The construction of pulsar time scale and its possible application

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Outline

- Introduction to time-scales
- Pulsar timing and pulsar time-scale
- Constructing ensemble pulsar time-scale (EPT)
- The applications of EPT
- Summary

Time is important

Time-scales

Proper time (local quantity):The time recorded by the standard clock carried by an observer in his own would line.

e.g. Atomic time: Maintained by atomic clocks;

Pulsar time: Described by local stable pulsars ignoring their self-gravity.

Properties of proper time:

- Independent on the choices of coordinate system
- A local quantity and can be measured directly
- Unable to compared with each other directly and must be recurred to coordinate time as a medium.

Coordinate time (global quantity): The time derived from proper time

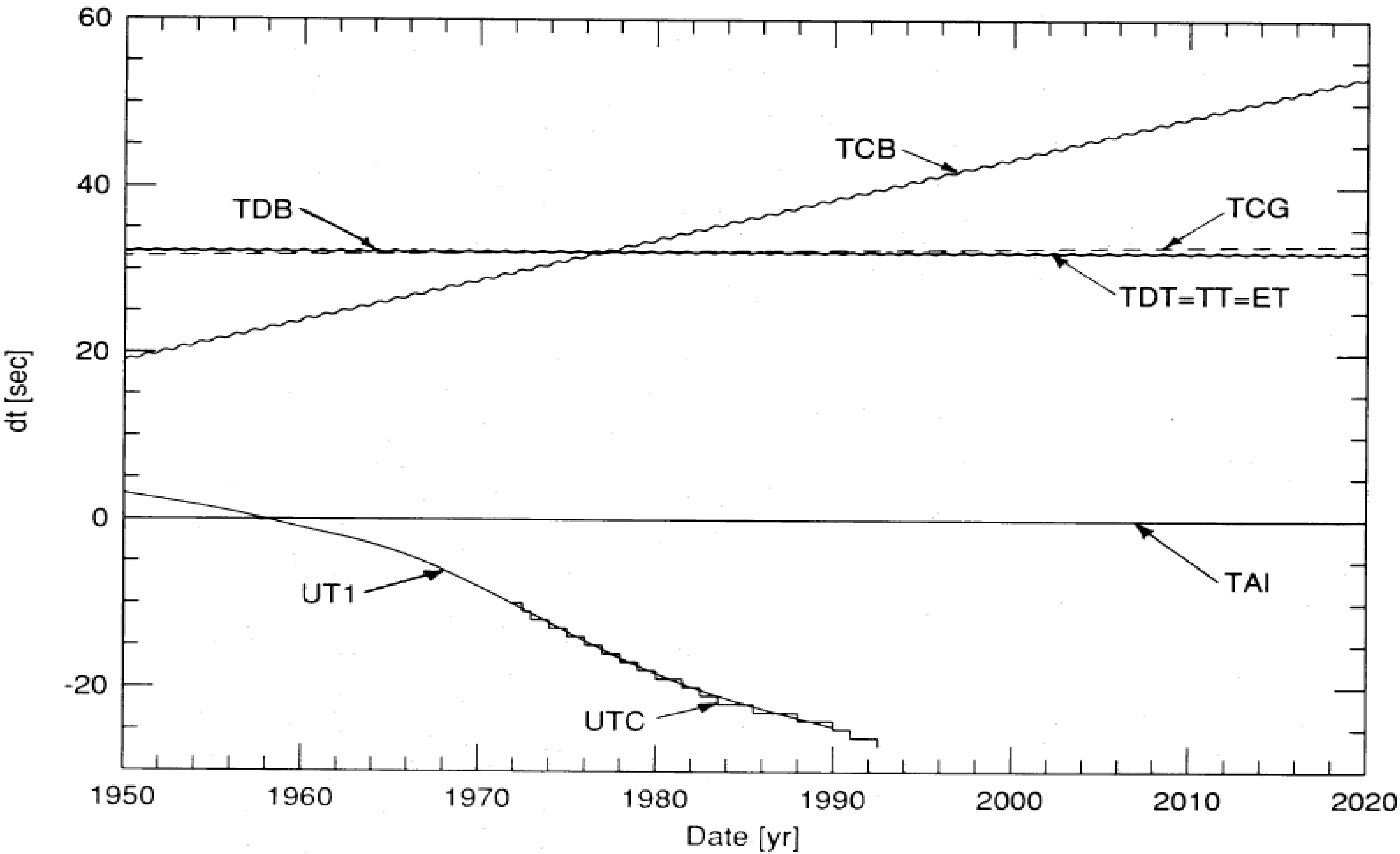
TAI: International Atomic Time (国际原子时)

TT: Terrestrial Time (地球时)

TCG: Geocentric coordinate time (地心坐标时)

TCB: Barycentric coordinate time (太阳系质心坐标时)

Different time scales



TAI、UTC、TA(k)与UTC(k)

1. TAI

- 76 time laboratories
- 500+ atomic clocks
- 16 primary standard clocks

2. UTC

- UT goes slower and slower
- The difference between UT and TAI

Is bigger an bigger

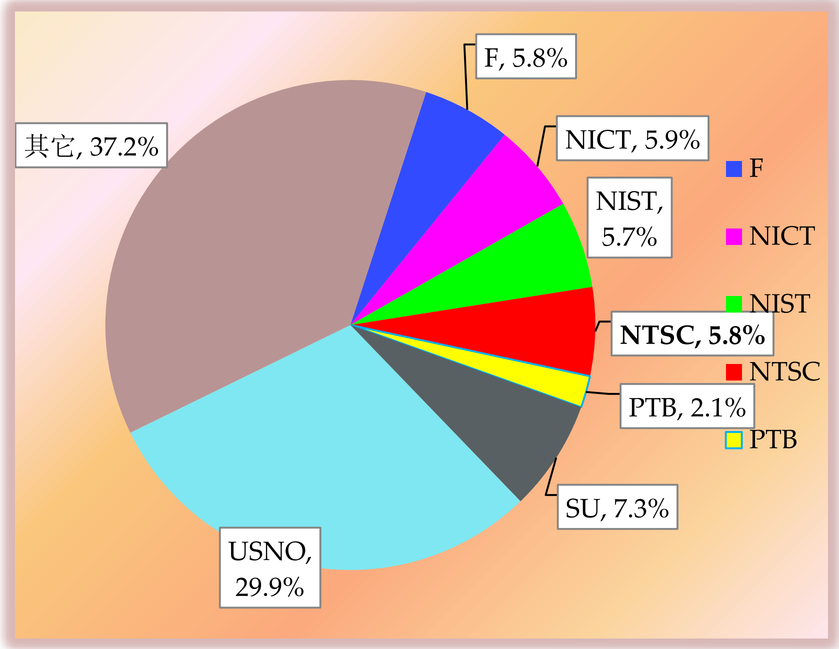
- January 1972，UTC was defined

3. TA(k)与UTC(k)

- 15 labs have their own TA(k)
- UTC(k) is the standard time of a

country kept by her time laboratory

- In China, UTC(NTSC)



Weights of the time laboratories

NTSC：29 5071A Cs + 9 HM(USA) + 1 HM (SHAO)

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Pulsar timing model

Phase model:

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

Timing model:

$$t_p = t_{obs} - t_0 + \Delta_C + \frac{DM}{\nu^2} + \Delta_{R\odot}(\alpha, \delta, \mu_\alpha, \mu_\beta, \pi) + \Delta_{E\odot} + \Delta_{S\odot}$$

$$+\Delta_R(x, e, P_b, T_0, \omega) + \Delta_E(\gamma) + \Delta_S(r, s) + \Delta_{AB}$$

Residuals: intrinsic timing noise,GWs,DM effects, solar system ephemeris errors

Noises in the time comparison of TT and PT:

$$\mathrm{TT(13)} - \mathrm{PT} = \Delta t_{\mathrm{red}} + \Delta t_{\mathrm{white}} + \Delta t_{\mathrm{gw}} + \Delta t_{\mathrm{eph}} - \delta t_c$$

