Galactic Science with SKA, precursors & pathfinders

Towards the sharpest view of Our Galaxy

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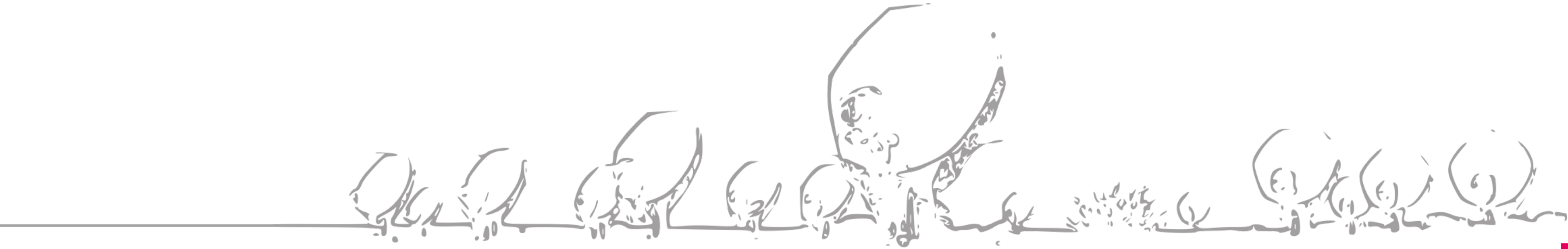
On behalf of the Our Galaxy SKA Science Working Group

The 4th National Workshop on the SKA Project
27 November – 1 December 2023

Scientific context



Why Galactic (Radio) Science?

- Our Galaxy is a **unique laboratory** for stellar evolution & fundamental physics
- We can learn by studying
  - **Individual sources** in detail: specific features & phenomena
  - **Populations** as a whole: statistical properties & overall behaviour
- Dust **absorbs** light at shorter wavelengths
- But radio waves **peer through** the dust, **revealing hidden sources & phenomena**

The Milky Way seen over the Very Large Array. ***Credit: NRAO/AUI/NSF***

Why Galactic (Radio) Science?

Pulsar wind nebulae
Astrometry (masers)
Supernova Remnants
Stellar outflows & jets Stellar clusters
Star-Planet interaction HII regions
Mass-loss Circumstellar envelopes Astrochemistry
Stellar winds High-spectral resolution Galactic Centre
Binary stars (XRBs) High-temporal resolution Radio stars
HI-H2 transition High-sensitivity observations
Polarization (continuum & lines) Cosmic rays
Non-thermal radio variability (flares)
Evolved low-mass stars (AGB, post-AGB, PNe)
Evolved high-mass stars (LBVs, WRs)
Transients High-energy particle acceleration
Stellar evolution Data processing & computing
Radio recombination lines Star formation
Galactic structure Galactic diffuse emission
Molecular clouds Molecular spectroscopy Cold gas
Large area surveys Cataclysmic variables
Magnetic fields Interstellar turbulence
Galactic ISM Young stellar objects
White-dwarf pulsars
Galactic HI emission

Fundamental questions

Radio astronomy can shed light on some of the **most challenging questions** in Galactic Science

- How do stars **form**?
- How do stars **evolve & lose mass**?
- How do stars **die**?
- What's the **origin of cosmic rays**?
- What's the role of **interstellar medium**?
- How's the **magnetic field** of extrasolar planets?
- and many others…

Fundamental questions

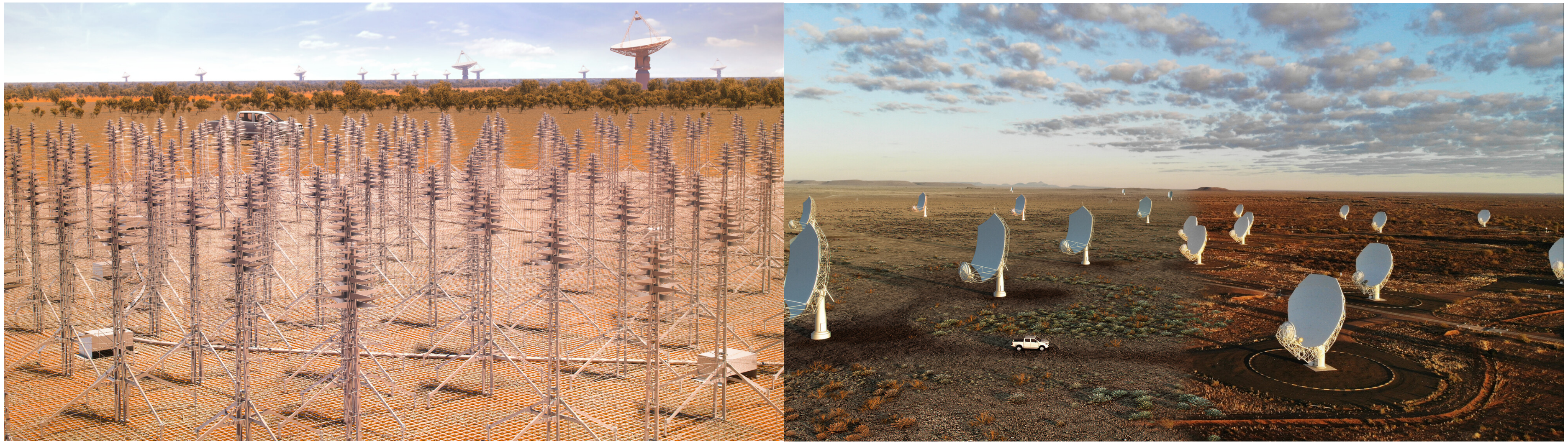
Radio astronomy can shed light on some of the **most challenging questions** of Galactic Science

- How do stars **form**?..*HII regions*
- How do stars **evolve & lose mass**?..........................*WRs, LBVs*
- How do stars **die**? ……………………………………..*PNe, SNRs*
- What's the **origin of cosmic rays**?............................*SNRs*
- What's the role of **interstellar medium**?....................*PNe, LBV, WRs, SNRs, Filaments*
- How's the **magnetic field** of extrasolar planets?.......*Star-Planet interaction*

The role of SKA & its precursors

SKA precursors

A significant leap forward in terms of angular resolution, sensitivity, and *uv*-coverage



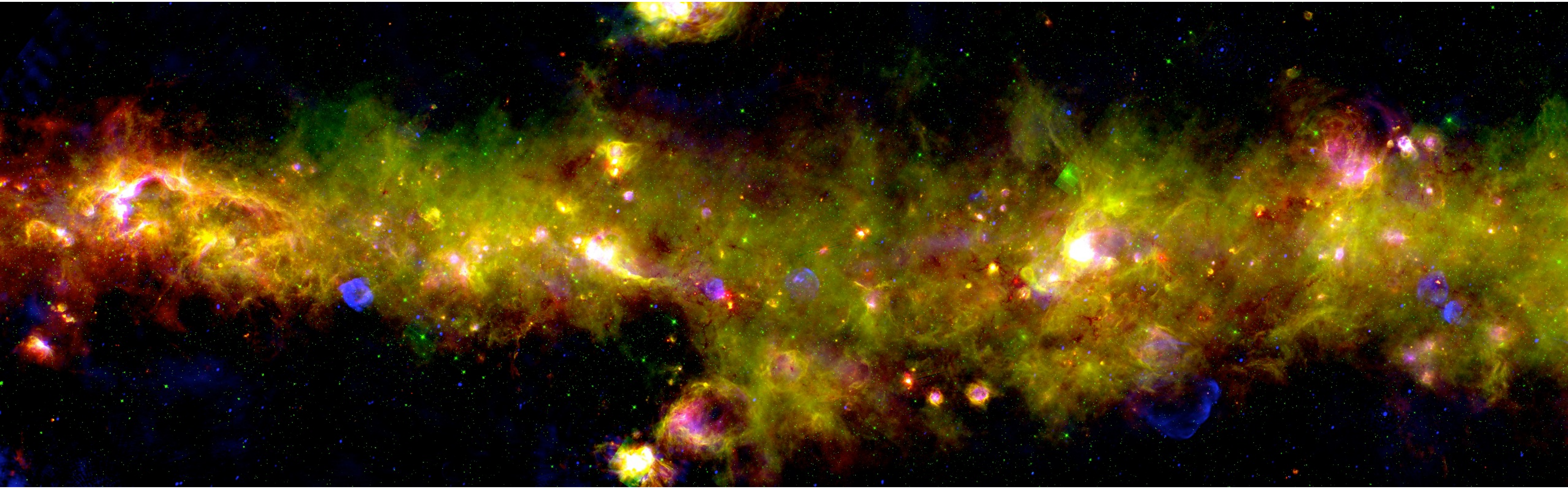
Artist impression of SKA-Low and SKA-mid. ***Credit: SKAO***

SKA will be even better but… how to **make the most of it**?

