Searching for gravitational wave bursts from cosmic string cusps with the Parkes Pulsar Timing Array

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in collaboration with
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and Parkes Pulsar Timing Array team

based on *Yonemal et al. MNRAS 501, 701–712 (2021)*

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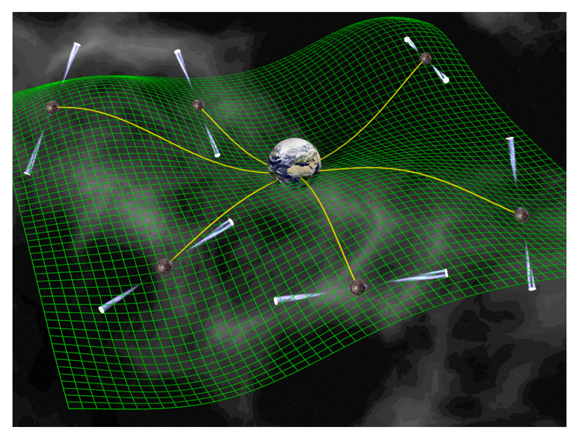
Gravitational Wave Probes of Physics Beyond Standard Model

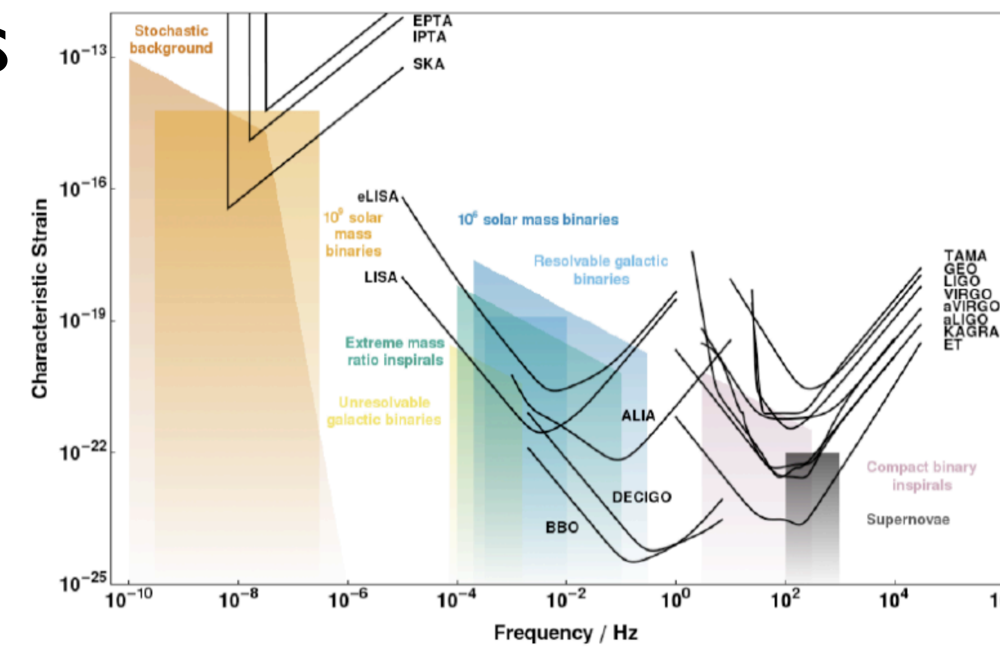
Introduction

- Cosmic strings may have been generated in the early Universe
  → unique way to access the early universe physics

- **Gravitational Waves (GWs)** is a powerful observational tool to probe cosmic strings

- **Pulsar timing** probes nanoHz GWs



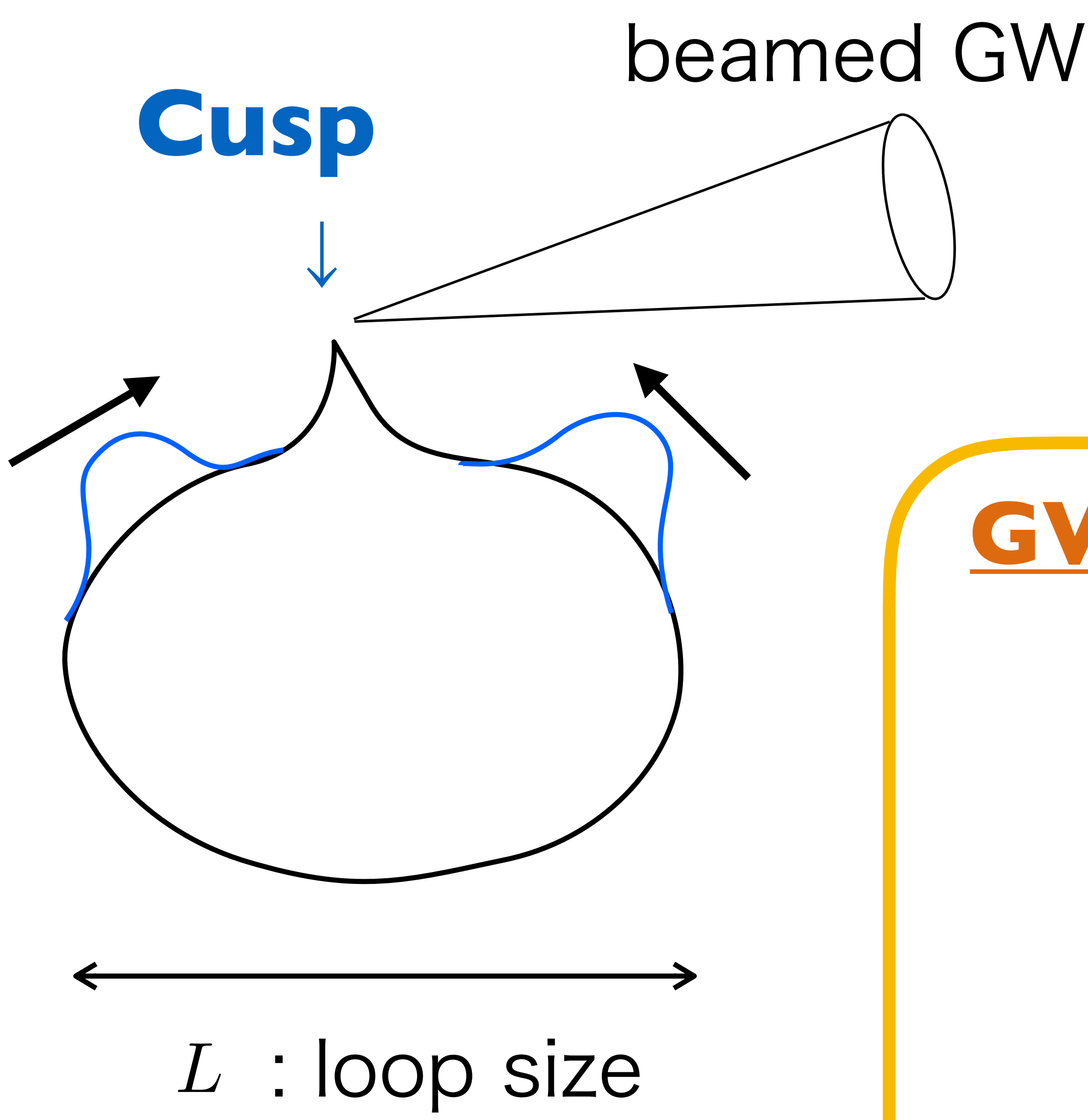


- GWs coming from different directions overlap one another and form a **stochastic GW background**

- Nearby events are observed as a **single burst event**

GW bursts from cosmic strings

Strong GW bursts are emitted from singular points called **cusps**



Damour & Vilenkin, PRD 64, 064008 (2001)

GW amplitude (in Fourier space)

$$\tilde{h}(f) = \frac{G\mu L}{[(1+z)fL]^{1/3} r(z) f}$$

Gμ : tension = line density

r(z) : distance to the source

GW bursts from cosmic strings

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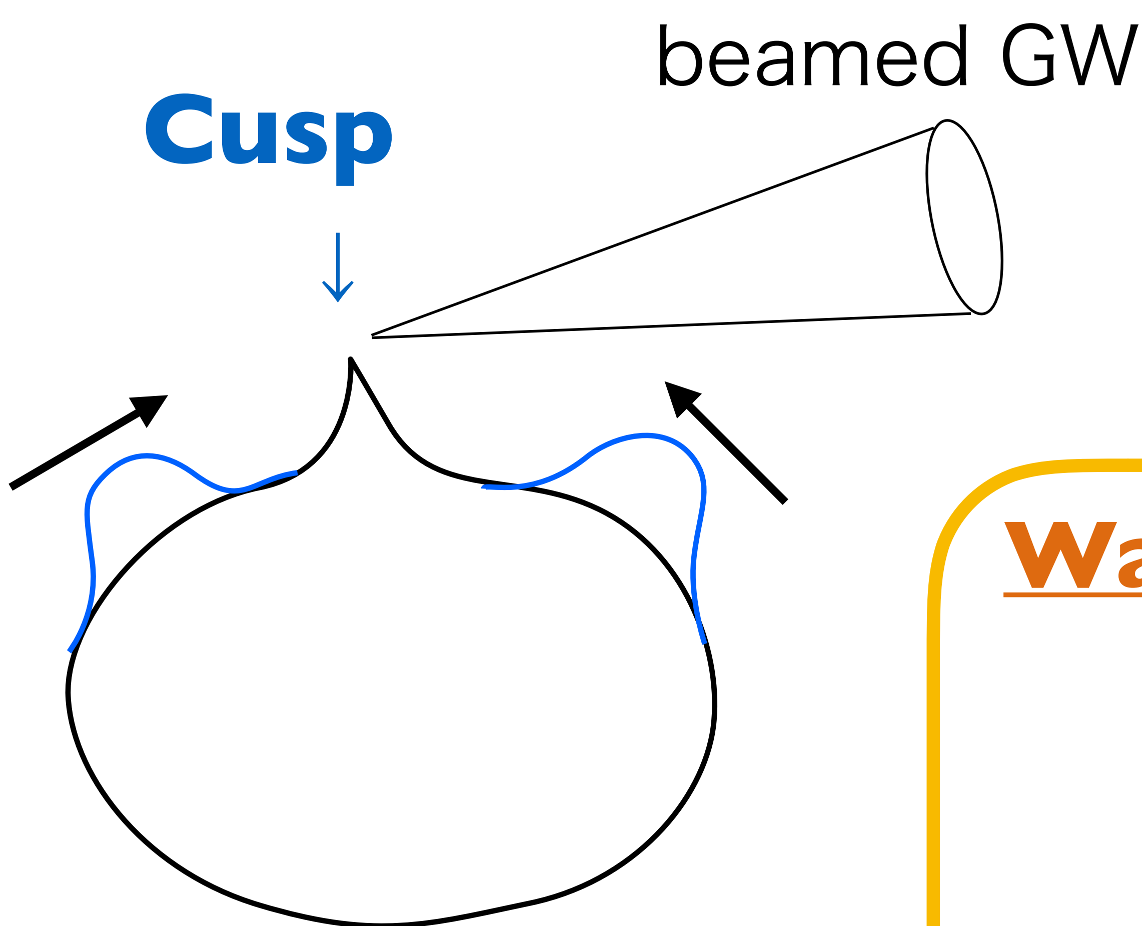
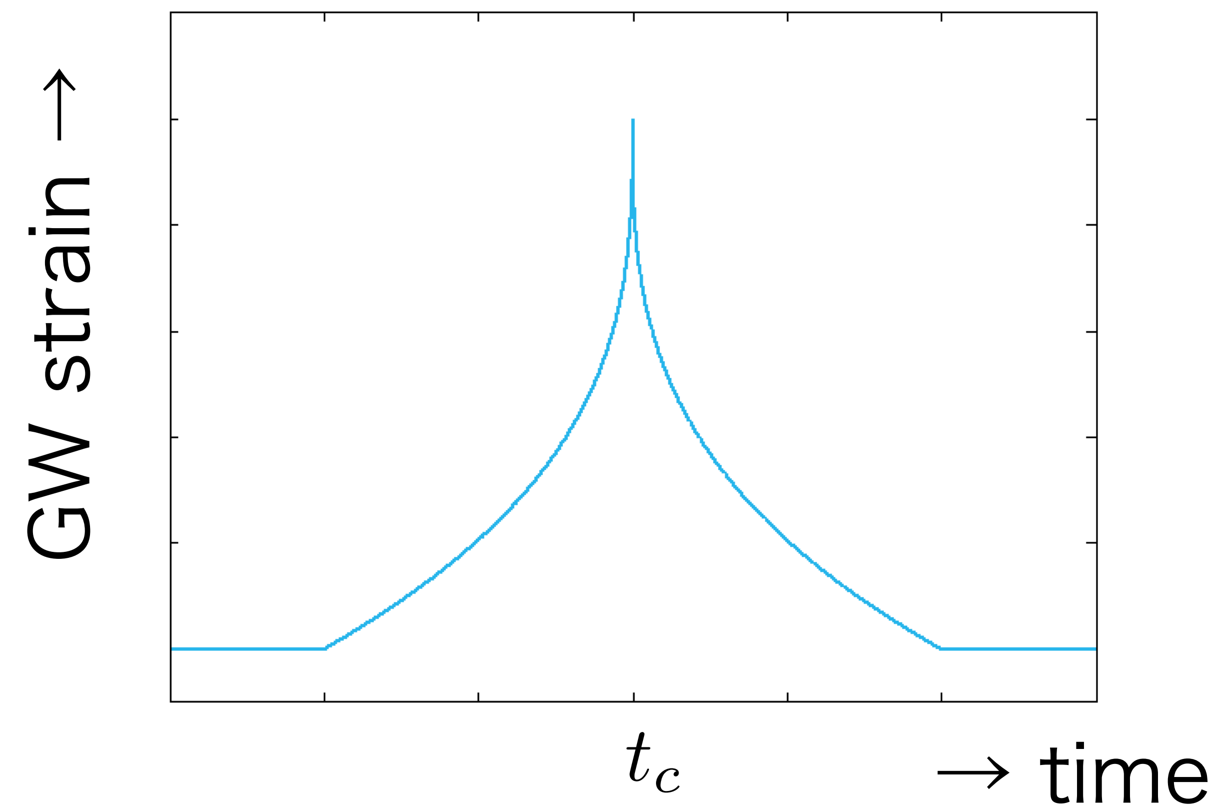


Waveform (in time domain)



GW bursts from cosmic strings

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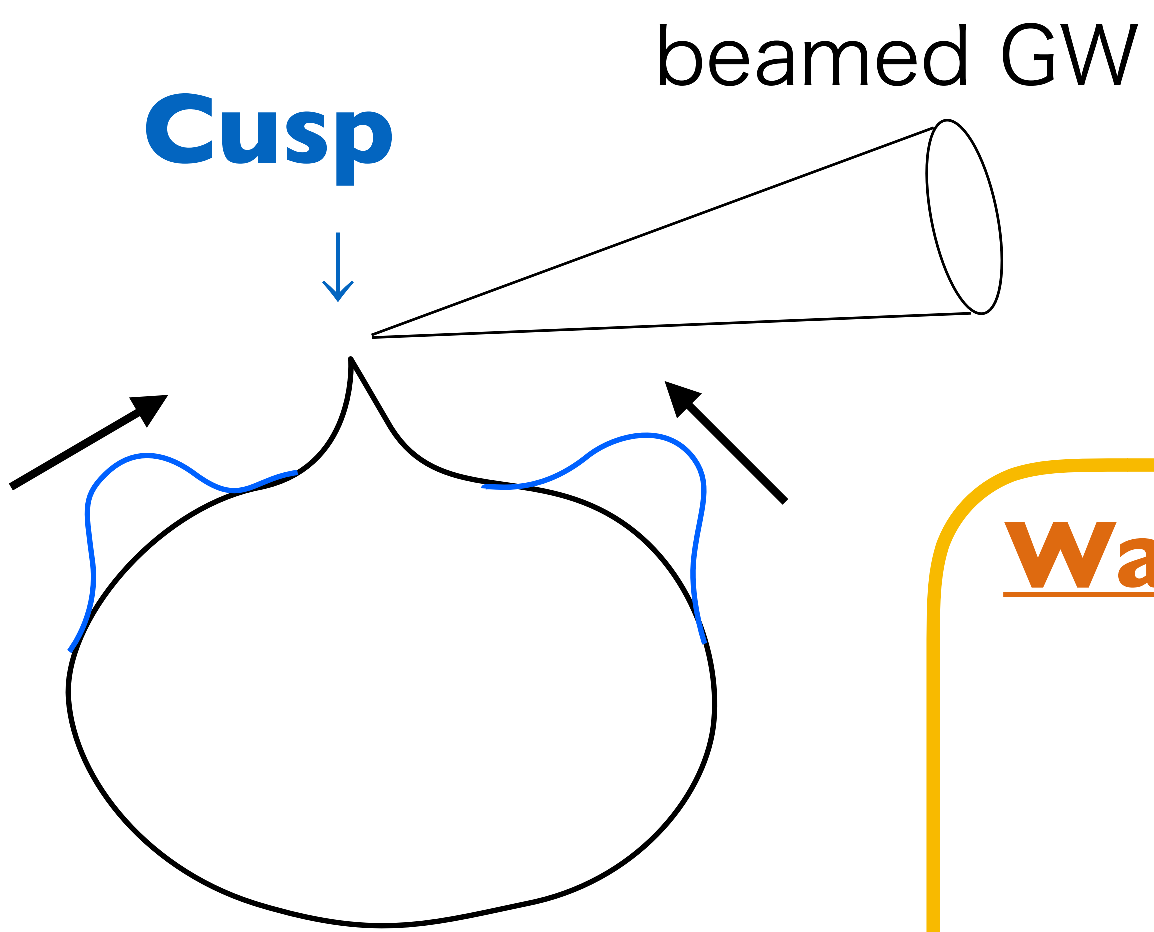

