# Emission of Nambu-Goldstone bosons from semilocal string networks

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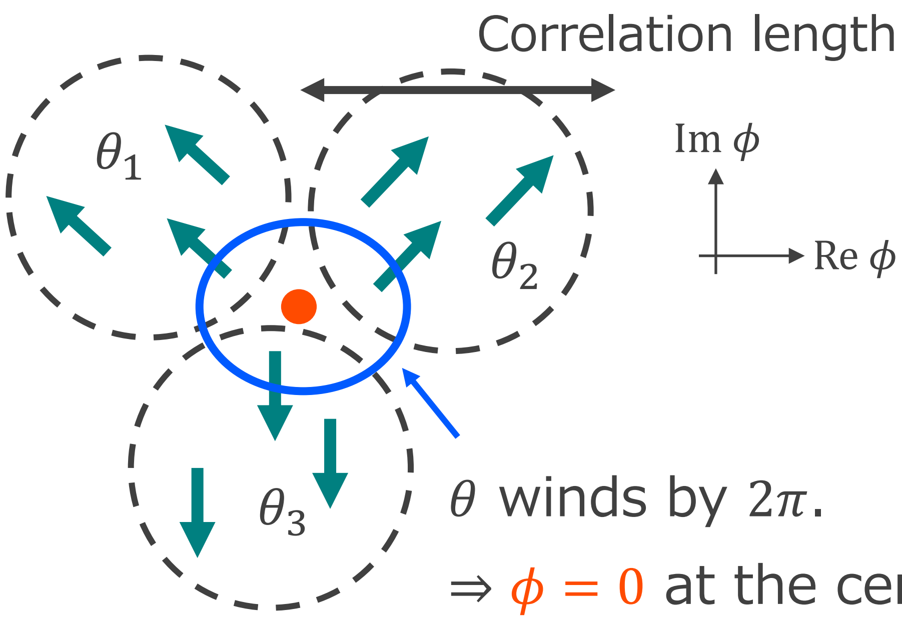
# Cosmic string

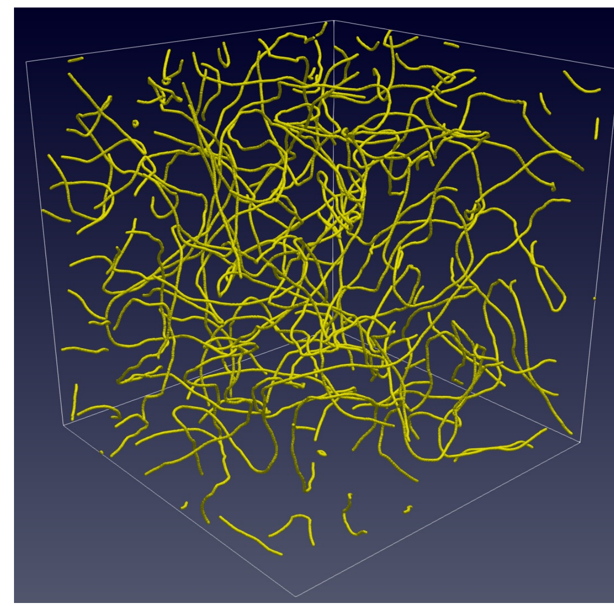
: 1d topological defects produced during ~~$U(1)$~~ [Kibble (1976), Zurek (1985)]

e.g., $V(\phi, T) = \lambda(|\phi|^2 - v^2)^2 + AT^2|\phi|^2$ ⇨ $\langle\phi\rangle = ve^{i\theta}$ $(\theta \in [0, 2\pi))$




$\theta$ winds by $2\pi$.

⇒ $\phi = 0$ at the center.



Gravitational waves,
Gravitational lensing,

Cosmic string ⟷

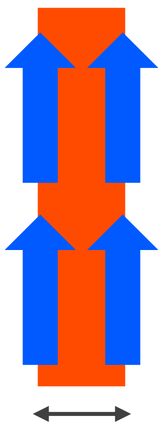
Broken symmetry,
BSM physics,

# Local string vs. Global string ①

$\cancel{U(1)}_{\text{gauge}}$ ➡ Local string

[Nielsen, Olesen (1973)]

e.g., Metastable string in GUT



Excited scalar radial mode

Magnetic flux of massive $U(1)_{\text{gauge}}$

$\sim v^{-1}$

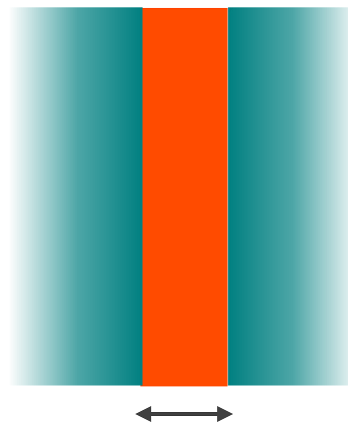
The string tension is finite.

