

LOFAR follow-up of sources in the First LHAASO Catalog

María Arias
IAA-CSIC

TeVPa, Tendo, 31/8/2026

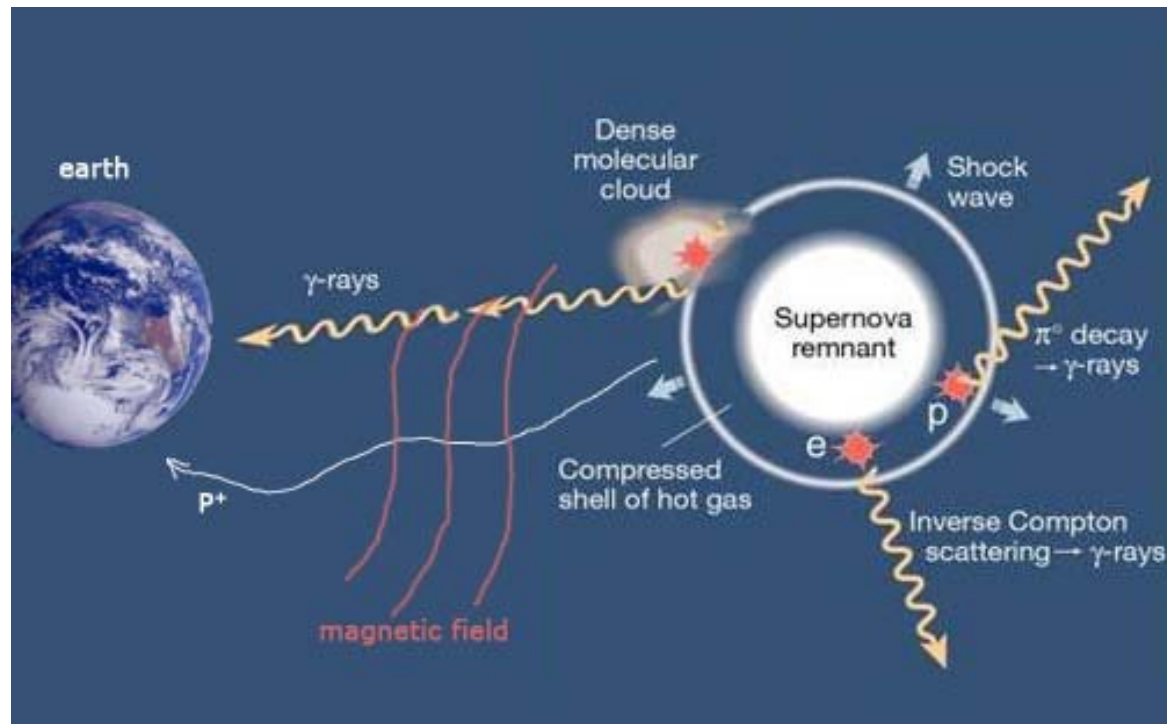
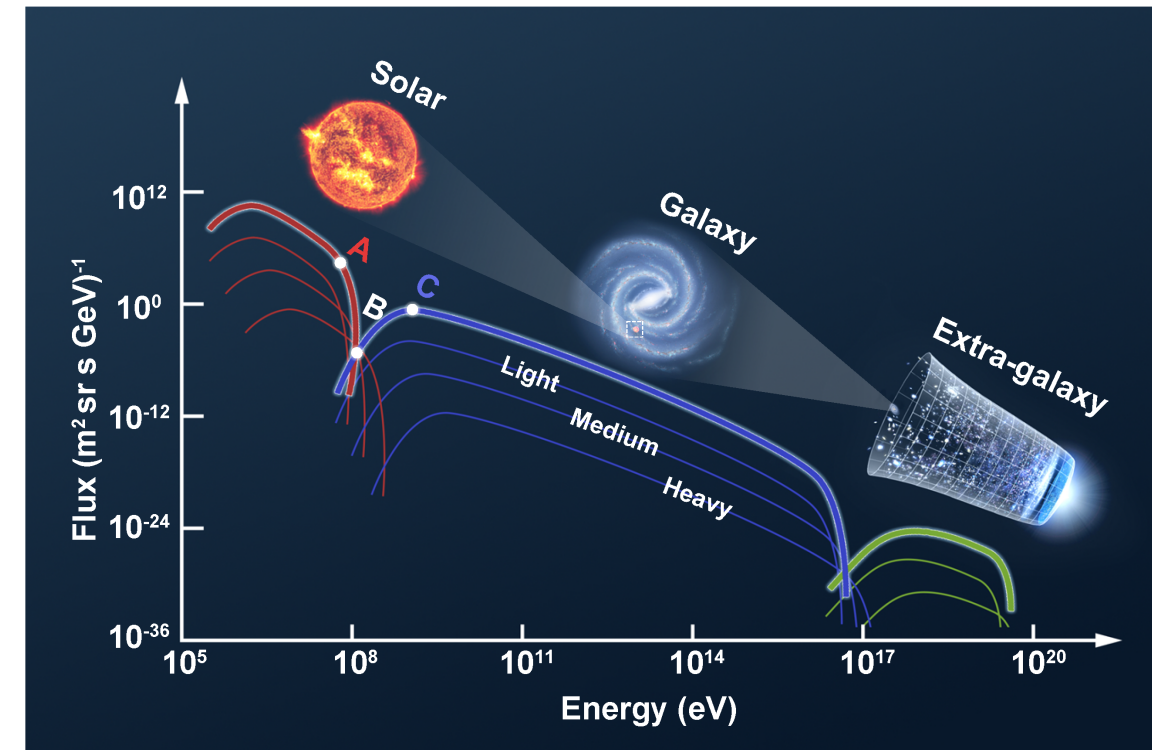


The changing understanding of Galactic CR acceleration

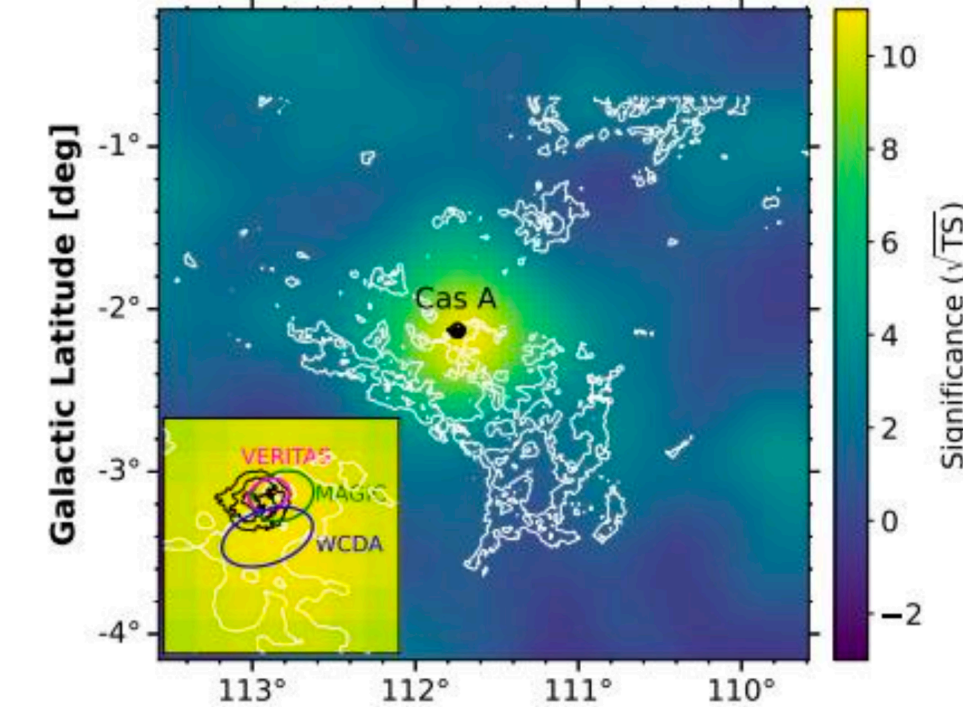
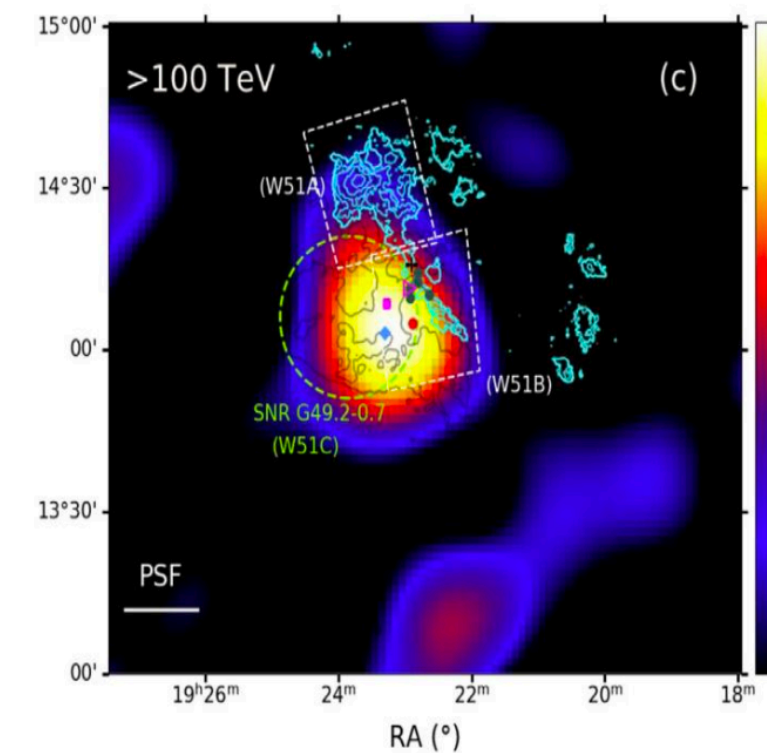
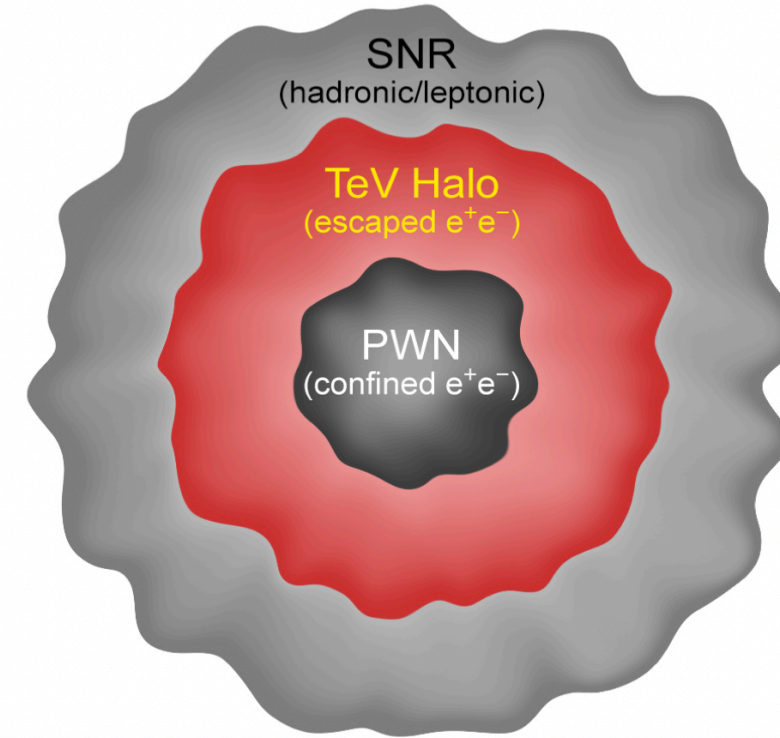
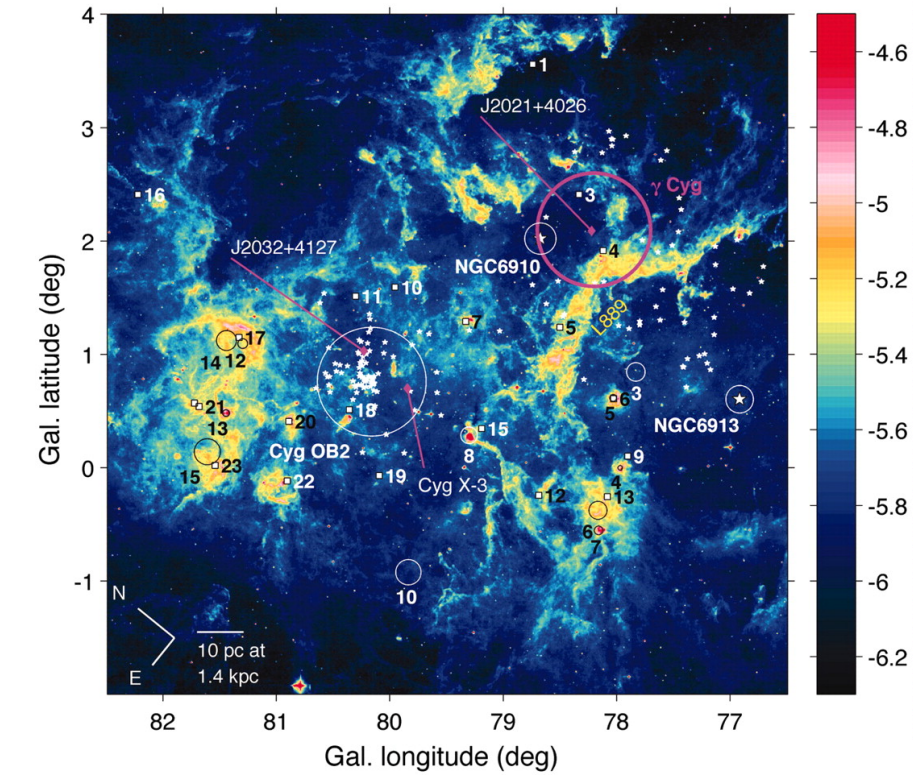
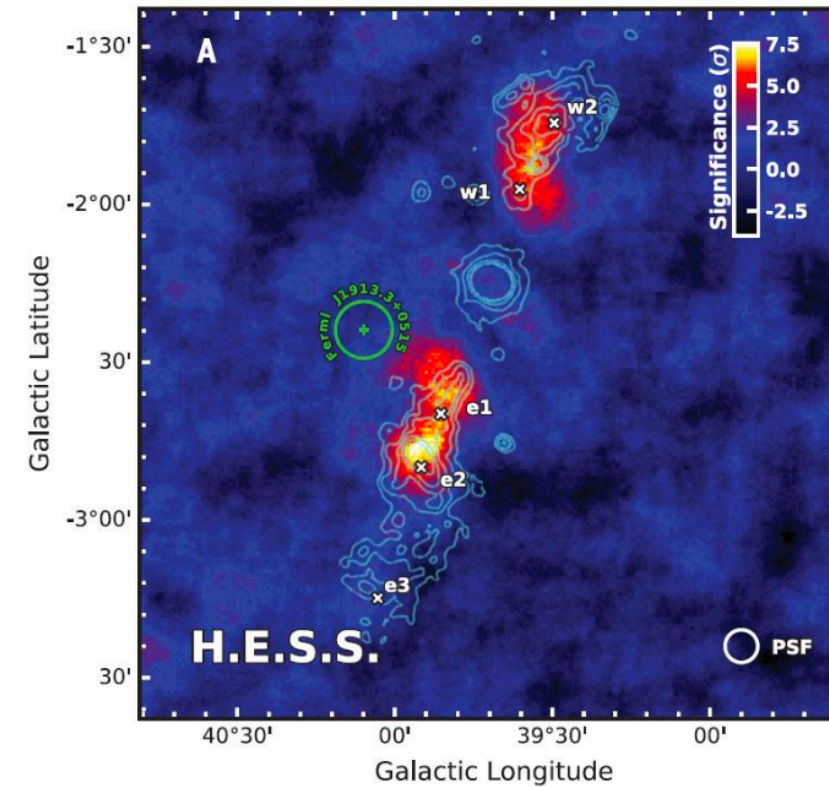
Aim: understanding Galactic CRs.

- How many classes of sources and what do they contribute to local CRs?
- What are acceleration mechanisms and limits of each class?
- What is the spatial distribution of CRs?
- How do they propagate in space?

These require knowing:
what are the counterparts of gamma-ray emitters?



Gamma-ray observations are critical to understand the origin of Galactic cosmic rays



Figures from:
H.E.S.S. Collaboration, *Science*, (2024)
Fermi-LAT Collaboration, (2014)
Sudoh et al., (2019)
LHAASO Collaboration, (2024)
LHAASO Collaboration (2025)

Recent results have made it clear that there is likely a combination of Galactic accelerators, including SNRs, PWN, TeV halos around pulsars, young massive star clusters, microquasars, gamma-ray binaries, superbubbles....

Follow-up of 1 LHAASO sources

LHAASO = Large High Altitude Air Shower Observatory (Sichuan, China, 4,410 m)



- Most sensitive UHE gamma-ray instrument (>100 TeV)
- New observational window on PeVatrons.

Before LHAASO, IACTs (imaging atmospheric Cherenkov telescopes): **H.E.S.S., MAGIC, VERITAS**

- Superb angular resolution and sensitivity up to a few tens of TeV, but small fields of view and limited duty cycles ($\sim 10\text{--}15\%$).
- Above ~ 100 TeV, detections sparse, and only a handful of sources *hinted* at PeV acceleration.



Why LHAASO has been so important

- Huge **collecting area** (~ 1 km²), unprecedented statistics at PeV energies
- **Hybrid design**: Water Cherenkov Detector Array (WCDA) + Kilometer-Square Array (KM2A) + muon detectors. Excellent gamma/hadron separation.
- $>90\%$ duty cycle, wide field of view (~ 2 sr): **continuous monitoring** of the northern sky
- First to detect **dozens of UHE sources >100 TeV**, reshaping our picture of the Galactic plane.

Follow-up of 1 LHAASO sources

THE ASTROPHYSICAL JOURNAL SUPPLEMENT SERIES, 271:25 (26pp), 2024 March

© 2024. The Author(s). Published by the American Astronomical Society.

OPEN ACCESS

<https://doi.org/10.3847/1538-4365/acfd29>



The First LHAASO Catalog of Gamma-Ray Sources

Zhen Cao^{1,2,3}, F. Aharonian^{4,5}, Q. An^{6,7}, Axikegu⁸, Y. X. Bai^{1,3}, Y. W. Bao⁹, D. Bastieri¹⁰, X. J. Bi^{1,2,3}, Y. J. Bi^{1,3}, J. T. Cai¹⁰,
Q. Cao¹¹, W. Y. Cao⁷, Zhe Cao^{6,7}, J. Chang¹², J. F. Chang^{1,3,6}, A. M. Chen¹³, E. S. Chen^{1,2,3}, Liang Chen¹⁴, Lin Chen⁸,
Long Chen⁸, M. J. Chen^{1,3}, M. L. Chen^{1,3,6}, Q. H. Chen⁸, S. H. Chen^{1,2,3}, S. Z. Chen^{1,3} , T. L. Chen¹⁵, Y. Chen⁹, N. Cheng^{1,3},
X. D. Cui^{1,3}, M. M. Guo¹², W. Guo¹¹, H. G. Guo¹⁶, D. M. He¹⁷, D. He¹⁸, H. H. He^{1,3,6}, G. D. Hu⁷, D. Hu^{1,3}, J. Hu¹⁵

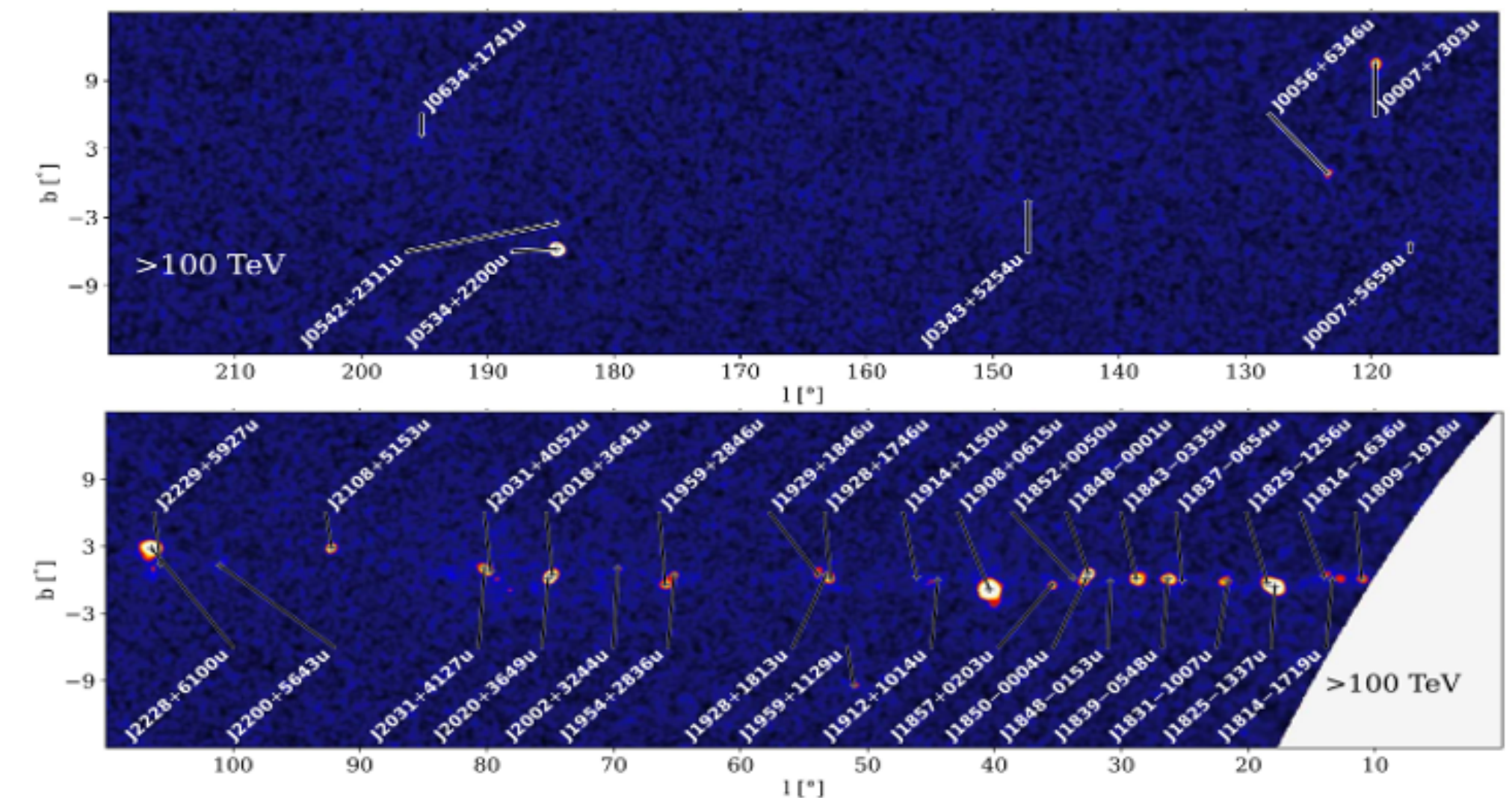
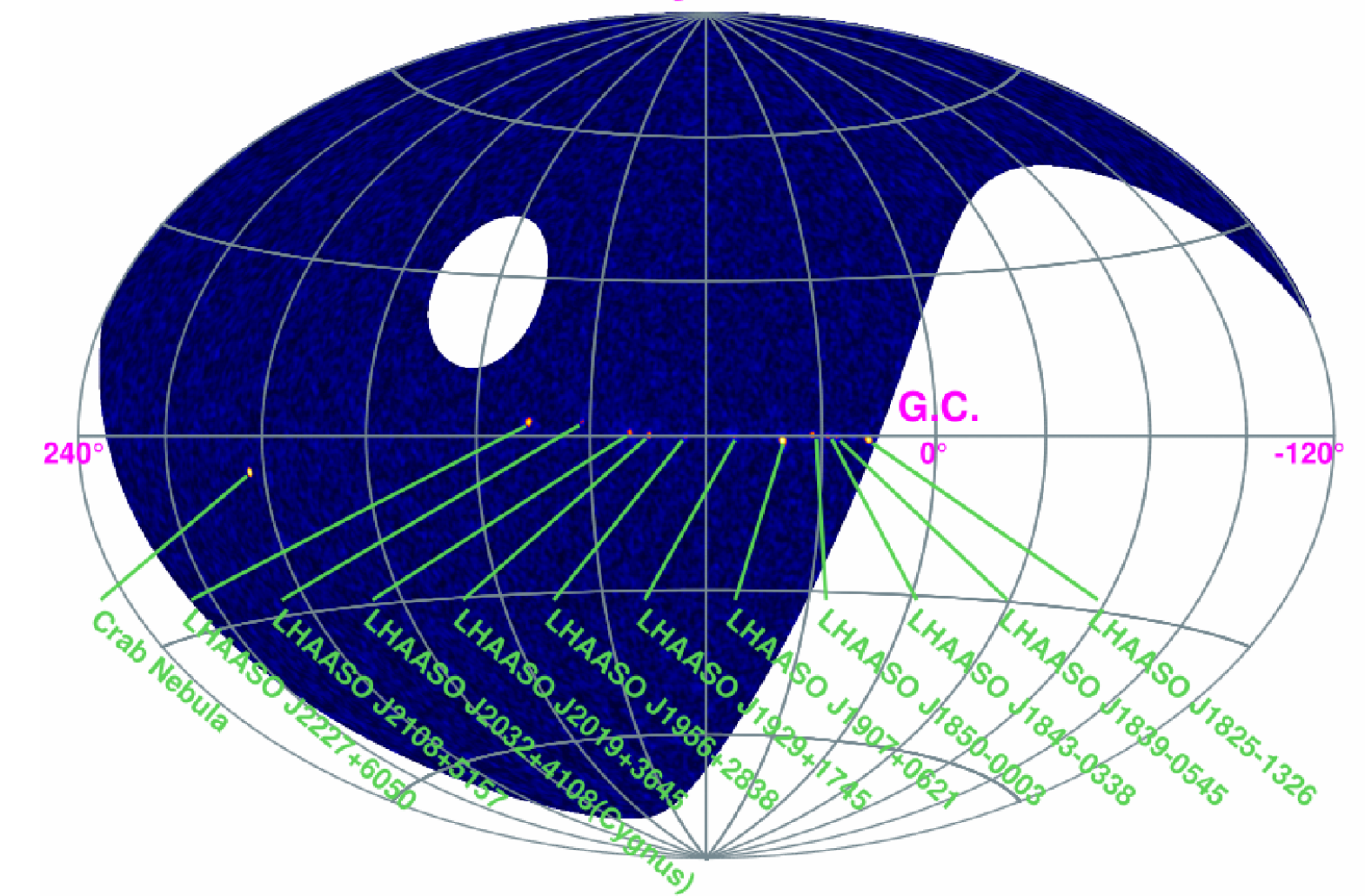
Received 2023 May 26; revised 2023 September 12; accepted 2023 September 12; published 2024 February 27

Abstract

We present the first catalog of very-high-energy and ultra-high-energy gamma-ray sources detected by the Large High Altitude Air Shower Observatory. The catalog was compiled using 508 days of data collected by the Water Cherenkov Detector Array from 2021 March to 2022 September and 933 days of data recorded by the Kilometer Squared Array from 2020 January to 2022 September. This catalog represents the main result from the most sensitive large coverage gamma-ray survey of the sky above 1 TeV, covering decl. from -20° to 80° . In total, the catalog contains 90 sources with an extended size smaller than 2° and a significance of detection at $>5\sigma$. Based on our source association criteria, 32 new TeV sources are proposed in this study. Among the 90 sources, 43 sources are detected with ultra-high energy ($E > 100$ TeV) emission at $>4\sigma$ significance level. We provide the position, extension, and spectral characteristics of all the sources in this catalog.

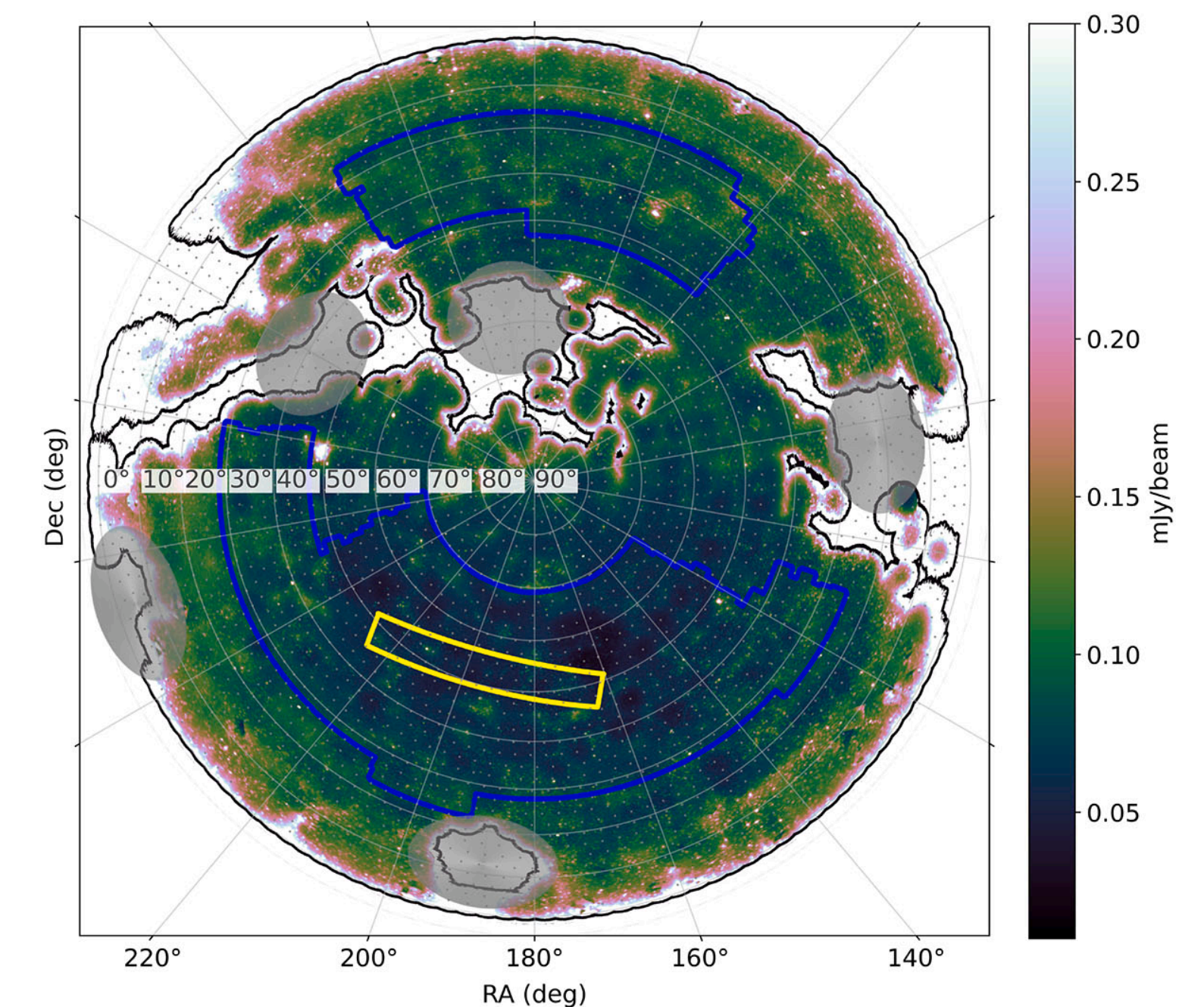
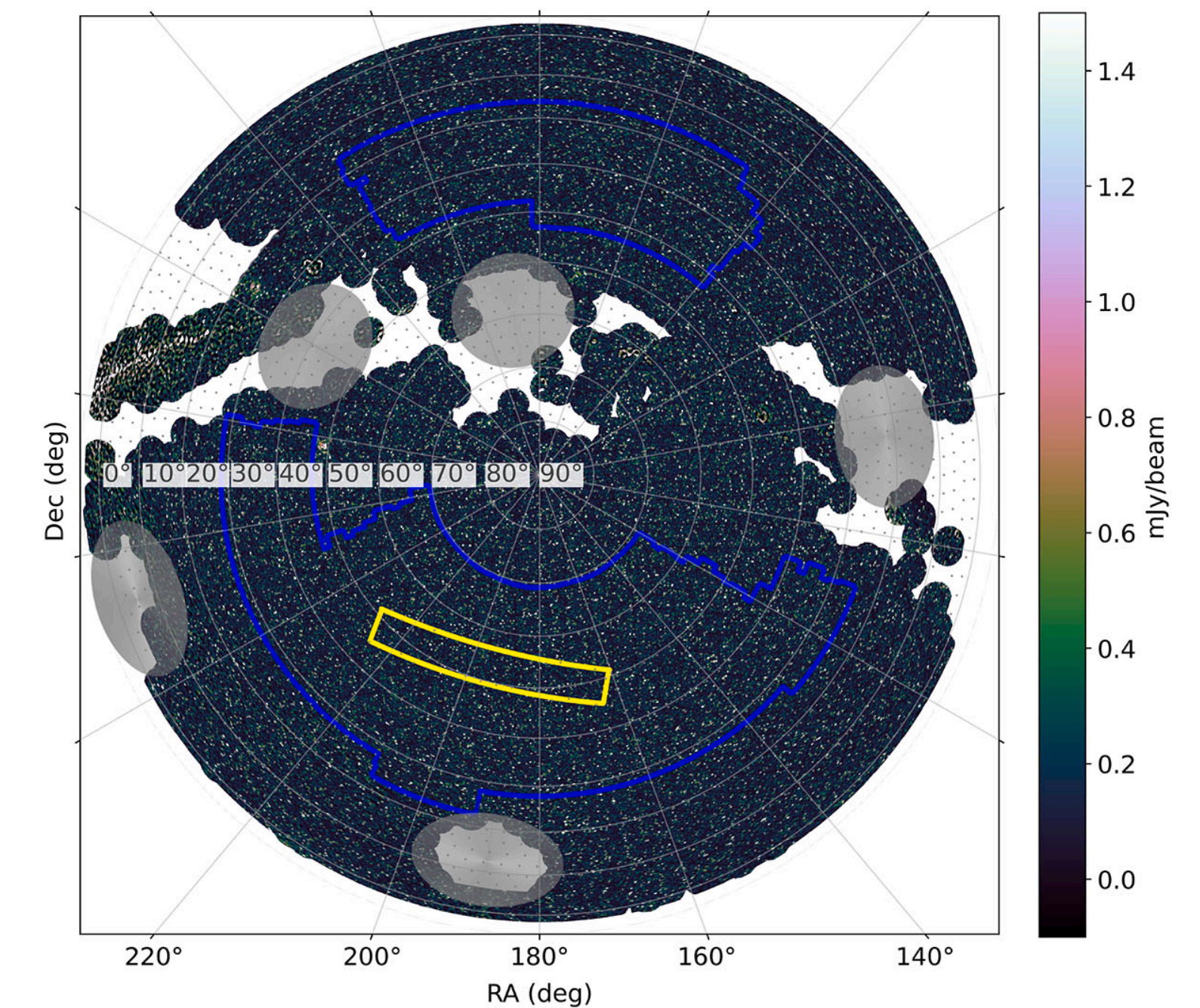
Unified Astronomy Thesaurus concepts: [Gamma-ray astronomy \(628\)](#); [Gamma-ray observatories \(632\)](#); [Catalogs \(205\)](#)