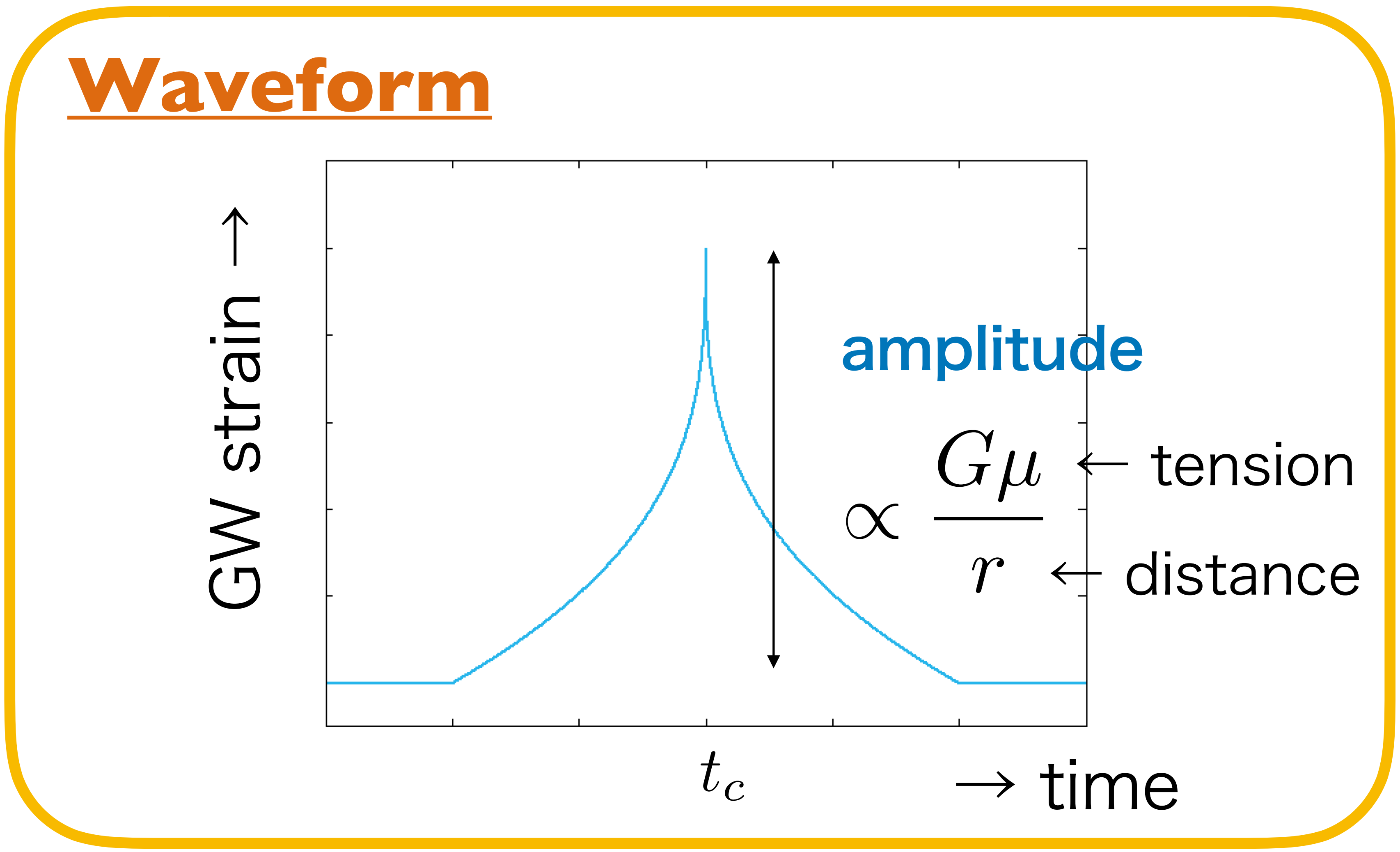

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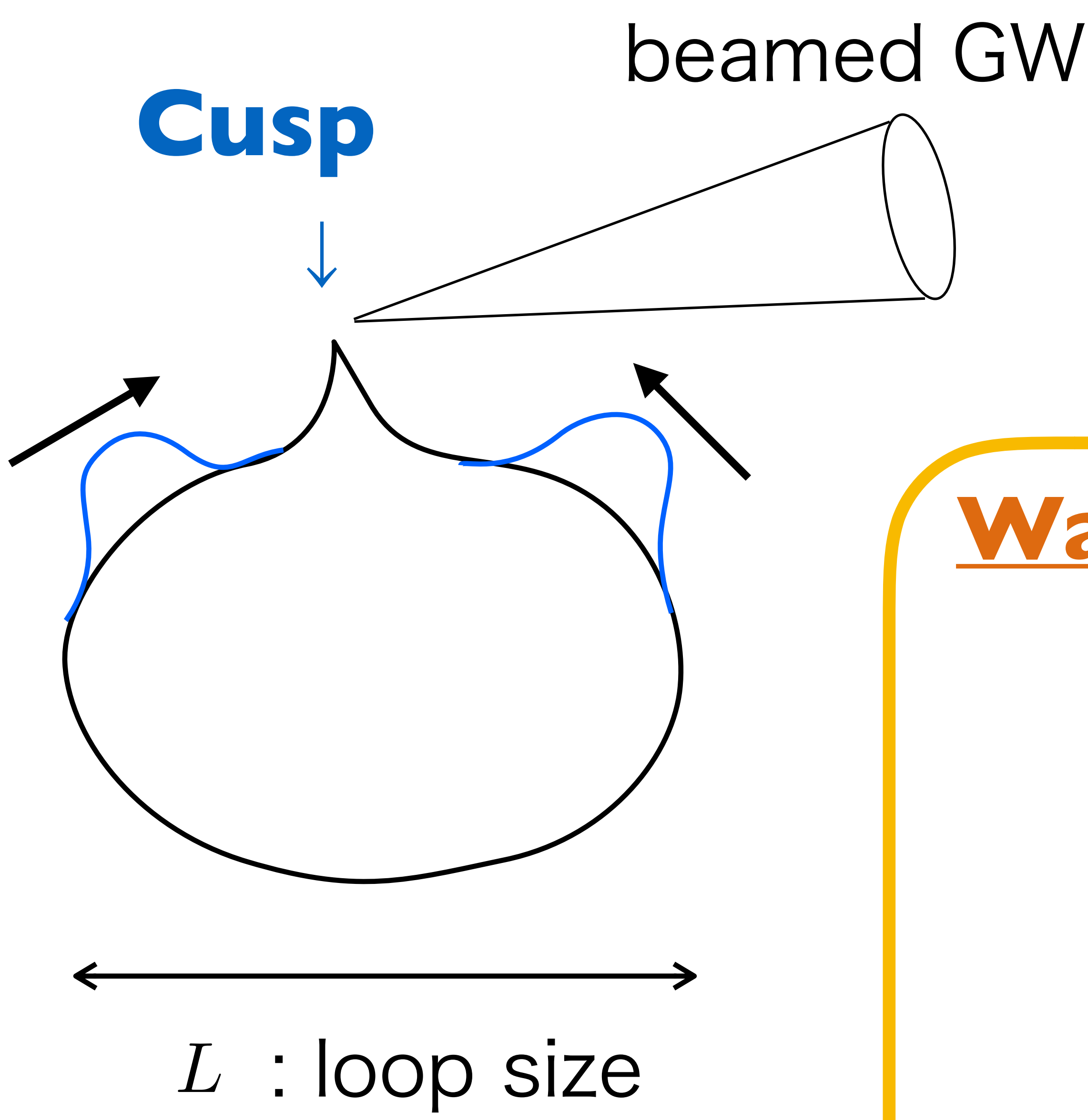

