Metastable defects and gravitational waves

Alberto Mariotti

HEP@VUB VRIJE UNIVERSITEIT BRUSSEL

Based on ArXiv:2605.03003 with
Simone Blasi and Maxime Grandjean



Why cosmic defects?

- ★ *They arise in cosmological phase transitions*
- ★ *Depends on structure of the vacuum manifold (symmetry breaking pattern) of the theory*
- ★ *Predicted in many BSM scenarios*
- ★ *Sources of gravitational waves*
- ★ *Can have other impact in early Universe dynamics*
- ★ *Unique signal of BSM physics (connect particle physics with early Universe cosmology)*

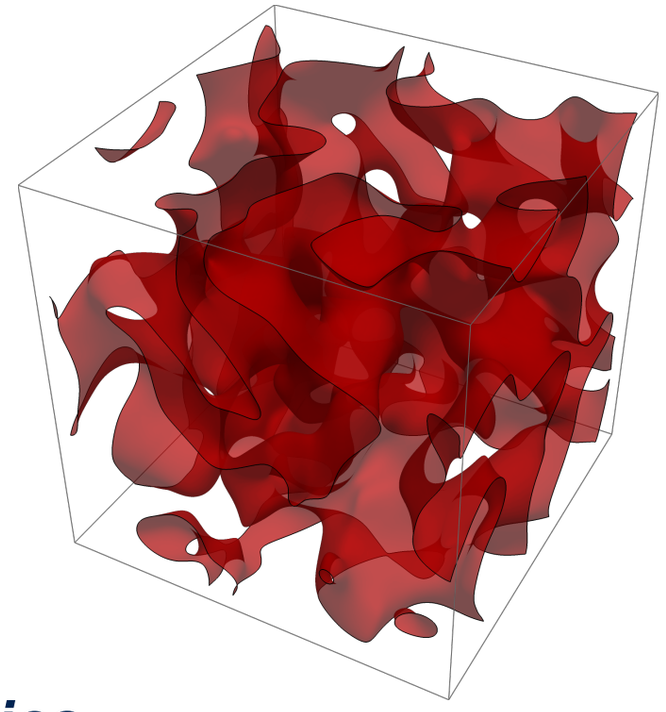


Fig. from A. Rase

Intro on topological defects

[Zel'dovich et al. '74, Kibble '76]

★Non trivial solutions to the EoM with finite energy

★Classification is based on topological properties of vacuum manifold

★Symmetry group G broken to a subgroup H

Vacuum Manifold $\mathcal{M} = G/H$

★Their existence depends on the homotopy group of the vacuum manifold

$$\pi_n(\mathcal{M}) \neq 1$$

★Extended dynamical objects carrying energy

Intro on topological defects

Defect	Dimension	Homotopy
Domain Walls	2	$\pi_0(\mathcal{M})$
Strings	1	$\pi_1(\mathcal{M})$
Monopoles	Point-like	$\pi_2(\mathcal{M})$

Of the vacuum manifold

$\mathbb{Z}_2$ Domain Walls

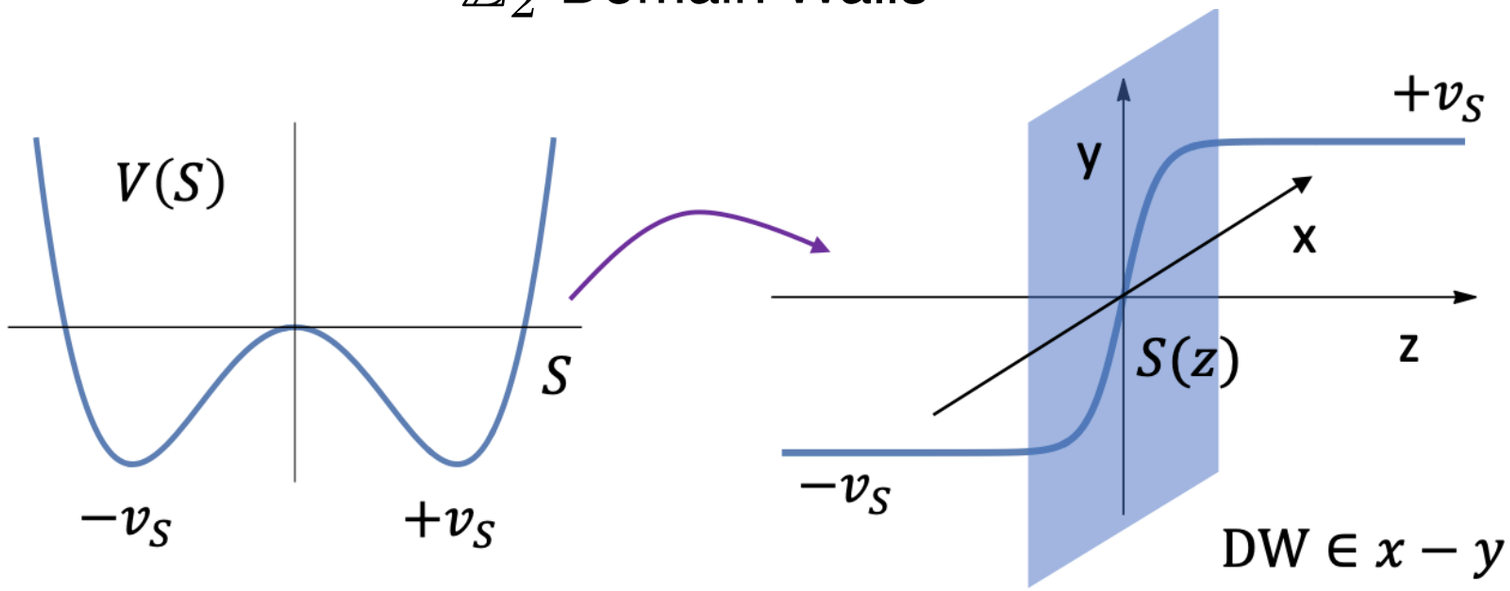


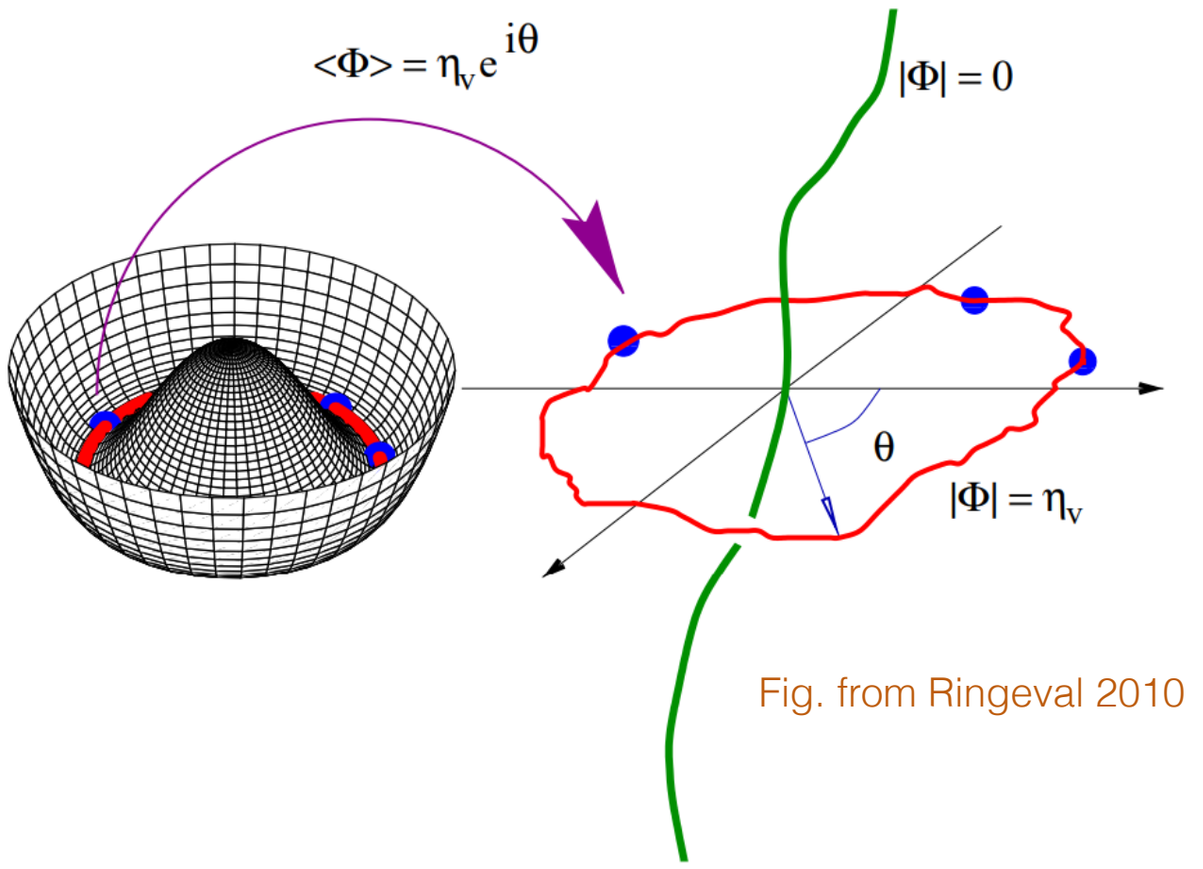
Fig. from Simone

Intro on topological defects

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Of the vacuum manifold

$U(1)$ Abrikosov-Nielsen–Olesen (ANO) String



$$\pi_1(U(1)) = \mathbb{Z}$$

Fig. from Ringeval 2010

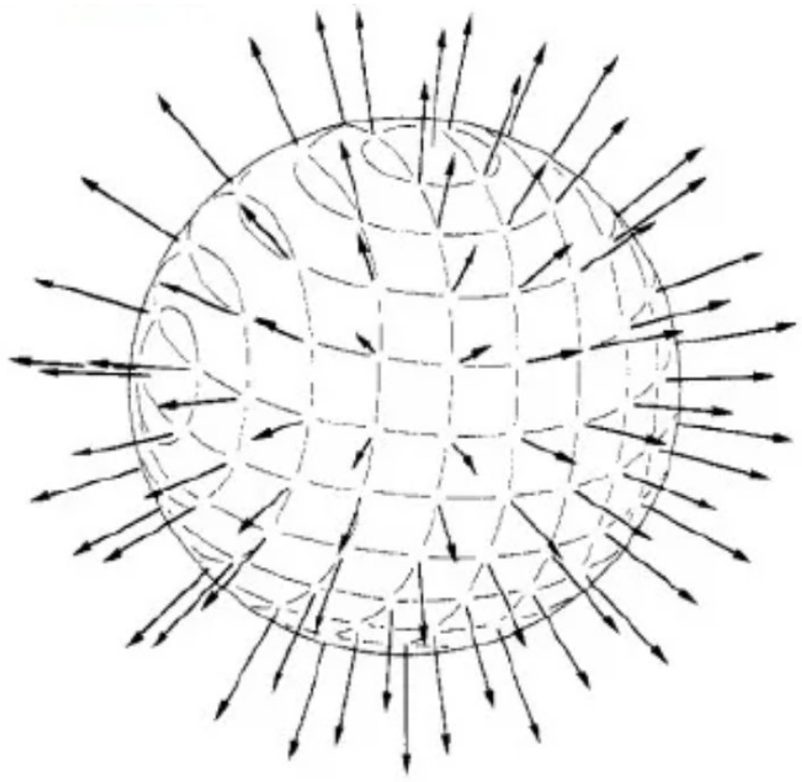
Intro on topological defects

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Of the vacuum manifold

$$SU(2) \to U(1) \qquad \pi_2(SU(2)/U(1)) = \mathbb{Z}$$

't Hooft–Polyakov Monopole

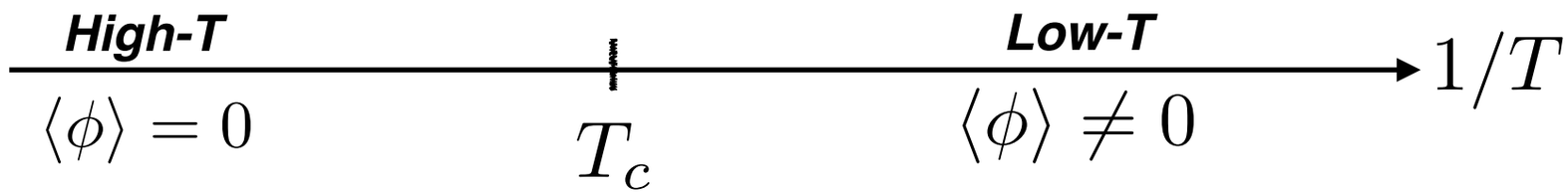


How topological defects form?

