Cosmological effects of decaying cosmic string loops with TeV-scale width


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What is a cosmic string?

cosmic string

⋯ "Strings" which contain large energy and randomly stretch across the universe

They appear at spontaneous symmetry breaking (SSB) or the end of inflation

an important probe for both cosmology and particle physics

upper limit of their tension (mass per unit length):

$$G\mu \lesssim 10^{-7}$$
a typical potential which leads to cosmic strings

\[ V(\phi) = \frac{\lambda}{4} |\phi|^4 - \frac{1}{2} m^2 |\phi|^2 + \frac{m^4}{4\lambda} \]  

(\(\phi\): complex scalar field)
SUSY breaking soft mass term can be relevant to SSB

Consider scalar fields $\phi_+, \phi_-$, which have charges for an additional U(1) gauge symmetry and R-symmetry, and form a flat direction.

lifted by (i) soft SUSY breaking terms
(ii) nonrenormalizable terms

ubiquitous in supersymmetric theories
SUSY breaking & cosmic string

- charge of $\phi_+, \phi_-$

<table>
<thead>
<tr>
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<th>$U(1)$</th>
<th>$R$</th>
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<tbody>
<tr>
<td>$\phi_+$</td>
<td>+1</td>
<td>+1/n</td>
</tr>
<tr>
<td>$\phi_-$</td>
<td>-1</td>
<td>+1/n</td>
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- superpotential

$$W = \frac{(\phi_+\phi_-)^n}{nM^{2n-3}}$$
(M: cut-off scale)

- total potential

$$V = V_F + V_D + V_{soft}$$

$$V_F = \frac{1}{M^{4n-6}} |\phi_+|^{2n-2} |\phi_-|^{2n-2} (|\phi_+|^2 + |\phi_-|^2)$$

$$V_D = \frac{g^2}{2} (|\phi_+|^2 - |\phi_-|^2)^2$$

$$V_{soft} = -m_+^2 |\phi_+|^2 - m_-^2 |\phi_-|^2 - \left( \frac{A (\phi_+\phi_-)^n}{nM^{2n-3}} + \text{h.c.} \right)$$

$m_+, m_-, A \sim \mathcal{O}(1\text{TeV})$
vacua: $|\phi_+| = |\phi_-| = \left[ \frac{M^{2n-3}}{4n-2} \left( A + \sqrt{A^2 + (4n-2)(m_+^2 + m_-^2)} \right) \right]^{1/(2n-2)}$

$\equiv v \sim (mM^{2n-3})^{1/2(n-1)}$

$\arg \phi_+ = -\arg \phi_-$

$(m: \text{energy scale of SUSY breaking} \sim 1\text{TeV})$

vacua $= S^1$ cosmic string

\[
\begin{align*}
\text{width: } w & \sim (V''|_{\phi=0})^{-1/2} \sim m^{-1} \sim (\text{TeV})^{-1} \\
\text{tension: } \mu & \sim v^2 \sim (mM^{2n-3})^{1/(n-1)}
\end{align*}
\]

$M \sim M_{pl} \Rightarrow \mu \sim (10^{14}\text{GeV})^2$, $G\mu \sim 10^{-10}$ for $n = 3$

\[\begin{align*}
\{ \text{negative soft mass terms } (m \sim \text{TeV}) \\
\text{higher dim. operators } (M \gg \text{TeV}) \\
\Rightarrow w \sim (\text{TeV})^{-1}, \; \mu \gg (\text{TeV})^2
\end{align*}\]
decay of loops with TeV scale width

- the way for loops with TeV scale width to emit energy

1. gravitational wave (GW): mainly from cusps
   - similar to ordinary cosmic strings
   \[ \frac{dE}{dt} = \Gamma G \mu^2, \quad \Gamma \sim 50 \]

2. particle creation at cusps
   Condensates of the scalar field overlap
   - non-perturbative effect
   - scalar particles are created
   \[ \frac{dE}{dt} \sim \mu \left( \frac{w}{l} \right)^{1/2} \]
   (l : the length of the loop)

- more efficient for \{ thicker smaller loops \}

- a pointed and highly Lorentz-boosted region which appear few times per oscillation period

- cusp
1: Lifetime of loops becomes short. 

decrease rate for length of a loop: \[ \mu \frac{dl}{dt} = -\Gamma G \mu^2 - \mu \sqrt{\frac{w}{l}} \]

gravitational wave background (GWB) induced by loops is affected

2: Heavy scalar particles from cusps finally decay to lighter particles (such as \( e^\pm, \gamma \)) and LSP

BBN is affected

dark matter (DM)

\[
\begin{align*}
\text{GWB} & \quad \text{BBN} \\
\text{DM abundance} & \quad \text{constraints on} \\
& \quad \{ \text{tension } G\mu, \alpha \text{ loop size } w \sim (\text{TeV})^{-1} \}
\end{align*}
\]
The spectrum of GWB \( \Omega_{GW} \equiv \frac{1}{\rho_{cr}} \frac{d\rho_{GW}}{d\ln f} (f) \) is suppressed in the high frequency region. (GWs of higher frequency are emitted earlier.)

This is remarkable especially for smaller loops, \( \frac{dE}{dt} \bigg|_{\text{particle}} \propto t^{-1/2} \). Older loops (length of a loop which is born at \( t = \alpha t \)) remains unspecified from \( \alpha \sim 0.1 \) to \( \alpha \sim (\Gamma G \mu)^{5/2} \).
$\Omega_{GW}$ including the effect of particle emission
(solid: including particle emission    dotted: not including)

$\alpha = 0.1$
$\omega = (1\text{TeV})^{-1}$
$\Gamma = 50$
Upper limit of energy injection to the thermal bath at BBN

\[ \frac{\rho_{\text{inj}}}{s} \lesssim 10^{-14} \text{ at } T \sim 10 \text{keV} \]

(Kawasaki, Kohri and Moroi, Phys.Rev. D71 (2005) 083502)

DM from cusps must be less than \( \Omega_{DM} h^2 \approx 0.1123 \)

dominant contribution

sum of those emitted since DM freeze-out by today

constraint from DM abundance

= constraint from energy injection at DM freeze-out \( T_{fo} \sim 10 GeV \)
Above each curve is the region the experiment can search. Colored regions are excluded.
solid: including particle emission   dotted: not including

\( w = \left(1\text{ TeV}\right)^{-1} \)
constraint on the above model

\[ w \sim m^{-1} \sim (\text{TeV})^{-1}, \mu \sim (mM^{2n-3})^{1/(n-1)} \quad n = 3 \]
When SSB is caused by scalar fields which have a potential which contains only SUSY breaking negative mass terms and higher dimensional operators, cosmic strings such that

$$w \sim (\text{TeV})^{-1}, \quad \mu \gg (\text{TeV})^2$$
	naturally appears.

Particle emission from cusp is important for loops of such a string. Decease of lifetime of loops affects GW background induced by loops. Besides, created particle may affect BBN or decay to DM particles.

The effect of particle emission changes the parameter region future GW experiments can search. Constraints from BBN or DM exclude substantial regions in $G\mu - \alpha$ plane.