# The MPIfR-MeerKAT Galactic Plane Survey: System setup and early results

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IMPRS astronomy & astrophysics Bonn and Cologne

TRAPUM

# Outline

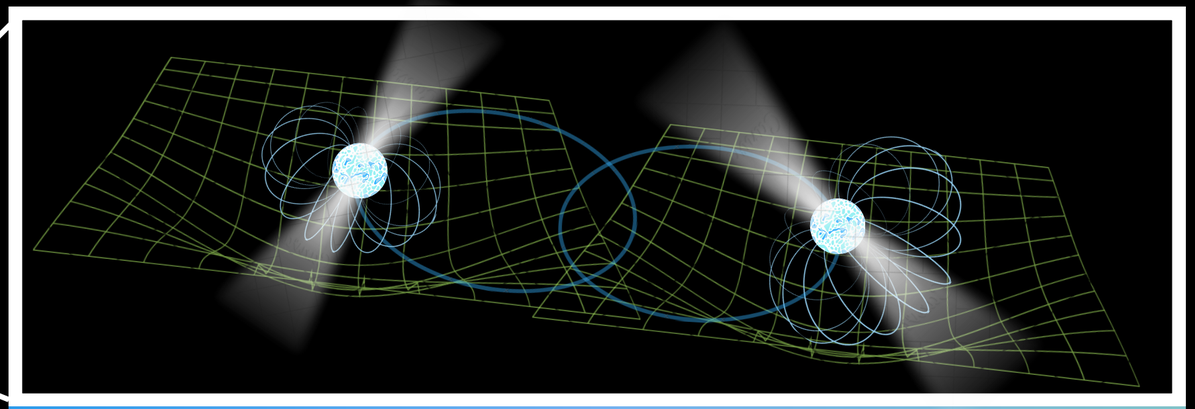
1. Motivation
2. System setup
3. Search pipeline
4. Results!
5. Ongoing/Future work
6. Summary

# Overview

The MMGPS is a 3000 hour commensal survey with MeerKAT, covering science cases including Imaging, spectral line and time domain science

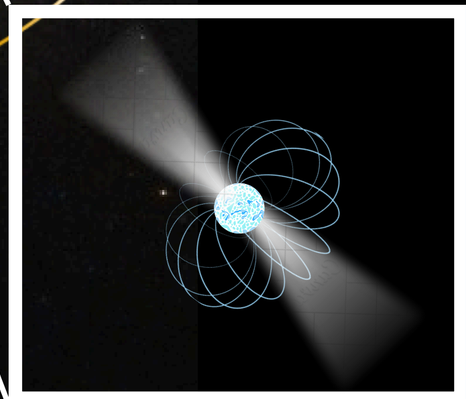
# Pulsars in the galactic plane

ESA/Hubble & NASA



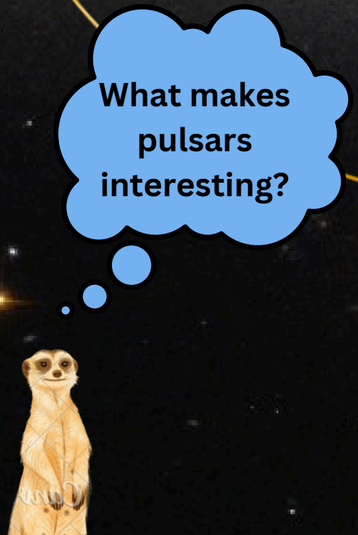
## Binary systems

- Test theories of gravity
- Constrain equations of state
- Study formation mechanisms



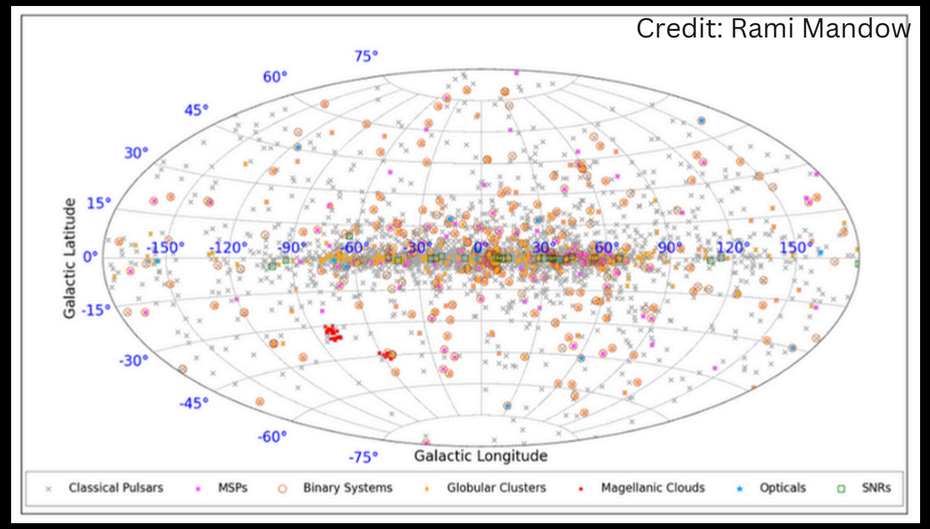
## Isolated pulsars

- Study Interstellar medium
- Study galactic magnetic fields
- Emission mechanisms
- Evolutionary trends



# Galactic plane surveys

## The current consensus




What do we expect to see?

# Galactic plane surveys

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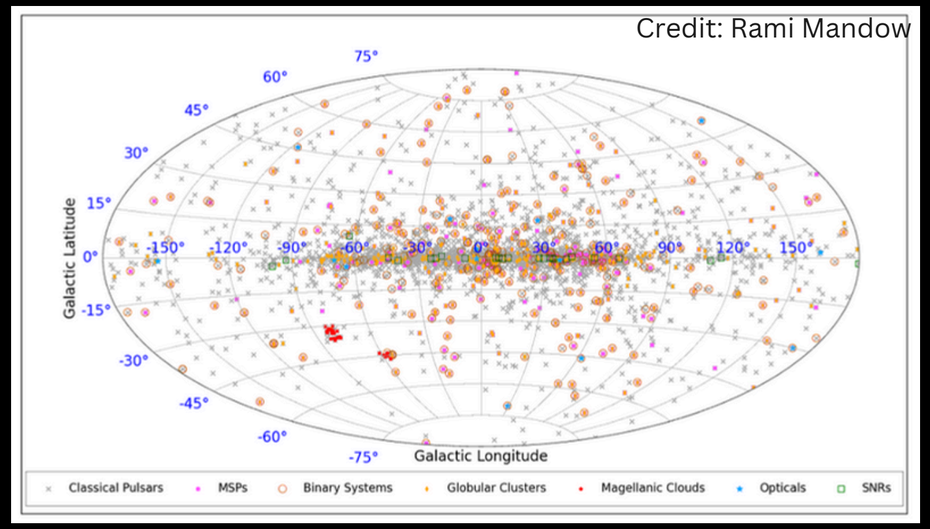


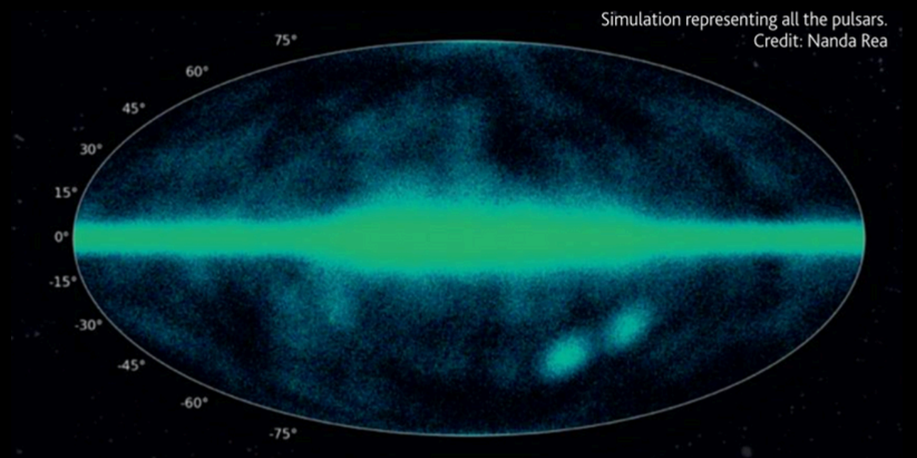

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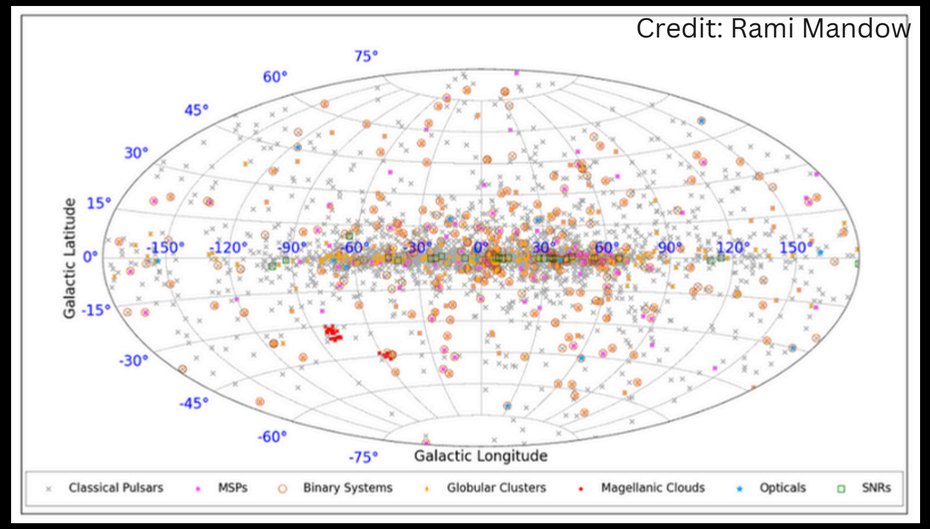
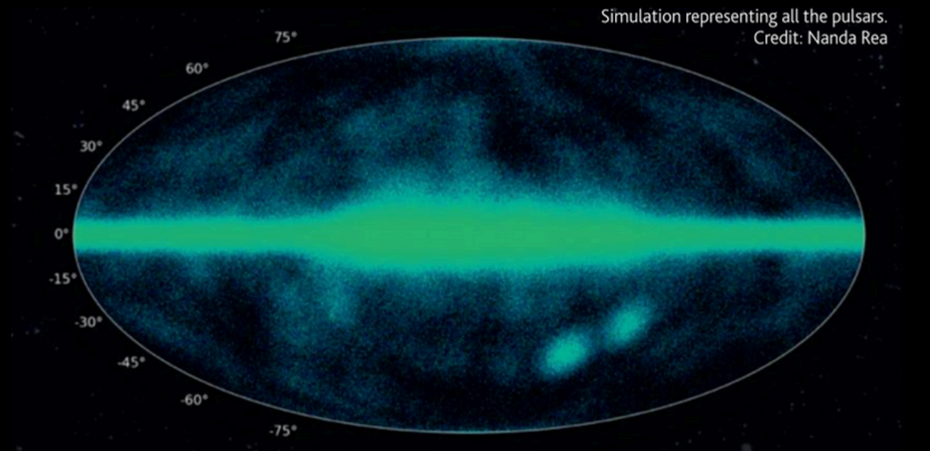
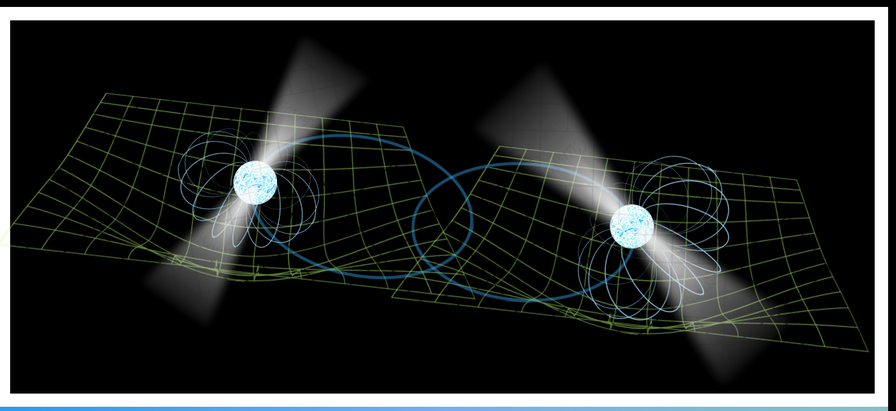



| | PMPS and HTRU South with Parkes | The MPIfR-MeerKAT Galactic Plane Survey |
|---|---|---|
| Gain | 0.735 K Jy−1 | 2.8 K Jy−1 |
| BW | 340 MHz | > 856 MHz |
| Tint | 4300 s | < 1300 s |







