The influence of the observational strategies and noise in pulsar timing on the properties of pulsar clocks

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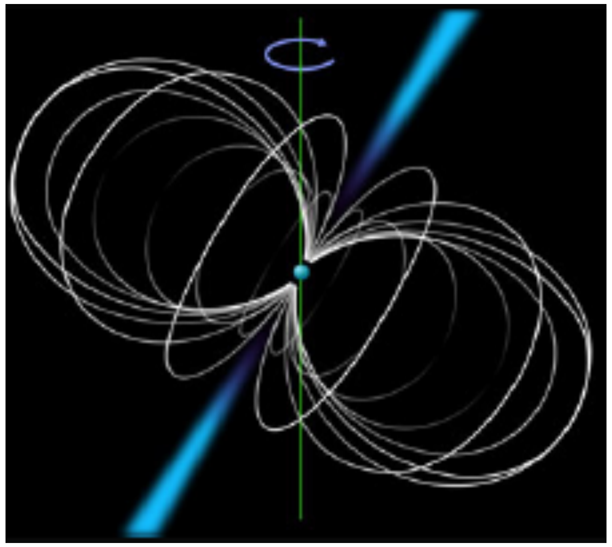
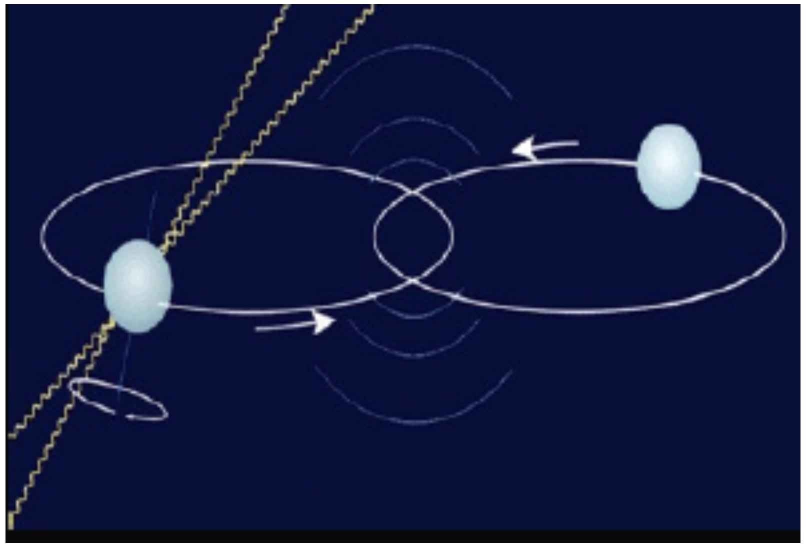
Outline

1. Pulsars and pulsar clocks
2. The effects of observational strategies
3. The effects of noise in pulsar timing
4. Summary

1.Pulsars and pulsar clocks



Isolated



Binary

Observed times of arrive(TOA), clock signal?
No! There are:
Relative motion between earth and pulsar
Disturbance of pulse signal

PT—pulsar timescale
BPT—binary pulsar timescale

Pulsar clock—observing one pulsar and timing to acquire pulse signals

Influencing factors of pulsar clocks
(contributions to pulsar arrival times)

Intrinsic variation in shape or phase of emitted pulse

Pulsar spindown and stochastic spindown variations

The distance of pulsar/binary barycenter to SSB

Pulsar position, proper motion and reflex motion from companions

Interstellar medium

Gravitational waves

Solar system(earth orbiting SSB, solar wind, EOP, atmosphere)

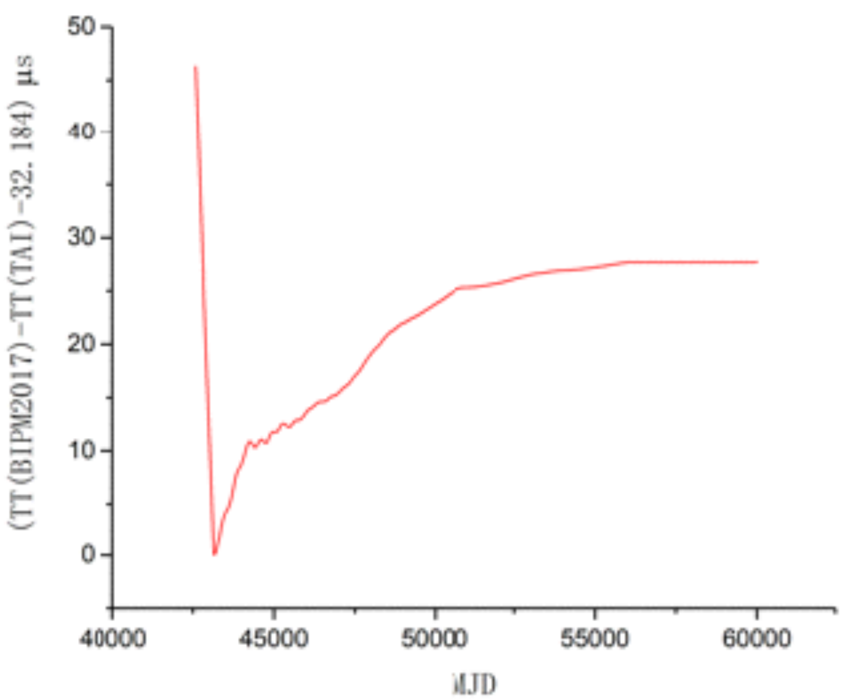
Receiving system

Establishment of pulsar clocks

The establishment of a pulsar clock is the process of pulsar timing, in which we decide the pulsar parameters in reference of TT(BIPM).

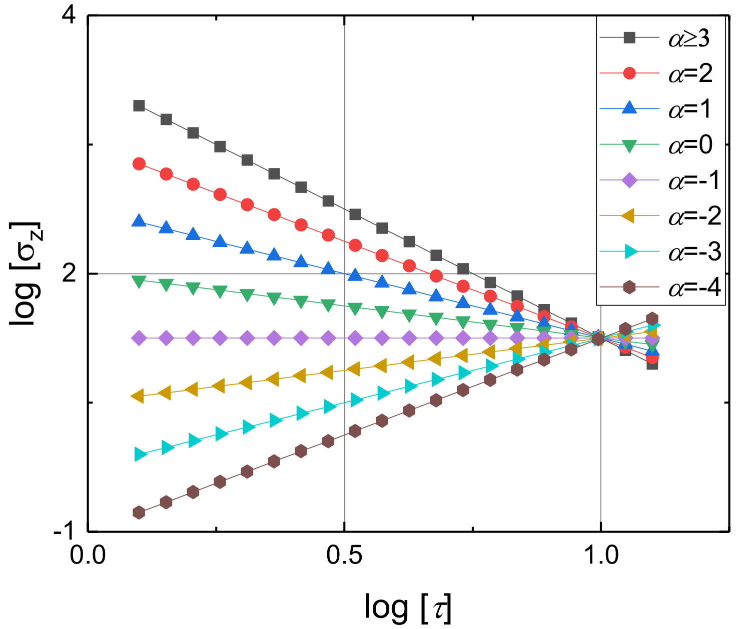
Why use TT(BIPM)?
TT(TAI) is steered by the primary frequency standard.

```
PSRJ           J0613-0200
RAJ             06:13:43.9756763          1  0.00000208270540753571
DECJ           -02:00:47.22539            1  0.00007388764334993888
F0             326.60056202349003024      1  0.00000000000366222887
F1             -1.02296466316698062270e-15 1  2.91112573627677194590e-20
PEPOCH         55000
POSEPOCH       55000
DMEPOCH        55000
DM             38.77811515181529776 8     1  0.00062623569759992731
DM1            -8.47084408671928601790e-05 1  0.00009536615602360003
DM2            -9.61580474470905969180e-06 1  0.00001237722340987982
PMRA           1.83441686276584696 43     1  0.00886393316150496831
PMDEC          -10.345082080617068295     1  0.02043693238438180210
PX             1.09213203160019729 08     1  0.10837428431949511221
BINARY         T2
```



Tools for stability analysis

Allan deviation



$\sigma_z = \frac{\tau^2}{2\sqrt{5}} \left\langle c_3^2 \right\rangle^{1/2}$ (Matsakis et al.1997)

τ ——data length

c_3 ——3rd order coefficient

$$X(t) = c_0 + c_1(t - t_0) + c_2(t - t_0)^2 + c_3(t - t_0)^3$$

σ_z regularity with noise spectral

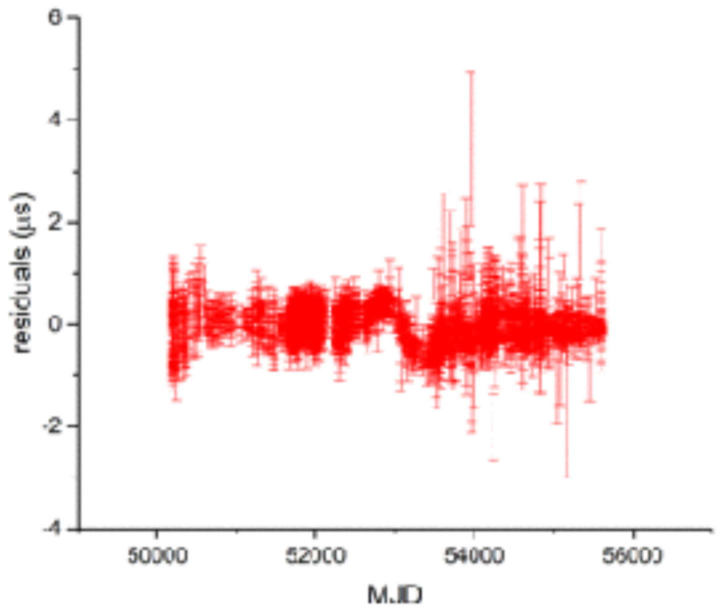
PSD of noise $S(f) \sim f^{\alpha-2}$

σ_z regularity $\sigma_z^2 \propto \tau^{\mu}$ (Linear after taking logarithm)

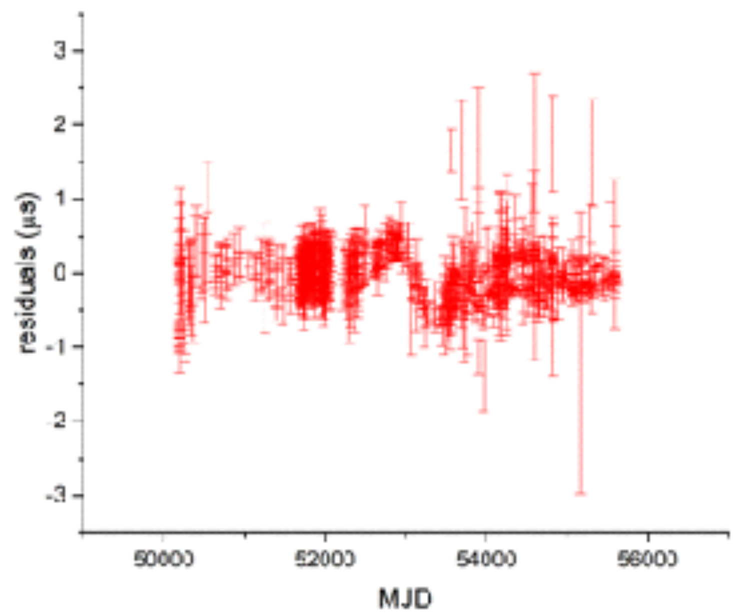
$$\mu = \begin{cases} -(\alpha + 1) & \alpha < 3 \\ -4 & other \end{cases}$$

2.The effects of observational strategies

Pulsar observation is discontinuous for many reasons, which lead to another problem—observational strategies, i.e., observational cadence, data span, period.



