TRAPUM

Transients and Pulsars with MeerKAT

MEERTIME

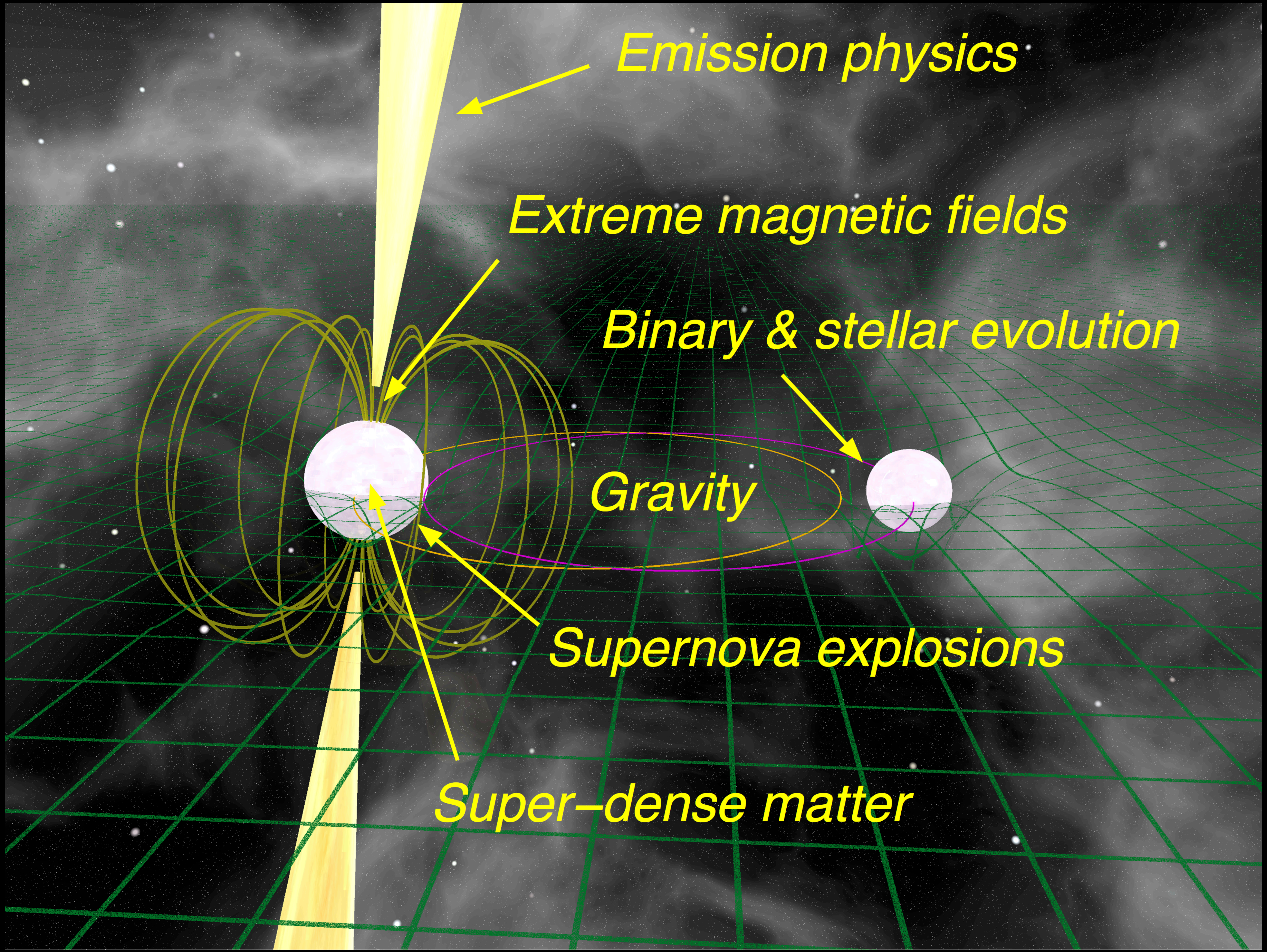
BEN STAPPERS — UNIVERSITY OF MANCHESTER

HUNTING & STUDYING EXTREME NEUTON STARS WITH MEERKAT

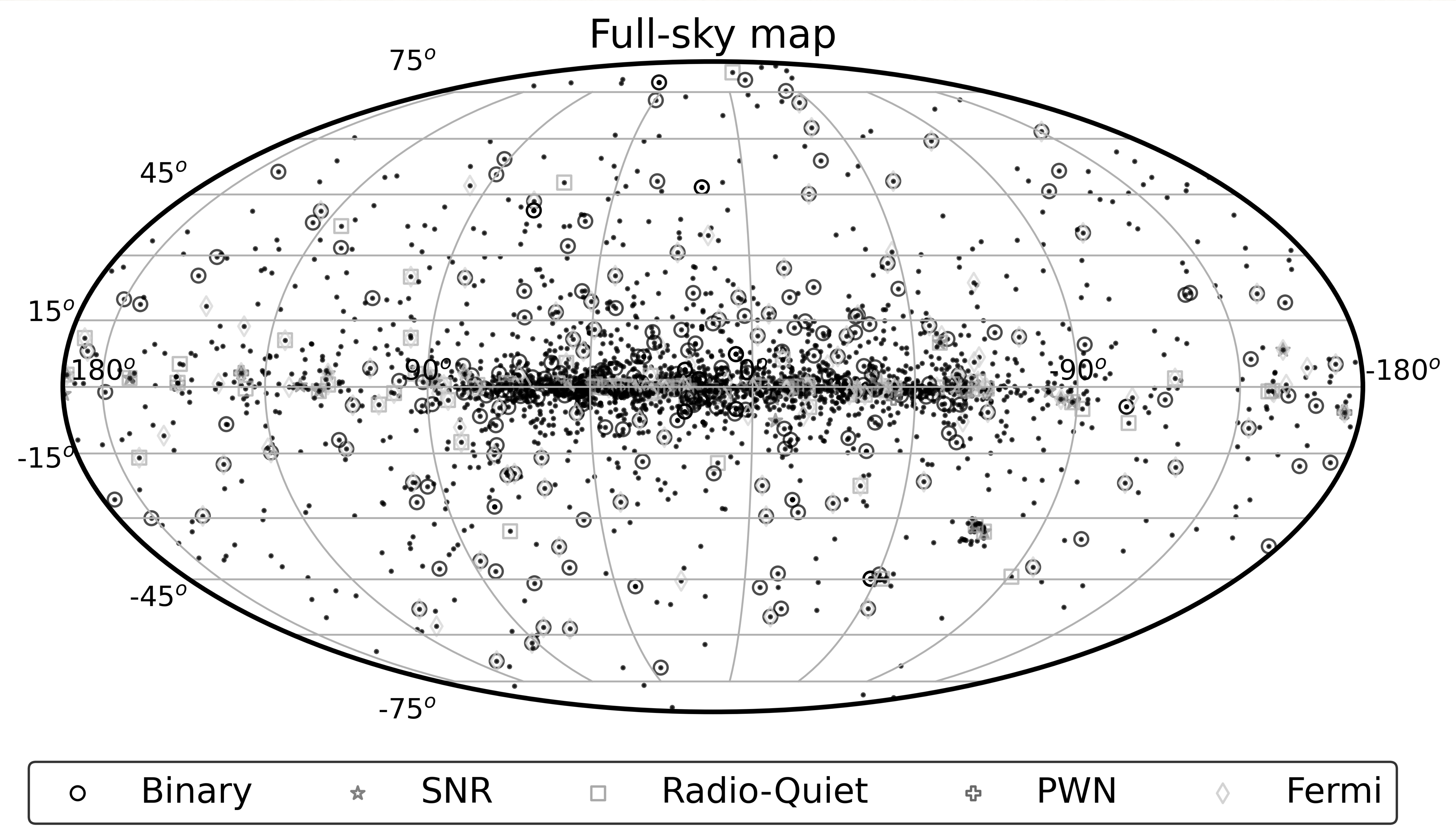
Thanks to the TRAPUM and MeerTIME teams for the shared slides!

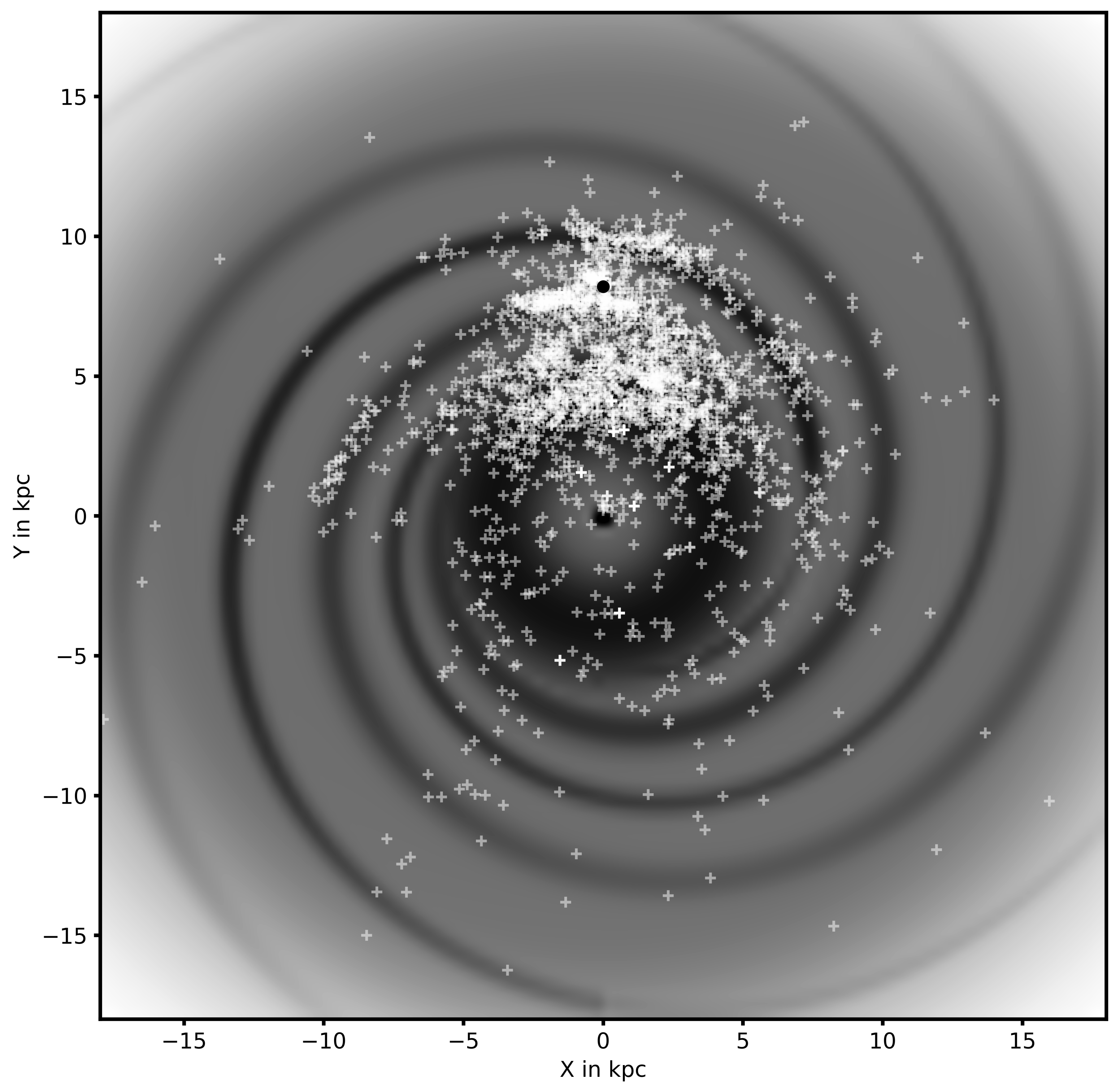
PULSARS ARE VERY SENSITIVE TOOLS FOR MEASURING ANYTHING THAT CAUSES A CHANGE IN THE TIME BETWEEN PULSES.

WHAT CAN WE USE THEM FOR?



Where to look?



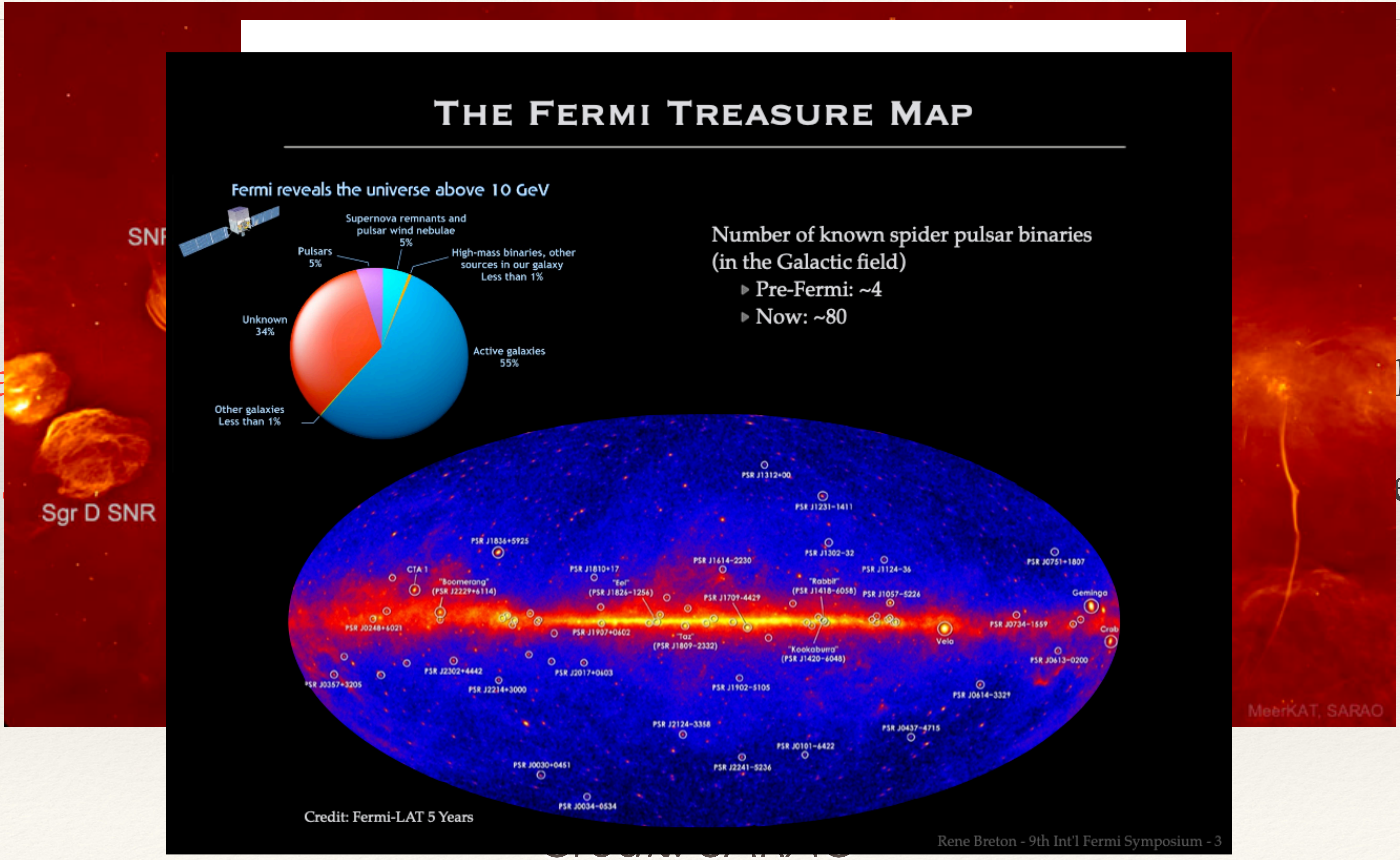


Pulsar Astronomy v5: Smith, Lyne, Stappers 2021

All Sky?

- Advantage is that it gives you an unbiased view of the population.
- Disadvantage it takes a long time and in many locations there will nothing

Targetted



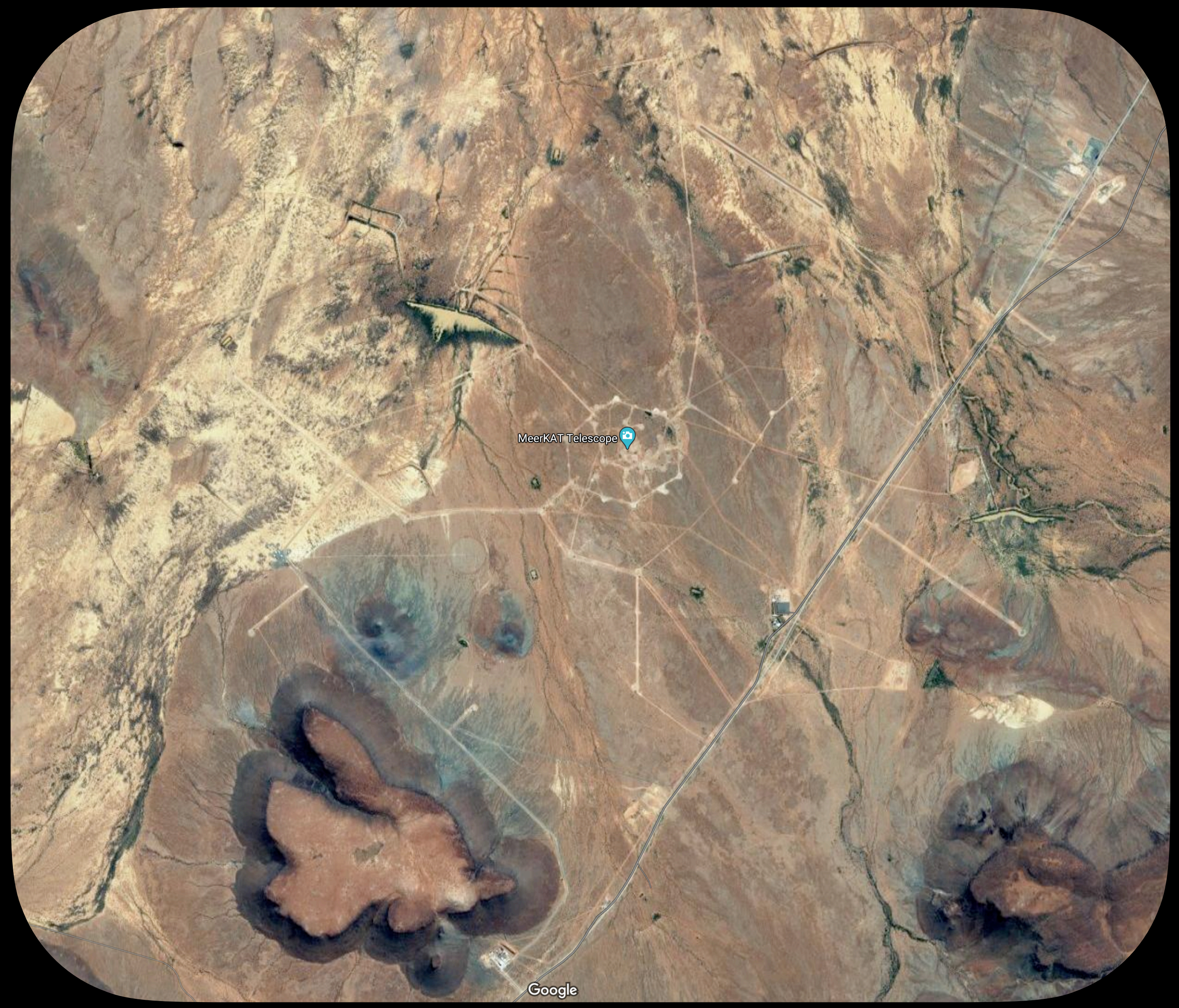
- Disadva … lation.
- Advant … ensitivity.

Credit: SARAO

WHY MEERKAT?

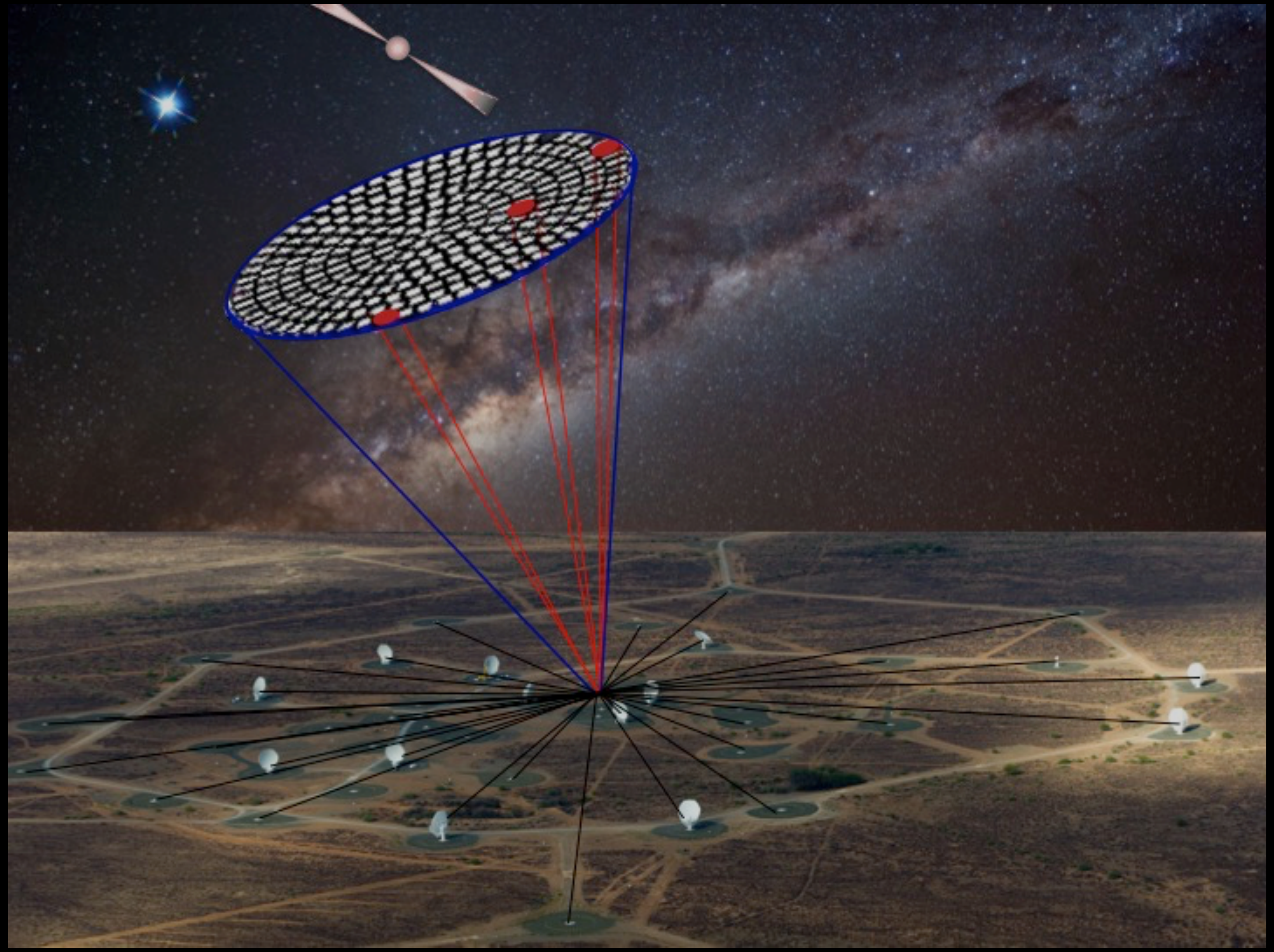
- Exceptional sensitivity
  - Large collecting area.
  - Wide bandwidths
  - Required for finding relativistic binaries.
- Wide field of view
  - Allows for fast surveys.
  - Access through combination of incoherent and coherent beams
- Resolution
  - Useful for searching in regions of diffuse high brightness temperature regions – e.g. SNRs & Galactic centre
  - Essential for accurate localisation of transients
- Wide range of frequencies
  - Optimise for searching in / through different parts of the Galaxy
  - S-band for deep in the Galactic Centre
  - L-band for intermediate Galactic latitudes
  - UHF band for wide area searches
- Location
- Flexibility & commensality

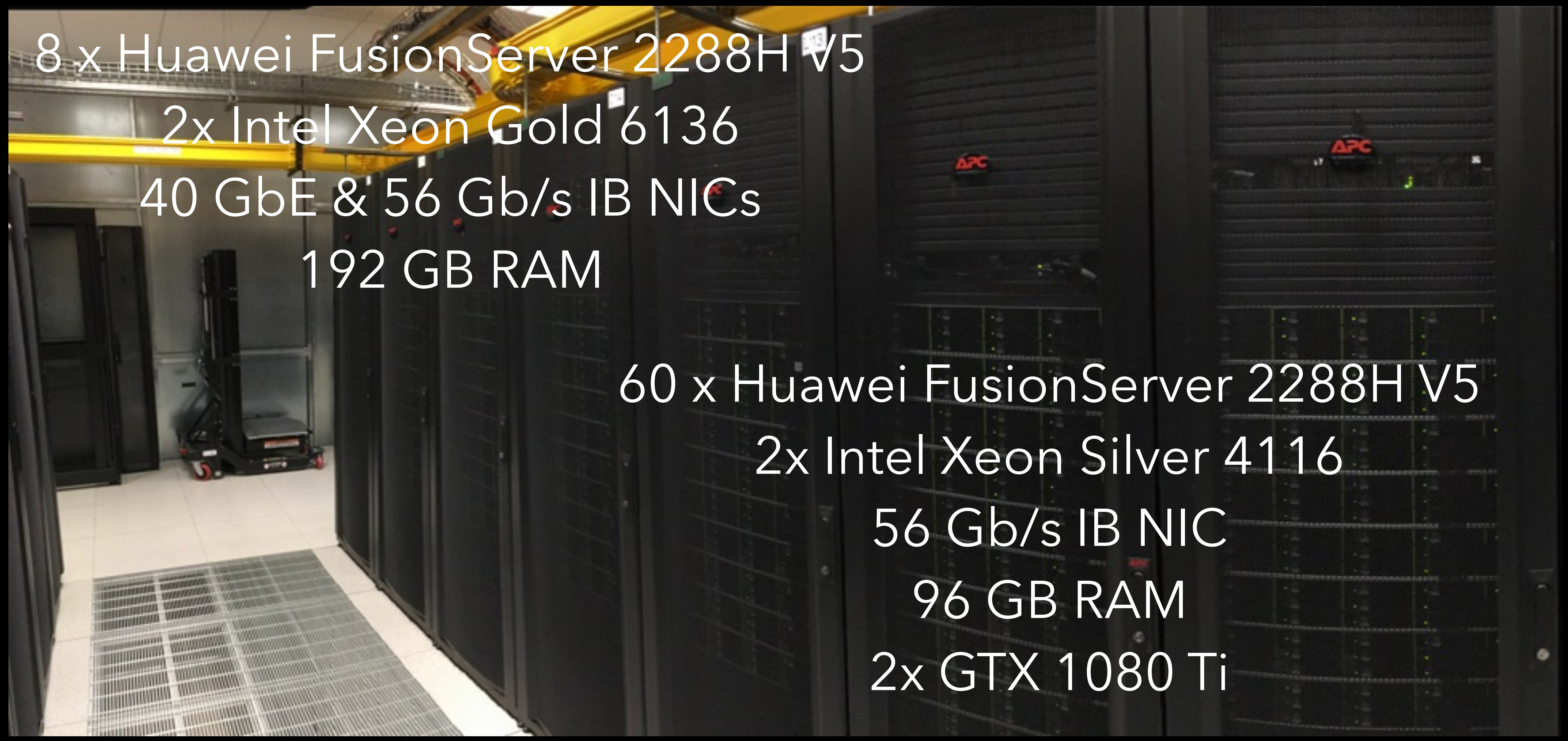
Number of antennas	64
Dish diameter	13.5 m
Minimum baseline	29 m
Maximum baseline	8 km
Frequency bands	544 – 1088 MHz (UHF-band) 856 –1712 MHz (L-band)
Instantaneous bandwidth	544 MHz (UHF-band) 856 MHz (L-band)
Gain 64 dishes (0.58 - 1.67GHz)	2.75 K/Jy



