Semilocal stringの時間発展と南部ゴールドストーン粒子放出

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Seminar at Tokyo University of Science on May 26th, 2026

自己紹介

神田行宏

2020年4月　名古屋大学大学院入学 (阿部さんと同じ研究室)

2023年8月　原子核三者夏学の運営 (宮尾くんと)

2025年3月　名古屋大学大学院修了

2025年4月-　東京大学宇宙線研究所　特任研究員

主な研究の興味

位相欠陥(topological defects)

とそれに着目した標準模型を超える物理の探索

1. Topological defects

2. Local and Global string

3. Semilocal string

4. Results of our work

1. Topological defects

2. Local and Global string

3. Semilocal string

4. Results of our work

対称性

標準模型を超える物理がもつ対称性を知りたい

標準模型のゲージ対称性: $SU(3)_c \times SU(2)_L \times U(1)_Y$

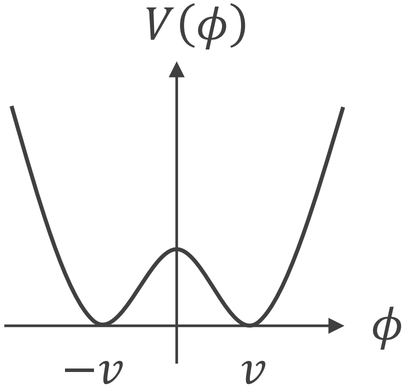
⇩

対称性の自発的破れ (ヒッグス機構)

$$\mathcal{L} = \frac{1}{2}\partial_\mu \phi \partial^\mu \phi - V(\phi)$$

$$V(\phi) = \lambda(\phi^2 - v^2)^2$$

$$\mathbb{Z}_2 : \phi \to -\phi$$



↓ $\phi = v + h$

$$\mathcal{L} = \frac{1}{2}\partial_\mu h \partial^\mu h - 4\lambda v^2 h^2 - 4\lambda v h^3 - \lambda h^4$$

$$\langle \phi \rangle = v \xrightarrow{\mathbb{Z}_2} \langle \phi \rangle = -v$$

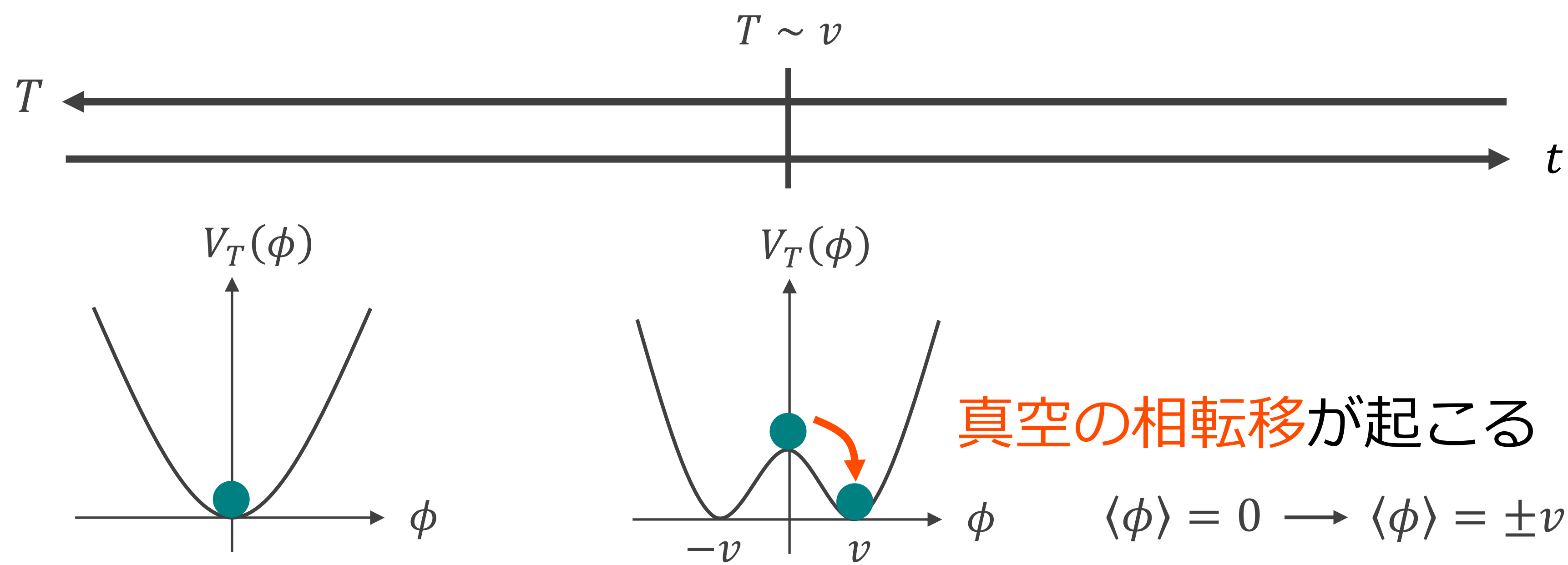
真空の相転移

ビッグバン宇宙論によれば、初期宇宙は温度Tのプラズマで満ちている

$V_T(\phi) = \lambda(\phi^2 - v^2)^2 + AT^2\phi^2 + BT\phi^3 + \cdots$ (簡単のため $A > 0, B = 0$ を仮定)

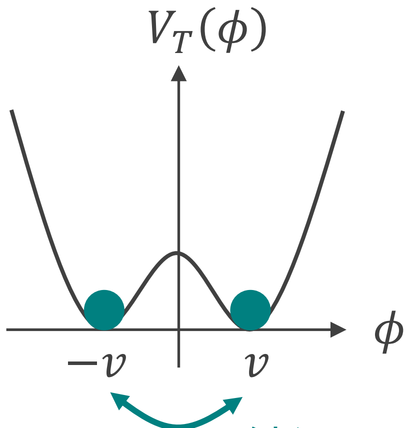
宇宙の膨張に伴い、プラズマの温度は低下する

一様等方な膨張でプラズマが支配的とすれば $T \propto t^{-1/2}$



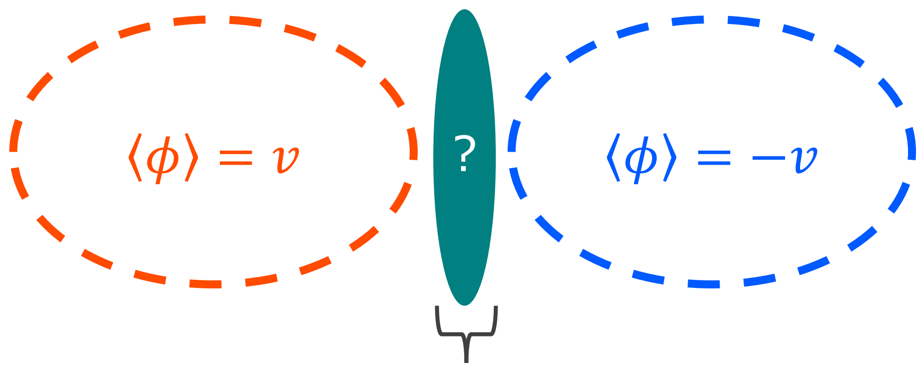
相転移と位相欠陥

場の理論：粒子 ＝ 場 ($\phi: x \mapsto \phi(x)$)



