Chinese pulsar timing array (CPTA)

K. J. Lee on behalf of the collaboration

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Outline

- Background
- Science from pulsar observation
- Science from pulsar timing observation
- GW detection and future

CPTA

- 2003 propose to build 50m Miyun for PTA by Shouguan Wang
- 20 Sept. 2019, Second CPTA meeting, before FAST commissioning, agreed to form the CPTA
- Finalised and agreed on the CPTA policy

Quick guide to the GW detection using pulsar timing array

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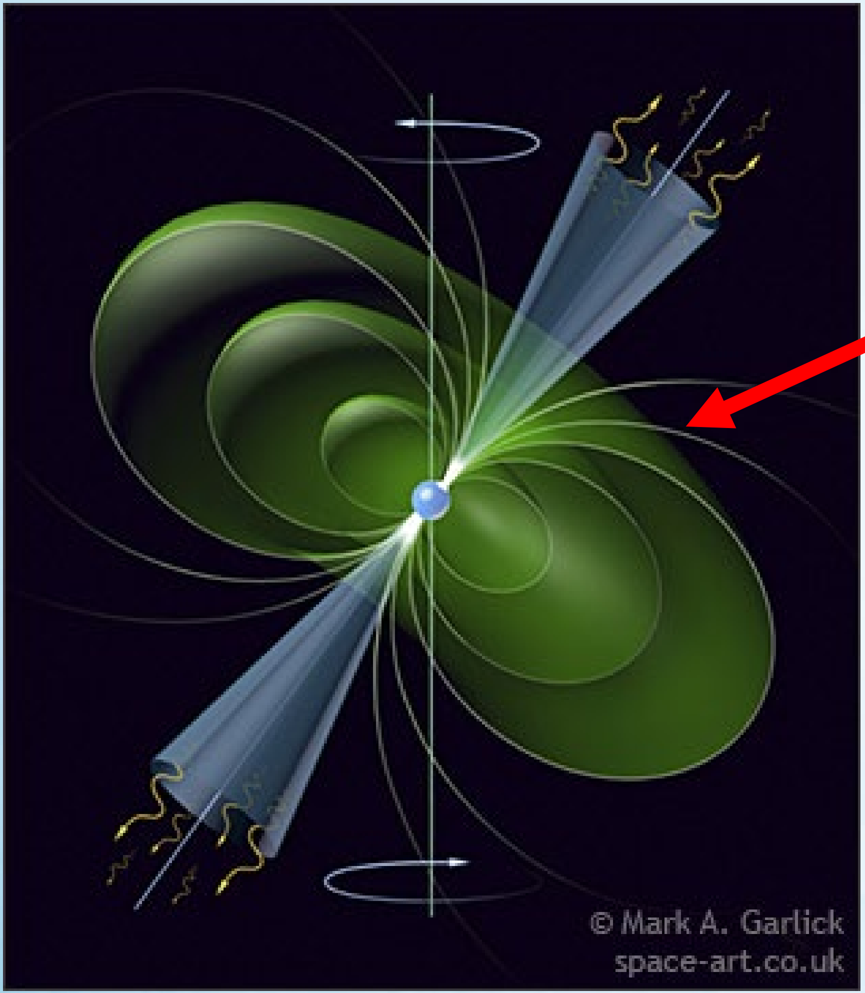
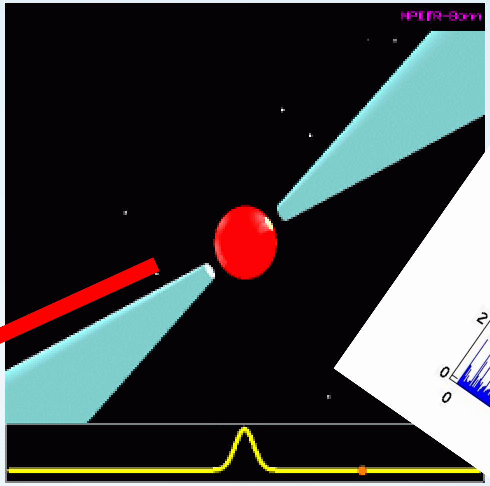
Phenomenology model





Frankly speaking, we do not know how pulsar radiates.

But the pulse time of arrivals are so accurate.

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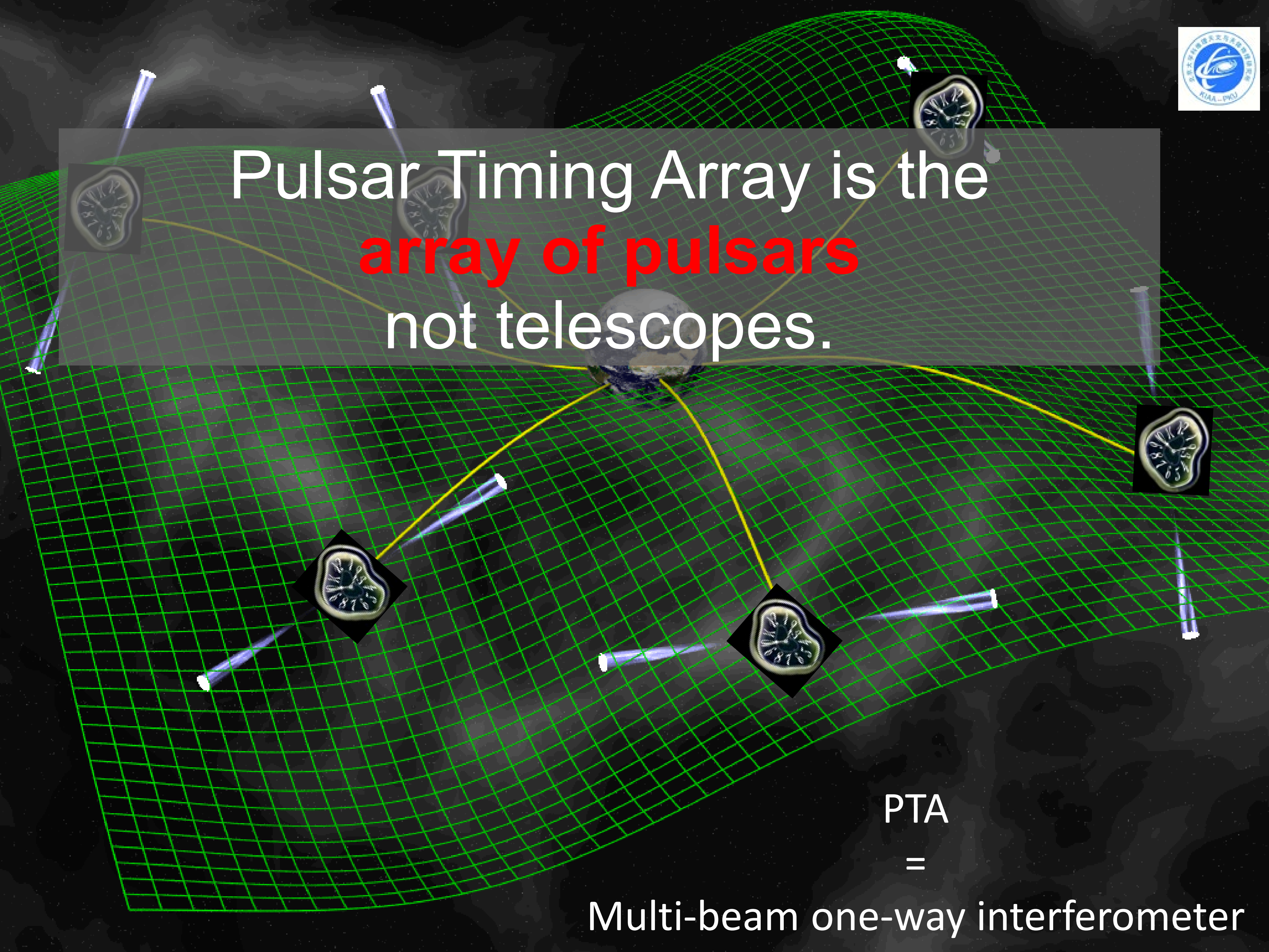
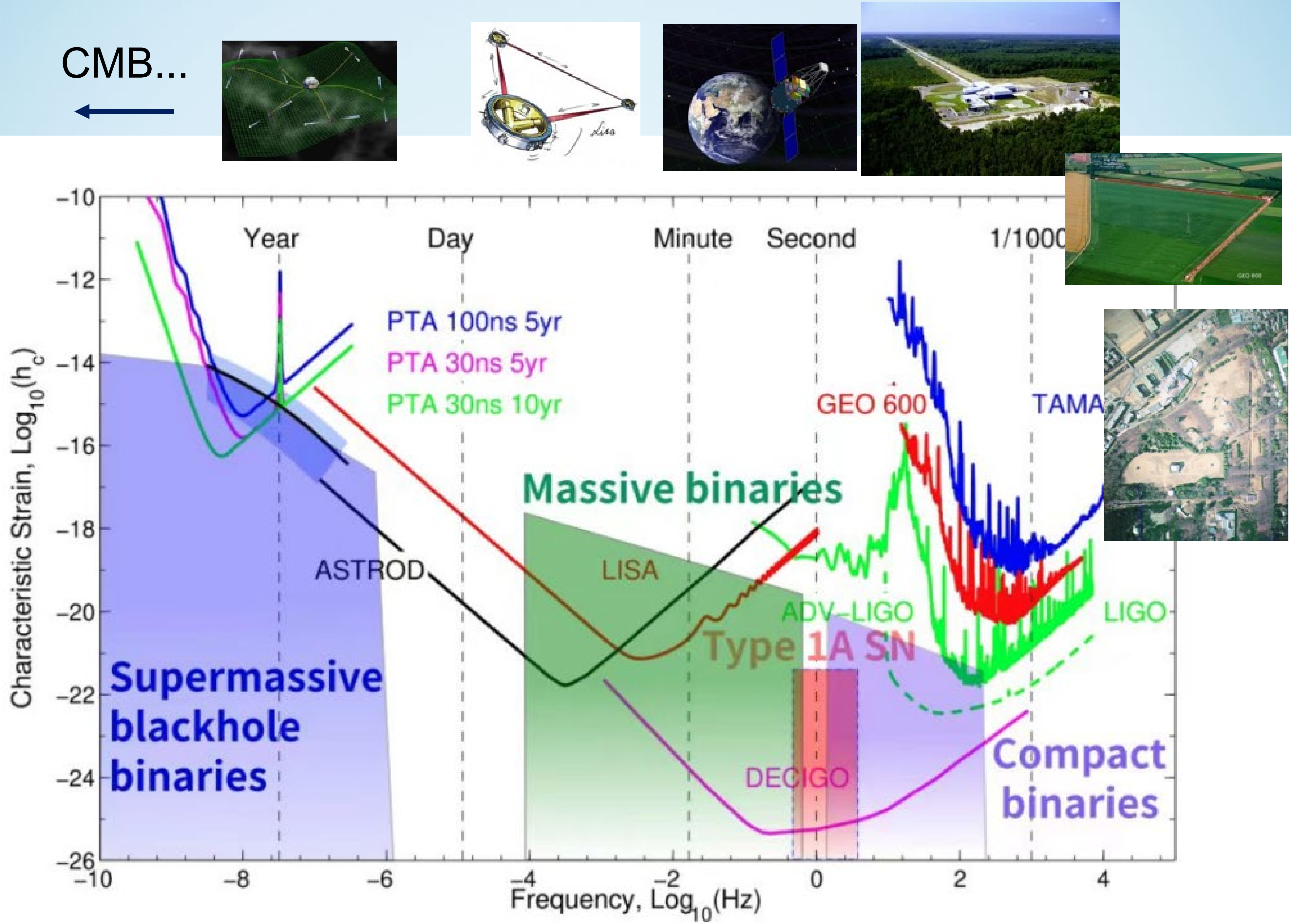


Pulsar Timing Array is the **array of pulsars** not telescopes.

PTA

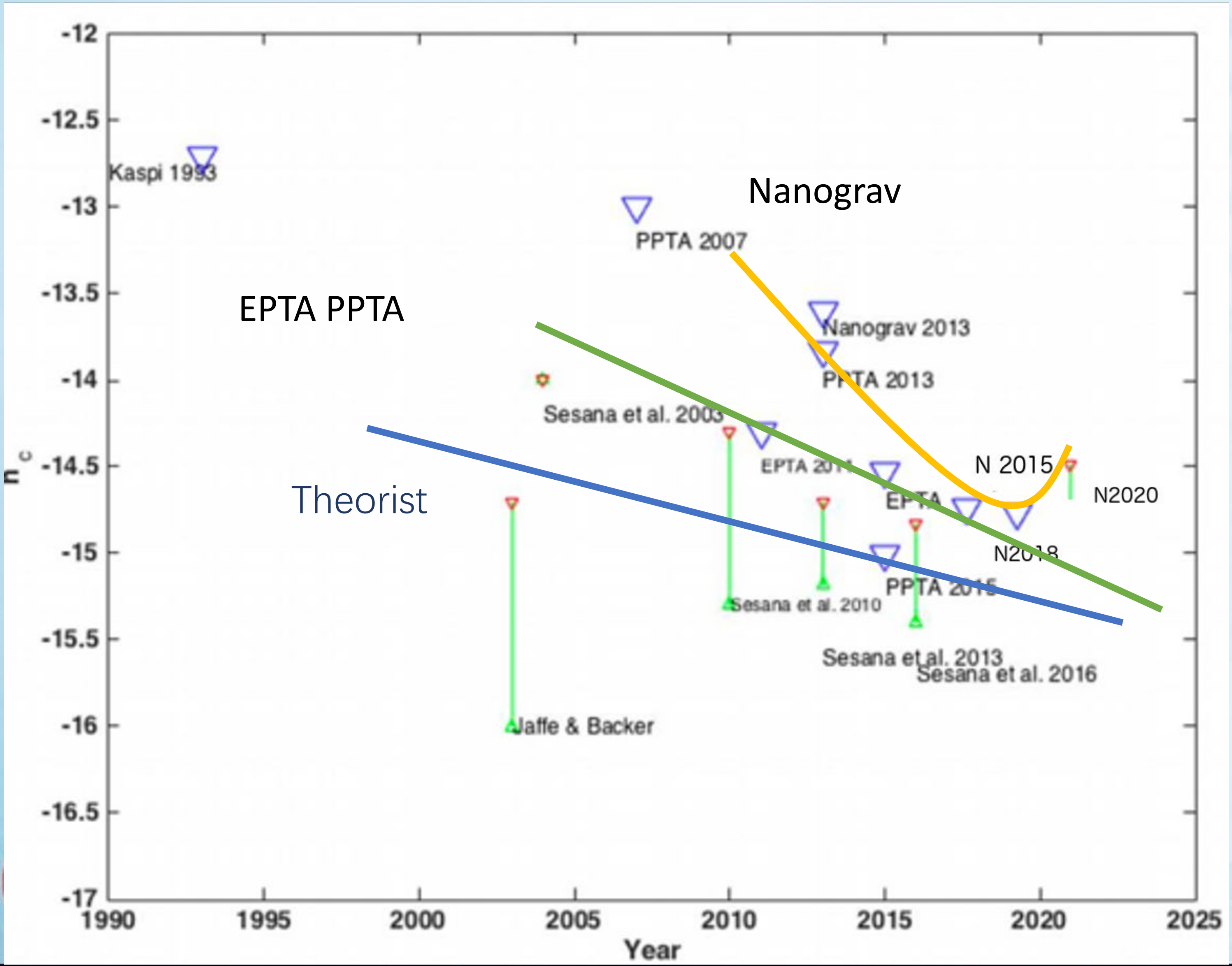
=

Multi-beam one-way interferometer


CMB...
Year
Day
Minute
Second
1/1000
PTA 100ns 5yr
PTA 30ns 5yr
PTA 30ns 10yr
GEO 600
TAMA
Massive binaries
ASTROD
LISA
ADV-LIGO
LIGO
Type 1A SN
Supermassive blackhole binaries
DECIGO
Compact binaries
Characteristic Strain, Log10(hc)
Frequency, Log10(Hz)
−10
−12
−14
−16
−18
−20
−22
−24
−26
−10
−8
−6
−4
−2
0
2
4

Where we were 2022?

Good news, Theorists low the bar slower than observation.
Bad news, Observer may contradict with eachother.



When to detect?

When?

---20 pulsar 100ns 5 year

IPTA now

--40 pulsar， 2-3 achive 200ns, but much much more data points

Key issue

--SNR limited the precision

THE ASTROPHYSICAL JOURNAL, 625:L123–L126, 2005 June 1

DETECTING THE STOCHASTIC GRAVITATIONAL WAVE BACKGROUND USING PULSAR TIMING

FREDRICK A. JENET,[1] GEORGE B. HOBBS,[2] K. J. LEE,[3] AND RICHARD N. MANCHESTER[2]
Received 2005 February 13; accepted 2005 April 19; published 2005 May 9

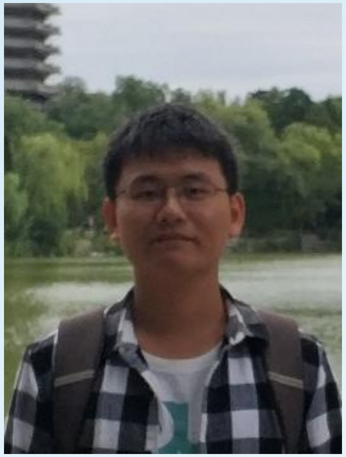
ABSTRACT

The direct detection of gravitational waves is a major goal of current astrophysics. We provide details of a new method for detecting a stochastic background of gravitational waves using pulsar timing data. Our results show that regular timing observations of 40 pulsars each with a timing accuracy of 100 ns will be able to make a direct detection of the predicted stochastic background from coalescing black holes within 5 years. With an improved prewhitening algorithm, or if the background is at the upper end of the predicted range, a significant detection should be possible with only 20 pulsars.