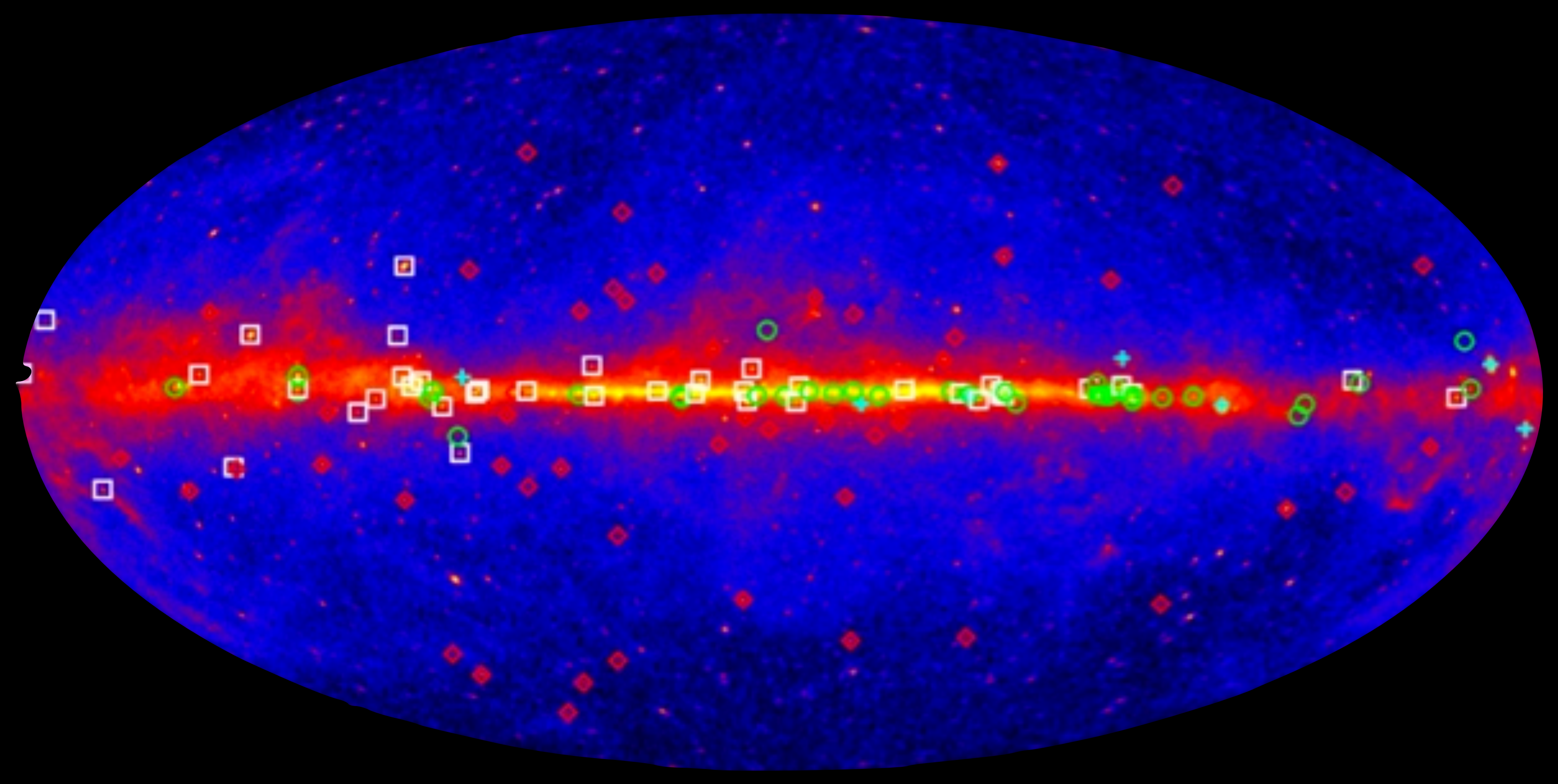
BEAMFORMING

- Large field of view is excellent…BUT
- We still need the excellent sensitivity
  - Processing time for binary searches scales as – (integration time)^3
- Form large numbers of tied-array or coherent beams — ~800
- Limited by compute power!
  - need to make all the beams
  - and need to process all the beams

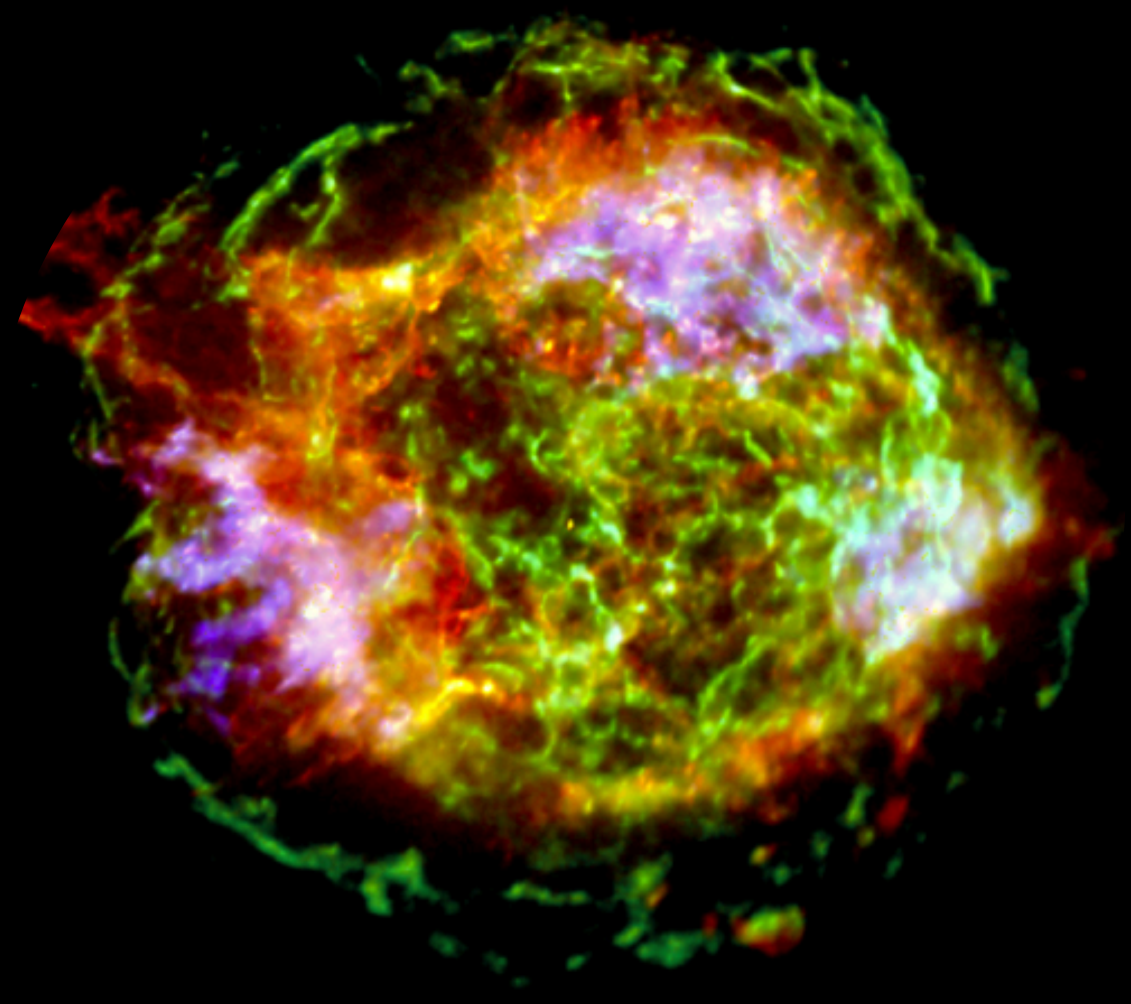




Nearby galaxies



Fermi sources



TRAPUM

Transients and Pulsars with MeerKAT

Globular clusters

TRAPUM

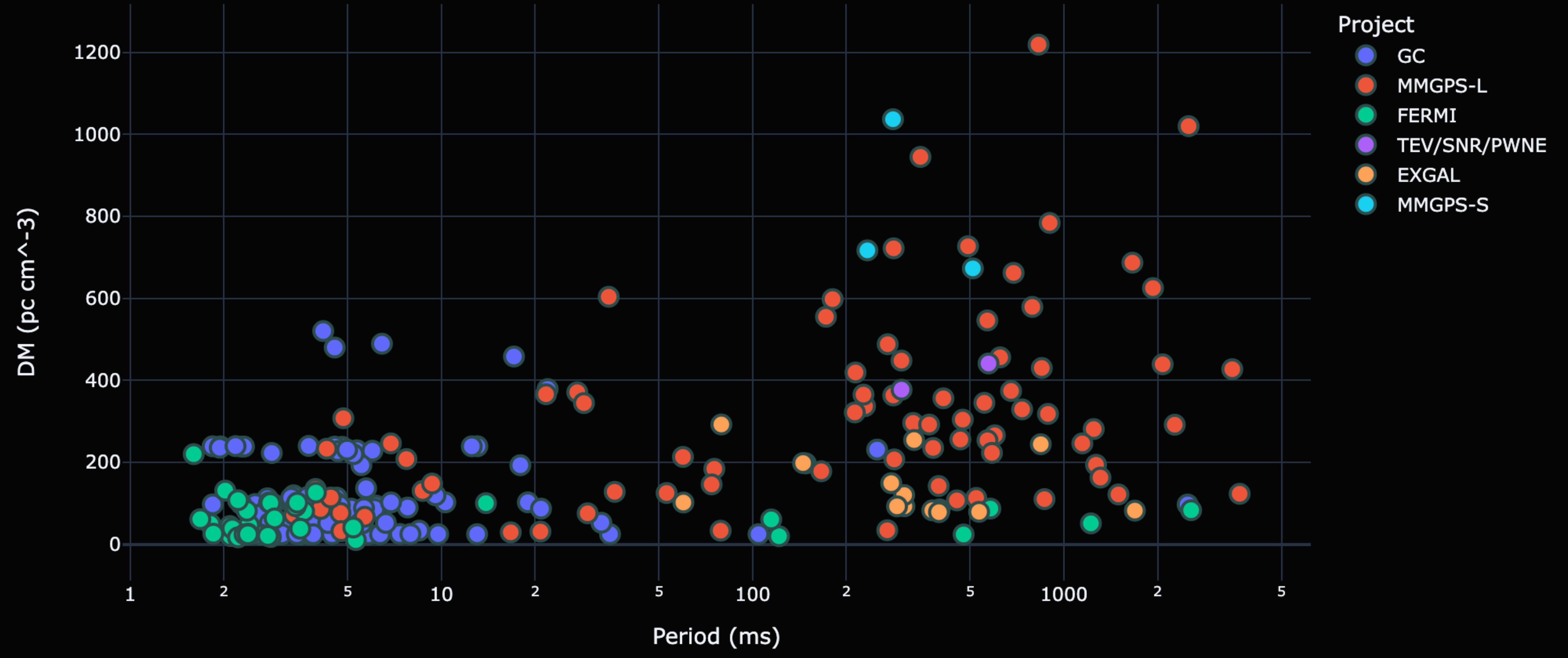
Transients and Pulsars with MeerKAT

TOTAL DISCOVERIES: 227

EXGAL: 14 **FERMI:** 36 **GC:** 94 **MMGPS-L:** 78 **MMGPS-S:** 3 **TEV/SNR/PWNE:** 2

LAST UPDATED: 2024-04-19 04:08

Graph | Table



x-axis

Period (ms)

y-axis

DM (pc cm^-3)

z-axis

Project

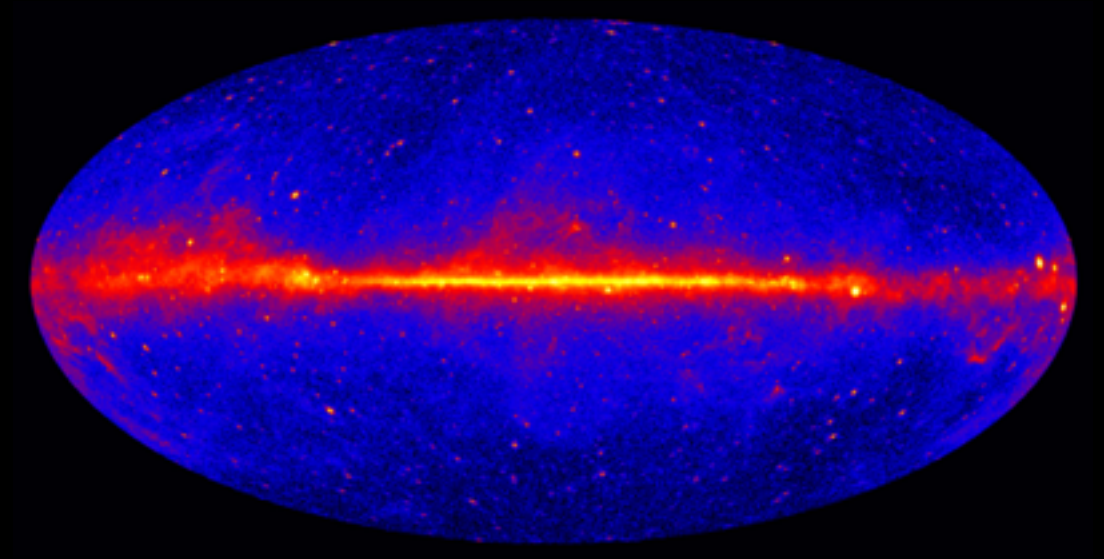
log-x

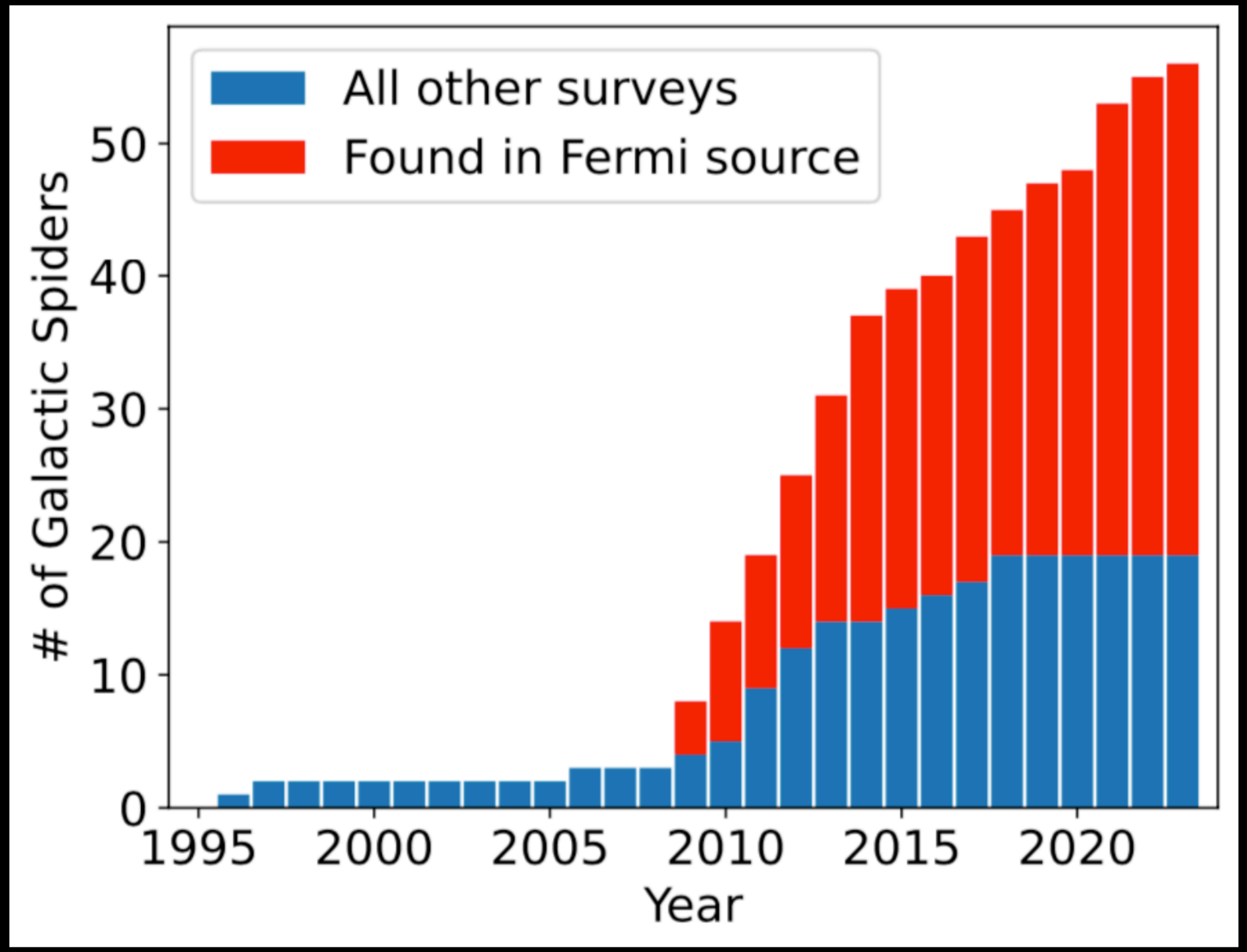
log-y

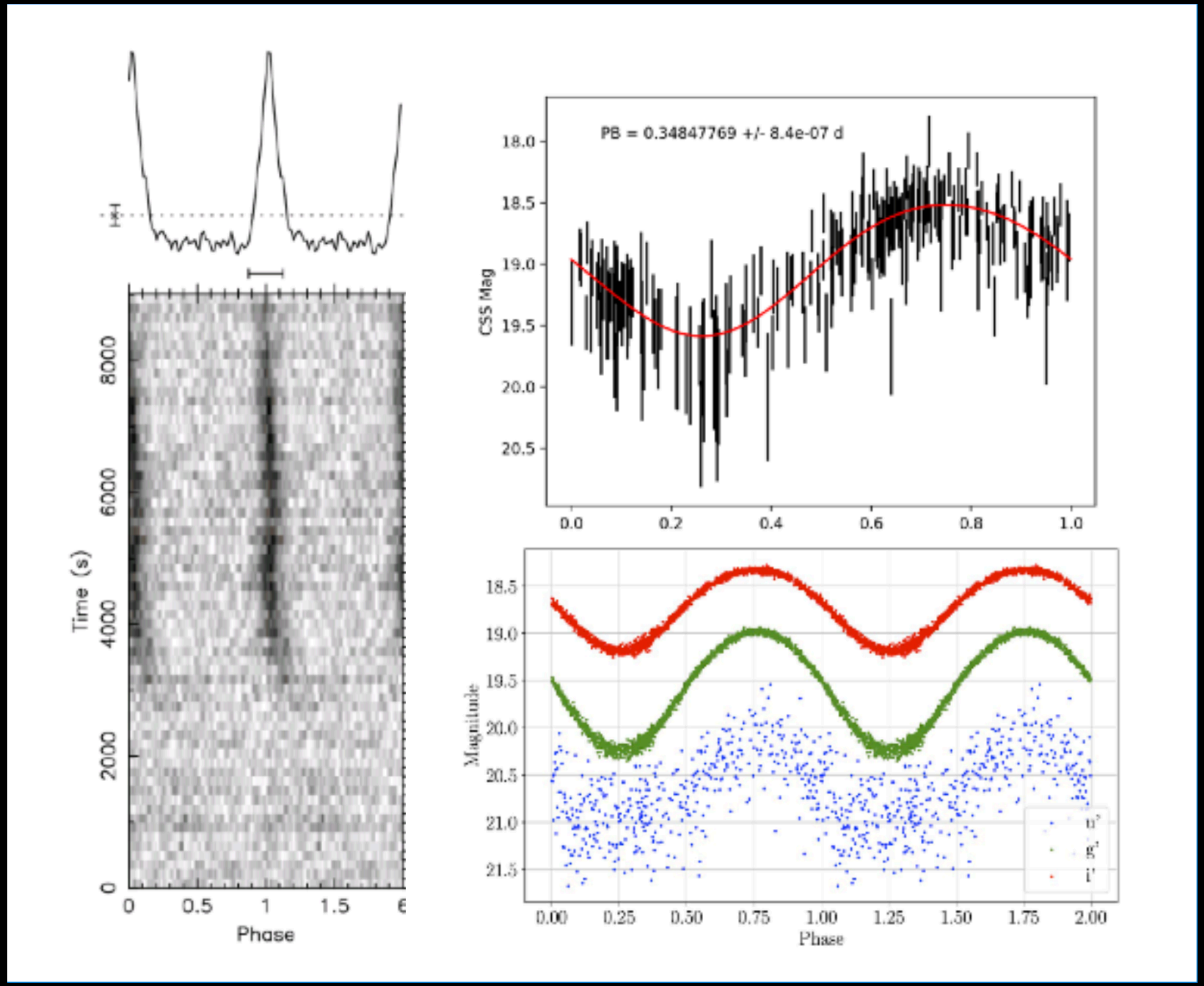
Update

trapum.org/discoveries

FERMI UNIDENTIFIED SOURCES



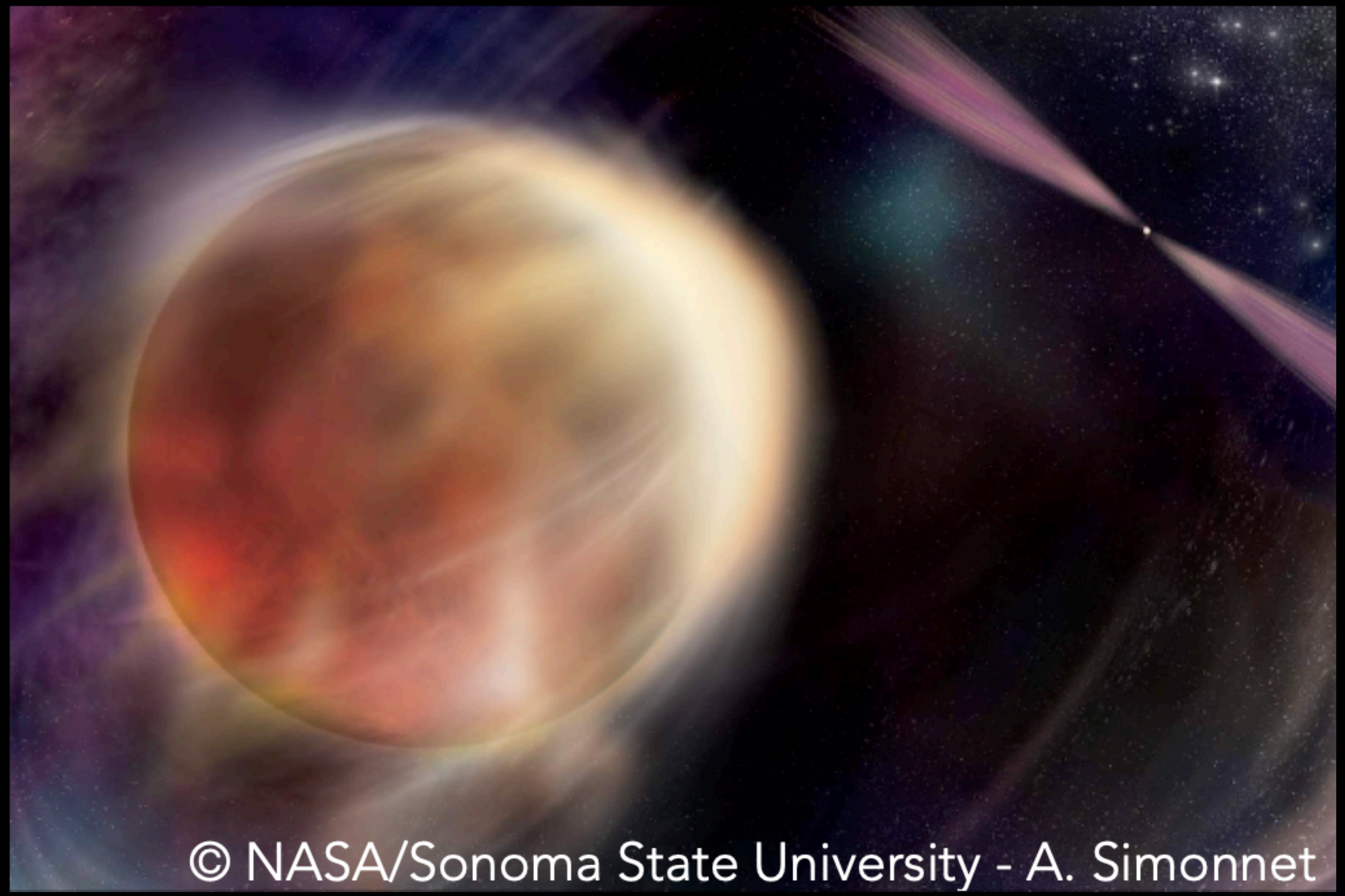




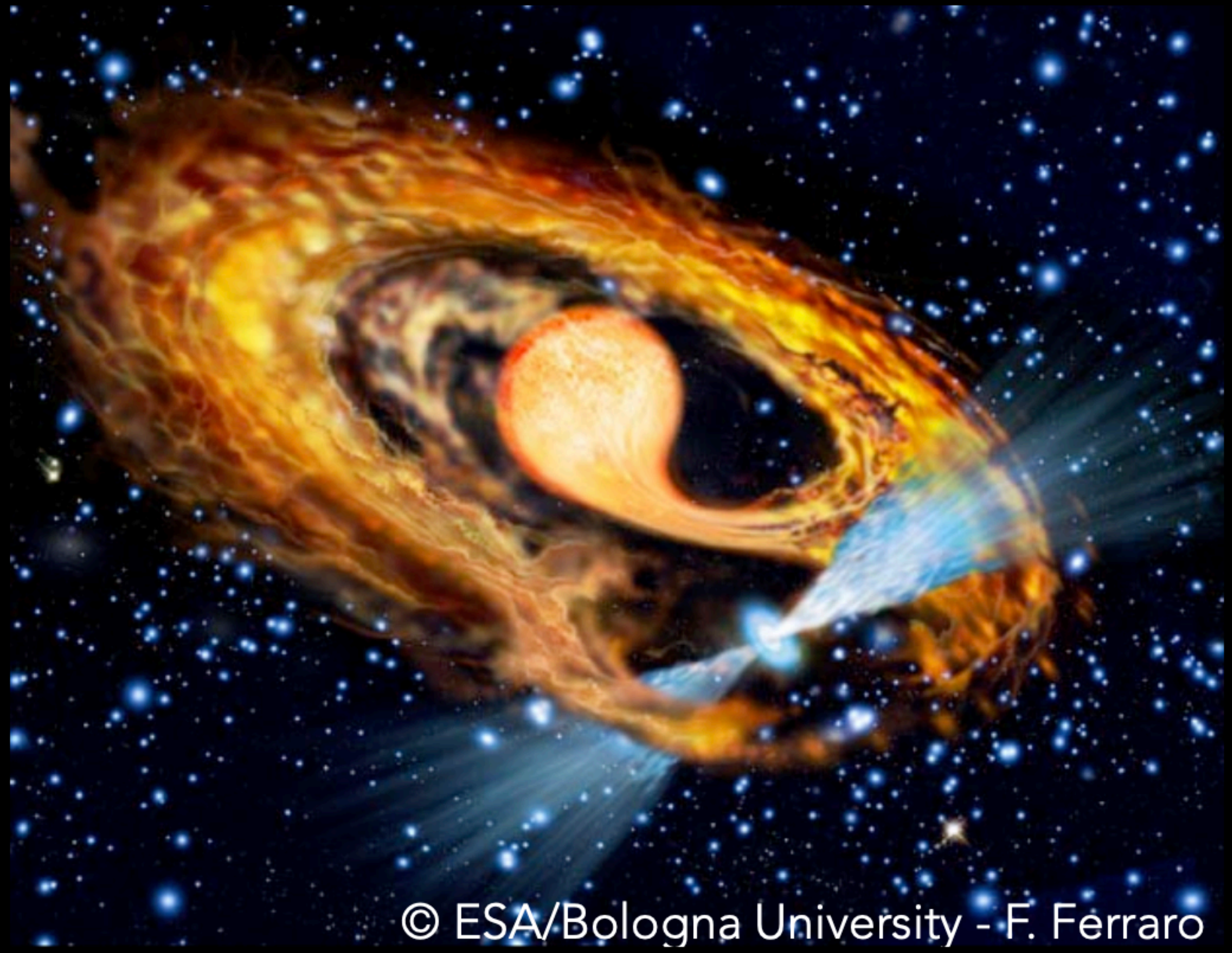
MeerKAT already discovered more than 42 new MSPs

