Monopoles, Domain Walls, Cosmic Strings, and Their Implications for Gravitational Waves

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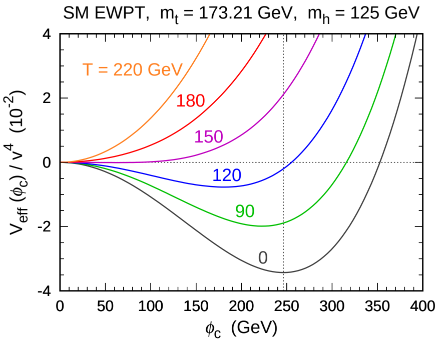
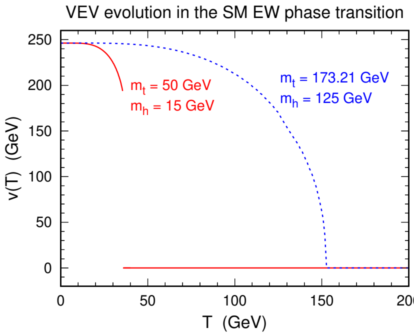
Cosmological Phase Transition

🔥 **Spontaneously broken symmetries** in field theories can be **restored** at **sufficiently high temperatures** due to **thermal corrections** to the **effective potential**

🌨️ In the history of the Universe, **spontaneous symmetry breaking** manifests itself as a **cosmological phase transition**

❄️ If the **vacuum manifold** has **nontrivial topological structures**, **topological defects** would be formed after the phase transition





Symmetry Breaking $G \to H$

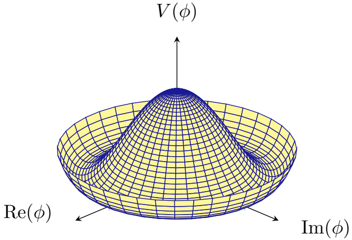
✂️ Consider that **some scalar fields** acquire nonzero **vacuum expectation values** (VEVs), which **break** a **symmetry group** G to a **subgroup** H ($G \to H$)

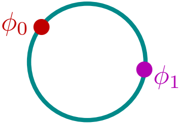
🗜️ For a **VEV** ϕ_0, the action by any element $h \in H$ is **trivial**: $h\phi_0 = \phi_0$

🔧 A **nontrivial** action on ϕ_0: $g\phi_0 = \phi_1$, $g \in G$, $g \notin H$ 👉 $gh\phi_0 = \phi_1$

🔩 All the **nontrivial** transformations are given by the **left cosets** of H (e.g., gH), which constitute the **coset space** G/H

⚖️ G/H is **isomorphic** to the **manifold** consisting of all **degenerate vacua**

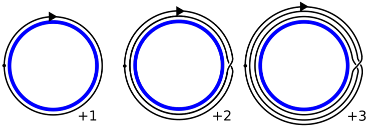




Vacuum manifold

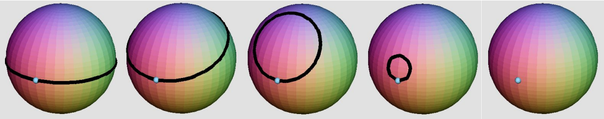
Homotopy Groups $\pi_n(G/H)$

The **topology** of the **vacuum manifold** G/H can be characterized by its **n-th homotopy group** $\pi_n(G/H)$, which is constituted by the **homotopy classes** of the mappings from an **n-dimensional sphere** S^n into G/H



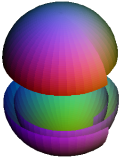
$\pi_1(S^1) = \mathbb{Z}$

A homotopy class is identified with a winding number n



$\pi_1(S^2) = 1$ **(trivial)**

Any continuous mapping from S^1 to S^2 can be continuously deformed to a 1-point mapping



$\pi_2(S^2) = \mathbb{Z}$

Mappings from S^2 toS^2 can be visualized as wrapping a twisted plastic bag around a ball n times

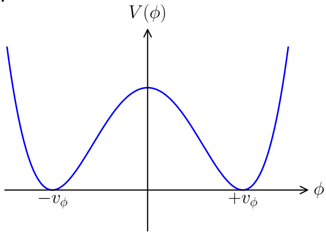
How S^2 can be wrapped twice around another S^2

Topological Defects

A **nontrivial** $\pi_n(G/H)$ leads **topological defects** [Kibble, J. Phys. A9 (1976) 1387]

Nontrivial $\pi_0(G/H)$: two or more disconnected components

- **Domain walls** (2-dim topological defects)



- $G/H \cong Z_2$
- $\pi_0(G/H) = Z_2$

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- **Nontrivial** $\pi_0(G/H)$: two or more disconnected components
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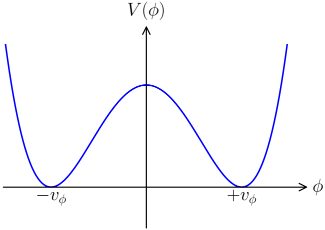
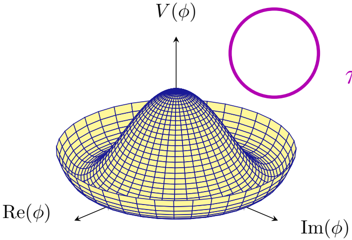
- **Nontrivial** $\pi_1(G/H)$: incontractable closed paths
  - **Cosmic strings** (1-dim topological defects)





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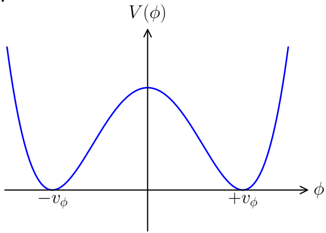
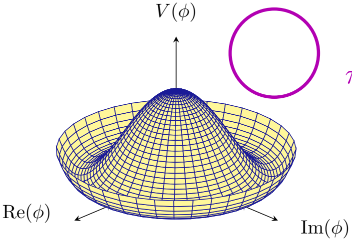
- **Nontrivial** $\pi_1(G/H)$: incontractable closed paths
  - **Cosmic strings** (1-dim topological defects)
- **Nontrivial** $\pi_2(G/H)$: incontractable spheres
  - **Monopoles** (0-dim topological defects)





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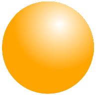
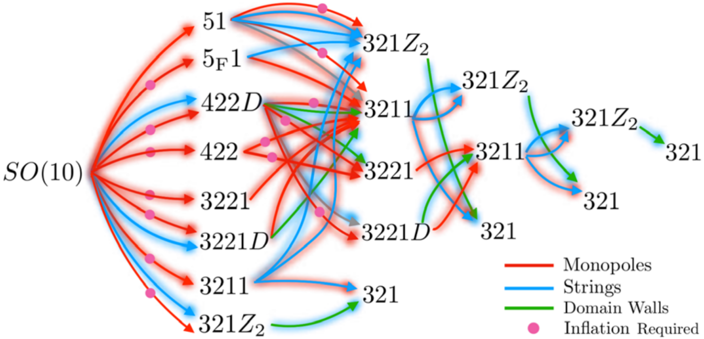


$$G/H \cong S^2$$
$$\pi_2(G/H) = \mathbb{Z}$$

Topological Defects in GUTs

🏭 **Monopoles**, **cosmic strings**, and **domain walls** are commonly predicted in **grand unified theories (GUTs)**



$$51 = \mathrm{SU}(5) \times \mathrm{U}(1)_X/Z_5, \quad 5_{\mathrm{F}}1 = \mathrm{SU}(5)_{\mathrm{flipped}} \times \mathrm{U}(1)_{\mathrm{flipped}}/Z_5$$

$$422 = \mathrm{SU}(4)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}}/Z_2, \quad 3221 = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{SU}(2)_{\mathrm{R}} \times \mathrm{U}(1)_{B-L}/Z_6$$

$$3211 = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y \times \mathrm{U}(1)_X/Z_6, \quad 321 = \mathrm{SU}(3)_{\mathrm{C}} \times \mathrm{SU}(2)_{\mathrm{L}} \times \mathrm{U}(1)_Y/Z_6$$

