Chinese pulsar timing array (CPTA) DR 1.0

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On behalf of CPTA team

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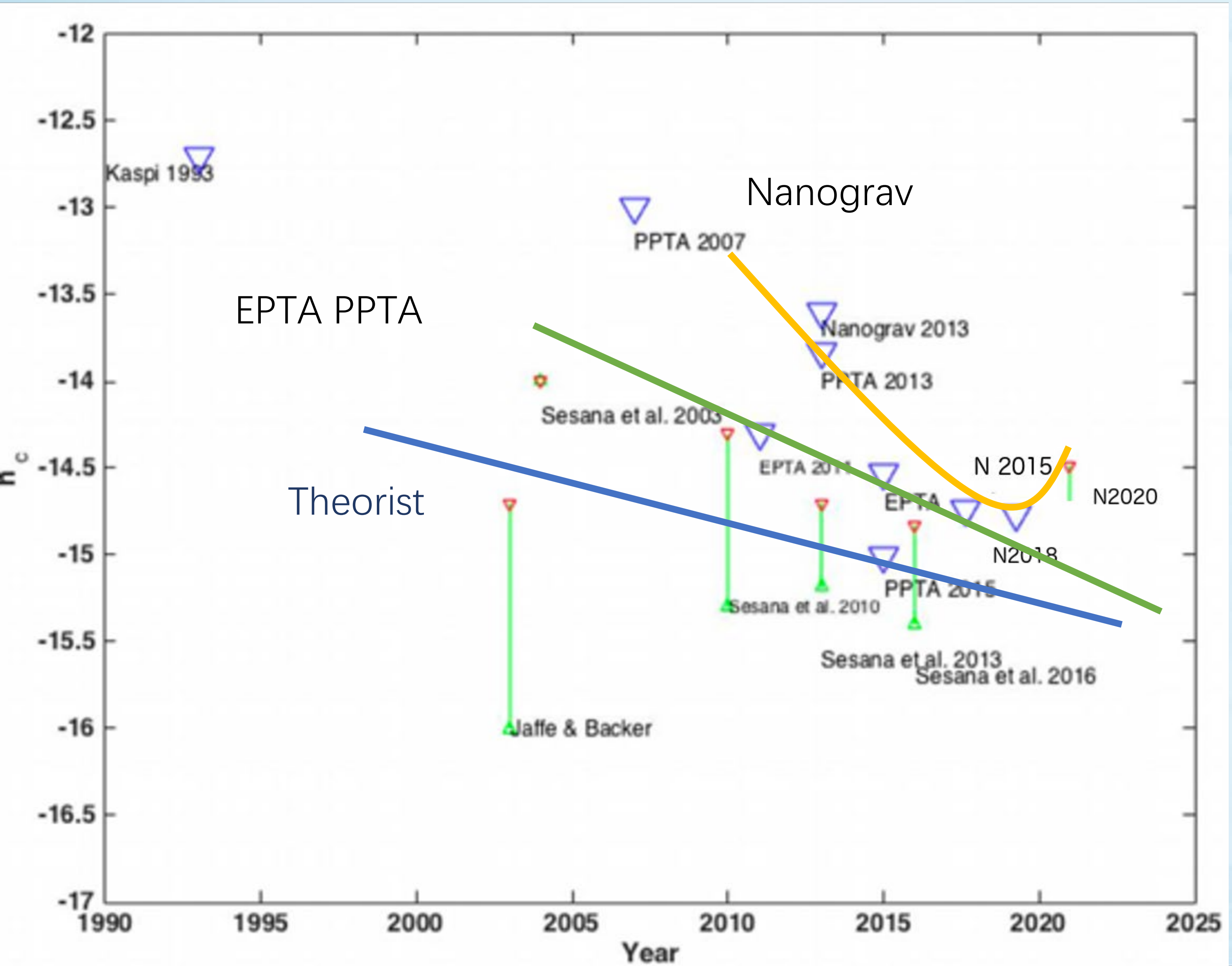
2023

32nd Texas Symposium on Relativistic Astrophysics

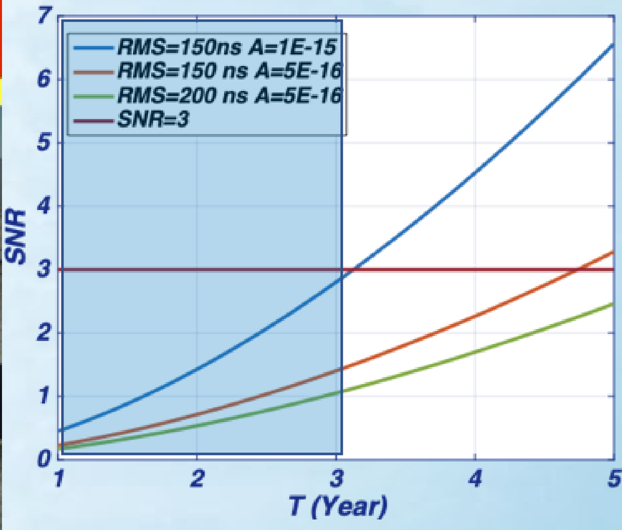
Historical expects before 2020

Optimistically, we will get something soon.
Pessimistically, we still need 10 years to catch up the prediction of theoriests' prediction.



CPTA

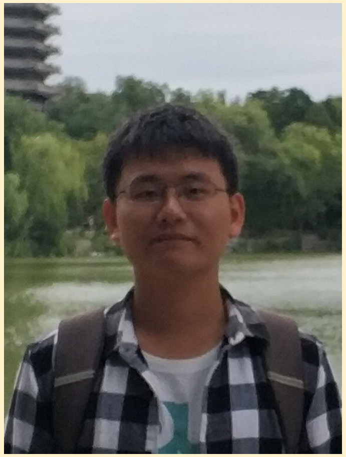
- 20 Sept. 2019, Second CPTA meeting, before FAST comissioning
- Agreed to form the CPTA
- Finalised and agreed on the CPTA policy
- Xiangping Wu, Dick Manchester, Michael Kramer Duncan Lorimer attended as supervise committee members



2019 proposal to FAST

Current data analysis team

Zihan Xue PhD
Single source
and axion



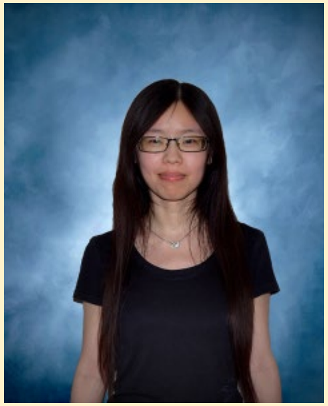
Jiangwei Xu PhD
Cosmic string,dark
matter

Bojun Wang
Post-Doc
Single pulse
jitter

Jinchen Jiang
Post-Doc
Polarisation
interferometry

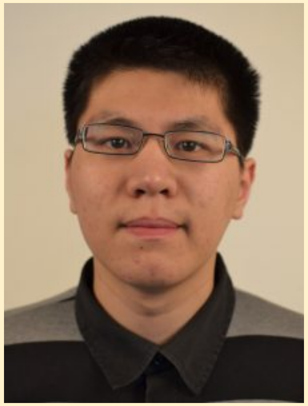
Nicolas Caballero
Post-Doc
Targeted source

Yonghua Xu
Researcher, ISM



Yanjun Guo Post-Doc
GW and noise

Heng Xu Post-Doc
timing and noise
analysis



Siyuan Chen
Post-Doc
GW and noise

Kejia Lee
Technician
GW and noise

Data quality

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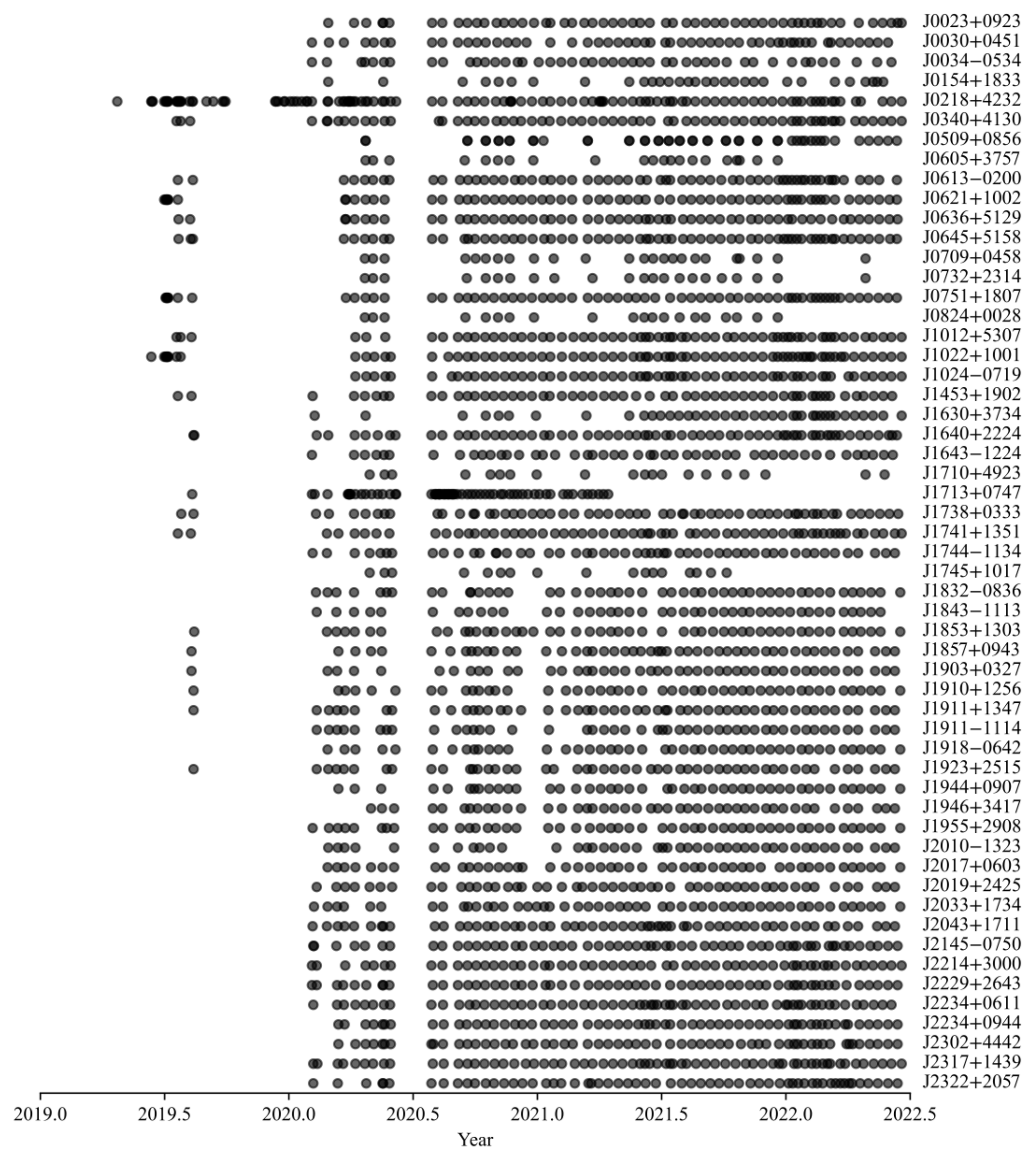
CPTA-DR1