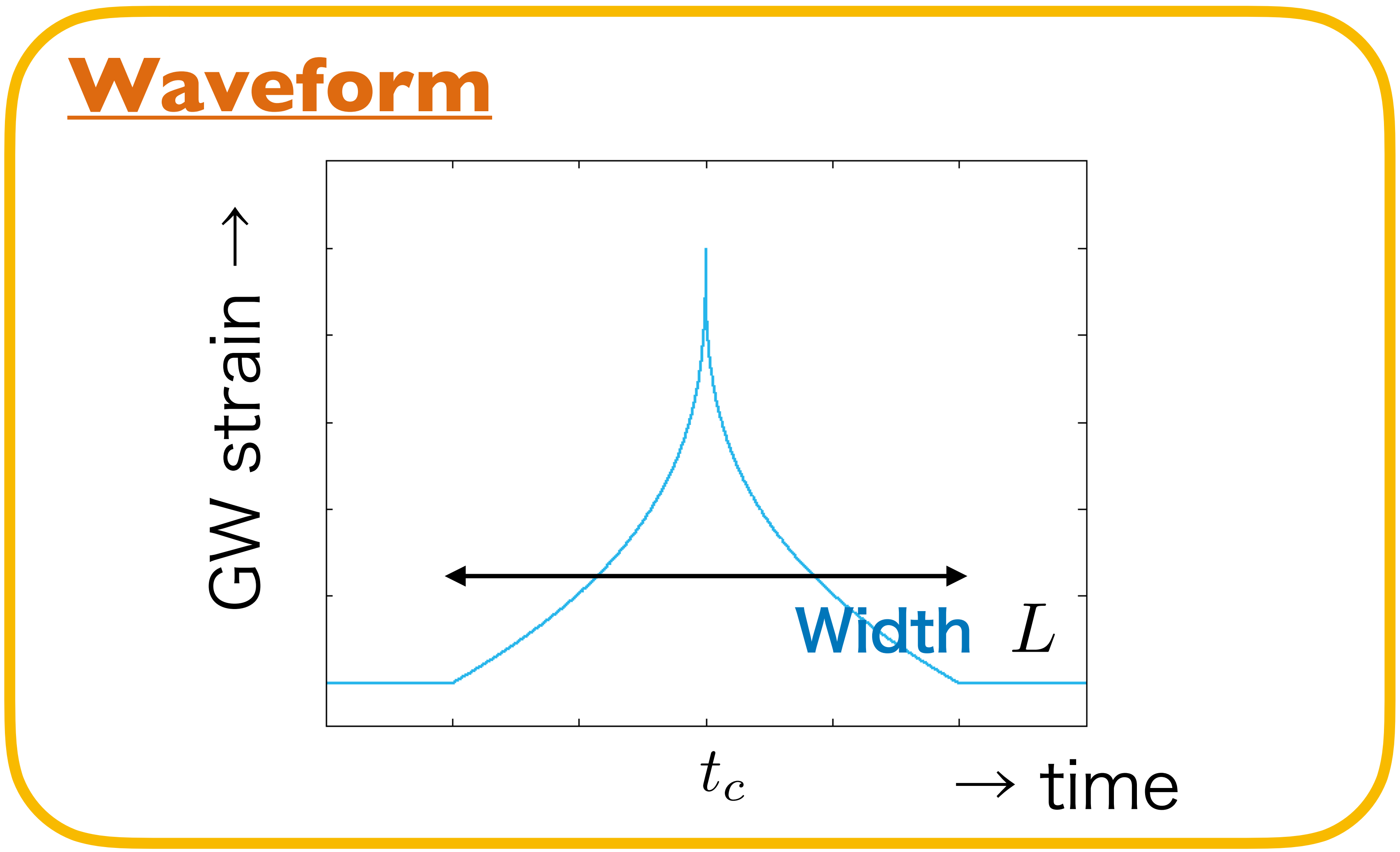

GW bursts from cosmic strings

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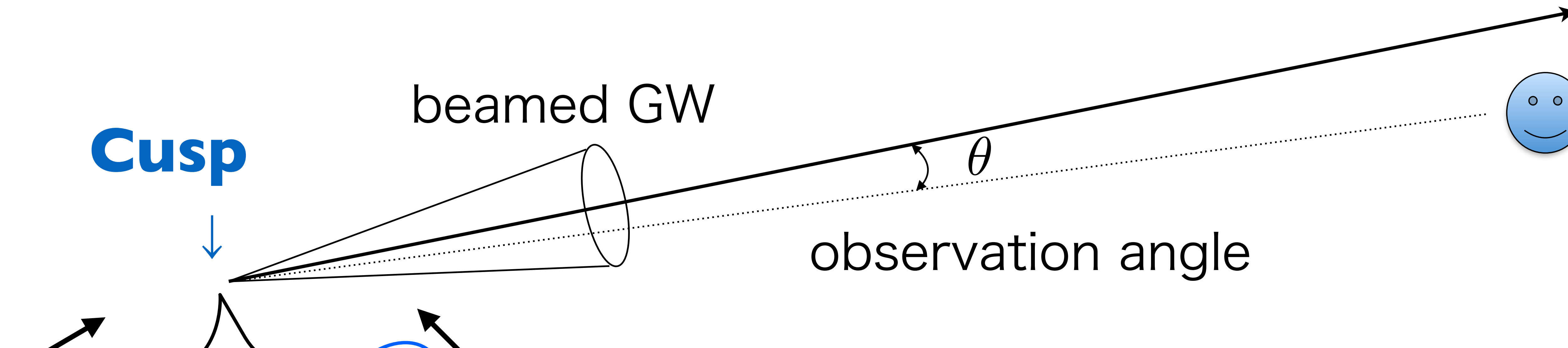
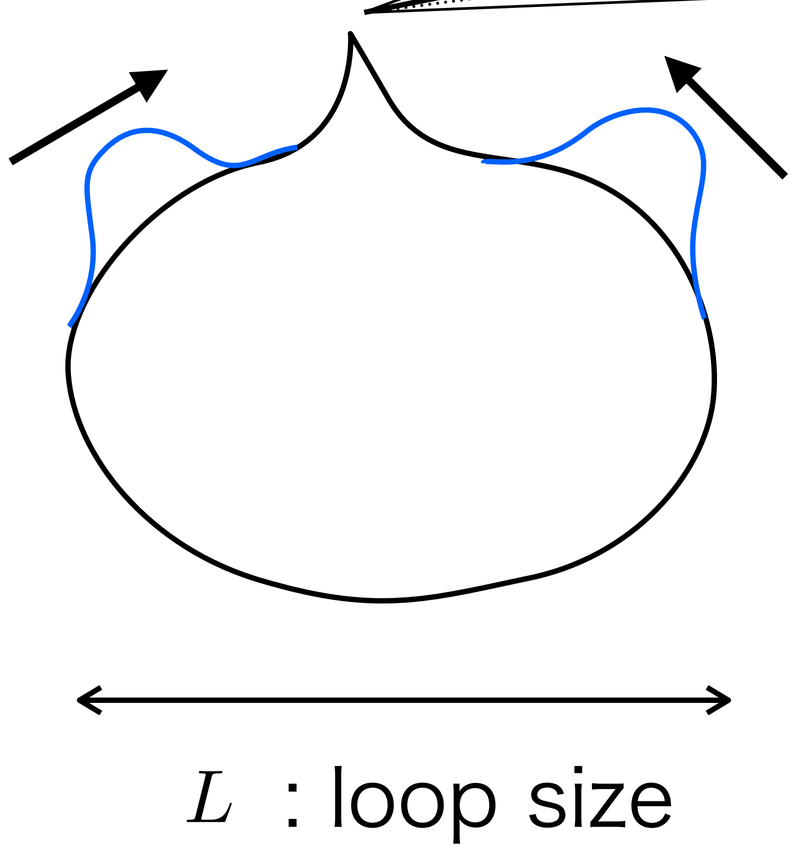
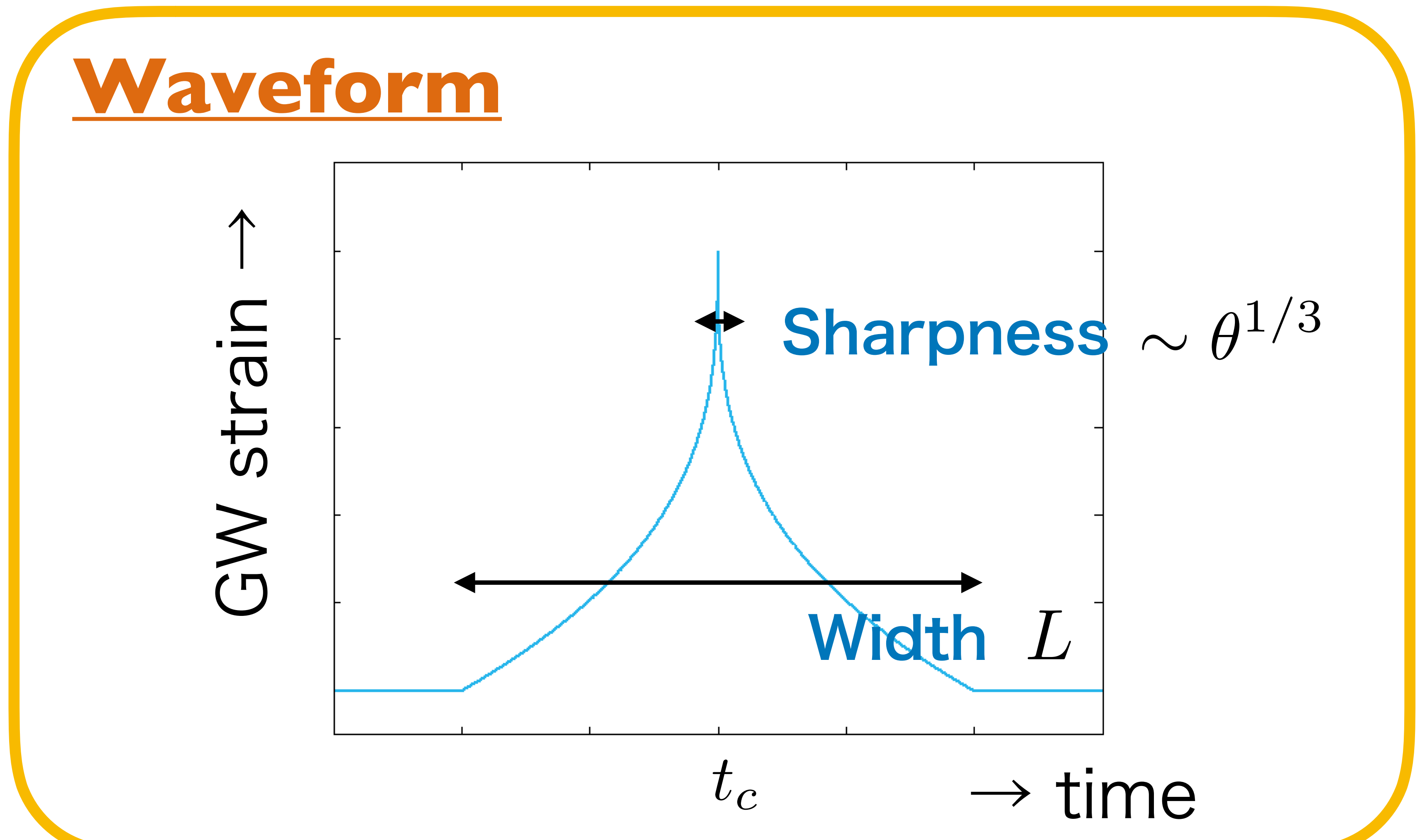




