Introduction to Pulsar Timing and Tempo2

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EPTA

Max-Planck-Institut für Radioastronomie

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INTERNATIONAL PULSAR TIMING ARRAY

IPTA

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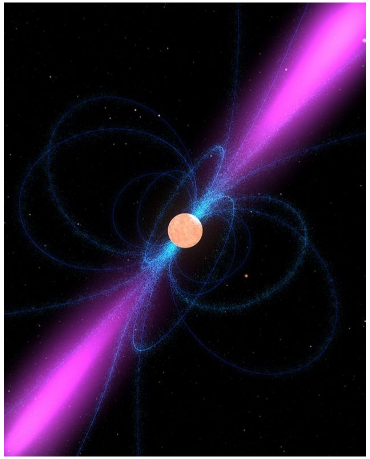
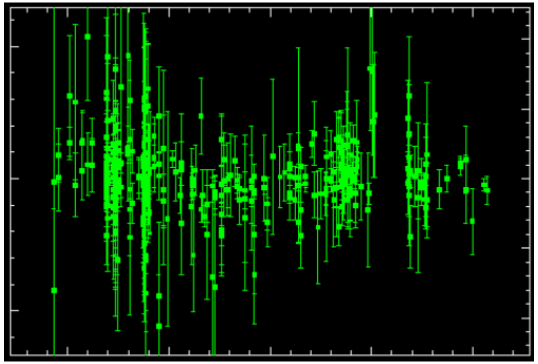
Part 1: Introduction to Pulsar Timing

Introduction

Pulsars spin with amazing stability, which allows us to use them as **highly-accurate clocks**, distributed all over the galaxy

Pulsar timing is a powerful technique which allows pulsar observations to be used (among other things) in tests of **plasma physics, gravitation, and nuclear physics,** under extreme conditions not achievable in Earth-based laboratories





Generating TOAs

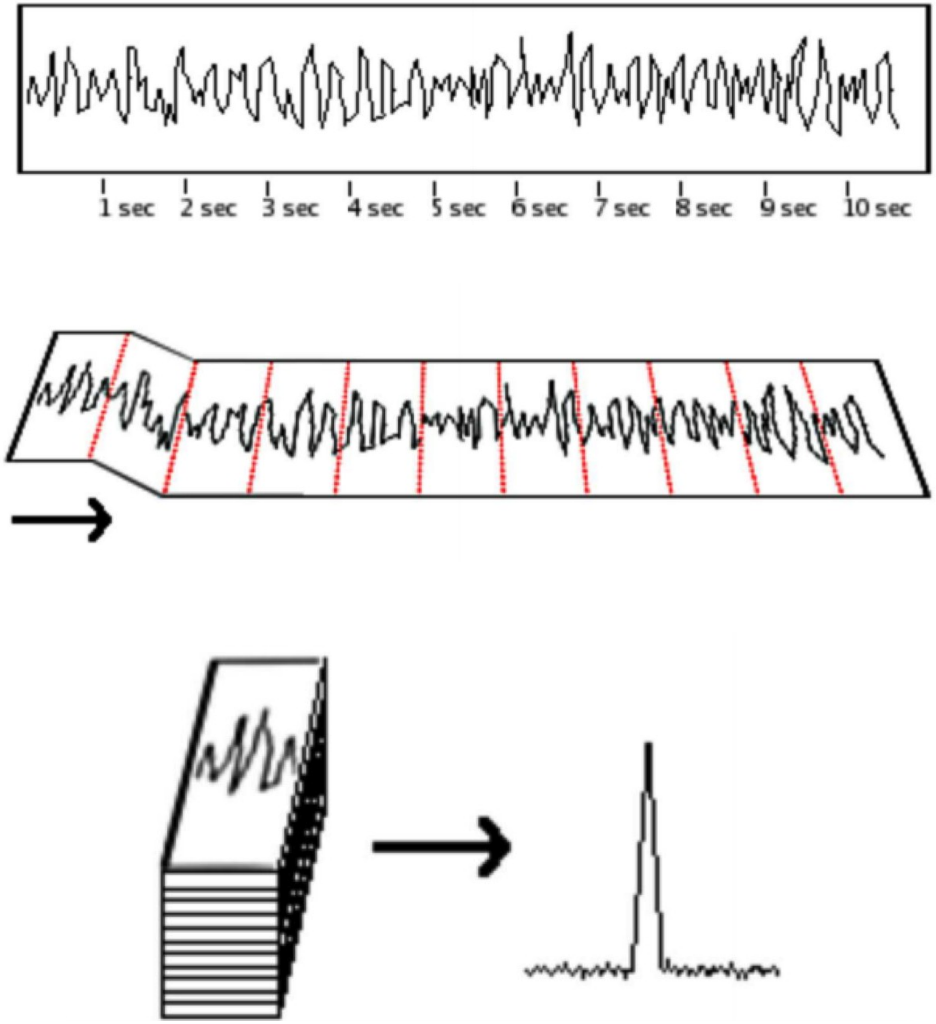
Pulsars are weak radio sources – we often can't distinguish the individual pulses from the **background noise**

Instead we **average many pulses** (in time and frequency) over the course of an observation to increase the signal to noise ratio

If the noise is Gaussian, it should be **cancelled out,** leaving the signal from the pulsar

This results in an average **'pulse profile'**

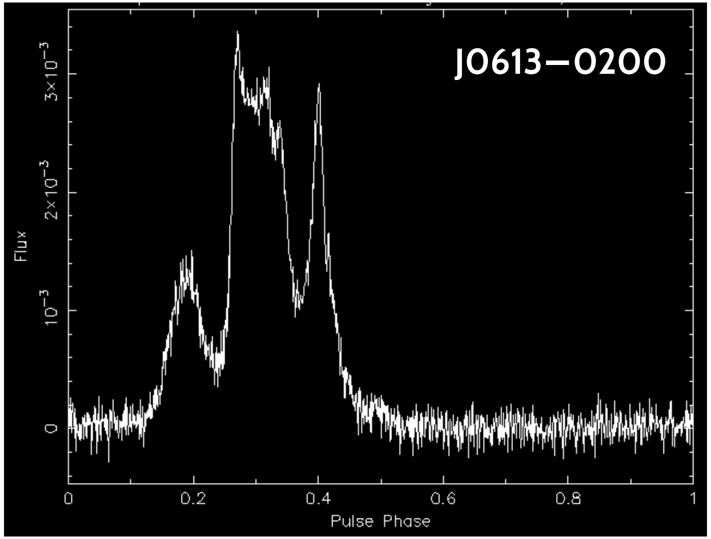
This technique is known as **'pulse folding'**

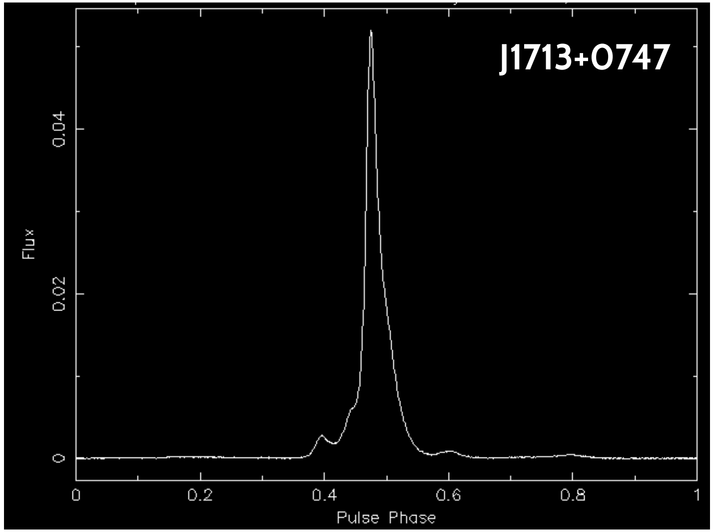


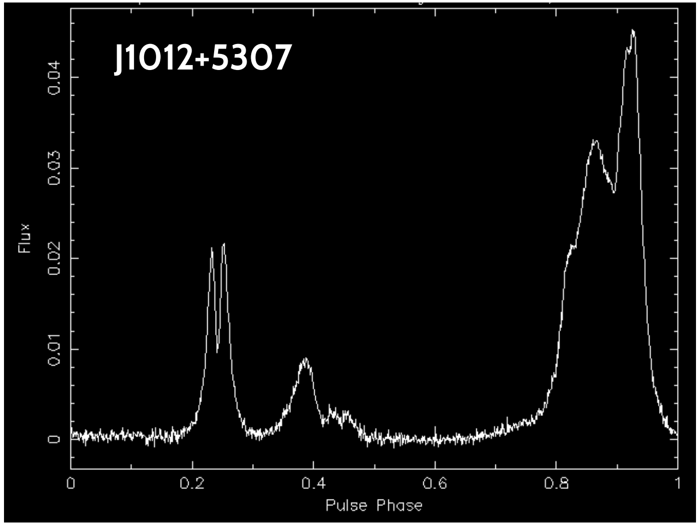
Pulse Profiles

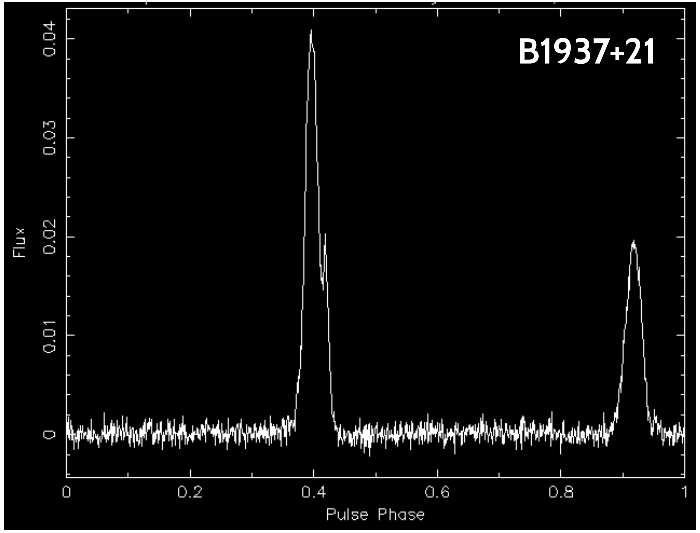
The pulse profile is like a unique **fingerprint** for the pulsar

Pulse profiles are many and varied









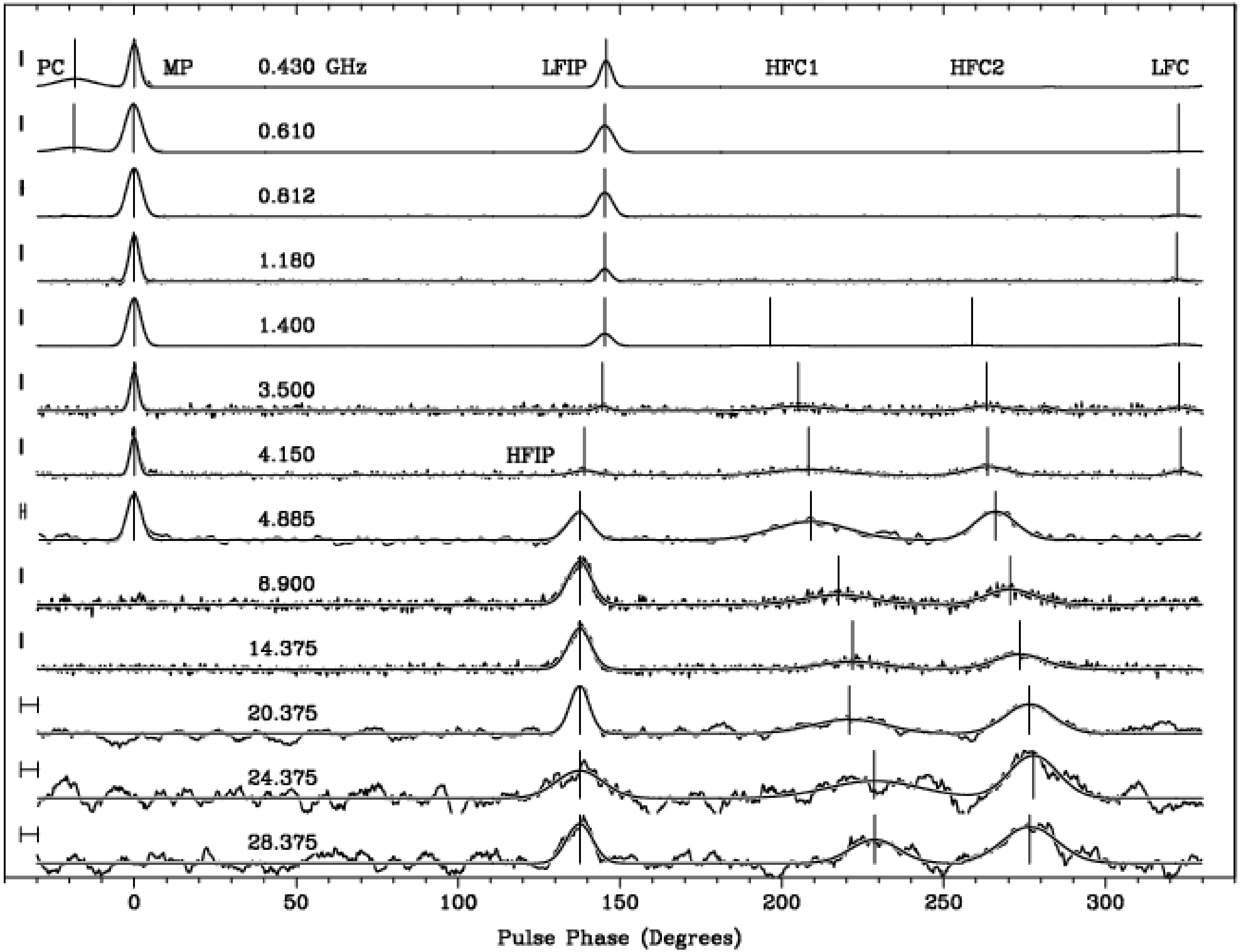
Frequency-Dependent Pulse Profiles

Eilek et al. (2016)

The pulse profile is **different** depending on the observing frequency

Some pulsars can vary **dramatically**

The plot shows the pulse profile of the Crab Pulsar over a wide range of **observing frequencies**



Generating TOAs

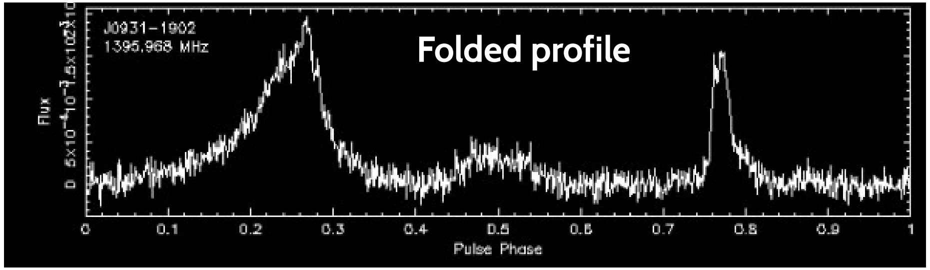
We measure an **average time of arrival (TOA)** for our folded observation using the pulse profile

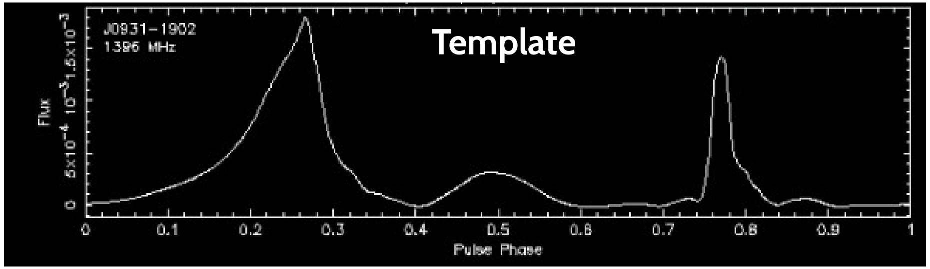
This is done by comparing the observed pulse profile with a **noise-free reference template** (template matching)

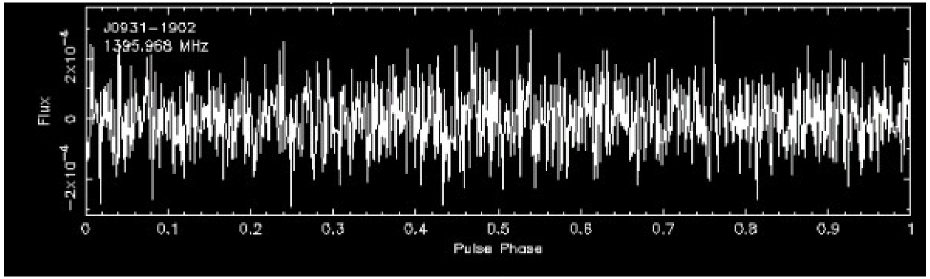
A reference point on the profile is chosen, and the average profile is **cross-correlated** in the Fourier domain with the template

This allows us to determine the **phase shift of the average profile** by minimising the χ^2 of the relative **phase shift in the Fourier domain**

$$\chi^2(a, \Delta\phi) = \sum_{k=1}^{k_{\max}} \frac{|d_k - a p_k \exp(-2\pi i k \Delta\phi)|^2}{\sigma^2}$$







p(φ) = average profile
d(φ) = template
a = scale factor

i = $\sqrt{-1}$
σ^2 = noise power in each harmonic component
Δφ = phase shift

TOA Precision

The precision to which we can measure a TOA from a pulsar observation depends on the **telescope** and the **backend** being used, as well as **factors intrinsic to the pulsar** itself

A pulsar is only detectable if the signal from the folded observation exceeds the **noise in the telescope receiver** ΔS_{sys} given by the radiometer equation:

$$\boxed{\Delta S_{\rm sys} = \frac{T_{\rm sys}}{\sqrt{n_{\rm p} t_{\rm obs} \Delta f}}}$$

T_{sys} = system temperature (20 K)
n_p = number of polarisations (2)
t_{obs} = integration time (1 hour)
Δf = bandwidth (500 MHz)

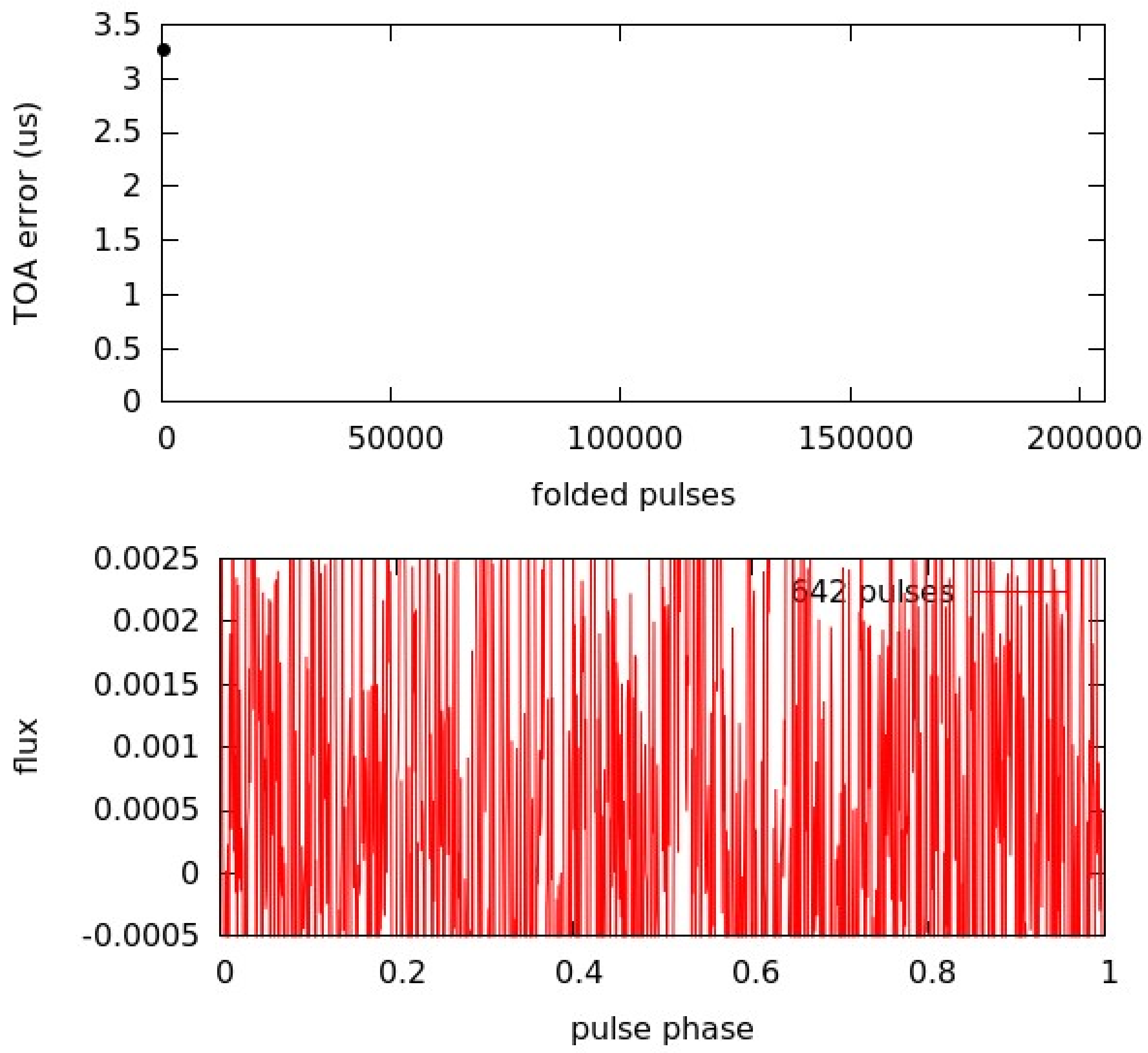
To achieve high TOA precision, we **cool the receiver**, record **both hands of polarisation**, use a **wide bandwidth**, and use **long observations**