★***Consider Universe with high reheating temperature***

★***Symmetry group G restored at high temperatures***

ϕ : order parameter of a symmetry



Phase transition during the cooling of the Universe at critical temperature $\sim T_c$

Two interesting consequences of cosmological PT:

A. If phase transition is first order: bubbles and GW

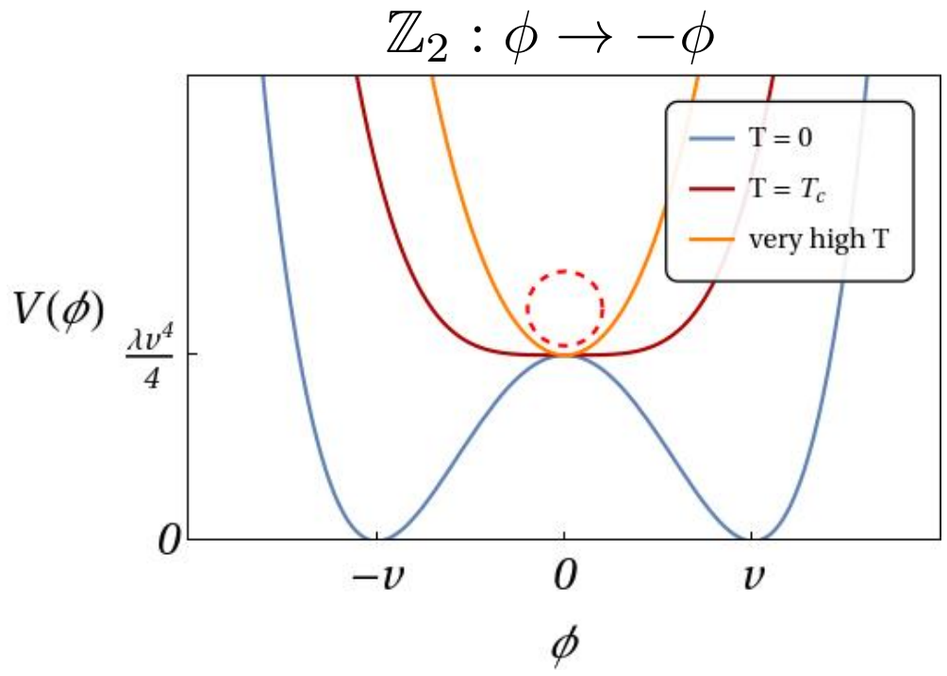
B. If homotopy of vacuum manifold non trivial: topological defects

How topological defects form?

[Zel'dovich et al. '74, Kibble '76]

★ ***Example of*** $\mathbb{Z}_2$ ***Domain Walls***

★ $\mathbb{Z}_2$ ***symmetry restored in early Universe and broken while temperature drops***



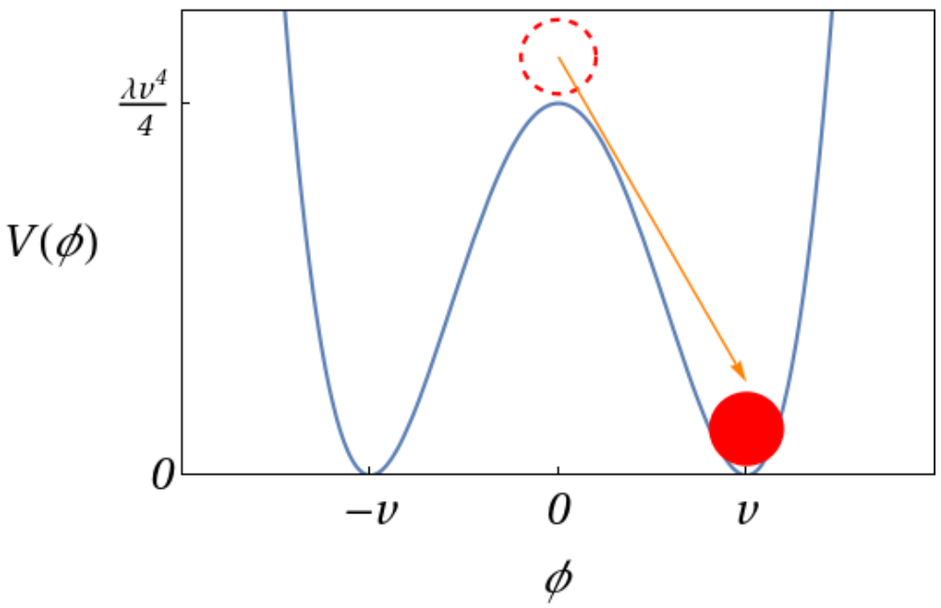
How topological defects form?

[Zel'dovich et al. '74, Kibble '76]

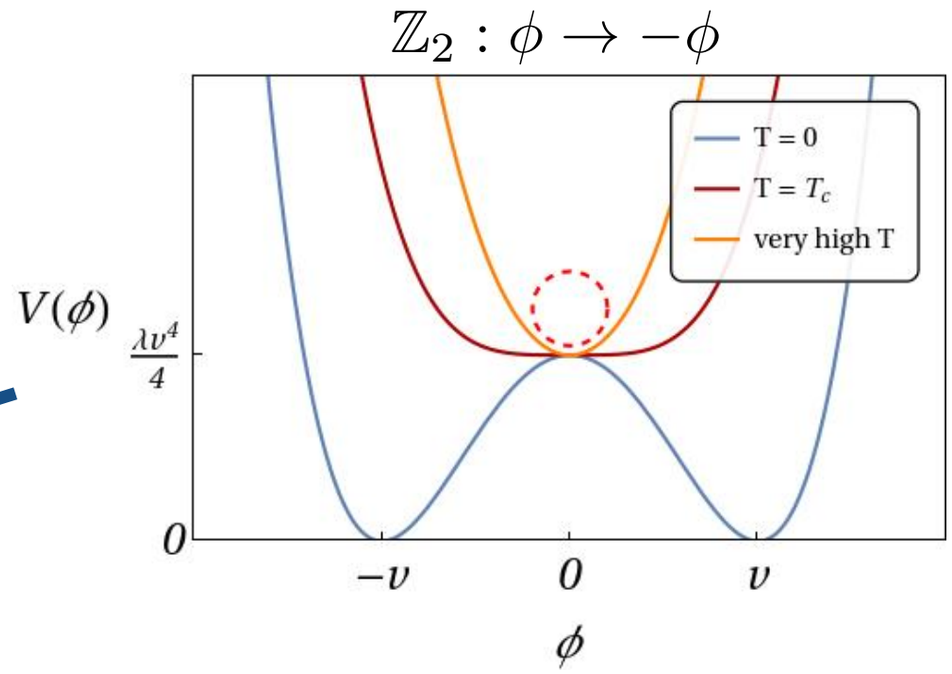
★ ***Example of*** $\mathbb{Z}_2$ ***Domain Walls***

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Spontaneous Z_2 breaking



$T < T_c$



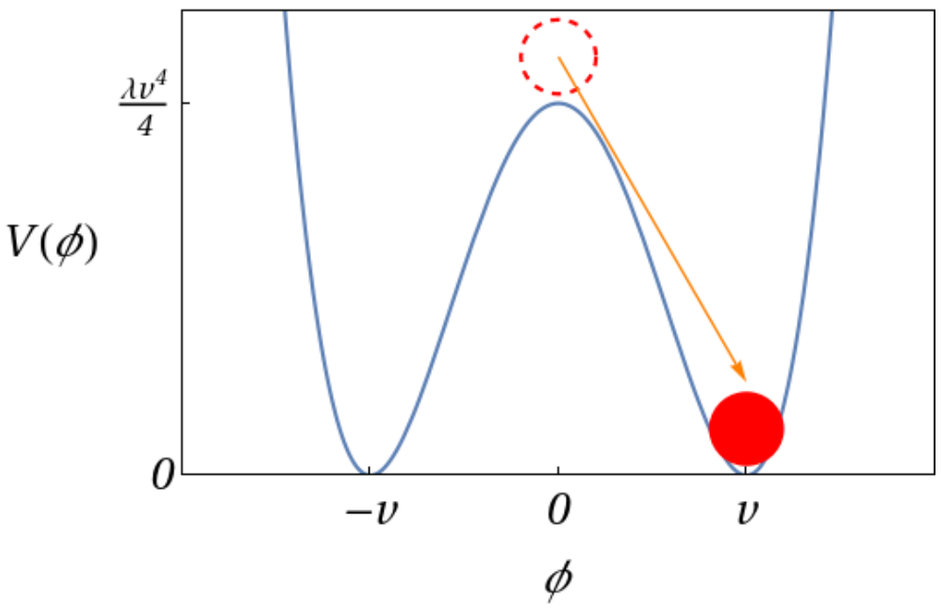
How topological defects form?

