Toological defects during cosmological phase transitions

Simone Blasi
DESY Hamburg

Based on:

SB, Mariotti [2203.16450], PRL

SB, Jinno, Konstandin, Rubira, Stomberg [2302.06952], JCAP

Agrawal, **SB**, Mariotti, Nee [2312.06749]

SB, Mariotti, [2405.08060]

4th EuCAPT Annual Symposium - CERN - 16.05.2024

Introduction

Higgs mechanism + Hot Big Bang = Cosmological phase transitions

Key to address SM open questions: e.g. matter/antimatter asymmetry, dark matter…

Aftermath of phase transitions **directly observable in gravitational waves**

QCD and EWPT are not first order in the SM: need for **new particles** or **new symmetries**

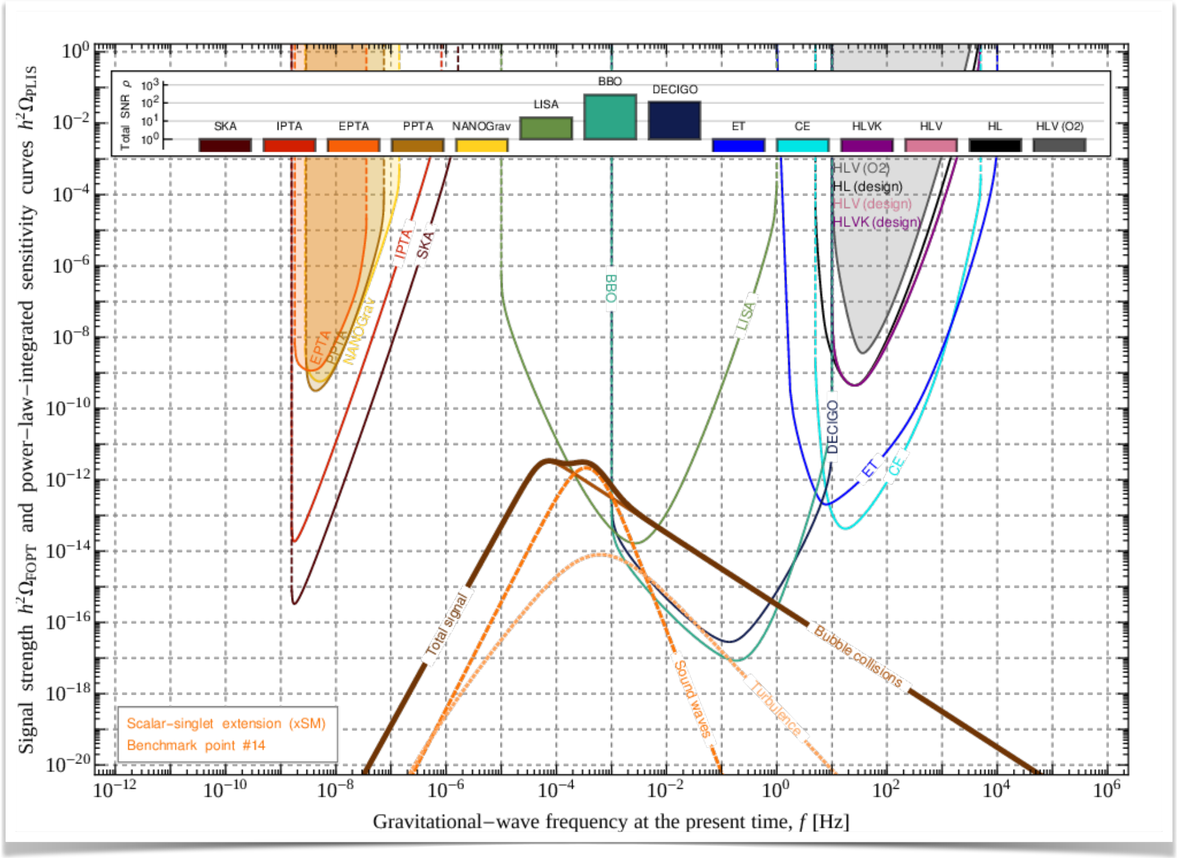
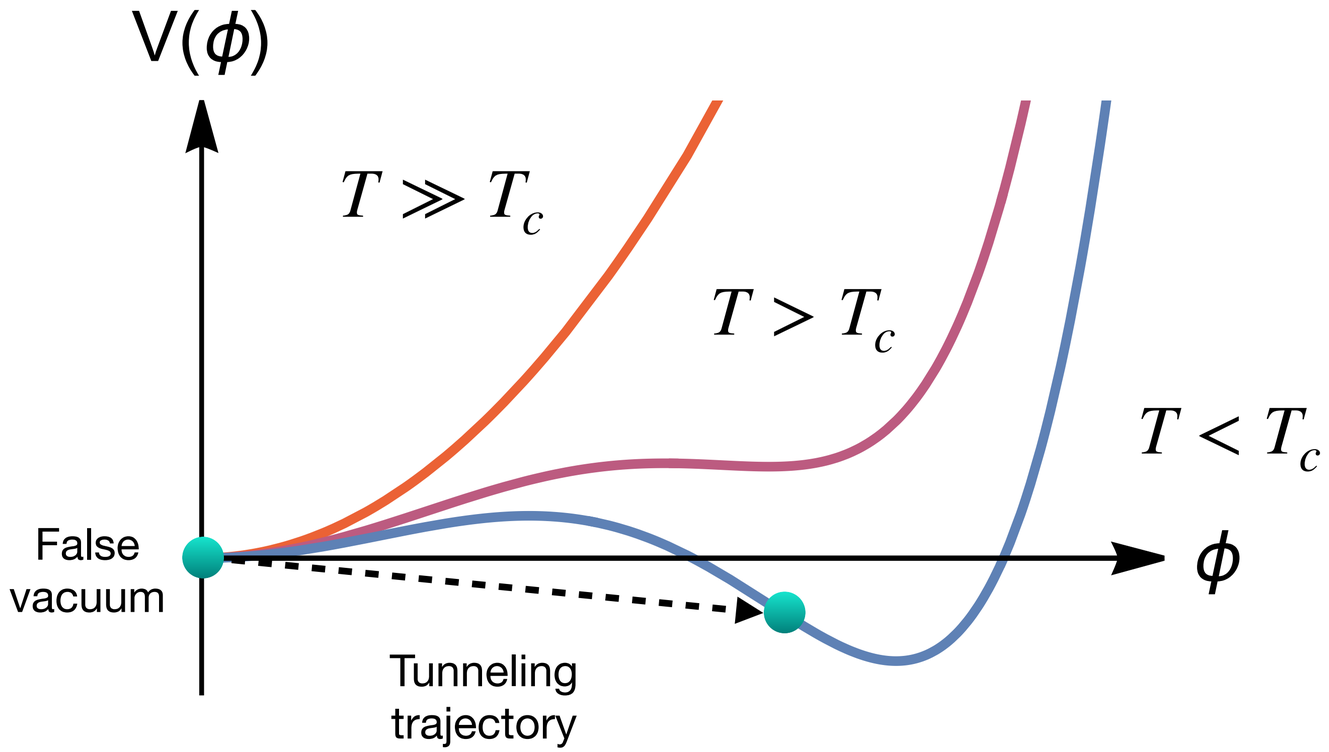


Fig. from Schmitz [2002.04615] JHEP

Nucleation theory

Coleman 1977 (PRD)
Callan, Coleman 1977 (PRD)
Linde 1983 (NPB)



