Introduction to Pulsar Timing

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IPTA Student Week 15 June 2026

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How to Snap a Pulsar in the Wild and Make Sense of the Picture!

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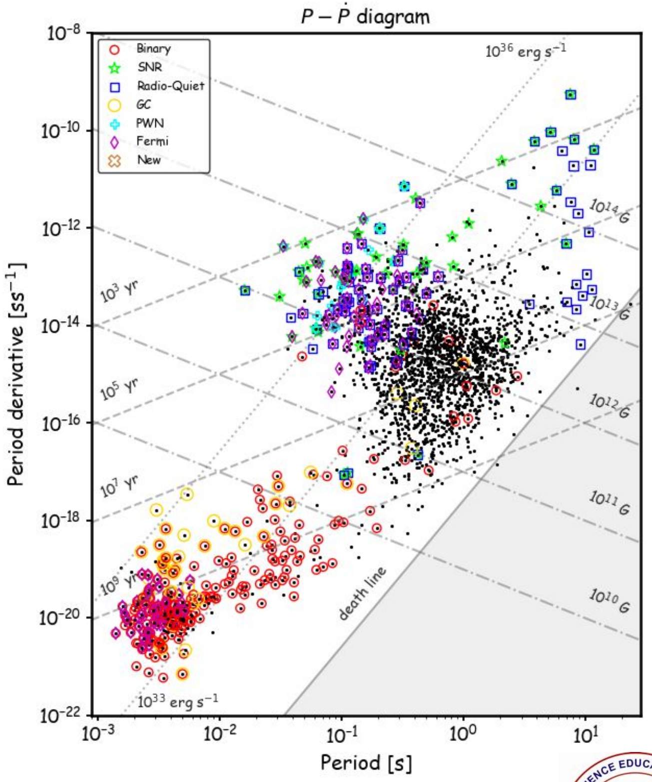
The Pulsar Safari: What all can you find??

- Normal Pulsars: Typical pulsars with periods between 30 ms to 2 s
- Millisecond Pulsars: Pulsars with periods between 1-30 ms.
- Binary Pulsars: Pulsars in binary systems
- High-B Pulsars: Pulsars with high magnetic field strength (~10^{13} G)
- RRATs: Rotating Radio Transients that emit sporadic pulses
- Magnetars: Pulsars with magnetic fields larger than 10^{14} G



Credit: Ben Stappers

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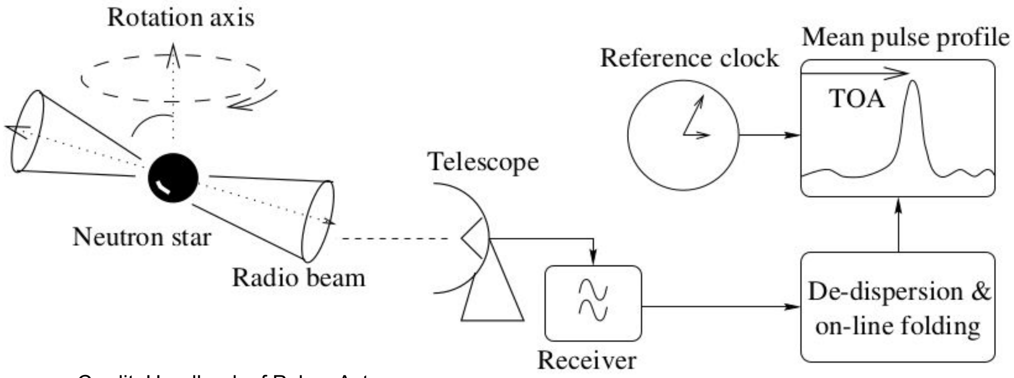
The Pulsar Safari: What can you do with all these pics??

- Pulsar dispersion measures (DMs), scatter-broadening and scintillation measurements allow the estimation of the plasma content of the Galaxy along various lines of sight
- Pulsar observations provide a tool to understand the plasma interactions in the magnetosphere that give rise to the radio and high-energy emission
- Precision timing observations resulted in the detection of first extrasolar planets (e.g. B1257+12)
- Pulsars in binary system (e.g. B1913+16, J0737-3039) allow the tests of gravity in the strong field regime
- Pulsar clocks spread across the Galaxy can be used to detect the nHz gravitational wave background formed by the merger of supermassive black hole binaries

Millisecond Pulsars as Clocks

- The time of arrival (ToA) of a pulse can be measured very accurately for pulsars
- ToAs measured over long time baseline allow the measurement of physical parameters like the spin-down rate (P_{dot}), position, magnetic field strength for isolated pulsars
- Further timing measurements allow the determination binary parameters for pulsars in binary systems
- The precision of ToAs and the stability of the pulsar rotation allows the measurement of the mass as well as post-Keplerian parameters for binary pulsars



