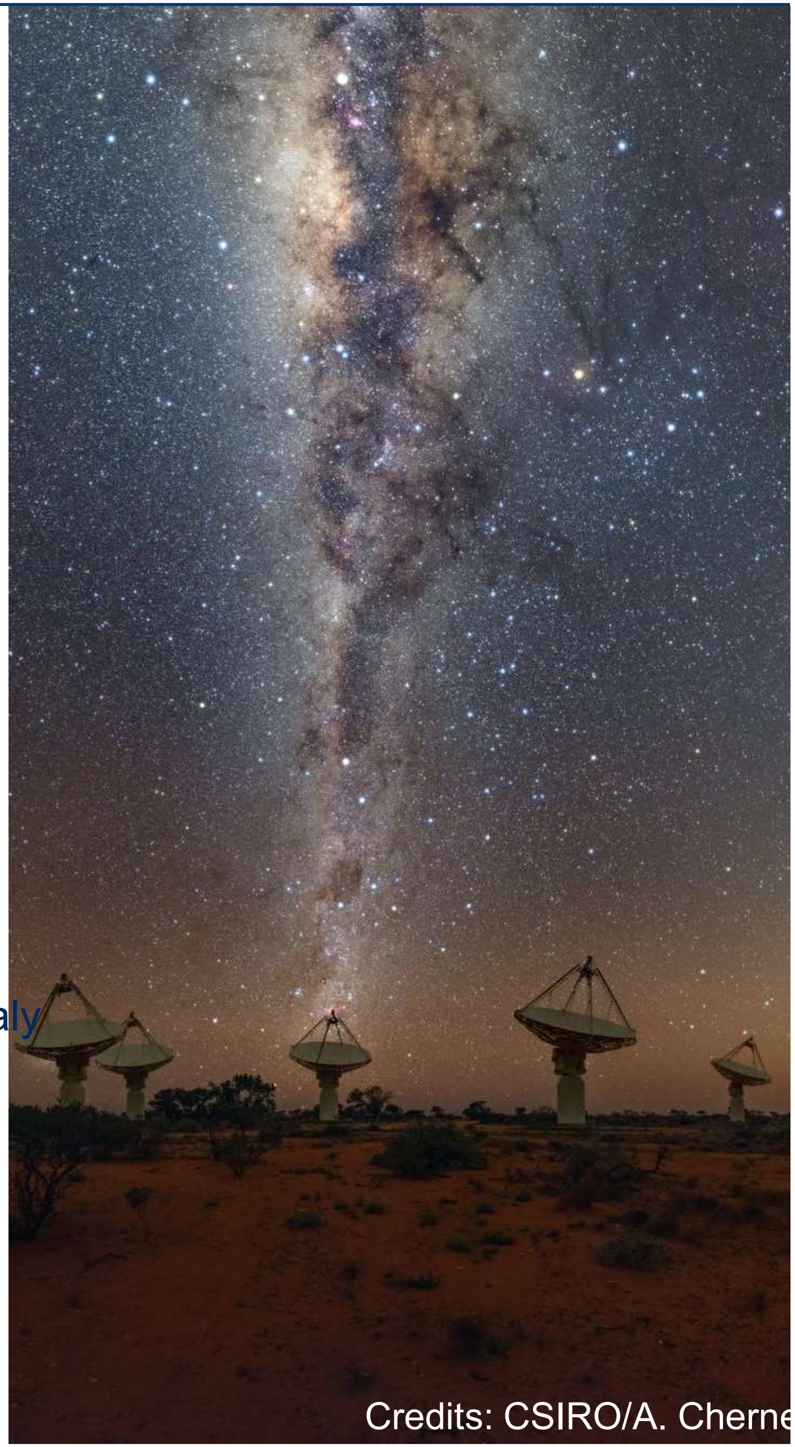
A first glimpse of the Galactic Plane with ASKAP: the **SCORPIO** field

G. Umana INAF-Osservatorio Astrofisico di Catania, Italy
on behalf of the Radio-ICT Catania group and
Galactic **EMU** team



INAF Osservatorio Astrofisico di Catania

One of the 16 INAF

HQs in Catania, inside University of Catania Campus

Synergy with UNICT

Staff: 62 (researchs/technicians/amministratives)
30 non-staff (Students, PdD students, post-doc)

SKA & precursors task force @ INAF-OACT

Grazia Umana
Corrado Trigilio
Paolo Leto
Carla Buemi
Milena Bufano
Francesco Cavallaro
Adriano Ingallinera
Sara Loru
Francesco Schillirò
Ugo Becciani
Alessandro Costa
Eva Sciacca
Fabio Vitello
Simone Riggi

- **Radio & ICT groups working together since 2012: Successful initial experience for Competence Center**
  - 14 people involved in different projects (see below): 10 TI + 2TD + 2 AdR
  - Galactic Radio Astronomy /Modeling/data reduction
  - Corrado Trigilio Radioastronomy course at UNICT
  - Software expertises: data reduction software, HPC/HTC, Visual analytic & Virtual Reality, …
- **OACT in SKA & precursors science groups**
  - SKA "*Our Galaxy*" KSP (co-lead: G. Umana); The SCORPIO project (PI Umana)
  - SKA AENEAS WP 3.3 (lead: U. Becciani) & WP 5.3 (lead. A. Costa)
  - ASKAP EMU Galactic Plane KSP (co-lead: G. Umana)
  - ASKAP EMU Dev. Projects "GP Imaging & Diffuse Sources" DP4 (leads: S. Riggi, F. Cavallaro), DP6 & Parkes GP survey
  - ASKAP SCORPIO Early Science Project (lead: C. Trigilio)

Large area Surveys

Statistical studies of different populations of radio emitting Galactic Objects

All-sky/deep

The place where you look at ***makes the difference***:
most of the Galactic sources localised in/close the GP

The concept of generic surveys:

- Maximize the return for "priority Science"
- Maximize the commensality

Survey	Freq (GHz)	Band (MHz)	Area (deg^2)	Time (khr)	$S(\theta_S)$ (μJy)	S_{Max} (μJy)	θ_S (")	θ_{Min} (")	$lg(N_C)$	θ_{10K} (")	θ_{1K} (")
SKA1-Mid-A	0.95 – 1.76	1000	31000	8	5	3.4	0.8	0.3	8.3	12	30
SKA1-Mid-A1	0.35 – 1.05	300	15000	8	5	3.6	1.0	0.5	8.1	-	-
SKA1-Mid-A2	0.95 – 1.76	1000	20000	8	4	2.8	0.8	0.3	8.1	-	-
"EMU+WLBY"	1.1 – 1.4	300	31000	10	45	40	10	5	7.3	-	-
"THOR"	1.0 – 2.0	800	480/Gal	1	18	18	15	8	5.9	20	100
SKA1-Mid-D	4.6 – 13.8	5000	480/Gal	2	6	4	0.2	0.05	6.0	2	9
"GLOSTAR"	4 – 8	2000	480/Gal	2	40	35	1	0.6	5.0	8	20

Better angular resolution and sensitivity (Continuum & Spectral) than
any ongoing/planned survey of the Galactic Plane

The concept of Generic Survey

SKA1_MID-A Generic Survey @ Band 2b (Full BW)
(rms 5μJy/b, 0.8”), ≈8000 hrs, All-sky

SKA1_MID-D Generic Survey @ Band 5 (Full BW)
(rms 6μJy/b, 0.2”), ≈2000 hrs, 480 deg^2/GAL

The most complete catalogue of the Galactic Plane to date

Much deeper and higher resolution than any other survey
Will bridge the gap in sensitivity and resolution between available GP surveys

High angular resolution, limited areas:

THOR (Bihr et al., 2016) 6cm, 10-20 arcsec, 100 deg^2, few mJy
CORNISH (Purcell and Hoare, 2010) 6cm, 1-6 arcsec, ≈100 deg^2, few mJy
MAGPIS (Helfand et al., 2006) 20/6cm “ “

Lower angular resolution, wide areas:

CGPS (Taylor et al., 2006), 20cm, arcmin, several 100 deg^2, few mJy
SGPS (McClure-Griffiths et al., 2005)

The impact of SKA on Galactic Science

A SKA-survey results will address several science topics:

(list not exhaustive!)

Massive stars formation

- A census of the early stage of massive stars formation in the GP
- Giant HII and interaction with their environments: triggered star formation

Evolved stars

- Detection of SNRs
- Detection of PNs

To derive accurate space density and rate formation
Radio needed for robust identification

Radio Stars

Serendipitous discoveries

Providing the most complete catalog of Galactic Sources to date

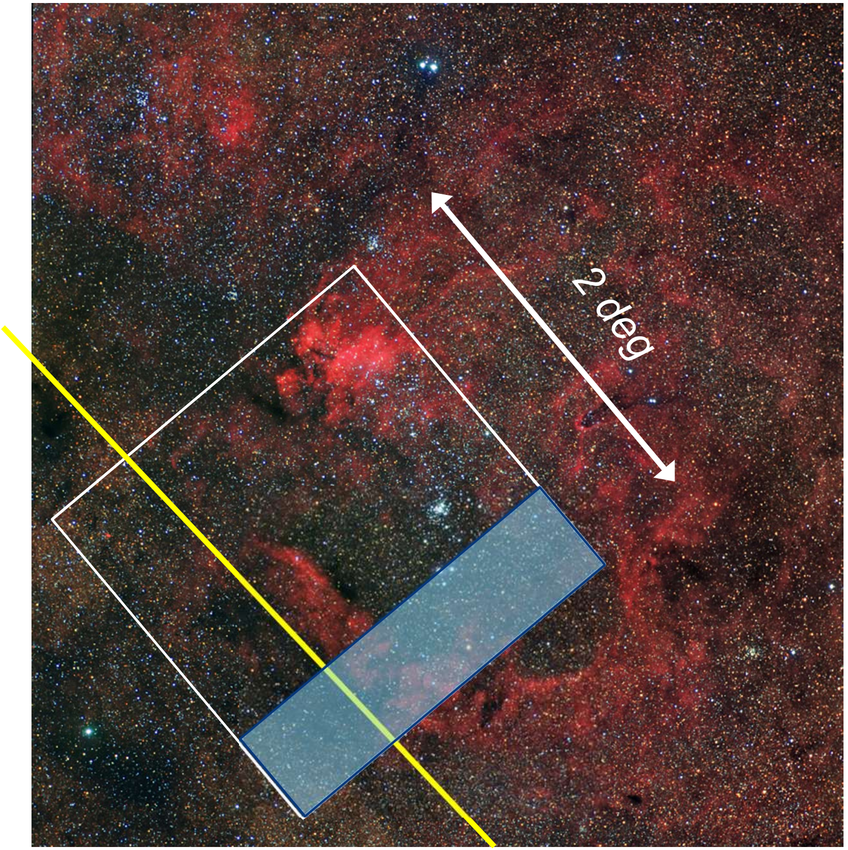
ASKAP Deep radio image of 75% of the sky (up to declination +30°), 1130-1430 MHz, 10 μJy/b, 10 arcsec .

Will detect and image ~70 million galaxies
Primary science goal: **How did galaxies form and evolve?**

But…..will provide a "good view" of the ***Galactic Plane @ L-Band***

EMU team currently involved in the ASKAP Early Science Programm

SCORPIO: A deep radio survey in the GP with the ATCA



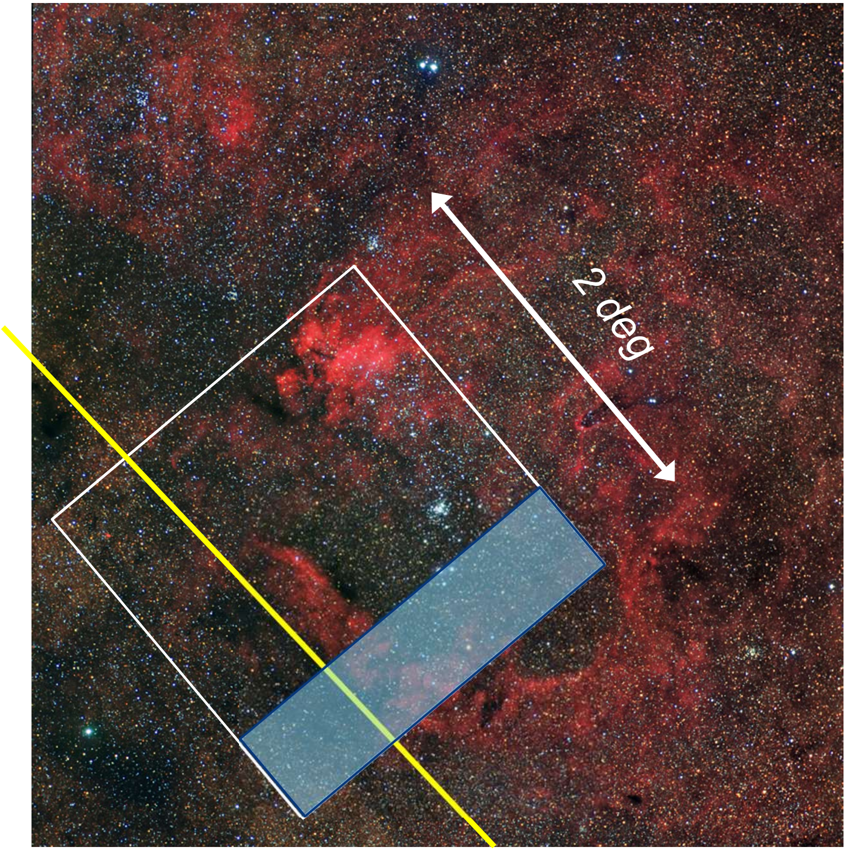
Frequency L-Band, comparable to EMU

High Sensitivity: approaching future radio facilities

Same observing strategy as ATLAS (to capitalize on previous experience)

At low Galactic latitude (well suited for stellar/Galactic work)

SCORPIO: A deep radio survey in the GP with the ATCA



Requirements:

Close to the GP, extending to higher b

A “sufficient” number of stars, good spread in potentially radio emitting objects.

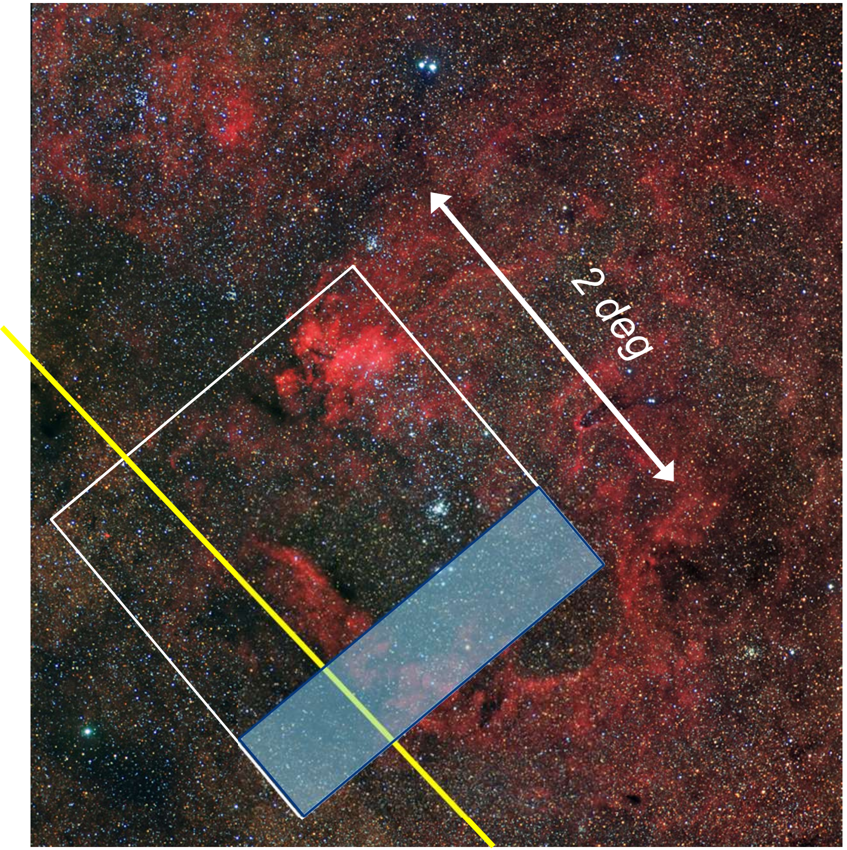
Few radio sources already detected in it: to be used as check

Multi-λ observations available for comparative studies.