LHAASO Sky @ >100 TeV

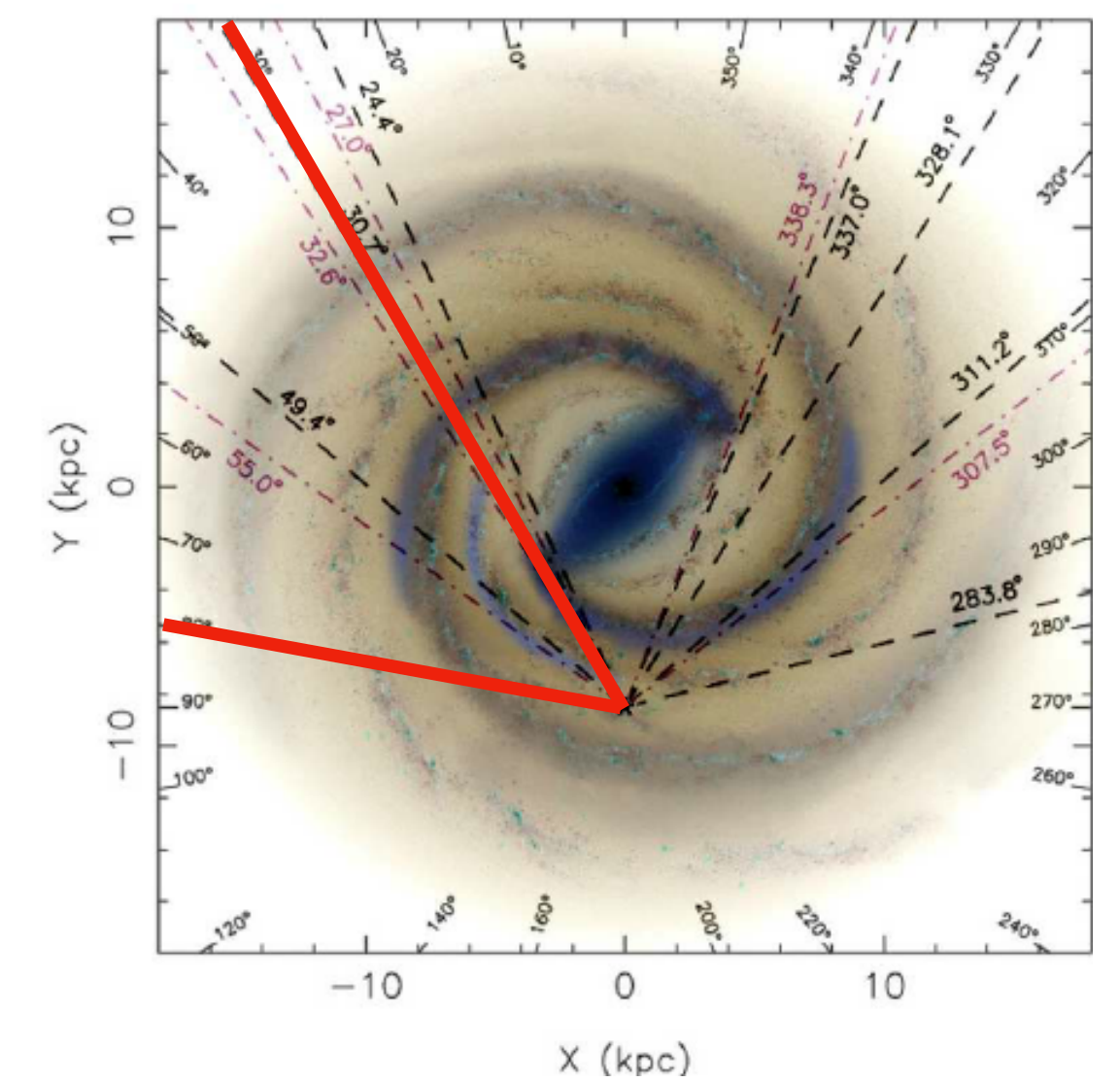
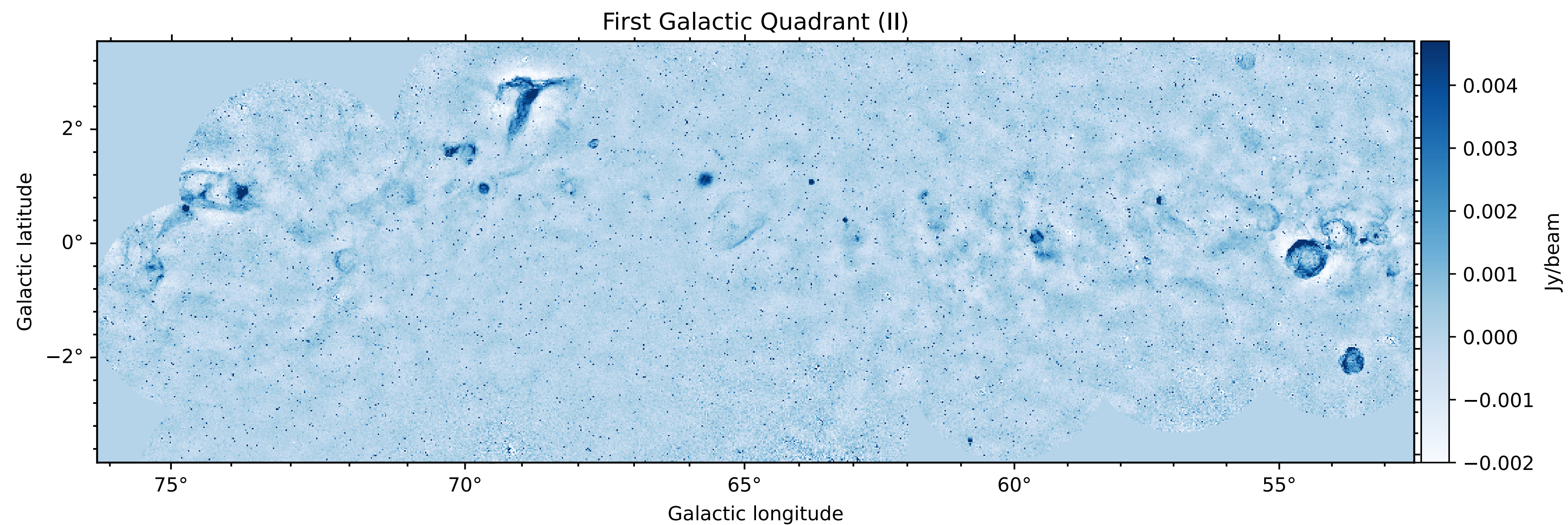
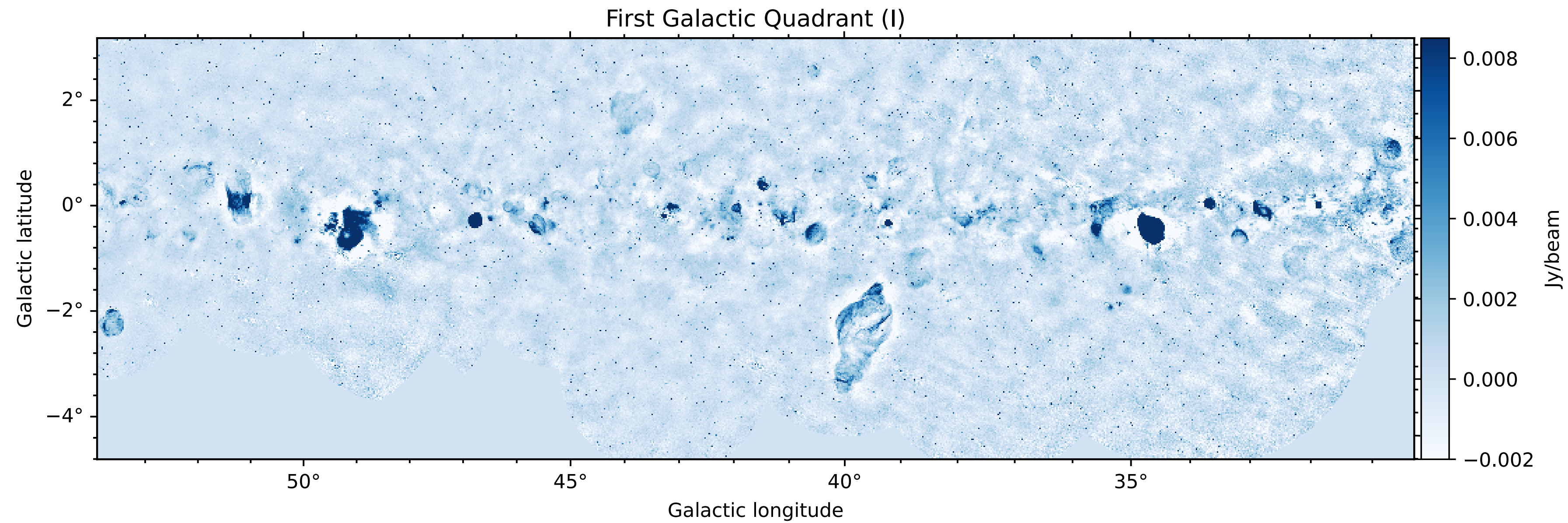
LHAASO Collaboration, *Nature*, 2021

The LOFAR Two-Metre Sky Survey

- All-sky (=88% of Northern sky) survey at 144 MHz
- Data products include Stokes I, Q, U, V at 6'' and 20'' resolution (noise ~ 80 μ Jy/bm at 6'' in extragalactic fields), plus catalogs and dynamic spectra
- Shimwell+ 17,19,22,26: 13,000 hours; 18.6PB of data
- <https://lofar-surveys.org/>

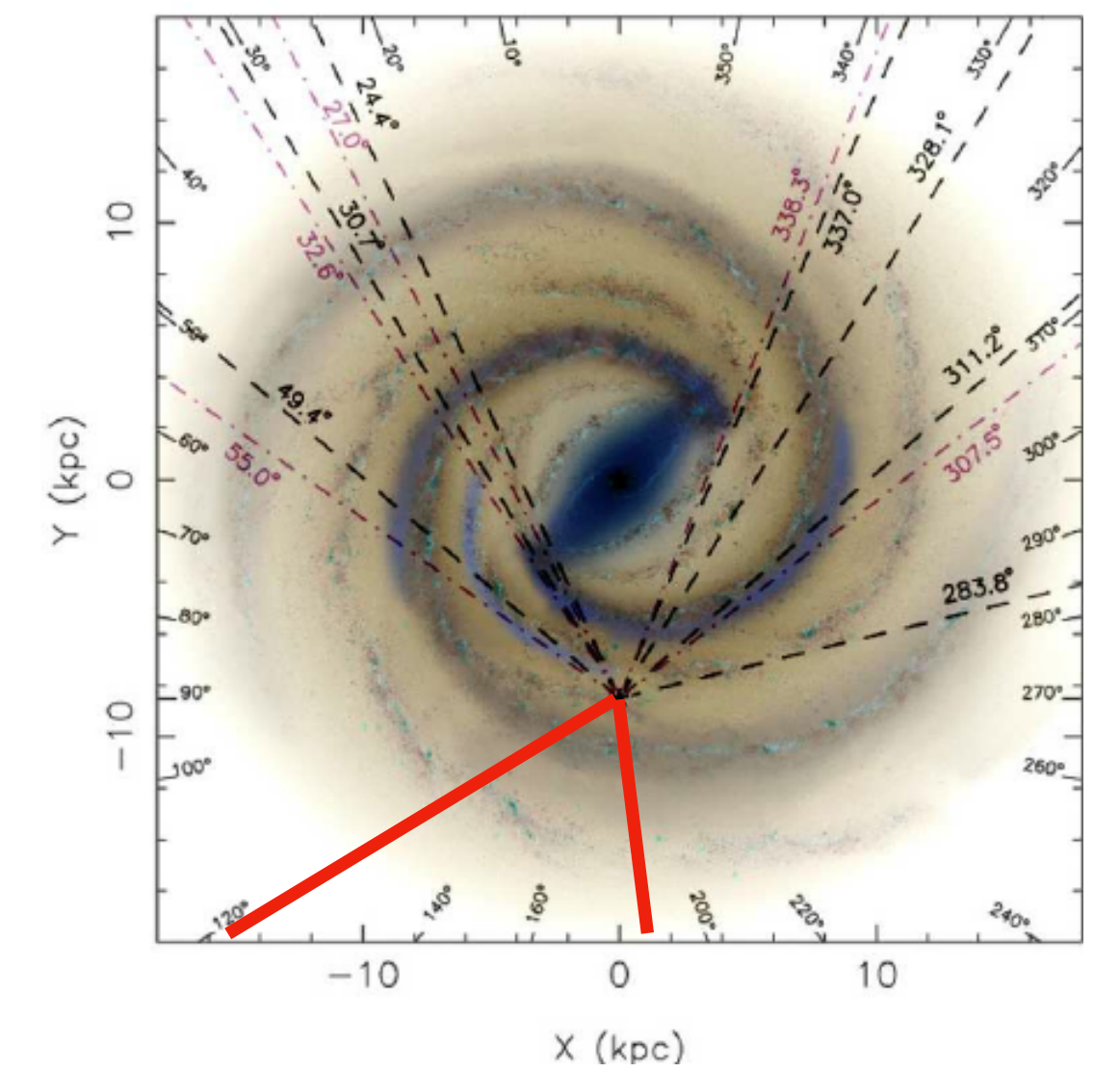
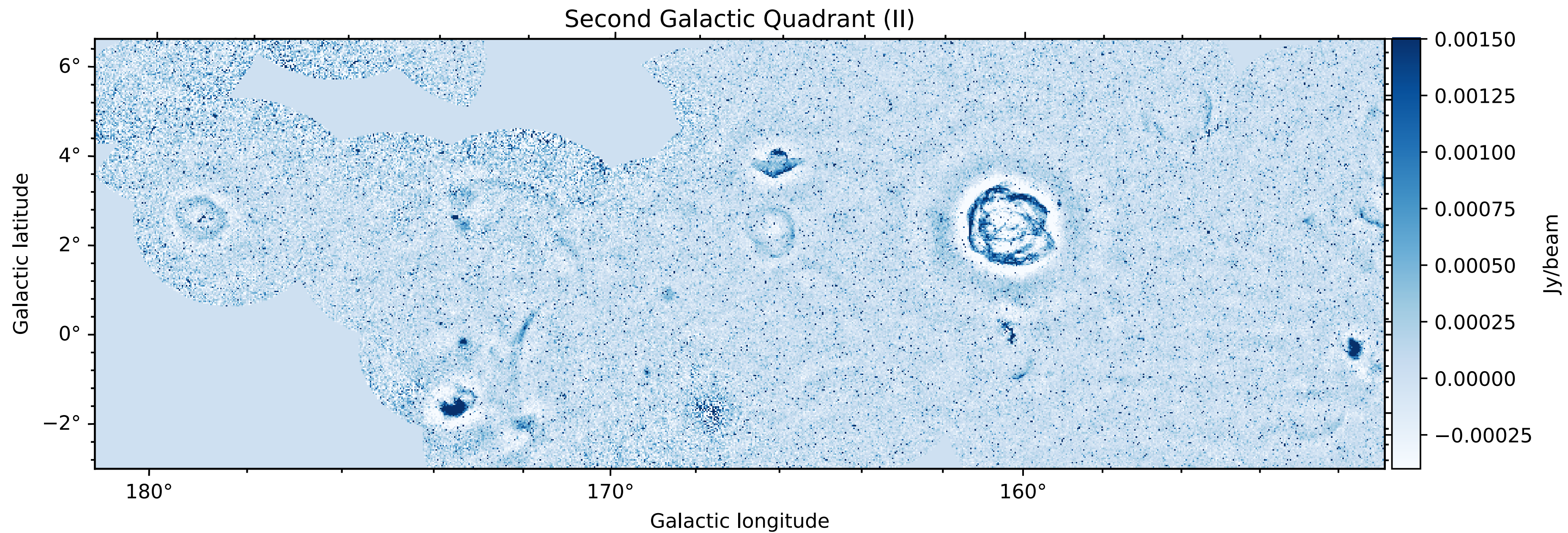
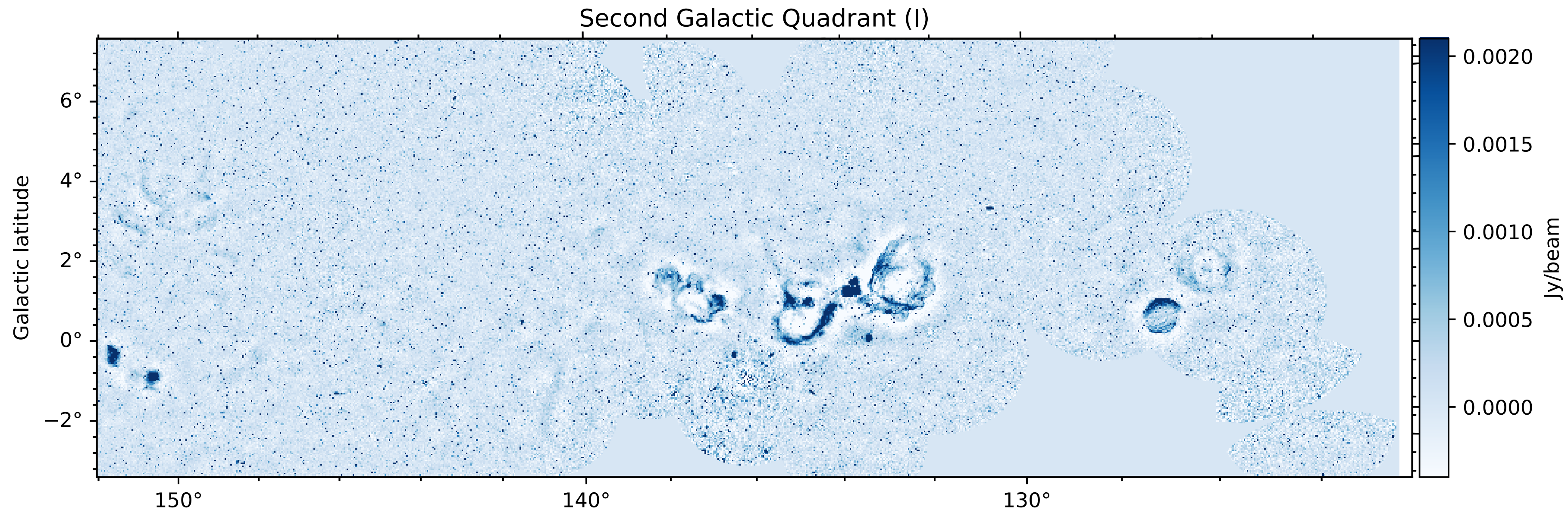


The LoTSS has observed quite a bit of the Milky Way, in patches,



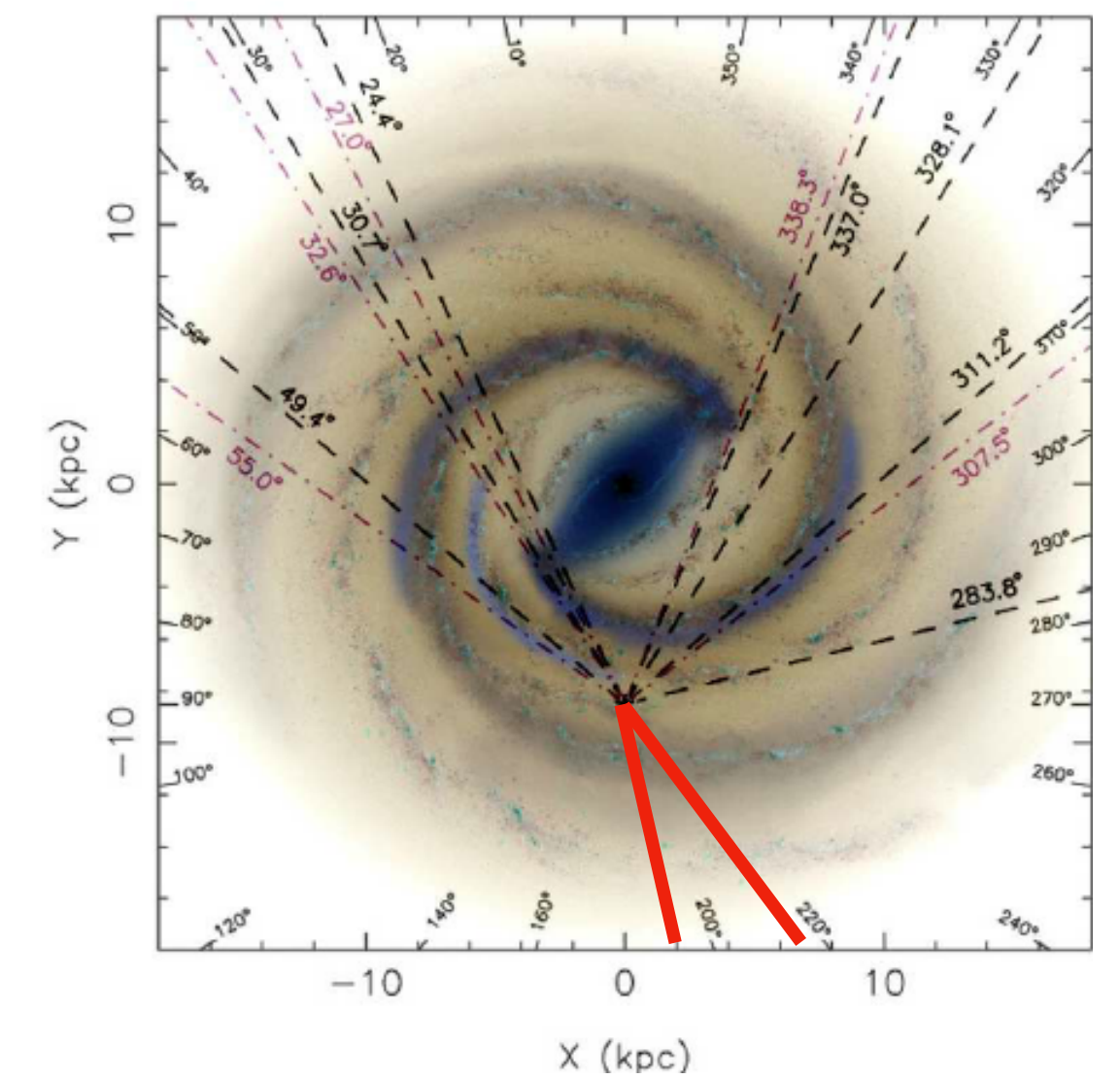
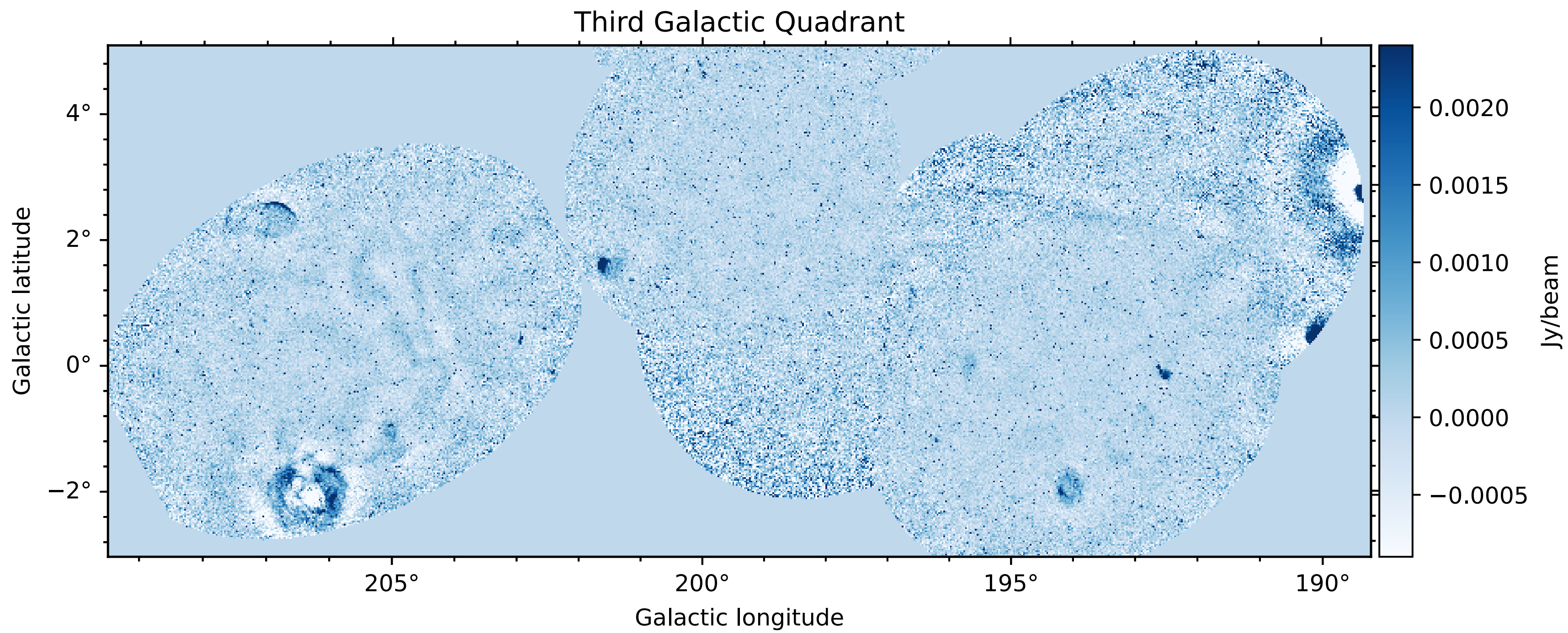
LoTSS DR-3
Shimwell+26,
Arias+ submitted

and with some gaps,



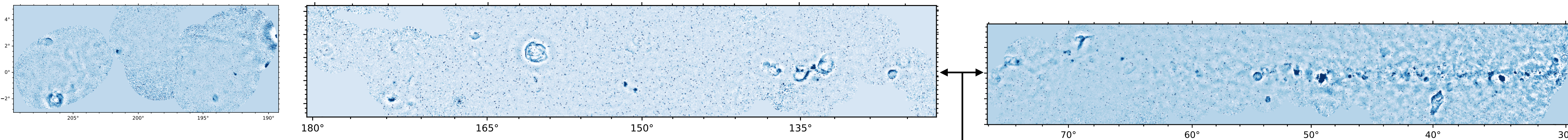
LoTSS DR-3
Shimwell+26,
Arias+ submitted

and the third Galactic quadrant is the patchiest

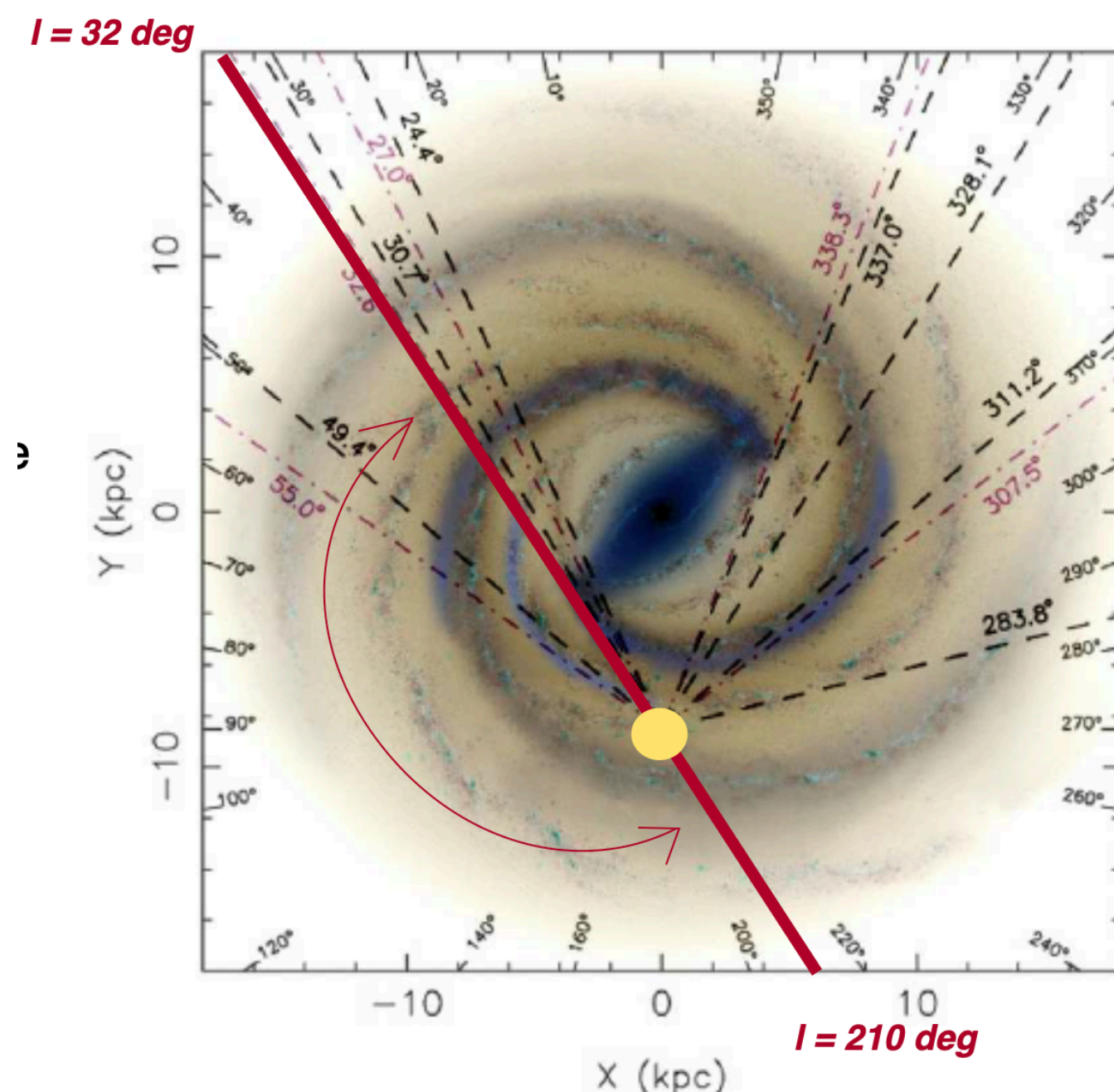


LoTSS DR-3
Shimwell+26,
Arias+ submitted

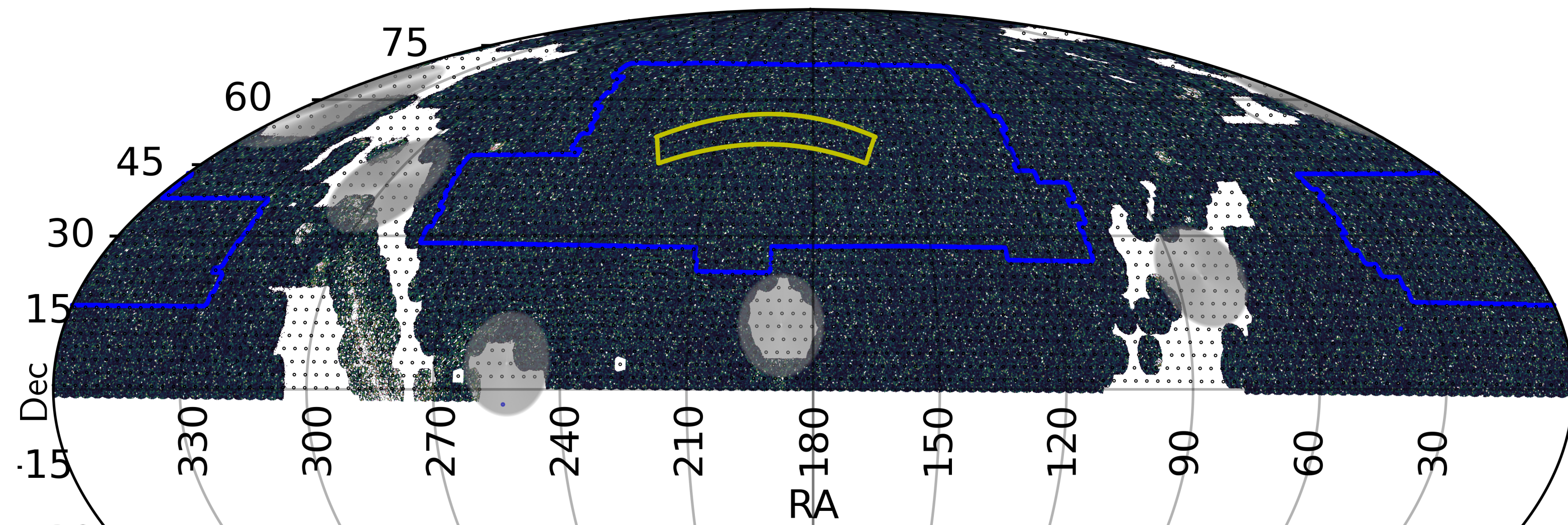
From NL, we see the Outer Galaxy



Cas A ($l=111.7$), Cyg A ($l=84.7$)

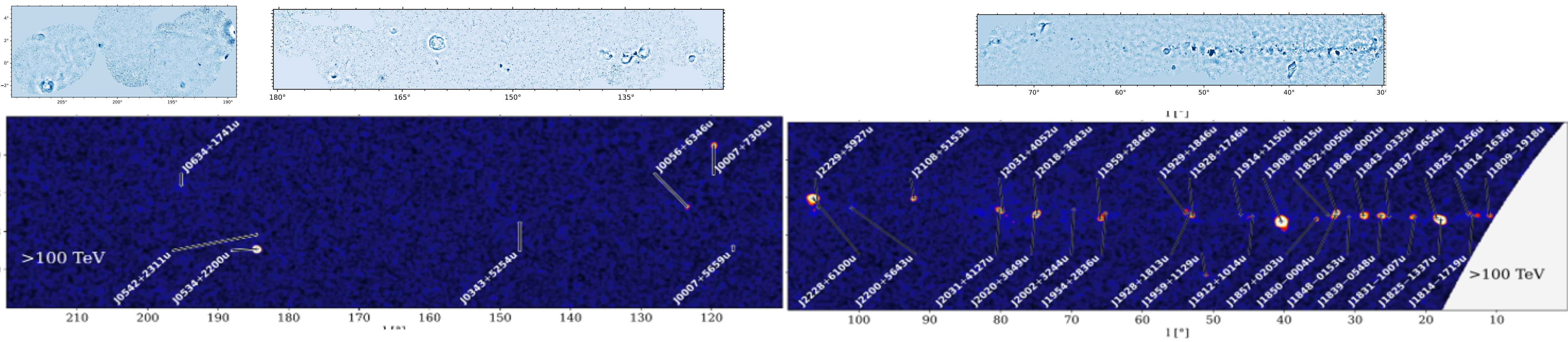


Observations of the MW in the LoTSS footprint from $l = 30$ to 210 degrees.