- Identify technical obstacles
- Find efficient solutions
- Evaluate scientific potential

Our Galaxy Working Group

*A patch of the Galactic Plane as seen at 912 MHz (blue, ASKAP), 8 micron (green, Spitzer) and 70 micron (red, Herschel) · **Umana+2021***



Uncover the ecology of baryons and understand the cycle of matter in the Milky Way

Specific science goals

Star formation: from the ISM to stars

Intermediate and high-mass stars in proto-clusters, study of flow of mass through the ionised ISM…

Stellar evolution: stars and their neighbourhoods

Interplay of stars with the ISM in terms of radio-emitting phenomena: flares, SPI, stellar winds …

Stellar death: from stars to the ISM

Evolved stars' mass-loss mechanisms, stellar feedback at Galactic scale, supernova remnants

The Galactic Centre

A unique astrophysical laboratory with the most extreme conditions

*"Our Galaxy as a **resolved** z=0 **template** to understand how other galaxies work"*

The team

Our Galaxy currently involves **100+ researchers** from **25+ countries**, with a broad expertise on many Galactic Science fields

The data

Several projects/surveys **involving SKA precursors & pathfinders**

focus on (or cover a significant part of) Our Galaxy,

enabling disruptive Galactic science

Evolutionary Map of the Universe (EMU)

SARAO MeerKAT L-band Galactic Plane Survey

Galactic ASKAP survey (GASKAP)

GaLactic and Extragalactic All-sky MWA Survey (GLEAM)

Transients and Pulsars with MeerKAT (TRAPUM)

Polarisation Sky Survey of the Universe's Magnetism (POSSUM)

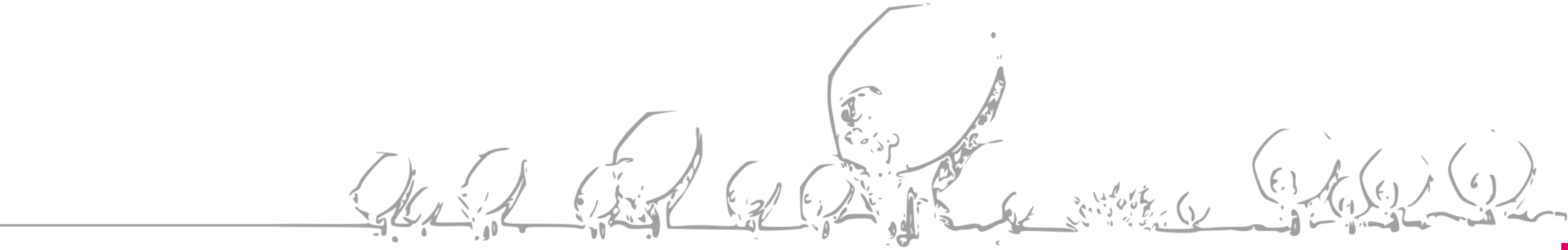
Rapid ASKAP Continuum Survey (RACS)

VLA Sky Survey (VLASS)

...

(in combination with follow-up **targeted observations**)

(Some) scientific highlights



Stellar lifecycle in Our Galaxy

SCORPIO · Stellar Continuum Originating from Radio Physics in Our Galaxy

(Umana+2015)

An **ATCA+ASKAP** pathfinder project to explore the potential of EMU for Galactic Science

Scientific goals

Characterization of radio-emitting stars

Comprehensive view of stellar evolution

Population studies

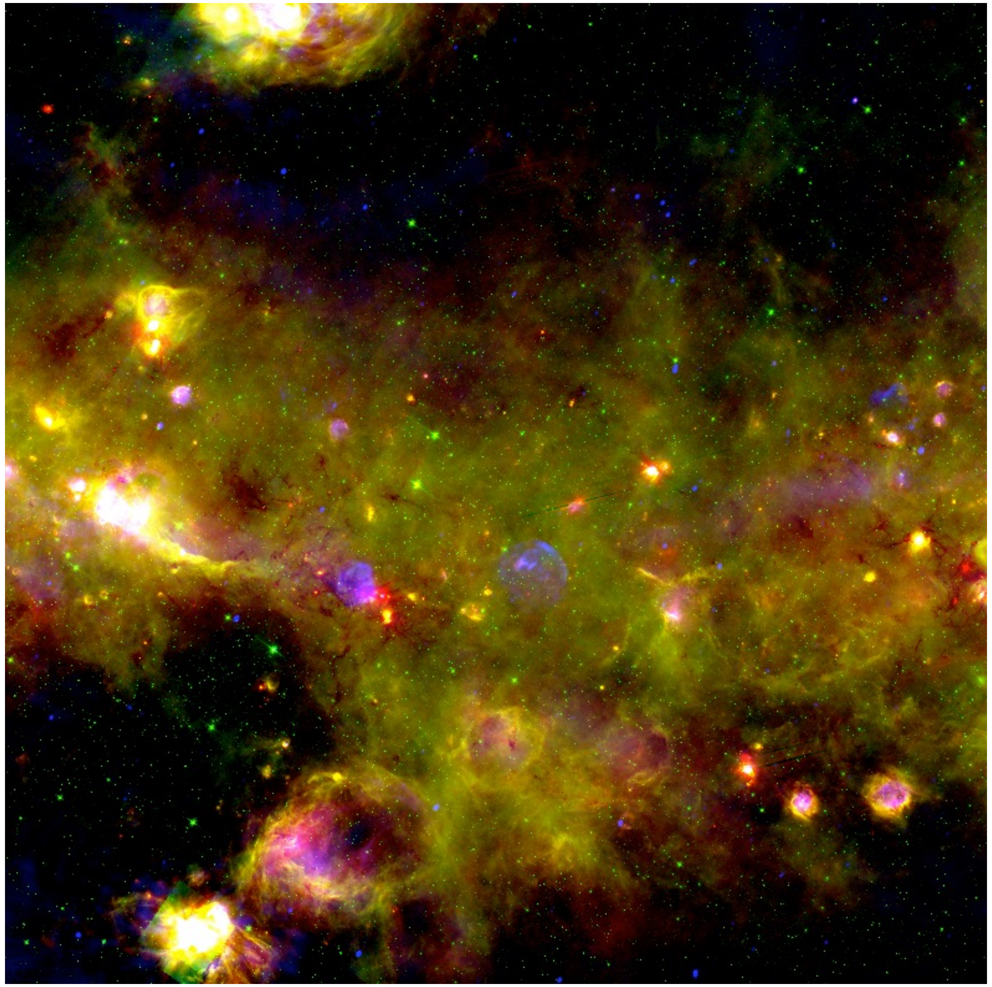
Technical goals

Anticipate imaging issues

Test and finetune calibration and reduction

Improve data analysis techniques

Stellar lifecycle in Our Galaxy



Part of the SCORPIO field at 912 MHz (blue), 8 micron (green) and 70 micron (red) · Umana+2021

Large & valuable scientific return

(publications, datasets/catalogues & technical know-how)

- Umana+2015 · *project presentation & ATCA data overview*
- Riggi+2016 · *compact source extraction*
- Cavallaro+2018 · *compact source characterization*
- Ingallinera+2019 · *extended source characterization*
- Umana+2021 · *ASKAP data overview*
- Riggi+2021 · *compact source characterization in ASKAP*
- Ingallinera+2022 · *discovery of OH masers in ASKAP*
- Bufano+ (in prep) · *new SNR candidates*

