

Pulsars – An Introduction

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17/09/2026

DARA

Dr Tom Scragg

- **DARA Technical Manager, University of Leeds**
- **Postdoctoral researcher at...**
 - Jodrell Bank Centre for Astrophysics & Jodrell Bank Observatory
 - Writing programs in C++ and python
 - Looking at Terabytes of data to find new quirks or behaviours
 - Searching for Fast Radio Bursts
- **Design / Build New Pulsar Timing Systems**
 - GPU based data processing engines
 - Interfacing to new and old receivers and digitisers
 - Installed at JBO and GRAO Kuntunse Ghana
- **The Study of Pulsars means ‘timing’ pulsars over many years**
 - To find variations in the time-of arrival of a pulse ($\sim 10^{-15} / 10^{-18}$ s)
 - Identify Physics involved
 - Discover how stars change and evolve
 - Use pulsars as probes of the Interstellar Medium, Relativity, Gravity, Galactic structure...

Jodrell Bank Centre for Astrophysics

- **JBCA**

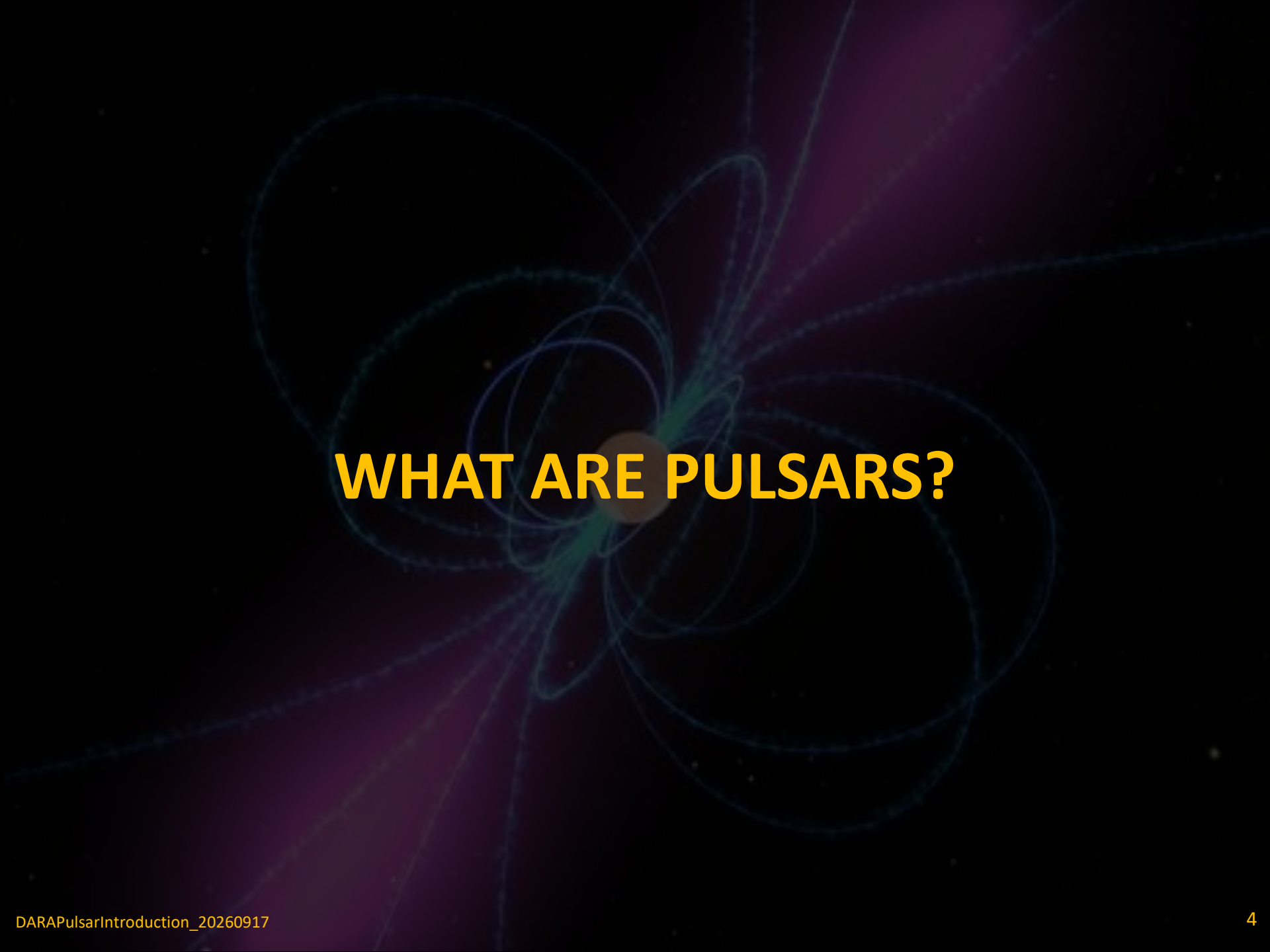
- Biggest Department in Europe ~ 215 people
- 28 Staff, 48 PDRA, 74 students / others



- **JBO**

- 60 people, mostly engineering, technical and maintenance
- 6 Controllers
- 3 Research Telescopes on site
- e-MERLIN, 5 other telescopes remotely sited
- 2 'student' telescopes.

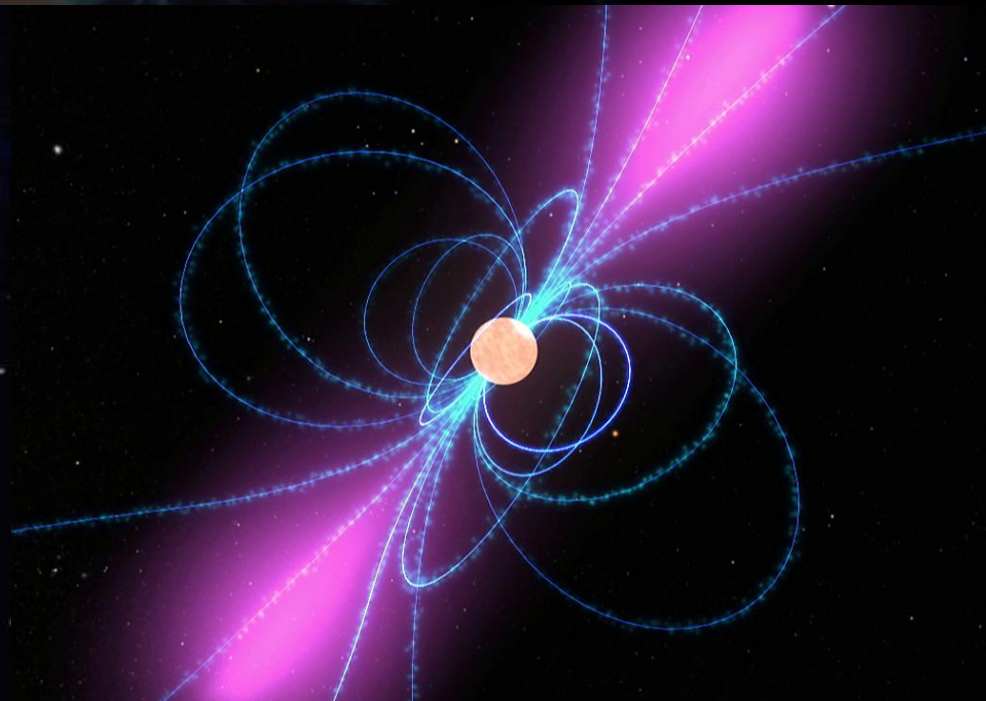


A diagram illustrating the emission pattern of a pulsar. It shows a central point from which multiple elliptical beams of light emanate, representing the pulsar's magnetic field and the resulting pulses of radiation. The beams are colored in shades of blue and purple, set against a dark background with faint star-like specks.

WHAT ARE PULSARS?

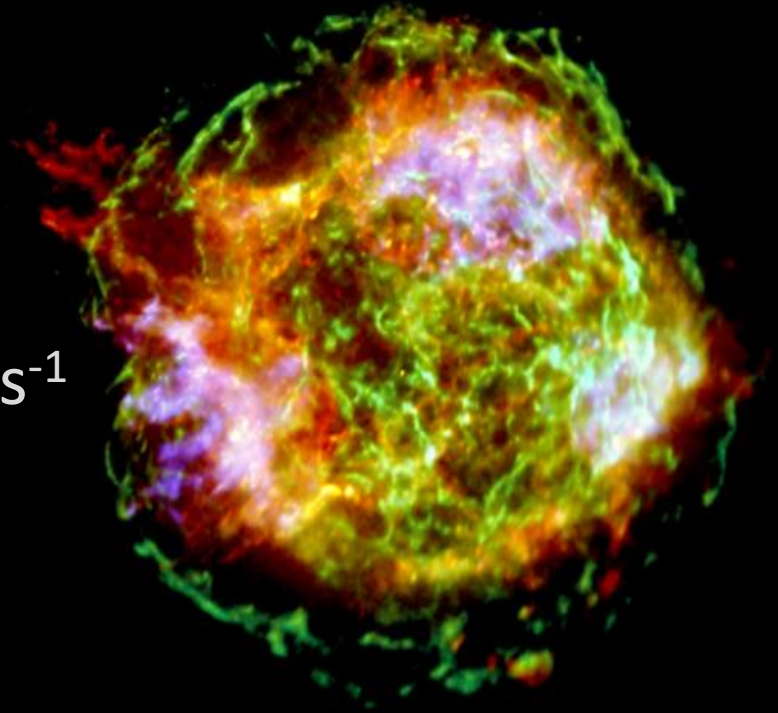
What are pulsars?

- They are not stars that pulse.
 - The fading heart of a supernovae – a neutron star
 - A pulsar is a neutron star where the magnetic pole is not aligned with the axis of rotation which therefore generates a beam of radiation that periodically aligns with our line of sight



Pulsars

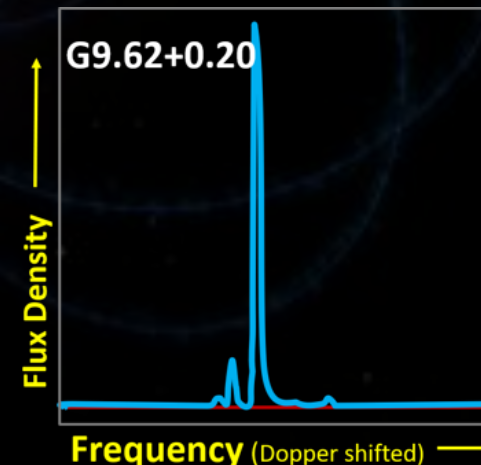
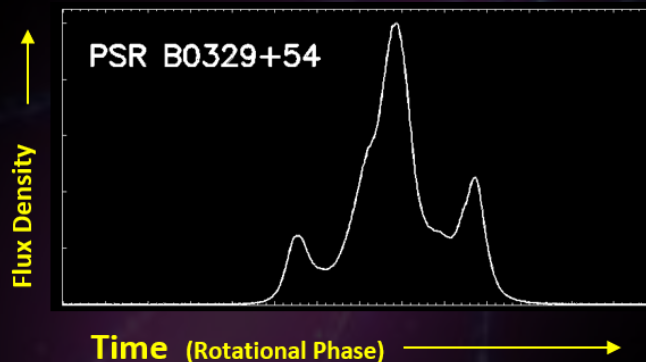
- Remnants of SuperNova - SNe
- Rotating Neutron Stars
- $M \sim 1.4 M_{\odot}$, $R \approx 10\text{km}$
- **P**eriod = 0.0013 to 8.5 s
- Spin down $\dot{P} \sim 10^{-10}$ to $10^{-20} \text{ s s}^{-1}$
- **B** High Surface magnetic field
 - $\sim 10^8$ to 10^{14} Gauss
 - Earth 0.25 to 0.65 G
- Mainly radio sources
- Emission typically in a narrow beam
- Clock-like stability



Cas A - X-ray - Chandra/NASA

Pulse Profiles – an aside

- With Pulsars we are looking at the variation over time in the rf energy received from the source
 - Not at a specific rf frequency (but a band)
 - The duration of a pulse is relative to the rotation period of the pulsar
 - Pulsars emit energy over a wide radio of frequencies simultaneously
 - Broadband emissions
- MASERs continually emit at a very narrow frequency
 - Corresponding to the frequency of the specific molecule and vibration frequency of the source



Model of a PULSAR's Interior

- A crust of normal matter floats on a fluid core of neutrons
- The crust holds the magnetic field
- The core is a super fluid with minimal interaction with the crust.

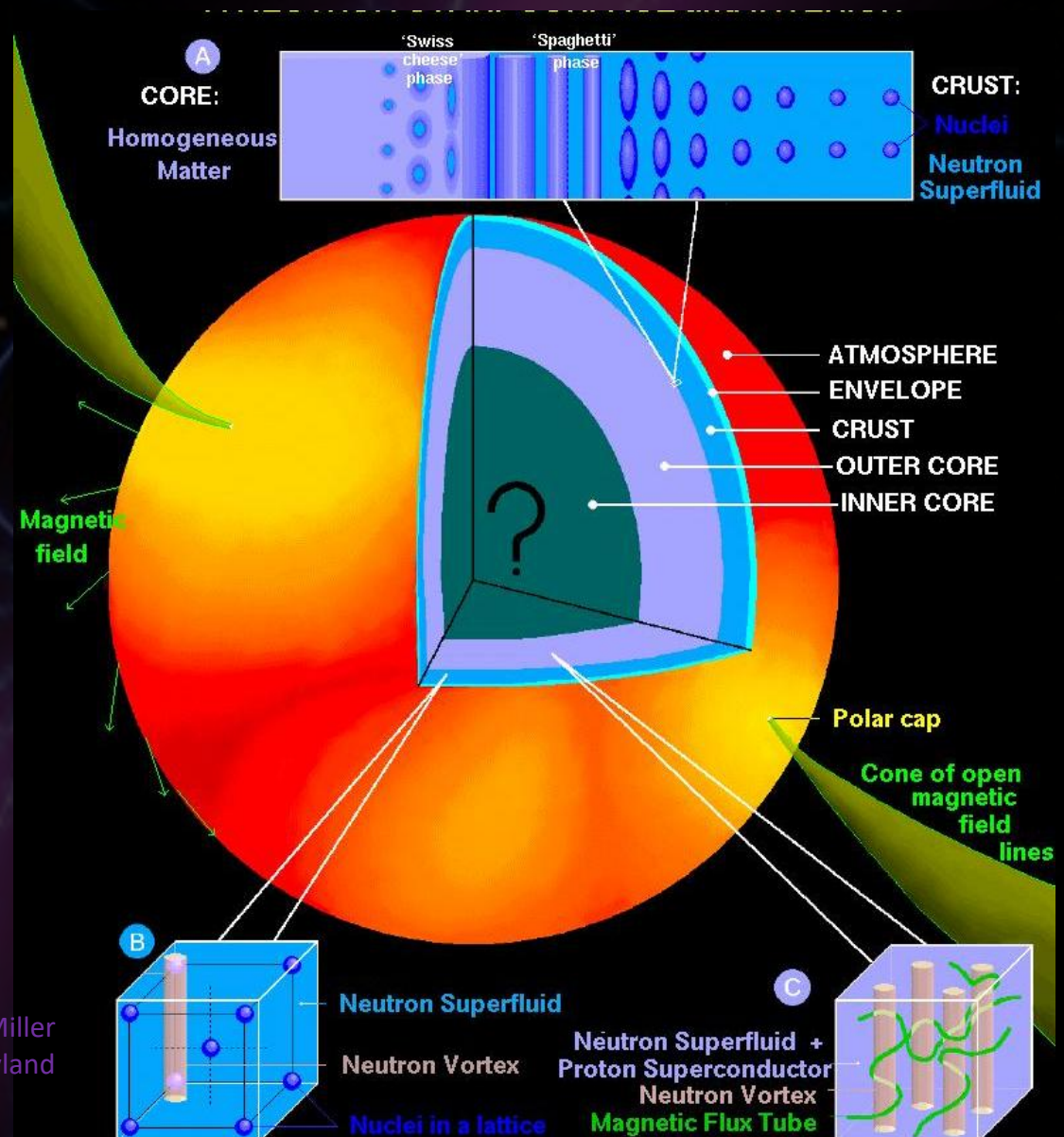
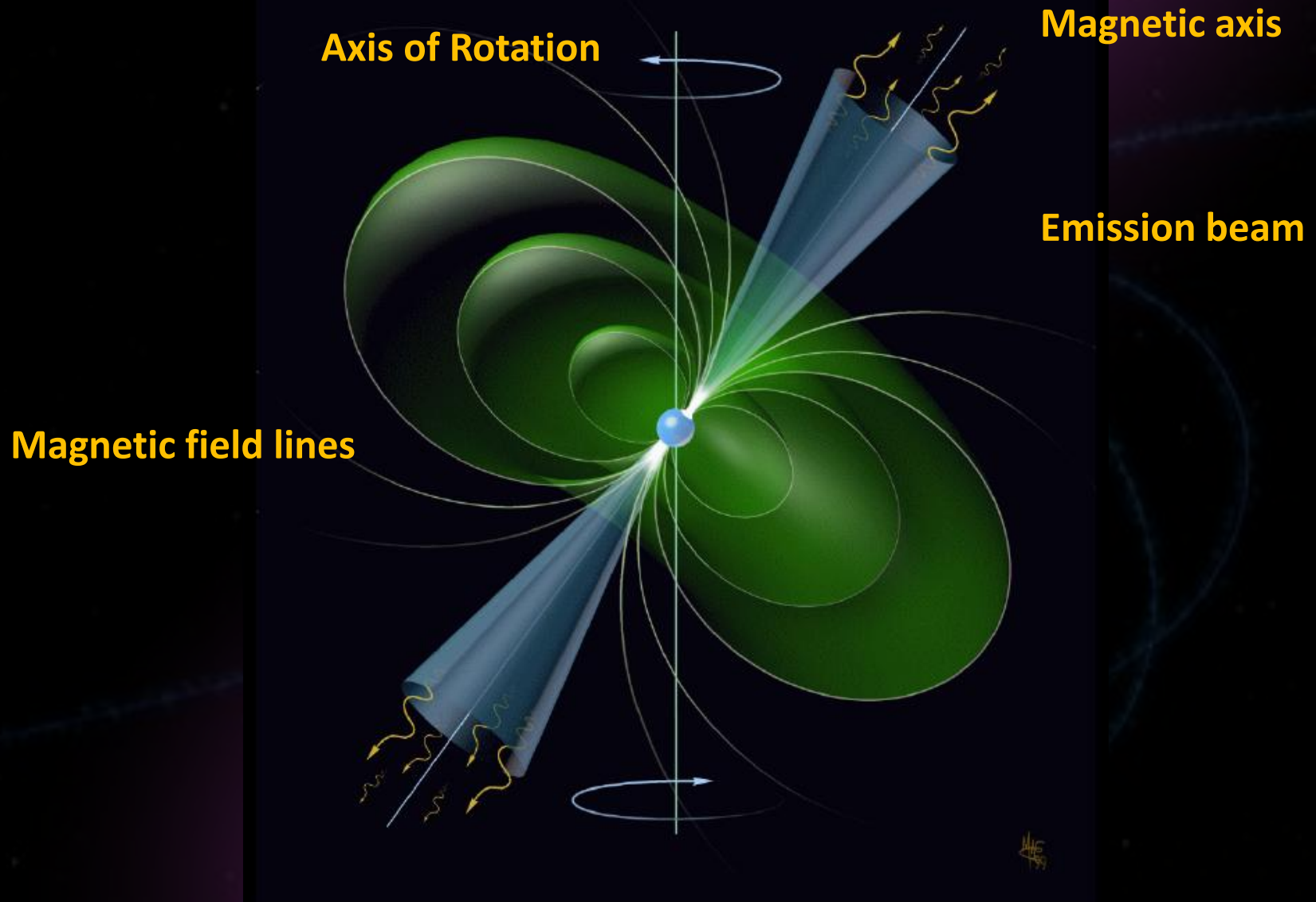