縮退した真空

因果関係のない領域では
$\langle\phi\rangle = \pm v$ の選び方に相関は無い



$$E = \int d^3x \left[\frac{1}{2}\partial_i\phi\partial_i\phi + \lambda(\phi^2 - v^2)^2\right]$$

$\langle\phi\rangle$の値が v から $-v$ に変わる領域
(厚さ v^{-1} 程度の面状の物体)

⇨ 位相欠陥 (ドメインウォール)が形成

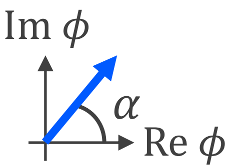
[Kibble (1976), Zurek (1985)]

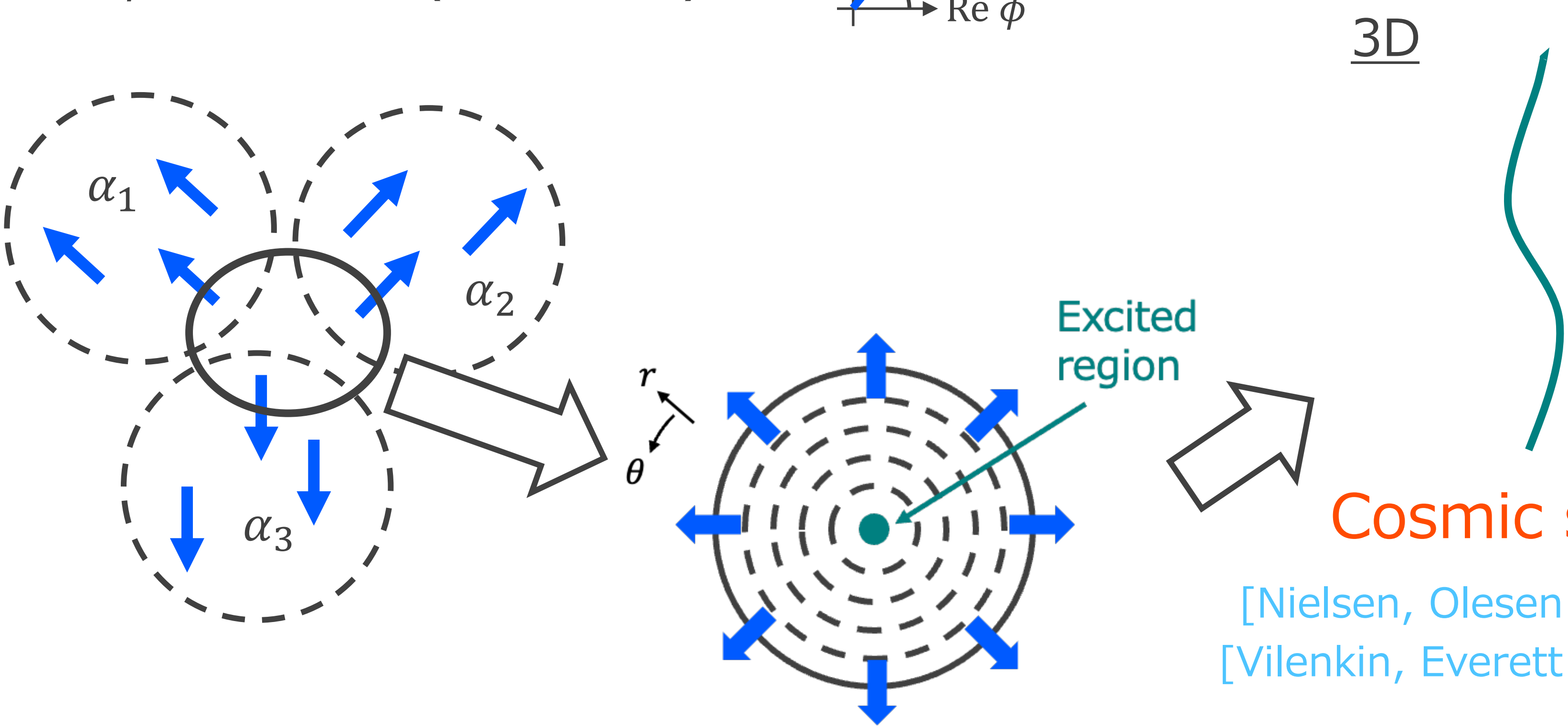
Cosmic string

$\mathcal{L} = \left(\partial_\mu \phi\right)^* \partial^\mu \phi - \lambda(|\phi|^2 - v^2)^2$ ϕ: Complex scalar field

$U(1)\colon \phi \to e^{i\alpha}\phi$

$\langle\phi\rangle = ve^{i\alpha} \qquad (\alpha \in [0, 2\pi))$





Cosmic string

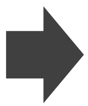
[Nielsen, Olesen (1973)]
[Vilenkin, Everett (1982)]

位相欠陥と対称性の破れ

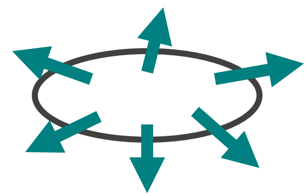
形成される位相欠陥の種類は、縮退している真空の形 $\mathcal{V}$ に依存する

= 破れた対称性 (南部ゴールドストーン定理)

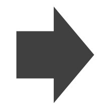
$\mathcal{V} \simeq \mathbb{Z}_2$

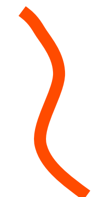


Domain wall

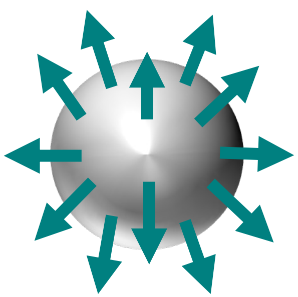


$\mathcal{V} \simeq U(1) \simeq S^1$

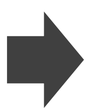




Cosmic string



$\mathcal{V} \simeq SU(2)/U(1) \simeq S^2$



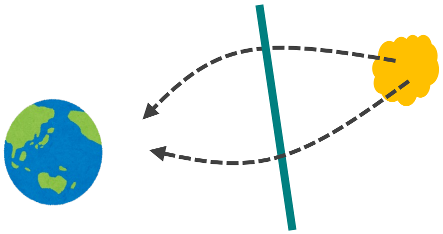
Monopole

[‘tHooft (1974), Polyakov (1974)]

宇宙に存在する位相欠陥の種類から過去の相転移で破れた対称性を探索することができる！

BSM and cosmic strings

Cosmic strings are good tools to detect new physics BSM.

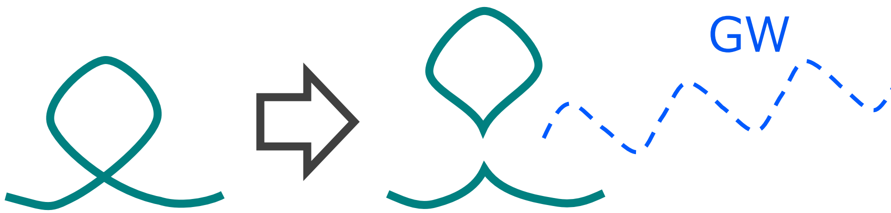


Gravitational lensing

$G\mu \lesssim 3.0\times10^{-7}$

$(\leftrightarrow v \lesssim 10^{15}\ \mathrm{GeV})$

[Christiansen et al. (2013)]



Stochastic gravitational waves

$G\mu \lesssim 4.7\times10^{-9}$

$(\leftrightarrow v \lesssim 10^{14}\ \mathrm{GeV})$

[NANOGrav collaboration (2023)]

μ: string tension

<u>Research motivation</u>

- The discussion of observables relies on simplified assumption about cosmic strings.
- Various string-like solitons have been proposed in field theory.