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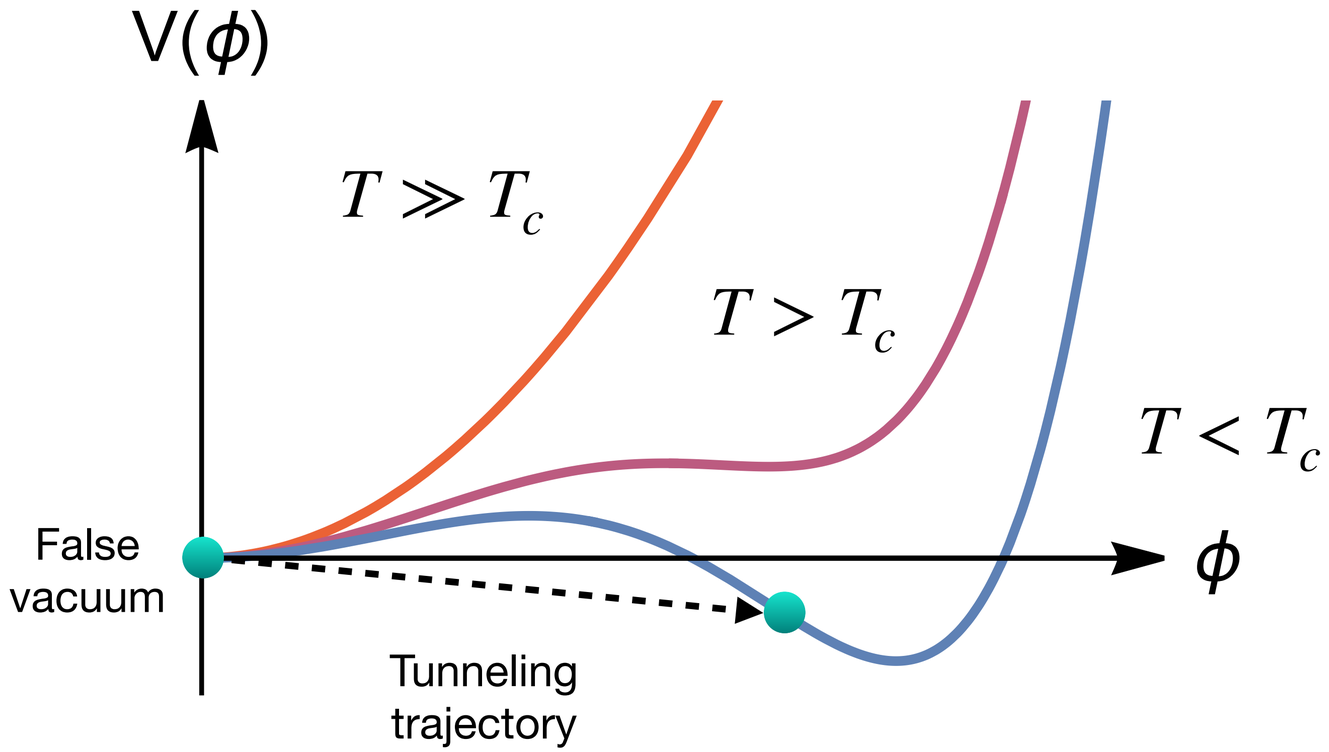
- Assume thermal fluctuations in homogeneous spacetime:

$$\phi(\mathbf{x}, \tau) = \phi(r), \quad r = |\mathbf{x}|$$

- Tunneling rate per unit volume given by O(3) action S_3/T

$$\gamma_V \sim T^4 \exp(-S_3/T)$$



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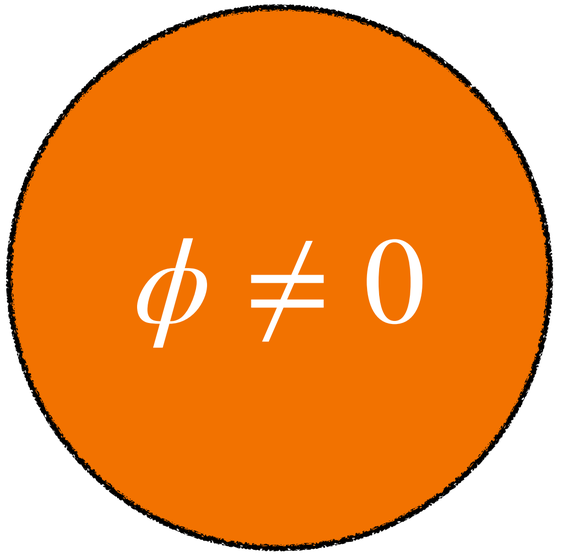


$$\phi = 0$$

What about impurities?

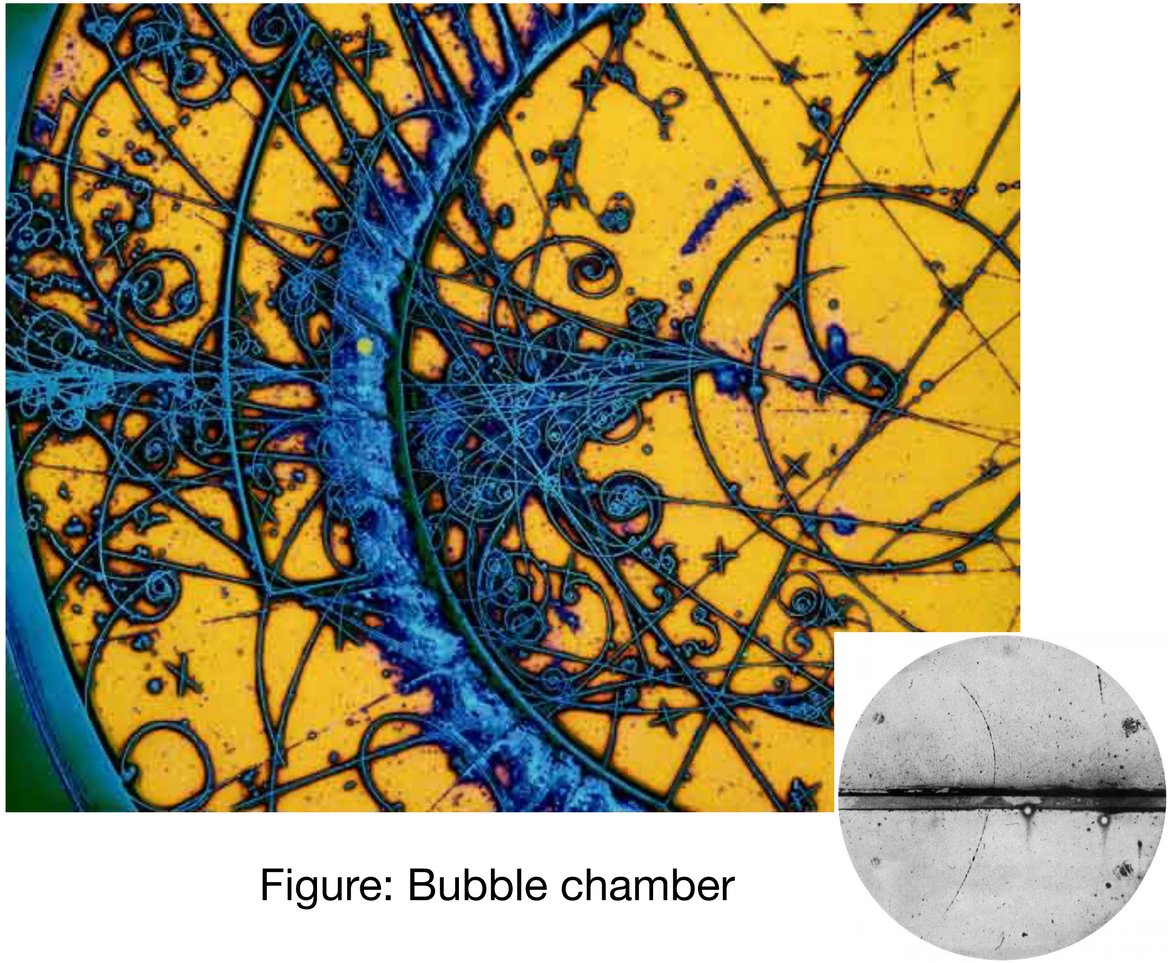
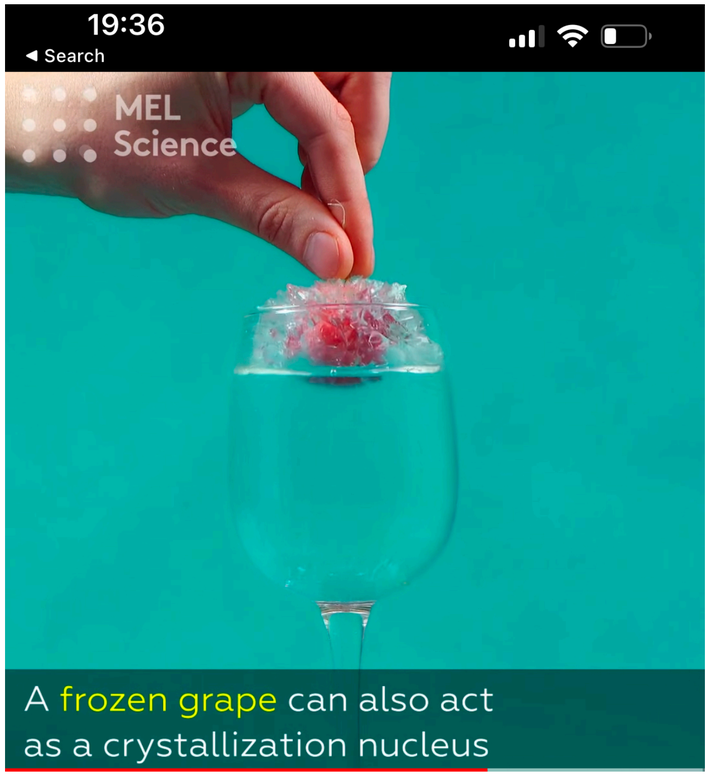


Figure: Bubble chamber



A supercool experiment

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MONOPOLE AND VORTEX DISSOCIATION AND DECAY OF THE FALSE VACUUM

Paul Joseph STEINHARDT

Lyman Laboratory of Physics, Harvard University, Cambridge, Massachusetts 02138, USA

Received 17 February 1981

"**If monopole** (or vortex) **solutions exist** for a metastable or false vacuum, **a finite density of monopoles** (or vortices) **can act as impurity sites that trigger inhomogeneous nucleation** and decay of the false vacuum."