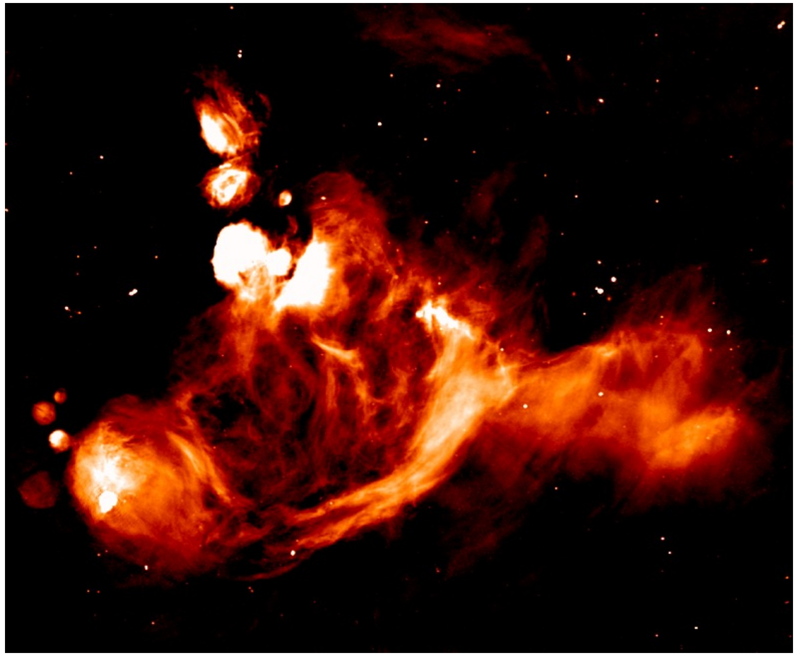
Stellar lifecycle in Our Galaxy

ASKAP

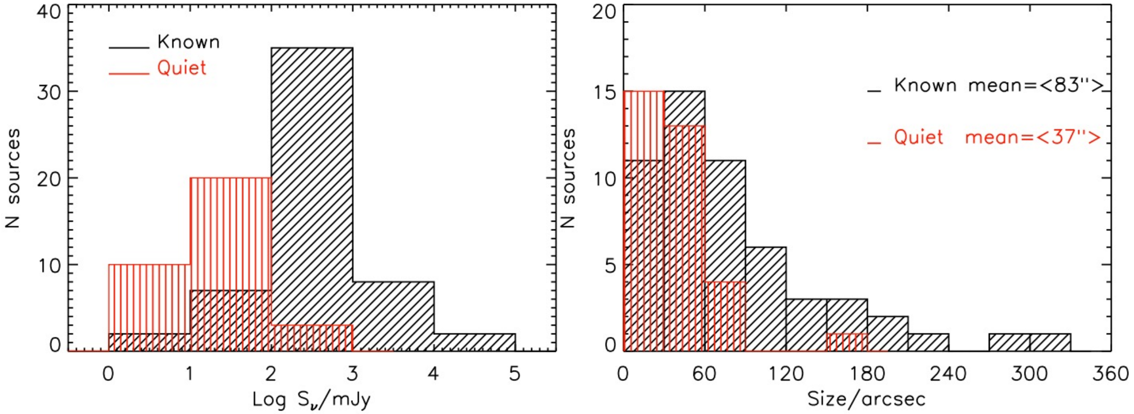
HII regions

Stellar nurseries, the most abundant extended source at these frequencies

- *Relation between HII region types & evolution of massive stars*
- *Massive stars – HII regions – ISM relationship*
- *Population completeness & biases*



*A complex HII region in the SCORPIO field · **Umana+2021***



*Flux/size distribution of known & radio-quiet (in literature) HII regions in SCORPIO · **Umana+2021***

Is radio-quietness just an **observational bias**?

Stellar lifecycle in Our Galaxy

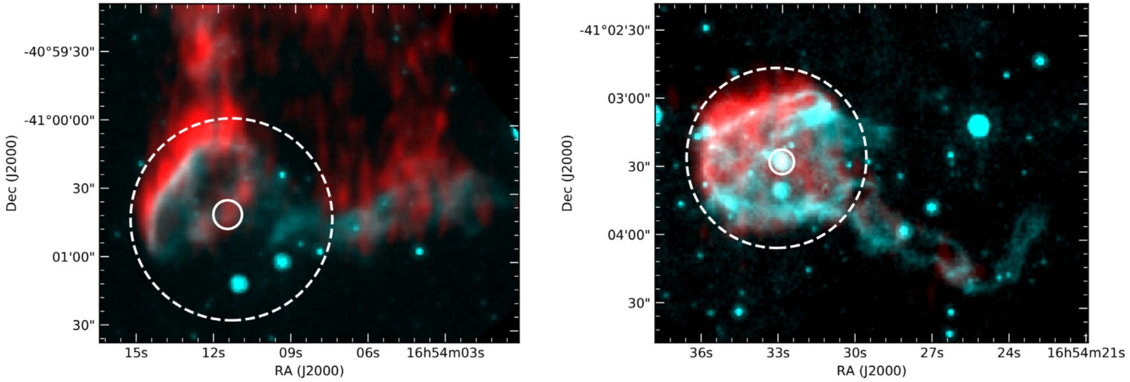
ASKAP

LBV & WR stars

Late evolutionary stages of the most massive stars

- *Enrichment of surrounding ISM*
- *Mass-loss mechanisms (winds, eruptions)*
- *Pre-SN evolutionary stages*

*Newly proposed LBV/WR candidates found in the SCORPIO field · **Ingallinera+2019***