➡ Formation models? Observational signatures?

1. Topological defects

2. Local and Global string

3. Semilocal string

4. Results of our work

Local string

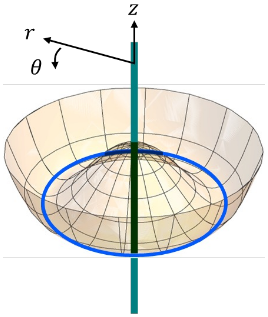
In field theory, a cosmic string is a classical solution (= soliton).

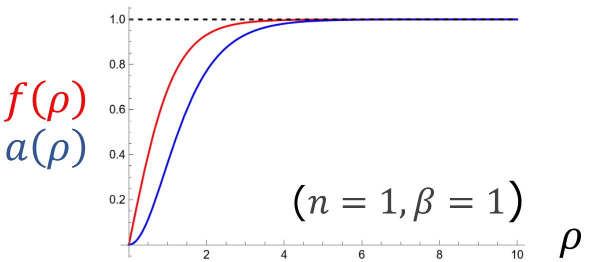
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left|D_\mu\phi\right|^2 - \lambda(|\phi|^2 - v^2)^2 \qquad \left(D_\mu\phi = \left(\partial_\mu - igA_\mu\right)\phi\right)$$

String solution [Abrikosov (1957), Nielsen, Olesen (1973)]

$$\phi(x) = f(r)ve^{in\theta},\ \vec{A}(x) = \frac{na(r)}{gr}\,\vec{e}_\theta,\ (\text{others}) = 0$$

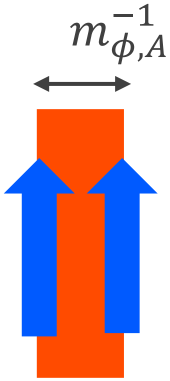
$(f(0) = a(0) = 0, f(\infty) = a(\infty) = 1$, n: winding number$)$





$\left(\rho \equiv gvr = m_A r/\sqrt{2}, \beta \equiv m_\phi^2/m_A^2 = 2\lambda/g^2\right)$

Schematic picture



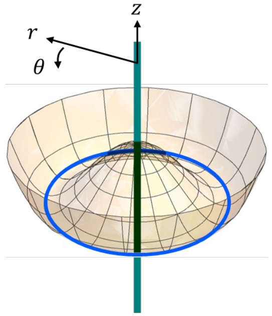
Excited scalar radial mode

$\vec{B} = \frac{na'}{gr}\vec{e}_z$

Tension

$$\mu = \int d^2x \left[\frac{1}{2}\left(\frac{na'}{gr}\right)^2 + (vf')^2 + \frac{n^2(1-a)^2}{r^2}v^2f^2 + \lambda v^4(1-f^2)^2\right] = (\text{finite})$$

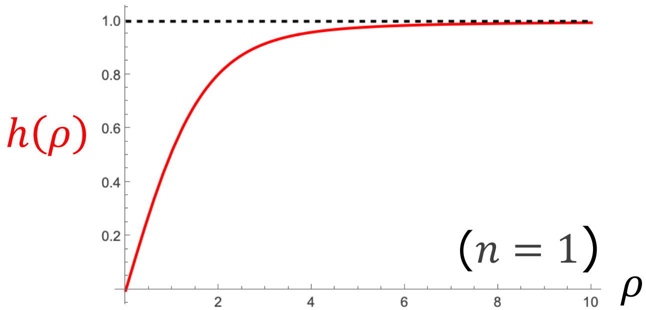
Global string



$$\mathcal{L} = \left|\partial_\mu \phi\right|^2 - \lambda(|\phi|^2 - v^2)^2$$

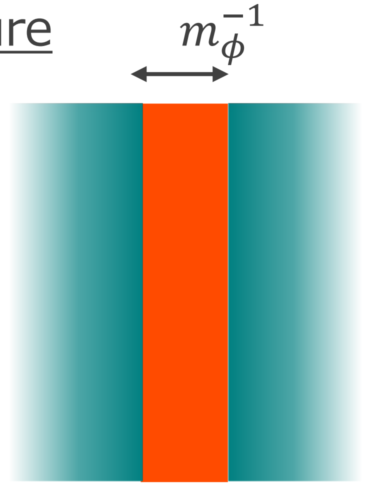
String solution [Vilenkin, Everett (1982)]

$$\phi(x) = h(r) v e^{in\theta} \qquad (h(0) = 0, h(\infty) = 1,\ n\text{: winding number})$$



$(\rho \equiv \sqrt{2\lambda} v r = m_\phi r/\sqrt{2})$

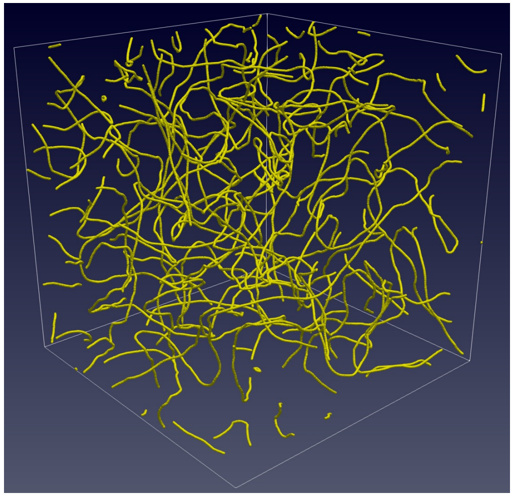
Schematic picture



Tension

$$\mu = \int d^2x \left[(vh')^2 + \frac{n^2}{r^2} v^2 h^2 + \lambda v^4 (1-h^2)^2\right] \simeq 2\pi v^2 \int_{m_\phi^{-1}}^{H^{-1}} dr\, r \left(\frac{n}{r}\right)^2 = 2\pi n^2 v^2 \log \frac{m_\phi}{H}$$

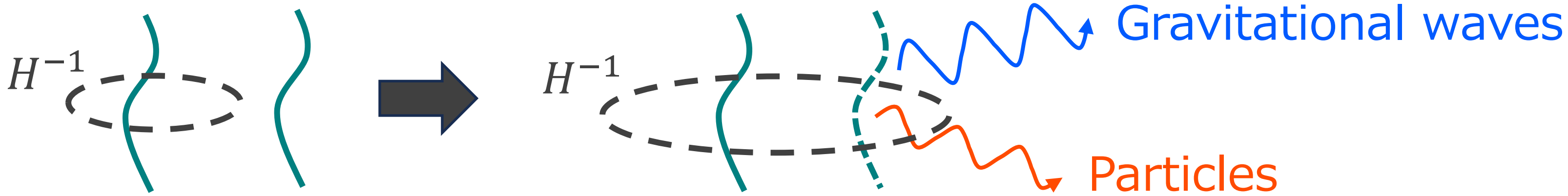
Evolution in the universe



After the phase transition, cosmic strings form a network across the universe.

A network evolves in the expanding universe while losing energy.

