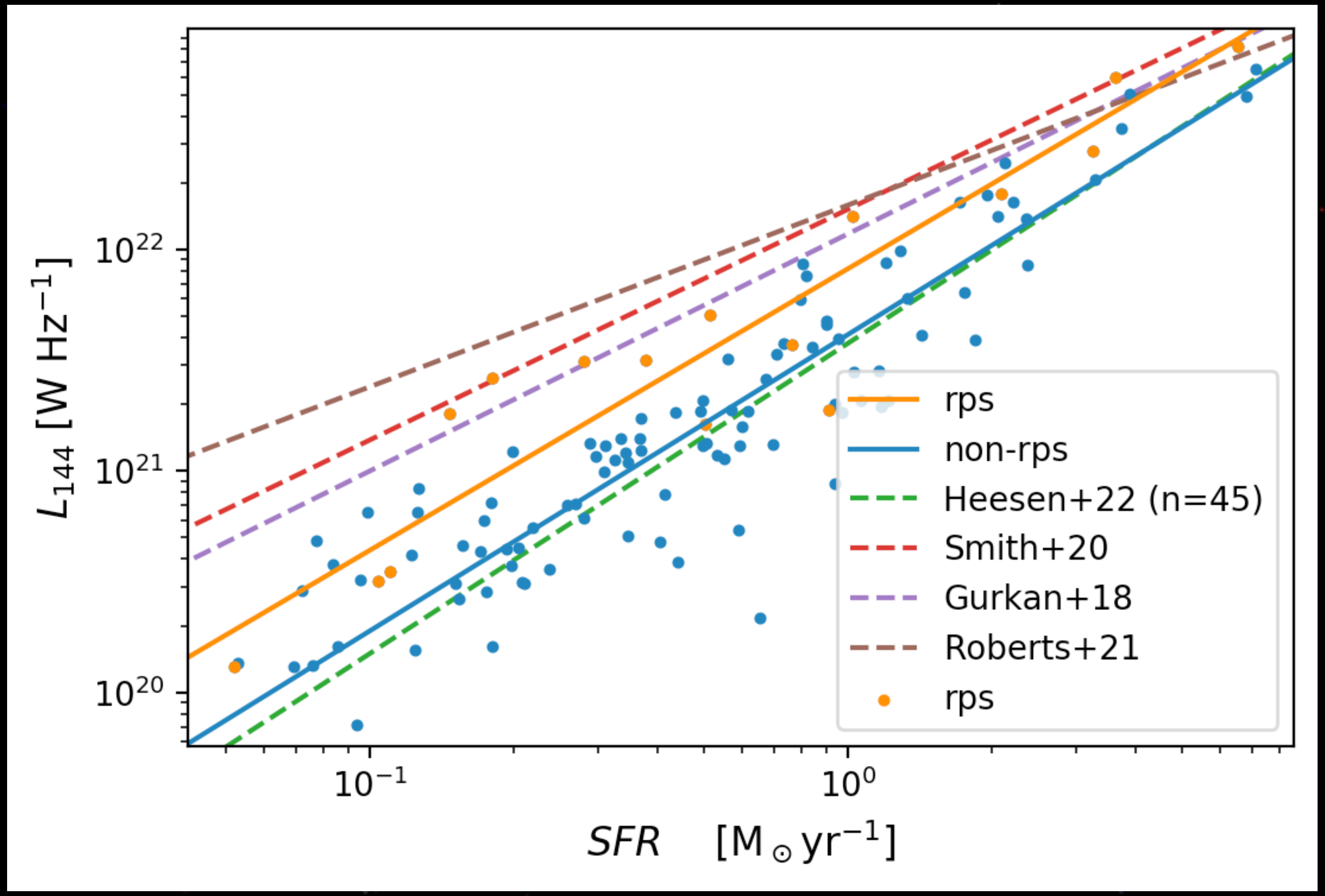
Galaxy	l_{CR} [kpc]
NGC 4254	**5.4**
NGC 4302	**4.0**
NGC 4330	1.8
NGC 4396	1.3
NGC 4402	1.6
NGC 4424	1.4
NGC 4501	0.9
NGC 4522	1.3
NGC 4569	1.9
NGC 4607	1.4
NGC 4654	3.0
IC 800	1.65
IC 3105	1.2
IC 3258	1.8
IC 3476	1.74

Radio-SFR-Correlation at 144 MHz

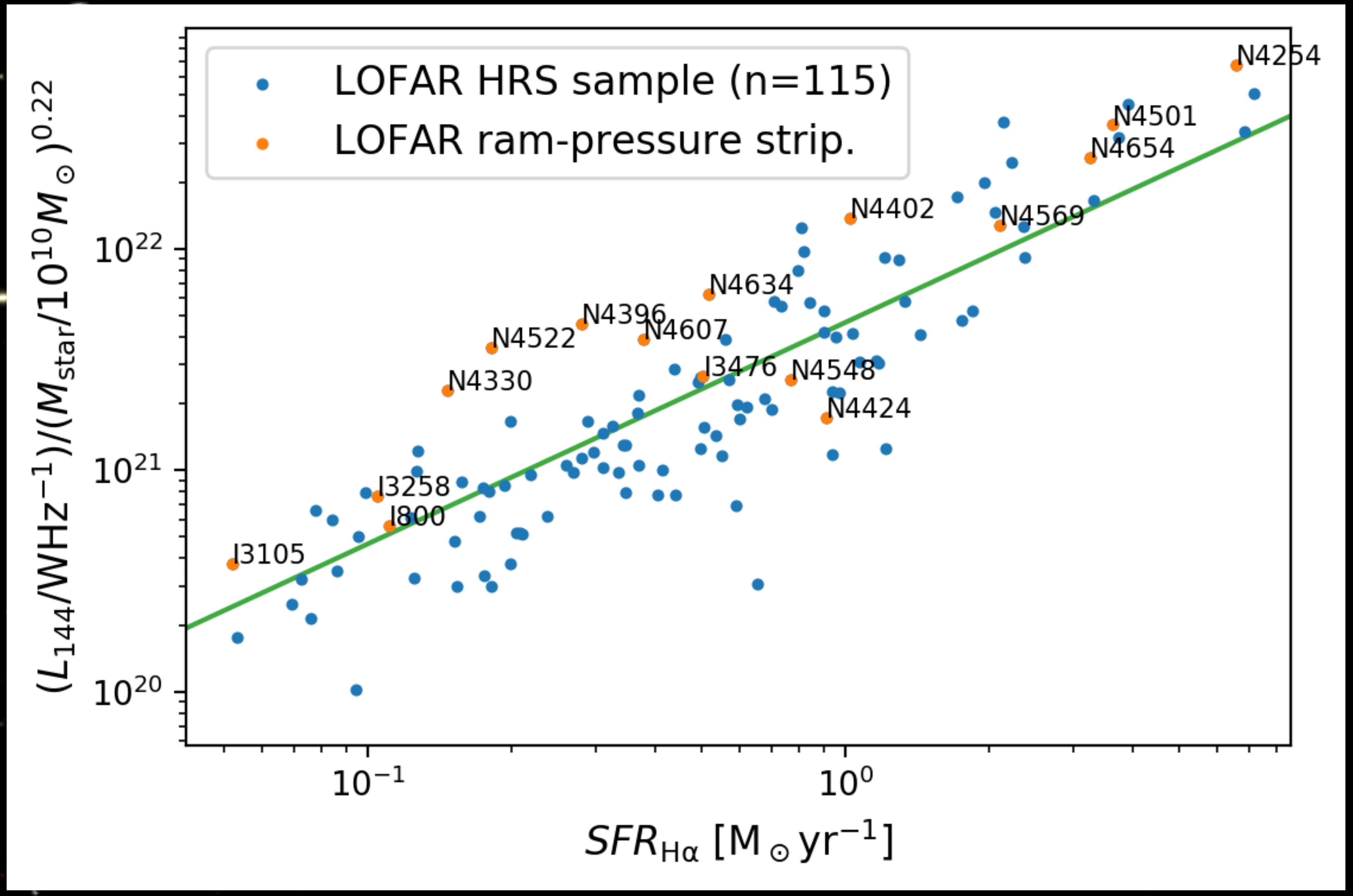
Correlation-fitting

Tension between radio-SFR relation of nearby galaxies [Virgo/this work; Heesen+22] and more distant samples [Gurkan+18; Smith+20]?

➡Caused by different mass selection (~factor 10 difference!)