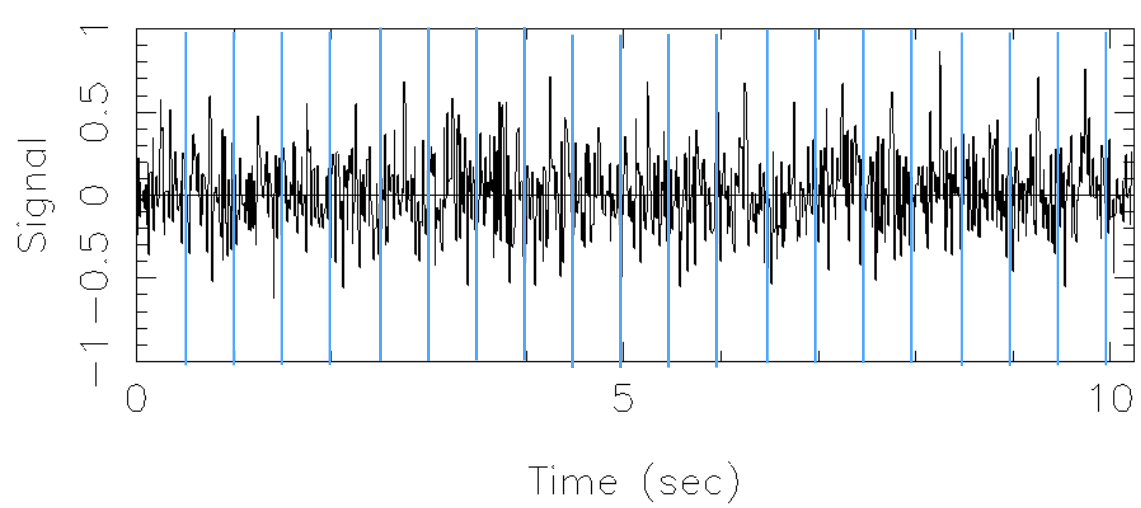


Observation

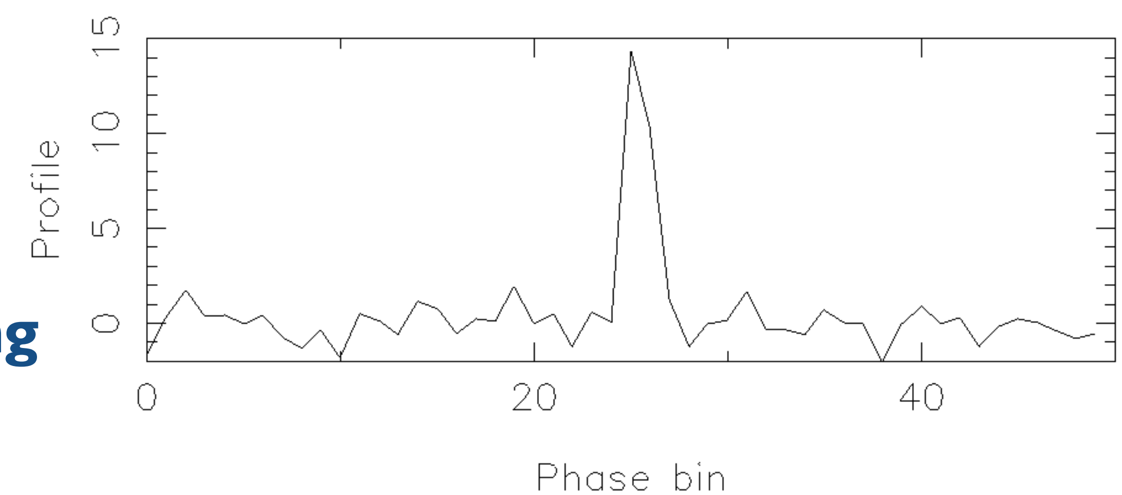
Parkes Pulsar Timing Array

~ 20 pulsars
1 hour for each every 2 weeks

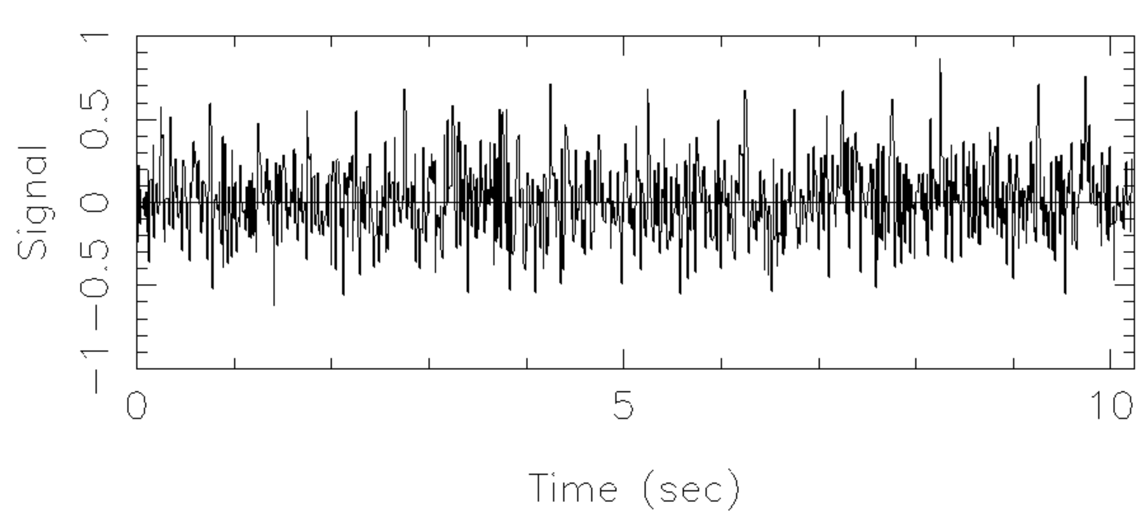
sum up all the bins



folding

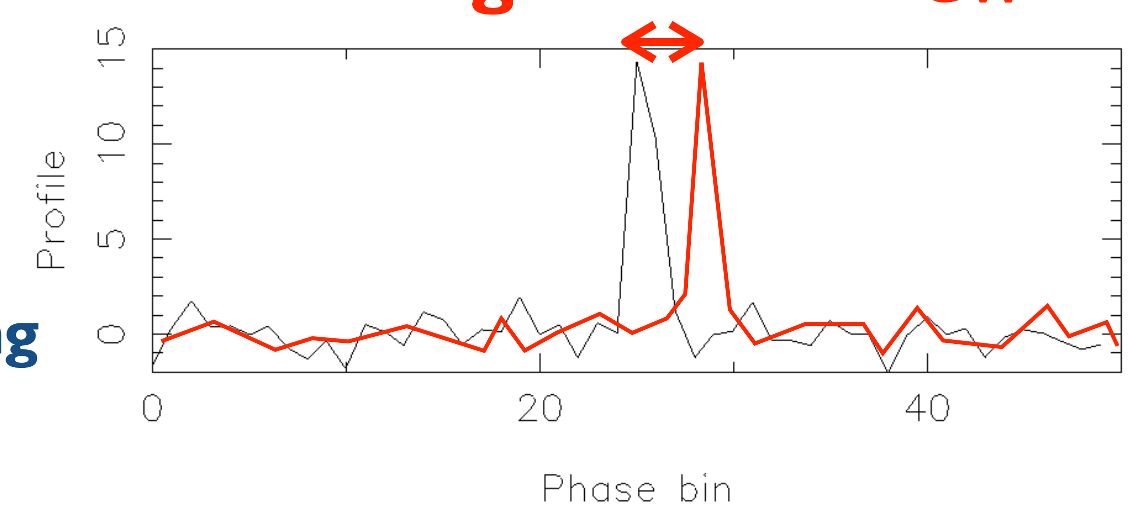


2 weeks later



folding

timing residual r_{GW}

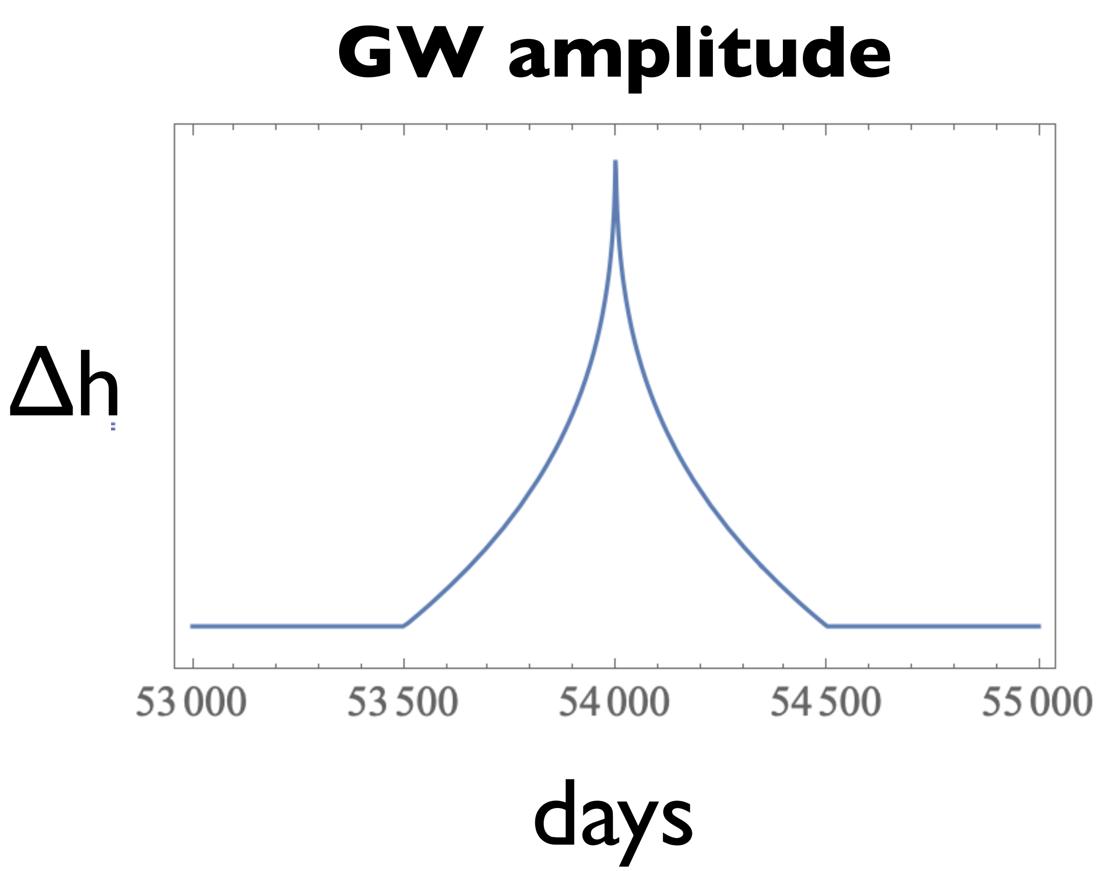


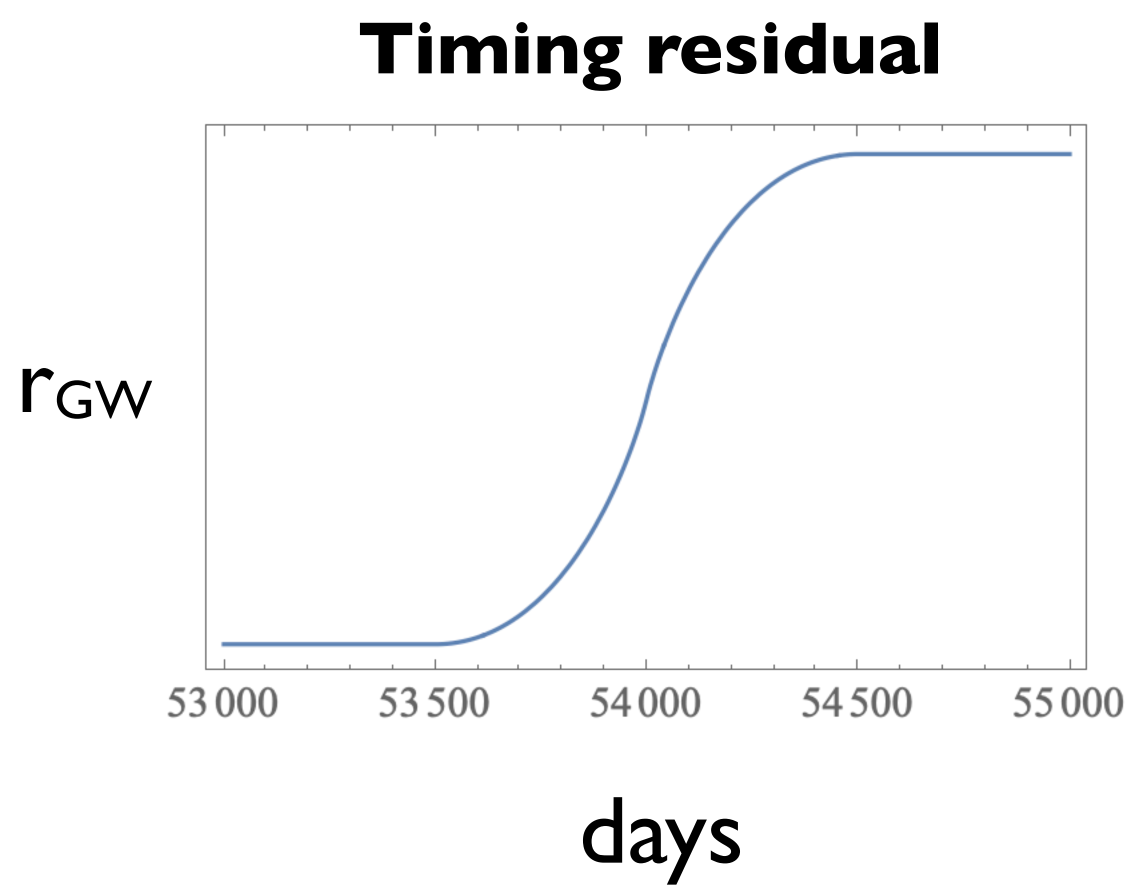
Timing residual induced by GWs

Timing residual: $$r_{\rm GW}(t) = \sum_{A=+,\times} \underline{F^A(\hat{\Omega},\hat{p})} \int^t \underline{\Delta h_A(t',\hat{\Omega})}dt'$$

antenna pattern (response function)