Application of pulsar timing

- Pulsar time scale--------------Time
- Pulsar-based navigation----Space
- Detection of GWs------------Physics
- Measurement of Planets---Astronomy

Pulsar time-scale

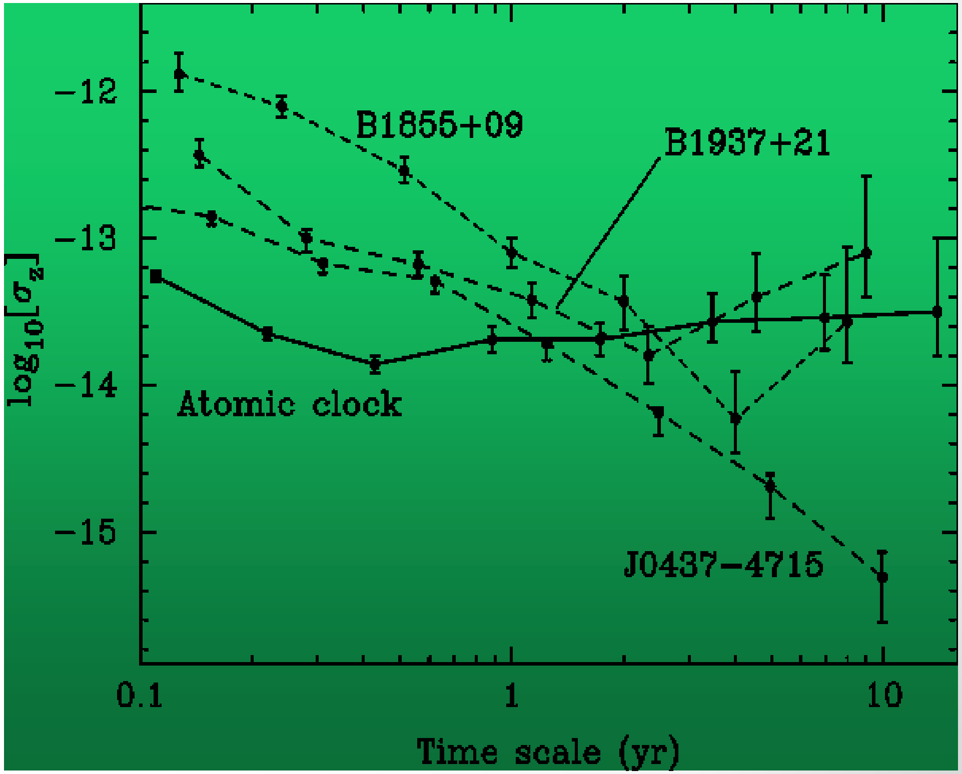
- Spin parameters
- Astrometric parameters

→ **Predict the TOAs at SSB**

$$\varphi_{ssb} = \varphi_0 + f \cdot (t - t_0) + \frac{1}{2} \dot{f} \cdot (t - t_0)^2 + \cdots + \Delta_B$$

Properties of PT:

- Independent of AT but relying on AT for the measurement of TOAs
- High stability at long-term time scale (more than one year)
- Very wide frequency band(radio, visible, X-rays, Gamma rays)
- Long-term timing data needed
- Pulsars are natual, safe and long lived



The stability of pulsar time-scale

Stability of atomic time-scale: Allan variance

$$\sigma_y^2 = \left\langle \frac{1}{2}(\bar{y}_n - \bar{y}_{n-1})^2 \right\rangle$$

$\bar{y}_n = (x_n - x_{n-1})/\tau$ is average fractional frequency offset during the *n*th measurement interval of length tau. x is the instantaneous time offset.

$$D_2(t,t) = \frac{x(t+t) - 2x(t) + x(t-t)}{\sqrt{2}t}$$

Stability of pulsar time-scale:

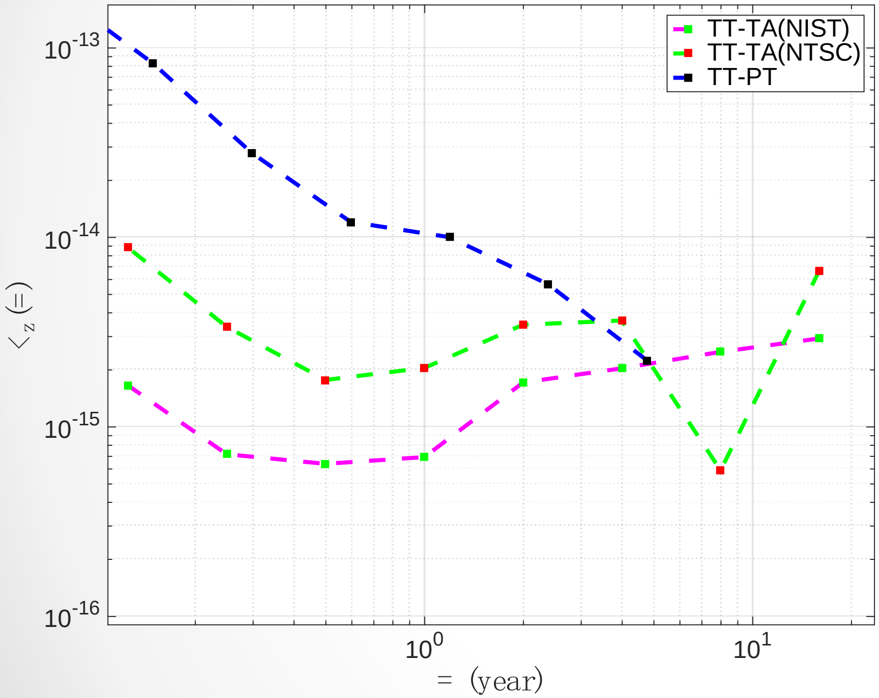
$$D_3(t,t) = \frac{x(t+t/2) - 3x(t+t/6) + 3x(t-t/6) - x(t-t/2)}{2\sqrt{5}t}$$

for the consideration of frequency drifts. Since pulsar timing observations are made at irregular intervals, one should fit the cubic function

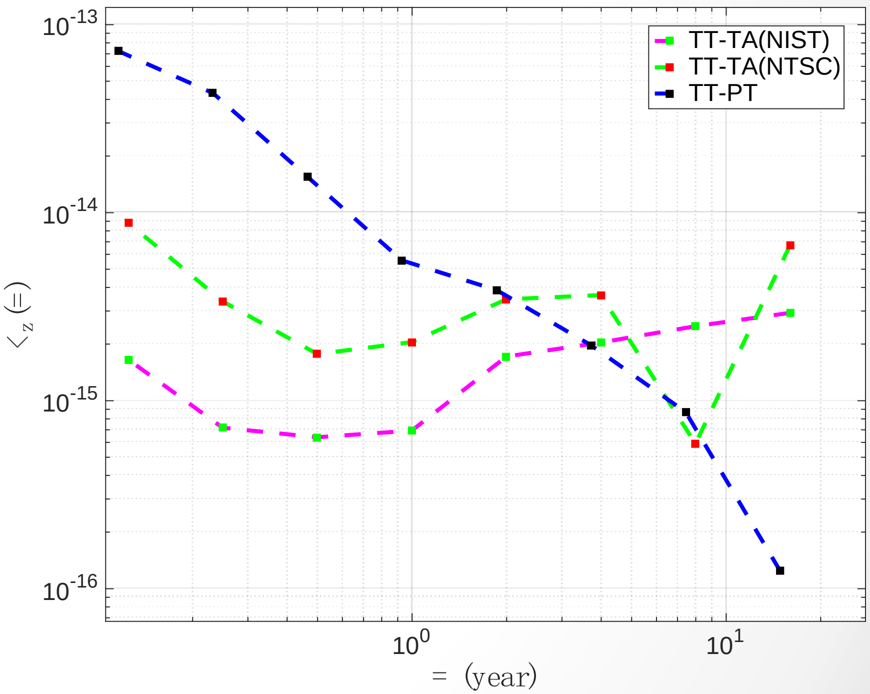
$$s_z(t) = \frac{t^2}{2\sqrt{5}} \left\langle c_3^2 \right\rangle^{1/2}$$