$$\mu \sim v^2$$

$\cancel{U(1)}_{\text{global}}$ ➡ Global string

[Vilenkin, Everett (1982)]

e.g., Axion string



Excited scalar radial mode

Gradient of NG mode

$\sim v^{-1}$

The string tension is logarithmically divergent.

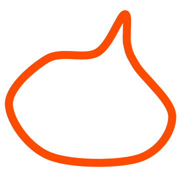
$$\mu \sim v^2 + v^2 \log \frac{v}{H}$$

# Local string vs. Global string ②

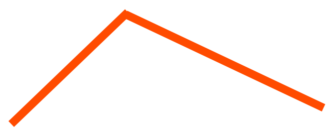
<u>Local string</u>

Particle emission is dominated by core-scale dynamics.

“Cusp”



“Kink”



The characteristic momentum of emitted particle is set by the core scale $v$.

[Olum, Blanco-Pillado (1998)],...

<u>Global string</u>

Global strings store most of their energy in long-range Goldstone gradients.

The characteristic momentum of emitted NG bosons is set by the Hubble scale $H$.

[Vilenkin, Vachaspati (1987)],...

# Semilocal string

$\phi_1, \phi_2$: scalar fields with the same $U(1)_{\mathrm{gauge}}$ charge

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \left| D_\mu \phi_1 \right|^2 + \left| D_\mu \phi_2 \right|^2 - \lambda \left( |\phi_1|^2 + |\phi_2|^2 - \frac{v^2}{2} \right)^2$$

$$\left( D_\mu \phi_{1,2} = \left( \partial_\mu - igA_\mu \right) \phi_{1,2} \right)$$

- The vacuum space $\mathcal{V} = \left\{ (\phi_1, \phi_2) \middle| |\phi_1|^2 + |\phi_2|^2 - \frac{v^2}{2} \right\} \simeq S^3$

  $(\because SU(2)_{\mathrm{global}} \times U(1)_{\mathrm{gauge}} \to U(1)_{\mathrm{global}})$

- The winding configurations induce a nontrivial magnetic flux $\Phi$.

$$\Phi = \frac{2\pi}{g} n \qquad (n\text{: winding number})$$

➡ The flux cannot be removed continuously, and the stable string solutions appear when $g \gg \lambda$.

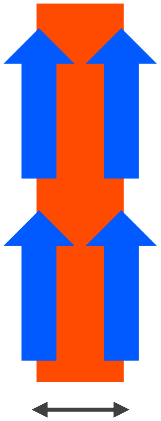
: Semilocal string [Achucarro, Vachaspati (1991)]

# Features of semilocal string

- Their configuration resembles a local string.
 (scalar core + confined magnetic flux)

- Their string tension is finite.

- There are two Nambu-Goldstone modes due to
 $SU(2)_{\rm global} \times U(1)_{\rm gauge} \to U(1)_{\rm global}$.




$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \varphi_r \cos\vartheta \, e^{i\theta_1} \\ \varphi_r \sin\vartheta \, e^{i\theta_2} \end{pmatrix} = \varphi_r e^{i\theta_+} \begin{pmatrix} \cos\vartheta \, e^{i\theta_-} \\ \sin\vartheta \, e^{-i\theta_-} \end{pmatrix} \qquad \theta_\pm \equiv \frac{\theta_1 \pm \theta_2}{2}$$

$\theta_+$: longitudinal mode of a massive $U(1)_{\rm gauge}$ gauge boson

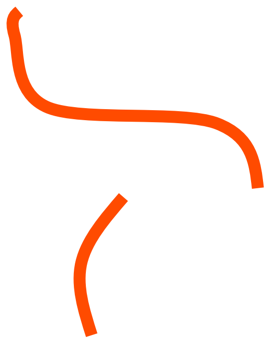
$\theta_-, \vartheta$: NG bosons due to $SU(2)_{\rm global}$ breaking