Image Credit: M. Coleman Miller
Professor of Astronomy, University of Maryland

Pulsar 'Toy' Model

© Mark A. Garlick / space-art.co.uk



Lighthouse 'Toy' Model

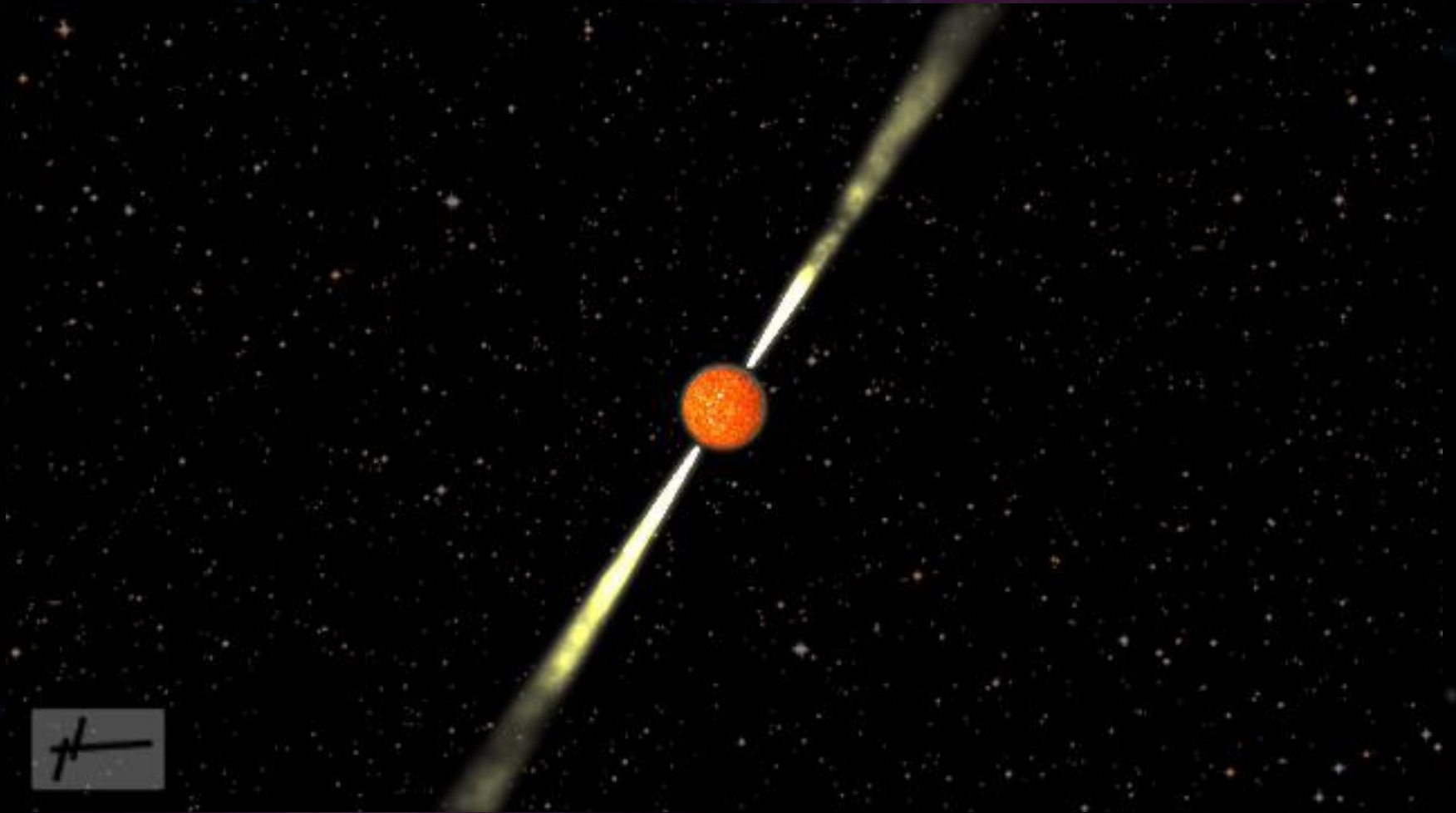
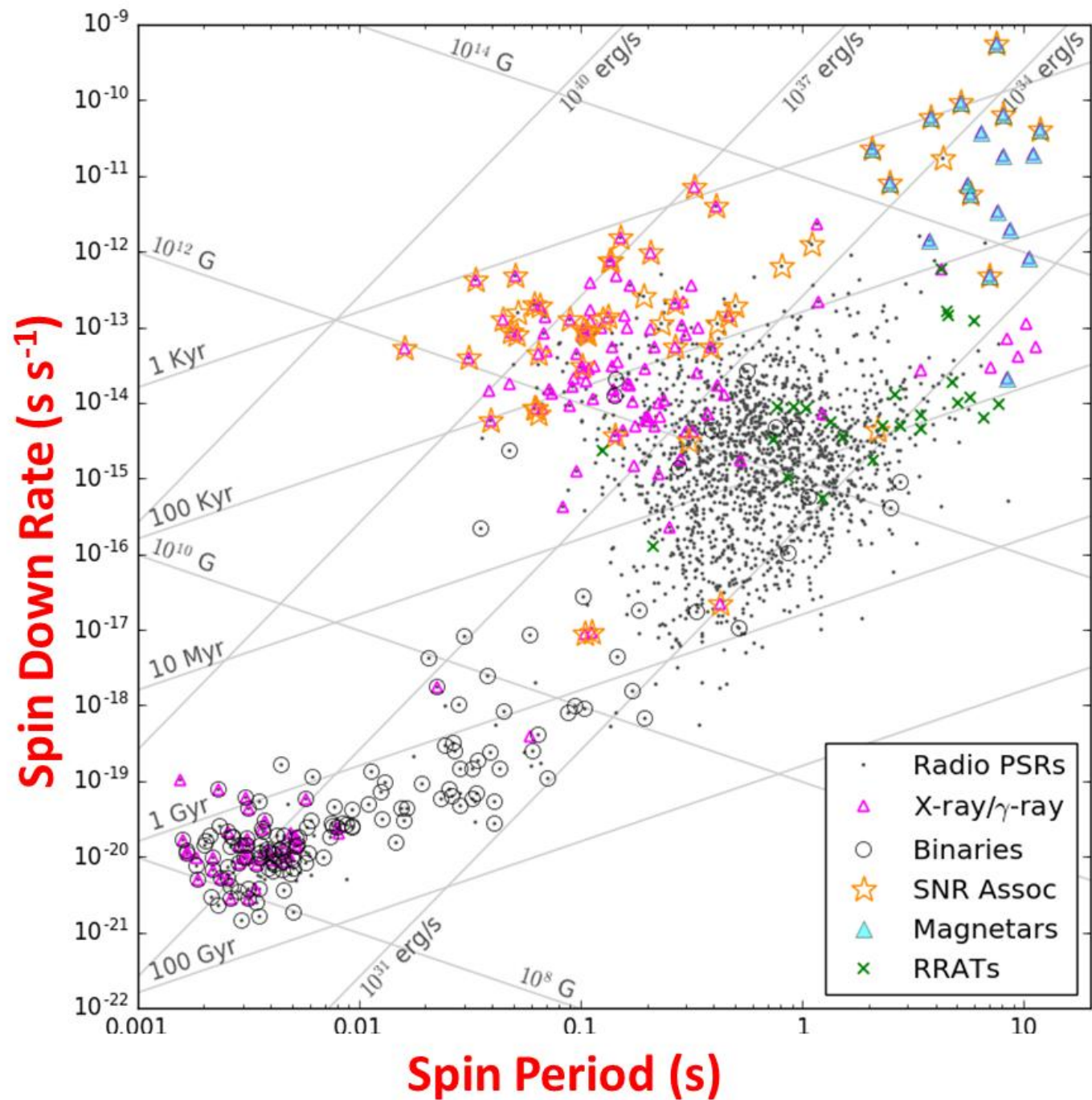


Image credit: ASTRON

P vs $\dot{P}$ Diagram



Two Main Populations

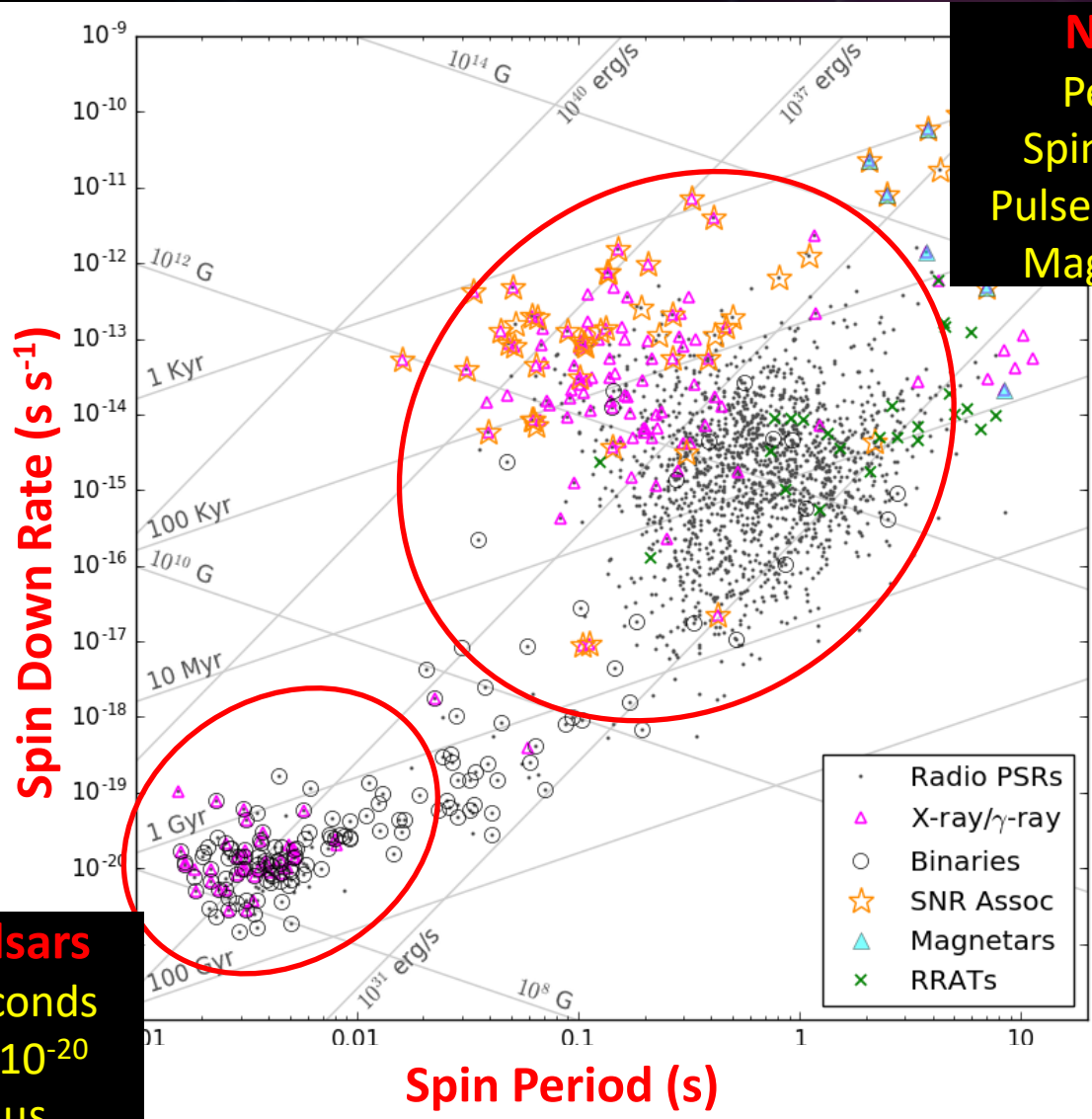
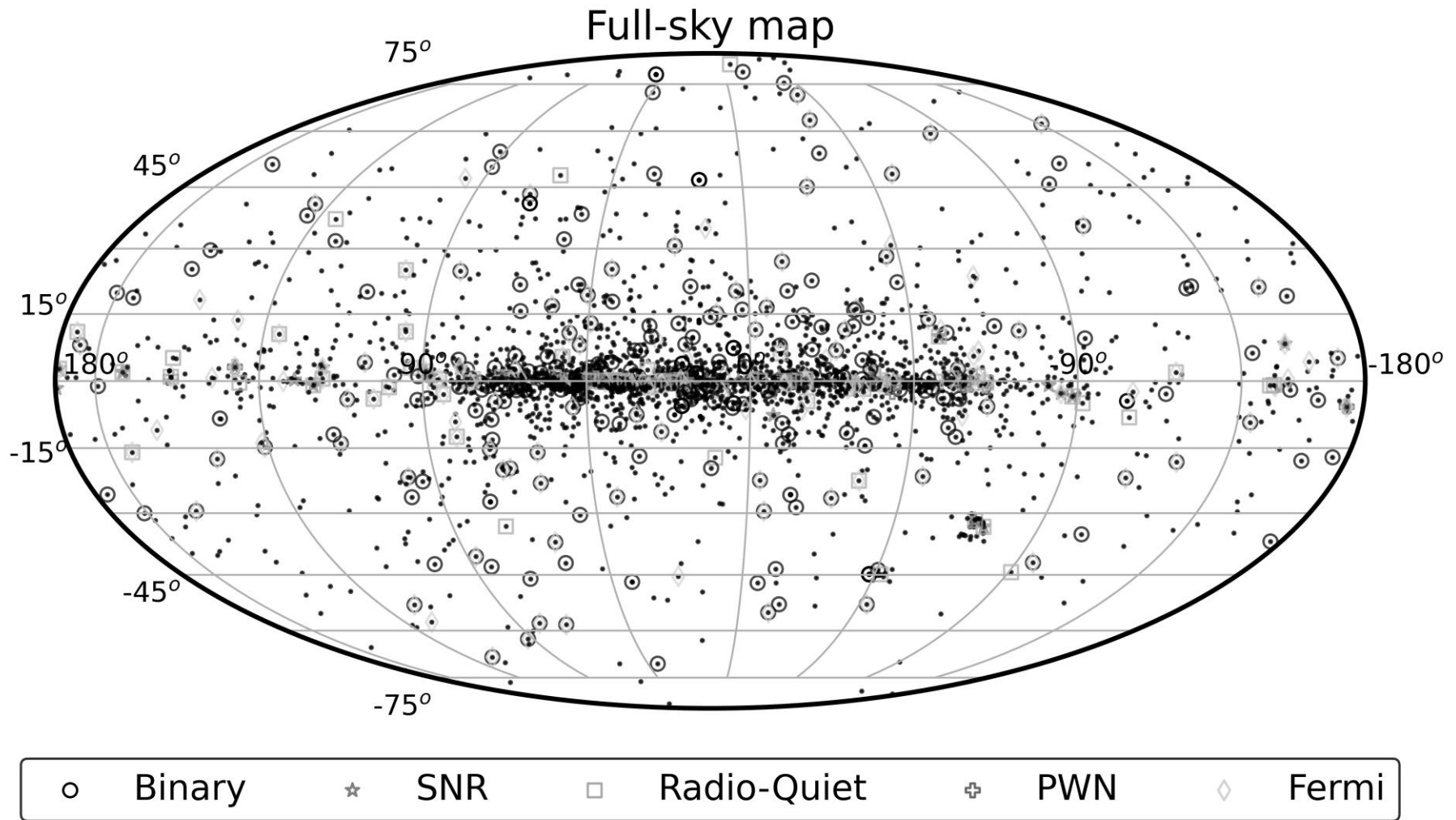
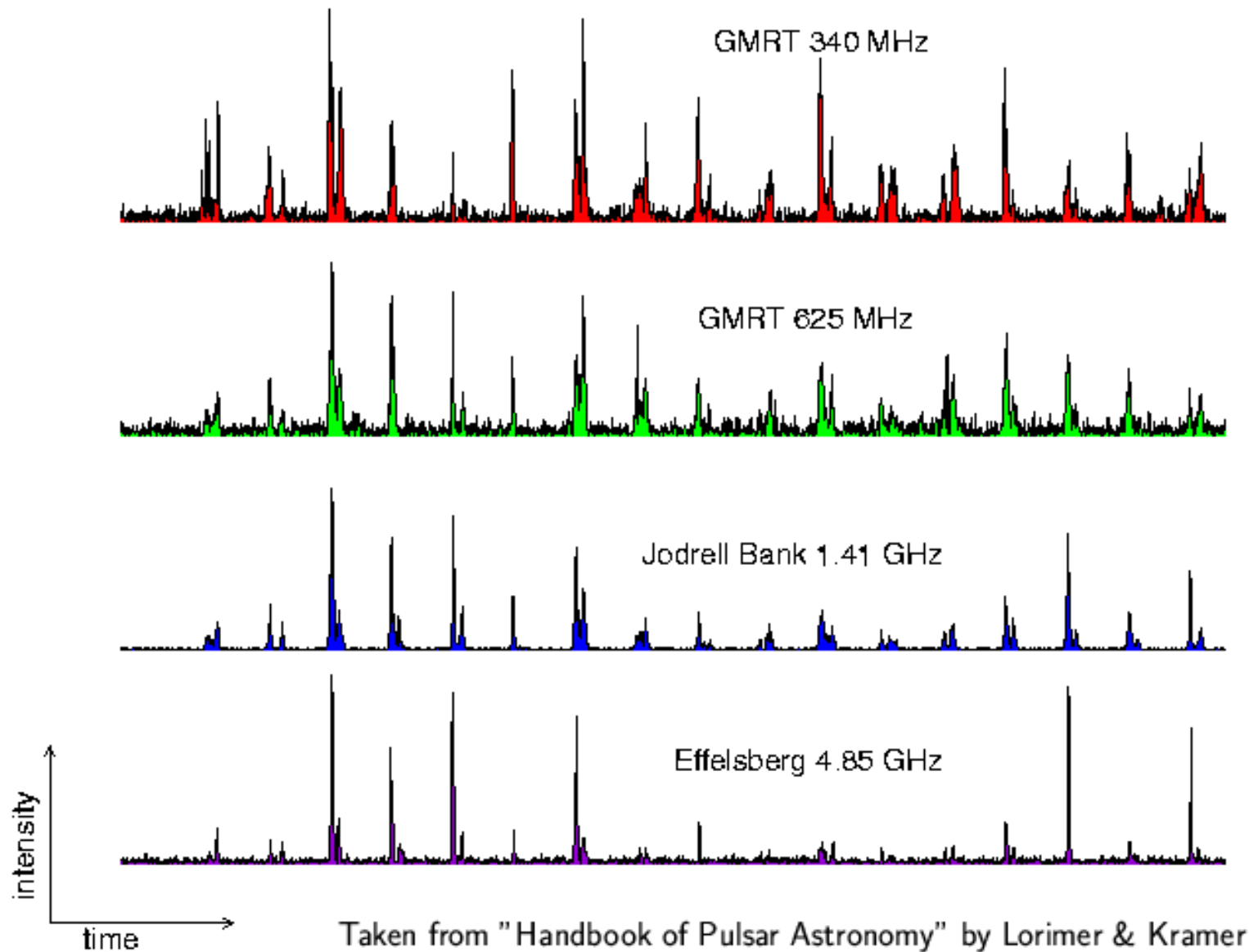


Image Credit:
JBCA Internal Plot

Where do we find Pulsars?