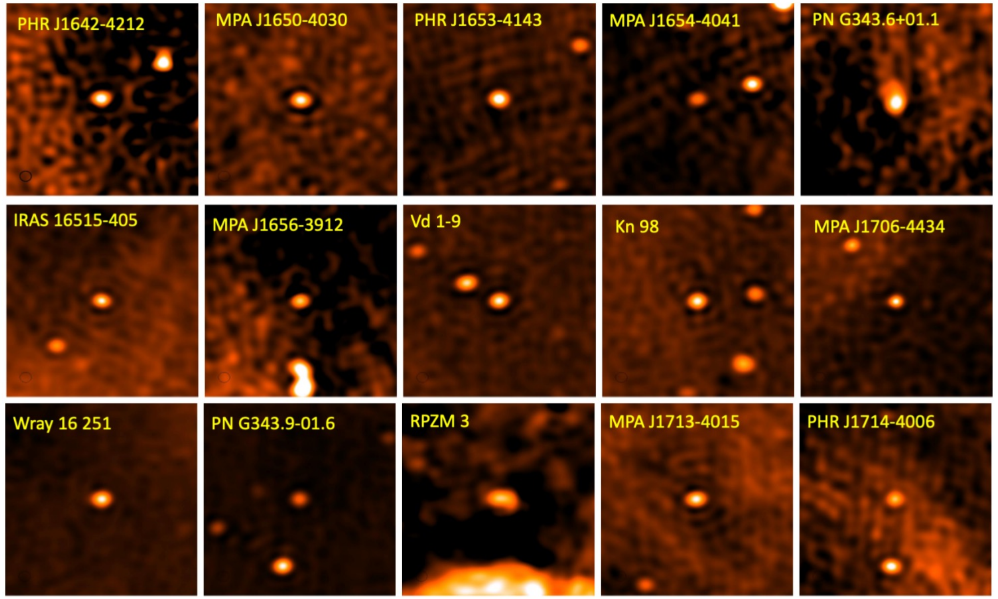


Planetary nebulae

Endpoint of stars between 0.8-8 solar masses

- *Morphologies (bipolarity)*
- *Galactic distribution*
- *Formation mechanisms*

*Newly detected PNe in the SCORPIO field · **Ingallinera+2019***



Stellar lifecycle in Our Galaxy

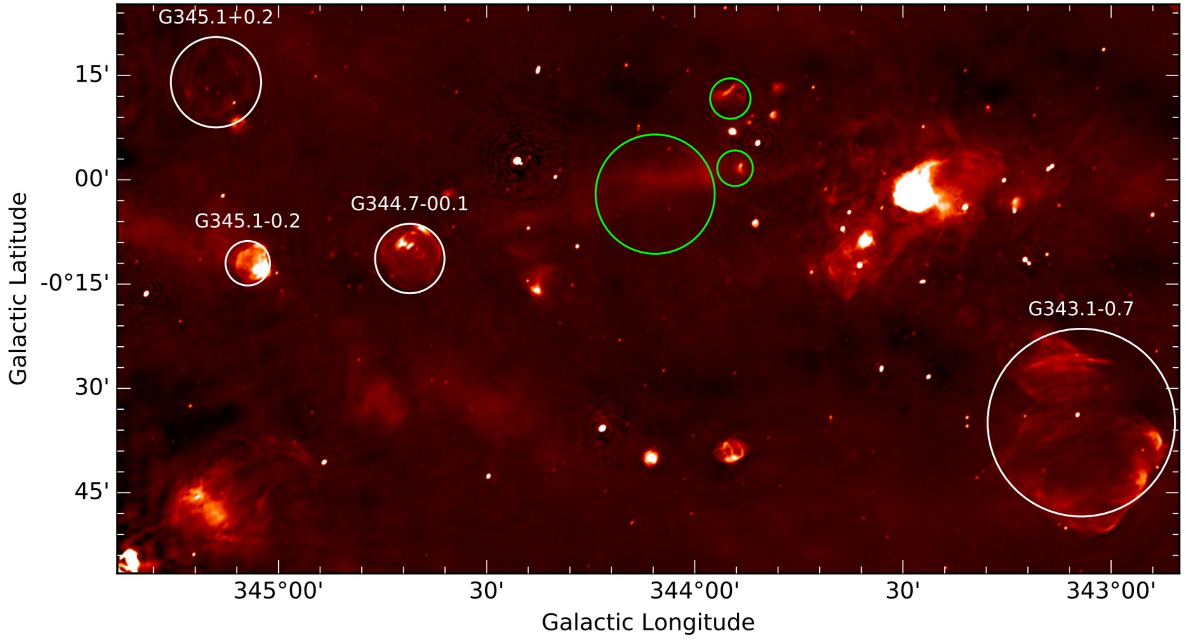
ASKAP

Supernova Remnants

Interaction between SN shockwave and CSM

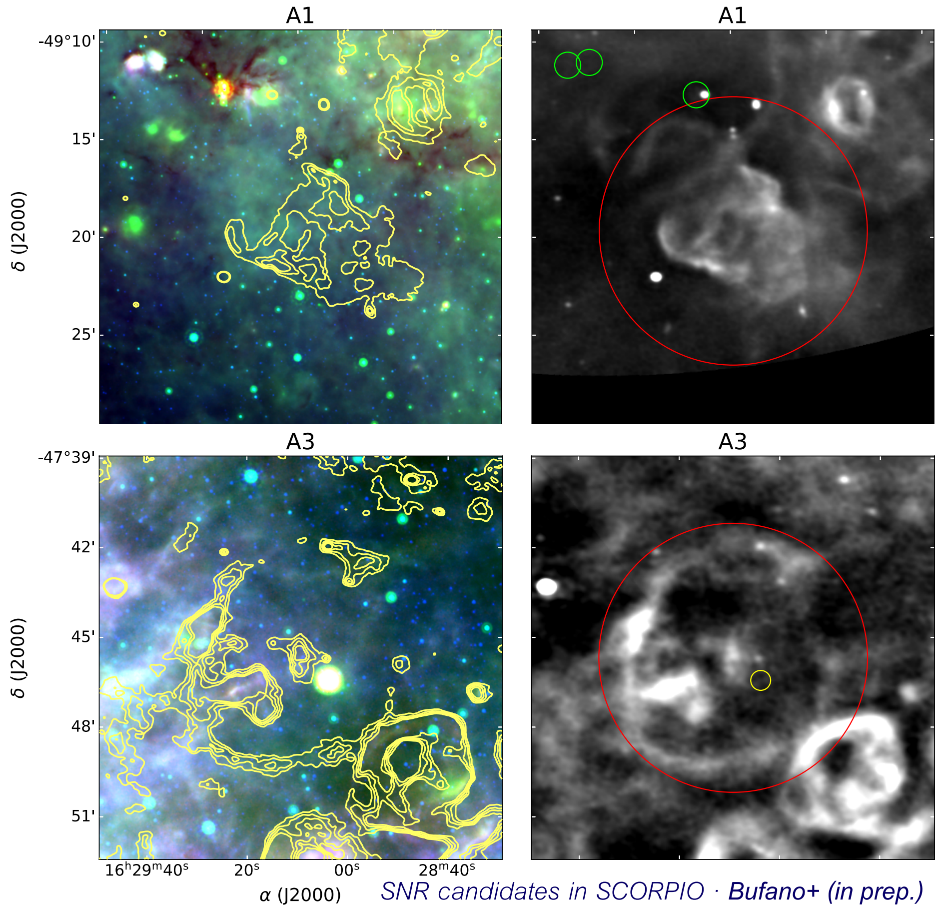
- *How do they accelerate particles?*
- *How do they contribute to Galactic CRs?*
- *How do they influence star formation?*

*Known and candidate SNRs in SCORPIO · **Umana+2021***



Discovery of many **new SNR candidates**

(infrared comparison, spectral index analysis)

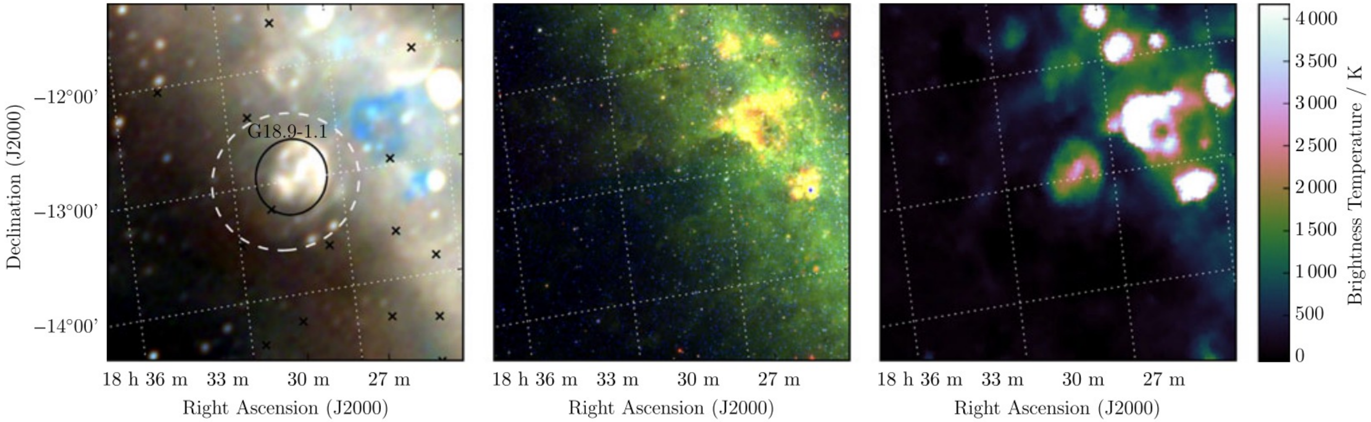


*SNR candidates in SCORPIO · **Bufano+ (in prep.)***

Stellar lifecycle in Our Galaxy

MWA

GLEAM RGB, WISE RGB and Effelsberg image of SNR G18.9-1.1 · Hurley-Walker+2019

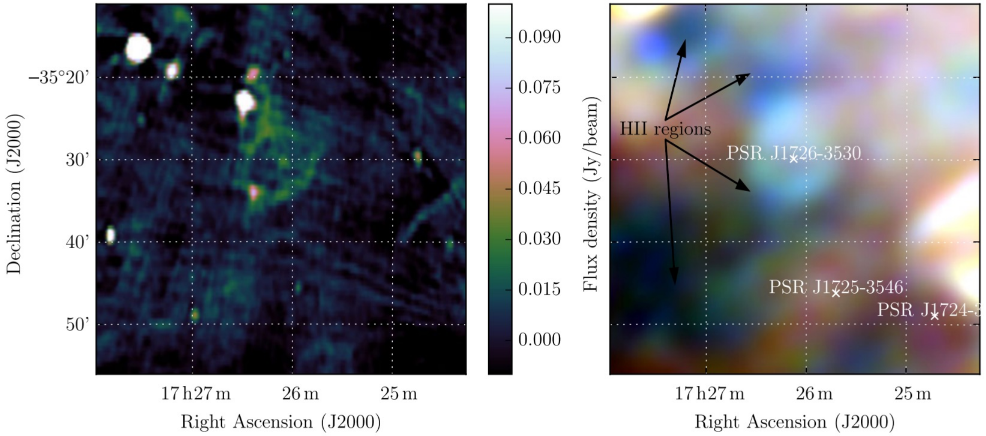


New SNRs in GLEAM

Detection of **27 new candidate SNRs**

(spectral index analysis & radio-IR comparison)

cSNR G352.2-0.1 in MOST (left) / GLEAM (3 bands, right) · Hurley-Walker+2019



Existing SNRs in GLEAM

Confirmation of several candidate SNRs in literature:

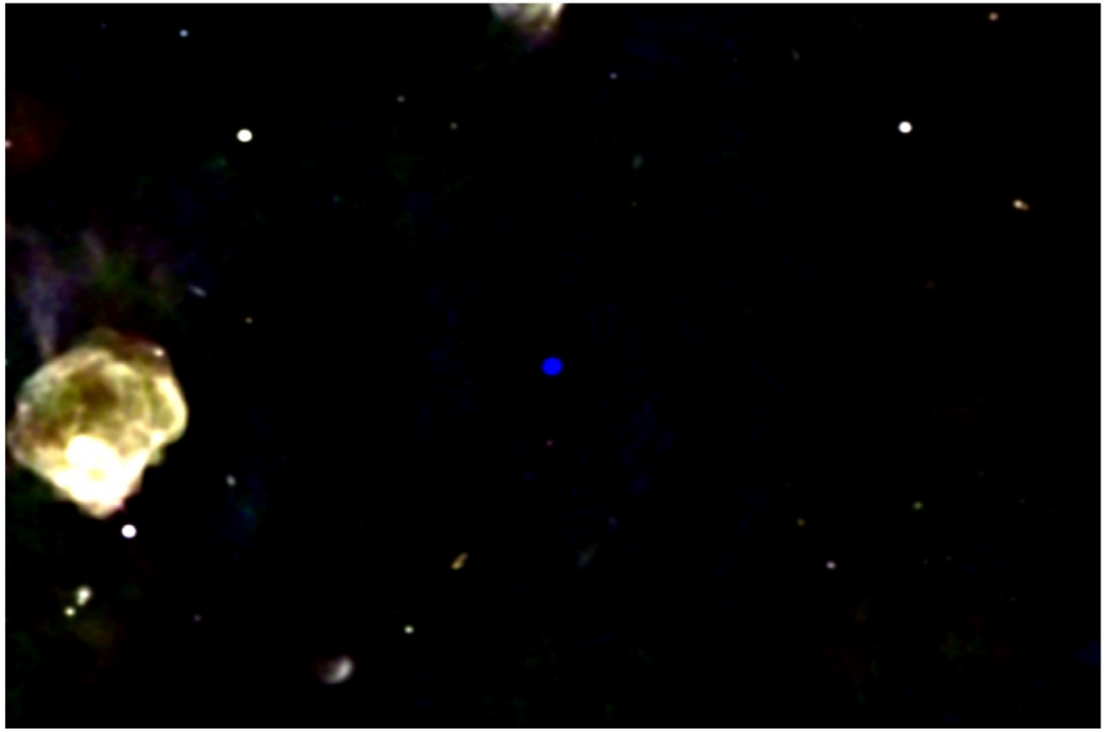
- 10/12 out of 101 non-MAGPIS candidates confirmed
- 3 out of 18 MAGPIS candidates confirmed

