Pulsars – An Introduction

Tom Scragg

13/11/2024

DARA / HartRAO

Image credit: NASA

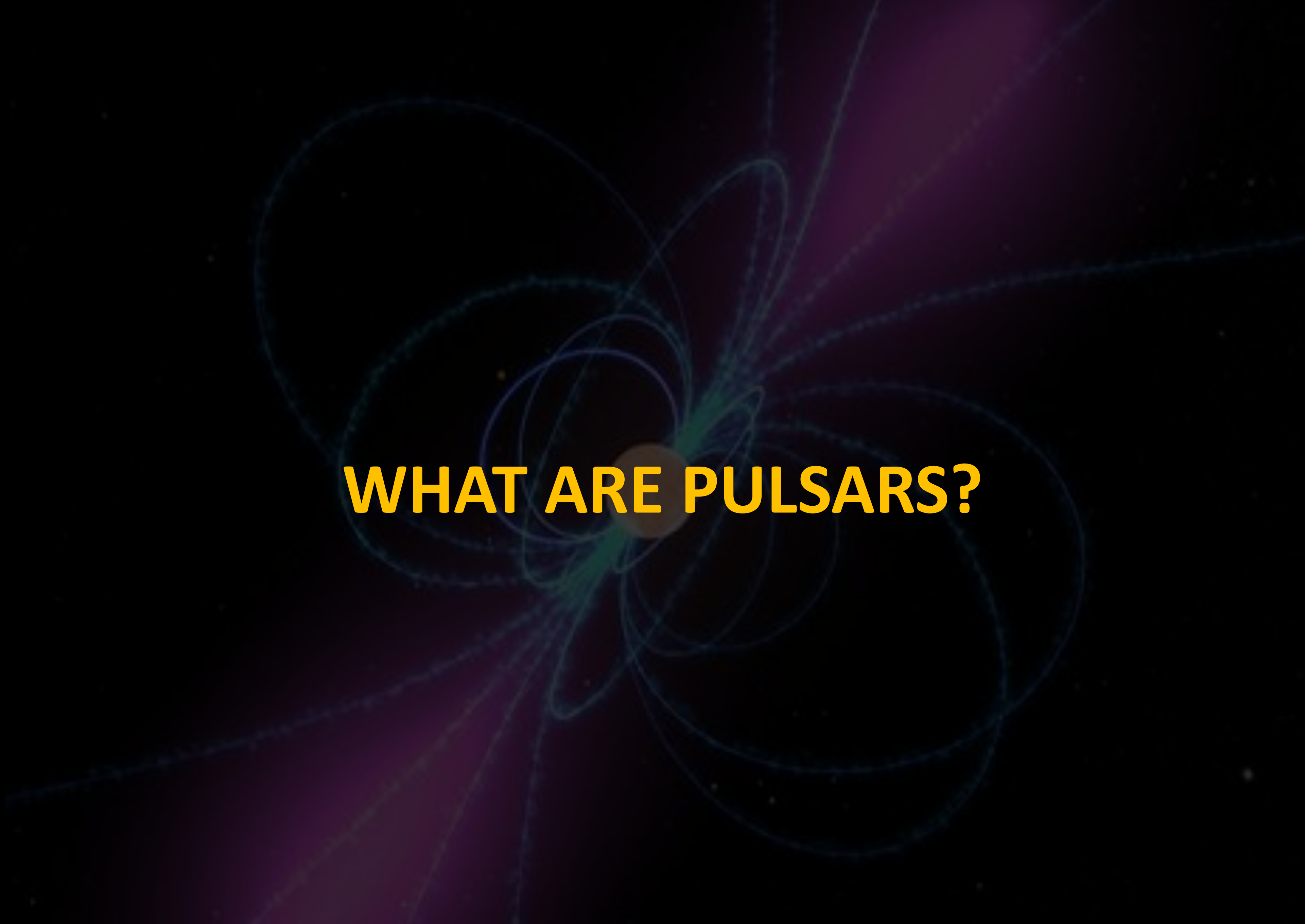
Dr Tom Scragg

- **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 (~ 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.



WHAT ARE PULSARS?

What are pulsars?

- **They are <u>not</u> 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

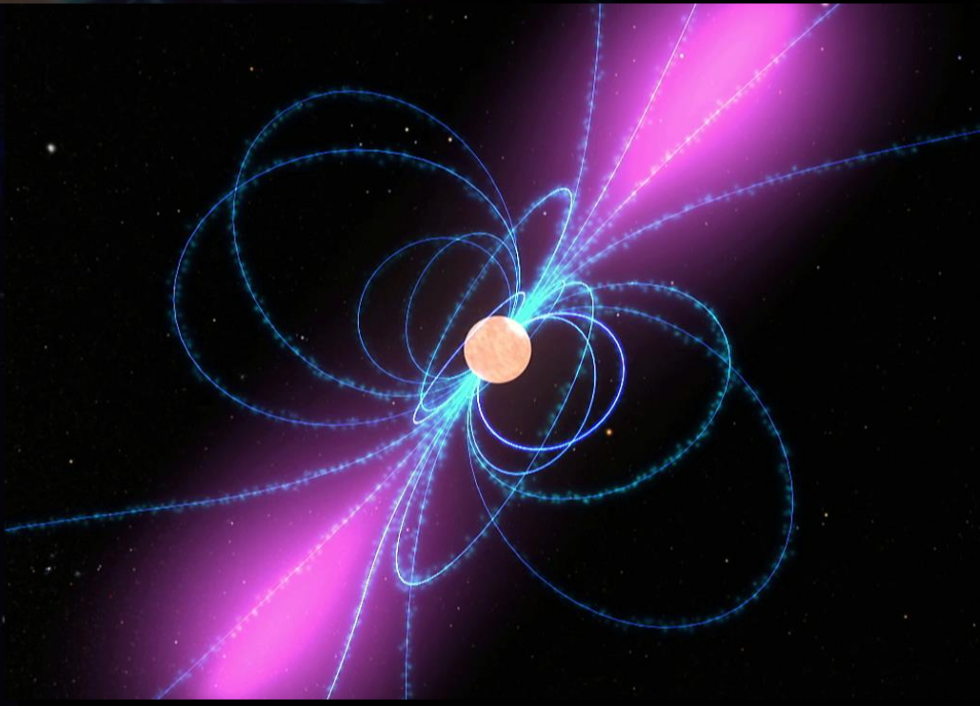
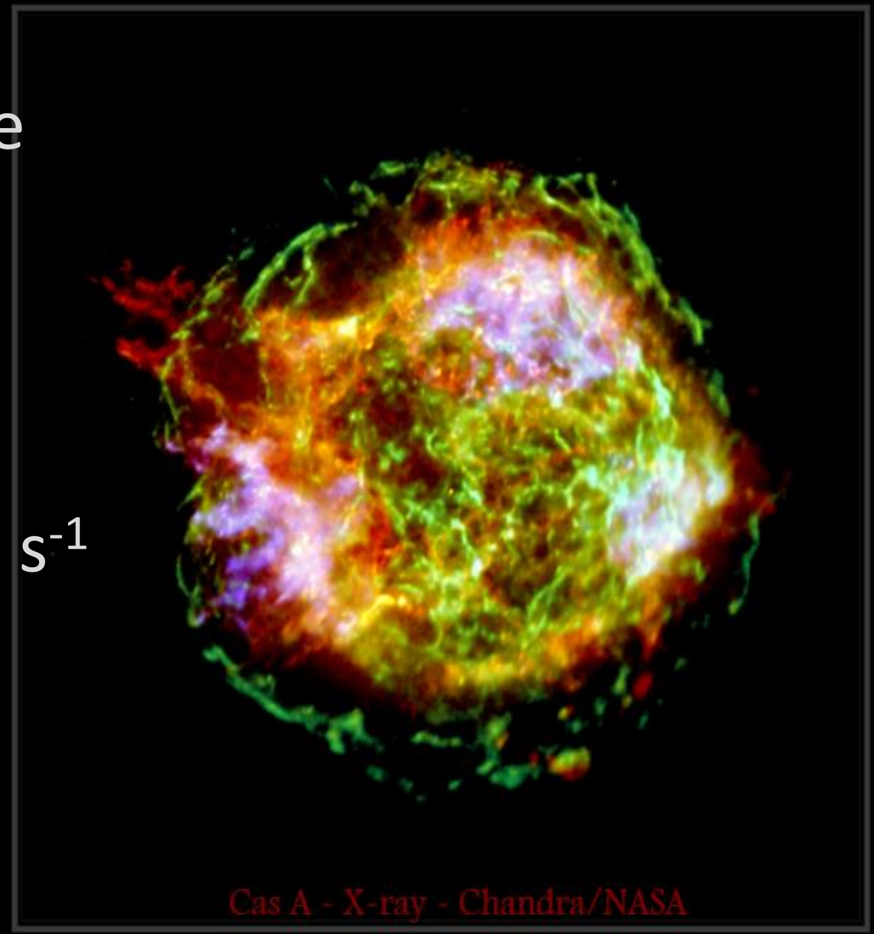


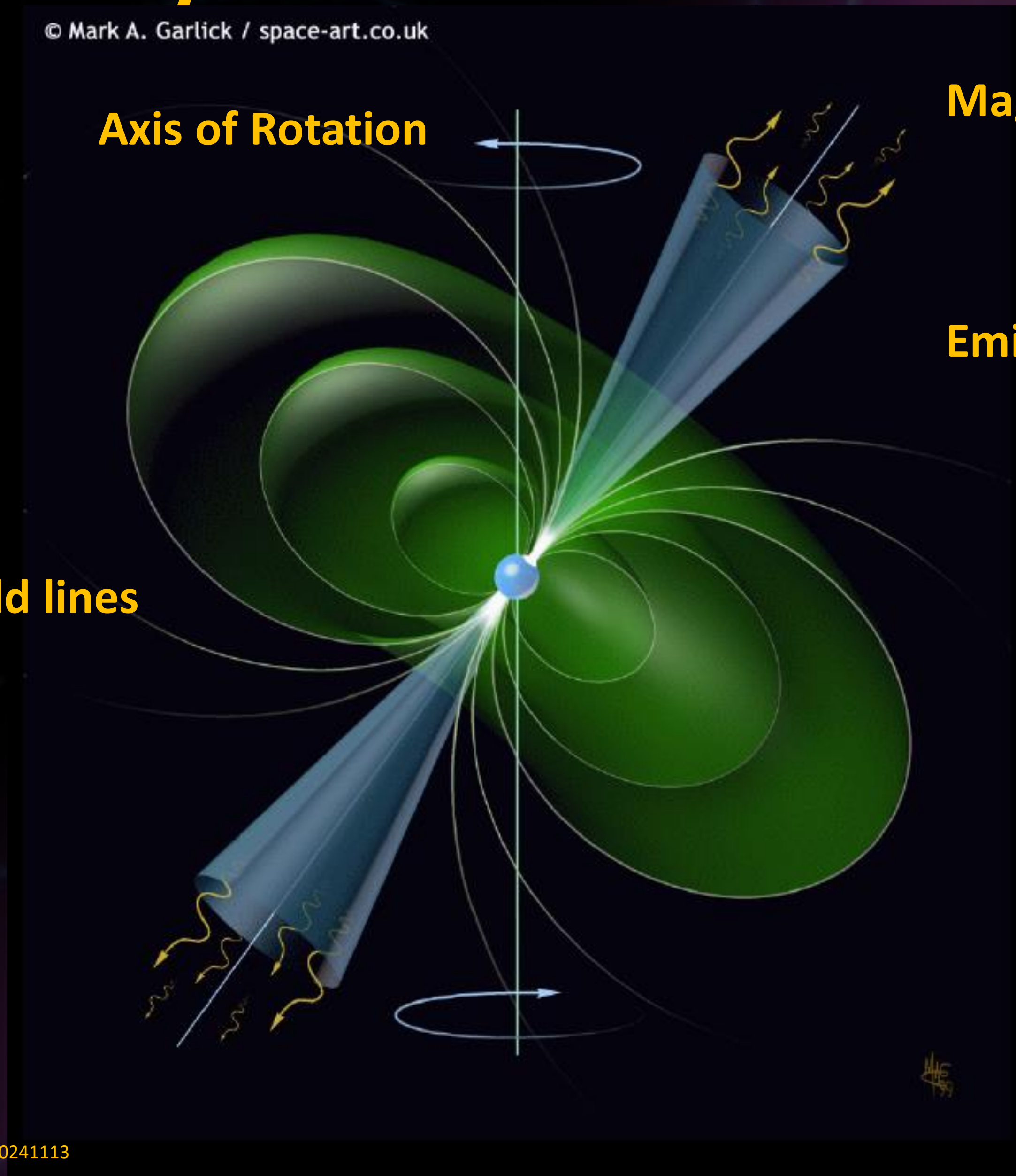
Image Credit: NASA/GSFC

Pulsars

- Remnants of SuperNova - SNe
- Rotating Neutron Stars
- **M** ~ 1.4 $M_\odot$, **R** ≈ 10km
- **P**eriod = 0.0013 to 8.5 s
- Spin down $\dot{P}$ ~ 10^{-10} to 10^{-20} s s^{-1}
- **B** High Surface magnetic field
  - ~ 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