[Dunsky, Ghoshal, Murayama, Sakakihara, White, 2111.08750, PRD]

't Hooft-Polyakov Monopole

The **'t Hooft-Polyakov monopole** is a **static solution** with **finite energy** in a **nonabelian gauge theory** ['t Hooft, NPB **79** (1974) 276; Polyakov, JETP Lett. **20** (1974) 194]

Consider a $\mathrm{SU}(2)$ **gauge theory**, **spontaneously broken** to $\mathrm{U}(1)_{\mathrm{EM}}$ by a $\mathrm{SU}(2)$-**triplet Higgs field** ϕ^a ($a = 1, 2, 3$; e is **elementary electric charge**)

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \frac{1}{2} (D_\mu \phi)^a (D^\mu \phi)^a - V(\phi), \quad V(\phi) = \frac{\lambda}{4} (|\phi|^2 - v^2)^2$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + e\varepsilon^{abc} A^b_\mu A^c_\nu, \quad D_\mu \phi^a = \partial_\mu \phi^a + e\varepsilon^{abc} A^b_\mu \phi^c$$

Defining $r \equiv |\mathbf{x}|$, the **'t Hooft-Polyakov monopole** corresponds to the **ansatz**

$$\phi^a(\mathbf{x}) = \frac{v f(r) x^a}{r}, \quad A^{ai}(\mathbf{x}) = \frac{a(r) \varepsilon^{aij} x^j}{e r^2}, \quad f(\infty) = a(\infty) = 1, \quad f(0) = a(0) = 0$$

Its **mass** (the total energy of the solution) is given by

$$M = \int \mathrm{d}^3 x \left[\frac{1}{2} B^{ai} B^{ai} + \frac{1}{2} (D^i \phi)^a (D^i \phi)^a + V(\phi) \right], \quad B^{ai} = \frac{1}{2} \varepsilon^{ijk} F^{ajk}$$

Magnetic Charge and Mass

Rewrite $\frac{1}{2}B^{ai}B^{ai} + \frac{1}{2}(D^i\phi)^a(D^i\phi)^a = \frac{1}{2}[B^{ai} + (D^i\phi)^a]^2 - \nabla\cdot(\mathbf{B}^a\phi^a)$

For vacuum field configuration with **winding number** $n = 1$, Gauss's theorem gives

$$\int d^3x\, \nabla\cdot(\mathbf{B}^a\phi^a) = \int d\boldsymbol{\sigma}\cdot\mathbf{B}^a\phi^a = Q_\mathrm{M}v$$

[Srednicki, *Quantum Field Theory*, Chapter 92]

$Q_\mathrm{M} = -\frac{4\pi}{e}$ is the **magnetic charge** of the **'t Hooft-Polyakov monopole** with

$$M = |Q_\mathrm{M}|v + \int d^3x \left\{\frac{1}{2}[B^{ai} + (D^i\phi)^a]^2 + V(\phi)\right\}$$

Bogomolny bound $M \geq |Q_\mathrm{M}|v$ [Bogomolny, Sov.J.Nucl.Phys. **24** (1976) 449]

In the limit $\lambda \to 0$ with $B^{ai} = -(D^i\phi)^a$, the **Bogomolny bound** is **saturated**, leading to **explicit solution** for the **'t Hooft-Polyakov monopole** with $M = |Q_M|v$:

$$\phi^a = \frac{x^a}{er^2}\left(\frac{evr}{\tanh evr} - 1\right), \quad A^{ai} = \frac{\varepsilon^{aij}x^j}{er^2}\left(1 - \frac{evr}{\sinh evr}\right)$$

[Prasad & Sommerfield, PRL **35**, 760 (1975)]

Generic Monopoles

The **magnetic charge** of a **generic monopole** with a **winding number** n is

$$Q_{\mathrm{M}} = -\frac{4\pi n}{e}, \quad n \in \mathbb{Z}$$

Its **mass** is given by $M = |Q_{\mathrm{M}}|v + \int \mathrm{d}^3x \left\{ \frac{1}{2}[B^{ai} + \mathrm{sign}(n)(D^i\phi)^a]^2 + V(\phi) \right\}$

Bogomolny bound becomes $M \geq |Q_{\mathrm{M}}|v = \dfrac{4\pi|n|v}{e}$

$n = +1$ and $n = -1$ corresponds to the **'t Hooft-Polyakov monopole** and its **antimonopole**, respectively

For $\lambda > 0$, a **monopole** with **winding number** $n \neq \pm 1$ is **unstable** against breaking up into $|n|$ **monopoles** with **winding number** ± 1, which are **stable**

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- If a $\mathrm{SU}(2)$**-doublet** field is added, then its components have **electric charges** $\pm\dfrac{e}{2}$, which is the smallest charges; all **possible electric charges** is $Q_\mathrm{E} = \dfrac{je}{2}$, $j \in \mathbb{Z}$

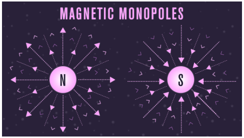
- Therefore, the possible **electric** and **magnetic** charges obey $Q_\mathrm{E} Q_\mathrm{M} = 2\pi k$, $k \in \mathbb{Z}$

- This is the **Dirac charge quantization condition** from general considerations

Magnetic Monopoles in GUTs

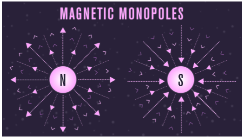
- The **homotopy group** relevant to **monopoles** is $\pi_2(G/H)$
- If $\pi_1(G) = \pi_2(G) = \mathbf{1}$, then $\pi_2(G/H) = \pi_1(H)$

  [Vachaspati, hep-ph/0101270]



- Because of $\pi_1[\mathrm{U}(1)] = \mathbb{Z}$, $H = \mathrm{U}(1)$ leads to **monopoles**
- For a **GUT** with $G \to \mathrm{SU}(3)_\mathrm{C} \times \mathrm{SU}(2)_\mathrm{L} \times \mathrm{U}(1)_Y \to \mathrm{SU}(3)_\mathrm{C} \times \mathrm{U}(1)_\mathrm{EM}$, generation of **stable magnetic monopoles** with a typical mass $M \sim 10^{15}$ GeV is **inevitable**

Magnetic Monopoles in GUTs



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- Such magnetic monopoles would be **copiously produced** in the early universe

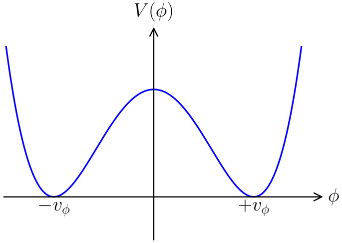
  [Guth & Tye, PRL **44**, 631 (1980)]
- They should remain to the **present day** with a **large number density** against the **null observation** [Zel'dovich & Khlopov, PLB **79** (1978) 239; Preskill, PRL **43**, 1365 (1979)]
- This **magnetic-monopole problem** can be solved by assuming that the **cosmic inflation** occurs below the temperature where magnetic monopoles can be produced