Credit: Handbook of Pulsar Astronomy

Measuring the Pulse ToA

Timing an Isolated Pulsar

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Obtaining the ToA

- Obtain high signal to noise ratio (S/N) template profile

- Calculate the topocentric ToA by cross-correlating observed profiles with the template profile

$$\mathcal{P}(t) = a + b\mathcal{T}(t - \tau) + \mathcal{N}(t),$$

Obtaining the ToA

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$$\mathcal{P}(t) = a + b\mathcal{T}(t - \tau) + \mathcal{N}(t),$$

- Convert the topocentric ToA to barycentric ToA using:

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot}.$$

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Pulsar Timing Procedure

- The rotation frequency can be expressed as a Taylor's series expansion

$$\nu(t) = \nu_0 + \dot{\nu}_0(t - t_0) + \frac{1}{2}\ddot{\nu}_0(t - t_0)^2 + \cdots,$$

- In terms of the pulse number

$$N = N_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3 + \cdots$$

- Do a least squares fit to calculate pulsar parameters using

$$\chi^2 = \sum_i \left(\frac{N(t_i) - n_i}{\sigma_i}\right)^2$$

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Timing a Binary Pulsar

Obtaining the ToA

- Obtain high signal to noise ratio (S/N) template profile

- Calculate the topocentric ToA by cross-correlating observed profiles with the template profile

$$\mathcal{P}(t) = a + b\mathcal{T}(t - \tau) + \mathcal{N}(t),$$

- Convert the topocentric ToA to barycentric ToA using:

$$\begin{aligned} t_{\mathrm{SSB}} = \quad & t_{\mathrm{topo}} + t_{\mathrm{corr}} - \Delta D/f^2 + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot} \\ + \quad & \Delta_{\mathrm{RB}} + \Delta_{\mathrm{SB}} + \Delta_{\mathrm{EB}} + \Delta_{\mathrm{AB}}. \end{aligned}$$

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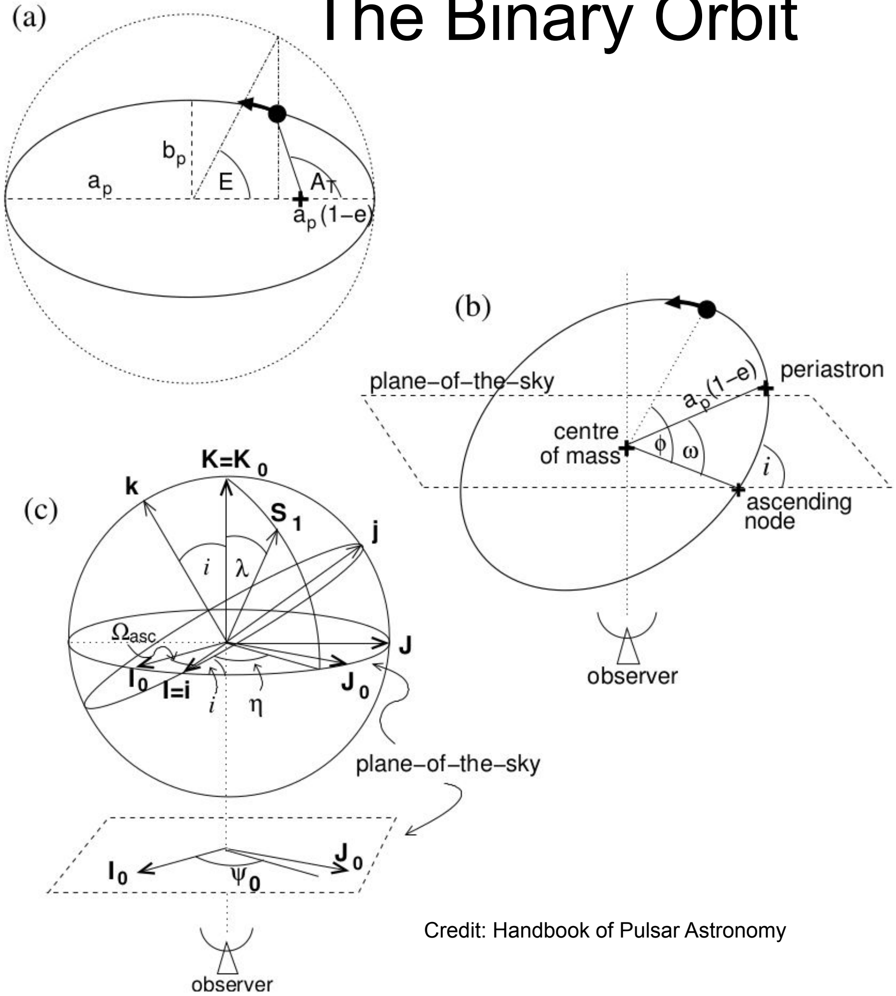
The Binary Orbit



