2026 9/3 TeVPA

Gravitational-Wave signals in Pulsar Timing Array from Confined Flux Tubes as Cosmic Strings

Kazuto Nakamura (Tohoku U.), Masaki Yamada (Tohoku U.)

Particle and Cosmology group D1

(arXiv:2512.16821 published in PRD)

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- Background
- Color flux tube as cosmic string
- Theory for string networks
- Our result: Delayed scaling and GWs spectrum
- Summary

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- **Background**
- Color flux tube as cosmic string
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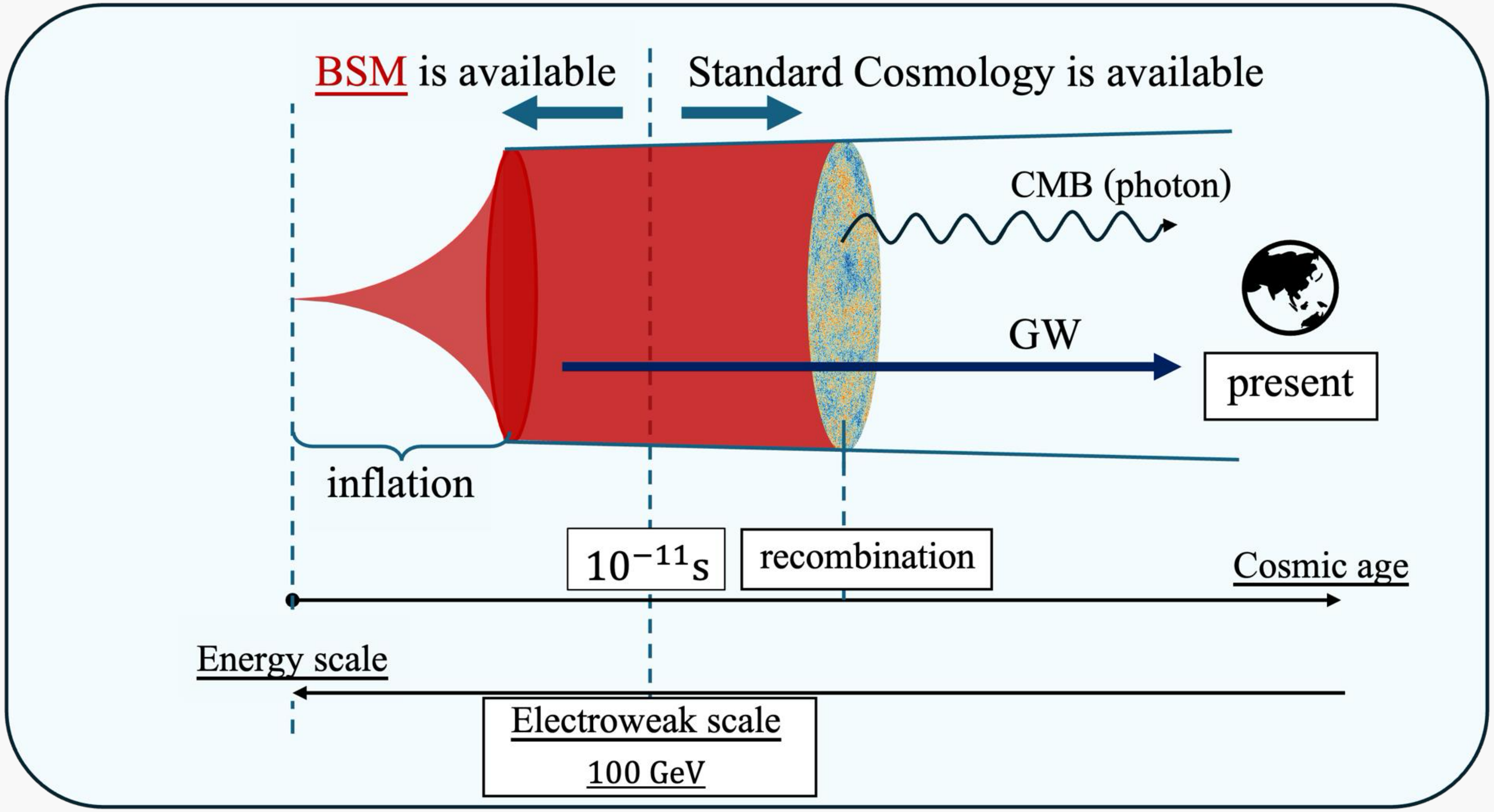
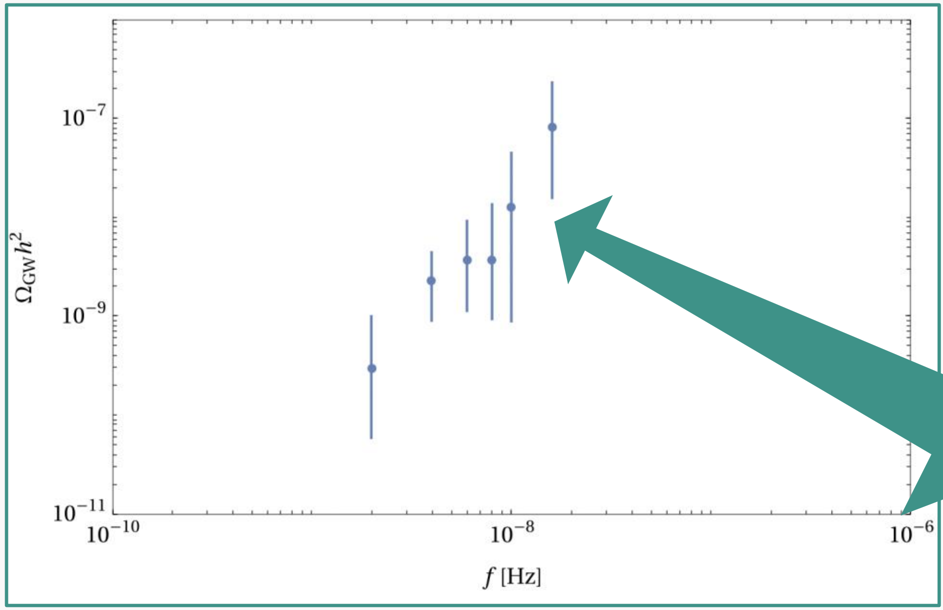
- Our result: Delayed scaling and GW spectrum
- Summary

Gravitational waves from BSM physics in the early universe can reach today

- GWs undergo almost no scattering and carry early-universe information
- They are observed as a stochastic GW background



Cosmic Superstring(CSS) can be a source of GWs



NANOGRAV collaboration, G. Agazie et al., Astrophys. J. Lett. 951 (2023) L8 [2306.16213].

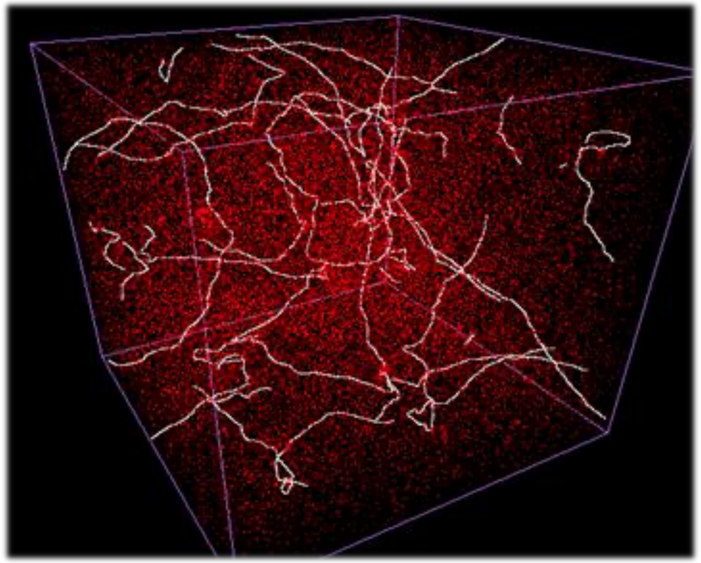
Multi-type CSS also arise in Gauge theory

Yamada,Yonekura 2022

(Bodiut, Victor Andrei. (2016). The Multiverse. 10.13140/RG.2.1.4131.0323)

Cosmic Superstring

- Macroscopic 1D object in string theory
- GWs are distributed over a wide range
- Quantum property



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- **Color flux tube as cosmic string**
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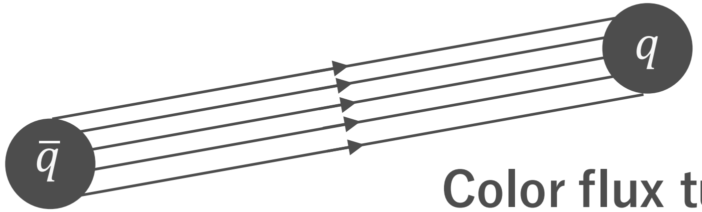
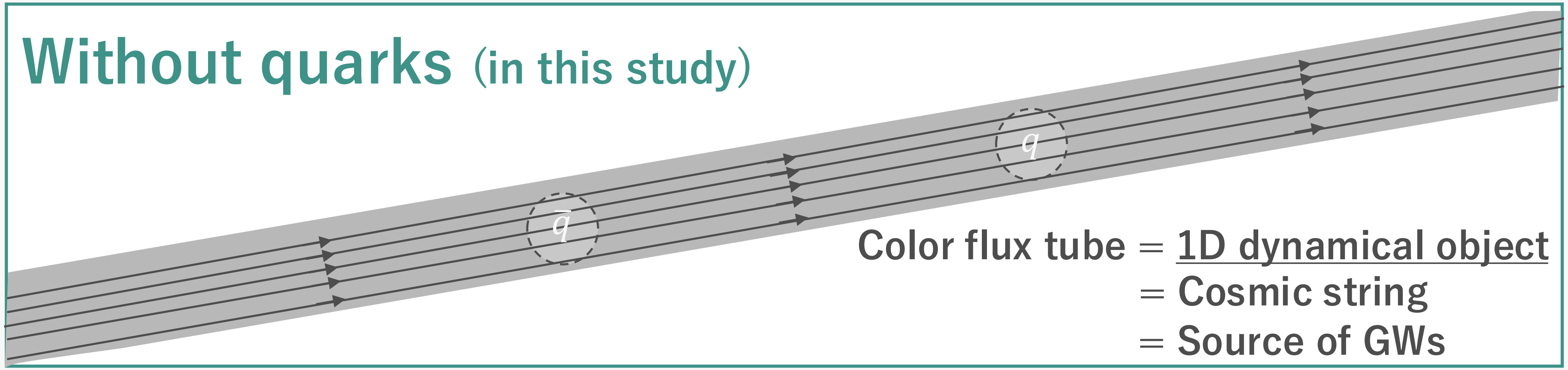
Stabel color flux tube behave as dynamical object

