The Impact of SKA on Galactic Science: a glimpse at the Galactic plane with SKA precursors.

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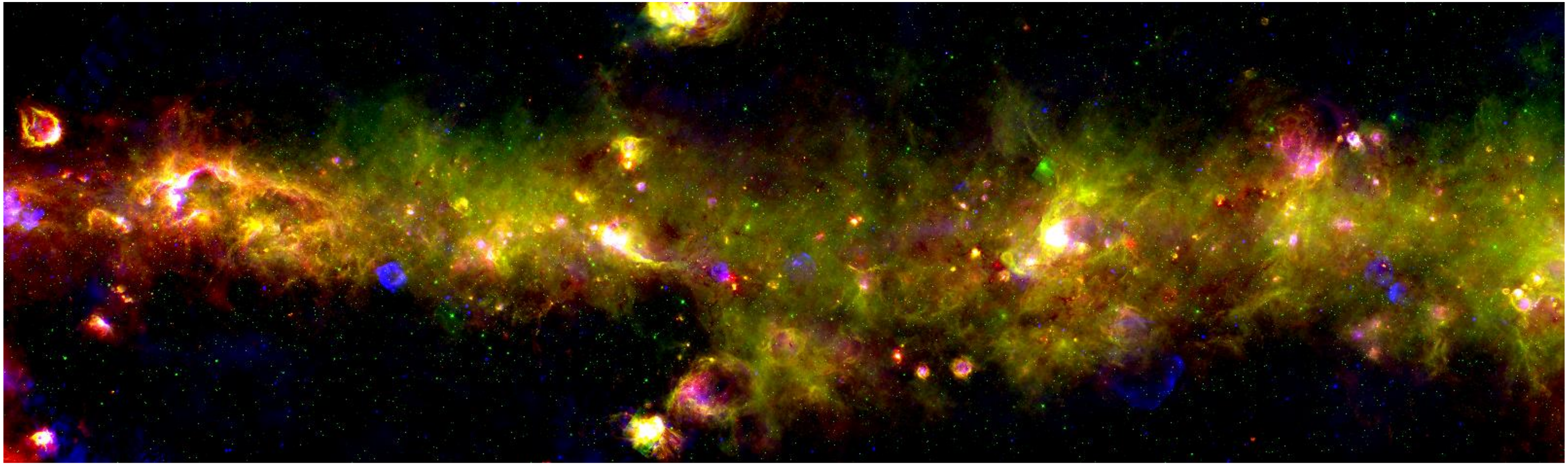
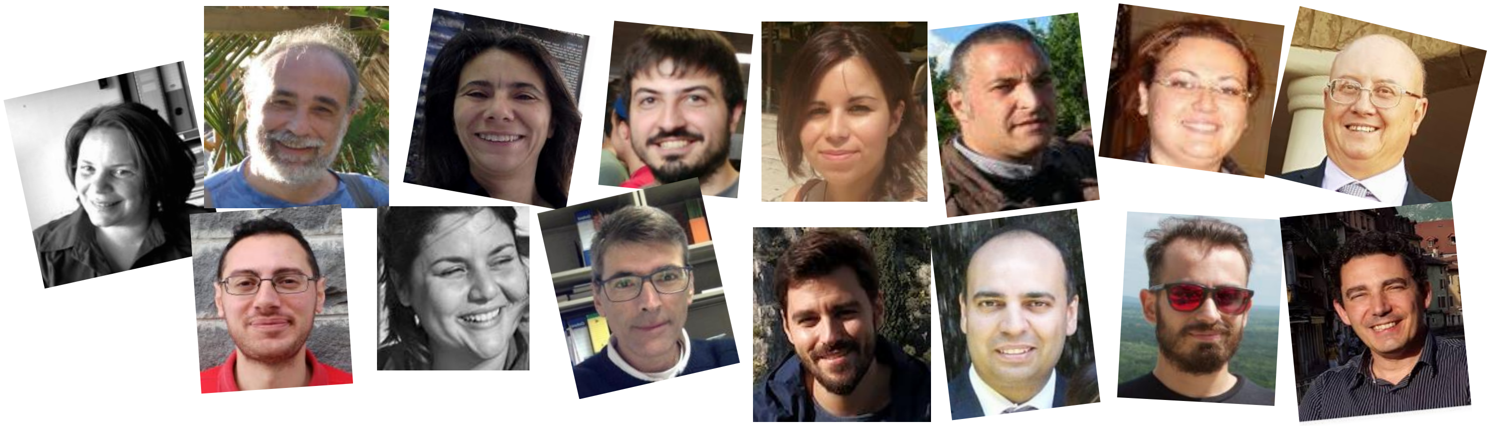


SKA & precursors task force @ INAF-OACT/IRA



Grazia Umana
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Milena Bufano
Francesco Cavallaro
Adriano Ingallinera
Sara Loru
Francesco Schillirò
Ugo Becciani
Alessandro Costa
Eva Sciacca
Fabio Vitello
Simone Riggi
Cristobal Bordiu

- **Radio & ICT groups working together since 2012: Successful initial experience for Competence Center**
  - 15 people involved in different projects (see below): 12 TI (INAF staff) + 3 post-doc (Cavallaro, Uni Cape Town)
  - 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: A. Ingallinera); 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)
  - Partecipation in the MeerKAT projects ThunderKAT and MIGHTEE
  - Members of the SARAO GP survey consortium (G. Umana board)

Why a Galactic Plane survey with SKA precursors?

Scientific aims

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 aims

Test bed for the 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 impact of SKA and SKA precursors on GP science

The Galactic plane precursors 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
Important for evolutionary models!

Radio Stars

Serendipitous discoveries

Providing the most complete catalog of Galactic Sources to date

Norris et al., 2011

EMU
Evolutionary Map of the Universe

Deep radio image of 75% of the sky

Will detect and image ~40 million galaxies
Primary science goal: How did galaxies form and evolve?

With its foreseen **sensitivity and angular resolution** will provide a "good view" of the Galactic Plane @ L-Band

Will bridge the gap in sensitivity and resolution between available GP surveys:

- high angular resolution, limited areas or
- lower angular resolution, wide areas:

