

Time-Domain Astronomy

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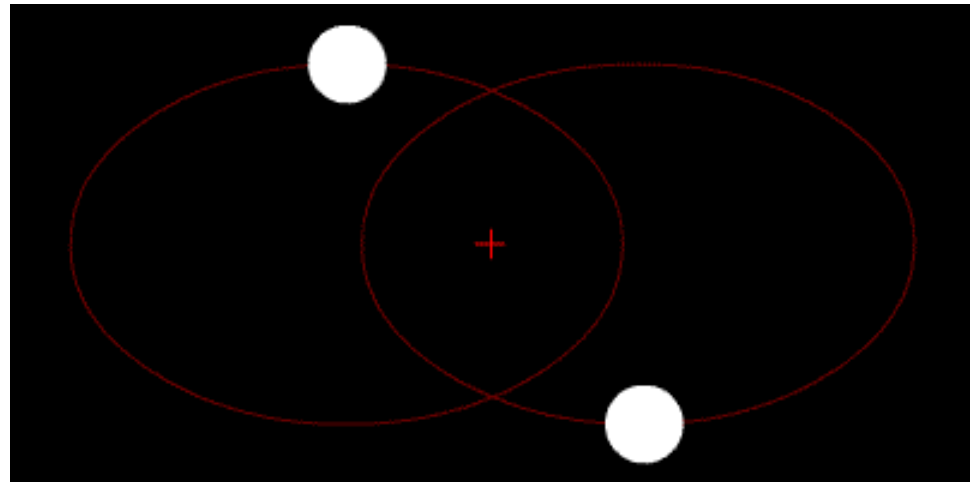
How do we tell that a pulsar is in a Binary?

Of course - by timing it.

Even with a least massive companion a pulsar is moving around the centre of mass of the binary system.

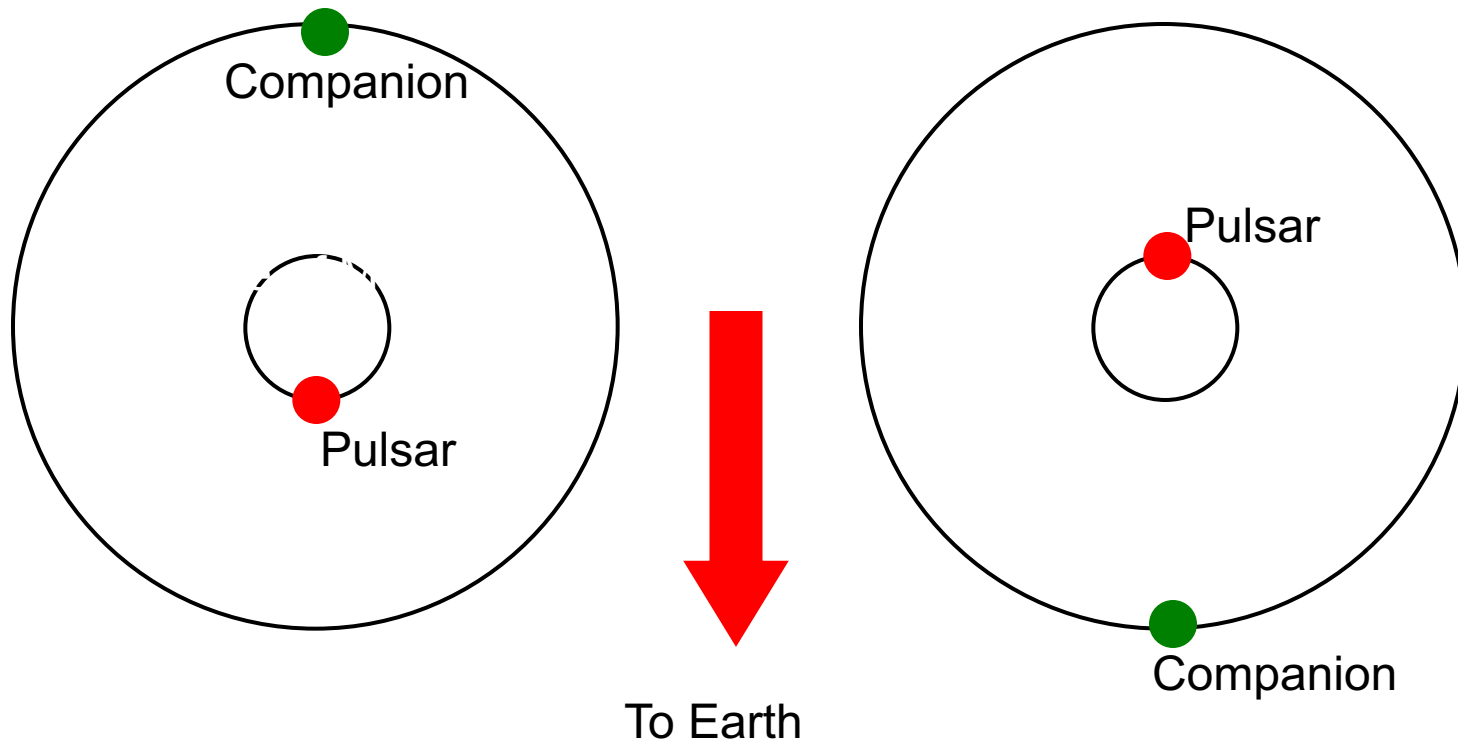
So at some times it is closer to us, than its average distance, and at the other times - is further away.

That is just a Roemer delay inside the binary!



If the pulsar is closer, the radiowaves have shorter way to travel - and they come early. If it is further away - they come late.

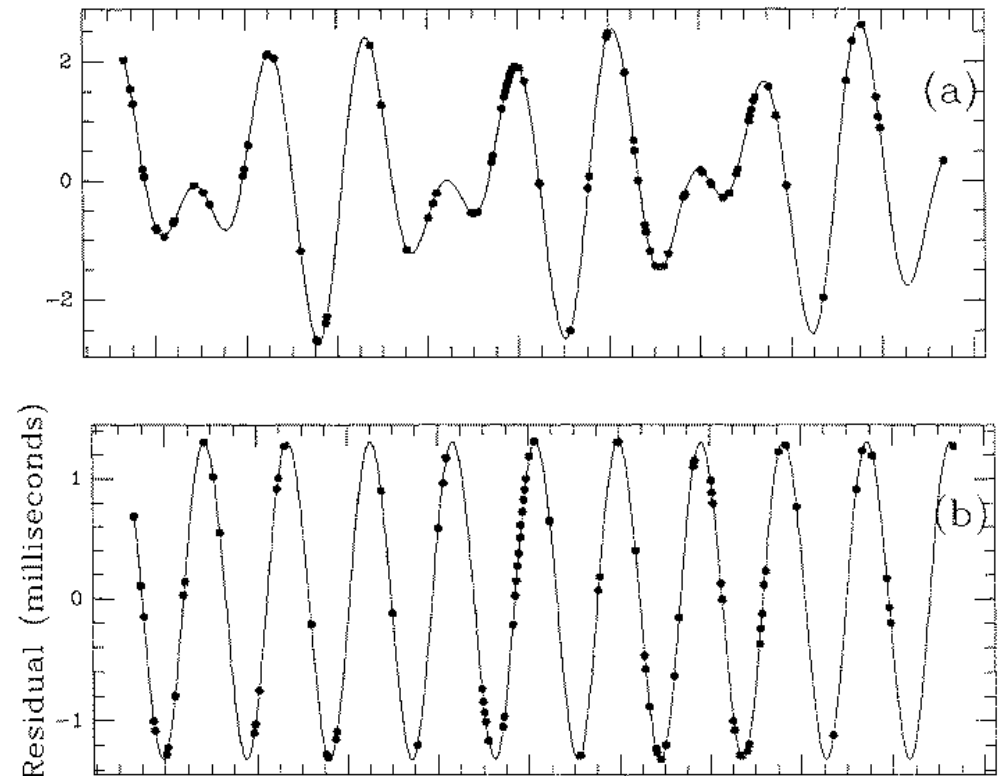
The maximum delay is of course the pulsar semi-major axis divided by the speed of light.