Domain Walls

☯ **Domain walls (DWs)** are **two-dimensional topological defects** which could be formed when a **discrete symmetry** of the **scalar potential** is **spontaneously broken** in the early Universe

🌈 Consider a **real scalar field** $\phi(x)$ with a **spontaneously broken** Z_2 **symmetry** $\phi \to -\phi$

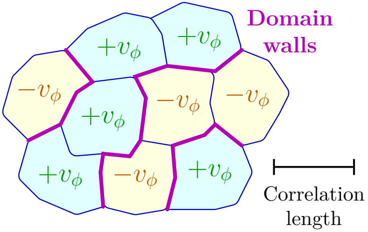
$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)\partial^\mu \phi - V_0, \quad V_0 = \frac{\lambda}{4}(\phi^2 - v_\phi^2)^2$$



⛱ The Z_2**-conserving potential** V_0 has **two degenerate minima** at $\phi = \pm v_\phi$

💧 After the **spontaneous symmetry breaking**, $\phi(x)$ takes either $+v_\phi$ or $-v_\phi$, and **two different domains** can appear

♊ **DWs** are produced around the **boundary** of the **two domains**

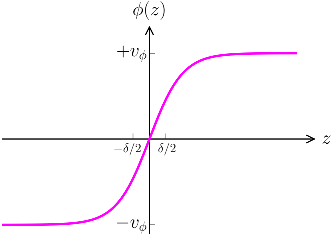


Domain Wall Configuration

Consider a **static planar DW configuration** lying perpendicular to the z-axis

Solving the **equation of motion** $\frac{d^2\phi}{dz^2} - \frac{dV_0}{d\phi} = 0$ with **boundary conditions** $\lim_{z\to\pm\infty} \phi(z) = \pm v_\phi$, we obtain a **kink solution**

$$\phi(z) = v_\phi \tanh\frac{z}{\delta}, \quad \delta \equiv \left(\sqrt{\frac{\lambda}{2}}\, v_\phi\right)^{-1}$$



The **DW** locates at $z = 0$ with a **thickness** δ, separating **two domains** with $\phi(z) > 0$ and $\phi(z) < 0$

The **energy-momentum tensor** for **this static solution** is

$$T^{\mu\nu}(z) = \left[\frac{d^2\phi(z)}{dz^2}\right]^2 \mathrm{diag}(+1, -1, -1, 0)$$

The **DW tension** (surface energy density) is $\sigma = \int_{-\infty}^{+\infty} dz\, T^{00}(z) = \frac{4}{3}\sqrt{\frac{\lambda}{2}}\, v_\phi^3$

[Saikawa, 1703.02576, Universe]

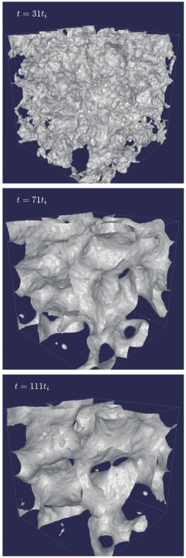
Evolution of Domain Walls

After **DWs** are created, the **tension** σ acts to **stretch** them up to the **horizon size** if the **friction** F_f is **small**, and they would enter the **scaling regime** with **energy density** $\rho_{\mathrm{DW}} = \dfrac{\mathcal{A}\sigma}{t}$

[Press, Ryden, Spergel, ApJ **347**, 590 (1989)]

$\mathcal{A} \approx 0.8 \pm 0.1$ is a numerical factor given by lattice simulation

[Hiramatsu, Kawasaki, Saikawa, 1309.5001, JCAP]



[Hiramatsu *et al.*, 1002.1555, JCAP]

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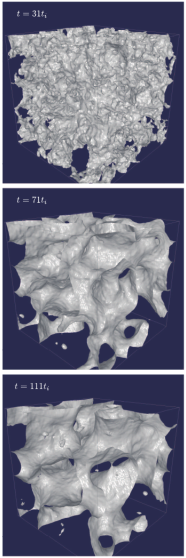
- This implies that **DWs** are **diluted more slowly** than **radiation** $(\rho_{\rm r} \propto t^{-2})$ and **matter** $(\rho_{\rm m} \propto t^{-3/2})$ as the Universe expands

- If DWs are **stable**, they would soon **dominate** the Universe with a **state parameter** $w = \frac{p_{\rm DW}}{\rho_{\rm DW}} = -\frac{2}{3}$

- This implies that the **scale factor** evolves as $a(t) \propto t^2$; such a **rapid expansion** is **incompatible** with **standard cosmology**

- Therefore, **stable DWs** results in a **cosmological problem**

  [Zeldovich, Kobzarev, Okun, Zh.Eksp.Teor.Fiz. **67** (1974) 3]



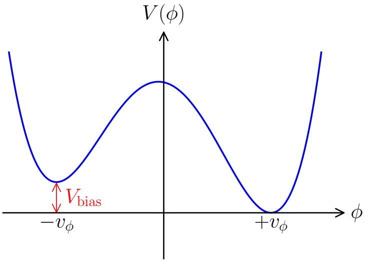
[Hiramatsu *et al.*, 1002.1555, JCAP]

Biased Domain Walls

It is **allowed** if **DWs collapse** at a very early epoch [Vilenkin, PRD **23** (1981) 852; Gelmini, Gleiser, Kolb, PRD **39** (1989) 1558; Larsson, Sarkar, White, hep-ph/9608319, PRD]

Such **unstable DWs** can be realized if the Z_2 **symmetry** is **explicitly broken** by a **small potential term**

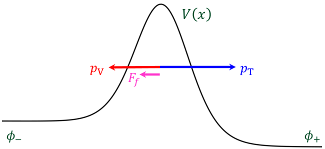
$$V_1 = \epsilon v_\phi \phi \left(\frac{\phi^2}{3} - v_\phi^2 \right)$$



This gives an **energy bias** among the two minima of the potential:

$$V_{\text{bias}} \equiv V(-v_\phi) - V(+v_\phi) = \frac{4}{3}\epsilon v_\phi^4$$

The potential bias provides a **pressure** $p_{\text{V}} \sim V_{\text{bias}}$ acting on the DWs, against the **tension force per unit area** $p_{\text{T}} \sim \rho_{\text{DW}} \propto T^2$



Collapsing Domain Walls and Gravitational Waves

💪 Since $p_{\mathrm{T}} \propto T^2$, the **pressure** p_{V} would eventually **surpass** the **tension force** at **sufficient low temperatures**

🥀 This makes **DWs collapse** and **false vacuum domains shrink**

🌪️ The **annihilation temperature** T_{ann}, at which **DWs collapse**, can be estimated by solving $p_{\mathrm{V}}(T_{\mathrm{ann}}) \simeq p_{\mathrm{T}}(T_{\mathrm{ann}})$:

$$T_{\mathrm{ann}} = \frac{34.1\ \mathrm{MeV}}{\sqrt{\mathcal{A}}} \left[\frac{g_*\left(T_{\mathrm{ann}}\right)}{10}\right]^{-1/4} \left(\frac{\sigma}{\mathrm{TeV}^3}\right)^{-1/2} \left(\frac{V_{\mathrm{bias}}}{\mathrm{MeV}^4}\right)^{1/2}$$