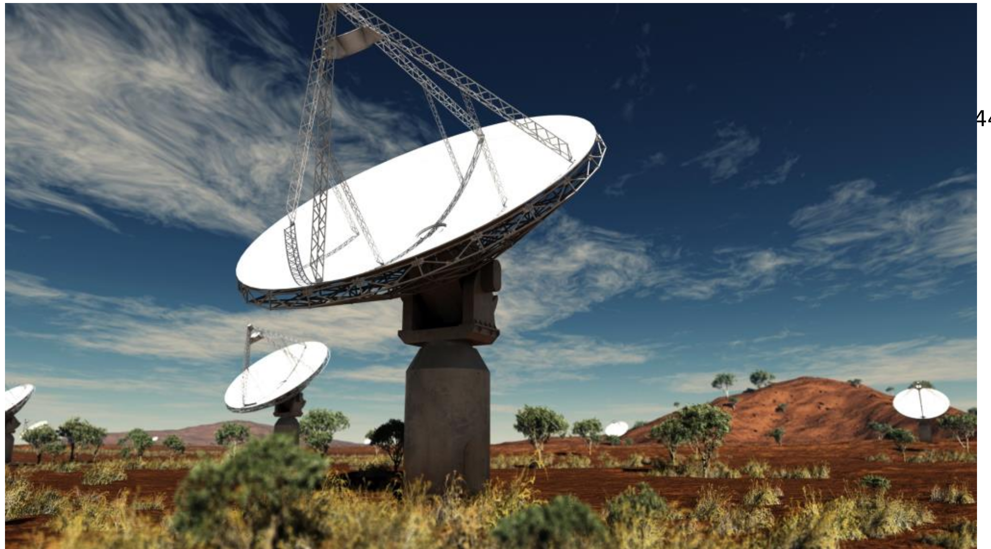
The SCORPIO field with ASKAP

ATCA- 133 pointings, rms= 90 µJy, 4 deg^2

Total integration time: 320 hrs

ASKAP-12 **1 pointing 40 deg^2**

Jan 2018- 3 pointings

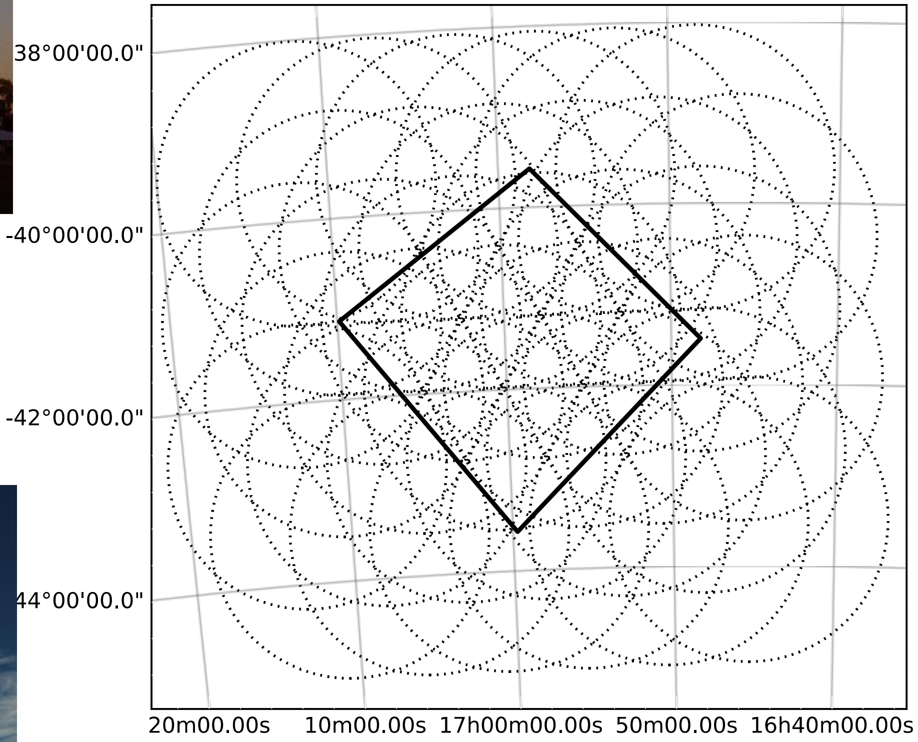


ASKAP Early Science

A much larger region of SCORPIO field observed during ASKAP Early Science

Freq: 792-1032 MHz (912 MHz)

Ang. Res. 24.1x 21.1 $arcsec^2$



Total integration time: 32 hrs

(including overheads for calibration)

rms ≅ 130µJy (outside GP)

<rms> ≅ 500µJy

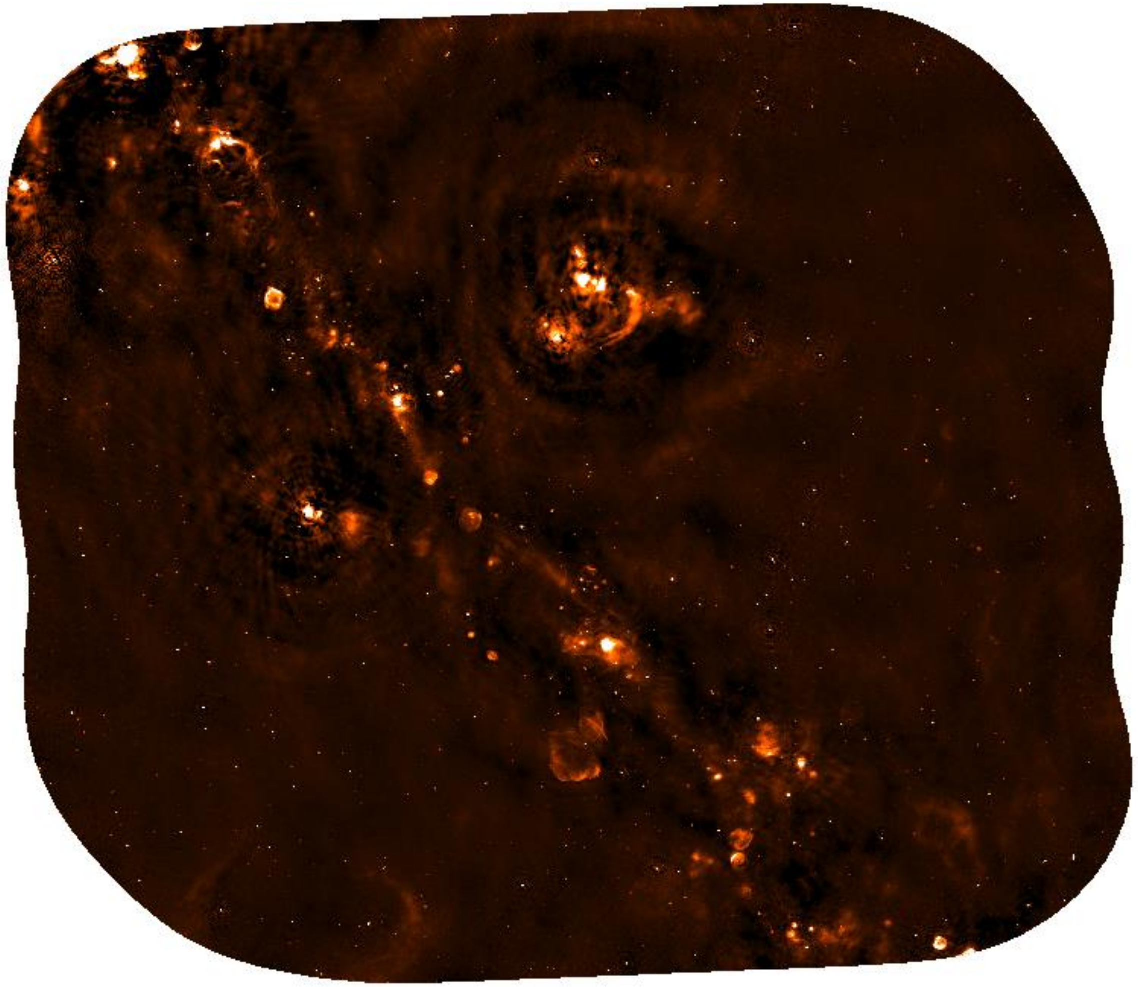
The SCORPIO field

ASKAP map

Field center 343.5, 0.75
Dimensions 6x6 deg^2

Band 1 (920 MHz, B=288 MHz)

ASKAP-12 (15 antennas)



Umana+, 2021; Riggi+, 2021

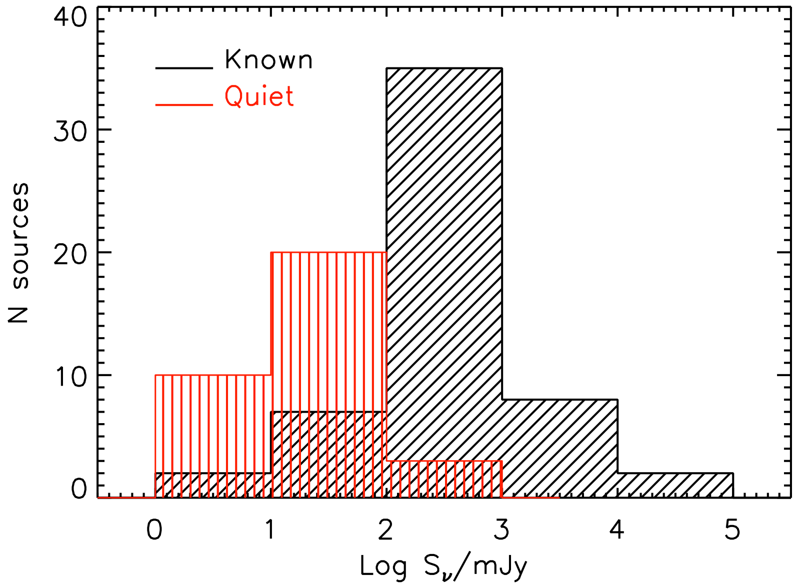
The SCORPIO field

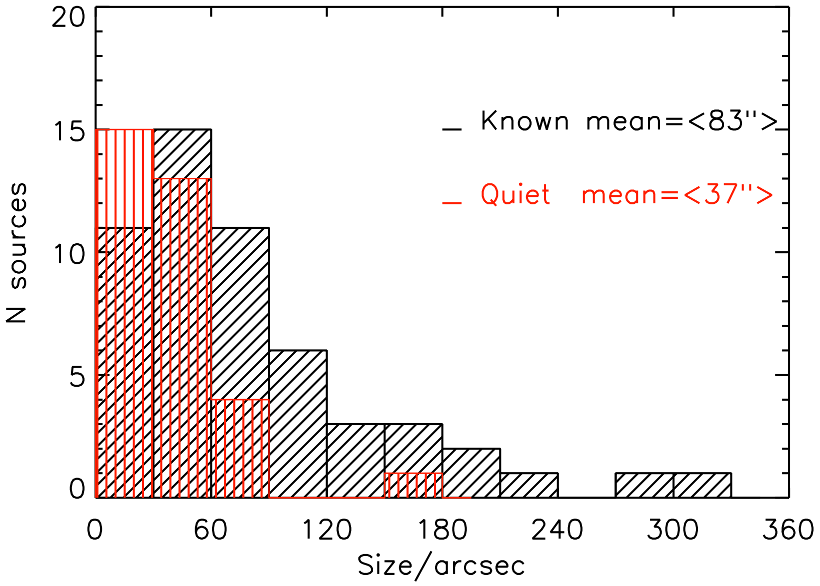
ASKAP map: HII

A total of 382 HII in SCORPIO/ASKAP field

- All the known and candidate HII are detected
- 99/220 (45%) of the radio quiet are detected
- 5/5 reported without radio data, detected