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★ ***Example of $\mathbb{Z}_2$ Domain Walls***

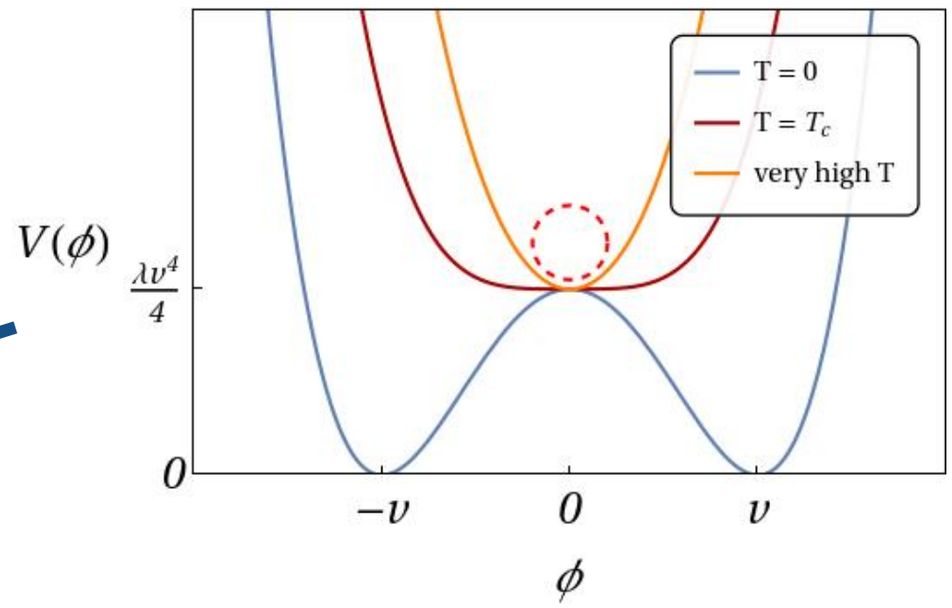
★ ***$\mathbb{Z}_2$ symmetry restored in early Universe and broken while temperature drops***

Spontaneous Z_2 breaking

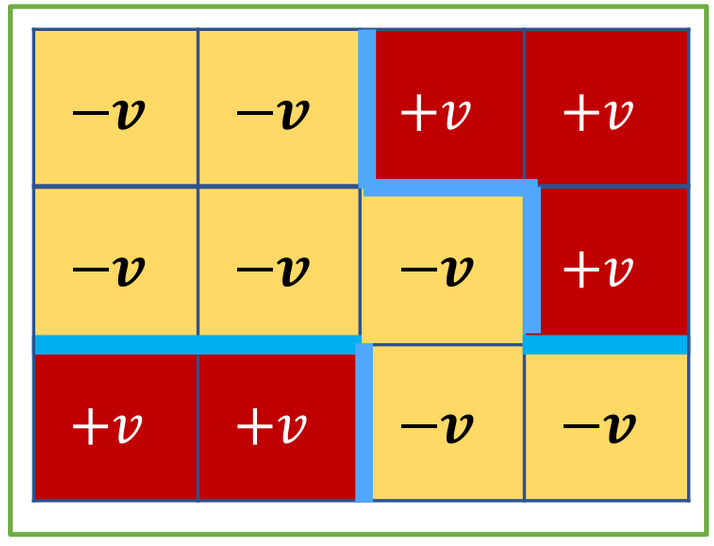


$T < T_c$

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



Domain Walls get formed



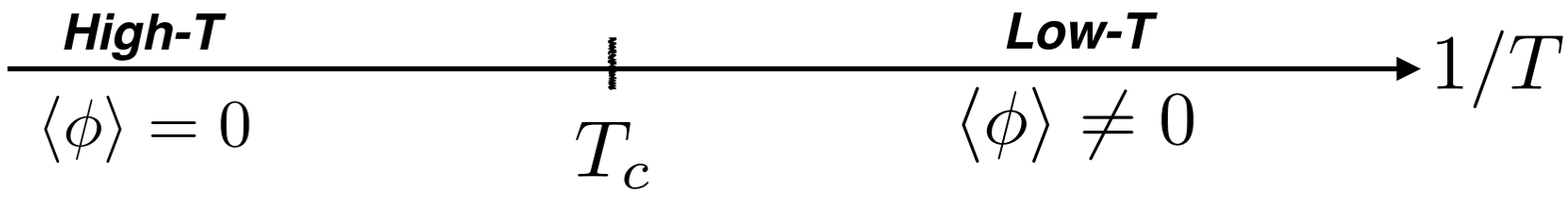
Universe

Universe get filled with "walls" separating regions with the two possible field values in the vacua

Figures from Aaron

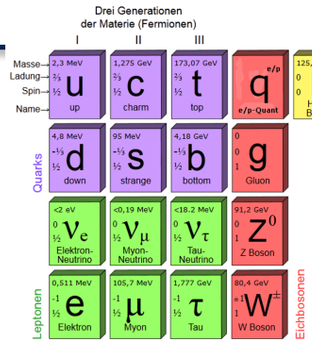
Cosmological phase transitions in the SM

ϕ : order parameter of a symmetry



Phase transition during the cooling of the Universe at critical temperature $\sim T_c$

★*In the Standard Model*



- ✳QCD Phase Transition (T ~ GeV)?
- ✳EW Phase Transition (T~ 100 GeV)?

  (If very light Higgs it could have been strongly first order) **'81 Witten**

- ✳No stable defects created in the SM phase transitions (we'll discuss this later)

Defects (or FOPT) would be signal of BSM

Cosmological Phase Transitions in BSM

BSM theories typically implies extension of SM symmetry group with spontaneously broken symmetries

Rich pattern of symmetry breaking

★***Few examples:***

- Grand Unified Groups like $SO(10)$
- Gauged B-L: $G_{\rm SM} \times U(1)_{\rm B-L}$
- Gauged Flavour Symmetries: $G_{\rm SM} \times SU(3)_F \to G_{\rm SM}$

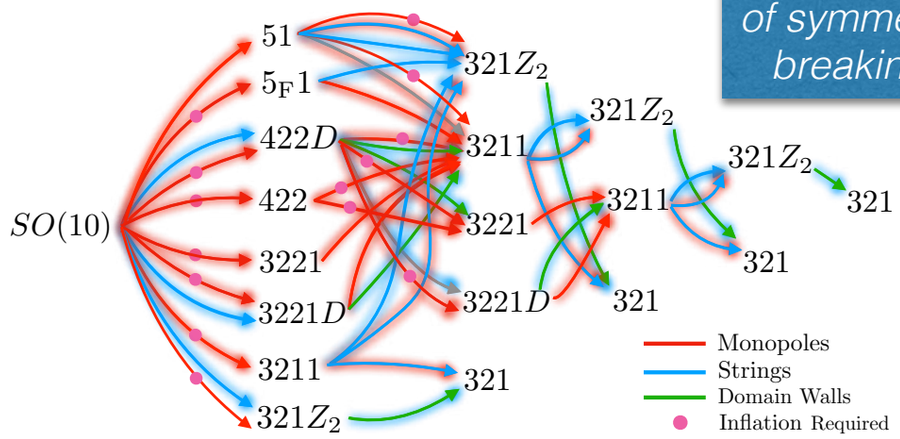


Fig. from arXiv:2111.08750

- Symmetries related to Dark Matter Stability: $G_{\rm SM} \times U(1)_{\rm DM} \to G_{\rm SM} \times \mathbb{Z}_2$ (*DM parity*)
- Composite Higgs, Supersymmetry $\mathcal{N} = 1$

★***Generic assumption is that symmetry are restored at high temperatures and broken while Universe cool down***

★***Cosmological Phase Transition are generic prediction of BSM theories with spontaneously broken symmetries***

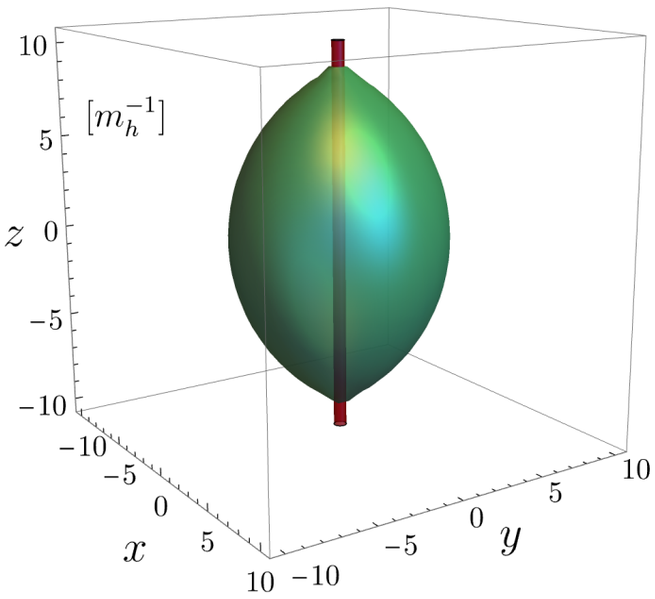
★***If non-trivial homotopy, defects are formed !***

Impact of cosmological defects

Topological defects impact cosmology in many directions:

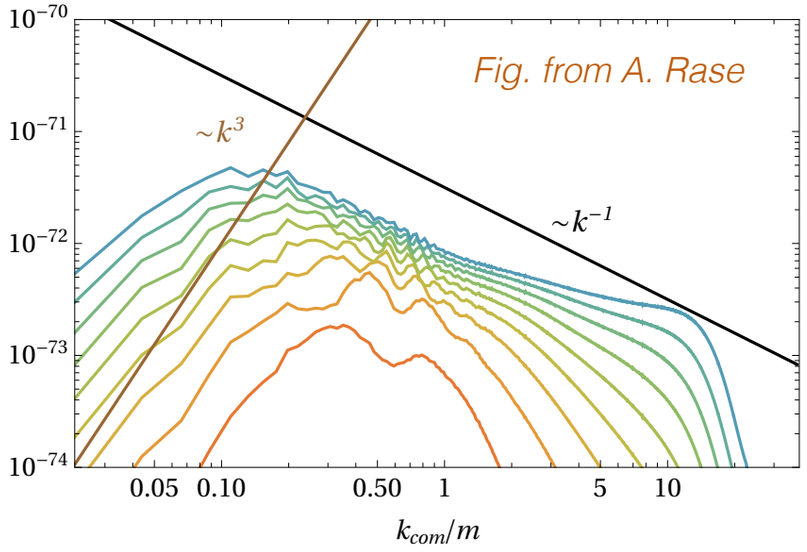
Impact of cosmological defects

Topological defects impact cosmology in many directions:



Blasi, AM '24

- **Induce matter antimatter asymmetry**
- **Seeds for first order (Electro-Weak) PT**
- **Contribute to dark matter**
- **Link to primordial black holes**
- **Also observable effects on late time**
- **Sources of gravitational waves**



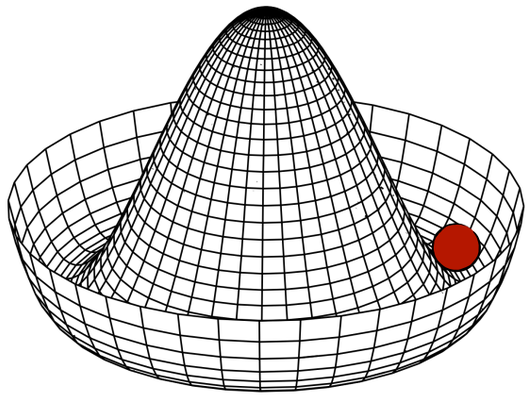
Defects are signal of BSM physics: testable in GW

...

