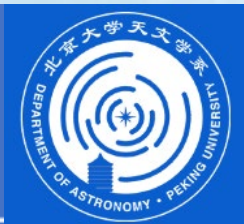


From nHz to uHz GW sky ---CPTA and something new

K. J. Lee

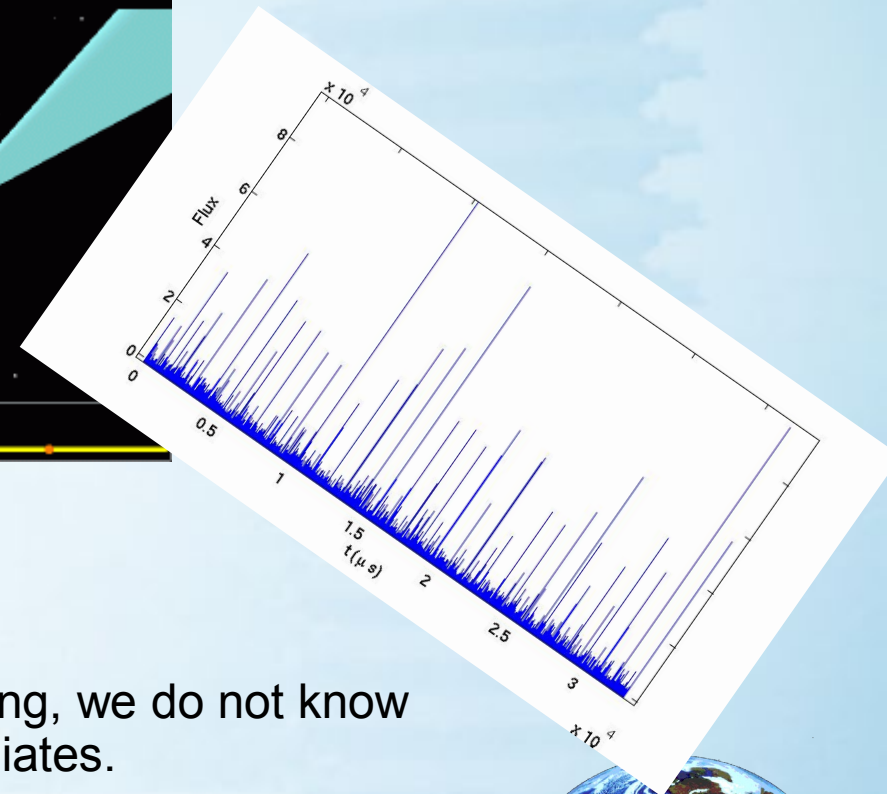
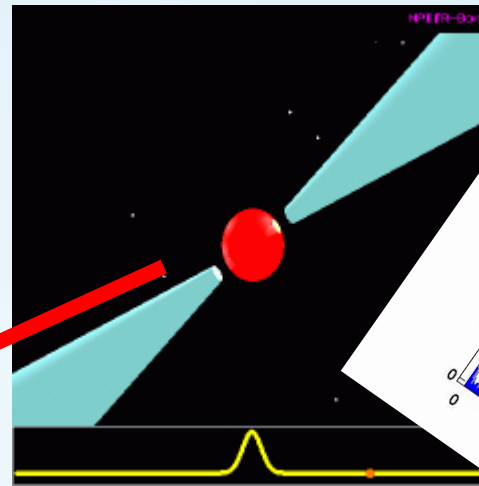
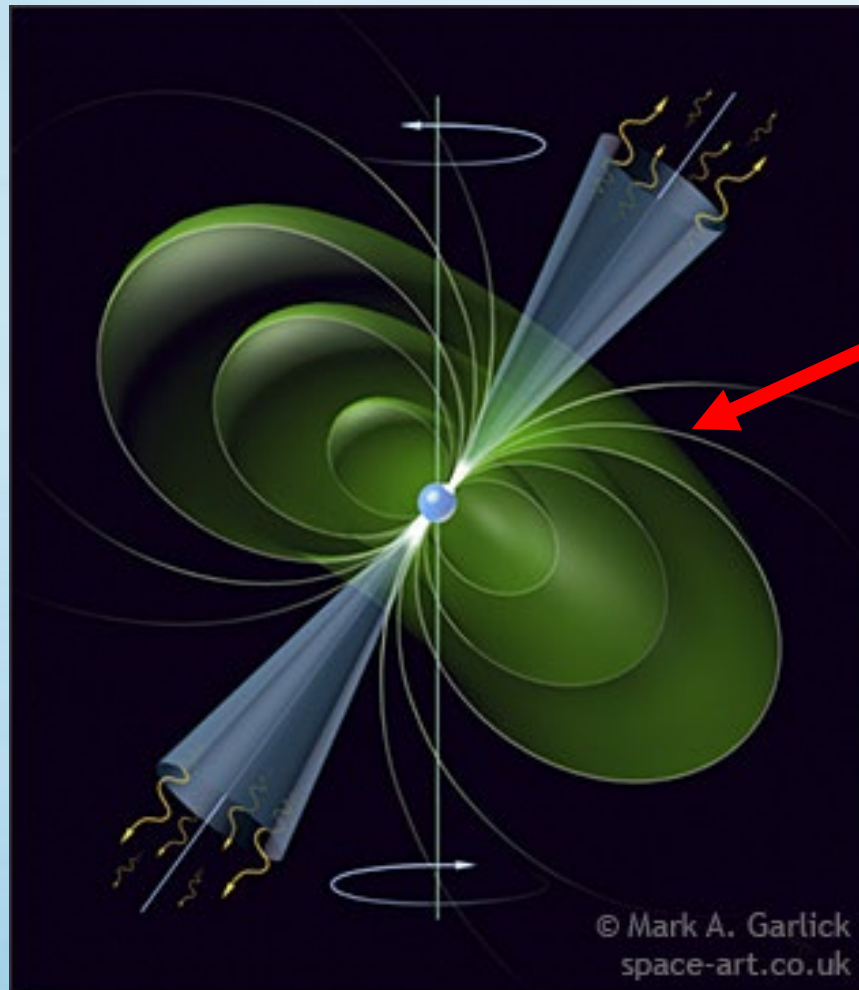
Department of Astronomy, Peking university
National astronomical observatory, CAS

kjlee@pku.edu.cn
@Guiyang 2025



Quick guide to the GW detection using pulsar timing array

Phenomenology model



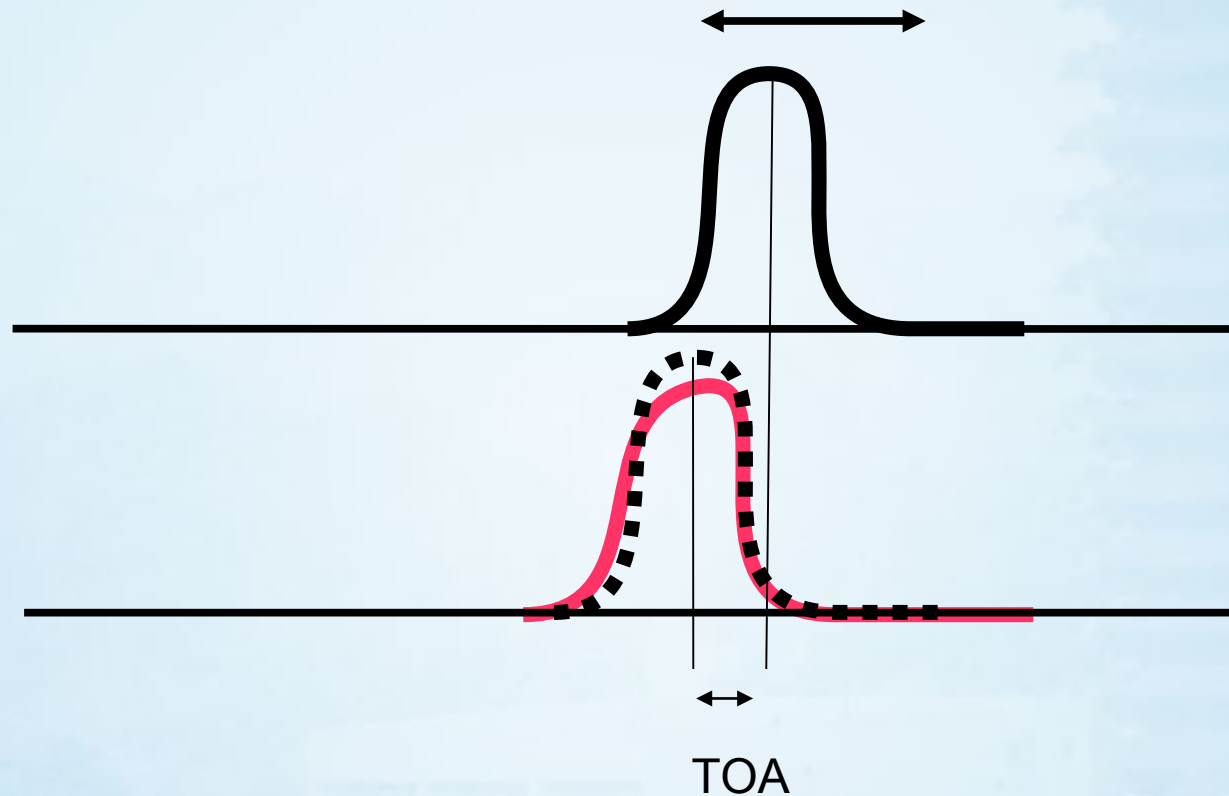
Frankly speaking, we do not know how pulsar radiates.

But the pulse time of arrivals are so accurate.



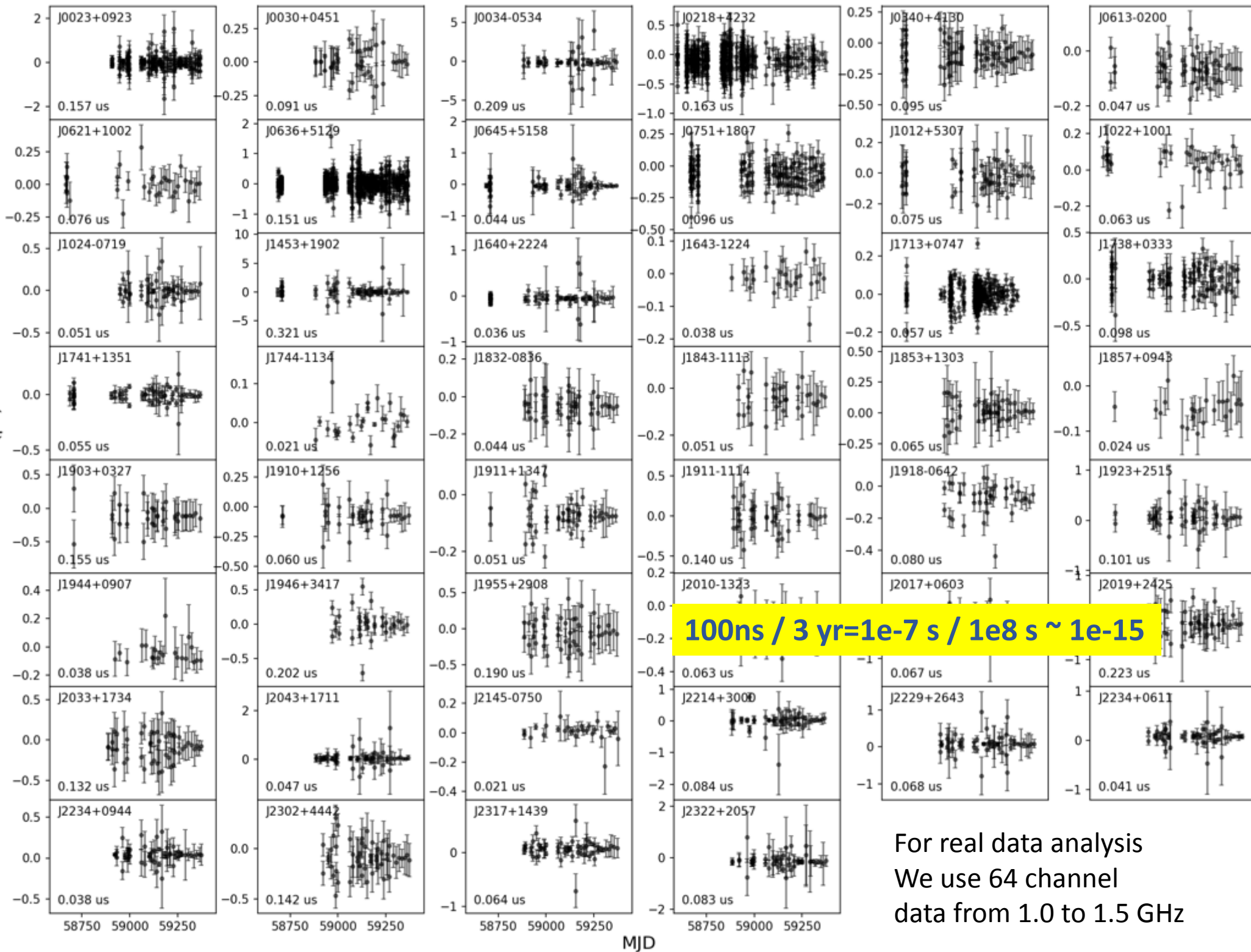
Determine the TOA

template matching



$$\sigma_{\text{TOA}} = 19.2_{[\mu s]} \frac{T_{\text{sys}} [10\text{K}]}{G_{[\text{K/Jy}]} S_{[\text{mJy}]}} w_{[1]}^{3/2} t_{\text{obs}}^{-1/2} [\text{1hr}] \Delta f_{[100\text{MHz}]}^{-1/2} P_{[\text{ms}]}.$$

