TRAPUM: Pulsar Surveys with MeerKAT and Lessons for the SKA Era

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on behalf of the TRAPUM collaboration

TRAPUM

Transients and Pulsars with MeerKAT

Presentation layout

- The future of pulsar surveys with SKA
- Interferometric surveys with MeerKAT
- TRAPUM surveys and scientific highlights
- Conclusions

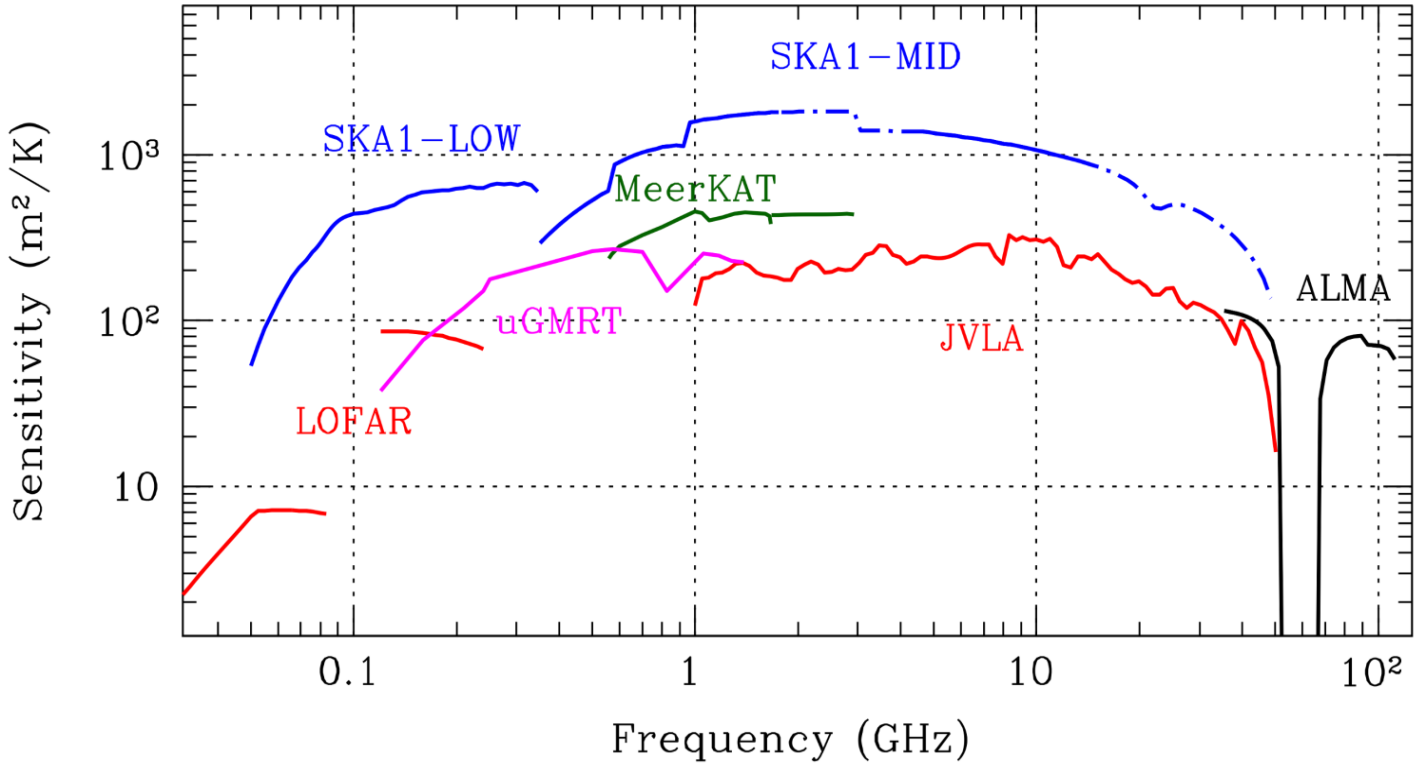
TRAPUM

Transients and Pulsars with MeerKAT

The future of pulsar surveys with the SKA

SKA: a promise for pulsar science in the Southern hemisphere

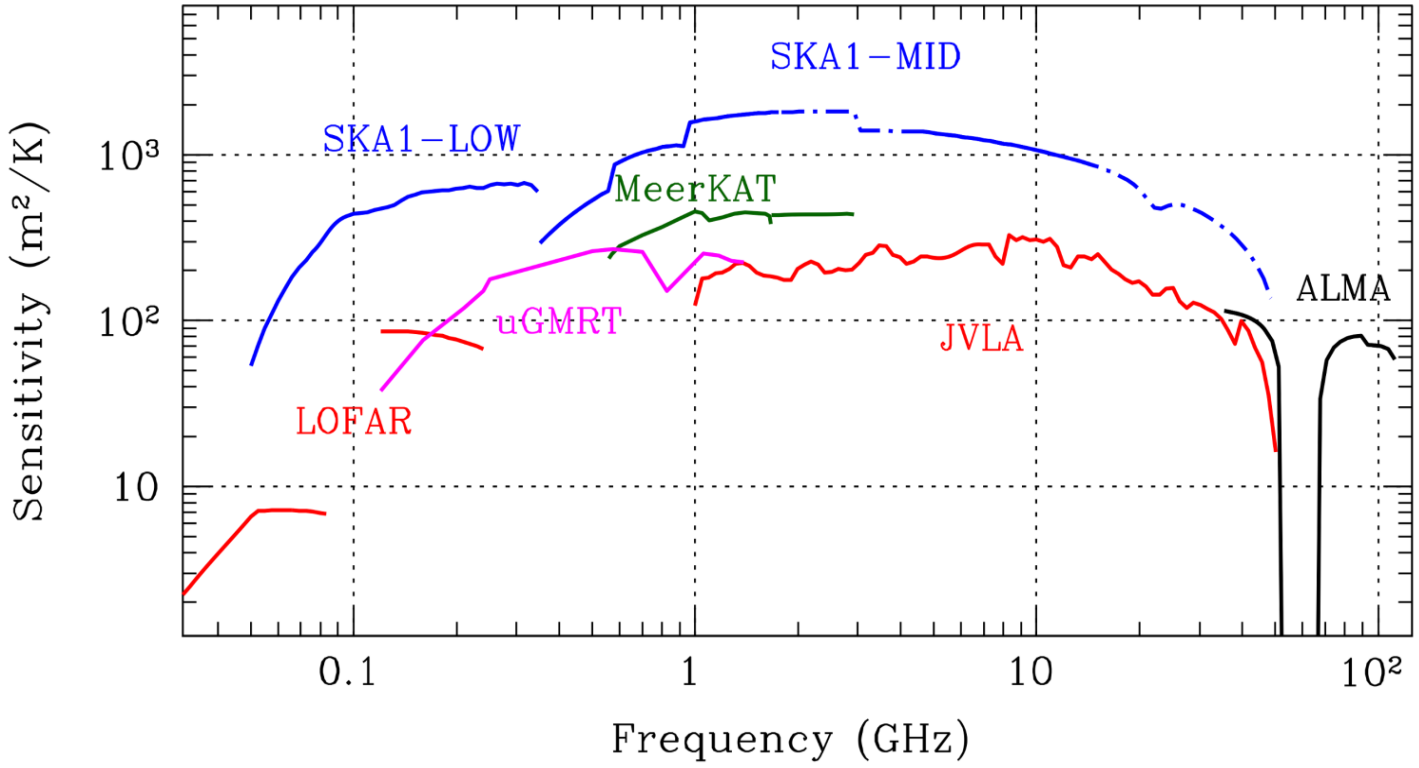
- The SKA-mid will revolutionize pulsar astronomy.
- Curretly, we know of 4,000 pulsars in the Milky way, 360 in globular clusters
- Expectations from SKA-mid:
  - **AA*: 6k – 8k discoveries in MW**
    ~200 discoveries in GCs
  - **AA4: 8k – 12k discoveries in MW**
    ~300 discoveries in GCs



Sources: Keane et al., SKA chapter
Bagchi et al., SKA chapter

SKA: a promise for pulsar science in the Southern hemisphere

- The SKA-mid will be the most powerful interferometer in the world
- What challenges and opportunities arise from interferometric for pulsar surveys with the SKA?



SKA: a promise for pulsar science in the Southern hemisphere

- We do not need to speculate!
- We have experience from interferometric pulsar surveys with MeerKAT:
  the **TRAPUM** and its 280+ discoveries!

TRAPUM

Transients and Pulsars with MeerKAT

Interferometric surveys with MeerKAT

PIs

- Ben Stappers (UK)
- Michael Kramer (DE)

Project Scientist

- Ewan Barr (DE)

Working Group Chairs

- Lina Levin-Preston (UK, Nearby Galaxies)
- Ben Stappers (UK, PWNe/SNR/TeV WG)
- Rene Breton (UK, Fermi WG Co-chair)
- Colin Clark (DE, Fermi WG Co-chair)
- Alessandro Ridolfi (IT, Globular Clusters WG)
- Marta Burgay (IT, Follow-up WG)

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- Vishnu Balakrishnan (DE)
- Werner Becker (DE)
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- Sarah Buchner (SA)
- Francesca Calore (NL)
- Emma Carli (UK)*
- David Champion (DE)
- Weiwei Chen (DE)
- Ismaël Cognard (FR)
- Oliver Dodge (UK)*
- Andrew Douglas (USA)*
- Liam Dunn (AUS)*
- Arunima Dutta (DE)*
- Ralph Eatough (CH)
- Elisabeth Ferrara (USA)
- Paulo Freire (DE)
- Tasha Gautam (DE)*
- Lucía Gebauer Werner(UK)*
- Marisa Geyer (SA)
- Heinrich Hurter (SA)*
- Jean-Mathias Griessmeier (FR)
- Tana Joseph (NL)
- Ramesh Karuppusamy (DE)
- Evan Keane (IRL)
- Lars Künkel (DE)*
- Yunpeng Men (DE)
- Vanessa McBride (SA)
- Lars Nieder (DE)
- Prajwal Voraganti Padmanabh (DE)
- Adipol Phosrisom (UK)*
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- Andrea Possenti (IT)
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- Scott Ransom (US)
- Shalini Sengupta (DE)*
- Maciej Serylak (UK)
- Tinn Thongmeearkom (UK)*
- Naomi Titus (SA)
- James Turner (UK)*
- Vivek Venkatraman Krishnan (DE)
- Laila Vleeschower Calas (UK)*
- Stefan Wagner (DE)
- Patrick Weltevrede (UK)
- Christoph Weniger (NL)
- Norbert Wex (DE)

SKA: a promise for pulsar science in the Southern hemisphere

The TRAPUM Surveys:

- Interferometric surveys
- Coherent beams: 200-900
- Quasi-real-time processing
  (in some of the surveys)

Future SKA-mid (AA*) surveys:

- Interferometric surveys
- Coherent beams: 1100 (200)
- Real-time processing

TRAPUM has been a training ground for future SKA surveys!

- TRAPUM is a collection of pulsar surveys with MeerKAT:

  Galactic plane, Globular clusters, nearby galaxies, Fermi sources, supernova remnants

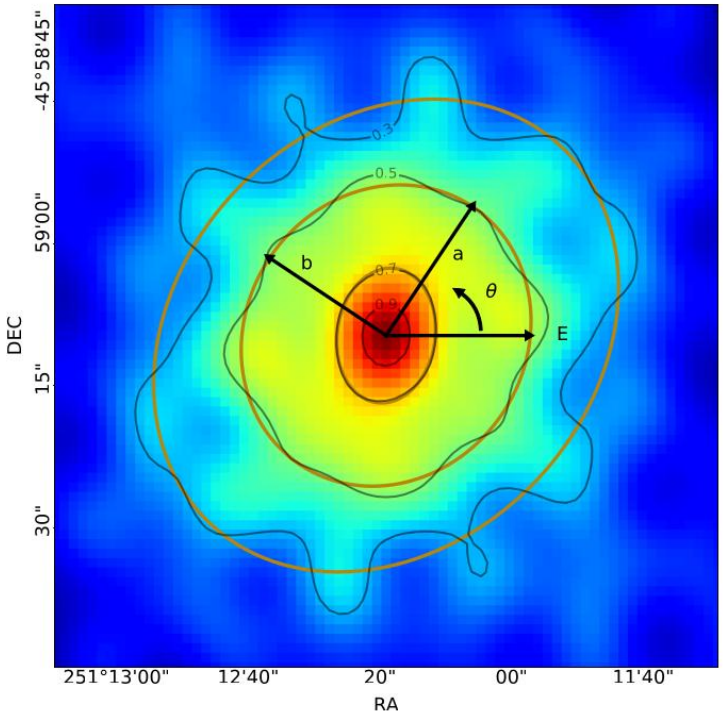
- **TRAPUM has led to the development of pulsar processing techniques applicable only to interferometric surveys.**

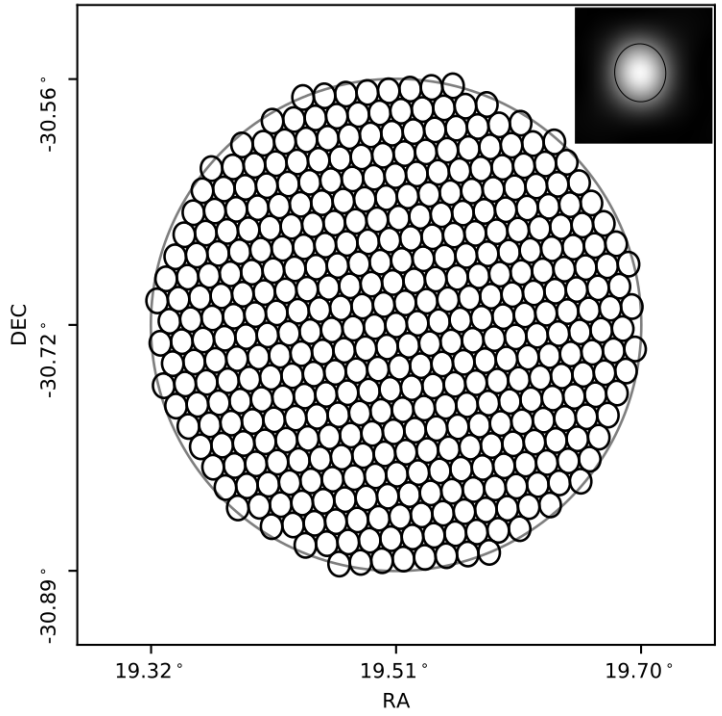
The MeerKAT pulsar processing equipments

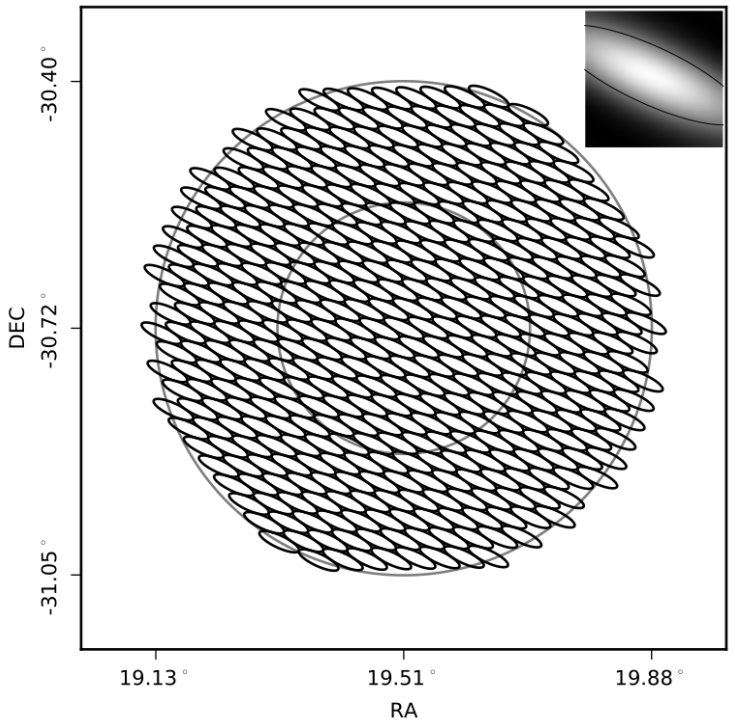
- **FBFUSE** and **APSUSE** are user-supplied, **GPU-based** processing clusters **at MeerKAT site**
- **FBFUSE:** beamforming
- **APSUSE:** storage and processing

Figure 3.2: A fish-eye view of the TRAPUM user supplied equipment (USE) at the KAPB. Top panel is the FBFUSE rack. Bottom panel shows APSUSE consisting of 7 racks from the left with the rest belonging to TUSE. (Credits: E. Barr)

Beamforming and tilings with FBFUSE and Mosaic







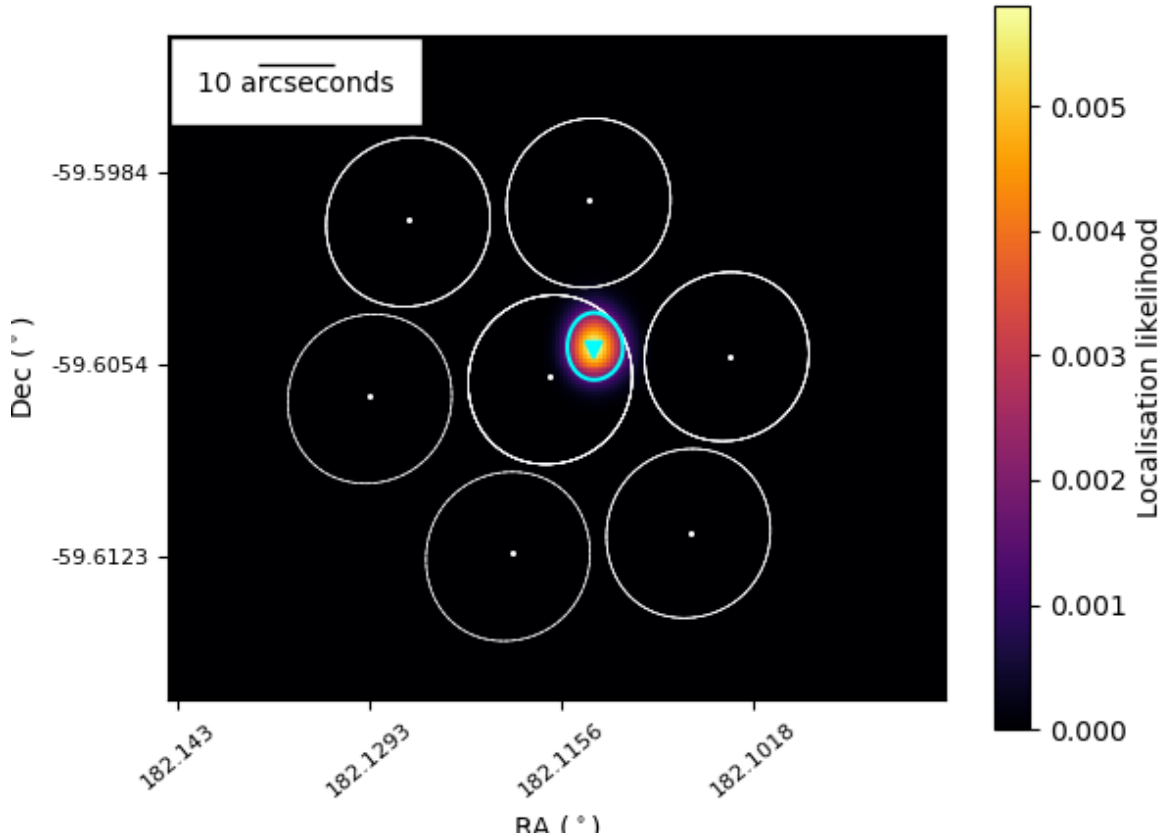
The *Mosaic* software simulates the beam shape from the instantaneous UV coverage, and spreads the coherent beams in a position tiling within the bore-sight with efficient coverage.