Pulsar ‘Toy’ Model



Lighthouse ‘Toy’ Model

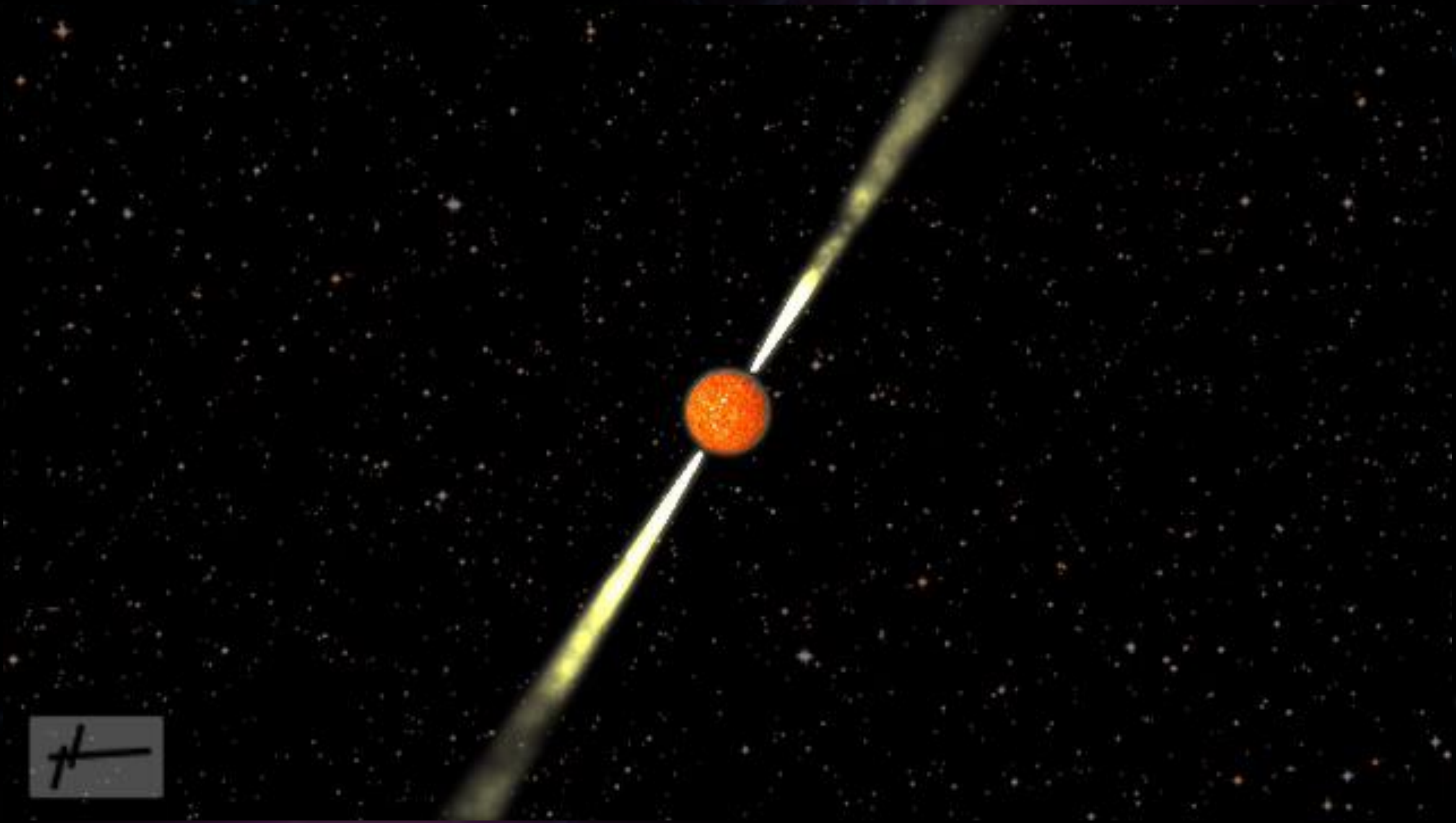
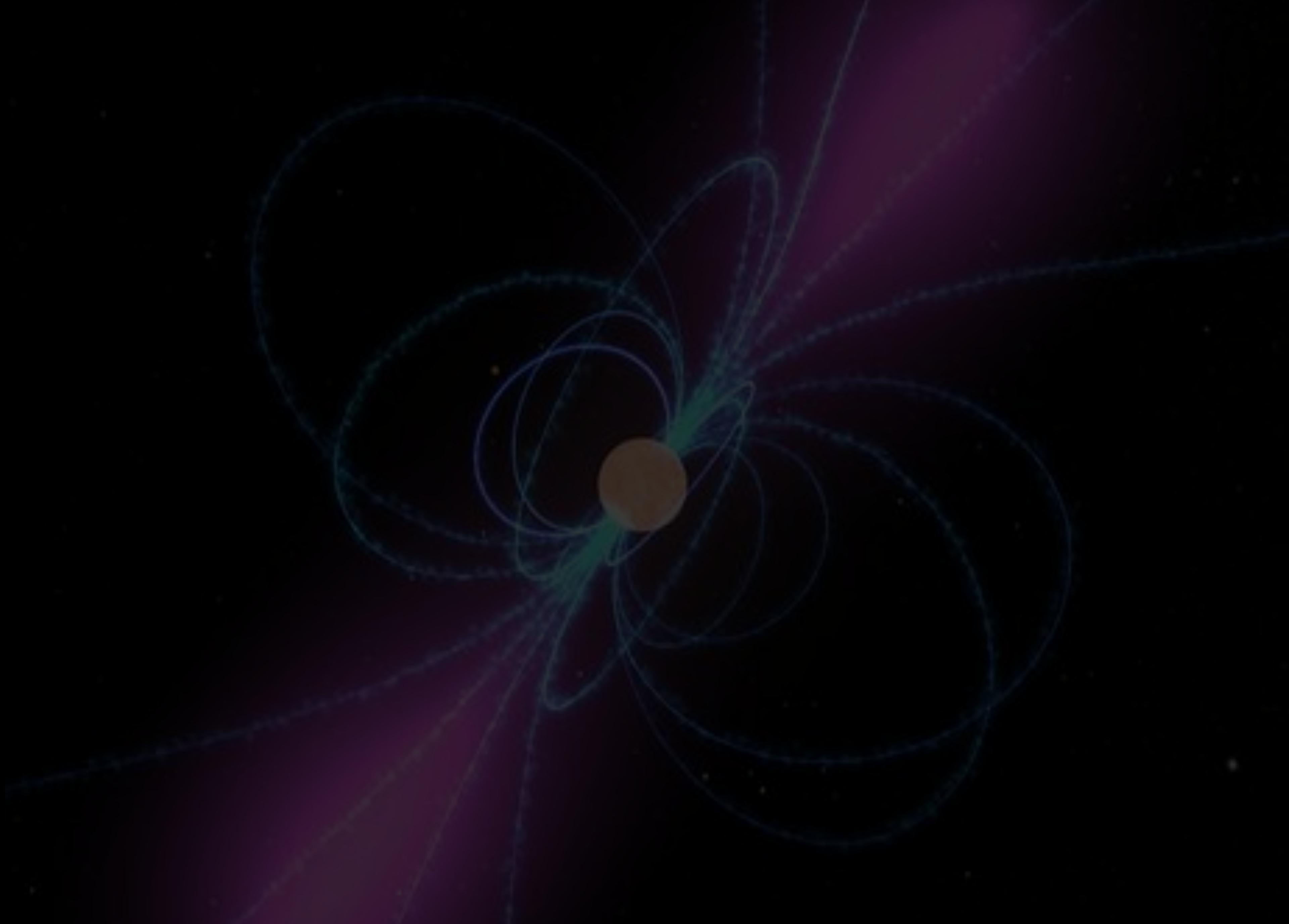
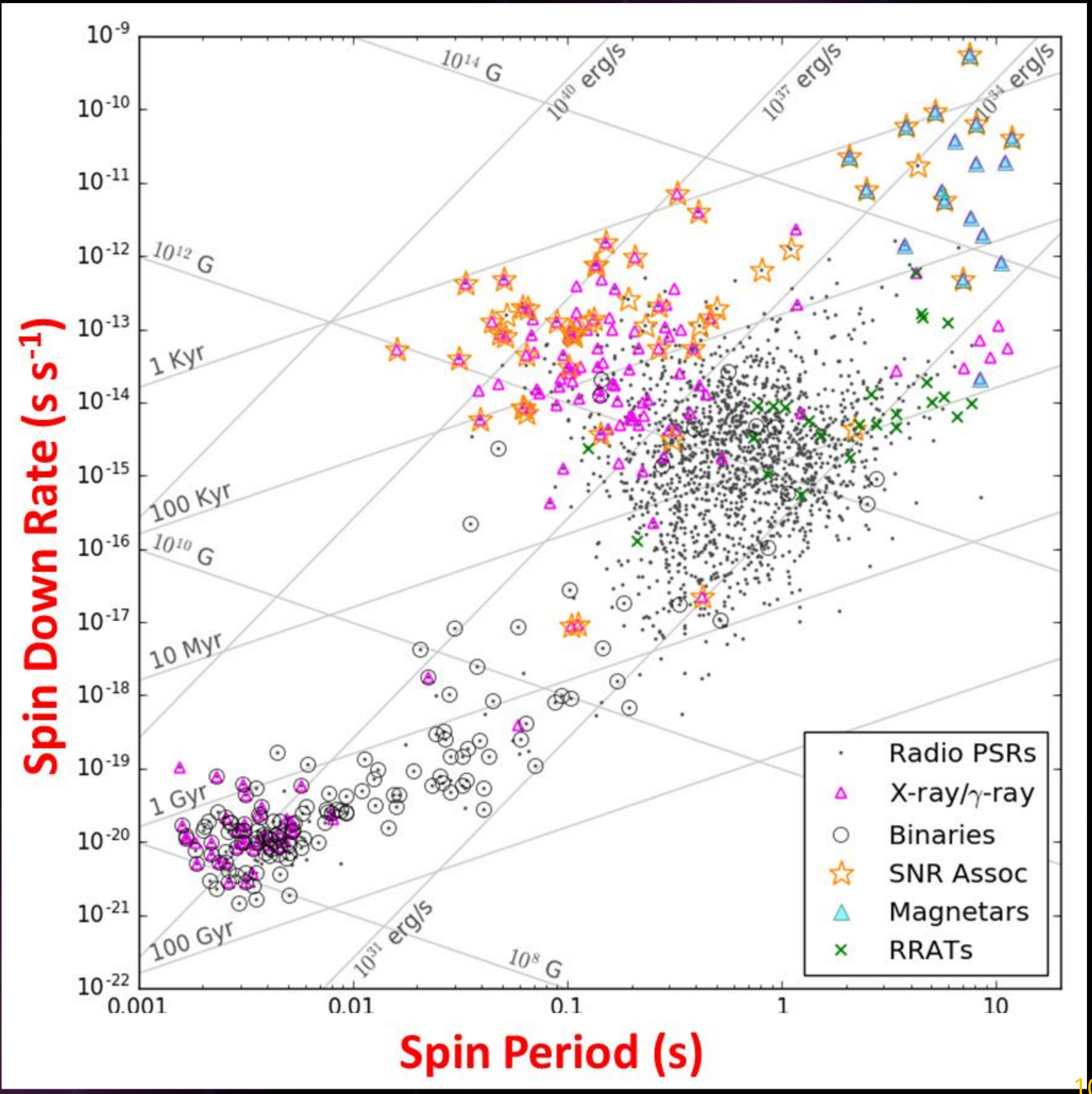


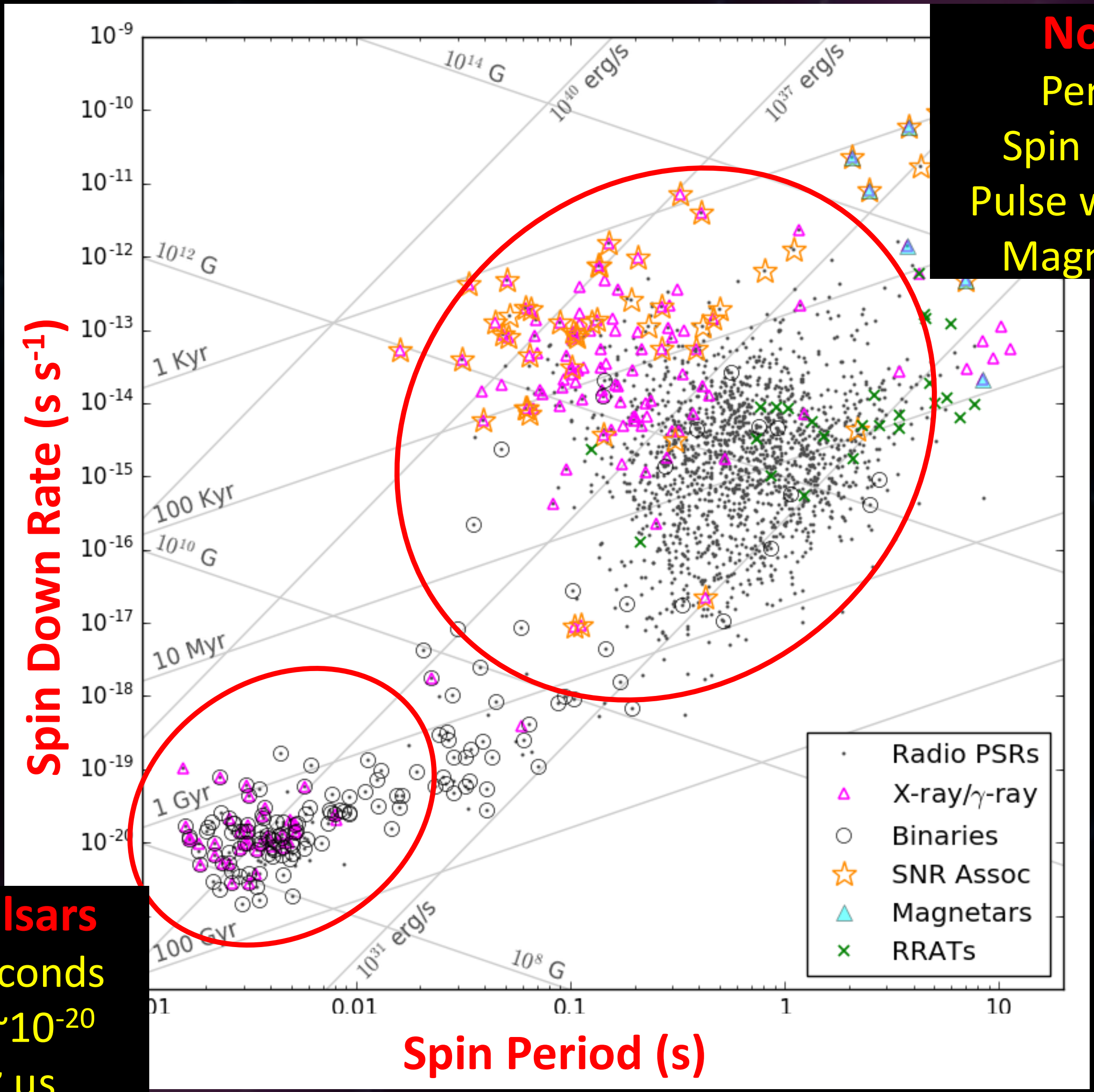
Image credit: ASTRON



P vs Ṗ Diagram



Two Main Populations



Normal pulsars

Period ~ seconds

Spin down rate ~10^{-15}

Pulse widths 100's of ms

Magnetic fields 10^{12}G

Millisecond pulsars

Periods ~ milliseconds

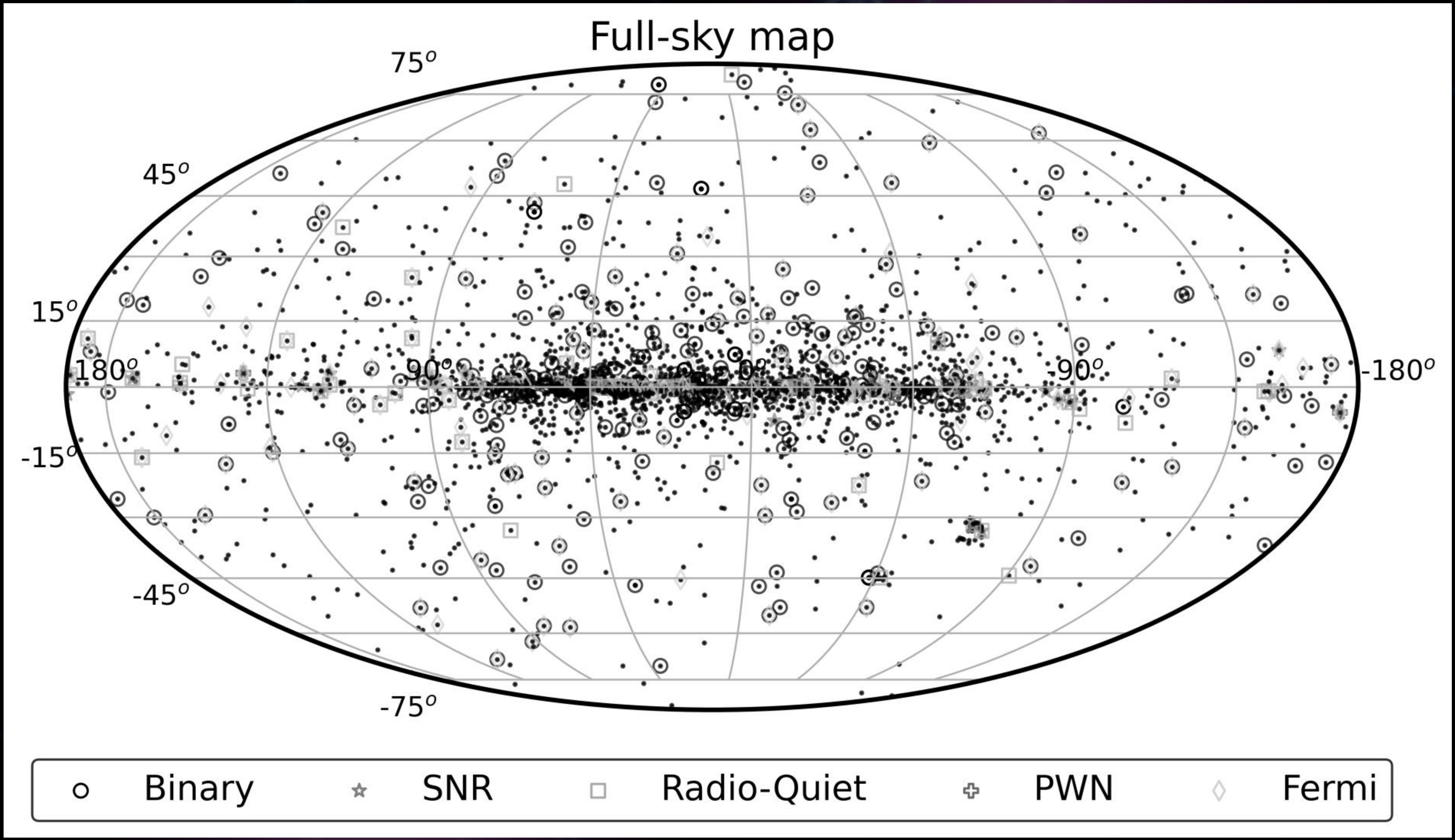
Spin down rate ~10^{-20}

Pulse widths ~ μs

Magnetic fields 10^{8}G

Image Credit:
JBCA Internal Plot

Where do we find Pulsars?