A total of 261 detections,
96 new detections



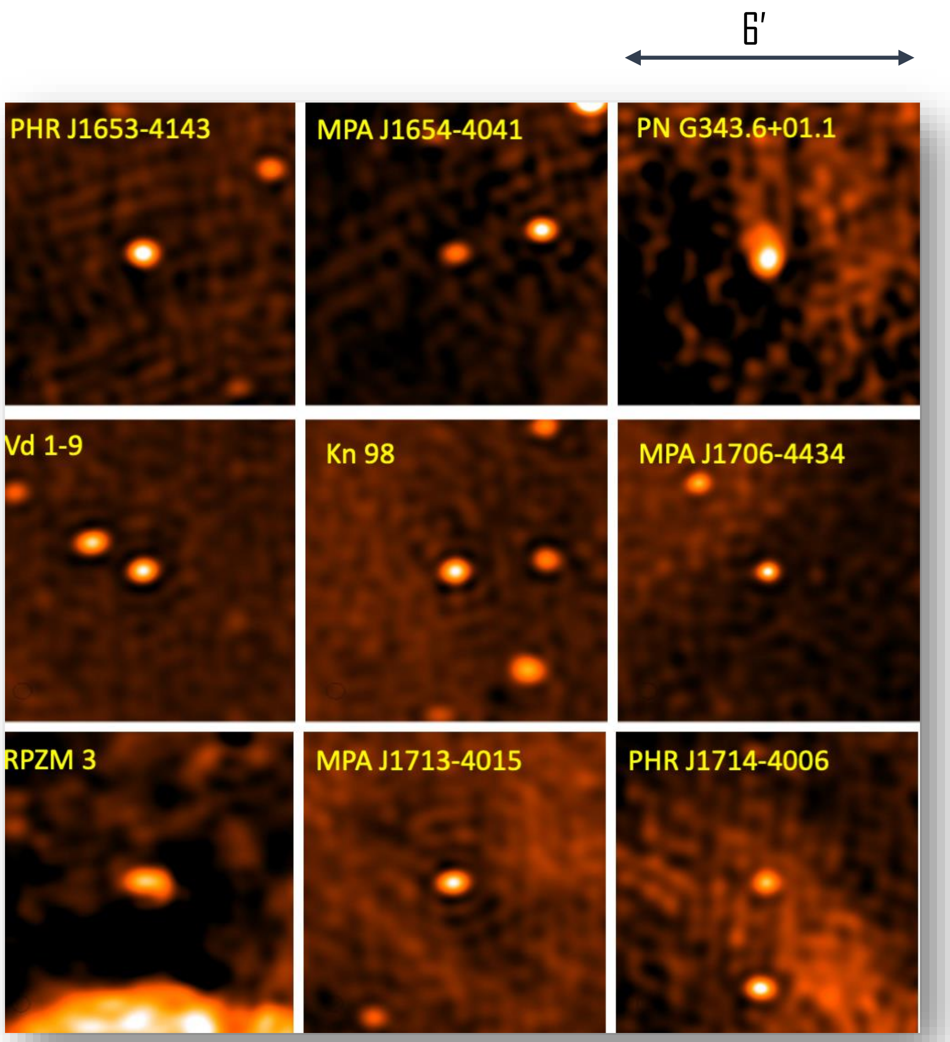


Radio quiet H II regions appear to be fainter and more compact than known H II s

Previous non detections related to sensitivity limits

The SCORPIO field

ASKAP map: PNe



A total of 48 HASH PNe
in SCORPIO/ASKAP field

- 29/35 True/confirmed PNe are detected
- 3/6 Likely PNe, detected
- 2/7 Probably PNe, detected

A total of 34 detections,
20 new detections

According to HASH classification: T, morphologies and spectral features of PN
L, as above, but not conclusive
P, as above, poor data with poor S/N

The SCORPIO field

ASKAP map: SNRs

- ✓ 14 SNRs from Green 2019
- ✓ 2 SNR candidates from Whiteoak and Green (1996)
- ✓ 3 SNR candidates from Ingallinera et al., 2019

in SCORPIO/ASKAP field , all detected

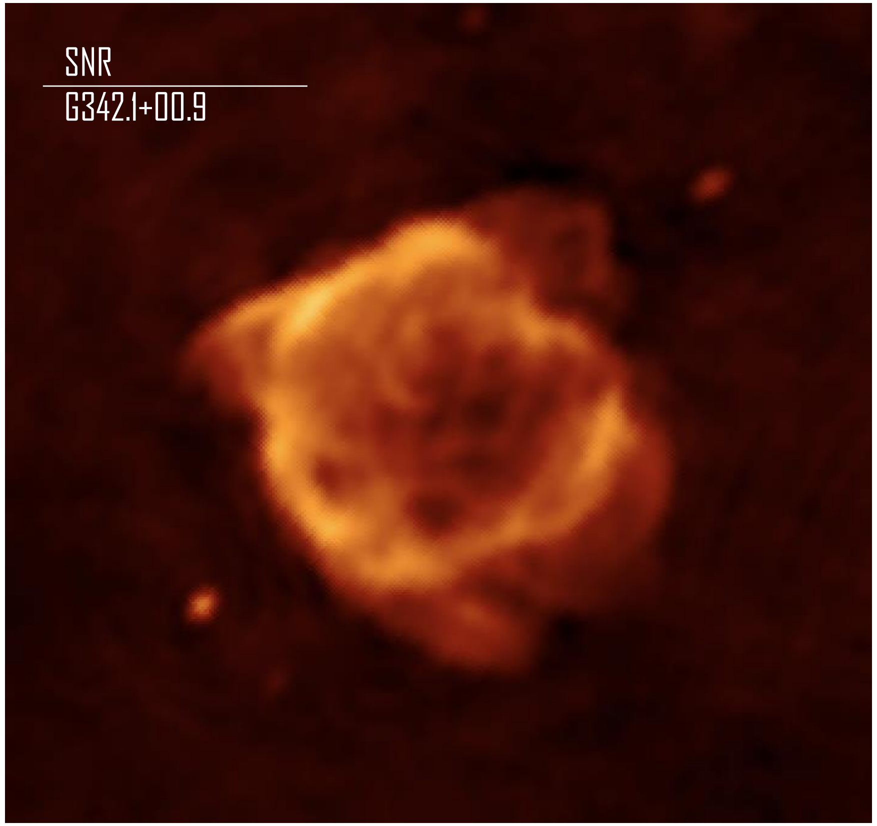
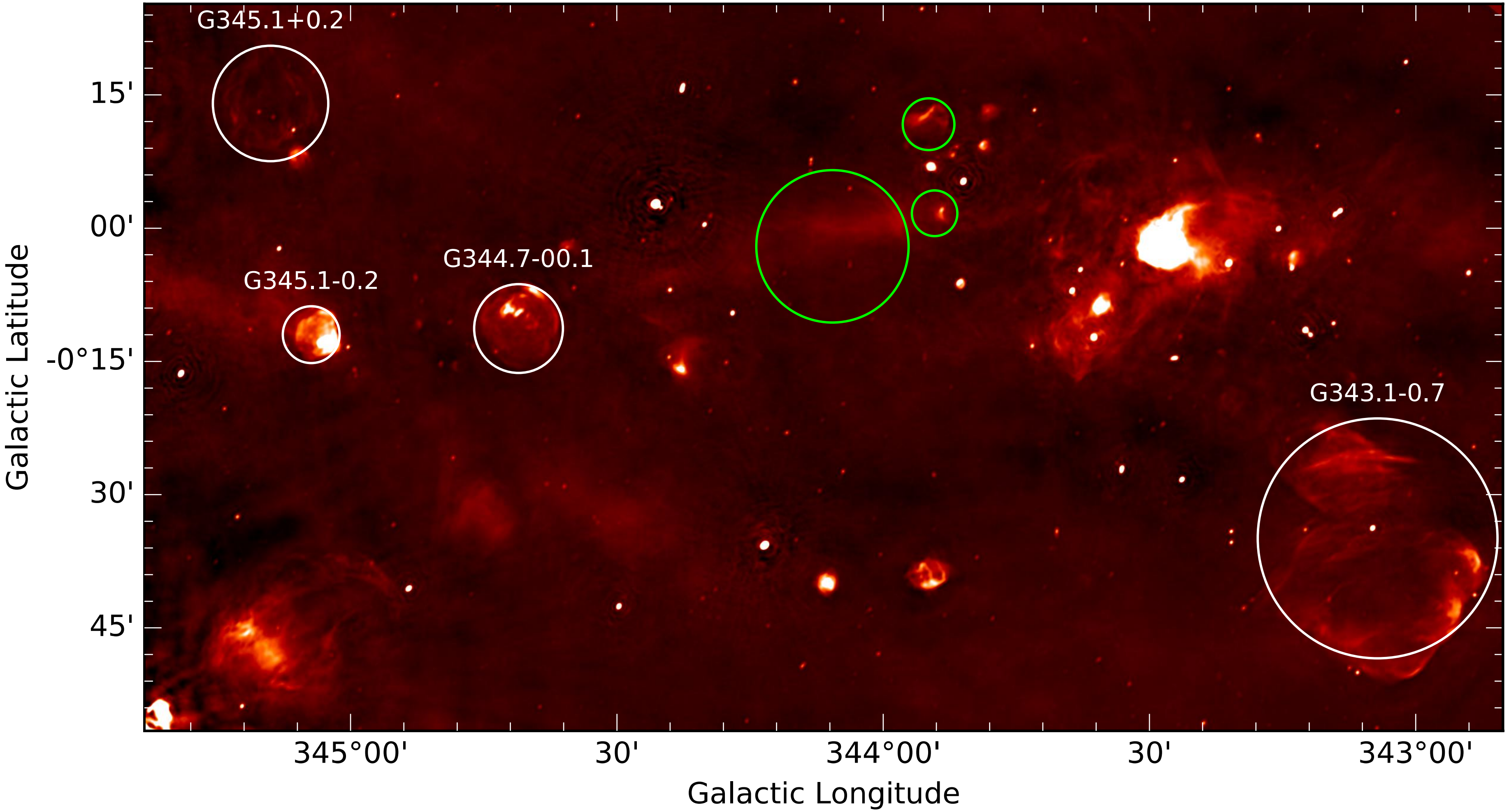