With quarks



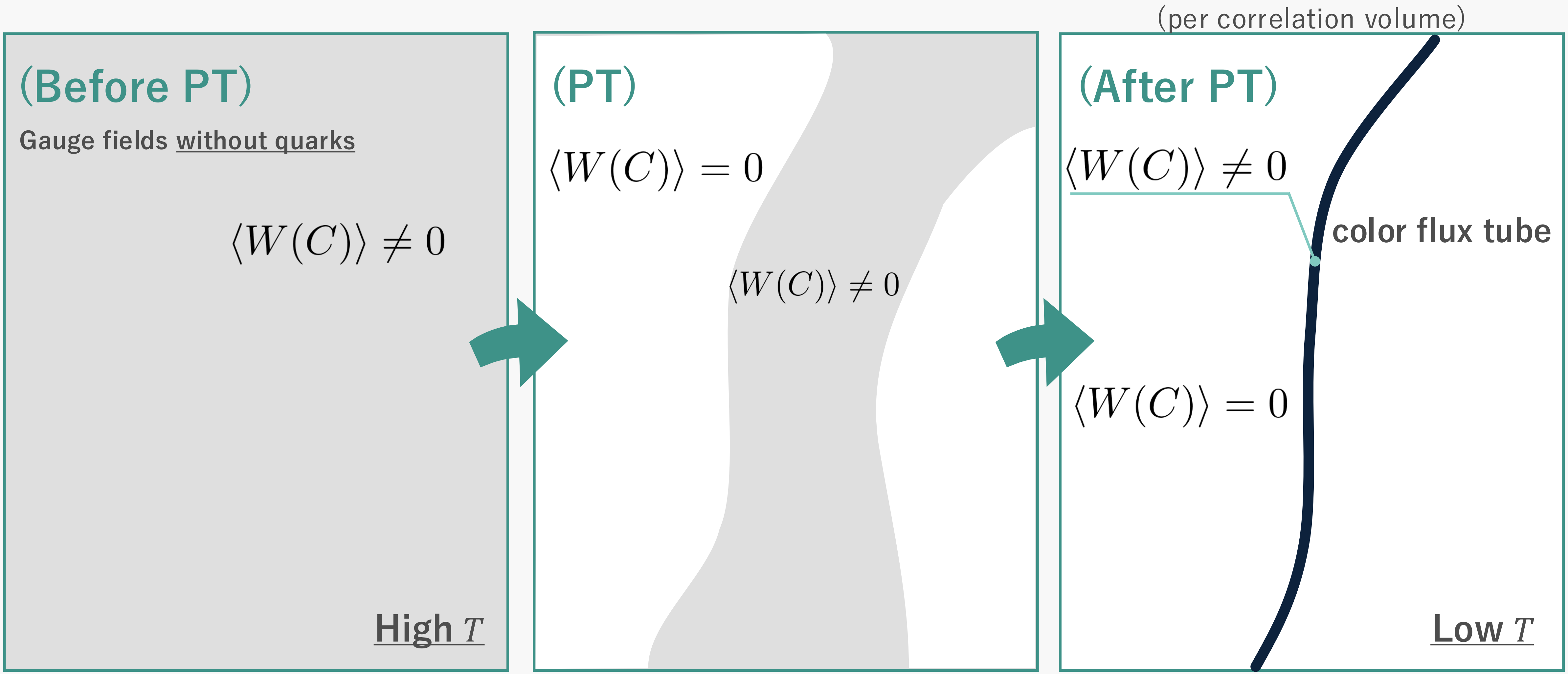
Color flux tube is cut by quarks

Without quarks (in this study)



Color flux tube = <u>1D dynamical object</u>
= Cosmic string
= Source of GWs

1st order Phase Transitions make color flux tube

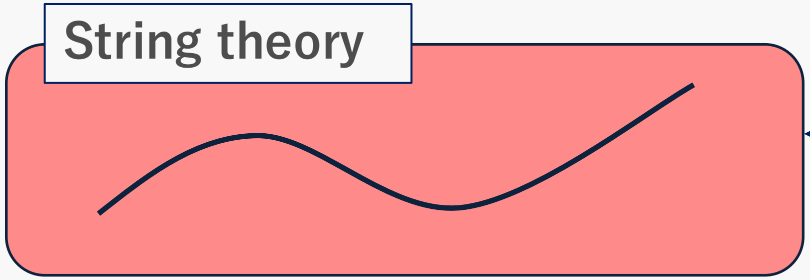


Color flux tube has Holographic dual description

$$S_{\mathrm{ws}} = \frac{1}{4\pi\alpha'}\int d^2\sigma\,\sqrt{h}\,h^{ab}G_{\mu\nu}(X)\partial_a X^\mu \partial_b X^\nu + \frac{1}{4\pi}\int d^2\sigma\,\sqrt{h}\,\Phi(X)R^{(2)} + \cdots$$

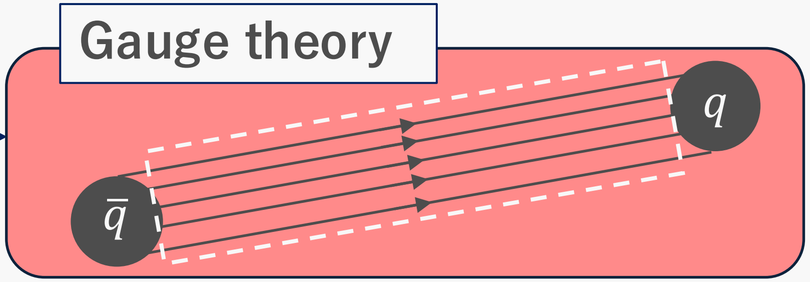
$$S_{\mathrm{YM}} = -\frac{1}{4g^2}\int d^4x\, F^a_{\mu\nu}F^{a\,\mu\nu},$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + f^{abc}A^b_\mu A^c_\nu$$



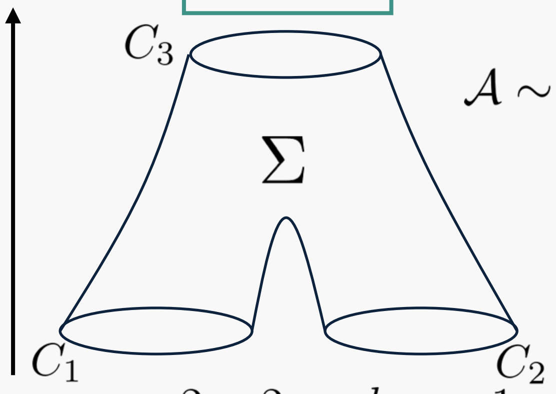
Same property

Holographic dual



$$\boxed{g_s \sim \frac{1}{N}}$$

$$\mathcal{A} \sim Z_{\mathrm{string}}[\Sigma] \sim g_s^{-\chi} = g_s$$



$$\chi = 2 - 2g - h = -1$$

$$\mathcal{A} \sim \left\langle W_F^\dagger(C_3)\,W_F(C_1)\,W_F(C_2)\right\rangle \sim N^\chi = N^{-1}$$

(for large N)

contents

The Network approaches the scaling regime

Reconnection of strings

- When strings collide, loop are produced via interactions called reconnection.

When long strings are dense

- Frequent reconnection

⇒ String number density decreases faster than cosmic expansion.

When long strings are dilute

- Suppressed reconnection

⇒ String number density decreases more slowly than cosmic expansion.

Quantitative modeling of this network ＝VOS model

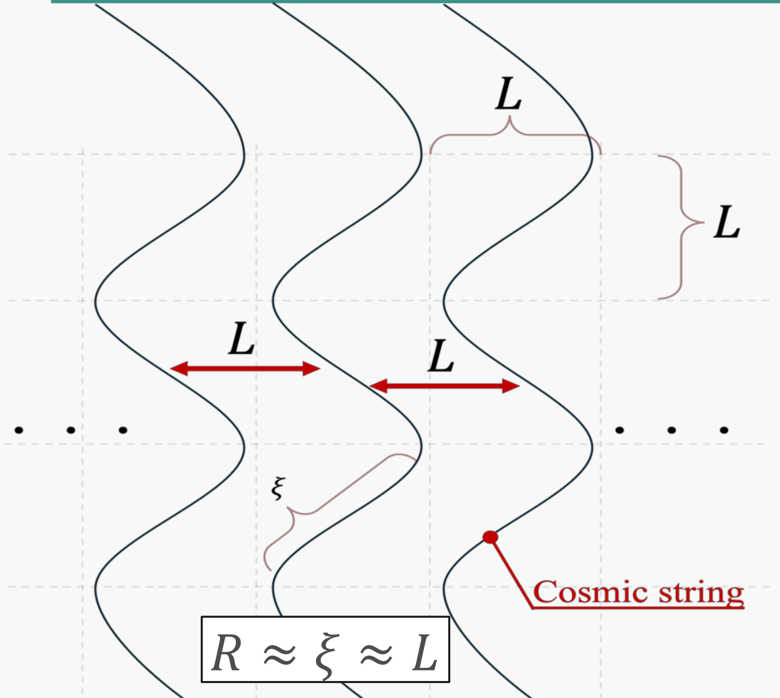
We can use the VOS model to study network

Statistical quantities

$$v,\ \rho = \frac{\mu L}{L^3} = \frac{\mu}{L^2},\ L \equiv \gamma(t) \cdot t$$

Nambu-Goto action

$$S_{\mathrm{NG}} = -\mu \int d^2\zeta \sqrt{-\gamma}$$



(Background: expanding universe)

μ : Tension of string

$k(v) = \frac{2\sqrt{2}}{\pi}\frac{1-8v^6}{1+8v^6}$

$\tilde{c}$: loop chopping efficiency

$$\frac{\dot{\gamma}}{\gamma} = \frac{1}{2t}\left(2Ht(1+v^2) - 2 + \frac{\tilde{c}v}{\gamma}\right)$$

$$\dot{v} = \frac{1-v^2}{t}\left(\frac{k(v)}{\gamma} - 2Htv\right)$$

VOS model
(Velocity-dependent One Scale model)

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We consider color flux tube in pure Yang-Mills theory

Feature①

Color flux tubes in $\mathrm{Spin}(4N)$ $(N \geq 2)$

- We consider the gauge group $\mathrm{Spin}(4N)$ $(N \geq 2)$.
- Fermion doesn't exist.