Abelian Gauged Cosmic strings

★*Strings correspond to vacuum manifold with non-contractible circle*

★*Consider an abelian Higgs model with U(1) gauge*



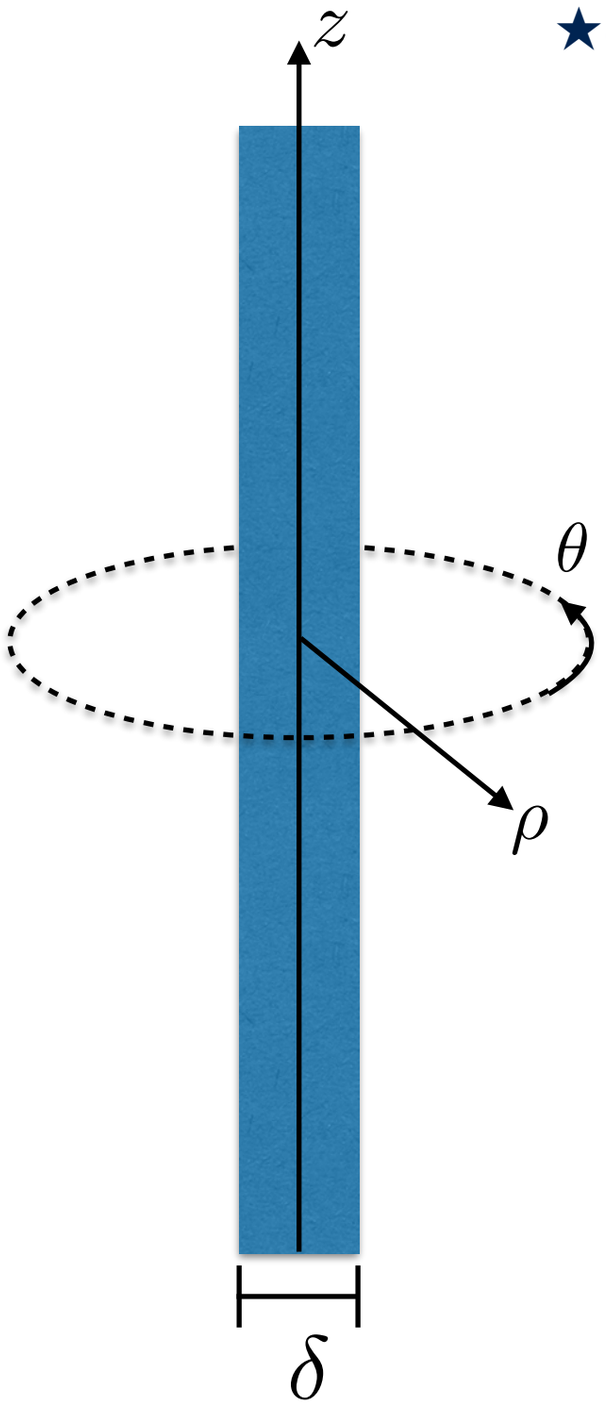
$$V(\phi) = \lambda\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$U(1) \to 1$$

$$\pi_1(U(1)) = \mathbb{Z}$$

Abelian Gauged Cosmic strings

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$$V(\phi) = \lambda\left(|\phi|^2 - \frac{v^2}{2}\right)^2$$

$$U(1) \to 1$$

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String ansatz (cylindrically symmetric)

Winding number

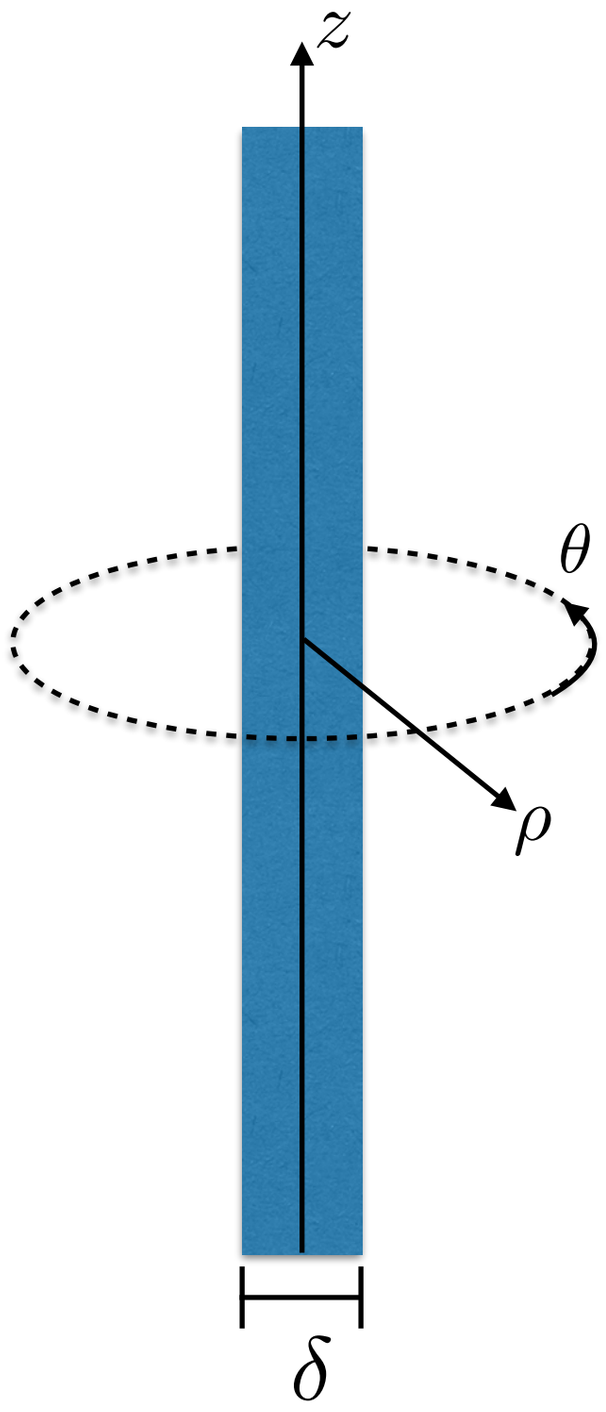
$$\phi = e^{in\theta} f(\rho)$$

$$A_\theta = \frac{n}{e\rho}\zeta(\rho)$$

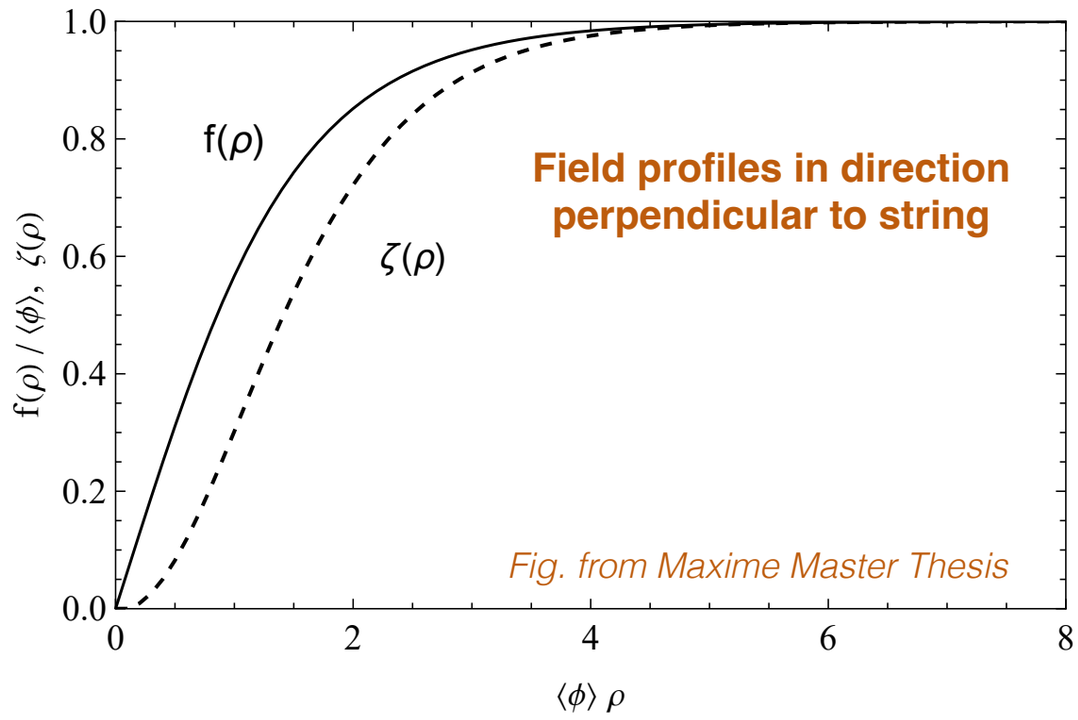
- ✴ *Static solutions to eqn of motion*
- ✴ *Vanishing energy at infinity*

Abelian Gauged Cosmic strings

★*Consider an abelian Higgs model with U(1) gauge*



$$\phi = e^{in\theta} f(\rho) \qquad A_\theta = \frac{n}{e\rho}\zeta(\rho)$$



String Properties

- **Tension** $\mu \sim 2\pi v^2$
- **Width** $\delta \sim m_\phi^{-1}$

Abelian strings evolution and GW

★***Cosmic string network reach scaling with***

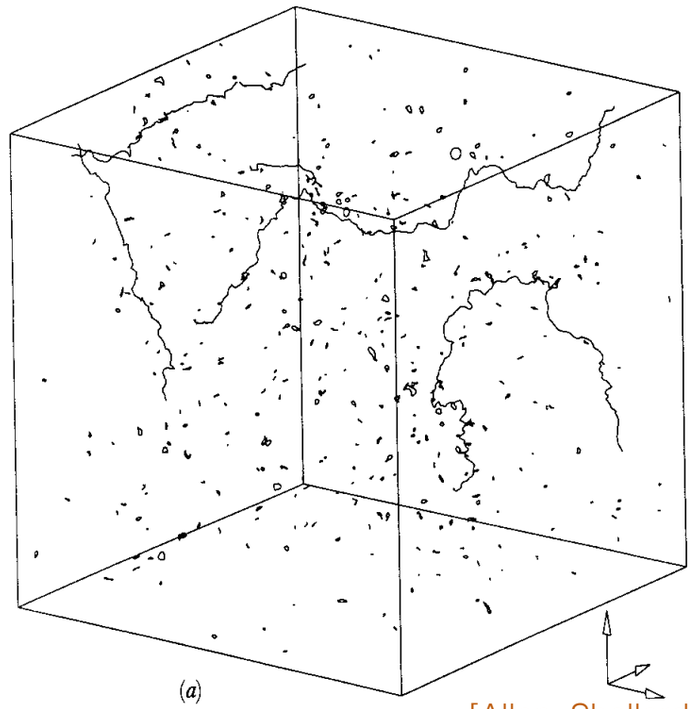
$\xi \sim O(1)$ ***defects per Hubble volume***