The tidal disruption of the white dwarf companion (so called "black widow scenario") was possibly the case of origin of the PSR B1257+12 planetary system.

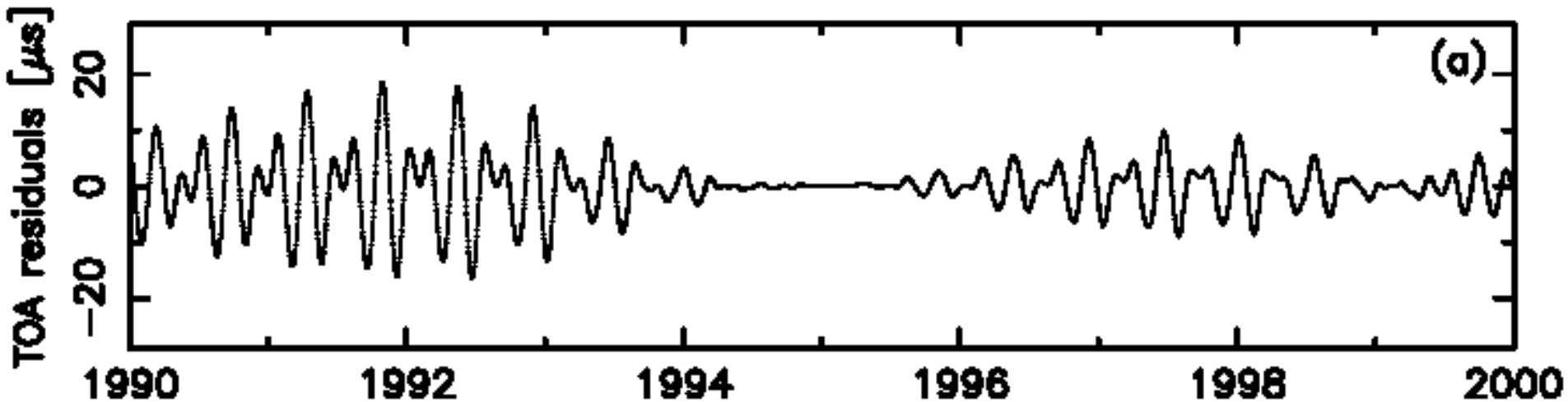
There are three planets in this system. Two larger ones have the masses of approx. 4 Earths and periods of 66 and 98 days.

Third one is small - comparable to Earth's Moon - and orbits the pulsar in 25 days.



Not only we see the planets, but we can see them interacting gravitationally with each other!

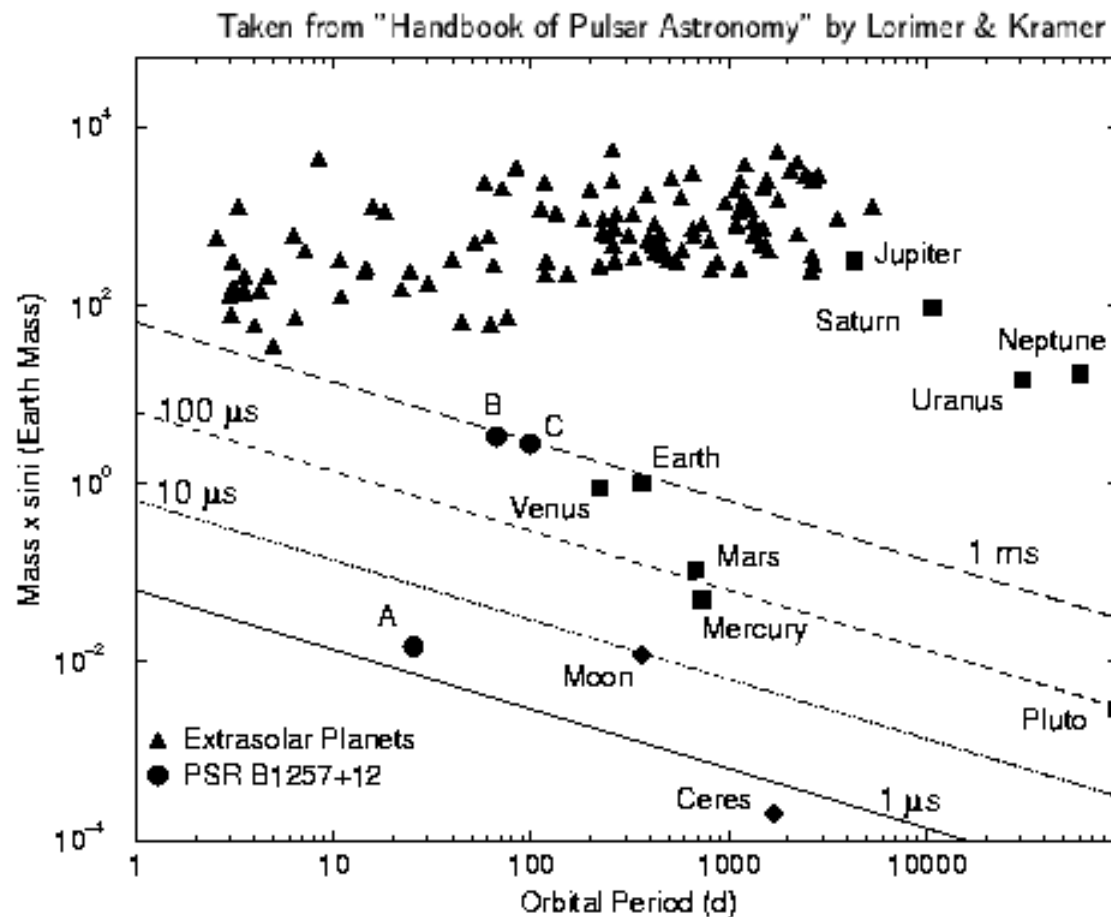
As the two larger planets are almost exactly in 2/3 resonance (66 and 98 days) these interactions are quite severe, and visible by timing means:



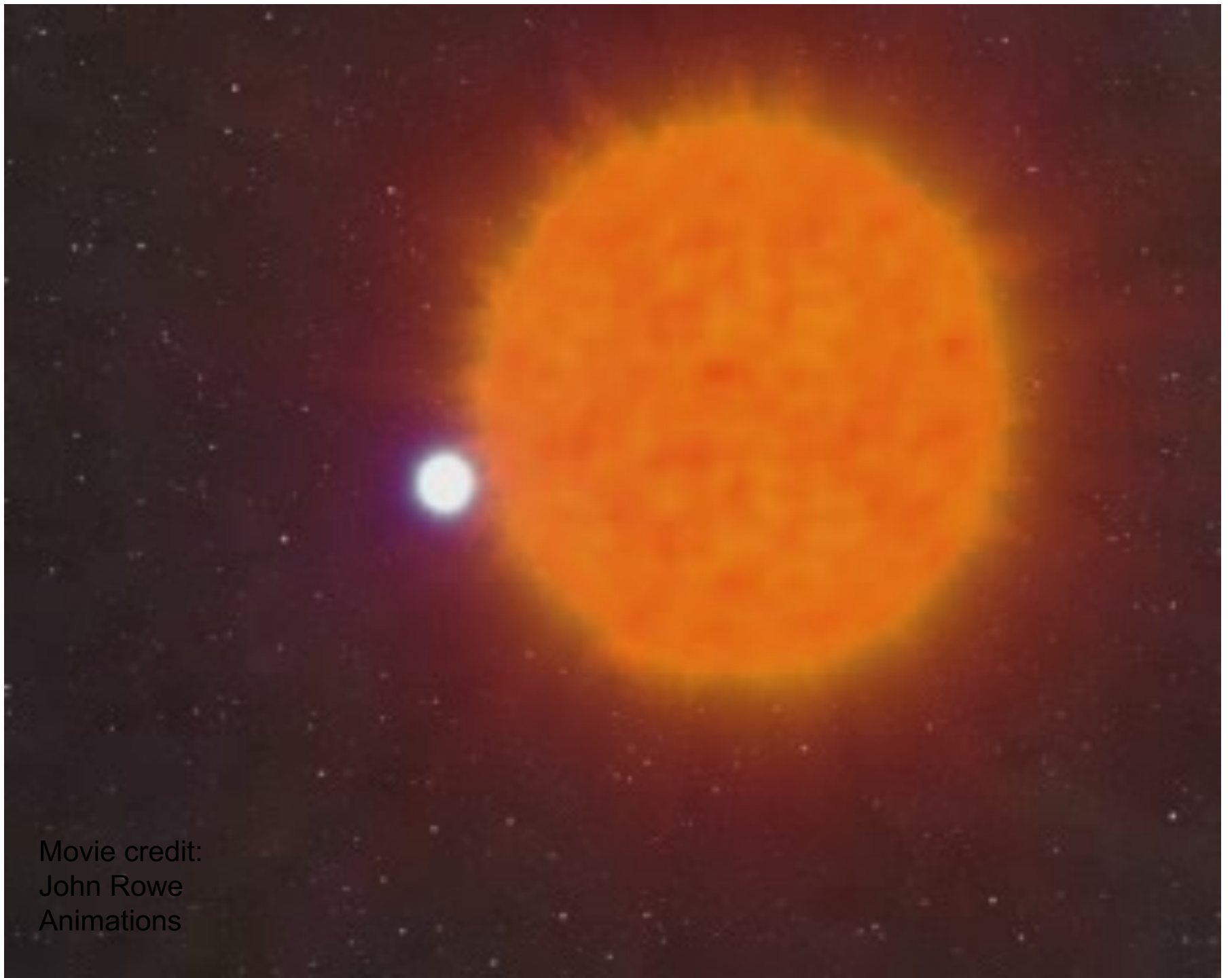
There is supposedly no other effect, that would mimic such behaviour, so the planets are really there.