H: Hubble scale

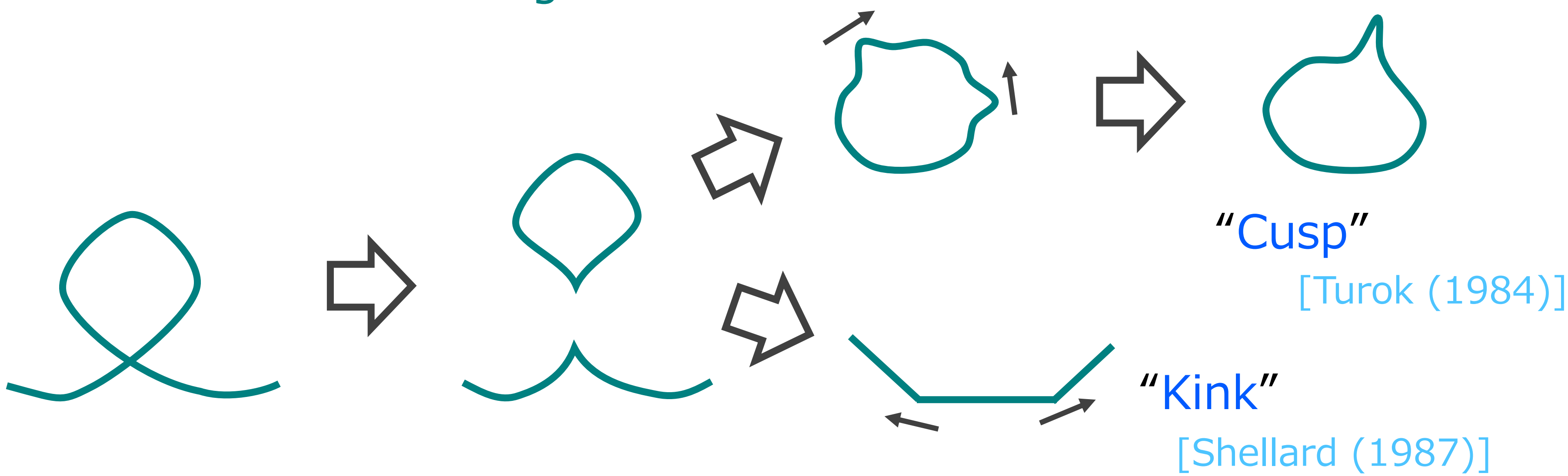


The number of strings per Hubble volume approaches a constant.
(= Scaling behavior [Martins, Shellard (2002)])

String density: $\rho_s \simeq \frac{c\mu t}{t^3} \propto t^{-2}$, Critical density: $\rho_{cr} = \frac{3H^2}{8\pi G} \propto t^{-2}$

Particle emission from local string

For local strings, particle emission mainly comes from structures on the scale of the string core.

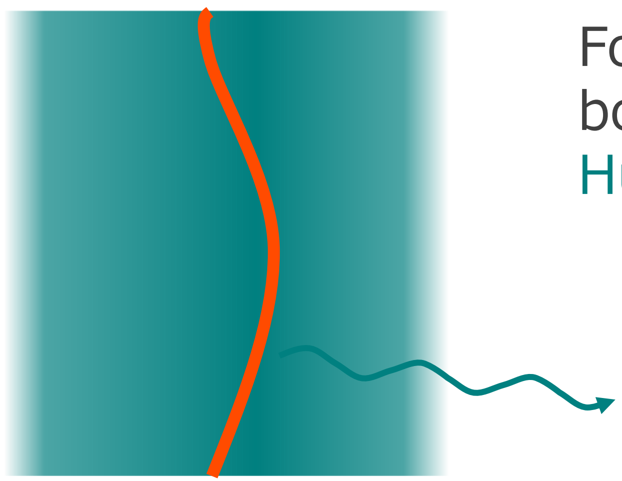


Cusps and kinks induce the emission of both string constituents and particles coupled to the string.

➡ The characteristic momentum of emitted particle is set by the core scale v. [Olum, Blanco-Pillado (1998)]

Particle emission from global string

Global strings store most of their energy in the Goldstone gradients outside the string core.



Curvature $\sim H$

For global strings, Nambu-Goldstone boson emission is dominated by Hubble-scale string dynamics.

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

This behavior has been studied both analytically and numerically.

[Vilenkin, Vachaspati (1987), Garfinkle, Vachaspati (1987), Davis, Shellard (1989)]

1. Topological defects

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4. Results of our work

Extension of the AH model

ϕ_1, ϕ_2: scalar fields with the same $U(1)$ charge

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

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

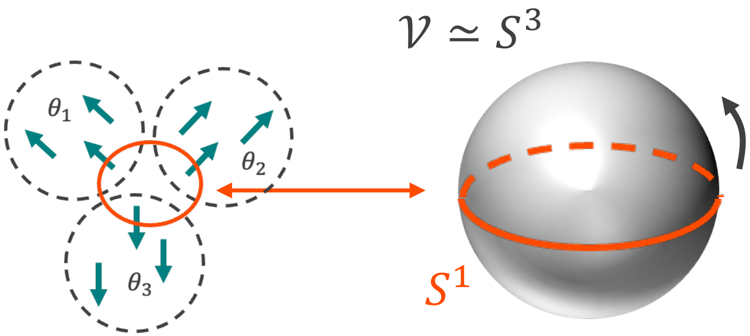
$$U(1)_{\rm gauge}: \quad \phi_{1,2} \to e^{ig\alpha(x)}\phi_{1,2}, \quad A_\mu \to A_\mu - \partial_\mu\alpha$$

$$SU(2)_{\rm global}: \quad \phi \equiv \begin{pmatrix}\phi_1 \\ \phi_2\end{pmatrix} \to U\phi, \quad A_\mu \to A_\mu \qquad (U \in SU(2))$$

The vacuum space

$$\mathcal{V} = \{\phi_1, \phi_2 \,|\, |\phi_1|^2 + |\phi_2|^2 = v^2/2\} \simeq S^3$$

No string formed?

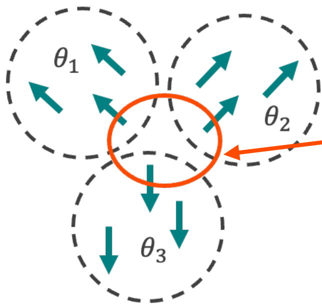


Finite energy condition and winding

$$E = \int d^3x \left[\frac{1}{2}\left(F_{0i}^2 + F_{ij}^2\right) + |D_i\phi_1|^2 + |D_i\phi_2|^2 + \lambda(|\phi|^2 - v^2)^2\right] \qquad \phi \equiv \begin{pmatrix}\phi_1 \\ \phi_2\end{pmatrix}$$

⇨ $F_{\mu\nu} = 0,\ D_i\phi_a = 0,\ |\phi|^2 = v^2$ at $r \to \infty$

Wind

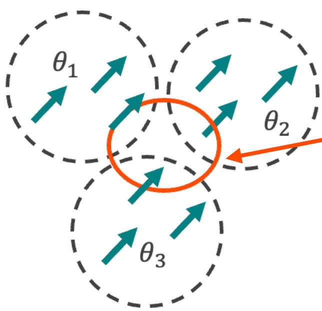


$\phi(\theta) = e^{i\theta} v\eta,\quad A_\mu(\theta) = \frac{\delta_{\mu\theta}}{gr}$ (η:constant doublet) $\eta^\dagger\eta = 1$

$U \in SU(2)$ ✖ $U \notin U(1)$

($|D_i\phi_{1,2}|^2$ diverges.)

