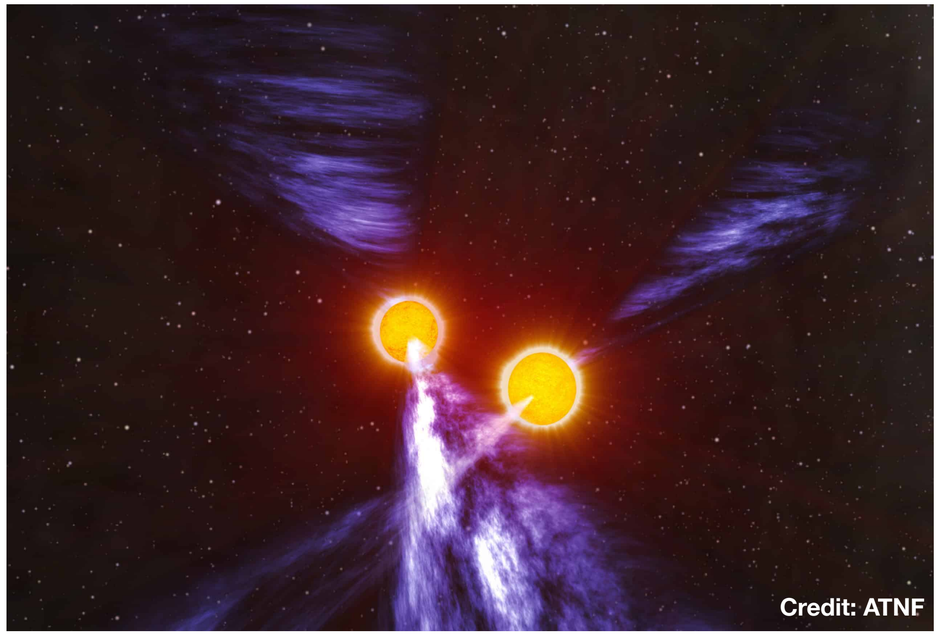
Transients and Pulsars with MeerKAT (TRAPUM)



Prajwal V. Padmanabh

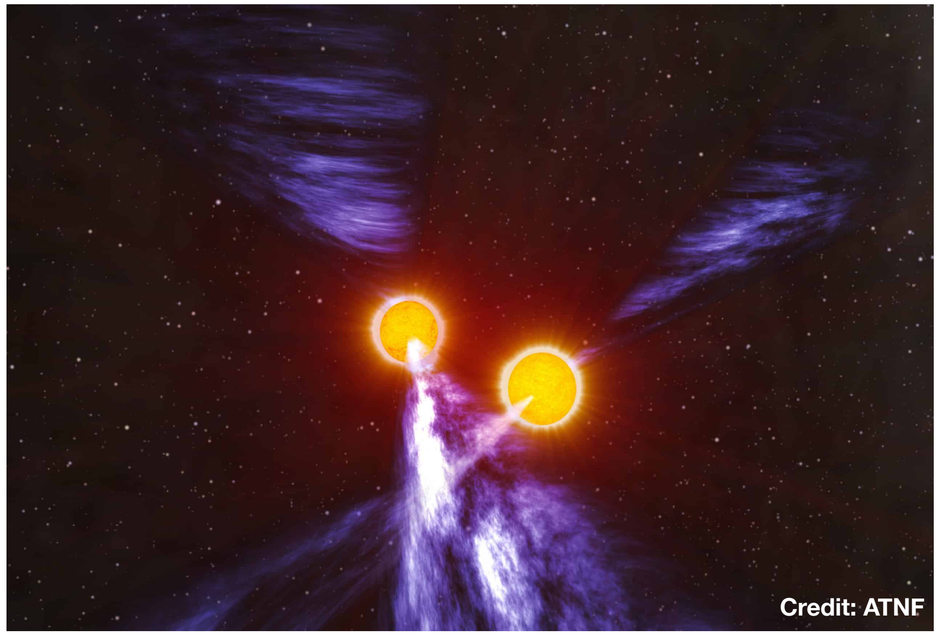
Max Planck Institute for Gravitational Physics (Albert Einstein Institute)

(On behalf of the TRAPUM consortium)

FTSky 2025 - October 17th 2025

~~Transients and~~ Pulsars with MeerKAT (TRAPUM)

TRAPUM
Transients and Pulsars with MeerKAT



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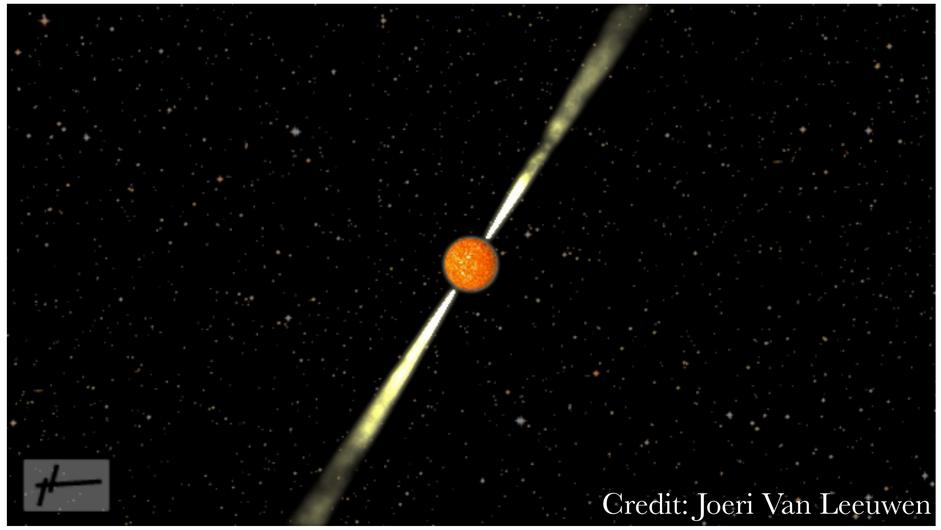
einstein @ home

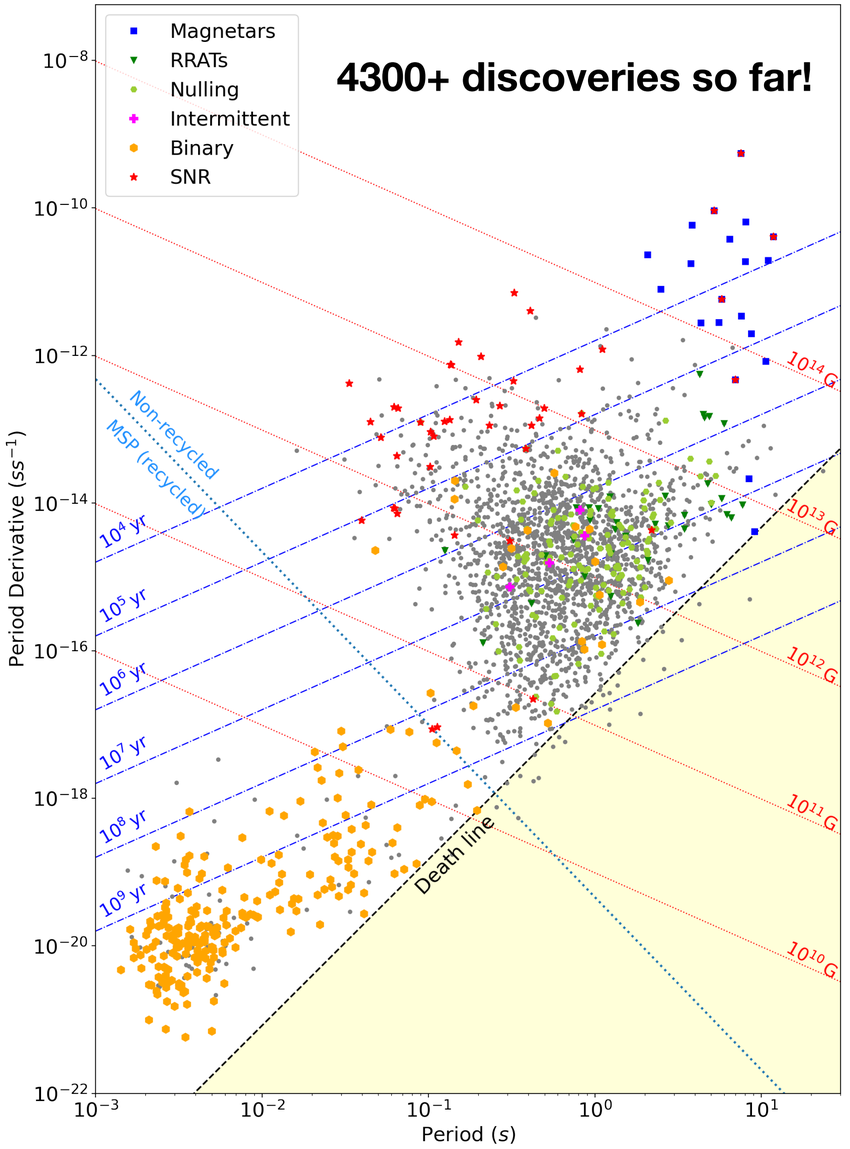
Talk overview

- **Pulsars:** a quick recap
- **Why** continue to **search** for pulsars ?
- **How** is it actually done ?
- Introduction to **MeerKAT**
- Introduction to **TRAPUM**
- **Scientific** and **technical** highlights
- **Future prospects**

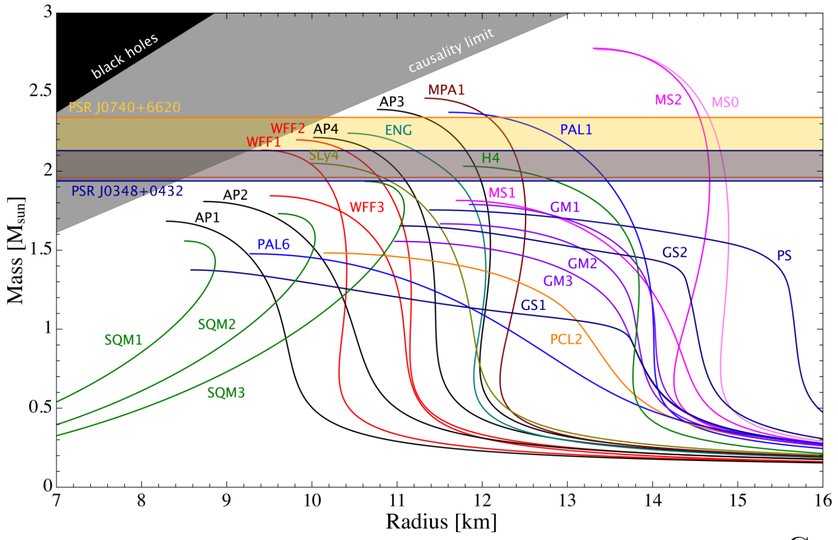
Pulsars



- Formed from supernovae explosions
- Massive neutron stars **(M ~ 1.4 M_{sun})**
- Compact objects **(R ~ 10-20 Km)**
- Highly magnetised **(~ 10^{12} G)**
- Rapidly rotating **(P ~ milliseconds to seconds)**
- Emit across multiple wavelengths (Radio to Gamma rays)

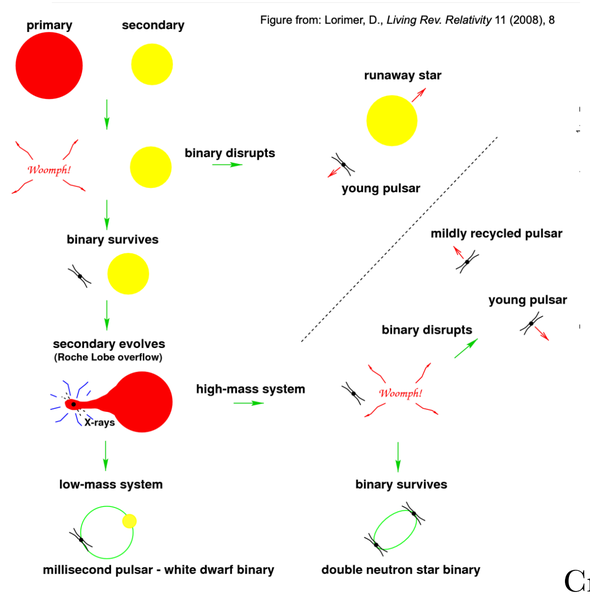


Why continue searching?



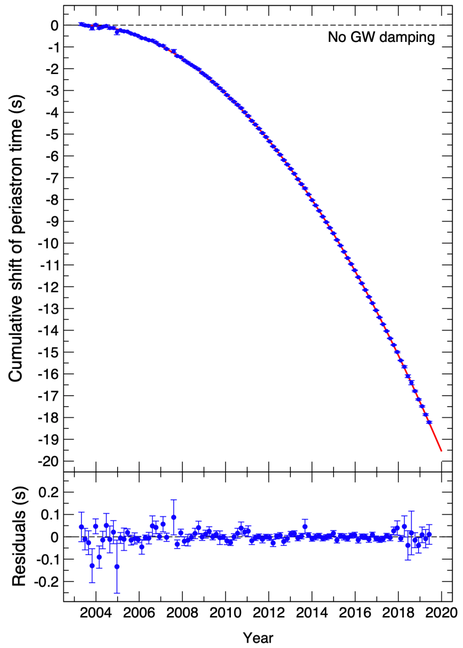
Credit: Norbert Wex

Constrain the neutron star equation of state



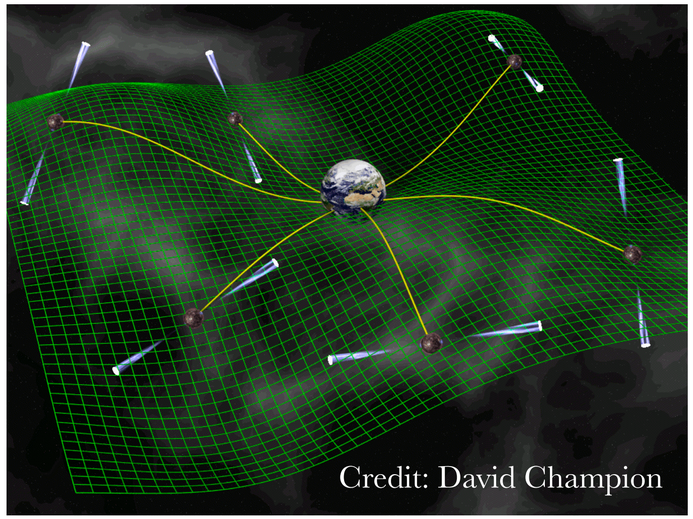
Credit: Duncan Lorimer

Stellar formation and evolution



Credit: Michael Kramer

Testing gravity in the strong field-regime

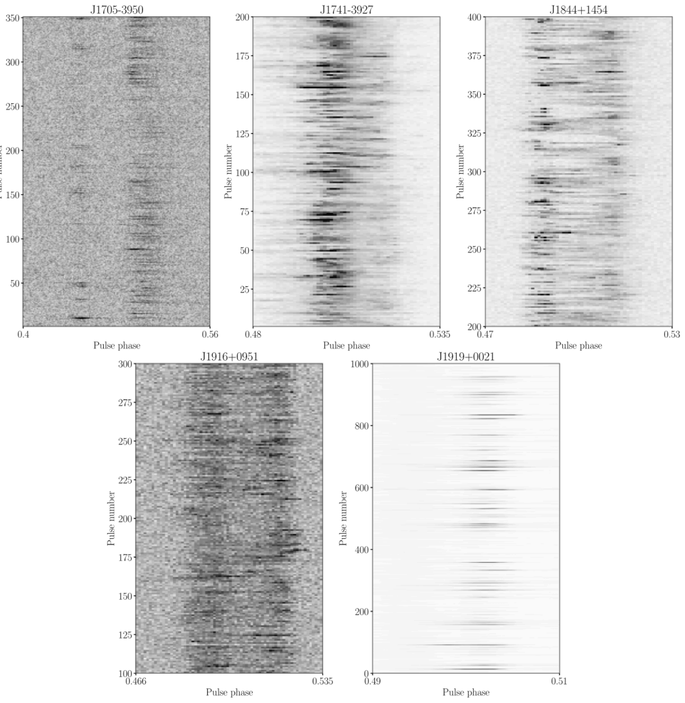


Credit: David Champion

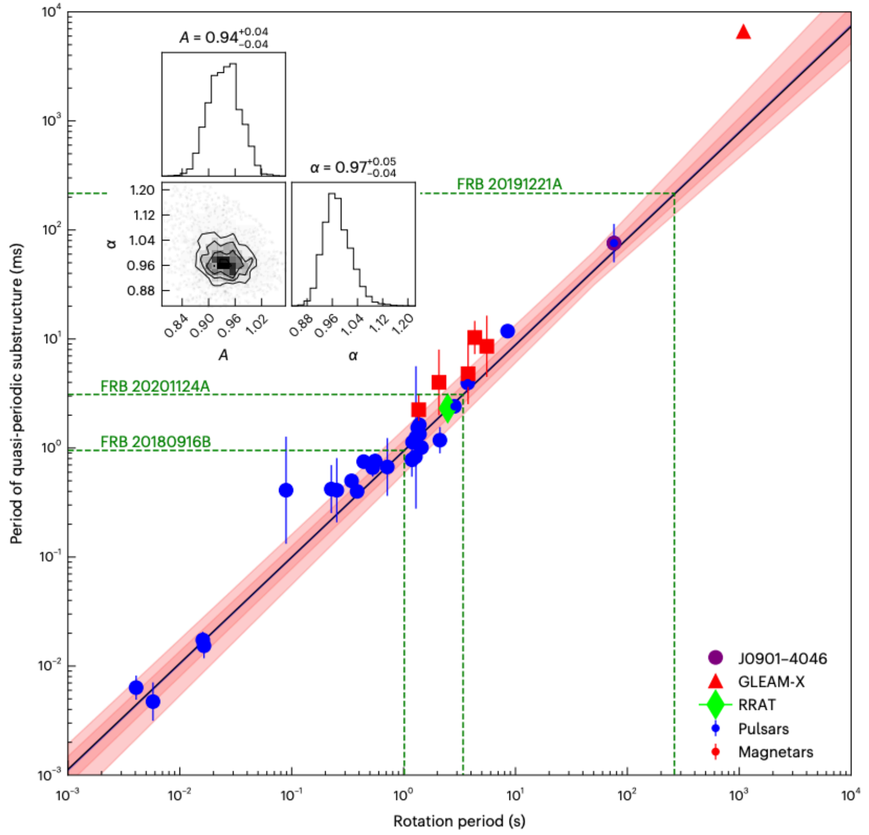
Detection of GW background

Understanding pulsar emission physics - links to FRBs?