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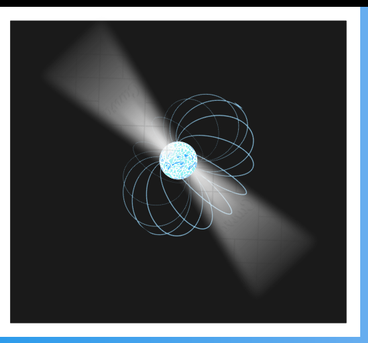

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- Study Interstellar medium
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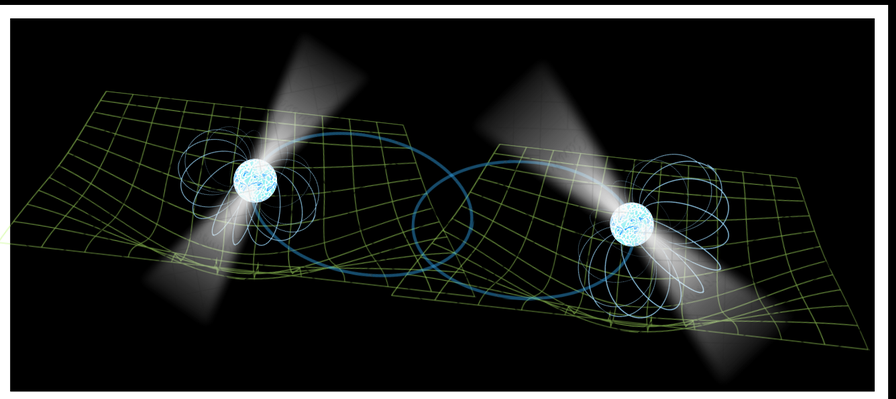

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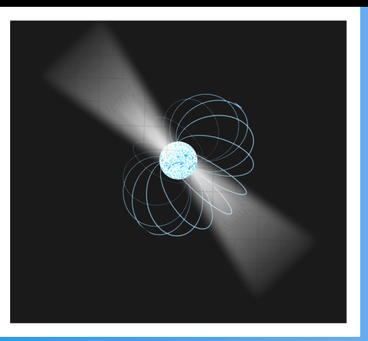

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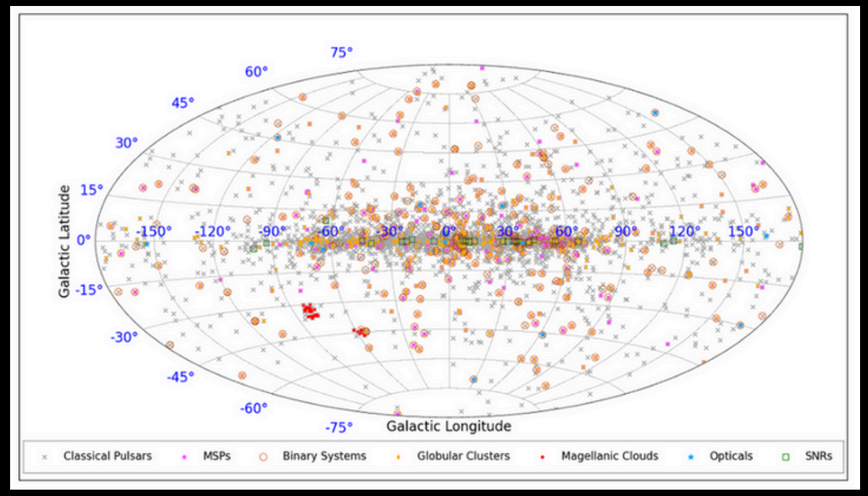


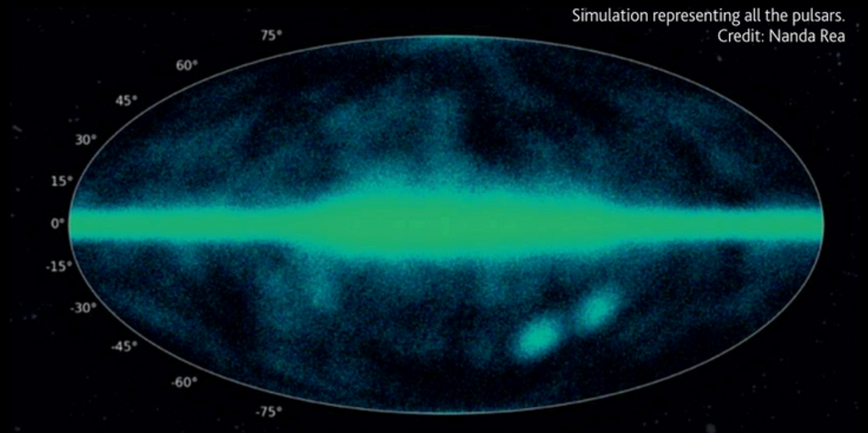

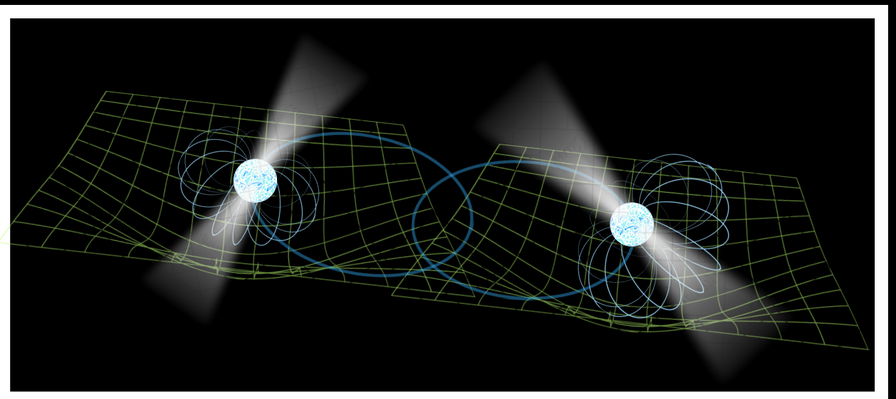

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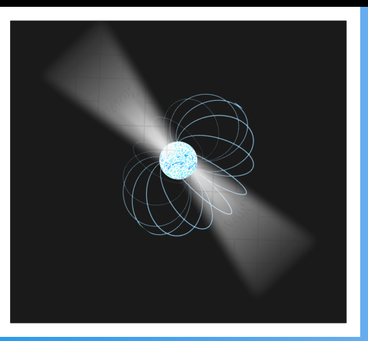

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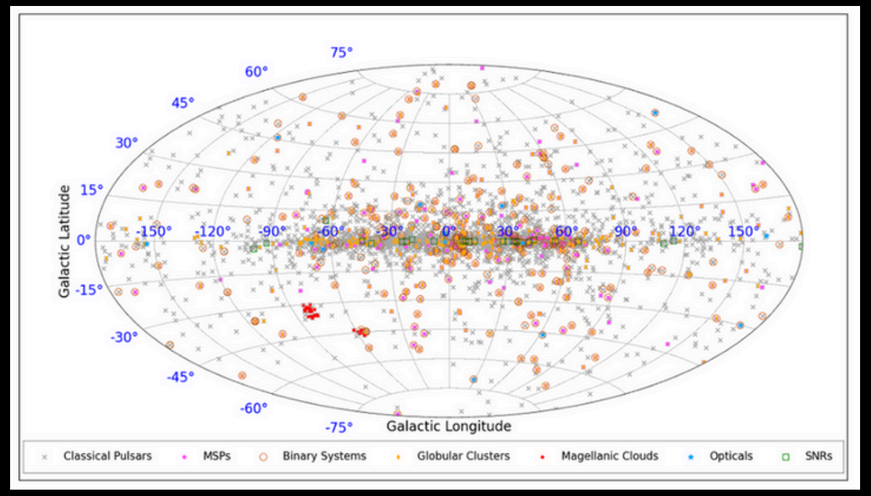
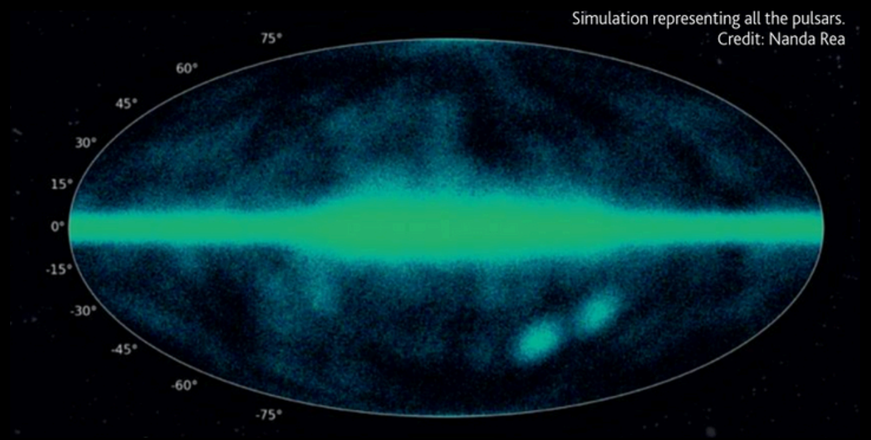


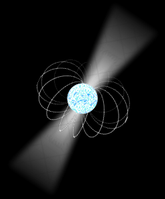





| | The MPIfR-MeerKAT Galactic Plane Survey |
|---|---|
| Gain | 2.8 K Jy−1 |
| BW | > 856 MHz |
| Tint | < 1300 s |

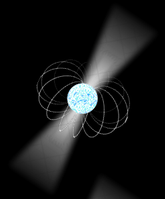

What are the scientific goals of the MMGPS?

# MMGPS pulsar science goals:



Discover compact relativistic binaries along the galactic plane.

# MMGPS pulsar science goals:



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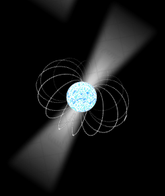
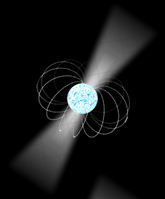


Find pulsar orbiting Sgr A*.

# MMGPS pulsar science goals:



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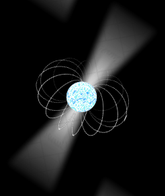

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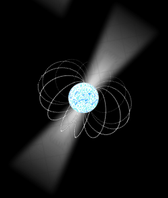

Enhance detection capabilities of pulsar timing arrays (PTA) to the gravitational wave background through discoveries of MSPs with stable timing properties

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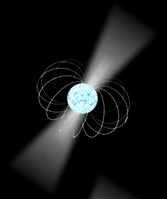

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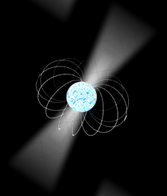

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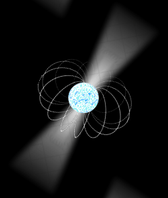

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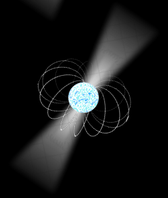
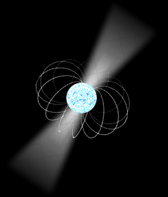
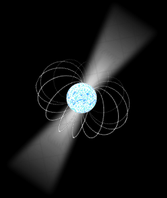


Discover pulsars that resolve open questions regarding binary evolution.