GW amplitude



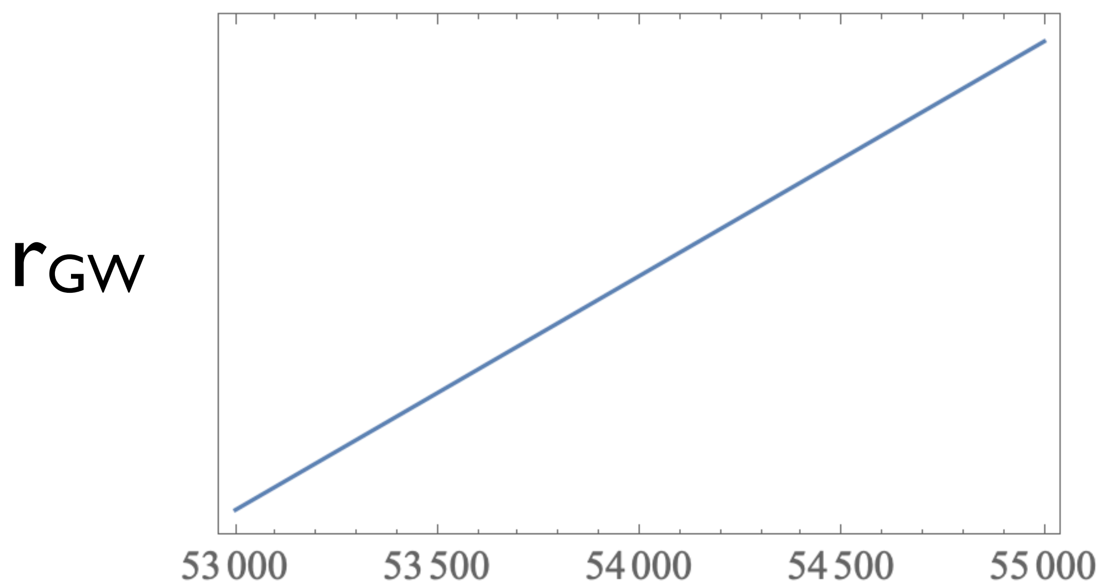


Post-fit effect

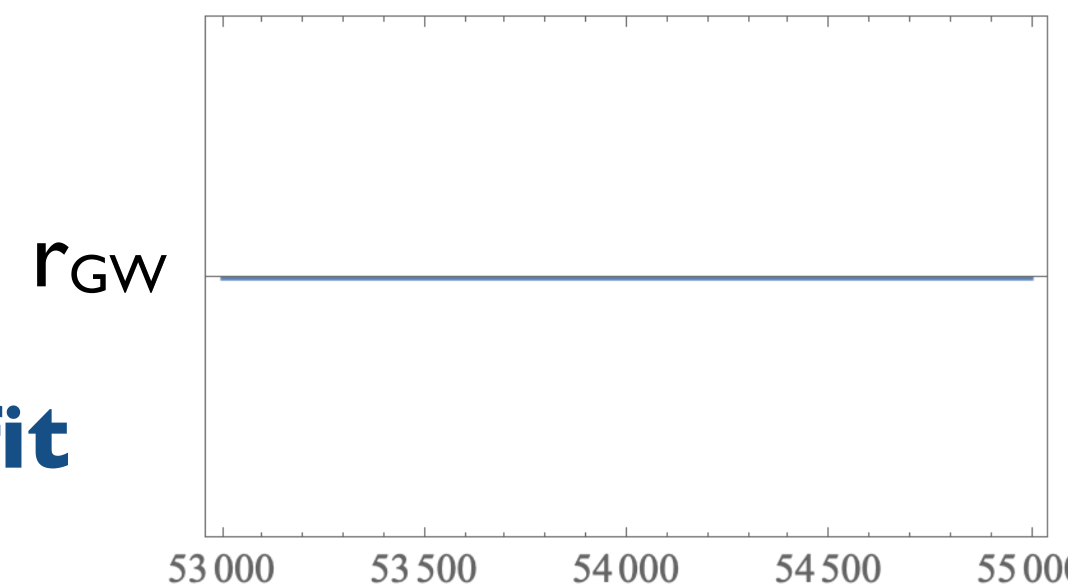
We do not know the true pulsar period

Even without GW signal, we get r_{GW} by assuming wrong pulse period

Correct the period and remove the linear trend

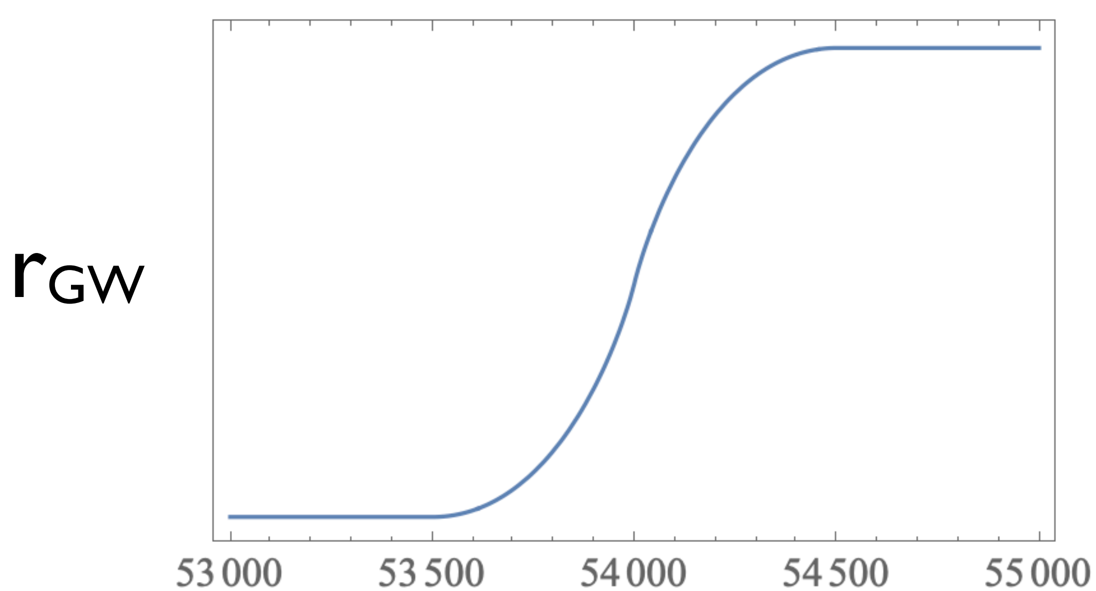


Post-fit

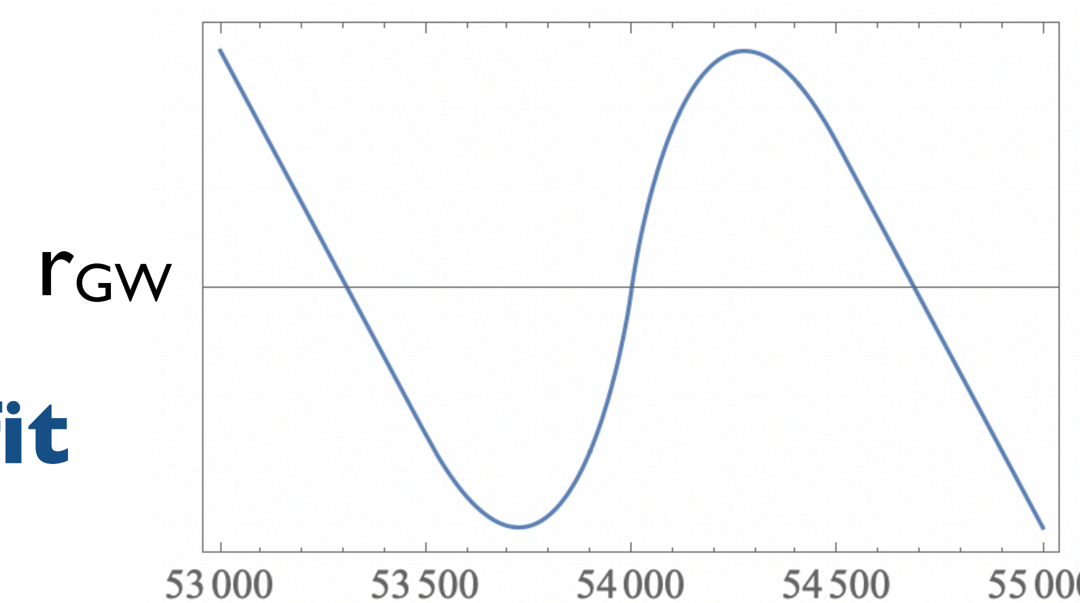


Timing residual by cosmic string GWs

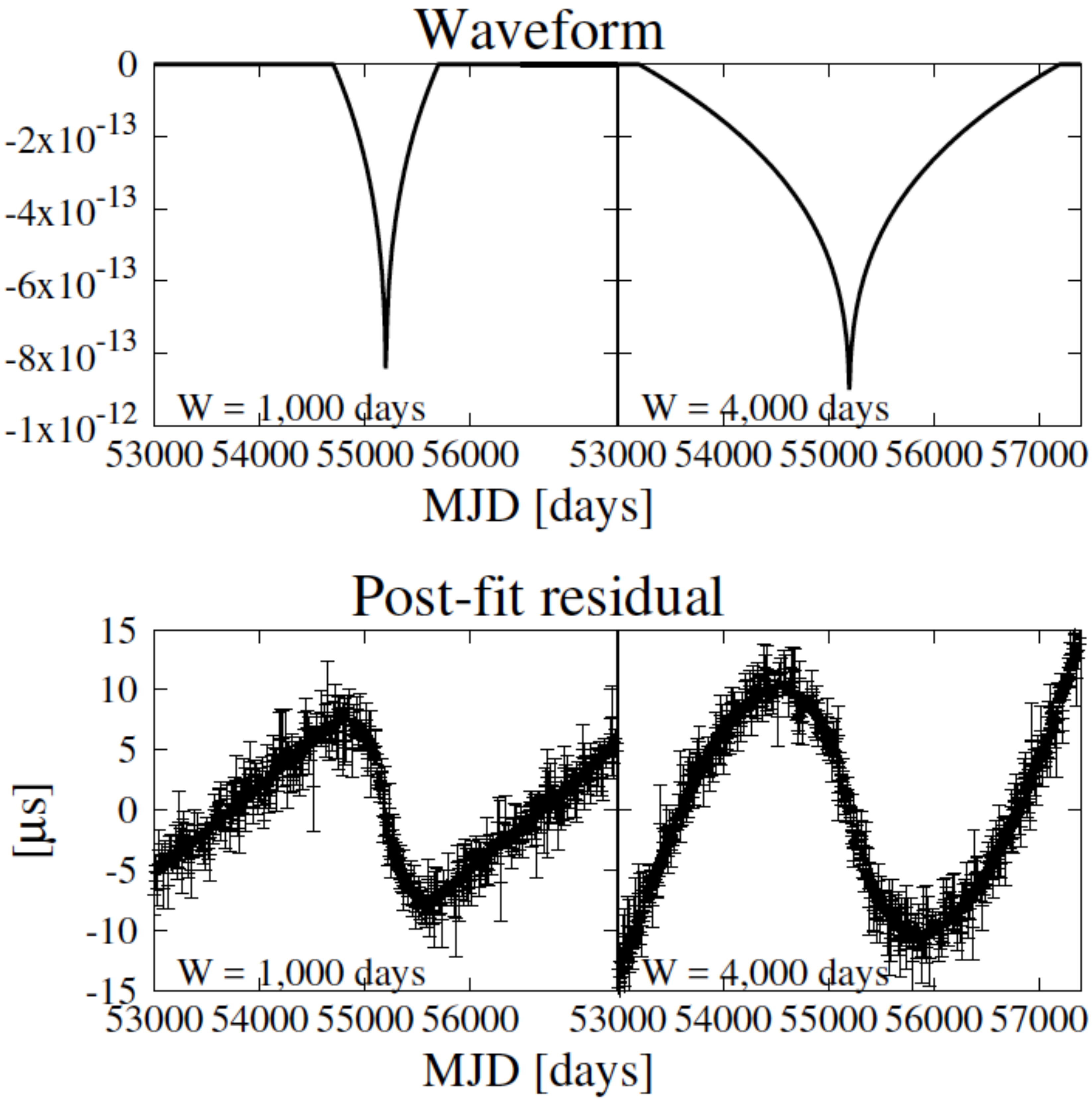
Post-fit residual



Post-fit



Simulated timing residual



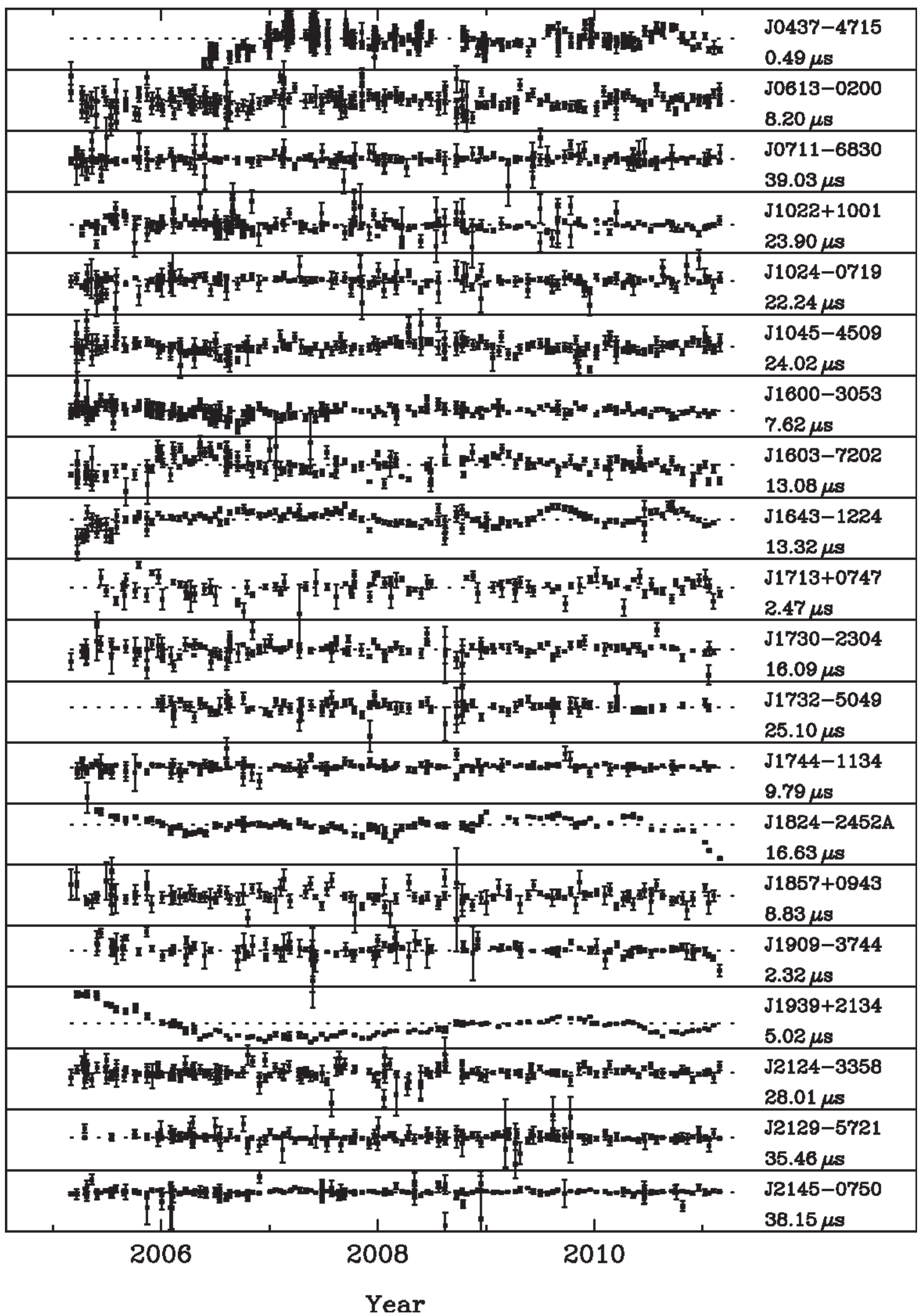
parameters

W: width

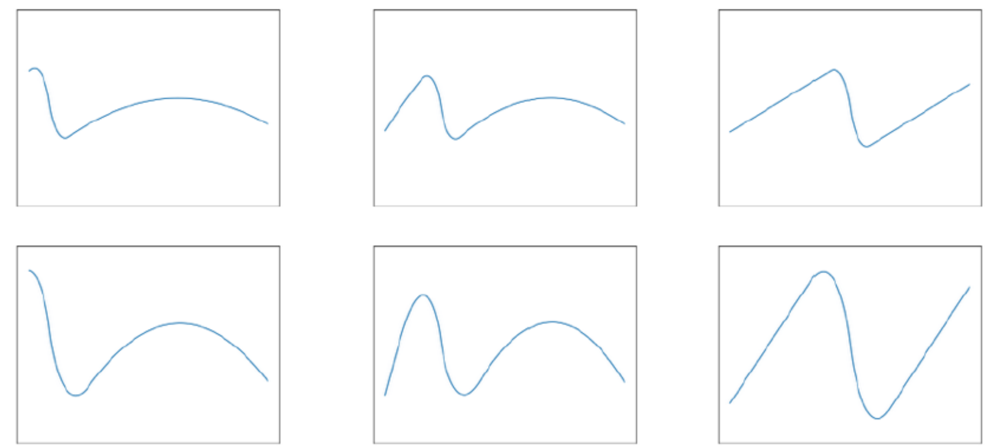
t_0: epoch

Template search

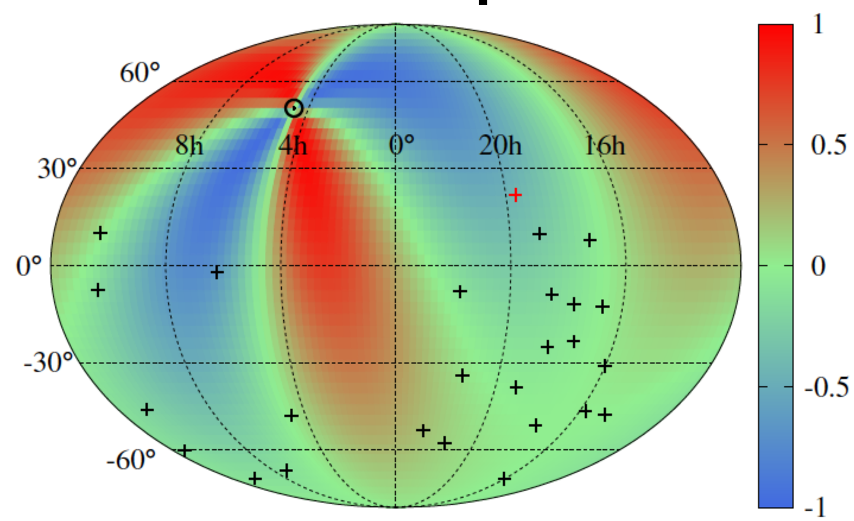
Data (Parkes PTA DR2)



Timing residual templates



Search the quadratic moment pattern



Detection statistics: $D = \mathbf{A}^t \mathbf{C}_0^{-1} \mathbf{A}$

amplitude $\mathbf{A} = [A_1; A_2]$

covariance matrix

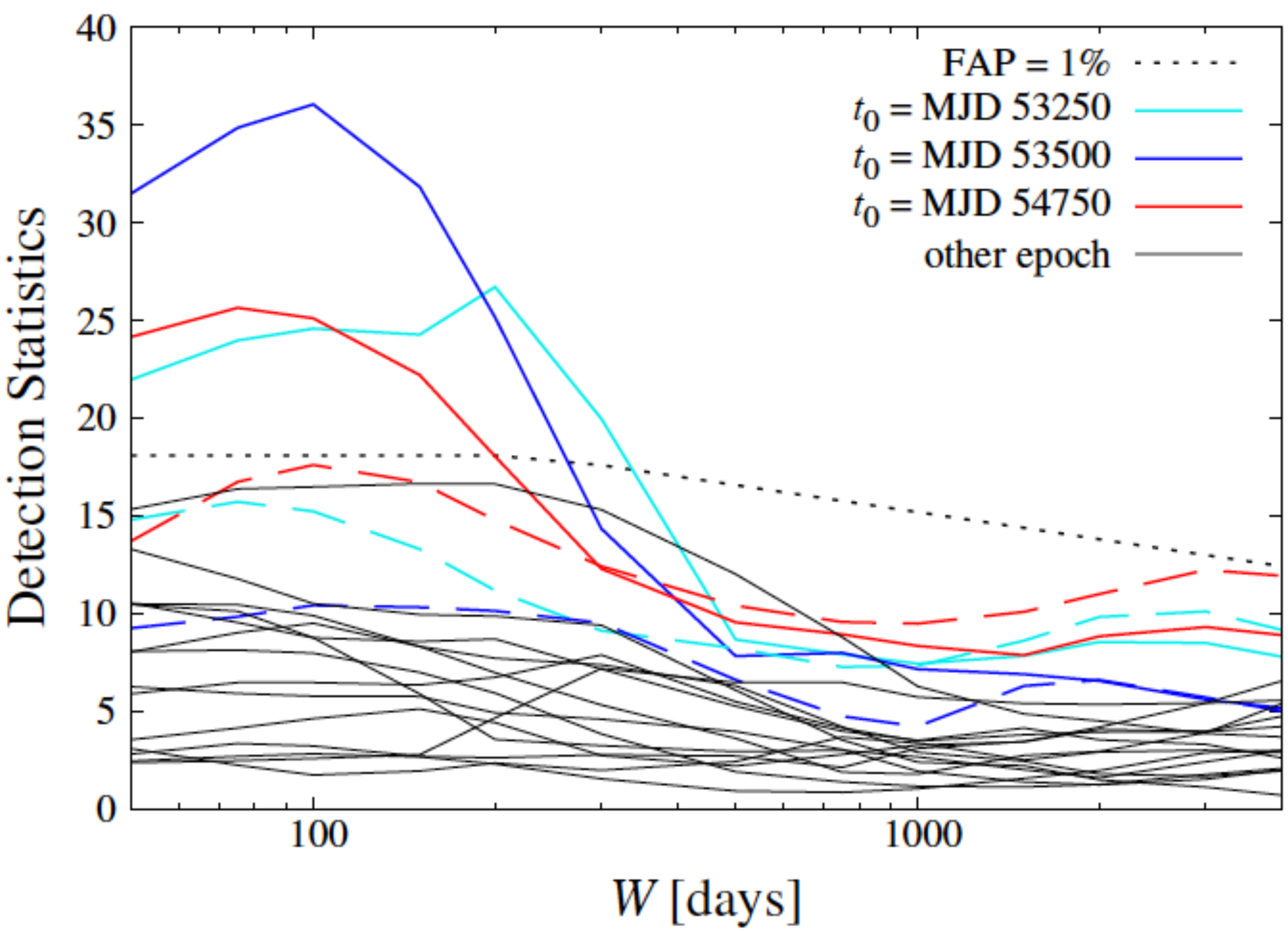
Search result

parameters

W: width

t_0: epoch

D_{max} (maximum value over the sky)