~3 years length

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



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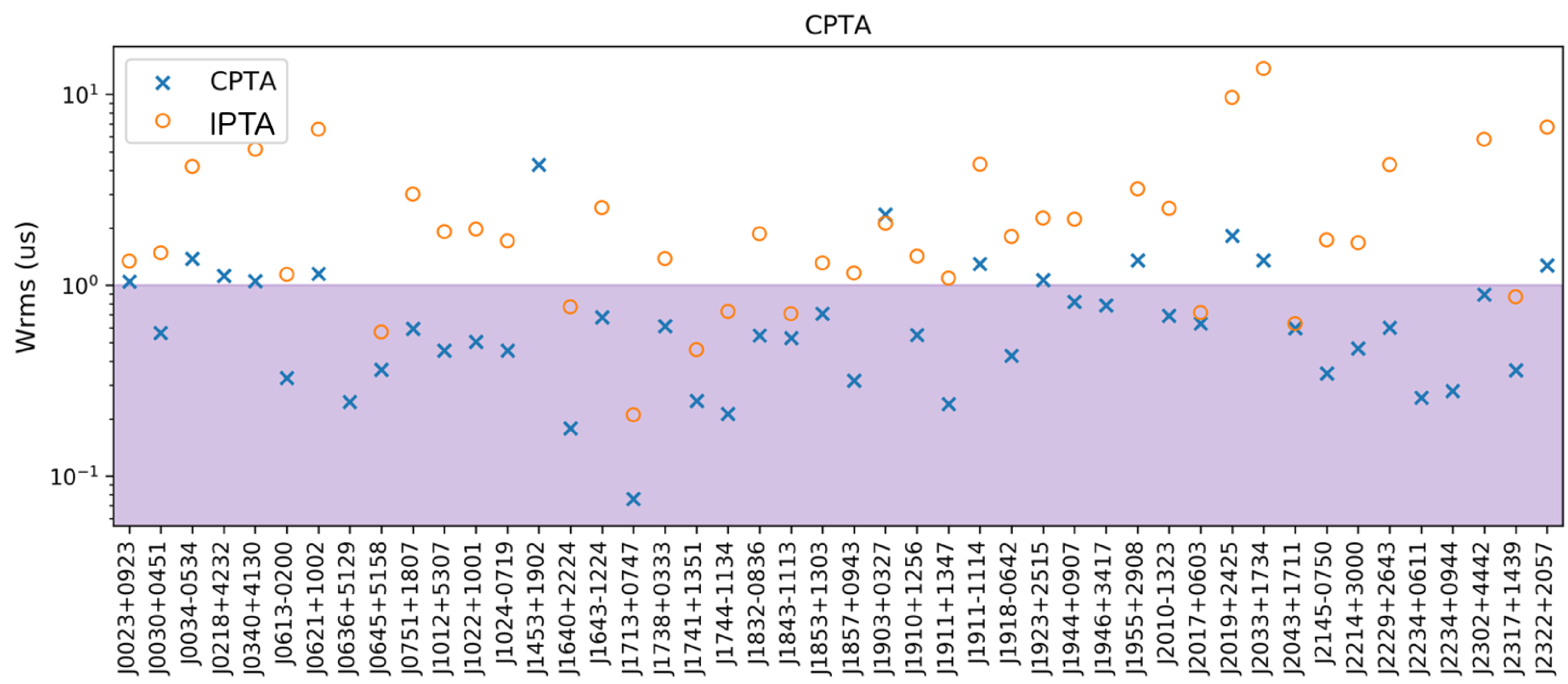
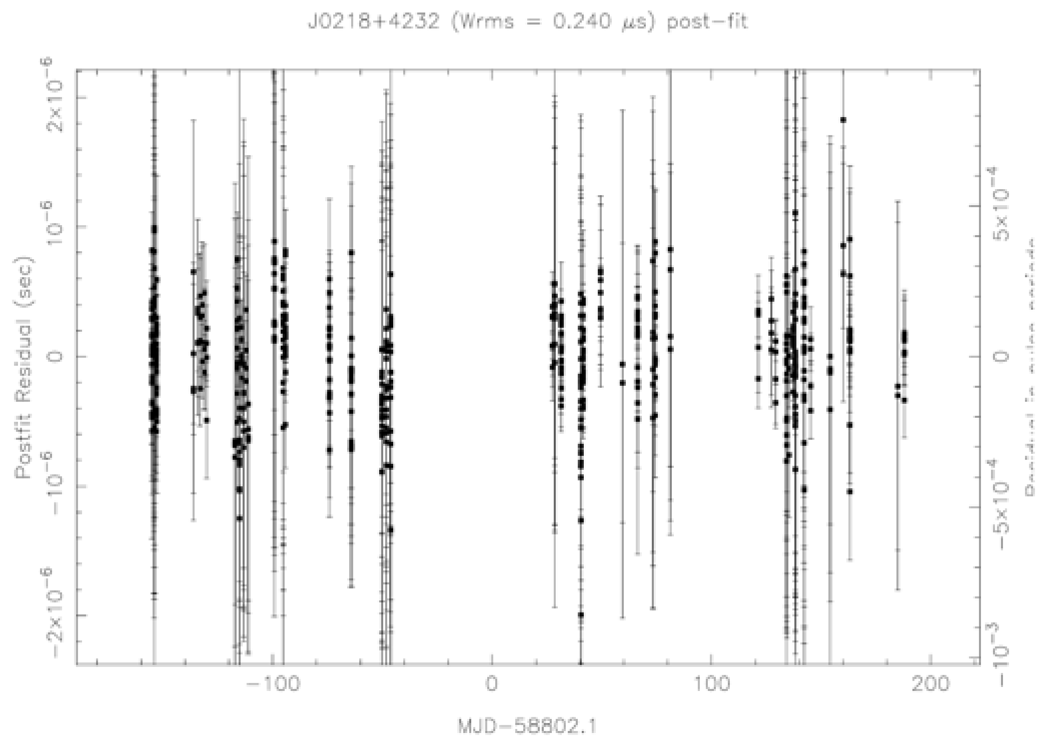
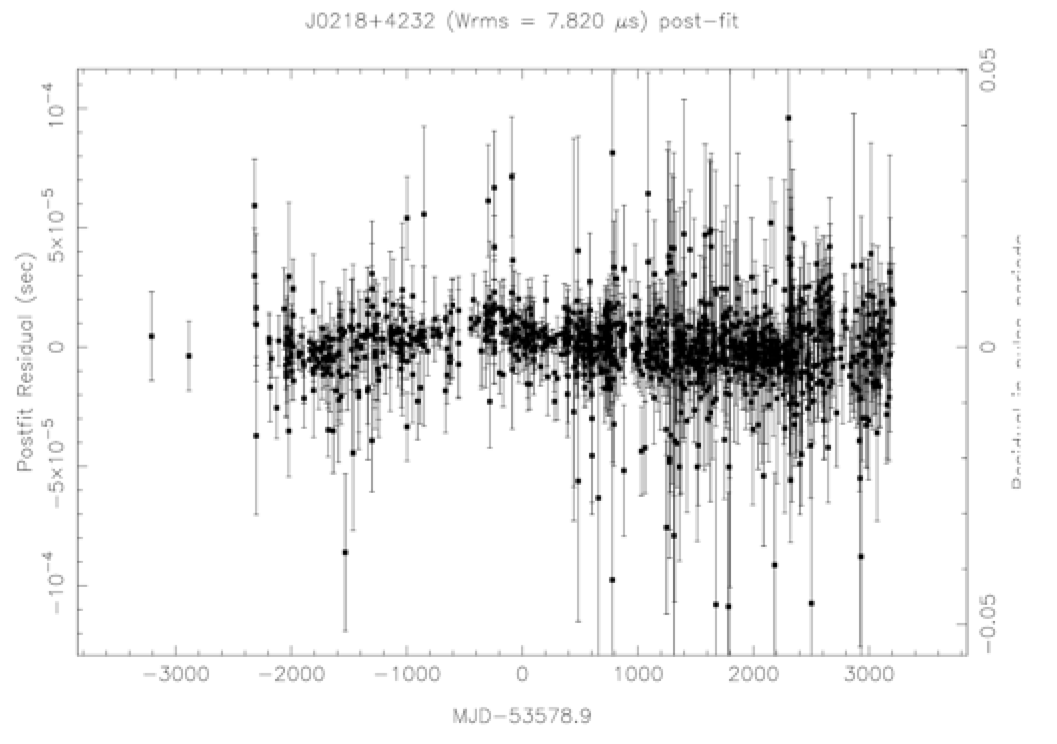
CPTA achive facotr of 4 to 50 improvement of precision for 2-year observation compare to current public IPTA data.



FAST

IPTA DR 2.0





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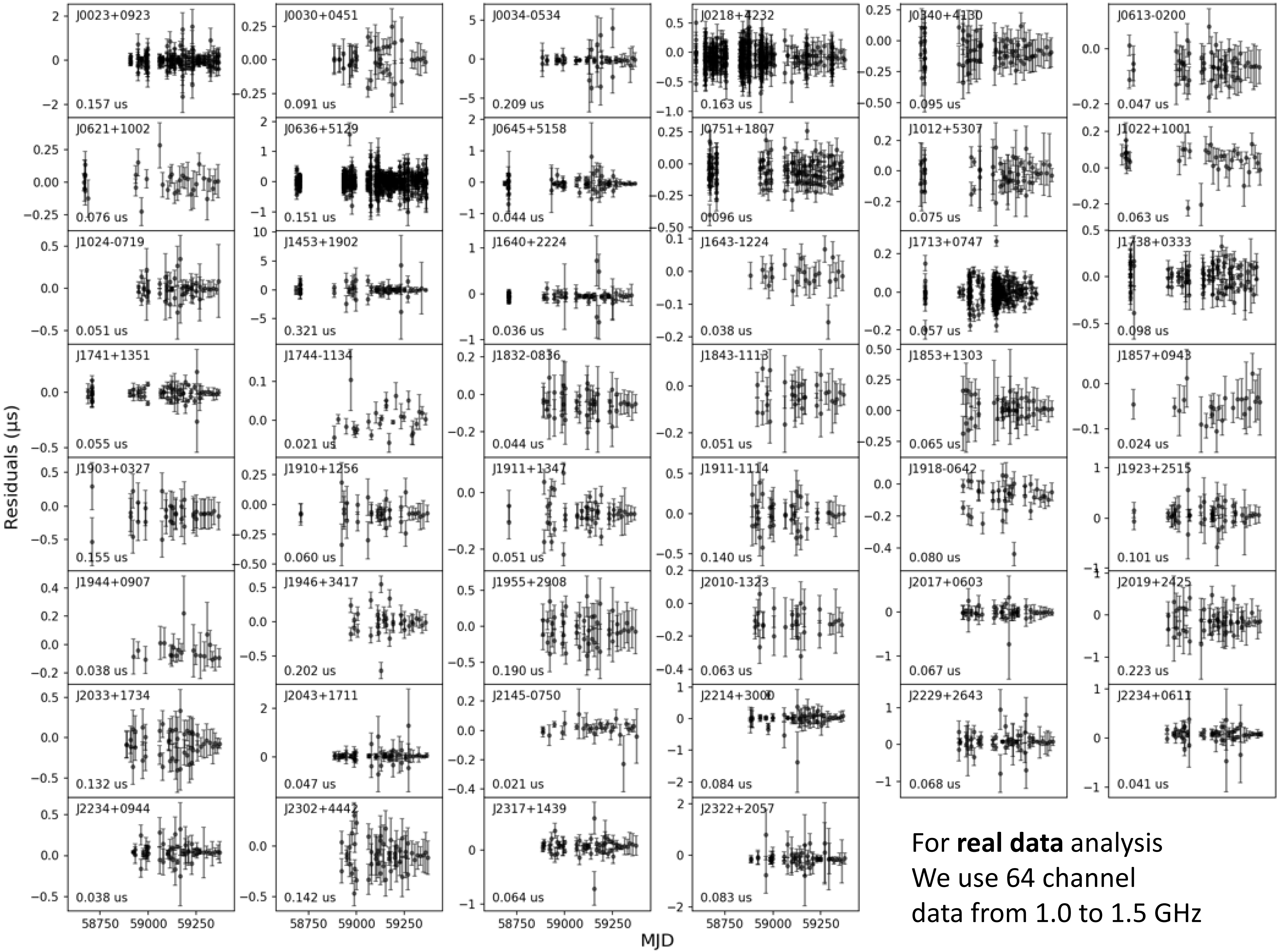
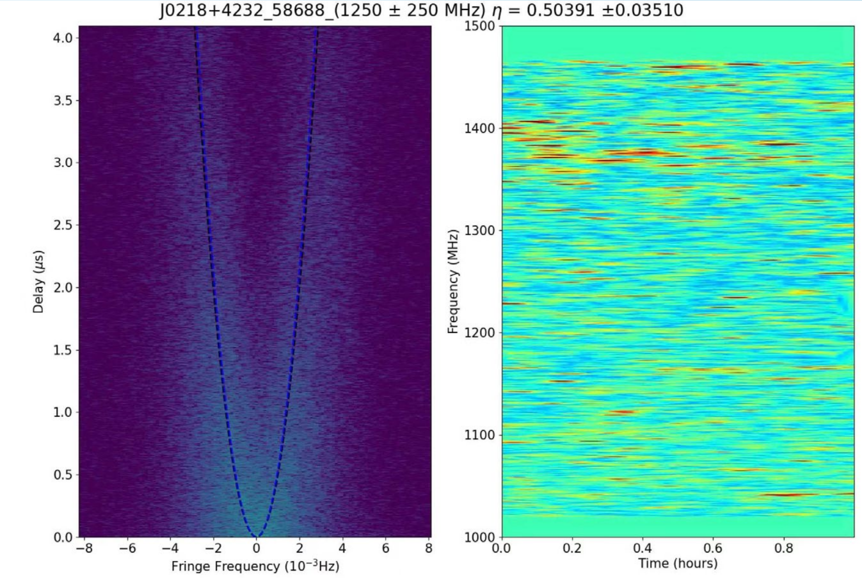


