

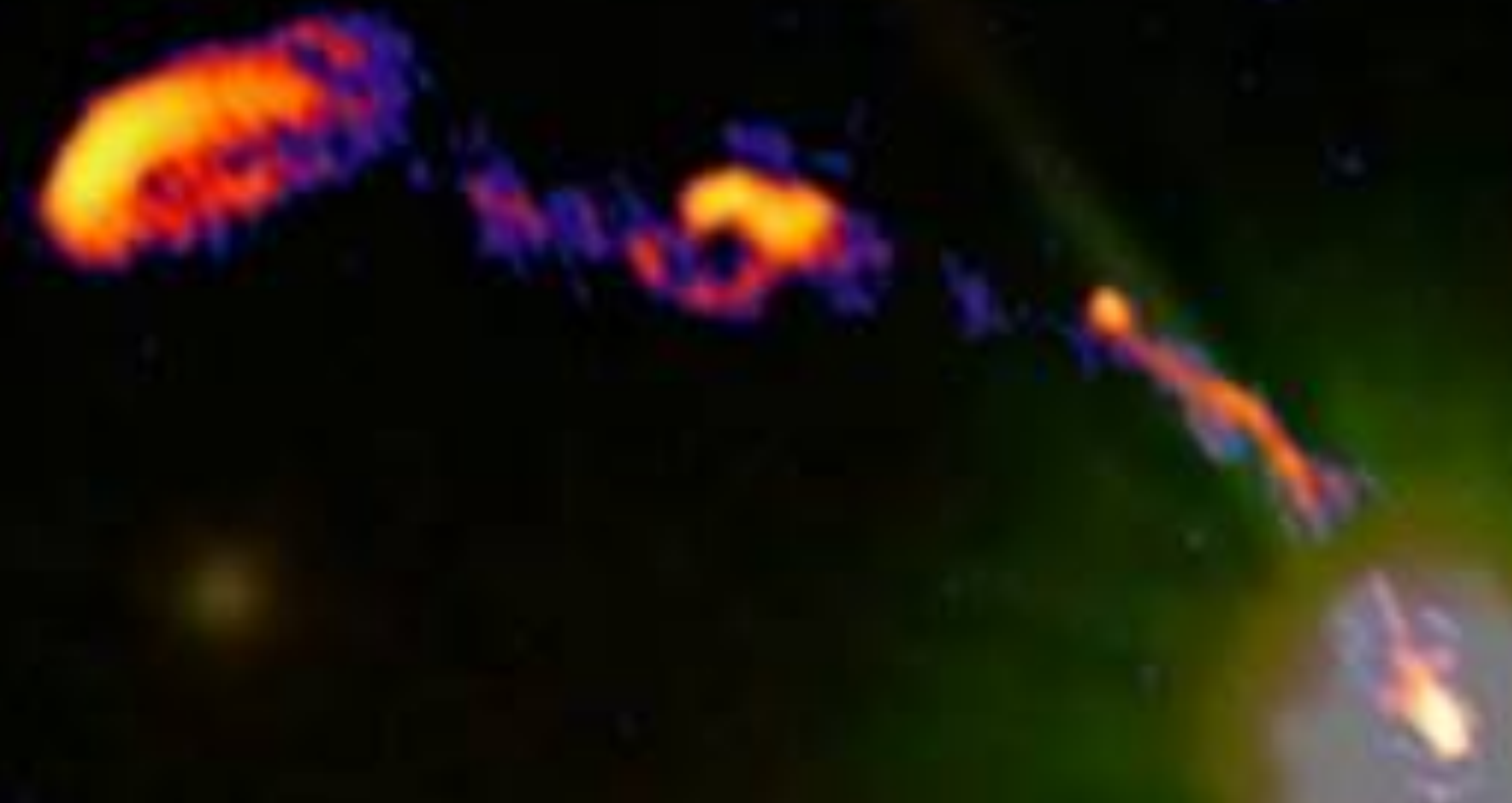


National
Research
Foundation

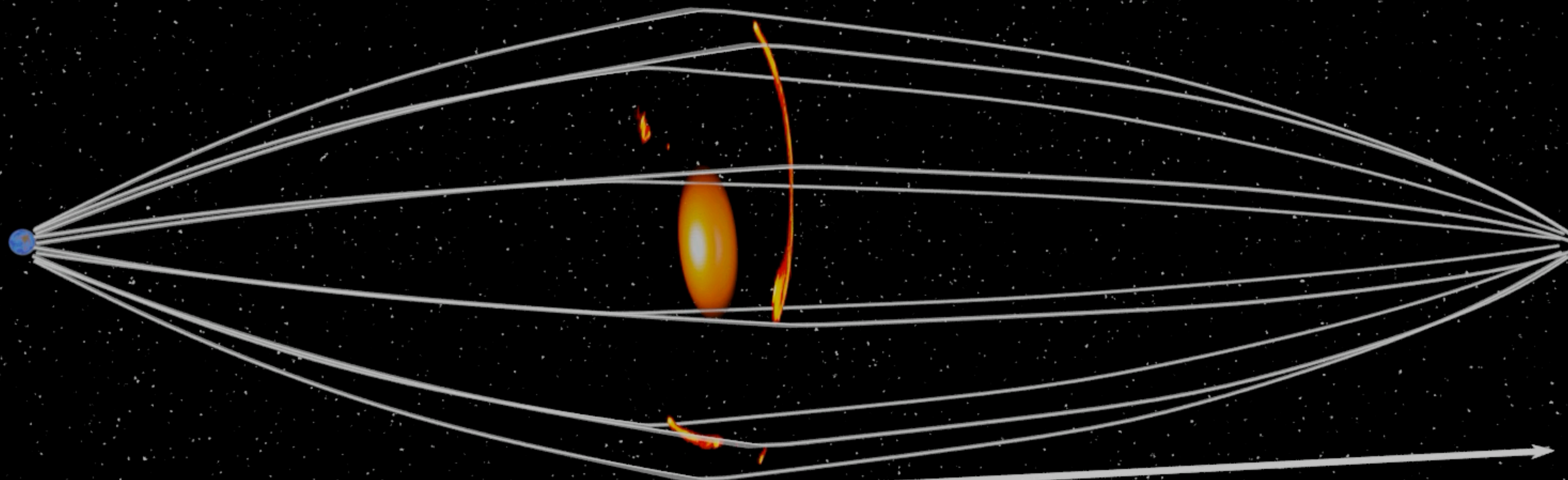
Gravitational lensing with the ILT: A new probe of dark matter, cosmology and the high redshift Universe

John McKean

Kapteyn Astronomical Institute, Univ. Groningen
South African Radio Astronomy Observatory (SARAO)
Univ. Pretoria



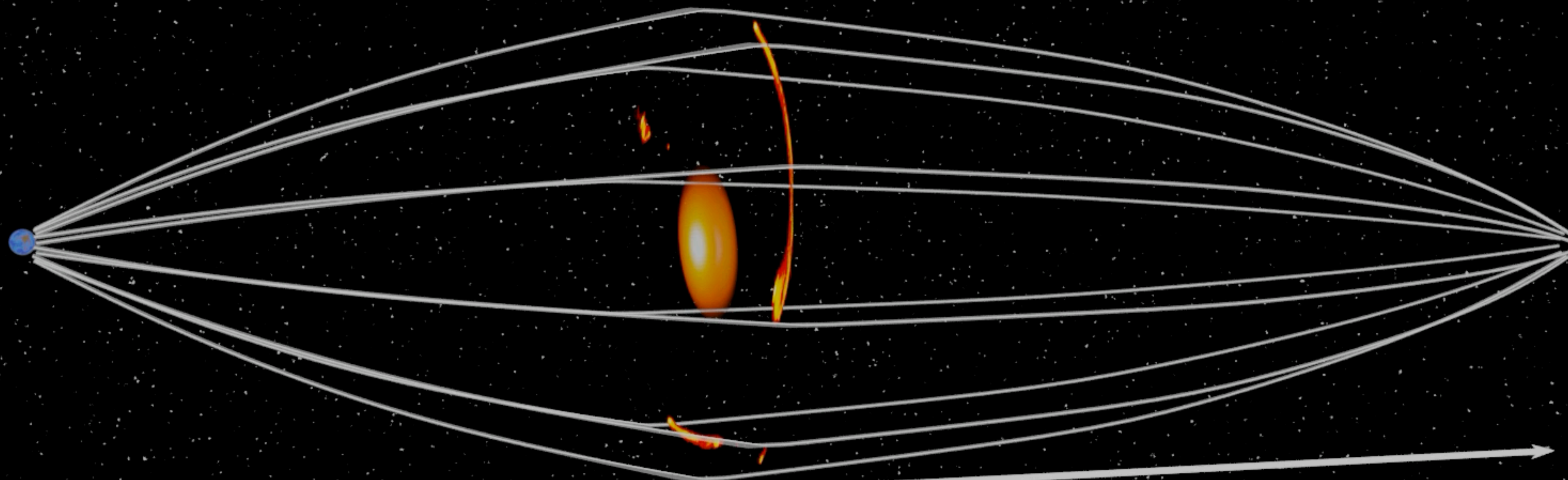
Earth



11.7 Billion light years

3.9 Billion light years

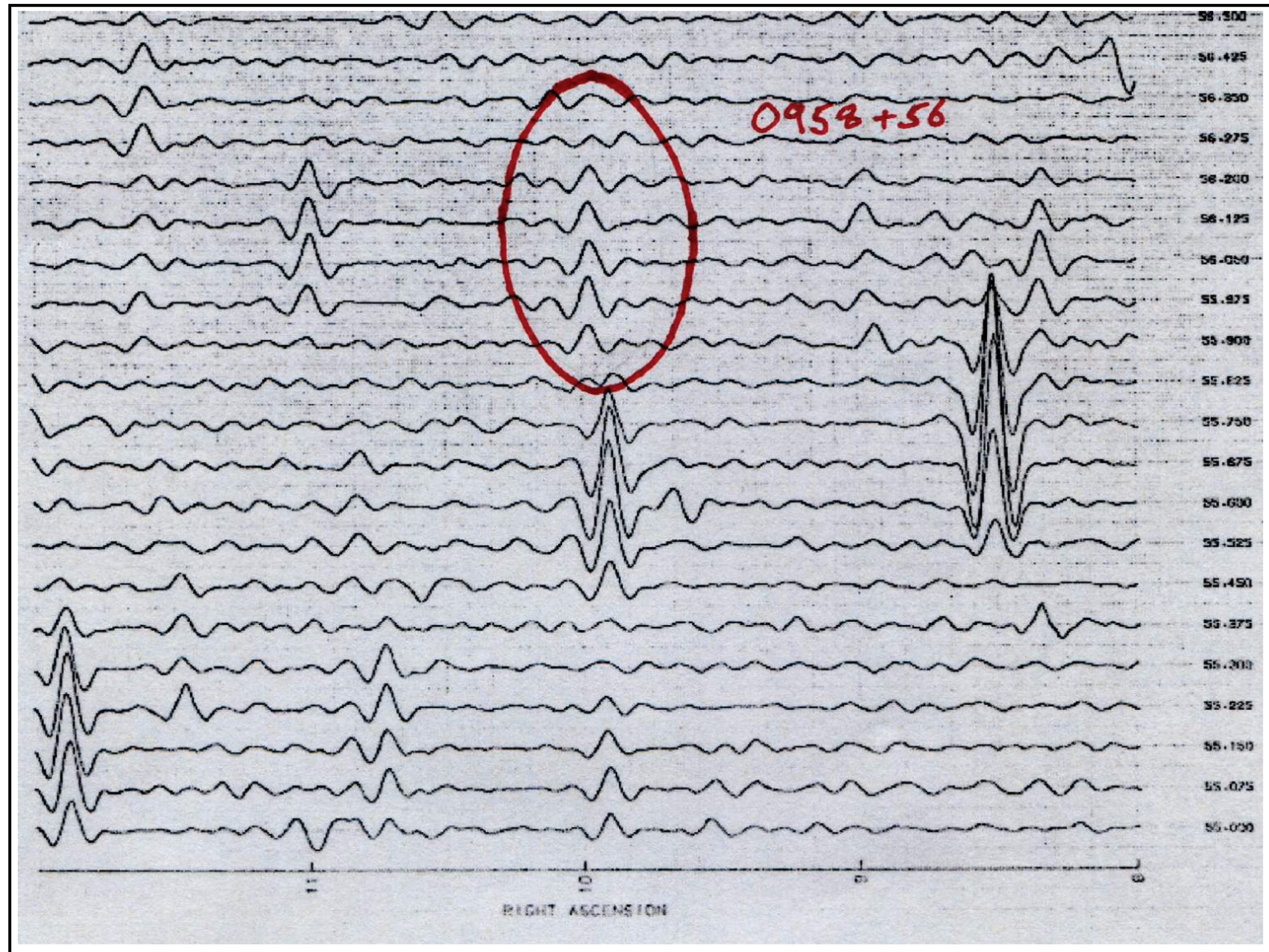
Earth



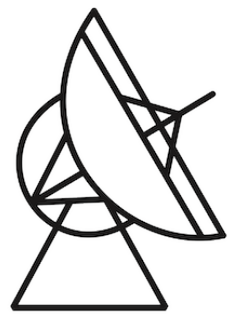
11.7 Billion light years

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From the early years to the state-of-the-art

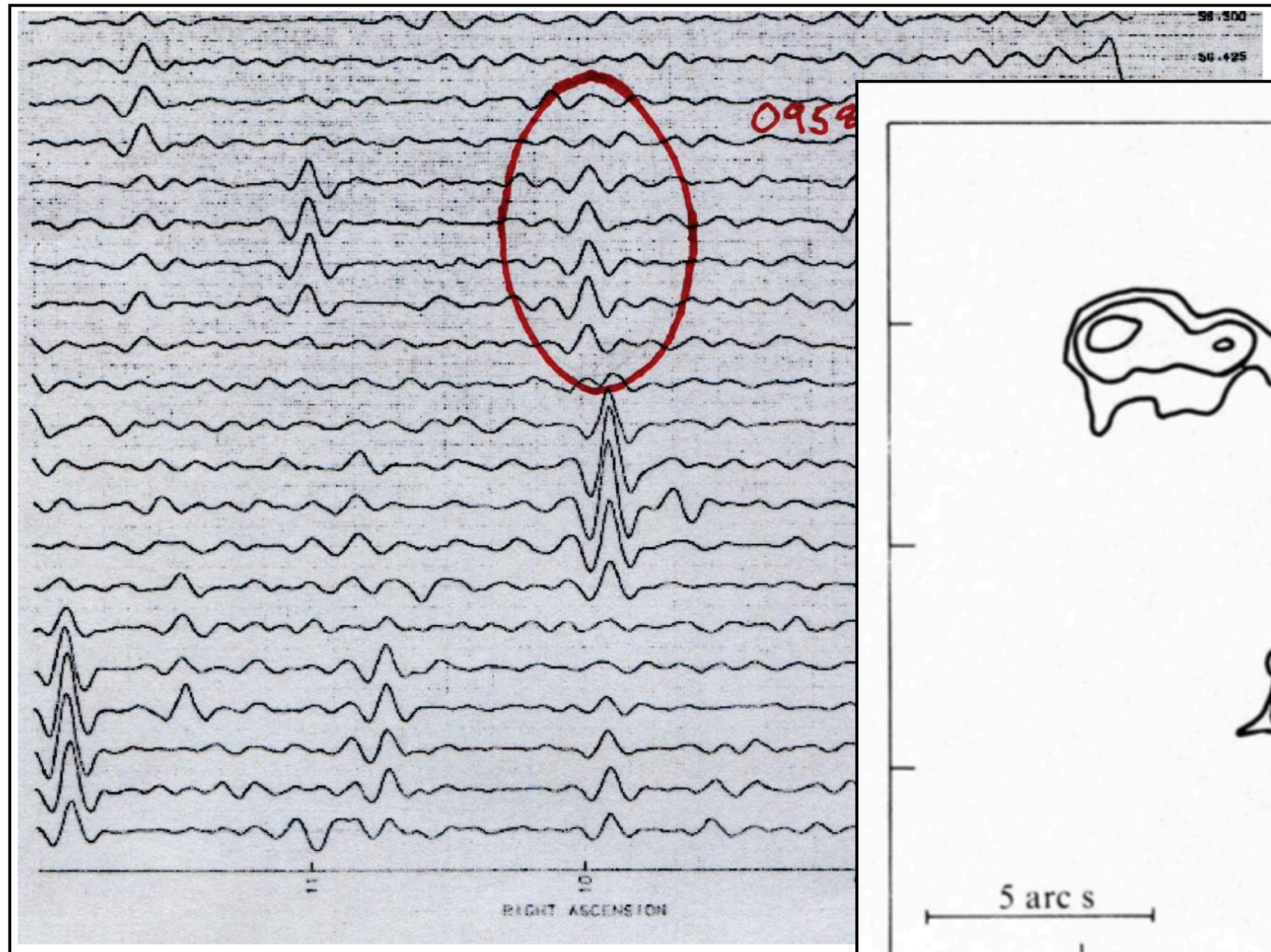


The first lens B0957+56
(Walsh et al. 1979)

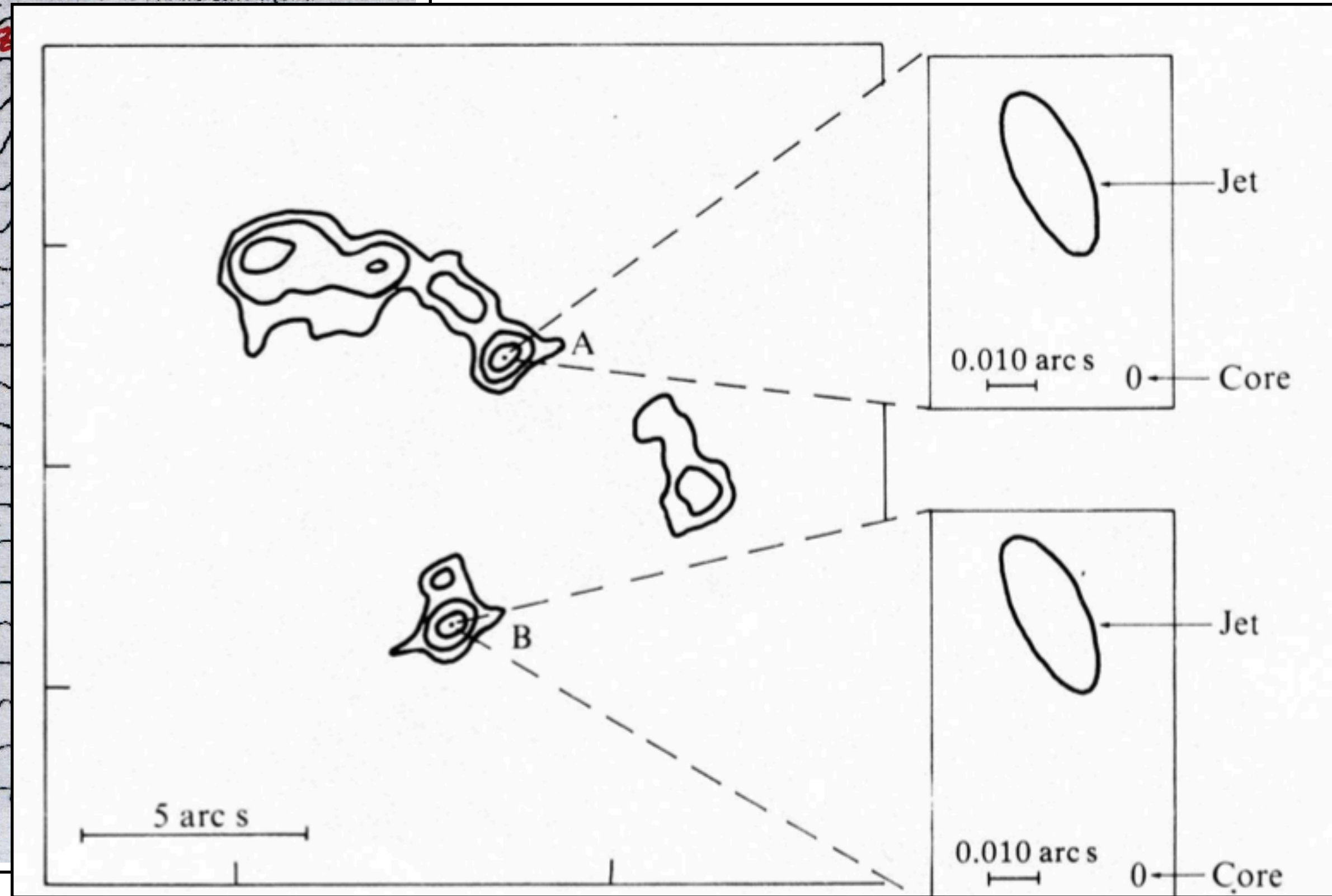


25 m (diameter)
Resolution = 0.5 degree

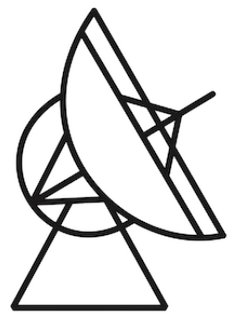
From the early years to the state-of-the-art



The first lens B0957+56
(Walsh et al. 1979)



MERLIN (+VLBI) 1.6 GHz
(Porcas et al. 1981)

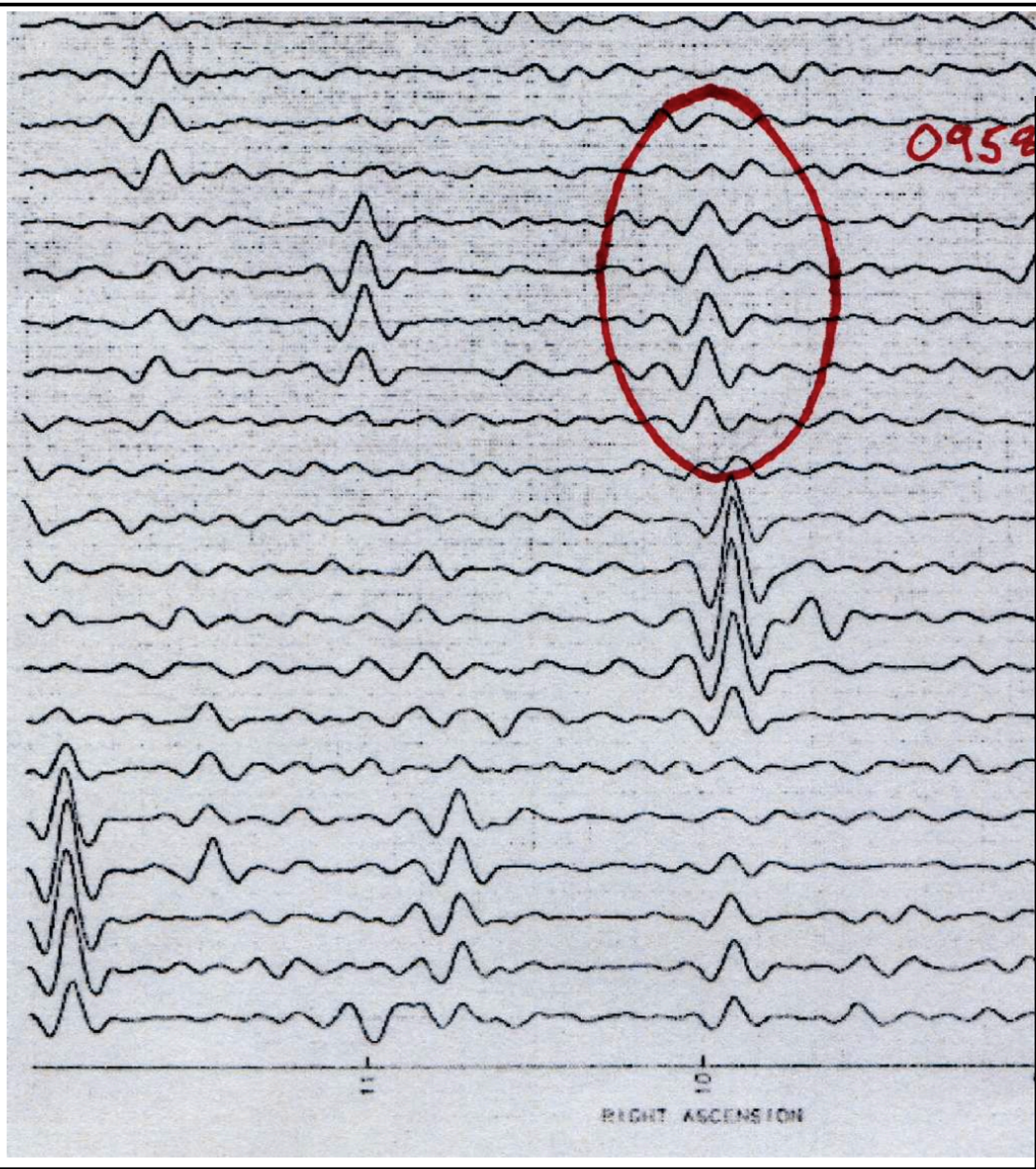


25 m (diameter)
Resolution = 0.5 degree



100 km

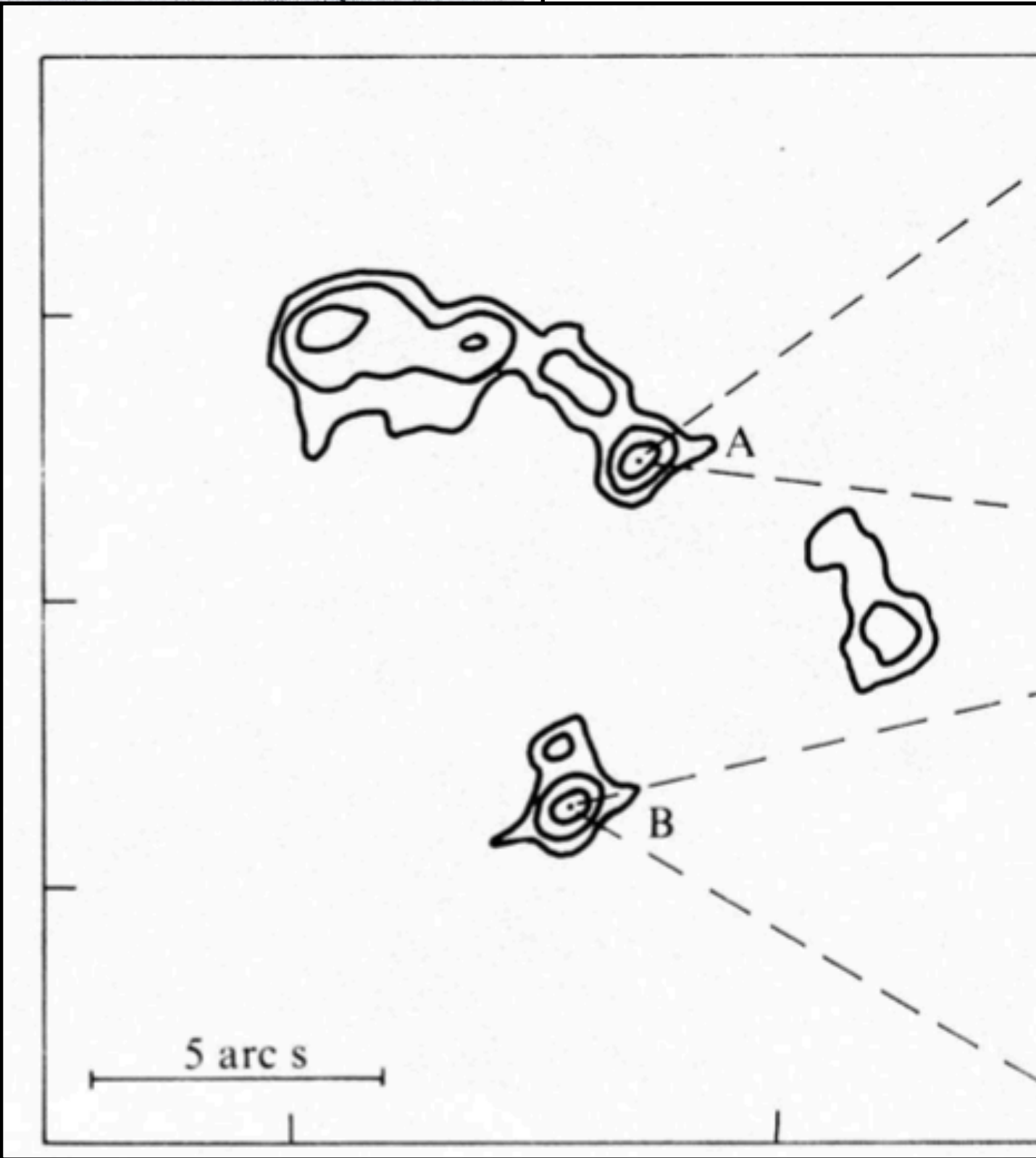
From the early years to the state-of-the-art



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(Walsh et al. 1979)



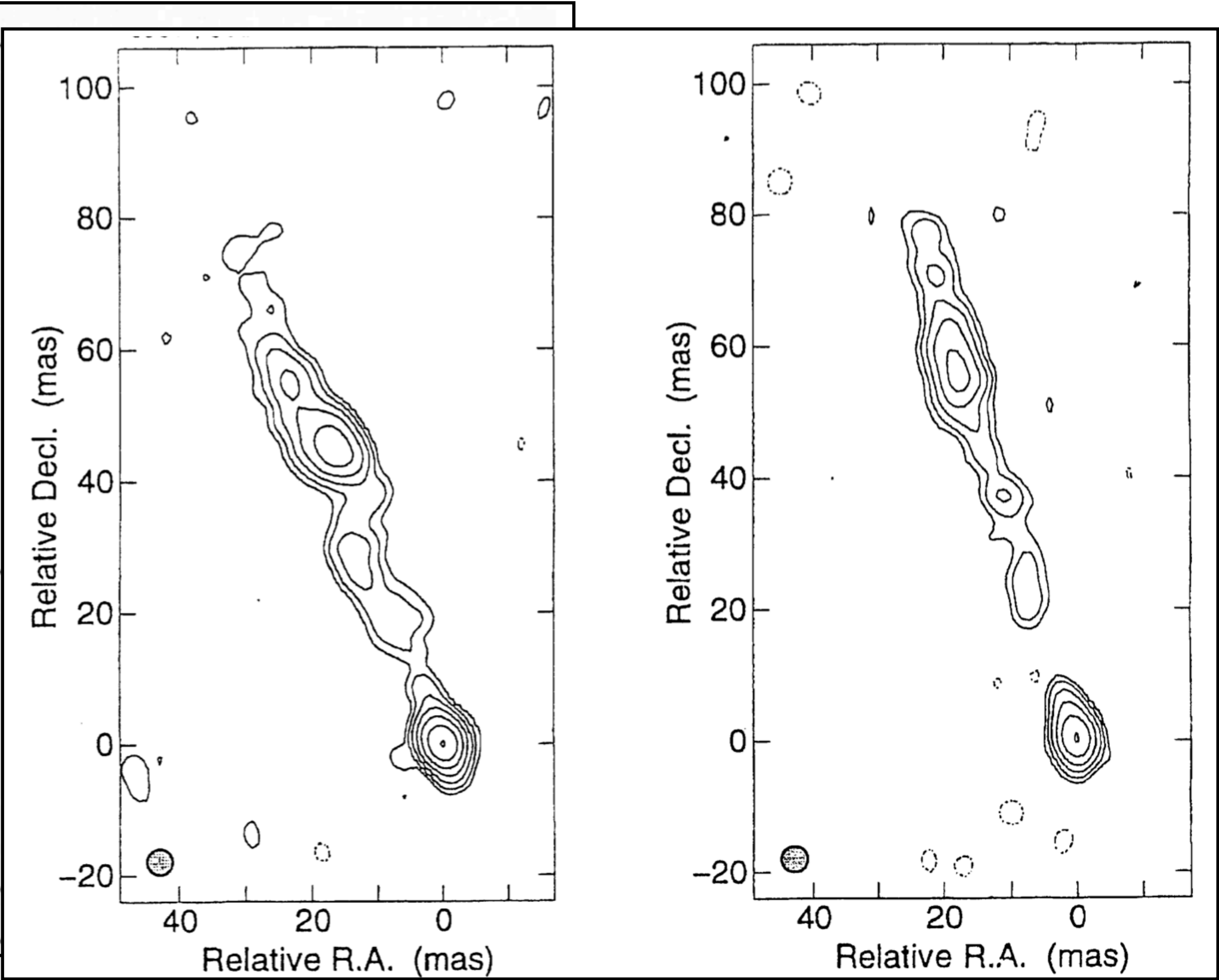
25 m (diameter)
Resolution = 0.5 degree



MERLIN (+VLBI) 1.6 GHz
(Porcas et al. 1981)



100 km

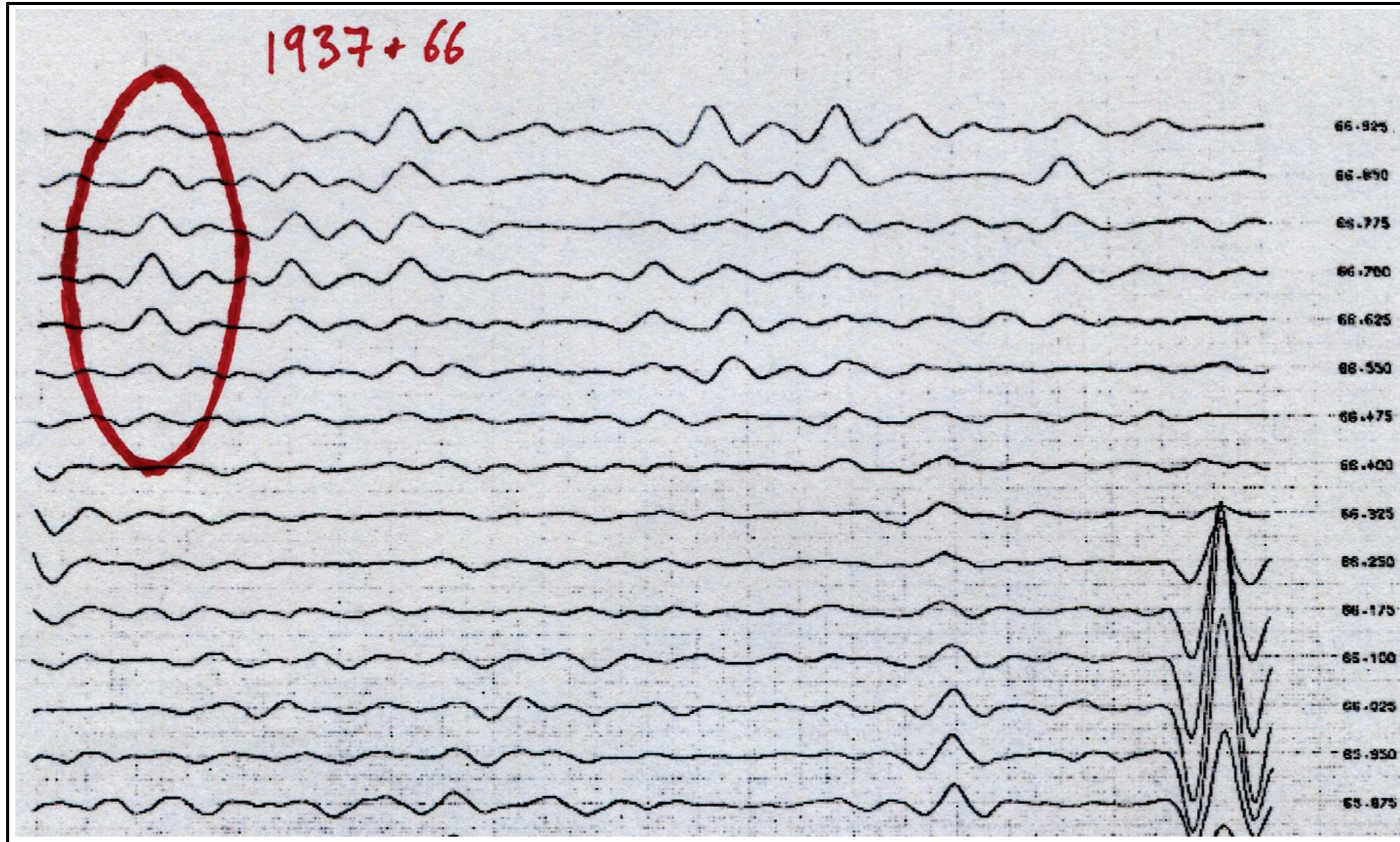


Global VLBI 1.6 GHz
(Garrett et al. 1994)