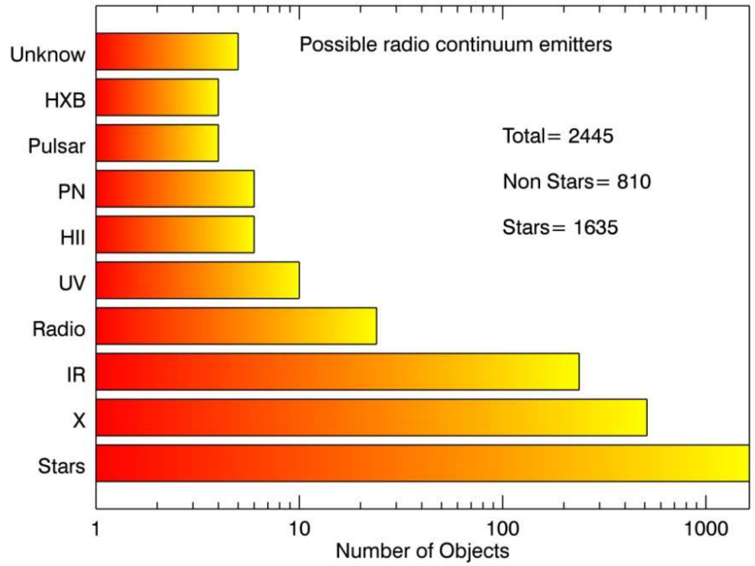
In the tail of SCORPIO

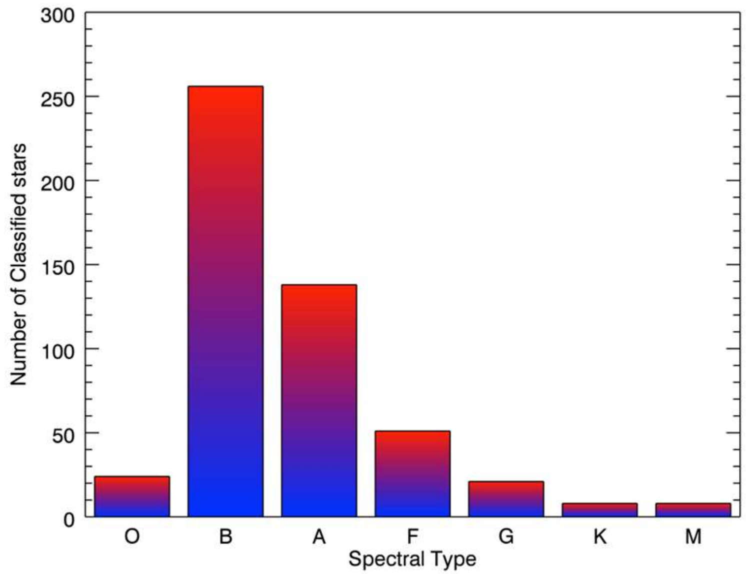
l=344.25
b=0.50

SCORPIO: A deep radio survey in the GP with the ATCA

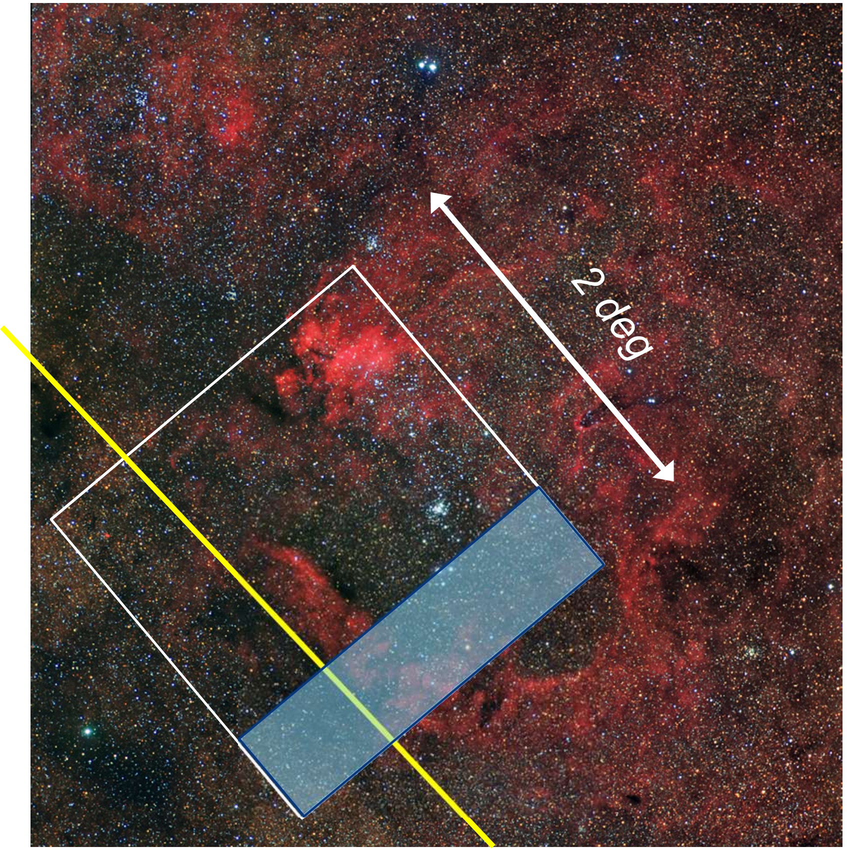


From SIMBAD database





SCORPIO: A deep radio survey in the GP with the ATCA



Part of the sky patch has been surveyed by:

Spitzer GLIMPSE 3.6, 4.5, 5.8 8.0 μm
MIPSGAL 24, 70
(Benjamin et al., 2003, Carey et al., 2009)

HERSCHEL Hi-GAL 70, 160, 250, 350, 500μm
(Molinari et al., 2010)

MOLONGLO 834 MHz (MGPS)
Sydney University Molonglo Sky Survey

Multi-wavelength observations will help:

The classification of new detections

Detailed studies of classified objects

SCORPIO Stellar Continuum Originating from Radio Physics In Ourgalaxy

Two aims:

Scientific

Provide a good estimation of the scientific potential of deep radio surveys in the field of stellar/Galactic radio astronomy.

- *Catalogues of different population of Galactic radio sources*
- *Define detection rates for different classes of radio stars.*
- *Prove the importance (uniqueness) of radio observations in the field of Stellar Astrophysics*

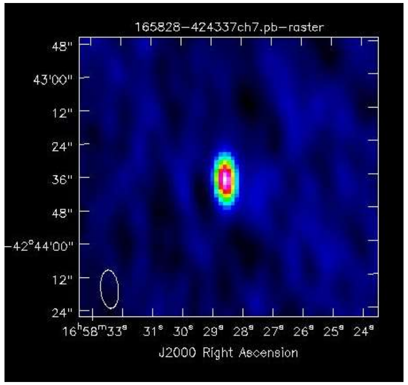
Technical

Test bed for the EMU/SKA surveys: strategy for the GP section

- *Source complexity: issues due to complex structures in the GP*
- *Source variability: issues due to the variable sources in the GP*
- *Source finding: issues due to the diffuse emission in the GP*
- *Source identification: how to identify/discriminate different populations (e.g. Galactic vs Extragalactic, different type of stars)?*

The SCORPIO zoo

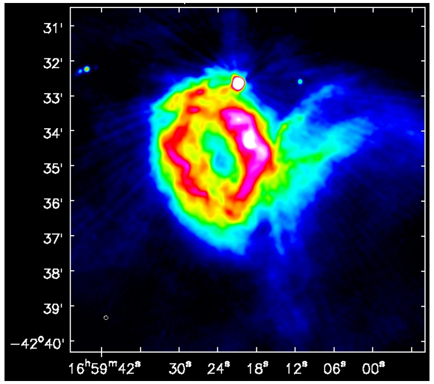
Found **2206** “point-like sources”, with a cut of 5σ
614 in the pilot experiment (Umana et al., 2015)



matches with SIMBAD

Stars
PNe
Pulsars
IR
HII

1Variable (z^1 Sco)
2 WR
3 in Open Cluster (in NGC6231)
1 YSO
1 Be
1 Cp star
13 stars with no references



Point Sources

6 pulsars
30 UCHII/HCHII
6 PNe
≈ 1900 without classification

Expected **many** extragalactic *“contaminants”*

Extended Sources

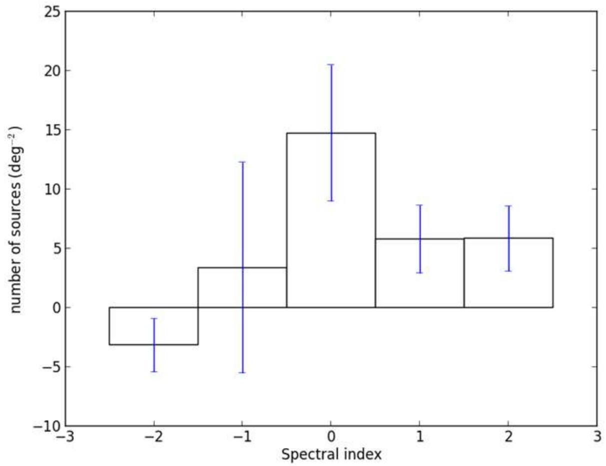
99 in total
35 new detections *64 known objects*

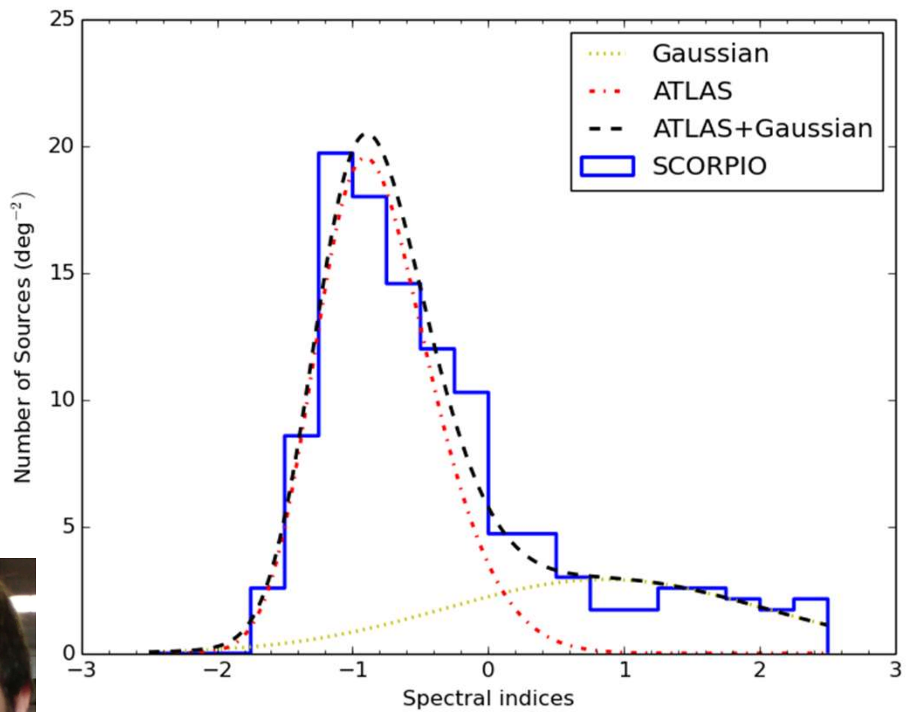
41 classified- 23 unclassified
39 classical HII
1 PNe

Radio spectral index analysis to characterize the point source emission

-disentagle between Galactic and extragalactic population?

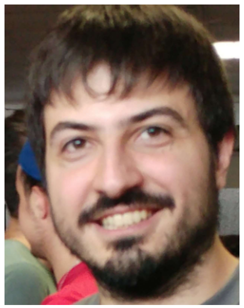
- -automatic procedure (run in Casa- *imfit, imstat*) to estimate the spectral index of source from multi frequency radio images.





Comparison with ATLAS:

no difference for α << 0
source excess for α ≥ 0



Cavallaro + 2018

Above 1 mJy, the source density in SCORPIO is 20% greater than in a typical extragalatic field

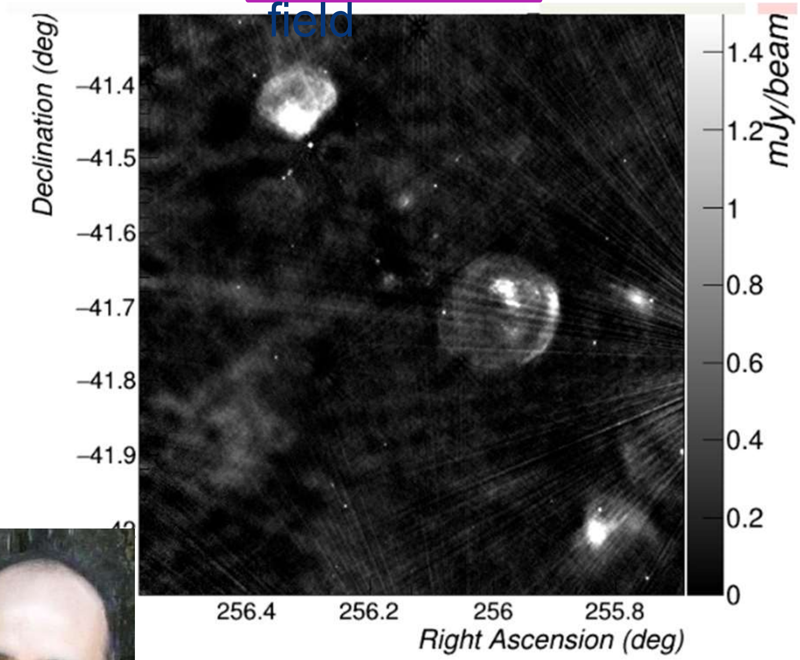
SCORPIO field is:

Small enough to allow source identification by visual inspection

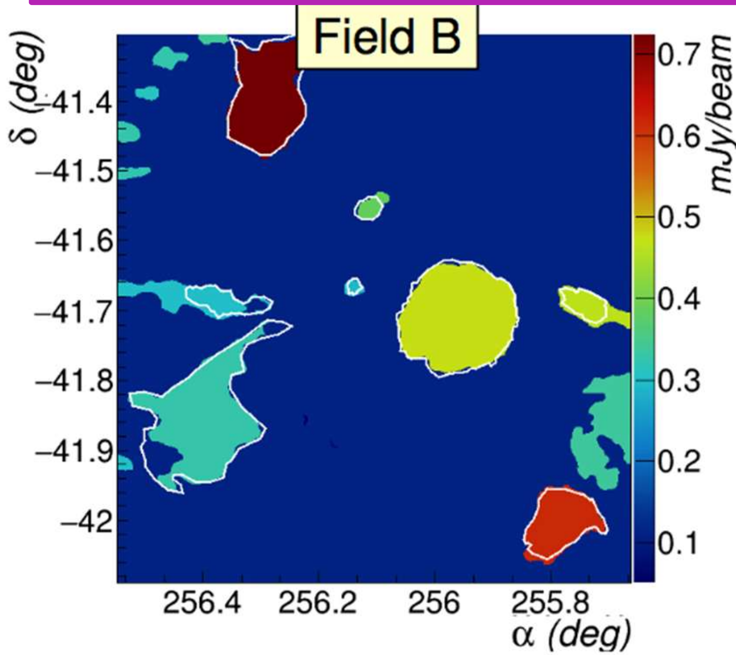
sufficiently large for testing and training automated algorithms

human-driven visual inspection can be used as a verification check of the automated algorithn

From a field



To a list of extended sources

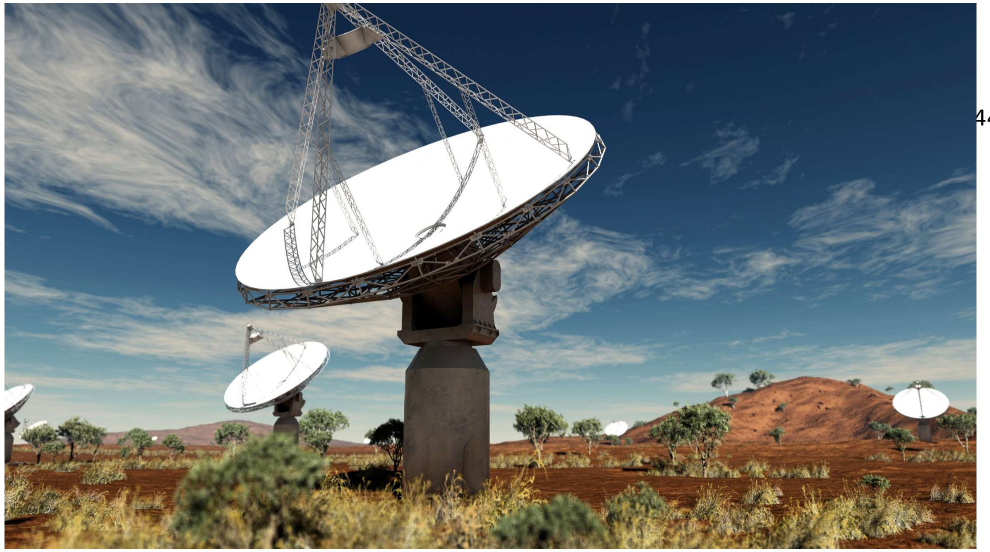


Riggi et al., 2016 Uses SCORPIO to test the automated extraction algorithms CAESAR (Compact And Extended Source Automated Recognition)

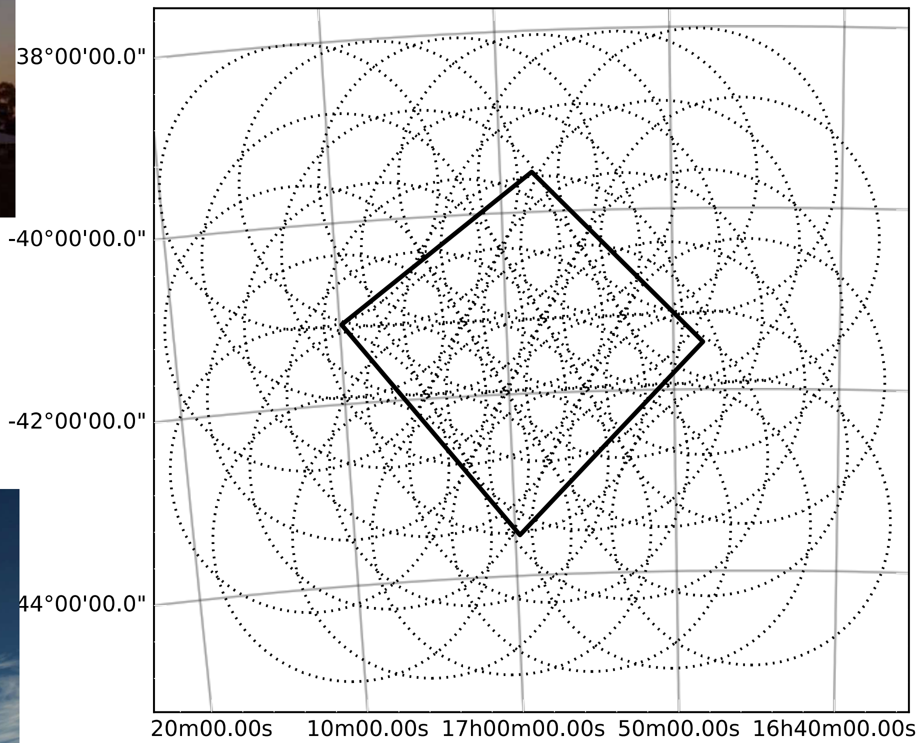
The SCORPIO field — ASKAP Early Science

ATCA- 133 pointings, 3σ= 90 μJy, 4 deg^2
Freq: **1.1-3.1 GHz (2.1 GHz)**
Total integration time: 320 hrs

ASKAP-12 1 pointing! 40 deg^2



A much larger region of SCORPIO field observed during ASKAP Early Science
Freq: 792-1032 MHz (240MHz)
Ang. Res. 24.1x 21.1 arcsec^2



Total integration time: 32 hrs
(including overheads for calibration)
rms ≅ 130μJy (outside GP)
<rms> ≅ 500μJy

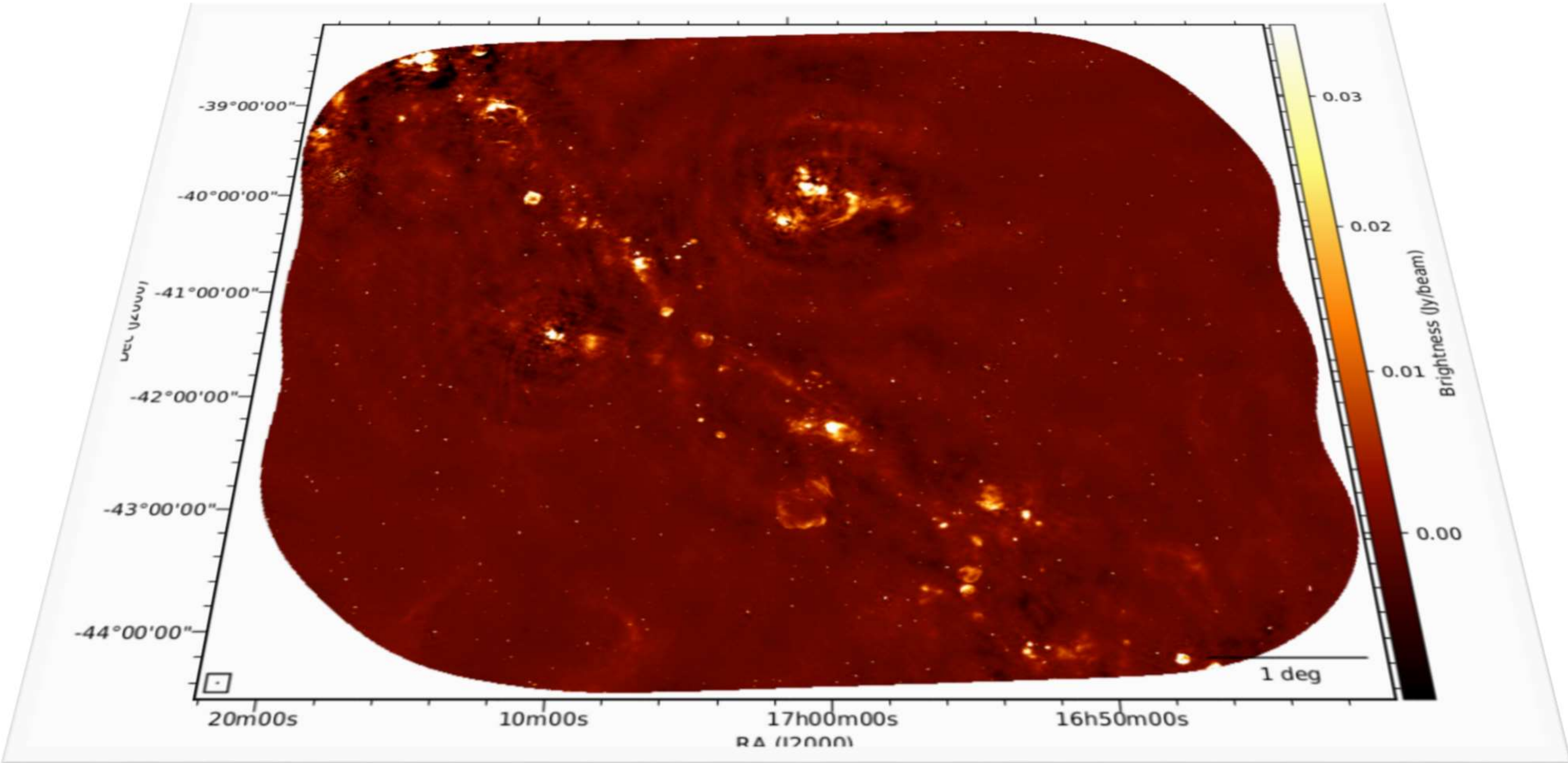
Umana+2019 in prep.

