

東北大學



NORTHEASTERN
UNIVERSITY

STORY OF THE WALLS BOUNDED BY STRINGS



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BF, Ghoshal, King & Rahat 2404.16931 Type I 2HDM
BF, Ghoshal & King 2507.08645 multi-Majoron

NPhIS 2026

New Physics and Interdisciplinary Science

新物理前沿与交叉科学研讨会

南京 · Nanjing · May 15-19, 2026

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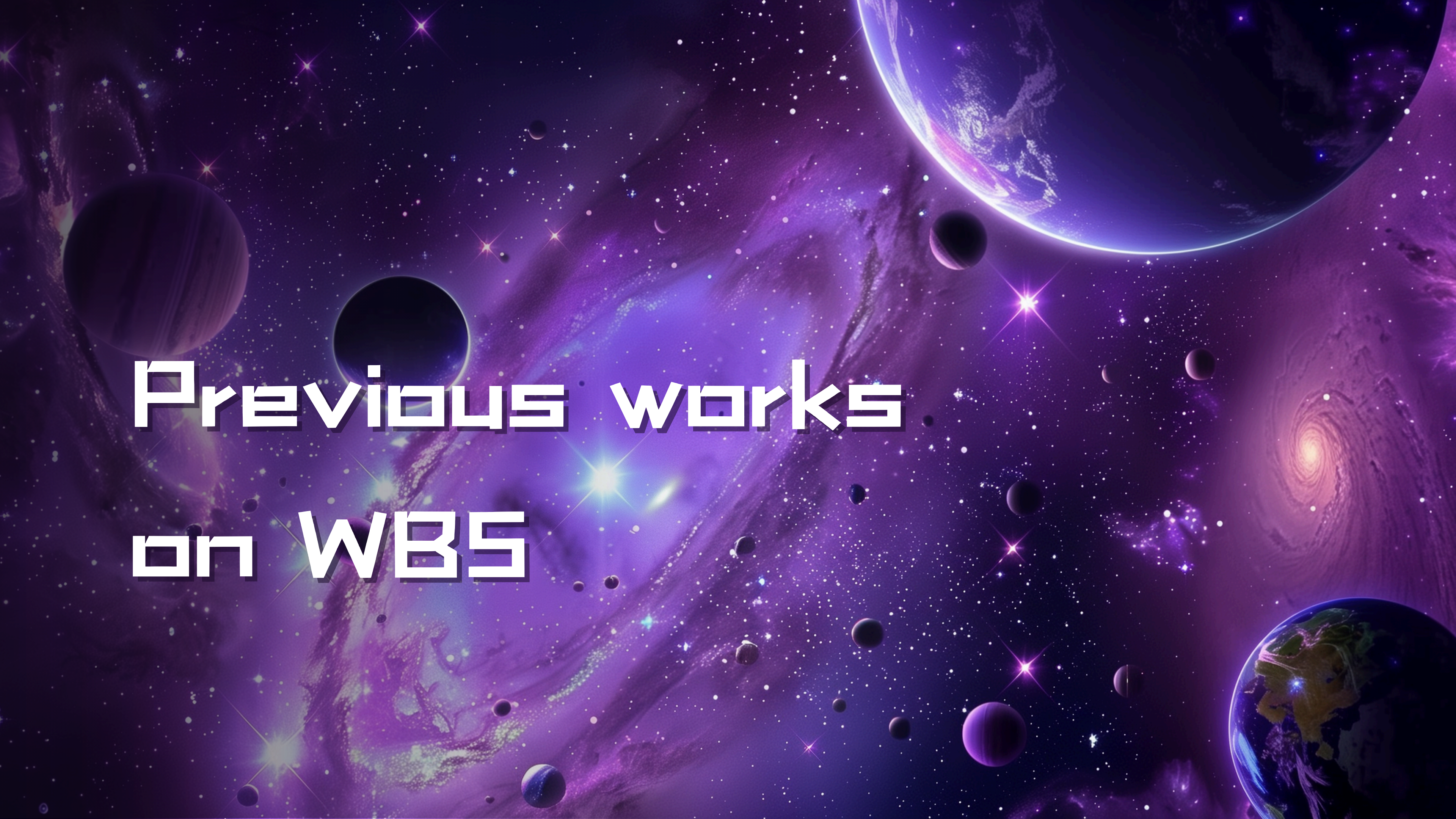
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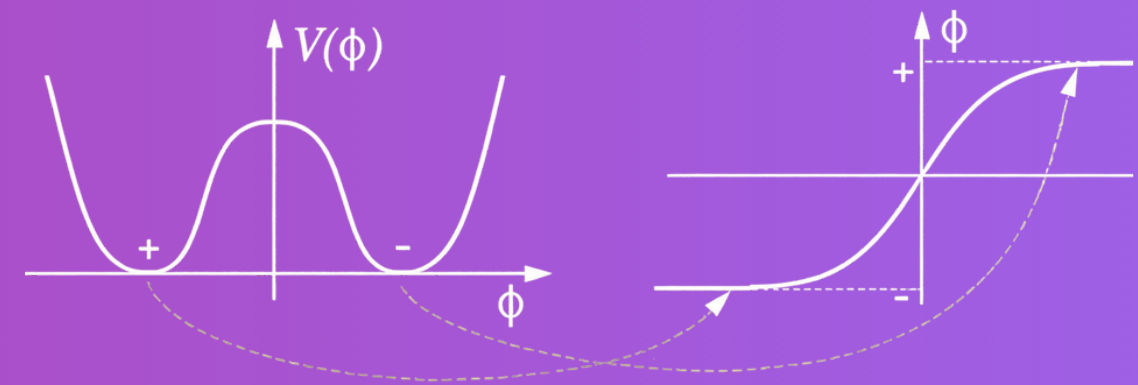