Chen et al., 2021

Interferometry after discovery

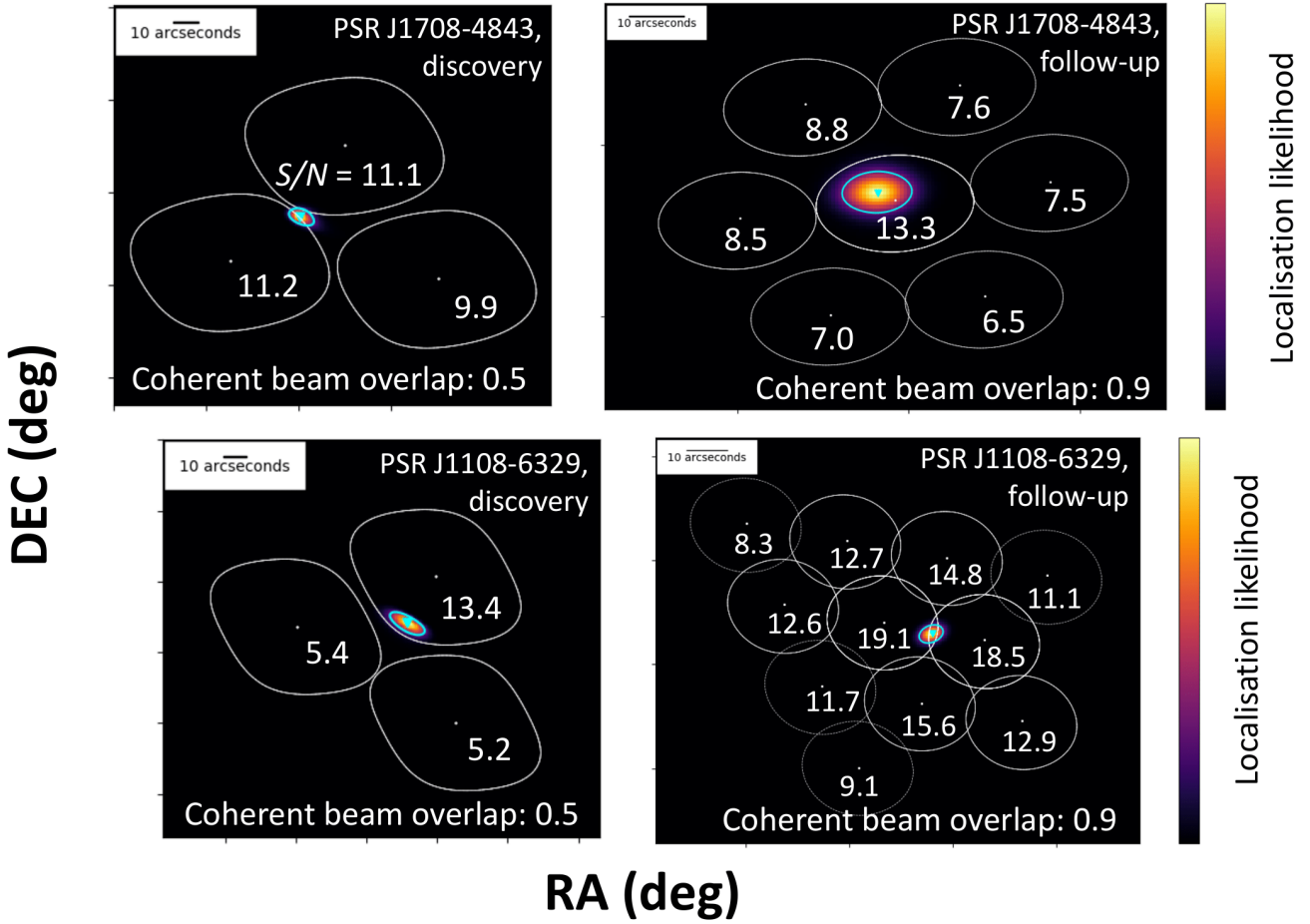
- The interferometric observations allow for **multibeam detections** of pulsars.
- The SeeKAT software triangulates the likely true source position from the S/N distribution.

Paper on SeeKAT: [Bezuidenhout et al., 2023]



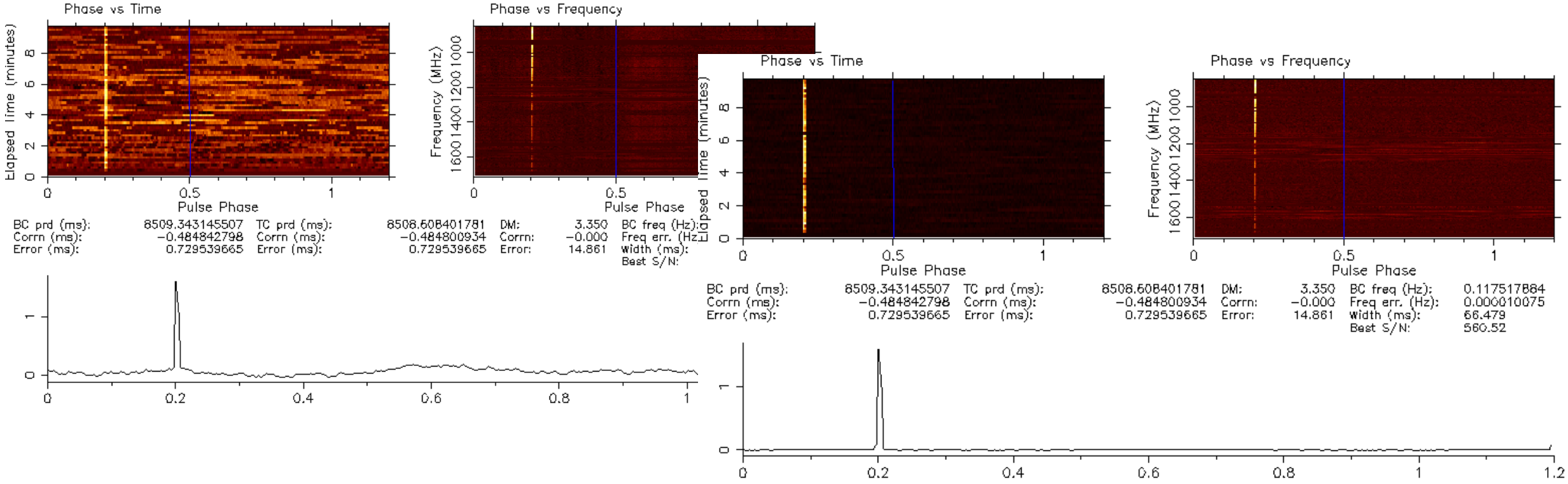
Interferometry after discovery

- Follow-up observations are perform after discovery for confirmation, at 90% coherent beam overlap.
- These reliable positions can then be used for accelerating the timing of pulsars.



New feature: incoherent beam subtraction

The incoherent beam is the “stupid” addition of all antenna powers. Subtracting incoherent beam power from the coherent beam power reduces RFI-induced noise significantly.



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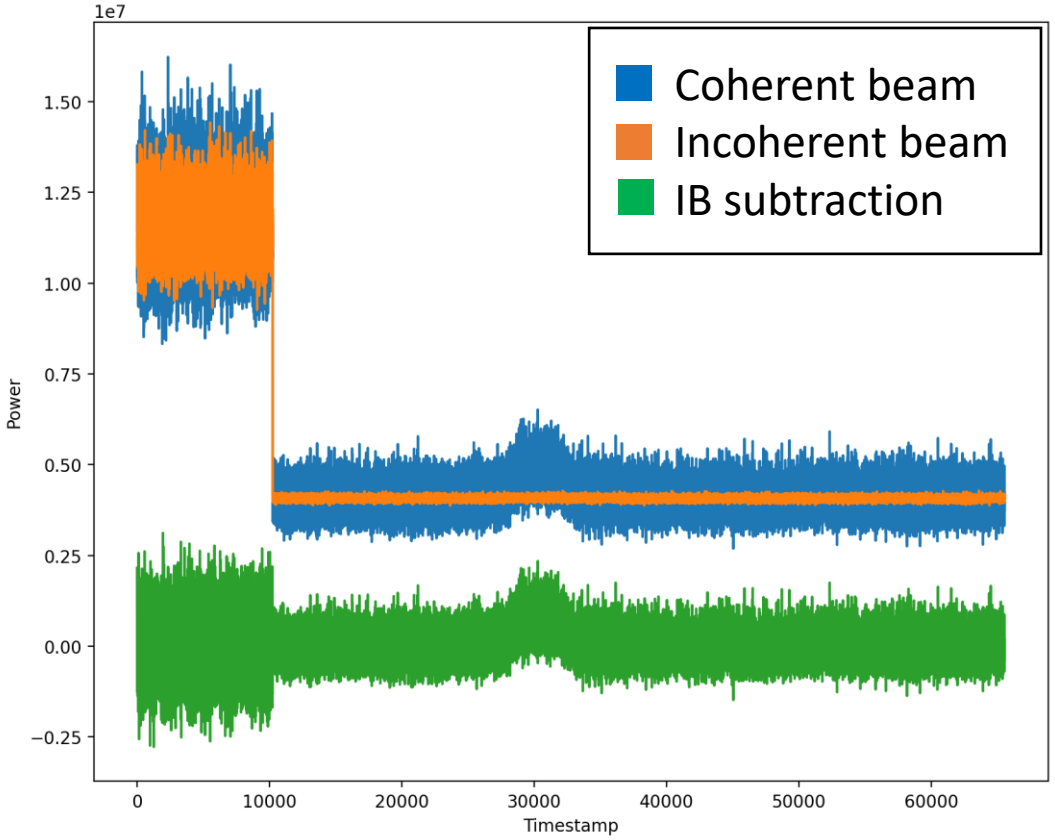
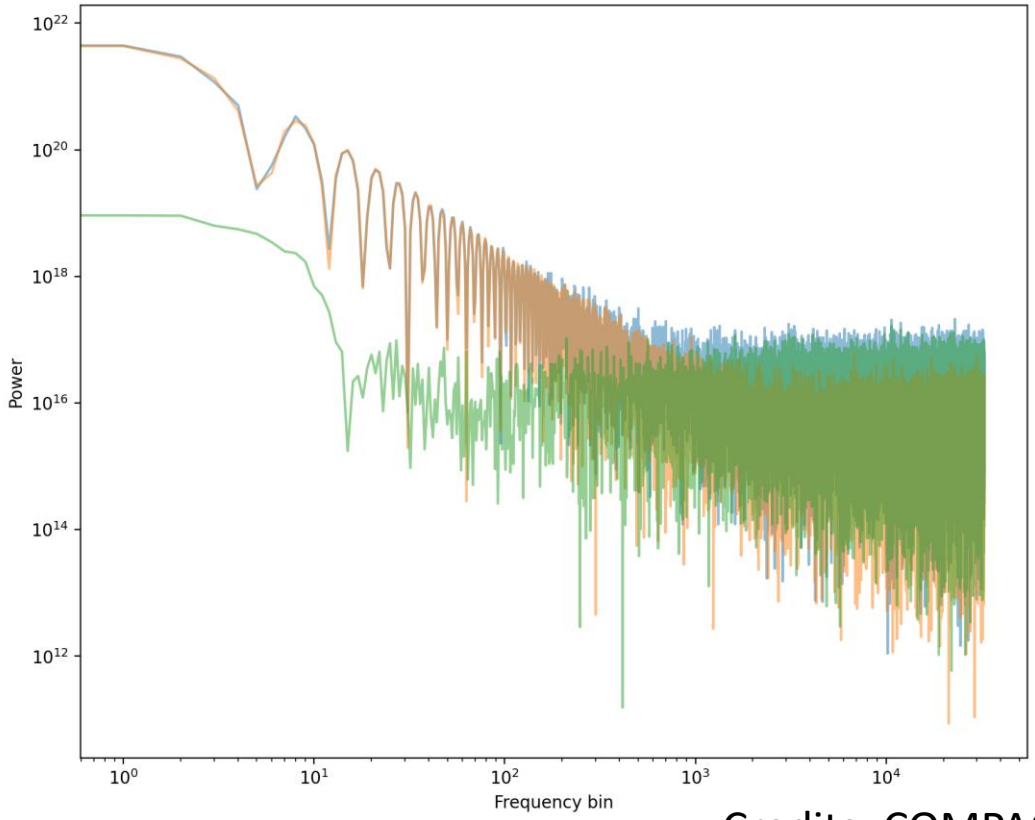
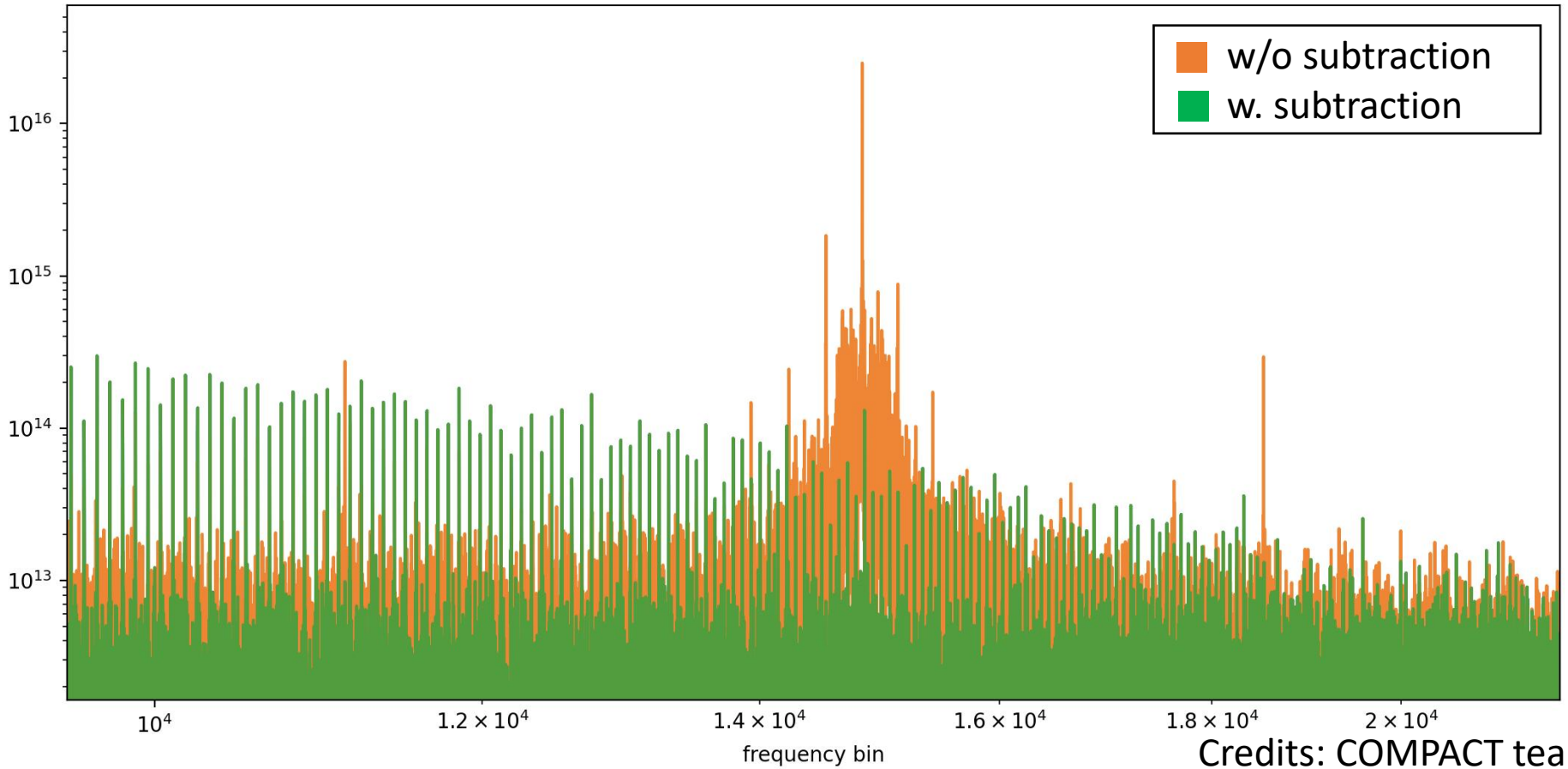




Credits: COMPACT team

New feature: incoherent beam subtraction

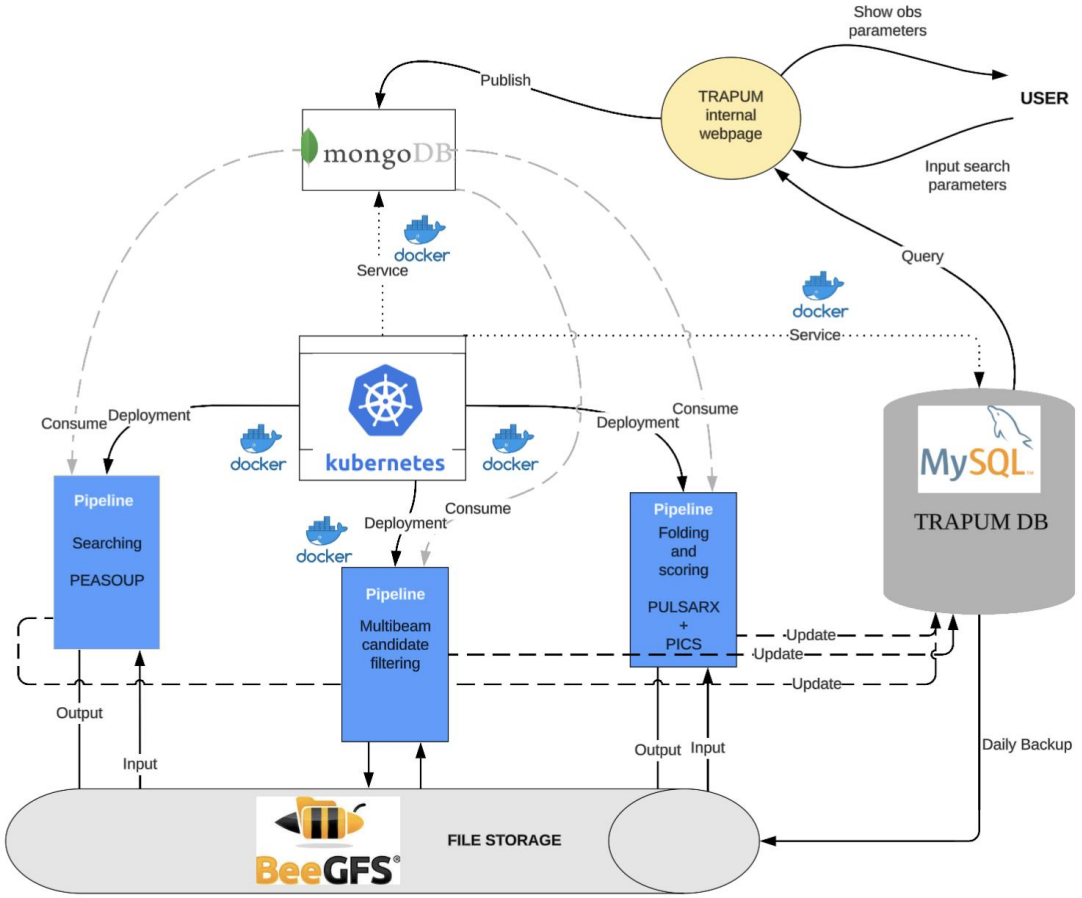
- This allows for a much improved detection of long-period pulsars
- Now implemented in TRAPUM



Credits: COMPACT team

The TRAPUM pipeline

- Clean the data from RFI.
- DM loop
  - De-disperse at DM
  - Acceleration loop
    - Resample at the assumed a
    - Search for candidates (FFT)
    - Rinse and repeat
  - Rinse and repeat
- Filter candidates
- Fold and optimize
- Classify with ML
- Inspect the candidates!