Actually timing is the most precise method of finding extrasolar planets.

It is much more accurate, than finding planets around regular stars by the means of spectroscopy.



Triangles - known extrasolar planets around normal stars
Squares - our solar system planets
Circles - the B1257+12 pulsar planets

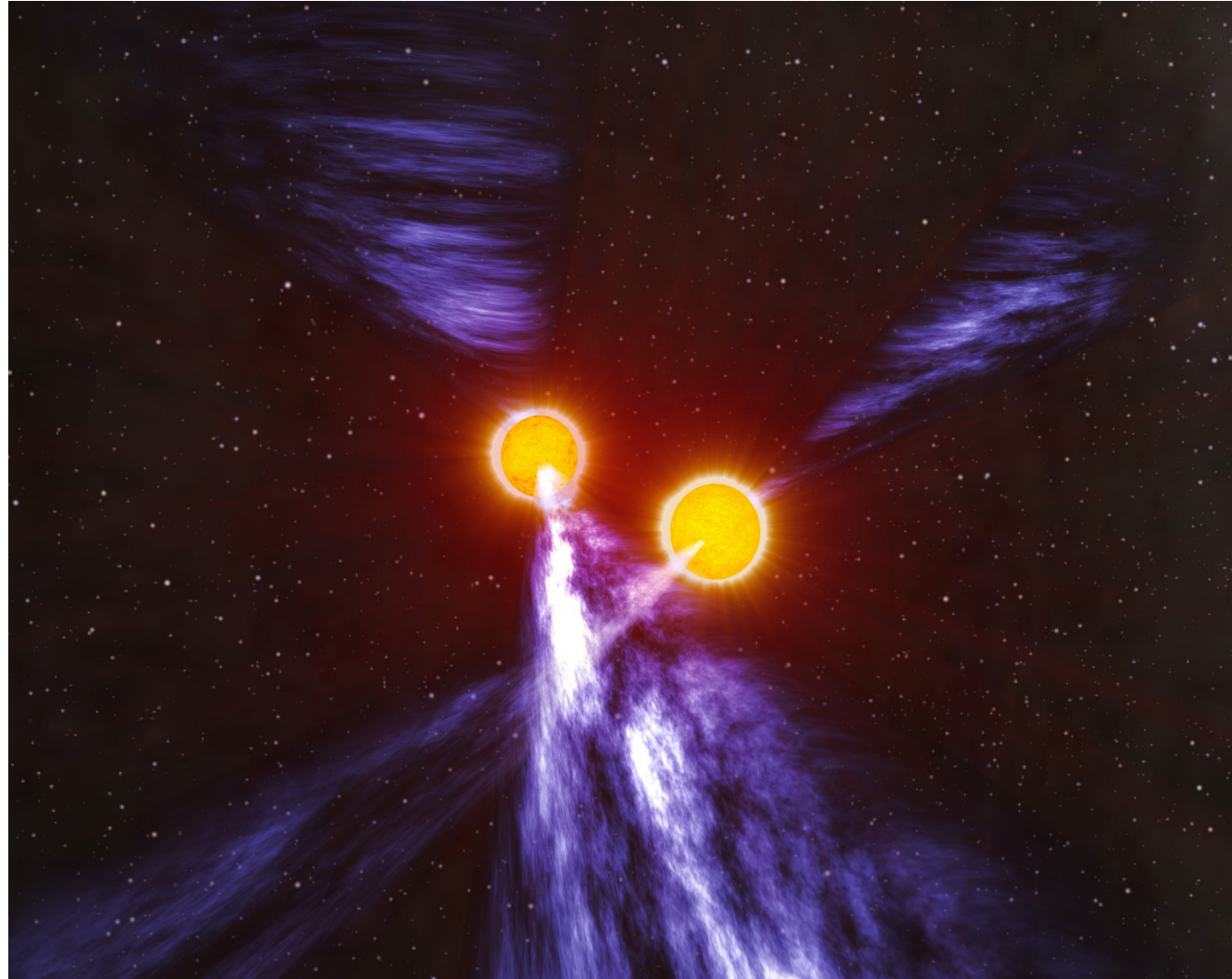


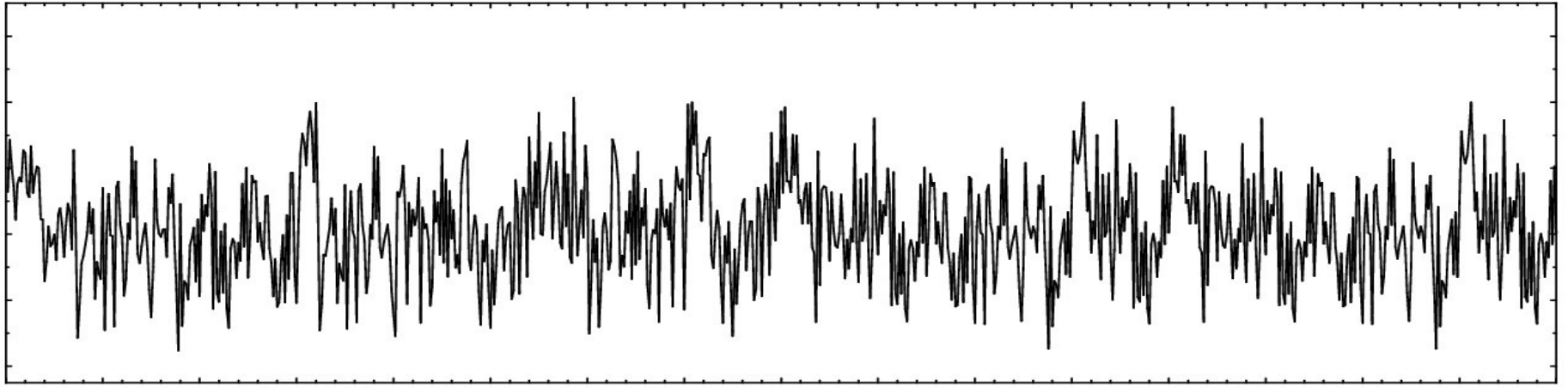
Movie credit:
John Rowe
Animations

The graph is actually made for a double-pulsar system, PSR J0737-3039AB, discovered in 2003. Pulsar A in this system is a 22.7 millisecond pulsar, and pulsar B has a period of 2.8 seconds.

They form a close binary, with orbital period of 2.4 hours.