Table 4. Summary of the known SNR detected with ASKAP at 912 MHz in the SCORPIO field, and related main characteristics. Type of the SNR: 'S' or 'C' if the remnant shows a 'shell' or 'composite' radio structure. We report the frequency range within which each source has already been observed. Source sizes are reported according to (Green 2019).

Source name	type	frequency range (GHz)	Source size (arcmin^2)
G340.4-0.4*	S	0.330− 5	10→7
G340.6+0.3	S	0.330− 5	6→6
G341.2+0.9	C	0.330− 1.425	22→16
G341.9-0.3	S	0.408− 5	7→7
G342.0-0.2	S	0.408− 5	12→9
G342.1+0.9	S	0.843− 1.384	22→16
G343.1-0.7	S	0.843− 8.55	27→21
G343.1-2.3	C?	0.330− 8.46	32→32
G344.7-0.1	C?	0.408− 11.2	8→8
G345.1-0.2	S?	0.843− 1.4	6→6
G345.1+0.2	S	0.843	10→10
G345.7-0.2	S	0.843− 5	6→6
G346.6-0.2	S	0.408− 5	8→8
G347.3-0.5	S?	1.36	65→55
G348.5+0.1	S	0.08− 14.7	15→15
G348.5-0.0*	S?	0.333− 5	10→10

* This SNR is only partially detected at the edge of our ASKAP map.

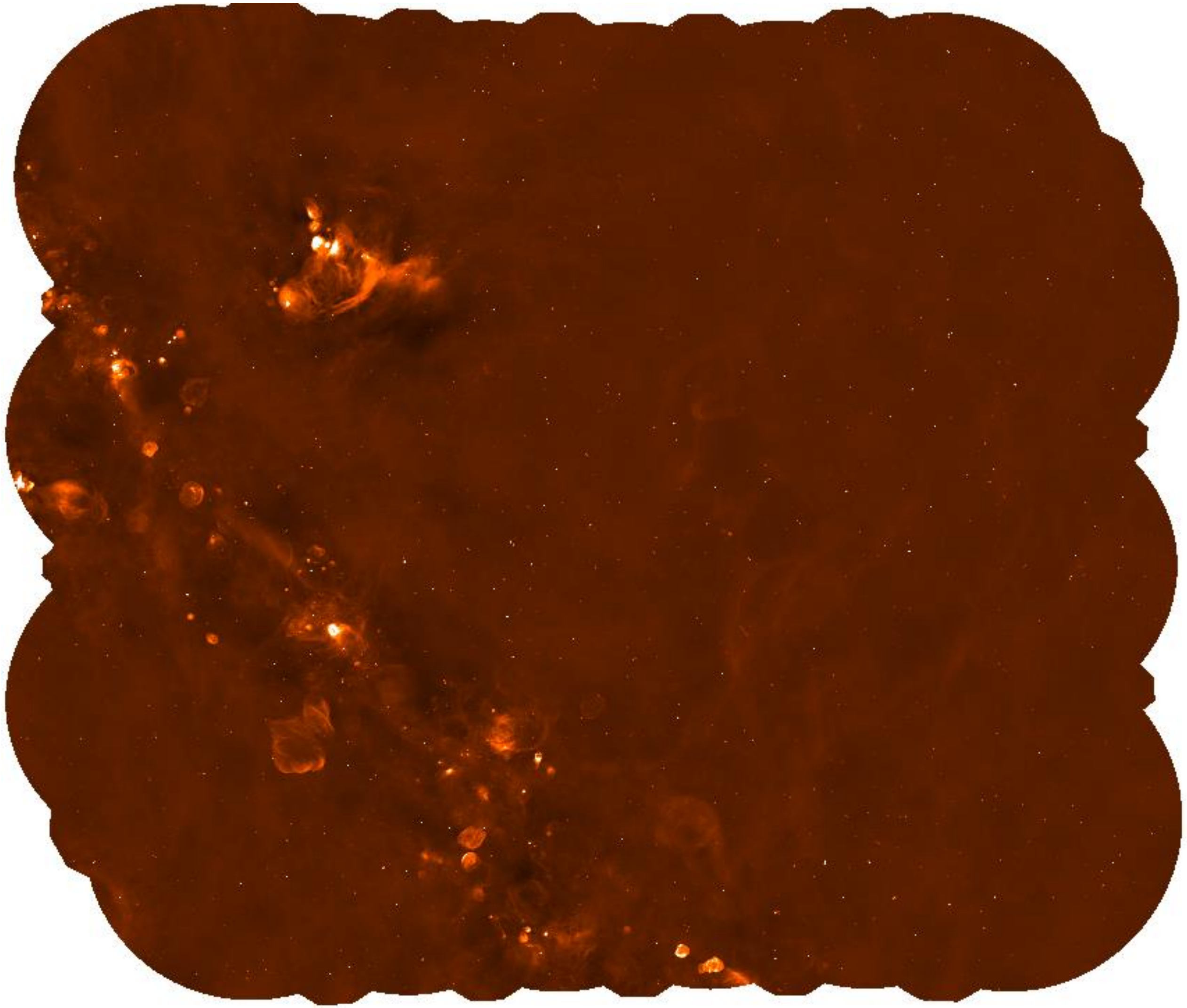
The SCORPIO field ASKAP map SNRs



A 2.3 x 1.3 deg2 portion of the map, centered at l=343.8, b=-0.2
4 SNRs (Green, 2019) are highlighted with white circles and the 3 SNR candidates , from Ingallinera et al., 2019, with green circles.