The missing fields will be covered as part of the LOFAR 2.0 Galactic Plane Survey (L2GPS), and in the continuation of LoTSS (part of ILoTSS) — **let me know if you want to join the collaboration!** [marias@iaa.csic.es]
Three of four A-team sources are (or along the line of sight to) in the Milky Way: Cas A, Cyg A, Tau A

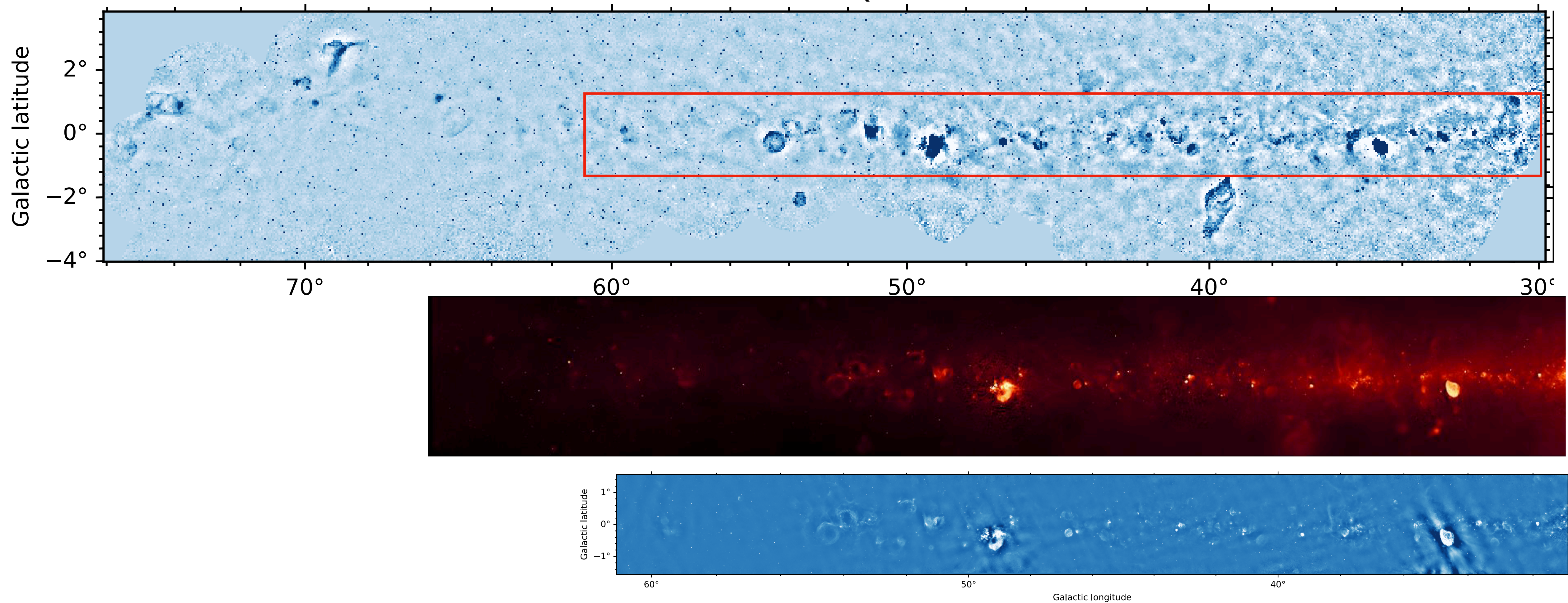
Follow-up of 1 LHAASO sources



LOFAR fields (top)
LHAASO Sky (bottom)

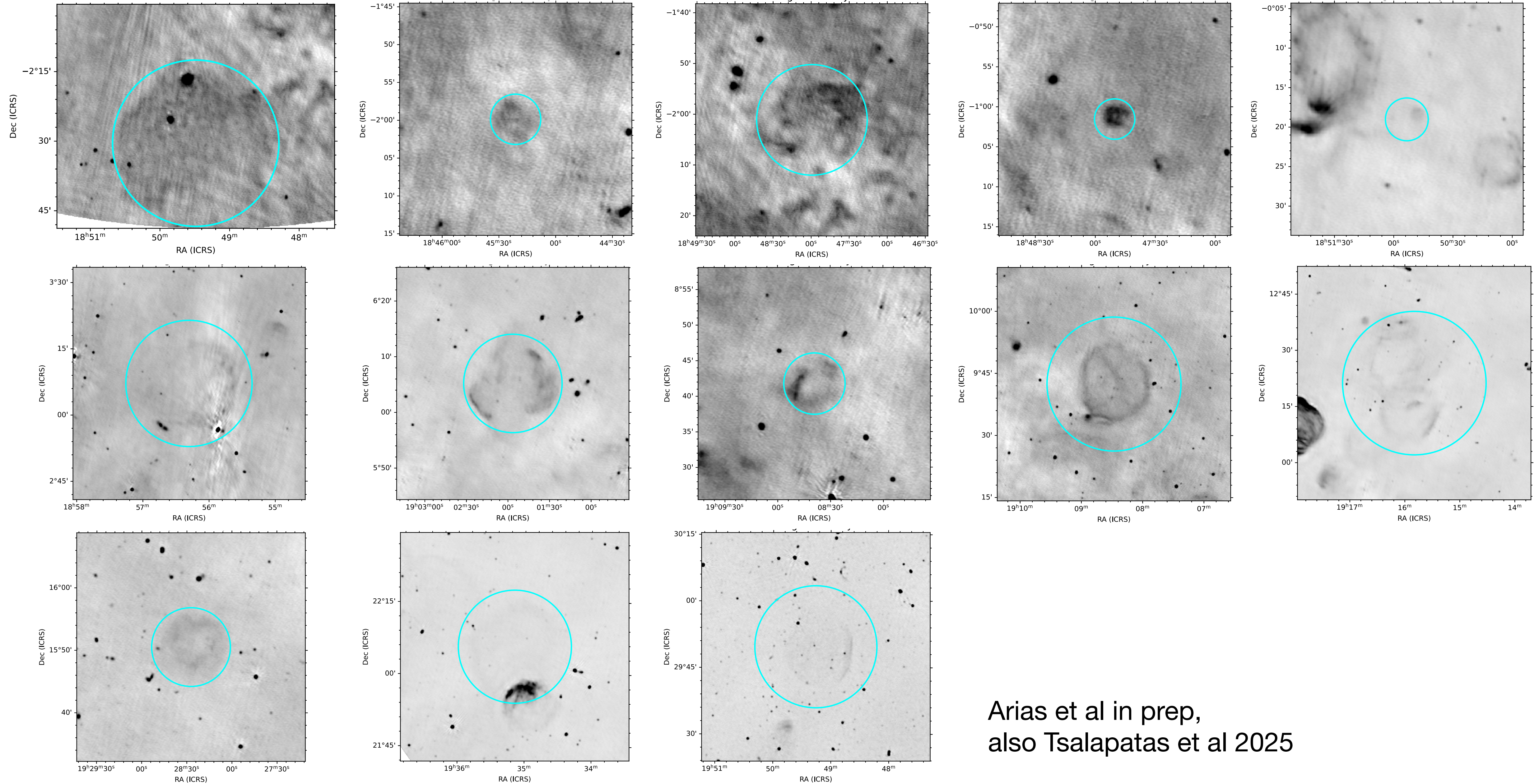
The first quadrant has a lot of ancillary data

First Galactic Quadrant



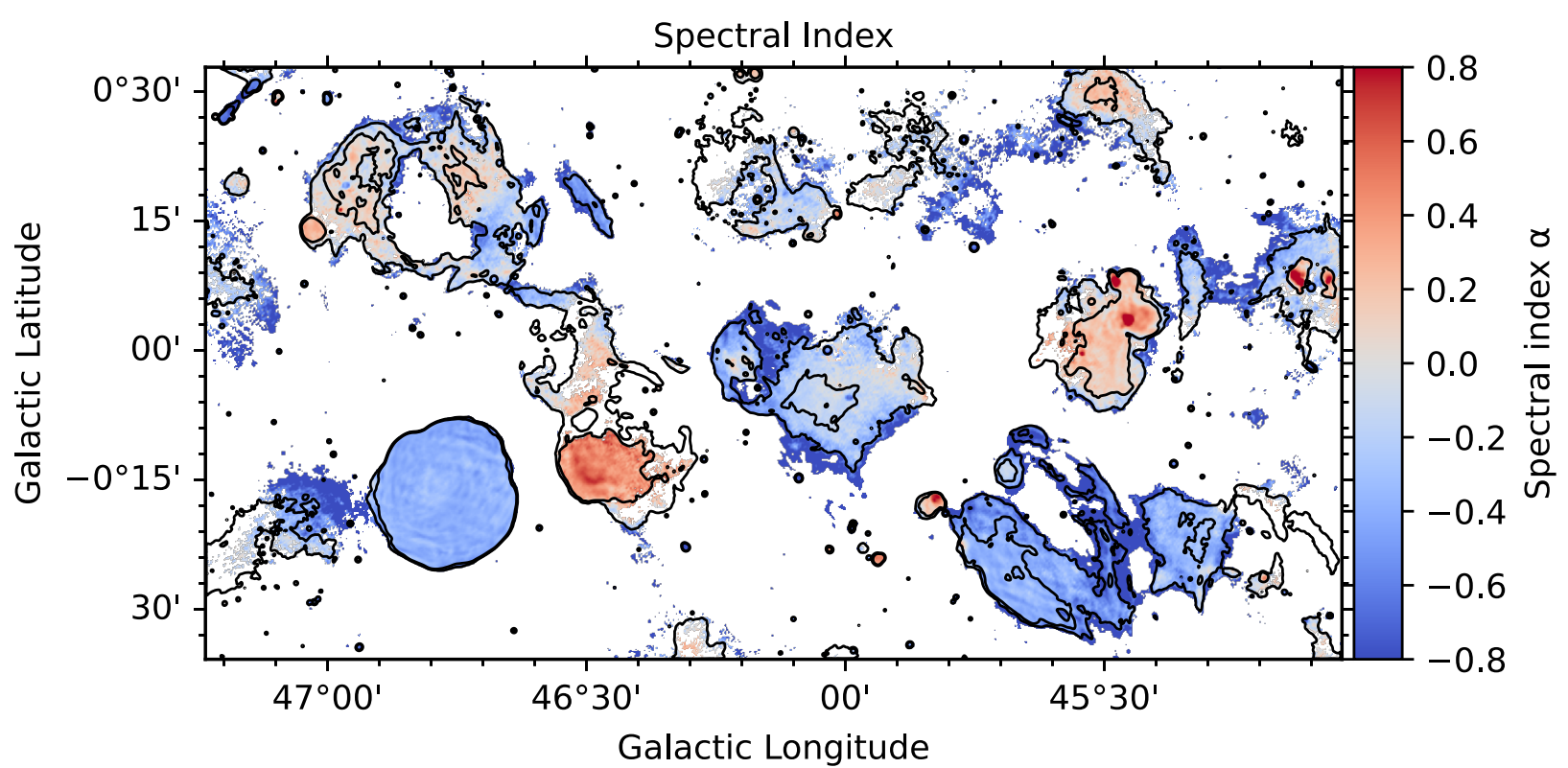
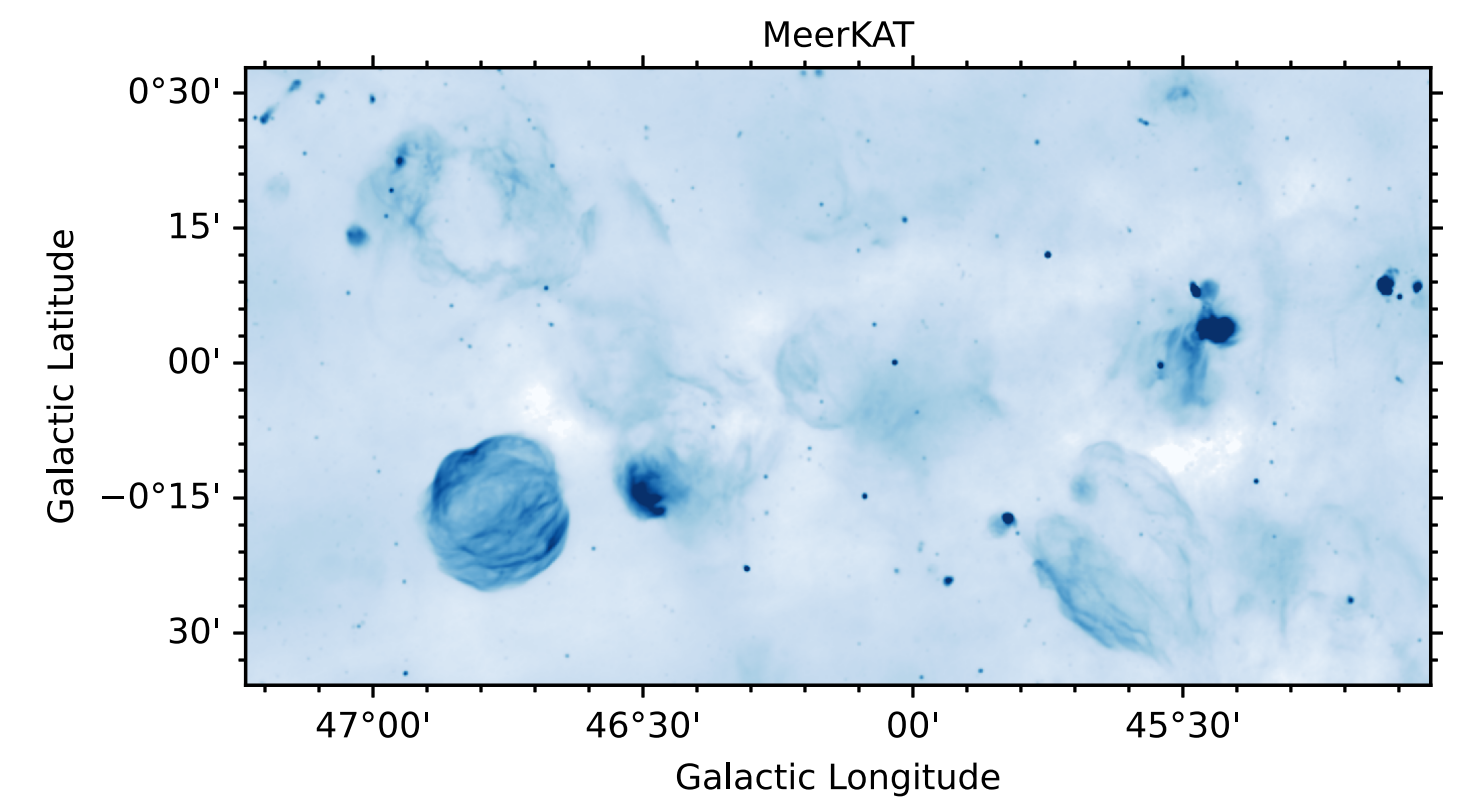
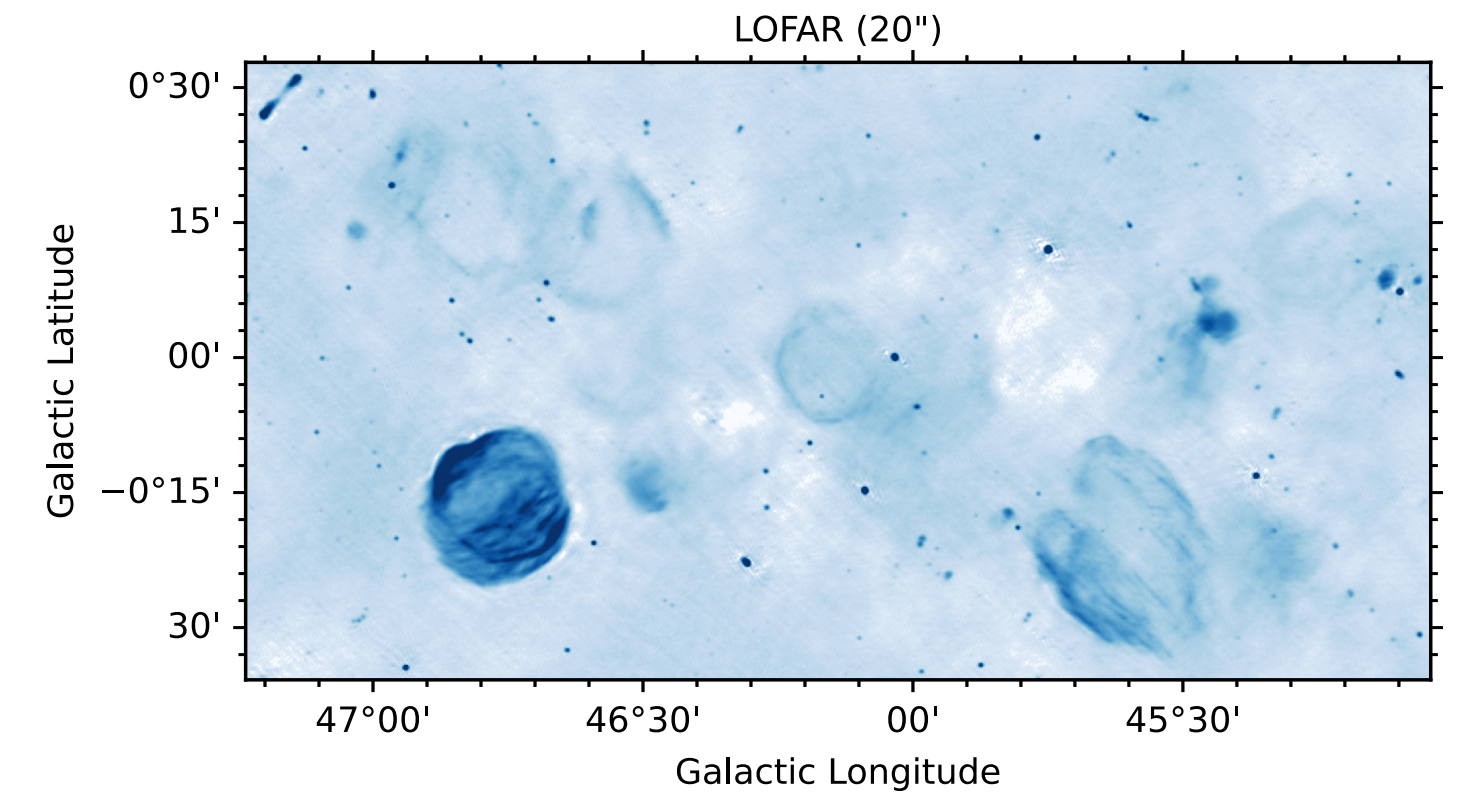
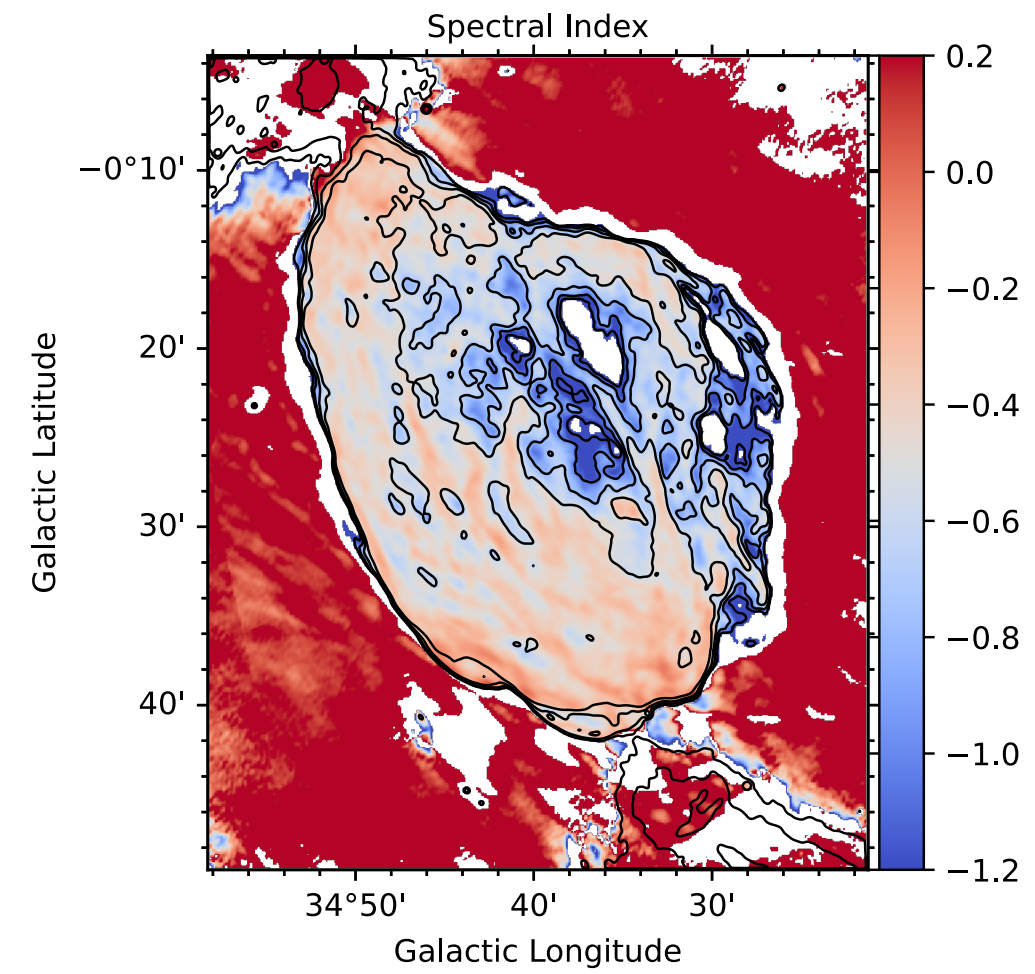
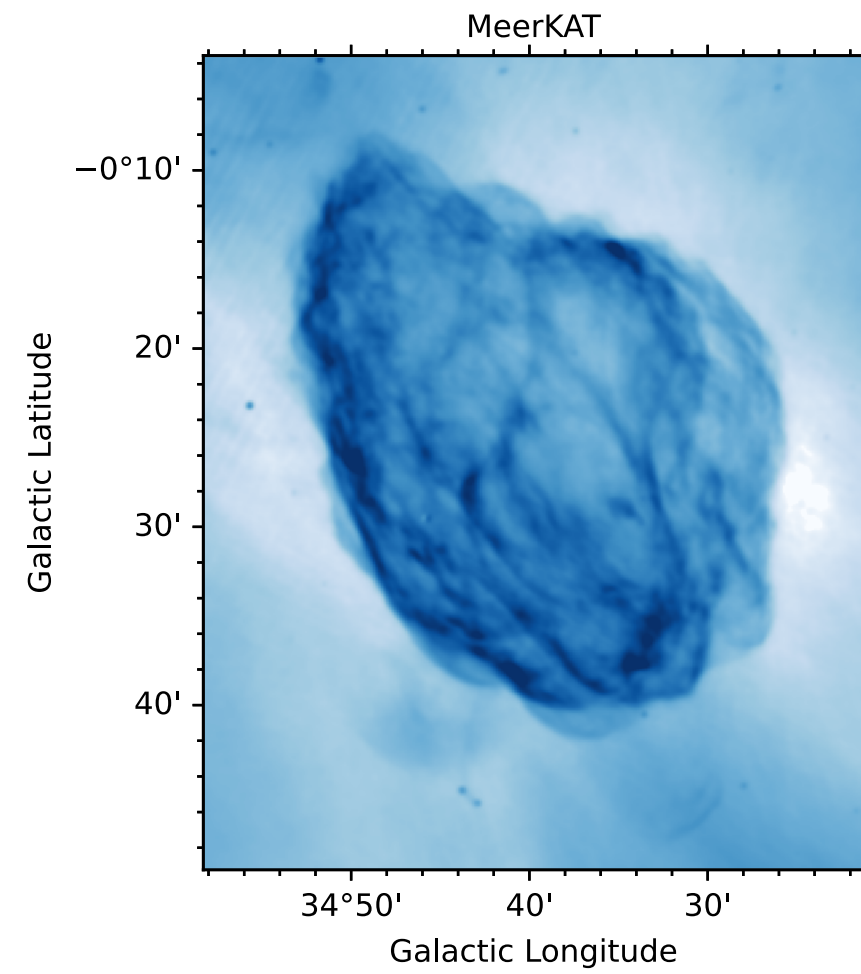
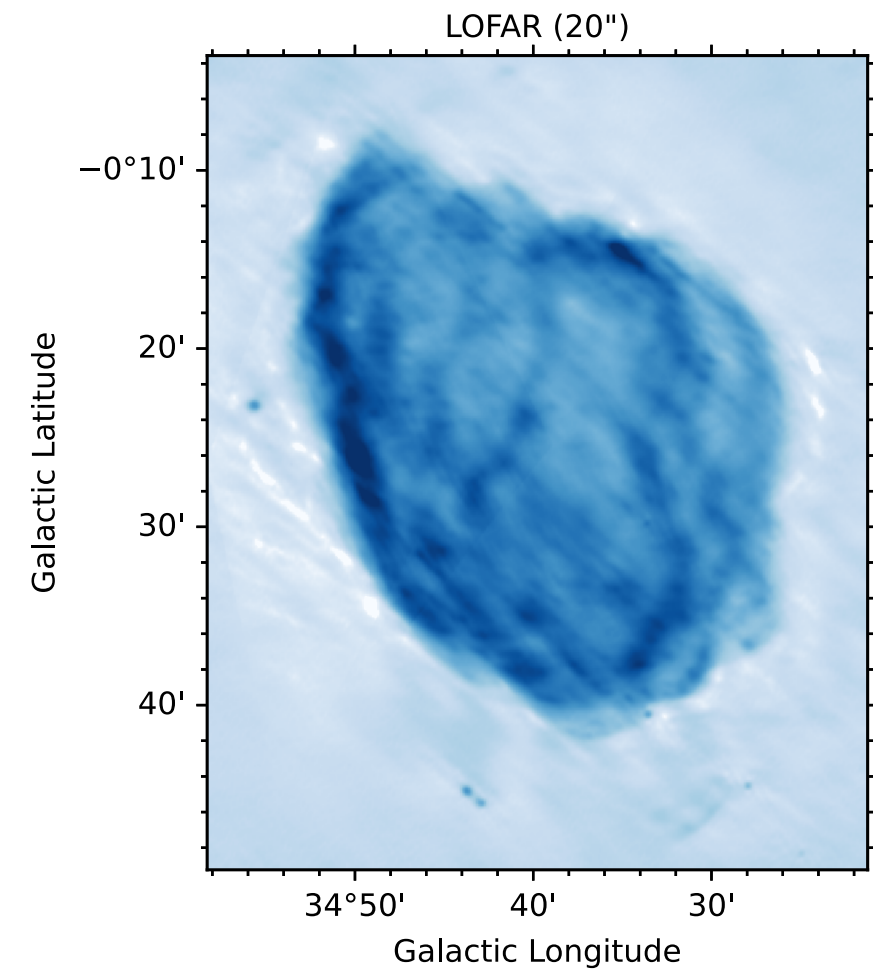
VGPS (top), MeerKAT GPS (bottom)

Even so, lots of new sources, e.g. new SNR candidates

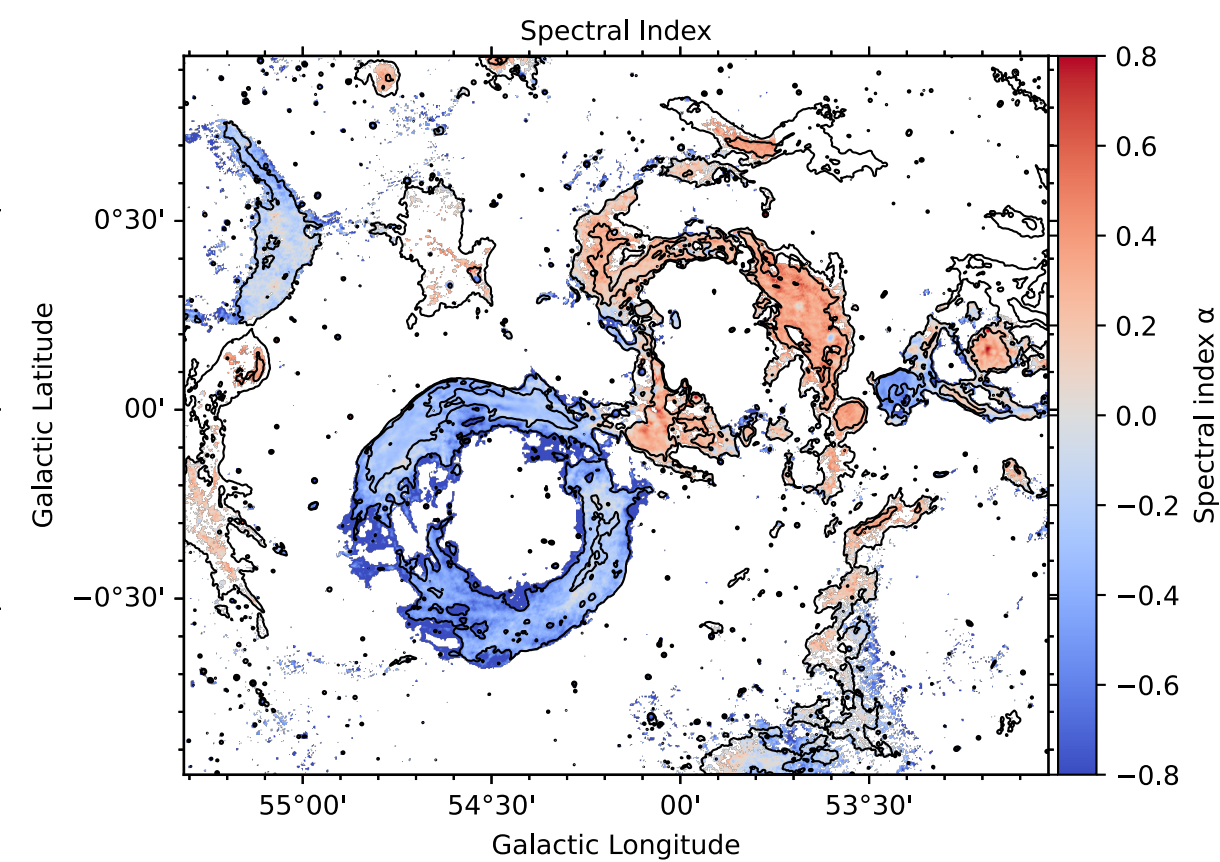
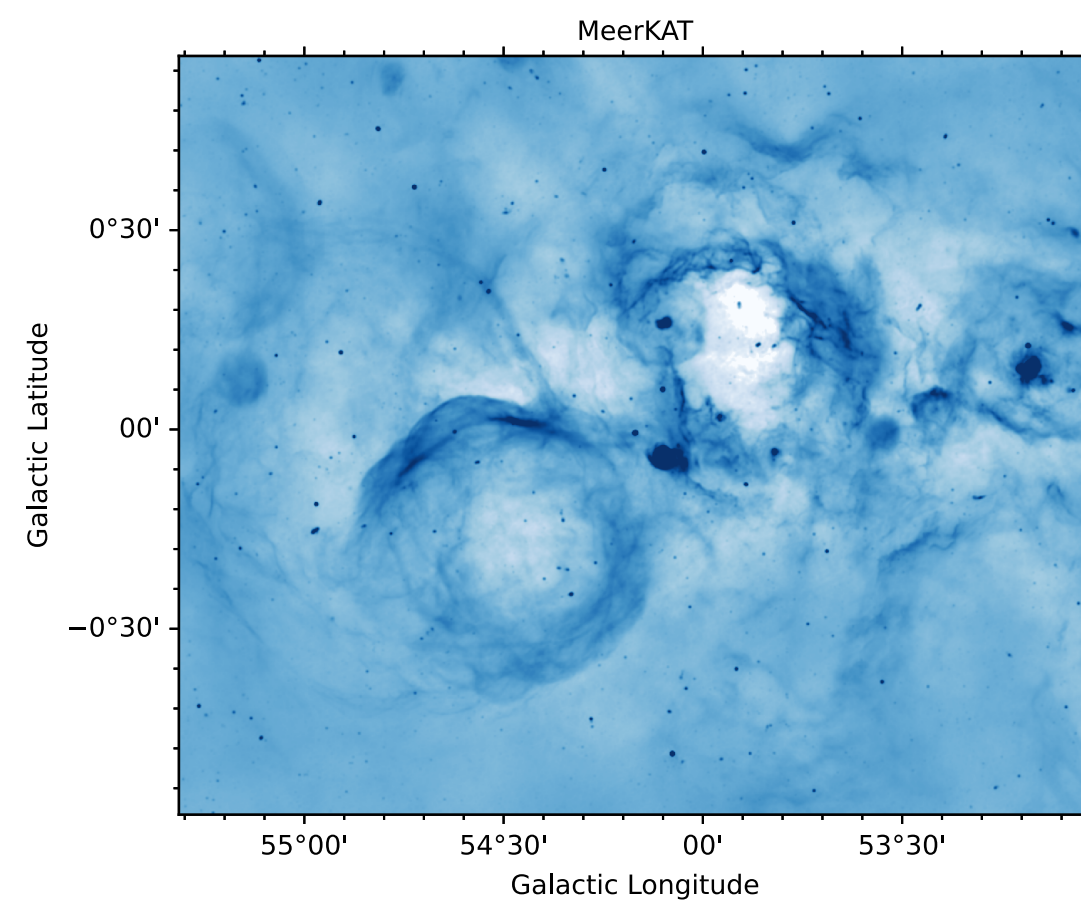
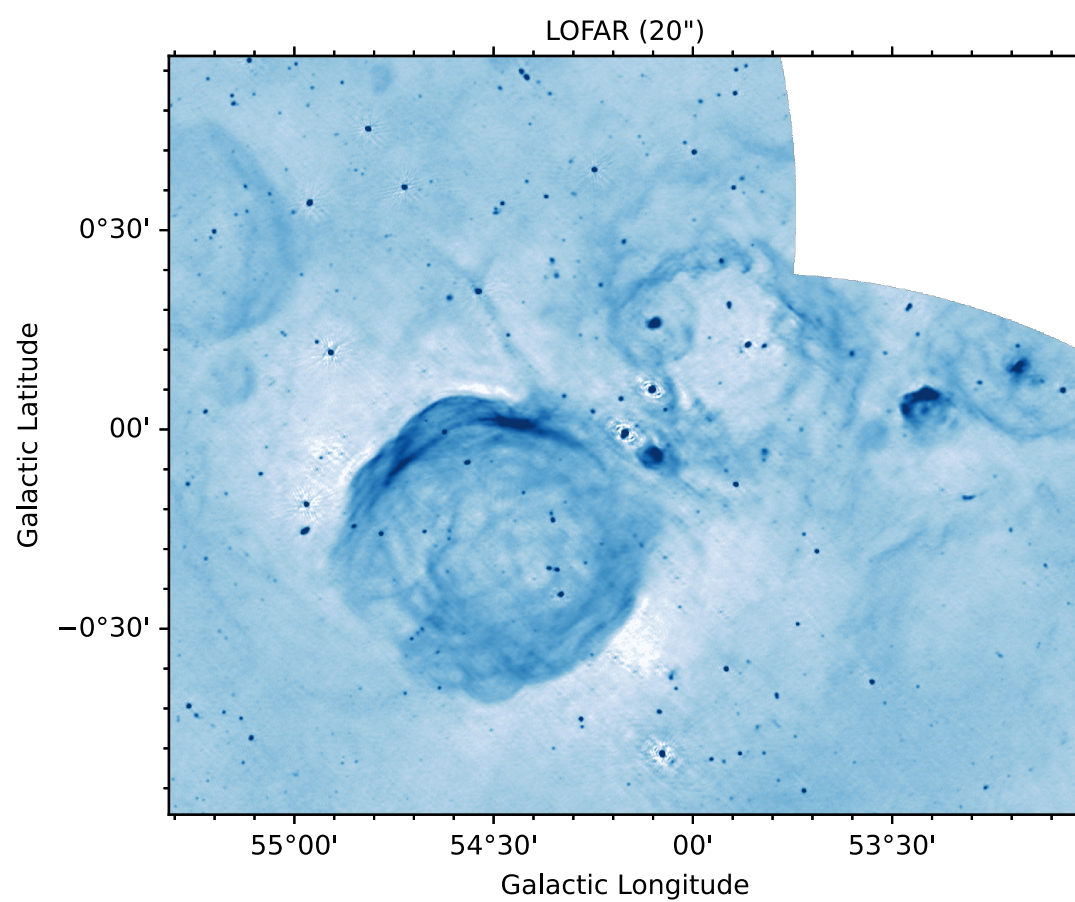