Pulse Shapes at Different Frequencies

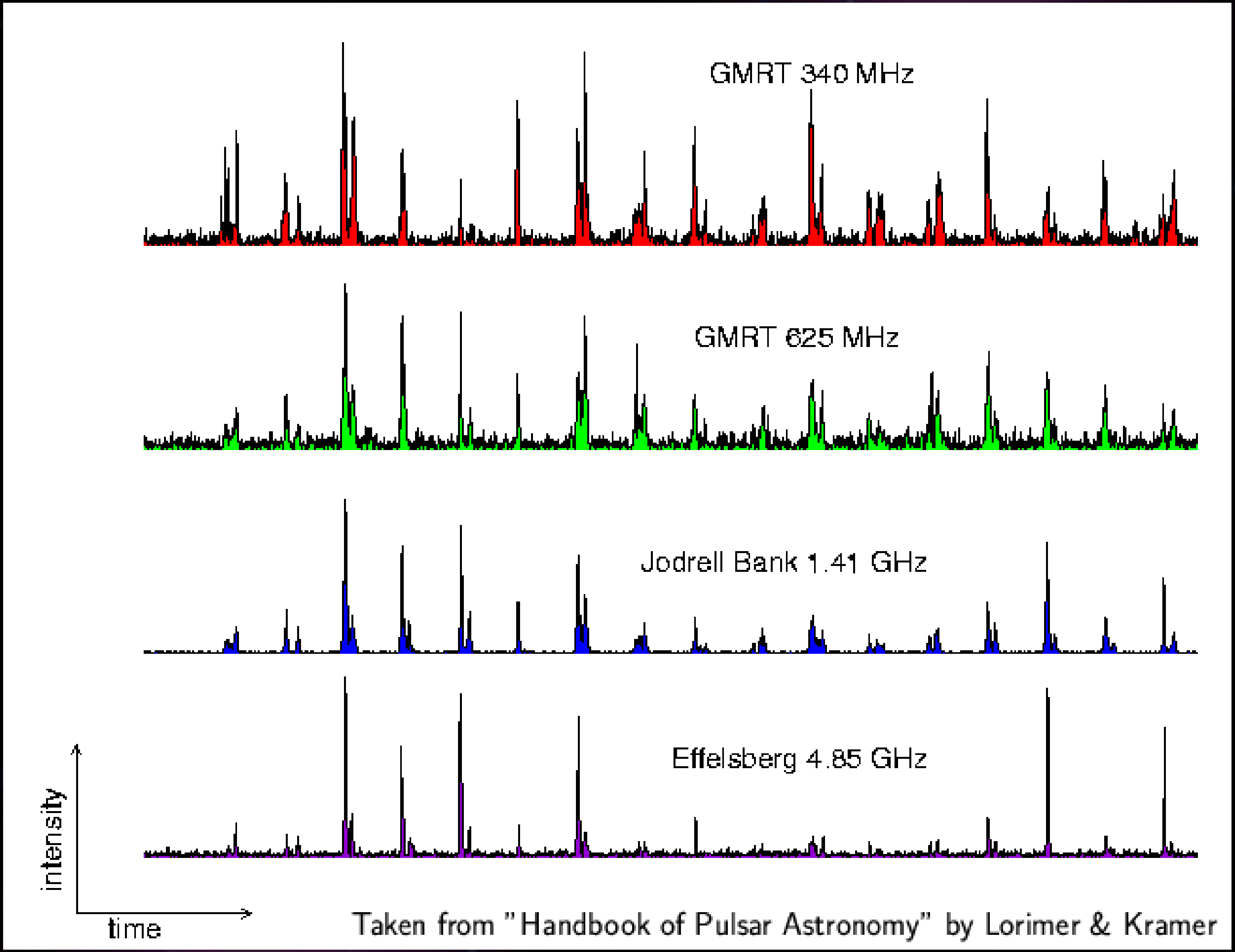


Image Credit: Lorimer & Kramer

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 gravity waves

Timing of Pulsars

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

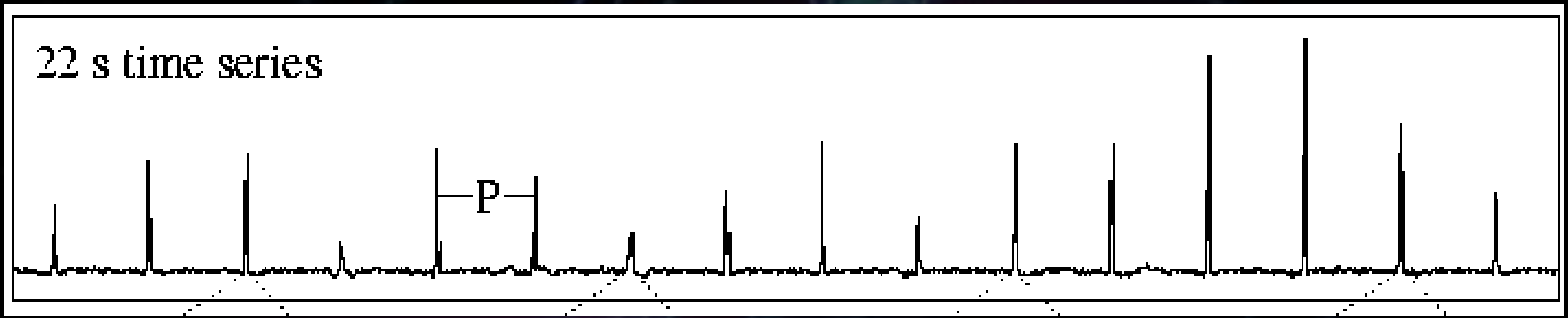


Image Credit: Adapted from Pulsar Astronomy

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).

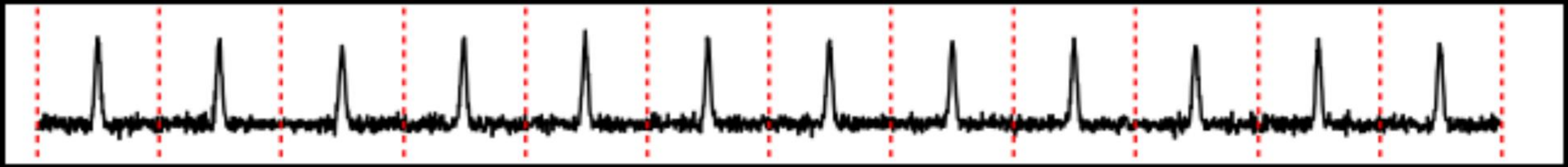
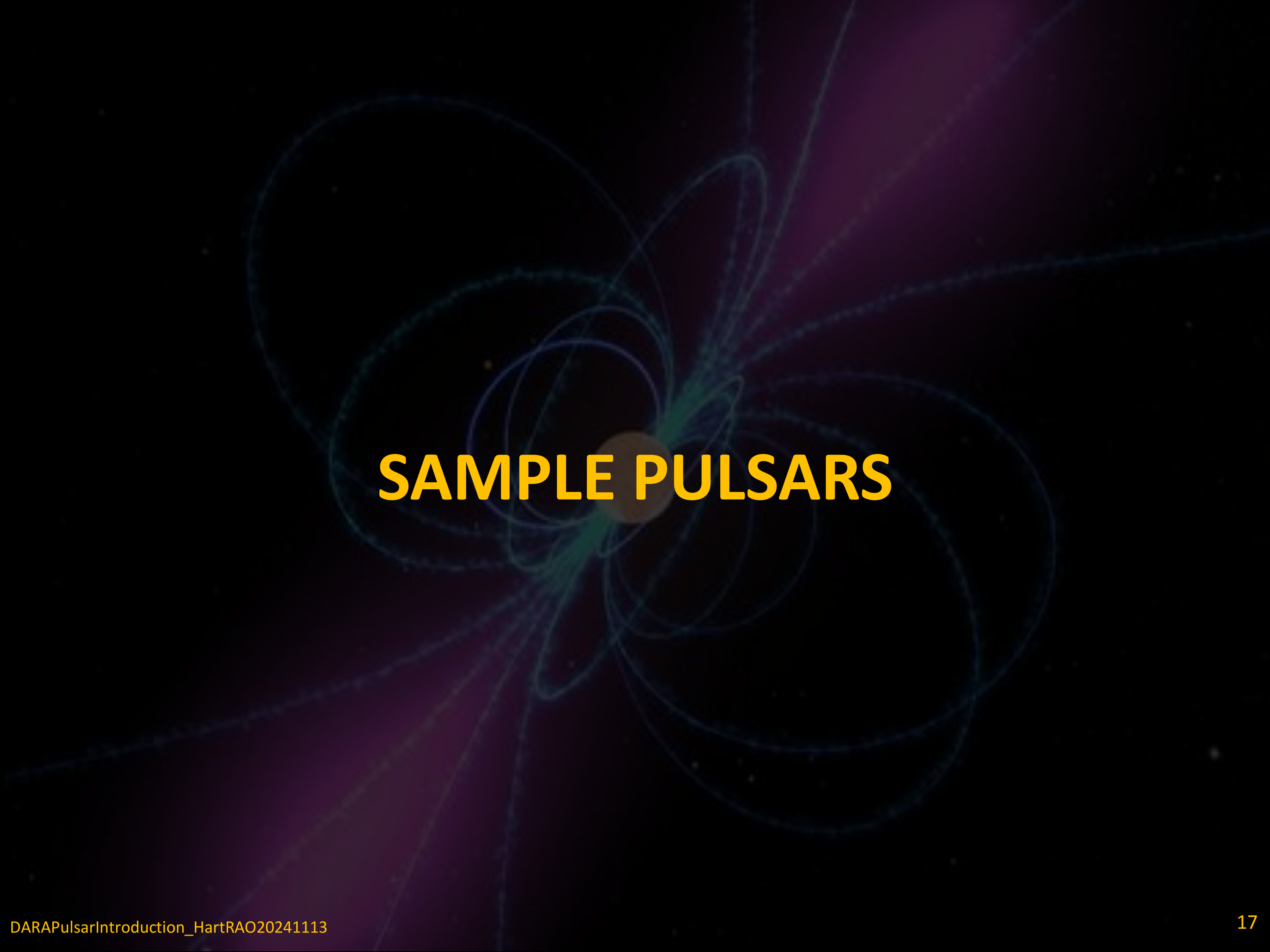


Image Credit: Scott Ransom

- 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 ms ± 0.1 x 10^{-8}ns



SAMPLE PULSARS

Pulse Profile

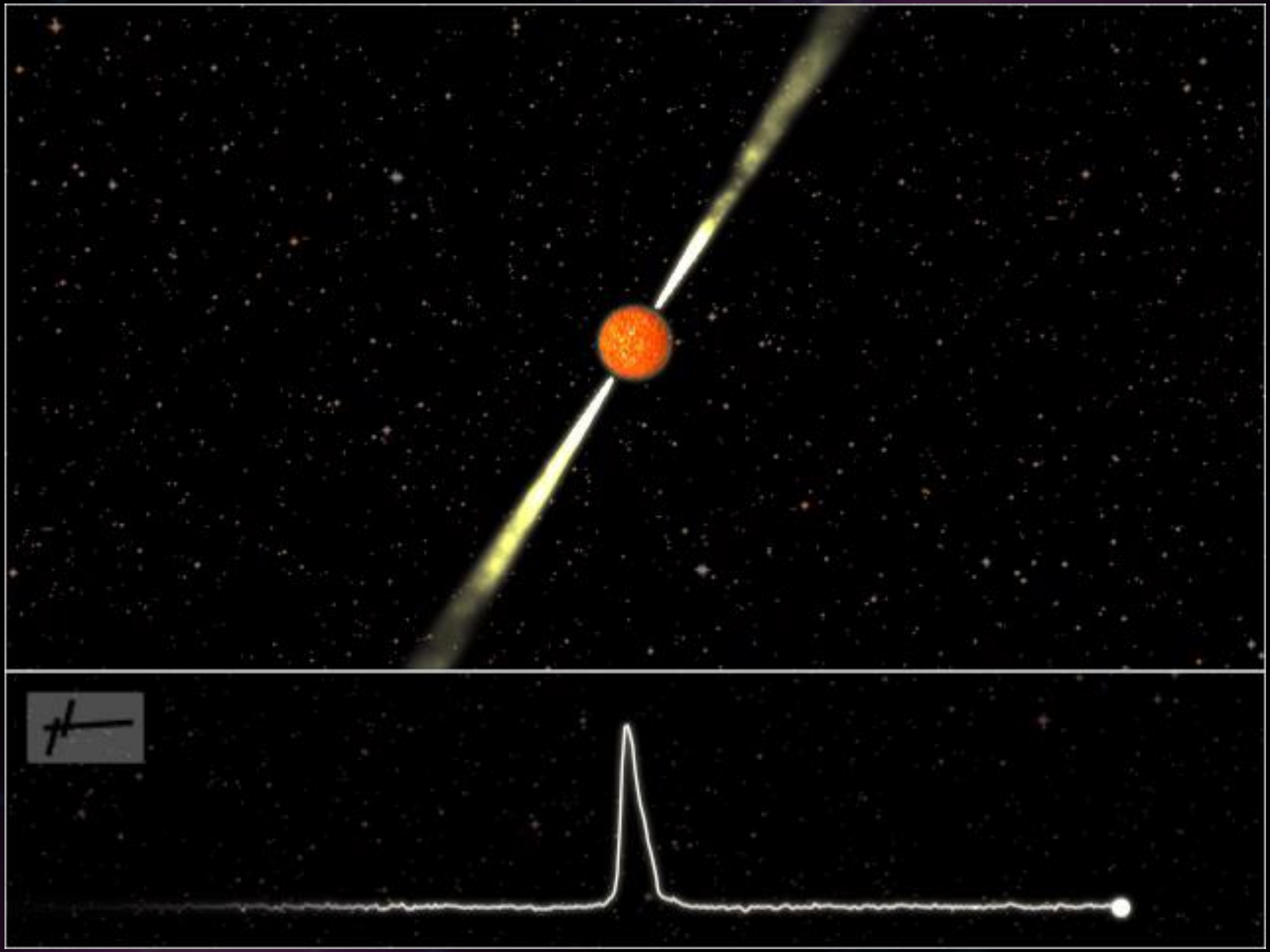


Image credit: ASTRON

Supernova Remnant

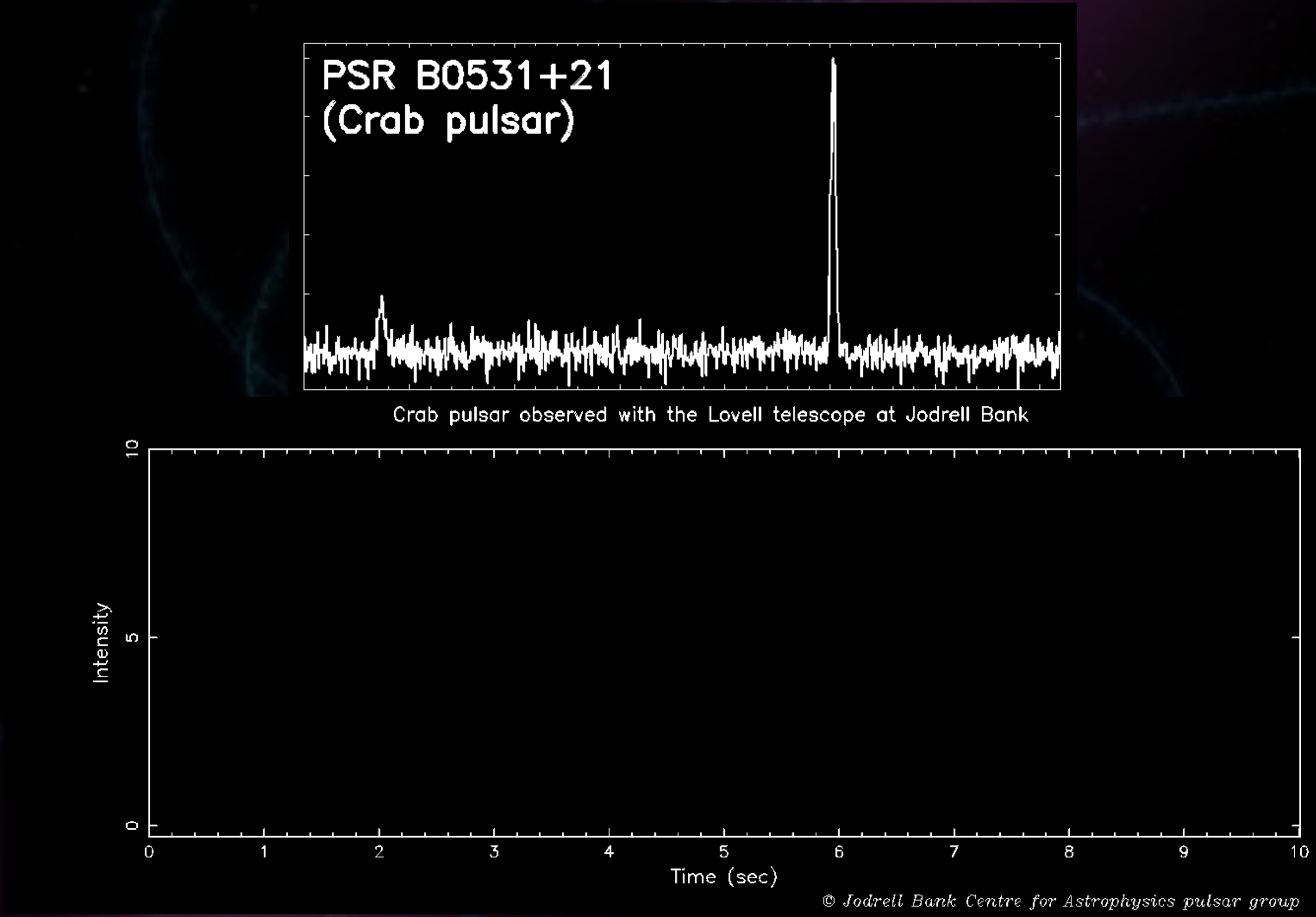
Crab Nebula

- **In the constellation Taurus**
  - Supernova in 1054 AD
  - Due to the neutron star '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