The choice of pulsar also helps – the lowest TOA errors come from pulsars that are **bright**, and have **small duty cycles** (fraction of the pulse period that contains signal)

$$\boxed{\sigma_{\rm TOA} \simeq \frac{S_{\rm sys}}{\sqrt{t_{\rm obs} \Delta f}} \frac{P \delta^{3/2}}{S_{\rm mean}}}$$

S_{mean} = mean pulsar flux density
P = pulse period
δ = duty cycle (pulse width/pulse period)

Example: TOA precision as a function of number of folded pulses



Timing Models

Pulsar timing uses the high rotational stability of pulsars to tell us something about their **intrinsic state**, orbital parameters, etc. to **incredibly high precision**

We construct a **timing model**, which we use to predict the arrival time of future pulses

We test our timing model by calculating **timing residuals** (i.e. the TOAs with the timing model subtracted)

Unmodelled or imprecise parameters produce **structures in the residuals**, and can give clues to the missing parameters

Upon discovery, we have **initial (low-precision) values** for the spin frequency, spin-down rate, sky position, and dispersion measure

Therefore we **continuously update our timing models**, and many of the parameters get more and more precise as the pulsar is observed for longer

Transformation to Solar System barycentre:

$$t_{\mathrm{SSB}} = t_{\mathrm{topo}} + t_{\mathrm{corr}} - \frac{\Delta D}{f^2} + \overbrace{\Delta_{\mathrm{R}\odot} + \Delta_{\mathrm{S}\odot} + \Delta_{\mathrm{E}\odot}}^{\text{Solar system terms}} + \overbrace{\Delta_{\mathrm{RB}} + \Delta_{\mathrm{SB}} + \Delta_{\mathrm{EB}}}^{\text{(pulsar binary terms)}}$$

Conversion to topocentric (time at observatory)

Clock corrections

Dispersion measure

Römer delay

Shapiro delay

Einstein delay

Timing Models and Residuals

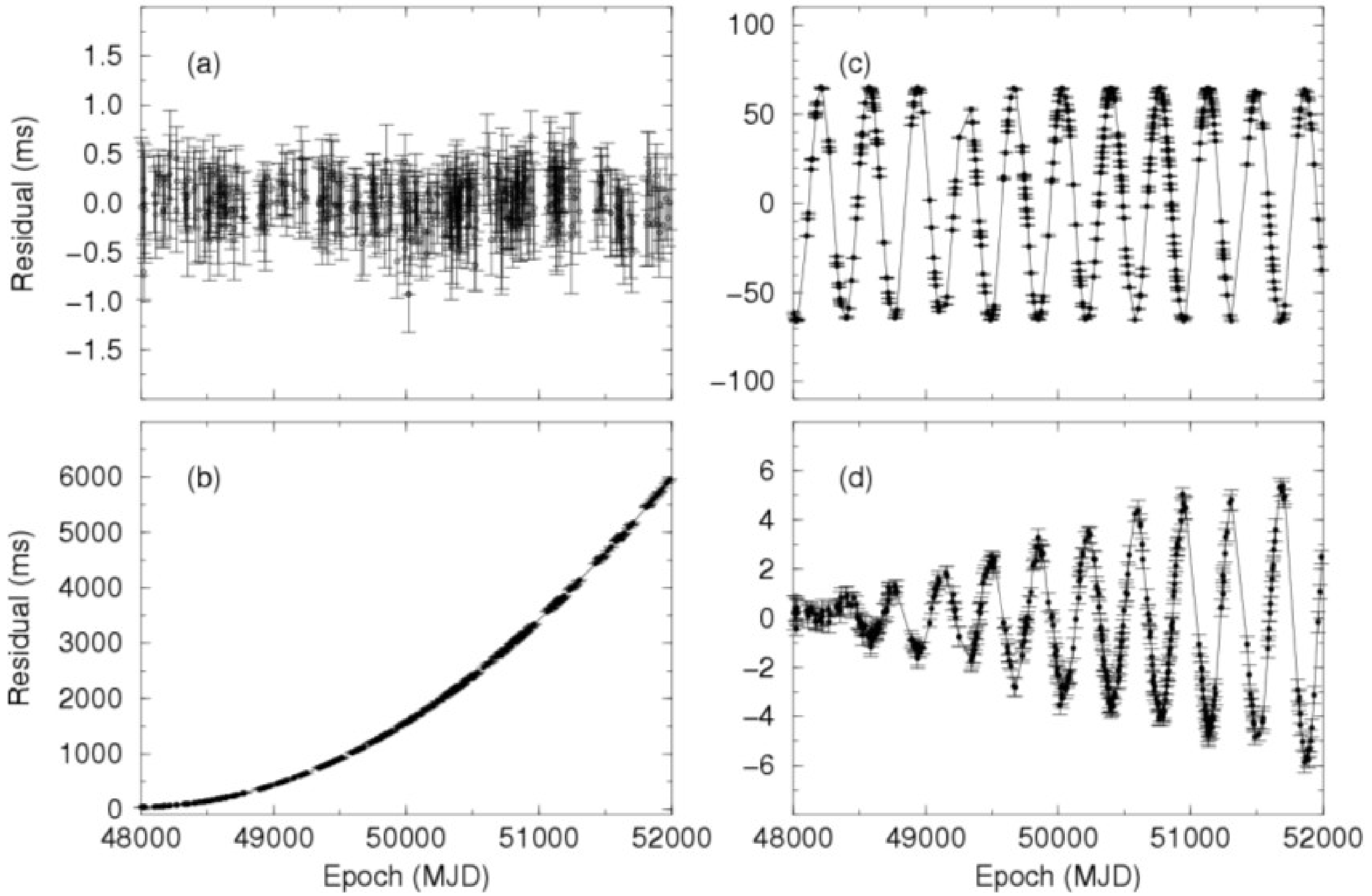
Lorimer & Kramer (2005)

We plot the TOAs with the timing model to see if any **structure** remains

The difference between the TOAs and the timing model are known as **timing residuals**

A good timing model will leave timing residuals clustered around zero, with only **white noise** remaining

Non-random deviations from the timing model arise from **unmodelled effects**, which usually induce a specific structure to the timing residuals



Timing Model Parameters – Pulsar Spin Evolution

Pulsars gradually **spin down** as they lose rotational energy via magnetic dipole radiation (i.e. they have a **spin period**, and a **period derivative**)

From the spinning magnetic dipole model, we also expect a **second period derivative** (although this term is very small and has not been measured for many pulsars)

We model the spin evolution as a **Taylor series**, describing the observed pulse phase as a function of time and spin-frequency

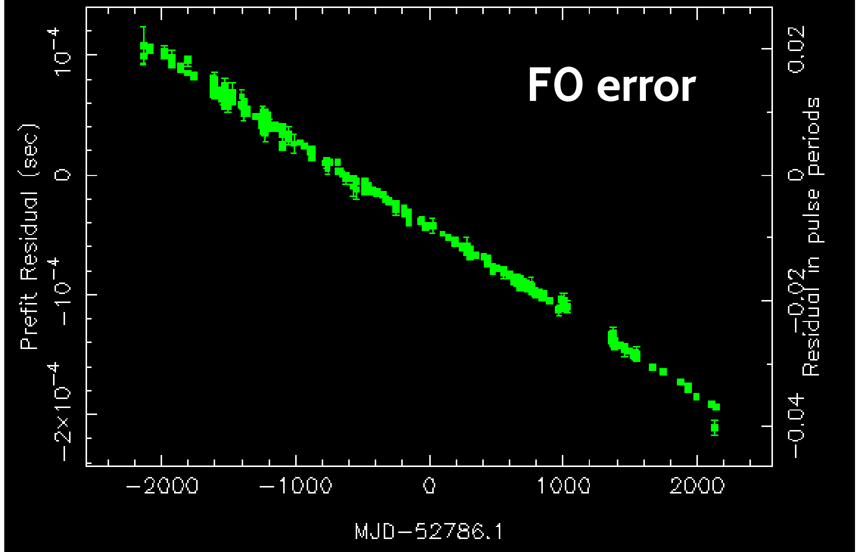
$$\phi(t) = \phi_0 + \nu_0 t + \frac{1}{2}\dot{\nu}_0 t^2 + \ldots$$

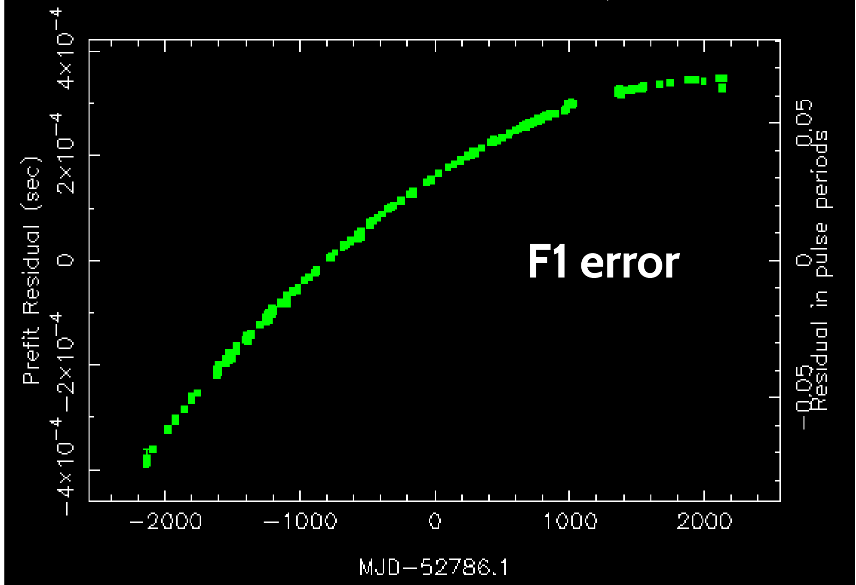
Φ_0 = pulse phase at t_0
ν_0 = spin frequency at t_0

The **initial value** for the spin frequency of a newly-discovered pulsar comes from the pulse folding (maximising the signal-to-noise ratio)

Errors in the spin frequency (F0) lead to a **linear trend** in the timing residuals, while errors in the spin-down rate (F1) lead to a **quadratic trend**

$$\Delta t_\nu = \frac{\Delta\nu_0}{\nu_0} T \qquad \Delta t_{\dot{\nu}} = \frac{1}{2}\frac{\Delta\dot{\nu}_0}{\dot{\nu}_0} T^2$$





Timing Model Parameters – Source Position

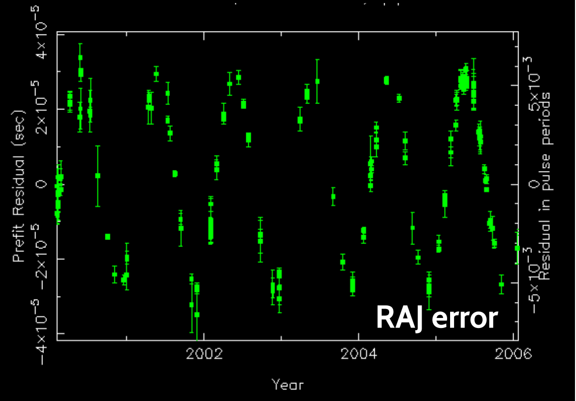
An error in the position of the source (or equivalently, an error in the SSB due to e.g. an incorrect planet mass) is known as the **Römer delay**

This contributes a **sinusoidal term** to the timing residuals with a period equivalent to the incorrect orbital period, due to the **difference in light travel time** across the system.

The difference in arrival time Δt_R due to the Römer delay is:

$$\Delta t_{R\odot} = -\frac{\overrightarrow{\mathbf{r}} \cdot \widehat{\mathbf{s}}}{c}$$

r = vector from SSB to observer
s = unit vector from SSB to pulsar



Timing Model Parameters – Source Position

If a pulsar has an unmodelled proper motion i.e. its sky position changes over time, this effect appears in the timing residuals as a **sinusoid multiplied by a quadratic term**

Proper motions of pulsars can be large, due to the **'kick' experienced during the supernova** in which they were created, leading to typical velocities of ~100 km s^{-1}, and as high as ~1600 km s^{-1}.

The transverse proper motion μ_T is given by

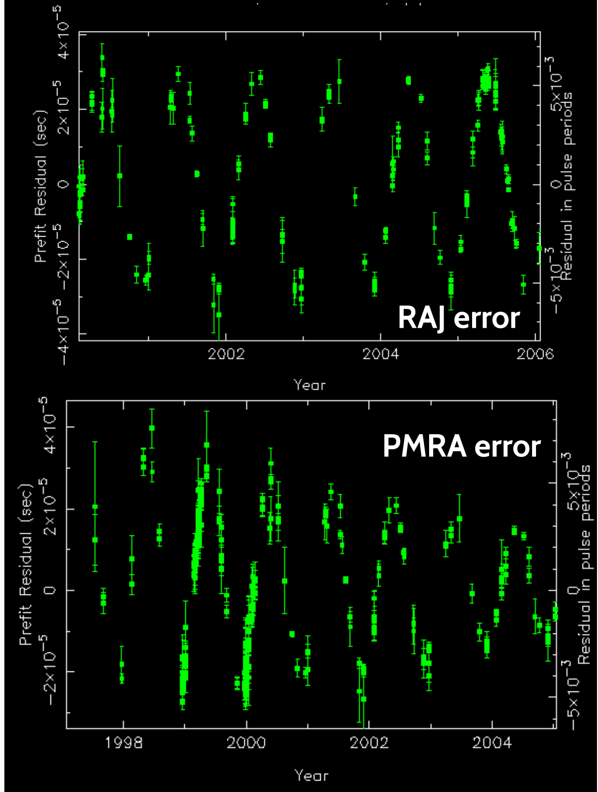
$$\boxed{\mu_{\mathrm{T}} = \sqrt{\mu_\alpha^2 + \mu_\delta^2}}$$

μ_α = proper motion in right ascension
μ_δ = proper motion in declination

This leads to TOA errors given by

$$\boxed{\Delta t_{\mathrm{PM}} = \frac{V_{\mathrm{T}}^2}{2dc} t^2}$$

$V_T^2 = 4.74\, \mu_T\, d$ = transverse velocity of pulsar
d = distance



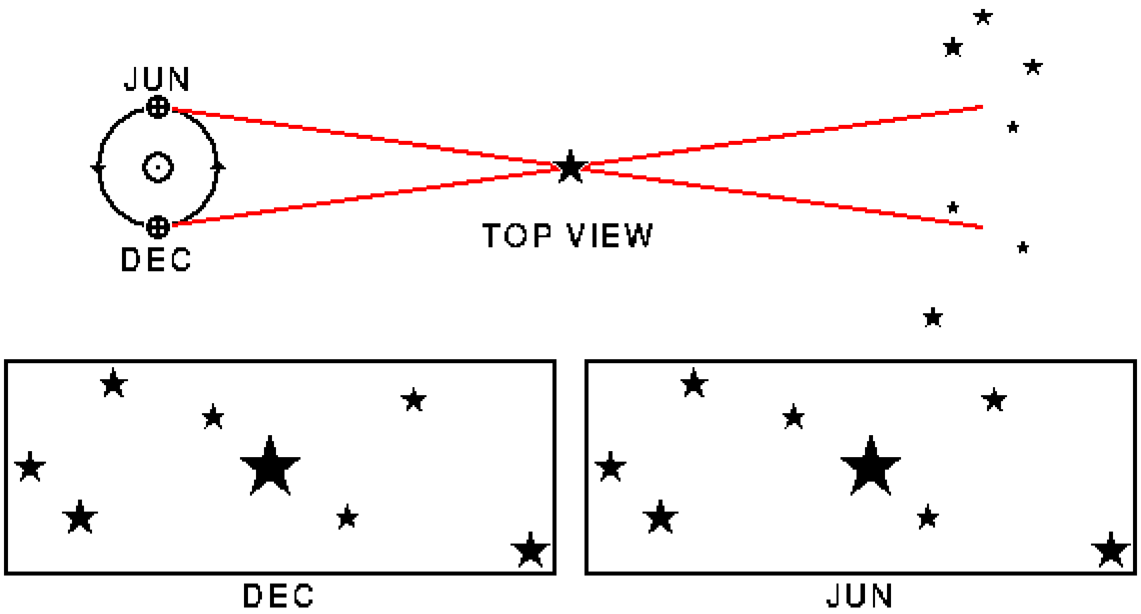
Timing Model Parameters – Source Position

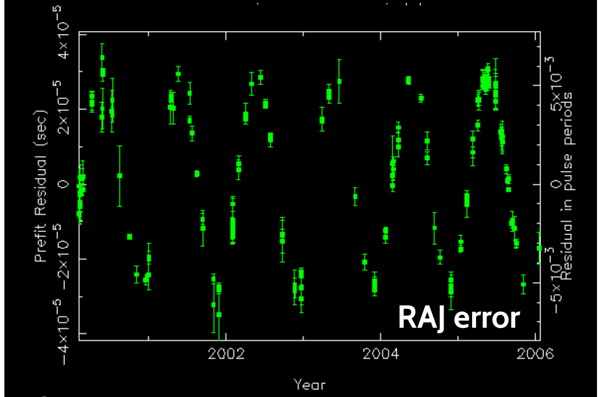
Pulsars close to the Earth may have a detectable **parallax delay**

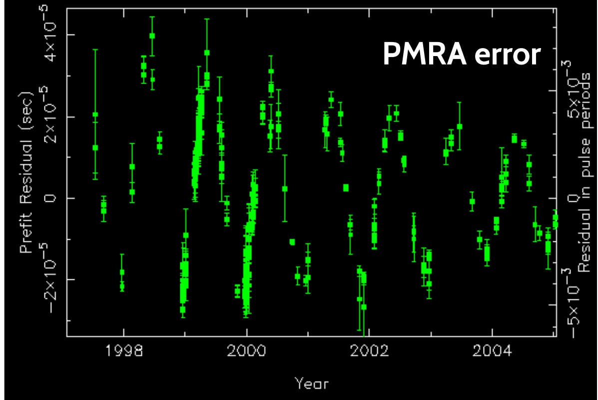
The delay in arrival time due to observing the wavefront from different positions introduces a **sinusoid** to the residuals with a **period of six months**, given by

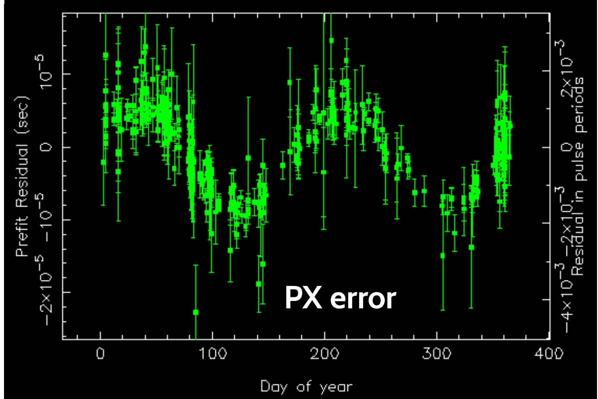
$$\boxed{\Delta t_{\pi} = -\frac{1}{2cd}(\vec{r} \times \hat{s})^2}$$

r = vector from SSB to observer
s = unit vector from SSB to pulsar
d = distance to pulsar









Timing Model Parameters – Keplerian Orbits

As with classical celestial mechanics, pulsars orbiting a companion can be described using **Kepler's laws of orbital motion**

Although in the case of massive binary companions at short orbital separations, the classical description is **not sufficient** and additional terms arising from **general relativity** must be included in the timing model

Classical Keplerian orbits are described in terms of:

$$M = E - e\sin E = \Omega_b \left[(t - T_0) - \frac{1}{2}\frac{\dot{P}_b}{P_b}(t - T_0)^2 \right]$$

$$A_T(E) = 2\arctan\left[\sqrt{\frac{1+e}{1-e}} \tan\left(\frac{E}{2}\right) \right]$$

$$\omega = \omega_0 + \frac{\dot{\omega}}{\Omega_b} A_T(E)$$

M = mean anomaly

E = eccentric anomaly

A_T = true anomaly

ω = longitude of periastron

e = orbital eccentricity

$\Omega_b = 2\pi/P_b$

P_b = binary period

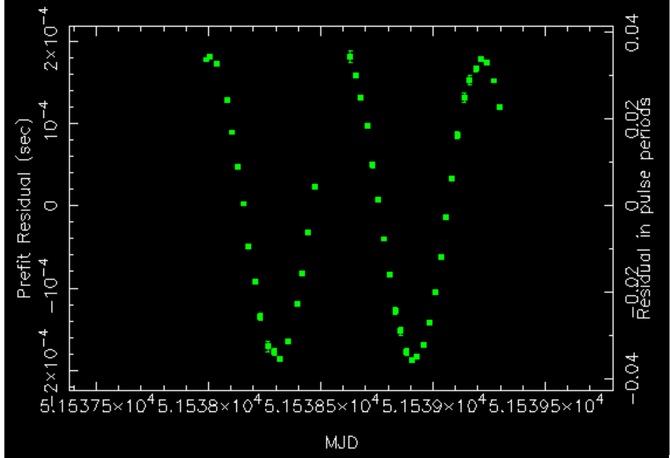
T_0 = epoch of periastron passage

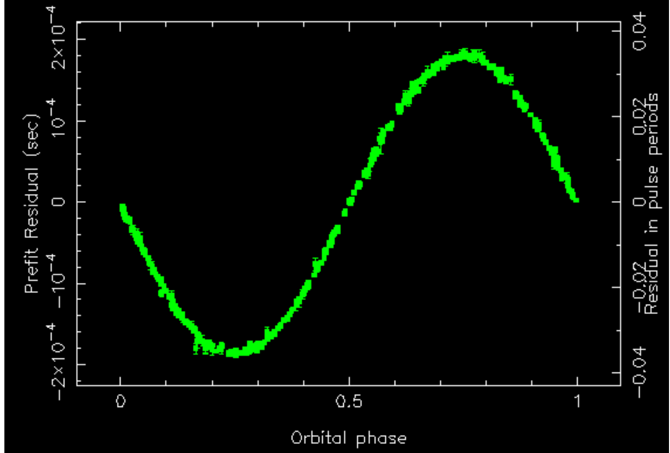
Similar to the Solar System model, the **Römer delay** across the pulsar binary system is

$$\Delta_R = x(\cos E - e)\sin\omega + x\sin E\sqrt{1-e^2}\cos\omega$$

$x = a_p \sin(i)/c$ = projected semi-major axis inclined at i degrees

This introduce a sinusoidal structure to timing residual, period equal to the binary orbit