Duration of the burst event

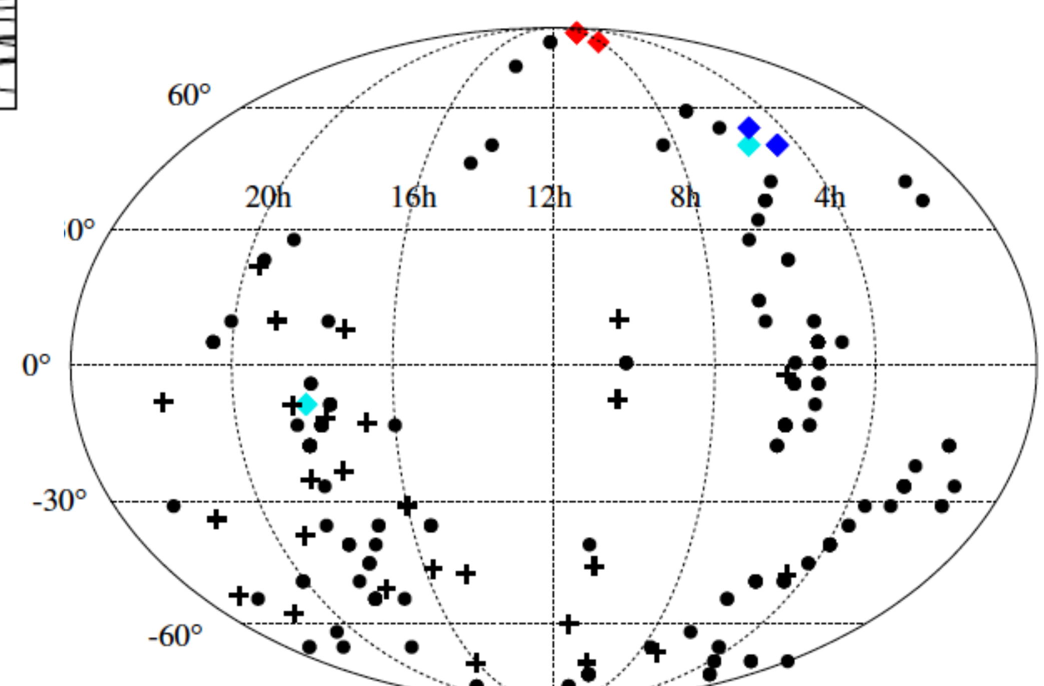
● Location of D_{max}

+ Location of pulsars

◆ t_0 = MJD53250

◆ t_0 = MJD53500

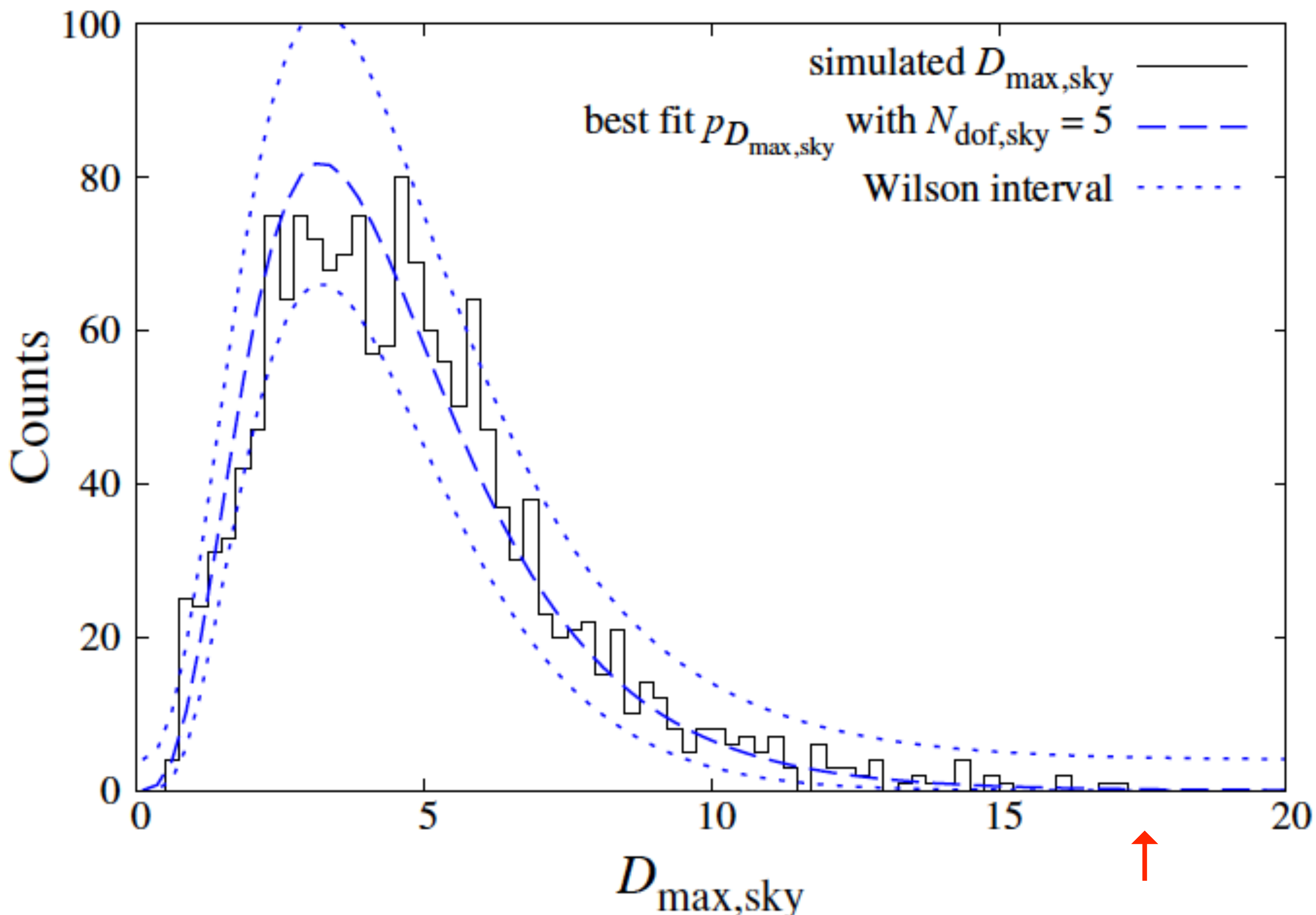
◆ t_0 = MJD54750



Simulation

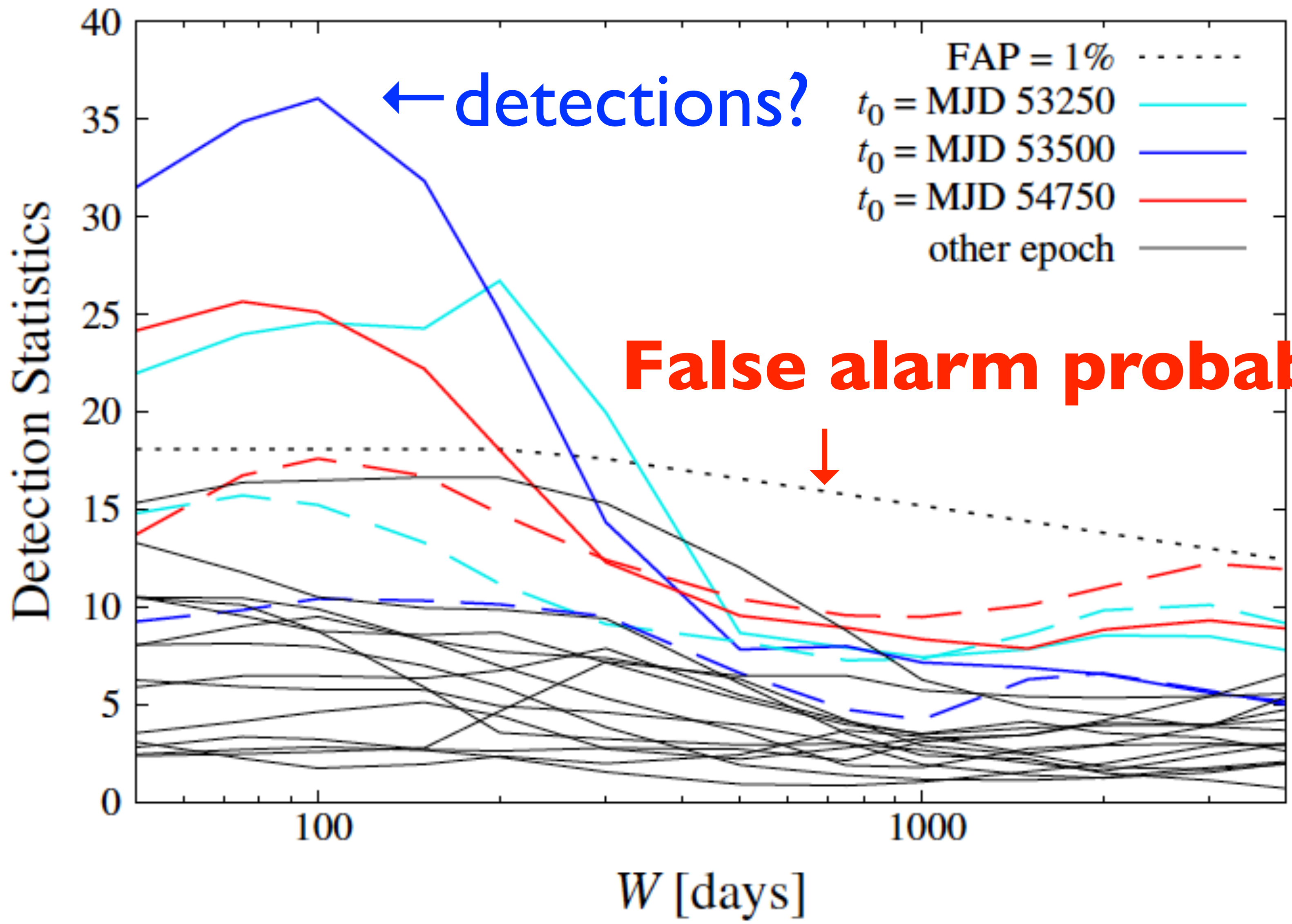
maximum values of D in simulated PPTA dataset (100 realizations)

without GW injection

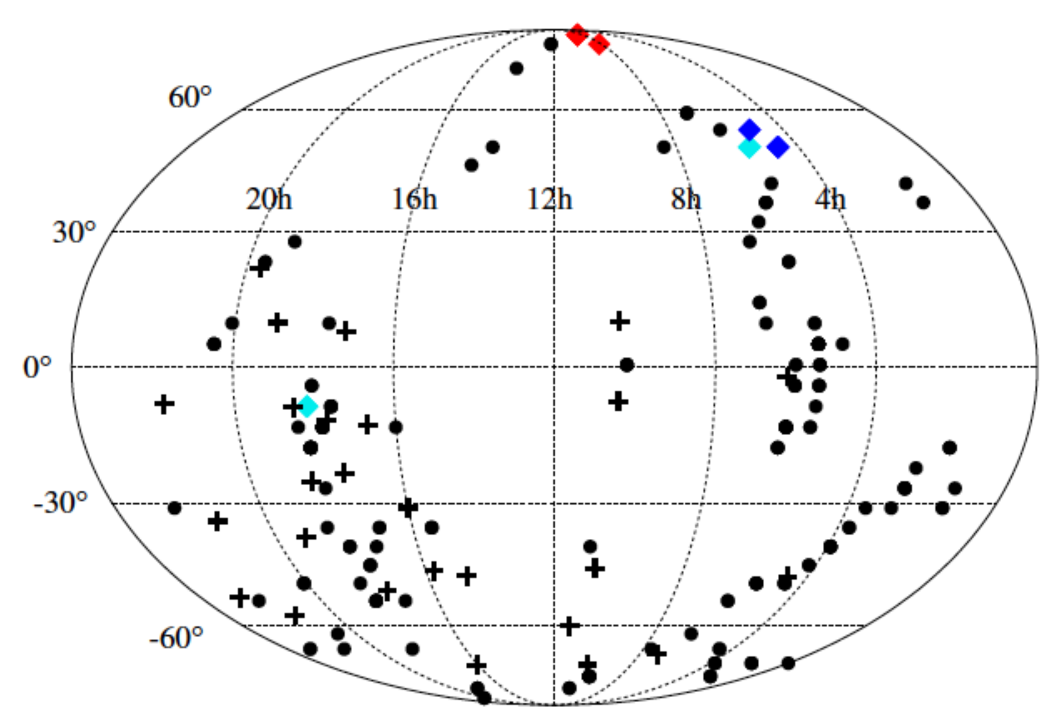


D ~ 17-18 is possible

Search result

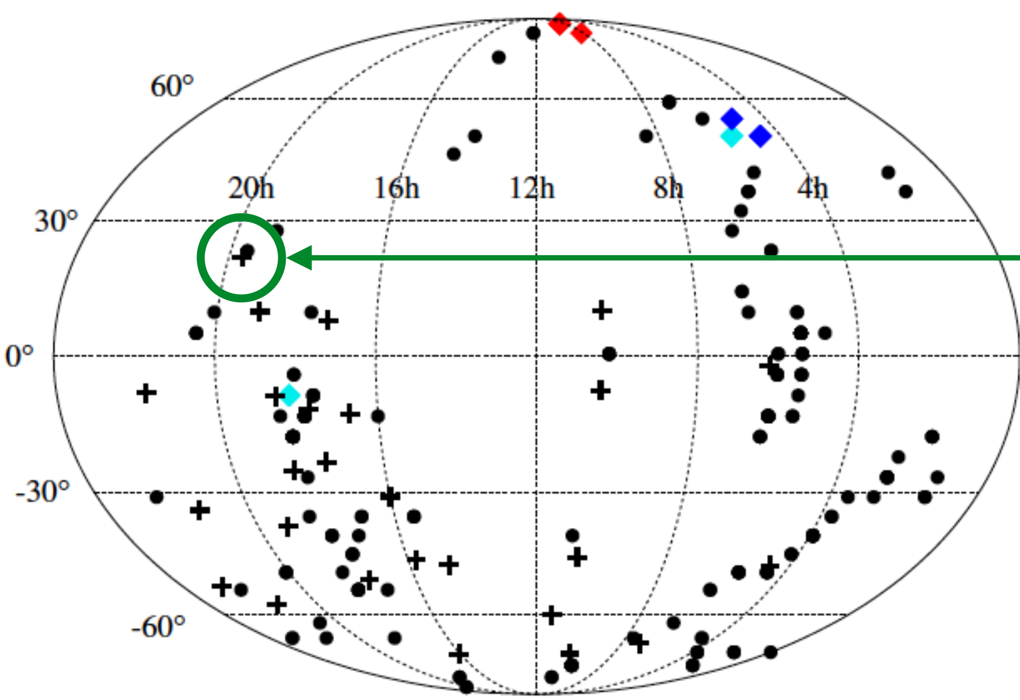


↑ Detection statistics for different epochs

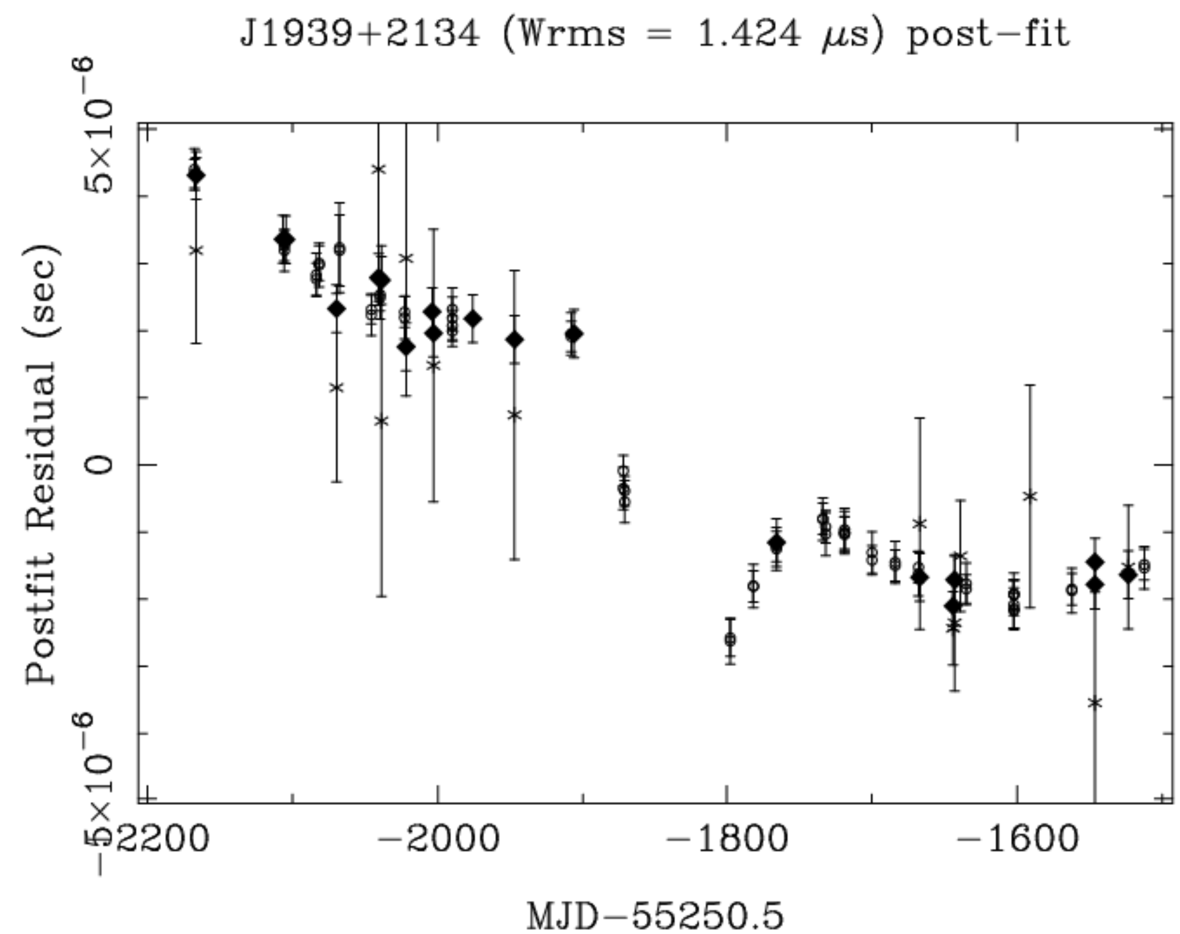


What is causing high D_{max}?

- ● Location of D_{max}
- \+ Location of pulsars
- ◆ t_0 = MJD53250
- ◆ t_0 = MJD53500



Post-fit residual of PSR J1939+2134

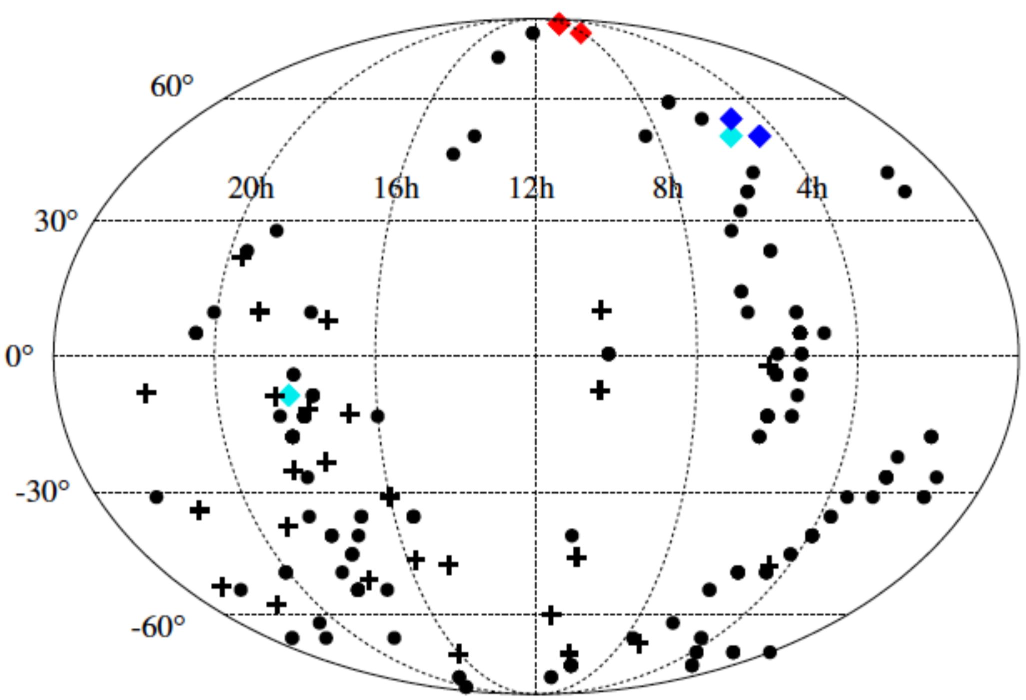


- A poor red noise modeling
- No other pulsars to confirm

(International PTA can help in future)

What is causing high D_{max}?