Pulse Shapes at Different Frequencies



Physics with Pulsars

Time of arrival at different frequencies

Frequency dispersion along the line of sight gives us information on the neutral hydrogen / electron number density of the ISM

By looking at the pulse profile

Changes in flux or phase or shape, we can derive structure in the emitting regions

Pulsar timing

Spin down rate, RRATs & Nulling emission mode, Glitches (neutron star interiors)

Pulsars in Binary Systems

Interactions between companions (Recycled pulsars / MSPs, Redbacks & Black Widows)

Post Keplerian Orbital mechanics, tests of General Relativity,
Constrain theories on gravitational waves

Timing of Pulsars

Regular monitoring of the rotation of a neutron star by noting the time of arrival of radio pulses.

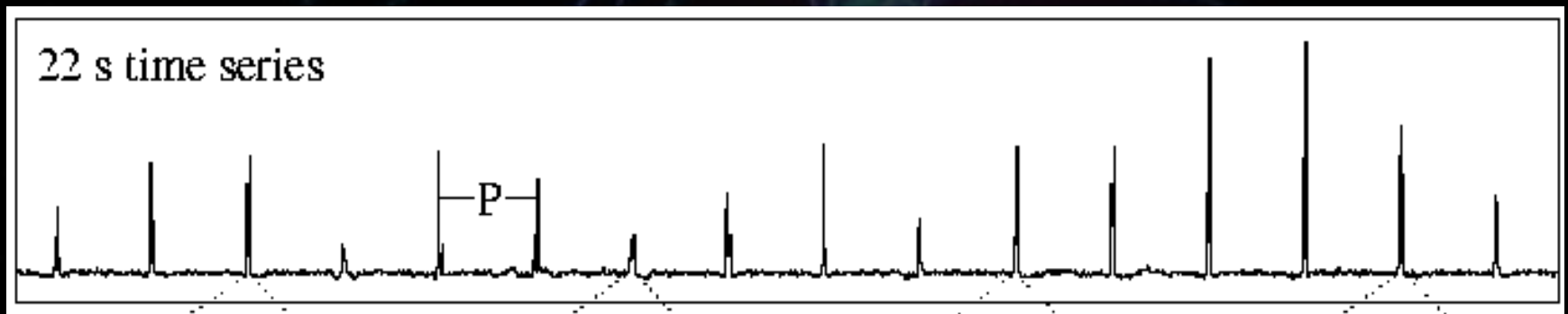


Image Credit: Adapted from Pulsar Astronomy

P is the period between peaks (or a prominent feature on the pulse)

Increasing the accuracy

Pick a point on the pulse and measure the time delay to the next occurrence

- Simple case: 1 second period, 10% duty cycle, assume our accuracy of the pulse peak is 10% = 0.1s (100ms).

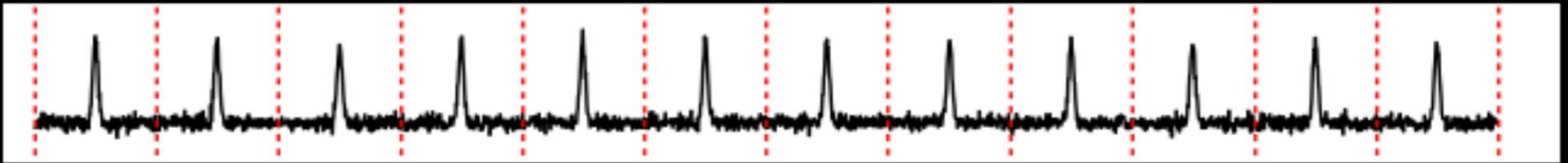
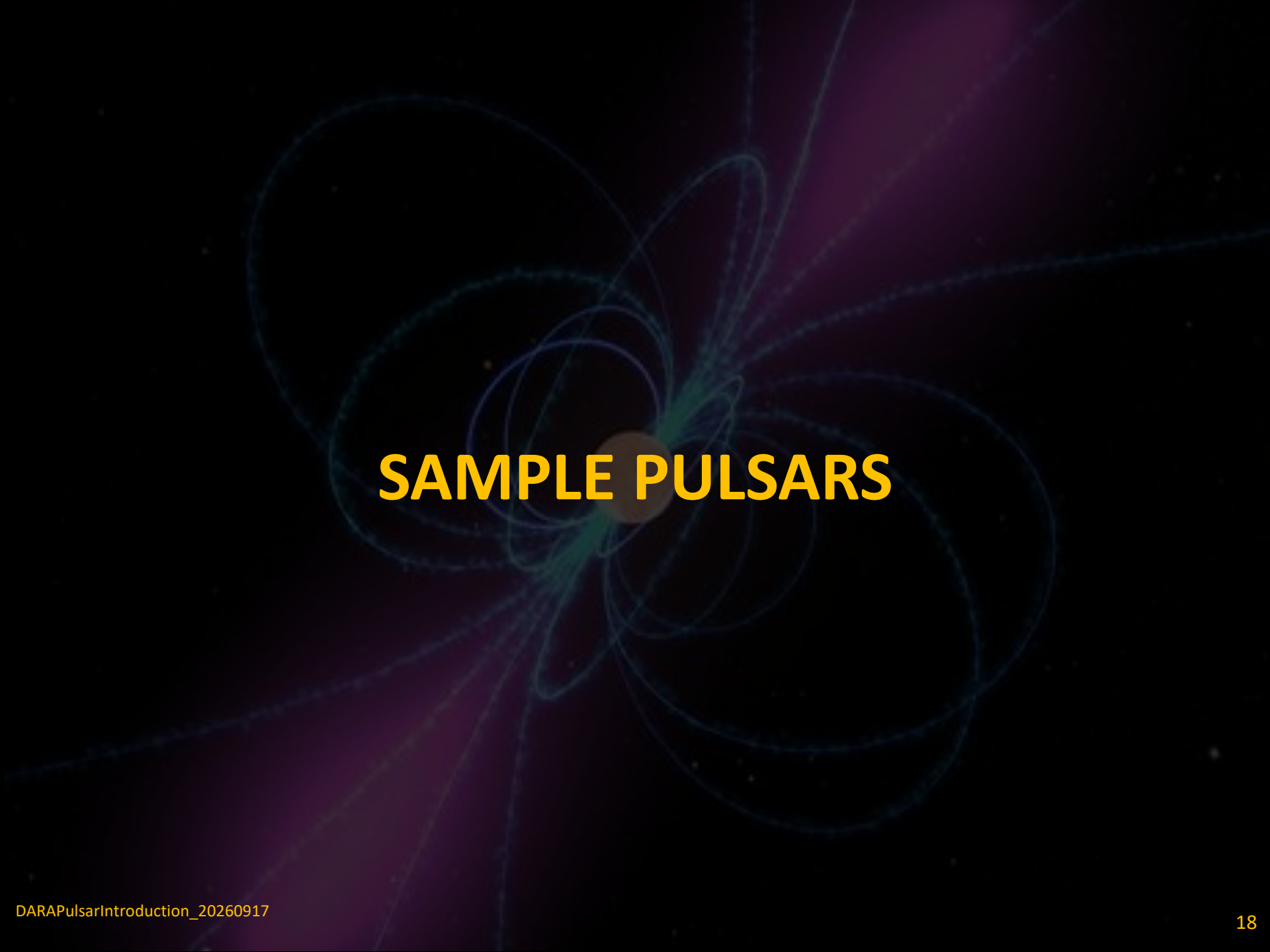


Image Credit: Scott Ransom

- Measure over n pulse periods and we can reduce the error in our estimation of the period by $1/n$

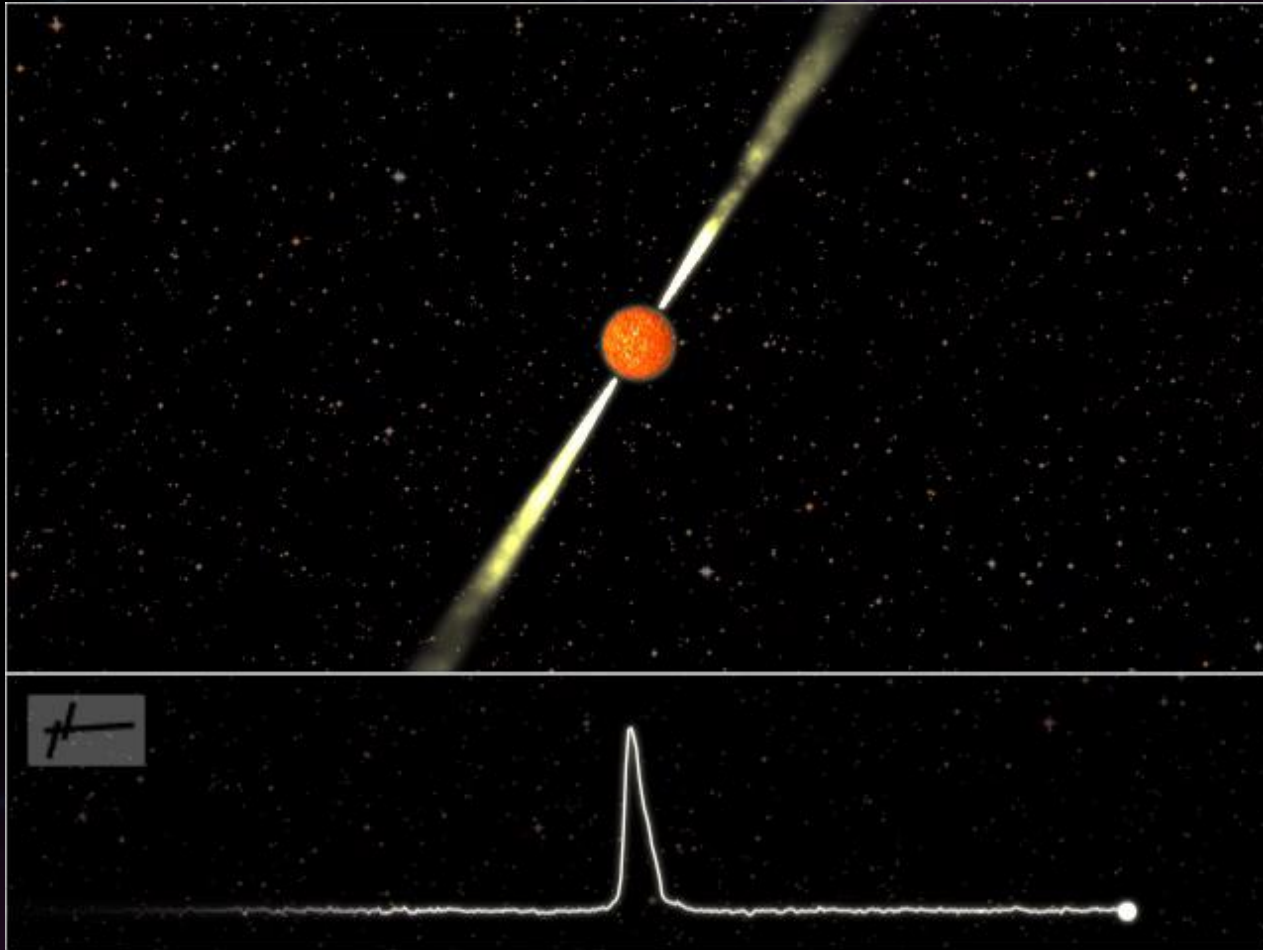
PSR J1737+0747 (a millisecond pulsar)

$$P = 4.570\,136\,529\,159\,926\text{ ms} \pm 0.1 \times 10^{-8}\text{ ns}$$



SAMPLE PULSARS

Pulse Profile



Supernova Remnant

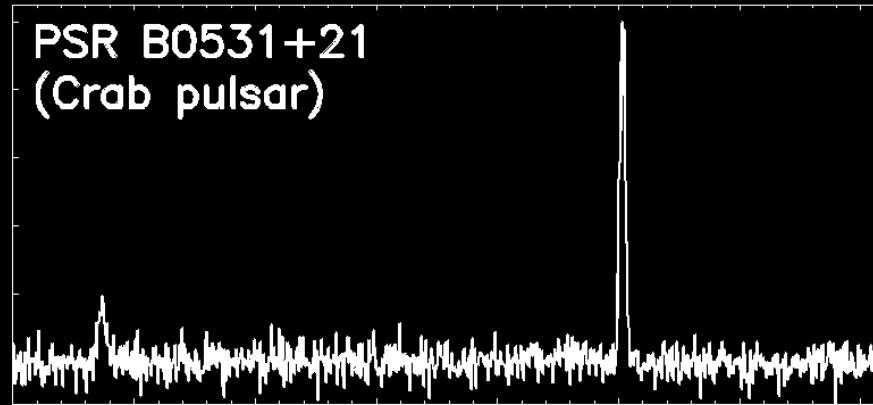
Crab Nebula

- **In the constellation Taurus**
 - Supernova in 1054 AD
 - Due to the neutron star's 'Proper Motion' over the last 1,000 years The pulsar is not in the centre of the nebula
- **Monitored by Jodrell Bank**
 - For ~12 hours a day
 - For 30+ years

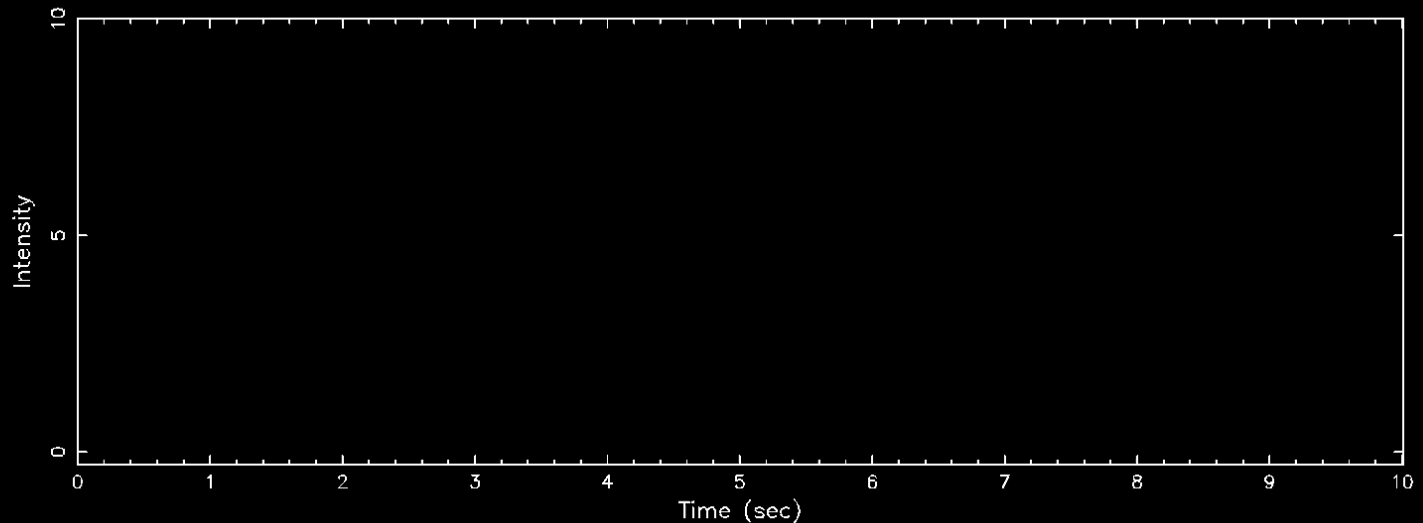


Image Credits: X-ray: NASA/CXC/SAO/F.Seward; Optical: NASA/ESA/ASU/J.Hester & A.Loll;
Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehr

Crab Pulsar PSR B0531+21



Crab pulsar observed with the Lovell telescope at Jodrell Bank

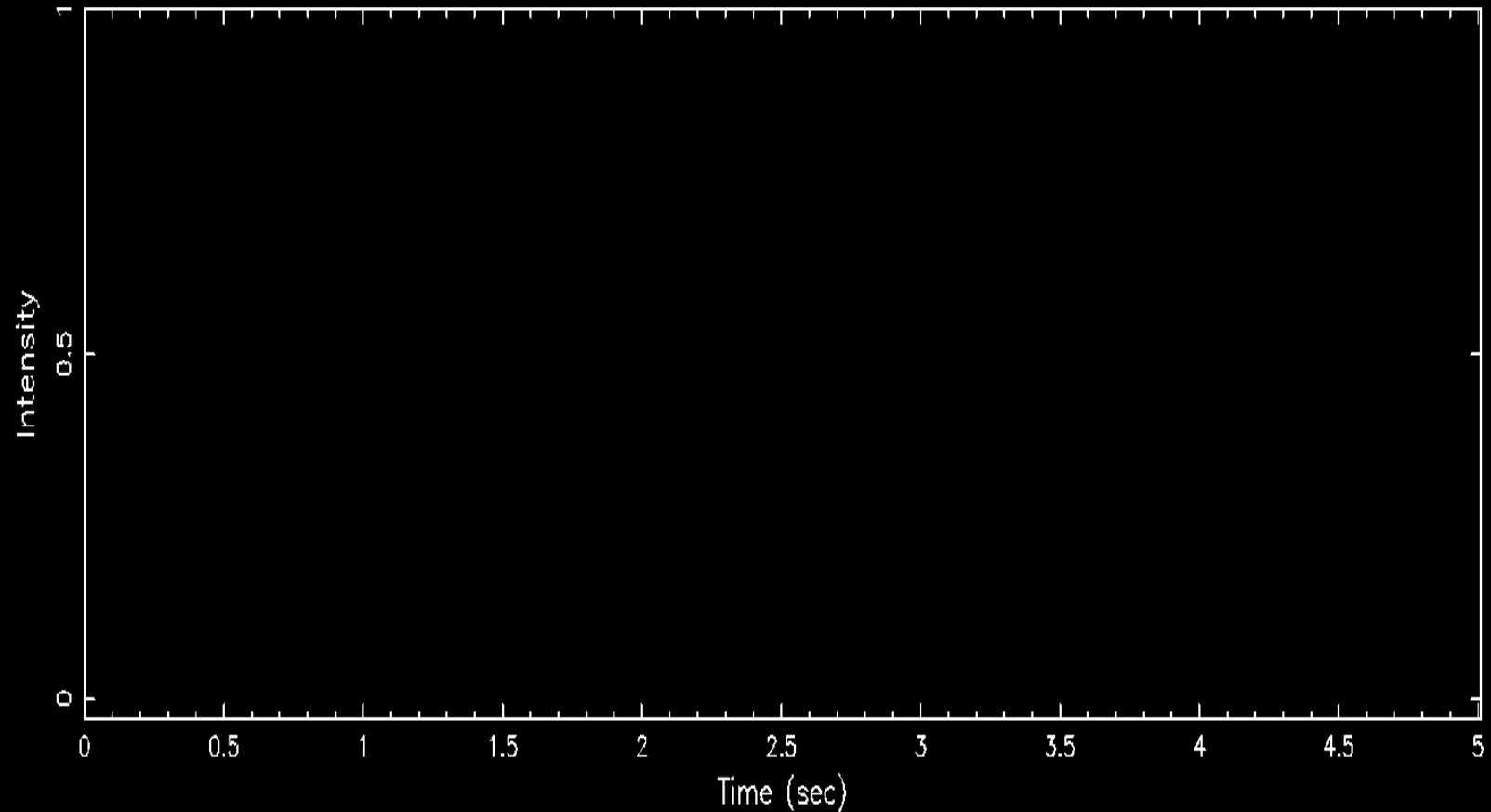


© Jodrell Bank Centre for Astrophysics pulsar group

Vela Pulse Train

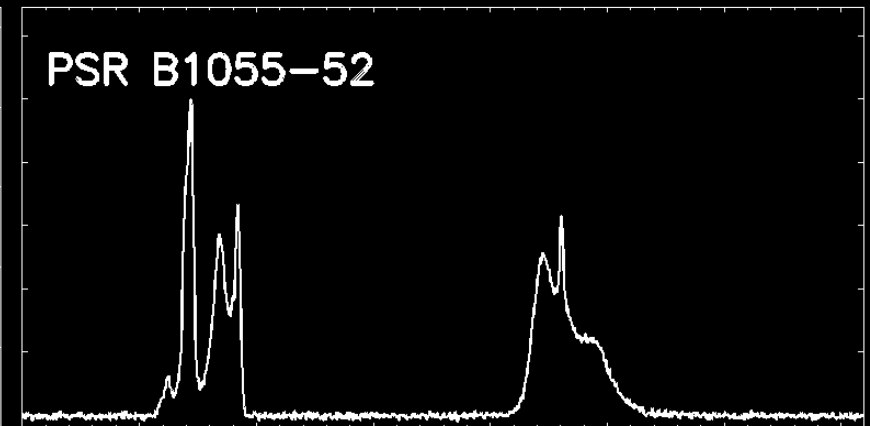
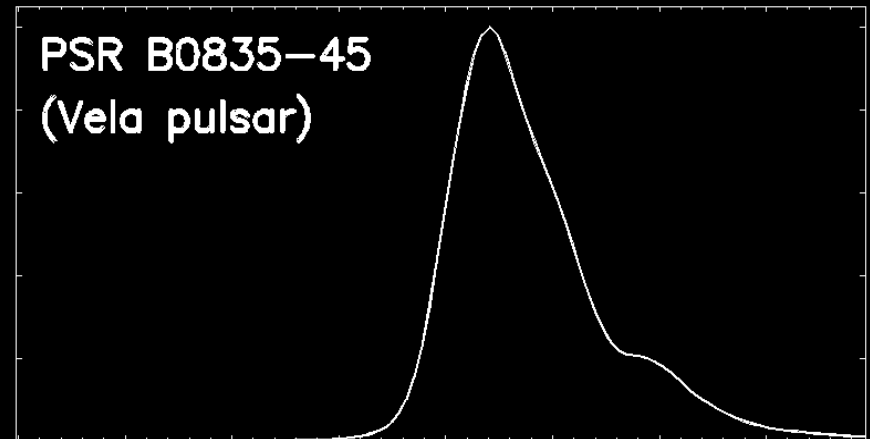
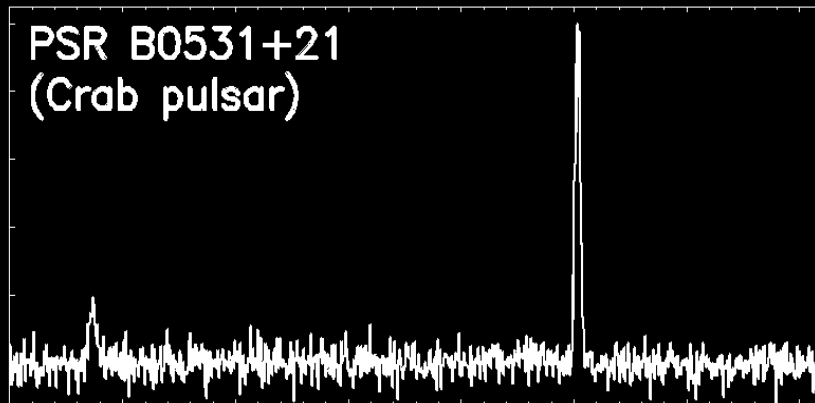
Brightest pulsar in the southern sky

Vela pulsar observed with the Parkes telescope in Australia



© Jodrell Bank Centre for Astrophysics pulsar group

Pulse Profiles

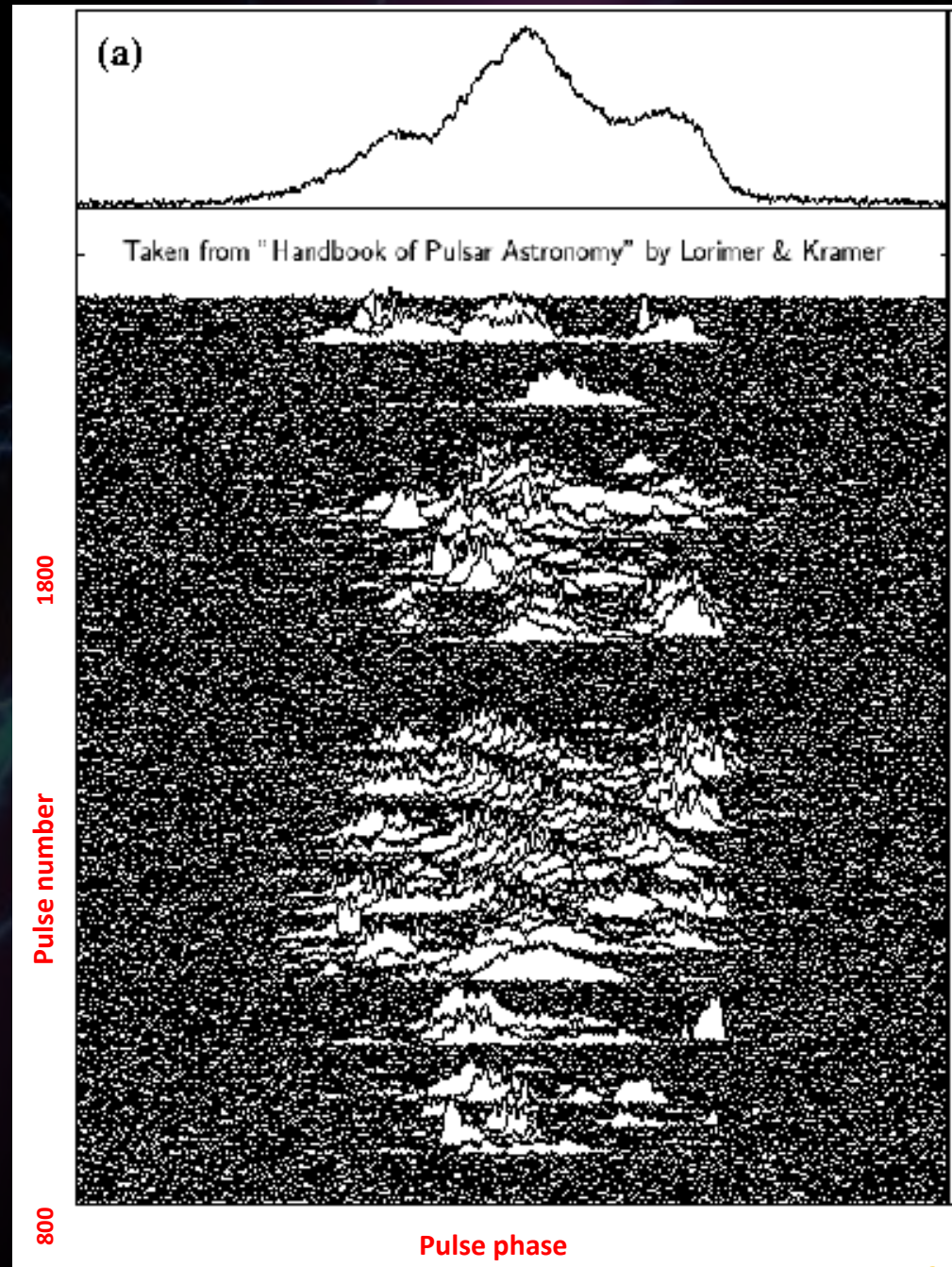


PULSE EMISSIONS OVER TIME

1600 pulse signals combined

Profile is constant per pulsar

Some rotations have no emissions



PSR B0329+54

Brightest Pulsar in the northern sky

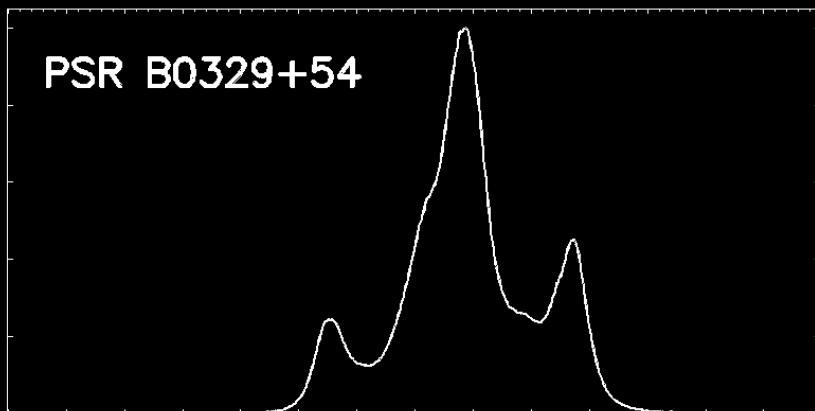
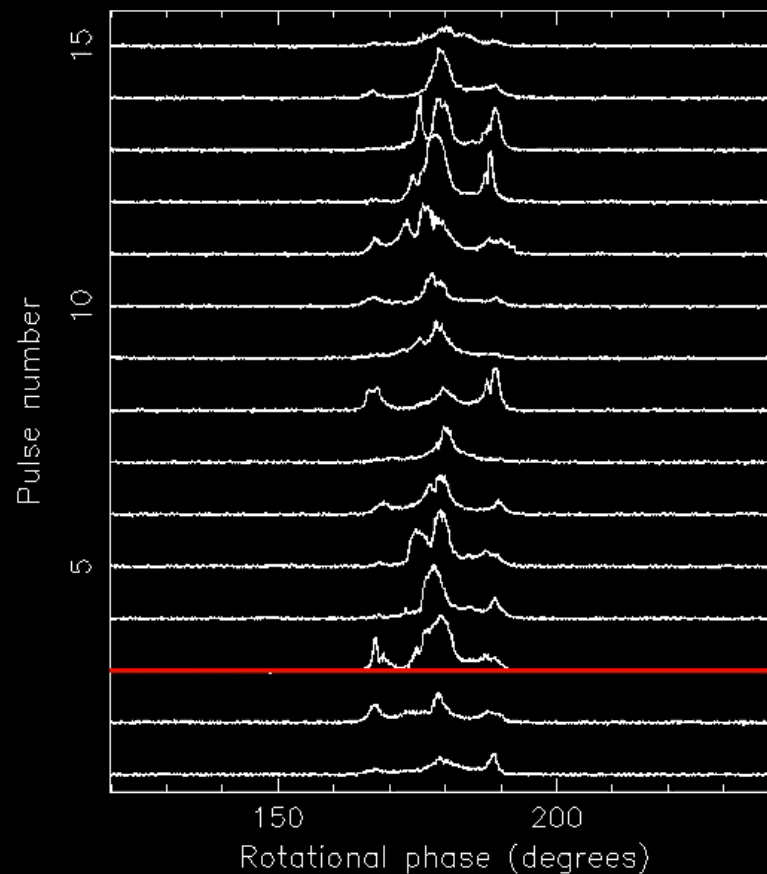


Image credit: JBCA

Pulsar B0329+54 observed at Jodrell Bank



© Jodrell Bank Centre for Astrophysics pulsar group

Timing and Residuals

- The pulse Time-of-Arrival is compared with prediction from the timing model.
- The timing model allows us to calculate the expected arrival of
 - Pulse number 1,000,000 (day 11)
 - Pulse number 10,000,000 (day 115)
 - Pulse number 1,000,000,000 (day 11,575 – in year 31)
- From that we can determine the error in the calculated ToA
 - ‘Residual error’
- Iterative process starting with a few closely grouped observations
 - Extend the time duration and precision as more data is available
- Look out for
 - Phase coherence
 - Geometric and relativistic effects
 - Glitches

Phase Coherence

- Simply that we have a timing solution that is accurate enough that the accumulated uncertainties do not exceed one pulse period.
- Start with Spin period and Pulse reference phase (template)
 - Spin frequency derivative ($\dot{P}$)
 - Position
- Precision improves with data span (time) and frequency of observation.
- Pulsars in Binary Systems have another set of orbital parameters to characterise

Glitches

A glitch is a sudden step change in spin frequency

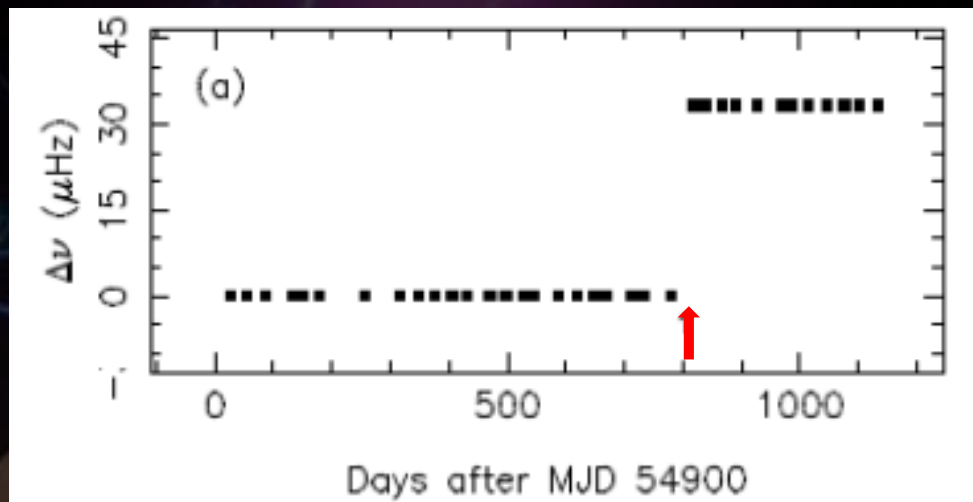
- The pulsar spins faster
- The slow down rate ($\dot{P}$) increases and then decays back to the original value.

- Glitch in PSRJ1757-2421

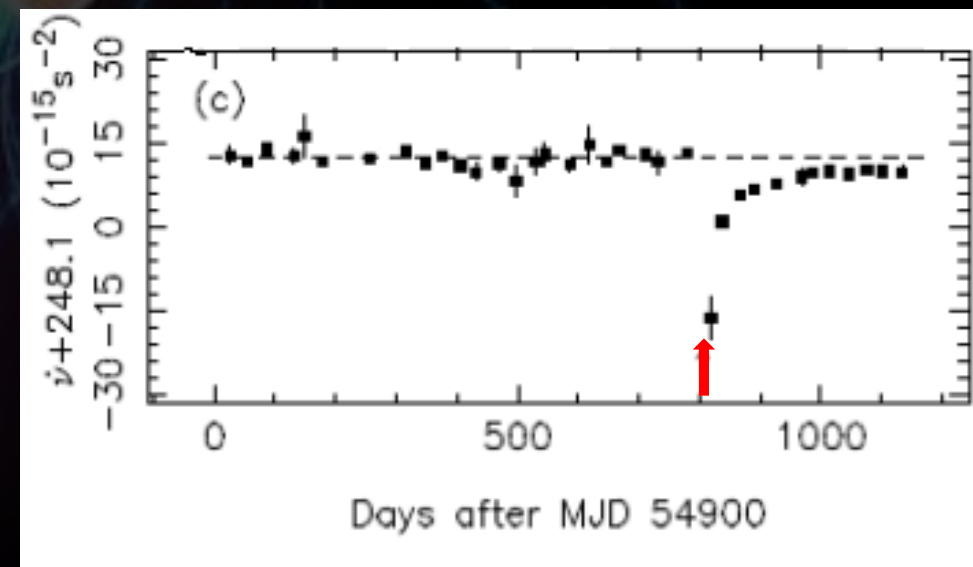
- at $\sim$ MJD 55700 (May 16 – 27 2011)
- Fractional increase of $\Delta\nu_g / \nu \sim 7.8 \times 10^{-6}$
- $\nu = 4.271\,592\,656\,55(4) \text{ s}^{-1}$
- $\Delta\nu_g = 4.271\,573\,098\,0(8) \text{ s}^{-1}$

Glitch in PSR J1757-2421

The top panel shows the spin-frequency residuals relative to the pre-glitch Spindown solution;



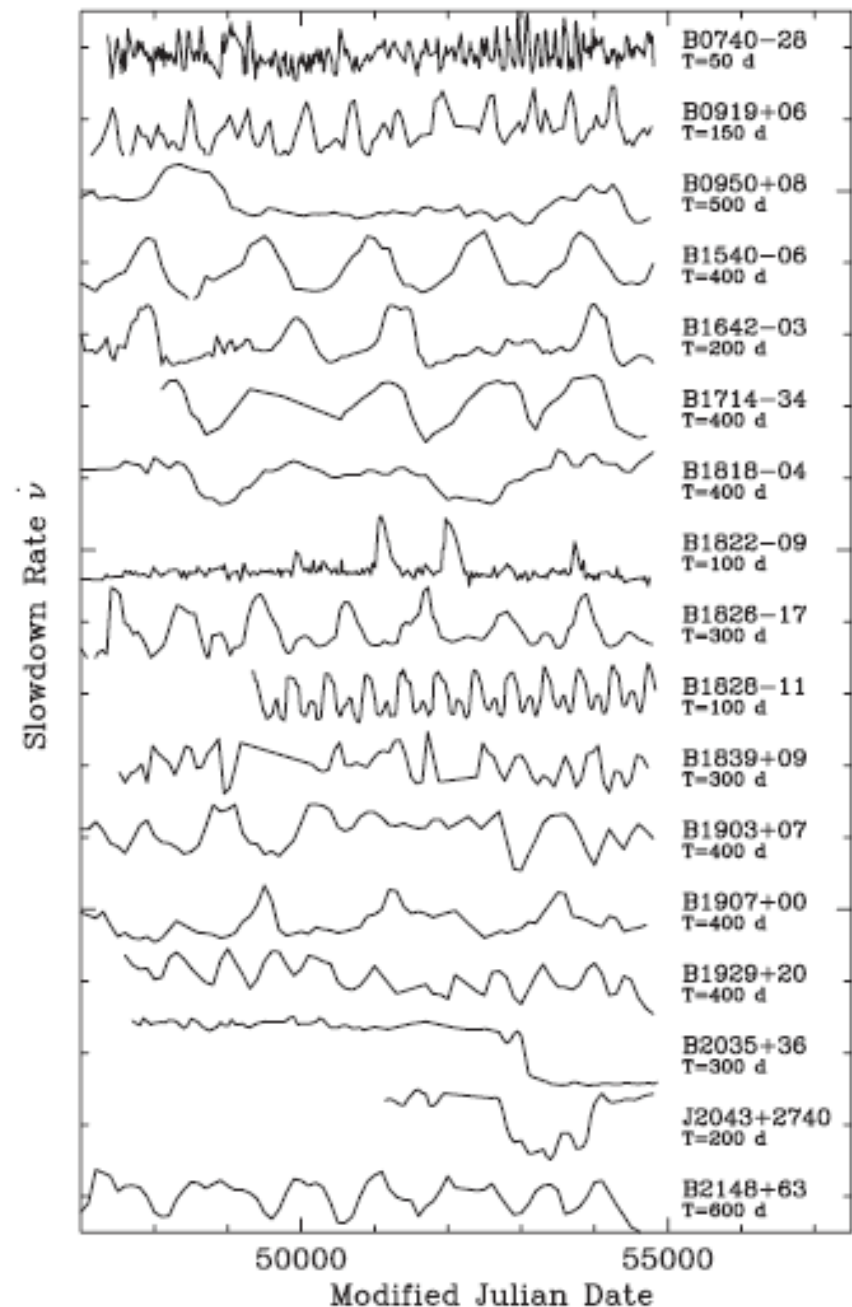
The bottom panel shows the variations of $\dot{P}$, and the horizontal dashes indicate the average pre-glitch level.