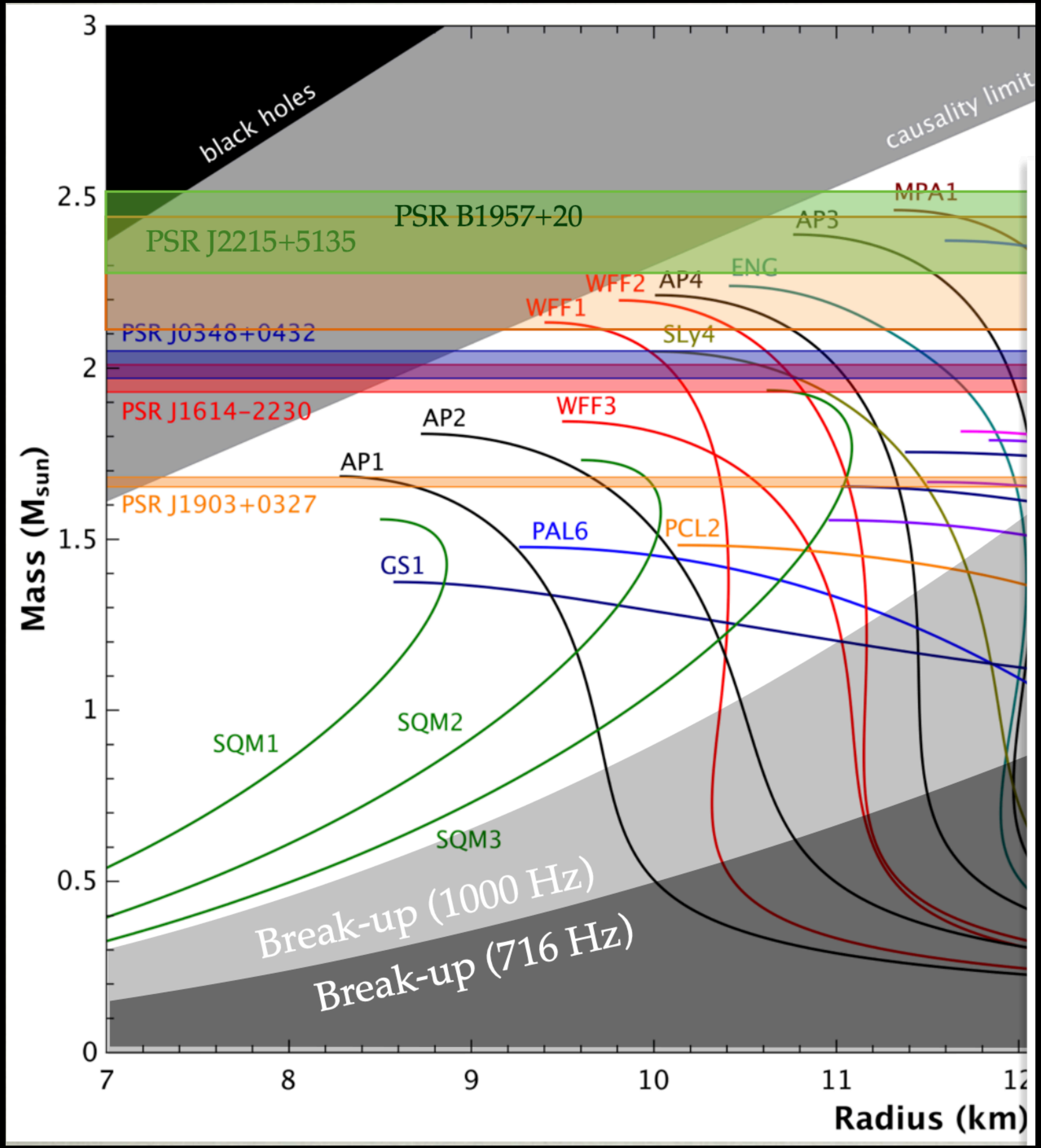
"SPIDER" BINARIES

Black Widows (~0.02 M⊙)



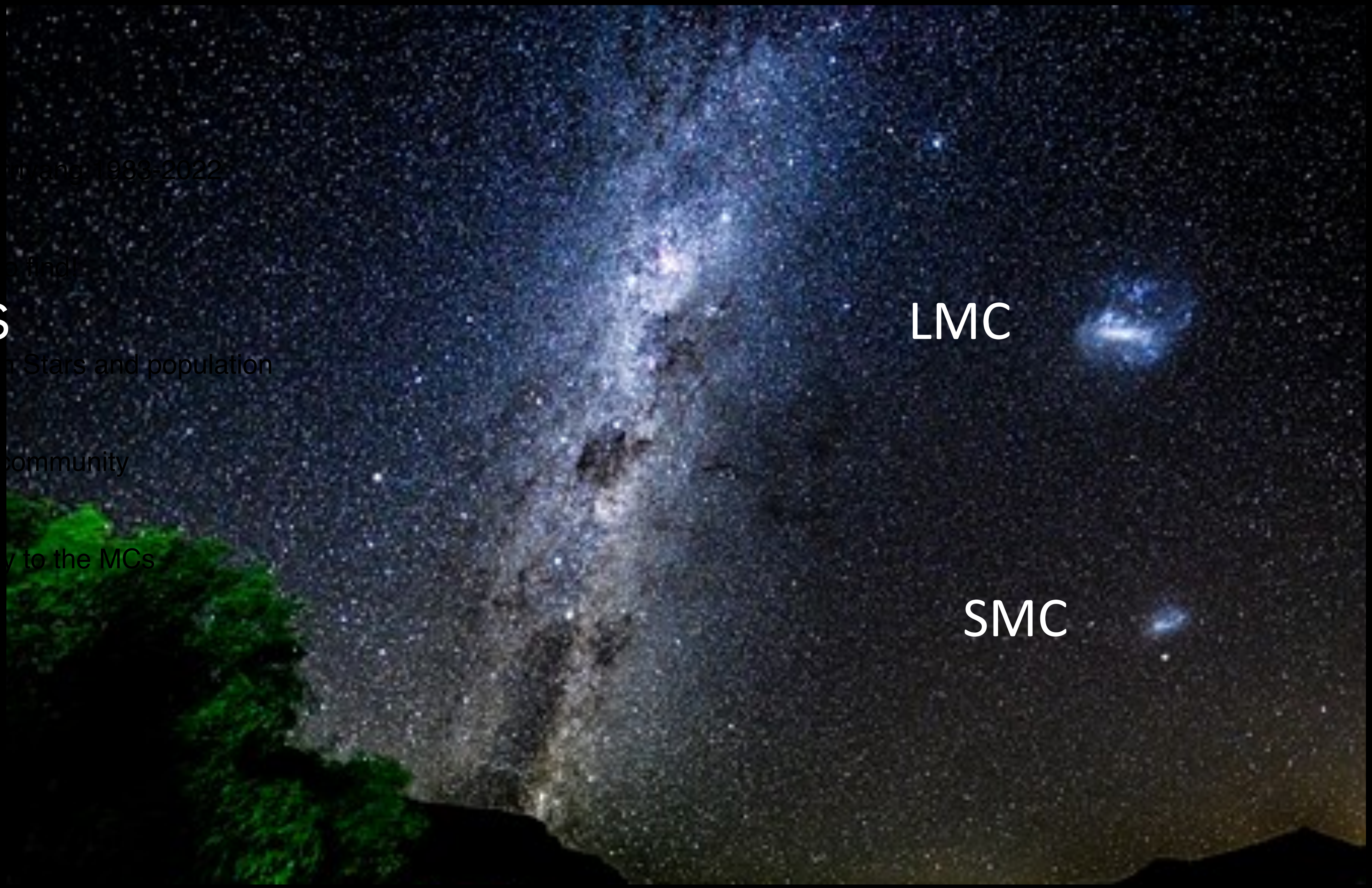
Redbacks (~0.2-0.4 M⊙)



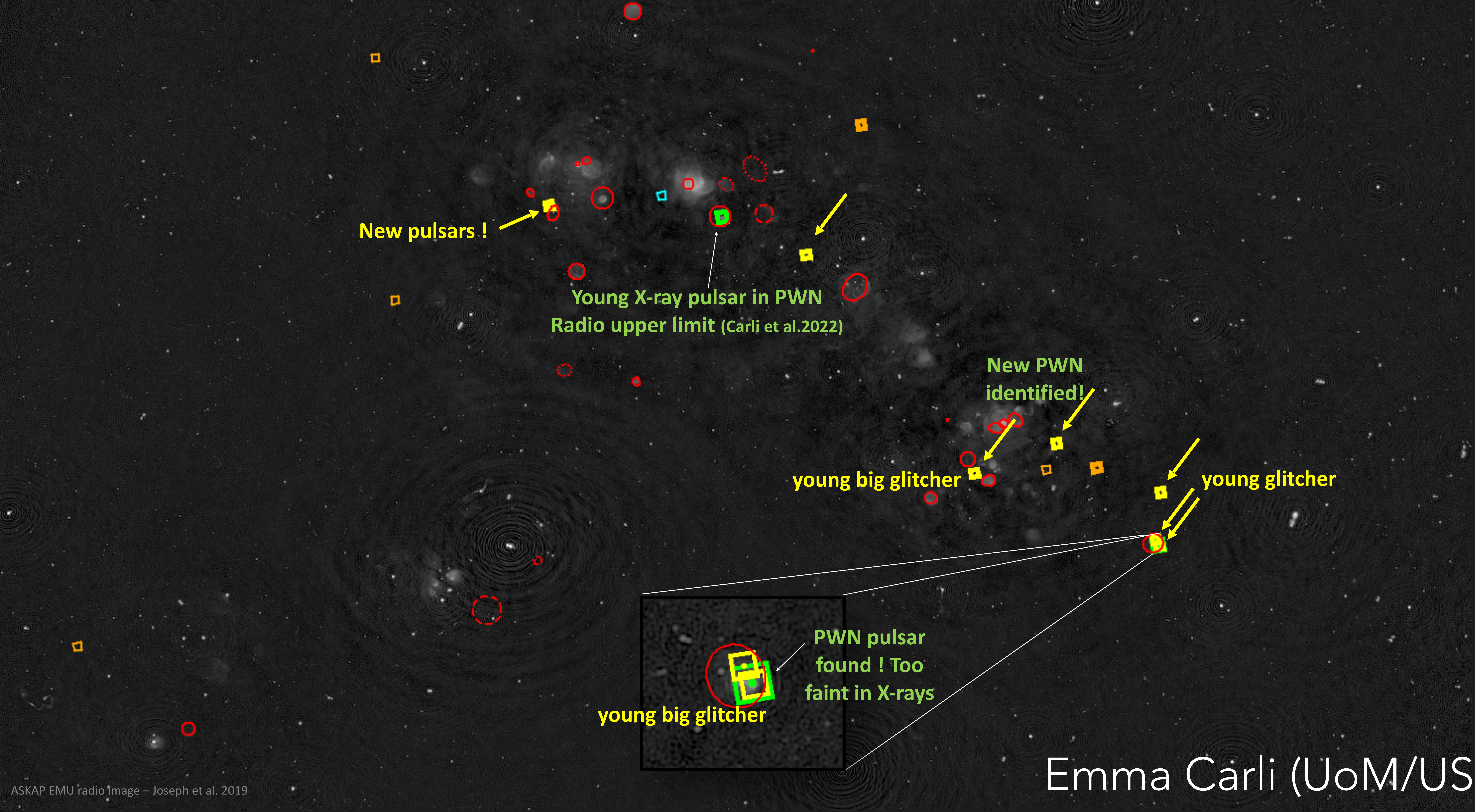


EXTRAGALACTIC PULSARS

- Rare: Of 3k pulsars discovered, 31 are extragalactic
- All in the Magellanic Clouds, radio discoveries with Murriyang 1983-2022
- New observatory with better sensitivity : more pulsars to find!
- Different galaxy: properties impact pathways to Neutron Stars and population
- Extragalactic NS merger rate update: interest to GW community
- FRBs are linked to NS, one repeater in a similar galaxy to the MCs



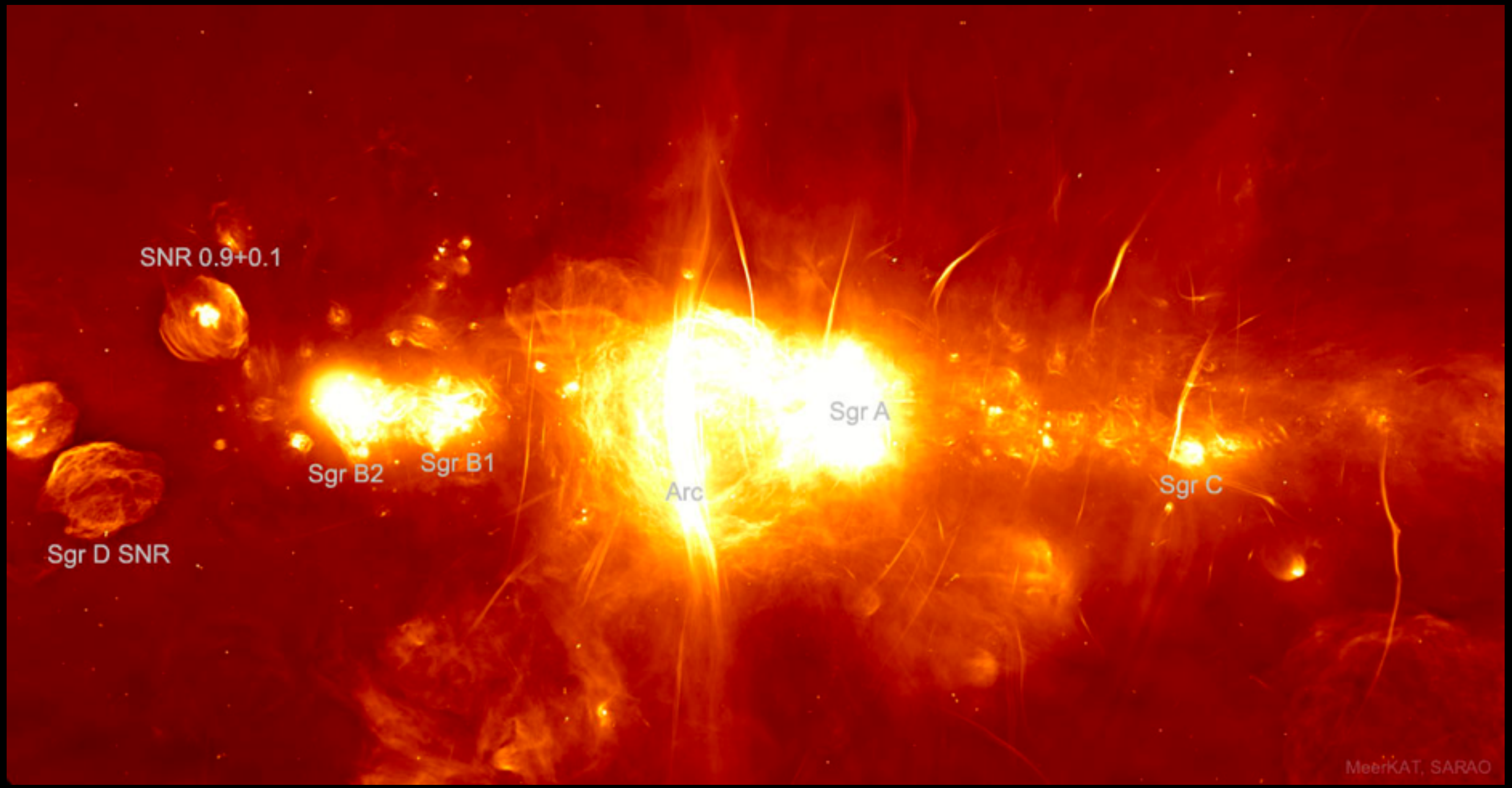
DISCOVERIES IN THE SMC



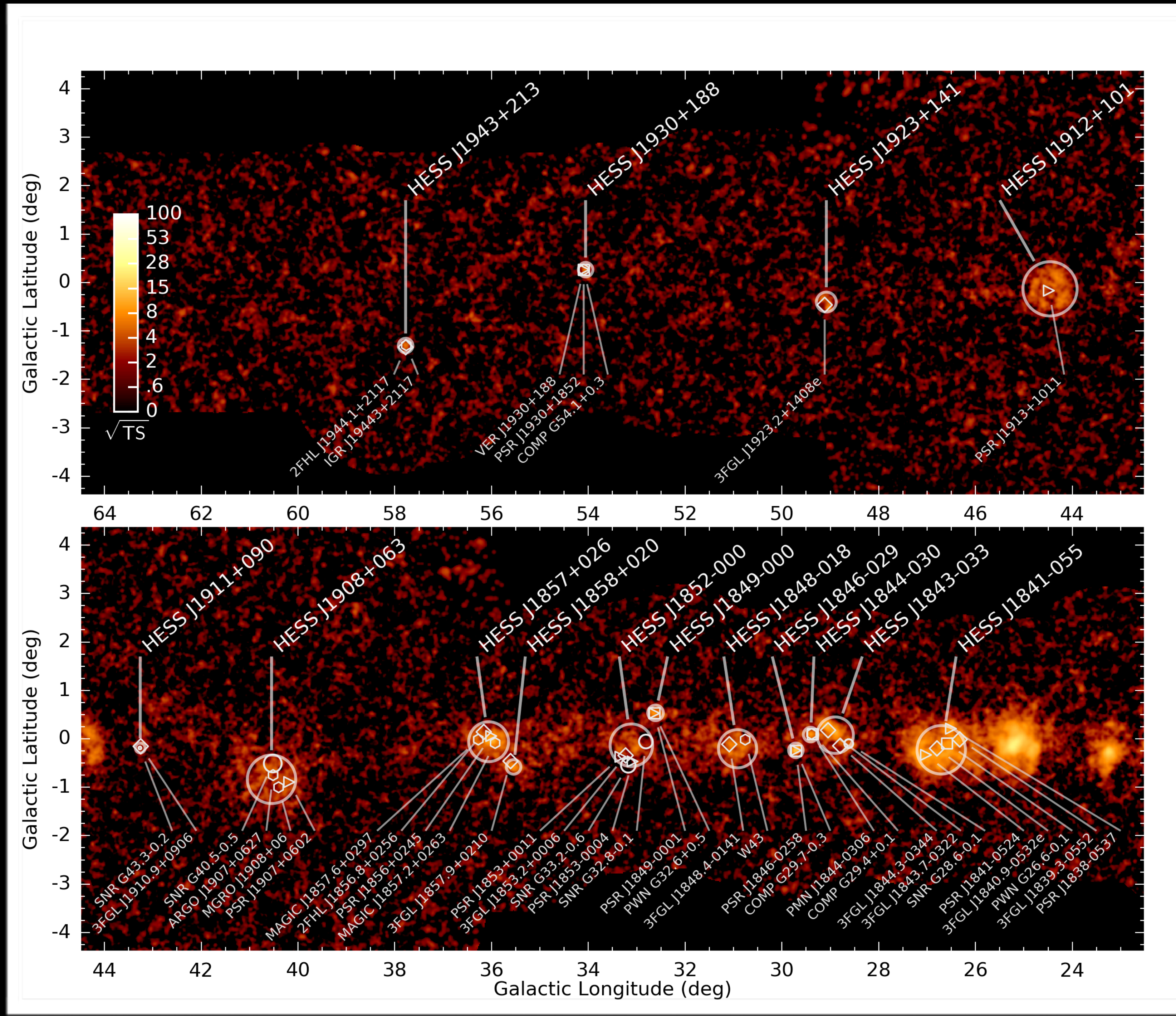
Emma Carli (UoM/USwin)

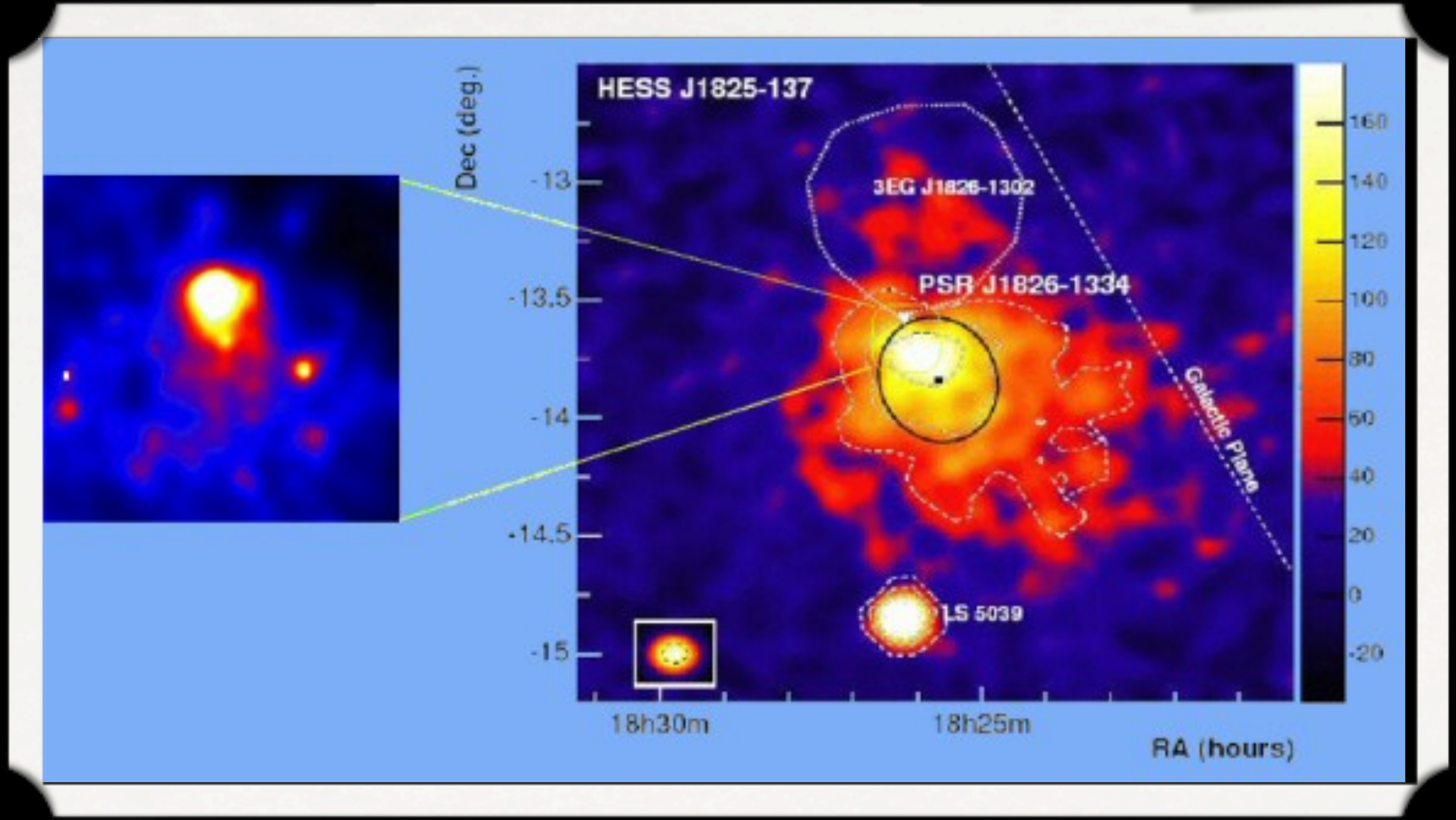

ASKAP EMU radio image – Pennock et al. 2022
DISCOVERIES IN THE LMC
Only part of LMC shown!
New pulsars !
UPDATE NOV 2024 — NOW 16 NEW PULSARS!!!!
Venu Prayag (UCT) and Heinrich Hurter (North-West University)

PULSAR WIND NEBULAE, SUPERNOVA REMNANTS AND TEV SOURCES



MeerKAT image of the Galactic Centre Region
Credit: SARAO





James Turner (UoM)

GLOBULAR CLUSTERS

About 50% of all the known MSPs are found in globular clusters (GCs)

Spherical, gravitationally bound groups of 10^4 - 10^6 stars, confined within a volume a few light-years across.

Among the oldest structures known in the universe (ages billions of years)

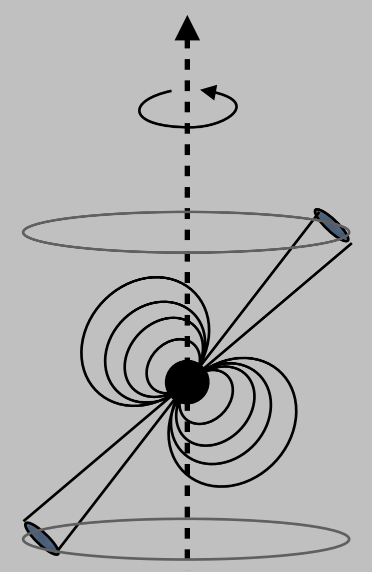
Extreme stellar densities, several orders of magnitude higher than those found in the Galaxy, favouring the formation and disruption of binaries.


M15 (Credit: HST)

→ GCs are extremely efficient factories of MSPs and exotic pulsars!