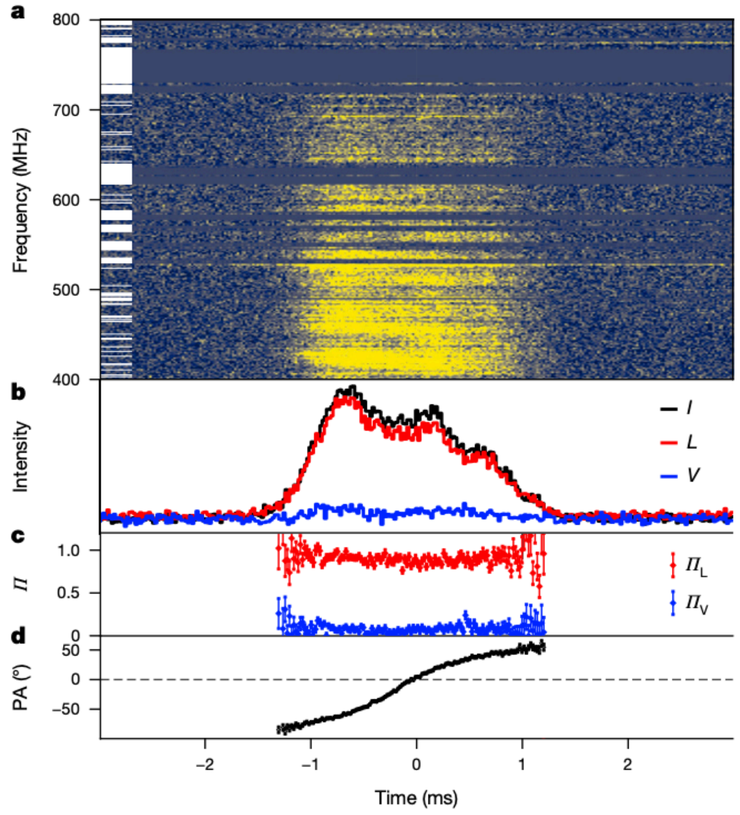
Intermittency, nulling, quasi-periodic substructure, profile evolution



(Basu et al. 2024)



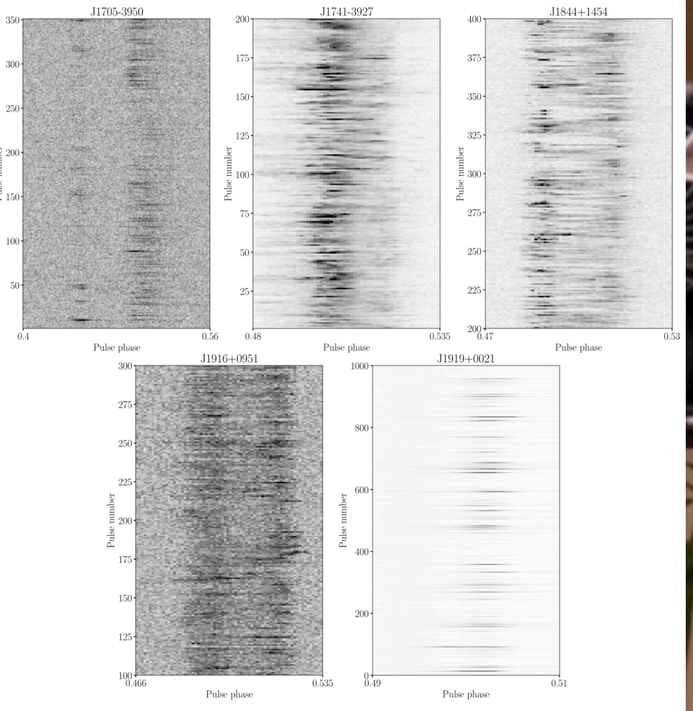
(Kramer et al. 2023)



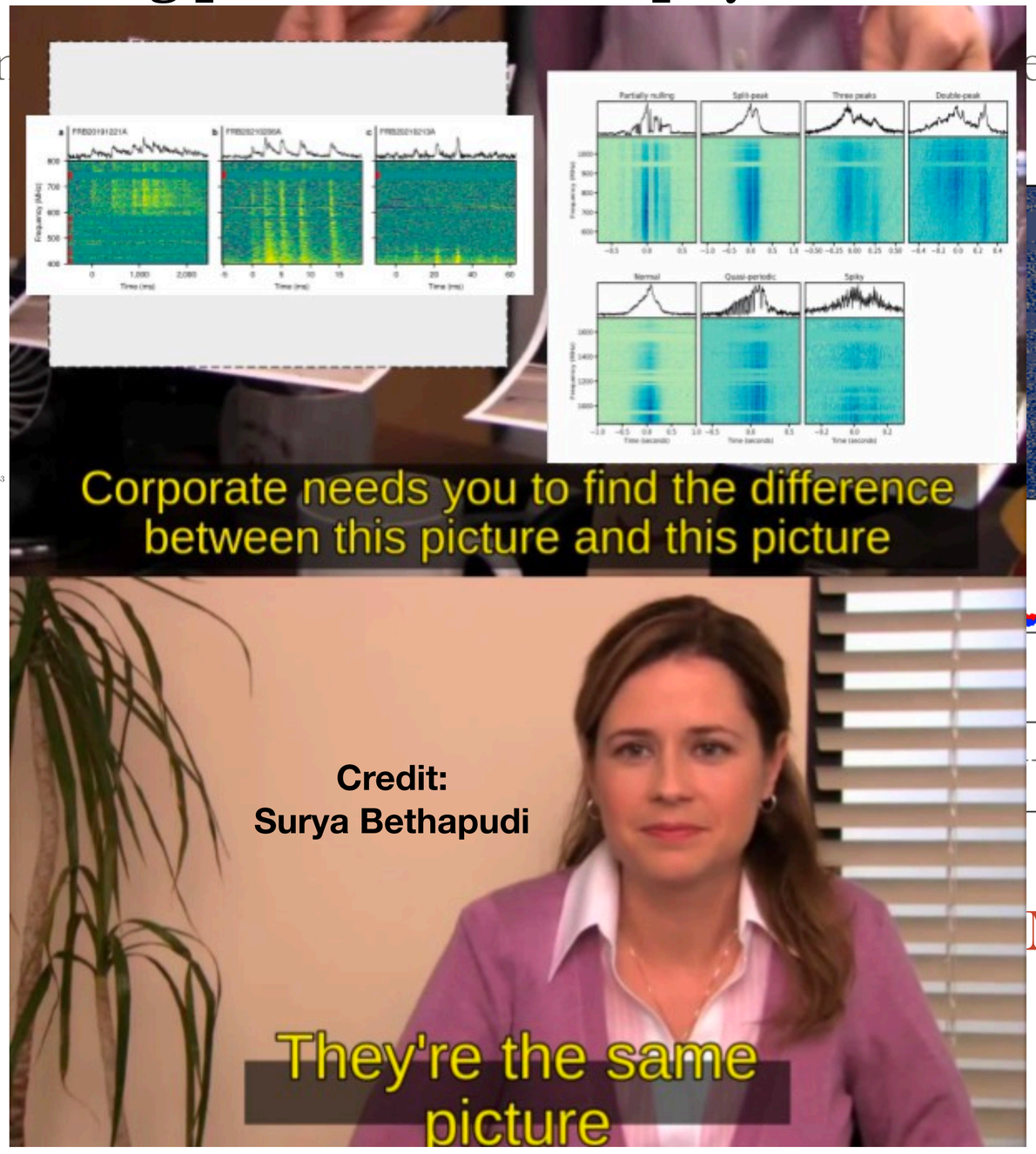
(Mckinven et al. 2025)

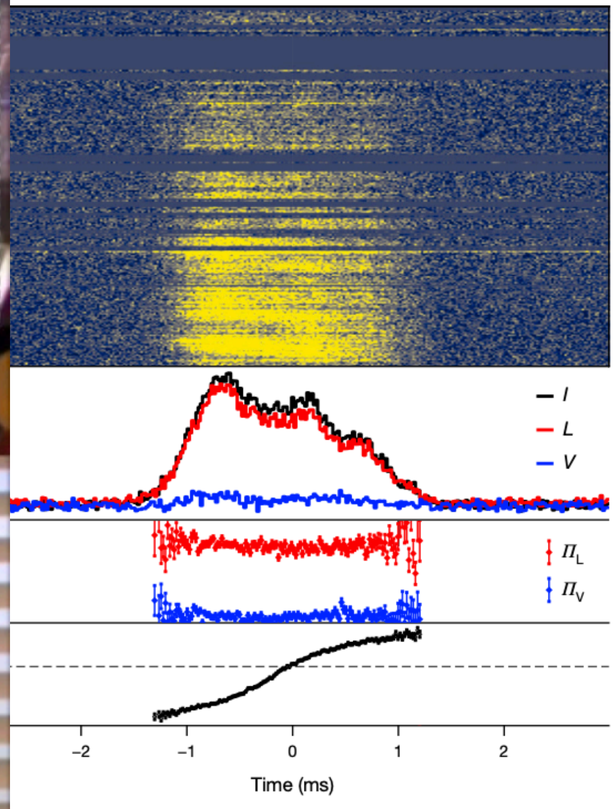
Understanding pulsar emission physics - links to FRBs?

Intermittency, r evolution



(Basu et al. 2024)



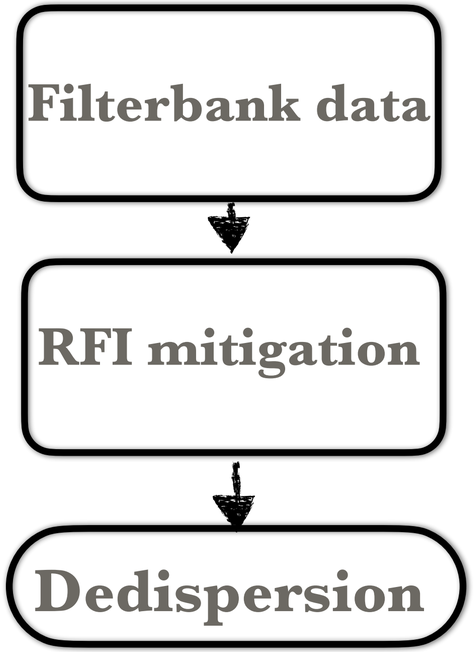


(Mckinven et al. 2025)

How to search?

Search Methodology

What's common with FRBs



Candidate Classification
(Typically ML based)

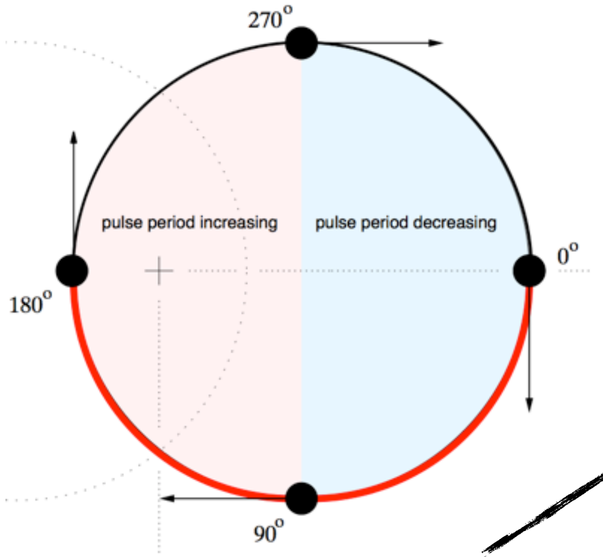
Search Methodology

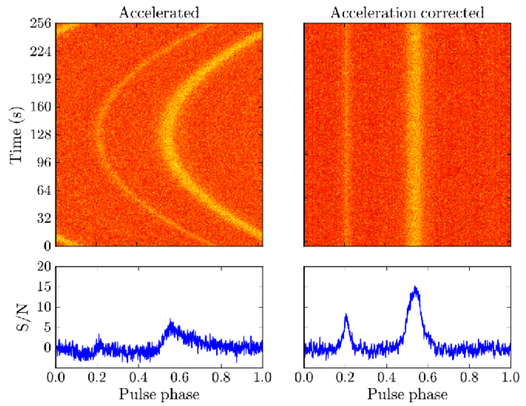
What's ~~common with FRBs~~ done for pulsars

Filterbank data

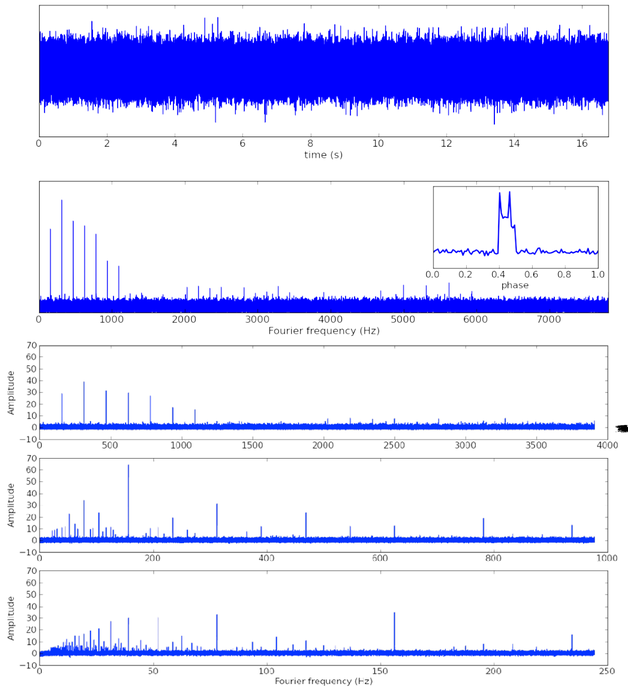
RFI mitigation

Dedispersion

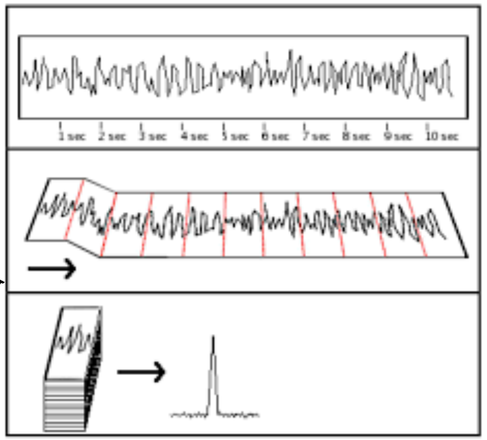




Binary motion correction



FFT based periodicity search



Folding

Candidate Classification
(Typically ML based)

Search Methodology

What's ~~common with FRBs~~ done for pulsars

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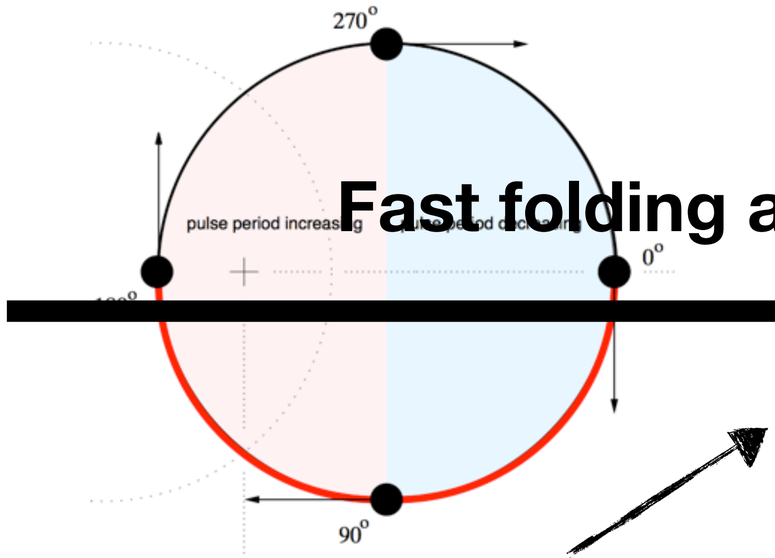
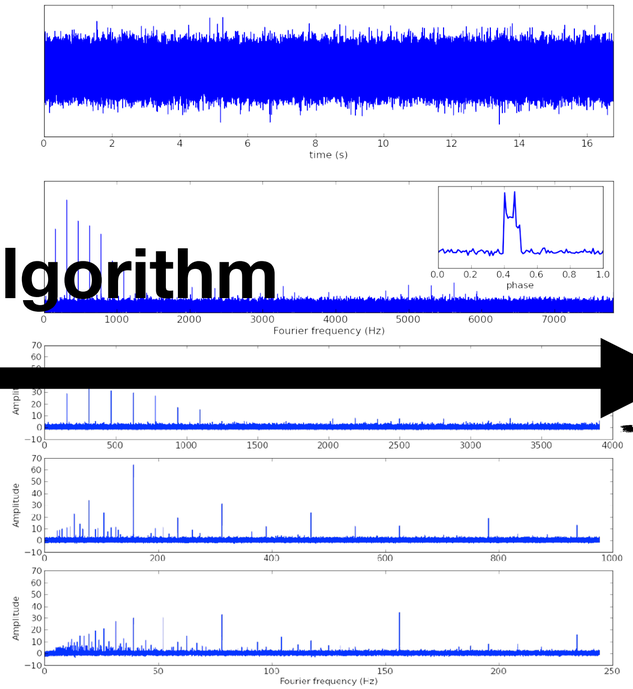
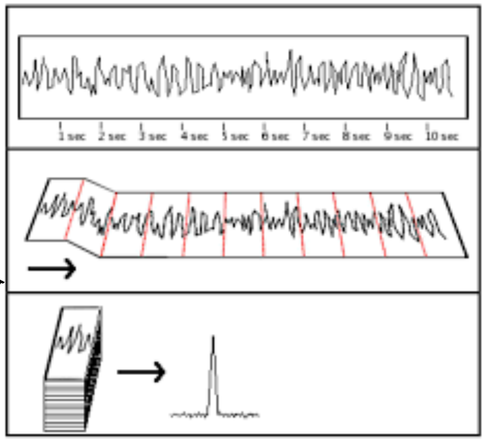


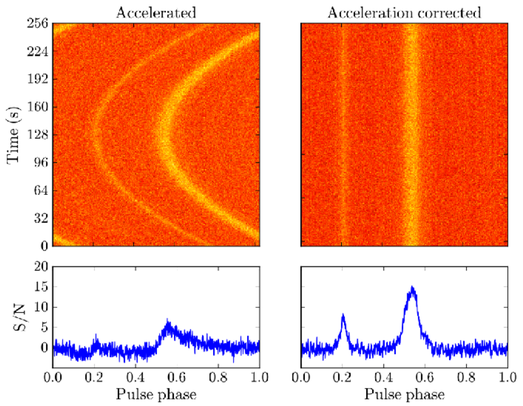
Fast folding algorithm



FFT based periodicity search



Folding



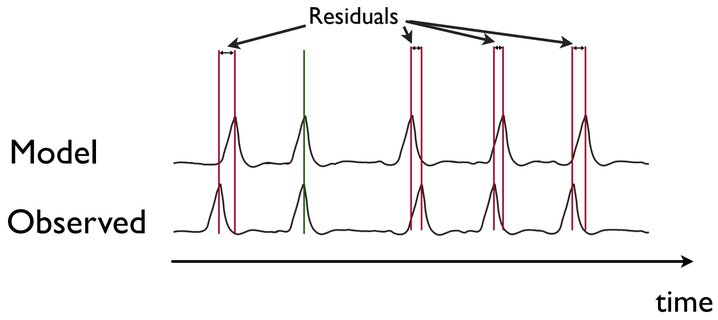
Binary motion correction

Candidate Classification
(Typically ML based)

What to do after discovering a pulsar?

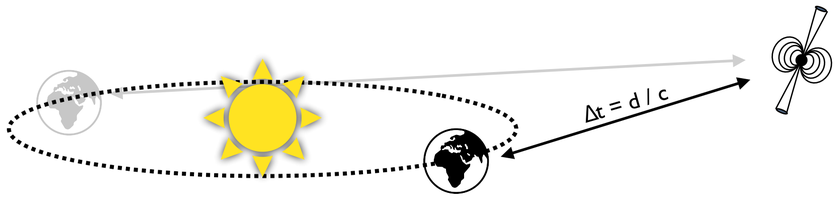
Pulsar Timing

Regular monitoring of incoming pulses

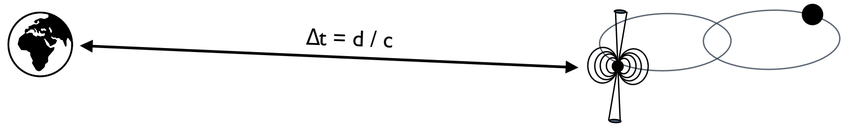


Aim: To provide a model that can predict time of arrival of every pulse!