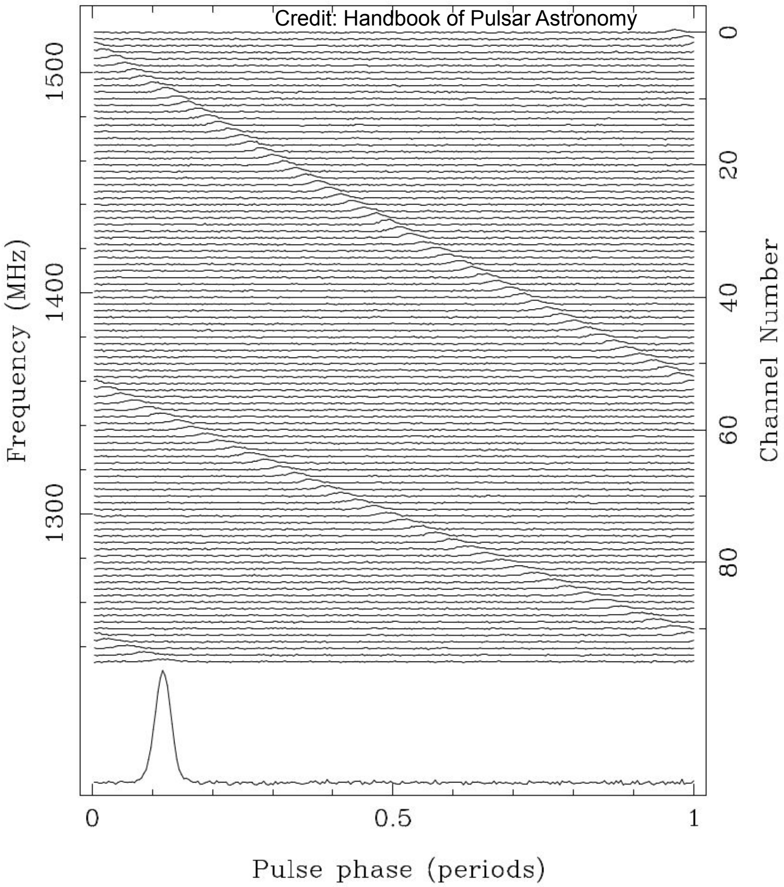
Credit: Handbook of Pulsar Astronomy

Time Standards

- Time stamps are typically given by the global positioning system (GPS) and are in universal coordinated time (UTC)
- This has to be finally converted to International Atomic Time (TAI), which is an average of an ensemble of atomic clocks
- As the Earth does not rotate uniformly, leap seconds have to be added to UTC to keep it within 0.9 s from the actual Earth rotation time UT1
- Thus, UTC is always an integral number of seconds away from TAI (TAI = UTC + δT)
- This time is then converted to a smooth running time standard called Terrestrial Time (TT)

The Interstellar Medium: Ruining your insta-worthy pic??

- Interstellar plasma has a different refractive index for different radio frequencies
- The lower frequency radio waves travel slower compared to higher frequencies
- Dispersion measure (DM) is the integrated line of sight electron density
- The delay due to dispersion is proportional to the inverse square of the frequency
- In a broad sense, it provides a proxy for the distance to the source



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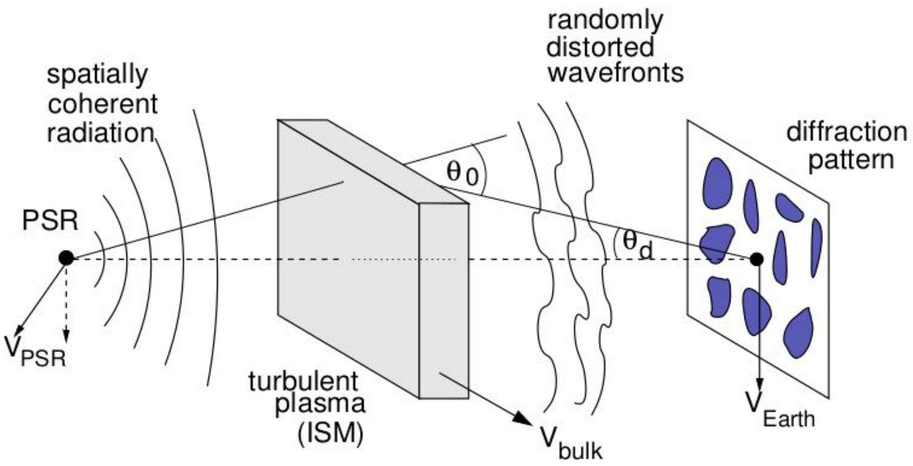
The Interstellar Medium: Ruining your insta-worthy pic??