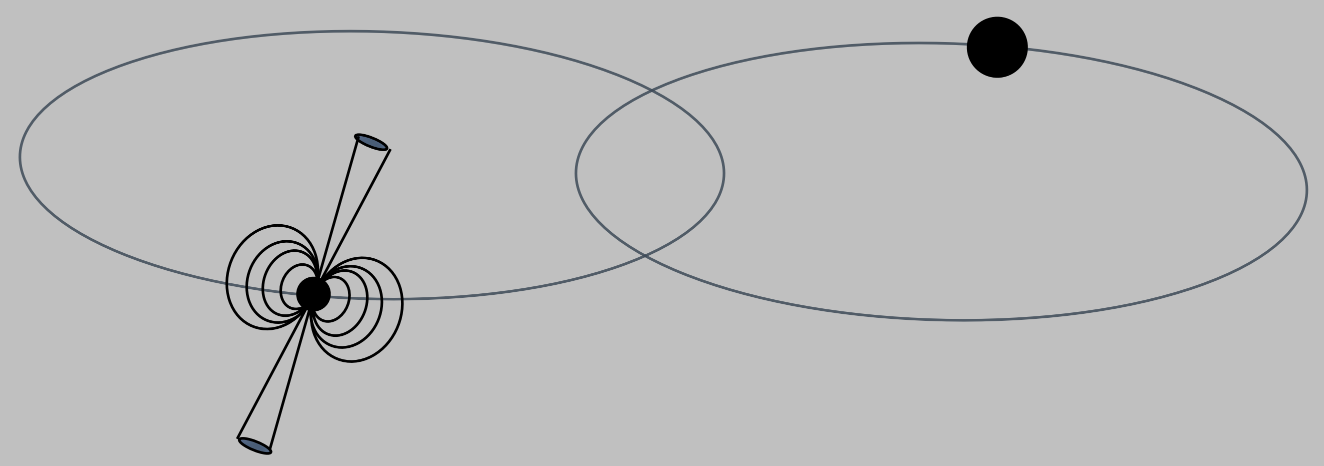
EXCITING PULSARS

Extremely recycled pulsars



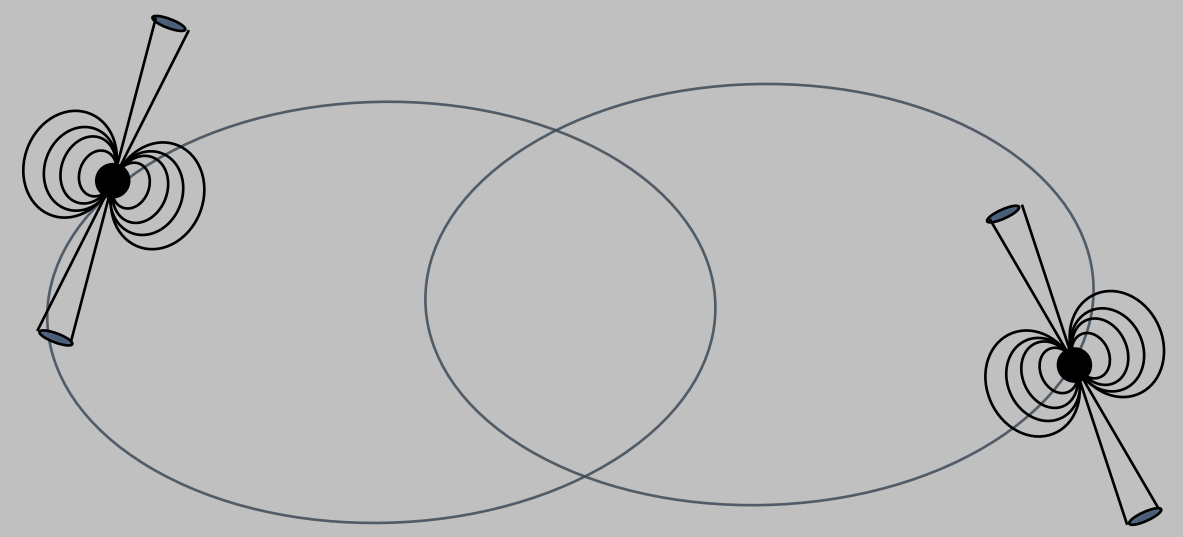
e.g.: Ter 5 ad (Hessels et al. 2006) ✔

Extremely eccentric binaries



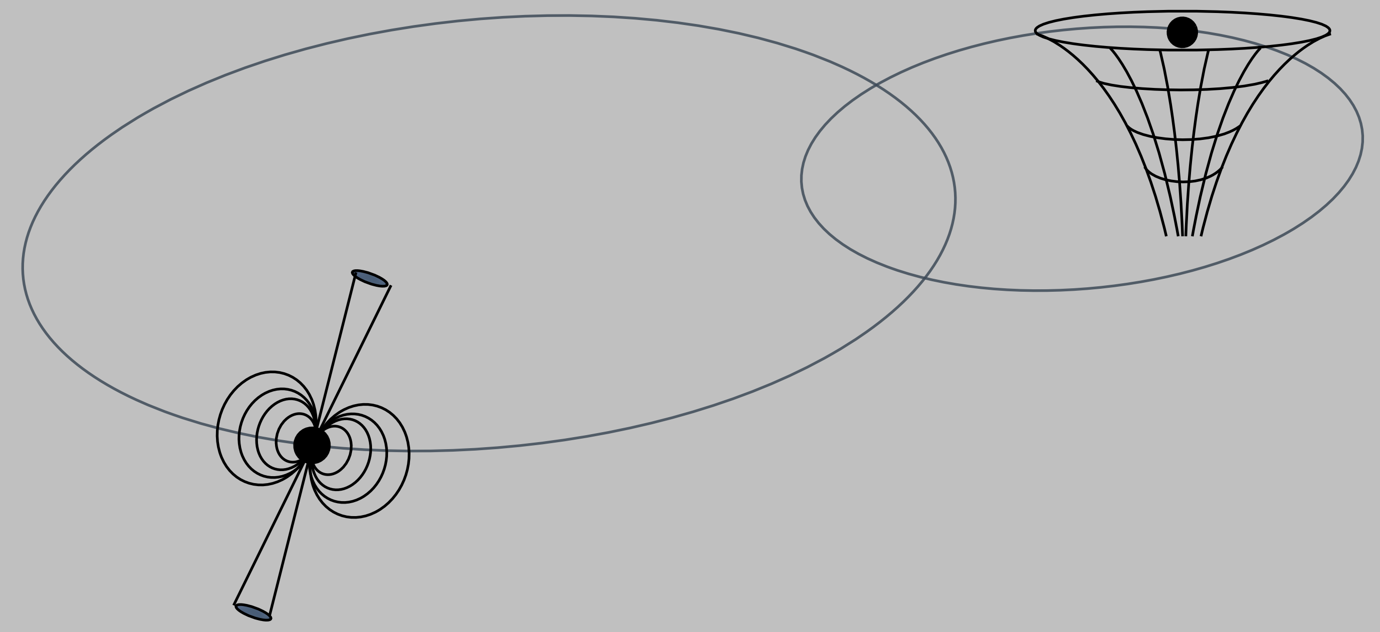
e.g.: NGC 6652 A (DeCesar et al. 2015) ✔

MSP - MSP



✘

Pulsar - BH



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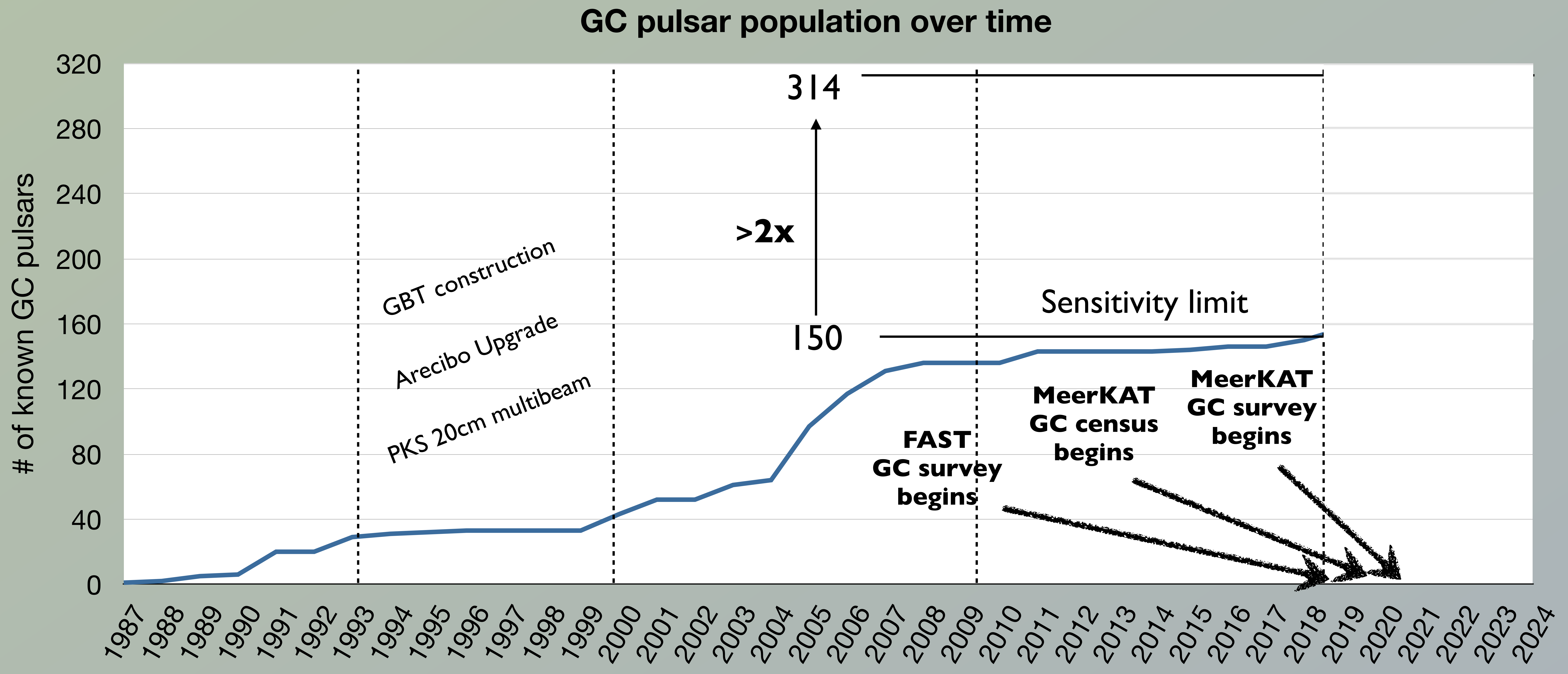
Where are we now?



MeerKAT	FAST	GBT	Parkes	GMRT
+105	+51	+8	+8	+3
Ridolfi et al. (2021) Vleeschower et al. (2022) Douglas et al. (2022) Ridolfi et al. (2022) Abbate et al. (2022) and many more…	Pan et al. (2020) Wang et al. (2020) Pan et al. (2021a, b) Qian & Pan (2021) Yan et al. (2021) Pan et al. (2023)	De Cesar et al. (in prep)	Dai et al. (2020) Zhang et al. (2022)	Gautam et al. (2022)

https://www3.mpifr-bonn.mpg.de/staff/pfreire/GCpsr.html

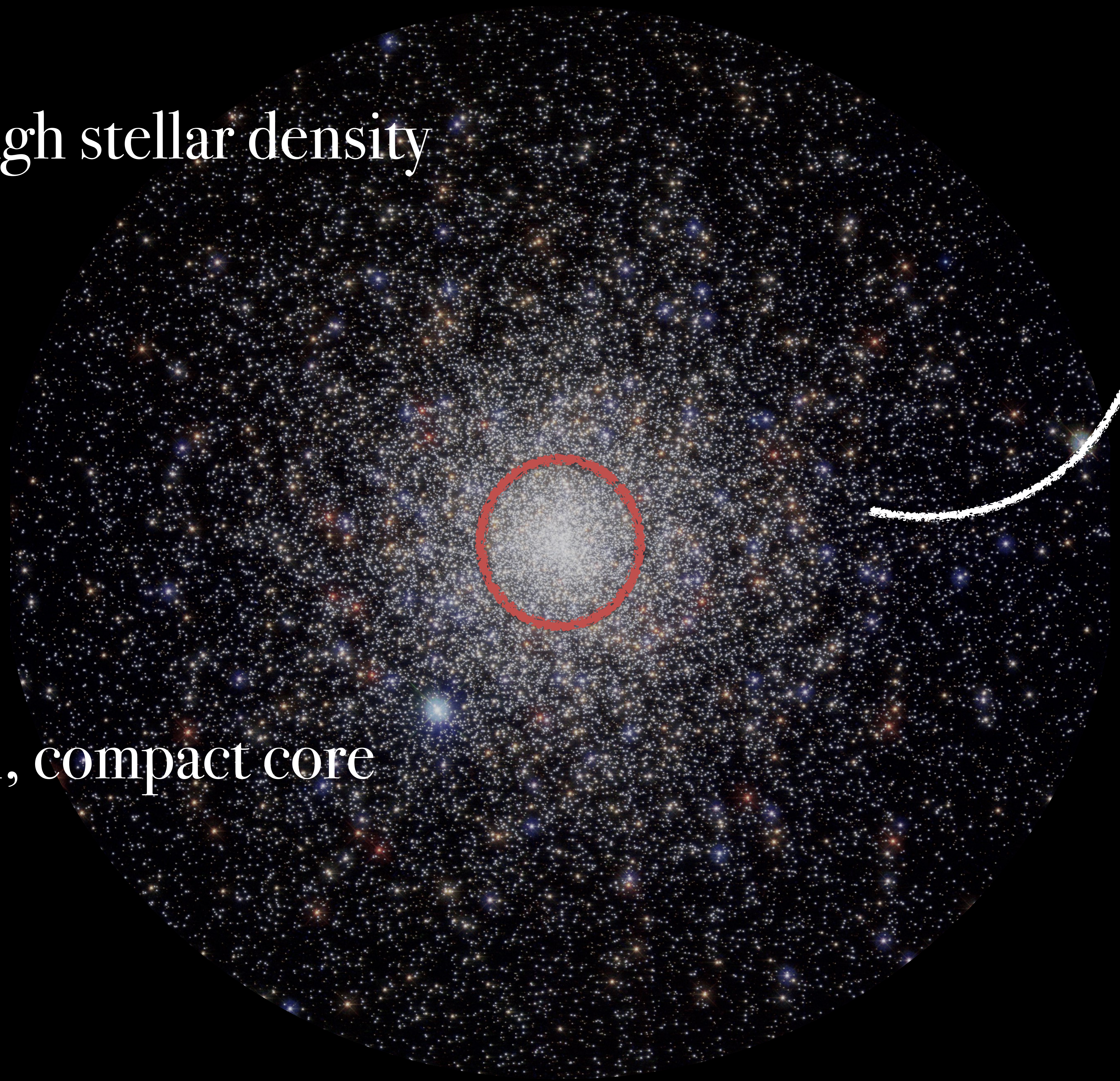
NGC 1851

Source: Hubble

- Southern constellation of Columba
- Distance $\sim$ 11.6 kpc
- Age $\sim$ 9 Gyr
- Stellar density $\sim 3 \times 10^6 M_\odot/pc^3$

(Libralato+22)

NGC 1851

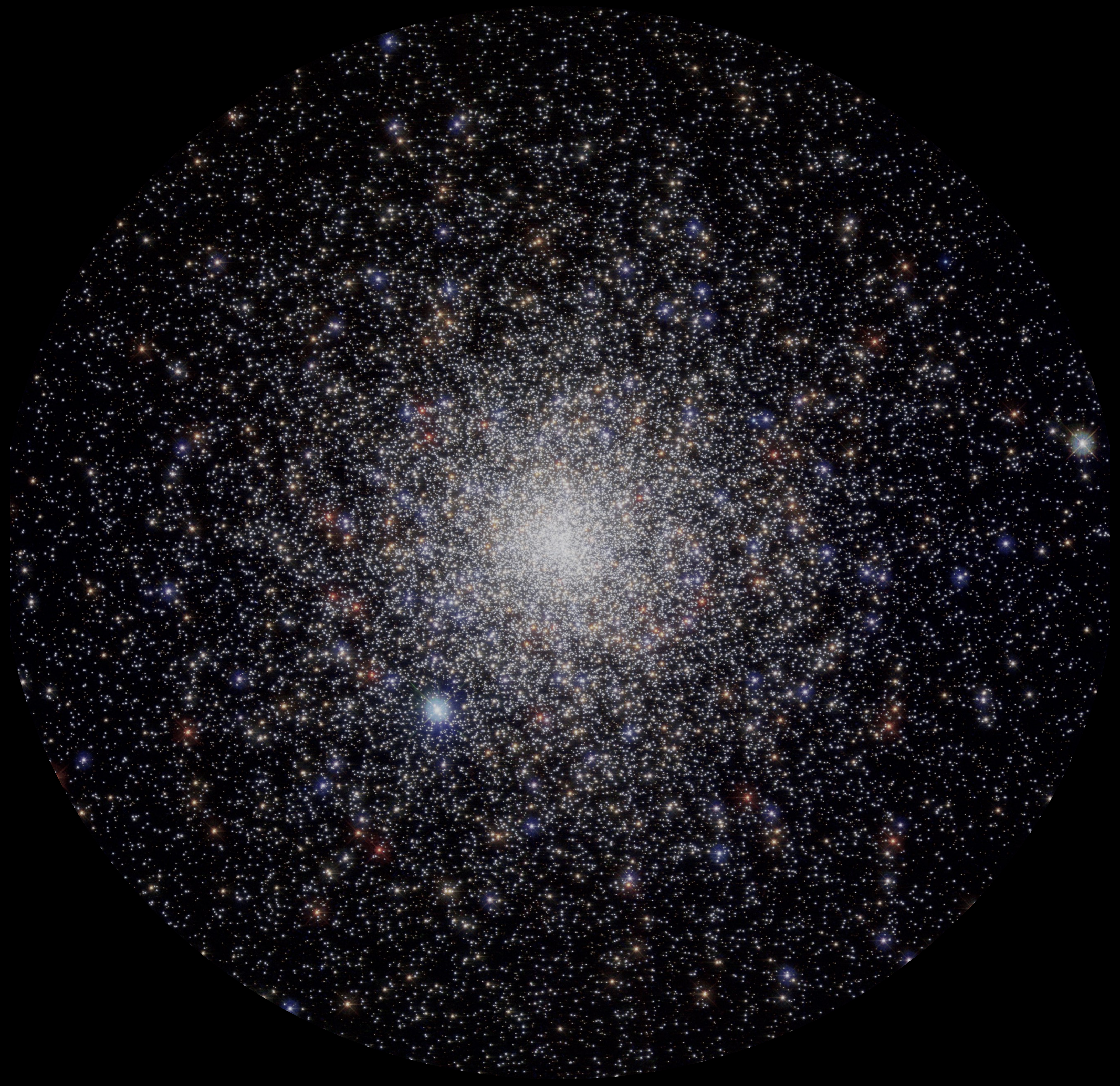


Multiple stellar interactions/ binary

Forms **exotic** systems:

Fully recycled pulsars, highly eccentric binaries

NGC 1851



One known pulsar NGC 1851A

Discovered with GMRT (Freire+2004)

MSP - heavy WD eccentric binary

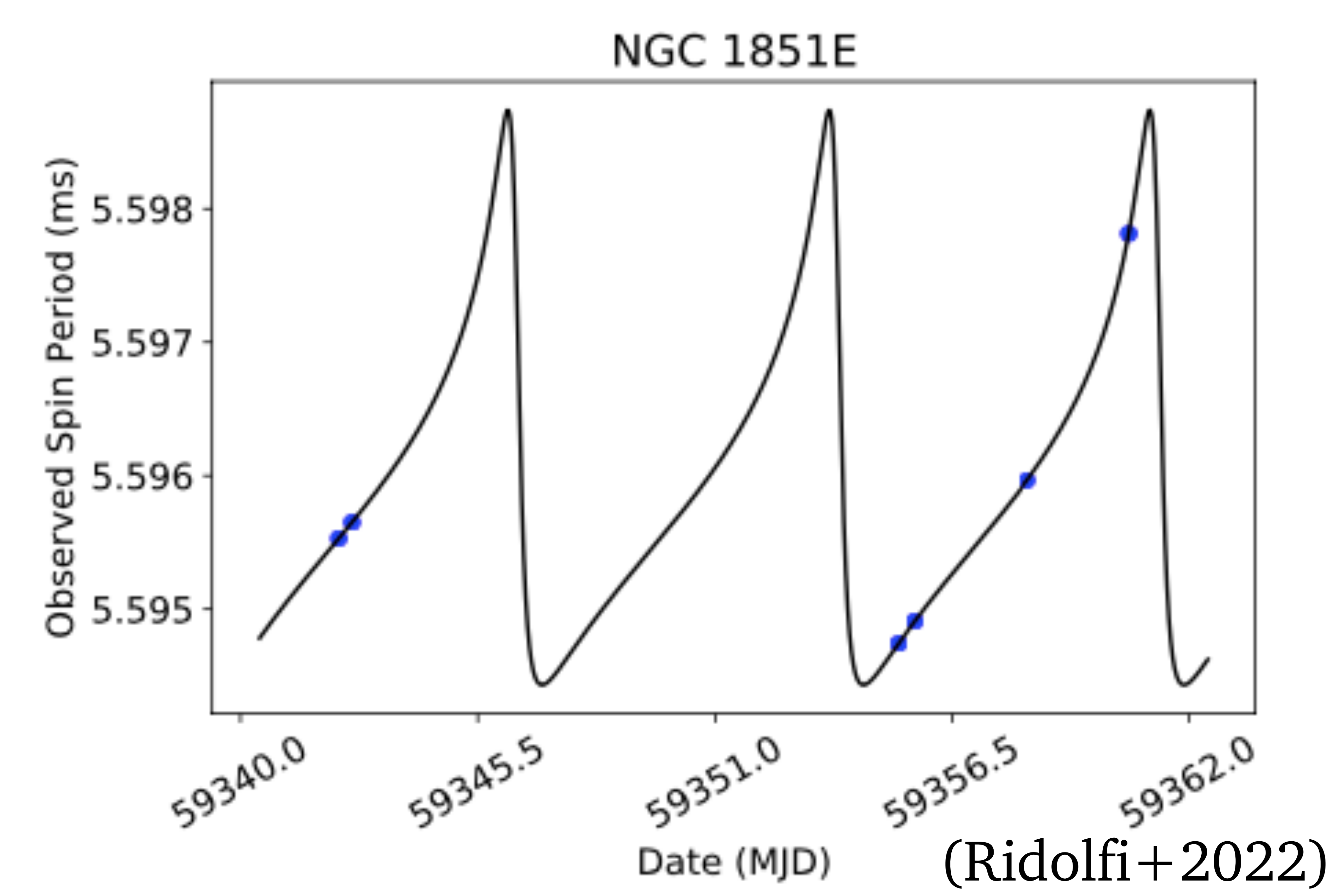
MeerKAT & TRAPUM

13 new pulsars
8 in binaries

↓

3 eccentric binaries:
MSP - heavy companions

NGC 1851E



(Ridolfi+2022)

What did we know?

5.6 ms pulsar in NGC 1851
Eccentric binary: 7.4 day orbit, $e = 0.7$

High mass function ⟶ **Massive companion**

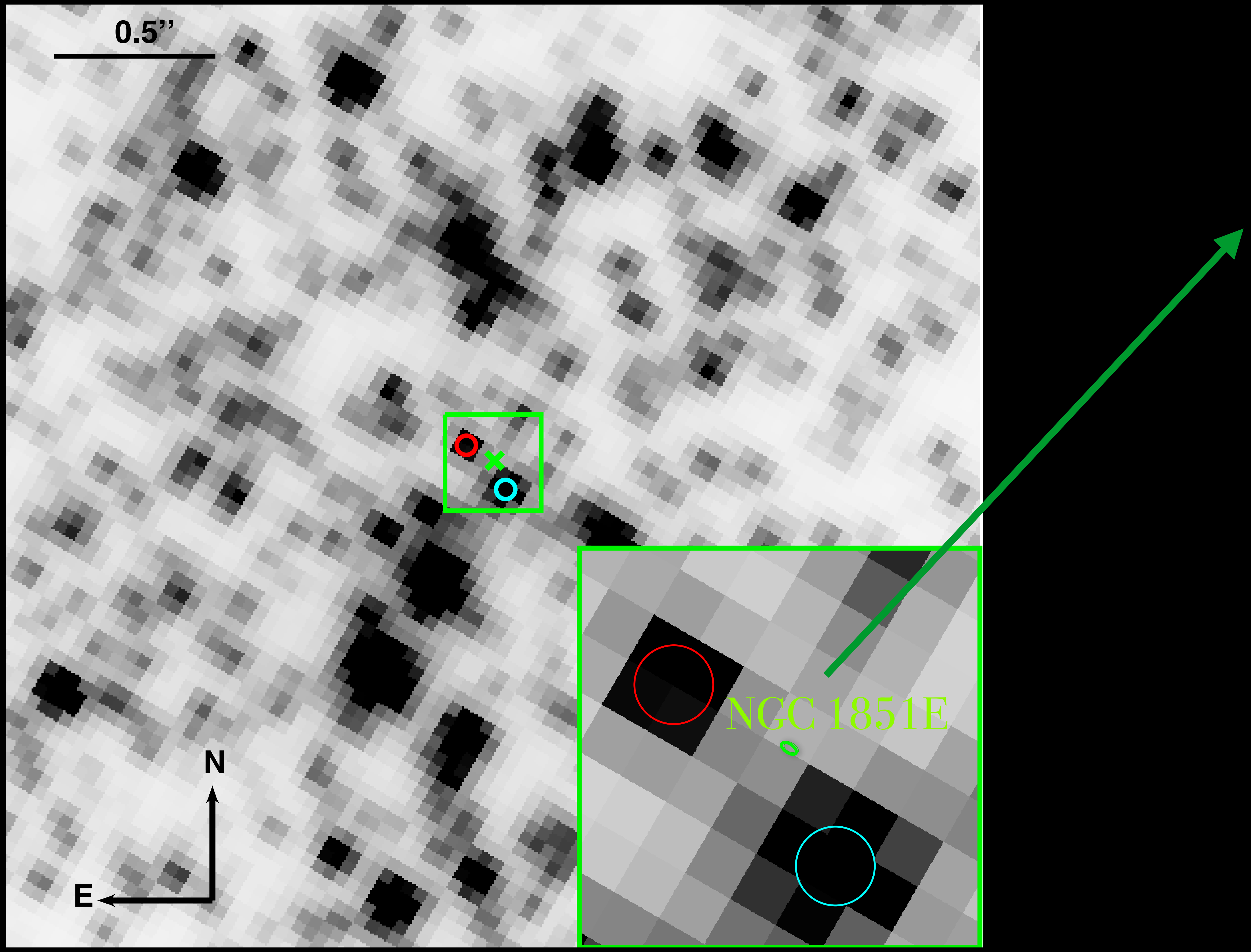
For $M_p = 1.17\,M_\odot$ and edge-on orbit, $M_{c,min} = 1.4\,M_\odot$

1.5 years, 24 observations and 476 TOAs later …

Credit: SARAO

Barr and Dutta (MPifR)

Compact companion - possible with accurate position



(Barr, Dutta et al., Science, 2024)

No optical companion detected in HST images
(Closest source offset by > 6σ)