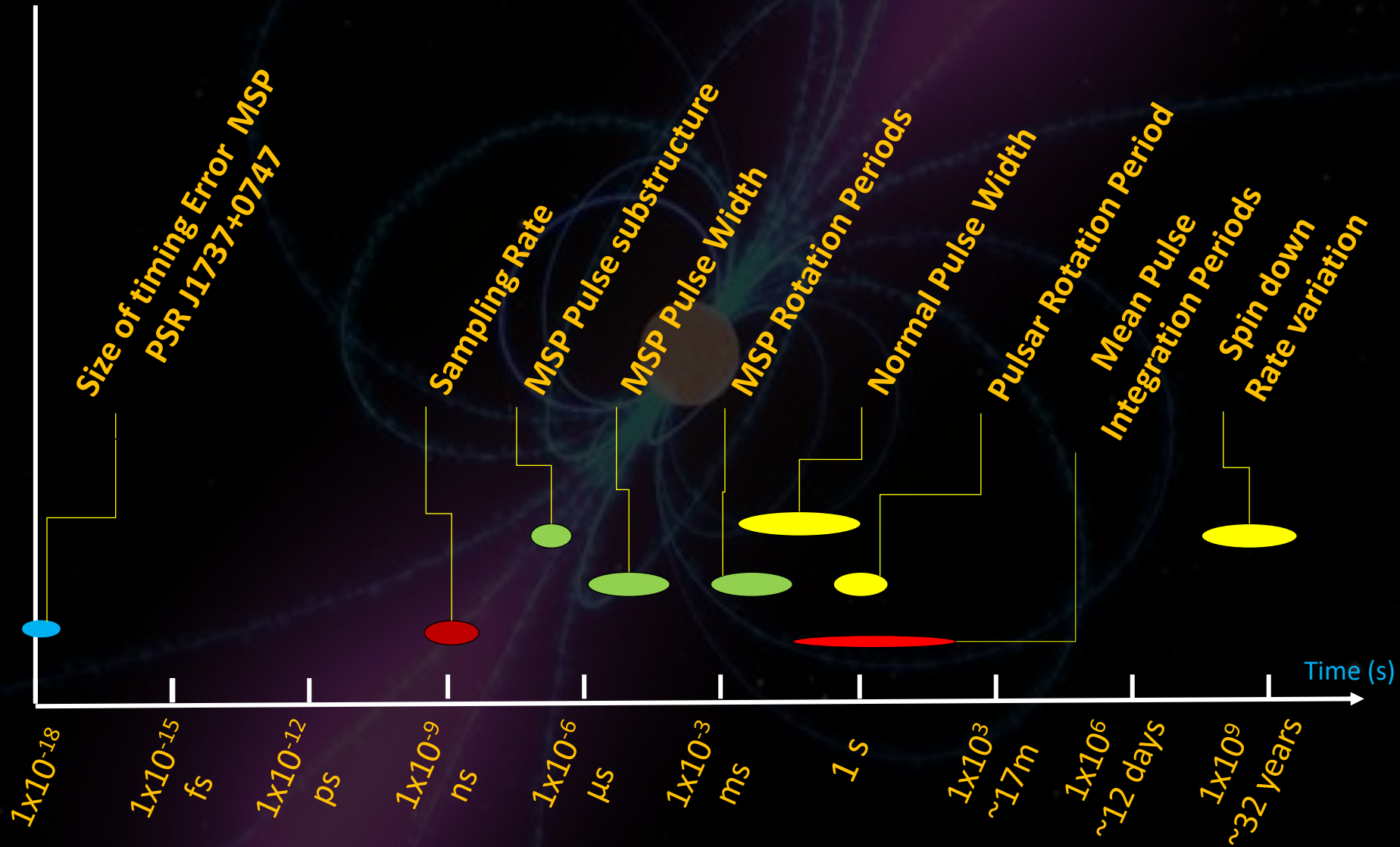
The glitch epoch is indicated by a red arrow.

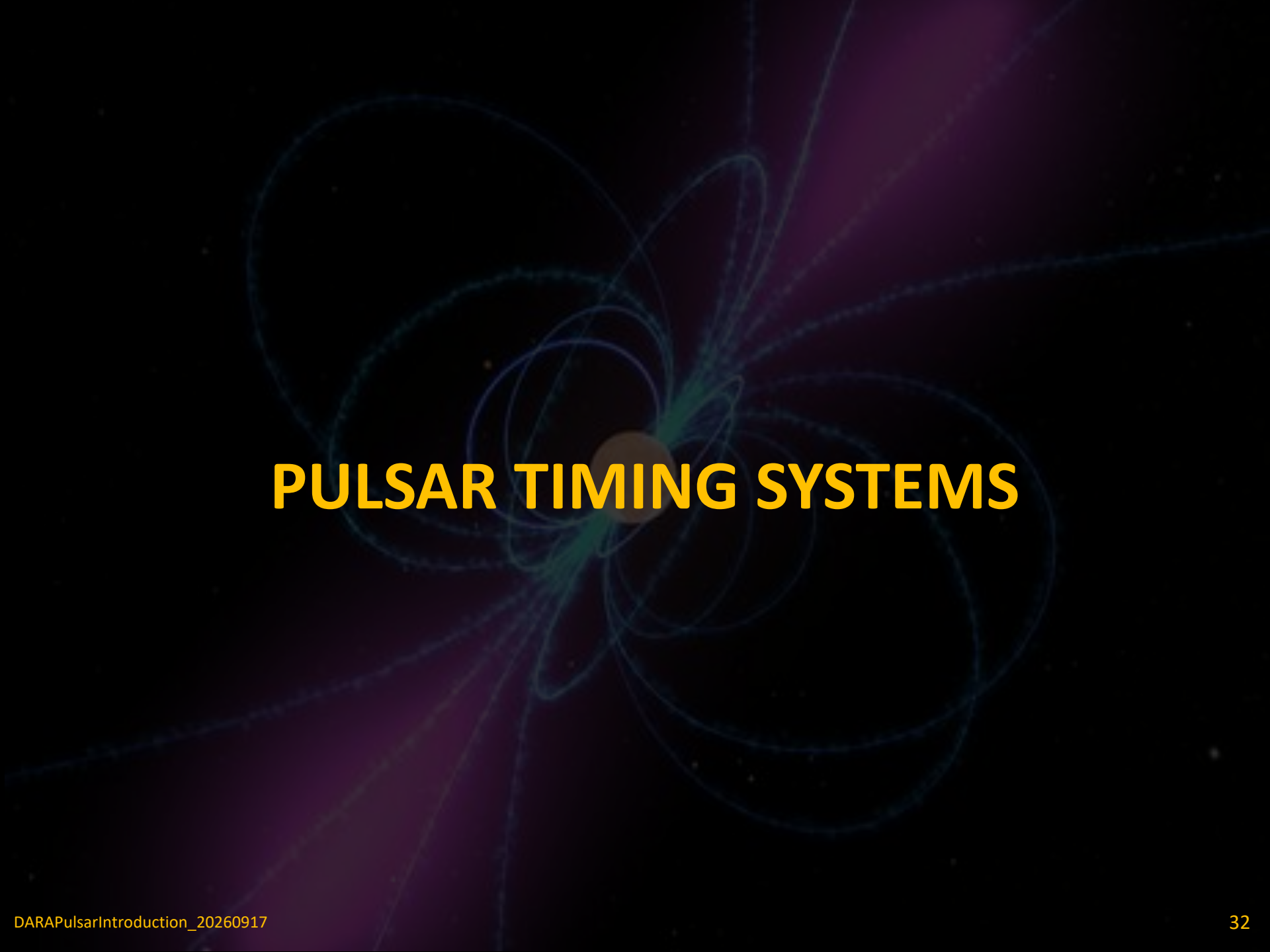
Changes over years

Changes in Pulsar Spin
down rates over ~ 30
years of observations at
Jodrell Bank



Timescales



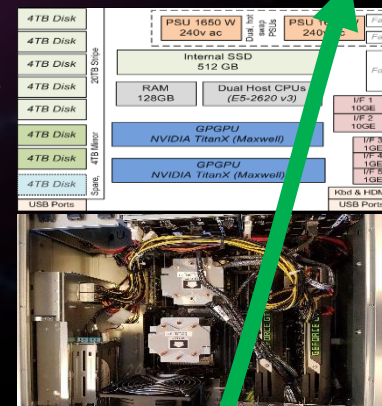


PULSAR TIMING SYSTEMS

Evolution of pulsar systems and compute power

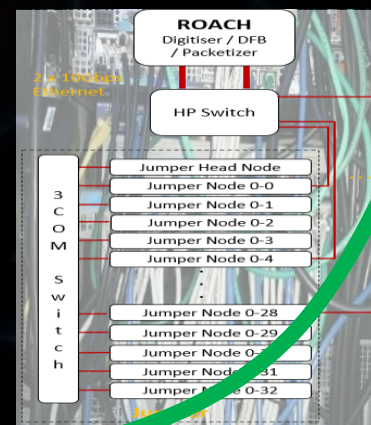
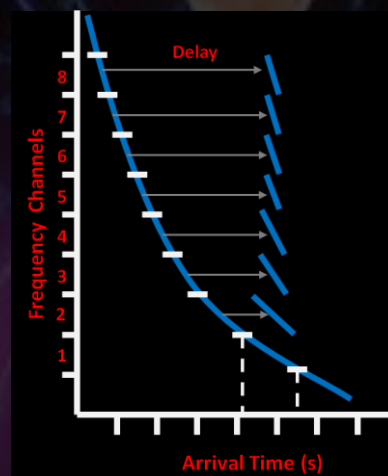
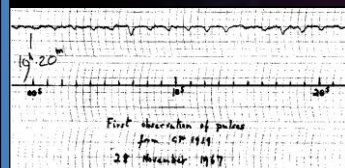
Processing Power

Next Generation – a Hybrid Cluster of dual CPUs & GPUs in a single 5U server (4.5 - 6 TFLOPS)



Analogue and Digital Filter banks

Chart Recorder



**Coherent
dedispersion on a
32 node Beowulf
Cluster in 2 racks
(~3 TFLOPS)**

1967

→ Years
2018

Analogue | Digital

Three New Pulsar Timing Systems

- **Ghana - Hebe**

- New PTS based on a Dual GPU Server
- Process 800MBytes per second in Real Time

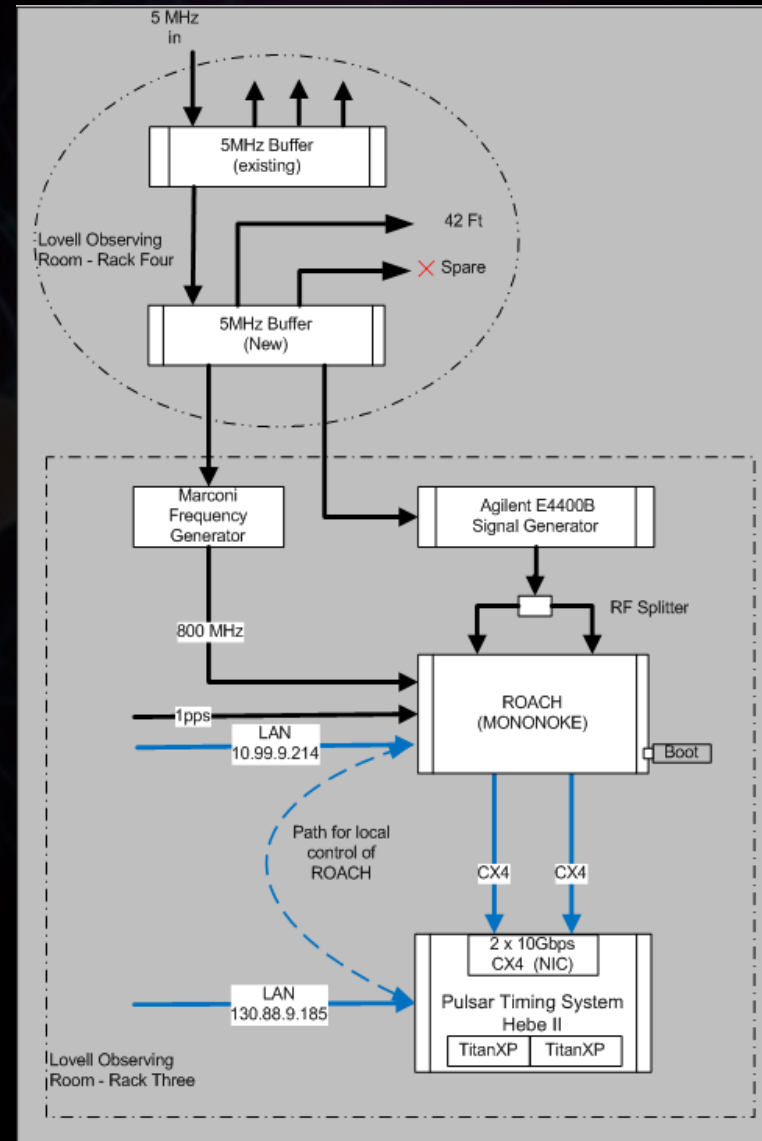
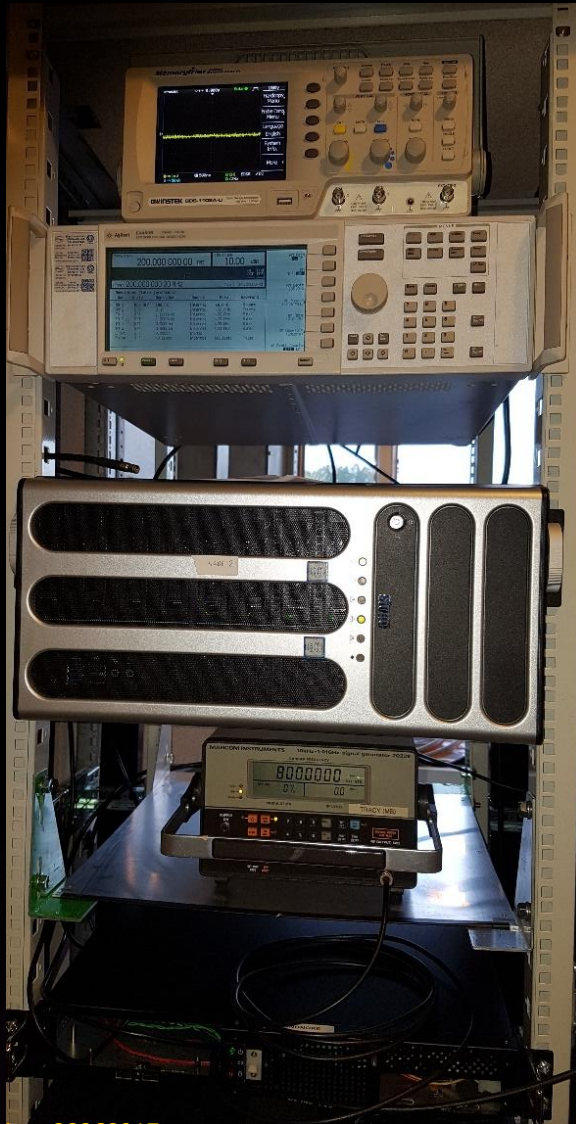
- **E-MERLIN**

- 5 x 25m + 1 x 32 m Dishes
- $\sim \frac{1}{2}$ the sensitivity of the Lovell
- Store and Process system on the three node LOFT-e cluster

- **Hebe 2**

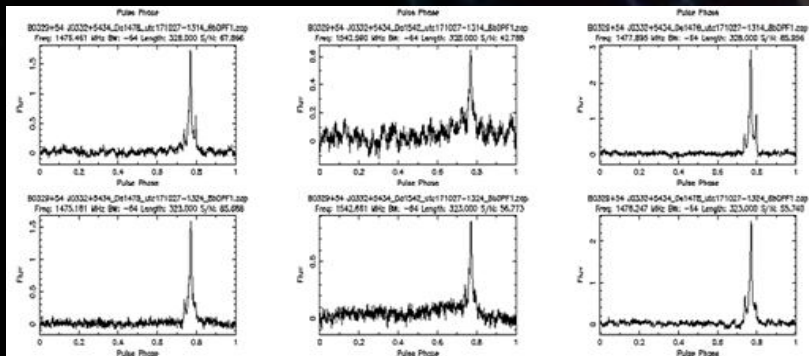
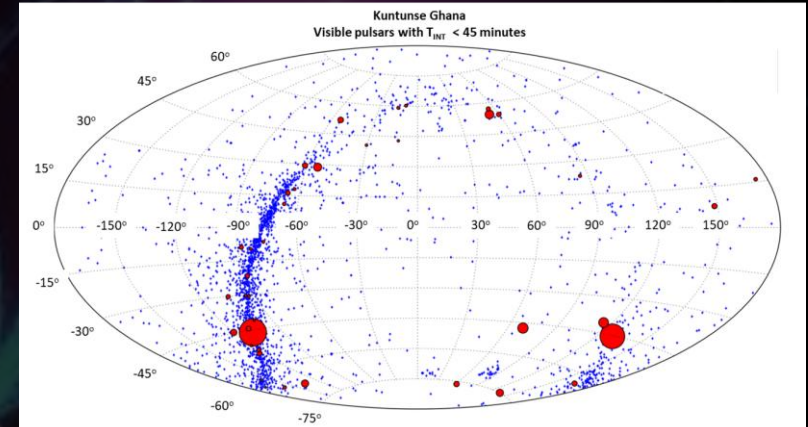
- Connect to the Lovell or Mark II
- Real Time Pulsar Processing

Hebe 2 at Jodrell Bank



Cool Science Stuff

- **Pulsars at 5 & 6.7 GHz**
 - < 50 Pulsar recorded at 5-7GHz
 - Emission mechanisms at these frequencies
 - Profile changes with frequency



- **Monitor pulsars with e-MERLIN**
 - Looking at faint Glitching pulsars
 - Combine 6 telescopes for sensitivity and RFI immunity
- **Change in Spin-down with emission mode**
 - Rotation powered pulsars slow down as they radiate energy
 - Measure the change in spin-down and correlate with pulse profile changes



WHAT CAN WE DO WITH PULSARS?