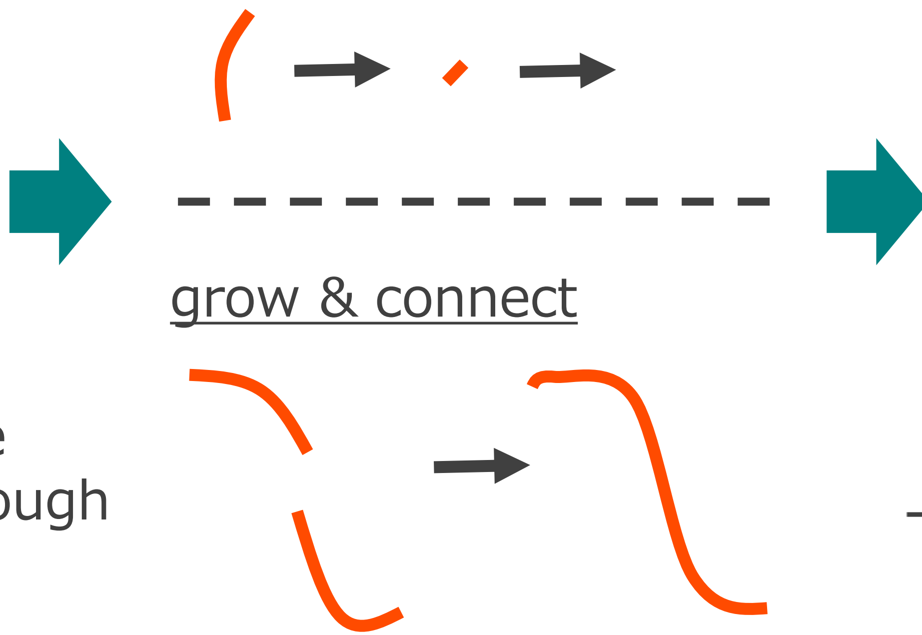
➡ What is the characteristic momentum of the emitted NG bosons?

# Previous semilocal string simulation

Semilocal string networks have been studied in several previous lattice simulations. [Achucarro et al. (2014)], [Lopez-Eiguren et al. (2017)]

shrink & collapse



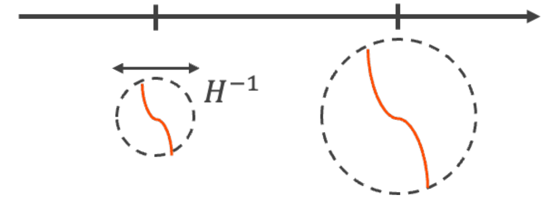



Segments are produced through Kibble-Zurek mechanism.

Network reaches a scaling regime.

$$\xi_{\mathrm{phys}} \propto t$$

(The mean string separation grows linearly with time.)



# Simulation setup

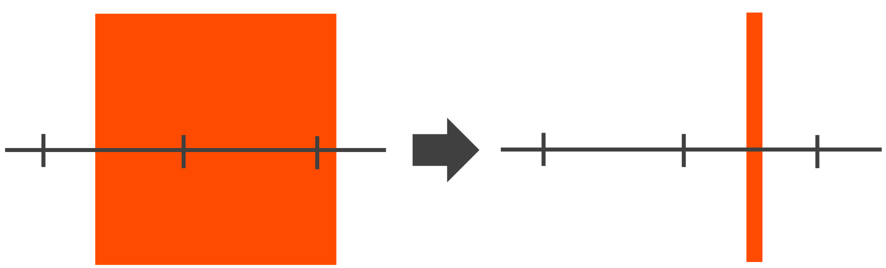
We performed lattice simulations of $\phi_{1,2}$ and $A_\mu$ in the $SU(2)_{\mathrm{global}} \times U(1)_{\mathrm{gaugel}}$ model.

- Radiation-dominated FLRW spacetime
- $N^3 = 4096^3$
- $2\lambda/g^2 = 0.05 \quad (g \gg \lambda)$

We performed simulations both with and without the core growth method.