The SCORPIO field

Field center 343.5, 0.75

Dimensions 6x6 deg^2

Band 1 (920 MHz, B=300 MHz)
ASKAP-12



ASKAP-36 to be processed

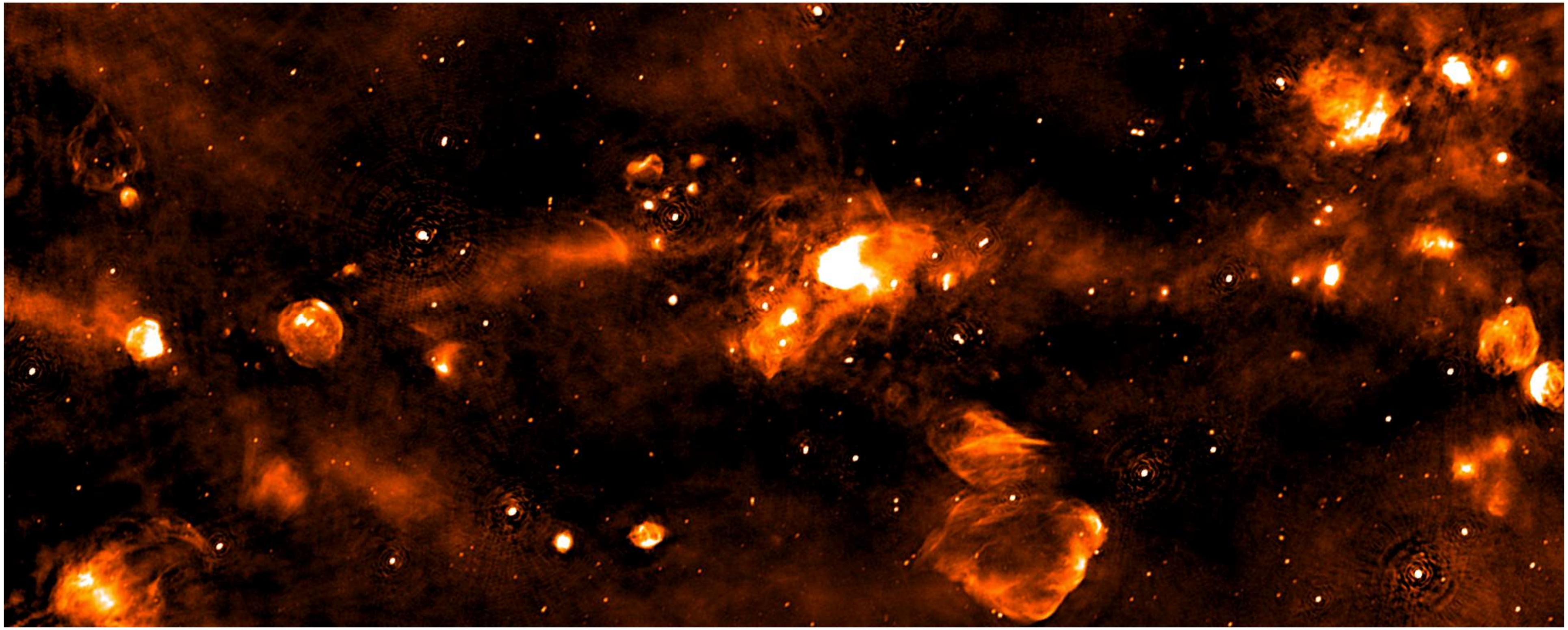
Band 1 (920 MHz, B=300 MHz)

Band 2 (1296 MHz)

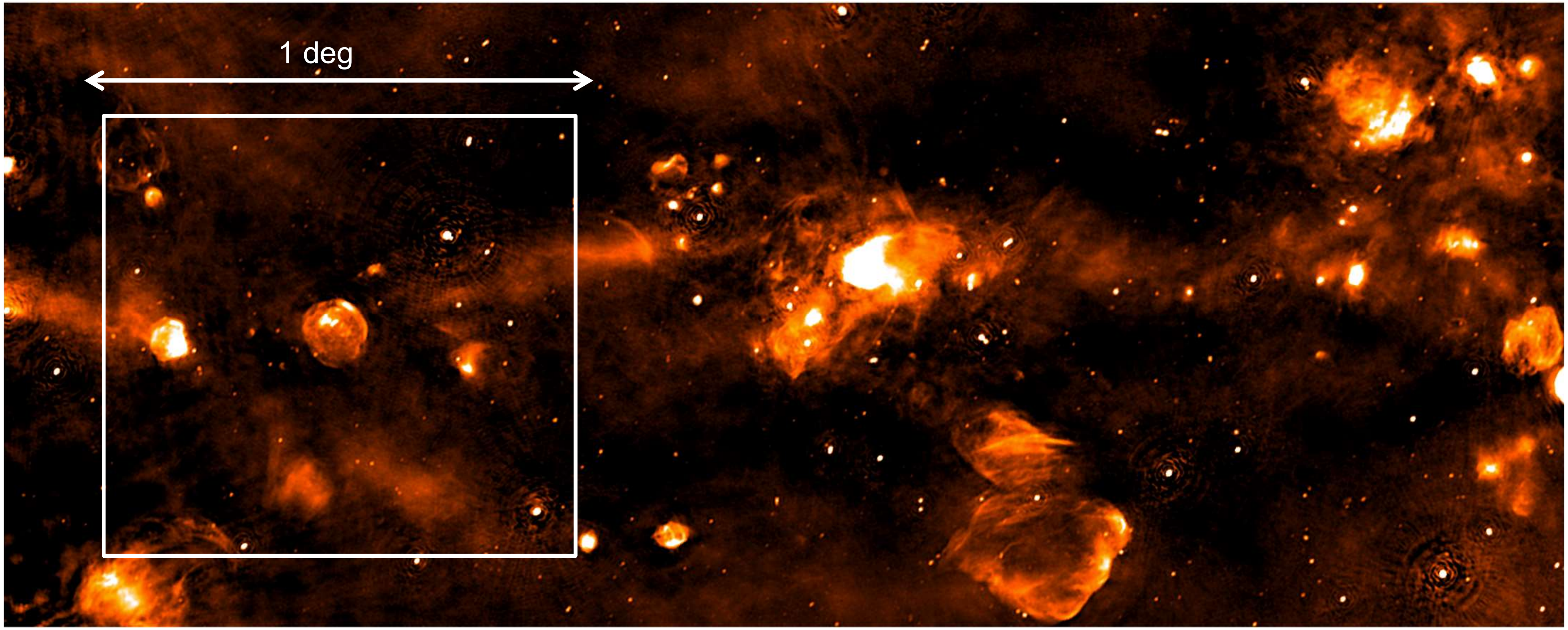
Band 3 (1630 MHz)

The SCORPIO field

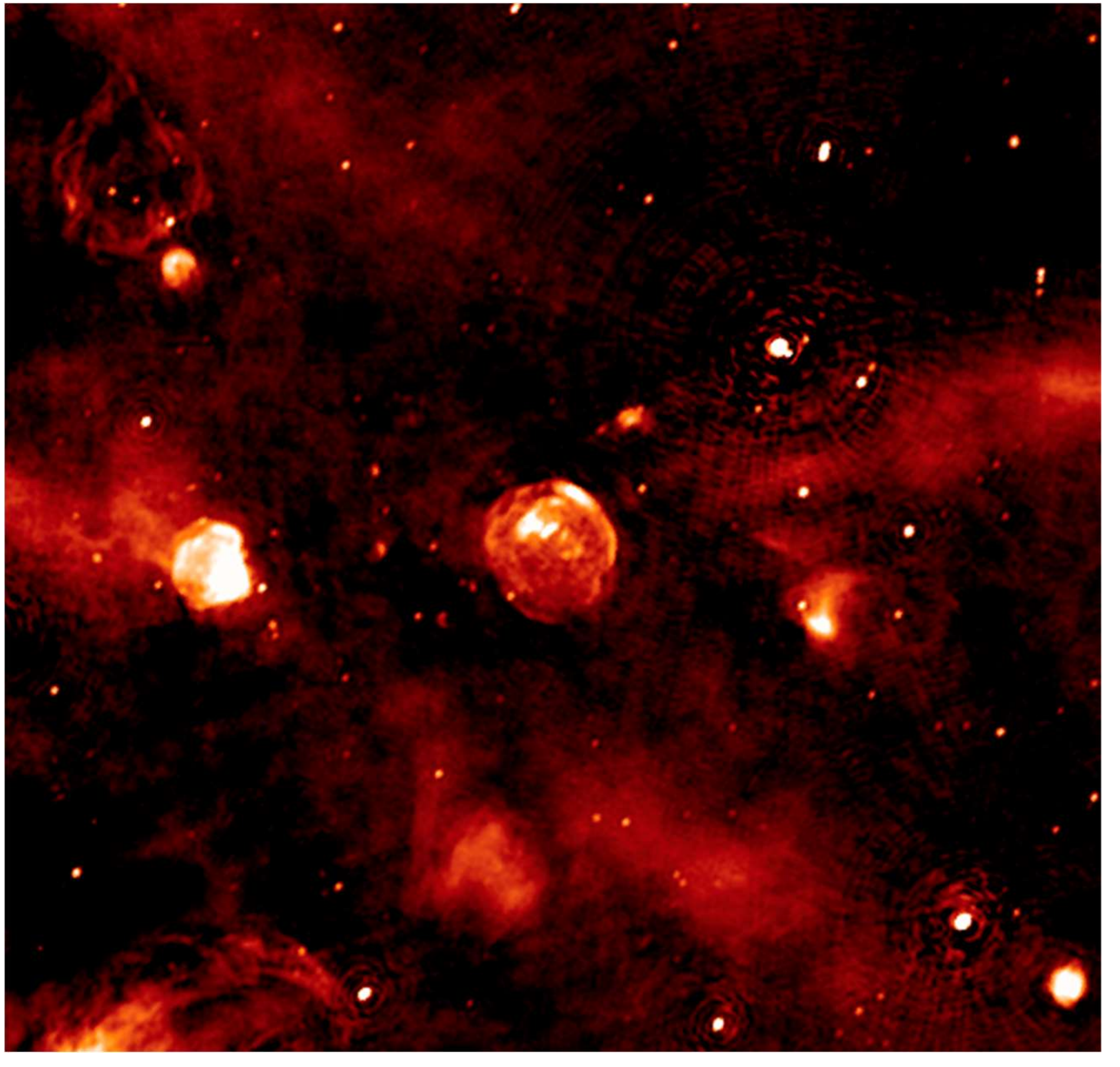
Field center 343.8 -0.2
Dimensions 5.4x1.3 deg^2
Band 1 (792-1032 MHz)



