Periodic Fast Radio Bursts from Axion Emission by Cosmic Superstrings

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Abstract

We propose that the periodic fast radio bursts of FRB 180916.J0158+65 are sourced by axion emission (mass $m_a \sim 10^{-14}$ eV) from cosmic superstrings. Some of the emitted axions are converted to photons by magnetic fields as they travel along the line of sight to Earth. An impulsive burst of axion emission generates a photon signal typically lasting for milliseconds and varying with frequency in the observed manner. We find a range of parameters in our cosmic string network model consistent with the properties of FRB 180916.J0158+65. We suggest followup gravitational wave observations to test our model.

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# 1 Introduction

Fast radio bursts (FRBs) are observed as short radio pulses typically lasting milliseconds \[1,2\]. Approximately 120 have been detected and the positions on the celestial sphere of a few have yielded associations with extragalactic objects \[5–7\]. Until this year all FRBs were either non-repeating or repeating with unpredictable temporal patterns \[8–11\]. That changed when FRB 180916.J0158+65 (FRB 180916) was found to possess a regular period \( T \approx 16.35 \) days \[12, 13\]. This FRB is clearly associated with a spiral galaxy at distance \( r \approx 149 \) Mpc, or redshift \( z = 0.03 \). It emits bursts lasting milliseconds during a 4-day window of activity followed by a 12-day quiescent period. The observed fluence of one burst at frequency \( \nu = 600 \) MHz for bandwidth \( \Delta \nu \approx \nu \) is \( F(\nu) \approx 6 \times 10^{-17} \) erg/cm\(^2\). Neutron stars, pulsars, magnetars and white dwarfs are just some of the astronomical objects that have been suggested as the generators of FRBs \[14–22\]. In this paper, we explore a different possibility involving cosmic superstrings.

Kibble \[23, 24\] first proposed that one dimensional topological defects might spontaneously form in grand unified theories (GUTs) as the Universe cooled. The defects quickly evolve into a scaling network of horizon-size long strings and loops of different sizes, with properties dictated largely by the string tension \( \mu \) (see \[25\] for review). The loops emit gravitational waves and eventually evaporate. Strings with GUT-derived \( \mu \) actively drive cosmological perturbations whose character conflicts with the scale invariant density perturbation spectrum favored by inflation and observed in the cosmic microwave background \[26\]. Cosmic strings as fundamental strings in string theory were first considered in the heterotic framework \[27\] but the tension proved too high. More recently a consistent story of string production after inflation was realized\footnote{See catalog at \url{http://www.frbcat.org/} and recent review \[4\]}.

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in the brane world scenario in Type IIB string theory [28–31]. Flux compactification and warped geometries can lower the string tension, satisfying present day observational bounds. Cosmic superstrings comprise a variety of physical objects in string theory [32]. Any discovery of them would provide solid evidence for the applicability of string theory to nature (see [35, 36] for review). Here, we consider the intriguing possibility that such evidence may already be in hand in the form of FRBs.

Cosmic superstring research has focused on strings interacting solely by gravity but a compelling possibility involves gravitons and axions. A string in string theory is charged under both gravitons $h_{\mu \nu}$ and a two-form potential $A_{\mu \nu}$ with

$$S_{\text{int}} \propto \int d^2 \sigma \sqrt{g} \left( h_{\mu \nu} g^{\alpha \beta} + \sqrt{\lambda} A_{\mu \nu} \epsilon^{\alpha \beta} \right) \partial_\alpha X^\mu \partial_\beta X^\nu ,$$

where $g$ is the induced metric on the worldsheet, $\epsilon^{\alpha \beta}$ is the corresponding Levi-Civita tensor and $X^\mu (\sigma)$ is the position of the string in spacetime. In 4-dimensional spacetime, $A_{\mu \nu}$ is dual to an axion $a$ i.e. $\partial^\mu a = \epsilon^{\mu \nu \rho \sigma} \partial_\nu A_{\rho \sigma}$

For massless axions, the emission of axions and gravitons by a string have almost identical behavior, except that the amplitude of the former is enhanced by $\sqrt{\lambda}$. In warped geometries of flux compactification, $\lambda$ can be as large as $10^7$ [38]. Massive axions can be emitted only when the excitation frequency $f$ exceeds the threshold energy $\gamma_a m_a$, where $\gamma_a$ is a kinematic factor and $m_a$ is axion mass.