And we can see the pulses coming from both of them - except the times they eclipse each other.





Assume, that you have the timeseries at one trial DM.

Most of the methods of finding periodicity in a dataset are Fourier-based methods, and probably the mostcommon is the FFT (Fast Fourier Transform).

$$\mathcal{F}_k = \sum_{j=0}^{N-1} \mathcal{T}_j \exp(2\pi i j k / N),$$

As a result of FFT you'll have a set of Fourier transform values at $N/2$ frequencies (where N is the number of samples in your timeseries);

$$\nu_k = \frac{k}{N t_{\text{samp}}} = \frac{k}{T} \quad 1 \leq k \leq N/2$$

The lag between the frequencies depends purely on the length of your timeseries.

$$\Delta \nu_k = \frac{1}{T}$$

The range of the frequencies is limited by the total timespan, and the Nyquist frequency.

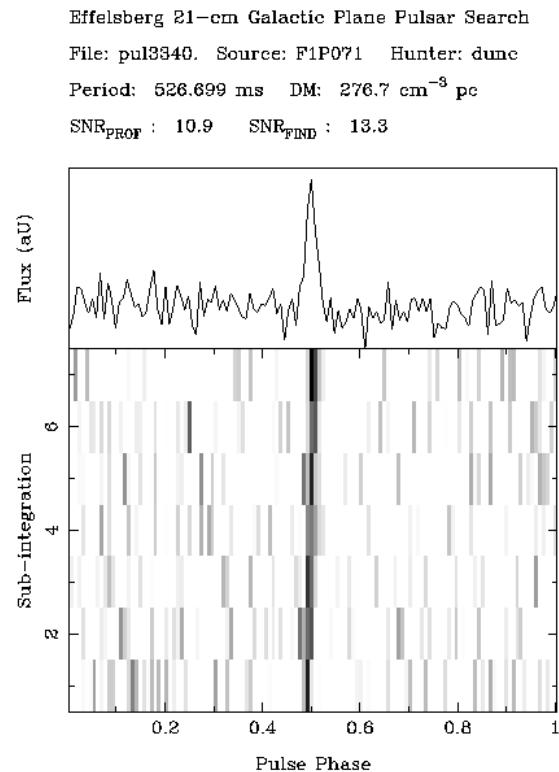
$$\frac{1}{T} < \nu_k < \frac{1}{2 t_{\text{samp}}} = \nu_{\text{Nyq}}$$

Then, when you have a power spectrum of the dedispersed timeseries, cleared of the RFI, summed over harmonics - you may start to search for potential pulsar candidates.

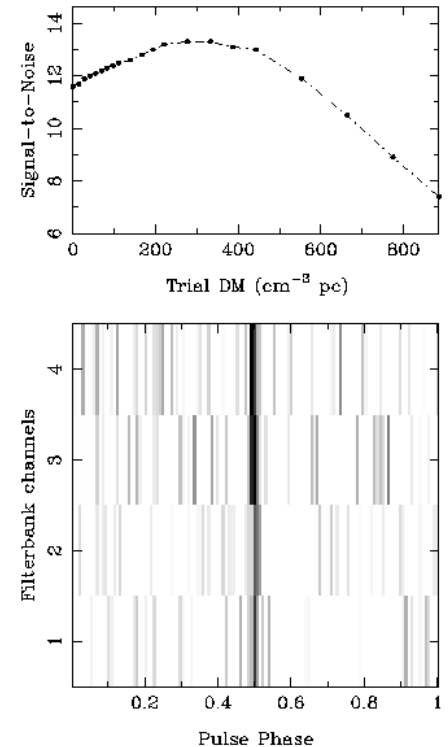
And you have to use the data from several (or all) trial DMs at each time - since the pulsar candidate should show the S/N varying with the DM.

So, you basically look for the candidates that show a maximum S/N at some non-zero DM.

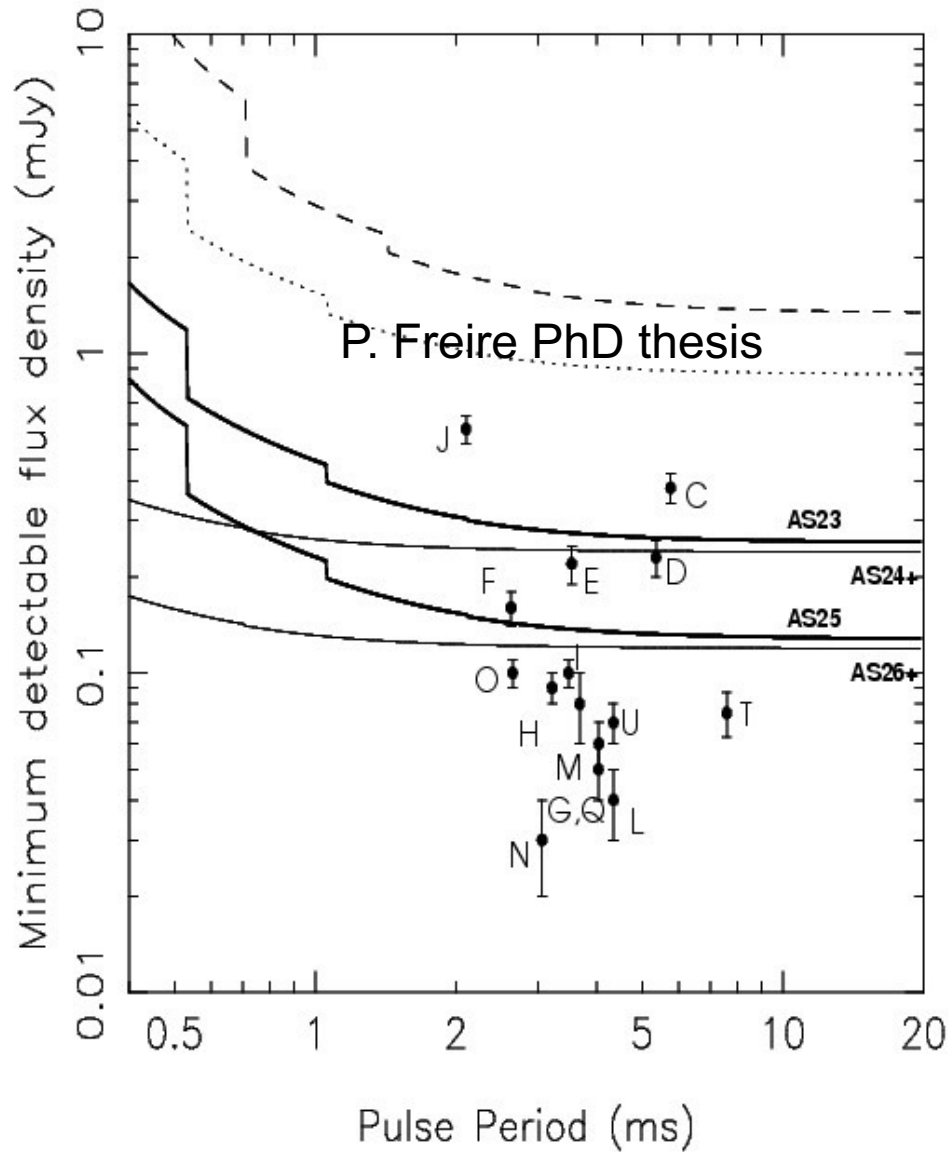
Then you fold the timeseries with the trial period and check, if it looks as a pulsar.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer



How to calculate your search sensitivity?