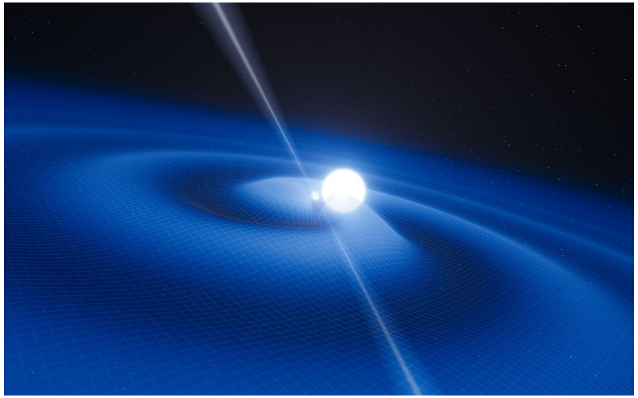


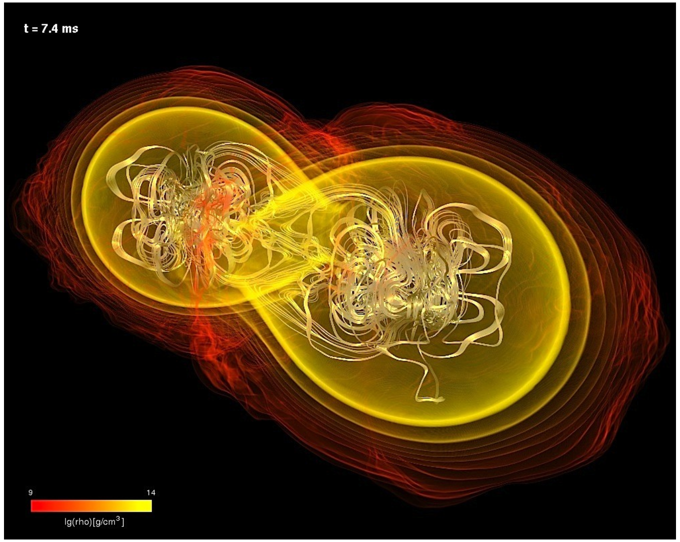
Keplerian orbit errors

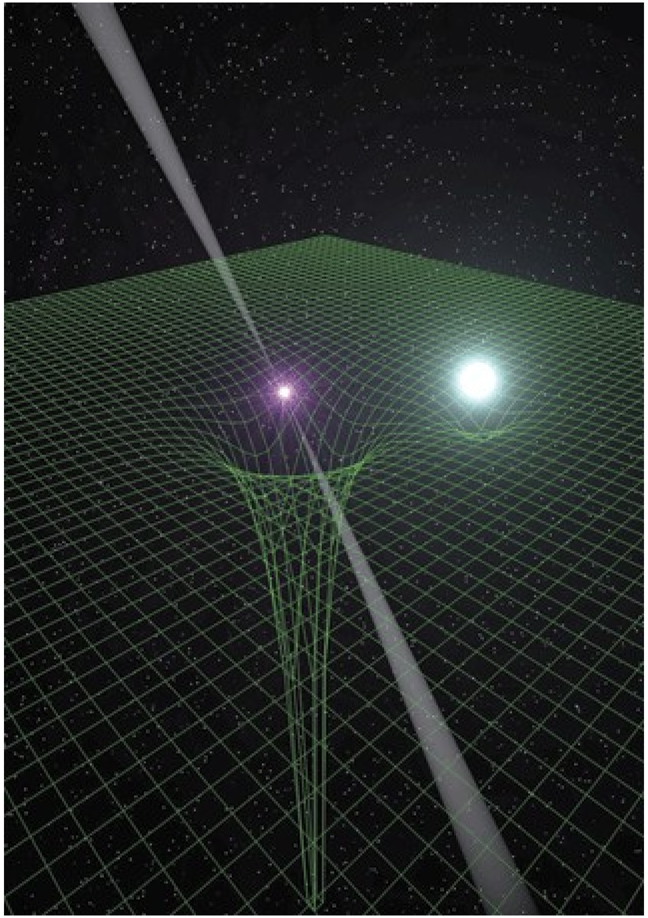
Timing Model Parameters – Post-Keplerian Parameters

In the case of pulsars that are in **highly relativistic orbits**, the effects of **general relativity** must be accounted for in the timing model

These effects are seen in **very close binaries**, and binaries with two (or more) **compact objects**







Timing Model Parameters – Shapiro Delay

The **gravitational curvature** of space-time around a mass increases the proper distance travelled by a pulse passing close to it, in an effect known as the **Shapiro delay**

Objects in the Solar System can also contribute a measurable Shapiro delay to timing residuals, which is removed with the aid of a precise **Solar System ephemeris**

The correction for the post-Keplerian Shapiro delay is given by

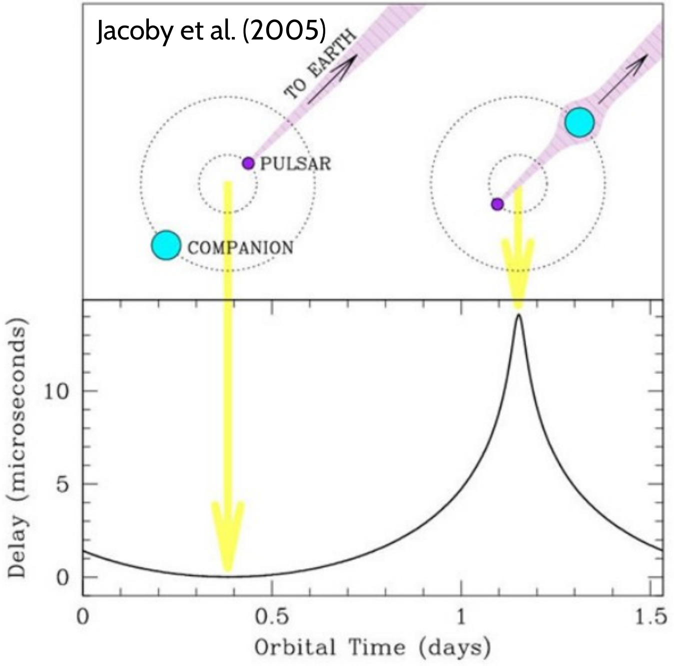
$$\Delta_S = -2r\ln[1 - e\cos E - s(\sin\omega(\cos E - e) + \sqrt{1-e^2}\cos\omega\sin E)]$$

where *r* and *s* are the **'range'** (the maximum time delay) and the **'shape'** (the logarithmic component of the induced delay) of the Shapiro delay

The range and shape are given by

$$s = \sin i = T_\odot^{-1/3}\left(\frac{P_b}{2\pi}\right)x\frac{(m_1+m_2)^{2/3}}{m_2} \qquad r = \frac{Gm_2}{c^3} = T_\odot m_2$$

The Shapiro delay is measurable in some systems, and provides a tool with which to **directly measure** the **mass of a pulsar's binary companion**, and the **orbital inclination** of the system



Shapiro delay signature in PSR J1909−3744 (companion mass: 0.2038± 0.0022 solar masses)

$$\boxed{T_\odot = \frac{GM_\odot}{c^3} = 4.9\,\mu s}$$

(**time constant** corresponding to the light travel time across a 1 Solar mass gravitational radius, allows the masses to be expressed in solar masses)

Timing Model Parameters – Einstein Delay (gravitational redshift)

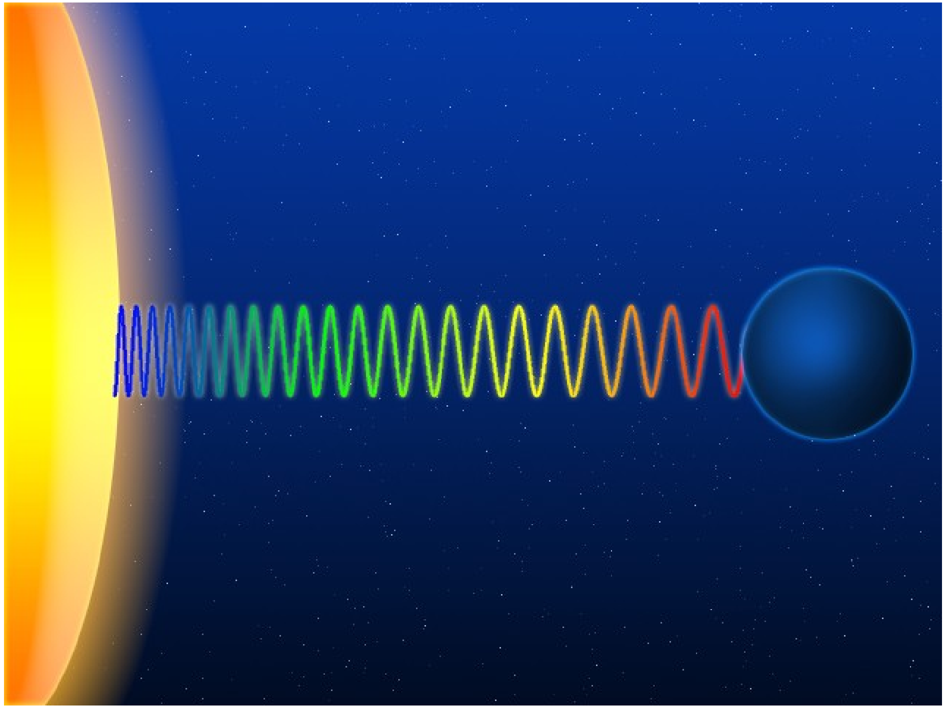
The Einstein delay is a combination of effects arising from the **relative change in distance** between the observatory and the pulsar over the Earth's and the pulsar's orbits, and variations in the **gravitational redshift** due to the masses in both orbital systems.

The Einstein delay induces a **sinusoid** in the residuals, given by

$$\Delta_{\mathrm{E}} = \gamma \sin E$$

Where γ is the amplitude of the sinusoid, given by

$$\gamma = T_{\odot}^{2/3} \left(\frac{P_{\mathrm{b}}}{2\pi}\right)^{1/3} e \frac{m_2(m_1 + 2m_2)}{(m_1 + m_2)^{4/3}}$$



Timing Model Parameters – Aberration Delay

High orbital velocities lead to the pulsar beam becoming **distorted**, and contributes a term known as the **aberration delay**

Although this phenomenon is described by **classical celestial mechanics**, it is usually referred to as a post-Keplerian parameter, as it is only significant in **highly relativistic binaries**

The correction due to the aberration delay is given by

$$\Delta_{\mathrm{A}} = A\,(\sin[\omega + A_{\mathrm{T}}(E)] + e\sin\omega] + B[\cos[\omega + A_{\mathrm{T}}(E)] + e\cos\omega)$$

A and *B* are parameters that describe the **orientation of the pulsar spin axis** and are given by

$$A = -\frac{T_{\odot}^{1/3}}{(2\pi)^{2/3}}\frac{P}{P_{\mathrm{b}}^{1/3}(1-e^2)^{1/2}}\frac{m_2}{(m_1+m_2)^{2/3}}\frac{\sin\eta}{\sin\lambda}$$

$$B = -\frac{T_{\odot}^{1/3}}{(2\pi)^{2/3}}\frac{P}{P_{\mathrm{b}}^{1/3}(1-e^2)^{1/2}}\frac{m_2}{(m_1+m_2)^{2/3}}\frac{\cos i\cos\eta}{\sin\lambda}$$

η , λ = angles of the pulsar spin vector (polar coordinates)

Timing Model Parameters – Orbital Decay

The **orbital energy** of objects in compact binary orbits is converted to **gravitational radiation**, leading to a **decrease in orbital period** given by

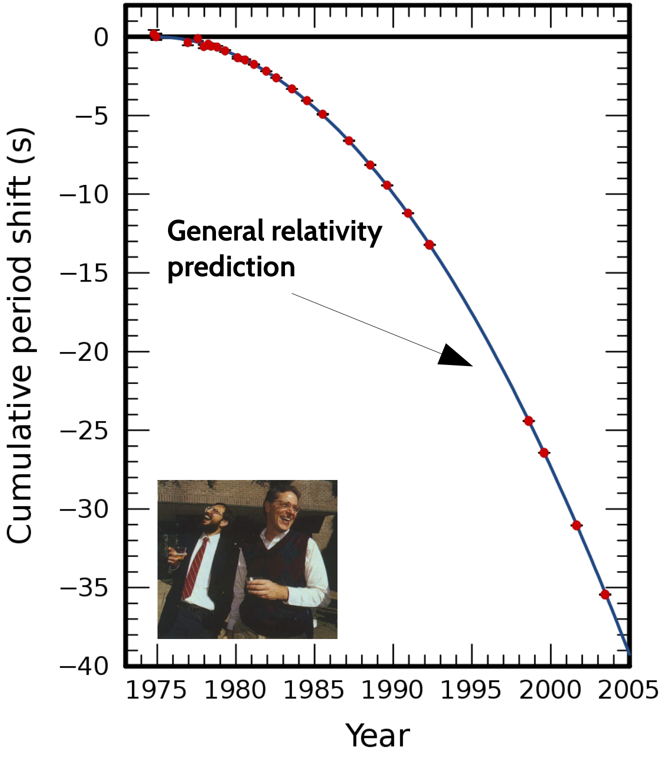
$$\dot{P}_{\mathrm{b}} = -\frac{192\pi}{5} T_{\odot}^{5/3} \left(\frac{P_{\mathrm{b}}}{2\pi}\right)^{-5/3} \left(1+\frac{73}{24}e^2+\frac{37}{96}e^4\right) \frac{1}{(1-e^2)^{7/2}} \frac{m_1 m_2}{(m_1+m_2)^{1/3}}$$

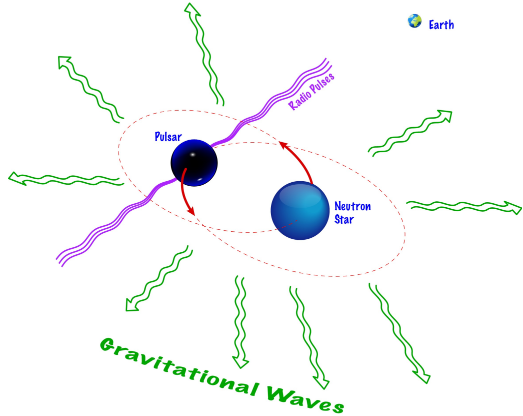
The **observed decrease in binary period** of the double neutron star binary containing PSR B1913+16 (aka PSR J1915+1606) provided the **first evidence for the existence of gravitational waves**

The **orbital decay** driven by gravitational radiation means that compact binary systems will eventually **inspiral and merge**

The **final stage** of the inspiral and the merger of compact binaries are targets of **ground-based gravitational wave detectors**

The **inspiral of supermassive black hole binaries** is expected to be detectable by **pulsar timing arrays** within the next decade





Timing Model Parameters – Periastron Advance

Relativistic effects cause the **orbital plane to rotate** about the barycentre of the orbital system

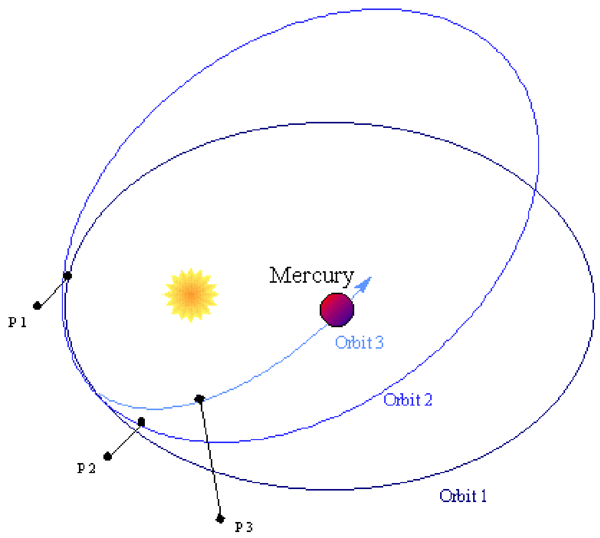
This is quantified by the **change in longitude of periastron** ω, given by

$$\dot{\omega} = 3T_{\odot}^{2/3}\left(\frac{P_b}{2\pi}\right)^{-5/3}\frac{1}{1-e^2}(m_1+m_2)^{2/3}$$

In **highly-relativistic binaries**, this effect is very significant

The advance of periastron in the **double pulsar** J0737−3039A/B is measured to be 16.89947(68)$^\circ$ yr^{-1}, meaning that the orbital plane makes **a full revolution every ~21 years**

For comparison, **Mercury's** periastron advance is **0.012° century^{-1}**



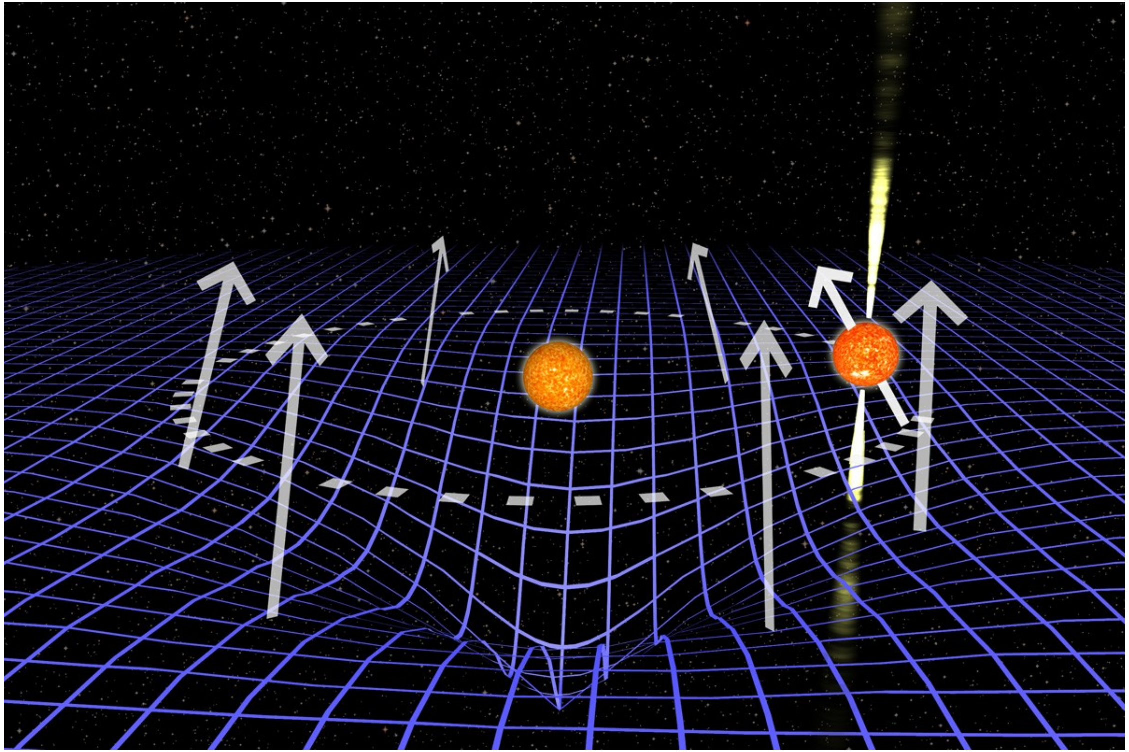
Timing Model Parameters – Geodetic Precession

The **highly-curved space-time** in the vicinity of compact binaries causes the **reference frame of the objects to precess** with respect to an external observer

This manifests as a **spin-orbital coupling** of the objects in the binary system

In the case of pulsars, the varying spin vector causes changes in the **polarisation** and **shape of the pulse profile**

The **geodetic precession** of a binary system is given by



$$\Omega_{\rm geo} = \left(\frac{2\pi}{P_{\rm b}}\right)^{5/3} T_{\odot}^{2/3} \frac{m_2(4m_1+3m_2)}{2(m_1+m_2)^{4/3}} \frac{1}{1-e^2}$$