Padamanabh et al., 2023

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PEASOUP

100s of beams per observation → ***thousands of candidates to inspect*!**

Padamanabh et al., 2023

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PEASOUP

100s of beams per observation → ***thousands of candidates to inspect***!

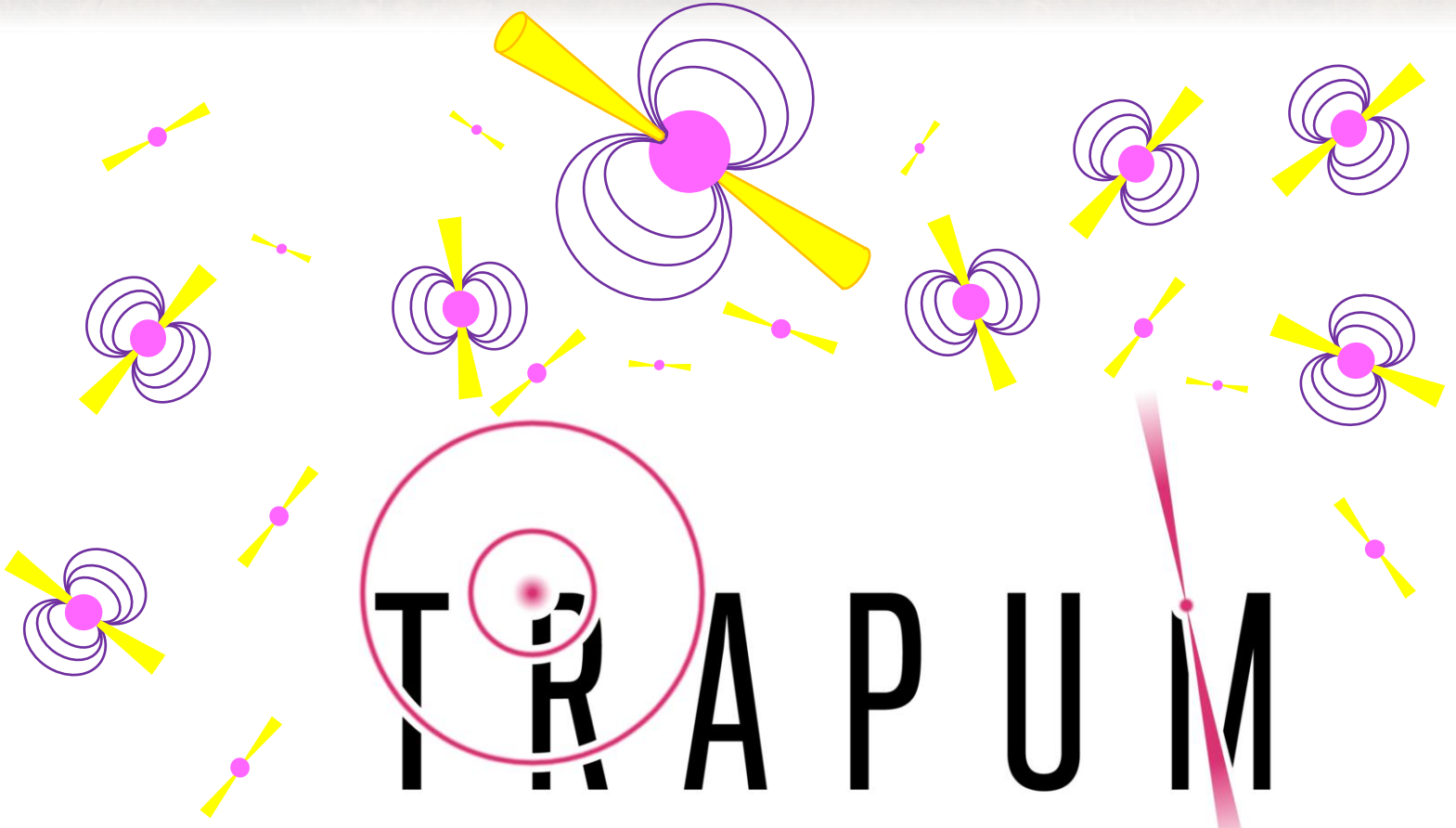
Multibeam coincidenting and **machine-learning classifications** reduce the amount of candidates to a few tenths/hundreds.

Padamanabh et al., 2023

TRAPUM SURVEYS AND SCIENTIFIC HIGLIGHTS

The TRAPUM surveys

- New pulsar discoveries: **283**
  - In Globular Clusters: **109**
  - In Galactic plane: **96**
  - In Fermi γ-ray sources: **47**
  - In Nearby Galaxies: **27**
  - In Supernova Remnants: **2**



t al., 2023

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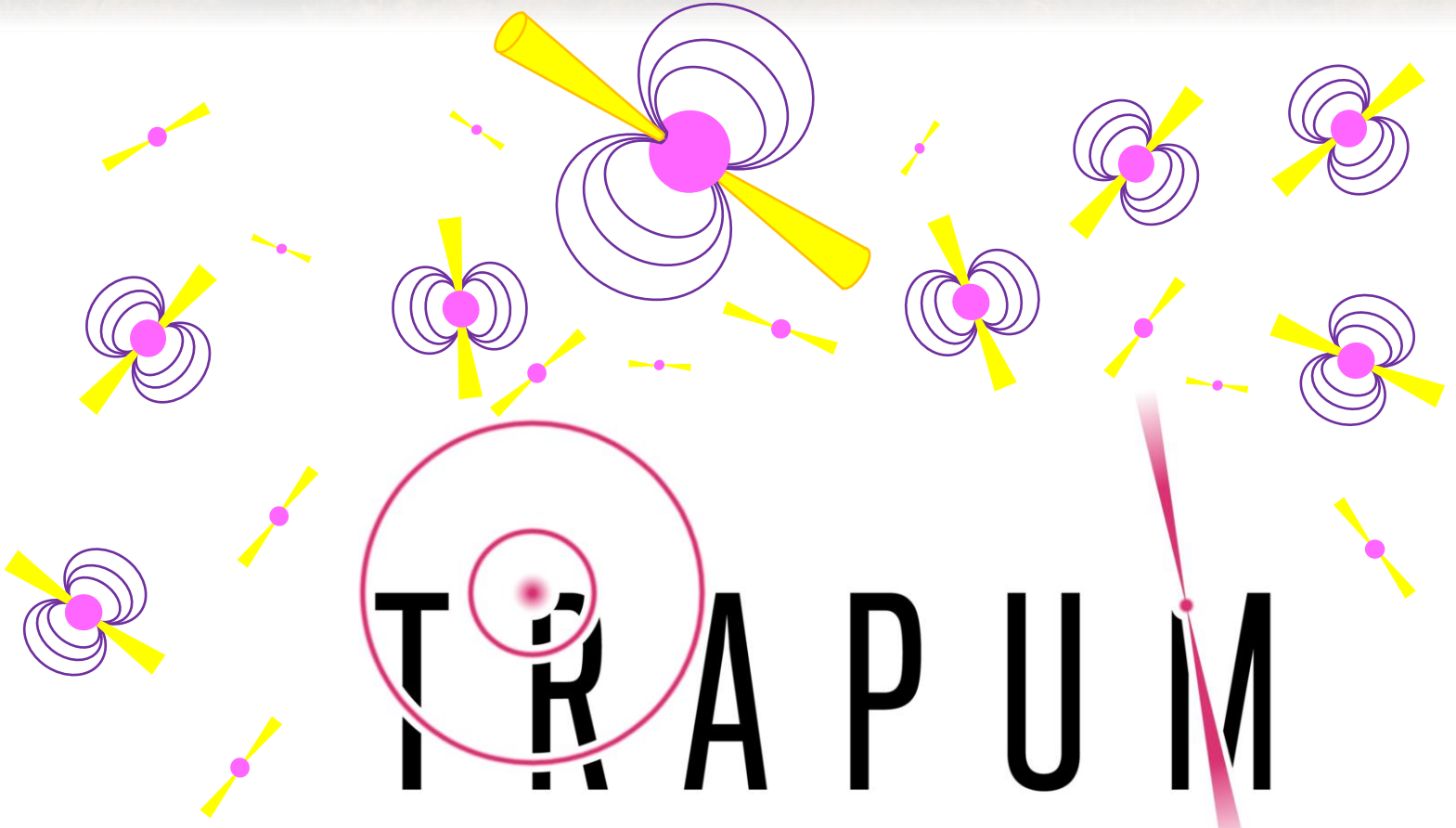
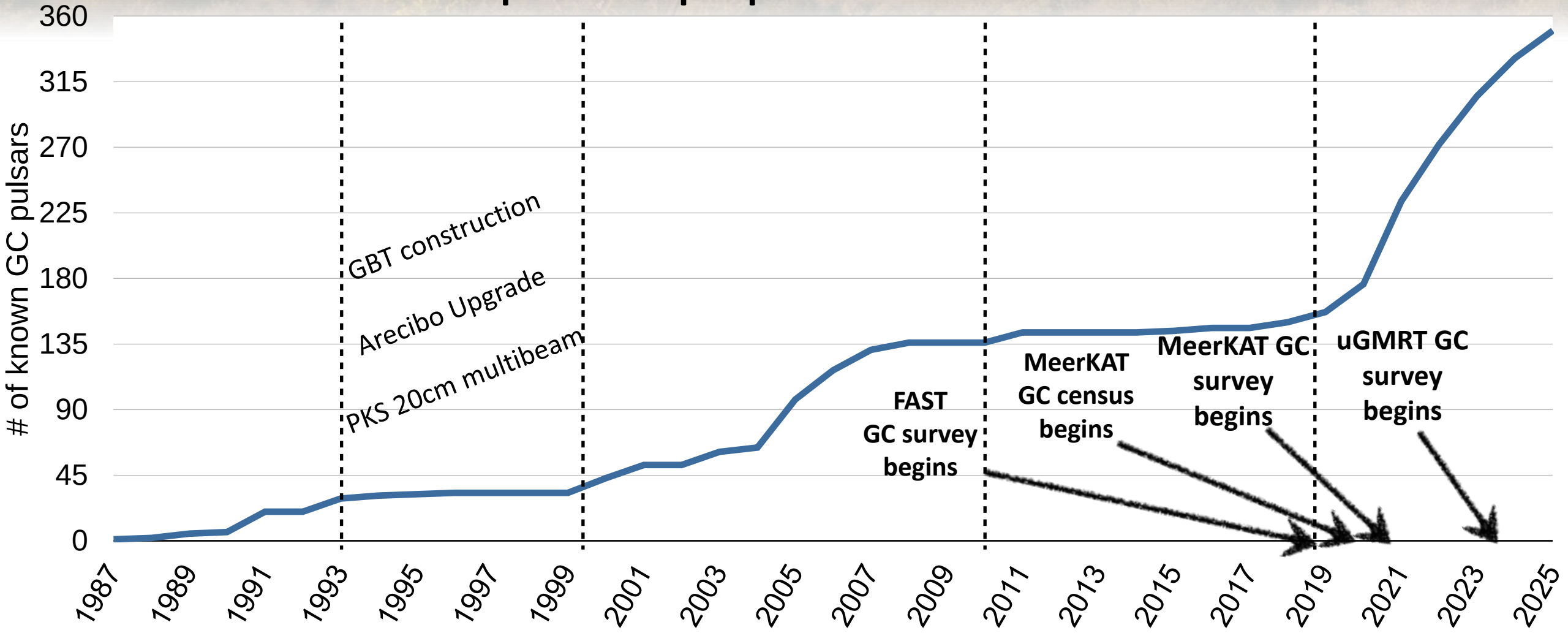


t al., 2023

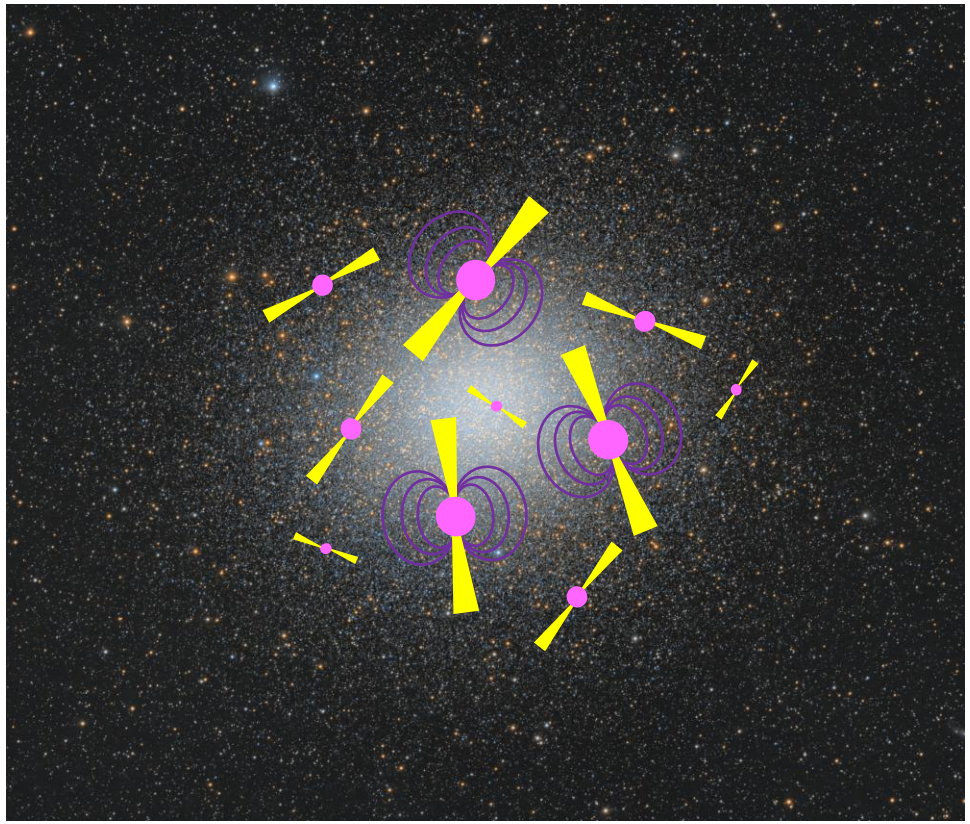
TRAPUM SURVEYS IN GLOBULAR CLUSTERS

GC pulsar population over time



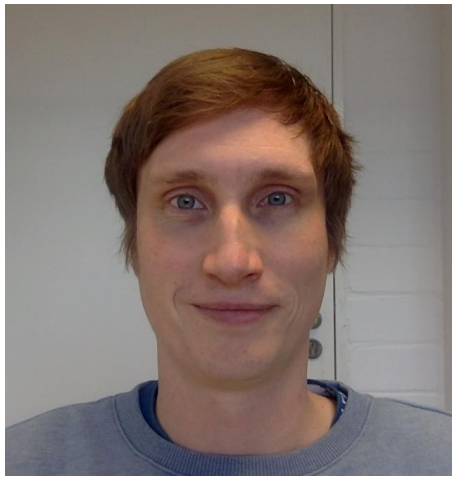
TRAPUM SURVEYS IN GLOBULAR CLUSTERS

- **Ridolfi et al. 2021:** 8 discoveries in 6 globular clusters
- **Douglas et al. 2022:** 2 in M28
- **Ridolfi et al. 2022:** 13 in NGC 1851
- **Vleeschower et al. 2022:** 2 in NGC 6440
- **Abbate et al. 2022:** 4 in NGC 6624
- **Chen et al. 2023:** 13 in ω Centauri
- **Abbate et al. 2023:** 2 in NGC 6522
- **Vleeschower et al. 2024:** 3 in M62
- **Padmanabh et al. 2024:** 10 in Terzan5



TRAPUM SURVEYS IN GLOBULAR CLUSTERS

- **Science highlight: a possible pulsar-black hole binary in NGC 1851 (Barr & Dutta et al., 2024)**