Energy Density

$$\rho_{\rm strings} \sim \xi^2 \mu H^2$$

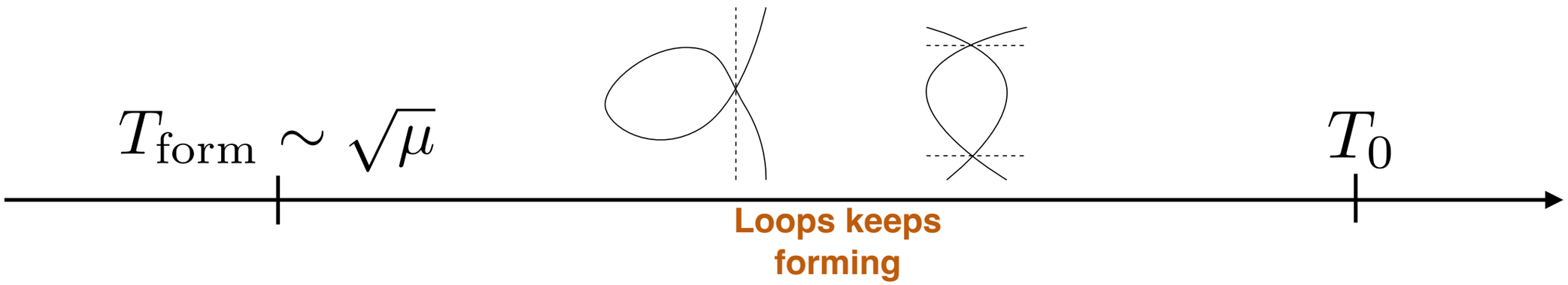
Energy Fraction

$$\Omega_{\rm cs} \sim G\,\mu$$



[Allen, Shellard, 90

★***String network evolves with loops and kinks/cusps and emit GW***



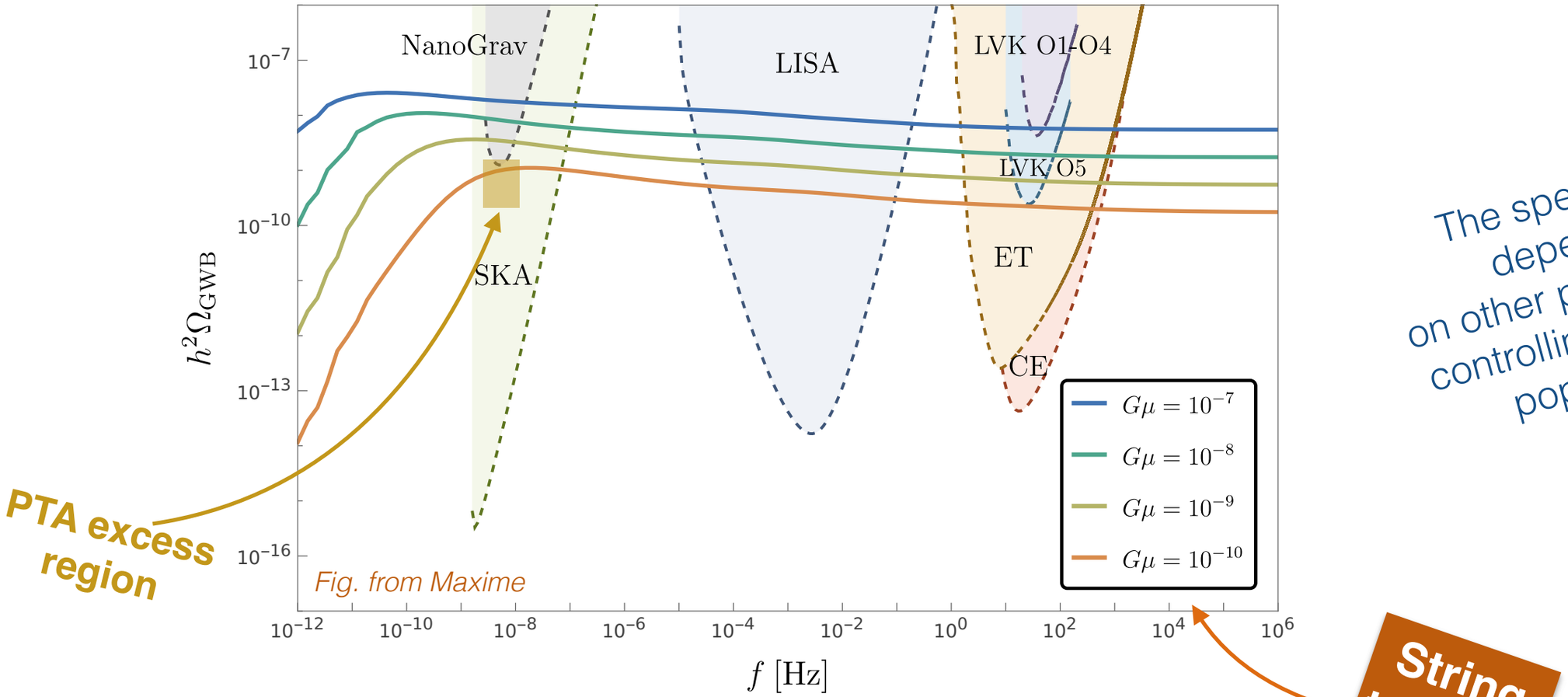
★***A background of GW is generated during network evolution***

Ringeval, Suyama '17; Blanco-Pillado, Olum '17

See e.g. also 1909.00819 and references therein

Abelian strings evolution and GW

★*Typical GW spectrum from string network*



The spectrum depends on other parameters controlling the loop population

★***Adding stable string contribution to SMBH signal do not improve the PTA fit***

Nanograv collaboration 2306.16219

★***Spectral shape disfavoured by data:*** ✳Low tension: not enough amplitude

✳High tension: too flat spectrum

Metastable defects

Preskill Vilenkin '92

Can defects be only (meta)-stable?

If symmetry is not exact in the first place

$$G_{\rm approx} \xrightarrow{f} H_{\rm approx}$$

with $G_{\rm approx}$ broken explicitly by small parameter $\epsilon \ll f$

Example: axion models with N_DW=1

If symmetry breaking is part of a longer chain

$$G \xrightarrow{V} H_1 \xrightarrow{v} 1$$

✳Suppose $\pi_n(H_1) \neq 1$ but $\pi_n(G) = 1$

Defects created in step $H_1 \to 1$ might decay
by exploring larger symmetry group at scale V

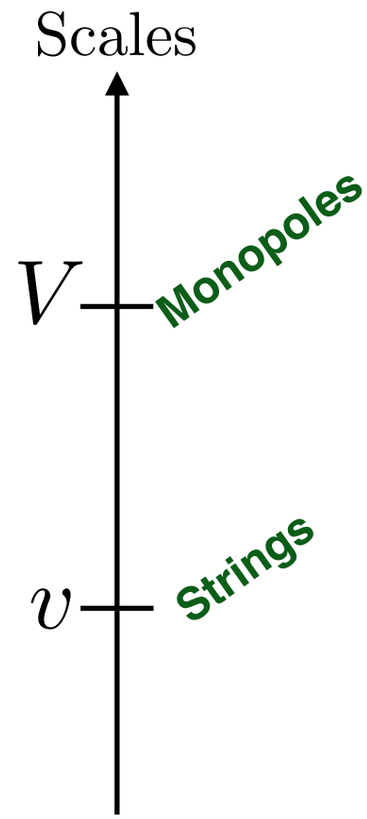
Example: metastable strings

Metastable strings

Preskill Vilenkin '92
Shifman, Yung 2002

$$\pi_1(U(1)) \neq 1$$
$$\pi_1(SU(2)) = 1$$

$$SU(2) \xrightarrow[\textit{Monopoles}]{V} U(1) \xrightarrow[\textit{Strings}]{v} 1$$



★Strings formed at second step are not topologically stable

★If there is separation between V and v strings can be metastable

★They can decay via quantum tunnelling with suppressed rate

★If monopoles are present at the moment of string formation, the entire network collapse

★If monopoles have been espelled from the Universe, strings are metastable

relevant for PTA GW signal

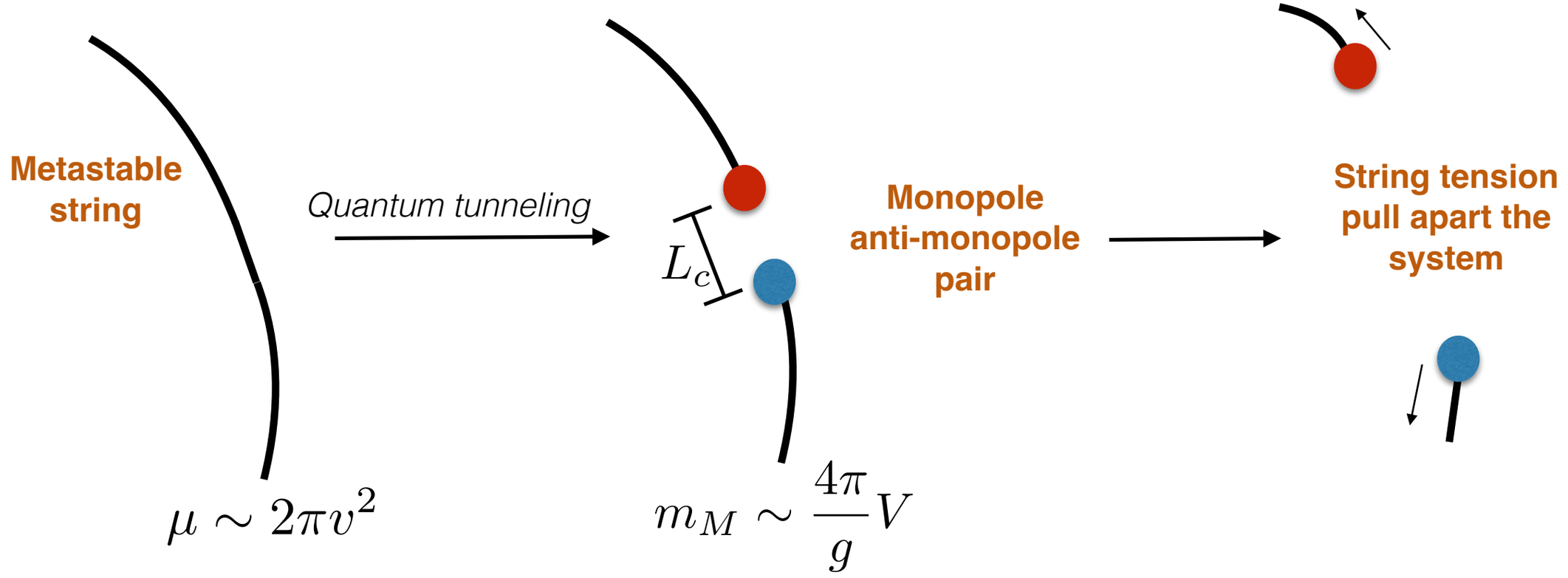
Why are these interesting?

connection with EW strings

Metastable string tunneling

Preskill Vilenkin '92
Shifman, Yung 2002

$$SU(2) \xrightarrow[\text{Monopoles}]{V} U(1) \xrightarrow[\text{Strings}]{v} 1$$



Decay rate in thin defect approximation

Preskill Vilenkin '92
Leblond, Shlaer, Siemens '09

$$L_c \sim \frac{m_M}{\mu}$$

Critical distance

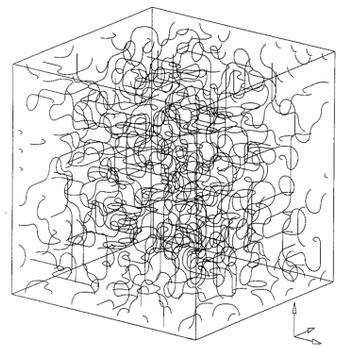
$$\Gamma = \frac{\mu}{2\pi} e^{-\pi\kappa}$$