- Earth motion

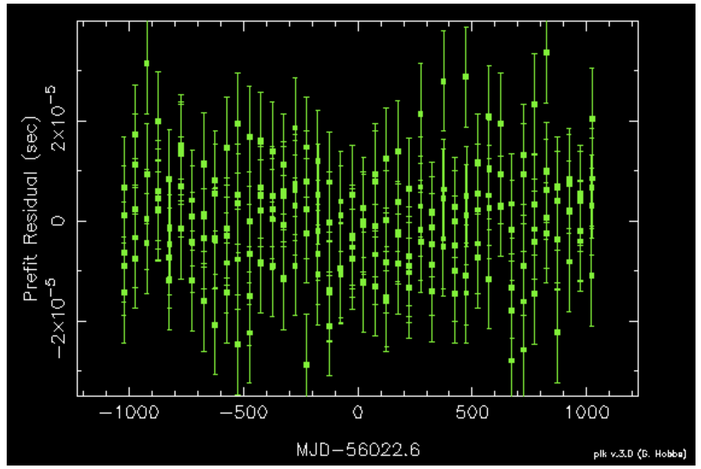


- Binary motion



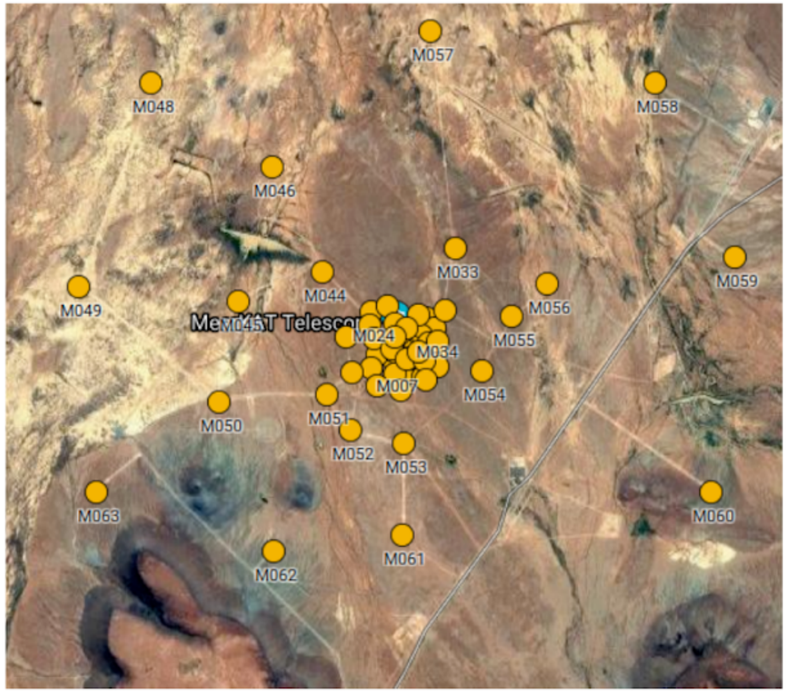
- Interstellar medium

If successful,



Good timing model

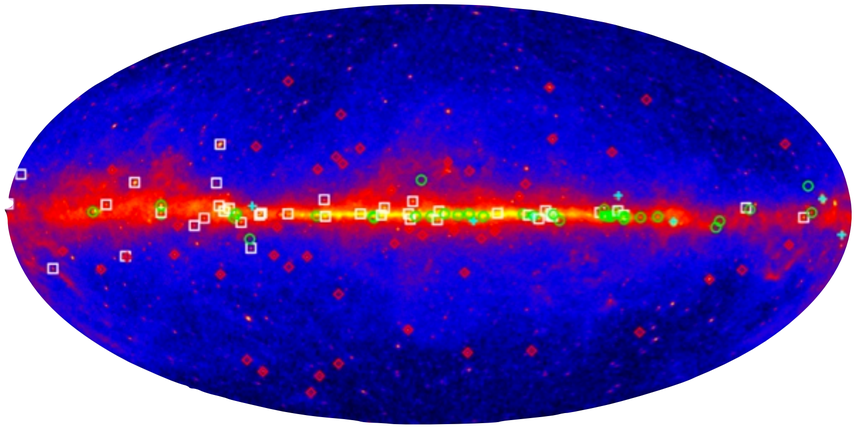
Introduction to MeerKAT



- Most sensitive in the Southern Sky
- Fully steerable
- Large frequency coverage (0.5 - 3.5 GHz)
- Sub-array feature
- Beamforming / localisation capability

Has the makings of a pulsar search instrument!

Nearby galaxies



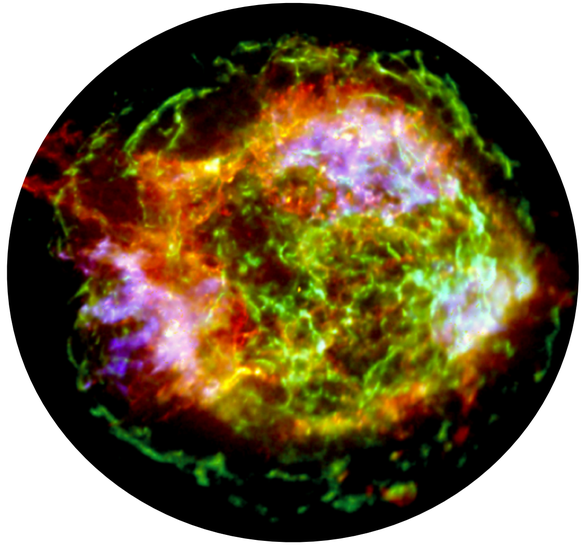
Unassociated Fermi sources

TRAPUM

Transients and **Pu**lsars with **M**eerKAT

Targeted survey for finding pulsars

Globular clusters



SNR/PWN/TeV sources

Who are we?

TRAPUM

MANCHESTER 1824
The University of Manchester

UBC

Universität Bielefeld

MAX PLANCK INSTITUTE
FOR RADIO ASTRONOMY

NRF
National Research Foundation
SARAO
South African Radio Astronomy Observatory

MPE

UNIVERSITÄT HEIDELBERG
ZUKUNFT SEIT 1386

NWU®
NORTH-WEST UNIVERSITY
NOORDWES-UNIVERSITEIT
YUNIBESITI YA BOKONE-BOPHIRIMA

Max-Planck-Institut
für Gravitationsphysik
Albert-Einstein-Institut

NRAO

cnrs

SWINBURNE UNIVERSITY OF TECHNOLOGY

UNIVERSITY of VIRGINIA

SKAO

University of Cape Town • iYunivesithi yaseKapa • Universiteit van Kaapstad

UNIVERSITY OF AMSTERDAM

INAF
ISTITUTO NAZIONALE DI ASTROFISICA
NATIONAL INSTITUTE FOR ASTROPHYSICS

NUI Galway
OÉ Gaillimh

Who are we?

Prof. Michael Kramer

PIs

Prof. Ben Stappers

Working group chairs

SNR/PWN/TeV

Fermi

Prof. Rene Breton & Dr Colin Clark

Nearby galaxies

Dr Lina Levin-Preston

Globular clusters

Dr Alessandro Ridolfi

Follow up

Dr Marta Burgay

Project scientist

Dr Ewan Barr

70+ members from 20+ institutes, 30+ Masters and PhD students (10+ graduations so far)

State-of-the-art Instrumentation

In every branch of knowledge the progress is proportional to the amount of facts on which to build, and therefore to the facility of obtaining data.
- James Clerk Maxwell

Need:
Receiver for deep pulsar searches
(high DM)

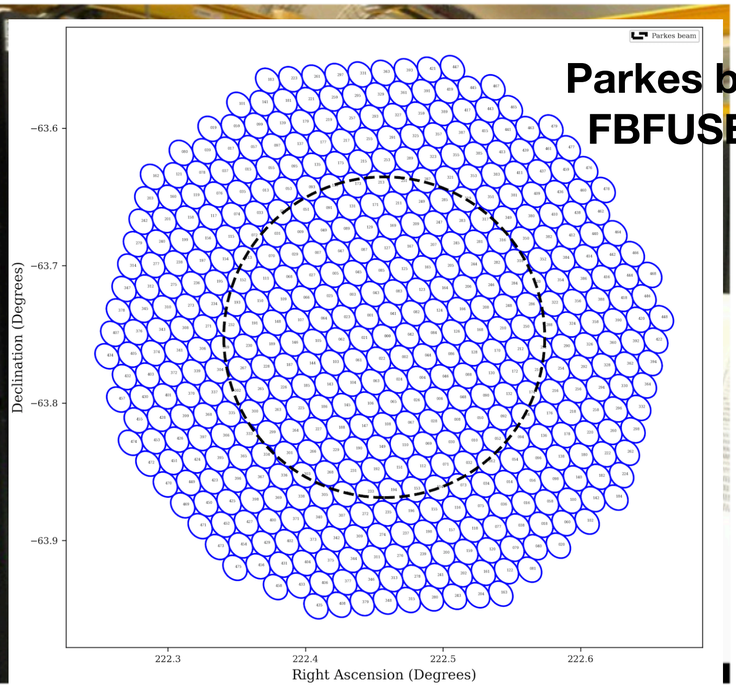
Solution:
S-Band receivers
1.7-3.5 GHz, 875 MHz inst. BW

State-of-the-art Instrumentation

In every branch of knowledge the progress is proportional to the amount of facts on which to build, and therefore to the facility of obtaining data.
- James Clerk Maxwell

Need:
Maximum sensitivity and coverage for an interferometer

Solution:
FBFUSE
Multibeam beam former
Can produce 100s of beams



Parkes beam vs FBFUSE tiling

State-of-the-art Instrumentation

In every branch of knowledge the progress is proportional to the amount of facts on which to build, and therefore to the facility of obtaining data.
- James Clerk Maxwell

Need:
Back-end for deploying pulsar search software

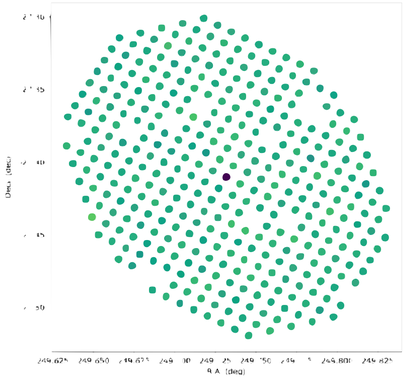
Solution:
APSUSE
HPC facility equipped with 120 GPUs
Quasi-real time searching

APSUSE

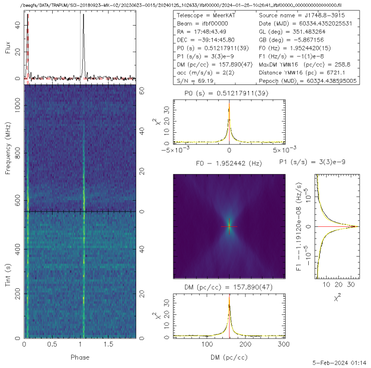
RECORD DATA

Search all beams

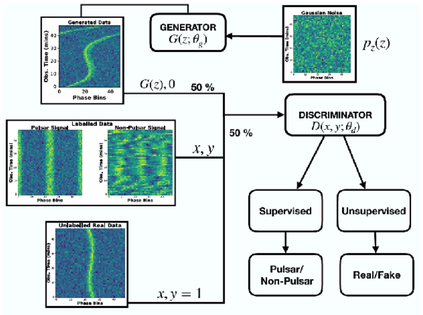
Spatial filter



Fold candidates

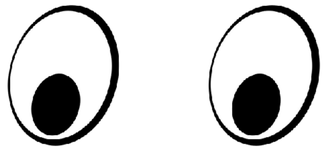


ML classification



Cut candidates

Visual inspection



Delete data

Credit: Ewan Barr

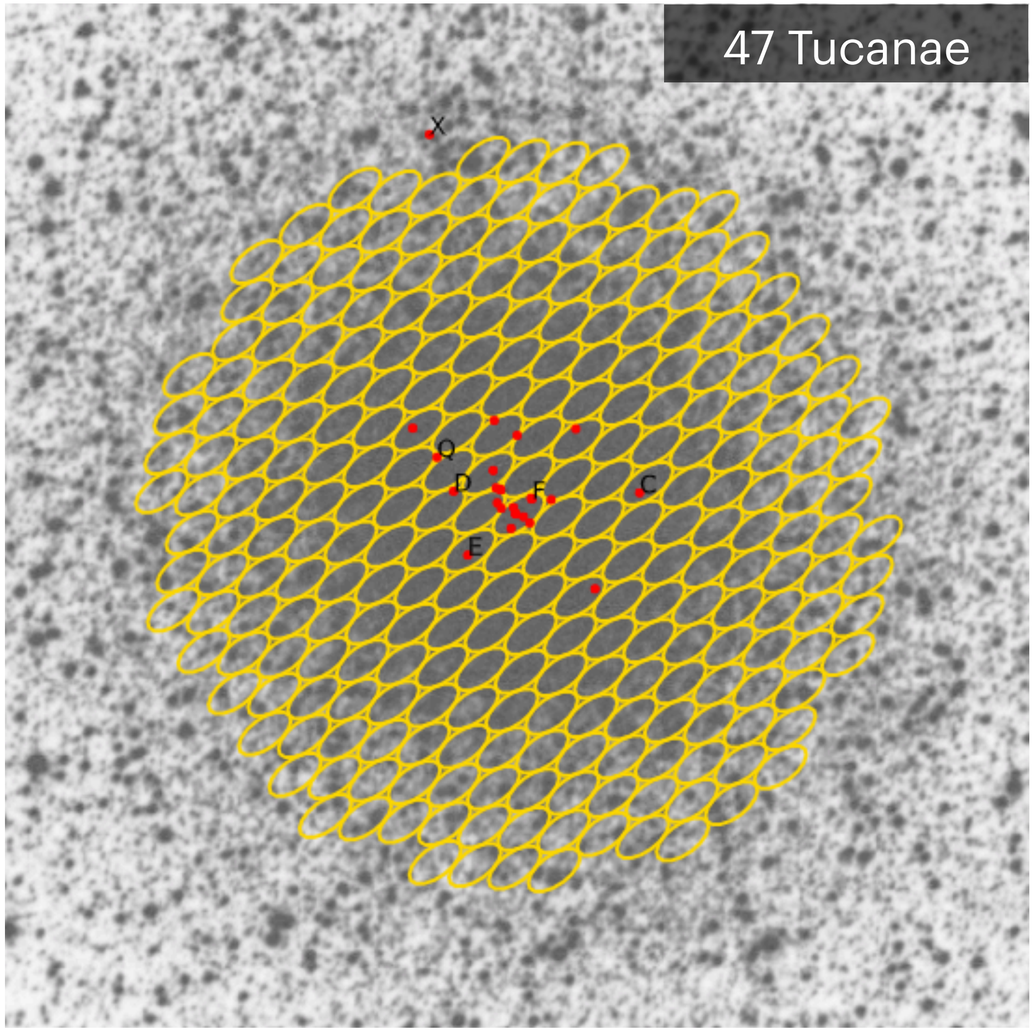
Why Globular clusters?

Dense → Dynamic interactions → **Unique binaries**

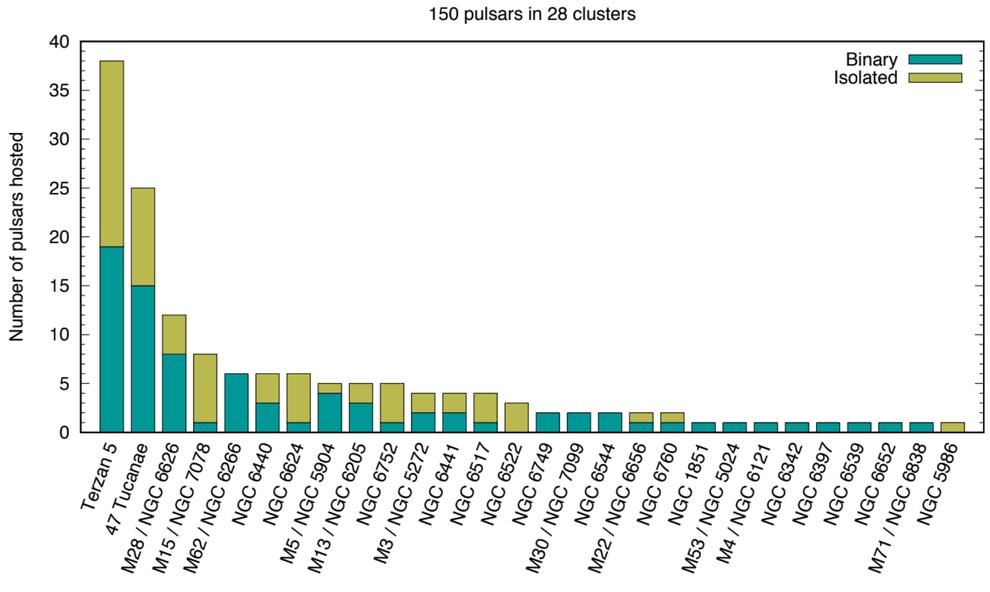
Search Strategy

- Subbanded to reduce data volume
- FFT based
- Acceleration search to find binaries
- Segmented searches to boost sensitivity to compact binaries
- Tiling of nearly 300 beams with high overlap
- Targets:

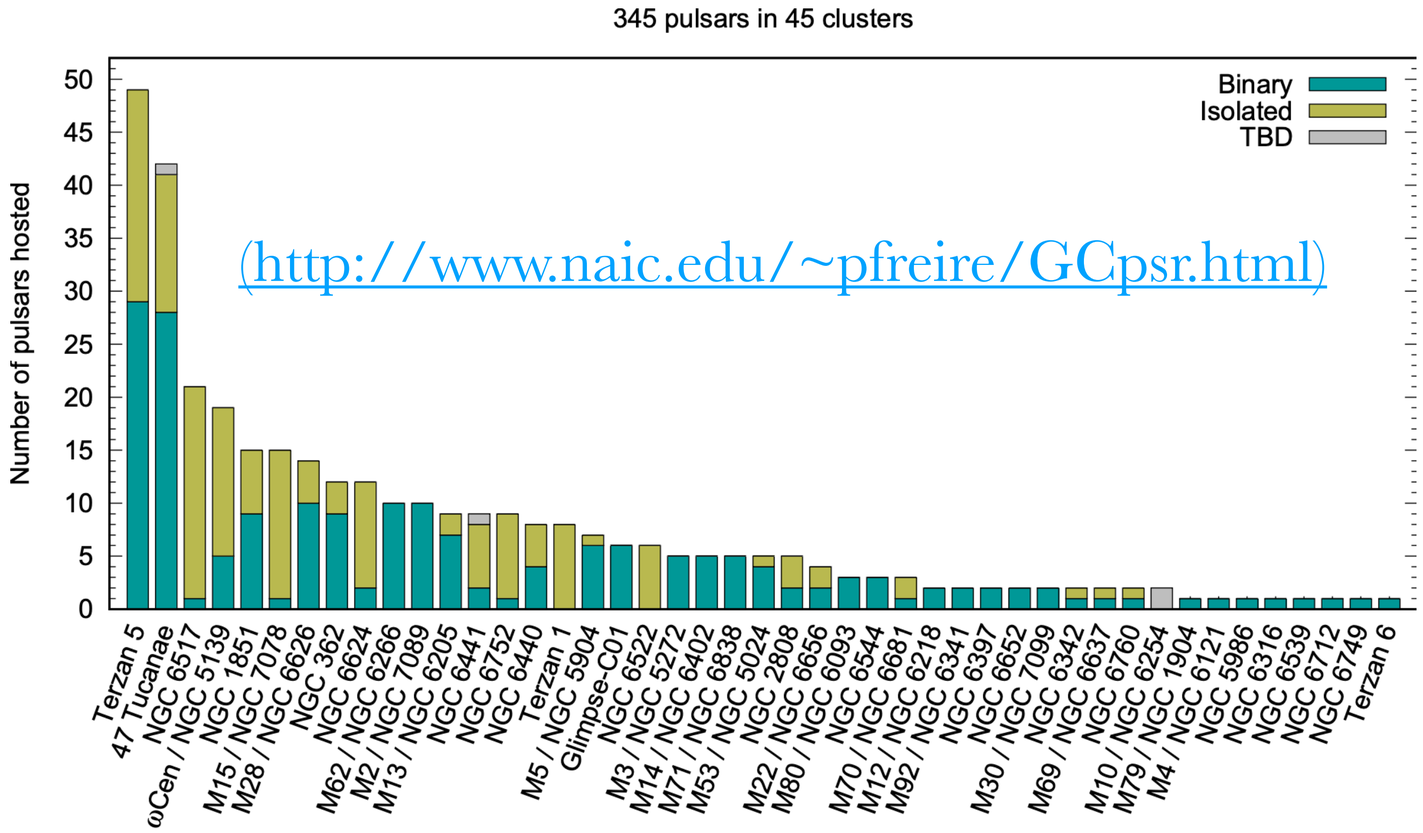
  Large area | high number of pulsars | core-collapsed | high gamma-ray flux



Globular cluster searches: Current status



Pre MeerKAT and FAST era



(http://www.naic.edu/~pfreire/GCpsr.html)