Timing Model Parameters – Rotational Glitches

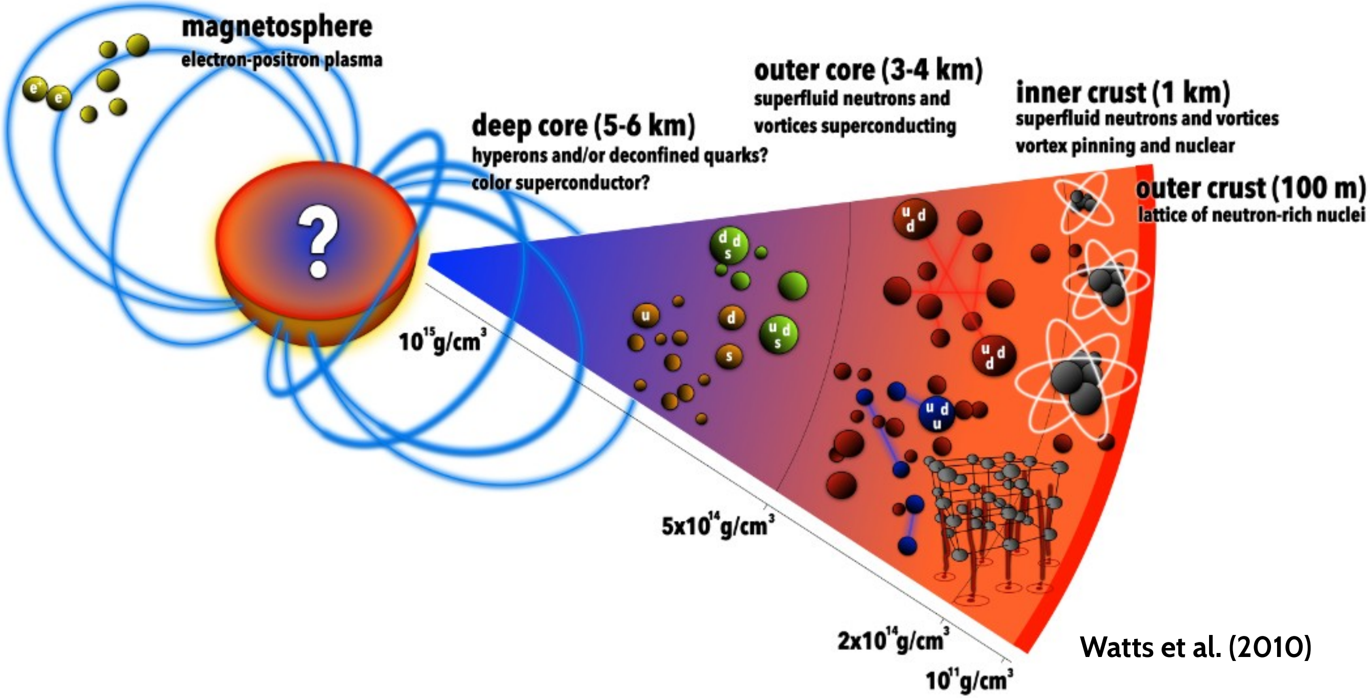
Some pulsars occasionally exhibit **sudden steps** in spin frequency and/or frequency derivative, known as **rotational glitches**

This is thought to be a consequence of the **transfer of angular momentum** between **superfluid neutron vortices** and the **solid crust**, which spins **independently to the superfluid neutron layer**

It is thought that the **internal structure** of neutron stars is **highly variable** after their formation, before settling down over their lifespans

Glitches are commonly observed in **young pulsars** such as the **Crab** and **Vela** (25 and 19 glitches respectively in ~45 years of observations)

Glitches are one of the only observables that are able to **probe the neutron star interior**



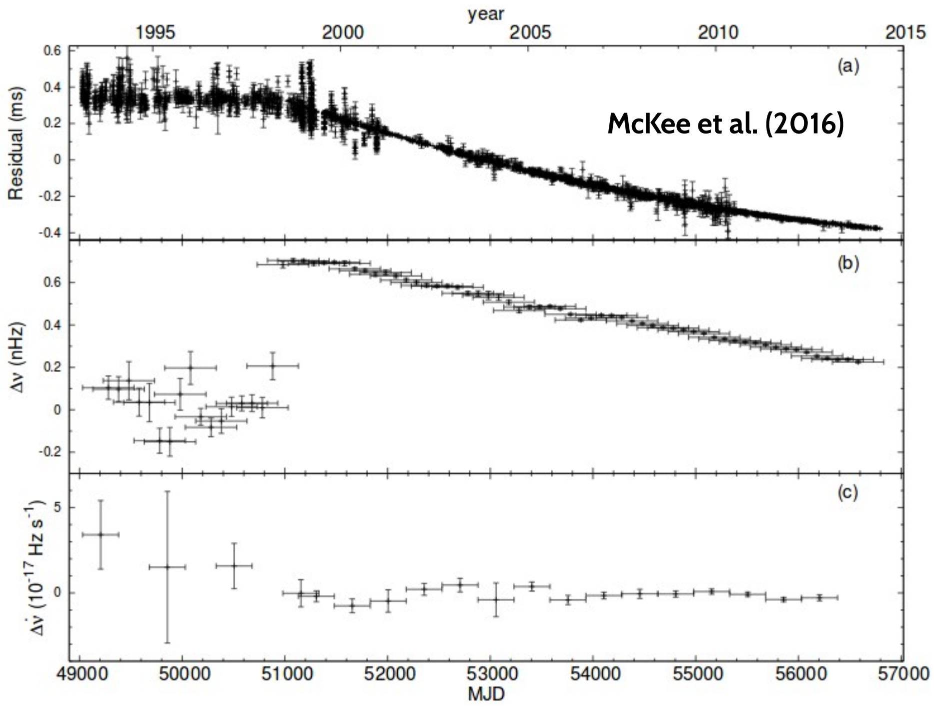
Watts et al. (2010)

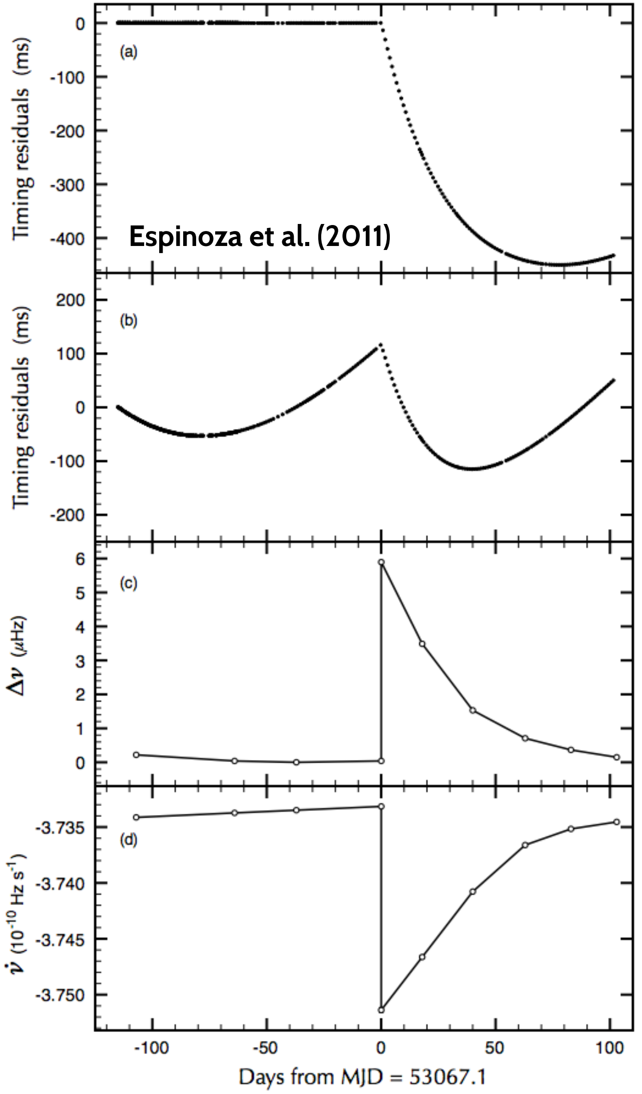
Timing Model Parameters – Rotational Glitches

Glitches are **typically modelled** in the timing solution through an additional set of **epoch-specific spin parameters**

Usually the post-glitch **spin frequency and spin-down**

The change in spin parameters can be **permanent**, or can gradually **relax back** to the pre-glitch state





Glitch sizes are measured in terms of the **fractional change** in spin-frequency $\Delta\nu/\nu$

The **range of glitch sizes** is large:
$2.5\times10^{-12} < \Delta\nu/\nu < 6.5\times10^{-4}$

The list of known pulsar glitches is recorded in the Jodrell Bank Glitch Catalogue
http://www.jb.man.ac.uk/pulsar/glitches.html

Timing Noise

Timing noise describes a phenomenon where TOAs **deviate from the timing solution** through a process that in some cases may appear to be analagous to a **random walk in the spin parameters**

Timing noise is thought to arise through **unmodelled small-scale instabilities** in the rotation of the pulsar

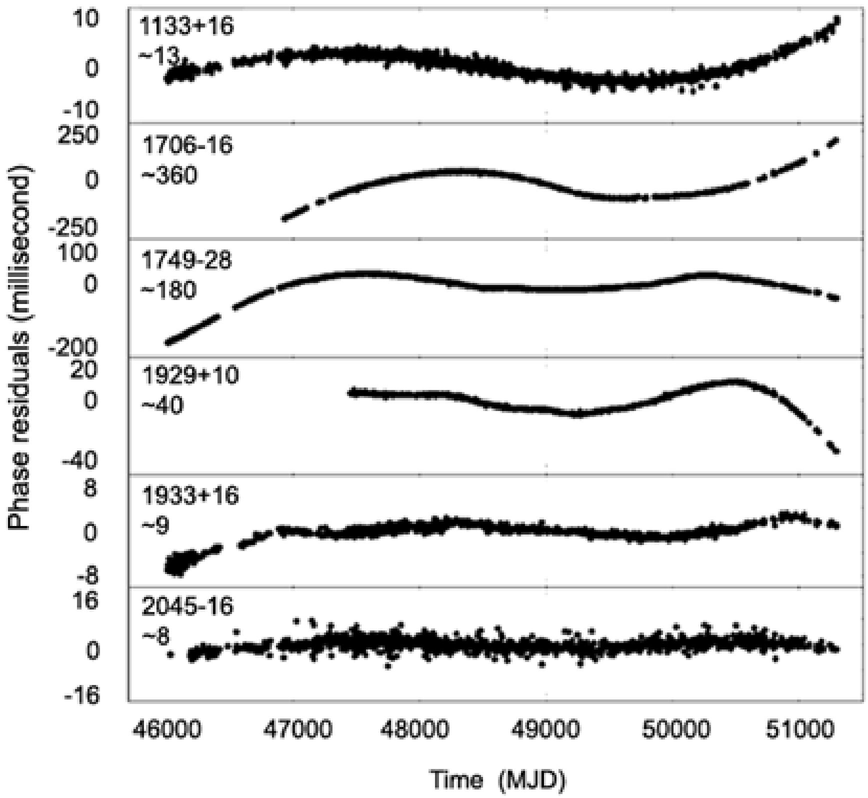
This process **adds structure** to the timing residuals and **limits the precision** to which pulsars can be timed.

In general, timing noise is much more pronounced in **slow pulsars** than in MSPs

As the timing noise effect is **much smaller in MSPs**, pulsar timing arrays are comprised of **fast-spinning pulsars** with **low spin-down rates**

Even so, timing noise is projected to **become significant** at timing precisions of ~100 ns

Time-correlated noise is often modelled as a **power-law** in the Fourier domain

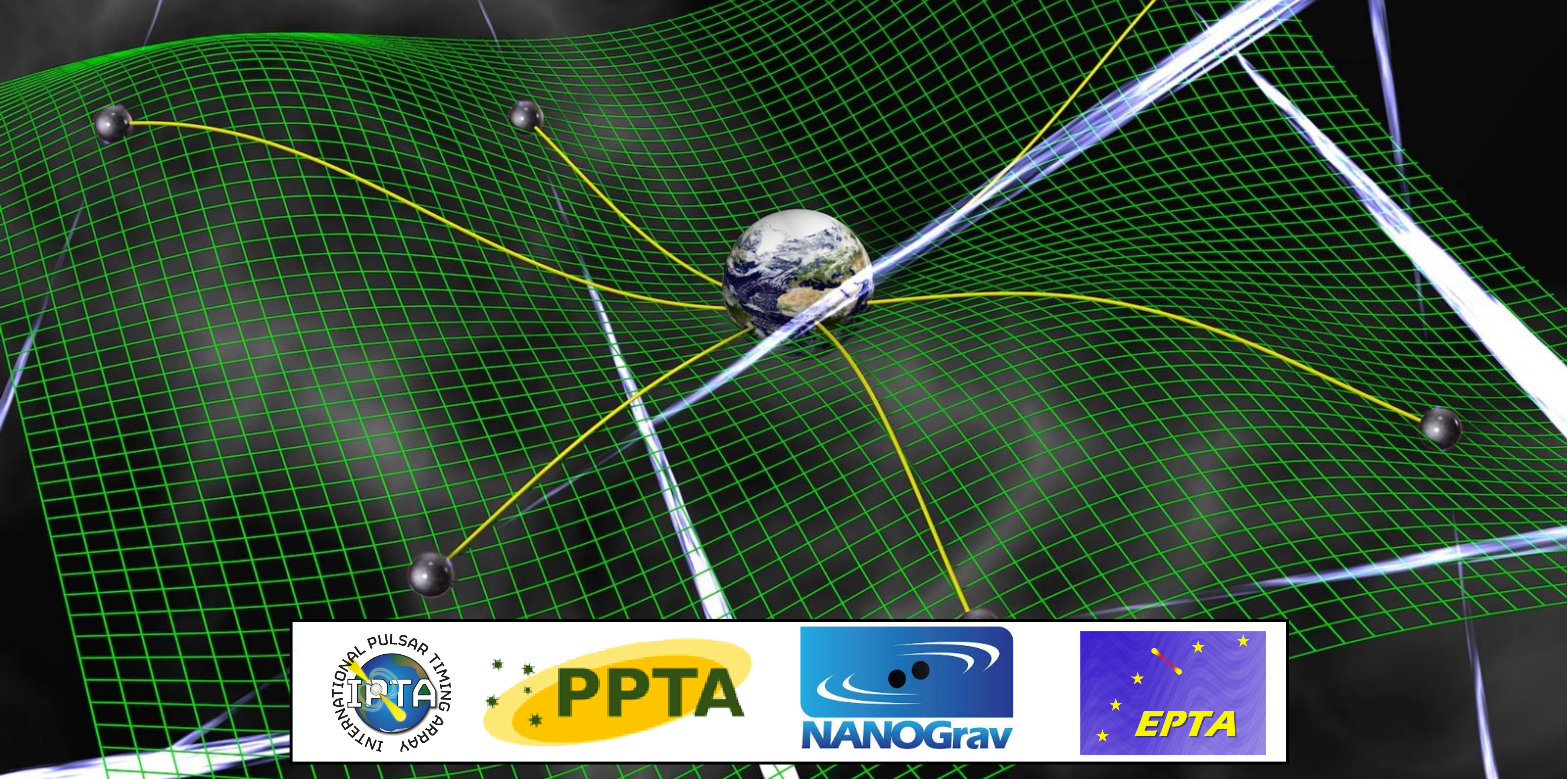


Liu et al. (2010)

$$\phi(f, A, \gamma) = \frac{A^2}{12\pi^2}\left(\frac{f}{f_{\rm r}}\right)^{-\gamma}$$

Φ = Fourier power
f = Fourier frequency
A = spectral amplitude
γ = spectral index

Pulsar Timing Array Targets



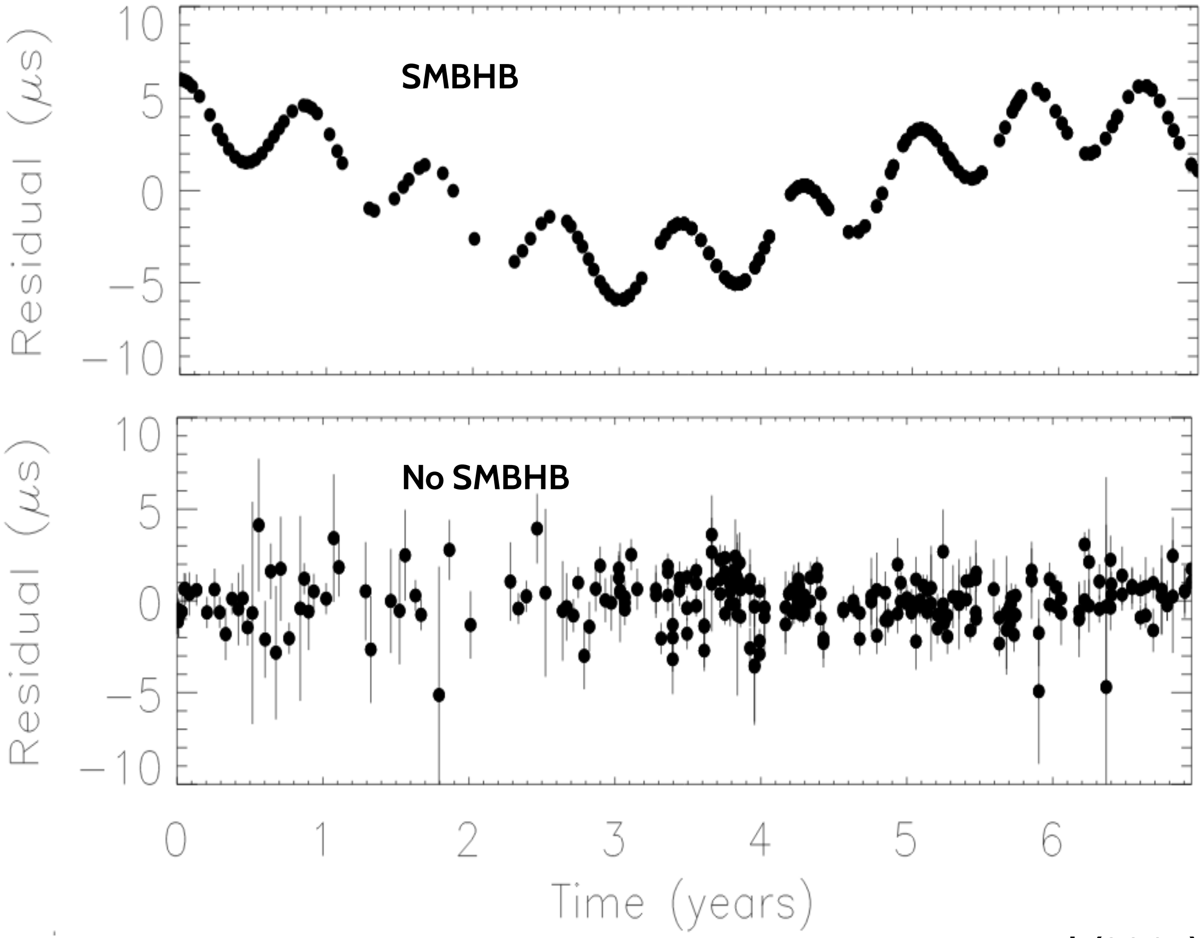
Single-Source Gravitational Waves

PTAs exploit the **high timing precision** achievable by MSPs to search for timing residuals attributable to **gravitational waves**

This can be understood by considering the effect of gravitational waves from an **inspiralling compact binary** in a single-pulsar case

The **unmodelled gravitational wave term** induces timing residuals over a timing baseline

Although single-sources are not expected to be detected any time soon, it has been possible to **refute claims** of nearby **supermassive black hole binaries** using pulsar timing data



Jenet et al. (2004)

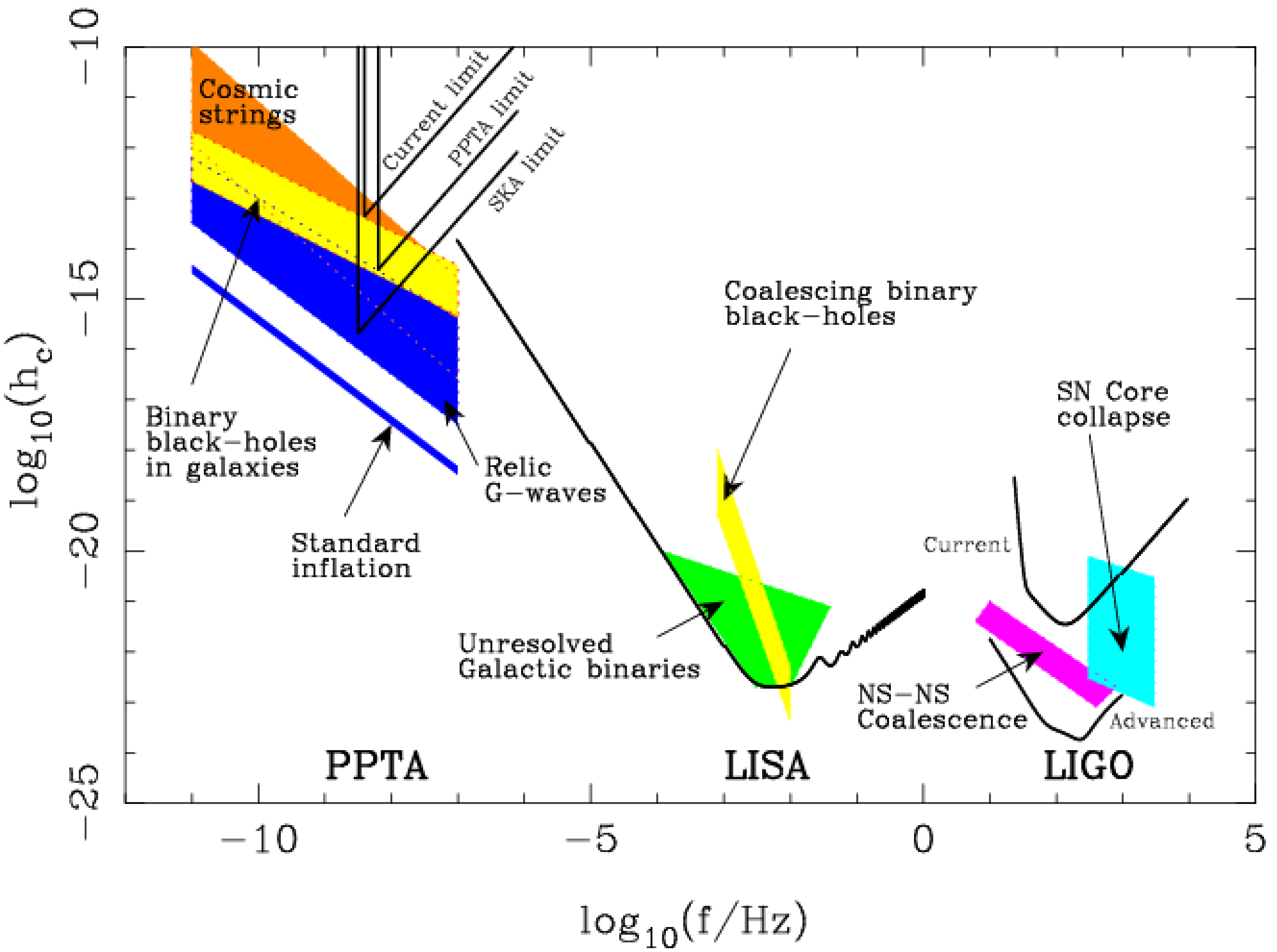
Stochastic Gravitational Wave Background