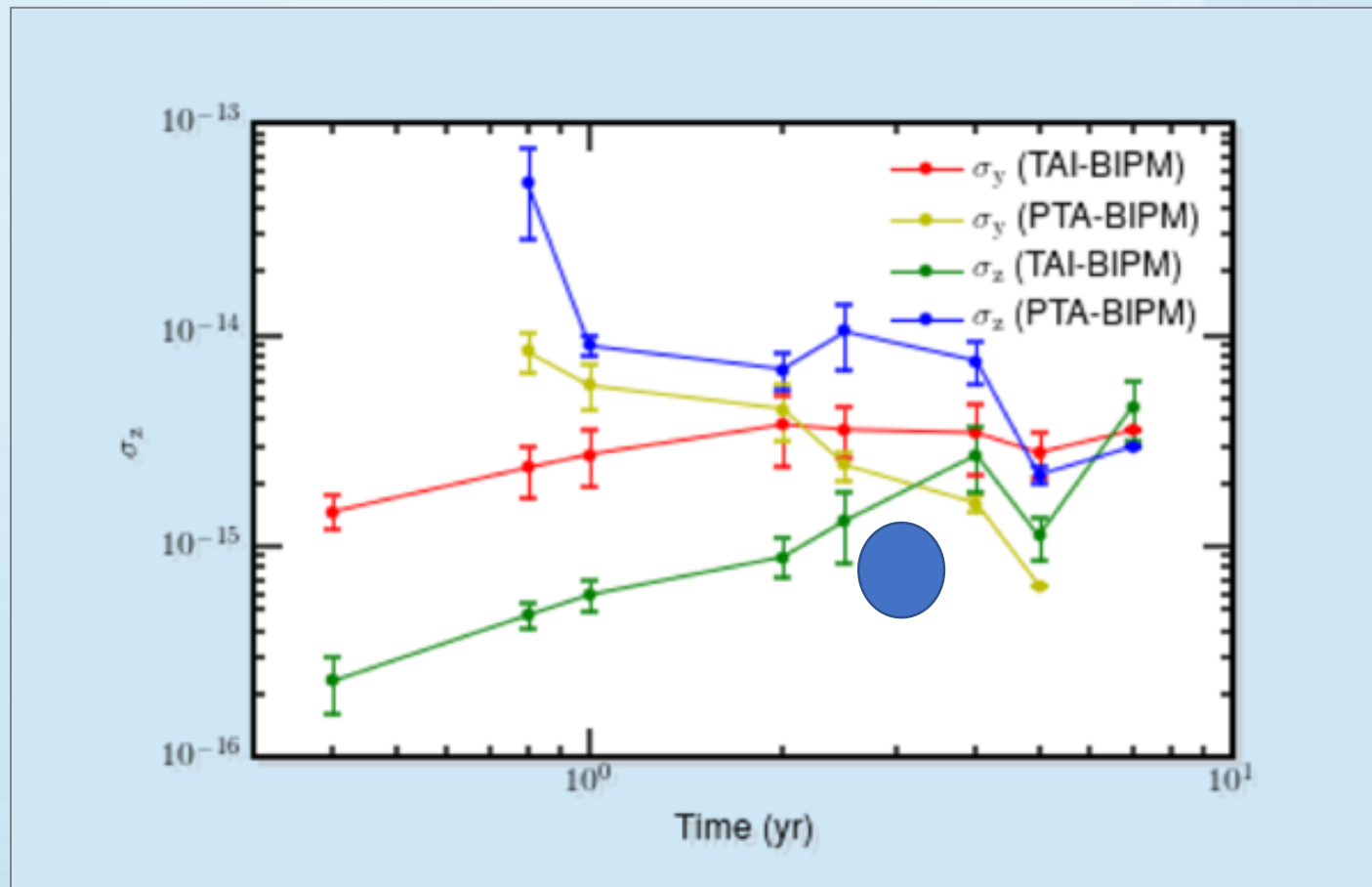
Residuals (μs)



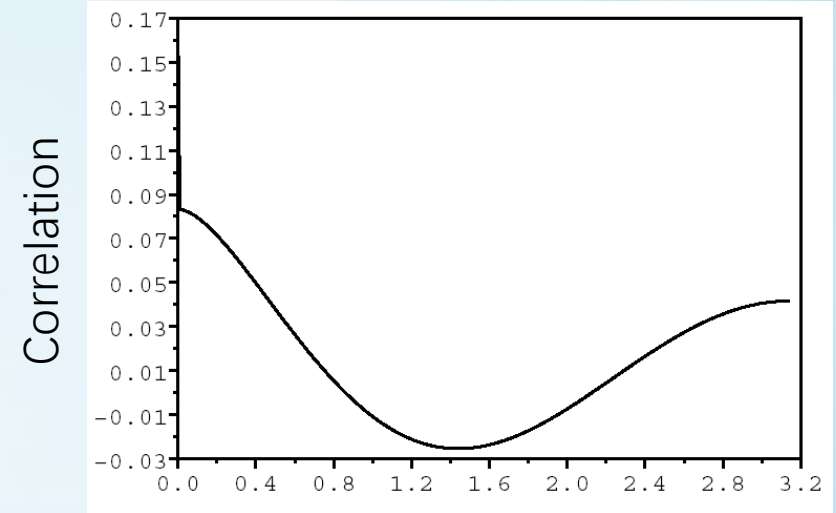
What does it means

$$100\text{ns} / 3 \text{ yr} = 1\text{e-}7 \text{ s} / 1\text{e}8 \text{ s} \sim 1\text{e-}15$$

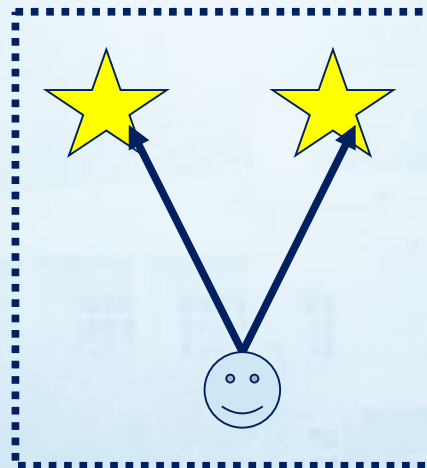
~Measure 1 proton radius over 1 meter and do it over years



How to identify GW signal?

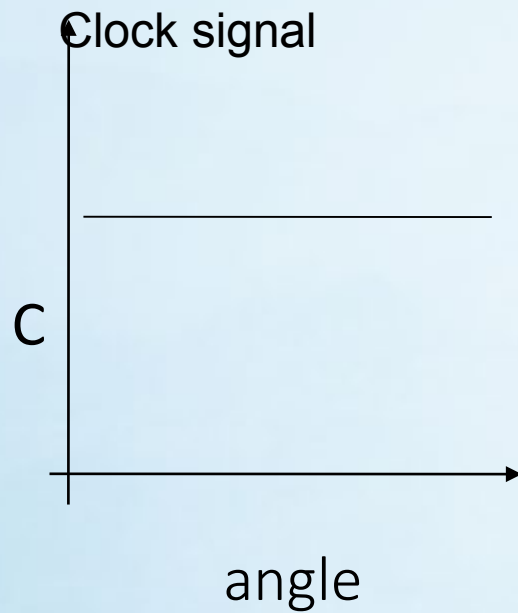
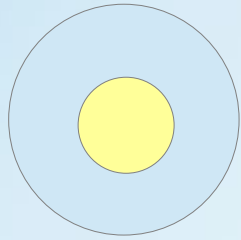


Angle between psr pairs

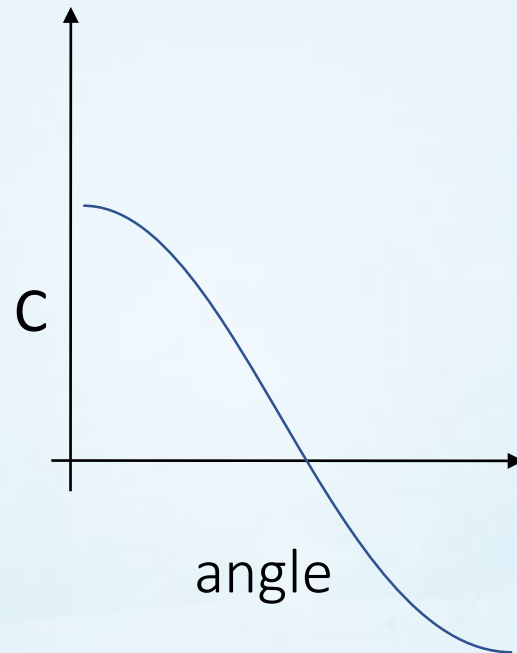


Hellings and Downs 1983

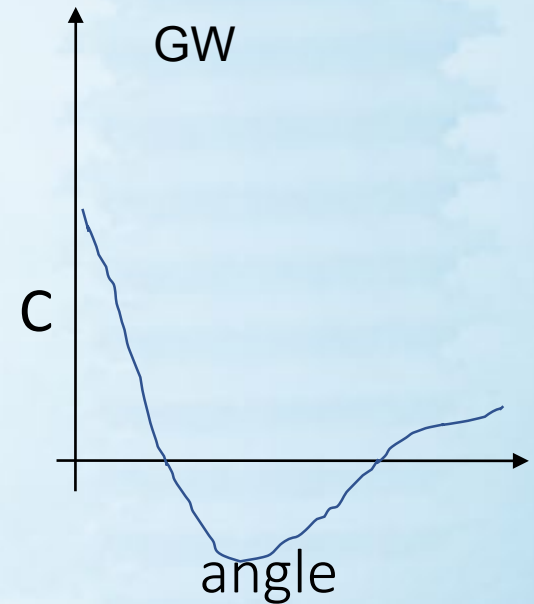
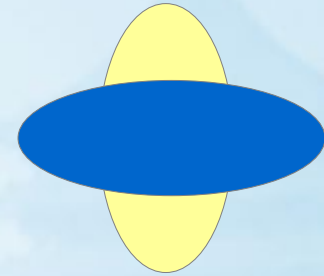
Other correlation



Clock noise

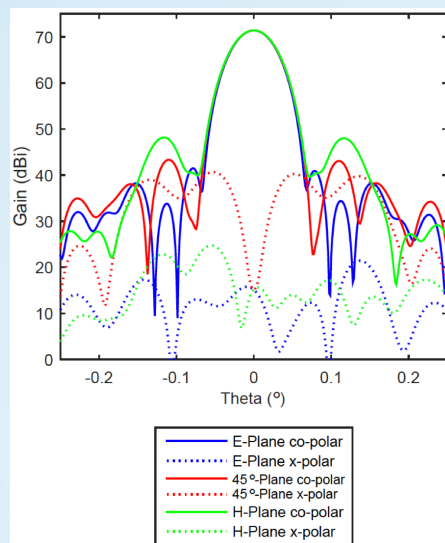


Planet ephemeris

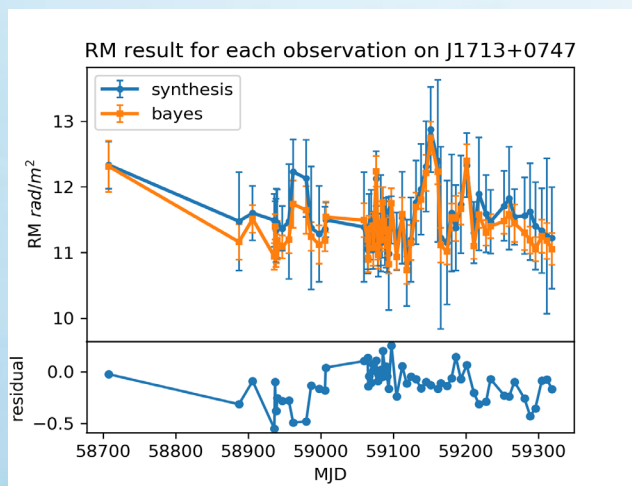
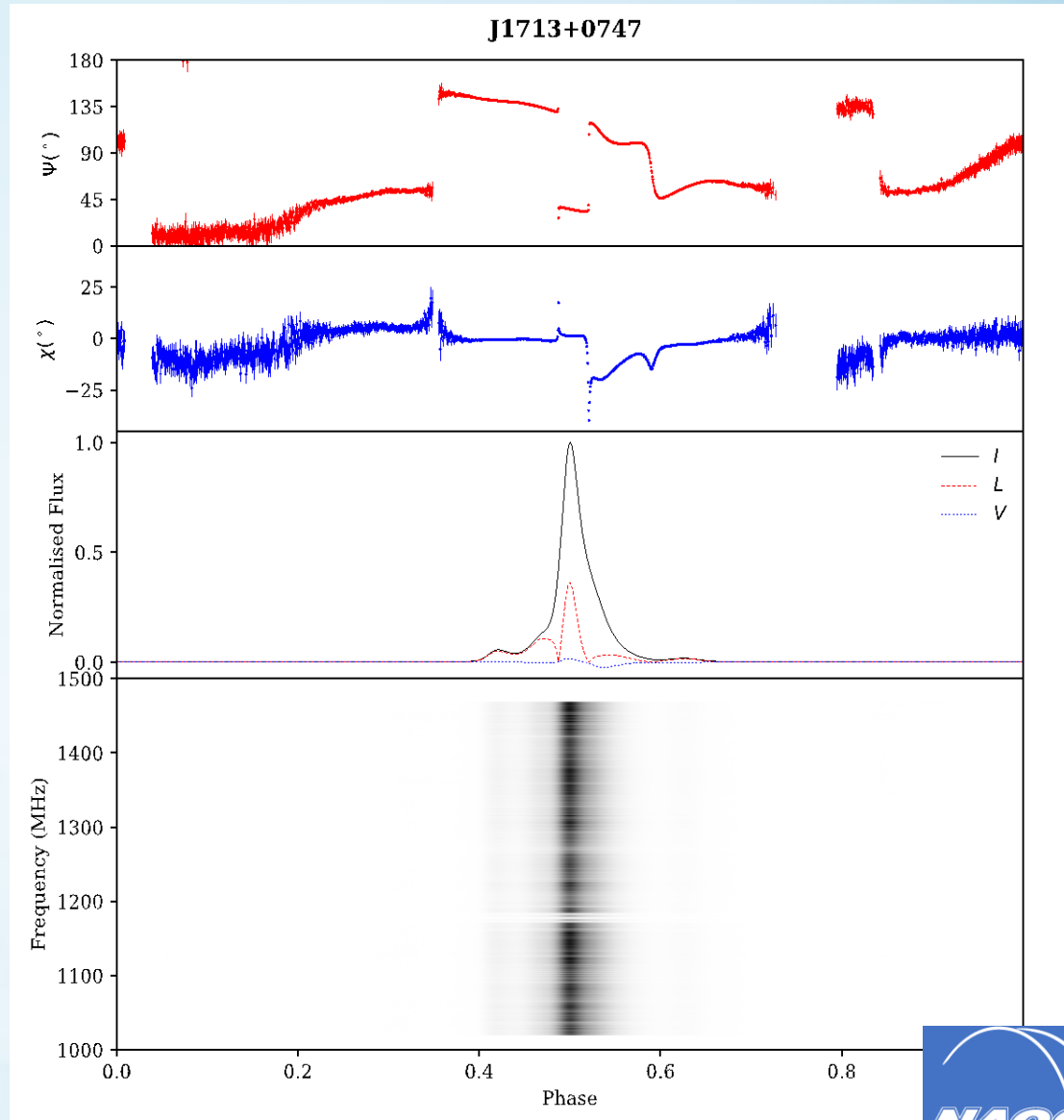


Science from pulsar observation

FAST polarimetry
Low feed leakage
easy to calibrate
Fitting RM
RM synthesis
Bayesian method