Subject headings: gravitational waves — pulsars: general

Current core team

Zihan Xue
PhD



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Bojun Wang
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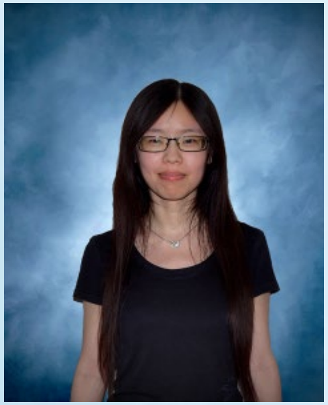
Jinchen Jiang
Post-Doc

Nicolas Caballero Post-Doc



Yanjun Guo
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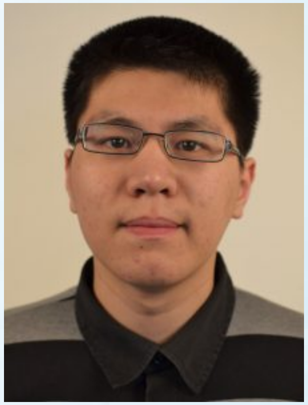

Siyuan Chen
Post-Doc

Kejia Lee
Technician

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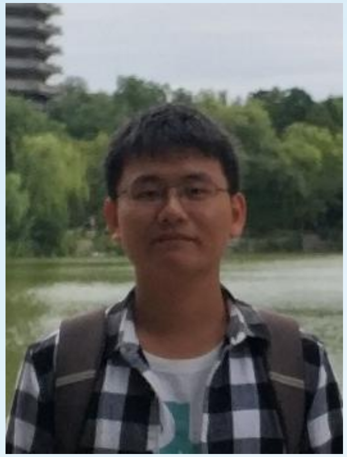
Current core team

Single source and axion

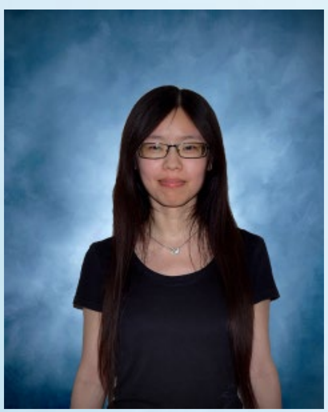


Cosmic string and dark matter

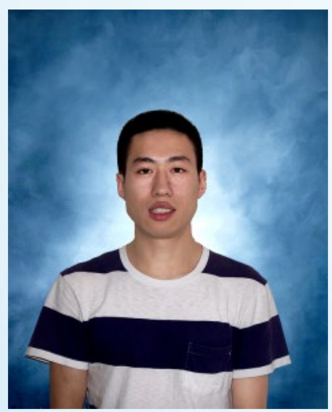
Single pulse and jitter

Polarisation and interferometry and designed CPTA logo

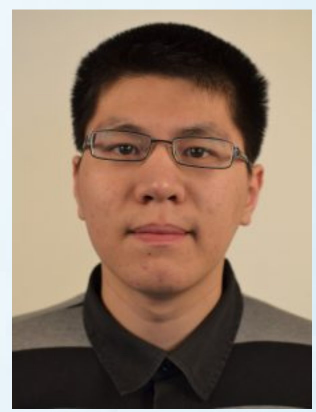
Nicolas Caballero
Targeted source



GW background



Observation timing and noise analysis



GW background

Technical and educational supports

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Current CPTA data

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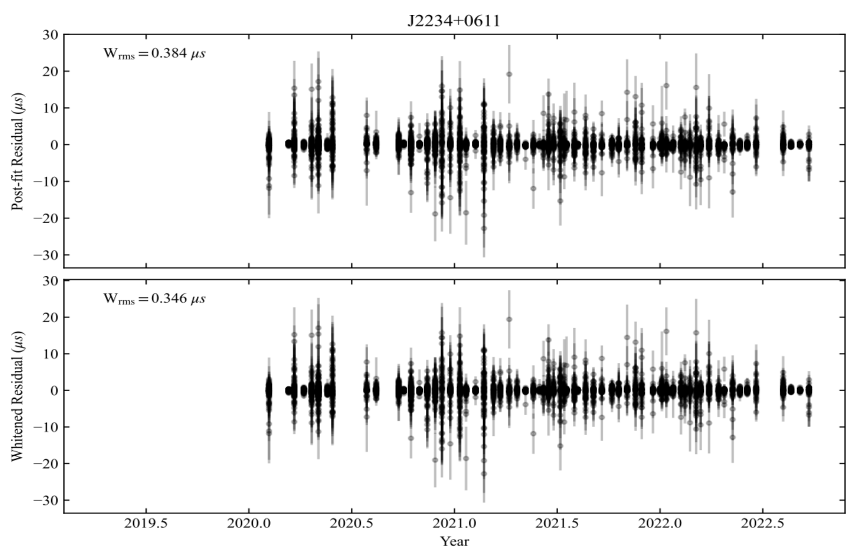
CPTA-DR1

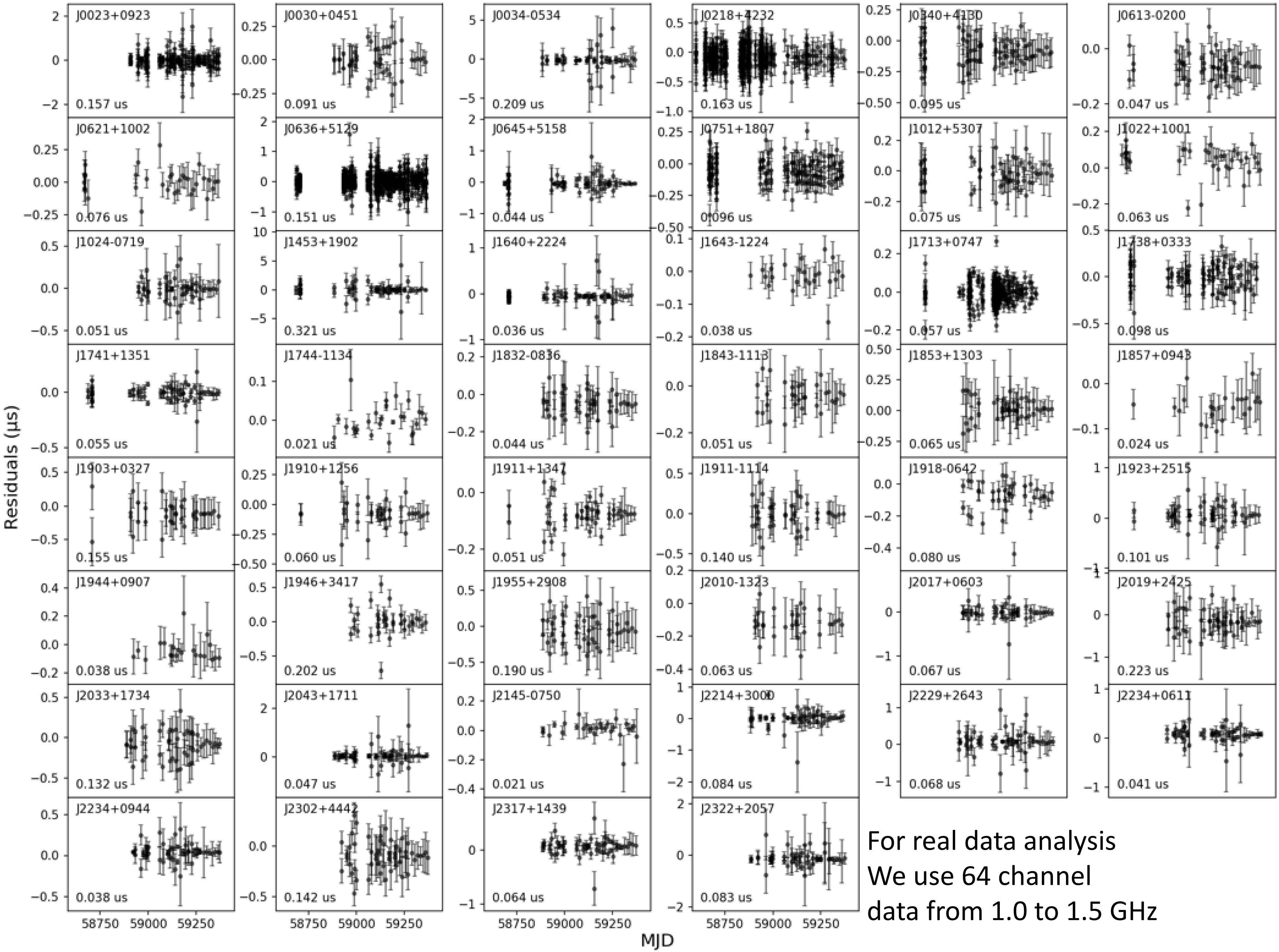
~3.4 years length

100ns for ~35 pulsars, and
200ns for ~55 pulsars.

All polarization calibrated



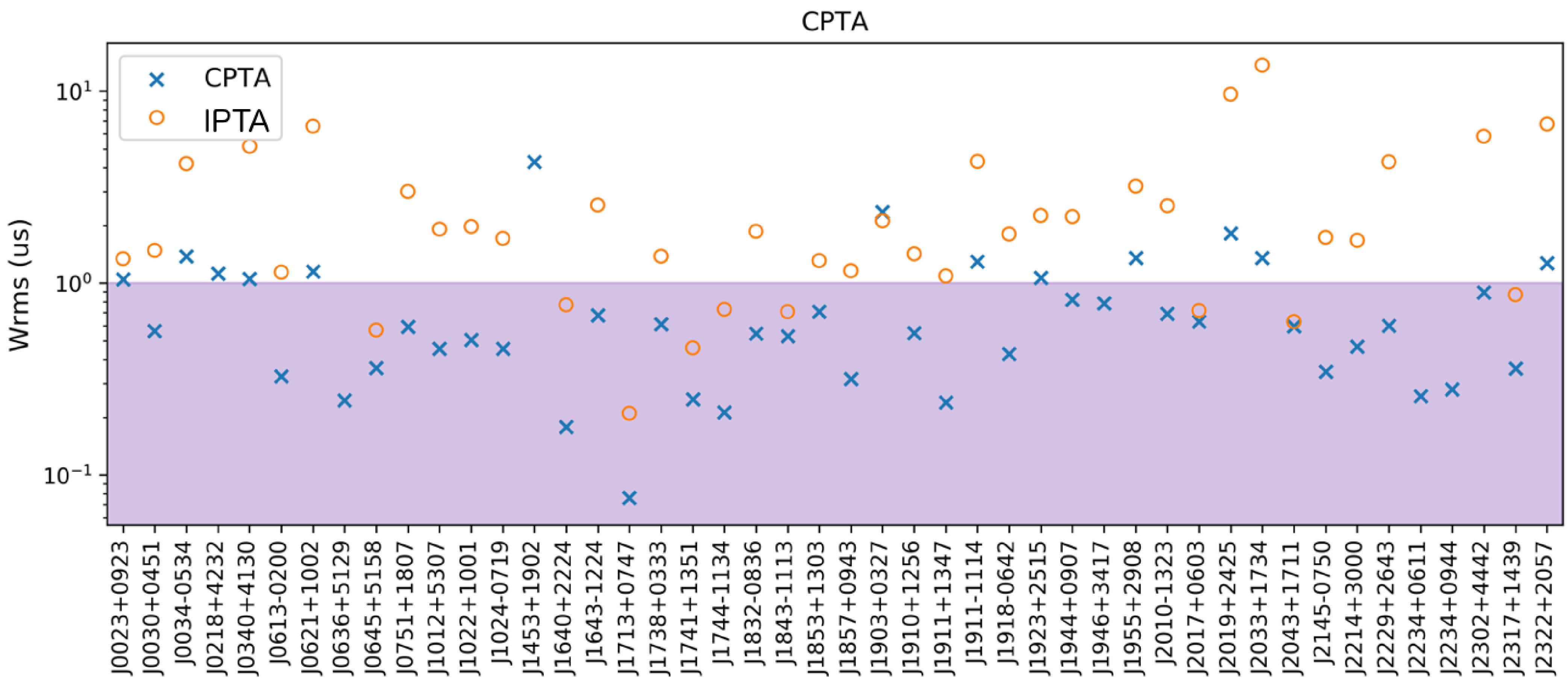
Pulsar J2000	EQUAD	ECORR	DMNoise	RedNoise
J0023+0923		√	√	√
J0030+0923		√	√	√
J0034+0923			√	√
J0154+0923		√		√



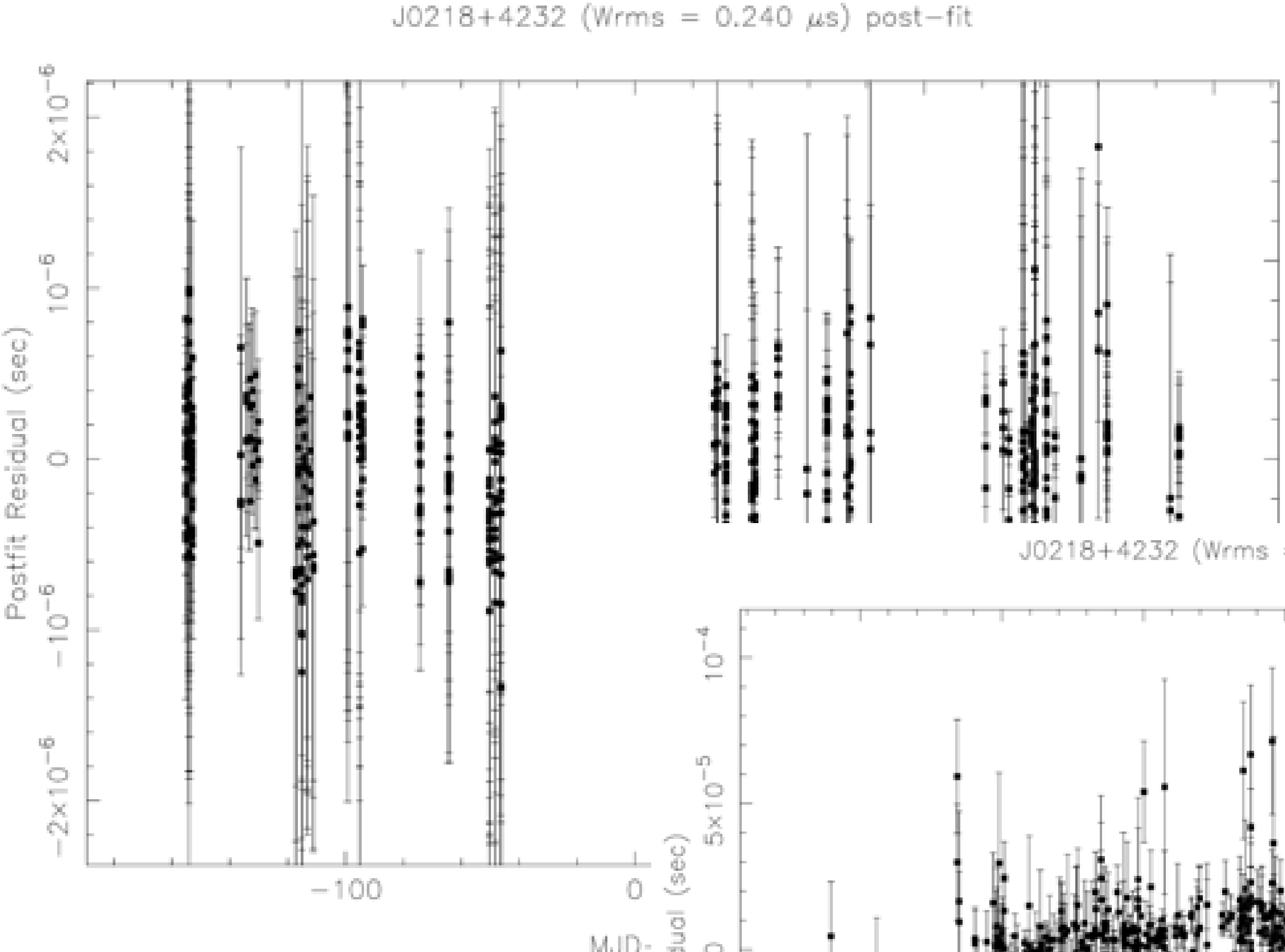
For real data analysis
We use 64 channel
data from 1.0 to 1.5 GHz

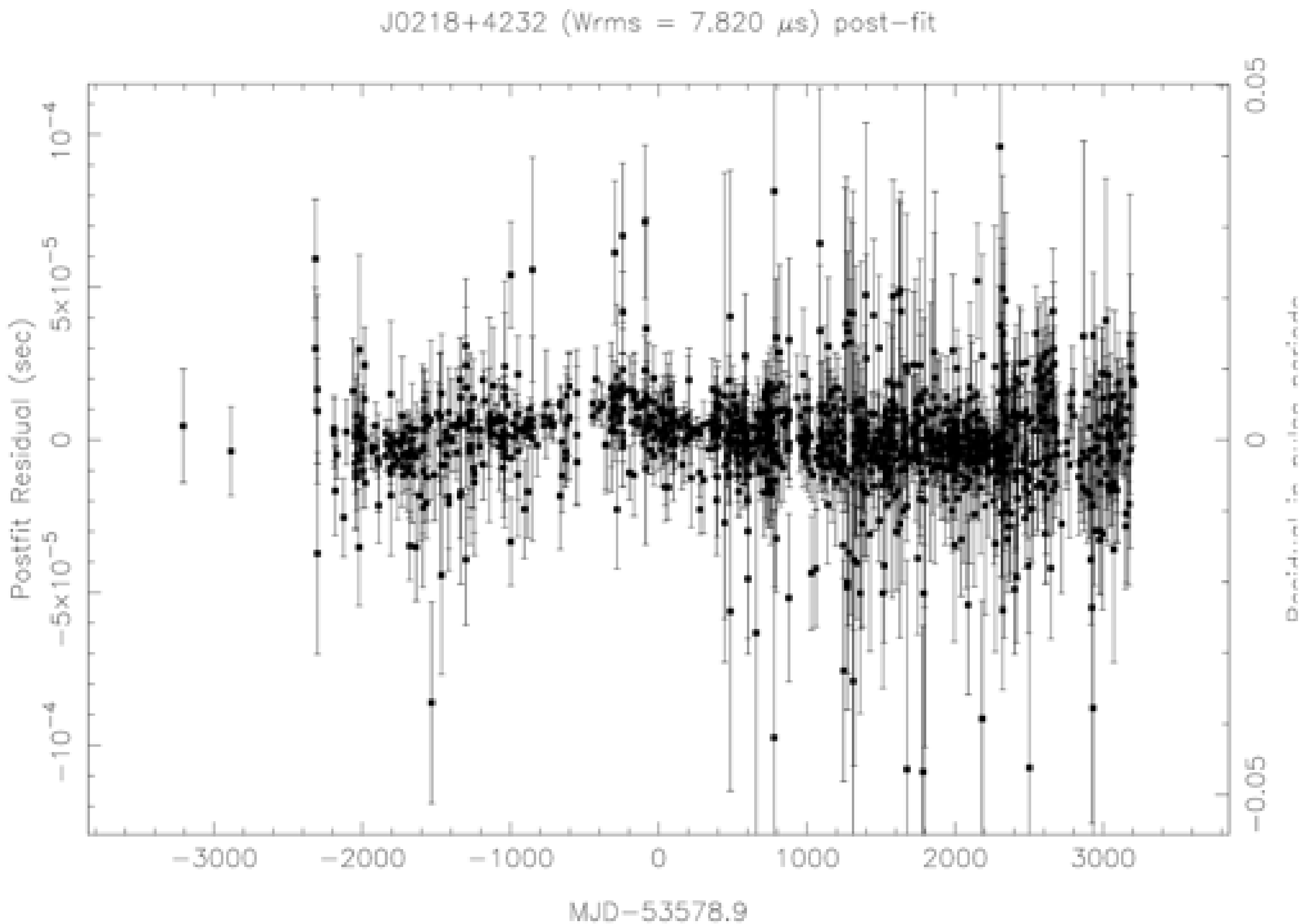
Data quality

CPTA achive facotr of 4 to 50 improvement of precision compare to best internation data set.