See also:

"Impurities in the early Universe", Hosotani (1982)

"Cosmic separation of Phases", Witten (1984)

The nature of impurities

- Compact objects and gravitational effects

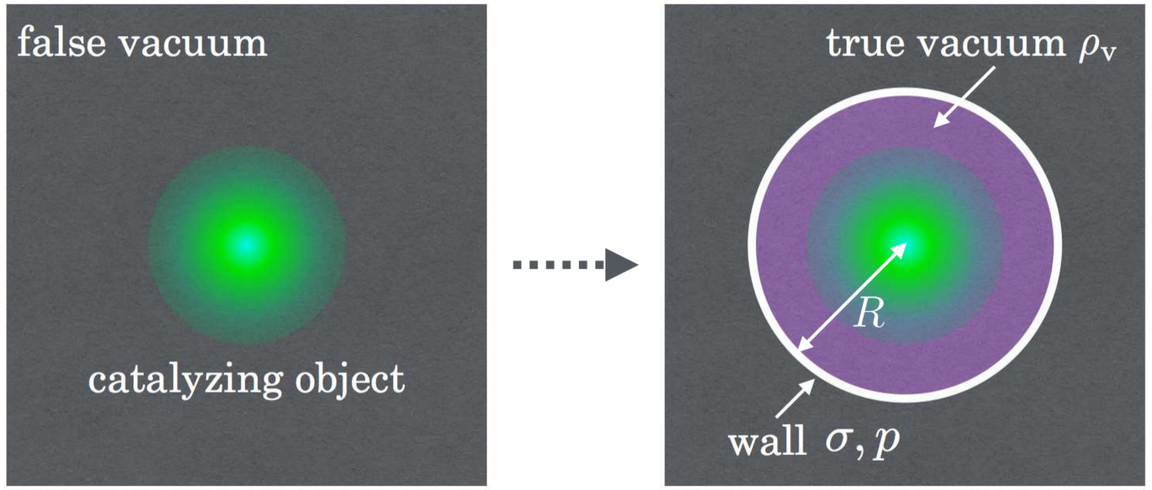

Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

- Primordial density fluctuations

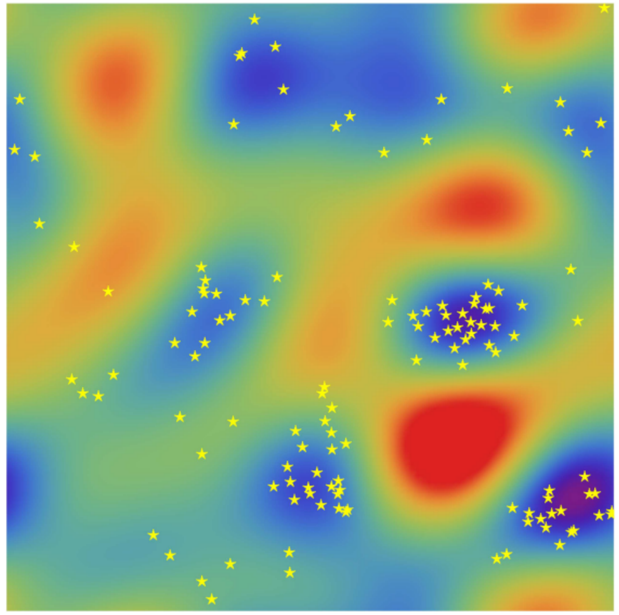

Fig. from Jinno, Konstandin, Rubira, van de Vis, [2108.11947], JCAP

The nature of impurities

- Topological defects (this talk)

Domain walls

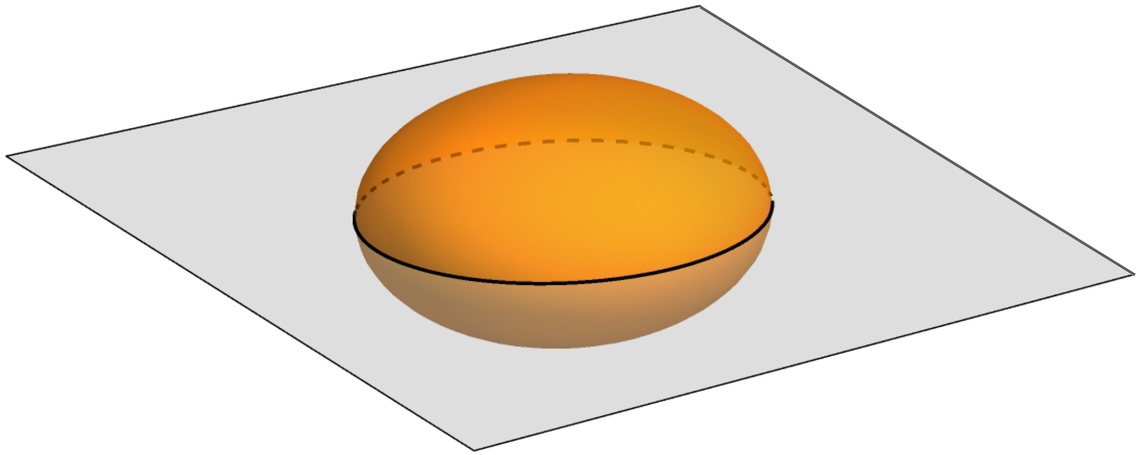

Fig. From Agrawal, **SB**, Mariotti, Nee [2312.06749]

Strings

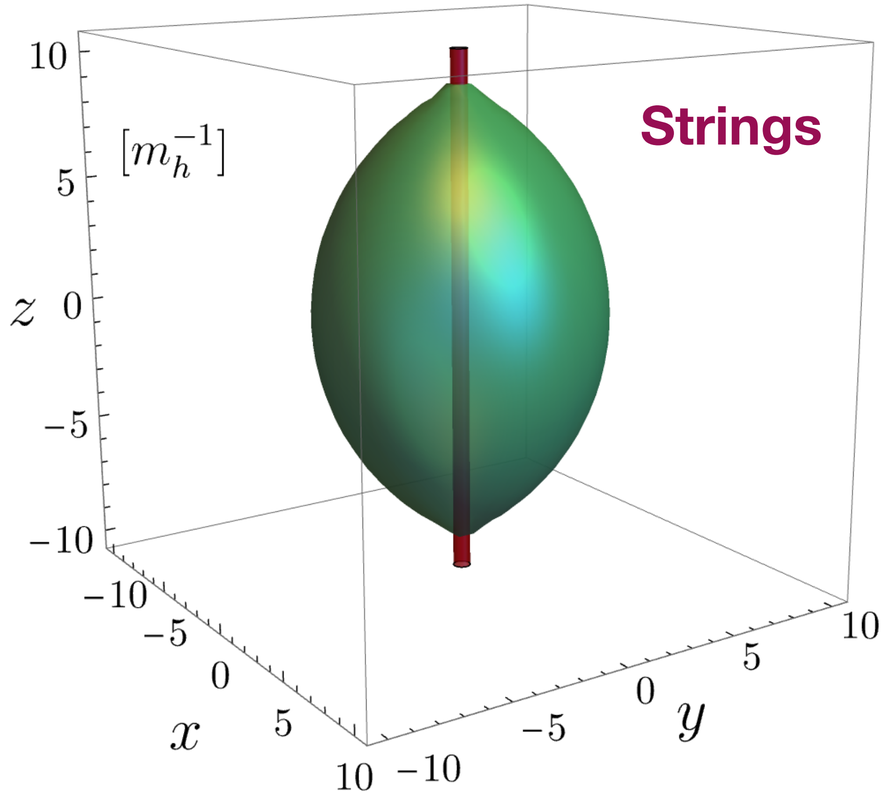

Fig. From **SB**, Mariotti, [2405.08060]

Topological classification

Defect	Dimension	Homotopy	Mass
Domain walls	2	$\pi_0(\mathscr{M})$	σL^2
Strings	1	$\pi_1(\mathscr{M})$	μL

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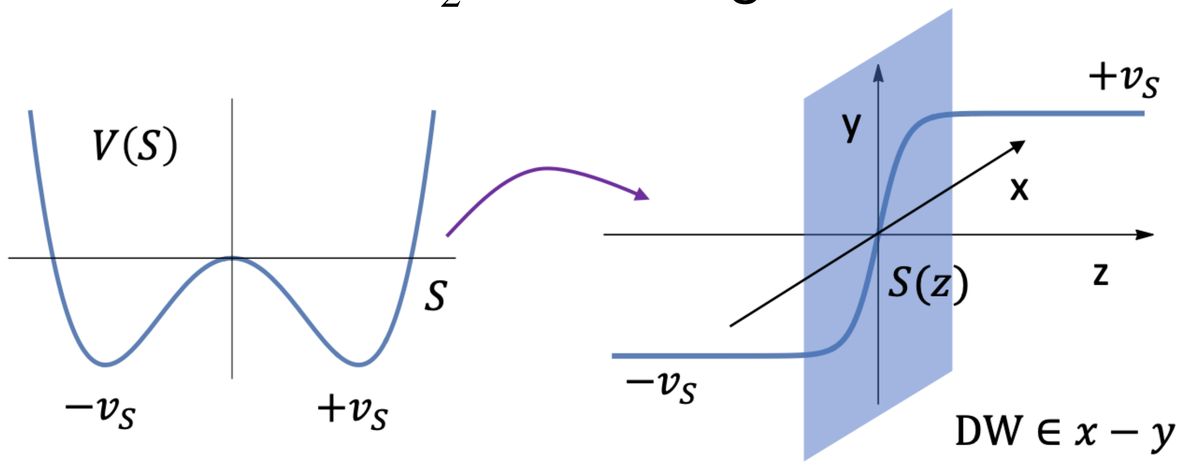