Physical string

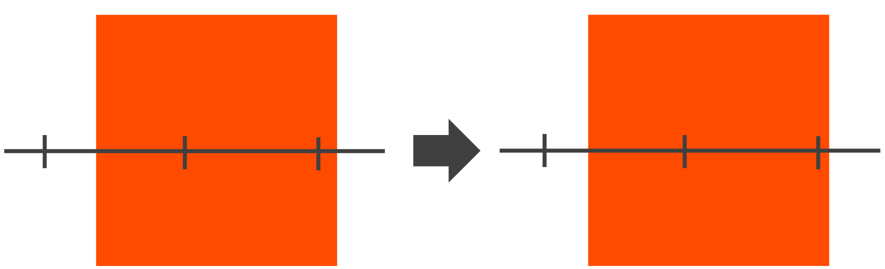
$\lambda = \text{const.} \quad g = \text{const.}$



Comoving time range: $v^{-1}$ to $48v^{-1}$

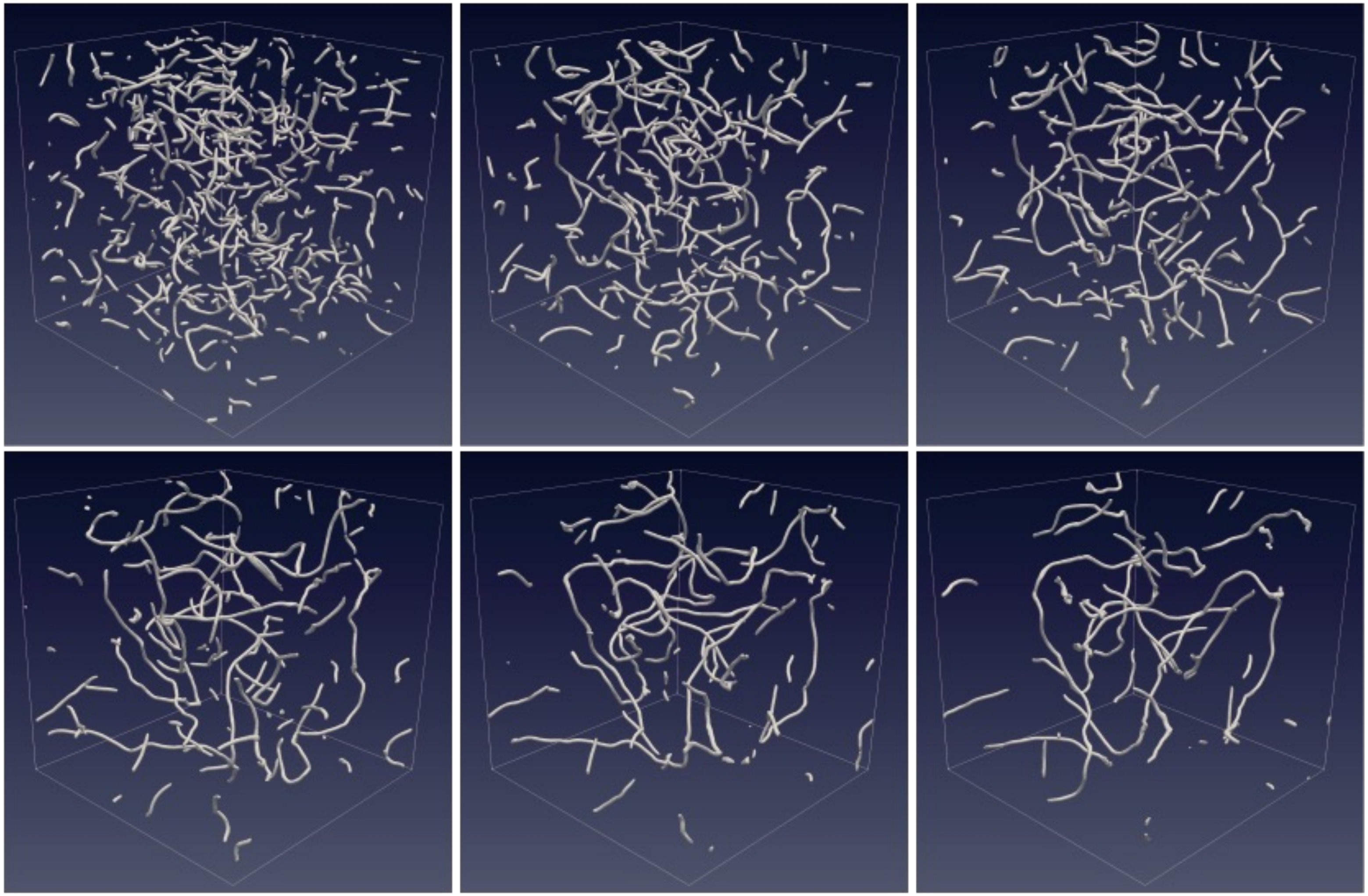
Fat string [Press, Ryden, Spergel (1989)]