⇒ color flux tube is stable even when it is macroscopic

⇒ color flux tube behave as cosmic string

Feature②

Three types of strings coexist

- The center of $\mathrm{Spin}(4N)$ $(N \geq 2)$ is given by $\mathbb{Z}_2 \times \mathbb{Z}_2$.
- Three string types arise: $(1,0), (0,1), (1,1)$.
- Two of them are symmetric.

Feature③

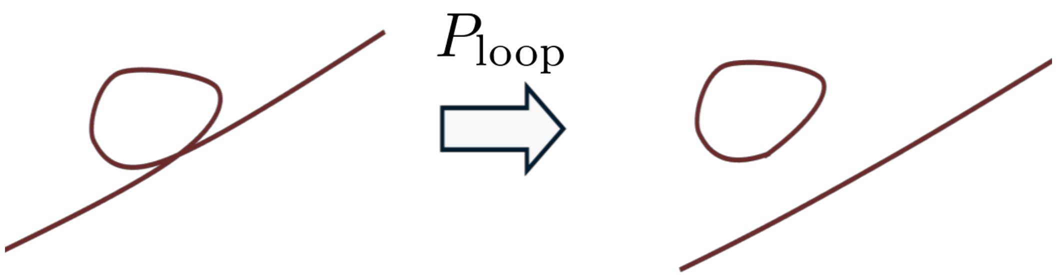
Interactions with reconnection probabilities $P_i < 1$

- All three strings possess quantum properties.
- Each string type has two types of interaction.
  - Loop formation
  - Zipper interaction

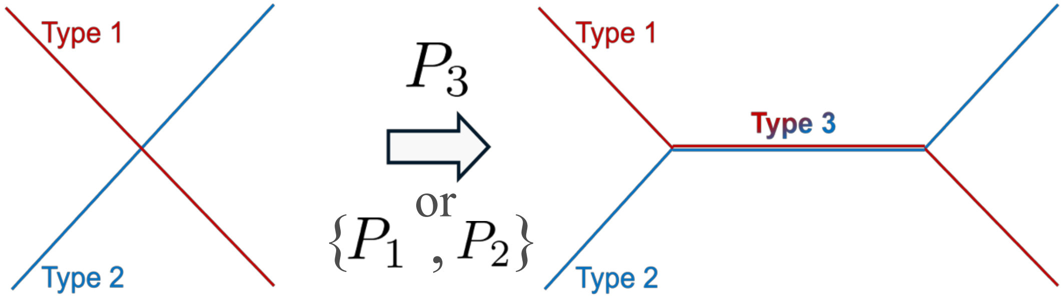
String networks have two quantum interactions

- Two interactions are included phenomenologically

Loop production



Zipper type interaction



Due to quantum effects, interactions occur probabilistically

⇒Introduced the reconnection probability P_i

VOS model with interaction and reconnection probability

VOS equations derived in this work $\{i,j,k\}=\{1,2,3\}$

$$\frac{\dot{\gamma}_i}{\gamma_i}=\frac{1}{2t}\left(2Ht(1+v^2)-2+P_{\rm loop}\frac{c_\xi\tilde{c}v_i}{\gamma_i^2}+P_k d\bar{v}_{ij}\frac{c_\xi}{\gamma_j^2}+P_j d\bar{v}_{ki}\frac{c_\xi}{\gamma_k^2}-P_i d\bar{v}_{jk}\frac{c_\xi\gamma_i^2}{\gamma_j^2\gamma_k^2}\right)$$

$$\dot{v}_i=\frac{1-v_i^2}{t}\left(\frac{k(v_i)}{c_\xi}-2Hv_it\right)$$

- $P_{\rm loop}$: reconnection probability for loop production
- P_i : reconnection probability for Zipper type interaction
- $\bar{v}_{ij}$: average relative velocity between type i and type j

const parameters

d , $\tilde{c}$, c_ξ

Relation

$P_1=P_2$

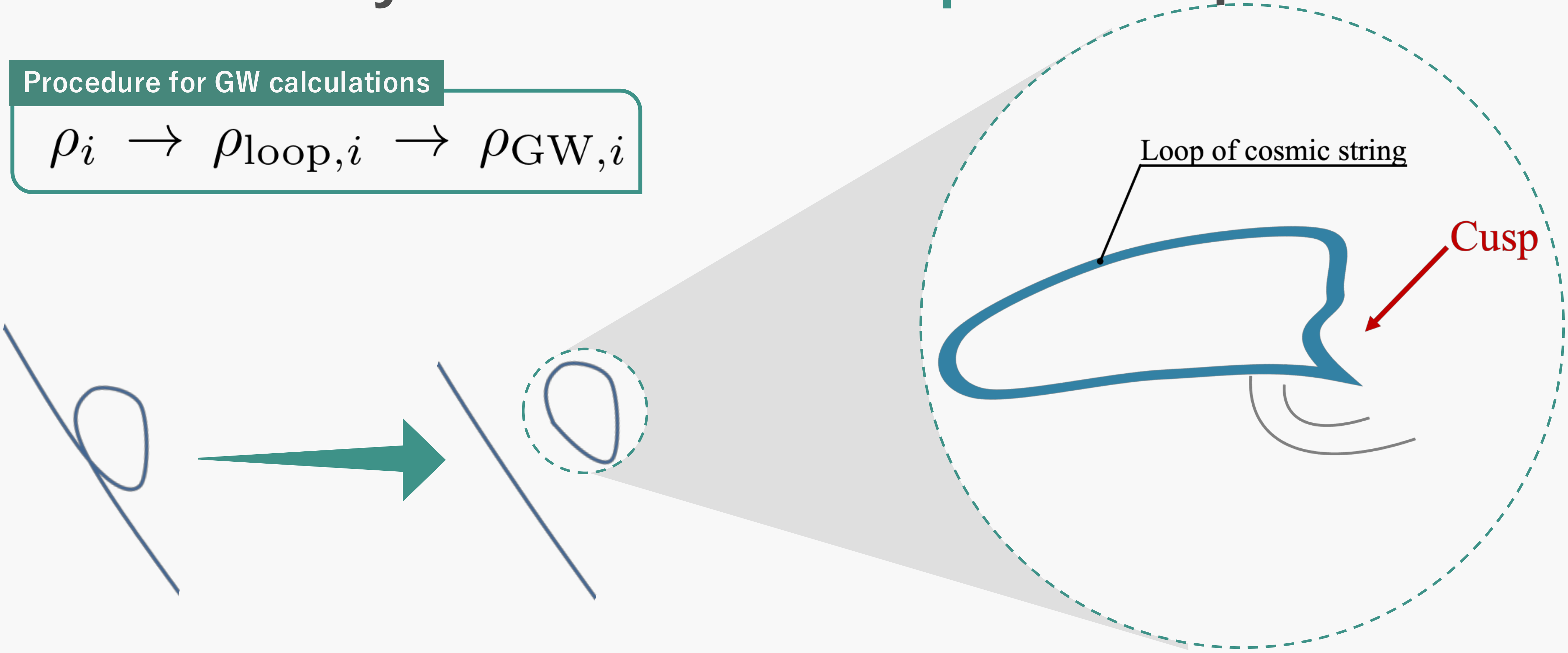
Two of three string types are symmetric.

⇒Only $\gamma_1=\gamma_2, \gamma_3$ are required.

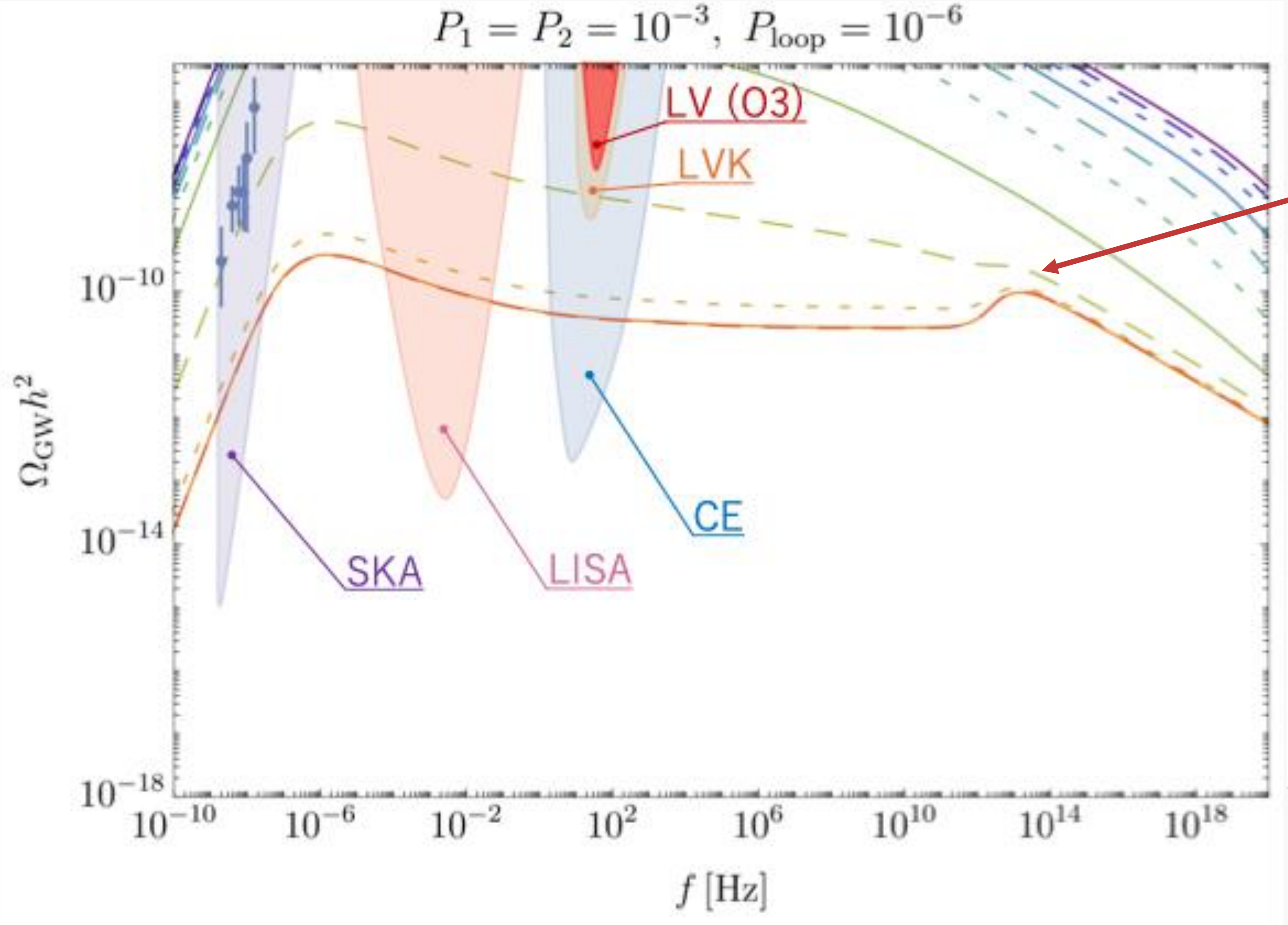
GW is mainly emitted from cusps on loops