Previous works on WBS

Topological Defects

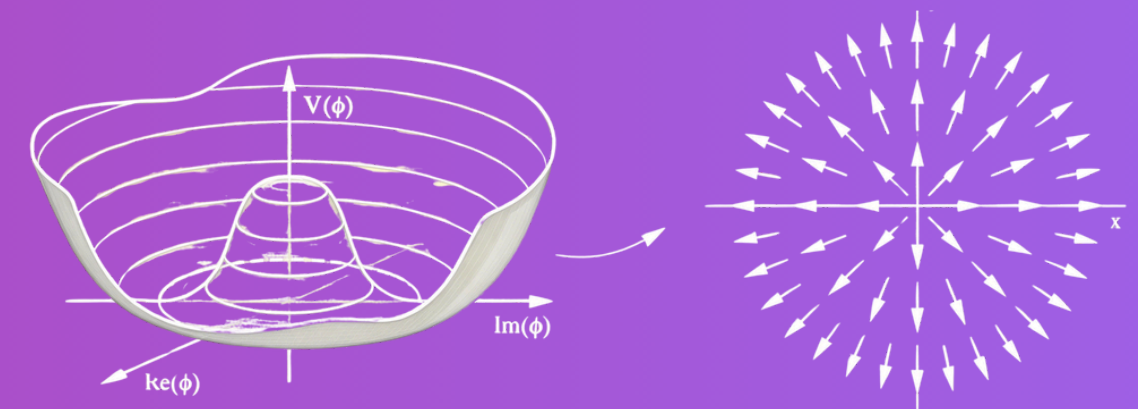
Domain wall

two-dimensional objects
discrete symmetry breaking at a phase transition.
partition the Universe into various 'cells'



Cosmic string

one-dimensional (line-like) objects
axial or cylindrical symmetry breaking
associated with GUT models



Different types of Walls bounded by Strings

Axion strings and axion walls

Strings form when the approximate $U(1)$ is broken
When the explicit $U(1)$ breaking term becomes significant,
the energy of the string gather to a particular angle

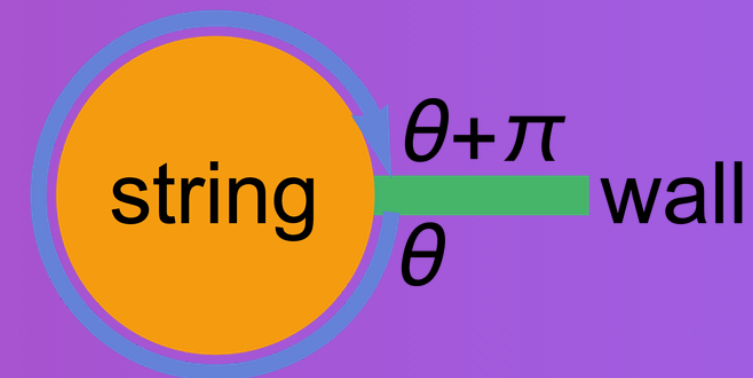
Vilenkin & Everett, 1982



Breaking chain $U(1)$ to Z_n to $\{e\}$

Strings form when the $U(1)$ is broken into Z_n
Walls form when the Z_n is broken

Kibble, Lazarides & Shafi, 1982



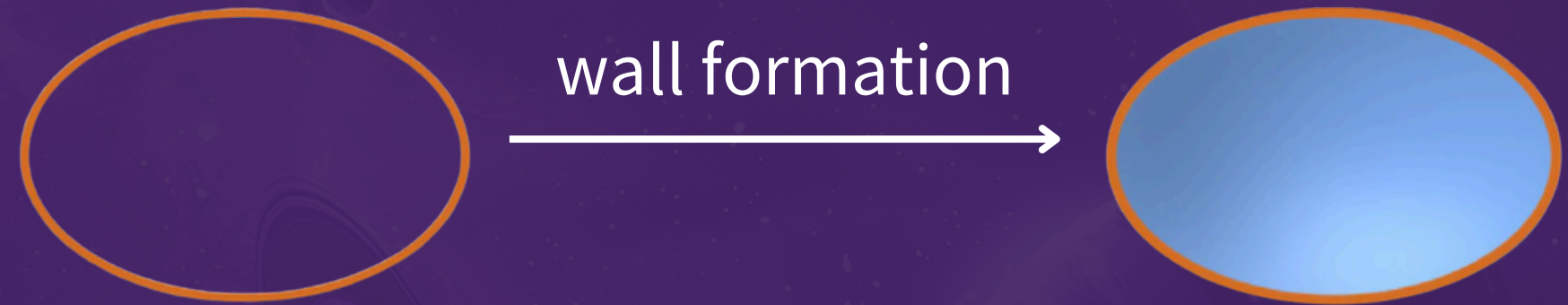
"Domain walls eating strings"