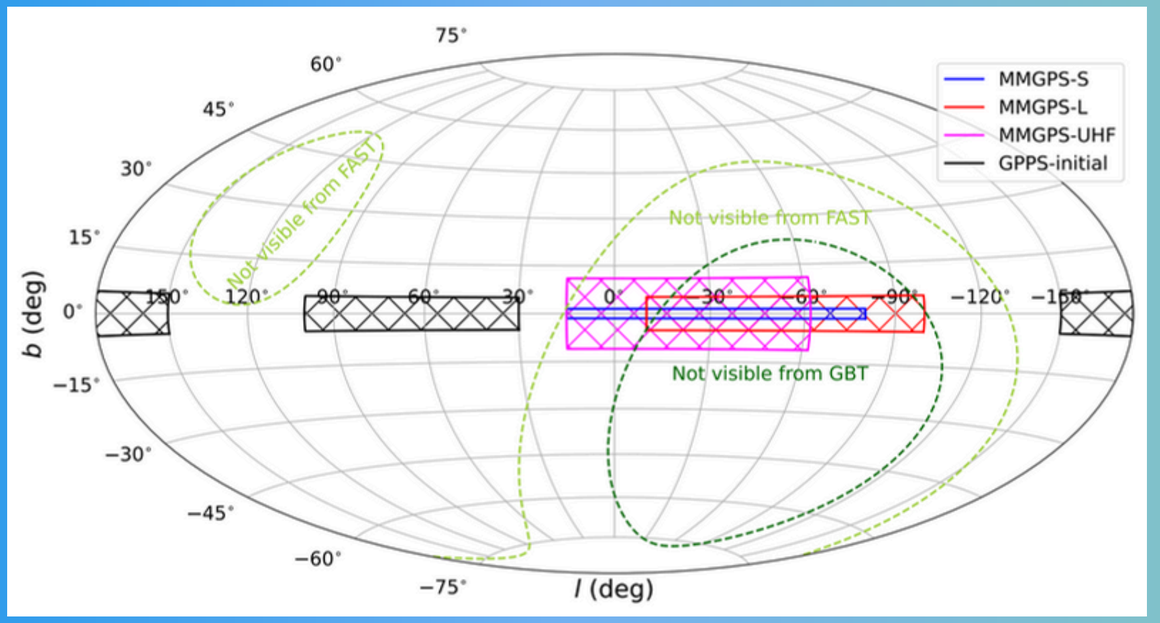
Discover pulsars with atypical emission properties including intermittency, nulling and mode-switching



Improving population models through the discovery of a large number of new canonical pulsars as well as MSPs

# Survey layout:

| Sub survey: | Integration time | Total time | Frequency |
|---|---|---|---|
| Shallow UHF band Galactic plane survey (MMGPS-UHF) | 8 min | 400 hrs | 816 MHz |
| Deep S-Band Galactic plane survey (MMGPS-S) | 20 min | 1380 hrs | 2406.25 MHz |
| Shallow L-Band Galactic plane survey (MMGPS-L) | 10 min | 800 hrs | 1283 MHz |
| Ultra-Deep S-Band Galactic centre survey (MMGPS- Sgr A*): | 20 min | 200 hrs | 3062.5 MHz |




**The survey region layout for the latest and most sensitive Galactic plane surveys (P. V. Padmanabh et al. 2023).**

**Note the regions not visible from FAST and GBT, and the region covered by the Galactic Plane Pulsar Snapshot survey with FAST**

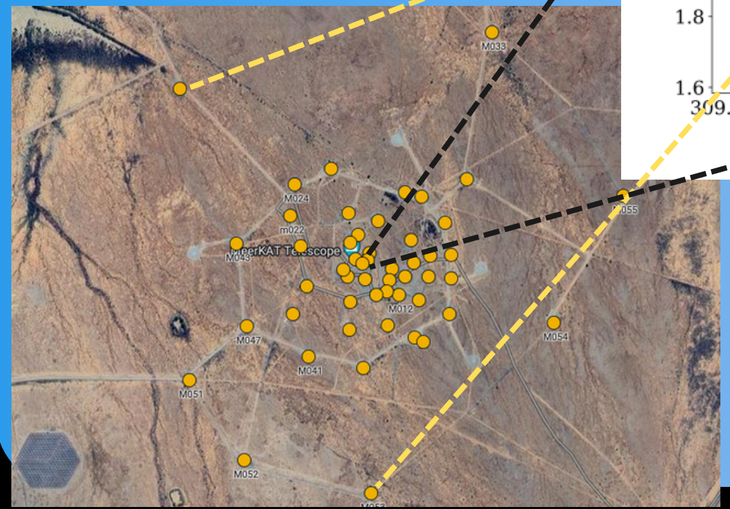
# Instrumentation

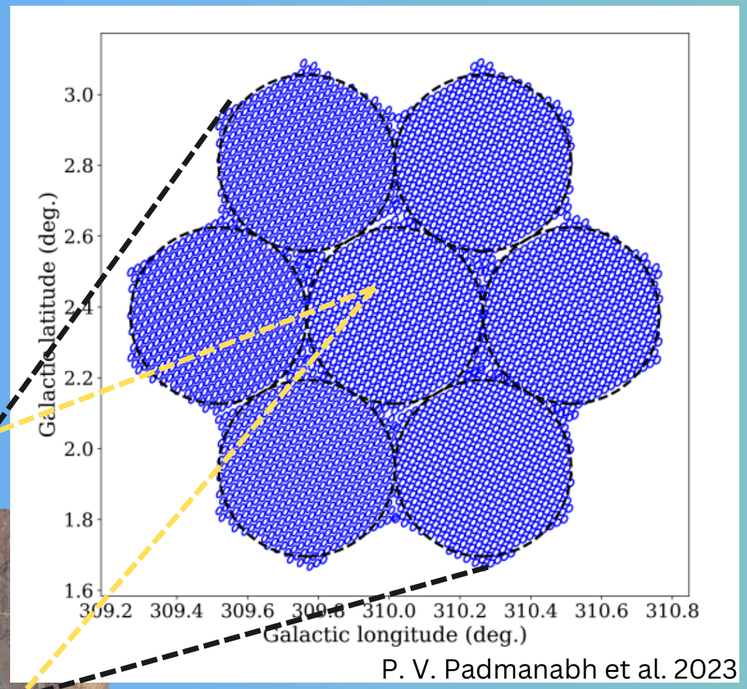
**MPIfR funded and developed state-of-the-art systems**

## Filterbanking beamformer user supplied equipment (FBFUSE):

- High-performance
- Real-time
- Multi-beam beamformer

Tile 480 beams within the incoherent beam to produce uniform sky coverage




P. V. Padmanabh et al. 2023

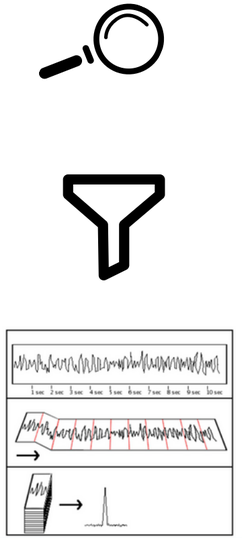
**Useful for:**

- Instantaneous localisation of source
- Spatial filtering

## Accelerated pulsar search user supplied equipment (APSUSE):

High-performance cluster that searches the data:

- Acceleration searching
- Multibeam candidate filtering
- Folding and post-folding candidate sifting

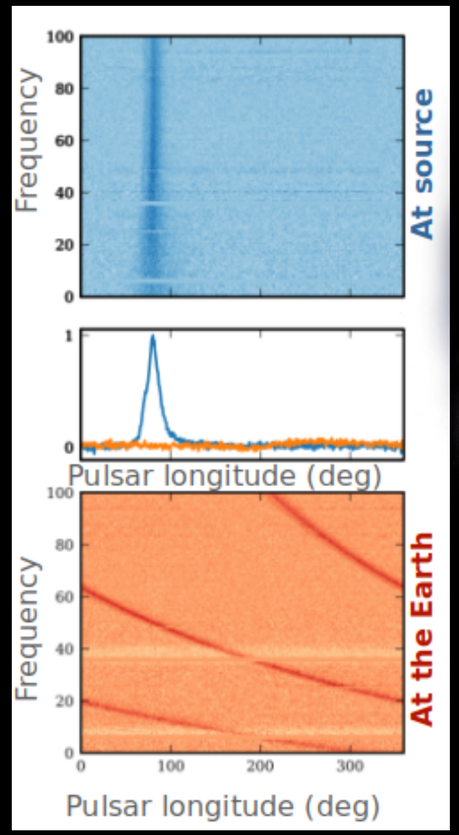


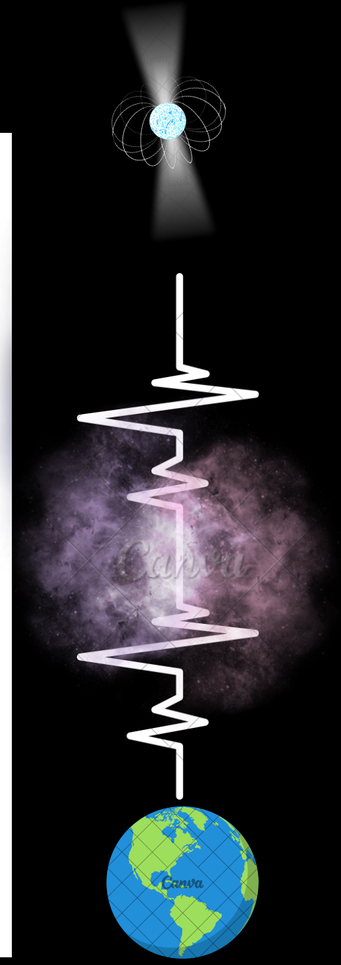
# Pulsar search processing: GPU based!