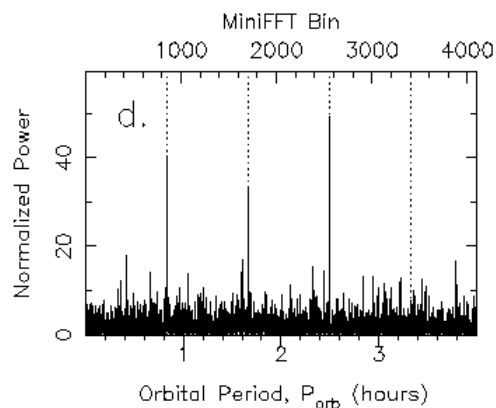
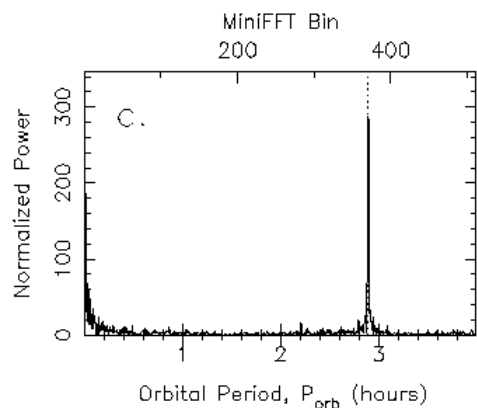
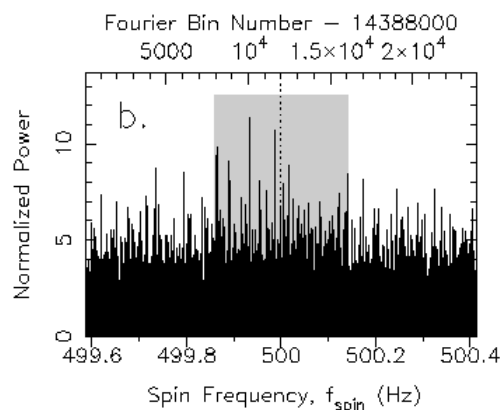
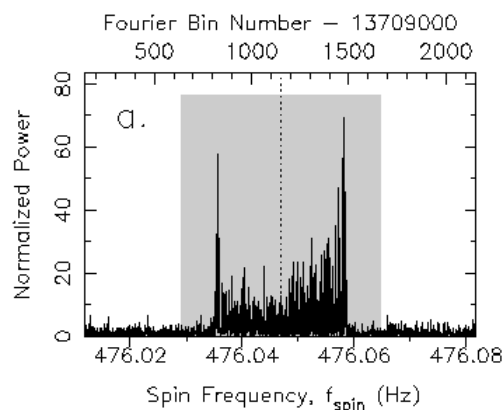
Minimum detectable flux depends on many factors:

$$S_{\min} = \frac{(S/N_{\min})\beta T_{\text{sys}}}{G\sqrt{n_p t_{\text{obs}}\Delta f}} \sqrt{\frac{\delta}{1-\delta}},$$

You have the control over some of them - especially if you are building your own backend.

So basically, for millisecond binary pulsar you have to search not the usual 2-dimensional $P - DM$ plane, but rather a 3-dimensional $P - DM - \dot{P}$ space!

And since you don't know beforehand what orbit to expect - it is a huge task.



Taken from "Handbook of Pulsar Astronomy" by Lorimer & Kramer

Mostly used is the padding method - you add/delete some bins from your timeseries to simulate the apparent period changes.

Other methods are Fourier based - such as the mini-FFT, performed on the fourier spectrum.

GW detection: Pulsars timing

Pulsar Timing Array (PTA) to detect low-frequency (10^{-9} to 10^{-6} Hz) GW

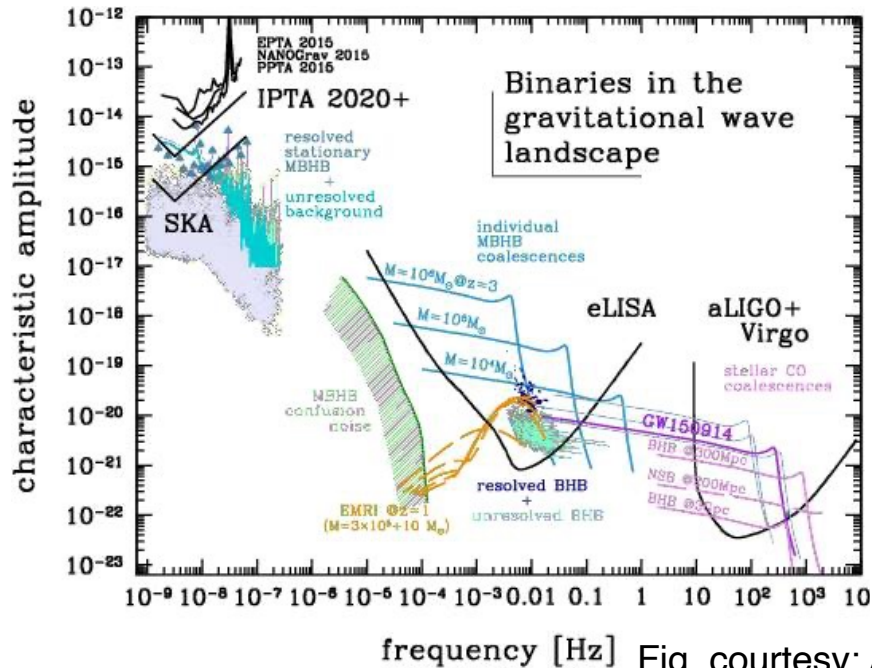
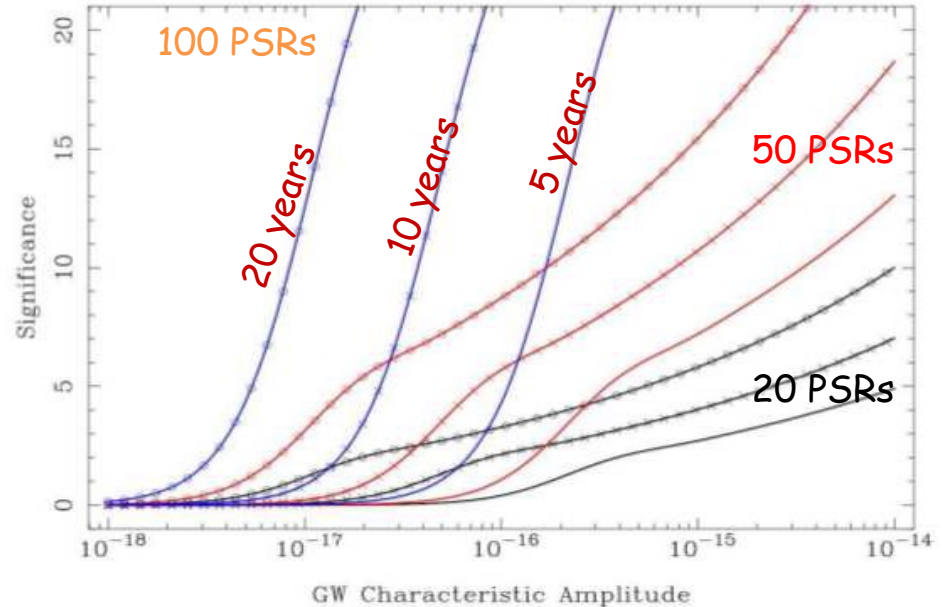


Fig. courtesy: Alberto Sesana



Manchester et al. 2013

$$h \sim \sigma_{rms} / T \sim 100\text{ns}/5 \cdot 10^{-15}$$

S/N of Hellings and Downs cross-correlation statistics

$$N_{\text{PSR}} (N_{\text{TOA}})^{3/26} (T_{\text{obs}})^{1/2} (h/\sigma_{rms})^{3/13} \quad (\text{Siemens et al. 2013})$$