Stellar lifecycle in Our Galaxy

ASKAP

Serendipitous discoveries

OH-maser emission detected in ASKAP continuum maps



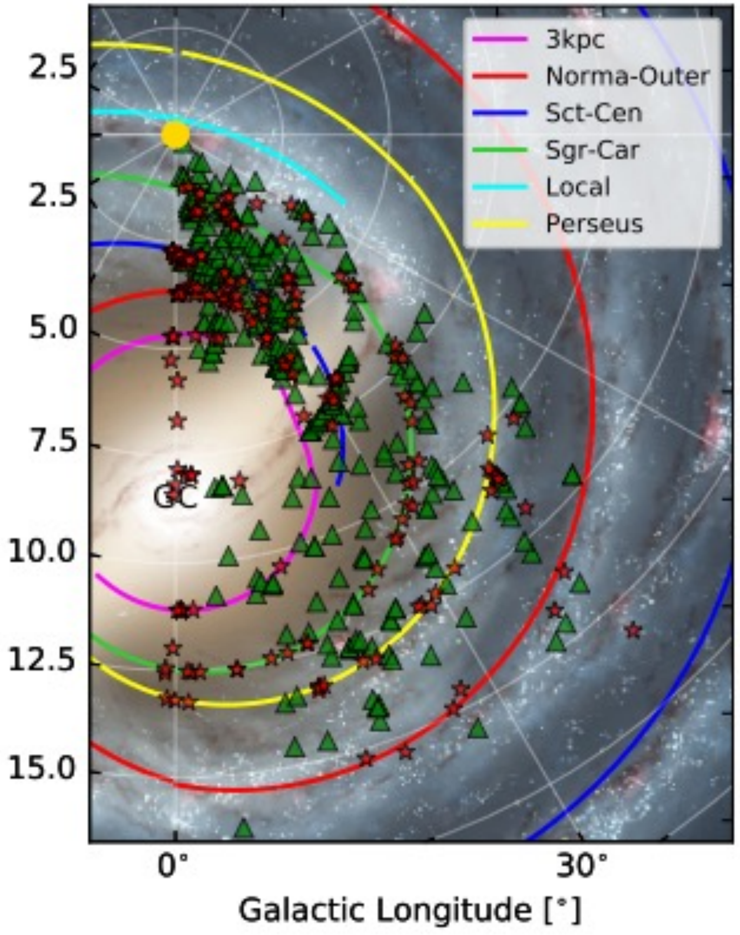
ASKAP RGB composition (R=1356 MHz, G=1480 MHz, B=1615 MHz) of the OH maser source OH344.929+0.014 · Ingallinera+2022

- **42** known masers + **7** candidates
- Spectral **confirmation** of candidates
- **New method** to detect masers in wide deep continuum surveys

Stellar lifecycle in Our Galaxy

VLA

Methanol masers in GLOSTAR · ***Nguyen+2022***



Methanol 6.7 GHz masers in GLOSTAR

CH_3OH masers trace recent high-mass star formation

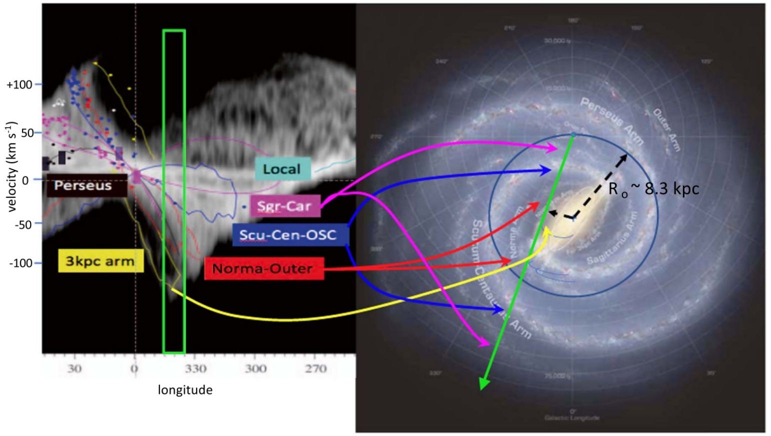
Most sensitive unbiased methanol maser survey to date

- **554 methanol masers** detected
- **84** are **new** detections
- 97% sources associated with **dust emission**
- 12% sources associated with **radio continuum**

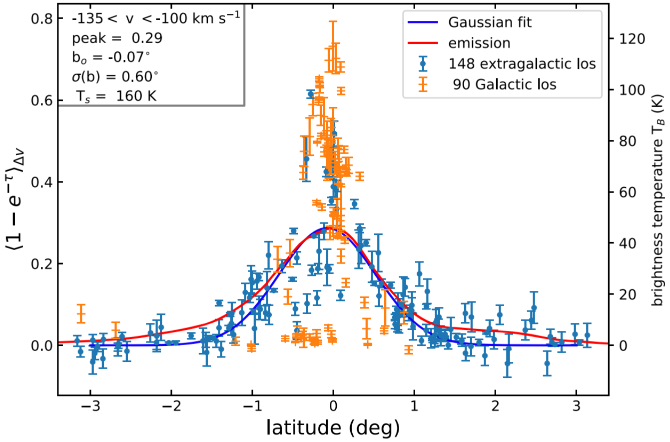
The structure of Our Galaxy

ASKAP

The GASKAP pilot field and LOS (green) · Dickey+2022



Mean absorption vs latitude· Dickey+2022



Tracing the Galactic 21 cm HI absorption

Observations of pilot field with 1 km/s resolution

Absorption spectra towards **295 continuum sources**

(105 Galactic + 195 extragalactic)

Structure of the MW disk near l=340º

- Flaring disk
- CNM scale height far end of the bar / 3 kpc arm – 50 pc
- CNM scale height far side of GC – up to 160 pc
- CNM follows the distribution of WNM to the edge of the disk

The SARAO MeerKAT Galactic Plane Survey

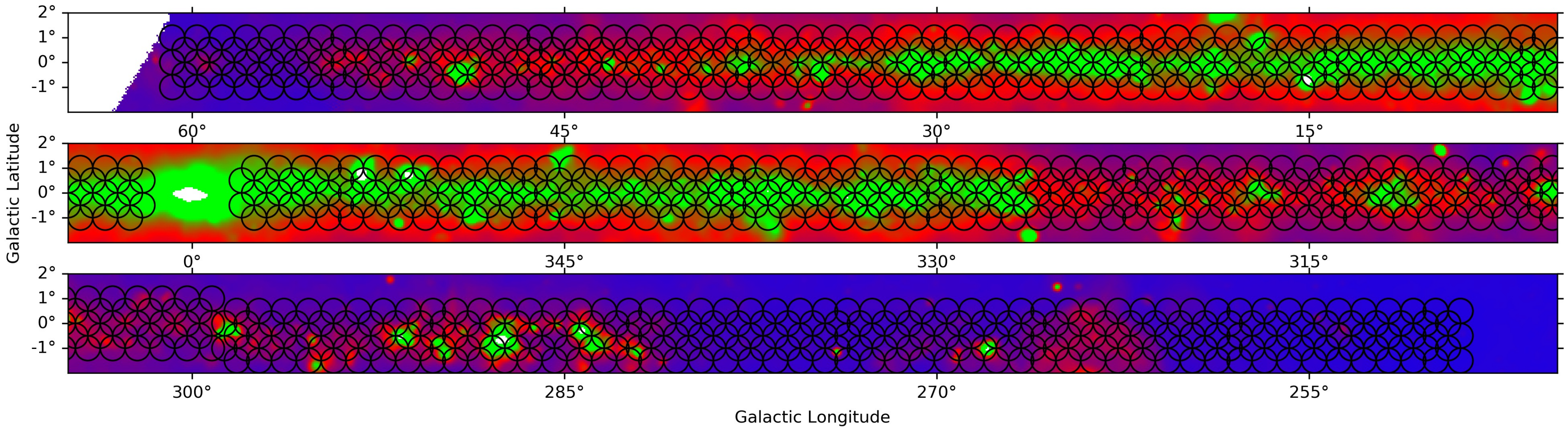
MeerKAT

L-band continuum survey of 1st, 3rd and 4th Galactic quadrants: 2º<*l*<61º and 251º<*l*<358º, with |*b*| <1.5º

(Goedhart+in prep)

1.28 GHz, 8 arcsec resolution, 10-20 micro Jy/beam sensitivity

Coverage of the MeerKAT L-band Galactic Plane Survey · Goedhart+ (in prep)



Insights on large-scale **ISM structure** (filaments, diffuse emission)

Enables (almost) unbiased **population studies**

Provides an unprecedented look at **stellar evolution**

The SARAO MeerKAT Galactic Plane Survey

MeerKAT

Science highlights include:

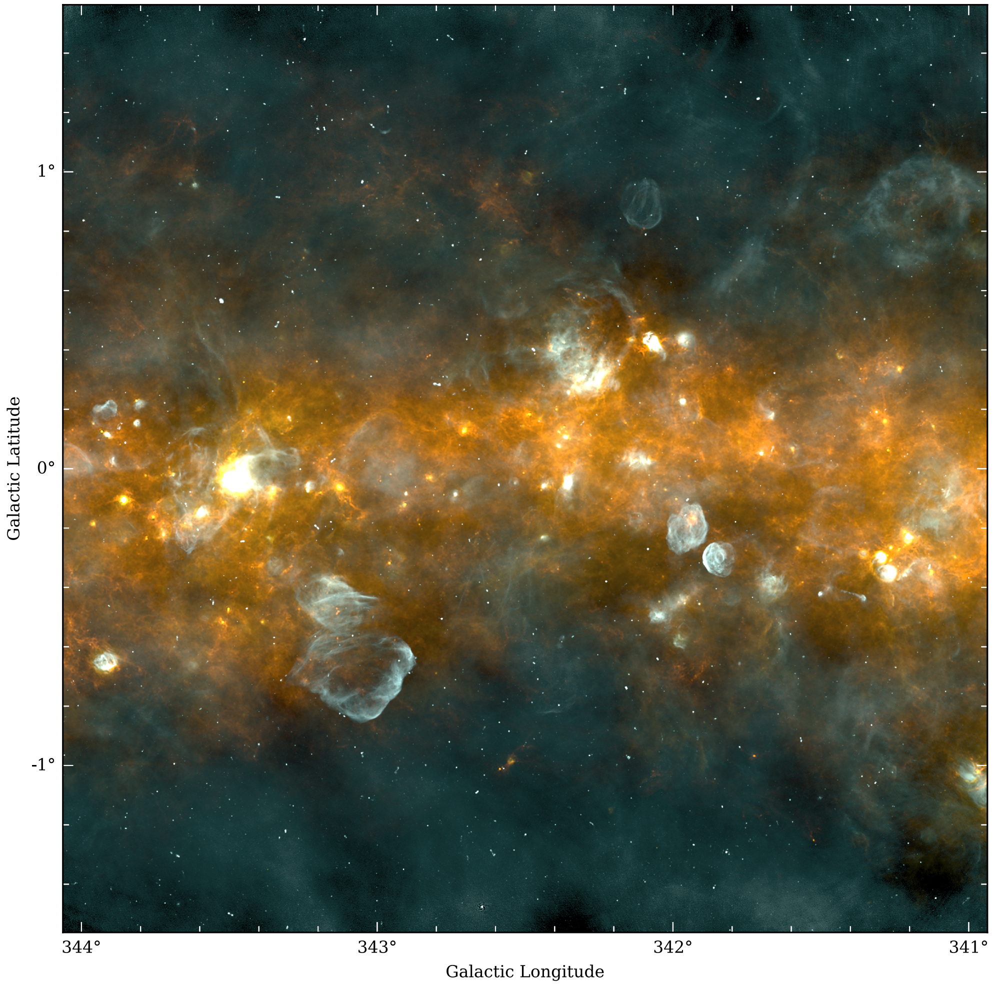
Radio filaments · SNRs: known & new candidates · pulsars · evolved stars: planetary nebulae, luminous blue variables, Wolf-Rayet stars· Other radio stars · HII regions · Massive protostars · Unknown radio sources

Science publications incoming:

- Umana+ (in prep) · *Luminous Blue Variables & bubbles*
- Loru+ (in prep) · *Known Supernova Remnants*
- Ingallinera+ (in prep) · *Planetary nebulae*
- Bordiu+ (in prep) · *Catalogue of extended sources*

…and more!

For more details, see the talks by F. Cavallaro and F. Bufano

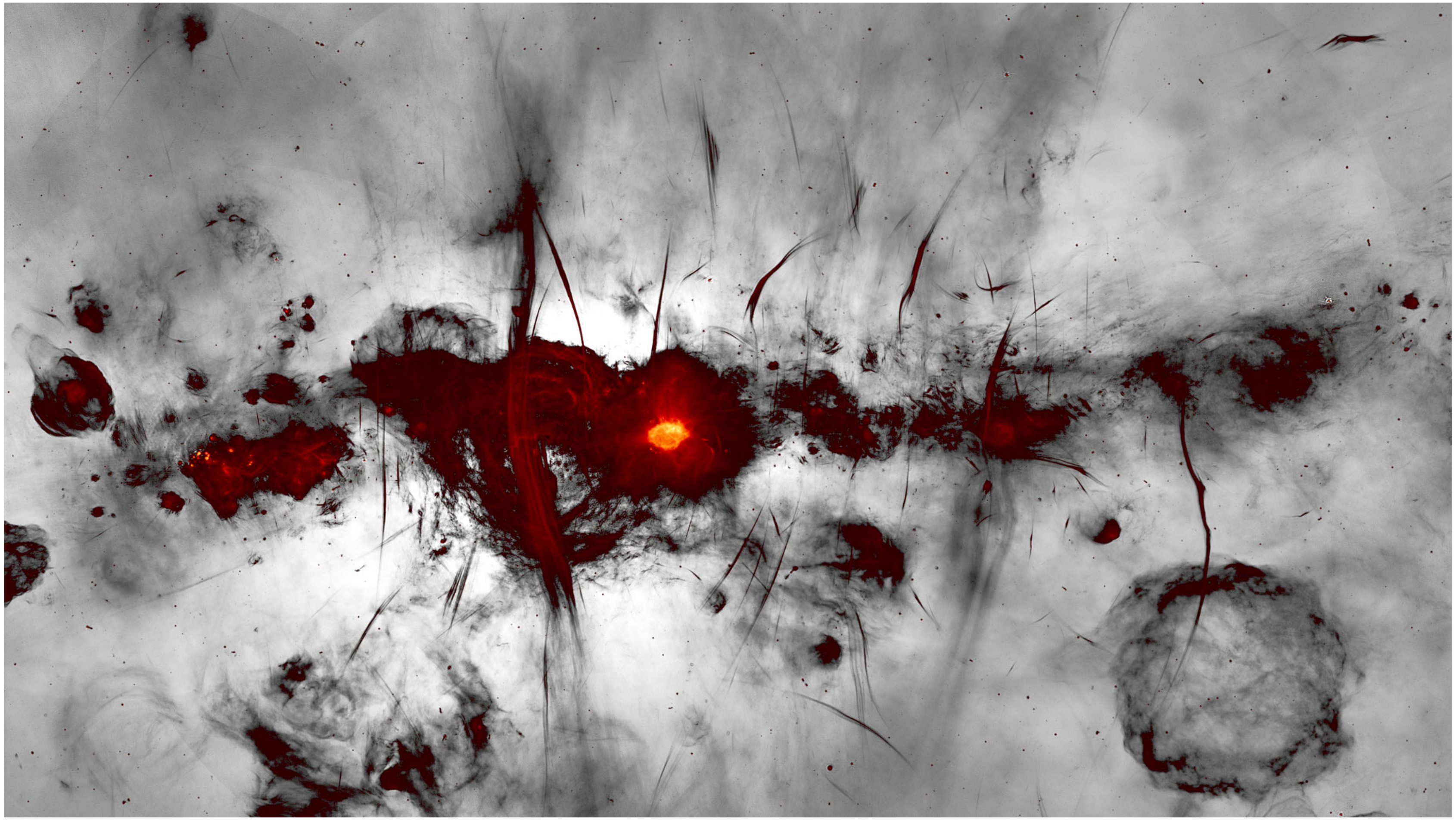


The SCORPIO field as seen by MeerKAT (white & cyan), Herschel 70 micron (yellow) and 250 micron (orange) · Goedhart+ (in prep)

The Galactic Centre

MeerKAT

MeerKAT revealed the **sharpest view** of the **most extreme environment** in Our Galaxy