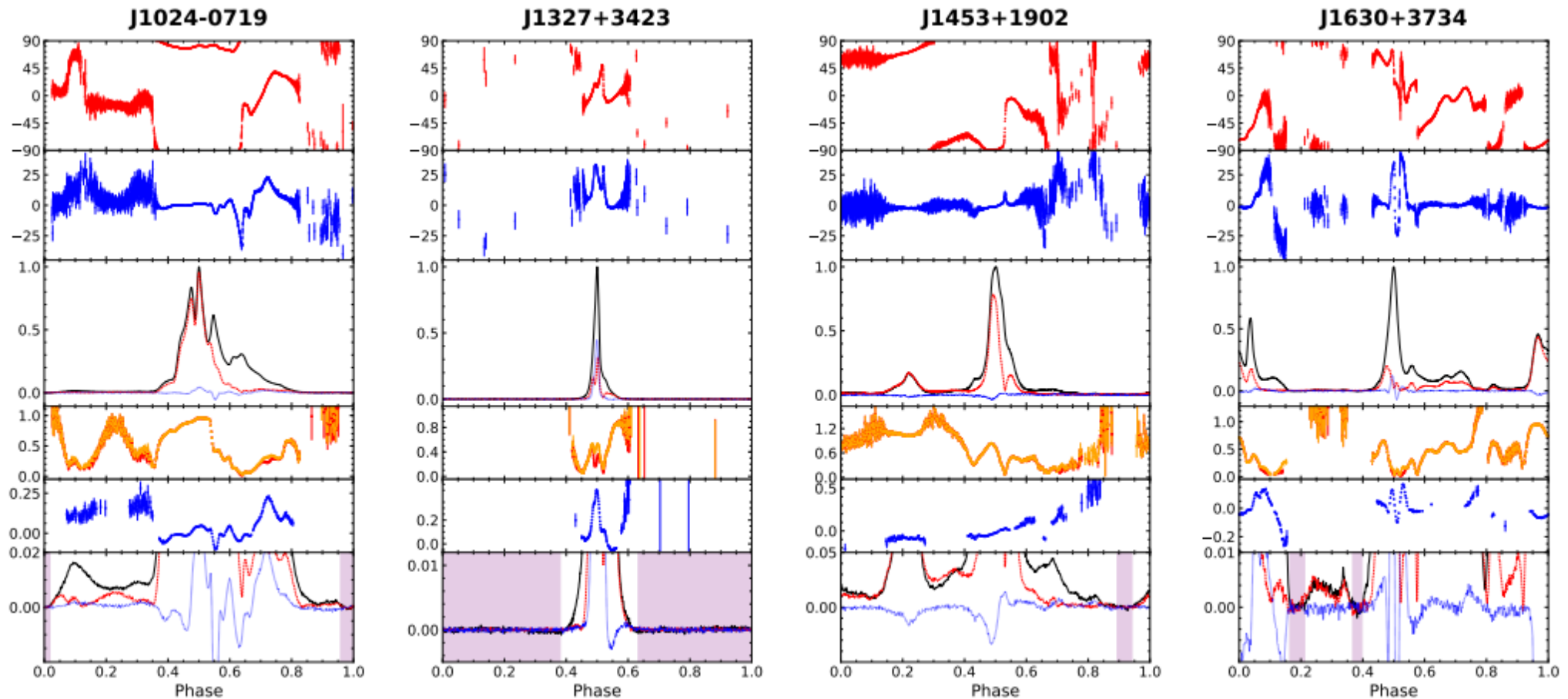
(Dunning et al. 2017)



Some pulsars are 360 degree emitter

MSPs are mostly 360 radiator

Most of MSPs show polarization angle jumps



Xu, J. et al., submitted

Xu, J. A&A

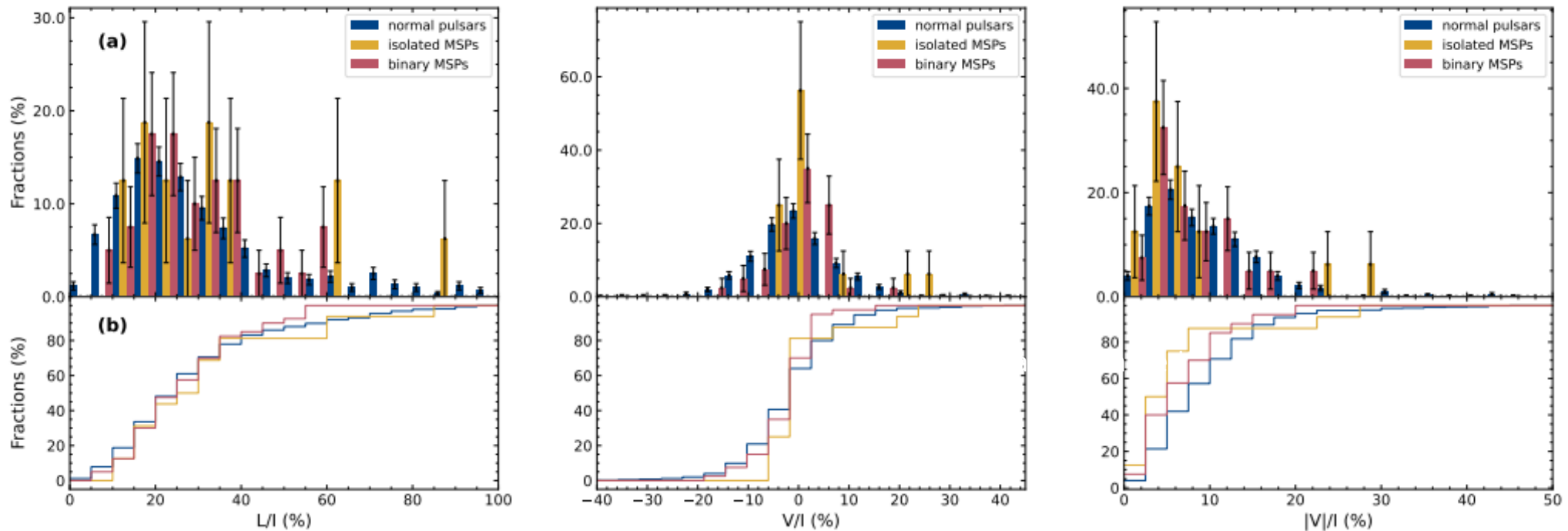
No difference between the distribution of polarization degrees between MSP and normal pulsars

Although

- Size of MSP magnetosphere is 100 times smaller than normal pulsar
- Magnetic field of MSP is 100 times weaker
- Pulse profiles are very different

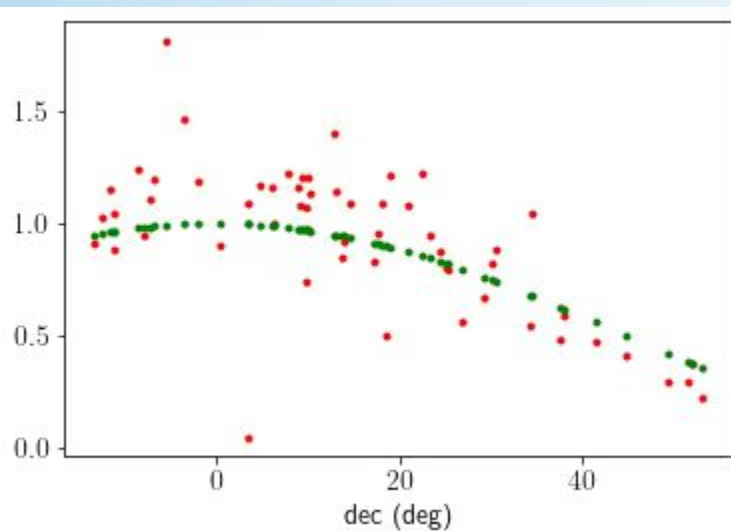
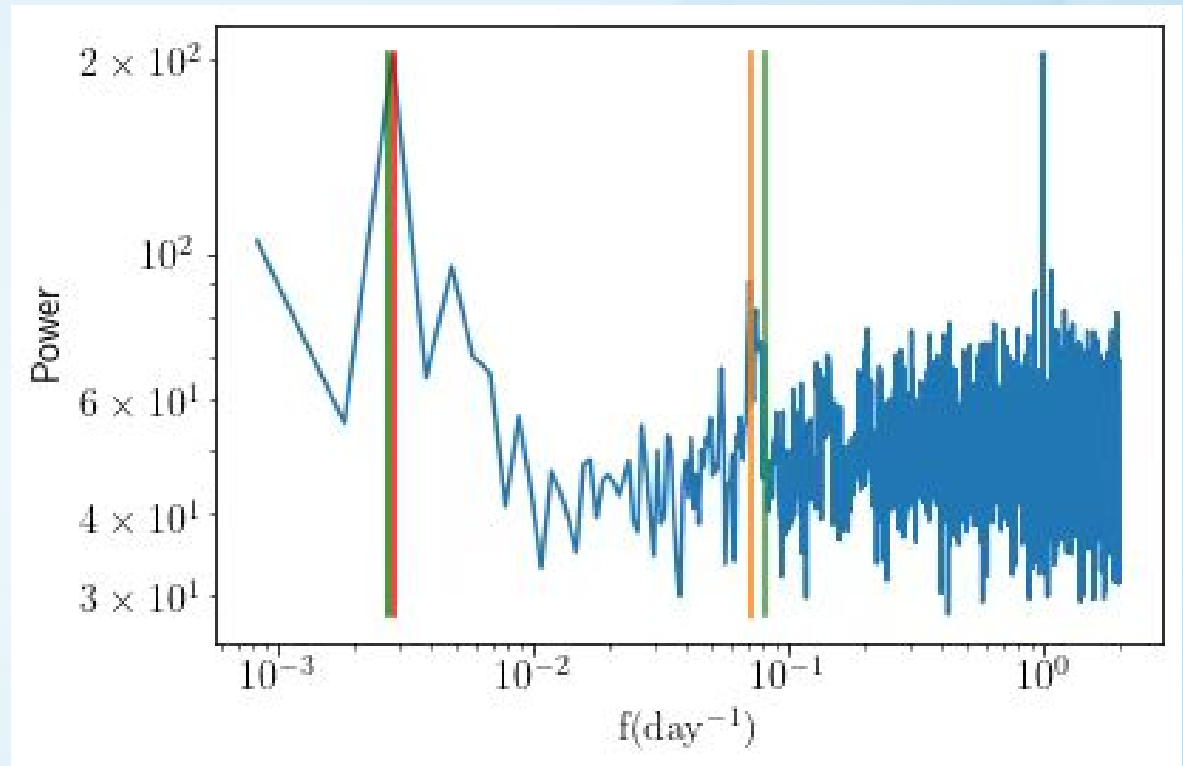
What happens to the wave propagation effects?

Xu, J. A&A



Probing the ionosphere

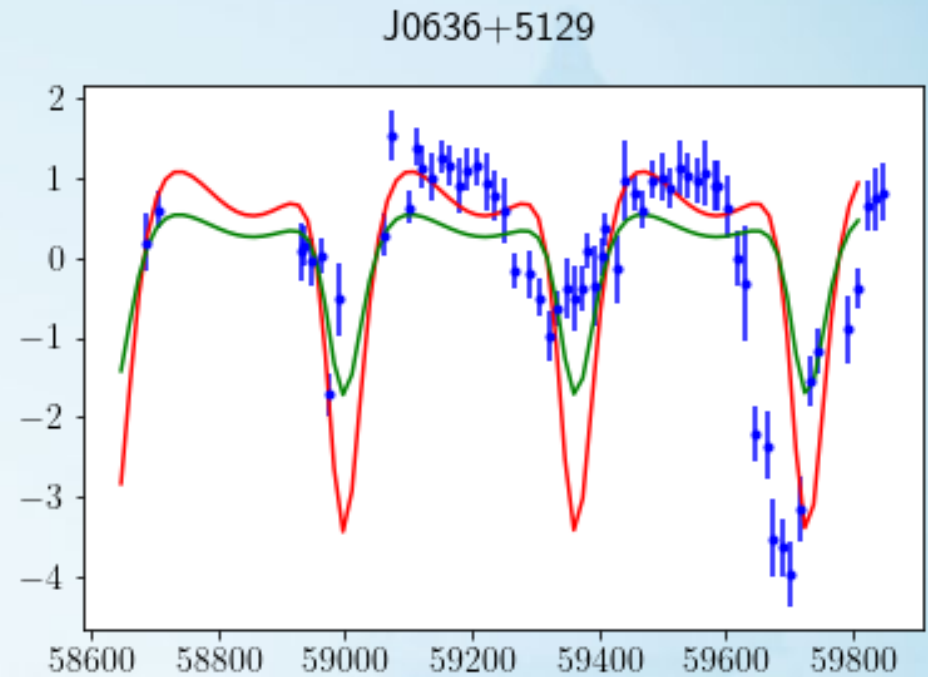
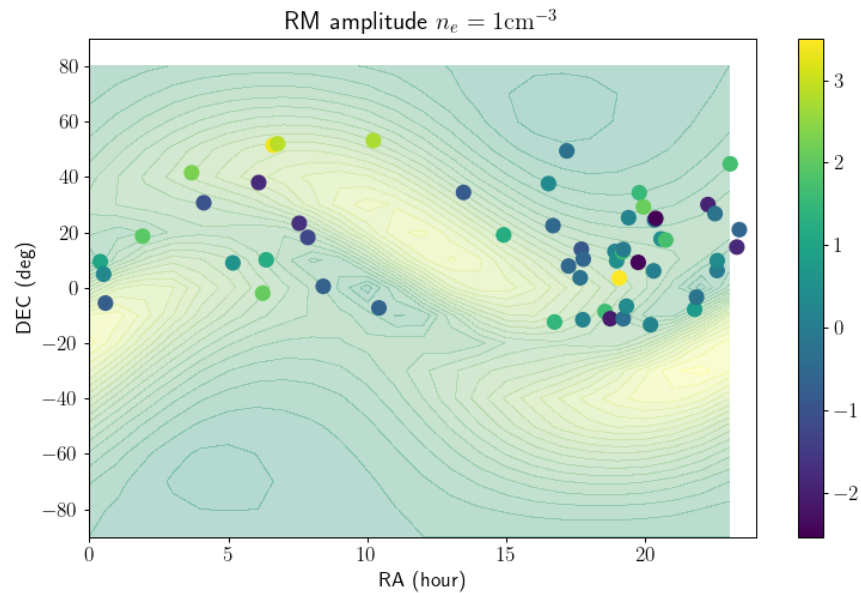
- Standard software IonFR **over estimates** the RM variation by a factor of 2-3 for high dec sources.
- We implement the **IONOF**, it produces nearly the same answers compared to IonFR
- **TEC is problematic**, different TEC model differs by more than factor of 2.
- We **saw 1-year and 28/2-days RM variation**. Indication solar wind –earth magnetosphere interaction is important for sub 1 Rad/m² RM precision



