Chinese Pulsar Timing Array First Data Release

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On behalf of the CPTA collaboration (PI: Kejia Lee)

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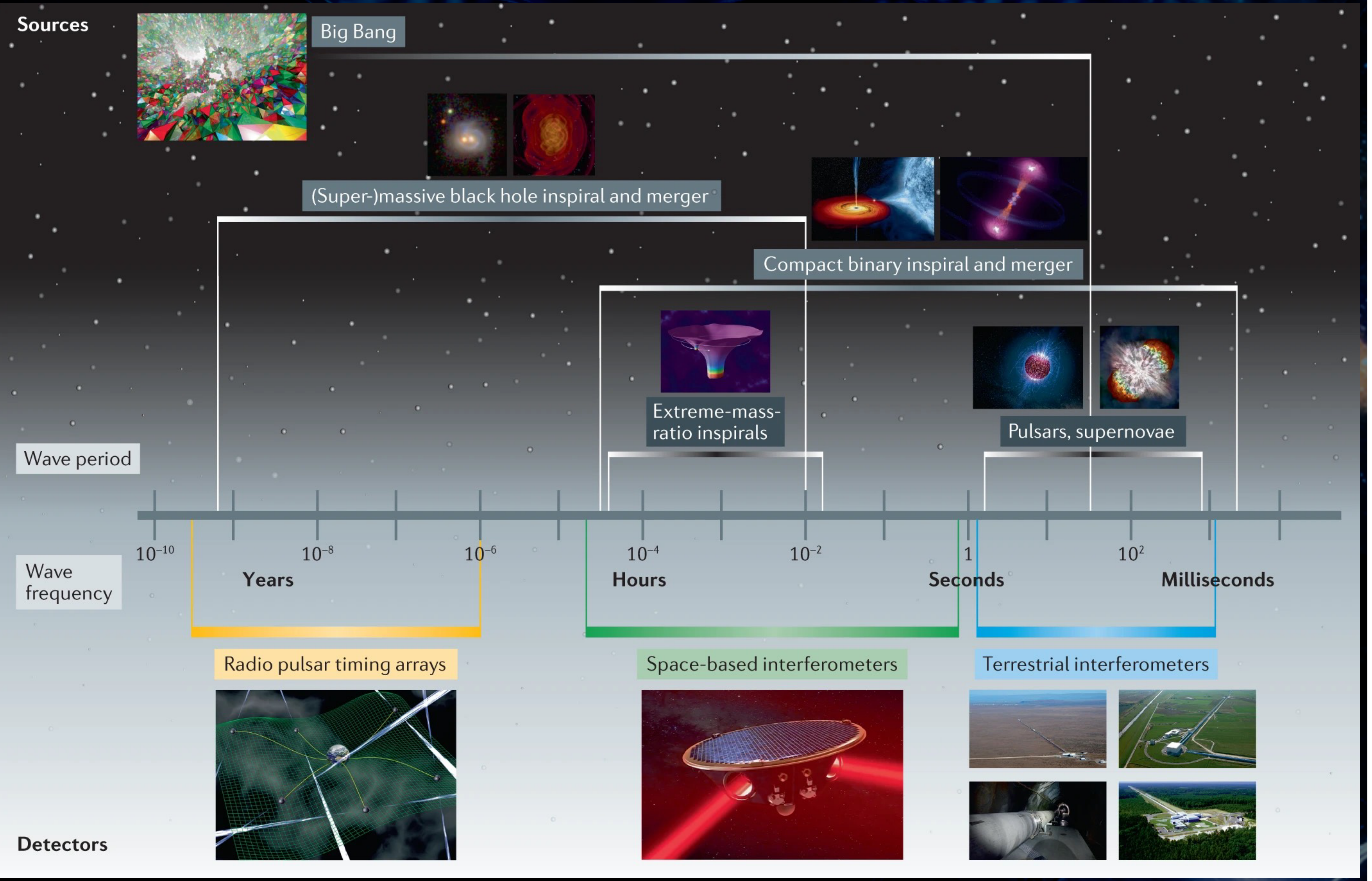
CPTA

@ Jinchen Jiang

Nanohertz Gravitational Wave & Chinese Pulsar Timing Array



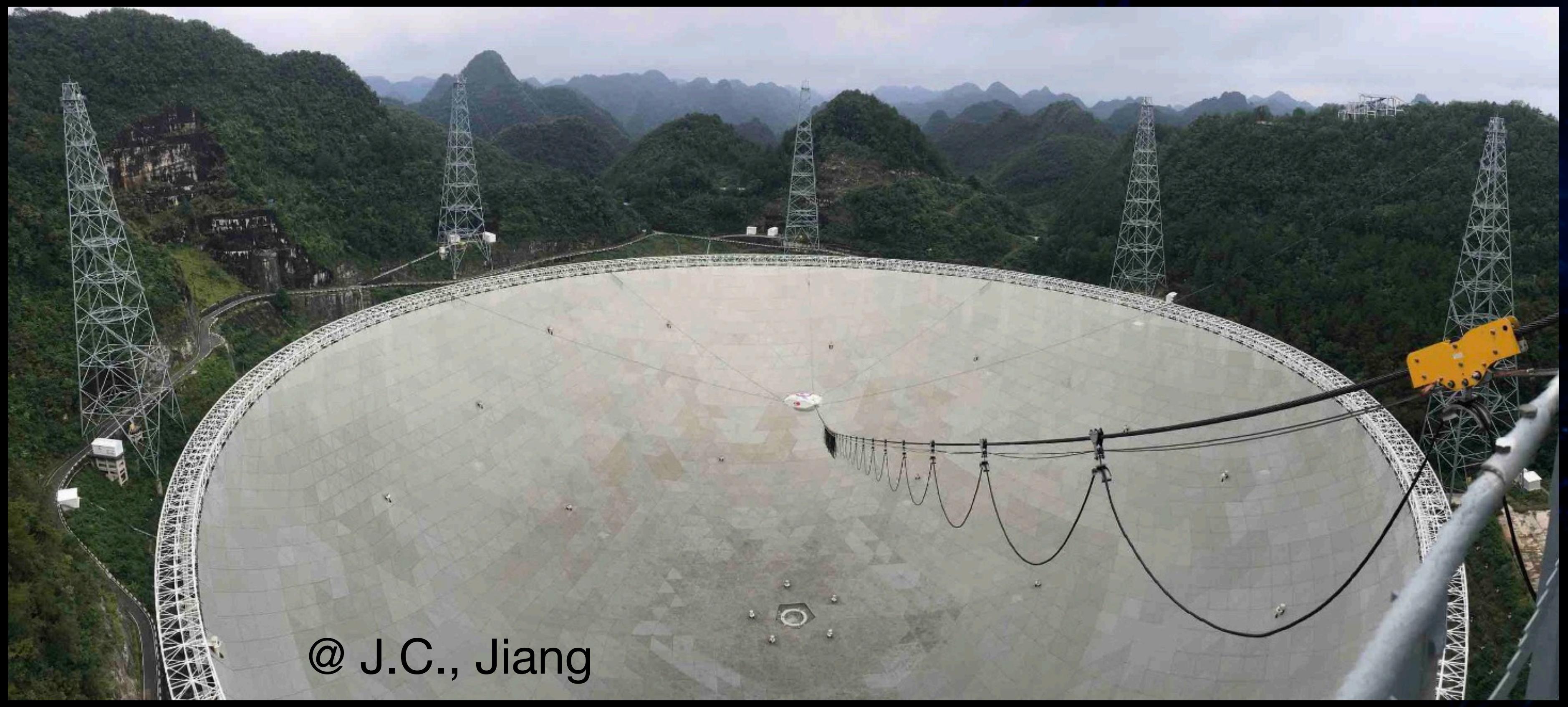
Bailes et al., 2021

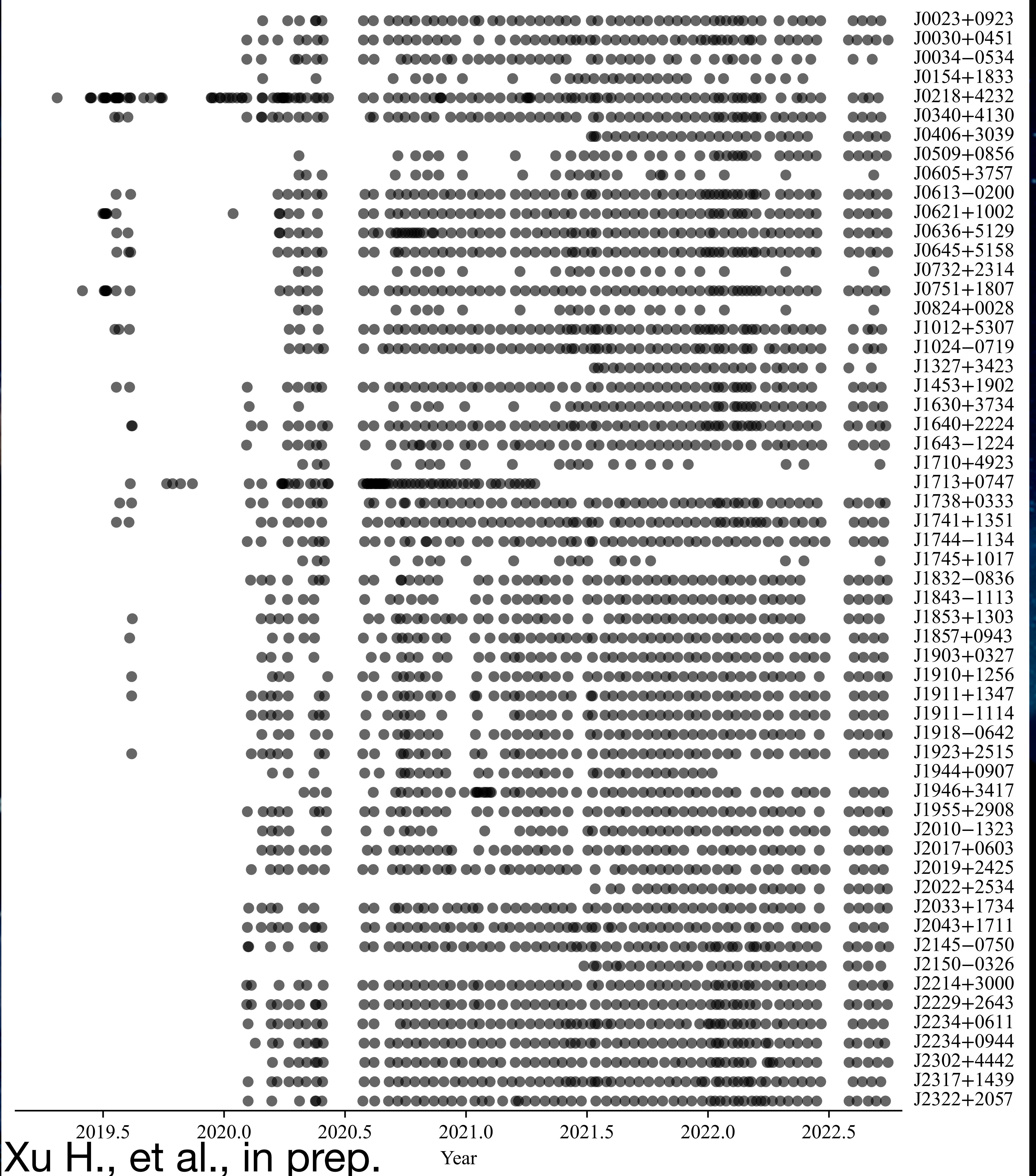
- Pulsar Timing Array is hitherto the only known way to directly detect the nanohertz (nHz) gravitational waves (GWs).