For **real data** analysis
We use 64 channel
data from 1.0 to 1.5 GHz

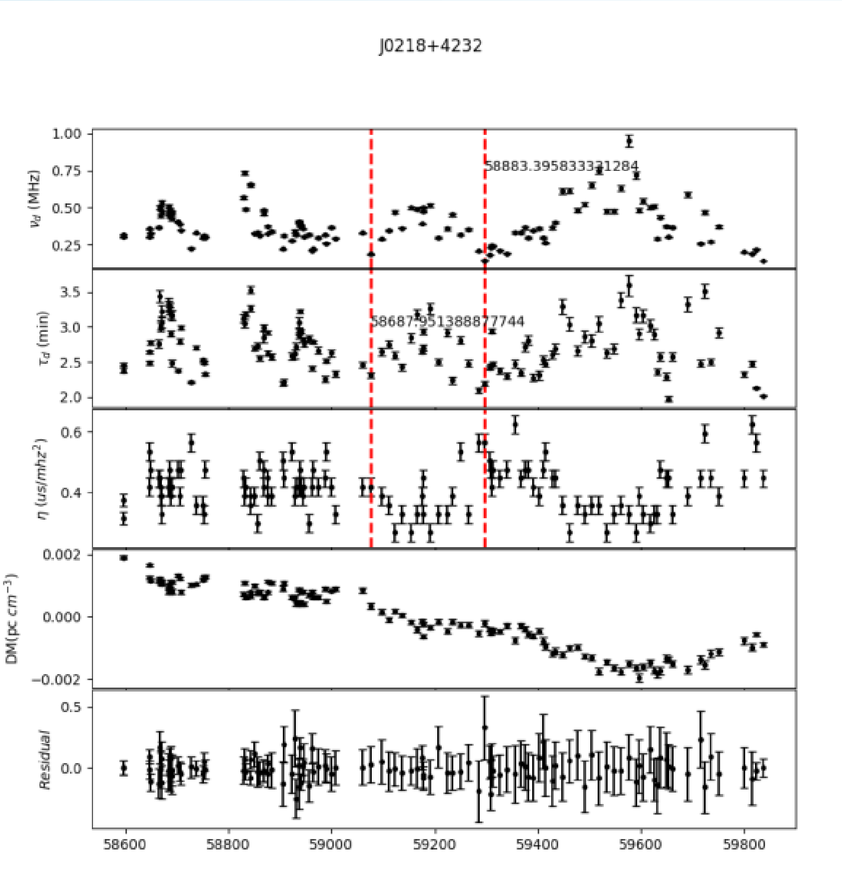
ISM effects

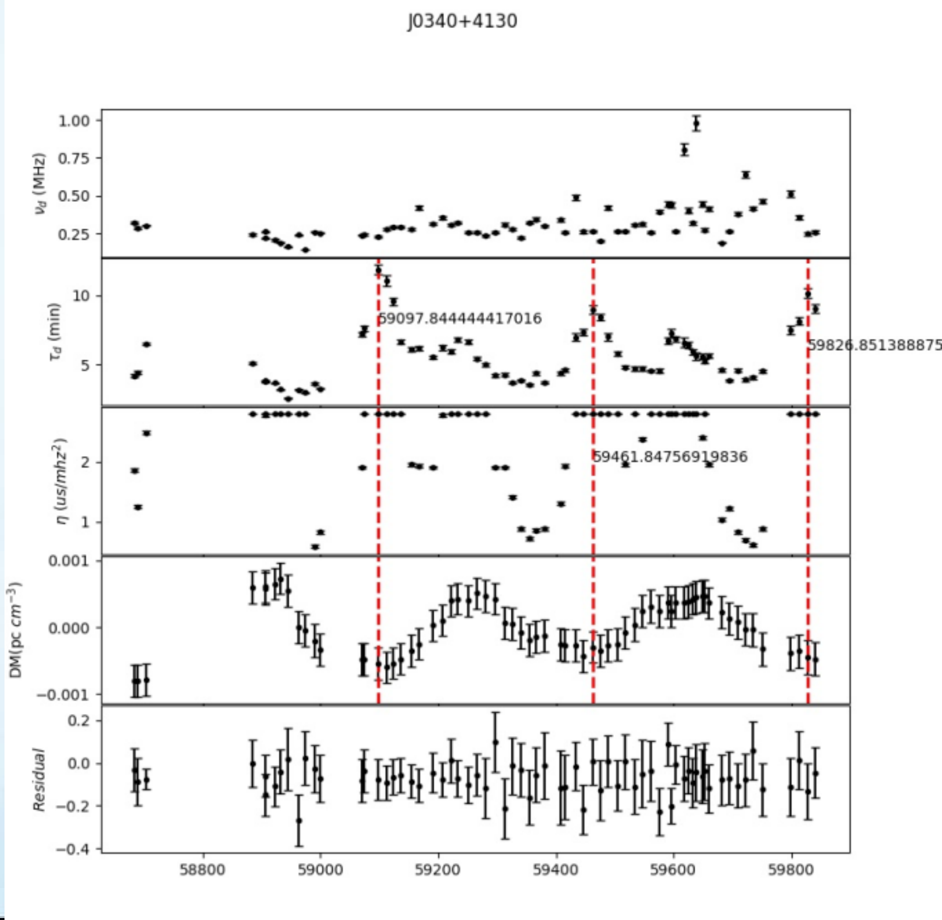
Time dependent ISM parameter variation

- For most pulsars, we can measure the scintillation parameters and ISM parameters
- Even for those weak pulsars
- There seems to be **quasi periodic** structures in scintillation parameters and ISM parameters
- The variation of the scintillation parameters, however, show little effects to timing.



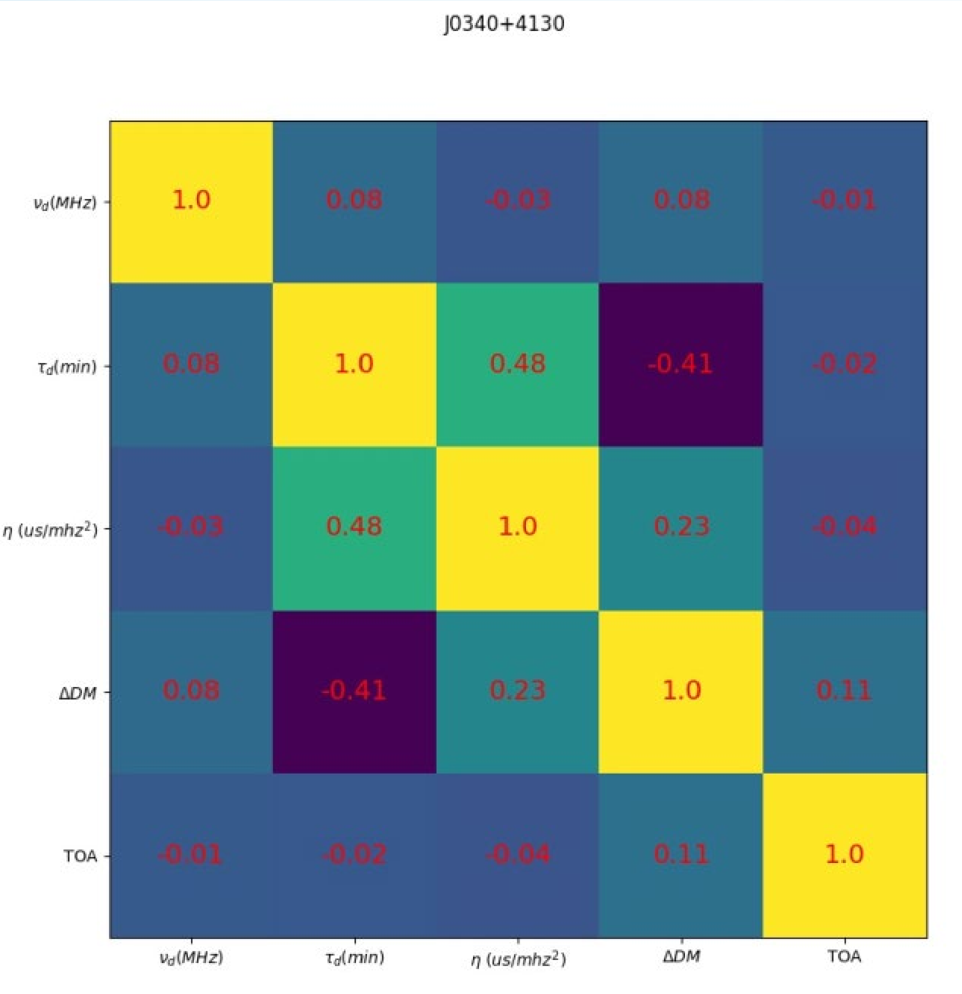
Xu et al., in prep

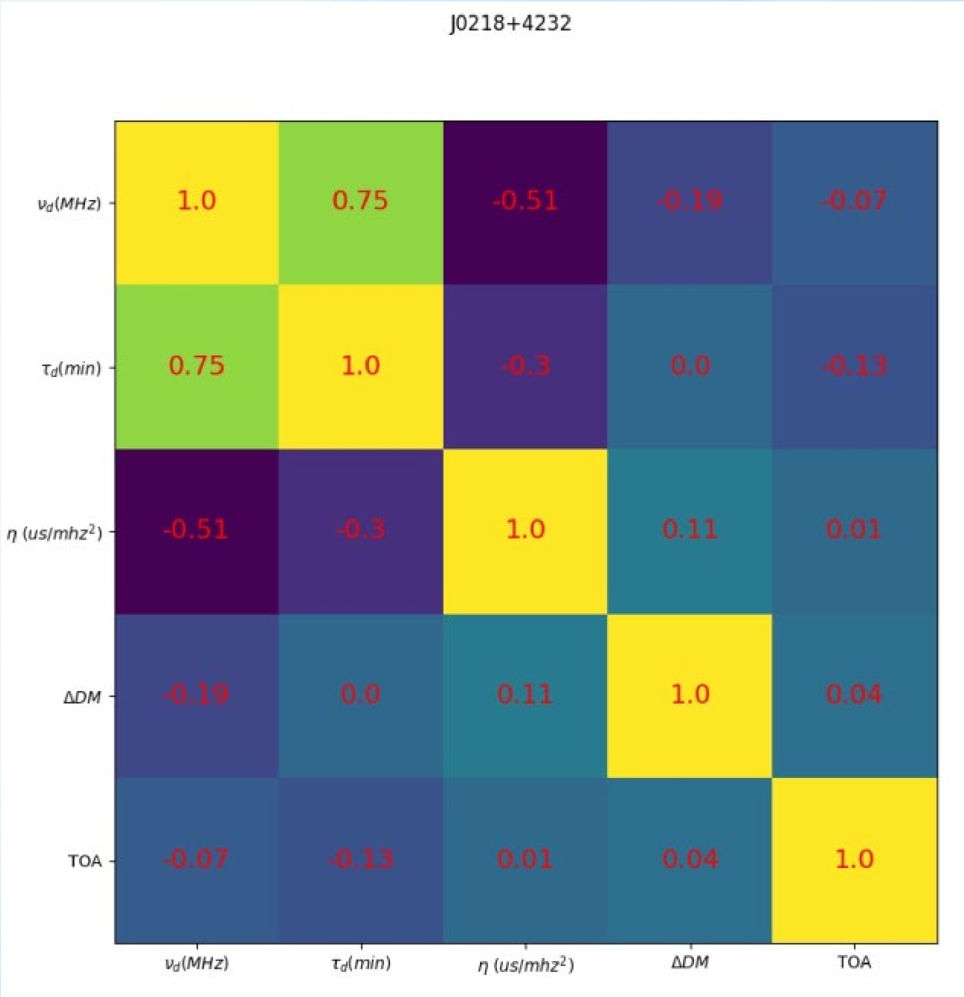




Depending on the pulsar, there could be correlation between arc curvature, DM variation and scintillation bandwidth. **Timing is not really affected.**