- Interstellar plasma distorts the wavefront of the travelling radio waves

- This produces random variations in the flux density as a function of time and frquency

- The delay due to the multi-path propagation or scattering produces an exponential tail in the pulse

- The effect of this pulse broadening goes as frequency$^{-4.4}$



Credit: Handbook of Pulsar Astronomy

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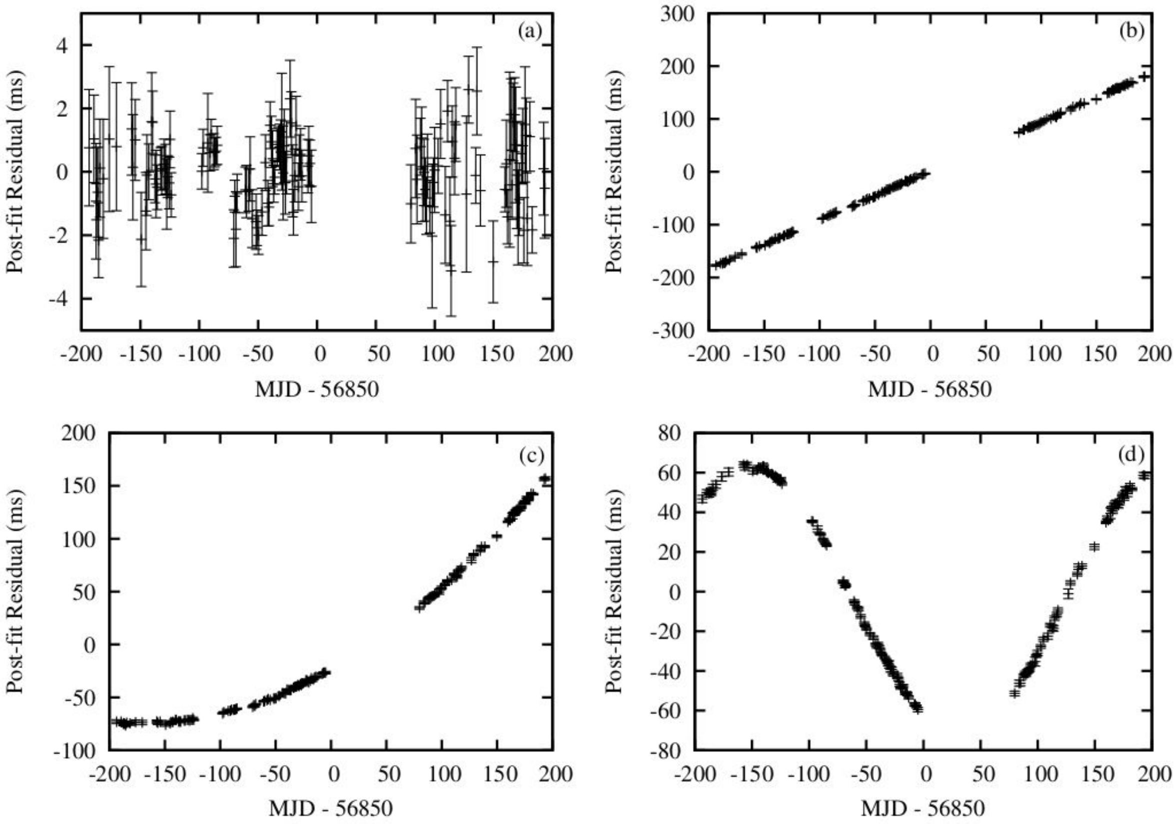
The Effect of Pulsar Parameters on Residuals



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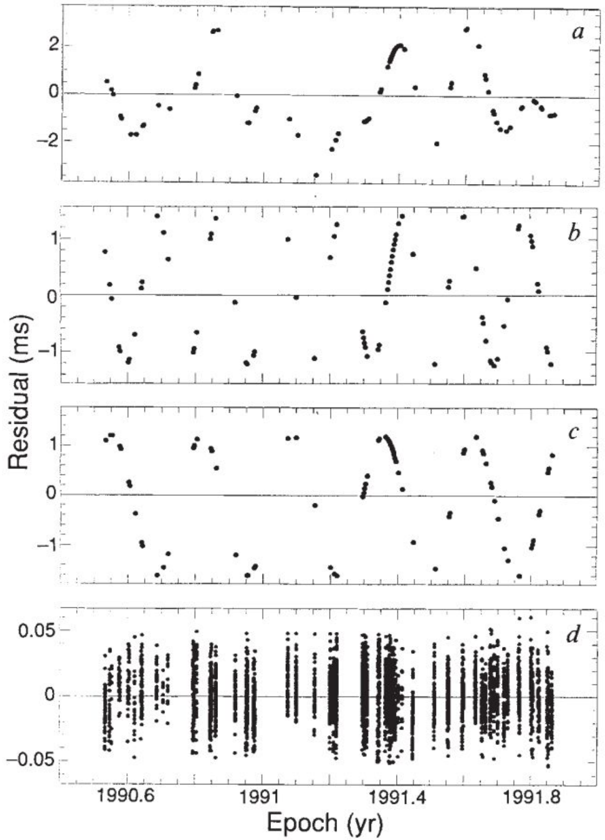
Cool things you can do with pulsar timing