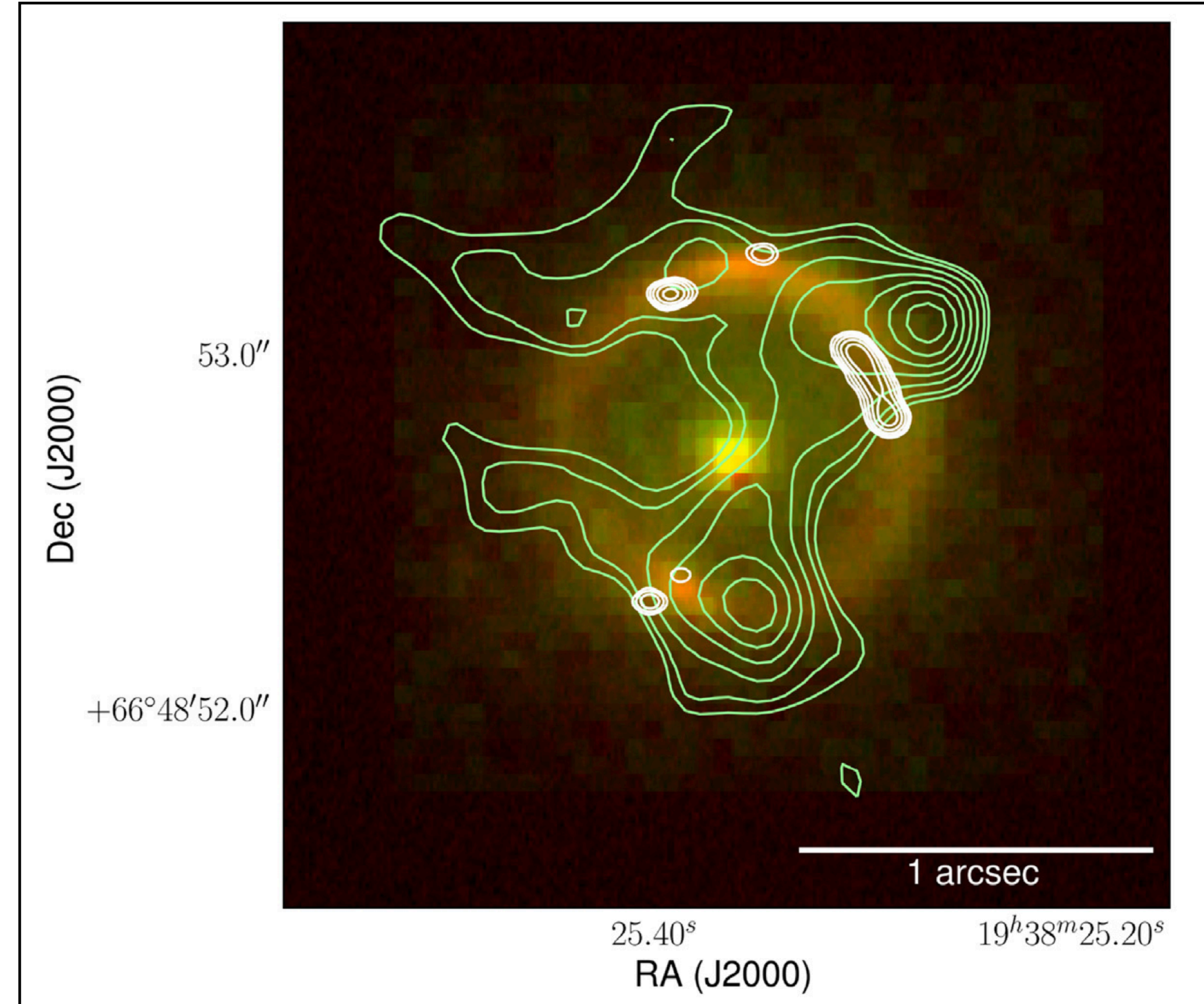
8000 km

From the early years to the state-of-the-art



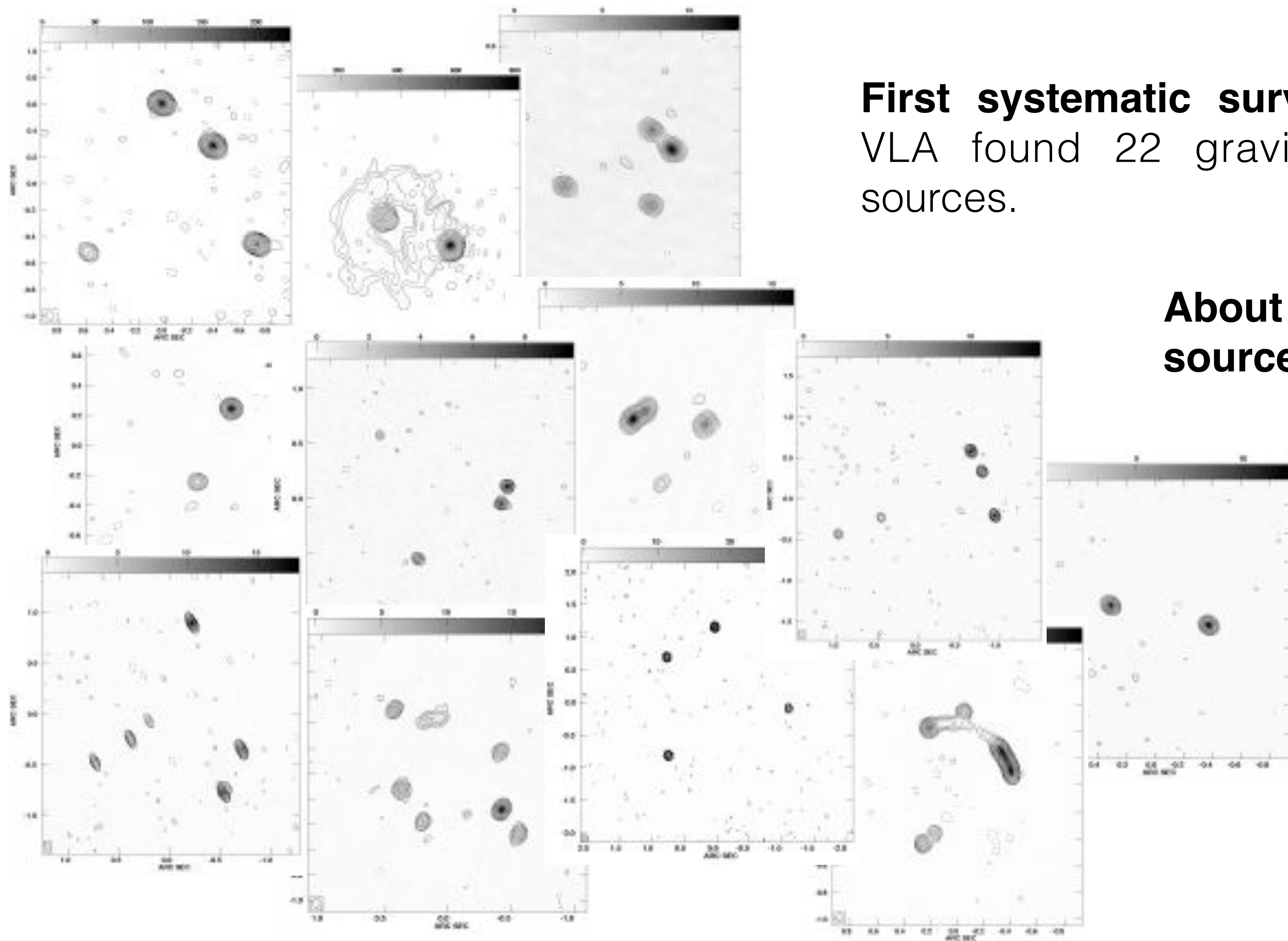
But, the first lens *could* have been B1938+666 (discovered ~15 years later).

(From Richard Porcas; EVN Historian)



(Spingola et al. 2020)

From the early years to the state-of-the-art



First systematic surveys: CLASS using the VLA found 22 gravitationally lensed radio sources.

About 35-40 radio-loud lensed sources known.

(Browne et al. 2003)

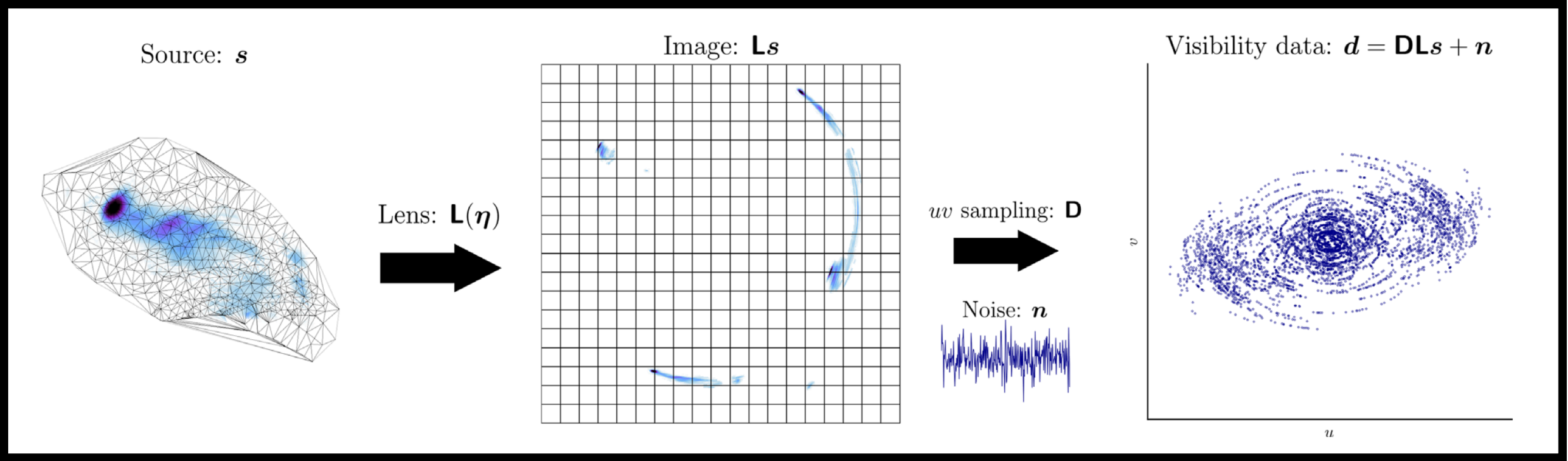
State-of-the-art Lens Modelling Algorithms

(Powell et al. 2019)

(Koopmans 2006; Vegetti & Koopmans 2009; Ritondale et al. 2019)

Fully Bayesian forward modelling of the visibility data —

$$P(\eta, \lambda_s \mid \mathbf{d}) = \frac{P(\mathbf{d} \mid \eta, \lambda_s) P(\eta) P(\lambda_s)}{P(\mathbf{d})}$$



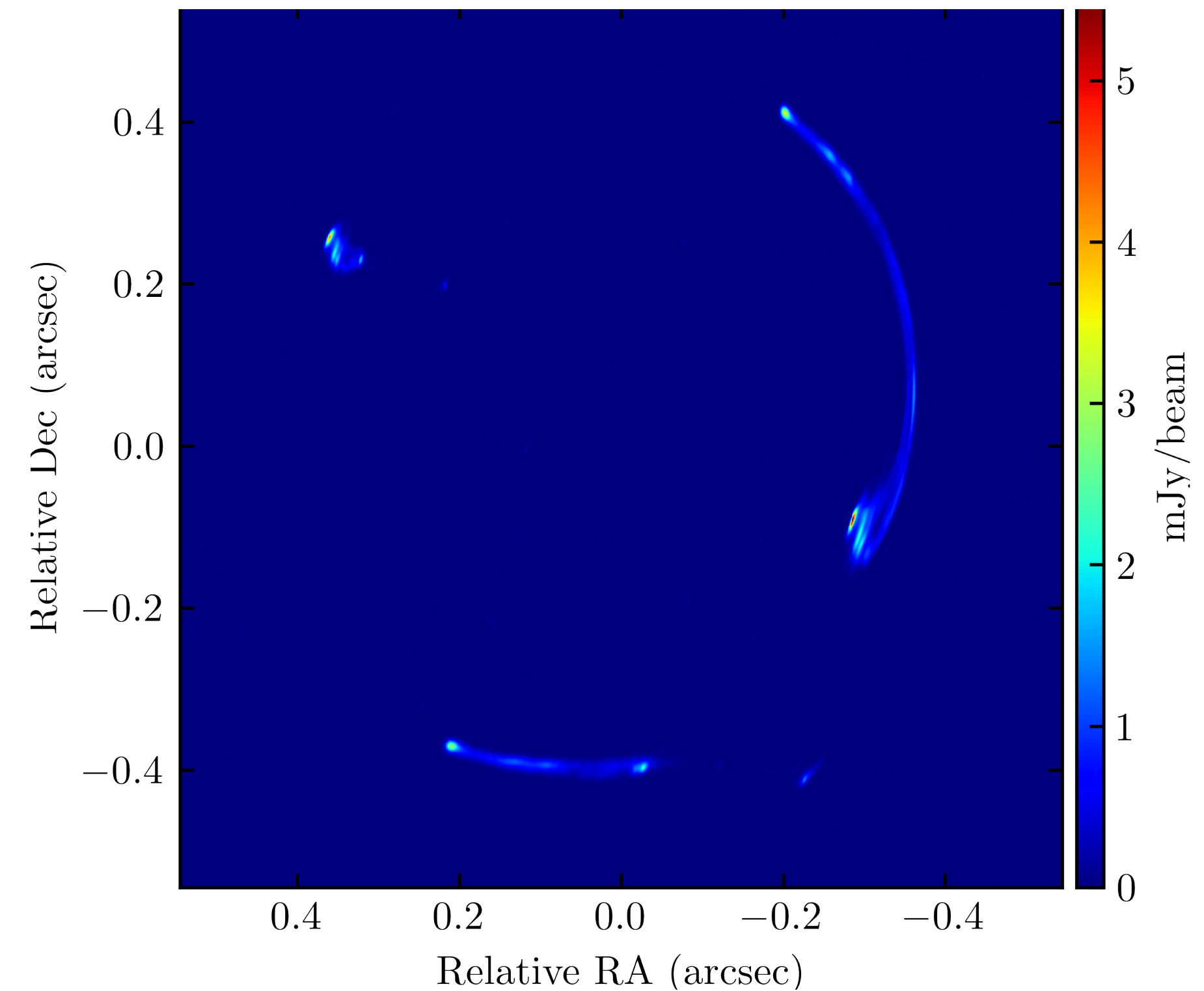
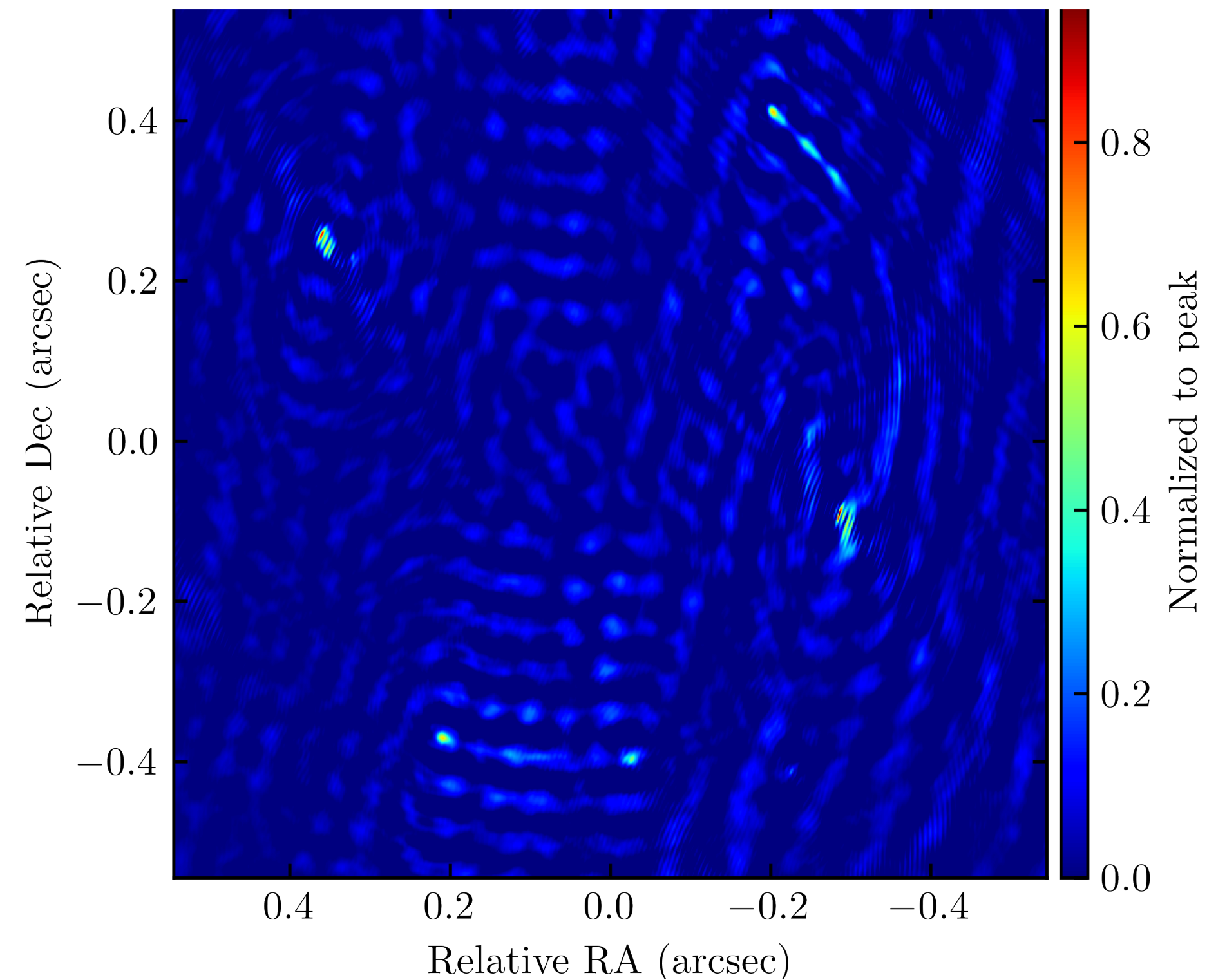
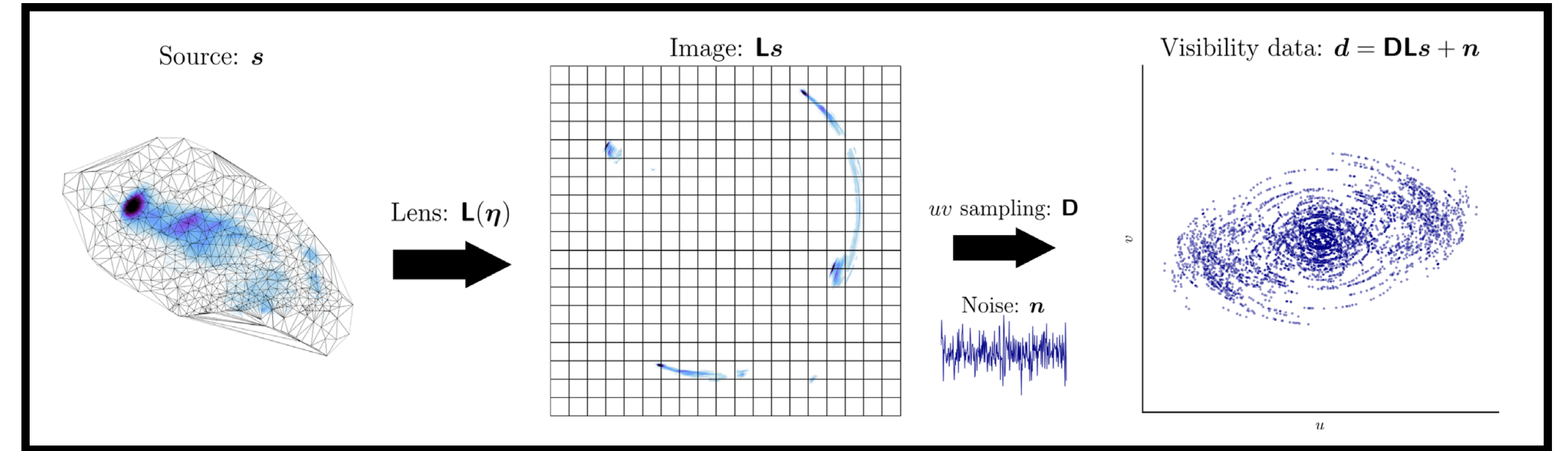
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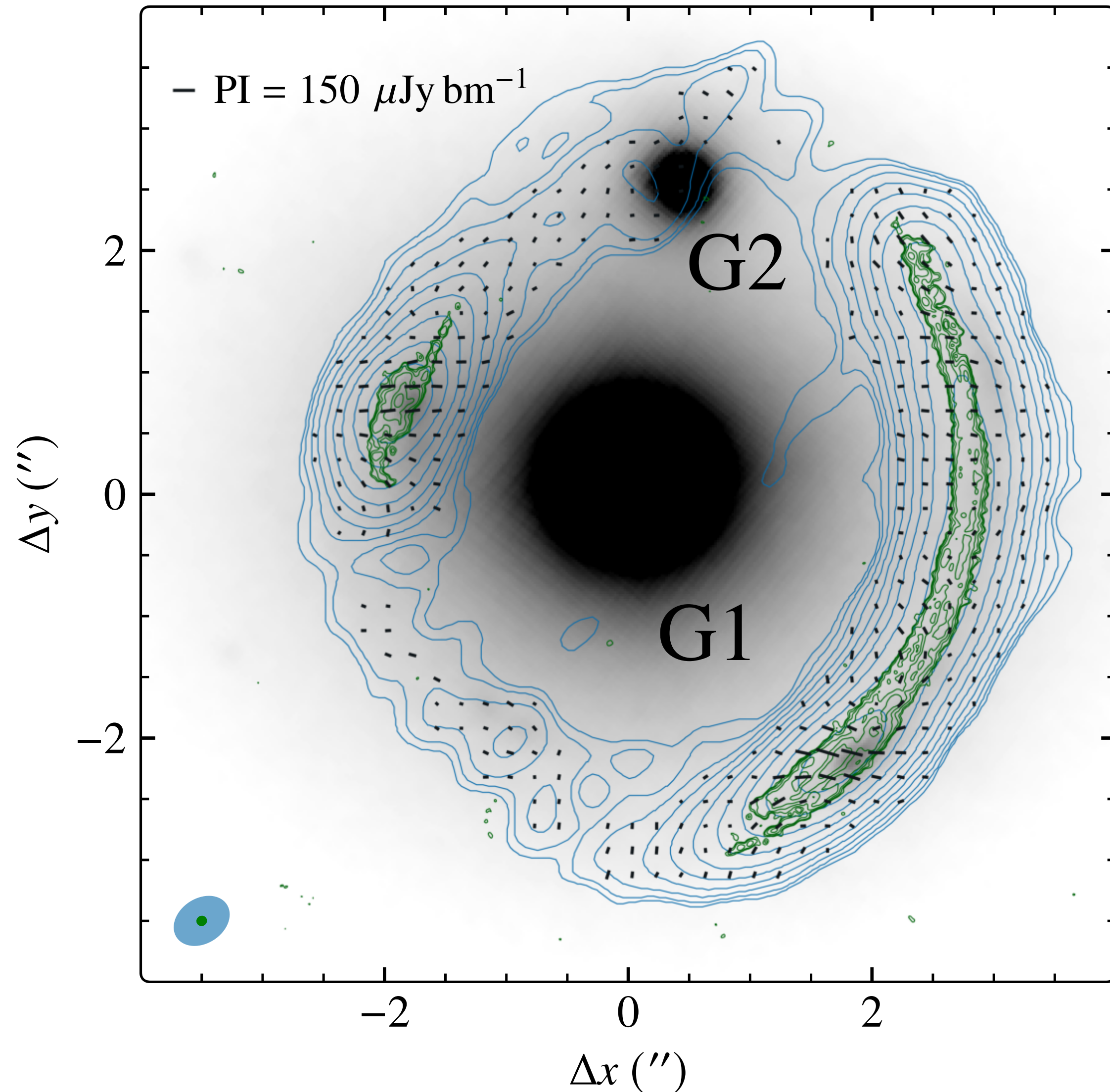
$$P(\eta, \lambda_s | \mathbf{d}) = \frac{P(\mathbf{d} | \eta, \lambda_s) P(\eta) P(\lambda_s)}{P(\mathbf{d})}$$



Resolving the high redshift Universe — Magnetic fields



- Reconstructing the magnetic field structures of high redshift galaxies (ALMA).

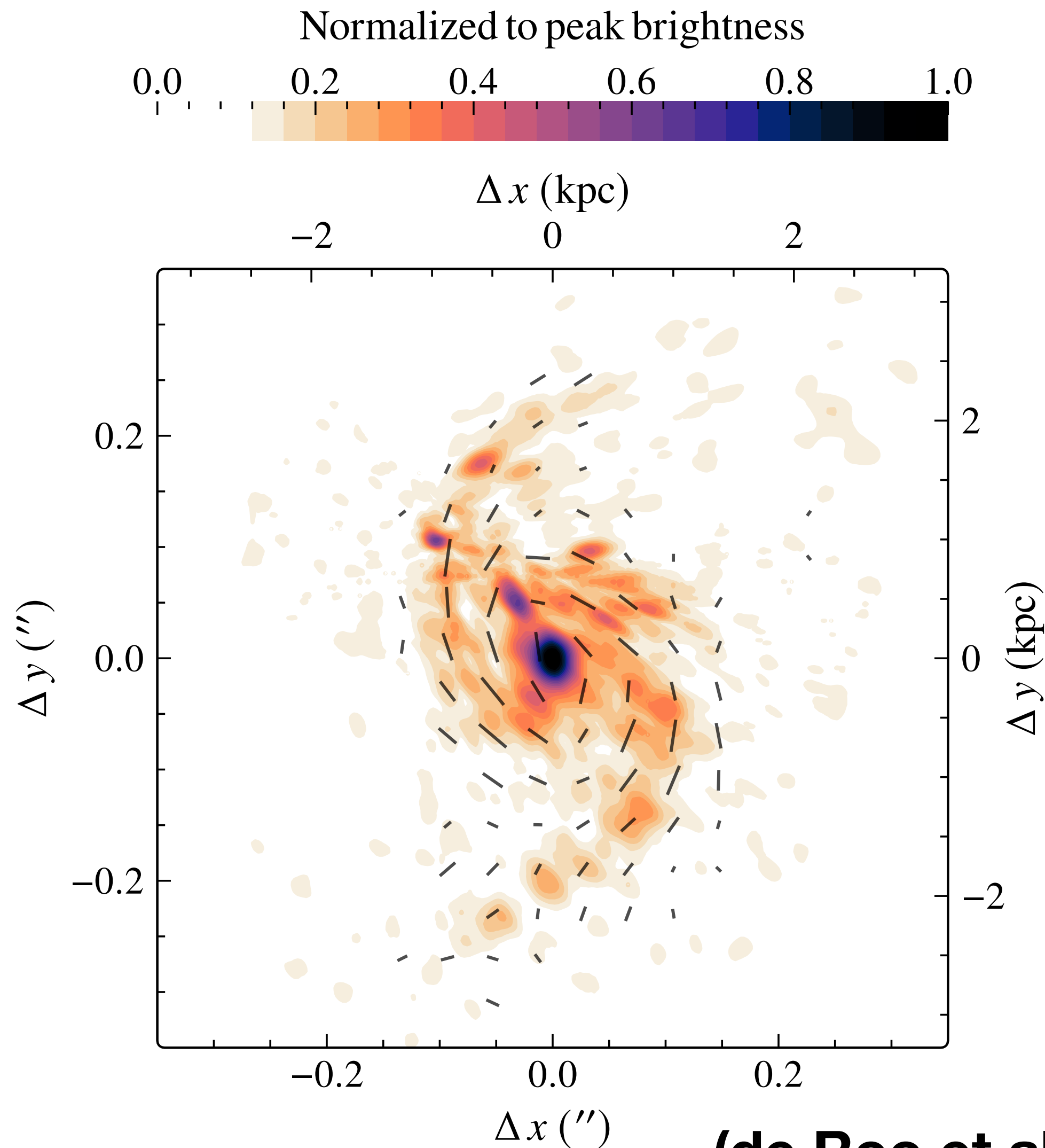
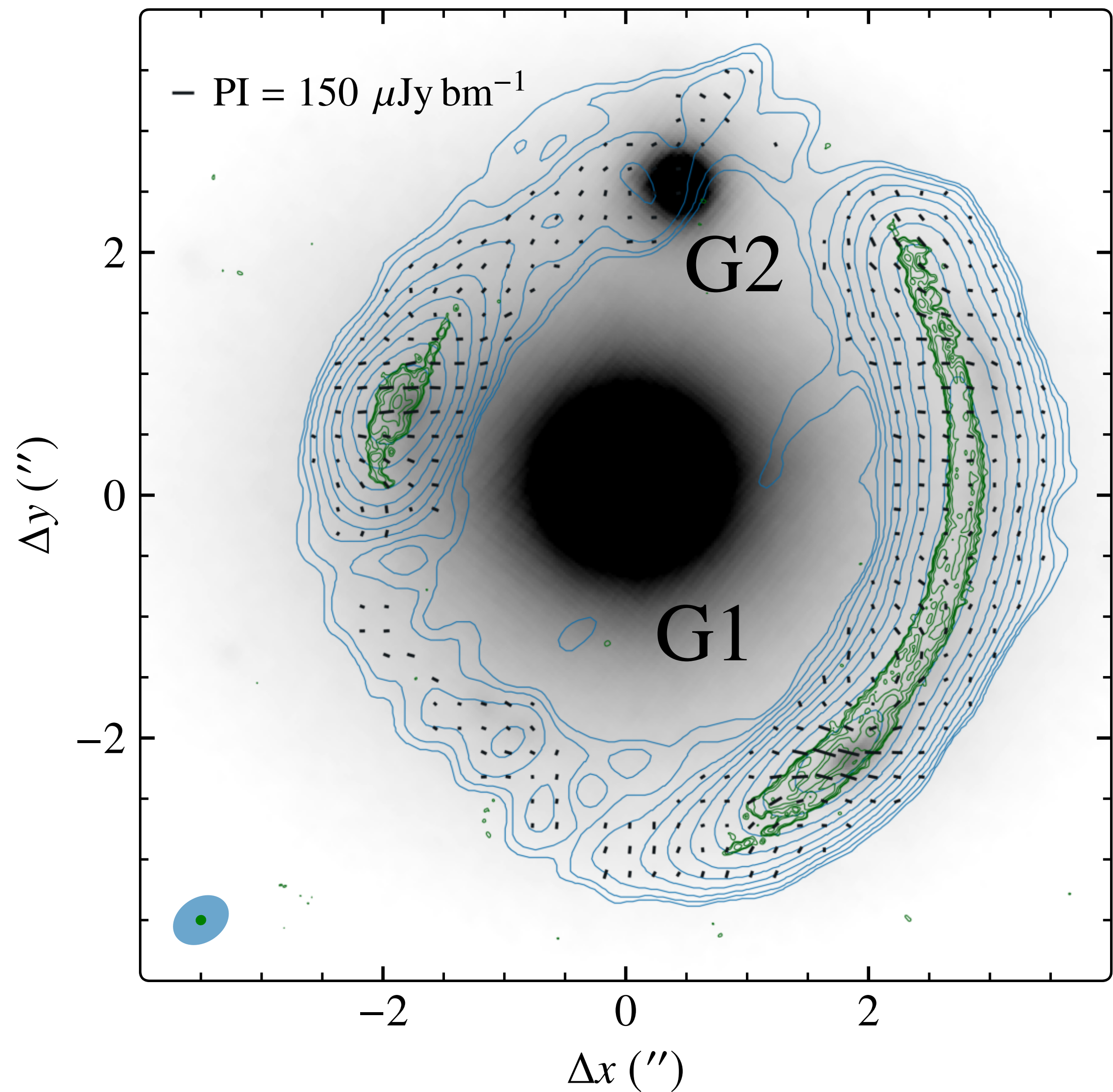


(de Roo et al. 2025)