Stability comparison between AT and PT

PSR J0437-4715



PPTA data



IPTA data

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The methods for EPT

We study two methods for constructing ensemble pulsar time-scale (EPT):

(1) The classical weighted average(CWA)

A. $$w_i = \sigma_{rms(i)}^{-2} \Big/ \sum_i \sigma_{rms(i)}^{-2}$$

B. $$w_i = \sigma_{z(i)}^{-2}(T) \Big/ \sum_i \sigma_{z(i)}^{-2}(T)$$

The methods for EPT

(2) The Winner Filter(WF)

$$\hat{\mathbf{s}}_{\mathbf{ens}} = \frac{2}{M(M-1)} \sum_{m=1}^{\frac{M(M-1)}{2}} {}_m\mathbf{Q}_{ss} \cdot \sum_{i=1}^{M} {}^i w \, {}^i\mathbf{Q}_{rr}^{-1} \cdot {}^i\boldsymbol{r}$$

$$\mathrm{cov}(r, r) = \langle r_i, r_j \rangle = \langle s_i, s_j \rangle + \langle \varepsilon_i, \varepsilon_j \rangle,$$

$$\mathrm{cov}(s, s) = \langle s_i, s_j \rangle,$$

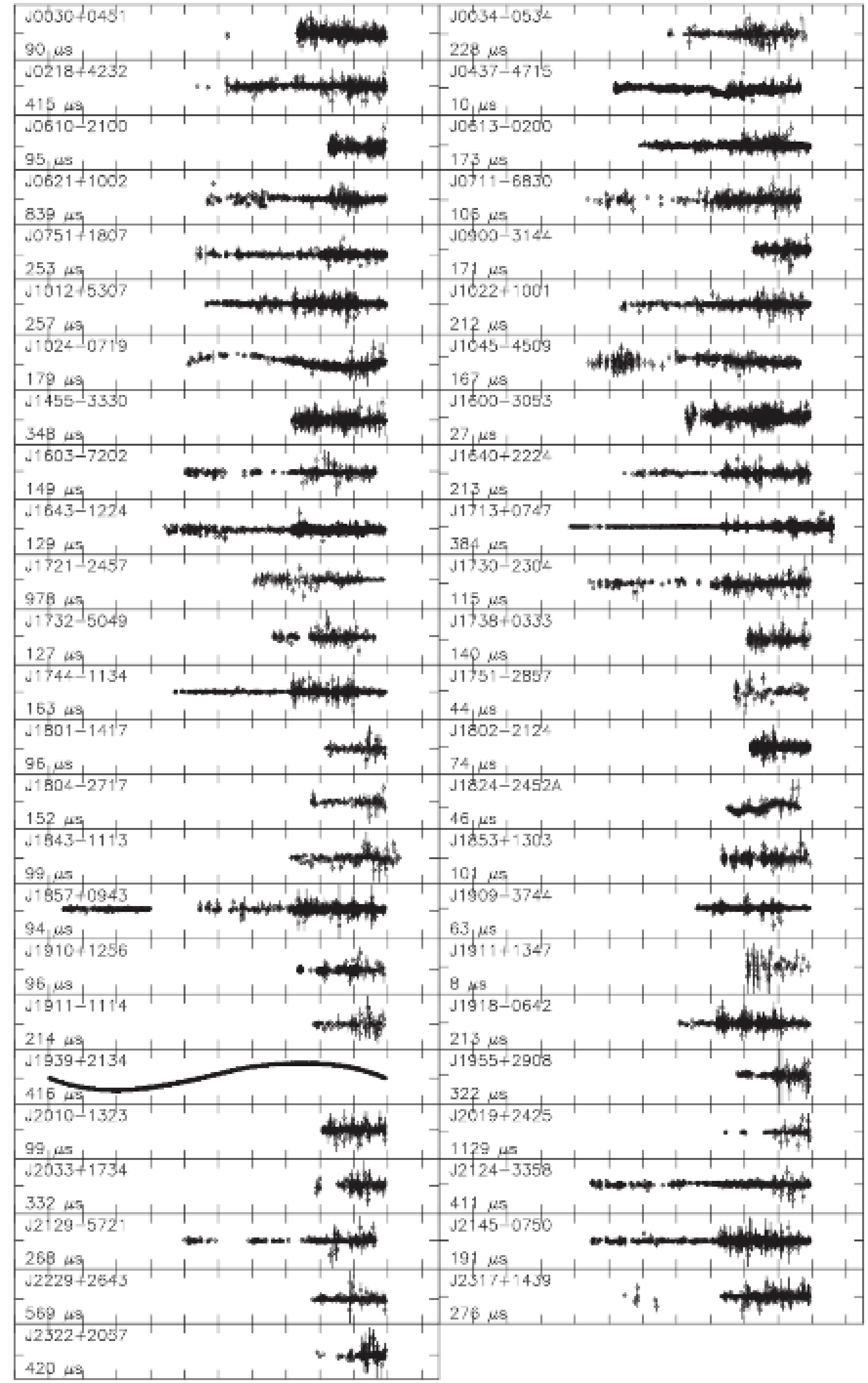
$$\mathrm{cov}(s, r) = \langle s_i, r_j \rangle = \langle r_i, s_j \rangle = \langle s_i, s_j \rangle,$$

$$\mathrm{cov}(\varepsilon, \varepsilon) = \langle \varepsilon_i, \varepsilon_j \rangle,$$

$$\left\langle a_i, a_j \right\rangle = q(t) = q(t_i - t_j) = q_{i-j}$$

Observable data (IPTA)

49MSPs
14 (Solitary)
35 (binary)
26 (more than a decade of data)