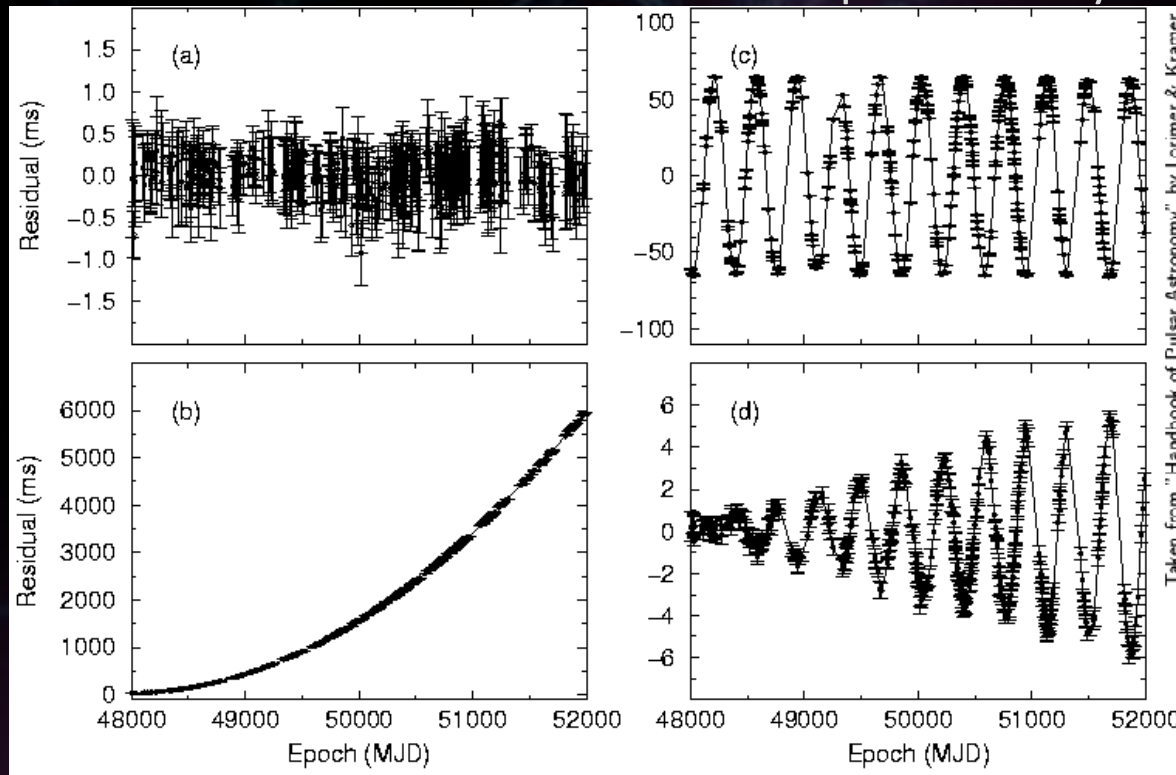
Residuals

Timing Residuals from PSR B1133+16

$$t_{\text{SSB}} = t_{\text{topo}} + t_{\text{corr}} + \Delta_{\text{R}_{\odot}} + \Delta_{\text{S}_{\odot}} + \Delta_{\text{E}_{\odot}}$$

a) Perfect fit – random distribution

c) Position error – sinusoidal error with a period of 1 year Romer delay

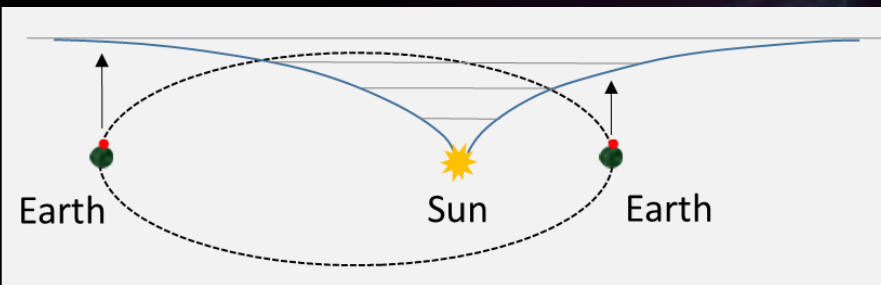
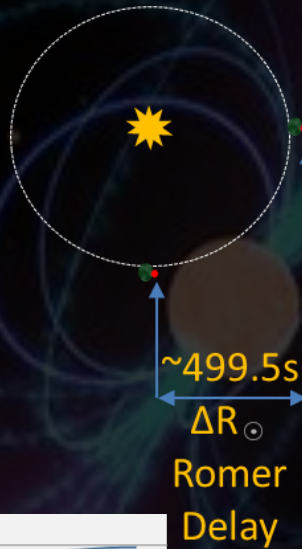
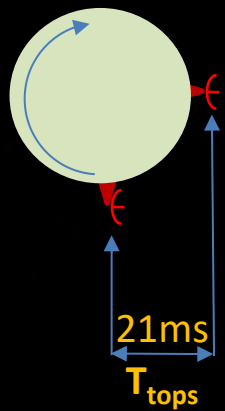


b) Parabolic increase - $\dot{P}$ underestimated
Timing model incorrect

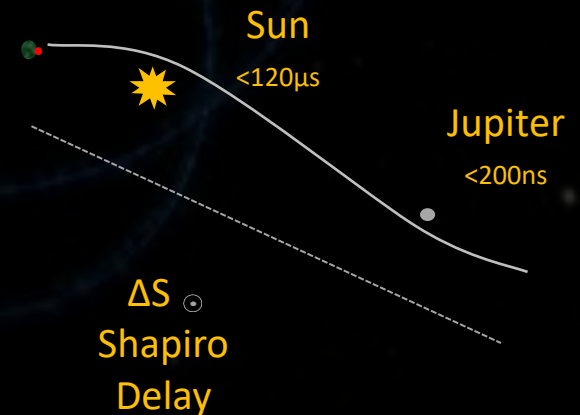
d) Position not corrected for proper motion – Romer delay error

Corrections to ToA

$$t_{\text{SSB}} = t_{\text{topo}} + t_{\text{corr}} + \Delta R_{\odot} + \Delta S_{\odot} + \Delta E_{\odot}$$



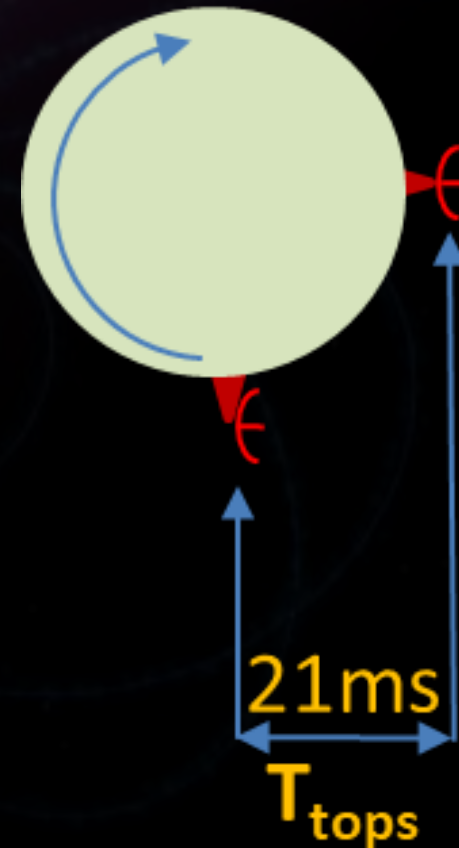
~1.6ms
 $\Delta E_{\odot}$ Einstein
Delay



Correction	Typical value/range
Observatory clock to TT	1 μs
Hydrostatic tropospheric delay	10 ns
Zenith wet delay	1.5 ns
IAU precession/nutation	~5 ns
Polar motion	60 ns
ΔUT1	1 μs
Einstein delay	1.6 ms
Roemer delay	500 s
Shapiro delay due to Sun	112 μs
Shapiro delay due to Venus	0.5 ns
Shapiro delay due to Jupiter	180 ns
Shapiro delay due to Saturn	58 ns
Shapiro delay due to Uranus	10 ns
Shapiro delay due to Neptune	12 ns
Second-order Solar Shapiro delay	9 ns
Interplanetary medium dispersion delay	100 ns ^b
ISM dispersion delay	~1 s ^b

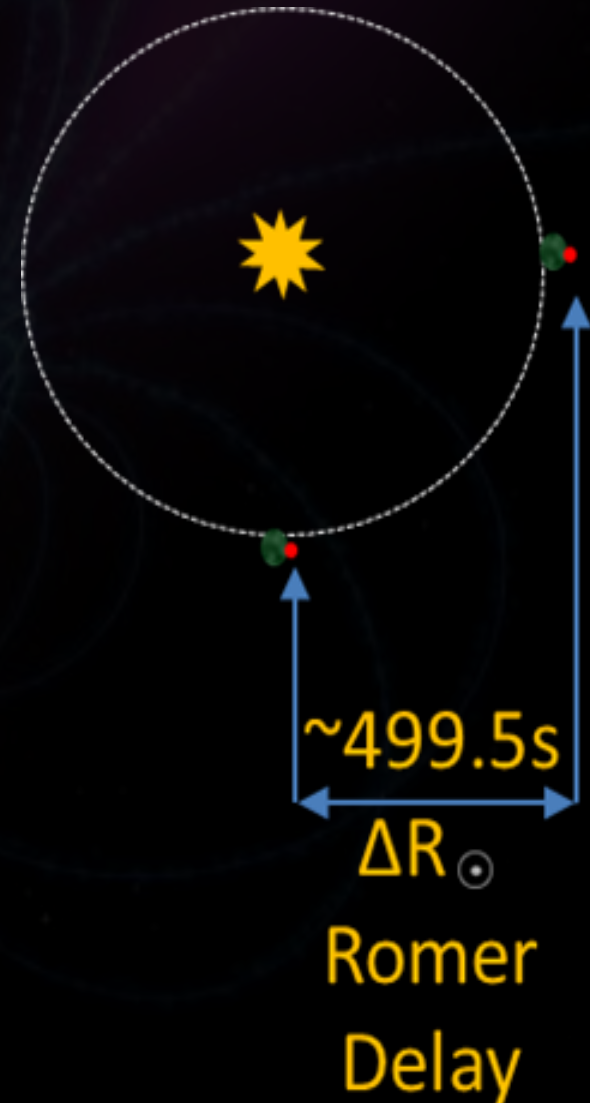
Geometry -1

- Earth's Rotation
- Determine size of the Earth by changes in the pulse delay
- Determine the position of telescopes with pulsars to within
 - ~300m if pulsar error is 1 in 10^6
 - ~0.3m if pulsar error is 1 in 10^9
 - ~0.3mm if pulsar error is 1 in 10^{12}



Geometry -2

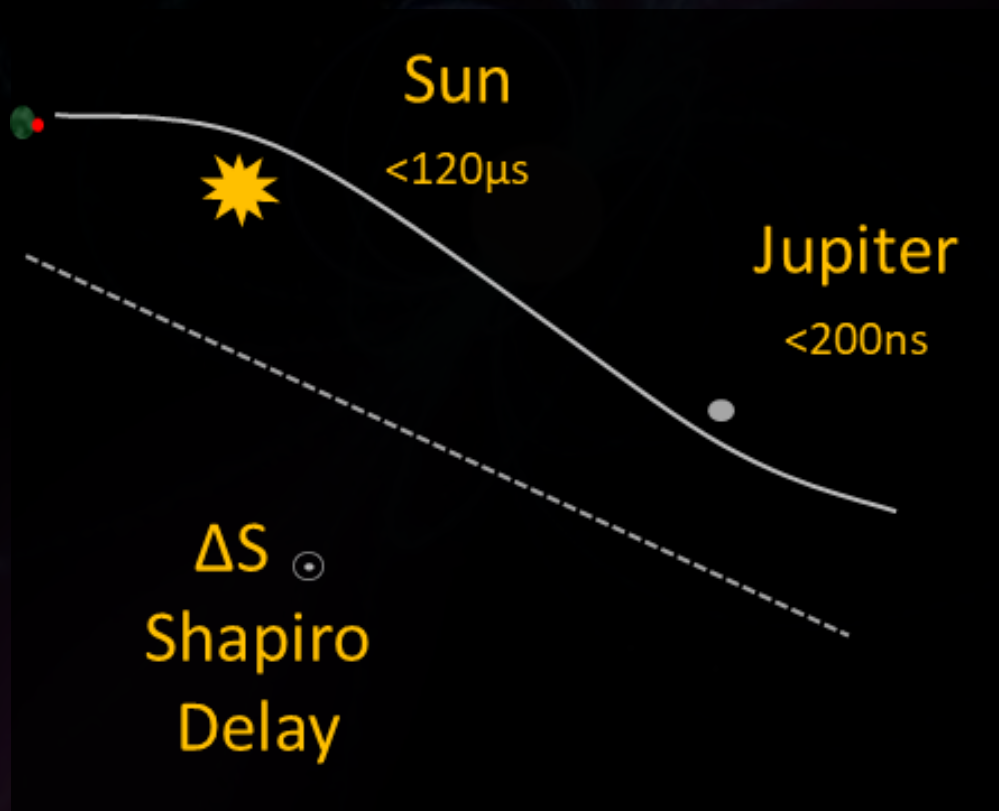
- Earth's Orbit
- Determine size and shape of the Earth's orbit by changes in the pulse delay
- Determine the relative change in position of telescopes to within
 - ~300m if pulsar error is 1 in 10^6
 - ~0.3m if pulsar error is 1 in 10^9
 - ~0.3mm if pulsar error is 1 in 10^{12}



Geometry -3

Bending of light by mass

- **Determine the mass of bodies in the solar system**
 - By the delay caused by distortions in the signal path

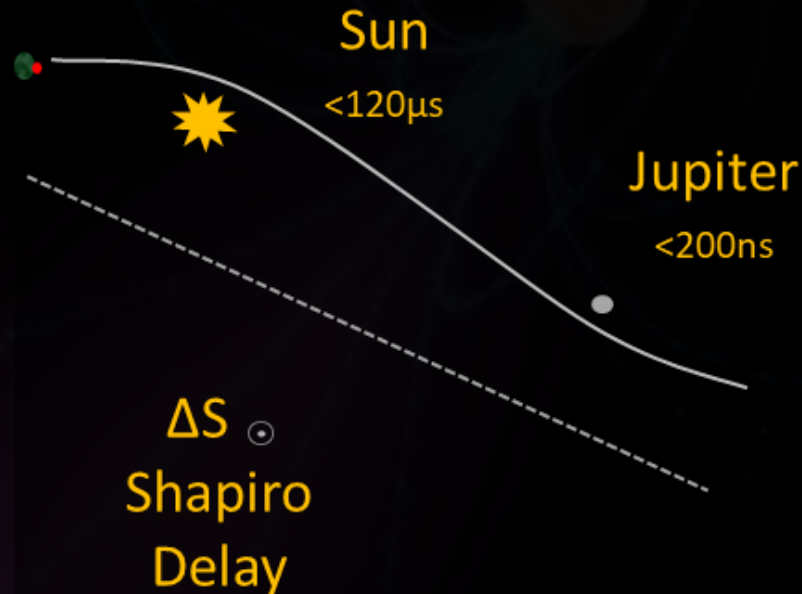


Geometry -4

Bending of light by mass

If we know the delay we can work out the mass of:

- Jovian system $9.5479189(3) \times 10^{-6} M_{\odot}$
- Ceres $4.7(4) \times 10^{-10} M_{\odot}$
- Vesta $1.3026846(9) \times 10^{-10} M_{\odot}$
- Six pulsars used with a typical timing error of $0.2 < t < 2 \mu\text{seconds}$