● Location of D_{max}
+ Location of pulsars
◆ t_0 = MJD54750



Removal of **PSR J1939+2134** does not eliminate the detection at MJD54750

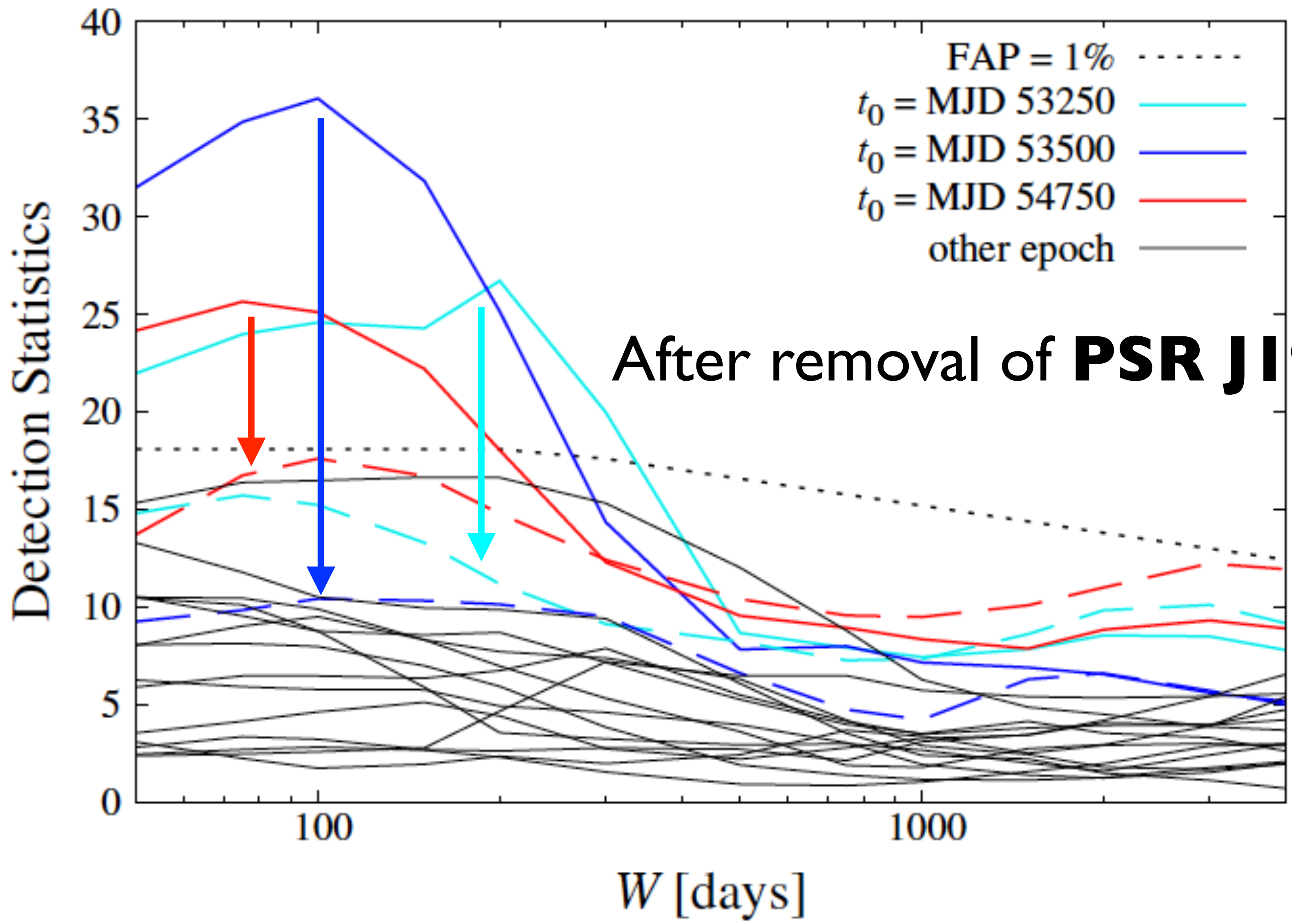
But the detection is not convincing because...

1. We had a receiver configuration change at MJD 54751(11th Oct. 2008)

2. Removal of **PSR J0437−4715** reduces D_{max} at MJD 54750

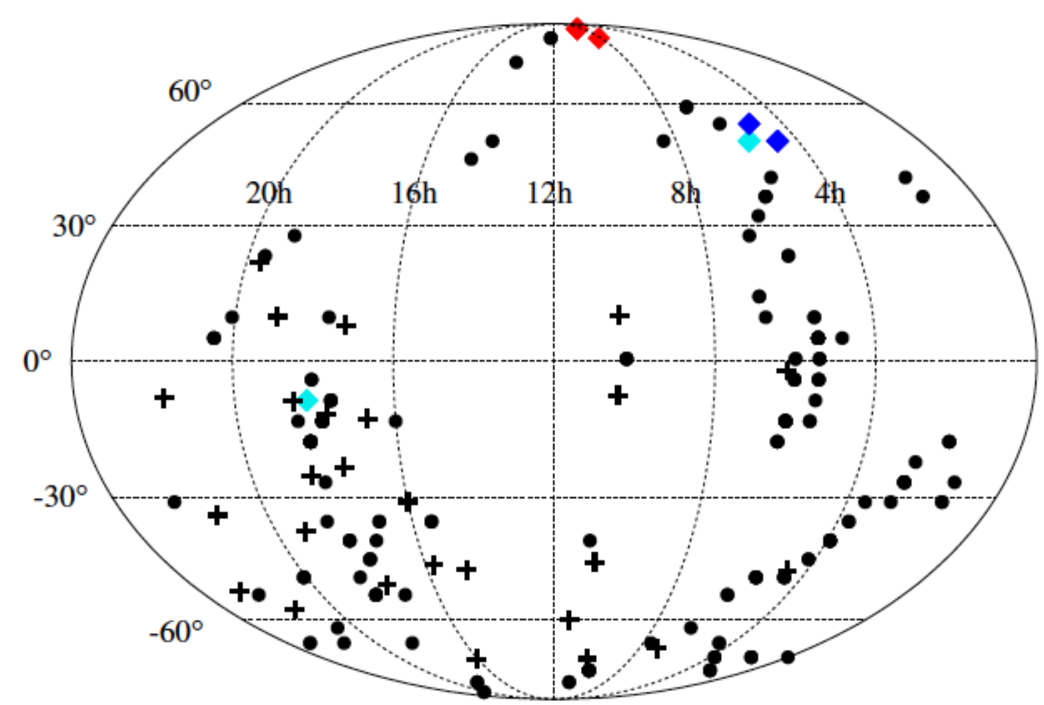
low white noise and high red noise
→ among the pulsars most difficult to model

Search result

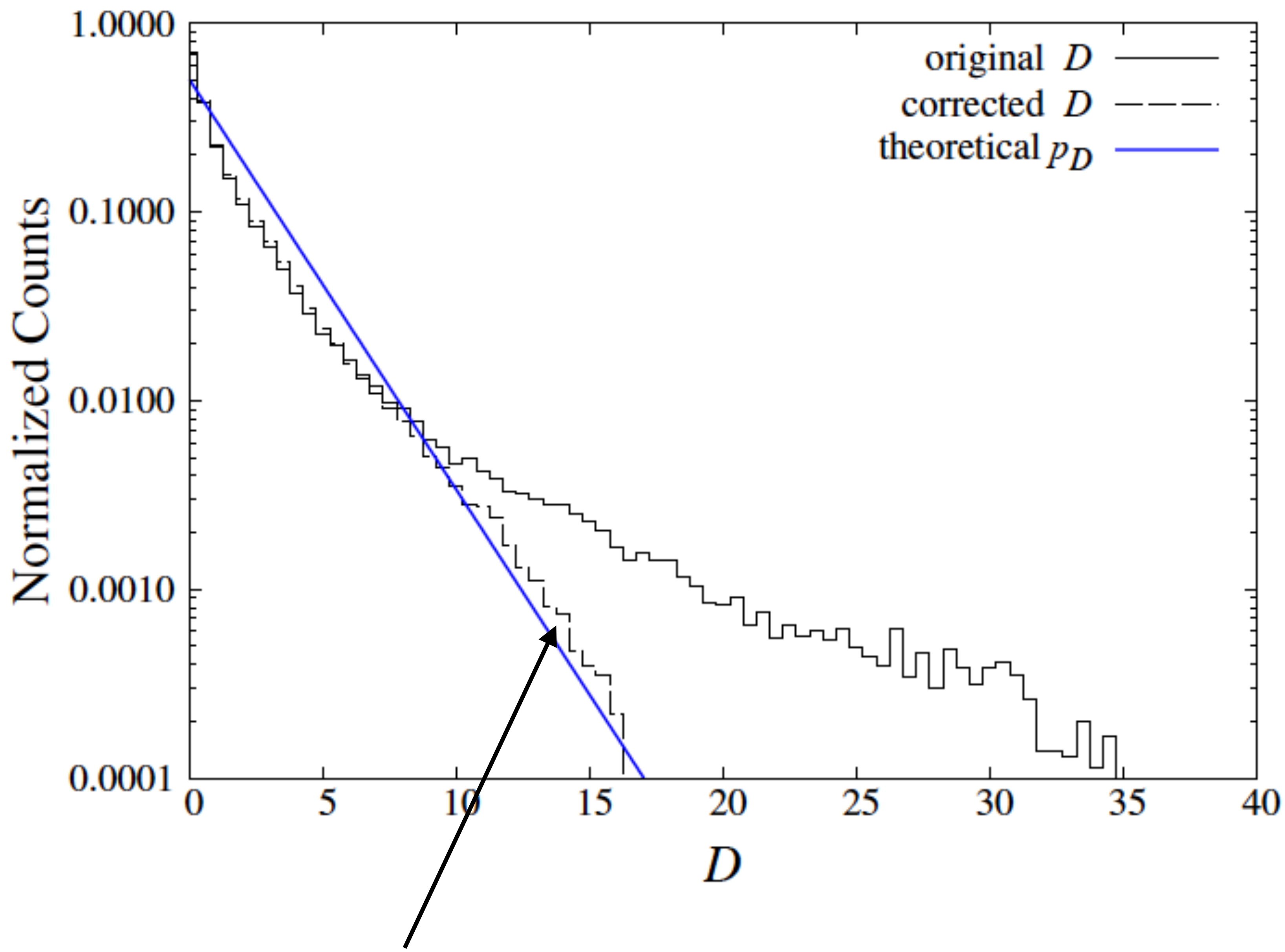


After removal of **PSR J1939+2134** and **J0437−4715**

↑ Detection statistics for different epochs



Histogram of D

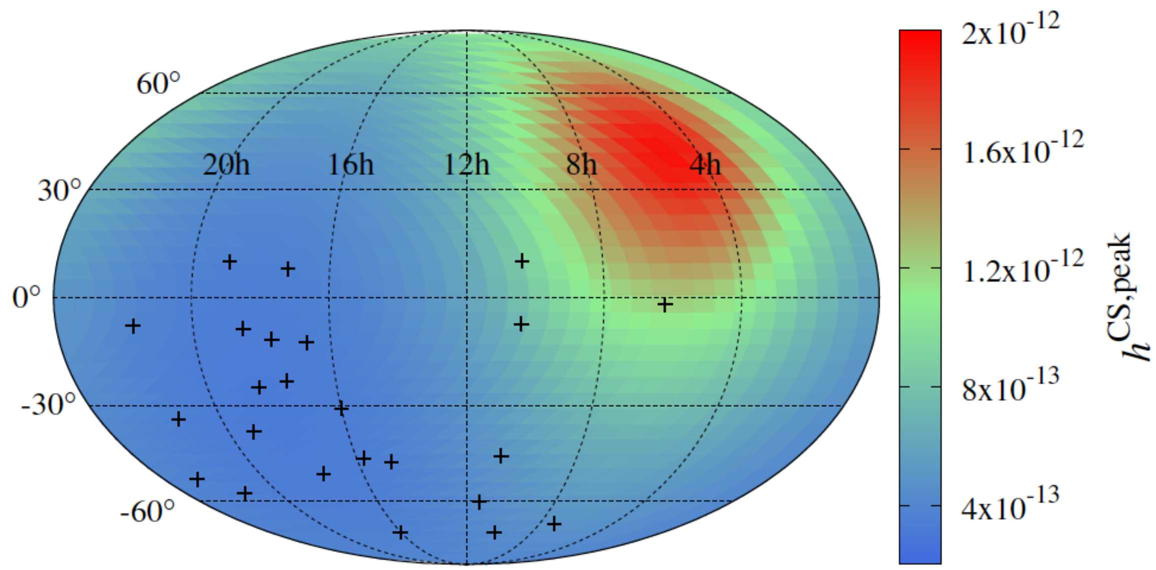


After removal of **PSR J1939+2134** and **J0437−4715**

Consistent with no detection of GWs

Upper bound on GW amplitude

Sensitivity depends on the direction of GWs



Sensitivity map

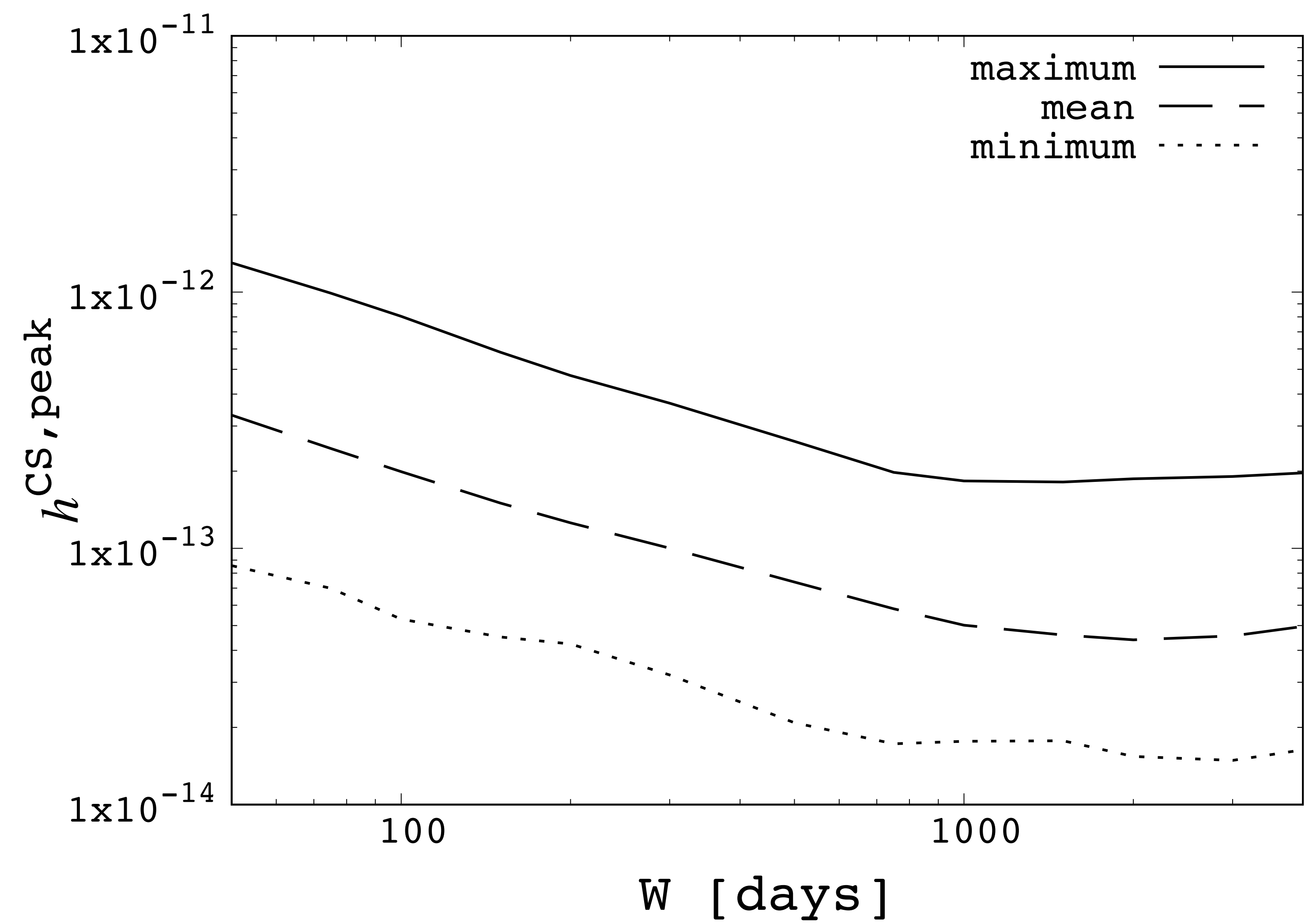
t_0 = MJD 54750

W =100 days

is assumed

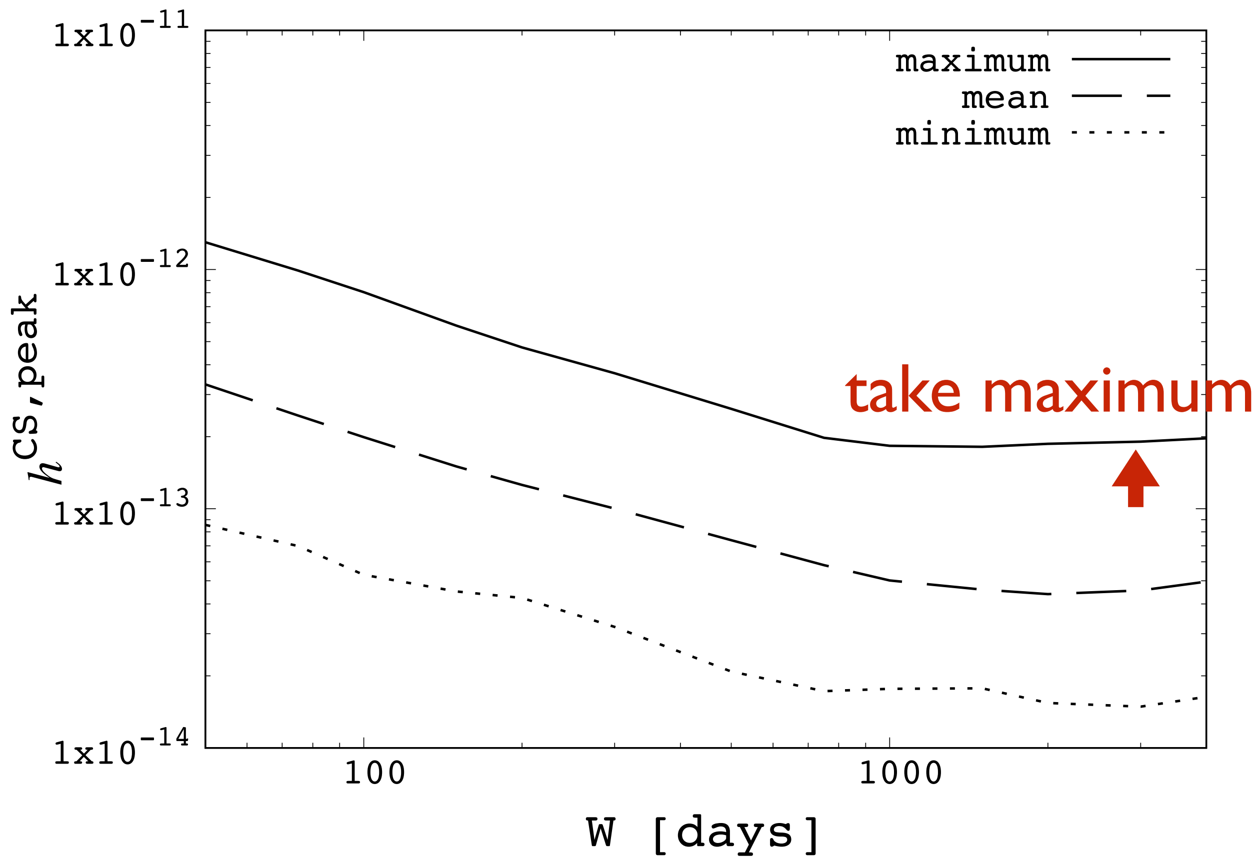
Dependence of sensitivity on W

(averaged over the epoch)