Procedure for GW calculations

$$\rho_i \to \rho_{\mathrm{loop},i} \to \rho_{\mathrm{GW},i}$$



The GW signal can be explained for certain $P_{\{i\}}$



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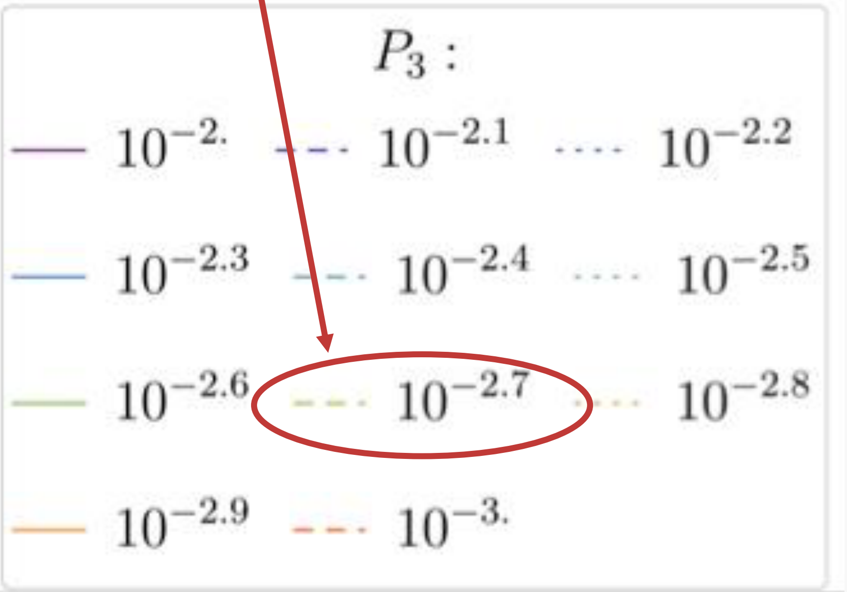
Best agreement with observations



contents

Distinct dynamics and GW emission are obtained

Dynamics of multi-species CSS networks

- Revealed the $P_{\{i\}}$ dependence of the scaling solution. (not shown here)
- Revealed the $P_{\{i\}}$ dependence of the scaling time. (not shown here)
- Demonstrated the existence of enhanced scaling time.

GW emission from multi-species CSS networks

- Revealed the $P_{\{i\}}$ dependence of the GW spectrum.
- Revealed the existence of parameter regions where high-frequency GWs are suppressed.

Comparison with GW observations

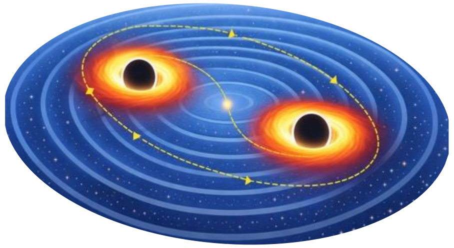
- May provide parameter regions that evade existing observational constraints while explaining PTA observations.
- Testable with future GW observation.

Other sources of GW

Candidate①

SMBHB

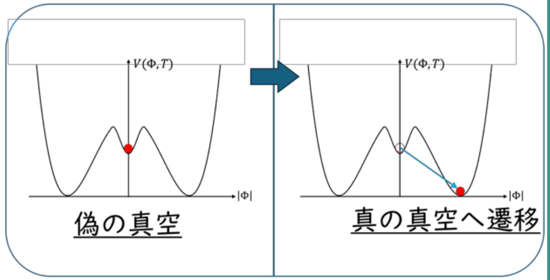
- Without BSM
- Final pc problem



Candidate②

1st-order PT in Dark Sector

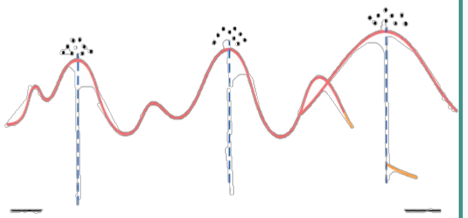
- Structure of DS
- Bubble creation



Candidate③

Scalar induced GW

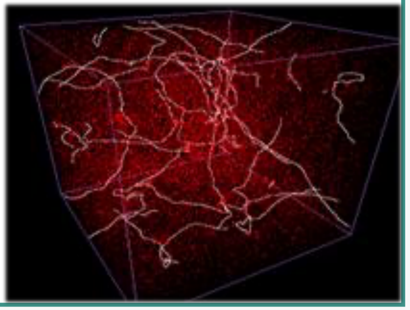
- Non-linear int
- PBH formation



Candidate④

Cosmic Superstring

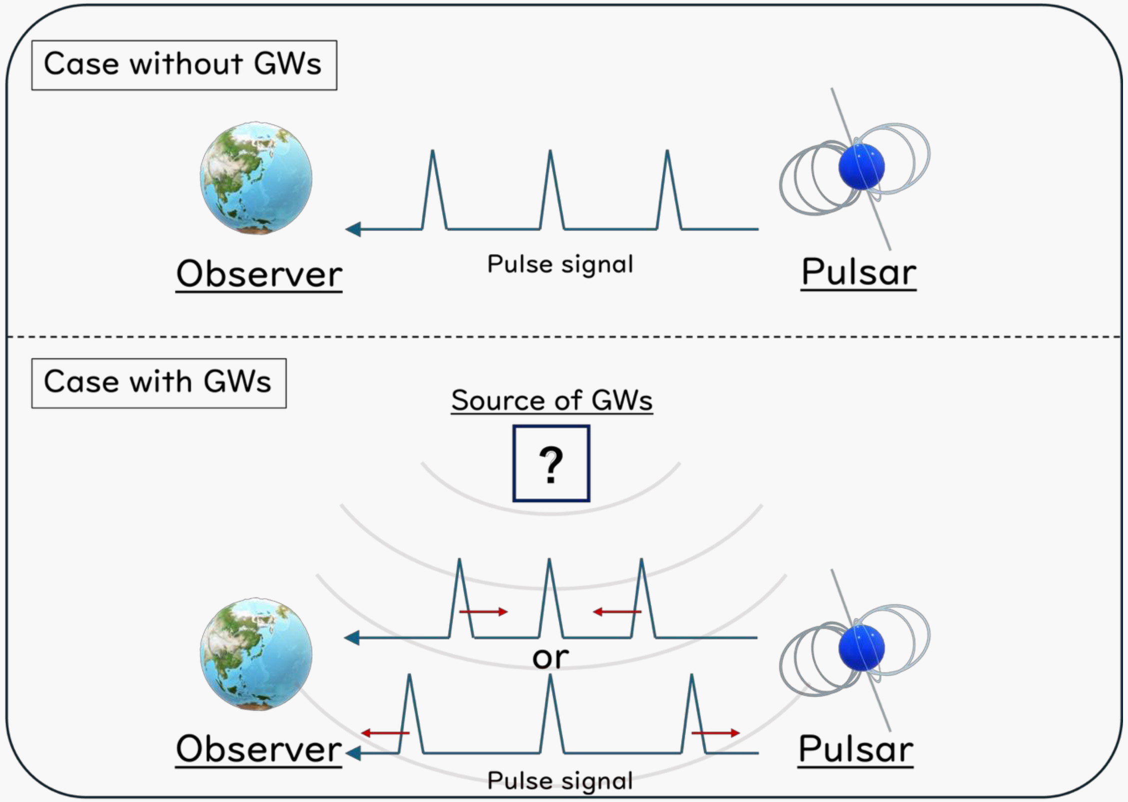
- Appear in string theory
- Over wide range