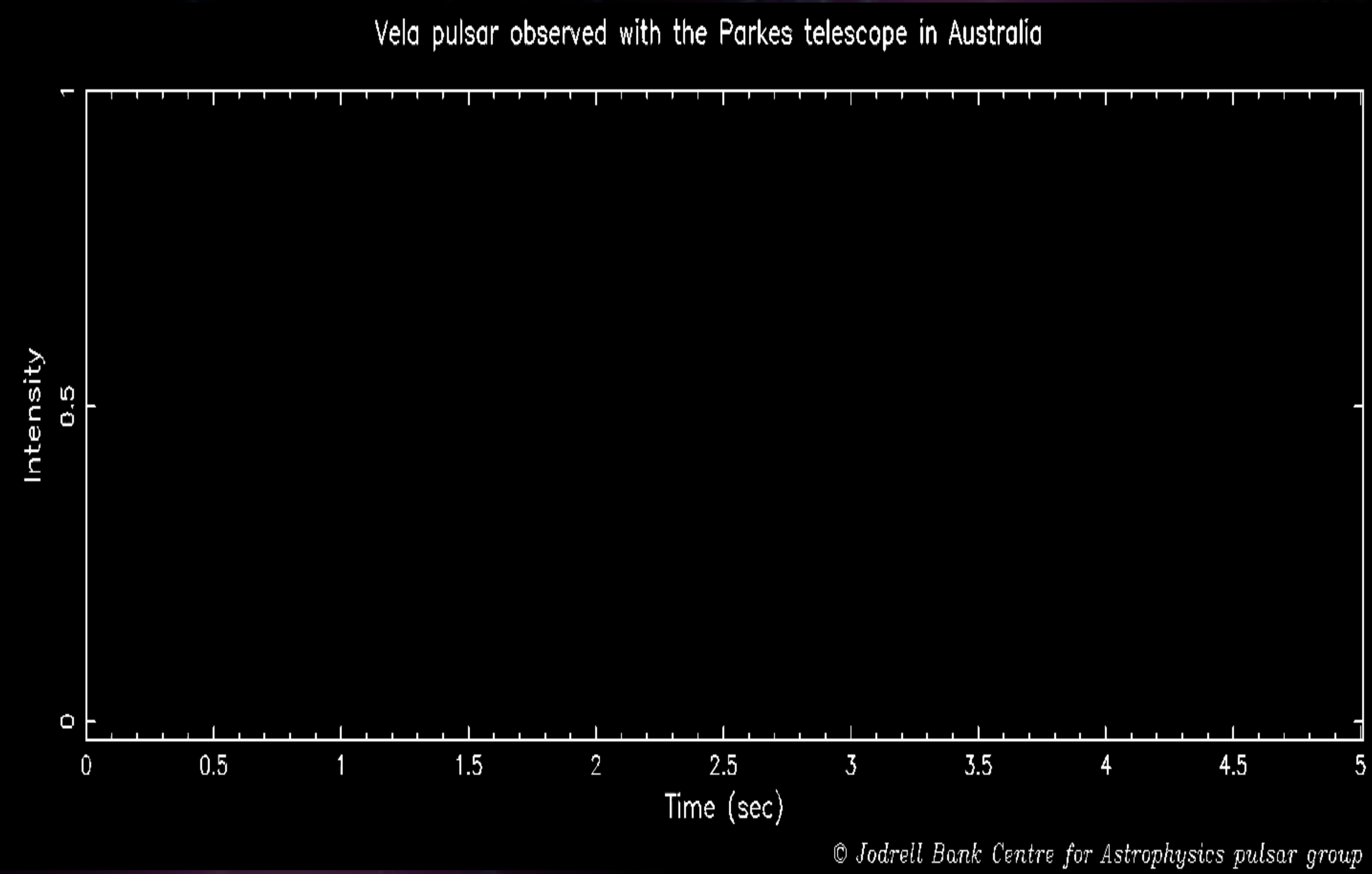
Image Credits: X-ray: NASA/CXC/SAO/F.Seward; Optical: NASA/ESA/ASU/J.Hester & A.Loll; Infrared: NASA/JPL-Caltech/Univ. Minn./R.Gehr

Crab Pulsar PSR B0531+21



Vela Pulse Train

Brightest pulsar in the southern sky



Pulse Profiles

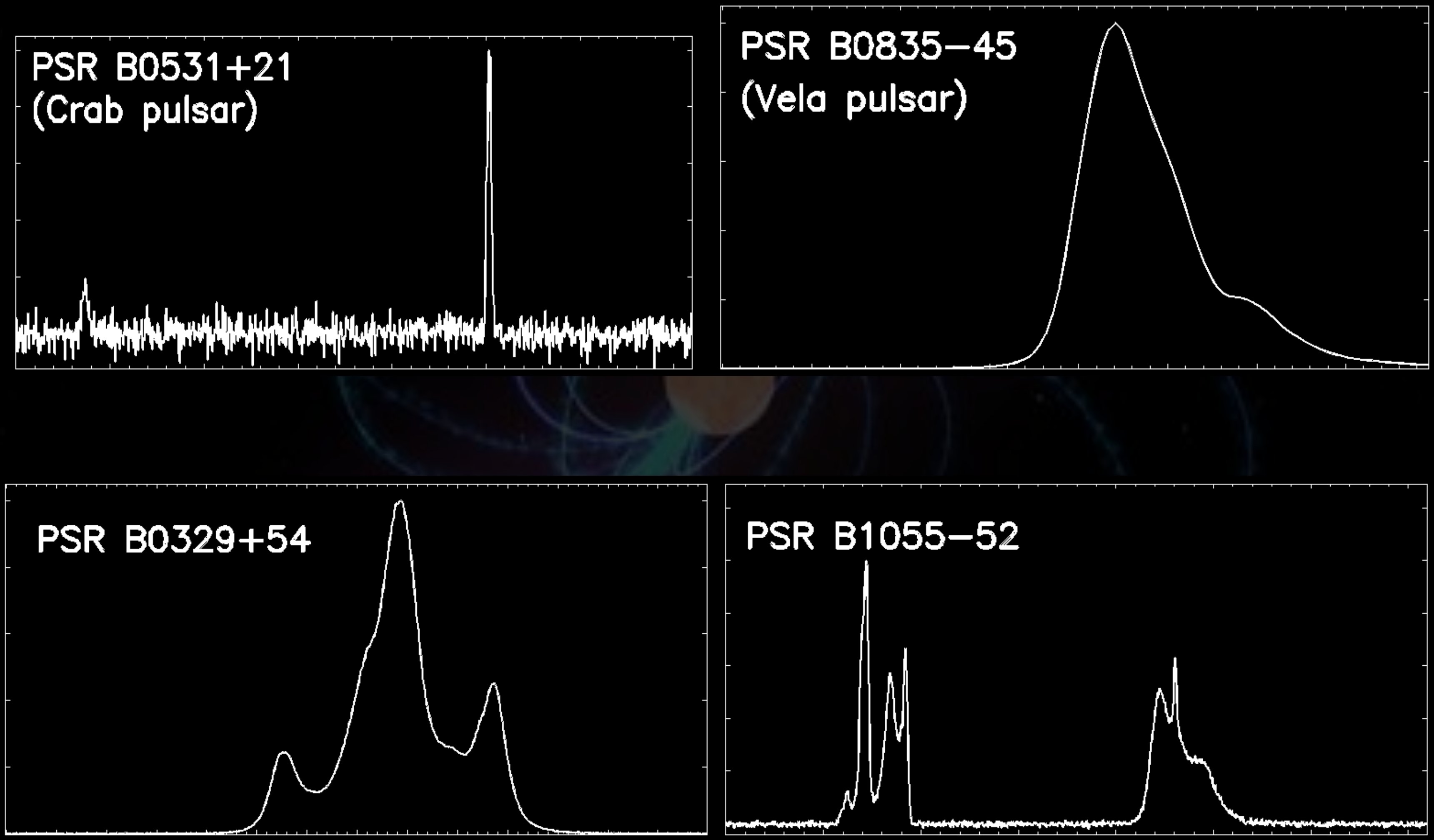


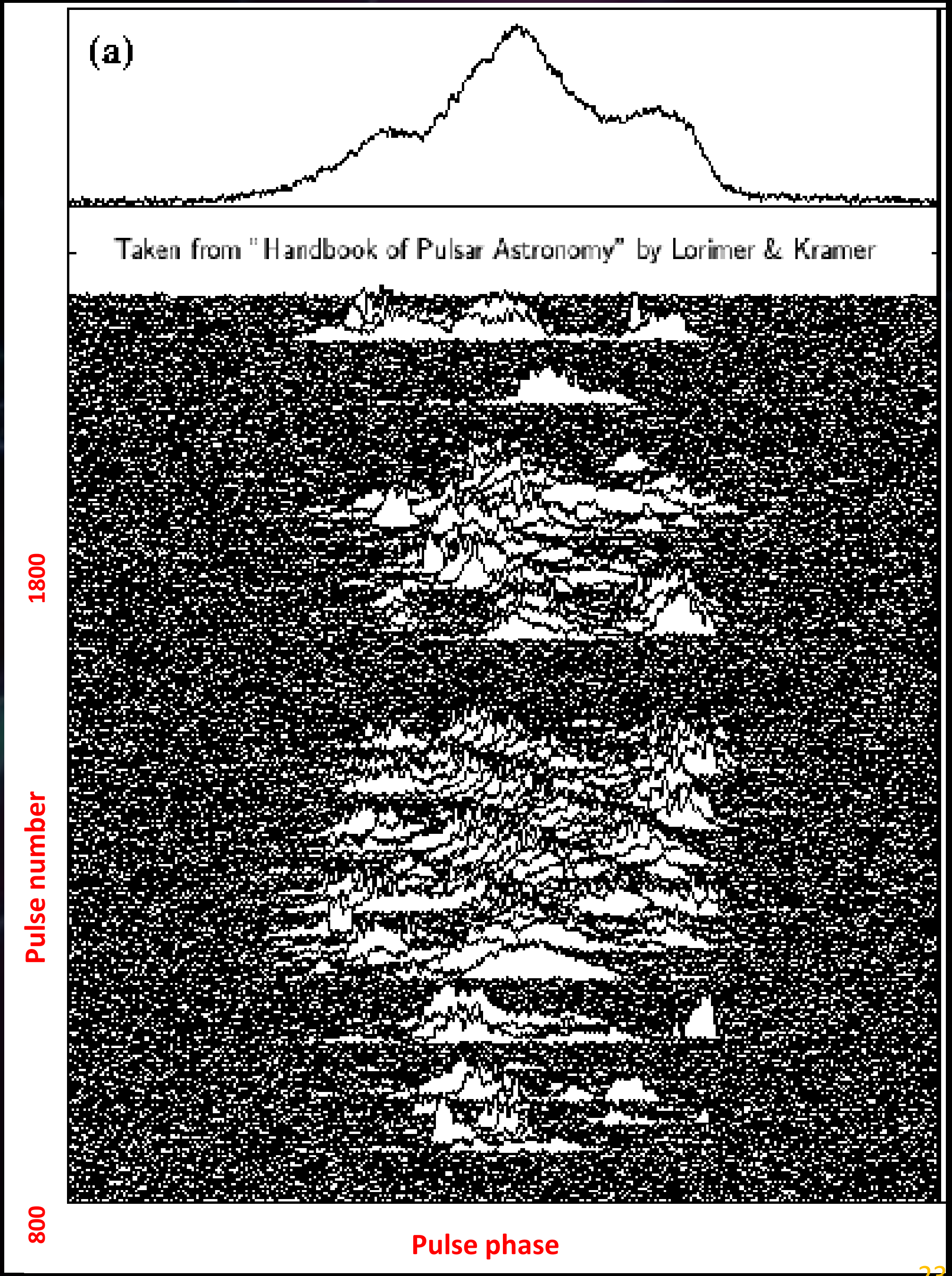
Image credits: JBCA

PULSE EMISSIONS
OVER TIME

1600 pulse signals combined

Profile is constant per pulsar

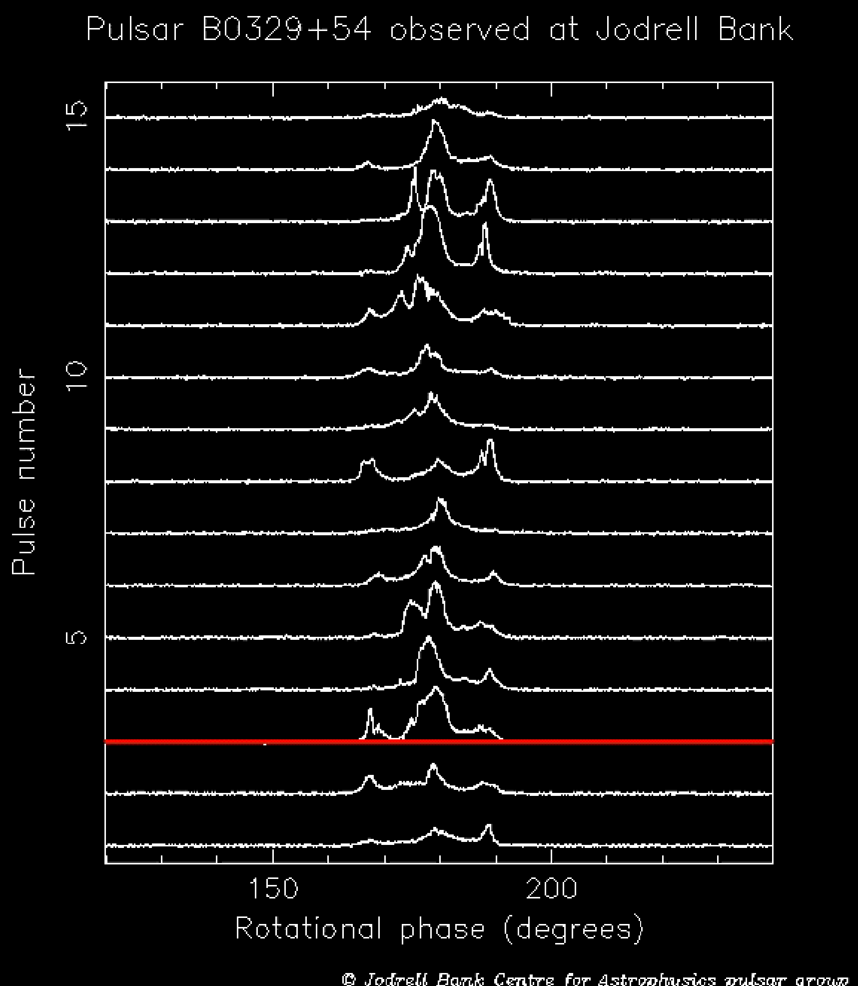
Some rotations have no emissions



PSR B0329+54

Brightest Pulsar in the northern sky

Image credit: JBCA



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

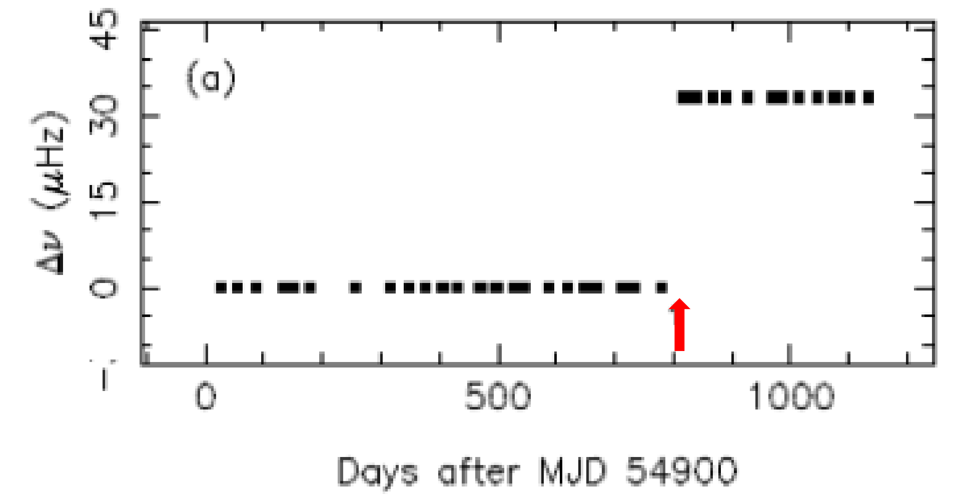
A glitch is a sudden step change in spin frequency