Resolving the high redshift Universe — Magnetic fields



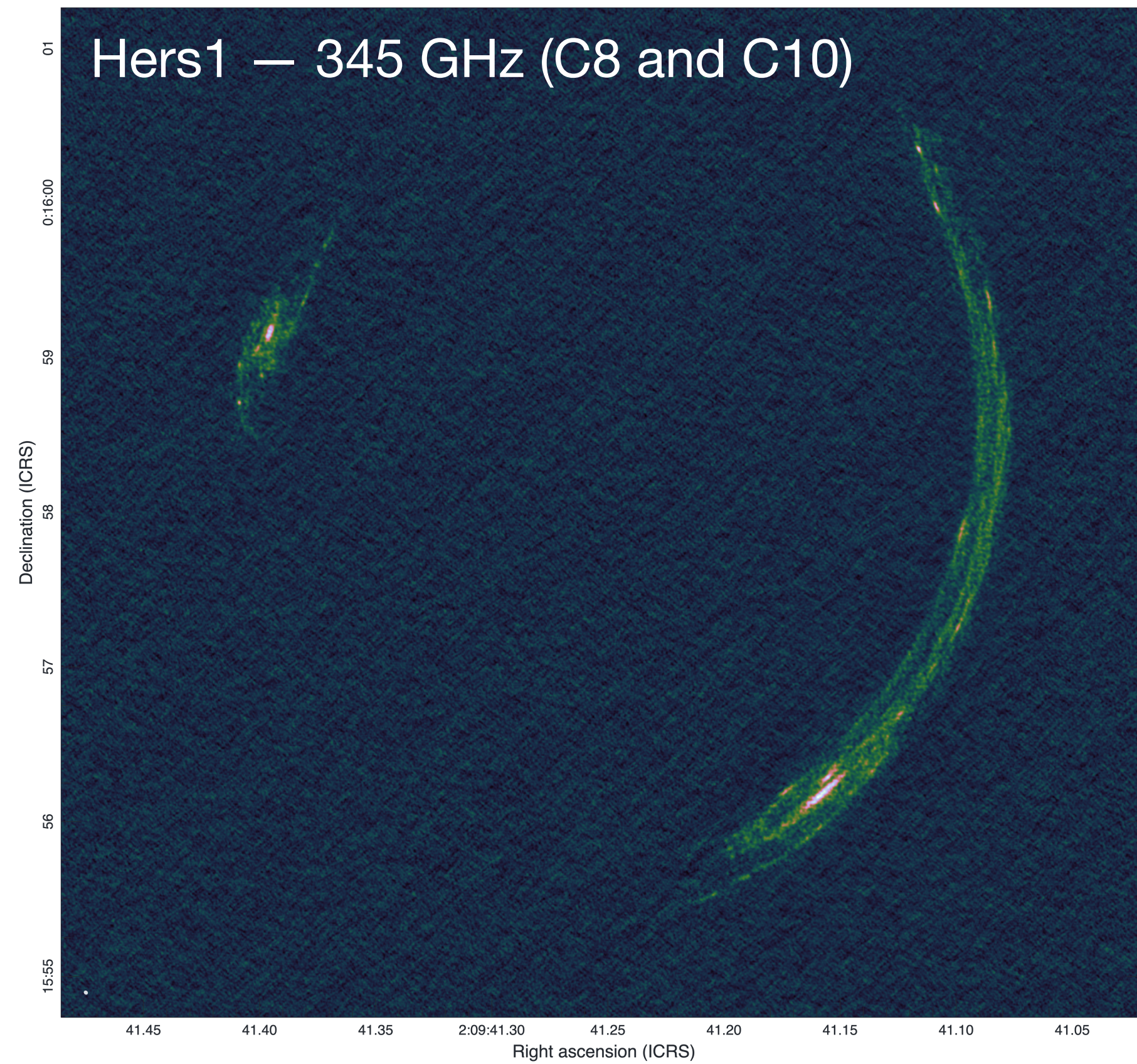
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(de Roo et al. 2025)

Resolving the high redshift Universe — Star-formation

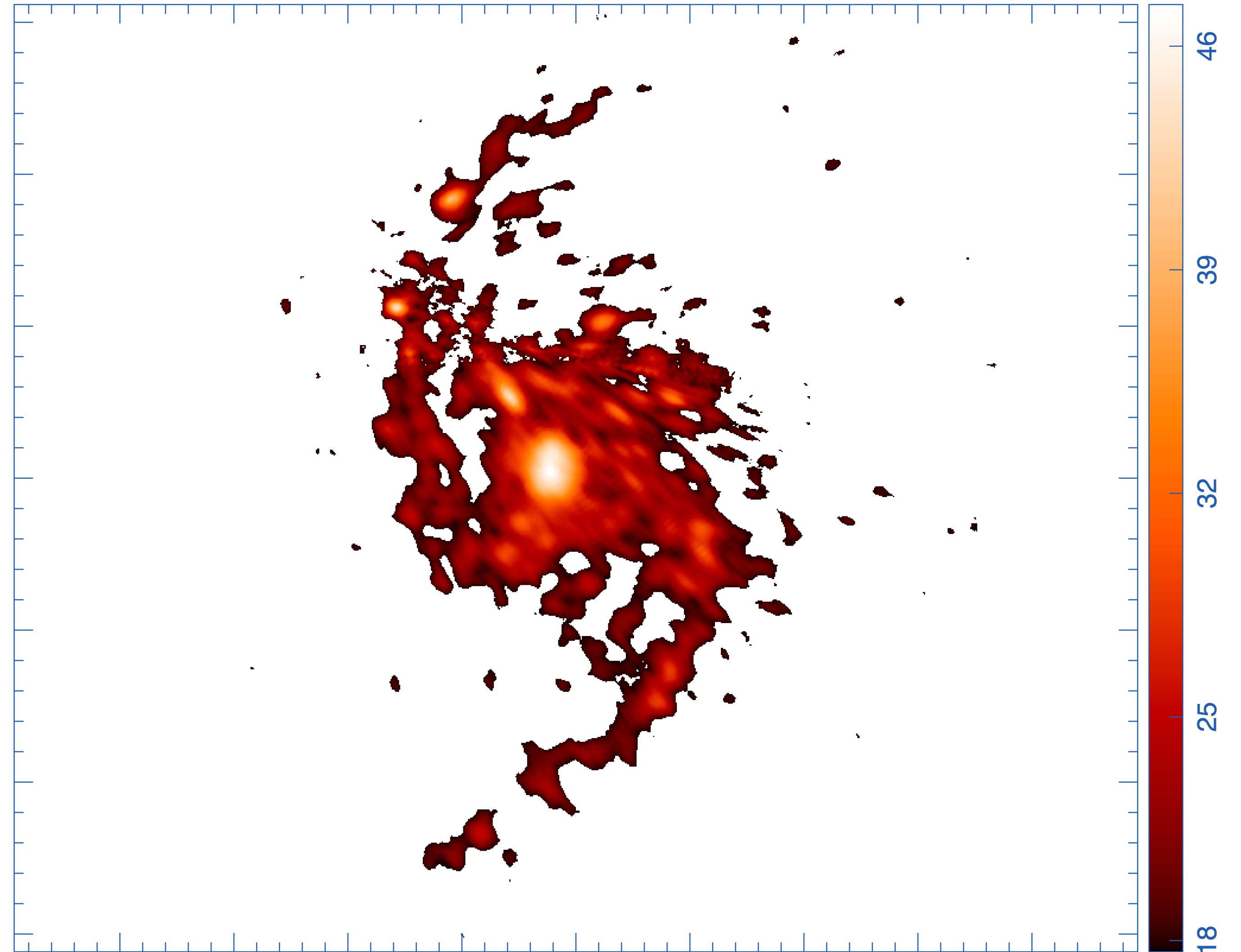
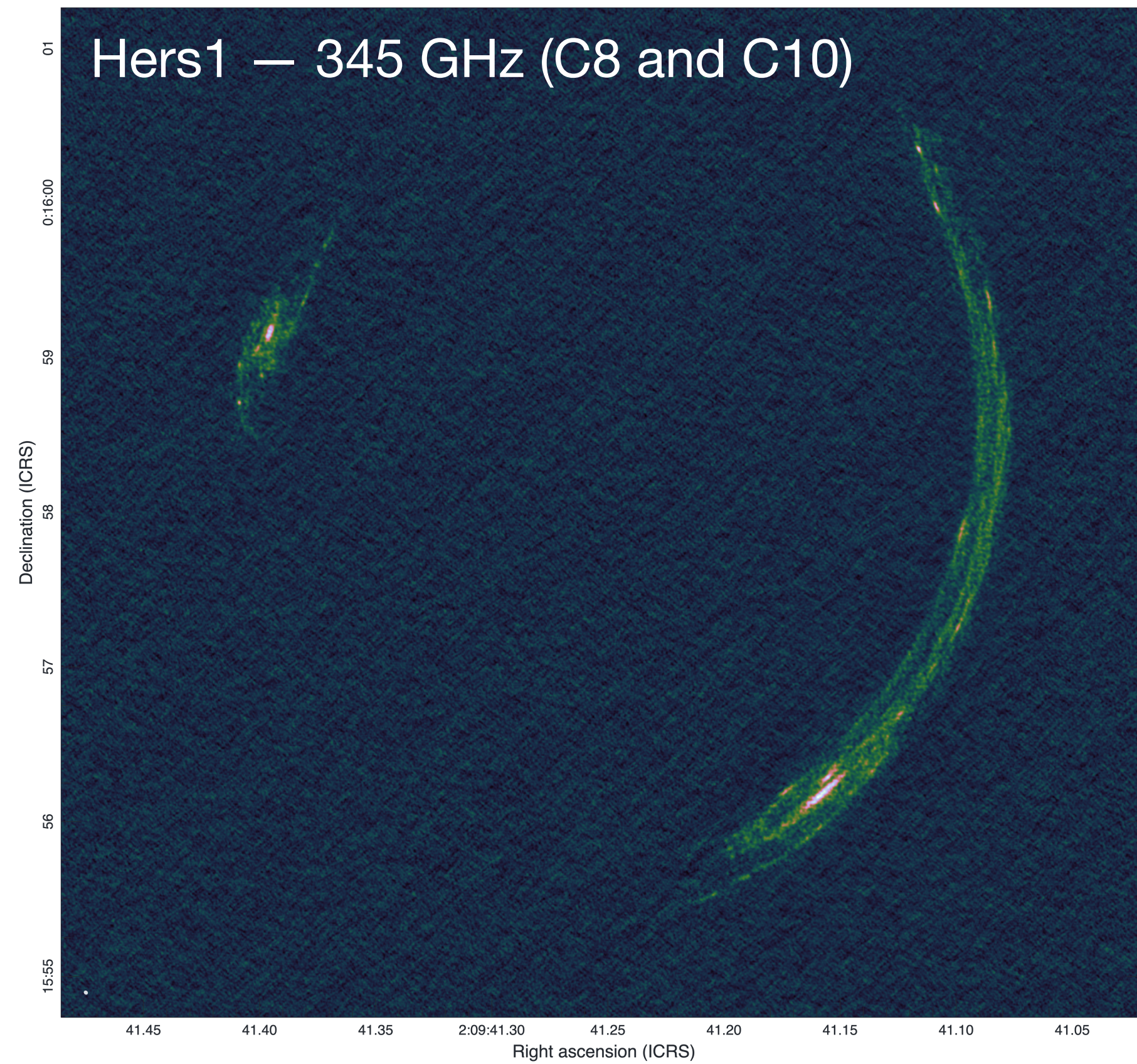
- Reconstructing the pc-scale structure of star-forming galaxies at high redshift (ALMA)



(McKean et al., in prep)

Resolving the high redshift Universe — Star-formation

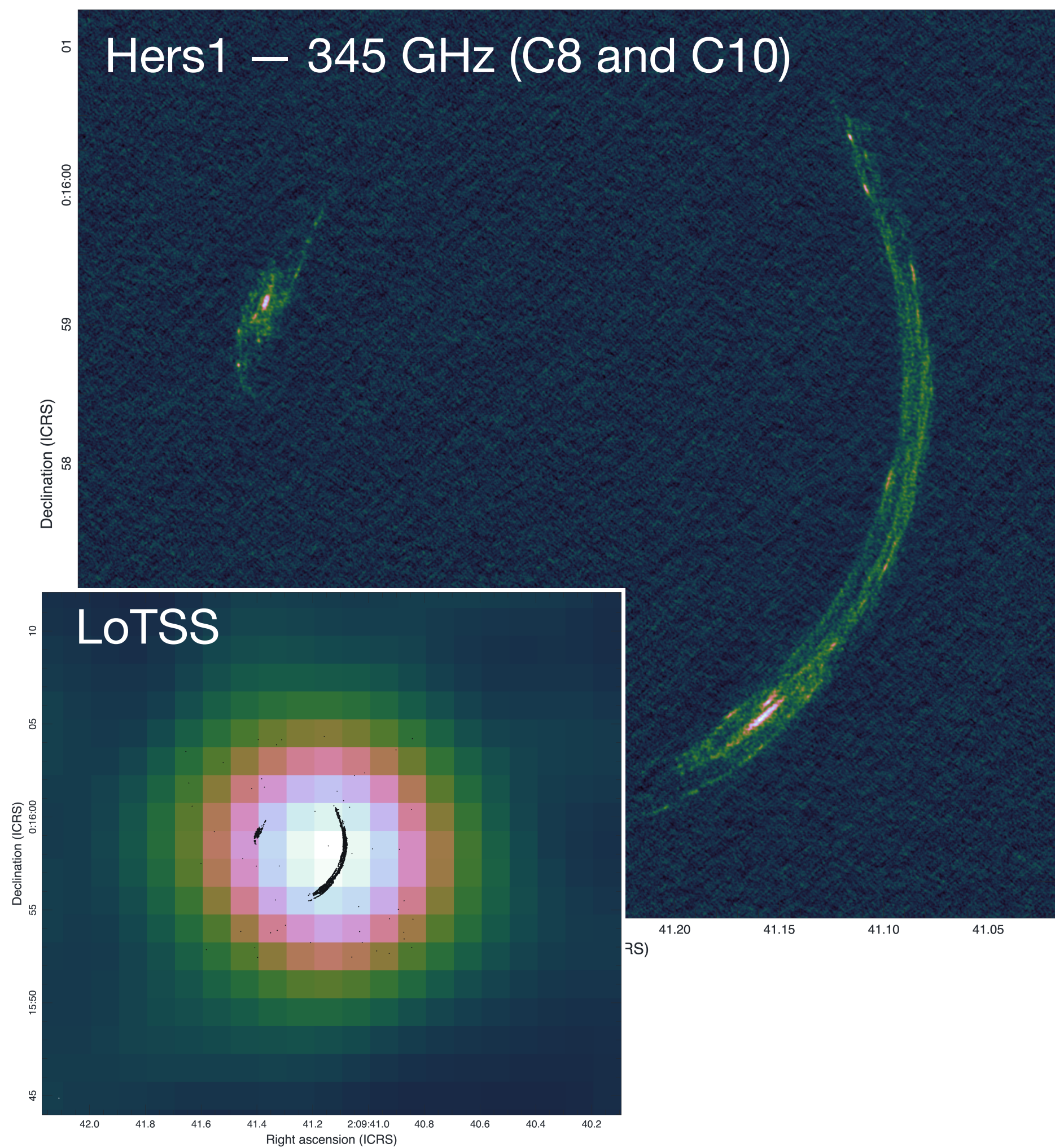
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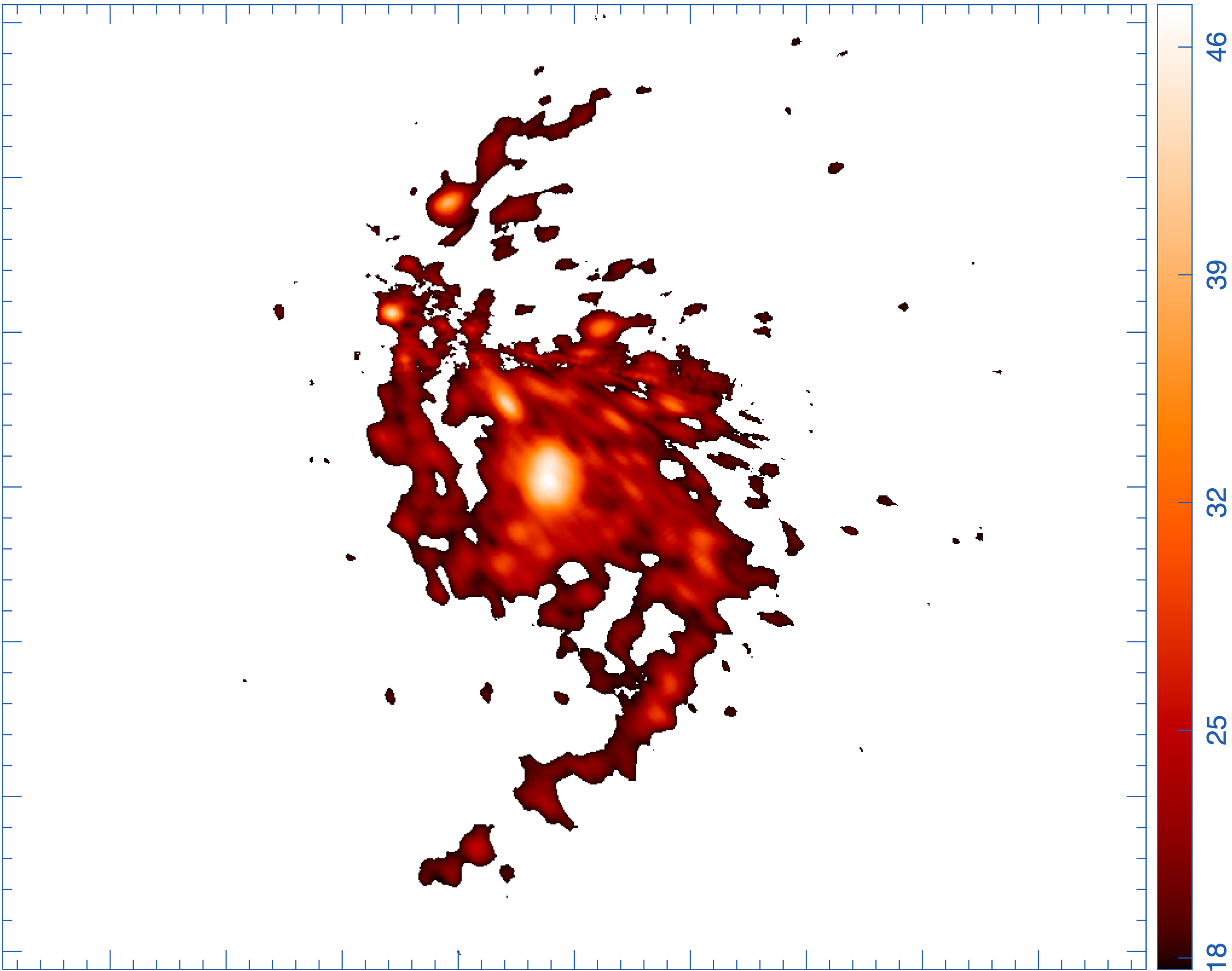
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Resolving the high redshift Universe — Star-formation

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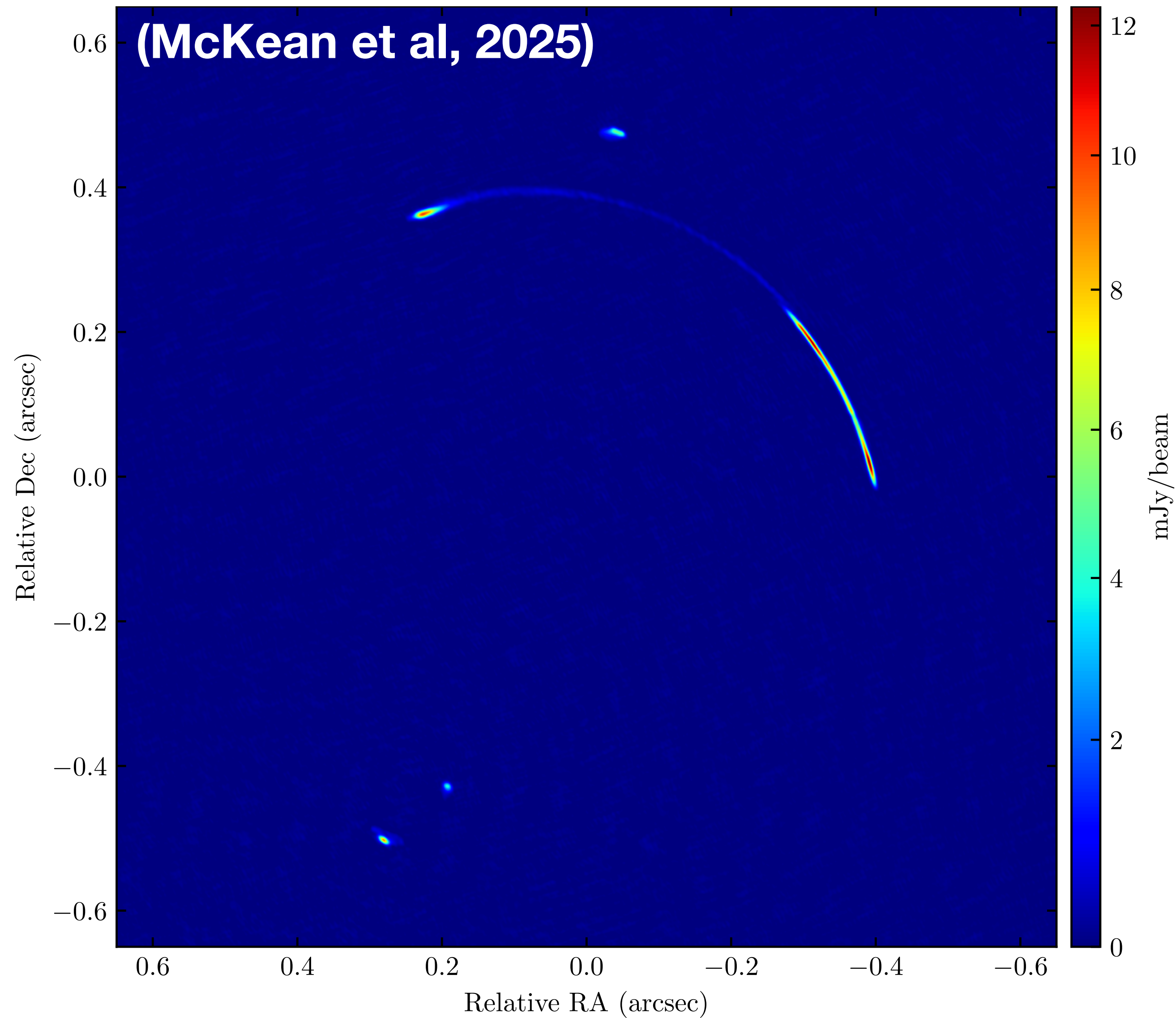


(McKean et al., in prep)



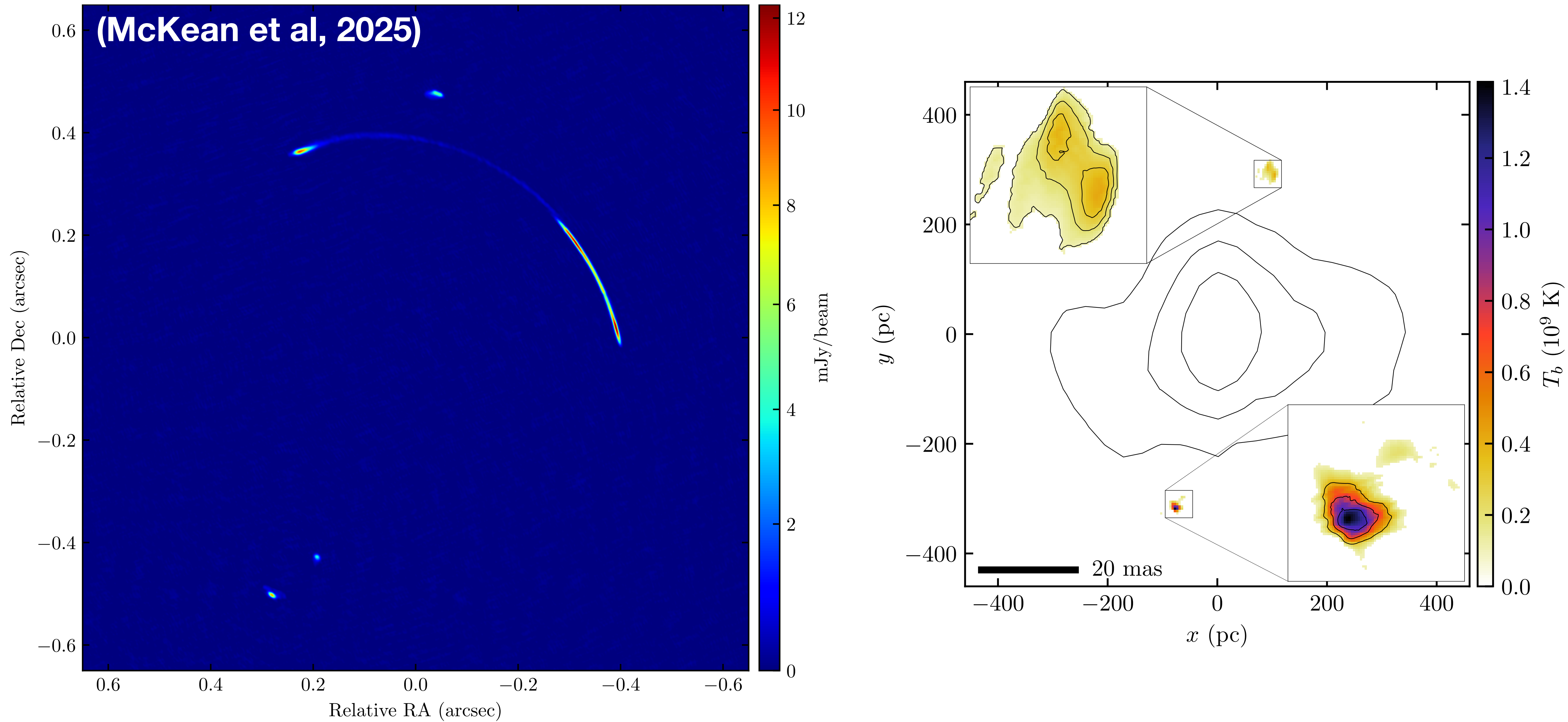
Resolving the high redshift Universe — Radio Jets

- Reconstructing the sub-pc-scale structure of radio galaxies at high redshift (EVN)



Resolving the high redshift Universe — Radio Jets

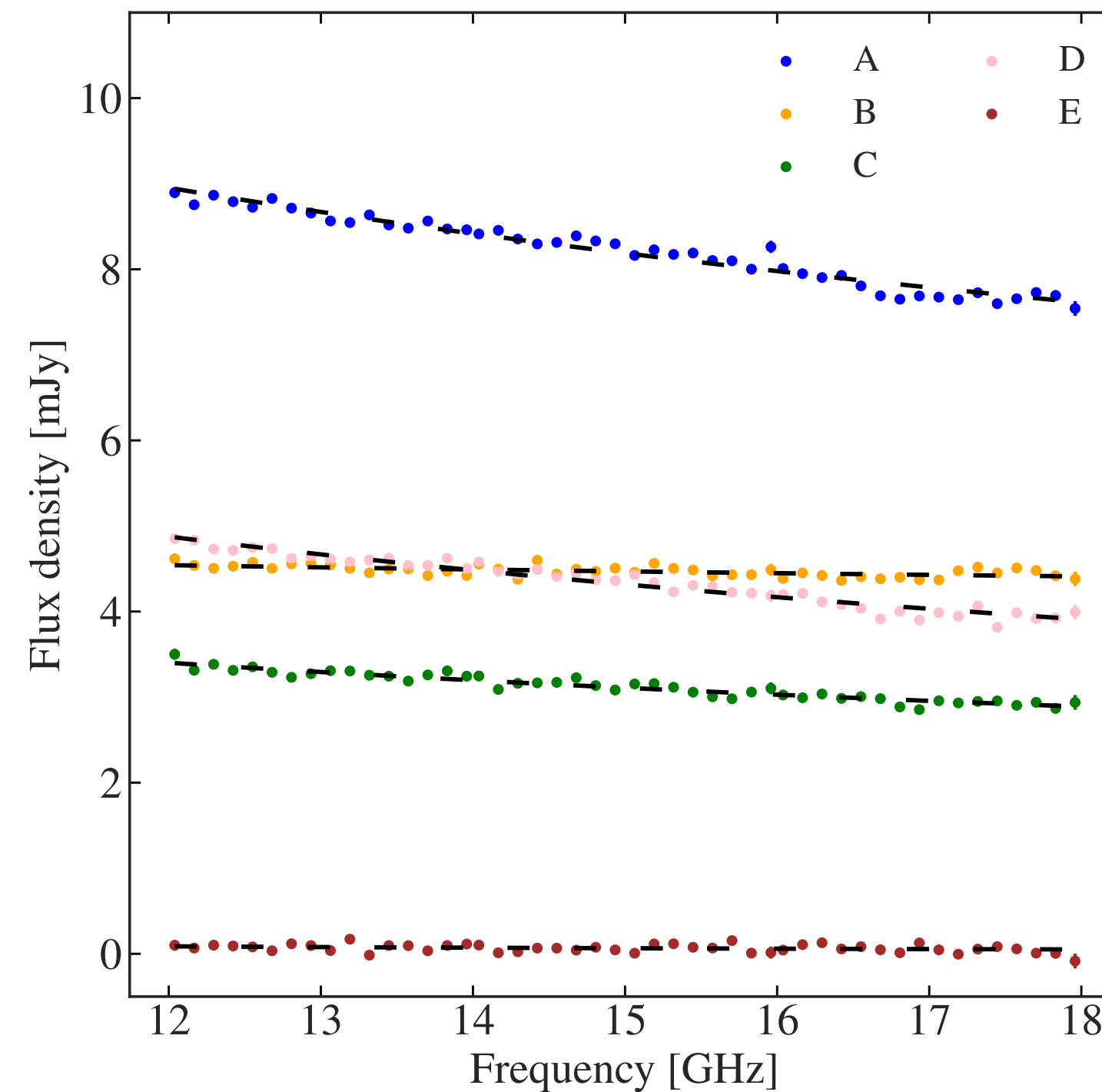
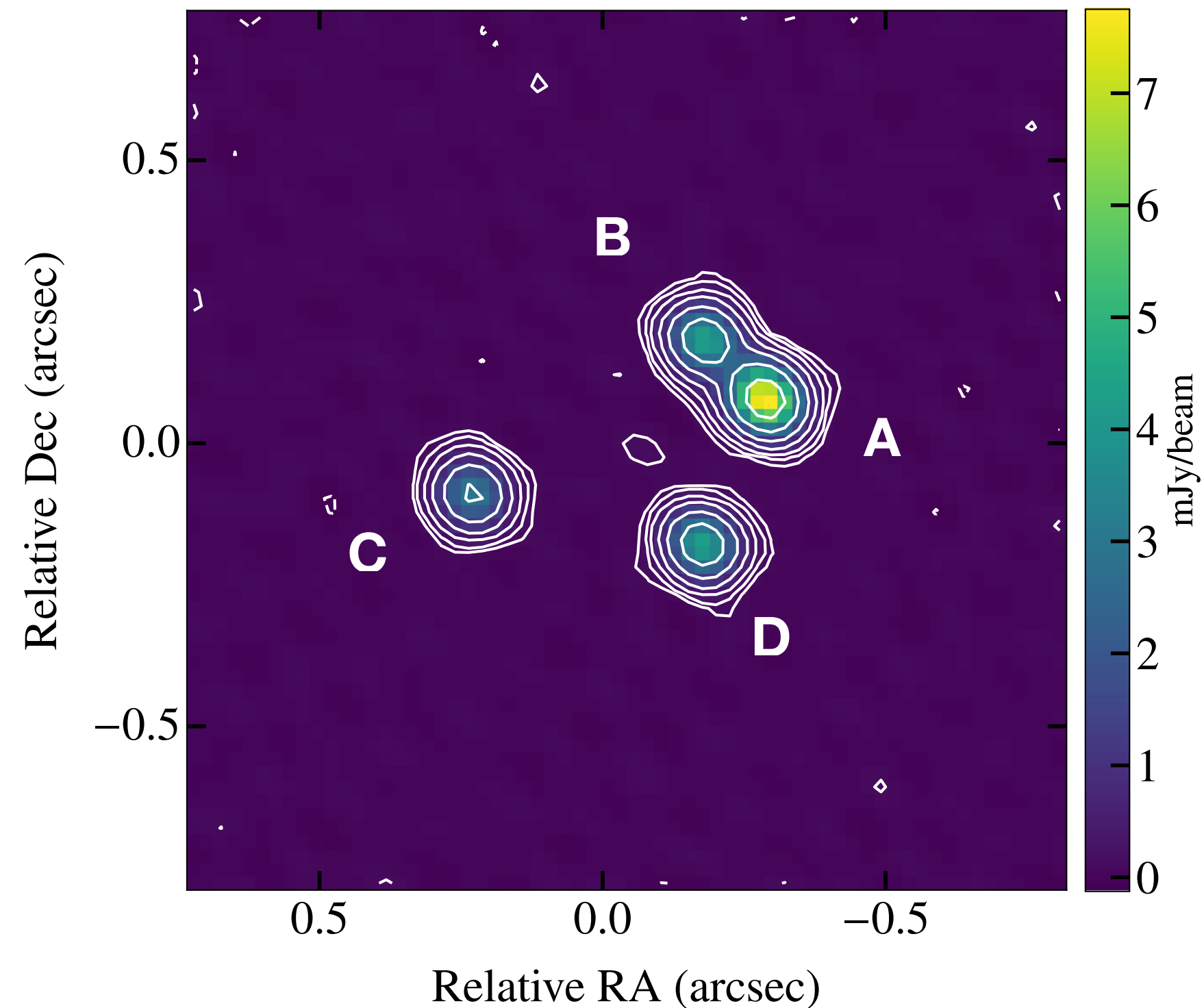
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Probing the ISM of intermediate galaxies

(Peters, MSc Thesis)

- Evidence for line-of-sight variations can determine the electron density and magnetic fields within massive intermediate lensing galaxies.