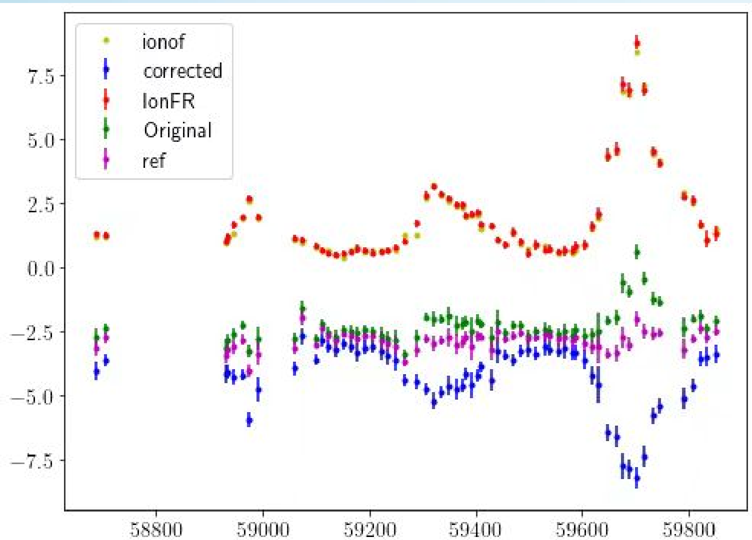
Xu et al., in prep

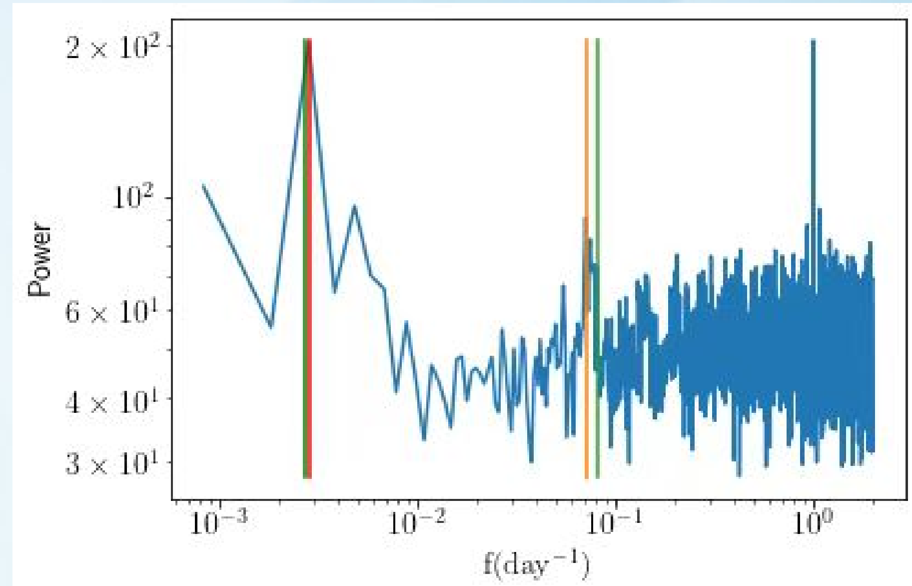


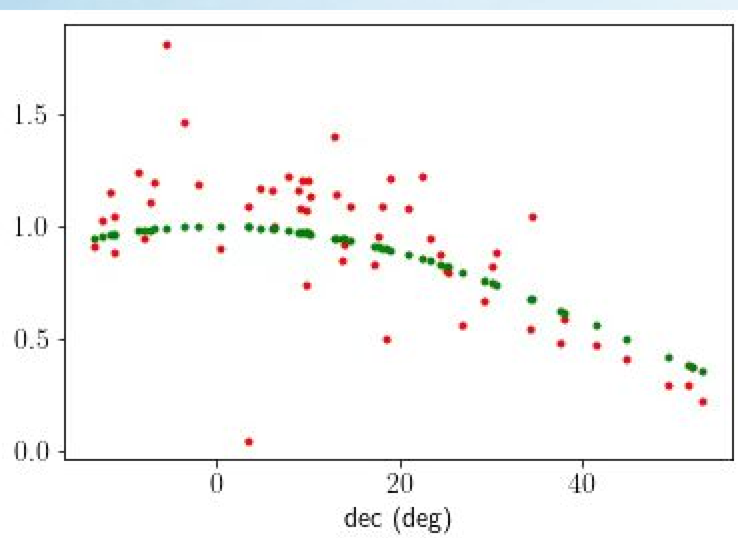


Faraday rotation probing the ionosphere

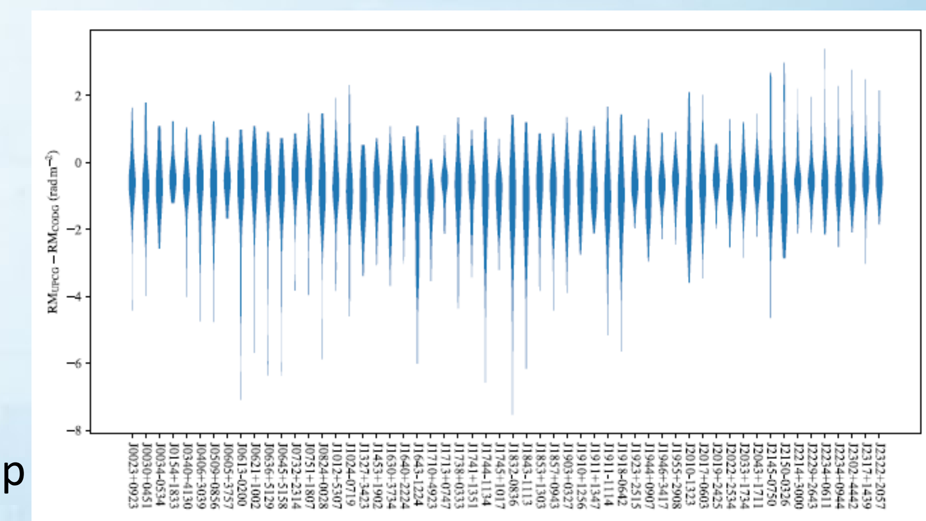
- Standard software IonFR **over estimates** the RM variation by a factor of 2-3 for high dec sources.
- We implement the **IONOF**, it produces nearly the same answers compared to IonFR
- Turns out **TEC is problematic**, different TEC model differs by more than factor of 2.
- We **saw 1-year and 24-and 28-days RM variation**. Indication solar wind –earth magnetosphere interaction is important for sub 1 Rad/m^2 RM precision



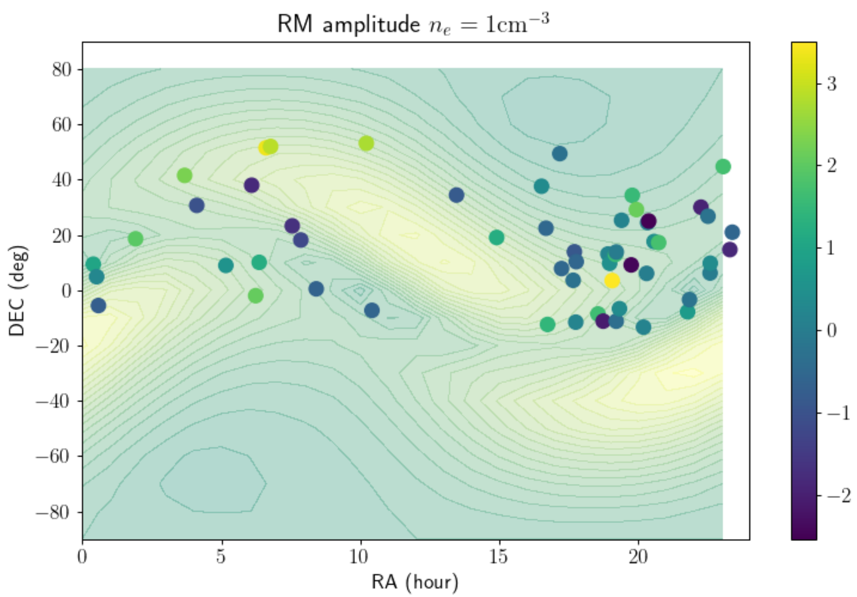


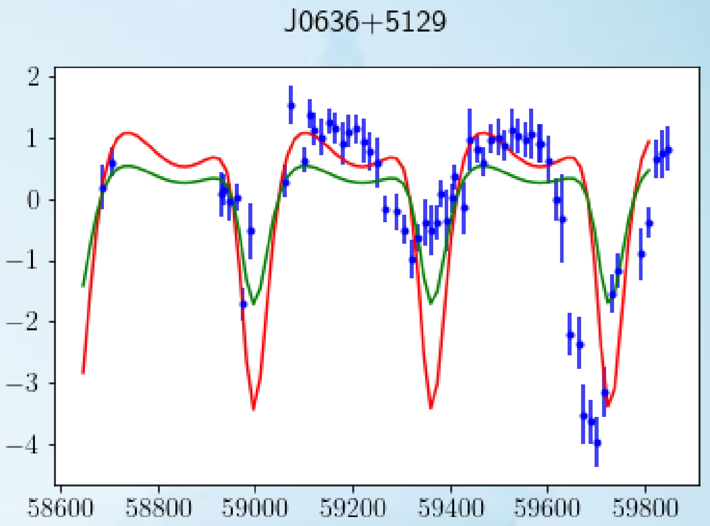


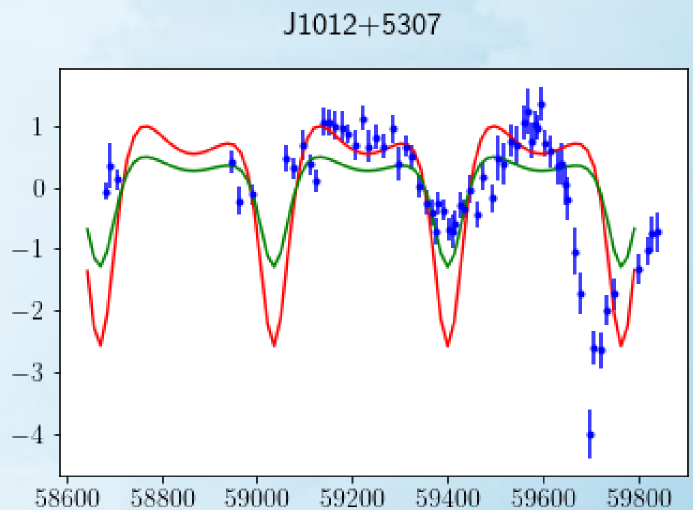
Xu et al., 2023 in prep

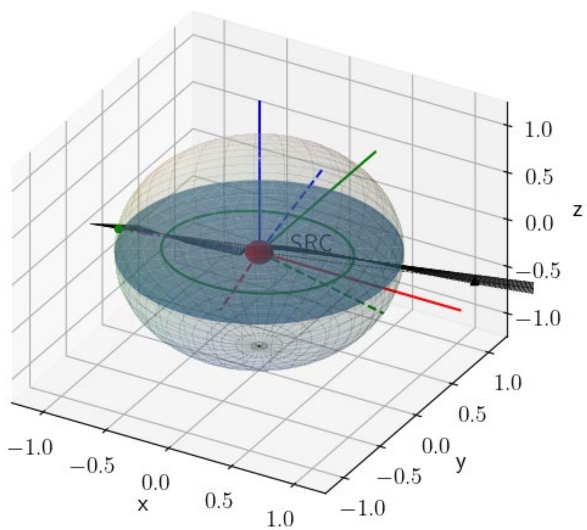


Solar system RM modeling









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

ISM analysis take home message

1. Timing is not really affected by scintillation.
2. CPTA data can be used to check the current earth Faraday rotation correction model.
3. It seems that we measured solar wind- earth magnetosphere interaction from Faraday rotation.