[Hiramatsu *et al.*, 1002.1555, JCAP]

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$$T_{\rm ann} = \frac{34.1\ {\rm MeV}}{\sqrt{\mathcal{A}}} \left[\frac{g_*(T_{\rm ann})}{10}\right]^{-1/4} \left(\frac{\sigma}{{\rm TeV}^3}\right)^{-1/2} \left(\frac{V_{\rm bias}}{{\rm MeV}^4}\right)^{1/2}$$

It is expected that such **collapsing domain walls** produce **Gravitational Waves** (GWs) [Preskill *et al.*, NPB 363 (1991) 207; Gleiser, Roberts, astro-ph/9807260, PRL]

A **stochastic gravitational wave background (SGWB)** could be formed and remain to the present time

[Hiramatsu *et al.*, 1002.1555, JCAP]

SGWB Spectrum from Collapsing DWs

- The **SGWB spectrum** is commonly characterized by $\Omega_{\rm GW}(f) = \dfrac{f}{\rho_c}\dfrac{d\rho_{\rm GW}}{df}$
- $\rho_{\rm GW}$ is the **GW energy density**, and ρ_c is the critical energy density
- The SGWB from **collapsing DWs** can be estimated by **numerical simulations**

[Hiramatsu, Kawasaki, Saikawa, 1002.1555, 1309.5001, JCAP]

- The **present SGWB spectrum** induced by collapsing DWs can be evaluated by

$$\Omega_{\rm GW}(f)h^2 = \Omega_{\rm GW}^{\rm peak}h^2 \times \begin{cases} \left(\dfrac{f}{f_{\rm peak}}\right)^3, & f < f_{\rm peak} \\ \dfrac{f_{\rm peak}}{f}, & f > f_{\rm peak} \end{cases}$$

$$\Omega_{\rm GW}^{\rm peak}h^2 = 7.2\times 10^{-18}\ \tilde{\epsilon}_{\rm GW}\mathcal{A}^2 \left[\frac{g_{*s}(T_{\rm ann})}{10}\right]^{-4/3} \left[\frac{\sigma(T_{\rm ann})}{\rm TeV^3}\right]^2 \left(\frac{T_{\rm ann}}{10\ \rm MeV}\right)^{-4}$$

$$f_{\rm peak} = 1.1\times 10^{-9}\ {\rm Hz} \left[\frac{g_*(T_{\rm ann})}{10}\right]^{1/2} \left[\frac{g_{*s}(T_{\rm ann})}{10}\right]^{-1/3} \frac{T_{\rm ann}}{10\ \rm MeV}$$

- $\tilde{\epsilon}_{\rm GW} = 0.7 \pm 0.4$ is derived from numerical simulation

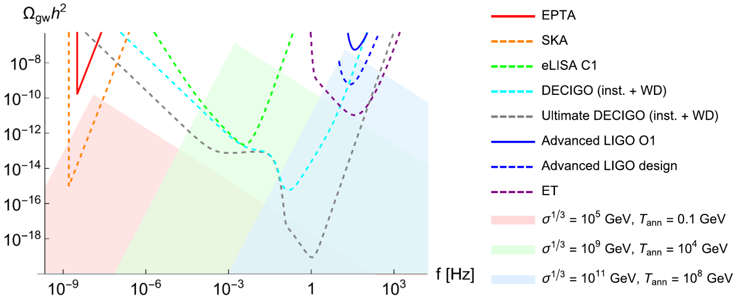
SGWB Spectra Compared to Sensitivity Curves

By adjusting the **DW tension** σ and the **potential bias** V_{bias}, the **SGWB spectra** from **collapsing DWs** could fall in the sensitivity bands of various GW experiments

Pulsar timing arrays (PTAs) in 10^{-9}–10^{-7} Hz: **NANOGrav**, **PPTA**, **EPTA**, **CPTA**, **IPTA**, **SKA**, $\cdots$

Space-borne interferometers in 10^{-4}–10^{0} Hz: **LISA**, **TianQin**, **Taiji**, **BBO**, **DECIGO**, $\cdots$

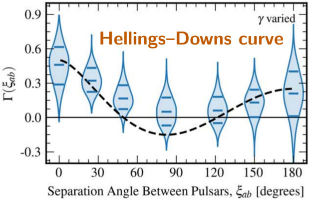
Ground-based interferometers in 10^{0}–10^{4} Hz: **LIGO**, **Virgo**, **KAGRA**, **CE**, **ET**, $\cdots$



[Saikawa, 1703.02576, Universe]

Strong Evidence for a nHz SGWB from PTAs

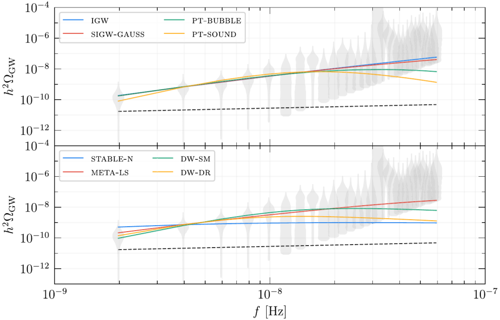
🔭 On June 29, 2023, four **PTA collaborations** **NANOGrav** [2306.16213, ApJL; 2306.16219, ApJL], **CPTA** [2306.16216, RAA], **PPTA** [2306.16215, ApJL], and **EPTA** [2306.16214, 2306.16227, A&A] reported **strong evidence** for a **nHz SGWB** with expected **Hellings–Downs correlations**



[NANOGrav Coll., 2306.16213]

🌾 Potential **GW sources** include

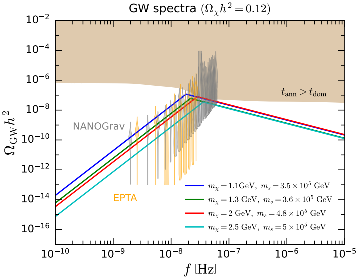
- 🫐 **Supermassive black hole binaries**
- 🍈 **Inflation**
- 🍉 **Scalar-induced GWs**
- 🍌 **First-order phase transitions**
- 🍆 **Cosmic strings**
- 🥥 **Collapsing domain walls**

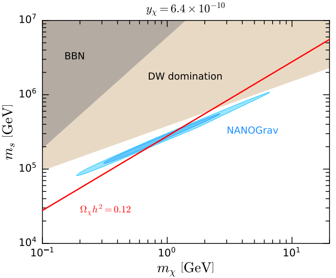


[NANOGrav Coll., 2306.16219]

nHz SGWB from DWs and Freeze-in Dark Matter

- For interpreting the **nHz SGWB observation**, we assume that it comes from **collapsing DWs** arising from the **spontaneous breaking** of a Z_2 **symmetry** in a scalar field theory
- A **tiny Z_2-violating potential term** with $\epsilon \sim \mathcal{O}(10^{-26})$ is required to reproduce the result
- We propose that this Z_2-violating potential is **radiatively induced** by a **feeble Yukawa coupling** y_χ between the scalar field and a **fermion field** χ
- It is also responsible for **dark matter** (DM) production via the **freeze-in mechanism**
- Combining the **PTA data** and the **observed DM relic density**, the model parameters can be narrowed down to small ranges