$\lambda \propto a^{-2} \quad g \propto a^{-1}$



Comoving time range: $v^{-1}$ to $1024v^{-1}$

# Snapshots of our simulation

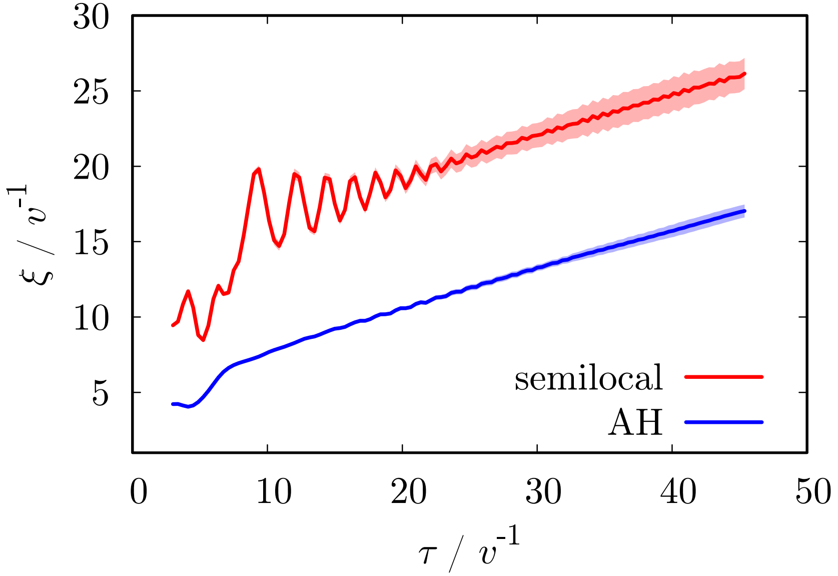


$v\tau = 61, 101, 141, 181, 221, 261$

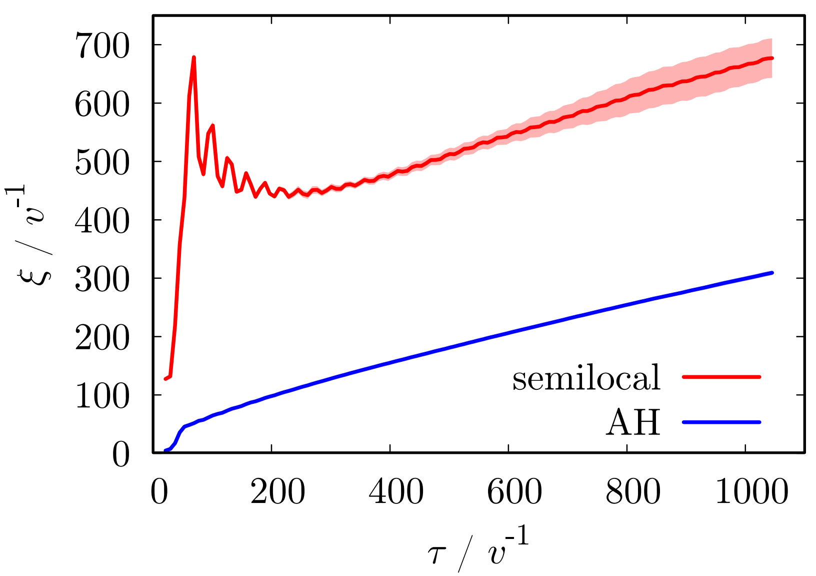
# Scaling behavior

We investigate the (comoving) mean string separation: $\xi(\tau)$

(Physical string)




(Fat string)