Arias et al in prep,
also Tsalapatas et al 2025

Useful spectral information



Supernova remnant W44

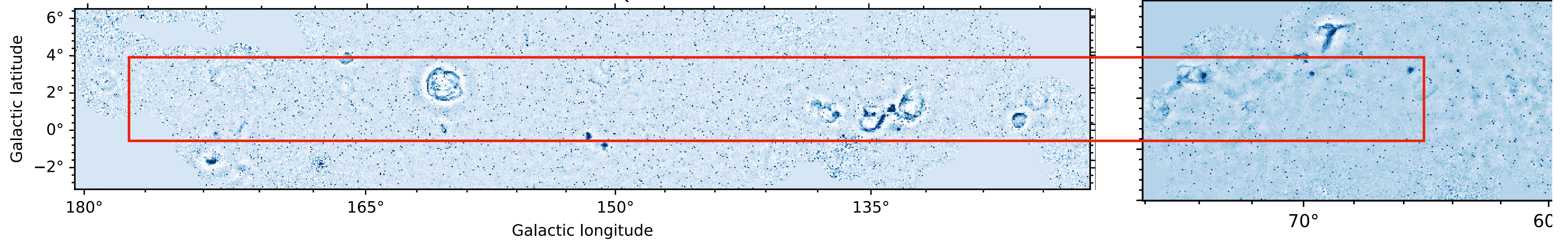


Region around $l = 54$

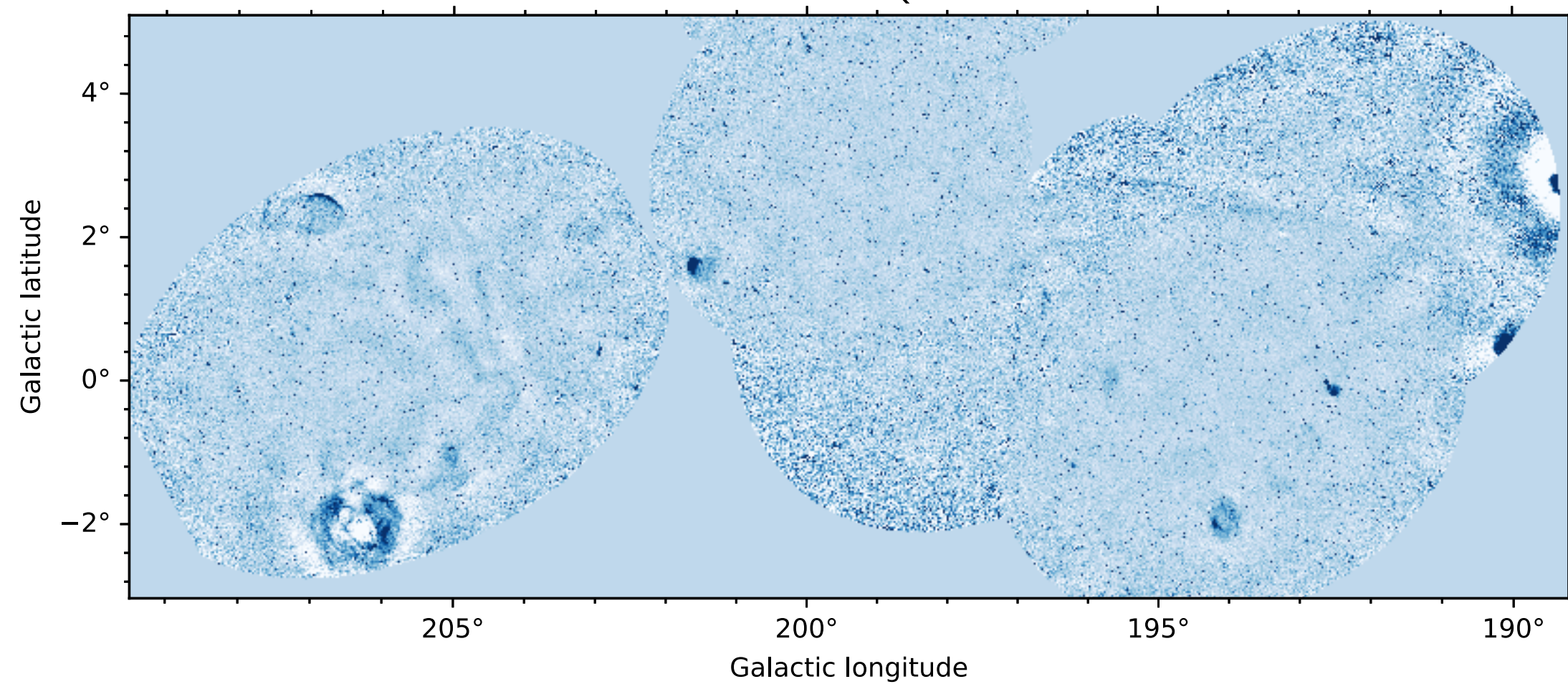
Region around $l = 46$

The second and third quadrants have less ancillary data

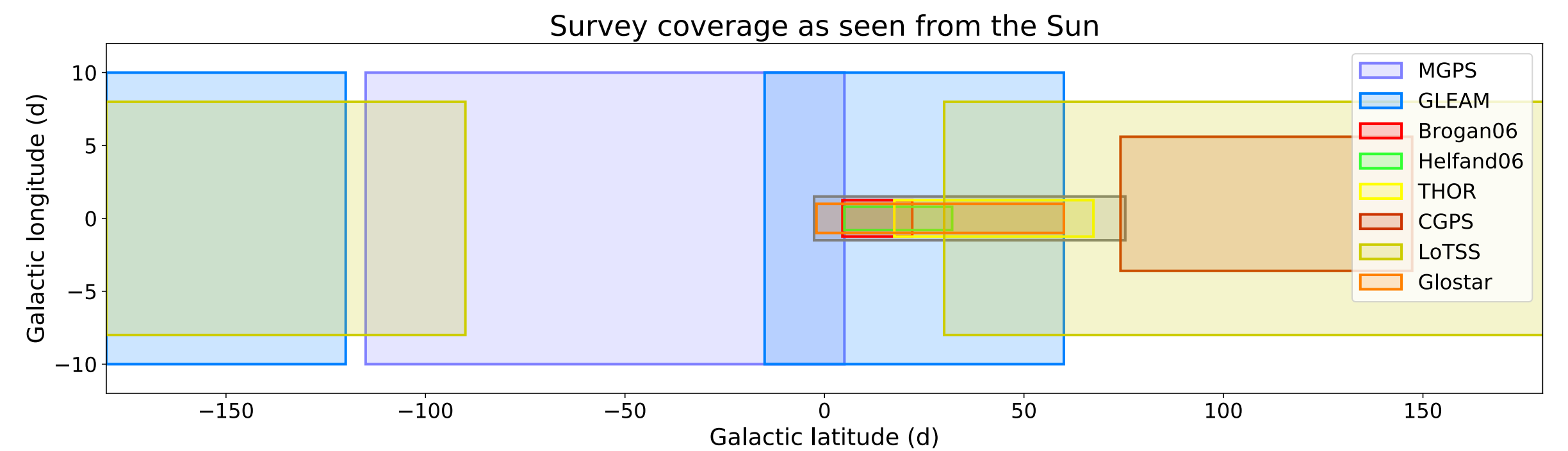
Second Galactic Quadrant



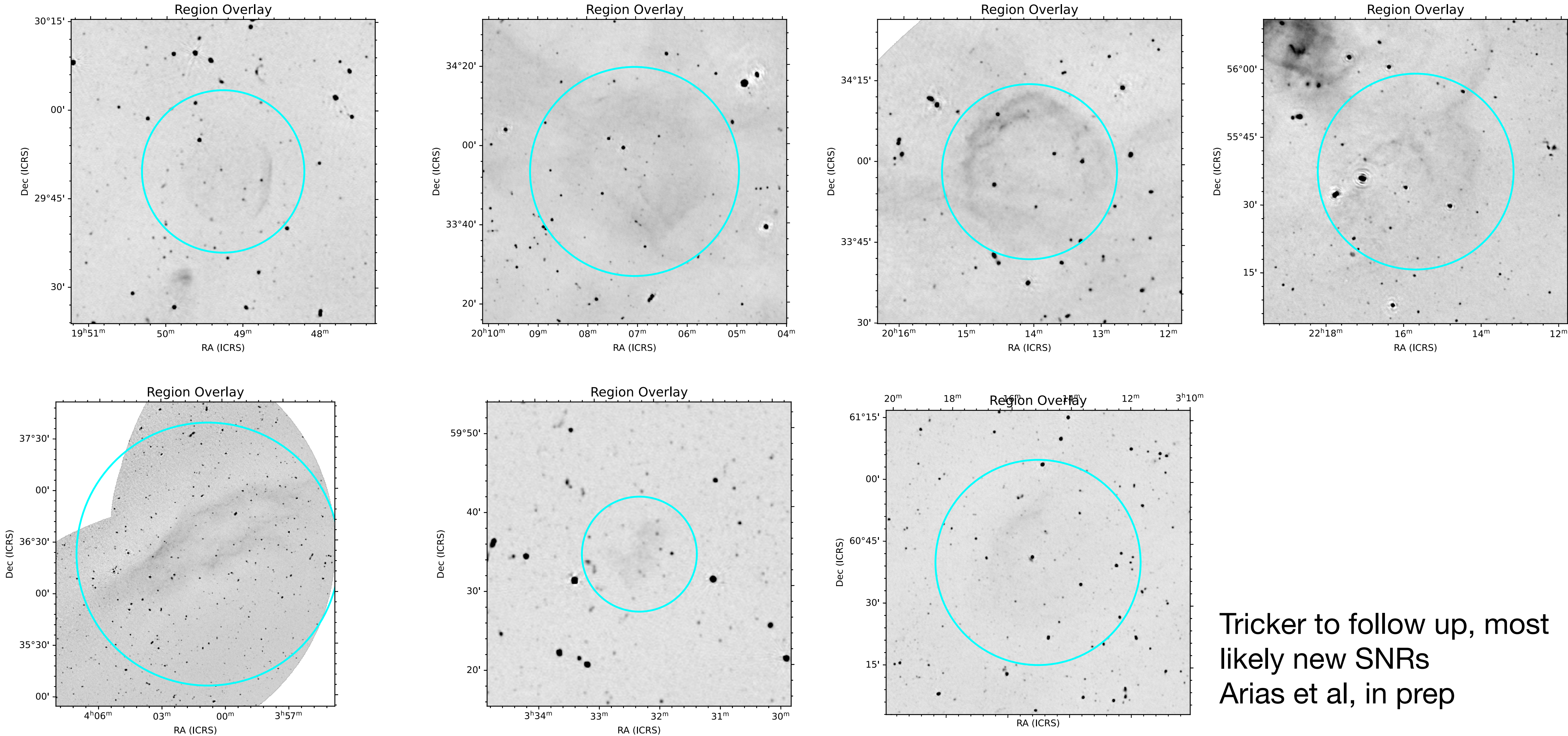
Third Galactic Quadrant



CGPS, $l = 66 - 175$

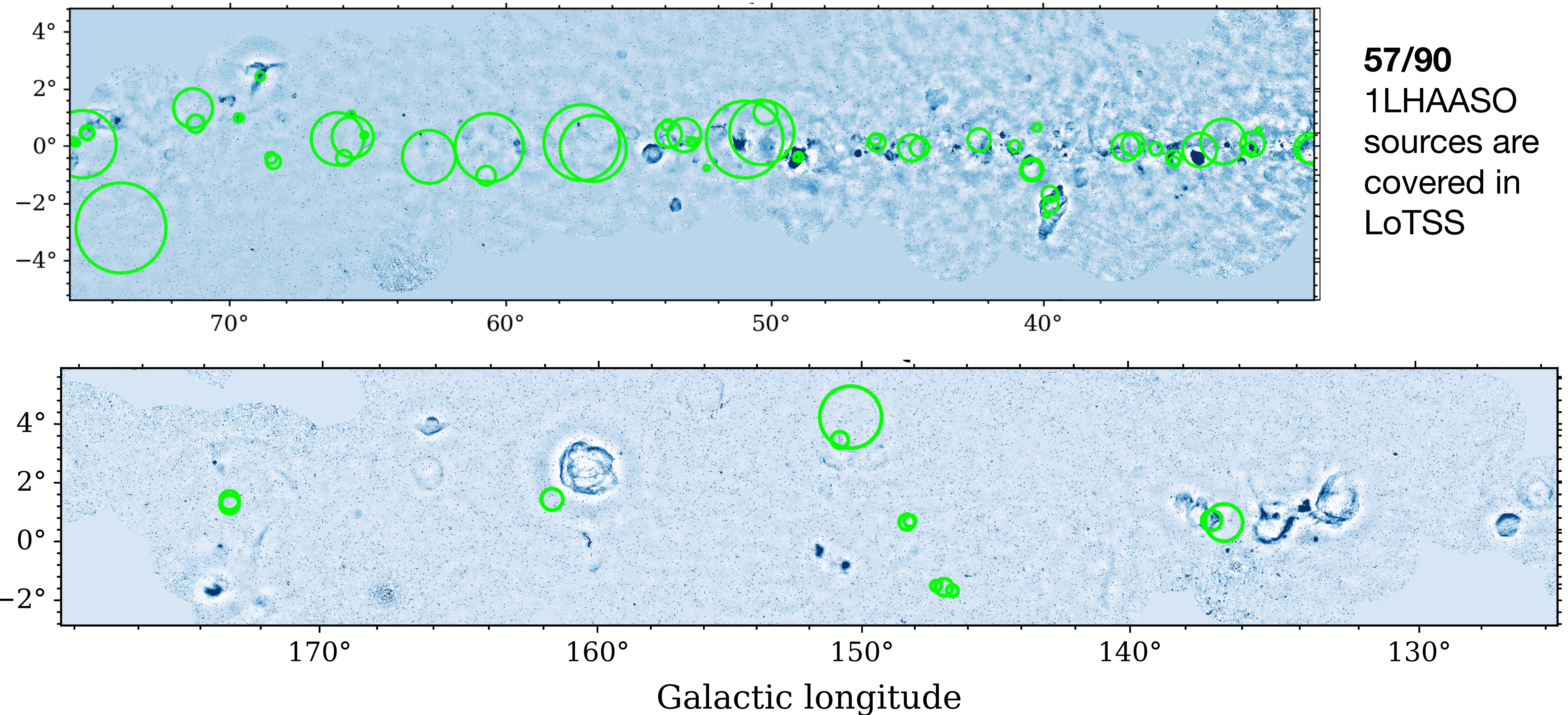


Emptier fields, new sources faint & extended

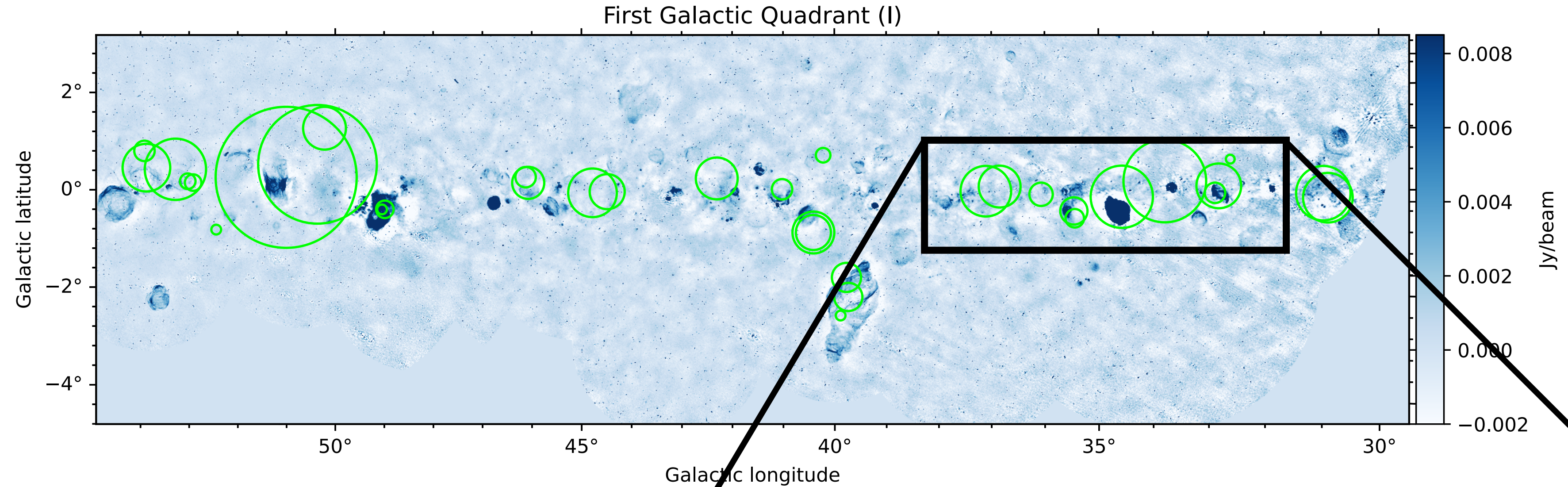


Tricker to follow up, most likely new SNRs
Arias et al, in prep

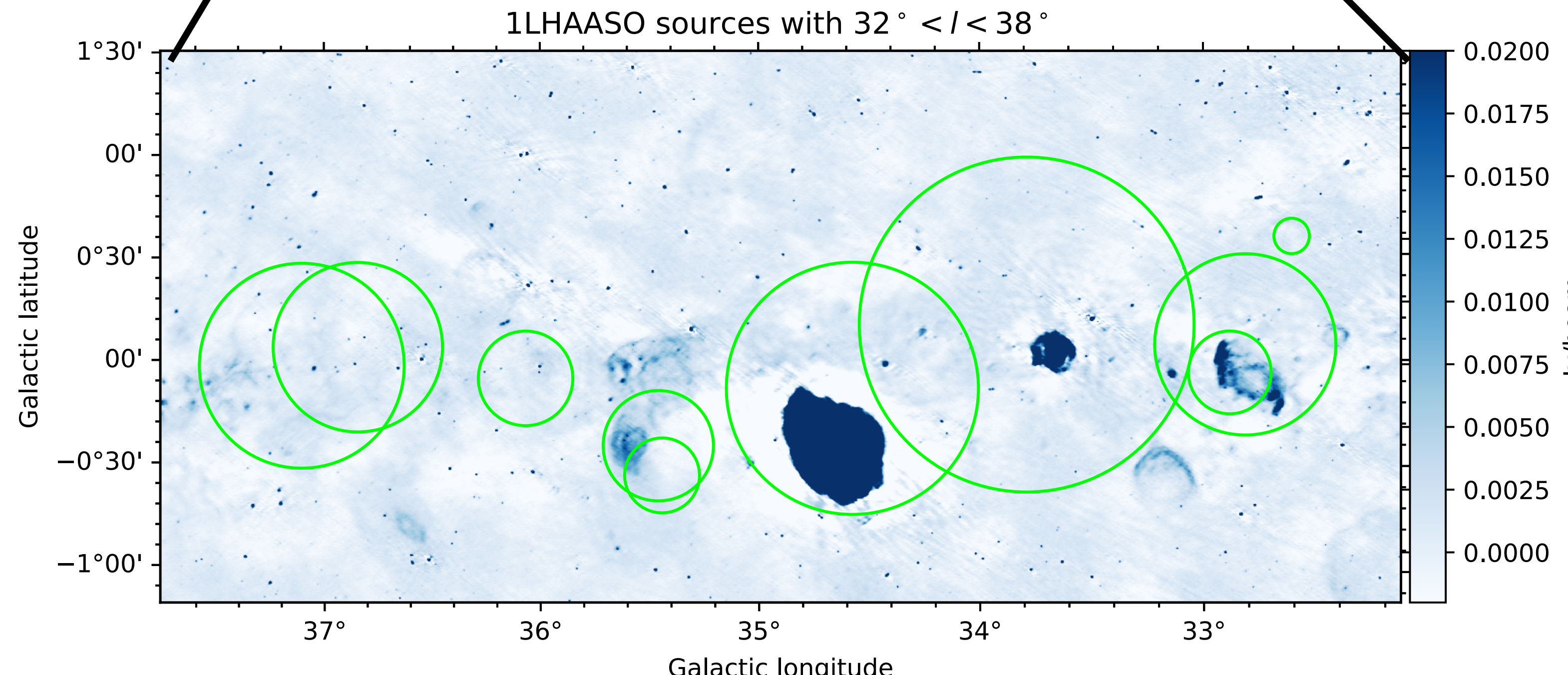
Follow-up of 1LHAASO sources



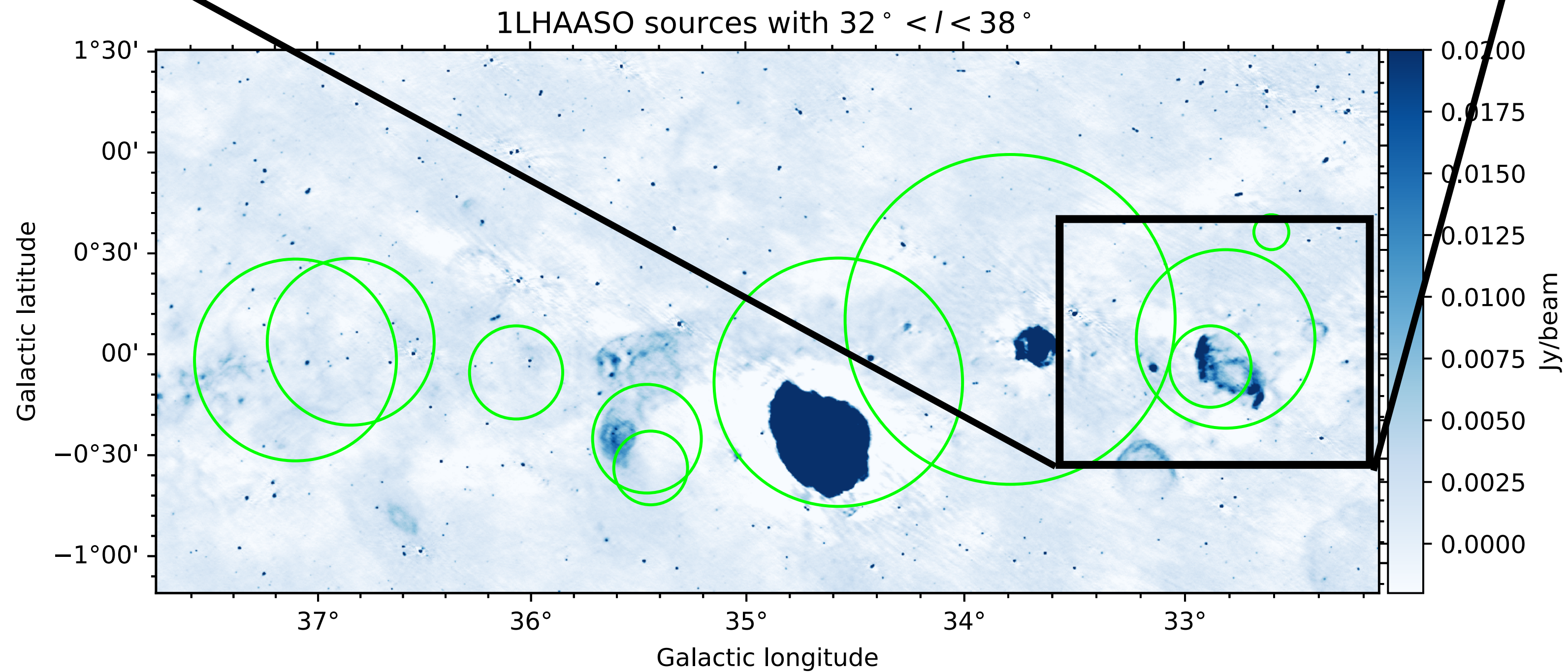
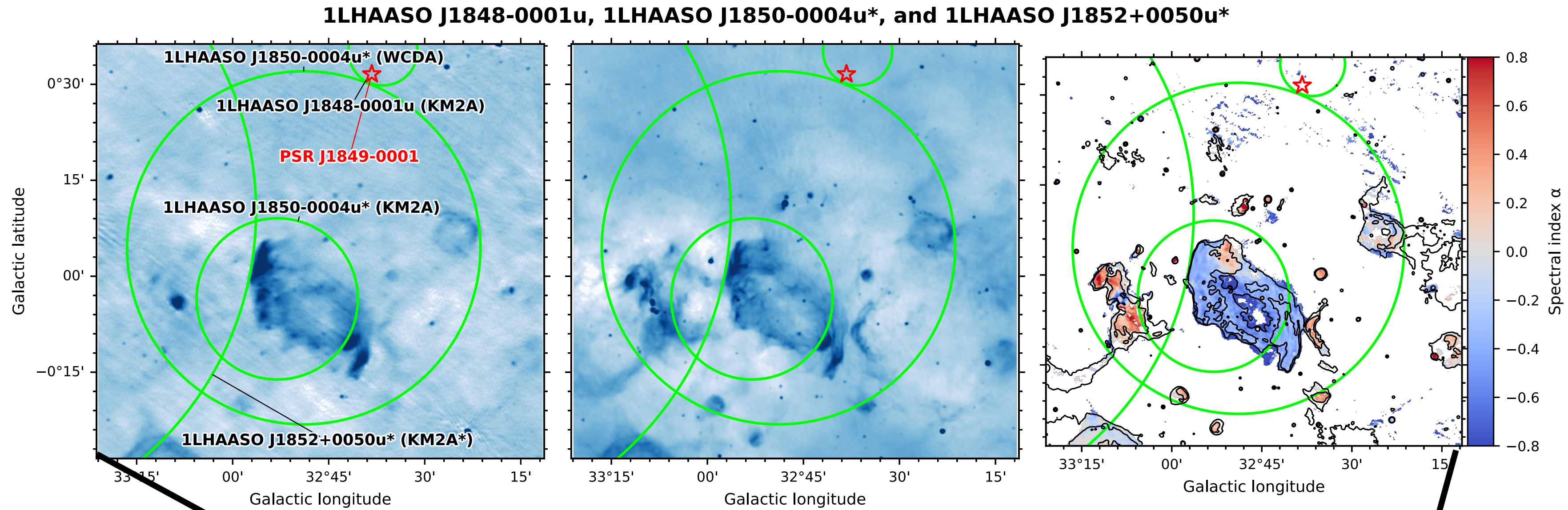
Main issue with LHAASO follow-up: source confusion



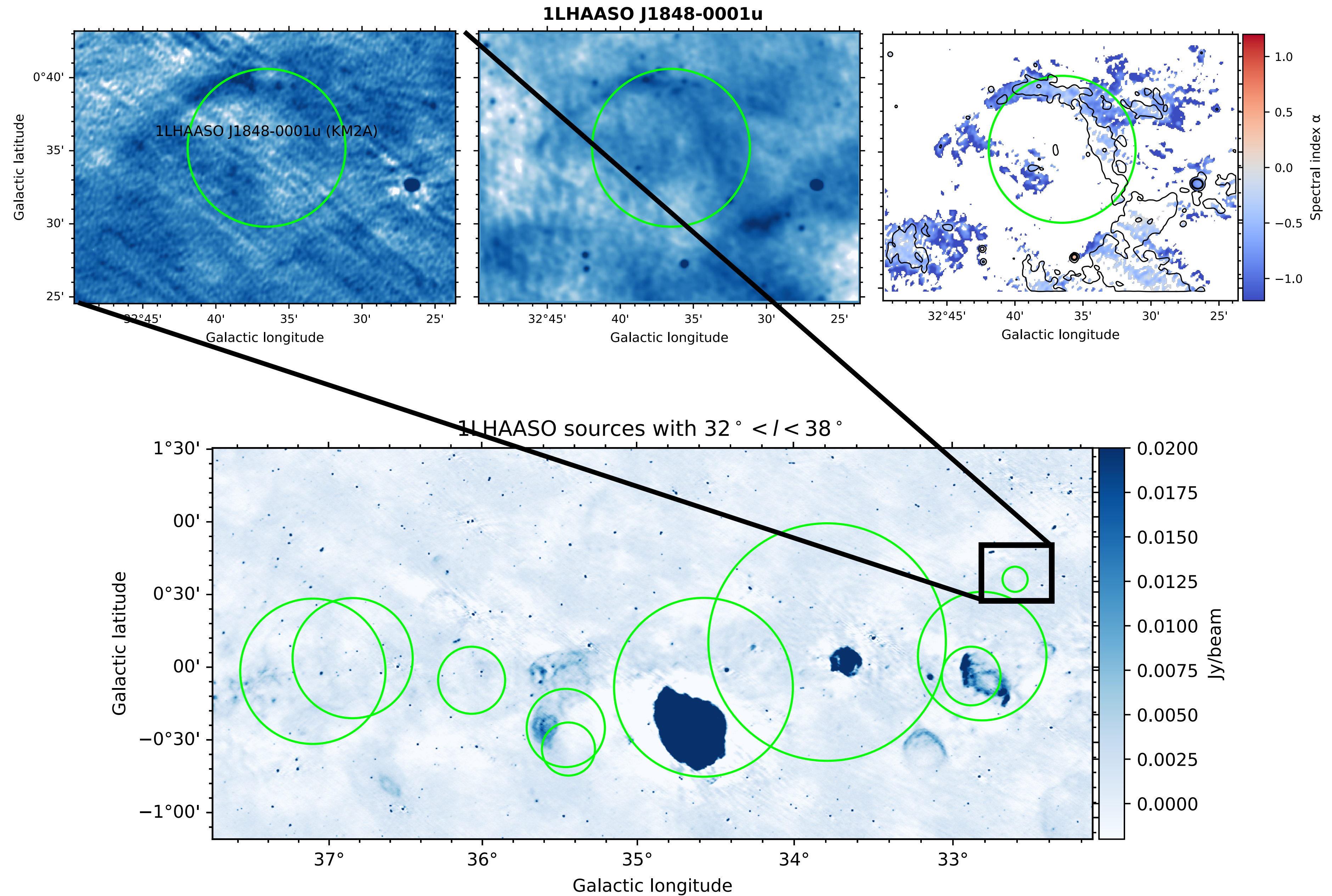
The majority of sources are at low Galactic latitudes, where the probability of chance alignment is high — difficult to establish that a radio source is a counterpart to a 1LHAASO source



LHAASO sources with LoTSS - MeerKAT GPS observations

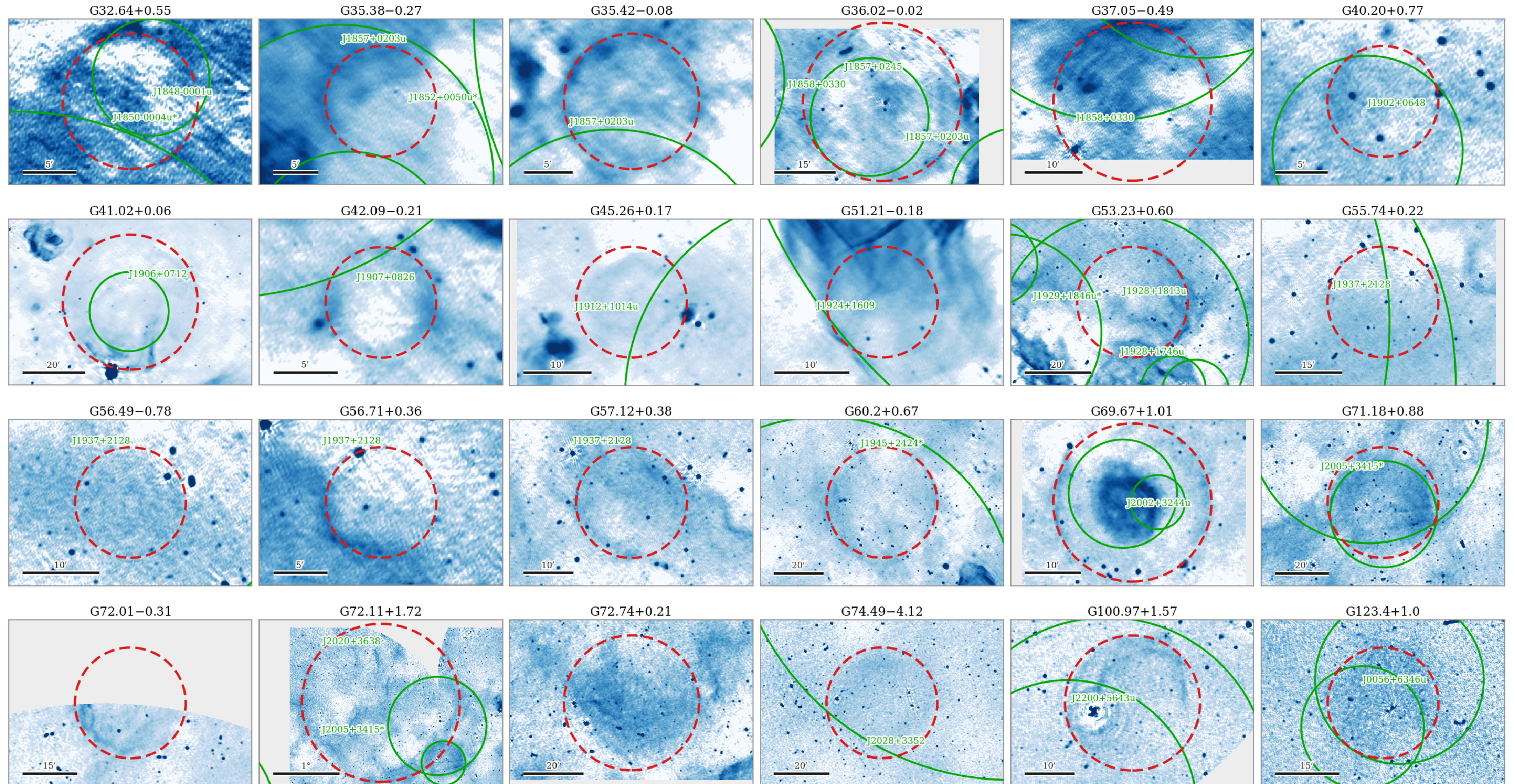


LHAASO sources with LoTSS - MeerKAT GPS observations



24 new SNR candidates discovered in or nearby a 1LHAASO source

--- new SNR candidate (this work) — 1LHAASO r_{39}

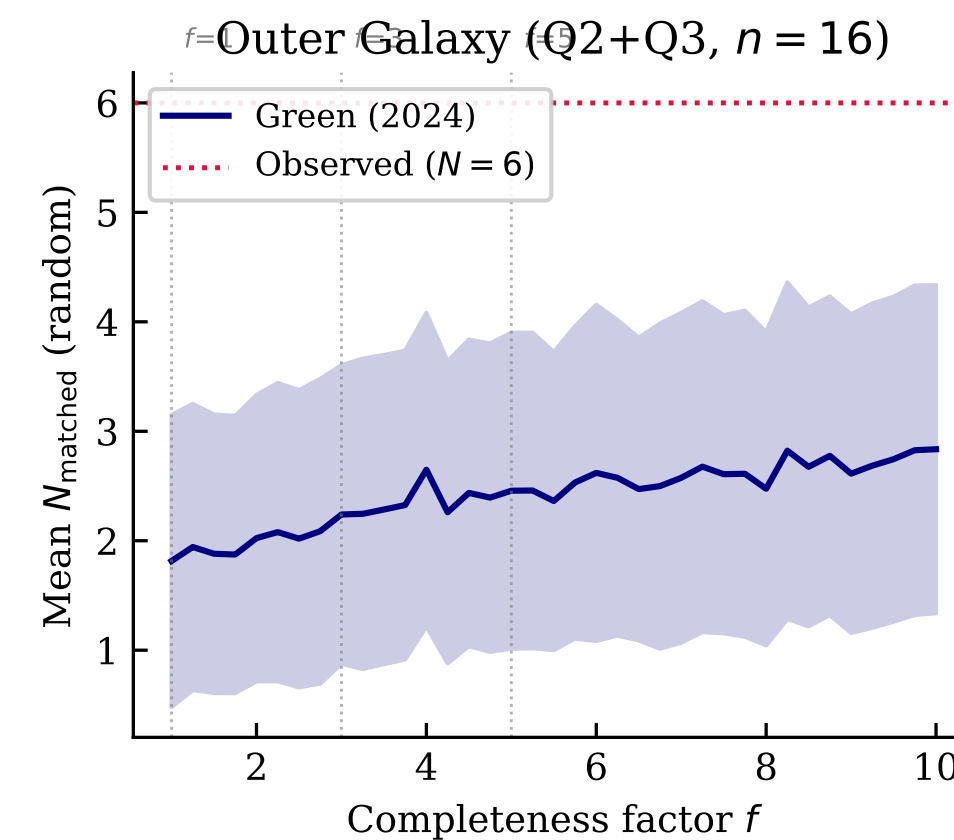
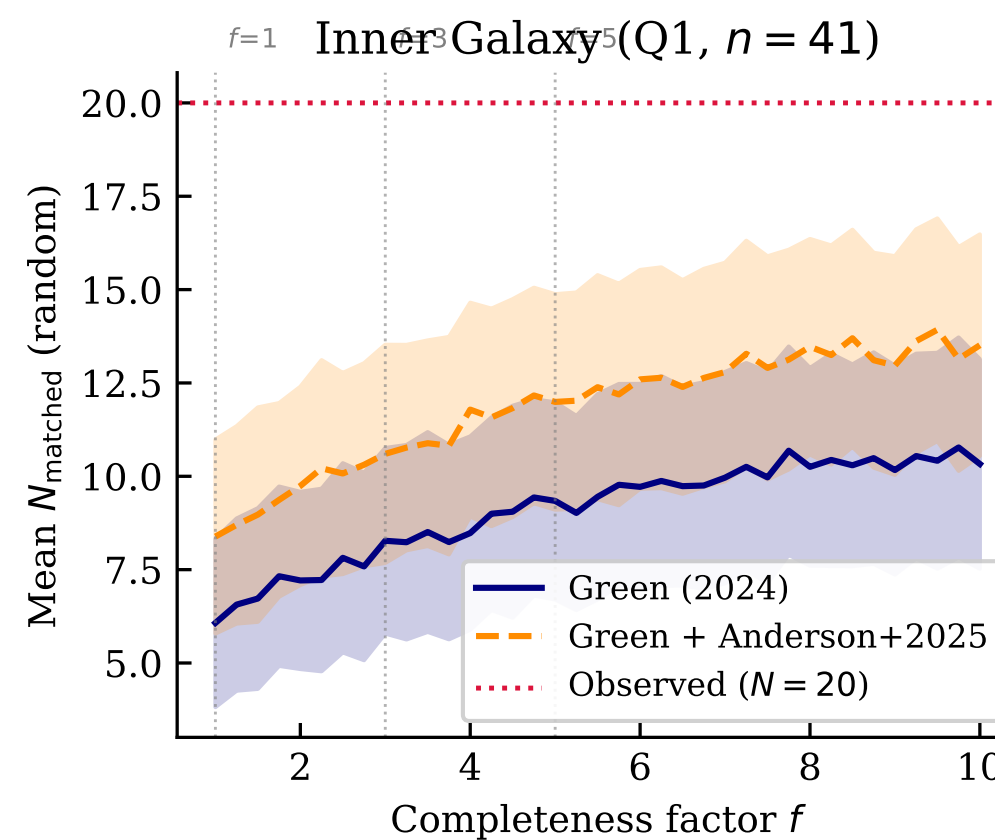
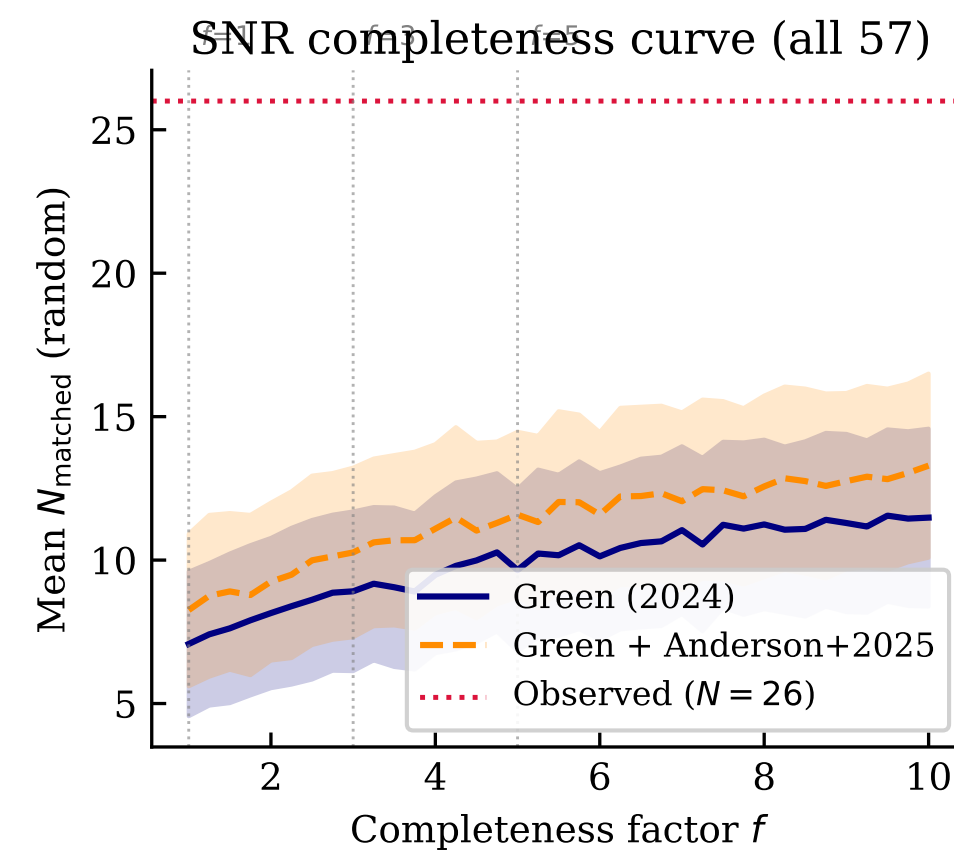
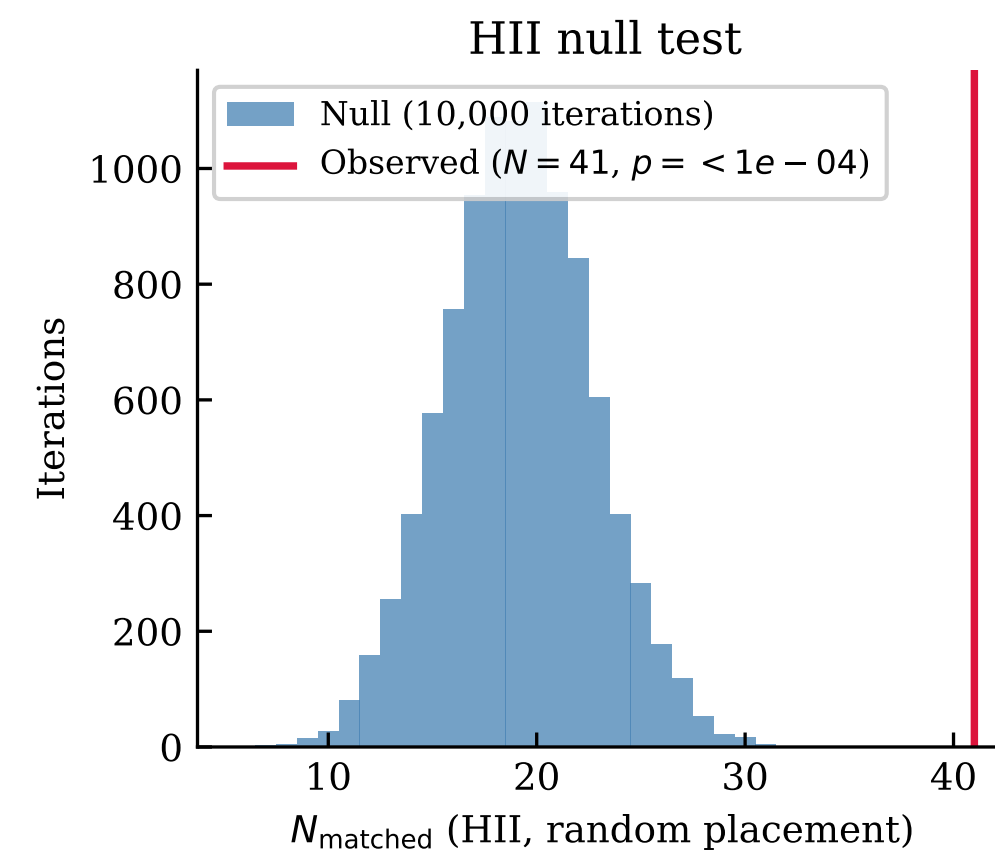