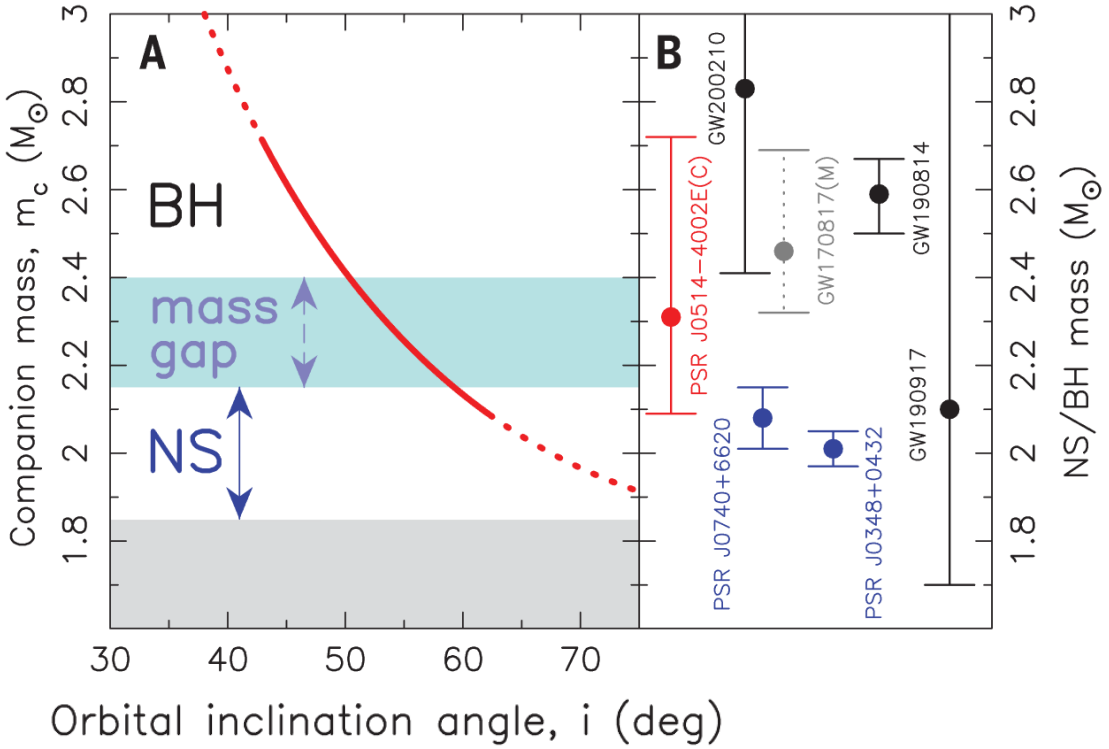
Ewan Barr

Arunima Dutta

TRAPUM SURVEYS IN GLOBULAR CLUSTERS

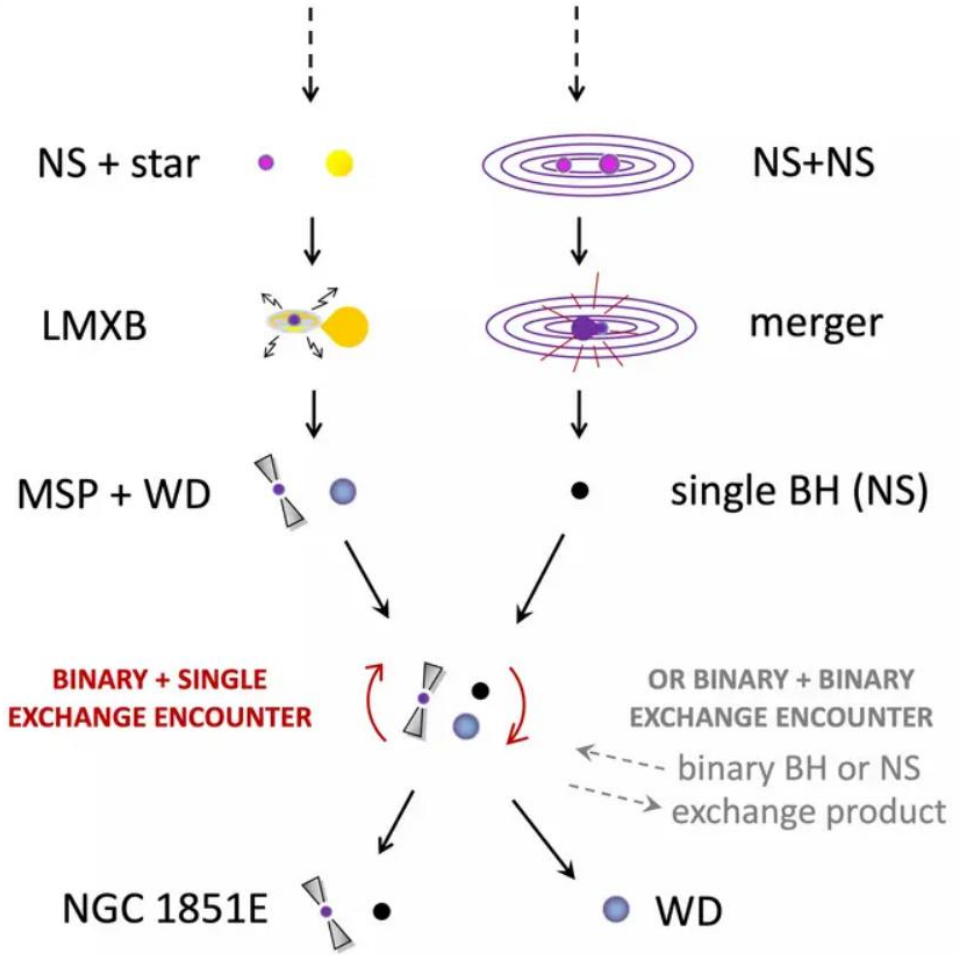
- **Science highlight: a possible pulsar-black hole binary in NGC 1851 (Barr & Dutta et al., 2024)**

- Timing measurements place the companion mass across the mass gab.



TRAPUM SURVEYS IN GLOBULAR CLUSTERS

- **Science highlight: a possible pulsar-black hole binary in NGC 1851 (Barr & Dutta et al., 2024)**
- Timing measurements place the companion mass across the mass gab.
- Likely formed via encounters in the dense environment of globular clusters.



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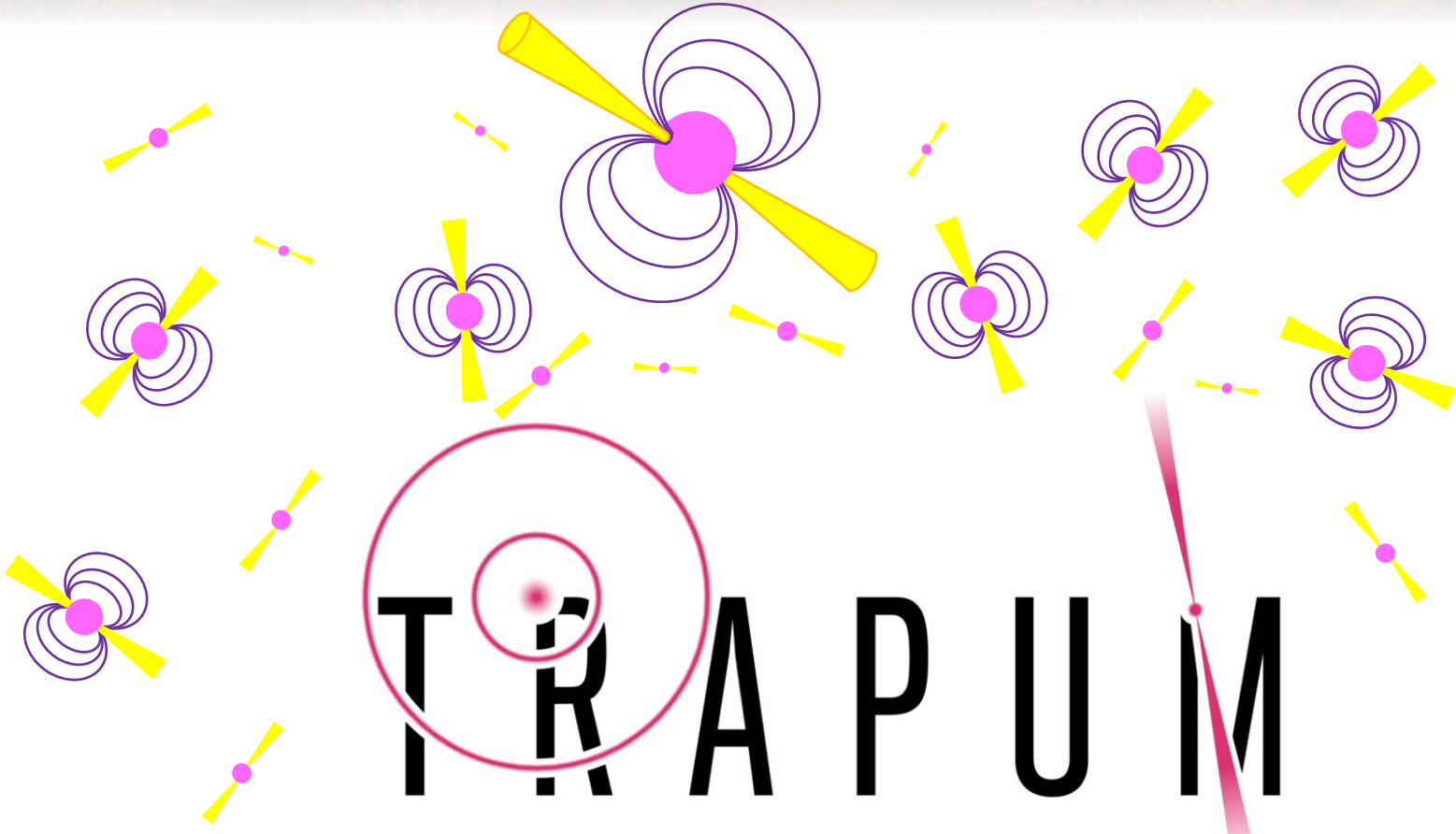

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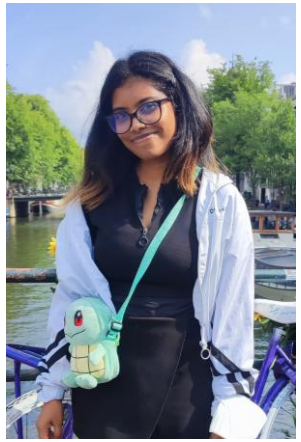
(Postdoc)

Miquel Colom i Bernadich
(PhD student)

Prajwal V. Padmanabh
(Postdoc)

Shalini Sengupta
(PhD student)



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(PhD student)

Robert Senzel
(PhD student)

Vishnu Balakrishnan
(Postdoc)

Vivek V. Krishnan
(Member)

Yunpeng Men
(Postdoc)

Ewan Barr
(Project chair)

Jędrzej Jawor
(PhD student)

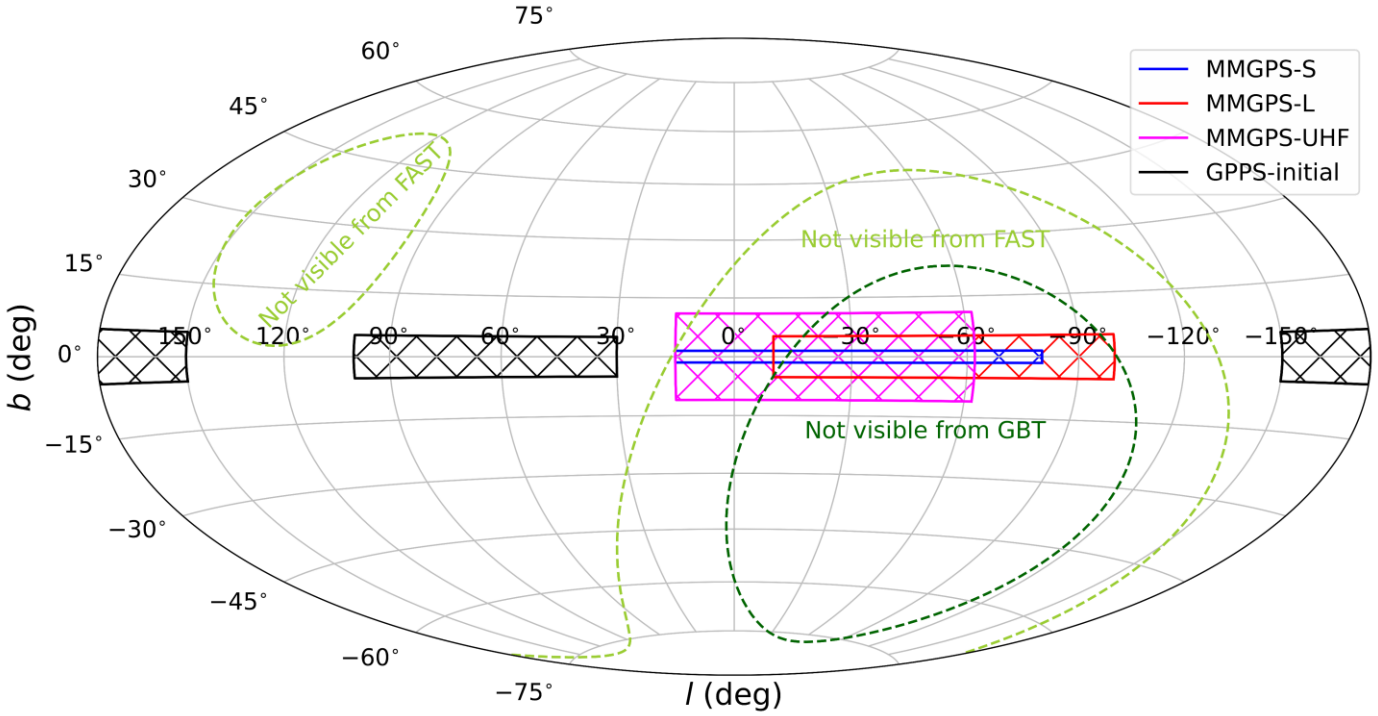
Isabella Rammala
(Postdoc)

Fazal Kareem
(PhD student)

Robert Warton
(PhD student)

The MPIfR-Max Plank Galactic Plane Survey

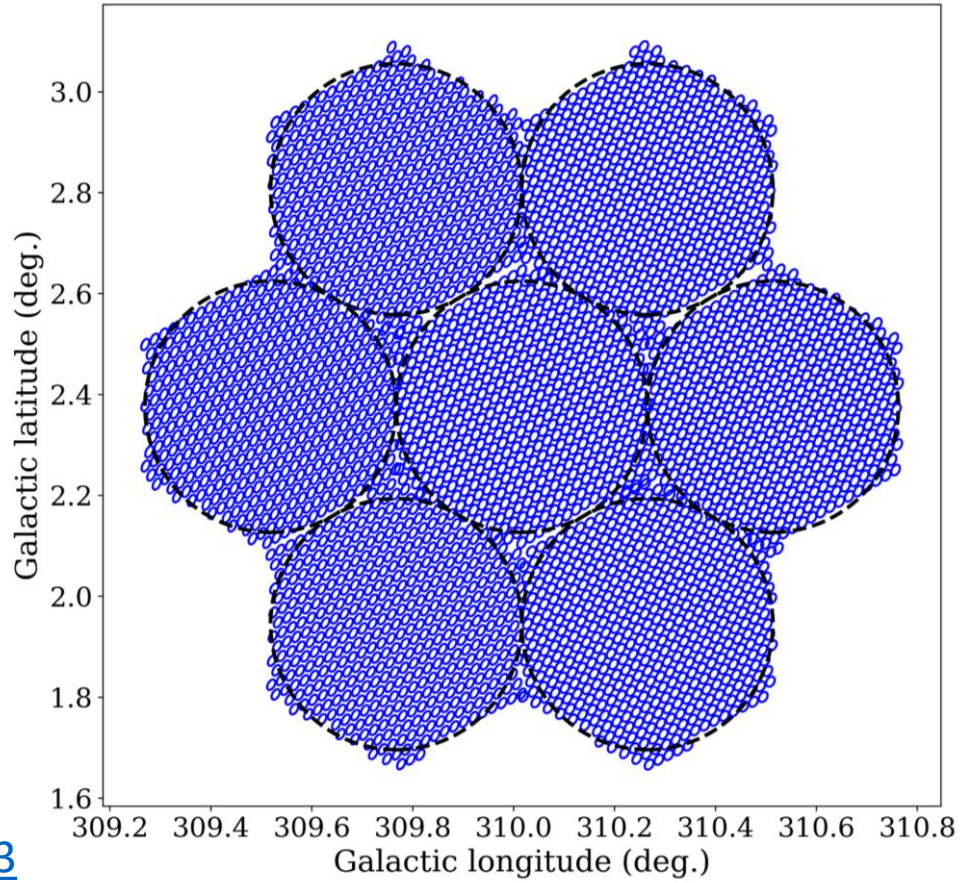
- The MMGPS contains three wide-field surveys:
  - L-band: 1.3 GHz, |b|< 5.2
    Target: faint pulsars missed by Parkes
  - S-band: 2.4 GHz, |b|< 1.5
    Target: pulsars with high DM/scattering
  - UHF: 0.8 GHz, |b|< 11
    Target: pulsars with steep spectrum
- In addition:
  - Sgr A*: 2.0-3.5 GHz, Galactic center
- The MMGPS is a commensal survey pulsars, imaging, and continuum.



Padamanabh et al., 2023

The MMGPS observing strategy

- The MMGPS uses *Mosaic* to efficiently fill the pointings with 480 beams in an hexagonal tiling:
  - L-band: 4,500 pointings of 10 minutes
  - S-band: 3,905 pointings of 20 minutes
  - UHF: 2,800 poitings of 8 minutes



Padamanabh et al., 2023

The MMGPS data rate

- 480 beams per pointing
- 20 pointings per observing session
- 2 sessions per week

Padamanabh et al., 2023

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350 TB/week !

Padamanabh et al., 2023

The MMGPS data rate

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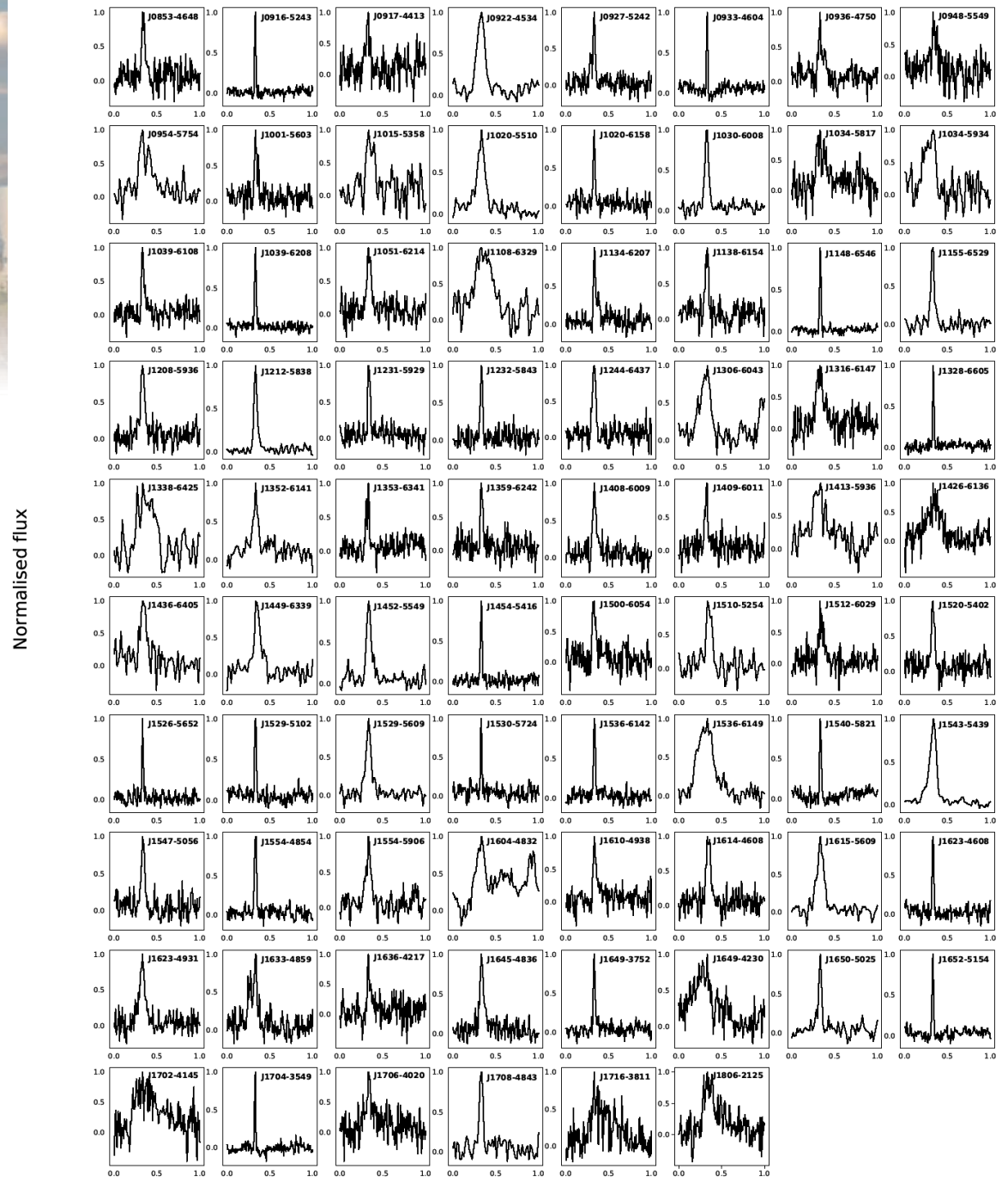
- Processed at the APSUSE cluster in quasi-real time
- The coherent beams are deleted after candidate inspection
- Only beams with discoveries are stored long-term

