Introduction to **Pulsar**, **Pulsar Timing**, and measuring of **Pulse Time-of-Arrivals**

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EPTA

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LEAP

Once upon a time…

Far far away…

In the Galaxy…

We found a pulsar…

Well…in fact…there are many of them!

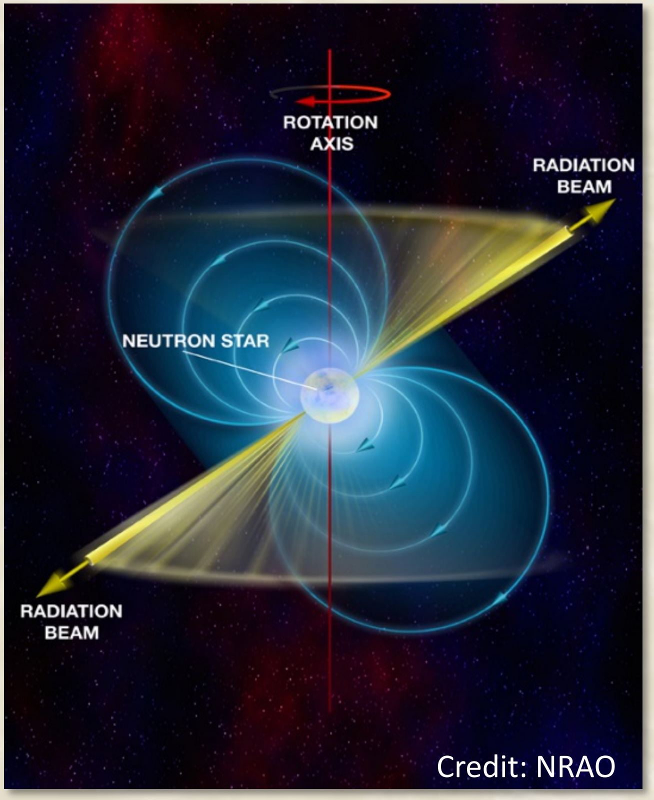
Up to 22/06/2017, there are over 2600 pulsars that have been discovered “officially”.

What are pulsars?

Pulsars

Externally**, pulsars** are:

- Fast-rotating magnetic dipoles;
- Emitting electromagnetic wave at radio wavelength / X-ray / γ-ray…;
- Cosmic "light houses";



Credit: NRAO

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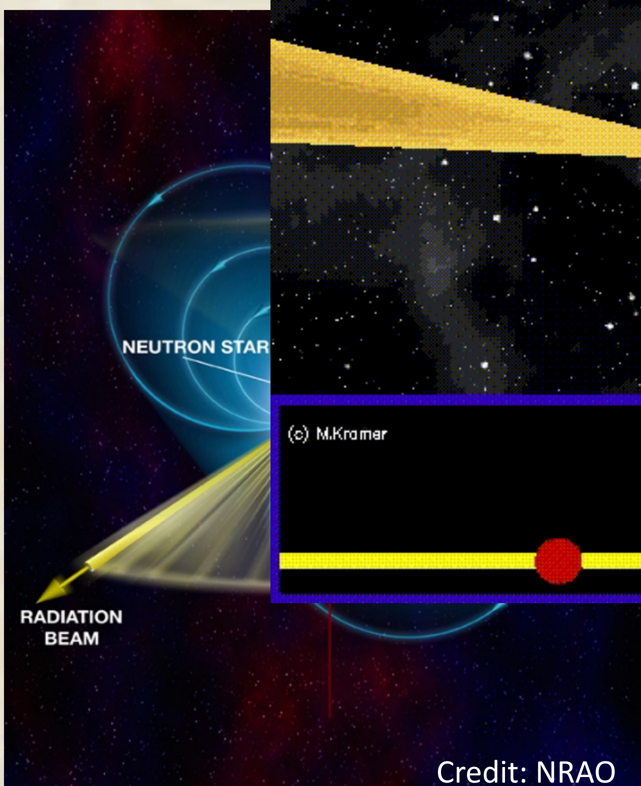
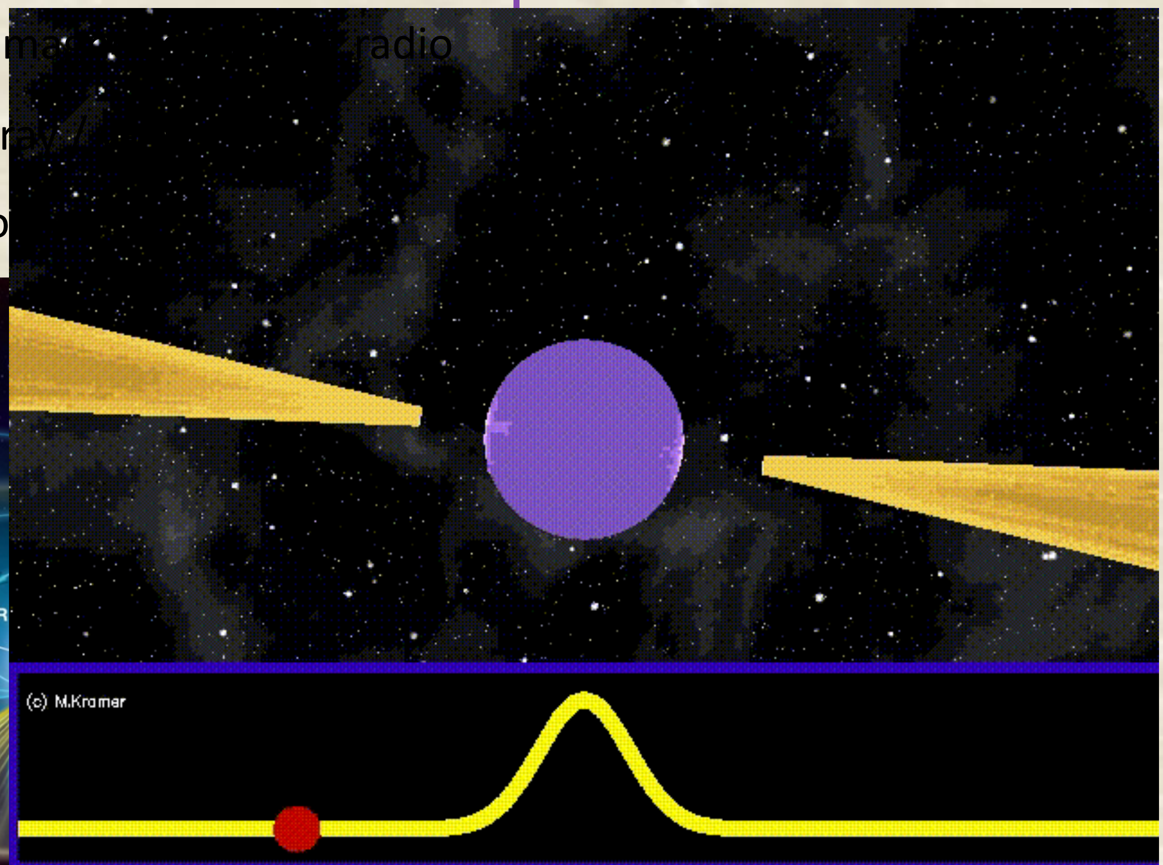


Credit: NRAO



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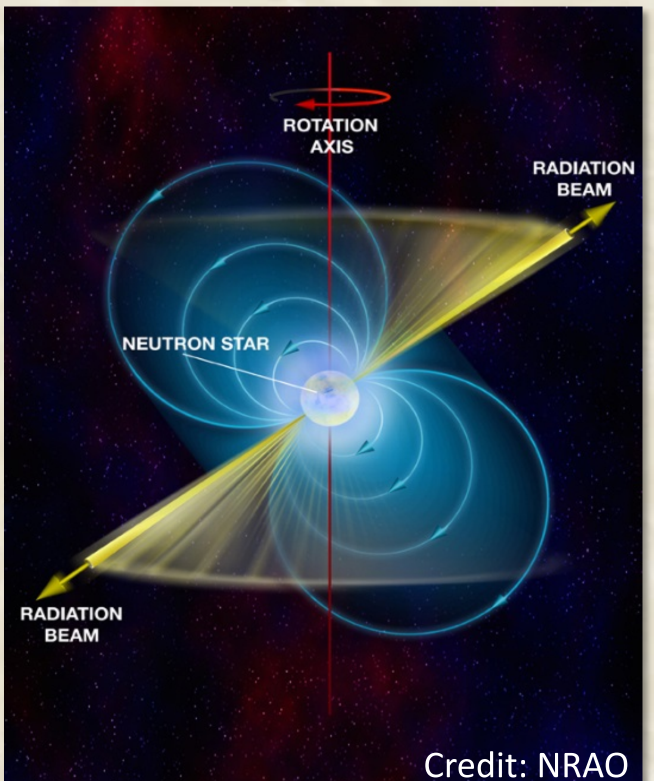
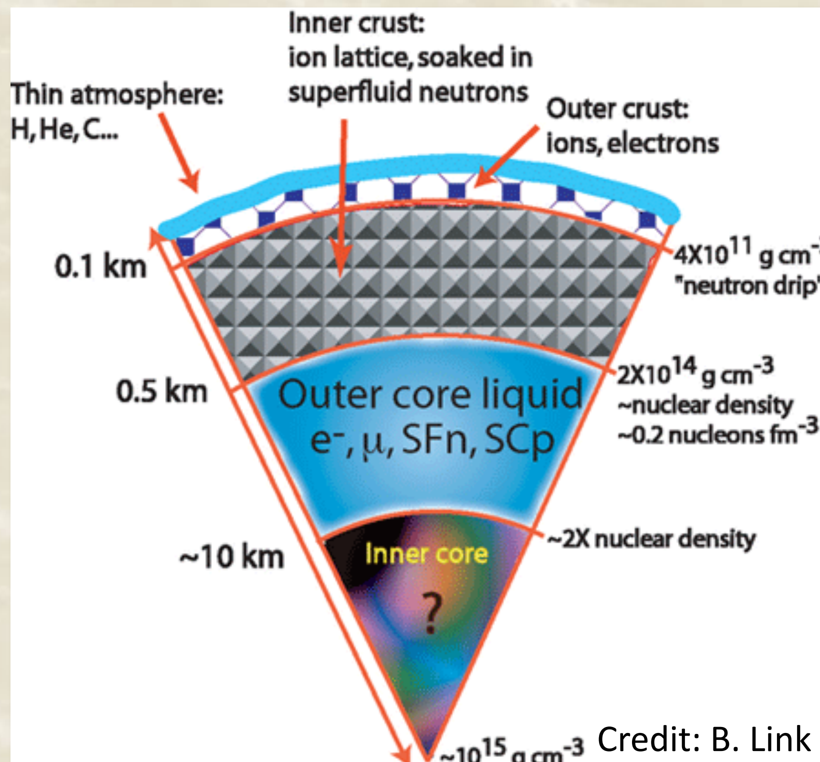


Credit: NRAO

Internally, **pulsars** are:

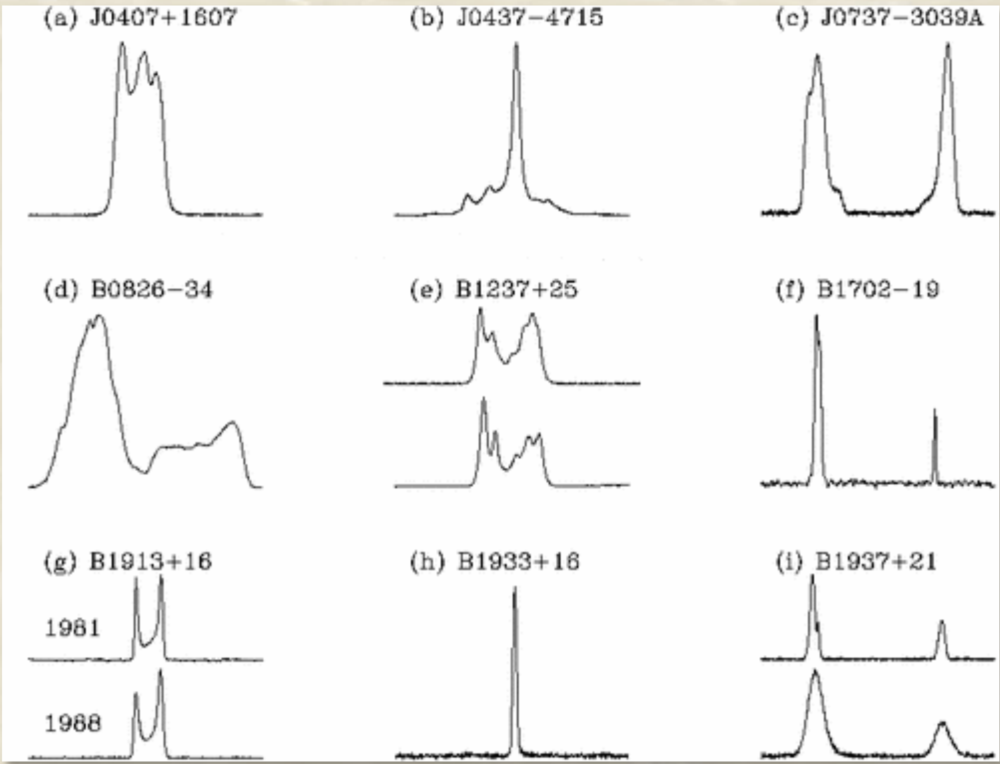
- Small objects, ~20 km in diameter;
- Heavy objects, ~1 solar mass;
- Multi-layer structure;
- Commonly believed to be neutron stars;



Credit: B. Link

Integrated pulse profile: pulsar's fingerprint

- Pulsar produces **periodic pulsation** signals **->** often too **weak** to detect;
- **Fold / Integrated** pulsar signals with respect to its **rotational period ->** increase signal quality and form **integrated pulse profile**;
- Pulsars are **distinguished by their integrated pulse profiles** (not by their names!) **->** all pulsars have their **unique** profile shape, just like human's **fingerprint**!