Peasoup

DM loop, 5 - 3000 pc cm−3

Dedisperse at trial DM



# Pulsar search processing: GPU based!

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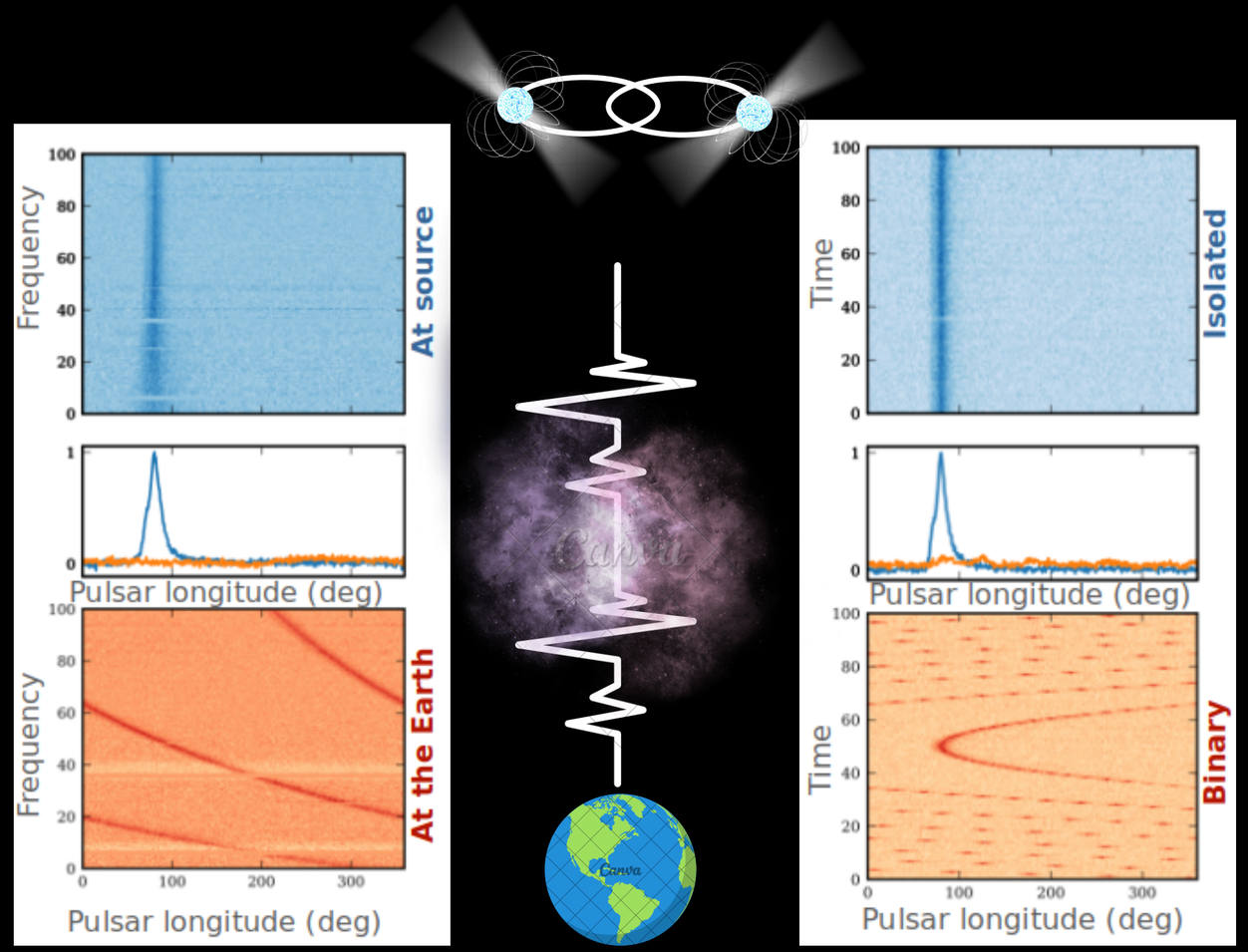
- **DM loop, 5 - 3000 pc cm−3**
  - Dedisperse at trial DM
  - **Acceleration search loop, -50 to +50 m s−2**
    - Resample data at assumed ‘a’



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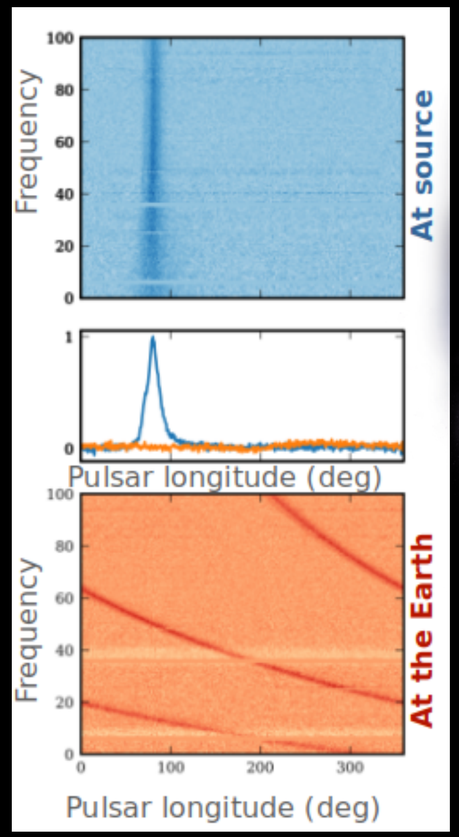
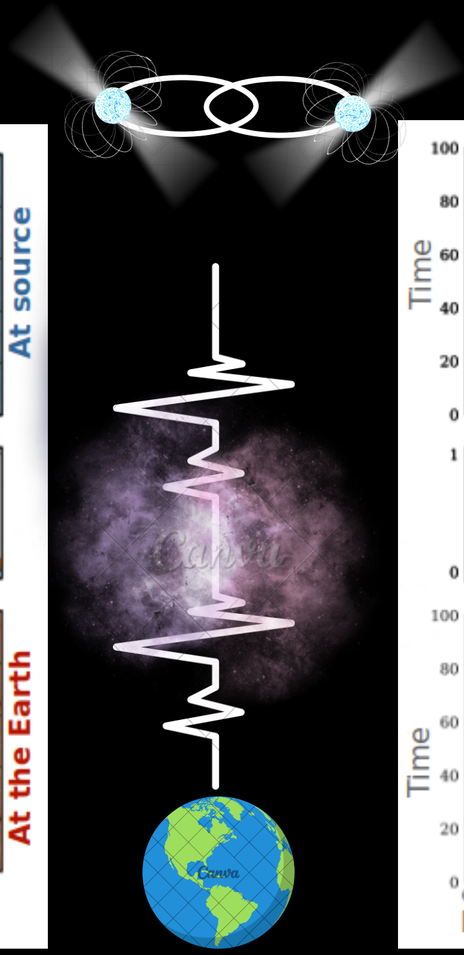
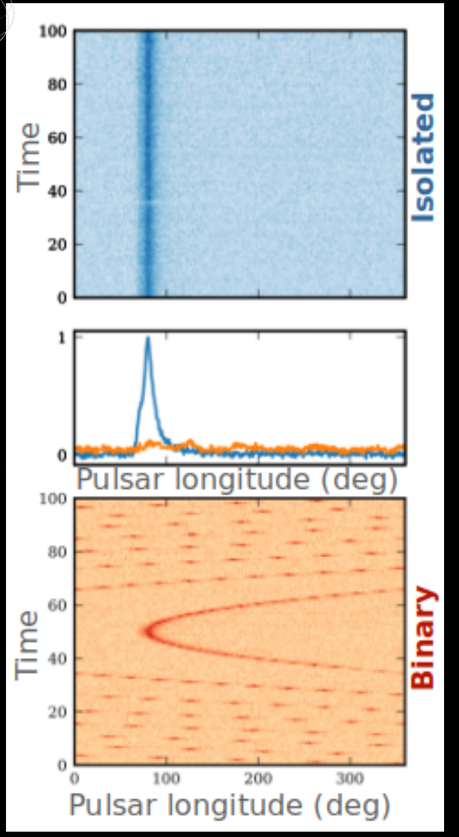
- Repeat
- Repeat
- Inspect candidates!





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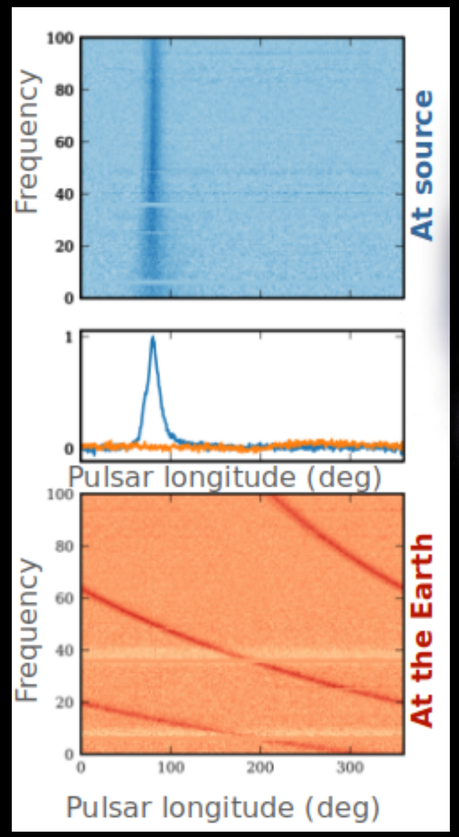
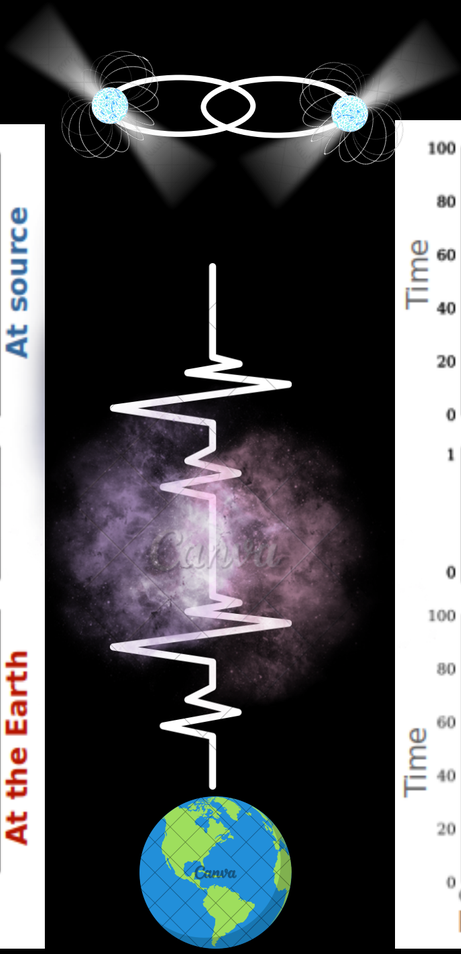


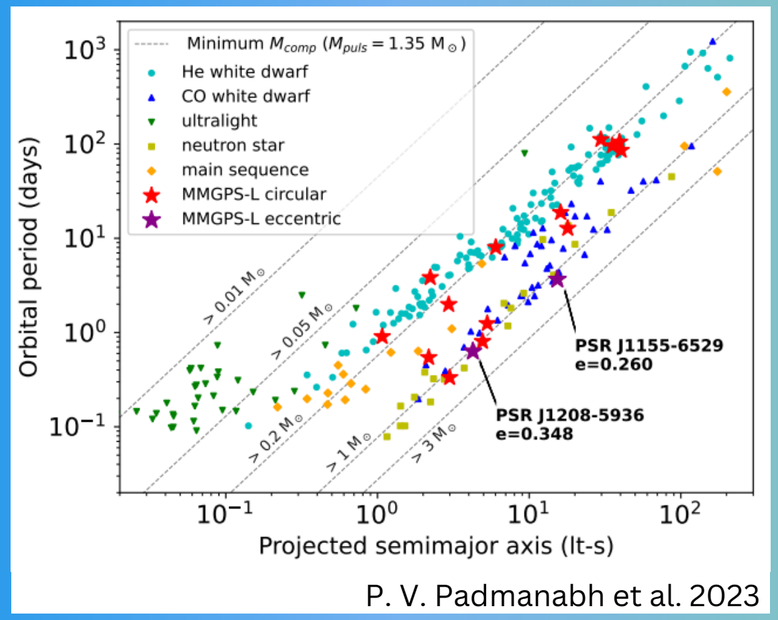




- 480 beams per pointing >>
- 20 pointings per observing session>>
- 2 Sessions per week>>
- ~ 350 TB/week!