- FAST timing experiment started at Apr 2019.
- CPTA formally formed in 2019, aiming at directly detect the nHz GWs using Chinese radio telescopes.
- CPTA became one of the key projects of FAST in 2019.

Observation Overview

- FAST: Tsys~20 K, Gain~16 K/Jy (Jiang et al., 2020, RAA).
- 19Beam receiver @1.25 GHz (500 MHz bandwidth).
- Data: search mode data, incoherent dedispersion.
- 57 pulsars, 17 Isolated pulsars, 40 binary pulsars.
- Data from Apr 2019 to Sep 2022, data span >~2.5 years.

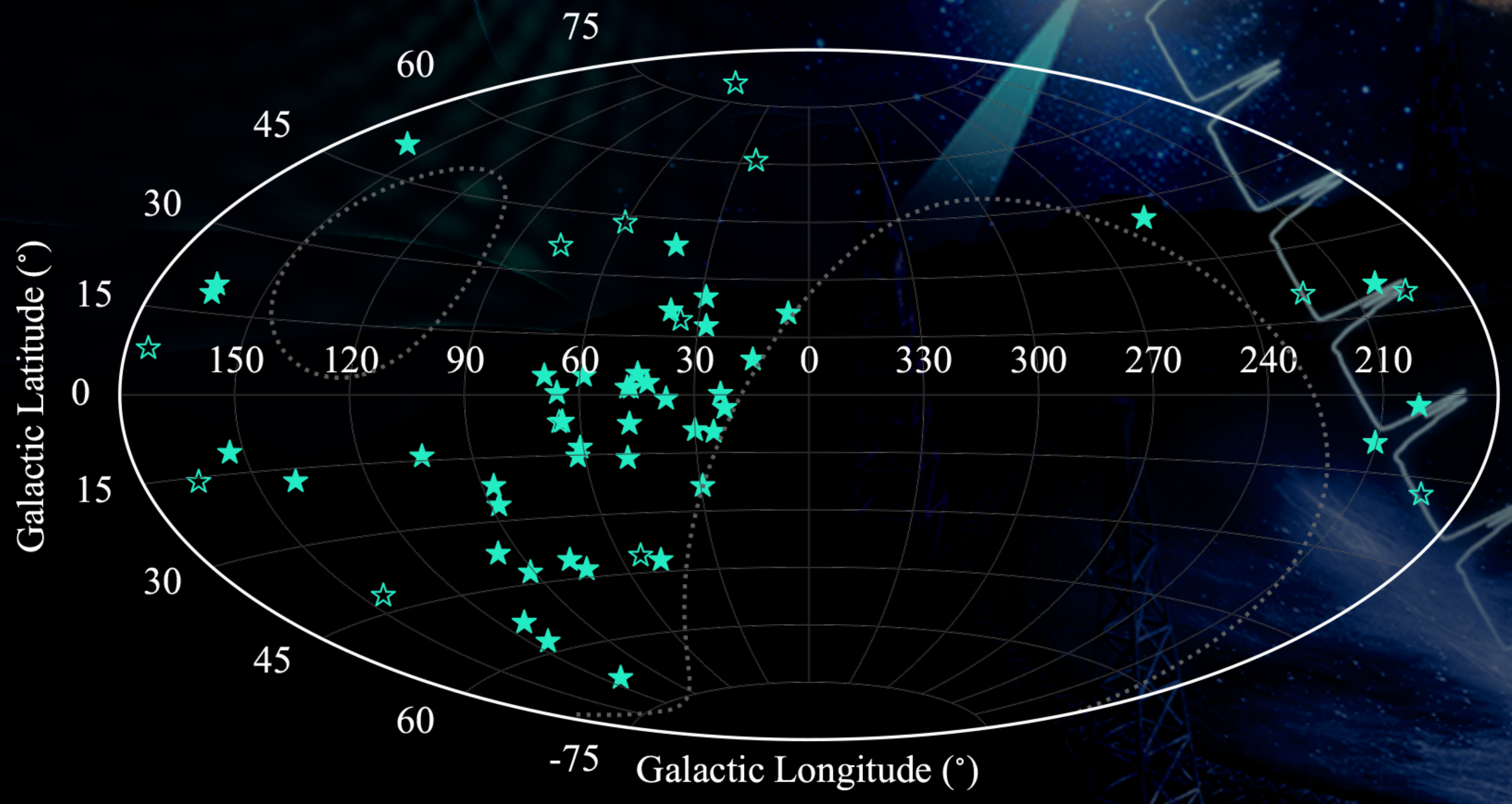


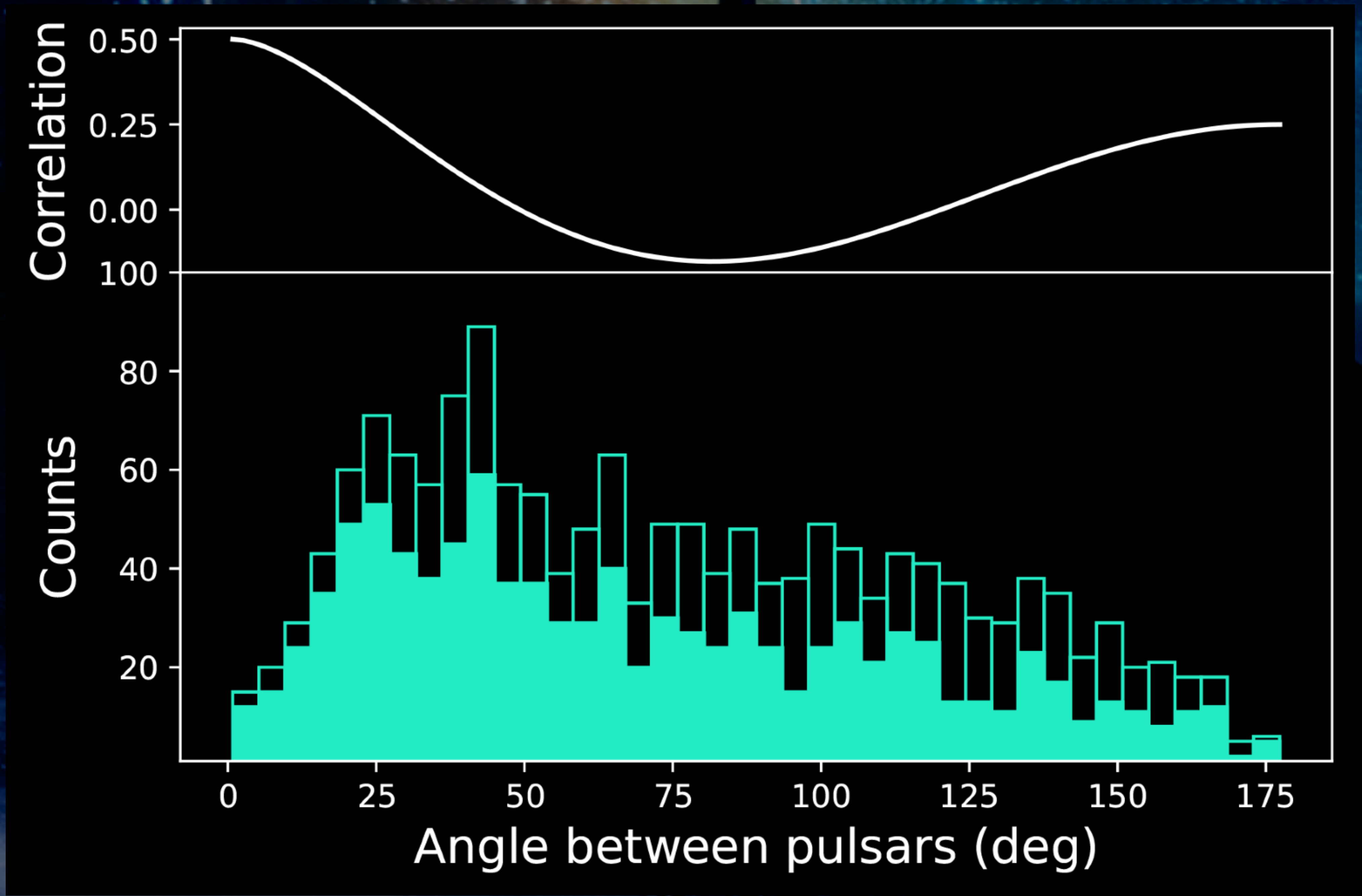


Xu H., et al., in prep.

Sky Position

- 45 pulsars from EPTA/NANOGrav/PPTA/IPTA.
- Widely spreading over the sky, and good sampling in the parameter of the angular separation.

