Cosmic strings and their future detectability

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Cosmic strings

... are something like rubber bands, which

- Are 1-dimensional objects
- Have a tension
- Are VERY USEFUL!
Cosmic strings

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- Are 1-dimensional objects
- Have a tension
- Are VERY USEFUL!
Phase transition
Scalar field settles down to true vacuum due to Hubble friction
Strings begin to appear

Hiramatsu+Sendouda+Takahashi+DY+Yoo, 1307.0308
[Exercise 1]

Since the correlation cannot establish on scales greater than the causal horizon, the sign must be randomly chosen!
Topological defects can be produced through (spontaneous) symmetry breaking.

Field space

The phase $\vartheta$ must be randomly chosen.

$\vartheta = 0$

$\vartheta = 3\pi/2$

Real space

$V[\varphi]$

[Exercise 2]
COSMIC STRING

- Inner structure
- String tension

$\mu \sim (\text{phase transition energy})^2$

[ Nielsen+Olsen (1973) ]

$\sim 1/m$

Energy-density per unit length
Why are cosmic strings still interesting?

![Equation Image]

Cosmic strings have a potential to reveal the high-energy physics during phase transition!

For GUT scale...

$$G_N \mu = 10^{-6} \left( \frac{\mu}{10^{-3} M_{pl}} \right)^2$$
Contents

1. Introduction

2. Basic properties
   - String network dynamics
   - Reconnection
   - String gravity

3. Observational prospects

4. Discussion
Question 1

How does string network evolve?

- Comoving: $L_{\text{str}} \propto a(t)$?
- Scaling: $L_{\text{str}} \propto 1/H(t)$?
- Anything else?

Hubble length when simulation starts.

Hiramatsu+Sendouda+Takahashi+DY+Yoo, 1307.0308
Q1: How does a string network evolve?

- Comoving evolution
- Scaling evolution

(comoving grid size)
Scaling

- Number of strings inside the Hubble volume is always $O(1)$!
- Length of a string is always given by Hubble length $1/H$.
Scaling

- Number of strings inside the Hubble volume is always $O(1)$!
- Length of a string is always given by Hubble length $1/H$.

[Hiramatsu+DY+, 1307.0308]

Scaling is the stable attractor!

Scaling is the general property!
Cosmic strings do not dominate the subsequent Universe due to their late-time evolution.
Q2 : What happens when 2 strings collide?

- Reconnection
- Pass-through

正解
不正解
Reconnection

- Reconnection almost always happens! ($P \sim 1$)
- But in some case, a junction may form:

[Hiramatsu+DY+Steer, in progress]
Loop formation and energy loss

When a string crosses itself, a loop separate from the string. The energy of long strings is converted into small string loops, which eventually shrink due to GW & scalar radiation.
String gravity

The nonvanishing energy-momentum tensor, $T_{\alpha\beta}$, modifies the spacetime metric $g_{\alpha\beta}$ through the Einstein eq.

For a static straight string lying along z-axis,

$$T^{00} = T^{z z} = \mu \delta^2(x - x_{\text{str}})$$

$$T^{x x} = T^{y y} = 0$$

[Vilenkin (1981)]
**Conical structure**

The spacetime around a straight cosmic string is “locally” flat.

\[
ds^2 = -dt^2 + dz^2 + dr^2 + r^2 d\theta^2 \]

\[
0 \leq \theta \leq 2\pi(1 - 4G\mu)
\]

An angular wedge of width \(\Delta = 8\pi G\mu\) is removed from the space and the remaining edges identified.
Take-home message

- We can obtain the robust predictions because...

1. Scaling

2. Reconnection

3. Conical structure
SOME LOOPHOLES
When do strings form?

- Standard cosmic strings are produced at the phase-transition during radiation-dominated era.
- The scaling can be achieved just after the formation.


Strings form.
Scaling starts.
When do strings form?

Strings form. Scaling starts.

Inflation era

Radiation dominated era

They are diluted and the mean separation expands exponentially until end of inflation.

The network enters the scaling regime at the later epoch because $L >> 1/H$ and collision cannot occur.
Cosmic superstrings:
 Observable remnants of string theory

- Fundamental strings, which are elementary objects in string theory, could stretch to macroscopic scale by the expansion of the Universe (without suffering instability).

Cosmic superstrings: Observable remnants of string theory

- There are several differences from the standard cosmic strings:
  - Reconnection probability $P$
  - Appearance of bound states
  - Multiple tension network
  - ...

For standard strings $P \sim 1$
For cosmic superstrings $P \ll 1$

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Observational prospects for strings

- Cosmic Microwave Background
- Gravitational waves
- Weak/strong gravitational lensing
- 21cm line
- ...
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Cosmic strings on the CMB sky

Simulated CMB sky from only cosmic strings

Planck(2013)XXV
CMB temperature anisotropies

Cosmic strings create line-like discontinuities in the CMB signal (through Integrated Sachs-Wolfe).

\[
\frac{\delta T}{T} = 8\pi G \mu \frac{v}{\sqrt{1 - v^2}}
\]

[For curved strings, \textbf{DY}+, 1004.0600, For kinks/cusps, Takahashi+\textbf{DY}+, 0811.4698]
CMB temperature anisotropies

Last scattering surface

As the string moves across the line of sight, the CMB photons are boosted towards the observer.

A relative CMB temp shift across the string

[Kaiser+Stebbins (1984), Gott III(1985)]
The observations of the acoustic oscillation in the CMB have excluded strings as the dominant source of the CMB anisotropies:

\[ G_N\mu < 1.3 \times 10^{-7} \text{ (95\%CL, standard)} \]  

[Planck(2013)XXV]
Detectability from future CMB obs.