RPS galaxies on correlation when taking into account mass dependence

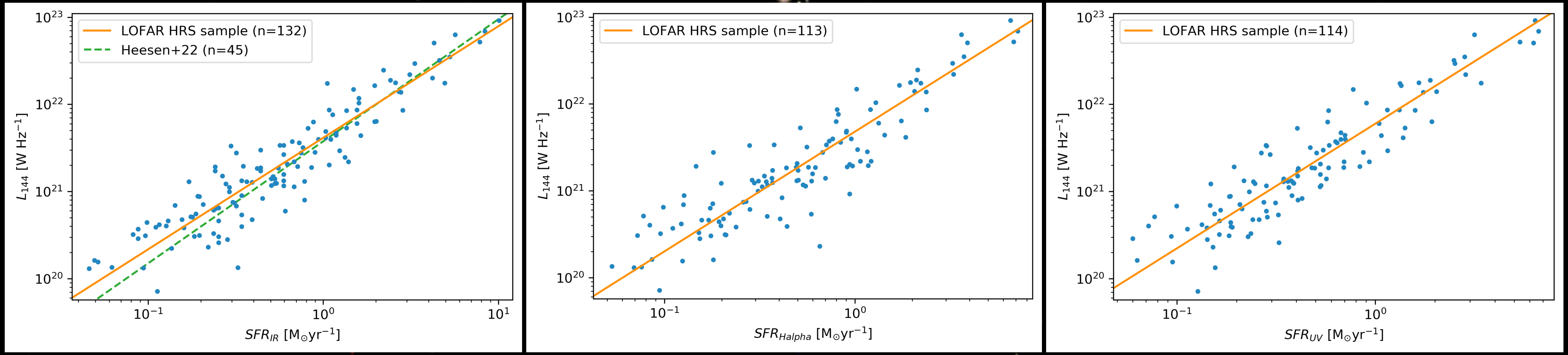


Radio-SFR-Correlation at 144 MHz

Correlation-fitting

SFR-tracer	Sample	β
IR	132	1.28±0.04
Hα	113	1.39±0.05
UV	114	1.43±0.06

- Radio-SFR relation $L_{144\,\mathrm{MHz}} = N_0\,\mathrm{SFR}_X^{\beta}$
- Super-linear slope ~1.3-1.4, in agreement with recent LOFAR results [Heesen+22]



- Explanation: mass-dependent CR-escape: $\tau_{\mathrm{esc}} = \tau_{\mathrm{esc}}(M)$

Radio-SFR relation

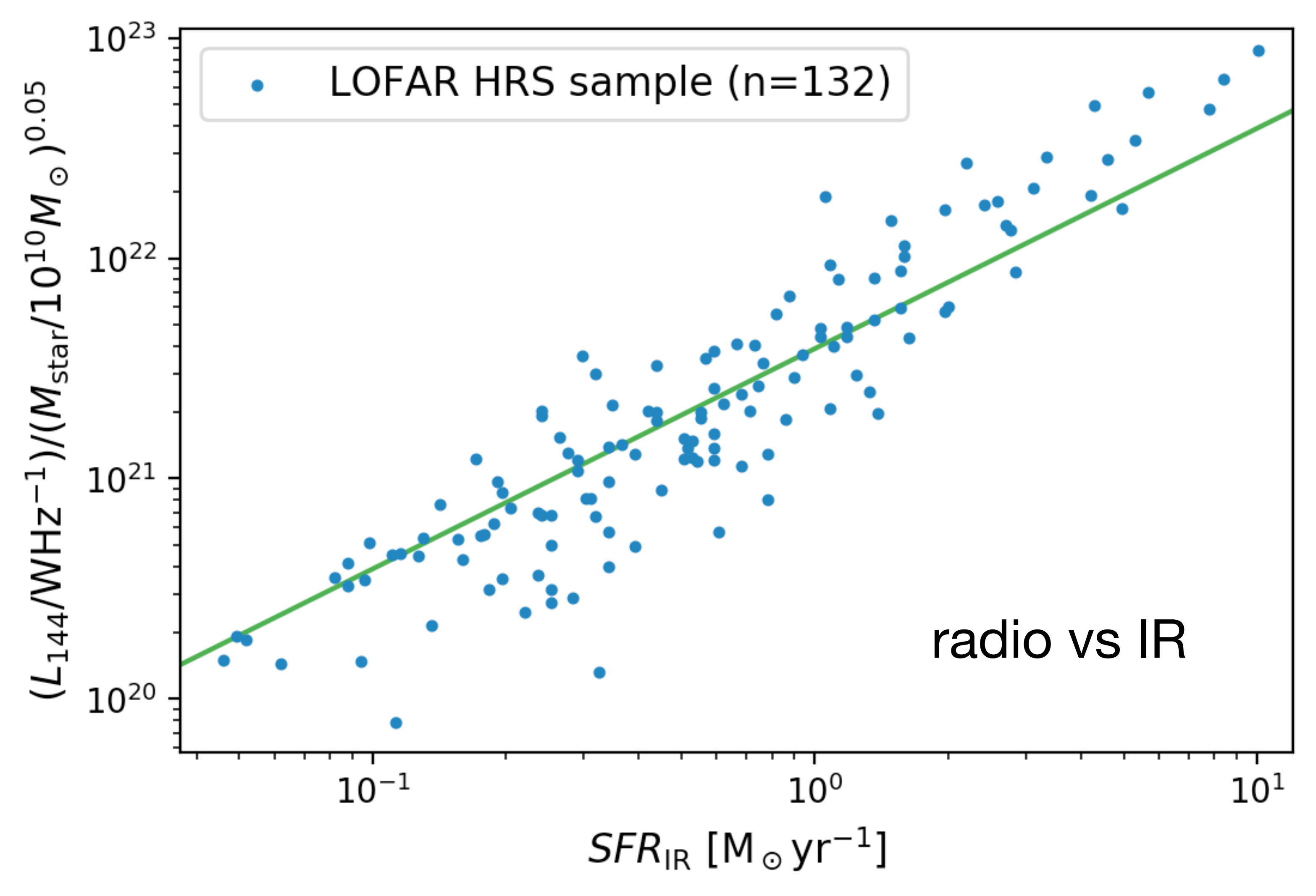
Including stellar mass

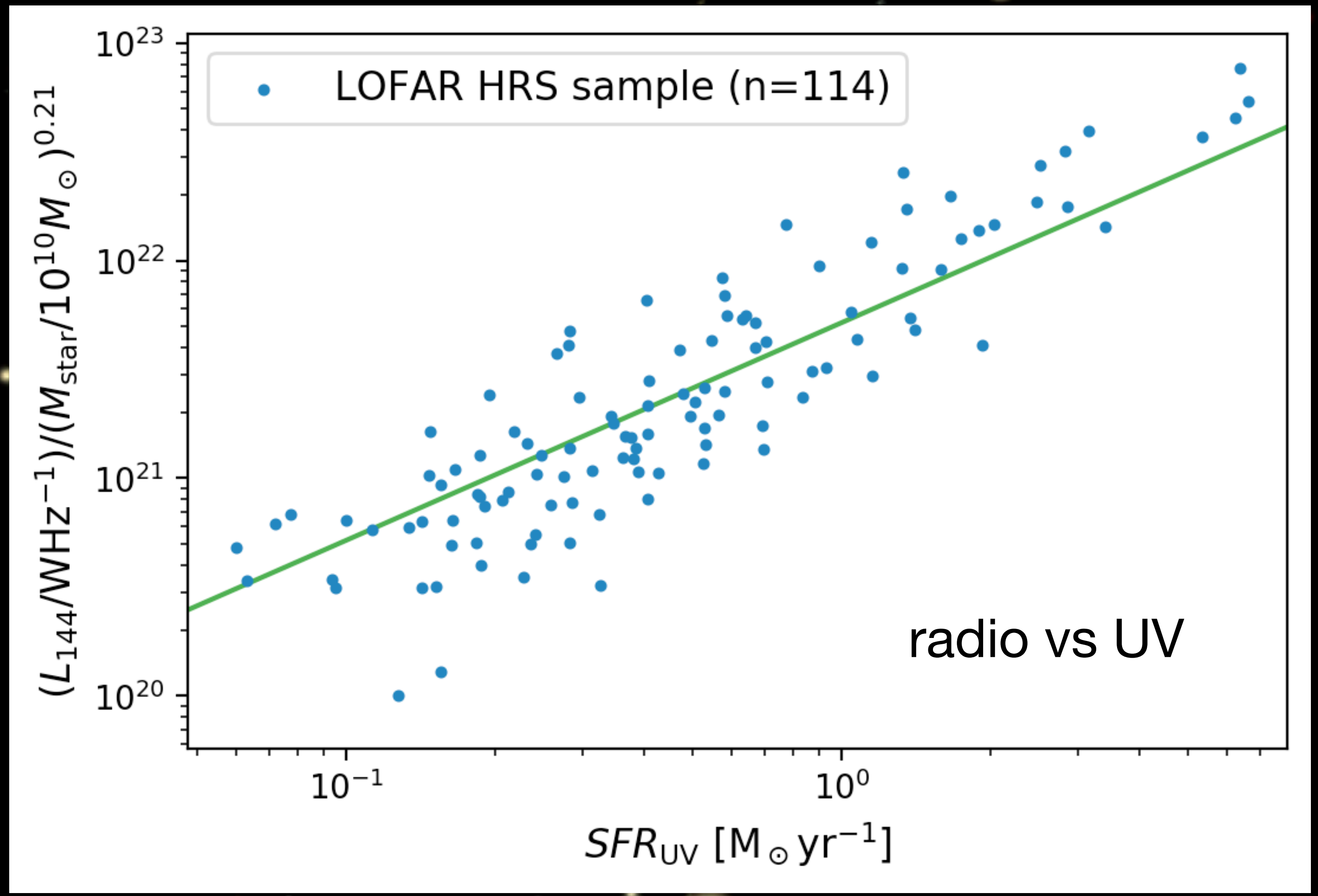
- Non-linearity: can be explained by calorimetric efficiency $\eta = \eta(M_{star})$ [Gürkan+18, Heesen+22]