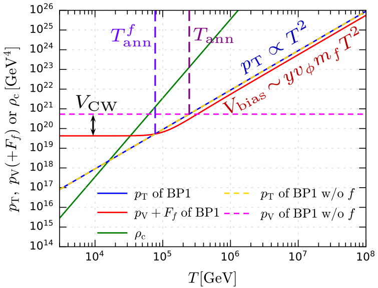


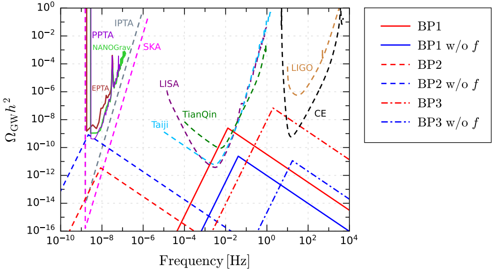


[Z Zhang, CF Cai, YH Su, SY Wang, **ZHY**, HH Zhang, 2307.11495, PRD]

Z_2-violating Coupling to Thermalized Fermions

- We study **DWs** formed through **spontaneous breaking** of an **approximate Z_2 symmetry**
- Dynamics of DWs is influenced by **quantum** and **thermal corrections** induced by a **Z_2-violating coupling** to **thermalized fermions**
- The thermal effects make the **potential bias V_{bias}** dependent on the **temperature** and may lead to notable variations in the **DW annihilation temperature T_{ann}**, in addition to the shift caused by **Coleman-Weinberg corrections**
- This could substantially alter the **SGWB spectrum** produced by DWs, providing observable signatures for future GW detection experiments





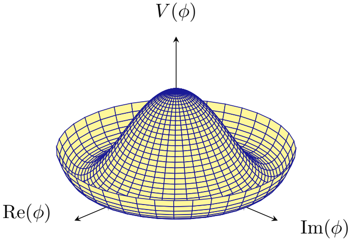
[QQ Zeng, X He, **ZHY**, JM Zheng, 2501.10059, PRD]

Cosmic Strings from U(1) Gauge Symmetry Breaking

- Consider the **Abelian Higgs model** with a **complex scalar field** ϕ

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu}(D^\mu\phi)^\dagger(D_\mu\phi) - V(\phi), \quad V(\phi) = \frac{\lambda_\phi}{4}(|\phi|^2 - v_\phi^2)^2$$

- The covariant derivative of ϕ is $D_\mu\phi = (\partial_\mu - \mathrm{i}gA_\mu)\phi$
- The field strength tensor of the $\mathrm{U}(1)$ **gauge field** A^μ is $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$
- The **Mexican-hat potential** $V(\phi)$ leads to **degenerate vacua** $\langle\phi\rangle = v_\phi \mathrm{e}^{\mathrm{i}\theta}/\sqrt{2}$



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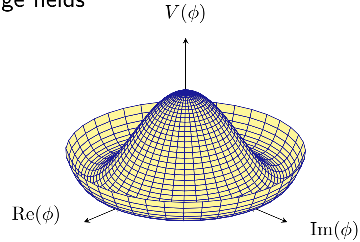
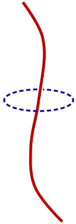
- The **Mexican-hat potential** $V(\phi)$ leads to **degenerate vacua** $\langle\phi\rangle = v_\phi \mathrm{e}^{\mathrm{i}\theta}/\sqrt{2}$
- The **spontaneous breaking** of the $\mathrm{U}(1)$ **gauge symmetry** in the early Universe would induce **cosmic strings (CSs)**, which are concentrated with energies of scalar and gauge fields





Degenerate vacua

$v_\phi \mathrm{e}^{\mathrm{i}\theta}/\sqrt{2}$

$\theta = \theta + 2\pi n$

$n \neq 0$ leads to

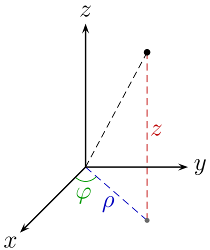
cosmic stirngs

Soliton Configuration

The **ansatz** for a **static solution (soliton)** representing a **string** along the z **axis** is

$$\phi(\rho,\varphi) = v_\phi f(\rho) U(\varphi), \quad \mathbf{A}(\rho,\varphi) = \frac{\mathrm{i}}{g} a(\rho) U(\varphi) \nabla U^\dagger(\varphi)$$

$$U(\varphi) \equiv \mathrm{e}^{\mathrm{i}n\varphi}, \quad f(\infty) = a(\infty) = 1, \quad f(0) = a(0) = 0$$



- (ρ, φ) are polar coordinates in the xy plane
- $n \in \mathbb{Z}$ is the **winding number**
- The **soliton** with $n = 1$ is called a **Nielsen-Olesen vortex**

[Nielsen & Olesen, NPB **61** (1973) 45]

- The **energy per unit length** of the **soliton** is [Srednicki, *Quantum Field Theory*]

$$\mu = 2\pi v_\phi^2 \int_0^\infty \mathrm{d}\rho\, \rho \left[f'^2 + \frac{n^2}{\rho^2}(a-1)^2 f^2 + \frac{\lambda v_\phi^2}{4}(f^2-1)^2 + \frac{n^2 a'^2}{g^2 v_\phi^2 \rho^2} \right]$$

- For $\lambda_\phi > g^2$, one can prove a **Bogomolny bound** $\mu > 2\pi v_\phi^2 |n|$
- A **soliton** with **winding number** $n \neq \pm 1$ is **unstable** against breaking up into $|n|$ **stable solitons**, each with **winding number** ± 1

Cosmic Strings

🎮 We can **translate** and **boost** a **stable soliton** with $n = \pm 1$

🕹️ It behaves like a **particle** in **two space dimensions**

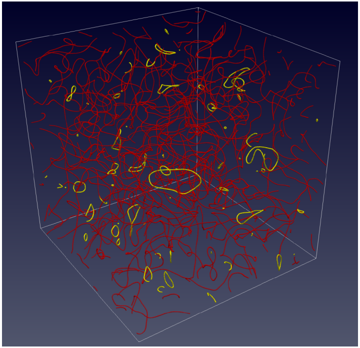
🎲 In **three space dimensions**, the soliton becomes a **Nielsen–Olesen string**

🎄 It is a structure **localized** in **two directions**, but **extended** in the **third**

🎋 Such strings can **bend**, and even form **closed loops**

🌌 When they are formed in the early universe, we call them **cosmic strings**

🕸️ Therefore, a **network** of **cosmic strings** would be formed after the **spontaneous breaking** of the $\mathrm{U}(1)$ **gauge symmetry**



[Kitajima, Nakayama, 2212.13573, JHEP]

Cosmic String Tension

🧵 The **tension** of **cosmic string** (energy per unit length) can be estimated as

$$\mu \simeq \begin{cases} 1.19\pi v_\phi^2 b^{-0.195}, & 0.01 < b < 100, \\ \dfrac{2.4\pi v_\phi^2}{\ln b}, & b > 100, \end{cases} \qquad b \equiv \frac{2g^2}{\lambda_\phi}$$

[Hill, Hodges, Turner, PRD **37**, 263 (1988)]

🎆 As $\mu \propto v_\phi^2$, a **high symmetry-breaking scale** v_ϕ would lead to cosmic strings with **high tension**

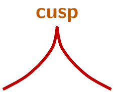
🎇 Denoting G as the **Newtonian constant of gravitation**, the **dimensionless quantity** $G\mu$ is commonly used to describe the **CS tension**