FAST





IPTA DR 2.0

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Science from pulsar observation

CPTA polarimetry

FAST polarimetry

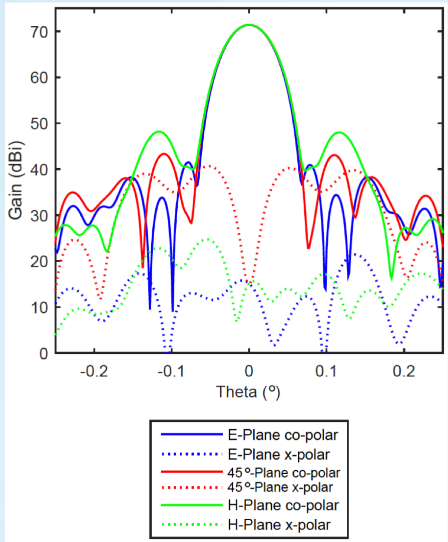
Low feed leakage

easy to calibrate

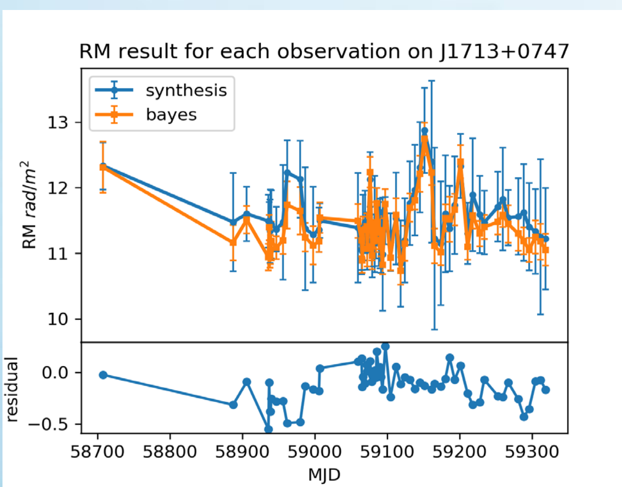
Fitting RM

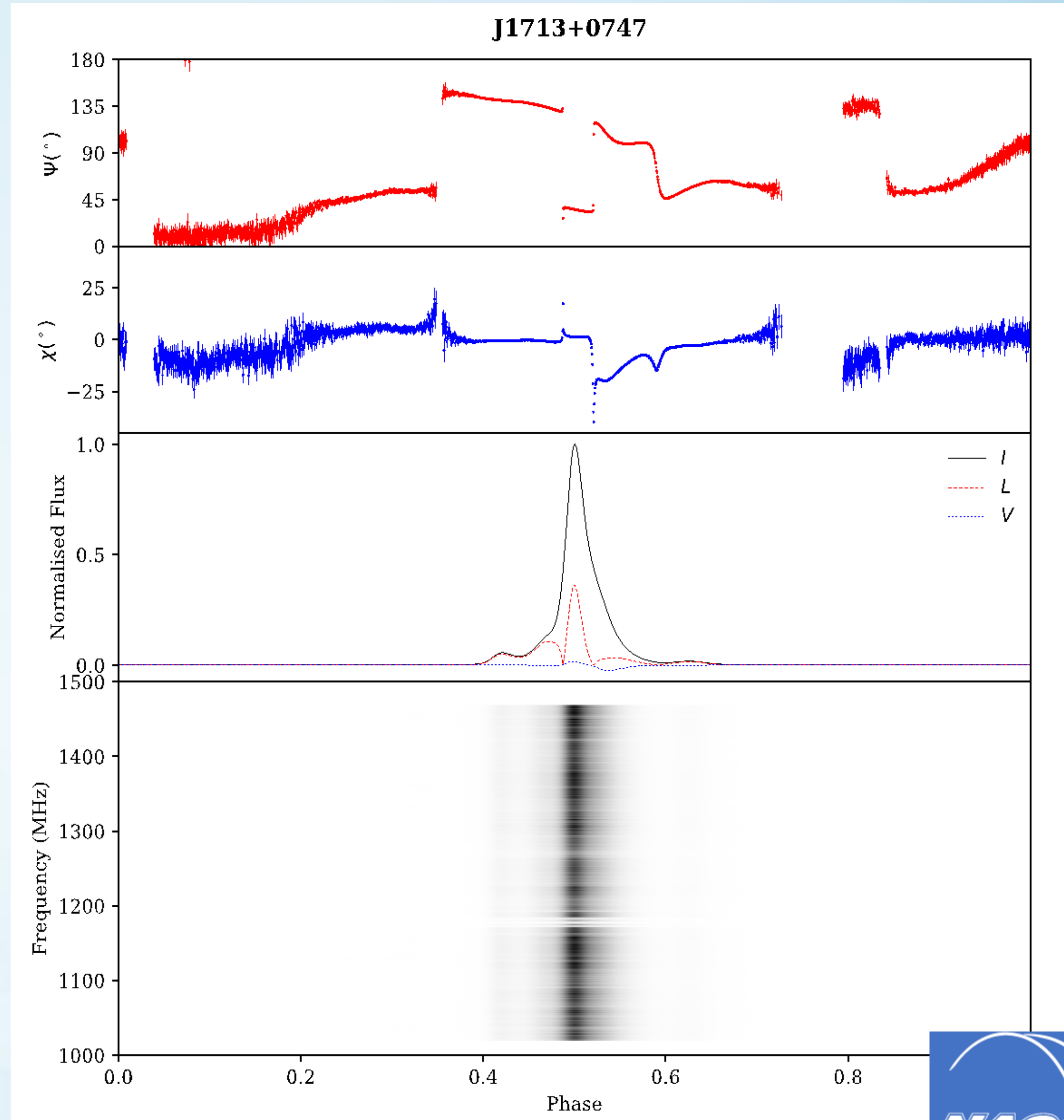
RM synthesis

Bayesian method



(Dunning et al. 2017)





Some pulsars are 360-degree emitter

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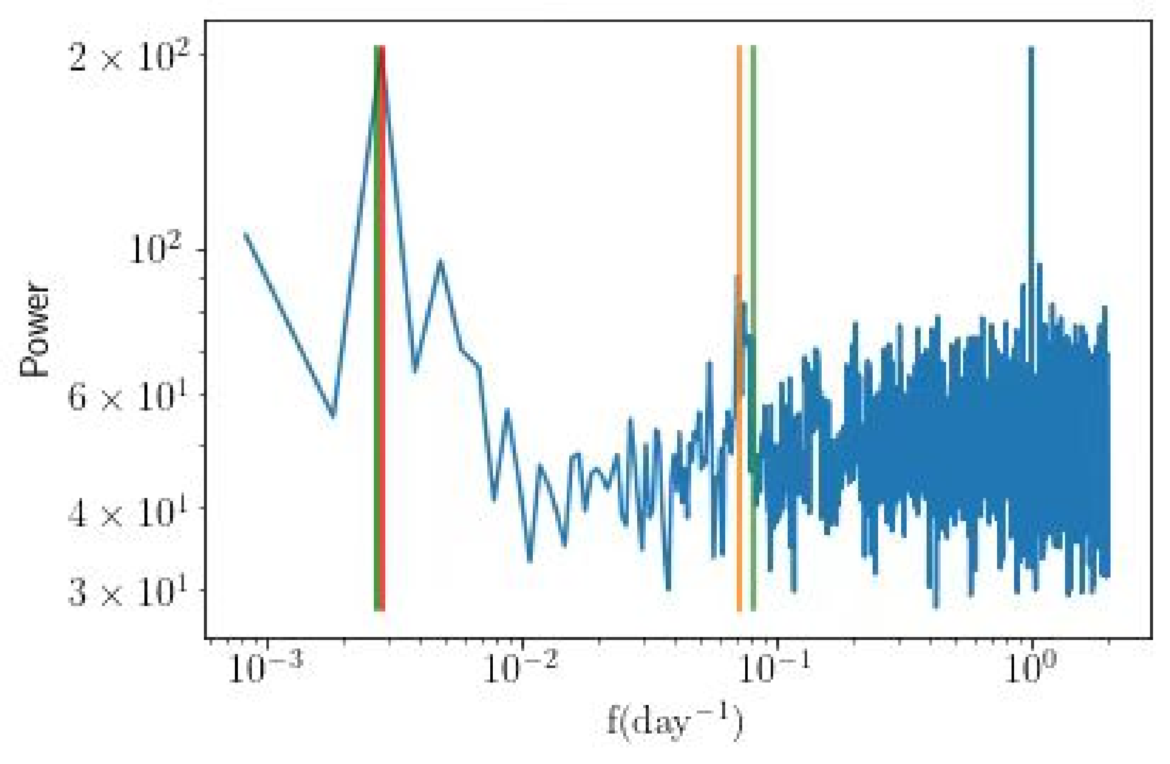
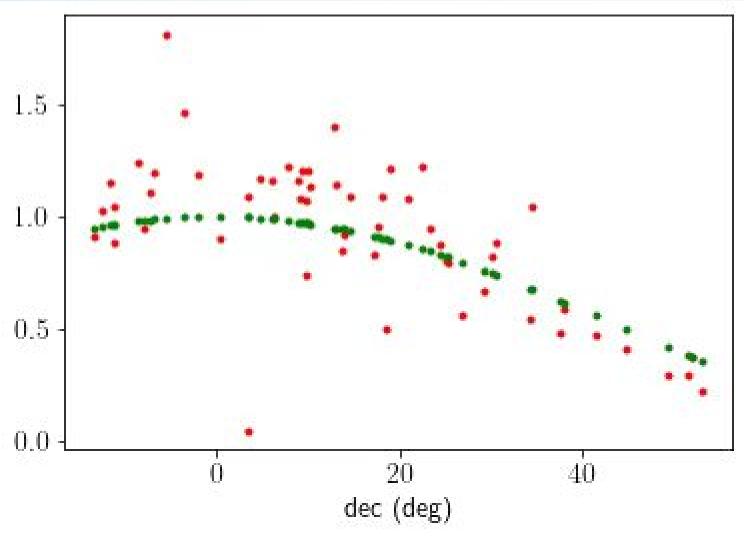
Probing the ionosphere

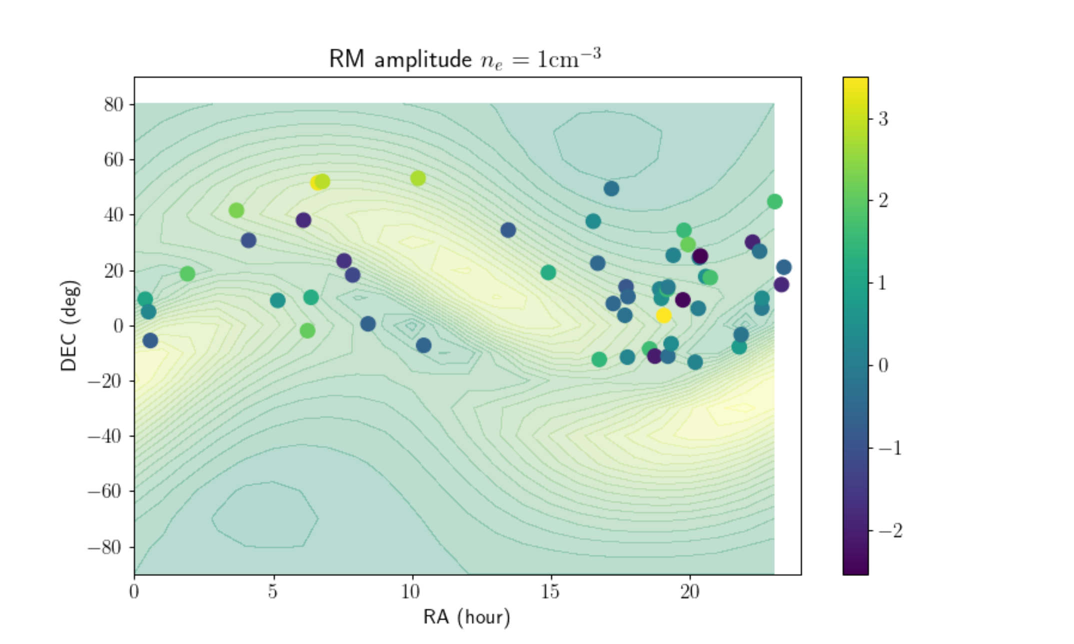
- Standard software IonFR **over estimates** the RM variation by a factor of 2-3 for high dec sources.
- We implement the **IONOF**, it produces nearly the same answers compared to IonFR
- **TEC is problematic**, different TEC model differs by more than factor of 2.
- We **saw 1-year and 28/2-days RM variation**. Indication solar wind –earth magnetosphere interaction is important for sub 1 Rad/m^2 RM precision