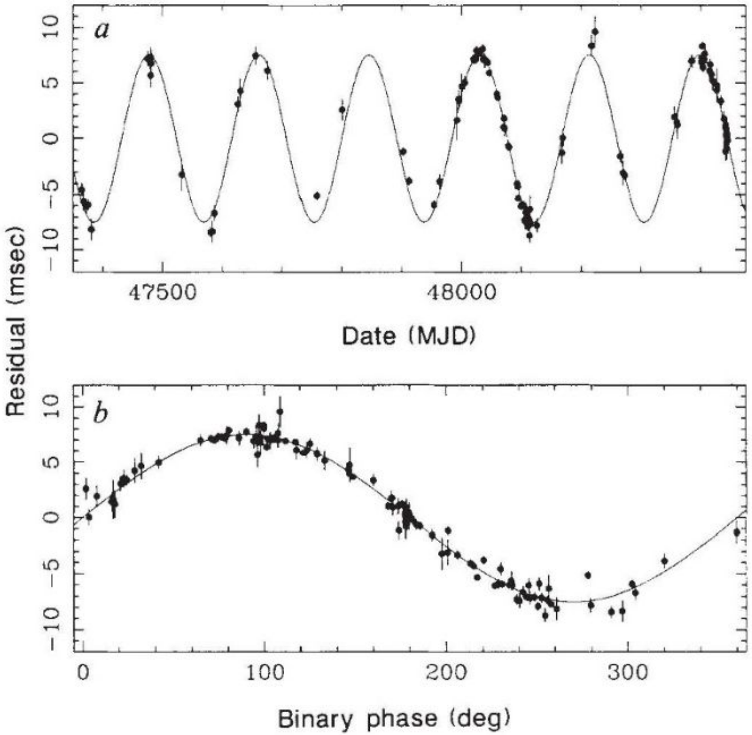
Discover Extrasolar Planets!



Wolsczan and Frail 1992

PSR B1829-10 (Right) was the first pulsar with a 10 Earth mass planetary companion

PSR B1257+12 (Left) was the first millisecond pulsar with 2.8 and 3.4 Earth mass planets



Bailes, Lyne and Shemar 1991

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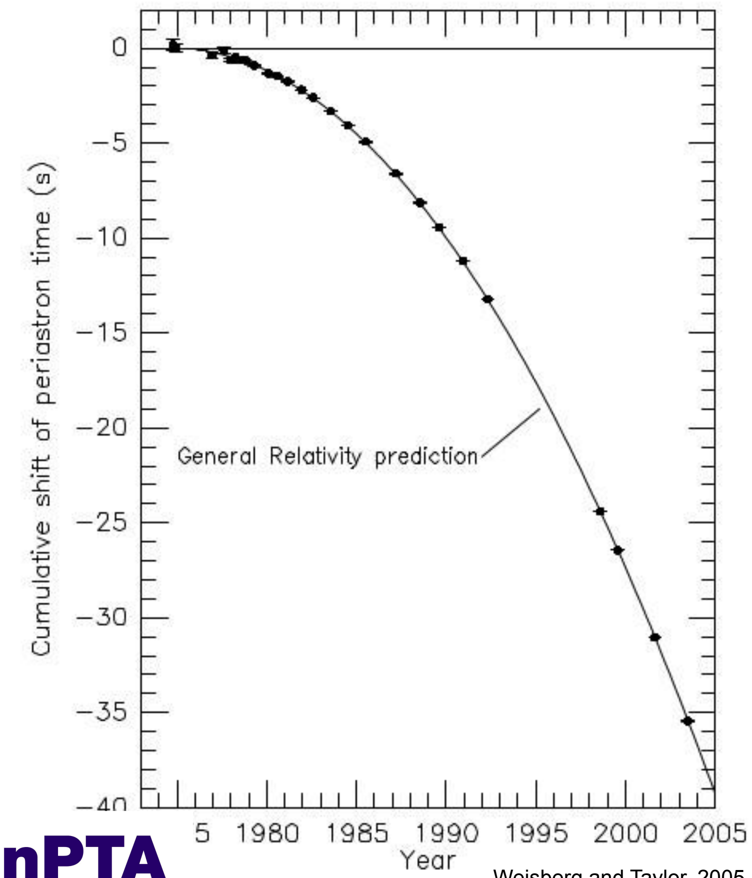
Prove Gravitational Waves Exist! (and get a Nobel!!)