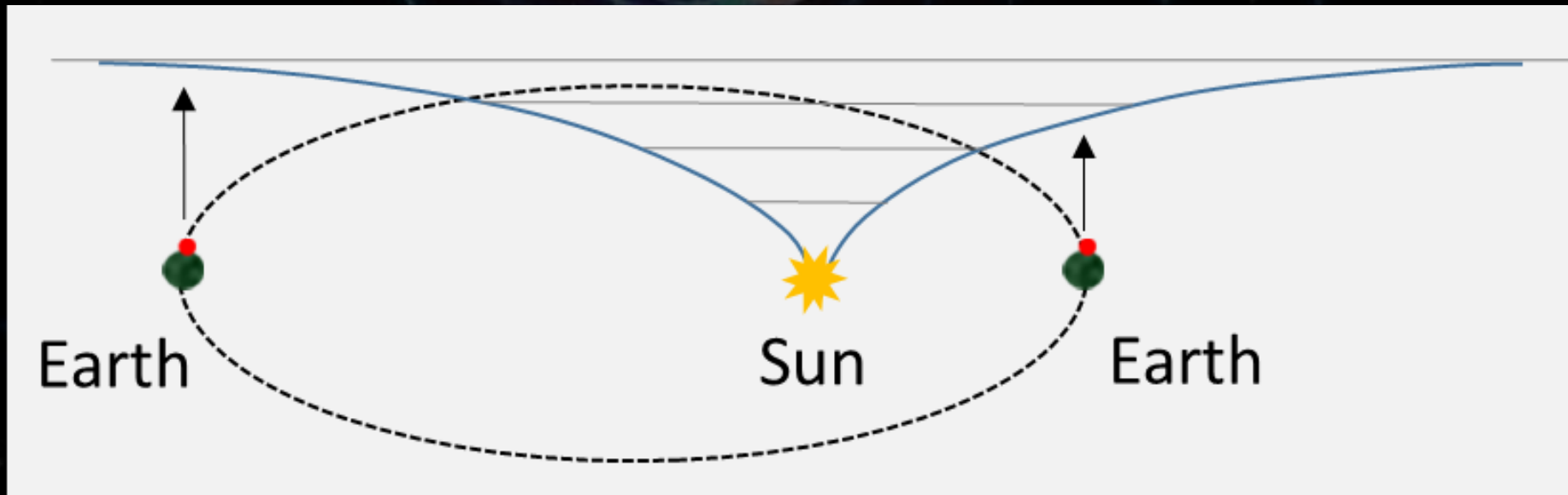


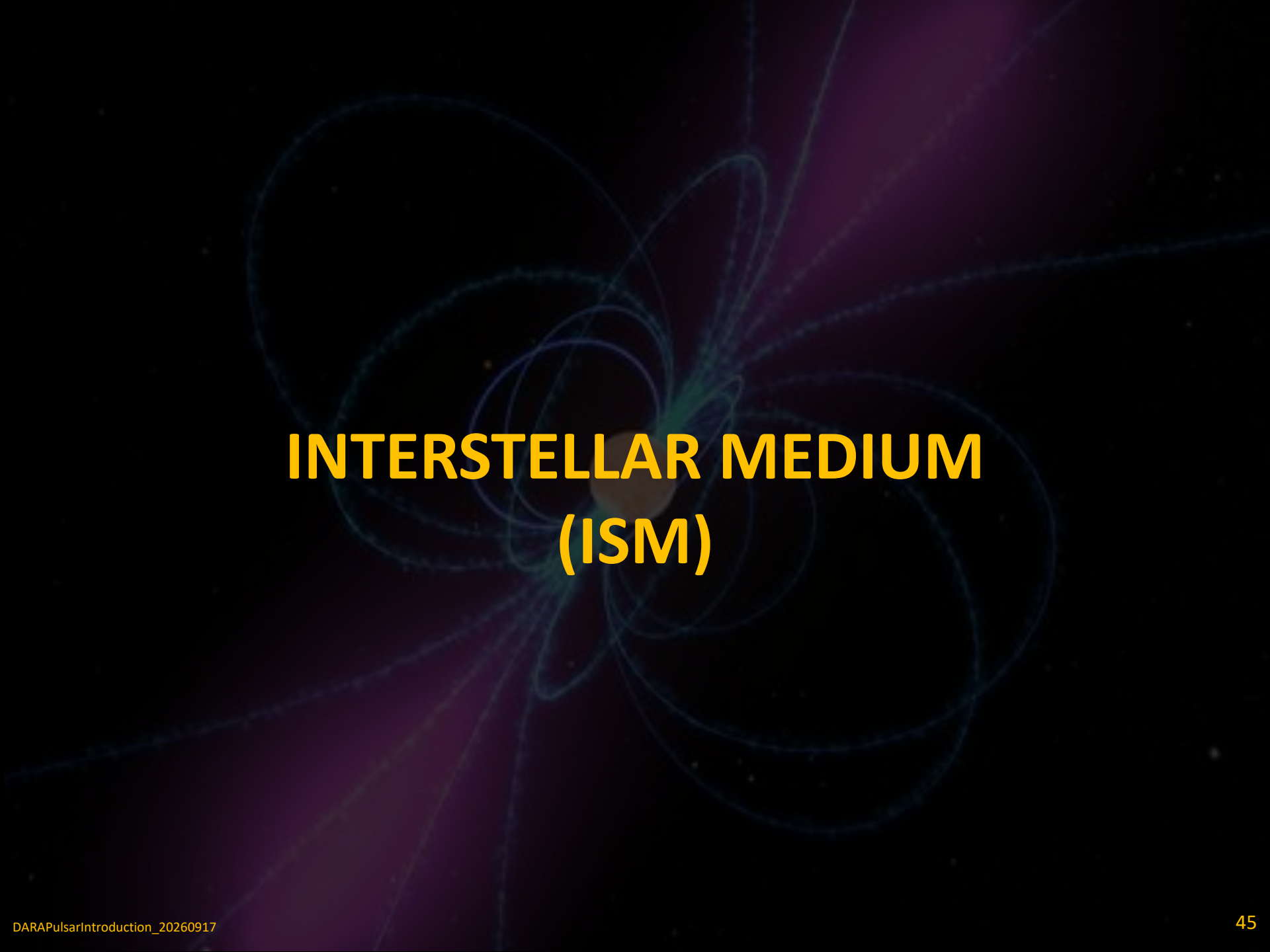
R.N.Caballero et. al 2018

Relativity

- **Delay Caused by**

- Earth based clocks run slower in a more intense gravitational field
- Time-dilation
- ~ 1.6 ms





INTERSTELLAR MEDIUM (ISM)

ISM - Dispersion

- **The ISM delays the radio signal as it passes through.**
 - Higher frequencies are delayed less than lower frequencies
 - We can analyse this to give an idea of the average electron density along our line of sight to the pulsar
 - Hence the presence of dust and gas

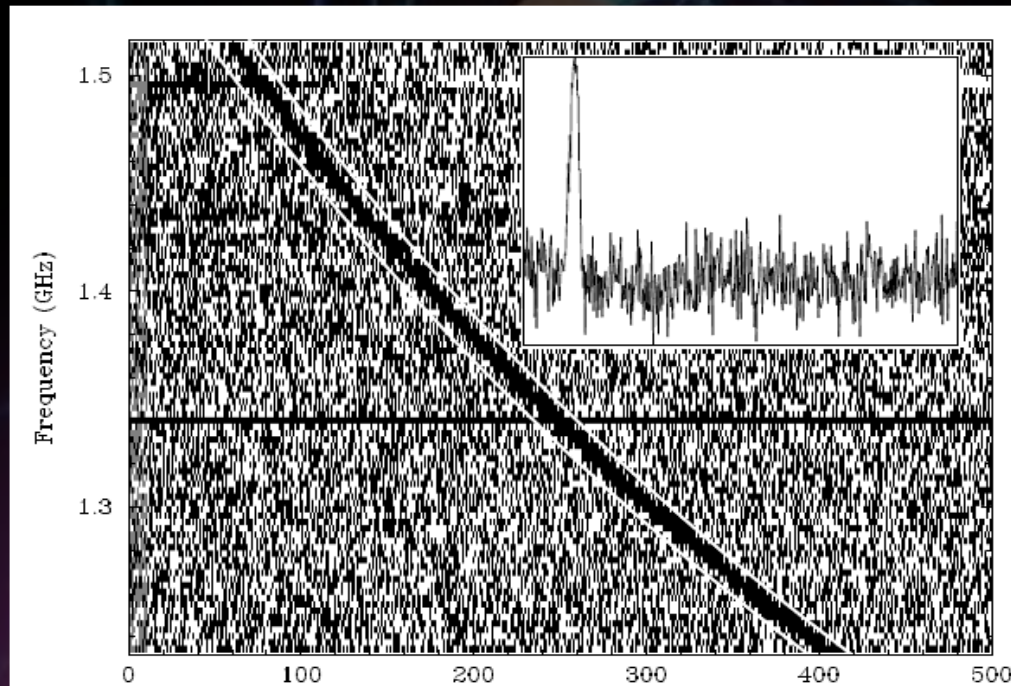
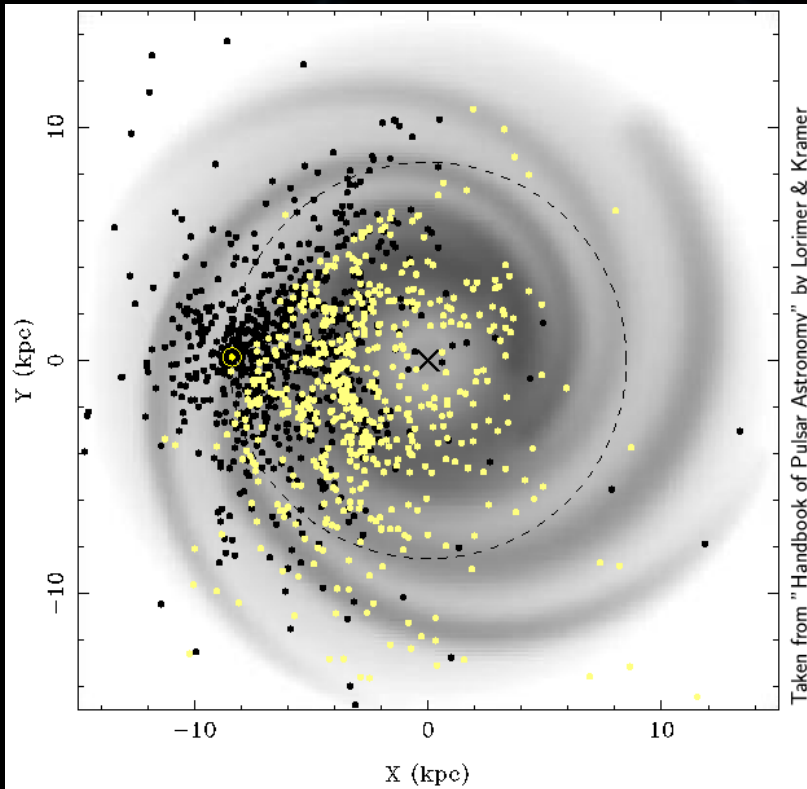


Image Credit: Handbook of
Pulsar Astronomy
Lorimer & Kramer

ISM Electron density distribution models

NE2001 Cordes and Lazio (2002a)



- Pulsars detected at ~430 MHz are black dots, at ~1.4 GHz yellow dots
- Darker grey corresponds to higher electron number density

YMW16 (2016)

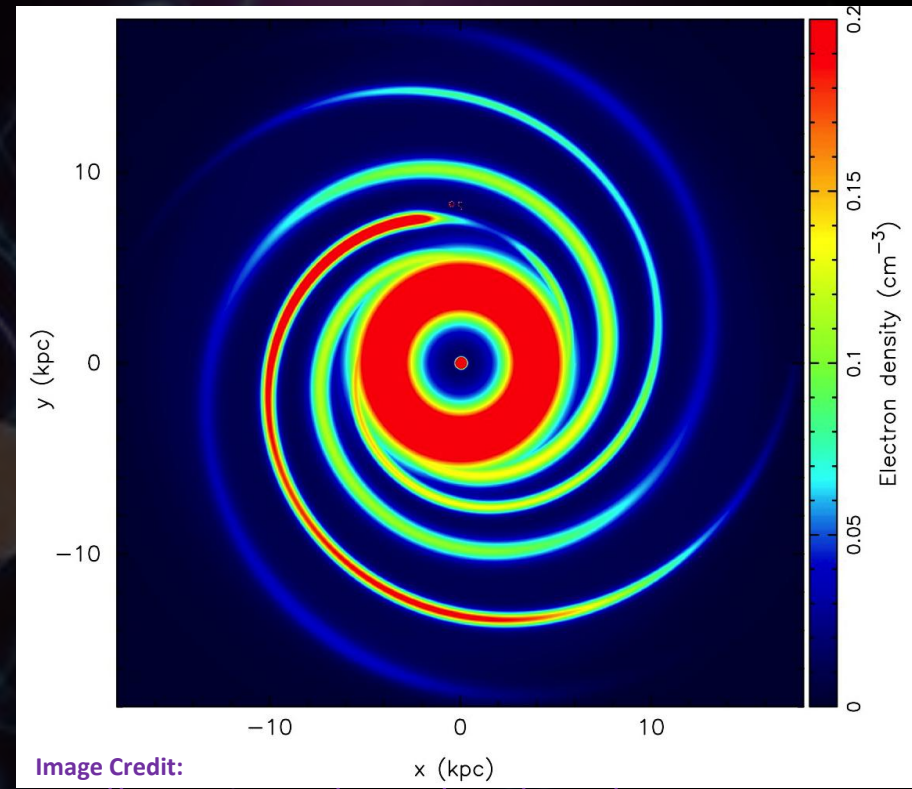


Image Credit:

<https://www.atnf.csiro.au/research/pulsar/ymw16/>

- YMW16, Yao, Manchester and Wang Astrophysical Journal, vol. 835, eid 29 (2017) (via [arXiv](#) (1610.09448v2)).
- YMW16 is the first electron-density model to estimate extragalactic pulsar and FRB distances.



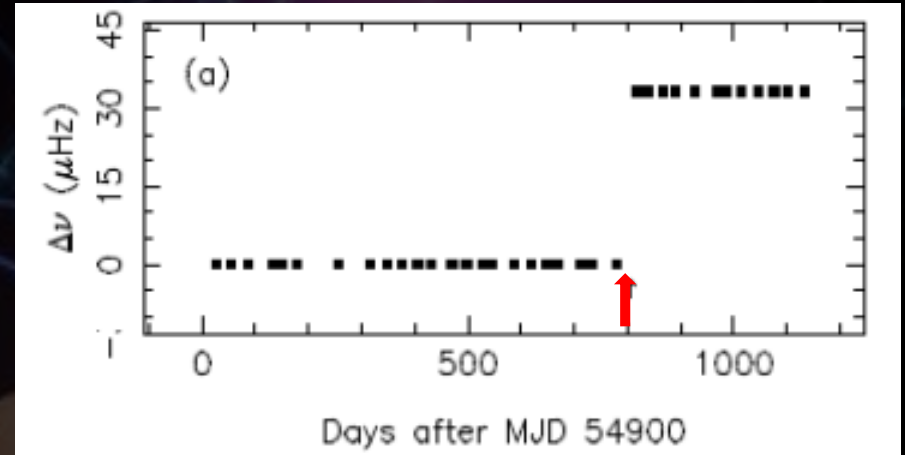
NEUTRON STAR BEHAVIOUR

Glitches

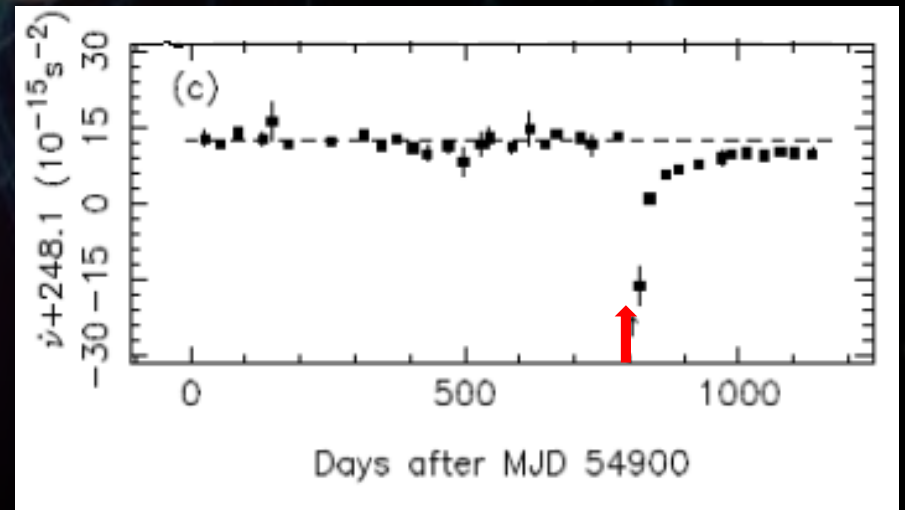
- **A glitch is a sudden step change in spin frequency**
 - The pulsar spins faster
 - The slow down rate ($\dot{P}$) increases and then decays back towards it's original value.
- **Glitch in PSRJ1757-2421**
 - at $\sim$ MJD 55700 (May 16 – 27 2011)
 - Fractional increase of $\Delta\nu_g / \nu \sim 7.8 \times 10^{-6}$
 - $\nu = 4.271\,592\,656\,55(4) \text{ Hz}$
 - $\Delta\nu_g = 4.271\,573\,098\,0(8) \text{ Hz}$

Glitch in PSR J1757-2421

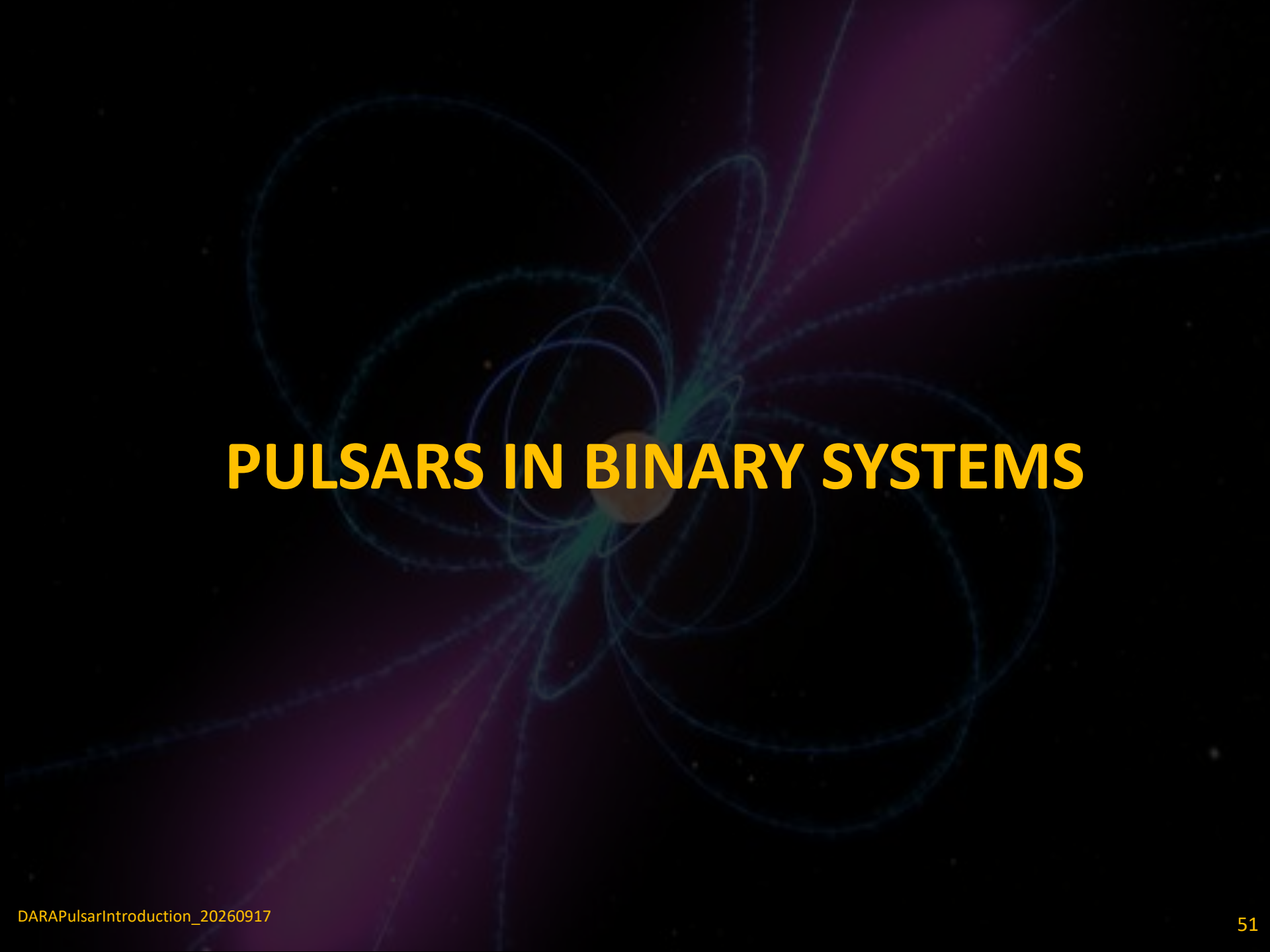
The top panel shows the spin-frequency residuals relative to the pre-glitch Spindown solution;



The bottom panel shows the variations of $\dot{P}$, and the horizontal dashes indicate the average pre-glitch level.



The glitch epoch is indicated by a red arrow.