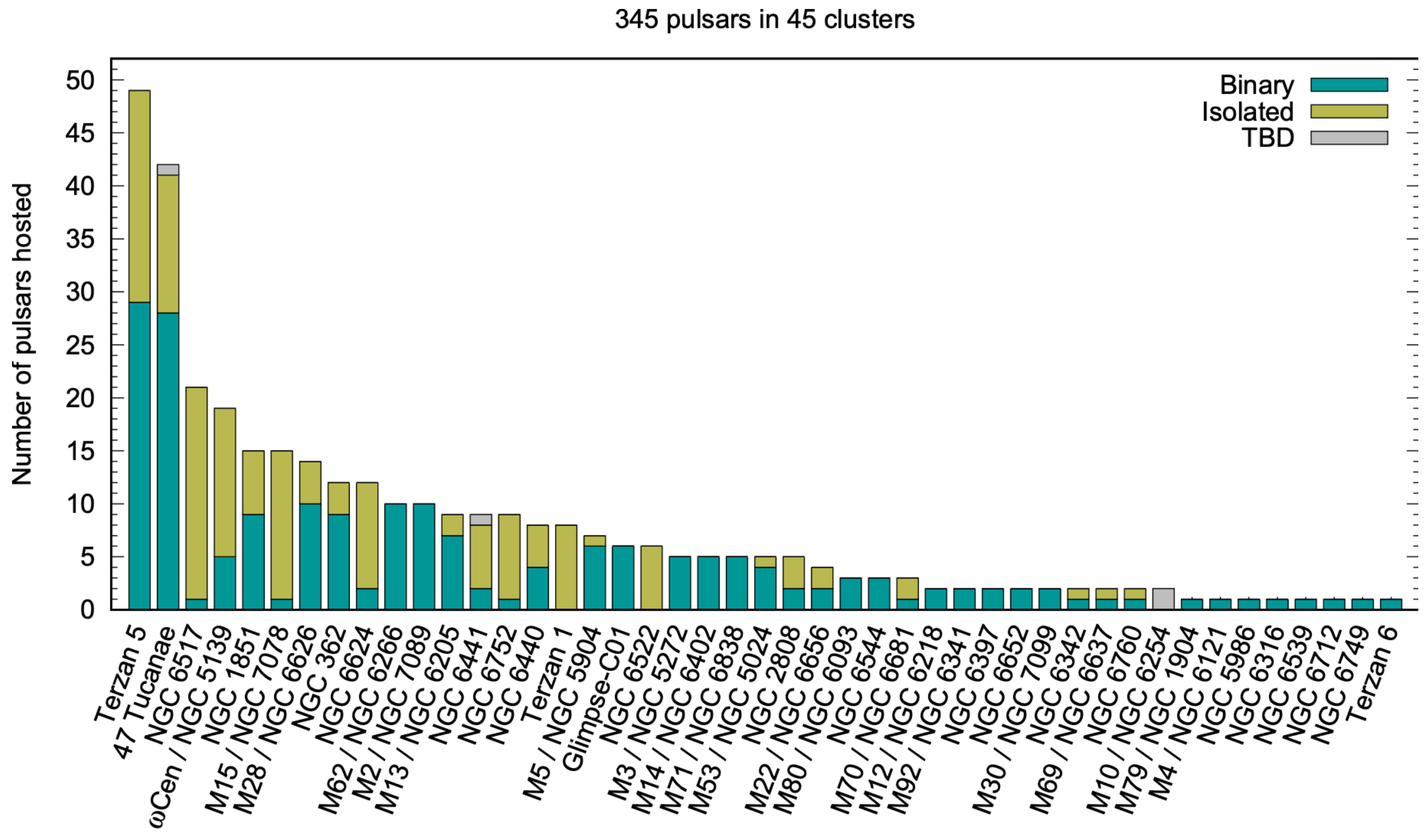
106 discoveries from MeerKAT

http://trapum.org/discoveries/

Past

Now

Globular cluster searches: Highlights



High DM

Nag et al., in prep

Eccentric

Ridolfi et al. 2021
Padmanabh et al. 2024

Eclipsing

Douglas et al. 2022
Chen et al. 2023

Exchange products

Ridolfi et al. 2022

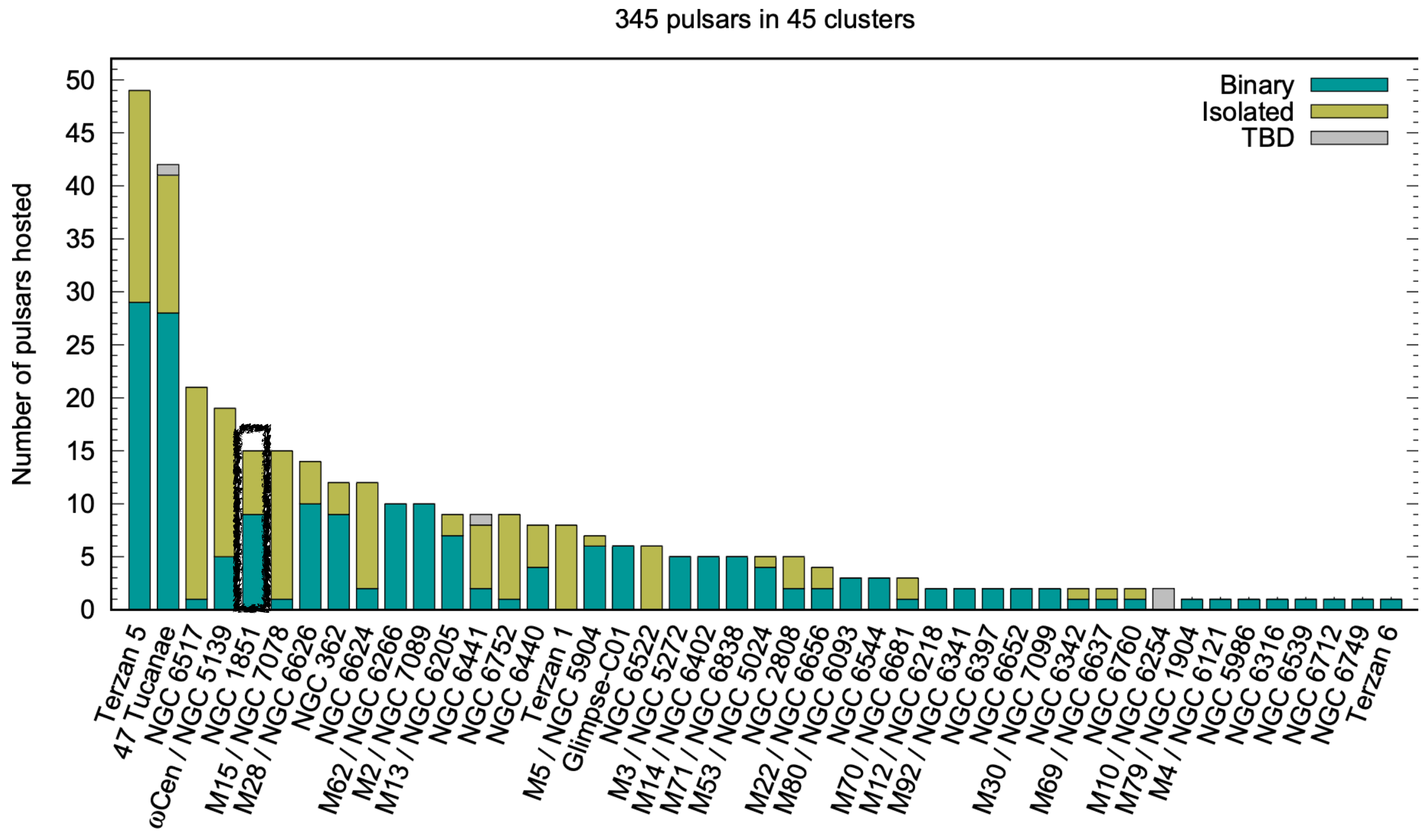
Slow spinning

Abbate et al. 2022

New discoveries with unknown DM

Jawor et al., in prep

Globular cluster searches: Highlights



High DM

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Jawor et al., in prep

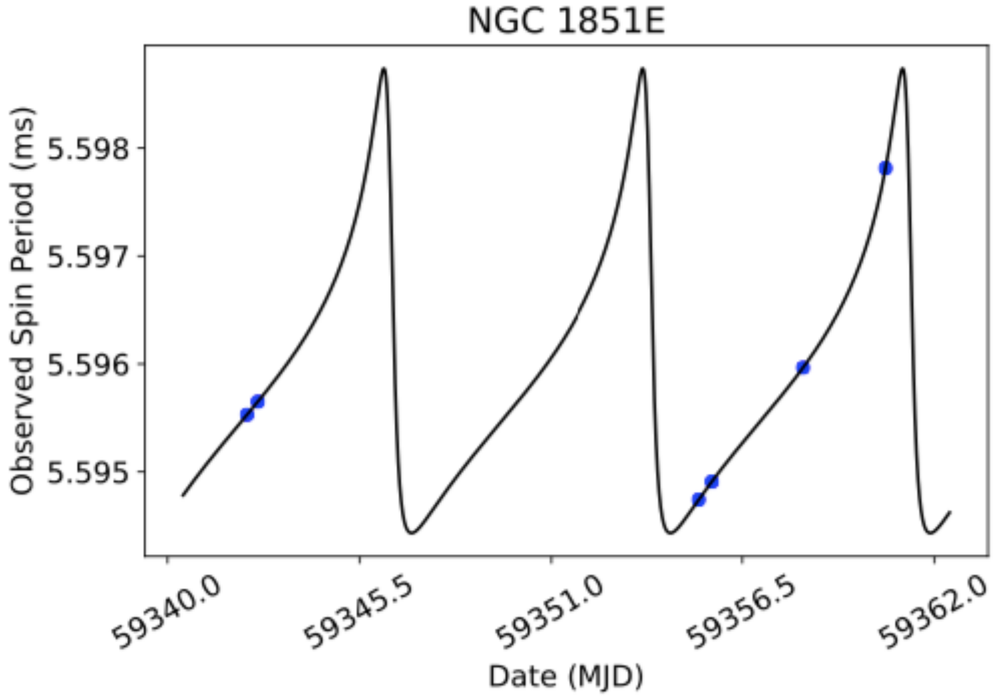
Globular cluster searches: Highlights

A&A 664, A27 (2022)
https://doi.org/10.1051/0004-6361/202143006

Astronomy & Astrophysics

TRAPUM discovery of 13 new pulsars in NGC 1851 using MeerKAT★

A. Ridolfi[1,2], P. C. C. Freire[2], T. Gautam[2], S. M. Ransom[3], E. D. Barr[2], S. Buchner[4], M. Burgay[1], F. Abbate[2], V. Venkatraman Krishnan[3], L. Vleeschower[5], A. Possenti[1,6], B. W. Stappers[5], M. Kramer[2,5], W. Chen[2], P. V. Padmanabh[2,7], D. J. Champion[2], M. Bailes[8,9], L. Levin[5], E. F. Keane[10], R. P. Breton[5], M. Bezuidenhout[5], J.-M. Grießmeier[11,12], L. Künkel[13], Y. Men[2], F. Camilo[4], M. Geyer[4], B. V. Hugo[4,14], A. Jameson[8,9], A. Parthasarathy[2], and M. Serylak[15,16]

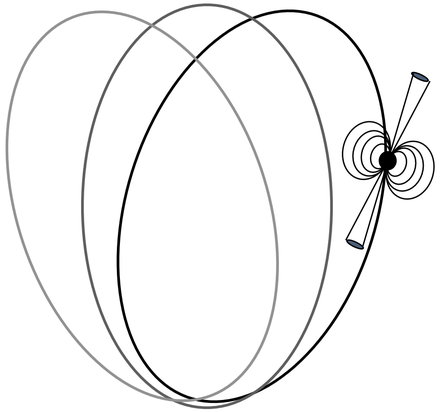


5.6 ms , 7.4 day orbit, e= 0.7

$M_{c,\,min}$ =1.4 M_{sun}

Post-Keplerian parameters

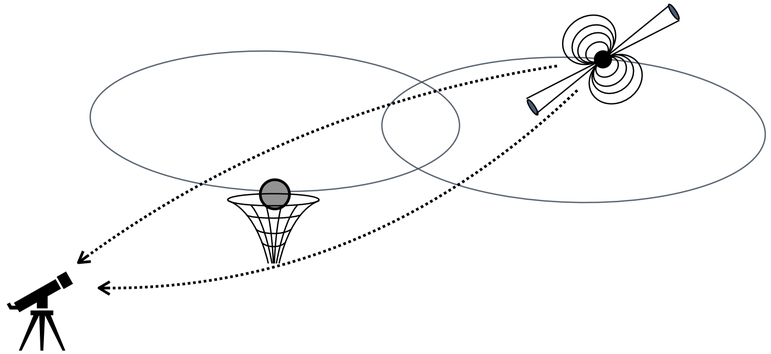
Rate of advance of periastron



$$\dot{\omega} = 3\left(\frac{G}{c^3}\right)^{2/3}\left(\frac{P_{\rm B}}{2\pi}\right)^{-5/3}\frac{M_{\rm T}^{2/3}}{1-e^2}$$

$M_T \approx 3.88\, M_{sun}$

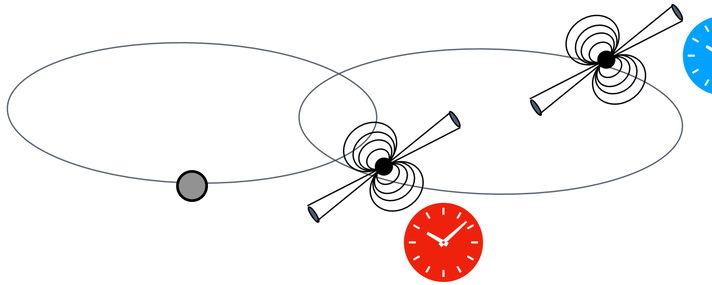
Shapiro delay



$$\varsigma = \frac{\sin i}{|\cos i| + 1}$$

$$h_3 = M_{\rm c} T_{\odot} \varsigma^3$$

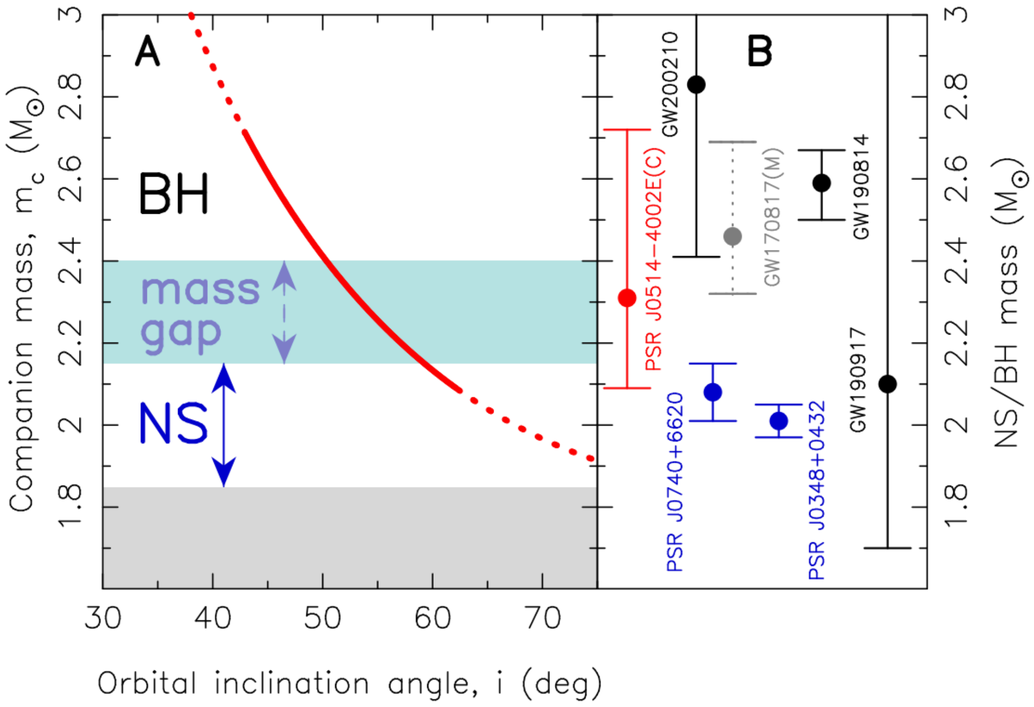
Einstein delay

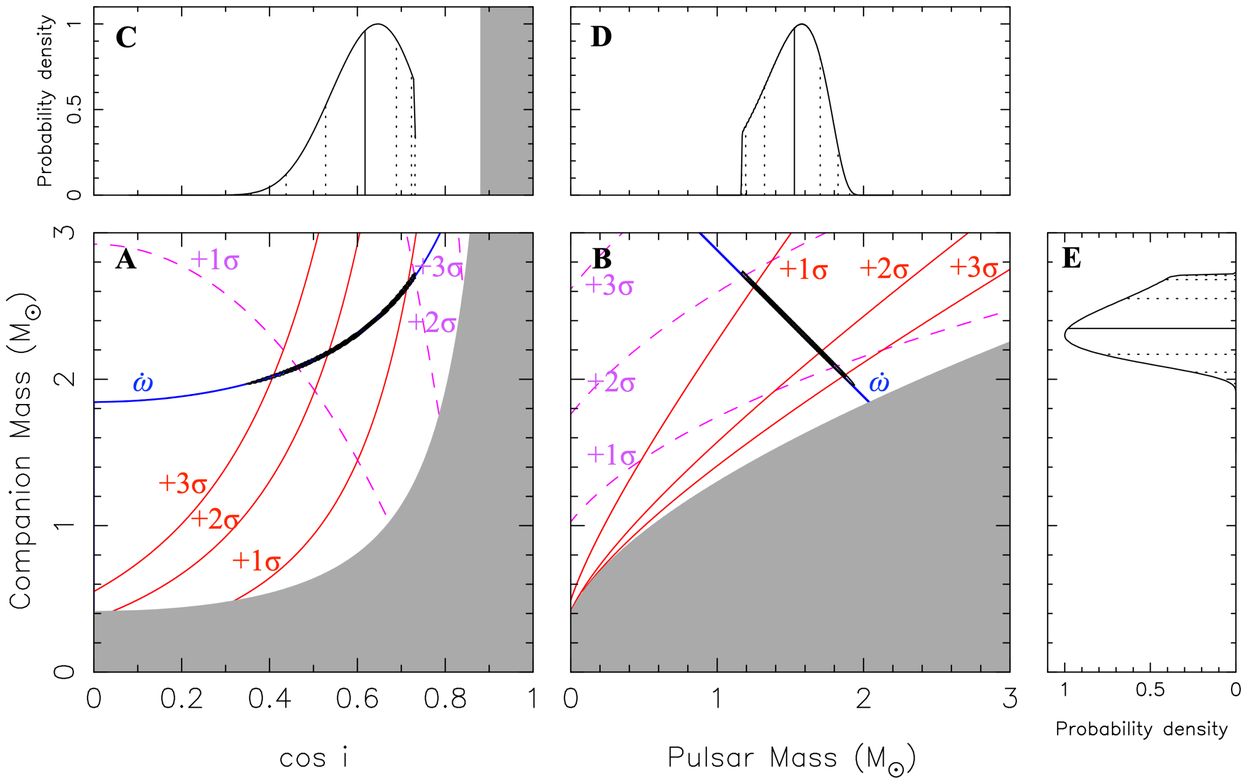


$$\gamma = \left(\frac{P_b}{2\pi}\right)^{1/3} T_{\odot}^{2/3} e \frac{M_c(M_{\rm tot} + M_c)}{M_{\rm tot}^{4/3}}$$

No significant detection

Post-Keplerian parameters





No optical companion found

Mc > **2.09** M_{sun}, i < 62° (**95%** confidence)

Massive NS/Light BH companion?