Energy of the string $2\pi R\mu$

Energy of the wall $\pi R^2\sigma$

$$\frac{dE_{\text{tot}}}{dR} = 2\pi(\mu + R\sigma)$$

Critical radius $R_c = \mu/\sigma$



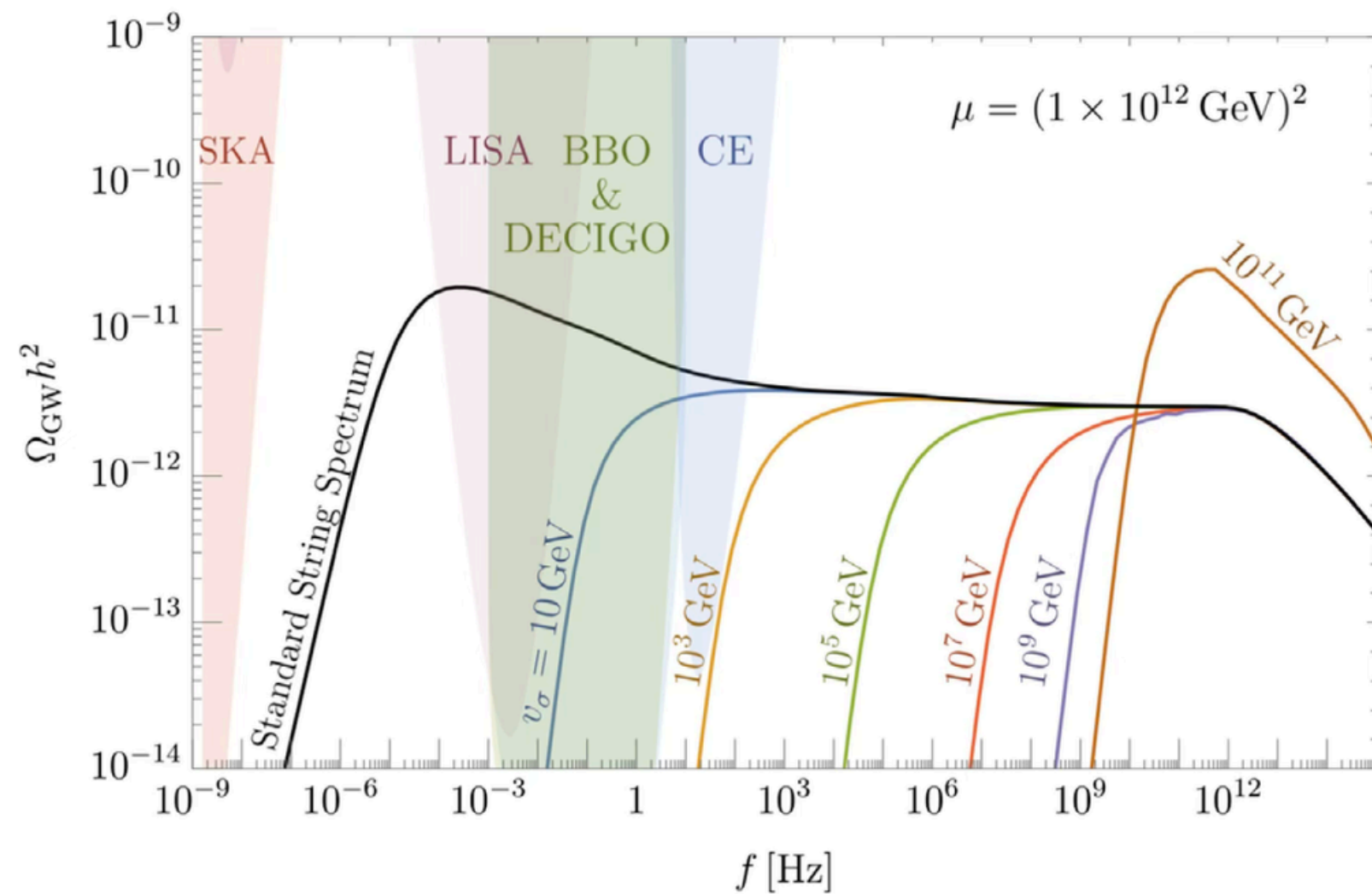
$R > R_c$ wall dominant

$R < R_c$ string dominant

Dunsky, Ghoshal, Murayama, Sakakihara & White, 2022

Phenomenology

Gravitational wave spectrum



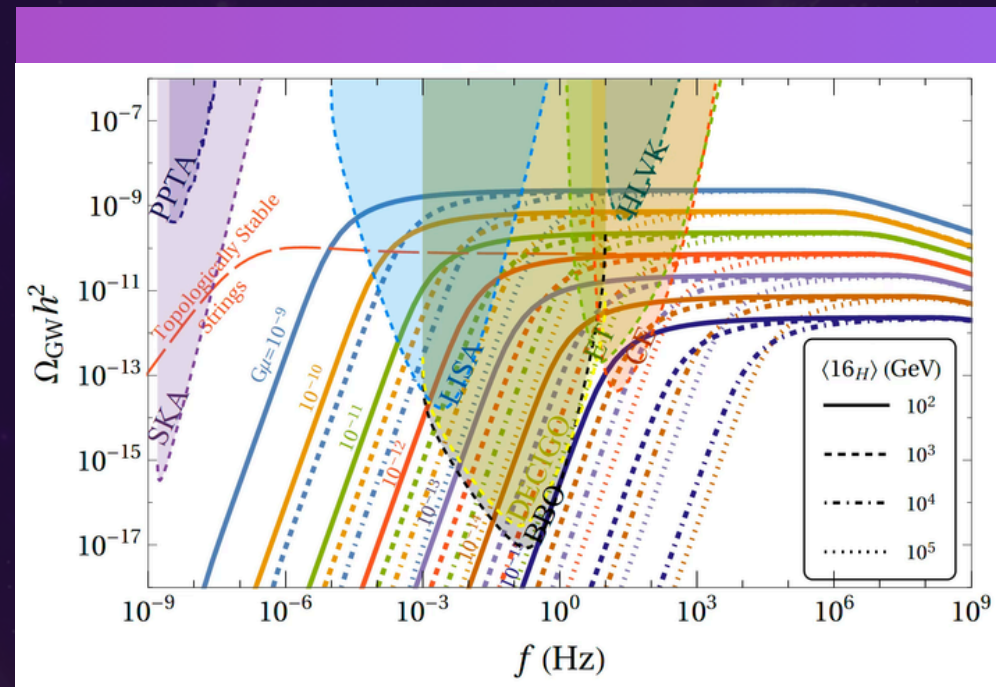
Strings are pulled by the walls to collapse soon after the walls dominate the dynamics

$$t_* \equiv \max(R_c, \mathcal{H}^{-1}|_{T=v_{\text{DW}}})$$

$$\Omega_{\text{GW}}(f) = \sum_n \frac{G\mu^2}{\rho_c} \int_{t_{\text{sc}}}^{t_0} d\tilde{t} \left(\frac{a(\tilde{t})}{a(t_0)} \right)^5 \left[\frac{\mathcal{F}C_{\text{eff}}(t_k)}{\alpha t_k^4} \left(\frac{a(t_k)}{a(\tilde{t})} \right)^3 \right] \mathcal{P}_n \frac{\xi n}{f} \left[1 + \frac{1}{2\pi R_c} \frac{\xi n}{f} \frac{a(\tilde{t})}{a(t_0)} \right] \frac{\Gamma(\alpha t_k) \theta(t_* - t_k)}{\Gamma(\alpha t_k) G\mu + \alpha \left(1 + \frac{\alpha t_k}{2\pi R_c} \right)}$$