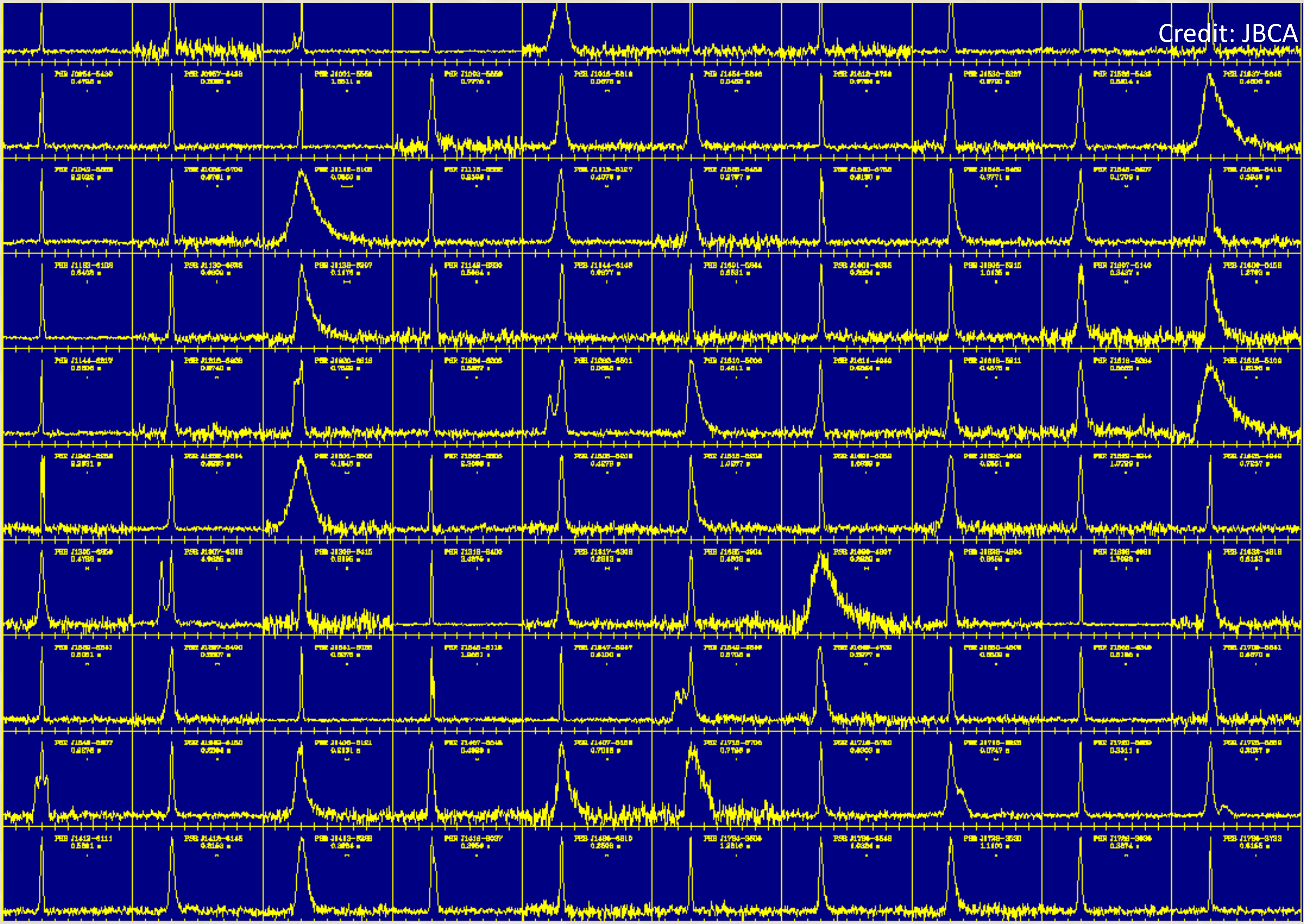


Not enough samples?

Get your eyes ready…

[Lorimer & Kramer 2005]

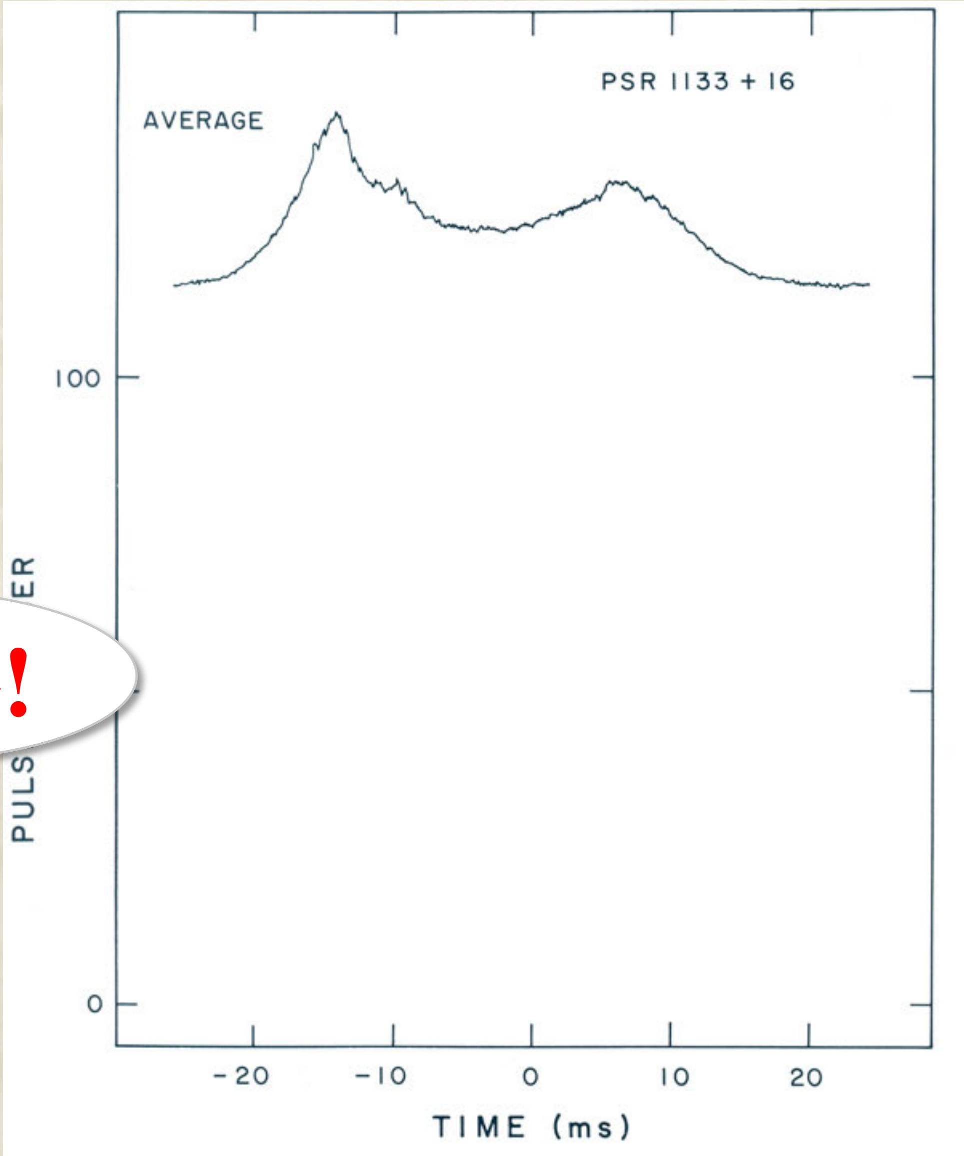
Integrated pulse profile: pulsar’s fingerprint



Integrated pulse profile vs single pulses

- **Integrated profiles** are seen to be consistent from different observations and in general **stable** in time;

- Pulse emissions from each individual rotations, i.e**., single pulses**, are seen to be highly **variable from pulse to pulse**!



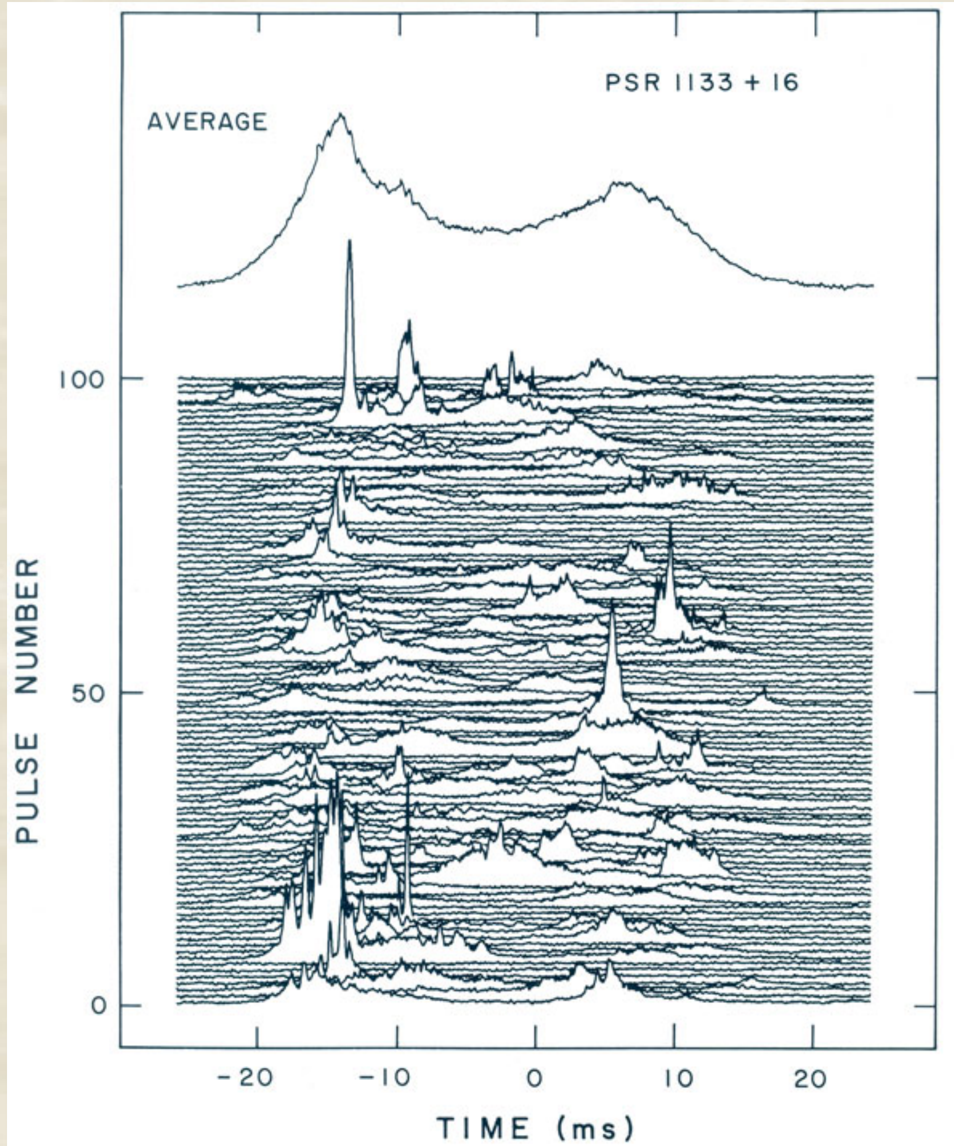
Credit: A. Lyne

Integrated pulse profile vs single pulses

- **Integrated profiles** are seen to be consistent from different observations and in general **stable** in time;

- Pulse emissions from each individual rotations, i.e**., single pulses**, are seen to be highly **variable from pulse to pulse**!