Weisberg and Taylor, 2005

PSR B1913+16 is in a relativistic binary

Both neutron stars go around their center of mass at relativistic speeds

The GWs take energy out and the orbit shrinks over time

This was the first indirect experimental evidence for the presence of GWs

Russel Hulse and Joseph Taylor received the Nobel prize in physics in 1993 for this discovery

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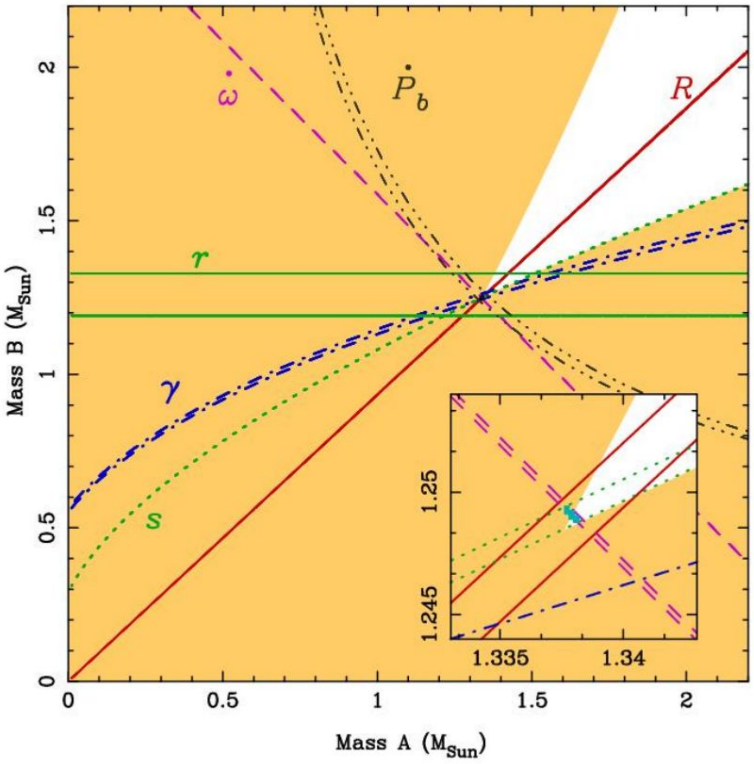
Prove Einstein was Right! (Yawn!!)



Kramer et al., 2006

PSR J0737-3039 is the only known double pulsar system

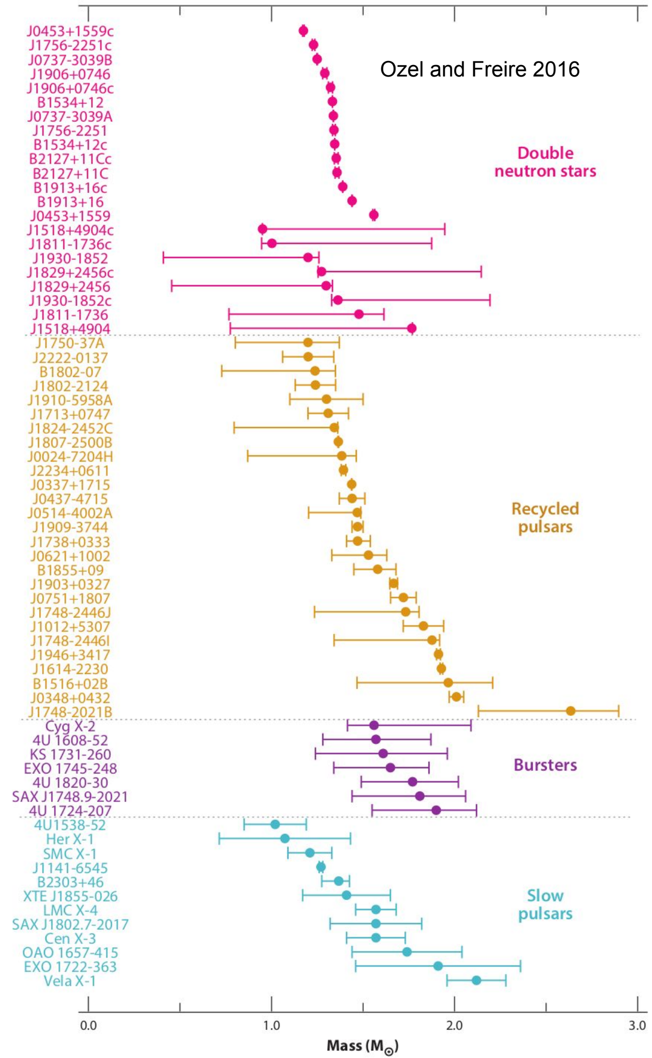
Both neutron stars are seen as radio pulsars