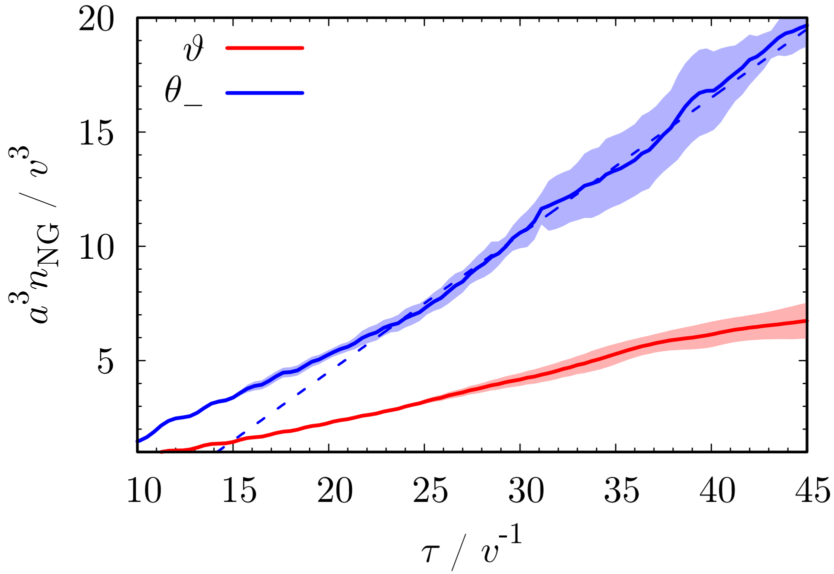



- Scaling behavior is confirmed. ($\xi \propto \tau$ )
  (consistent with the previous works. [Achucarro *et. al.* (2014)] )
- Fat string simulation reproduce the qualitative behavior of physical string simulation.

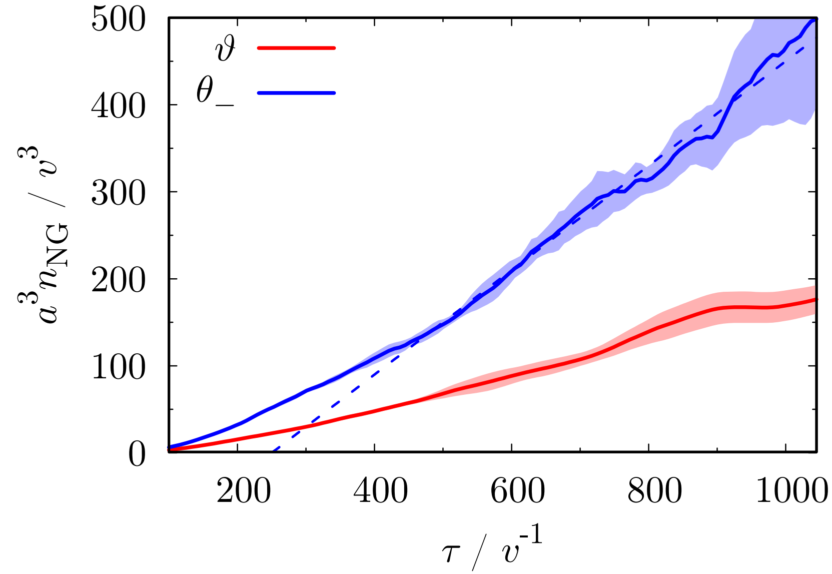
# NG boson emission

The number density of NG bosons: $n_{\mathrm{NG}}(\tau)$

(Physical string)




(Fat string)




- $a^3 n_{\mathrm{NG}}$ grows linearly with comoving time. ($n_{\mathrm{NG}} \simeq 0.6 v^2 H.$)

$$\left(\because \dot{\rho}_{NG} + 4H\rho_{NG} = \mathcal{P} \xrightarrow{\frac{\partial \mathcal{P}}{\partial k} \simeq \mathcal{P}\,\delta(k - cH)} n_{NG} \propto H\right)$$

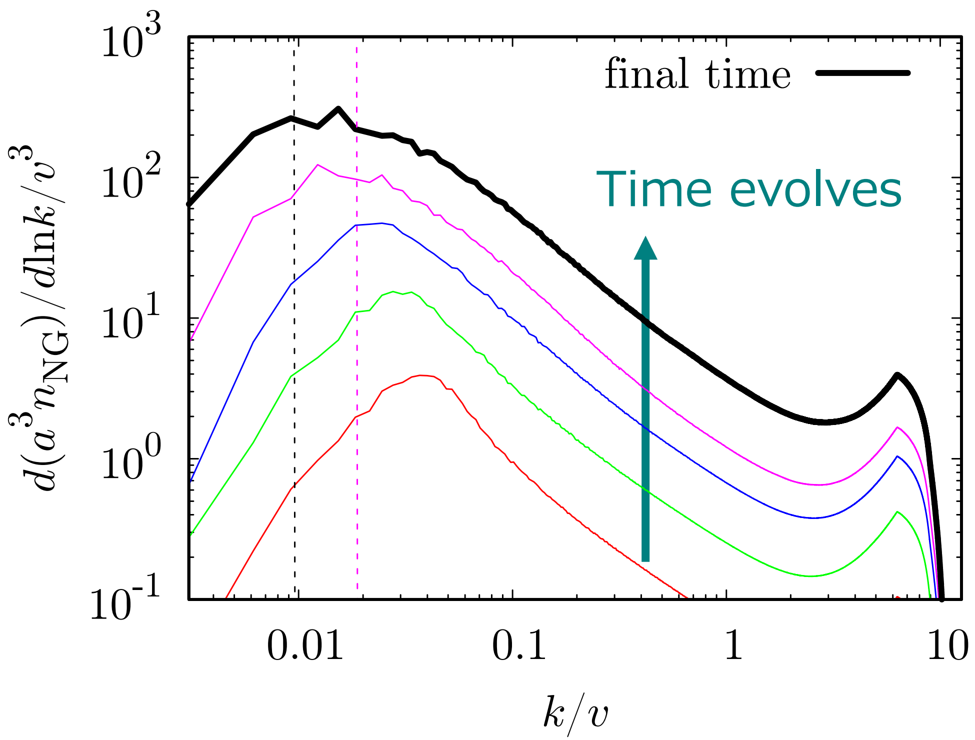
$$\dot{\rho}_s + 2H\rho_s = -\mathcal{P}$$