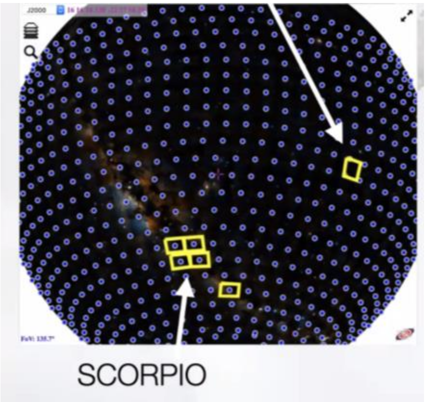
The SCORPIO field

Field center 343.5, 0.75
(EMU_1650_41 16:50:46.153 -41:52:44.08)
Dimensions 6x6 deg2
Band 1 (943 MHz, B=288 MHz)



EMU Pilot 2

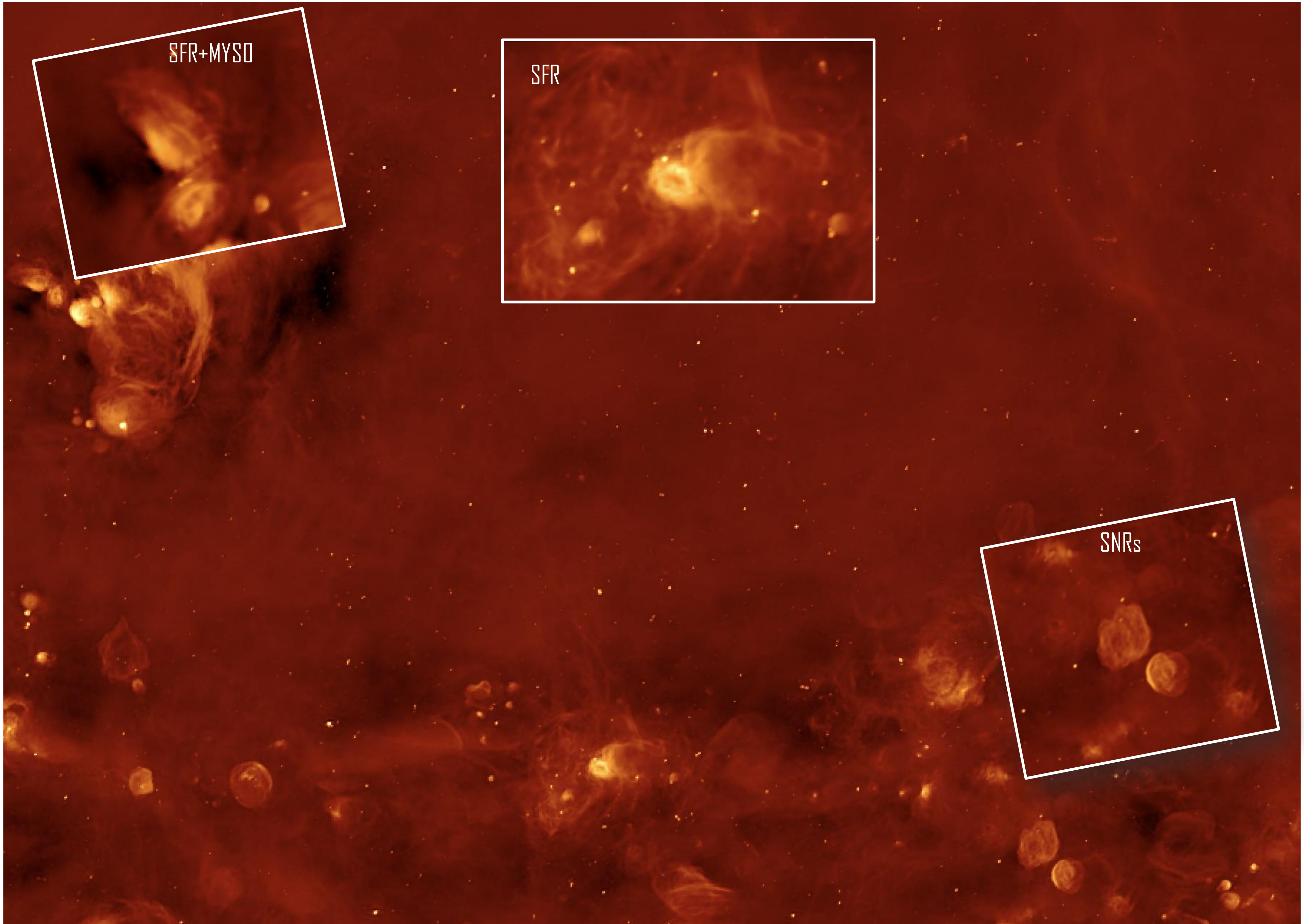
3 further tiles will be observed
EMU_1718-41
EMU_1714-46
EMU_1644-46



Covering the SCORPIO region

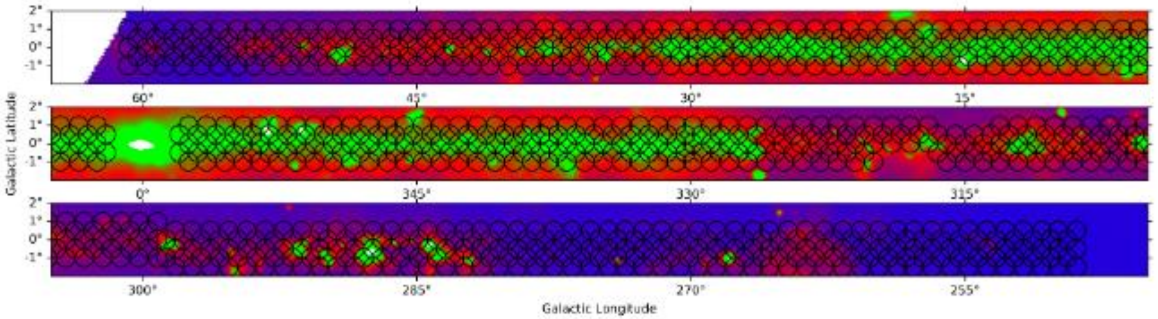
The SCORPIO field

PILOT



MeerKAT Galactic Plane Survey

- Observed in L band (856-1712 MHz)
- 10 hour sessions, 9 pointings each session
- Spacing of about 0.5°
- rms in non dinamic range limited environment around 10-15 μJy
- rms in the GP around 100-200 μJy



Goedhart et al., in progress

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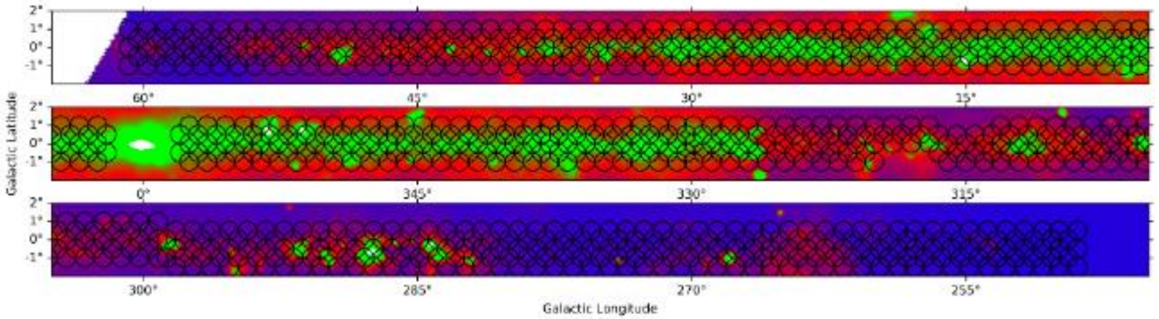
Several approved papers, list of papers with an INAF leadership:

- Paper 3, Searching and characterizing extended sources in the MeerKAT Galactic Plane Survey (P.I. Simone Riggi);
- Paper 5, Properties of known SNRs (P.I. Francesco Cavallaro);
- Paper 6, Characterisation of known SNRs (P.I. Sara Loru)
- Paper 8, Catalogue of Planetary Nebulae (P.I. Adriano Ingallinera)
- Paper 10, Known LBV and WR stars (P.I. Grazia Umana)



