Introduction to Pulsar Timing

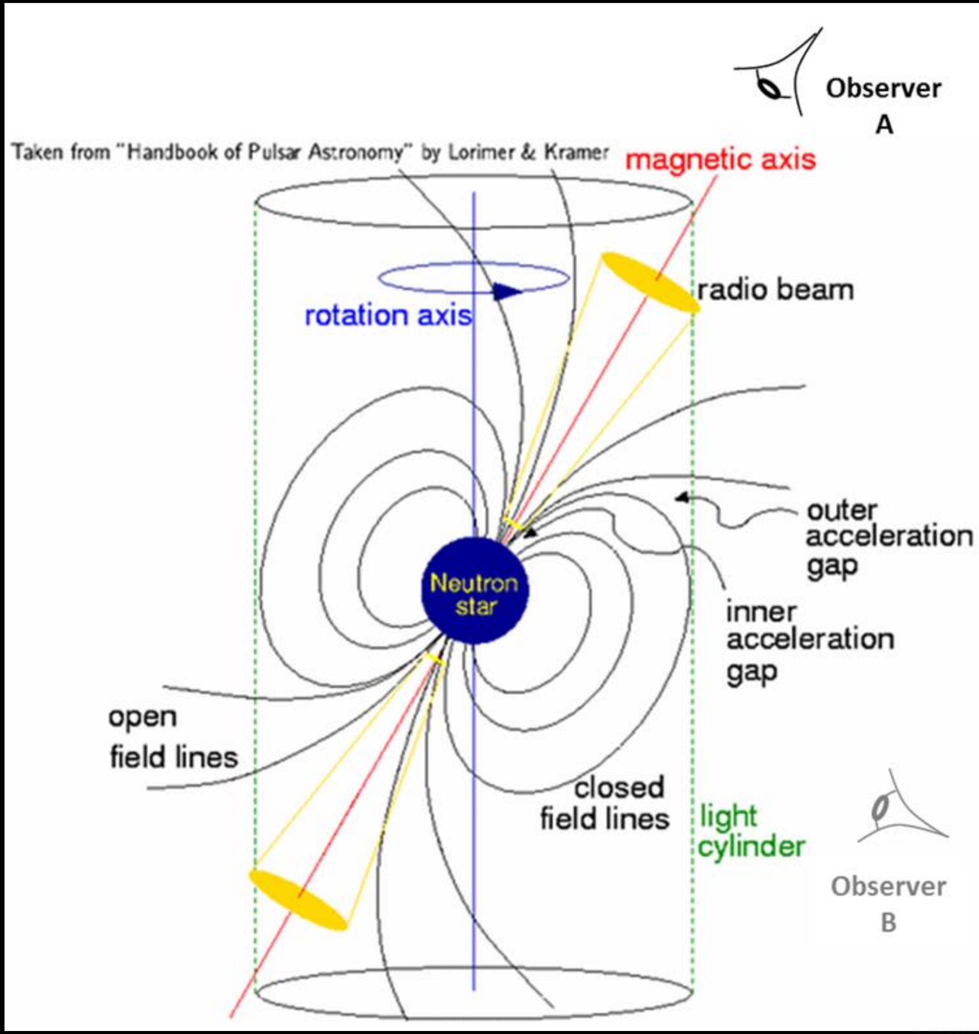
Image credit: NASA

Dr Tom Scragg

13/11/2024

DARA / HartRAO

What are pulsars?



They are **not** stars that pulse.

A pulsar is a neutron star where the magnetic pole is not aligned with the axis of rotation and generates a beam of radiation that periodically aligns with our line of sight

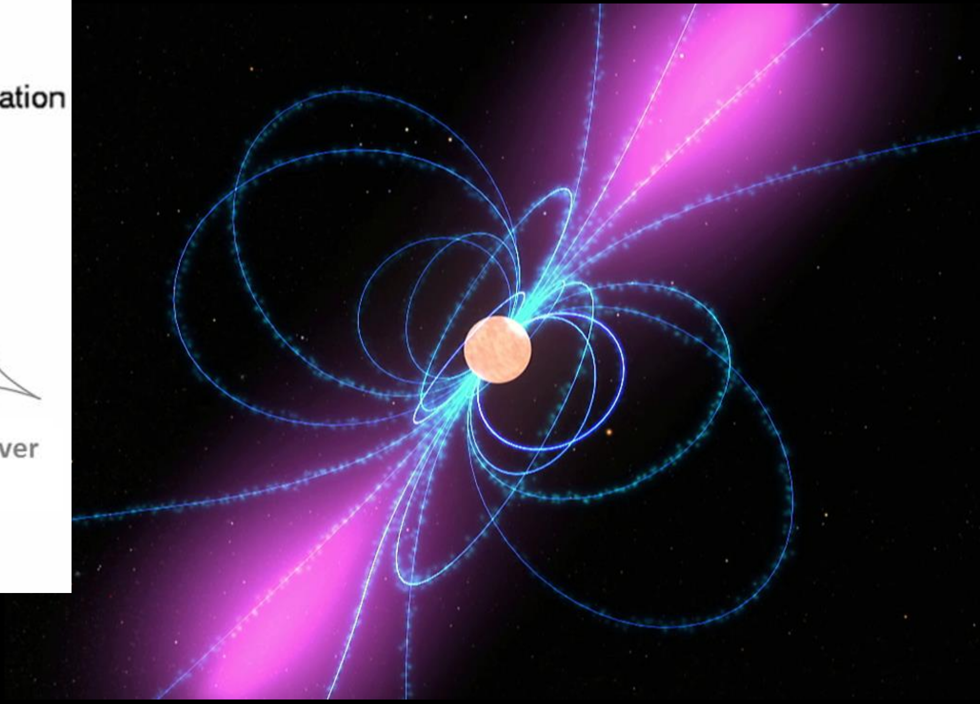


Image Credit: NASA/GSFC

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 modes, Glitches (neutron star interiors)