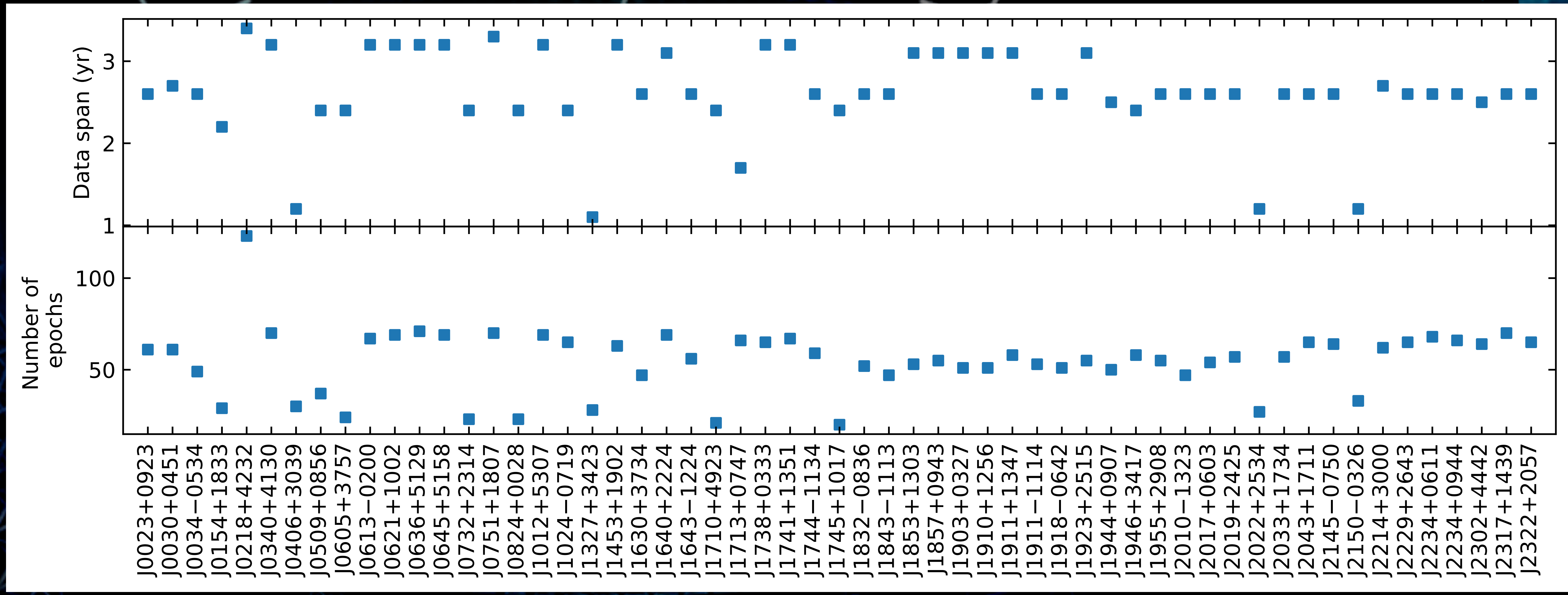




Observation and Data

- 50 of them are regularly monitored biweekly, less observations for other pulsars due to the limited observing time.
- Each observation lasts for 20 or 30 mins.
- Folding, polarization calibration (Xu J-W et al., in prep.) and RFI excision using DSPSR, PSRCHIVE, Tempo2, python.
- Sub-integrations are time-scrunched every 15 or 20 mins, or no longer than ~1/40 of the orbital period.
- The full 500-MHz band is splitted into 64 channels (except for J0218+4232 and J0636+5129).
- Subbands ToAs are generated with 1-D templates (Taylor 1992).

Pulsar name J2000	P (ms)	DM (pc cm^{-3})	P_b (day)	W_{50} (ms)	W_{10} (ms)	S_{1400} (mJy) 16%	S_{1400} (mJy) 50%	S_{1400} (mJy) 84%	Number of Epochs	Span (yr)	Number of TOAs
J0023+0923	3.05	14.3	0.14	0.21	0.56	0.08	0.22	0.93	61	2.6	13477
J0030+0451	4.87	4.3	-	0.56	1.57	0.90	1.37	1.72	61	2.7	4614
J0034−0534	1.88	13.8	1.59	0.35	0.95	0.04	0.14	0.49	49	2.6	2331
J0154+1833	2.36	19.8	-	0.07	0.31	0.02	0.07	0.14	29	2.2	1327
J0218+4232	2.32	61.2	2.03	0.93	1.50	0.51	0.64	0.90	123	3.4	5940
J0340+4130	3.30	49.6	-	0.22	0.53	0.44	0.52	0.63	70	3.2	5827
J0406+3039	2.61	49.4	6.96	0.20	0.47	0.45	0.60	0.78	30	1.2	1751
J0509+0856	4.06	38.3	4.91	0.71	2.65	0.98	1.12	1.25	37	2.4	2061
J0605+3757	2.73	20.9	55.67	0.16	0.55	0.04	0.10	0.26	24	2.4	2123
J0613−0200	3.06	38.8	1.20	0.37	0.93	1.58	2.05	3.16	67	3.2	5077
J0621+1002	28.85	36.6	8.32	0.58	5.10	1.17	1.50	2.23	69	3.2	4492
J0636+5129	2.87	11.1	0.07	0.14	0.31	0.22	0.54	1.31	71	3.2	12495
J0645+5158	8.85	18.3	-	0.13	0.53	0.05	0.17	0.52	69	3.2	5152
J0732+2314	4.09	44.7	30.23	0.98	2.08	0.25	1.10	2.63	23	2.4	1294
J0751+1807	3.48	30.2	0.26	0.24	0.84	0.89	1.28	1.82	70	3.3	14379
J0824+0028	9.86	34.6	23.21	0.29	3.16	0.49	0.79	0.95	23	2.4	1307



Timing Model

- For all pulsars, five astrometric parameters in ecliptic coordinate (RA,DEC, proper motions in RA DEC, and parallax) are fitted.
- Two spin parameters (except for J1024-0719).
- DM + DM1 + DM2 + (DM noise).
- Binary models: DD, ELL1, DDH, ELL1H (DDK for J1713+0747)
    - Keplerian parameters
    - Post-keplerian parameters, depends on the binary systems
- Frequency dependent parameters (Arzoumanian et al., 2015), up to 1 for each pulsar.

Single Pulsar Noise Modeling

- White noise + DM noise + Red Noise.
- White noise: Efac, Equad, Ecorr:

$$C_{W,ij} = (E_f{}^2 \sigma_i^2 + E_q{}^2)\, \delta_{ij} + E_c{}^2\, C_{E_c,ij}$$

- DM noise and Red noise are characterized with a power-law spectrum:

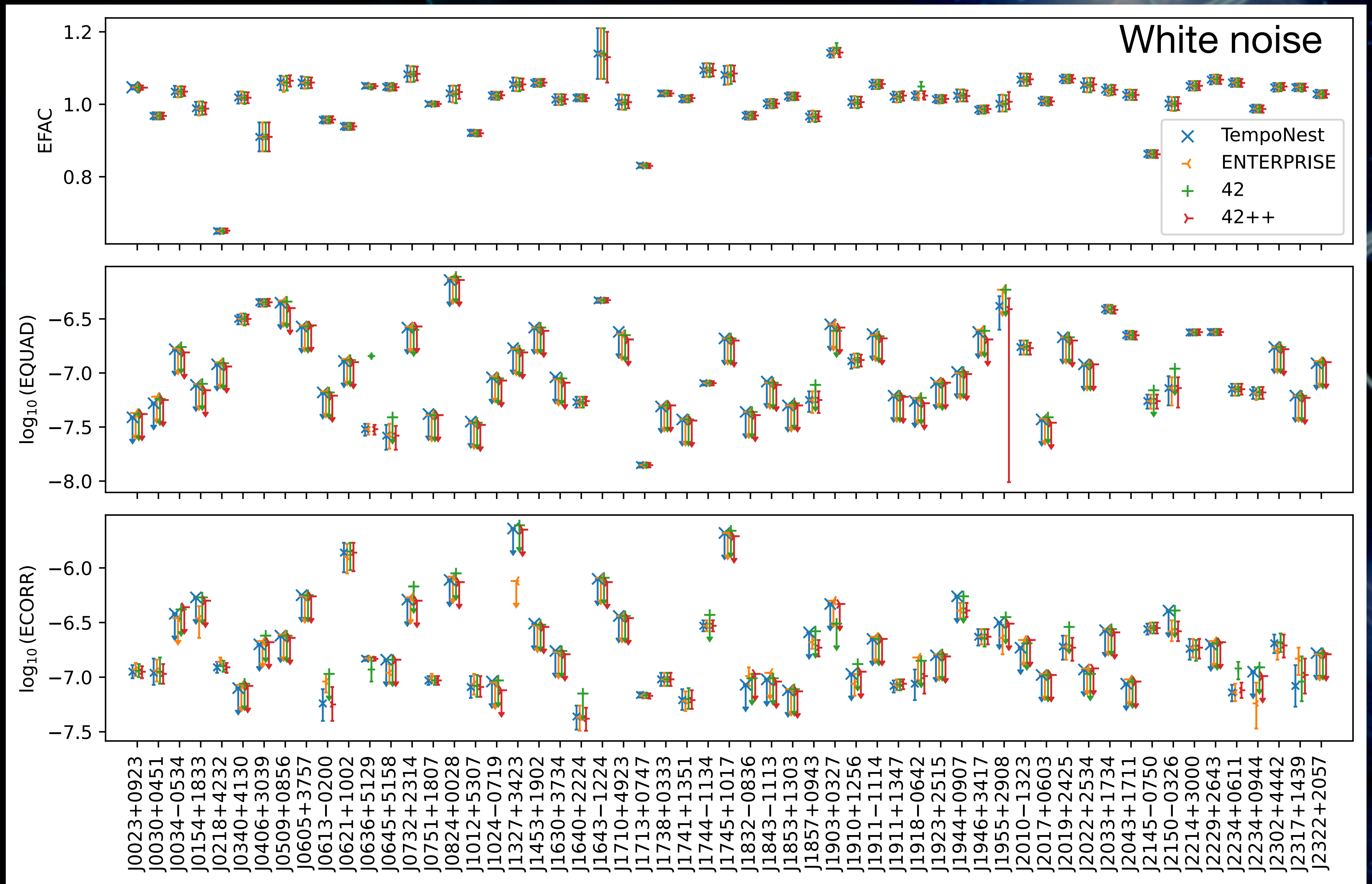
$$P(f) = A^2 \left(\frac{f}{f_{yr}} \right)^{-\gamma}$$