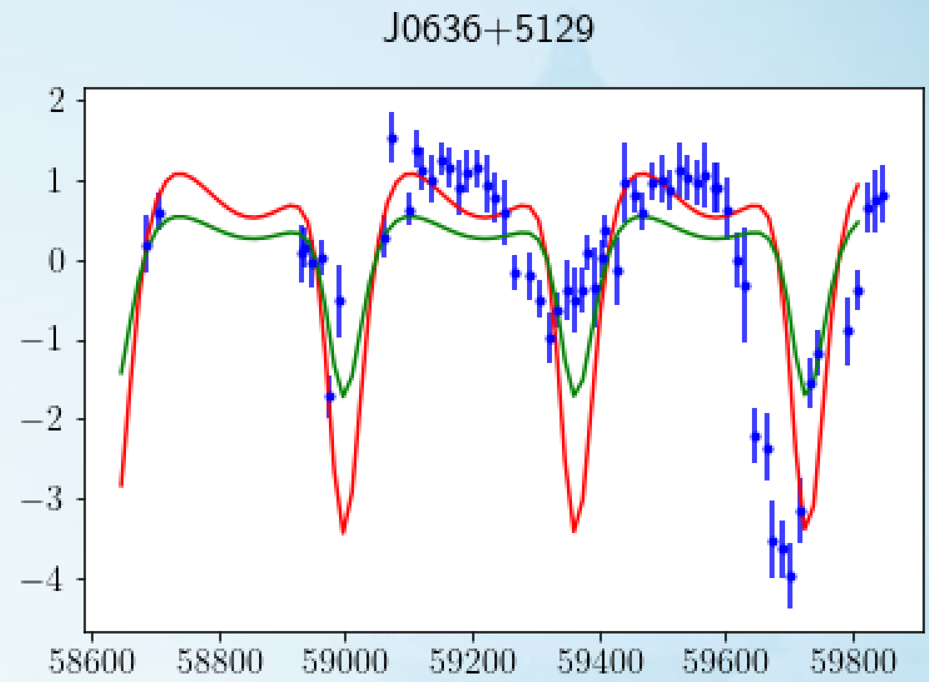


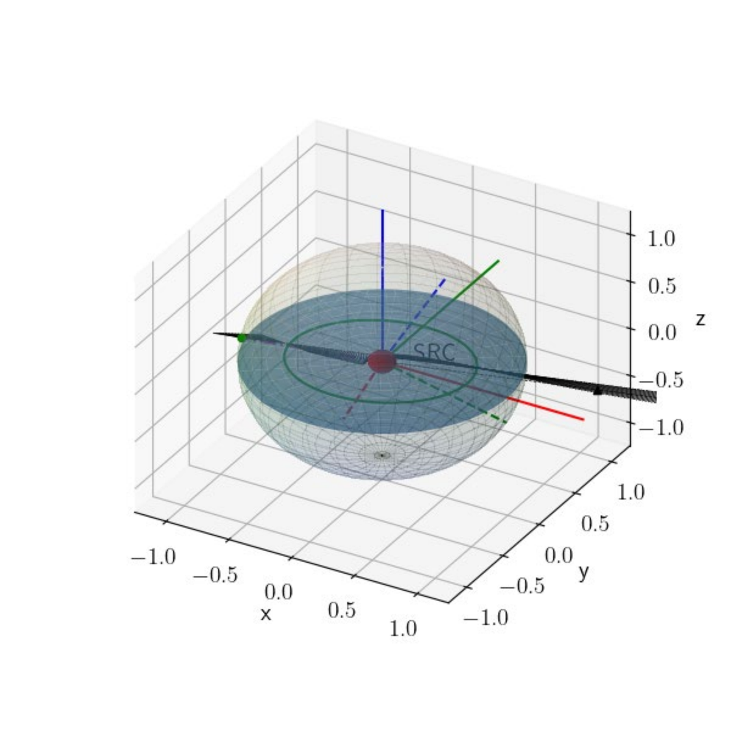


Xu et al., 2023 in prep

Solar system RM modeling



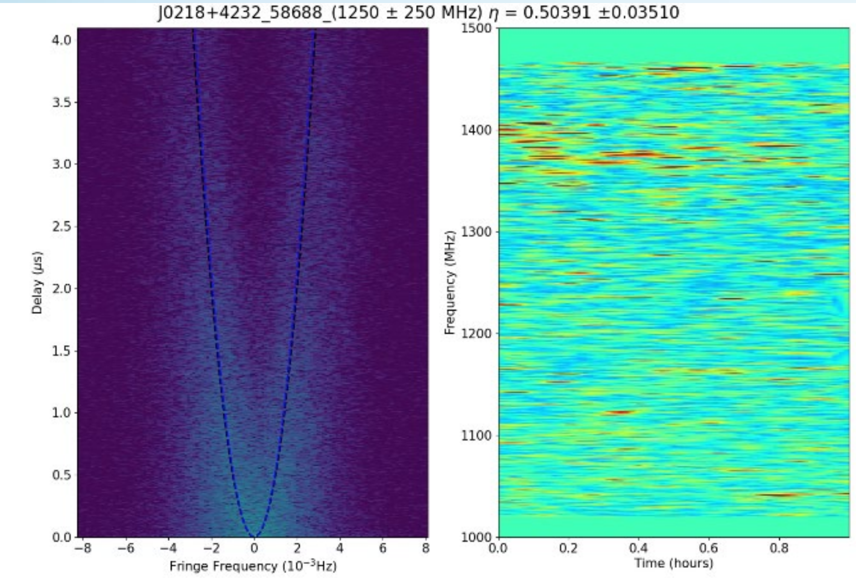


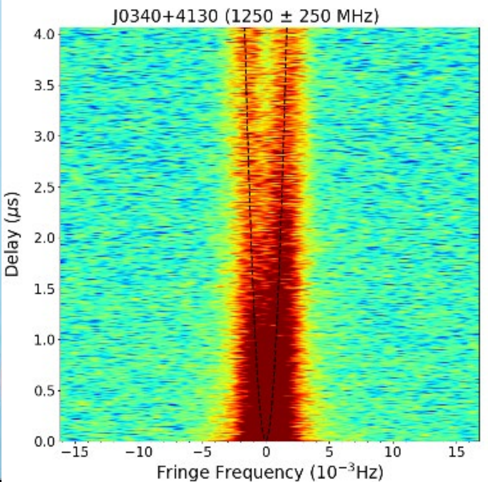


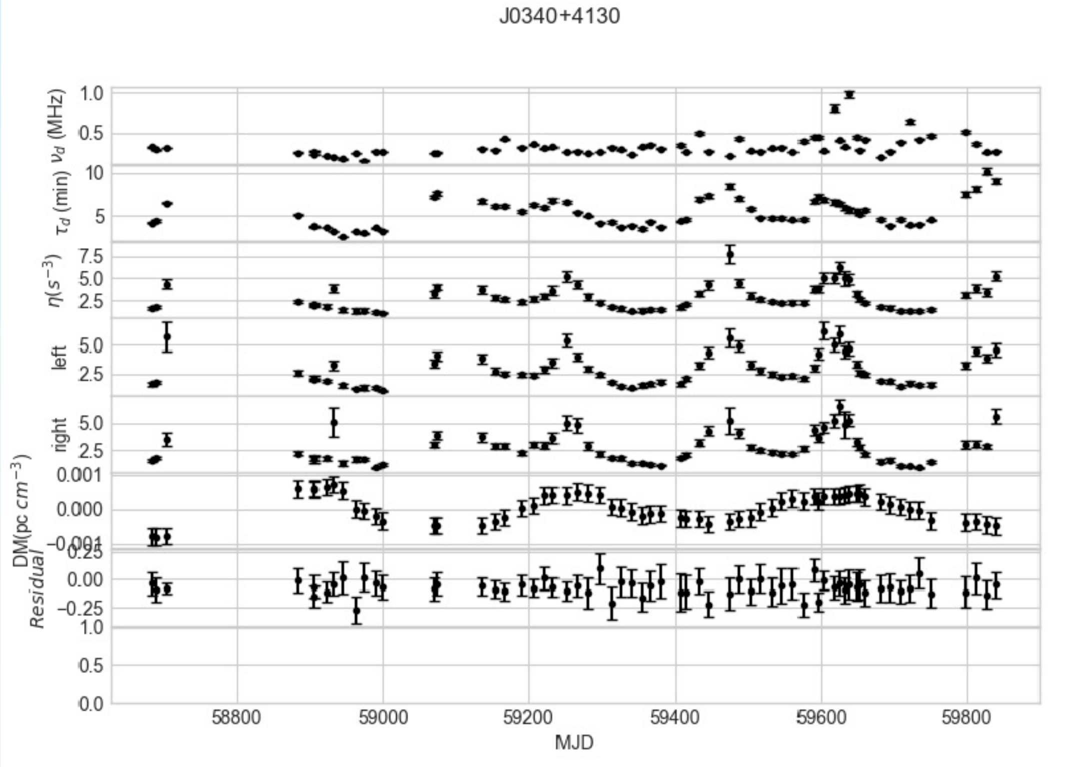
The naïve model can fit observation. However, one artificially requires 100-1000 times higher electron density or B field in the solar wind. It seems that we need consider the solar-wind-earth magnetosphere interaction.

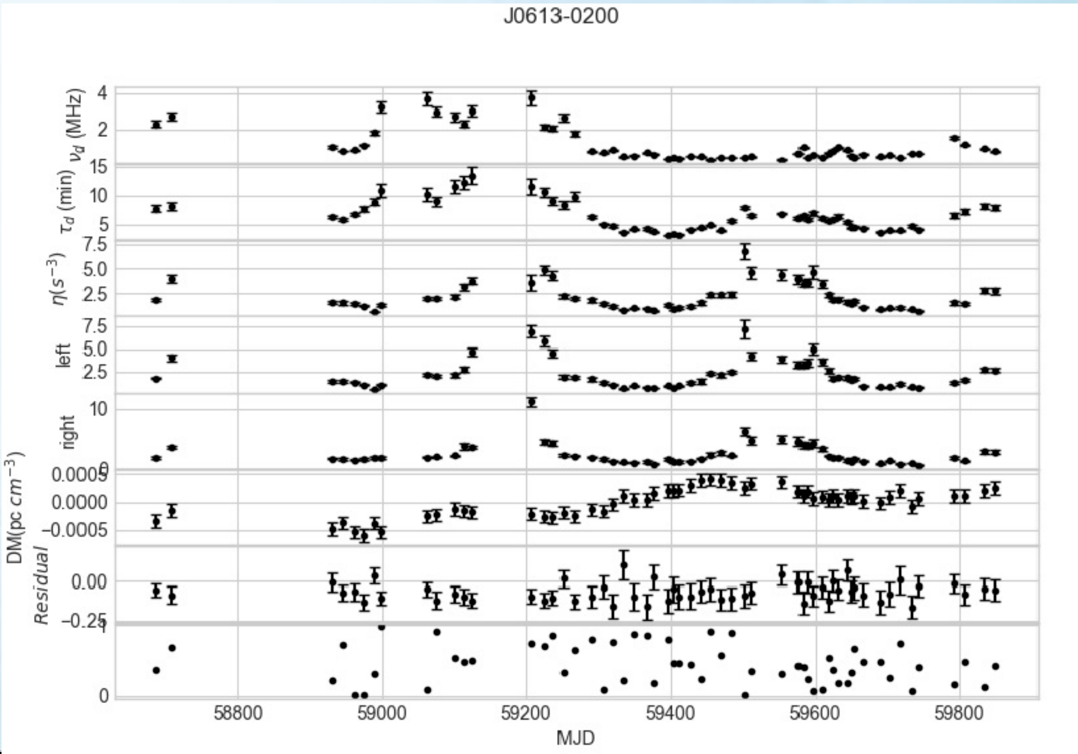
Scintillation

- For most of pulsars, we detect clear variation in scintillation effects including 2nd spectra arc curvature.
- Systematic study of ISM turbulence









Science from pulsar timing observation

- 34 pulsar with distance measured, most of them are of best precision.

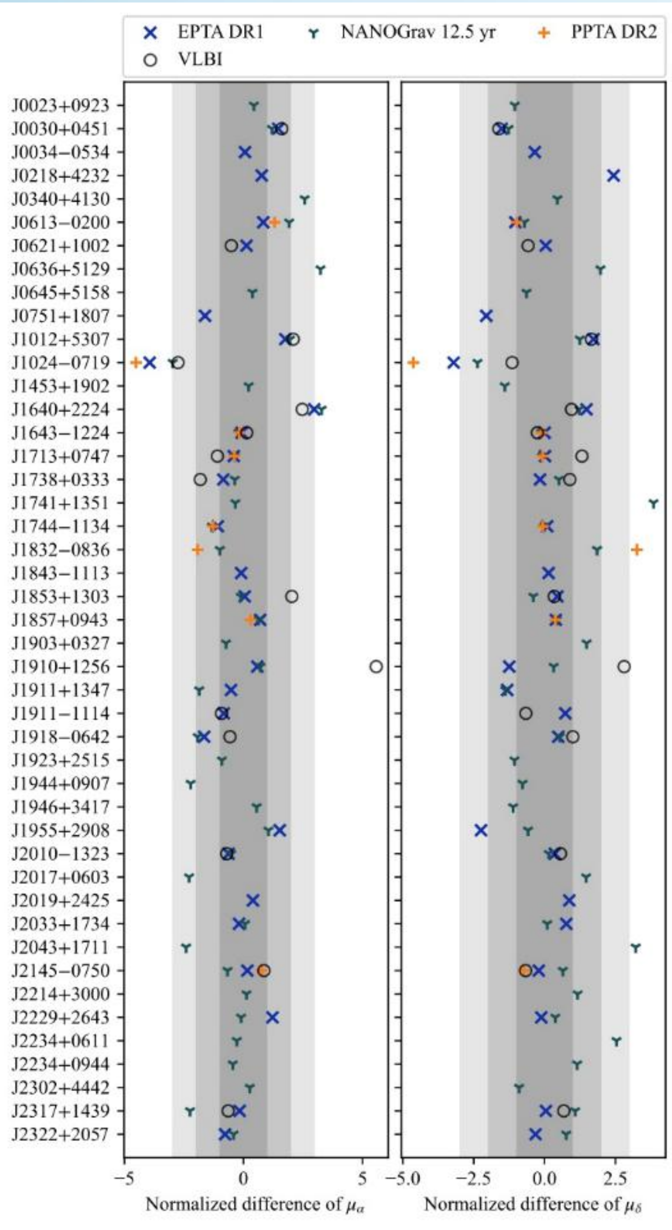
- More than 20 systems get binary post-keplerian parameters. 19 systems measured Shapiro delay. Approximately 10 systems are first-time detection.

Pulsar name J2000	CPTA DR1	EPTA DR1	NANOGrav 12.5 yr	PPTA DR2	Previoud Measurements Value	Reference	Method
J0023+0923	0.46(15)		0.54(12)				
J0030+0451	3.09(7)	2.79(23)	3.09(6)		3.02(7)	Ding et al. (2023)	VLBI
J0509+0856	0.82(11)						
J0613−0200	0.93(10)	1.25(13)	0.90(11)	1.01(9)			
J0636+5129	0.97(4)		1.38(23)				
J0645+5158	0.69(7)		0.82(16)				
J0751+1807	0.78(6)	0.82(17)			0.66(15)	Guillemot et al. (2016)	Timing
J1012+5307	1.41(27)	0.71(17)	1.13(35)		$1.17^{+0.04}_{-0.05}$	Ding et al. (2023)	VLBI
J1024−0719	0.98(5)	0.80(17)	1.00(22)	0.83(13)	0.94(6)	Ding et al. (2023)	VLBI
					0.77(11)	Bassa et al. (2016)	Timing
					0.89(14)	Guillemot et al. (2016)	Timing
J1713+0747	0.91(8)	0.90(3)	0.83(2)	0.763(21)	$0.95^{+0.06}_{-0.05}$	Chatterjee et al. (2009)	VLBI
J1738+0333	0.72(16)				0.50(6)	Ding et al. (2023)	VLBI
					0.68(5)	Freire et al. (2012)	Timing
J1741+1351	0.43(9)		0.42(11)				
J1744−1134	2.55(11)	2.38(8)	2.38(10)	2.44(5)			
J1832−0836	0.70(10)		0.48(13)	0.64(20)			
J1843−1113	0.53(10)	0.69(33)					
J1853+1303	0.66(8)		0.48(14)		0.49(7)	Ding et al. (2023)	VLBI
J1857+0943	0.89(13)	0.70(26)	0.71(12)	0.85(16)			
J1910+1256	0.55(11)	1.44(74)			0.254(35)	Ding et al. (2023)	VLBI
J1911+1347	0.44(6)						
J1918−0642	0.71(10)		0.85(11)		0.60(12)	Ding et al. (2023)	VLBI
J1944+0907	1.12(27)						
J2010−1323	0.38(12)		0.41(12)		$0.484^{+0.166}_{-0.120}$	Deller et al. (2019)	VLBI
J2017+0603	0.66(7)						
J2019+2425	0.96(18)						
J2033+1734	0.51(12)						
J2043+1711	0.76(12)		0.72(6)				
J2145−0750	1.88(11)		1.24(20)	1.40(8)	$1.603^{+0.063}_{-0.009}$	Deller et al. (2016)	VLBI
J2214+3000	1.00(22)		1.70(54)				
J2229+2643	0.61(11)						
J2234+0611	0.77(4)		0.84(10)				
J2234+0944	0.75(22)		0.69(23)				
J2302+4442	1.79(28)						
J2317+1439	0.60(9)	0.7(3)	0.60(8)		$0.6^{+1.533}_{-0.241}$	Deller et al. (2019)	VLBI
J2322+2057	0.89(11)		0.98(26)				

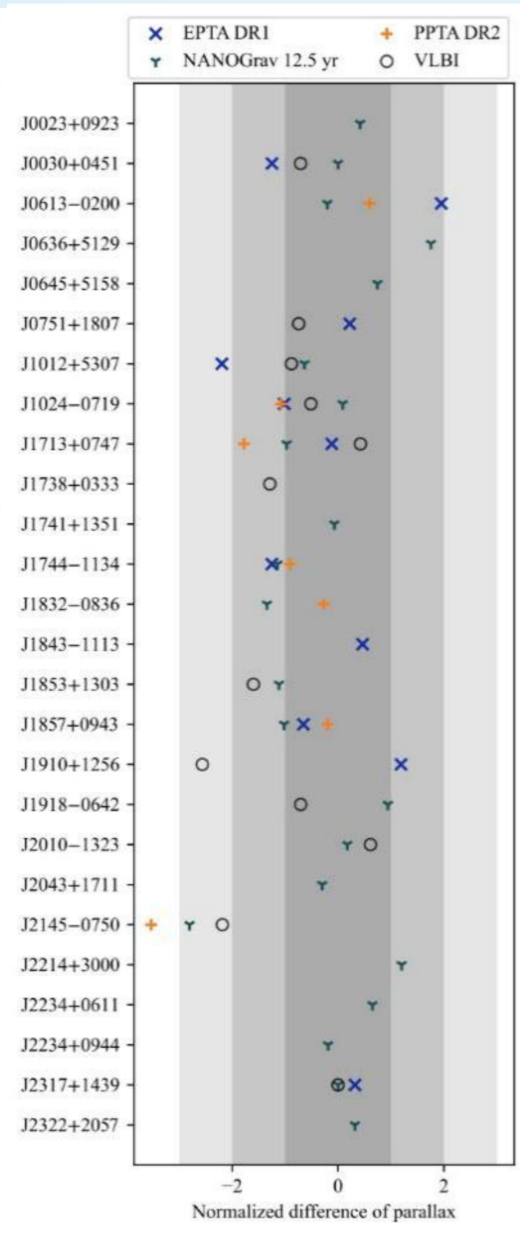
Pulsar name	$\dot{\omega}$ (deg yr^{-1})	$\dot{x}$ (10^{-14})	h_3 (μs)	ς	$\sin i$	m_2 ($M_\odot$)
J0218+4232	-	-	-	-	0.9925(6)	0.234(6)
J0613−0200	-	-	0.22(2)	0.62(6)	-	-
J0621+1002	0.010(1)	-	-	-	-	-
J0751+1807	-	-	0.21(1)	0.63(5)	-	-
J1012+5307	-	-	0.13(3)	-	-	-
J1630+3734	-	-	-	-	0.9990(3)	0.26(1)
J1640+2224	-	1.9(6)	0.49(8)	0.58(12)	-	-
J1713+0737	-	-	-	-	0.945(5)	0.31(2)
J1741+1351	-	-0.5(1)	-	-	0.963(8)	0.24(3)
J1853+1303	-	1.5(2)	0.20(2)	0.49(8)	-	-
J1857+0943	-	-	-	-	0.9991(2)	0.25(1)
J1903+0327	0.0002399(7)	-	-	-	0.978(9)	1.05(13)
J1910+1256	-	-2.1(2)	0.10(2)	0.74(14)	-	-
J1918−0642	-	-	-	-	0.9955(7)	0.24(1)
J1946+3417	0.00134(5)	-	0.67(9)	0.74(7)	-	-
J2017+0603	-	-	-	-	0.95(2)	0.18(4)
J2019+2425	-	4.3(2)	0.65(6)	0.55(7)	-	-
J2043+1711	-	-	-	-	0.991(2)	0.18(1)
J2150−0326	-	-	-	-	0.98(1)	0.21(6)
J2145−0750	-	-	0.13(4)	-	-	-
J2229+2643	-	2.4(2)	-	-	-	-
J2234+0611	0.000887(2)	-2.6(1)	0.12(2)	0.51(12)	-	-
J2302+4442	-	-	-	-	0.990(3)	0.31(2)
J2317+1439	-	-	0.16(3)	-	-	-

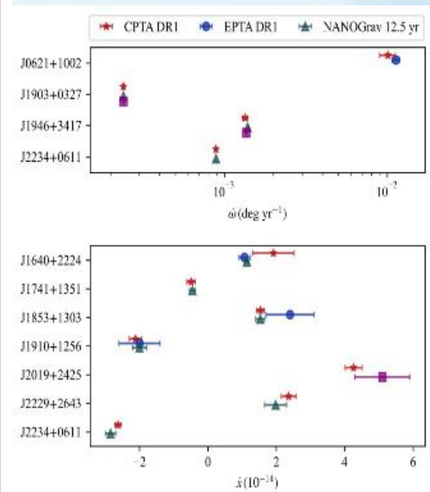
Pulsar proper motion, distance, and post-keplerian parameters are compatible with published values.