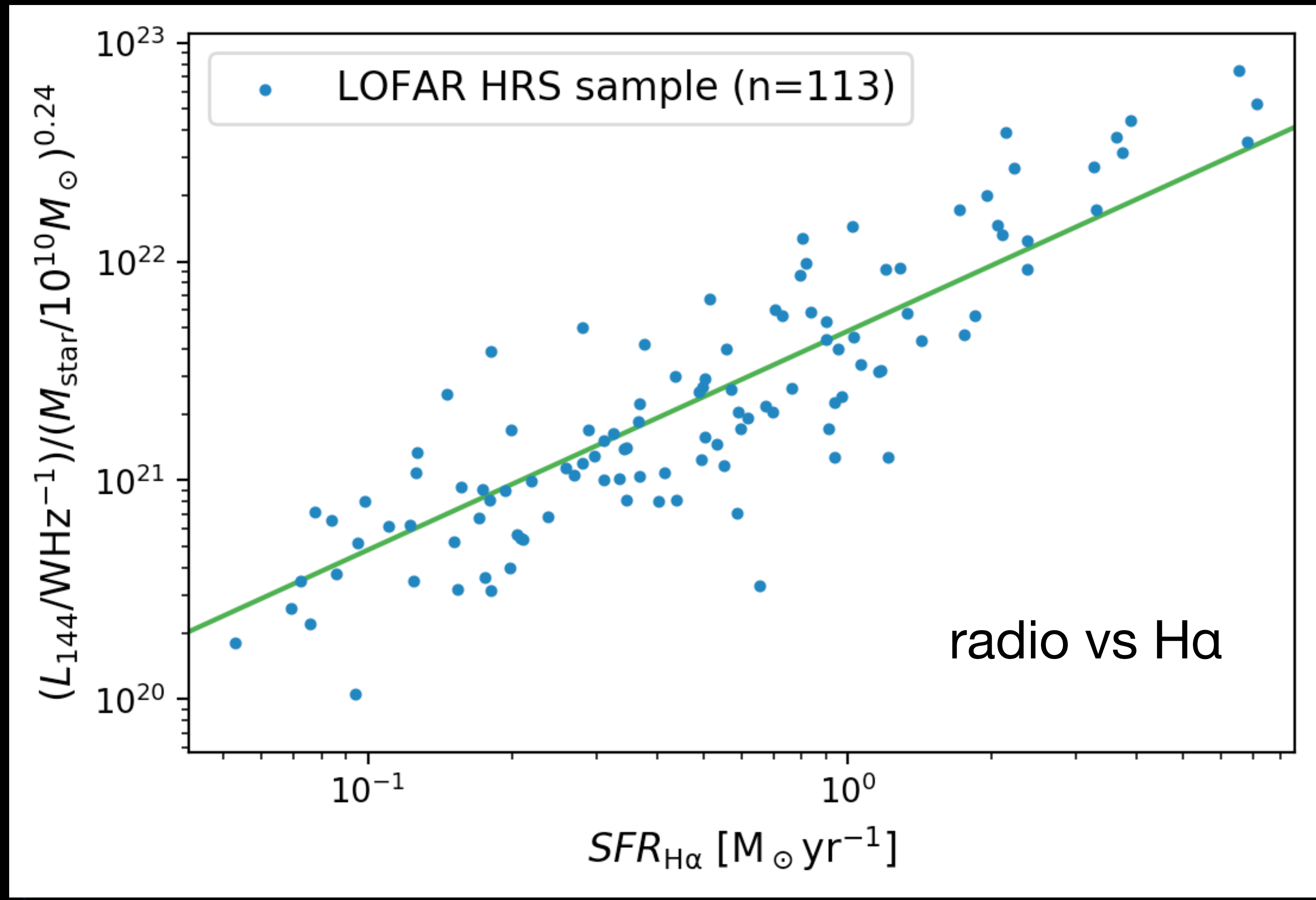
$$L_{144} \propto \eta \mathrm{SFR} = \mathrm{SFR} \cdot M_{\mathrm{star}}^{\gamma}$$