SNR association

— 24 new SNR candidates overlapping or surrounding the LHAASO sources

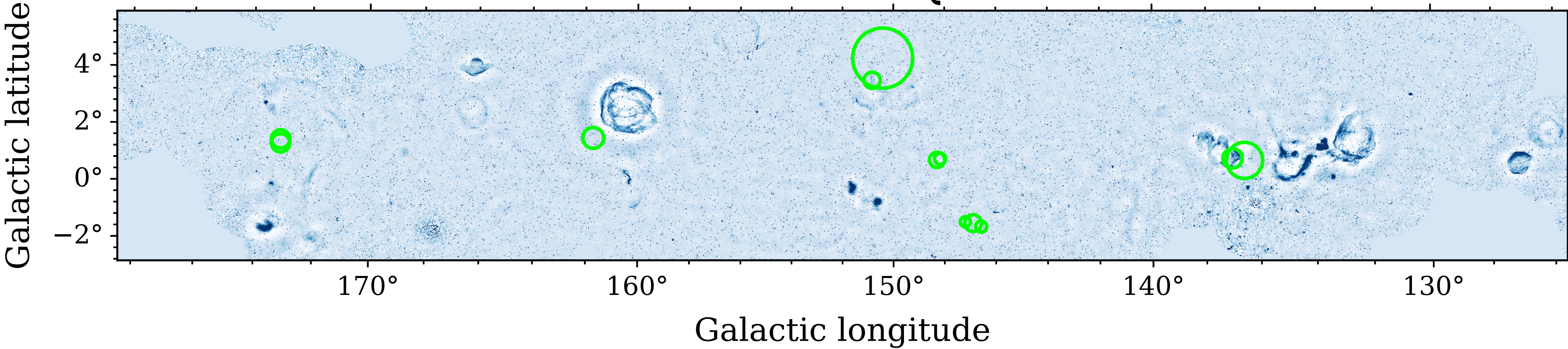
— Very difficult to establish association, can make statistical claims:

- 46% (26/57) of LHAASO sources overlap a known SNR; even at a 10× larger than catalogued SNR population, random placement yields at most ~12 overlaps
- Including the 19 new LOFAR SNR candidates that overlap a LHAASO source, 40/57 sources (70%) are coincident with an SNR or SNR candidate
- After correcting for expected chance alignments, **$\geq 25\text{--}33\%$ of LHAASO sources are genuinely associated with SNR environments**, ~50% including the new candidates
- **At least 30%** show zero SNR signal even in LOFAR

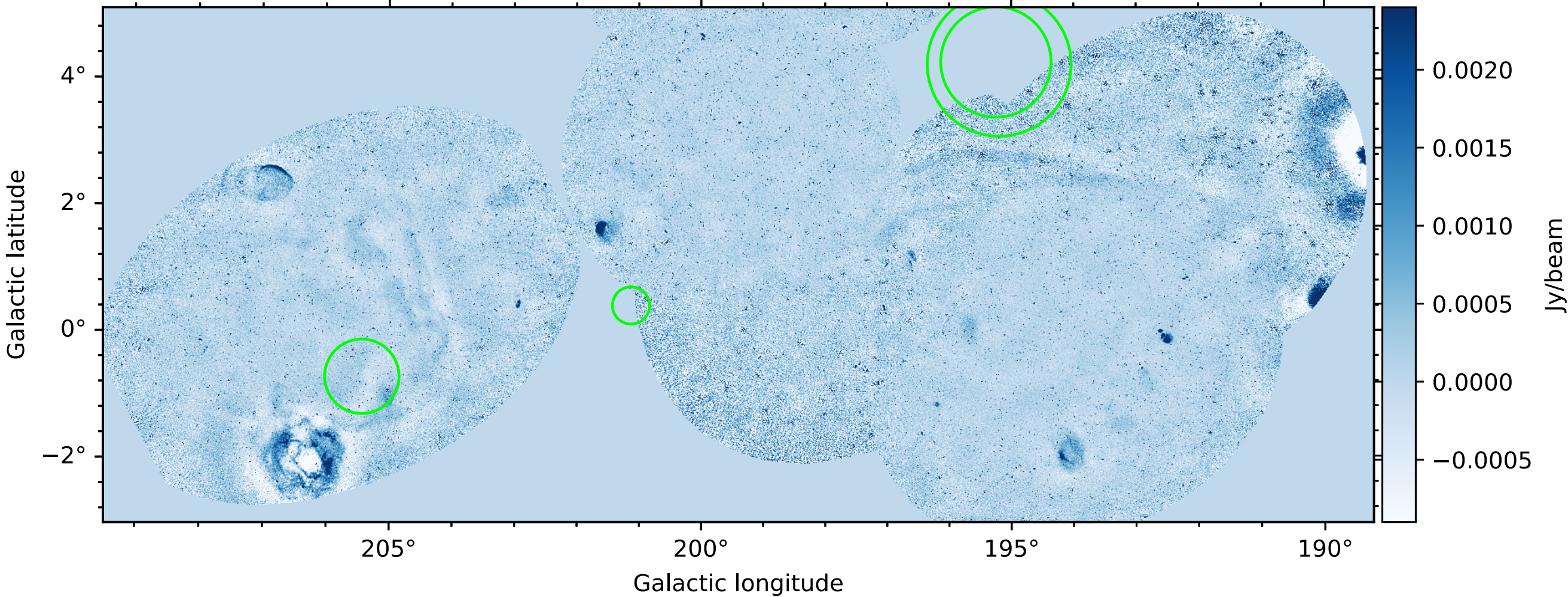


On the other side of the Galactic Plane...

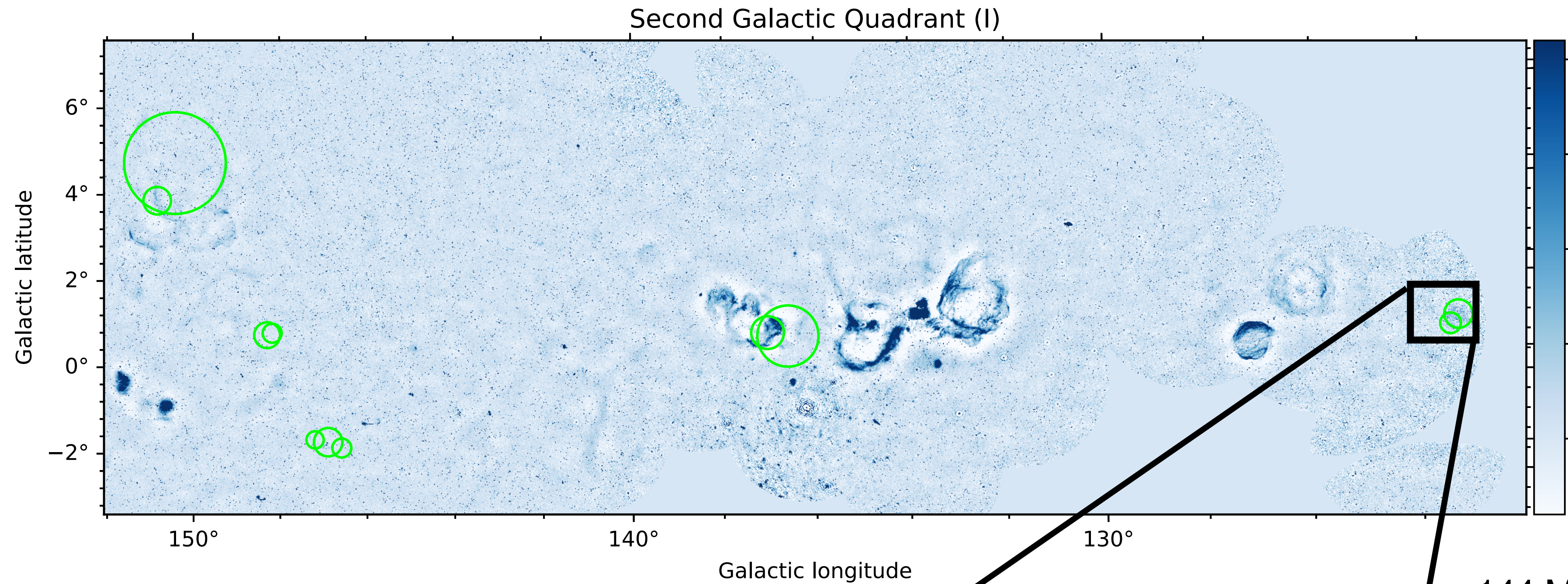
Second Galactic Quadrant



Third Galactic Quadrant

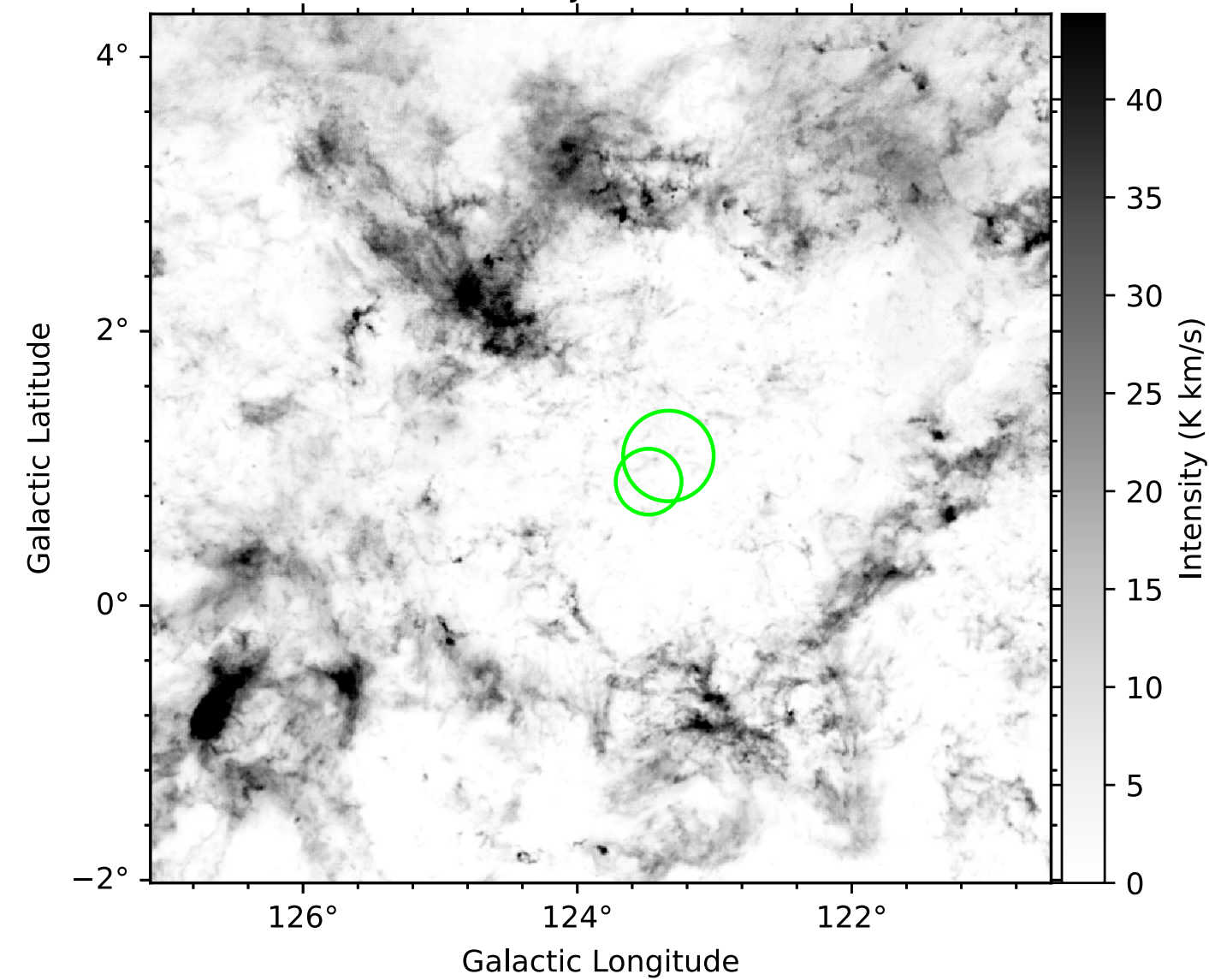


The density of both 1LHAASO and radio sources is much lower; lower probability of chance alignment



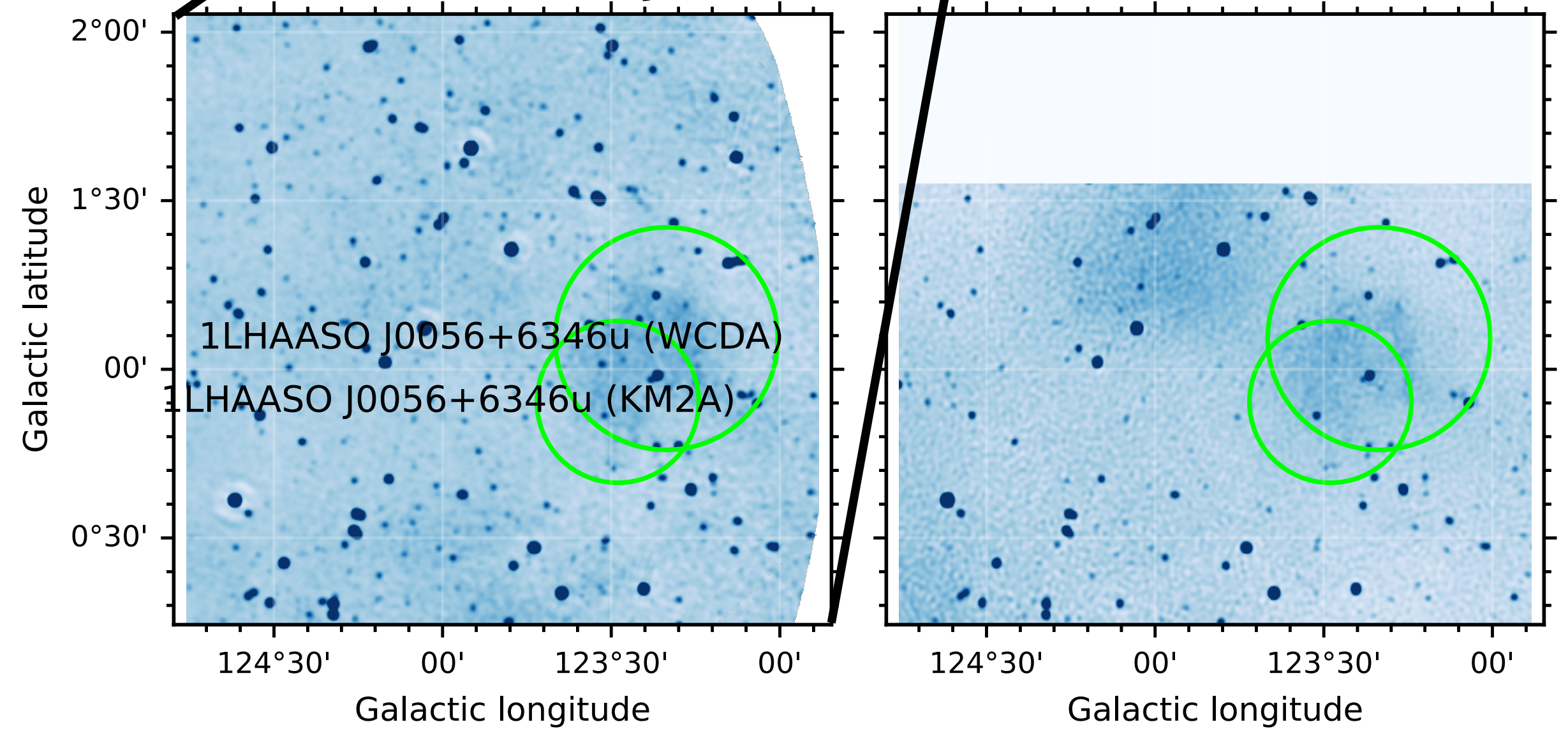
144 MHz (left) 1.4 GHz (right)

1LHAASO J0056+6346u



Molecular cavity
described in
LHAASO collab.
et al 2025

1LHAASO J0056+6346u



9 new (seemingly) thermal, IR-dark shells: PWN, evolved HII regions, ?

G32.24−0.22

G33.85−0.06

G36.67−0.14

G42.62+0.16

G42.25+0.19

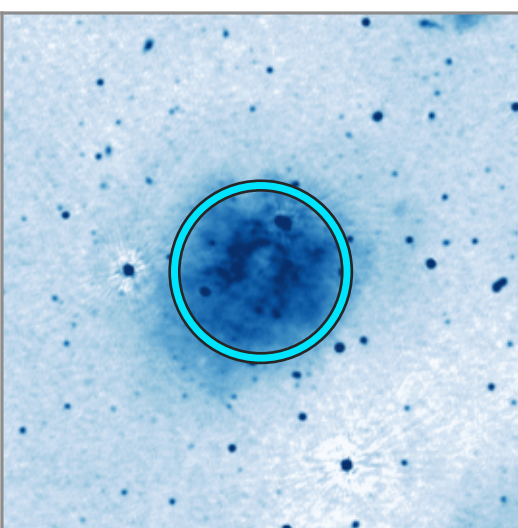
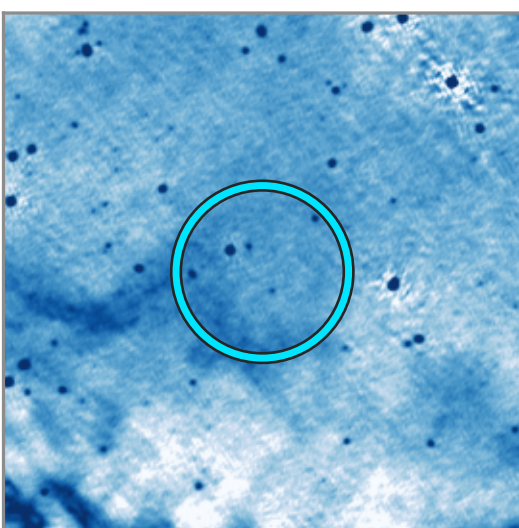
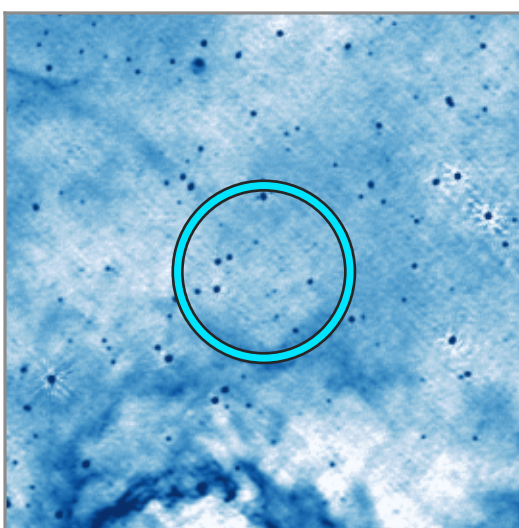
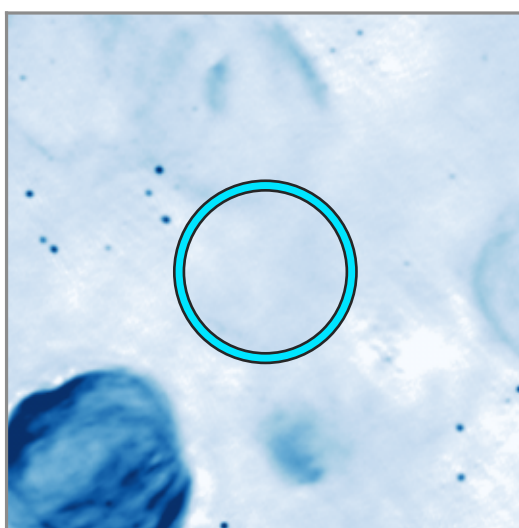
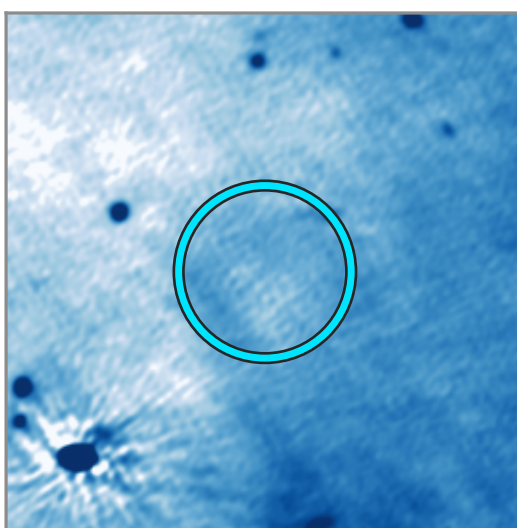
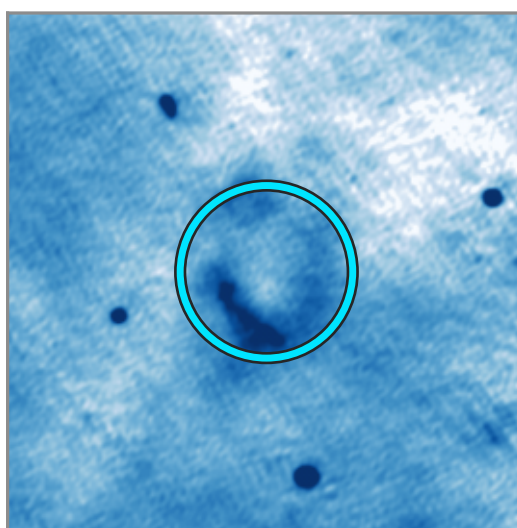
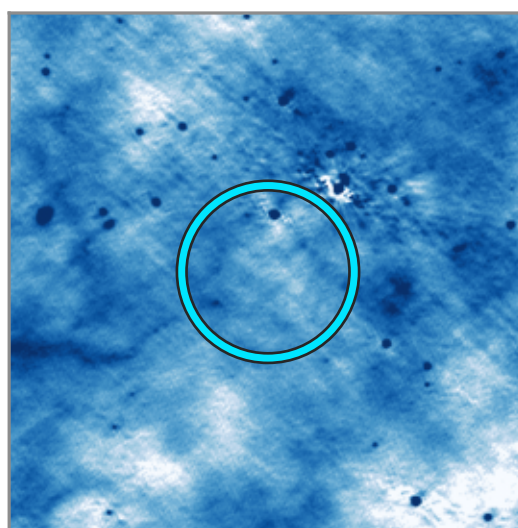
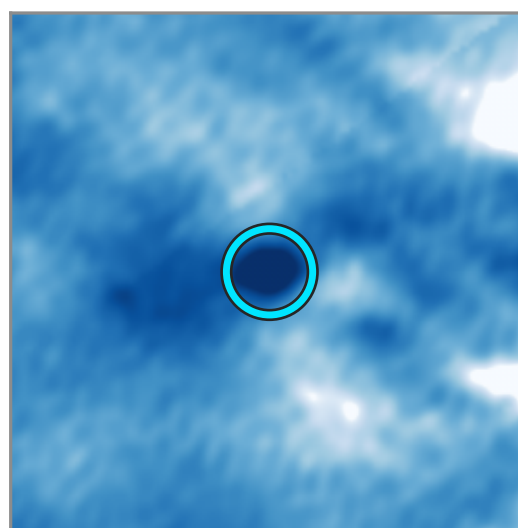
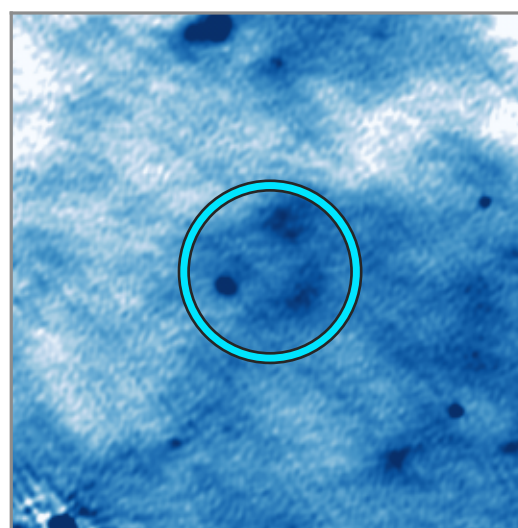
G46.53−0.00

G53.79+0.88

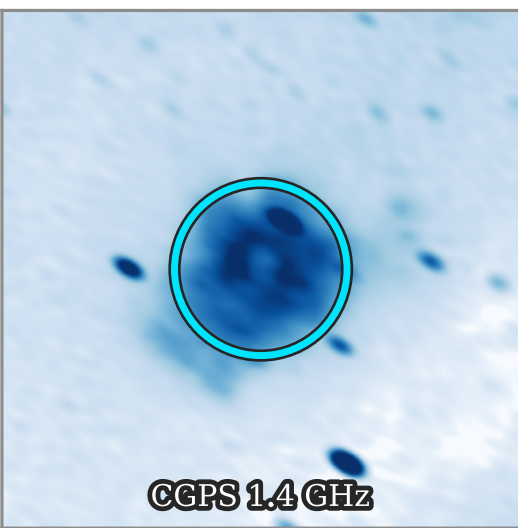
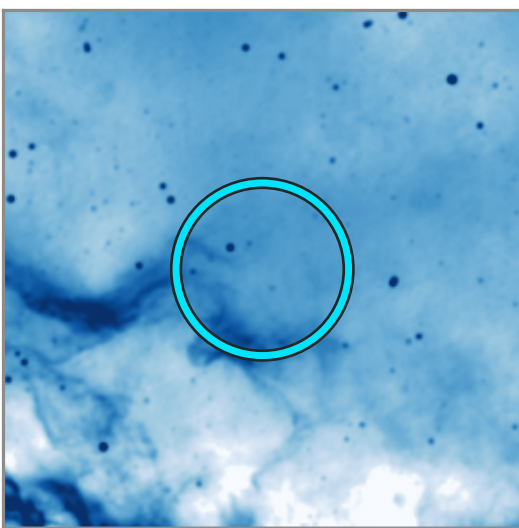
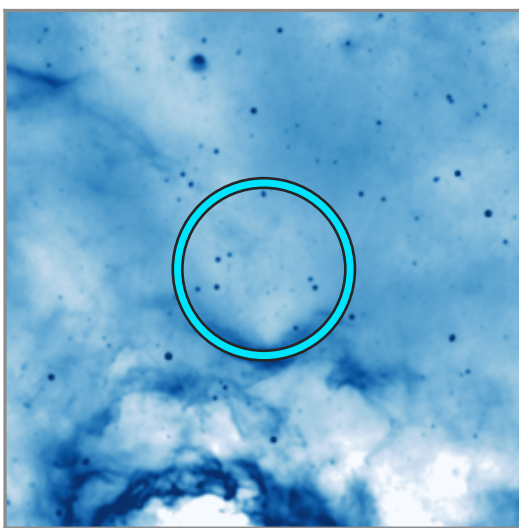
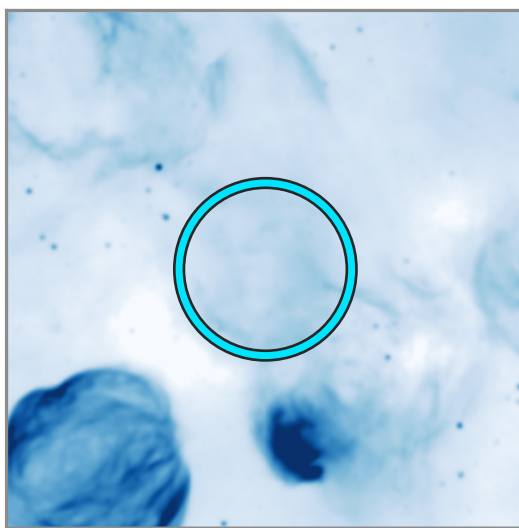
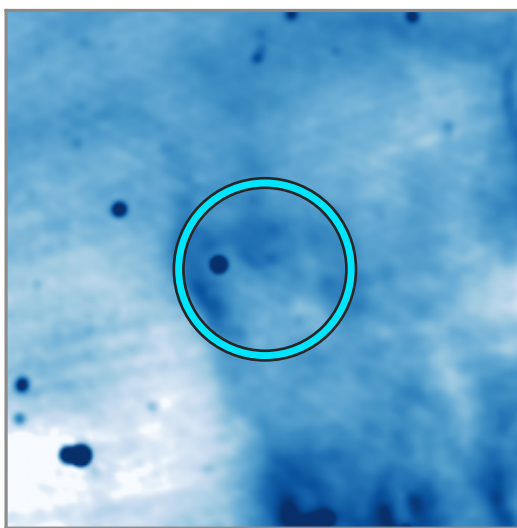
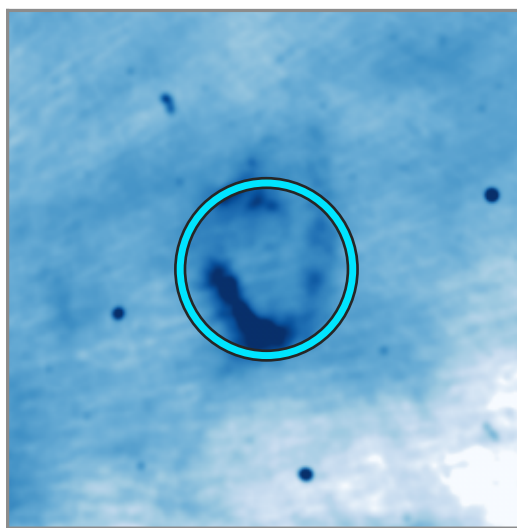
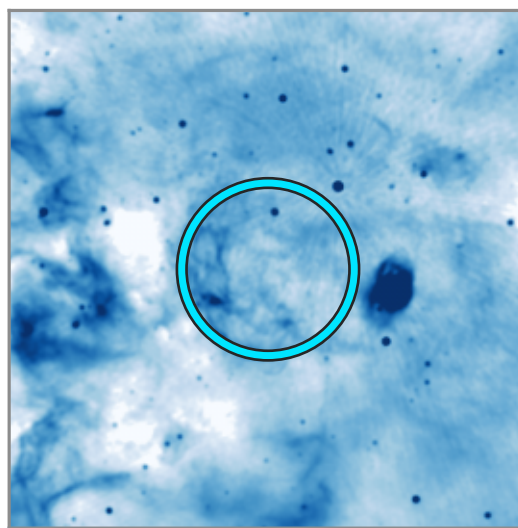
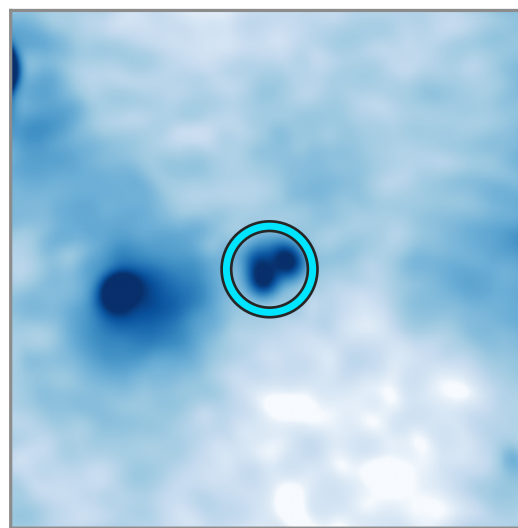
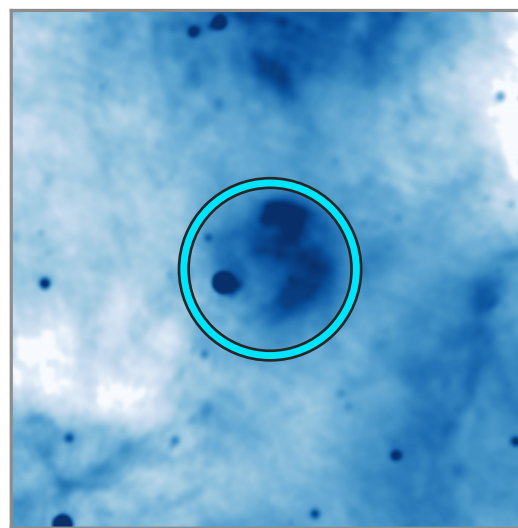
G53.57+0.75