Proper motion

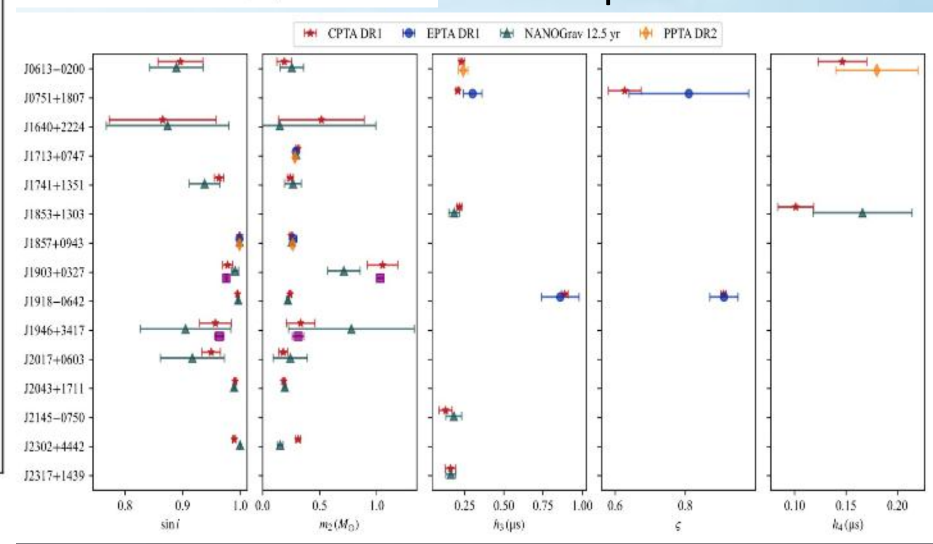


Distance





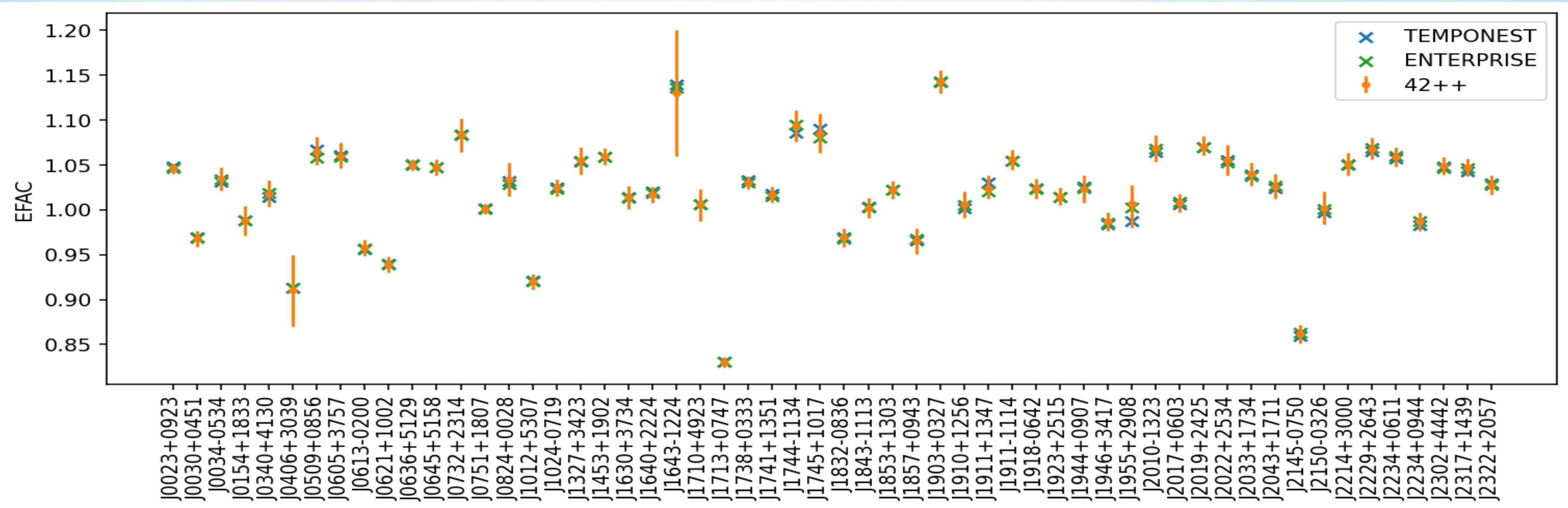
Post-Keplerian



White noise analysis

Our recipe:

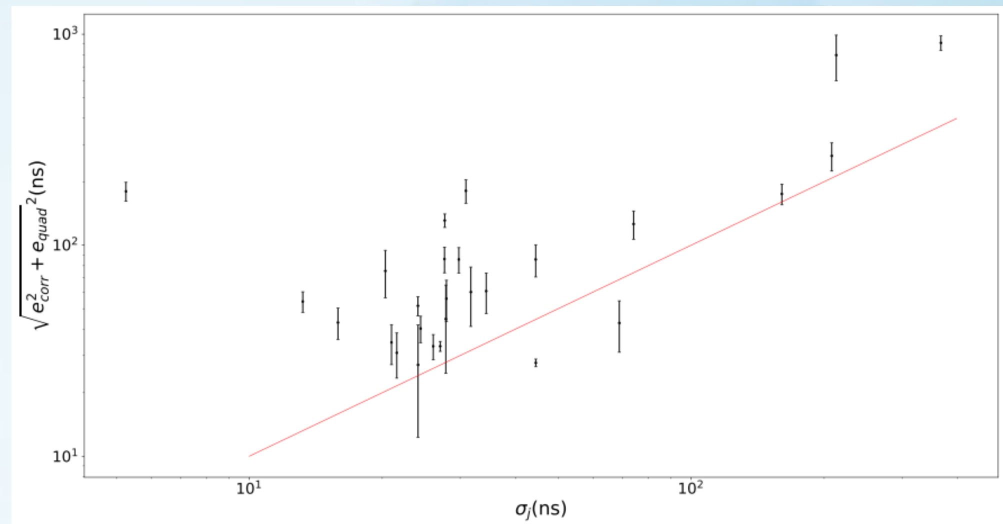
- Four independent pipelines are used, and the results are checked.
- Final model is selected among all possible combination of white+red+DM noise with highest Bayesian factor (16 models)
- Results are further checked by adding extra 1 year data.

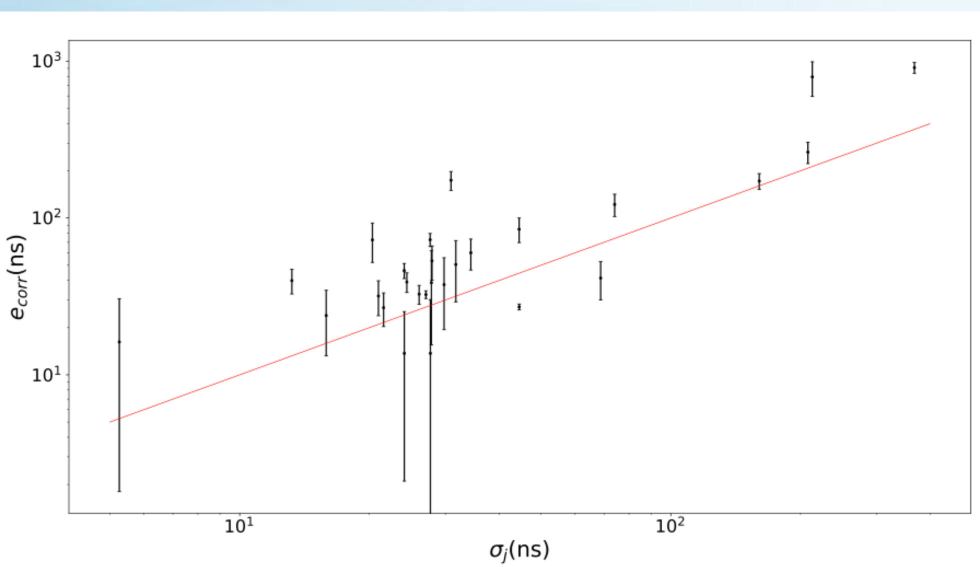


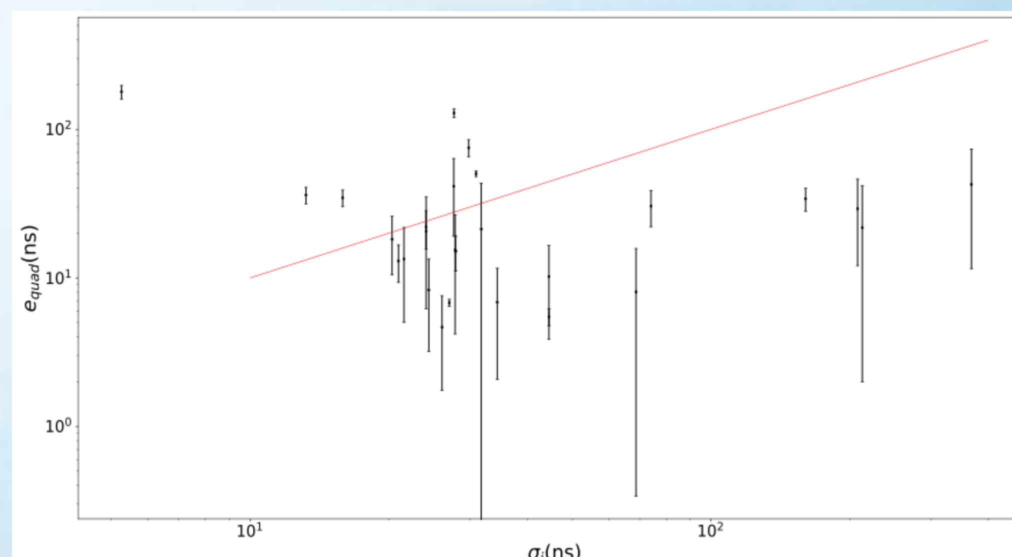
Compare jitter modeled in timing and single pulse domain

In general, the jitter parameter Ecorr agrees with single pulse domain modeling.
For some pulsars, short timescale DM variation affect the white noise measurement.

Probably the first time we get agreement between timing and single pulse domain modeling.

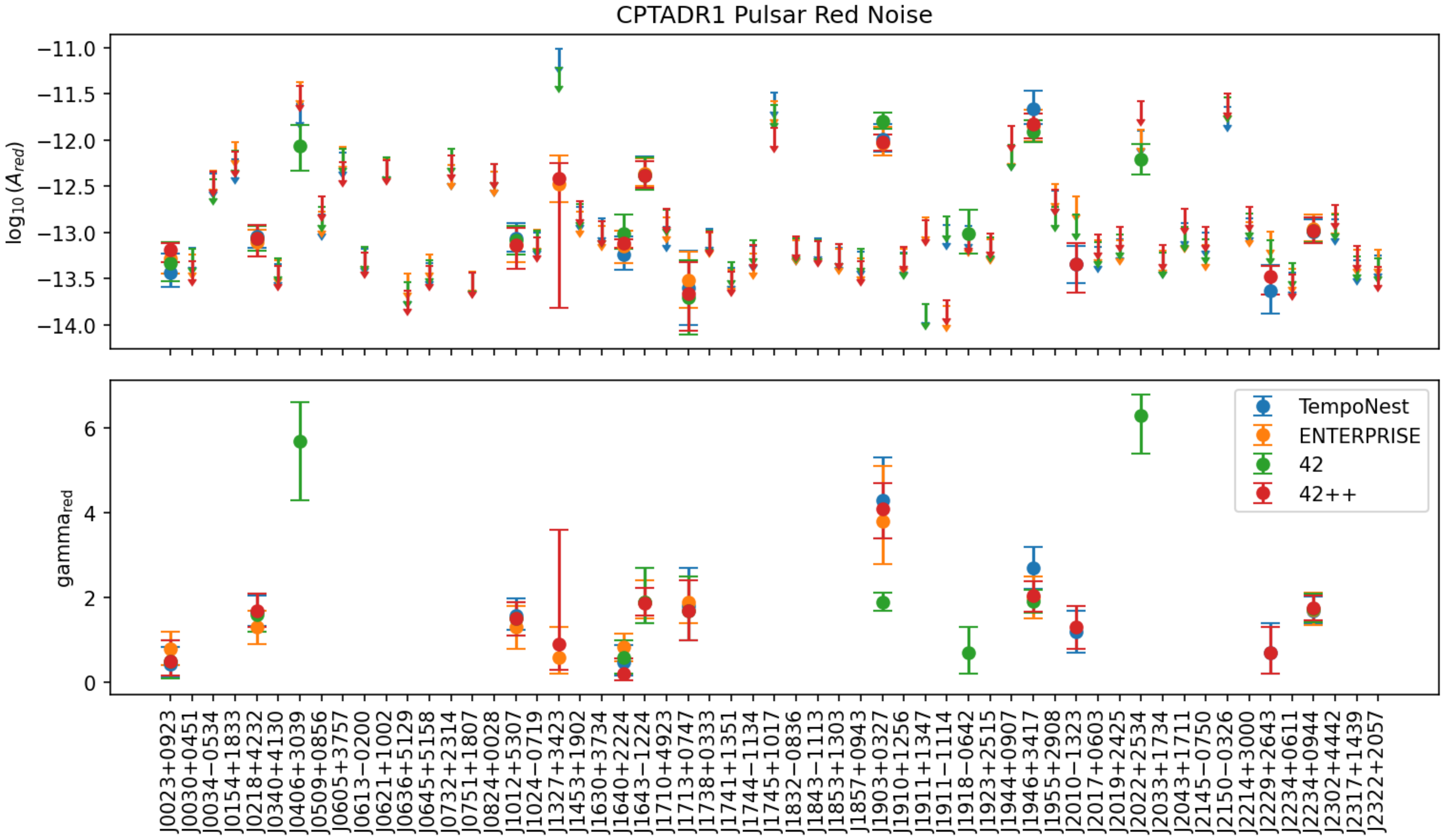




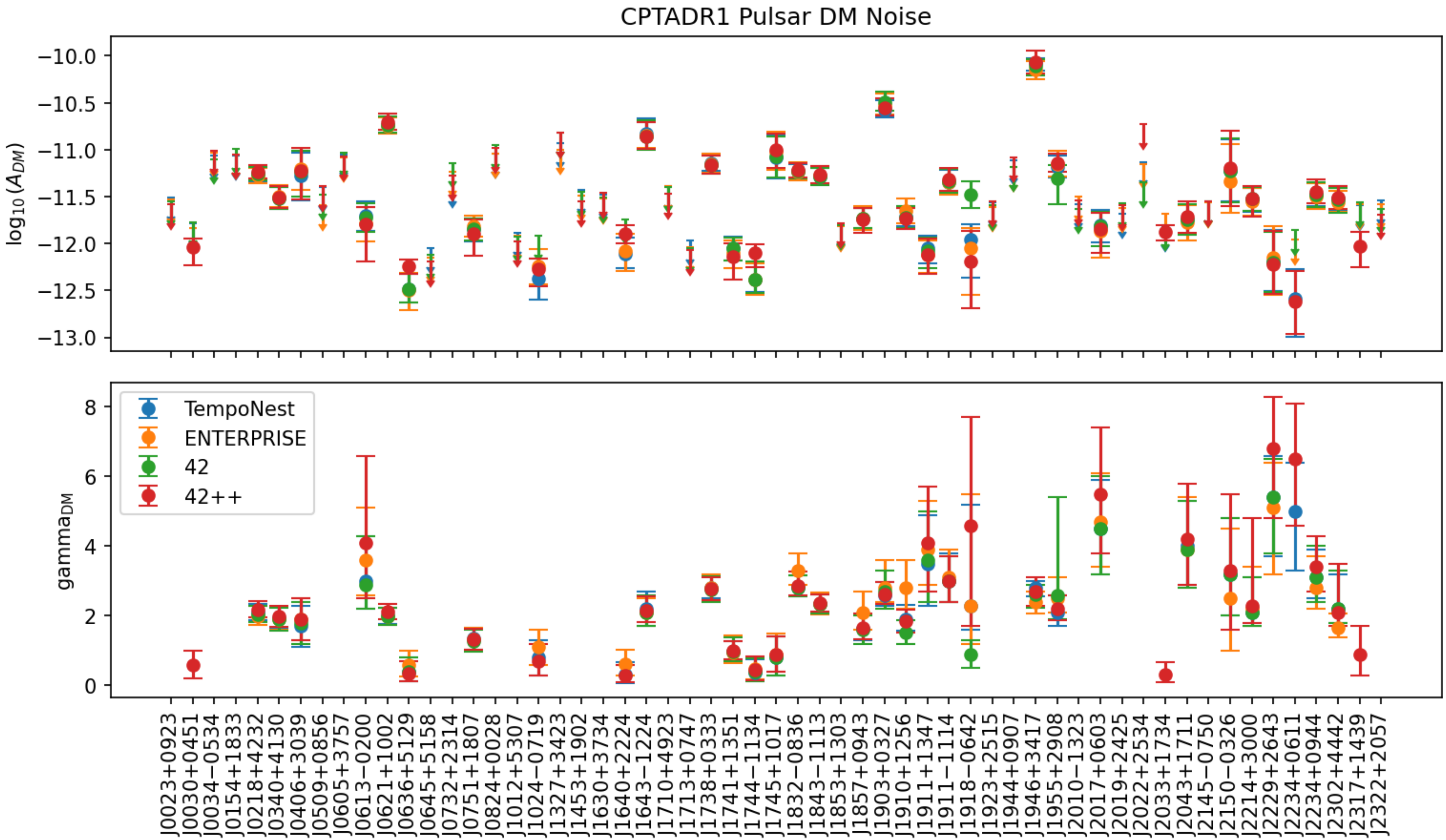


Red noise

Four independent pipelines are used, and the results are compatible.