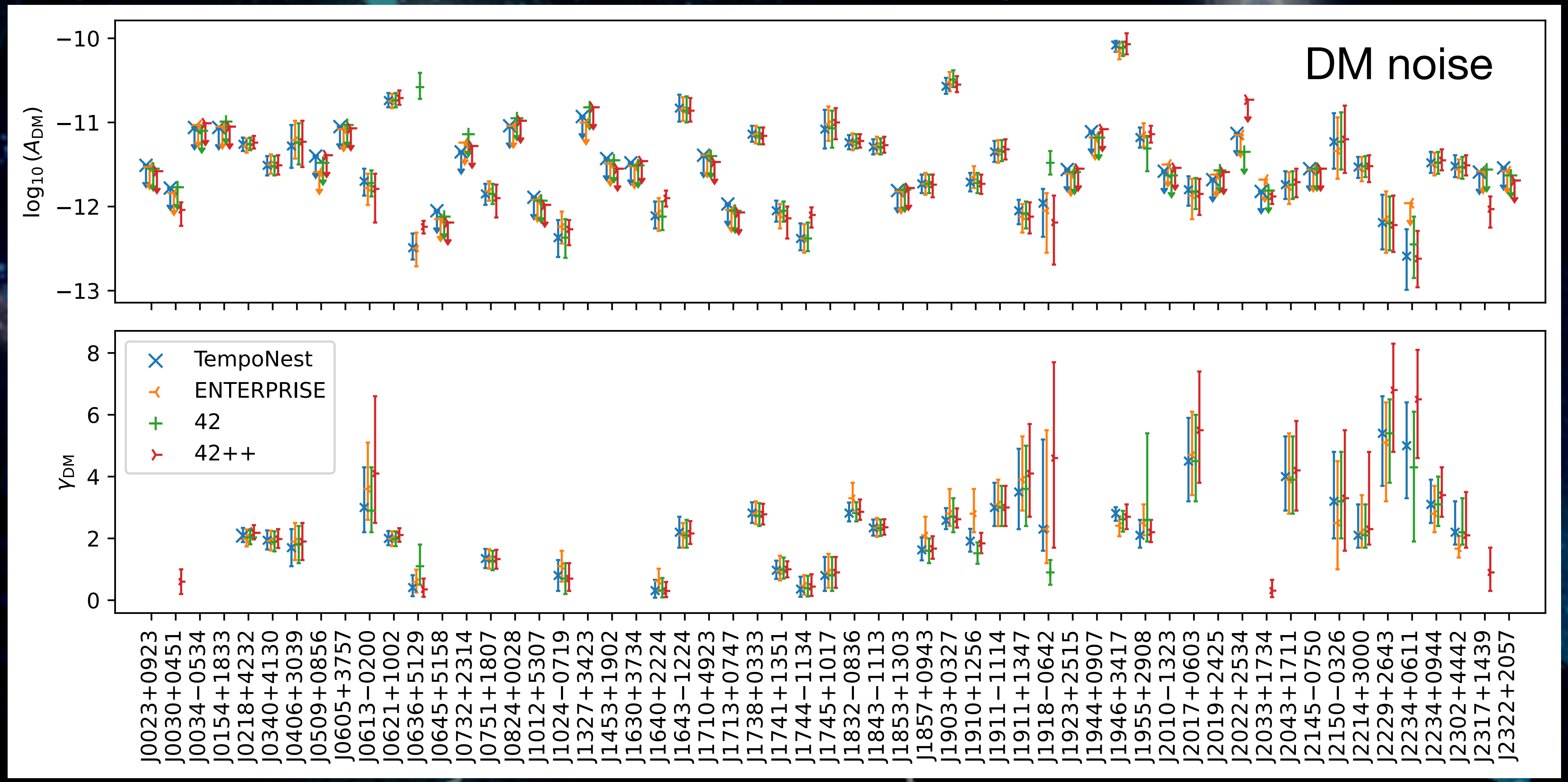
- Noise analysis using TEMPONEST(Lentati et al., 2014).
- Best model: Equad? + Ecorr? + DM noise? + Red noise?

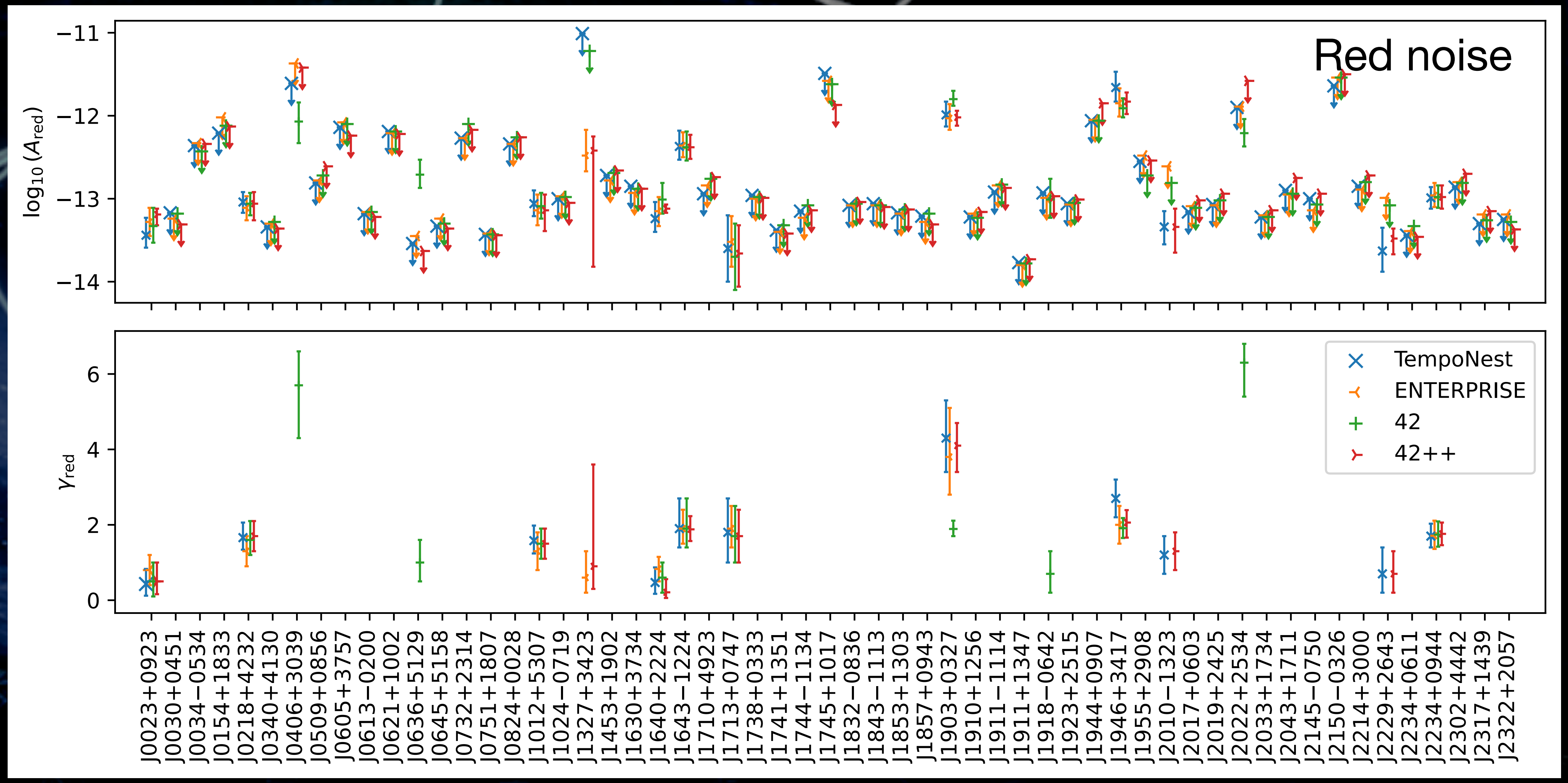
Pulsar name	Number of Fit Parameters				Best Noise model				Subband RMS (μs)		Band-averaged RMS (μs)	
J2000	Astrometry	Spin	Binary	FD	EQUAD	ECORR	DM Noise	Red Noise	Full	Whitened	Full	Whitened
J0023+0923	5	2	9	1		√	√	√	0.916	0.884	0.325	0.191
J0030+0451	5	2	0	0		√	√	√	0.514	0.506	0.135	0.096
J0034−0534	5	2	5	1			√	√	1.846	1.711	0.733	0.240
J0154+1833	5	2	0	0		√		√	0.750	0.618	0.426	0.032
J0218+4232	5	2	7	0		√	√	√	0.716	0.607	0.422	0.182
J0340+4130	5	2	0	1	√		√		0.974		0.095	
J0406+3039	5	2	5	1	√		√		0.769		0.038	
J0509+0856	5	2	5	0					1.298		0.171	

Single Pulsar Noise Modeling

- Noise analysis results are consistent using four pipelines: TEMPONEST, ENTERPRISE, 42, 42++ (Chen et al., in preparation).