Typical momentum is proportional to $H$!

[Gorghetto, Hardy, Villadoro (2018)]

# Energy spectrum of NG bosons

The evolution of the spectrum of $n_{\mathrm{NG}}(\tau)$




$k$: comoving momentum
$(k_{\mathrm{phys}} = k_{\mathrm{com}}/a)$

$v\tau = 85, 149, 277, 533, 1045$

The peak shifts as $\tau$ increases.

$$k_{\mathrm{com}} \simeq \frac{10}{\tau}$$

$$\Leftrightarrow \ k_{\mathrm{phys}} \simeq 10H$$

The typical momentum of emitted NG bosons is set by $H$.
(This is similar to the behavior of the global string.)

# Pseudo NG boson dark matter

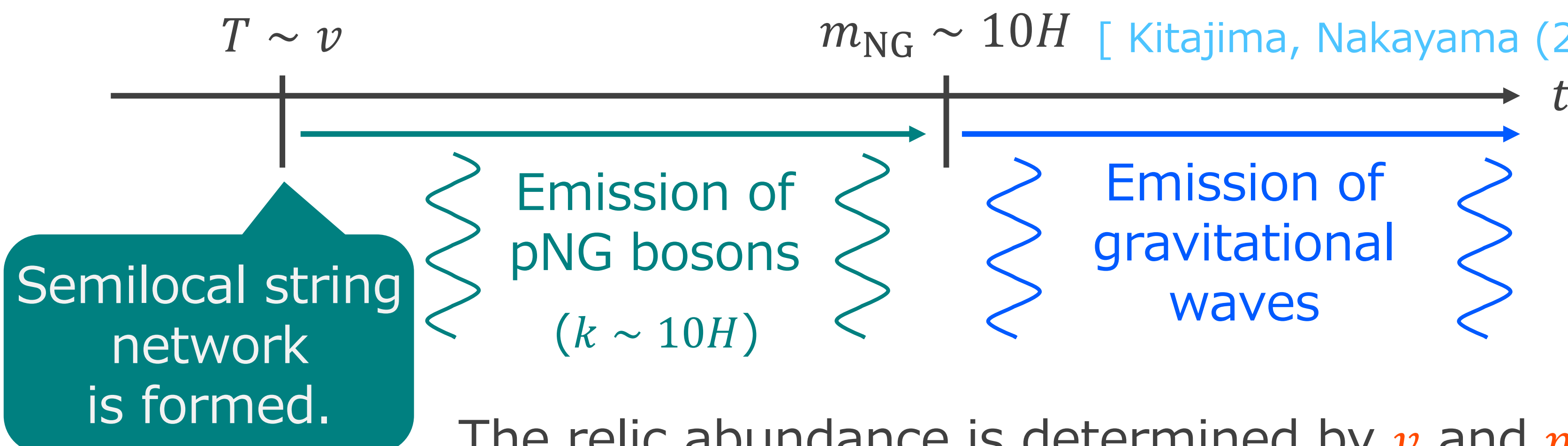
If we introduce a soft-breaking term, NG bosons acquire mass.
= pseudo NG bosons

e.g., $\mathcal{L}_{\mathrm{soft}} = m_{\mathrm{NG}}^2 |\phi_1|^2 - m_{\mathrm{NG}}^2 |\phi_2|^2 \quad (m_{\mathrm{NG}} \ll v)$

They can potentially play the role of dark matter.

We propose a production mechanism of pNG DM from the semilocal string network.