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

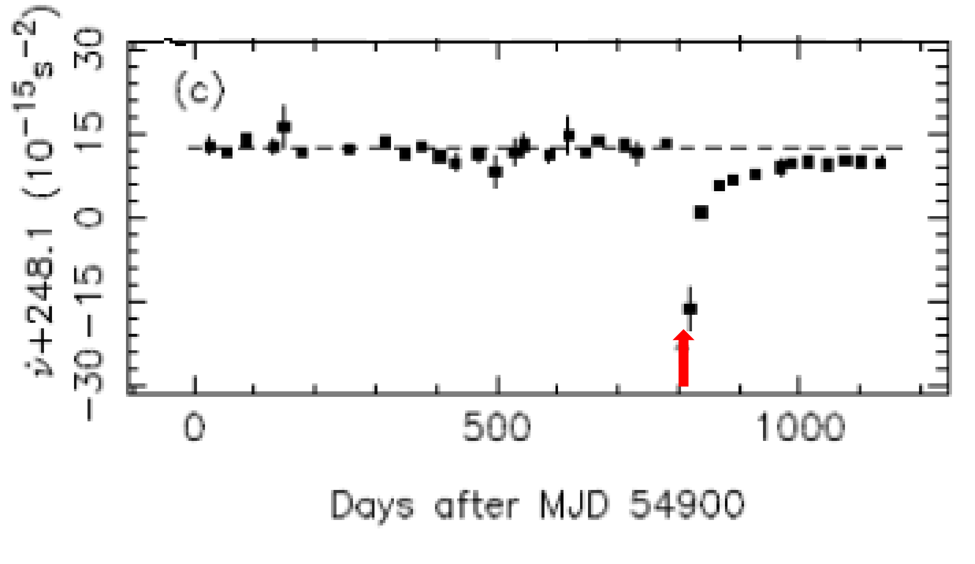
- Glitch in PSRJ1757-2421
  - at ~ MJD 55700 (May 16 – 27 2011)
  - Fractional increase of $\Delta\nu_g / \nu \sim 7.8 \times 10^{-6}$
  - $\nu = 4.271\,592\,656\,55(4)\ s^{-1}$
  - $\Delta\nu_g = 4.271\,573\,098\,0(8)\ s^{-1}$

Glitch in PSR J1757-2421

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



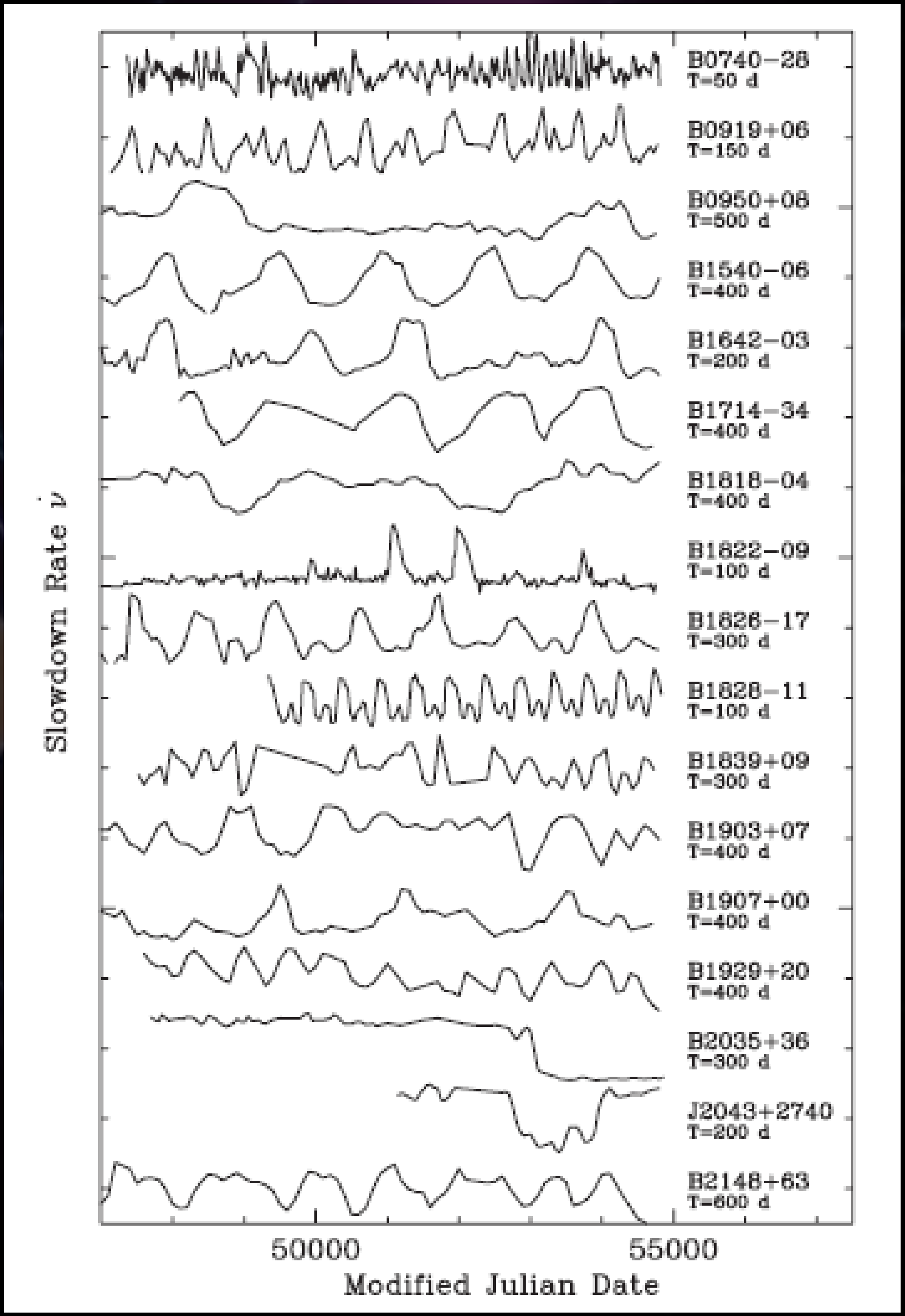
The bottom panel shows the variations of Ṗ, and the horizontal dashes indicate the average pre-glitch level.



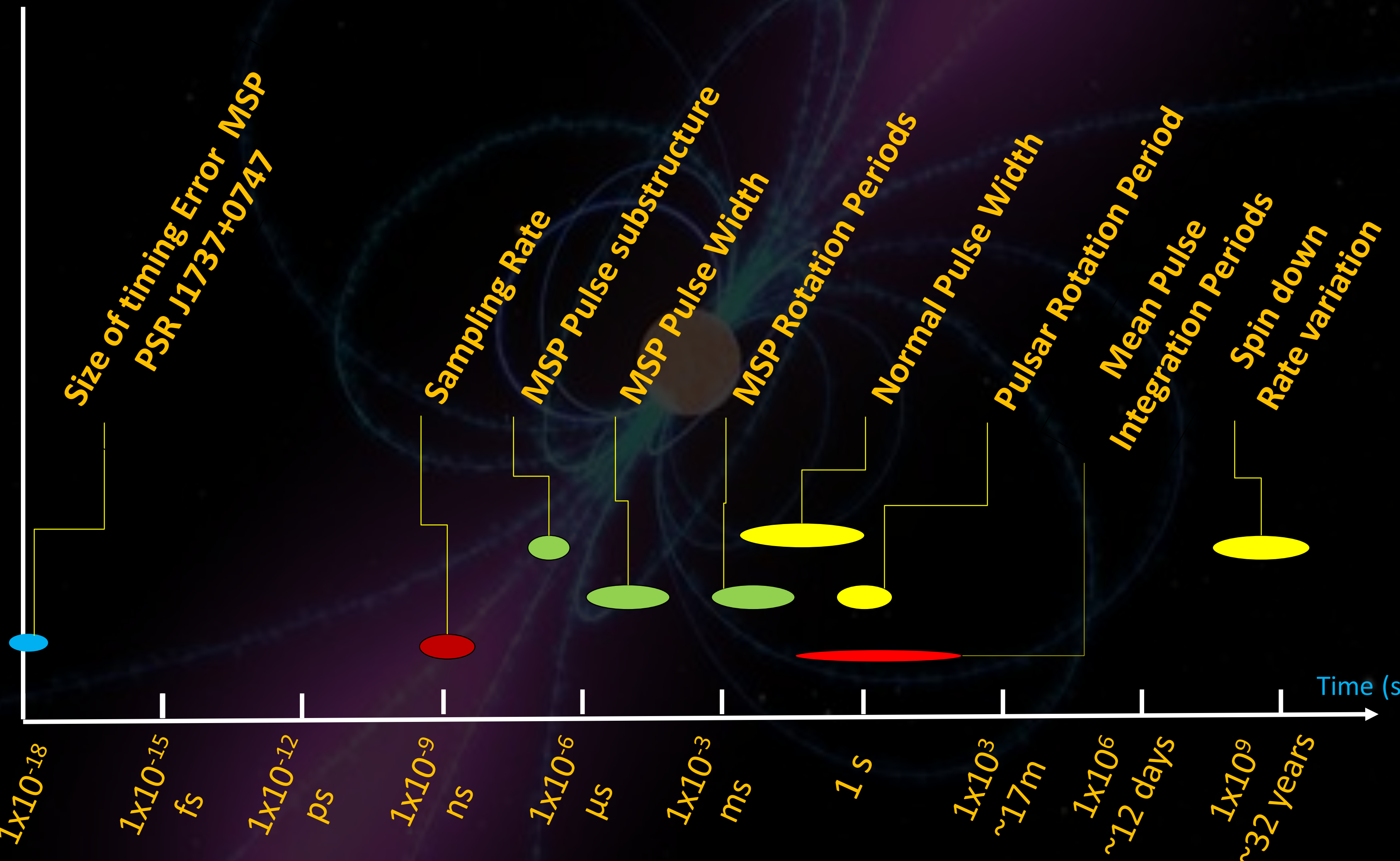
The glitch epoch is indicated by a red arrow.

Changes over years

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



Timescales



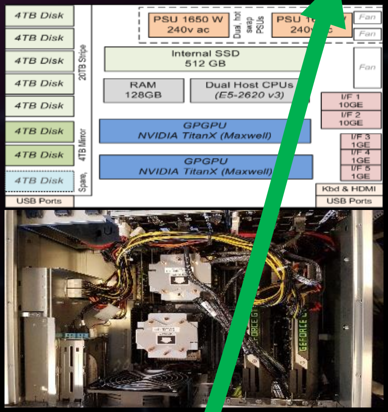
Size of timing Error MSP
PSR J1737+0747
Sampling Rate
MSP Pulse substructure
MSP Pulse Width
MSP Rotation Periods
Normal Pulse Width
Pulsar Rotation Period
Mean Pulse
Integration Periods
Spin down
Rate variation
Time (s)
1x10-18
1x10-15
fs
1x10-12
ps
1x10-9
ns
1x10-6
µs
1x10-3
ms
1 s
1x103
~17m
1x106
~12 days
1x109
~32 years

PULSAR TIMING SYSTEMS

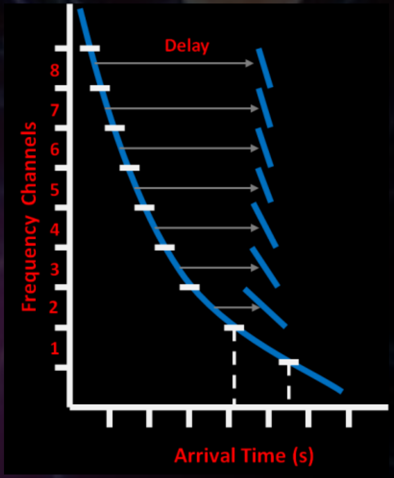
Evolution of pulsar systems and compute power

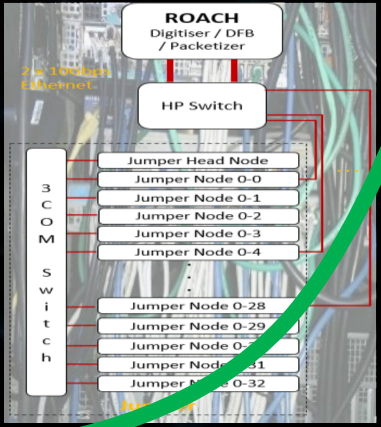
Processing Power

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



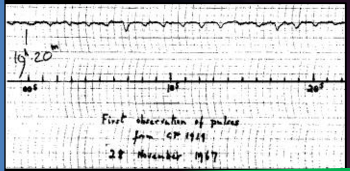
Analogue and Digital Filter banks





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

Chart Recorder



1967

Years

2018

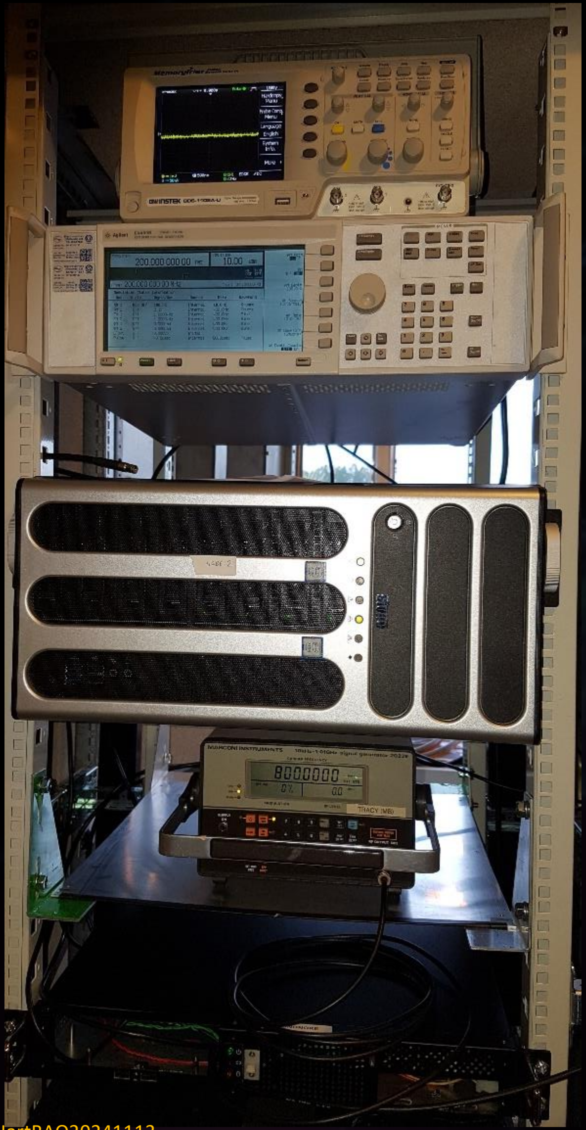
Analogue | Digital

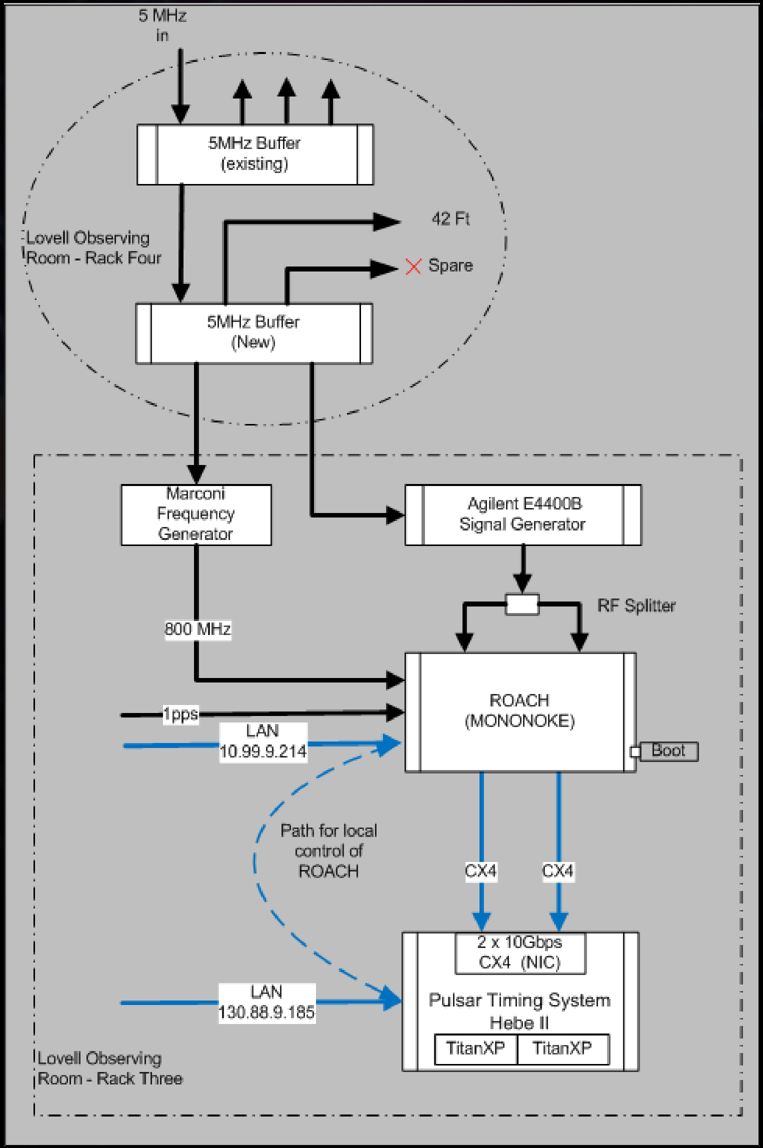
Image Credits: Adapted from Handbook of Pulsar Astronomy ; Tom Scragg