Barr, Dutta et al. 2024

Post-Keplerian parameters

https://www.science.org/doi/10.1126/science.adg3005
https://doi.org/10.48550/arXiv.2401.09872

RESEARCH

RESEARCH ARTICLE

RADIO ASTRONOMY

A pulsar in a binary with a compact object in the mass gap between neutron stars and black holes

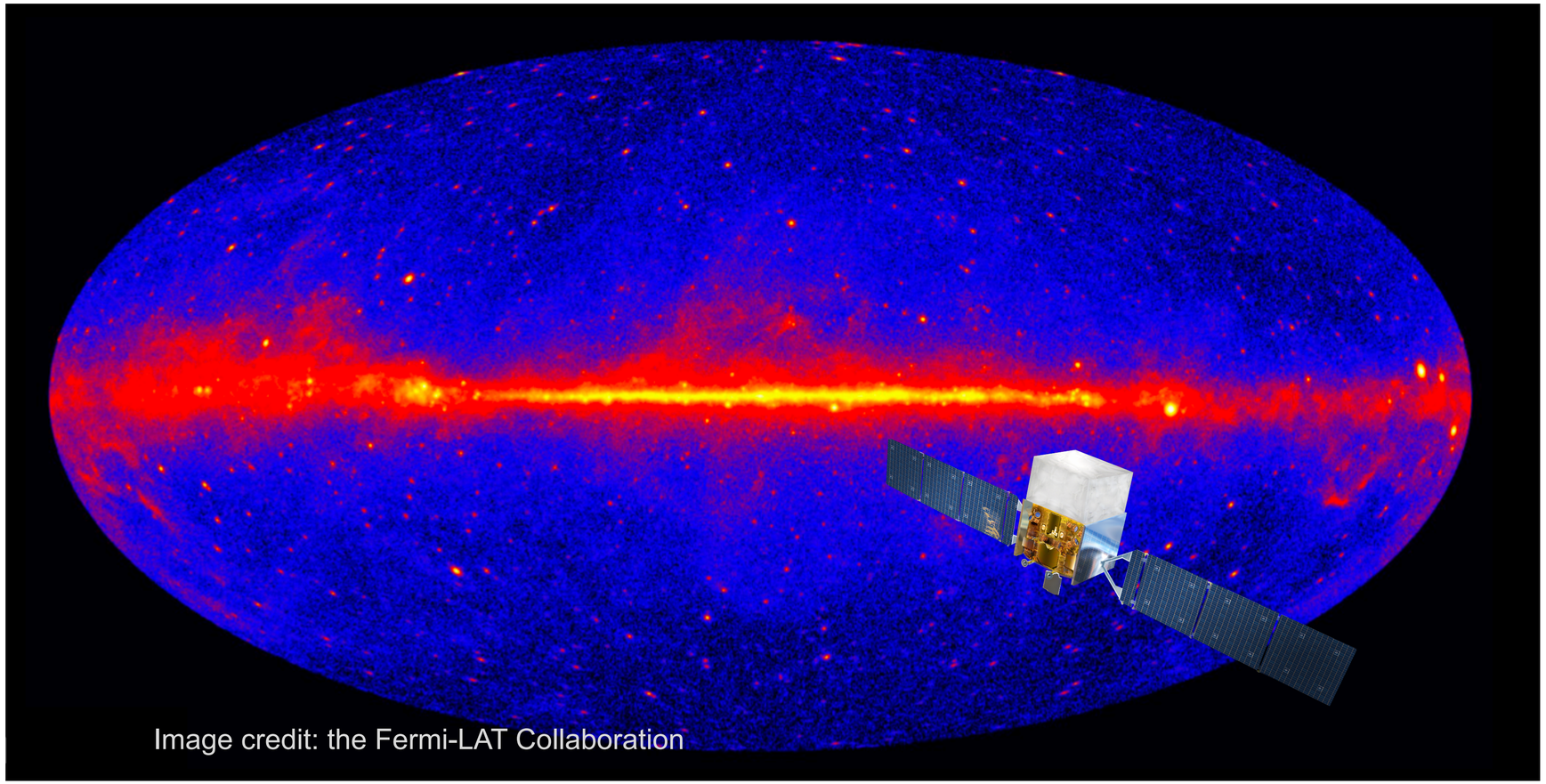
Ewan D. Barr[1*†], Arunima Dutta[1*†], Paulo C. C. Freire[1], Mario Cadelano[2,3], Tasha Gautam[1], Michael Kramer[1], Cristina Pallanca[2,3], Scott M. Ransom[4], Alessandro Ridolfi[1,5], Benjamin W. Stappers[6], Thomas M. Tauris[1,7], Vivek Venkatraman Krishnan[1], Norbert Wex[1], Matthew Bailes[8,9], Jan Behrend[1], Sarah Buchner[10], Marta Burgay[5], Weiwei Chen[1], David J. Champion[1], C.-H. Rosie Chen[1], Alessandro Corongiu[5], Marisa Geyer[10,11‡], Y. P. Men[1], Prajwal Voraganti Padmanabh[1,12,13], Andrea Possenti[5]

No op fidence)

Massive NS/Light BH companion?

Barr, Dutta et al. 2024

Why Fermi ?



5000 sources

240 pulsars

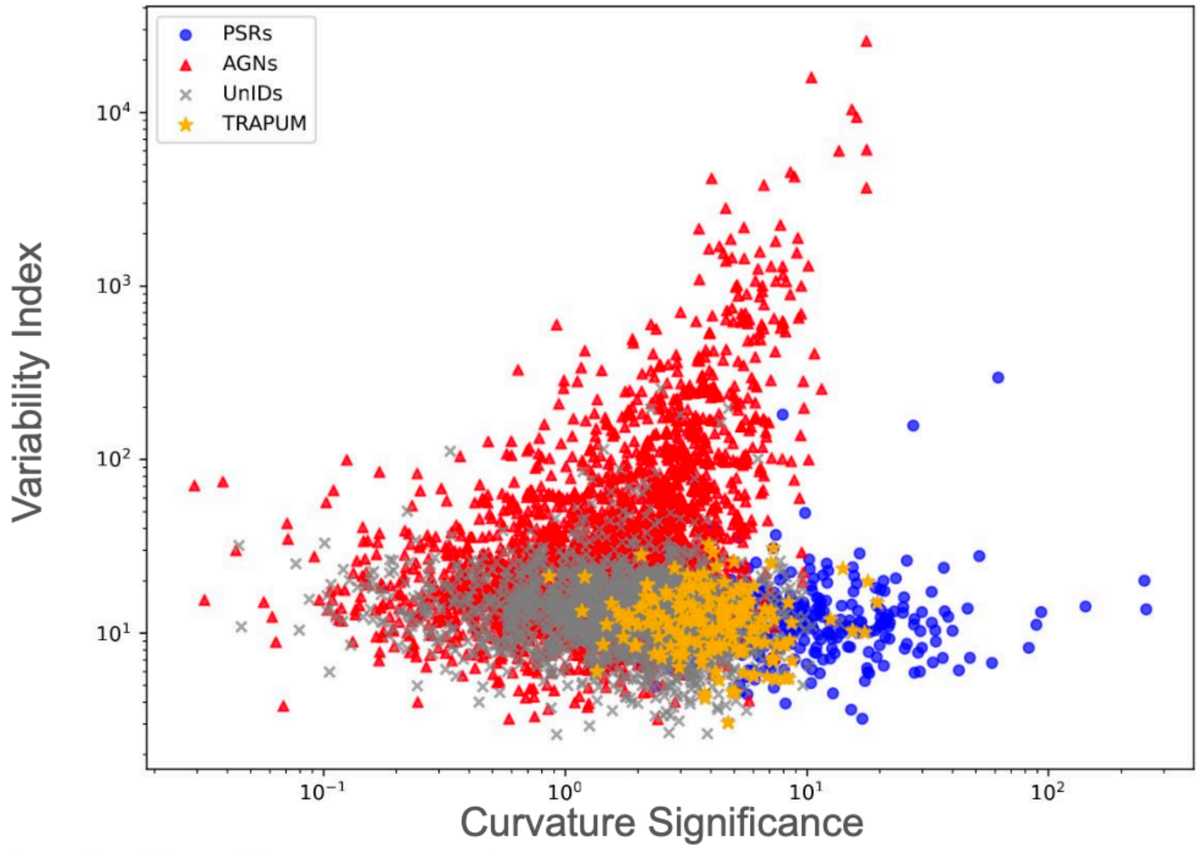
1300 unidentified sources

Applications

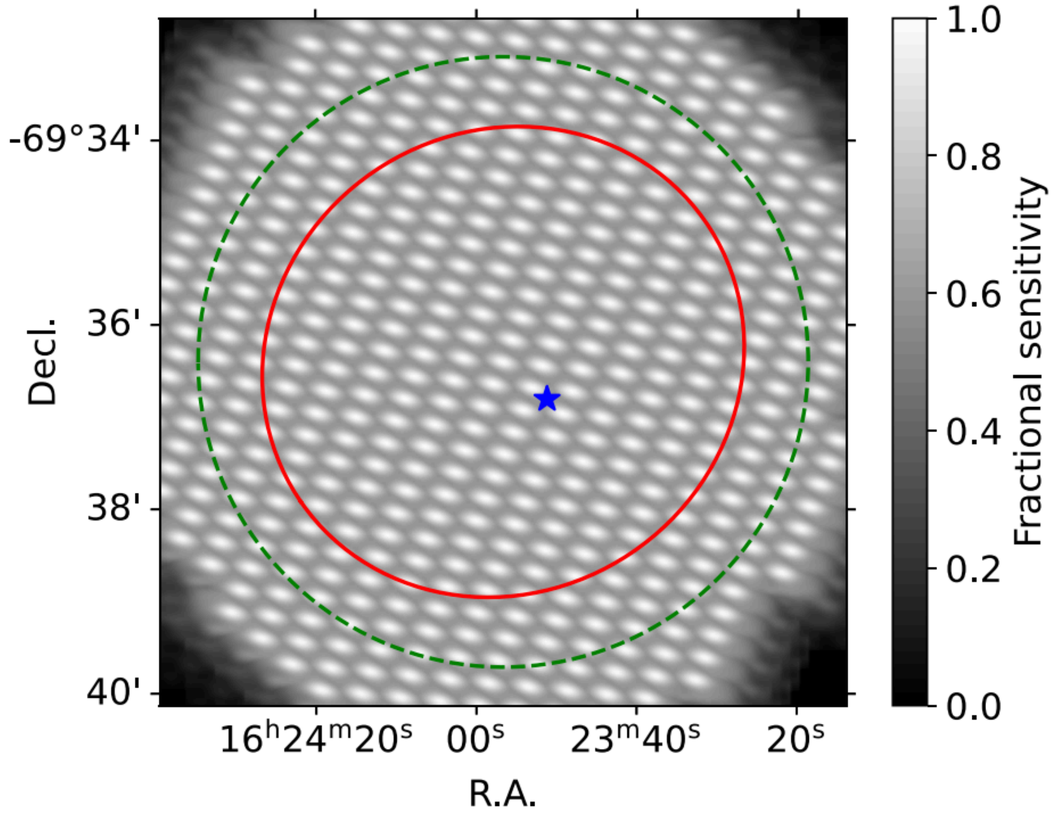
Pulsar emission energetics

Building a gamma-ray PTA!

Fermi source selection and observing strategy



Credit: Tinn Thongmeearkom



Clark et al. 2023

Pulsar-like spectrum?

High curvature significance

Low variability

95% confidence region tiled

Nearly 300 beams

Fermi survey: current status

Survey	T_{obs} (min)	Target	Sources	Bands
Shallow	10 x 4	pulsar-like γ-ray spectrum	79	L and UHF
Deep Spider	60 x 4	pulsar-like γ-ray spectrum **+ Optical/X-ray LC**	6	L and UHF

Fermi survey: current status

Survey	T_{obs} (min)	Target	Sources	Bands
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Deep Spider	60 x 4	pulsar-like γ-ray spectrum **+ Optical/X-ray LC**	6	L and UHF

Survey	Sources	Total Discoveries	MSP	Slow pulsar
Shallow	79	24	19	5
Deep Spider	6	3	3	0
Expanded Shallow	89	15	14	1
Expanded Deep Spider	5	2	2	0
Shallow 2025 (on-going)	56	5	4	1
Deep Spider 2025 (on-going)	1	0	0	0

Credit: Tinn Thongmeearkom

Clark et al. 2023

Thongmeearkom et al. 2024

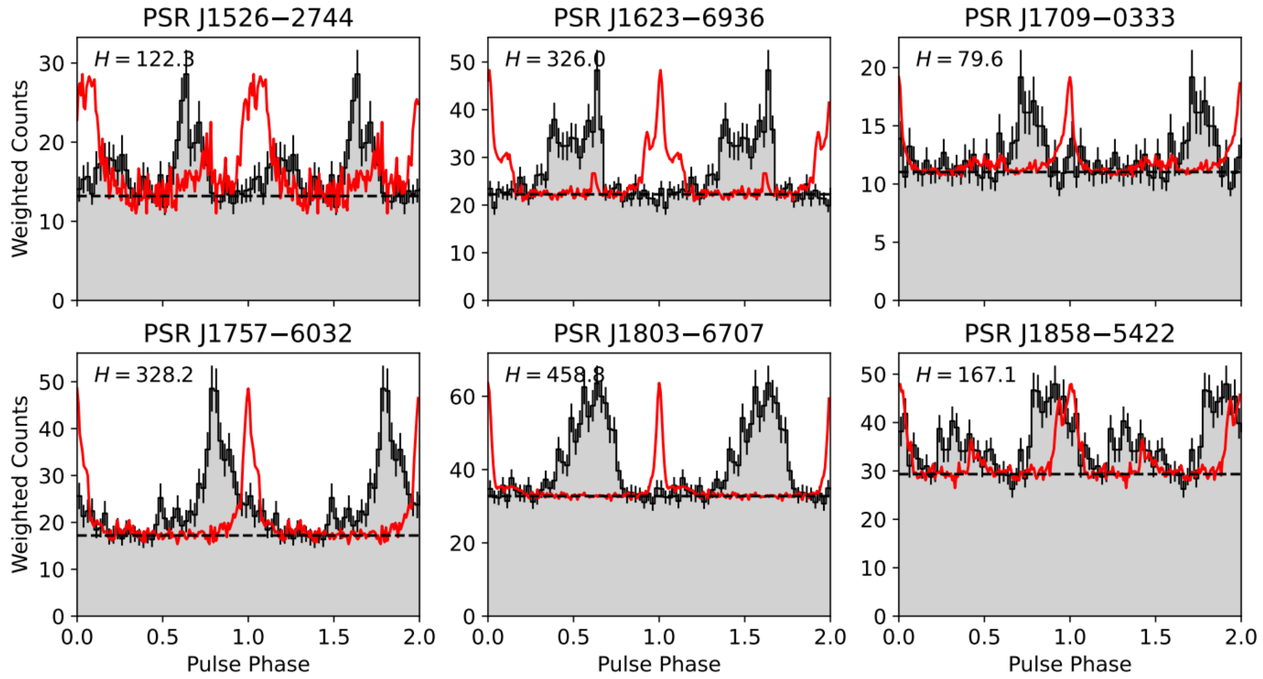
Burgay et al. 2024

Dodge et al. 2025

Belmonte Diaz et al. 2025

Atleast **49** new pulsars (**3** more pulsars in the last few weeks)

Fermi survey: highlights



Burgay et al. 2024

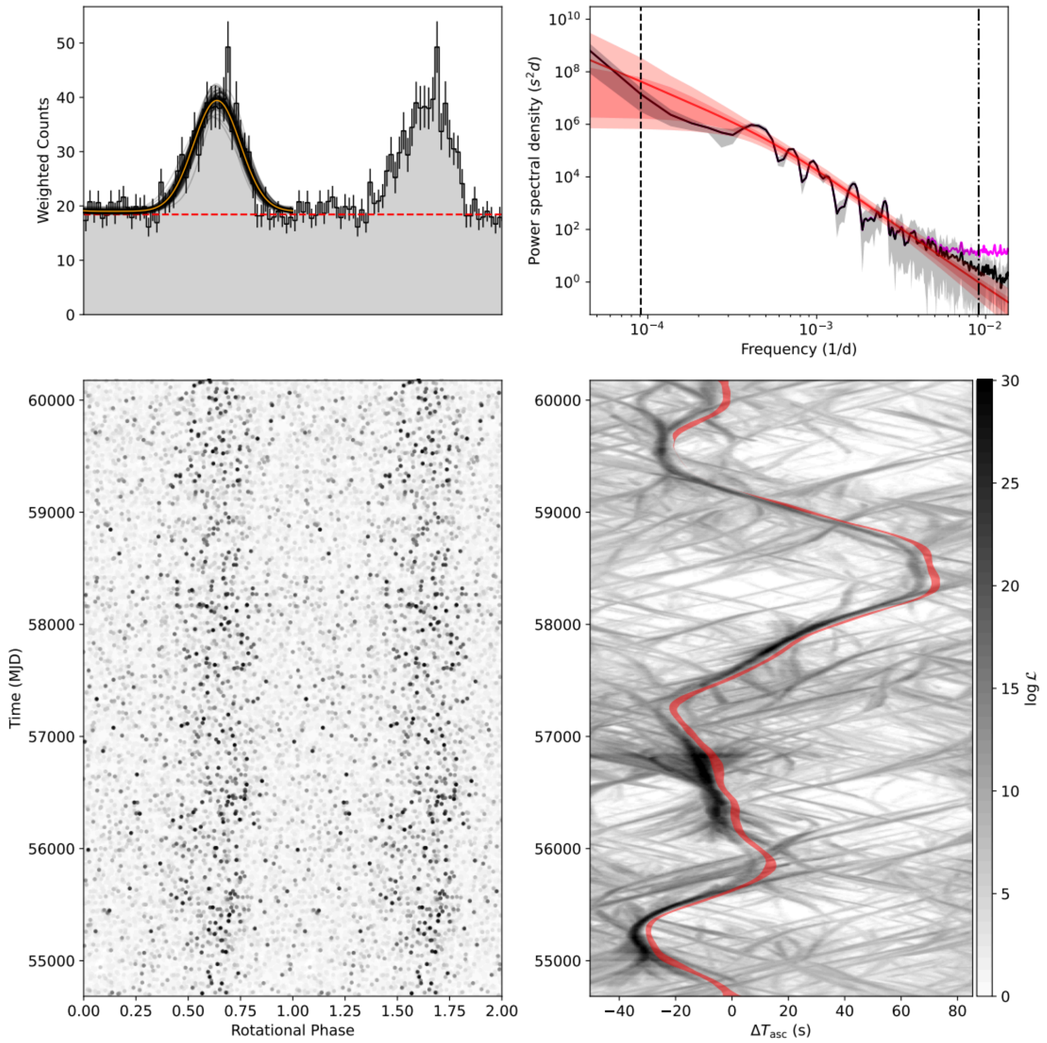
Radio timing ephemeris

↓

Fold gamma-ray data

↓

Obtain gamma-ray pulsations!



Credit: Colin Clark

Need to account for long term instability!