- Positive relation with mass

SFR-tracer	ɣ
IR	0.05
Hα	0.24
UV	0.21







Star formation tracers

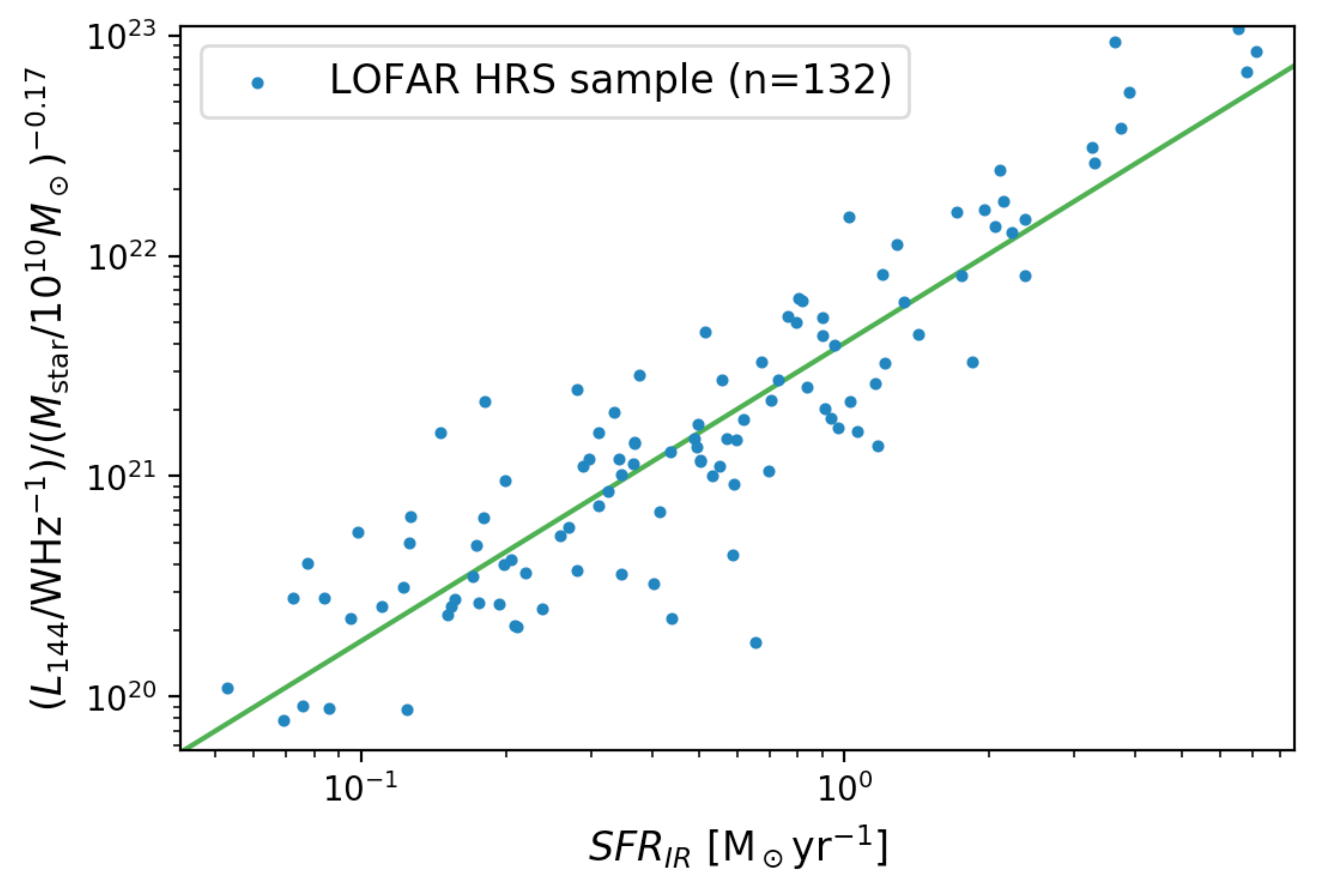
Double-Power law

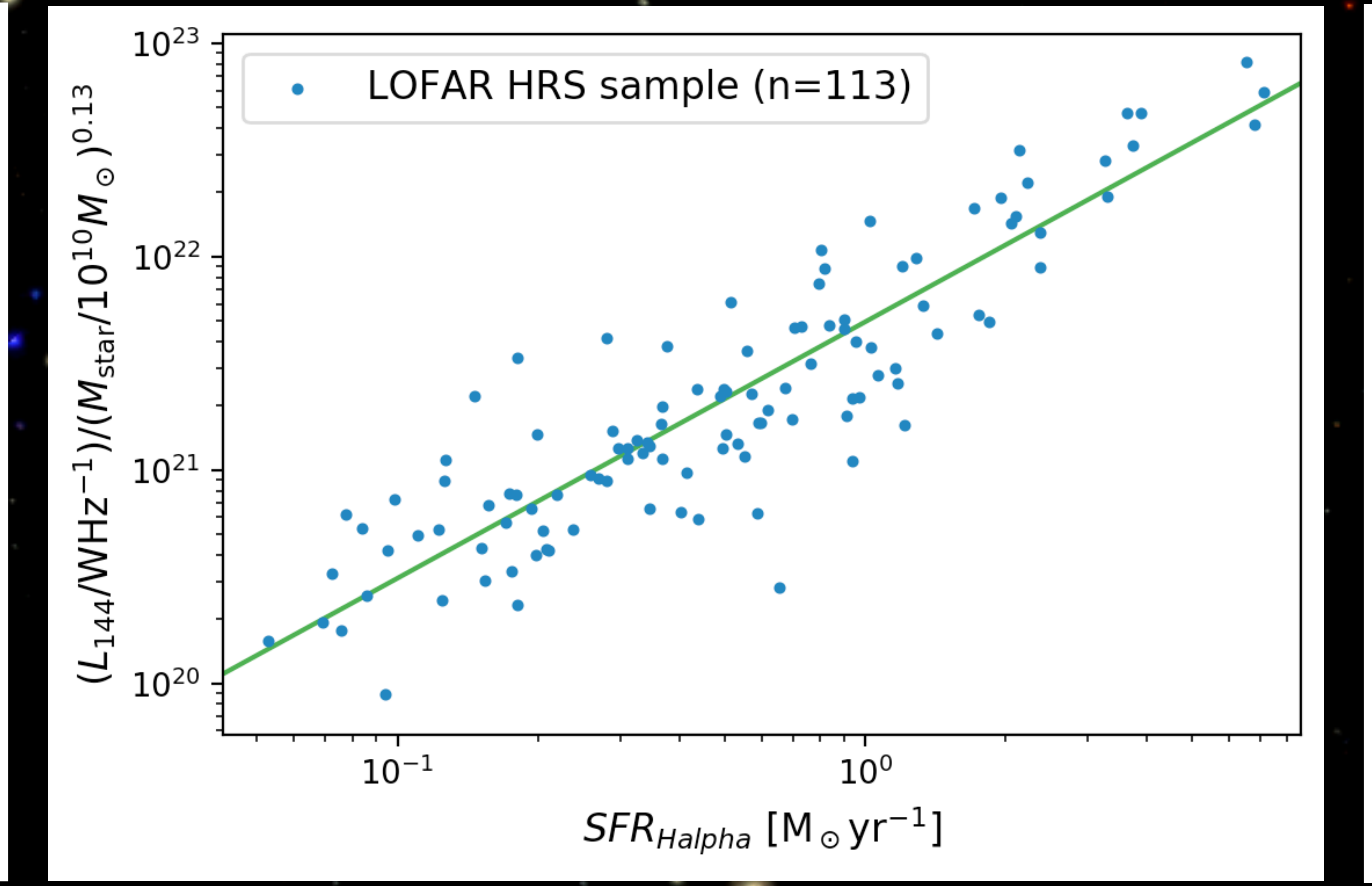
- Test: Fit power-law in both SFR and mass:

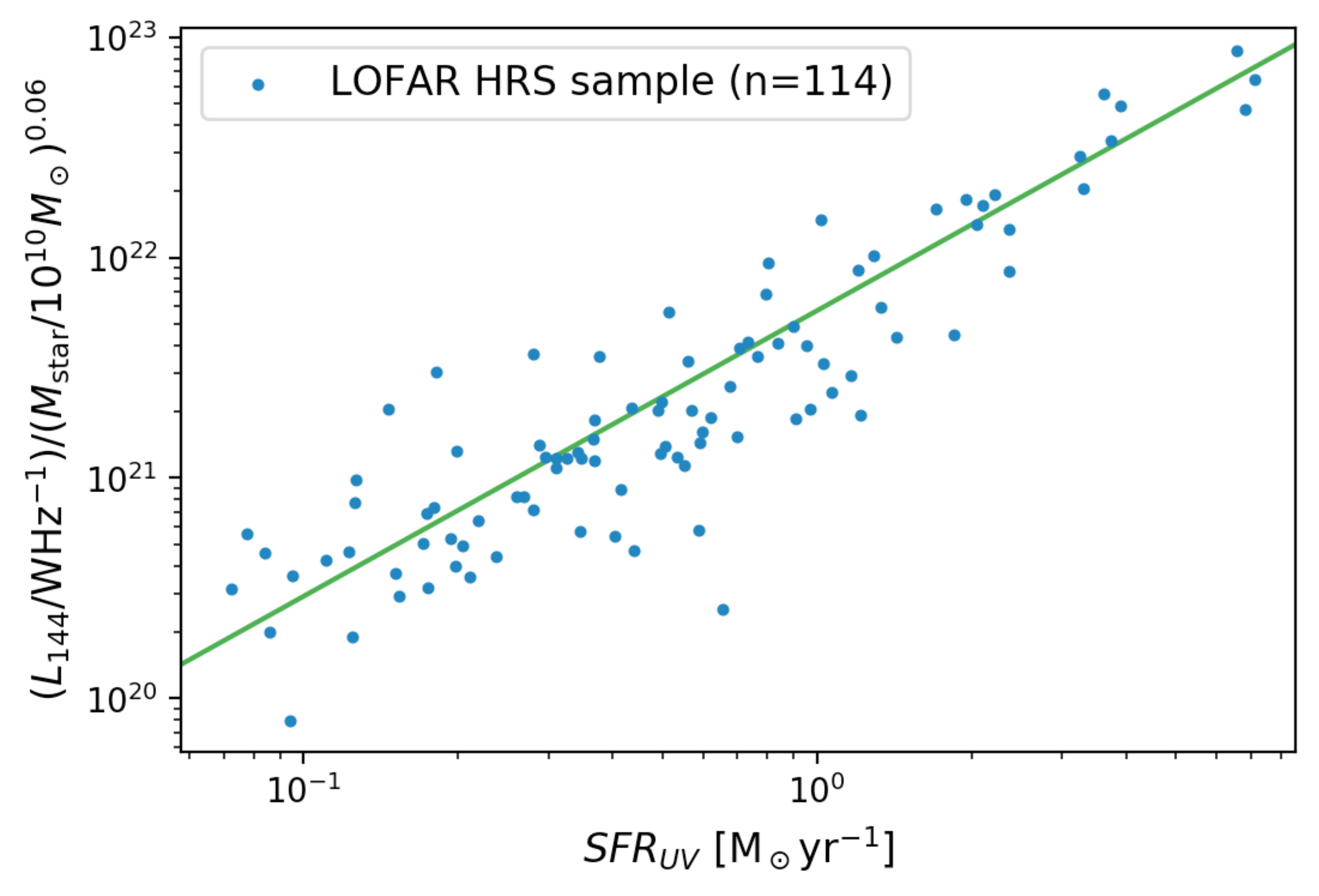
$$L_{144} = N_0 \mathrm{SFR}^{\beta} M_{\mathrm{star}}^{\gamma}$$

- Find positive dependence on mass, SFR-dependence closer to linear (for Hα, UV)