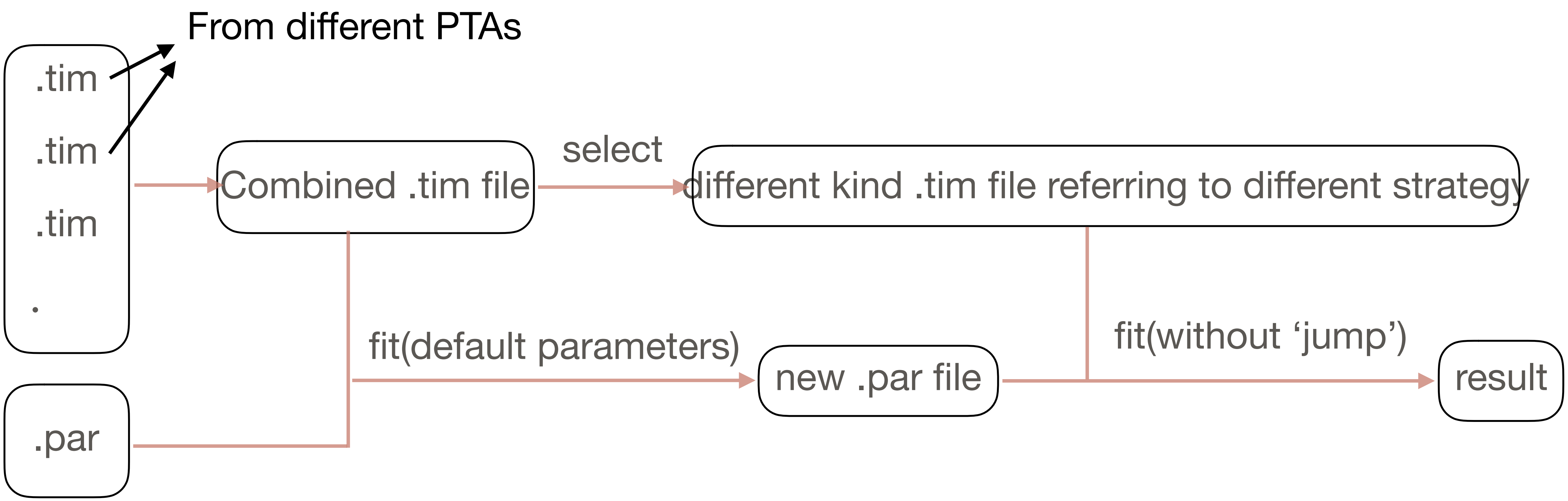
original data



25% of original data

Pulsar clocks are primarily affected by various noises. Generally, only those of weak noise and high precision are selected as clocks.
The pulsars chosen: PSR J0437-4715, J1713+0747, J1744-1134, J1909-3744 from the IPTA first data release.

Influence on pulsar clocks



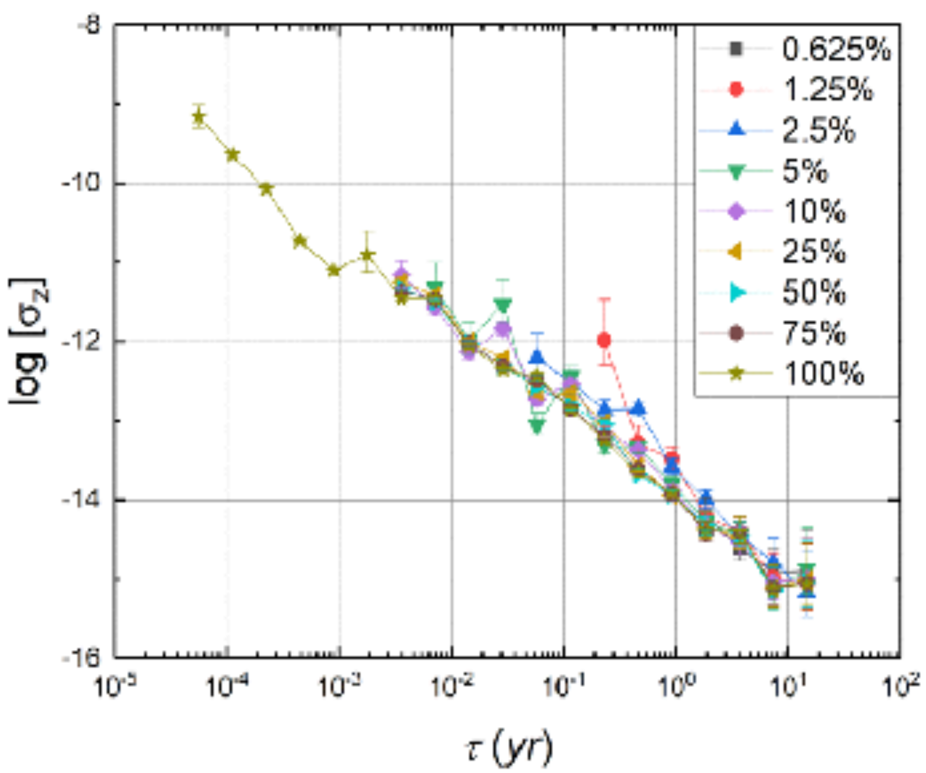
'Jump' is the delay from observing system to recording system, it is not correlated with other parameters.

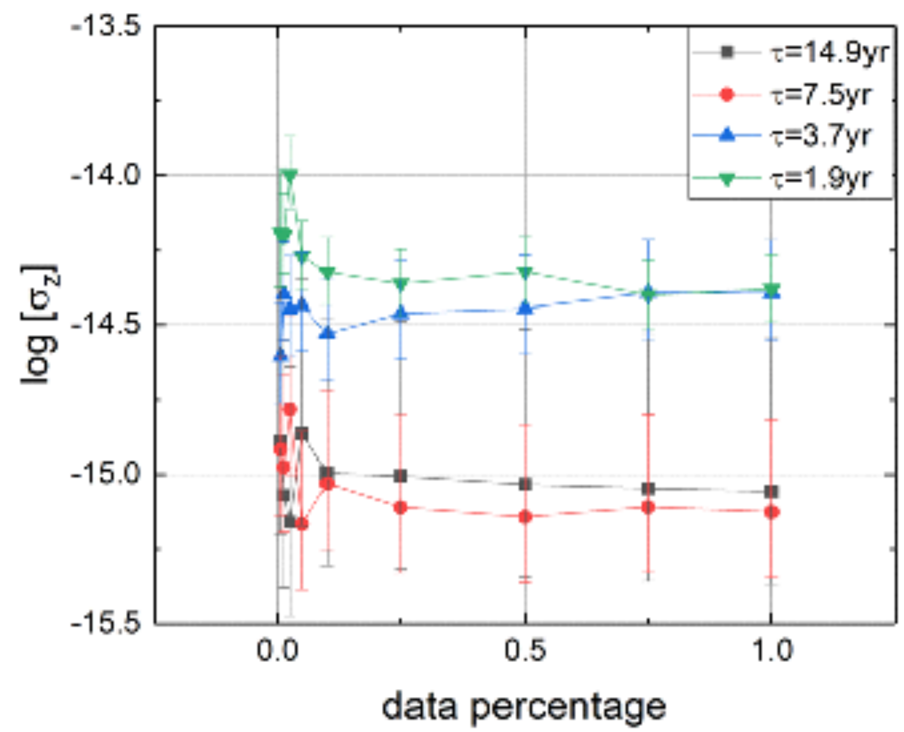
Influence on pulsar clocks

—cadence

Selection of combined .tim file: evenly kick certain percentage data with saving the first and last TOA to form a constant span.

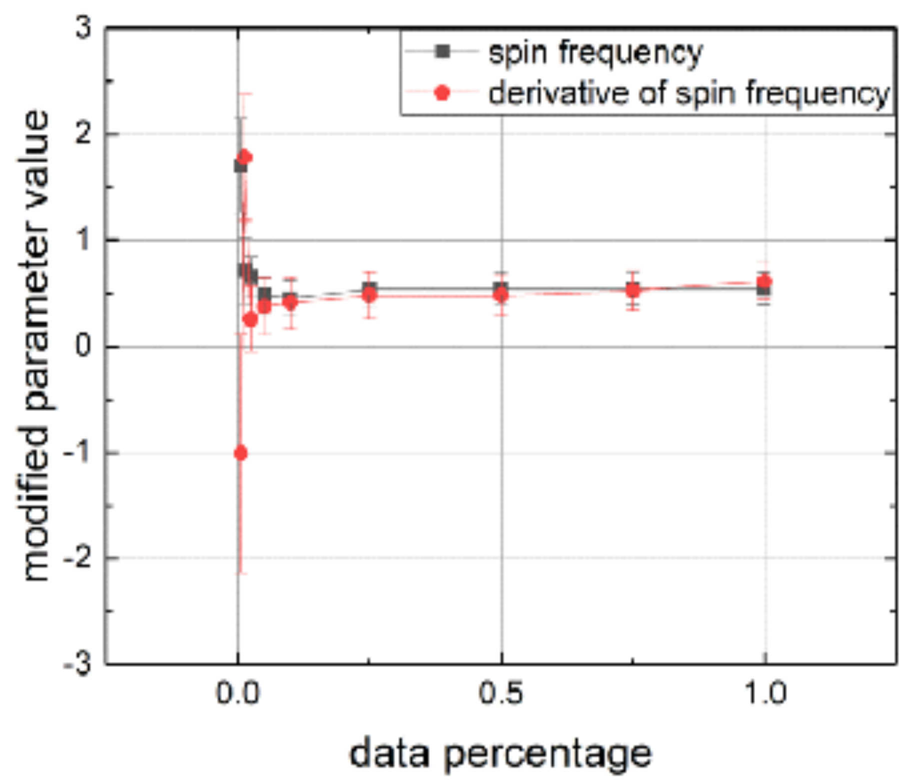
Results for PSR J0437-4715





Pulsar	wrms change	relative change of wrms
J0437-4715	0.007	3.4%
J1713+0747	0.006	2.5%
J1744-1134	0.089	10%
J1909-3744	0.005	2.8%