# Discoveries!

**The MMGPS-L survey has discovered 78 new pulsars, 17 in confirmed binaries, two of which are double neutron star systems**

## 17 confirmed binaries

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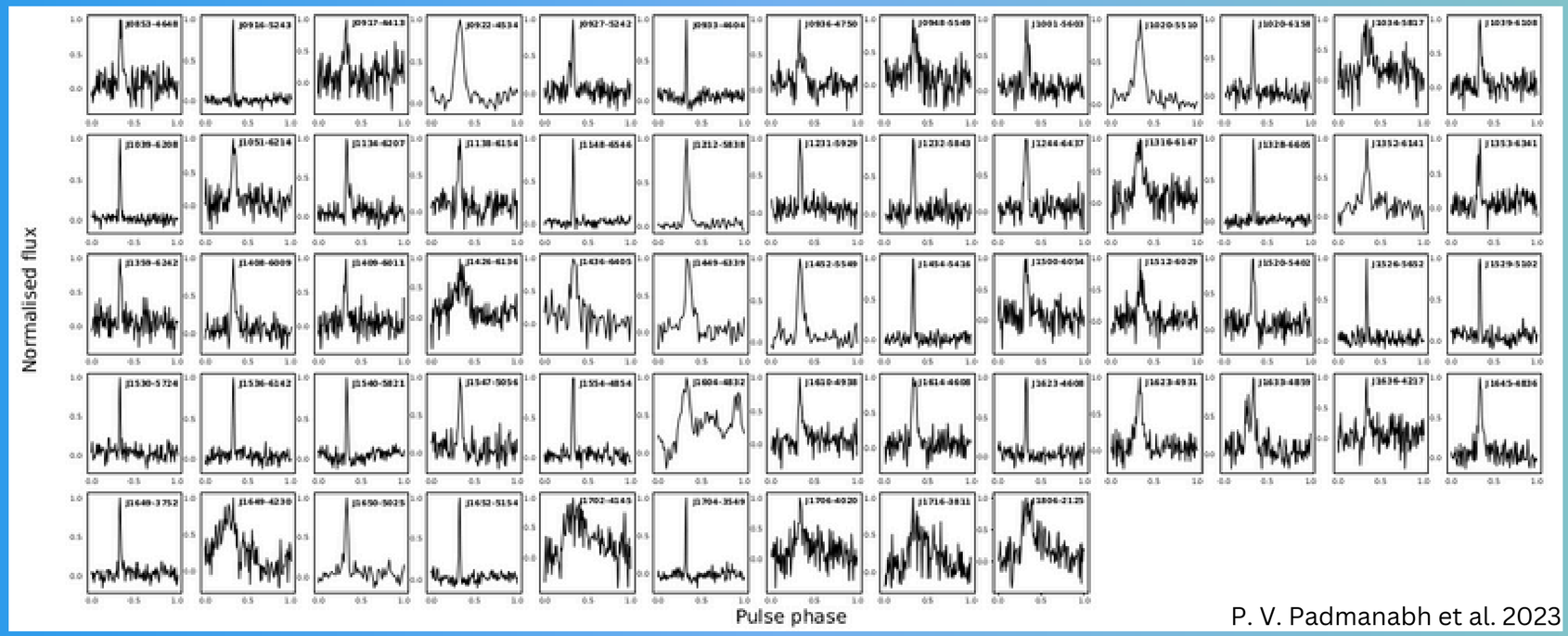
Comparison of binary pulsars discovered in MMGPS-L with known binaries.

## 61 slow period pulsars

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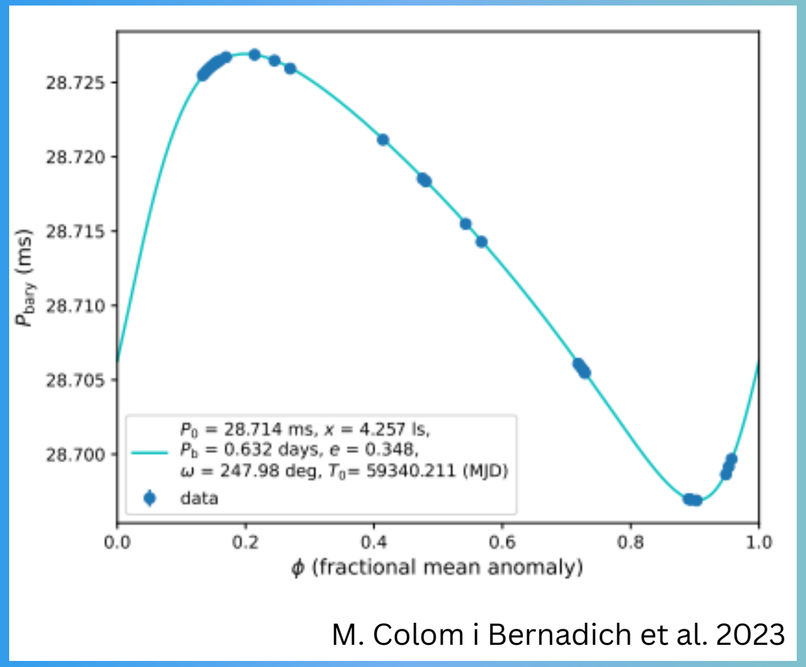
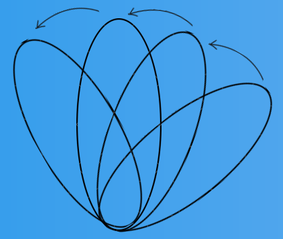
Integrated pulse profiles for the 61 isolated pulsars. We see varying complexity in the profiles

# Discoveries: The eccentric double neutron star system PSR J1208−5936

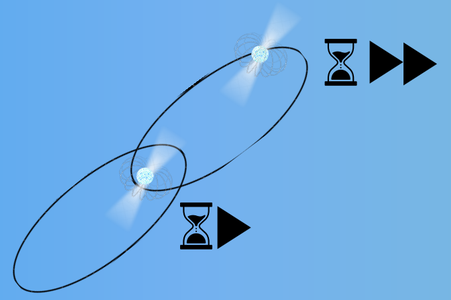



M. Colom i Bernadich et al. 2023

- Spin period, P: 28.7 ms
- DM:  344 pc cm^−3
- Eccentricity, e = 0.348
- Pb: 16 hr
- Companion minimum mass ~ 1.1M⊙

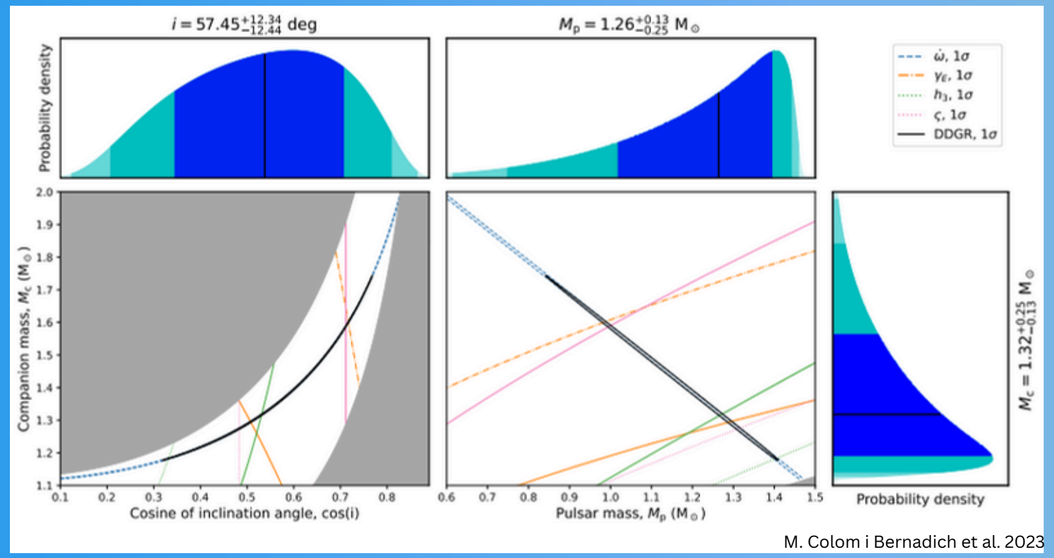


Advance of periastron
dw/dt = 0.918 ± 0.001 deg/yr



Einstein delay
γE = 2.93 ± 0.98 ms

Shapiro delay
h3 = 1.01 ± 0.97 μs
ς = 0.41 ± 0.18

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M_tot = 2.586(6) M⊙
Mp =  1.26-0.25+0.13 M⊙
Mc =  1.32-0.13+0.25 M⊙

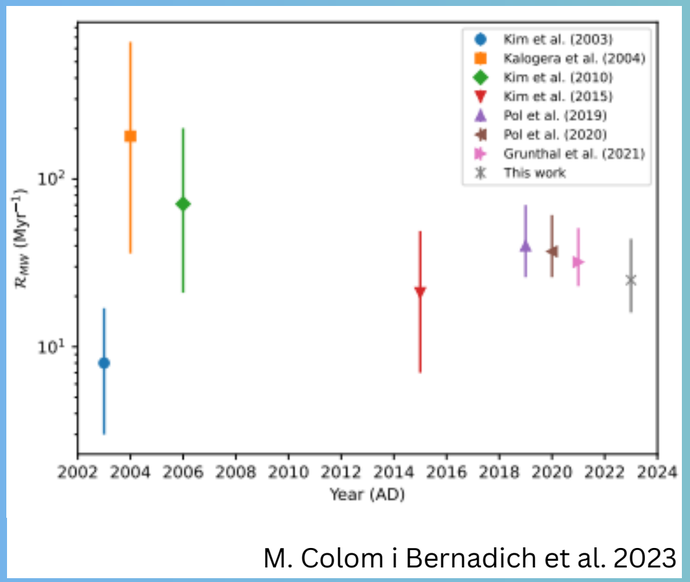
PSR J1208−5936 has a merger time of 7.2(2) Gyr and is a progenitor of the neutron star mergers seen by LIGO!

**Check out the published paper here: arXiv:2308.16802**

# PSR J1208-5936: Past, present, and future

| PSR | $P_0$ (ms) | $M_c$ ($M_\odot$) | $M_p$ ($M_\odot$) | $\tau_m$ (Gyr) |
|---|---|---|---|---|
| J1946+2052[1] | 16.960 | >1.18 | <1.31 | ~0.0455 [a] |
| J1757−1854[2] | 21.497 | 1.3917(4) | 1.3412(4) | 0.0761 |
| J0737−3039A[3] | 22.699 | 1.248868(13) | 1.338185(14) | 0.0860 |
| J0737−3039B[3] | 2773.5 | 1.338185(14) | 1.248868(13) | 0.0860 |
| B1913+16[4] | 59.030 | 1.390(1) | 1.438(1) | 0.301 |
| J1906+0746[5] | 144.07 | 1.322(11) | 1.291(11) | 0.308 |
| J1913+1102[6] | 27.285 | 1.27(3) | 1.62(3) | 0.470 |
| J0509+3801[7] | 76.541 | 1.46(8) | 1.34(8) | 0.576 |
| J1756−2251[8] | 28.462 | 1.230(7) | 1.341(7) | 1.66 |
| B1534+12[9] | 37.904 | 1.3455(2) | 1.3330(2) | 2.73 |
| **J1208−5936[10]** | **28.714** | $\mathbf{1.32^{+0.25}_{-0.13}}$ [c] | $\mathbf{1.26^{+0.13}_{-0.25}}$ [c] | **7.2(2)** |

M. Colom i Bernadich et al. 2023

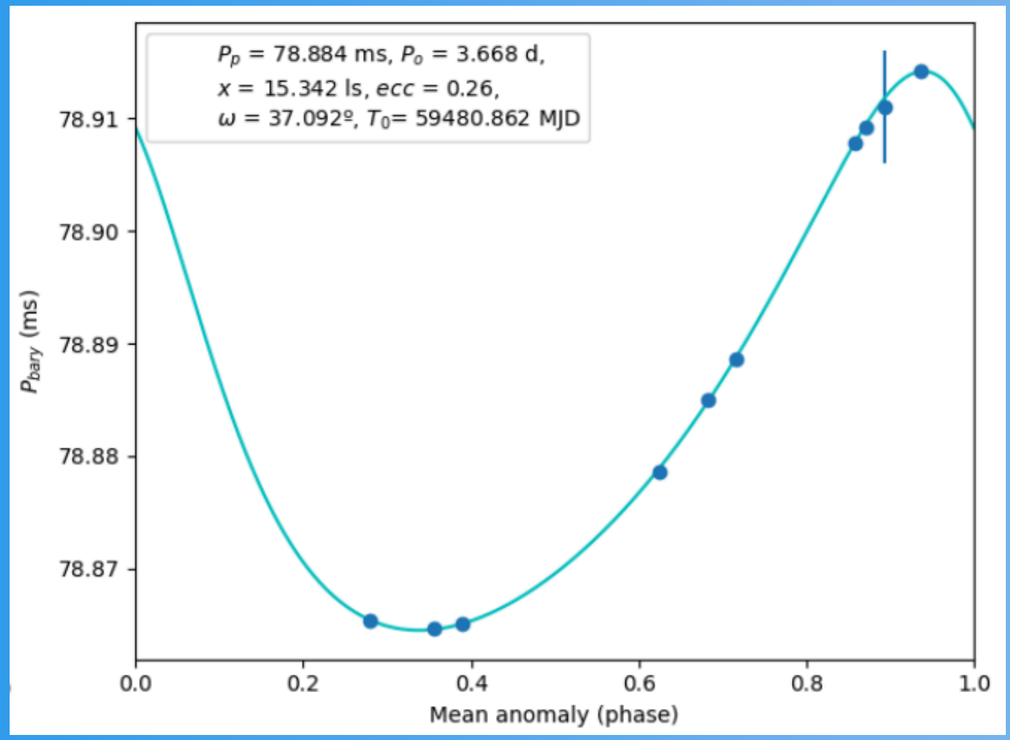



M. Colom i Bernadich et al. 2023

- Updated galactic merger rate estimation to 25-9+19 events per Myr, confirming a decreasing trend on the estimation from galactic binaries with increasing survey sensitivity.