Decay per unit length

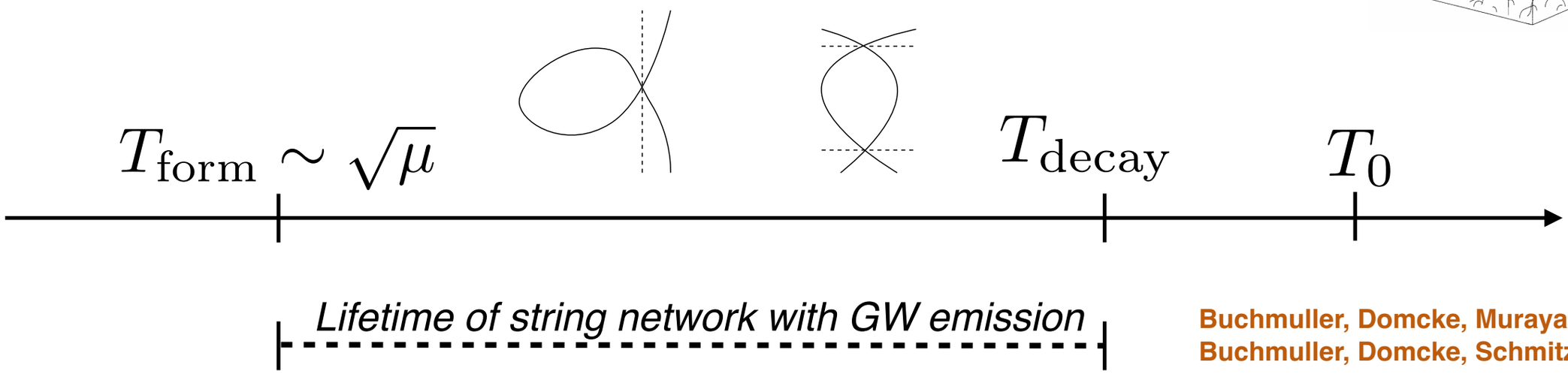
$$\kappa \equiv \frac{m_M^2}{\mu}$$

GW from metastable strings

★Suppose long-lived metastable strings (no monopoles in the Universe)



★***Metastable strings evolve as abelian strings and emit GW***

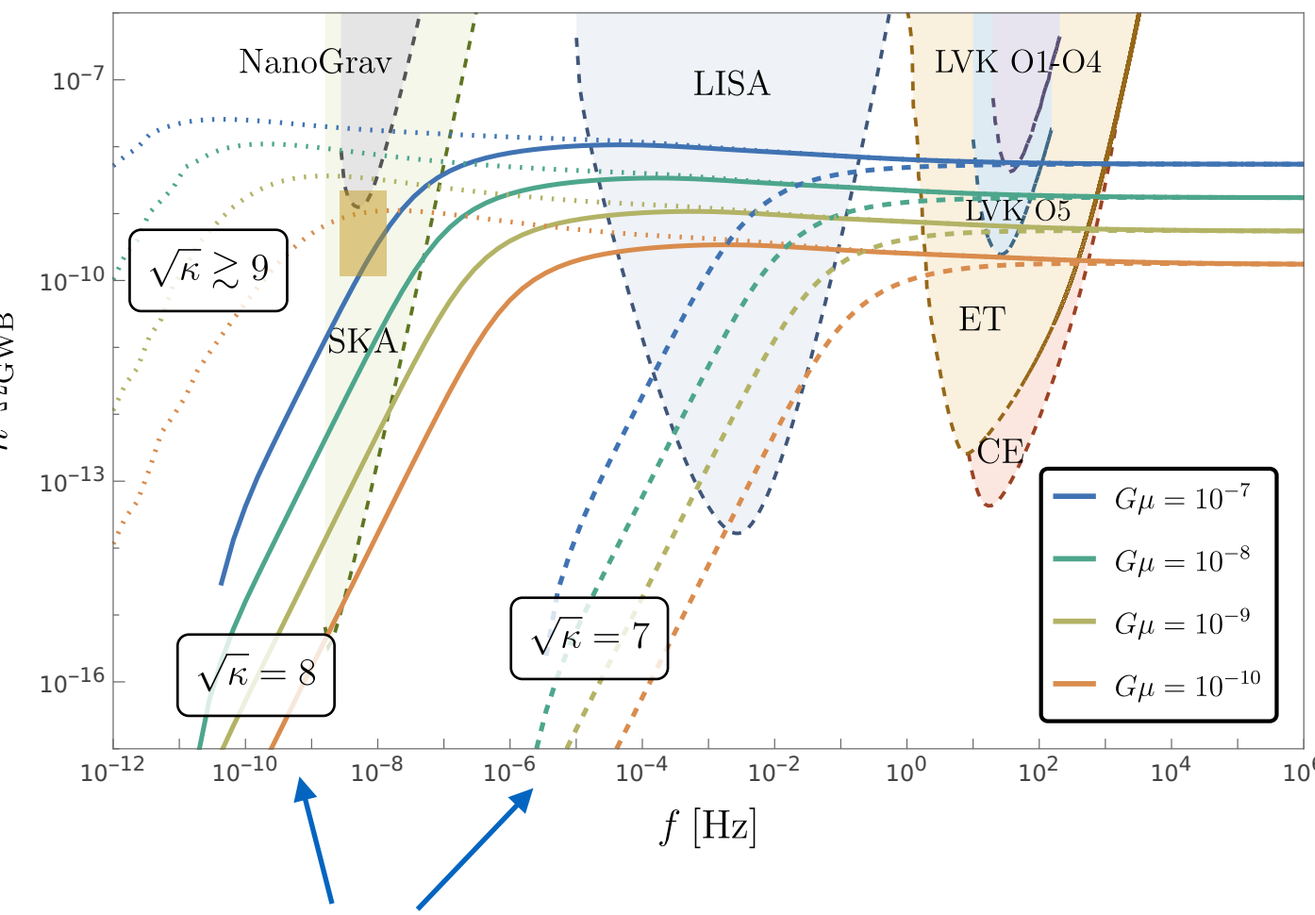


Buchmuller, Domcke, Murayama, Schmitz ’19
Buchmuller, Domcke, Schmitz ‘21

★***Finite lifetime implies that GW spectrum has now IR cutoff when string decay***

$$T_d \simeq 204\ \text{MeV} \left(\frac{G\mu}{10^{-7}}\right)^{1/4} \left(\frac{\Gamma_d/\mu}{10^{-30}}\right)^{1/4} \left(\frac{g_\star}{10}\right)^{-1/4}$$

PTA Nanograv Interpretation



IR cutoff depends on decay rate

✳ ***Better fit to the data because of steeper slope***

✳ ***PTA points to moderate values of*** κ

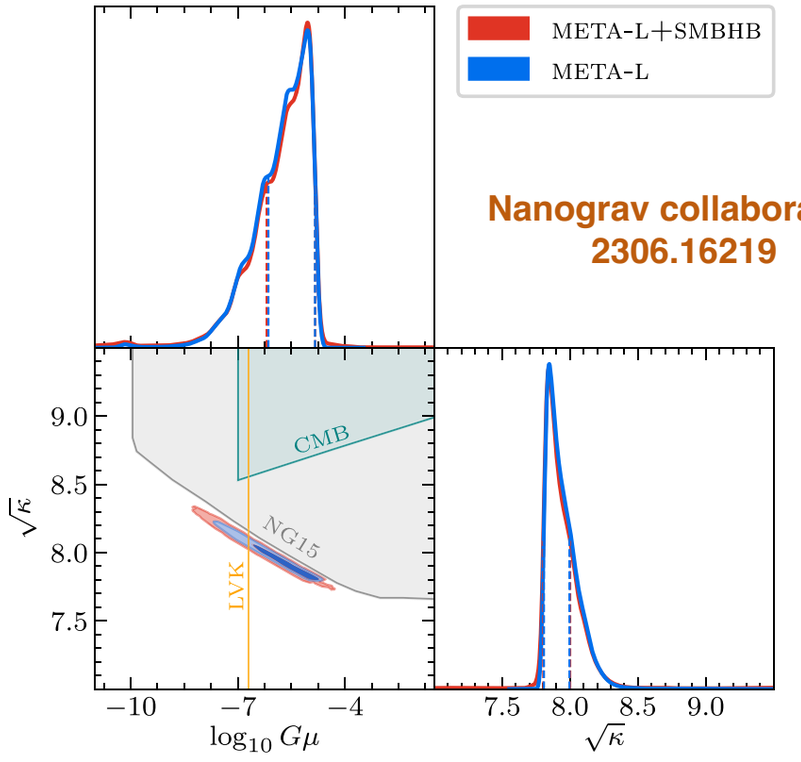
$$\sqrt{\kappa} = \sqrt{\frac{m_M^2}{\mu}} \simeq \frac{2\sqrt{2\pi}}{g}\frac{V}{v} \sim 8$$

Network of metastable strings is promising candidate

✳ ***Favourite values***

$$G\mu \sim 10^{-7} \qquad \sqrt{\kappa} = \sqrt{\frac{m_M^2}{\mu}} \sim 8$$

✳ ***Testable at LVK***



Nanograv collaboration 2306.16219

Are metastable string classically stable?

Consider moderate hierarchy between V and v

★Even before correcting the quantum decay estimate we should verify that the strings are classically stable

Are strings in this model

$$SU(2) \xrightarrow[\textit{Monopoles}]{V} U(1) \xrightarrow[\textit{Strings}]{v} 1$$

classically stable for which range of V/v and other couplings?

★If strings are classically unstable they just dissolve

No string network nor GW

To study this problem, we first remind simpler well known cases

EW strings!

Intermezzo: Electro-weak strings

Achucarro Vachaspati '99
Goodband, Hindmarsh '95

$$SU(2)_{\rm local} \times U(1)^{Y}_{\rm local} \to U(1)^{\rm EM}_{\rm local}$$

$$\mathcal{L} = (D_\mu \Phi)^\dagger D^\mu \Phi - \lambda \left(\Phi^\dagger \Phi - \frac{v^2}{2} \right)^2 - \frac{1}{4} W^a_{\mu\nu} W^{a\,\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

★Consider string associated to the U(1) aligned with the Z-boson: ***Z-string***

Intermezzo: Electro-weak strings

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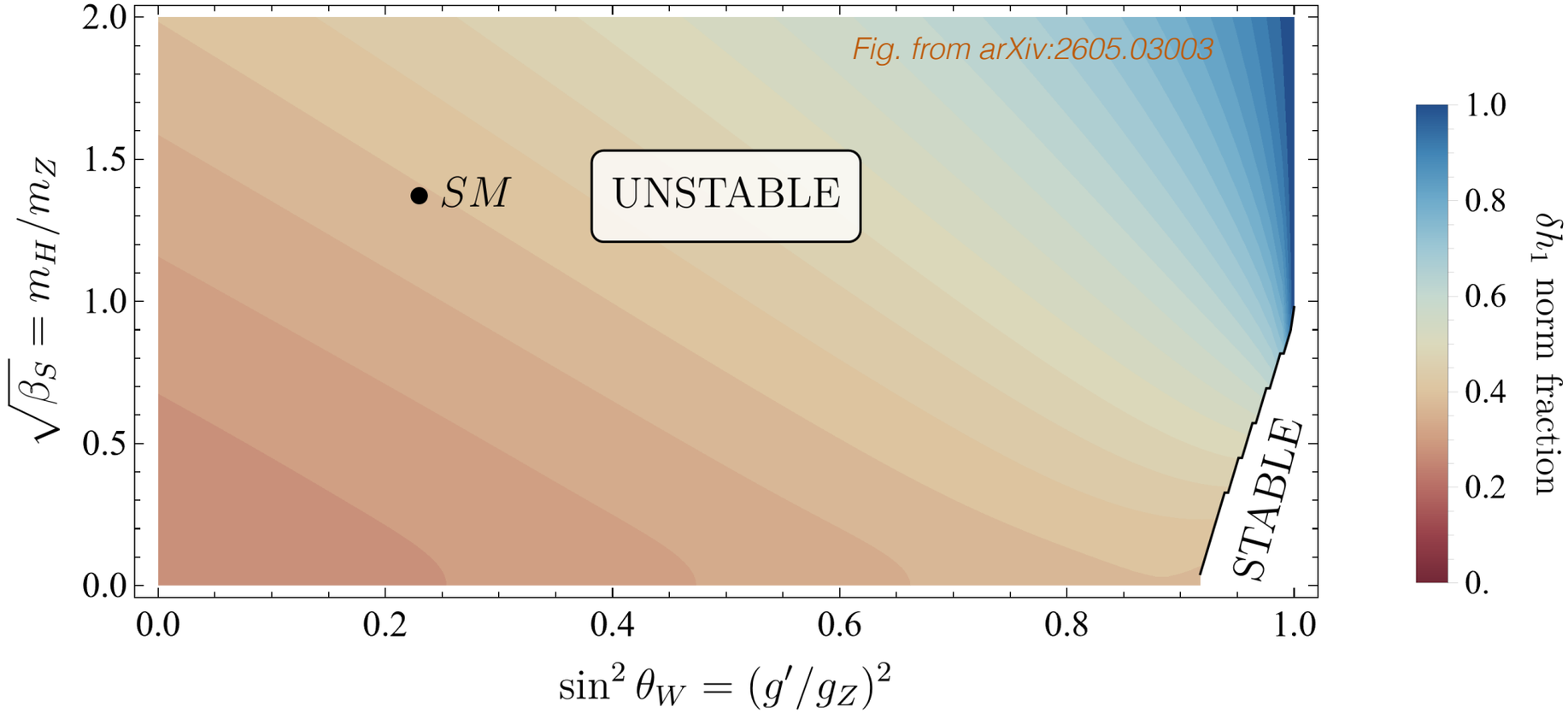
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★Consider string associated to the U(1) aligned with the Z-boson: ***Z-string***