No evidence of plasma from companion

↓

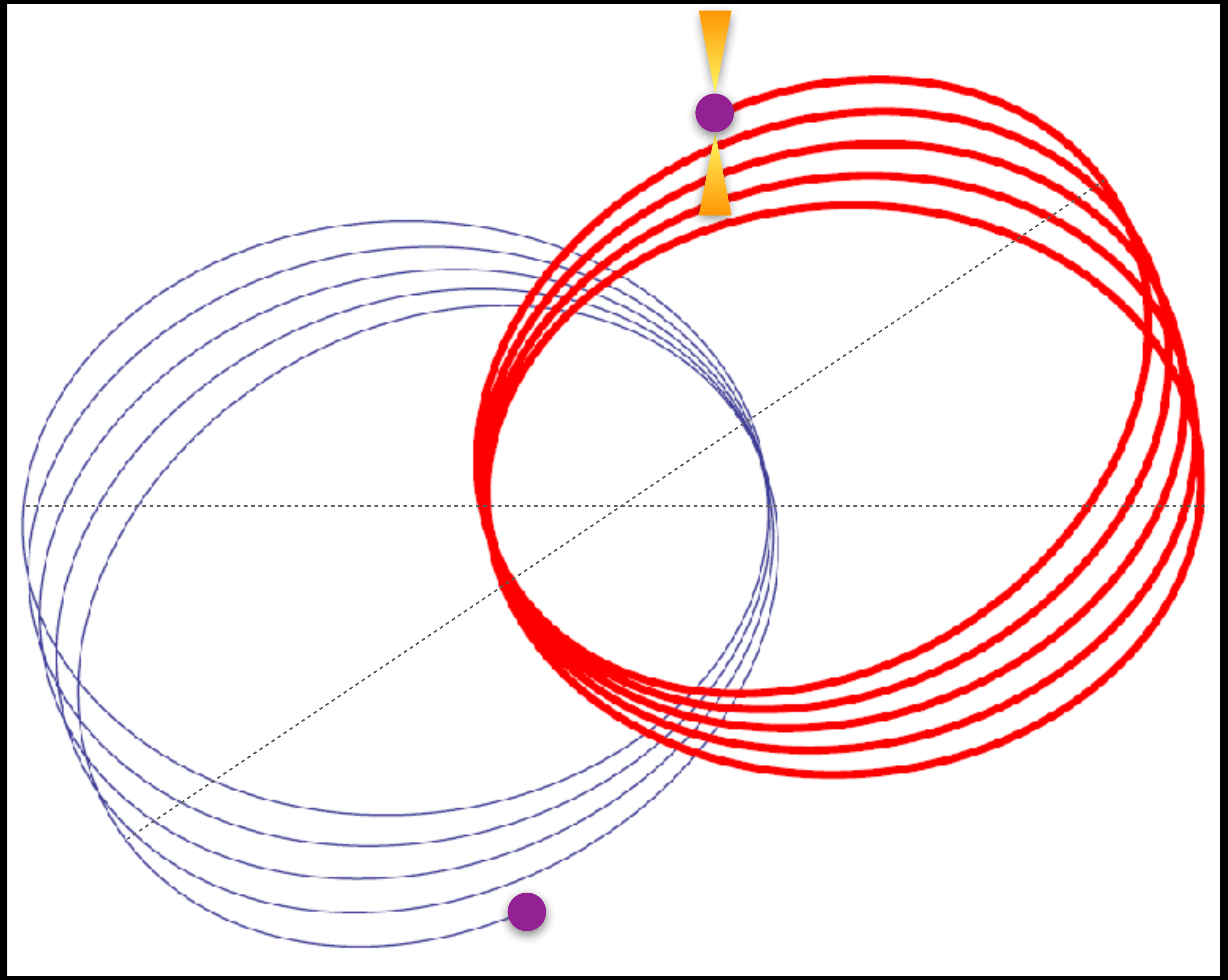
Compact companion

Advance of periastron: possible with precision timing

Post Keplerian Effect

Rate of advance of periastron

$$\dot{\omega}_{\rm obs} = 0.03468 \pm 0.00003 \text{ deg yr}^{-1}$$



Credit: N.Wex

Advance of periastron

$$\dot{\omega}_{\rm GR} = \left(\frac{3}{c^2(1-e^2)}\right)\left(\frac{P_{\rm b}}{2\pi}\right)^{-5/3}(GM)^{2/3} \rightarrow 3.887 \pm 0.004\ \mathrm{M}_\odot$$

Most massive Galactic DNS

$2.8887 \pm 0.0006\ \mathrm{M}_\odot$ (Ferdman+ 2020)

Heaviest LIGO-Virgo

NS-NS Merger GW190425

$3.4^{+0.3}_{-0.1}\ \mathrm{M}_\odot$ (Abbott+ 2020)

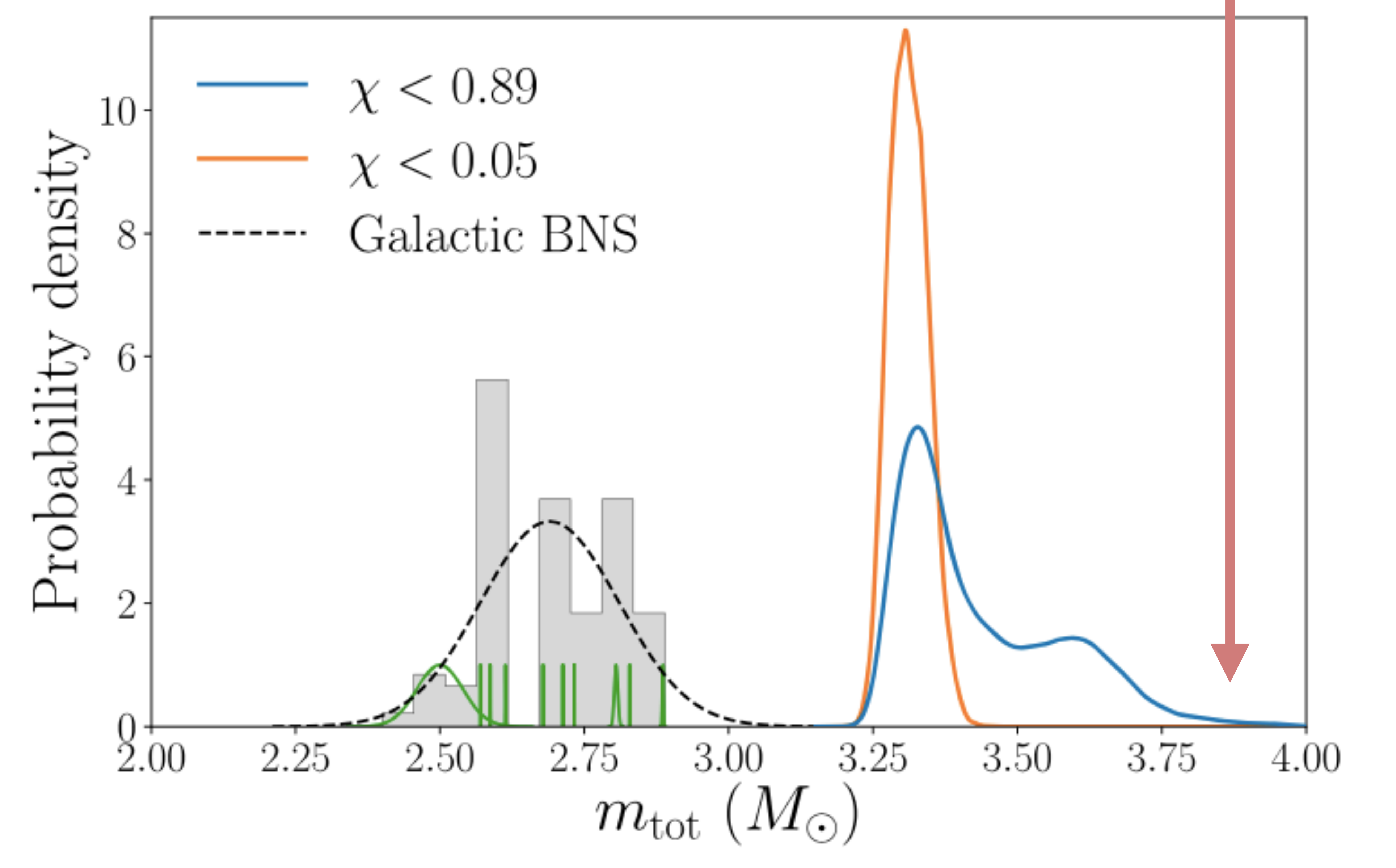


Figure 5. Total system masses for GW190425 under different spin priors, and those for the 10 Galactic BNSs from Farrow et al. (2019) that are expected to merge within a Hubble time. The distribution of the total masses of the latter is shown and fit using a normal distribution shown by the dashed black curve. The green curves are for individual Galactic BNS total mass distributions rescaled to the same ordinate axis height of 1.

(Abbott+2020)

Mass measurements

Mass function ⟷ total system mass

$M_p \leq 2.04\,M_\odot$, $M_c \geq 1.84\,M_\odot$

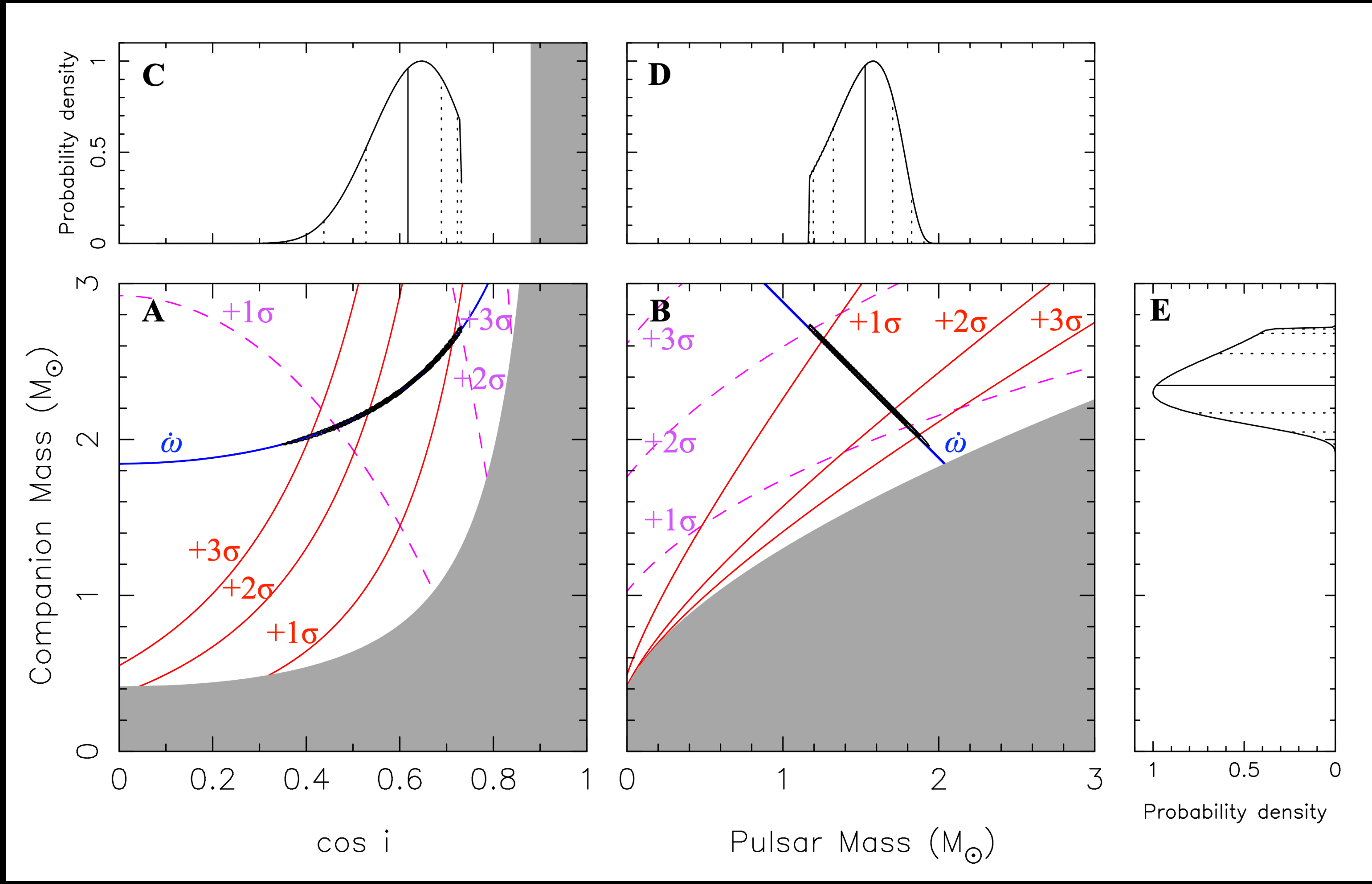
($i = 90°$)

Einstein delay (2σ upper-limit)

$\gamma = 27.96$ ms

Shapiro delay (2σ upper-limit)

$h_3 = 1.8\,\mu$s



(Barr, Dutta et al., Science, 2024)

$M_c > 2.09\,M_\odot$, $i < 62°$ (95% probability)

Prospects

Continued timing in progress

Upgraded facilities: MeerKAT+, SKA

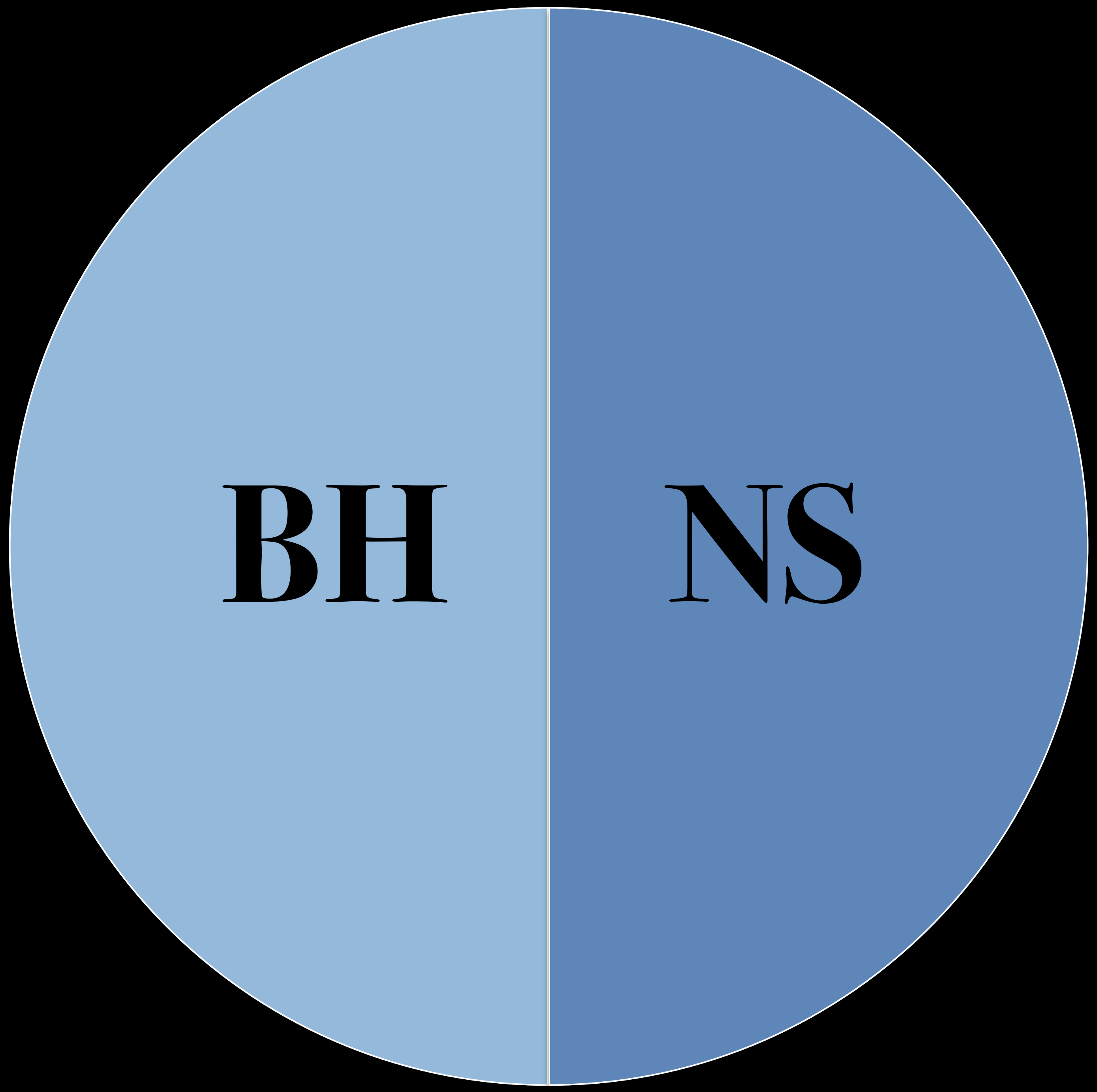
Improved masses with Einstein delay measurement (in ~ 5-6 years)

Change in projected semi-major axis of binary

Spin of companion > 0.6

First pulsar-black hole binary

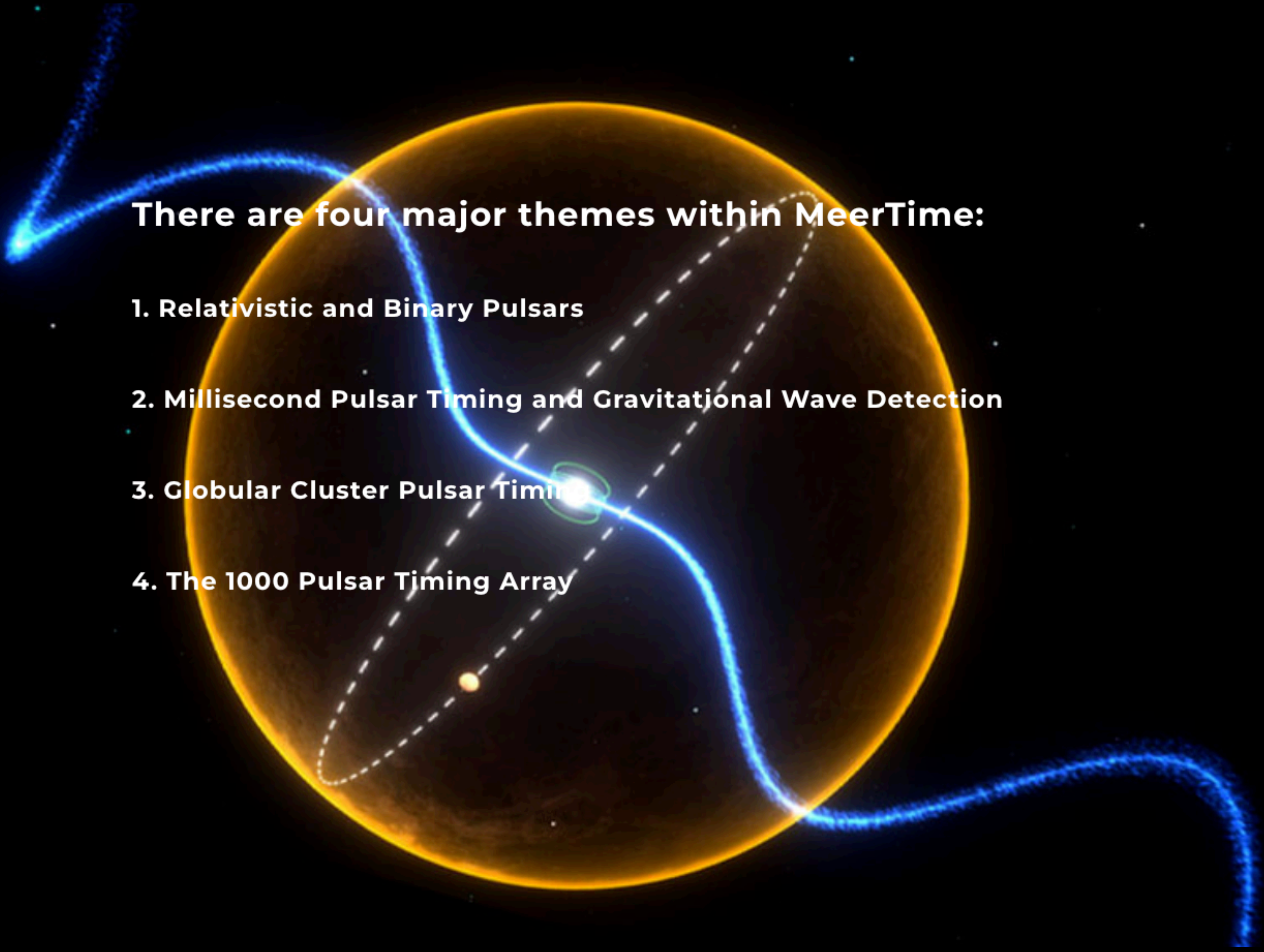
Tests of BH properties



Most stringent mass constraints on NS EoS

Fig. 1: *An artist's impression of the system assuming that the massive companion star is a black hole. The brightest background star is its orbital companion, the radio pulsar* PSR J0514-4002E. *The two stars are separated by 8 million km and circle each other every 7 days.*

[less]



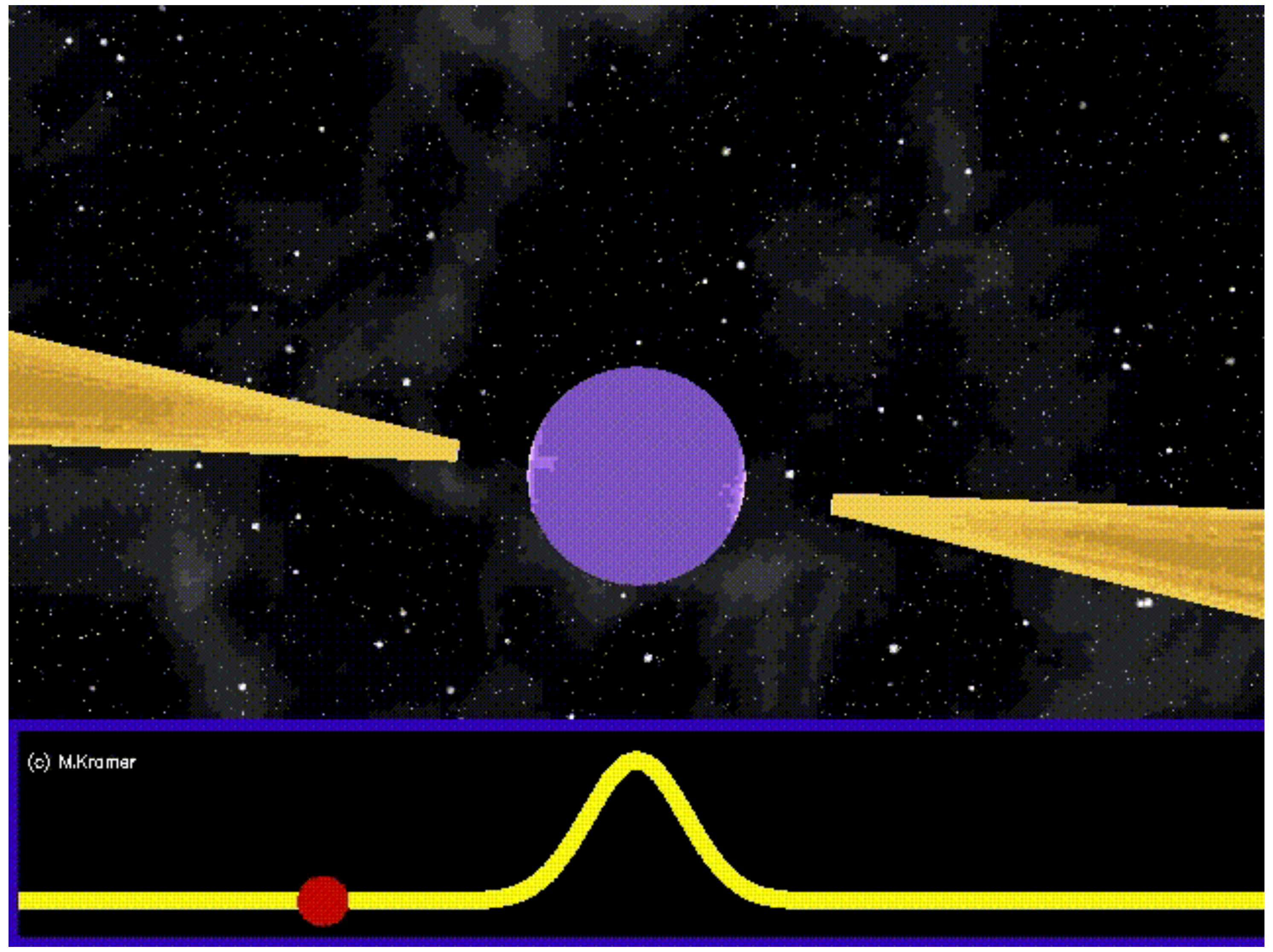
There are four major themes within MeerTime:

1. Relativistic and Binary Pulsars
2. Millisecond Pulsar Timing and Gravitational Wave Detection
3. Globular Cluster Pulsar Timing
4. The 1000 Pulsar Timing Array