- Variation of single pulses can be both **stochastic** and **systematic (**periodic intensity modulation, drifting sub-pulse, mode-changing, nulling, etc.);



Credit: A. Lyne

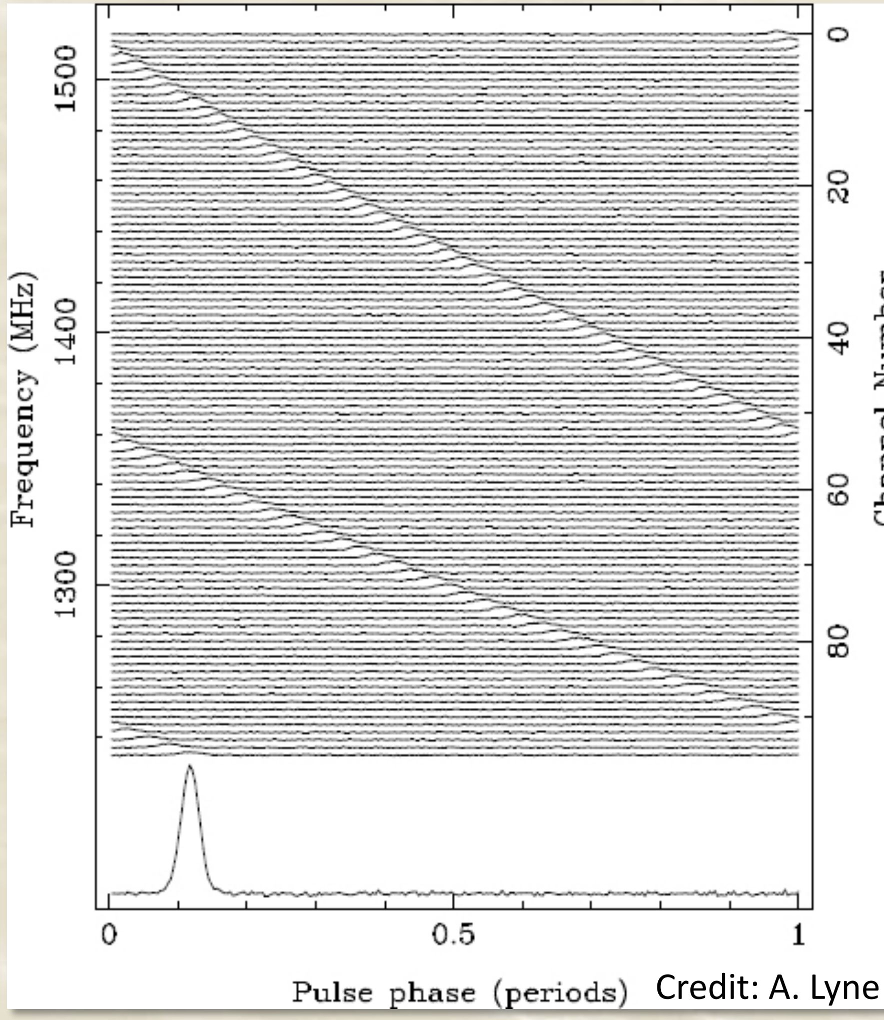
Pulsar signal and dispersion delay

- In between the pulsar and the earth, there is **interstellar medium** (ISM), containing cold plasma of ionized free electrons, etc.;

- Electromagnetic waves in radio frequency propagating through the ISM will endure a **time delay** (smaller group velocity) depending on their frequencies.

- The difference in time delay between signals at two different frequencies are given by:

$$\Delta t = 4.15 \text{ ms} \times \left[\left(\frac{\nu_{\rm lo}}{\rm GHz} \right)^{-2} - \left(\frac{\nu_{\rm hi}}{\rm GHz} \right)^{-2} \right] \times \left(\frac{\rm DM}{\rm cm^{-3}\ pc} \right)$$

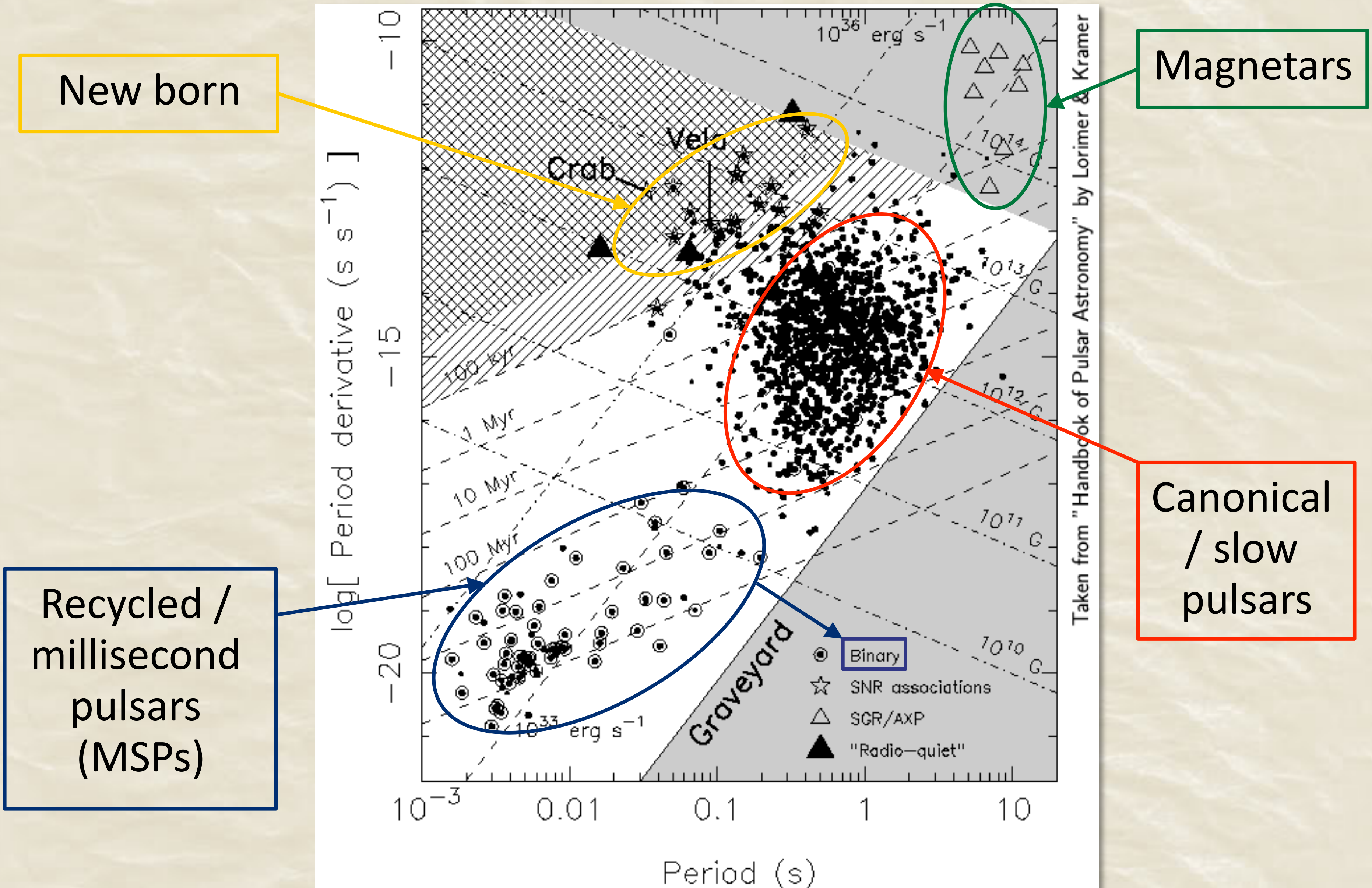


Credit: A. Lyne

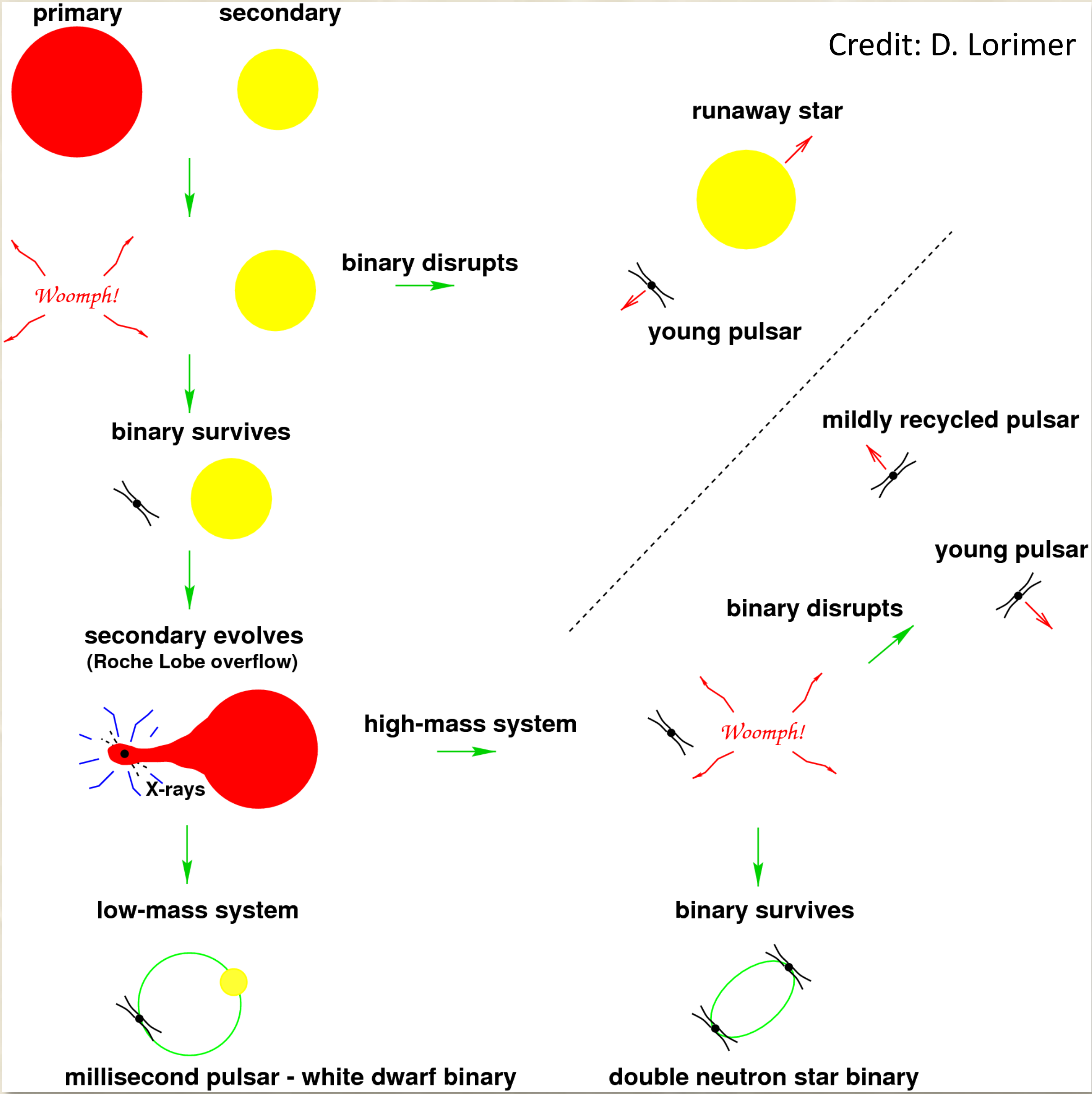
where the dispersion measure (DM) is defined by the column density of free electrons along the line of sight:

$$\mathrm{DM} = \int_0^d n_{\rm e}\, dl$$

P-Pdot diagram and classification



Formation and evolution of binary pulsar



- Binary pulsar in the end:

1). Mildly recycled pulsars (P > 20 ms) with heavy companion (neutron star);

2). Fully recycled pulsars (P < 20 ms), i.e., MSPs, with light companion (white dwarf);

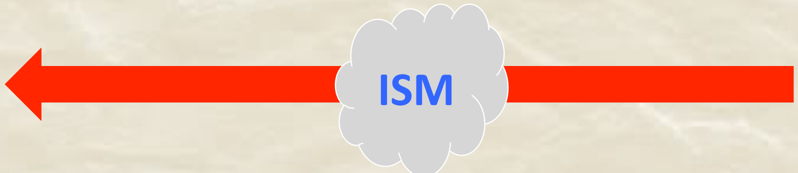
3). Pulsar-black hole possible;

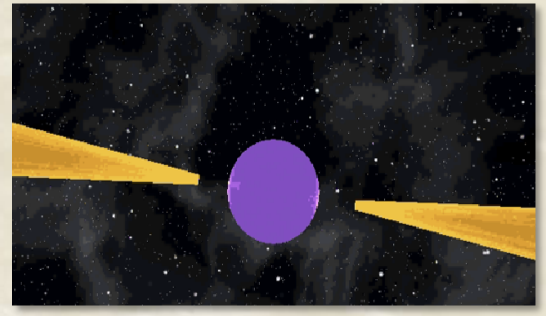
- Companion of binary pulsars found so far: white dwarf, neutron star, pulsar, main-sequence star, planet;

Only black hole missing!