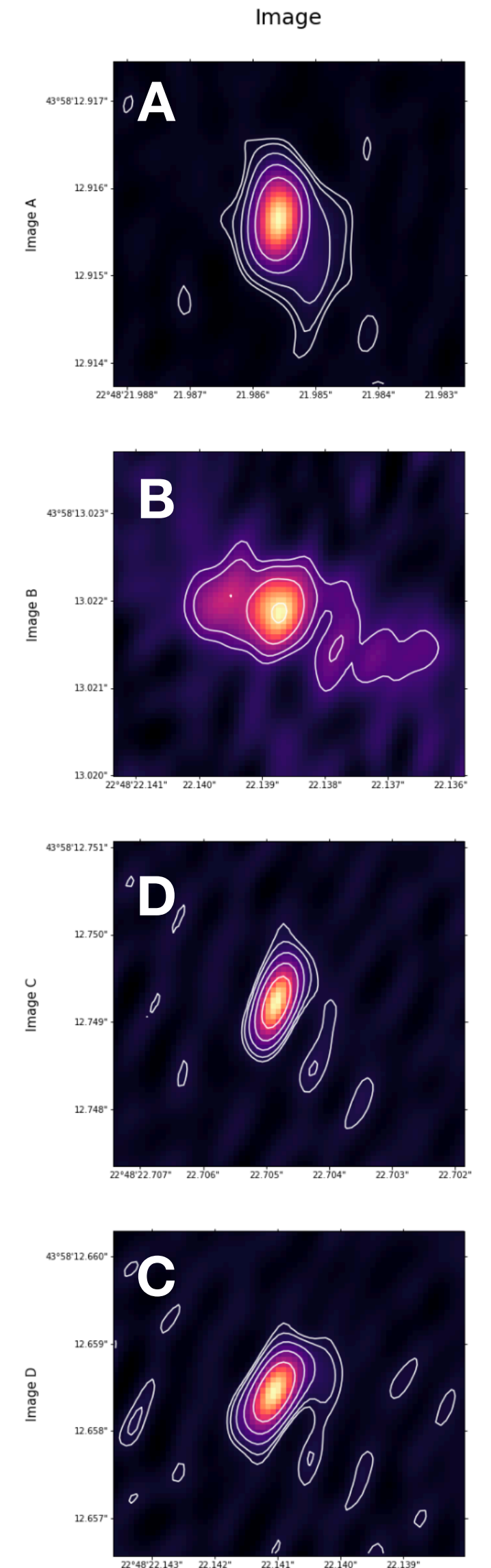
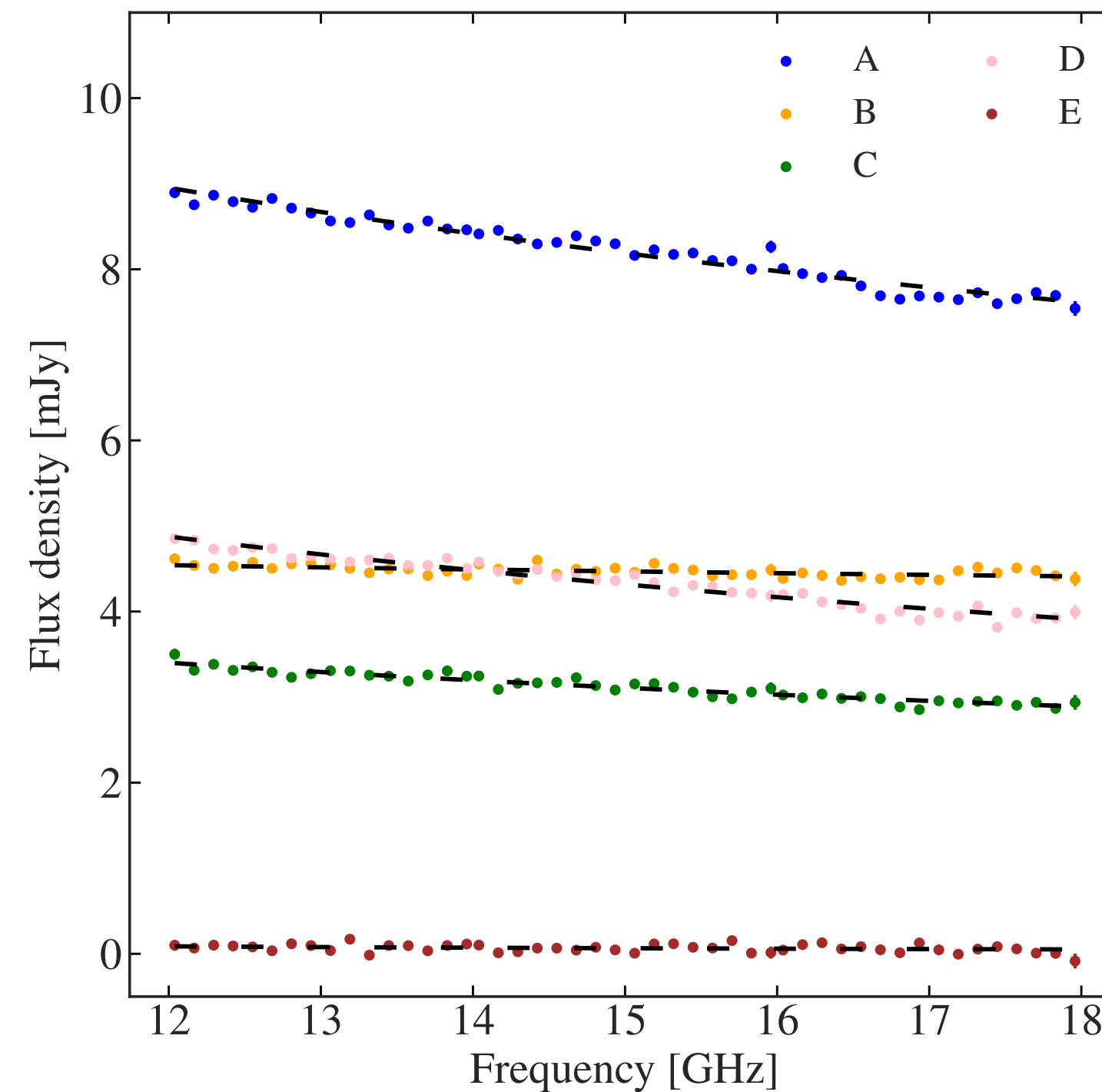
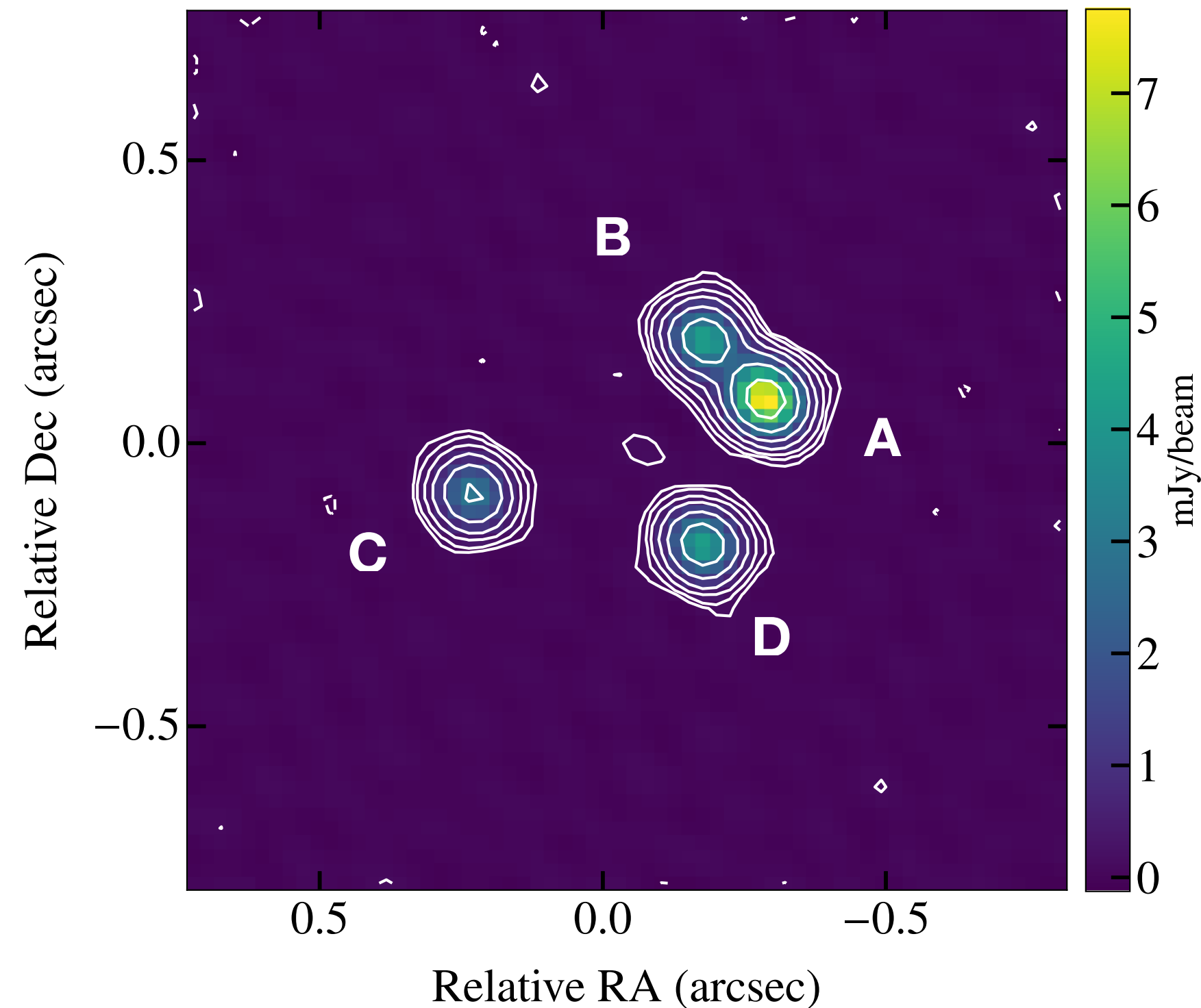
- Frequency dependent flux-ratio between 12-18 GHz.

FFA: $n_e \sim 300\text{--}2800 \text{ cm}^{-3}$

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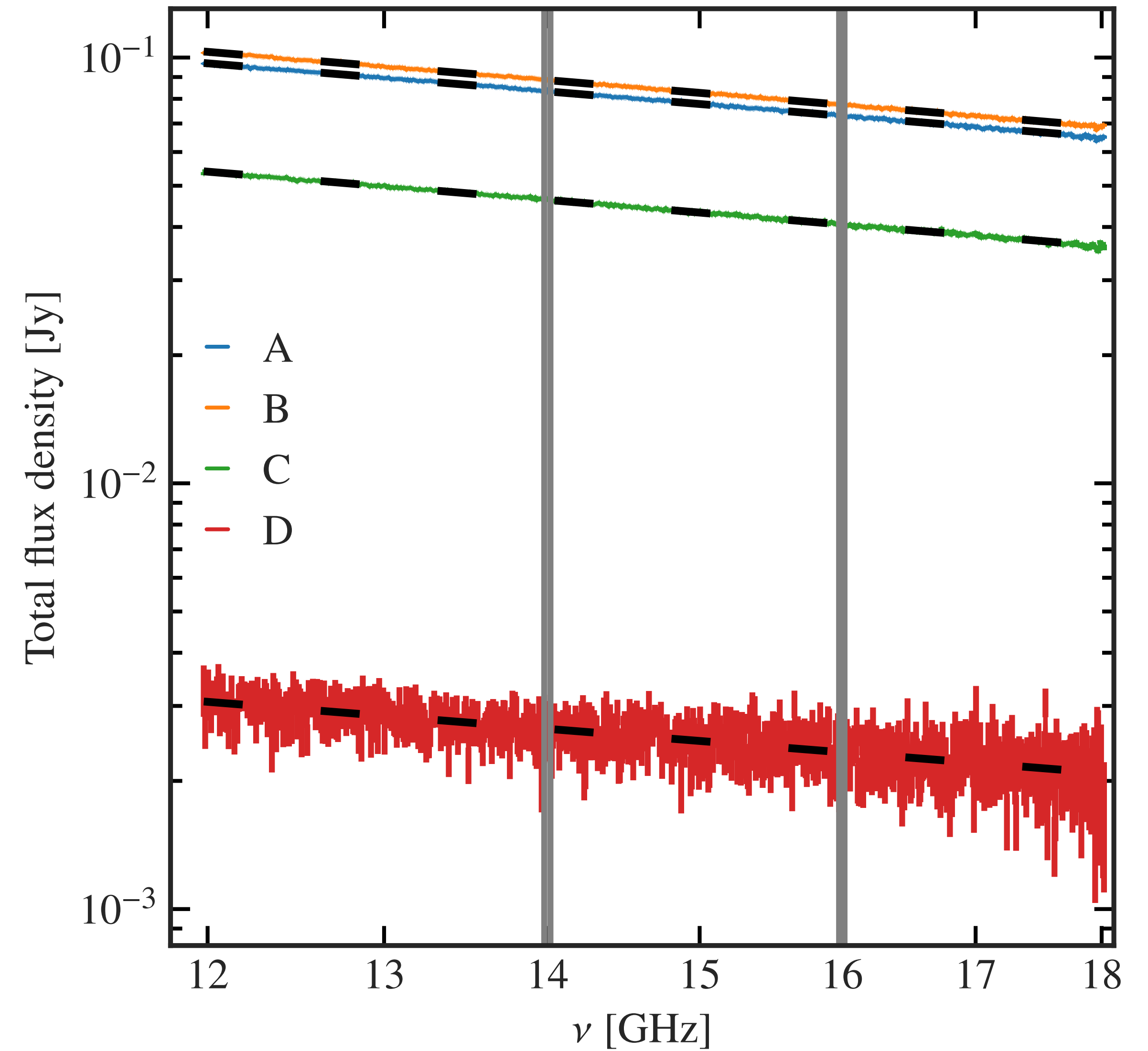
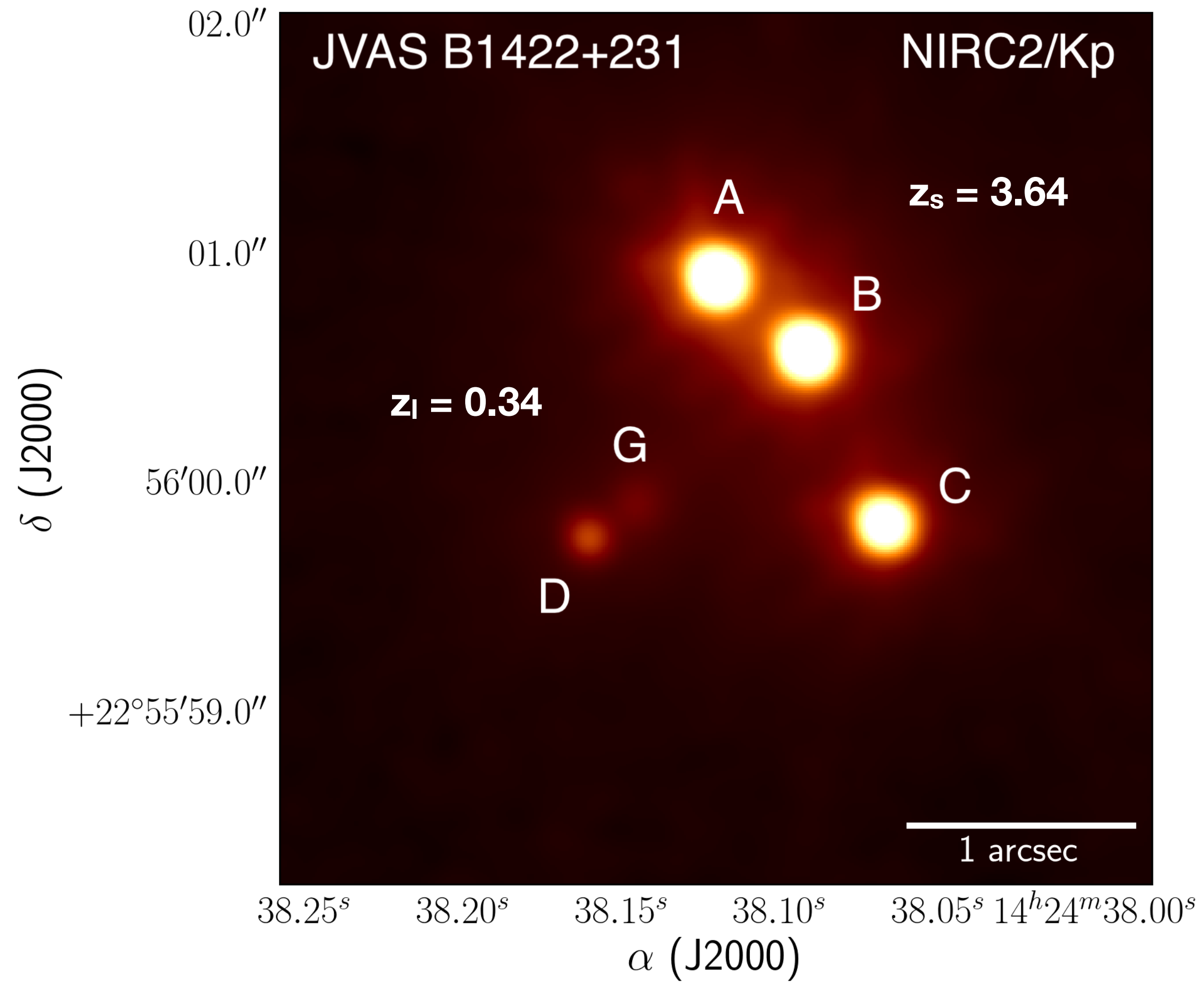


- Frequency dependent flux-ratio between 12-18 GHz.
- Change in VLBI surface brightness.

$$SM = 420 \text{ kpc m}^{-20/3}$$

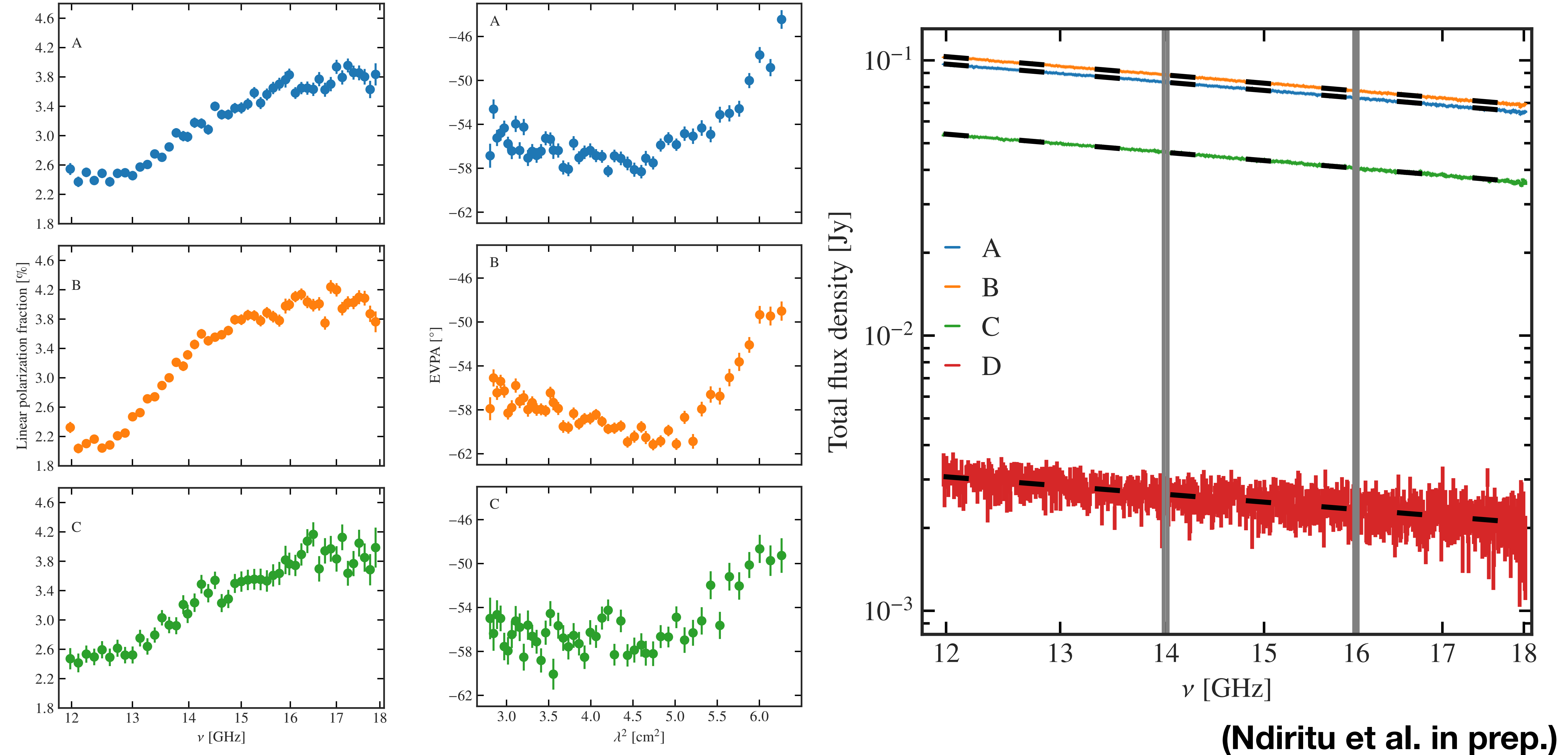
$$\text{FFA: } n_e \sim 300\text{--}2800 \text{ cm}^{-3}$$

Probing the ISM of intermediate galaxies

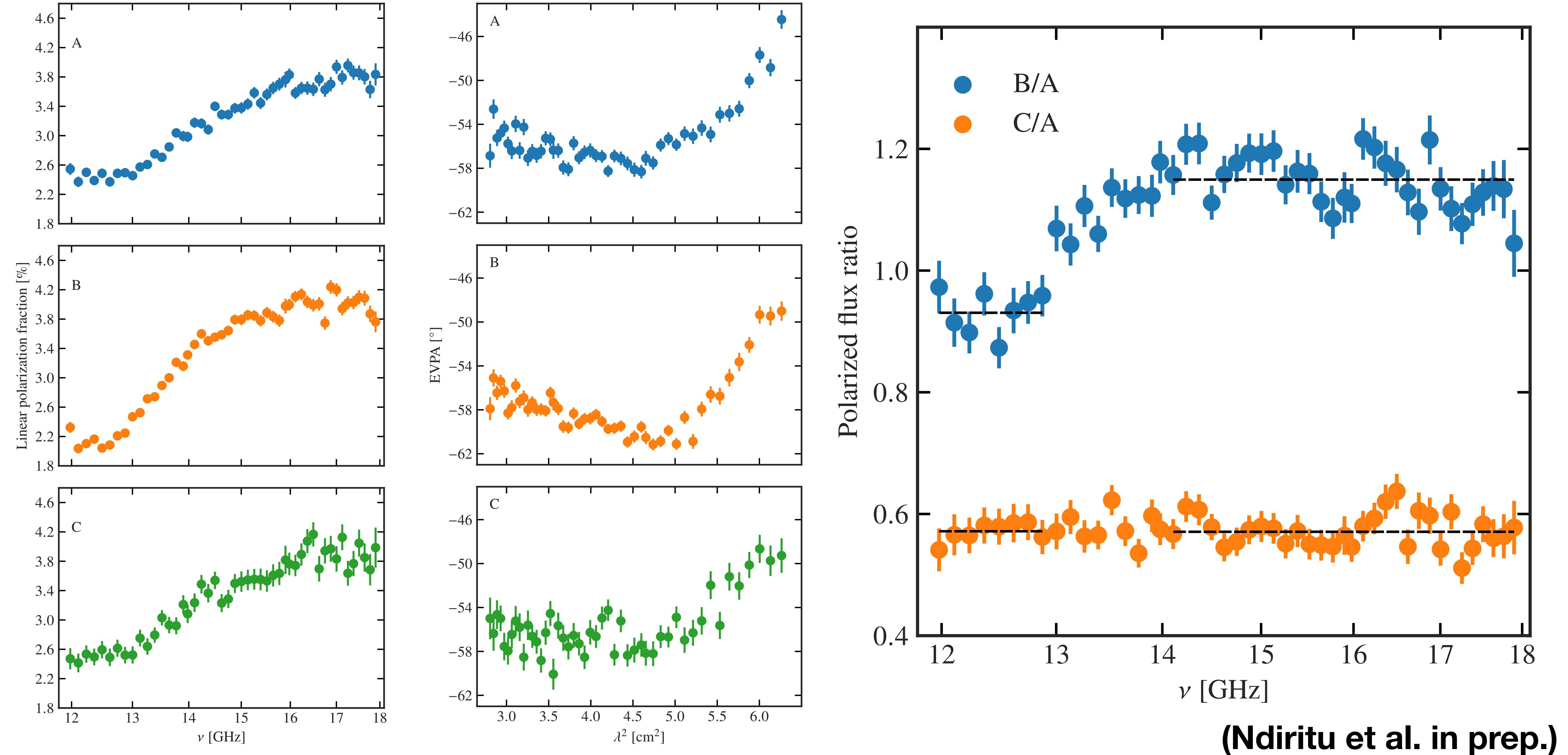


(Ndiritu et al. in prep.)

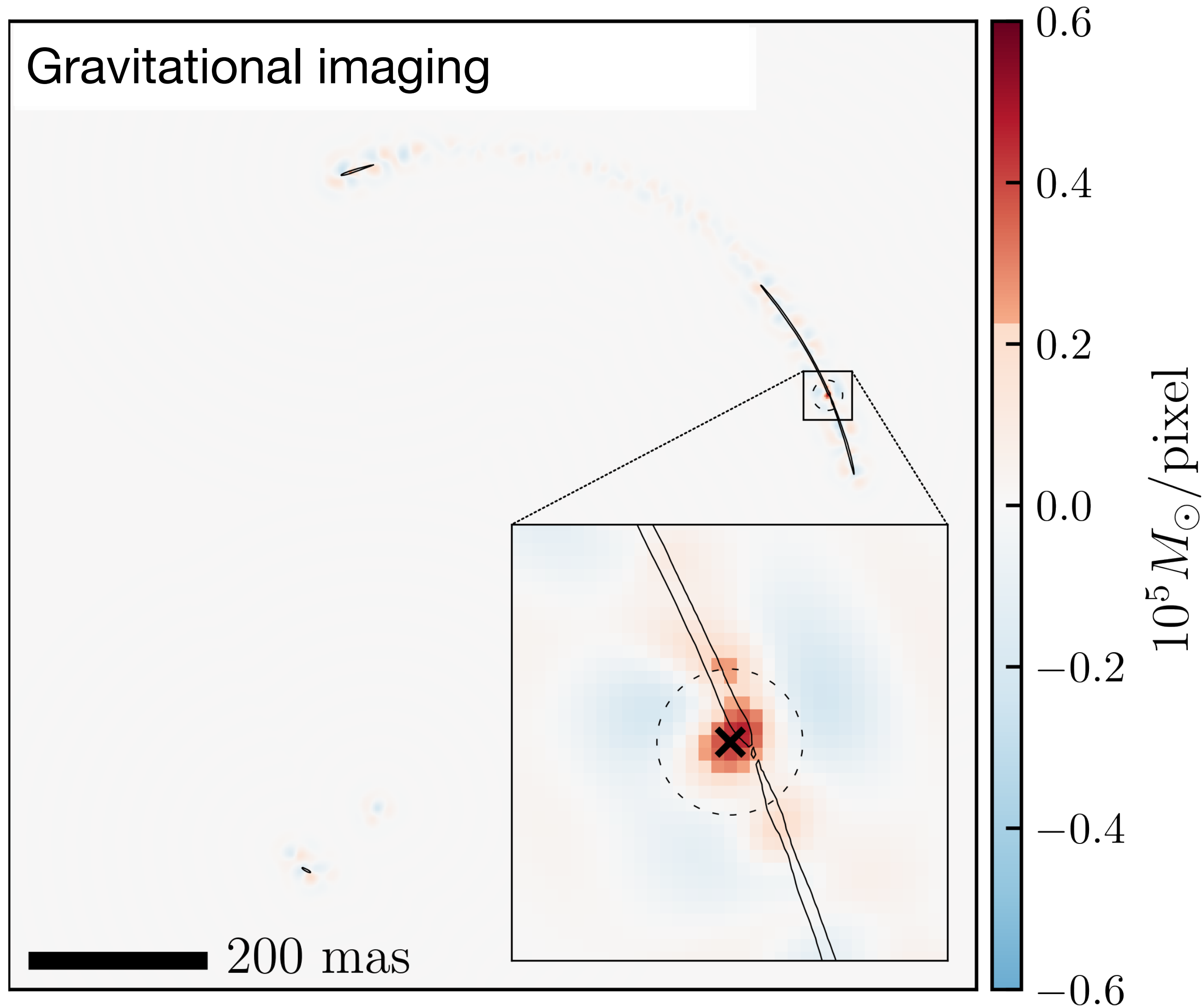
Probing the ISM of intermediate galaxies



Probing the ISM of intermediate galaxies



Testing models for Dark Matter



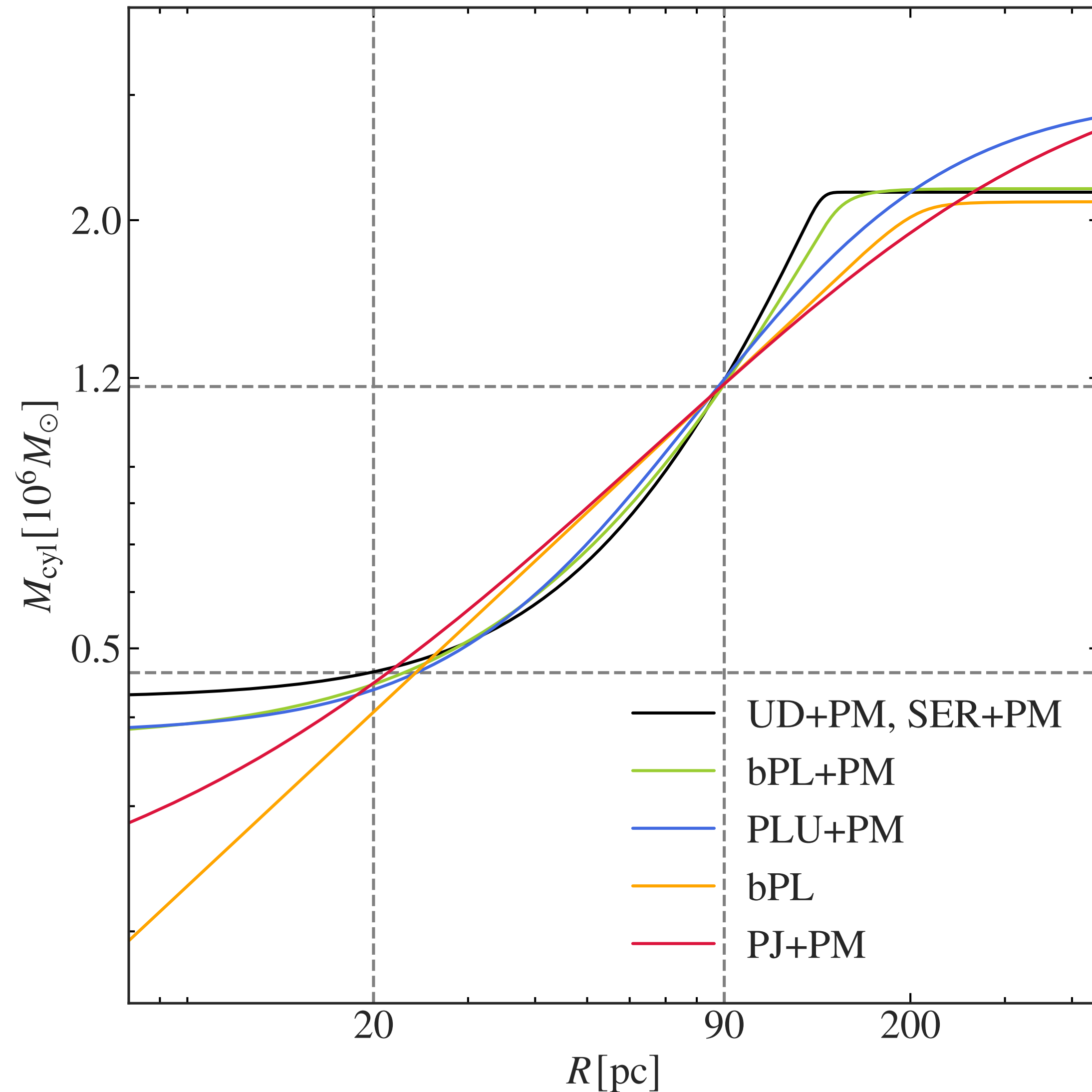
Abundance consistent with CDM

In a $1.06 \times 10^{-2} \text{ arcsec}^2$ region, the probability of detecting at least one CDM subhalo in the $[10^6, 10^7] M_{\text{sun}}$ mass bin is **$p(n > 1) = 0.65$** .

Probability $p = 0.36$ for 9.1 keV thermal relic warm dark matter (WDM) and $p = 0.14$ for 4.6 keV WDM.

(Powell et al. 2026)

Testing models for Dark Matter

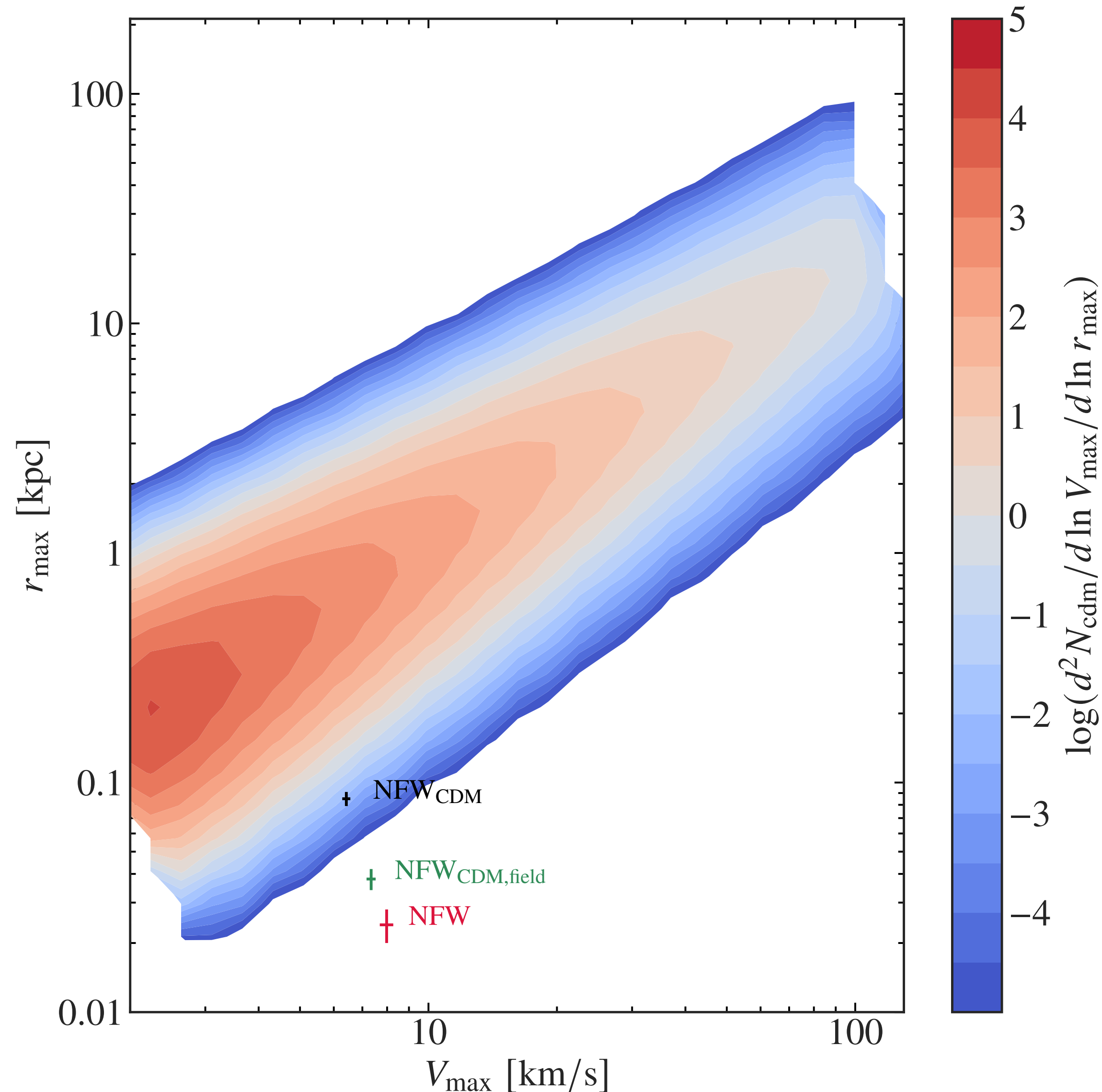


In total 25 parametric models were tested

- Point mass (compact nuclear or black hole)
- King or Plummer profile (Globular cluster)
- Power-law, broken power law, NFW (dark matter dominated halo/sub-halo)
- Sérsic (baryon dominated ultracompact dwarf)

Best fit is an uniform disk with a sharp cut-off at 140 pc and a central compact component that takes up 30% of the mass.