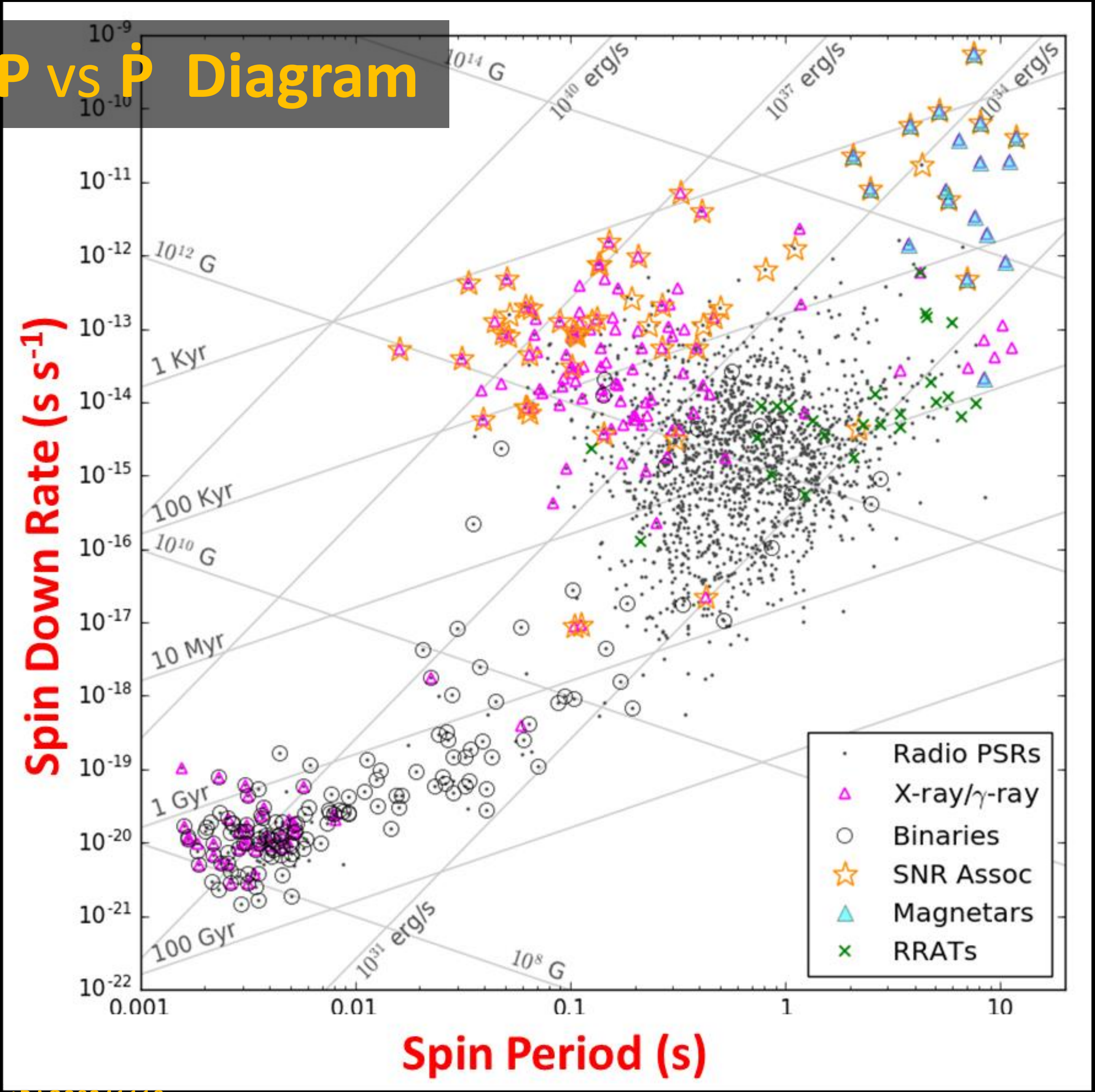
Pulsars in Binary Systems

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

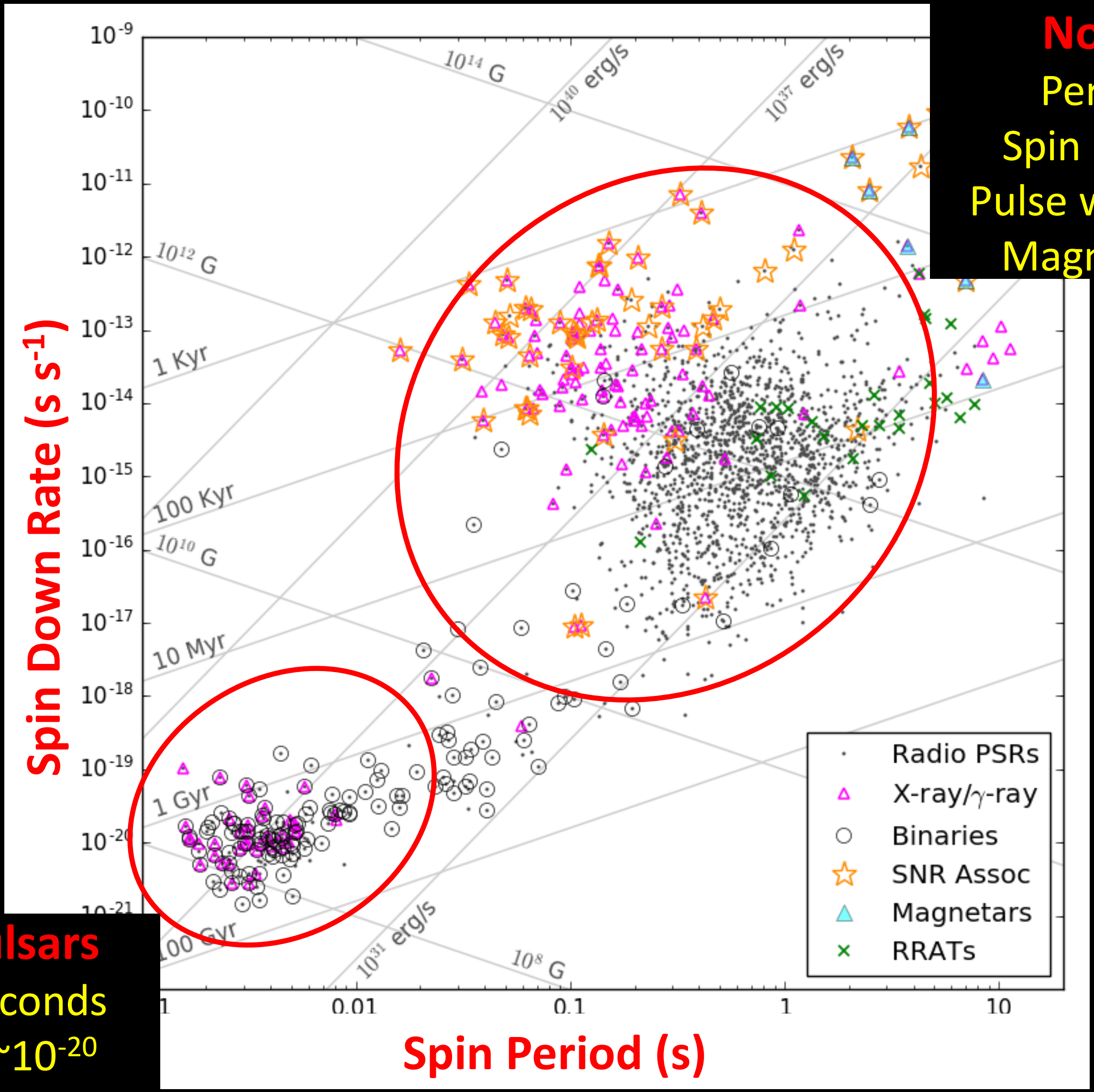
Post Keplerian Orbital mechanics, tests of General Relativity,

Constrain theories on gravity waves

Pulsar 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

Timing of Pulsars

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

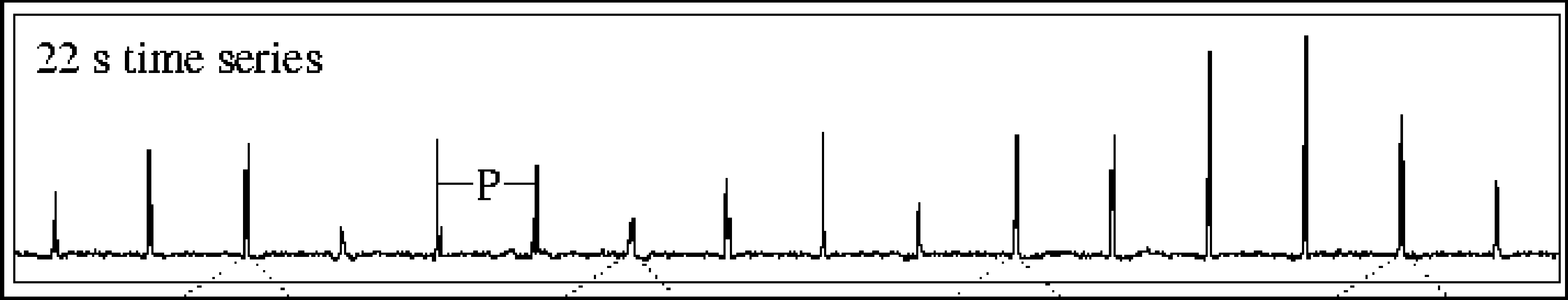


Image Credit: Adapted from Pulsar Astronomy

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

Ways of Measuring the Period

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).

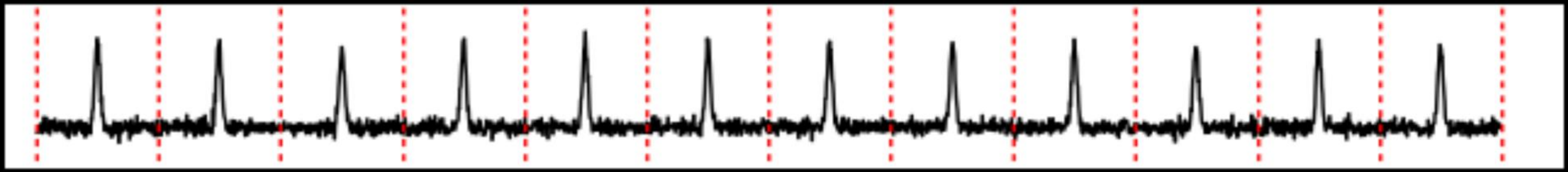


Image Credit: Scott Ransom

- 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 = 4.570136529159926 ms ± 0.1 x 10^{-8}ns

Search: Periodogram & FFT Analysis

- **A data stream of N samples is folded at *N* different values of period P.**
  - If N = 10,000 and we fold in steps of 1 sample period (1,2,3 …100..1000) we have over 90,000 profiles to search for a pulse
  - Each profile will have a different value for improved SNR because the number of samples in each profiles is different.
- **FFT of the data sample**
  - Take the frequency transform of the time series data and looking for frequency components:
  - The width of the frequency peak, Δf is proportional to 1/T (T= length of the data series in time). So for a 5 minute observation 1/T ~ 3ms for a 1Hz pulsar)

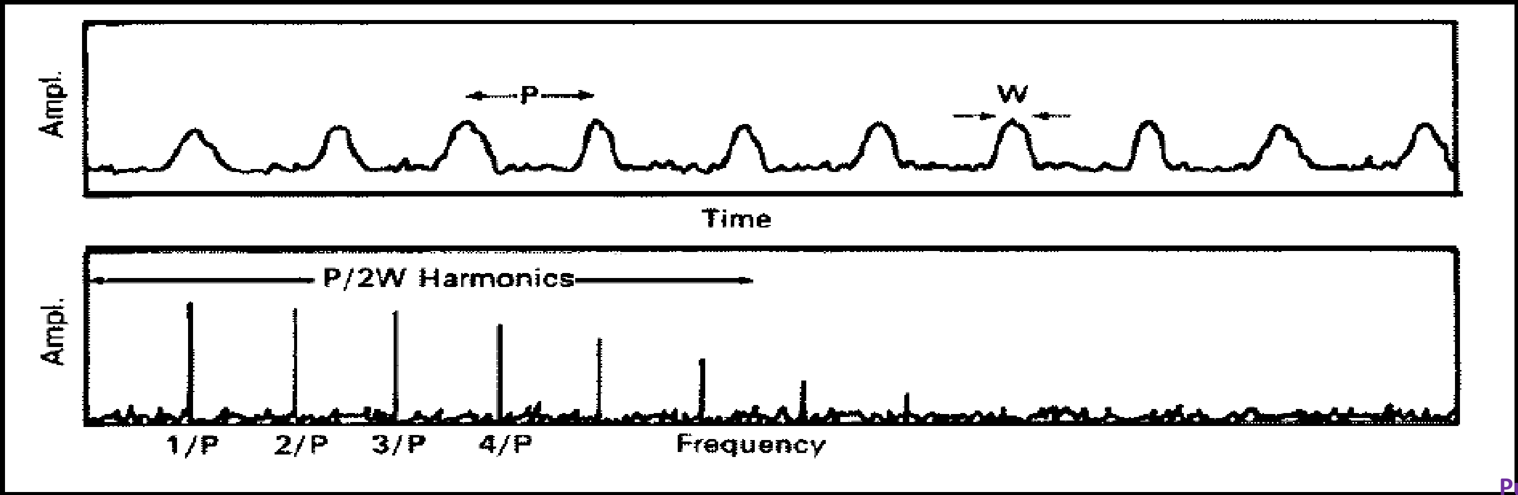
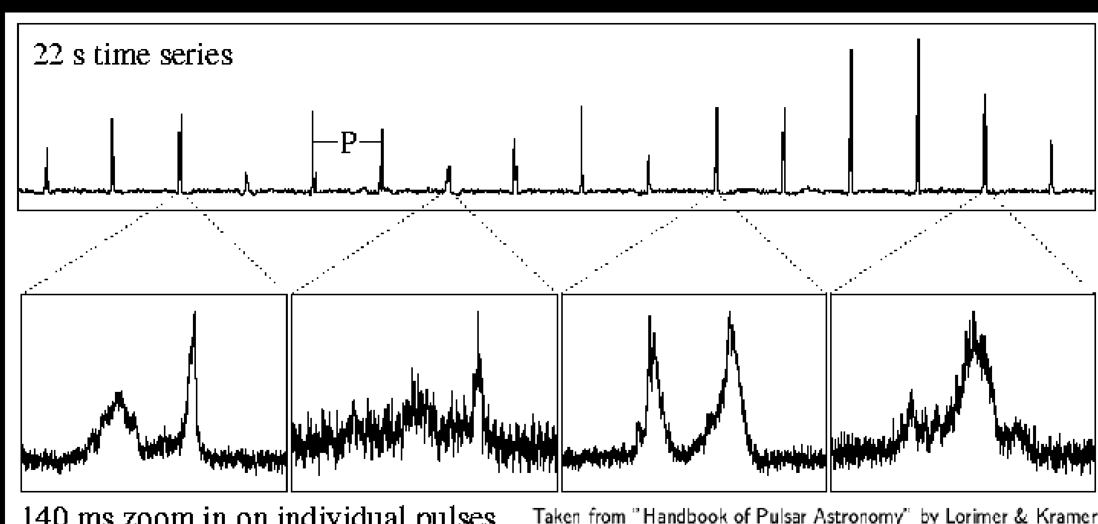


Image Credit: Pulsar Astronomy

Integrated Pulse Profile

- **Pulses may be below the noise floor of our instrument**
  - Sum many observations to improve signal to noise
- **Pulses are not simple consistent shapes**
  - Profile Stabilisation Time: few 100's to a many 1000s of pulse periods.