Padamanabh et al., 2023

MMGPS discovery summary

- MMGPS-L (complete): 78 discoveries
  17 binaries, 2 publications, more planned
- MMGPS-S (ongoing): 10 discoveries
  High-DM discoveries
- MMGPS-U (ongoing): 8 discoveries
  Discovery rate of 1 PSR every 7 pointings



Padamanabh et al., 2023

MMGPS discovery summary

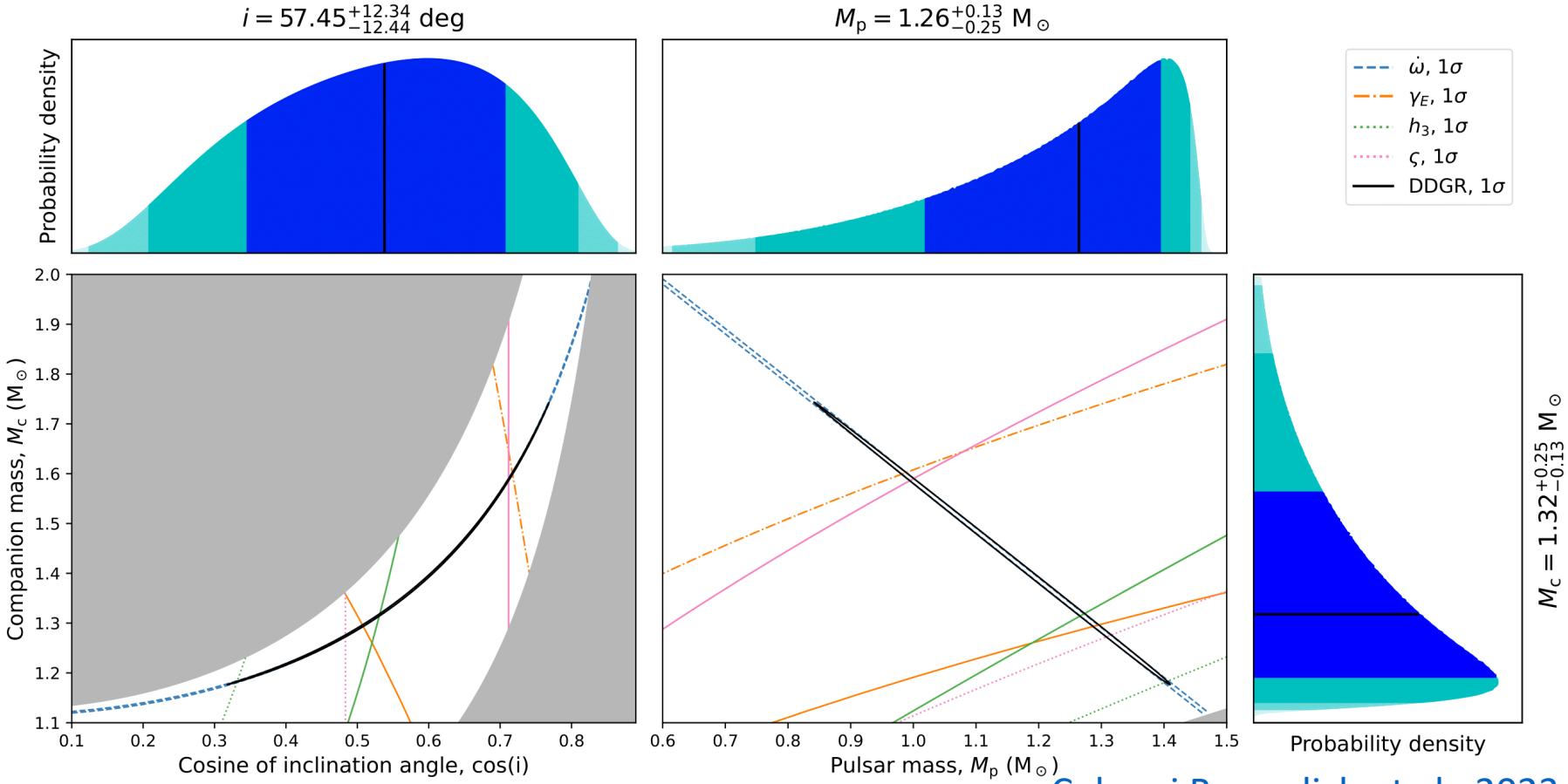
Mass measurements for two of the double neutron star discoveries:

- PSR J1208-5936:

  Mtot= 2.586(5) $M_\odot$

- PSR 1155-6529:

  Mtot= 2.61 ± 0.02 $M_\odot$



Colom i Bernadich et al., 2023

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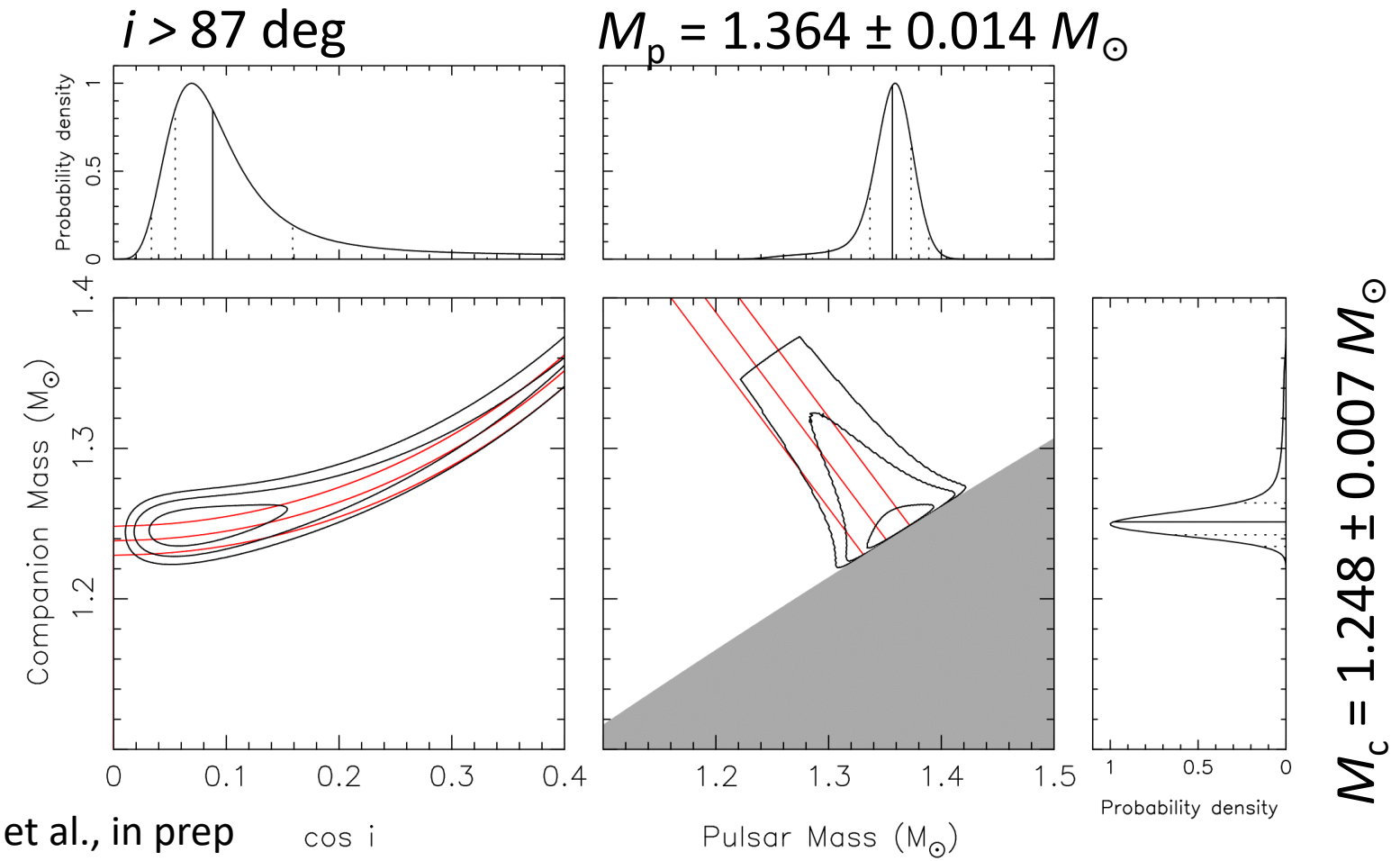
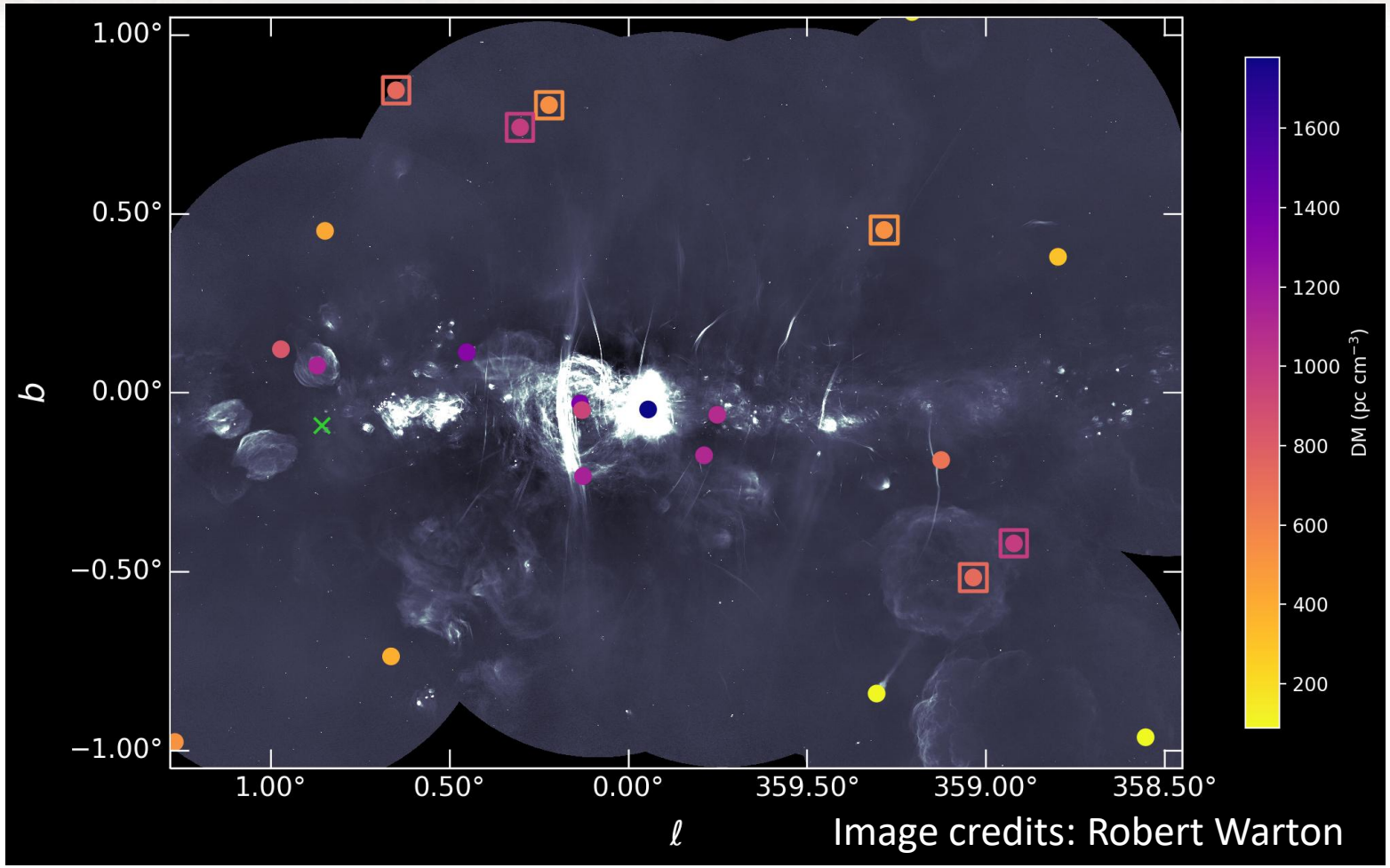


Berezina et al., in prep

MMGPS discovery summary

S-band discoveries close to the Galactic center!

MMGPS-S discoveries (squares) vs. known pulsars (circles)



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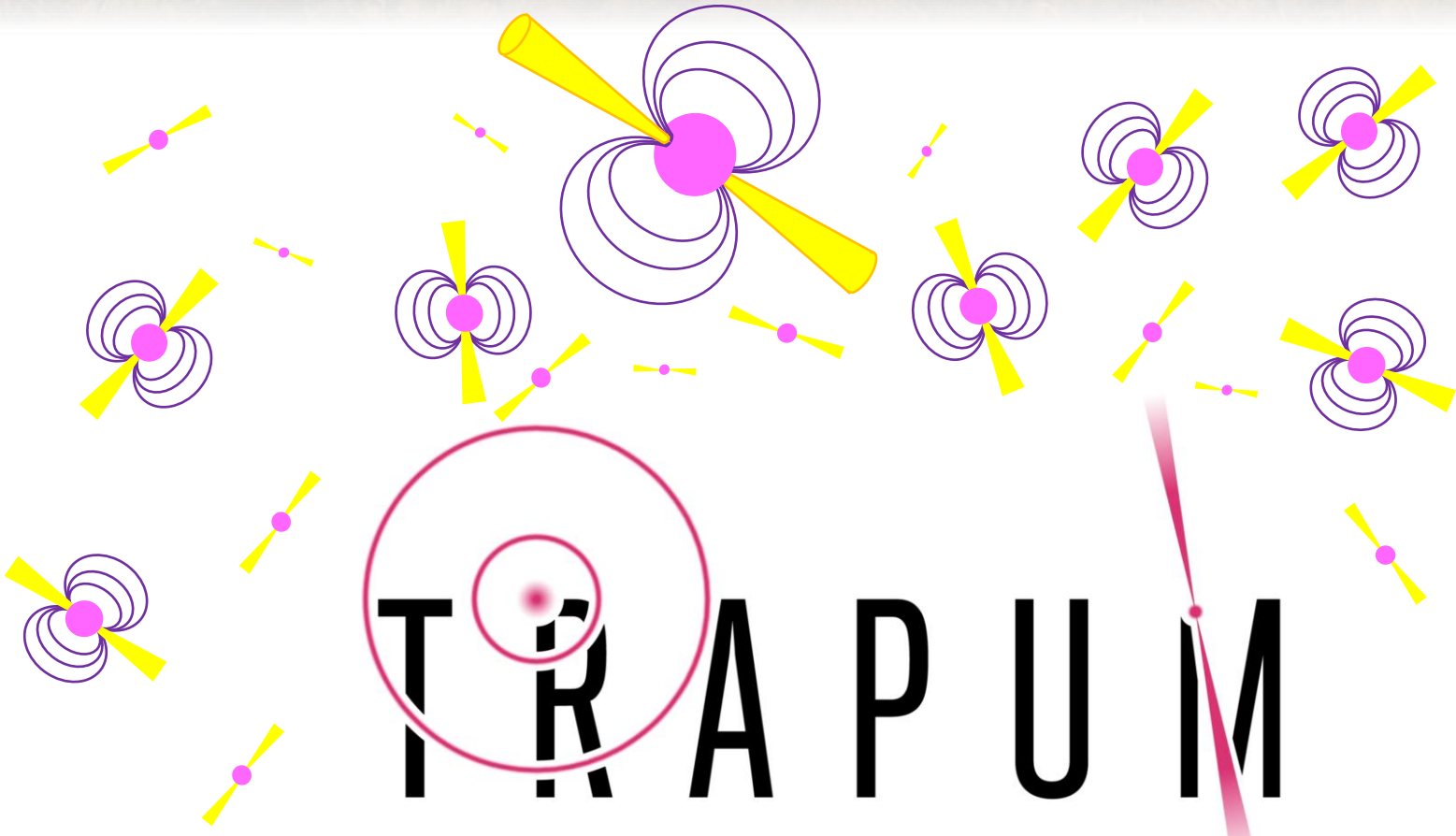
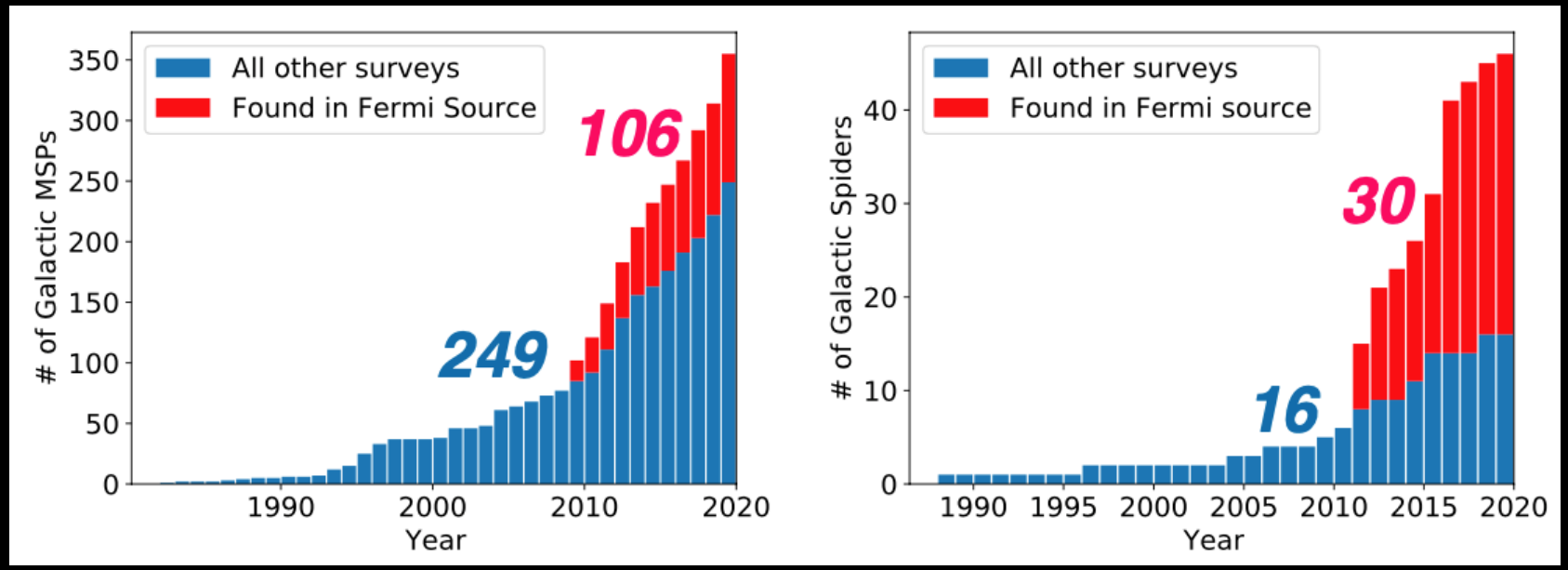