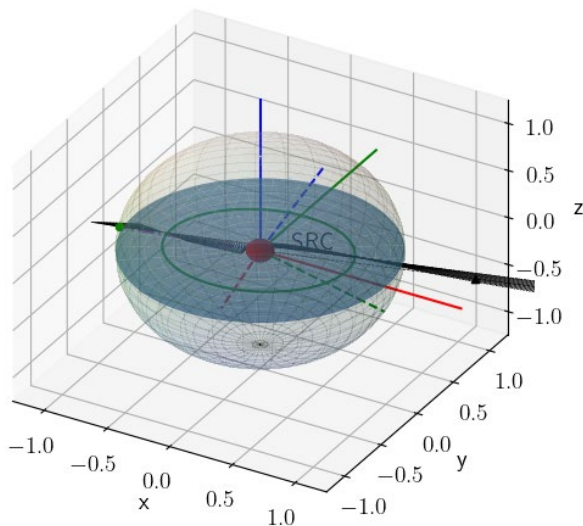
Xu J. et al., in prep



Solar system RM modeling



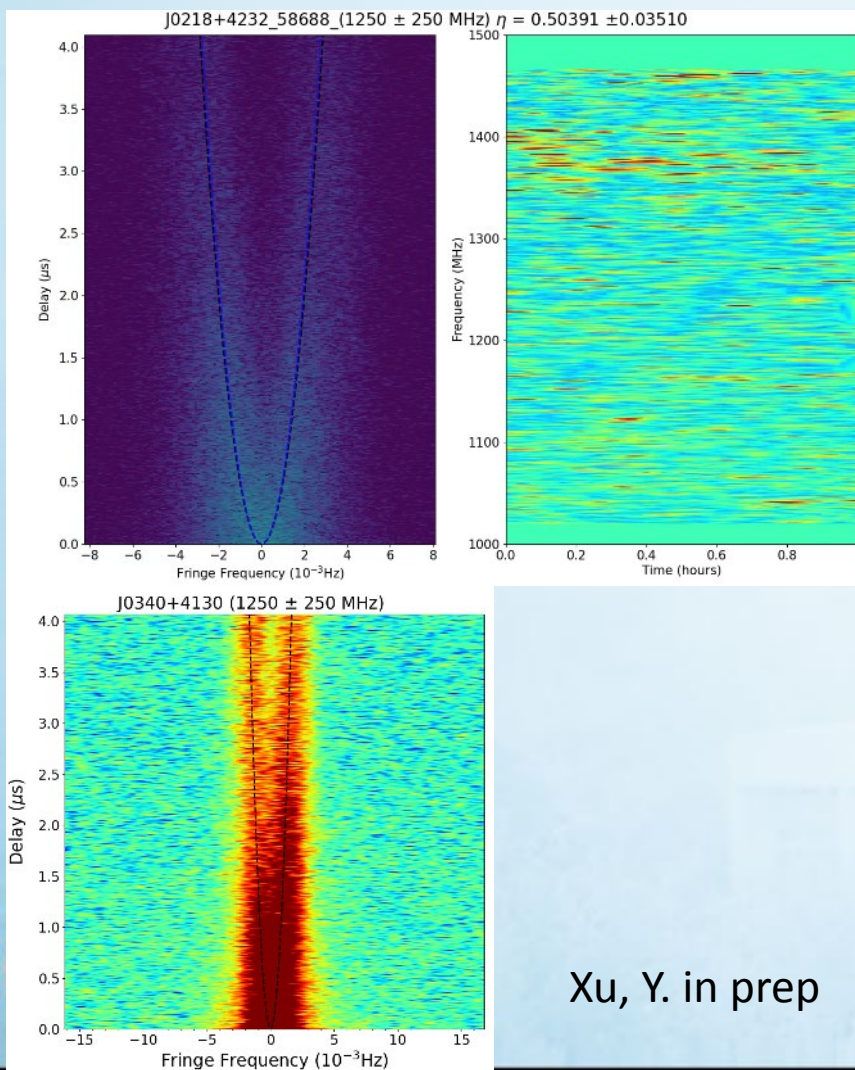
Xu, J. in prep



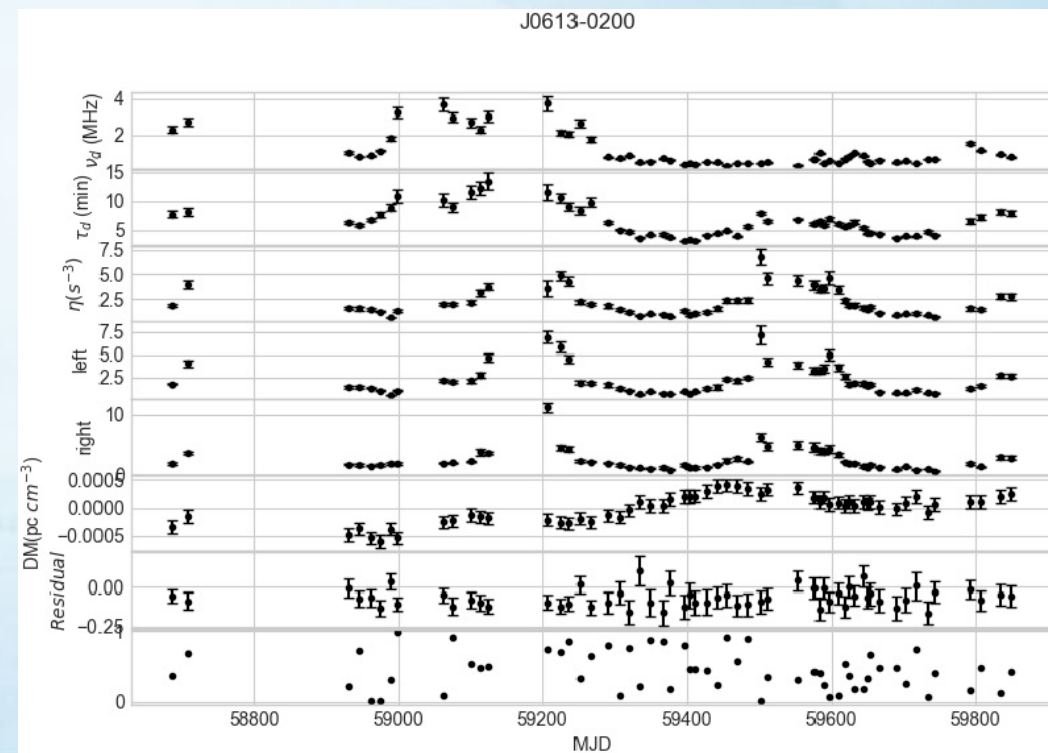
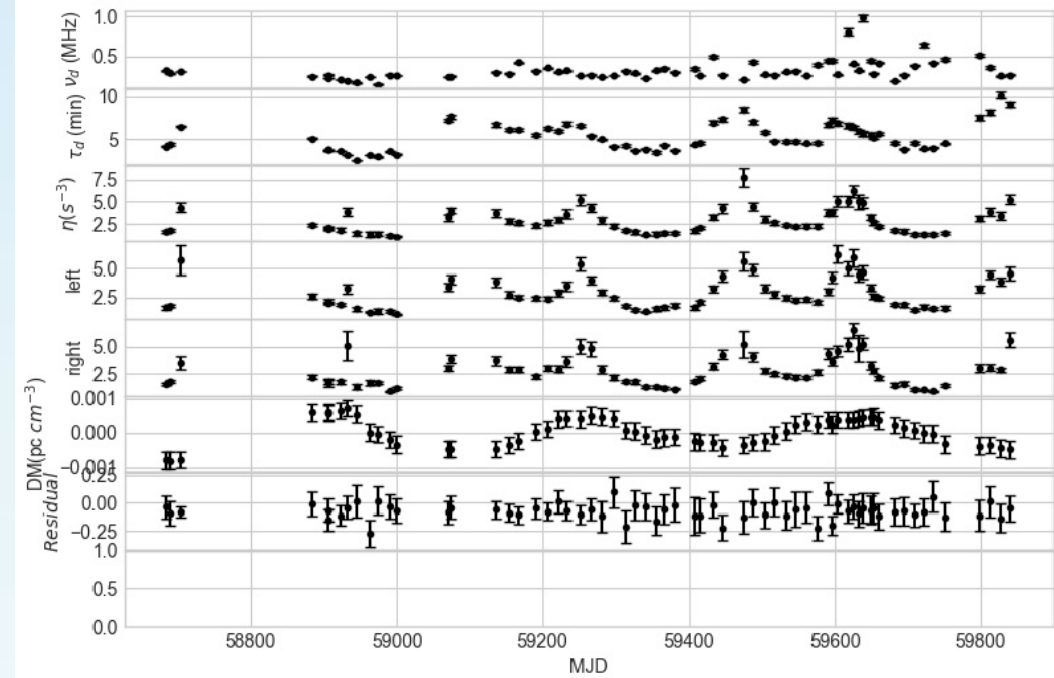
The naïve model can fit observation. However, one artificially requires 100-1000 times higher electron density or B field in the solar wind. It seems that we need consider the solar-wind-earth magnetosphere interaction.

Scintillation

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



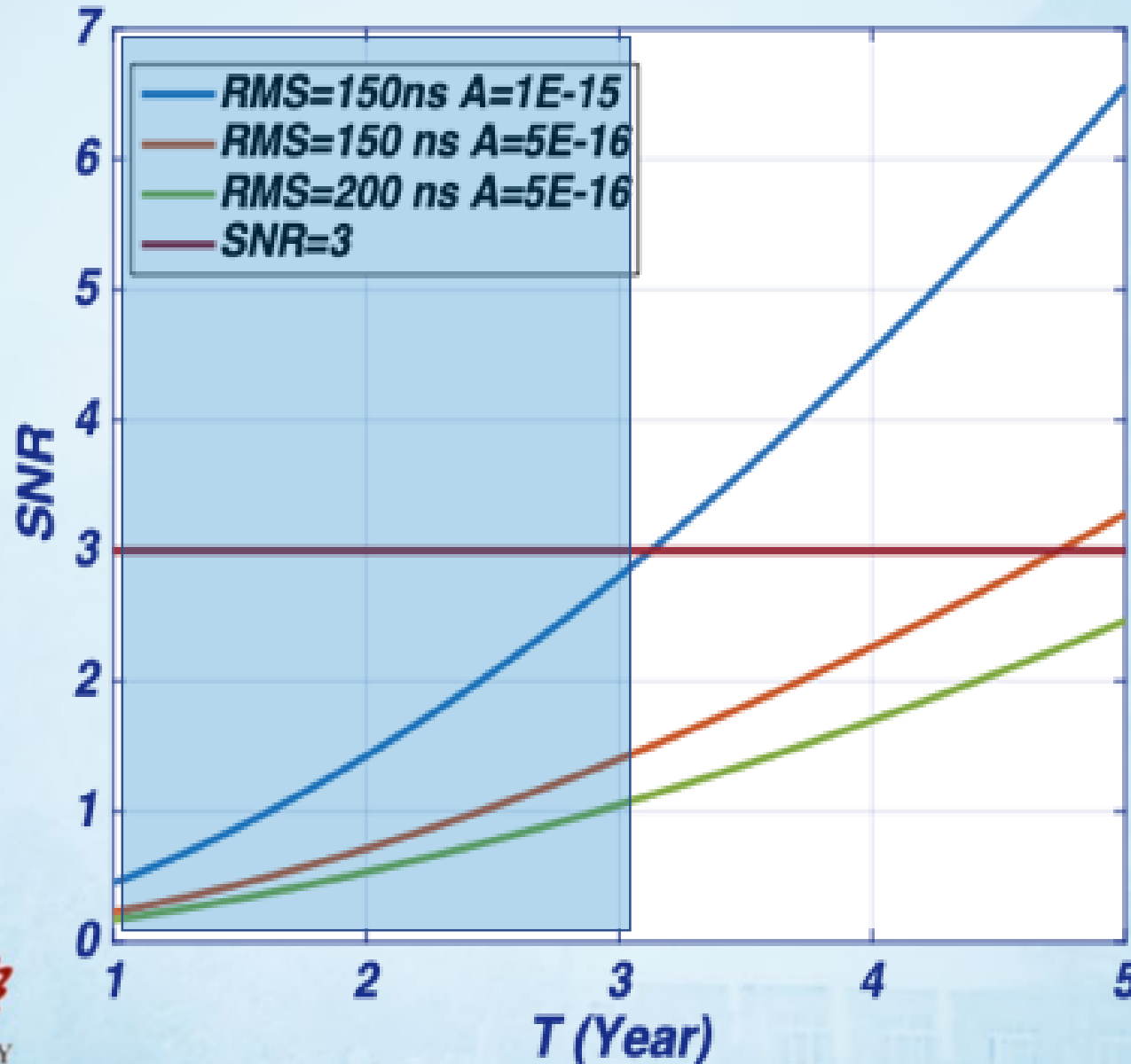
Xu, Y. in prep



GW detection

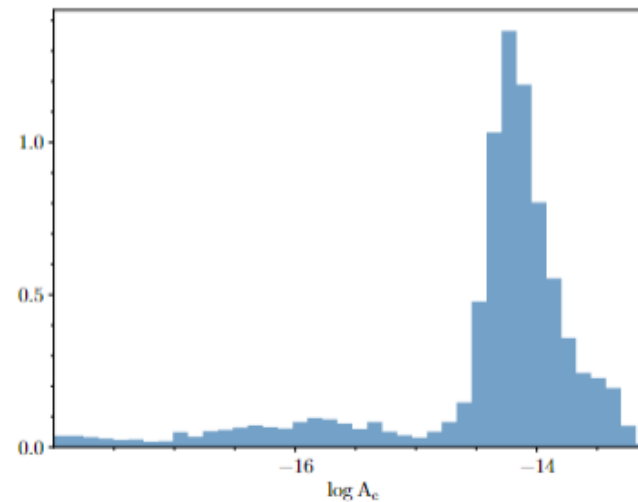
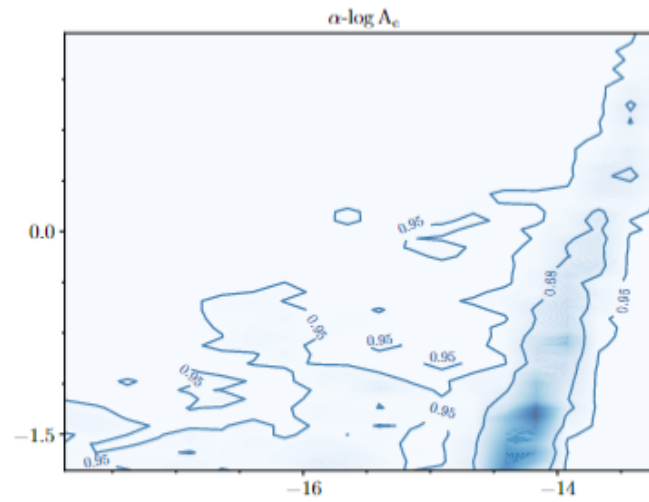
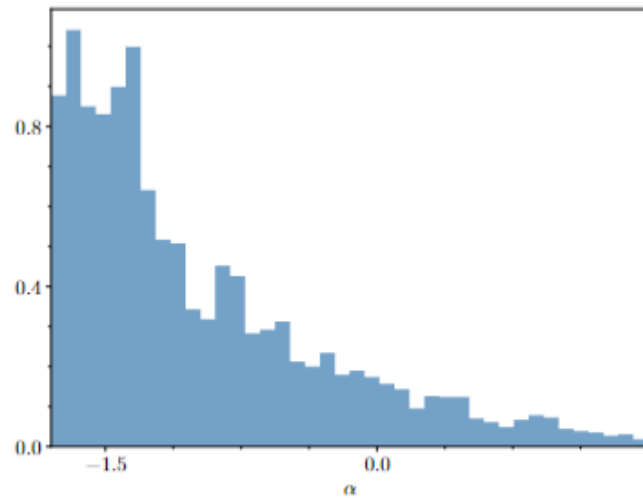
Stochastic background

- 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

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



Xu.H. et al, RAA

H0

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

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

H1

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

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

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

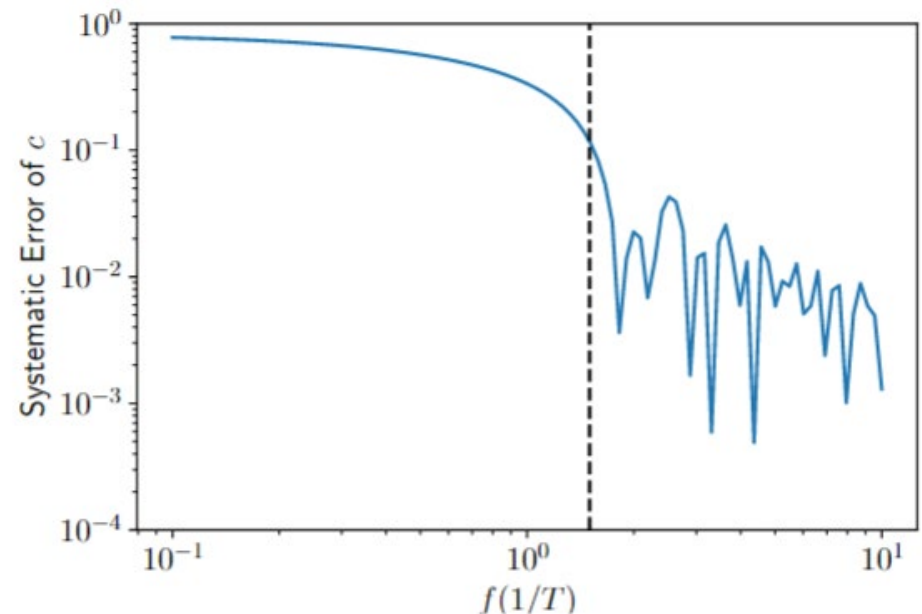
We focus on the part of signal with minimal error in correlation curve inference. The lowest frequency bin is a good guess, but not exactly.

$$A, \phi_i = \operatorname{argmax}_{A, \phi_i} \int \int \cdots \int \frac{1}{\sqrt{\prod_i |C_i|}} \exp \left[-\frac{1}{2} \sum_i r_i'^T C_i^{-1} r_i \right] \prod_i d\lambda_{T,i},$$

where r_i' is

$$r_i' = r_i - D_i \lambda_{T,i} - A \sin(2\pi f t - \phi_i).$$

- The sweet spot for short data set is to look for correlation above $f \sim 1.5/T$.
- For CPTA, data is short, we look at $1.5/T$.