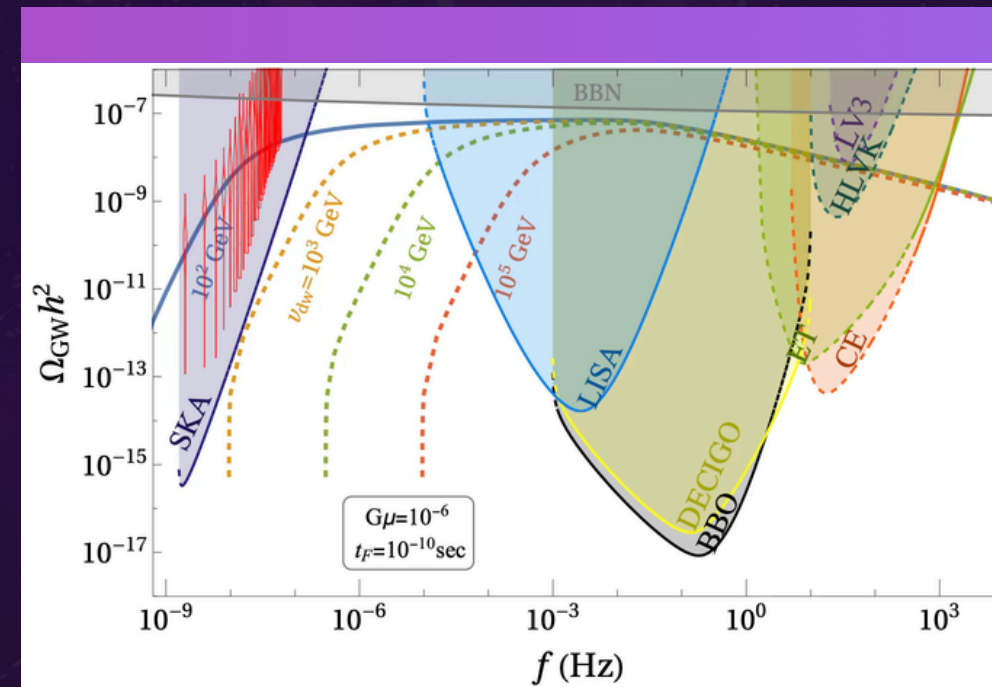
Phenomenology

Such a gravitational wave spectrum has been applied to different models



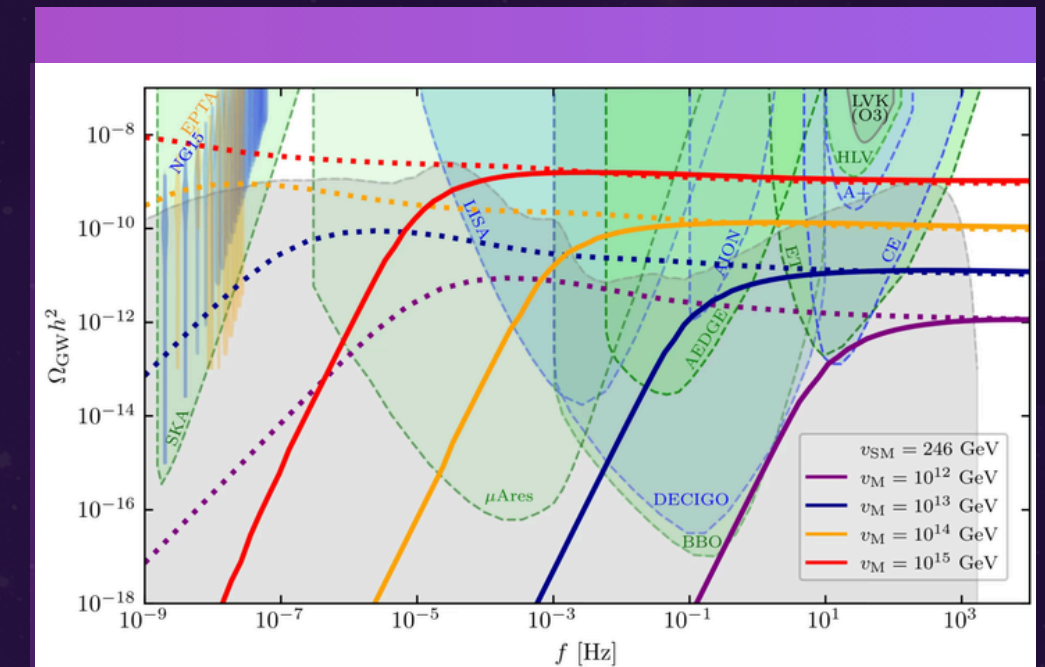
$SO(10)$

Maji, Park, Shafi 2023



$SU(5) \times U(1)_X$

Lazarides, Maji, Shafi 2023

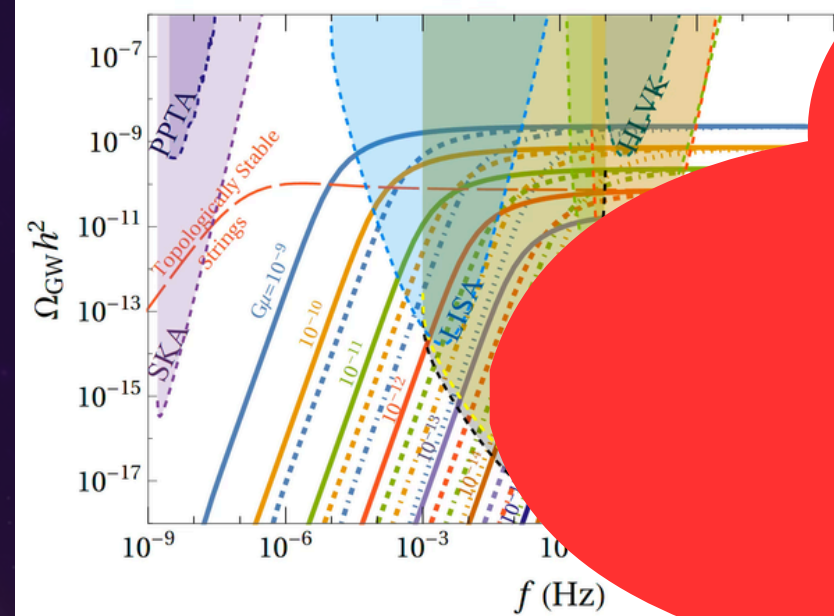