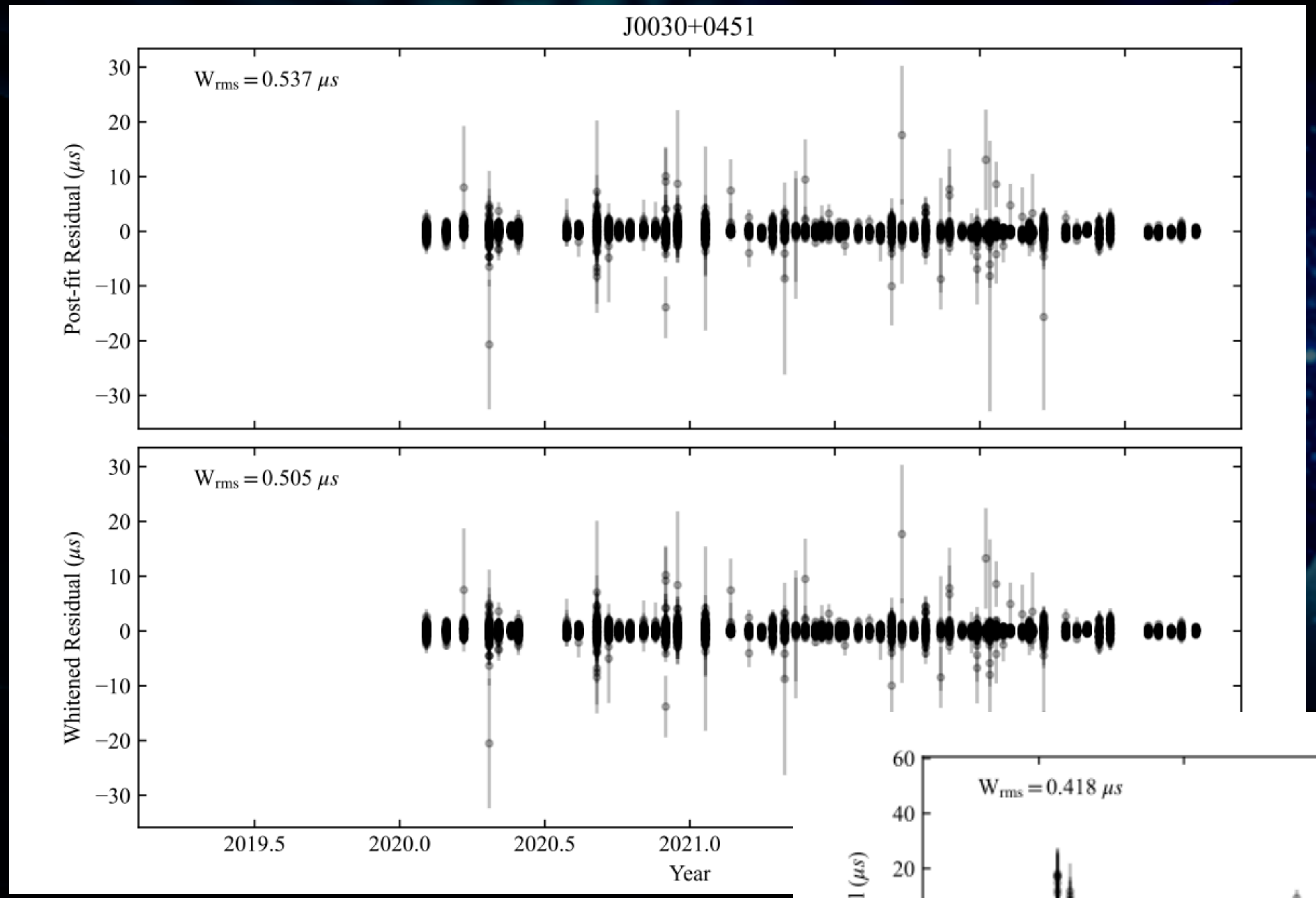


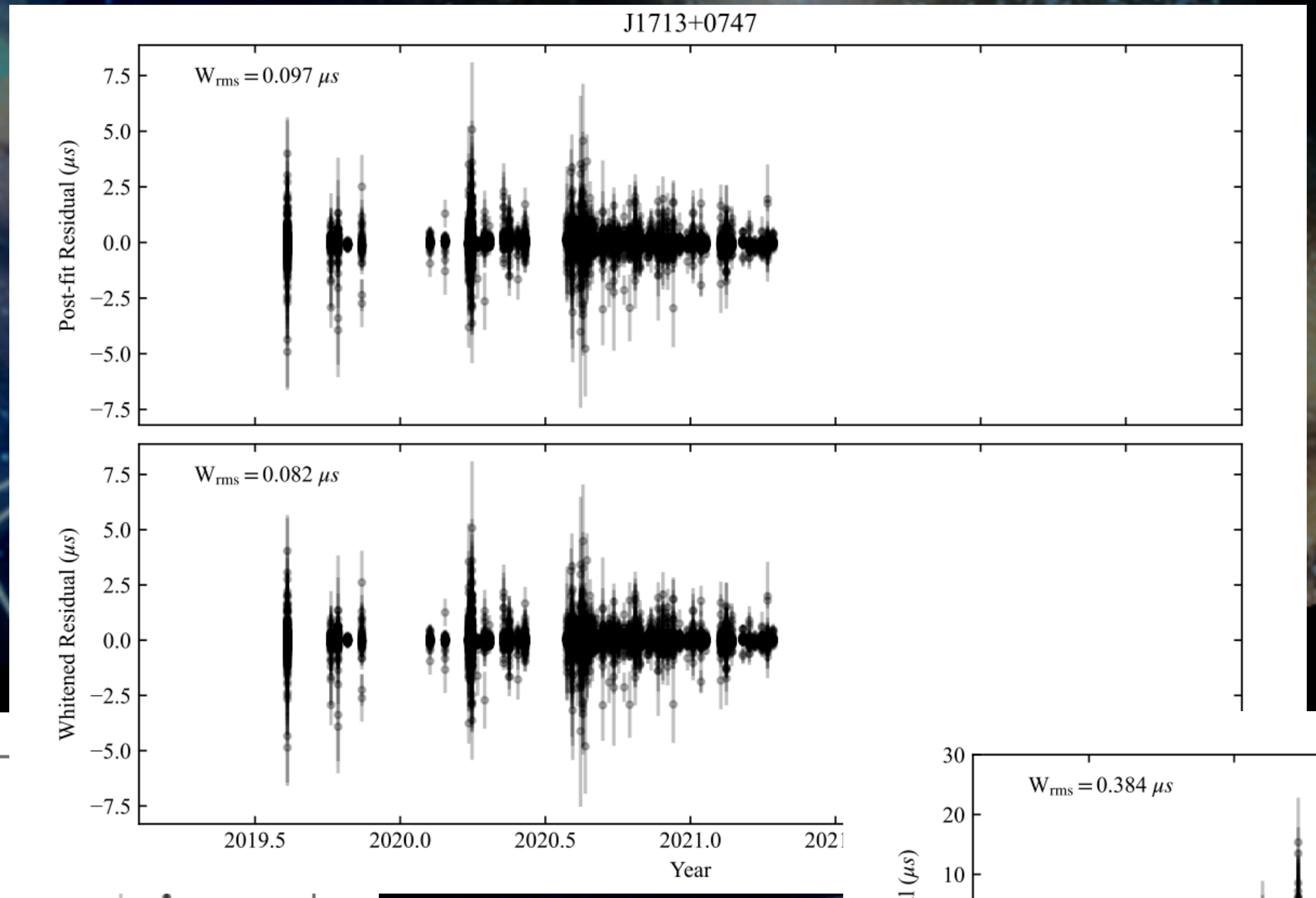


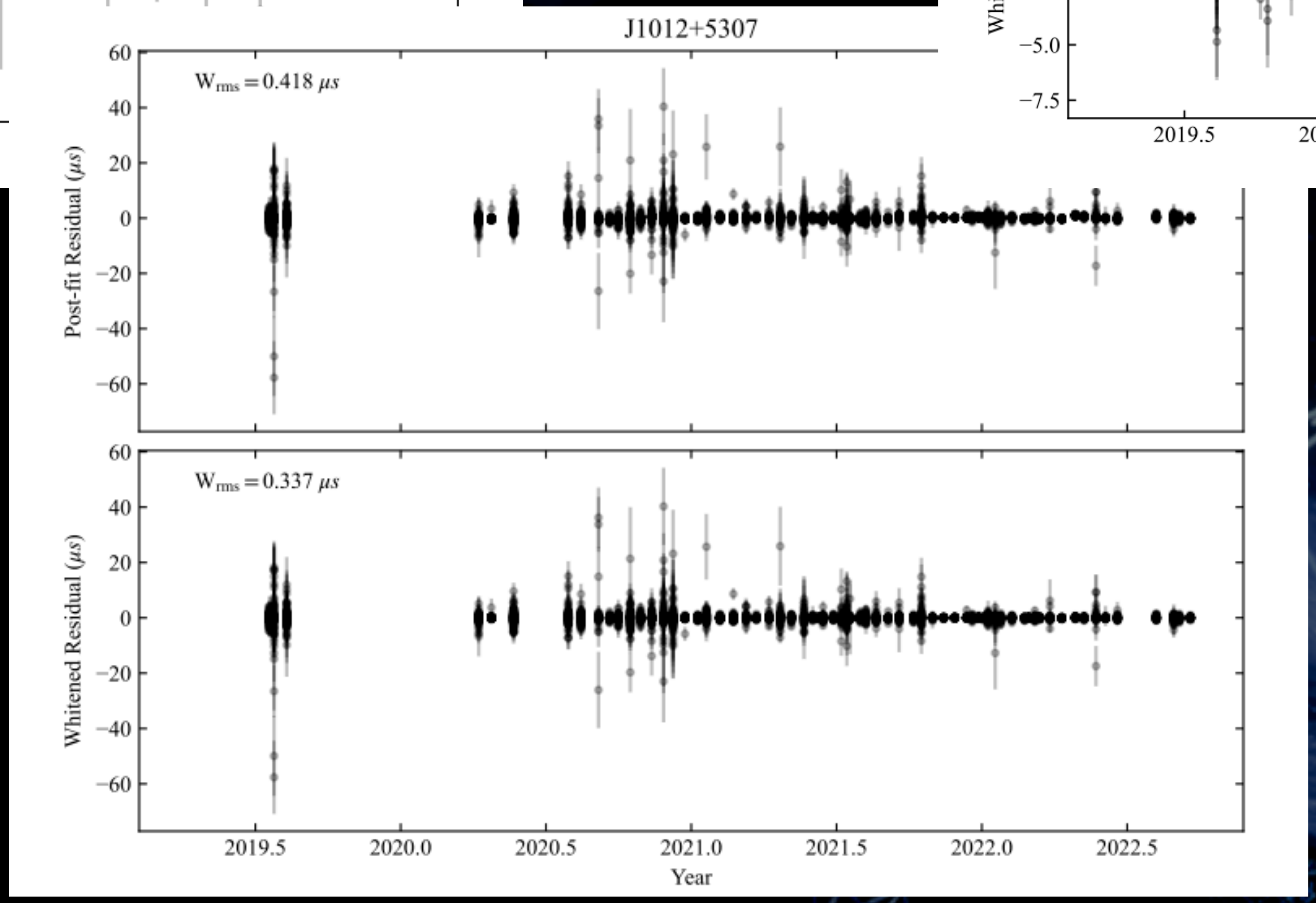
Chen et al., in preparation

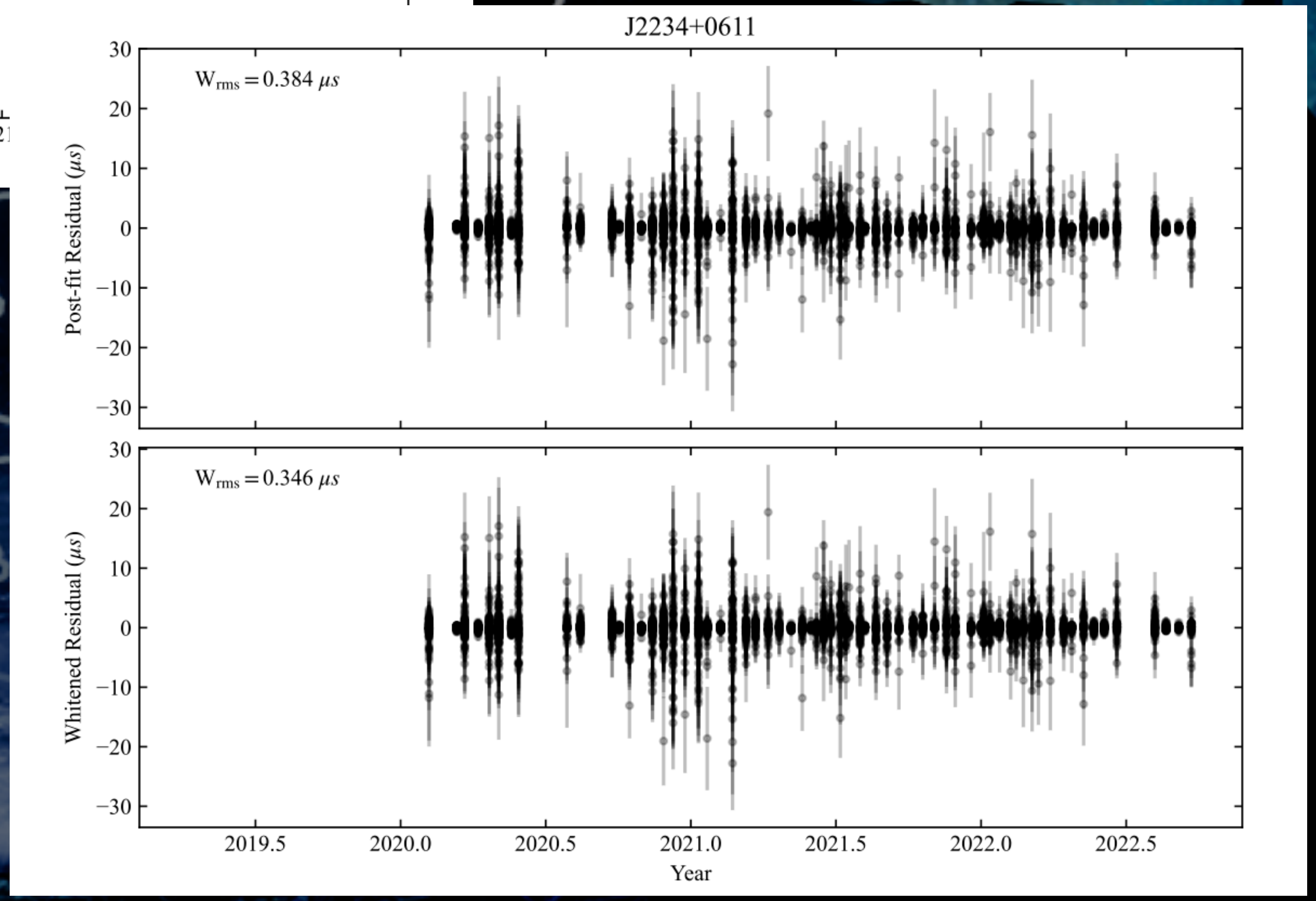
Timing Residuals

- 100ns timing precision for ~35 pulsars, 200ns timing precision for ~50 pulsars.