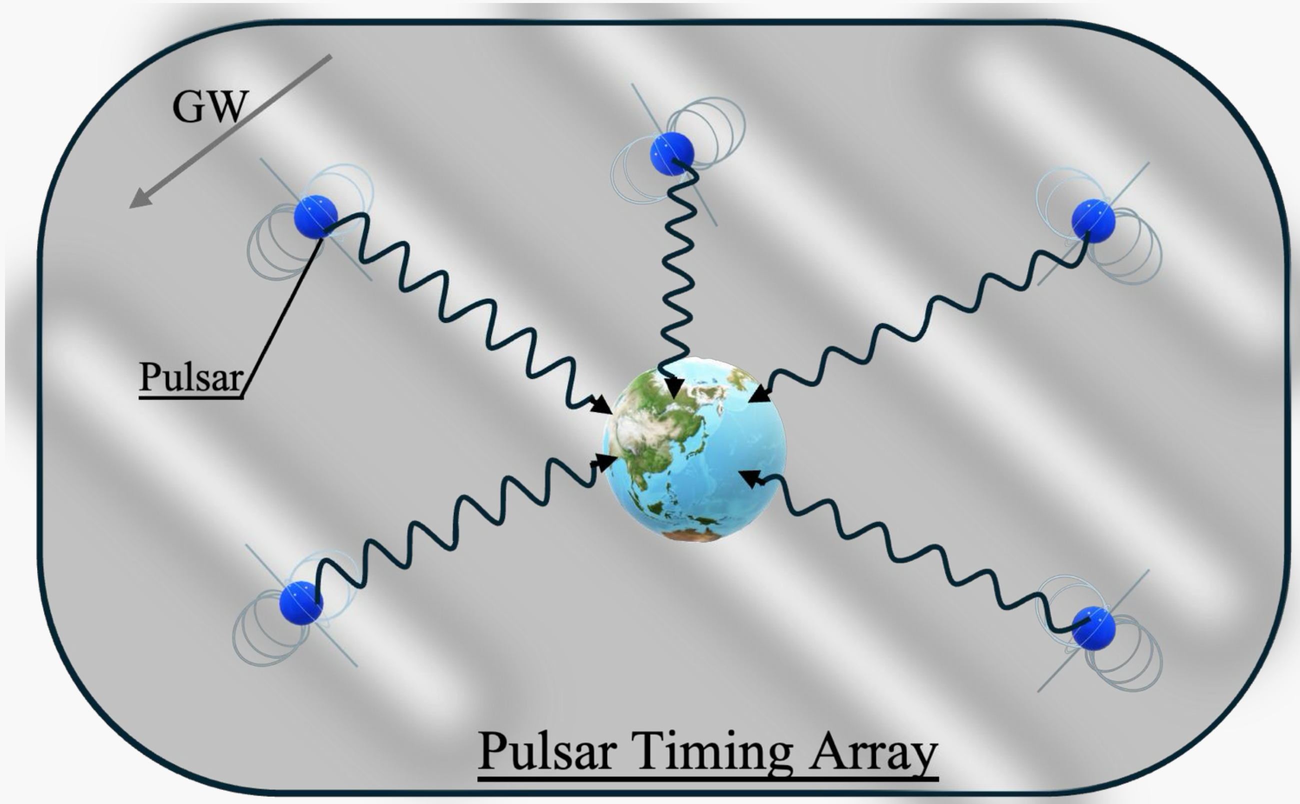


PTAs have detected a GW signal of unknown origin

- **Galaxy-scale GW detection with pulsars**

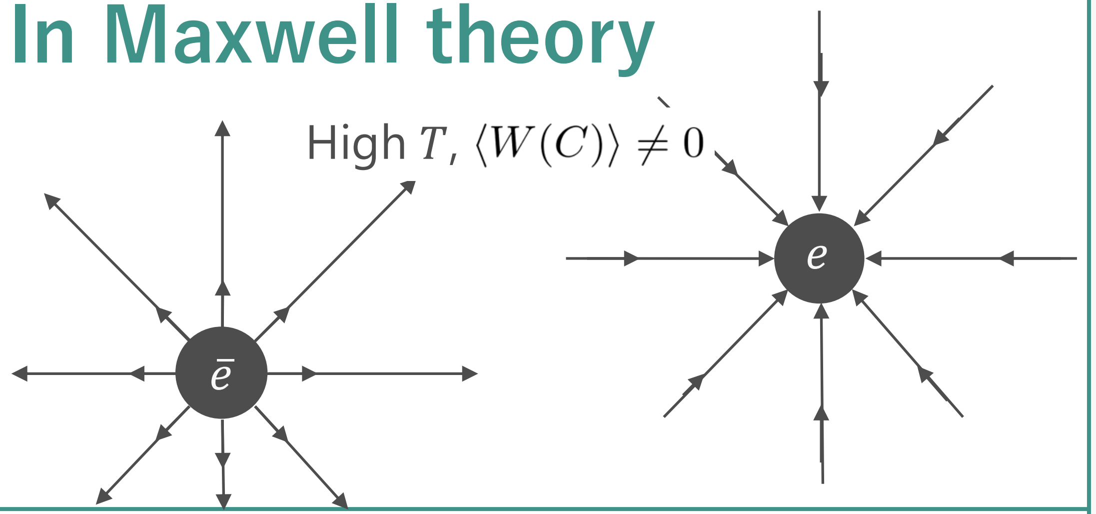
  Sensitive to low-frequency (long-wavelength) GWs.

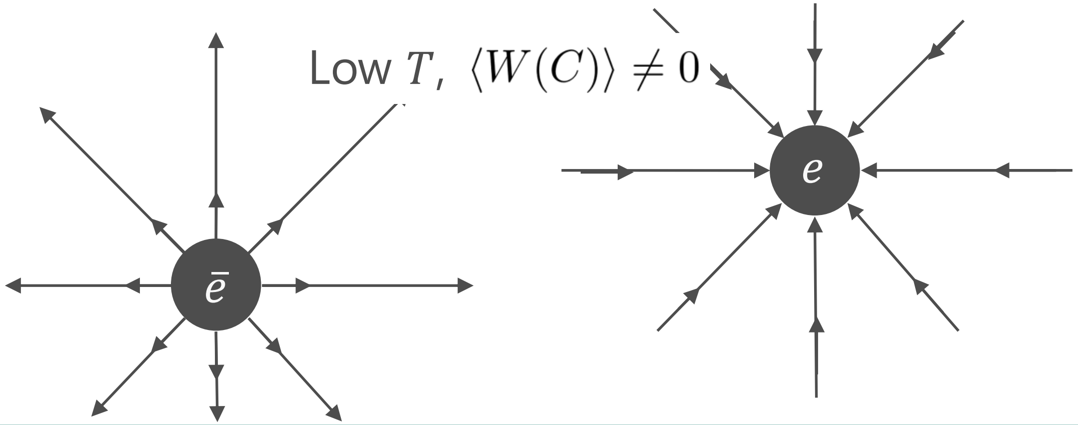




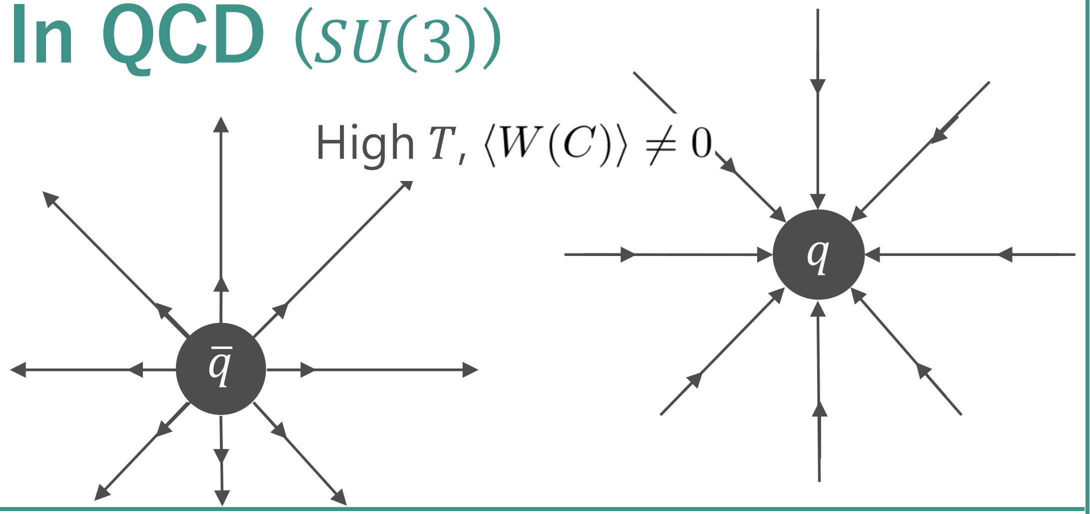
Existence of the confined/deconfined phase

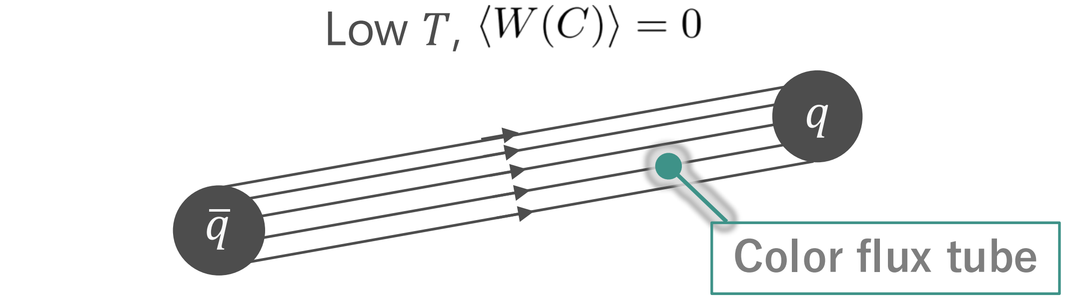
In Maxwell theory





In QCD ($SU(3)$)





Confinement

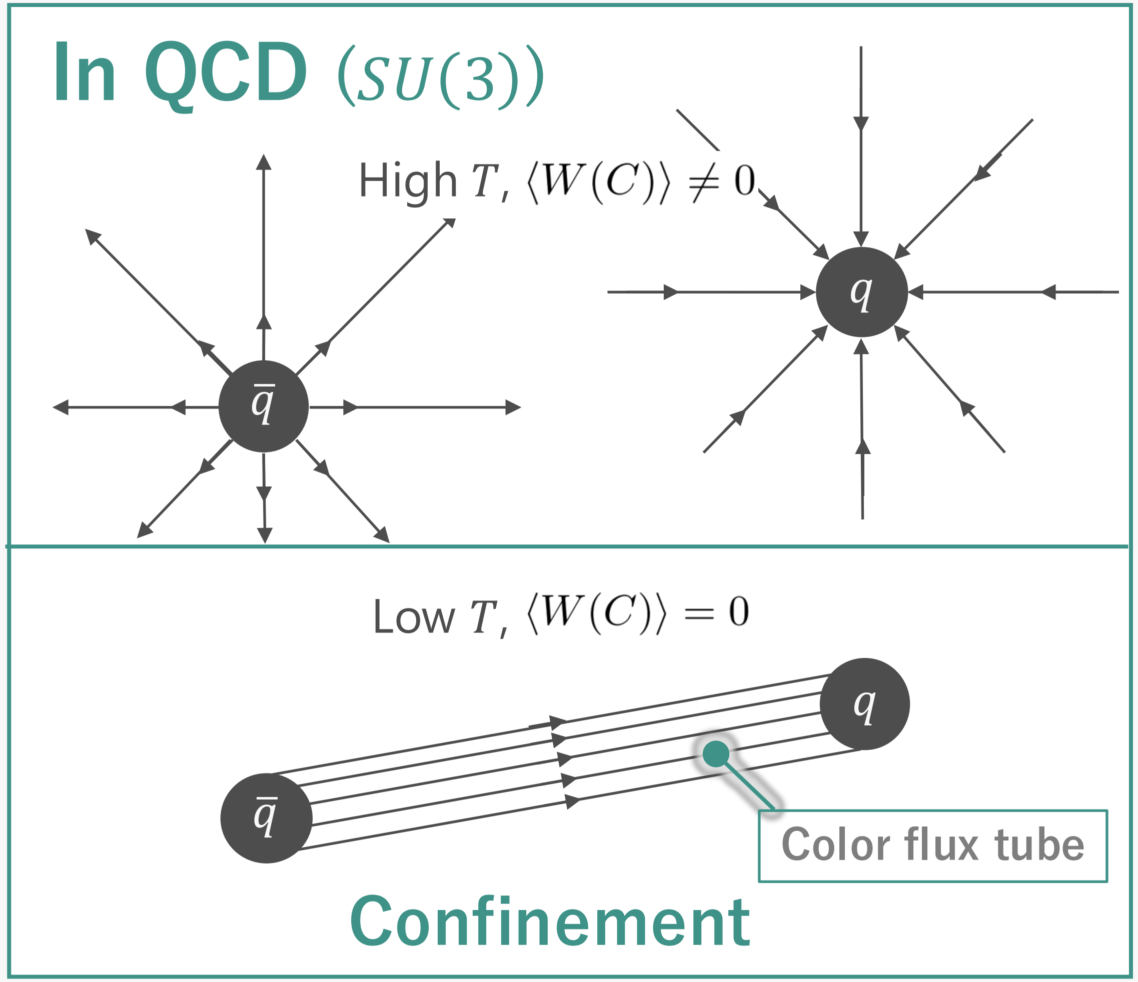
Color flux tube is formed in Yang-Mills theory