Type I 2HDM

BF, Ghoshal, King & Rahat 2024

Phenomenology

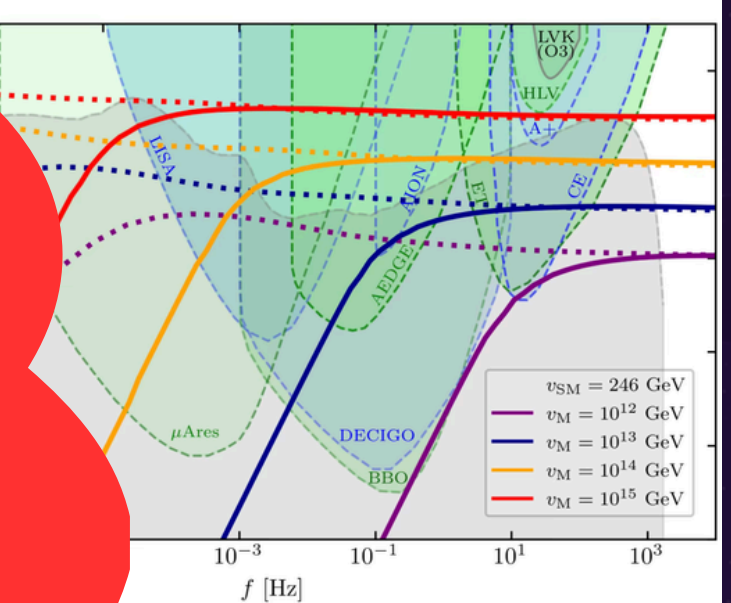
Such a gravitational wave spectrum has been applied to different models



SO(10)

Maji, Park, Shafi 2023

Is it correct?



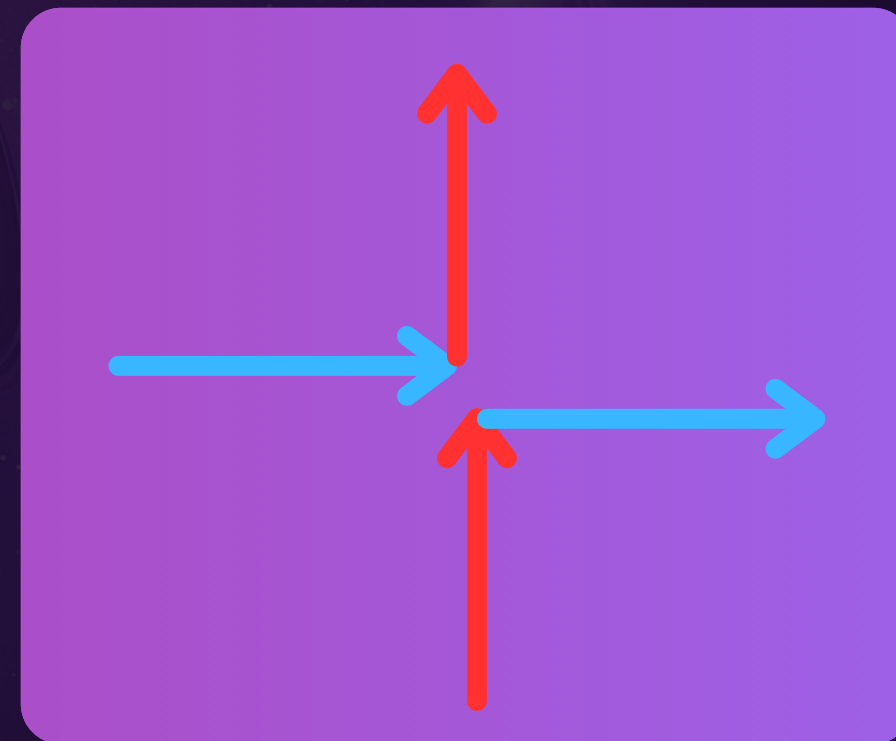
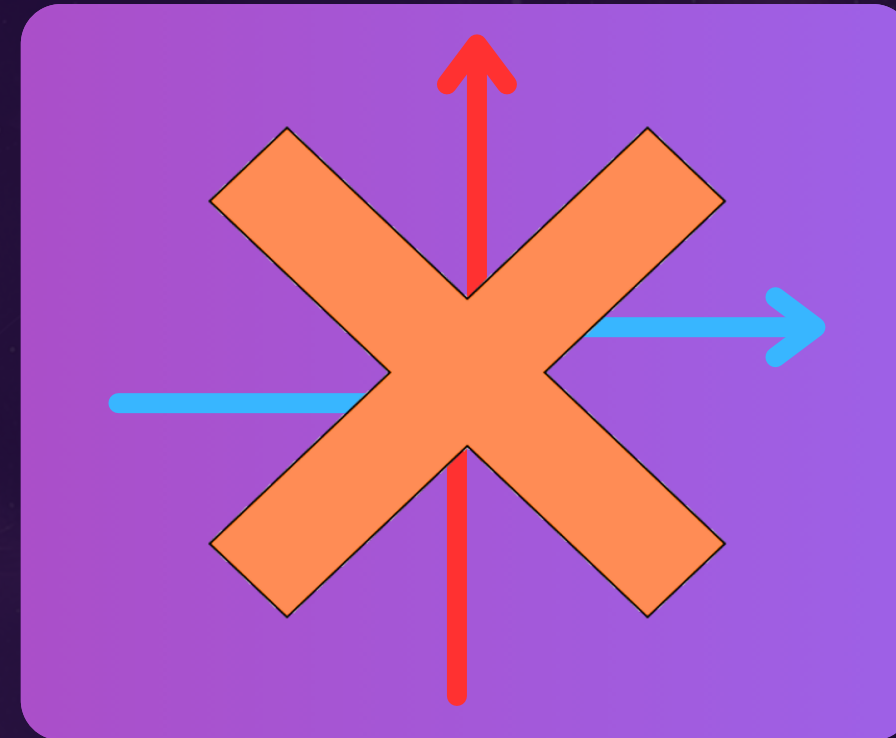
2HDM