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Noise analysis

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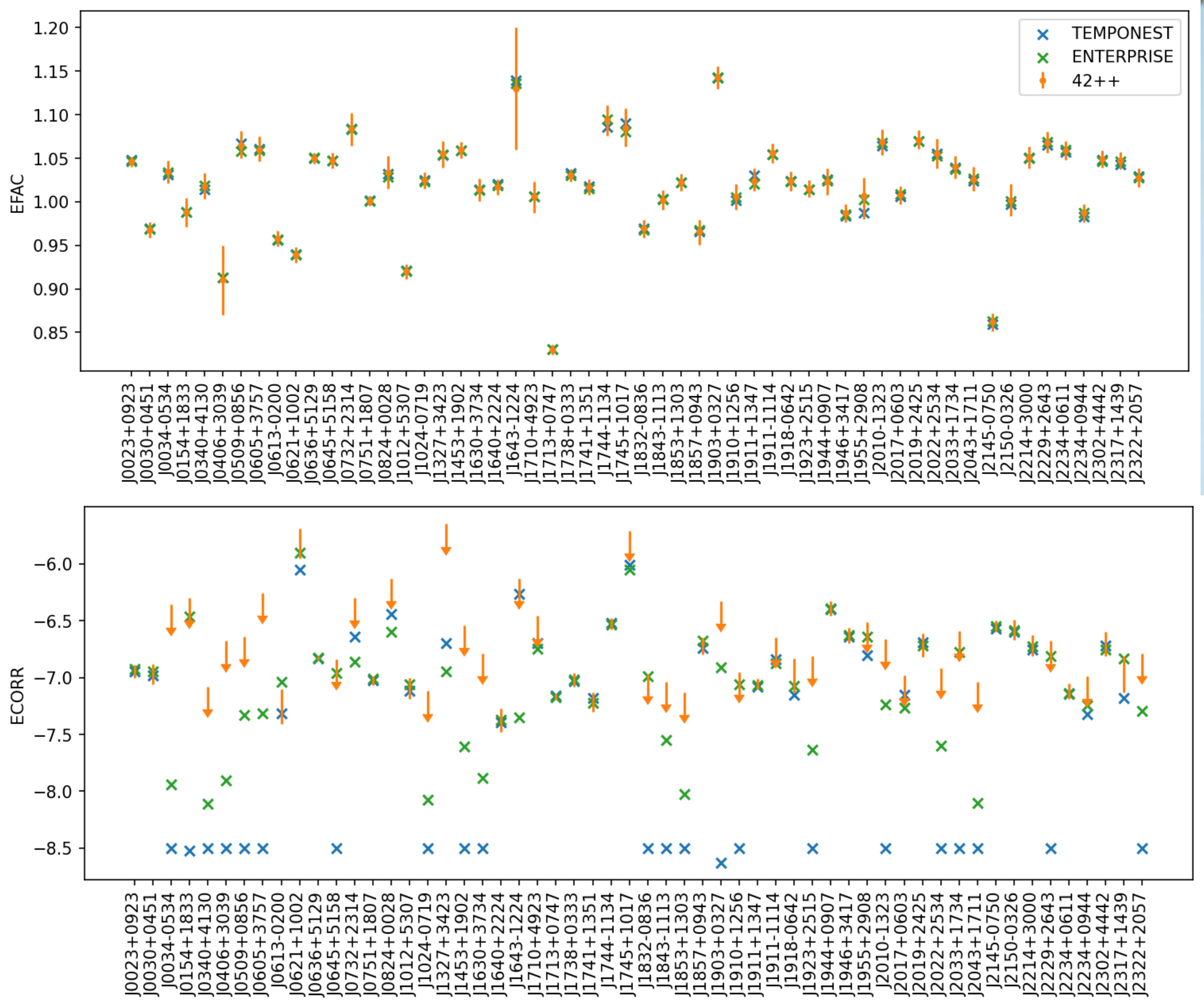
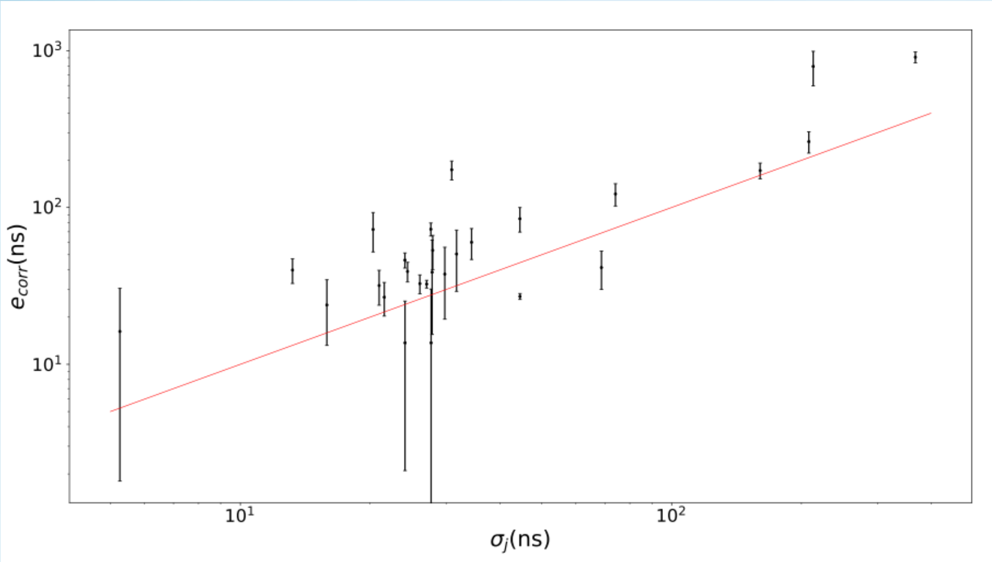
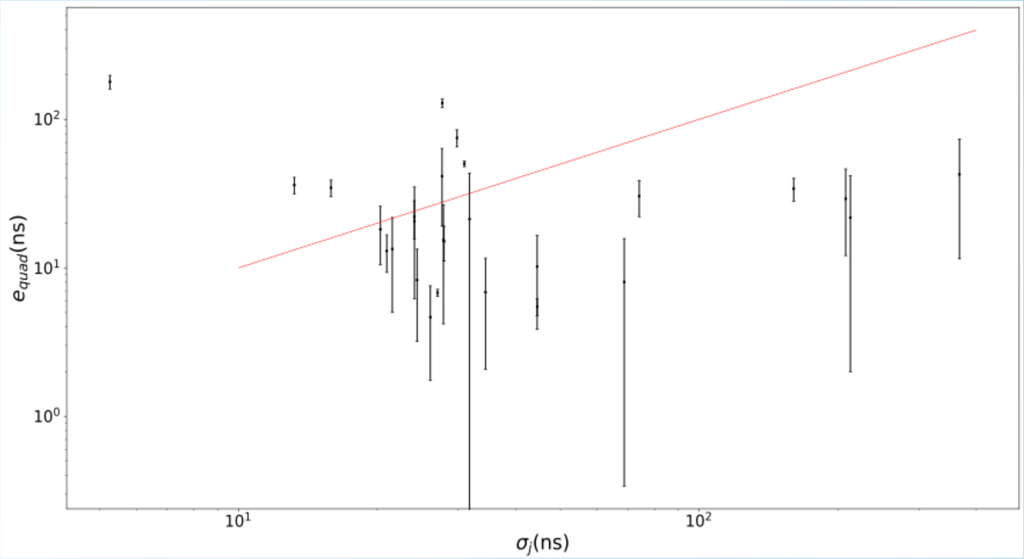
White noise analysis

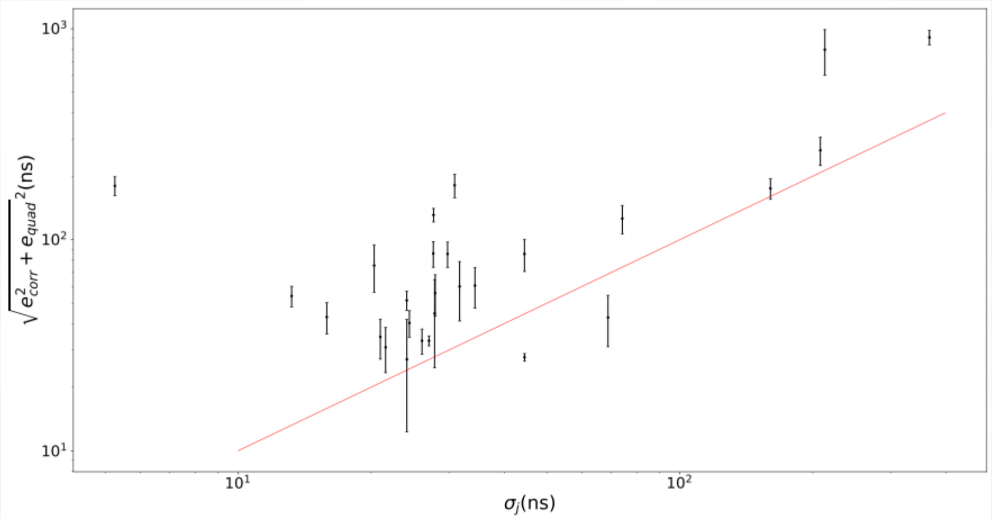


Chen et al.,
in prep

Compare jitter modeled in timing and single pulse domain







The jitter parameter also agrees with single pulse domain modeling.