$$S_{\mathrm{YM}} = -\frac{1}{4g^2}\int d^4x\, F^a_{\mu\nu}F^{a\,\mu\nu},$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + \underline{\underline{f^{abc}A^b_\mu A^c_\nu}}$$

Confinement happen in the other Yang-Mills (non-abelian gauge) theory.

Color flux tube is also created in the other Yang-Mills theory.



Color flux tube is stable due to 1-form symmetry

Stability of particle (electron)

0-form symmetry (conventional symmetry)

$$\hat{U}(t)\hat{\psi}(x,t)\hat{U}^\dagger(t) = e^{-iq\alpha}\hat{\psi}(x,t)$$

Symmetry exist
⇒Electron is stable due to the conserved charge q

No possible decay channel

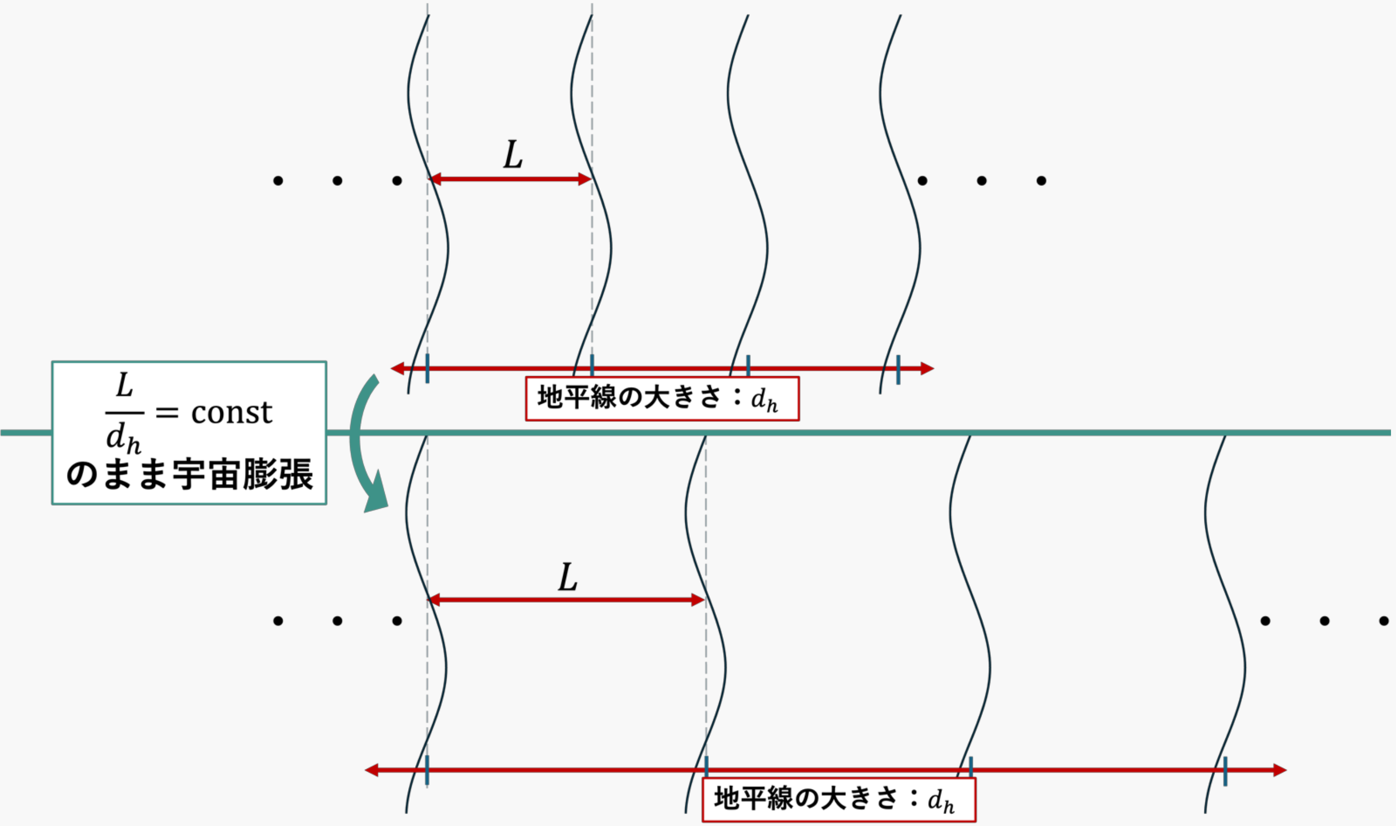
Stability of color flux tube in pure YM

1-form center symmetry (charge of Wilson loop)

$$\hat{U}(\Sigma)\hat{W}(q,C)\hat{U}^\dagger(\Sigma) = e^{-iq\alpha\,\mathrm{Link}(\Sigma,C)}\hat{W}(q,C)$$

1-form symmetry exist
⇒Color flux tube is stable due to the conserved charge q

Scaling law is defined by $\gamma(t) = \mathrm{const}$



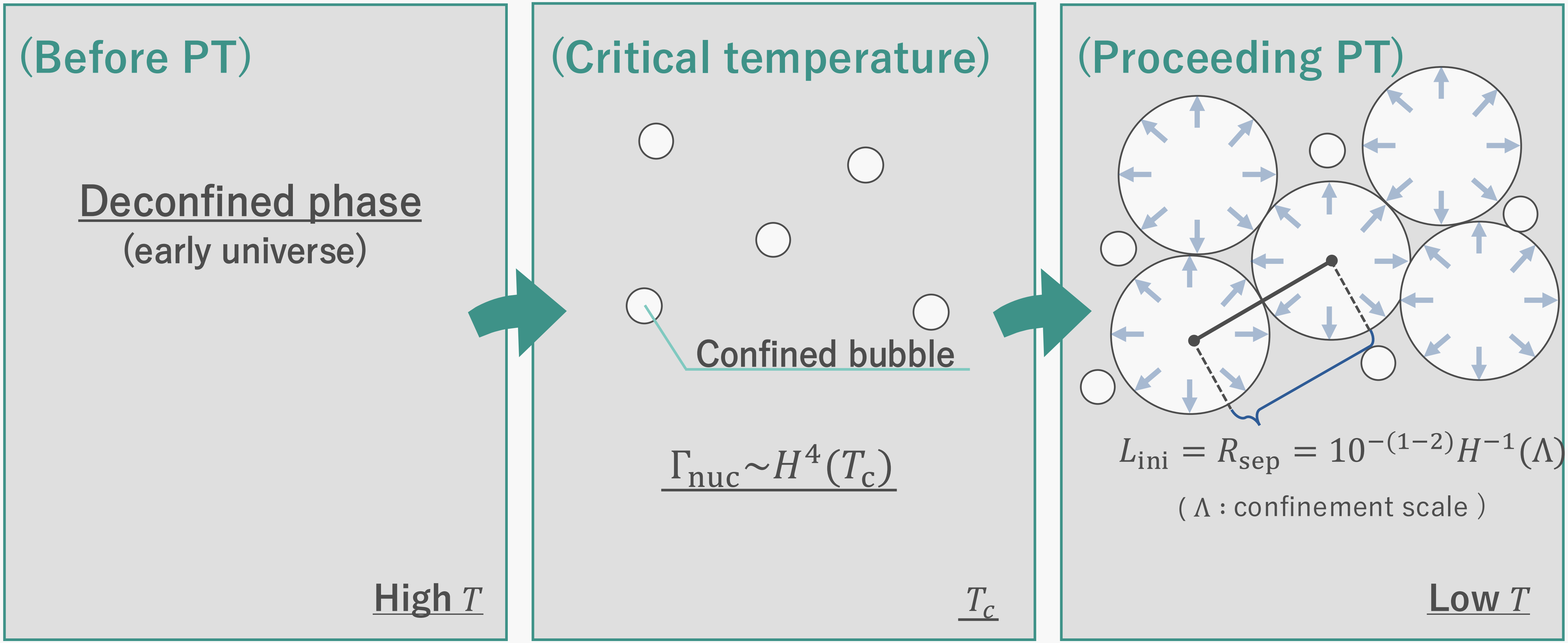
Horizon

$$d_h(t) = a(t)\int_0^t \frac{c\,dt'}{a(t')} \sim t$$

Scaling law ⇔ $\gamma(t) = \mathrm{const}$

$$L \equiv \gamma(t)\cdot t$$

1st order Phase Transitions make color flux tube



Baryonic glue ball and Domain wall

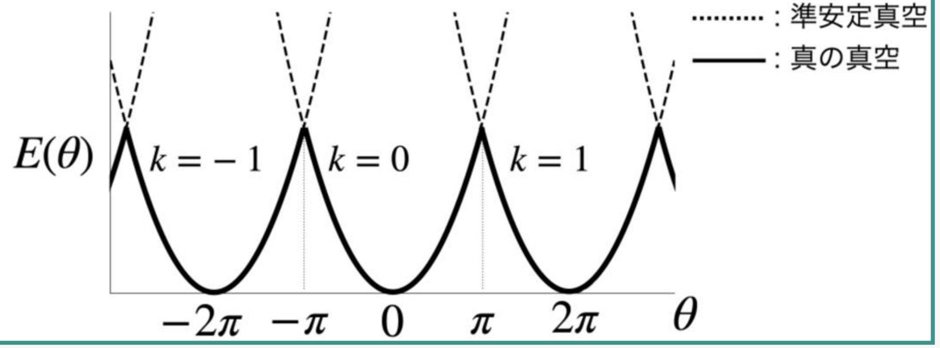
Baryonic glue ball come from accidental $\mathbb{Z}_2$ symmetry

$$O(2N)/SO(2N) = \mathbb{Z}_2$$

$$B_{\mu_1 \cdots \mu_{2N}} = \epsilon_{i_1 \cdots i_{2N}} \left(F_{\mu_1 \mu_2}\right)_{i_1 i_2} \cdots \left(F_{\mu_{2N-1} \mu_{2N}}\right)_{i_{2N-1} i_{2N}}$$