BF, Ghoshal, King & Rahat 2024



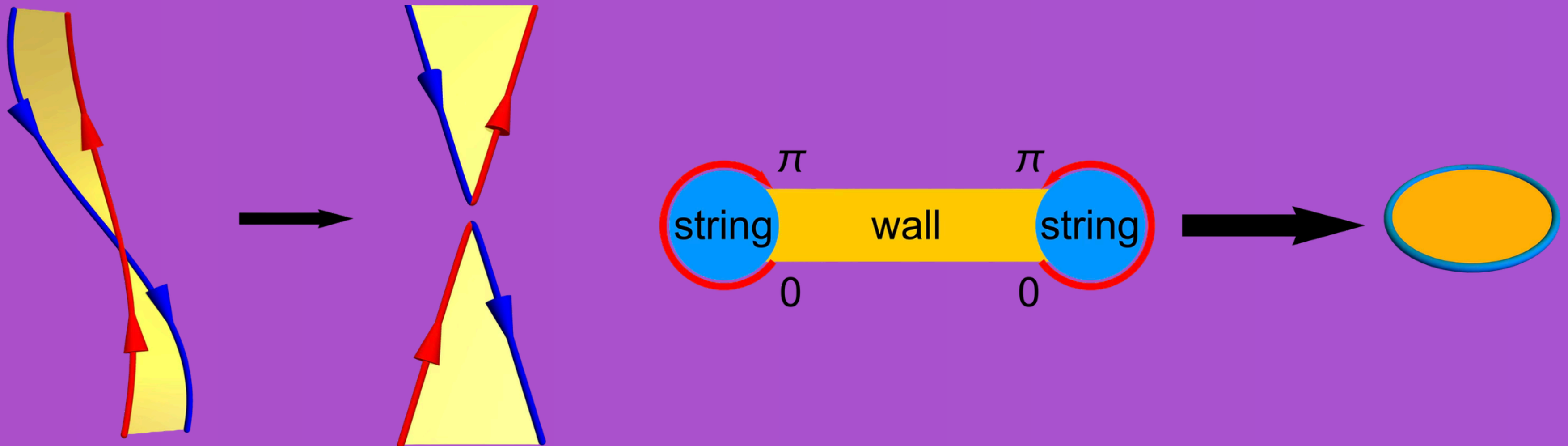
Fate of long strings

Long strings



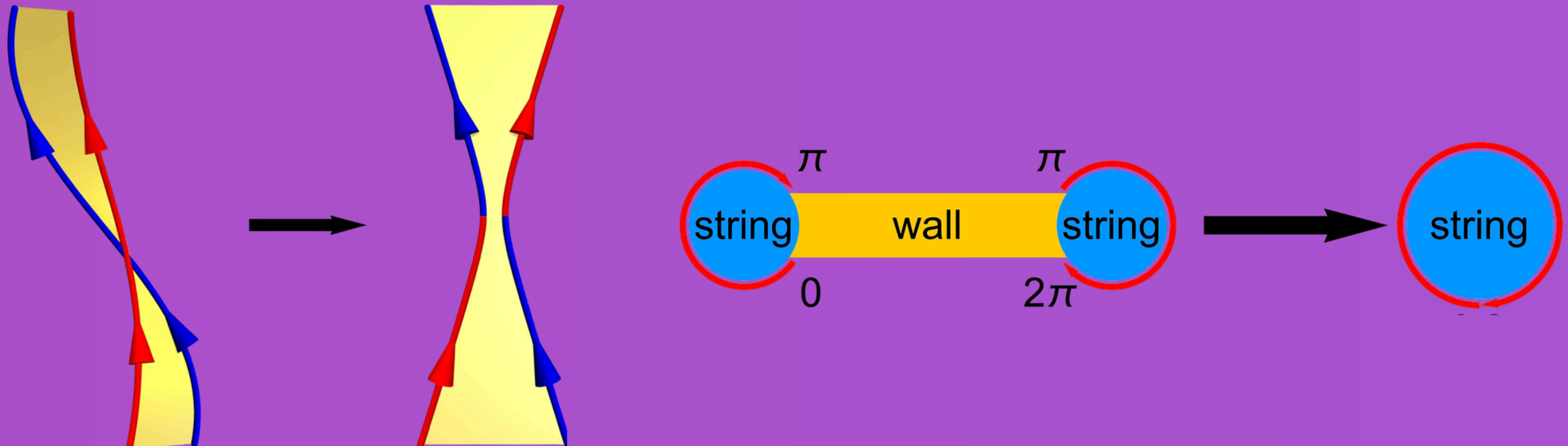
Wall bounded by Long strings

Two strings winding in the **opposite** direction



Wall bounded by Long strings

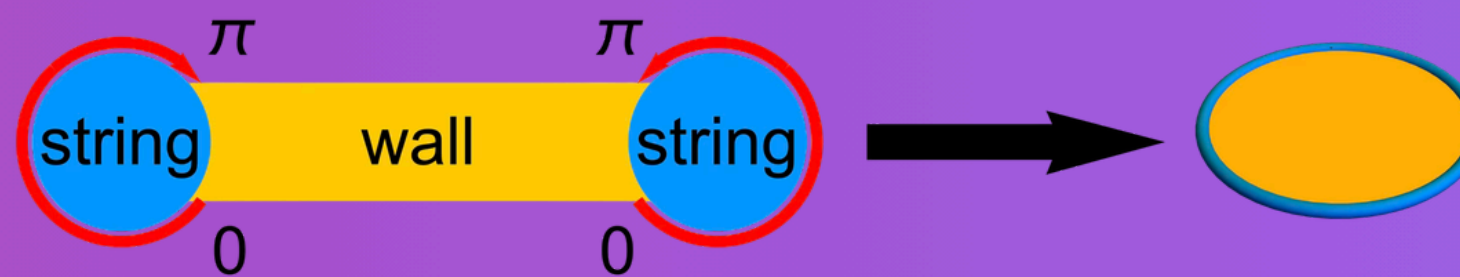
Two strings winding in the **same** direction