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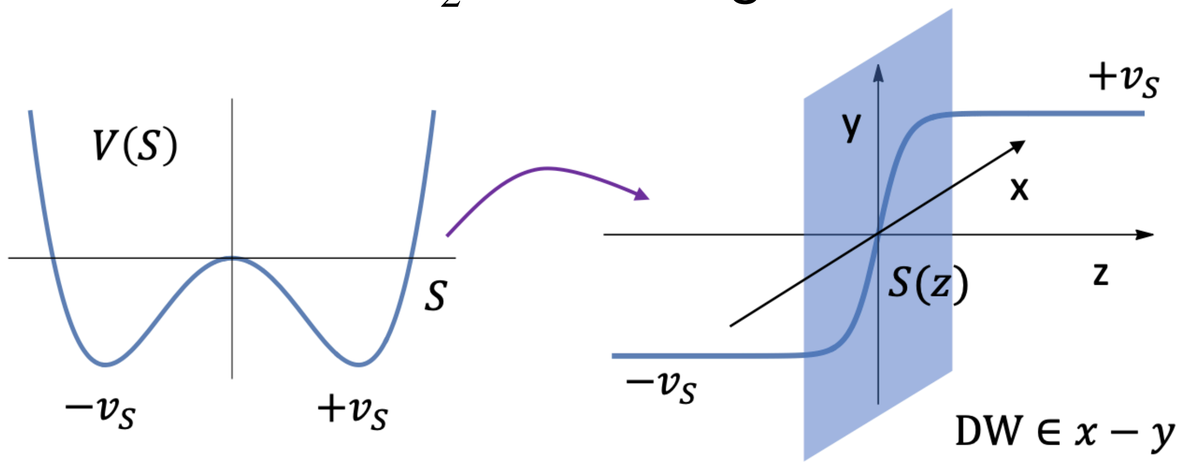


U(1) $\rightarrow$ nothing

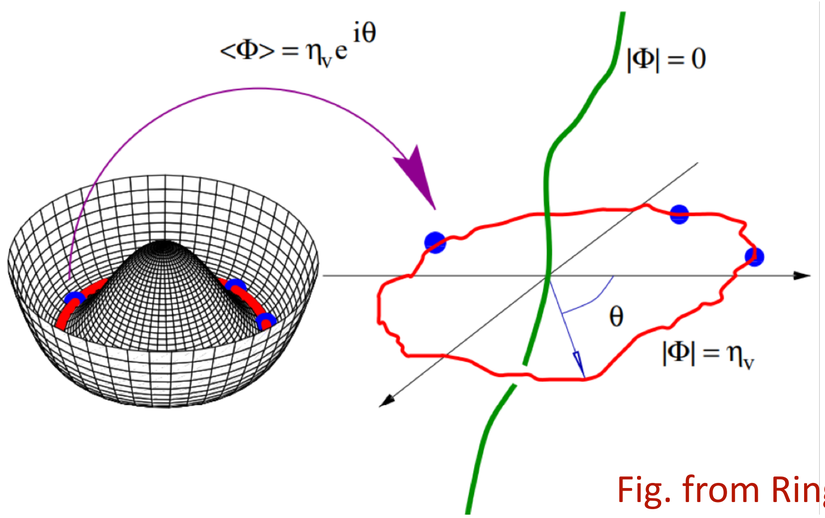
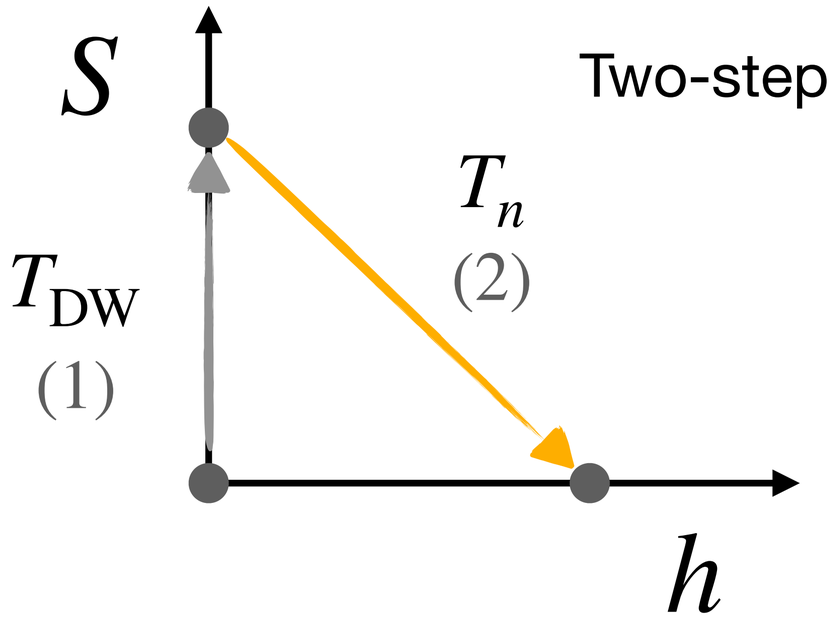


Fig. from Ringeval 2010

Electroweak phase transition with a singlet

- SM + scalar singlet with $\mathbb{Z}_2 : S \to -S$



Two-step transition

See e.g. Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

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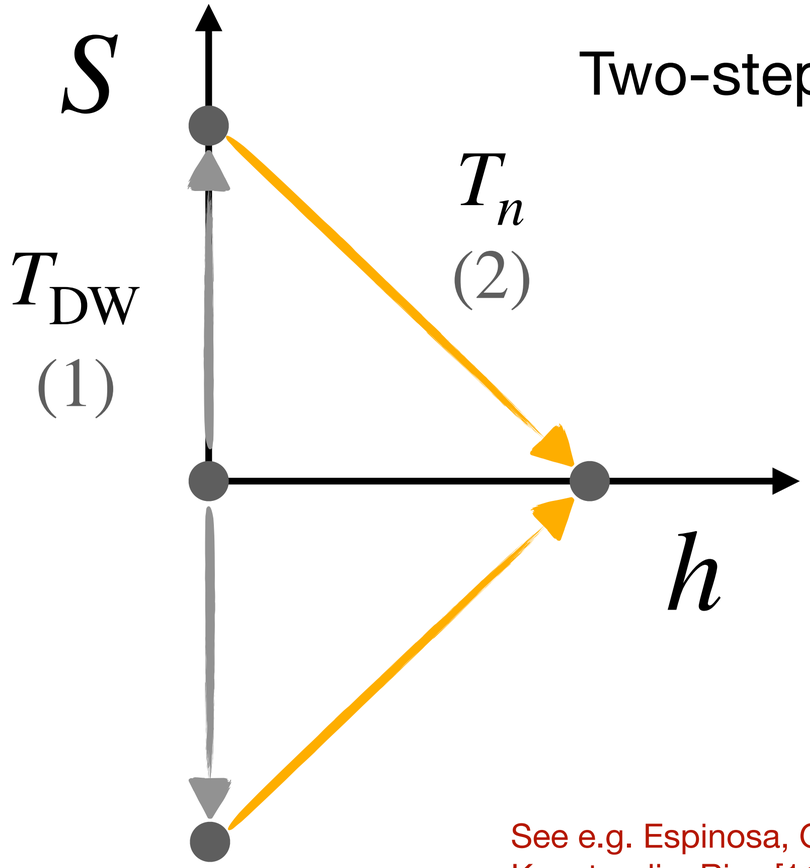