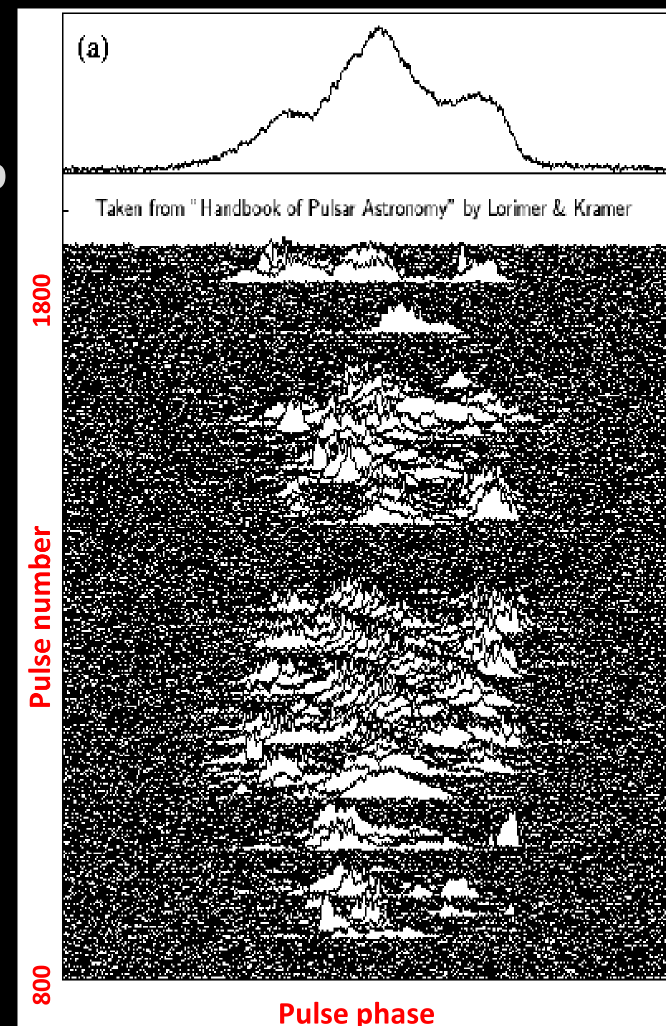


Image Credit: Adapted from Handbook of Pulsar Astronomy

MANCHESTER 1824
The University of Manchester

Profile changes over Time

examples: Thesis T W Scragg 2020 JBCA, University of Manchester

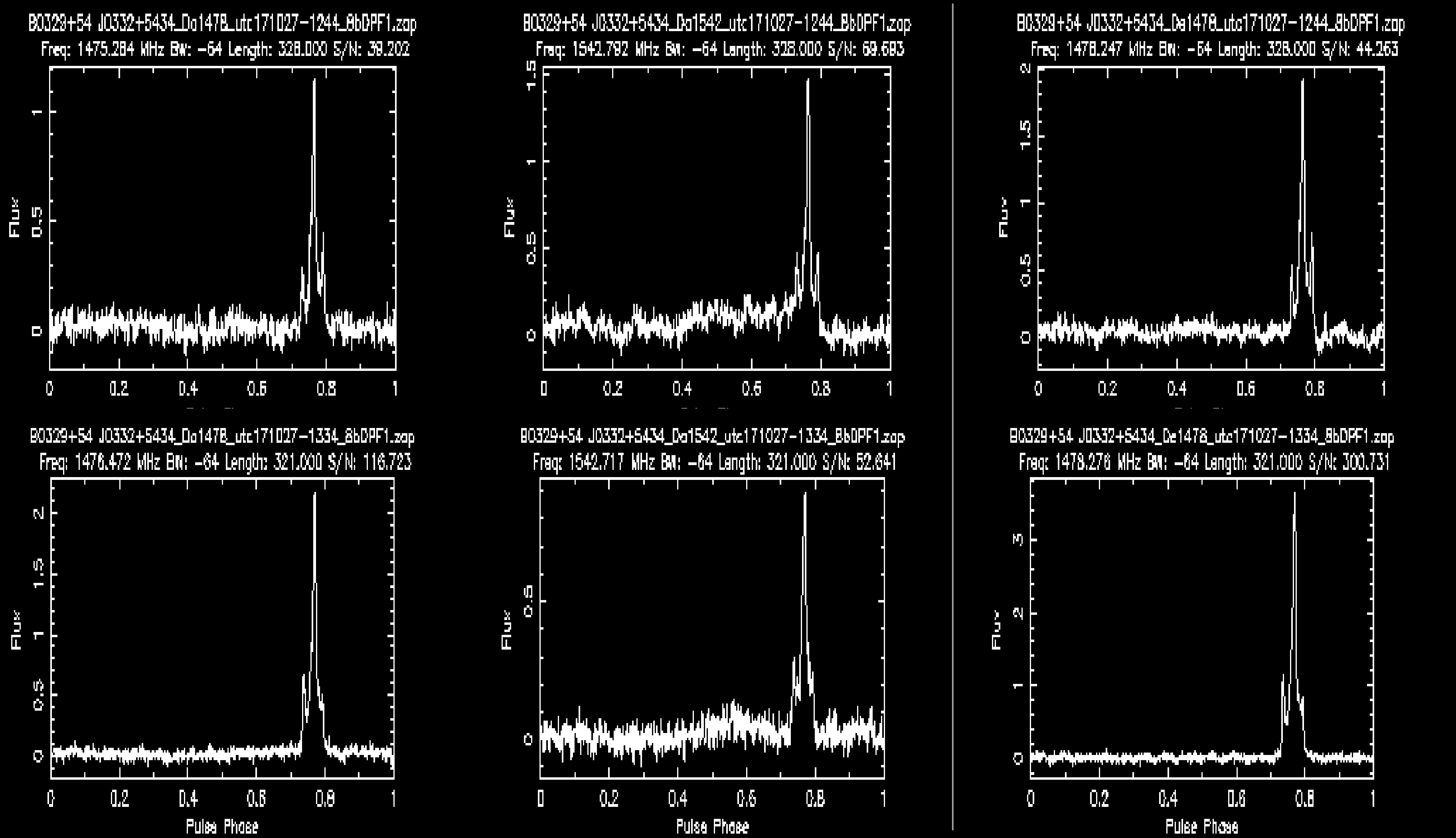


Image Credit: Tom Scragg, JBCA, Unpublished Research

Pulse Shapes at Different Frequencies

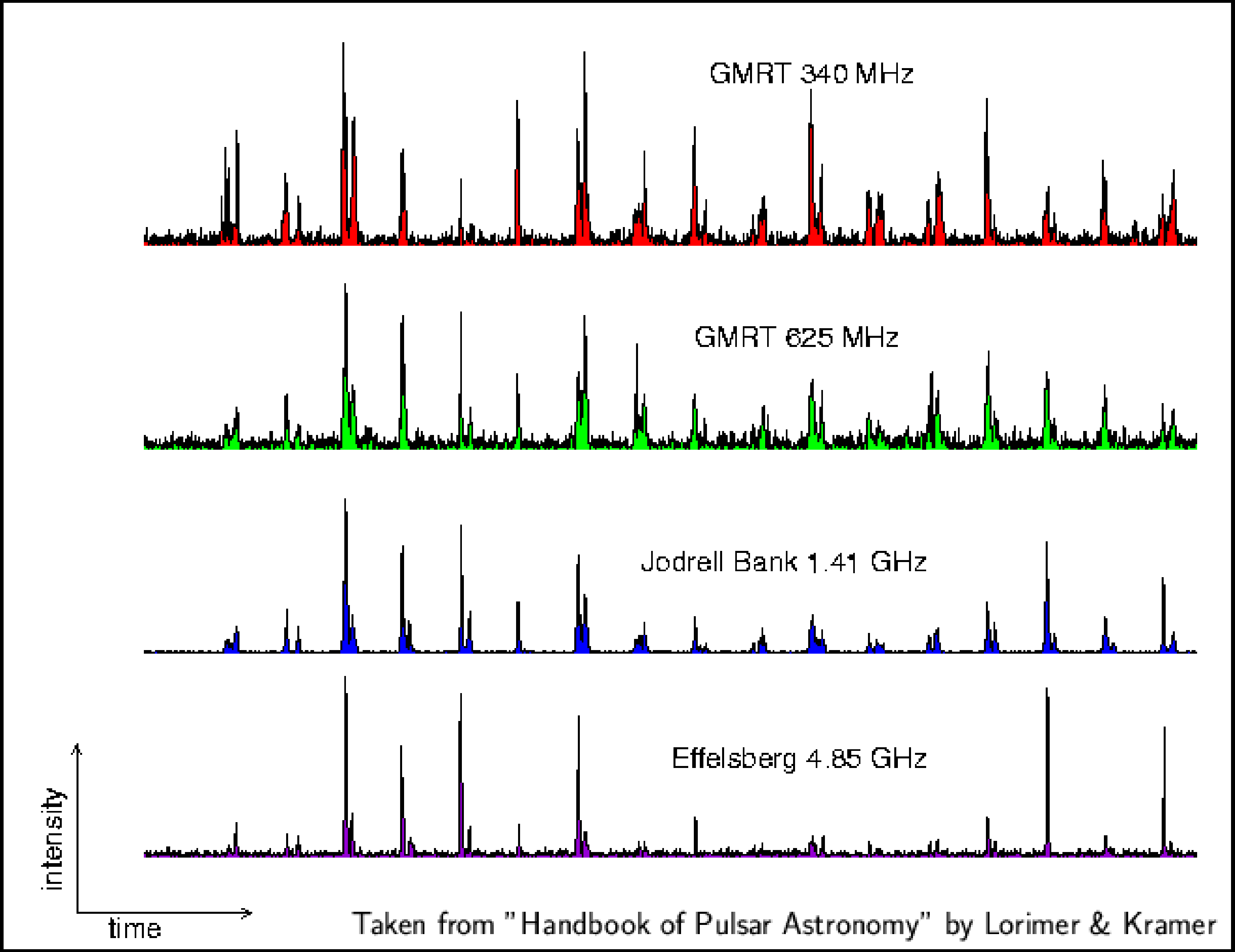
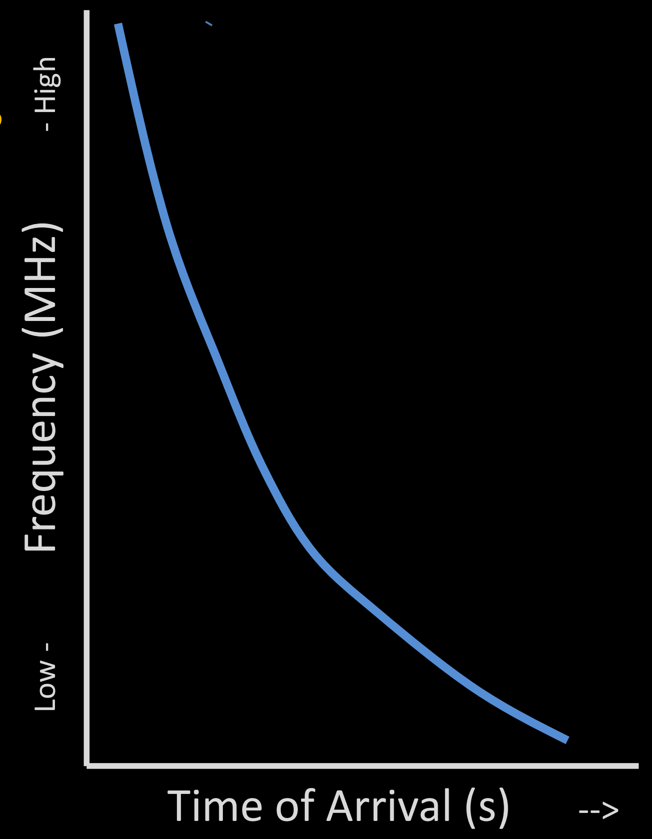