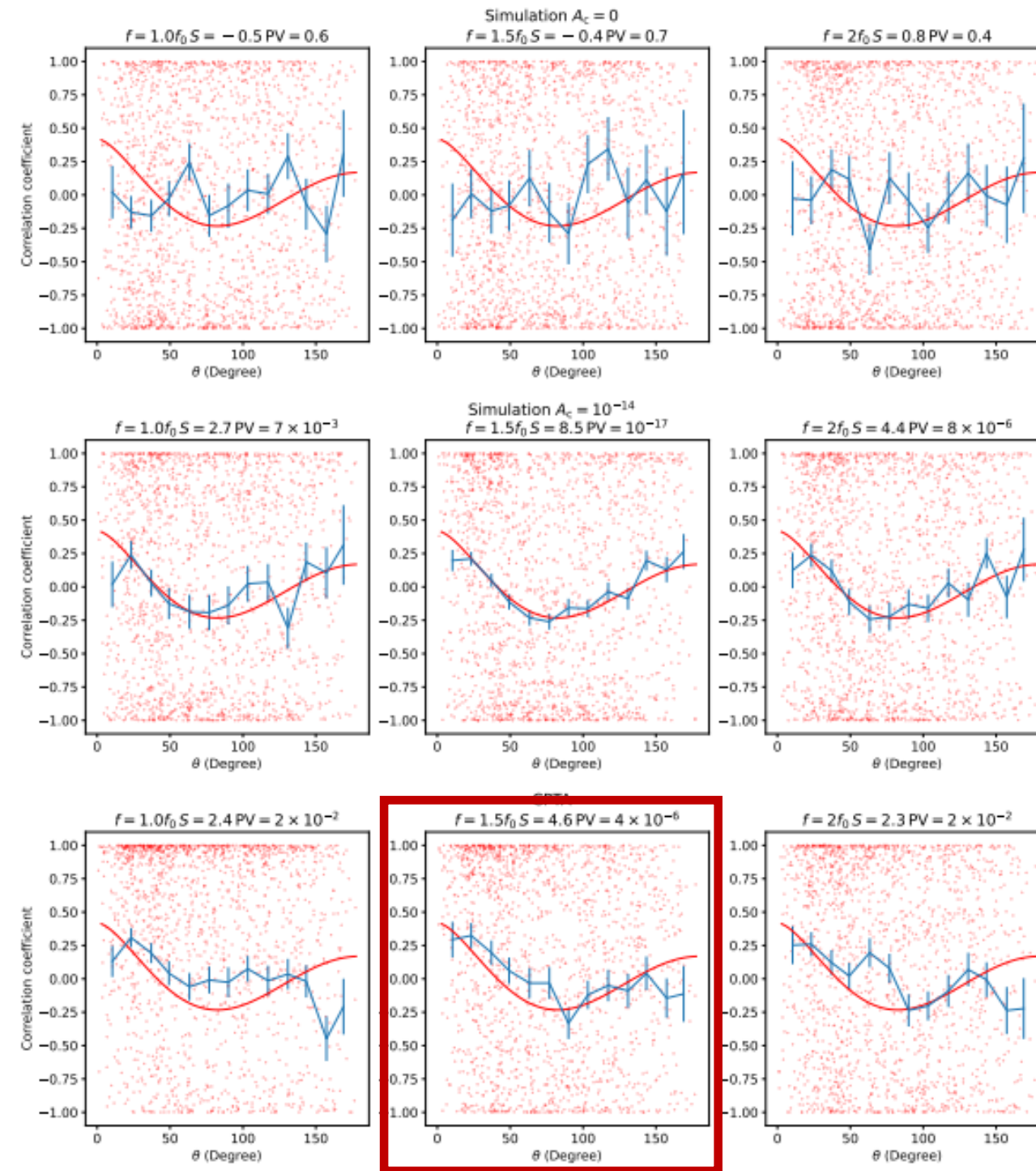
HD curve

Null control group

Positive control group

Real data

Xu.H. et al, RAA

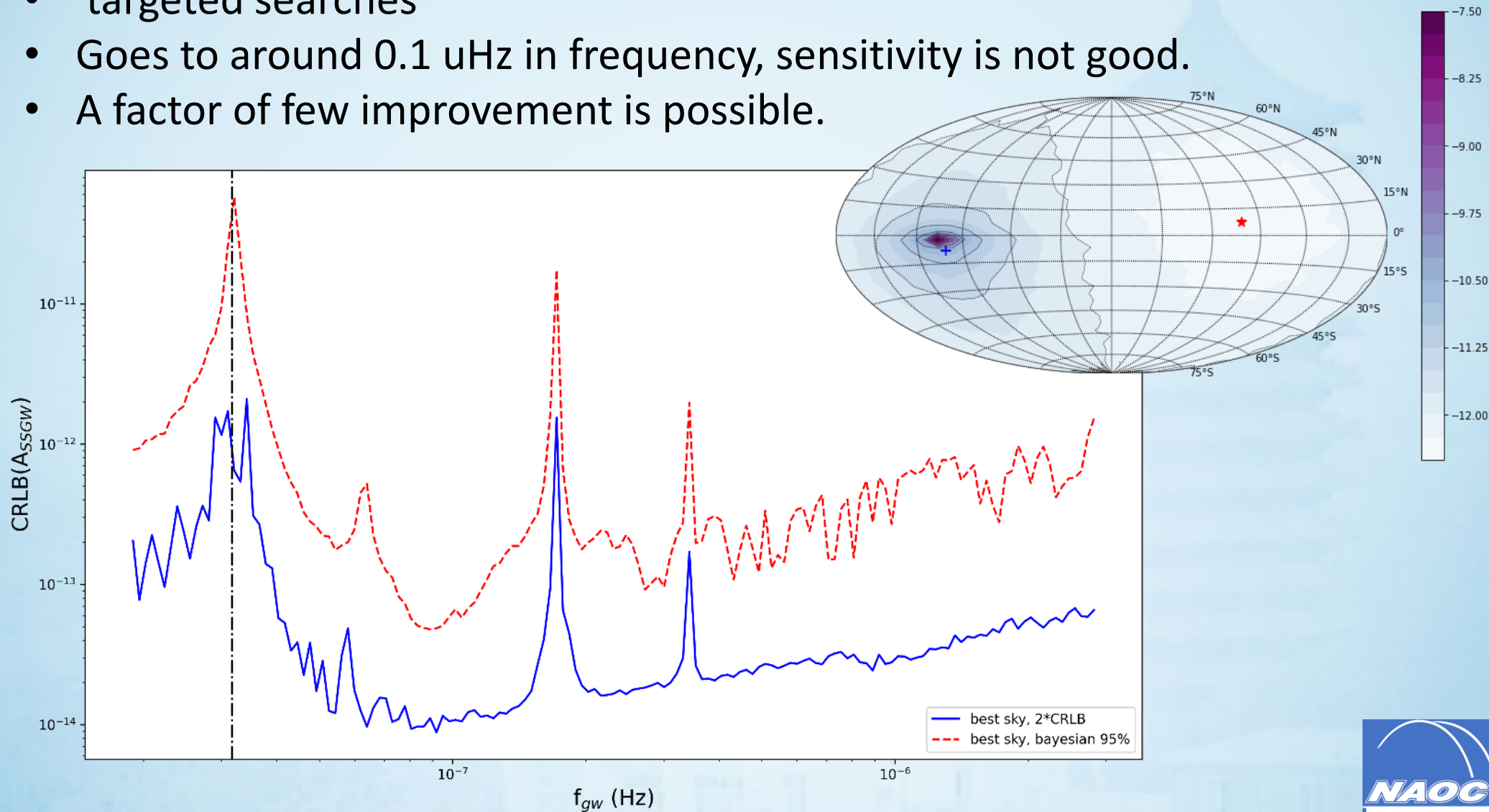


Other related science

- GW Single source
- Test solar system ephemerides, reference frame tie
- $V > C$ propagation around H I line.
- Gravity test in radiative regime
- GW dispersion
- Axion limit
- PBH, cosmic string, and inflation index

Single pulsar bounds for single GW sources

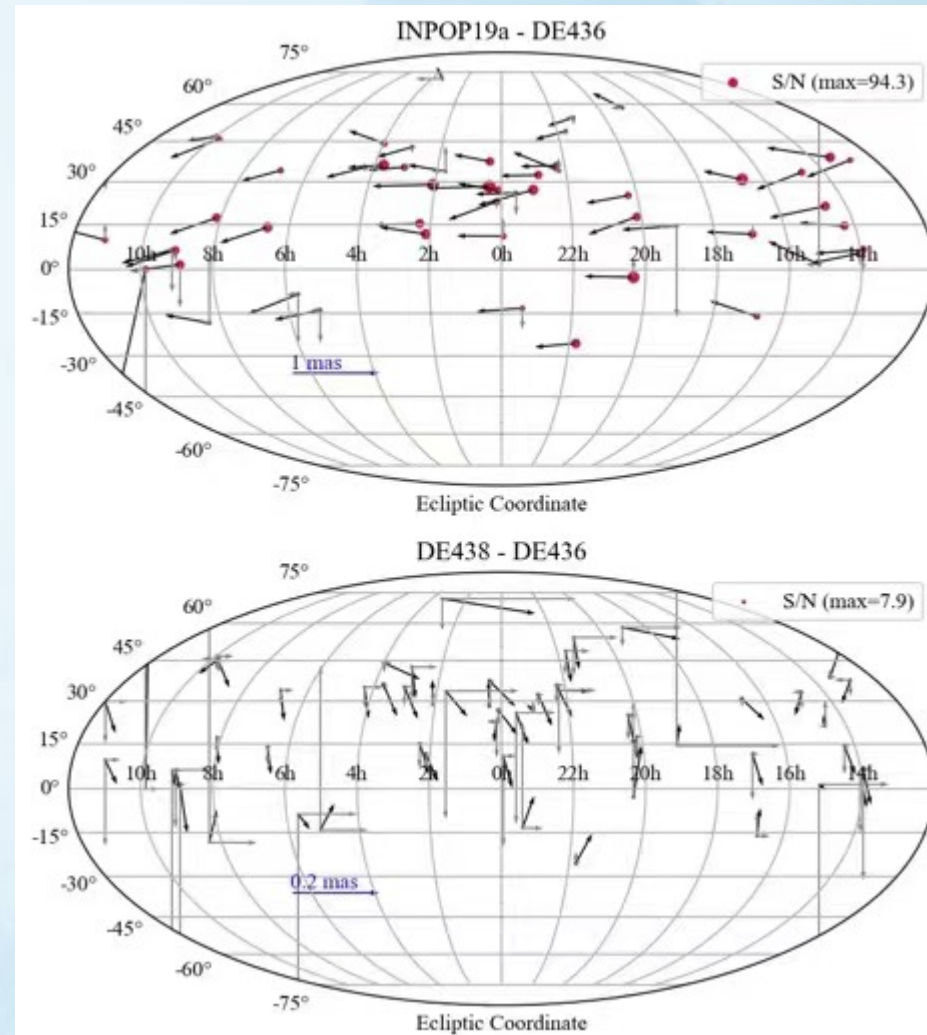
- single source blind search
- targeted searches
- Goes to around 0.1 μHz in frequency, sensitivity is not good.
- A factor of few improvement is possible.



Ephemerides comparison and tests

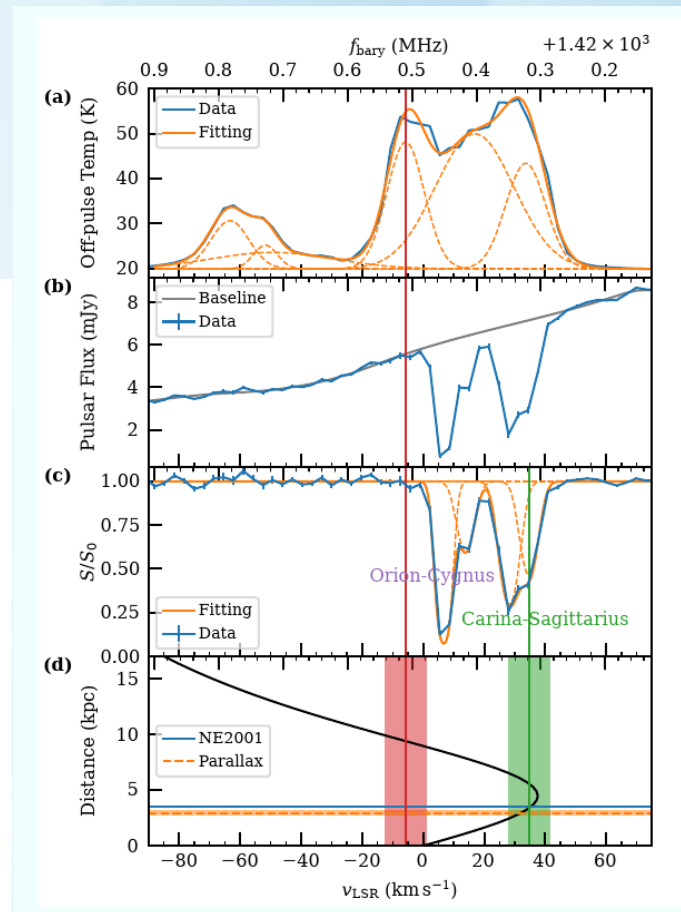
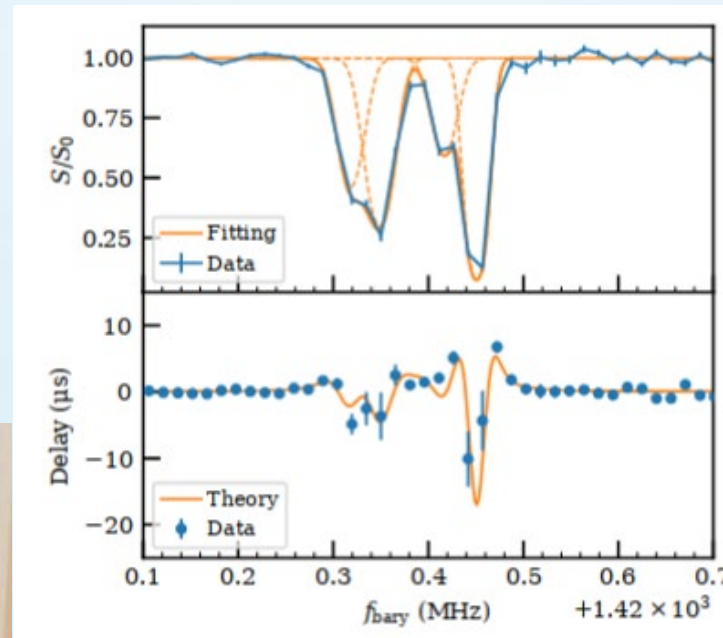
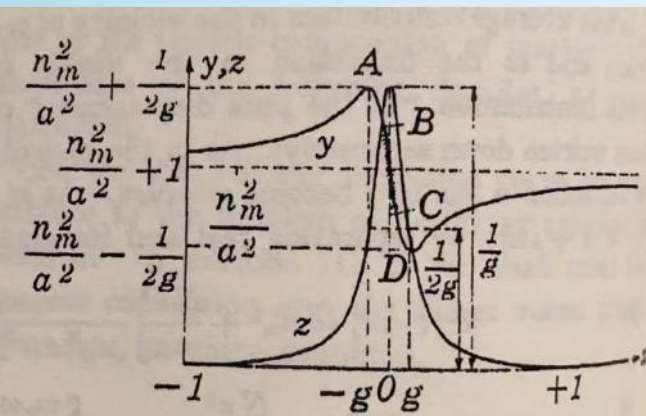
- One can immediately check if the reference frame is well defined.
- We are working on ephemerides orbit element measurement.