wrms change when data percentage is over 10%

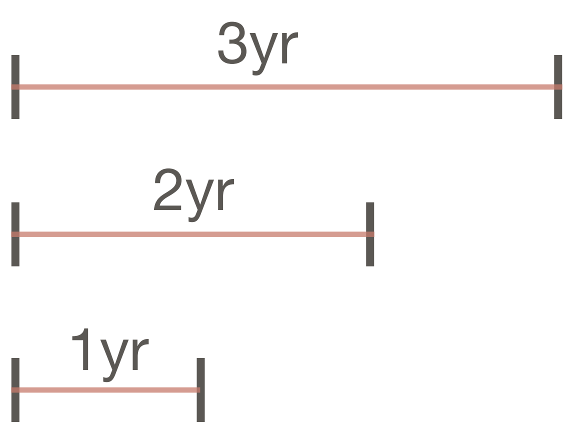


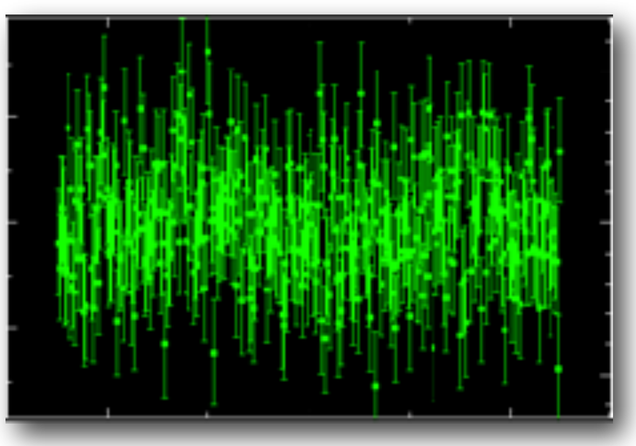
The stability of pulsar clocks is not sensitive to cadence to a considerable extent.

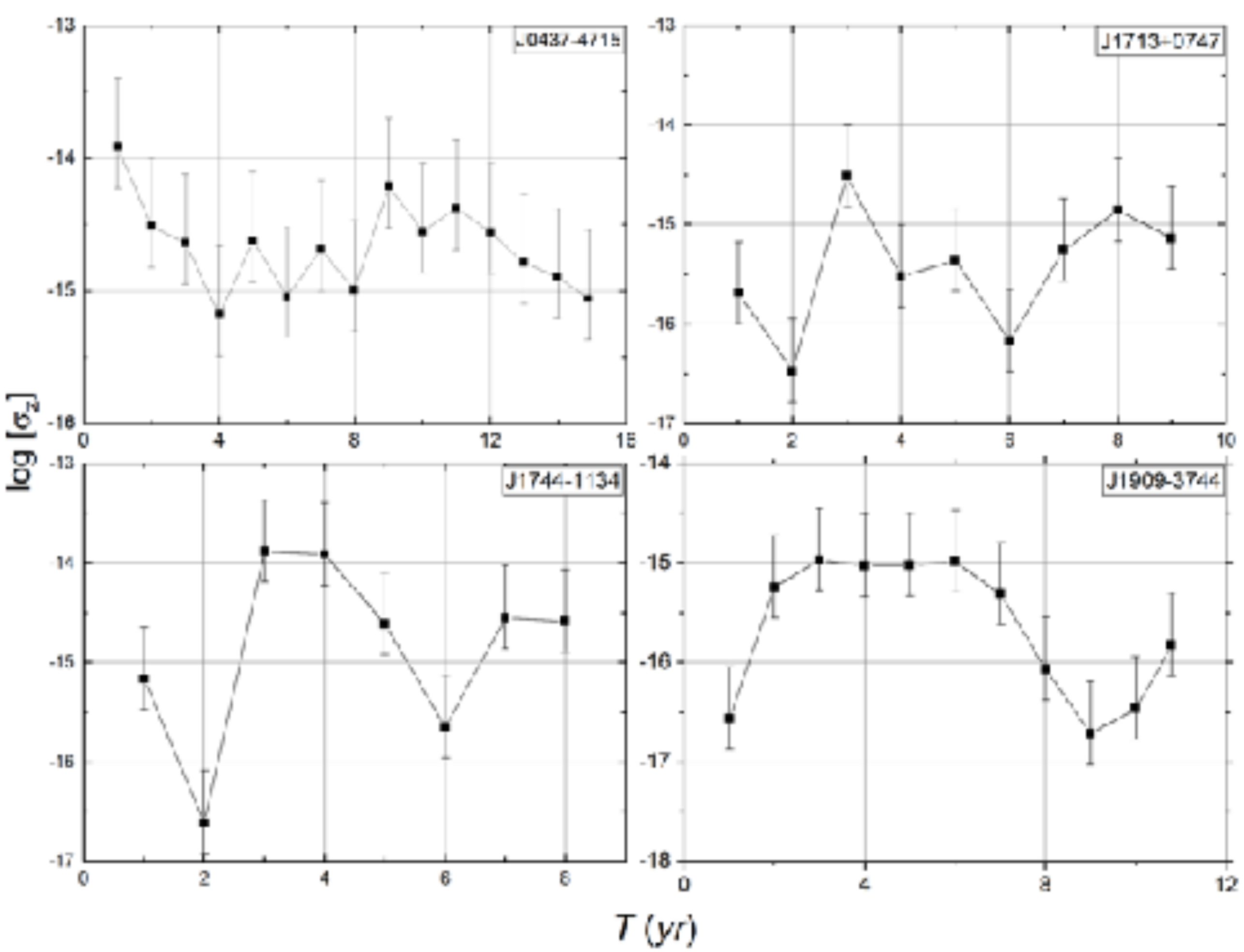
Influence on pulsar clocks

—data span

Selection of combined .tim file: intercept various length data since certain epoch.





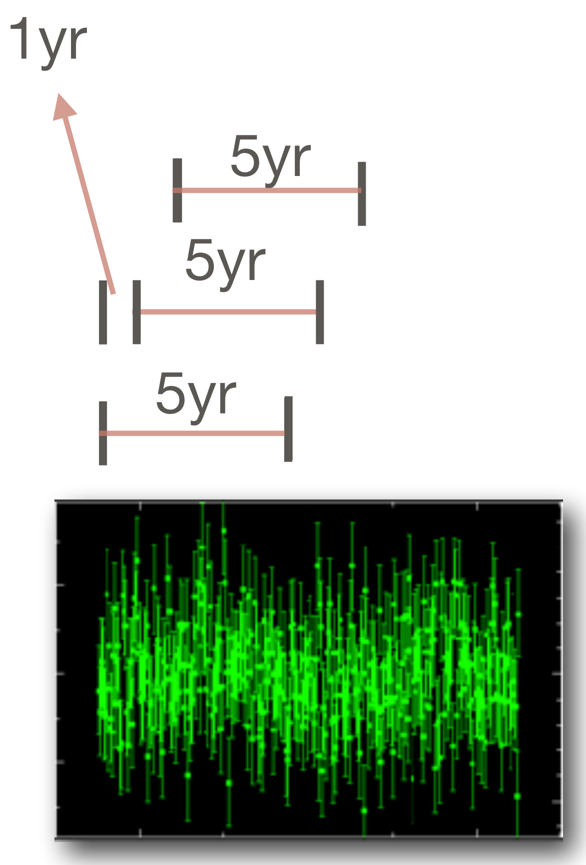


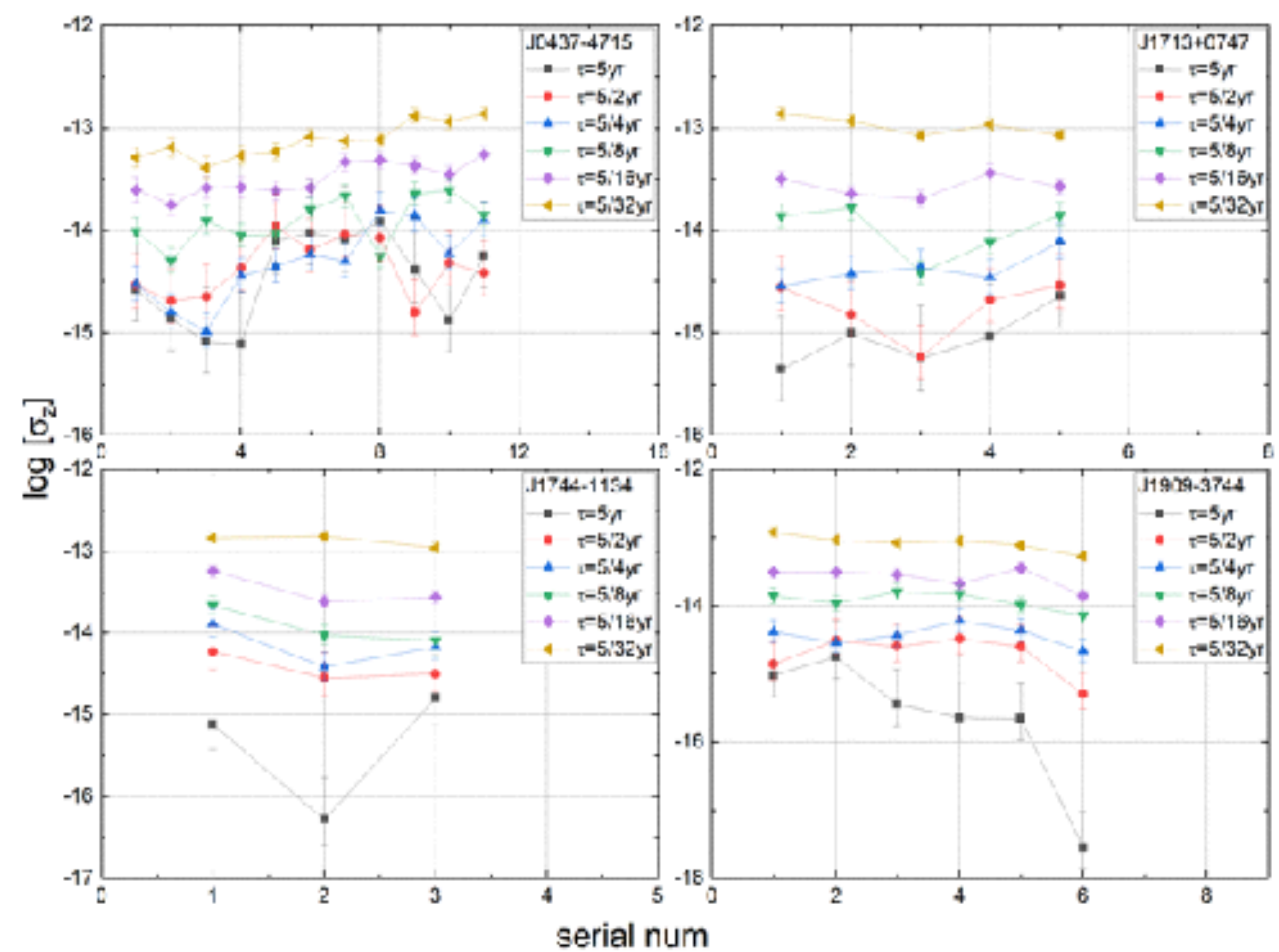
Red noise existence!