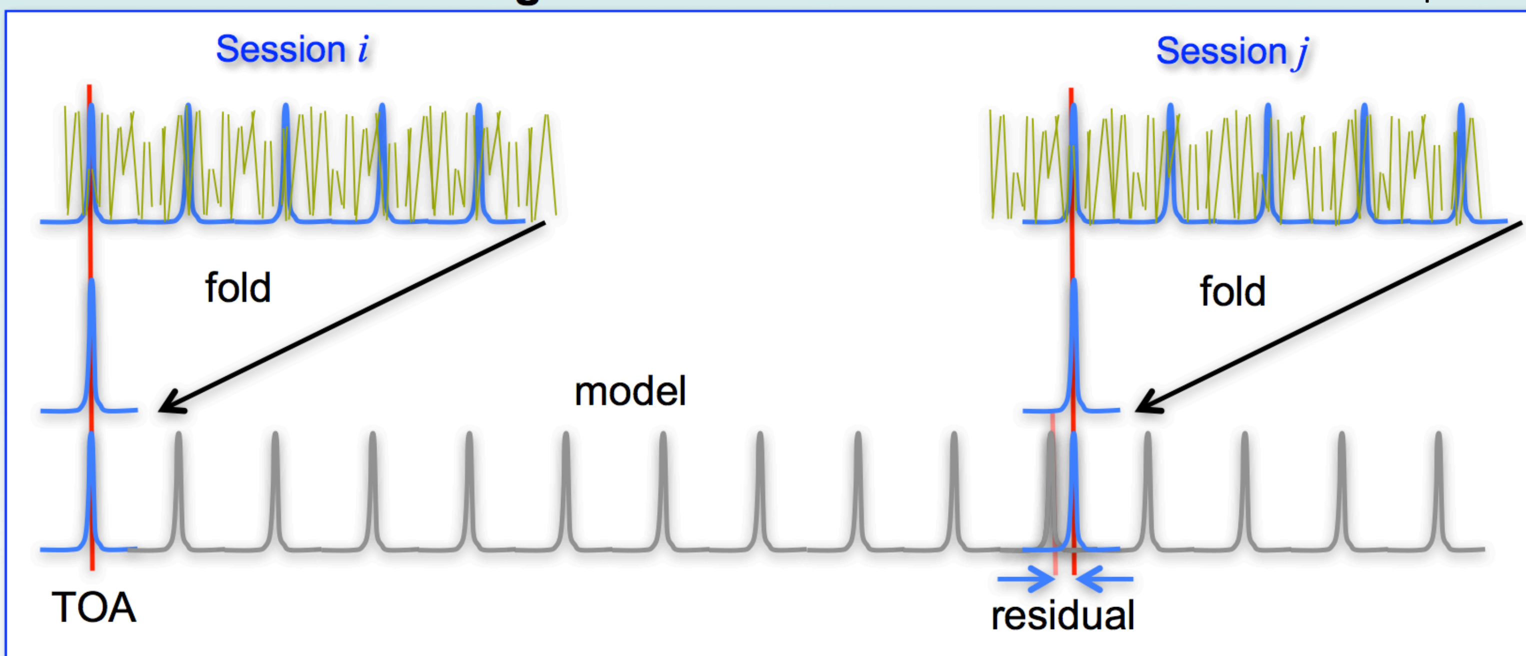
Pulsar timing

The first principle of timing experiment





Phase-connected timing solution: Credit: D. Champion



PSR J1012+5307: P= 0.005255749010197010 3(19) **s** (Desvignes et al. 2016);

<- By counting all pulses (3×10^{13} rotations!!) in **20 years**!!

Time transformation in timing experiment

- Pulse phase / **"counts" of pulses** at pulsar proper time:

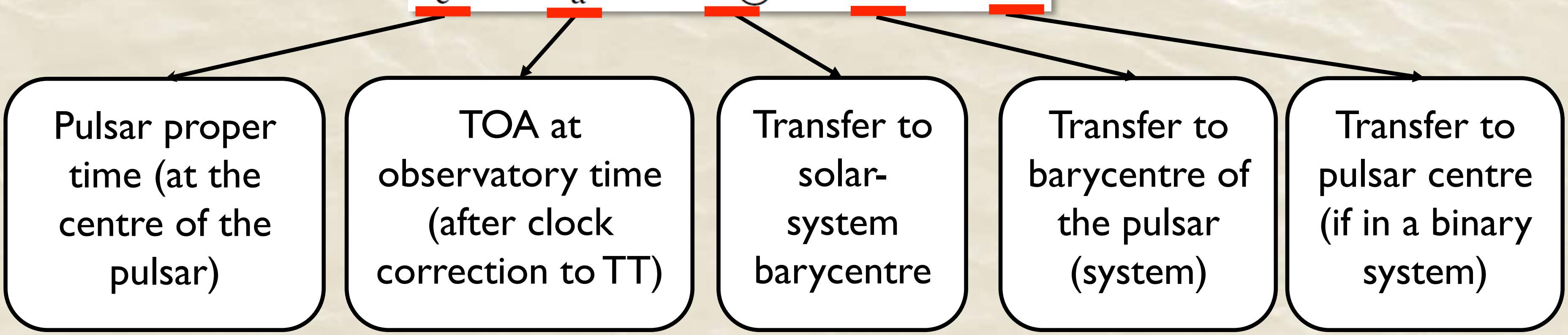
$$\phi(t) = \sum_{n \geqslant 1} \frac{\nu^{(n-1)}}{n!} \left(t_{\rm e}^{\rm psr} - t_{\rm P}\right)^n + \phi_0$$

The fractional part of $\varphi(t)$ is the **timing residual**.

Pulsar is intrinsically a precise clock -> It is a clock ONLY WHEN we measure with respect to its proper time!

- Top-level **timing formula**:

$$t_{\rm e}^{\rm psr} = t_{\rm a}^{\rm obs} - \Delta_{\odot} - \Delta_{\rm IS} - \Delta_{\rm B}$$



Time model

- Components of time transformation:

$$\Delta_{\odot} = \Delta_{\mathrm{A}} + \Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{p}} + \Delta_{\mathrm{D}\odot} + \Delta_{\mathrm{E}\odot} + \Delta_{\mathrm{S}\odot}$$

$$\Delta_{\mathrm{IS}} = \Delta_{\mathrm{VP}} + \Delta_{\mathrm{ISD}} + \Delta_{\mathrm{FDD}} + \Delta_{\mathrm{ES}}$$

$$\Delta_{\mathrm{B}} = \Delta_{\mathrm{RB}} + \Delta_{\mathrm{AB}} + \Delta_{\mathrm{EB}} + \Delta_{\mathrm{SB}}$$

[Edwards et al. 2006]

- **Timing model parameters:**

a). **Spin parameters**: period, period derivative, glitches, spin noise, …

b). **Astrometry parameters**: RA, DEC, proper motion, parallax, …

c). **ISM parameters**: DM, derivative(s) of DM, …

d). **Keplerian binary parameters**: orbital period (P_b), projected semi-major axis (x), longitude of periastron (ω), eccentricity (e), epoch of periastron passage (T_0);

e). **Post-Keplerian (relativistic) parameters**: advance of periastron ($\dot{\omega}$), second Doppler & gravitational time dilation (Einstein delay, γ), orbital decay ($\dot{P}_b$), curvature of space-time (Shapiro delay, sin i, M_2), variation of projected semi-major axis ($\dot{x}$), …

To better understand the gravitational time dilation…

Timing residuals

- For the N_ith TOA, given the values of the timing parameters, one can calculate its corresponding timing residual in pulsar proper time, by subtracting the integer part of φ_i (number of rotations):

$$R_i = \frac{\phi_i - N_i}{\nu}$$

Note: You may well have ambiguity of an integer number (i.e., lose coherency in pulse phase) if the initial values of the timing parameters are not good enough to keep residuals within ± half a period;

- The timing parameters are fitted based on a linear singular-value decomposition, weighted least-squares algorithm, minimising:

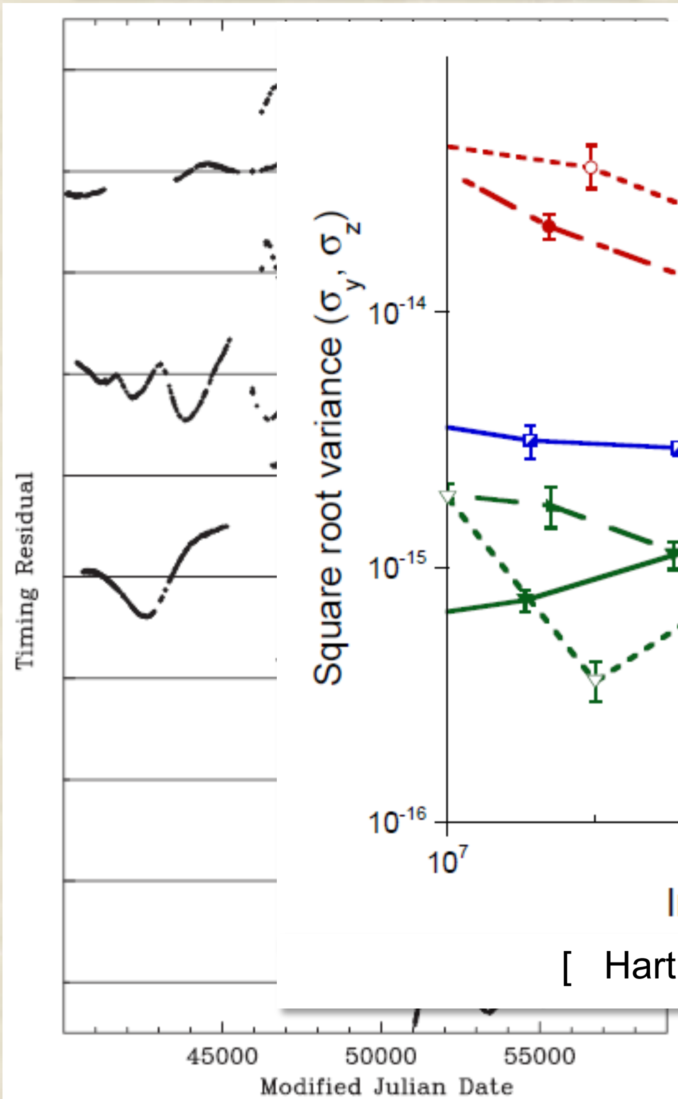
$$\chi^2 = \sum_{i=1}^{N} \left(\frac{R_i}{\sigma_i} \right)^2$$

- The timing residuals are supposed to be Gaussian / white noise when the model & model parameters describe the data perfectly.