Testing models for Dark Matter



- The properties of the models, for the dark matter halo interpretation, are not consistent with the predictions from CDM/WDM (8 to 17σ level).
- Could point to more exotic models, such as self-interacting dark matter.

(Vegetti et al. 2026)



Onsala

Dutch stations

Chilbolton

Norderstedt

LOFAR Core (NL)

Potsdam

Baldy

Borówiec

Jülich

Effelsberg

Tautenburg

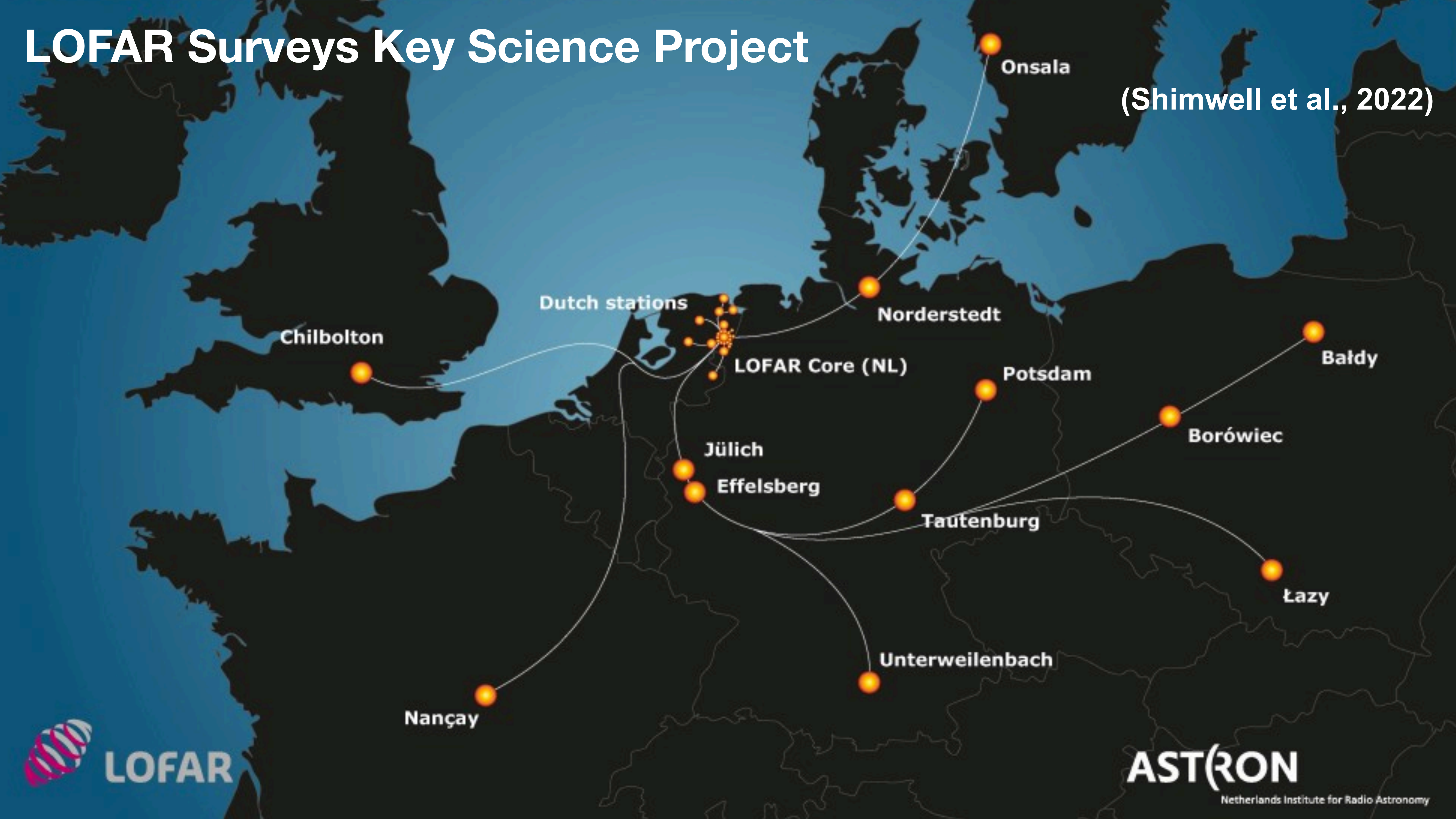
Łazy

Unterweilenbach

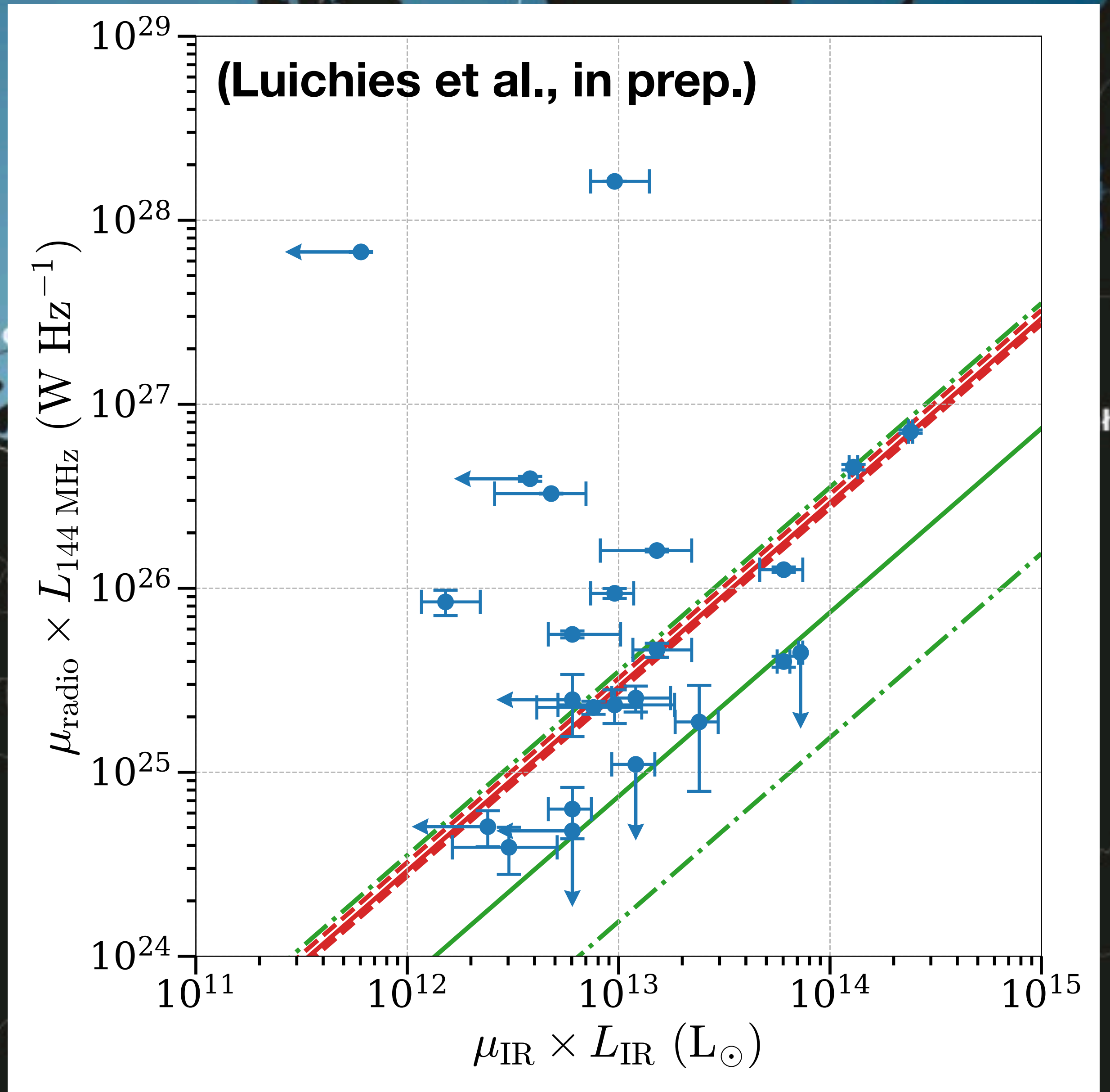
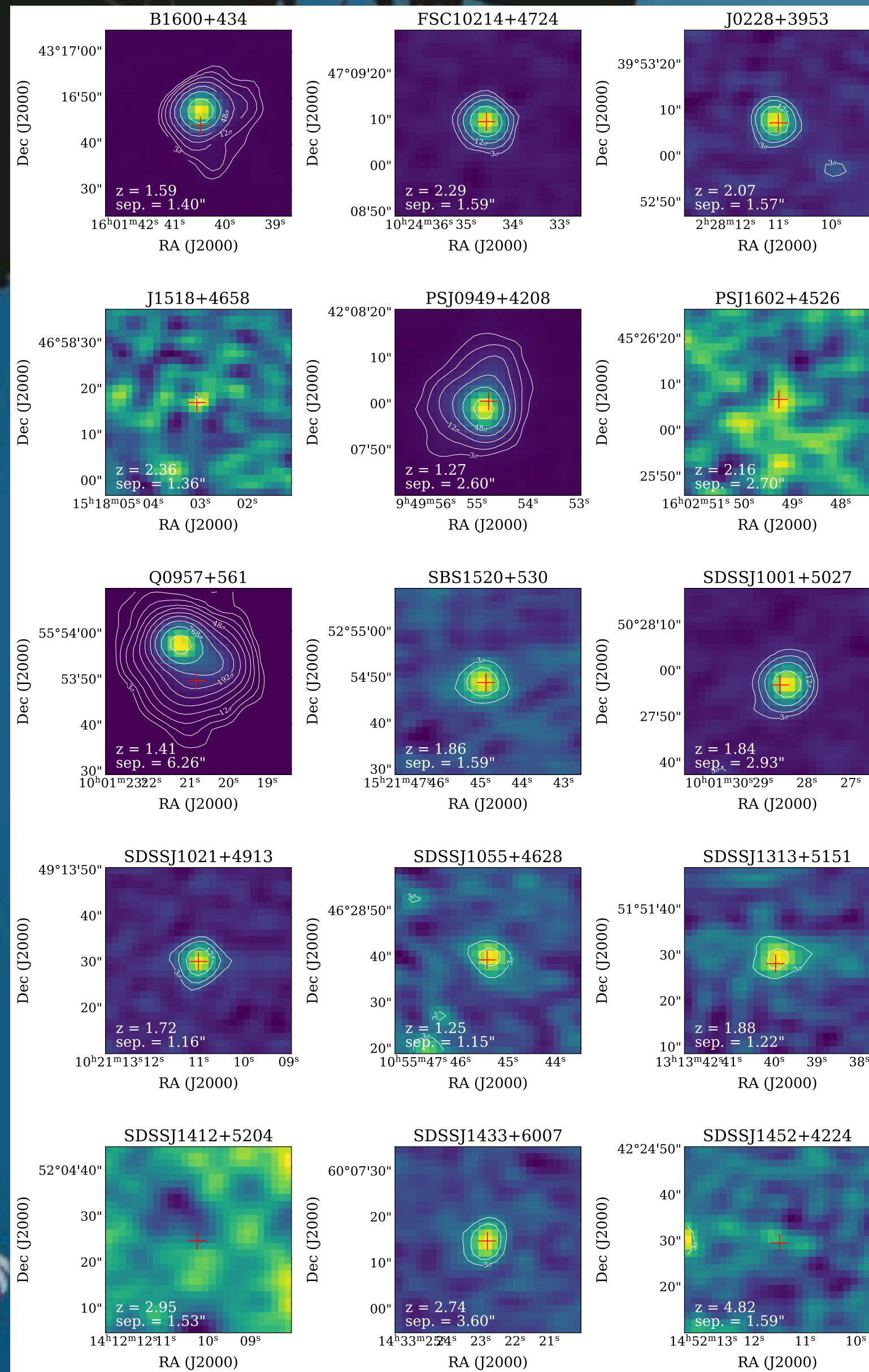
Nançay

LOFAR Surveys Key Science Project

(Shimwell et al., 2022)



Radio-loud? 63% of known lensed quasars detected with LOFAR



First resolved detections from cluster lensing

(McKean et al., 2021)

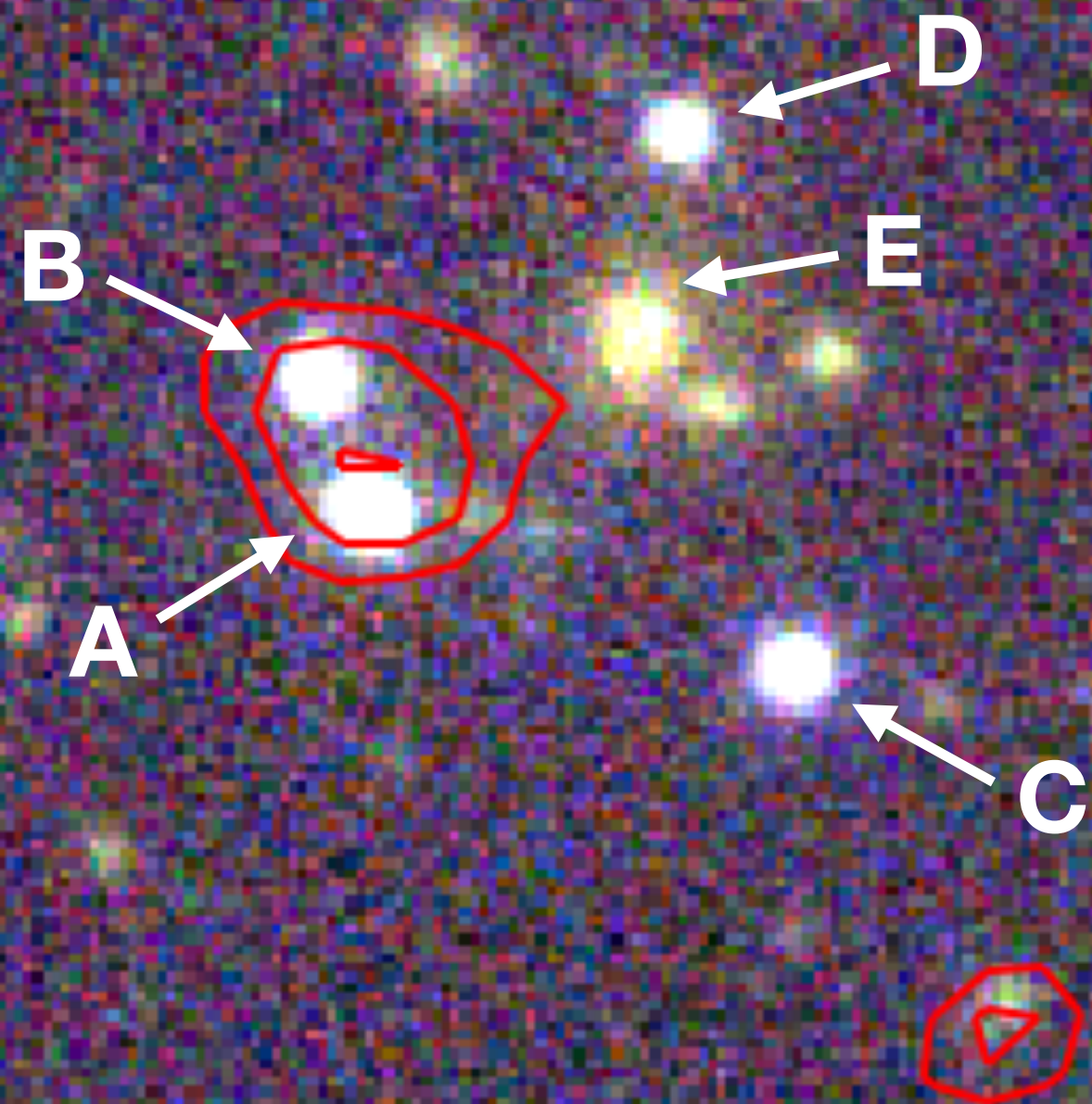
SDSS J1004+4112 ($z = 1.730$)

Total mag = 67

$S_{144 \text{ MHz}} = 13 \text{ uJy}$ ($\sigma_{\text{rms}} = 2.5 \text{ uJy / beam}$)

$L_{144 \text{ MHz}} = 10^{23.2} \text{ W / Hz}$

(SFR = 5.5 M / yr)



10 arcsec

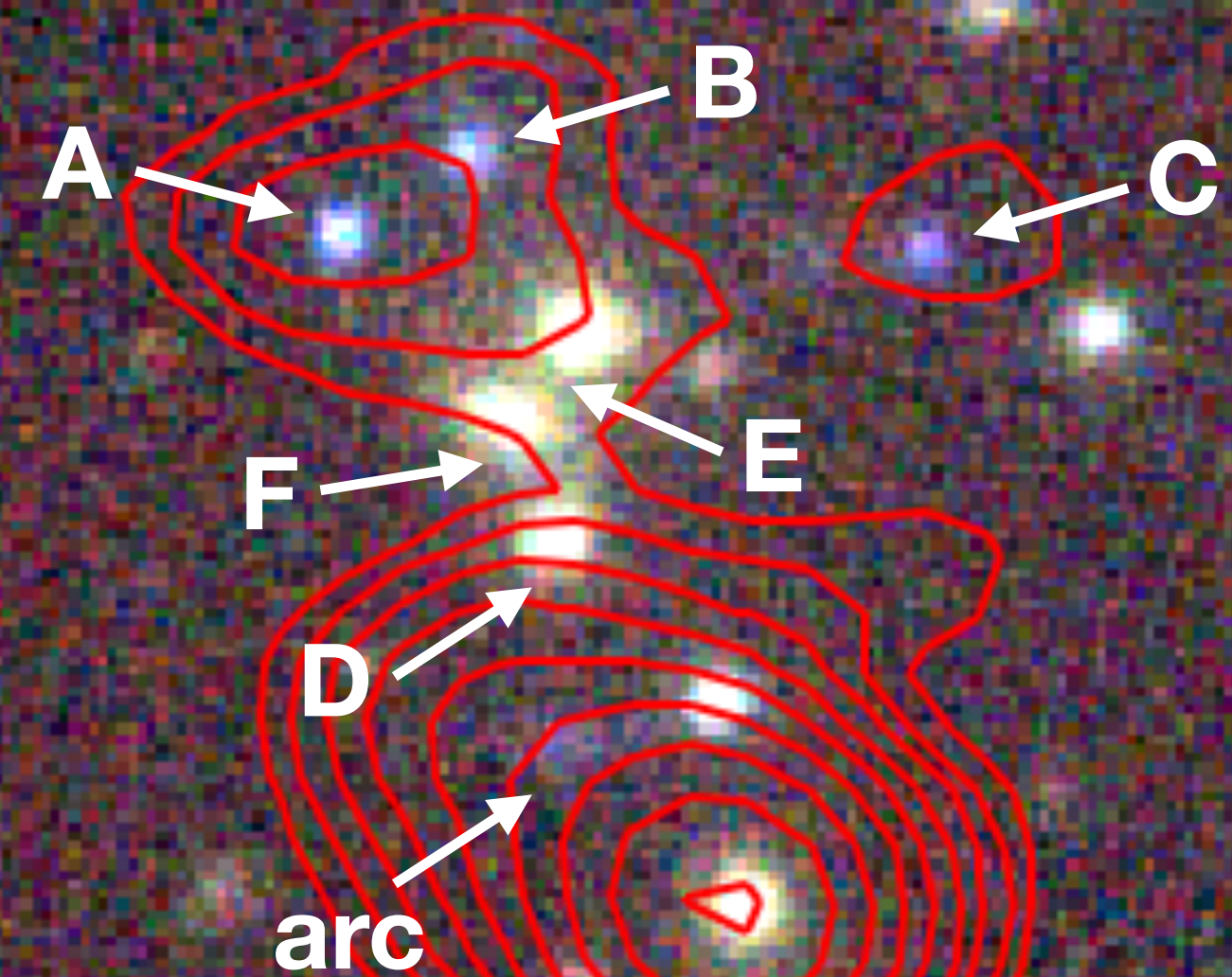
SDSS J2222+2745 ($z = 2.805$)

Total mag = 32

$S_{144 \text{ MHz}} = 58 \text{ uJy}$ ($\sigma_{\text{rms}} = 7 \text{ uJy / beam}$)

$L_{144 \text{ MHz}} = 10^{24.4} \text{ W / Hz}$

(SFR = 73 M / yr)

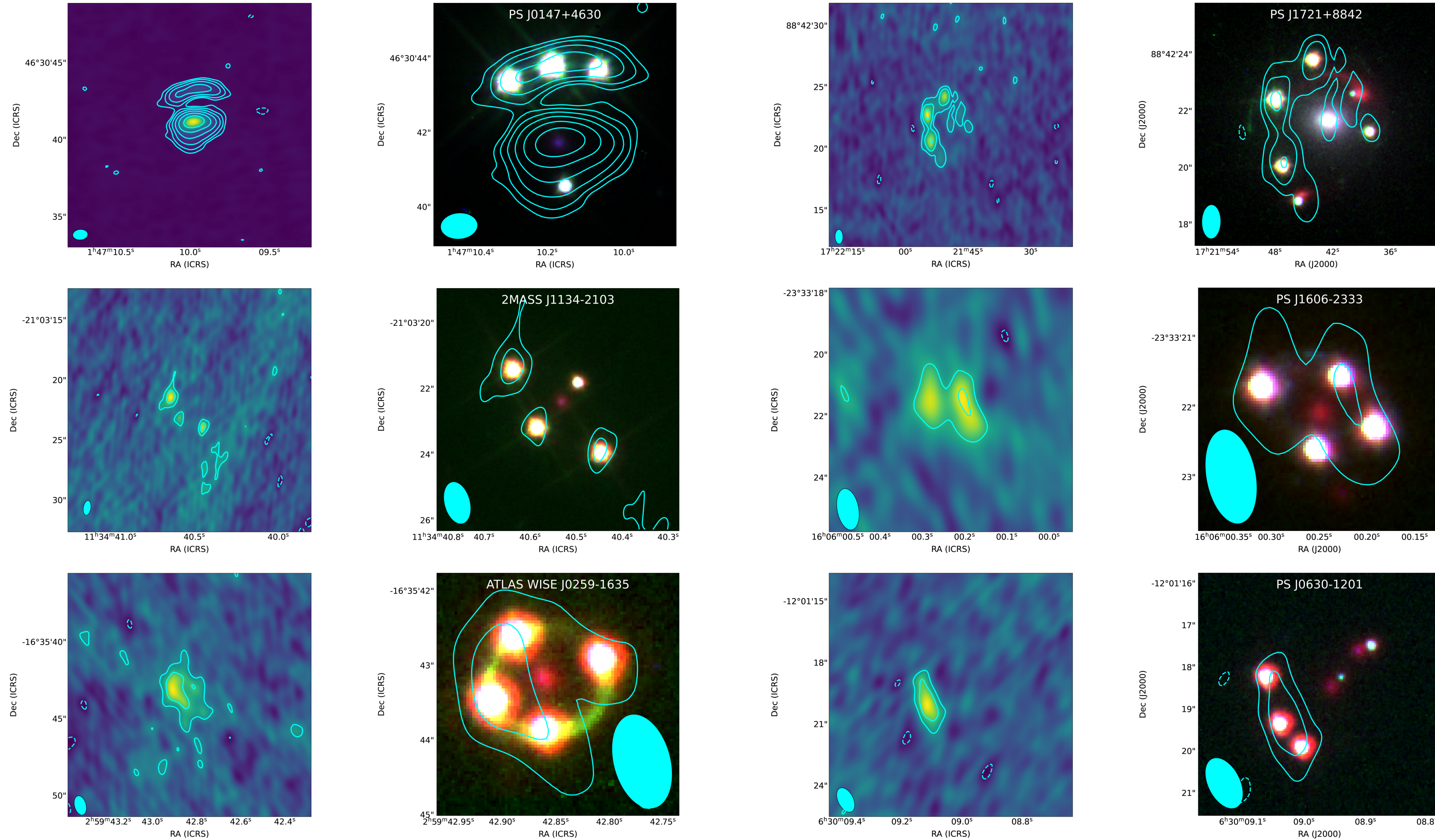


10 arcsec

Radio-loud? 72% of known lensed quasars detected with VLA

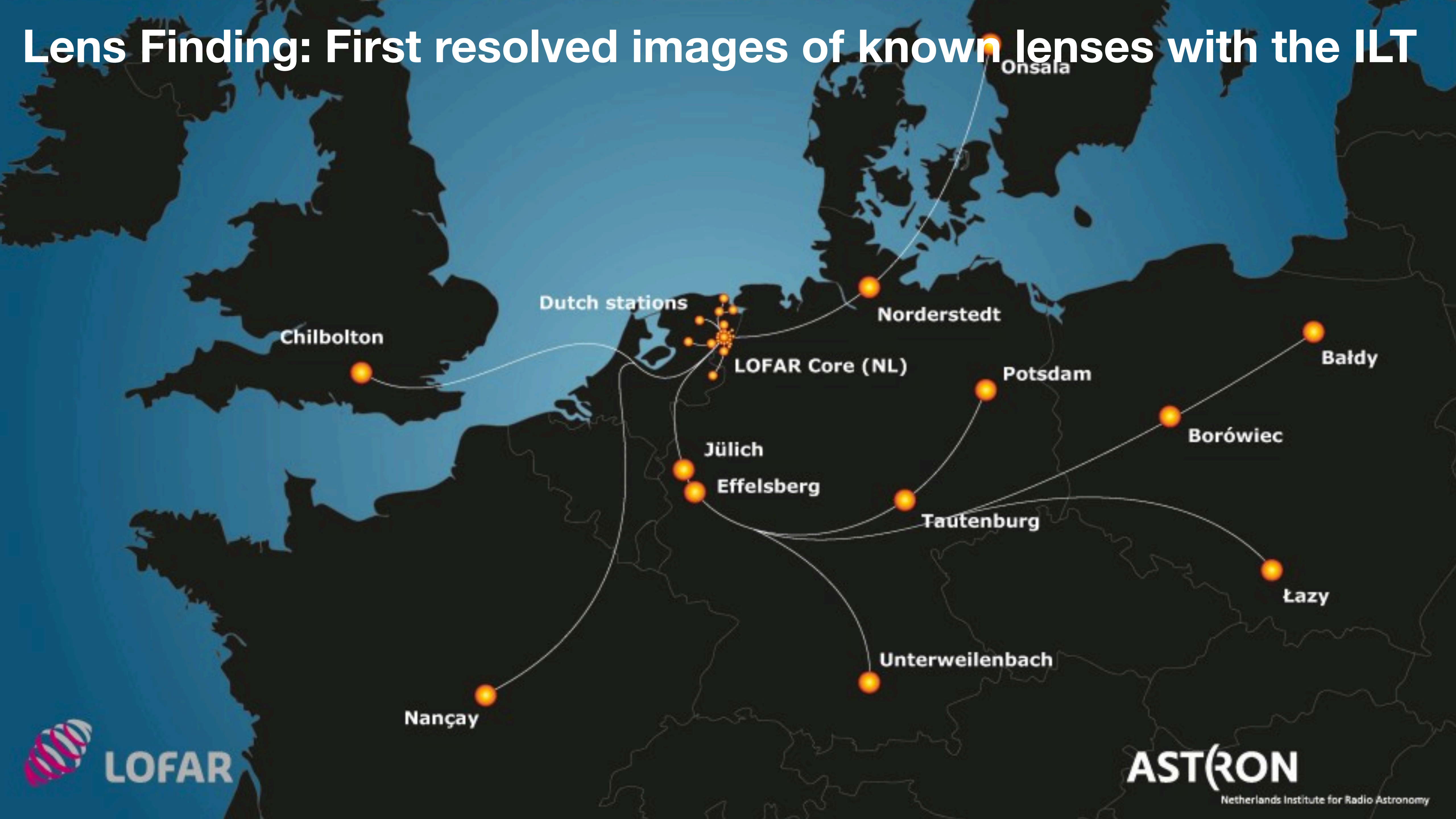
(Brilenkov et al., in prep.)

(Mangat et al., 2021)

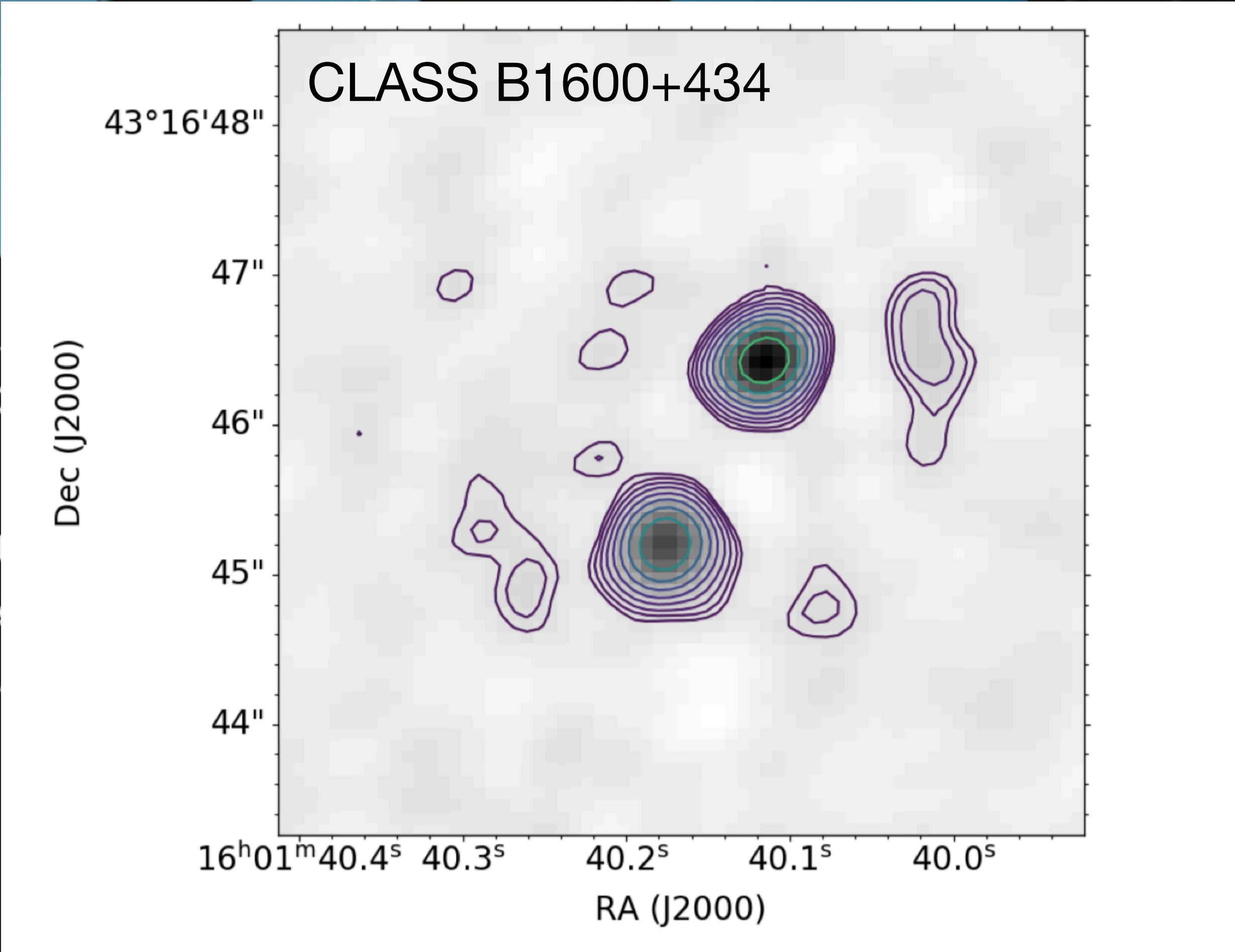
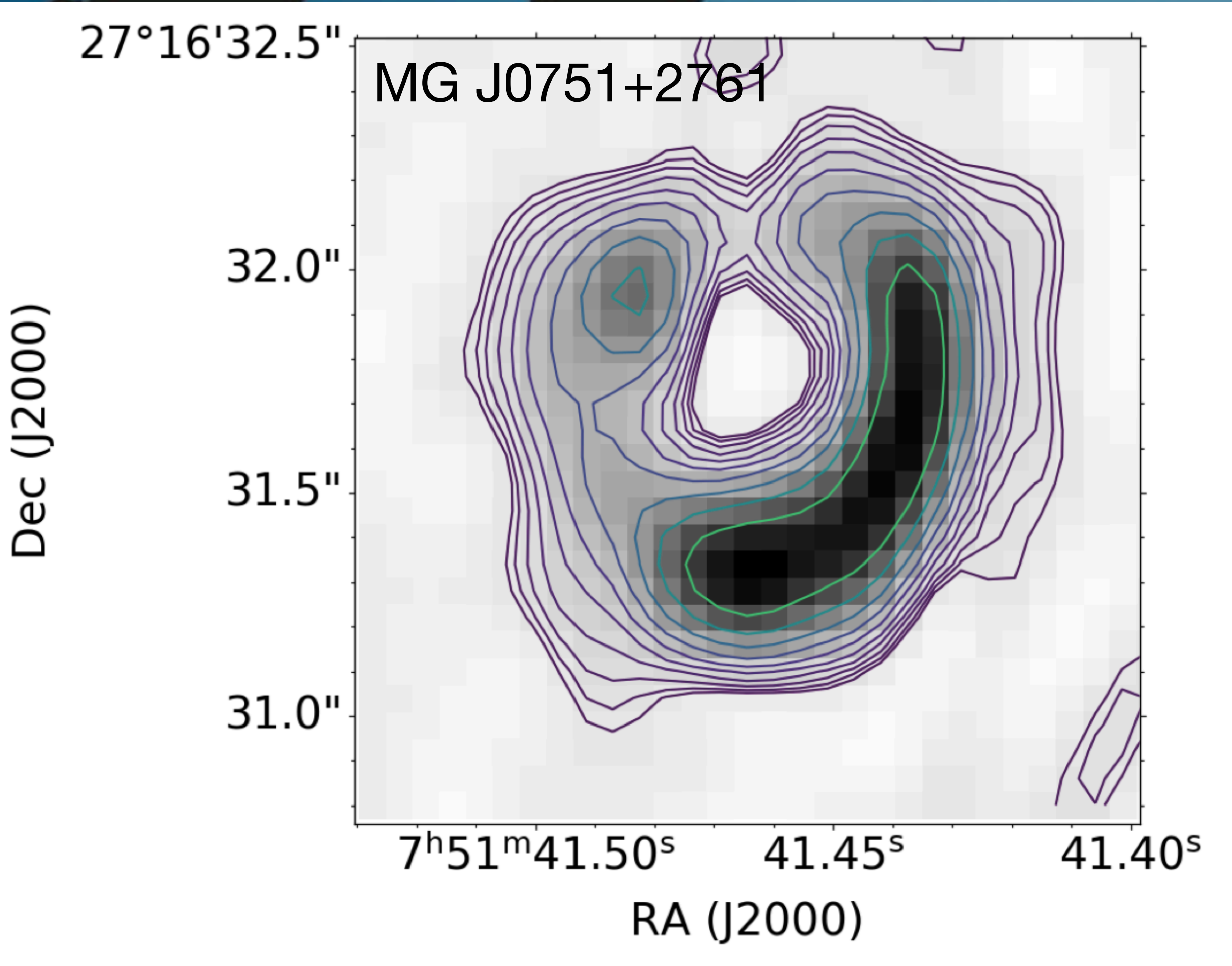


- VLA (3 GHz; ~6 min) snapshot imaging of optically-bright lensed quasars (e.g. DES; c.f. *Euclid*).
- HSA (1.7 GHz; 60 h) imaging of 5 targets and EVN (1.7 GHz; 88 h) imaging of 5 targets.