Fermi survey: highlights

Light curve modelling

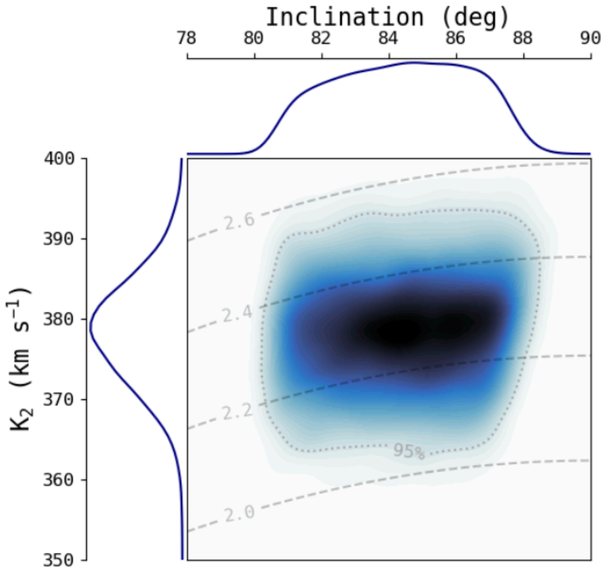
Spectroscopy modelling

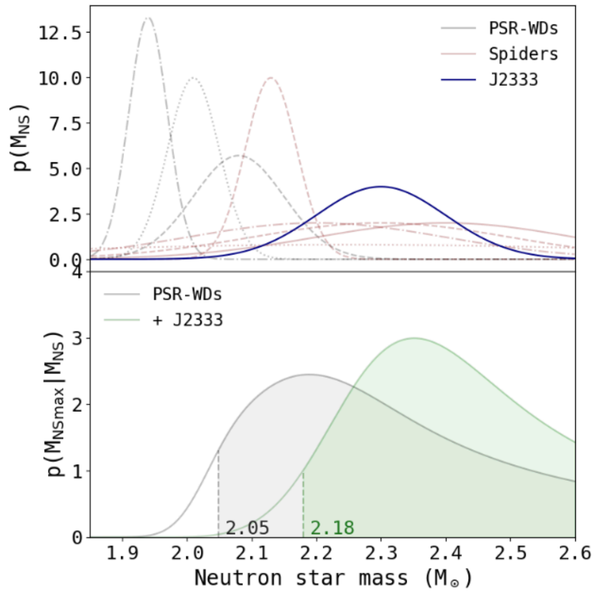
$$\frac{M_P^3 \sin^3 i}{(M_C + M_P)^2} = \frac{P_B K_C^3}{2\pi G}$$

$$q = \frac{K_C}{2\pi P_B A_1} \qquad q = \frac{M_P}{M_C}$$

Pulsar Timing

$$M_P = \frac{P_B \left(1 + \frac{1}{q}\right)^2}{2\pi G} \left(\frac{K_C}{\sin i}\right)^3$$





Multi-wavelength modelling
(Radio + optical)

$M_P = 2.3 \pm 0.1\ M_\odot$

Credit: Oliver Dodge

Dodge et al., in prep

Fermi survey: highlights

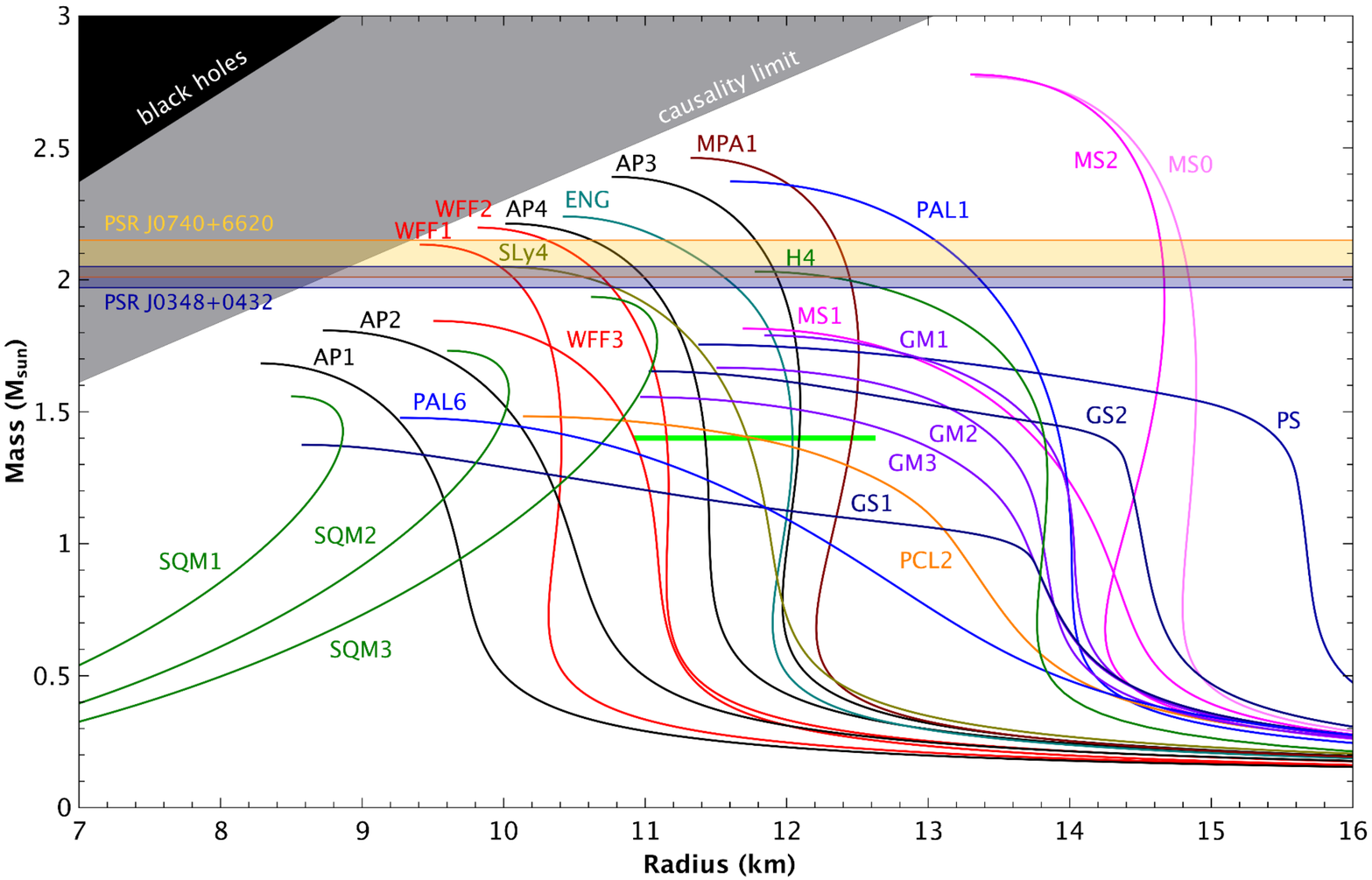
Light curve model

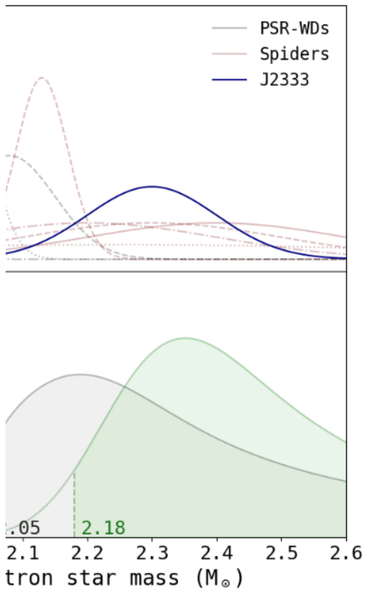
$$\frac{M_P^3 \sin^3}{(M_C + M}$$

$$q = \frac{K_C}{2\pi P_B}$$

Pulsar Timing

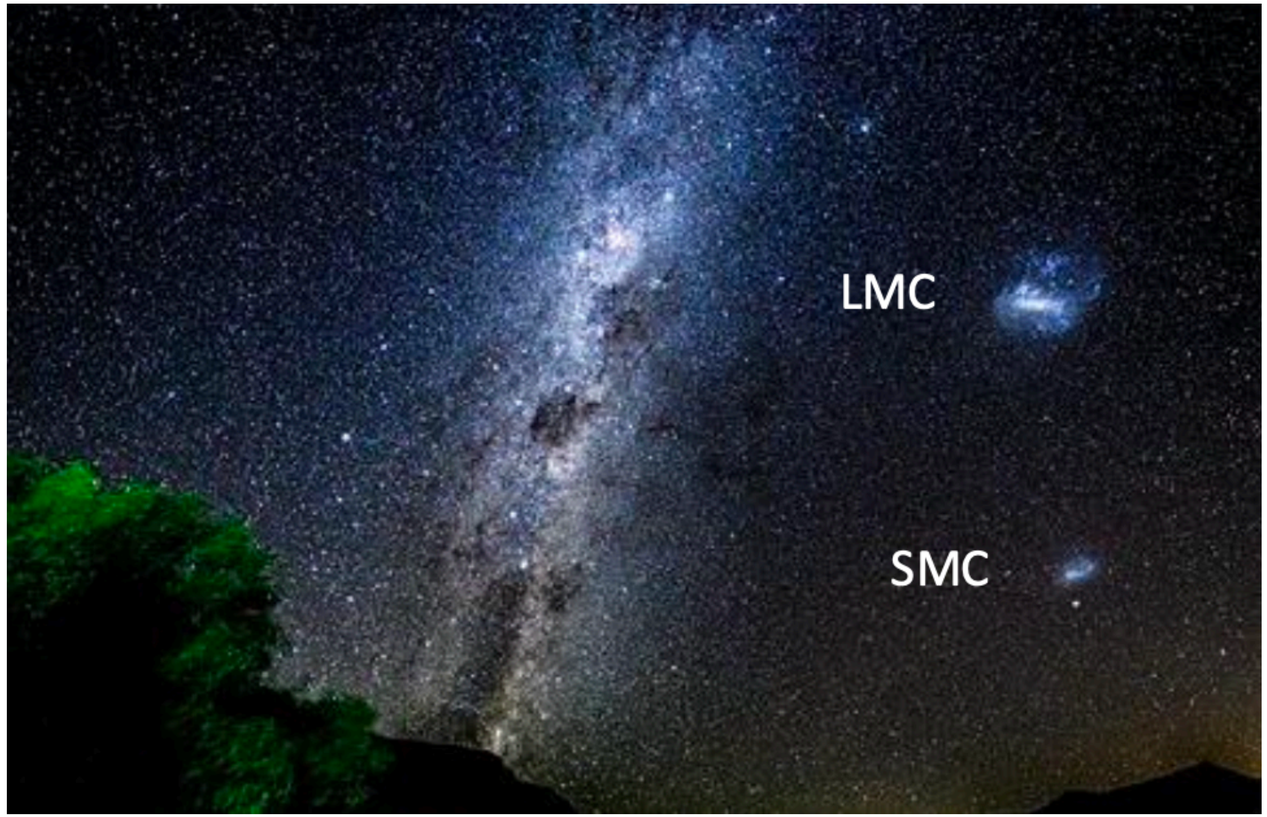
$$M_P = \frac{P_B}{}$$





Dodge et al., in prep

Why Nearby Galaxies?



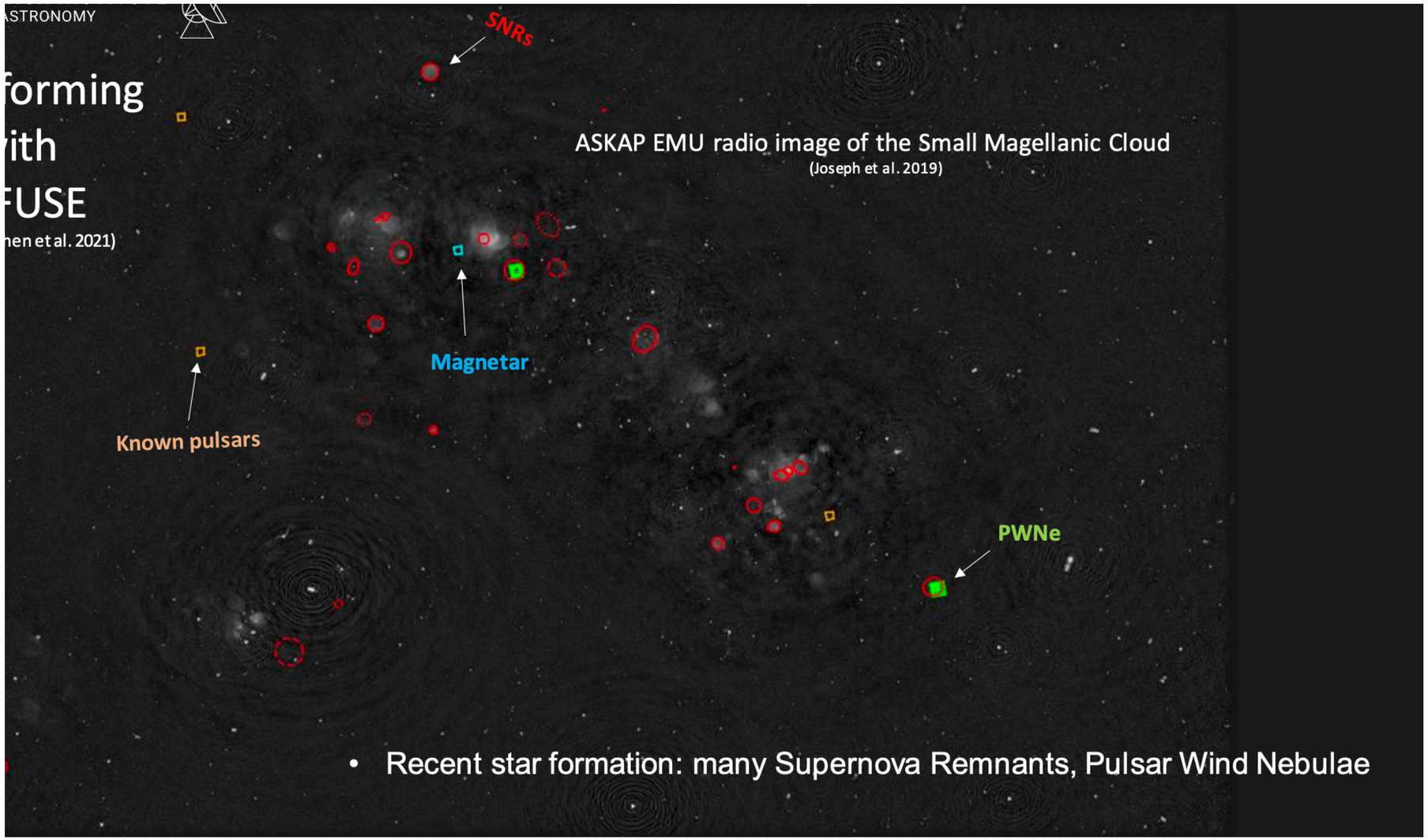
About 30 out of 4300+ in MCs

Galactic properties <-> NS formation

Extragalactic Merger rate <-> GW events

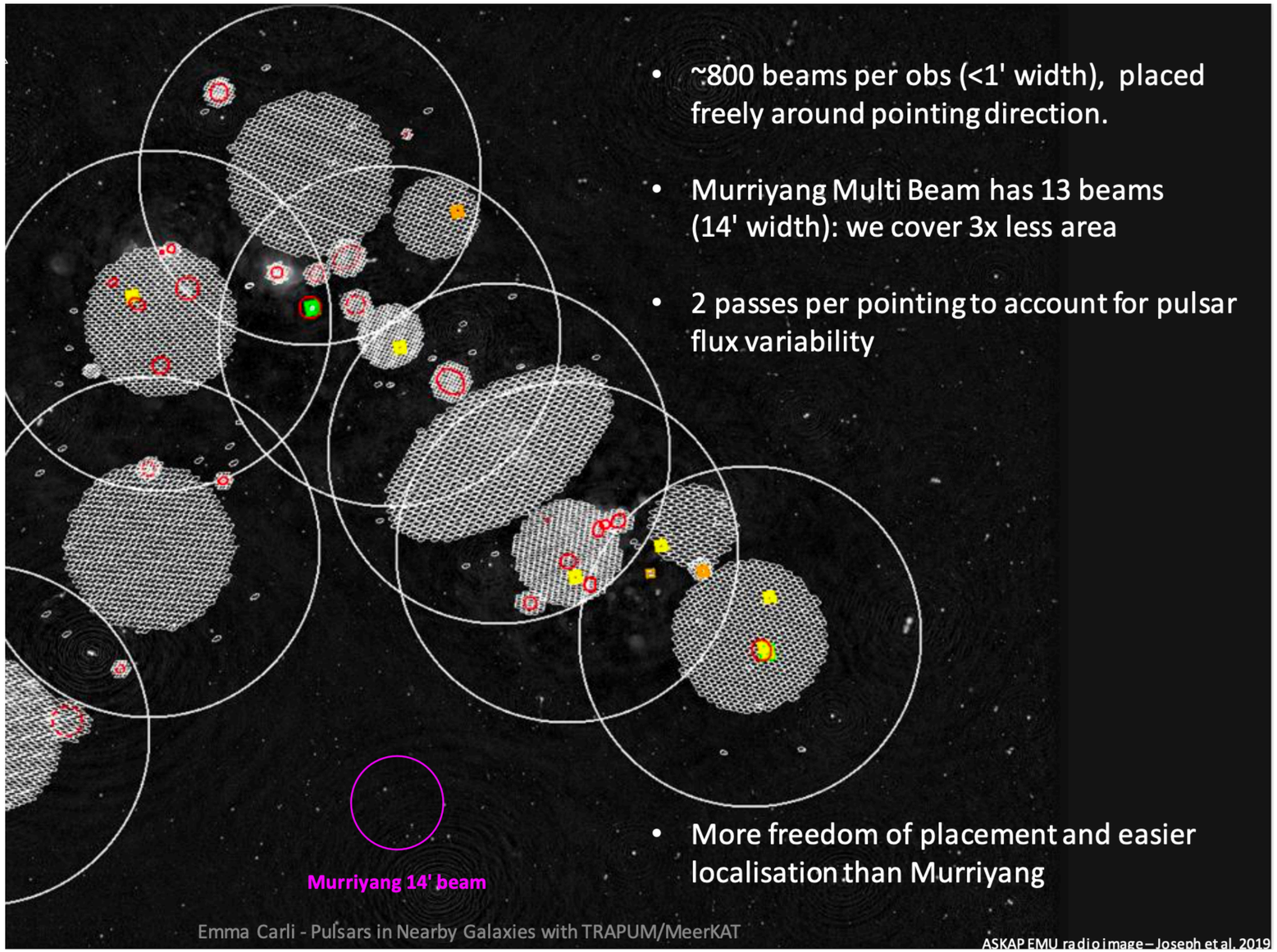
FRBs <-> Pulsars?

Nearby Galaxies: Strategy



Credit: Emma Carli

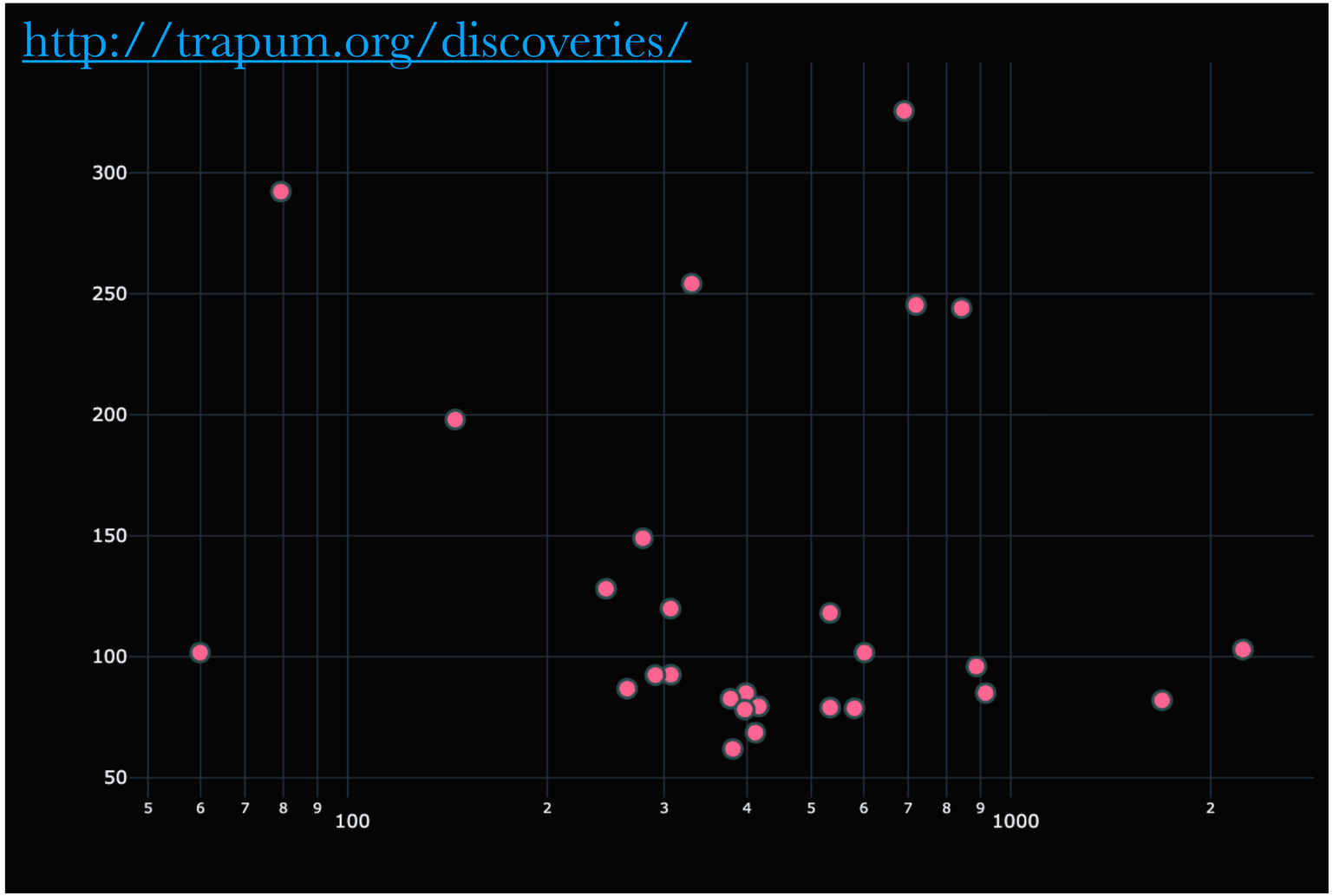
Nearby Galaxies: Strategy



Credit: Emma Carli

Nearby Galaxies: Current status

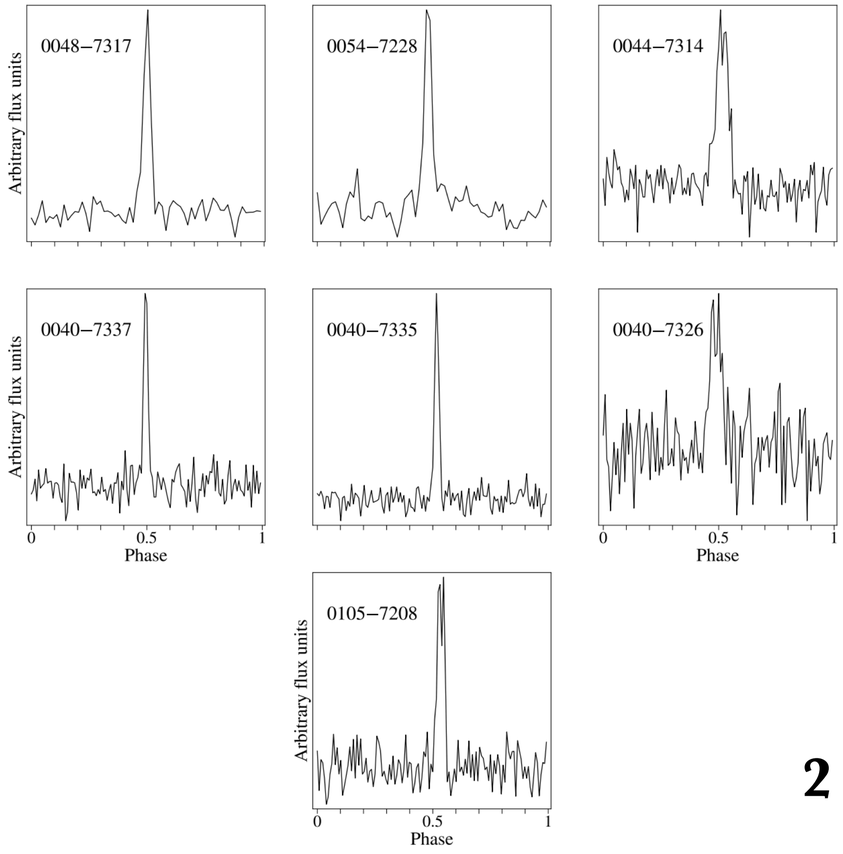
DM (pc cm^{-3})