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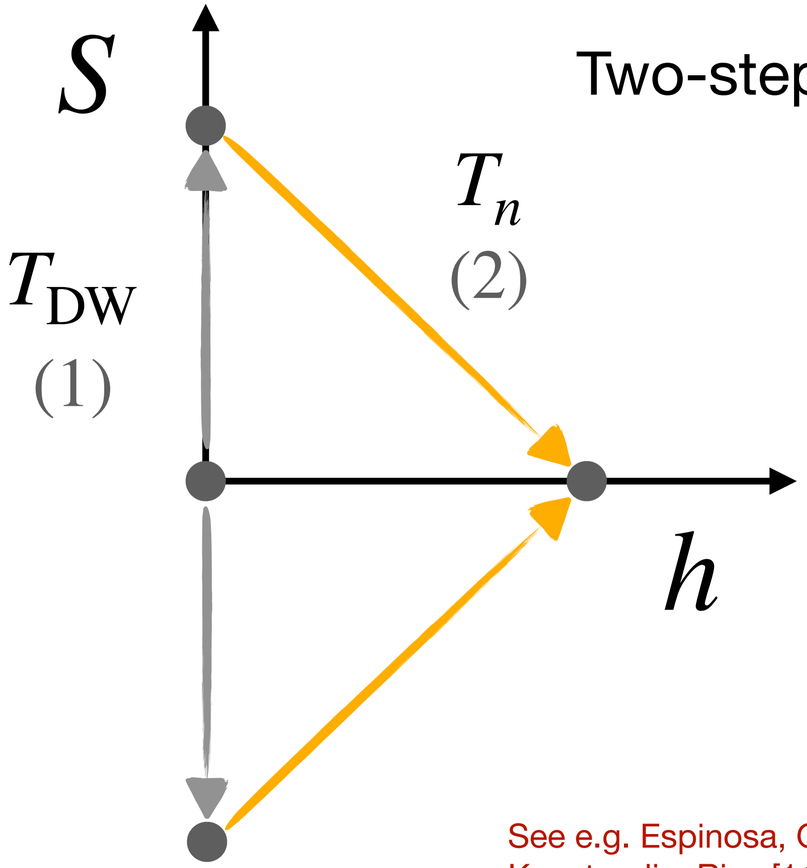

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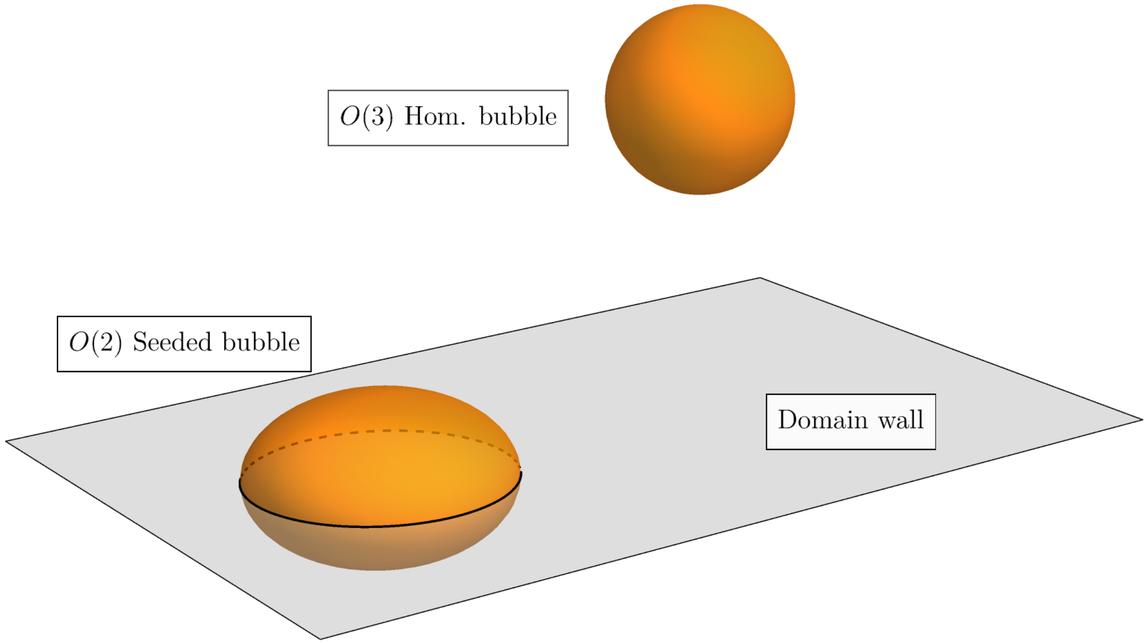
See e.g. Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

- Competition between homogenous and seeded nucleation for 2nd step:



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Electroweak phase transition with a singlet

- Seeded tunneling is faster whenever there is a two—step transition
- New parameter space becomes viable thanks to the walls
- Phenomenology of the phase transition is drastically changed

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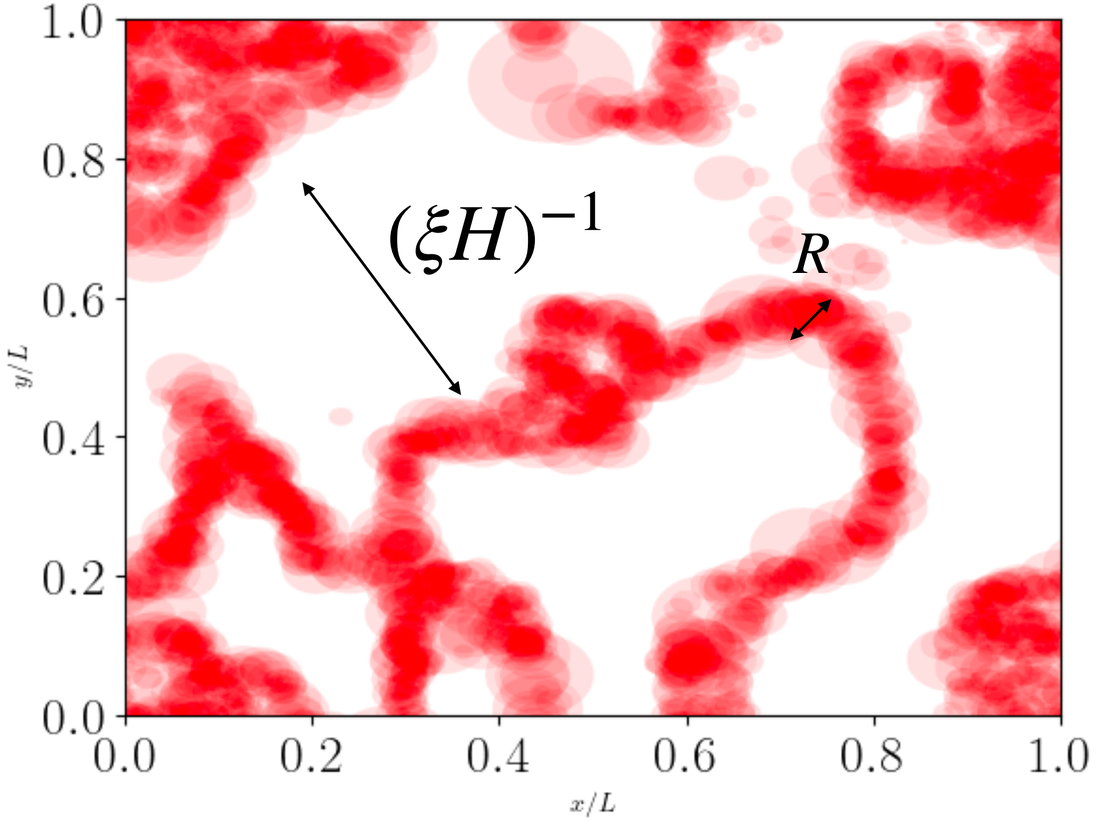
- Seeded tunneling is faster whenever there is a two—step transition
- New parameter space becomes viable thanks to the walls
- Phenomenology of the phase transition is drastically changed

- Previous studies can still apply if explicit Z_2 breaking is introduced, implications need to be taken into account consistently