ECLIPSING ‘SPIDER’ PULSARS

- Accretion physics
- Plasma physics
- Binary evolution
- NS masses and EoS

WHY FERMI?

http://astro.phys.wvu.edu/GalacticMSPs/GalacticMSPs.txt



- >1/4 MSPs have been found in Fermi sources
- 2/3 of 'spiders' have been found in Fermi sources

TRAPUM FERMI SEARCHES

Marta Burgay

Colin Clark

Lars Nieder

Tinn Thongmeearkom

SHALLOW SURVEYS:

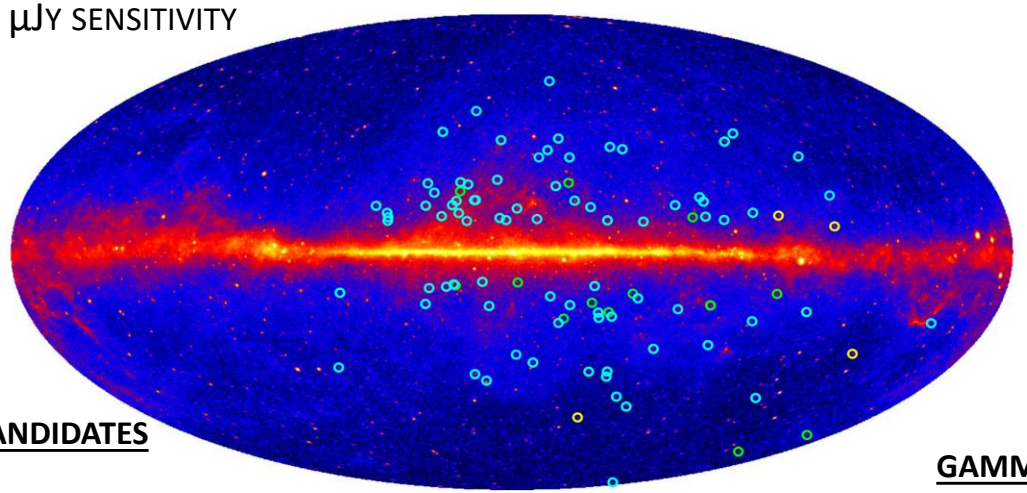
79 SOURCES AT L-BAND

102 SOURCES AT UHFX10-MIN POINTINGS AT 100 μJY SENSITIVITY

TARGETED REDBACK SURVEY:

13 PERIODIC OPTICAL CANDIDATES

4X1HR OBSERVATIONS



BULGE X-RAY MSP CANDIDATES

3 SOURCES AT S-BAND

90 MIN OBSERVATIONS

10 μJY SENSITIVITY

AMXP SAX J1808.4-3658

RADIO+OPTICAL

6X1 HR OBSERVATIONS AT L-BAND

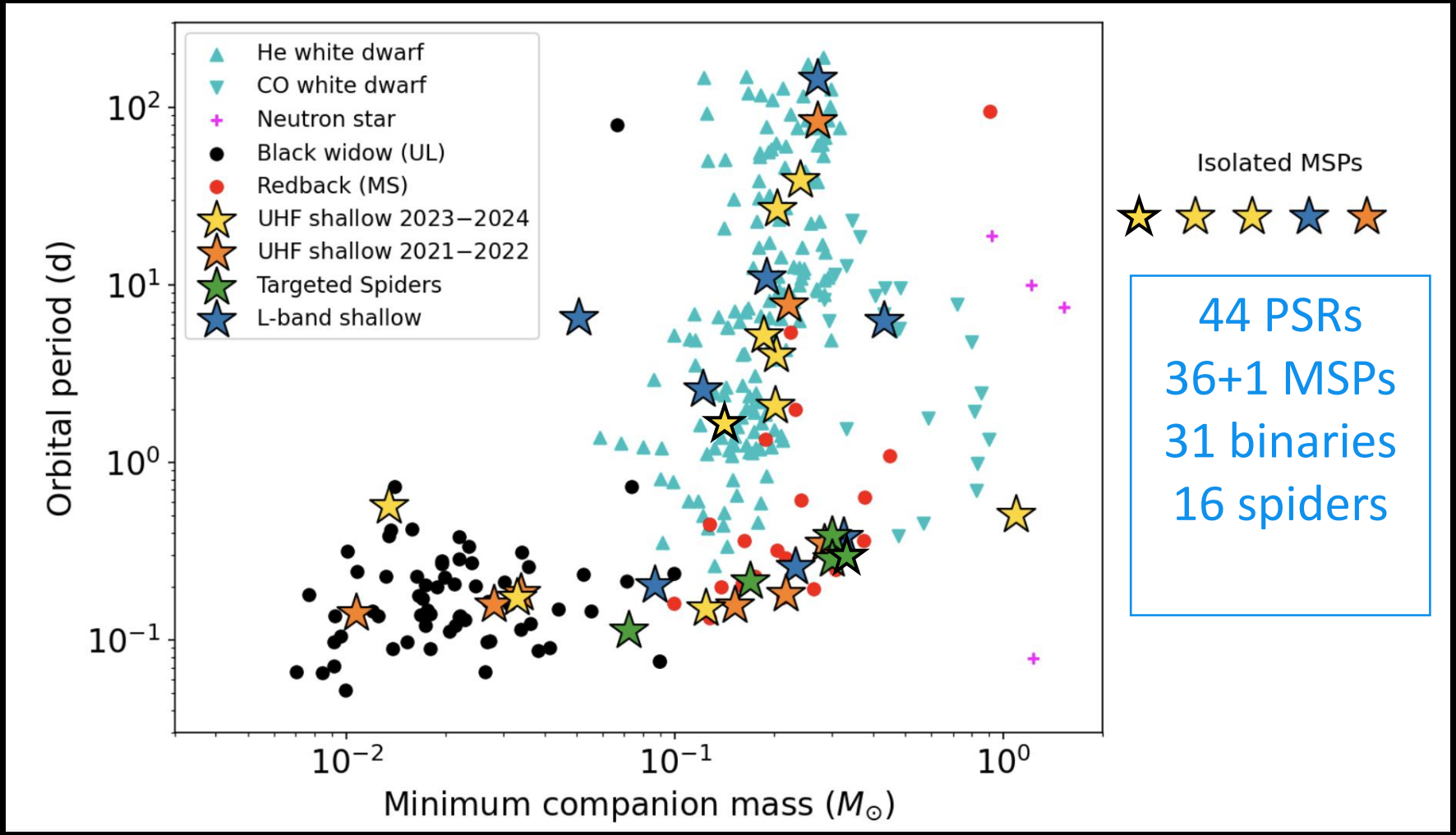
GAMMA-RAY BINARIES

5 SOURCES AT S-BAND(SIMILAR TO LS I +61◦ 303)

120 MIN OBSERVATIONS

Credit: C. Clark (MPIGF)

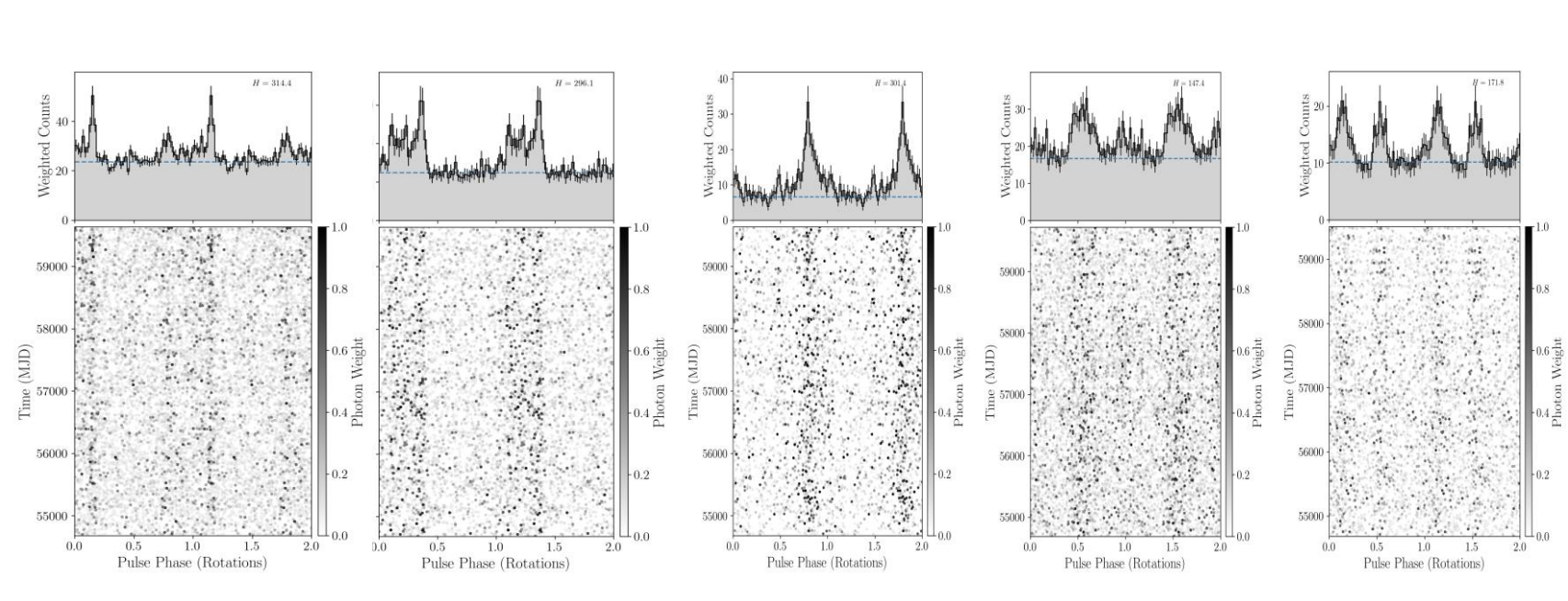
RESULTS


He white dwarf
CO white dwarf
Neutron star
Black widow (UL)
Redback (MS)
UHF shallow 2023−2024
UHF shallow 2021−2022
Targeted Spiders
L-band shallow
Orbital period (d)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-1}
10^0
Minimum companion mass ($M_\odot$)
Isolated MSPs
44 PSRs
36+1 MSPs
31 binaries
16 spiders

TIMING AND Γ-RAY FOLLOW-UP

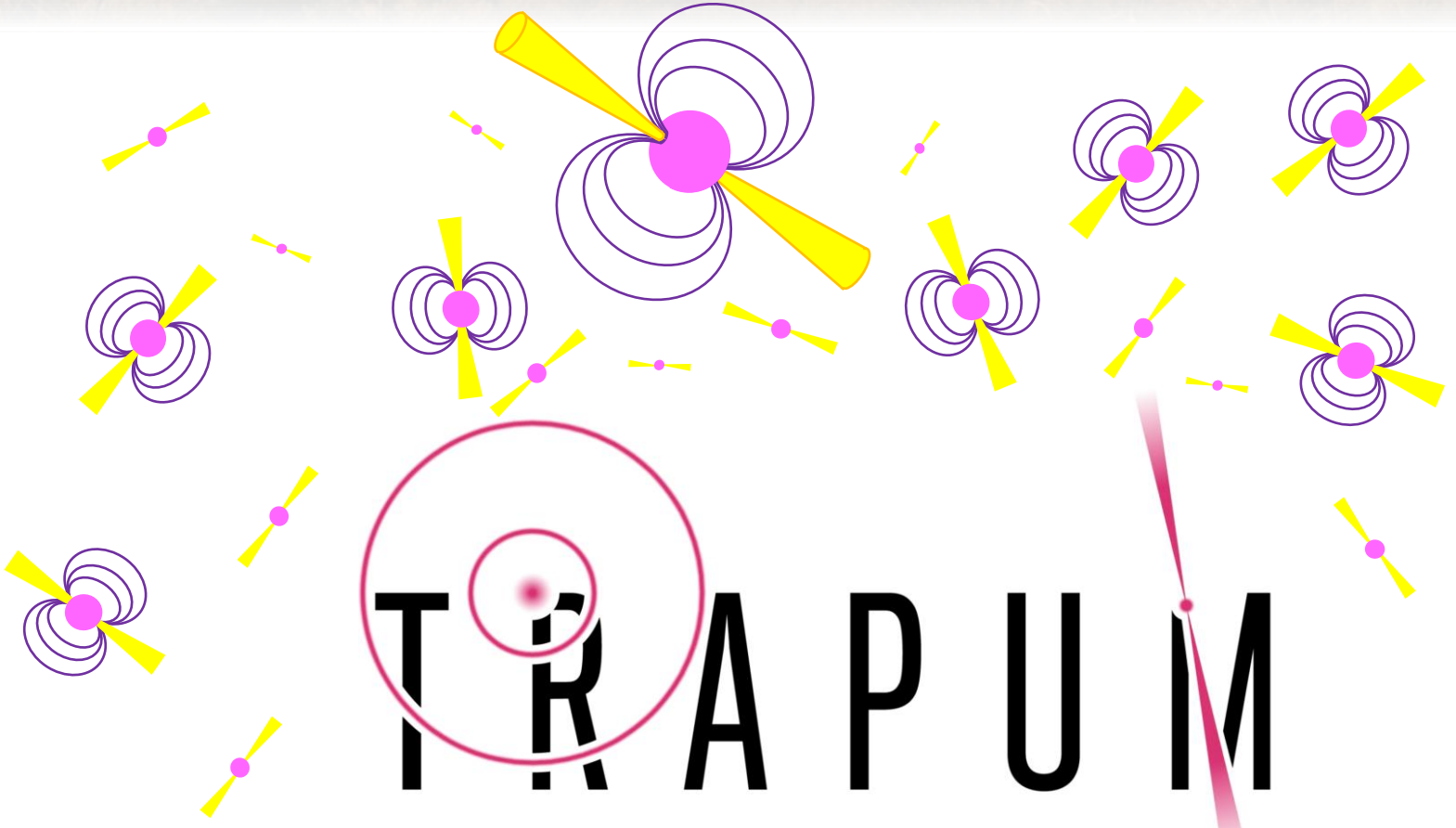
- TIMING ONGOING AT MEERKAT + PARKES, NANÇAY, EFFELSBERG + FERMI
- FROM 36 +1 NEW MSPS:
  - 32 +1 HAVE COHERENT TIMING SOLUTION
  - 21 HAVE FERMI PULSATIONS OVER 15 YEARS

J1259-8148 J1623-6939 J1757-6032 J1858-5422 J2029-4239



The TRAPUM surveys

- New pulsar discoveries: **283**
  - In Globular Clusters: **109**
  - In Galactic plane: **96**
  - In Fermi γ-ray sources: **47**
  - **In Nearby Galaxies: 27**
  - In Supernova Remnants: **2**

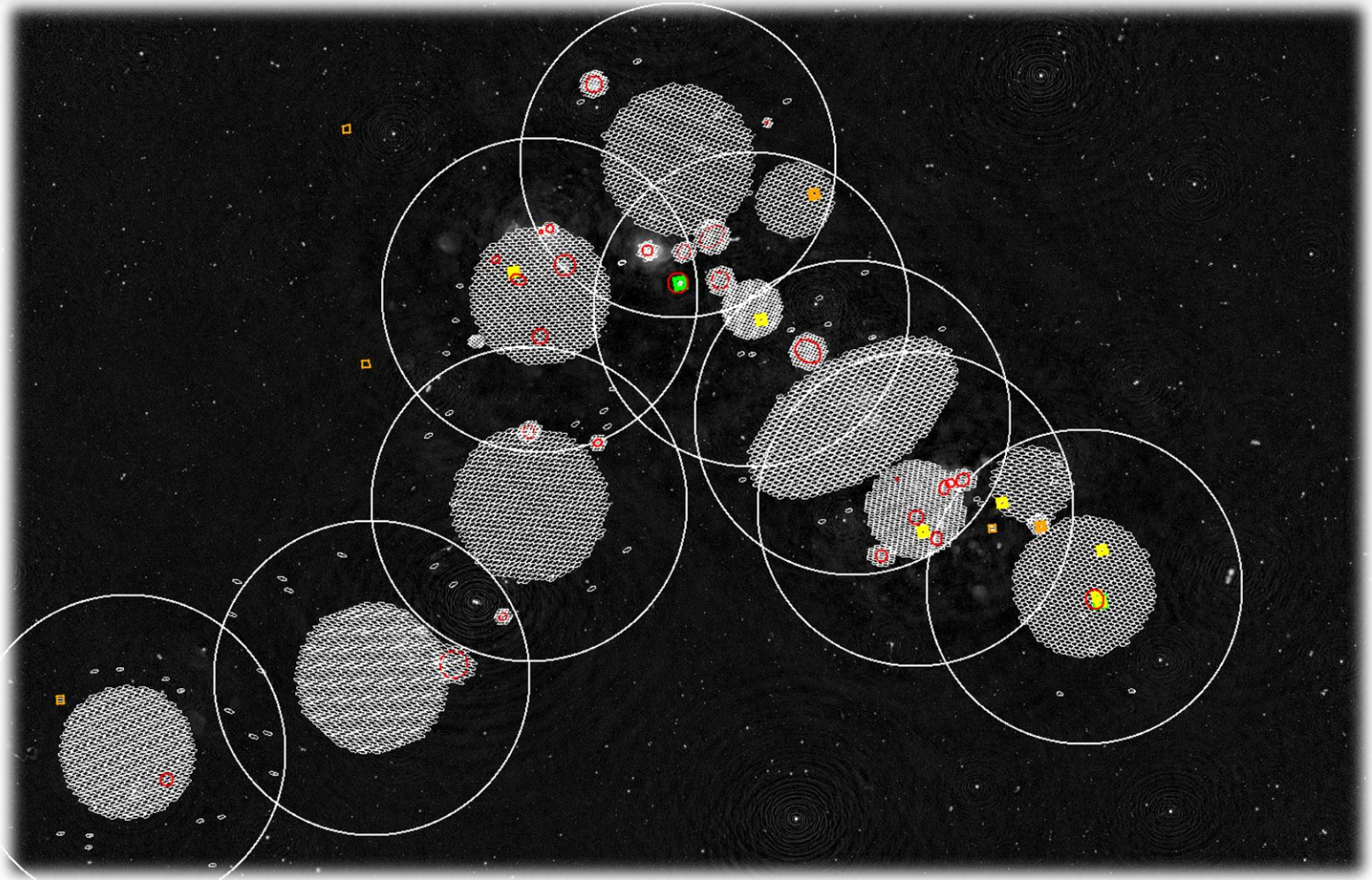


[et al., 2023]