Image Credit: Lorimer & Kramer

Dispersion - 1

- **The transmission of a radio signal through the interstellar medium (ISM) is delayed proportional to it's frequency**
  - High frequencies arrive earlier than lower frequencies
- **Dedispersion**
  - We process the data to reverse the effect of the Interstellar Medium on the pulsar signal.
- **Dispersion Measure**
  - A measure of the electron density along the line of sight to the pulsar (cm^{-3} pc)
  - Above 300 can be considered extragalactic



Dispersion - 2

Δt = time delay
v_g = group velocity through a plasma
D = Dispersion Constant
DM = Dispersion Measure
e = charge on the electron
m_e = mass of the electron

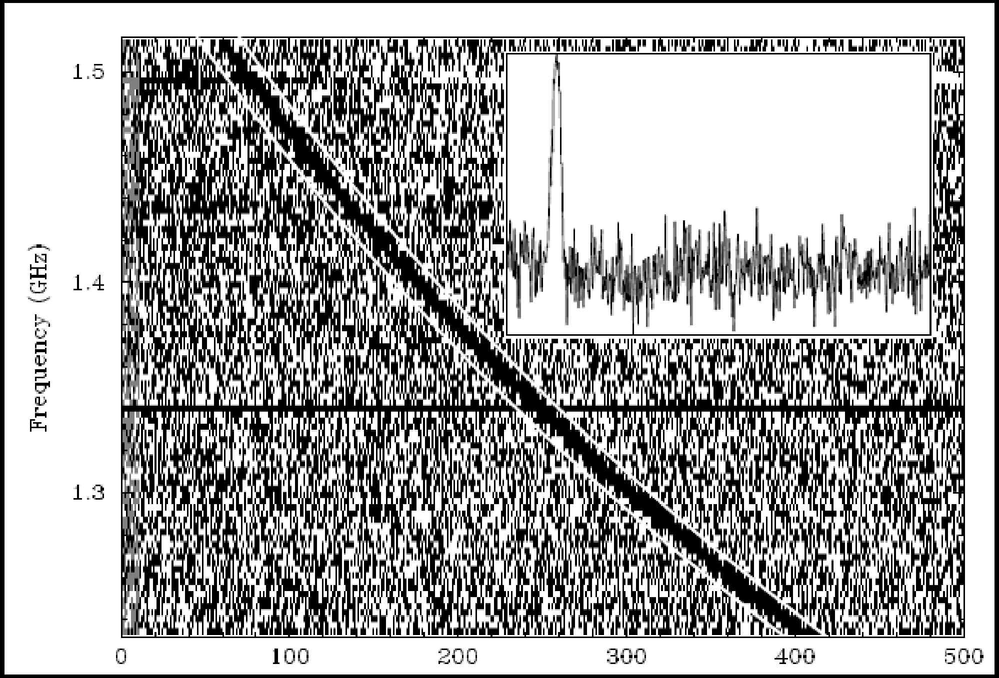


Image Credit: Handbook of Pulsar Astronomy Lorimer & Kramer

$$t = \left(\int_0^d \frac{dl}{v_g}\right) - \frac{d}{c} \quad s$$ (a

$$\Delta t = D \times ({f_1}^{-2} - {f_2}^{-2}) \times DM \quad s$$ (b

$$D = \frac{e^2}{2\pi m_e c} \approx 4.148808 \pm 0.00003 \times 10^3 \quad MHz^2\, pc^{-1}\, cm^3\, s$$ (c

$$DM = \int_0^d n_e dl \quad cm^{-3}\, pc$$ (d

Scrunching and Folding

- **The noise within a pulsar signal is not correlated with respect to frequency or time.**
- **Scrunching in frequency**
  - Filter banks separate the incoming signal into frequency channels
  - After dedispersion the signal is correlated wrt to time but the noise is not
  - Combining the separate frequency channels increases the signal and reduces the noise S/N.
- **Folding in time**:
  - We observe the pulsar for a much longer time than a single period of rotation.
  - Adding multiple periods together reduces the noise and improves signal gain (S/N)
  - *And generates a stable pulse profile*

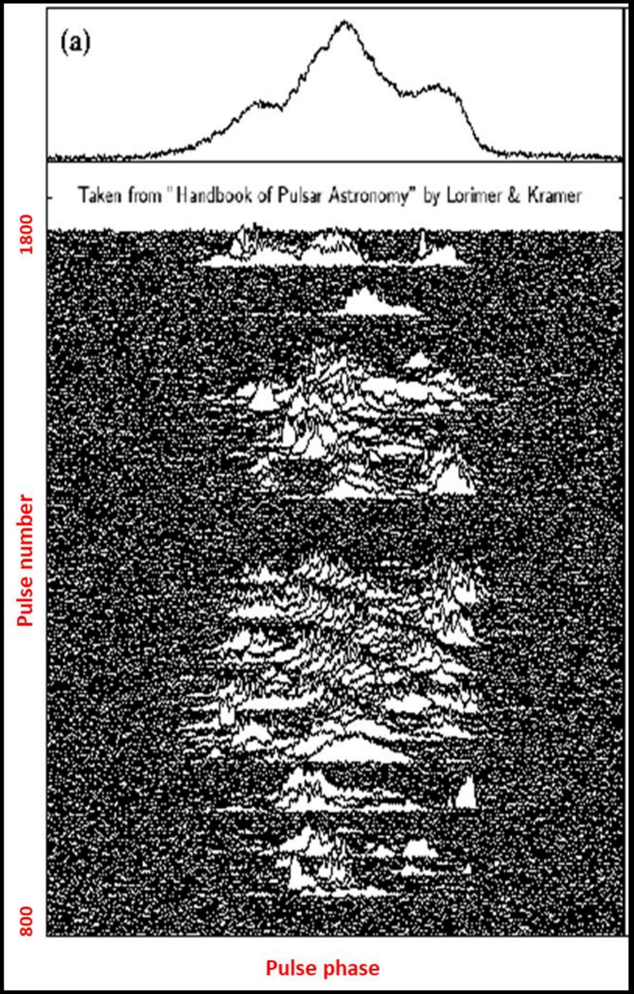


Image Credit: Adapted from Handbook of Pulsar Astronomy

Spin-Down $\dot{P}$

Pulsars are 'Rotation Powered'

- A rotating magnetic dipole radiates energy
- The pulsar slows down at a rate $\dot{P}$
- $\dot{P} = -KP^{2-n}$
- *n* is the 'braking index' and canonically is = 3 but,
- Measured values range from 1.4 to 2.9 indicating other energy loss process are in play.

$\dot{P}$ itself varies over time:

- Change in $\dot{P}$ over 27 years for 17 pulsars
- ***?***

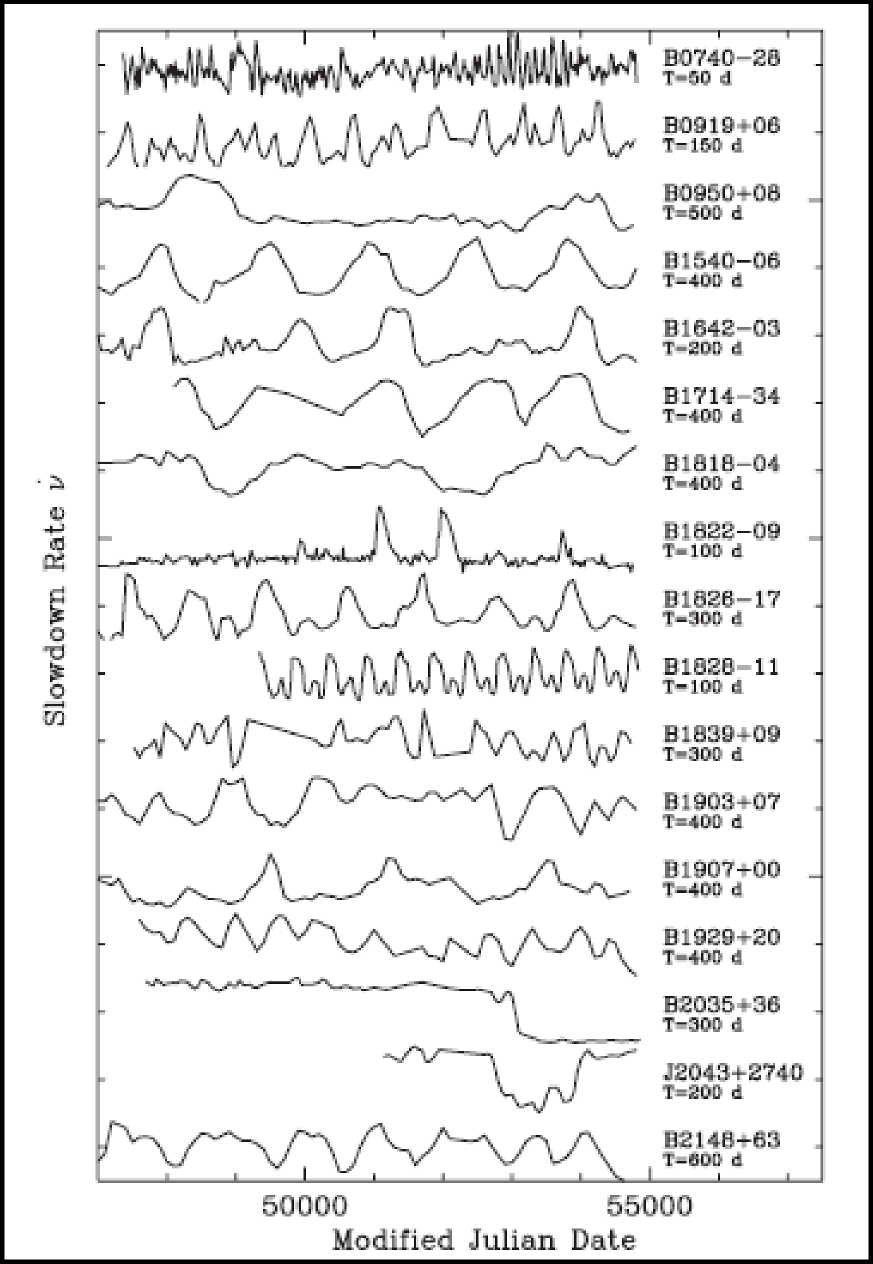


Image Credit: Figure 3 A Lyne IAU Symposium 2013

Pulse Time-of-Arrival

- **Individual pulses may not be identical but integrated pulse profiles are very stable between Observations**
  – Profile Stabilisation Time: few 100's to 1000s of pulse periods.