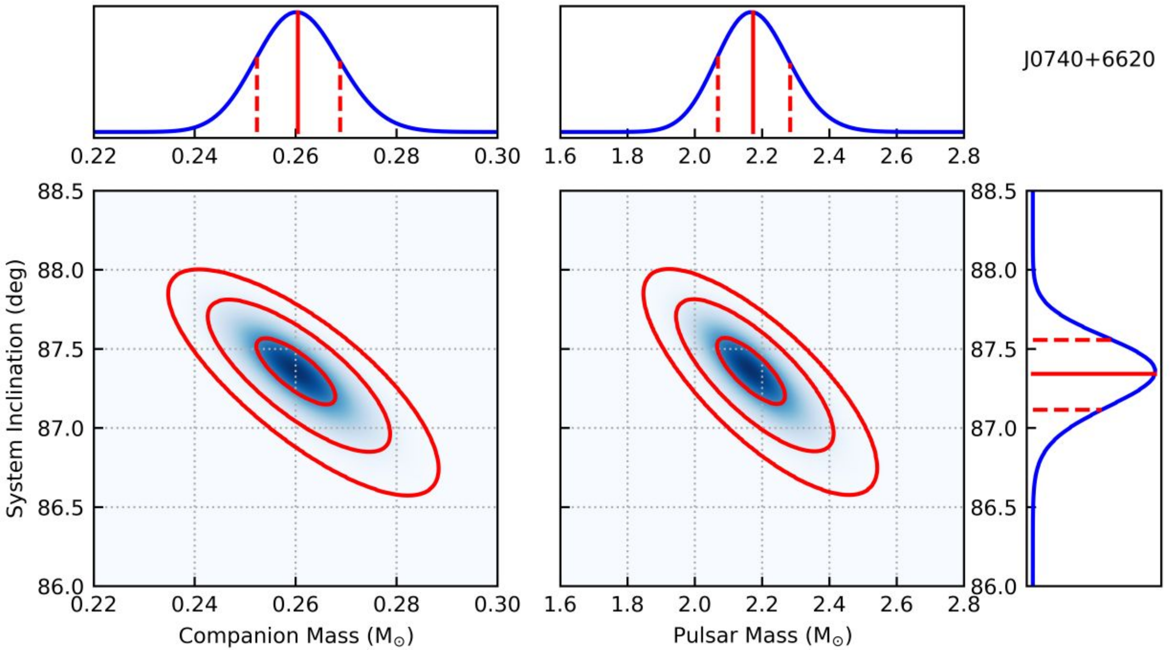
The timing observations have provided the most stringent constraints on the GTR

The masses of the neutron stars are known to crazy accuracy of 1.3381(7) and 1.2489(7) Solar masses!

Accuracy of 0.05% with just 2.5 years of observations!

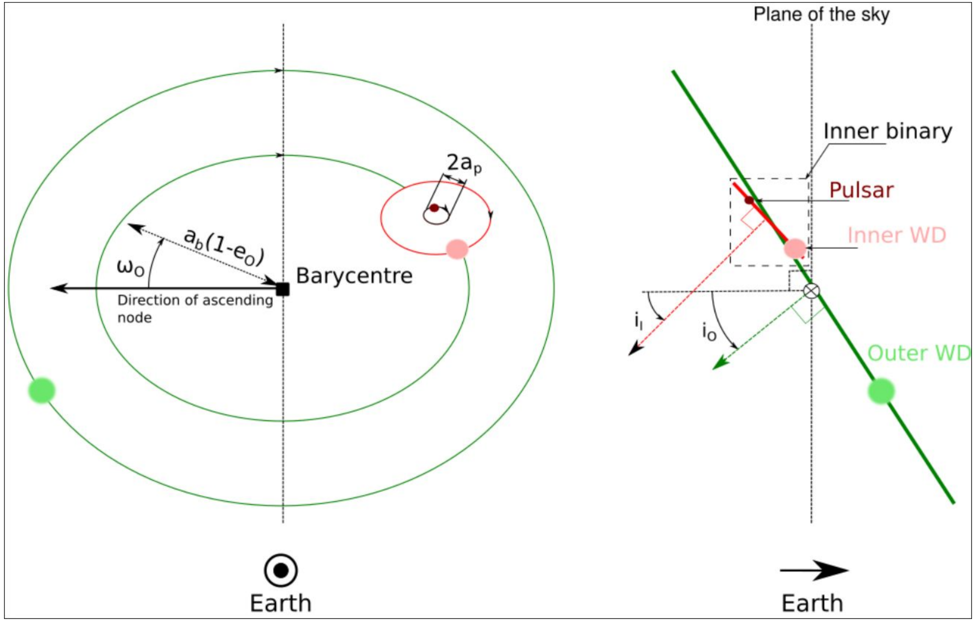
Weigh Neutron Stars from Earth!





Cromartie et al. 2020

Test the Equivalence Principle (while you are at it!)