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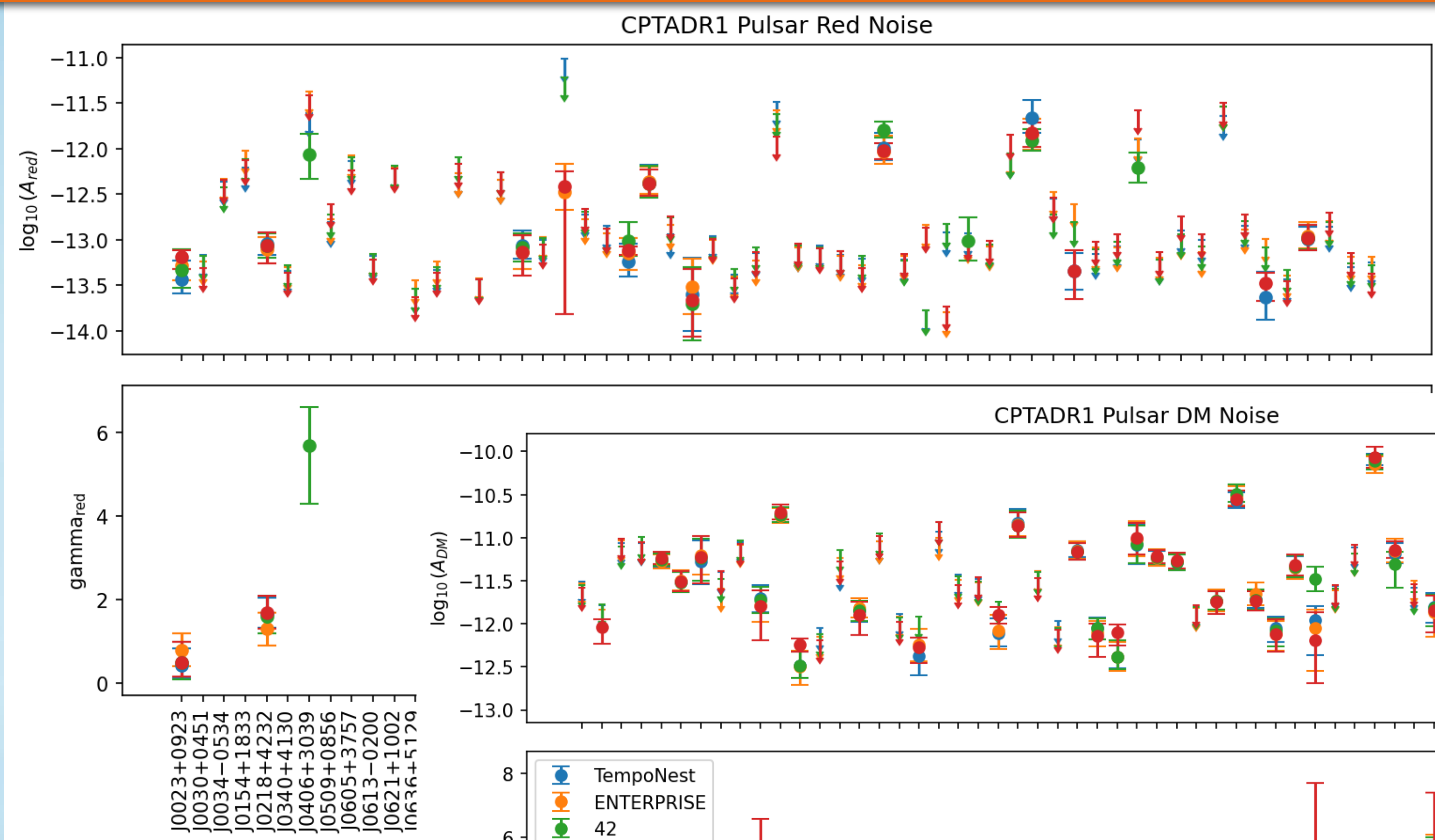
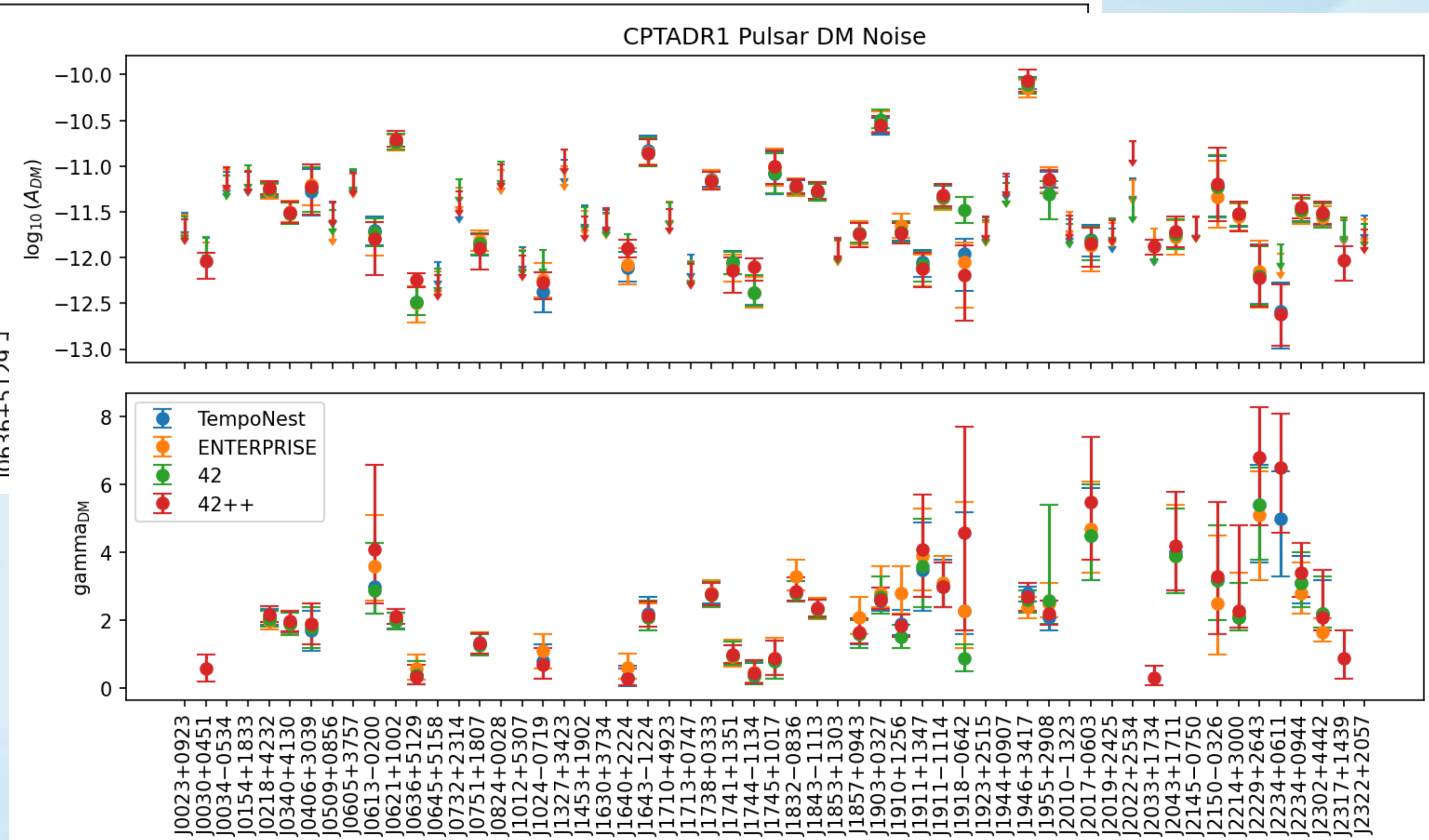
Wang et al., 2023 in prep

Red noise and DM noise analysis





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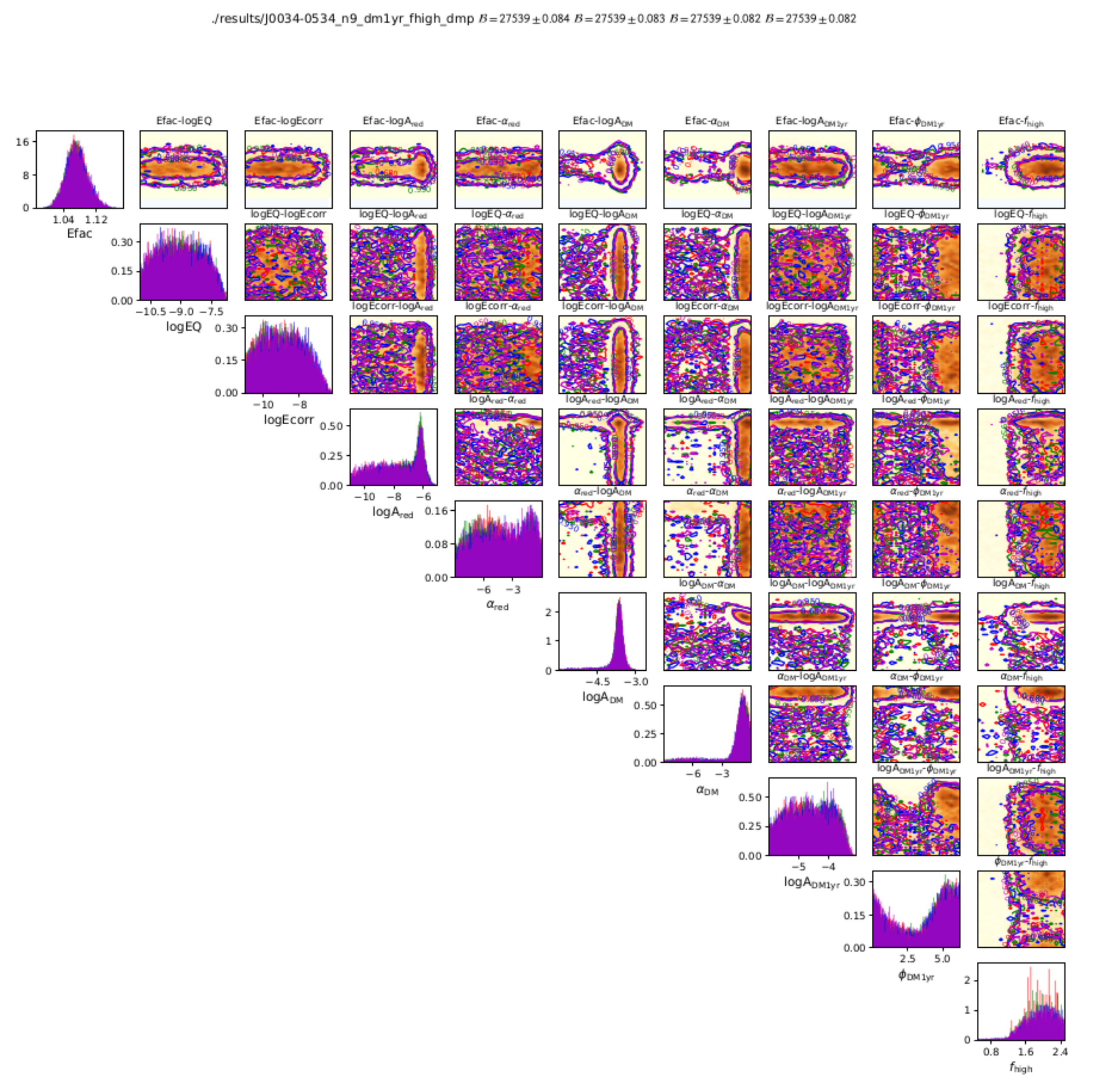
Selection of best model

CPTA Recipe:

- **Model the high frequency cut-off as free parameter, and compare Bayesian factor of different choice of number of frequencies.**
- **Compare all possible combination of modeling (16 combinations) and choose according to the Bayesian evidence.**



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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. **Jitter modeling in timing agrees with the single pulsar domain analysis**
3. **DM power law modeling is preferred over DMX** for CPTA data sets.
4. For each pulsar, we build the best model (highest evidence).
5. For some pulsar, **jitter effects should be taken into account**.

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GW detection and future

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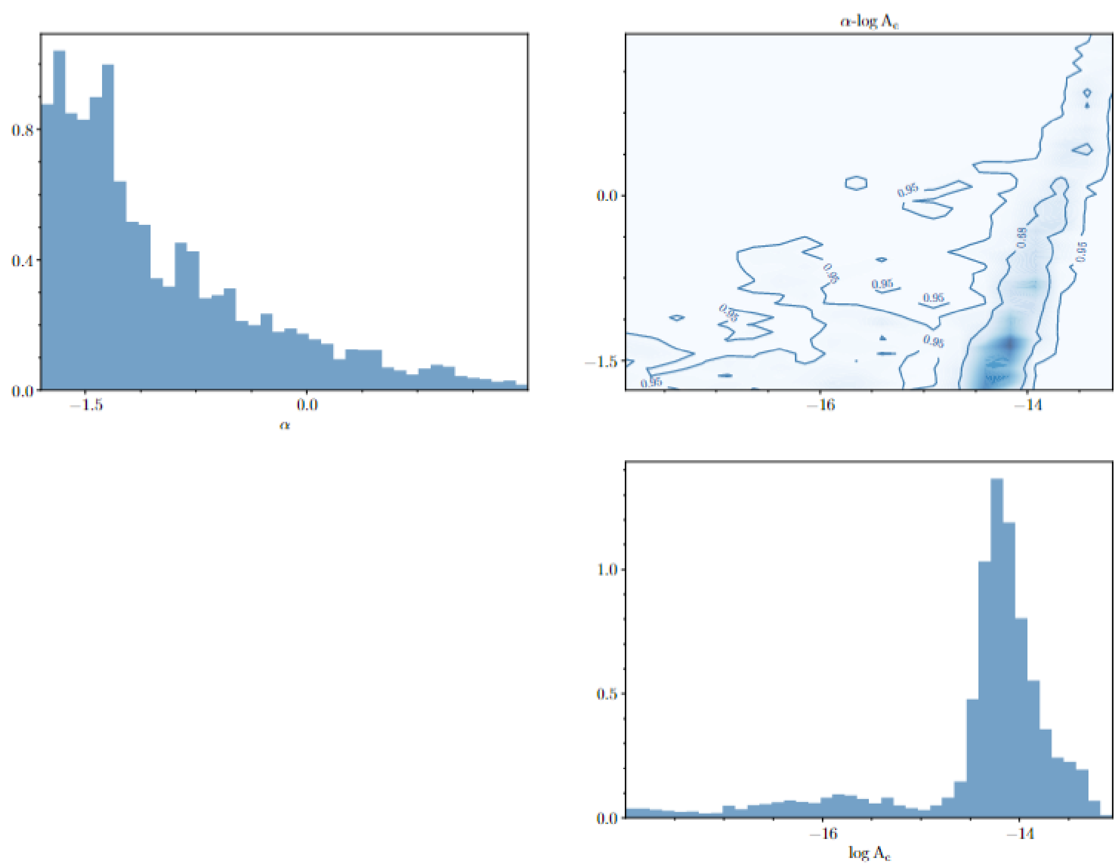
GW Parameter inference

- GW spectral index was not well measured with CPTA, because of
  1) marginalization of white noise in GW analysis
  2) short data length



Ac=2e-15, 3yr data
Induced GW signal RMS=30ns

```
In[101]:= α := 2/3
          Ac := 2 × 10^-15
          Fl := 1/3
          N[10^9 × 24 × 3600 × 365 Sqrt[Integrate[Ac^2/(12 π^2 f) f^(-2 α - 3), {f, Fl, ∞}]]]
Out[104]= 30.0918
```

Errorbar of 64 channel data ~1us, white noise parameter needs accuracy of 3 digits to be accurate.