Θ term produce domain wall around $\theta = \pi$

$$S_\theta = \frac{\theta}{32\pi^2} \int d^4x \, \epsilon^{\mu\nu\rho\sigma} \, \mathrm{Tr}(F_{\mu\nu} F_{\rho\sigma})$$



Hellings-Down curve

Frequency shift : $\dfrac{\delta\nu_i}{\nu} = \alpha_i\, h(t) + n_i(t)$

Correlation of the shifts : $c_{ij}(\tau) = \alpha_{ij} < h^2 > + \delta c_{ij}$

$$\alpha_{ij} = \frac{1}{4\pi}\int d\hat{\Omega} \sum_A F_a^A(\hat{\Omega})\, F_b^A(\hat{\Omega}) = \frac{1}{4\pi}\int d\hat{\Omega}\, F_a(\hat{\Omega})\, F_b^*(\hat{\Omega})$$

$$= \frac{1-\cos\theta_{ij}}{2}\ln\left(\frac{1-\cos\theta_{ij}}{2}\right) - \frac{1}{6}\frac{1-\cos\theta_{ij}}{2} + \frac{1}{3}$$

$$F_a^A(\hat{\Omega}) \equiv \frac{1}{2}\frac{\hat{p}^i\hat{p}^j}{1+\hat{\Omega}\cdot\hat{p}} e_{ij}^A(\hat{\Omega})$$

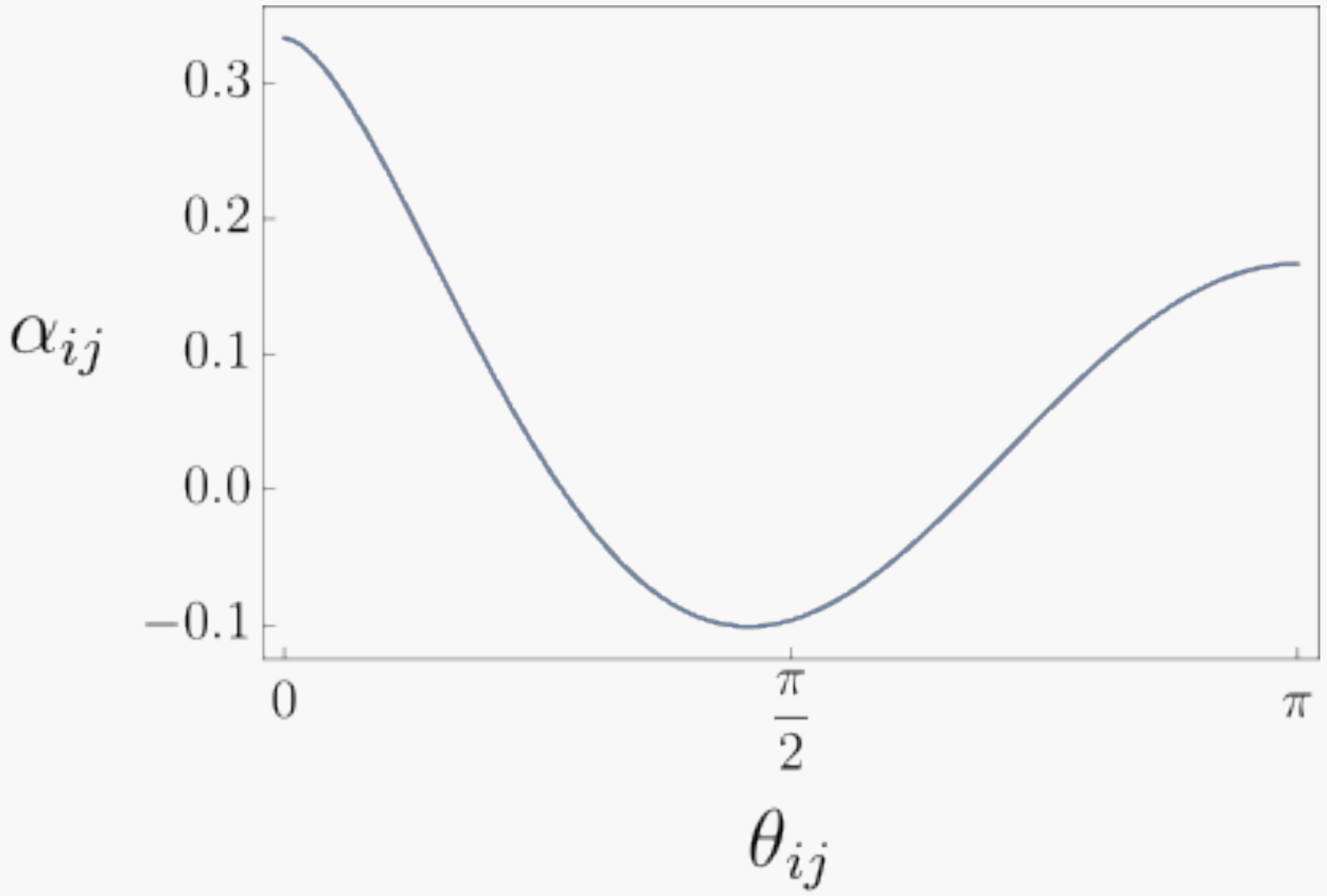
$$F \equiv F_+ + iF_\times$$

$e_{ij}^A(\hat{\Omega})$: Polarization tensor

$\hat{\Omega}$: Unit vector along the GW propagation direction

$\hat{p}$: Unit vector pointing from Earth to the pulsar

Hellings-Down curve



Longer scaling time for certain P_i

On the scaling time

- Cosmic strings typically reach the scaling regime relatively quickly.
- The significant increase in the scaling time is a new effect found in this work
- However, it requires fine-tuning.
- The increased scaling time plays an important role in the calculation of GWs.

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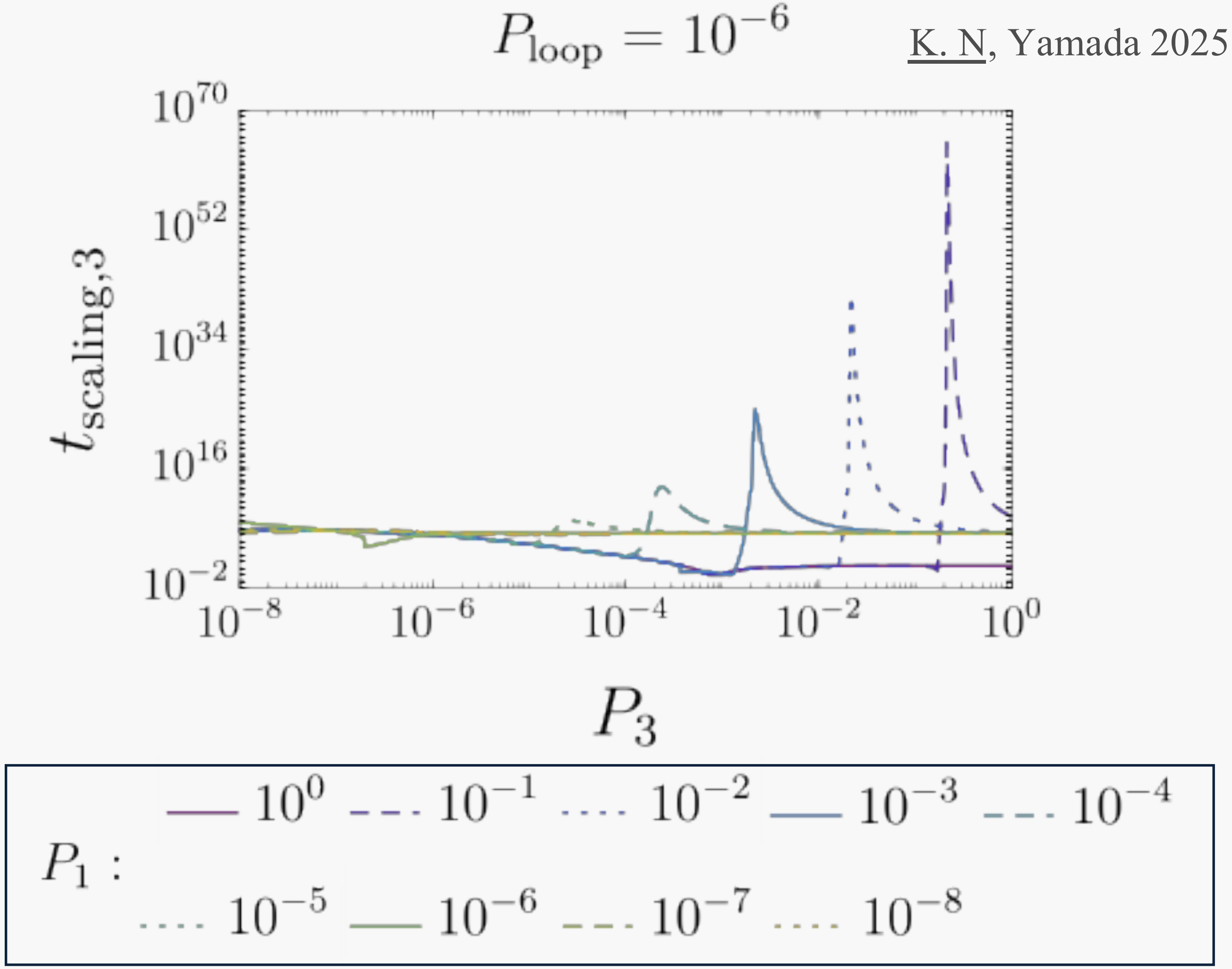
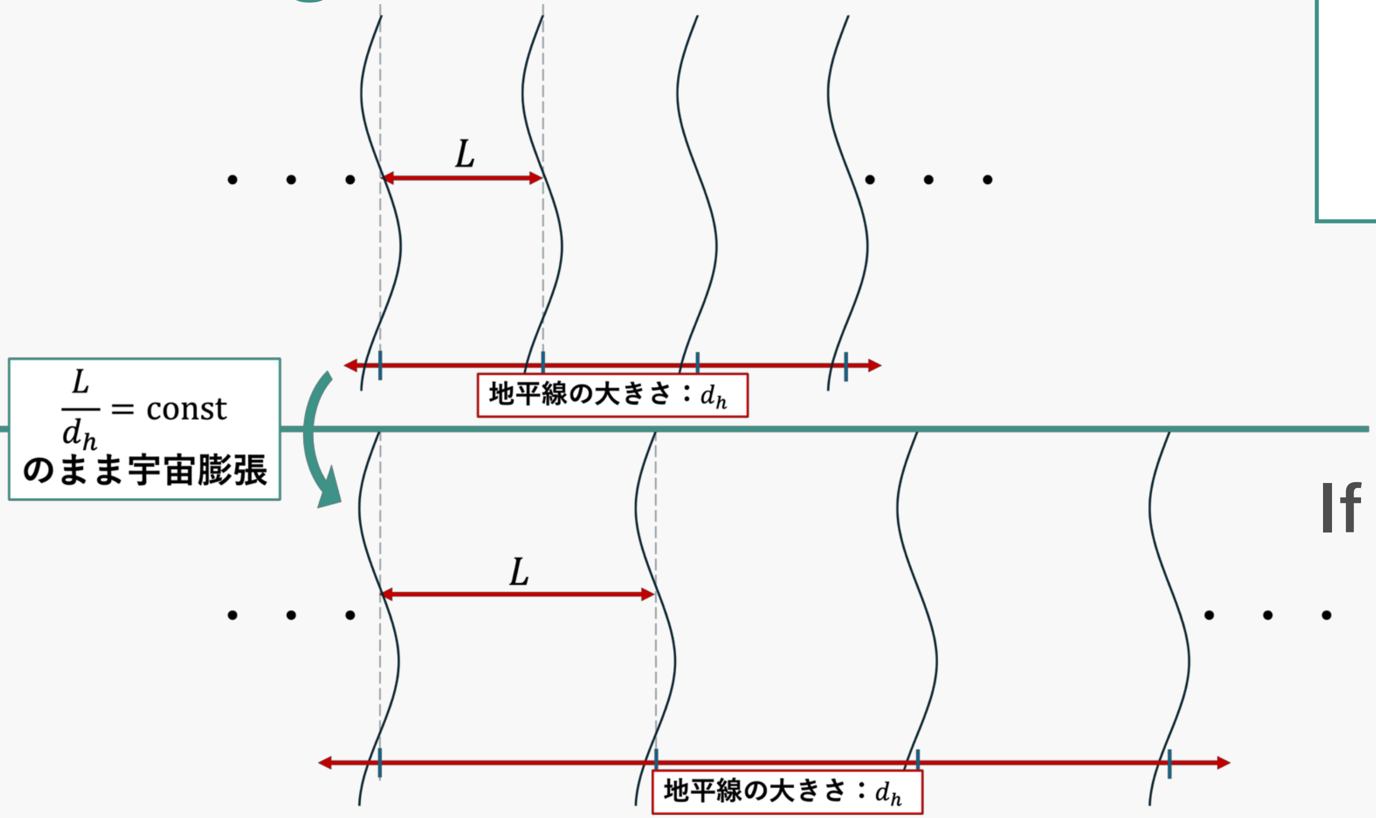