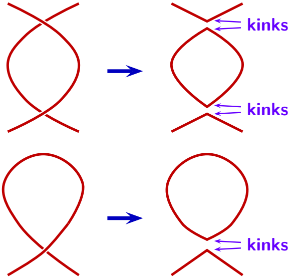
Gravitational Waves from Cosmic Strings

⚽ According to the analysis of string dynamics, the **intersections** of **long strings** could produce **closed loops**, whose size is smaller than the Hubble radius

🎳 **Cosmic string loops** could further fragment into **smaller loops** or reconnect to **long strings**

🪃 Loops typically have localized features called **"cusps"** and **"kinks"**





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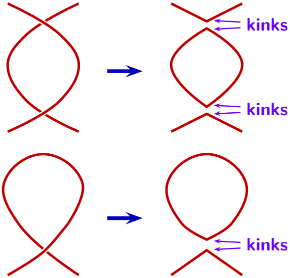

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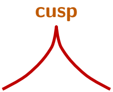
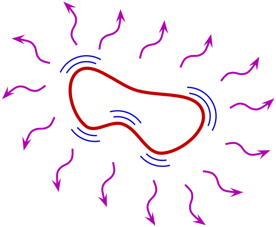


- The **relativistic oscillations** of the **loops** due to their **tension** emit **Gravitational Waves (GWs)**, and the loops would **shrink** because of **energy loss**



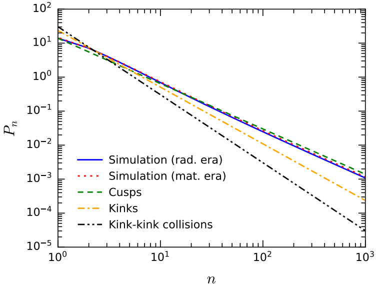
- Moreover, the **cusps** and **kinks** propagating along the loops could produce **GW bursts** [Damour & Vilenkin, gr-qc/0004075, PRL]

Power of Gravitational Radiation

At the **emission time** t_e, a **cosmic string loop** of **length** l emits GWs with **frequencies** $f_e = \frac{2n}{l}$

$n = 1, 2, 3, \cdots$ denotes the **harmonic modes** of the loop oscillation

Denoting P_n as the **power** of **gravitational radiation** for the harmonic mode n in units of $G\mu^2$, the total power is given by $P = G\mu^2 \sum_n P_n$



According to the **simulation** of **smoothed cosmic string loops** [Blanco-Pillado & Olum, 1709.02693, PRD], P_n for loops in the **radiation** and **matter** eras are obtained

The **total dimensionless power** $\Gamma = \sum_n P_n$ is estimated to be ~ 50

For comparison, analytic studies imply $P_n \simeq \frac{\Gamma}{\zeta(q) n^q}$ with $q = \frac{4}{3}, \frac{5}{3}, 2$ for **cusps**, **kinks**, and **kink-kink collisions**

Stochastic GW Background Induced by Cosmic Strings

- The **energy** of **cosmic strings** is converted into the **energy** of **GWs**, and an **SGWB** is formed due to **incoherent superposition**
- The **SGWB energy density** ρ_{GW} per unit frequency at the present is

$$\frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}f} = G\mu^2 \int_{t_{\mathrm{ini}}}^{t_0} a^5(t) \sum_n \frac{2nP_n}{f^2}\, n_{\mathrm{CS}}\left(\frac{2na(t)}{f}, t\right) \mathrm{d}t$$

- $n_{\mathrm{CS}}(l,t)$ is the **number density per unit length** of **CS loops** with length l at cosmic time t
- $a(t)$ is the **scale factor** satisfying $\dfrac{\mathrm{d}a(t)}{\mathrm{d}t} = a(t)H(t)$ and $a(t_0) = 1$
- $H(t)$ is the **Hubble rate** and t_{ini} is the cosmic time when the GW emissions start
- The **SGWB spectrum** is commonly represented by

$$\Omega_{\mathrm{GW}}(f) = \frac{f}{\rho_{\mathrm{c}}} \frac{\mathrm{d}\rho_{\mathrm{GW}}}{\mathrm{d}f}, \quad \rho_{\mathrm{c}} \equiv \frac{3H_0^2}{8\pi G}$$

Velocity-dependent One-scale Model

- The evolution of the **CS network** can be described using the **velocity-dependent one-scale (VOS) model** [Martins & Shellard, hep-ph/9507335, PRD]
- The parameters are the **correlation length** L and the **root-mean-square velocity** v of string segments; the **energy density** of **long strings** is expressed as $\rho = \mu/L^2$
- Introducing a **dimensionless quantity** $\xi \equiv L/t$, the evolution equations are

$$t\dot{\xi} = H(1+v^2)t\xi - \xi + \frac{1}{2}\tilde{c}v, \quad t\dot{v} = (1-v^2)\left[\frac{k(v)}{\xi} - 2Htv\right]$$

$$\tilde{c} \simeq 0.23, \quad k(v) = \frac{2\sqrt{2}}{\pi}(1-v^2)(1+2\sqrt{2}v^3)\frac{1-8v^6}{1+8v^6}$$

- The solutions converge to **constant values** [Marfatia & YL Zhou, 2312.10455, JHEP]:

$$\xi_{\mathrm{r}} = 0.271, \quad v_{\mathrm{r}} = 0.662, \quad \text{radiation-dominated (RD) era}$$

$$\xi_{\mathrm{m}} = 0.625, \quad v_{\mathrm{m}} = 0.582, \quad \text{matter-dominated (MD) era}$$

- This implies that the CS network quickly evolves into a **linear scaling regime** characterized by $L \propto t$

Loop Production Functions

- The **CS loop number density** is given by $n_{\rm CS}(l,t) = \dfrac{1}{a^3(t)} \displaystyle\int_{t_{\rm ini}}^{t} \mathcal{P}(l',t')\, a^3(t')\, \mathrm{d}t'$

- Motivated by **numerical simulations** [Blanco-Pillado, Olum & Shlaer, 1309.6637, PRD], the **loop production functions** can be approximated as

$$\mathcal{P}_{\rm r}(l,t) = \frac{\mathcal{F}_{\rm r}\tilde{c}v\,\delta(\alpha_{\rm r}\xi - l/t)}{\gamma_v \alpha_{\rm r}\xi^4 t^5}, \quad \text{RD era}$$

$$\mathcal{P}_{\rm m}(l,t) = \frac{\mathcal{F}_{\rm m}\tilde{c}v\,\Theta(\alpha_{\rm m}\xi - l/t)}{\gamma_v (l/t)^{1.69}\xi^3 t^5}, \quad \text{MD era}$$

- $\gamma_v = (1-v^2)^{-1/2}$ is the Lorentz factor

- At the **loop production time** $t_\star$, we have $l_\star = l + \Gamma G\mu(t - t_\star)$, $\alpha_{\rm r}\xi_\star \simeq 0.1$ and $\alpha_{\rm m}\xi_\star \simeq 0.18$

- Adopting $\mathcal{F}_{\rm r} = 0.1$ and $\mathcal{F}_{\rm m} = 0.36$, the obtained **loop number densities** in the **RD** and **MD eras agrees** with the **simulation results** in the **scaling regime**