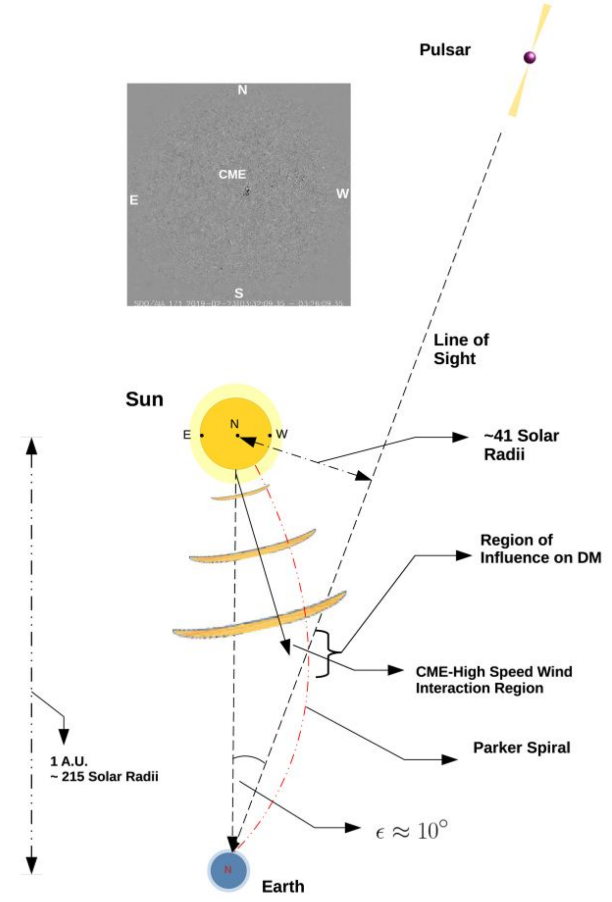
Voisin et al. 2020

PSR J0337+1715 is a hierarchical triple system

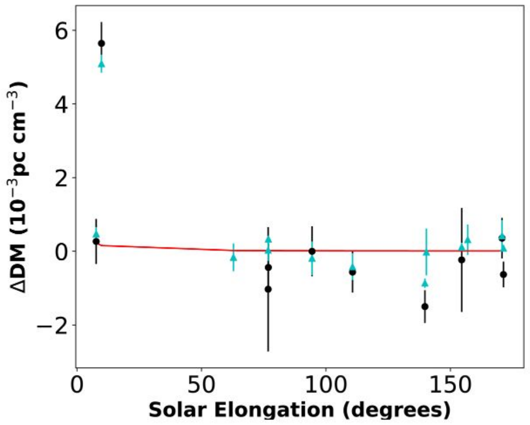
Considering this as a binary falling in the gravitational potential of the third star, the strong equivalence principle can be tested

Latest test shows that it is accurate to 2 X 10^{-6}

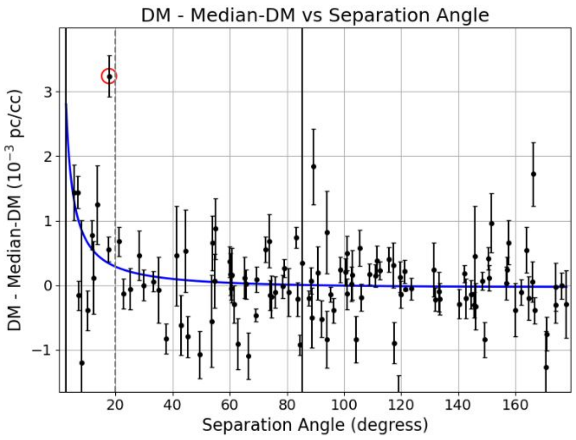
Did the Sun Just Do That ??



Krishnakumar et al. 2021

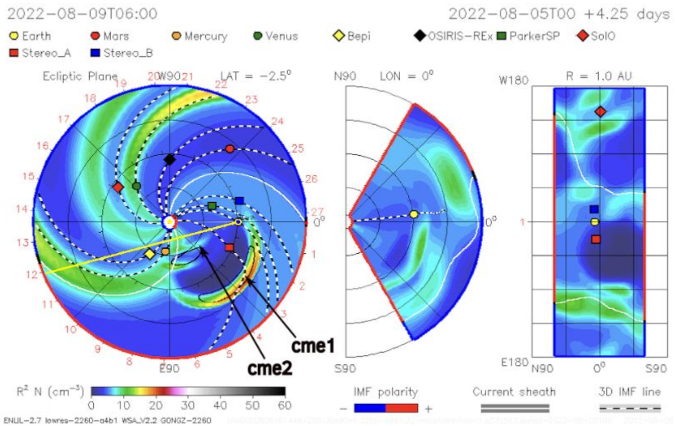


Krishnakumar et al. 2021



Chowdhury et al. 2026

Effects of the Coronal Mass Ejections (CMEs) on the DMs of PSR J2145-0750 (Left) and PSR J1022+1001 (Right)



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