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



Fast than speed of light

- We can detect the fast than light group velocity signal due to the HI absorption
- Alternative way to confirm the absorption features.



Jiang et al., submitted



Future

International efforts



VLA



SKA



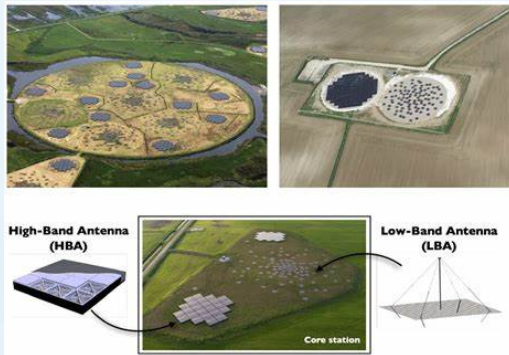
ngVLA



CHIME



MeerKAT



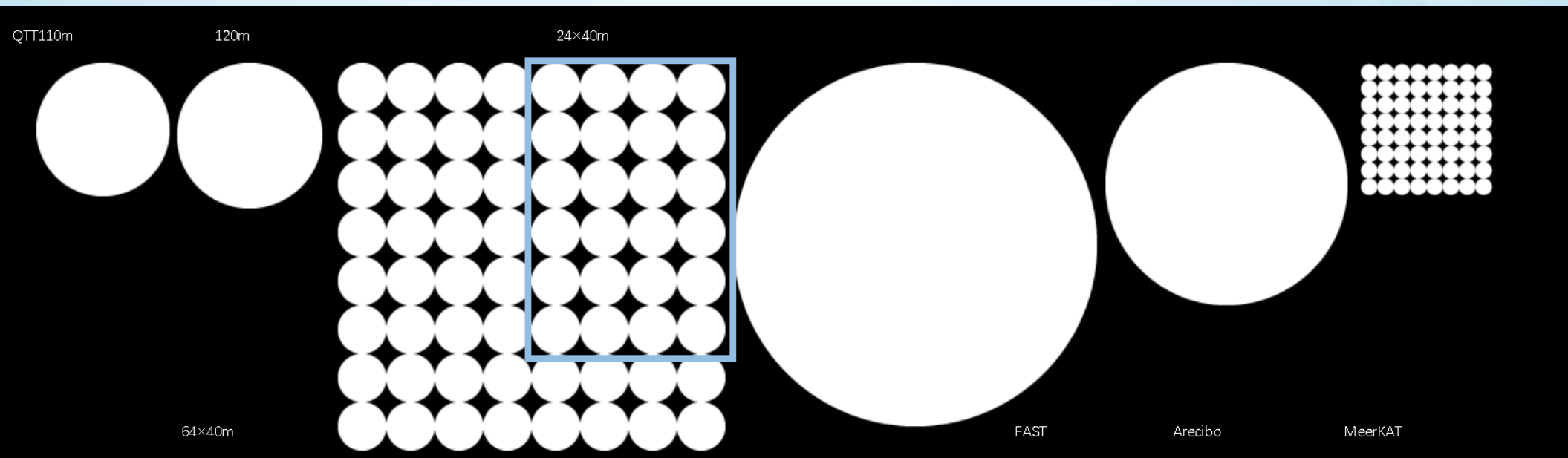
LOFAR

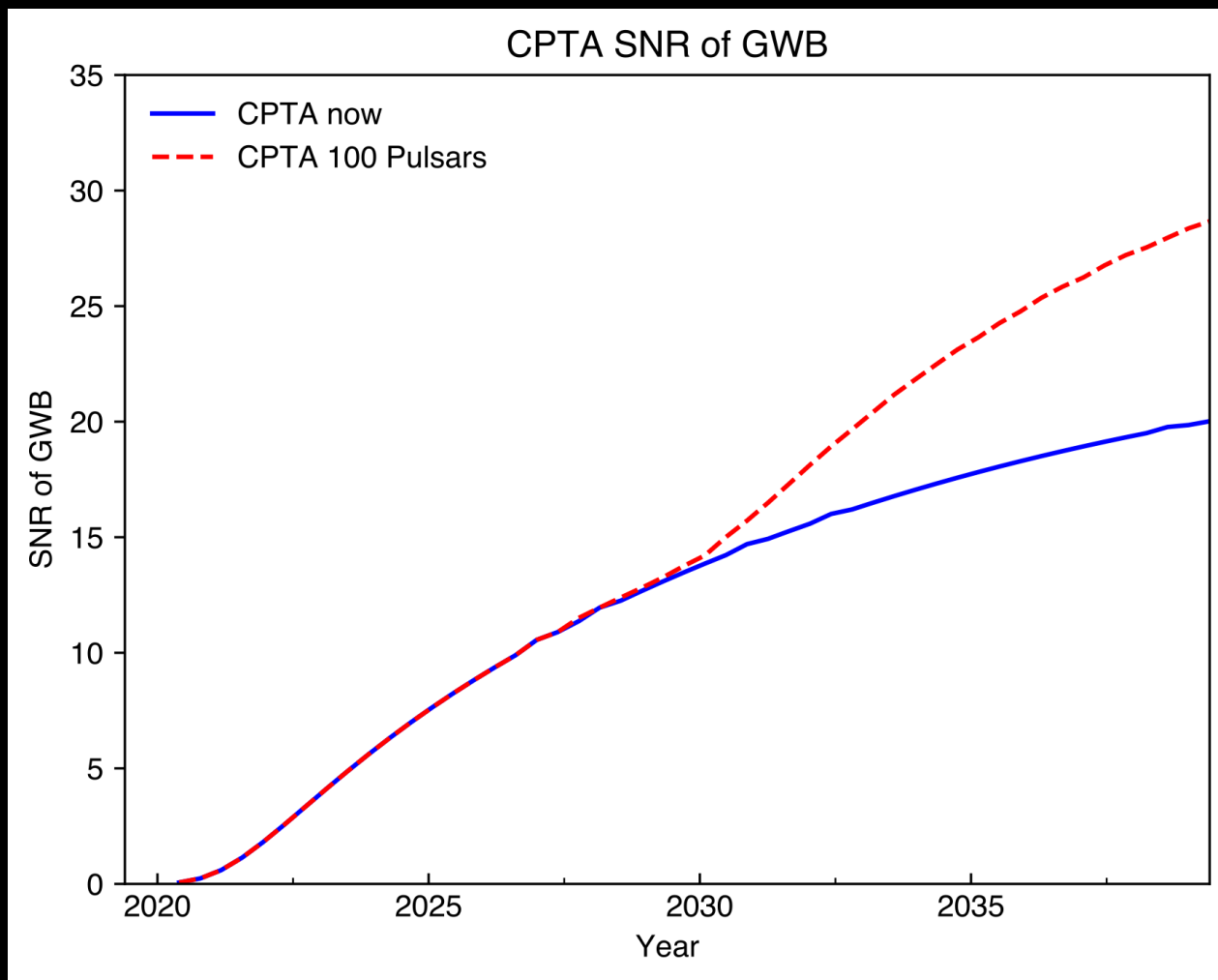


DSA2000

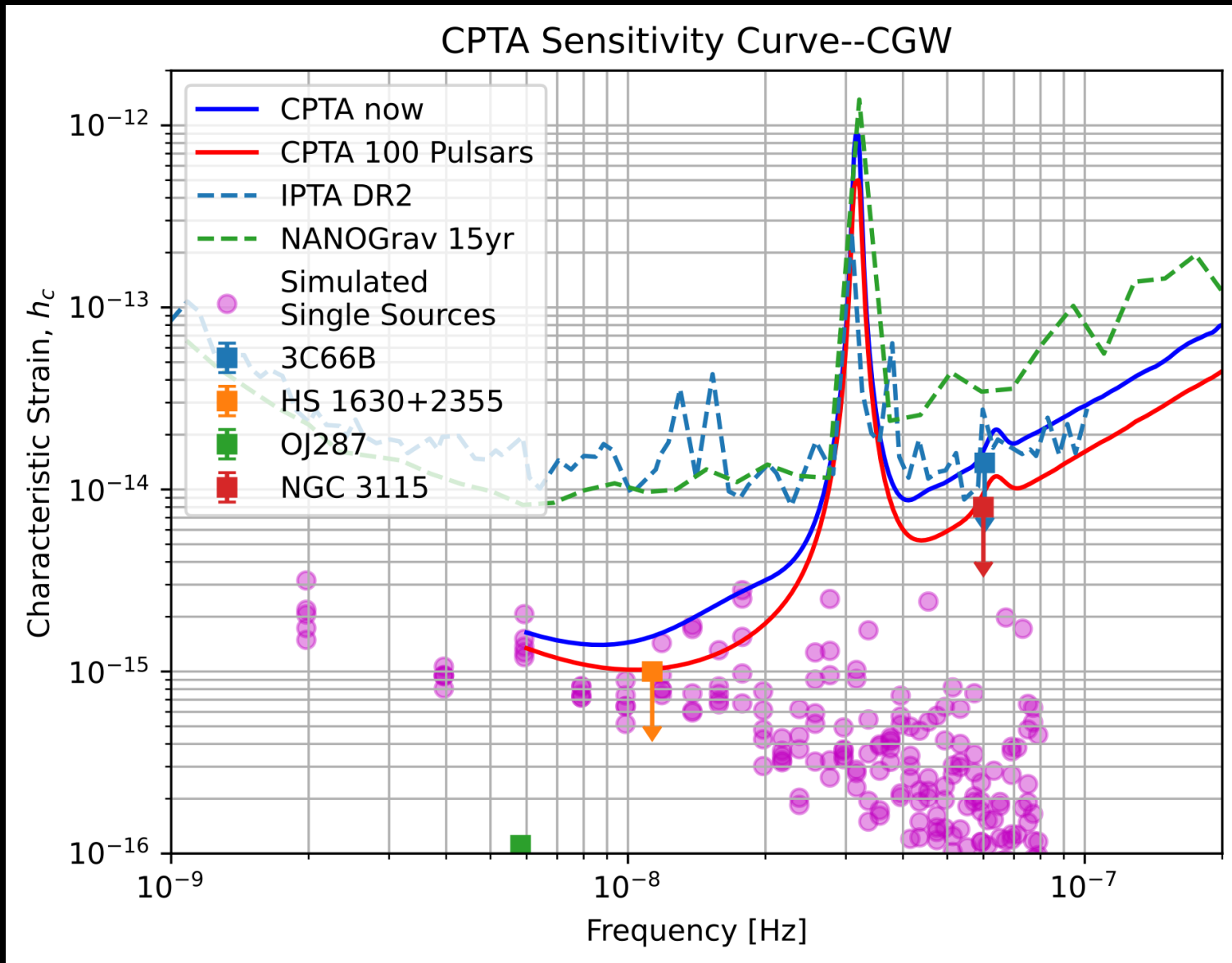
Domestic efforts

- 3 X 100m radio telescopes , 1-8GHz ultrawideband, high cadence, better sky coverage
- FAST Array (aims for $64 \times 40\text{m}$) , $\text{FAST} + 24 \times 40\text{m} = 1.4\text{-}1.7 \text{ FAST}$, 50% improvement of precision , 50 more MSPs
- Low frequency array of 21CMA, better DM correction





Anisotropy and single source



Progress of Chinese Radio Trinity

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



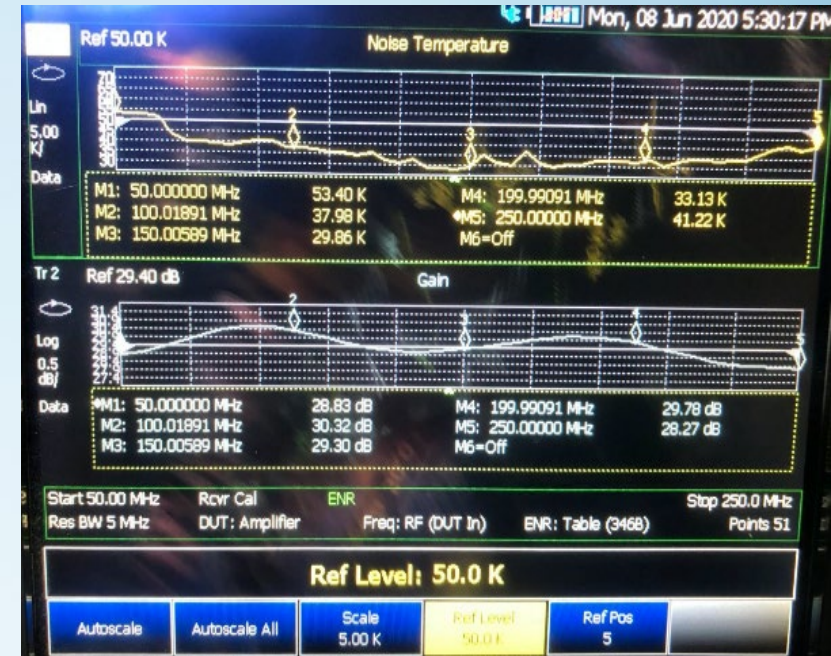
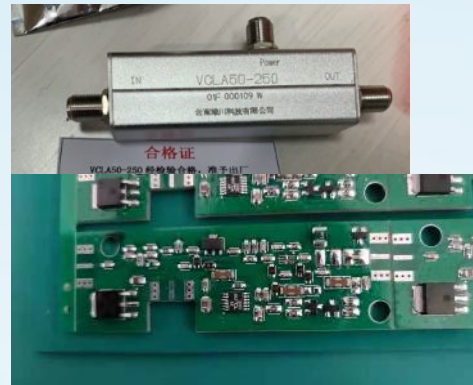
JRT/RST 120m lowband (10GHz) radio
telescope at Yunnan and Jilin. **Under
construction.**