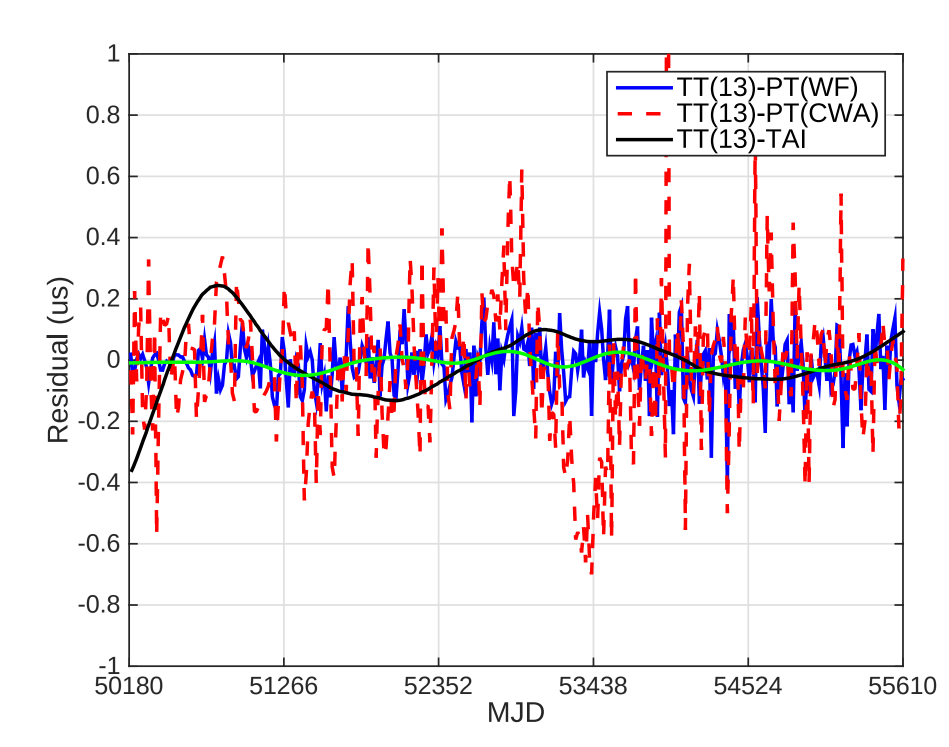


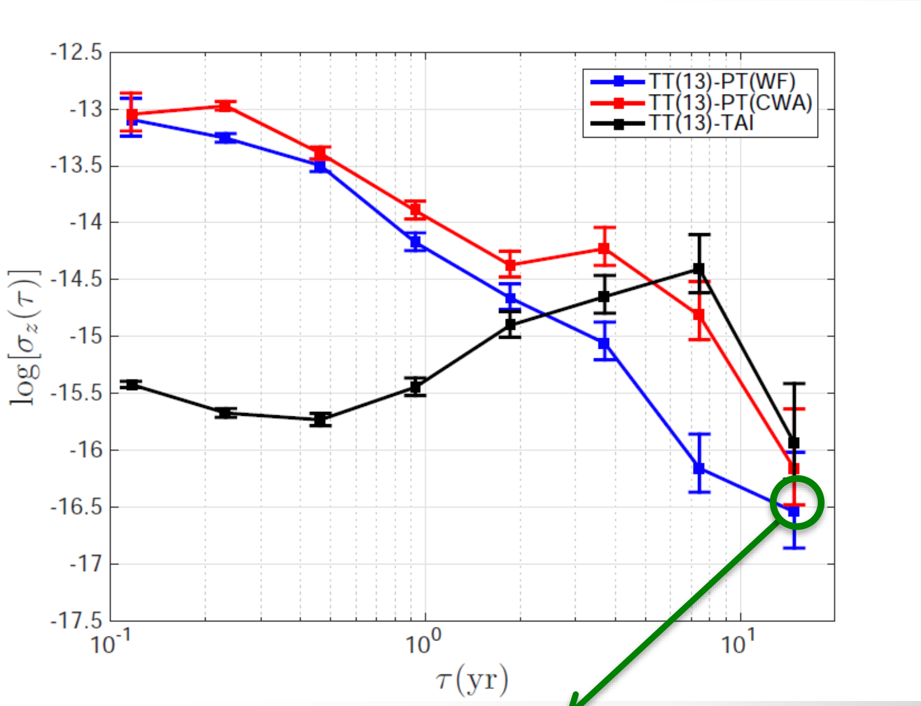
Verbiest et al. MNRAS, 2016, 458:1267

Time reference: TT(BIPM2013)

16 pulsars from IPTA

Time duration: 15yr (data span of J0437)



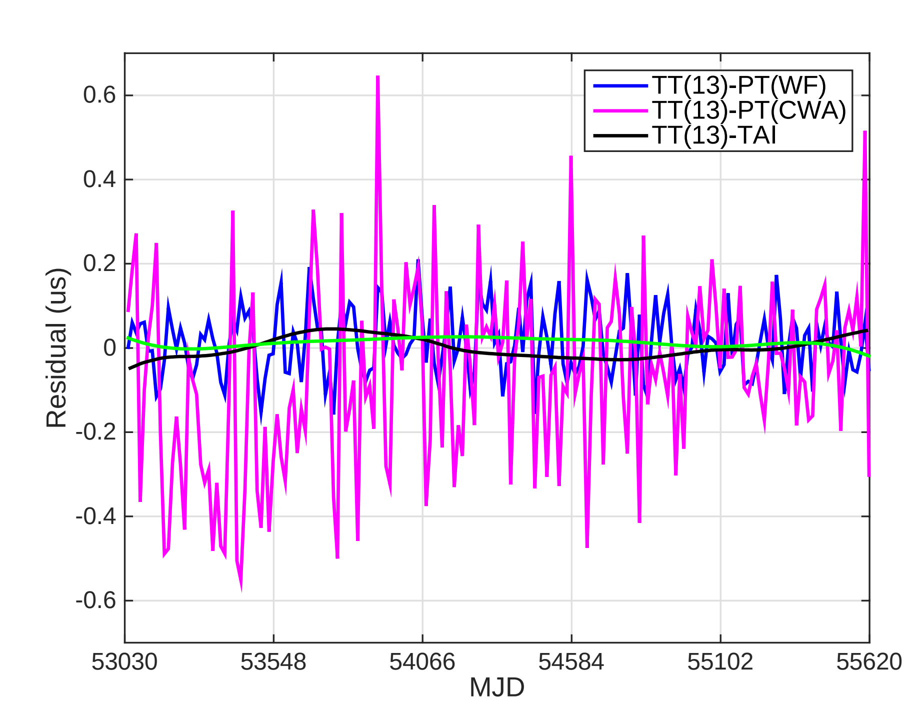


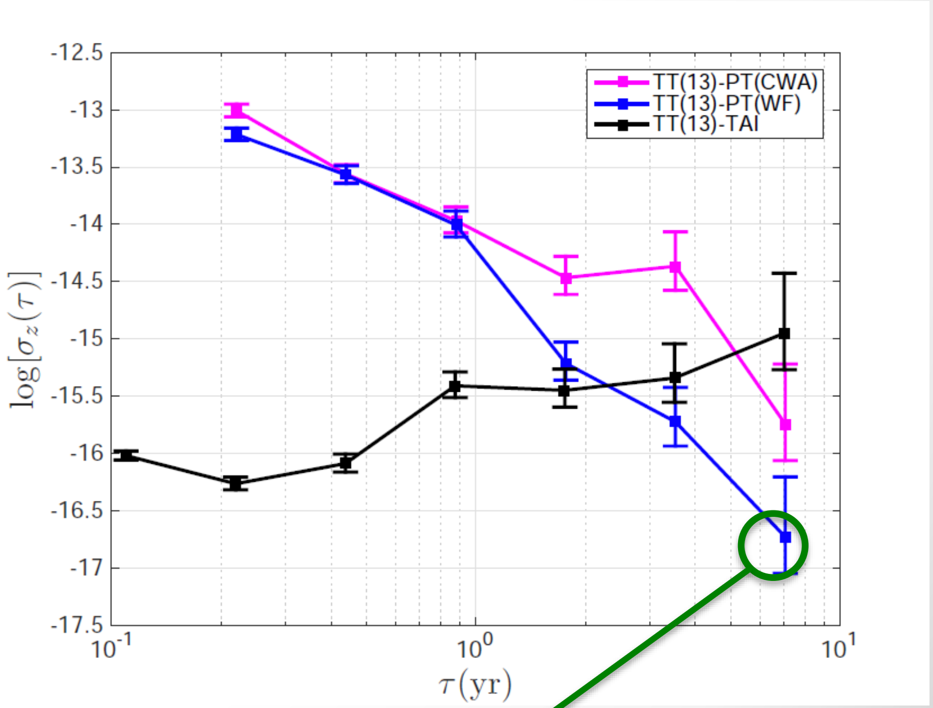
2.88E-17

Time reference: TT(BIPM2013)

24 pulsars from IPTA

Time duration: 7yr (partial data span of J1909)