Gravitational waves from seeded bubbles

- Domain wall network mimicked by Ising model



- Spectrum shifted to IR with enhanced amplitude

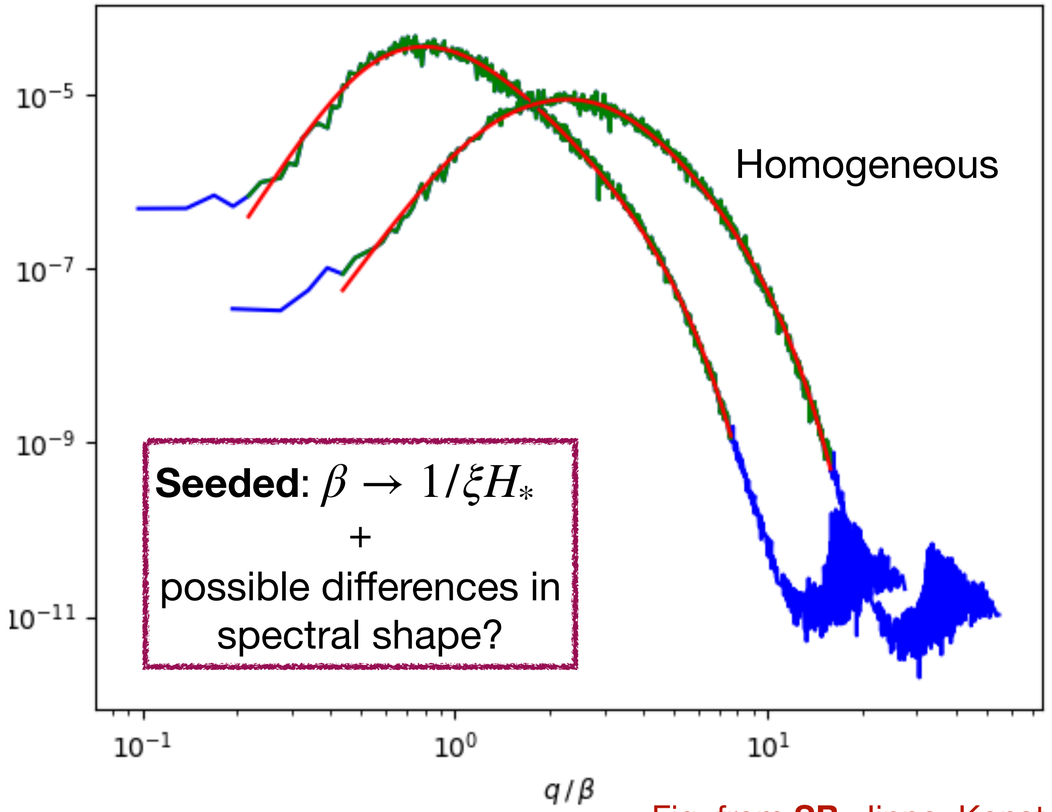
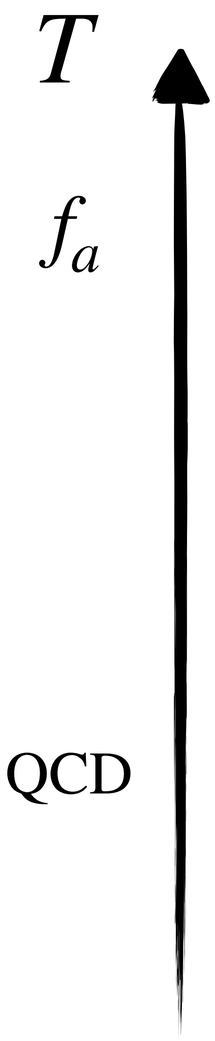


Fig. from **SB**, Jinno, Konstandin, Rubira, Stomberg [2302.06952] JCAP

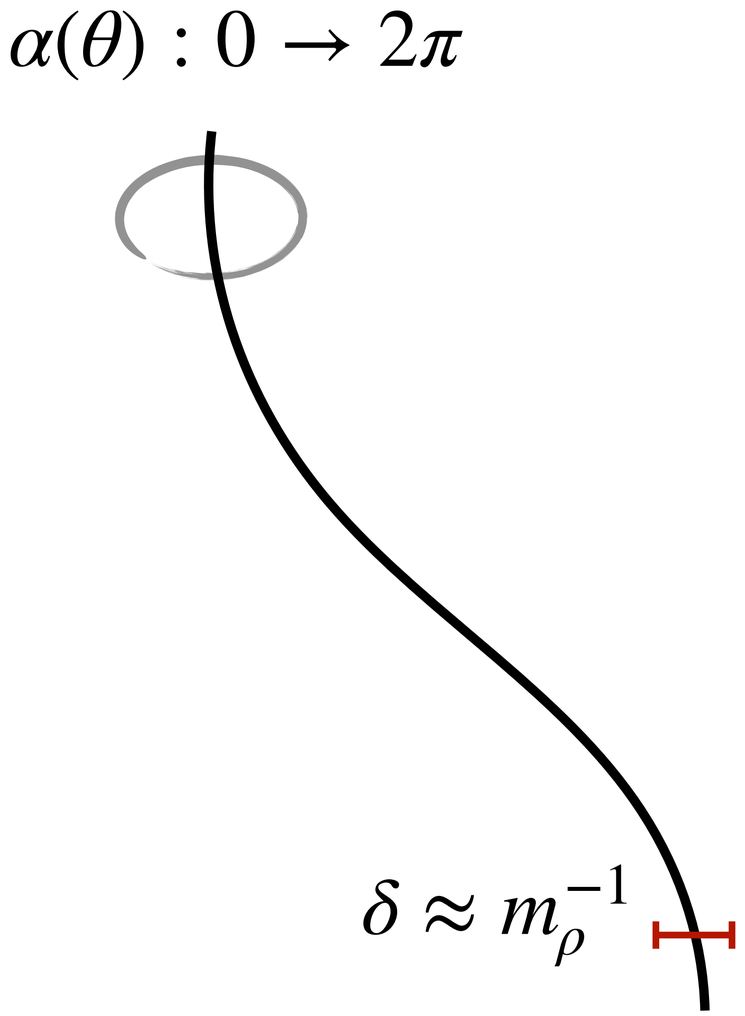
What about other defects?

SB, Mariotti [2405.08060]

QCD axion strings



- Strings form at PQ phase transition
- Strings connected by axion domain walls
- String—wall network collapses



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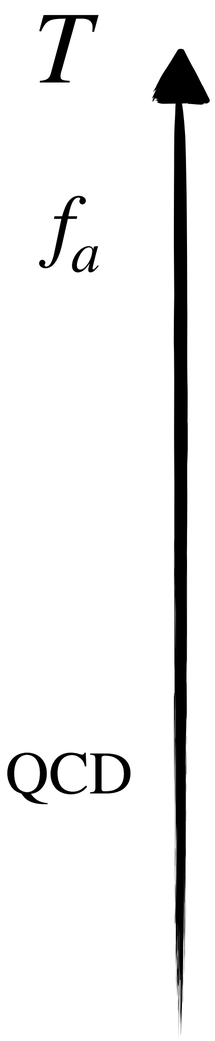

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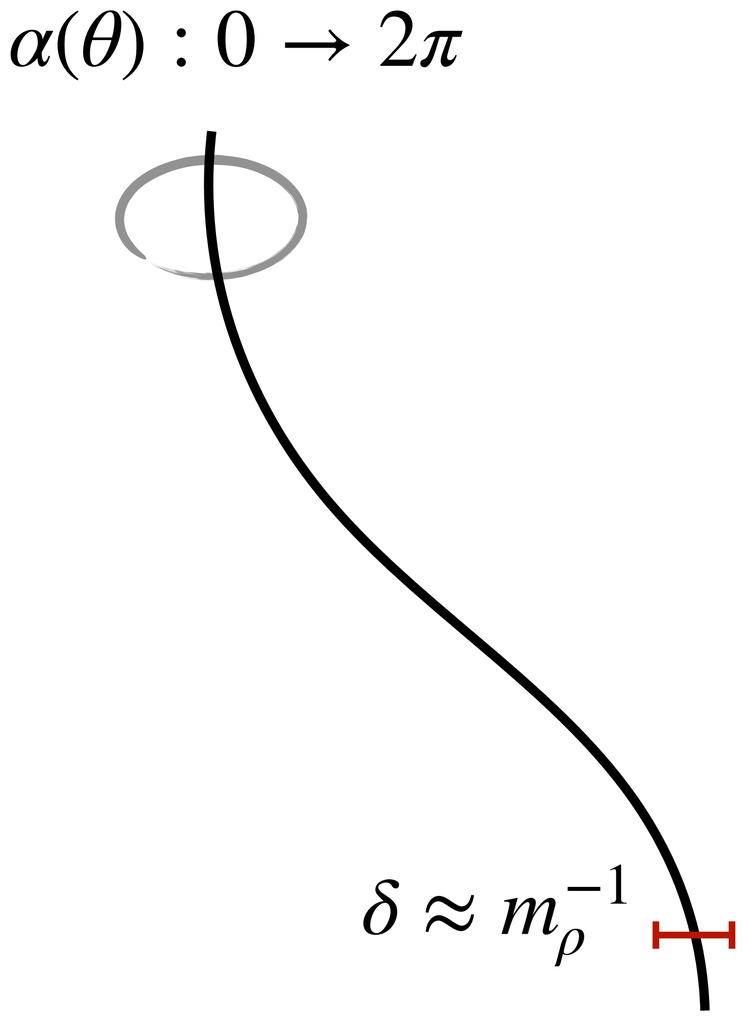
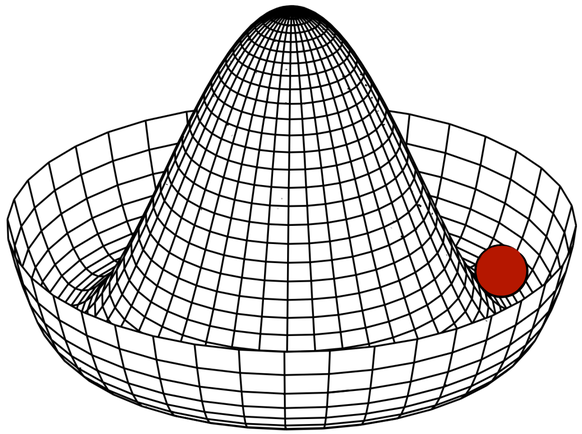