Goedhart et al., in progress

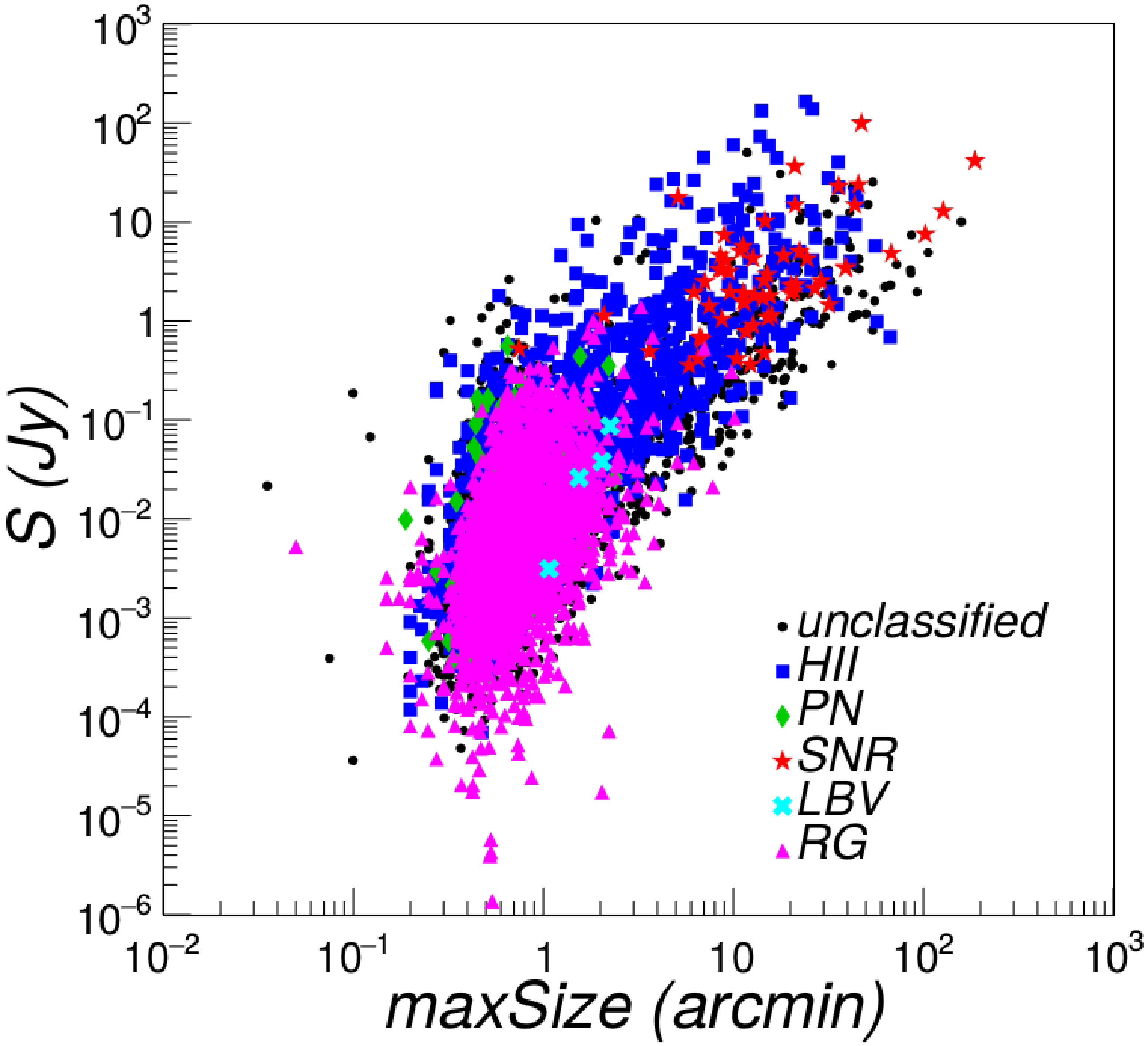
Searching and characterizing extended sources in the MeerKAT Galactic Plane Survey

Catalogue of **extended and diffuse** radio sources (1st release):
•1st quadrant: 2º < l < 12º
•3rd quadrant: 252º < l < 270º
•4th quadrant: 342º < l < 358º

•Source extraction combining **CAESAR** and **visual inspection/refinement**

Positions, flux measurements, morphological parameters and accurate segmentation for **5527** sources, of which:

•20% correspond to **known Galactic objects**
•40% **extragalactic** (e.g. radiogalaxies)
•40% **unknown** (new candidates? WTF?)