Influence on pulsar clocks

—data period

Selection of combined .tim file: intercept certain length data since one epoch.





The properties of pulsar clocks are affected by red noise while concerning different period.

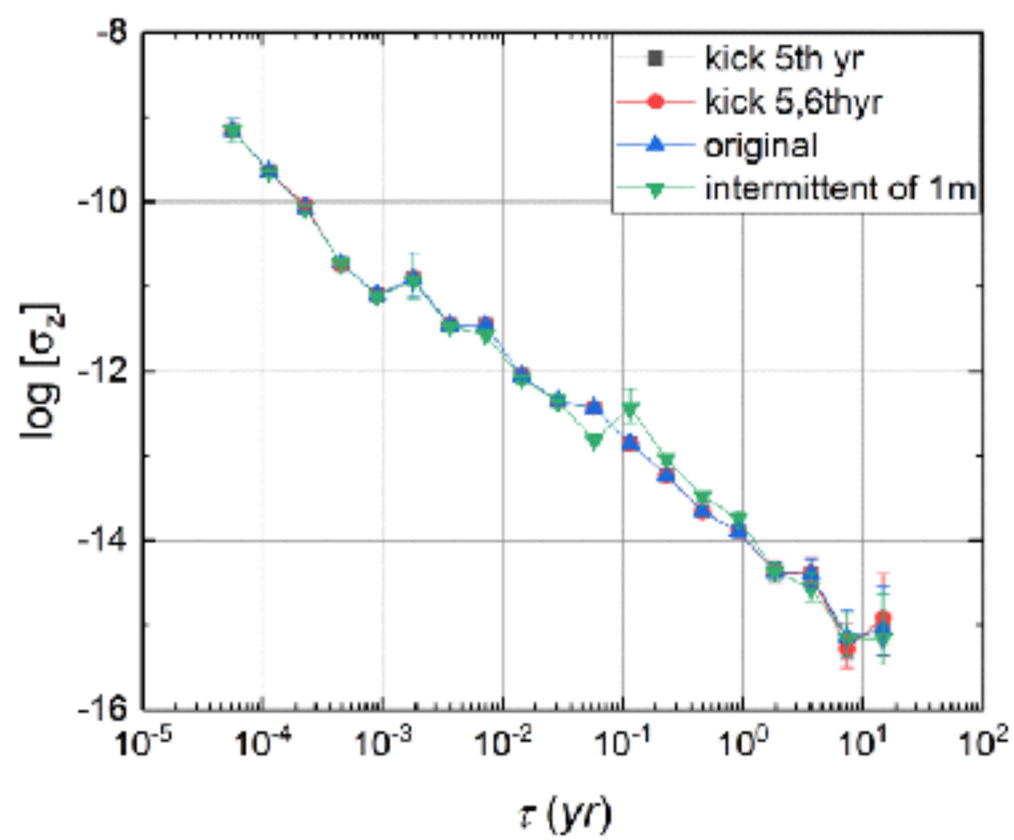
Influence on pulsar clocks
—gaps

Selection of combined .tim file: kick certain data from original combined .tim file.

kick the 5th year

kick 5-6th year

kick and save 1month data in turn

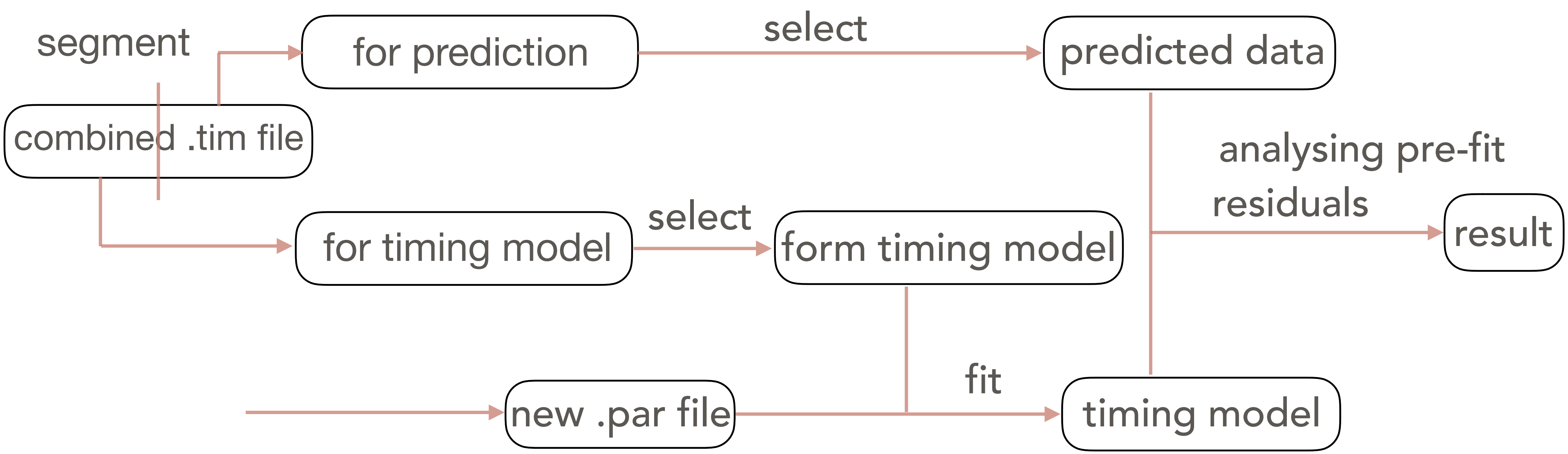


stability of PSR J0437-4715

Influence on prediction

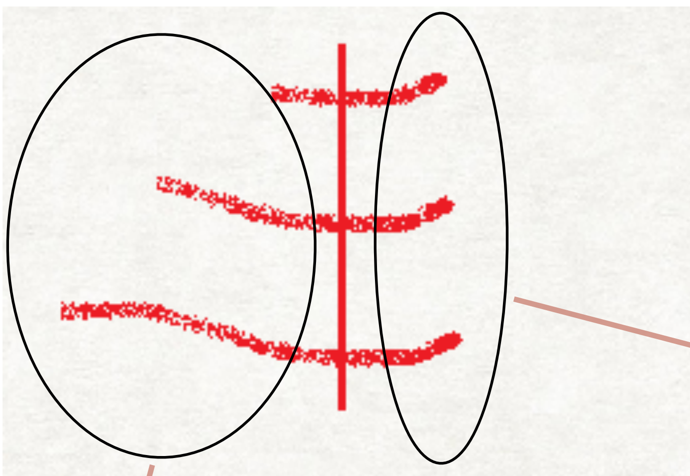
What is prediction?
When TOAs are observed in the past, the best timing model could be fitted then, the difference between latter observed TOAs and TOAs generated from the timing model, i.e. the pre-fit timing residuals can be acquired. This pre-fit timing residuals reflect the prediction of the timing model.

When do we need prediction?
To extract useful signal by pulsar timing observation, e.g. pulsar aided clock.