DM Noise



CPTADR1 Pulsar DM Noise
log10 (A_DM)
−10.0
−10.5
−11.0
−11.5
−12.0
−12.5
−13.0
gamma_DM
8
6
4
2
0
TempoNest
ENTERPRISE
42
42++
J0023+0923
J0030+0451
J0034−0534
J0154+1833
J0218+4232
J0340+4130
J0406+3039
J0509+0856
J0605+3757
J0613−0200
J0621+1002
J0636+5129
J0645+5158
J0732+2314
J0751+1807
J0824+0028
J1012+5307
J1024−0719
J1327+3423
J1453+1902
J1630+3734
J1640+2224
J1643−1224
J1710+4923
J1713+0747
J1738+0333
J1741+1351
J1744−1134
J1745+1017
J1832−0836
J1843−1113
J1853+1303
J1857+0943
J1903+0327
J1910+1256
J1911+1347
J1911−1114
J1918−0642
J1923+2515
J1944+0907
J1946+3417
J1955+2908
J2010−1323
J2017+0603
J2019+2425
J2022+2534
J2033+1734
J2043+1711
J2145−0750
J2150−0326
J2214+3000
J2229+2643
J2234+0611
J2234+0944
J2302+4442
J2317+1439
J2322+2057

Noise analysis take home message

1. We use **four different softwares**, each with different ways of modeling parameters. The results **agrees within the errorbars**.
2. We now understand jitter noise, and modeling in timing **agrees with the single pulse domain** analysis
3. DM noise dominates the long-term noise.

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GW detection and future

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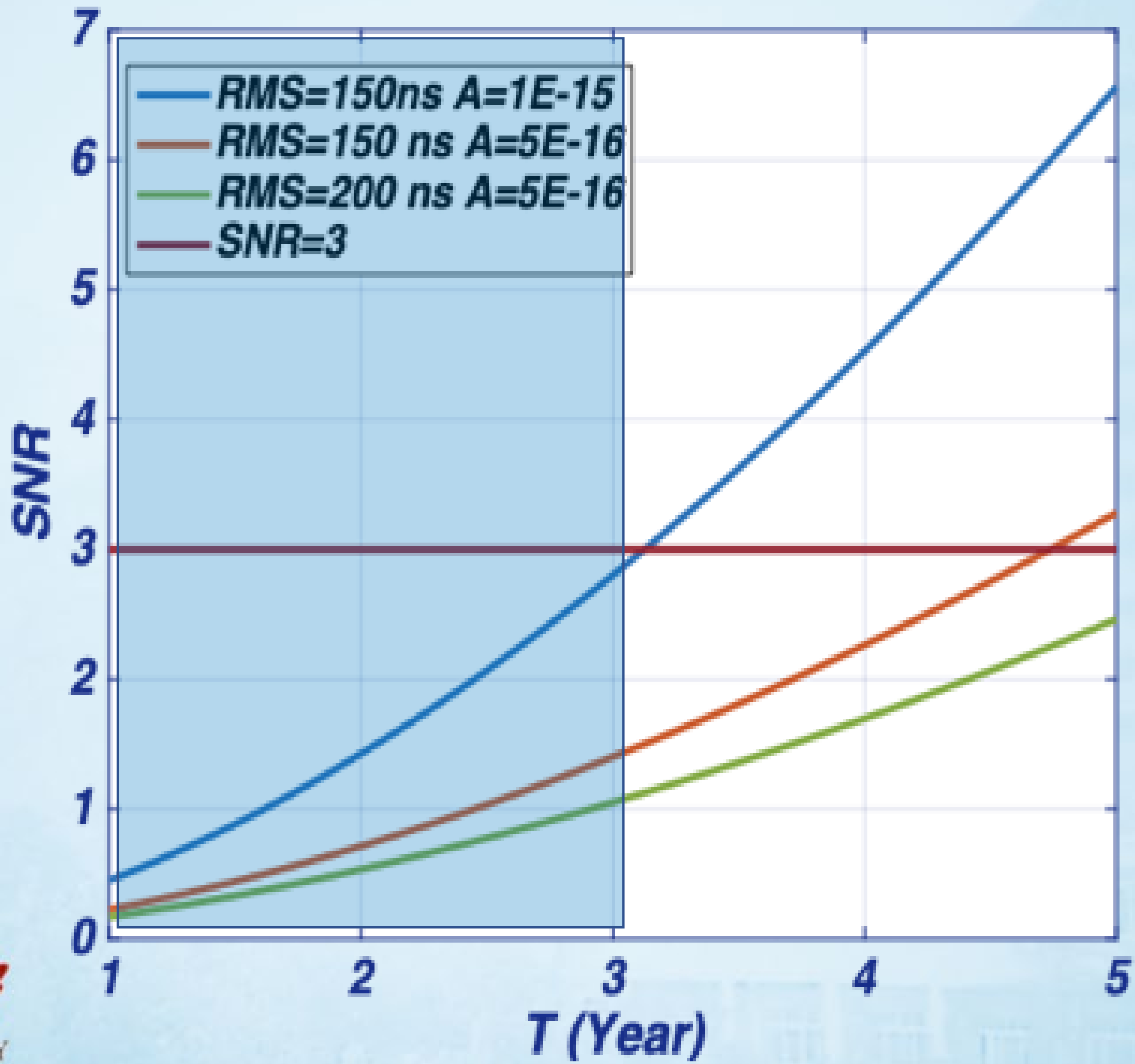
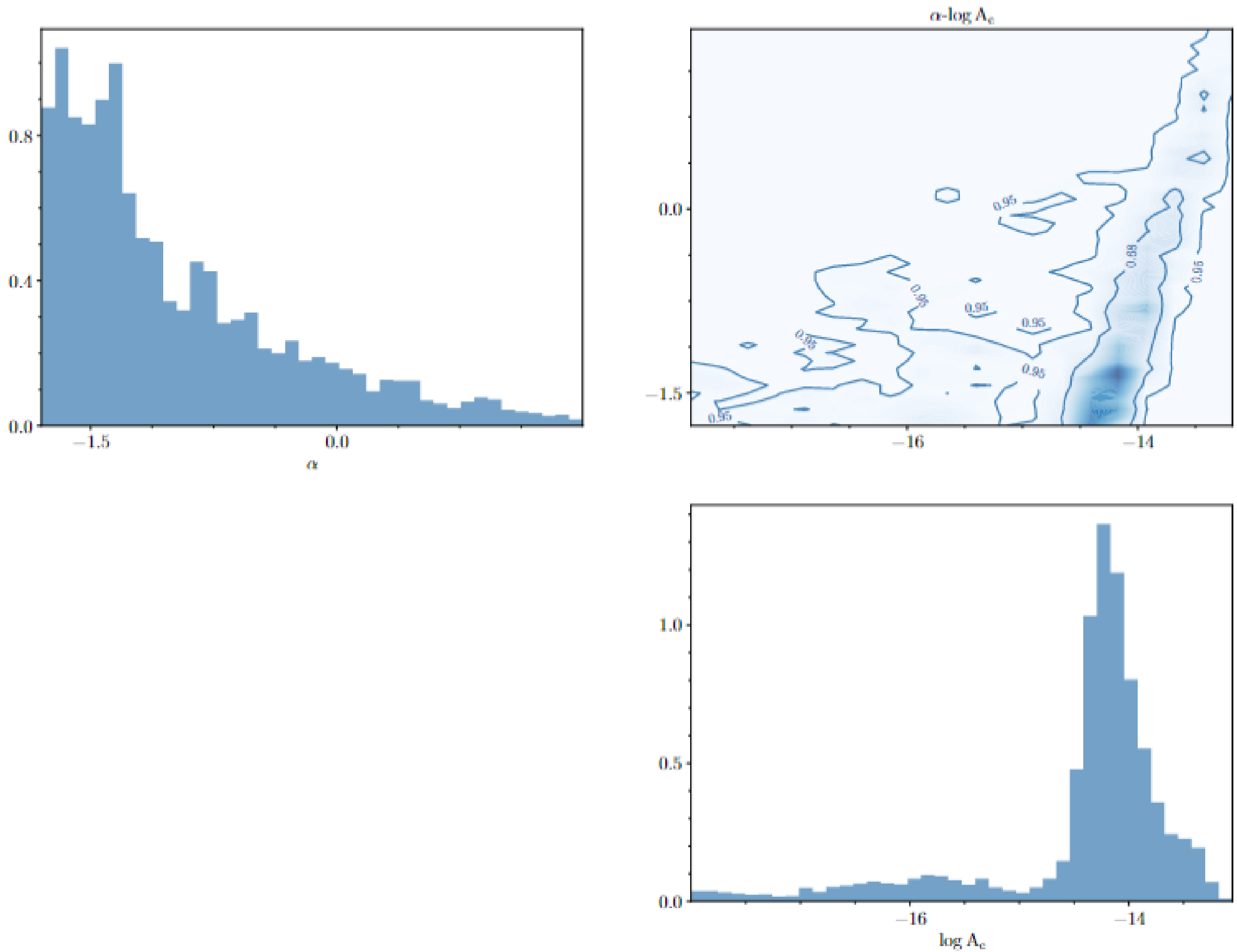
Stochastic background

- Our prediction in 2019, we claimed that we will get something in 5 years. If lucky, we will get something in 3 years.



GW Parameter inference

- A=4e-15, compatible with other PTA results and SMBH population prediction
- GW spectral index was not well measured with CPTA, because of
  1) short data length
  2) marginalization of white noise in GW analysis



Xu et al., 2023

Problem of Bayes method in heteroscedastic statistics

$$\Lambda_0(\sigma_1, \sigma_2 \ldots \sigma_N) \propto \prod_{i=1}^{N} \frac{1}{\sigma_i^{N_{pt,i}}} \exp\left[-\frac{1}{2}\frac{\boldsymbol{r}_i \cdot \boldsymbol{r}_i}{\sigma_i^2}\right].$$

$$\langle \mathrm{BE}_0 \rangle = \int \ldots \int \Lambda_0(\sigma_1, \sigma_2 \ldots \sigma_N) d\log\sigma_1 \ \ldots d\log\sigma_N$$
$$\propto \prod_{i=1}^{N} 2^{\frac{N_{pt,i}-2}{2}} (N_{pt,i}\sigma_i^2)^{-\frac{N_{pt,i}}{2}} \Gamma\left(\frac{N_{pt,i}}{2}\right).$$

$$\Lambda_1(\sigma_1, \sigma_2 \ldots \sigma_N; A) \propto \prod_{i=1}^{N} \frac{1}{(\sigma_i^2 + A^2)^{N_{pt,i}/2}} \exp$$
$$\times \left[-\frac{1}{2}\frac{\boldsymbol{r}_i \cdot \boldsymbol{r}_i}{\sigma_i^2 + A^2}\right].$$

$$\langle \mathrm{BE}_1 \rangle = \int \ldots \int \Lambda_1(\sigma_1, \sigma_2 \ldots \sigma_N) d\log\sigma_1 \ \ldots d\log\sigma_N \, dA,$$

BE1 will go infinite, no matter if the intrinsic signal has A or not, i.e. Asymptotic validity of Bayes evidence for heteroscedastic statistics is problematic.

HD curve inference

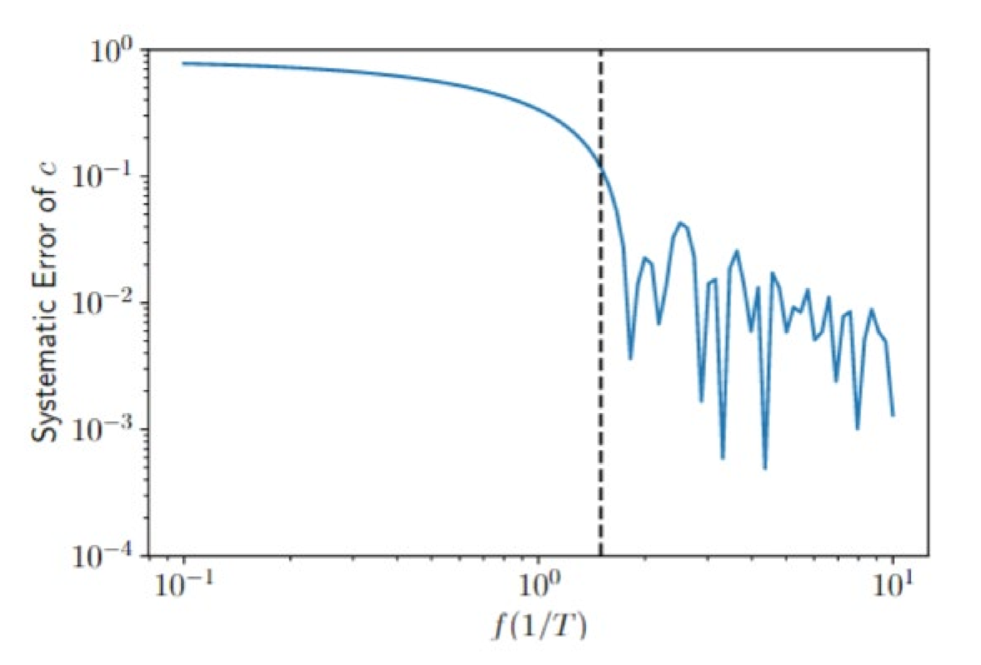
We focus on the part of signal with minimal error in correlation curve inference. The lowest frequency bin is a good guess, but not exactly.

$$A, \phi_i = \mathrm{argmax}_{A,\phi_i} \int\int\cdots\int \frac{1}{\sqrt{\prod_i |C_i|}} \exp\left[-\frac{1}{2}\sum_i \boldsymbol{r}_i'^T C_i^{-1} \boldsymbol{r}_i\right] \prod_i d\boldsymbol{\lambda}_{T,i} \,,$$

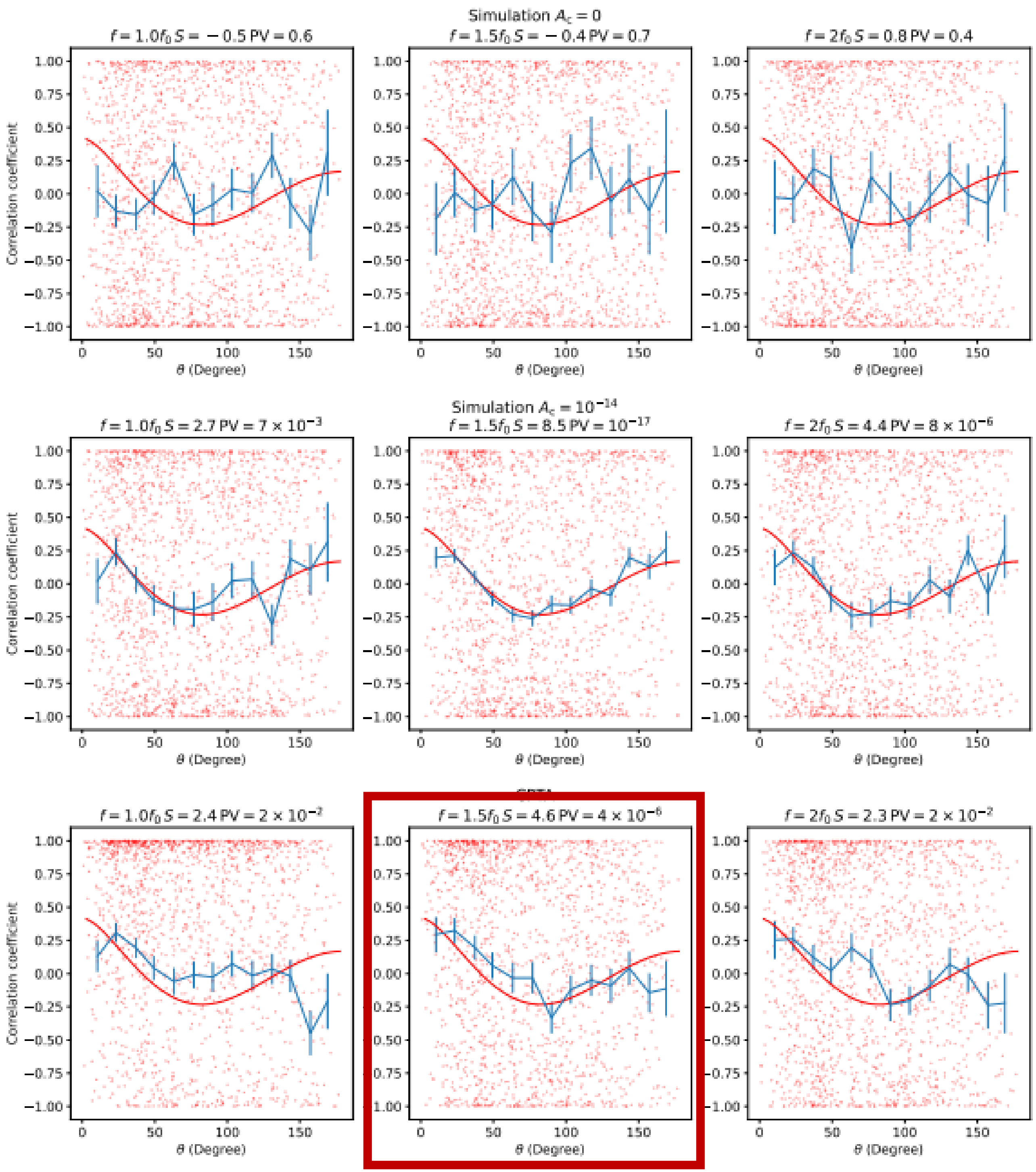
were $\boldsymbol{r}_i'$ is

$$\boldsymbol{r}_i' = \boldsymbol{r}_i - \boldsymbol{D}_i \boldsymbol{\lambda}_{T,i} - A\sin(2\pi f \boldsymbol{t} - \phi_i)\,.$$

- The sweat spot for short data set is to look for correlation above f~1.5/T.
- For CPTA, data is short, we look at 1.5/T.