SFR-tracer	β	ɣ
(IR)	(1.35)	(-0.17)
Hα	1.2	0.13
UV	1.30	0.06

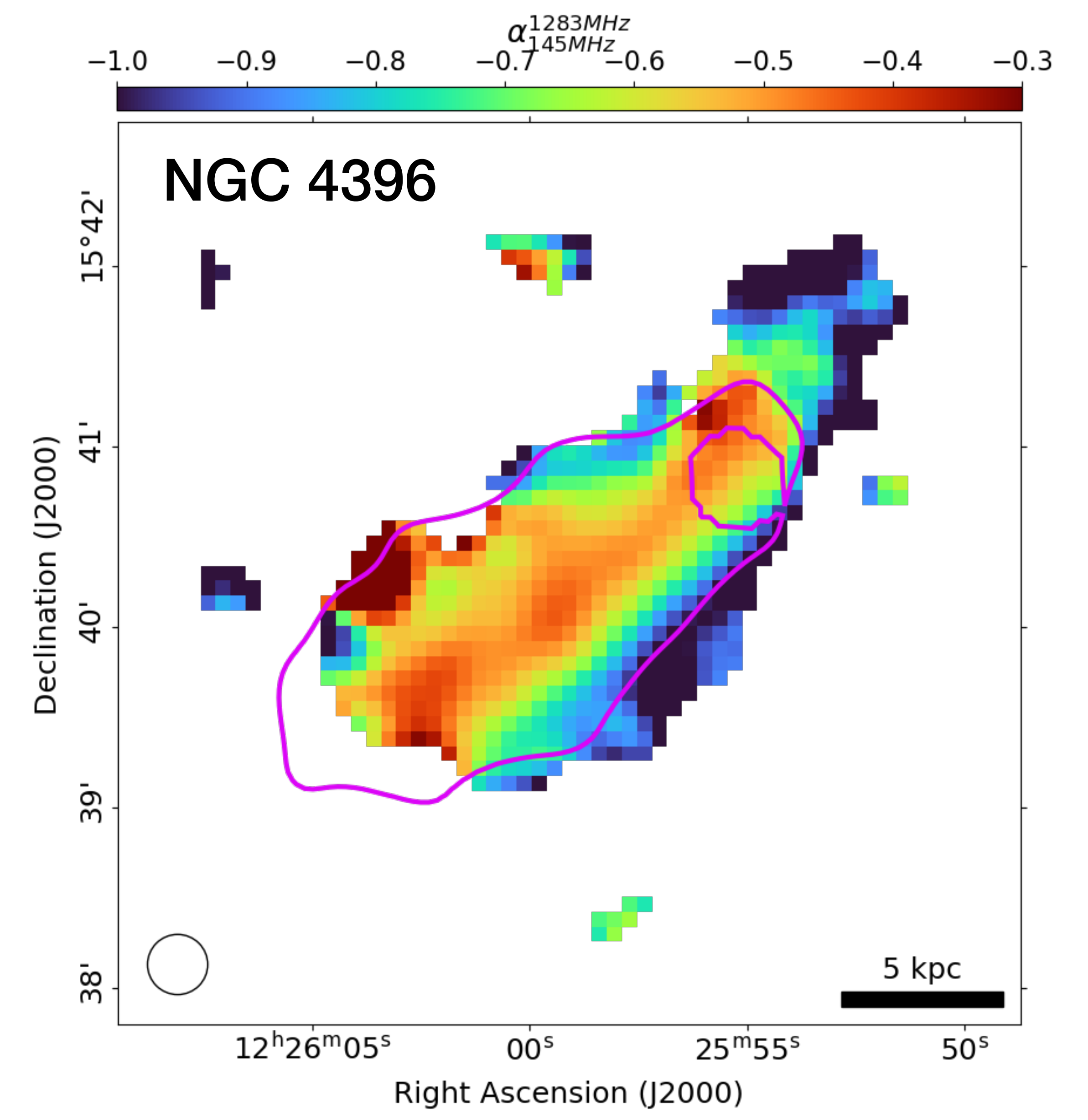






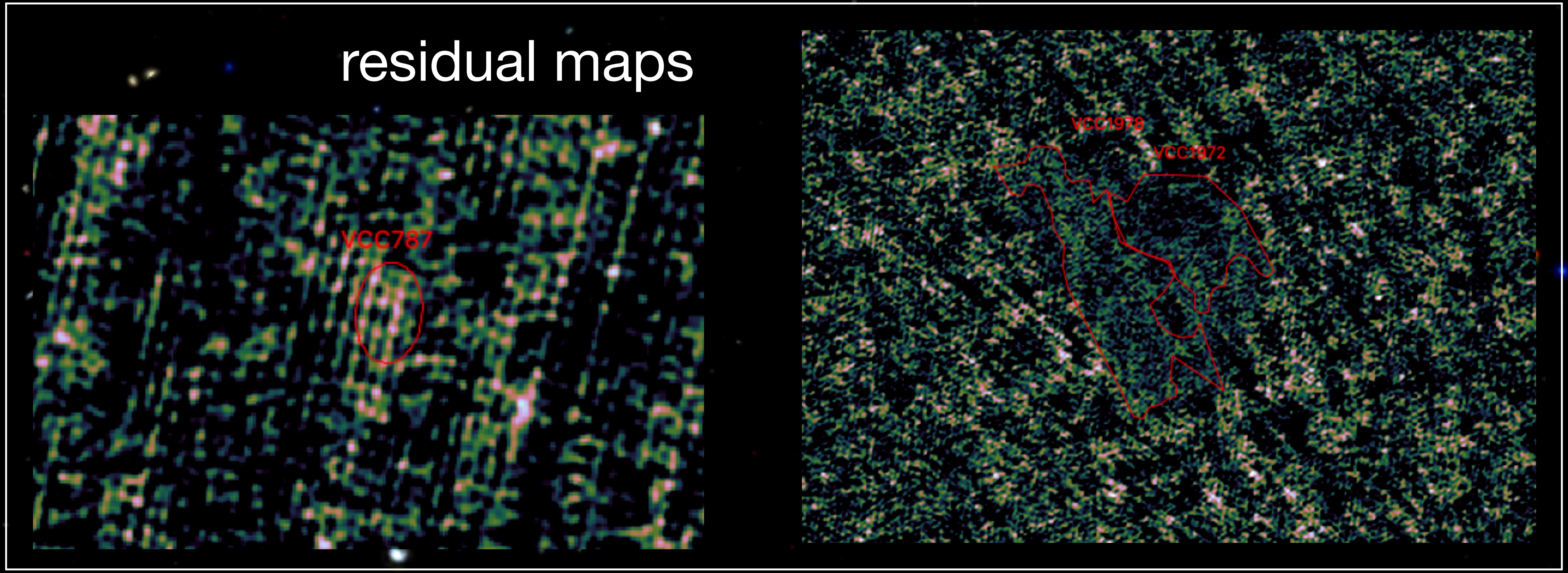
First MeerKAT - HBA Spectral Indices

Leading-edge flattening - ionization losses?