★Instability can arise from fluctuation of "other" doublet component (coupled with W boson)

$$\mathcal{D}_1 \begin{pmatrix} \delta\phi_u \\ \delta W^{+\,\mu} \end{pmatrix} = 0$$

Linear Stability Analysis



Metastable string: A concrete model

Shifman, Yung 2002

Consider a concrete model for the symmetry breaking pattern $SU(2) \to U(1) \to 1$

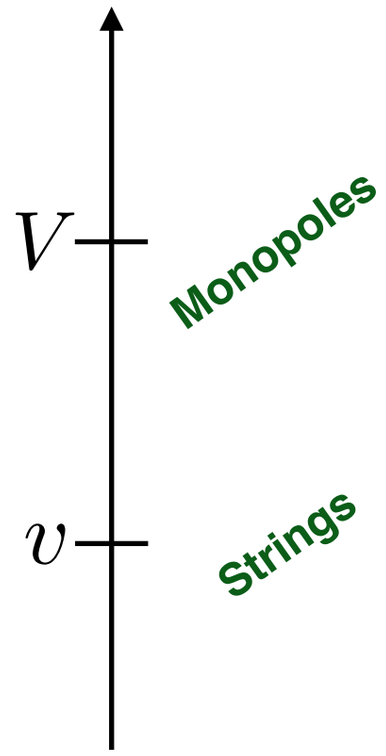
$$\mathcal{L} = \frac{1}{2}(D_\mu \phi^a)(D^\mu \phi^a) + (D_\mu h)^\dagger (D^\mu h) - \frac{1}{4} F^a_{\mu\nu} F^{a\,\mu\nu} - V(\phi, h)$$

$$V(\phi, h) = \lambda \left(h_1^\dagger h_1 + h_2^\dagger h_2 - v^2 \right)^2 + \tilde{\lambda} \left(\phi^a \phi^a - V^2 \right)^2 + \gamma \left| \left(\frac{\phi^a \sigma^a}{2} - \frac{V}{2} \right) h \right|^2$$

Mexican hat potentials

Portal

Vacuum: $\langle \phi^a \rangle = V \delta^{a,3} \qquad \langle h \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$



- ***First step breaking entails formation of monopoles***
- ***Second step breaking formation of strings***

String in the low energy theory

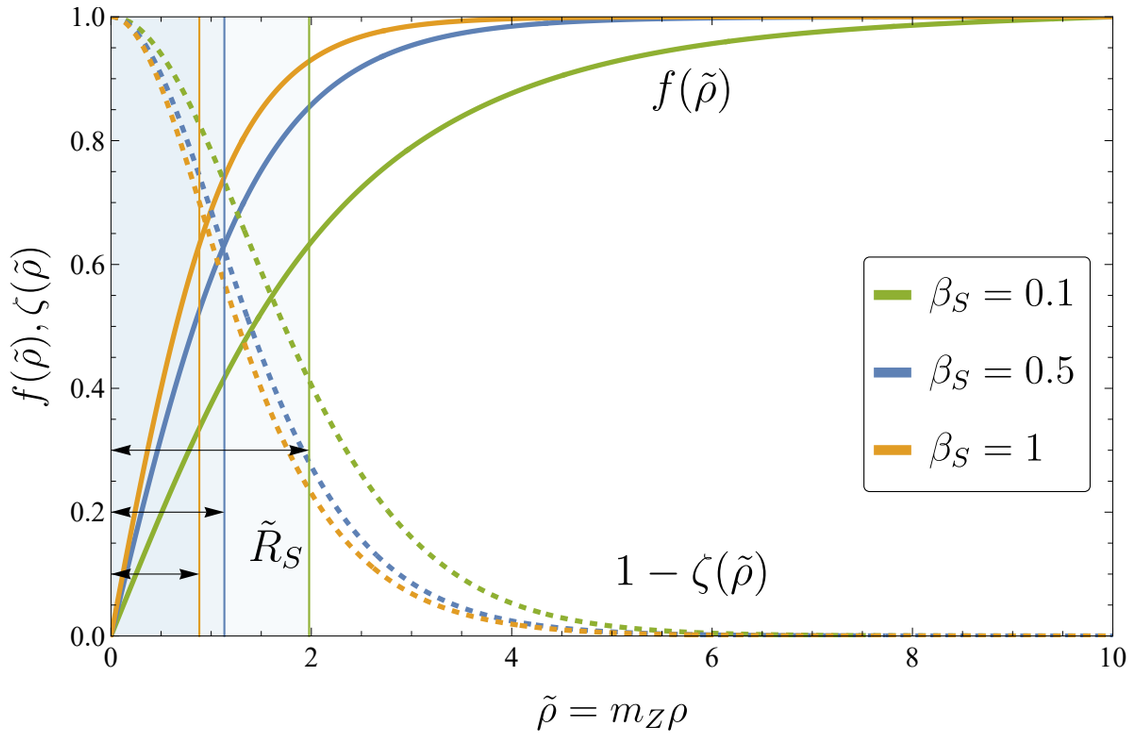
Theory admits manifestly string solution in limit $V \gg v$

Portal gives a mass for second Higgs component

Equivalent to abelian Higgs model

$$\mathcal{L} = (D_\mu h_1)^\dagger (D^\mu h_1) - \lambda(|h_1|^2 - v^2)^2 - \frac{1}{4} Z_{\mu\nu} Z^{\mu\nu}$$

String configuration along h_1



Solution of equation of motion of full theory

Is it classically stable when considering other fields fluctuations?

Tension: $\mu \sim 2\pi v^2$

S. Blasi, M. Grandjean, AM: arXiv:2605.03003

Linear stability analysis

Rough idea of methodology, perturb everything

Equation of motion

$$D_\mu D^\mu \phi^a = -4\tilde{\lambda}\left(\phi^b\phi^b - V^2\right)\phi^a - \frac{\gamma}{2}h^\dagger\left(\phi^a - V\sigma^a\right)h,$$
$$D_\mu D^\mu h = -2\lambda\left(h^\dagger h - v^2\right)h - \frac{\gamma}{4}\left(\phi^a\sigma^a - V\right)^2 h,$$
$$D_\nu F^{a\mu\nu} = g\epsilon^{abc}\phi^b D^\mu\phi^c + \frac{ig}{2}\left(h^\dagger\sigma^a D^\mu h - (D^\mu h)^\dagger\sigma^a h\right)$$

General field fluctuations

$$\Psi = \bar{\Psi} + \epsilon\delta\Psi \qquad \delta\Psi = \{\delta h, \delta h^\dagger, \delta\phi^\pm, \delta\phi^3, \delta A^\pm_\mu, \delta A^3_\mu\}$$

- ✳Keep linear order
- ✳Gauge fixing simplify equations

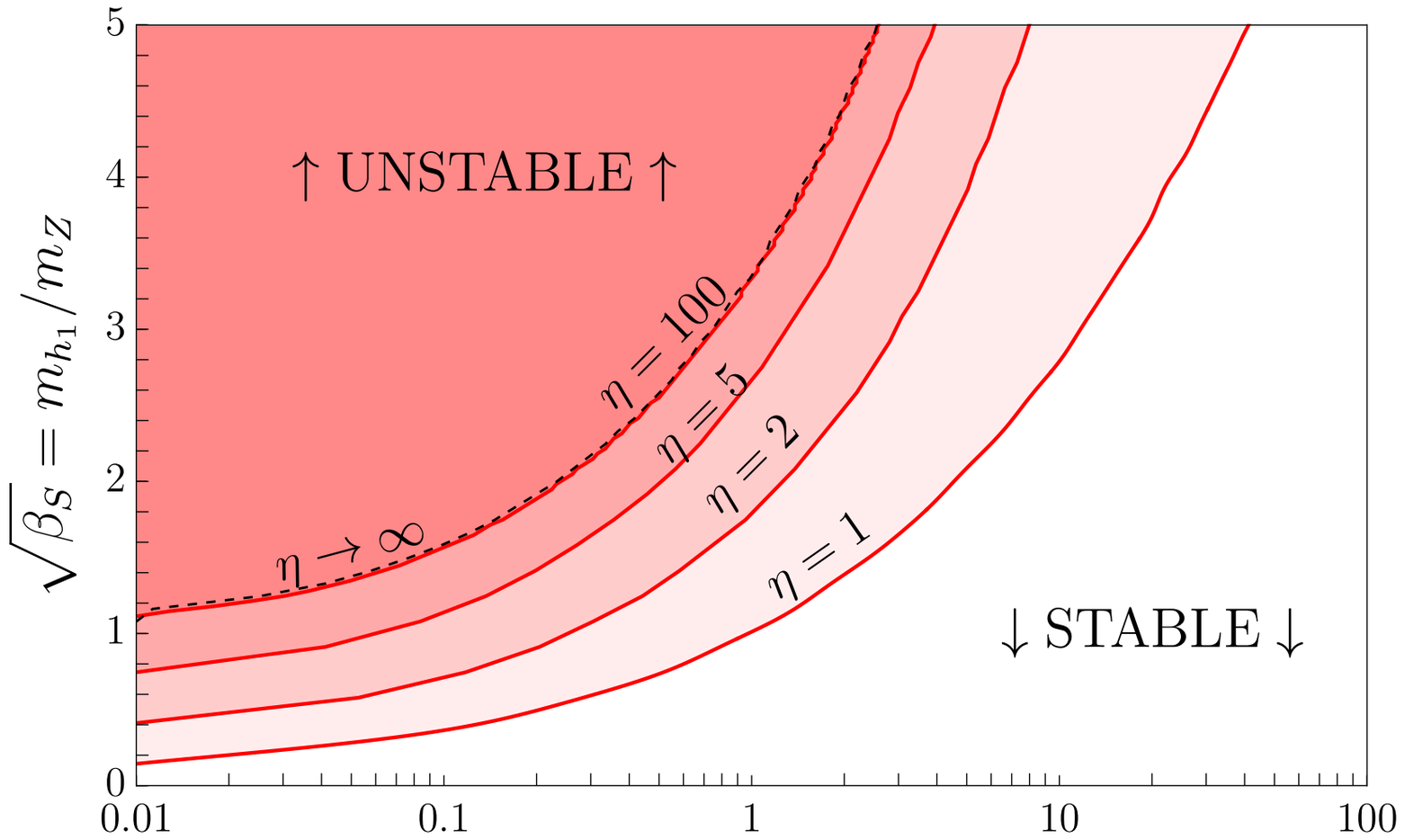
Instability arise from perturbation along other doublet component (coupled with W boson and adjoint field)

$$\mathcal{D}_3\begin{pmatrix}\delta h_2\\ \delta\phi^-\\ \delta A^-_\mu\end{pmatrix} = 0$$