Test theories of gravity

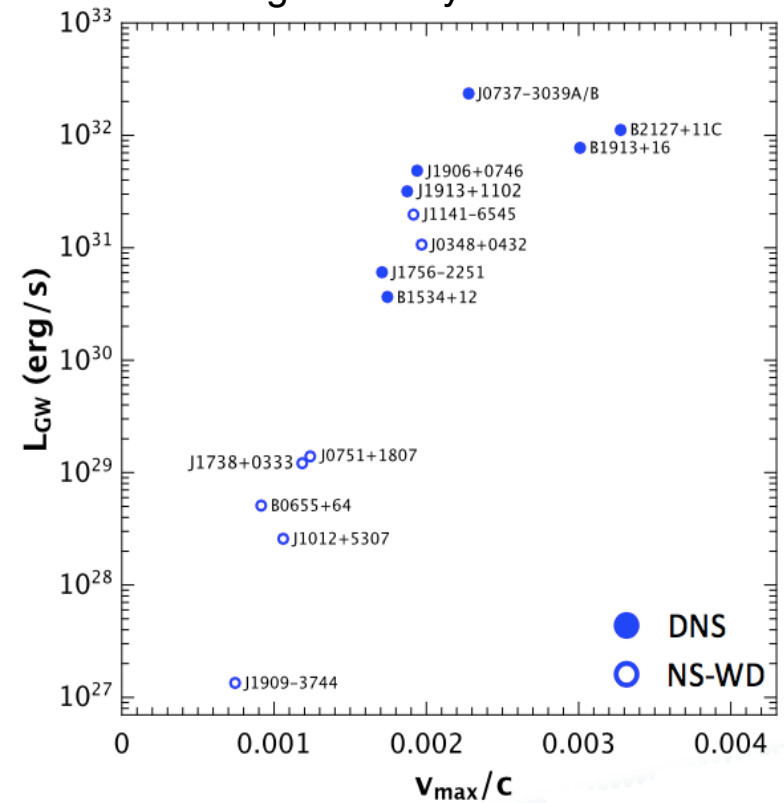
- Pulsars as tools to test theories of gravity
- Double pulsar: GR tested by PK parameters! (Kramer et al. 2006)
- Double NS systems promise improved test of GR:

PSR J1757-1854 (Cameron et al. 2017)
the most accelerated binary

PSR J1946+2052 (Stovall et al. 2018),
the shortest orbital period

- Searching for such extreme systems, SKA-Phase1 may find 100 such systems!
- One of the main goal of SKA to find and time at high precision of a PSR-BH system

Fig. courtesy: Michael Kramer



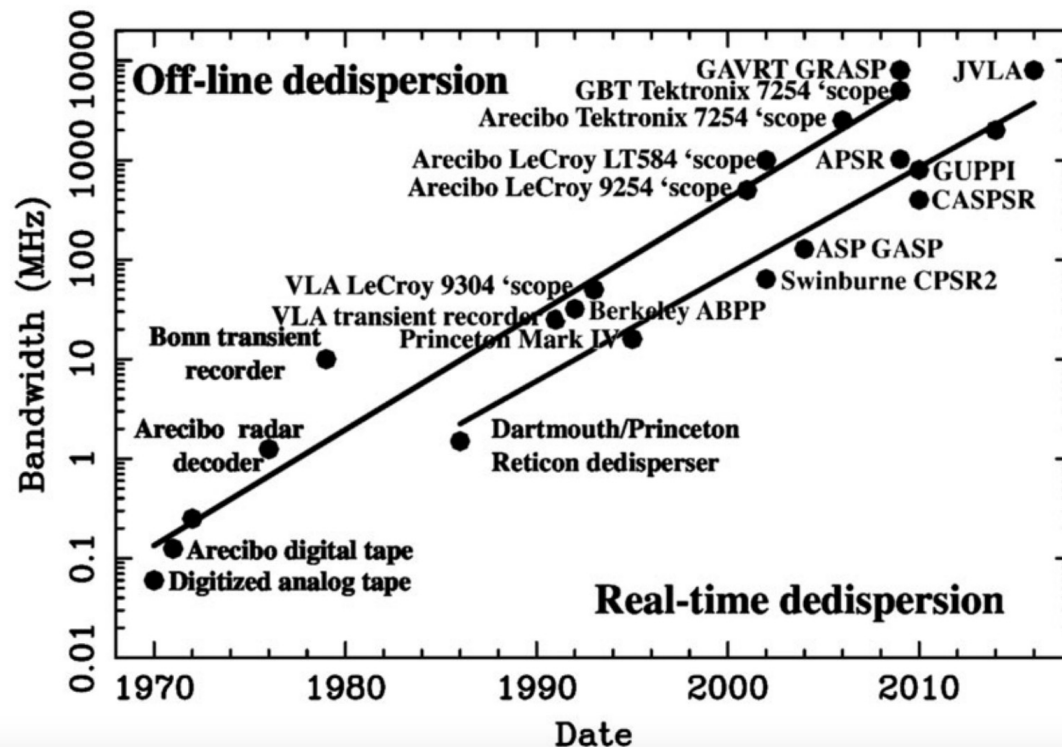
Coherent dedispersion

Coherent dedispersion perfectly removes this smearing at the voltage level

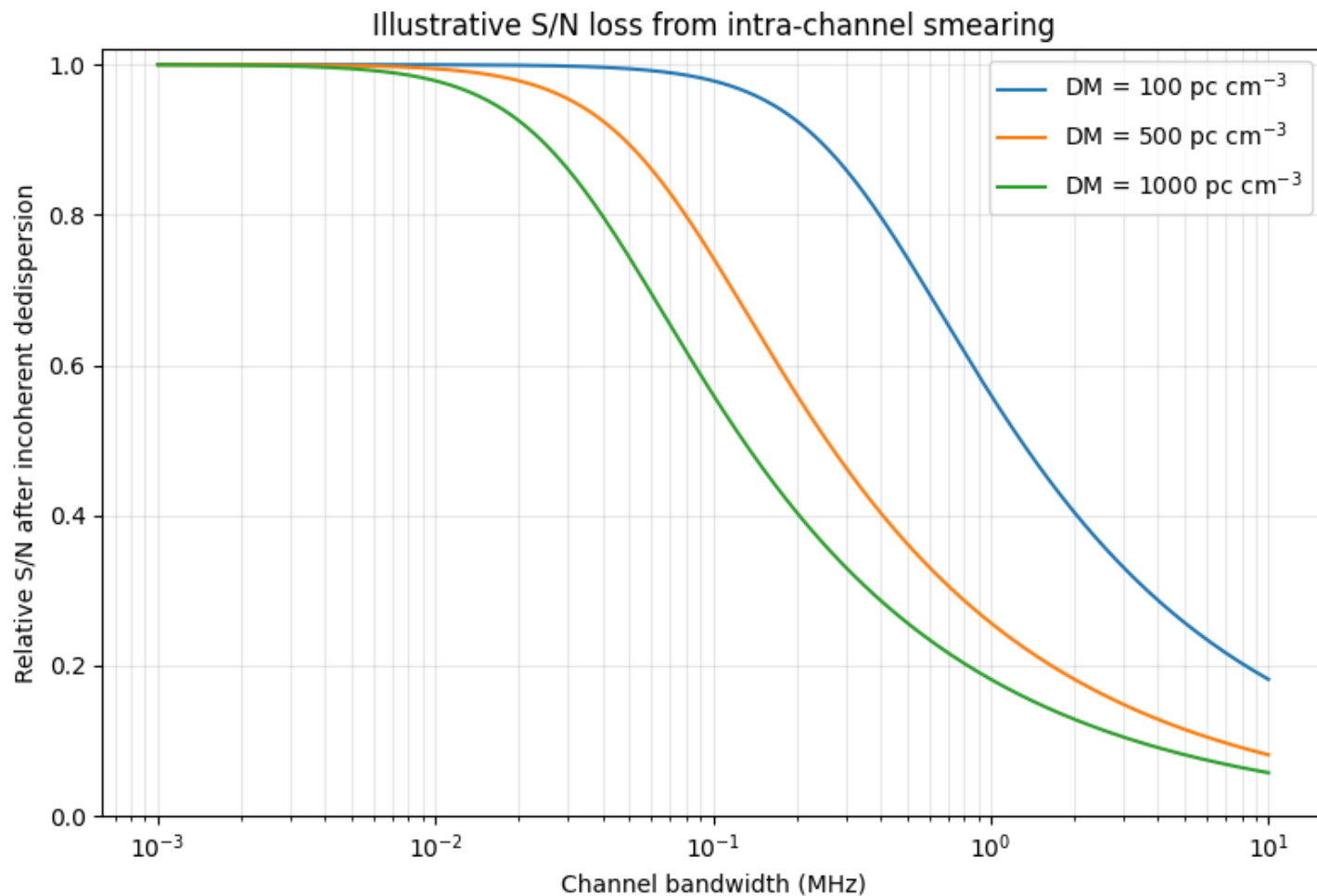
Works on the raw electric field (voltage) data