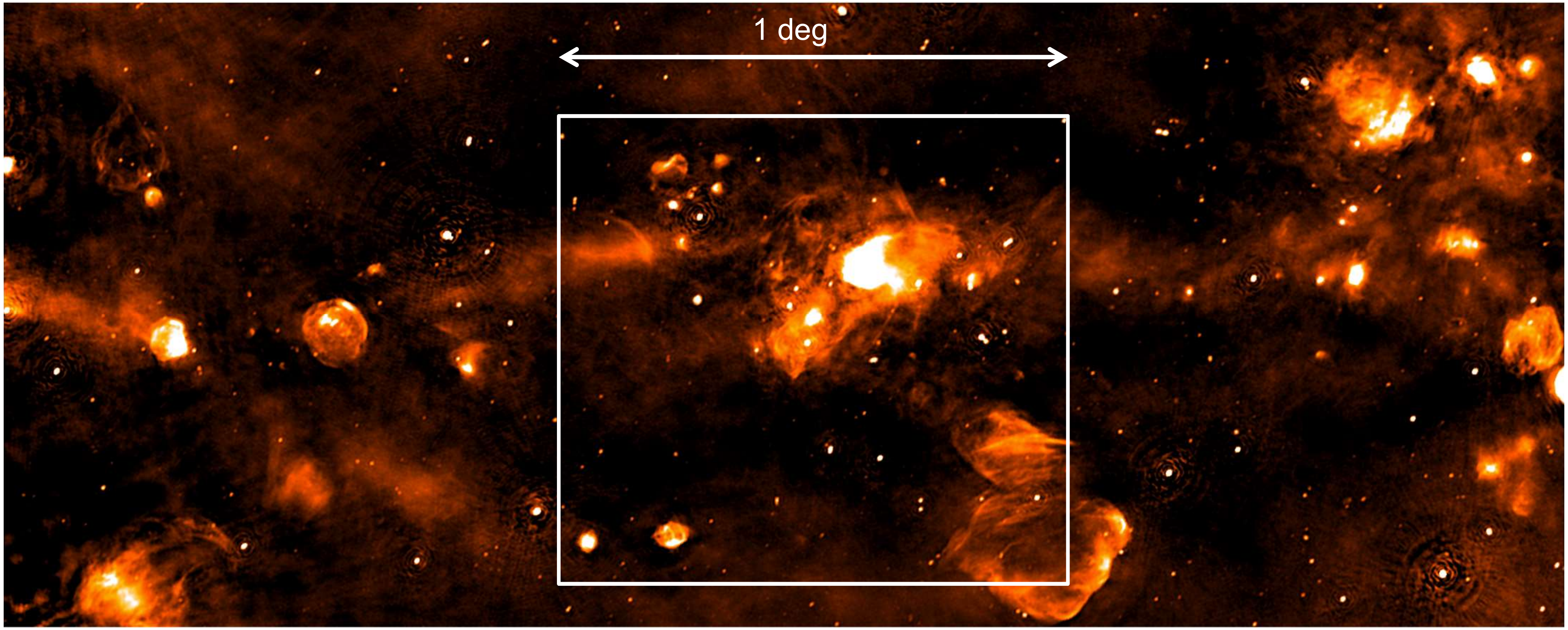
The SCORPIO field



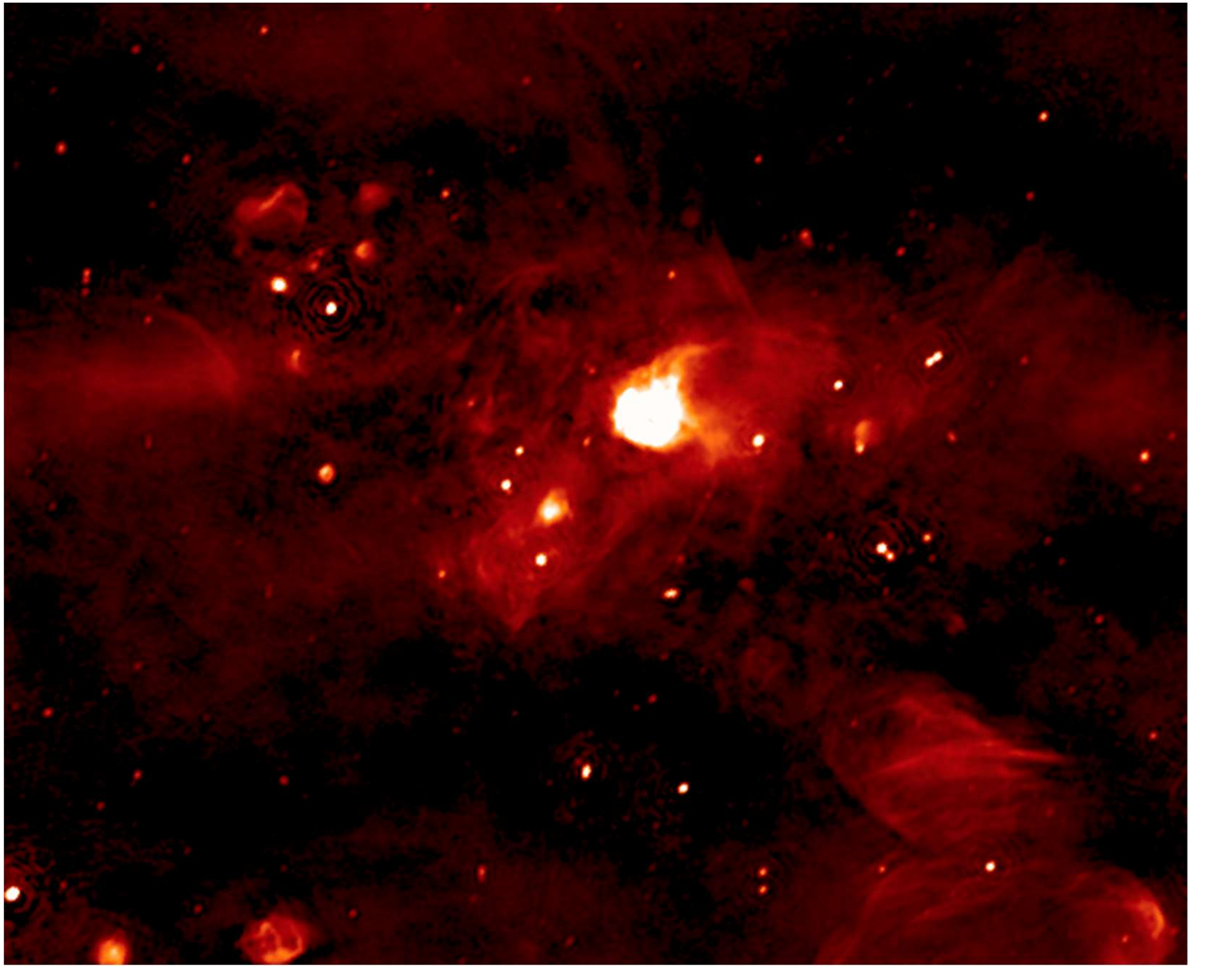
The SCORPIO field



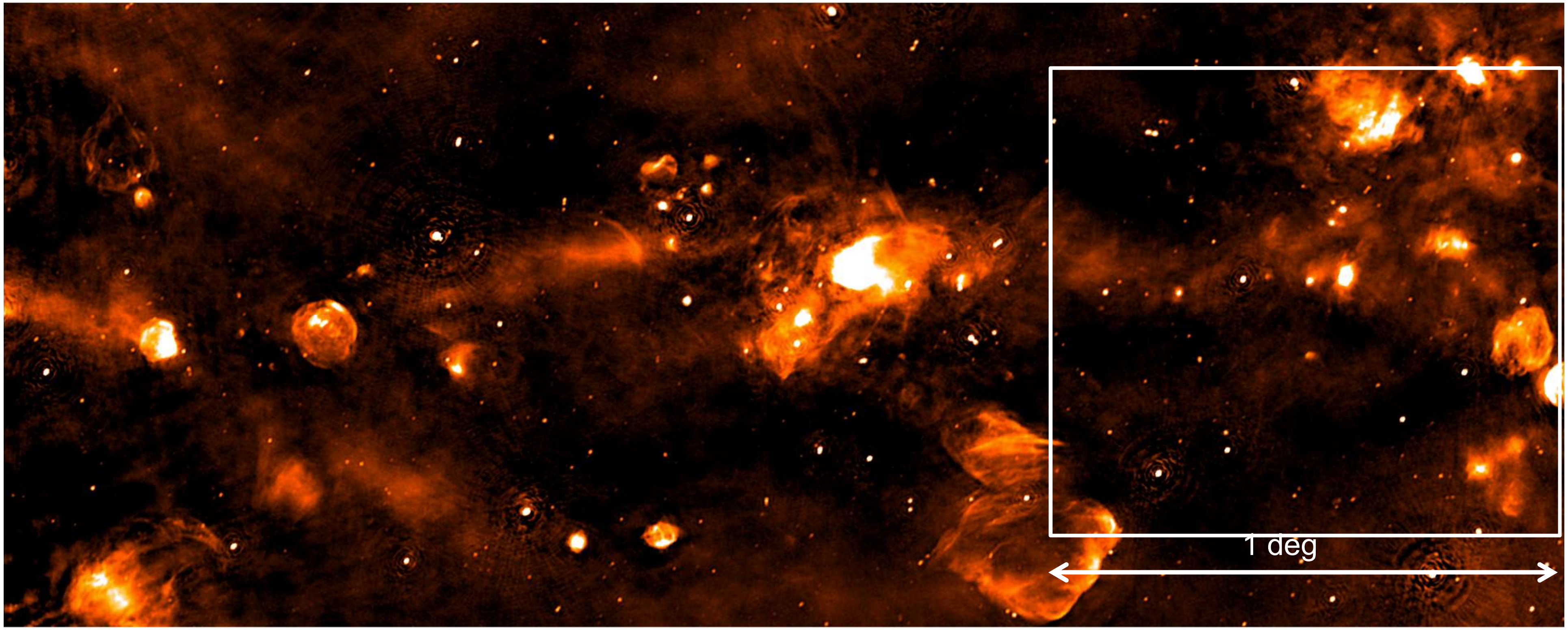
The SCORPIO field



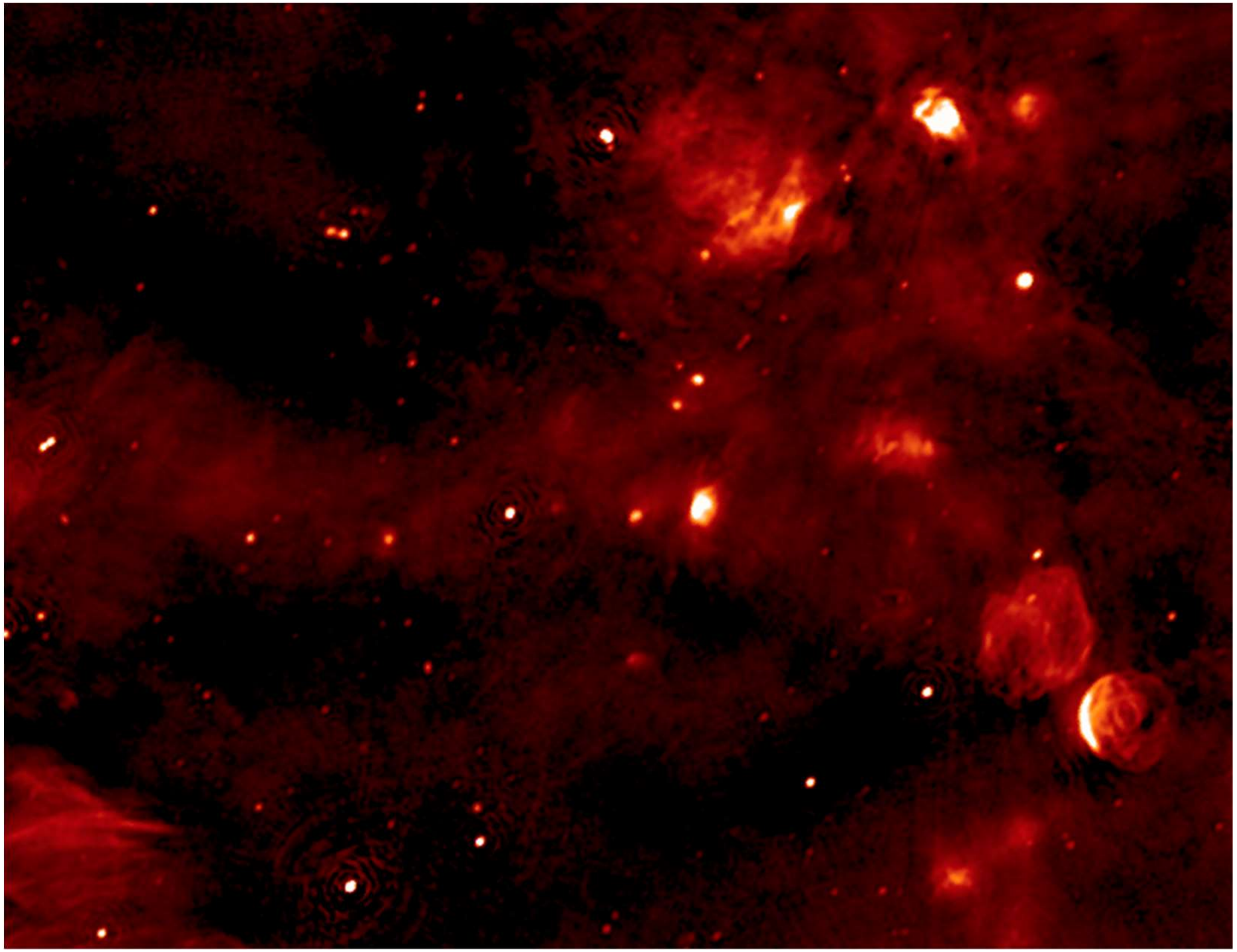
The SCORPIO field



The SCORPIO field



The SCORPIO field

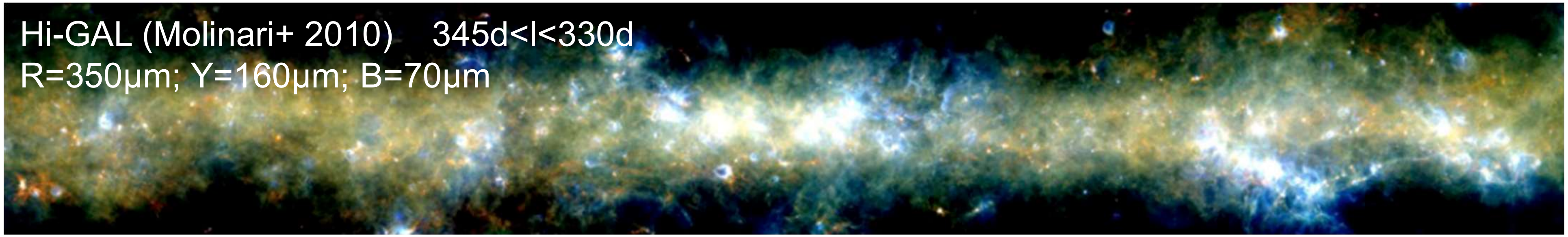


Synergy with multi-frequency Galactic Plane surveys

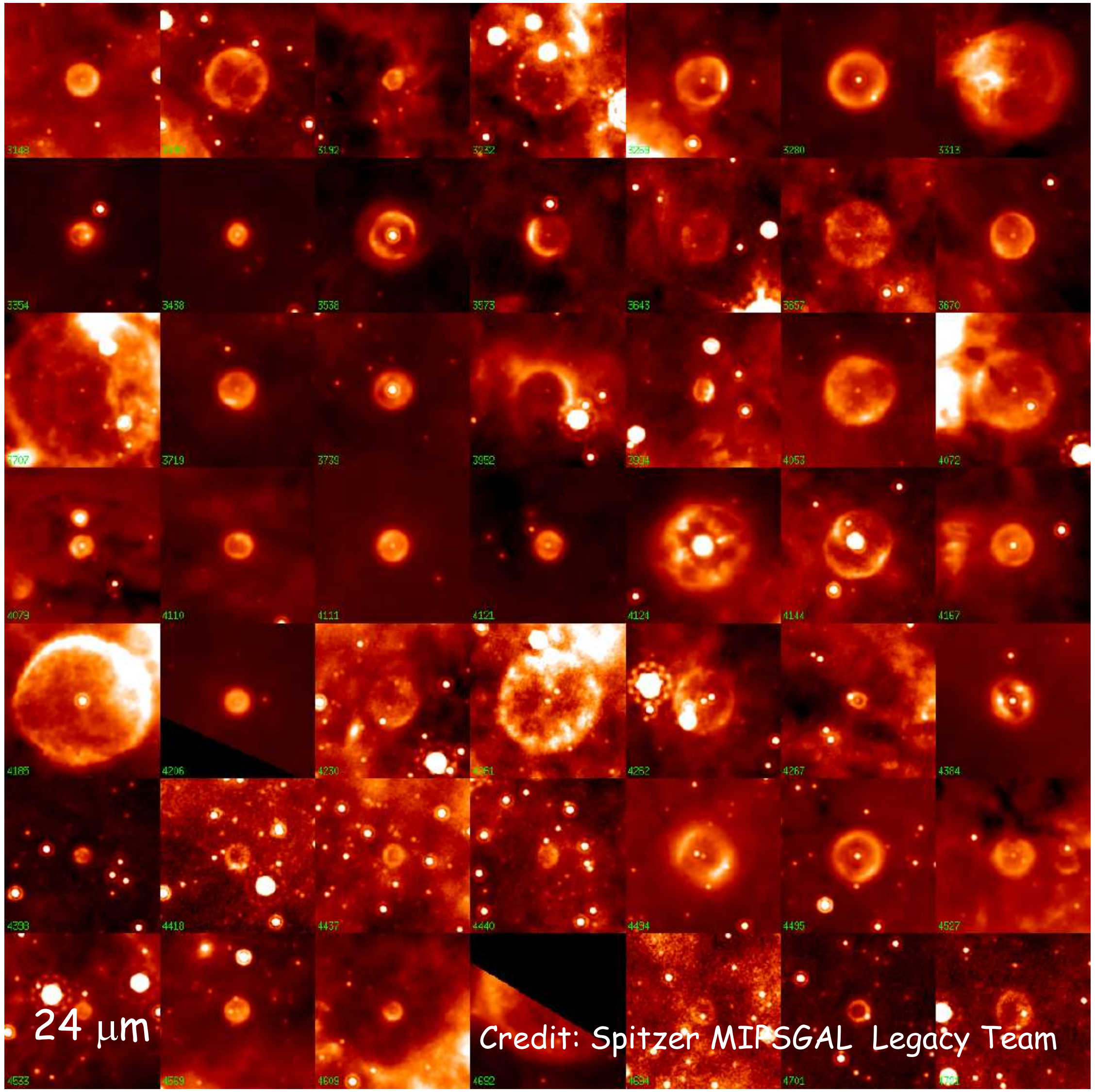
Adapted from Hoare + 2012

Survey	Wavelength	Beam (″)	l Coverage	b Coverage	Probe	Reference
IPHAS	Hα	1.7	$30^o < l < 210^o$	$\|b\| < 5^o$	Nebulae & stars	Drew et al. (2005)
UKIDSS	JHK	0.8	$-2^o < l < 230^o$	$\|b\| < 1^o$	Stars, Nebulae	Lucas et al. (2008)
VVV	ZYJHK	0.8	$-65^o < l < 10^o$	$\|b\| < 2^o$	"	Minniti et al. (2010)
GLIMPSE	4-8 μm	2	$-65^o < l < 65^o$	$\|b\| < 1^o$	Stars, Hot Dust	Churchwell et al. (2009)
MSX	8-21 μm	18	All	$\|b\| < 5^o$	Warm Dust	Price et al. (2001)
MIPSGAL	24,70 μm	6, 20	$-65^o < l < 65^o$	$\|b\| < 1^o$	"	Carey et al. (2009)
AKARI	50-200 μm	30-50	All sky		Cool Dust	White et al. (2009)
Hi-GAL	70-500 μm	10-34	All	$\|b\| < 1^{oa}$	"	Molinari et al. (2010)
JPS	450,850 μm	8-14	$10^o < l < 60^o$	$\|b\| < 1^o$	"	Moore et al. (2005)
ATLASGAL	850 μm	19	$-60^o < l < 60^o$	$\|b\| < 1.5^o$	"	Schuller et al. (2009)

For several classes of Galactic objects robust classification is possible only by combining radio and IR information



The **Bubbling** Galactic Plane



About 400 “bubbles” found
in MIPSGAL (24 μm)
Carey et al., 2009, Mizuno et al 2010

Possibly related to late stages
of stellar evolution
only 10% have been identifi

Radio observations:

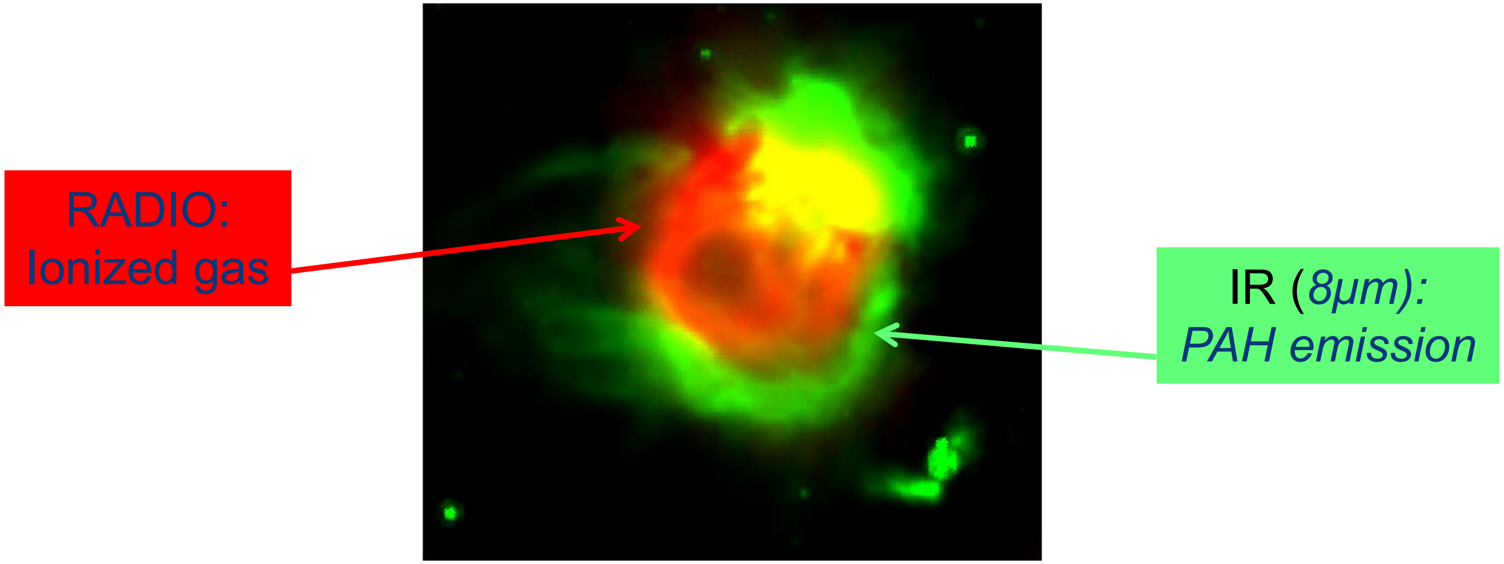
- ✓ Detailed morphology
- ✓ Spectral index
- ✓ Polarization

to discriminate

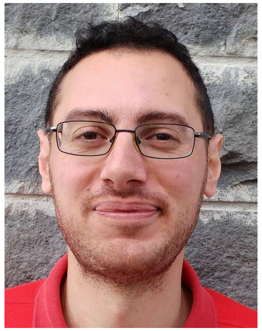
LBV, PN, WR (thermal)
from SNR (non-thermal)

Comparing radio and IR morphology, is possible to distinguish HII from evolved st

In HII, radio emission wrapped by 8μm emission (Deharveng +2010)
In PN radio and 8μm are cospatial (Ingallinera +, 2016)



Use of radio and IR morphology to classified extended sources in SCO
(Ingallinera + 2016; Ingallinera +2019)



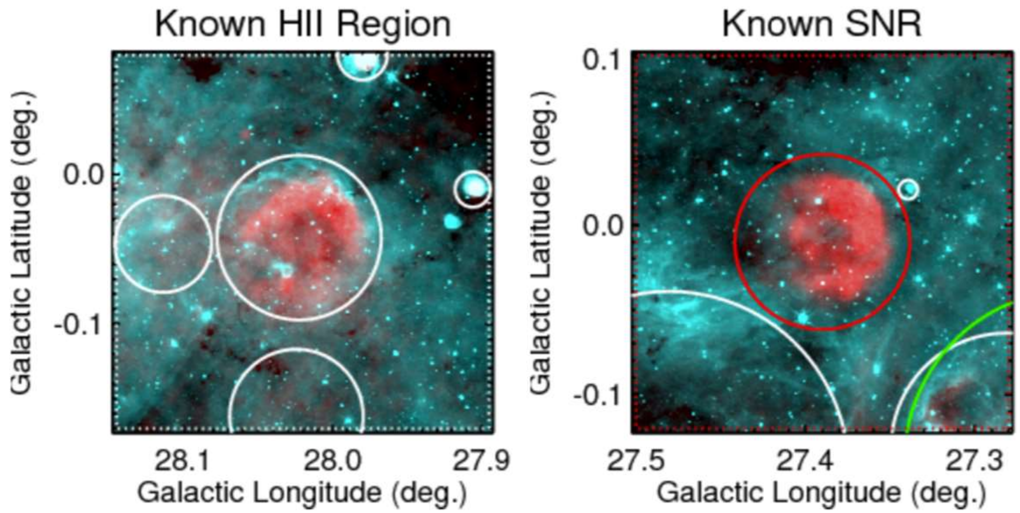
To explote the use of radio and IR morphology to automated source classification for large surveys by means of edge-sensitive algorithms

SCORPIO field of the “right” dimension for the human-driven visual inspection be used as a verification check.

