Imprints of cosmic strings in late-time scaling scenario

based on: KK, Y. Miyamoto, D. Yamauchi & J. Yokoyama, arXiv:1407.2951

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Introduction

Cosmic string...

- Line-like topological defect associated with symmetry breaking.
- Almost unavoidably produced when GUT breaks down to the Standard Model gauge group.

\[ \text{e.g.) R. Jeannerot+ (’03)} \]

\[
\begin{align*}
4C_{2L}2R & \overset{1}{\rightarrow} 3C_{2L}2R_{1B-L} \\
1 & \rightarrow 4C_{2L}1R \\
1 & \rightarrow 3C_{2L}1R_{1B-L} \\
1^{(1,2)} & \rightarrow G_{SM}(Z_2) \\
\end{align*}
\]

Study of cosmic string can lead to the understanding of the nature of the Standard Model and possibly the electroweak and strong forces.
Cosmic string formation

Symmetries can be restored in the early Universe, and broken down during the course of cosmic history.

Symmetry breaking

\[ G \rightarrow H \]

Field space

\[ |\Phi| = 0 \]

Real space

\[ |\Phi| = v \neq 0 \]
When a symmetry is broken, cosmic strings are formed if the vacuum manifold is $S^1$ or $\pi_1(G/H) \neq 0$. (or when U(1) symmetry is broken) Kibble mechanism (Kibble '76)

Higgs field in the vacuum manifold distributes randomly at the scale larger than the correlation scale.

There must be line-like points in the real space where Higgs field cannot fall down to the vacuum, $|\Phi| = 0$, from the topological reason. (At that point, the energy density remains high.)

Such field configuration is topologically stable and hence we call it "topological defects".
Scaling behavior of the cosmic string network  (Kibble '85)

The energy density of cosmic strings decays as $a^{-2}$ and hence they may overclose the Universe if they are produced in the early Universe...

However, cosmic string network forms loops when they intersect, and hence its characteristic scale remains constant relative to the Hubble length.

- They do not overclose the Universe!

=> They are still in our Universe, and it is possible to observe their traces in CMB, GWB, or cosmic rays.
Traces of cosmic strings in CMB (Albrecht+ ’97; Seljak+ ’97) cosmic strings between the last scattering surface and us generates the fluctuation of CMB temperature/polarization.
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cosmic strings between the last scattering surfaces and us generates the fluctuation of CMB temperature/polarization.

From slide of T.Suyama

From WMAP homepage

Lizarraga+, 1403.4924
Traces of cosmic strings in CMB (Albrecht+ ’97; Seljak+ ’97) cosmic strings between the last scattering surfaces and us generates the fluctuation of CMB temperature/polarization.

Planck temperature observation gives the strong constraint on the cosmic string tension; \( G\mu \lesssim (1 - 3) \times 10^{-7} \) (Planck collaboration, 1303.5085)

Related to the symmetry breaking scale. #CMB can see them only through gravity.
Delayed scaling scenario
(Lazarides+ ’84; Vishniac+ ’87; Yokoyama, ’88; KK+ ’12)
The discussion for the effect on CMB is based on the assumption that the cosmic string entered the scaling regime well before recombination.

-> Observational predictions are very generic.
It is true for the case of hybrid inflation or thermal-mass triggered phase transition.
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However, it is possible for the phase transition to take place DURING inflation, since the symmetry is naturally restored during inflation due to the “Hubble-induced” mass, \( c^2 H^2 \phi^2 \) coming from

- non minimal coupling to gravity: \( \xi \phi^2 R \)
- direct coupling between inflaton and Higgs: \( \kappa \phi_{\text{inf}}^2 \phi^2 \)
- gravitational coupling in SUSY F-term inflation: \( e^{\phi^2/M_{Pl}^2} V_{\text{inf}} \)
- and so on...

If the Hubble-induced mass and zero-temp. mass are comparable and Hubble parameter decreases relatively largely, cosmic string can be formed during inflation.
The characteristic length, which would be the Hubble length at CS formation, gets exponentially long at the end of inflation.