G65.72+1.19

LOFAR
144 MHz

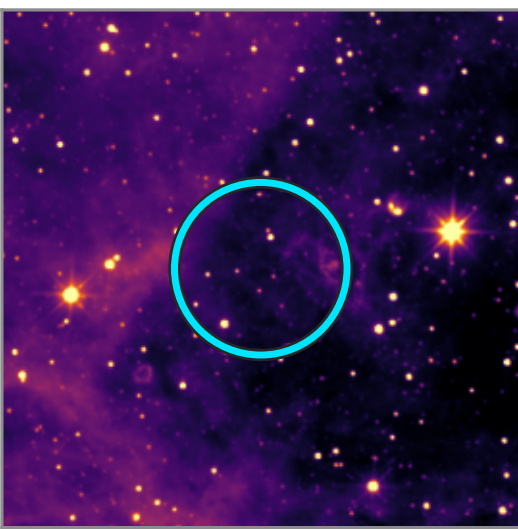
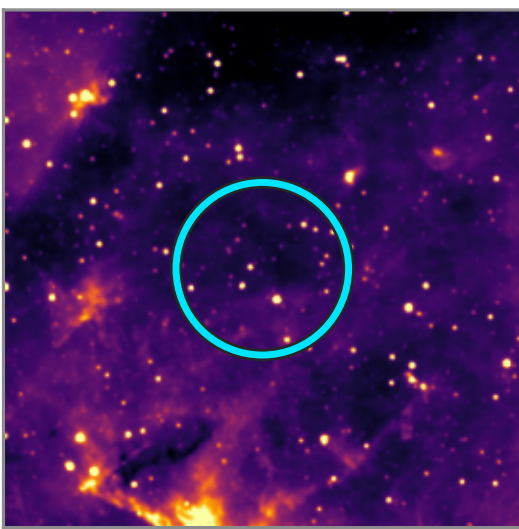
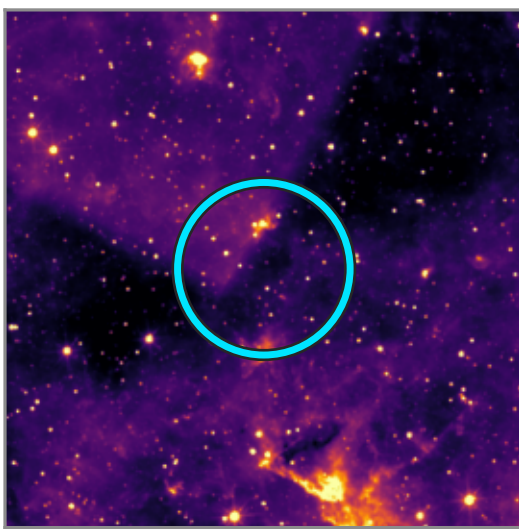
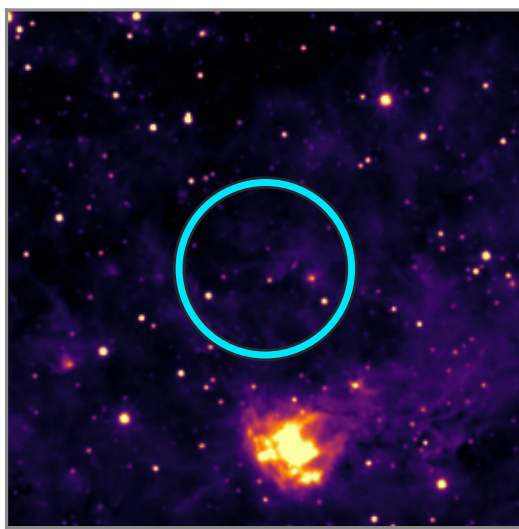
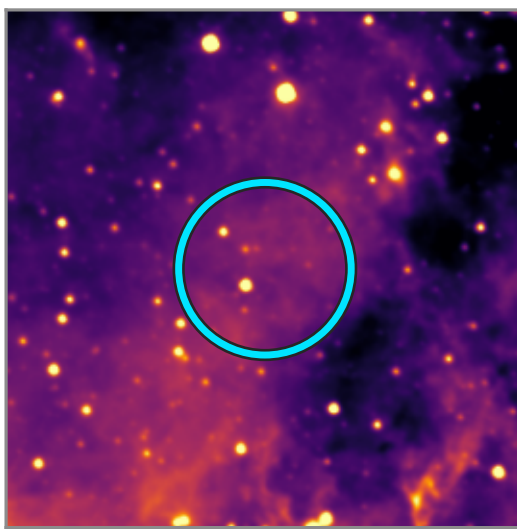
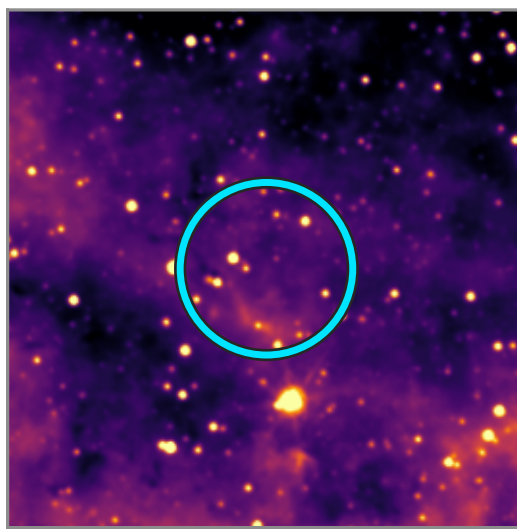
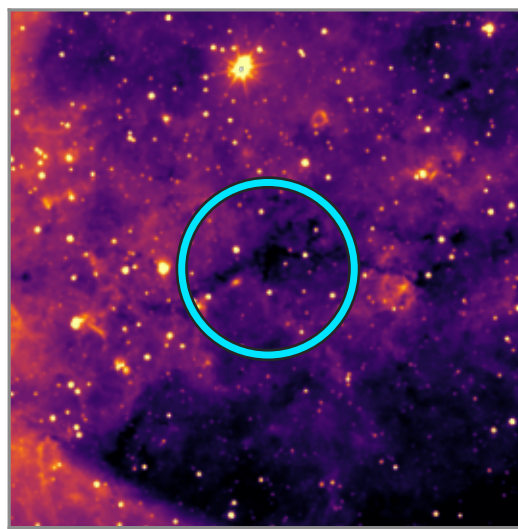
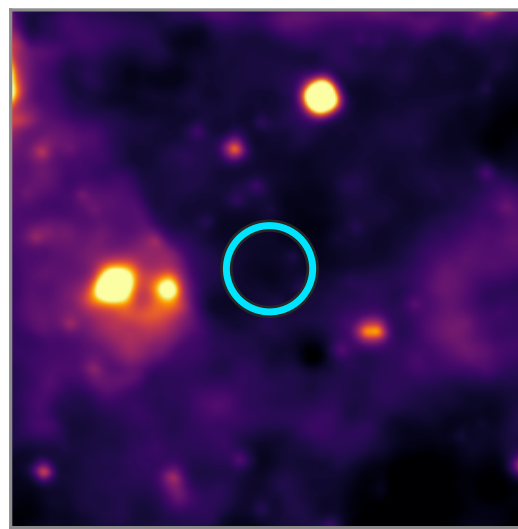
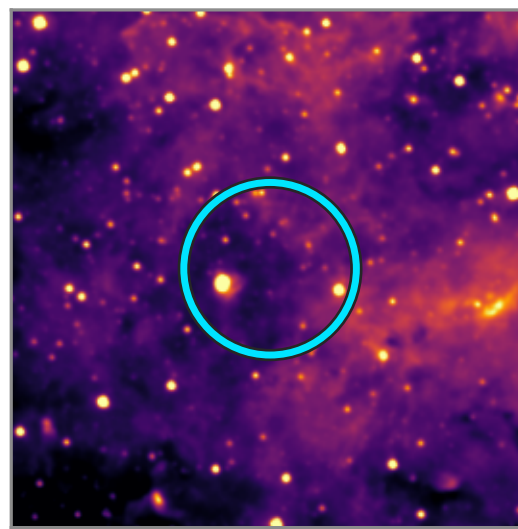


MeerKAT
1.3 GHz

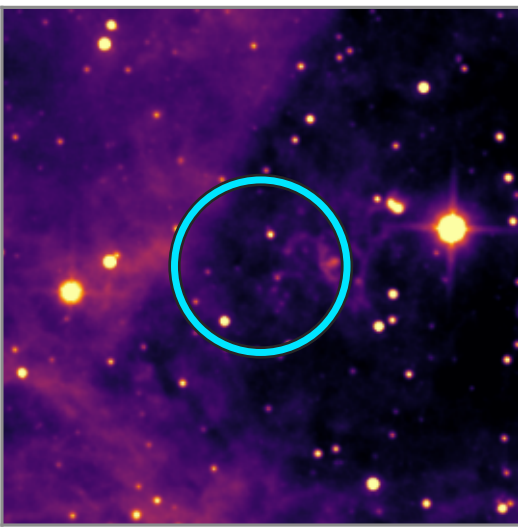
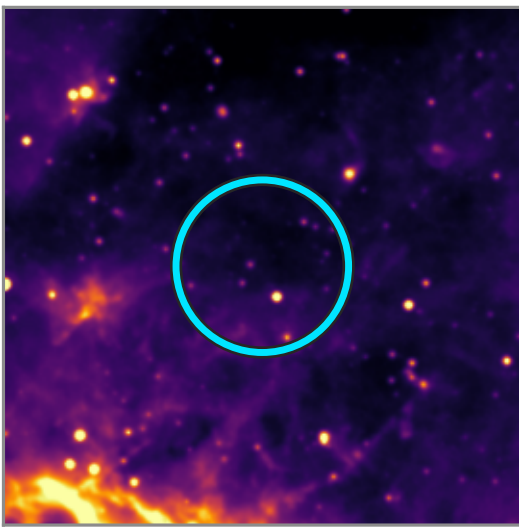
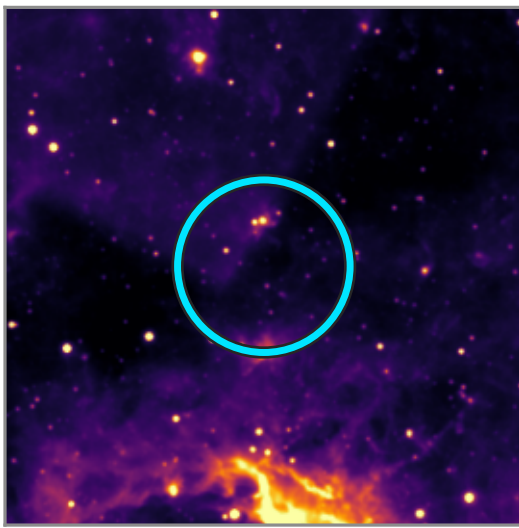
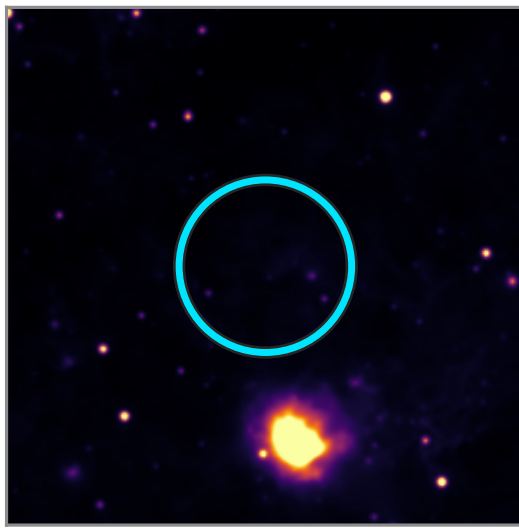
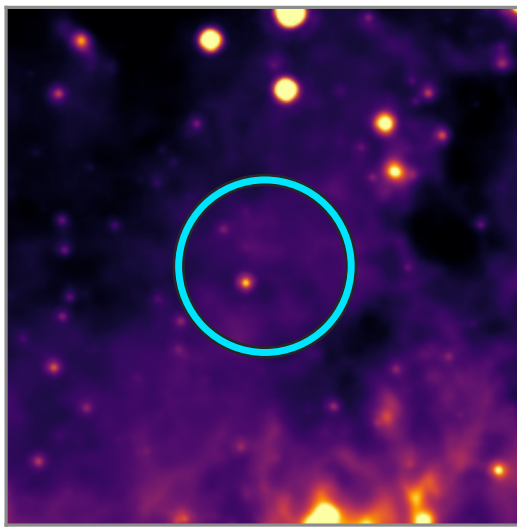
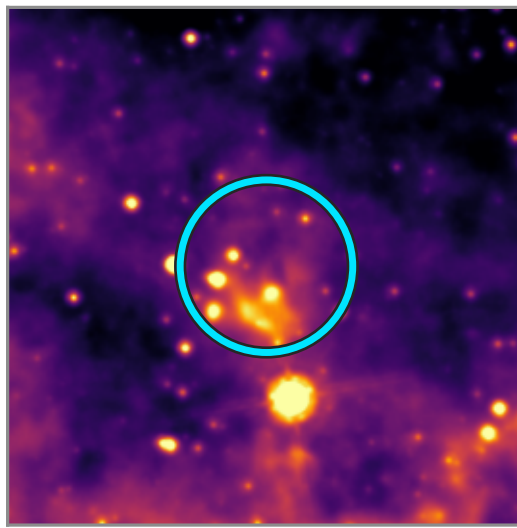
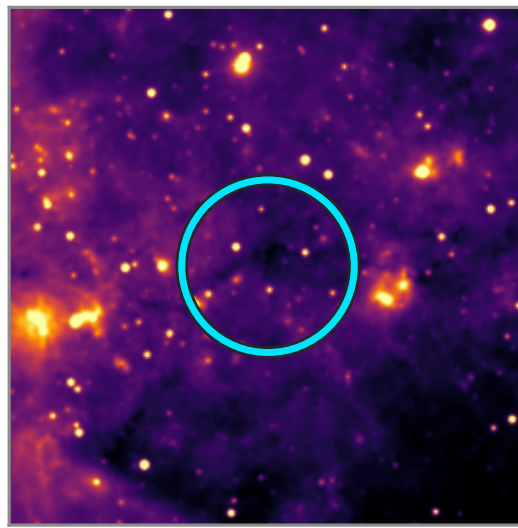
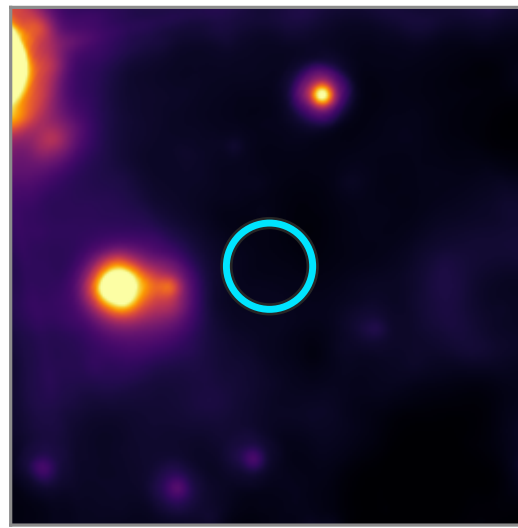
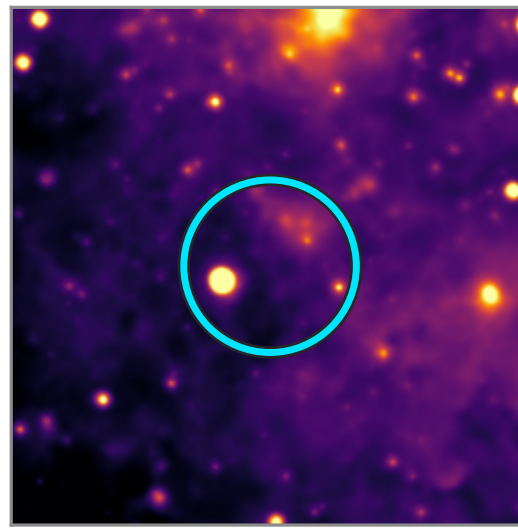


CGPS 1.4 GHz

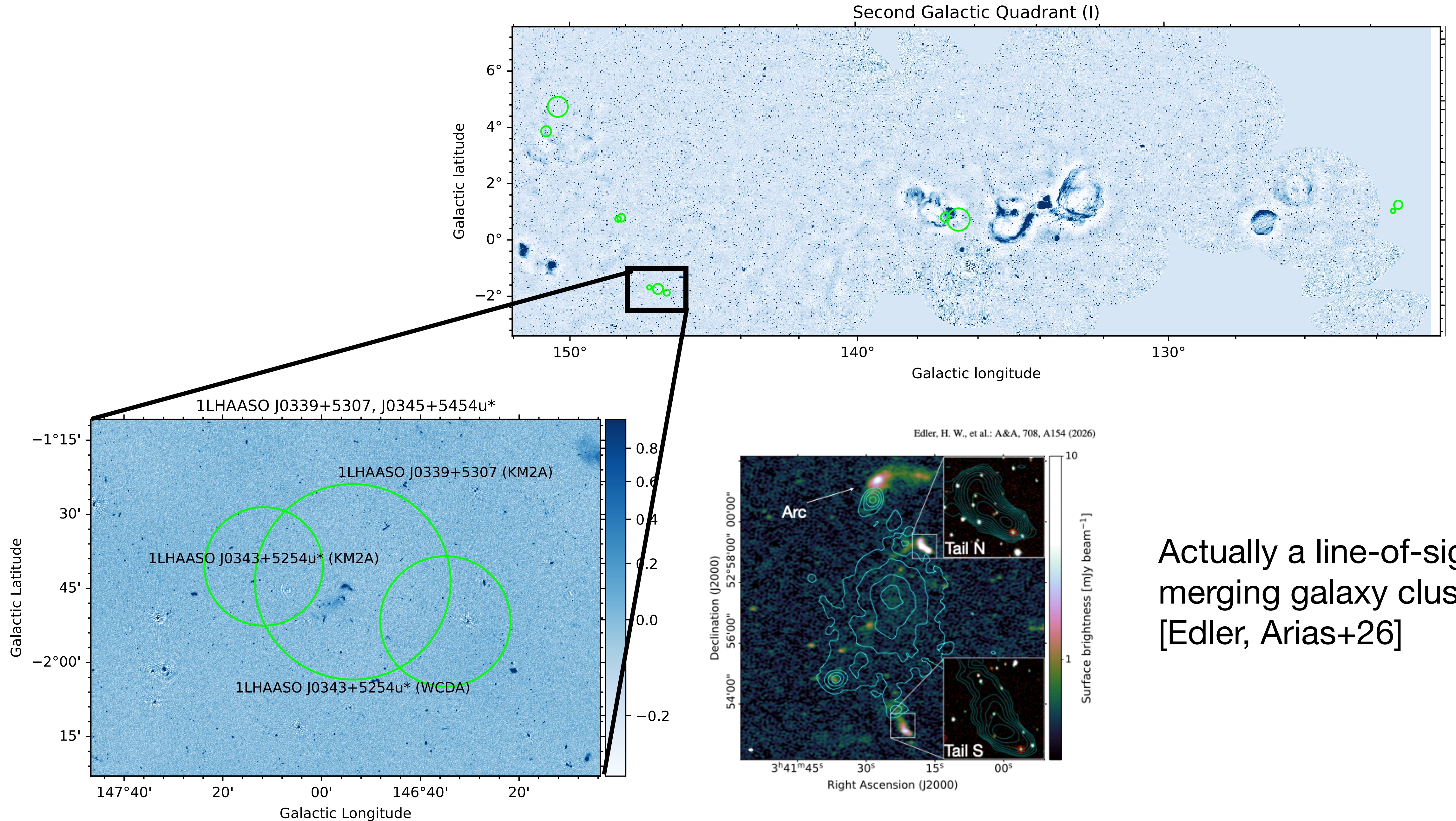
WISE
12 μm



WISE
22 μm



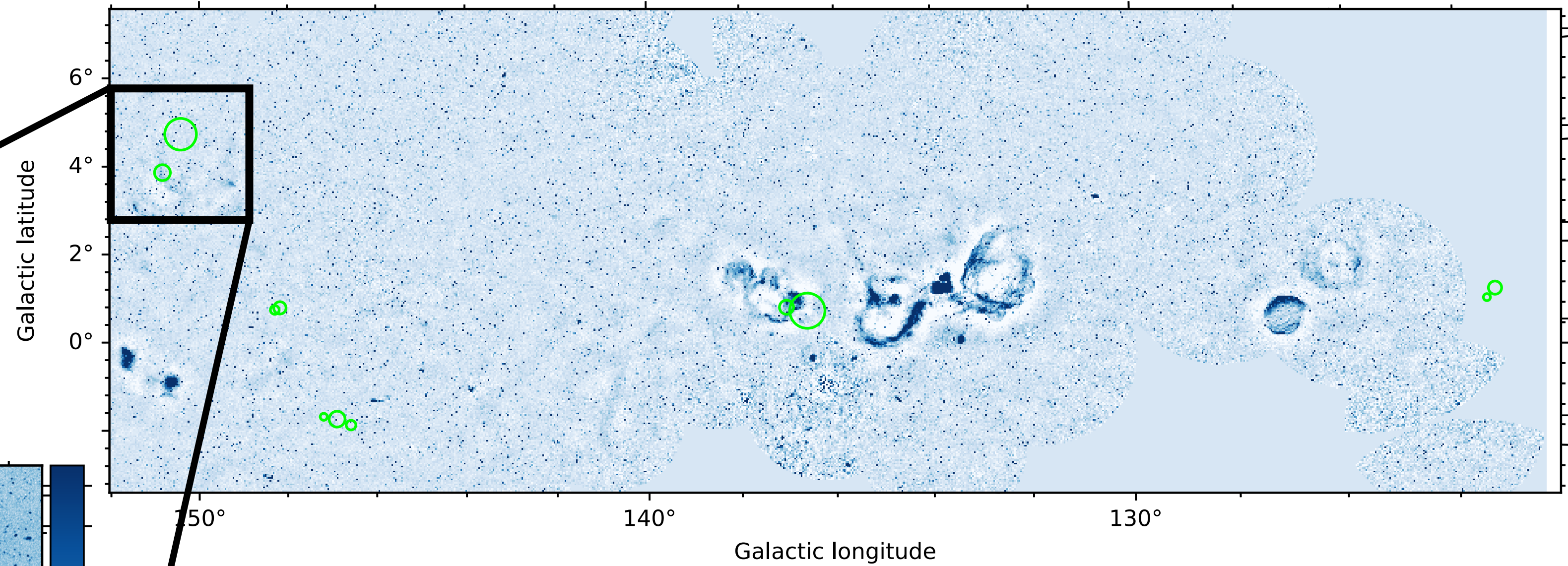
The Outer Galaxy



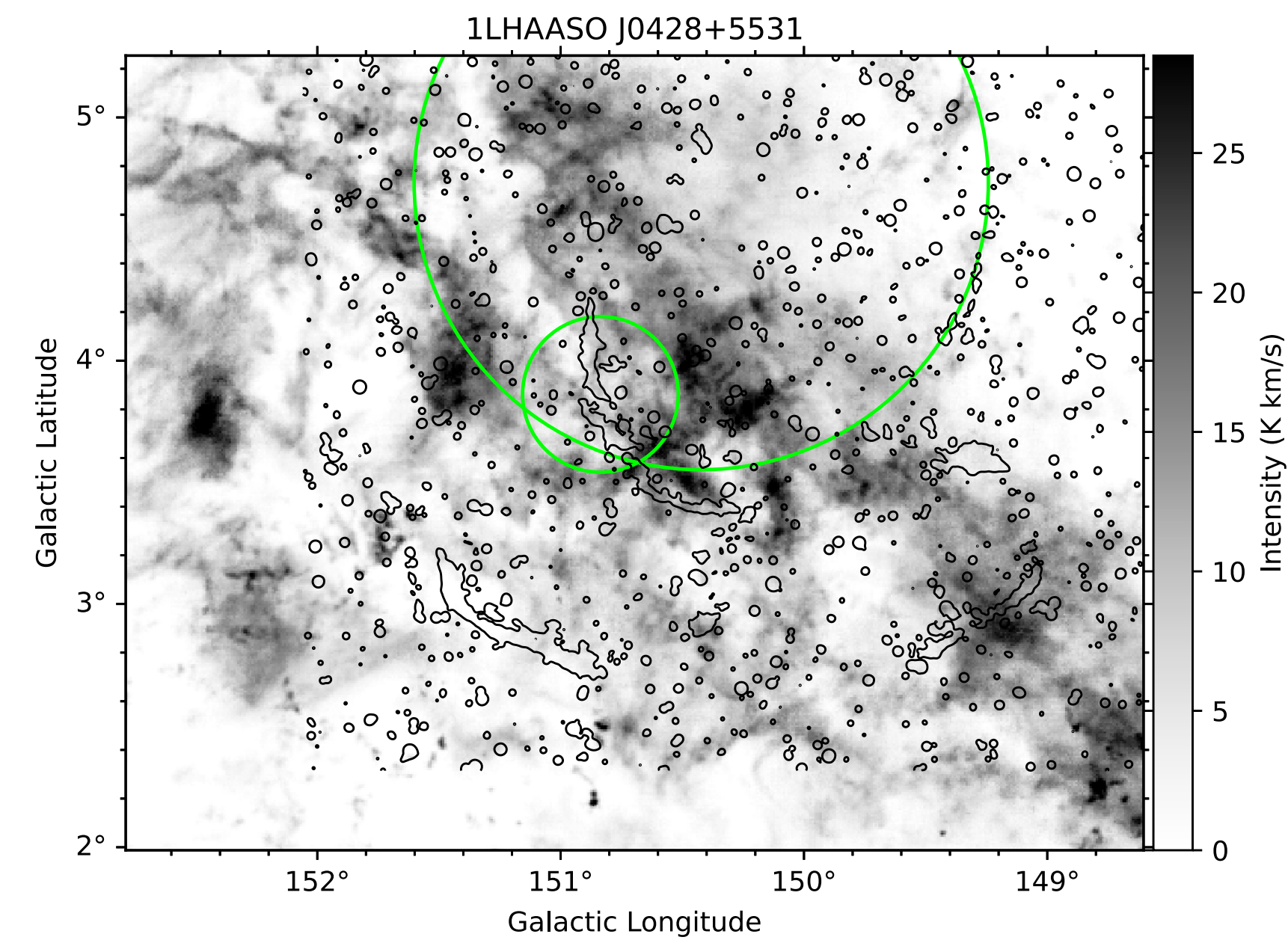
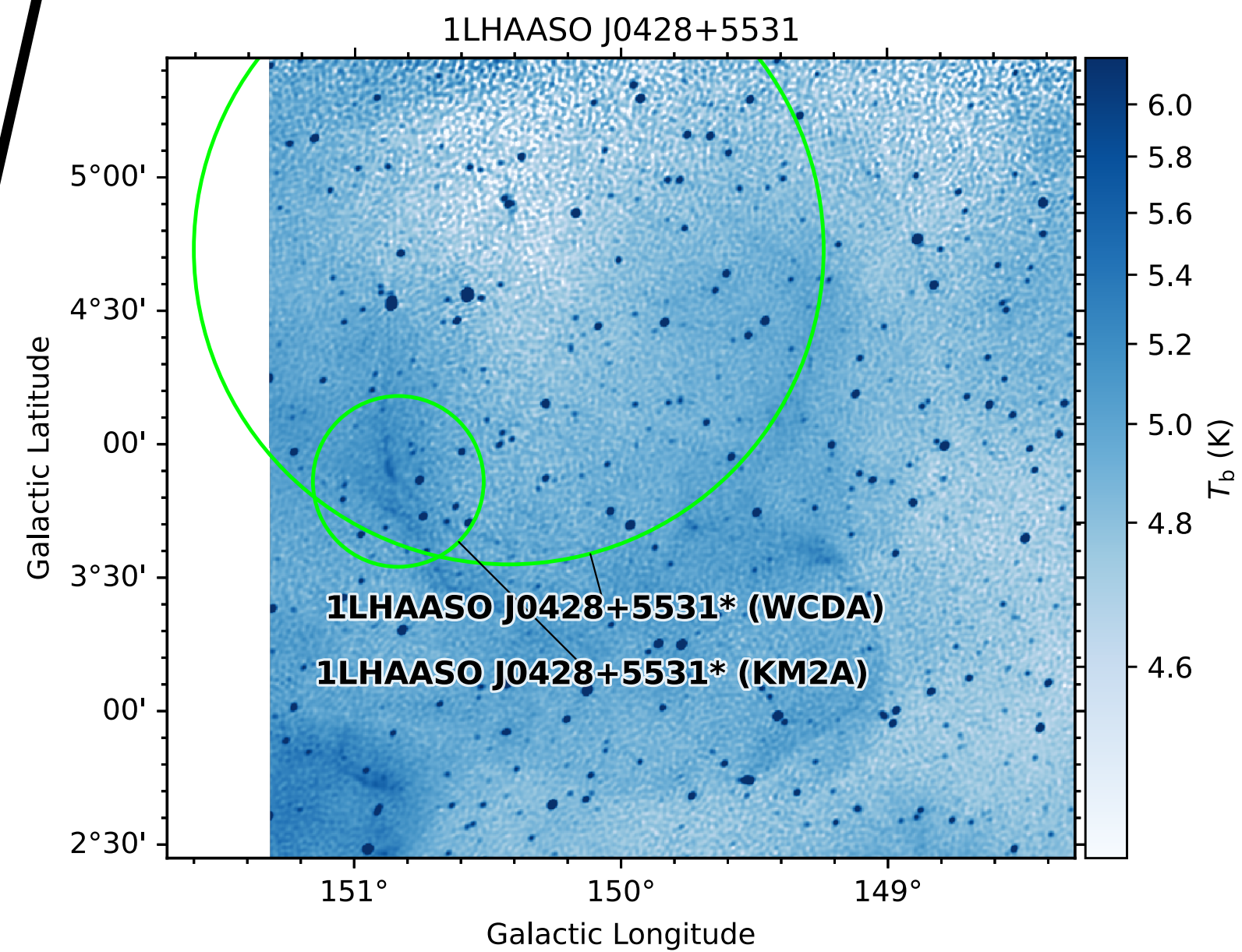
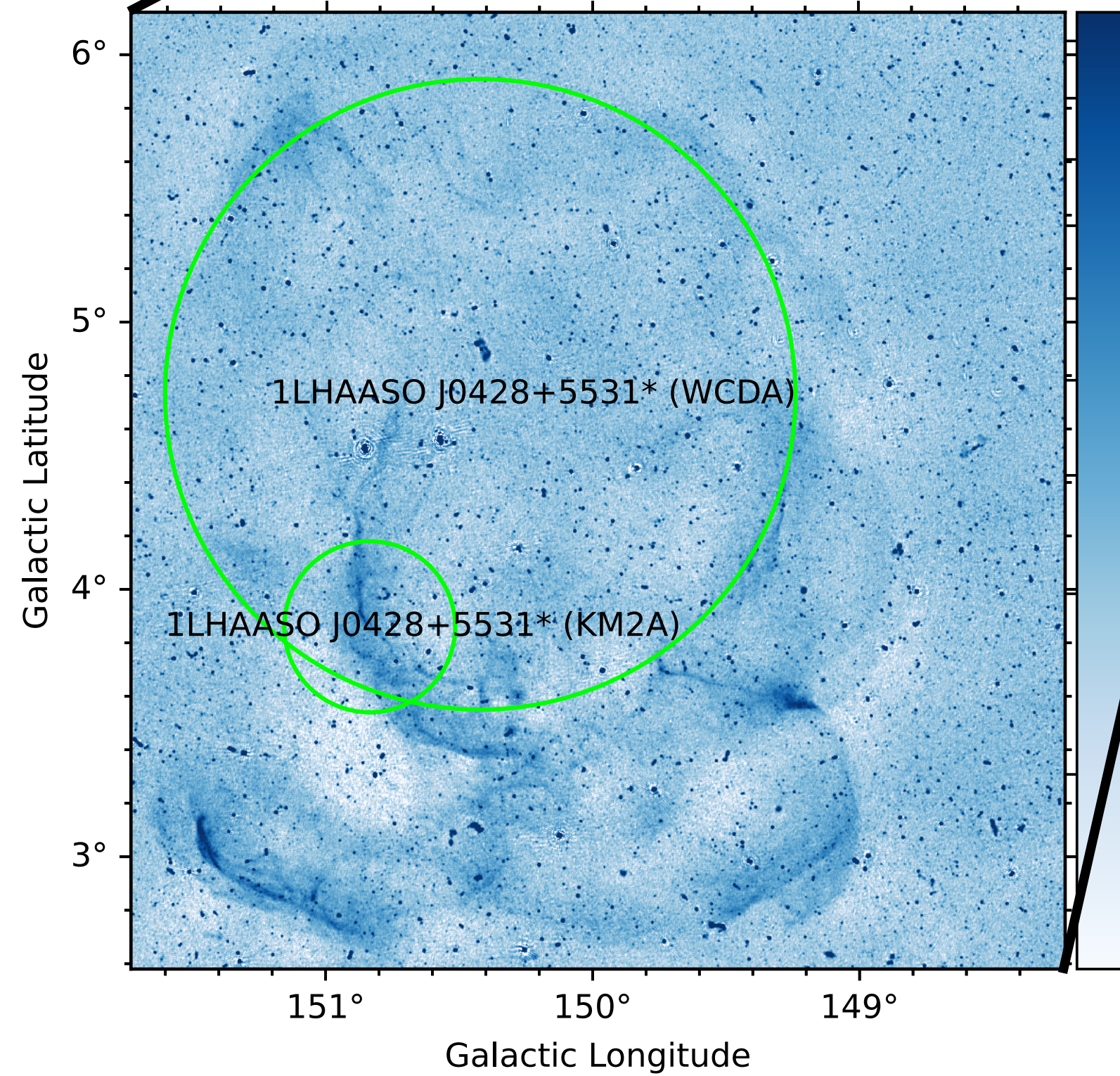
Actually a line-of-sight
merging galaxy cluster
[Edler, Arias+26]