The emitted axions are converted to photons with probability $p$ when they pass through regions of the universe with magnetic field $B$. These photons are the FRBs we observe. To be precise, suppose the gravitational wave flux from a cosmic superstring is $F_g (f)$. Then the FRB flux is given by

$$F (f) = p \lambda F_g (f) \Theta (hf - \gamma_a m_a) .$$

The probability $p$ is negligibly small unless there is a resonance in which the axion mass equals the effective photon mass derived from the plasma frequency. Therefore we require $m_a \simeq 10^{-14}$ eV [39, 41] to match the IGM electron density. In short, we fit the periodic FRB observation with a cusp from a small string loop with $G\mu \sim 10^{-8}, \lambda \sim 10^3$ and $p \sim 10^{-6}$.

In Section 2, we quantify the production of FRBs from cosmic superstrings, including the power of the axion emission and details of axion-photon conversion. We explain the observed

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fluence and time dependence of FRB 180916. In Section 3, we estimate the expected event rate of FRBs by calculating the string length and string network evolution. The rate helps delimit the possible range of model parameters consistent with the observations. We conclude and give remarks in Section 4.

2 Axion Emission and FRBs

In this section, we describe how cosmic superstrings emit axions, and how these axions are converted into FRBs.

2.1 Power of Axion Emission

Cosmic superstring loops emit both gravitons and axions. The total power of graviton emission \( P_{g,\text{tot}} = \Gamma G \mu^2 \), where \( \mu \) is the string tension and \( \Gamma \simeq 50 \) based on numerical calculations for representative loops. Axion emission differs from graviton emission in two ways:

- The axion coupling can be much stronger than the graviton coupling in warped geometries. The emission power for massless axions is enhanced by \( P_a(f) = \lambda P_g(f) \).
- Axions are not massless but gain a mass \( m_a \) from non-perturbative effects. Massive axions can be emitted only when the emitting frequency \( f \) exceeds the minimum axion energy. The frequency cutoff is \( f \geq f_k = \max \{ f_1, \gamma_a m_a / h \} \), corresponding to the mode number \( k = \max \{ 1, \gamma_a m_a l / 2h \} \), where \( l \) is the length of the string loop defined as \( l = E/\mu \) and the fundamental frequency is \( f_1 = 2/l \).

Cosmic superstrings are macroscopic and the production of axions requires high frequencies characteristic of cusp and kink motions. The gravitational emission by cusps and kinks has been well-studied \([12, 42, 43]\). The gravitational wave amplitude \( h_m \) with mode number \( m \) in the direction of the cusp is asymptotically \( h_m \propto m^{-4/3} \)[5]. The power per solid angle is \( dP_m / d\Omega \propto (f_m h_m)^2 \propto m^{-2/3} \) and \( \sum_m dP_m / d\Omega \) diverges in the exact direction of the cusp. In fact, the emitted gravitons of the \( m \)-th mode form a narrow beam with width \( \Theta_m = m^{-1/3} \) and solid angle \( \Omega_m \simeq \pi \Theta^2 \). The power within \( \Omega_m \) is \( P_m \simeq (dP_m / d\Omega) \Omega_m \propto m^{-4/3} \). Assuming the asymptotic limit for all \( m \) gives \( P_{g,\text{tot}} = \sum_m P_m = P_1 \zeta(4/3) \) and \( P_m = \Gamma G \mu^2 m^{-4/3} / \zeta(4/3) \). The same procedure for kinks leads to \( P_m \propto m^{-5/3} \), implying that the power at large \( m \) from kinks is subdominant when cusps are present. Therefore, below we focus on gravitons and axions emitted by cusps.