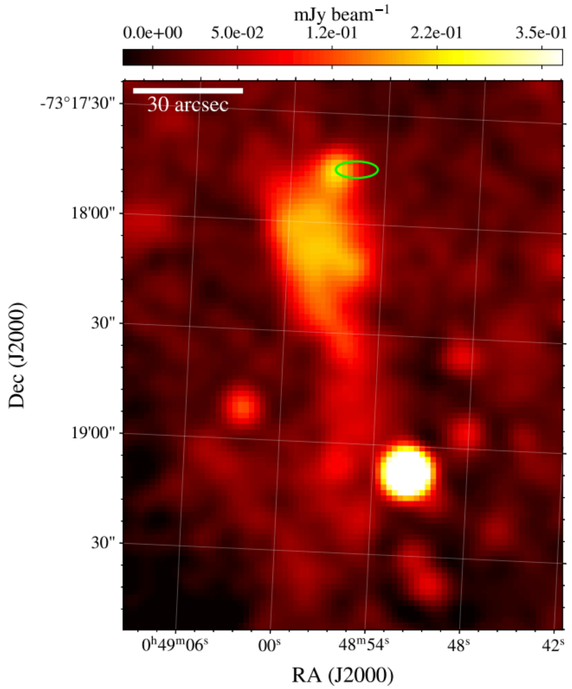


Period (s)

27 new pulsars
(**7** SMC +
20 LMC)

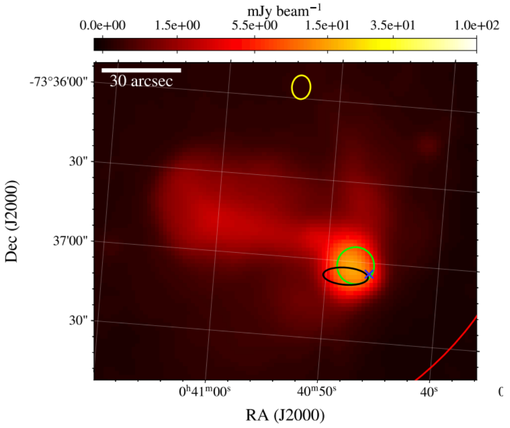
Nearby Galaxies: SMC Highlights



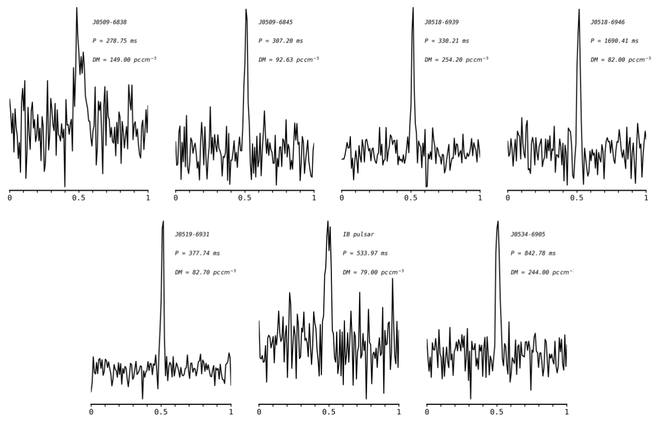


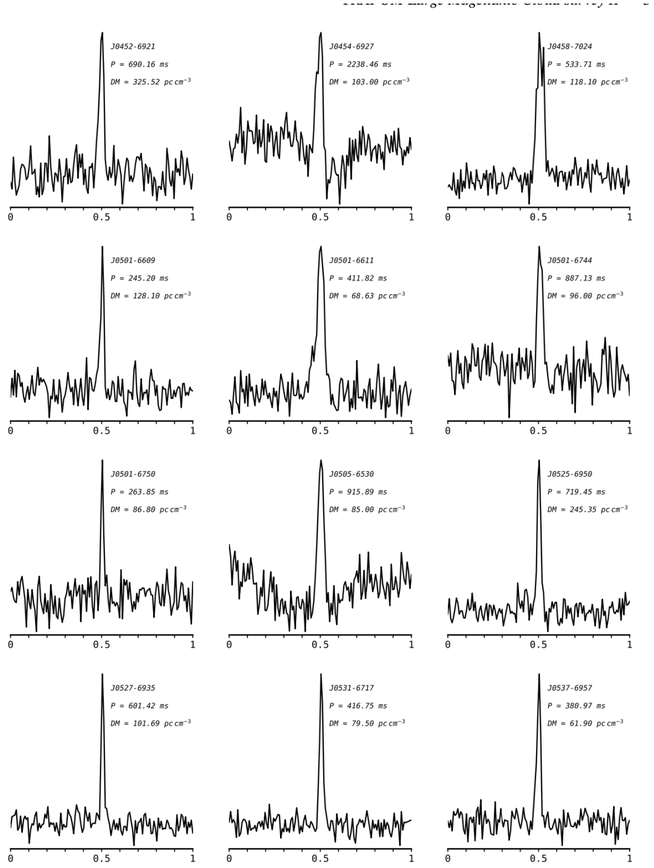
Carli et al. 2024

7 pulsars including
2 PWN associations and a **glitching** pulsar

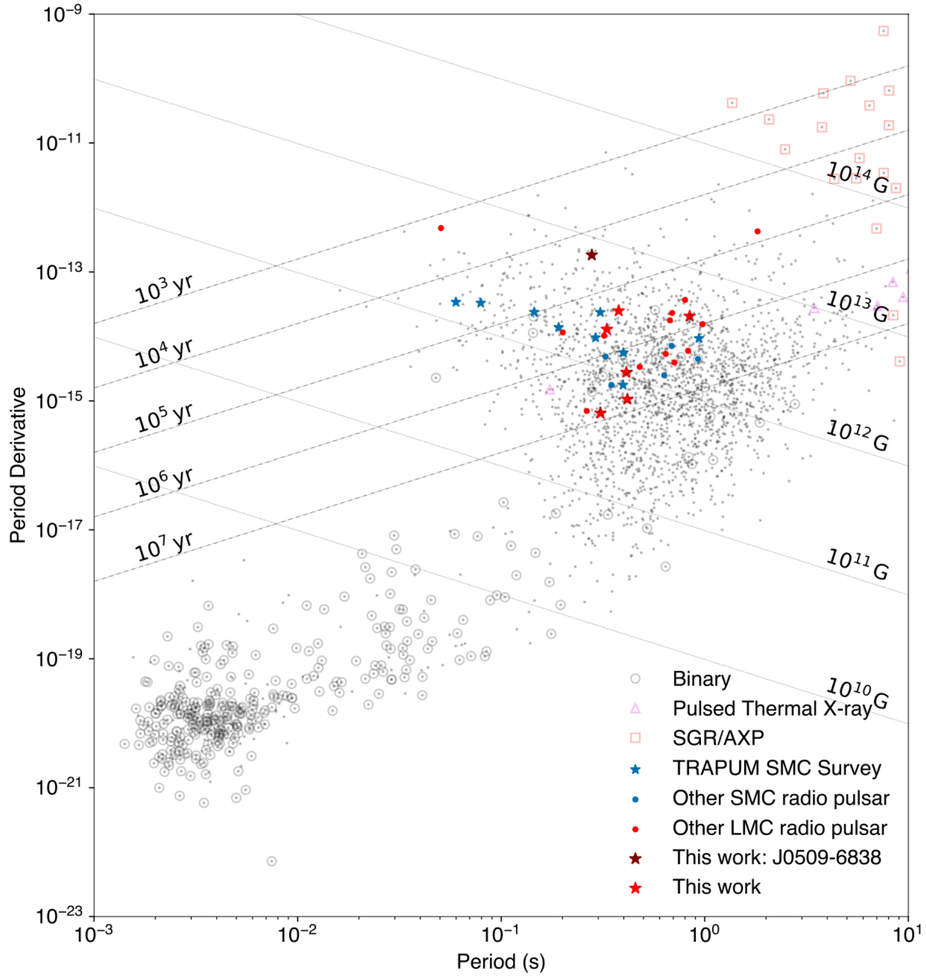


Nearby Galaxies: LMC Highlights





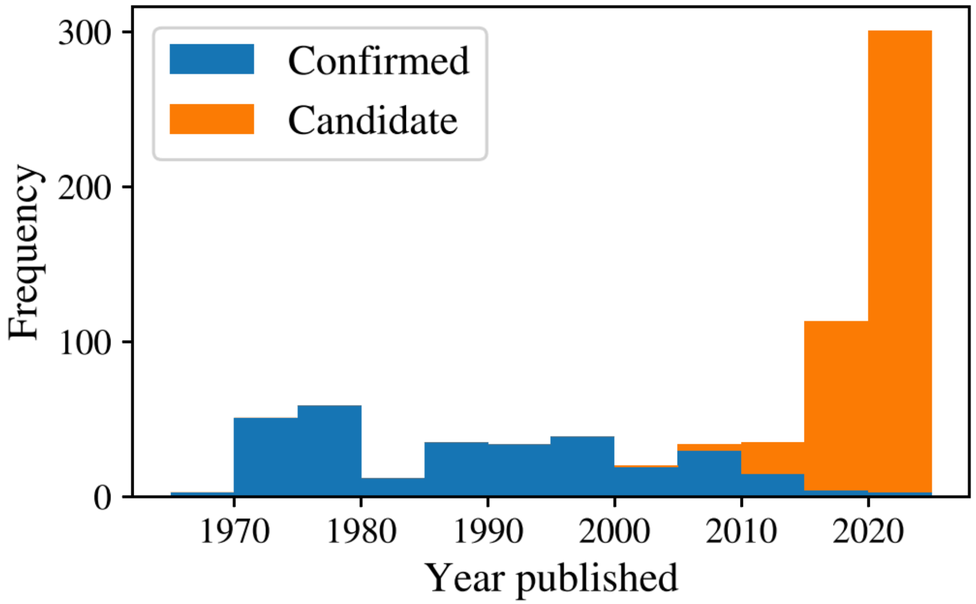
20 new pulsars
7 timing solutions
1 possible long period binary (P_b ~ yrs)



Prayag et al. 2024

Prayag et al., in prep

Why SNR/TeV/PWN?



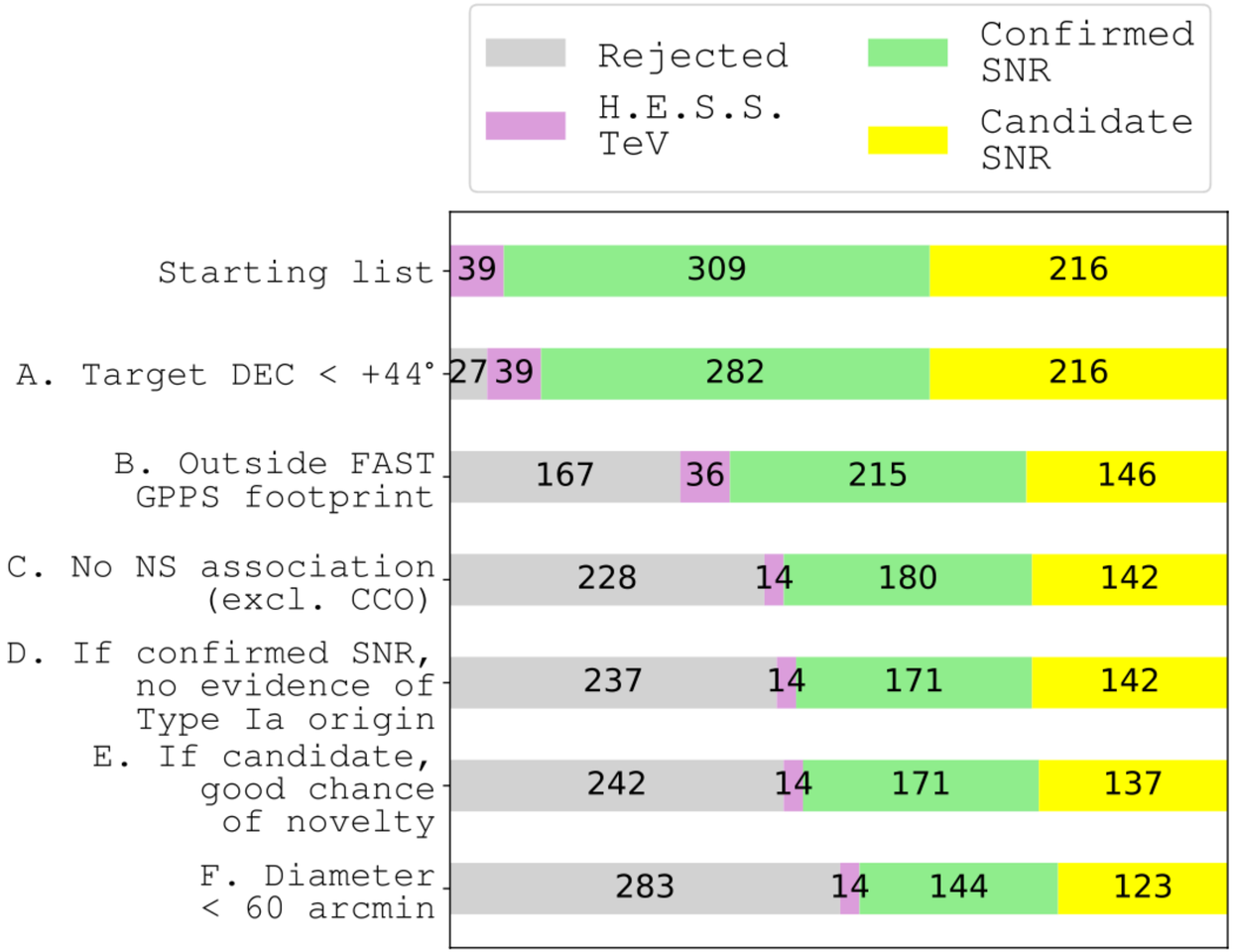
Huge potential for
discovering several **young pulsars!**

$$N_{\mathrm{PSR}} = N_{\mathrm{target}} \cdot f_{\mathrm{beam}} \cdot f_{\mathrm{L}} \cdot f_{\mathrm{NS}} \cdot (1 - f_{\mathrm{magnetar}}) \cdot (1 - f_{\mathrm{CCO}}) \cdot \ldots$$

Factors precluding SNR detection not well constrained..

Credit: James Turner

SNR/TeV/PWN: Source selection

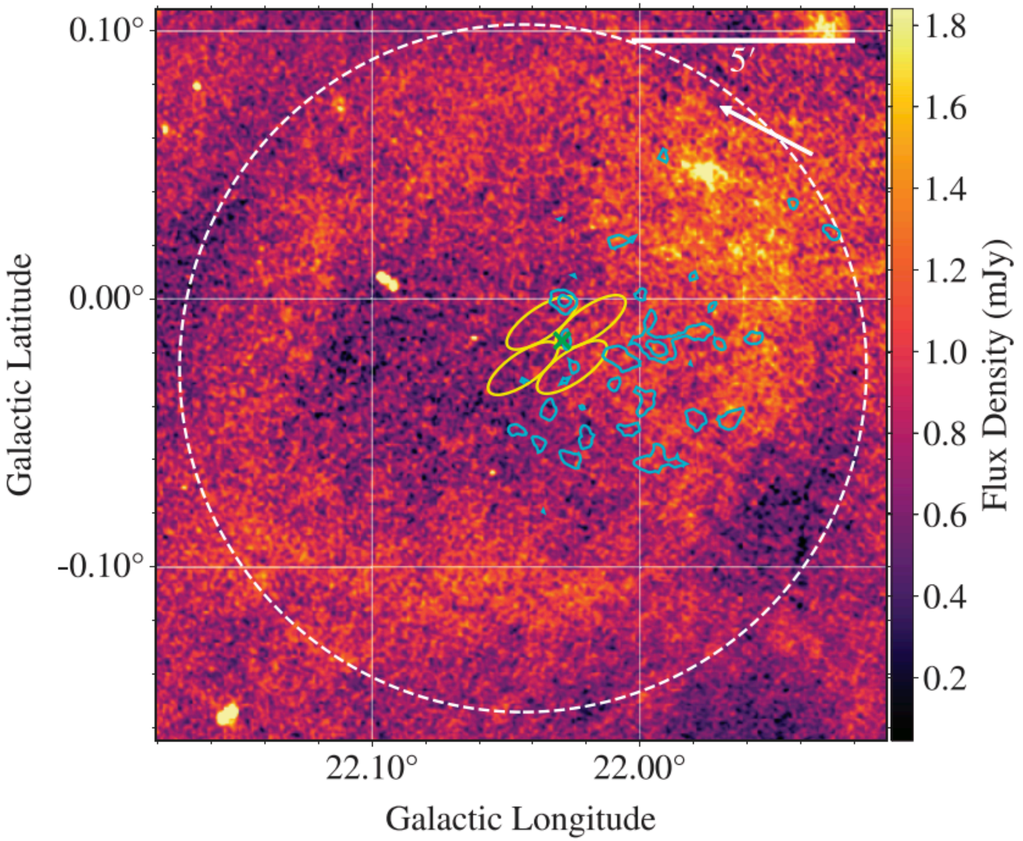


Turner et al. 2025 (accepted)

SNR/TeV/PWN: Current status

134 targets …

1 NEW ASSOCIATED PULSAR
(PSR J1831-0941 in G22.045-0.028)



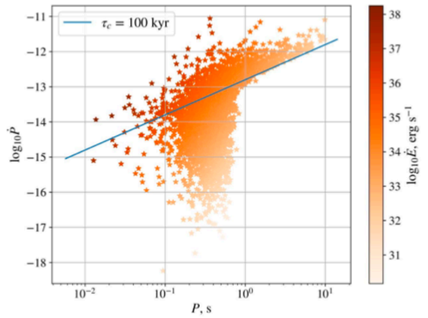
Turner et al. 2024

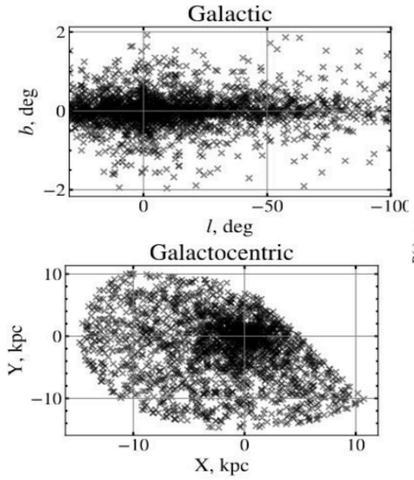
Why low success rate?