Nearby Galaxies Surveys: Small Magellanic Cloud

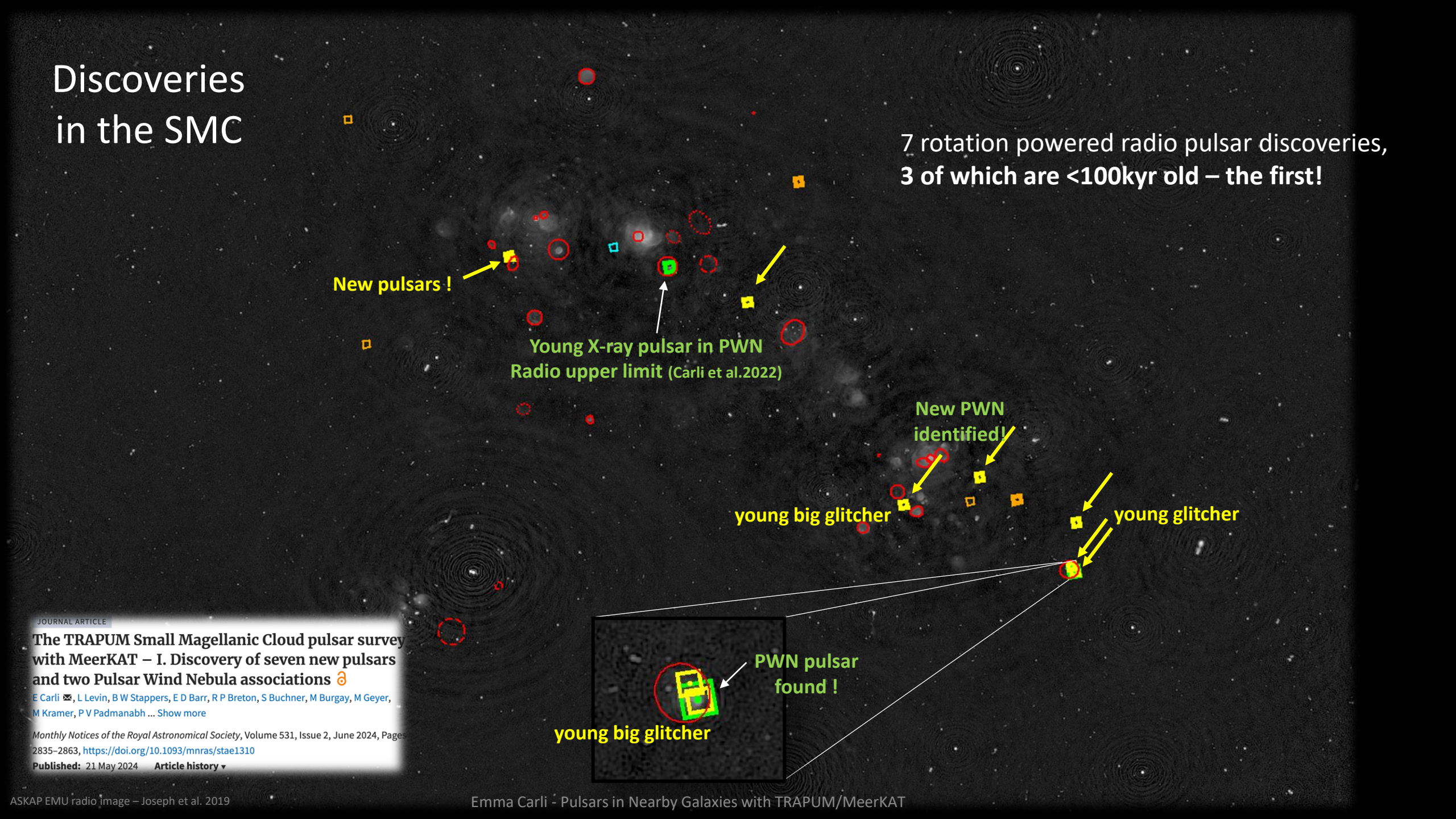
- Known pulsars before survey: 7
- Number of pointings:
  8 fields of 2x2 hours
- New discoveries: 7

Led by Emma Carli



Discoveries in the SMC

7 rotation powered radio pulsar discoveries,
3 of which are <100kyr old – the first!



JOURNAL ARTICLE

The TRAPUM Small Magellanic Cloud pulsar survey with MeerKAT – I. Discovery of seven new pulsars and two Pulsar Wind Nebula associations

E Carli ✉, L Levin, B W Stappers, E D Barr, R P Breton, S Buchner, M Burgay, M Geyer, M Kramer, P V Padmanabh ... Show more

Monthly Notices of the Royal Astronomical Society, Volume 531, Issue 2, June 2024, Pages 2835–2863, https://doi.org/10.1093/mnras/stae1310

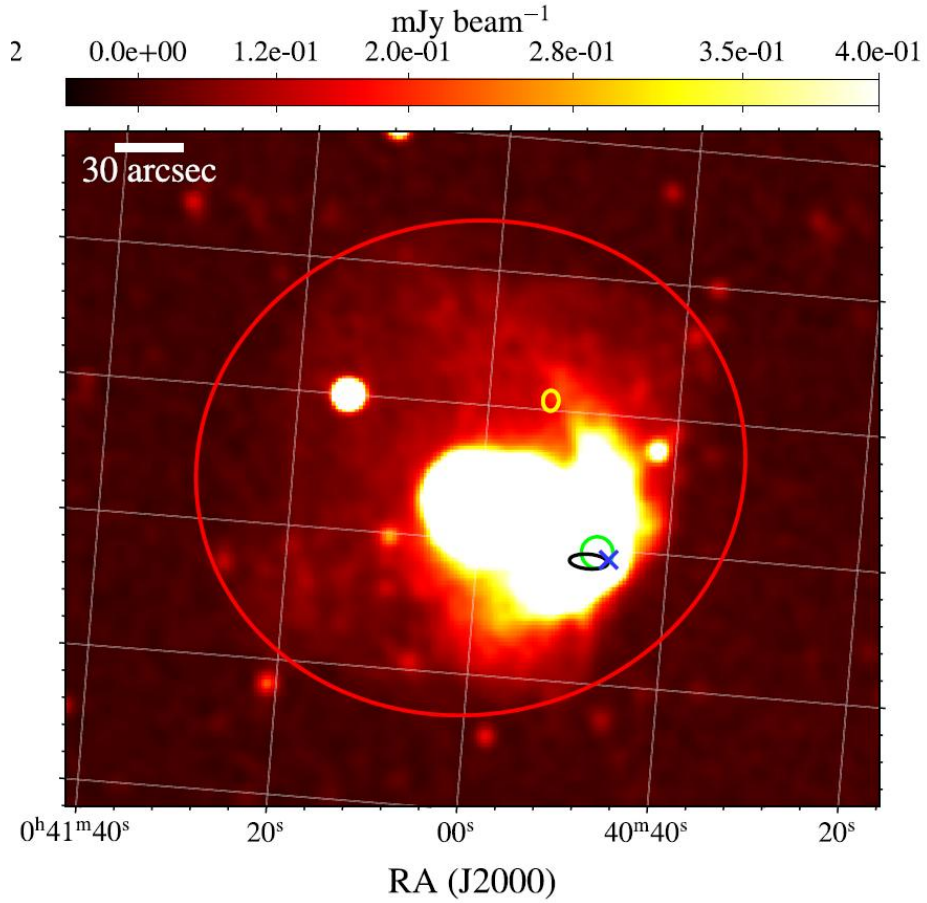
Published: 21 May 2024 **Article history**

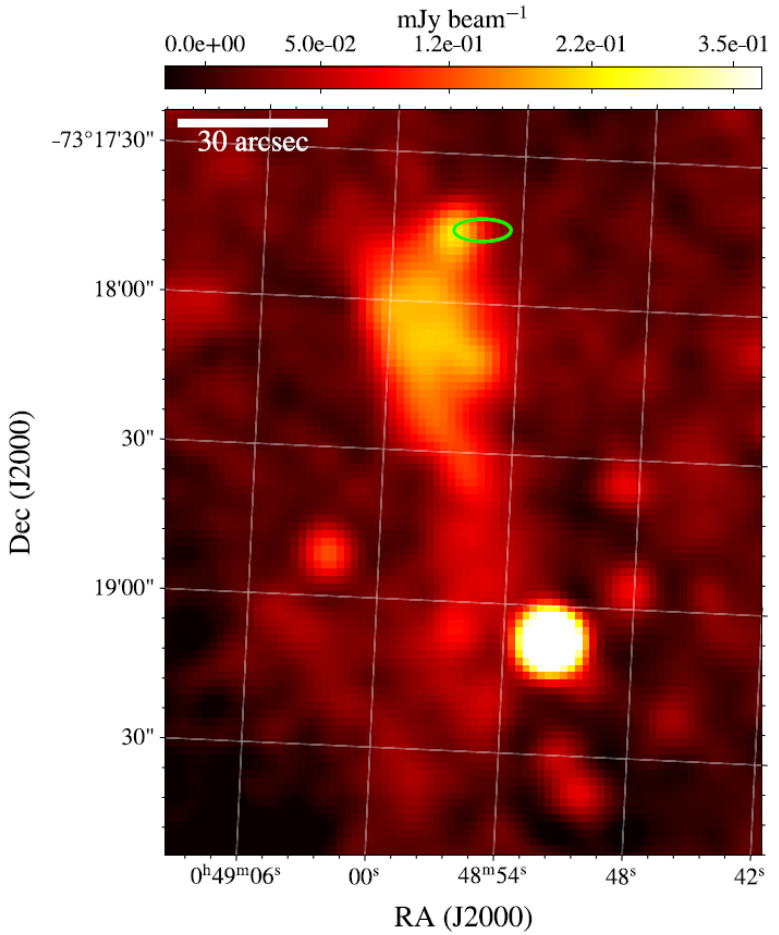
ASKAP EMU radio image – Joseph et al. 2019

Nearby Galaxies Surveys: Small Magellanic Cloud

Pulsars in PWD:

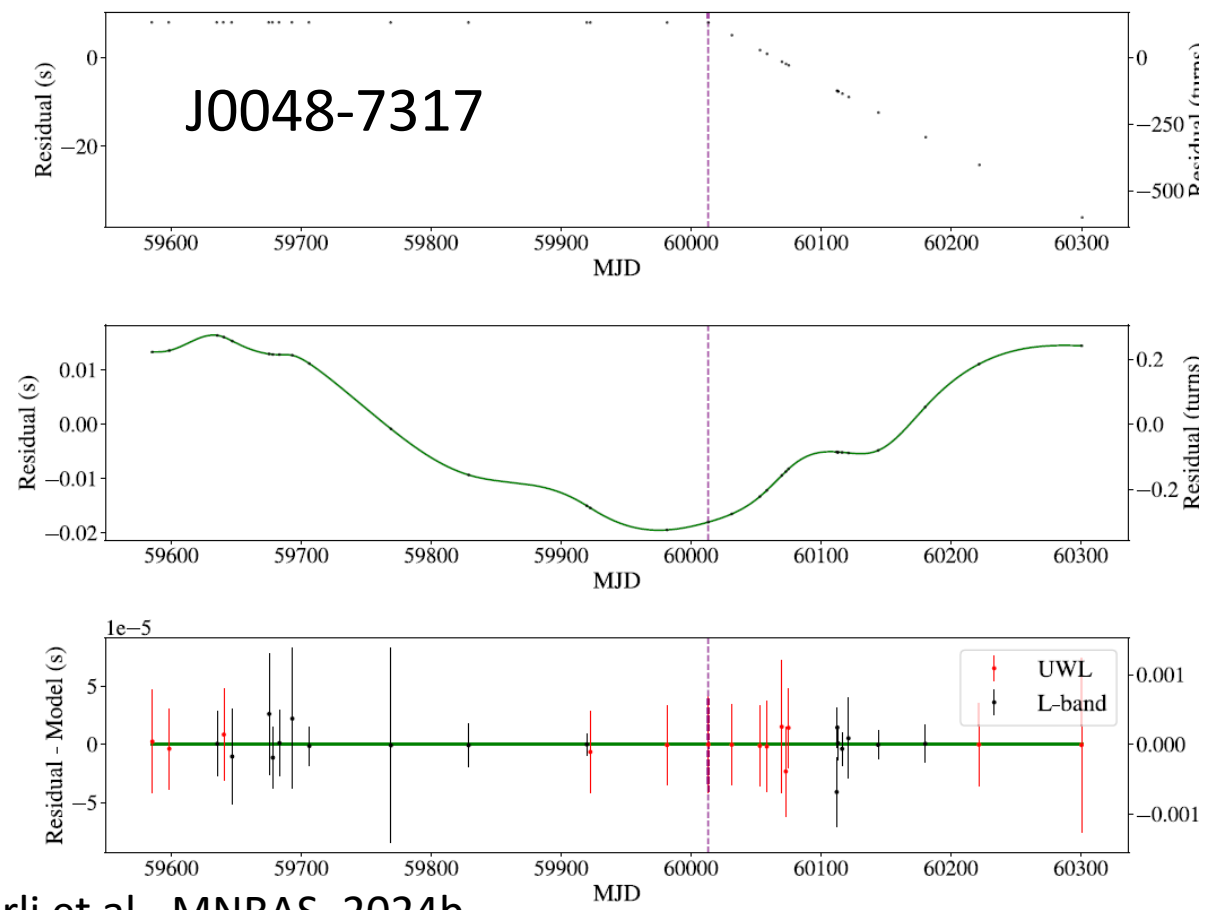
- PSR J0048-7317
- PSR K0040-7339

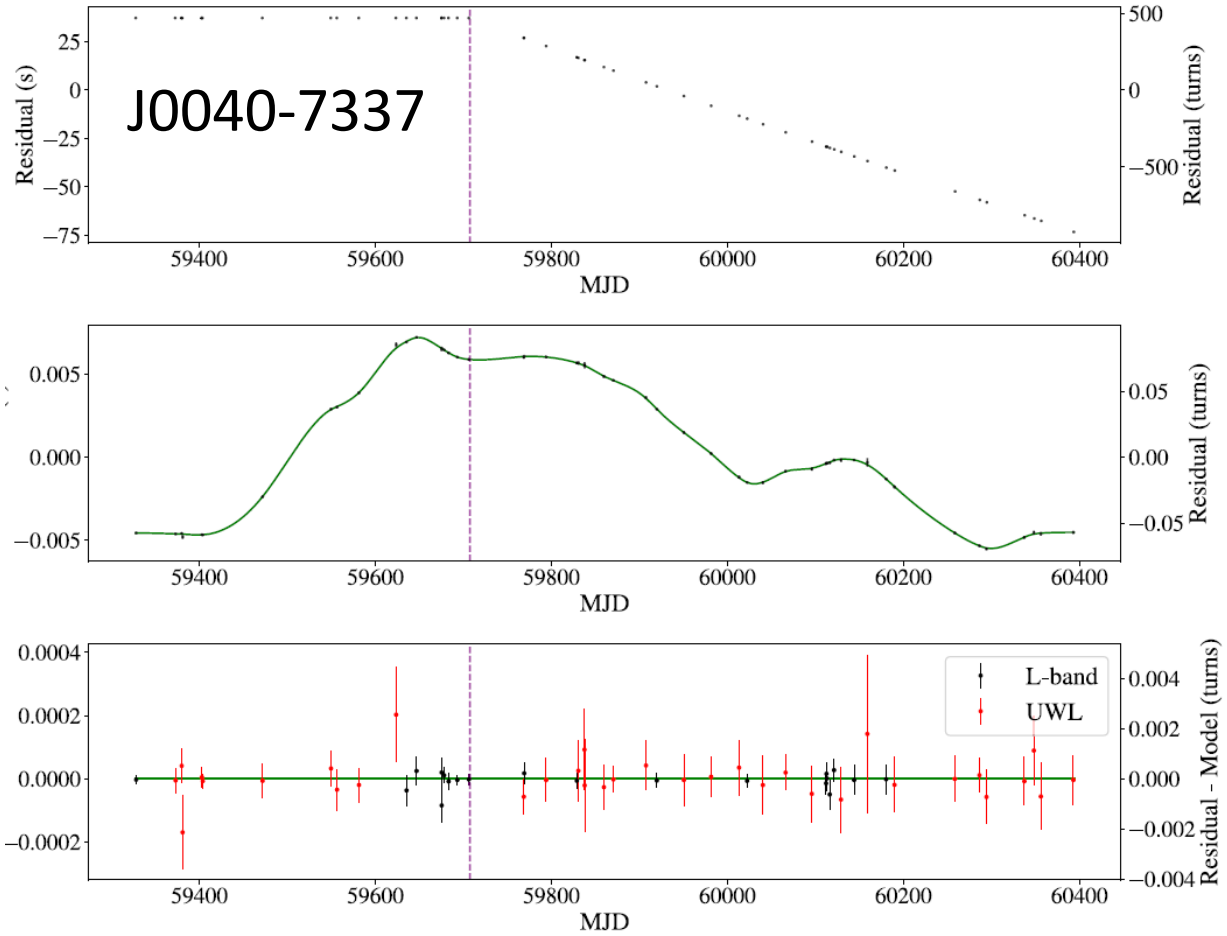




Carli et al., MNRAS, 2024a

Nearby Galaxies Surveys: Small Magellanic Cloud

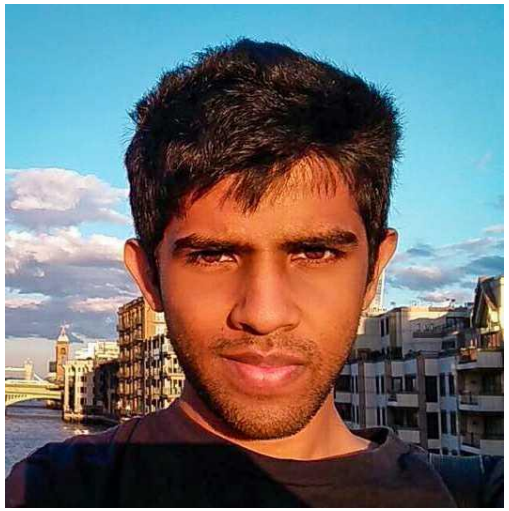




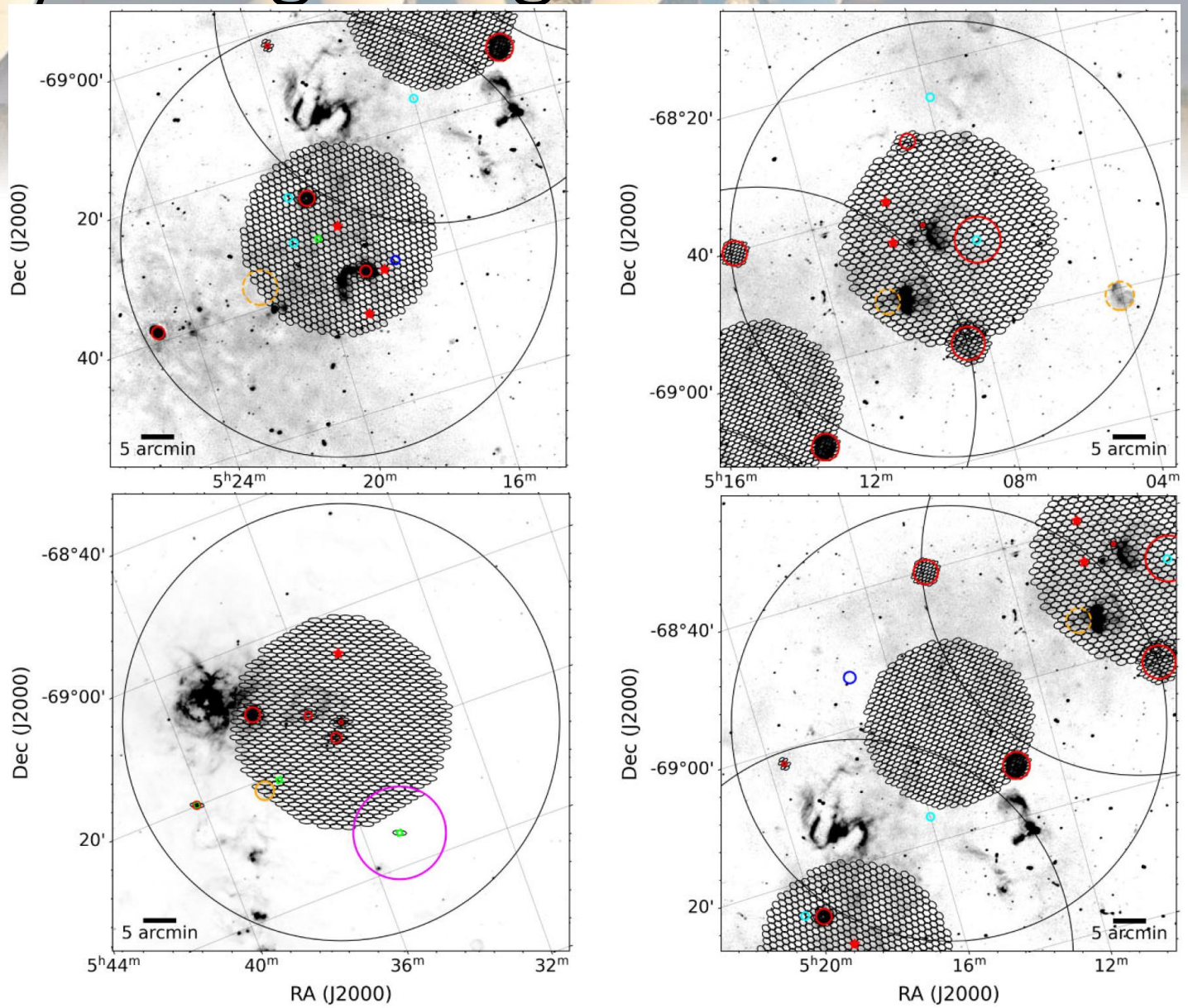
Carli et al., MNRAS, 2024b

Nearby Galaxies Surveys: Large Magellanic Cloud

- Known pulsars before survey: 23
- Number of pointings:
  26 fields of 2x2 hours
- New discoveries: 20