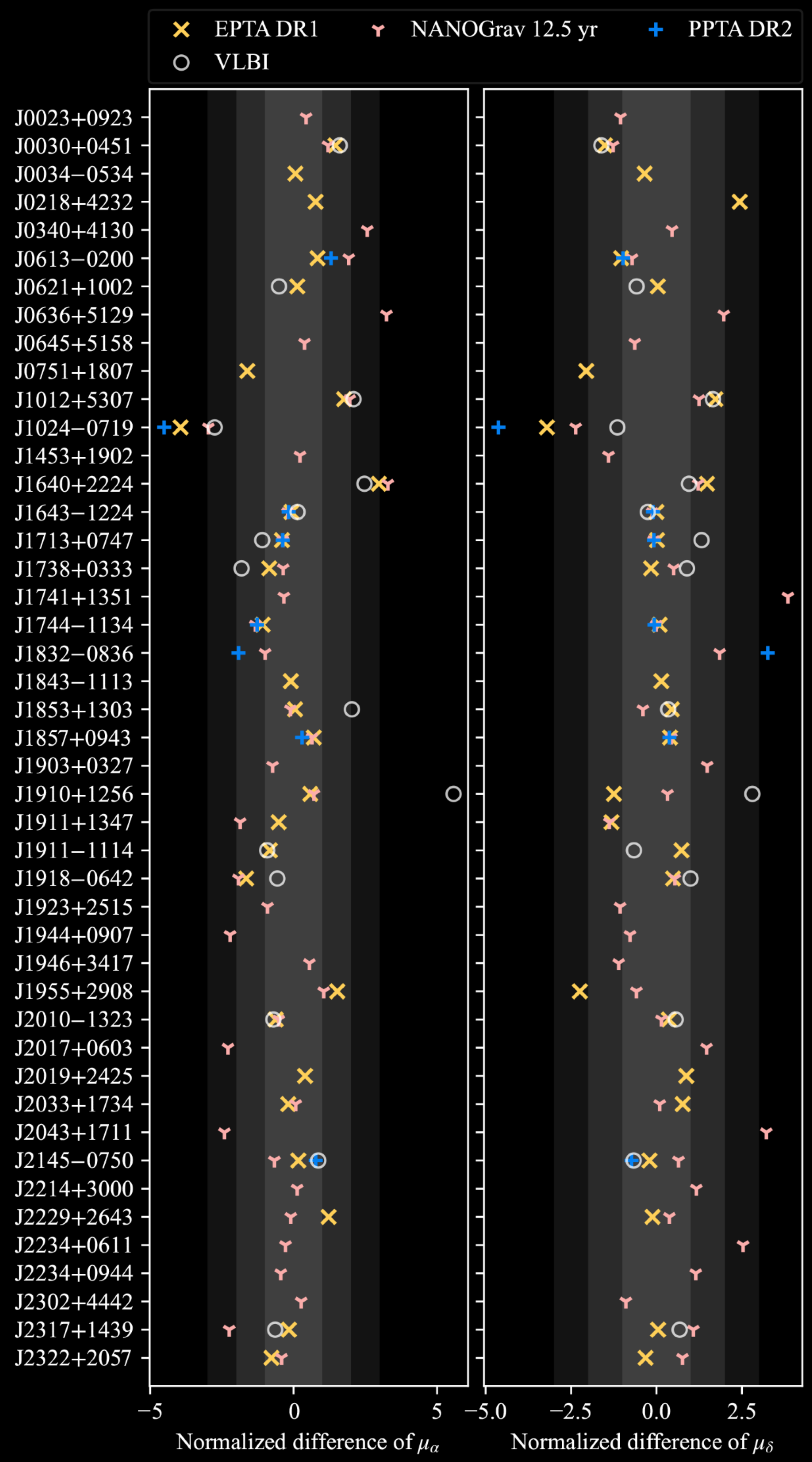
Astrometry: CPTA vs VLBI

- For most pulsars, the astrometric results from CPTA timing are consistent with VLBI (except for PSRs J1024-0719, J1910+1256).
- The position of J1024-0719 from CPTA is different from VLBI, (IPTA DR2 also differs), the proper motions are not consistent (see next slide)
- Ding et al., (2023) also notice the discrepancy between timing and VLBI for J1910+1256.

Pulsar name J2000	Epoch MJD	Method	α	δ	μ_α (mas yr^{-1})	μ_δ (mas yr^{-1})	Parallax (mas)	Reference
J0030+0451	57849	VLBI	00:30:27.42502(6)	+04:51:39.7159(2)	-6.13(7)	$0.34^{+0.15}_{-0.16}$	3.02(7)	Ding et al. (2023)
		Timing	00:30:27.4252(1)	+04:51:39.707(5)	-6.9(5)	2(1)	3.09(7)	CPTA DR1
J0621+1002	57685	VLBI	06:21:22.11617(12)	+10:02:38.7261(3)	3.5(2)	-1.37(35)	0.86(15)	Ding et al. (2023)
		Timing	06:21:22.1161(1)	+10:02:38.722(6)	3.2(3)	-0(1)	1(1)	CPTA DR1
J1012+5307	57700	VLBI	10:12:33.43991(4)	+53:07:02.1110(1)	2.67(5)	$-25.39^{+0.14}_{-0.15}$	$1.17^{0.04}_{-0.05}$	Ding et al. (2023)
		Timing	10:12:33.43983(6)	+53:07:02.1128(6)	2.4(1)	-25.7(1)	1.41(27)	CPTA DR1
J1024−0719	57797	VLBI	10:24:38.65725(6)	-07:19:19.8014(2)	-35.32(7)	-48.1(2)	0.94(6)	Ding et al. (2023)
		Timing	10:24:38.657196(9)	-07:19:19.8049(3)	-35.11(3)	-47.83(7)	0.97(5)	CPTA DR1
J1640+2224	57500	VLBI	16:40:16.74587(7)	+22:24:08.7642(1)	2.19(9)	$-11.30^{+0.16}_{-0.13}$	0.68(8)	Ding et al. (2023)
		Timing	16:40:16.74595(2)	+22:24:08.7643(6)	1.94(4)	-11.46(11)	7(5)	CPTA DR1
J1643−1224	57700	VLBI	16:43:38.16407(10)	-12:24:58.6531(4)	6.2(2)	3.3(6)	$1.31^{+0.17}_{-0.18}$	Ding et al. (2023)
		Timing	16:43:38.1645(2)	-12:24:58.651(14)	6.1(7)	4(3)	0(1)	CPTA DR1
J1713+0747	52275	VLBI	17:13:49.5306(1)	+07:47:37.519(2)	$4.75^{+0.17}_{-0.07}$	-3.67(16)	0.95(6)	Chatterjee et al. (2009)
		Timing	17:13:49.5307(1)	+07:47:37.522(2)	4.96(8)	-3.91(8)	0.91(8)	CPTA DR1
J1738+0333	57829	VLBI	17:38:53.97001(6)	+03:33:10.9124(1)	6.98(8)	5.18(16)	0.50(6)	Ding et al. (2023)
		Timing	17:38:53.97006(1)	+03:33:10.9118(4)	7.14(4)	5.01(11)	0.72(16)	CPTA DR1
J1853+1303	57846	VLBI	18:53:57.31785(6)	+13:03:44.0471(1)	-1.4(1)	-2.8(2)	0.49(7)	Ding et al. (2023)
		Timing	18:53:57.31794(1)	+13:03:44.0463(3)	-1.62(3)	-2.87(6)	0.66(8)	CPTA DR1
J1910+1256	57847	VLBI	19:10:09.70165(3)	+12:56:25.43160(6)	0.50(4)	-6.85(9)	0.254(35)	Ding et al. (2023)
		Timing	19:10:09.701606(8)	+12:56:25.4317(3)	0.22(3)	-7.17(7)	0.55(11)	CPTA DR1
J1911−1114	57768	VLBI	19:11:49.27544(10)	-11:14:22.5547(3)	-13.8(2)	-10.3(4)	$0.38^{+0.13}_{-0.14}$	Ding et al. (2023)
		Timing	19:11:49.27531(3)	-11:14:22.554(2)	-13.6(1)	-9.9(5)	0.29(18)	CPTA DR1
J1918−0642	57768	VLBI	19:18:48.02959(10)	-06:42:34.9335(2)	-7.1(1)	-5.7(3)	0.60(12)	Ding et al. (2023)
		Timing	19:18:48.02948(2)	-06:42:34.9345(9)	-7.03(7)	-6.06(21)	0.71(10)	CPTA DR1
J2010−1323	56000	VLBI	20:10:45.9211(1)	-13:23:56.083(4)	$2.358^{+0.329}_{-0.210}$	$-5.611^{+0.257}_{-0.303}$	$0.484^{+0.166}_{-0.120}$	Deller et al. (2019)
		Timing	20:10:45.92108(9)	-13:23:56.082(5)	2.6(1)	-5.9(5)	0.38(12)	CPTA DR1
J2145−0750	56000	VLBI	21:45:50.4588(1)	-07:50:18.513(2)	-9.46(5)	-9.08(6)	1.63(4)	Deller et al. (2016)
		Timing	21:45:50.4589(1)	-07:50:18.516(4)	-9.6(2)	-8.9(5)	1.85(11)	CPTA DR1
J2317+1439	56000	VLBI	23:17:09.2364(1)	+14:39:31.265(1)	$-1.476^{+0.465}_{-0.065}$	$3.806^{+0.272}_{-0.704}$	$0.6^{+1.533}_{-0.241}$	Deller et al. (2019)
		Timing	23:17:09.23632(4)	+14:39:31.266(1)	-1.18(6)	3.32(11)	0.60(9)	CPTA DR1