PTAs search for evidence of a **nano-Hertz stochastic GWB**, composed of the superposition of **gravitational waves from many sources** throughout the local universe

Observationally, it is known that a supermassive black hole exists at the **core of most (or all) galaxies** and that **galaxy mergers have occurred** throughout the history of the universe

Therefore, it is thought that **pairs of supermassive black holes** in post-merger galaxies will become gravitationally bound and form a **binary system**

The orbital separation **decreases via GW emission** to the point where the frequency and amplitude are in a range that can be **probed by PTAs**



Stochastic Gravitational Wave Background

PTAs are used in attempts to detect the stochastic GWB through timing residuals in an **ensemble of pulsars**

The residuals should be **correlated** as a function of their **angular separation**

The **minimum strain amplitude** capable of being measured by a PTA is limited only by the **time scale** over which observations are taken, the **observing cadence**, the **number of pulsars** being observed, and the **precision** to which the RMS residuals can be measured

$$h_{\mathrm{min}} \sim \frac{\sigma_{\mathrm{RMS}}}{T\sqrt{N_{\mathrm{TOA}} N_{\mathrm{pulsar}}}}$$

The **characteristic strain** of the GWB as a function of **gravitational wave frequency** is usually parameterised as a **power law** (with an index expected to be $\alpha = 2/3$), relative to a reference frequency of 1 yr^{-1}

$$h_c(f) = A f^{-\alpha}$$

The **induced residuals** in the PTA data by the stochastic GWB are given by

$$R(f) = \frac{h_c(f)^2}{12\pi^2 f^3} = \frac{A^2 f^{-13/3}}{12\pi^2}$$

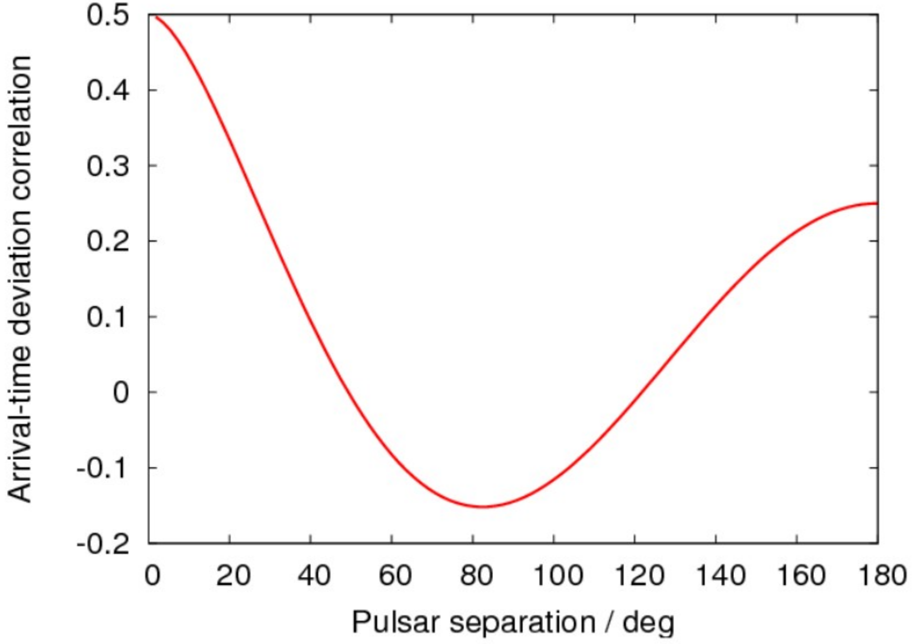
Stochastic Gravitational Wave Background

A stochastic GWB should be **correlated across all pulsars in a PTA**, as a function of the **angle between Earth-pulsar baselines**

This is used as a potential means of **distinguishing a gravitational wave signal** in a PTA from other effects

The **sky-averaged** and **polarisation-averaged correlation** as a function of baseline angle is known as the **Hellings and Downs curve**, and has the analytical form

$$\chi(\zeta) = \frac{1}{2} - \frac{1-\cos\zeta}{8} + \frac{3(1-\cos\zeta)}{4}\ln\left(\frac{1-\cos\zeta}{2}\right)$$



Part 2: Introduction to Tempo2

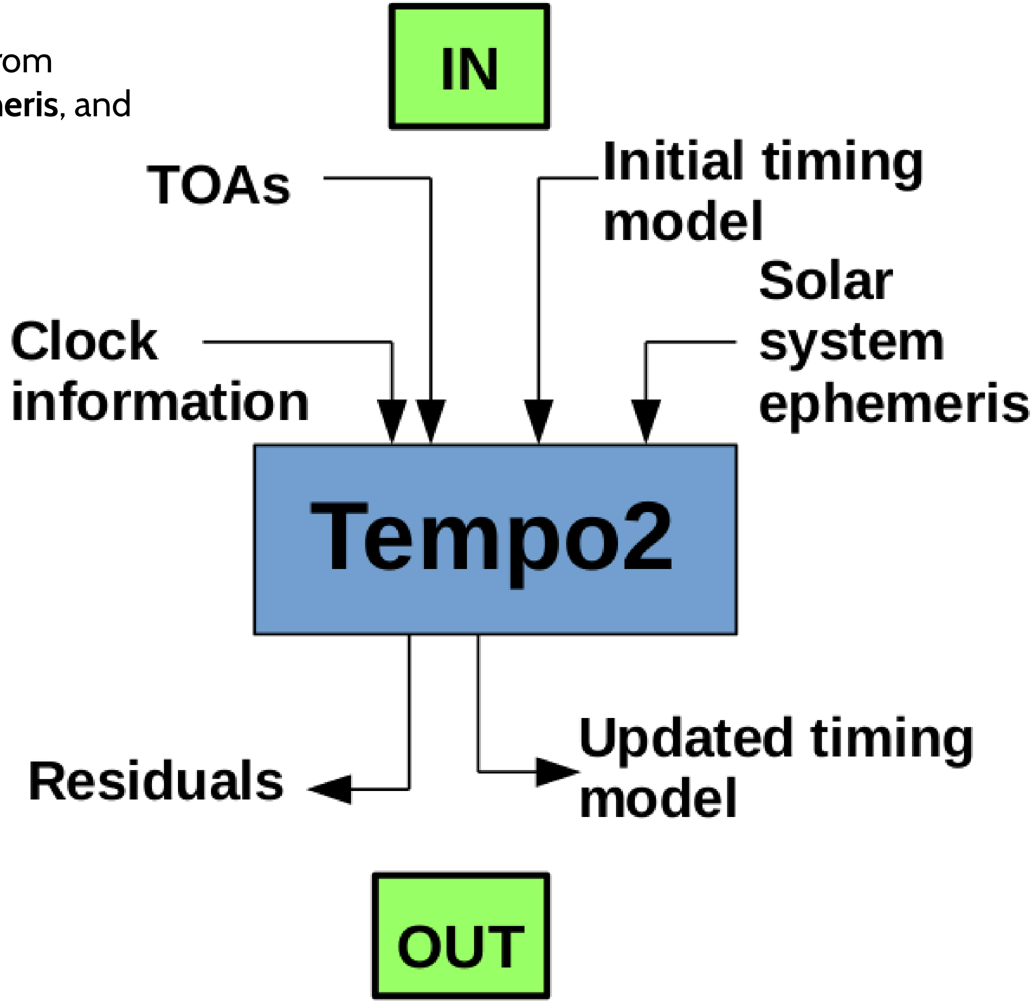
Basic Idea

Tempo2 is a software package that allows us to analyse the TOAs from observations, together with a **timing model**, a **solar system ephemeris**, and **clock information** from the observatory

In most cases, you don't need to worry too much about the solar system ephemeris (unless you're doing very high-precision timing e.g. with the goal of direct gravitational wave detection)

You also will not typically need to worry about the clock files - these are generally maintained by your resident Tempo2 expert

However if you are starting a new project using data from another institute's telescope, it is a good idea to contact their observers to obtain an up-to-date clock correction file!



Basic Idea

Tempo2 fits for parameters in the timing model using a weighted least-squares algorithm, where the χ^2 statistic is minimised

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

Where:
N = number of data points
σ_i = uncertainty of the i^{th} TOA (or 1 if unweighted)
R_i = i^{th} pre-fit residual

As more data are recorded, we can measure the timing model parameters to higher precision and update the timing model accordingly

.tim file

A .tim file is an ascii file, with columns describing relevant information about the TOAs

A basic .tim file looks like this:

```
FORMAT 1
J090207_132244.FT    1400.000  54869.5638524282505  0.632  8
J090302_011417.FT    1400.000  54892.0580767783864  1.146  8
J090304_004147.FT    1400.000  54894.0354149627799  0.785  8
J090306_011052.FT    1400.000  54896.0556498613889  0.553  8
```

.tim file

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A basic .tim file looks like this:

```
FORMAT 1
J090207_132244.FT  1400.000  54869.5638524282505  0.632  8
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J090304_004147.FT  1400.000  54894.0354149627799  0.785  8
J090306_011052.FT  1400.000  54896.0556498613889  0.553  8
```

Name of the file from which the TOA was generated

Centre frequency of observation (MHz)

TOA (MJD+fraction of the day)

TOA uncertainty (microseconds)

Telescope ID (in this case, The Lovell telescope at Jodrell Bank)

(Full list of telescope IDs used by your installed version in $TEMPO2/observatory/aliases)

.tim file

We can also choose to add some additional columns ('flags') to lines in the .tim file

For example:

Use a fixed DM for this TOA (in this case, 15.993 cm^{-3} pc)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -dm 15.993
```

.tim file

We can also choose to add some additional columns ('flags') to lines in the .tim file

For example:

Use a fixed DM for this TOA (in this case, 15.993 cm^{-3} pc)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -dm 15.993
```

Apply a time offset to this TOA (in this case, 0.001 seconds)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -addsat 0.001
```

.tim file

We can also choose to add some additional columns ('flags') to lines in the .tim file

For example:

Use a fixed DM for this TOA (in this case, 15.993 cm^{-3} pc)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -dm 15.993
```

Apply a time offset to this TOA (in this case, 0.001 seconds)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -addsat 0.001
```

Assign this TOA a custom flag (this can be anything that isn't defined in Tempo2 by default)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -flag JBO
```

.tim file

We can also choose to add some additional columns ('flags') to lines in the .tim file

For example:

Use a fixed DM for this TOA (in this case, 15.993 cm^{-3} pc)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -dm 15.993
```

Apply a time offset to this TOA (in this case, 0.001 seconds)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -addsat 0.001
```

Assign this TOA a custom flag (this can be anything that isn't defined in Tempo2 by default)

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -flag JBO
```

These flags can all be used together as well (in any order):

```
J090302_011417.FT 1400.000 54892.0580767783864 1.146 8 -dm 15.993 -addsat 0.001 -flag JBO
```

Full list of flags that can be added to a TOA

Flag	Parameter	Type
-dm	Fixed DM (cm^{-3} pc)	float
-dmo	DM offset from model (cm^{-3} pc)	float
-dme	DM uncertainty (cm^{-3} pc)	float
-p	Phase offset	float
-t	Telescope identifier	string
-addsat	Time offset (seconds)	float
-to		float
-radd	Residual offset (seconds)	float
-padd	Phase offset	float
-pn	Pulse number (rotations)	integer
-c	Clock correction path (underscore-separated)	string
-telx, -tely, -telz	Telescope position (for barycentred TOAs)	float

Anything not listed in this column can be used as a custom flag

We can also add commands to a .tim file

These are on a separate line, and (in general) act on all of the TOAs below them

For example, include a time offset to several TOAs (in this case -0.04 seconds):

```
FORMAT 1
J090207_132244.FT    1400.000   54869.5638524282505   0.632   8
J090302_011417.FT    1400.000   54892.0580767783864   1.146   8
J090304_004147.FT    1400.000   54894.0354149627799   0.785   8
TIME -0.04
J090306_011052.FT    1400.000   54896.0556498613889   0.553   8
J090313_014227.FT    1400.000   54903.0775958015678   1.867   8
J090317_005615.FT    1400.000   54907.0455326159608   0.043   8
J090320_011526.FT    1400.000   54910.0588492388774   1.085   8
TIME +0.04
J090321_234832.FT    1400.000   54911.9984633458142   3.275   8
J090418_224043.FT    1400.000   54939.9513862758354   0.185   8
```

We can also add commands to a .tim file

These are on a separate line, and (in general) act on all of the TOAs below them

For example, include a time offset to several TOAs (in this case -0.04 seconds):