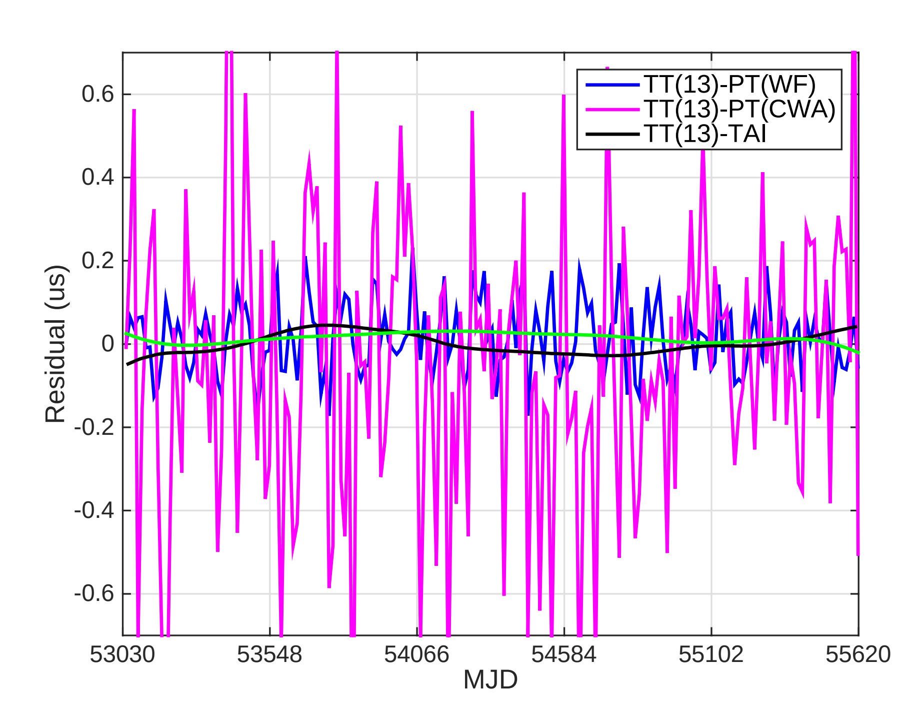


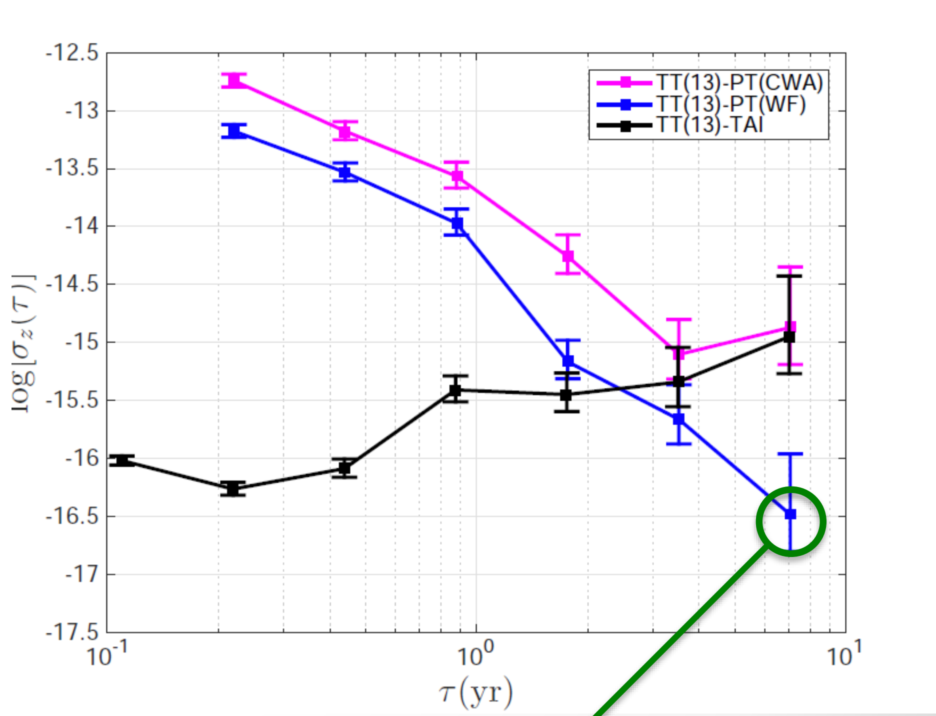
1.87E-17

Time reference: TT(BIPM2013)

23 pulsars from IPTA(remove J0437)

Time duration: 7yr (partial data span of J1909)





3.28E-17

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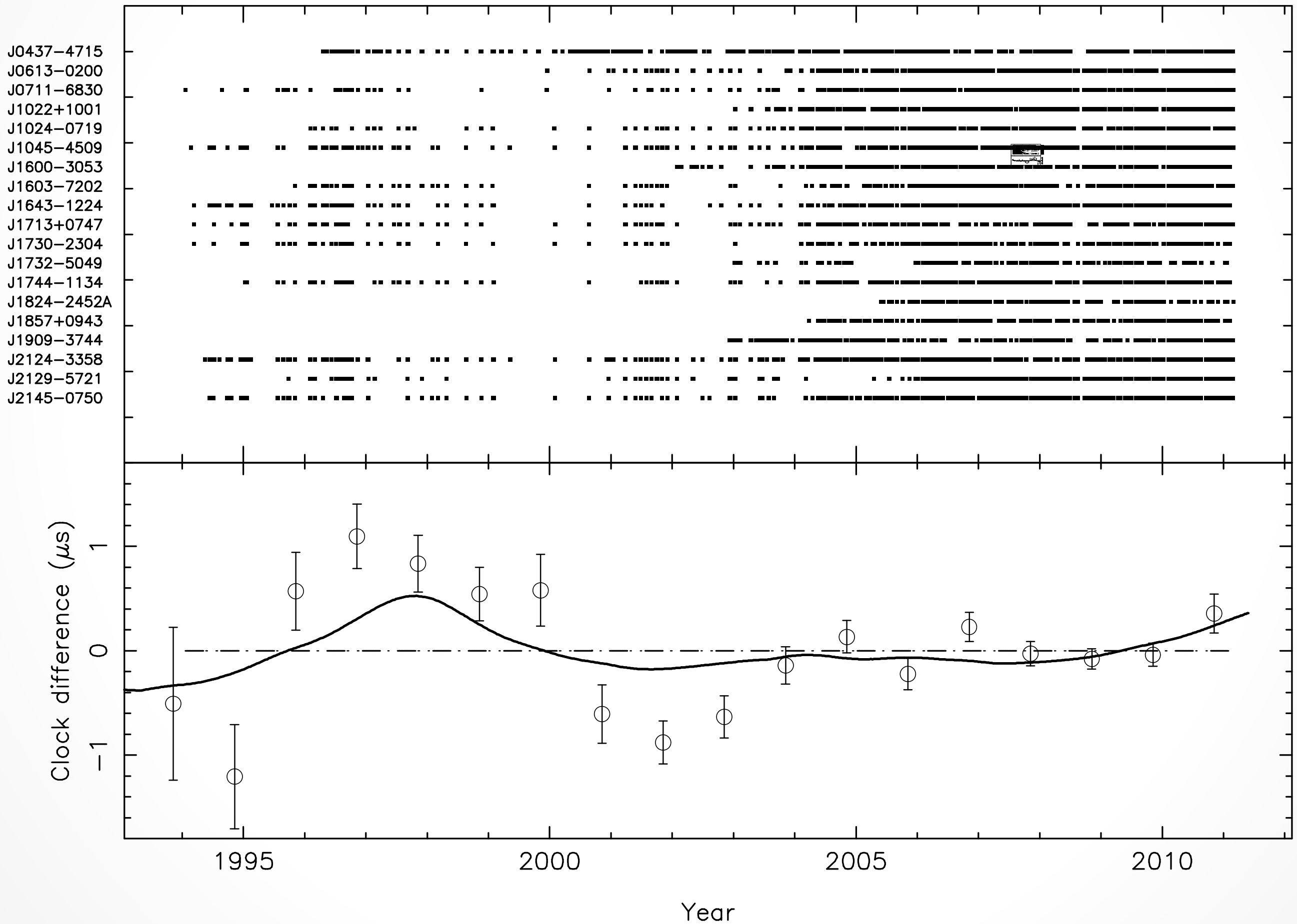
Global fitting the clock differences

PPTA data:



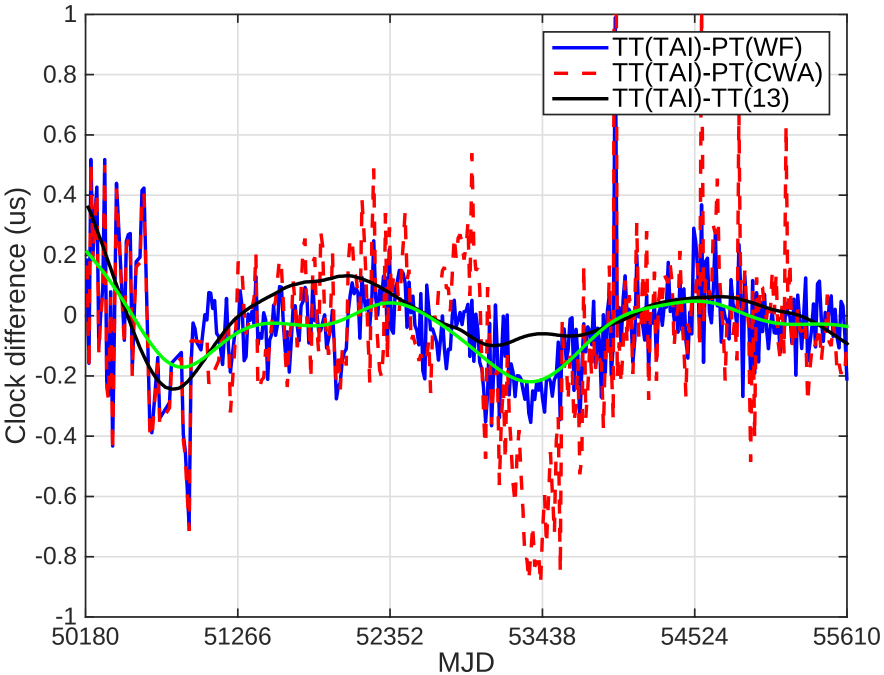
Hobbs et al., MNRAS, 427, 2780 （2012）

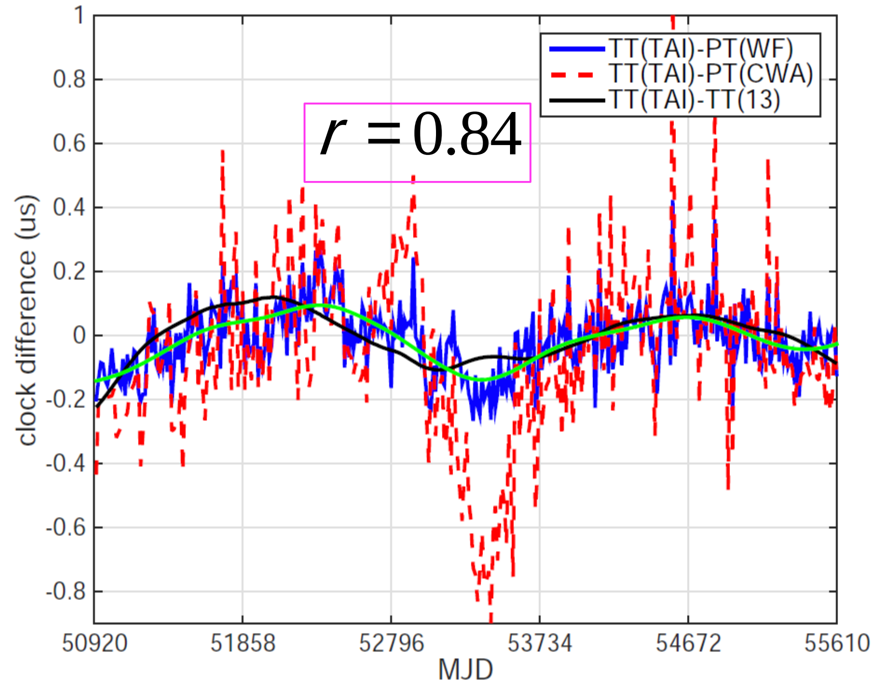
Application I： detect the fluctuations of TAI referred to TT(BIPM)

$$TT = \boxed{TAI + 32.184} + \text{fluctuations}$$

TT(TAI)

J0437-4715 & J0613-0200

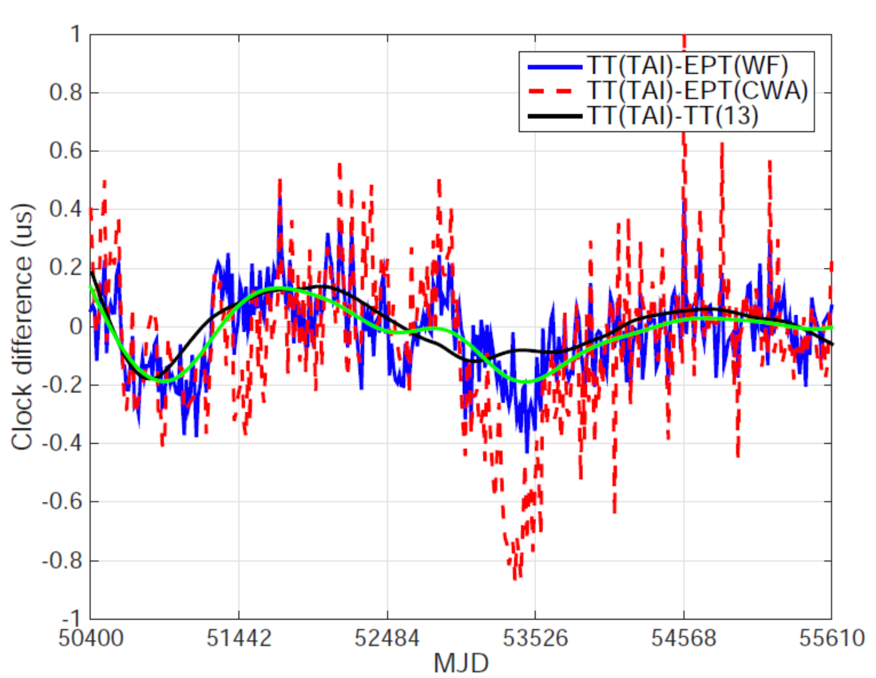




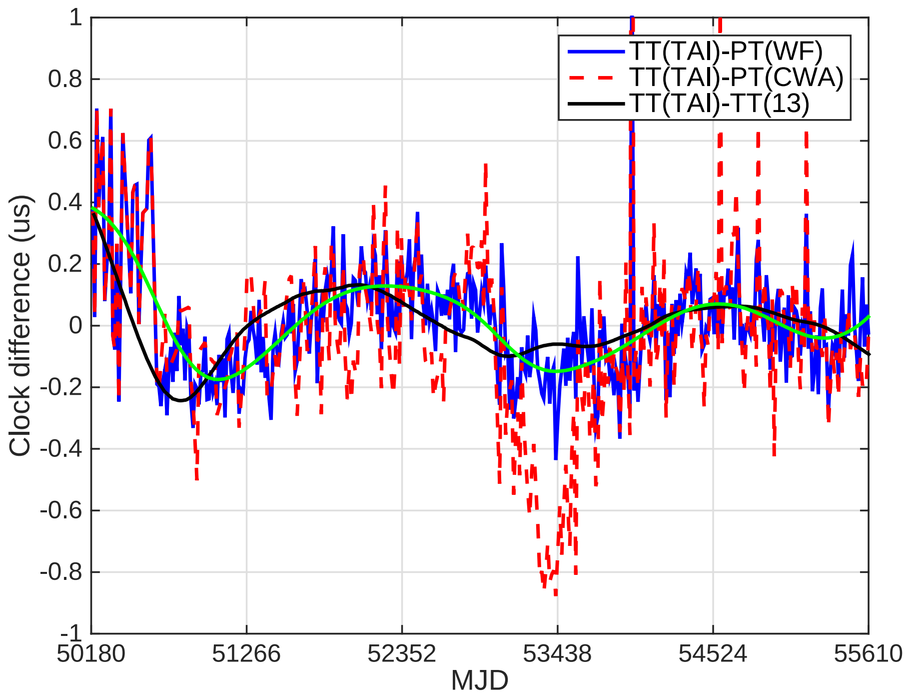
Time reference: TT(TAI)

Application I： detect the fluctuations of TAI referred to TT(BIPM)