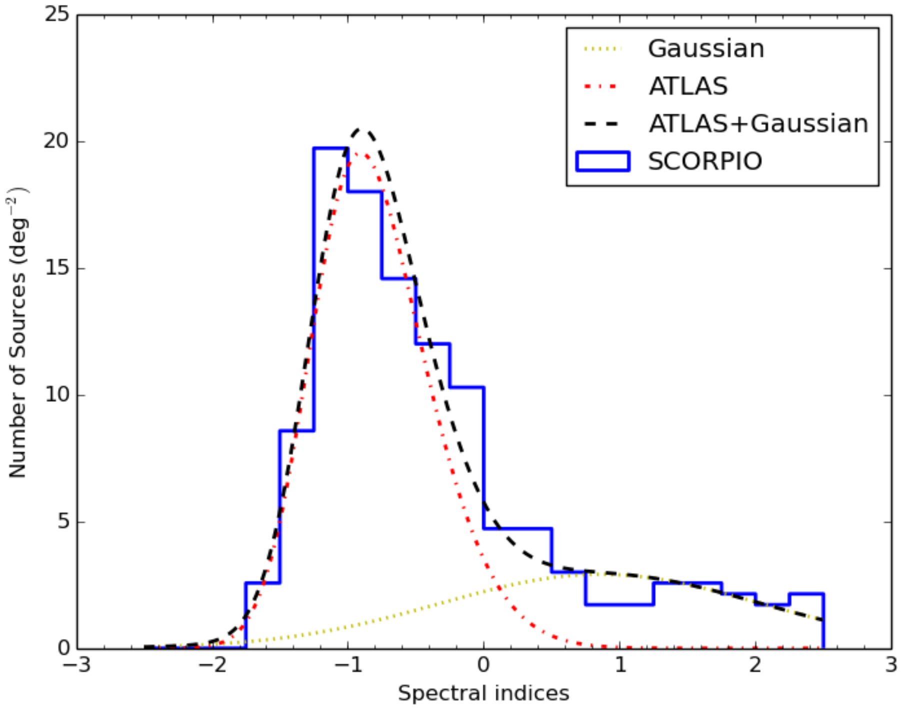


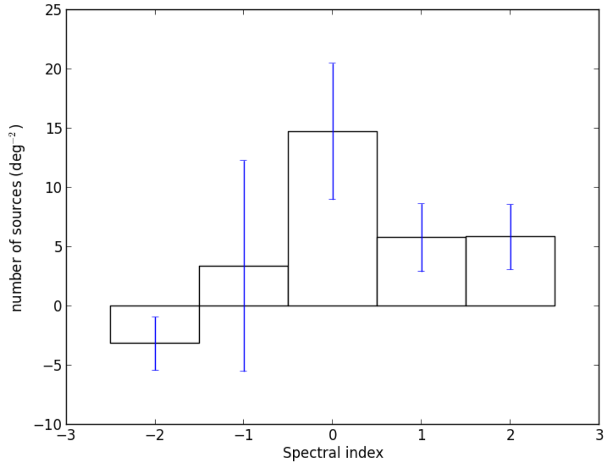
Spectral indices of pointlike sources

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

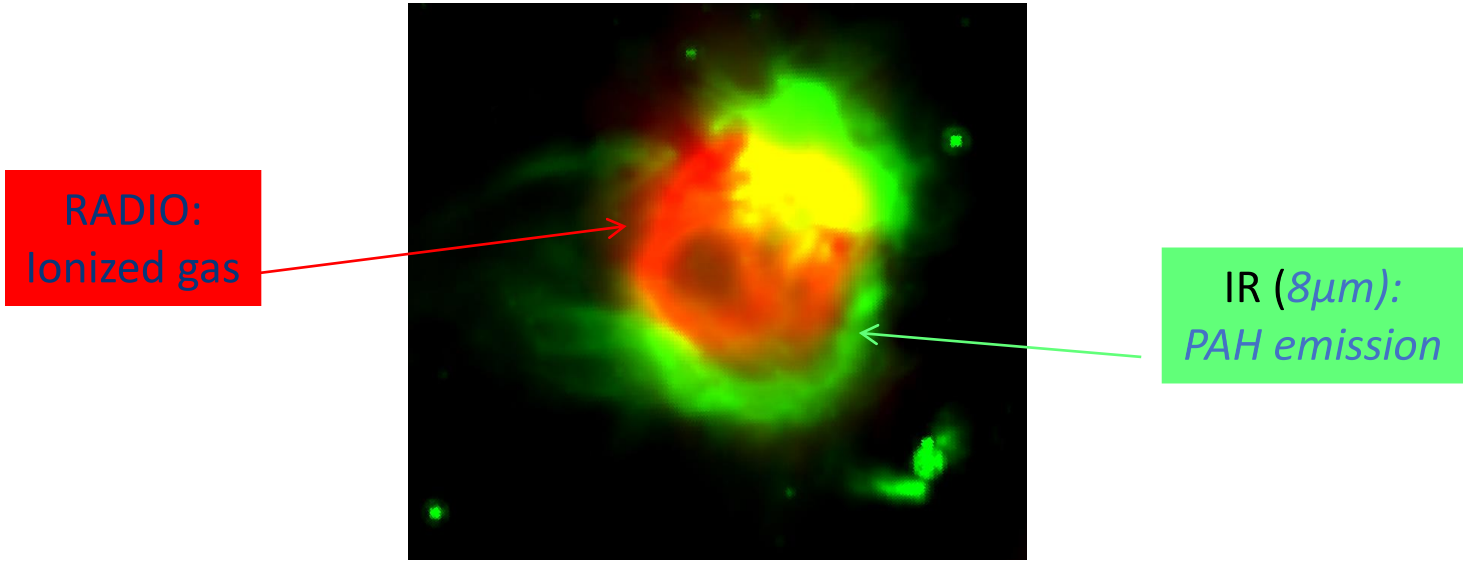
Above 1 mJy, **the source density in SCORPIO is 20% greater than in a typical extragalatic field**

Cavallaro + 2018

Dealing with extended sources

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

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



Exploiting 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.

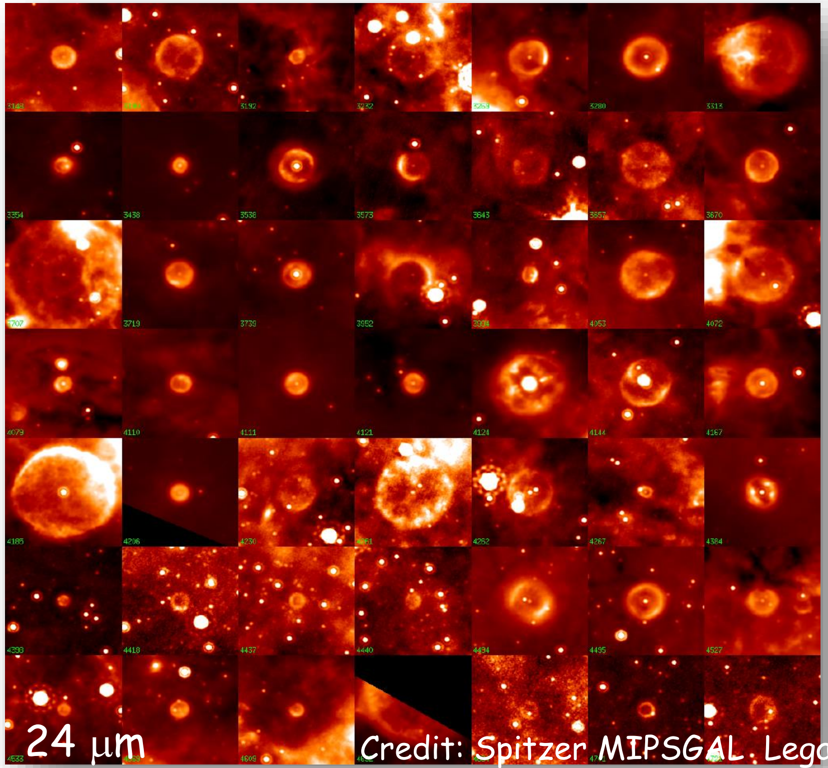
Ingallinera +2019

Evolved stars

There are about 3000 known PNe but the models predict about 20000 of them
Radio and infrared can be the key to find the others

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

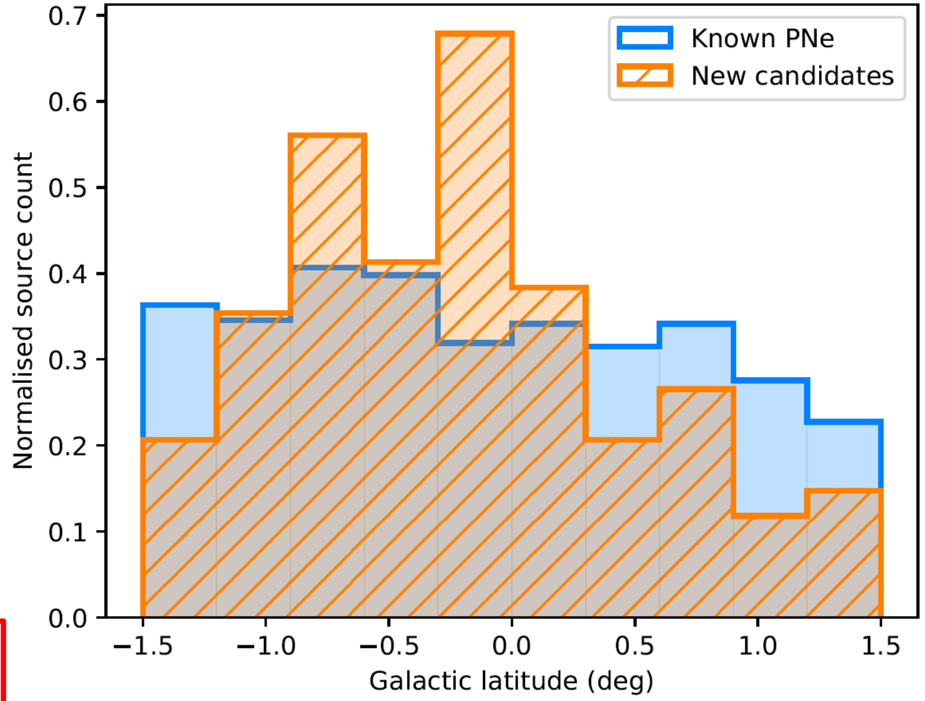
Possibly related to late stages of stellar evolution
only 30% have been identified

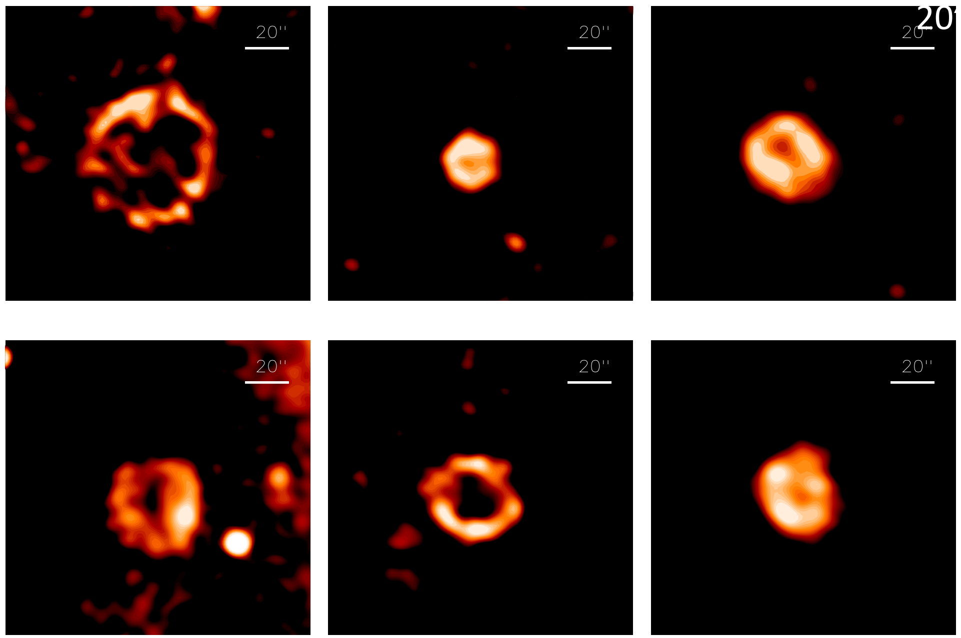


Radio observations:
Morphological , Spectral index , Pol.
to discriminate
LBV, PN, WR (thermal)
from SNR (non-thermal)