Led by Venu Prayag



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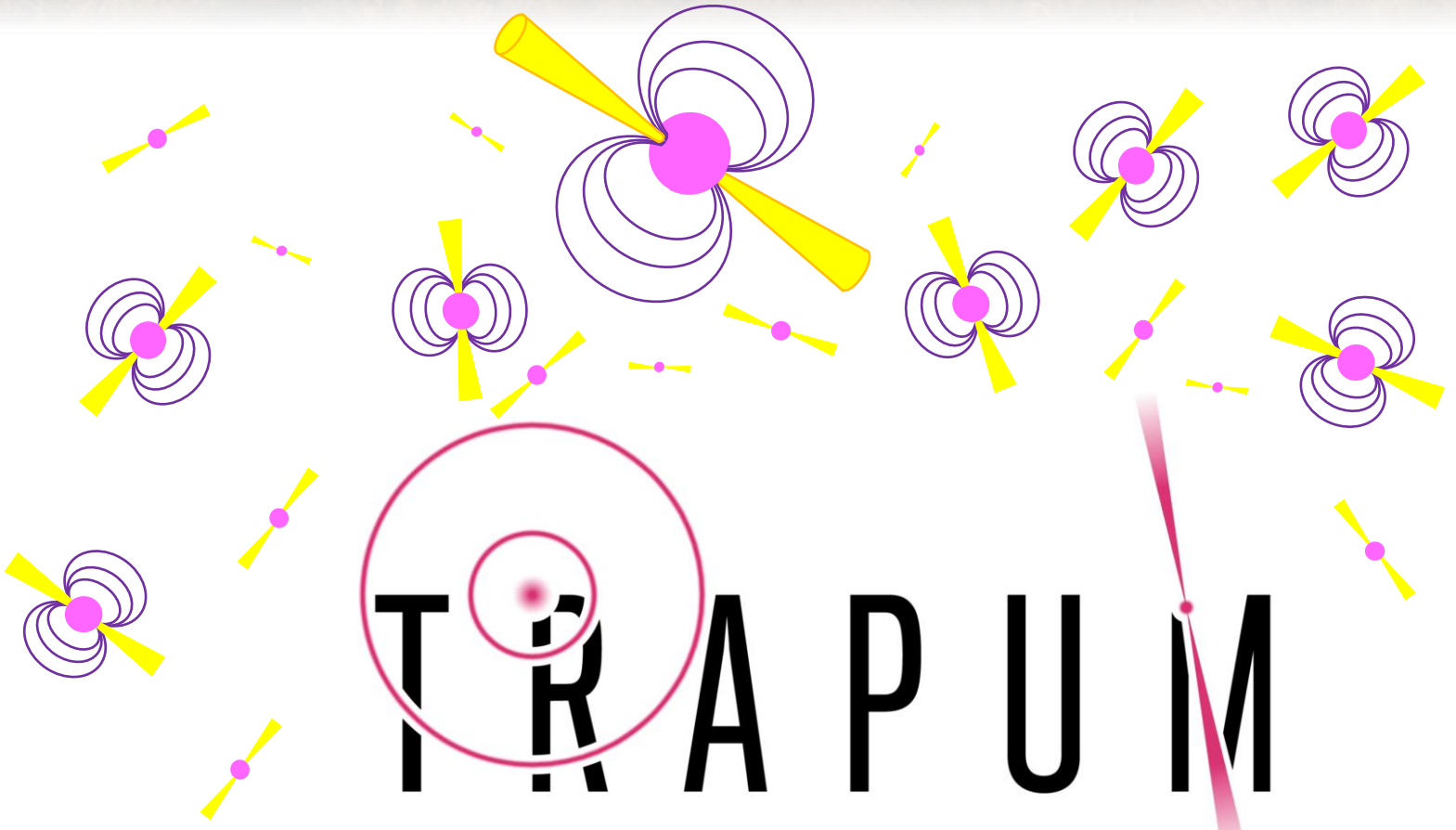
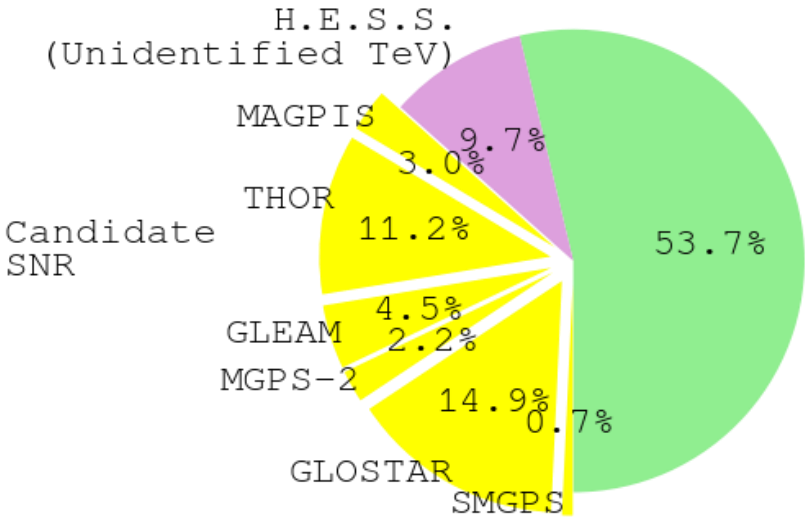
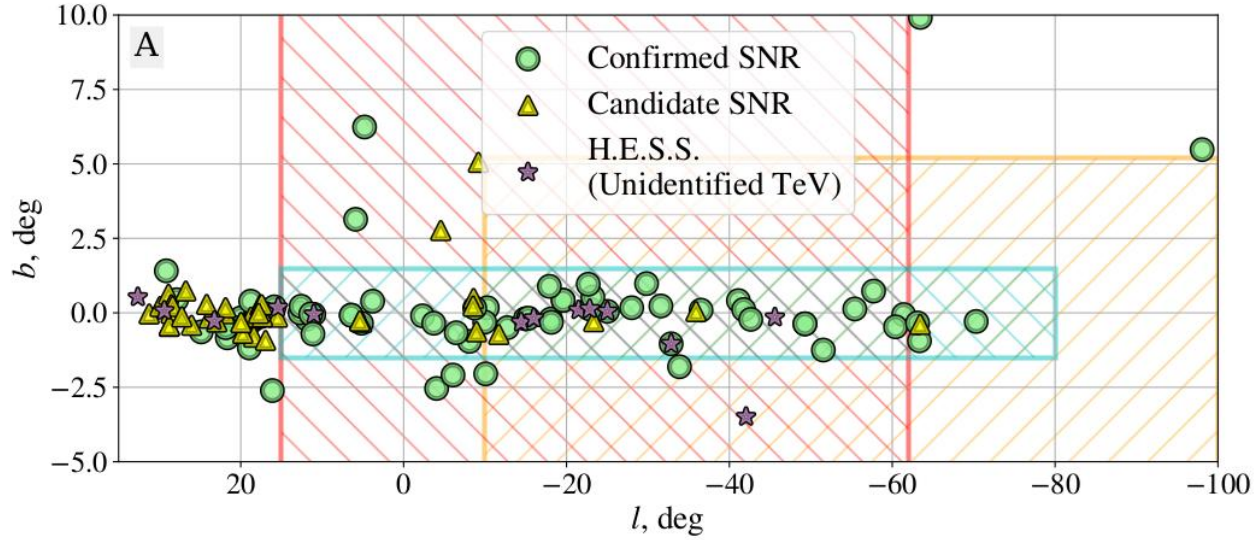
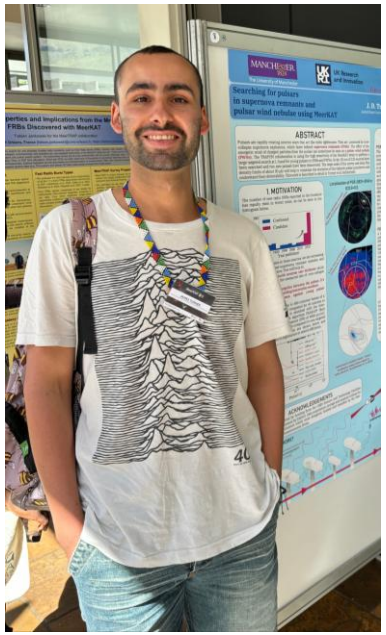


Search for young pulsars in supernova remnants and pulsar wind nebulae

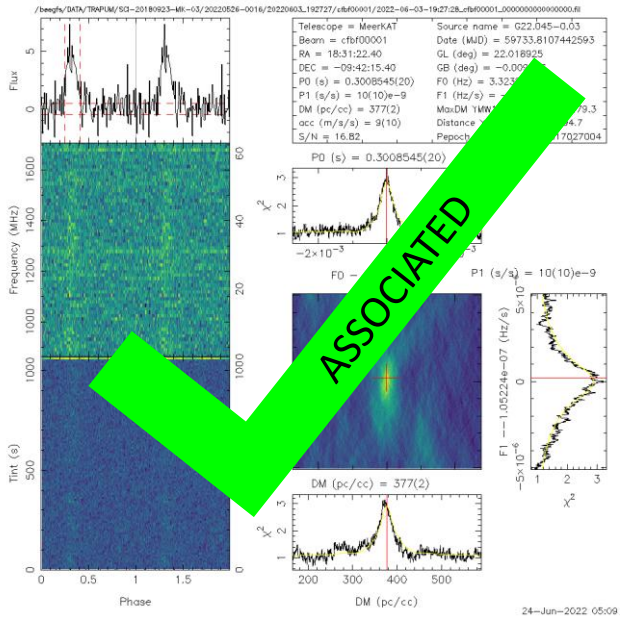




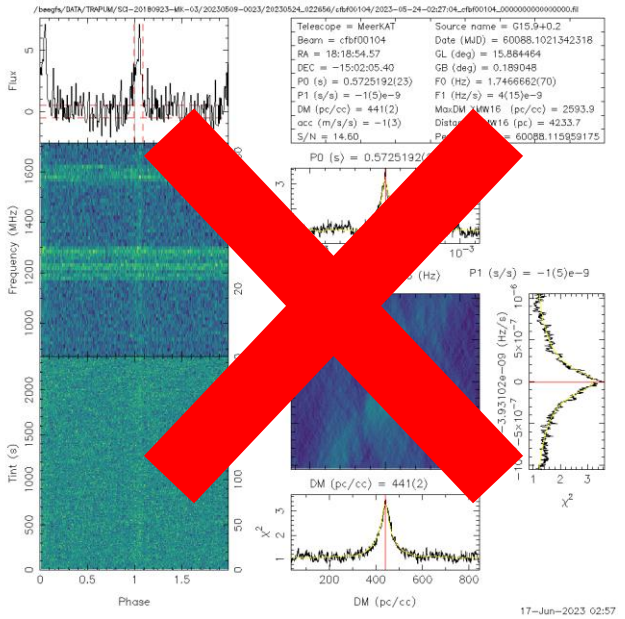


James Turner

- 134 targets searched
- 2 pulsars discovered, only 1 is young and associated with the SNR/PWN (Turner et al. 2024)
- Low discovery rate largely due to strong scattering on the Galactic plan (Turner et al. 2025)

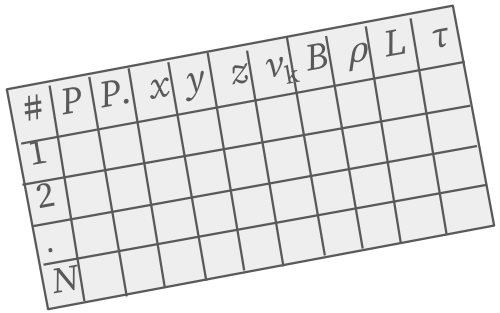


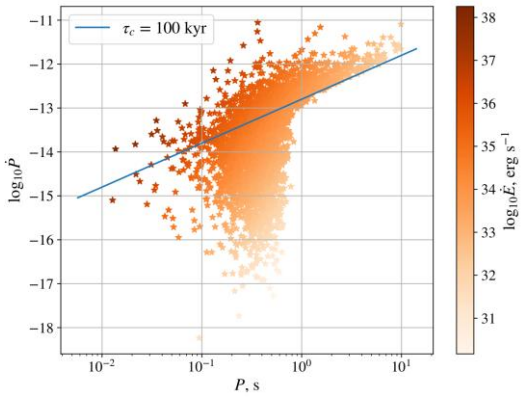
PSR J1831−0941

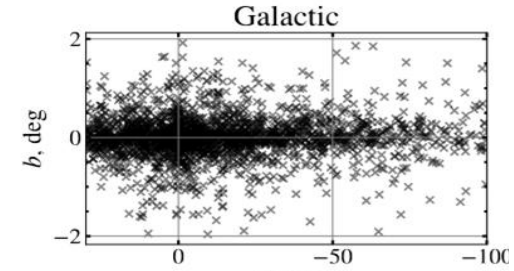


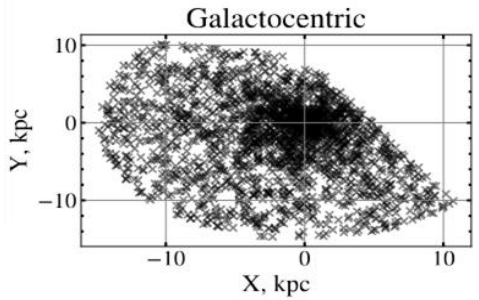
PSR J1818−1502

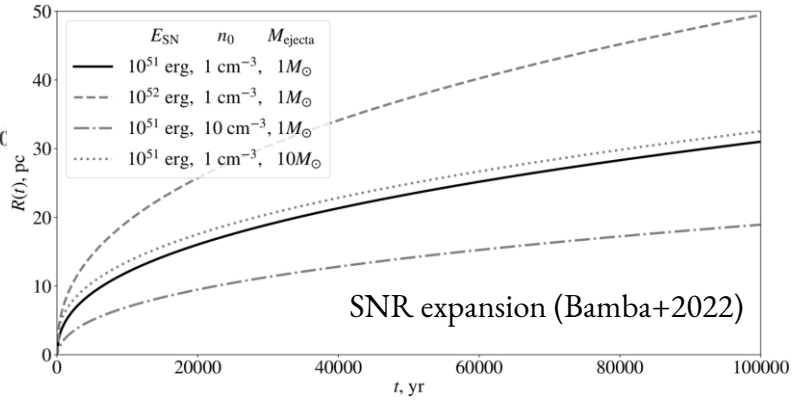
The population analysis - see Turner et al. 2025!









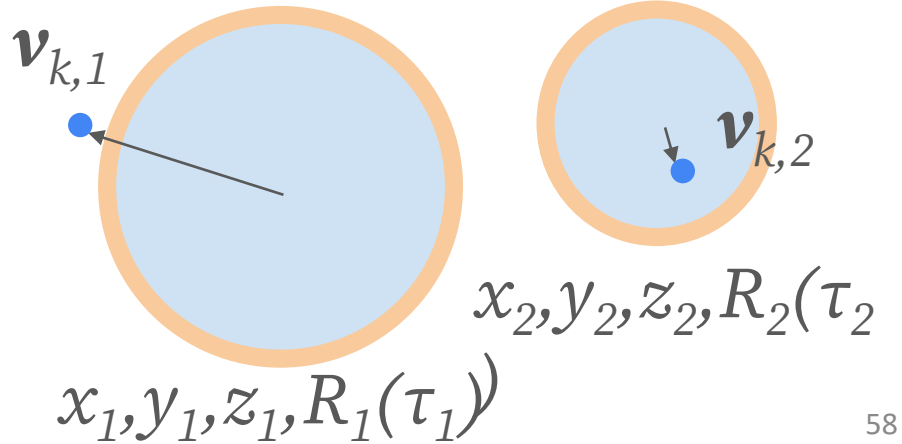


1. Simulate a pulsar population in PsrPopPy2 (**evolve** mode)

2. Cut pulsars with age, **τ > 100 kyr** (SNR-PWN dissipation time)

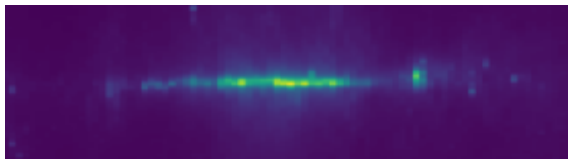
3. Apply 3D sky filter

4. Assign each pulsar a SNR size and birth velocity. Check projected location

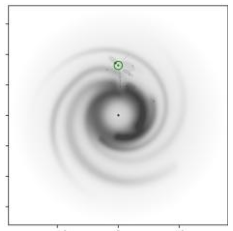


5. Calculate sky temperature, DM & scattering timescale and TRAPUM S/N

Repeat 100×



GSM2016 (Zheng+2016)



NE2001 (Cordes+Lazio, 2002)

Conclusions

- The TRAPUM surveys have pioneered pulsar searches with interferometry with an SKA pathfinder
- TRAPUM is an international collaboration with many science cases
- TRAPUM has led to the discovery of 280+ new pulsars

TRAPUM: Pulsar Surveys with MeerKAT and Lessons for the SKA Era

by Miquel Colom i Bernadich, INAF ISTITUTO NAZIONALE DI ASTROFISICA

on behalf of the TRAPUM collaboration

TRAPUM

Transients and Pulsars with MeerKAT