PULSARS IN BINARY SYSTEMS

Black Widows and Redbacks

- **Spiders**

- Fast millisecond pulsars ($\leq 5\text{ms}$)
- Short, circular orbits (75m – 15 hours)
- Large spin-down luminosity ($\dot{E} 10^{34} \text{ Ergs/s}$)
- Radio Eclipses (0-70% of the orbit)
- Optical flux and/or colour modulation

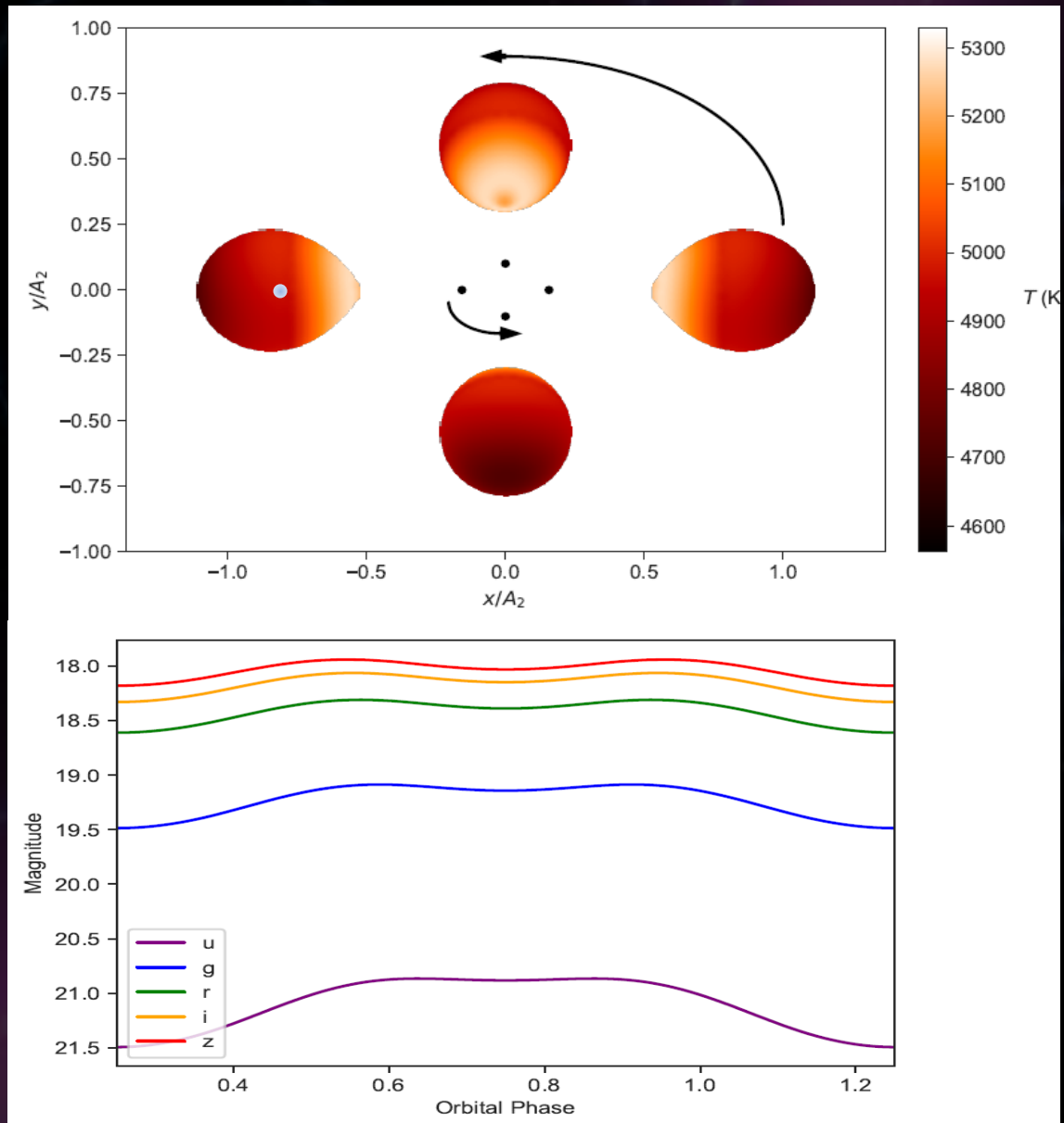
- **Black Widows**

- First PSR B1957+20 (1988)
- Very low companion mass ($\sim 0.02 M_{\odot}$)
- ~ 25

- **Redbacks**

- First PSR J1023+0038 (2009)
- Low Companion Mass ($\sim 0.2 M_{\odot}$)
- Some show state transitions 'MSP $\leftrightarrow$ LMXB'
- ~ 25

Redback



Redback Binary Systems

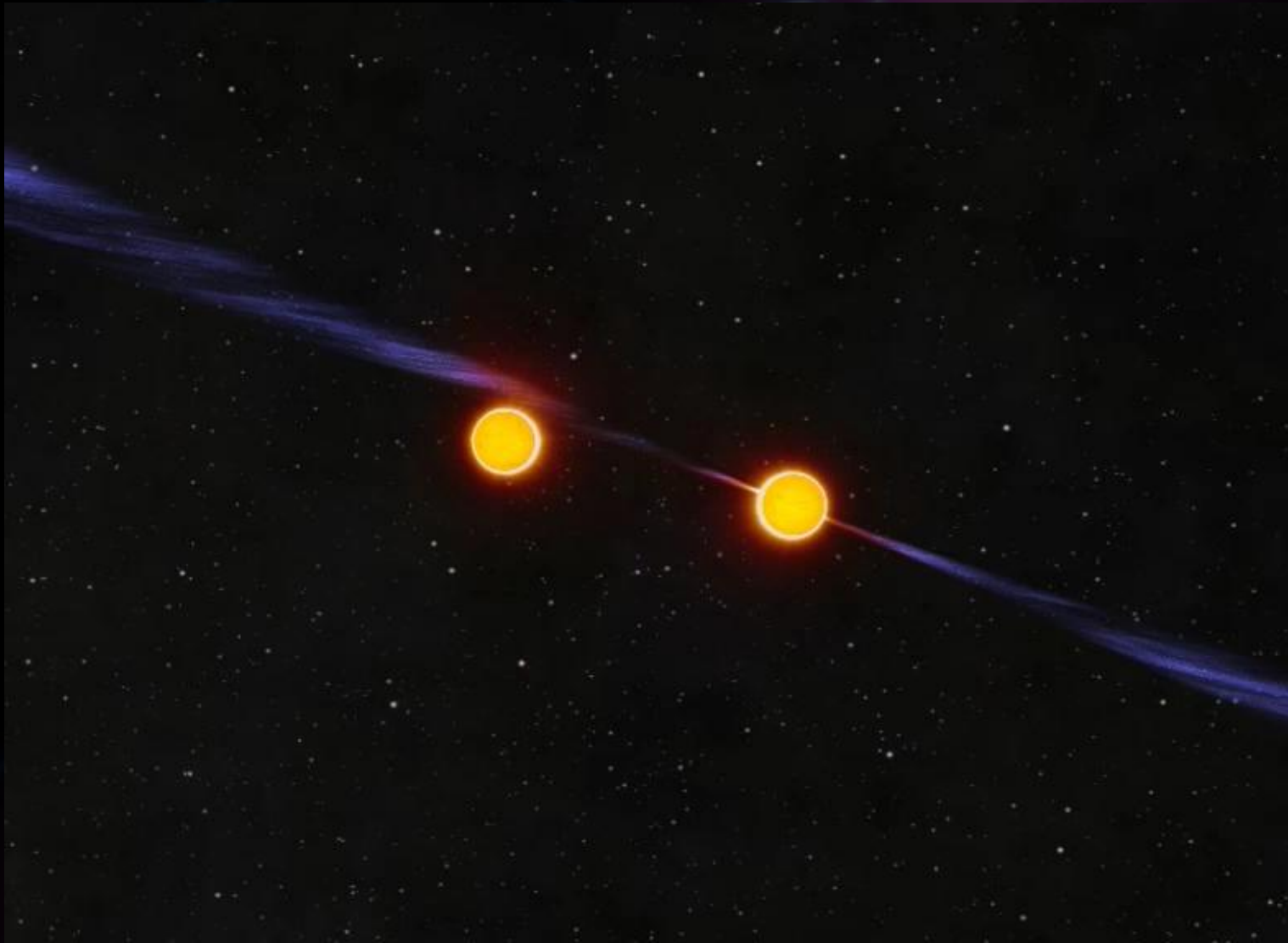


Image credit:
ASTRON

Black Widow Pulsar

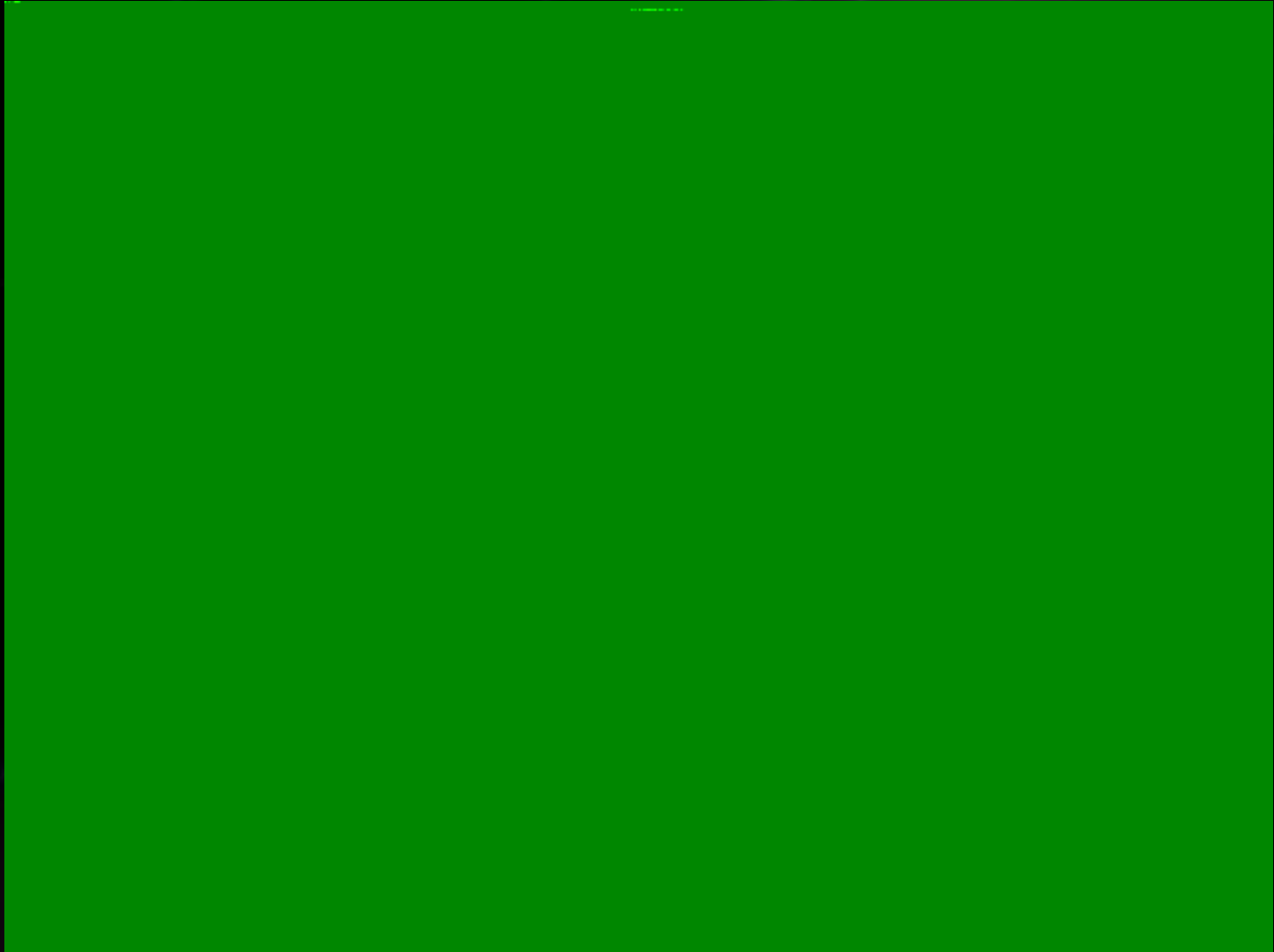


Image credit:
NASA

Reference Books

CAMBRIDGE OBSERVING HANDBOOKS FOR RESEARCH ASTRONOMERS

4

Handbook of Pulsar Astronomy

Duncan Lorimer and Michael Kramer



CAMBRIDGE ASTROPHYSICS SERIES

57

Andrew Lyne, Francis Graham-Smith
and Benjamin Stappers

Pulsar Astronomy

Fifth Edition

Thank you

www.Jodcast.net



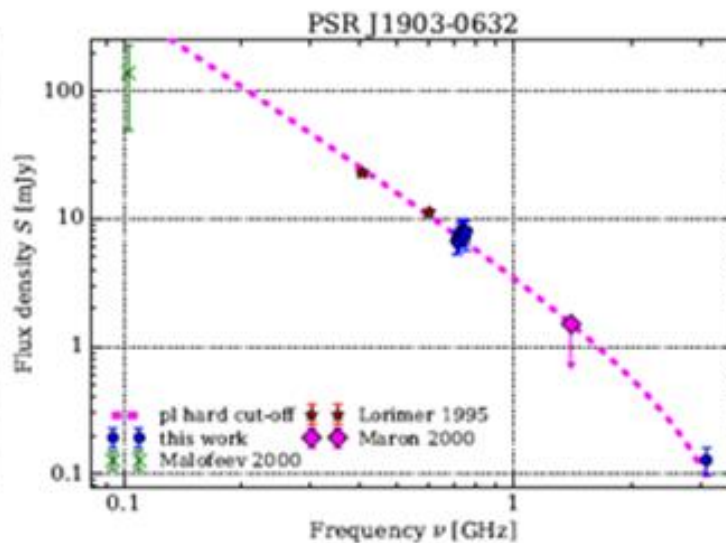
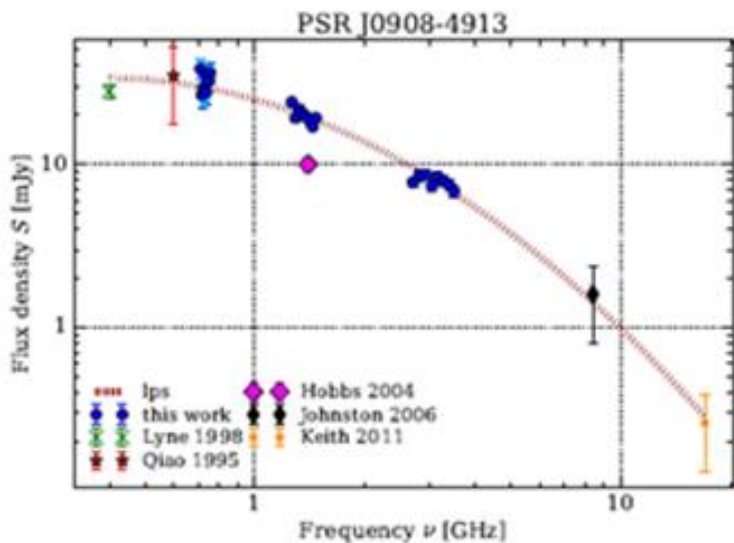
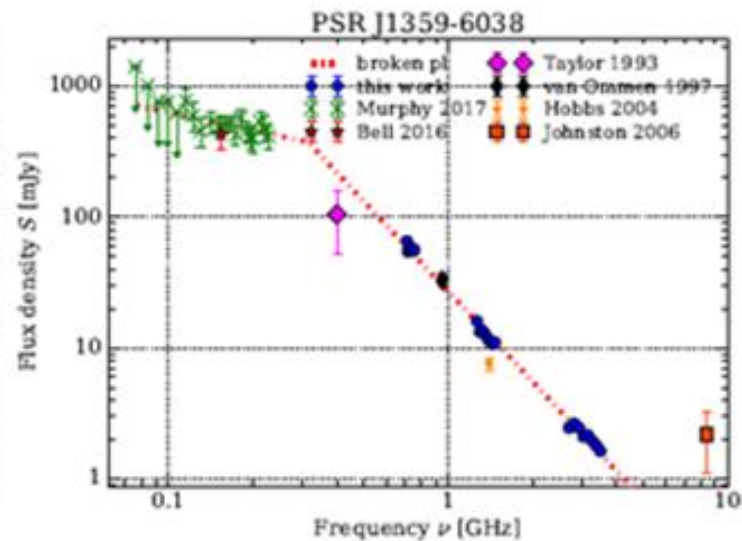
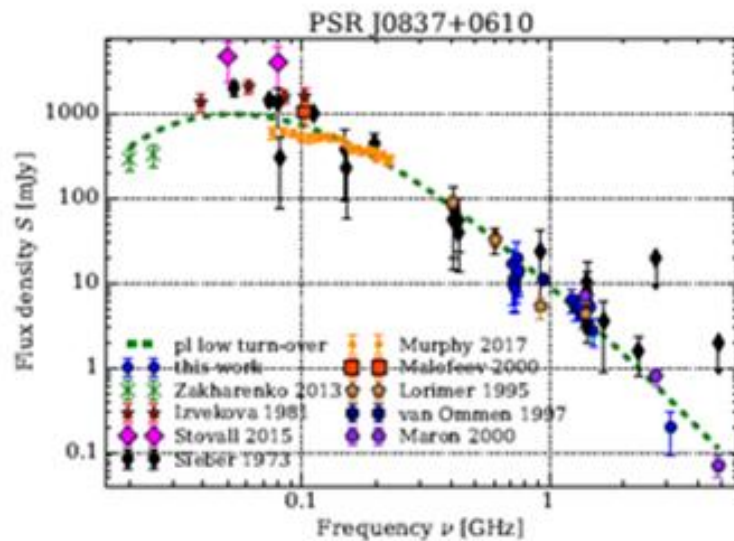
<http://www.jodrellbank.manchester.ac.uk/>

JBCA Notes

- **Slowest Pulsar, J2252-37, 12.1 seconds (Vincent)**
- **New slowest pulsar J0250+5854, 22.5 Seconds (Chia Min)**
- **Studying the Solar System with the International Pulsar Timing Array. October 2018 (Caballeros et.al 2018)**

Spectra

Typical spectra selected from a compilation by Jankowski *et al* 2018 *MNRAS* 473, 4436



Pulsar Timing Software

- Observing software is typically specific to the data-taking system, many recent systems employ either the **dspsr** software package or a system based on the **casper** platform
 - (van Straten and Bailes, 2011) / (DuPlain et al., 2008).
- The observational data are most commonly stored in the **psrfits** format
 - (Hotan et al., 2004)
- Initial data reduction is typically carried out with the **psrchive** package
 - (van Straten et al., 2012)..
- For the analysis of the ToAs and the optimization of the timing models, the **tempo2** package is most commonly used outside North America
 - (Hobbs et al., 2006),
- The NANOGrav collaboration uses **tempo2** and the independent, python-based **pint** package in order to support independent verification of the timing results.
 - (Luo et al., 2021),
- The mathematical basis of the timing-model fit is fundamentally the same
 - (Edwards et al. (2006).

A new pulsar timing system (PTS) for the GRAO

- **Ghana Radio Astronomy Observatory**
 - Converted telecommunication dish
 - Located 5° north of equator (just northwest of Accra)
- **32m main dish**
 - Ambient temperature receiver
 - 150MHz @ 5GHz
 - 300MHz @ 6.7GHz
 - Three other dishes on site
- **Initial Science**
 - Methanol Masers at 6.7GHz
 - Pulsar Observations and Timing
 - VLBI Imaging
- **Pulsar Timing System**
 - Hybrid CPU and GPU cluster
 - Low cost COTS hardware



GRAO Pulsar Science

A number of pulsar science goals can be suggested.

- **Very few pulsars have been observed in the 5–7GHz band and GRAO could be used to study the pulse profile and spectra of known pulsars.**
 - Study the evolution and variability of pulse profiles
 - Spectral index at different frequencies.
- **With repetitive scans GRAO may also be used to find new intermittent pulsars missed by other search programmes.**
- **Long term pulsar timing at C & L band**
- **Pulsar Census / Survey**

Pulsar census / survey at 5GHz and 6.7GHz