HD curve



Null control group

Positive control group

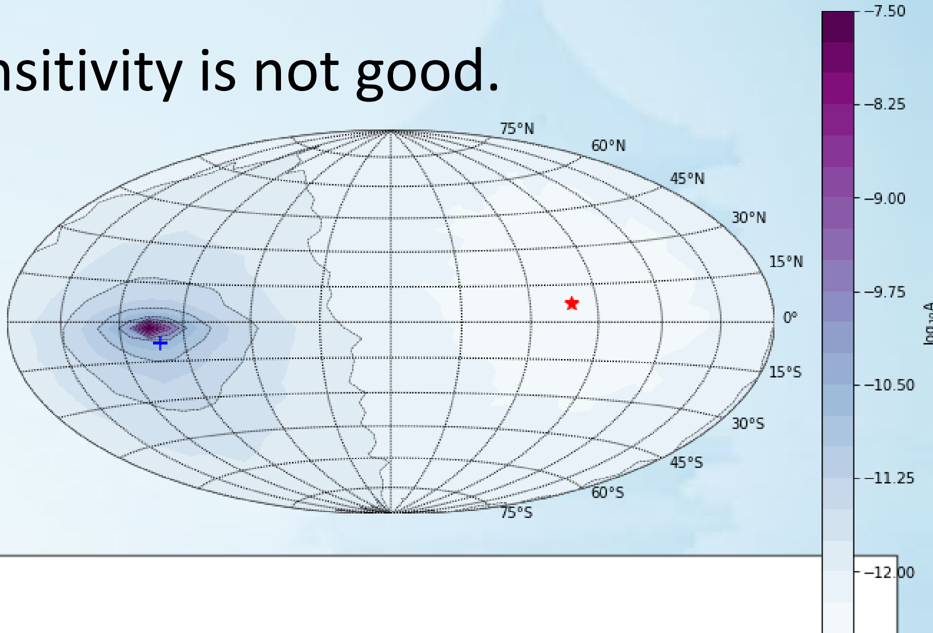
Real data

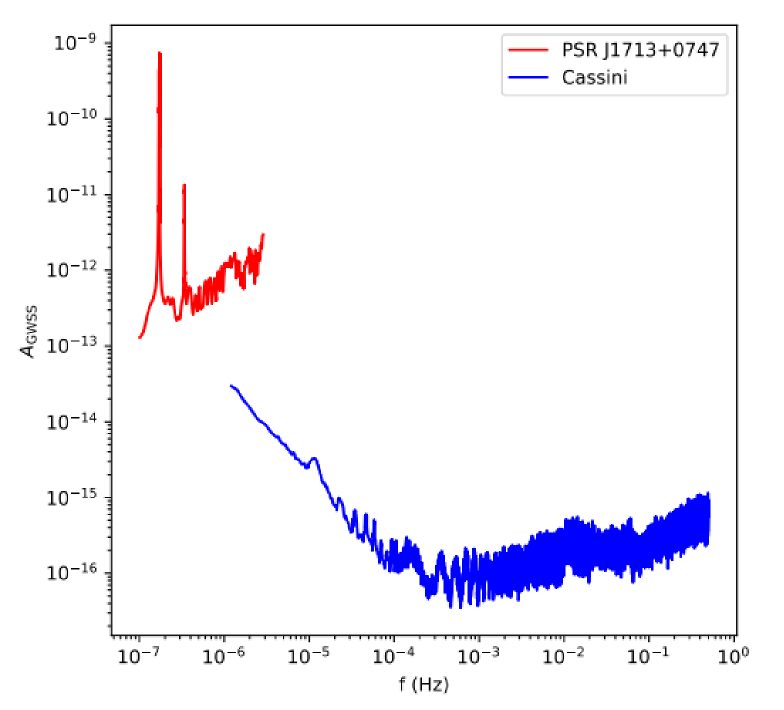
Other related science

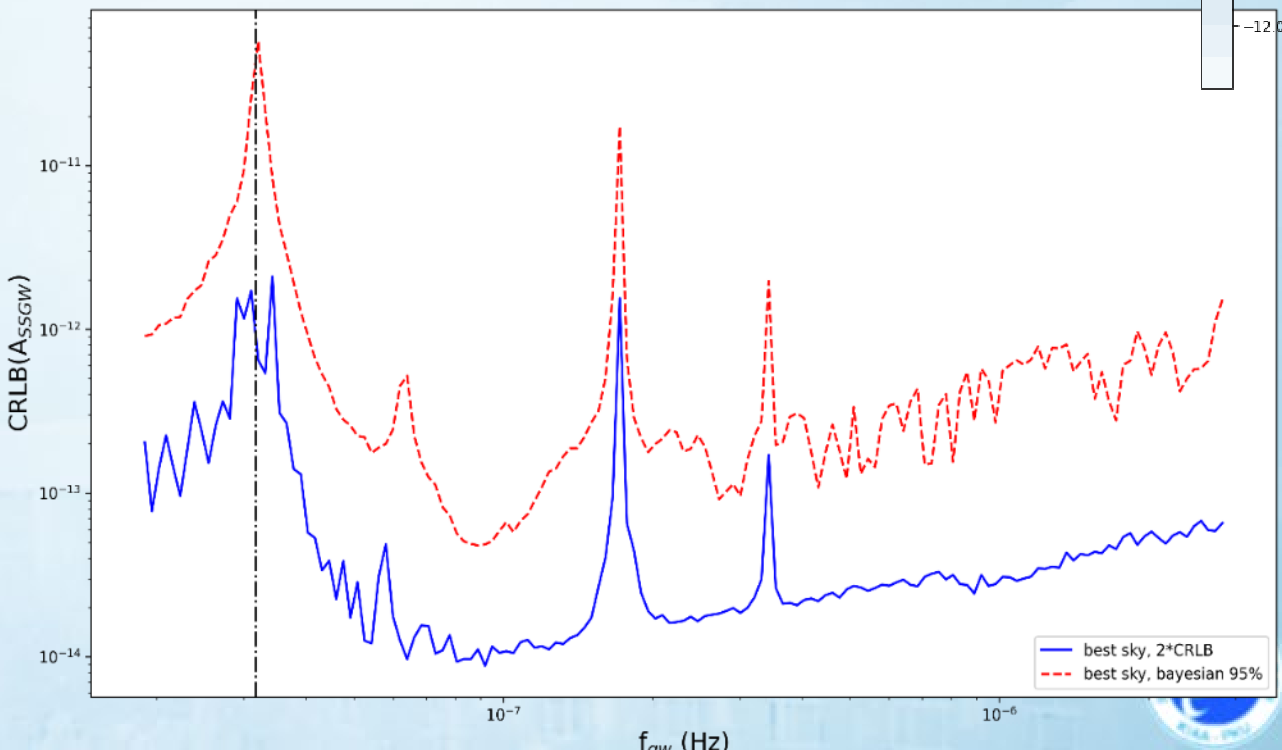
- GW Single source
- Test solar system ephemerides, reference frame tie
- Gravity test in radiative regime
- GW dispersion

Single pulsar bounds for single GW sources

- single source blind search
- targeted searches
- Goes to around 0.1 uHz in frequency, sensitivity is not good.
- A factor of few improvement is possible.

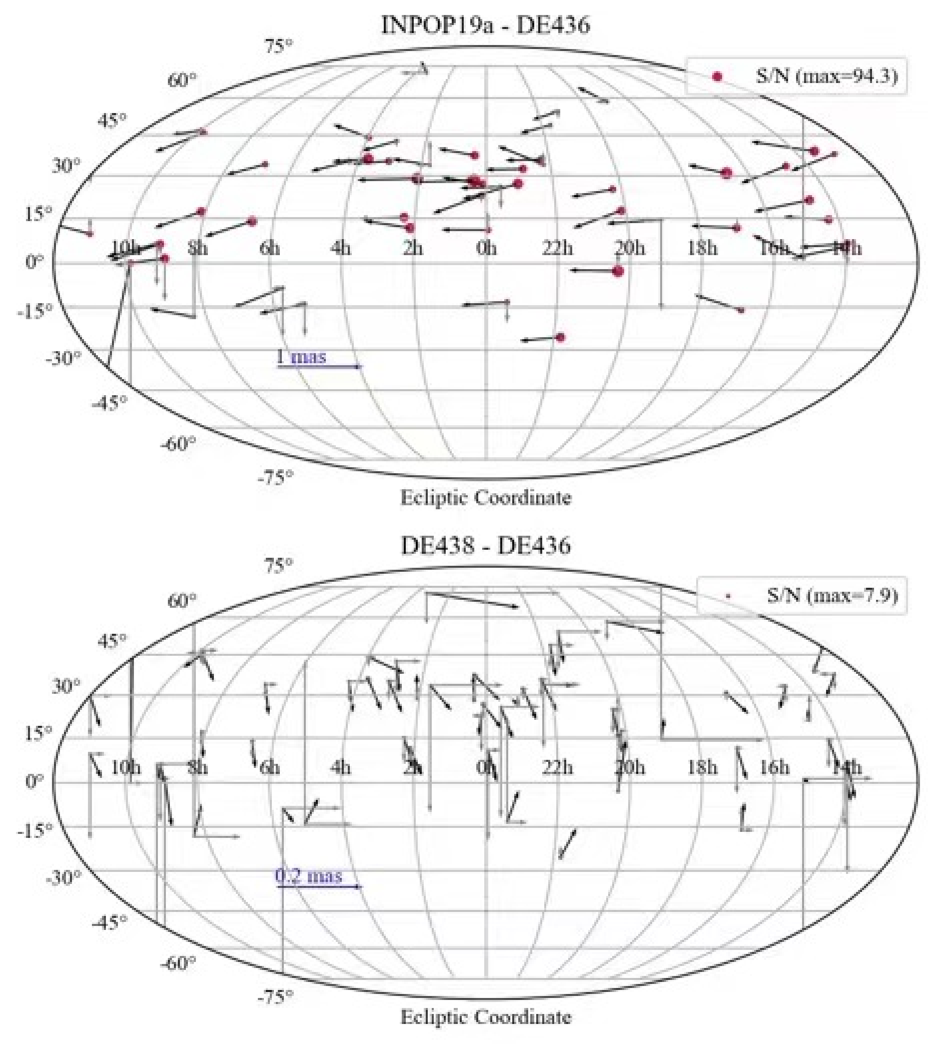






Ephemerides comparation and tests

- One can immediately check if the reference frame is well defined.
- We are working on ephemerides orbit element measurement.



Counter intuitively, frame tie is **not simple rotation**. There is twister and squeeze between different modeling somehow.

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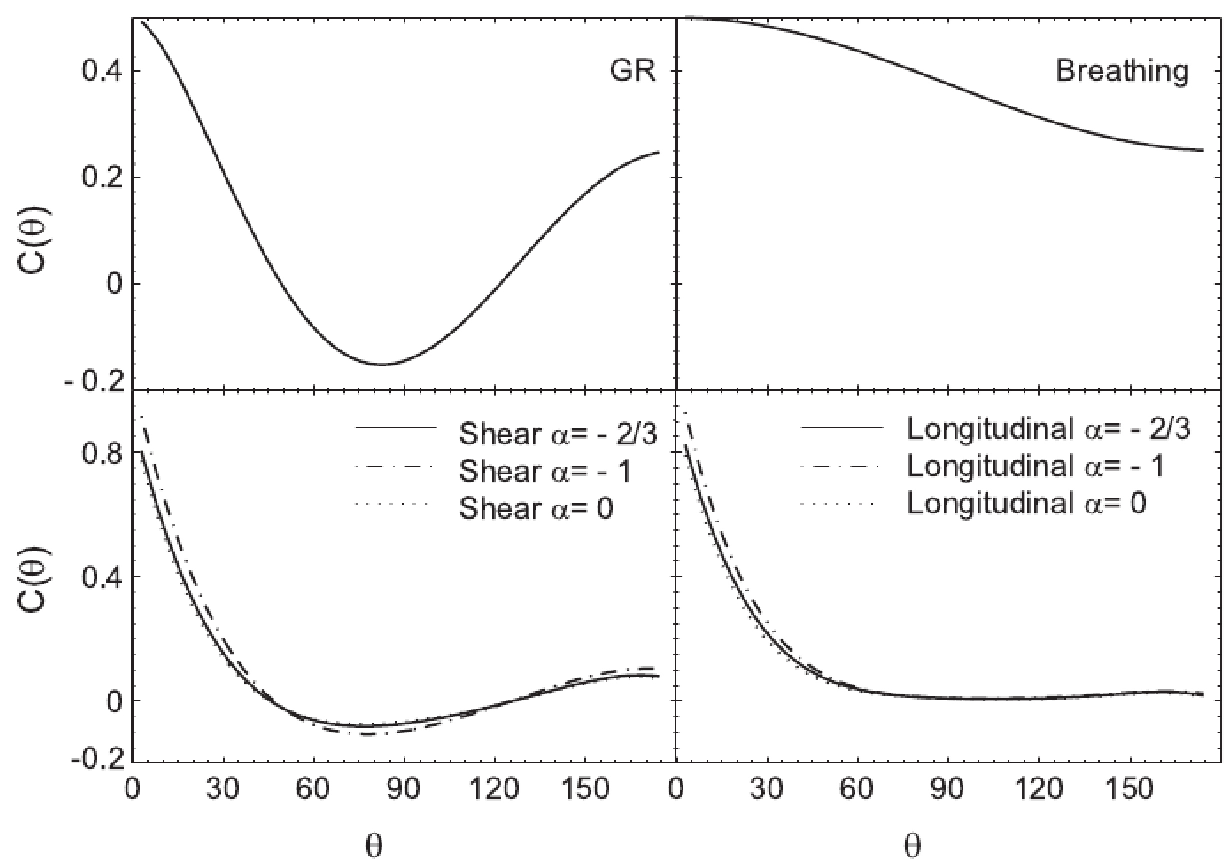
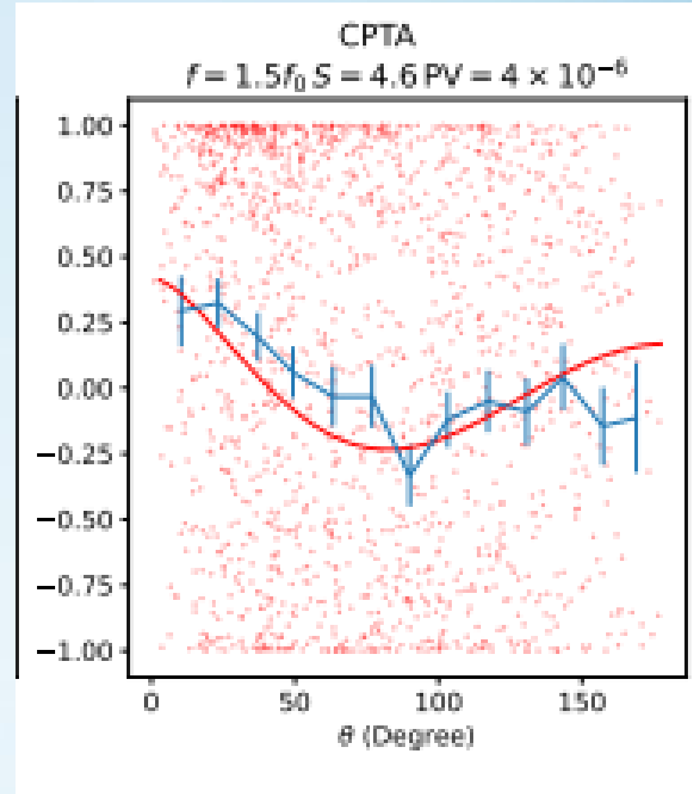
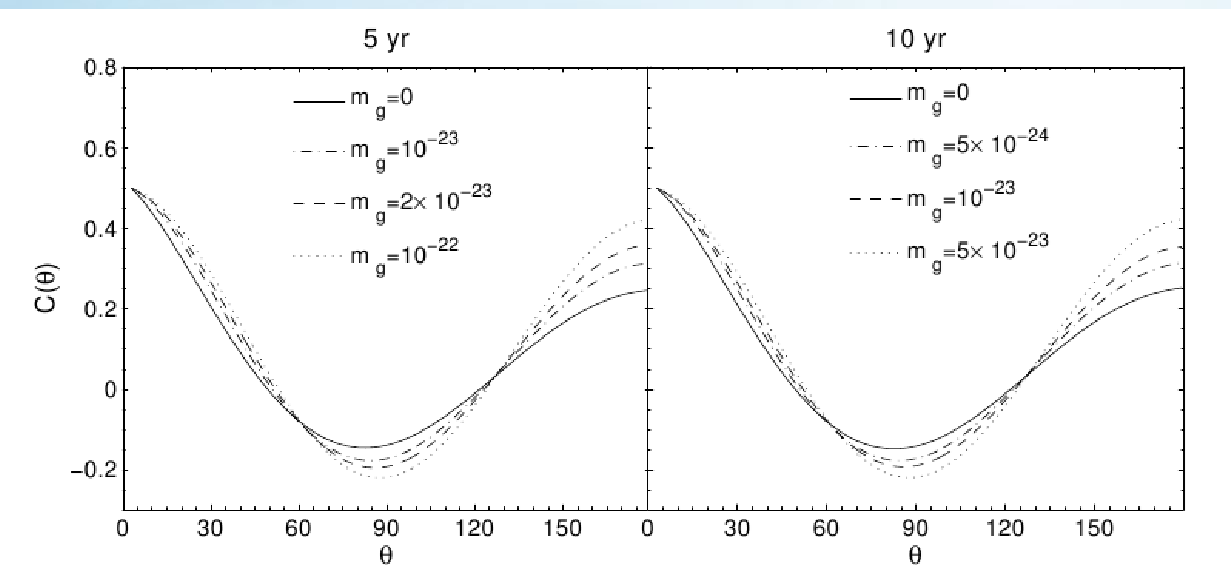






Gravity theory test needs more pulsars and better S/N.