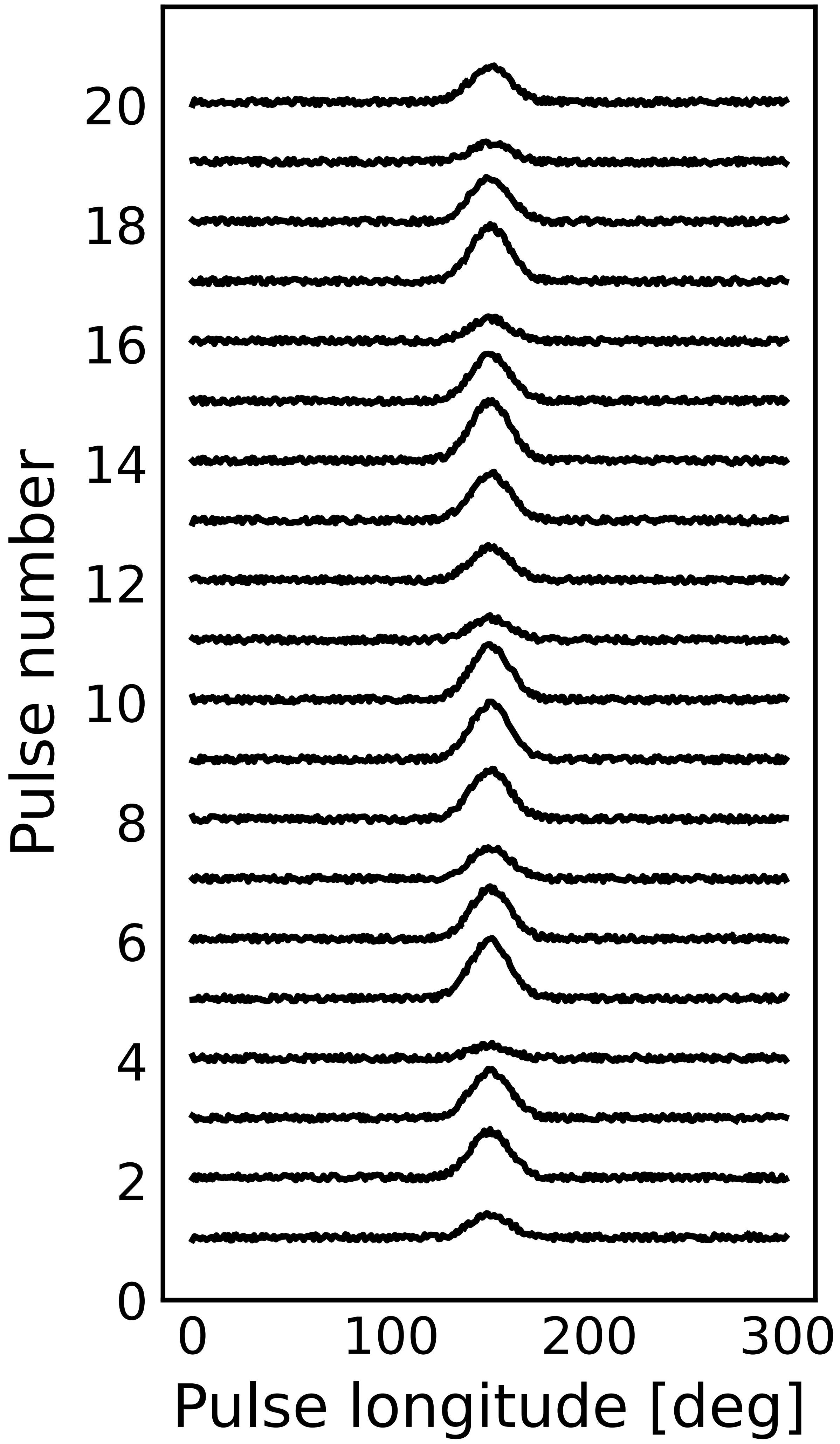
meertime.org

Clocklike pulsar signals

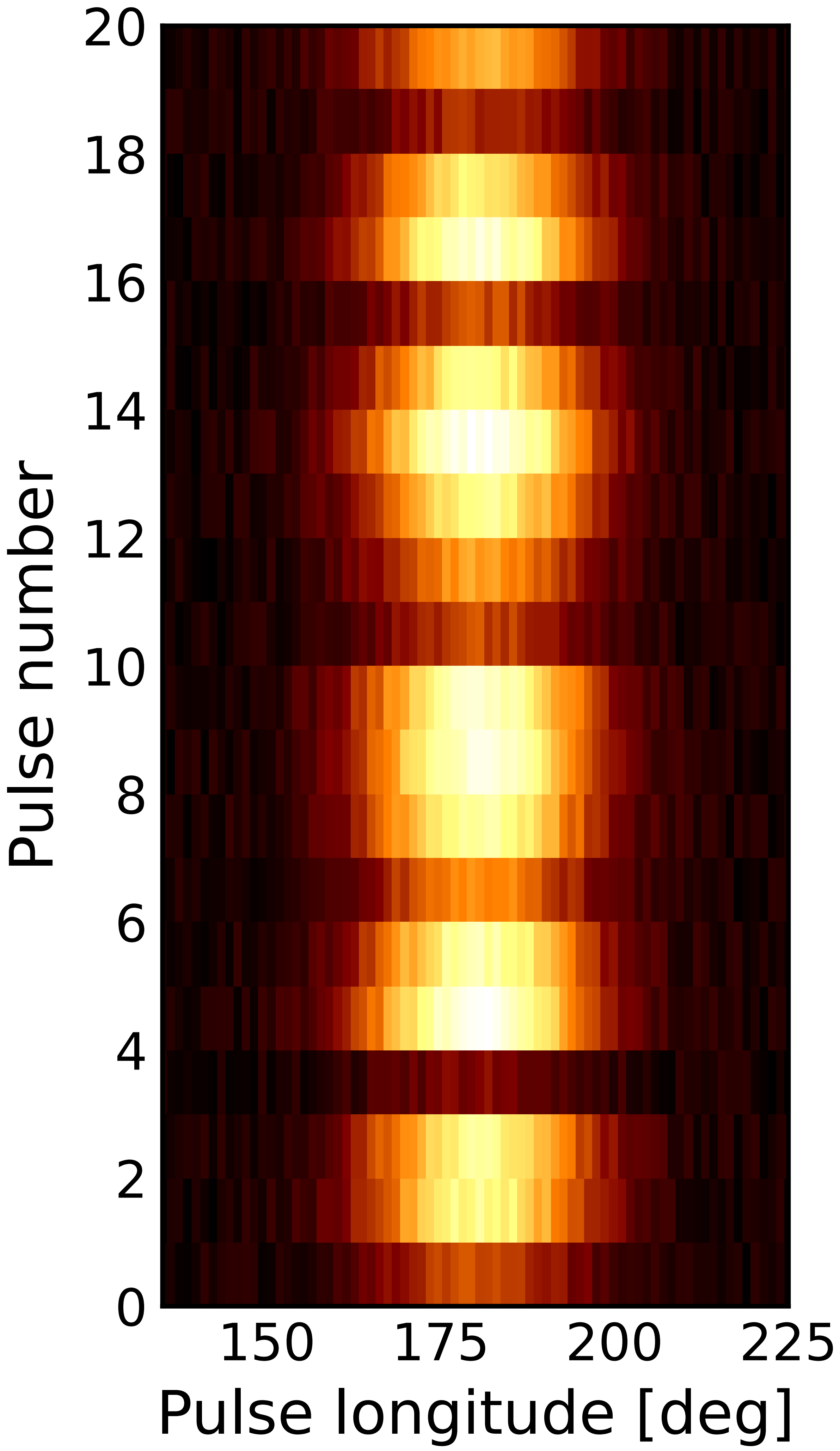
Lighthouse effect



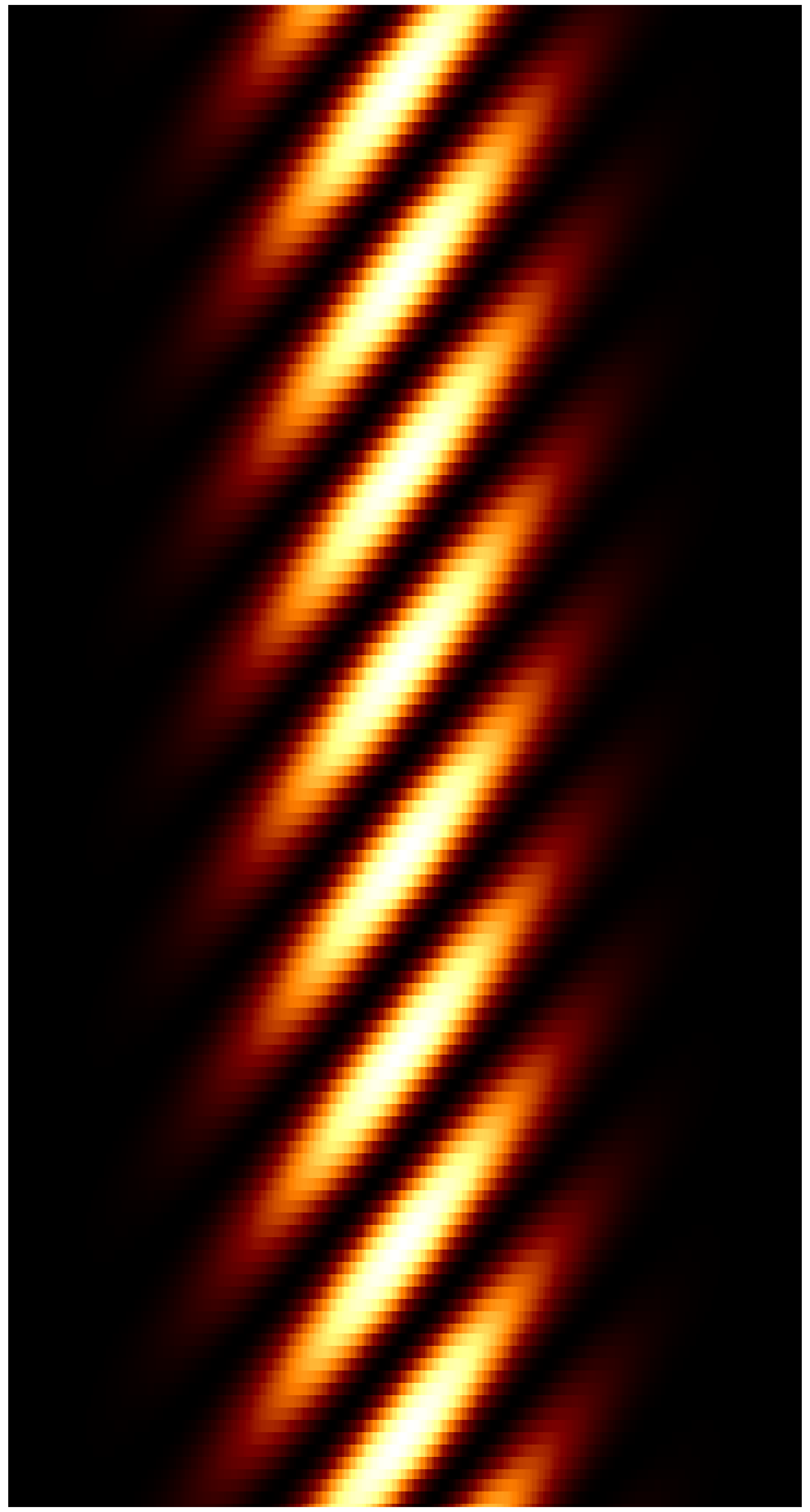
Credit to M. Kramer.



Pulse stack

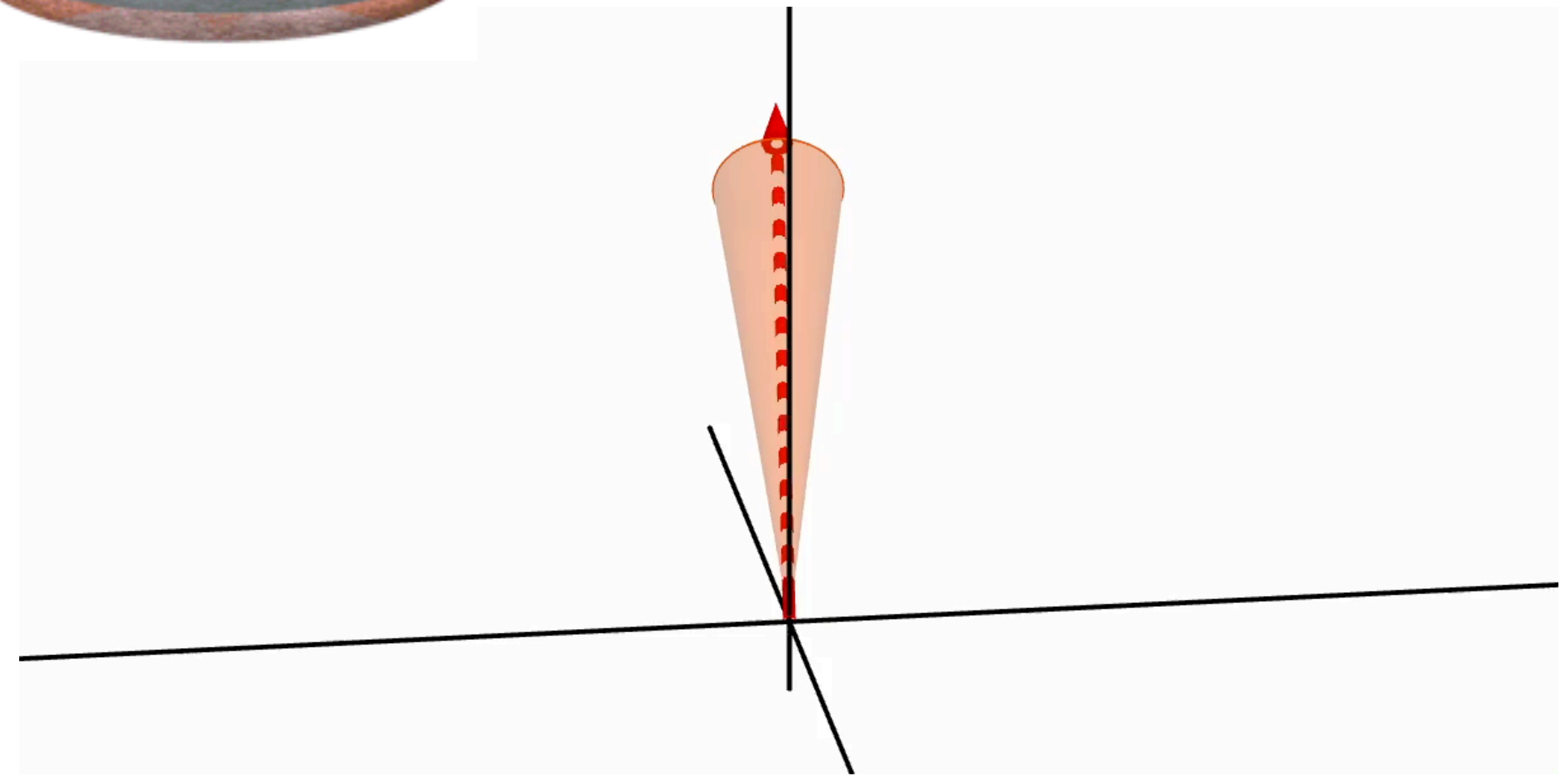


Drifting subpulses



slide courtesy of Ray (Jui-An) Hsu - UoM

Carousel model & Drifting subpulses



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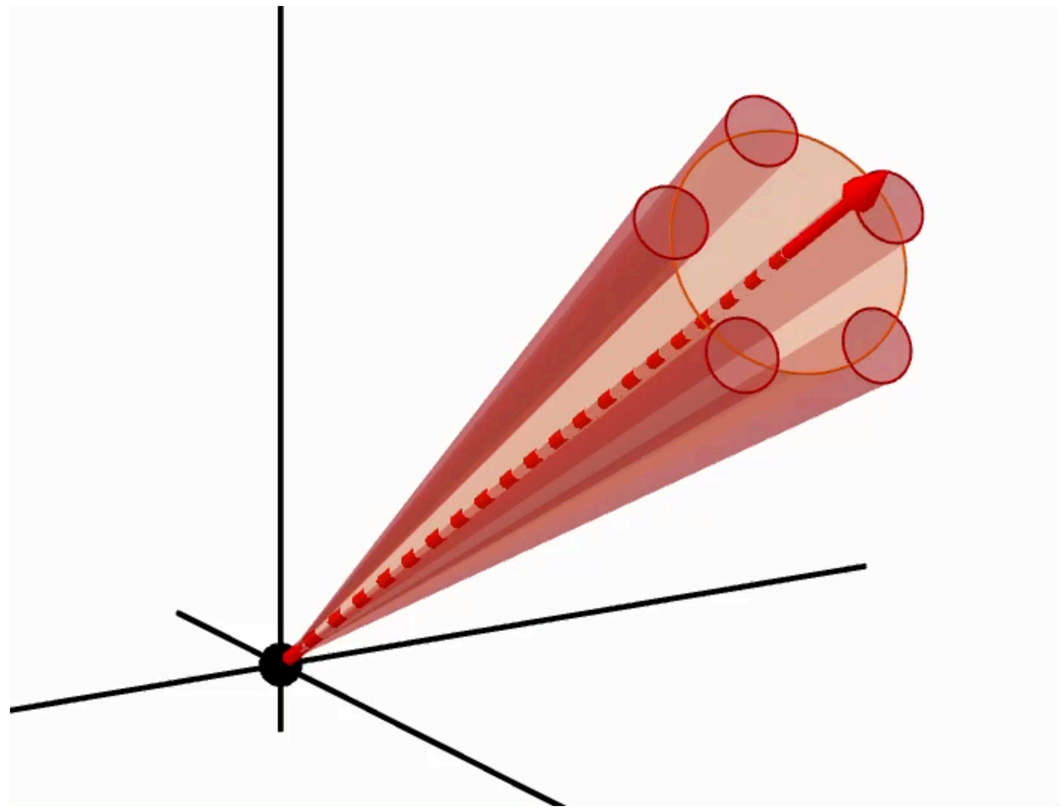

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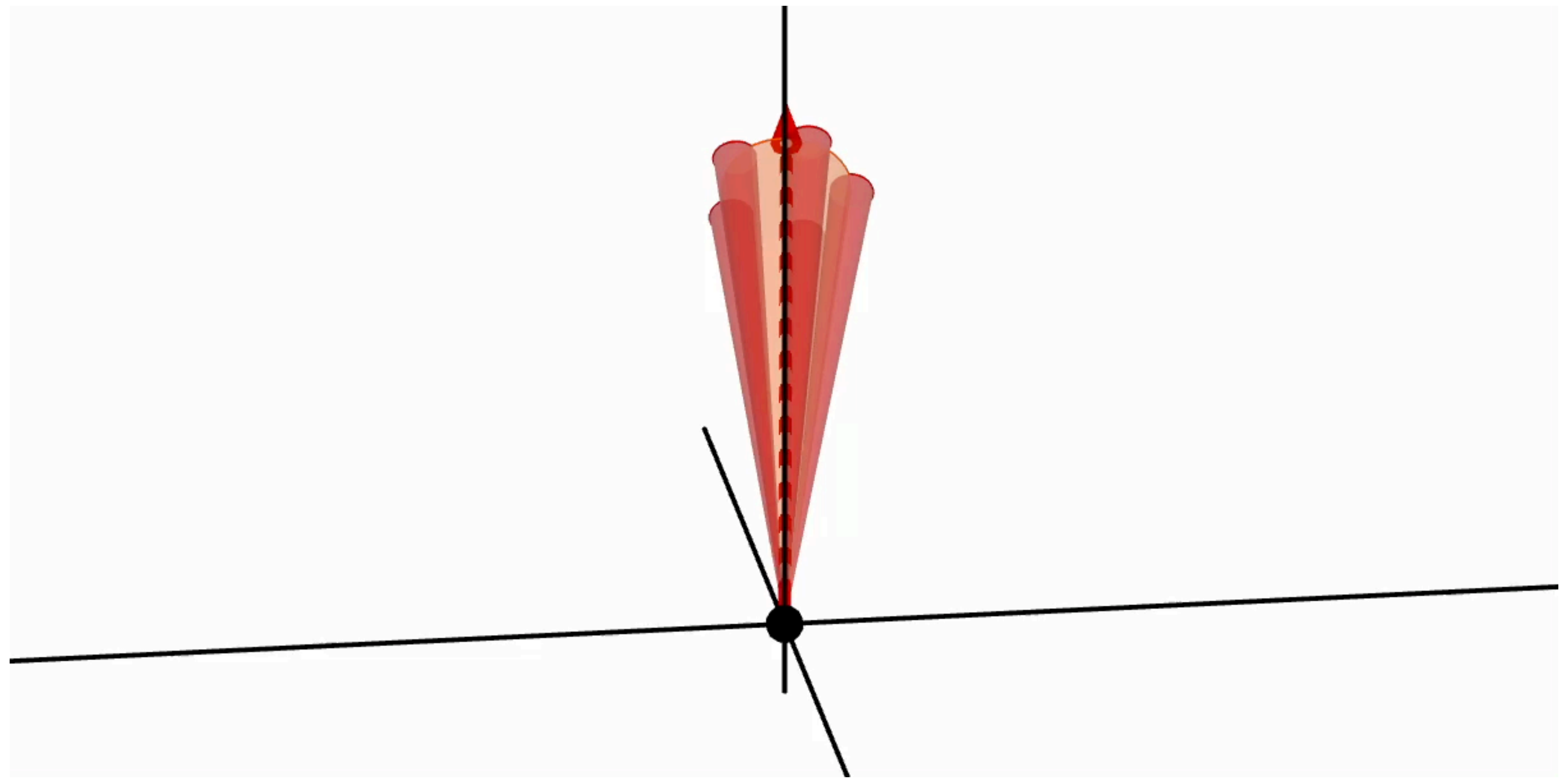
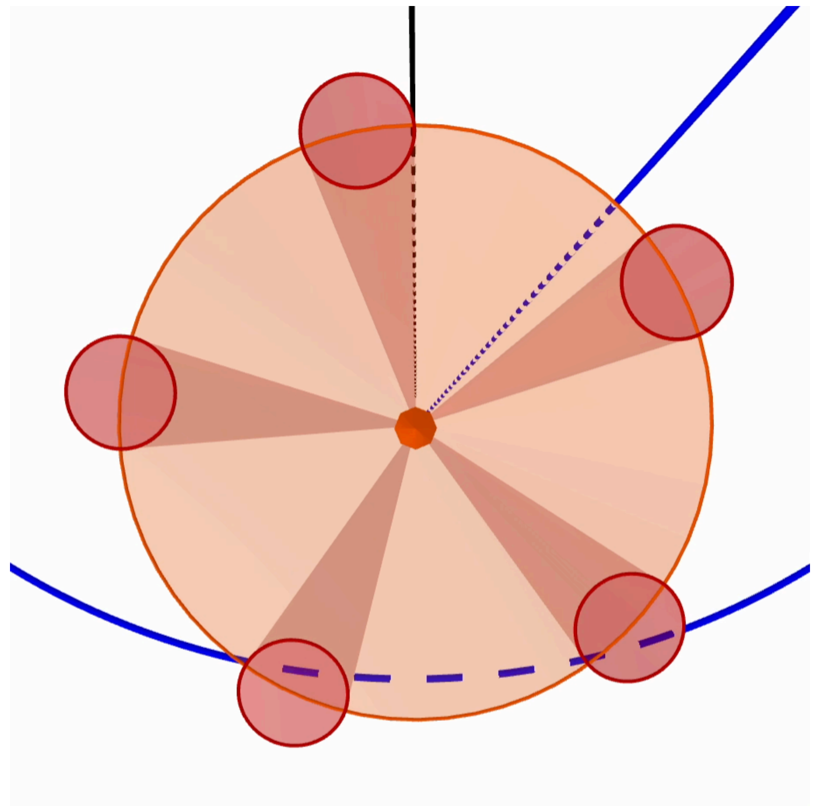