Extend frequency/sky coverage



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

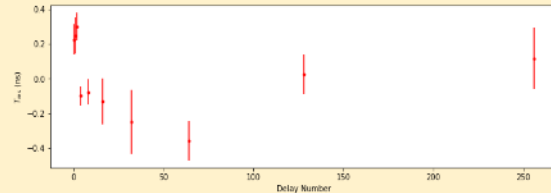
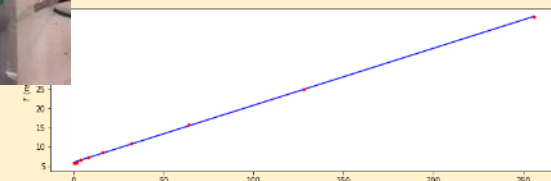
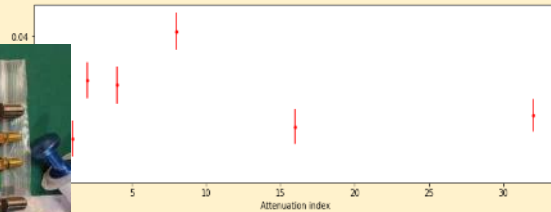
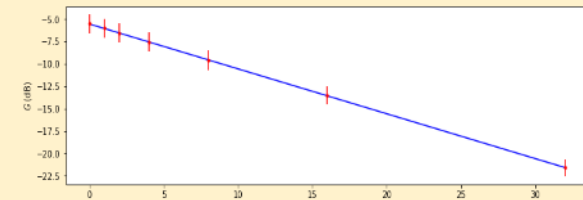
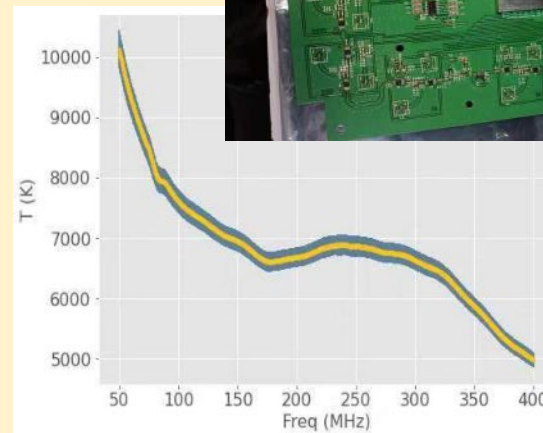
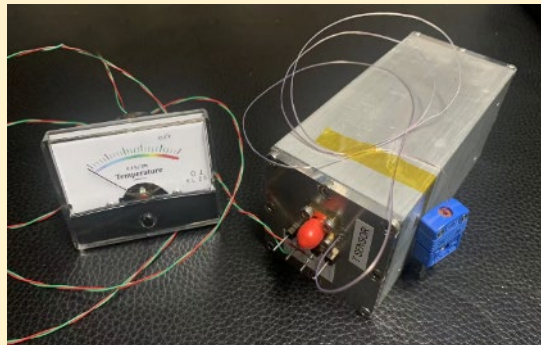


21CMA 127X81 dipoles

SKA-low pilot project

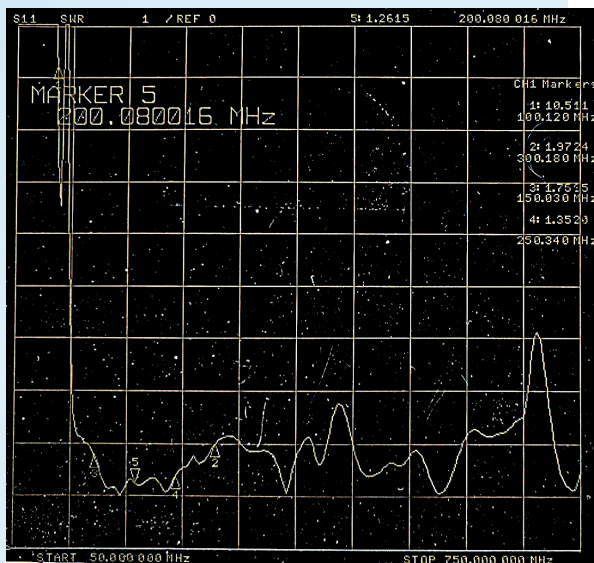
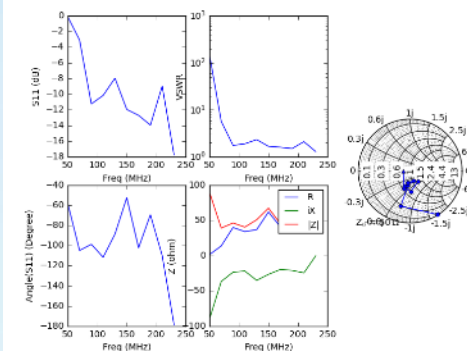
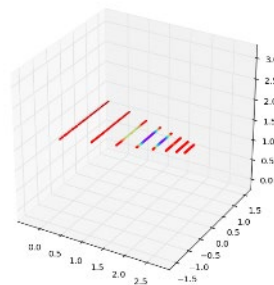
Designed all components of the RF front-end.

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

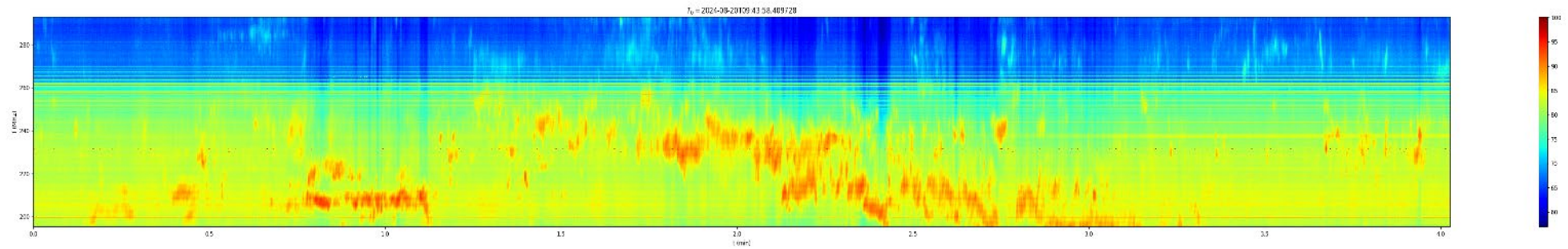
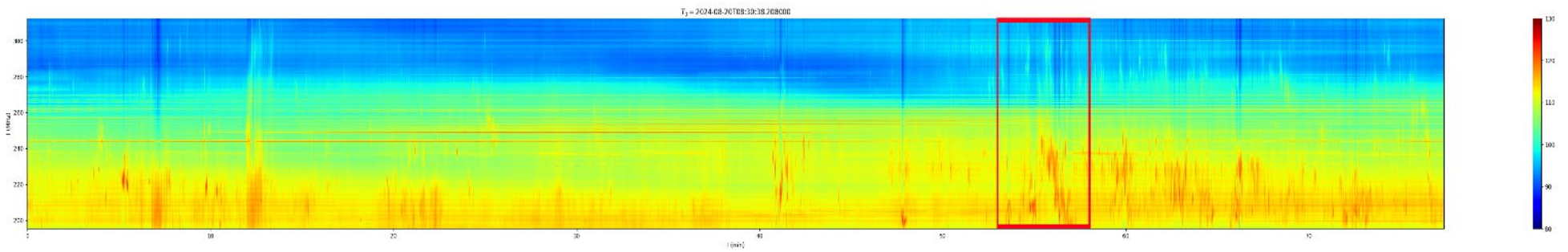


Noise standard, 0.01% variation/90 hour,
 $T_{noise} > 6500$ K, VSWR < 1.12

Progress

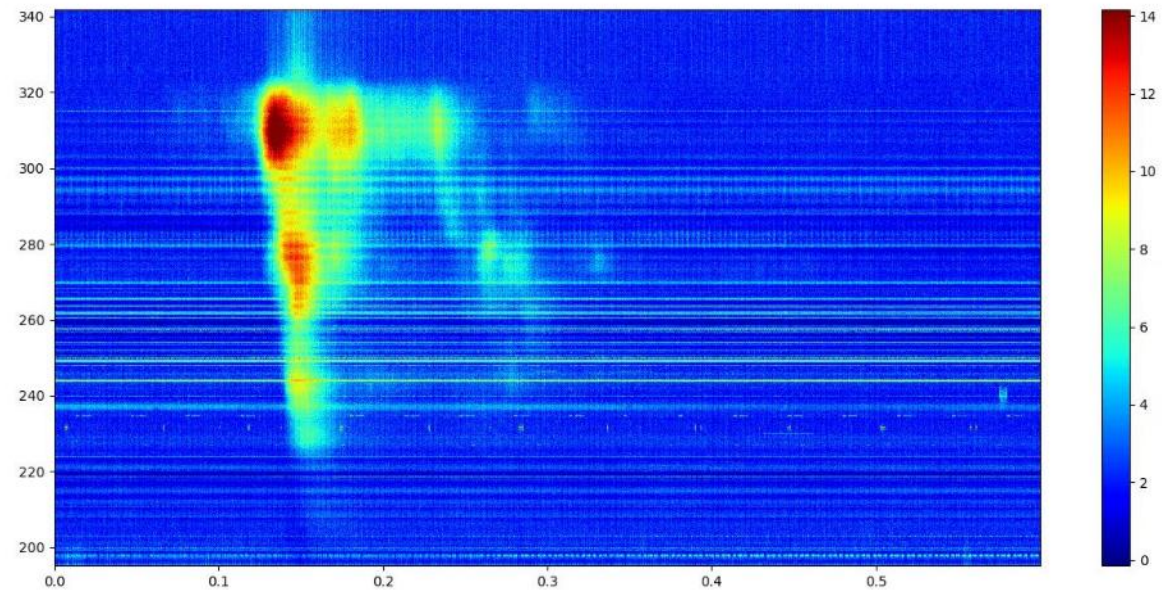
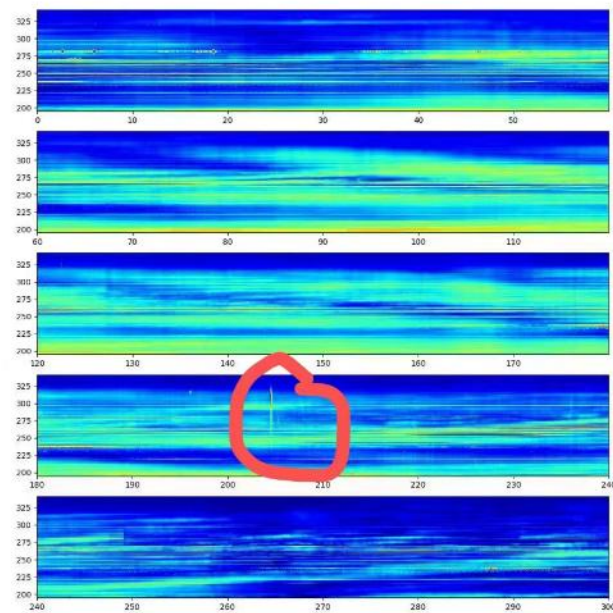


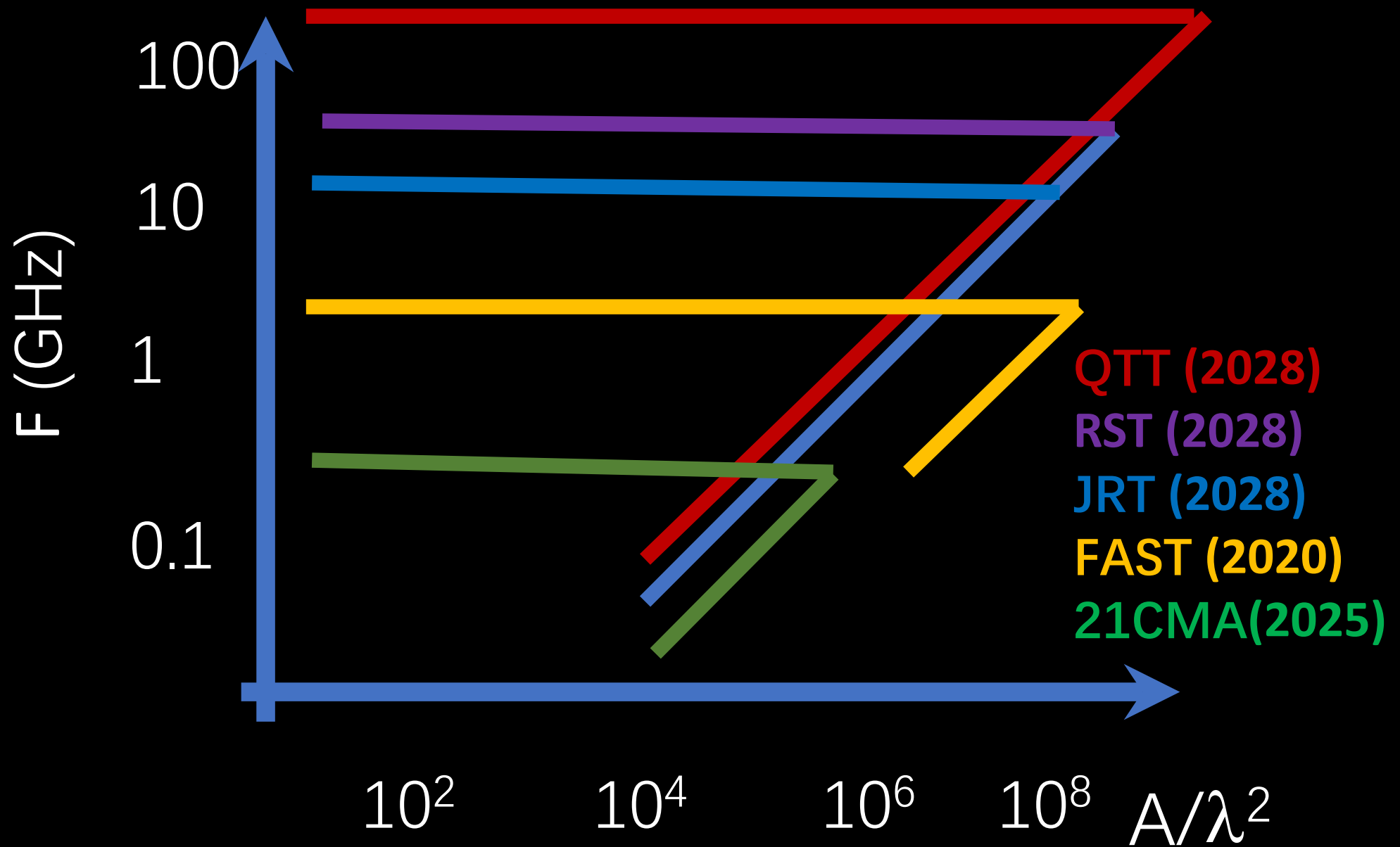
- Home-brewing EM simulation software to design antenna element, and experiment tuning to determine the geometry
 - 120-300MHz VSWR<2.0
 - 120-700MHz VSWR<2.5
 - 80-100MHz VSWR>10 suppress FM RFI
- Firmware of digital backend is nearly done
- Pilot array is constructed



Baseband recording @ 800 Msps
 Here: 100kHz spectral resolution
 1ms time resolution