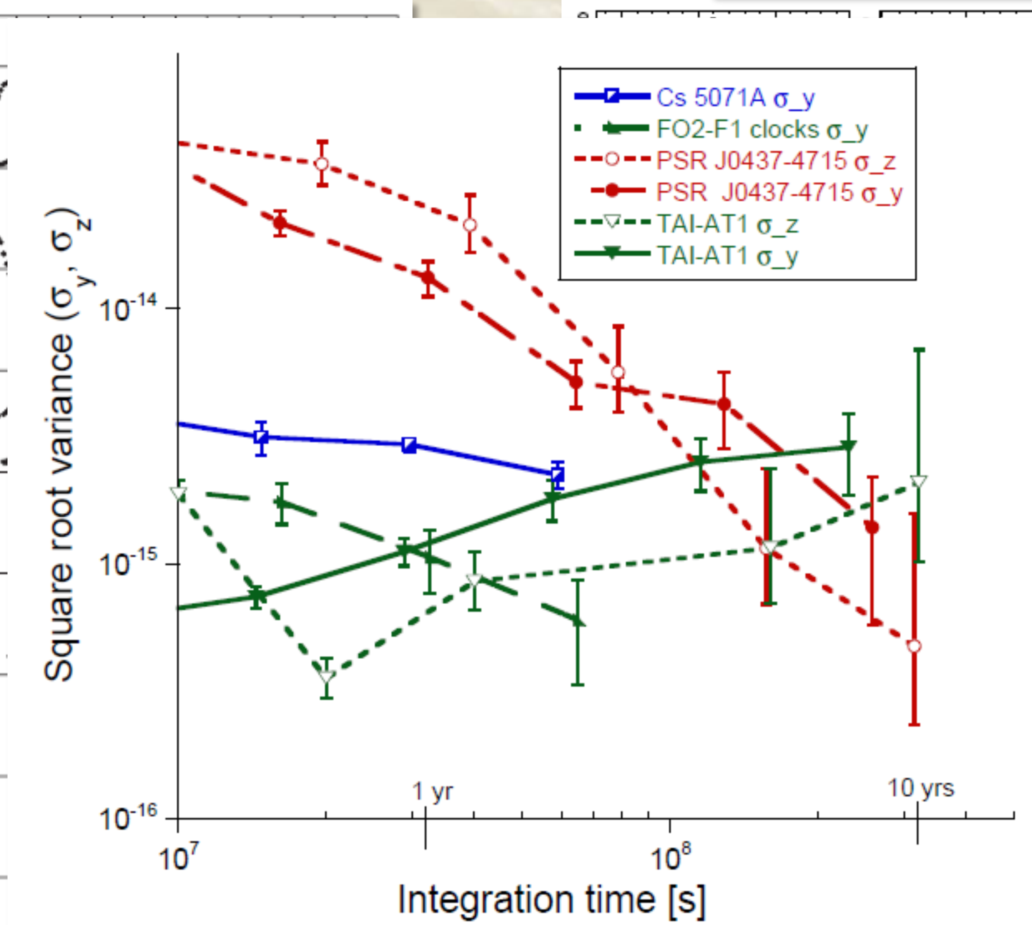
Timing stabilities

Canonical Pulsars

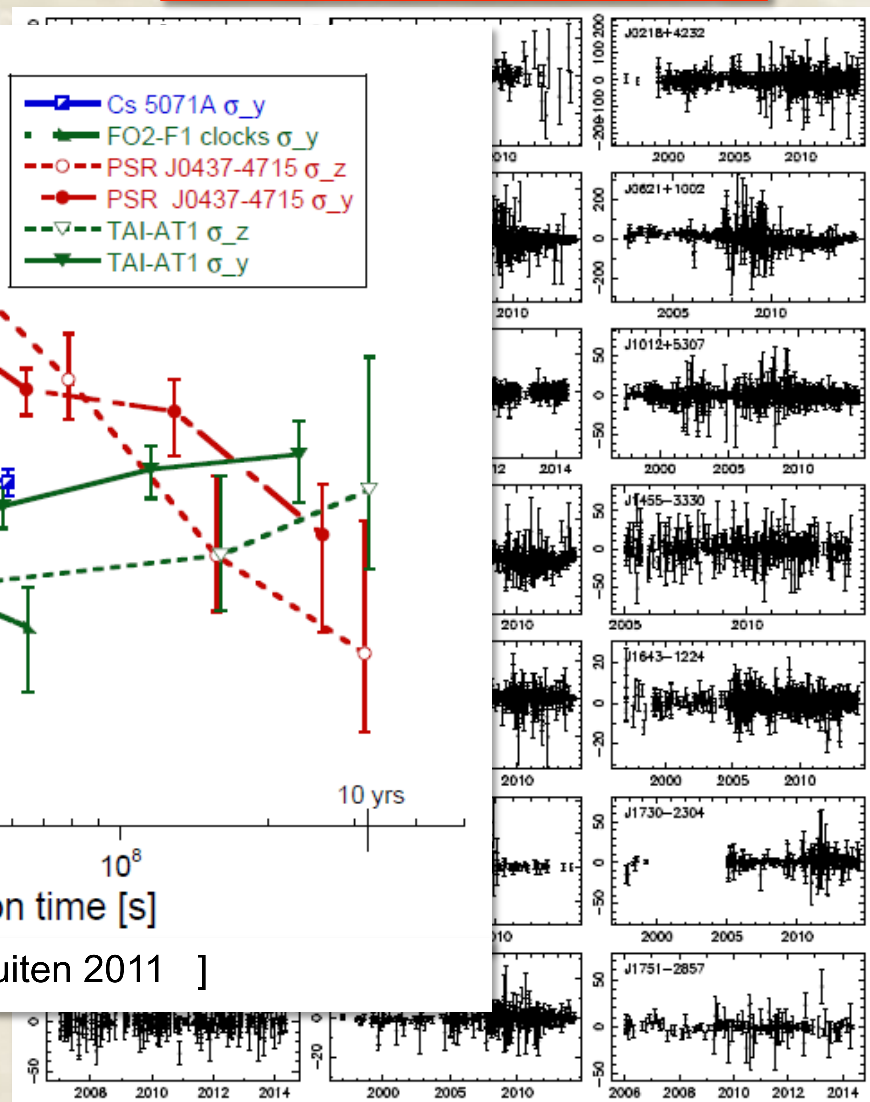
Millisecond pulsars



[Lyne et al. 2010]



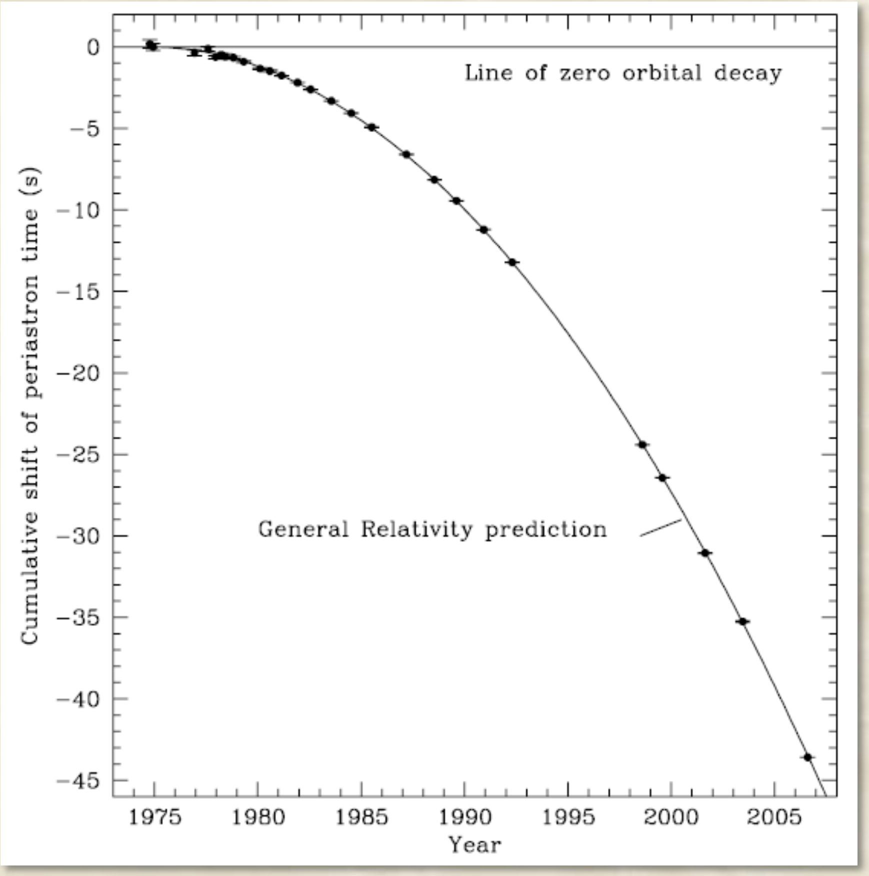
[Hartnett & Luiten 2011]



[Desgivnes et al. 2010]

Testing General Relativity with pulsar timing

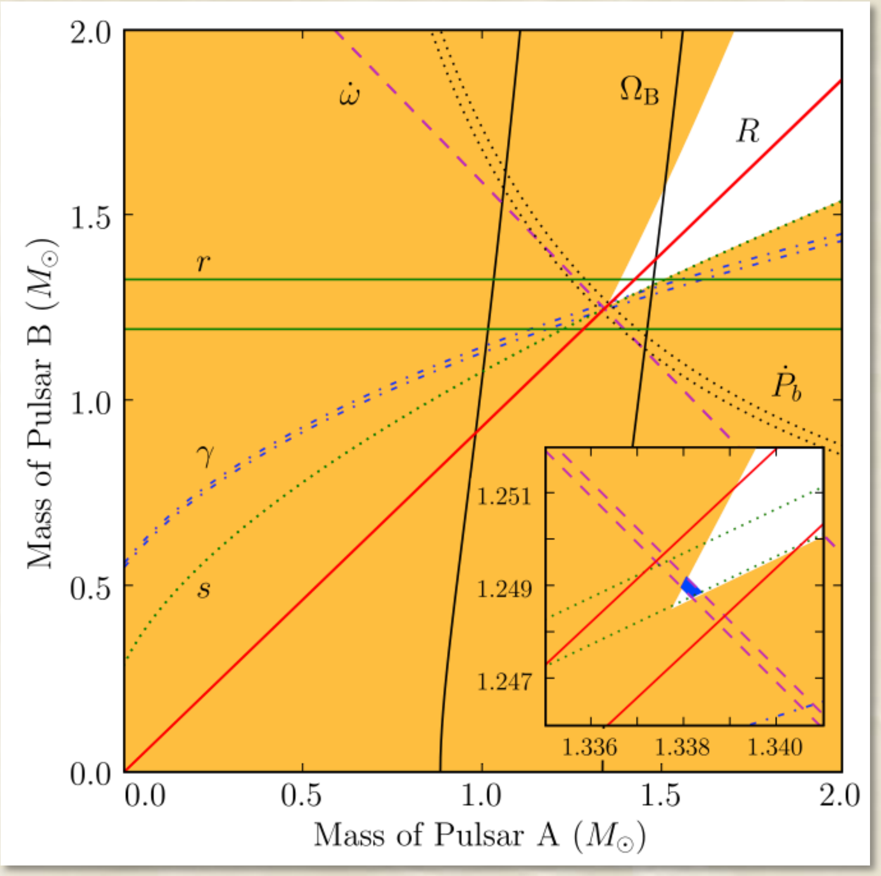
Hulse-Taylor Pulsar



[Weisberg et al. 2010]

Physics 1993

The double-pulsar system



[Kramer et al. 2006]

The most constraining test of General Relativity (better than 99.95%) !

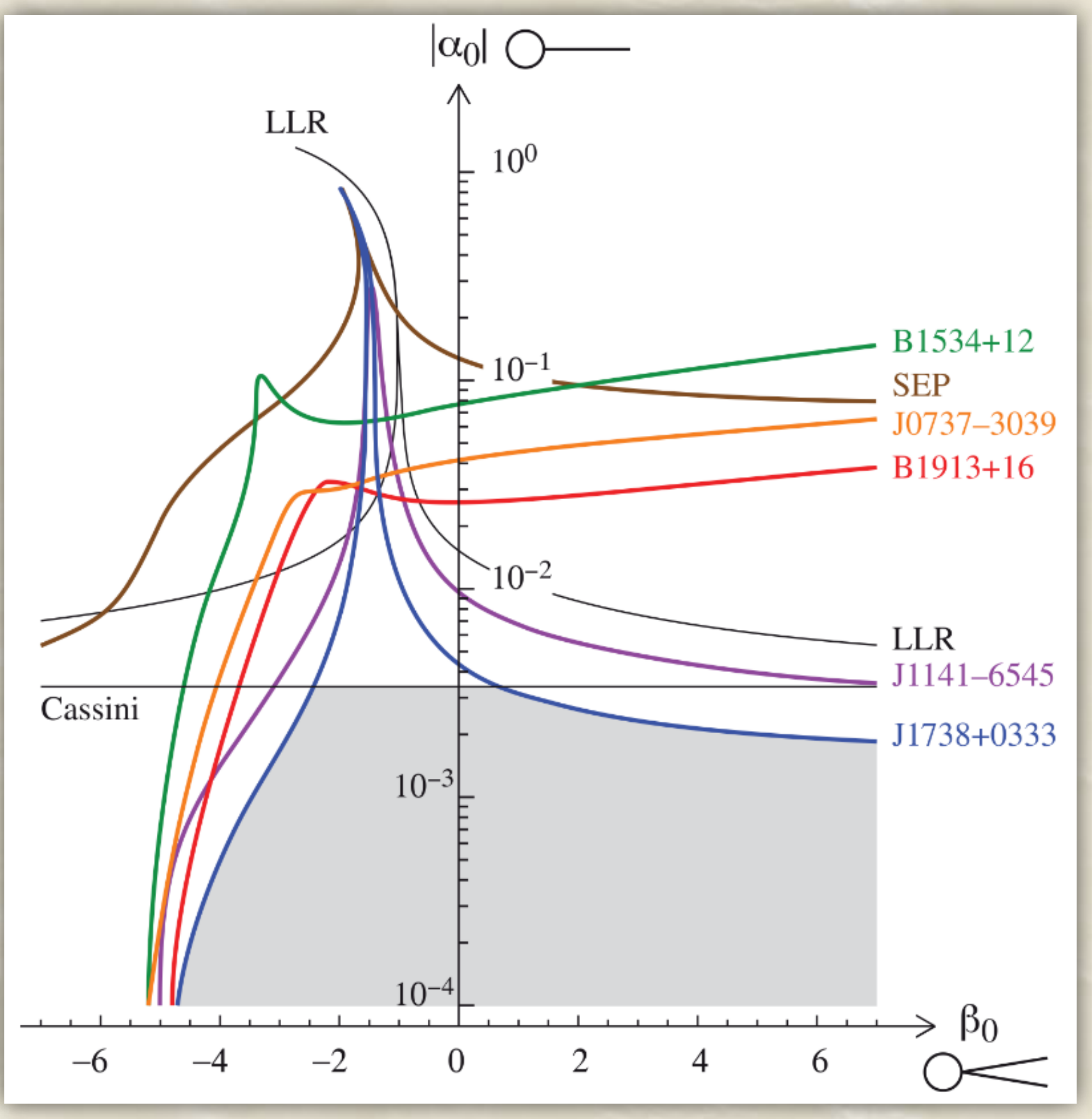
Constraining alternative theory of gravity