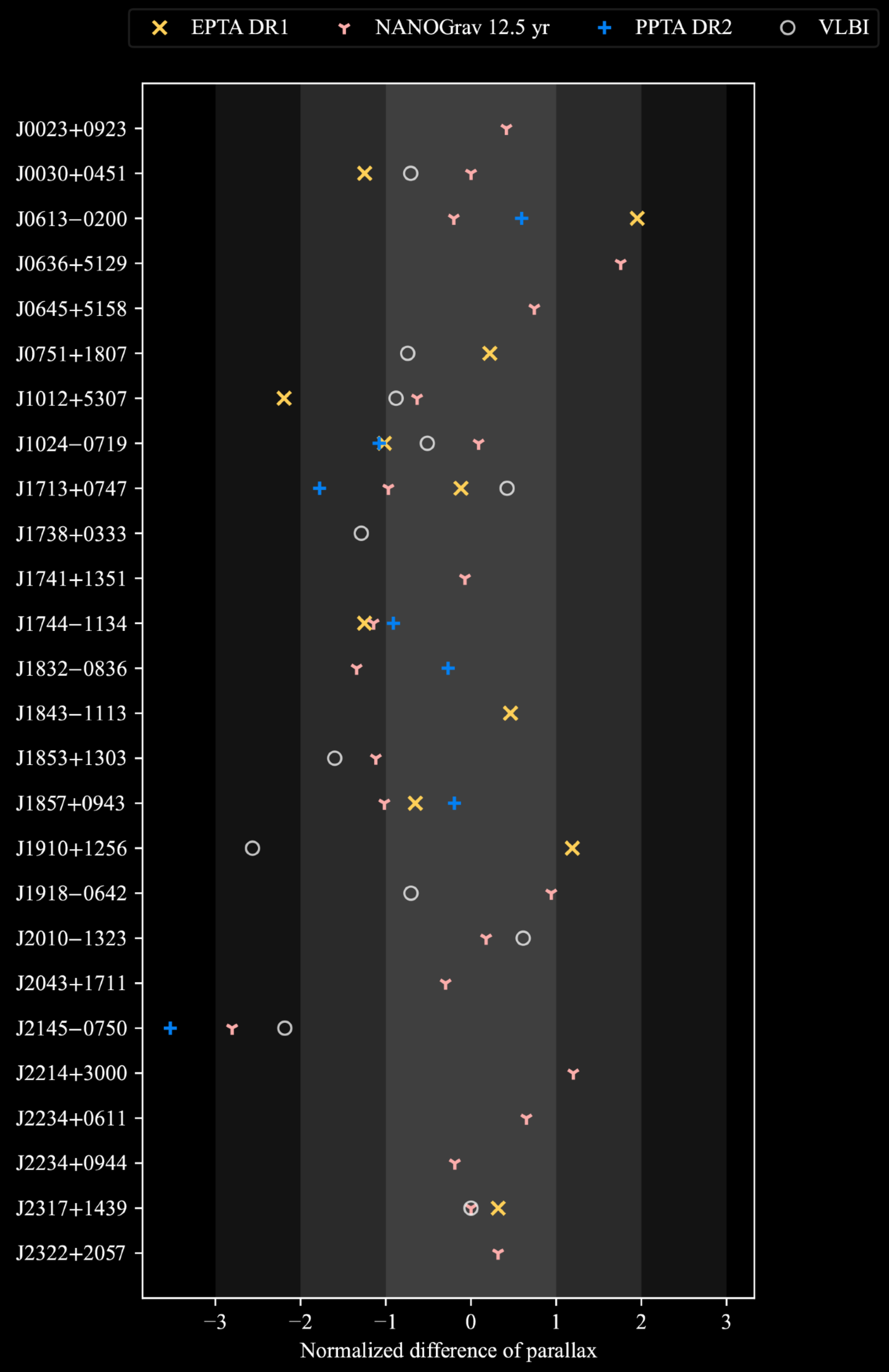
Proper Motion

- PM results from CPTA DR1 and other PTAs are very consistent, excepts for J1024-0719 and 3σ deviations for several pulsars.
- Further half-year data of J1024-0719 fix the discrepancy.
- Possible reasons: long orbital period and short data length, and the coverage of the data point is not good enough.



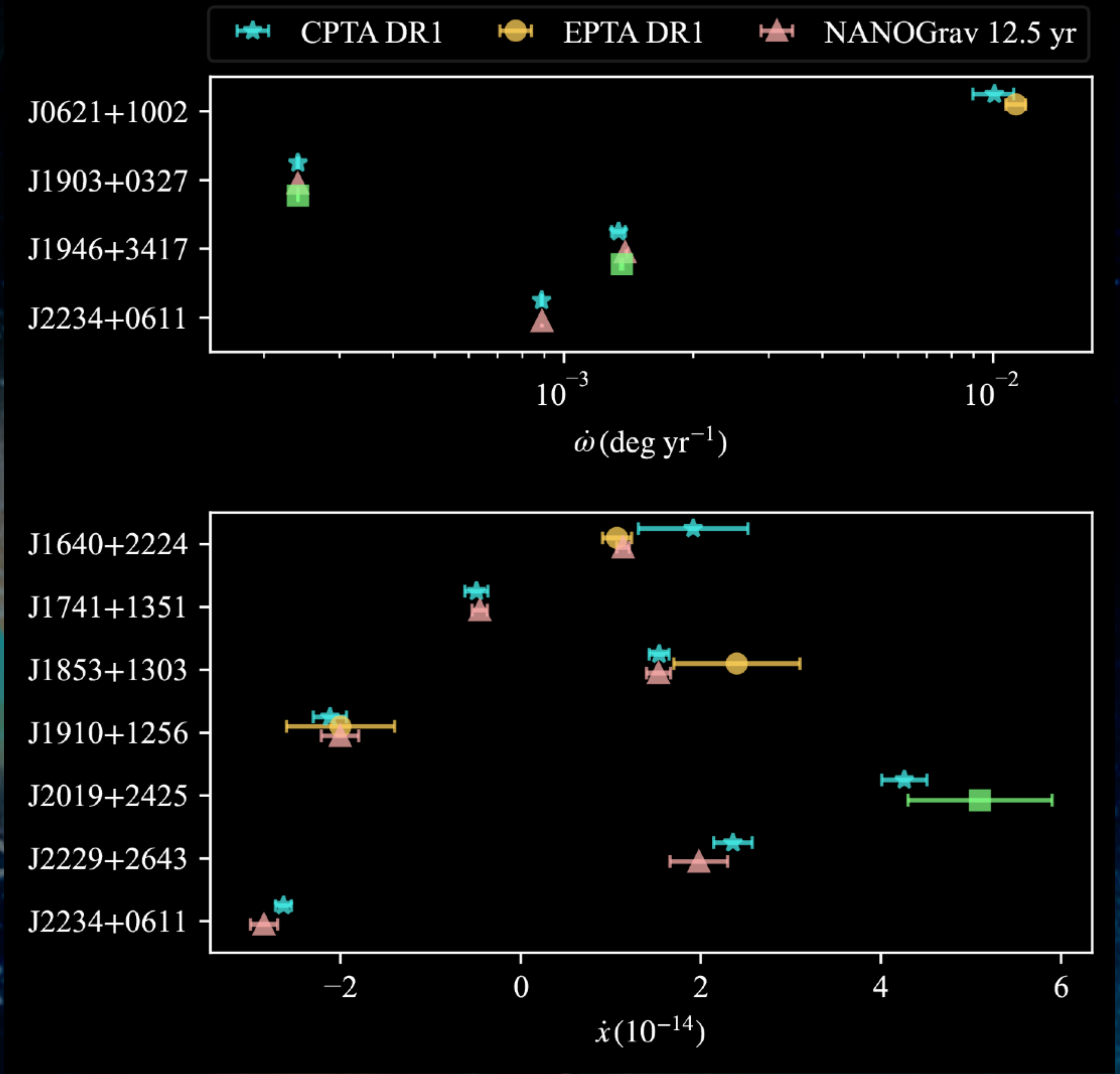
Parallax

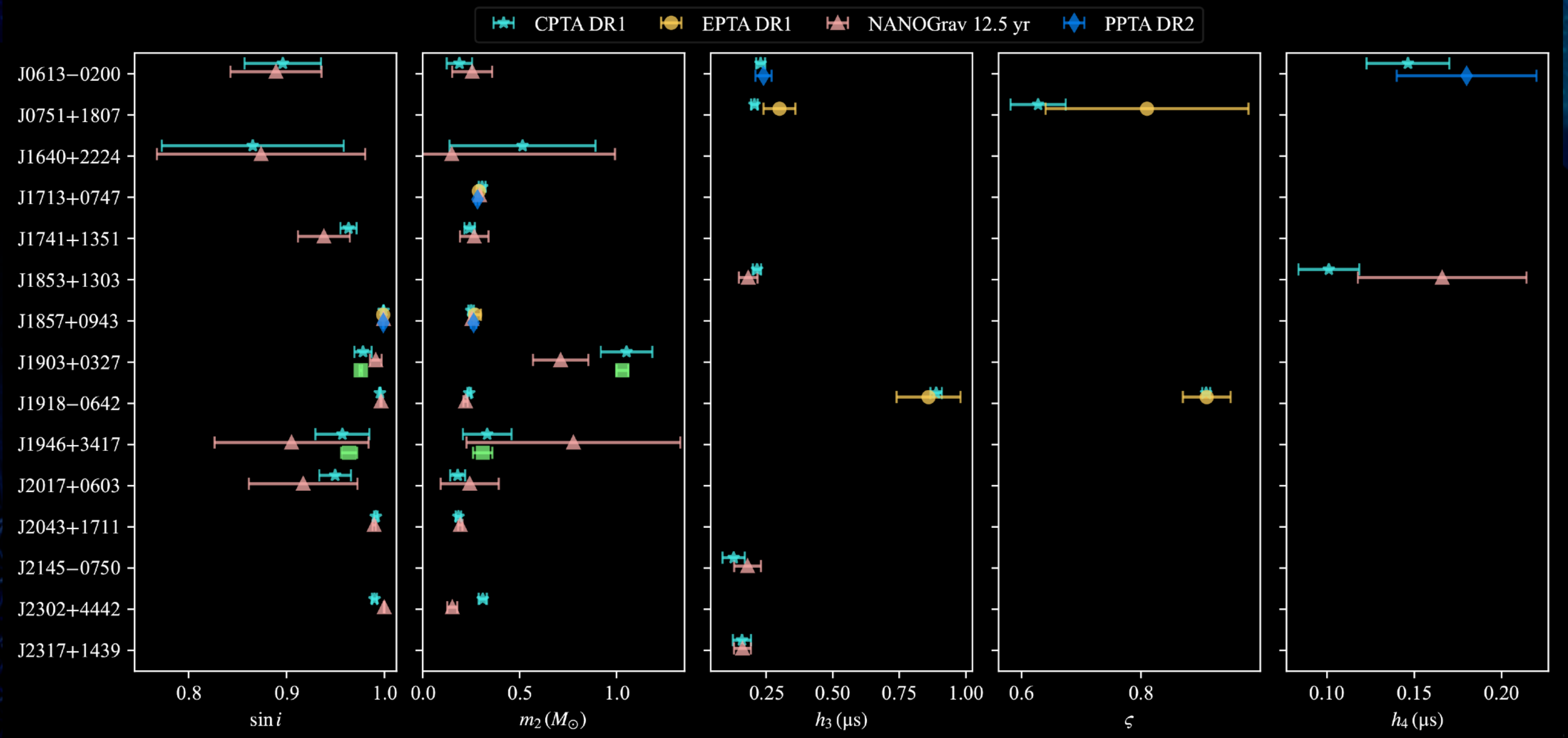
- Significant parallax measurements in 34 out of 57 pulsars.
- First parallax measurements for 8 pulsars, PSRs J0509+0856, J1911+1347, J1944+0907, J2017+0603, J2019+2425, J2033+1734, J2229+2643 and J2302+4442.
- 15 measurements are improvements on previous results.
- PSR J1012+5307, our value differs from EPTA DR1 for 2.2σ.
- PSR J2145-0750, our result differ from NANOGrav12.5 for 2.8σ, PPTA DR2 for 3.5σ and VLBI for 2.1σ.
- Probably due to difference in red noise modeling and DM variation modeling.