Marginalization of white noise seems to be necessary.

Xu et al., 2023 RAA

Asymtotic validity of Bayesian factor for heteroscedastic statistics

"I guess next step you will use Bayesian factor to evaluate the detection significance?"

1. "Yes, it is straight forward" Answer if you ask me before 2022
2. "No, it is not rigorous from the first principle." Answer if you ask me after 2022

Modeling pulsar intrinsic noise only

$$\Lambda_0(\sigma_1, \sigma_2 \ldots \sigma_N) \propto \prod_{i=1}^{N} \frac{1}{\sigma_i^{N_{pt,i}}} \exp\left[-\frac{1}{2}\frac{\boldsymbol{r}_i \cdot \boldsymbol{r}_i}{\sigma_i^2}\right]. \quad \text{(A2)}$$

Bayesian factor is well defined.

$$\langle \mathrm{BE}_0 \rangle = \int \ldots \int \Lambda_0(\sigma_1, \sigma_2 \ldots \sigma_N) d\log\sigma_1 \ \ldots d\log\sigma_N \propto \prod_{i=1}^{N} 2^{\frac{N_{pt,i}-2}{2}} (N_{pt,i}\sigma_i^2)^{-\frac{N_{pt,i}}{2}} \Gamma\left(\frac{N_{pt,i}}{2}\right). \quad \text{(A3)}$$

Add a common mode

$$\Lambda_1(\sigma_1, \sigma_2 \ldots \sigma_N; A) \propto \prod_{i=1}^{N} \frac{1}{(\sigma_i^2 + A^2)^{N_{pt,i}/2}} \exp \times \left[-\frac{1}{2}\frac{\boldsymbol{r}_i \cdot \boldsymbol{r}_i}{\sigma_i^2 + A^2}\right]. \quad \text{(A4)}$$

Bayesian factor will be infinite, i.e. one needs to be careful about the interpretation of BF.

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

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HD curve inference

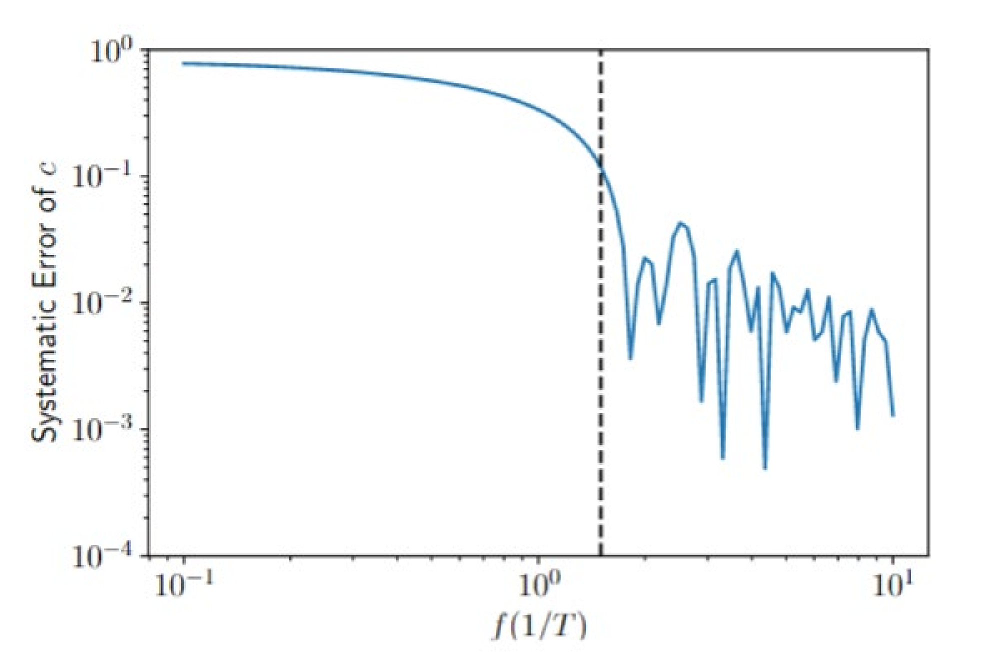
Pulsars have unknown period and period derivative. They affect the correlation of lowest frequency.
We focus on the part of signal with minimal systematics in the correlation curve inference.

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

were $\boldsymbol{r}_i'$ is

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

- One should search for correlation above f~1.5/T.
- For CPTA, data is short, we look at 1.5/T. For longer dataset, one can combine multiple higher frequencies above 1.5/T to increase S/N.



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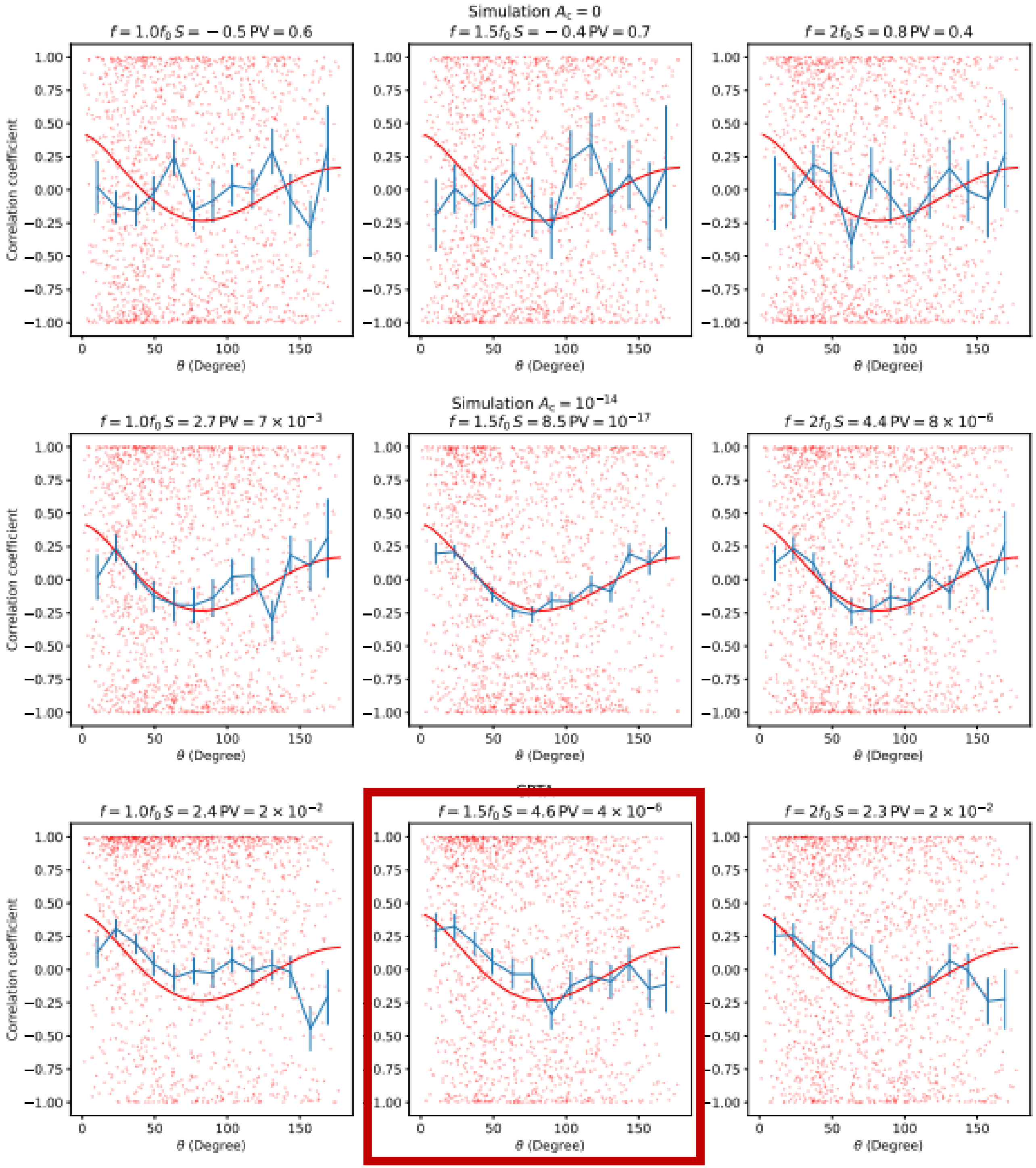
Xu et al., 2023 RAA

HD curve



Null control group

Positive control group

Real data

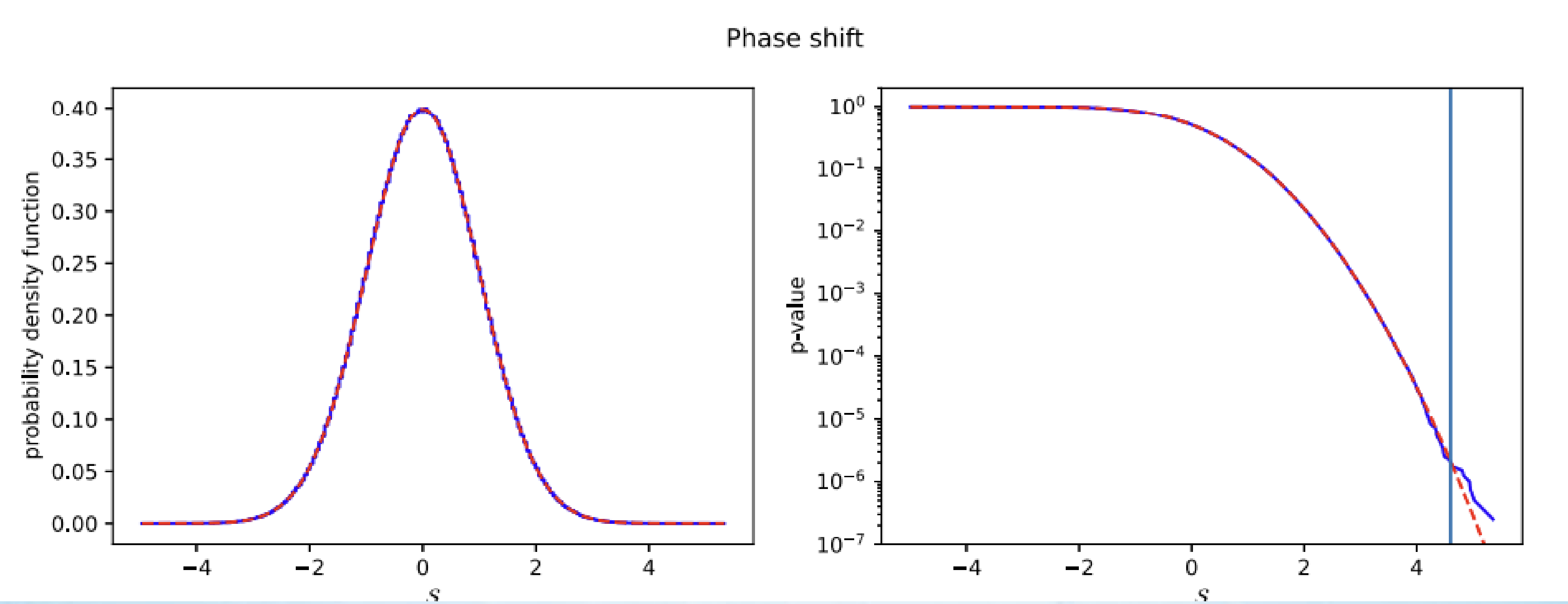
Xu et al., 2023 RAA

False alarm probability

1. False alarm probability can be computed from direct analytic method
2. False alarm probability can be computed from randomize the phase shifts.

Results agreed.