- Alternative theories of gravity predict a variety of **deviations from General Relativity.**
- Mono-scalar-tensor theory introduces scaler field (φ) which couples with matter (strength denoted by α_0, β_0):

$$\Box_{g_*}\phi = -\frac{4\pi G_*}{c^4}(\alpha_0 + \beta_0\phi)\,T_*$$

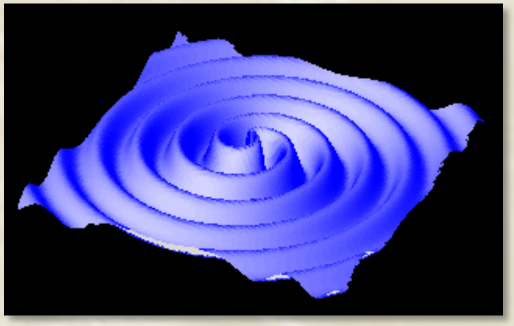
- Dipole gravitational radiation when asymmetry in mass components (e.g., NS-WD):

$$\dot{P}_b^{\rm dipolar} \simeq -\frac{4\pi^2 G}{c^3 P_b}\frac{M_{\rm PSR}M_{\rm WD}}{M_{\rm PSR}+M_{\rm WD}}(\alpha_{\rm PSR}-\alpha_{\rm WD})^2$$



[Freire et al. 2012]

The gravitational wave astronomy



- Gravitational waves are:

  a). Ripples in the curvature of space-time propagating as a wave;

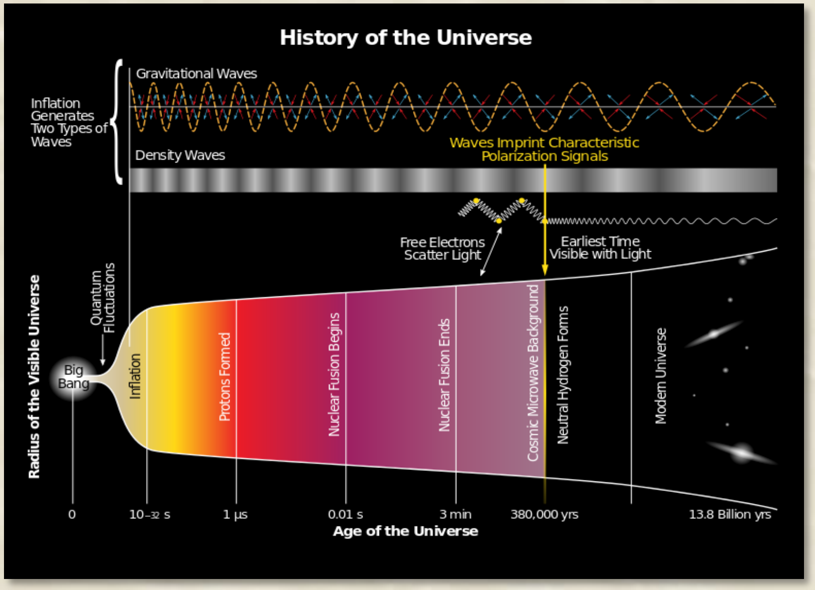
  b). Predicted by General Relativity and alternative theories;

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

  c). Indirect evidence found from the **Hulse-Taylor pulsar**'s orbital decay;

  d). Direct detection can be from both stochastic background (GWB) and single sources (e.g., supermassive black hole pairs);

  e). **Window now opened by the LIGO detection!**



- The GWB:

  a). Generated from the **early universe !**

  b). Origin of major component: still not clear ! (large number of supermass black hole binaries? Cosmic strings? …?)

Detecting gravitational wave with a pulsar timing array

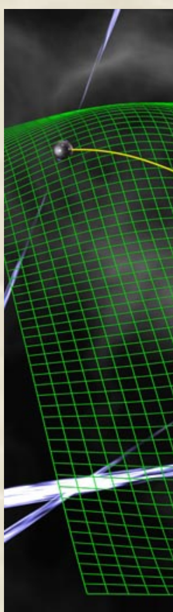
- A pulsar

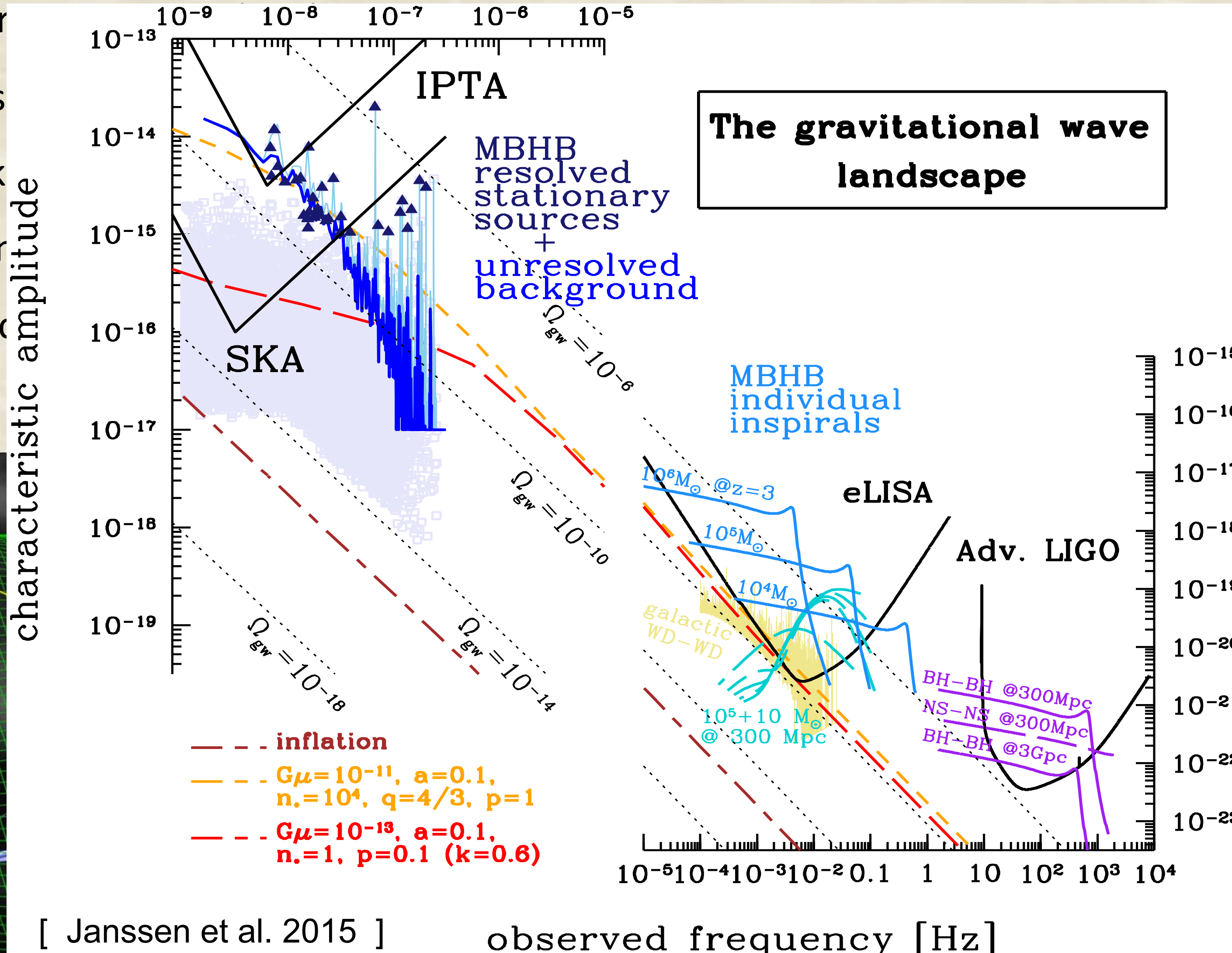
  a). Cons ns;

  b). Look

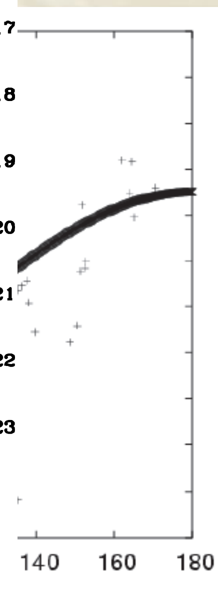
  c). A cor

  d). The c





[Janssen et al. 2015]



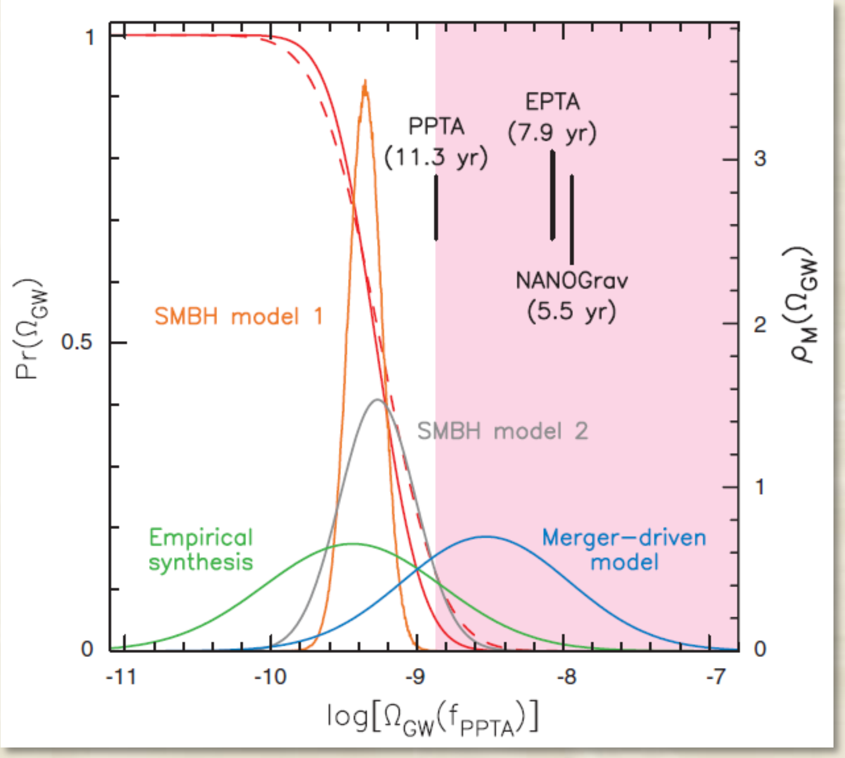
Credit: D. Champion

[Helling & Downs 1983]

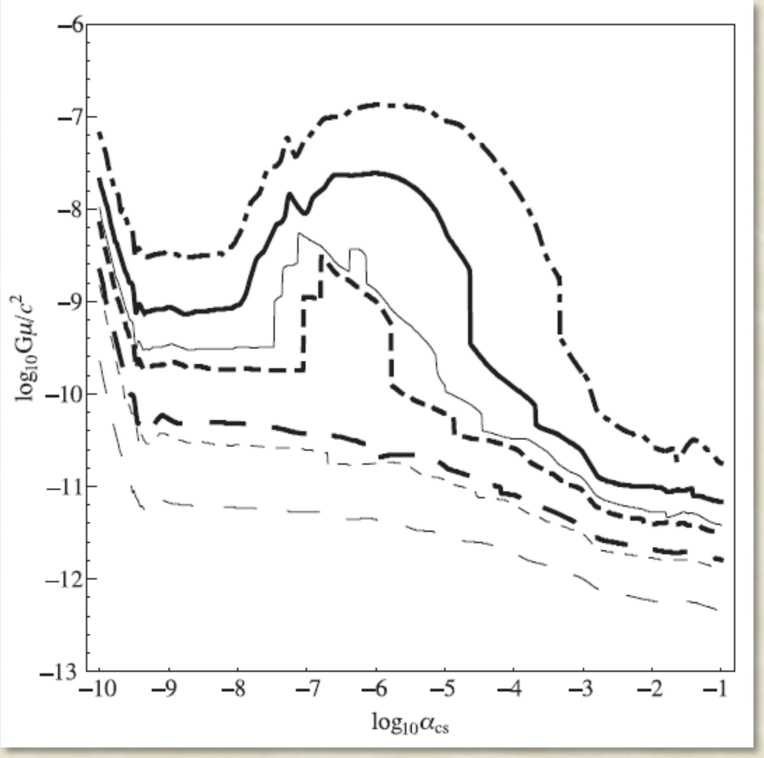
Gravitational wave experiments with PTA

- Detect gravitational wave / place an upper limit on GWB can:

a). Constrain cosmological models of supermassive black hole population;



[Shannon et al., 2013]



[Lentati et al., 2015]

b). Constrain string tension of cosmic strings and models of the early universe;