QCD axion strings

- Potential for PQ field

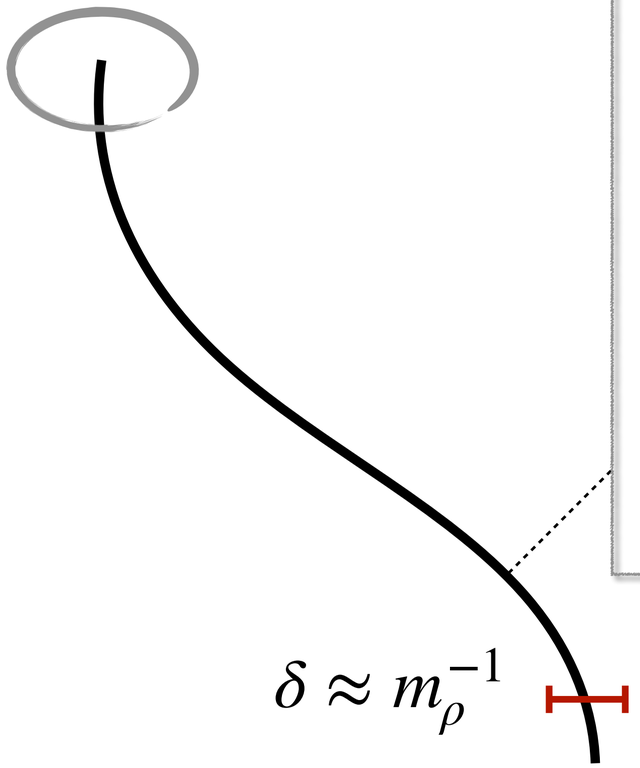
$$\Phi = \rho e^{i\alpha}$$

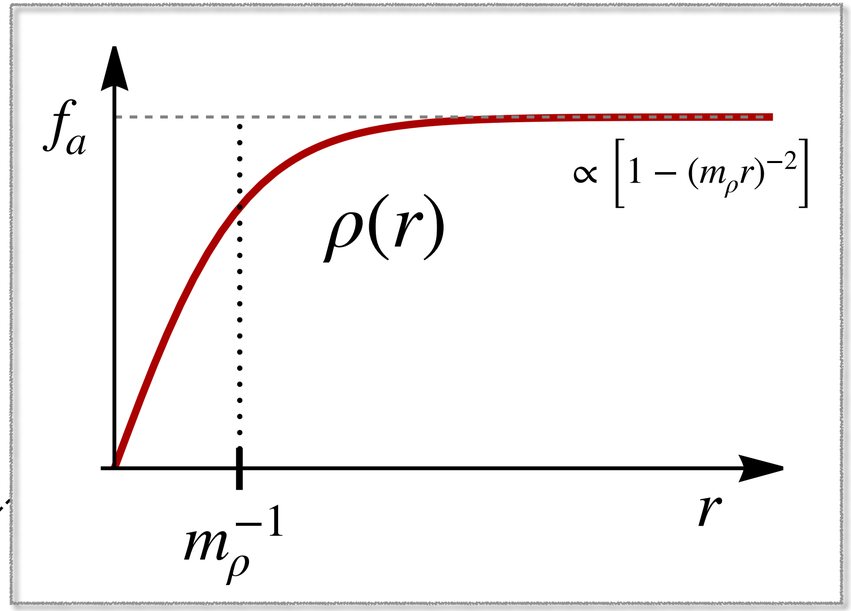


$$V_{\mathrm{PQ}}(\Phi)$$

- Global string solution

$$\alpha(\theta) : 0 \to 2\pi$$





QCD axion strings

- Relevant contribution to dark matter abundance
- Source of gravitational waves

Hiramatsu et al. [1012.5502] PRD

Gorghetto, Hardy, Villadoro
[1806.04677] JHEP; [2007.04990] SciPost

Gorghetto, Hardy, Nicolaescu [2101.11007] JCAP

Baeza-Ballesteros, Copeland, Figueroa, Lizarraga [2308.08456]

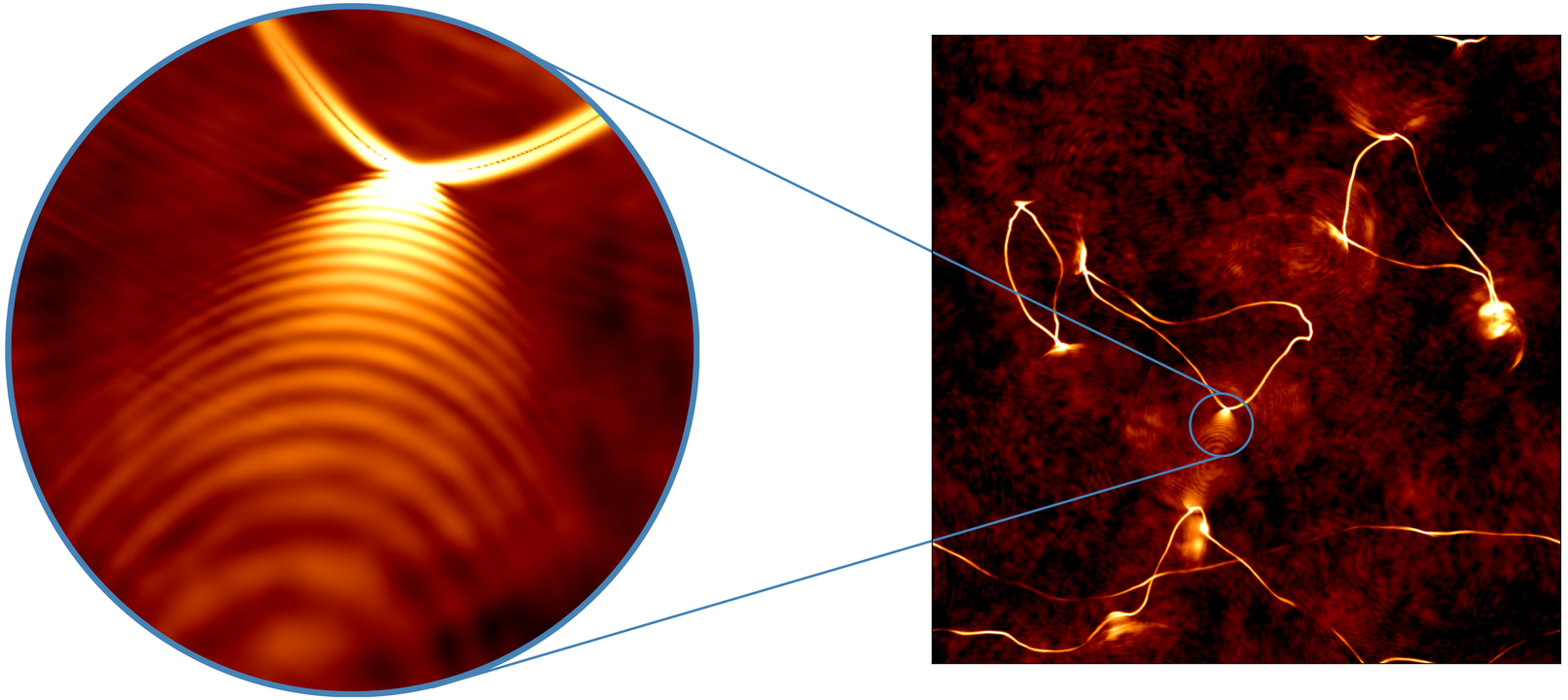


Fig. from Benabou, Buschmann,
Kumar, Park, Said [2308.01334], PRD

Axion strings during the EWPT

- Consider the minimal KSVZ axion model with a Higgs portal:

$$\mathcal{V} = V_{\rm PQ}(|\Phi|) + V_{\rm EW}(|\mathcal{H}|;T) + \kappa\left(|\Phi|^2 - \frac{f_a^2}{2}\right)\left(|\mathcal{H}|^2 - \frac{v^2}{2}\right)$$