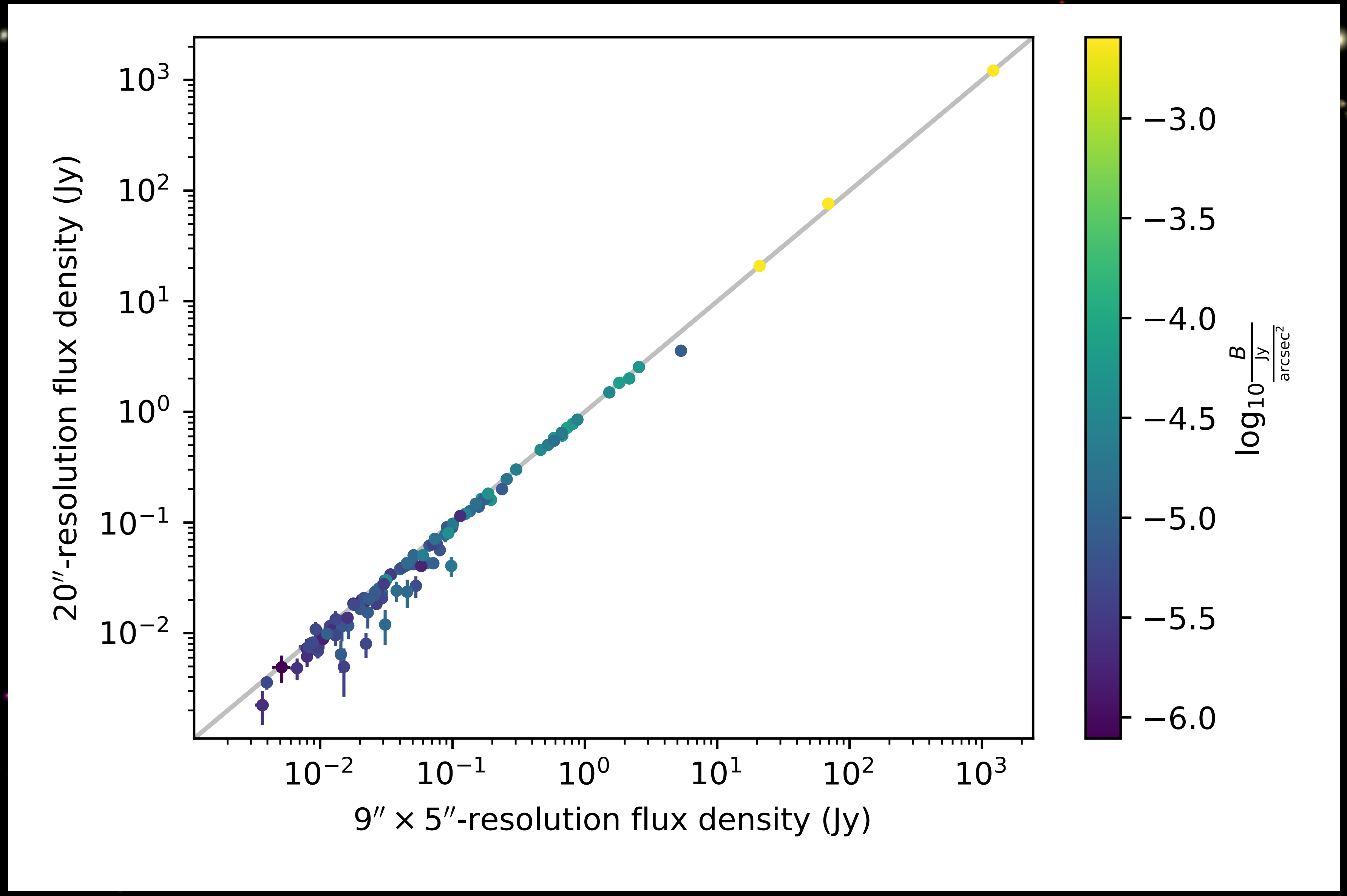


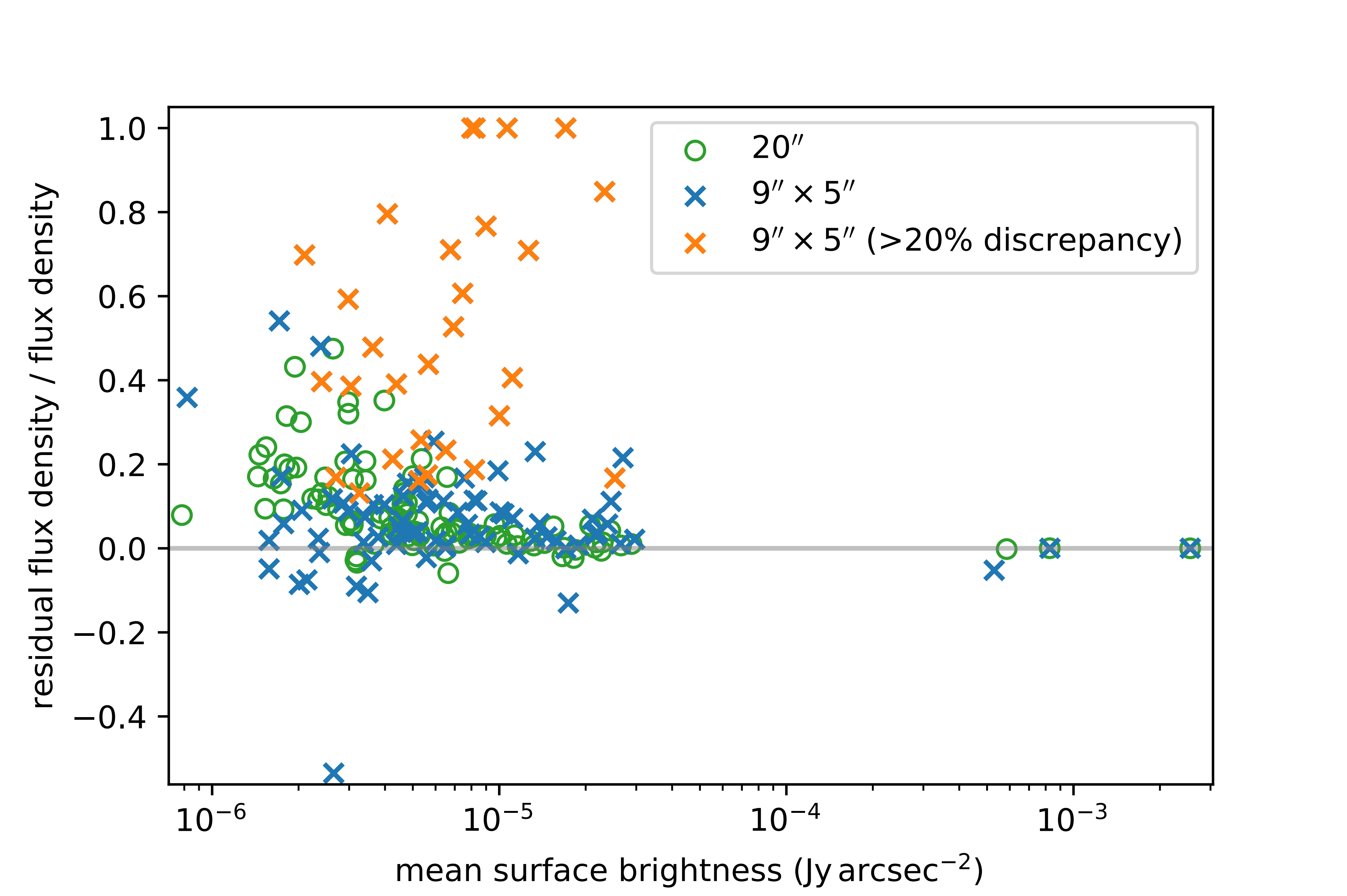
LOFAR Virgo Catalog

Completeness of Deconvolution



- Low surface-brightness, highly resolved sources → manual masking during imaging
- Still in some cases (usually high noise fields) flux density estimate in high-resolution mosaics not reliable!