244 MBs falling in MeerKAT tiles
146/244 detected (**137 new det.**)

Providing a very promising sample to look for evolved stars candidates

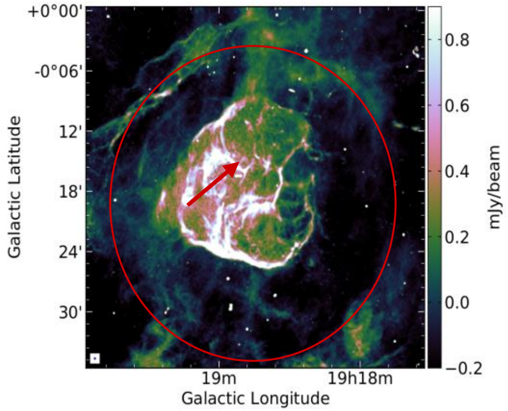




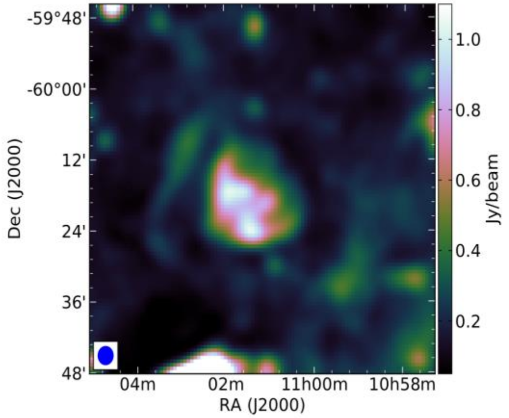
Detection and characterization of SNRs in the MeerKAT survey

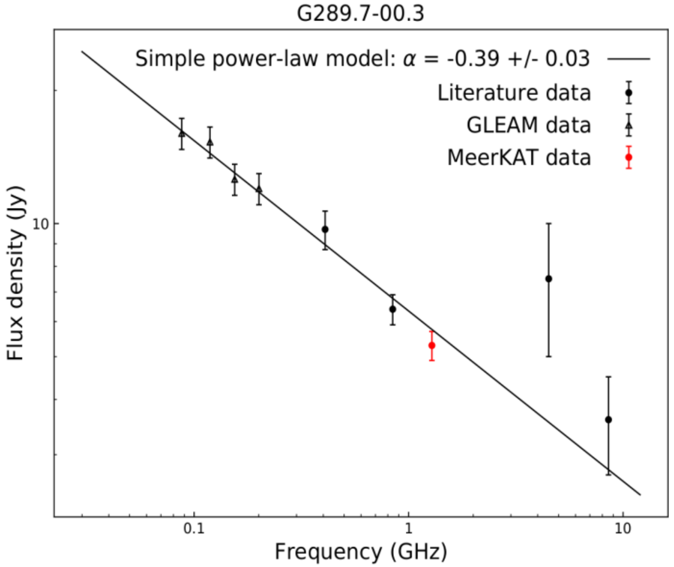
MOST @
0.843 GHz

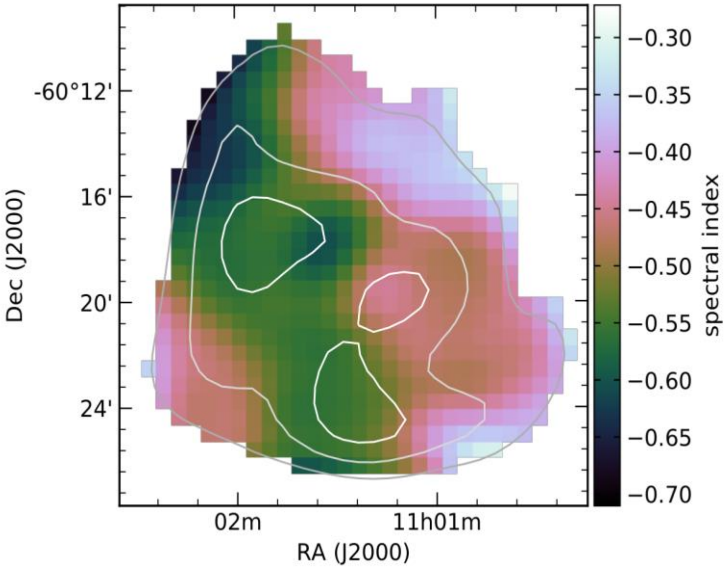
MeerKAT @
1.284 GHz



GLEAM @
0.155 GHz







Spectral index significantly steeper than the literature value of ~ -0.2

Unreliable measurements at 5 and 8.55 GHz

The filamentary structures detected in the MOST image are well resolved with MeerKAT

The central-bright source is resolved as a typical radio galaxy

A nearly complete concentric shell is highlighted

Significant spectral variation across the central SNR region:

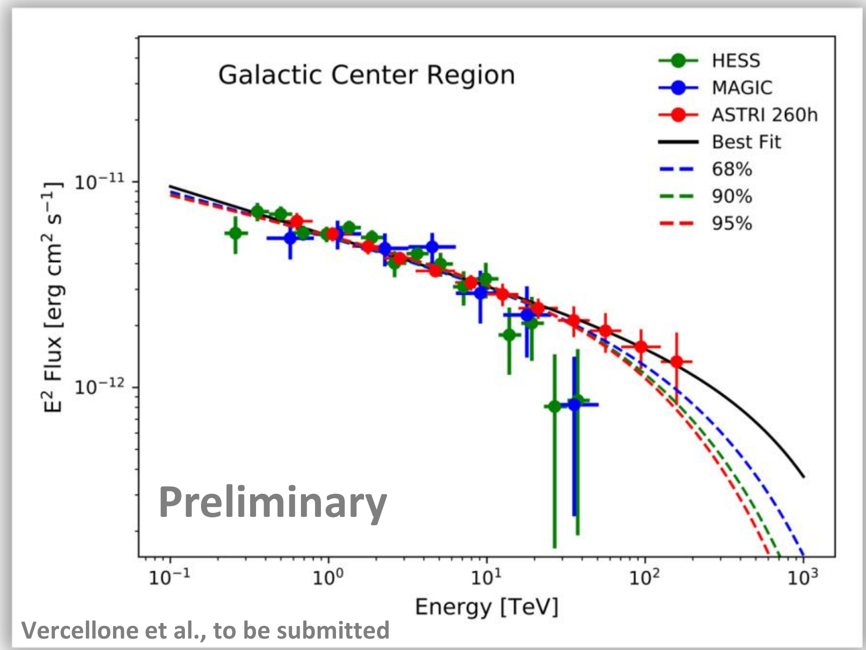
- steep spectral index (~ -0.6) related with the bright central object
- different spectral behavior between the three bright central spots.

Synergies with the ASTRI Mini-Array

Array of 9 ASTRI telescopes

INAF-led Project with several partners: IAC (Spain), Univ. of Sao Paulo/FAPESP (Brazil), North-West Univ. (S. Africa), FGG, ASI/SSDC, Univ. of Padova, Perugia and INFN

First 4 years dedicated to **Core Science, Observatory Science** afterwards



Exclude a cut-off in proton pop. below 3.5 PeV, 2.0 PeV, and 1.7 PeV at 68%, 90%, and 95% C.L.

ASTRI Mini-Array assets

- **the large FoV** will allow us to map the **whole GC region in a single observation**
- **the excellent angular resolution** could help to **identify any HE source** among several candidates
- Promising synergies with SKA and its precursors!

Outlook for SKA and conclusion

- The precursor Galactic Plane observations demonstrates how they are capable of **mapping complex sources**, at different angular scales, with a great level of detail

- Thanks to the unparalleled sensitivity and resolution, we are able to study a **very large number of galactic objects**, both extended (SNRs, Hii, evolved stars) and point-like (mostly stars) with a lot of scientific implication, including statistical study on the population and more detailed study on smaller samples.

- To help us study and classify them we are working on the developing of **source finding** and **classification algorithm**.

- To complete the samples and to completely characterize sources we will need to wait for **SKA** and to continue building expertise.