1 2 3 4 5 6 7 8 9

# Another one! PSR J1155−6529

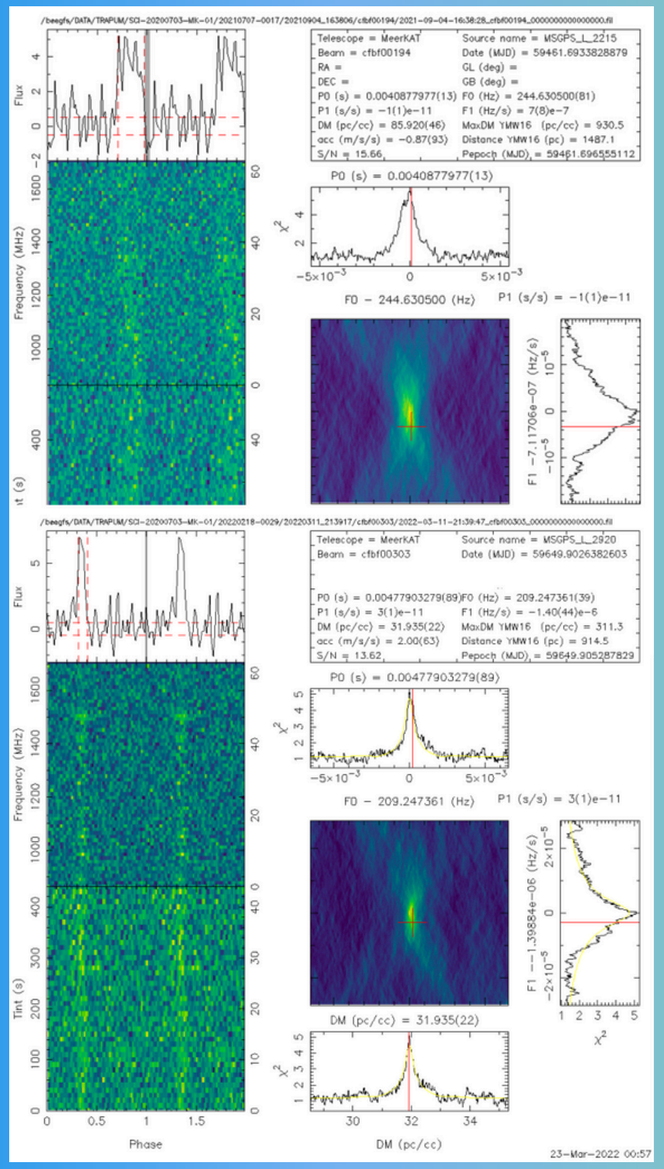



- Spin period, P: 78.88 ms
- DM: 33.078 pc cm^−3
- Eccentricity, e = 0.26
- Pb: 3.668 days
- Companion minimum mass ~ 1.238 M⊙

Orbital campaign observed!

Berezina et al., in prep

# Binary pulsars: Rare MSP-CO White dwarf binaries

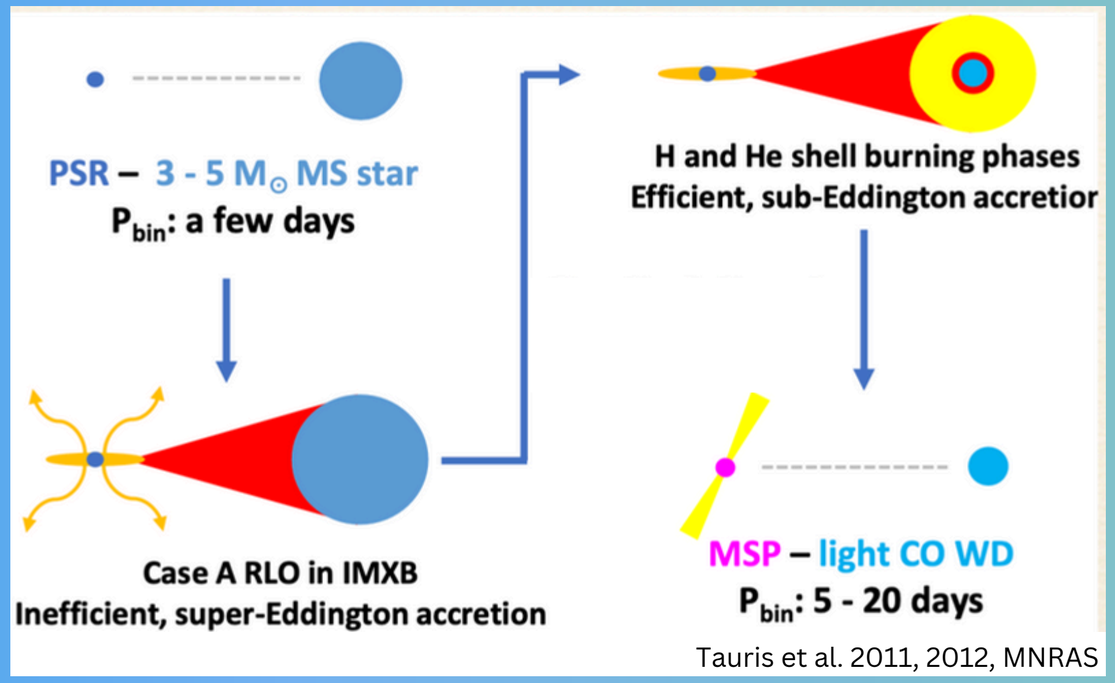



| | P (ms) | Pb (days) | e | x (lt-s) | M_c (M⊙) |
|---|---|---|---|---|---|
| J1338-6425 | 4.088 | 18.80 | ~ 0.0 | 16.12 | > 0.39 |
| J1510-5254 | 4.780 | 12.78 | ~ 0.0 | 17.96 | > 0.50 |

- Spin period, P < 10 ms
- Pb: 5-20 days
- Companion minimum mass > 0.33 M⊙

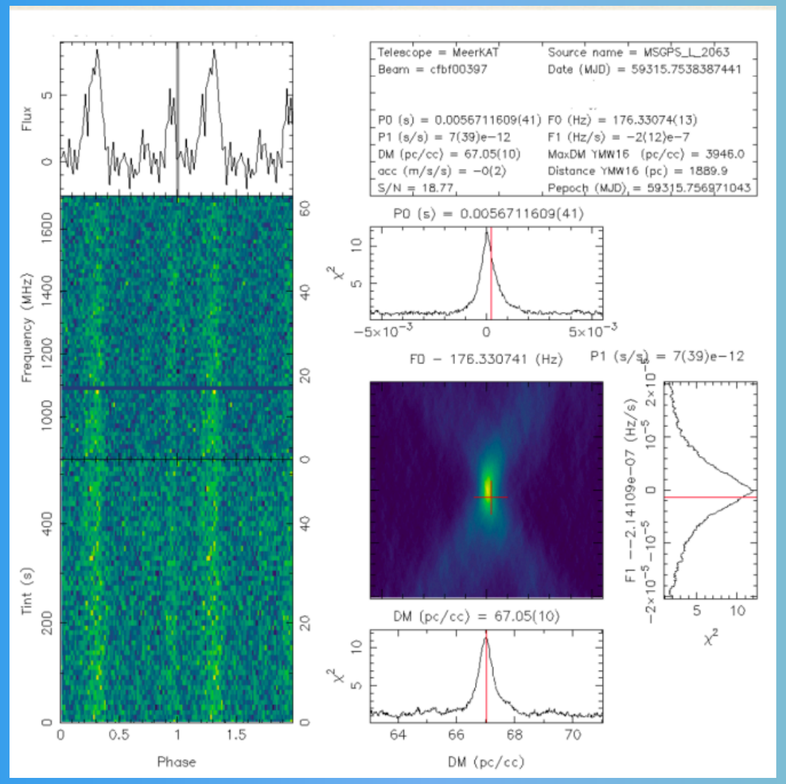
Only a handful are known!

Men et al. in prep




Tauris et al. 2011, 2012, MNRAS

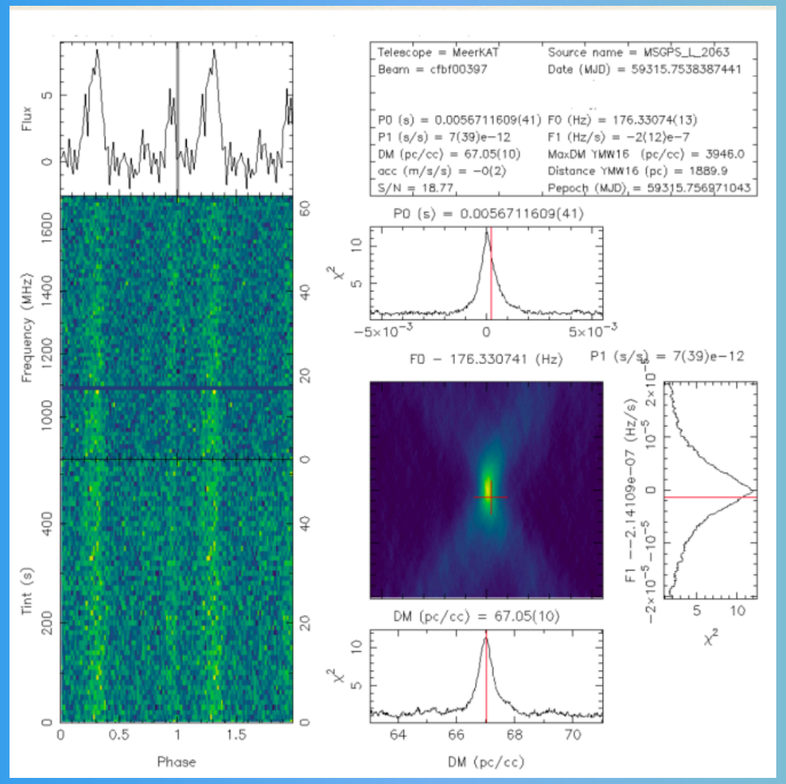
# Binary pulsars: PSR J1306-6043, A bright gamma-ray emitter!




- Spin period, P = 5.671 ms
- Pb = 85.91 days
- Eccentricity, e = 1.3e-4
- x = 40.41 lt-s
- M_c > 0.29 M⊙

Typical parameters for a HeWD companion!