Comparing radio and IR morphology is possible to spot Supernova Remnant

In HII, radio emission wrapped by 8μm emission (Deharveng +2010)
In SNR the 8μm emission in essentially absent and MIR/radio ratio much lower than HII regions (e.g. Anderson+2017)

GLIMPSE 8 μm
THOR+VGPS 21 cm



Anderson+17

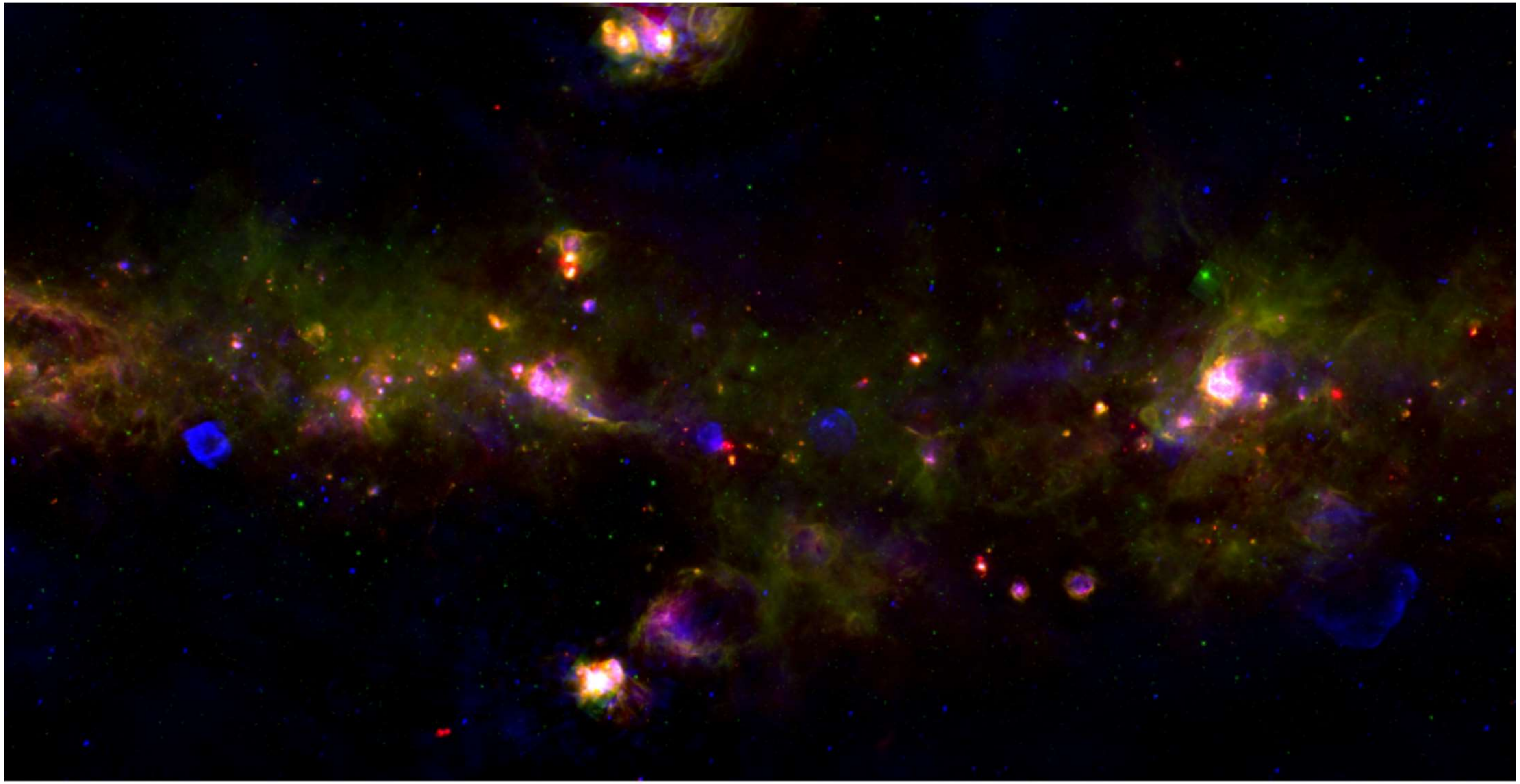
- Finding Missing SNR population: use of radio and IR morphology to individuate new SNR candidates in SCORPIO field (ASKAP vs Hi-Gal images; Bufano+in prep.)

- Study of the origin of dust in SNRs: use of IR data to produce 2D maps of the dust physical properties (T, β and τ_V) distribution, from the pixel to pixel SED.

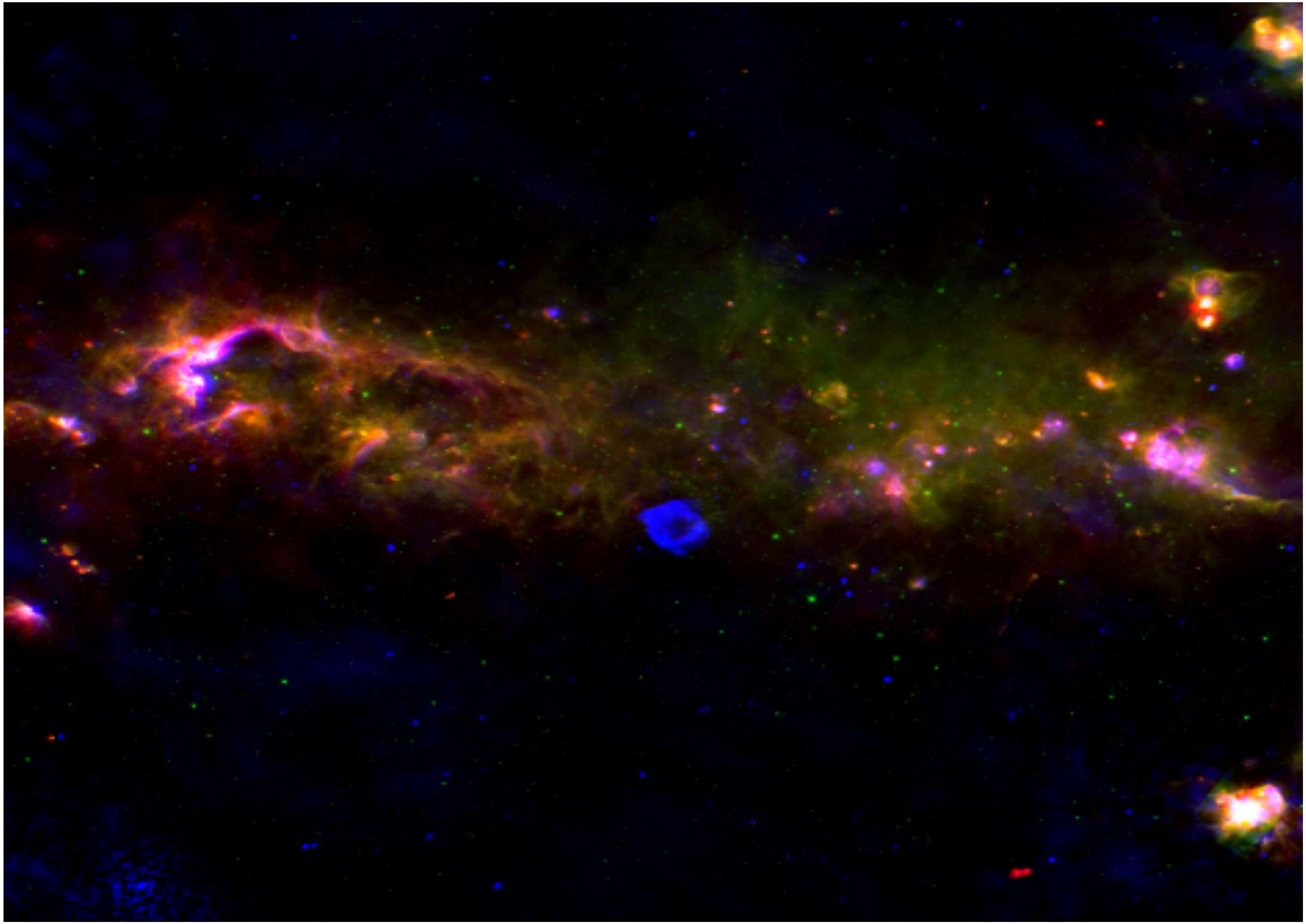
The SCORPIO field ASKAP map

Field center 343.8 -0.2
Dimensions 5.4x1.3 deg^2

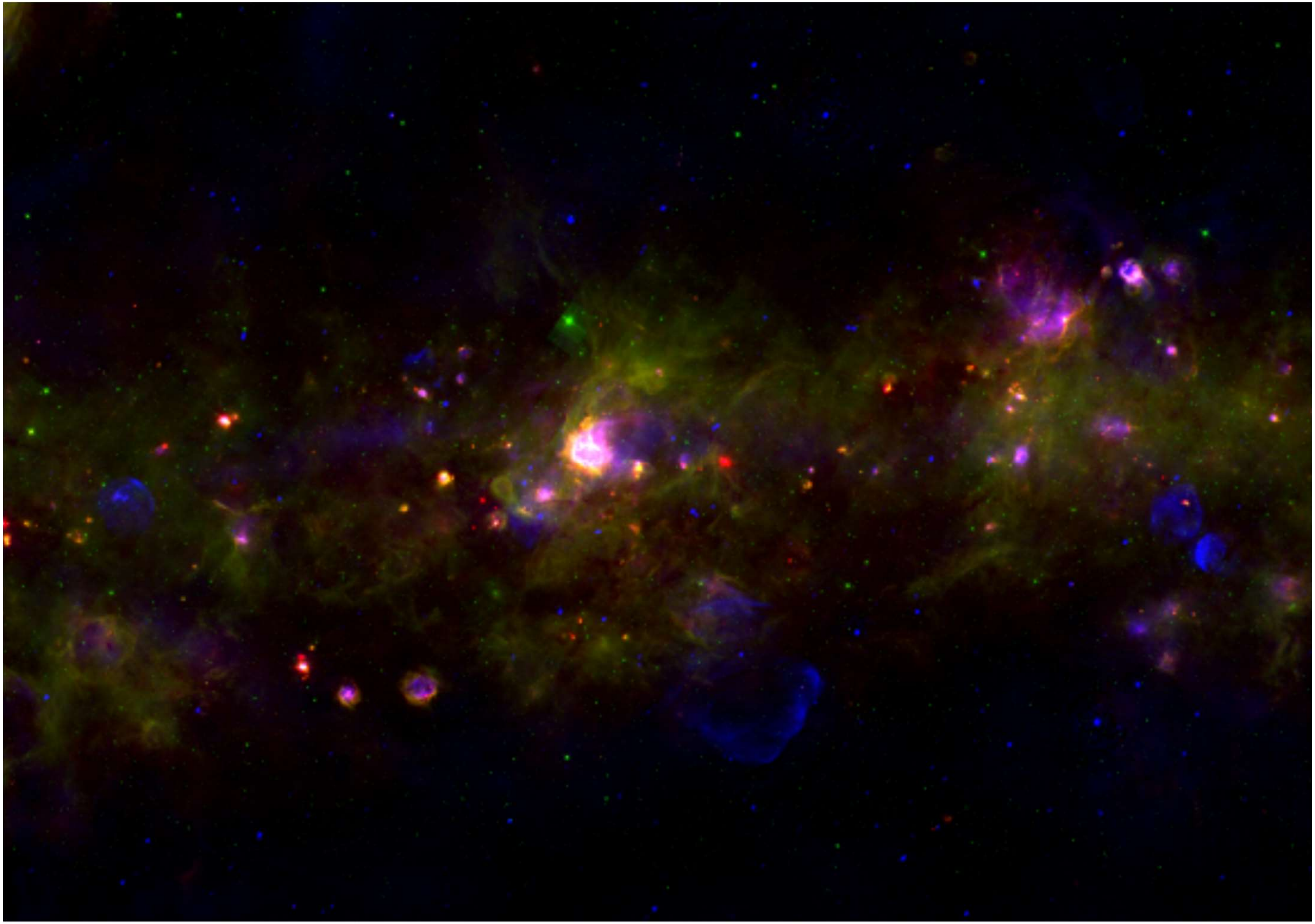
Green 8μm GLIMPSE
Red 70μm Hi-GAL
Blue ASKAP 912 MHz



The SCORPIO field ASKAP map

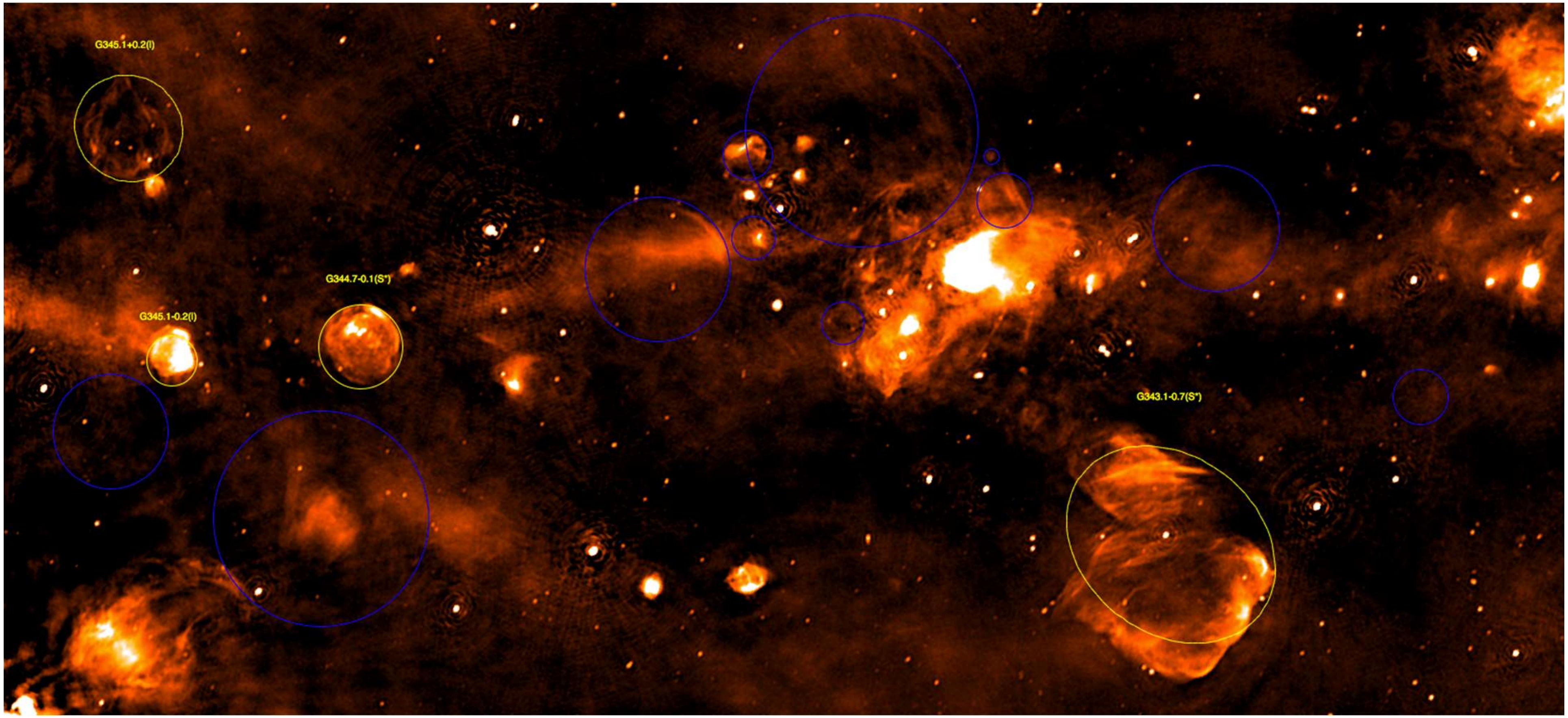


The SCORPIO field ASKAP map



The SCORPIO field

Field center 343.8 -0.2
Dimensions 5.4x1.3 deg^2

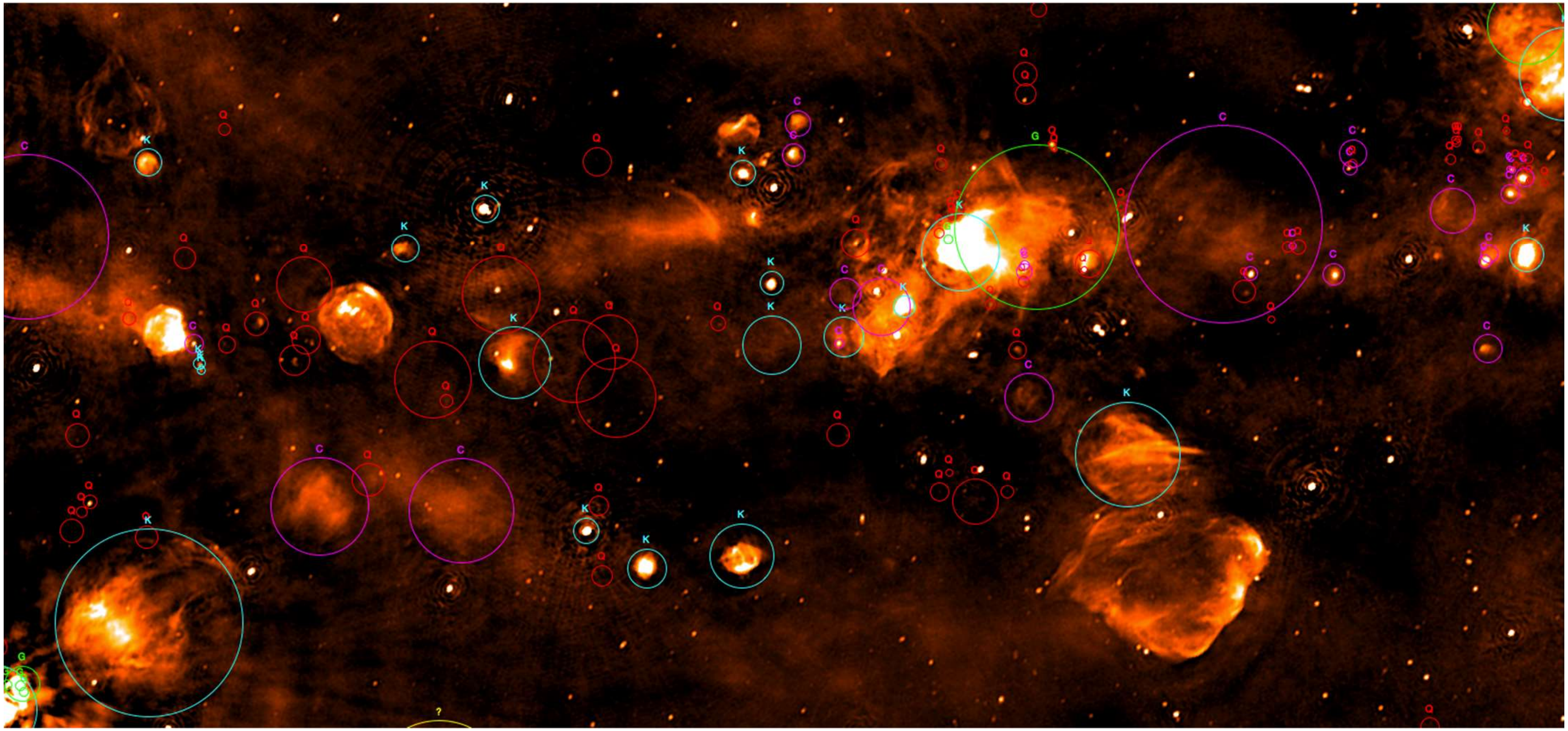


Yellow –17 known SNRs from Green et al. 2014
Blue 23 new SNRs *candidates* (FIR much weaker or absent with respect to HII regi