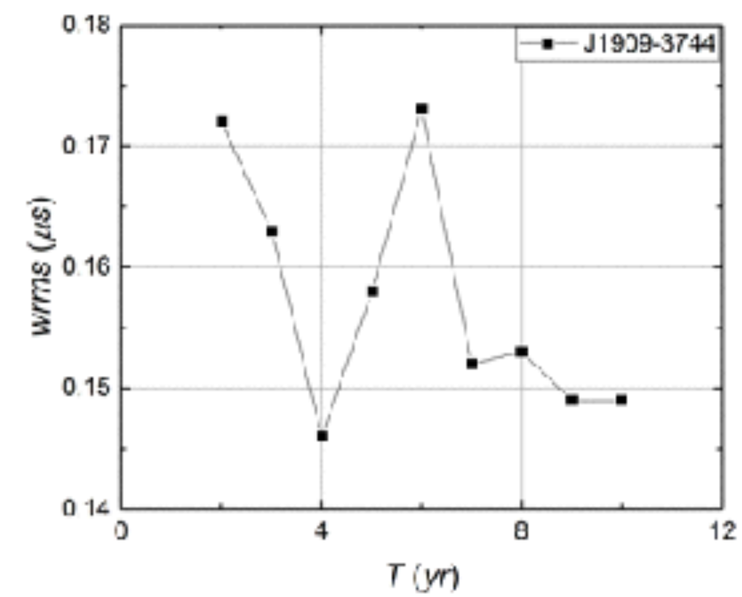
Influence on prediction

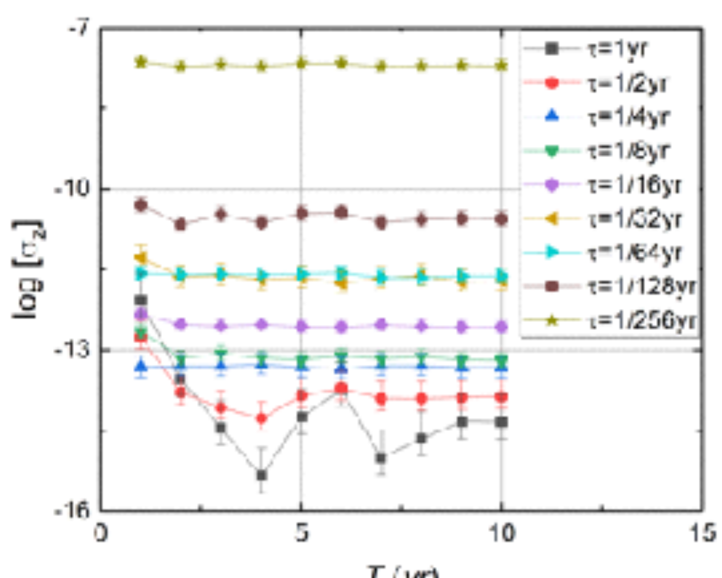
—model by different data span

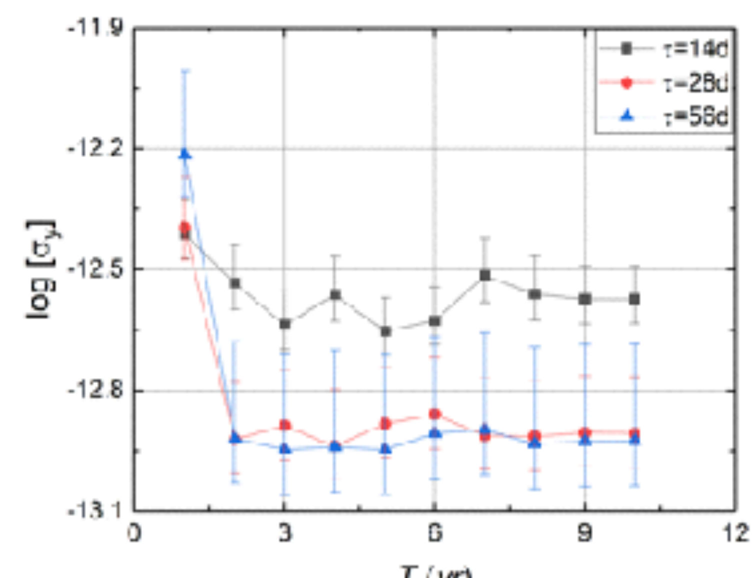


last 1yr as predicted data

Increasing the data length for forming timing model

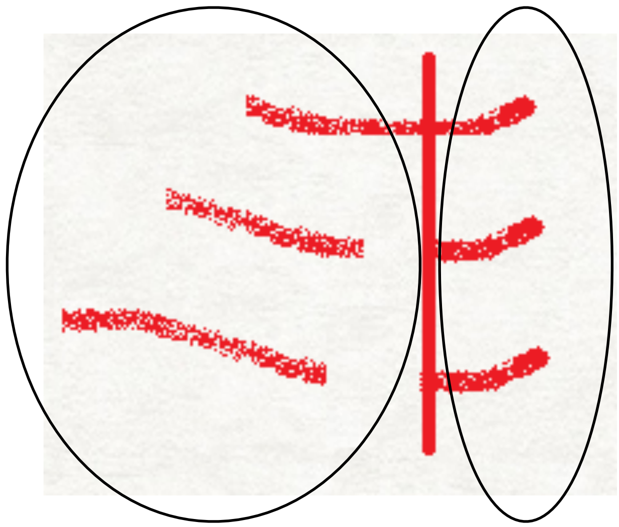






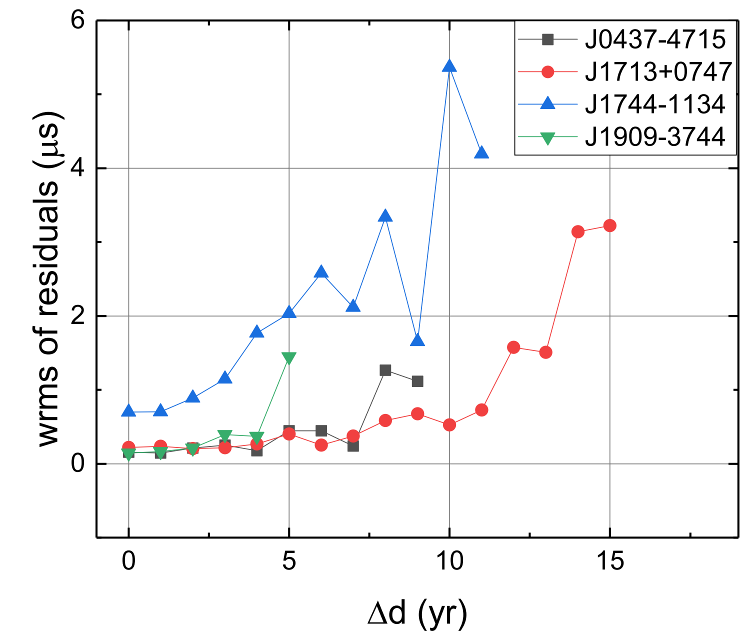
Influence on prediction

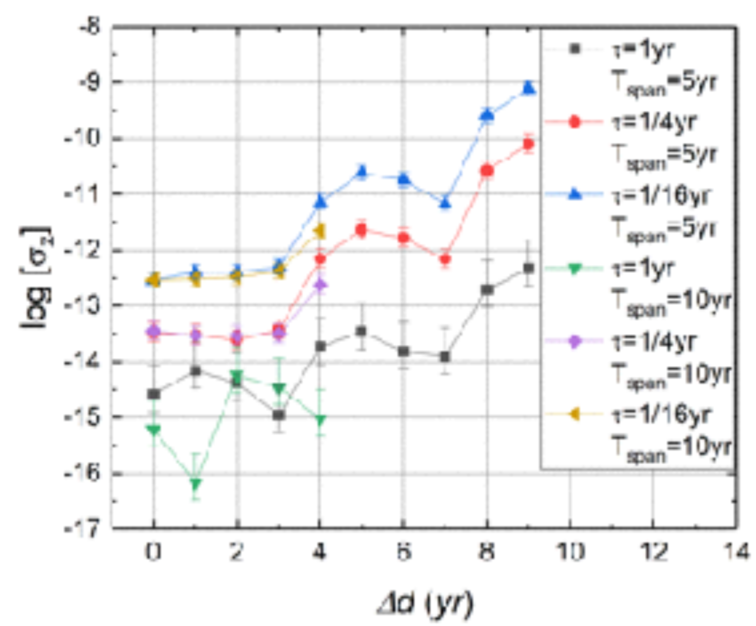
—model by different period

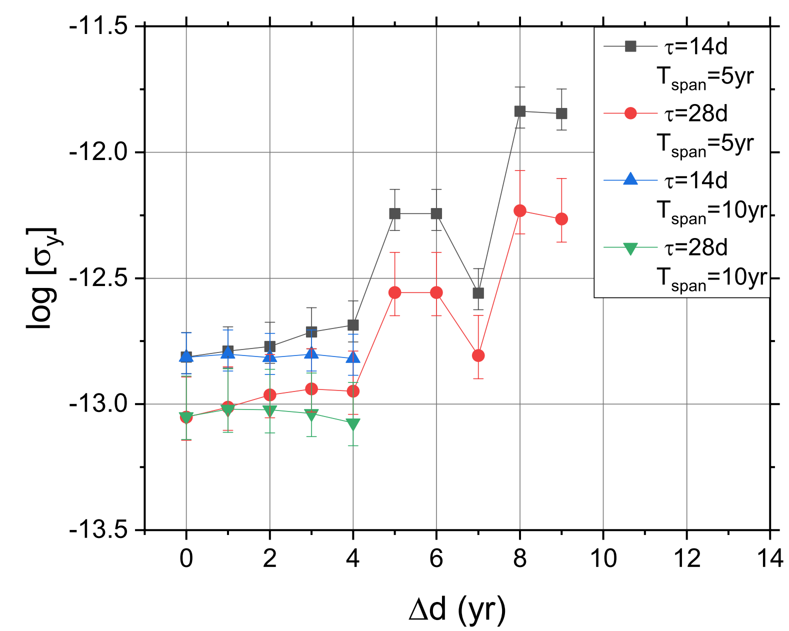


Intercepting different period data for forming timing model