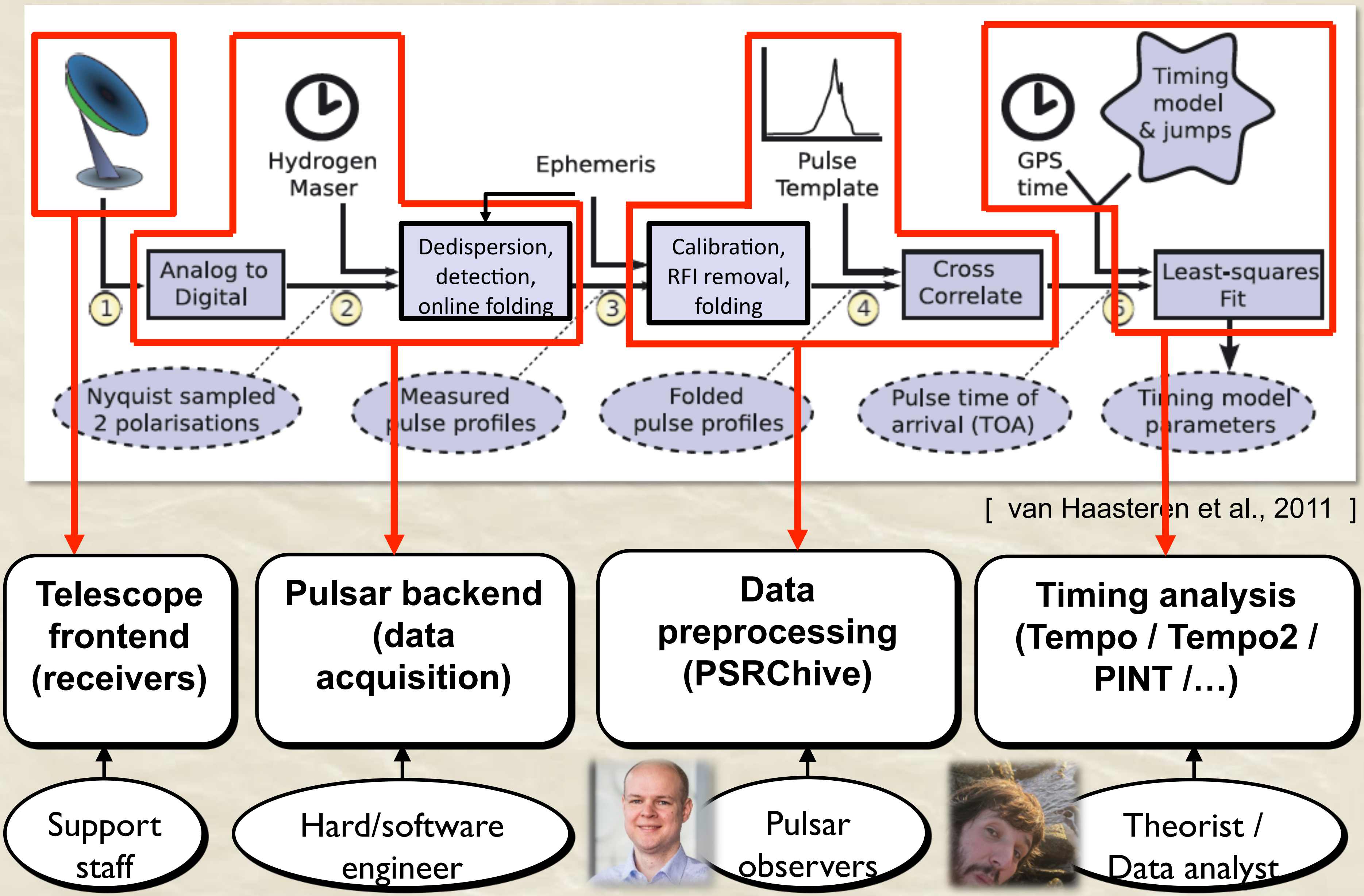
c). Measure properties (e.g., polarisation, speed) of gravitational wave and test General Relativity;

Processing pulsar data

to obtain pulse time-of-

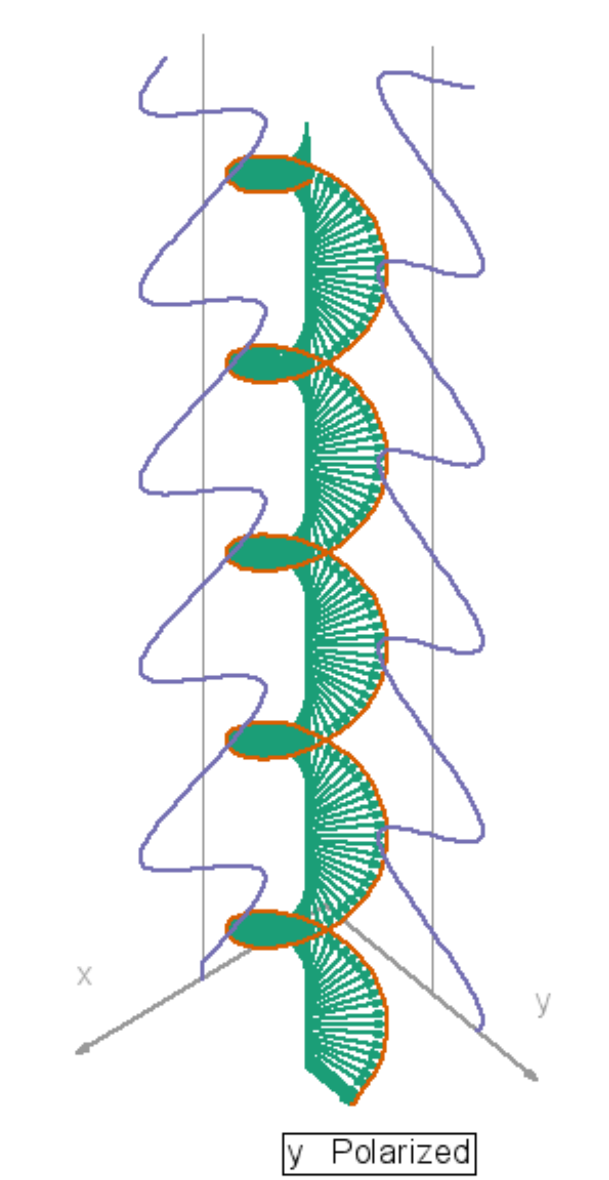
arrival

The pulsar timing signal chain

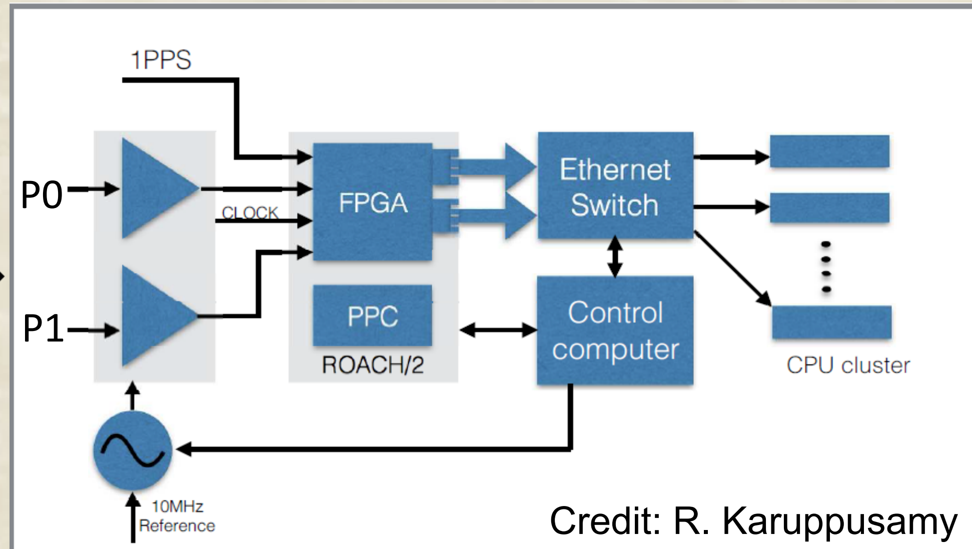


[van Haasteren et al., 2011]

Signal with polarisation



Credit: wikipidia



Credit: R. Karuppusamy

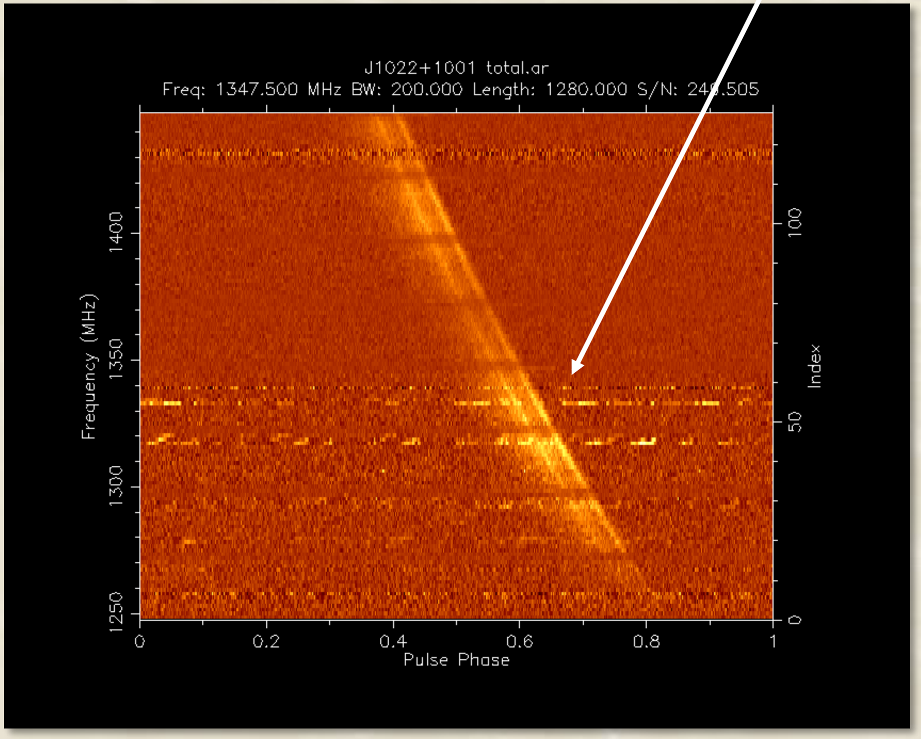
- Pulsar EM signal usually has significant **polarisations** (specific orientation of oscillation during propagation);
- The signal can be fully represented by sampling in dual polarisation on either **linear** or **circular** basis, and is detected in the form of **stokes parameters** (**I, Q, U, V**);
- Calibration needed to obtain the original polarized signal (correct for feed rotation & receiver imperfection):

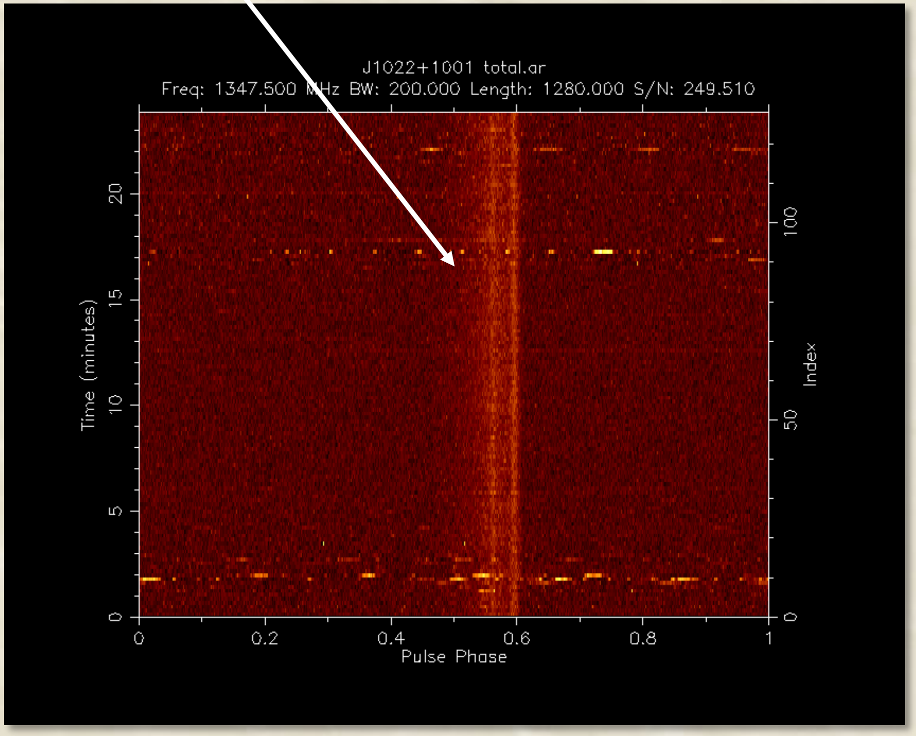
$$\rho' = \mathbf{J}\rho\mathbf{J}^{\dagger}$$

$$\mathrm{M} = \mathrm{A}(\mathrm{J} \otimes \mathrm{J}^{*})\mathrm{A}^{-1}$$

Radio interference

- Radio interference (RFI) is common in observations of Radio Astronomy!
- Terrestrial artificial radio signal, many possible origins: satellite, plane, radio broadcast, wifi, cell phone, lightening, mircowave, …
- ”Most common” feature: strong, narrow band, time-variant, with zero DM, appear in multiple beams (if any) simultaneously (near-field), …





Data needs to be cleaned to minimize systematics !!!