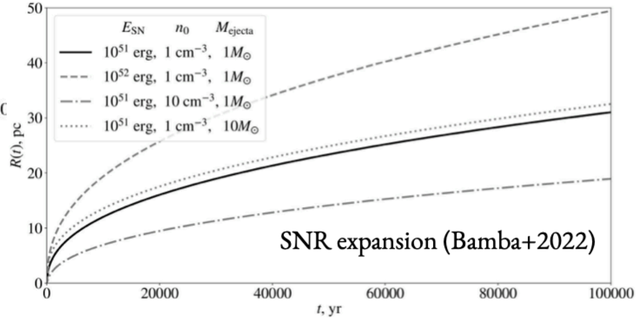
SNR/TeV/PWN: What can we learn?

The population synthesis

#	P	$\dot{P}$	x	y	z	v_k	B	ρ	L	τ
1										
2										
.										
N										







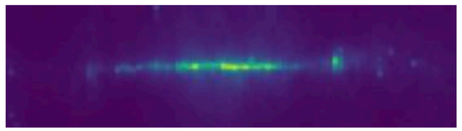
1. Simulate a pulsar population in PsrPopPy2 (**evolve** mode)

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

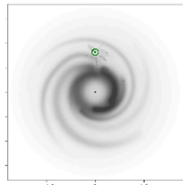
3. Apply 3D sky filter

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

Repeat 100×

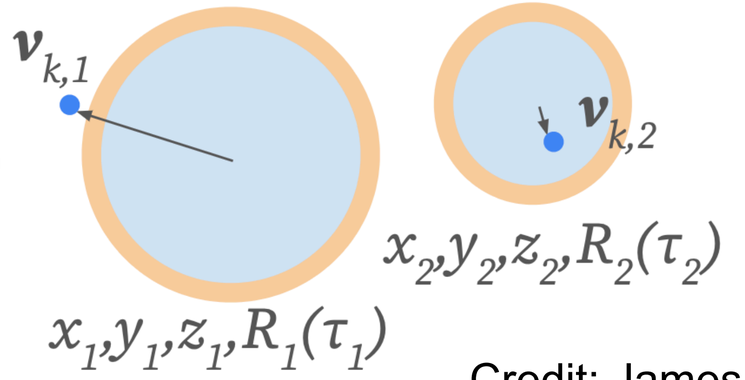


GSM2016 (Zheng+2016)



NE2001 (Cordes+Lazio, 2002)

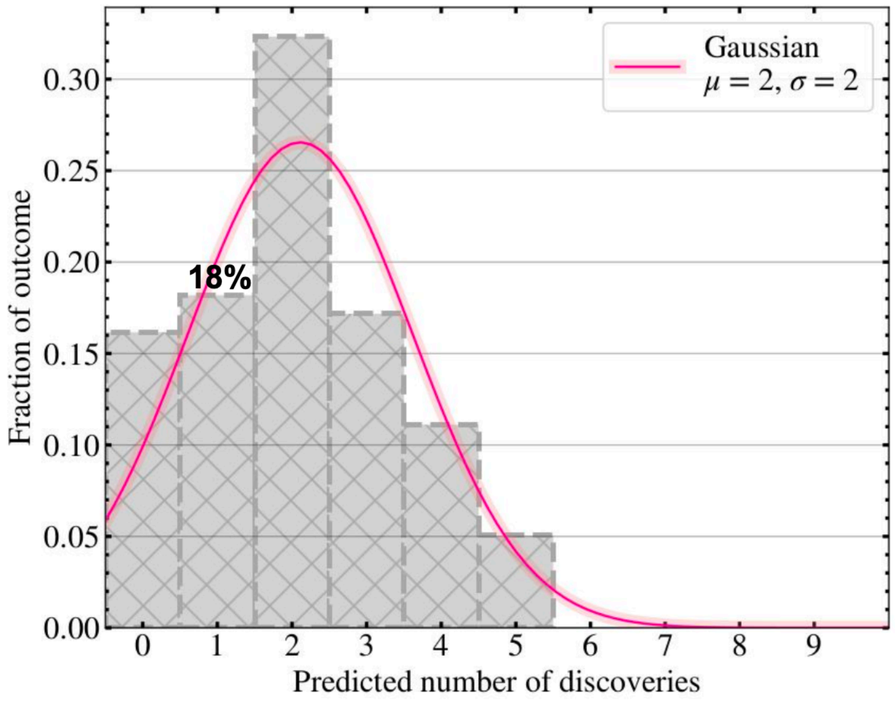
5. Calculate sky temperature, DM & scattering timescale and TRAPUM S/N



Credit: James Turner

SNR/TeV/PWN: Lessons learnt

Here's what we found...



RESULTS

- The real result overlaps with population-based prediction
- Too faint (45%) and too scattered (30%) are the largest selection effects
- An S-band 2.4 GHz survey recovers 50-150% more pulsars

MAIN CONCLUSIONS

- 1.2 GHz is now too low, go >2 GHz for future searches!
- Match or beat our 52 μJy upper limits to maximise discoveries!

Credit: James Turner

Pushing the boundaries
via computing and techniques…

Einstein@Home

- Volunteer distributed computing project (https://einsteinathome.org/)
- Dedispersed files and zap lists sent to volunteers. Post processing (sift and fold) done in-house
- Compatible with different OS architectures (CPU and GPU)
- Previously run searches with PALFA and PMPS data (e.g. Allen et al. 2013, Knispel et al. 2015)

Computing	FGRP5	BRP7
CPU TFLOPS (from successful tasks last week)	2,939	173
CPU weeks (from successful tasks last week)	7,825	505
Granted credit / 100 (from successful tasks last week)	2,069,618	24,558,611
Workunits finished last week	274,553	410,280

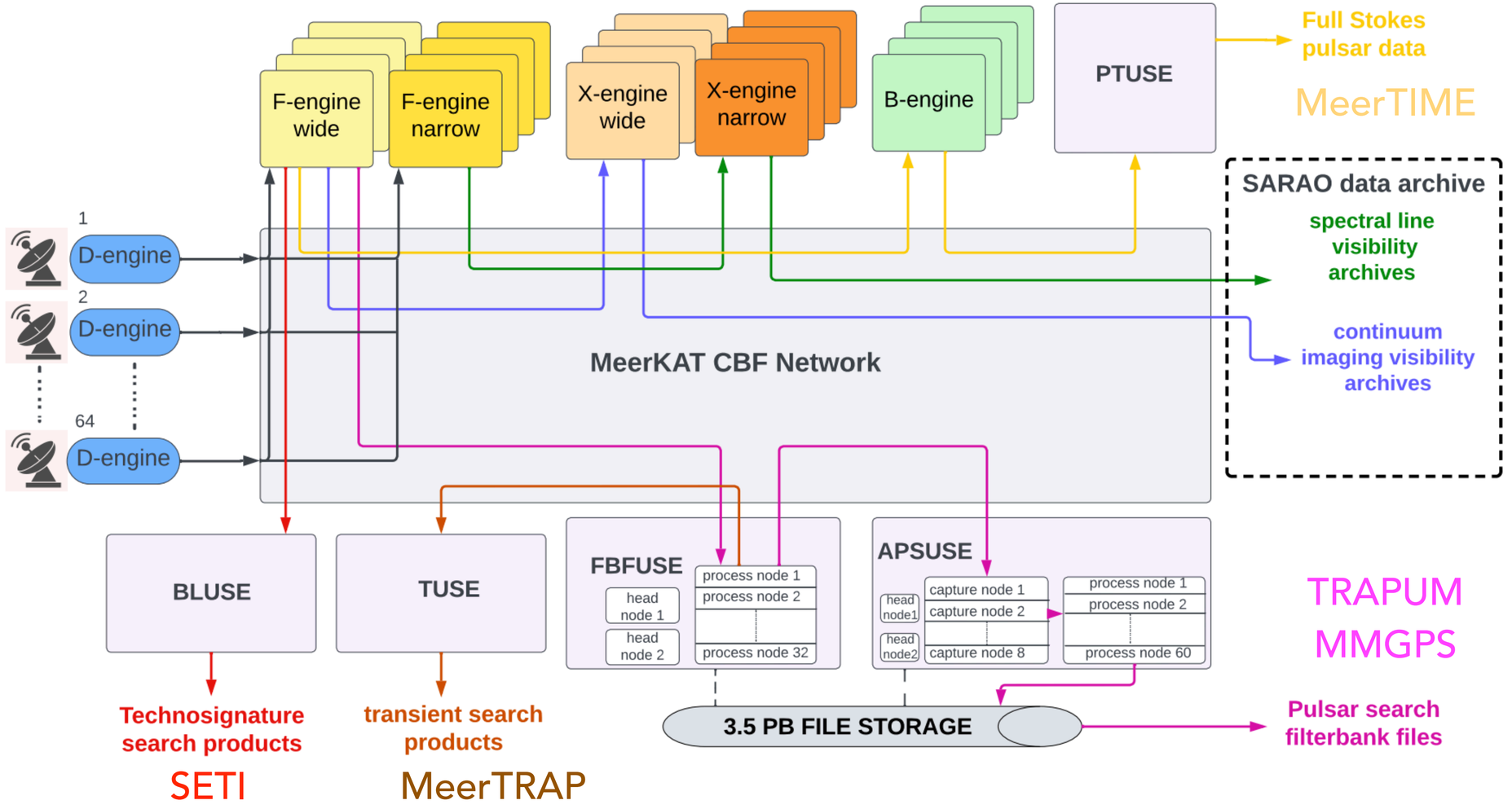
GPU productivity (last 7 days)	
Hosts w/ ATI/AMD GPU	3,230
Hosts w/ NVIDIA GPU	8,528
Hosts w/ INTEL HD GPU	8,258
Hosts w/ Apple M GPU	721

Currently applied to MeerKAT globular cluster data

https://einsteinathome.org/server_status.php

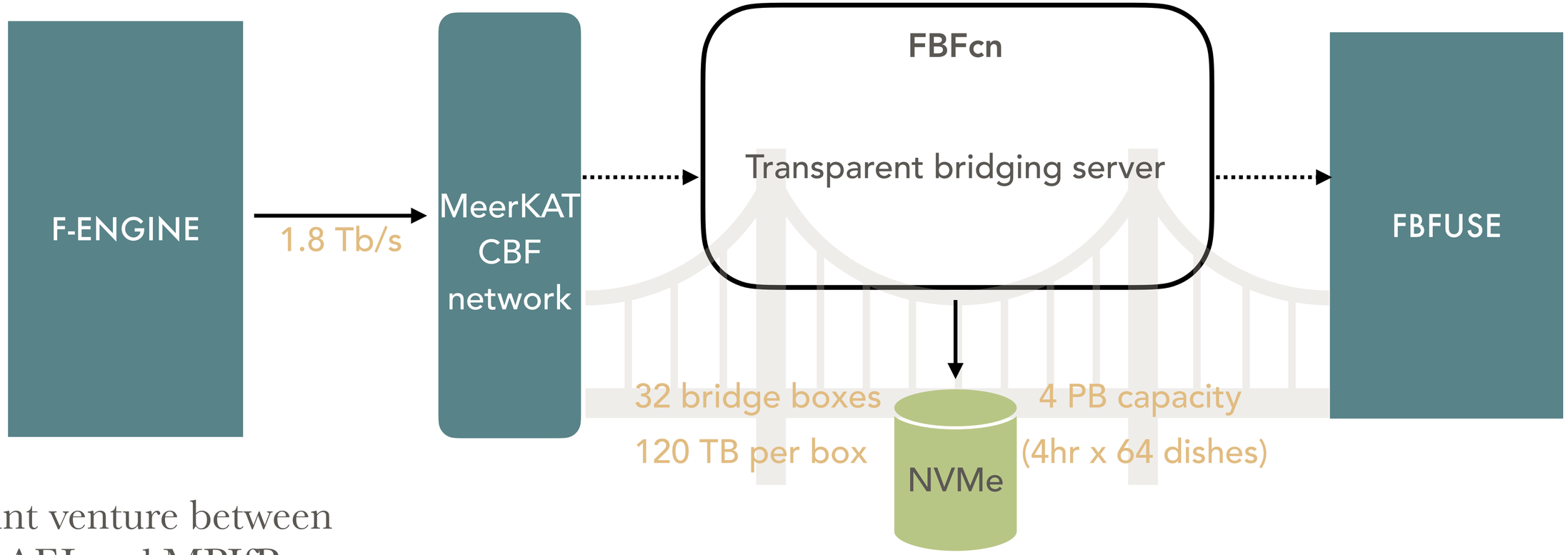
Sign up and help find more pulsars!

MeerKAT data flow



Flexbility to intergrate new back-end systems

FBFUSE-BVR



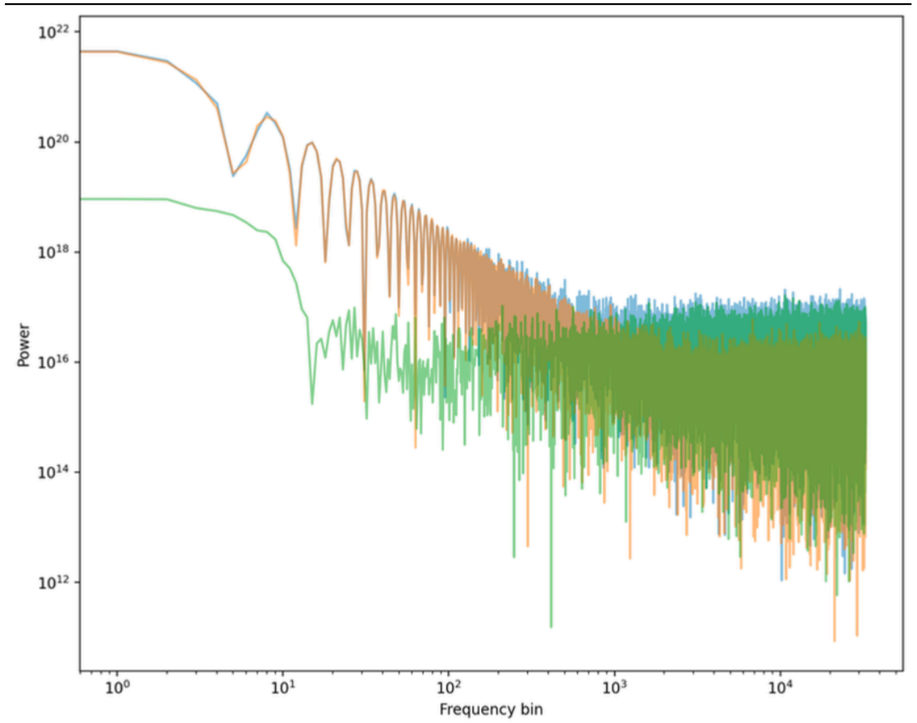
Joint venture between AEI and MPIfR

Baseband data passively recorded

Installed in Feb 2024

Can be used for high impact targets (Currently for Galactic centre, globular clusters)

IB subtraction

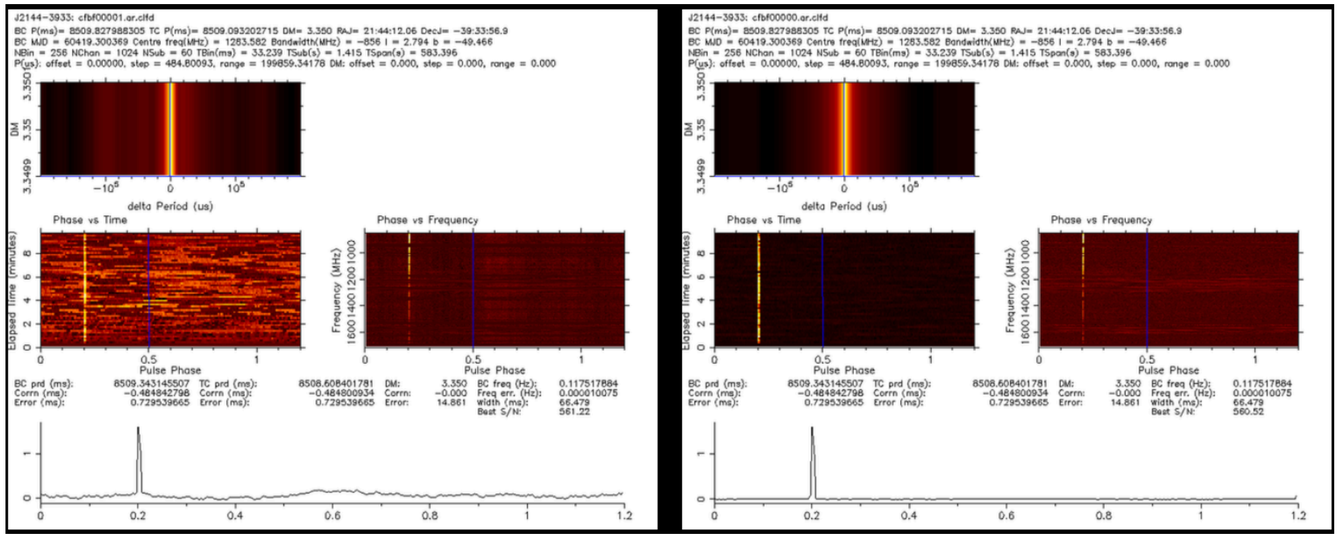


Remove/subtract the **autocorrelation** products from the beamformed products

Mitigates baseline variations

↓

Improves sensitivity to slow pulsars



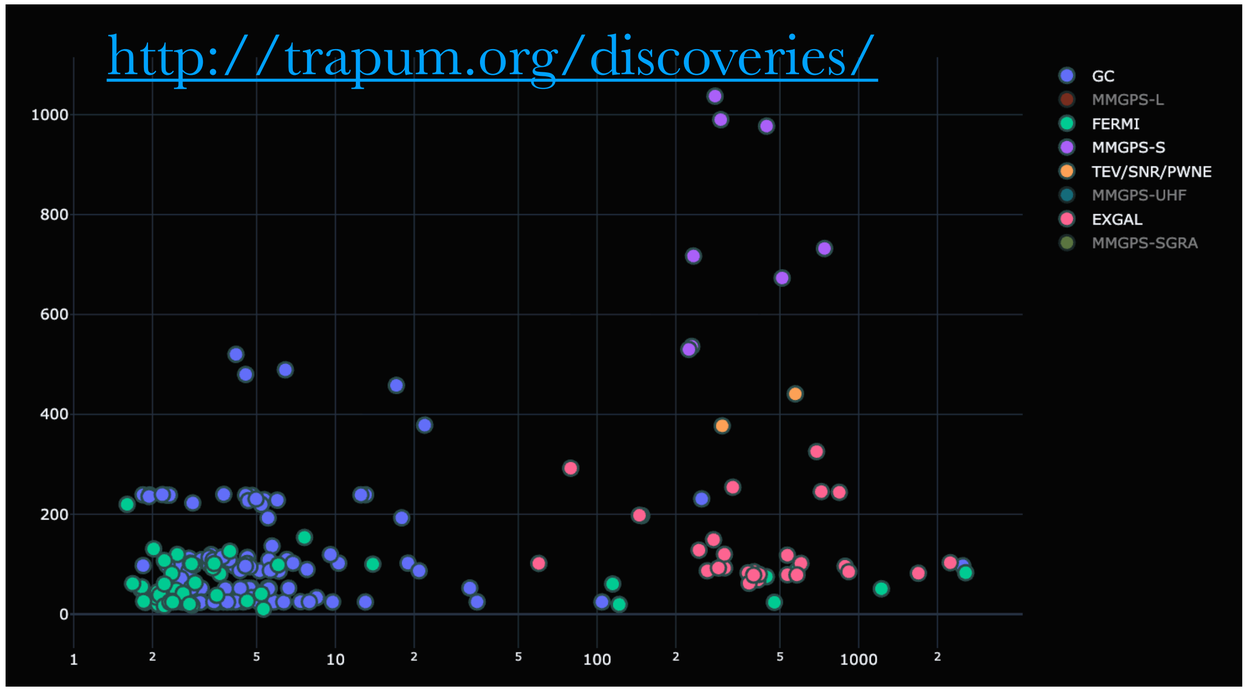
Credit: Vivek Krishnan

Conclusions

The TRAPUM survey has run for **5** years with nearly **1000** hours of observing

Nearly **200 pulsars** across globular clusters, Fermi sources, Magellanic Clouds and SNR/PWN sources

The next goal is to **continue following up** interesting sources **(Searching or timing)**



This survey has also laid a foundation to learn and plan for the next gen surveys - DSA 2000, ngVLA and SKA