Wall bounded by Long strings

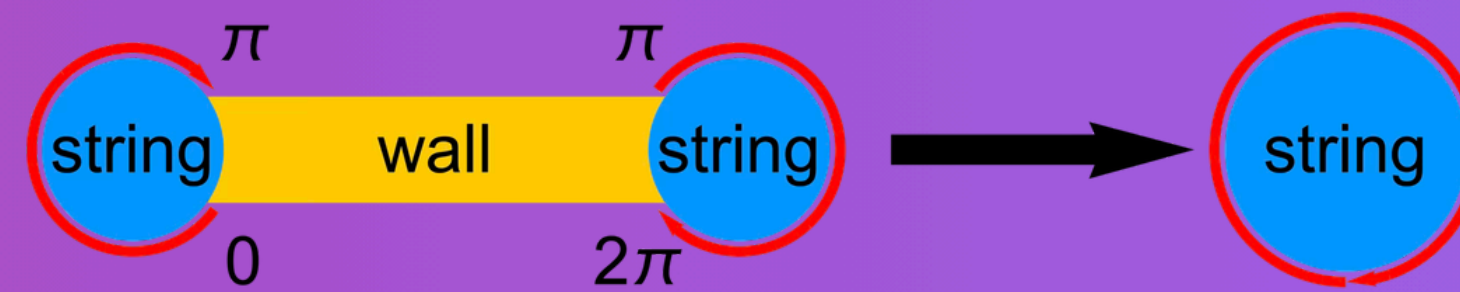
loop formation

from two strings winding in the opposite direction



relic string network

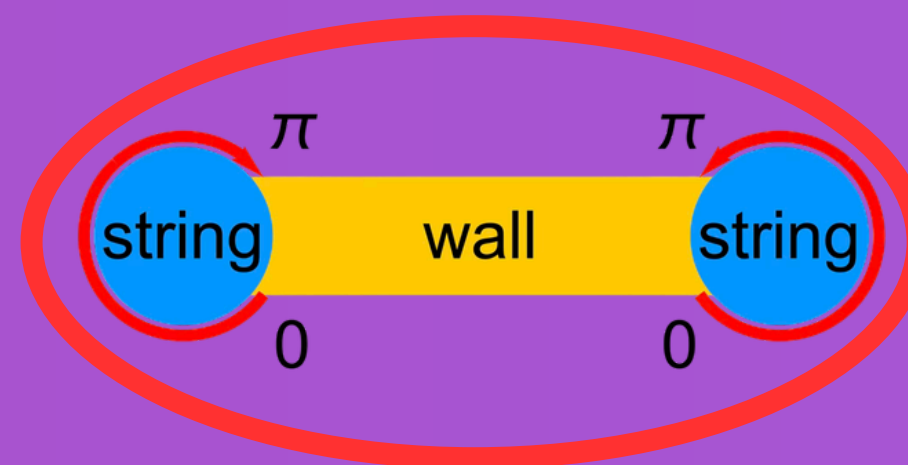
from two strings winding in the same direction



Wall bounded by Long strings

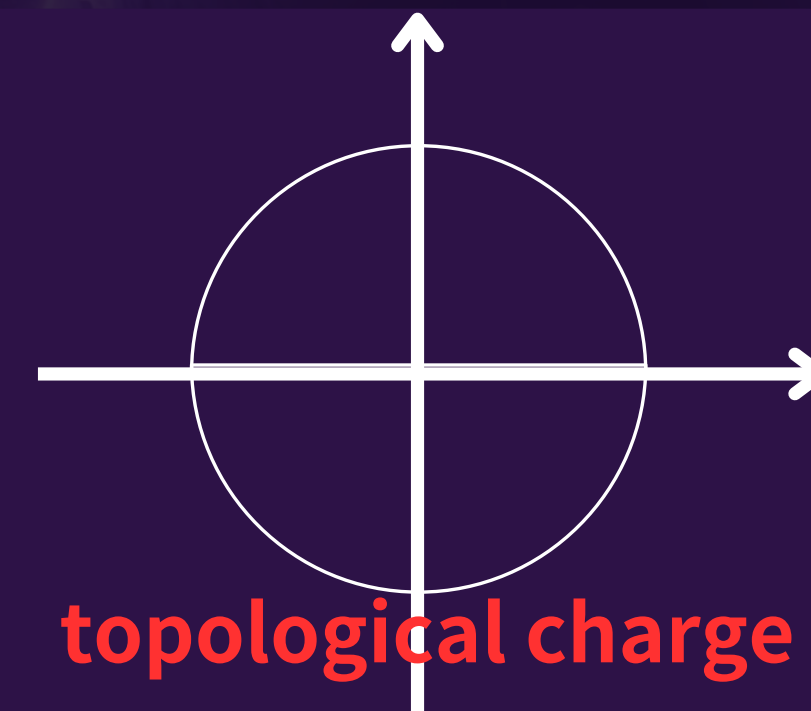
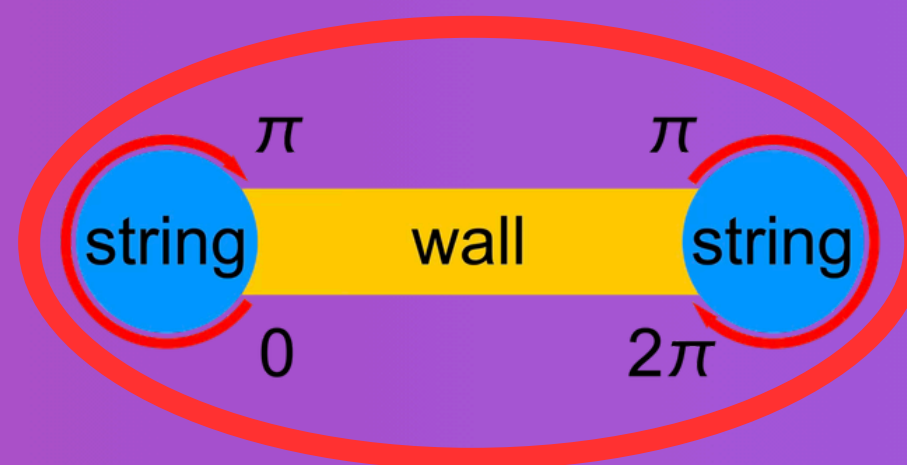
loop formation