Spectral index image of the Galactic Centre. ***Credit: SARAO, Heywood+2022***

The Galactic Centre

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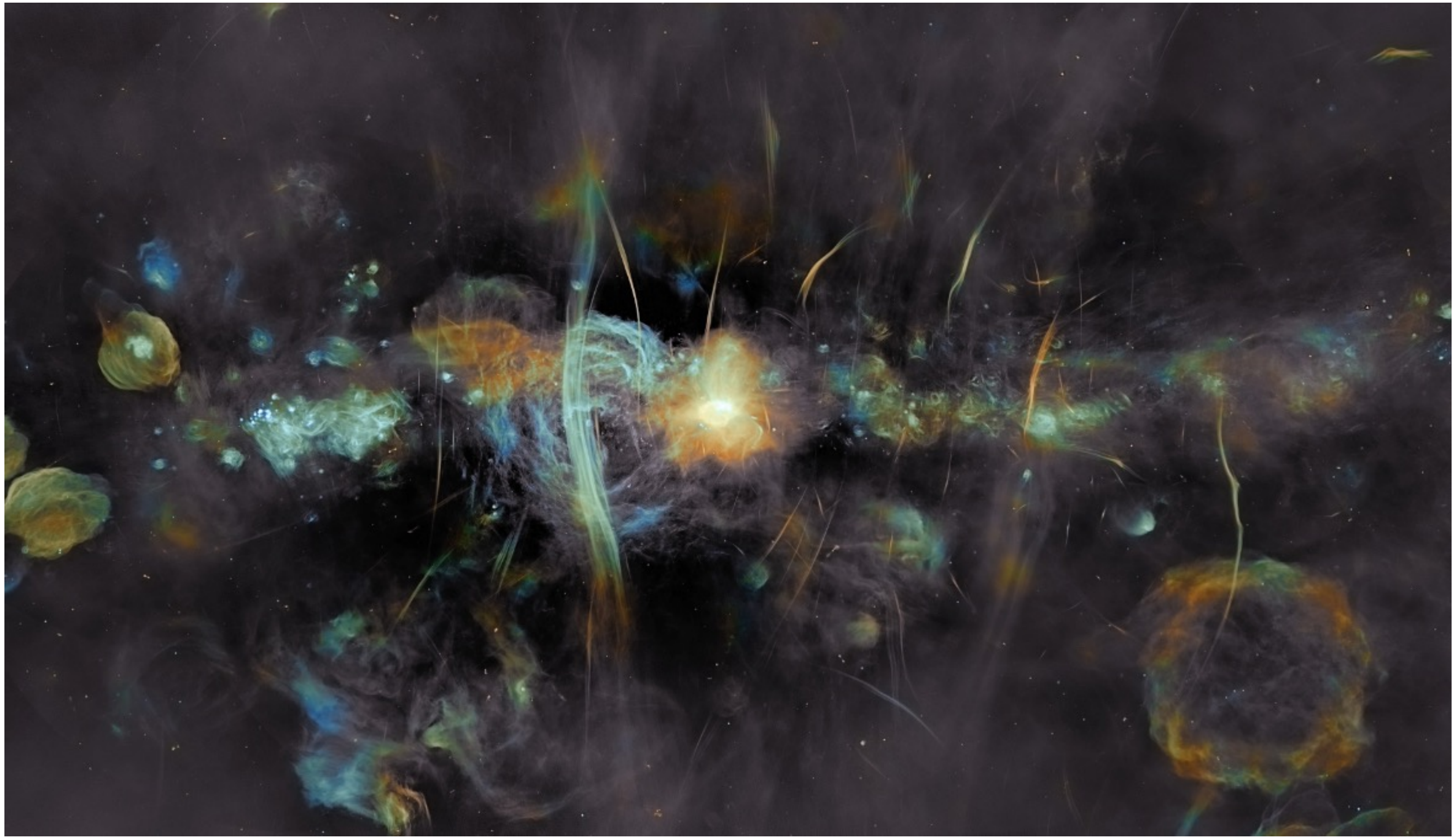


Spectral index image of the Galactic Centre. Credit: SARAO, Heywood+2022, J. C. Muñoz-Mateos

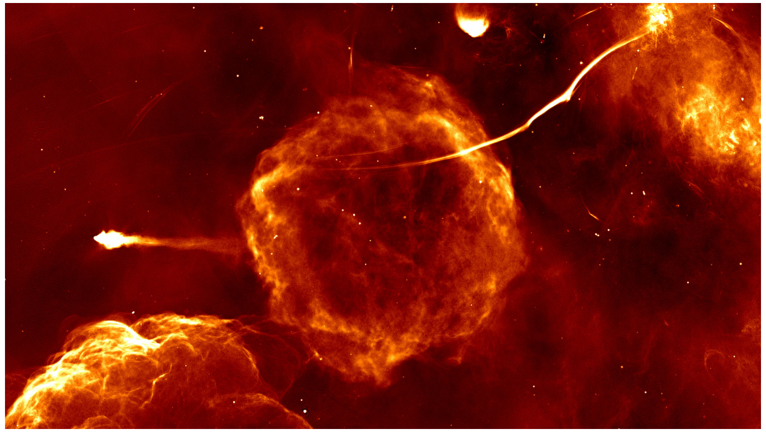
The Galactic Centre

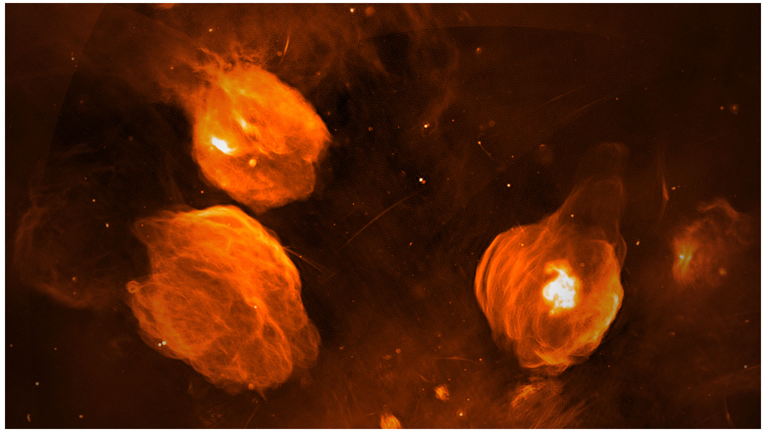
MeerKAT

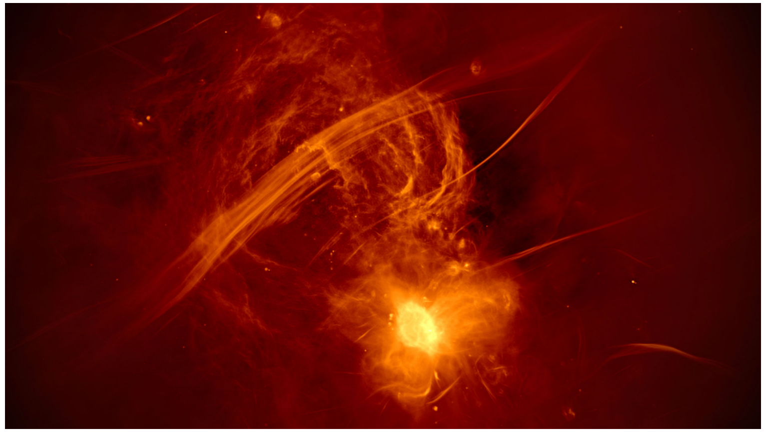
The diversity of ‘Galactic fauna’ in the Galactic Centre provides unique insights on

stellar evolution & Galactic structure

Credit (all images): SARAO / Heywood+2022







SNR G359.1-0.5 , the “Mouse” **PWN** and the “snake” **radio filament**

SNRs, **HII regions** and **shell-like structures** tracing the different stages of **stellar evolution**

The Galactic Centre **radio bubble** and radio filaments tracing **magnetic fields**

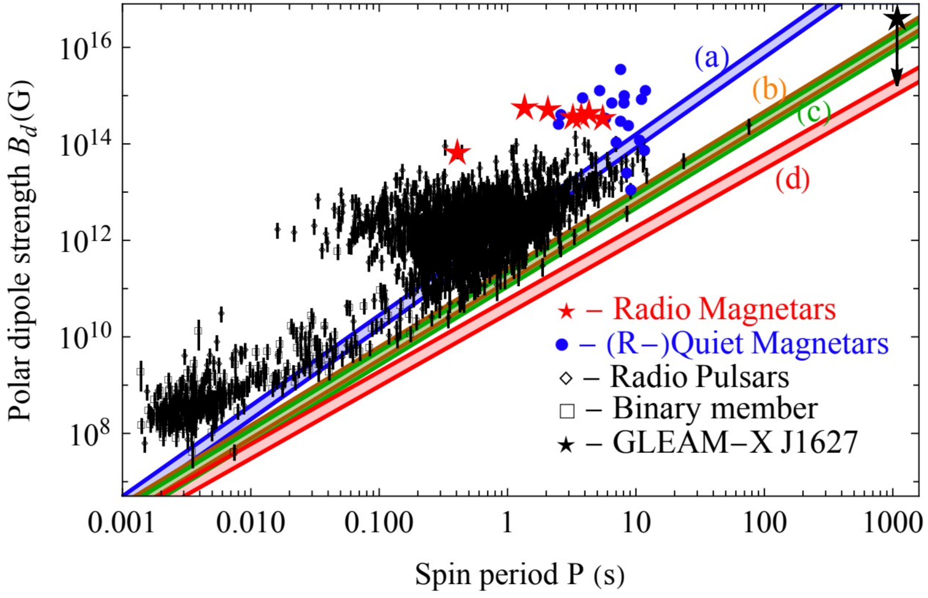
Stranger things

MWA

GLEAM X-J162759.5–523504.3

A pulsating Galactic source, highly linearly polarised and with P = 1091 s, that is spinning down

B_d-P diagram of known pulsars and magnetars · *Suvorov+2023*



Uncertain nature, ongoing observational and theoretical work.