Post-Keplerian Parameters

- Measuring the secular variations terms strongly depends on the data span.
- We Measured PK parameters in 24 among the 40 binaries.
- PBDOT not measurable in the 2-3 years dataset except for high order of derivatives in these black widow pulsars.





Damour & Taylor 1992

TABLE II. Dependence of fractional parameter uncertainties on T^a and $(P_b)^b$, computed by numerical simulations and by analytical approximations.

Parameter	*a* Numerical	*a* Analytical	*b* Numerical	*b* Analytical
$\dot{\omega}$	−1.3	−3/2	1.1	1
γ	−1.5	−3/2	1.4	4/3
$\dot{P}_b$	−2.3	−5/2	3.0	3
r	−0.5	−1/2	0.0	0
s	−0.5	−1/2	0.0	0
δ_θ	−2.3	−5/2	3.2	10/3

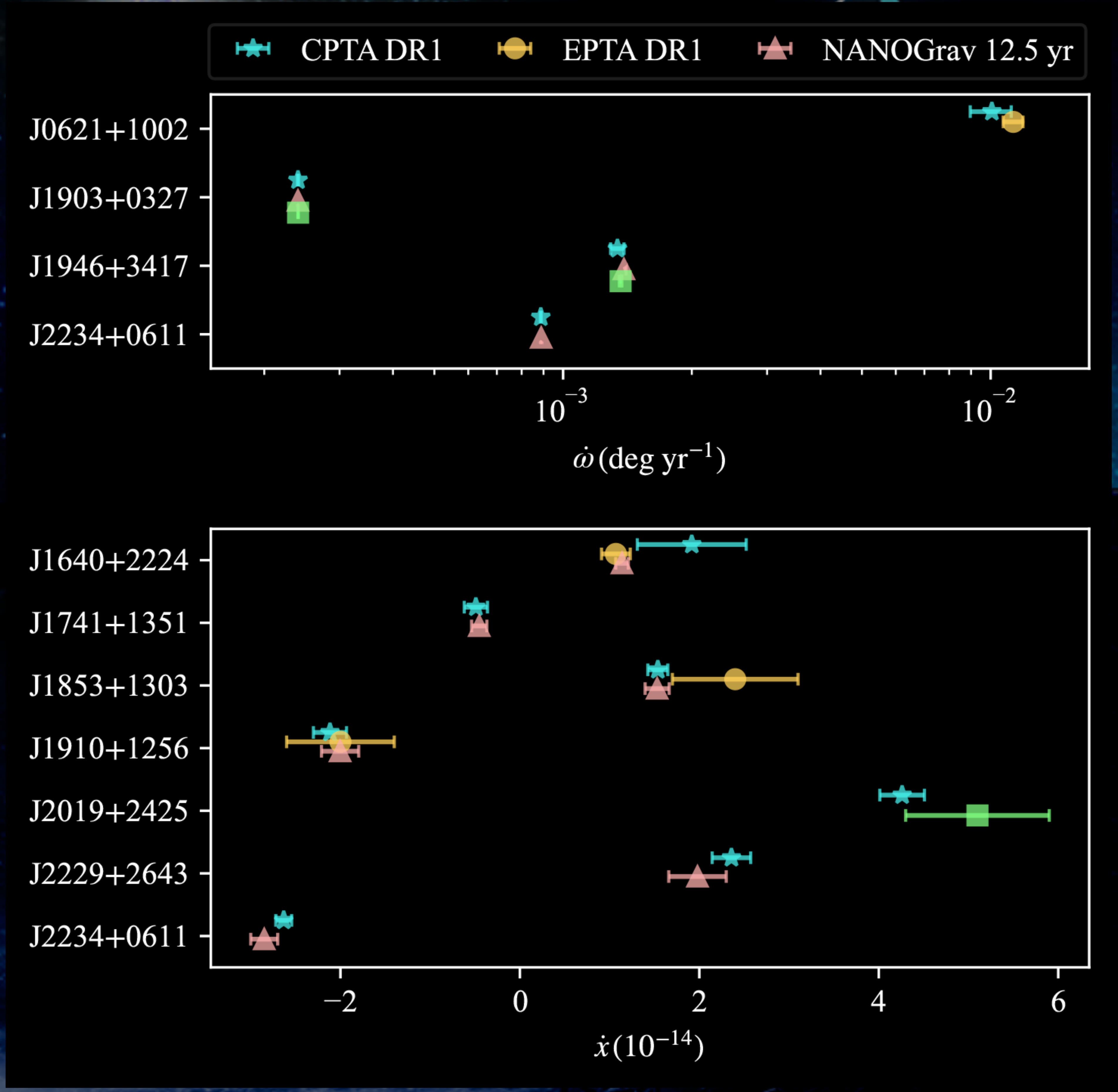
OMDOT and XDOT

- The omdot measurements are comparable for less precise with previous works.

- xdot mainly contributed by the proper motion of the system, and can be used to constrain the inclination angle of binary systems.

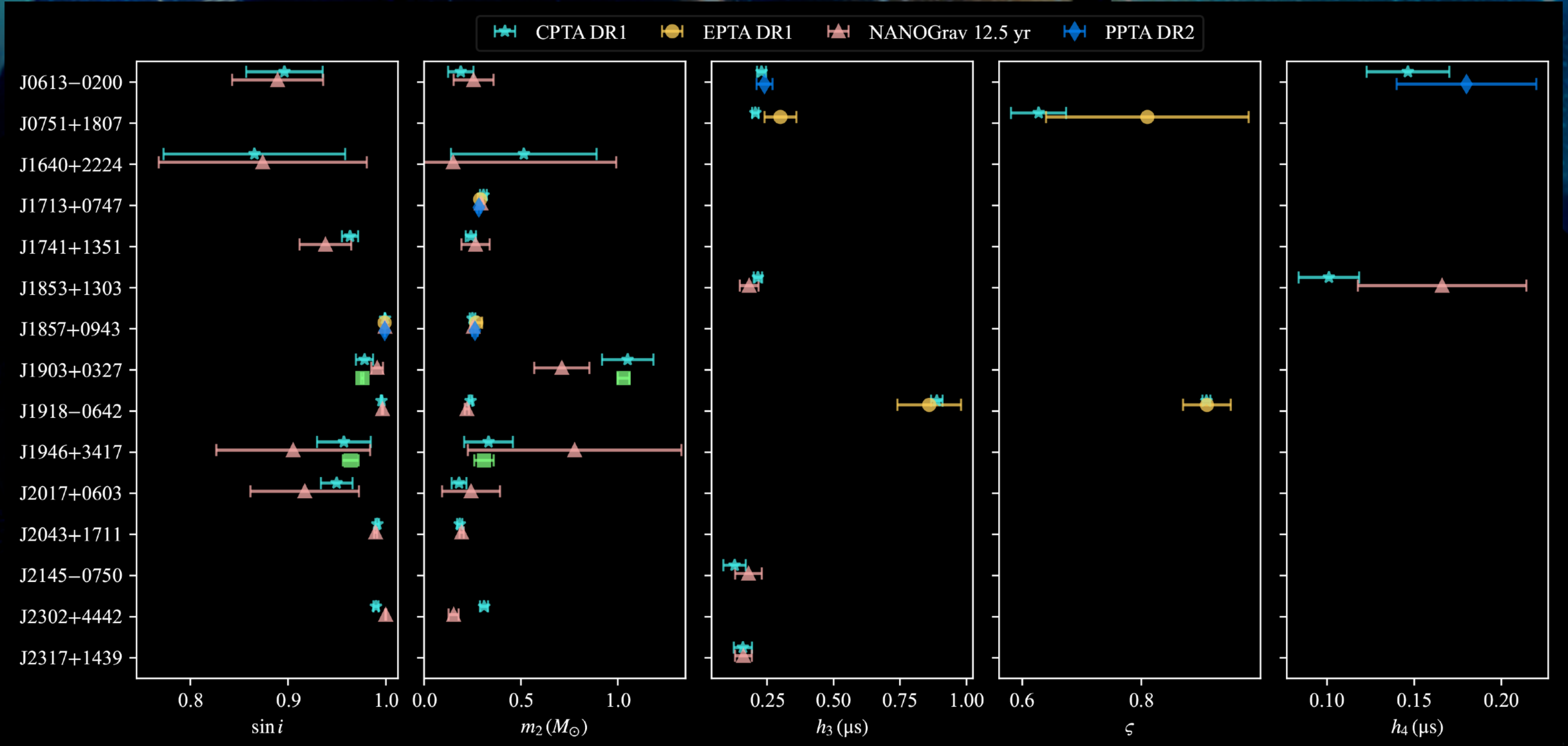
$$i < \arctan\left[\frac{x\mu}{|\dot{x}|_{\rm obs}}\right]$$

- The upper limits of orbital inclination angle i at 95% confidence interval are I<57.5 deg, I<53.1 deg, I<74.3 deg, I<42.6 deg and I<67.0 deg for PSRs J1853+1303, J1910+1256, J2019+2425, J2229+2643 and J2234+0611 respectively.



Shapiro Delays

- We have measured significant Shapiro delay elements in 19 binary pulsars, and detect only first harmonic signal in 3 binary systems.
- For six pulsars among the 19 binaries (PSRs J0218+4232, J1630+3734, J1910+1256, J2019+2425, J2150-0326 and J2234+0611), the detections are for the first time.
- Most of these measurements are consistent with other PTAs or former other results.
- The only exception is J2302+4442, CPTA DR1 results do no agree with NG12.5yr results: CPTA DR1 gives a pulsar mass of 1.46±0.16 solar mass; where NG12.5yr results indicate Mp=0.45±0.12 solar mass.



Summary

- CPTA DR1 contains 57 MSPs, data length is about 2.5 years.
- Noise analyses using different pipelines give consistent results.
- We got very high timing precision data.
- Parallax measured in 34 out of the total 57 pulsars.
- Post-Keplerian parameters measured in 24 binary systems, including several first measurements of Shapiro delays.
- Results pulsar parameters from CPTA DR1 are broadly consistent with previous works (PTAs and VLBI).

Thank you!