[ Kitajima, Nakayama (2022)]

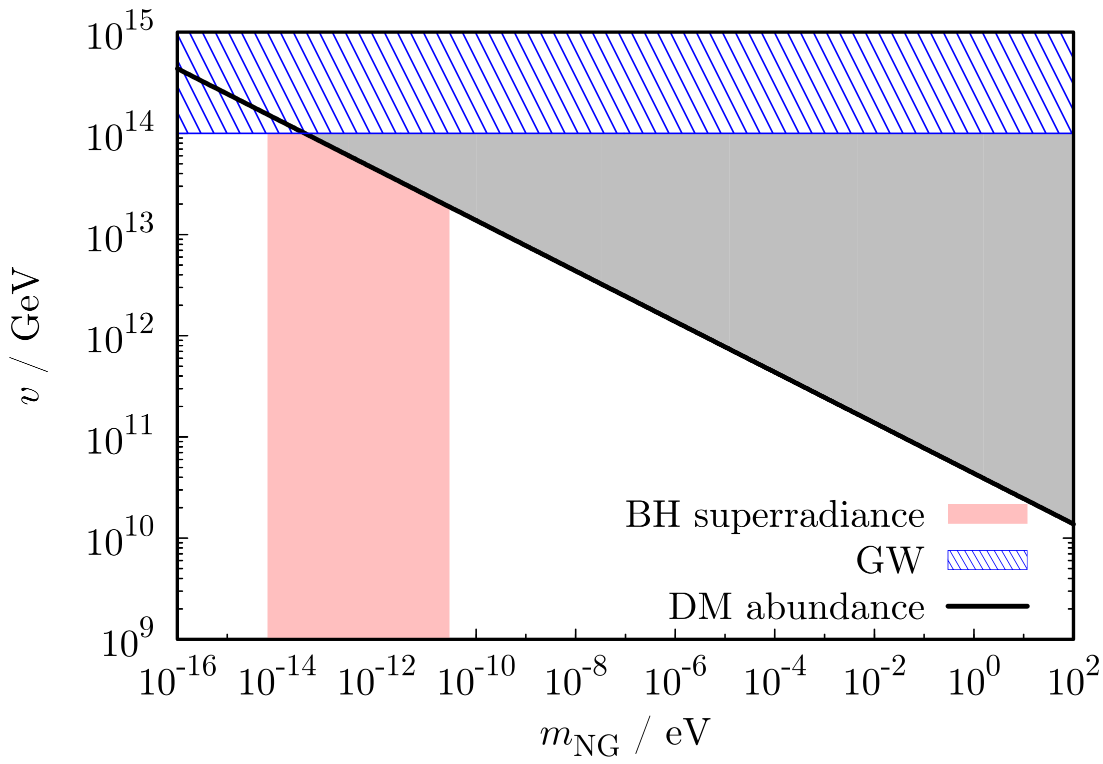



The relic abundance is determined by $v$ and $m_{NG}$.

# Relic abundance of pNG boson

Our simulation shows $n_{\rm NG} \simeq 0.6 v^2 H$.

$$\Omega_{\rm NG} h^2 = \frac{m_{\rm NG} n_{\rm NG}/s(T_{\rm NG})}{\rho_{cr}/s_0} h^2 \simeq 0.2 \left(\frac{m_{NG}}{10^{-13}\ \rm eV}\right)^{\frac{1}{2}} \left(\frac{v}{10^{14}\ \rm GeV}\right)^2$$




Constraints

- Black Hole superradiance

  $10^{-14}\ {\rm eV} \lesssim m_{\rm NG} \lesssim 10^{-11}\ {\rm eV}$

  [Cardoso et al. (2018)]

- Gravitational waves at nHz

  $v \lesssim 10^{14}\ {\rm GeV}$

  [NANOGrav collaboration (2023)]

Produced pNG bosons with $m_{NG} \gtrsim 10^{-10}$ eV can account for DM.

# Summary

- Cosmic strings emit particles during their evolution. Local strings mainly emit high-energy particles ($k \sim v$), whereas global strings emit low-energy NG bosons ($k \sim H$).
- Although semilocal strings are not topological defects, they can be produced during a phase transition and behave as cosmic strings.
- We performed lattice simulations of the semilocal string network. We confirm that it reaches a scaling regime.
- We found that NG bosons are continuously emitted from the string network, with a characteristic momentum $k_{\mathrm{phys}} \sim 10H$.
- We propose a scenario in which pNG bosons emitted from the semilocal string network can account for ultralight DM in a viable parameter region.