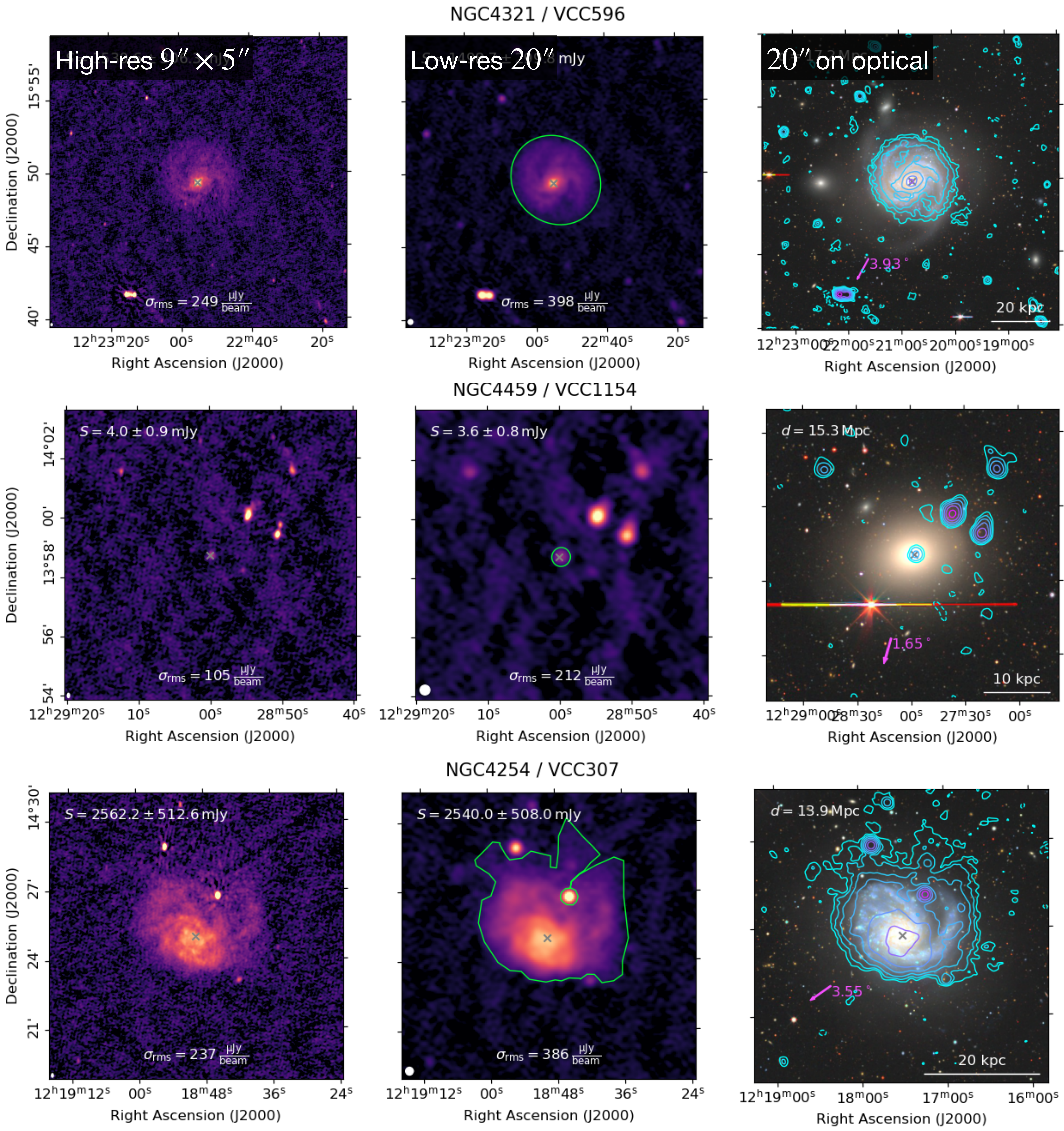


➡ Use low-resolution mosaics for measurements, flag sources that are affected

LOFAR Virgo Catalog

Flux density measurement

- Inspect galaxies in optical catalog[1]
- Visible emission? → construct manual source region
- Require S/N > 4
- Remove misidentifications using optical overlay

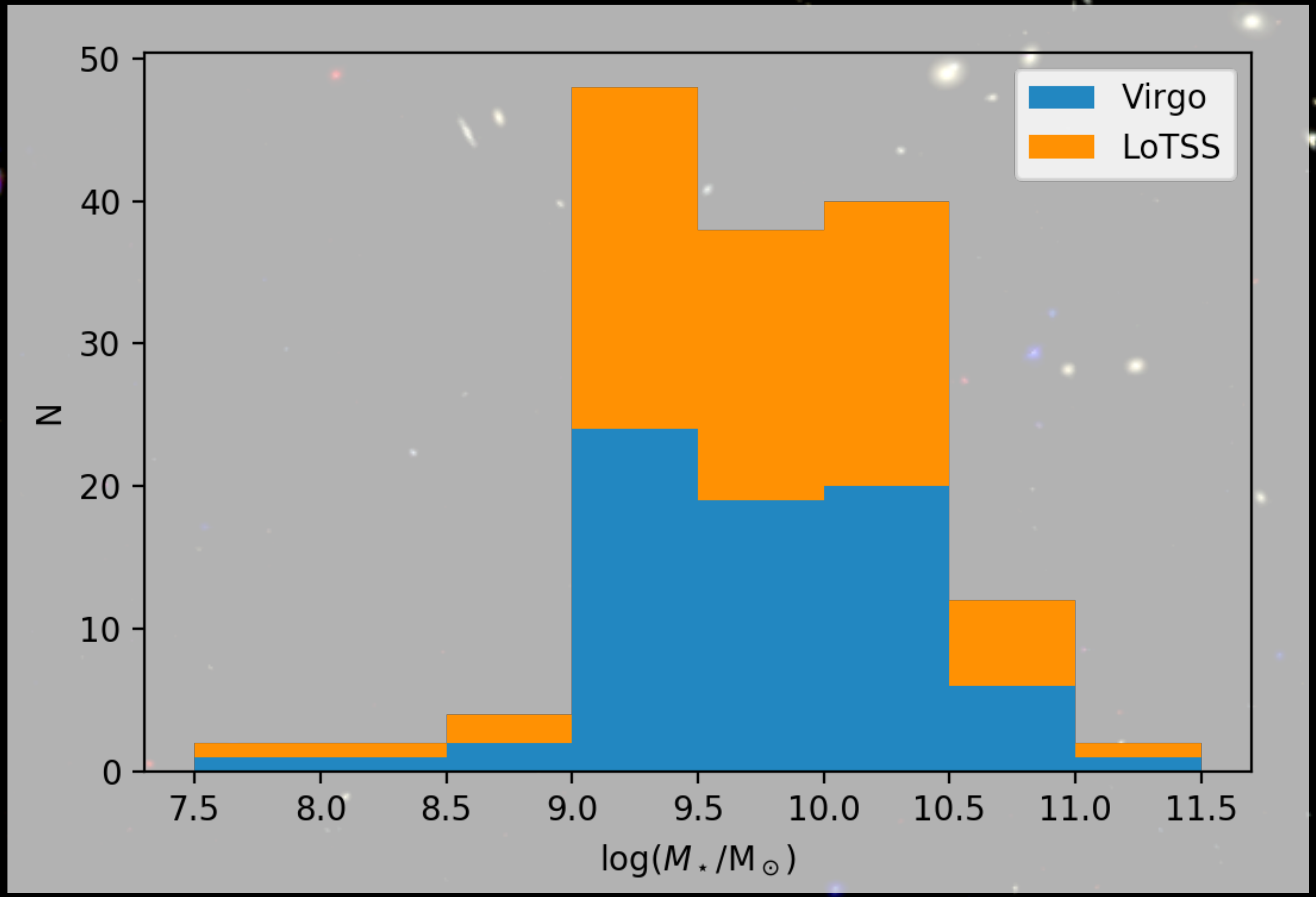


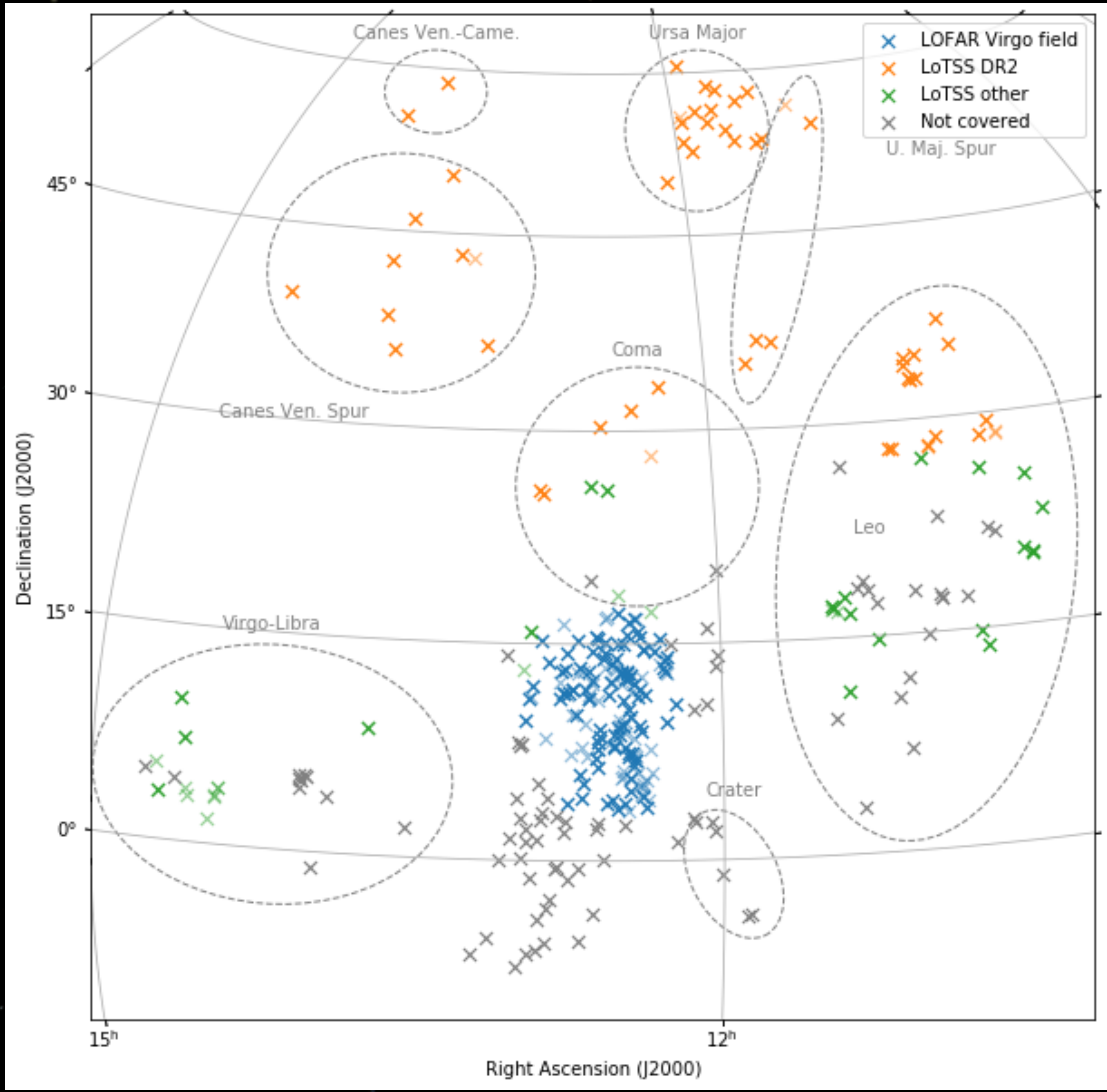
[1]Extended Virgo Cluster Catalog [Kim+2015]