Lens Finding: First resolved images of known lenses with the ILT



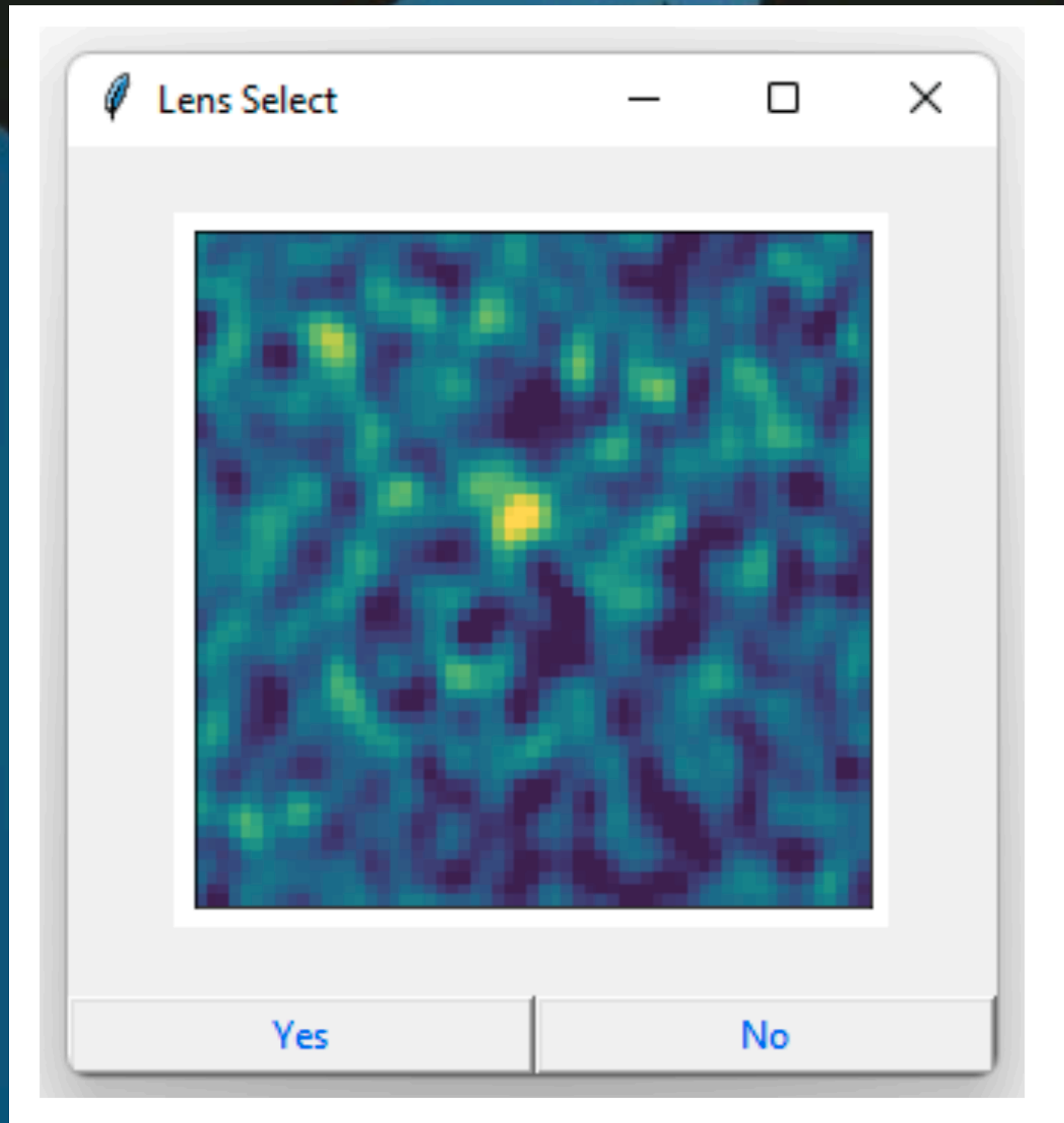
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(Badole et al., 2022)

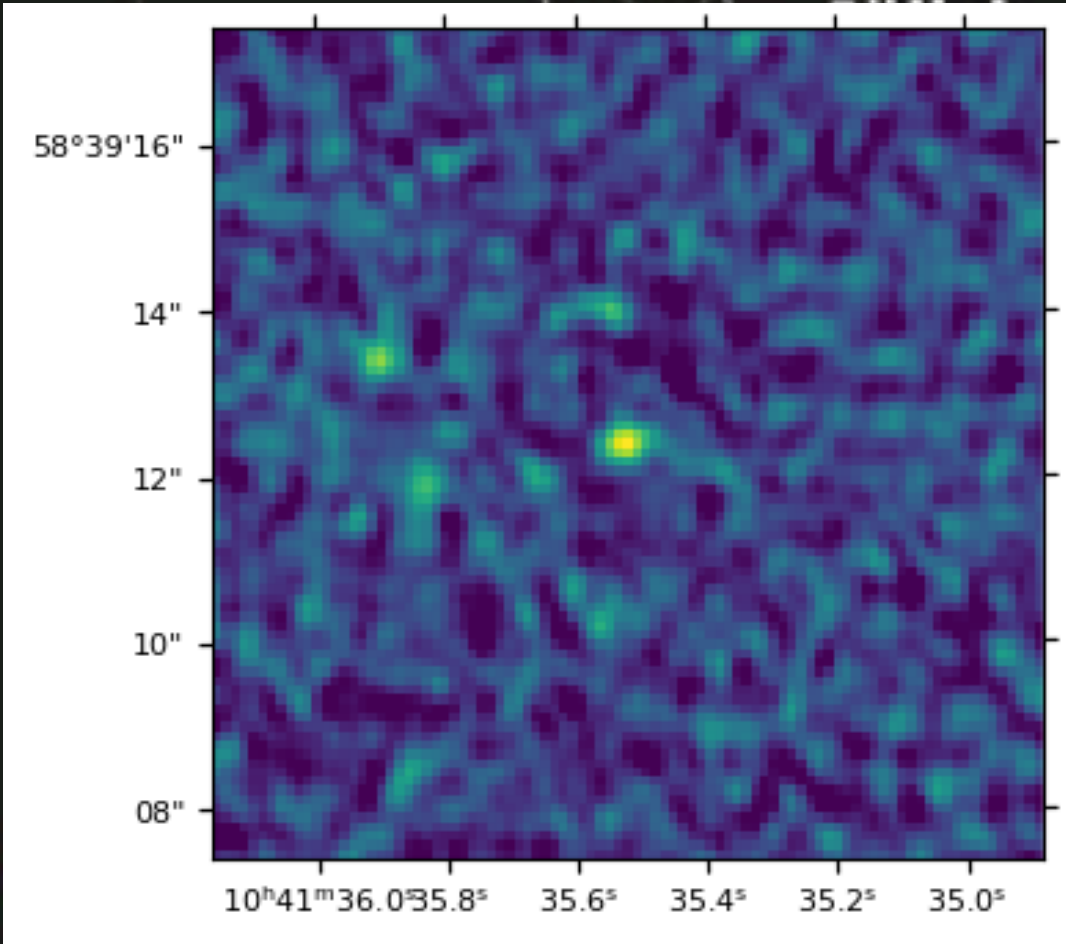
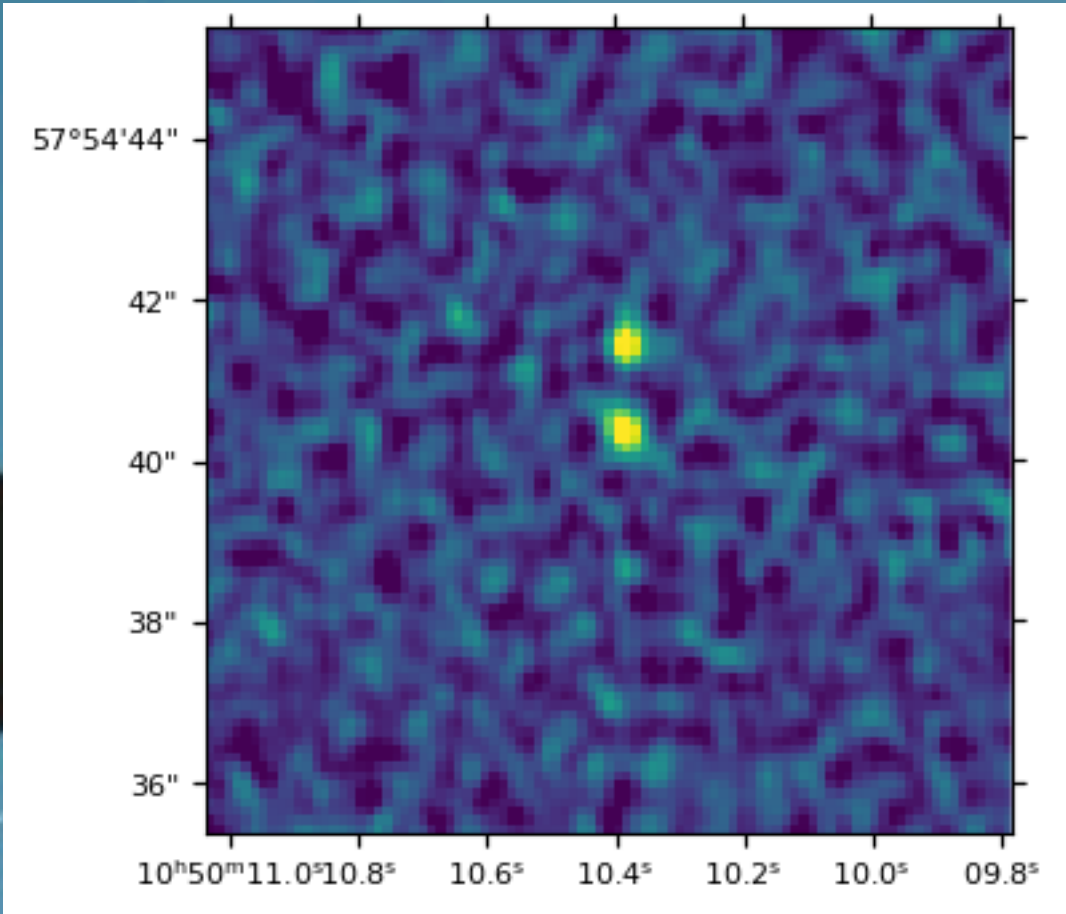
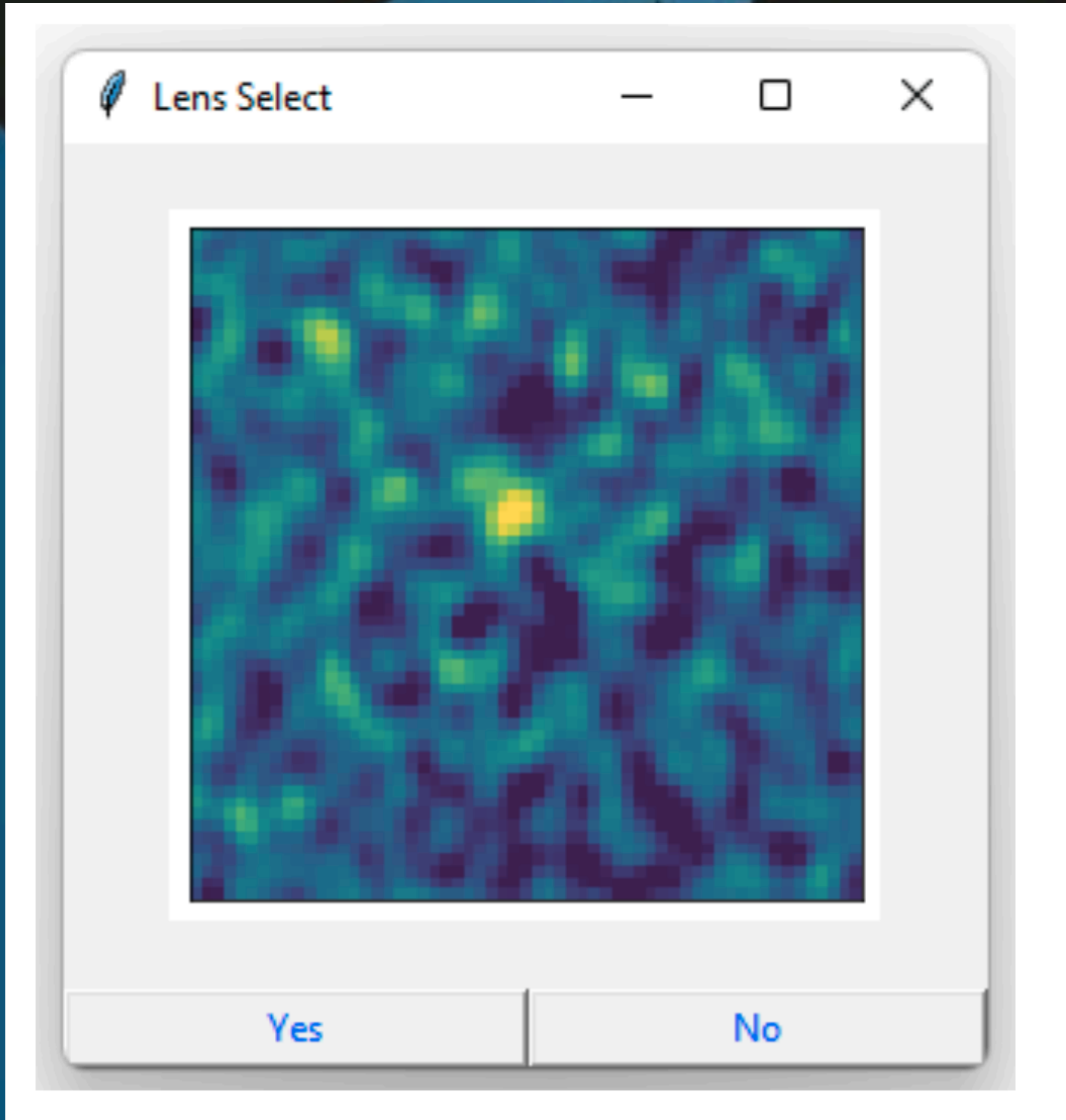
Lens Finding: The first gravitational lens candidates

(Bethlehem et al., in prep)



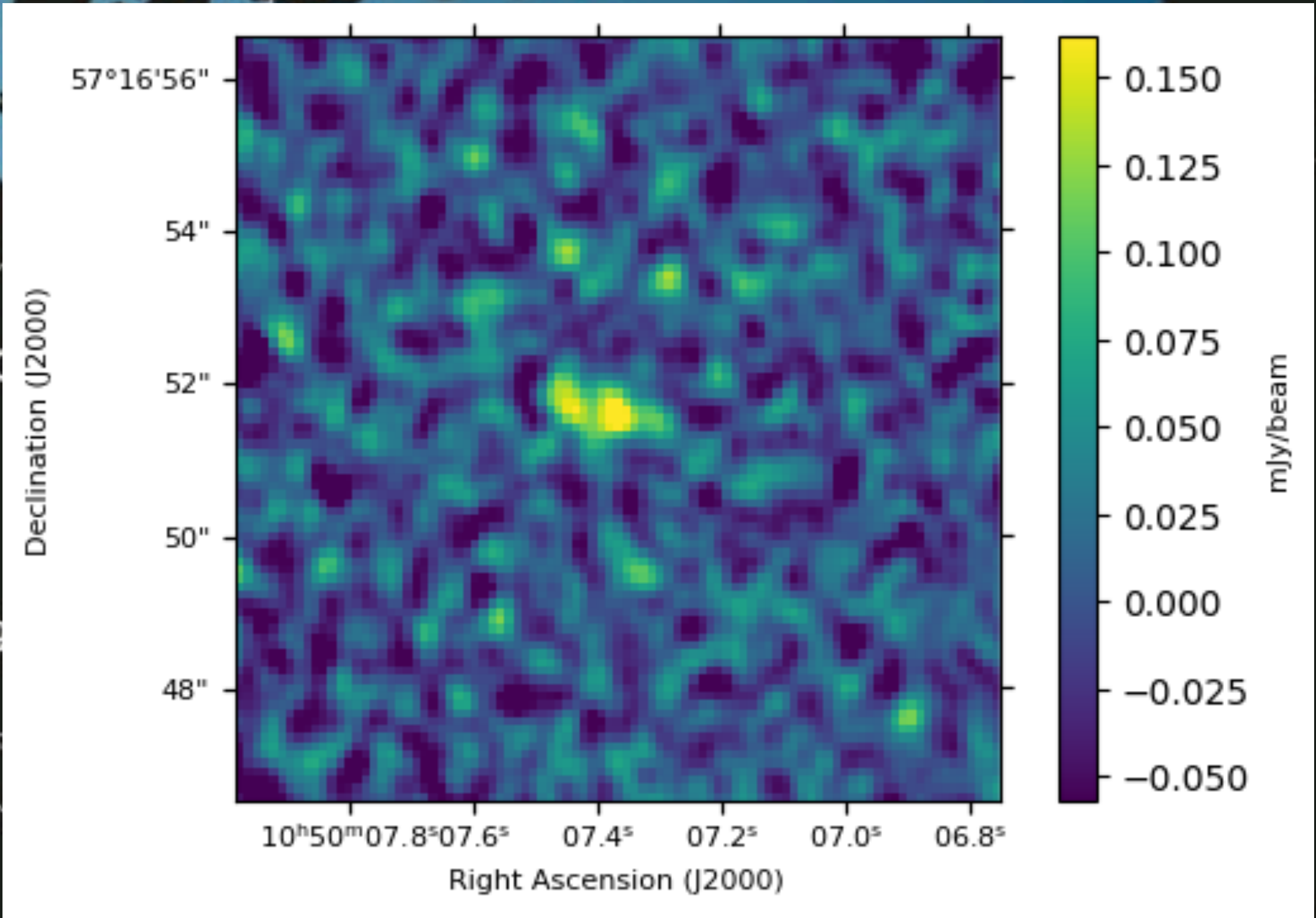
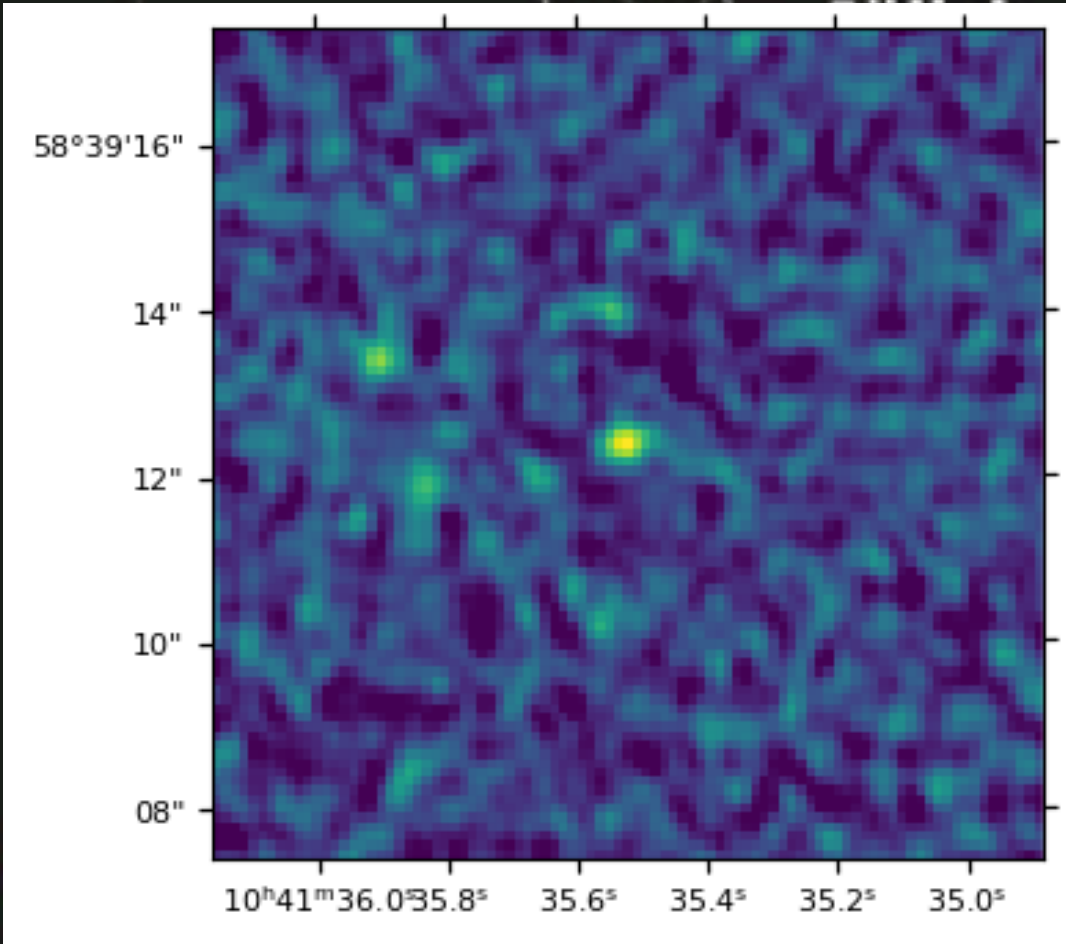
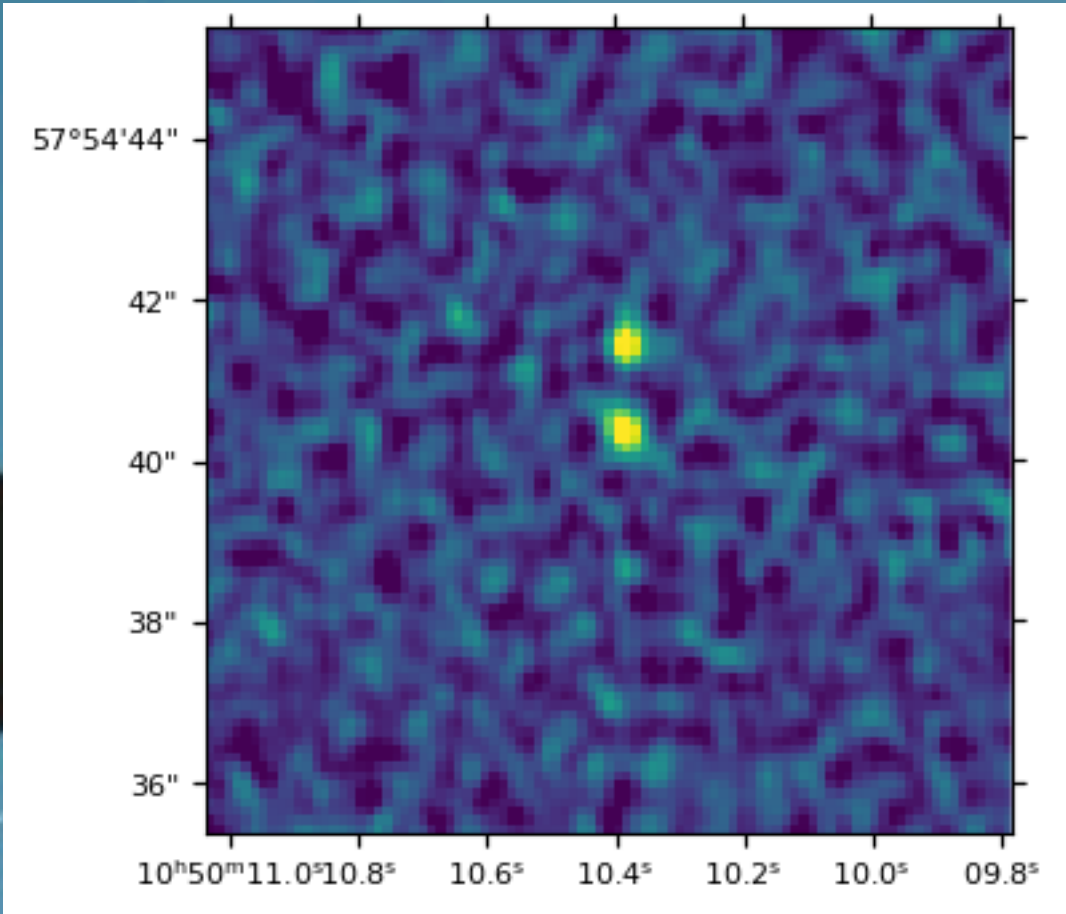
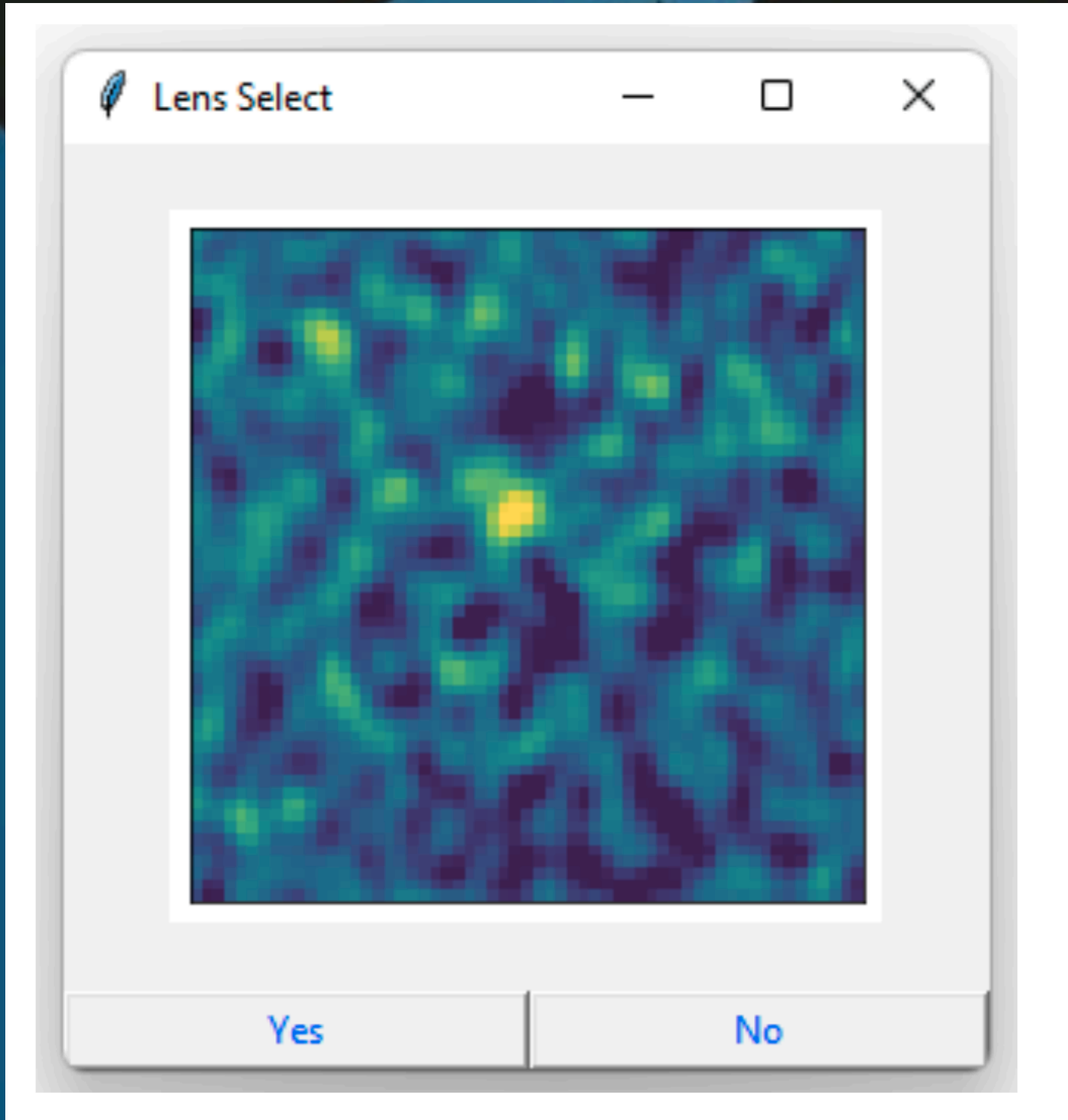
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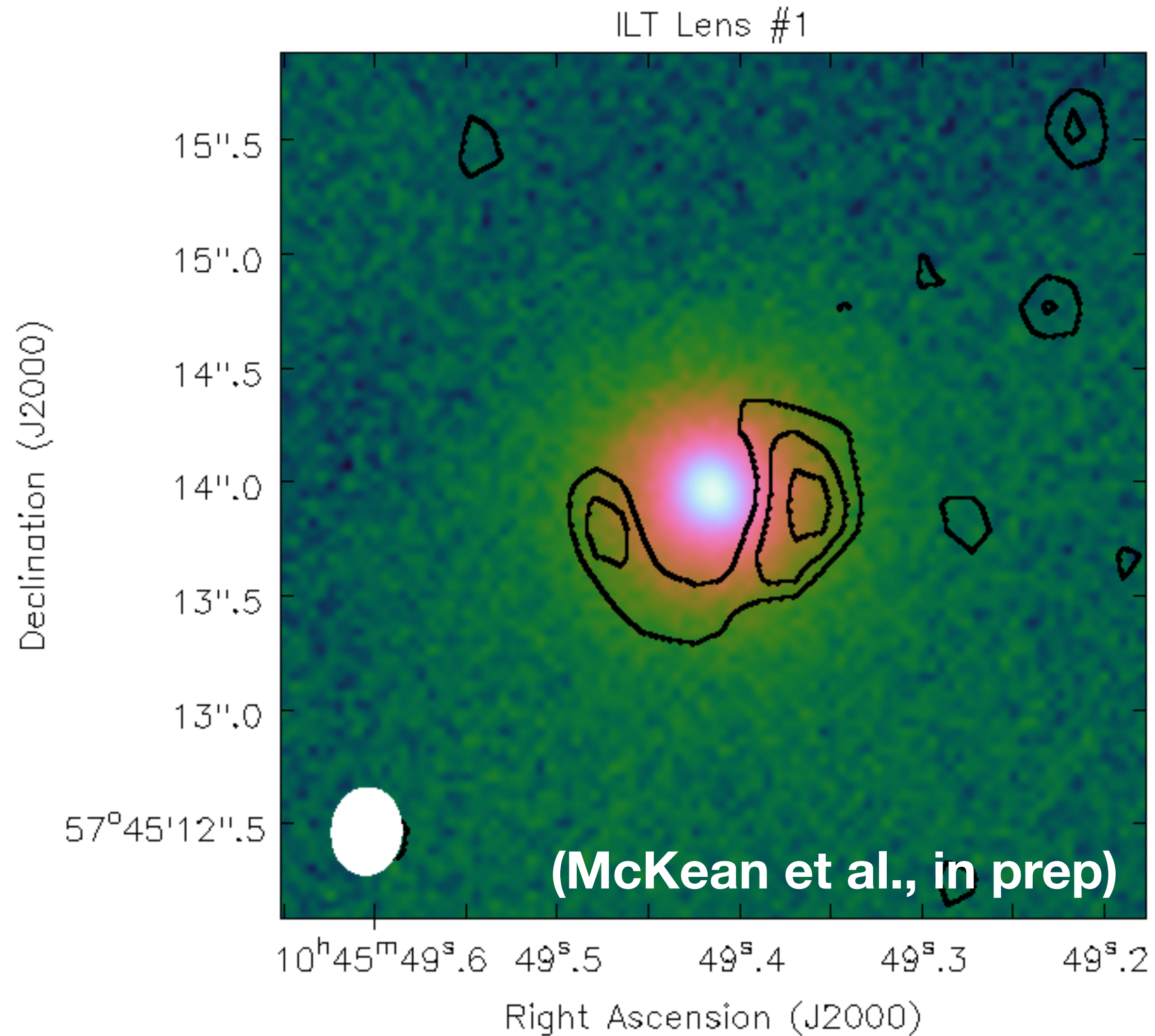


Lens Finding: The first gravitational lens candidates

(Bethlehem et al., in prep)

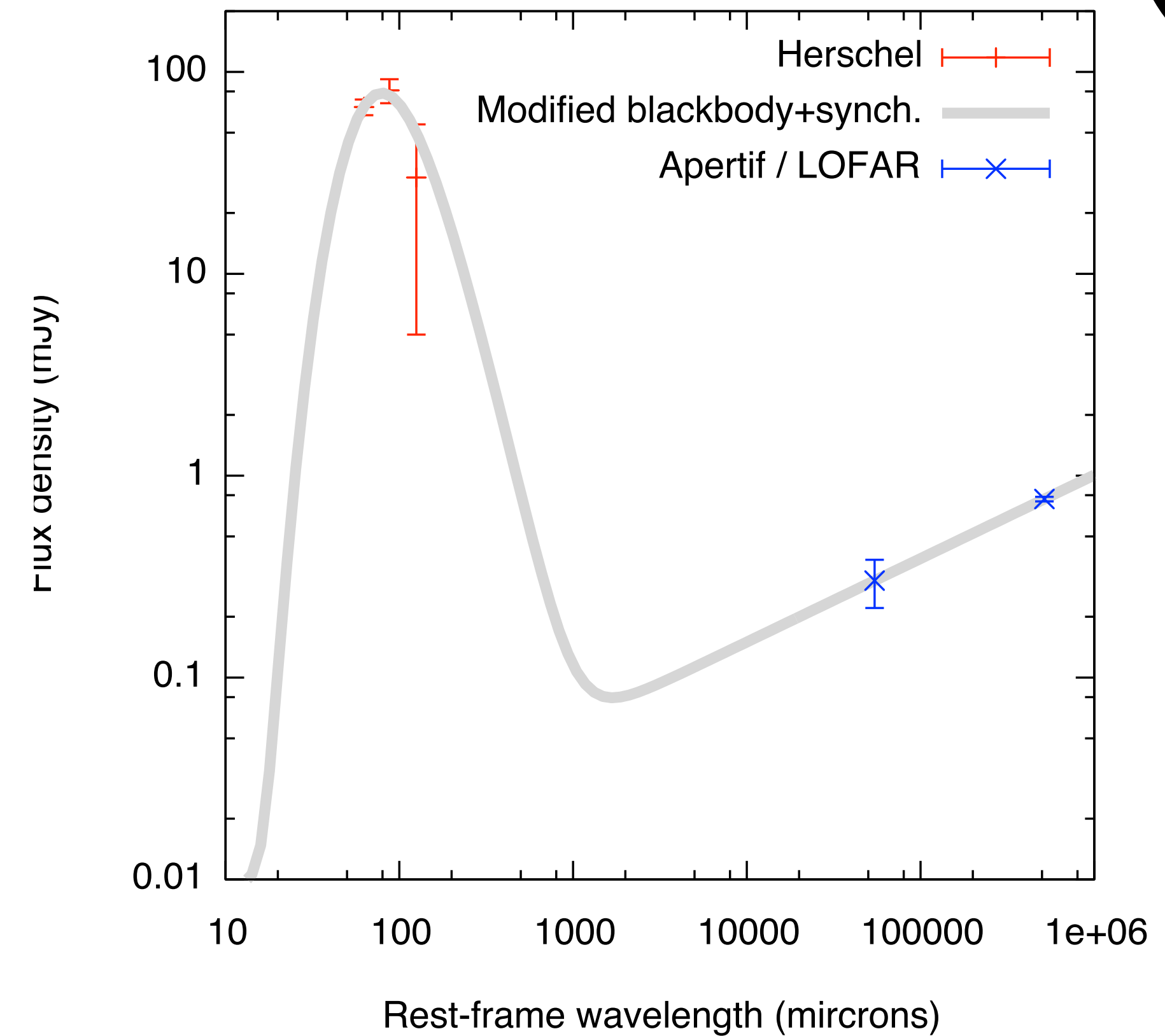


Lens Finding: The best gravitational lens candidate



$z_{l, \text{photo}} \sim 0.3$

$z_{s, \text{spec}} \sim 2.991?$ (CO line reported in the field)