(1) String-induced temperature 3-point functions

\[= (\text{SSS-type}) + (\text{PS-type}) + (\text{SP-type})\]

We could detect the superstring-induced bispectrum with \(G_N \mu \sim 10^{-8}\)

\(G_N \mu \sim 10^{-7}\) for standard cosmic strings
Detectability from future CMB obs.

(2) String-induced B-mode polarization

The presence of delayed-scaling strings improves the fit to the BICEP2+POLARBEAR data, although more data are required.

\[ \delta \chi^2 = -9 \ [+2 \text{dof}] \]
Detectability from future CMB obs.

(3) String-induced CMB lensing

: can provide evidence for the intervening strings along a line of sight by measuring the spatial patterns of the deformation of the photon path.
Detectability from future CMB obs.

(3) String-induced CMB lensing

Strings continuously generate vector and tensor pert. even at late time, which induce the parity-odd mode signal.

- **Planck (current)**
  \[ G_N \mu < 3 \times 10^{-8} \left( \frac{P}{10^{-3}} \right) \]
  [95\%C.L., curl-mode]

- **Future**
  \[ G_N \mu < 2 \times 10^{-9} \left( \frac{P}{10^{-3}} \right) \]
  [(S/N)=1, curl-mode]

\[ G_N \mu = 10^{-8} \]
\[ P = 10^{-3} \text{ (superstrings)} \]

[For parity-even mode for CMB lensing, DY+Takahashi+Sendouda+Yoo, 1110.0556]
Observational prospects for strings

- Cosmic Microwave Background
- Gravitational waves
- Weak/strong gravitational lensing
- 21cm line
- ...
Gravitational waves from strings

- Oscillating loops of string can generate a potentially observable GW.

- GW burst: GW with shot duration [<1s]

- Stochastic background: produced by superposition of bursts from a string network.
Stochastic background:
\[ \Omega_{GW} = \frac{1}{\rho_c} d\rho_{GW} / d\log f \]

\[ \Omega_{BBN} = \int \Omega_{GW}(f) \, d(\ln f) < 1.1 \times 10^{-5} (N_v - 3) \]
Constraints on tension and initial loop length

Note: the amplitude of GW strongly depends on the loop distribution.

The allowed parameters: 
\( P = 10^{-3} \) case

- \( G_N \mu < 10^{-11} \)  
  (long loop model)
- \( G_N \mu < 3 \times 10^{-8} \)  
  (small loop model)

For delayed-scaling strings, Deno+DY+Yokoyama, in progress...
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Can we see bound states in a network?

When two (type-I or super-)strings collide, bound states and Y-junctions would be produced.

- Nearly parallel
- Low relative velocity

It is open question whether the (type-I) string network can dynamically create the bound states.
But 3-dim simulation requires heavy computational costs...

- **2-dim toy model**: Impose translation sym along z-axis

**merits**
- Reduce the computational costs
- Restrict the spatial degree-of-freedom
- Enhance the production rate of bound states
- May lead to the maximum fraction of bound state

Easy to produce a bound state
Anyway, you can see bound states!

$|\varphi|$ There is a doublet!

$\beta=0.1$

[Hiramatsu+DY, work in progress...]
Anyway, you can see bound states!

...and a triplet!

$|\varphi|$ $\beta=0.1$

By Hiramatsu

[Hiramatsu+DY, work in progress...]
Anyway, you can see bound states!

Type-I string network in 2-D simulations have the bound states!

- The evolution of the network with bound states
- How large is the fraction of higher winding strings?

By Hiramatsu

\[ \beta = 0.05 \]

[Hiramatsu+DY, work in progress...]
Cosmic strings are line-like objects, which are expected to be produced

- at PT after inflation via SSB (for standard ones)
- at PT during inflation via SSB (for delayed-scaling ones)
- at the end of stringy inflation (for superstrings)
A cosmic string network has the unique properties:

- Scaling attractor
- Reconnection
- Conical structure

Thanks to these, we can obtain the robust predictions.
The presence of cosmic strings would leave a variety of traces such as:

- Cosmic microwave background
- Gravitational waves
- Weak/strong gravitational lensing
- 21cm line

[ DY+Namikawa+Taruya 1205.2139, Yoo+DY+ 1209.0903 ]

[Square Kilometre Array]
Future

➢ Modeling for loop distributions
  • The constraint from GW amplitude strongly depends on it!

➢ Formulation for strong lensing
  • E.g. double images

➢ Bound states / Y-junctions
  • Observational consequence?

Thank you!
Summary

Anyway,...

_Cosmic strings are fun!_
Direct detection : strong lensing

The string with the deficit angle creates the double image with the very similar amplitude with a separation angle of order $G\mu$. 

![Double Image](image.png)
Detectability from future CMB obs.

(2) String-induced CMB lensing

\[ G\mu P^{-1} \leq 3.4 \times 10^{-5} \]  

(95\%CL, Planck curl-mode)

- Curl mode is more sensitive to small values of P compared to the power spectrum.

[Namikawa+DY+Taruya, 1205.2139, 1308.6068]
(a) $p = 1$
Other possibilities from CMB

- Non-Gaussianity
  - ISW-lensing non-Gaussianity \([\text{DY}+, 1309.5528]\)

- B-mode polarization
  - Vector/tensor modes \([\text{Kamada+DY}+, 1407.2951]\)
  - Lensing-induced B-mode \([\text{DY}+, 1110.0556]\)

- CMB lensing reconstruction
  - Vector/tensor modes \([\text{Namikawa+DY+Taruya}, 1205.2139, 1308.6068]\)
2-D is NOT real world!!!

In 2-D system, it is probably impossible to obtain the true features of the string network.

✓ It is definitely impossible to construct the web-like string network.
✓ There are no energy release mechanisms which corresponds to the loop production in the 3-D cases. The only mechanism is pair annihilation!