The scaling law corresponds to $\gamma(t) = \mathrm{const}$

Scaling law :



Horizon (causally connected distance)

$$d_h(t) = a(t) \int_0^t \frac{c\,dt'}{a(t')} \sim t$$

If the network obeys the scaling law,

$\gamma(t) = \mathrm{const}$

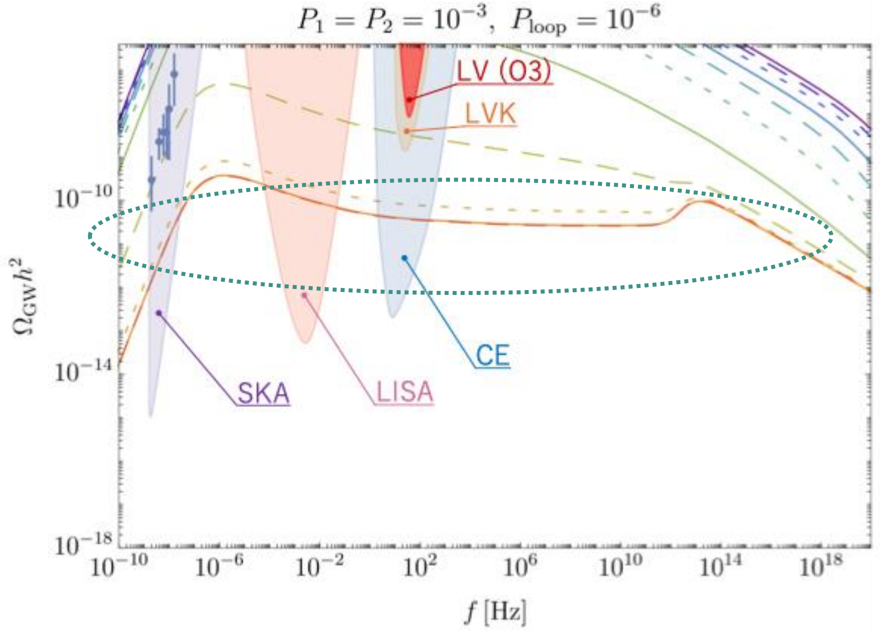
$$L \equiv \gamma(t) \cdot t$$

$P_{\{i\}}$ dependence appear in the GW spectrum

- **Including the P_i dependence of the scaling solution of γ_i**

$$\Omega_{\rm GW}h^{2\,(\rm scaling)} \propto \sum_i \Omega_{\rm rad}\sqrt{G\mu_i}\frac{P_{\rm loop}}{\gamma_i^4}$$

$$\propto \begin{cases} P_{\rm loop}/P_3^2 & \text{for } P_{\rm loop} \ll P_3 \ll P_1 \\ P_{\rm loop}^{-1} & \text{for otherwise} \end{cases}$$



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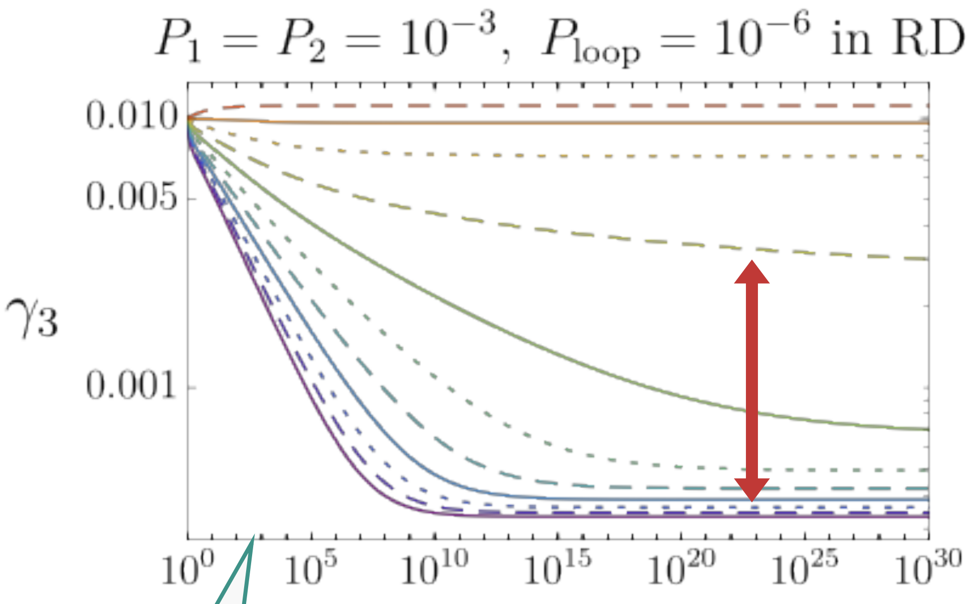
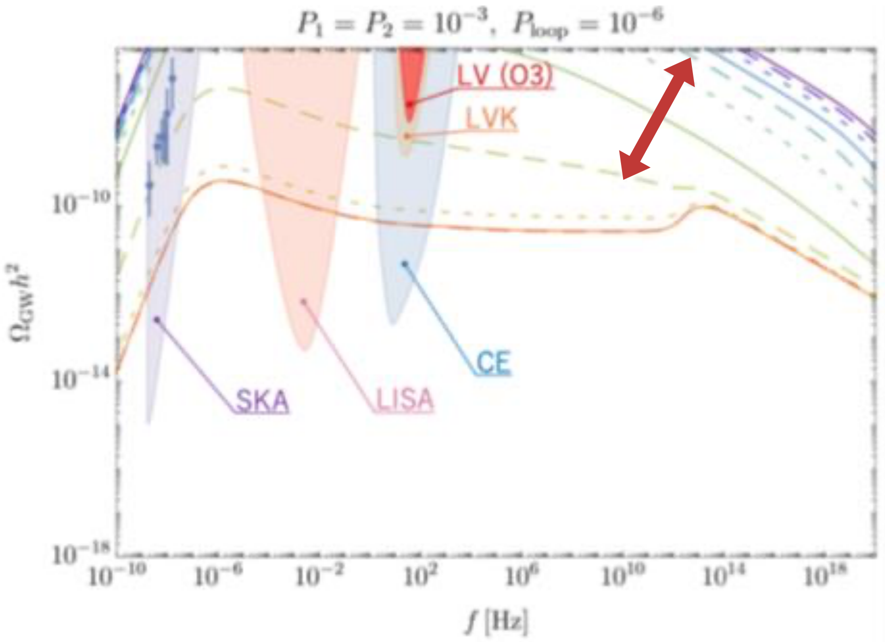
GWs emitted from a network in the scaling regime produce a flat spectrum

GW is suppressed in the high-frequency region

- **Non-flat spectrum ＝ Longer scaling time**





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If the scaling time is strongly delayed,
high-freq suppression and characteristic slope appear

The path to the scaling solution varies

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