# Binary pulsars: PSR J1306-6043, A bright gamma-ray emitter!

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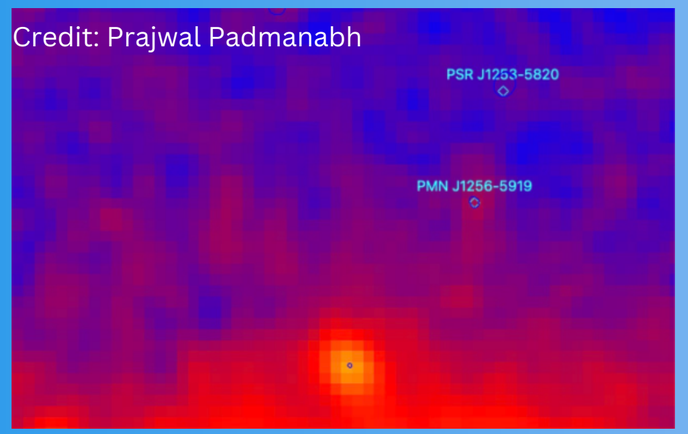
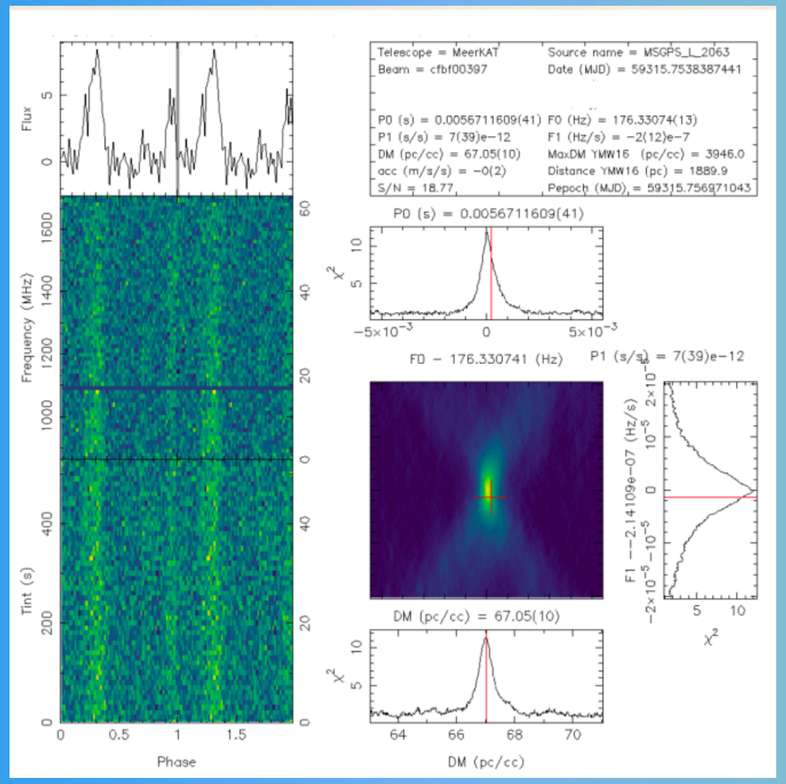
- x = 40.41 lt-s
- M_c > 0.29 M⊙

Typical parameters for a HeWD companion!

Found an associated Fermi source...



# Binary pulsars: PSR J1306-6043, A bright gamma-ray emitter!

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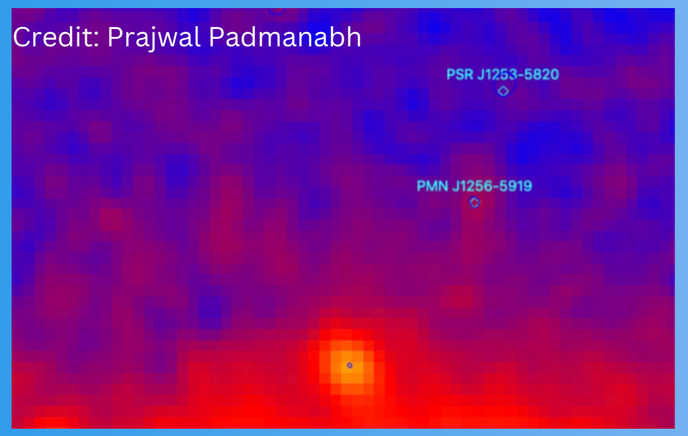
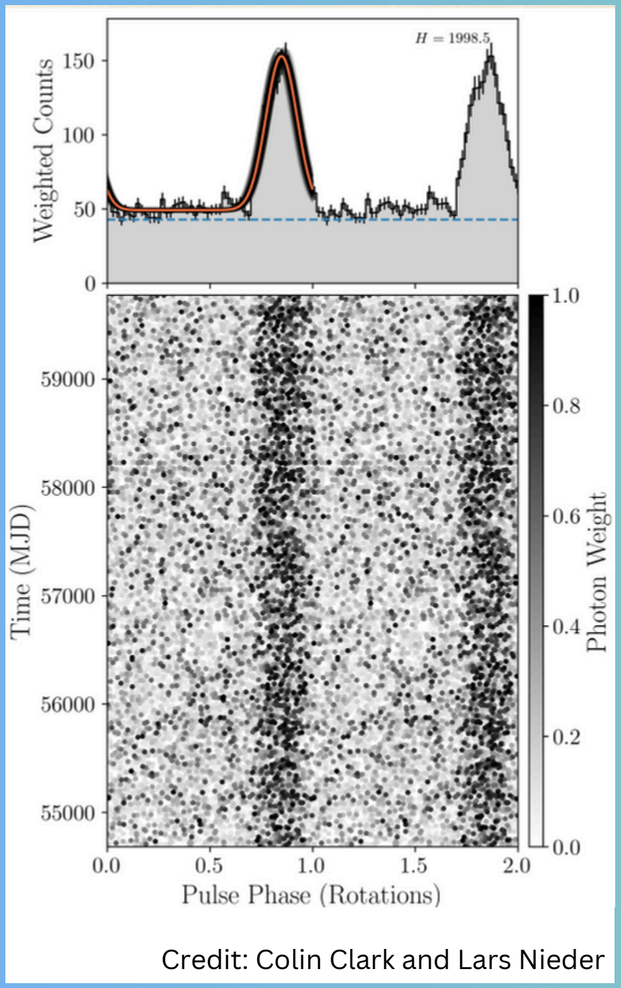
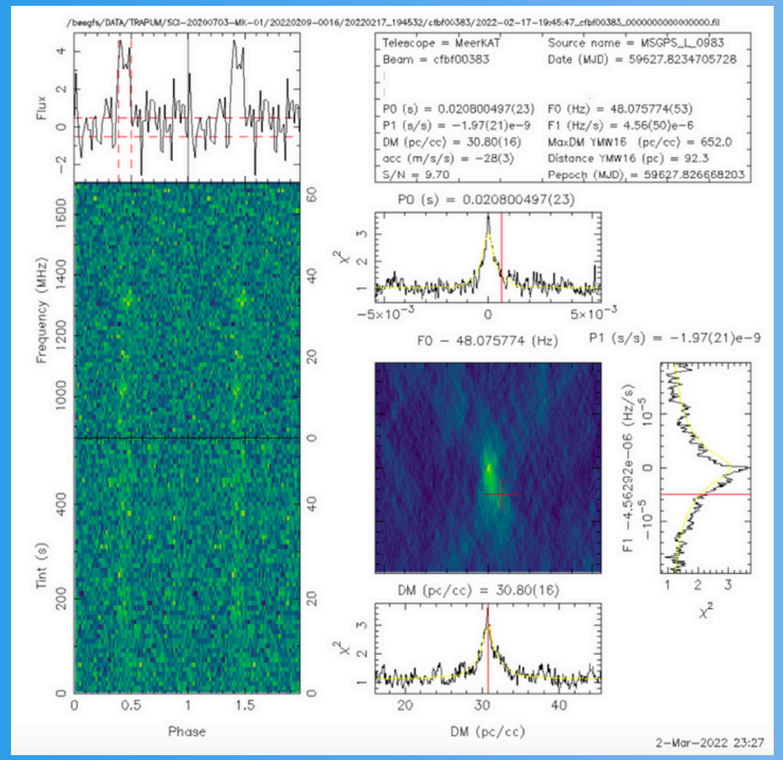



that revealed Gamma-ray pulsations!




Credit: Colin Clark and Lars Nieder

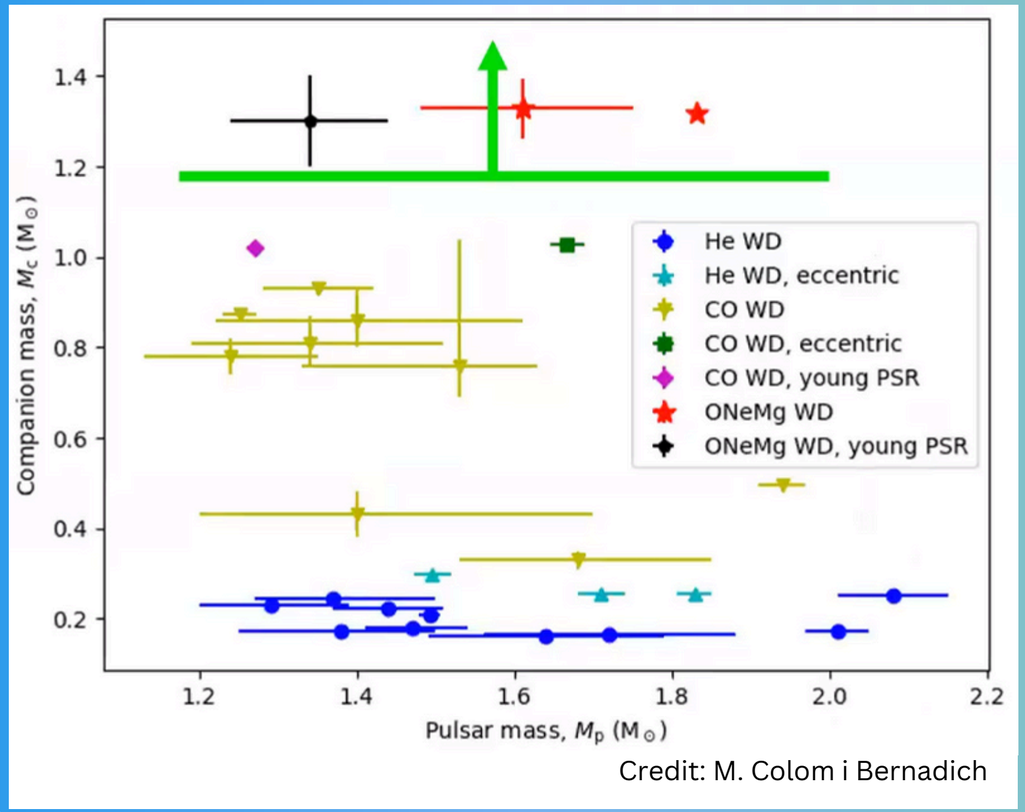
# Binary pulsars: PSR J1015-5359, a compact heavy WD system




- Spin period, P = 20.81 ms
- Pb = 0.333 days
- Eccentricity, e < 3e-4
- x = 2.991 lt-s
- M_c > 1.18 M⊙