```
FORMAT 1
J090207_132244.FT    1400.000   54869.5638524282505   0.632   8
J090302_011417.FT    1400.000   54892.0580767783864   1.146   8
J090304_004147.FT    1400.000   54894.0354149627799   0.785   8
TIME -0.04
J090306_011052.FT    1400.000   54896.0556498613889   0.553   8
J090313_014227.FT    1400.000   54903.0775958015678   1.867   8
J090317_005615.FT    1400.000   54907.0455326159608   0.043   8
J090320_011526.FT    1400.000   54910.0588492388774   1.085   8
TIME +0.04
J090321_234832.FT    1400.000   54911.9984633458142   3.275   8
J090418_224043.FT    1400.000   54939.9513862758354   0.185   8
```

(used +0.04 seconds to 'end' the time offset)

Command	Meaning
EFAC x	Multiply uncertainties by x
EQUAD x	Additional uncertainty, added in quadrature (microseconds)
T2EFAC -backend dfb x	Multiply uncertainties of all TOAs with a particular flag by x (in this case, the flag is -backend dfb)
T2EQUAD -backend dfb x	Add x (in microseconds) to uncertainties of all TOAs with a particular flag (in this case, the flag is -backend dfb)
GLOBAL_EFAC x	Multiply all uncertainties by x. Note: TOAs that already have an "EFAC y" flag, will have their TOA uncertainties multiplied by x times y
EMAX x	Ignore TOAs with uncertainties greater than x (in microseconds)
EMIN x	Ignore TOAs with uncertainties less than x (in microseconds)
EFLOOR x	Change uncertainties that are less than x (microseconds) to equal x (microseconds)
END	Ignore all remaining lines in the .tim file
FMAX x	Ignore TOAs recorded at centre frequencies greater than x MHz
FMIN x	Ignore TOAs recorded at centre frequencies less than x MHz
INCLUDE x	Include the arrival times in file 'x'
INFO x	Identify all following observations with a given highlighting code
MODE	MODE 0 (default) indicates that the TOA uncertainty is ignored during the fitting procedure. MODE 1 uses the uncertainties
SKIP	Skip all following lines until NOSKIP is reached
NOSKIP	End of skip statement
SIGMA x	Set uncertainties of following TOAs to x (in microseconds)
PHASE x	Offset following TOAs in phase by x
TIME x	Offset following TOAs by x seconds
TRACK x	Tracks phase wrap-arounds (can also occur in parameter files)

Full list of commands that can be included in a .tim file

.par file

As pulsar rotation is incredibly stable, with a suitable timing model we can account for every single rotation of the pulsar

Although the pulses are emitted extremely regularly by the pulsar, the time at which they are observed on the Earth depends on many factors

An ephemeris (the .par file) is a set of parameters used to construct a timing model of the pulsar

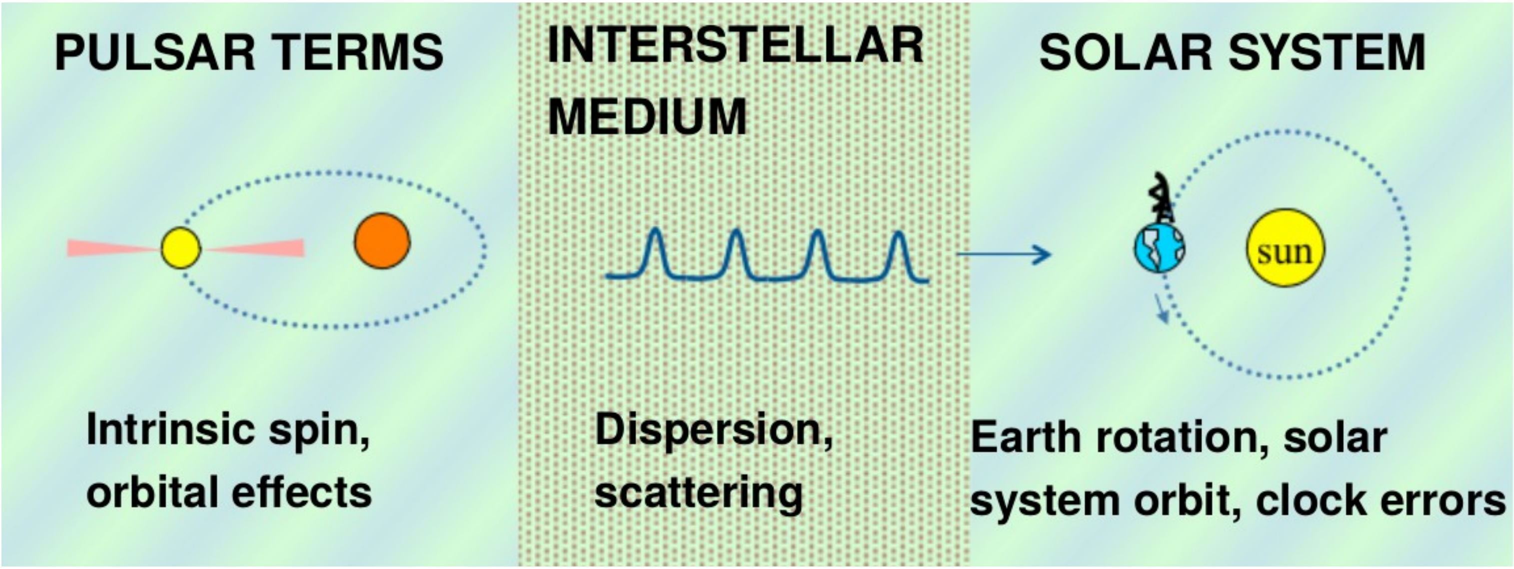


Image by David Nice

Example: .par file for PSR J0437−4715 (included in PPTA/IPTA analyses)

PSRJ	J0437-4715		
RAJ	04:37:15.7865145	1	7.000e-07
DECJ	-47:15:08.461584	1	8.000e-06
DM	2.6469		1.000e-04
PEPOCH	51194.000		
F0	173.687948999098	1	3.000e-13
F1	-1.728314E-15	1	1.600e-20
PMRA	121.438		6.000e-03
PMDEC	-71.438		7.000e-03
BINARY	DD		
PB	5.741046	1	3.000e-06
ECC	1.9186E-5	1	5.000e-09
A1	3.36669157	1	1.400e-07
T0	51194.6239	1	8.000e-04
OM	1.20	1	5.000e-02
OMDOT	0.016		1.000e-02
START	50640.928		
FINISH	52088.897		
CLK	UTC(NIST)		
EPHEM	DE200		
PBDOT	3.64E-12		2.000e-13
PX	7.19		1.400e-01
SINI	0.6788		1.200e-03
M2	0.236		1.700e-02

Obtained from the ATNF Pulsar Database: http://www.atnf.csiro.au/people/pulsar/psrcat/

Example: .par file for PSR J0437−4715 (included in PPTA/IPTA analyses)