The Outer Galaxy

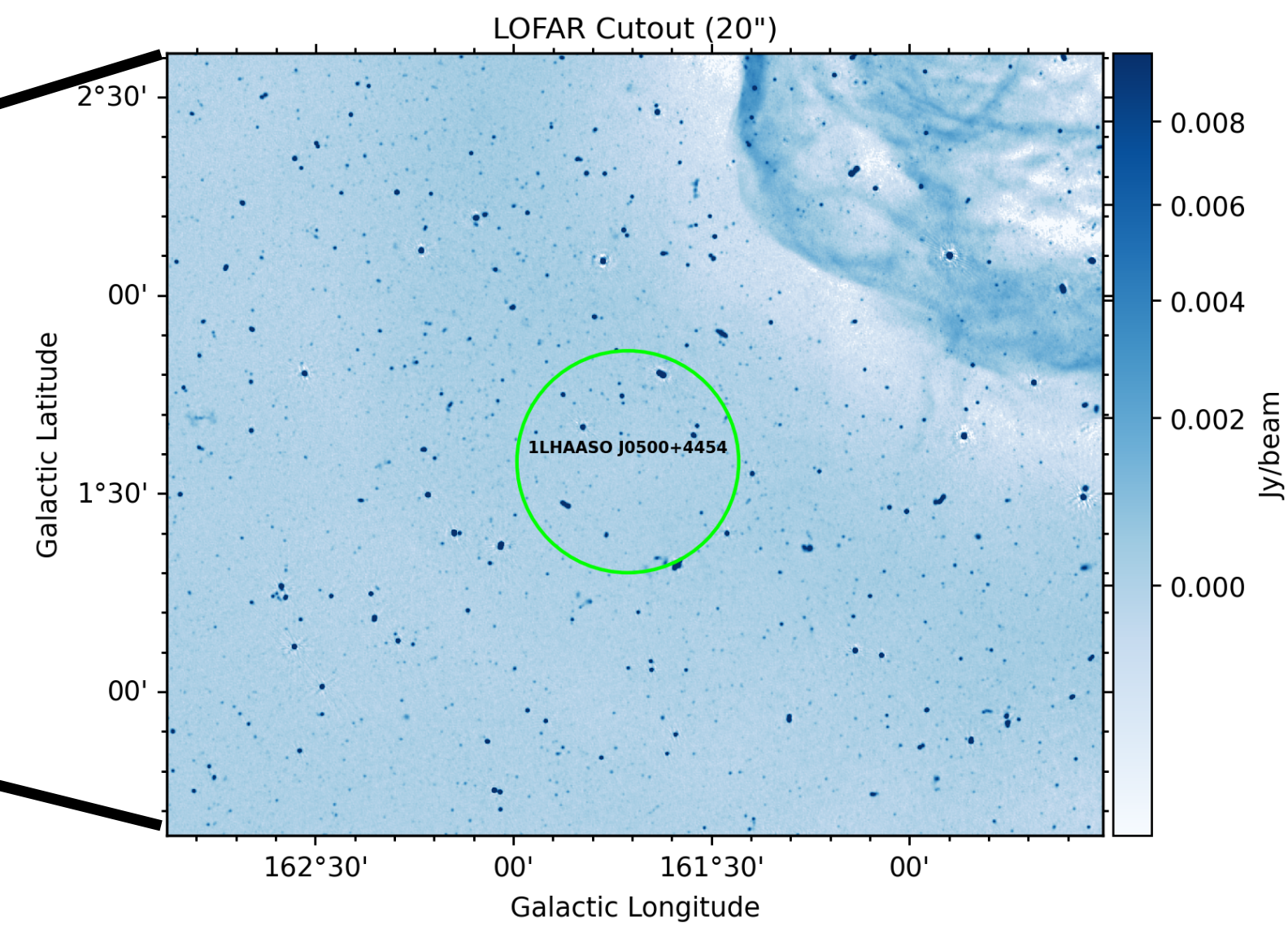
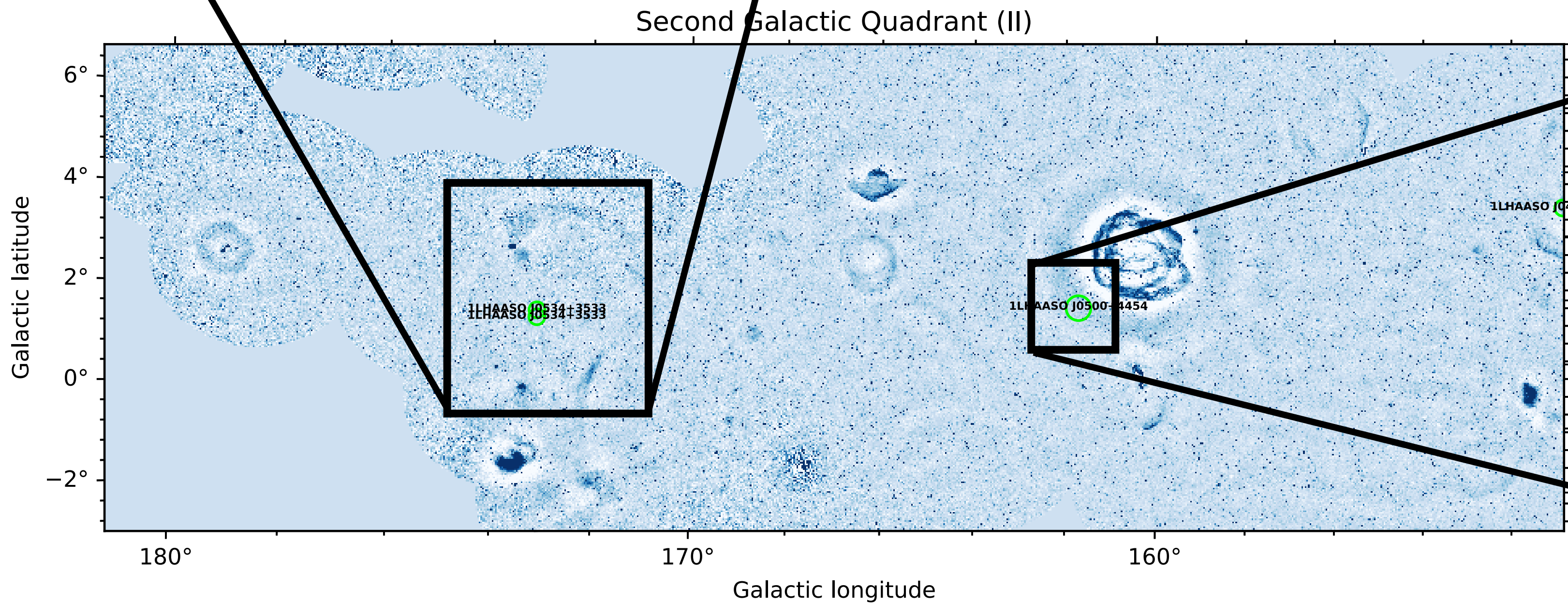
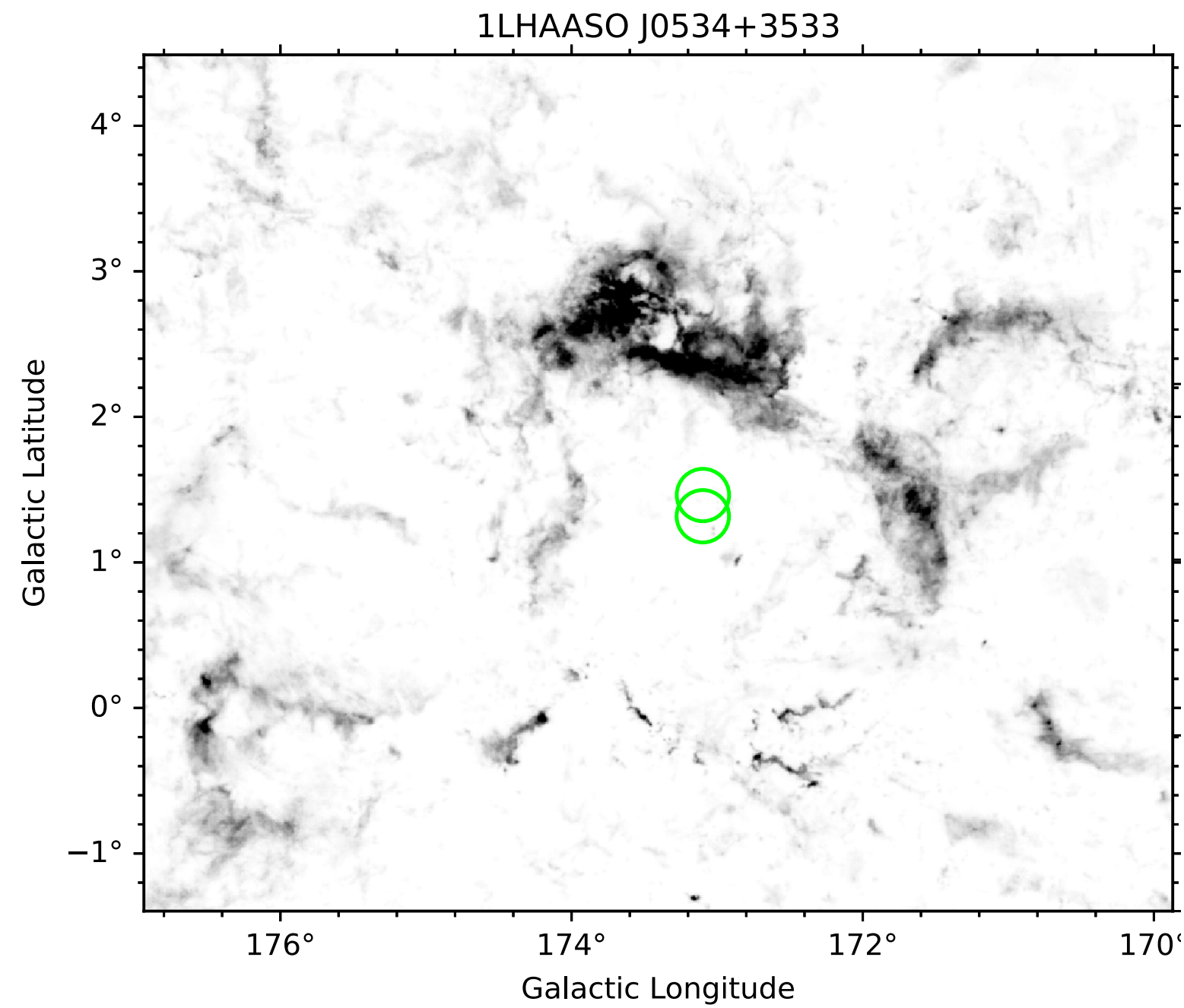
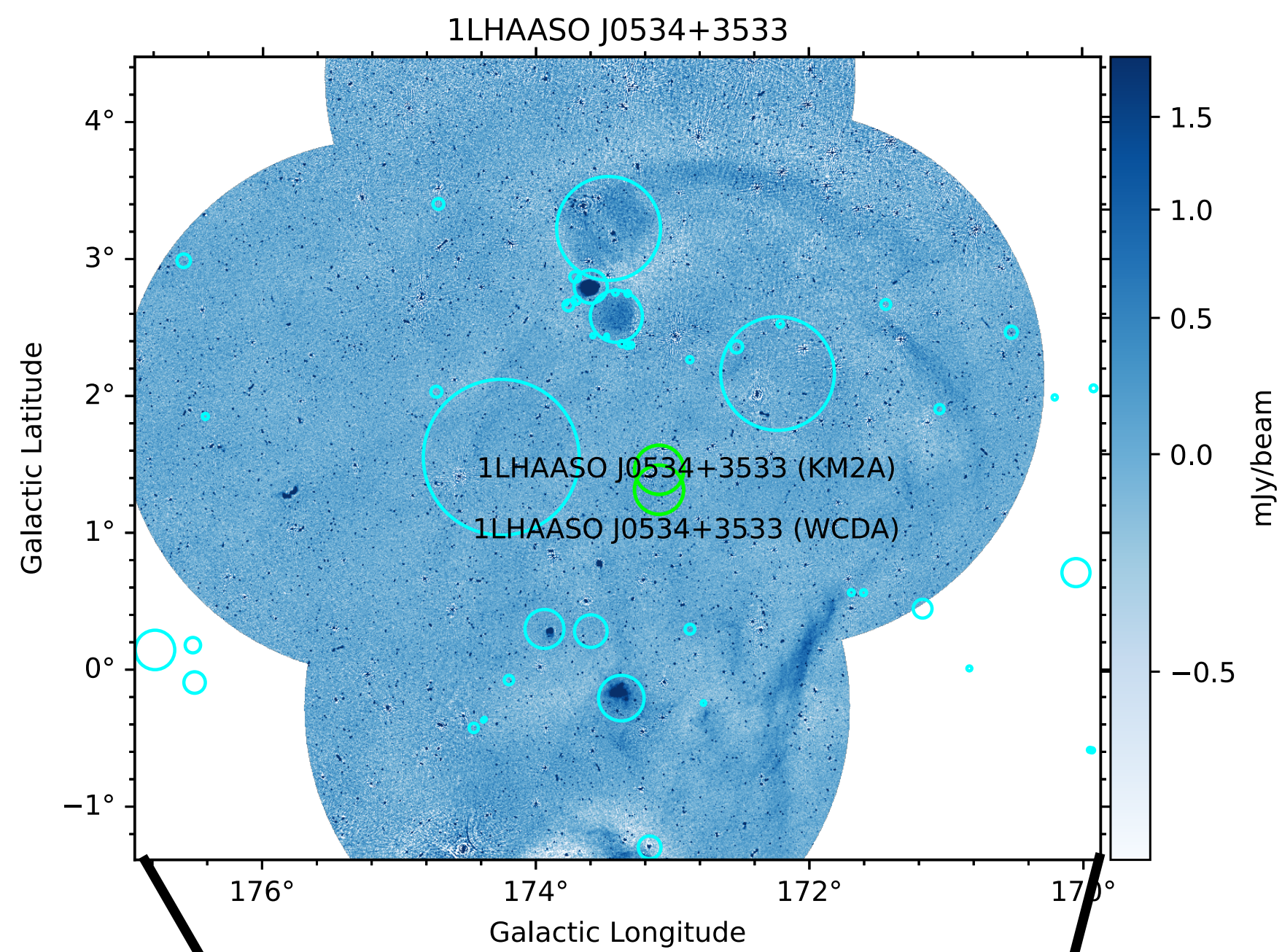
Second Galactic Quadrant (I)



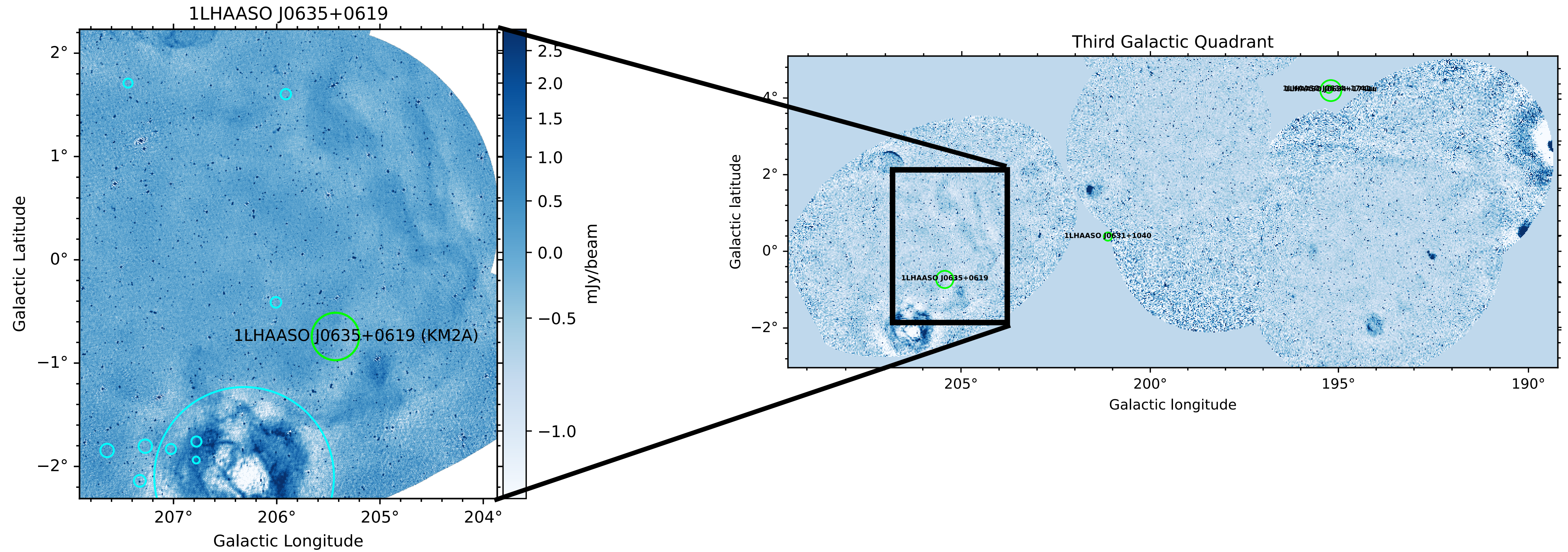
1LHAASO J0428+5531



The Outer Galaxy

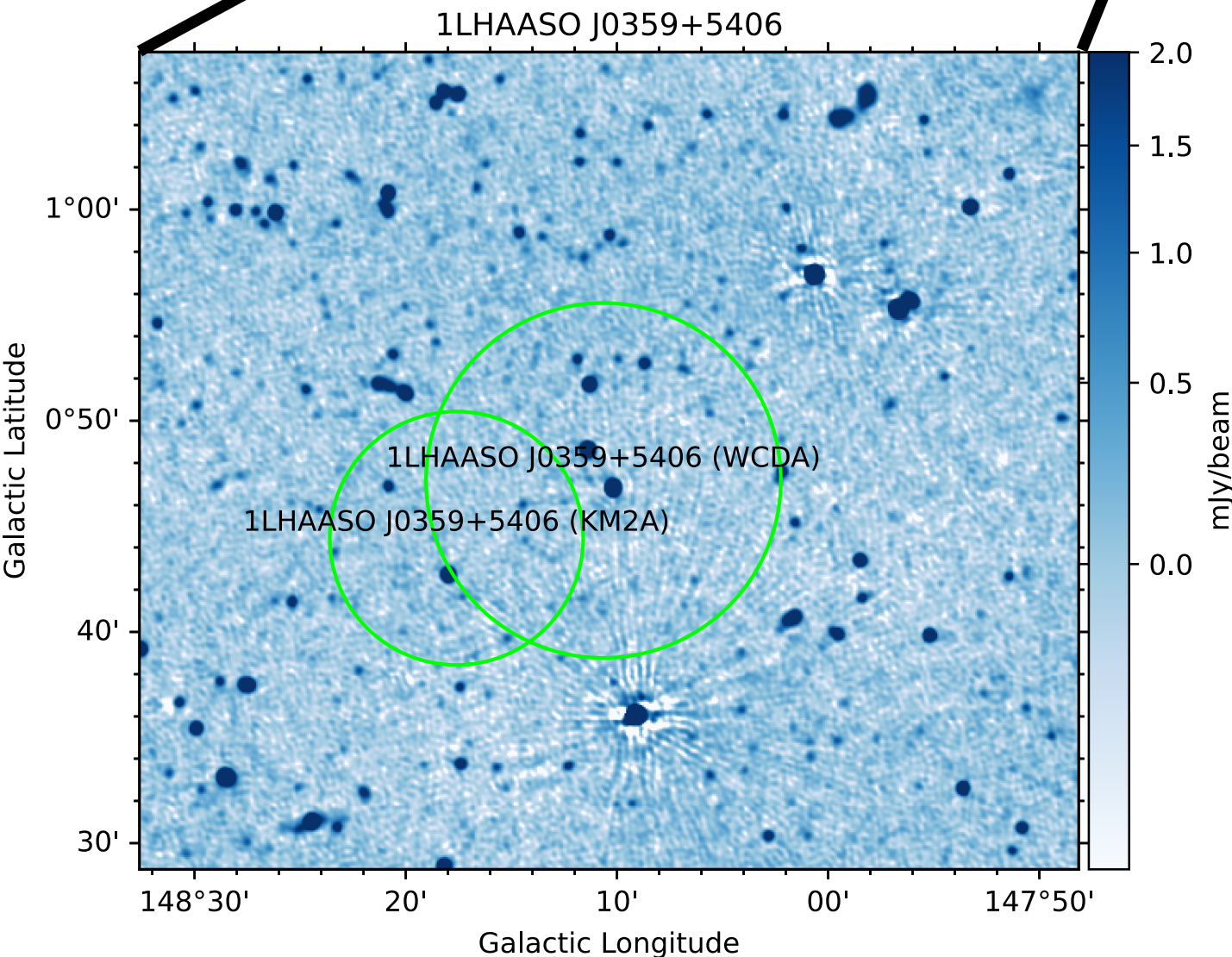
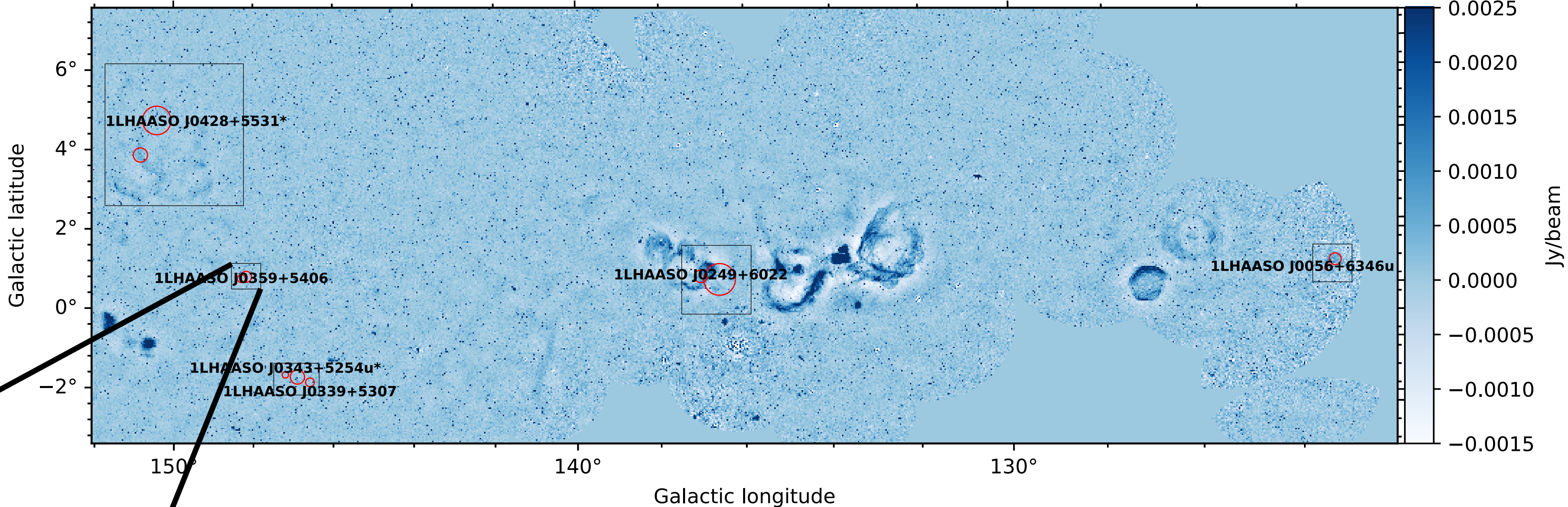


The Outer Galaxy

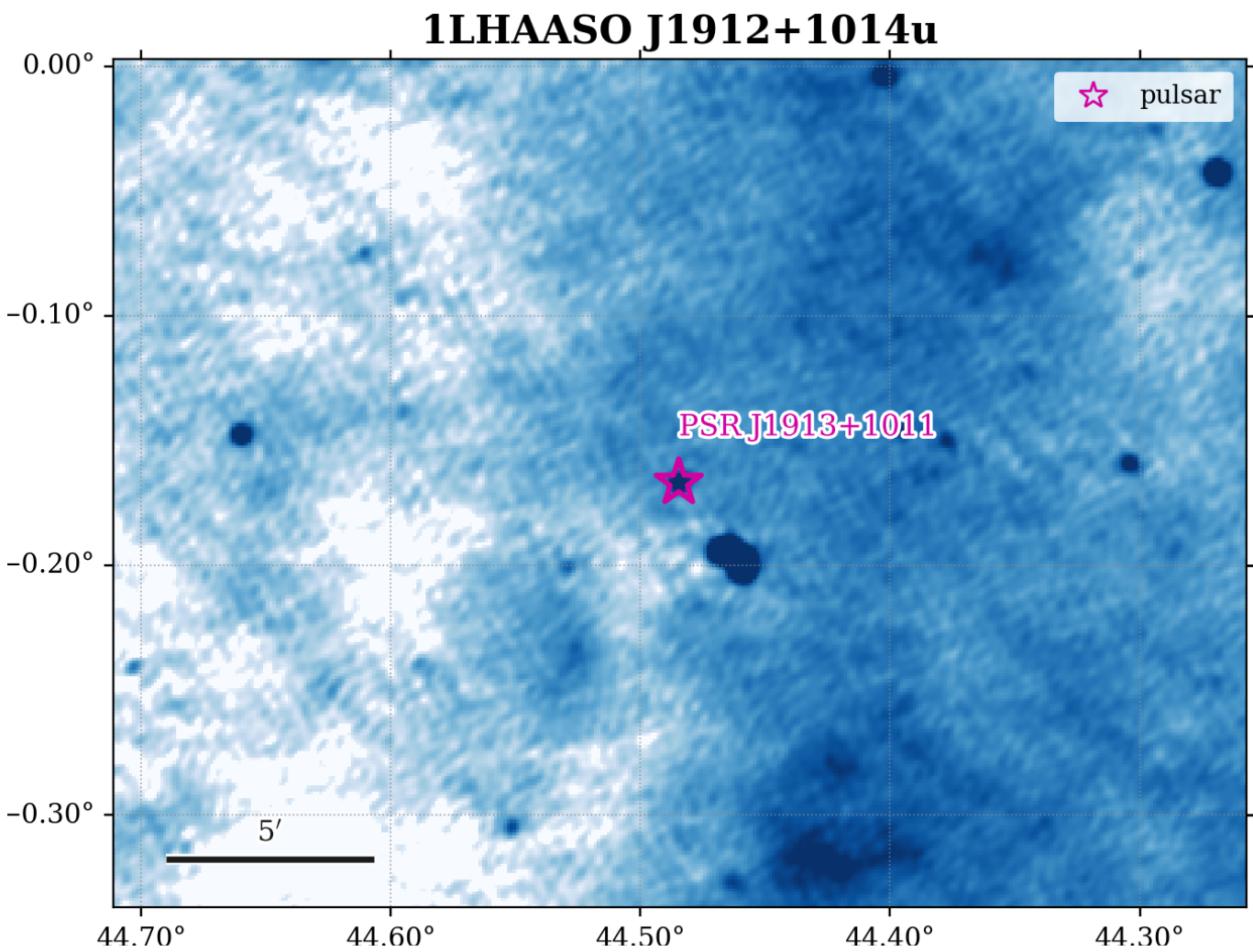


The Outer Galaxy — non-detections

Second Galactic Quadrant (I)



Cao+24 propose association with two pulsars, PSR B0355+54 and PSR J0359+4514, neither of which has a radio PWN visible in LOFAR

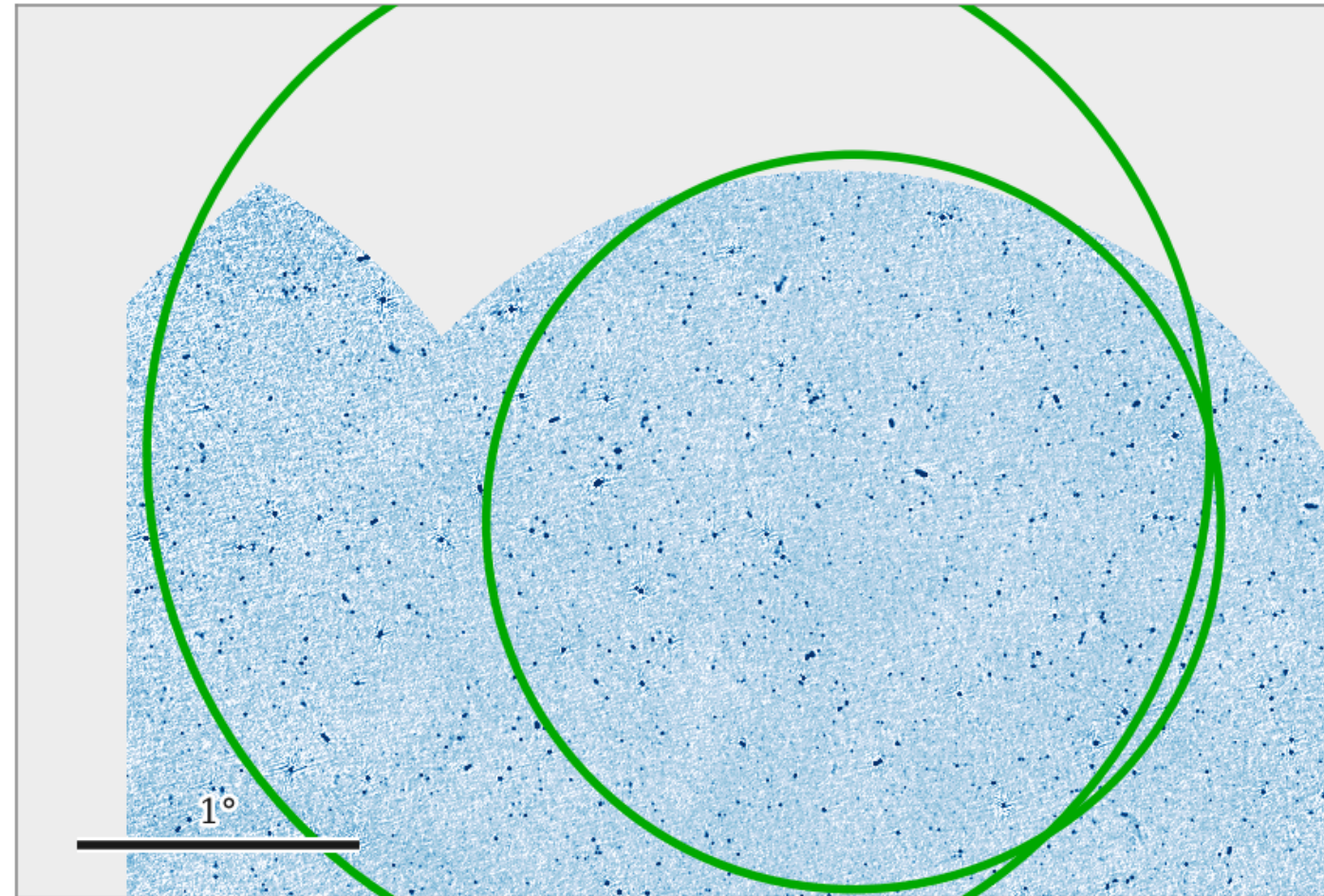


Also, no radio PWN at 144 MHz around PSR J1913+1011 and PSR B0355+54 (the latter to 0.3'')

Several sources show no associated radio emission

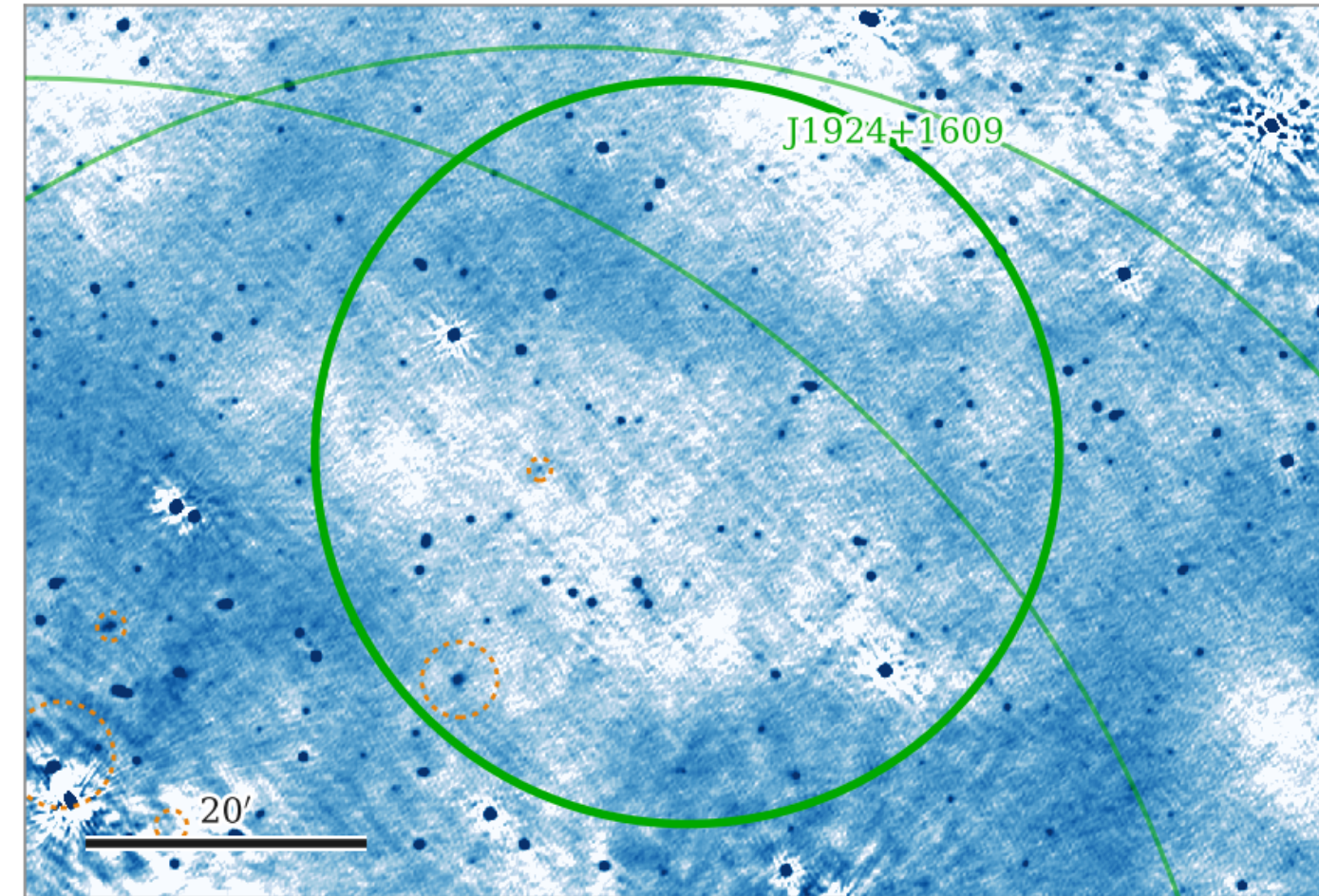
— 1LHAASO r_{39} - - - catalogued H II region - - - new SNR candidate (this work)

1LHAASO J0703+1405



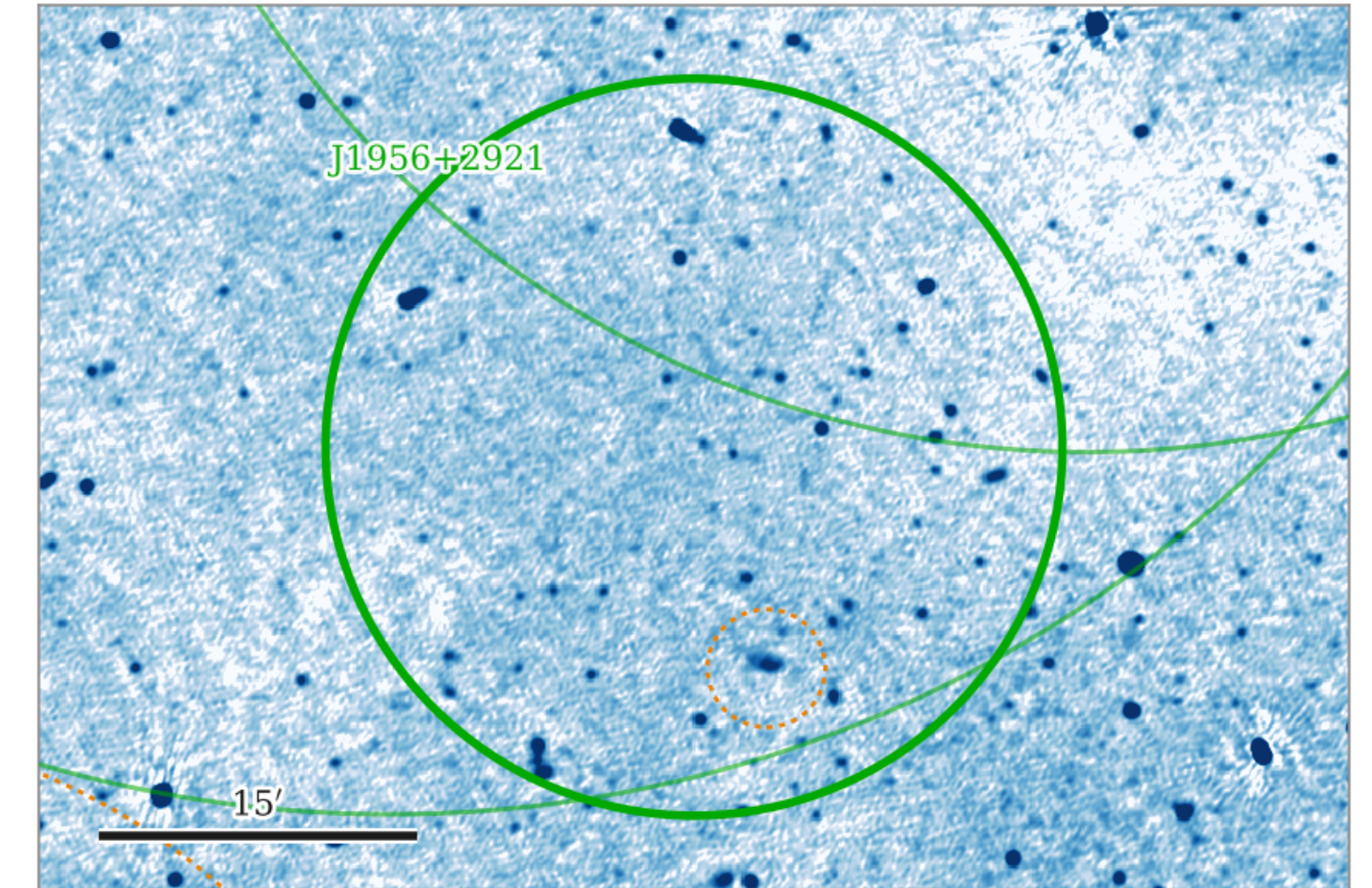
no extended emission, no large-scale shell