- Integrated pulses profiles are not simple shapes so which point to pick as the reference point?
- **Template:**
- Create a template model that will describe the integrated pulse profile
- Cross Correlate pulse and template

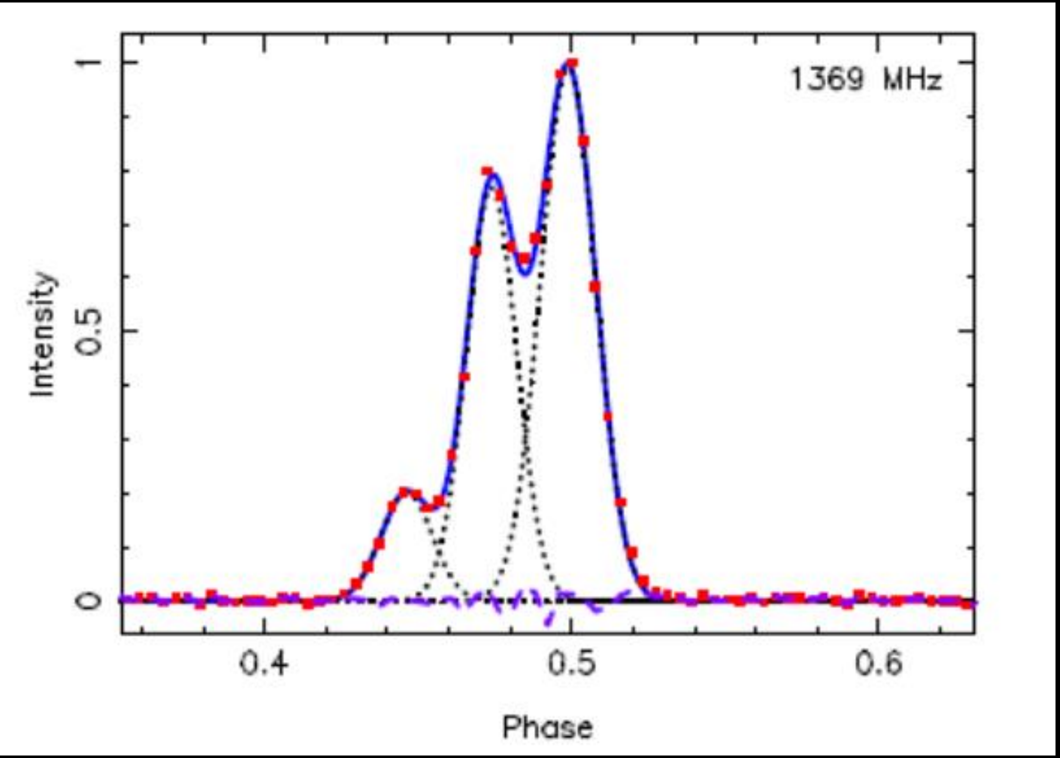


Image credit : Yuan, Manchester, Wang, et al. 2016

Template

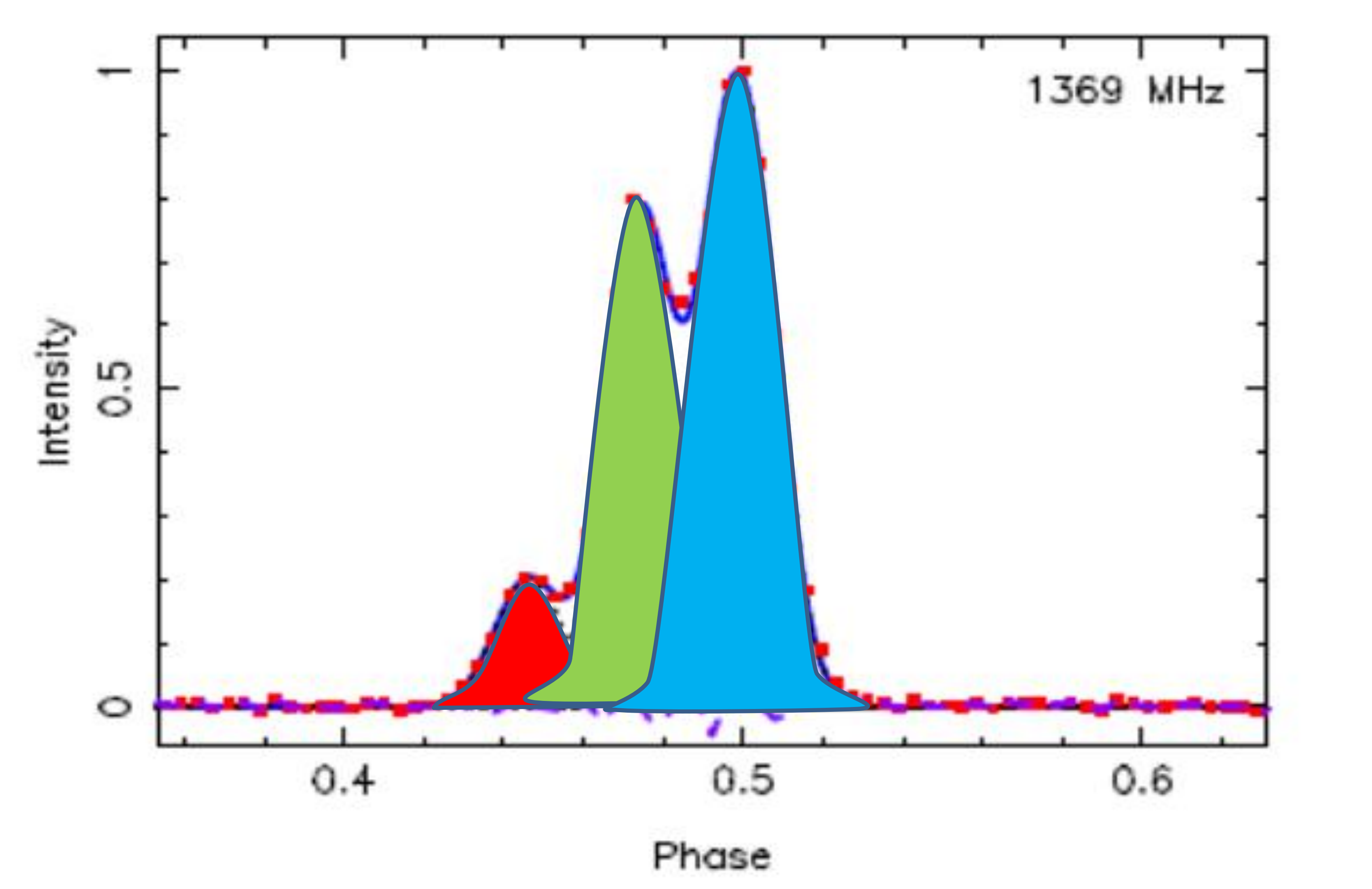
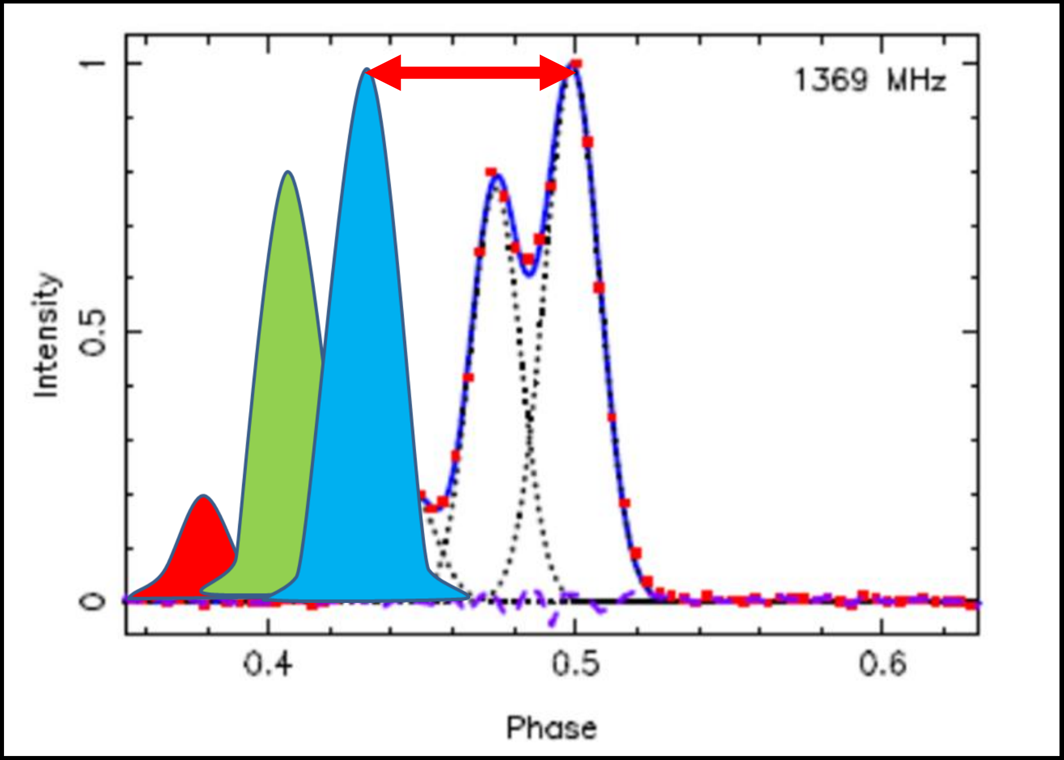


Image credit : Adapted from Yuan, Manchester, Wang, et al. 2016

Time of Arrival

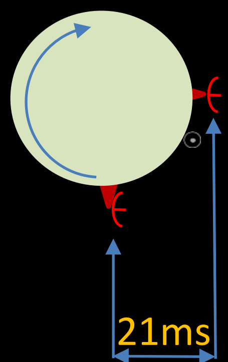
- **Determine the ToA of an integrated pulse profile by the reference to the template model**
  - Cross Correlation gives a phase difference between the expected and measured phase
  - Convert to a time and add to time of first bin to get the ToA