The SCORPIO field

Field center 343.8 -0.2
Dimensions 5.4x1.3 deg^2

HII Regions as from the WISE catalog (Anderson+201

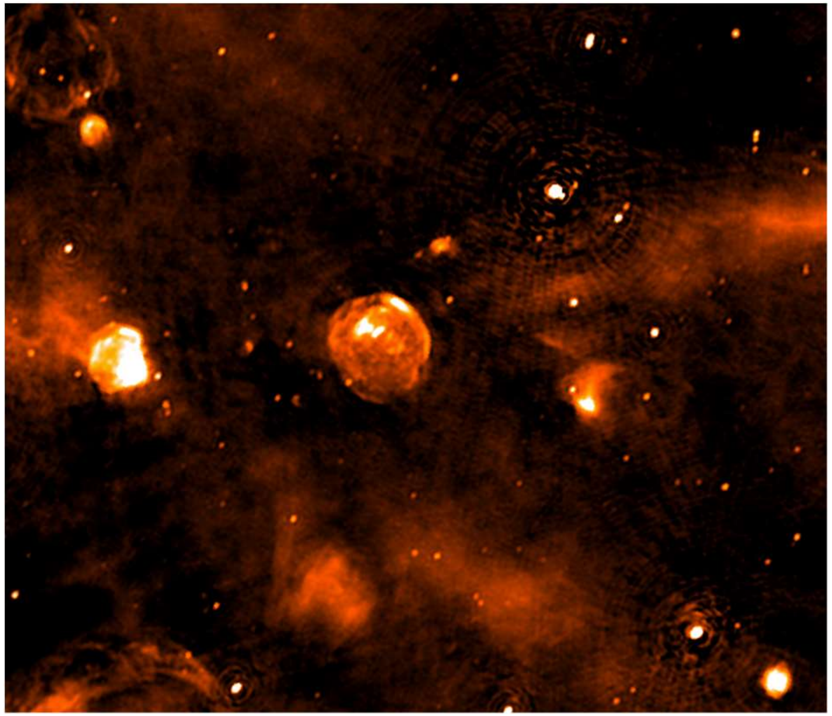


Light-blue	K	Known HII
Green	G	Group
Purple	C	Candidate
Red	Q	radio quite

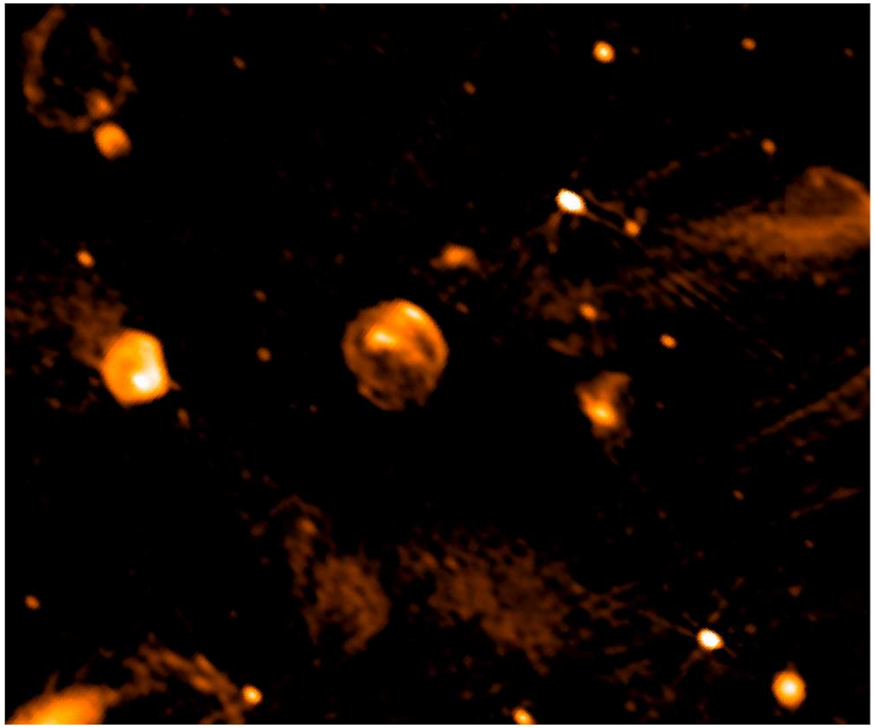
A total of **388 HII** in SCORPIO/ASKAP map
All the known and candidate HII are detected
220/388 are Q HII regions
99/220 (**45%**) are detected in SCORPIO/ASKAP

Field around SNR G344.7-0.1

912 MHz ASKAP



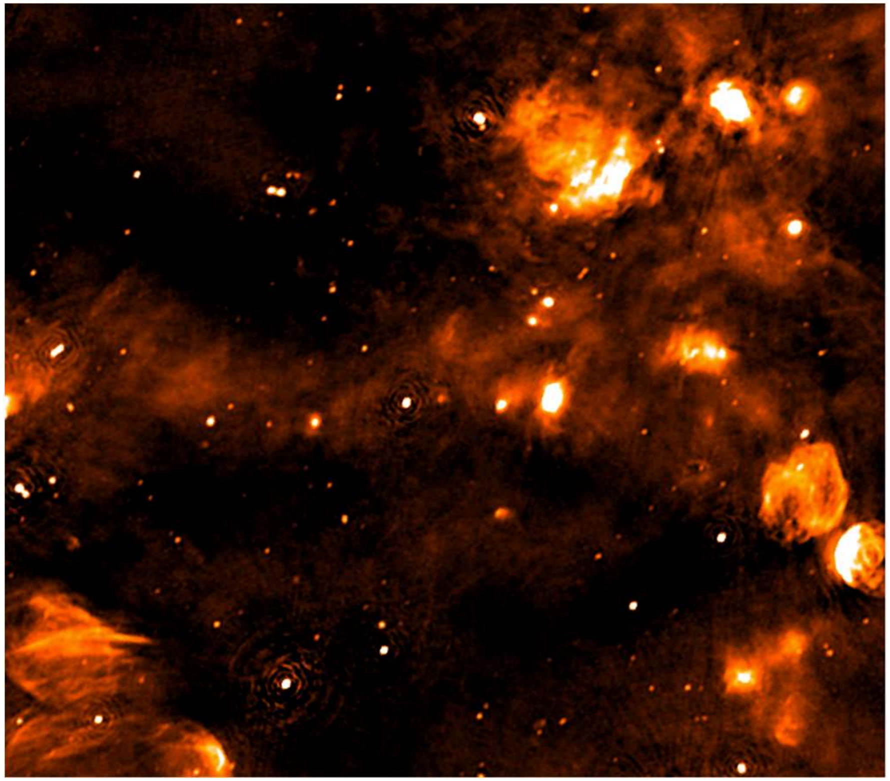
MOST 843 MHz



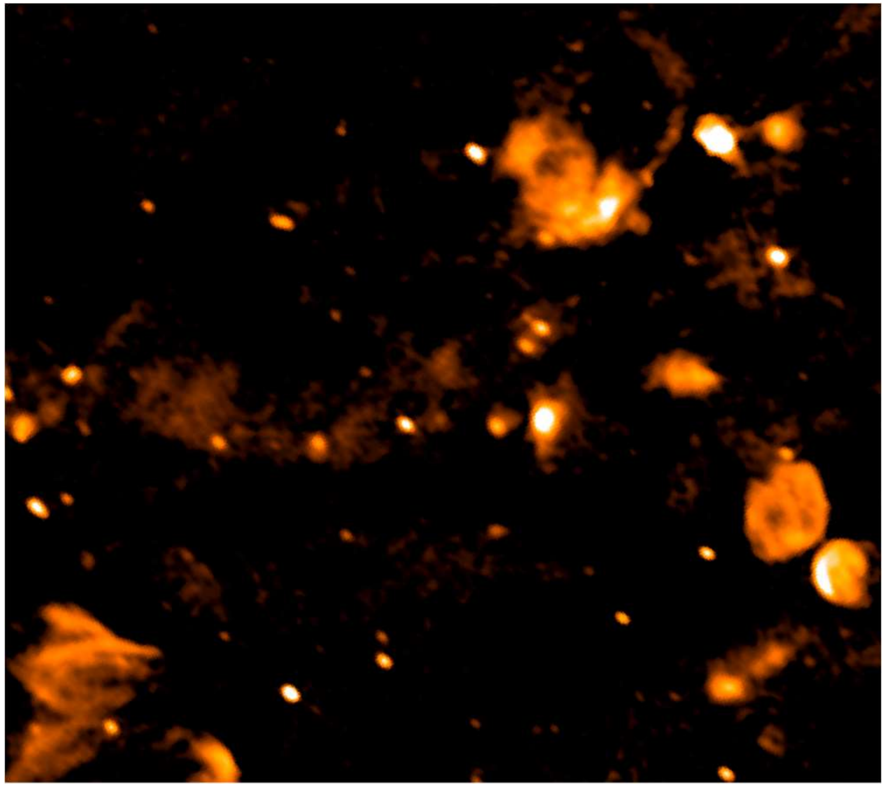
The ASKAP image is sharper and more sensitive, showing fainter diffuse features and additional details compared to the previous “best” image of the same patch in the sky

The SCORPIO field

912 MHz ASKAP



MOST 843 MHz

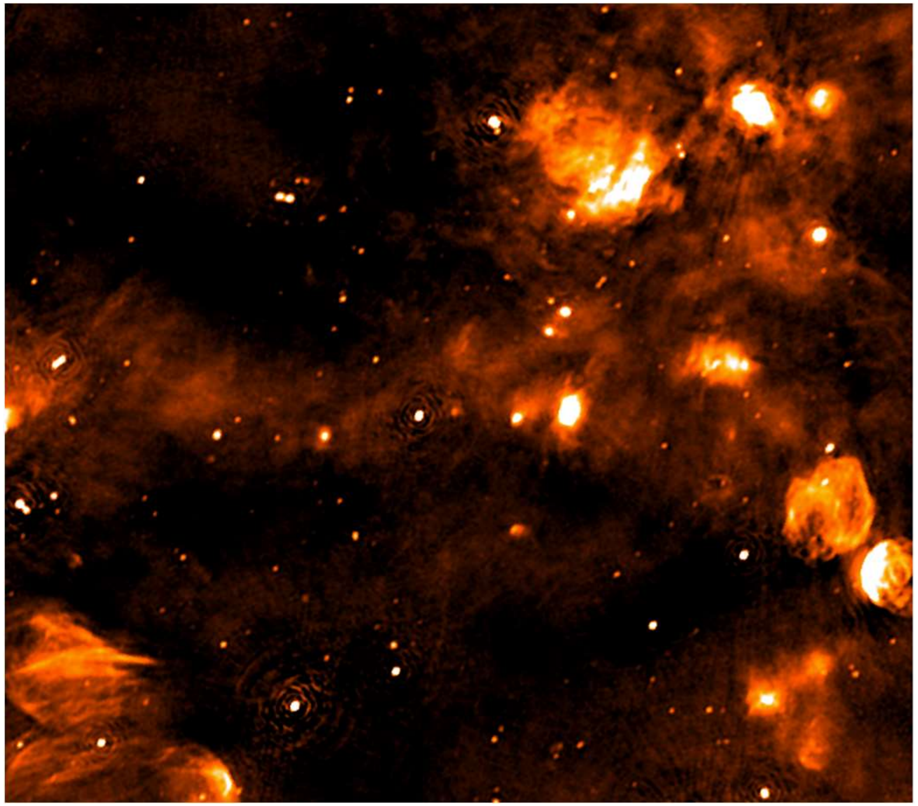


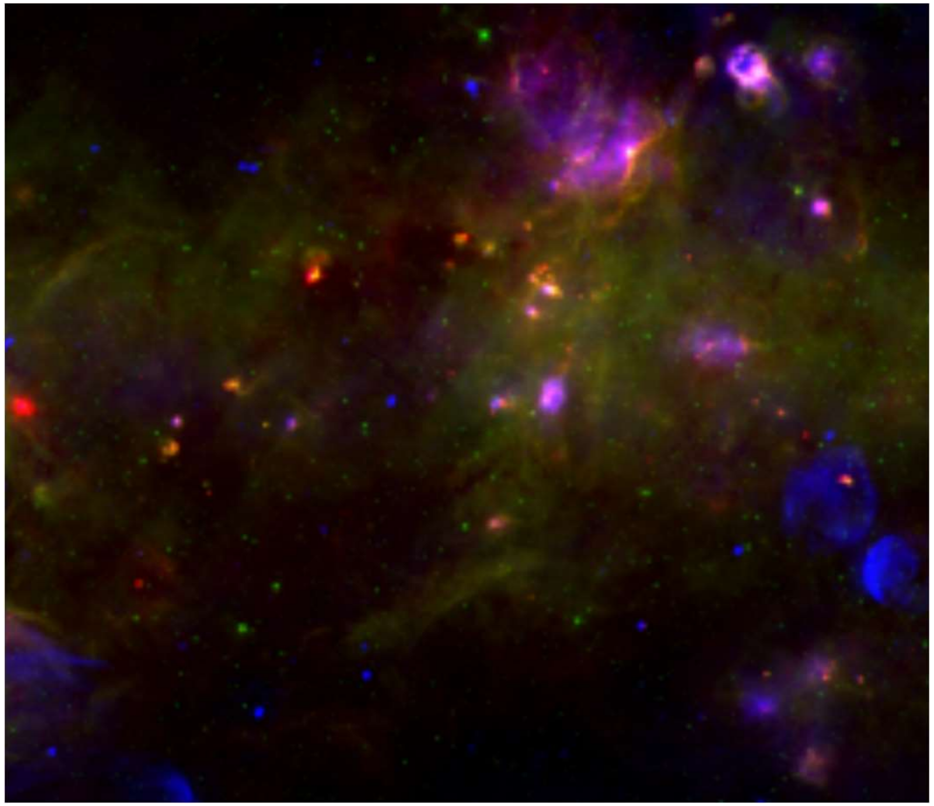
The ASKAP image is sharper and more sensitive, showing fainter diffuse features and additional details compared to the previous “best” image of the same patch in the sky

