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

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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**

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

- **GW amplitude** (in Fourier space)
- **\( G\mu \): tension = line density**
- **\( r(z) \): distance to the source**

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Damour & Vilenkin, PRD 64, 064008 (2001)
GW bursts from cosmic strings

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

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

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

**Cusp**

beamed GW

$L$: loop size

**Waveform**

GW strain

$t_c$ \(\rightarrow\) time

Width $L$
**GW bursts from cosmic strings**

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

Parkes Pulsar Timing Array

~ 20 pulsars
1 hour for each every 2 weeks

sum up all the bins

timing residual $r_{GW}$
Timing residual induced by GWs

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

- \( \Delta h \): GW amplitude
- \( F^A(\hat{\Omega}, \hat{p}) \): antenna pattern (response function)
- \( \Delta h_A(t', \hat{\Omega}) \): GW amplitude

![GW amplitude vs days](image1.png)

\( \Delta h \) vs days

![Timing residual vs days](image2.png)

\( r_{GW} \) vs days
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

Timing residual by cosmic string GWs

Post-fit residual

\( r_{GW} \)

Post-fit
Simulated timing residual

Waveform

Post-fit residual

parameters

W: width
t₀: epoch
# Template search

**Data (Parkes PTA DR2)**

<table>
<thead>
<tr>
<th>Year</th>
<th>Signal Strength</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>2.47 µm</td>
</tr>
<tr>
<td>2007</td>
<td>2.47 µm</td>
</tr>
<tr>
<td>2008</td>
<td>2.47 µm</td>
</tr>
<tr>
<td>2009</td>
<td>2.47 µm</td>
</tr>
<tr>
<td>2010</td>
<td>2.47 µm</td>
</tr>
</tbody>
</table>

**Timing residual templates**

**Search the quadratic moment pattern**

**Detection statistics:**

\[ D = A^t C_0^{-1} A \]

amplitude \( A = [A_1; A_2] \)  

covariance matrix
Search result

$D_{\text{max}}$ (maximum value over the sky)

- Location of $D_{\text{max}}$
- Location of pulsars
  - $t_0 = \text{MJD}53250$
  - $t_0 = \text{MJD}53500$
  - $t_0 = \text{MJD}54750$

Duration of the burst event

- W: width
- $t_0$: epoch

Parameters:
- FAP = 1%
- $t_0$ = MJD 53250
- $t_0$ = MJD 53500
- $t_0$ = MJD 54750
- other epoch
Simulation

maximum values of D in simulated PPTA dataset (100 realizations) without GW injection

$D \sim 17-18$ is possible
Search result

False alarm probability = 1%

Detection statistics for different epochs

Detection statistics for different epochs
What is causing high $D_{\text{max}}$?

- Location of $D_{\text{max}}$
- Location of pulsars
- $t_0 = \text{MJD}53250$
- $t_0 = \text{MJD}53500$

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 $D_{\text{max}}$?

- Location of $D_{\text{max}}$ + Location of pulsars
  - $t_0 = \text{MJD54750}$

Removal of \textbf{PSR J1939+2134} does not eliminate the detection at MJD54750

But the detection is not convincing because...

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

2. Removal of \textbf{PSR J0437–4715} reduces $D_{\text{max}}$ at MJD 54750

low white noise and high red noise → among the pulsars most difficult to model
After removal of PSR J1939+2134 and J0437-4715

↑ Detection statistics for different epochs
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
$\tau_0 = \text{MJD 54750}$
$W = 100 \text{ days}$
is assumed

Dependence of sensitivity on $W$
(averaged over the epoch)
Constraints on cosmic strings

Upper bound on GW amplitude

GW amplitude (in Fourier space)

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

G\(\mu\) : tension = line density
r(z) : distance to the source

\(\alpha\) : initial loop size

(changes the loop distribution)

Constraint on G\(\mu\)

Upper bound on GW amplitude

can be obtained by modeling distribution of loops
Constraint on cosmic string parameters

This work

Stochastic

Initial loop size

tension = line density

CMB

burst search in SKA

with loop clustering inside our galaxy
Constraint on cosmic strings

This work

Stochastic

burst search in SKA

initial loop size

with loop clustering inside our galaxy

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.