Measuring TOA with template-matching

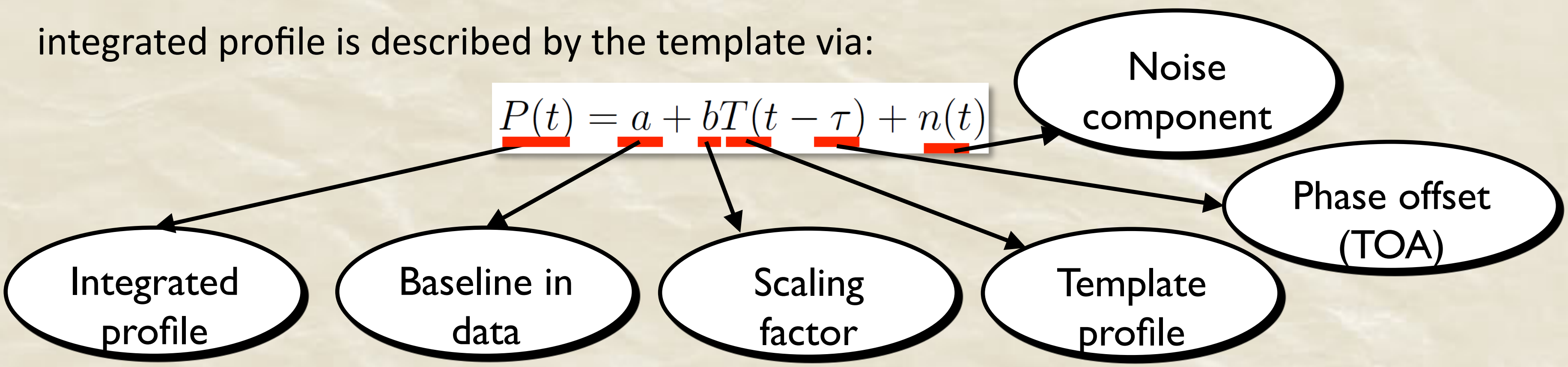
- Expected uncertainty of TOA given the signal-to-noise (S/N) of detection of the integrated profile (averaged N pulses), when only radiometer noise (white noise) is on top of the profile:

$$\sigma_{\rm rn} = \frac{1}{ß \times {\rm S/N}_1}\sqrt{\frac{\Delta}{\rm N}} \qquad ß = \sqrt{\int [U'(t)]^2 {\rm d}t}$$

[Downs & Reichley, 1983; Liu et al., 2011]

- In practice, TOAs are measured by cross-correlating the integrated profile with a **template profile** (normally formed from independent observations), assuming the integrated profile is described by the template via:

$$P(t) = a + bT(t-\tau) + n(t)$$



- The template profile needs to be of **high S/N**, or **noise free** (analytic), or **after noise-removal** technique.

Frequency-domain fitting algorithm

- The template-matching is normally carried out in the frequency-domain, after Discrete-Fourier-Transform of the data:

$$P_k \exp(\mathrm{i}\theta_k) = \sum_{j=0}^{N-1} p_j \, \mathrm{e}^{\mathrm{i}2\pi jk/N}$$

$$S_k \exp(\mathrm{i}\phi_k) = \sum_{j=0}^{N-1} s_j \, \mathrm{e}^{\mathrm{i}2\pi jk/N}$$

- The model becomes:

$$P_k \exp(\mathrm{i}\theta_k) = aN + bS_k \exp[\mathrm{i}(\phi_k + k\tau)] + G_k, \quad k = 0, \ldots, \quad (N-1),$$

- The parameters (b, τ) are then obtained by minimising the goodness-of-fit:

$$\chi^2(b, \tau) = \sum_{k=1}^{N/2} \left| \frac{P_k - bS_k \exp[\mathrm{i}(\phi_k - \theta_k + k\tau)]}{\sigma_k} \right|^2$$

- The errors are obtained from standard error propagation (covariance matrix):

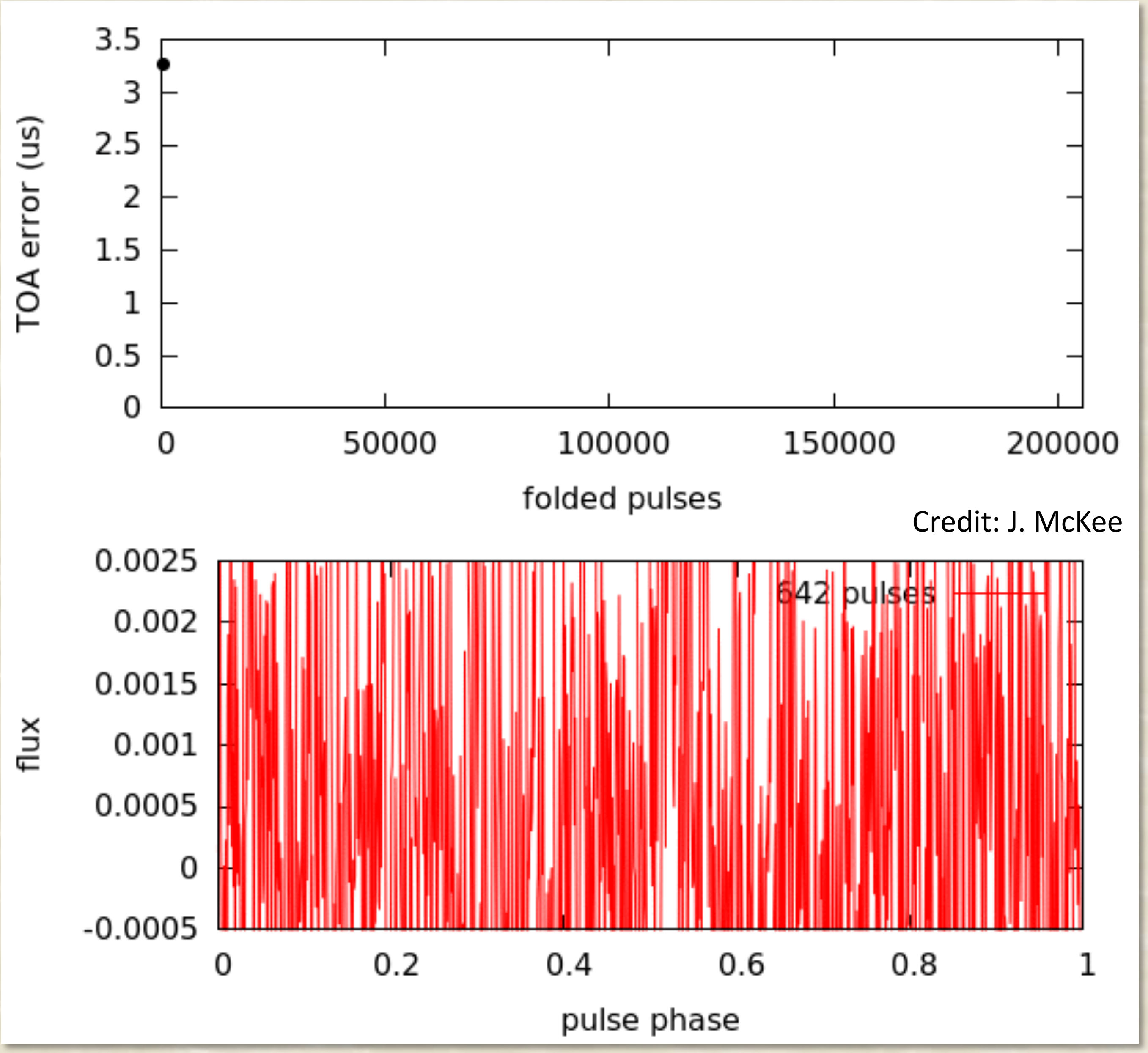
$$\sigma_\tau^2 = \left(\frac{\partial^2 \chi^2}{\partial \tau^2}\right)^{-1} = \frac{\sigma^2}{2b \sum k^2 P_k S_k \cos(\phi_k - \theta_k + k\tau)},$$

$$\sigma_b^2 = \left(\frac{\partial^2 \chi^2}{\partial b^2}\right)^{-1} = \frac{\sigma^2}{2 \sum S_k^2}.$$

Frequency-domain fitting algorithm

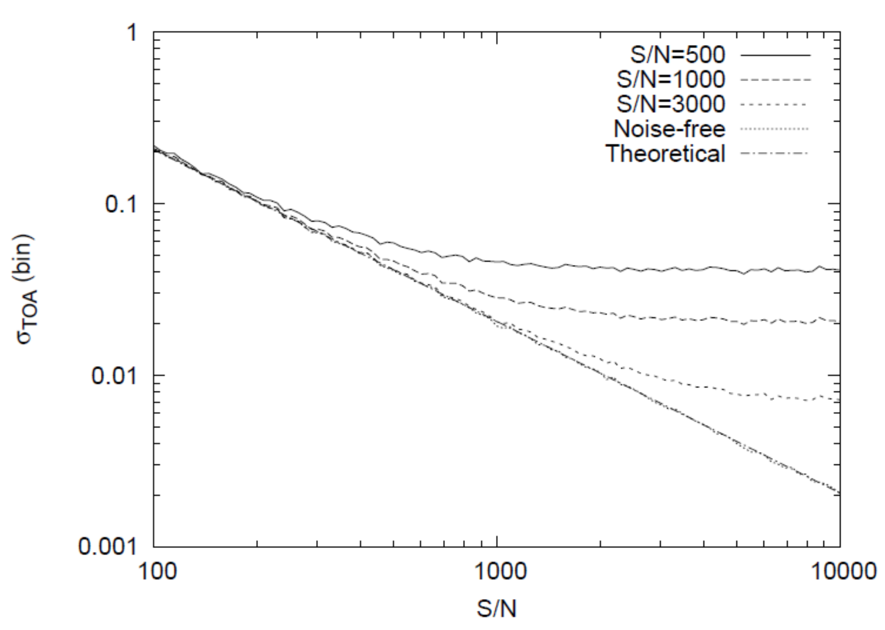
$$\sigma_{TOA} \propto \frac{1}{\sqrt{N}}$$

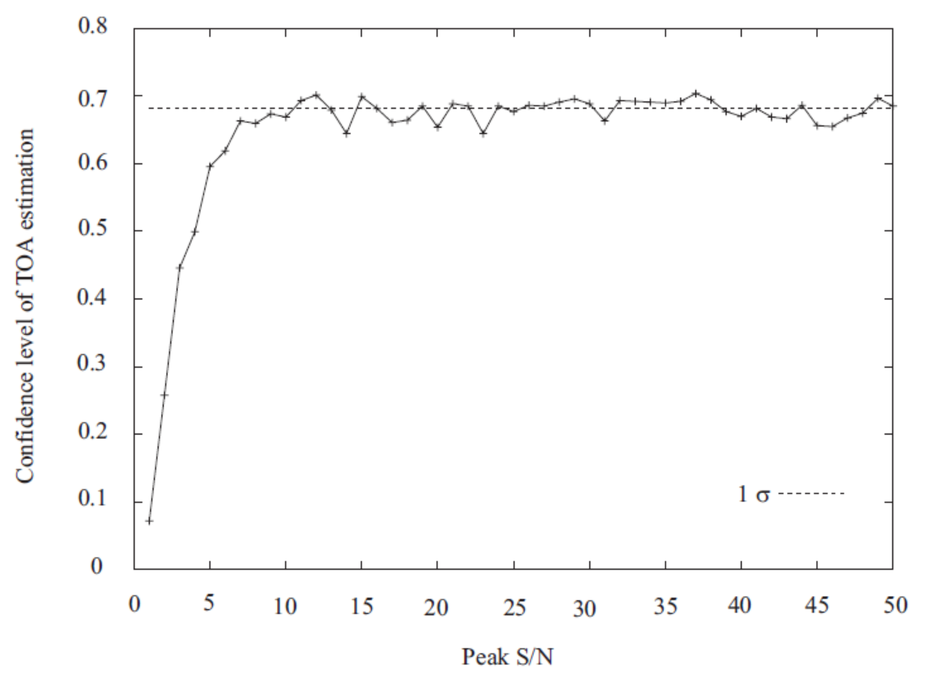
$$S/N \propto \sqrt{N}$$



Frequency-domain fitting algorithm

- If the template profile used is not perfect, e.g., of a different shape from the integrated profile or of significant noise, the accuracy of the TOA will be affected, i.e., less than expected from theory.





- In low S/N region, the error scales non-linearly with S/N, and the standard error propagation in template-matching underestimate the uncertainty;
- There are other approaches (e.g., the FDM method) that can be used to obtain a more reliable error estimate.