$T_0 = 2024-09-19T11:36:00.001280$

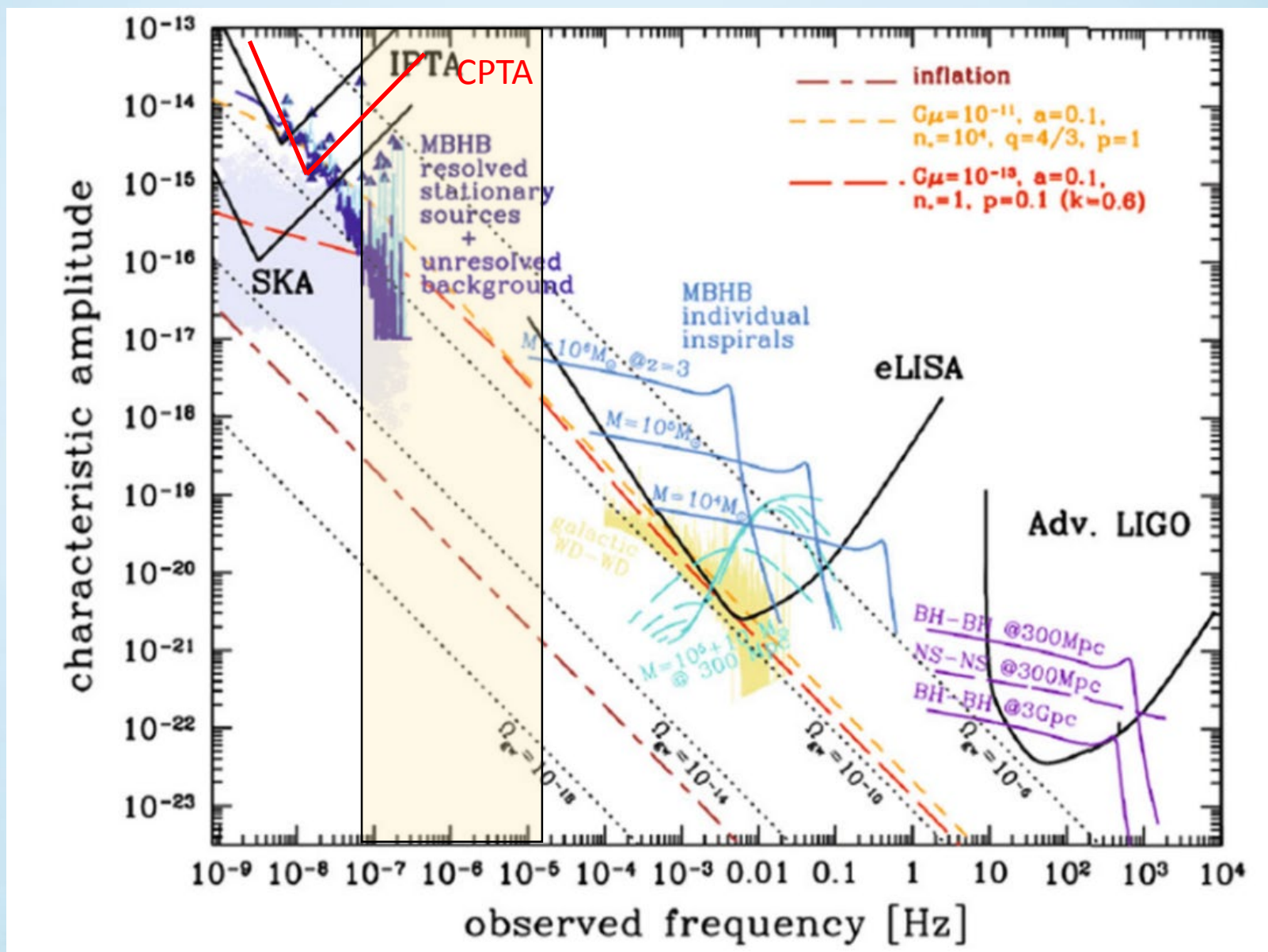




This is not a dream! This is what are really happening.



Something for uHz?



Coherent radar for GW searching



$$\frac{S}{N}_{\text{radiometer}} = 1.7 \times 10^{12} \frac{\eta}{0.1} \frac{P}{1 \text{ MW}} \left(\frac{D_{\text{recv}}}{100 \text{ m}} \right)^2 \left(\frac{t}{1 \text{ hr}} \right)^{\frac{1}{2}} \left(\frac{T}{35 \text{ K}} \right)^{-1} \left(\frac{B_i}{\text{kHz}} \right)^{-\frac{1}{2}} \left(\frac{R}{3.8 \times 10^8 \text{ m}} \right)^{-2}$$

$$\sigma_{\text{radiometer}} = \lambda / \sqrt{\text{SNR}_{\text{radiometer}}}$$



$$\sigma_{\text{radiometer}} = 28 \text{ nm} \left(\frac{\eta}{0.1} \right)^{-1/2} \left(\frac{P}{1 \text{ MW}} \right)^{-1/2} \left(\frac{D_{\text{recv}}}{100 \text{ m}} \right)^{-1} \left(\frac{t}{1 \text{ hr}} \right)^{-\frac{1}{4}} \left(\frac{T}{35 \text{ K}} \right)^{1/2} \left(\frac{B_i}{\text{kHz}} \right)^{\frac{1}{4}} \left(\frac{R}{3.8 \times 10^8 \text{ m}} \right)$$

How well we can detect GW?

GW sensitivity – distance measurement error transfer function

$$\sigma_h \equiv \sqrt{S_h(f)f} = \frac{1}{2} \frac{\sigma}{R} \frac{1}{\text{sinc}(2\pi f_{\text{GW}} R/c)}$$

$$\sigma_h = \frac{1}{2} \frac{\sigma}{R} = 1.3 \times 10^{-15} \left(\frac{\sigma}{\mu\text{m}} \right) \left(\frac{R}{3.8 \times 10^8 \text{m}} \right)^{-1} \quad \text{For } f < 0.5 \text{ Hz}$$

Radiometer noise of GW sensitivity

$$\sigma_h = 3.6 \times 10^{-17} \left(\frac{\eta}{0.1} \right)^{-1/2} \left(\frac{P}{1 \text{ MW}} \right)^{-1/2} \left(\frac{D_{\text{recv}}}{100 \text{ m}} \right)^{-1} \left(\frac{f}{1 \text{ hr}^{-1}} \right)^{1/4} \left(\frac{T}{35 \text{ K}} \right)^{1/2} \left(\frac{B_i}{\text{kHz}} \right)^{1/4}$$

Seismic noise

$$S_{\text{seismic}}(f) \sim 1 \text{ nm}^2 \text{ Hz}^{-1} \left(\frac{f}{\text{Hz}} \right)^{-2}$$

$$\sigma_h = 1.3 \times 10^{-15} \left(\frac{f}{\mu \text{ Hz}} \right)^{-1}$$

Earth tides, complicated, but due to the Q value, does not affect much.

Ionosphere delay:

$$\sigma_h = 1 \times 10^{-18} \left(\frac{\eta}{0.1} \right)^{-1/2} \left(\frac{P}{1 \text{ MW}} \right)^{-1/2} \left(\frac{D_{\text{recv}}}{100 \text{ m}} \right)^{-1} \left(\frac{t}{1 \text{ hr}} \right)^{-\frac{1}{4}} \left(\frac{T}{35 \text{ K}} \right)^{1/2} \left(\frac{B_i}{\text{kHz}} \right)^{\frac{3}{4}} \left(\frac{R}{3.8 \times 10^8 \text{ m}} \right) \left(\frac{f_{\text{radio}}}{\text{GHz}} \right) \left(\frac{\text{BW}}{100 \text{ MHz}} \right)^{-\frac{3}{2}}$$

Telescope deformation calibration:

$$\sigma = 20 \text{ nm} \left(\frac{N}{50} \right)^{-1}$$

Frequency stability: 1e-17

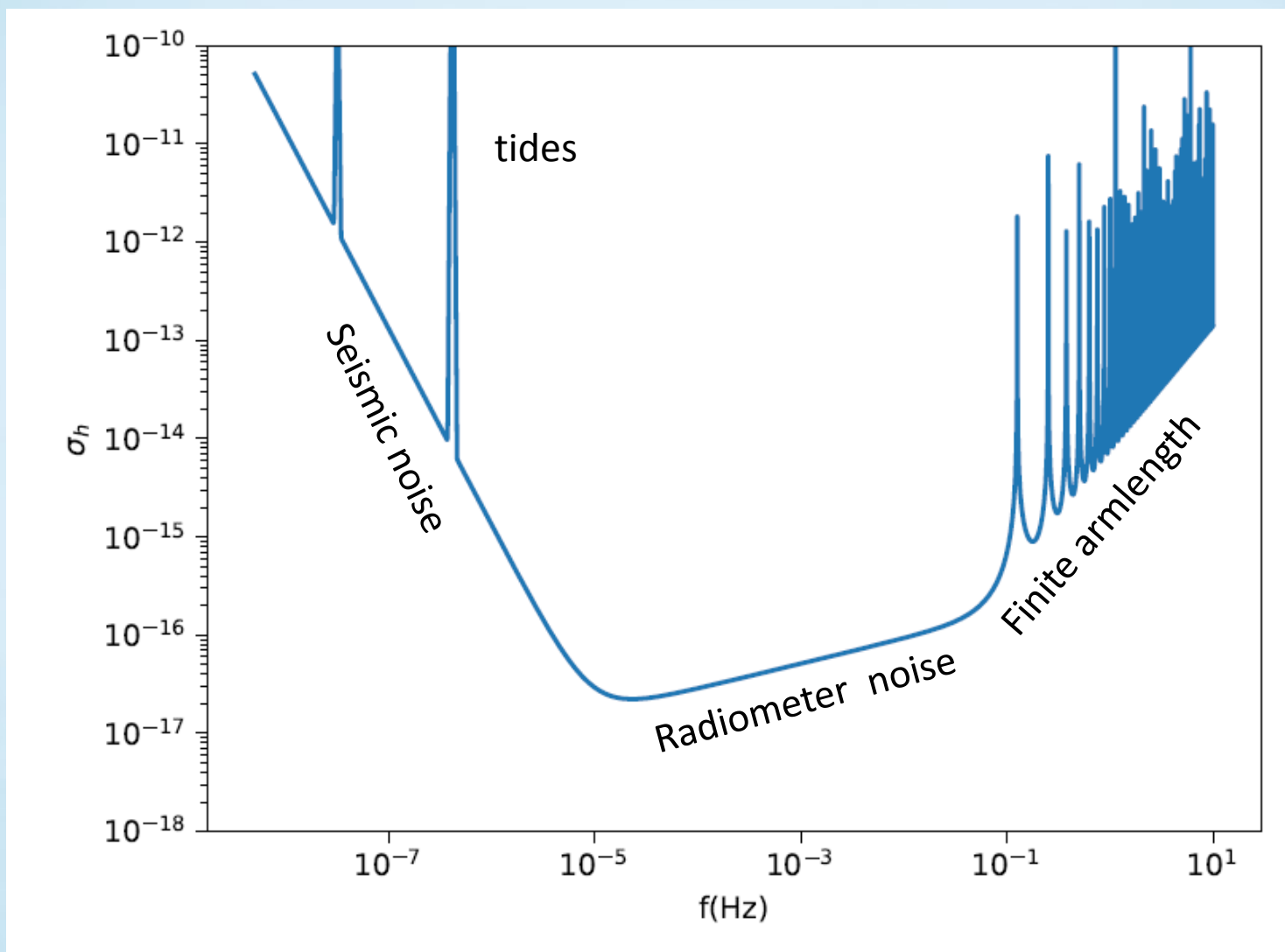
Solar acceleration noise: 1e-19

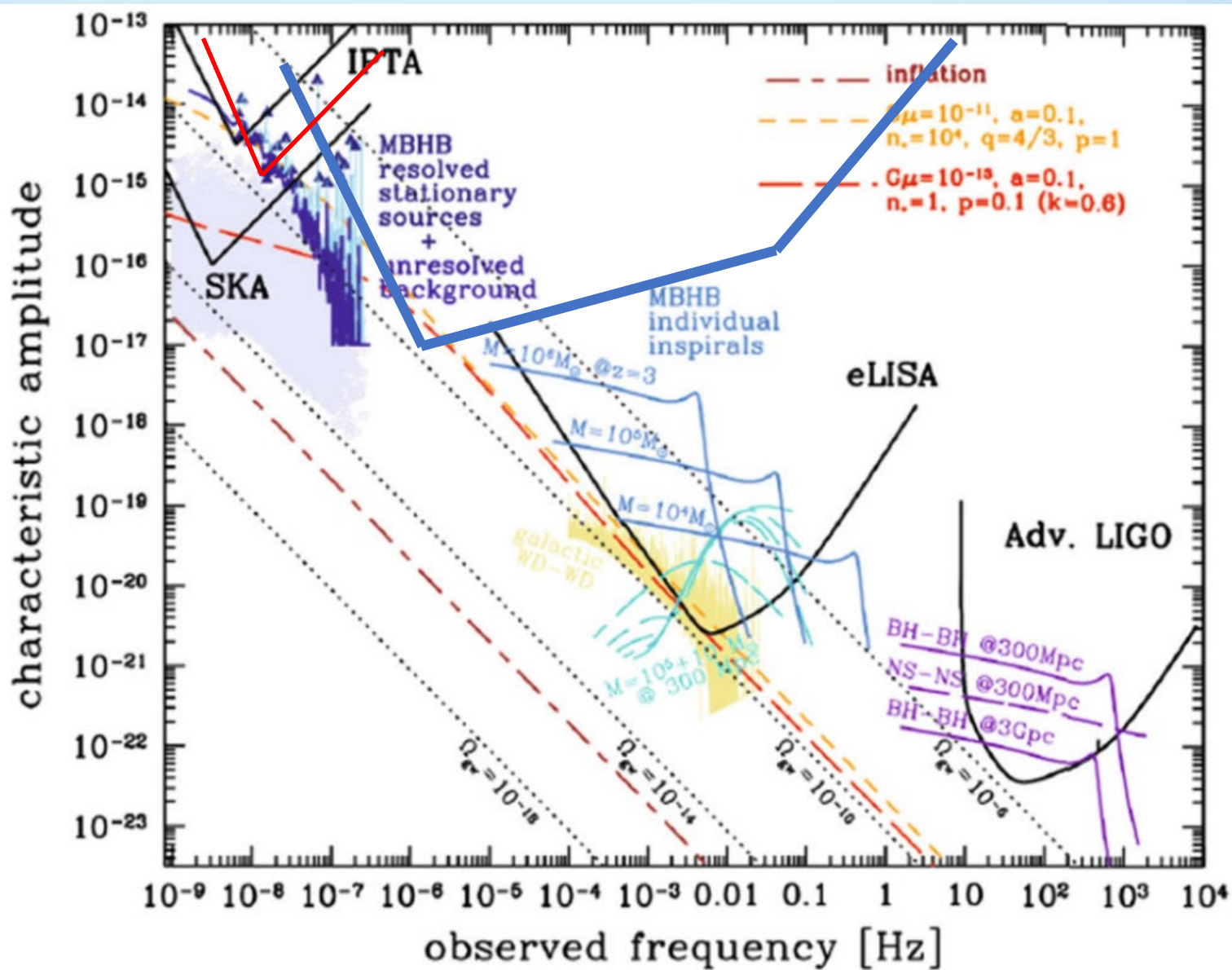
Potential issues:

wind disturbing --- solution: reference antenna

pointing error --- radar image correction

Phase noise of radar amplifier --- TDI or active correction





1. Radar is now building, expected to run 2027
2. We are in the initial stage to propose radar –GW detector experiment.
3. Anyone is welcome to join the science / engineering team.



- Expected GW sources (astronomer)
- Searching algorithm (astronomer, data analyst, statistician)
- Noise and mitigation (mechanic engineer, geophysist, space scientist)
- Solar system dynamics (astronomer)
- Radio engineering (electric engineer)
- Radar experts



Thanks for organizing the fun meeting!

We will have the dual 120m meeting July 25th in Jilin, you are more than welcome to join.

Meeting wechat group



二维码7天内(5月15日前)有效, 重新进入将更新