Unwind



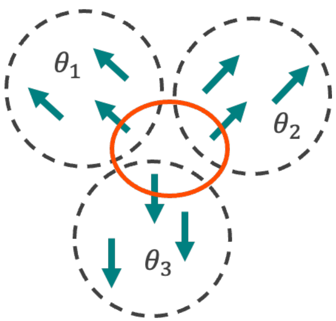
$\phi(\theta) = v\eta,\quad A_\mu(\theta) = 0$

Unwinding is energetically forbidden.

String-like or texture-like

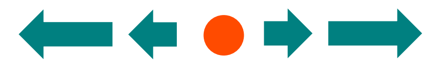
$$\phi(\theta) = \frac{v}{\sqrt{2}} e^{i\theta} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

at $r \sim \infty$



- String-like configuration

$$\phi(x) = \frac{v}{\sqrt{2}} e^{i\theta} \begin{pmatrix} f(r) \\ 0 \end{pmatrix} \qquad (f(0) = 0)$$

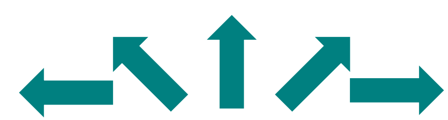


$|\langle\phi\rangle|^2 = 0$ at the center.

$\rightarrow$ The potential energy ($\propto \lambda$) is dominant.

- Texture-like configuration

$$\phi(x) = \frac{v}{\sqrt{2}} \begin{pmatrix} e^{i\theta} \tilde{f}(r) \\ \tilde{h}(r) \end{pmatrix} \qquad (\tilde{f}(r)^2 + \tilde{h}(r)^2 = 1)$$



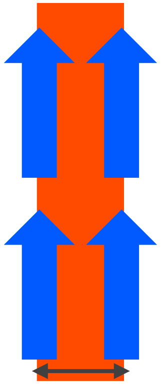
$|\langle\phi\rangle|^2 = v^2/2$ in the circle.

$\rightarrow$ The gradient energy ($\propto g^2$) is dominant.

If $2\lambda < g^2$, string-like configuration is realized. = Semilocal string

[Achucarro, Vachaspati (1991)]

Semilocal string



$\sim v^{-1}$

- Configuration resembles a local string.

$$\phi(x) = \frac{v}{\sqrt{2}} e^{in\theta} \begin{pmatrix} f(r) \\ 0 \end{pmatrix}, \quad A_\mu(x) = \frac{\delta_{\mu\theta} n a(r)}{g r}$$

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

$$\phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix} = \begin{pmatrix} \varphi_r \cos(\vartheta/v)\, e^{i\theta_1/v} \\ \varphi_r \sin(\vartheta/v)\, e^{i\theta_2/v} \end{pmatrix} = \varphi_r e^{i\theta_+/v} \begin{pmatrix} \cos(\vartheta/v)\, e^{i\theta_-/v} \\ \sin(\vartheta/v)\, e^{-i\theta_-/v} \end{pmatrix}$$

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

θ_-, ϑ: NG bosons due to $SU(2)_{\text{global}}$ breaking

$$\theta_\pm \equiv \frac{\theta_1 \pm \theta_2}{2}$$

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

1. Topological defects

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3. Semilocal string

4. Results of our work

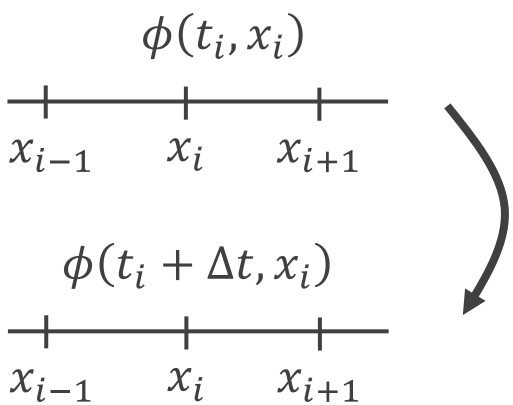
Field-theoretic lattice simulation

① $SU(2)_{global} \times U(1)_{gauge}$ model in the FLRW universe

$$ds^2 = g_{\mu\nu}dx^{\mu\nu} = -dt^2 + a^2(t)\left(dx^i\right)^2 = a^2(t)\left(-d\tau^2 + \left(dx^i\right)^2\right)$$

$$S = -\int \sqrt{-g}\, d^4x \left[\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \left|D_\mu\phi_1\right|^2 + \left|D_\mu\phi_2\right|^2 + \lambda\left(|\phi_1|^2 + |\phi_2|^2 - \frac{v^2}{2}\right)^2\right]$$

② Calculating time evolution of fields in a lattice space



EoM

$$\frac{d^2\phi_{1,2}}{dt^2} + 3H\frac{d\phi_{1,2}}{dt} - \frac{D_iD_i\phi_{1,2}}{a^2} + \frac{\partial V}{\partial\phi_{1,2}^*} = 0$$

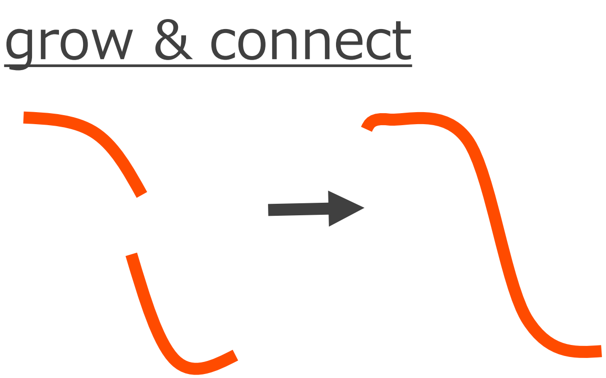
$$\frac{d^2A_i}{dt^2} + H\frac{dA_i}{dt} - \frac{1}{a^2}\left(\partial_j\partial_jA_i - \partial_i\partial_jA_j\right) - 2g\mathrm{Im}(\phi^*D_i\phi) = 0$$

(Temporal gauge $A_0 = 0$)

Assuming the radiation-dominated universe ($a \propto t^{\frac{1}{2}} \propto \tau, H = \frac{1}{2t} \propto \tau^{-2}$), we evolve $\phi_{1,2}$ and A_i in the lattice space ($N^3 = 4096^3$).

Previous works

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

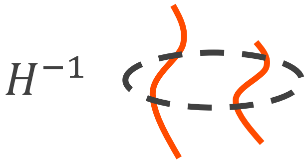


Various length of segments are produced through Kibble-Zurek mechanism.