The SCORPIO field

912 MHz ASKAP

Green 8µm GLIMPSE
Red 70µm Hi-GAL
Blue ASKAP 912MHz

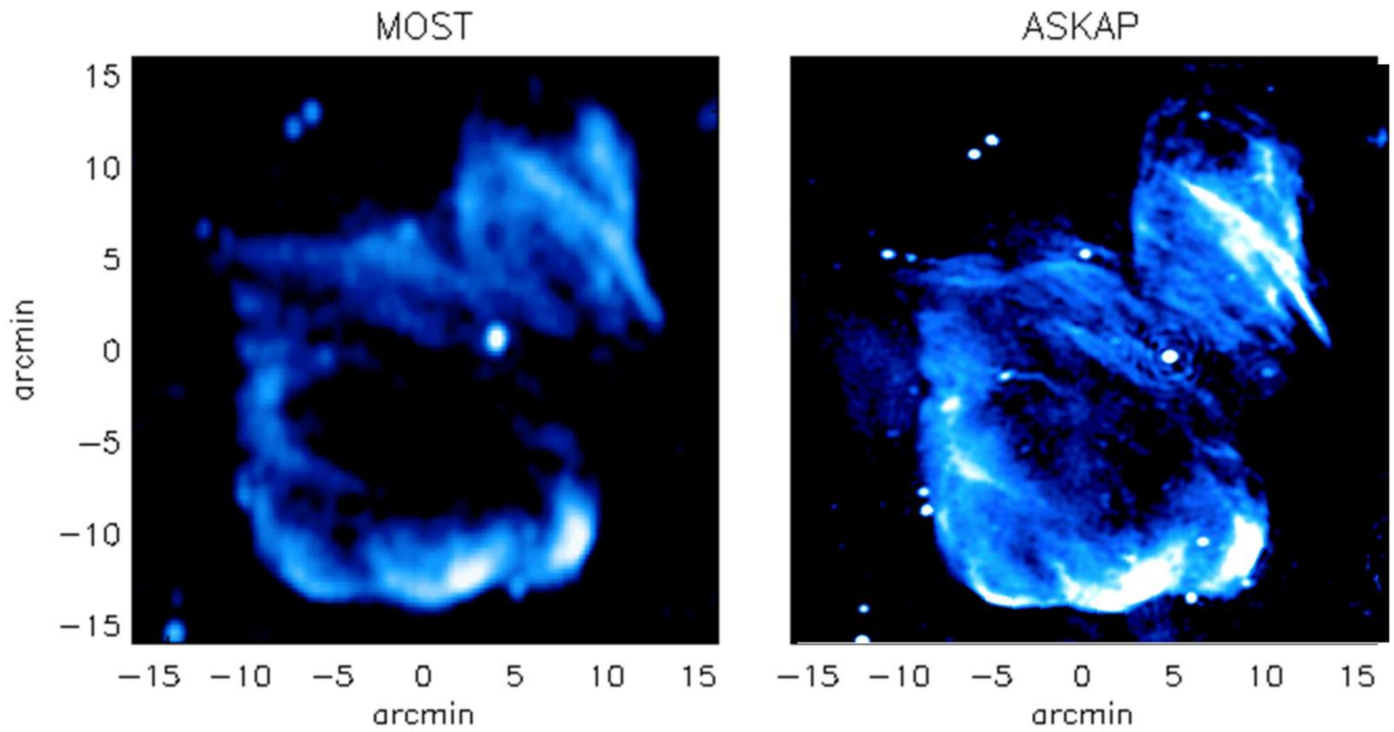




SNR G343.1-0.7

MGPS conducted with the Molongo Observatory Synthesis Telescope

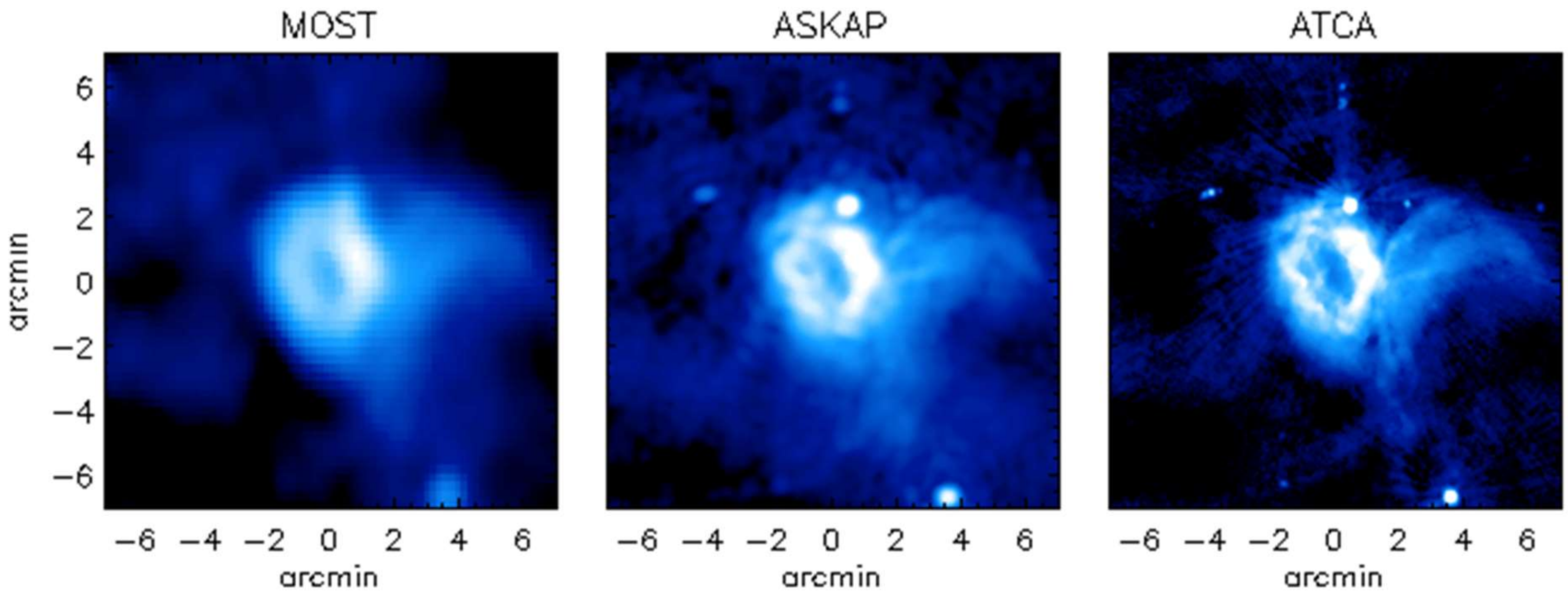
843 MHz 912 MHz



Overall structure of the remnant recovered by the two instruments

The better resolution of ASKAP (20” vs 45”) allow to appreciate finer details

Bubble S17 -Churchell et al., 2006

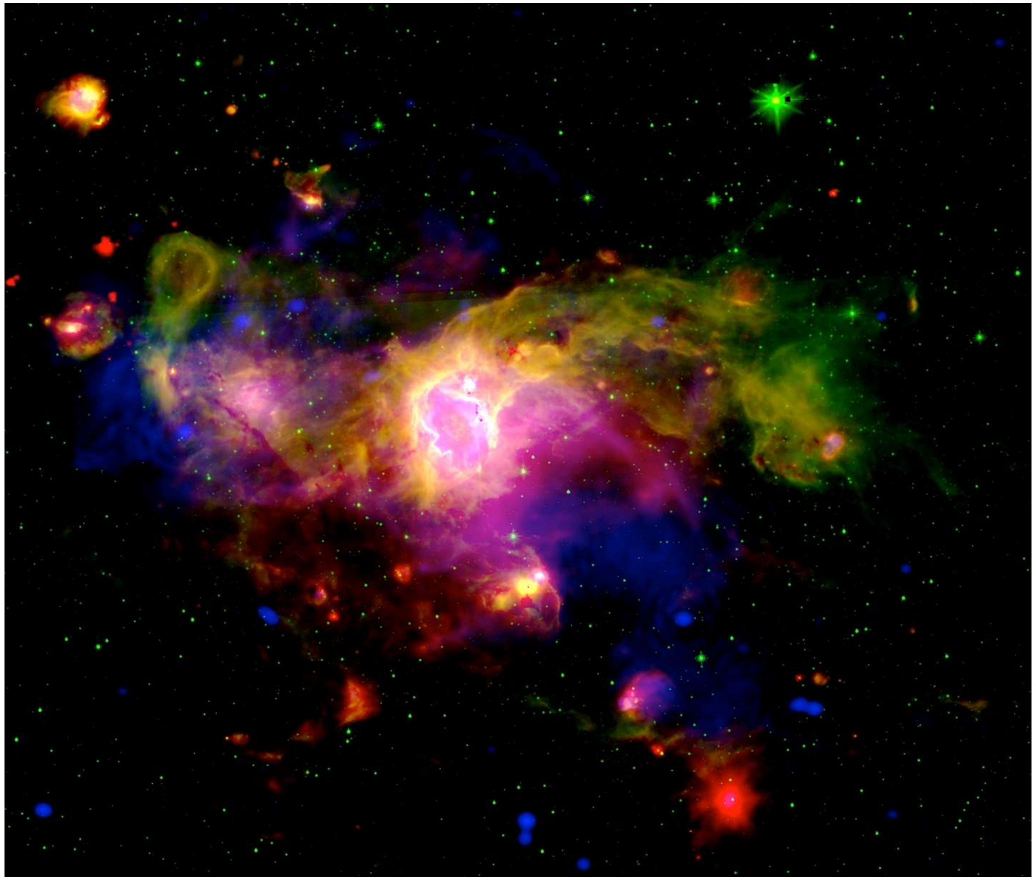


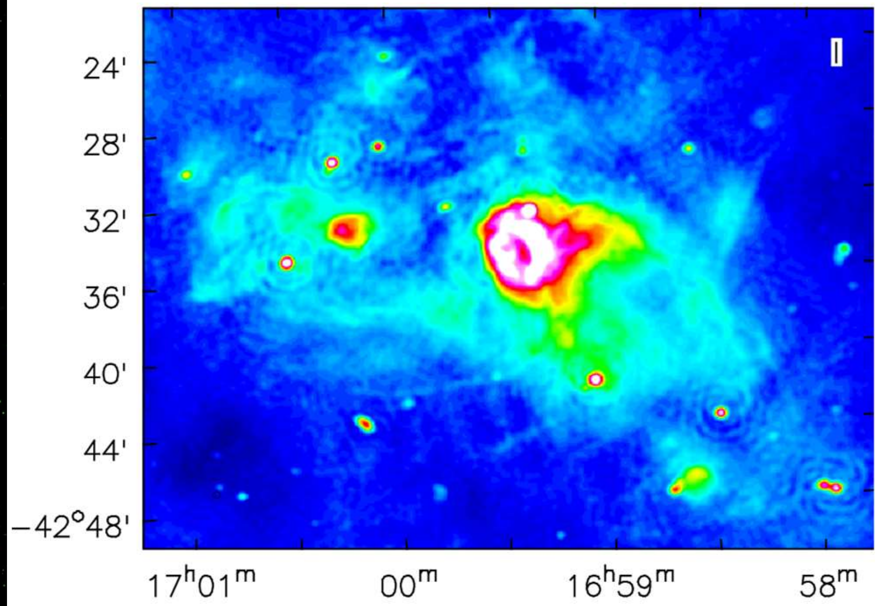
ASKAP provides the best compromise between fine details and diffuse emission

Great potentiality for Galactic Plane studies.

Bubble S17 -Churchell et al., 2006

Green 8μm GLIMPSE
Red 70μm Hi-GAL
Blue ASKAP 912MHz





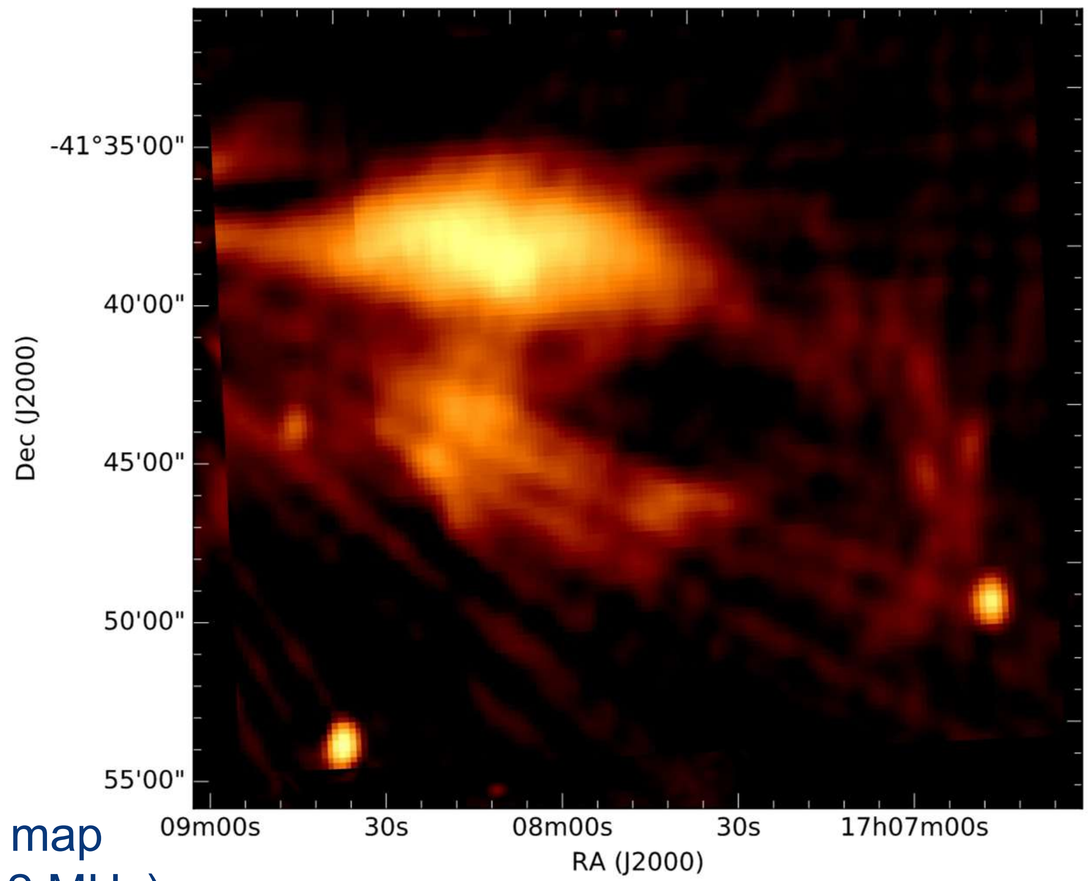
The VIALACTEA knowledgebase: a unique tool for source identification and classification

G345.94-00.779

HII (Caswell 1987, Anderson 2014)

MGPS conducted with the Molongo Observatory Synthesis Telescope

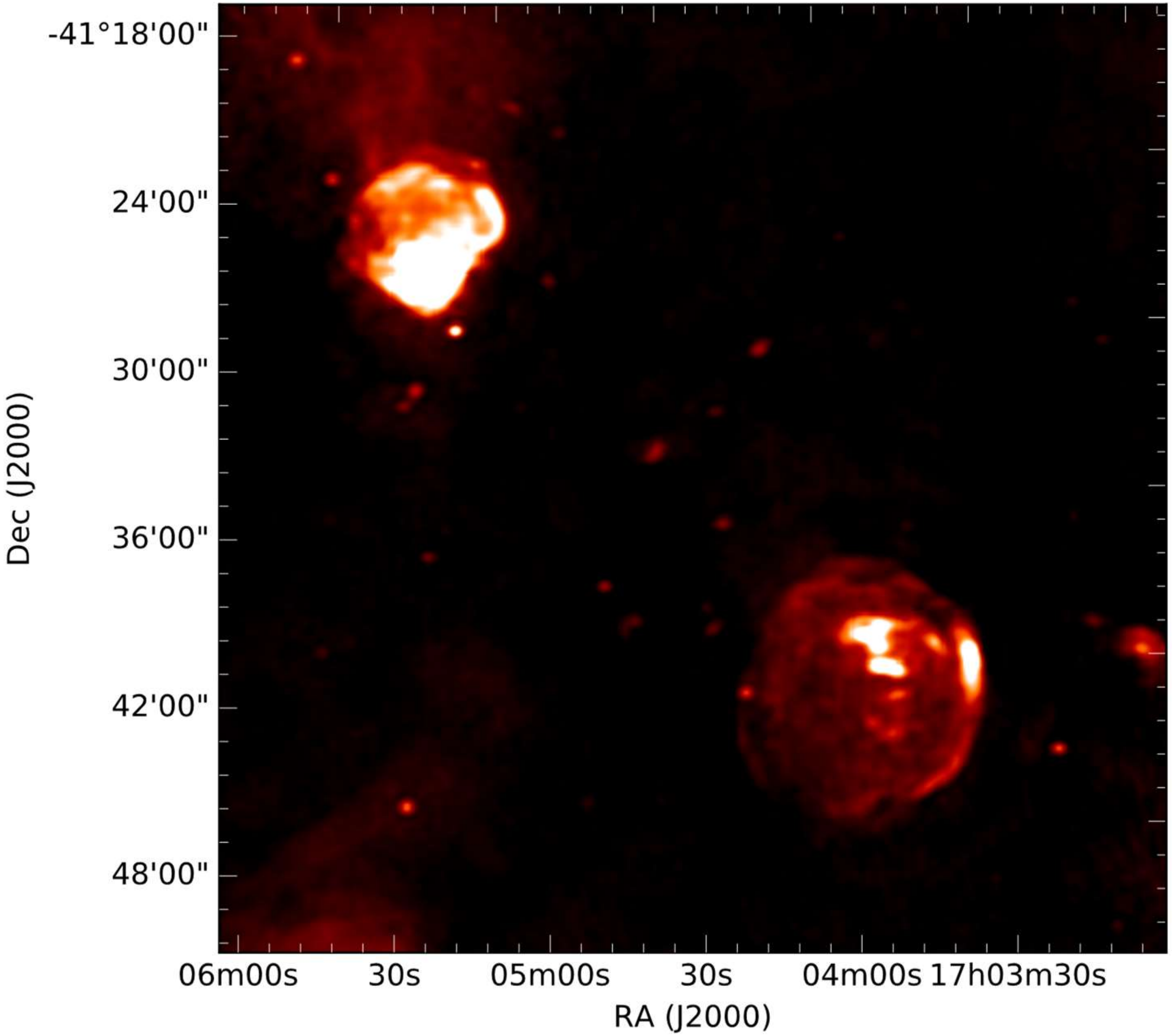
843 MHz



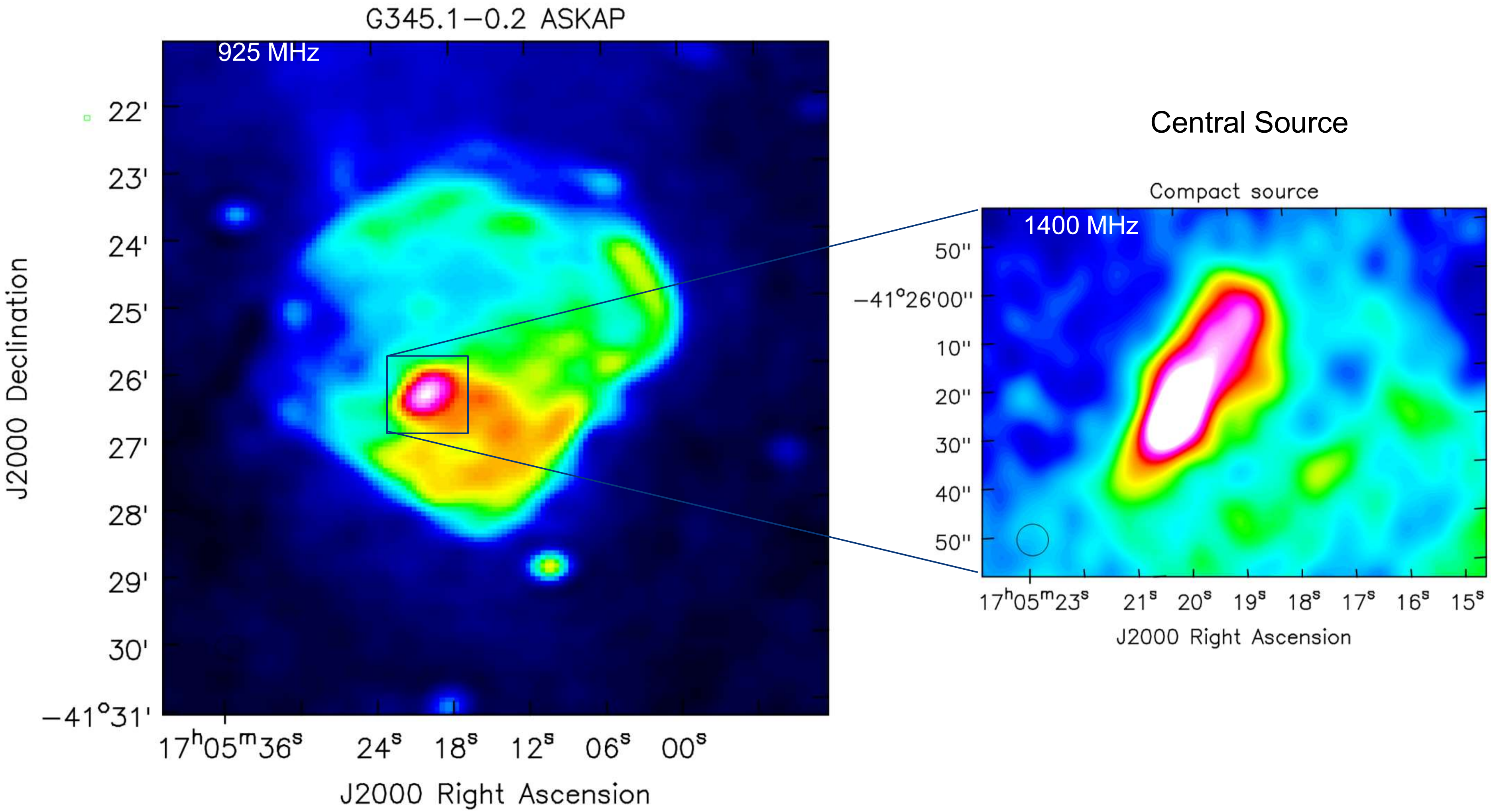
SCORPIO/ASKAP@912 MHz
Finer details and overall structure