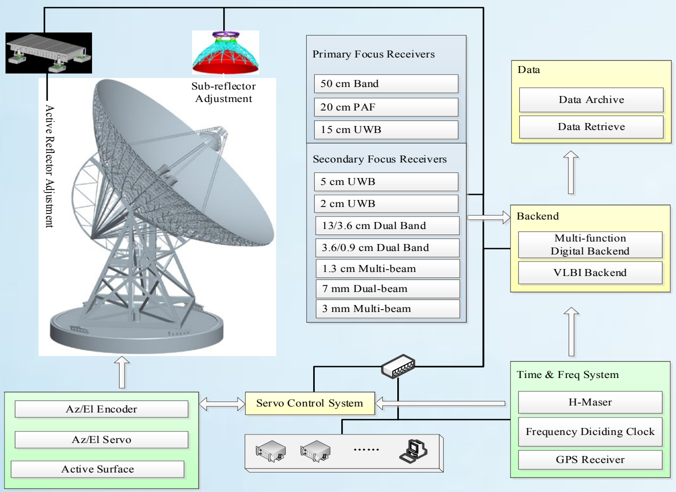
Can we improve?

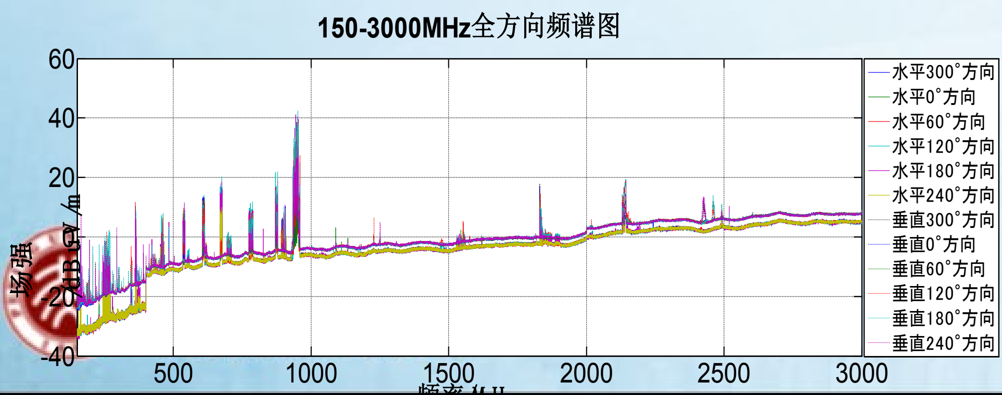
Current CPTA suffers from three major issues

1. Limited sky coverage
   1. Pulsars are in the Milky way
   2. FAST does not cover a few very good pulsars.
2. Limited bandwidth
   1. FAST had only 500MHz BW
   2. The most significant noise in the current CPTA dataset is DM noise
   3. DM noise can only be mitigated with wider observation band
3. Limited observation resource
   - We can barely observe 57 pulsars with FAST under the help and support of FAST team, that the total obs time per year is about 500 hours.
   - NANOGRAV are observing 80+ pulsars, total time per year > 2000 hours

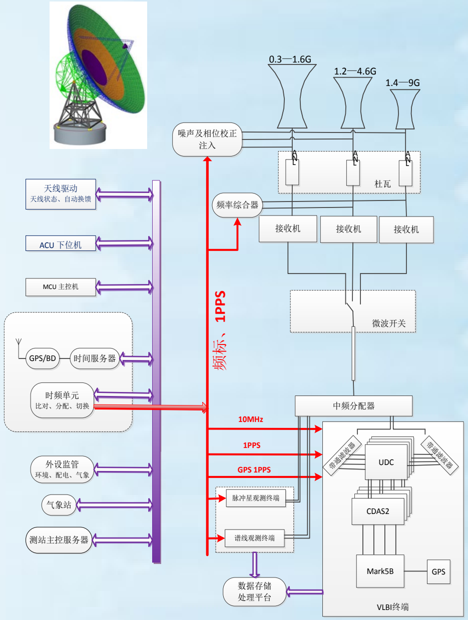
Progress of Chinese **Radio Gemini**

QTT 110m fullband radio teelscope at Qitai **In construction**, should be ready in 3-5 years.



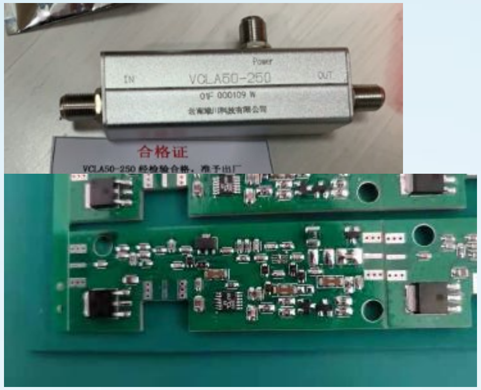


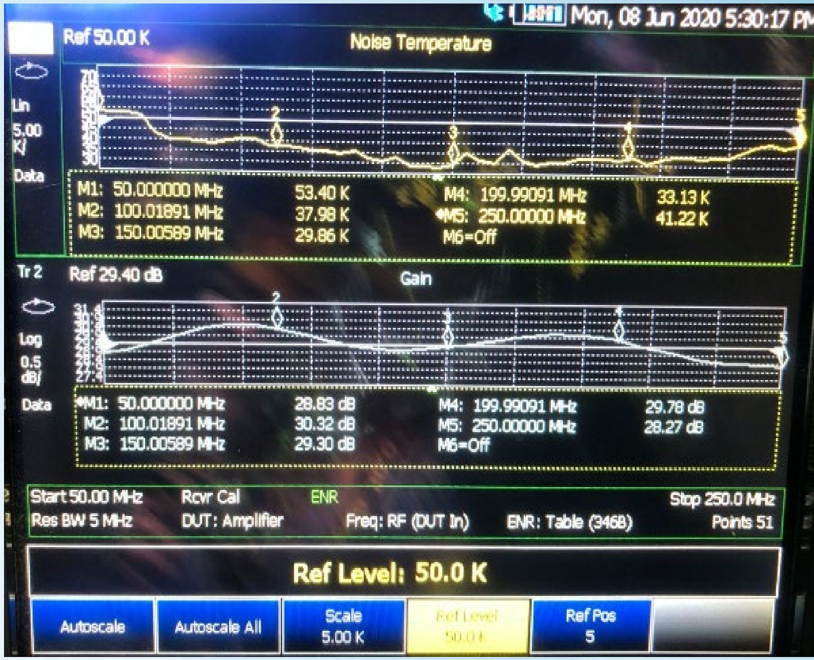
JRT 120m lowband (10GHz) radio teelscope at Jindong. Contract signed **waiting for the green light.**



Extend frequency/sky coverage

LNA 50-250MHz NF 0.4dB
VSWR < 1.5 δDB<1dB



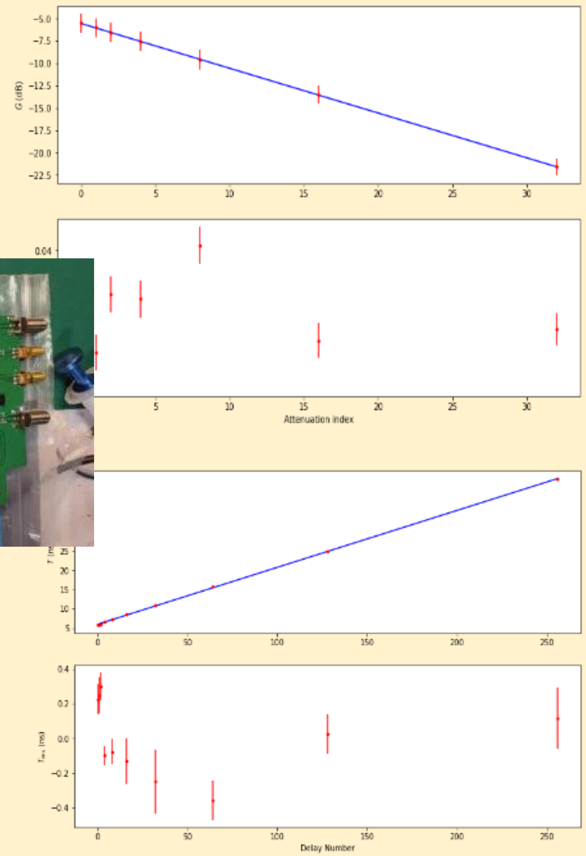


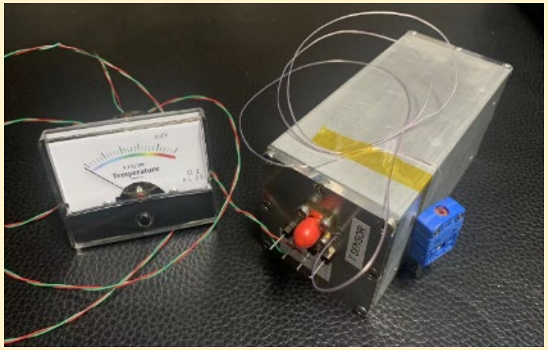
21CMA 127X81 dipoles

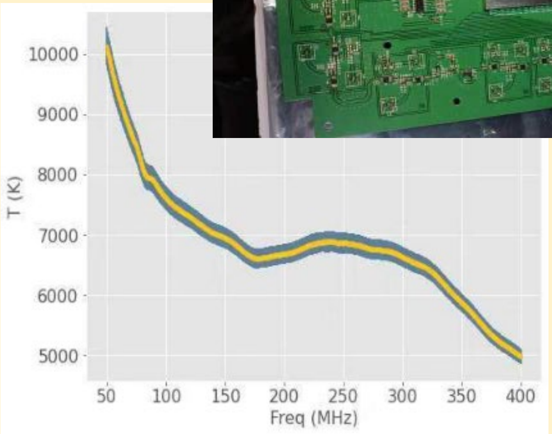
SKA-low pilot project

Designed all components of the RF front-end.

Analog beam former, 512 steps, 0.03 dB and 30 ps precision

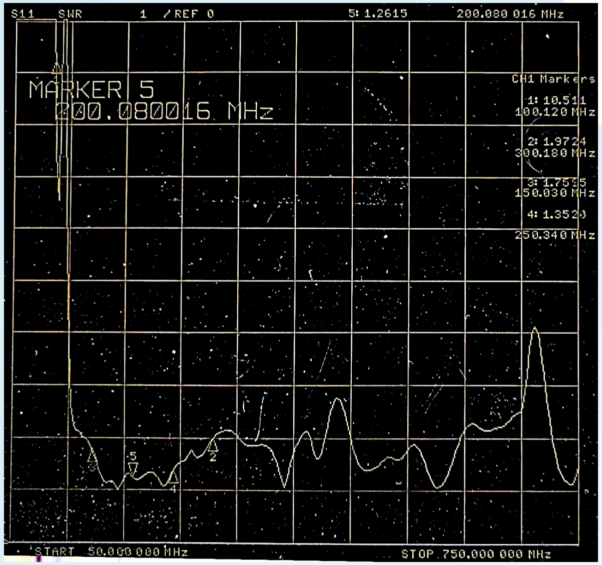


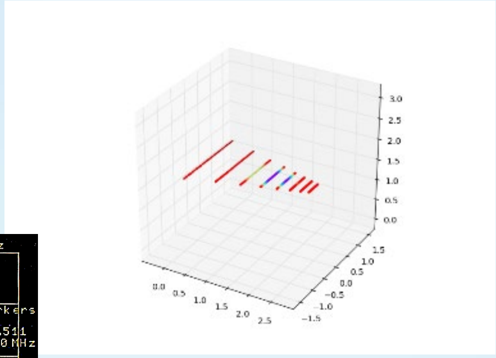


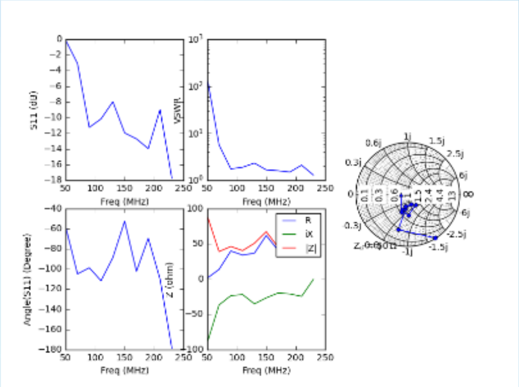


Noise standard, 0.01% variation/90 hour, Tnoise> 6500 K, VSWR < 1.12

Progress







- Home-brewing EM simulation software to design antenna element, and experiment tuning to determine the geometry
    - 120-300MHz, VSWR<2.0
    - 120-700MHz, VSWR<2.5
    - 80-100MHz, VSWR>10 suppress FM RFI
    - 50-80MHz, VSWR<6 allow for low-band application
- Firmware of digital backend is nearly done
- Pilot array is constructed

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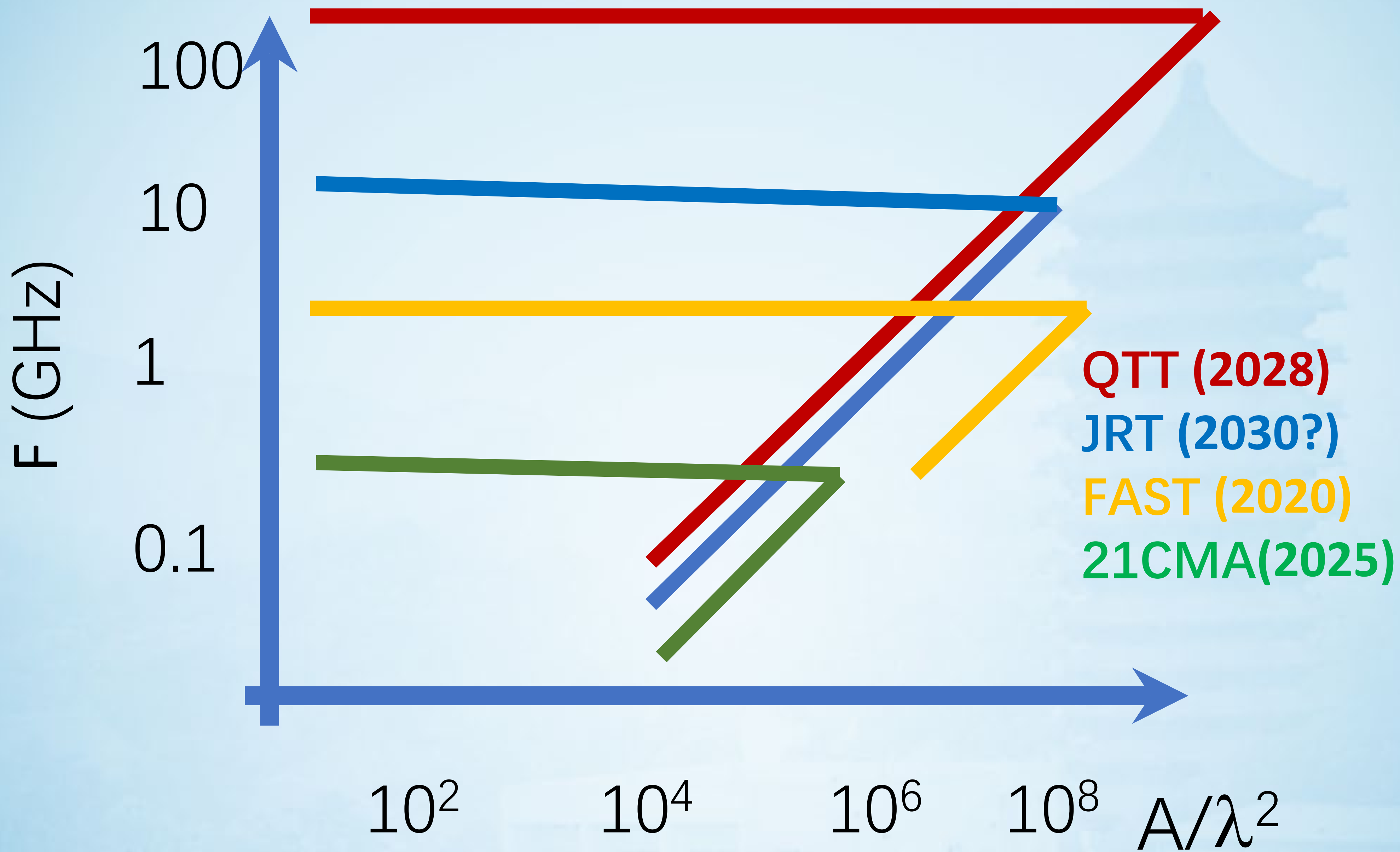

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Thanks!

Conclusions:

- Pulsar observation is very cool.
- We are working on the data analysis.
- We are working on instrumentation.
- We are working on theories.
- There are many science we can work with the PTA dataset
- There will be further improvement for the CPTA data quality

For questions: drop me a message kjlee _AT_ pku.edu.cn

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