Parameter name	Value	Fit turned on (1) or off (0, or blank)	Uncertainty
PSRJ	J0437-4715		
RAJ	04:37:15.7865145	1	7.000e-07
DECJ	-47:15:08.461584	1	8.000e-06
DM	2.6469		1.000e-04
PEPOCH	51194.000		
F0	173.687948999098	1	3.000e-13
F1	-1.728314E-15	1	1.600e-20
PMRA	121.438		6.000e-03
PMDEC	-71.438		7.000e-03
BINARY	DD		
PB	5.741046	1	3.000e-06
ECC	1.9186E-5	1	5.000e-09
A1	3.36669157	1	1.400e-07
T0	51194.6239	1	8.000e-04
OM	1.20	1	5.000e-02
OMDOT	0.016		1.000e-02
START	50640.928		
FINISH	52088.897		
CLK	UTC(NIST)		
EPHEM	DE200		
PBDOT	3.64E-12		2.000e-13
PX	7.19		1.400e-01
SINI	0.6788		1.200e-03
M2	0.236		1.700e-02

Obtained from the ATNF Pulsar Database: http://www.atnf.csiro.au/people/pulsar/psrcat/

Pulsar name	PSRJ	J0437-4715		
Right ascension (h:m:s)	RAJ	04:37:15.7865145	1	7.000e-07
Declination (deg)	DECJ	-47:15:08.461584	1	8.000e-06
Dispersion measure (cm^{-3} pc)	DM	2.6469		1.000e-04
Epoch of position measurement (MJD)	PEPOCH	51194.000		
Spin-frequency (Hz)	F0	173.687948999098	1	3.000e-13
Spin-down rate (Hz s^{-1})	F1	-1.728314E-15	1	1.600e-20
Proper motion in right ascension (mas yr^{-1})	PMRA	121.438		6.000e-03
Proper motion in declination (mas yr^{-1})	PMDEC	-71.438		7.000e-03
Choice of binary model	BINARY	DD		
Binary period (days)	PB	5.741046	1	3.000e-06
Orbital eccentricity	ECC	1.9186E-5	1	5.000e-09
Projected semi-major axis (light-seconds)	A1	3.36669157	1	1.400e-07
Time of periastron (MJD)	T0	51194.6239	1	8.000e-04
Longitude of periastron (degrees)	OM	1.20	1	5.000e-02
Rate of advance of periastron (deg yr^{-1})	OMDOT	0.016		1.000e-02
Start fitting from this date (MJD)	START	50640.928		
End fitting from this date (MJD)	FINISH	52088.897		
Definition of clock correction files to use	CLK	UTC(NIST)		
Choice of solar system ephemeris	EPHEM	DE200		
Rate of change of binary period (s s^{-1})	PBDOT	3.64E-12		2.000e-13
Parallax (mas)	PX	7.19		1.400e-01
Sine of the inclination angle	SINI	0.6788		1.200e-03
Companion mass (solar masses)	M2	0.236		1.700e-02

For a list of many useable parameters (but not a complete list!) you can look at http://www.atnf.csiro.au/research/pulsar/tempo2/index.php?n=Documentation.Parameters

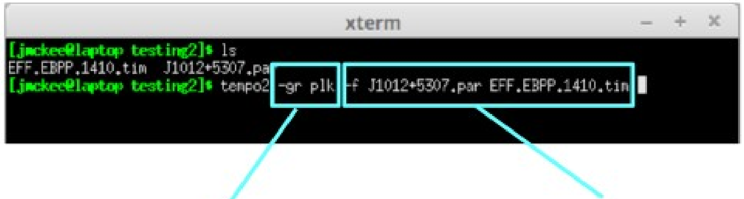
Part 3: Using Tempo2

We need some TOAs (.tim file) and an ephemeris (.par file)

Load these into tempo2, and choose the 'plk' graphical interface

We need some TOAs (.tim file) and an ephemeris (.par file)

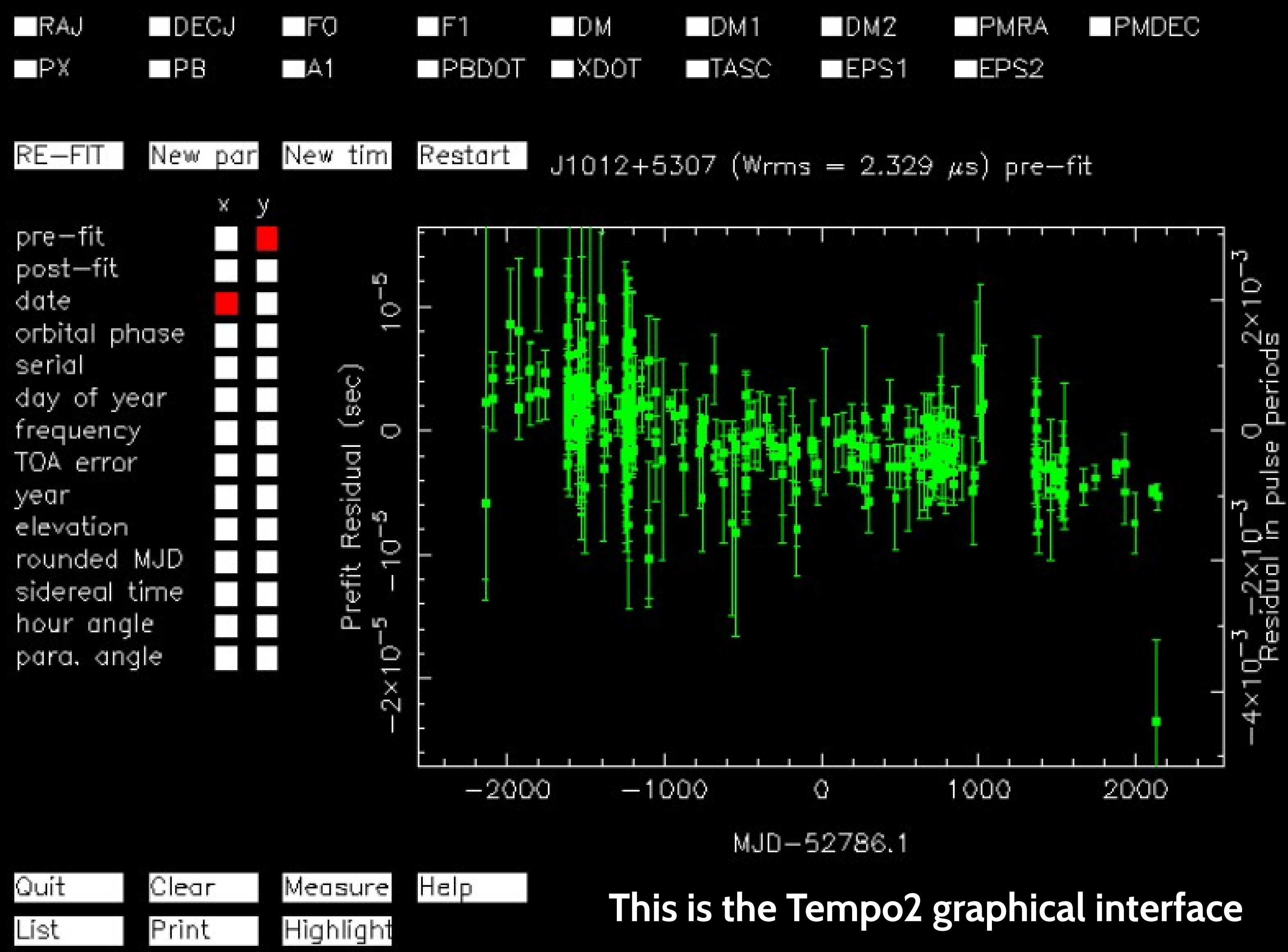
Load these into tempo2, and choose the 'plk' graphical interface



-gr plk:
run with the plk plugin

-f J1012+5307.par EFF.EBPP.1410.tim:
run with these two files

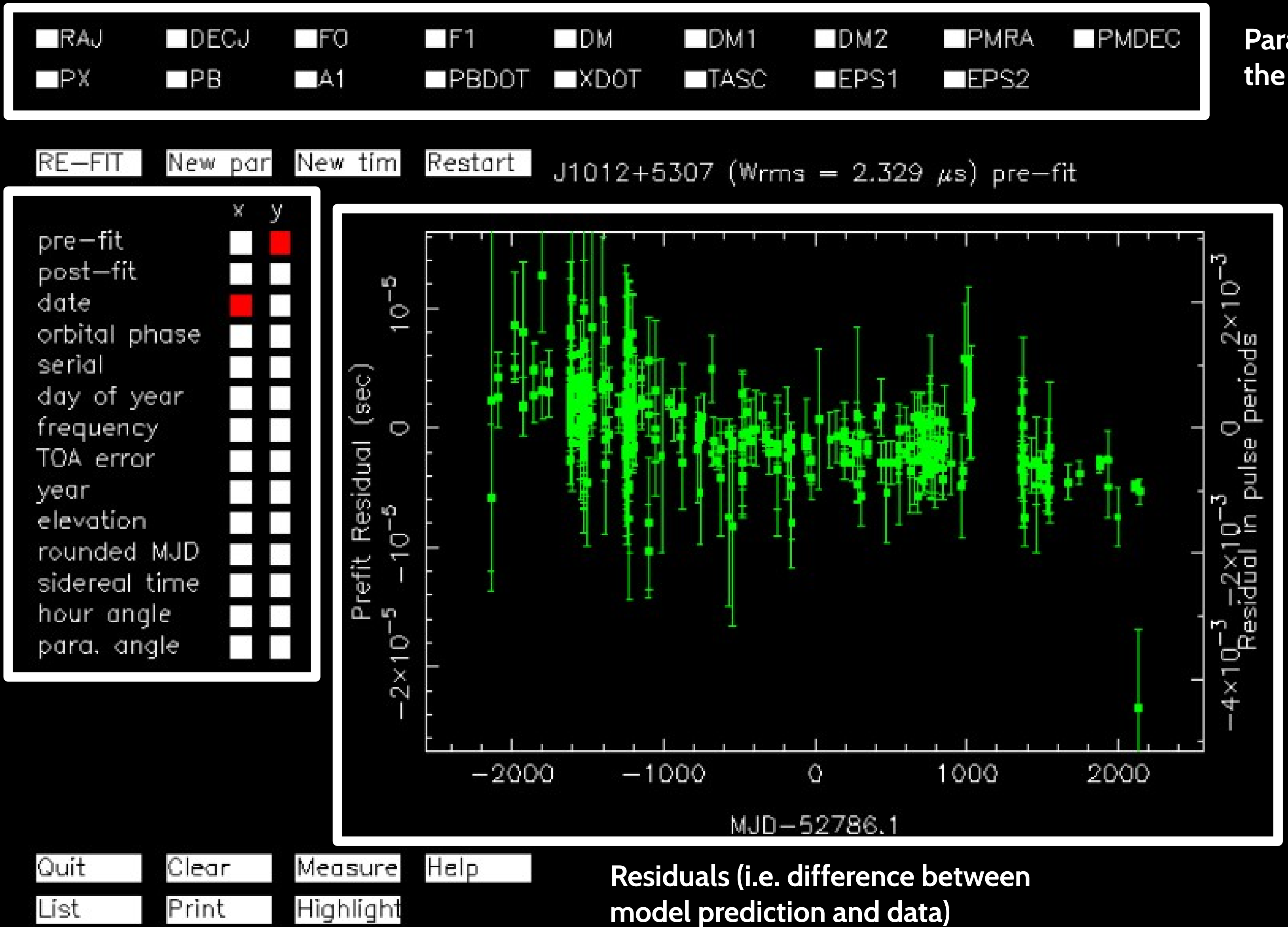
Note: the files must be called in this order (.par file then .tim file)!



This is the Tempo2 graphical interface

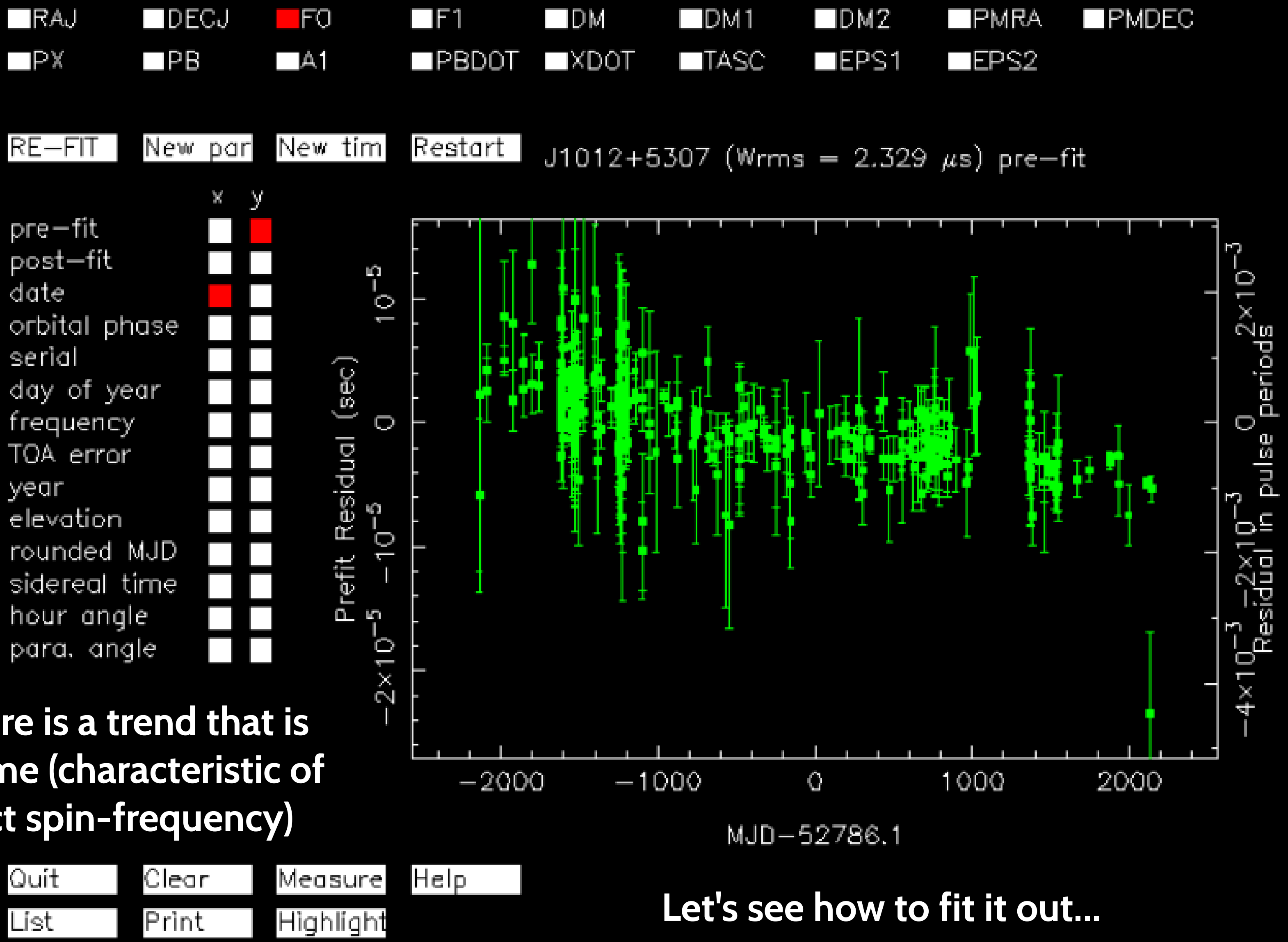
Parameters in the timing model

Choice of plot axes



Residuals (i.e. difference between model prediction and data)

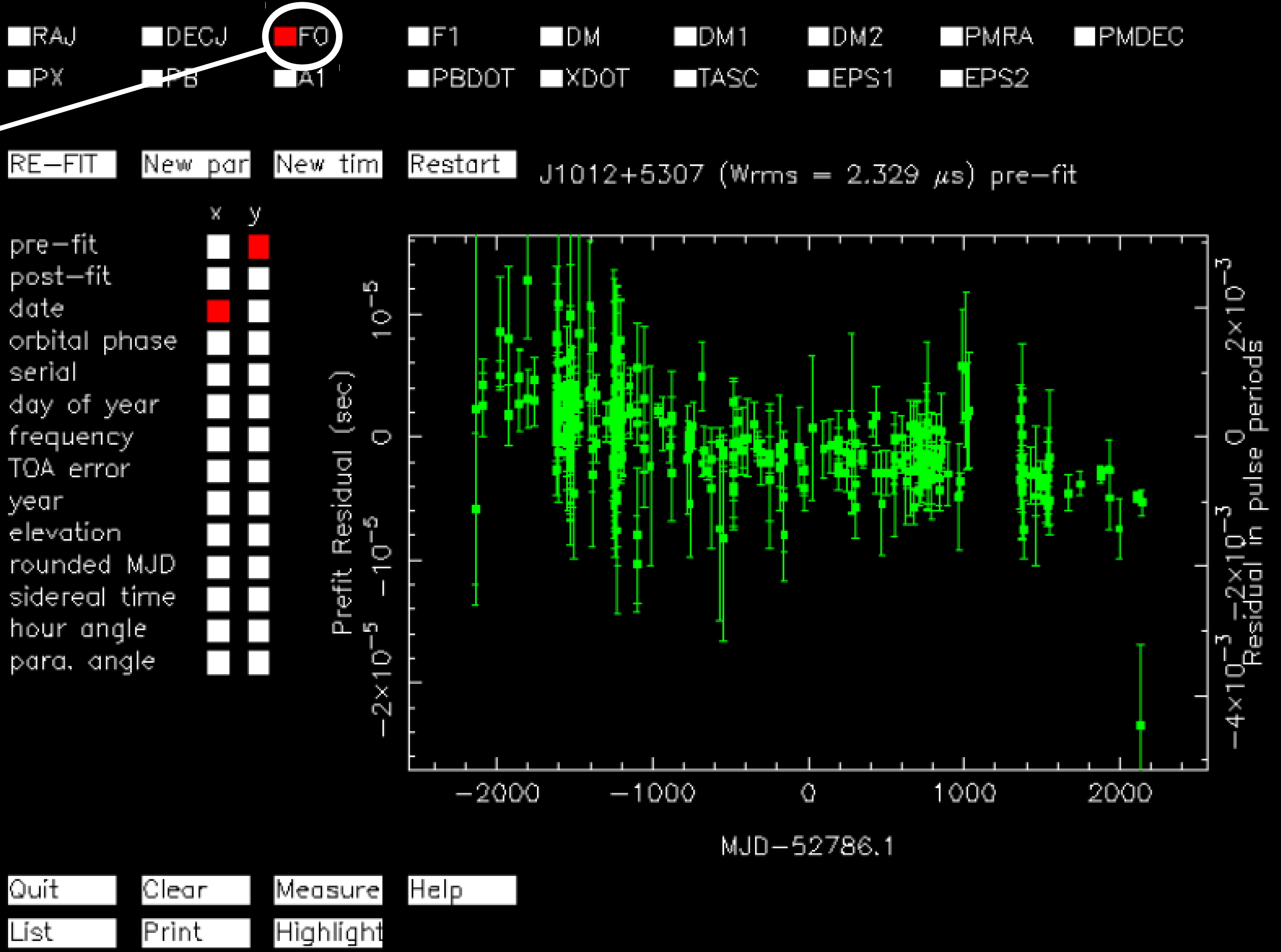
Example: Fitting for Spin Frequency



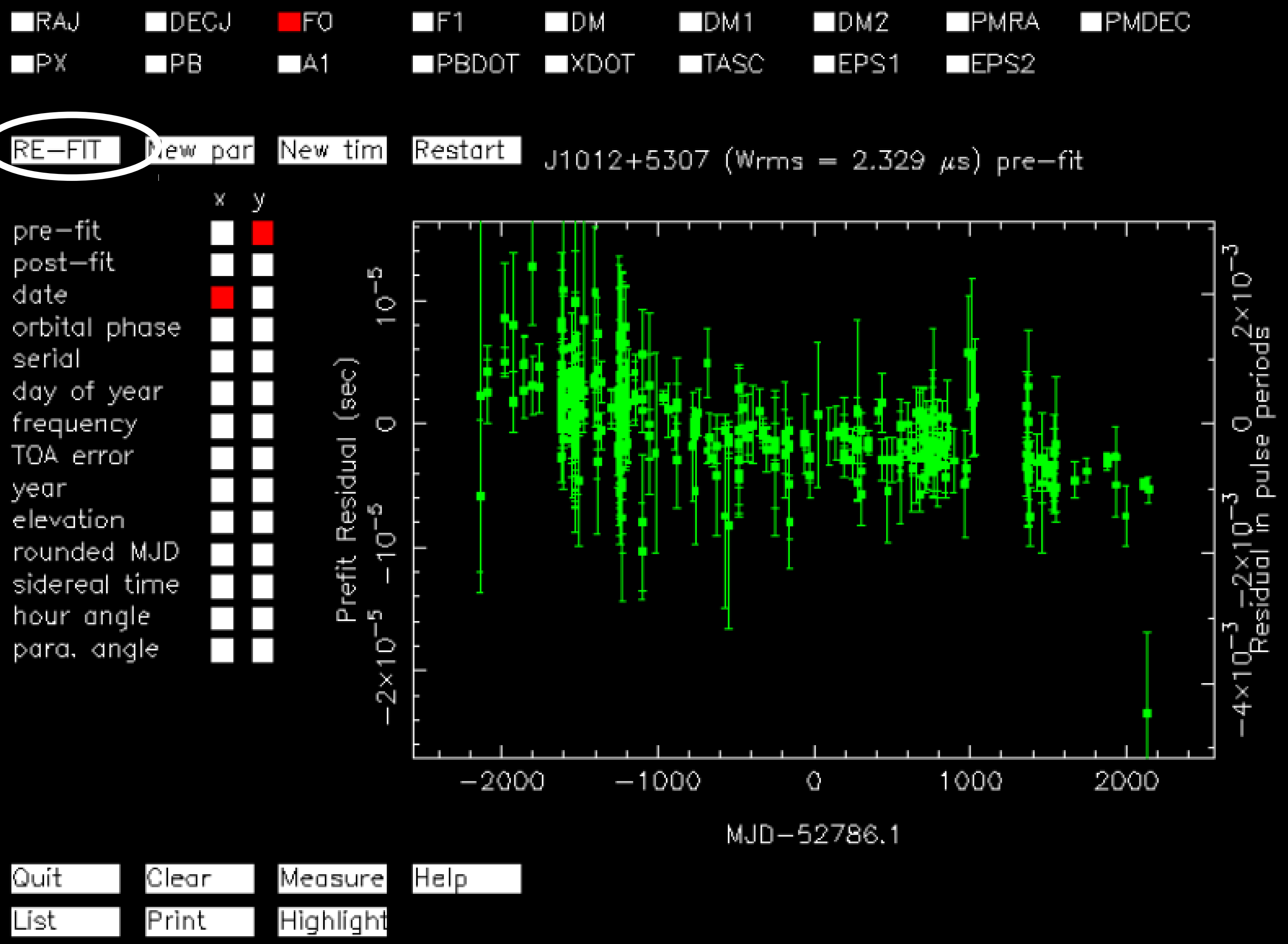
Clearly there is a trend that is linear in time (characteristic of an incorrect spin-frequency)

Let's see how to fit it out...

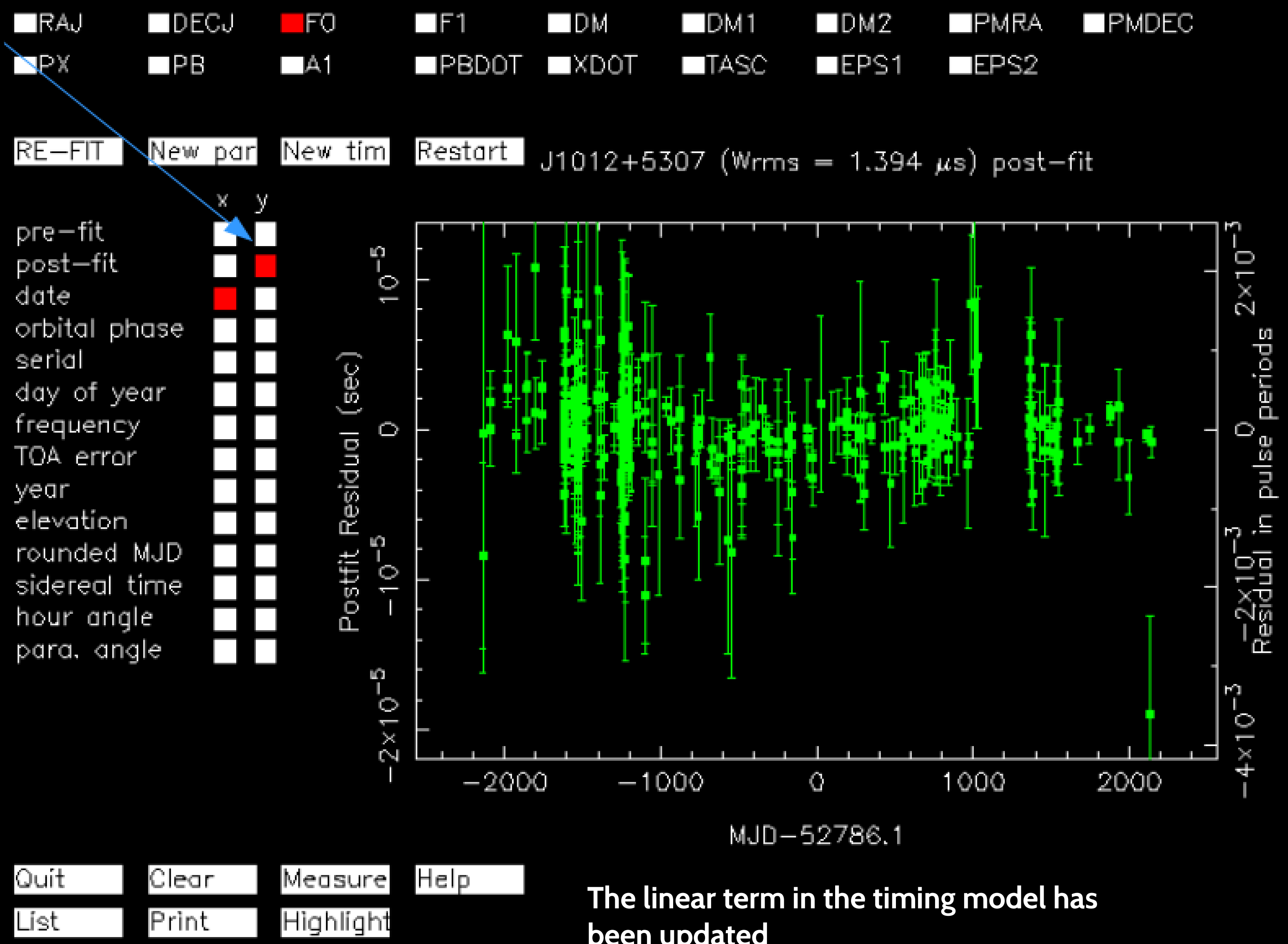
...click the parameter(s) you would like to fit for...



...click refit...

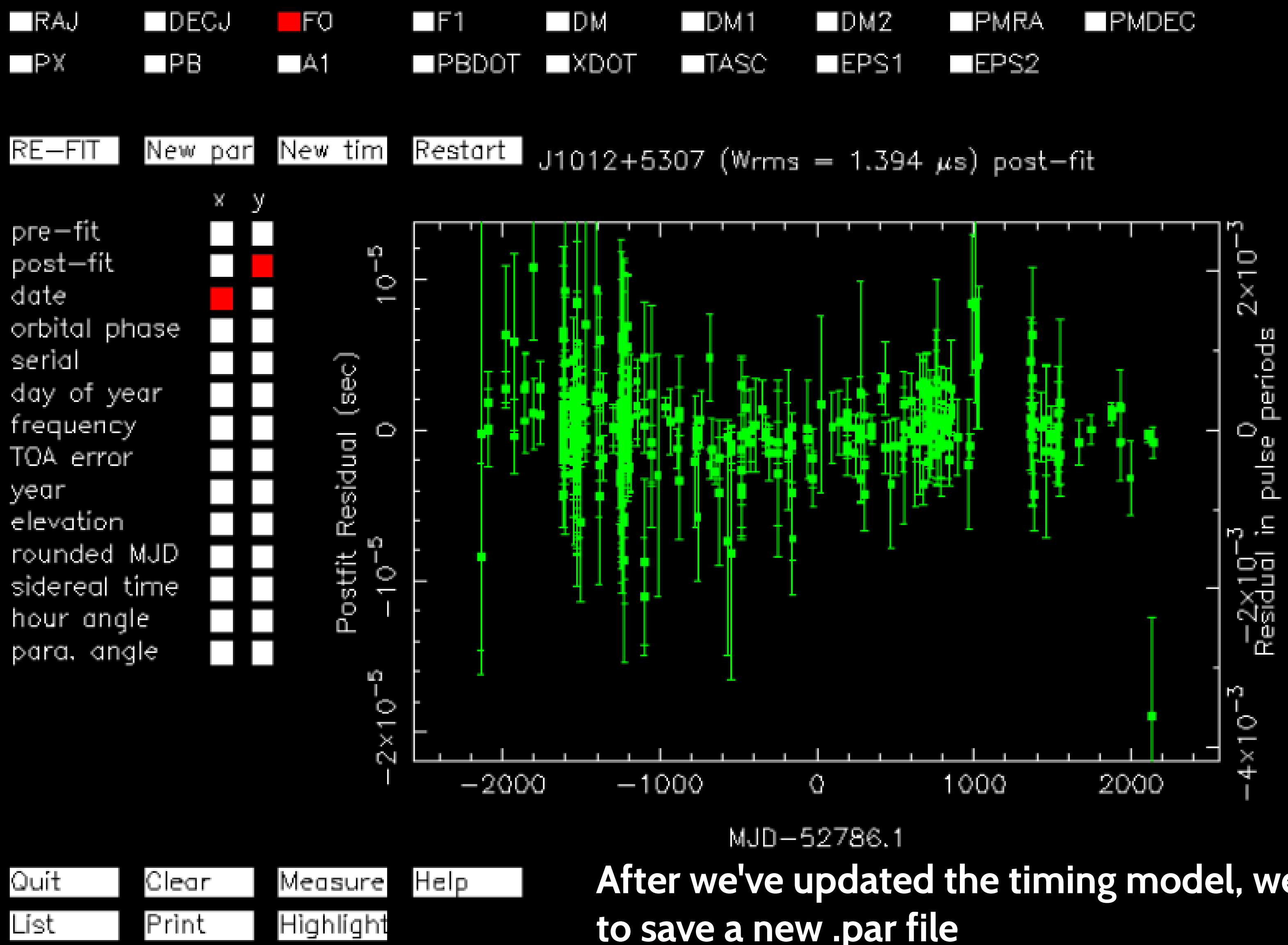

RAJ
DECJ
F0
F1
DM
DM1
DM2
PMRA
PMDEC
PX
PB
A1
PBDOT
XDOT
TASC
EPS1
EPS2
RE–FIT
New par
New tim
Restart
J1012+5307 (Wrms = 2.329 μs) pre–fit
x
y
pre–fit
post–fit
date