Uses the exact physical transfer function of the ISM

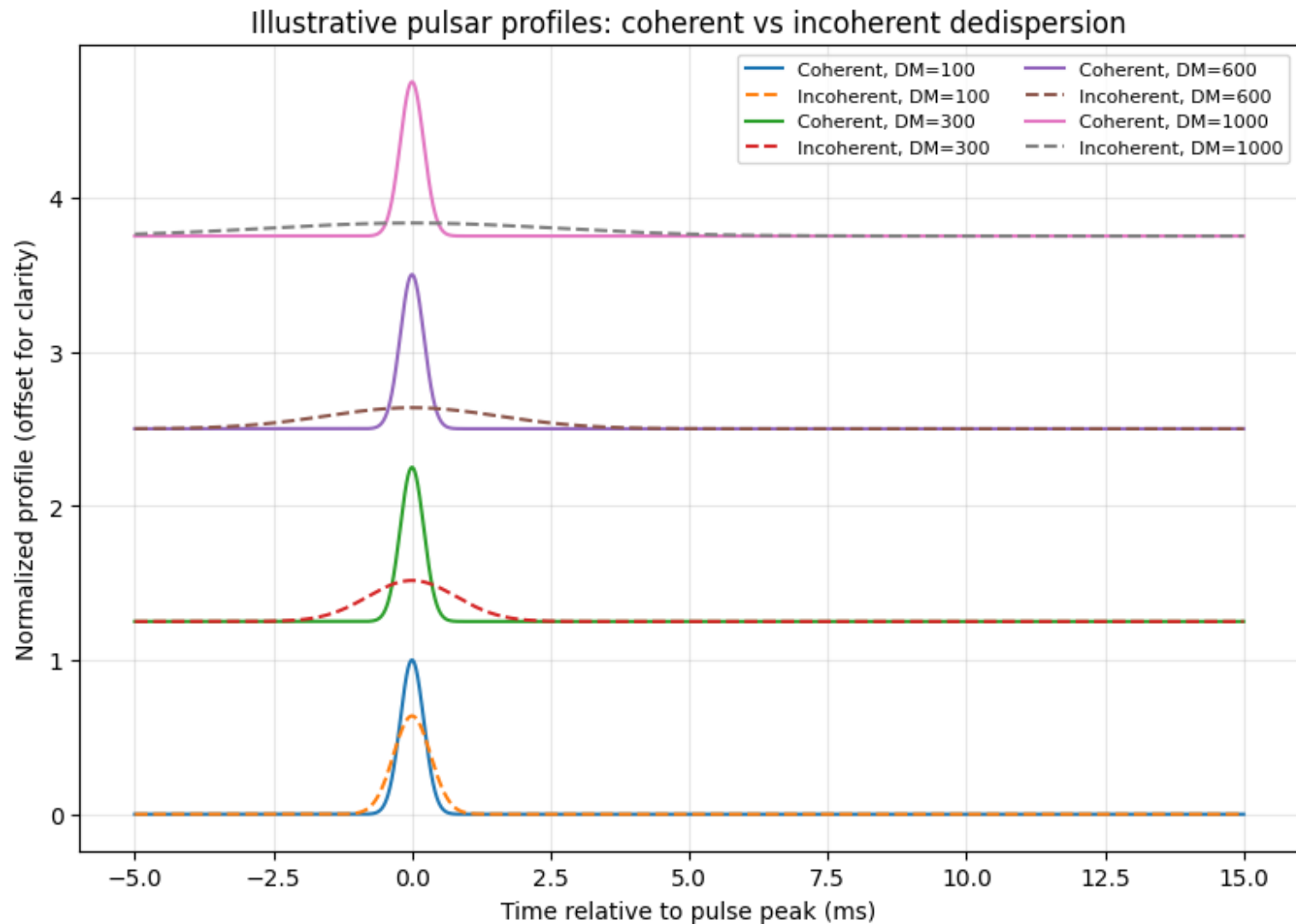
Applies the inverse filter to reconstruct the original signal



Loss of SNR from incoherent dedispersion



Incoherent Vs Coherent dedispersion



Coherent dedispersion

The coherent dedispersion transfer function

$$H(f_0 + f) = \exp \left(i \frac{2\pi D f^2}{f_0^2(f_0 + f)} \right)$$

the coherently dedispersed signal is obtained by applying the inverse filter:

$$V_{\text{dedisp}}(f_0 + f) = V_{\text{obs}}(f_0 + f) H^{-1}(f_0 + f)$$

$$H^{-1}(f_0 + f) = \exp \left(-i \frac{2\pi D f^2}{f_0^2(f_0 + f)} \right)$$

$$V_{\text{dedisp}}(f_0 + f) = V_{\text{obs}}(f_0 + f) \exp \left(-i \frac{2\pi D f^2}{f_0^2(f_0 + f)} \right)$$

The FFT length in coherent dedispersion is chosen long enough to contain the impulse response of the ISM dispersion filter

$$\Delta t_{\text{DM}} \approx 8.3 \times 10^6 \text{ DM} \frac{\Delta \nu}{\nu_0^3} \mu\text{s} \quad N_{\text{DM}} = \left\lceil \frac{\Delta t_{\text{DM}}}{t_s} \right\rceil \quad N_{\text{FFT}} \gtrsim 2 N_{\text{DM}}$$

What coherent dedispersion has enabled

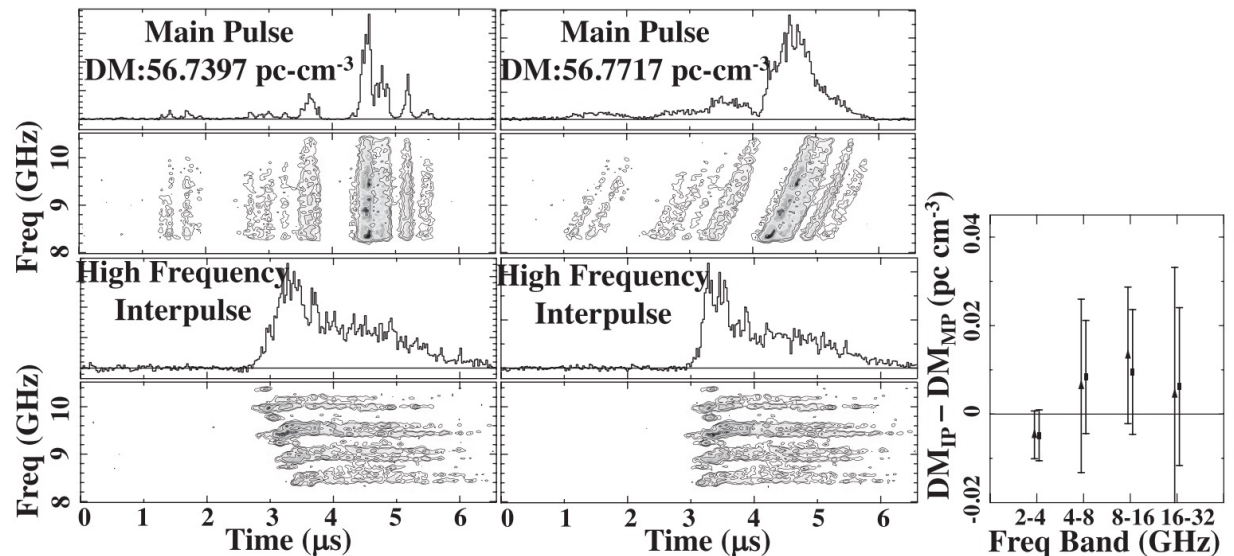
The nanosecond intensity structure resulting from plasma turbulence in the pulsar magnetosphere was found using coherent dedispersion

Precision determination of DM is used for ISM turbulence studies

The accurate, high-definition average profiles afforded by coherent dedispersion are essential for high precision timing

Many discoveries of fast fainter MSPs

The differences in DM between the bright Main Pulses and the High-Frequency Interpulses