S. Blasi, M. Grandjean, AM:
arXiv:2605.03003

Linear stability analysis

Quartic doublet coupling over Gauge coupling



$$\alpha = m_{h_2}^2/m_Z^2$$

Portal coupling

★**Sizeable portion of parameter space the string is unstable**

★**Instability enhanced by:** ✳Small portal coupling

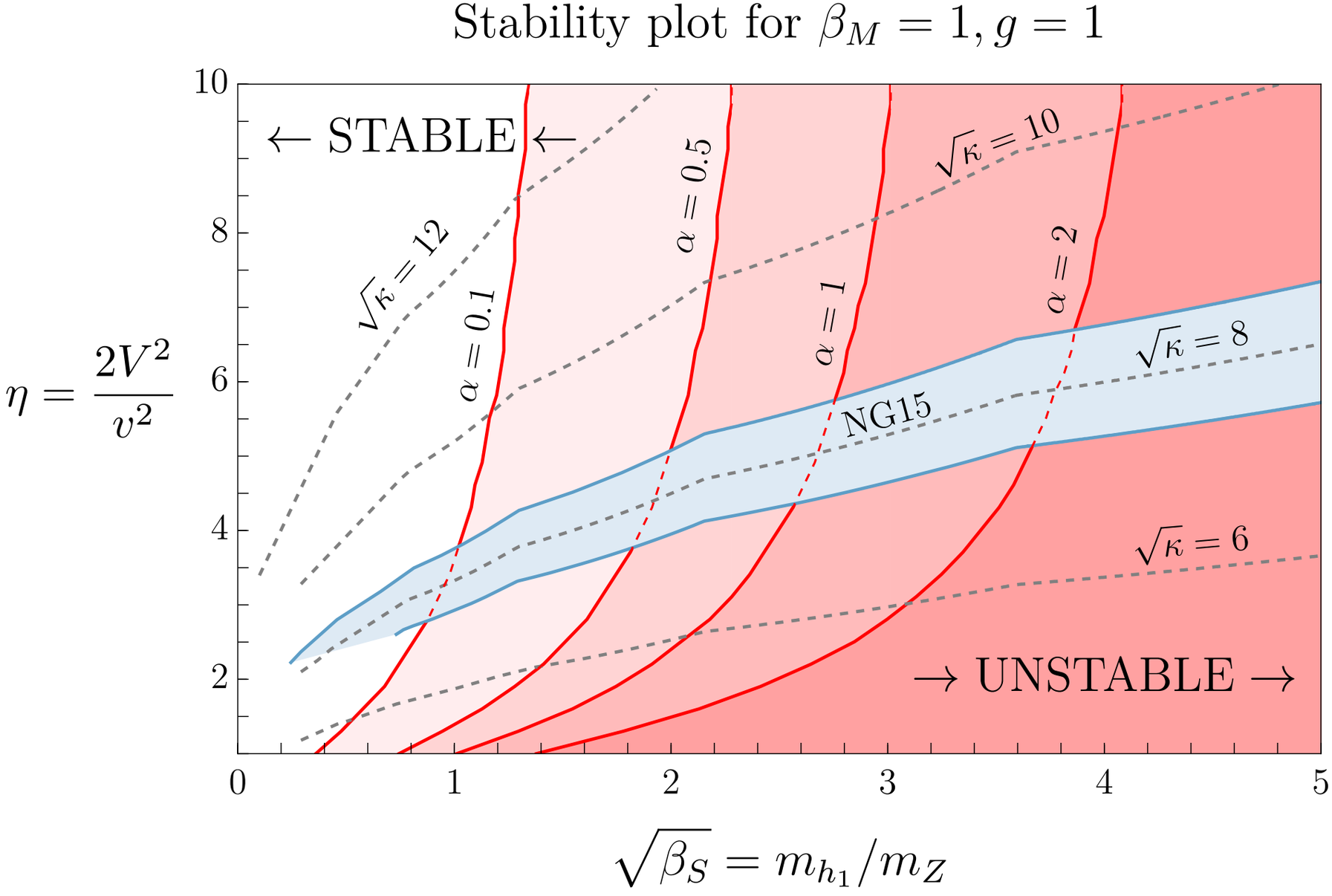
✳Small gauge coupling

★**Instability region shape asymptote when taken large** $\eta = 2V^2/v^2$

S. Blasi, M. Grandjean, AM: arXiv:2605.03003

Linear stability analysis

Impact on parameter space of PTA pheno interpretation



Portal coupling

α

Monopole mass over tension

$\sqrt{\kappa} = \frac{m_M^2}{\mu}$

★Only some portion of parameter space can support classically stable strings

★Unstable regions cannot explain PTA signal

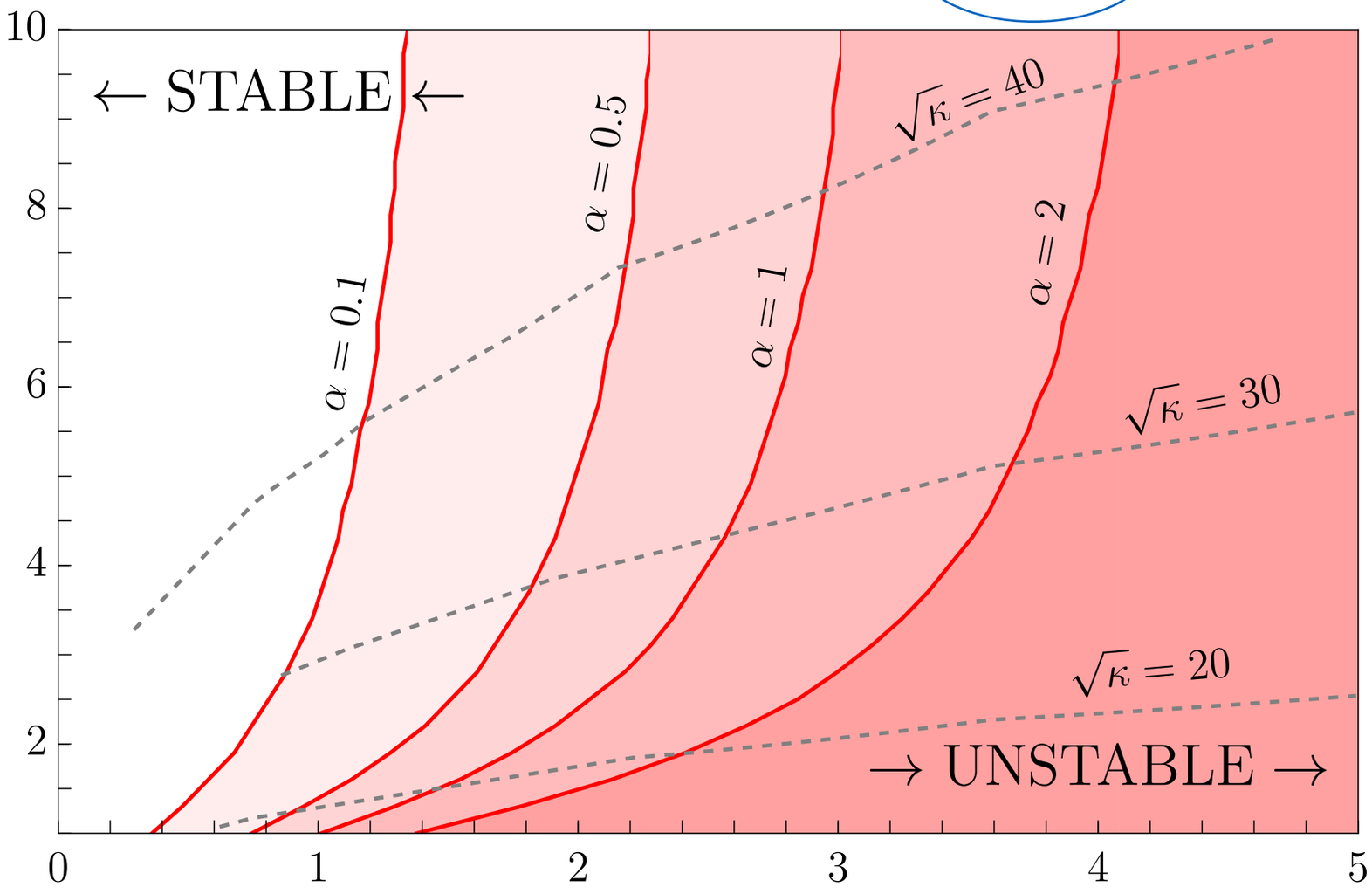
S. Blasi, M. Grandjean, AM: arXiv:2605.03003

Linear stability analysis

Impact on parameter space of PTA pheno interpretation

Stability plot for $\beta_M = 1, g = 0.25$

$$\eta = \frac{2V^2}{v^2}$$



$$\sqrt{\beta_S} = m_{h_1}/m_Z$$

Portal coupling

$$\alpha$$

Monopole mass over tension

$$\sqrt{\kappa} = \frac{m_M^2}{\mu}$$

★It can affect also large value of the monopole mass over tension ratio

S. Blasi, M. Grandjean, AM:
arXiv:2605.03003

Chasing the instability

We showed that standard string solution is classically unstable in relevant portion of param space

★Where the instability goes?

String Unwinds

- Analogous to EW string
- Network does not even form
- No GW generation

String develop a core

- String Network forms
- Different dynamics:
  - Decay rate
  - Friction
  - GW
  - ? ….?

S. Blasi, M. Grandjean, AM:
arXiv:2605.03003

Chasing the instability

We showed that standard string solution is classically unstable in relevant portion of param space

★Where the instability goes?

$V < v$ $\qquad$ $V > v$

String Unwinds

- ✳Analogous to EW string
- ✳Network does not even form
- ✳No GW generation

String develop a core

- ✳String Network forms
- ✳Different dynamics:
  - ✳ Decay rate
  - ✳ Friction
  - ✳ GW
  - ✳ ? ….?

In both scenarios impact for PTA interpretation with metastable strings

Conclusions

Cosmic defects interesting for BSM applications and GW signals

★*Arise in models with broken symmetry groups*

★*Their dynamics in the early Universe can be linked to open SM questions*

Cosmic defects can be only metastable when not topologically protected

★*Arise naturally in models with multiple step chain of group breaking*

★*Prototypical examples: axion models*

SM like theory

⋮

Can nevertheless play a role in early Universe in BSM scenarios

★*Metastable strings interesting in light of PTA evidence of a GWB*

$$SU(2) \to U(1) \to 1$$

String might be classical unstable in relevant portion of the parameter space

Implication for string network dynamics and GW generation

Thanks!