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
  - ~ ½ 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

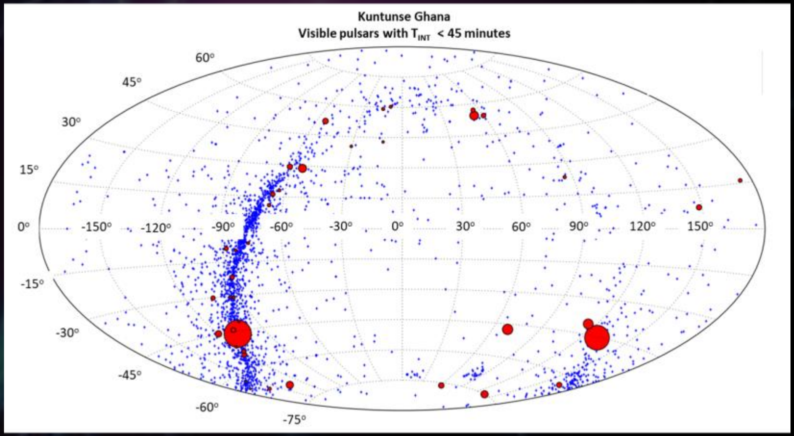
Hebe 2 at Jodrell Bank

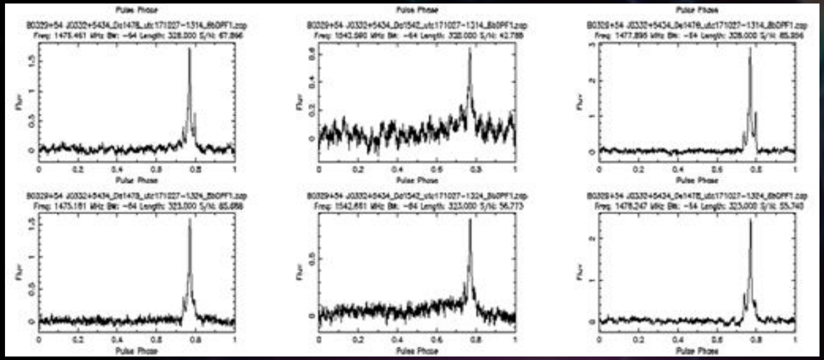




Cool Science Stuff

- **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?

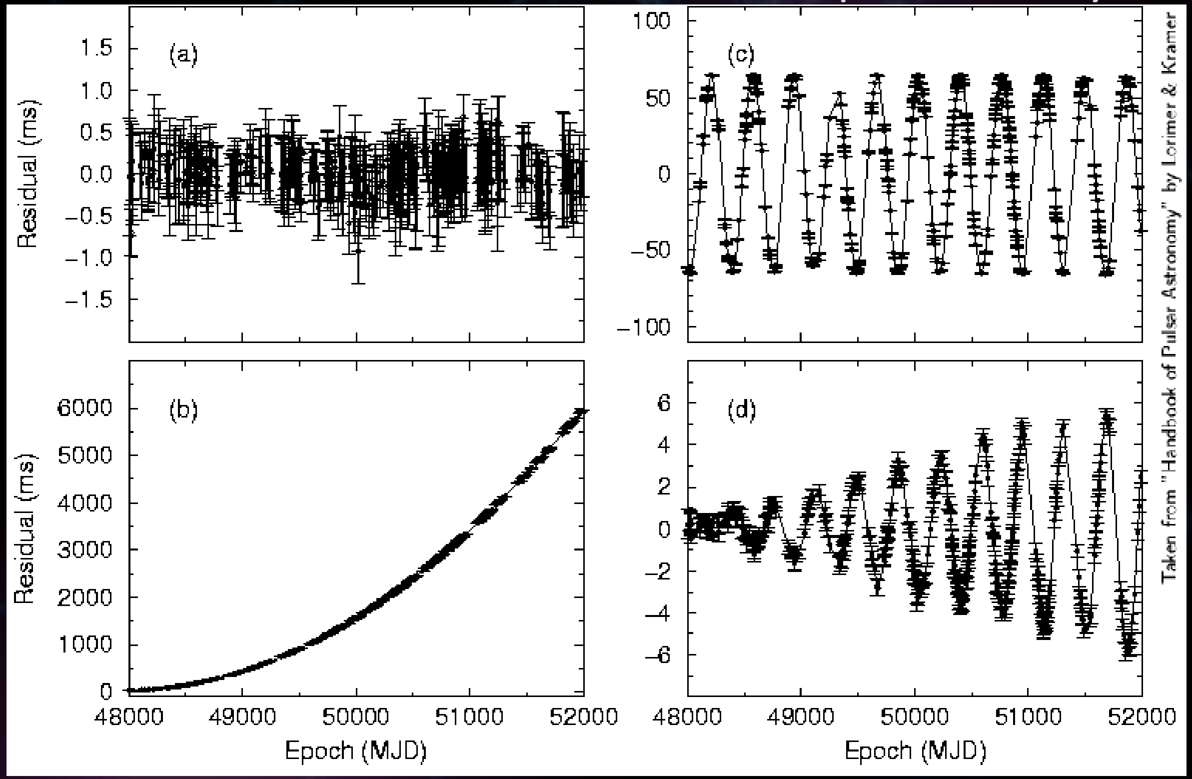
Residuals

Timing Residuals from PSR B1133+16

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

a) Perfect fit – random distribution

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



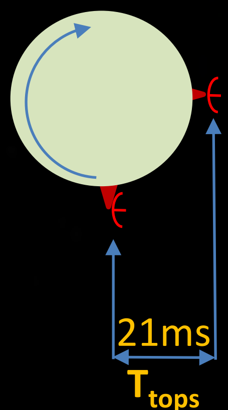
b) Parabolic increase - $\dot{P}$ underestimated Timing model incorrect

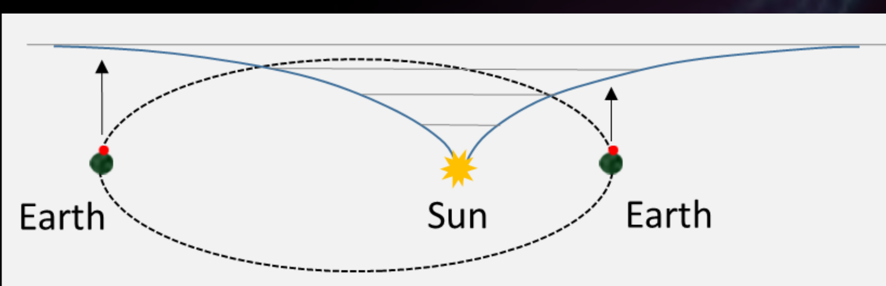
d) Position not corrected for proper motion – Romer delay error

Corrections to ToA

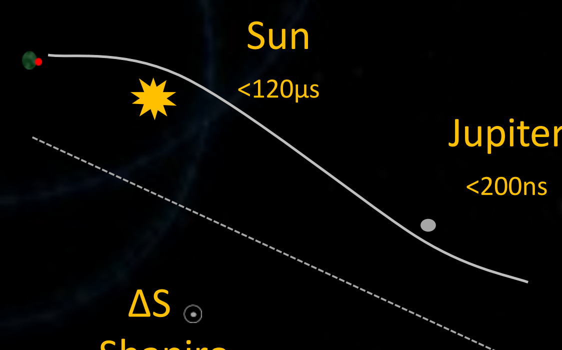
$$t_{SSB} = t_{topo} + t_{corr} + \Delta_{R_\odot} + \Delta_{S_\odot} + \Delta_{E_\odot}$$

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]





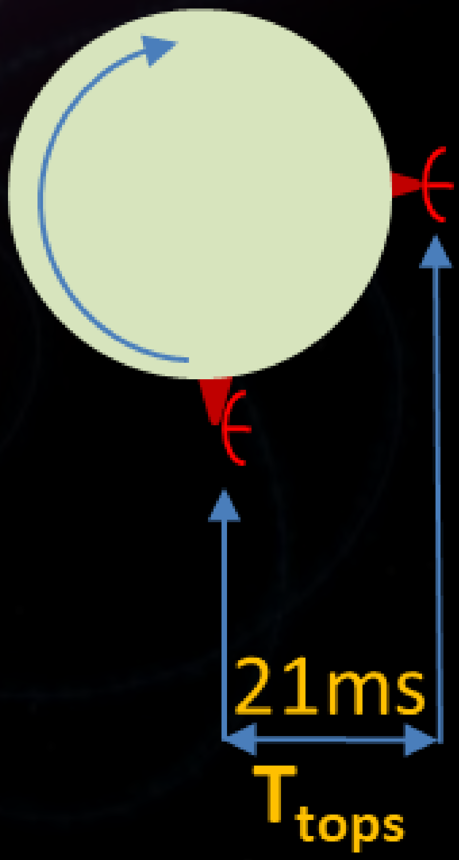
~1.6ms
$\Delta E_\odot$ Einstein
Delay



$\Delta S_\odot$
Shapiro
Delay

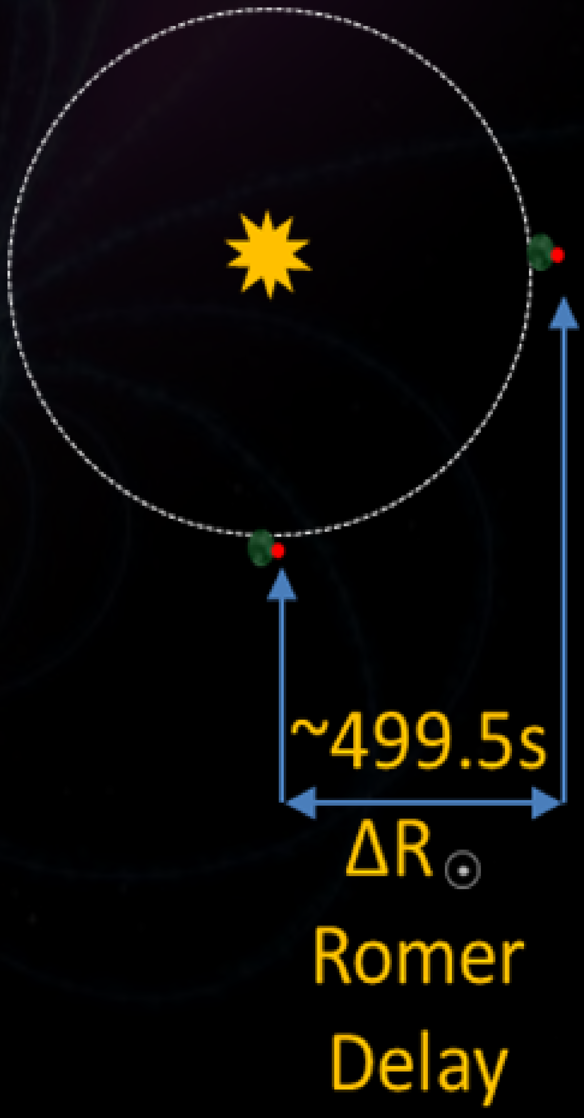
Geometry -1

- 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

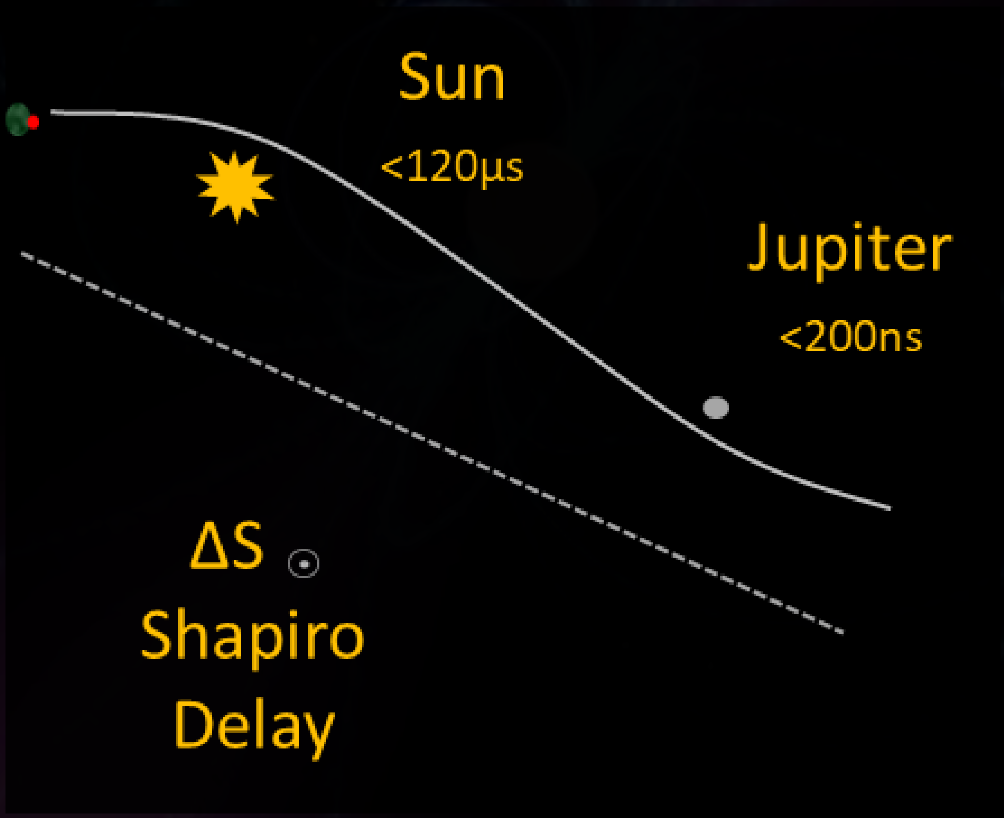
- Earth's Orbit
- Determine size and shape of the Earth's orbit by changes in the pulse delay
- Determine the relative change in position of telescopes to within
  - ~300m if pulsar error is 1 in 10^6
  - ~0.3m if pulsar error is 1 in 10^9
  - ~0.3mm if pulsar error is 1 in 10^{12}