orbital phase
serial
day of year
frequency
TOA error
year
elevation
rounded MJD
sidereal time
hour angle
para. angle
Prefit Residual (sec)
Residual in pulse periods
MJD–52786.1
Quit
Clear
Measure
Help
List
Print
Highlight

...and change the y-axis to 'post-fit'



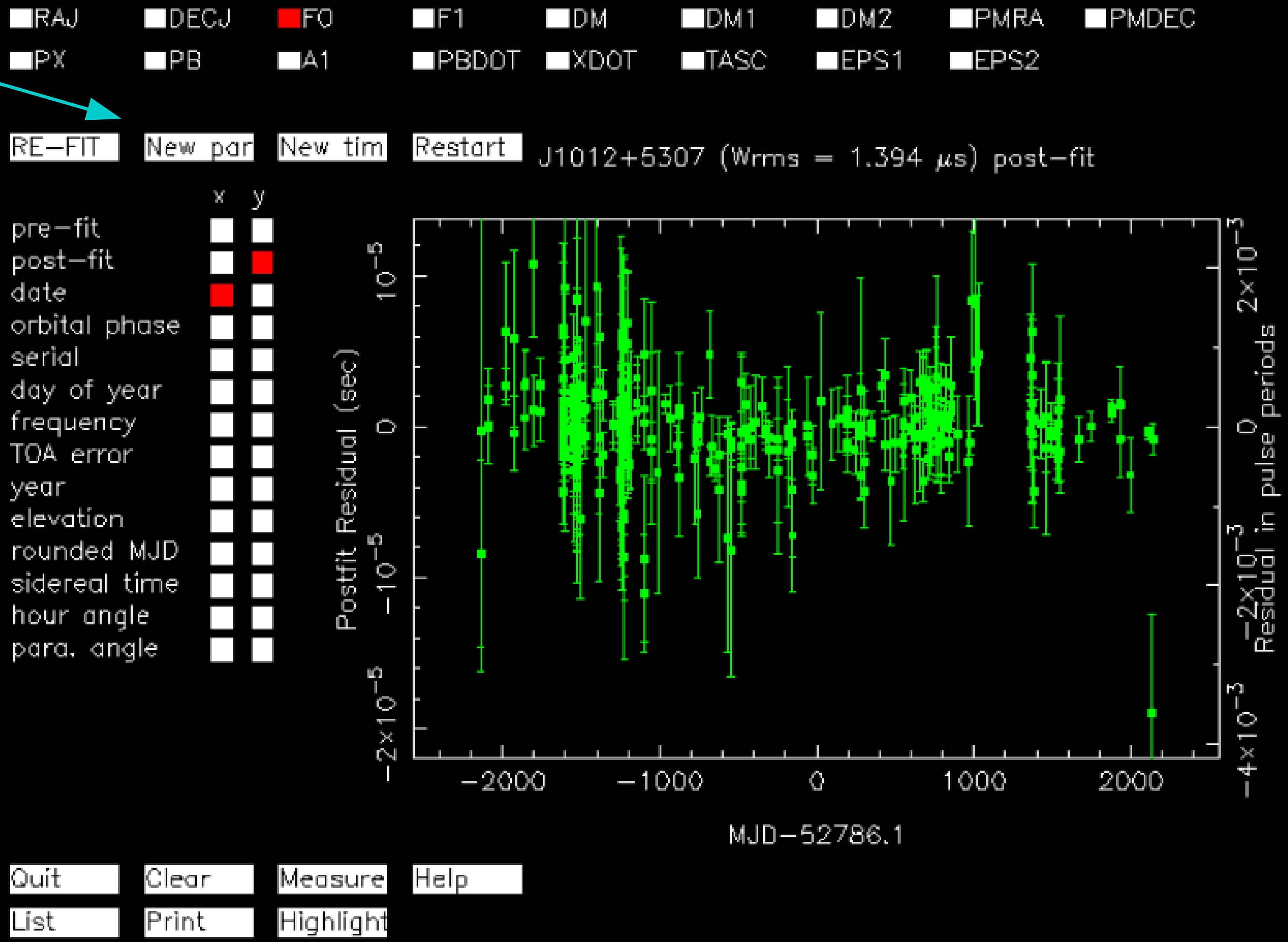
The linear term in the timing model has been updated

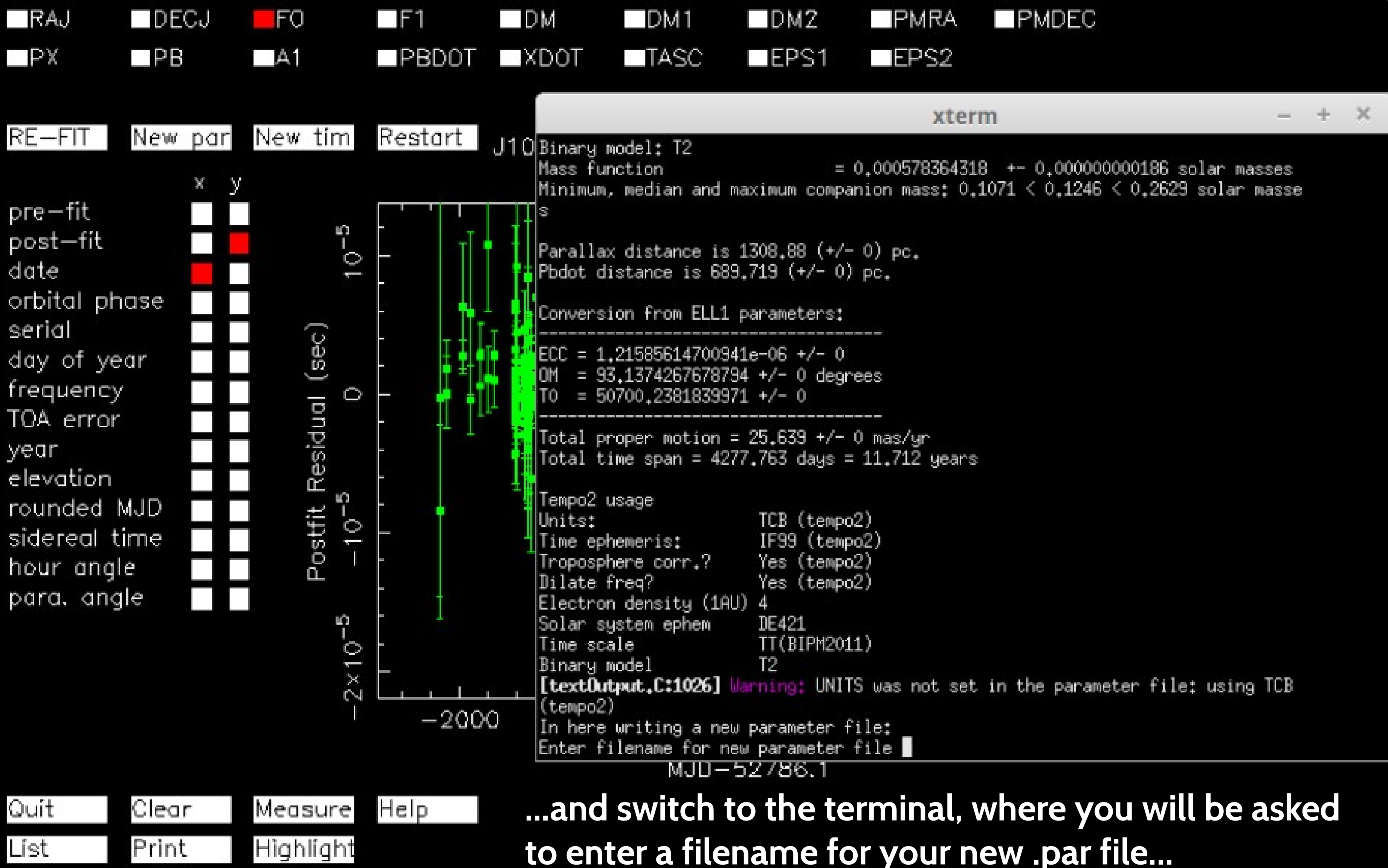
Example: Saving a new .par file



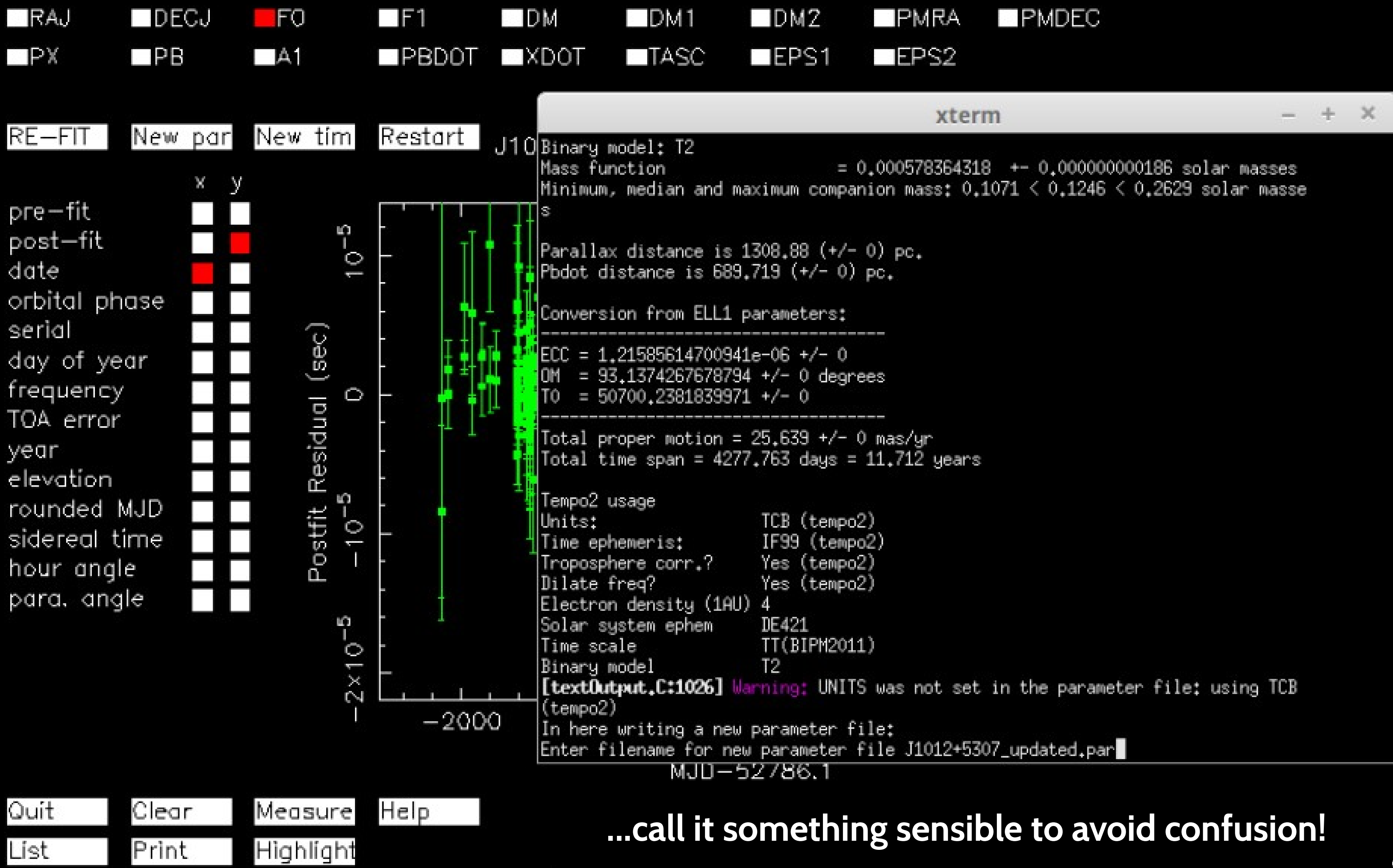
After we've updated the timing model, we will want to save a new .par file

Click 'new par'...



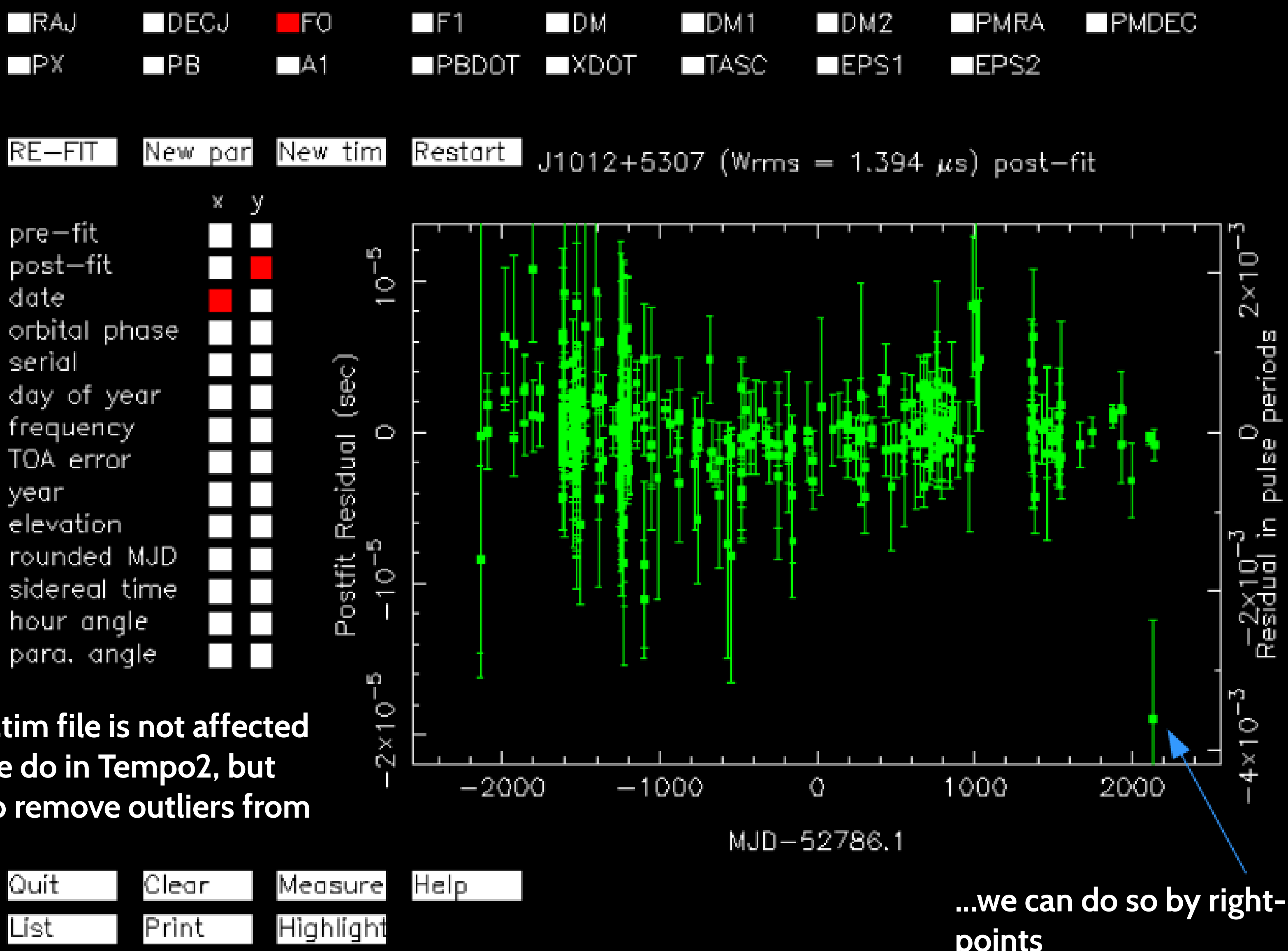


...and switch to the terminal, where you will be asked to enter a filename for your new .par file...



...call it something sensible to avoid confusion!

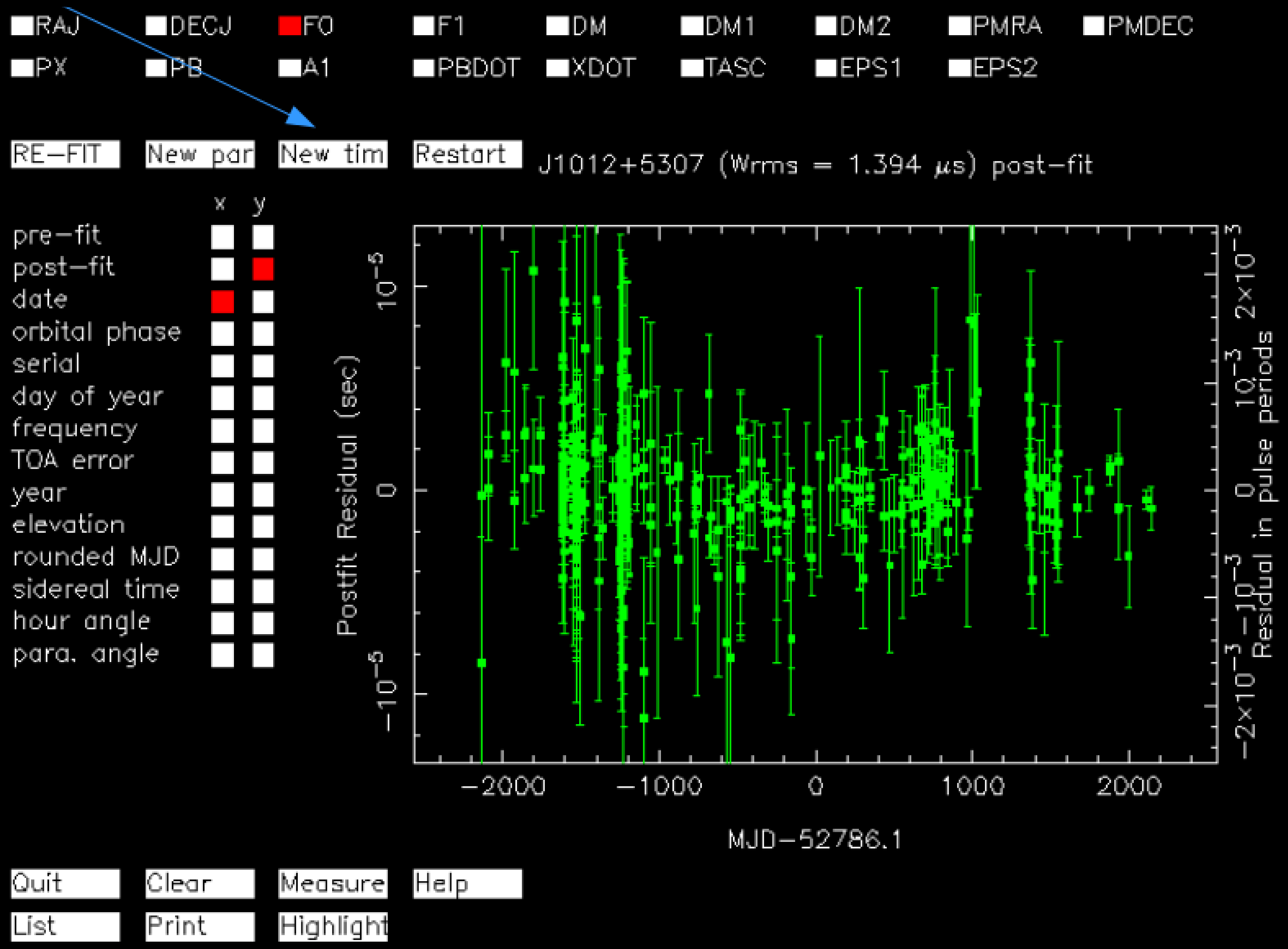
Example: Saving a new .tim file

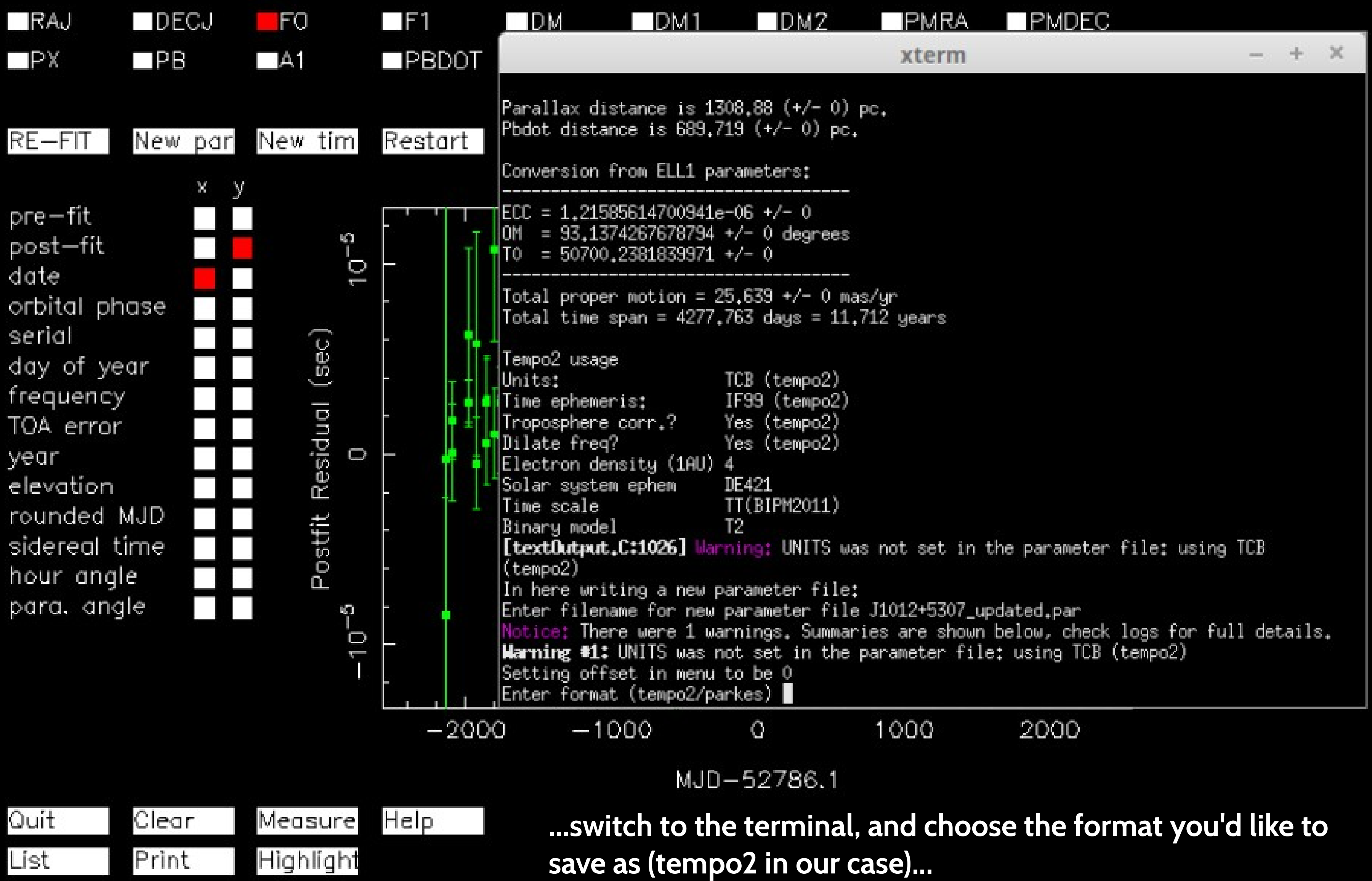


Generally the .tim file is not affected by anything we do in Tempo2, but say we want to remove outliers from our data...

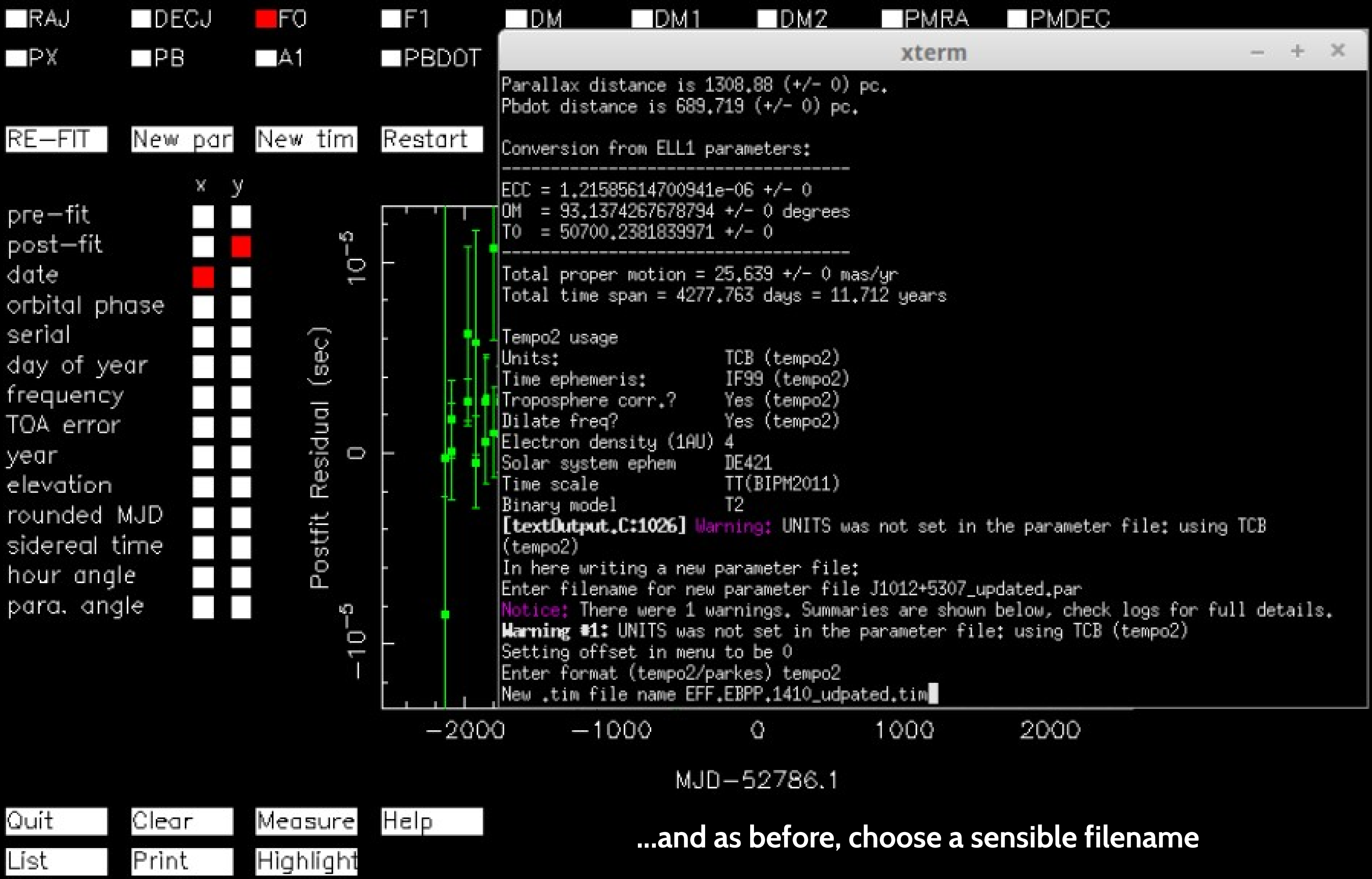
...we can do so by right-clicking data points

Click 'New .tim'...

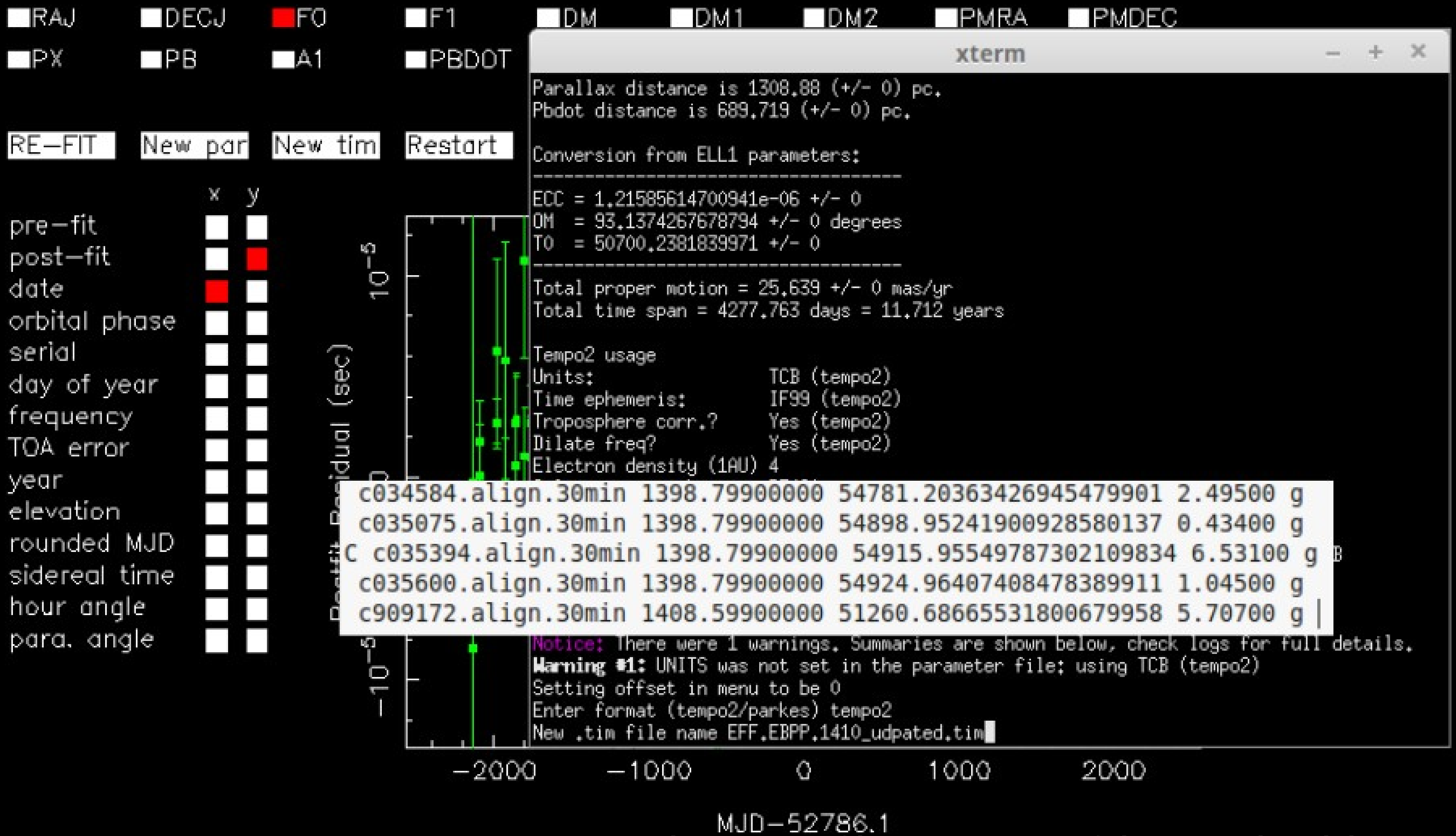




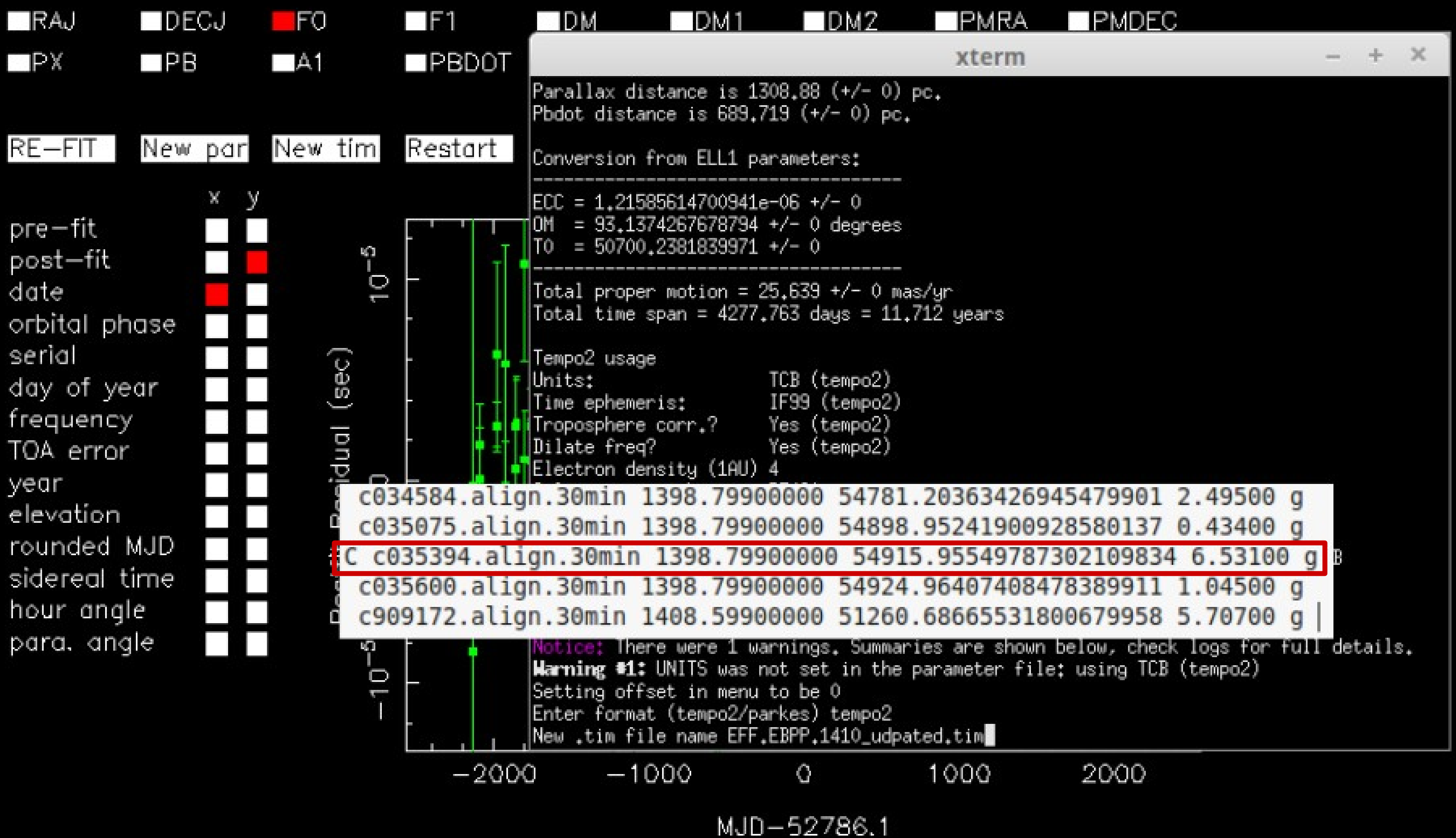
...switch to the terminal, and choose the format you'd like to save as (tempo2 in our case)...



...and as before, choose a sensible filename



Note: the new .tim file is just a copy of the original, with lines commented out (capital C in the first column), so don't worry about data loss!



Note: the new .tim file is just a copy of the original, with lines commented out (capital C in the first column), so don't worry about data loss!

List of Tempo2 command line options

Option	Description
-h	Display the help screen
-f <filename>	Load this .par file
-gr <option>	Use this graphhical plugin (see installed plugins with tempo2 -h)
-epoch <MJD>	Centres PEPOCH to this for the fit
-dcm <dcmFile>	Use a data covariance matrix file
-list	List the clock corrections, residuals, etc
-output <name>	Use this plugin for printing the output
-pred “<args>”	Create a predictive 2D Chebyshev polynomial
-polyco “<args>”	Create a Tempo1-style polyco file
-residuals	Output the residuals
-allInfo	Print information about the clock, Earth orientation, etc.
-reminder	Saves the command line to T2command.input for future reference
-norescale	Do not rescale parameter uncertainties by $(\chi_{\text{reduced}}^{2})^{1/2}$
-displayVersion	Display detailed CVS version number of every file used
-noaccel	Disable LAPACK/BLAS acceleration
-v	Print software version number
-polyco_file	Specify a leading string for file outputs

Conclusion

This session only scratches the surface of Tempo2

There are many features, and many plugins that you will encounter as a pulsar timer

In the workshop, you will play around with Tempo2 and become more familiar with it

The instructors are all experts (so are some students!), so don't hesitate to ask questions!

Thank you!

Some Useful Links

Current Tempo2 version (only attempt to install if you are confident with Linux!):
https://bitbucket.org/psrsoft/tempo2

Tempo2 user manual:
http://www.jb.man.ac.uk/~pulsar/Resources/tempo2_manual.pdf

Tempo2 overview paper (Hobbs et al. 2006):
https://arxiv.org/abs/astro-ph/0603381

Tempo2 timing model description (Edwards et al. 2006):
https://arxiv.org/abs/astro-ph/0607664

Tempo2 wiki page (tutorials, documentation, etc.):
http://www.atnf.csiro.au/research/pulsar/tempo2/index.php?n=Main.HomePage