$S_{144 \text{ MHz}} = 39 \text{ uJy}$ ($\sigma_{\text{rms}} = 1.3 \text{ uJy / beam}$)

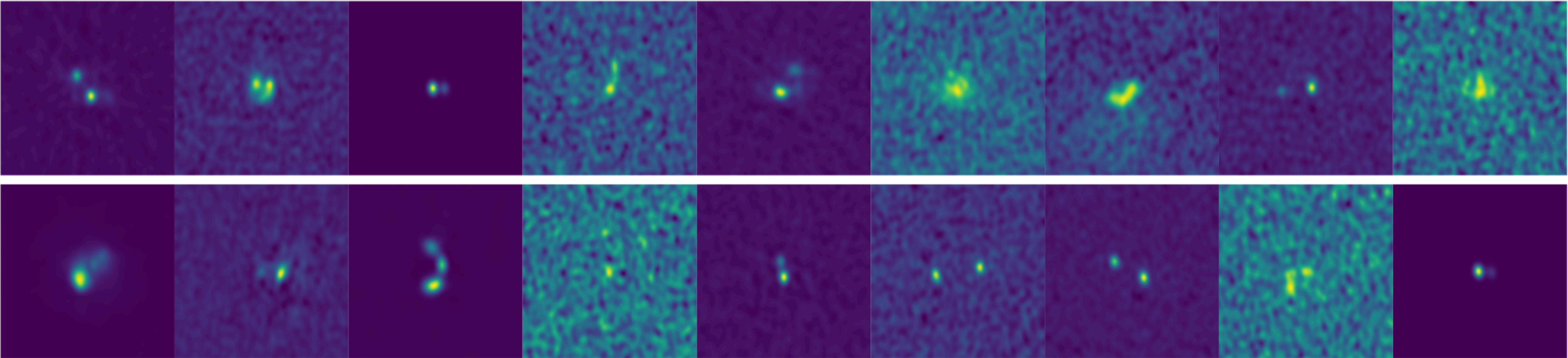
$L_{144 \text{ MHz}} = 10^{24.05} \text{ W / Hz}$

$L_{8-1000 \text{ } \mu\text{m}} = 10^{12.4} L_{\text{sol}}$

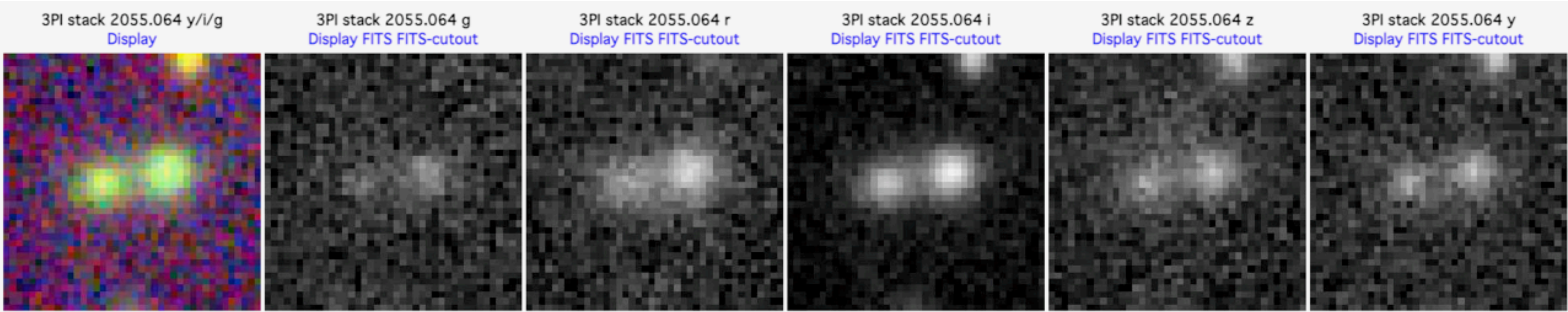
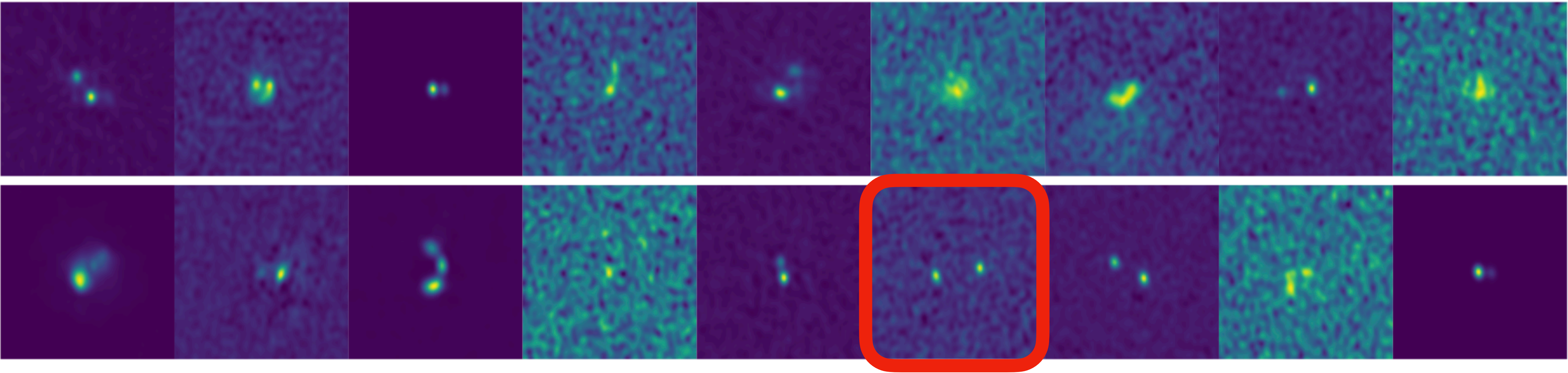
$\text{SFR} = 470 M_{\text{sol}} / \text{yr}$

$q_{144 \text{ MHz}} = 2.37$ (IR excess)

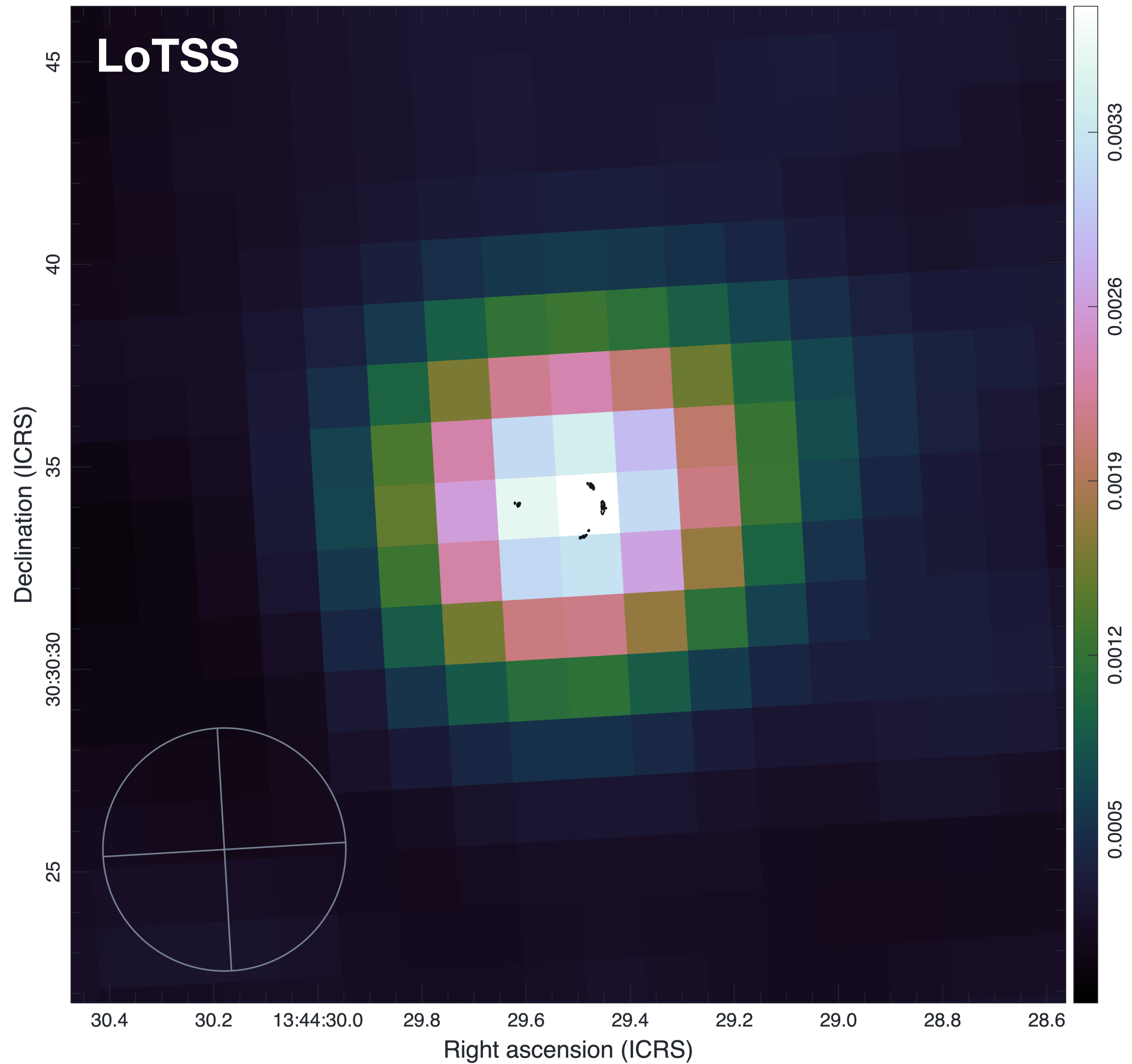
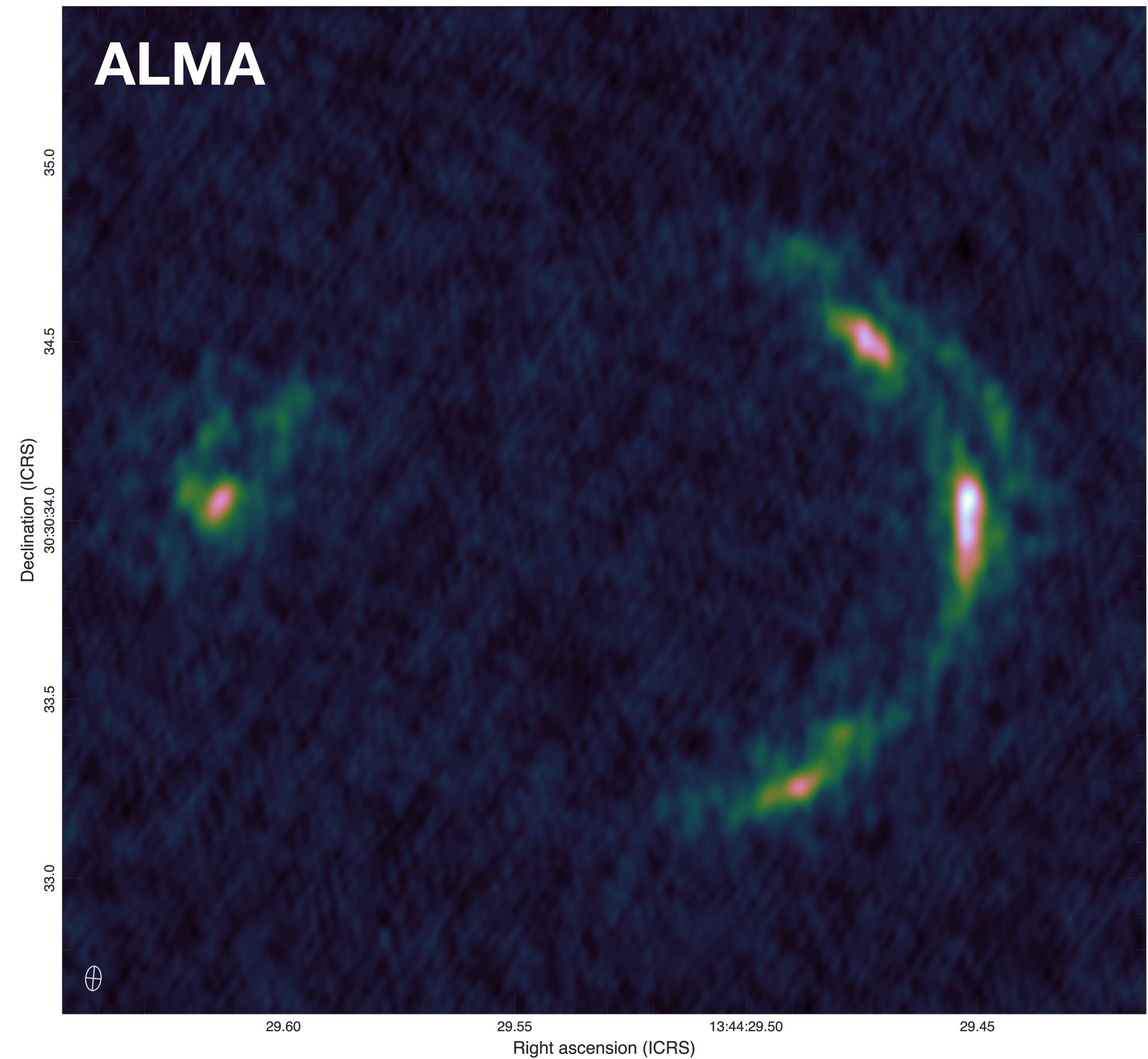
Lens Finding: Trawling the Deep Fields



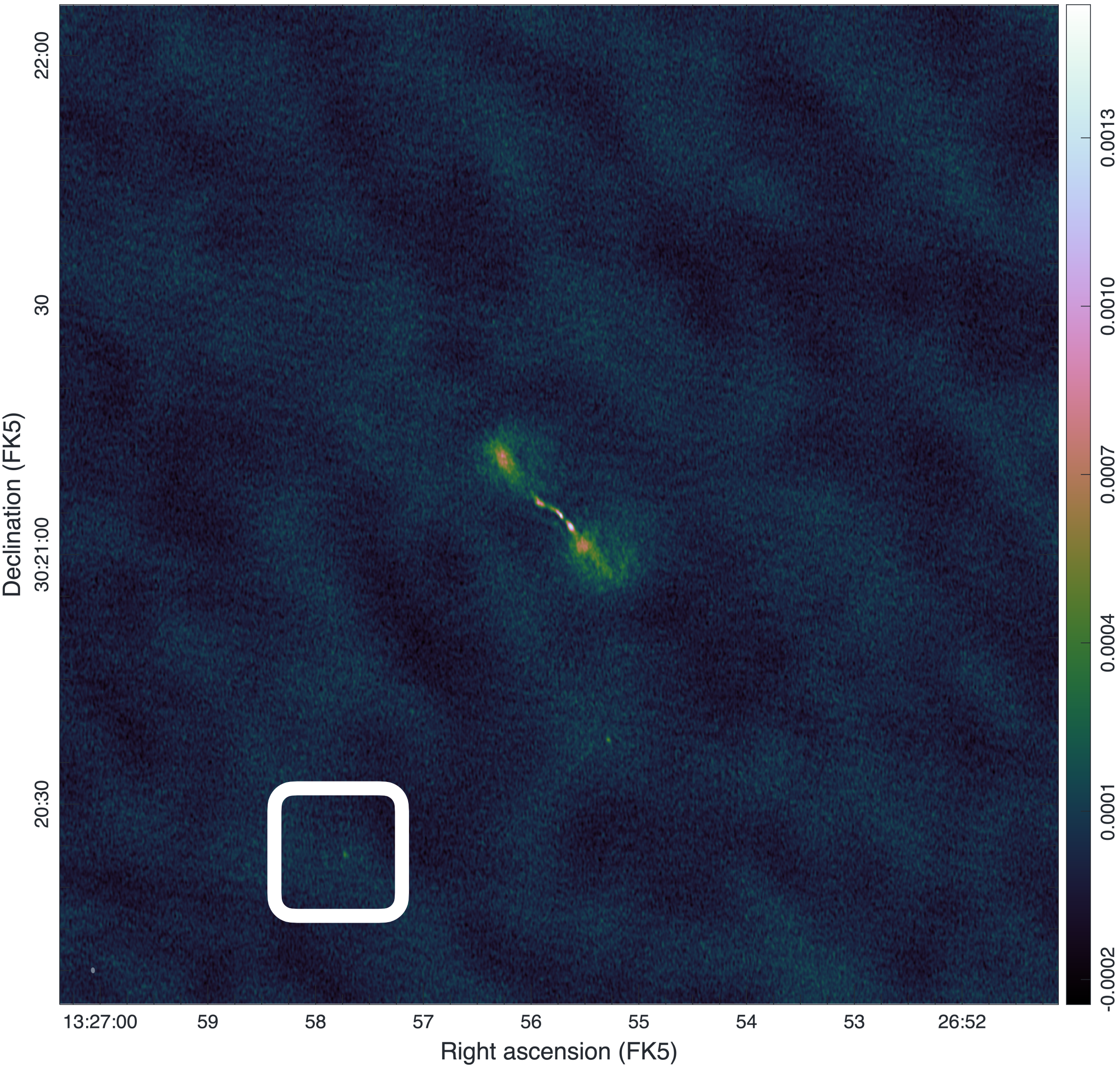
Lens Finding: Trawling the Deep Fields



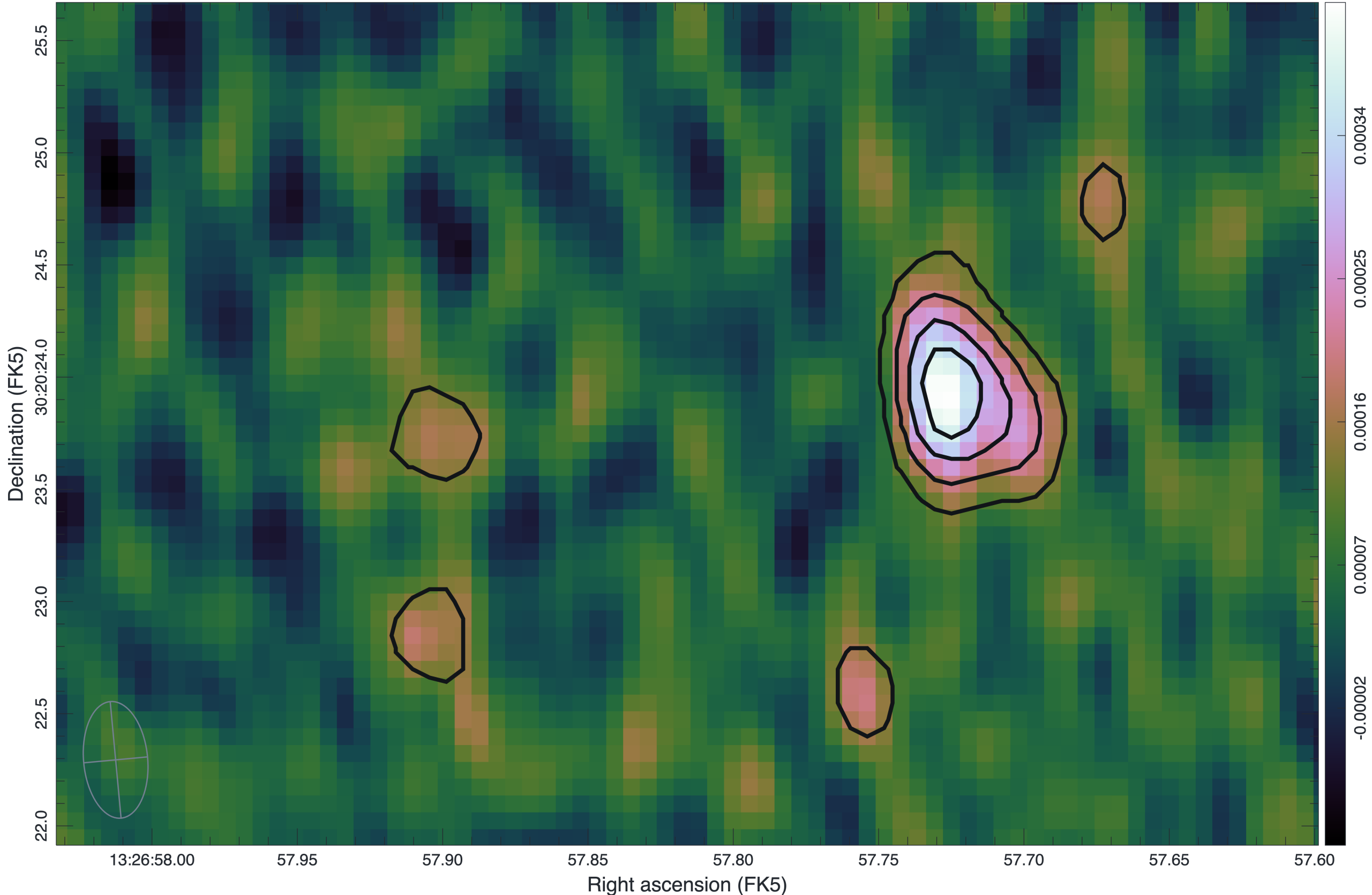
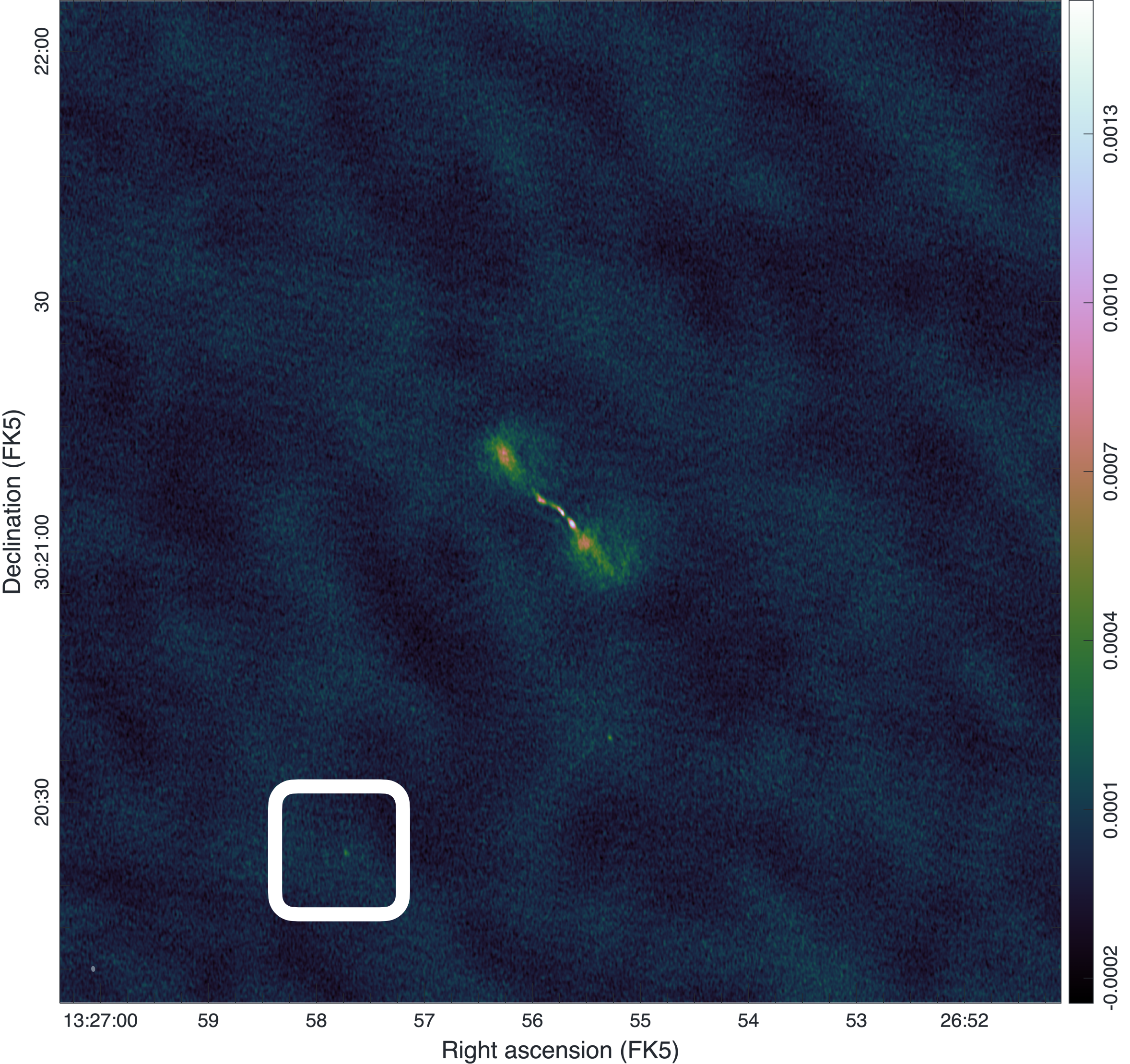
Lens Finding: Trawling LoTSS HR DR1



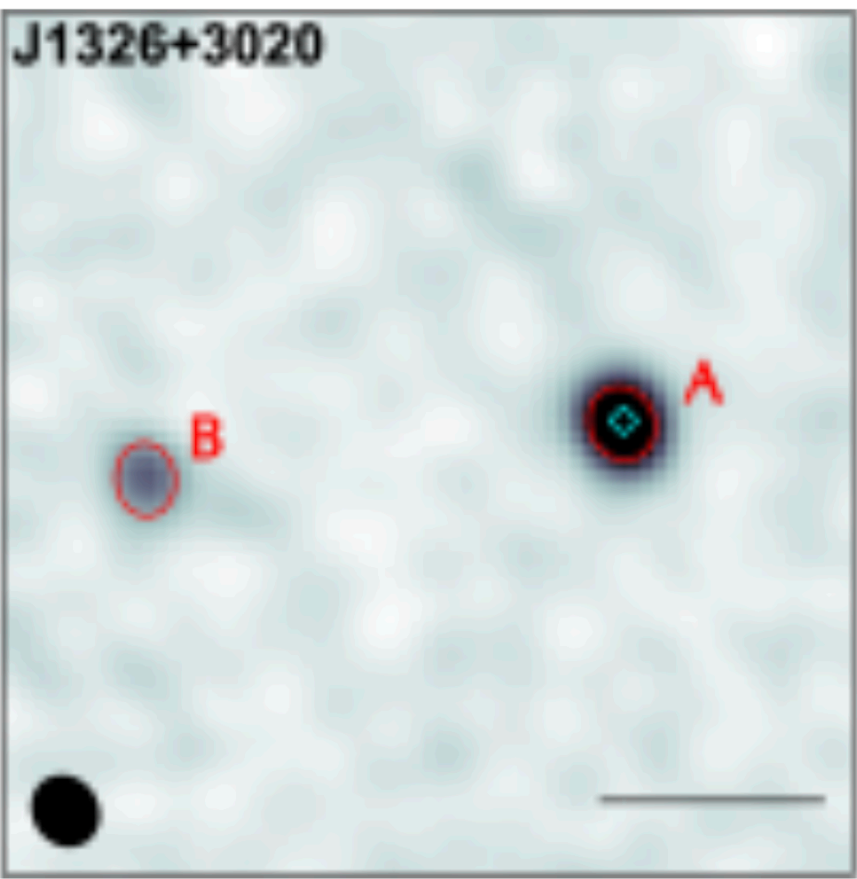
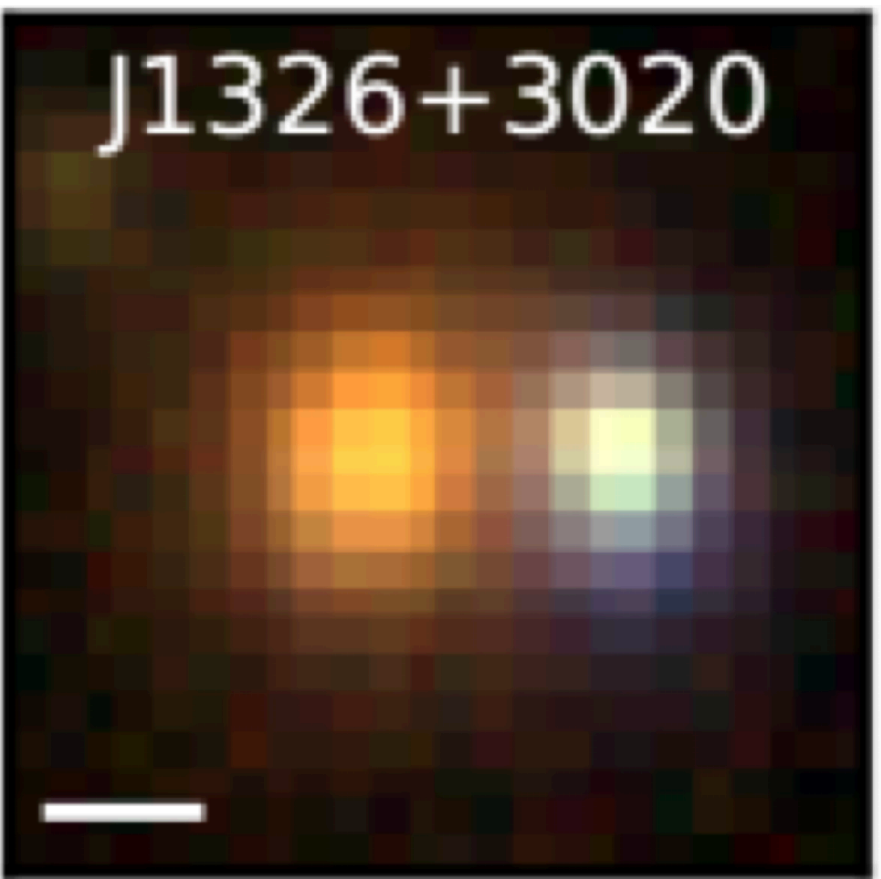
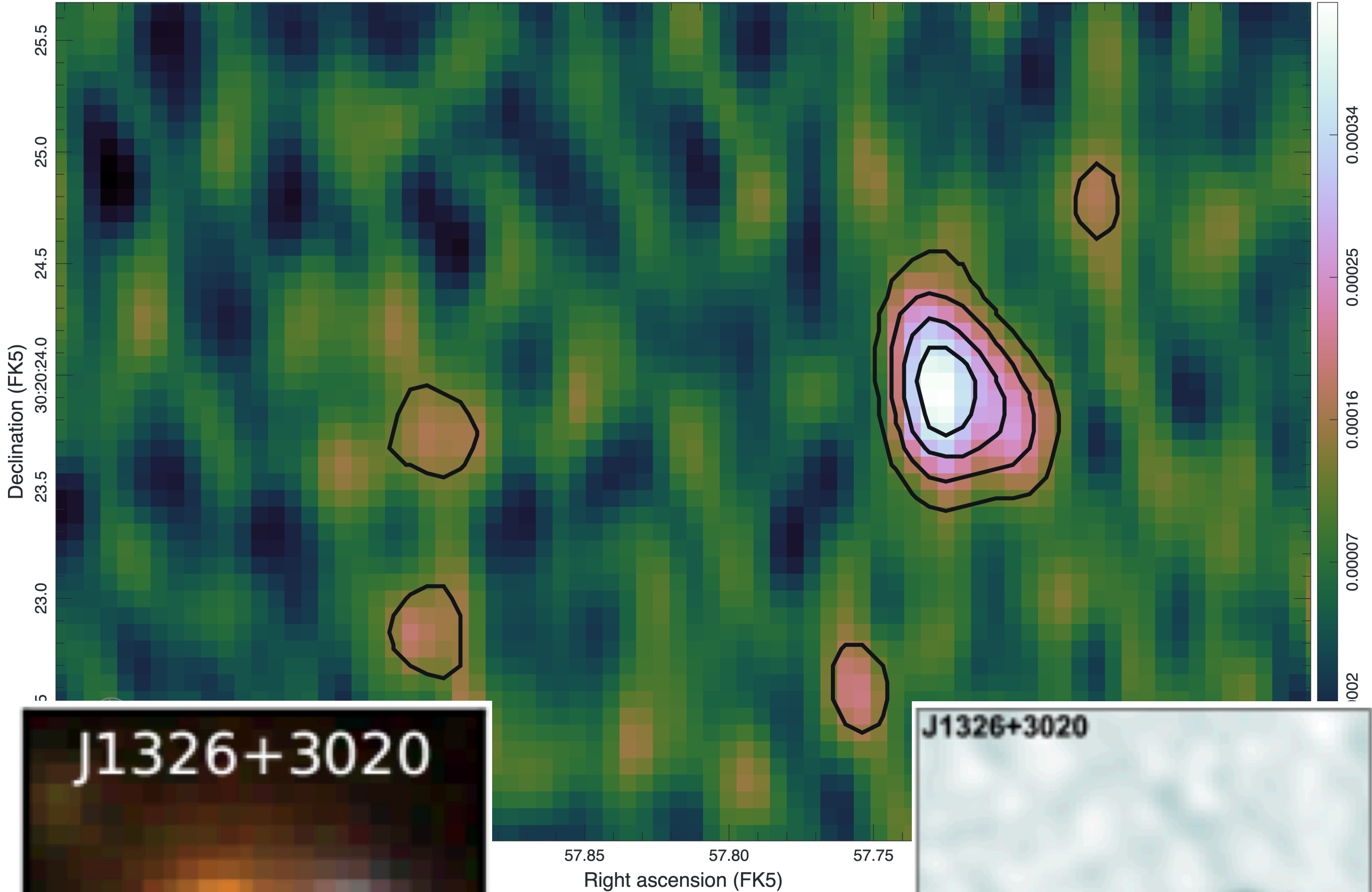
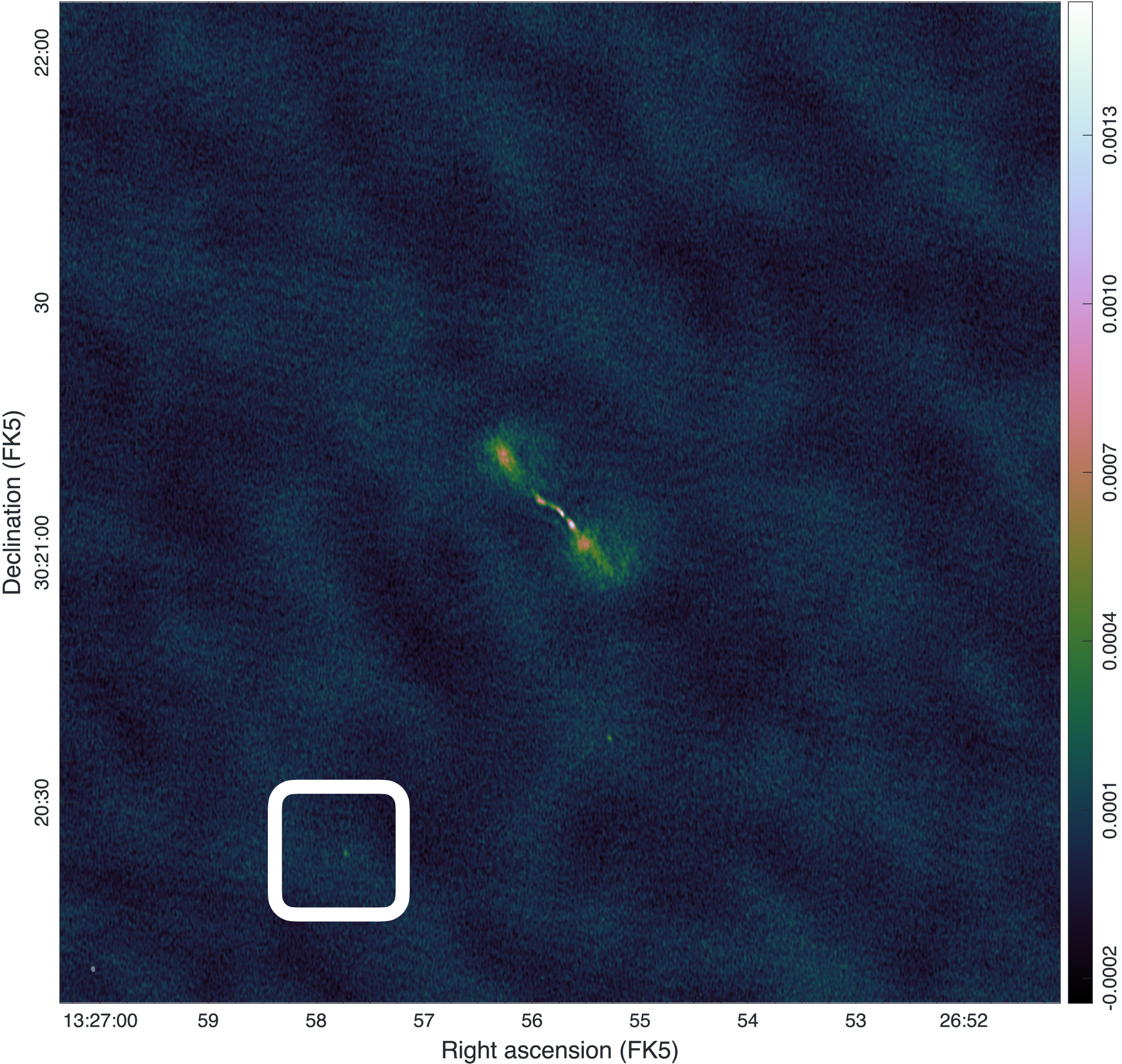
Lens Finding: Trawling LoTSS HR DR1