Long period pulsar? Radio-loud magnetar? Highly magnetized white dwarf?

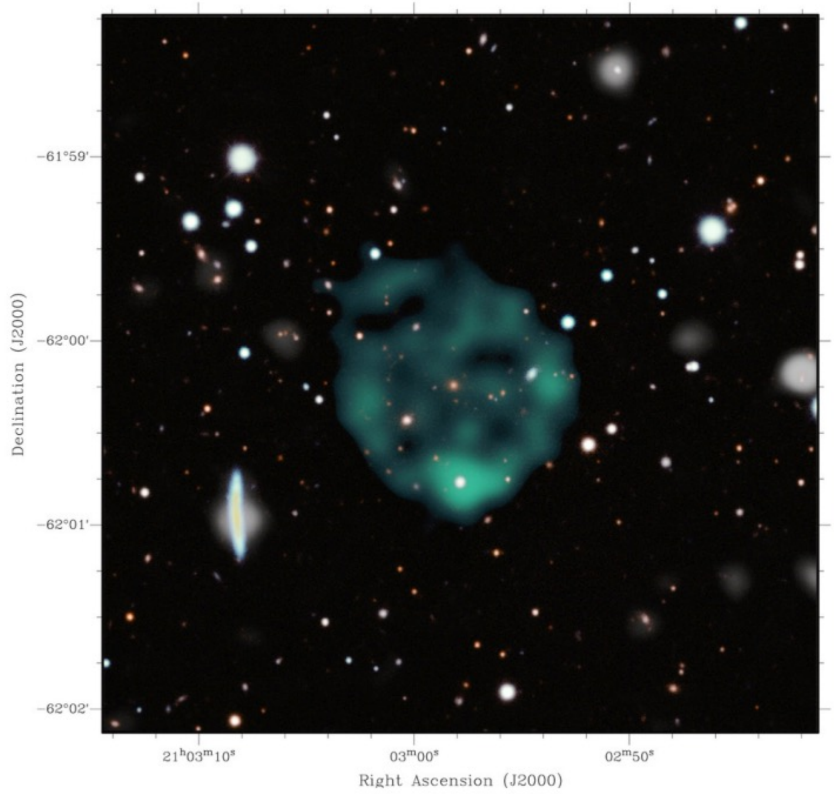
(see Gençali+2022, Erkut+2022, Tong+2023, Katz+2022, Rea+2022, Suvorov+2023)

Stranger things

ASKAP, MeerKAT, LOFAR…

"Odd Radio Circles" (ORCs): a new type of radio source?

Found in ASKAP, GMRT, MeerKAT & LOFAR images



ORC1 ASKAP 944 MHz continuum (EMU Pilot Survey) superposed to an optical image · Norris+2021

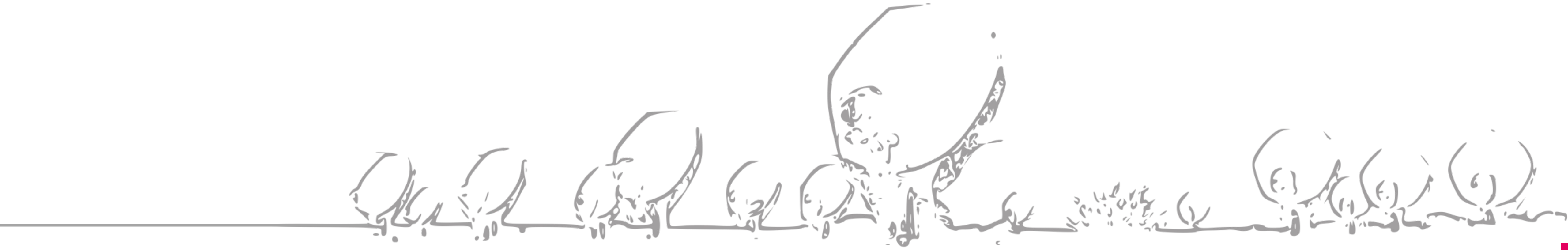
Main features:

- About ∼1 arcmin diameter
- Located at high galactic latitude
- Non-thermal spectral index ($\alpha << 0$)
- Without non-radio counterparts
- 3 out of 5 have a bright galaxy near the centre
- Are they **extragalactic sources** or **weird "local" SNRs**?

Hot discussion ongoing

(see Omar+2022, Filipovic+2022, Sarbadhicary+2023)

Future scientific perspectives



Prospects for SKA

Towards a Galactic Plane survey as a SKA Key Science Project

Scientific drivers

- Discriminating scenarios
- Galactic evolution understanding
- Fundamental physics

High & valuable scientific return

Complex technical challenges

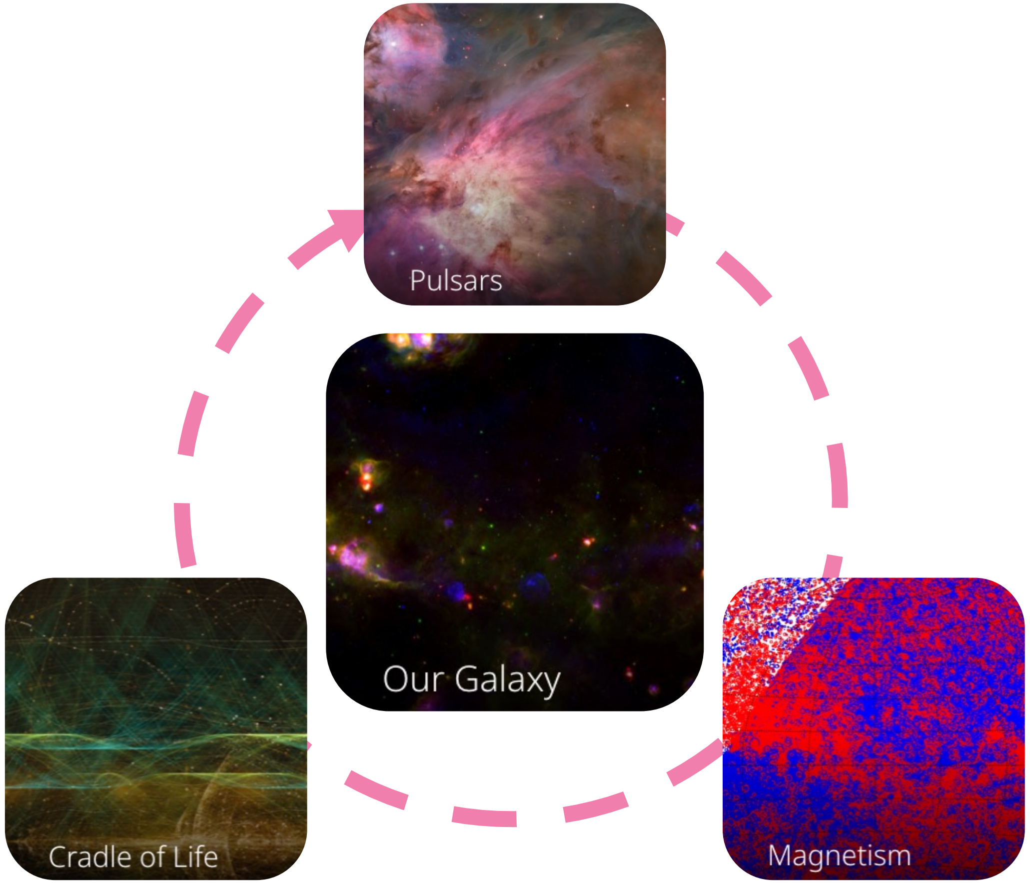
New science

- What cannot be done otherwise
- Unexpected findings

Exploitation of SKA precursors is key to "set the stage" for SKA

Synergies within the SKA community

Ongoing discussions to identify synergies with other WGs and define a joint SKA Early Science case



Commensality across science cases to

make the most of Early Science

Galactic Plane · Galactic Centre · Pulsar science ·

Exoplanets · Radio stars

(and many more!)

Synergies with other instruments

- Full potential of SKA to be unlocked by developing synergies with other instruments
  - Identification of **synergistic facilities** (e.g. ALMA, VLT, JWST, LSST, etc.)
  - Identification of **multiwavelength science cases** (e.g. massive stars, Galactic Centre science, etc.)

- Some **possible examples**:
  - Star formation in the Milky Way (SKA + ALMA + JWST…)
  - Stellar evolution & mass loss (SKA + ALMA + JWST…)
  - Particle acceleration in SNRs (SKA + CTA + Athena…)
  - Emergence of life (molecules, ices) (SKA + ALMA…)

- Also an opportunity for **multimessenger astronomy** – radio counterparts of **neutrinos** and **GWs** (LIGO/VIRGO, KM3NET…)

Final remarks

- SKA precursors are already revolutionizing Galactic Science

- A potential SKA Galactic Plane survey: huge scientific return + important technical challenges

- A SKA KSP needs to be carefully crafted: synergies with other WGs and facilities

- Exploiting SKA precursors is fundamental to be ready to make the most of SKA

The end

Many thanks for your attention.