last 1yr as predicted data



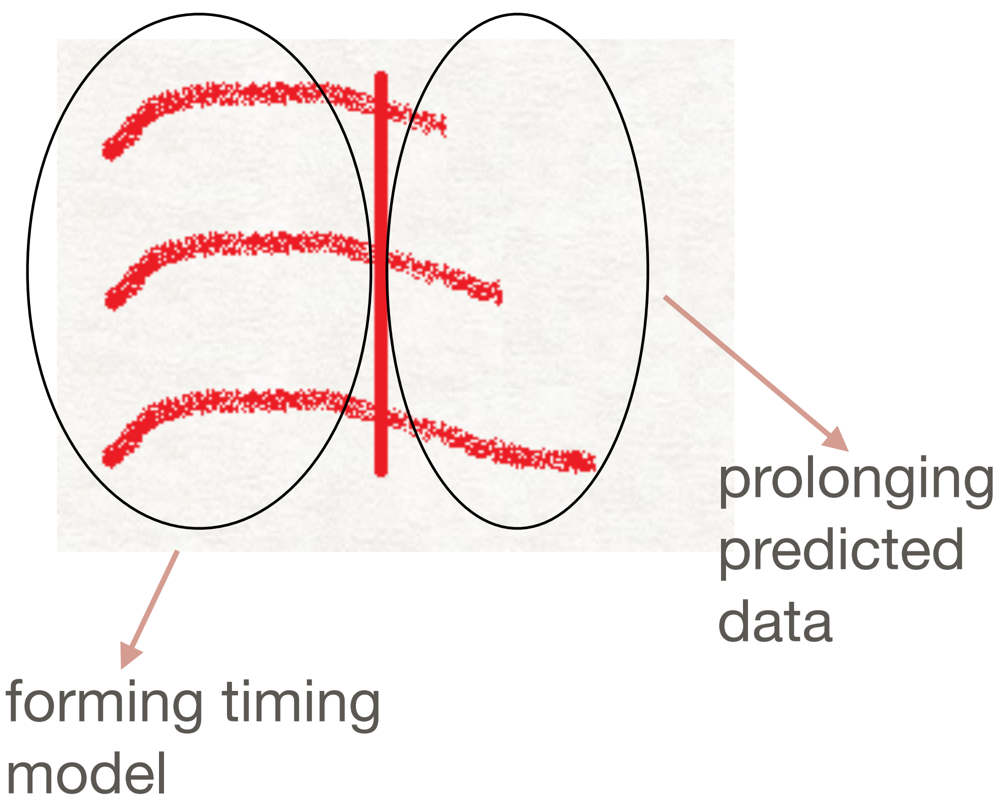


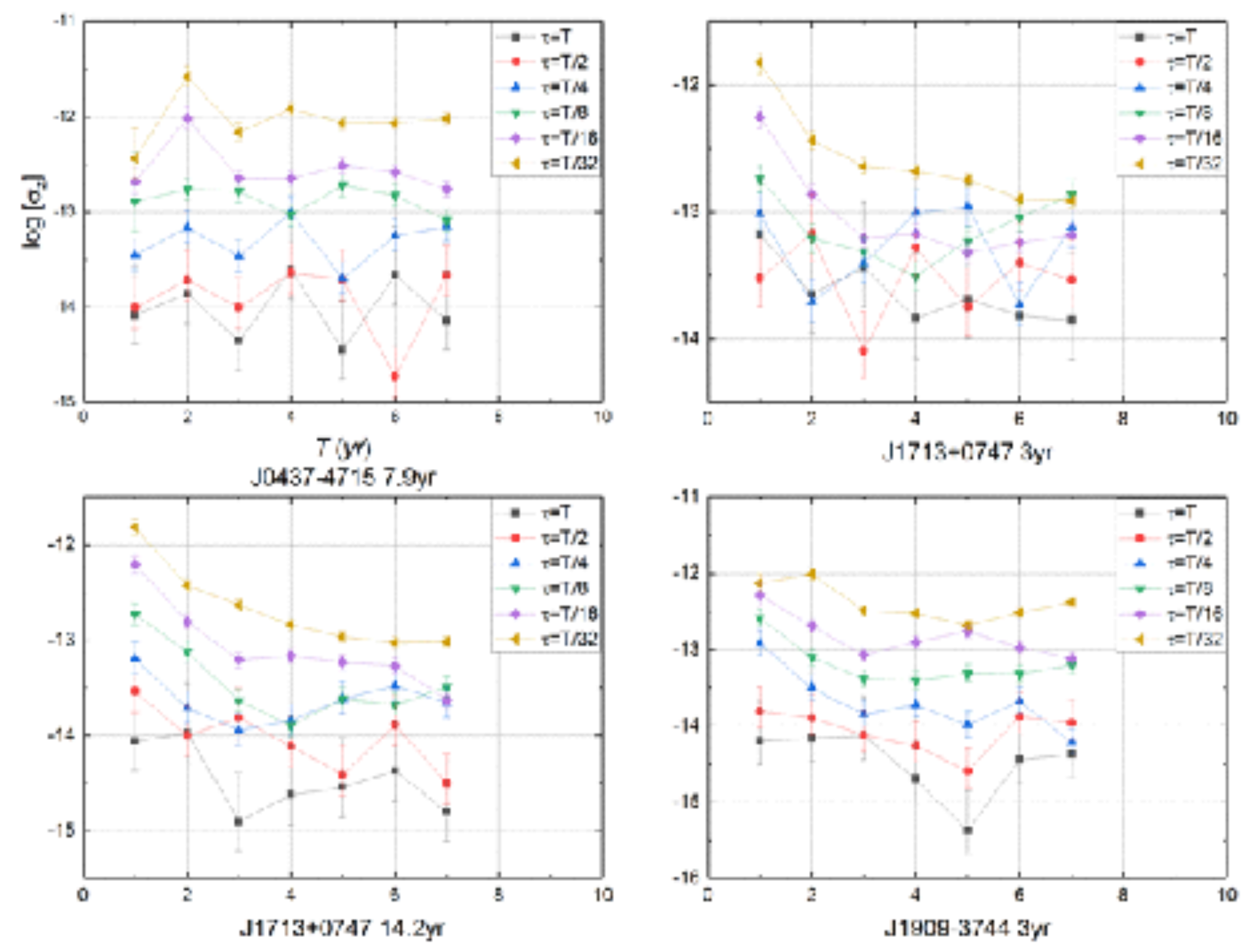


stability for PSR J0437-4715

Influence on prediction

—predict different length data



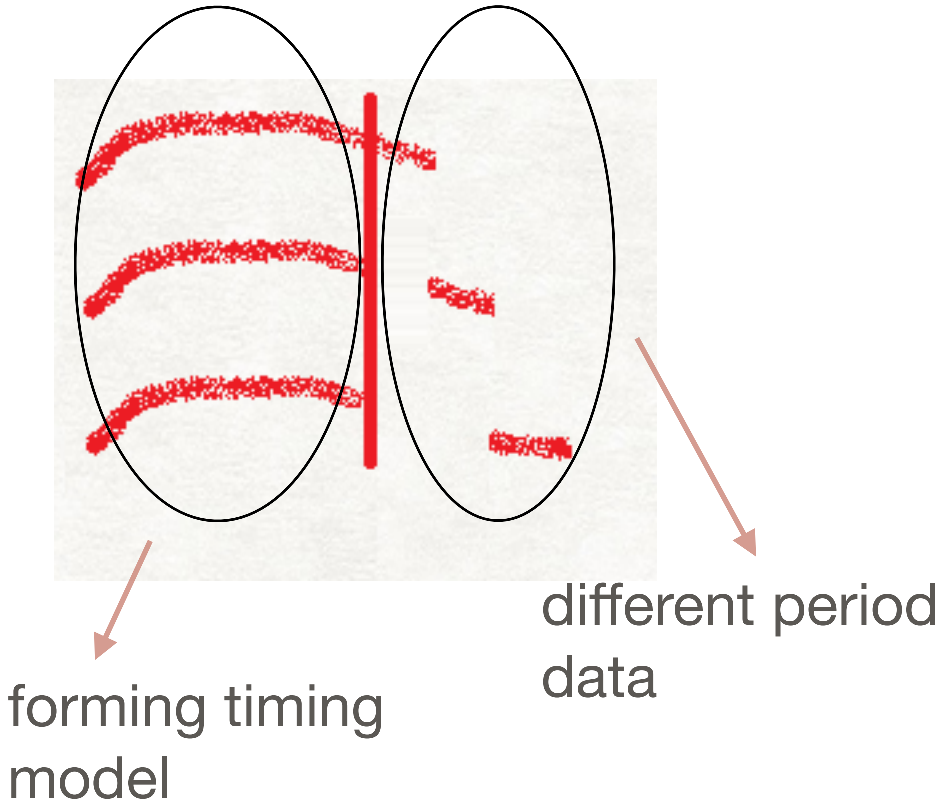


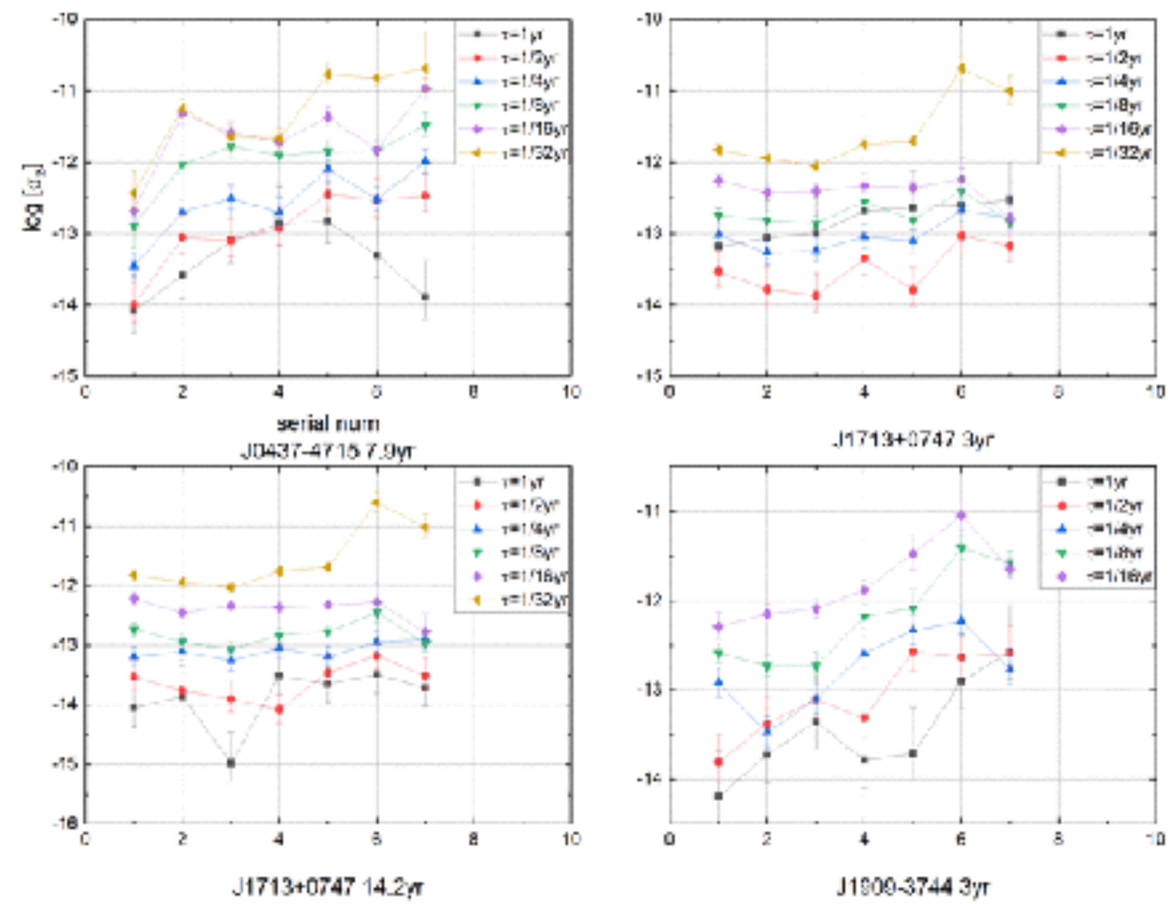
PSR J1713+0747 predicted residuals wrms(μs)

data length(T)	1yr	2yr	3yr	4yr	5yr	6yr	7yr
TOA number	690	1633	2694	5301	8361	11017	17255
form model by 3yr data	0.284	0.546	1.064	1.650	2.534	3.529	4.095
form model by 14.2yr data	0.273	0.308	0.302	0.389	0.466	0.595	0.595