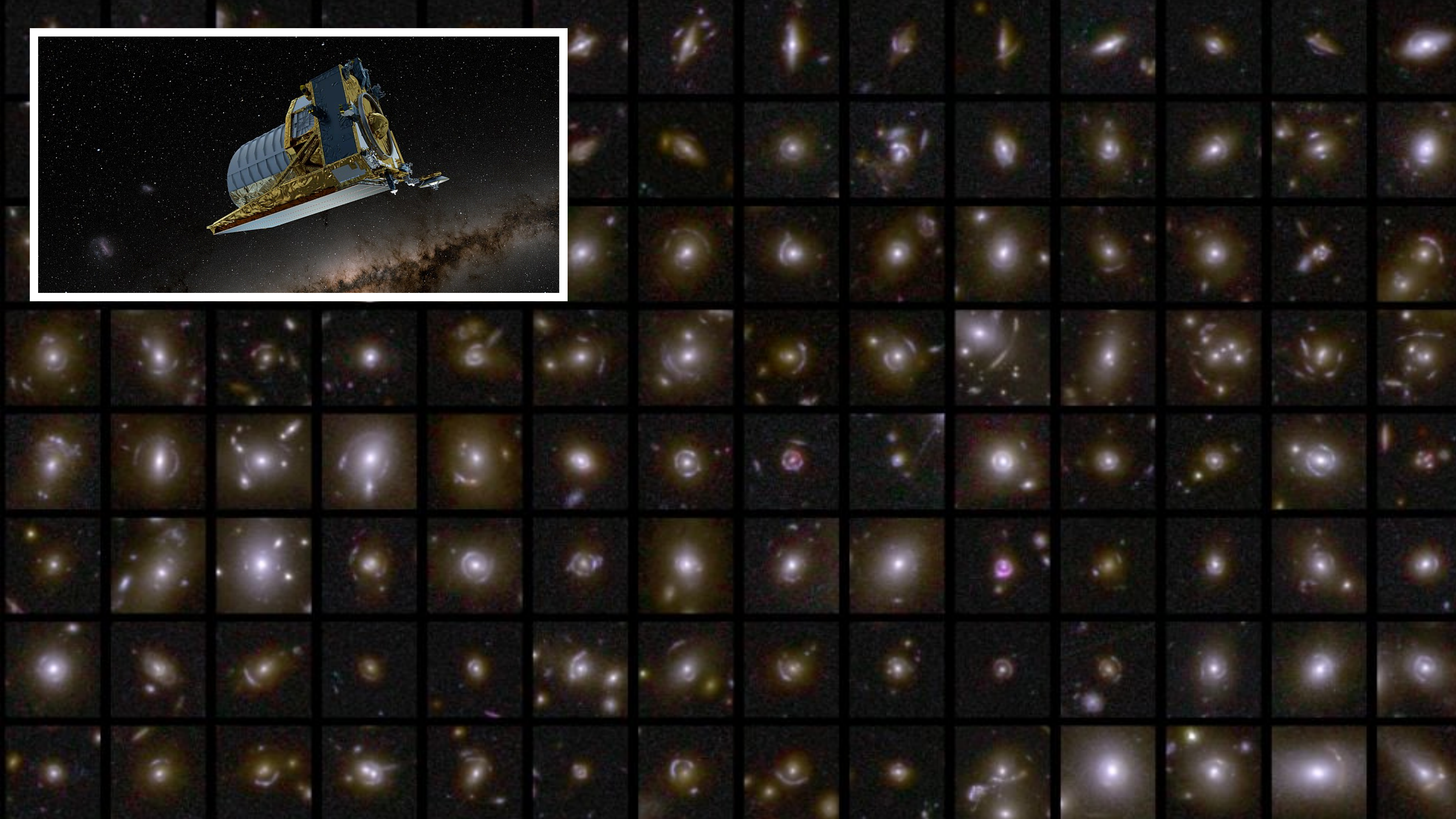
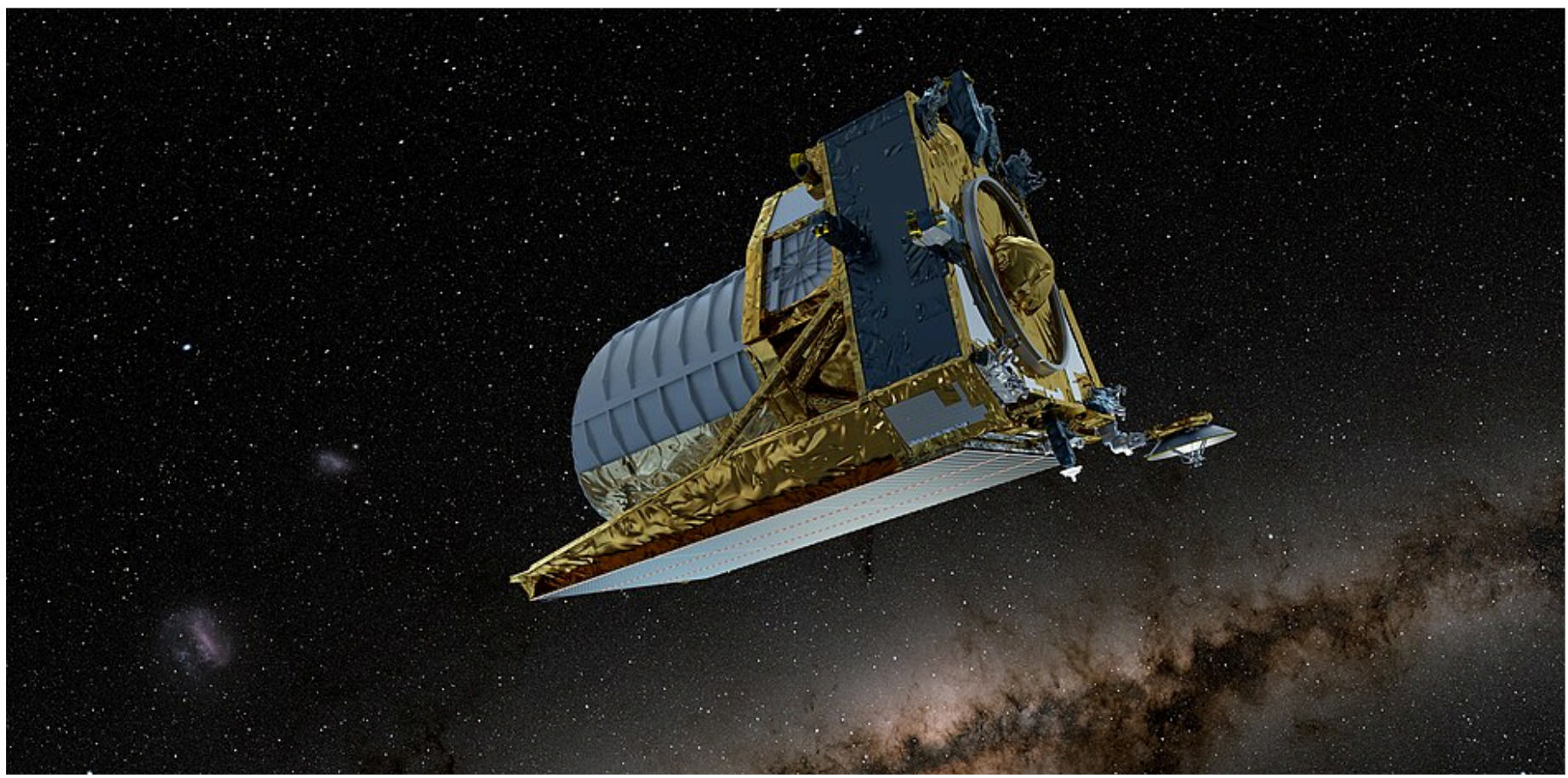


Lens Finding: Trawling LoTSS HR DR1

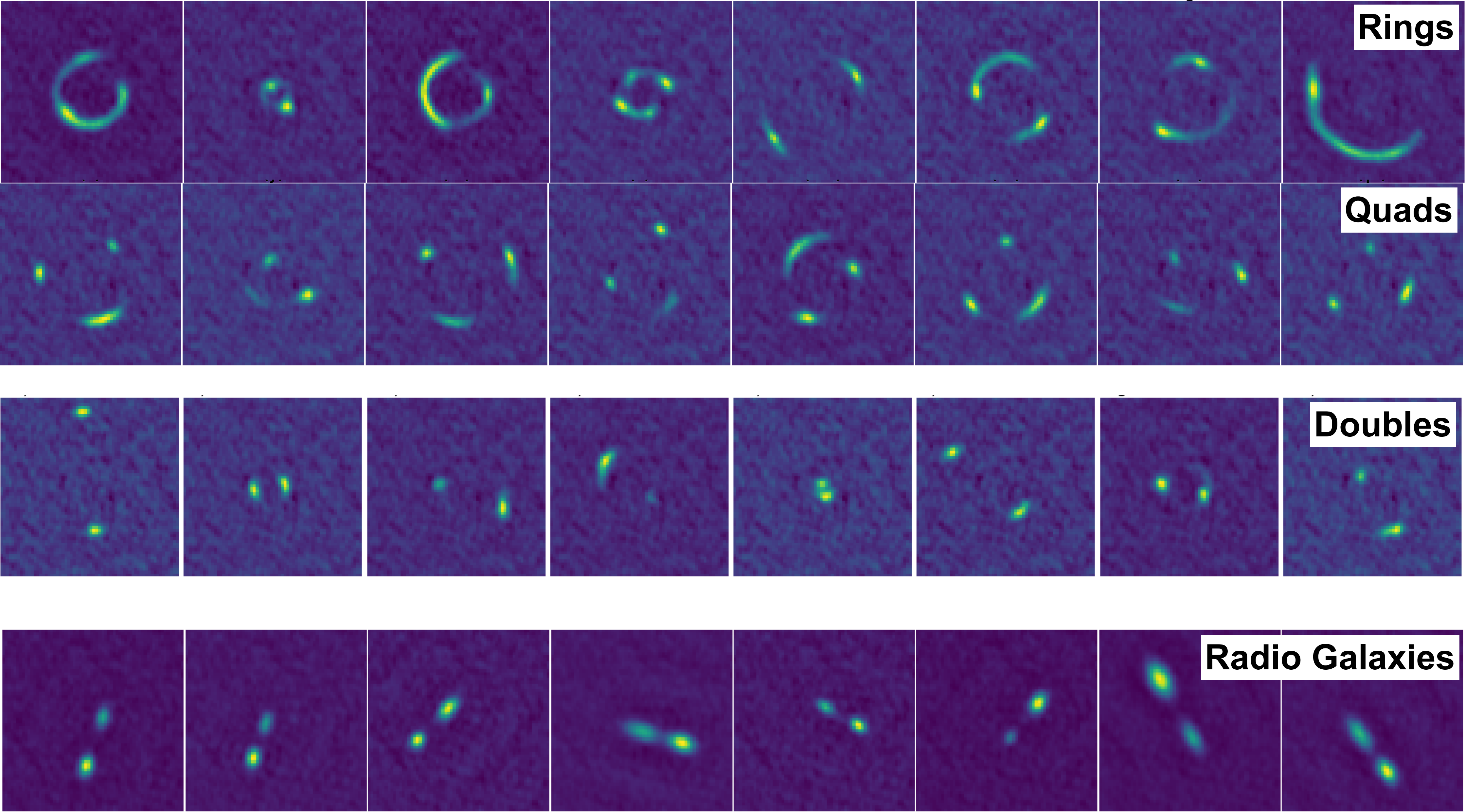


Lens Finding: Trawling LoTSS HR DR1





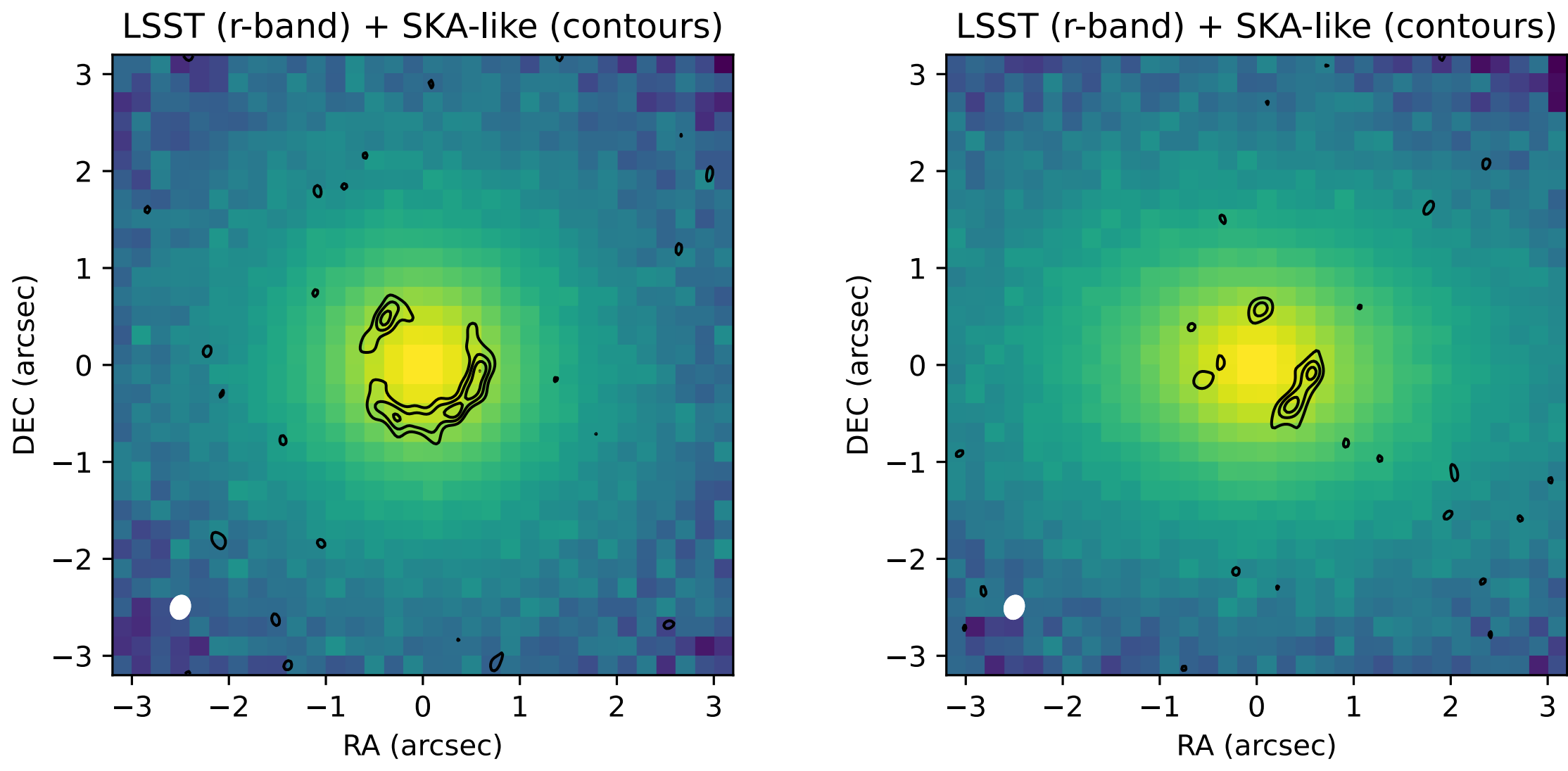
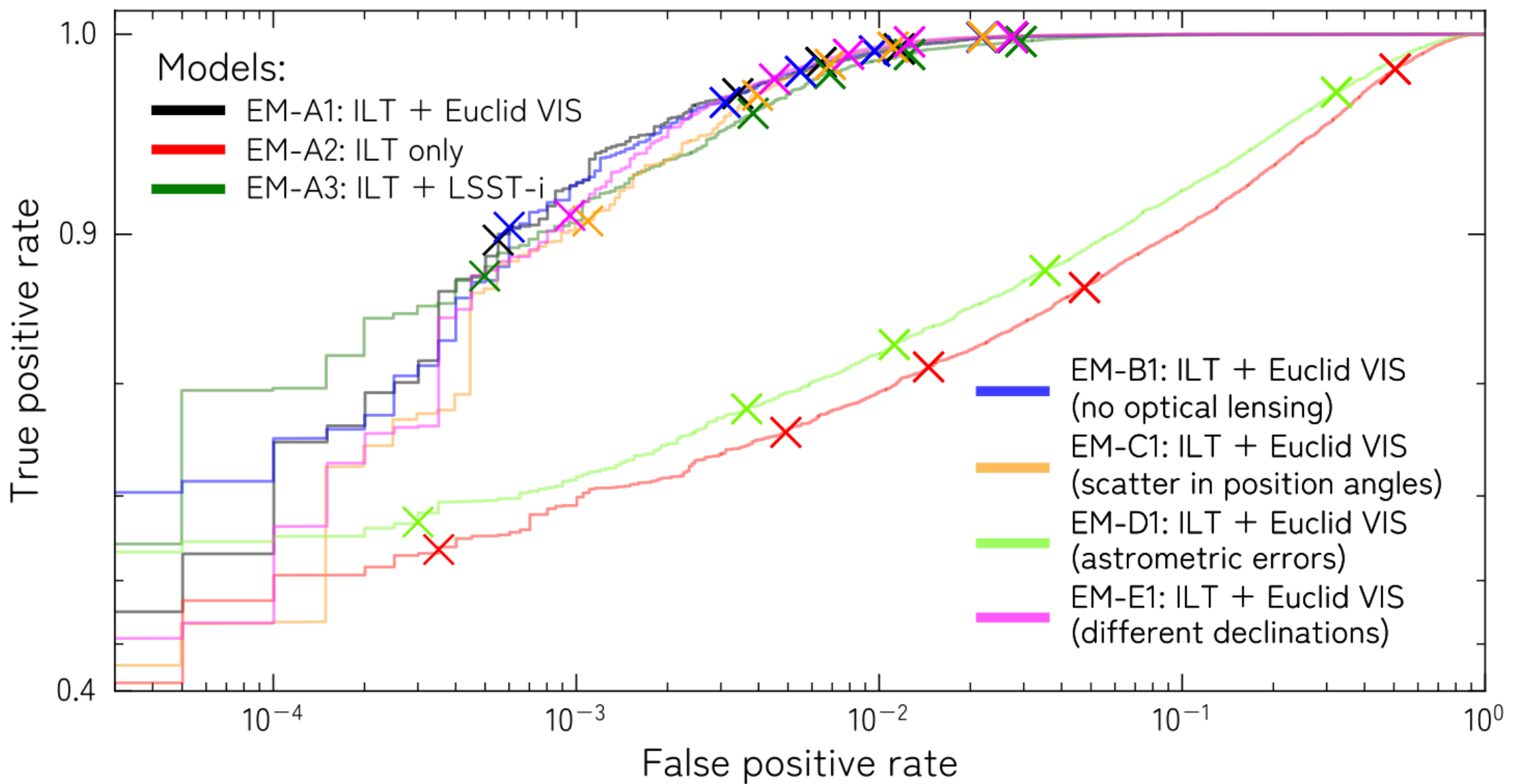
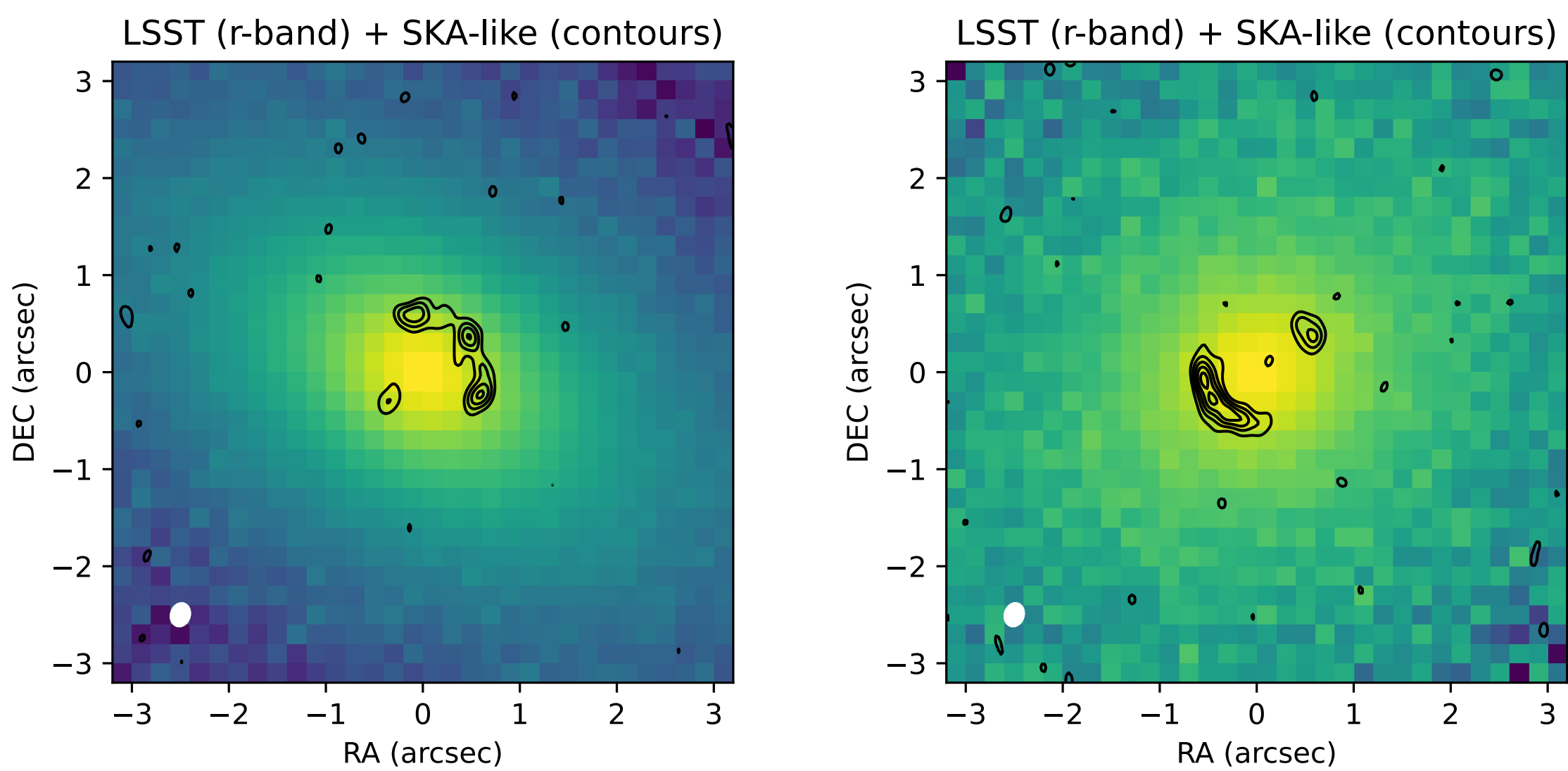
Realistic simulations / mock data (visibilities to images)



Combining Machine Learning with the LOFAR—LSST

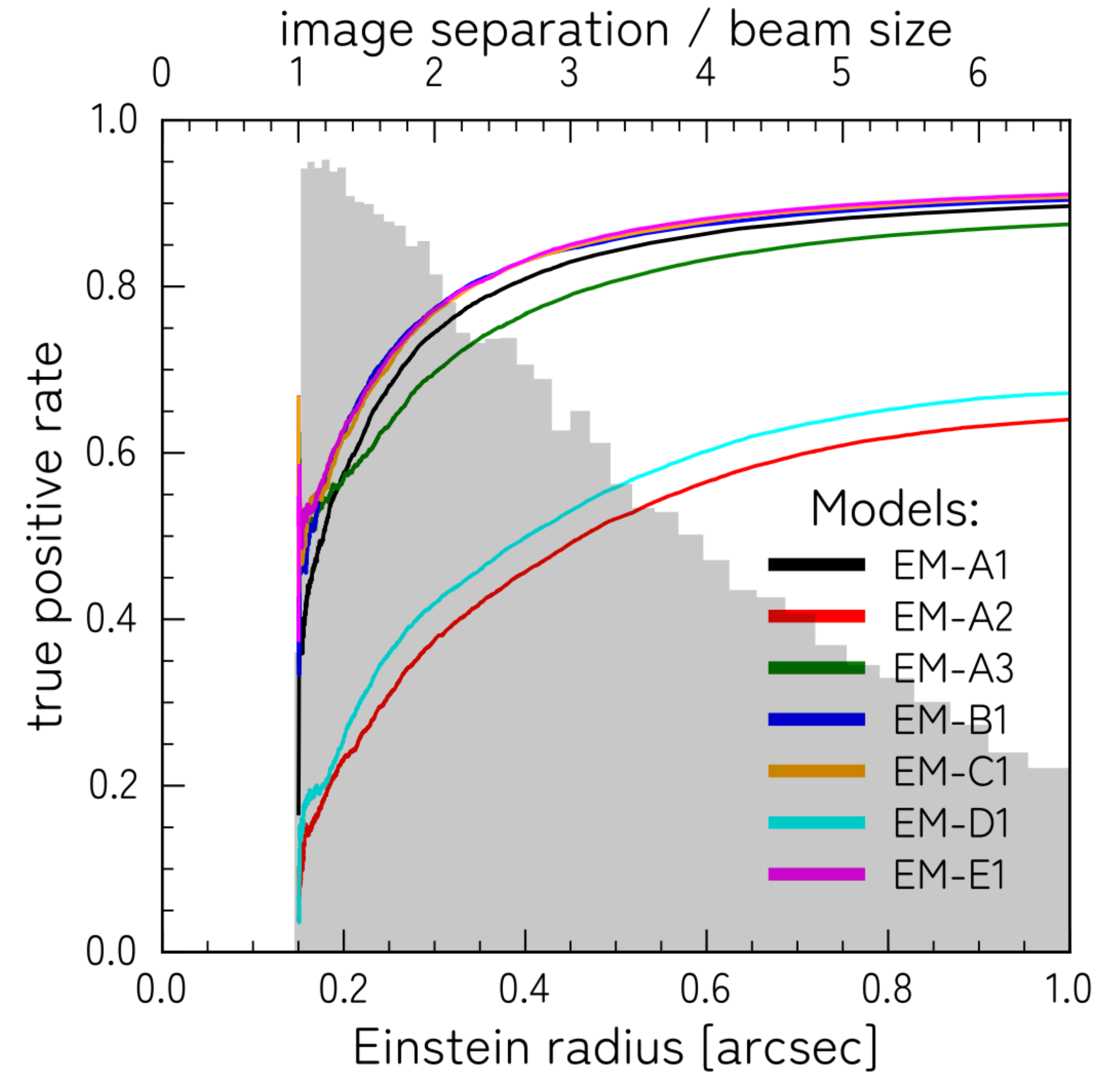
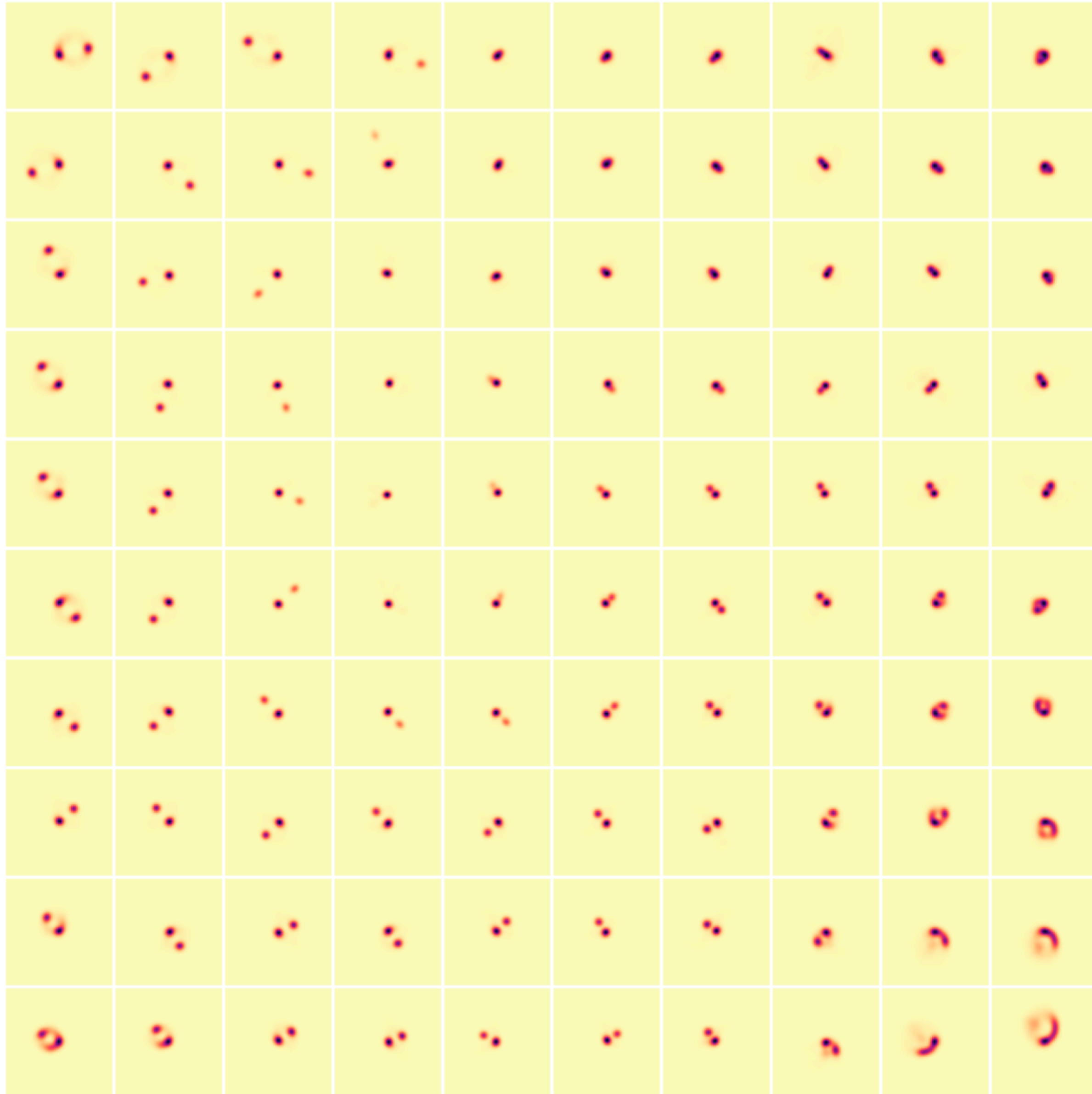
Synergies between LOFAR (0.3 arcsec resolution) and LSST (SA PI) / Euclid could find 10^3 lensed radio sources for dark matter studies.

The first deep learning lens finding algorithm has been developed for radio data (Rezaei et al. 2023).



(de Roo et al., in prep)

Combining Machine Learning with the LOFAR—LSST



(de Roo et al., in prep)

Summary

- LOFAR finds $>65\%$ of lensed quasars have detectable radio emission (likely SF).
- Simulations of ILT data show $>90\%$ of lenses found when
 - $>20\sigma$ detections
 - ~ 0.3 arcsec beam size (performance degrades with resolution).
- First lens candidate found from ILT survey observations (follow-up in progress).
- Pathfinder studies towards the SKA-MID surveys

3-4 PhD/postdoc positions available to work on VLBI / ALMA / VLA datasets and prepare for the SKA lensing survey.



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