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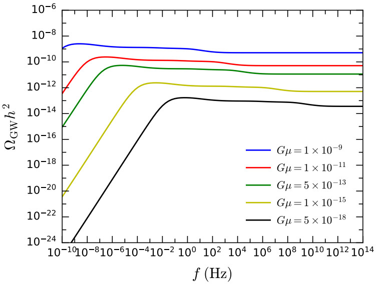

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- The **SGWB spectra** in the ΛCDM **cosmological model** can be calculated

Scaling Loop Number Density: BOS model

There are other approaches for modeling the $n_{\rm CS}(l,t)$ in the **scaling regime**

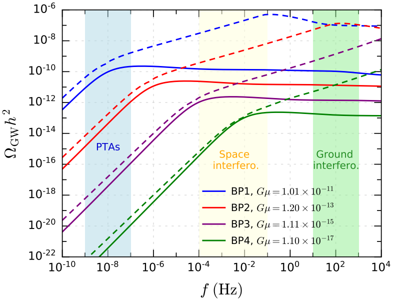
The **BOS model** [Blanco-Pillado, Olum & Shlaer, 1309.6637, PRD] extrapolates the loop production function found in simulations of Nambu-Goto strings

The loop number densities produced in the **radiation** and **matter** era, and that **produced in the radiation era and still surviving in the matter era** are given by

$$n_{\rm CS}^{\rm r}(l,t) \simeq \frac{0.18\,\theta(0.1t-l)}{t^4(\gamma+\gamma_{\rm d})^{5/2}}$$

$$n_{\rm CS}^{\rm m}(l,t) \simeq \frac{(0.27-0.45\gamma^{0.31})\,\theta(0.18t-l)}{t^4(\gamma+\gamma_{\rm d})^{2}}$$

$$n_{\rm CS}^{\rm r\to m}(l,t) \simeq \frac{0.18t_{\rm eq}^{1/2}\,\theta(0.09t_{\rm eq}-\gamma_{\rm d}t-l)}{t^{9/2}(\gamma+\gamma_{\rm d})^{5/2}}$$



BOS model: solid lines

$\gamma \equiv \dfrac{l}{t}$ is a **dimensionless variable**

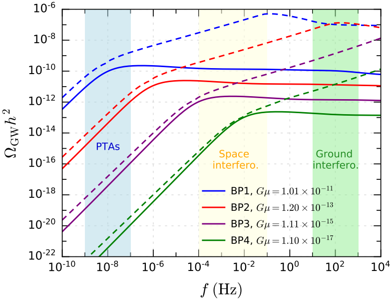
$\gamma_{\rm d} = -\dfrac{{\rm d}l}{{\rm d}t} \simeq \Gamma G\mu$ is the **loop shrinking rate**

$t_{\rm eq} = 51.1 \pm 0.8$ kyr is the cosmic time at the **matter-radiation equality**

Scaling Loop Number Density: LRS model

The **LRS model** [Lorenz, Ringeval & Sakellariadou, 1006.0931, JCAP] takes into account the **gravitational backreaction effect**, which prevents loop production below a certain scale $\gamma_c \simeq 20(G\mu)^{1+2\chi}$ [Polchinski & Rocha, gr-qc/0702055, PRD]

$$n_{\rm CS}(l,t) \simeq \begin{cases} \dfrac{C}{t^4(\gamma+\gamma_d)^{3-2\chi}}, & \gamma_d < \gamma \\ \dfrac{(3\nu-2\chi-1)C}{2t^4(1-\chi)\gamma_d\gamma^{2(1-\chi)}}, & \gamma_c < \gamma < \gamma_d \\ \dfrac{(3\nu-2\chi-1)C}{2t^4(1-\chi)\gamma_d\gamma_c^{2(1-\chi)}}, & \gamma < \gamma_c \end{cases}$$



RD era: $\nu = 1/2,\ C \simeq 0.0796,\ \chi \simeq 0.2$

MD era: $\nu = 3/2,\ C \simeq 0.0157,\ \chi \simeq 0.295$

LRS model: dashed lines

Smaller $G\mu$ means smaller GW emission power, and loops could survive longer, leading to **more smaller loops** radiating at **higher f**

The **LRS model** gives a **very high number density** of **small loops** in the $\gamma < \gamma_c$ regime, which significantly contribute to **high frequency GWs**

GWs from Cosmic Strings Associated with pNGB Dark Matter

- 🦁 We study the **SGWB** from **cosmic strings** generated in a UV-complete model for **pNGB DM** with a **spontaneously broken** $\mathrm{U}(1)_\mathrm{X}$ **gauge symmetry** [DY Liu, CF Cai, XM Jiang, **ZHY**, HH Zhang, 2208.06653, JHEP]
- 🐯 The DM candidate in this model can **naturally evade direct detection bounds**
- 🐮 The **bound** on the **DM lifetime** implies a symmetry-breaking scale $v_\Phi > 10^9$ GeV

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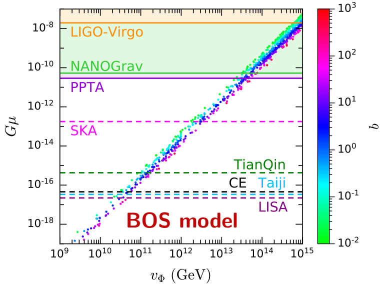
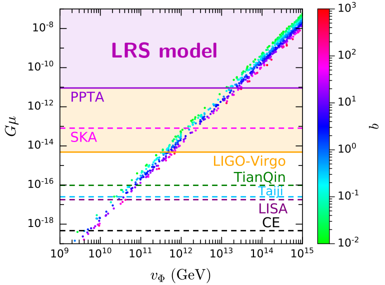
- The DM candidate in this model can **naturally evade direct detection bounds**
- The **bound** on the **DM lifetime** implies a symmetry-breaking scale $v_\Phi > 10^9$ GeV
- Constraints from **LIGO-Virgo**, **NANOGrav**, and **PPTA** have excluded the parameter points with $v_\Phi \gtrsim 5 \times 10^{13}$ (7×10^{11}) GeV
- The future experiment **LISA** (**CE**) can probe v_Φ down to $\sim 2 \times 10^{10}$ (5×10^9) GeV assuming the **BOS** (**LRS**) model for loop production

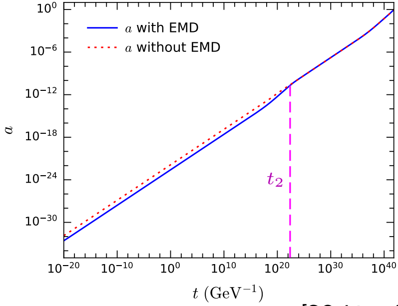
[ZY Qiu, **ZHY**, 2304.02506, CPC]

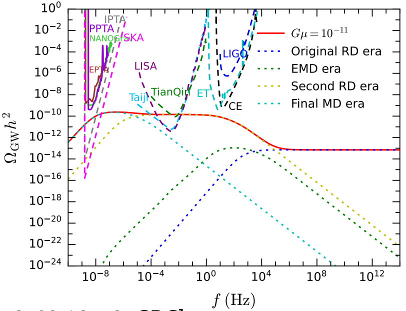




Early Matter-dominated Era and Cosmic String GWs

- We investigate the influence of an **early matter-dominated (EMD) era** in cosmic history on the **dynamics** of **cosmic strings** based on the **VOS model**
- For a particle model related to the **DM dilution mechanism**, we analyze the modifications to the **cosmological scale factor** and the **CS loop number density**
- The **EMD era** causes a **characteristic suppression** in the **high-frequency regime** of the **SGWB spectrum**