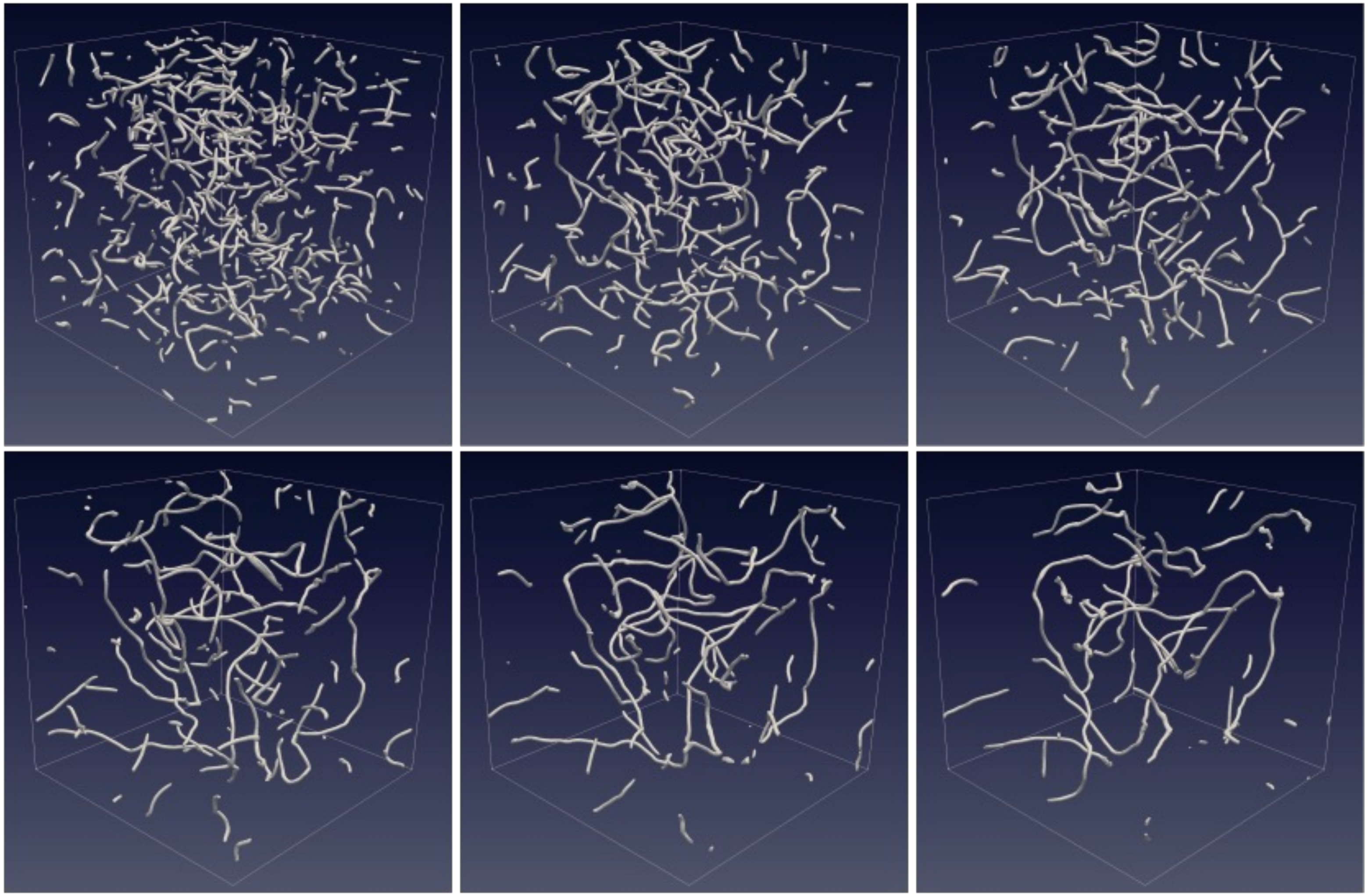
Network reaches a scaling regime.

$$L \propto t$$

L: total length per Hubble volume

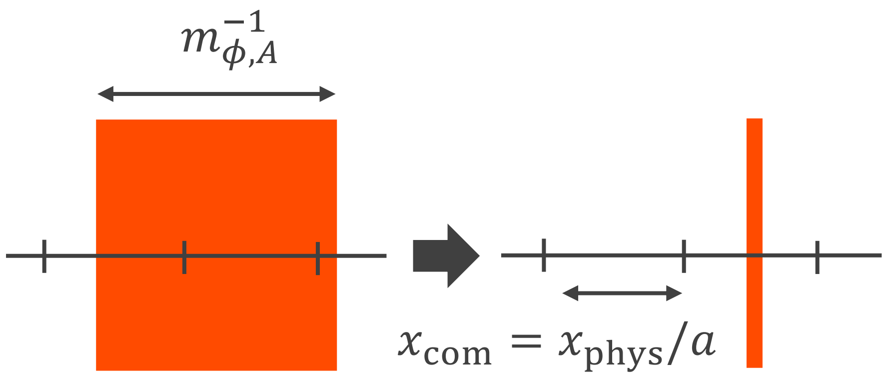


Snapshots of simulation



$v\tau = 61, 101, 141, 181, 221, 261$ (τ: conformal time in the FLRW metric)

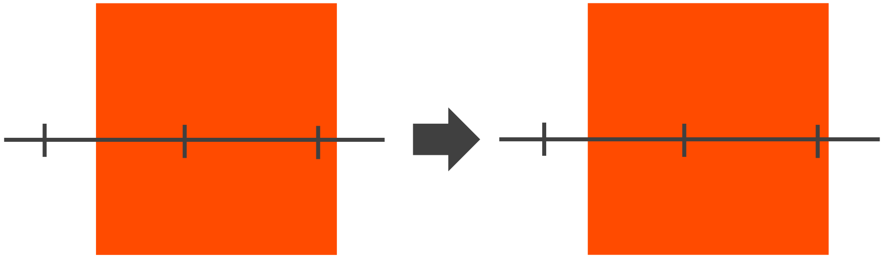
Physical string vs. Fat string



Physical string simulation

- Fixing the coupling constants
  ($\lambda = \text{const.} \quad g = \text{const.}$)
  ➡ The string width decreases on the comoving lattice.
- Short simulation time

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



- The coupling constants are time-dependent.
  ($\lambda \propto a^{-2} \quad g \propto a^{-1}$)
  ➡ The string width is fixed on the comoving lattice.
- Long simulation time

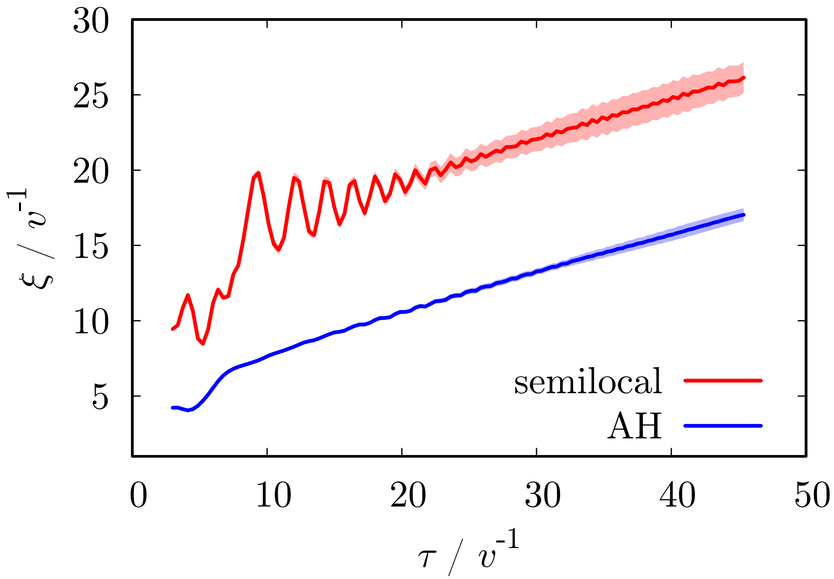
We performed simulations for both physical and fat strings.