Influence on prediction

—predict different period data



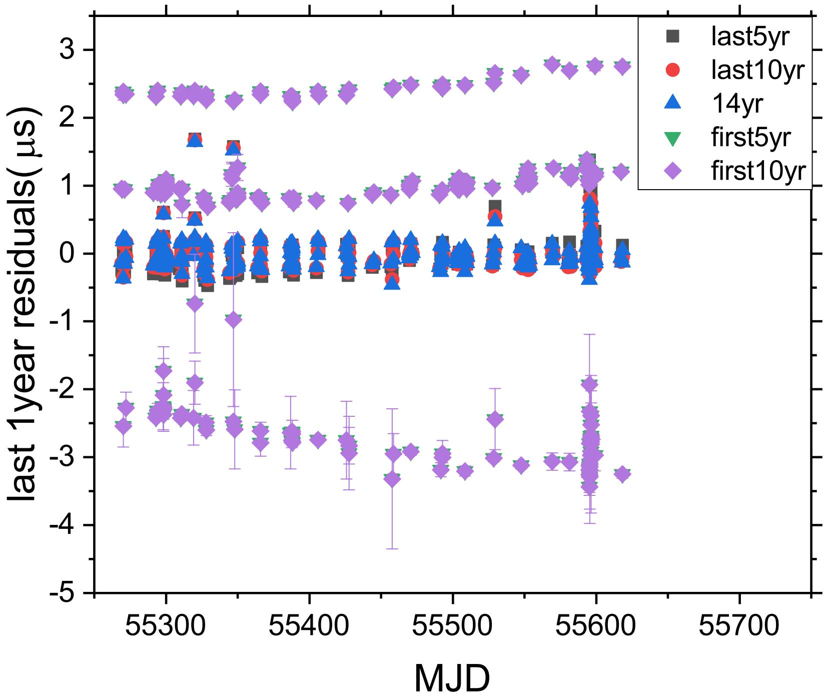


PSR J1713+0747 predicted residuals wrms(μs)

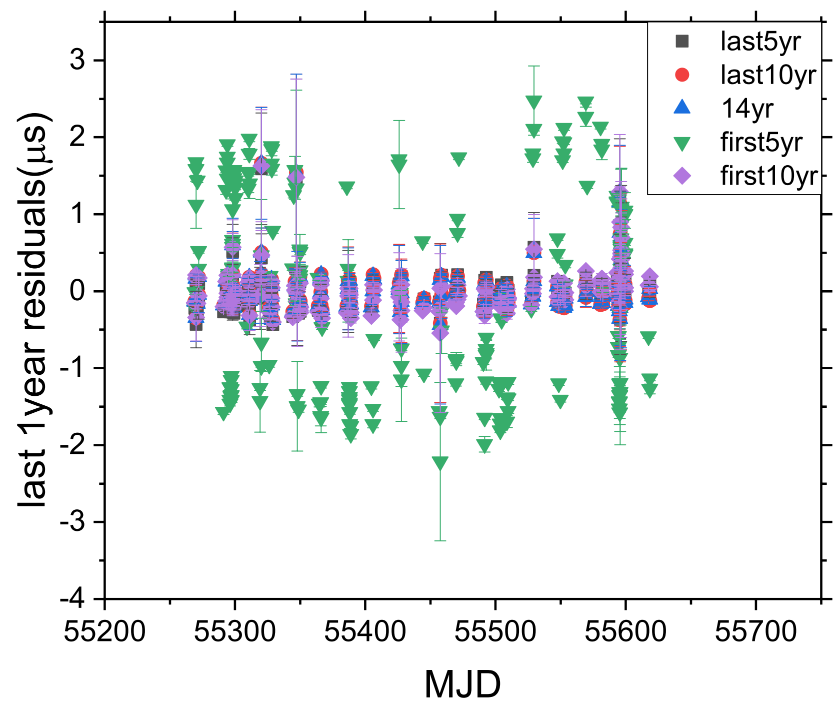
serial number	1	2	3	4	5	6	7
TOA number	690	1633	2694	5301	8361	11017	17255
form model by 3yr data	0.284	0.374	0.355	0.583	0.677	0.627	0.856
form model by 14.2yr data	0.273	0.315	0.238	0.392	0.339	0.467	0.315

Influence on prediction
—DM problem

The prediction of model fitted with and without DM parameters.

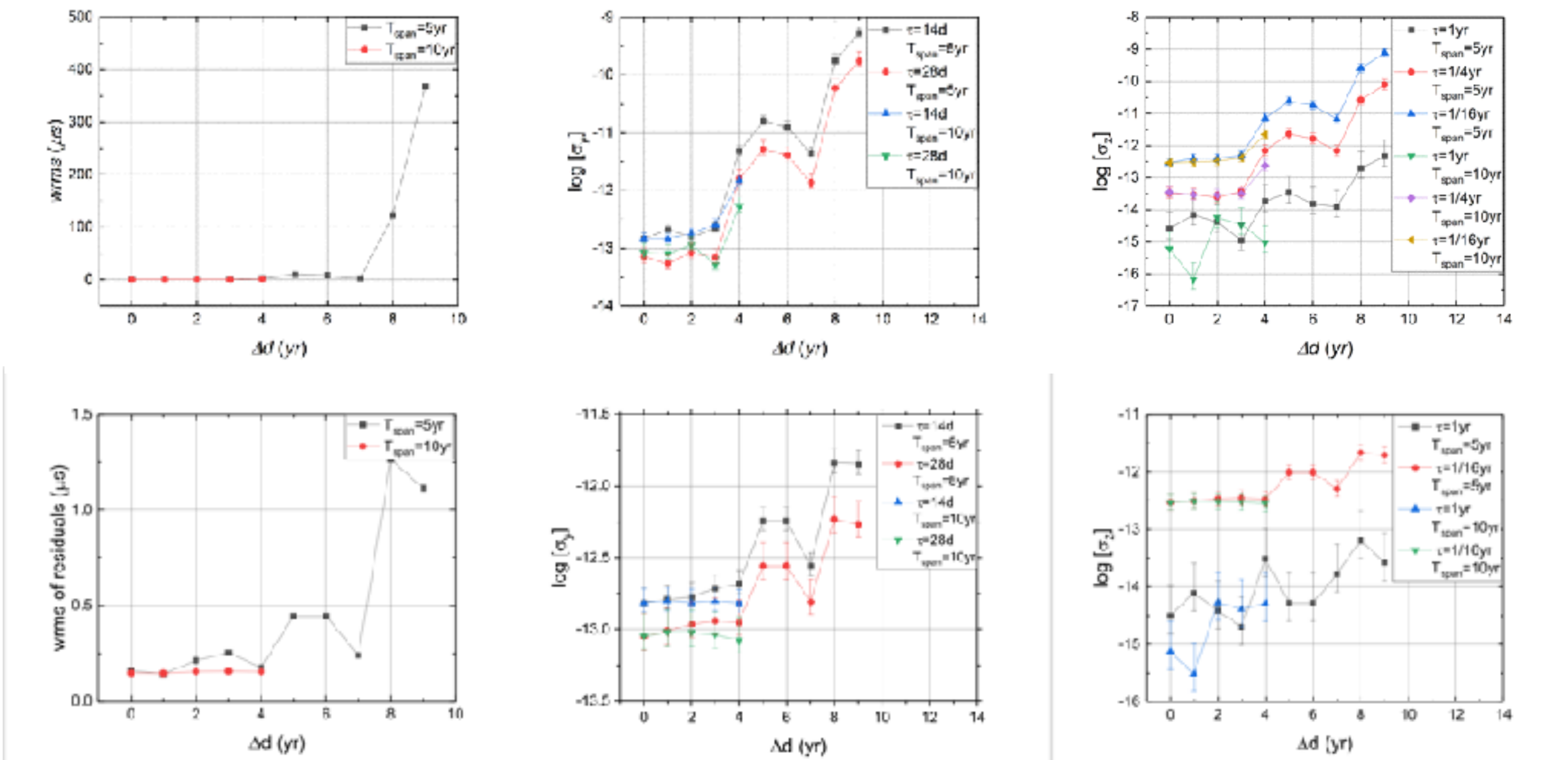


model fitted with DM parameters



model fitted without DM parameters

Comparison of correcting and not correcting DM for PSR J0437-4715

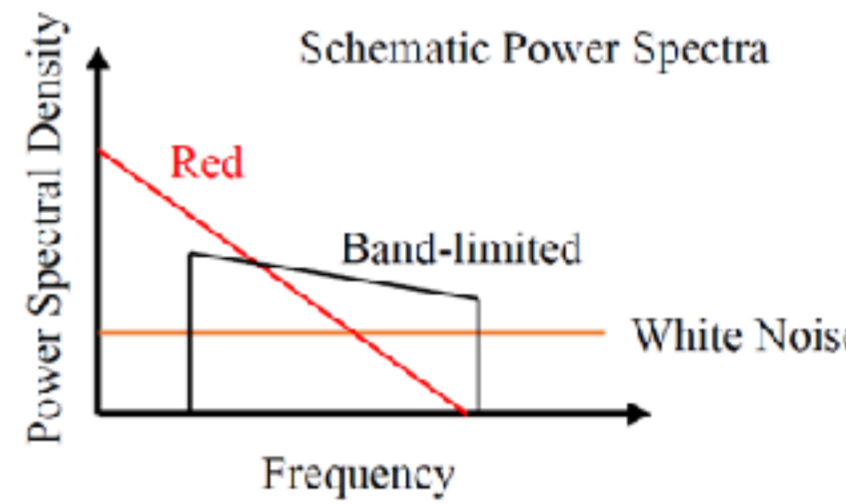


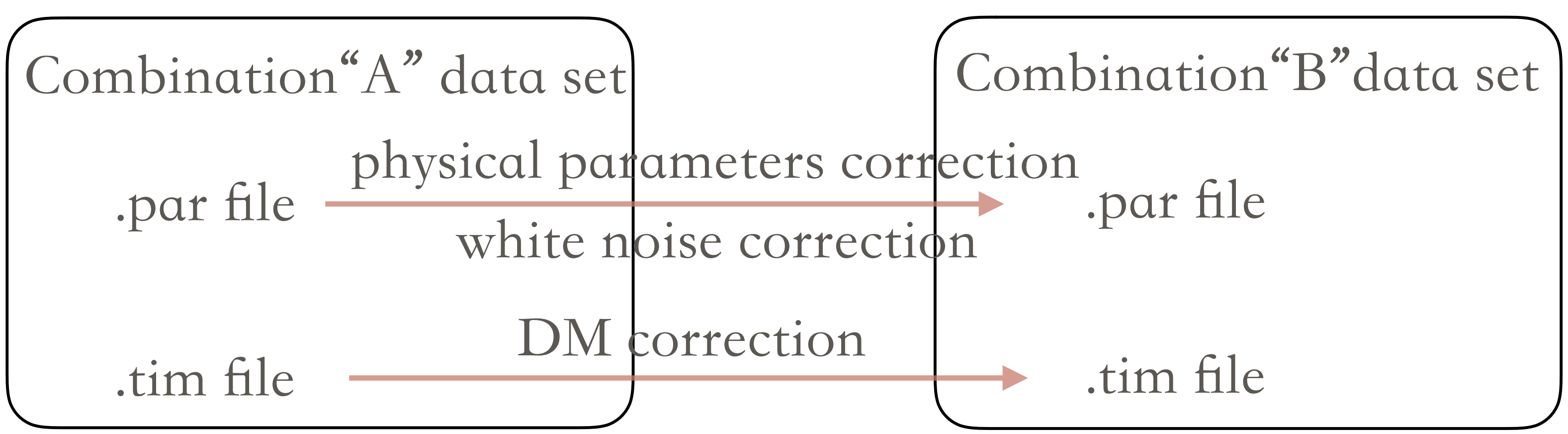
not correct DM

correct DM

3.The effects of noise in pulsar timing

Noise in pulsar timing is complicated, from the view of power spectral density, they can be divided into white noise, red noise, band limited noise. The origin of noise is broad, from pulsars to observing systems. IPTA corrected the noise from combination A data set to combination B data set in the following way:

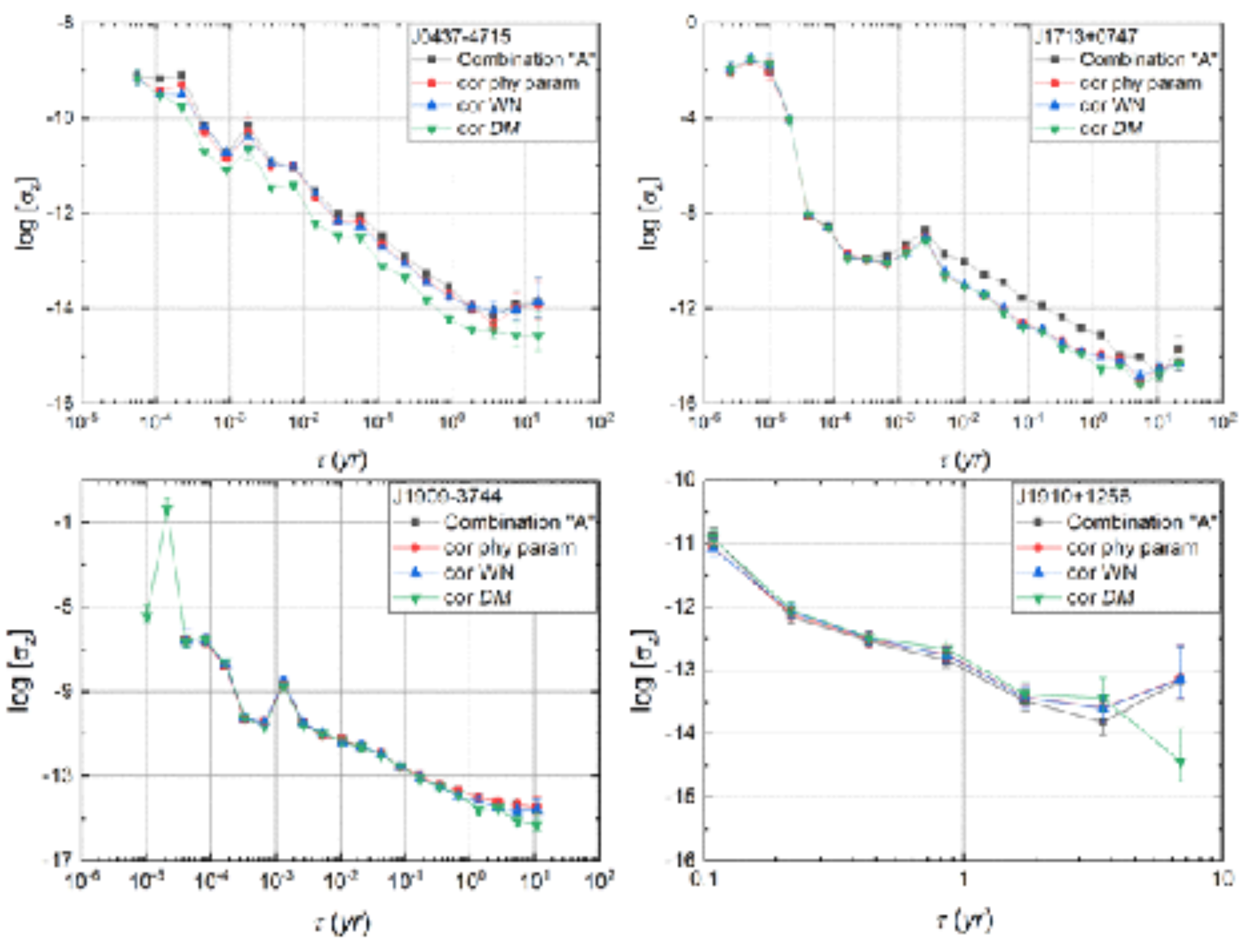




Sergei M. Kopeikin MNRAS 305, 563-590 studied the effects of red noise (spectral indices from 1 to 6) on pulsar parameters and residuals in theory.

The effects of noise on stability

Combination “A” → correct physical parameters → correct white noise → correct DM → Combination “B”



stability change

pulsar	Combin-ation “A”	correct physical parameters	correct white noise	correct DM
J0437-4715	0.703	0.602	0.958	0.202
J1713+0747	2.091	0.445	0.366	0.305
J1909-3744	0.258	0.258	0.238	0.194
J1910+1256	2.784	3.000	3.021	7.356

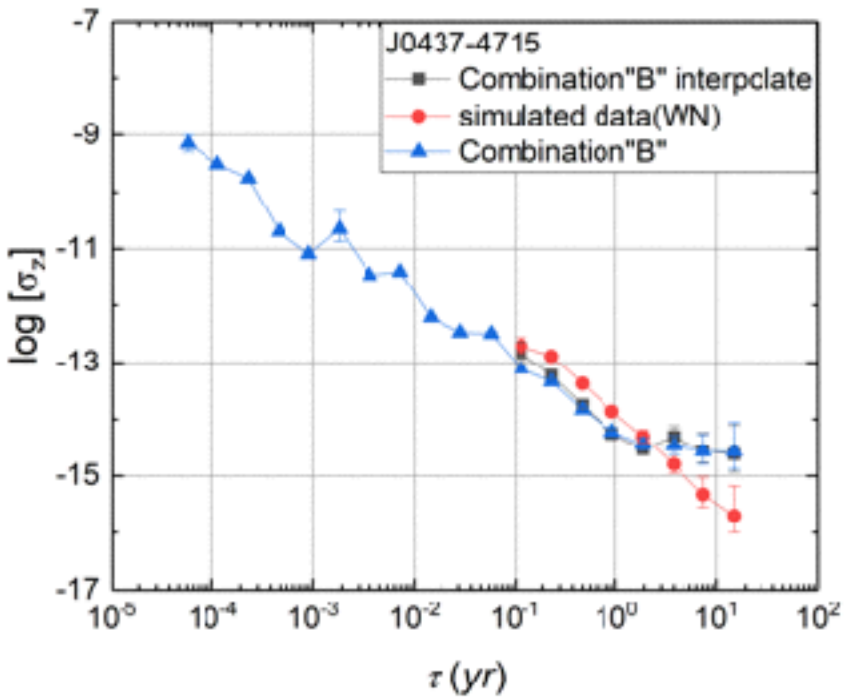
wrms change

Red noise model from IPTA first data release

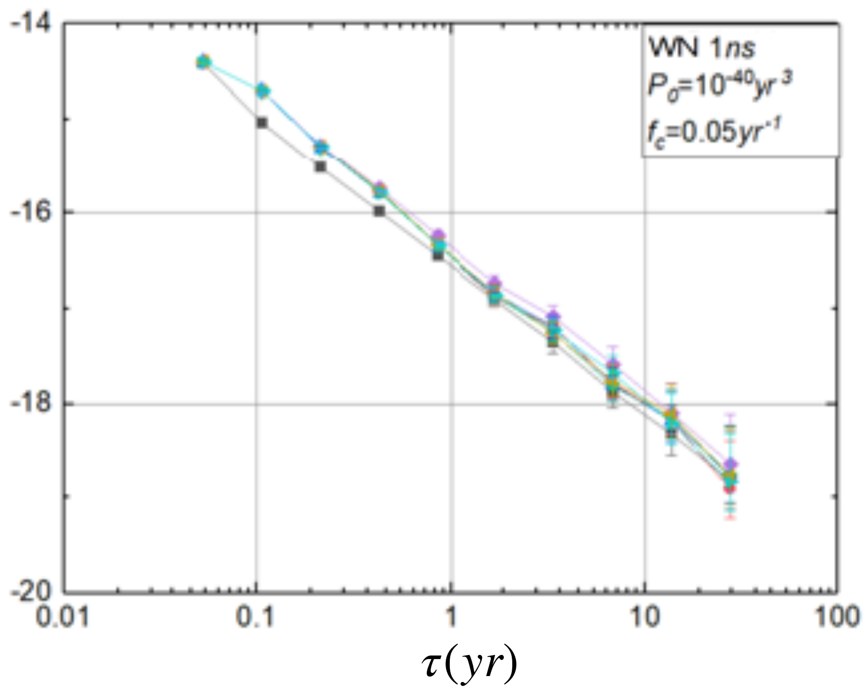
$$P(f) = \frac{P_0}{(1 + f^2/f_c^2)^{q/2}}$$

For PSR J0437-4715 (t2noise.model)

$$p_0 = 1.86509 \times 10^{-40} yr^3 \quad q = 2 \quad f_c = 0.067286 yr^{-1}$$



stability comparison



Simulated red noise and white noise

Summary

Under the noise level and timing precision in analysis, observational cadence do not has obvious effects on pulsar clock itself in general. But red noises limit the long term stability when prolonging the data span or considering different period data for forming timing models.

In prediction, prolonging data span for forming timing model do not increase prediction stability as expected, but that does increase the precision of timing model. Data period for forming timing model play an important role, early data make a bad prediction and need DM correction. Increasing the data length from 1yr to 7yr for prediction do not decrease the longterm stability.

In the IPTA first data release, DM correction and physical timing model parameters affect clock stability most.

If the precision of pulsar timing increased and noise are eliminated/constrained, the effects of observational strategies would not increase.

Thanks for listening