[SQ Ling & **ZHY**, 2502.16576, CPC]

Hybrid Topological Defects

🍱 For a field theory, such as a **GUT**, where **multiple stages** of **symmetry breaking** give rise to **topological defects**, **hybrid defects** may form [Vilenkin & Shellard, *Cosmic Strings and Other Topological Defects*; Dunsky, *et al.*, 2111.08750, PRD]

🍭 **Monopoles** attach to **cosmic strings** [Vilenkin, NPB **196** (1982) 240]

$$G \xrightarrow{\text{monopoles}} H \times \mathrm{U}(1) \xrightarrow{\text{strings}} H, \quad \pi_1(G/H) = \mathbf{1}$$

1. **Monopoles** form when G breaks to a subgroup containing a $\mathrm{U}(1)$ **symmetry**
2. **Strings** form and connect to **monopoles** when this $\mathrm{U}(1)$ **symmetry** is later broken

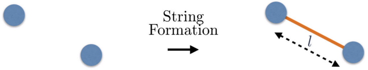
🌭 **Cosmic strings** attach to **domain walls** [Kibble, Lazarides, Shafi, PRD **26** (1982) 435]

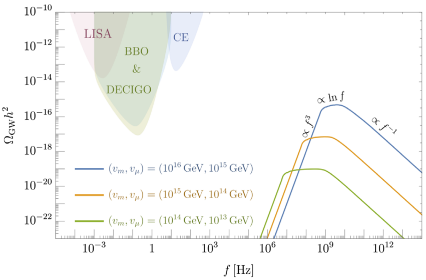
$$G \xrightarrow{\text{strings}} H \times Z_2 \xrightarrow{\text{walls}} H, \quad \pi_0(G/H) = \mathbf{1}$$

1. **Strings** form when G breaks to a subgroup containing a **discrete symmetry** with $\pi_1[G/(H \times Z_2)] \supset \pi_0(H \times Z_2) \neq \mathbf{1}$
2. **Walls** form and connect to **strings** when the same **discrete symmetry** associated with the strings is broken

Strings Eating Monopoles

- Such **hybrid defects** are **unstable**, with **one defect "eating" the other** via the conversion of the **rest mass** of **the latter** into the **kinetic energy** of **the former**, and subsequently, **decaying** via **gravitational waves**
- **Strings eating monopoles** [Lazarides, Shafi, Walsh, NPB **195** (1982) 157]
- A **monopole network** form at a **scale** v_m
- At temperatures below the **string symmetry breaking scale** v_μ, the magnetic field of the **monopoles** squeezes into **flux tubes (cosmic strings)** connecting each monopole-antimonopole pair
- **GW emission** occurs in a burst, **peaking** at **high frequencies** corresponding to the monopole-antimonopole separation distance at $T \simeq v_\mu$





[Dunsky, *et al.*, 2111.08750, PRD]

Monopoles Eating Strings

♋ **Monopoles eating strings** (metastable cosmic strings)

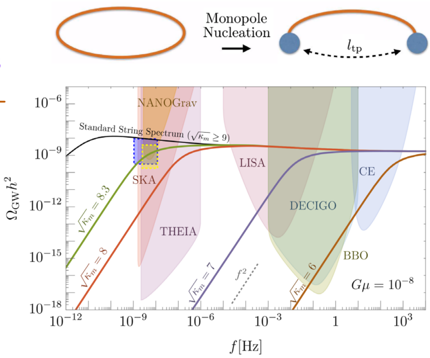
🥛 The **symmetry breaking chains** are the **same** as in the previous case

🥚 **Inflation** occurs after **monopole formation** but before **string formation**

🧇 Because of the **absence** of **monopoles**, a **normal string network** forms

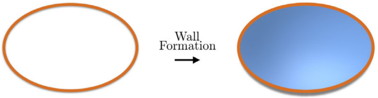
🌮 Nevertheless, the **strings** of **tension** μ can later become **bounded** by **monopoles** of **mass** m by the **Schwinger nucleation** of **monopole-antimonopole pairs**, which cut the strings into pieces bounded by monopoles

🌯 Conversion of the string rest mass into the monopole kinetic energy leads to **relativistic oscillations** of the monopoles before the system decays via **gravitational radiation** and monopole annihilation ($\kappa_m = m^2/\mu$)



[Dunsky, *et al.*, 2111.08750, PRD]

Domain Walls Eating Strings



Domain walls eating strings

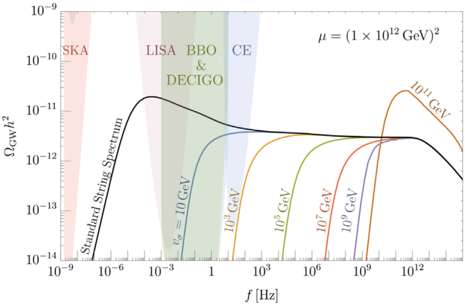
A **string network** form at a **scale** v_μ

At temperatures below the **wall symmetry breaking scale** v_σ, **walls** fill in the space between **strings**

A **wall-string network** forms, evolves, and finally **collapses** and **decays**

Prior to wall domination at t_*, the **wall-string network** behaves similarly to a **pure string network**, resulting the **GW spectrum** $\Omega_{\mathrm{GW}} \propto f^0$ at **high frequencies**

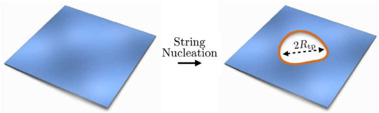
After the network collapses and the largest string-bounded walls decay, Ω_{GW} drops as f^3 at **low frequencies**



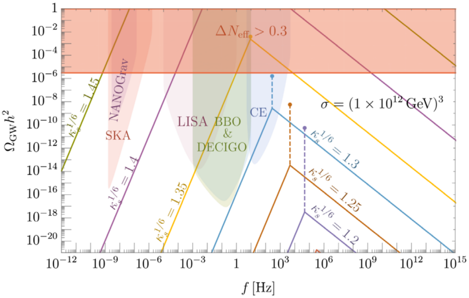
[Dunsky, *et al.*, 2111.08750, PRD]

Strings Eating Domain Walls

Strings eating domain walls



- The **symmetry breaking chains** are the **same** as in the previous case
- **Inflation** occurs after **string formation** but before **domain wall formation**
- Because of the **absence** of **strings**, a **normal wall network** forms
- Nevertheless, the **walls** can become **bounded** by **strings** later by the **Schwinger nucleation** of **string holes**
- Conversion of wall rest mass into string kinetic energy causes the **string** of **tension** μ to **rapidly expand** and **eat** the **wall** of **tension** σ, causing the **wall network** to **decay** with **GW emissions** ($\kappa_s = \mu^3/\sigma^2$)



[Dunsky, *et al.*, 2111.08750, PRD]

Summary

- In the early Universe, the **spontaneous breaking** of **symmetries** could lead to **topological defects**, such as **monopoles**, **domain walls** and **cosmic strings**
- **Collapsing domain walls**, **cosmic strings**, or various **hybrid defects** may result in a **stochastic GW background**, which could be probed in future GW experiments

Summary

- In the early Universe, the **spontaneous breaking** of **symmetries** could lead to **topological defects**, such as **monopoles**, **domain walls** and **cosmic strings**
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Thanks for your attention!