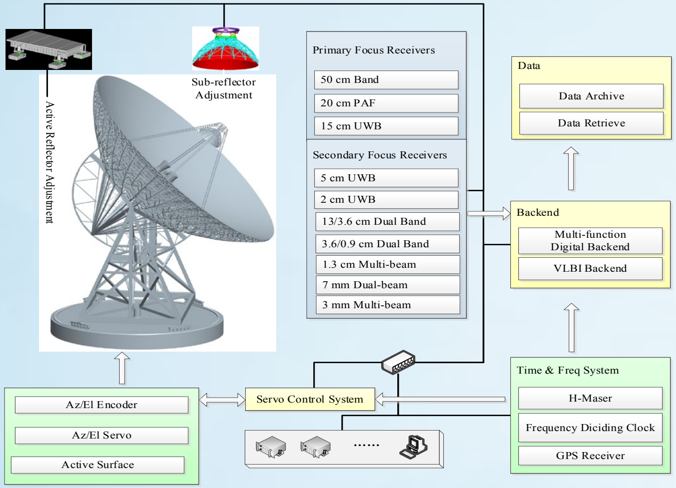
Sky scrambling does not work. The reason is the null sample space is not well defined, and correlation leaks in.
(See appendix C of Xu et al., 2023, RAA)

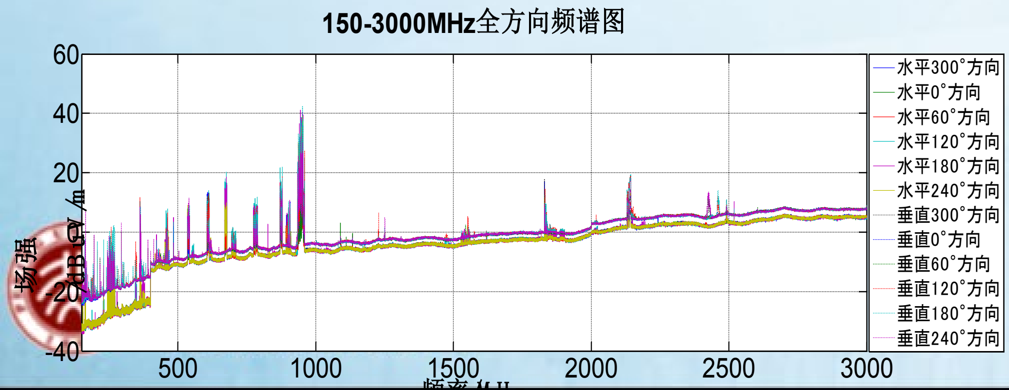


Xu et al., 2023 RAA

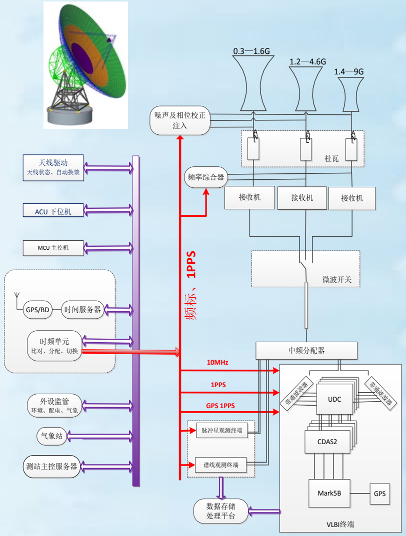
Progress of Chinese Radio Gemini

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

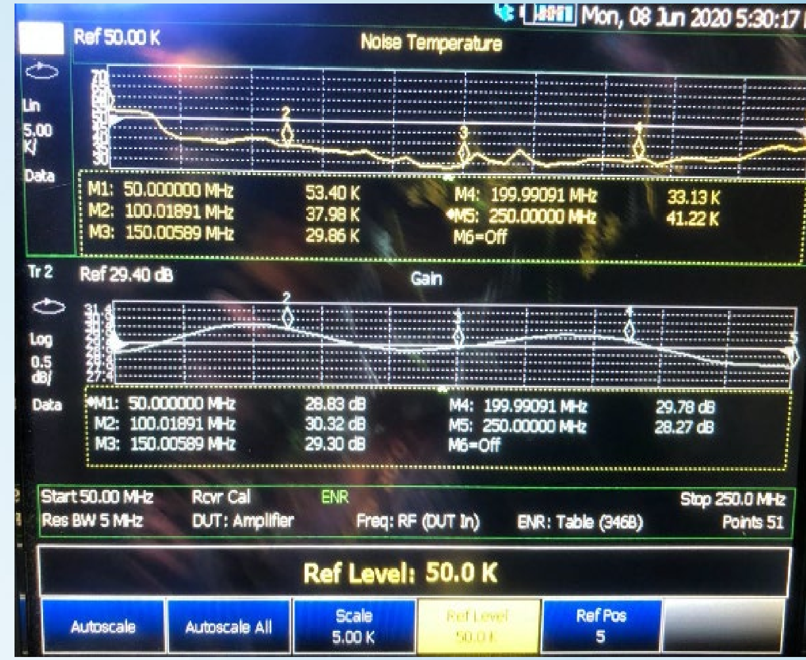




JRT 120m lowband (10GHz) radio teelscope at Jindong. Contract signed **waiting for the green light.**



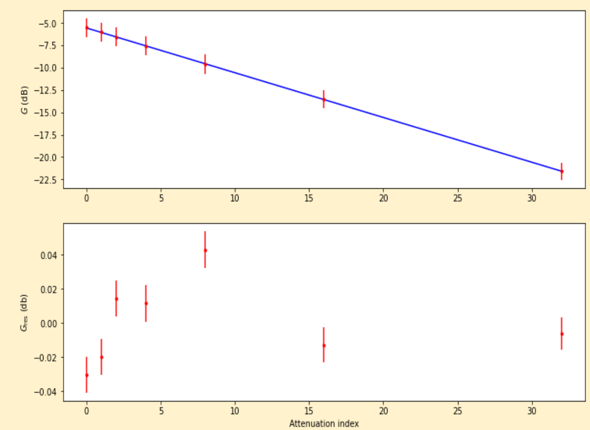
Extend frequency coverage

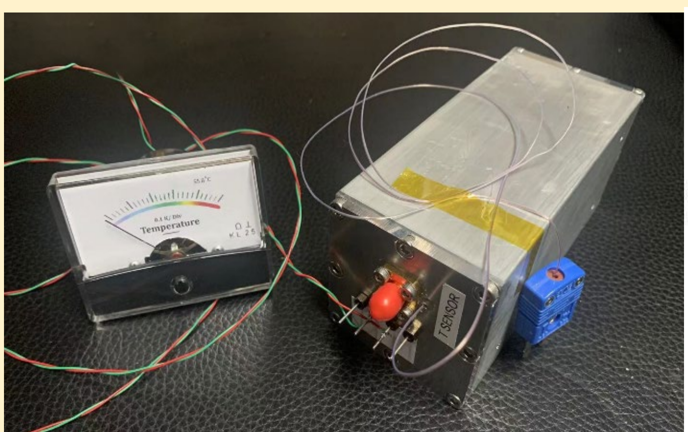


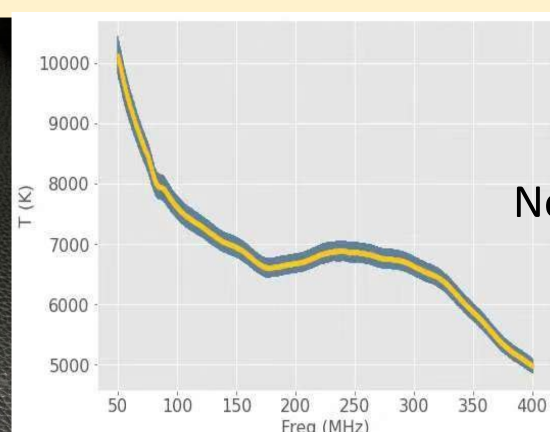
21CMA 127X81 dipoles

SKA-low pilot project

RF front-end is nearly ready

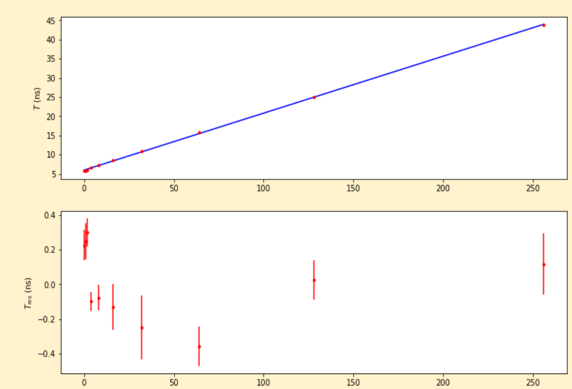


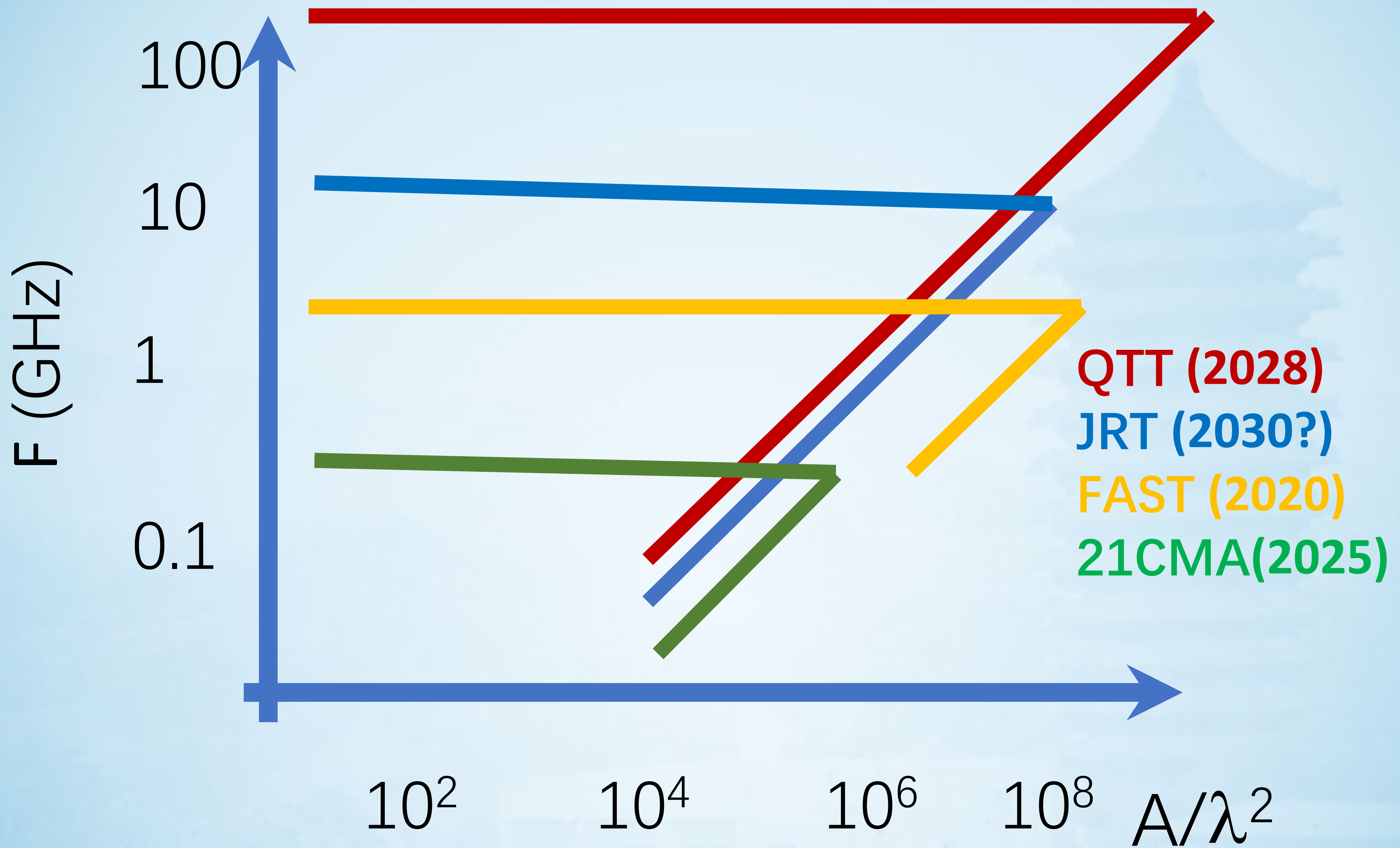




Beam former

Noise standard





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Thanks!

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