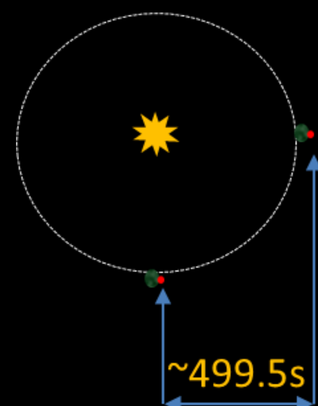
Corrections to ToA

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

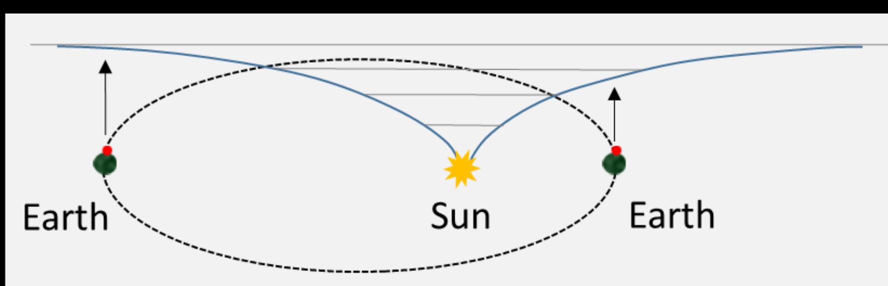
Correction	Typical value/range
Observatory clock to TT	1 µs
Hydrostatic tropospheric delay	10 ns
Zenith wet delay	1.5 ns
IAU precession/nutation	~5 ns
Polar motion	60 ns
ΔUT1	1 µs
Einstein delay	1.6 ms
Roemer delay	500 s
Shapiro delay due to Sun	112 µs
Shapiro delay due to Venus	0.5 ns
Shapiro delay 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]



T_{tops}

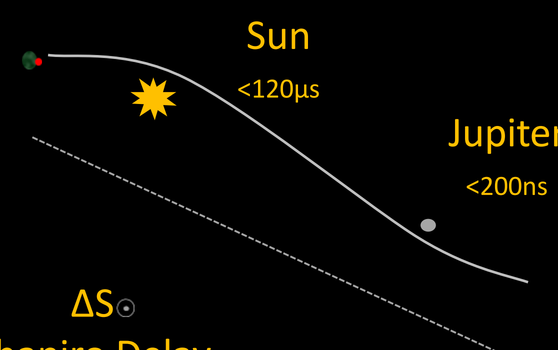


$\Delta R_\odot$ Romer Delay



~1.6ms

$\Delta E_\odot$ Einstein Delay



$\Delta S_\odot$

Shapiro Delay

Timing Model and Residuals

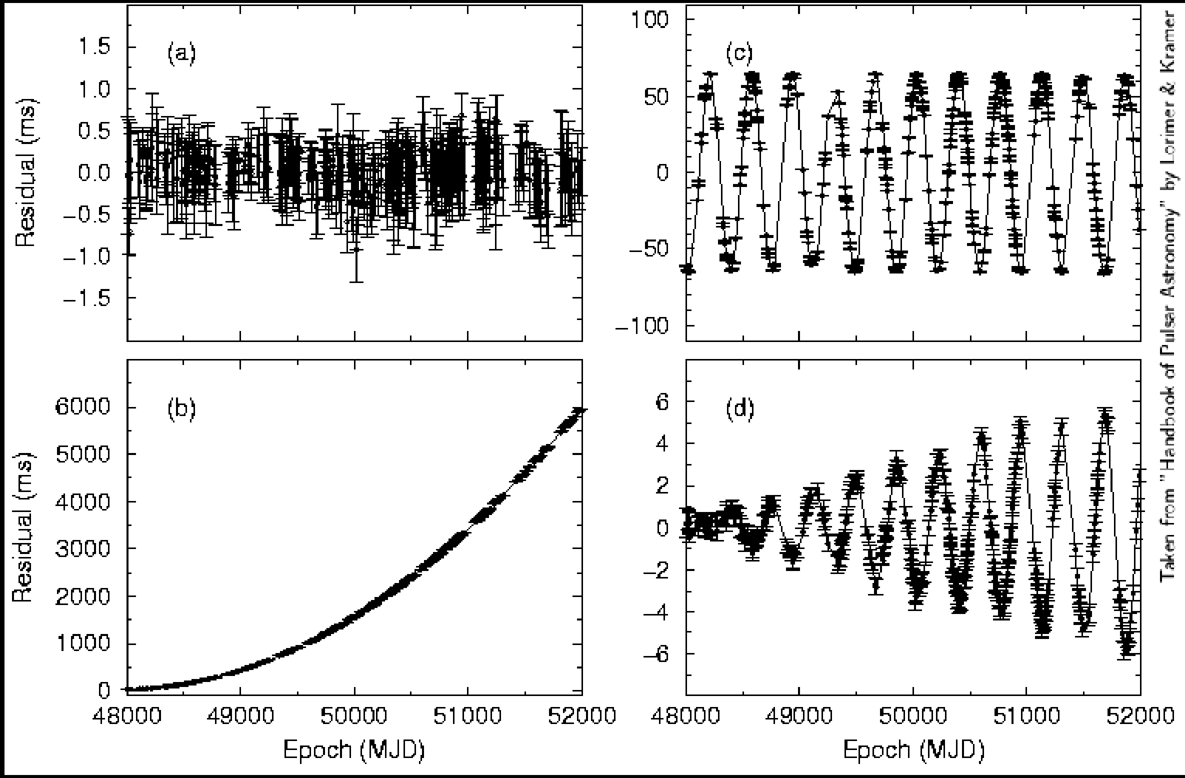
- A timing model allows us to calculate the expected arrival of
  - Pulse number 1,000,000 (day 11)
  - Pulse number 10,000,000 (day 115)
  - Pulse number 1,000,000,000 (day 11,575 – in year 31)
- Iterative process starting with a few closely grouped observations
  - Extend the time duration and precision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

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 = 'Timing noise'

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

Phase Coherence

- **Simply we have a timing solution that is accurate enough that the accumulated uncertainties do not exceed one pulse period.**
- **Building a Timing Model**
  - **Start with Spin period and Pulse reference phase (template)**
  - **Spin frequency derivative ($\dot{P}$)**
  - **Position**
- **Precision improves with**
  - **Data span (time) and**
  - **Frequency of observations.**

- ***Pulsars in Binary Systems have another set of orbital parameters to characterise***

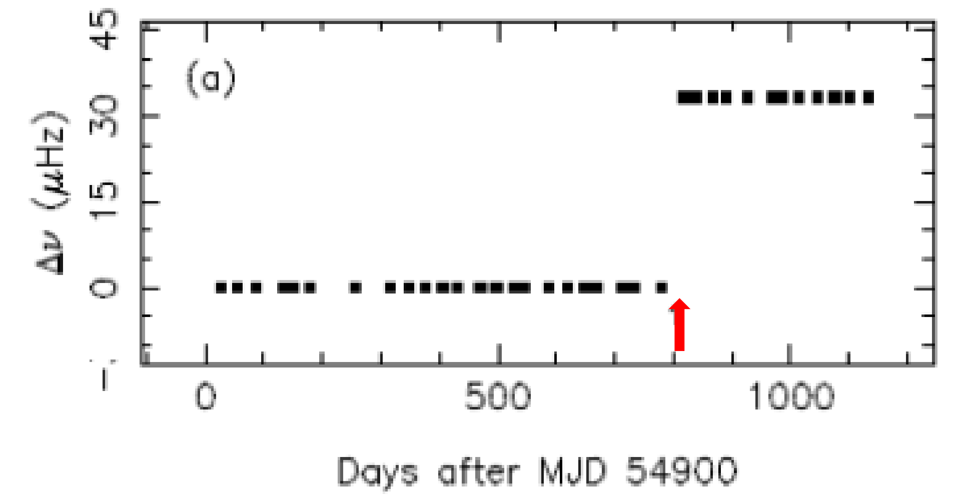
Glitches

- **A glitch is a sudden step change in spin frequency**
  - The pulsar spins faster
  - The spin down rate ($\dot{P}$) increases and then decays back to the original value.

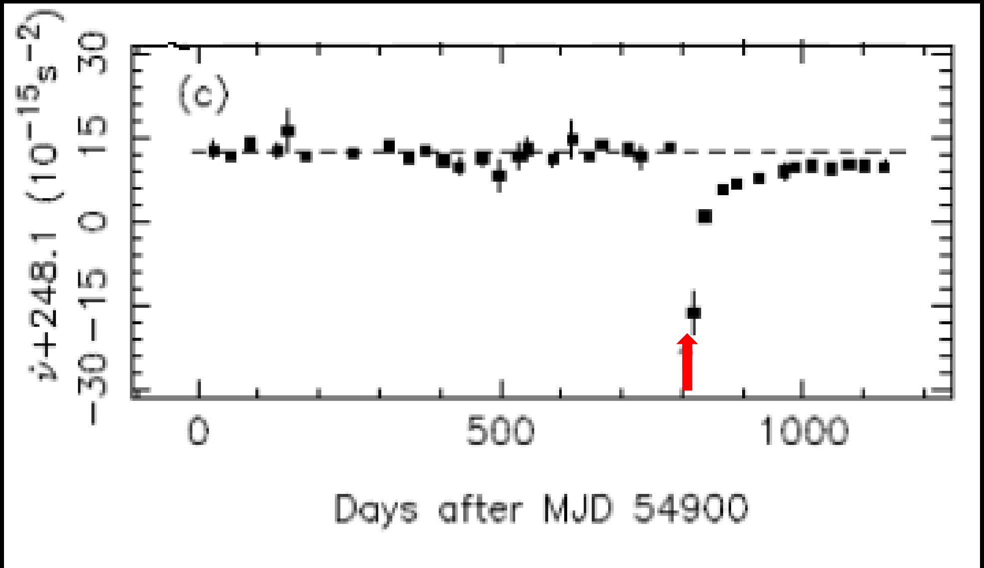
- **Glitch in PSRJ1757-2421**
  - at ~ MJD 55700 (May 16 – 27 2011)
  - Fractional increase of $\Delta\nu_g / \nu$ ~ 7.8×10^{-6}
  - ν = $4.271\,592\,656\,55(4)\ s^{-1}$
  - $\Delta\nu_g = 4.271\,573\,098\,0(8)\ s^{-1}$