The FRB appears smooth at frequency \( \nu \) over a bandwidth \( \Delta \nu \sim \nu \). The gravitational wave power within a frequency window \( [f_m, f_{2m}] \) is \( P_{m,2m} = \sum_{i=m}^{2m} P_i \simeq 3 m^{-1/3} \left( 1 - 2^{-1/3} \right) P_1 \) and

\[ \text{Due to the nonlinear periodic motion the loop can emit gravitons at all modes.} \]
the average brightness is \( dP_{m,2m}/d\Omega_{2m} \equiv P_{m,2m}/\Omega_{2m} = \Gamma G \mu^2 \frac{3^2/3 (1-2^{-1/3})}{\zeta(4/3)\pi} m^{1/3} \). The average flux received at Earth is \( F_{m,2m} = (1/r^2) dP_{m,2m}/d\Omega_{2m} \) and the gravitational wave fluence is \( \mathcal{G}(\nu) = F_{m,2m} \Delta t \), where \( \Delta t = 1/\nu \) is the characteristic time scale for the cusp at frequency \( \nu \). Finally the axion fluence is \( \lambda \mathcal{G}(\nu) \) and the FRB fluence is \( \mathcal{F}(\nu) = p \lambda \mathcal{G}(\nu) \) if \( \nu > \gamma_a m_a/\hbar \).

Let us apply this result to FRB 180916. If the source is a cosmic superstring loop with non-relativistic center of mass motion, its period \( T = 16.35 \) days corresponds to the string length \( l = 2T = 8.5 \times 10^{16} \) cm. Assume one cusp per period points towards us i.e. \( n_c = 1 \). The FRB frequency \( \nu = 600 \) MHz corresponds to the mode number \( m = \nu T = 8.5 \times 10^{14} \), which is much larger than the mode number cutoff \( k(l) = 3.4 \times 10^6 \) for \( \gamma_a m_a = 10^{-14} \) eV. The cosmological redshift is negligible. The fluence is

\[
\mathcal{F}(\nu) = p \lambda G \mu^2 \frac{3 \cdot 2^{2/3} (1-2^{-1/3}) m^{1/3}}{\pi \zeta(4/3) r^2 \nu} = 1200 p \lambda (G \mu)^2 \text{erg/cm}^2. \tag{2.1}
\]

The observed fluence \( \mathcal{F}(\nu) = 6 \times 10^{-17} \text{erg/cm}^2 \) implies the constraint \( p \lambda (G \mu)^2 = 5 \times 10^{-20} \) on the important string theory parameters \( \mu \) and \( \lambda \), and the axion-photon conversion probability \( p \).

If the center of mass of the cosmic superstring loop moves with Lorentz factor \( \gamma_s \gg 1 \) towards the Earth, all frequencies are Doppler shifted such that in the center-of-mass frame, the string length is \( l' = (2\gamma_s) 2T \) and the emitting frequency is \( \nu' = \nu/2\gamma_s \). This leads to the same \( m \). Moreover, the fluence is enhanced by relativistic beaming with factor of \( 8\gamma_s^3 \). The fluence constraint becomes \( \gamma_s^4 p \lambda (G \mu)^2 = 3 \times 10^{-21} \).

### 2.2 Axion-Photon Conversion

When axions pass through a magnetic field \( B \) they may be converted into photons. Such a process requires an axion-photon coupling, which can be described by the following effective theory

\[
\mathcal{L} = -\frac{1}{4} F^{\mu\nu} F_{\mu\nu} - \frac{1}{4 f_a} a F^{\mu\nu} F_{\mu\nu} - \frac{1}{2} \partial_\mu a \partial^\mu a - \frac{1}{2} m_a^2 a^2, \tag{2.2}
\]

where \( F_{\mu\nu} \) is the dual of the electromagnetic field strength \( F_{\mu\nu} \) and \( f_a \) is the effective axion decay constant. When transverse \( B \) is present, axion-photon oscillations happen with angular frequency \( \omega_{\text{osc}} \sim B/f_a \); in dimensional units with \( \chi = (B/nG)(10^{10} \text{GeV}/f_a) \) we have \( \omega_{\text{osc}} = 1.1 \times 10^{-14} \chi \text{ rad/s} \), period \( T_{\text{osc}} = 6.0 \times 10^{14}/\chi \text{ s} \), wave number \( k_{\text{osc}} = 1.1 \chi \text{ Mpc}^{-1} \) and wave length \( \lambda_{\text{osc}} = 5.8/\chi \text{ Mpc} \[44]\).

This process has been examined in the homogeneous early universe [40][41][45]. The variation of the electron density with epoch is equivalent to a time-dependent effective photon mass \( m_\gamma(t) \).