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



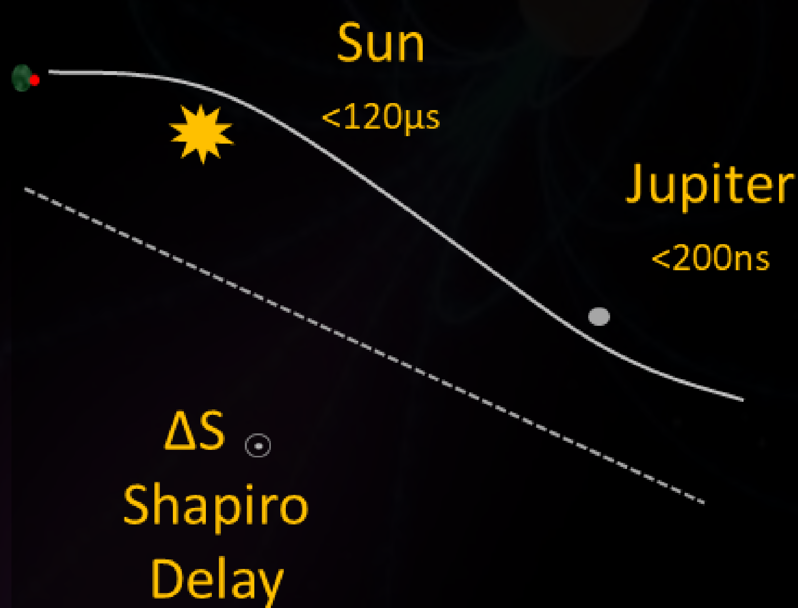
Geometry -4

Bending of light by mass

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

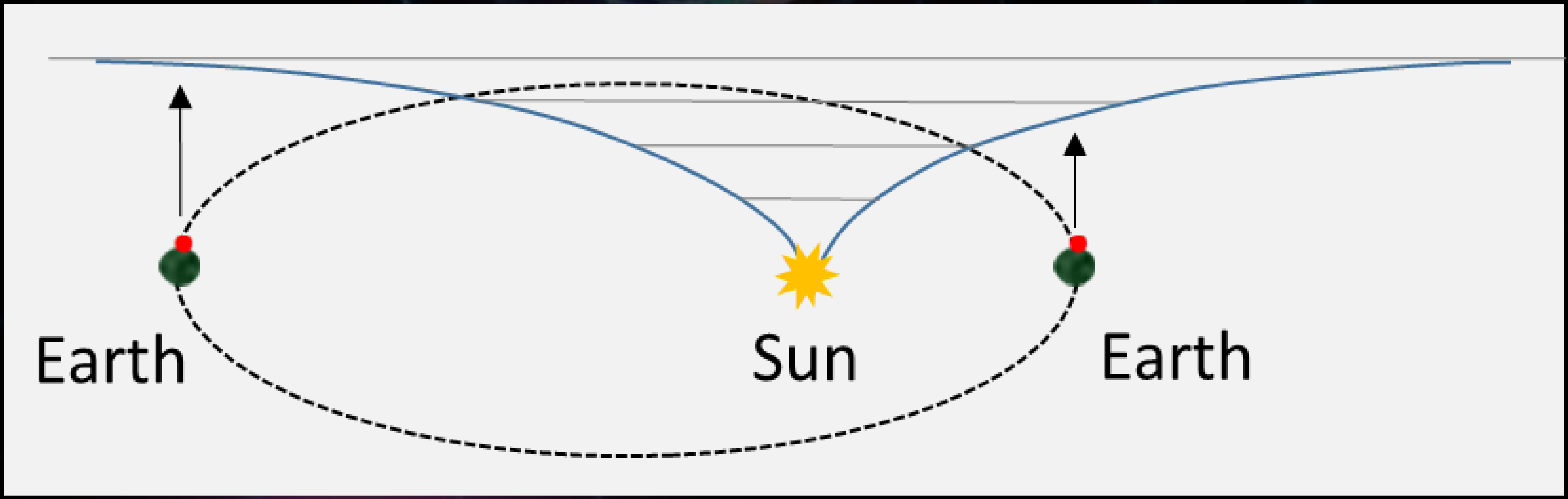
- Jovian system 9.5479189(3) x 10^{-6} $M_\odot$
- Ceres 4.7(4) x 10^{-10} $M_\odot$
- Vesta 1.3026846(9) x 10^{-10} $M_\odot$
- Six pulsars used with a typical timing error of 0.2 < t < 2 μseconds

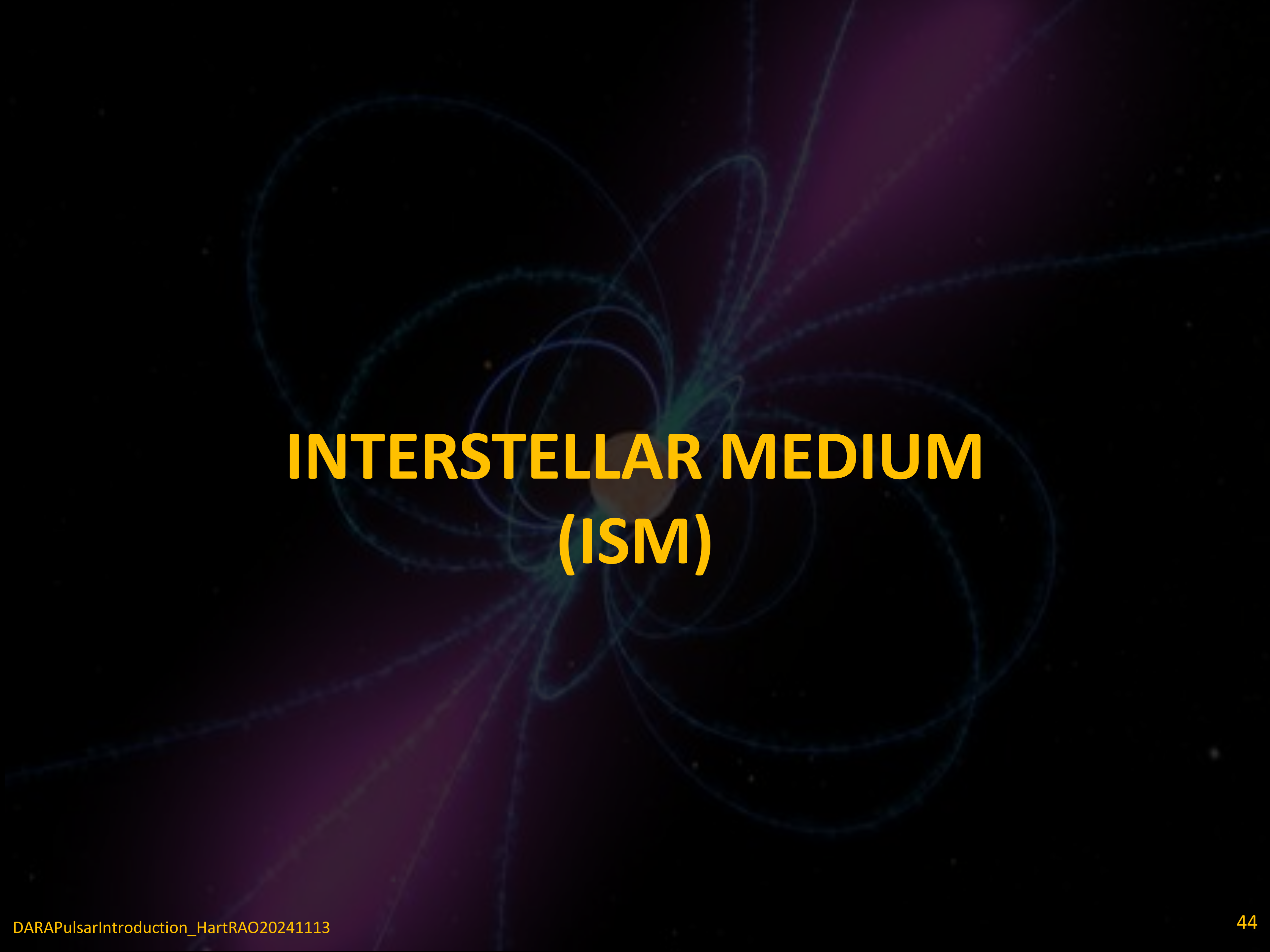
R.N.Caballero et. al 2018



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

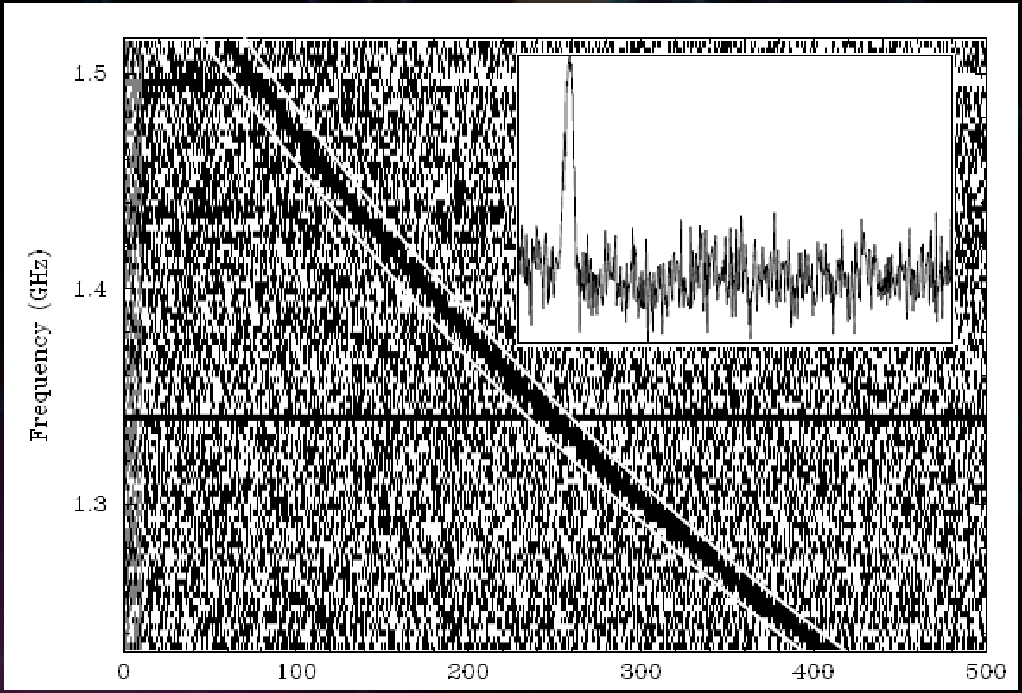
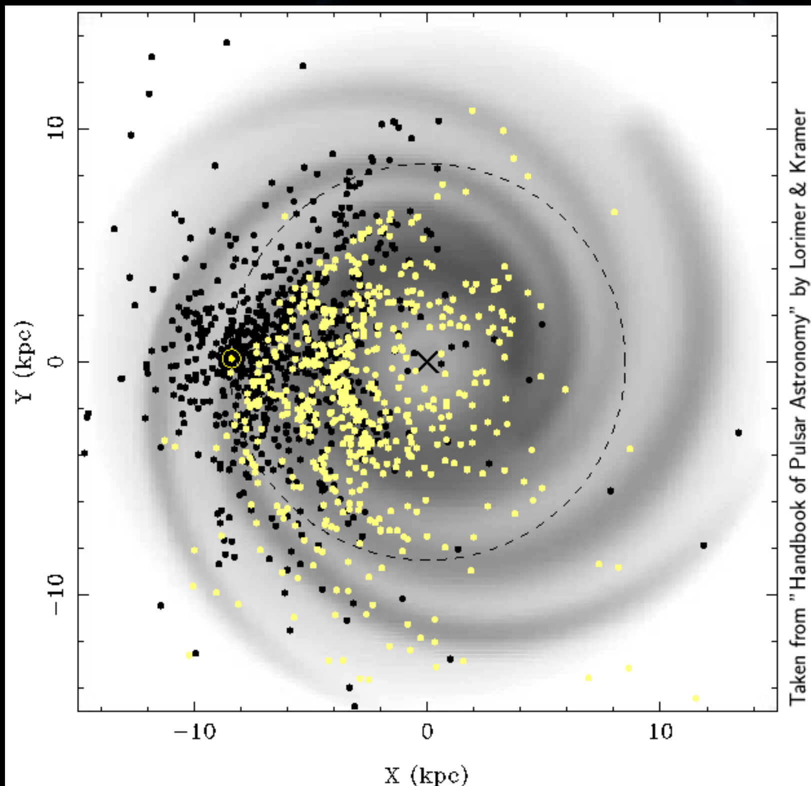


Image Credit: Handbook of Pulsar Astronomy Lorimer & Kramer

ISM Electron density distribution models

NE2001 Cordes and Lazio (2002a)



YMW16 (2016)

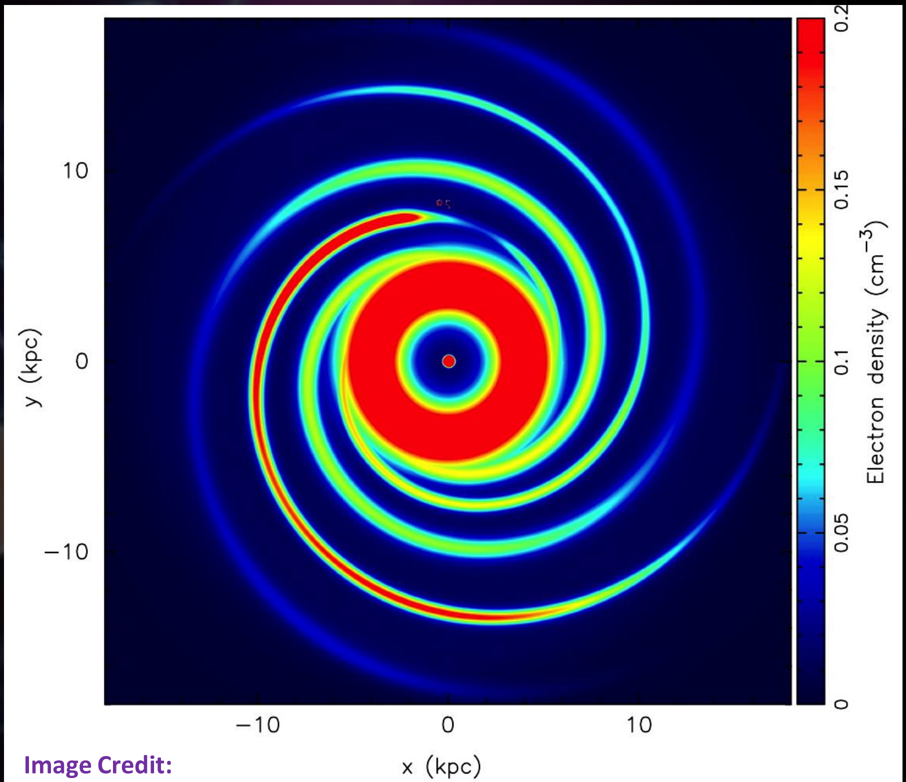


Image Credit: https://www.atnf.csiro.au/research/pulsar/ymw16/

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

- **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.**

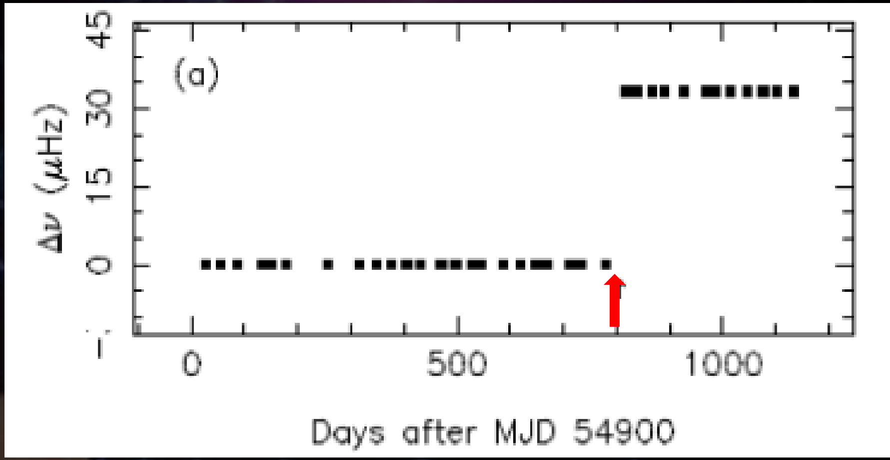
NEUTRON STAR BEHAVIOUR

Glitches

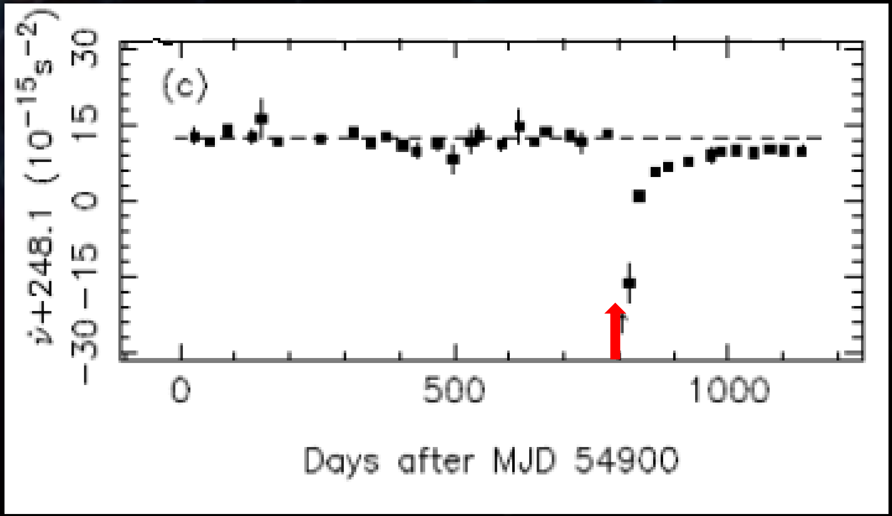
- **A glitch is a sudden step change in spin frequency**
  - The pulsar spins faster
  - The slow down rate ($\dot{P}$) increases and then decays back towards it's original value.
- **Glitch in PSRJ1757-2421**
  - at ~ MJD 55700 (May 16 – 27 2011)
  - Fractional increase of $\Delta\nu_g / \nu \sim 7.8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