simple case

rotating sparks

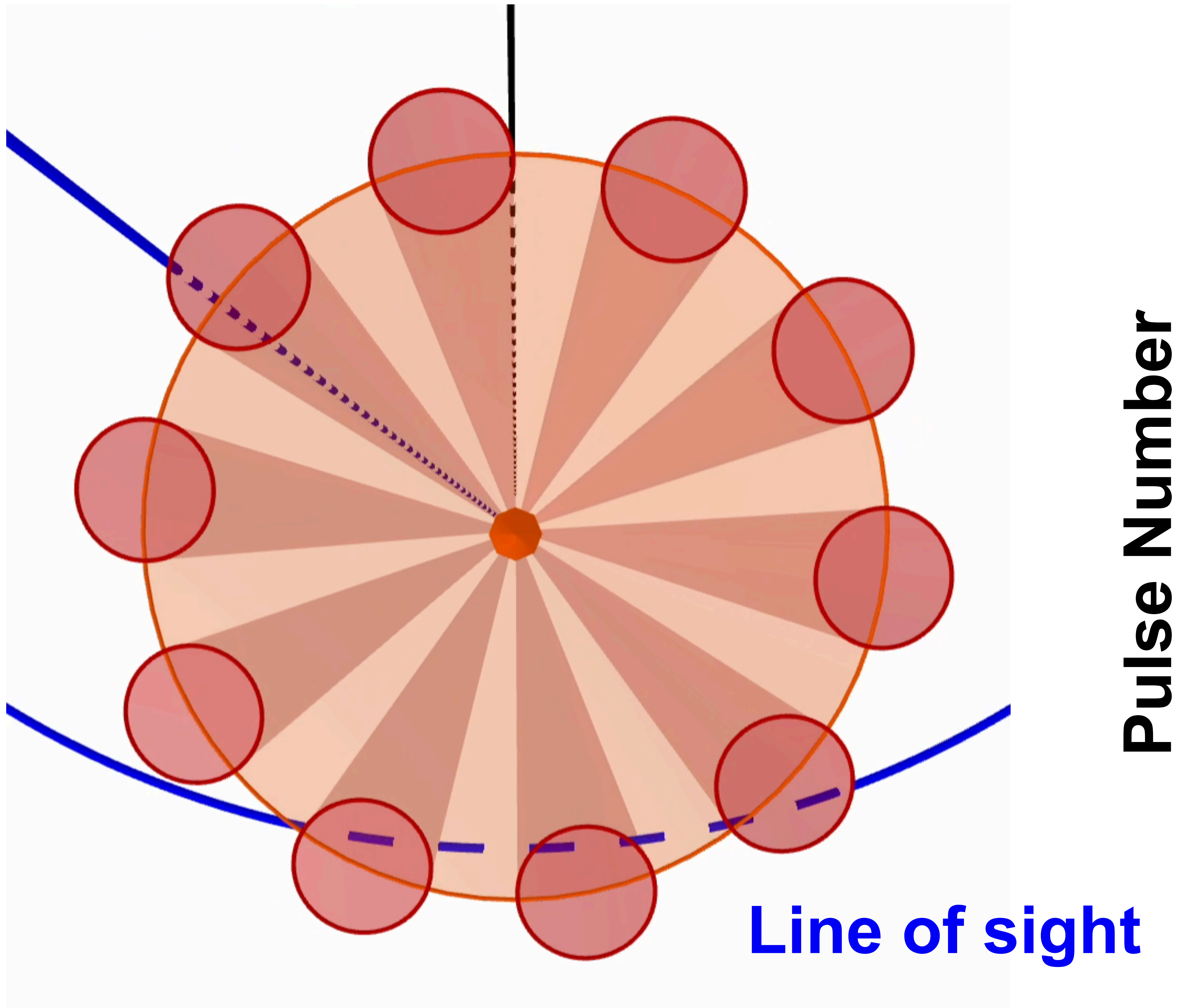
drifting subpulses

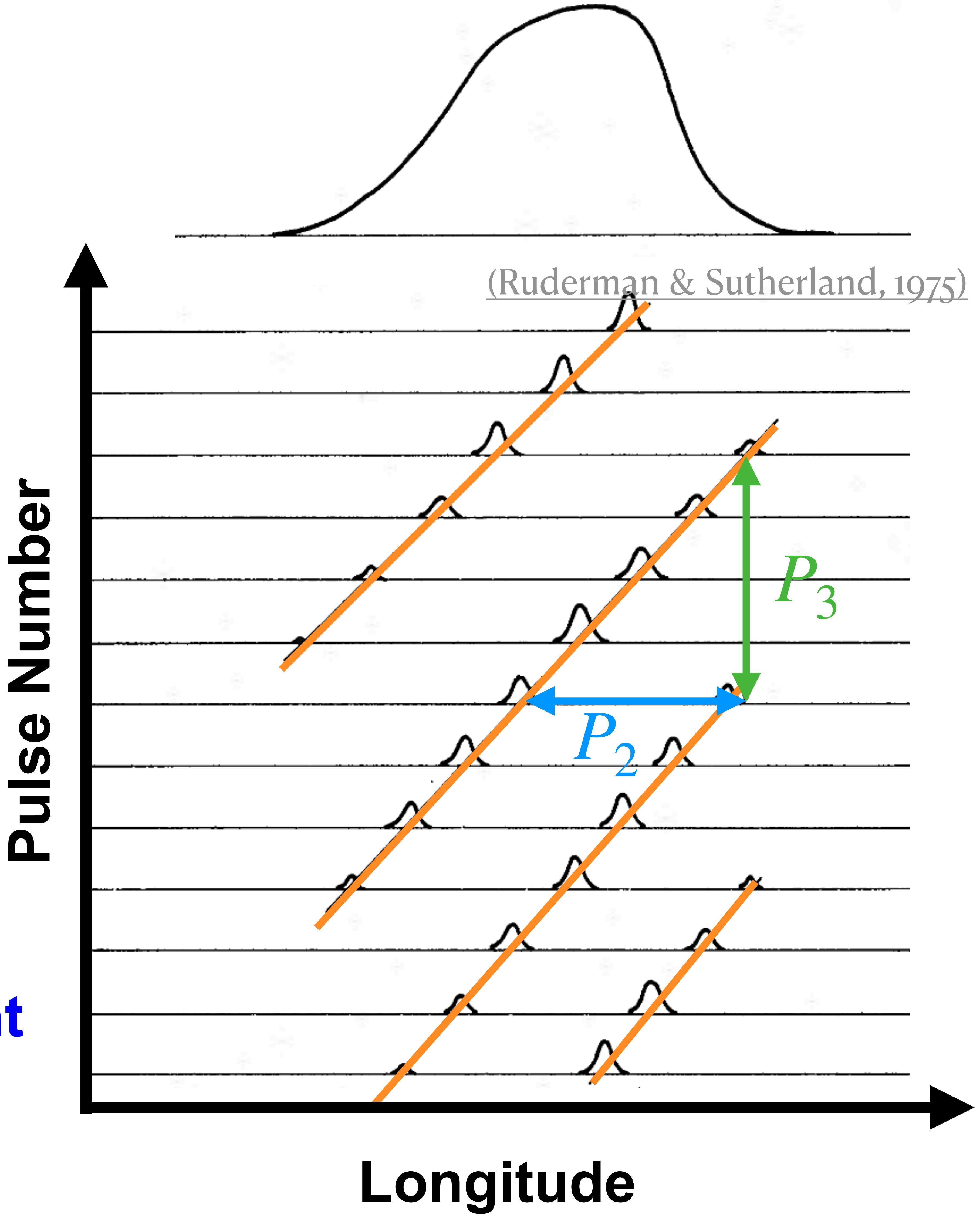


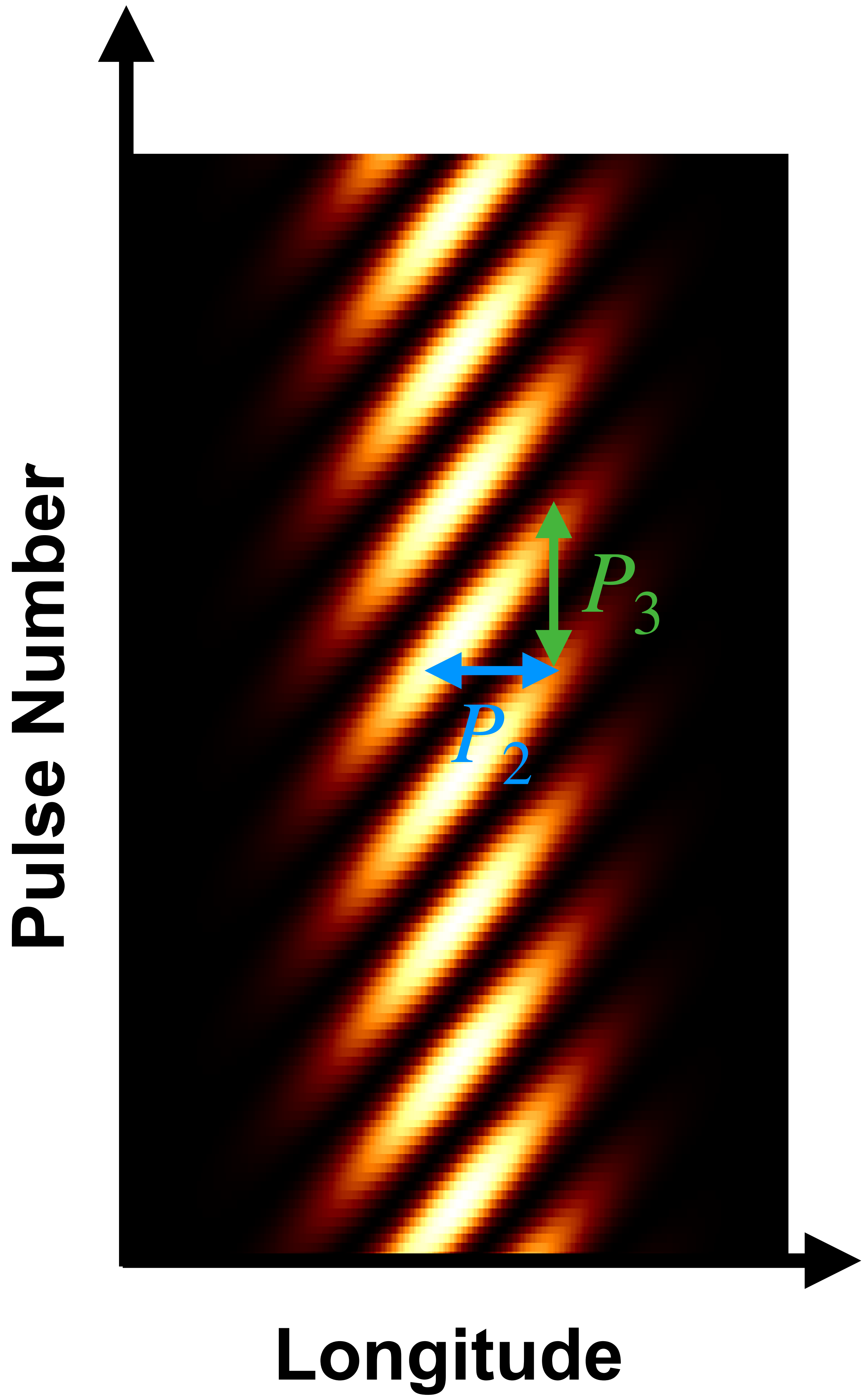
slide courtesy of Ray (Jui-An) Hsu - UoM

Drifting subpulse signals in pulse stack

Slower carousel ⟷ Larger P_3

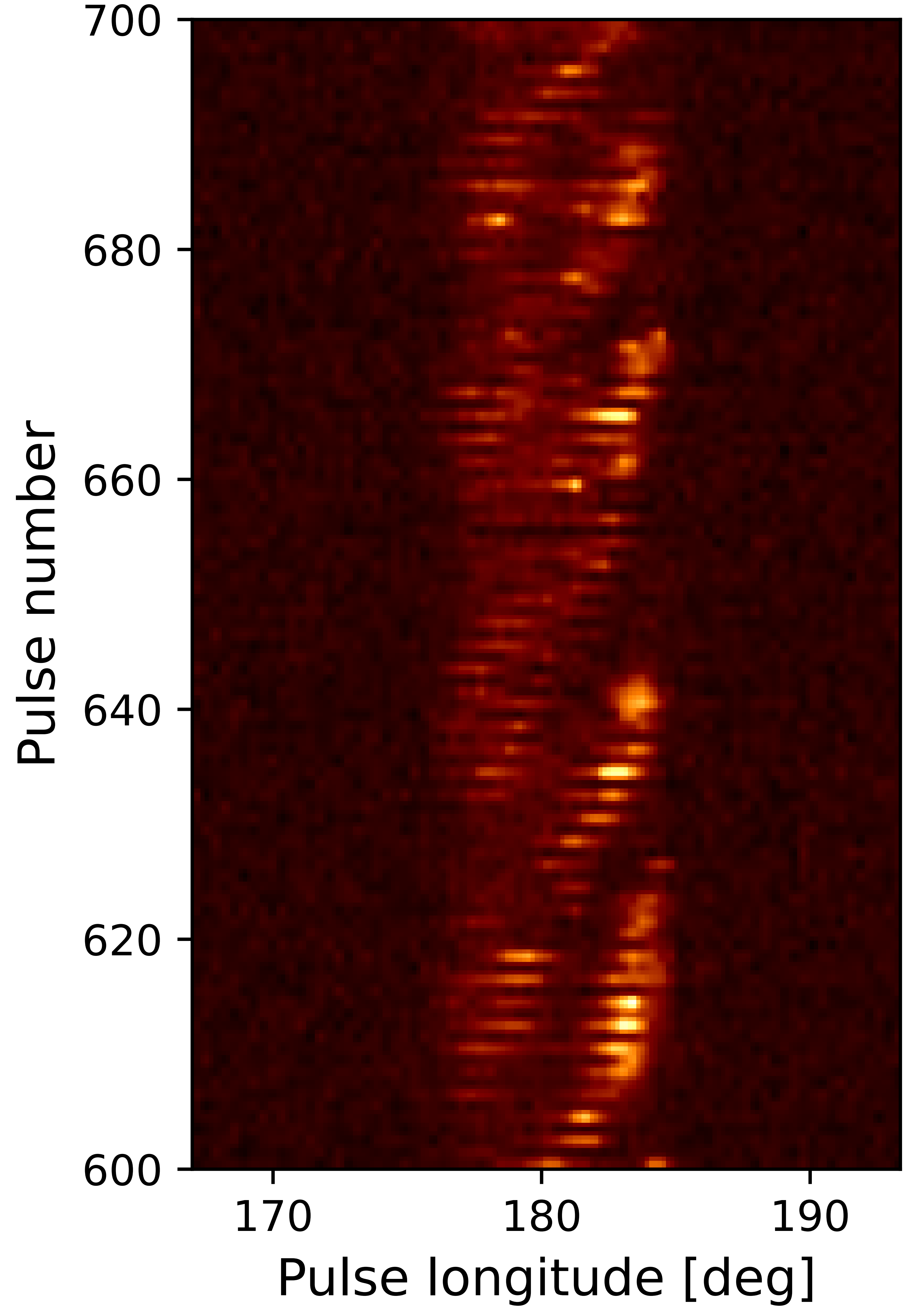


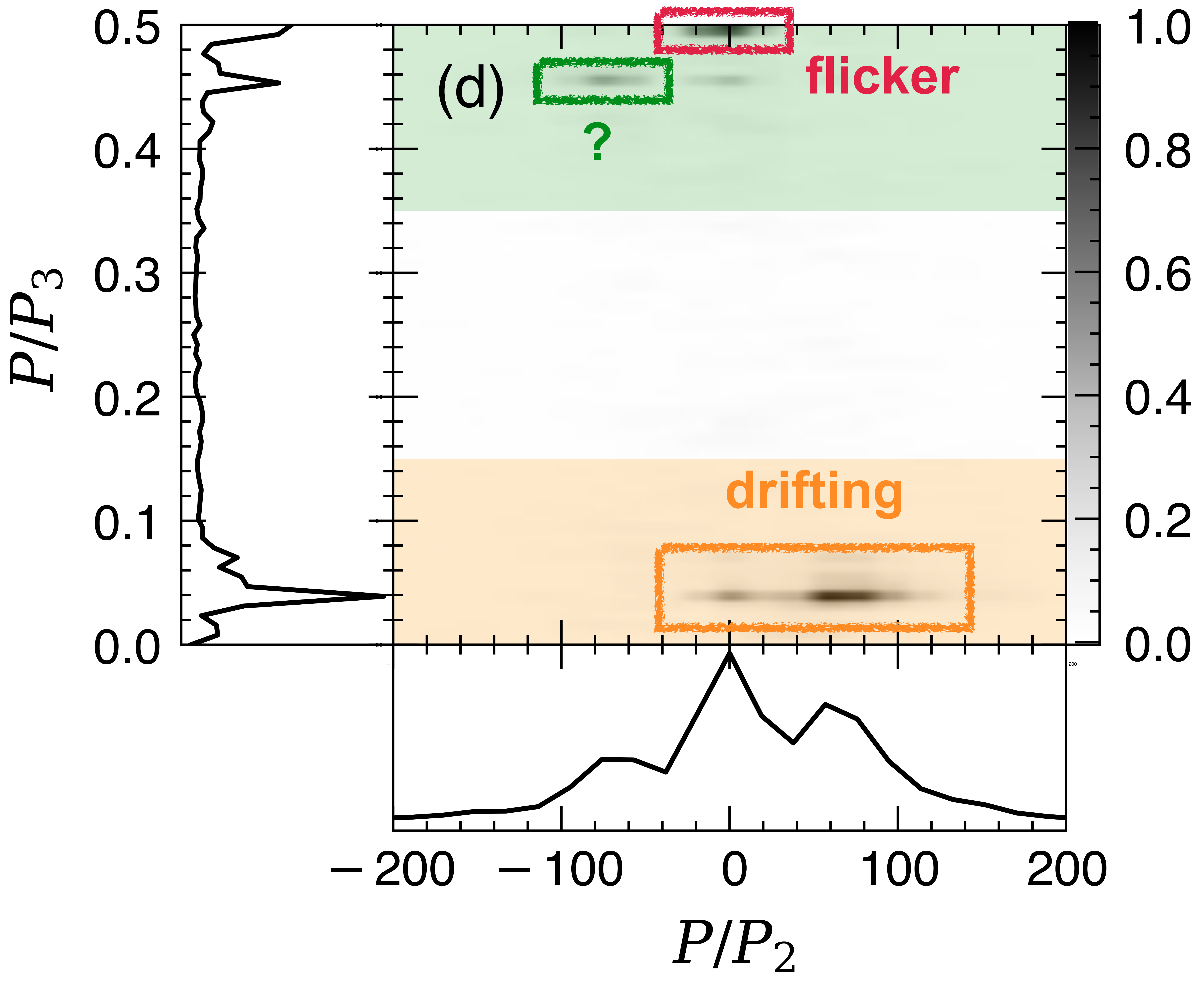




slide courtesy of Ray (Jui-An) Hsu - UoM

PSR J1514–4834 complex spectral features





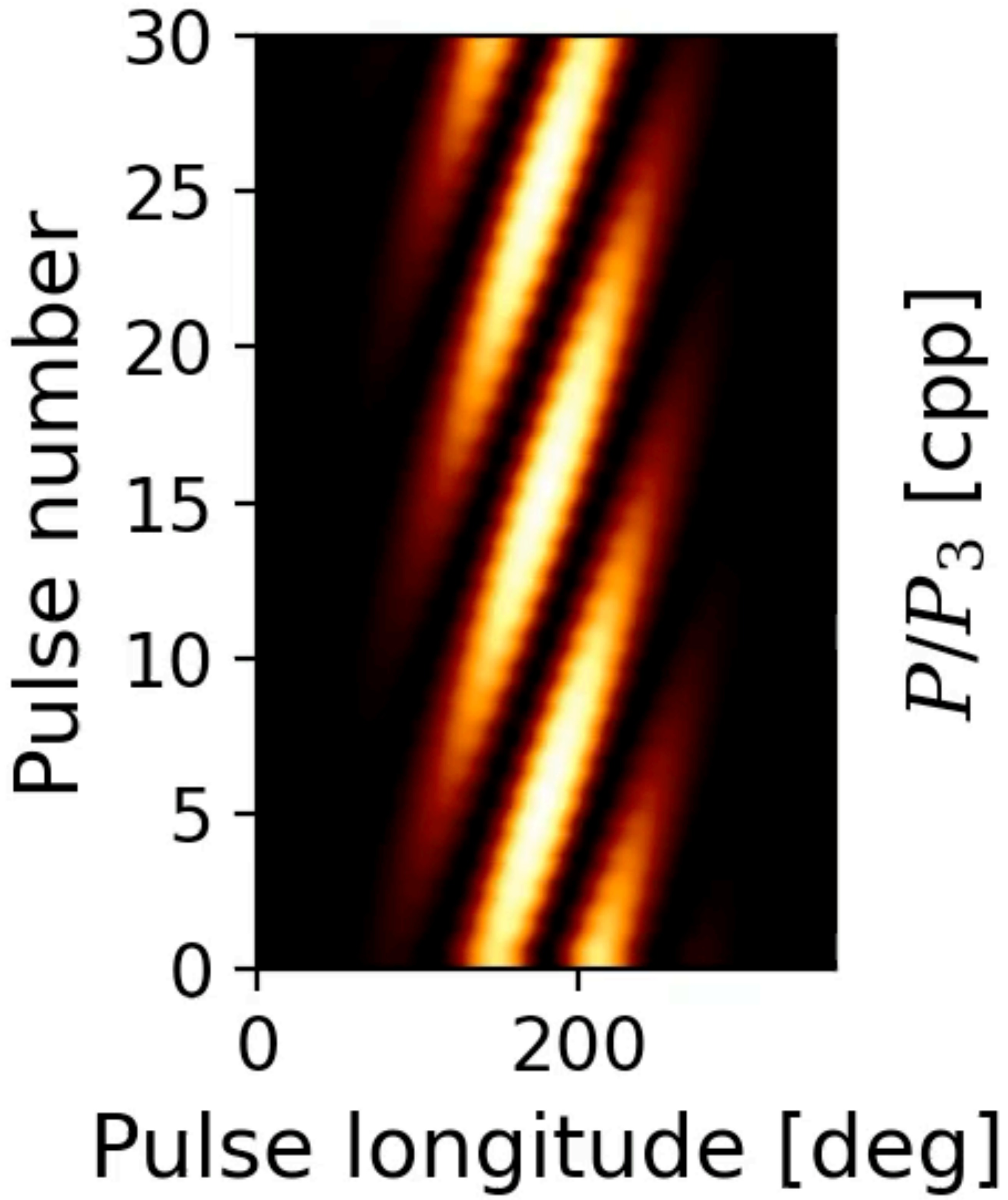
slide courtesy of Ray (Jui-An) Hsu - UoM

Nyquist–Shannon sampling theorem

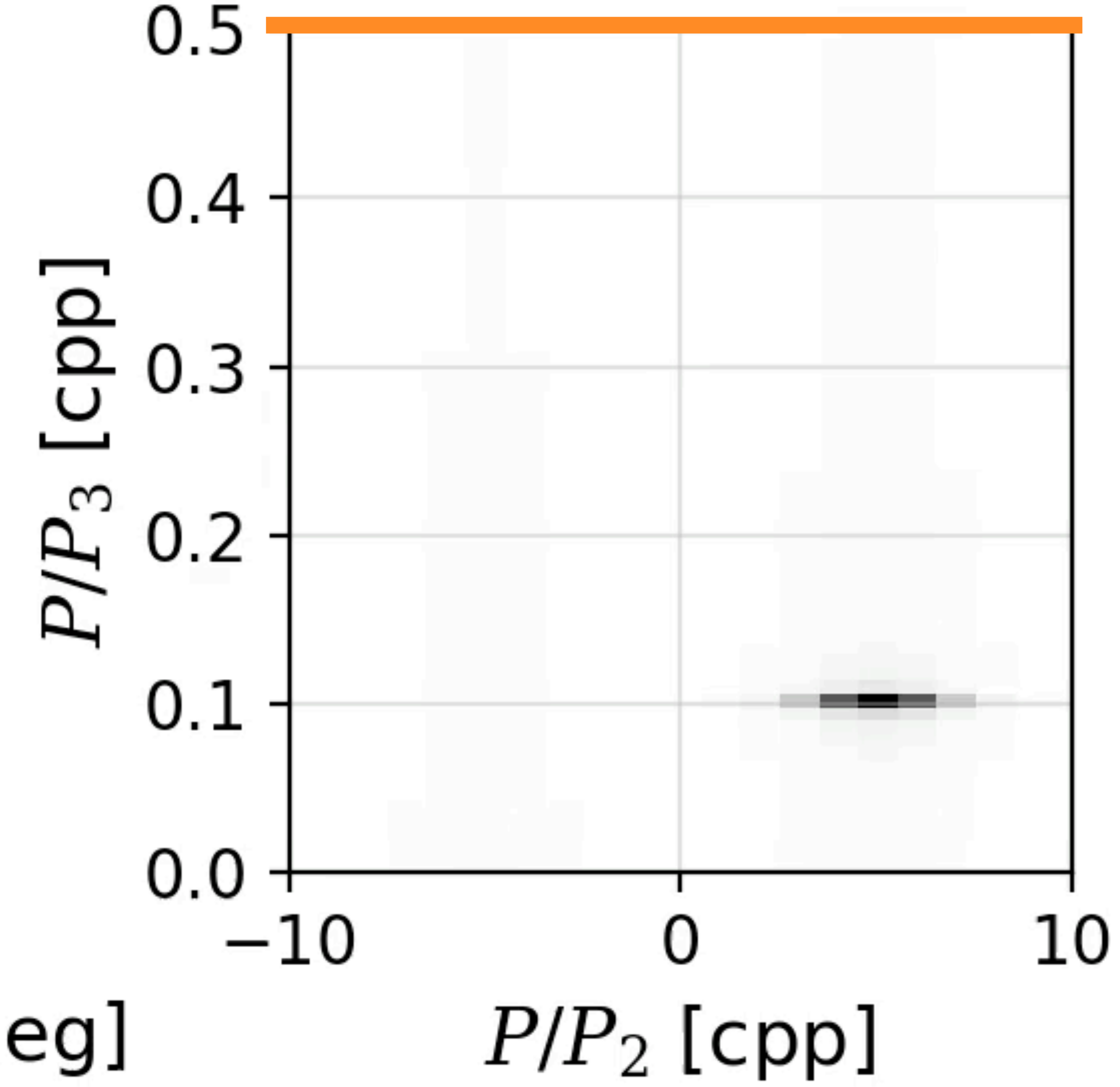
The highest frequency which can be represented accurately is one half of the sampling rate.

reverse rotation? → Aliasing effect

YouTube



Nyquist frequency (alias border)



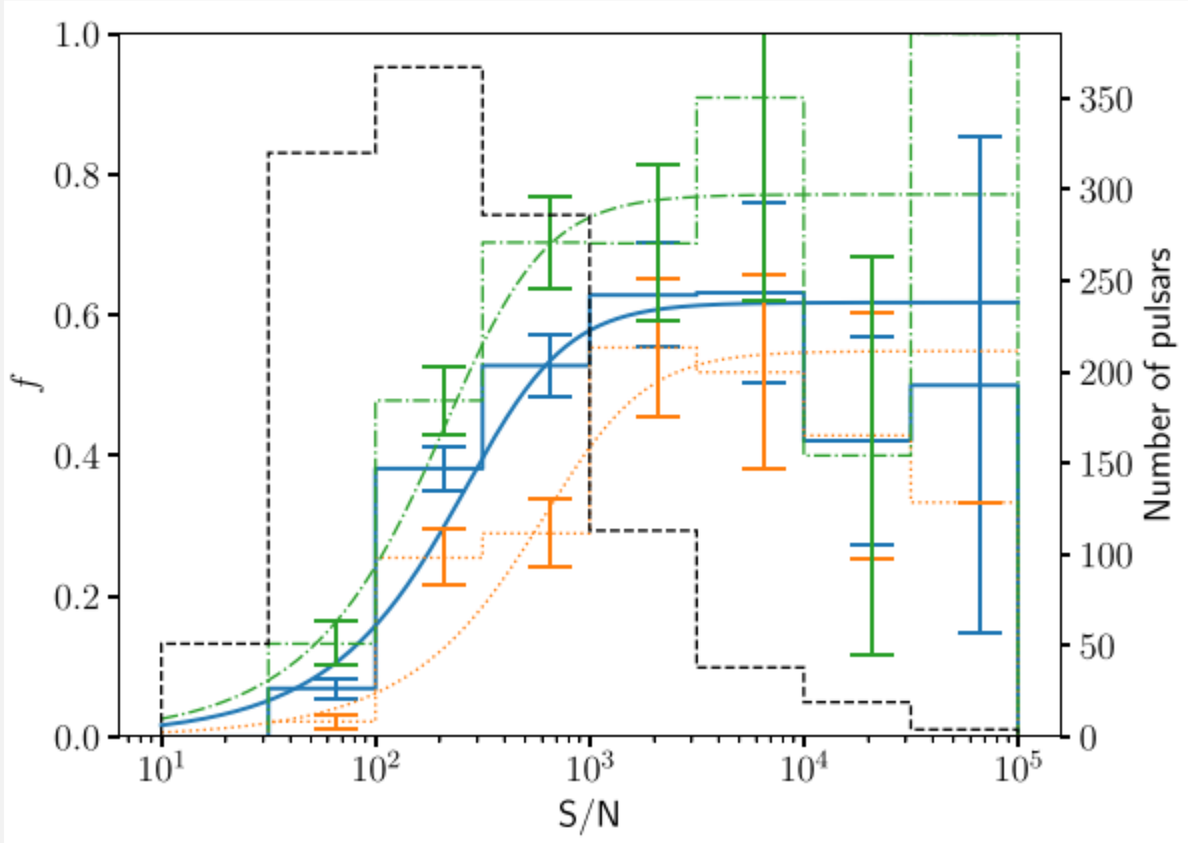
slide courtesy of Ray (Jui-An) Hsu - UoM

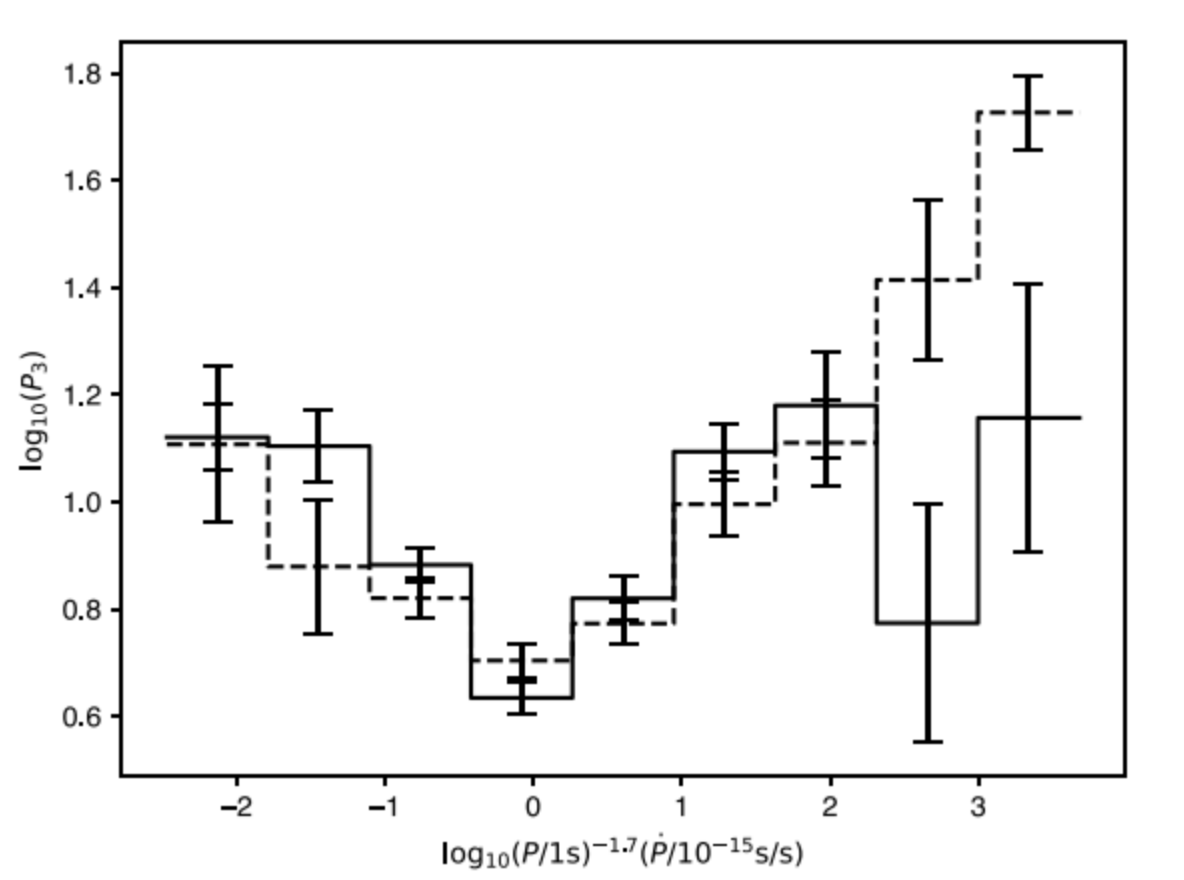
PSR J1514–4834 complex emission patterns