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\( ^6 \)The simplest loop forms two cusps per period but these generally point in different directions.
If the axion is emitted out of resonance and passes through resonance as the universe expands then some axions are converted to photons. The total distance traveled needs to be much larger than the oscillation wavelength. If we apply the same logic to FRB 180916 resonance must occur at $z \lesssim 0.03$. Numerically, $m_a \simeq m_\gamma (t_0) \simeq 10^{-14}$ eV, where $t_0$ is the age of universe. The photon mass is $m_\gamma (t) \simeq m_a (1 + 3H (t_0 - t)/2)$ for $t$ near $t_0$, where $H$ is the Hubble constant. The Landau-Zener solution $[40, 41, 46]$ for passing through resonance at constant rate gives the probability $p$ for conversion of axion to photon:

$$p \simeq \frac{\pi (B/f_a)^2 \nu}{9m_a^2 H}.$$  

Using typical values $\chi = 1$ (e.g. $B = 1$ nG and $f_a = 10^{10}$ GeV) we estimate $p \simeq 4.5 \times 10^{-5}$. The actual situation is, of course, more complicated. The transverse field component and the electron density may be inhomogeneous along the line of sight, impacting the resonance condition and the characteristic oscillation length scale $\lambda_{osc}$. We expect plasma outflows from AGN and star forming galaxies to carry magnetic fields into the IGM. In general, $\lambda_{osc}$ decreases and $p$ increases as $B$ increases so axion-photon conversion could be sensitive to the small scale inhomogeneous injection of fields. For now we regard $p$ as a parameter that could span a wide range of values much less than 1.

The burst of axions has intrinsic width $1/\nu$ at frequency of observation $\nu$, nearly a delta function in time. Despite the uncertainty in the size of $p$, the conversion process imprints a minimum width to the photon burst. For FRB 180916, the frequency $\nu = 600$ MHz corresponds to axions moving at $\gamma = h\nu/m_a \gg 1$, or $1 - \beta \simeq 1/(2\gamma^2) = 8 \times 10^{-18}(600 \text{ MHz}/\nu)^2(m_a/10^{-14} \text{ eV})^2$. If some axions are converted to photons later than others by time $\delta t$ then their arrival times will lag by $(1 - \beta) \delta t$. The axion-photon oscillation implies a minimum conversion time scale $\delta t = T_{osc}$ and a characteristic observed burst duration $t_{burst} = (1 - \beta) \delta t = 4(600 \text{ MHz}/\nu)^2(m_a/10^{-14} \text{ eV})^2/\chi$ ms. The minimum temporal spread for the FRB is milliseconds. The actual spread will be supplemented by dispersion (DM) and scattering (SM) effects of the medium $[47]$.

The DM time delay is a strict function of frequency that can be exactly removed for a pulsed, broadband radio source by fitting the known form of the delay $\propto 1/\nu^2$. In practice, the observer minimizes the variance of the observed and theoretically delayed signal. In the axion-photon case the size of the characteristic delay varies $\propto 1/\nu^2$. Part will be absorbed when the delay of the FRB is fitted. For FRB 180916 $DM = 349.02$ pc-cm$^{-3}$ implies 0.4 s delays at 600 MHz. The width of the sub-bursts after fitting is about 5 ms. Fitting cannot shrink the width of the burst back to a delta function which is governed by the quantum mechanical transition from axion to photon.

There are aspects of the signals that are not well-understood. In particular, the above simple model does not explain the 4-day active period. The loop might have multiple kinks and cusps. Although a kink signal is sub-dominant, it is more likely to be observed because the emission
is fan-like instead of point-like as is the case of a cusp emission. Gravitational lensing might magnify the signal and generate multiple bursts arriving at different times.

3 Event Rate and Estimation of Parameters

From above, we see that a large range of parameters can satisfy the fluence constraint for FRB 180916. We now impose the condition that the event rate for FRBs like 180916 should not be unobservably low.