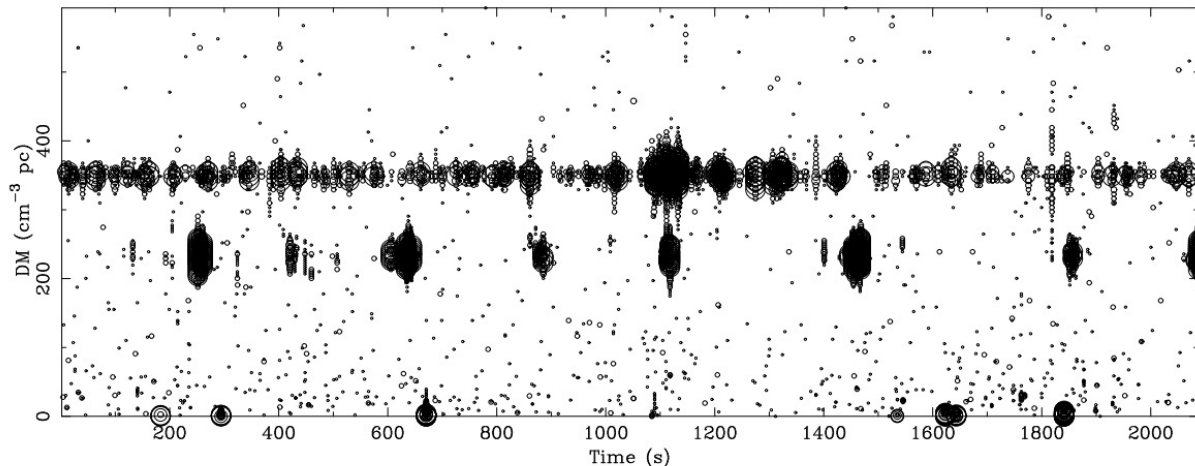
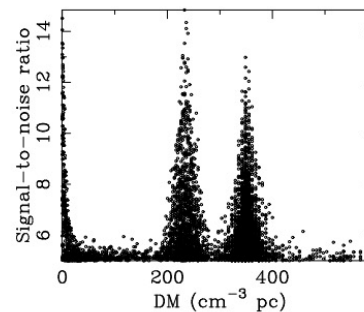
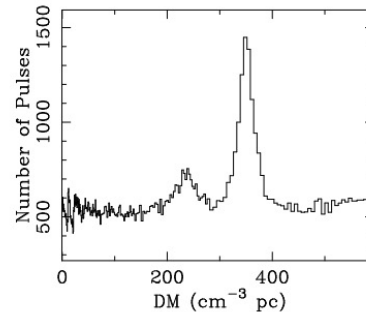
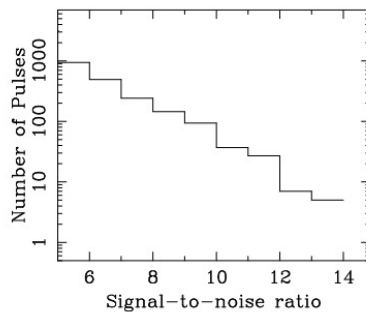
Single pulse Vs periodicity search

The ratio of signal-to-noise ratios of FFT and SP searches

$$r = \frac{(S/N)_{\text{SP}}}{(S/N)_{\text{FFT}}} = \frac{A}{\sqrt{N}} \frac{S_{\text{peak}}}{S_{\text{ave}}},$$

File: PM0089_00311.dat

5106 events. max S/N = 14.8. peak DM = 348.5 (cm⁻³ pc)



Radio pulses were detected at rates as low as once per three hours to as frequently as one every few minutes

Searching for Fast Transients

Noise in the data $\sigma_S = \frac{T_{\text{sys}}}{G\sqrt{2\Delta\nu t_{\text{samp}}}}$

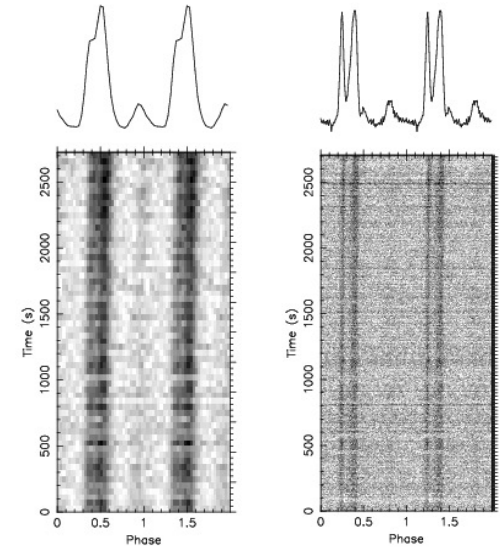
De-dispersion: Incoherent Vs Coherent dedispersion

Residual smearing in incoherent dedispersion

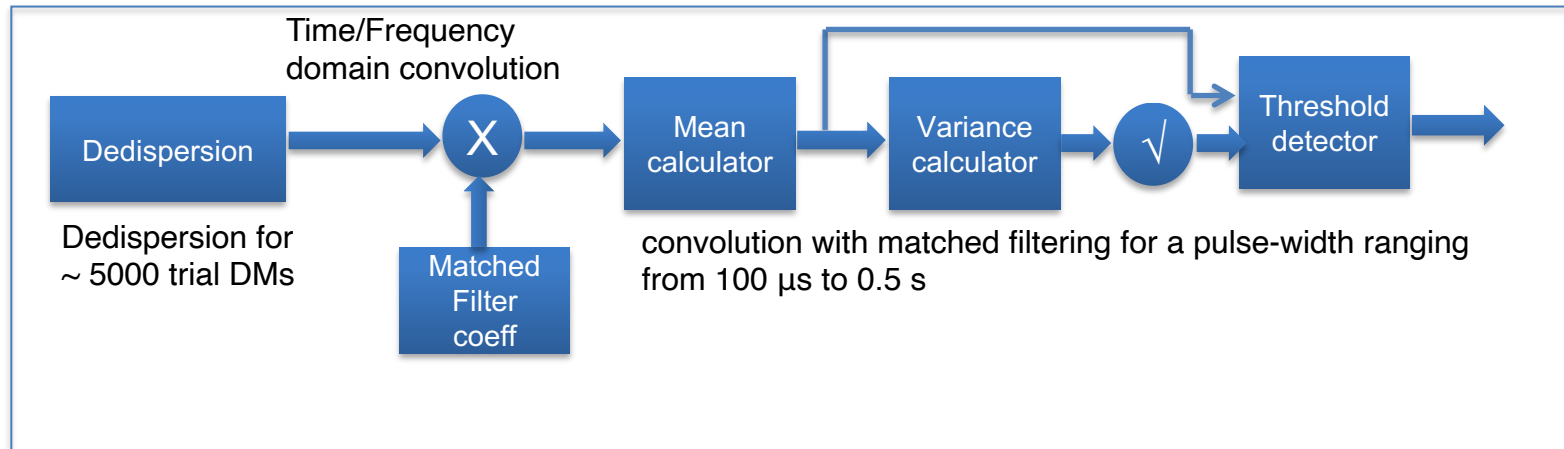
$$\Delta t_{\text{DM}} = 8.3 \times 10^6 \text{ DM } \Delta\nu_{\text{ch}} \nu^{-3} \text{ ms}$$

Detected width of FRB pulse

$$W = \sqrt{W_{\text{int}}^2 + t_{\text{samp}}^2 + \Delta t_{\text{DM}}^2 + \Delta t_{\text{DMerr}}^2 + \tau_s^2}$$



Detection Strategy



Rotating RAdio Transients

Rotating RAdio Transients (RRATs, Keane & McLaughlin, [2011](#)),

Currently, RRATalog has 335 RRATs are known

RRATs may be normal pulsars with very high nulling fractions

The pulsar magnetosphere may have: multiple stable states
It switches between: radio-loud and radio-quiete

Some RRATs lie close to the pulsar death line

Intermittency is caused by material fallback from a supernova debris disk

Radio emission from infalling circumstellar material affecting the charge density in the magnetosphere

RRAT burst rates on timescales ranging between ~ 0.5 hrs and ~ 5 yrs