Glitch in PSR J1757-2421

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

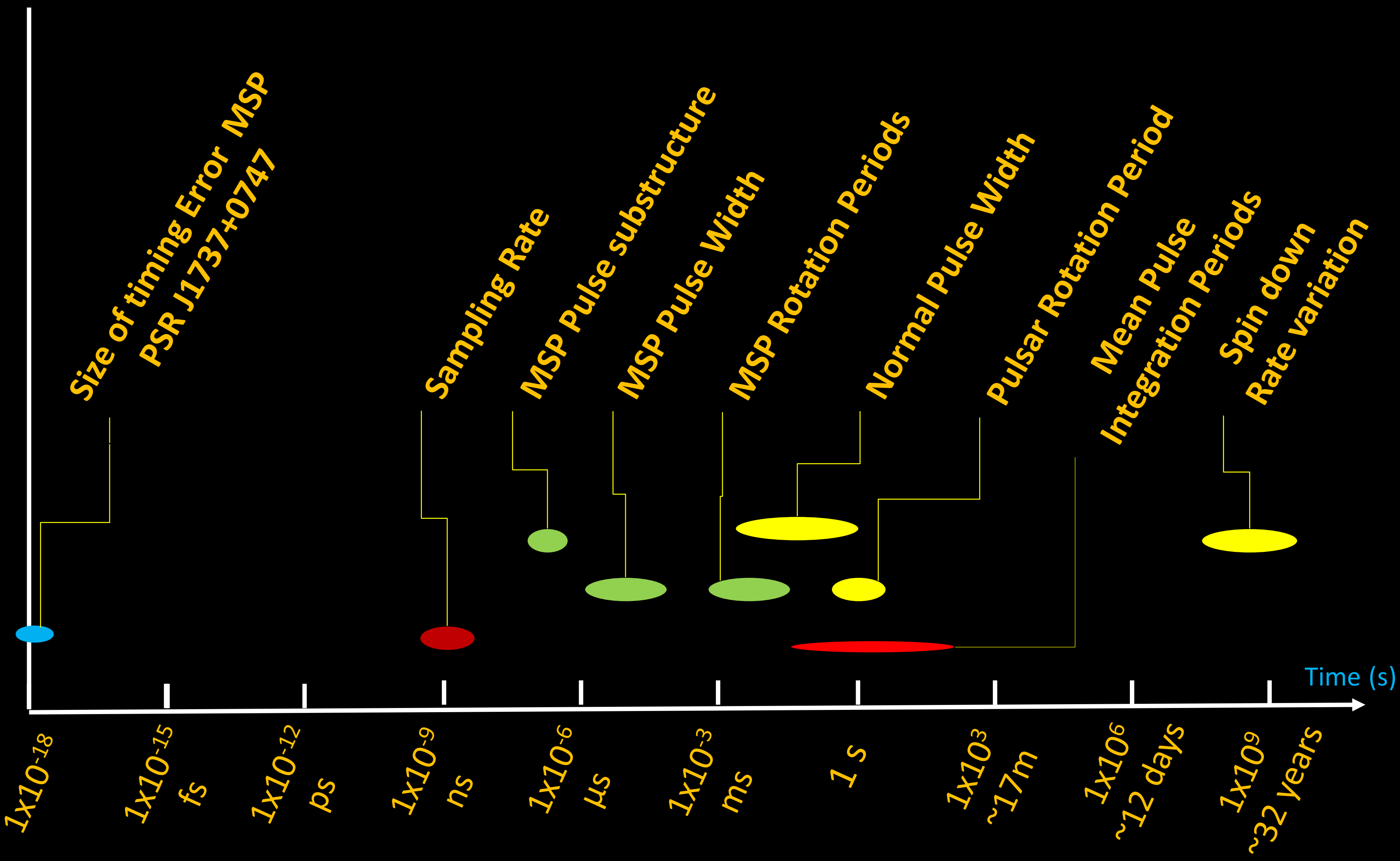


- The bottom panel shows the variations of Ṗ, and the horizontal dashes indicate the average pre-glitch level.



The glitch epoch is indicated by a red arrow.

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
$1x10^{3}$ ~17m
1x106 ~12 days
1x109 ~32 years

Thank you

Figures

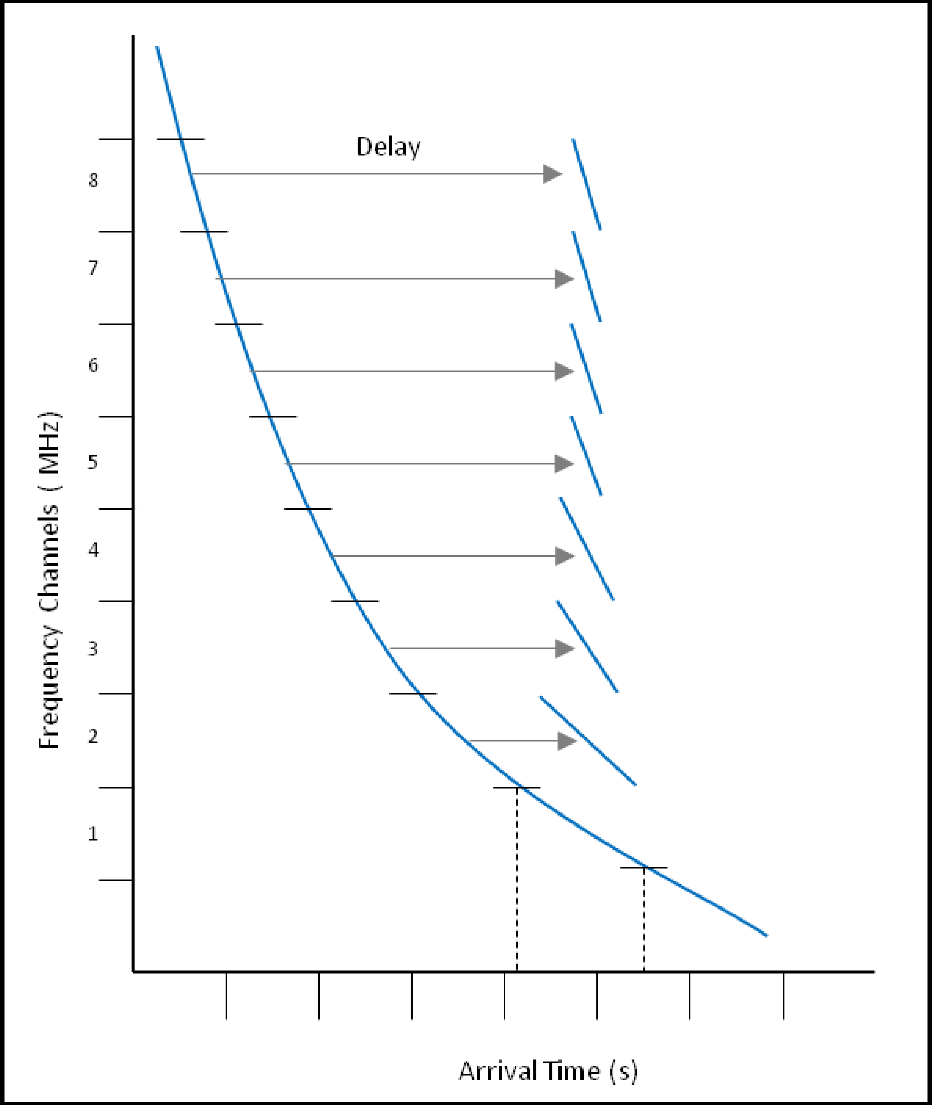
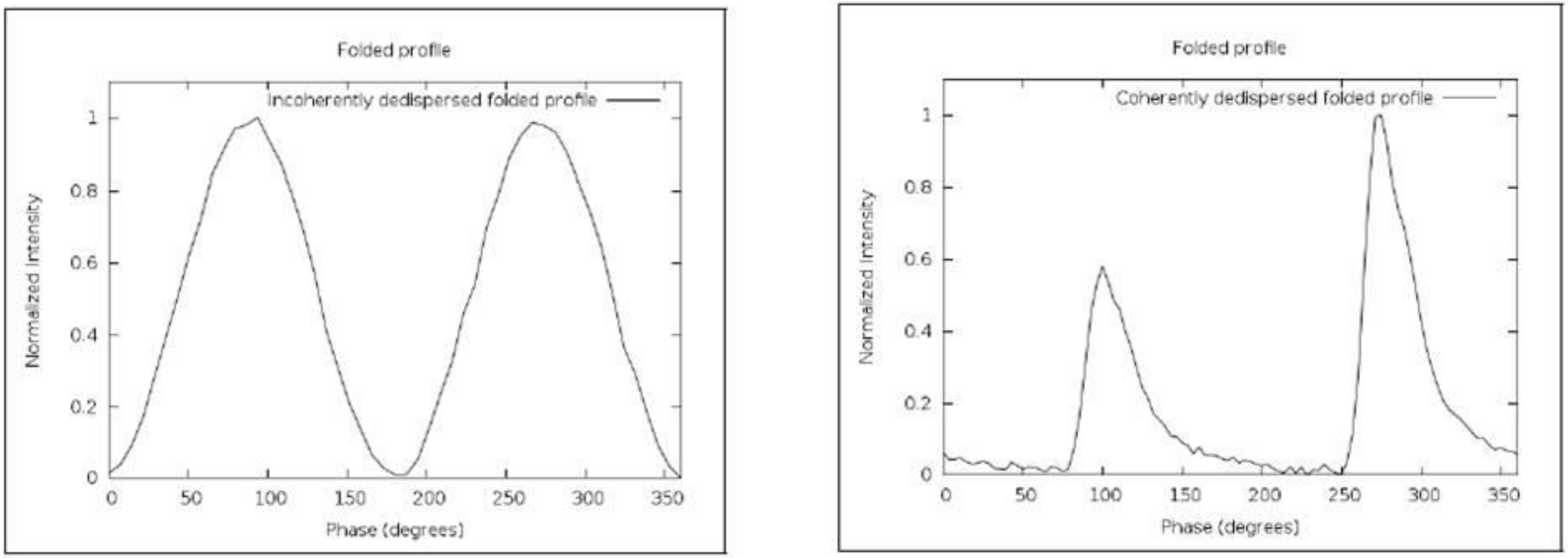


Figure 2.5.2 Incoherent De-dispersion. The signal phase in adjacent frequency channels is delayed by an amount depending on the channel centre frequency. The uncorrected frequency dispersion in each channel (indicated by the slope of the blue line segments) gives rise to pulse smearing in the pulse profile. (Adapted from Figure 3.6, Lyne & Graham-Smith (2012)).