At the end of inflation, CSs are distributed at the superhorizon scales, and characteristic length evolves just $\propto a$ after that.
Adopting velocity-dependent one-scale model (approximation), we find the typical evolution of the correlation length of CS network and how the system would approach the scaling regime.

It takes a few orders of redshift for the system to enter the scaling regime after the characteristic length comes to subhorizon scales.
String-induced CMB temperature fluctuations

The position of the peak is determined by the time when the network enters the scaling regime.
String-induced CMB polarization fluctuations

The position of the peak is determined by recombination and reionization. Their amplitude is determined by the number of strings at that time.

\[ @z = 2.3 \times 10^7 \]
\[ (L/H^{-1})_{ini} = 1.5 \]
\[ 7.5 \times 10^3 \]
\[ 4.5 \times 10^4 \]
\[ 1.5 \times 10^5 \]

used CMBACT[v4] (’99 Pogosian+Moss)
Constraint on the string tension

![Graph showing constraint on the string tension](image)

The graph illustrates the allowed maximum of the string tension $G\mu$ as a function of the initial correlation length $\left(\frac{L}{H} - 1\right)_{\text{ini}}$ at $z = 2.3 \times 10^7$. The data from BICEP2 and POLARBEAR are indicated by blue and red lines, respectively. The graph shows the constraints on the string tension for two different redshift components: low redshift ($0 < z < 20$) and high redshift ($z = 2$). The precision of the data provided by Planck is about 10% for $\ell \lesssim 50$ and $2250 \lesssim \ell \lesssim 2450$. The constraints are indicated by conservative limits, and the shapes of the constraint lines do not change significantly.
FIG. 6: B-mode polarization angular power spectra for gravitational lensing with primordial gravitational waves ($r=0.135$, black broken line) and contributions from cosmic strings with delayed scaling ($G\mu=3 \times 10^{-7}$, $\left(L/H^{-1}\right)_{\text{ini}}=7500$, green dashed line). If we combine them, the favorable value of $r$ would be smaller than 0.2.

FIG. 7: The contour of the difference of $\chi^2$ between the prediction in taking $r=0.2$ without strings ($\chi^2 \approx 15$) and that of cosmic strings with delayed scaling added to that for $r=0.135$ based on BICEP2 data. The value of $\chi^2$ gets worse in blank regions.

The key is to consider the scenario in which cosmic strings are formed not after but during inflation. Such strings have exponentially large separation due to the dilution during the subsequent inflation and their evolution is quite different from that of strings which enter the scaling regime at an earlier epoch. We have traced typical evolution of the string network by solving the velocity-dependent one-scale model. We have shown that if we take the relatively large correlation length at the initial time, the correlation length decays as $a^{-1/2}$ rather than $1/H$ at an earlier epoch and it takes a few orders of redshift for the system to enter the scaling regime [Figure 1]. Based on the evolution of the network, we have calculated the angular power spectra for the string-induced temperature anisotropies and B-mode polarizations. We found that the large initial correlation length and the consequent delay of the entrance into scaling regime allows the decrease in the number of strings at an earlier epoch, leading to the decay of the string signals mainly on higher multipoles [Figure 3]. As a result, the delayed scaling scenario can relax the constraint on the string tension from the measurements for both the temperature anisotropies and the B-mode polarizations.

We have further discussed the features of the B-mode signals produced by strings. For the string-only model with the contribution of the gravitational lensing, it is difficult to explain both BICEP2 and POLARBEAR data fully. $\Delta \chi^2 \sim -9$ for GW ($r=0.2$)+GL vs GW ($r=0.135$)+CS+GL.
Summary
- Cosmic strings are key ingredients for both cosmology and high energy physics.
- Their formation during inflation is an interesting possibility.
- The string network enters scaling regime later in this case, which can reduce the high multipole moment of both CMB temperature and polarization fluctuations.

Open issues
- We assumed several idealization, such as one-scale model.
  -> need numerical simulations.
- We gave just qualitative constraints.
  -> Combined analysis of Planck temperature/polarization data and other experiments (including BICEP2) is needed to give a precise constraint.