3.1 String Length Evolution

A single cosmic superstring loop emits axions at mode numbers \( m \geq k(l) \) only. When emission per mode scales like that of a cusp the loop has total axion power \( P_{a,tot} = \lambda P_{1} \sum_{n=k}^{\infty} n^{-4/3} \simeq \lambda k^{-1/3} P_{g,tot} \). As shown above, the observed emission from FRB 180916 requires \( k \gg 1 \). We focus on the case that the axion emission is large compared to gravitational emission: \( \lambda k^{-1/3} \gg 1 \). In this limit axion emission, not graviton emission, dominates the evolution in length of the string. Writing \( k = \tilde{k} l \), where \( \tilde{k} = \gamma a m_a / 2h \), the length evolves according to

\[
\frac{dl}{dt} = -\Gamma G \mu \frac{\lambda}{(\tilde{k} l)^{1/3}} \Rightarrow t - t_b = \frac{3\tilde{k}^{1/3}}{4\Gamma G \mu \lambda} \left( l_b^{4/3} - l^{4/3} \right), \tag{3.1}
\]

where \( t_b \) is the time when the loop was born and \( l_b \) is the length at that time.

The cosmic superstring network follows the scaling attractor solution in deep radiation or matter era \([23, 24]\). For simplicity, we assume scaling applies at all times in the cosmological model so that the loop size is always proportional to horizon size \( l_b = \alpha t_b \). The condition that a loop born at \( t_b \) hasn’t yet evaporated by the current epoch is \( t_b \geq t_{b,\text{min}} \). There are large and small \( \alpha \) limiting cases: if \( \alpha \gg (\Gamma G \mu \lambda)^{3/4} / \gamma_a^{1/4} \) then

\[
t_{b,\text{min}} = \frac{1}{\alpha} \left( \frac{2h}{\gamma a m_a} \right)^{1/4} (\Gamma G \mu \lambda t_0)^{3/4}. \tag{3.2}
\]

implying \( t_{b,\text{min}} \ll t_0 \) and if \( \alpha \ll \Gamma G \mu \lambda \) then \( t_{b,\text{min}} \approx t_0 \).

In the \( \Lambda \)CDM model, one of the crucial factors affecting the string network evolution is whether the universe is in radiation or matter era. The time of equipartition \( t_{eq} \) is \( 1.5 \times 10^{12} \) s. If \( t_{b,\text{min}} > t_{eq} \), the string loops we observe are all produced in matter-dominated era. If \( t_{b,\text{min}} < t_{eq} \), some small string loops we observe are produced in radiation-dominated era. For

\[\text{The evaporation of loops by the combined action of axions and gravitons does not alter the Velocity One Scale model solution.}\]
large $\alpha$, the latter condition is equivalent to an upper bound of string tension $\mu$:

$$\alpha^{-4/3} \gamma_a^{-1/3} G \mu \lambda < 8.4 \times 10^{-4}.$$  \hspace{1cm} (3.3)

where we have taken $m_a = 10^{-14}$ eV. All these results will be used in deriving the string network evolution.

### 3.2 String Size Distribution

To infer the event rate, we estimate the number densities $n$ of loops of different sizes with the Velocity One Scale (VOS) model \[48–51\] and loop production characterized in complementary analytic \[52,53\] and numerical treatments \[54–57\]. About $f = 80\%$ of the energy goes to small loops with $\alpha \simeq 20 (G \mu)^{1.2}$ in radiation era, and $\alpha \simeq 20 (G \mu)^{1.5}$ in matter era \[52,53\]. In both cases $\alpha \ll \Gamma G \mu \lambda$. The remaining $f = 20\%$ goes to large loops with $\alpha \simeq 0.1 \gg \Gamma G \mu \lambda$ as generally seen in simulations. The birth rate density of string loops at time $t_b$ during scaling is

$$\frac{dn}{dt} (t_b) = \frac{f A}{\alpha t_b^4}, \hspace{1cm} (3.4)$$

where $A = 7.65$ in radiation era and $A = 0.55$ in matter era \[36,59\]. When the universe expands, the loop number density $\propto a^{-3}$ for scale factor $a(t)$. Performing a change of variable the density of loops with size $l$ at time $t$,

$$l \frac{dn}{dl} (l,t) = \frac{f A}{\alpha t_b^4} \frac{a^3(t)}{a^3(t)} \left| \frac{dl}{dt_b} \right|,$$  \hspace{1cm} (3.5)

where $t_b$ and $|dl/dt_b|$ are determined from Eq. (3.1). To be precise,

$$\left| \frac{dl}{dt_b} \right| = \left( \frac{\alpha}{\lambda/(kl_b)^{1/3}} + \Gamma G \mu \right) \frac{\lambda}{(kl)}^{1/3}. \hspace{1cm} (3.6)$$

For cosmic superstrings, the Universe’s mean loop density is further enhanced by a factor $G \sim 10^3$, which is due to a combination of multiple throats in flux compactification, multiple string species and low intercommutation probability of superstrings \[36,59\]. The superstring size distribution is $G l \left( \frac{dn}{dl} \right) (l,t)$.