Figures

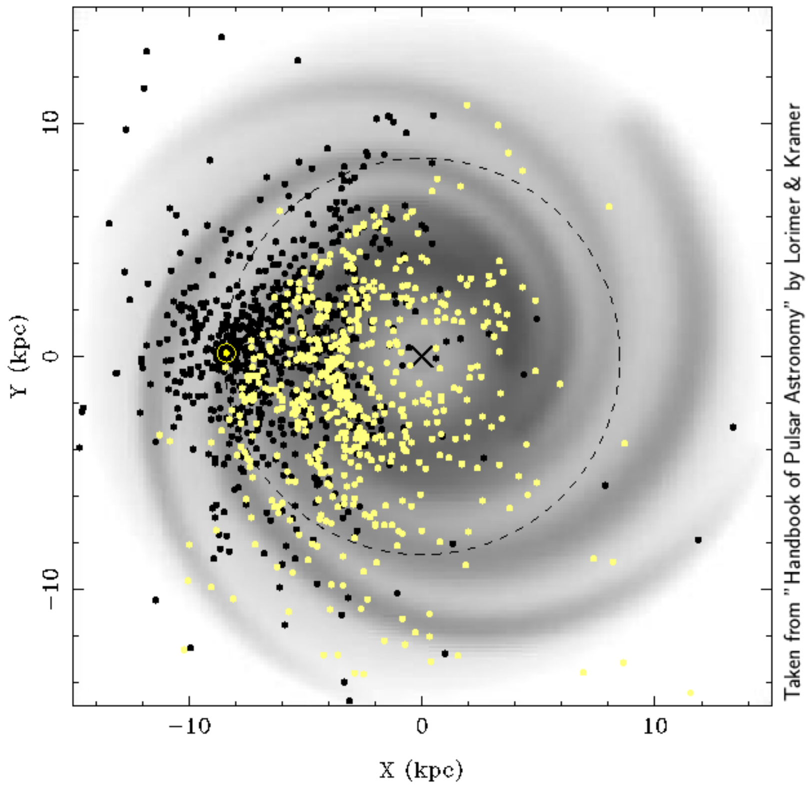


(a) Incoherently dedispersed and normalized folded profile for B1937+21. (b) Coherently dedispersed and normalized folded profile for B1937+21.

Figure 2.5.3 Comparison of incoherent and coherent de-dispersed and folded pulse profiles for PSR B1937+21 (period of 1.55ms and a DM of 71 pc cm^{-3}). The effect of pulse smearing in the incoherently dedispersed mean pulse profile is evident in (a) when compared with the coherently dedispersed mean pulse profile in (b). Panel (b) also shows evidence of the effect of scattering in the long tails on the right hand side of the pulse profile. Data observed with the GMRT @ 325 MHz and a bandwidth of 16 MHz (from Figure 1 De & Gupta, 2015).

ISM Electron density distribution models

NE2001 Cordes and Lazio (2002a)



YMW16 (2016)

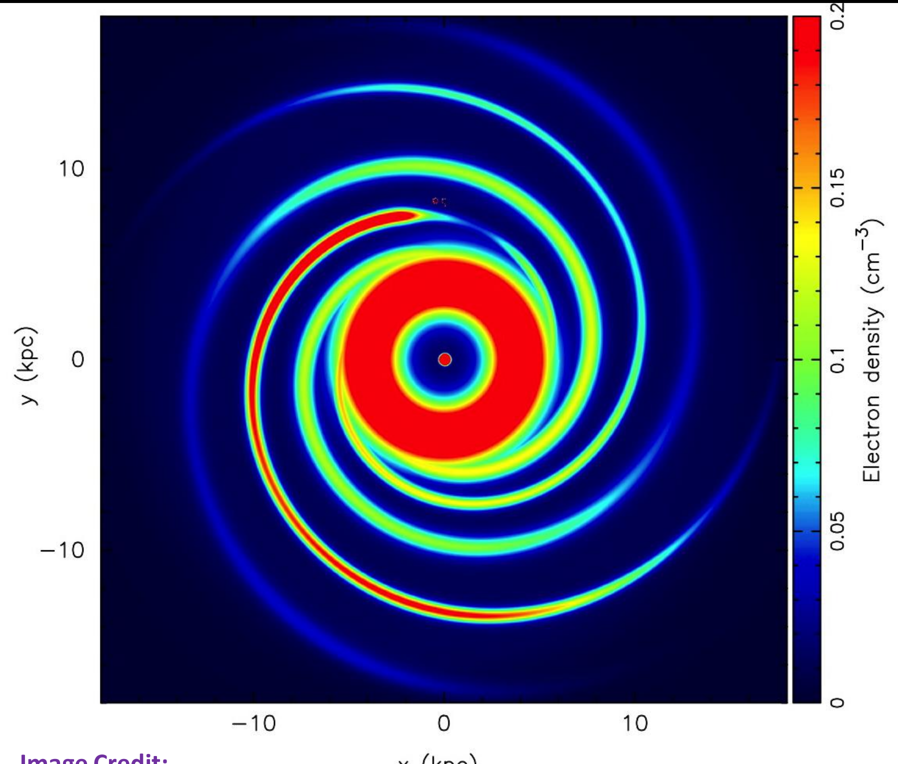


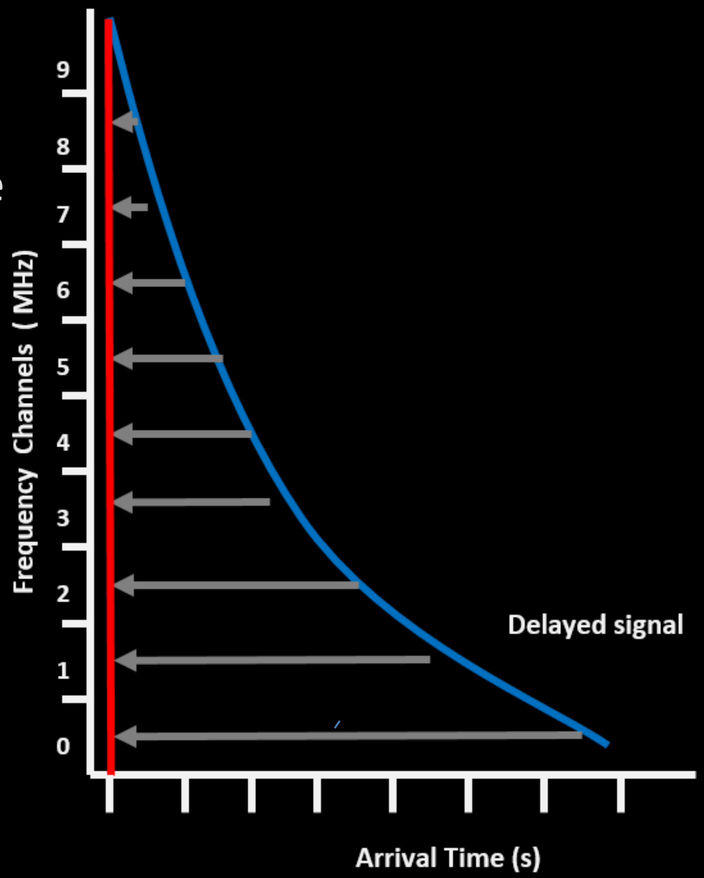
Image Credit: https://www.atnf.csiro.au/research/pulsar/ymw16/

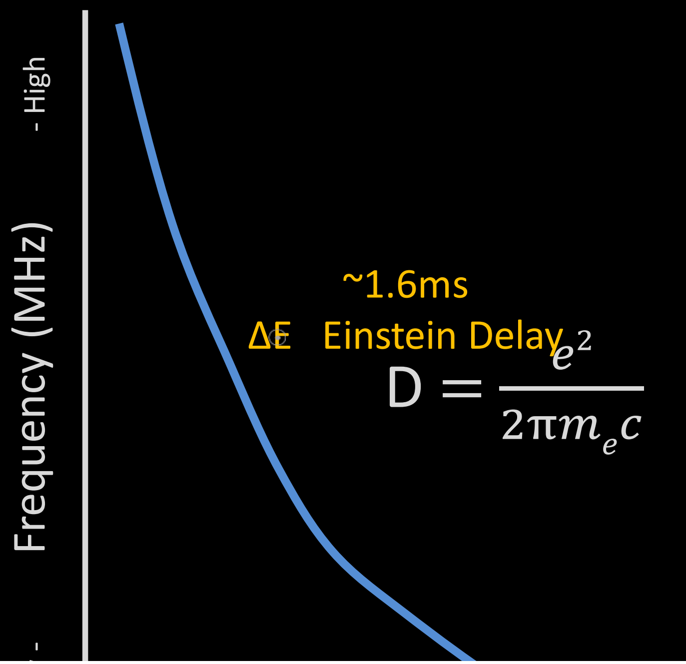
- Pulsars detected at ~430MHz are black dots, at ~1.4GHz yellow dots
- Darker grey corresponds to higher electron number density

- 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.

Coherent Dedispersion

- **Coherent Dedispersion**
  - Use a chirp filter to reverse the effect of the Interstellar Medium on the pulsar signal.
  - Gives a much better signal to noise and pulse shape resolution
  - Use a FFT to carry out dedispersion and filterbank synthesis
  - The processing load is proportional to the Fourier transform length.
- **Undertake processing in real time**
  - Alternatively store the input data and process later
  - Accumulating at 1.536 GBytes per second*





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$$D = \frac{e^2}{2\pi m_e c} \approx 4.148808 \pm 0.00003 \times 10^3\ MHz^2\ pc^{-1}\ cm^3\ s \qquad \text{(c}$$

$$DM = \int_0^d n_e dl \quad cm^{-3}\ pc \qquad \text{(d}$$

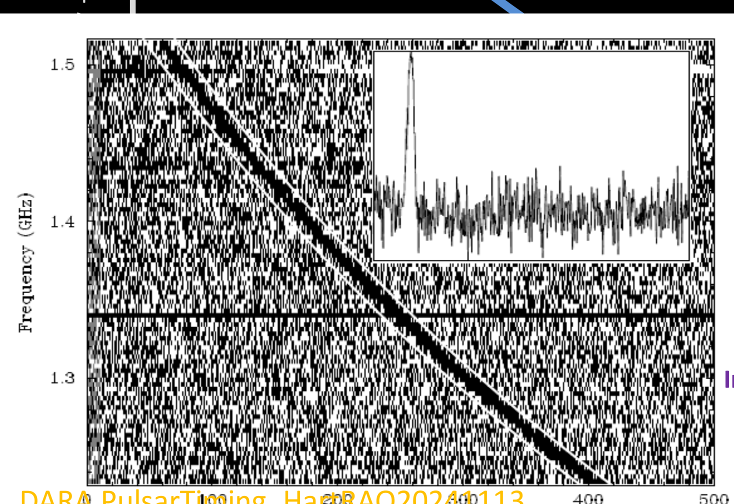

Image Credit: Handbook of Pulsar Astronomy Lorimer & Kramer

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