Scaling behavior

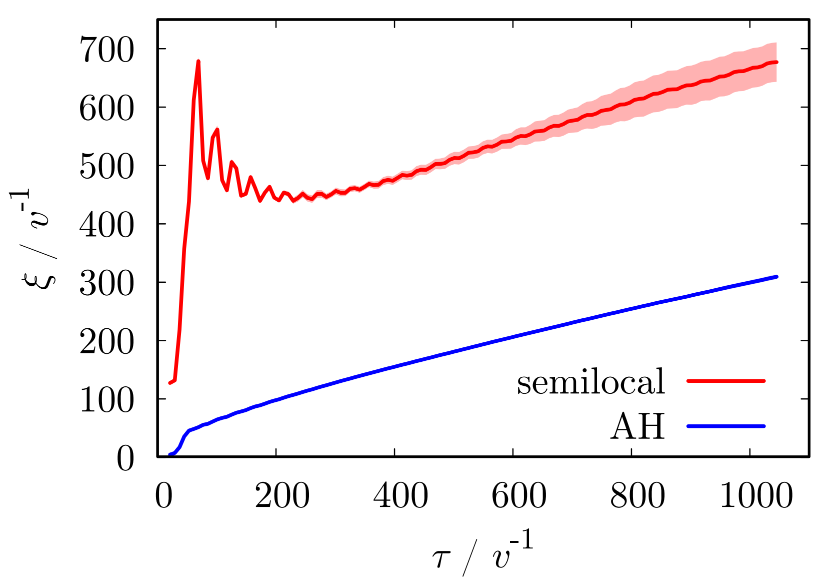
$$\xi = \sqrt{\frac{H^{-3}}{L}} \propto t$$

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

(Physical string)



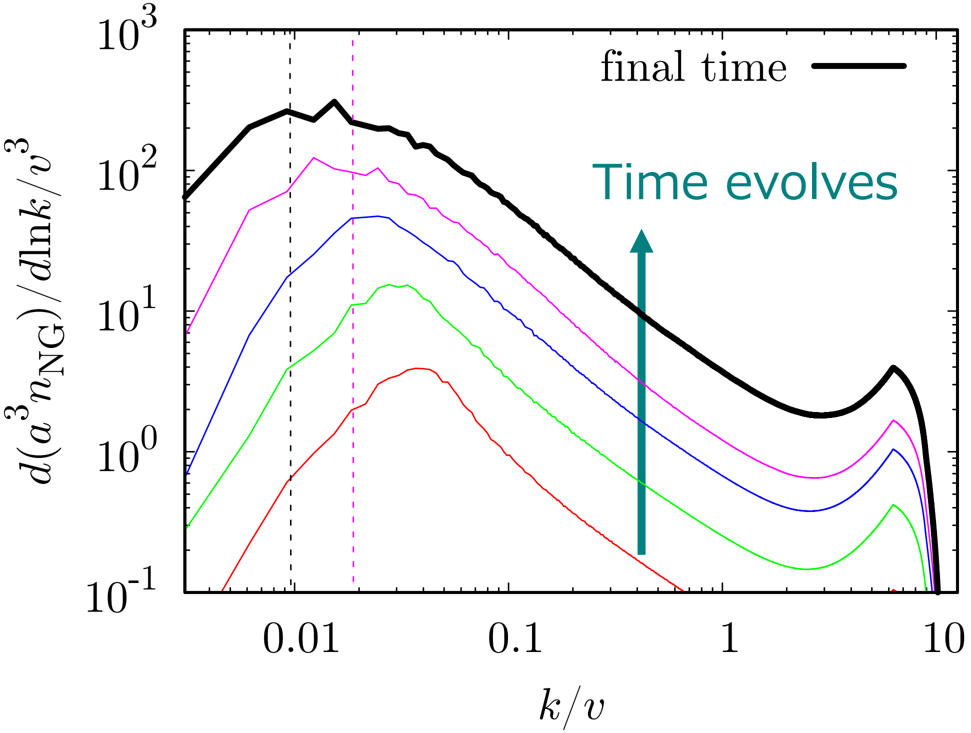
(Fat string)



- We confirm scaling behavior. ($\xi_{\rm com} \propto \tau \Leftrightarrow \xi_{\rm phys} \propto t$)
  (consistent with the previous works [Achucarro et al. (2014)])
- Fat-string simulations reproduce the qualitative behavior of physical-string simulation.

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 τ increases.

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

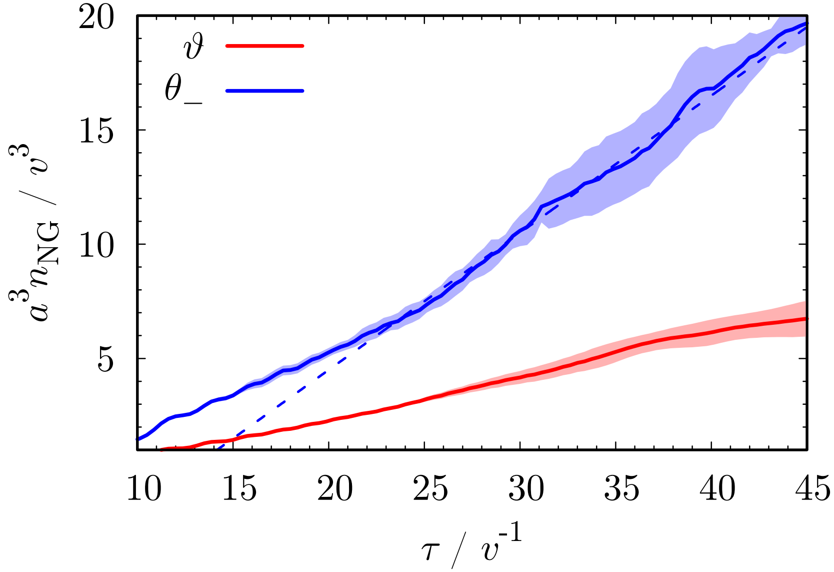
$$\Leftrightarrow \ k_{\mathrm{phys}} \simeq 10H$$

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

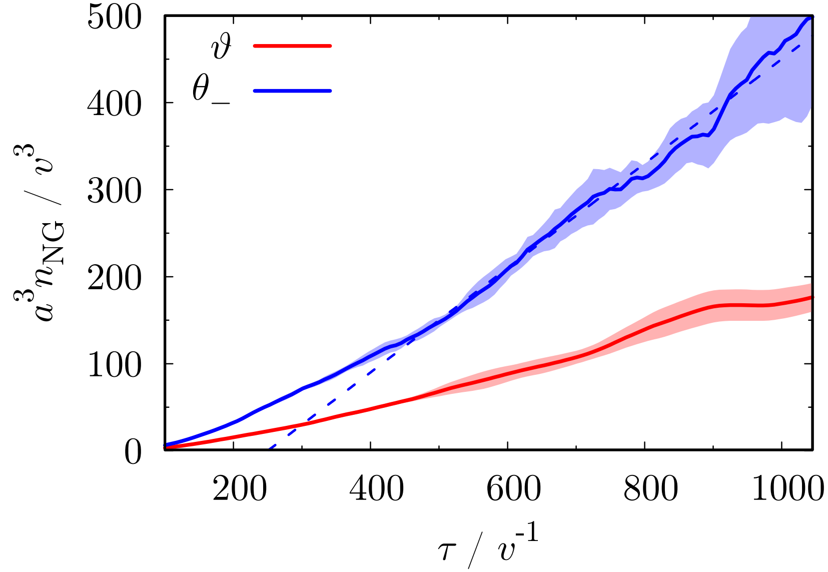
Number density of NG bosons

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

(Physical string)



(Fat string)



- $a^3 n_{\rm NG}$ grows linearly with the comoving time. ($\Leftrightarrow$ $n_{\rm NG} \propto H$.)