### 3.3 Estimation of Parameters

If FRB 180916 comes from a cosmic superstring, the loop density at the corresponding length and time should not be too low else detection will be highly improbable. This condition constrains the allowed range of parameters tightly.

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\[8\] There remain important differences in the number of small loops inferred by simulation. Our approach follows \[58,59\].
How can a lower bound of the loop density be set? The current FRB detectors can measure FRBs with fluence as small as $0.1\mathcal{F}(\nu)$. Sources within distance $r_{\text{max}} = 10^{1/2}r$ could have been seen by existing surveys. Write $V_{\text{max}} = (4/3)\pi r_{\text{max}}^3$. The expected number of superstrings $N(l, \nu)$ with length $l$ that can emit detectable FRBs with frequency $\nu$ in an all sky survey is

$$N(l, \nu) \simeq \mathcal{G}l \frac{dn}{dl} V_{\text{max}} \frac{\Omega}{4\pi},$$

(3.7)

where the solid angle of the cusp beam is $\Omega = \pi/m^{2/3}$. As a conservative choice, we impose $N > 10^{-5}$. For work below we assume $\gamma_a = 1$.

In conventional cosmic string scenarios, large loops source the potentially observable signals. Axions increase the rate of evaporation of all loops compared to gravitons alone. Consequently, suppression of $dn/dl$ occurs for both small and large loops and the suppression of signals is greater for the large loops. Hence, we must consider both types as potential FRB sources. In general, small loops are born with highly relativistic motions $\gamma_s \gg 1$. In such cases, the string length is $l = (2\gamma_s^2)2T$ and $\Omega$ is suppressed by relativistic beaming with factor of $1/2\gamma_s^2$. Overall, when comparing to the non-relativistic case, $N$ is enhanced by factor of $(2\gamma_s^2)^{1/3}$, giving modestly larger allowed parameter ranges. We will assume $\gamma_s = 1$, thus $l = 8.5 \times 10^{16}$ cm, $m = 8.5 \times 10^{14}$ and $k(l) = 3.4 \times 10^6$.

First consider the possibility of a small loop. If the string is a recently born small loop, we have $\alpha = 20(G\mu)^{1.5}$ and $t_b \simeq t_0$. To be consistent, we must require $l_b(t_0) > l$, which implies a minimum tension $G\mu > 4.7 \times 10^{-5}$\textsuperscript{10}. We have $\lambda > k(\alpha t_0)^{1/3} = 2 \times 10^6(G\mu)^{0.5} \gtrsim 150$ if axion emission dominates. Assuming so, we can approximate $|dl/dt_b| = \Gamma G\mu\lambda/k(l)^{1/3}$. The condition on $N$ then implies $(G\mu)^{2.5} \lambda < 6.3 \times 10^{-18}$, hence $G\mu < 1.4 \times 10^{-8}$. The minimum tension yields $\lambda < 4.2 \times 10^2$. The constraint from the observed fluence implies $5.4 \times 10^{-7} < p < 1.5 \times 10^{-5}$, which is close to our estimation in Section \textsuperscript{2}. Overall, the allowed range of parameters is plotted in Figure \textsuperscript{1}. The range is narrow but possible.

If the string was a large loop in the past, we have $\alpha = 0.1$. Since the string loop size is much smaller than the horizon size nowadays, it must be born in the early universe with length $l_b = \alpha t_b$. We estimate that it was born at $t_{b,\text{min}}$, which is given by Eq. (3.2). We further assume axion emission dominates and $t_{b,\text{min}}$ is in radiation era, which means $G\mu\lambda < 4 \times 10^{-5}$. We approximate the scale factor as $a(t_b)/a(t_0) = (t_b/t_{\text{eq}})^{1/2}(t_{\text{eq}}/t_0)^{2/3}$ and $|dl/dt_b| = \alpha(l_b/l)^{1/3}$. The constraint on $N$ then gives $G\mu\lambda < 3.0 \times 10^{-7}$. The lower limit of $\lambda$ is given by the axion emission domination $\lambda > k(l_b)^{1/3}$, which implies $\lambda > 3 \times 10^6(G\mu)^{1/3}$ and $G\mu < 1.8 \times 10^{-10}$.