J0437-4715 & J1713+0747

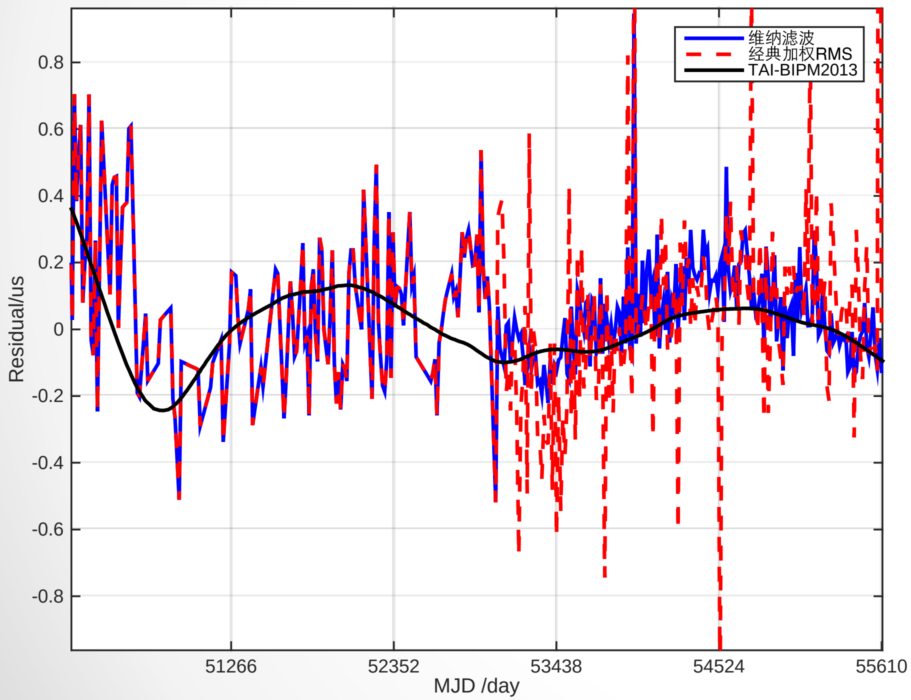


J0437-4715 & J1012+5307

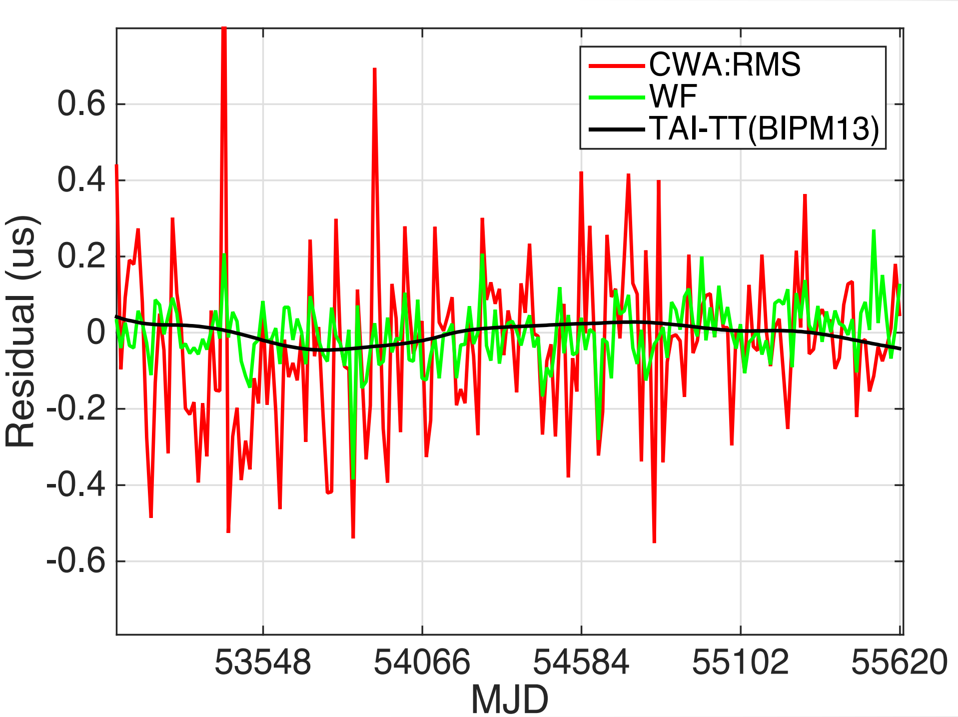


Application I： detect the fluctuations of TAI referred to TT(BIPM)

J0437-4715 & J1909-3744

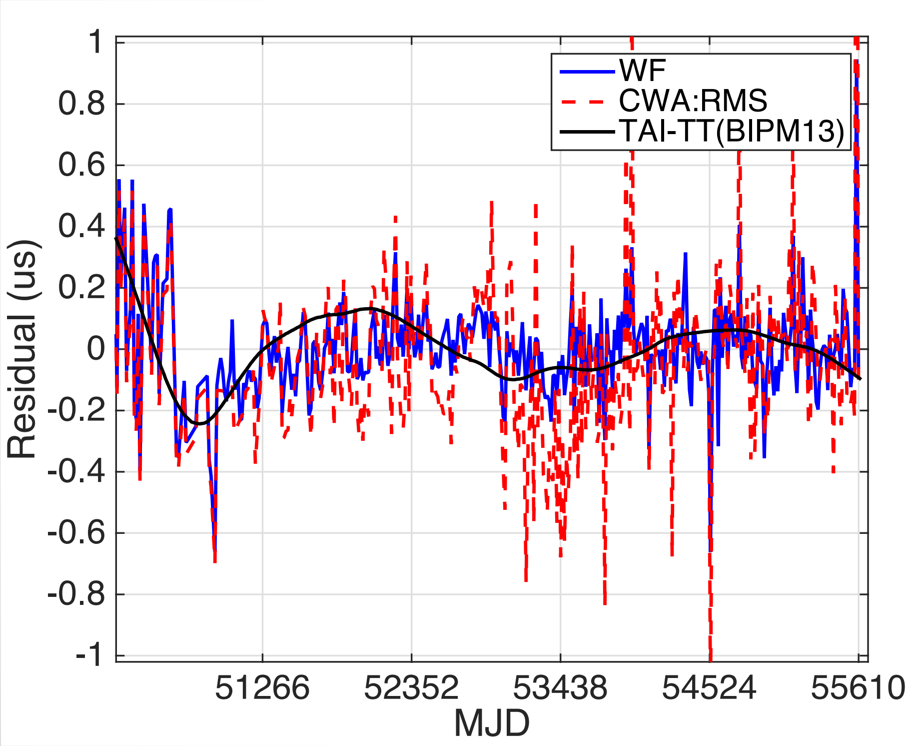


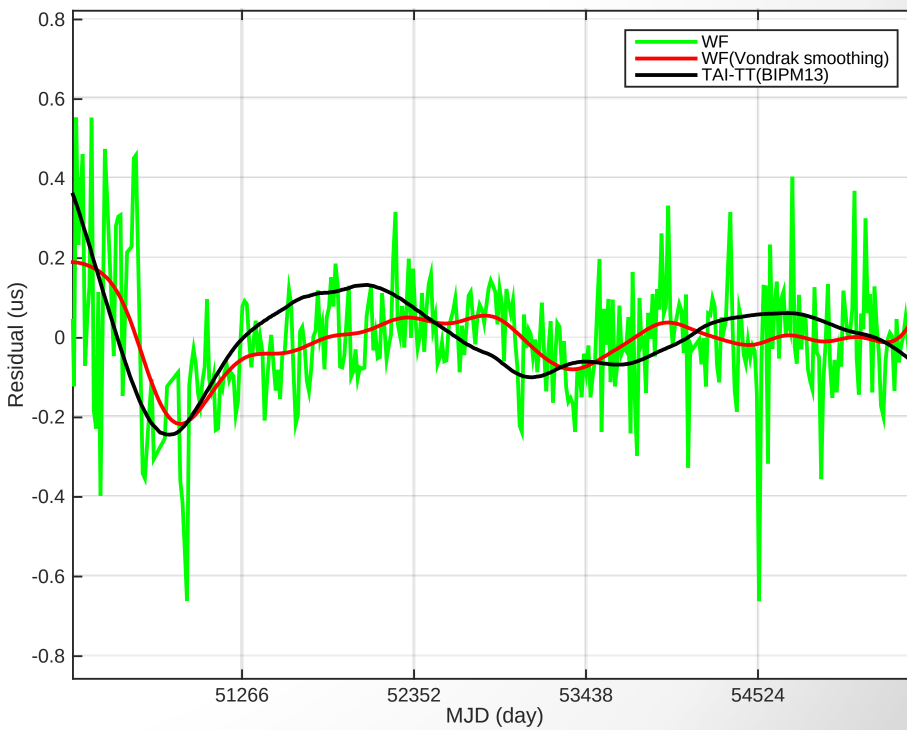
J0437-4715, J0613-0200，
J1713+0747& J1909-3744