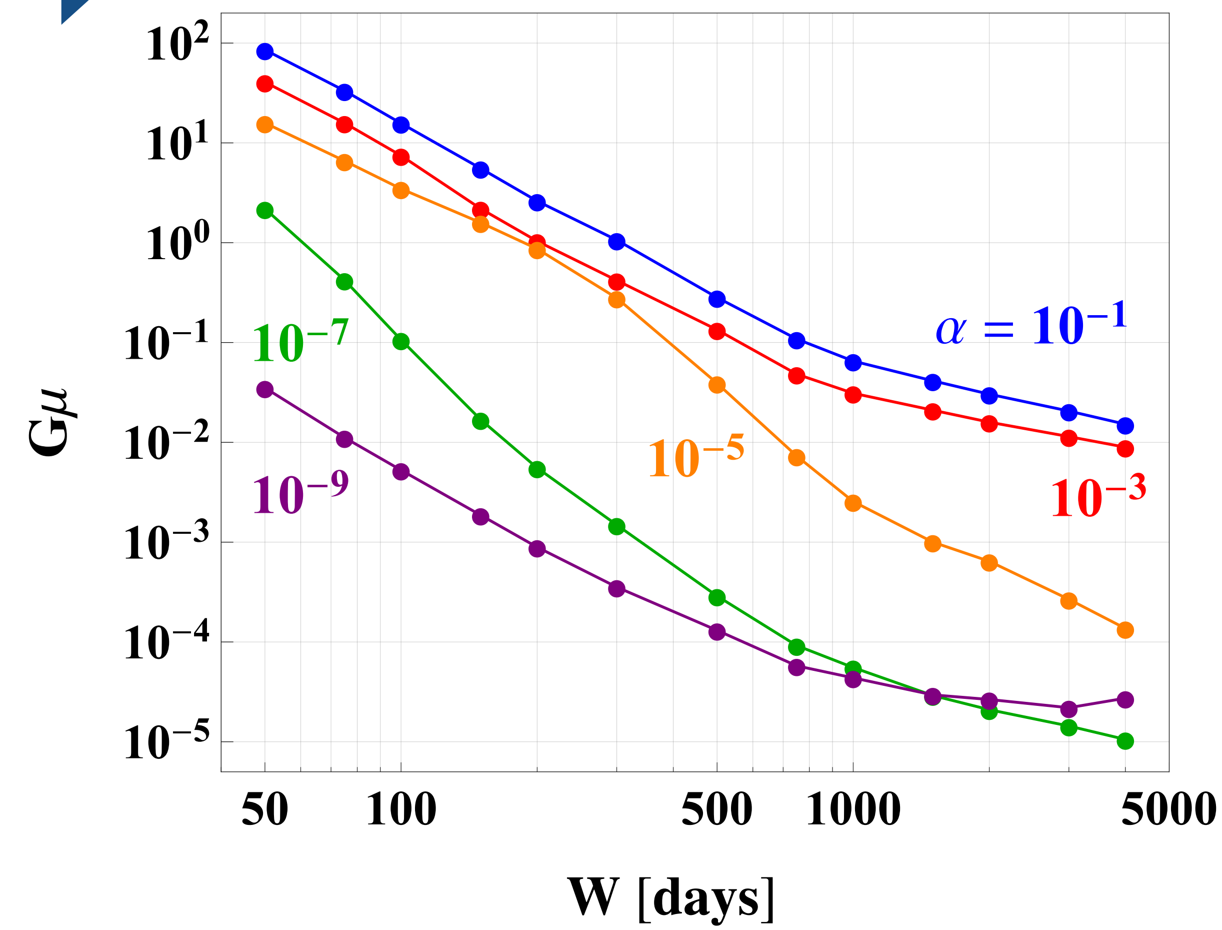


Constraints on cosmic strings

Upper bound on GW amplitude



Constraint on Gμ



GW amplitude (in Fourier space)

$$\tilde{h}(f) = \frac{G\mu L}{[(1+z)fL]^{1/3} r(z) f}$$

Gμ : tension = line density

r(z) : distance to the source

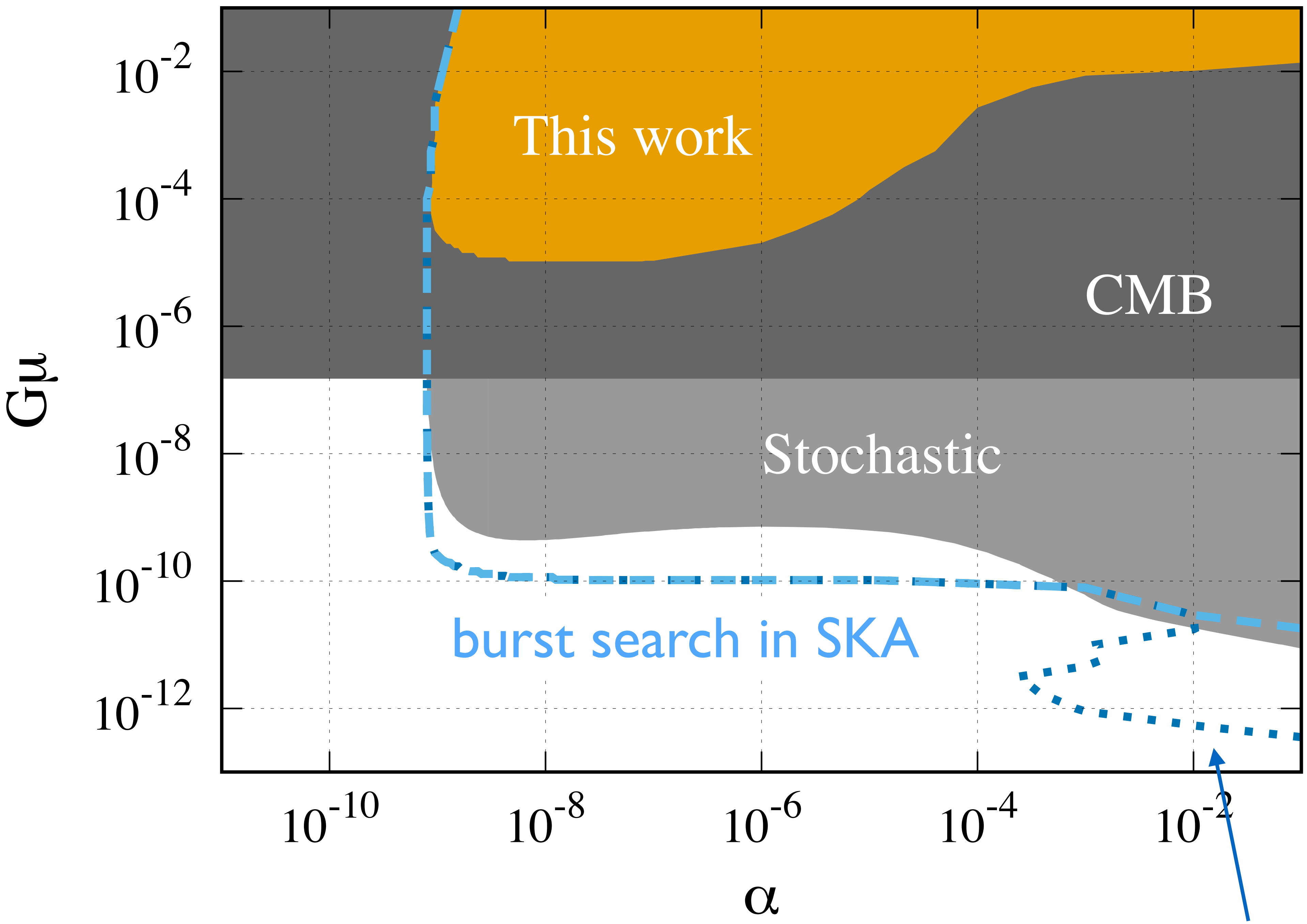
α: initial loop size

(changes the loop distribution)

can be obtained by modeling distribution of loops

Constraint on cosmic string parameters

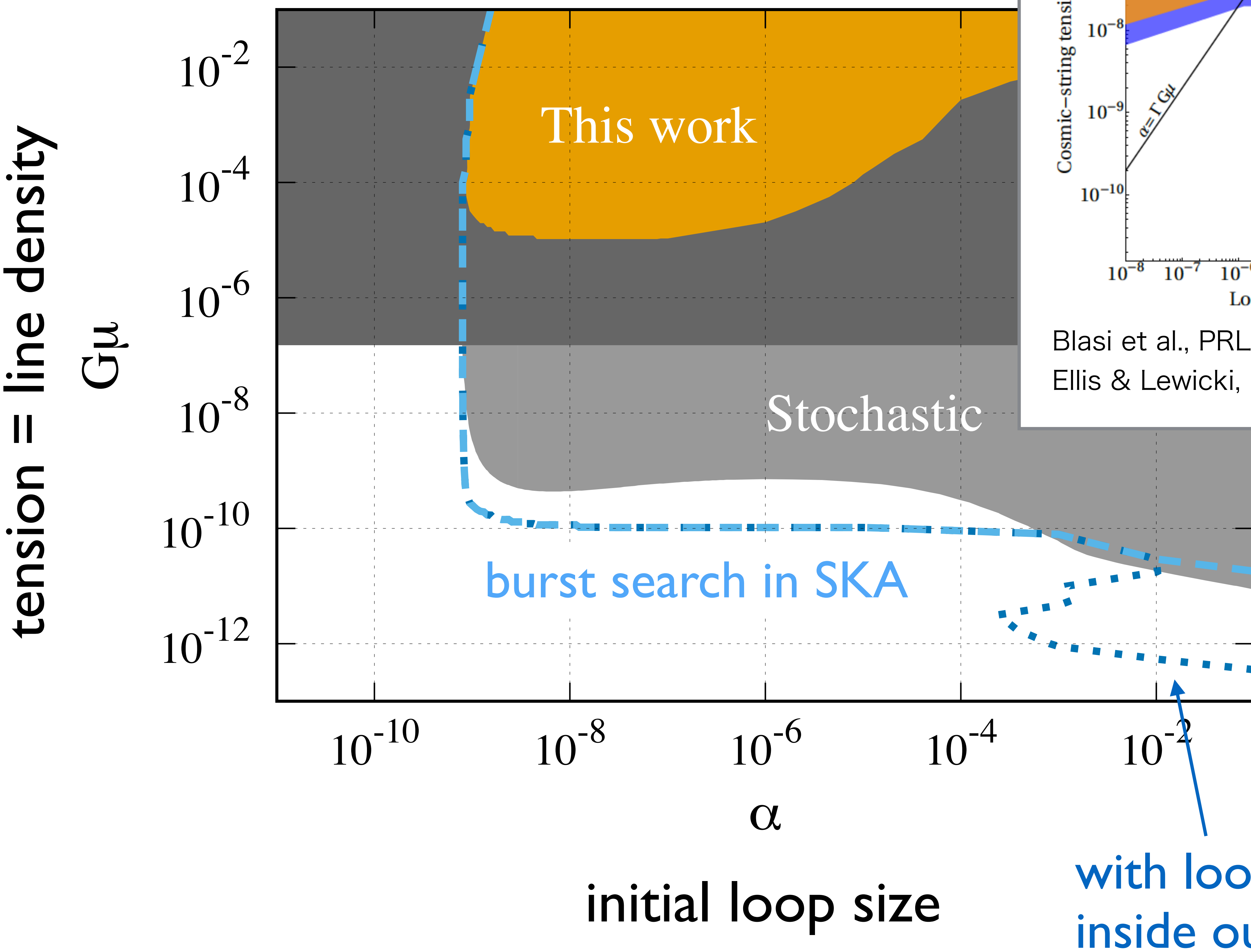
tension = line density



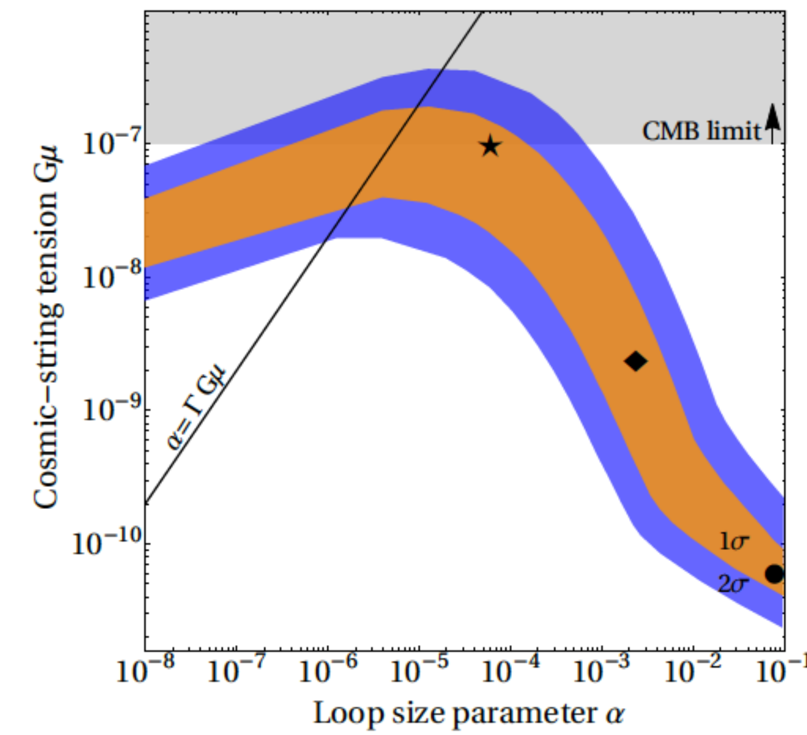
initial loop size

with loop clustering inside our galaxy

Constraint on cosmic strin



Note: NANOGrav 12.5 yr



Blasi et al., PRL 126, 041305 (2021)

Ellis & Lewicki, PRL 126, 041304 (2021)

Summary

- We searched for a signal of cosmic string GW burst in **Parkes Pulsar Timing Array** data.

- **No detection of GWs** provided constraints on cosmic string parameters.

- It turned out to be weaker than the other types of observations, but it's independent test of cosmic strings.

- In future, **SKA** will improve the sensitivity.