\textsuperscript{9}The string length in the lab frame $l$ is related to that in the rest frame $l'$ by $l = \gamma l'$, i.e. the so-called loop invariant length transforms like energy.

\textsuperscript{10}This exceeds the constraint from pulsar timing array $G\mu < 10^{-9}$ for strings coupled only to gravity\textsuperscript{60}. With $\lambda \gg 1$ the loop density and stochastic gravitational wave background are lowered, and the bounds from null results of gravitational wave measurements are much relaxed. Moreover, such observations bound the characteristic tension only (see Footnote \textsuperscript{2}). Here $G\mu$ can be higher if the loop is a bound state.
Figure 1: Range of allowed parameters $p, \lambda, G\mu$ if FRB 180916 is from a recently born small superstring loop with $\alpha \simeq 20 (G\mu)^{1.5}$. The parameters are allowed if they give the observed fluence $F(\nu) = 6 \times 10^{-17}$ erg/cm$^2$ and expected number of such loop $N > 10^{-5}$ within radius $10^{1/2} r = 470$ Mpc, and axion emission dominates the string evolution. For simplicity we assume a non-relativistic loop, and relativistic loops give larger range of parameters.

Combining with the observed fluence, we get $p > 10^{-3}$. If we assume that $t_{b,\text{min}}$ is in matter era, we require $G\mu\lambda > 4 \times 10^{-5}$ which will contradict with the constraint on $N$.

Since the allowed $p$ is exceptionally high in the large loop case, the observed FRB probably comes from a recently born small loop. The estimated typical parameters are $G\mu \sim 10^{-8}$, $\lambda \sim 10^3$ and $p \sim 10^{-6}$ for $\gamma_s = 1$ and $N > 10^{-5}$. There are considerable observational and/or theoretical uncertainties in $F(\nu), n_c, \Gamma, m_a, G$ and number density of small loops.

4 Conclusion

We have demonstrated that observable periodic FRBs such as FRB 180916 can be produced from axion emission by low-tension cosmic superstrings, following by axion-photon conversion. We have developed a simple model of cosmic superstrings coupled to both gravitons and axions with large axion coupling. The evolution of strings and the nature of the emission differs from previously studied models. We have found a range of parameters that gives the observed fluence $F(\nu)$, and estimated a small but potentially detectable number of sources like FRB 180916. Of the options considered we favor that the FRB is produced by a recently born small loop with $\alpha \simeq 20 (G\mu)^{1.5}$ as opposed to an older loop born with large size. The proposed tension

\[11\] It falls within the range of $(p,q)$ string tension [31,61] in the KKLMMT scenario [62].
\( G\mu \sim 10^{-8} \) is quite high but self-consistent since the upper bounds from experiments probing gravitational waves are relaxed for large \( \lambda \). The process of axion-photon conversion provides a not fully quantitative explanation of the time dependence of FRBs, specifically the intrinsic burst duration. All the mechanisms outlined here will function for large string loops. The FRB repetition time is related to the fundamental period of the loop which may exceed the time span of observations to date.

The results here can be improved with more data and theoretical studies. Cosmic super-strings may generate observable gravitational wave bursts. Writing \( G\mu = 10^{-8} \mu_{-8} \), in our model the gravitational wave burst fluence at frequency \( \nu_1 \) Hz associated with FRB 180916 is

\[
G(\nu_1 \text{ Hz}) = 8.5 \times 10^{-8} \mu_{-8}^{-2/3} \nu_1^{-2/3} \text{erg/cm}^2.
\]  

We suggest searching for gravitational wave emission at the source position of the FRB. The signal-to-noise ratio can be enhanced by folding the signal at the known periodicity.

If FRBs are confirmed experimentally to be generated by cosmic superstrings they will provide important insights into string theory and the cosmological history of the Universe.

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