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

Pseudo NG boson dark matter

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

= pseudo NG bosons

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

$$\supset -m_{\text{NG}}^2 v^2 \cos(2\vartheta/v)\left|e^{i\theta_-/v}\right|^2 \supset -2m_{\text{NG}}^2\left|\vartheta e^{i\theta_-/v}\right|^2$$

They can potentially play the role of dark matter.

[Many works by Abe-san]

- Produced via thermal freeze-out

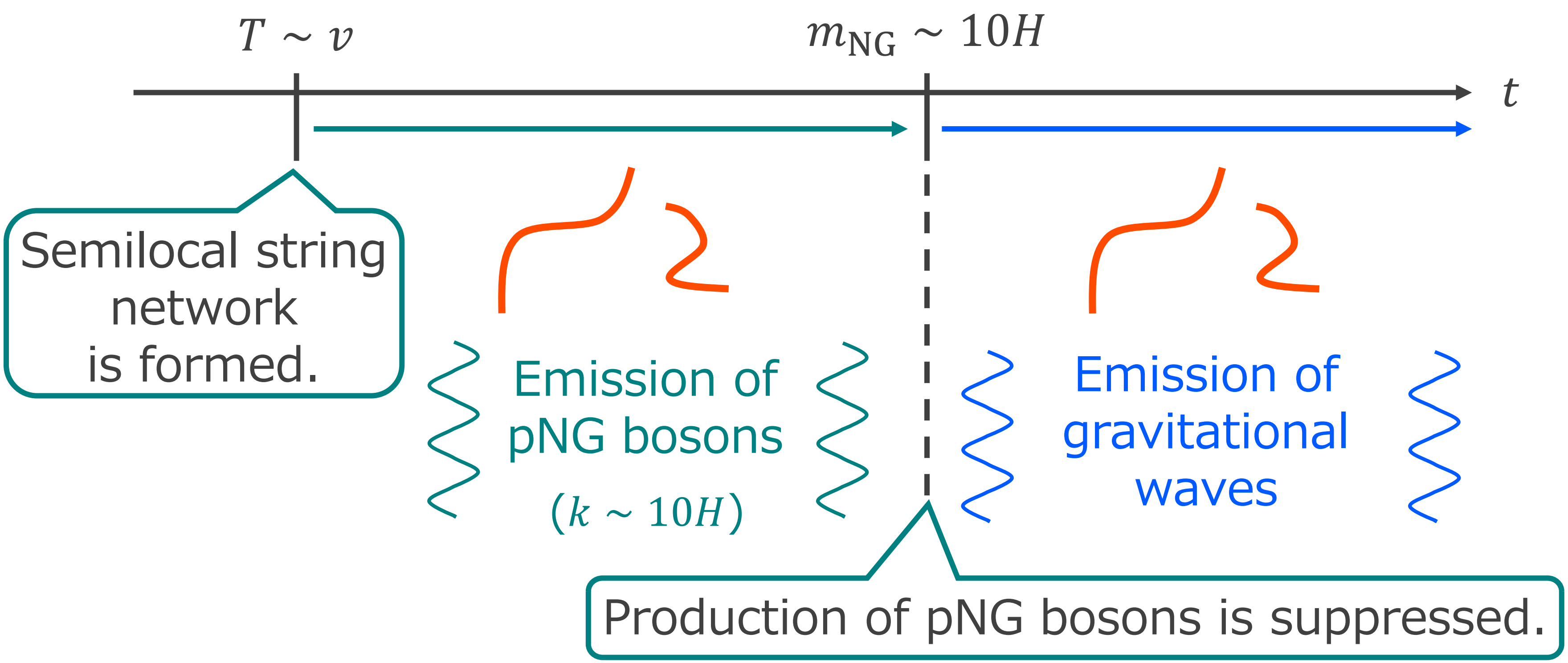
  $m_{\text{NG}} \sim 50\ \text{GeV} - \mathcal{O}(10)\ \text{TeV}$

  (depends on portal coupling with SM particles)

We propose another production mechanism by using the semilocal string network.

Production from semilocal string

We propose a non-thermal production mechanism for pNG DM from the semilocal string network. (no coupling with SM particles)

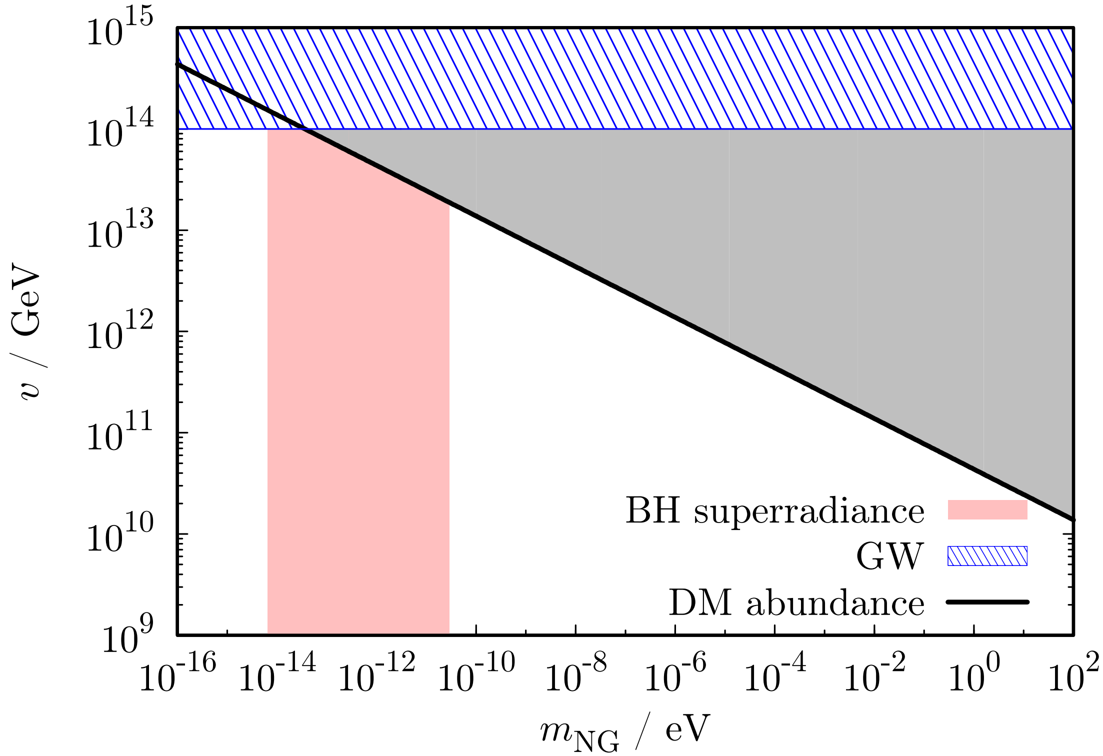


The relic abundance is determined by v and m_{NG}.

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

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

  [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 DM in a viable parameter region.