Glitch in PSR J1757-2421

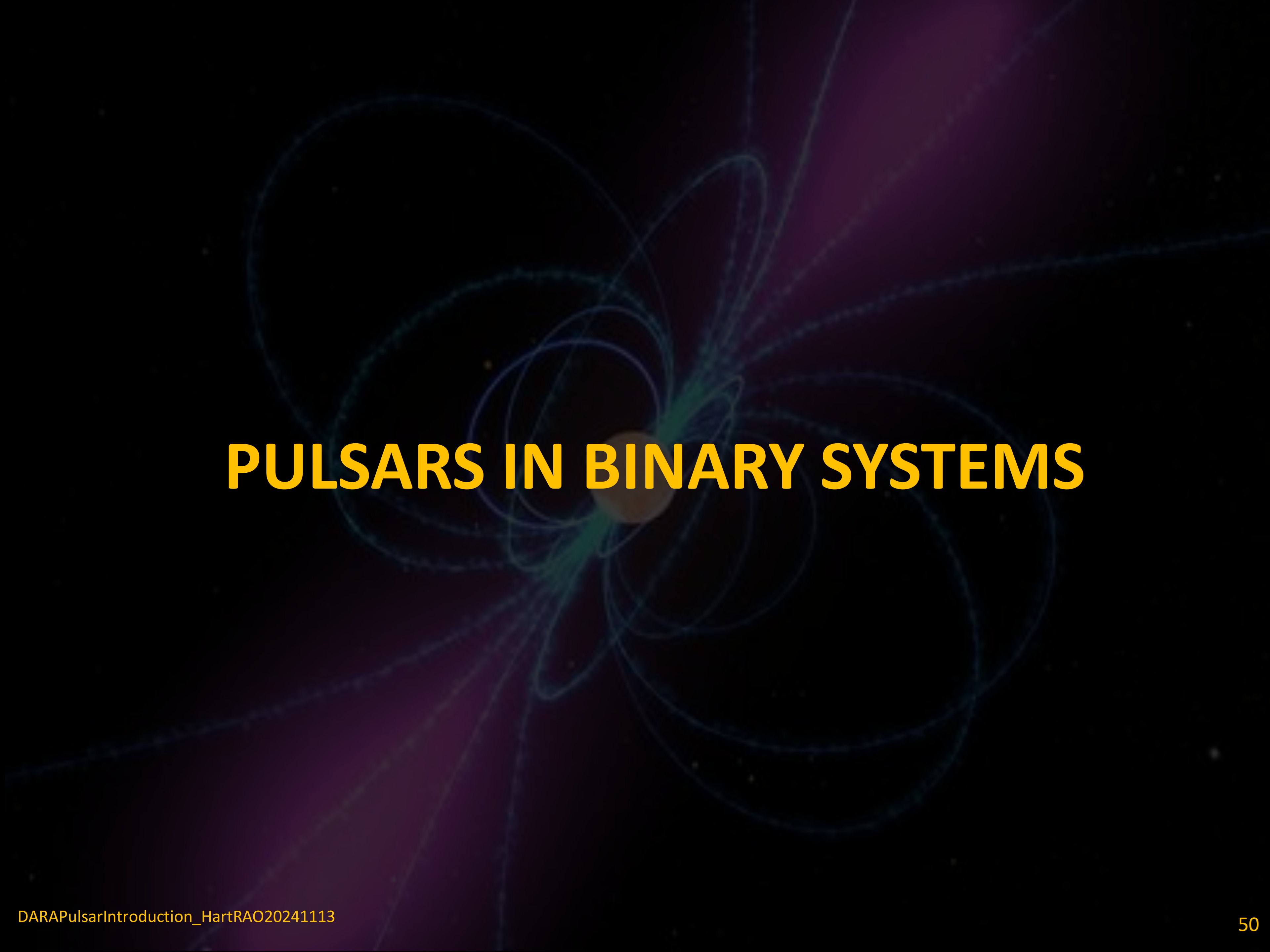
The top panel shows the spin-frequency residuals relative to the pre-glitch Spindown solution;



The bottom panel shows the variations of Ṗ, and the horizontal dashes indicate the average pre-glitch level.



The glitch epoch is indicated by a red arrow.



PULSARS IN BINARY SYSTEMS

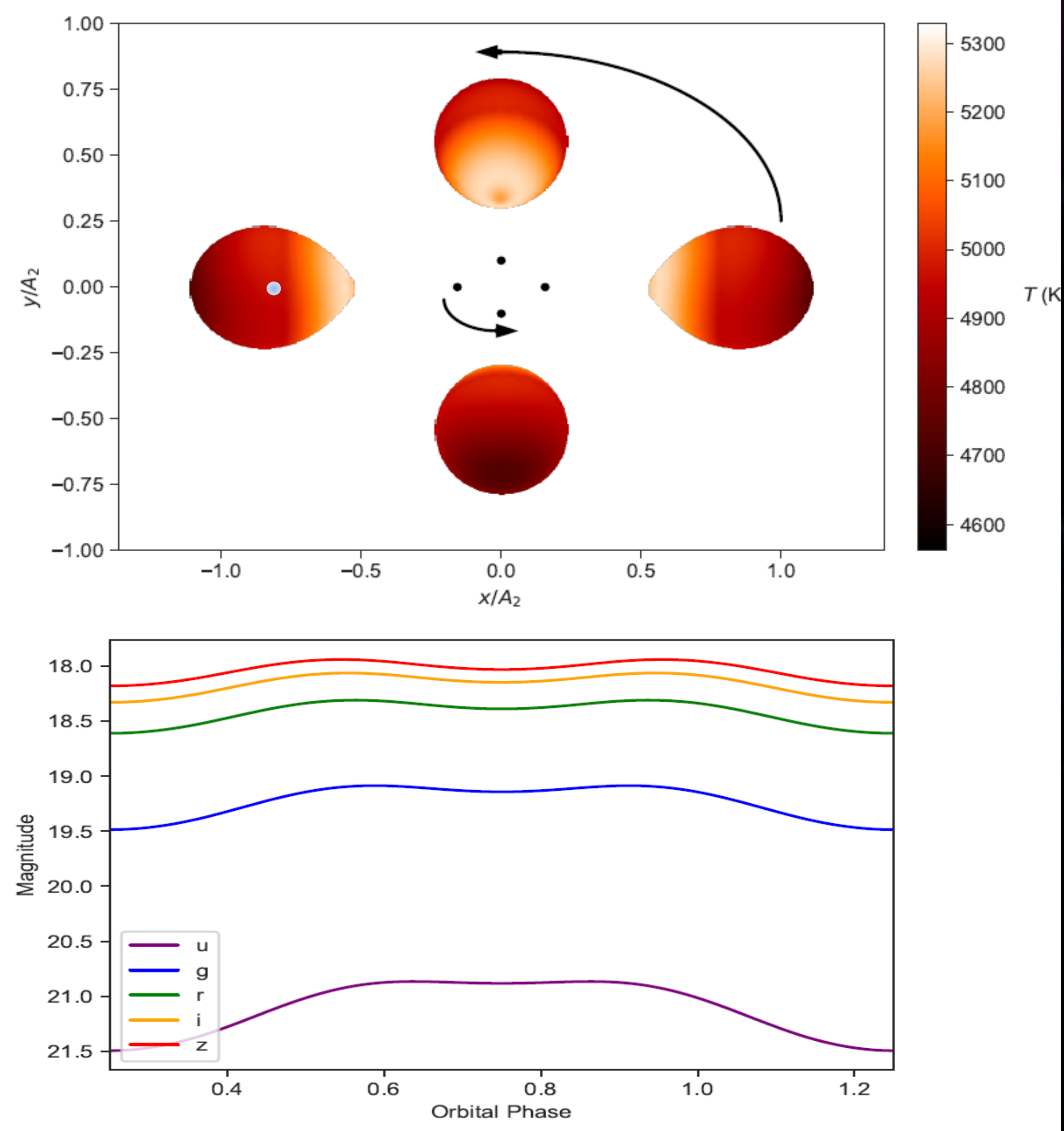
Black Widows and Redbacks

- **Spiders**
  - Fast millisecond pulsars ($\lesssim$ 5ms)
  - Short, circular orbits (75m – 15 hours)
  - Large spin-down luminosity (Edot 10^{34} 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 (~0.02 $M_\odot$)
  - ~25

- **Redbacks**
  - First PSR J1023+0038 (2009)
  - Low Companion Mass (~0.2 $M_\odot$)
  - Some show state transitions ‘MSP <-> LMXB’
  - ~25

Redback


1.00
0.75
0.50
0.25
0.00
−0.25
−0.50
−0.75
−1.00
y/A2
−1.0
−0.5
0.0
0.5
1.0
x/A2
5300
5200
5100
5000
4900
4800
4700
4600
T (K
18.0
18.5
19.0
19.5
20.0
20.5
21.0
21.5
Magnitude
u
g
r
i
z
0.4
0.6
0.8
1.0
1.2
Orbital Phase

Redback Binary Systems

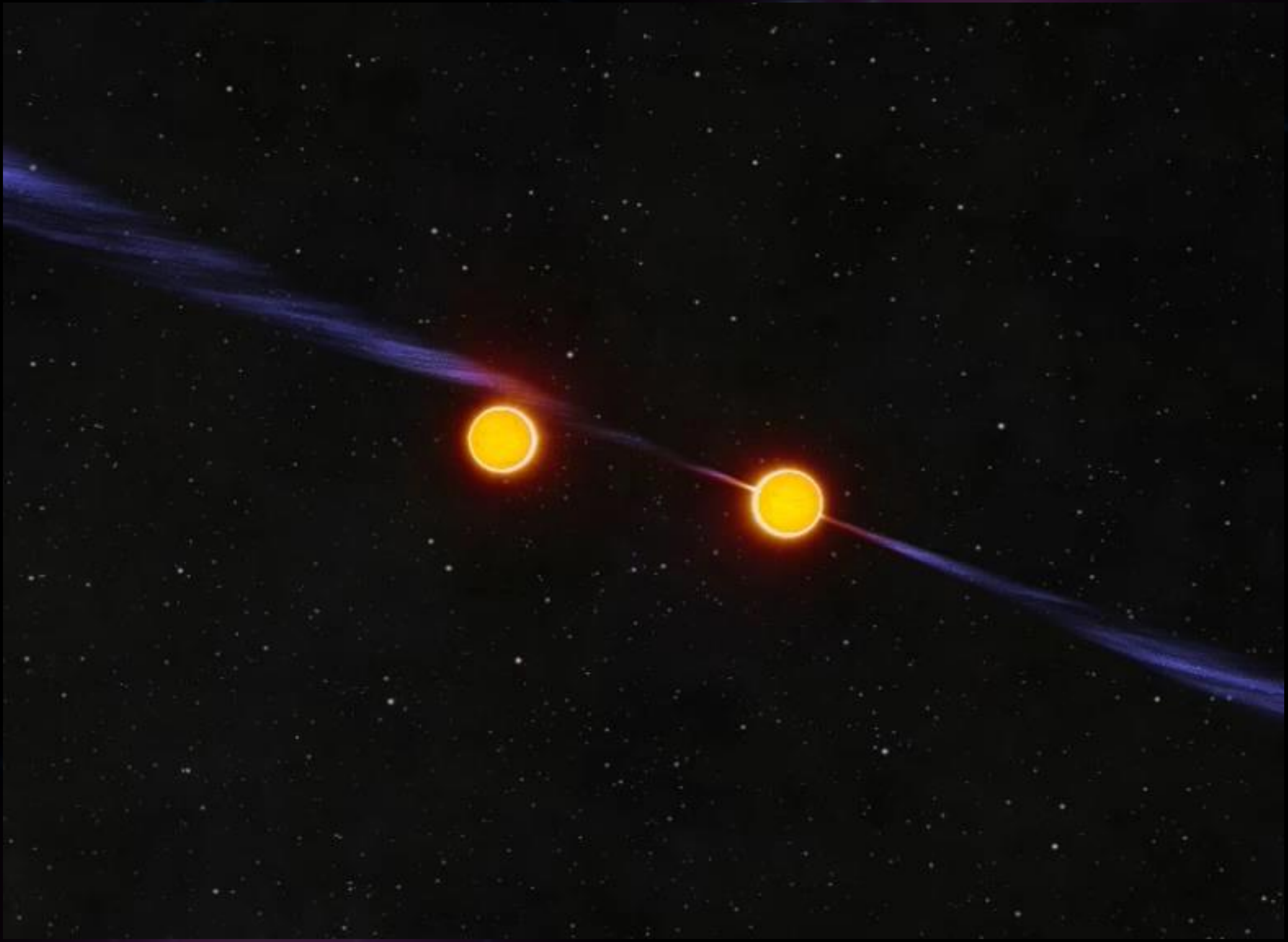


Image credit: ASTRON

Black Widow Pulsar

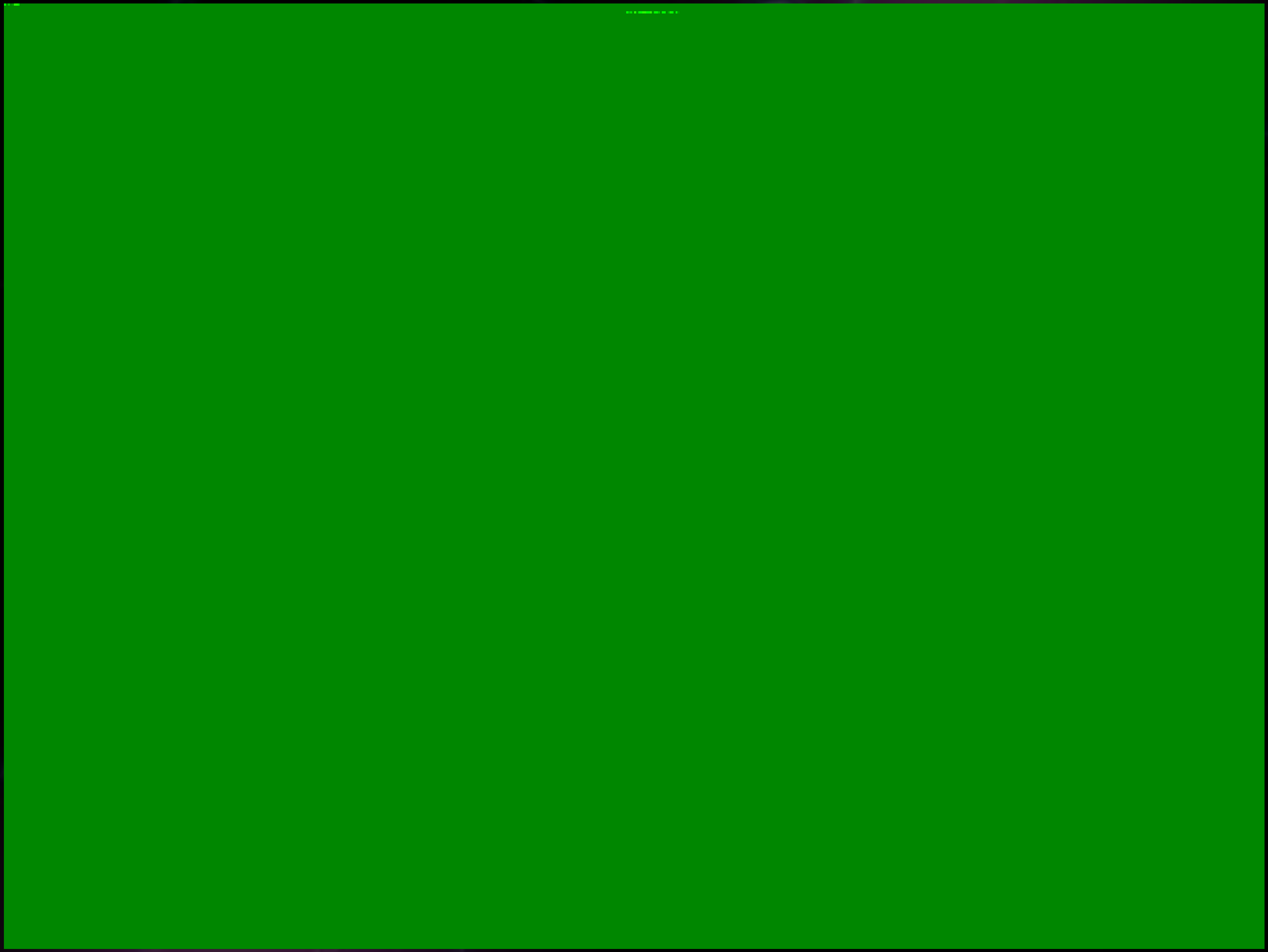


Image credit: NASA

Thank you

www.Jodcast.net

Pulsar-Hunters.org

www.zooniverse.org/projects/zooniverse/pulsar-hunters

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

A new pulsar timing system (PTS) for the GRAO

- **Ghana Radio Astronomy Observatory**
  - Converted telecommunication dish
  - Located 5º 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

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)