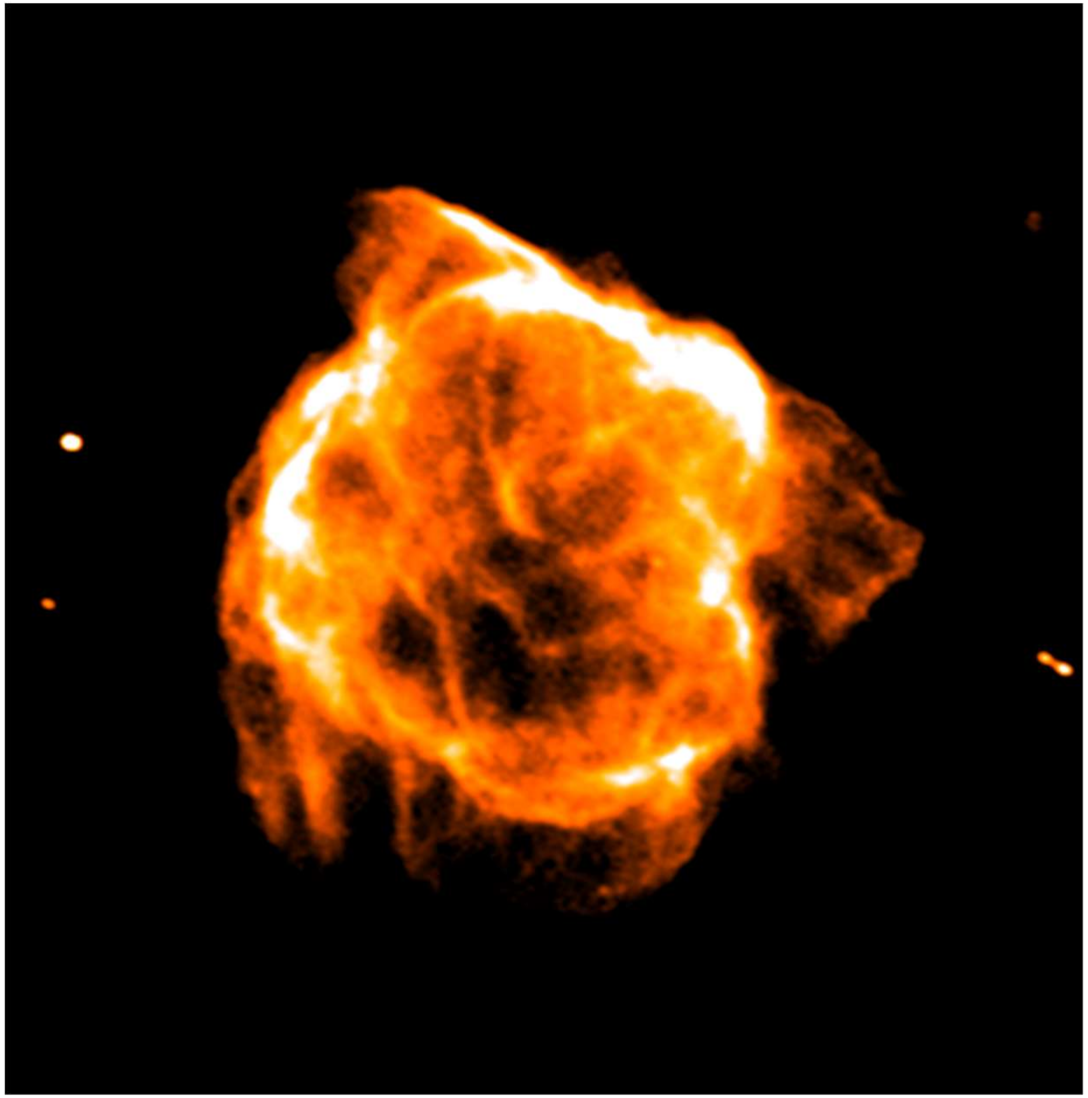
Extrordinary capability of ASKAP to map
Galactic sources up to 50' (LAS@912 MHz)

SNR candidate SNR



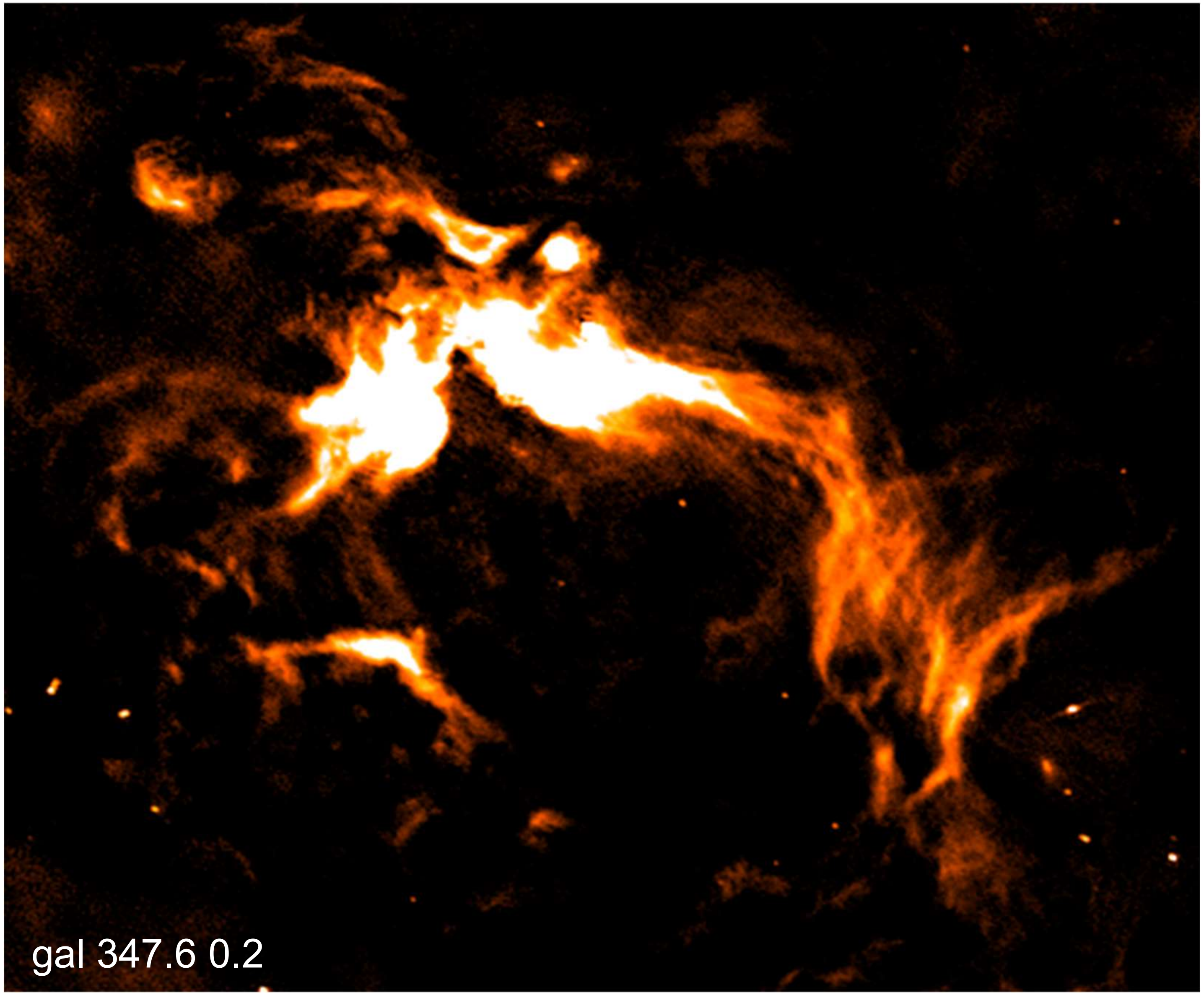
Central Source





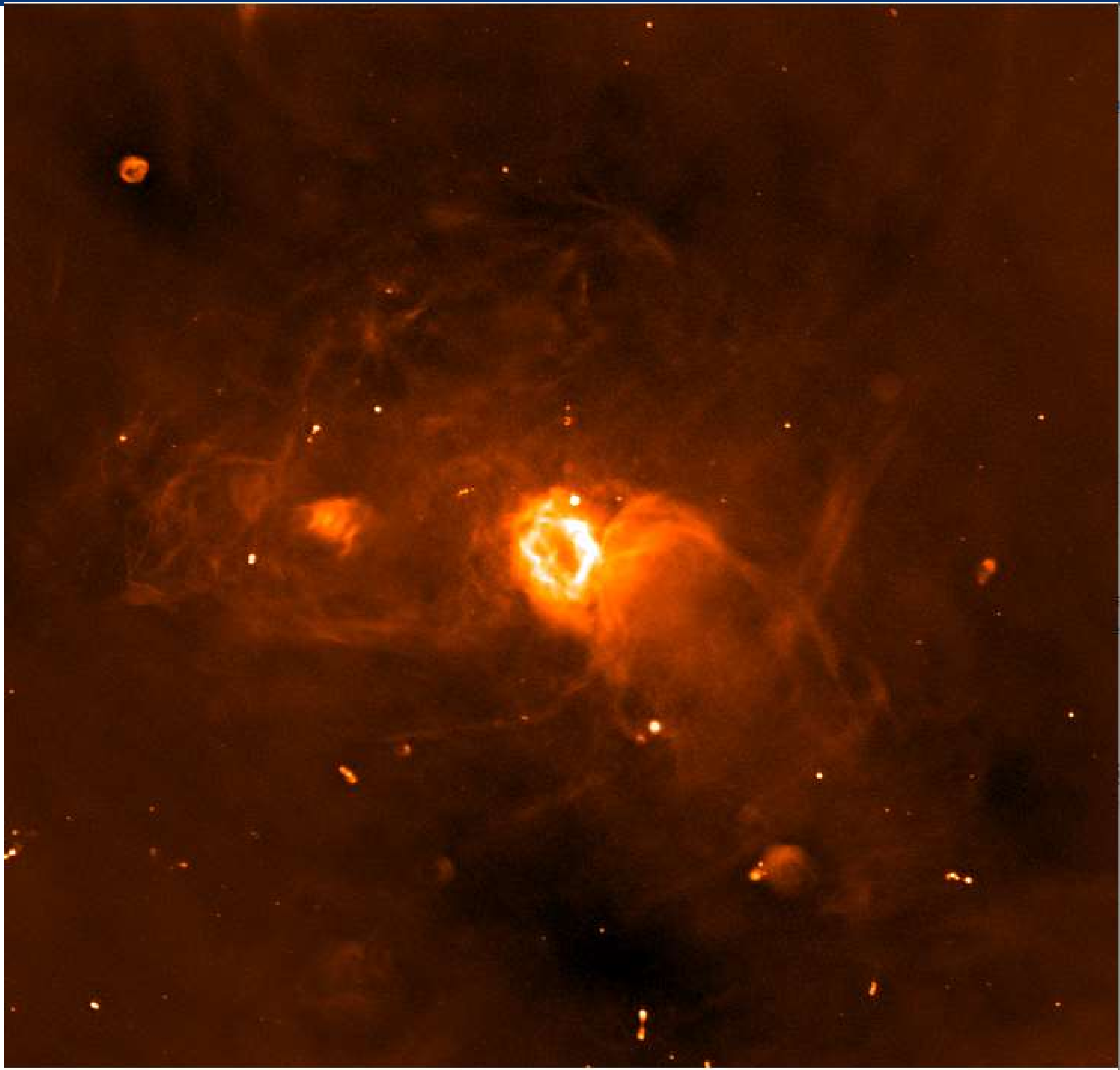
15’

Band 3 (1630 MHz)

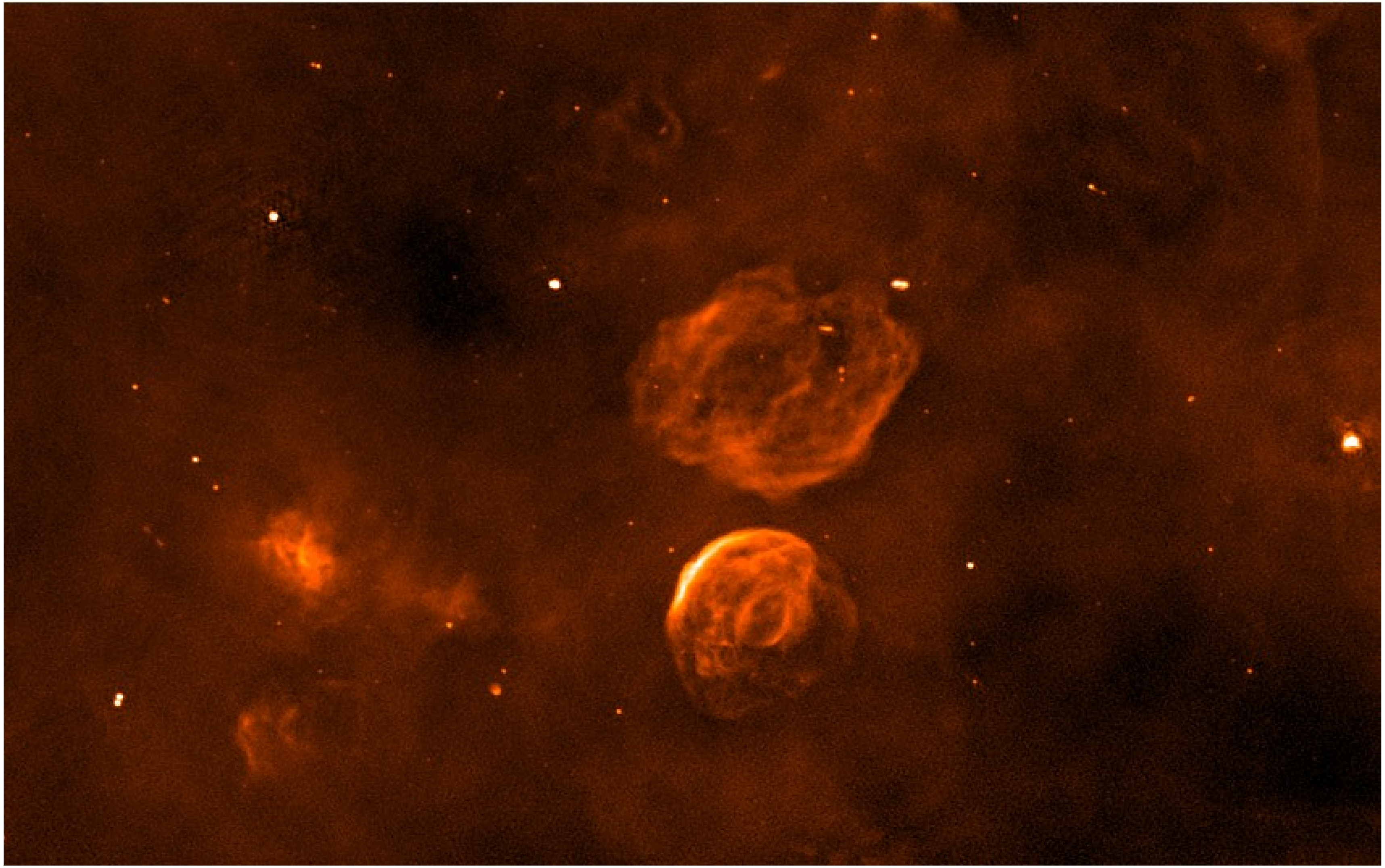


30’

Bubble S17 -Churchell et al., 2006

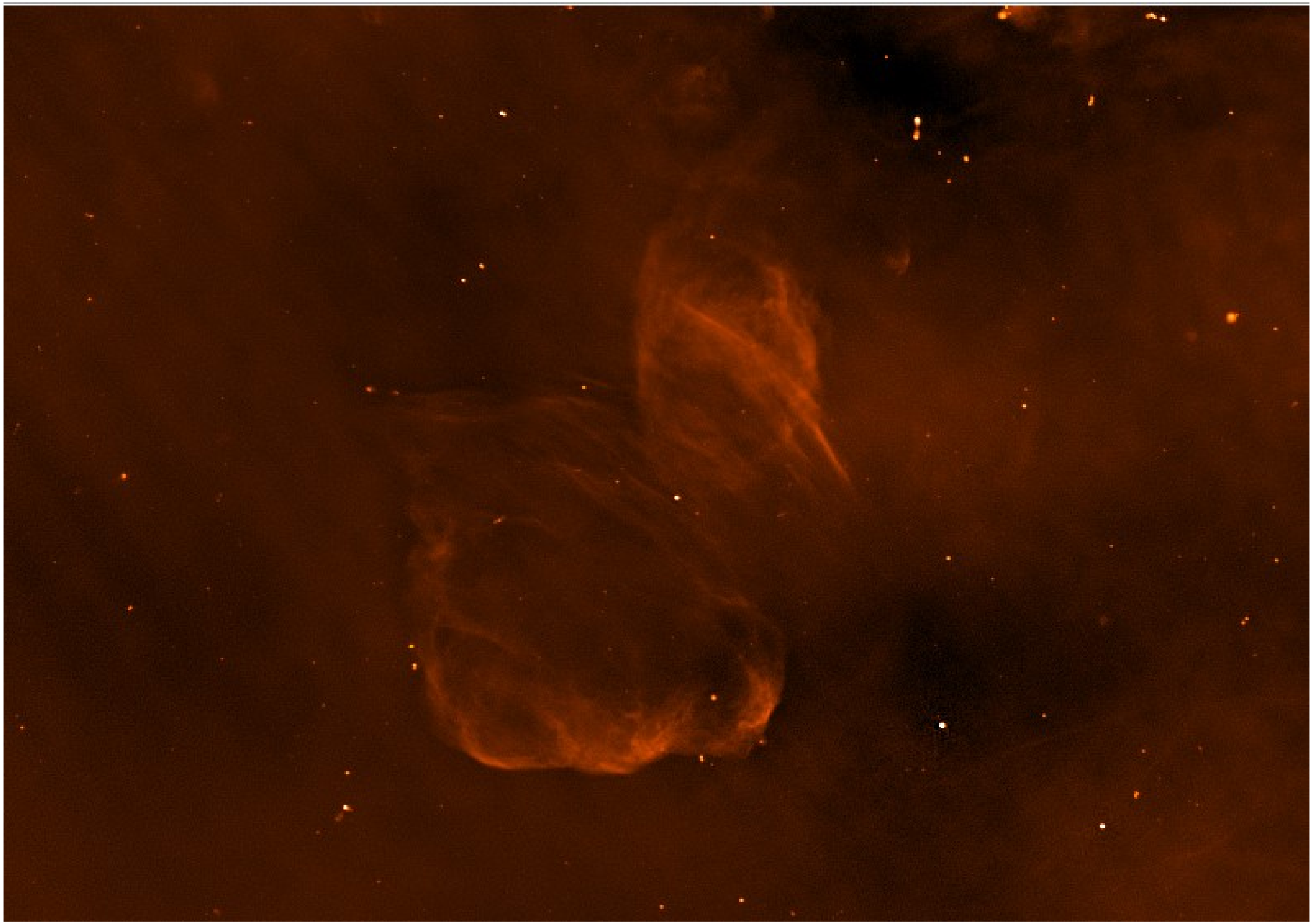


SNR G342.0-0.2 and SNR G341.9-0.3



1 deg

SNR G343.1-0.7



SCORPIO as design study for EMU

SCORPIO has proven to be an extremely valuable project from a scientific and a technical point of view.

The expertise and the knowledge acquired on this patch of the sky have been helpful in the ASKAP early science phase and can be considered as a design study for the Galactic section of EMU

SCORPIO used as testbed to test the ASKAP capability on the GP:

- to evaluate the limitations in depth of EMU close to the GP (bright, extended Galactic sources and diffuse emission)
- To evaluate the need for single-dish data

SCORPIO

- Provides inputs for ASKAP data reduction and analysis
  fulfillment of SCORPIO technical goals ✓
- Provides reliable forecasts for EMU discovery potential
  fulfillment of SCORPIO scientific goals. ✓

The SCORPIO field

Field center 343.8 -0.2
Dimensions 5.4x1.3 deg^2

Green 8μm GLIMPSE
Red 70μm Hi-GAL
Blue ASKAP 912MHz