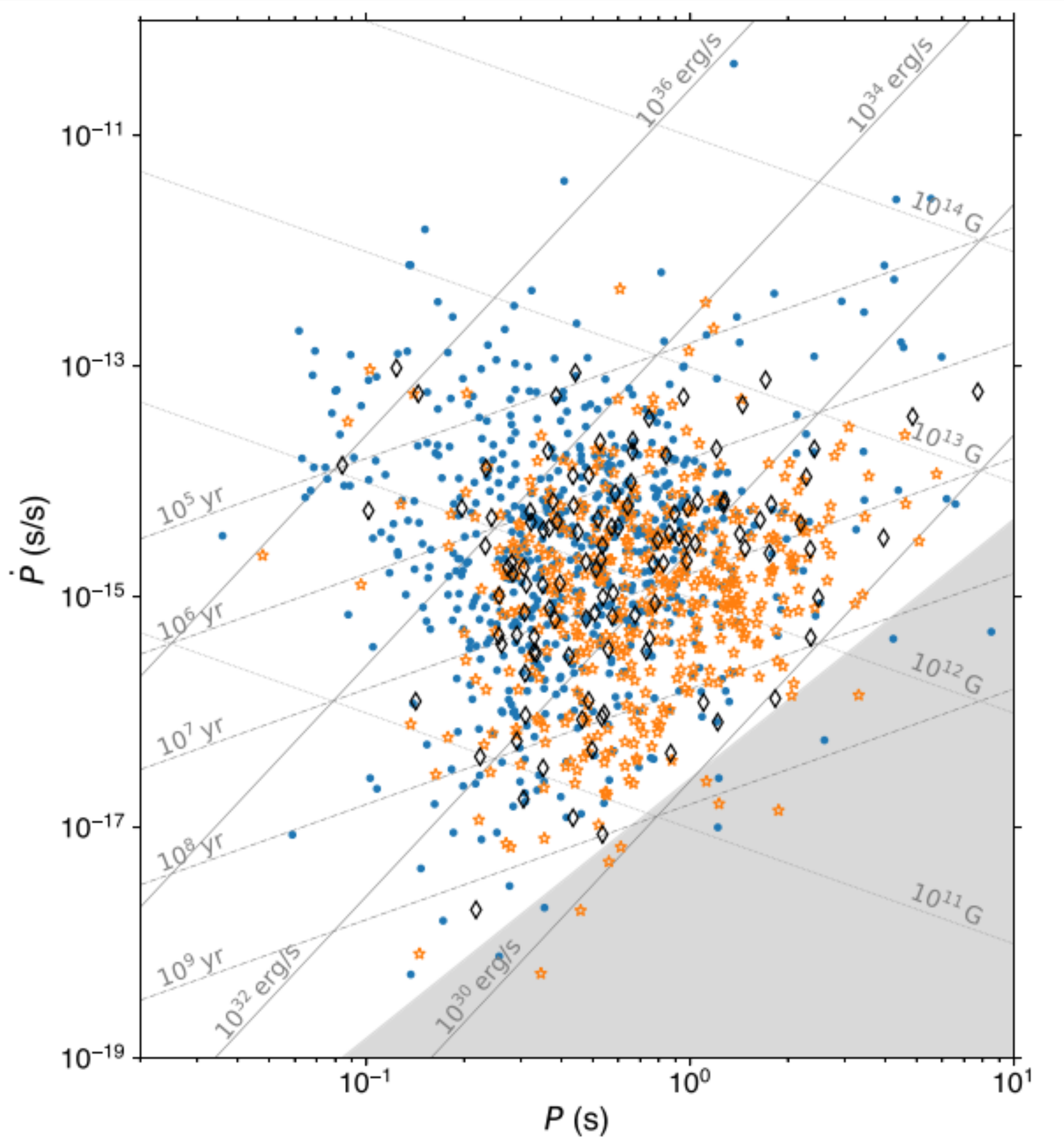
Mode change (slow & fast) + Drifting + Flicker (on/off amplitude modulation)

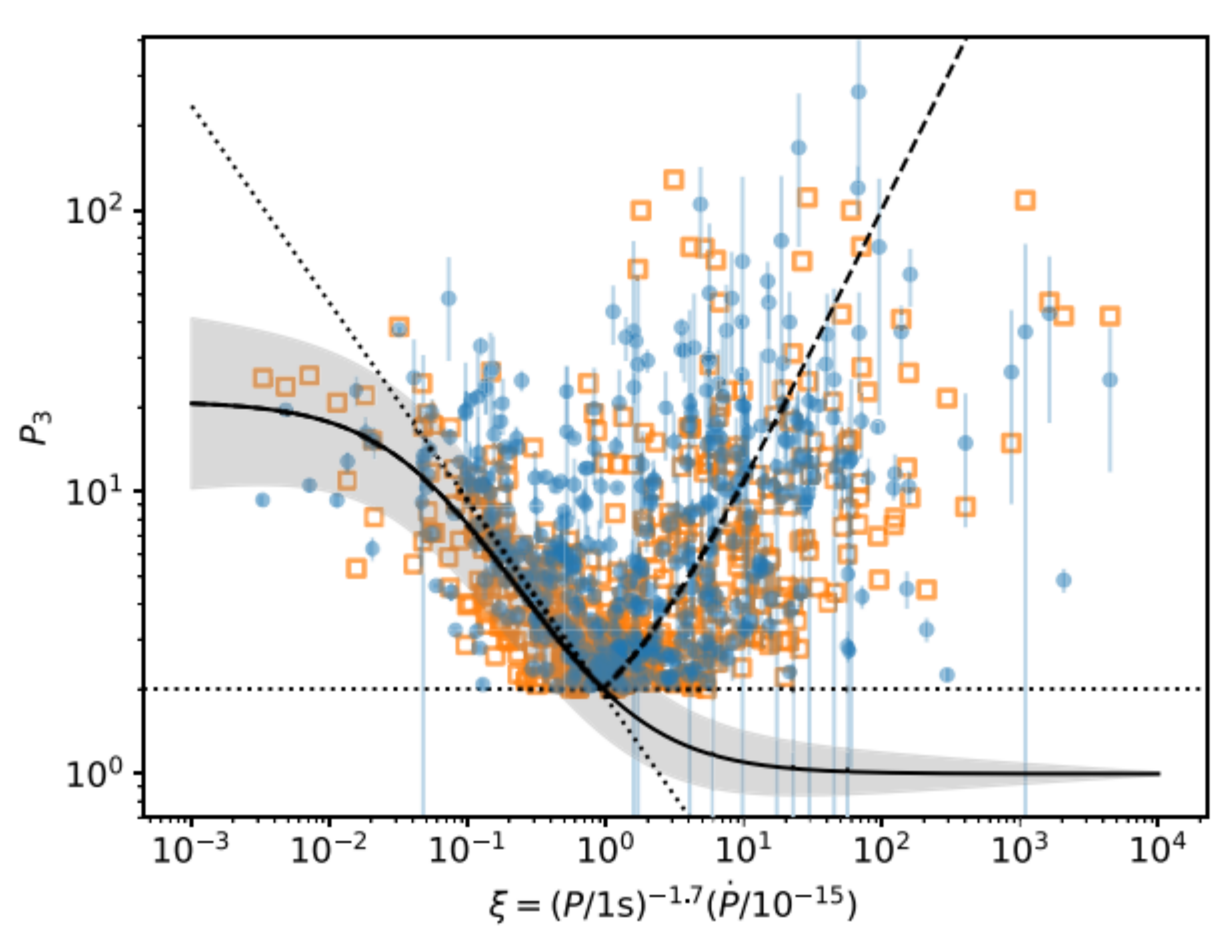
slide courtesy of Ray (Jui-An) Hsu - UoM

SUBPULSE MODULATION PROPERTIES





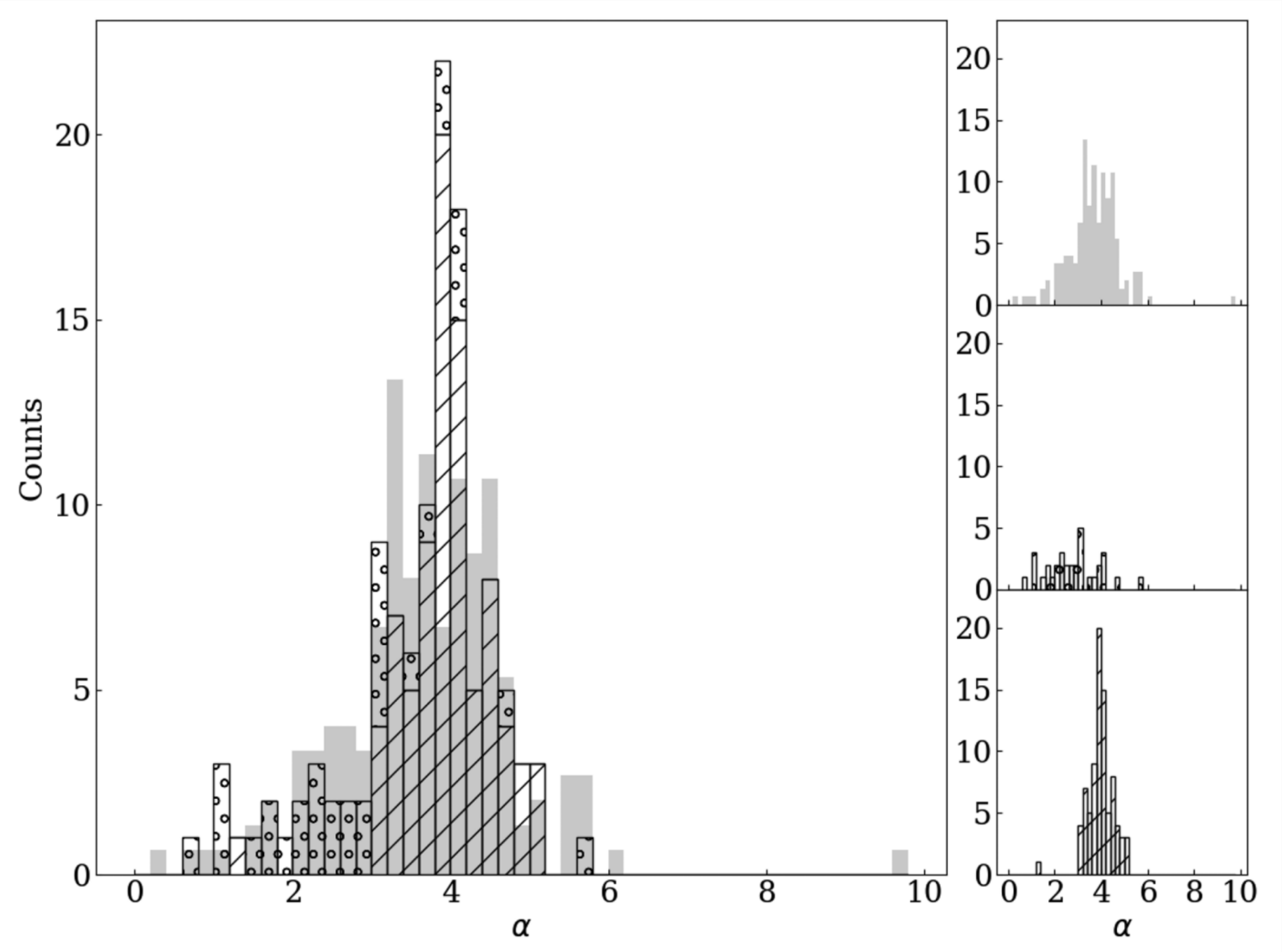


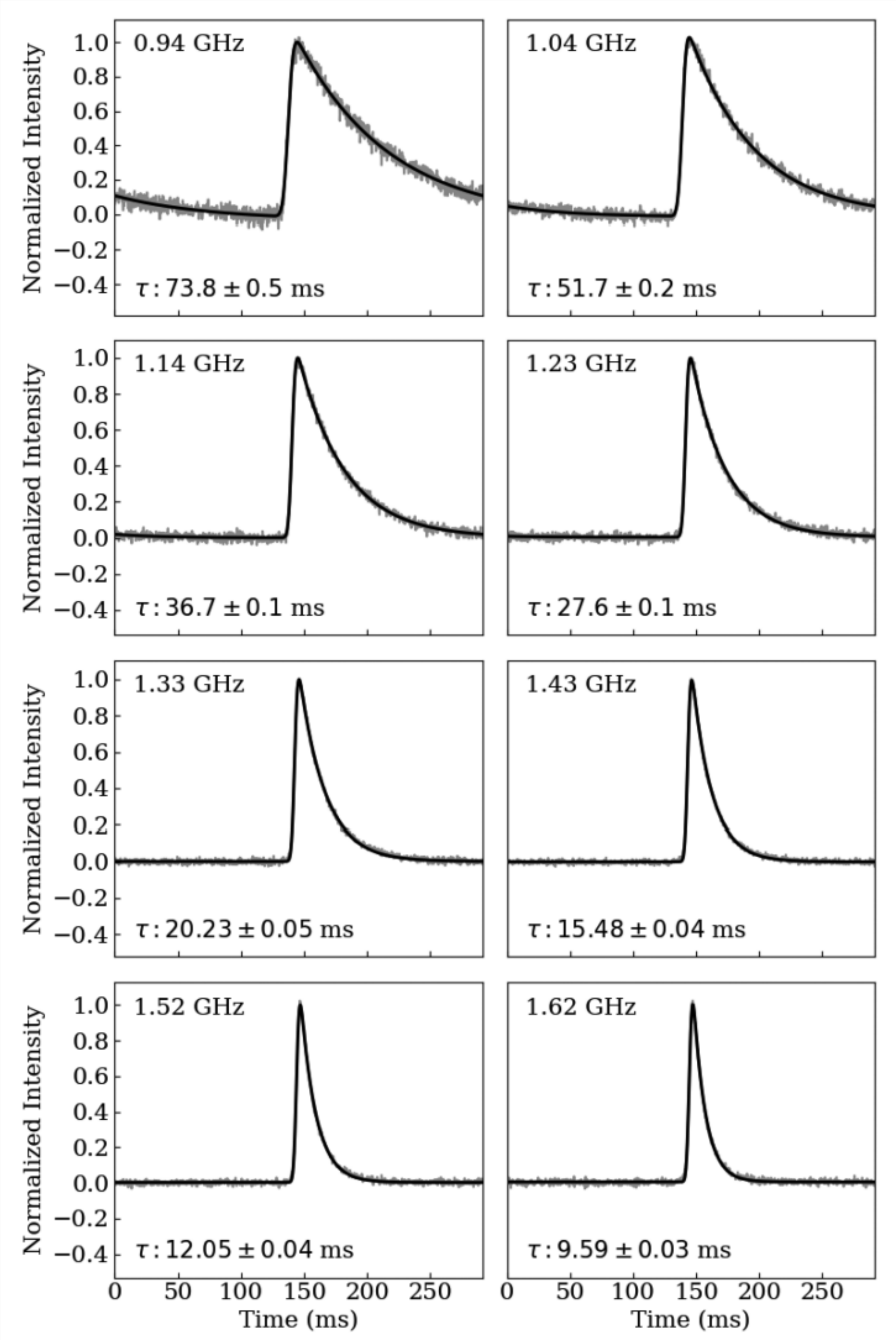


Song et al. 2023

Data available on request

TIME-DOMAIN MEASUREMENTS OF SCATTERING

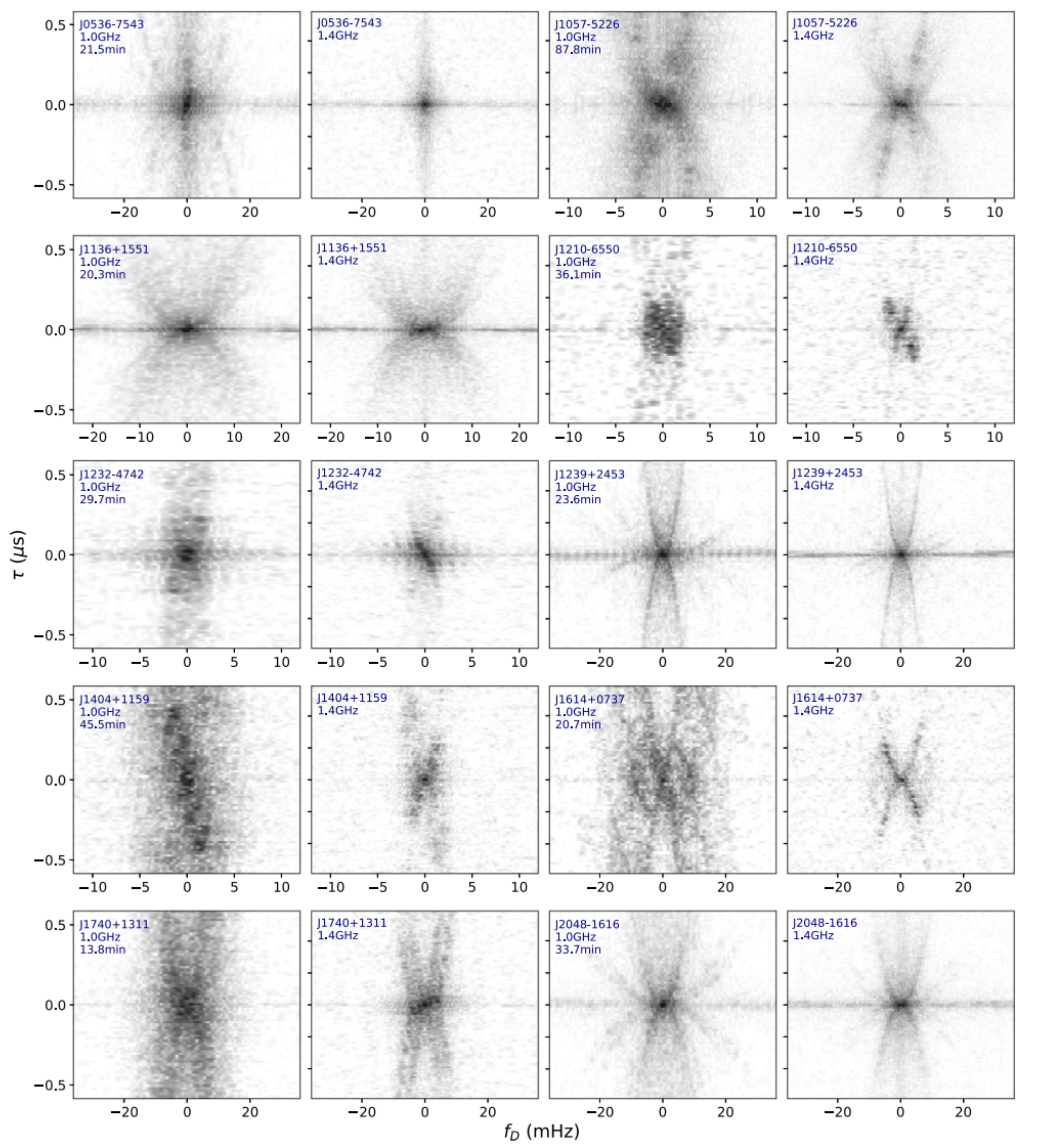




Oswald et al. 2021

High frequency and low frequency results (LOFAR) show a difference between the frequency scaling of scattering for high and low DM pulsars → suggesting multiple anisotropic screens result in isotropic scattering

SCINTILLATION ARCS OF 107 PULSARS



- Arcs are ubiquitous
- Multiple parabolic arcs
- Inverted arclets
- Arc curvature → screen distances
- or estimate of proper motion

Main et al. 2023

WHAT DOES IT ALL MEAN?

Thousand Pulsar Array monthly monitoring campaign continues…

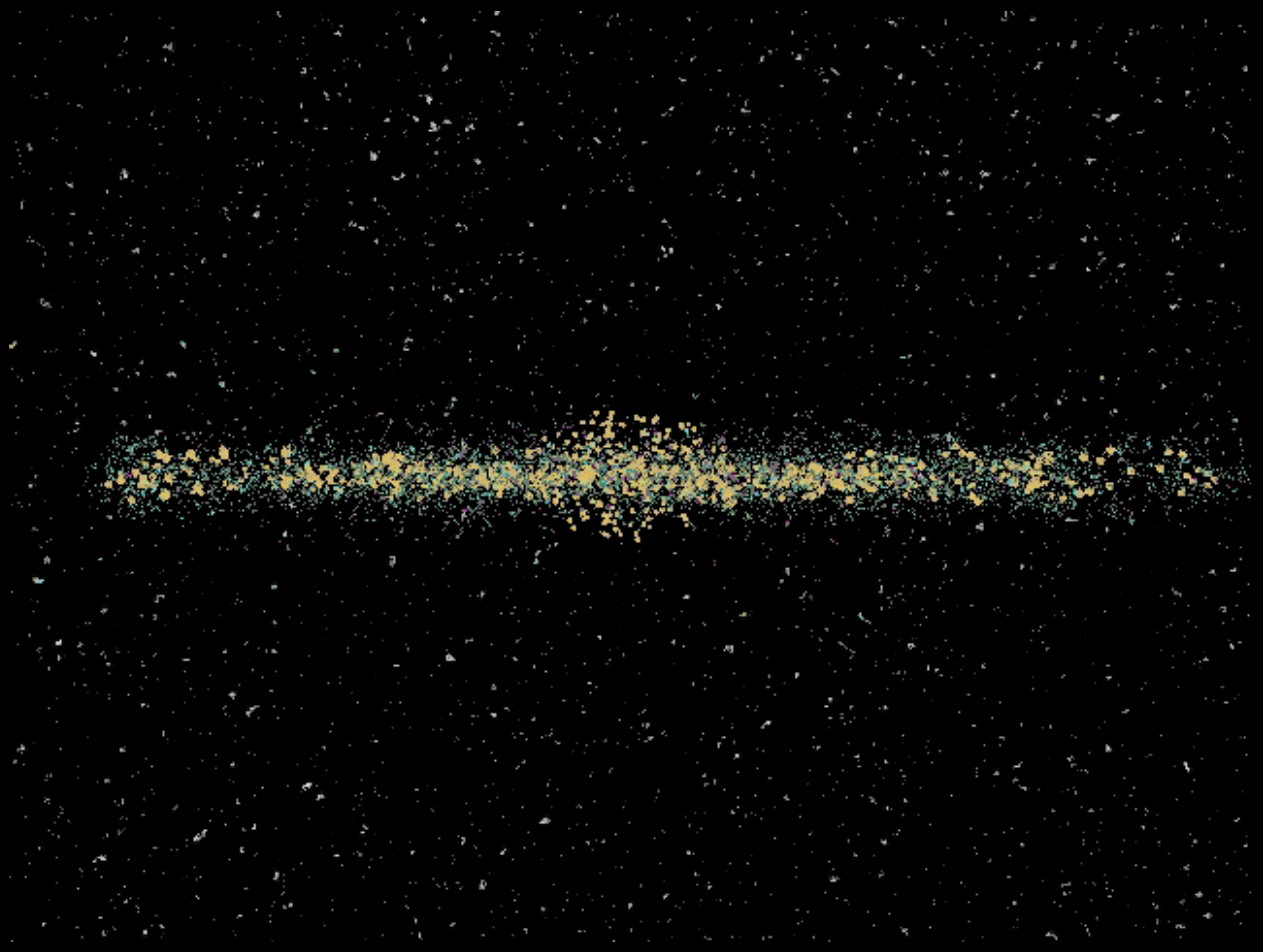
Average profiles

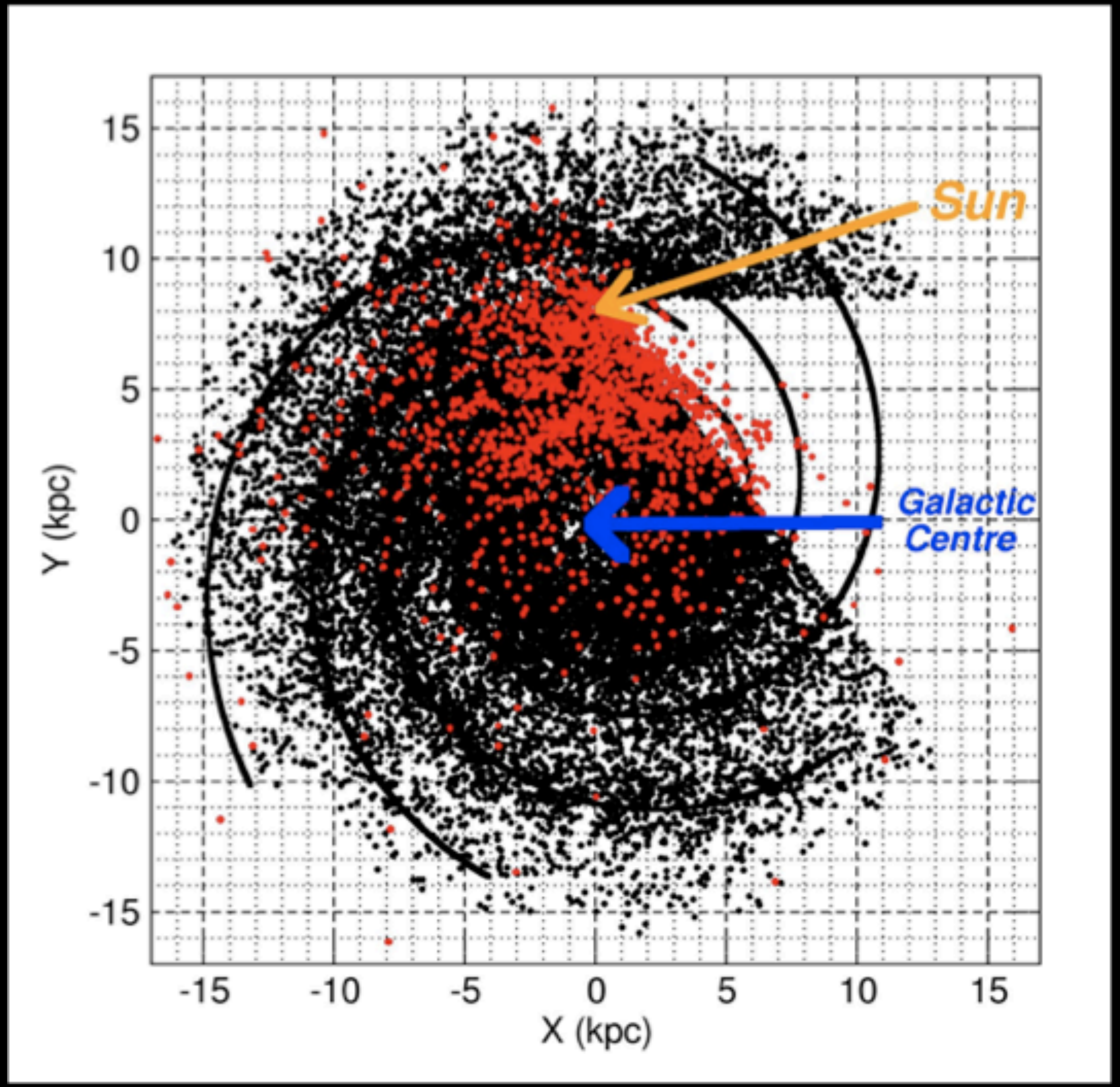
- Radio pulsars show organized properties.
- The pulse width – period relationship holds over many orders of magnitude.
- Polarization properties are very similar across the population, with the exception of the highest Edot sources.
- Can be used (with caution) to associate other types of sources with radio pulsar (NSs).
- The similarities of emission properties between MSPs and SPs suggests further importance of Edot.
- MSPs may be as luminous as SPs.

Timing

- Young pulsars evolve in a complicated way on short timescales.
- Correlations between spindown and the radio profile.
- Pulsar braking indices are not measured to be 3 on human timescales. Dominant spindown mechanism? Estimates of Bsurf and age?
- Glitches play a part in long term braking index measurements.
- Possible interplay between the interior and magnetosphere.

PULSARS WITH THE SKA





30000 pulsars/2000 MSPs

More pulsar-black hole binaries

100s relativistic binaries

Tests of Gravity & BH properties

CONCLUSIONS