The LOFAR-HRS-Sample

SF-Galaxies in different environments

- Herschel Reference Survey (HRS, [Boselli+10])
  - Volume-limited, K-band selected
  - Great data on SFR-tracers available (Hα, IR, UV…)
- 247 galaxies covered by LOFAR
  - **Sample of 135** galaxies detected after removing early-types and AGN

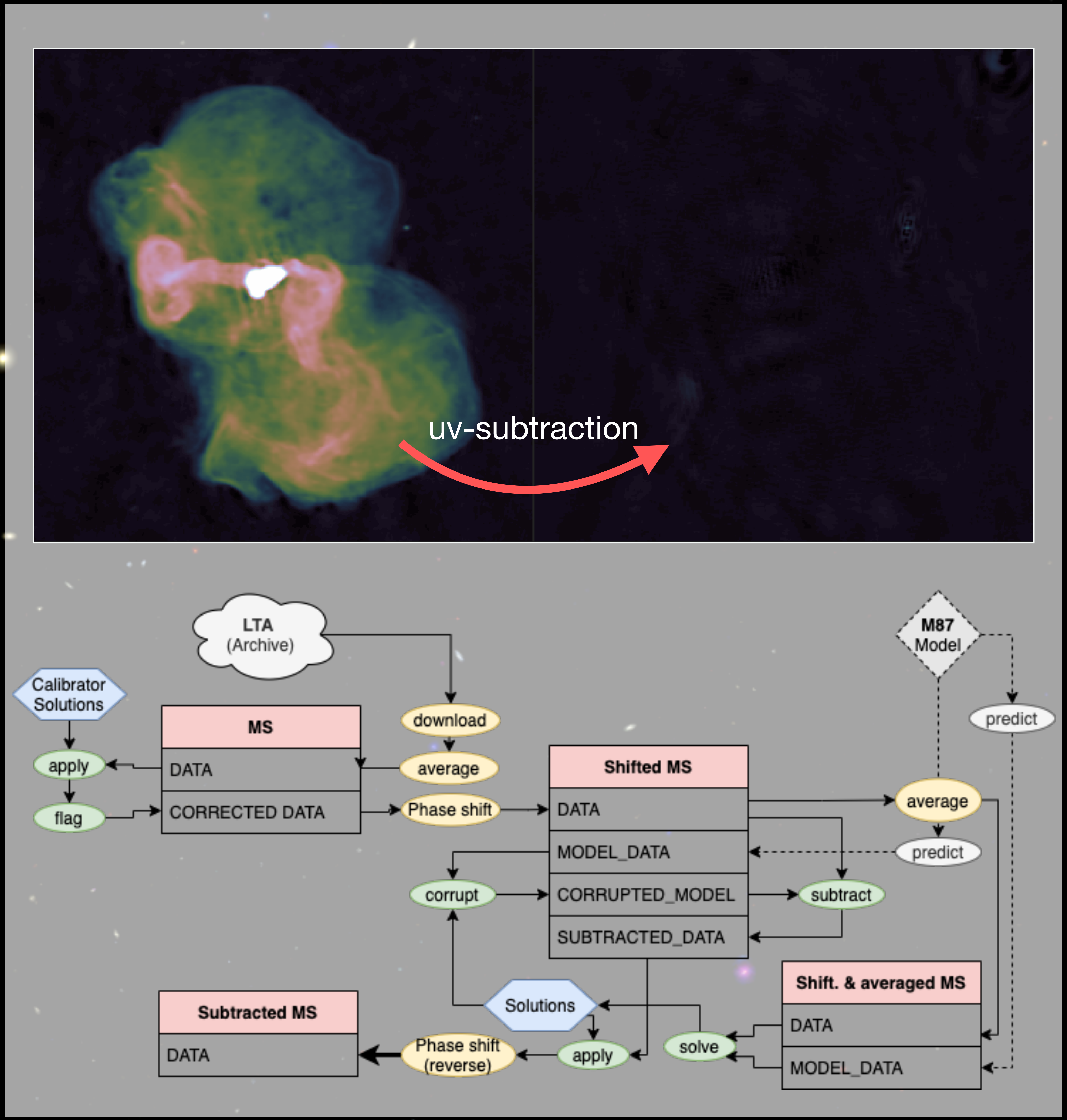




LOFAR Virgo Cluster Survey

Survey Strategy

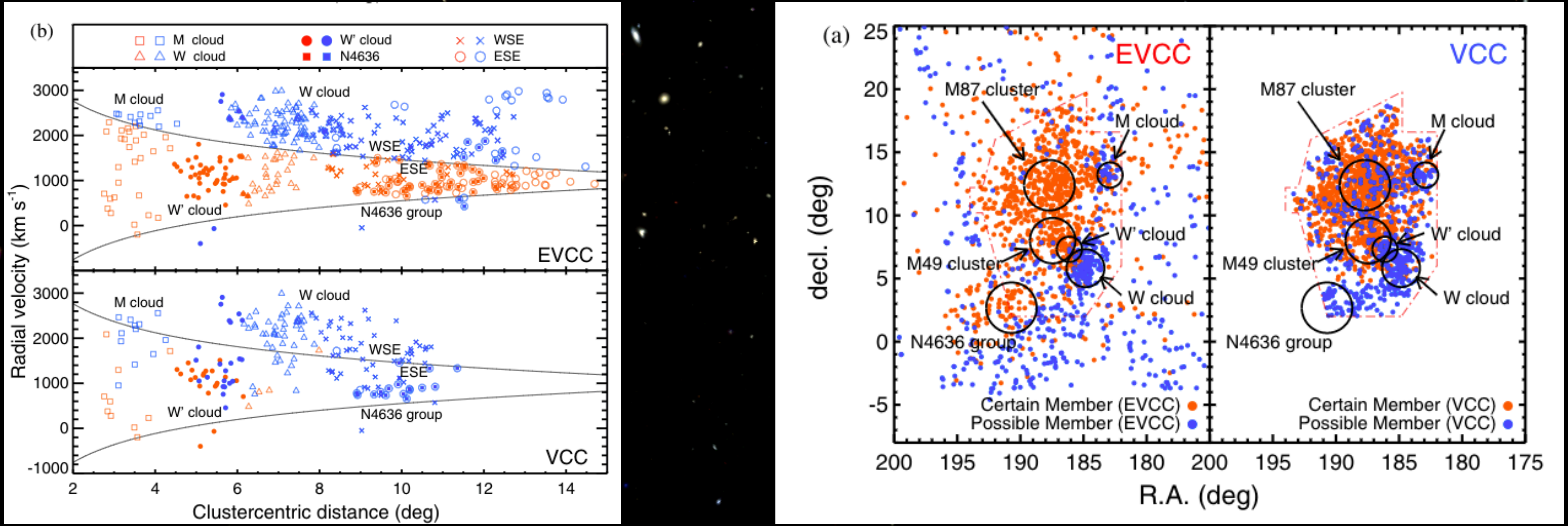
- Area: 132 deg^2
- 9 fields: 64h central / 8h outer fields
- Frequency: 144 MHz
- “Peeling”-strategy to handle M87
    1. High-quality model
    2. Peeling-pipeline
    3. DD-calibration (ddf-pipeline)



EVCC: Membership Classification

Kim et al. 2015

- Redshift-based spherical infall model



Early-type galaxies in the Virgo Cluster

LOFAR detections of ACS Virgo cluster survey early-type sample (100 galaxies Coté+ 2004)
VLA study of this sample (Capetti+ 2009) detected radio emission for twelve of them)