1LHAASO J1919+1556



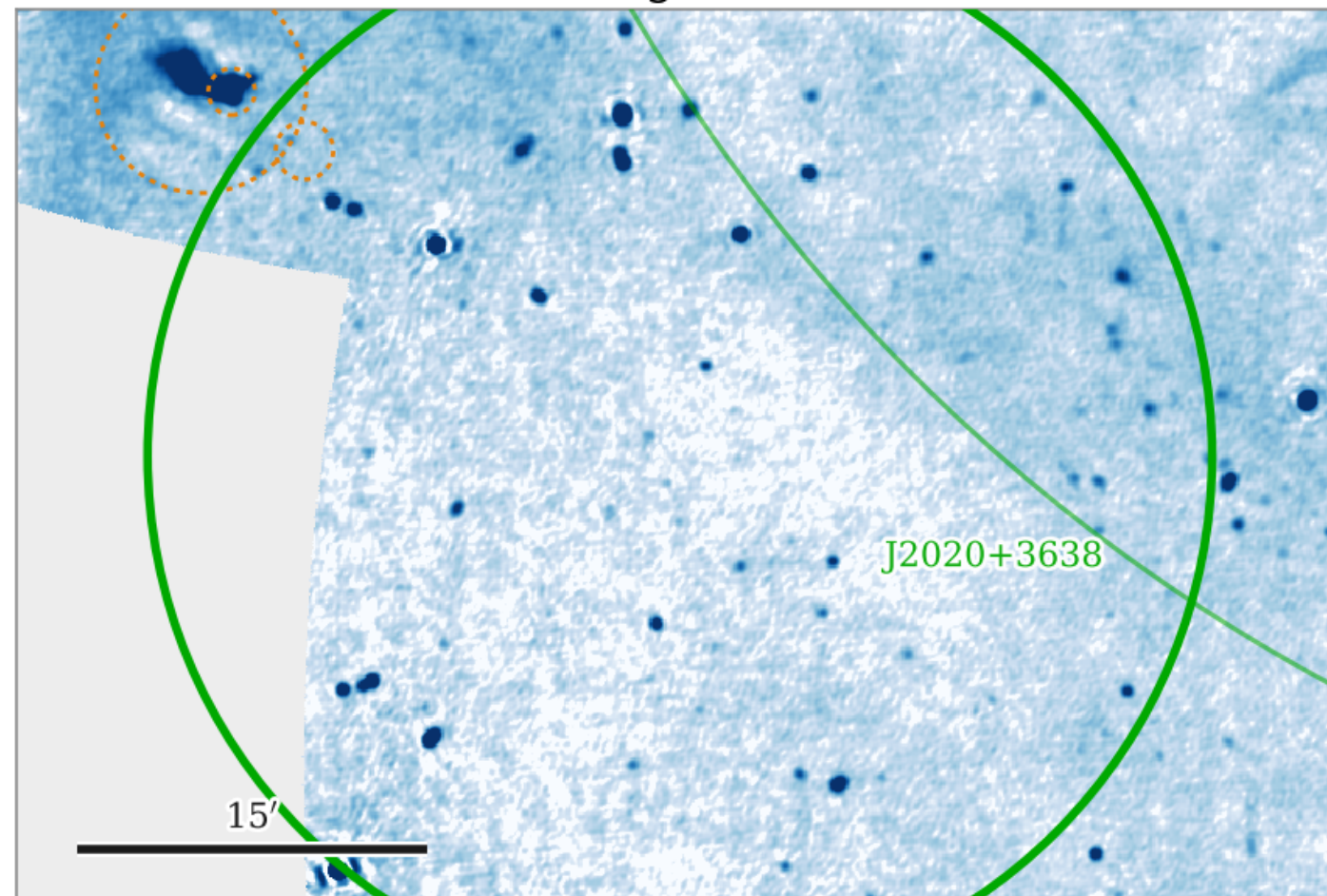
no clear features; sits inside J1924+1609 (KM2A)

1LHAASO J1959+2846u



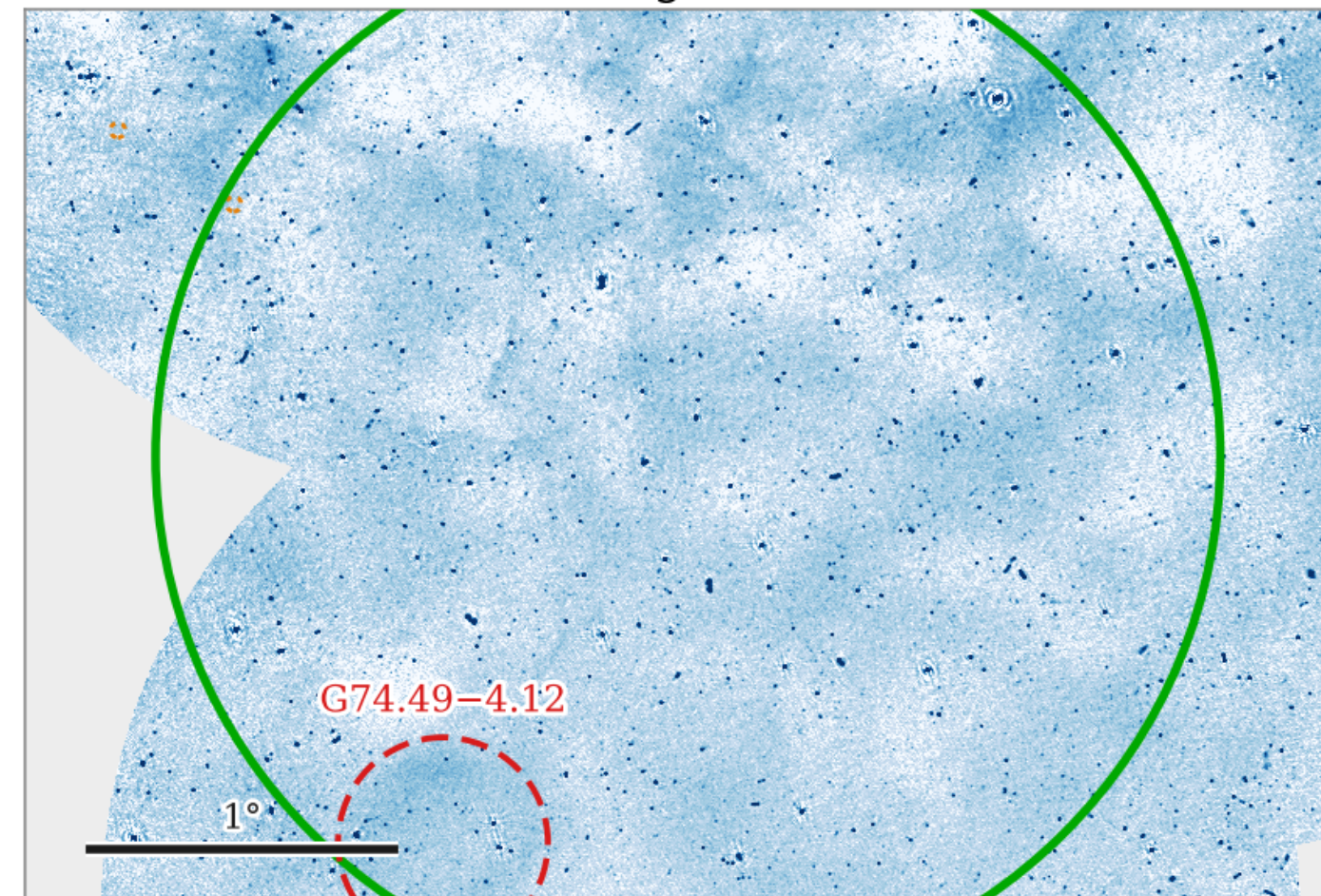
one compact H II region only; CO-rich field

1LHAASO J2027+3657



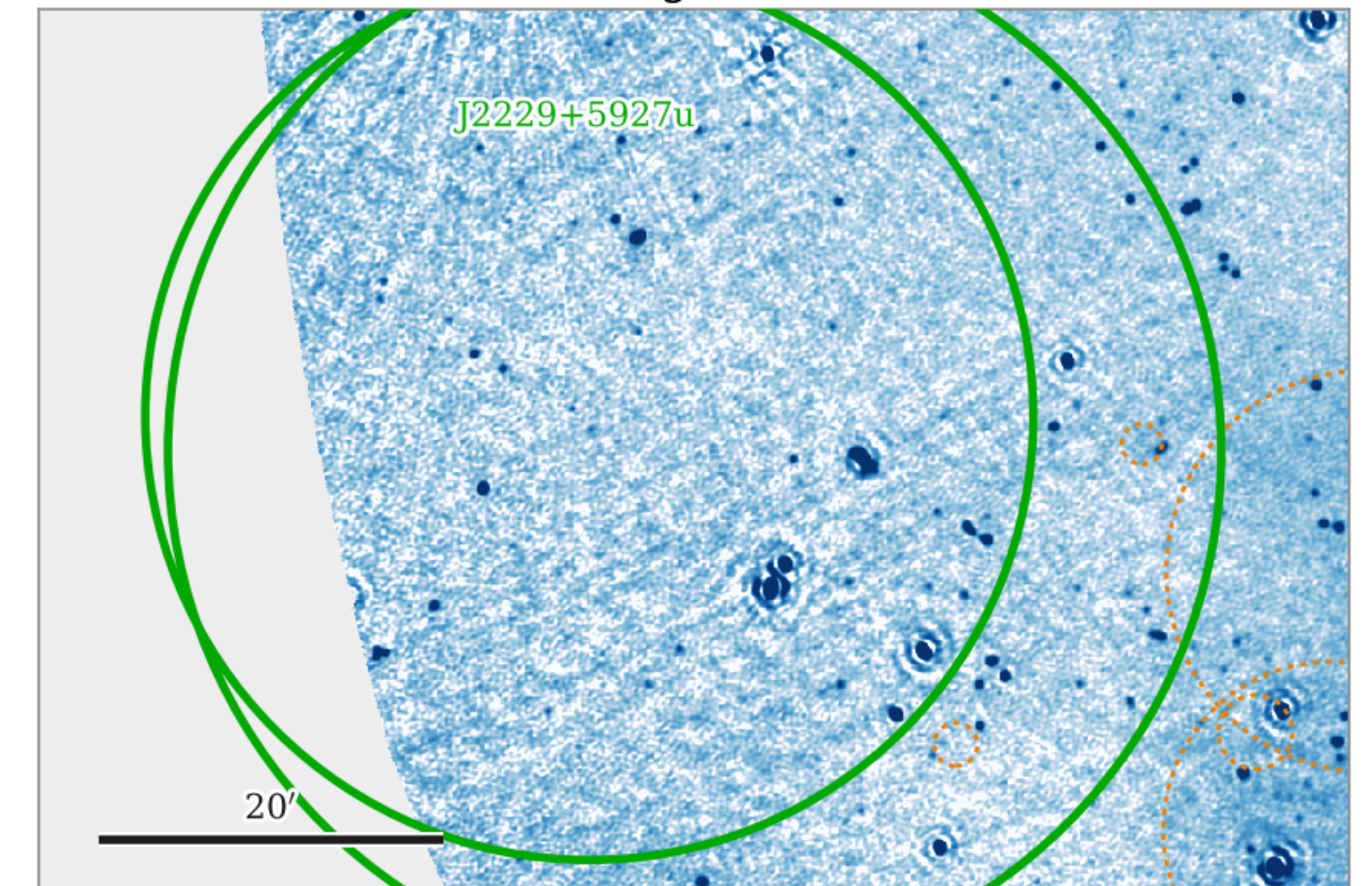
H II cluster at the boundary only

1LHAASO J2028+3352



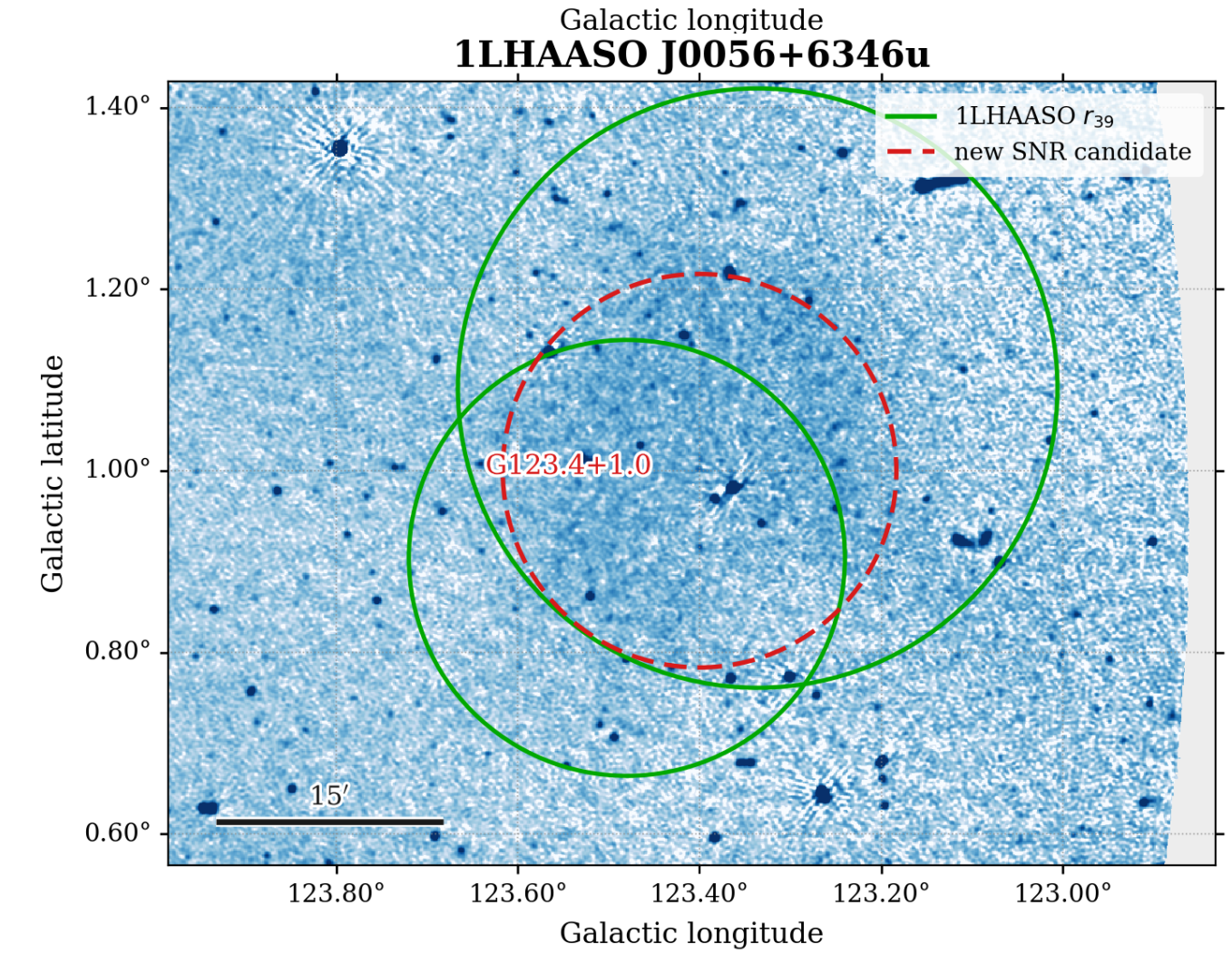
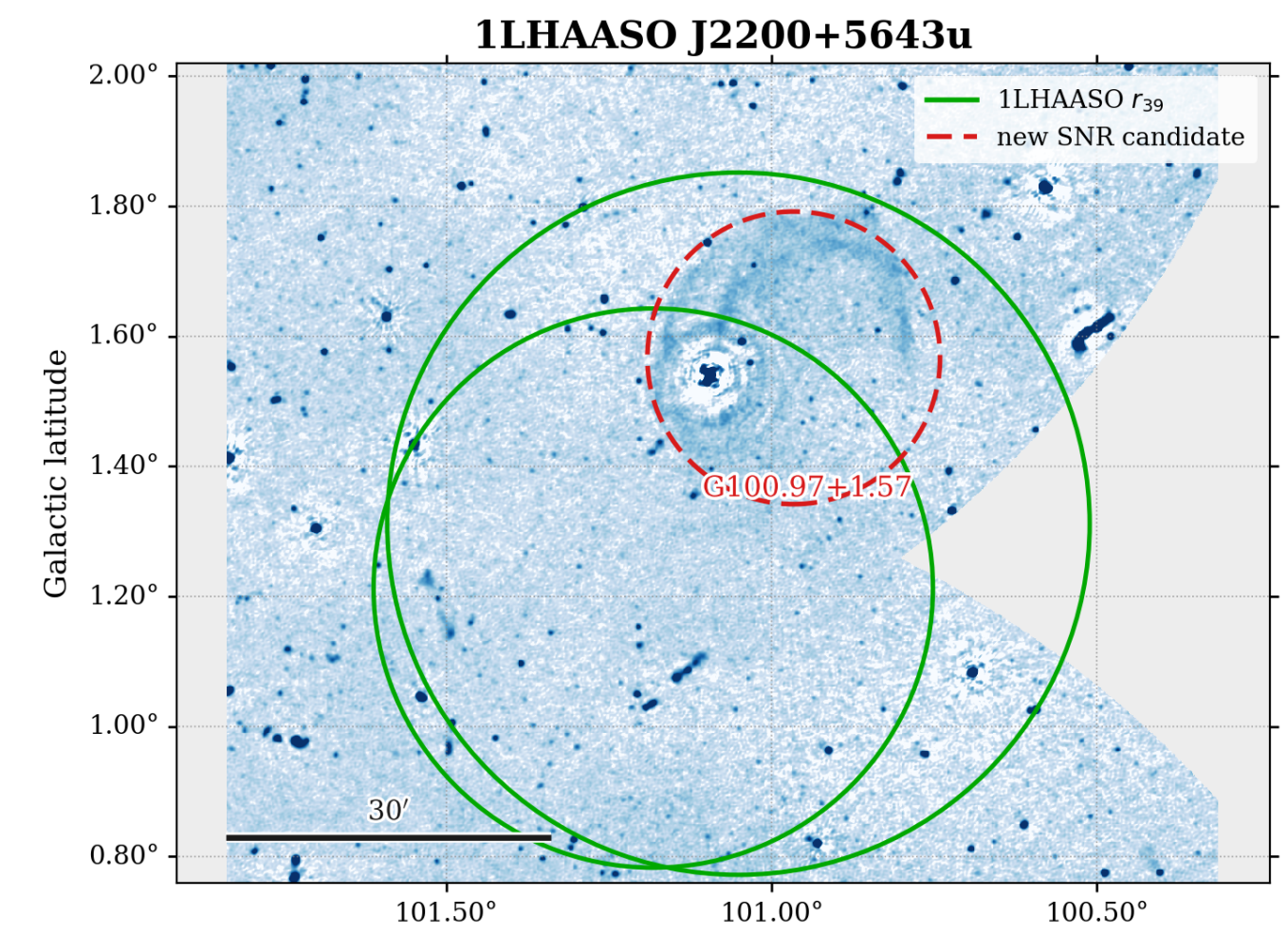
$b \approx -3^\circ$; SNR cand. G74.49-4.12 at the edge

1LHAASO J2238+5900

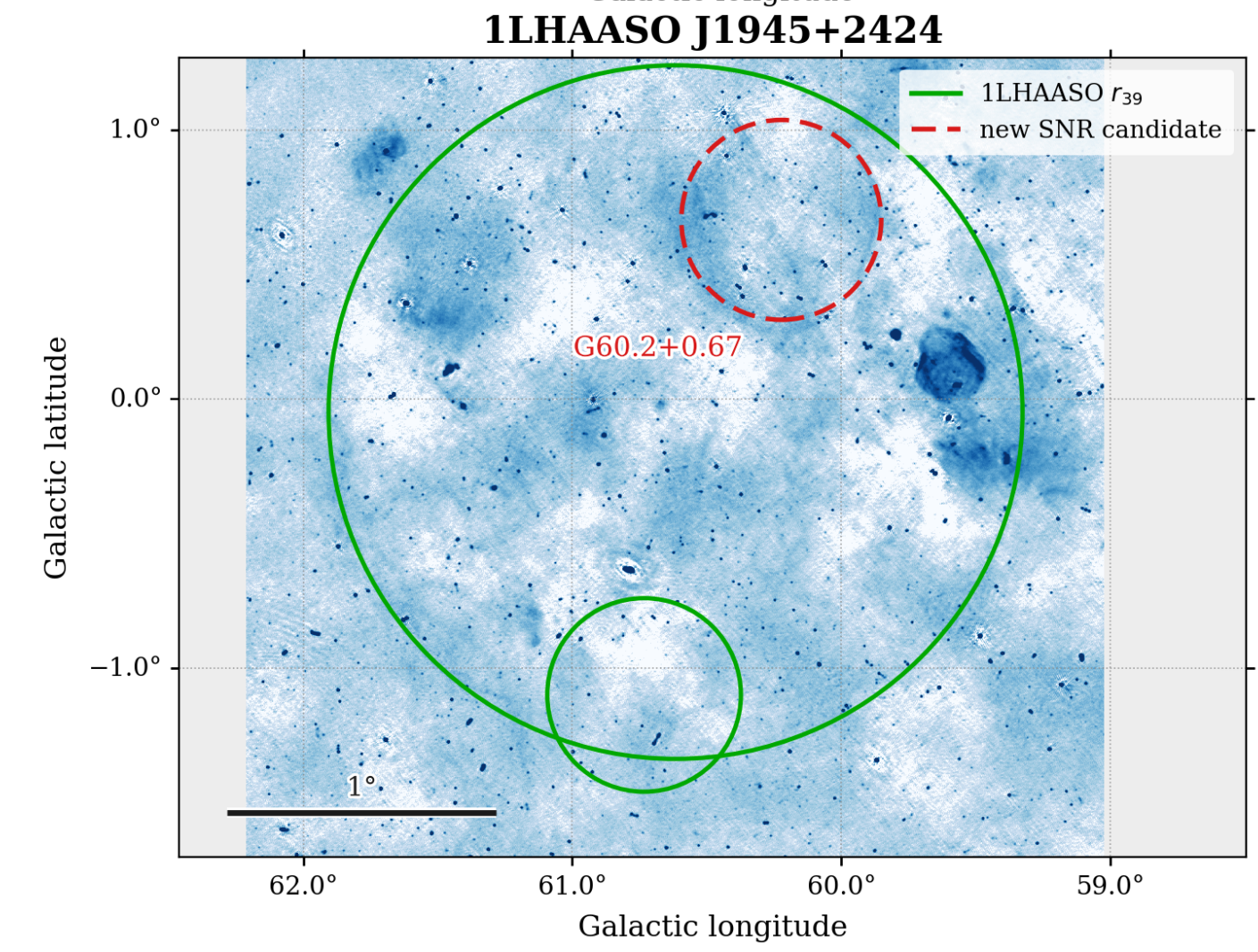
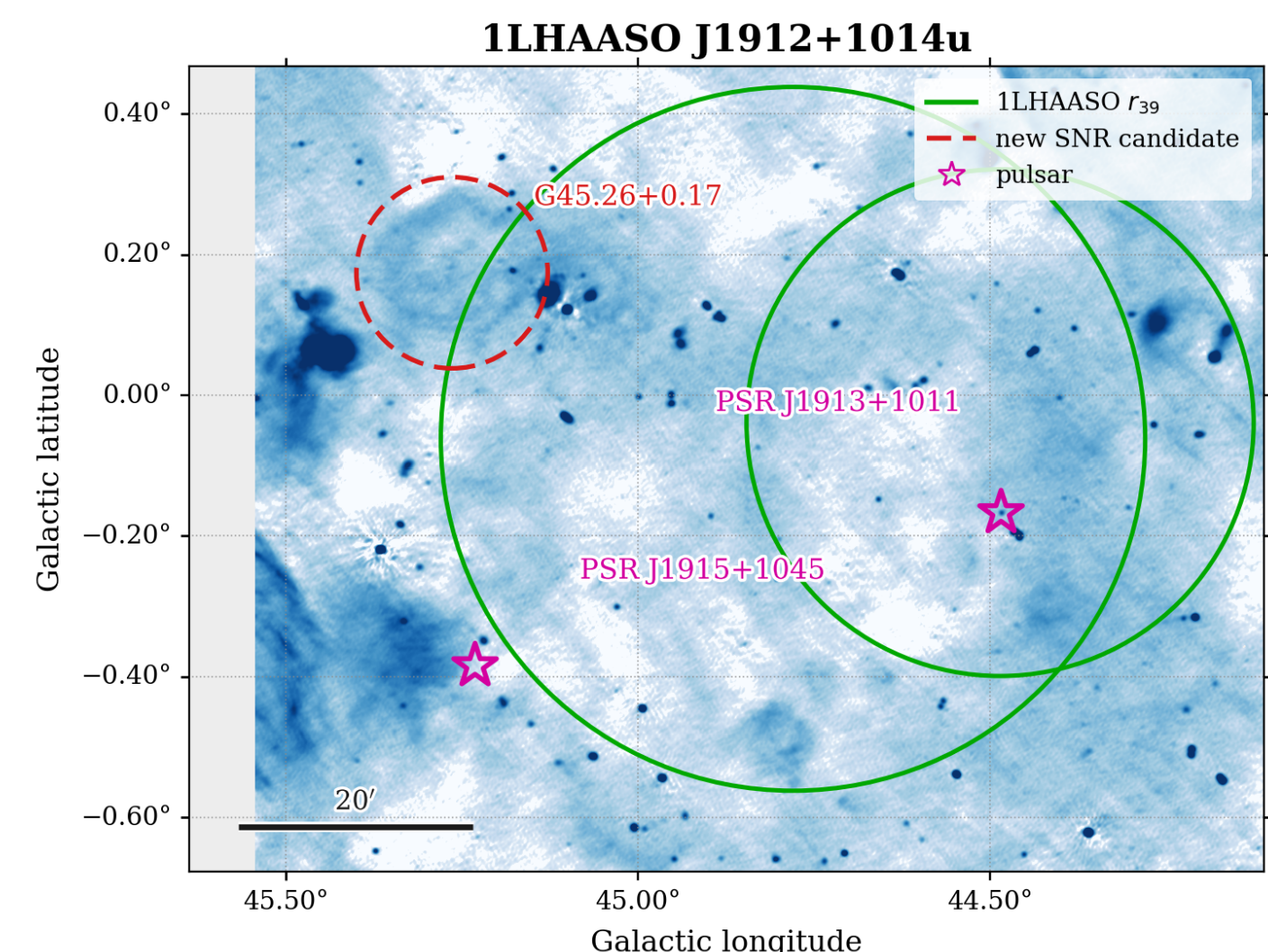


nothing in LOFAR or CGPS; inside J2229+5927u

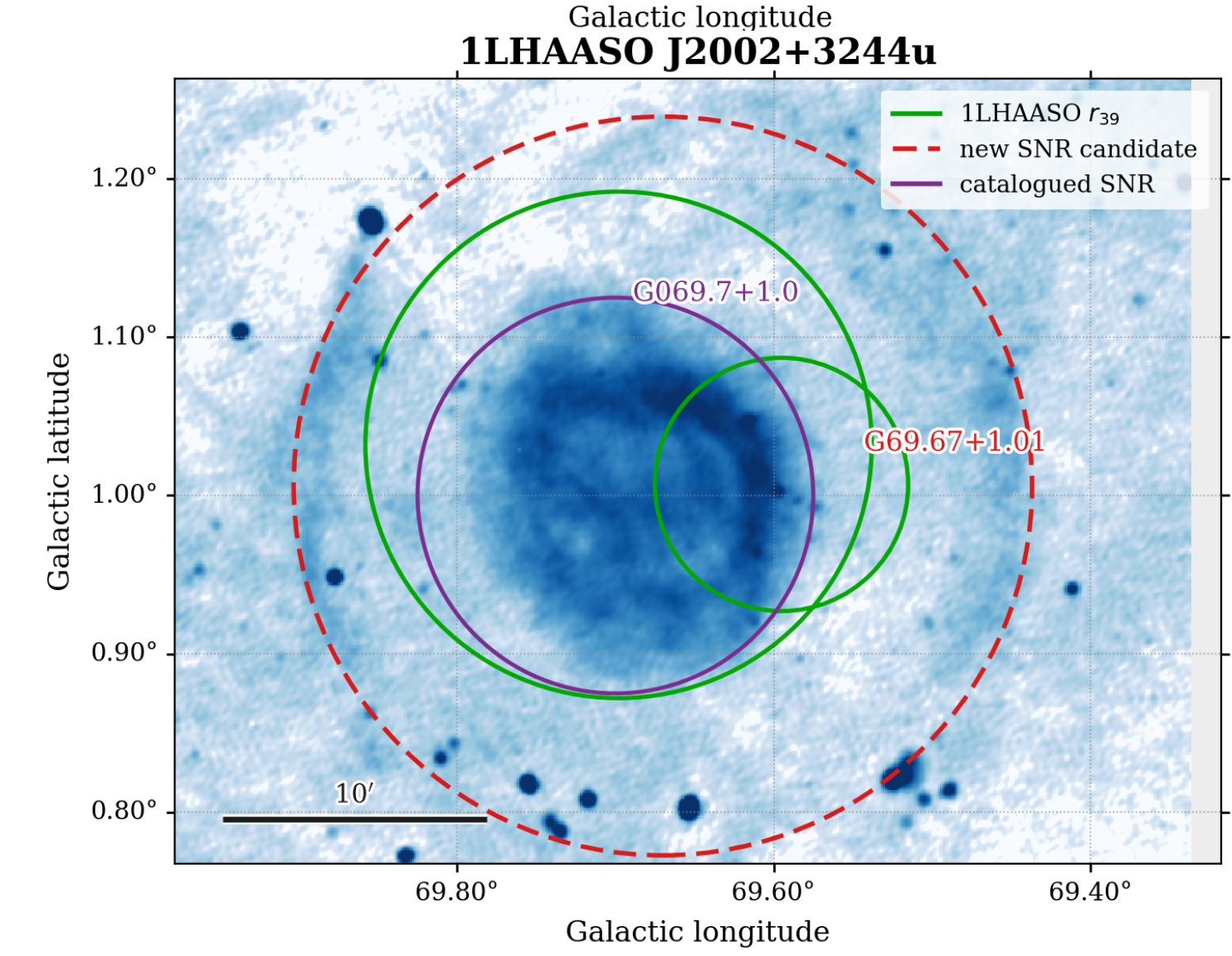
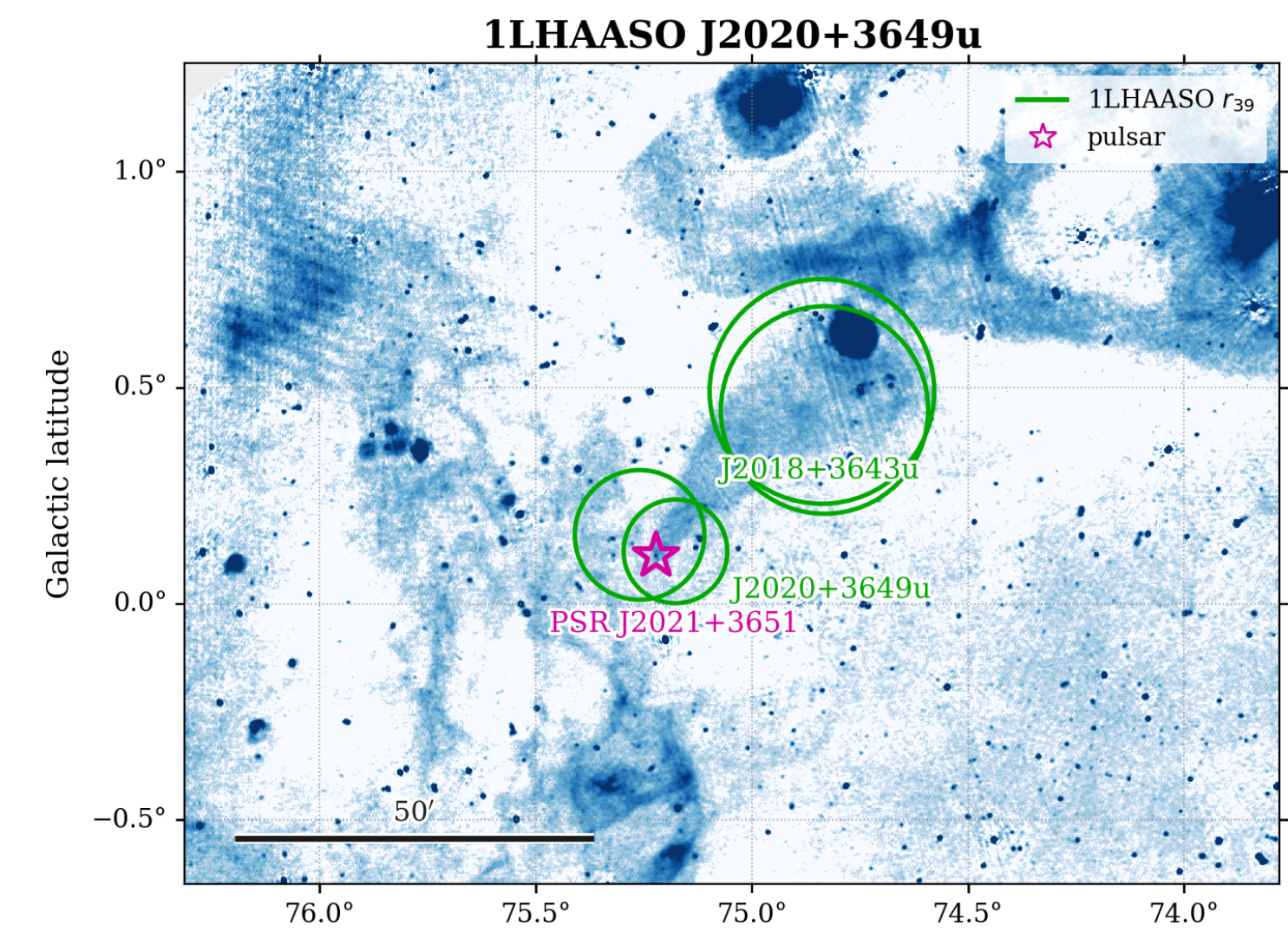
Other notable results



First proposed counterpart to J2200+5643u and J0056+6346u



A radio candidate inside the TeV shell HESS J1912+101, and the SNR hypothesised for 1LHAASO J1945+2424 from GeV (Araya & Álvarez-Quesada, 2024)



A 50' tail of the Dragonfly PWN, and two shells around SNR G69.7+1.0

Conclusions

- We provide an overview of the 144 MHz emission towards **55 1LHAASO sources**. We identify, for each source, the radio structures potentially related to the gamma-ray emission.
- We identify **24 new SNR candidates**, 19 of which lie within the r39 region of a 1LHAASO source, found by inspecting the 1LHAASO fields, and **9 flat-spectrum shells with faint or no infrared counterpart**.
- A **bootstrap** analysis shows at least ~26–33% of the 1LHAASO Galactic-plane sources genuinely reside in SNR environments, up to ~50% when the new SNR candidates are included.
- Consistent with a population consisting of PWNe, SNR–PWN composites, pulsar TeV halos, and clouds illuminated by cosmic rays escaping nearby remnants: all end **products of recent core-collapse supernovae**.
- Many quirky individual results!

Paper soon to be appearing on ArXiv and A&A: **Arias, Shimwell, Hardcastle, Timmerman (2026)**

THANK YOU!