**Low eccentricity hints to a massive WD companion!**

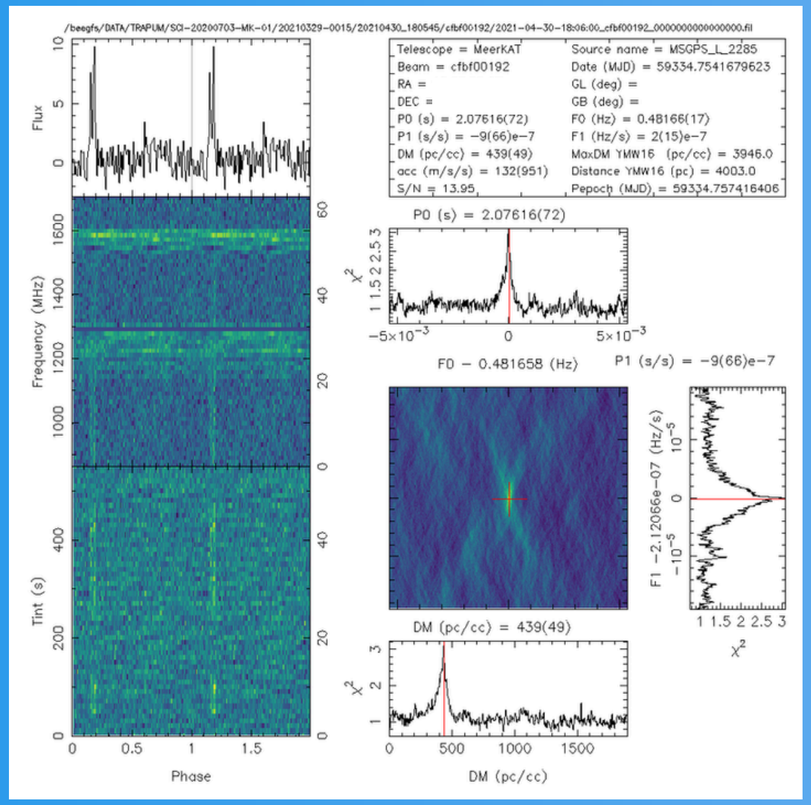
Venkatraman Krishnan et al., in prep



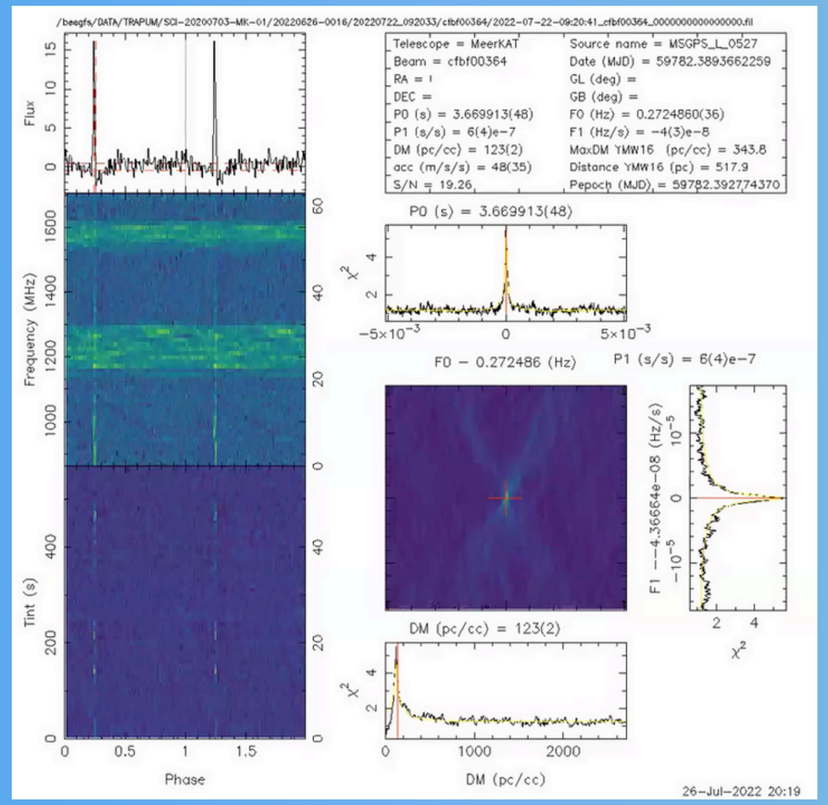

Credit: M. Colom i Bernadich

# Isolated pulsars and nulling

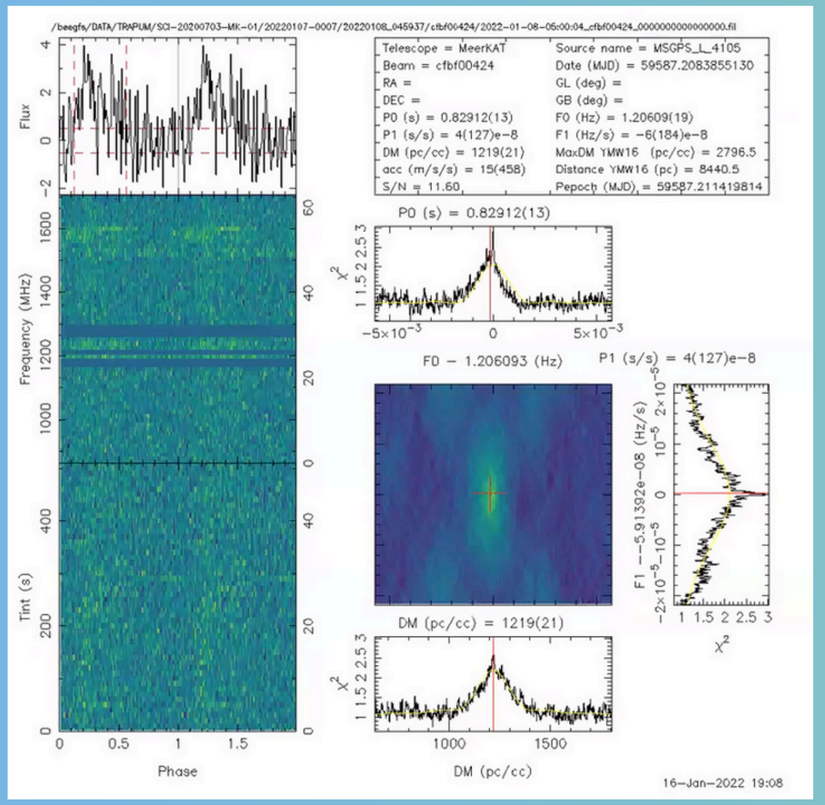
## PSR J1353-6341




## PSR J0933-4604

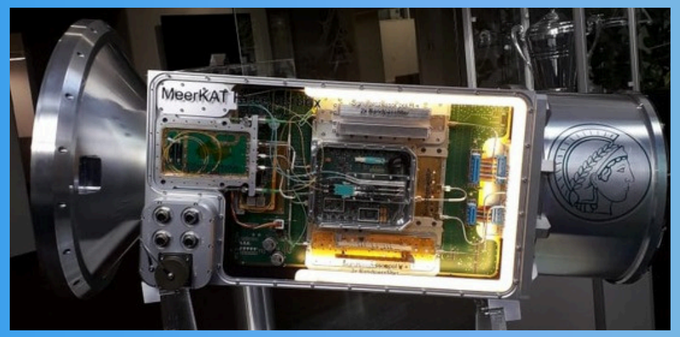



## PSR 1716-3811



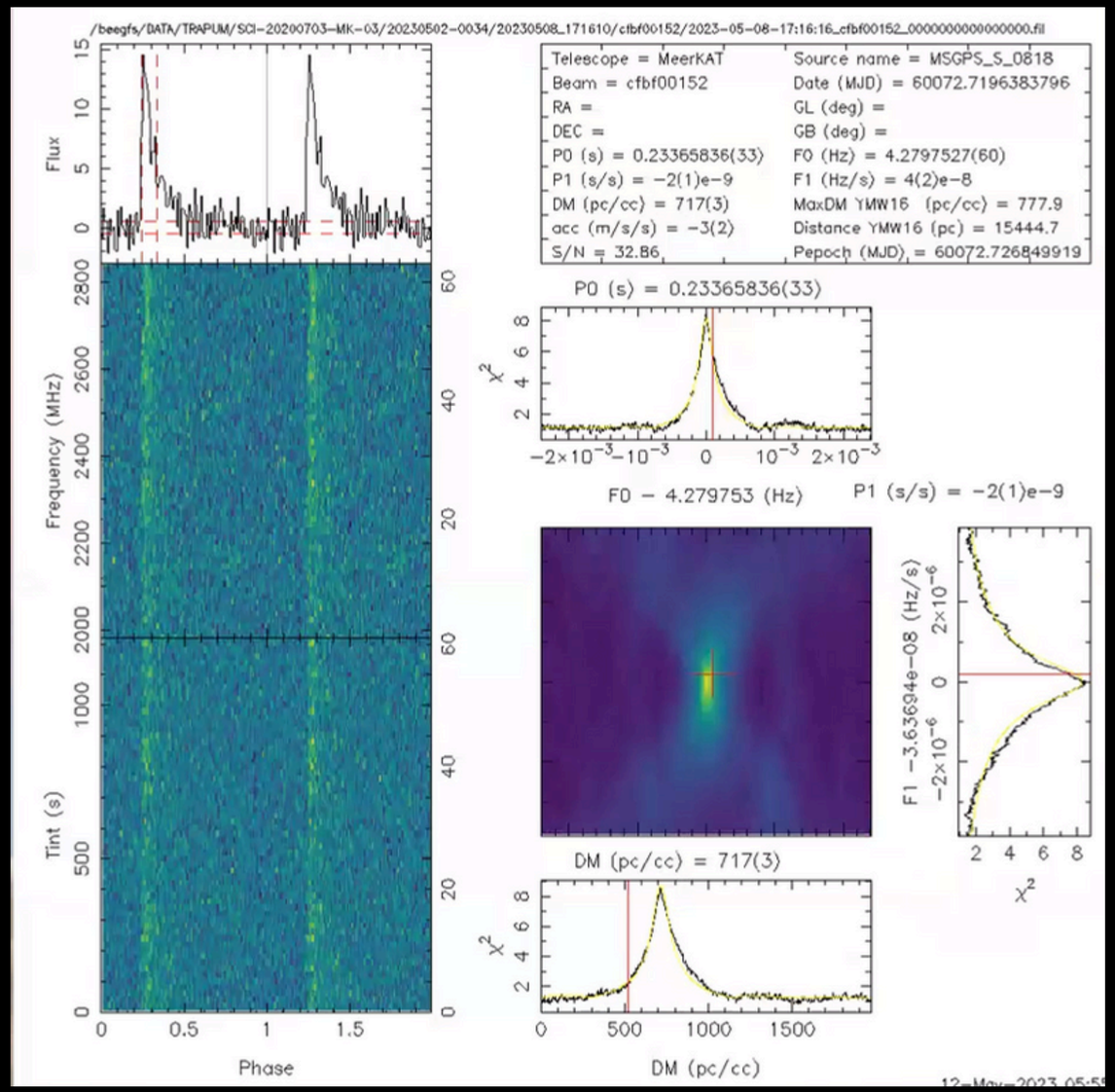
# Ongoing work:

- **S-band survey observations @ 2.4GHz**




MPIfR funded and developed S-band receivers

- **A follow-up of all isolated pulsars**
  - **Spin down (Ṗ ) measurement: Implications on formation, evolution, magnetic field and age**
  - **Polarization profile studies: magneto-ionic ISM studies**
  - **Spectral index measurements: Pulsar emission mechanisms**
- **MMGPS-UHF and MMGPS-SgrA* planning**

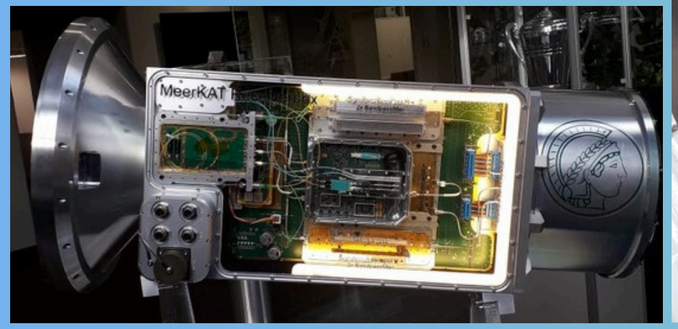


# Summary

- Previous surveys have provided high-impact science results, but with current-generation radio telescope sensitivity, new surveys are needed to probe deeper into the Galactic plane.

- The pulsar science objectives of the MMGPS are to find compact relativistic binaries, a pulsar orbiting SgrA*, MSPs with stable timing properties, and study binary evolution, and emission mechanisms

- We have discovered many pulsars using the instrumentation (APSUSE and FBFUSE) and S-band receivers designed and developed by the MPIfR.
  - MMGPS-L:
    - 78 pulsars
      - 17 in binary systems
        - 2 DNS systems
        - Variety of WD companions
        - 1 Gamma-ray pulsar
      - Nulling/Intermittent pulsars
  - MMGPS-S:
    - 3 pulsars





- Ongoing work:
  - S-band survey
  - Follow-up L band isolated discoveries
  - MMGPS-UHF and MMGPS-SgrA* planning