Application I： detect the fluctuations of TAI referred to TT(BIPM)

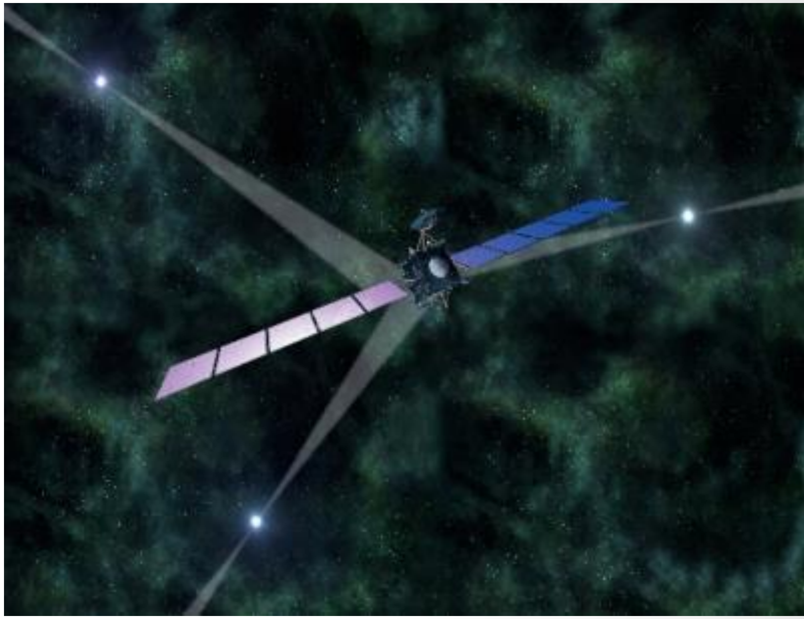
J0437-4715, J0613-0200 & J1909-3744





Other possible applications:

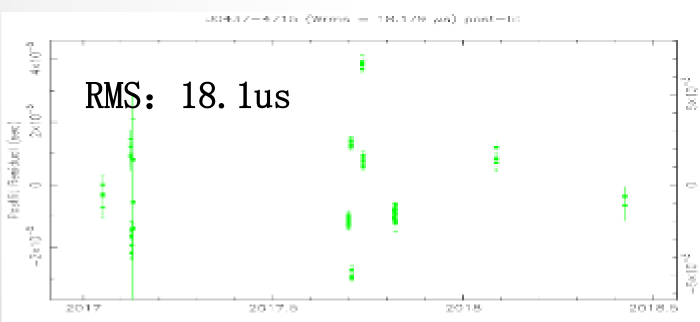
- Correct the local atomic time –scale kept by time laboratories
- Join the work of time-keeping combing with atomic clocks
- Pulsar navigation in deep space
- Timing in deep space



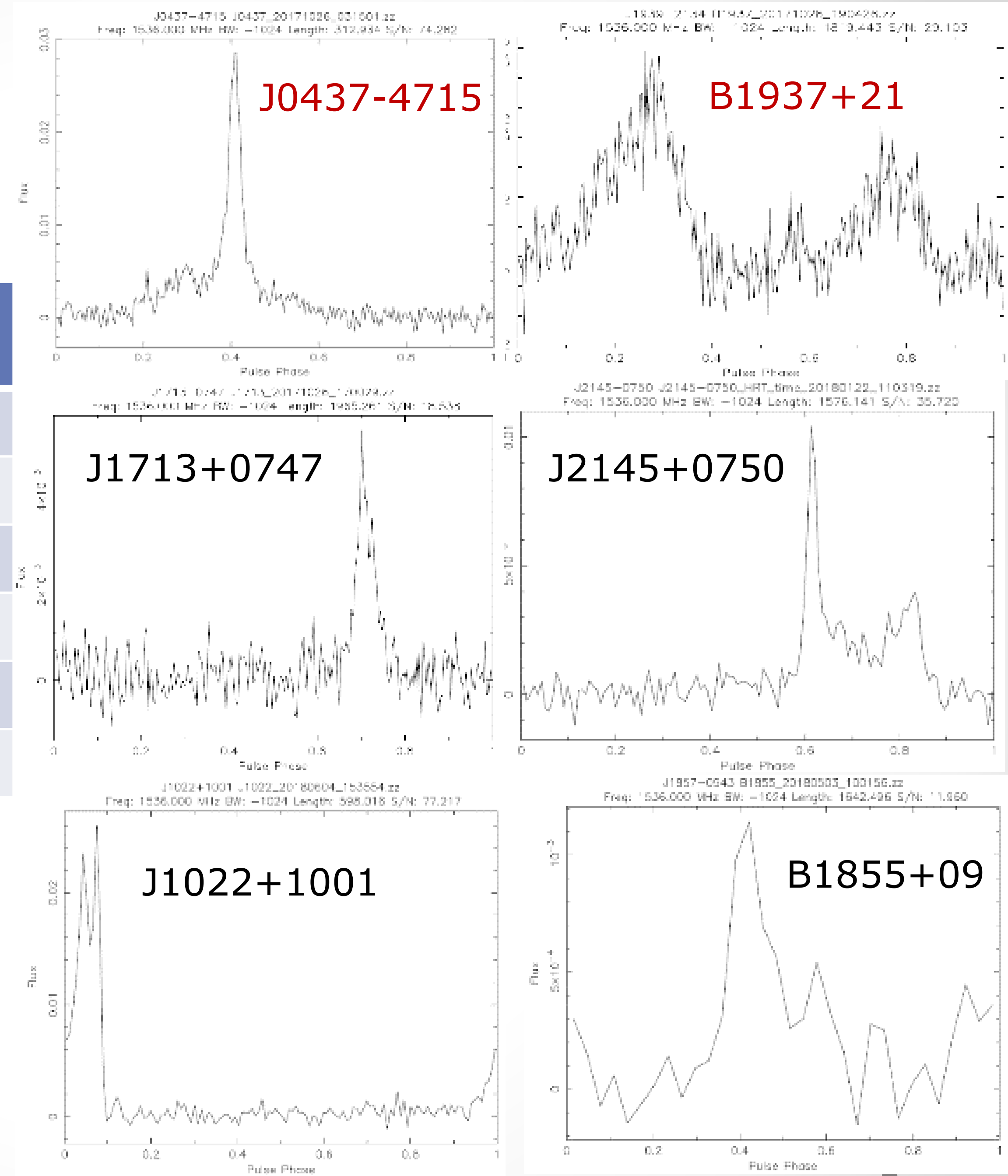
Radio Telescopes in China

6 MSPs observed by HRT

	Name	Period (ms)	Flux (mJy)
1	J0437-4715	5.76	149
2	B1937+21	1.56	13.2
3	J1713+0747	4.57	10.2
4	J2145+0750	16.05	8.9
5	J1022+1001	16.45	6.1
6	B1855+09	5.36	5



J0437-4715 timing residuals



Summary

- Pulsar time-scale has a high long-term stability
- Wiener Filter is a effective method to construct EPT for the existence of weak red noises
- The EPT for a time scale of 7-15 years would reach a stability of E-16~E-17 order of magnitude
- The high stability of EPT make it can detect the fluctuations of TAI (or TA(k)) relative to TT

Thanks for your attention!