from two strings winding in the opposite direction



relic string network

from two strings winding in the same direction





Property of the string relic

String tension

The tension of global string is given by

$$\mu \sim \eta^2 \int \left[\frac{1}{r} \frac{\partial \alpha}{\partial \theta} \right]^2 2\pi r dr \propto \left[\frac{\partial \alpha}{\partial \theta} \right]^2$$

$$U(1) \rightarrow I \quad \alpha = \theta$$

$$\mu \sim 2\pi\eta^2 \ln \frac{R}{\delta}$$

$$U(1) \rightarrow Z_n \rightarrow I \quad \alpha = \theta/n$$

$$\mu \sim \frac{1}{n^2} 2\pi\eta^2 \ln \frac{R}{\delta}$$

$$\mu \propto \frac{1}{n^2}$$

Gravitational wave



Evolution of the network

Walls are created on strings. The walls stretch the strings together, forming loops or merging into strings with a larger winding angle, until all the walls disappear. The string number density is reduced by 1/2 in this process.

02 Z_2 to $\{e\}$

As the string number density is lower than the scaling regime, the chopping rate is lower, and thus the GW emitting power is lower. The string number density starts to grow.

Cooled network **03**

01 $U(1)$ to Z_2

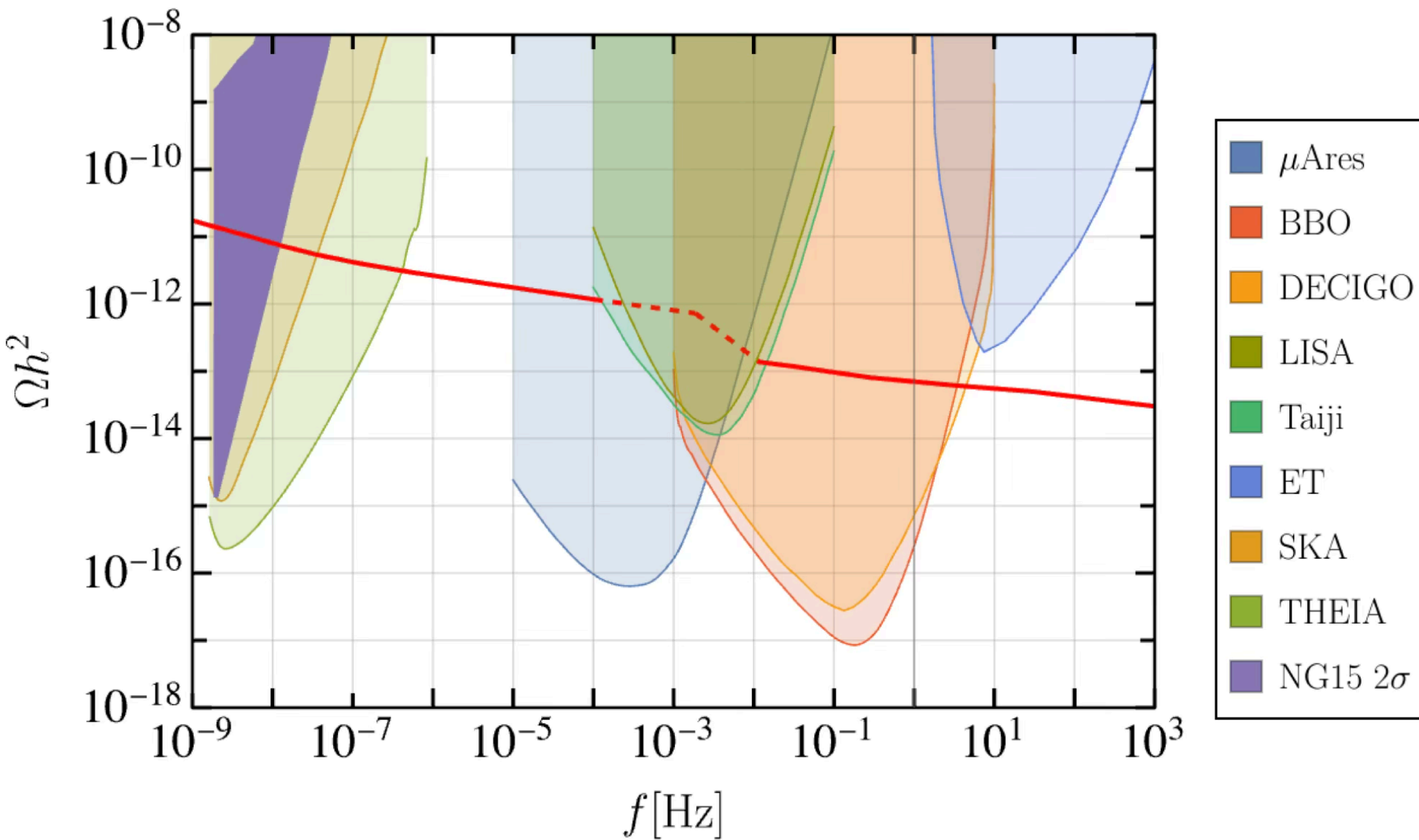
Strings winding from 0 to π are generated. The string network evolves normally and enters the scaling regime.

Network

Back to scaling **04**

The string network reenters the scaling regime.

Gravitational wave



wall formation

$$f \simeq 4.7 \times 10^{-6} \text{ Hz} \cdot \left(\frac{\langle \theta \rangle}{\text{GeV}} \right)$$

GW strength

$$\Omega_{\text{GW}} h^2 \propto \mu^2 \propto \left(\oint d\vartheta \right)^4$$

Possible future improvement

velocity-dependent
one-scale model

$$2\frac{dL}{dt} = 2HL(1 + v^2) + cv$$

$$\frac{dv}{dt} = (1 - v^2) \left[\frac{k(v)}{L} - 2Hv \right]$$

new term from wall tension
different loop chopping efficiency
string with different winding

lattice simulation

comoving Hubble distance grows
with comoving time and finally
exceed the comoving size of the
simulation box

string network as initial condition
of simulation



感谢您的观看

THANK YOU



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