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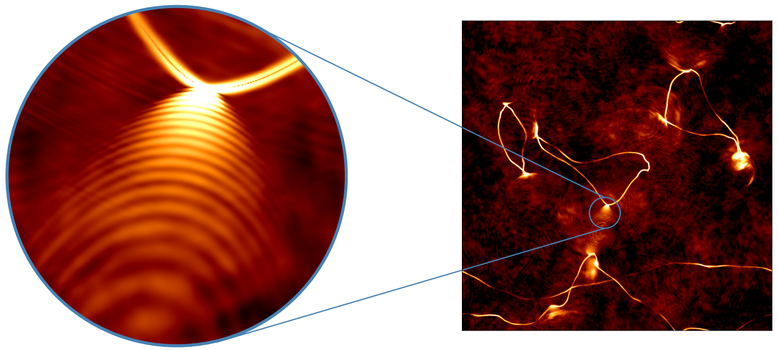
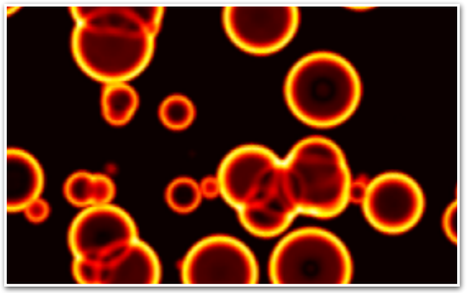
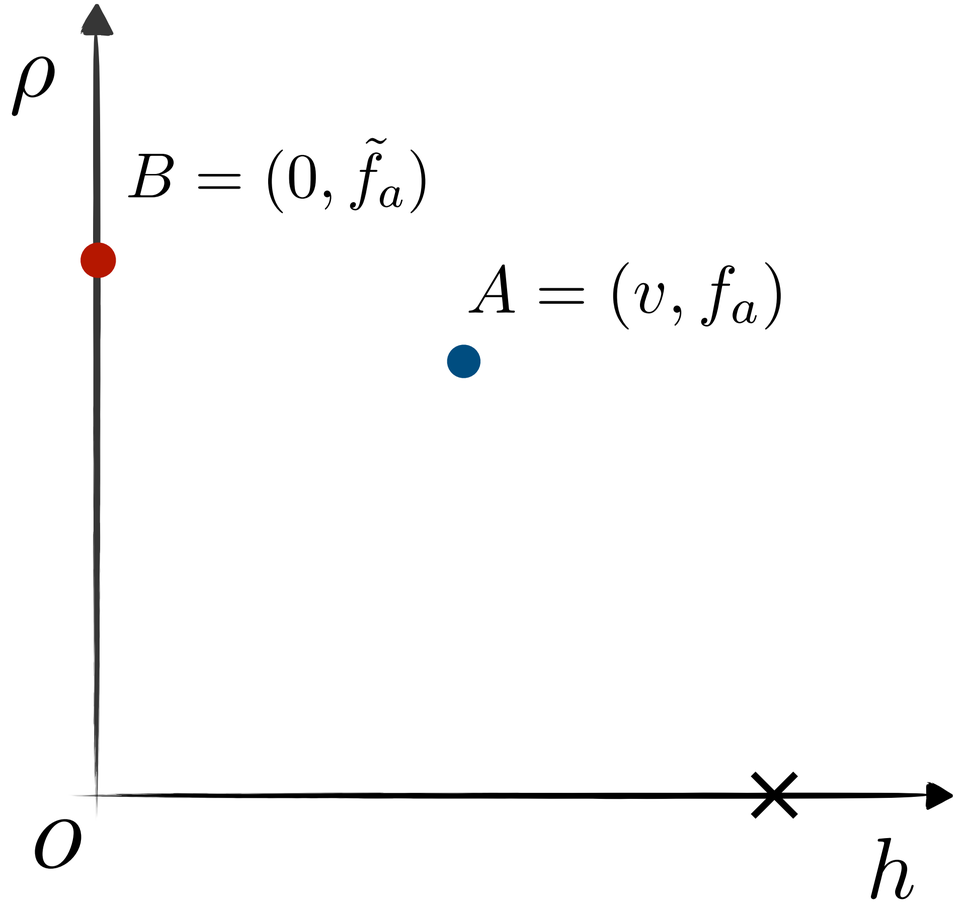


How does this affect electroweak symmetry breaking?



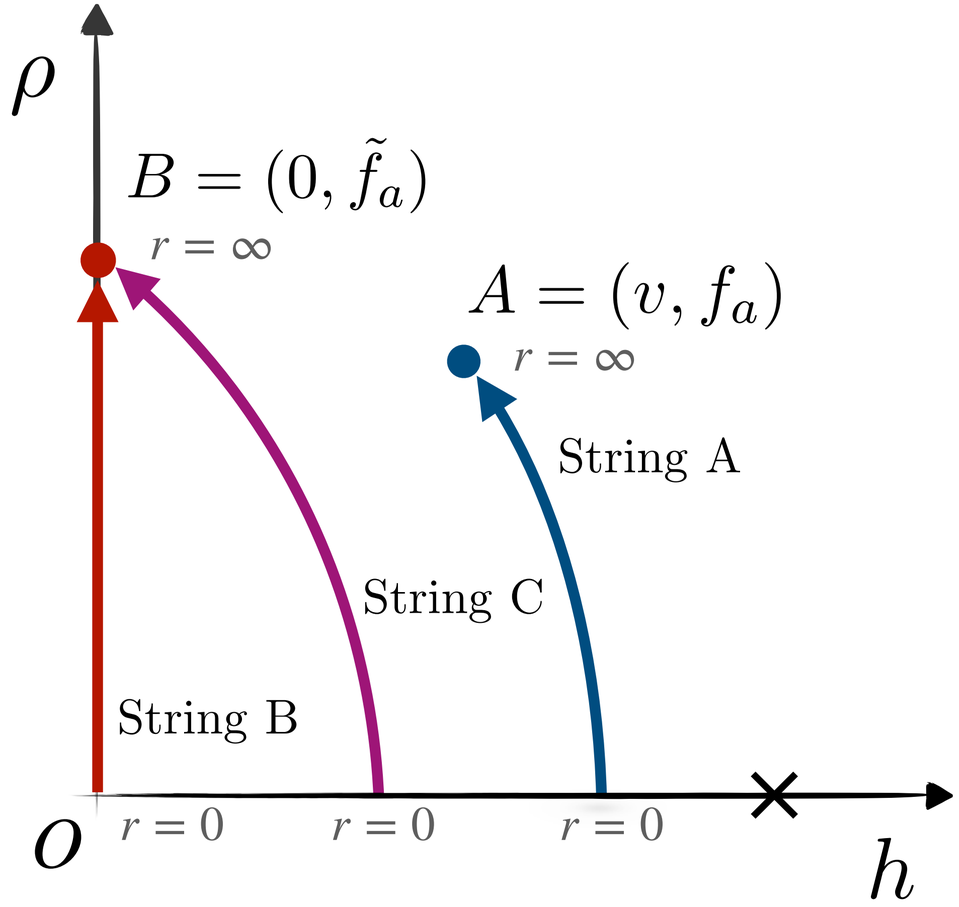
Axion strings during the EWPT

- Relevant points in field space



Axion strings during the EWPT

- Relevant points in field space and possible string solutions:



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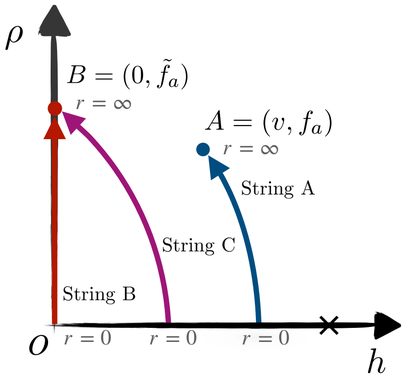

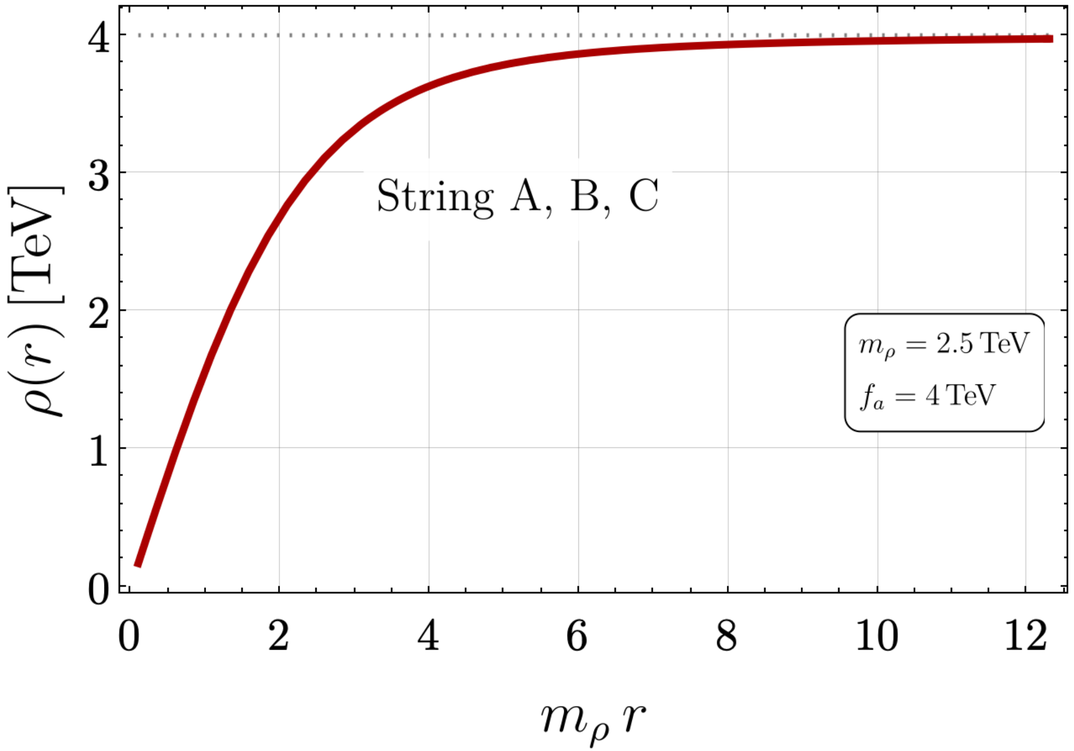

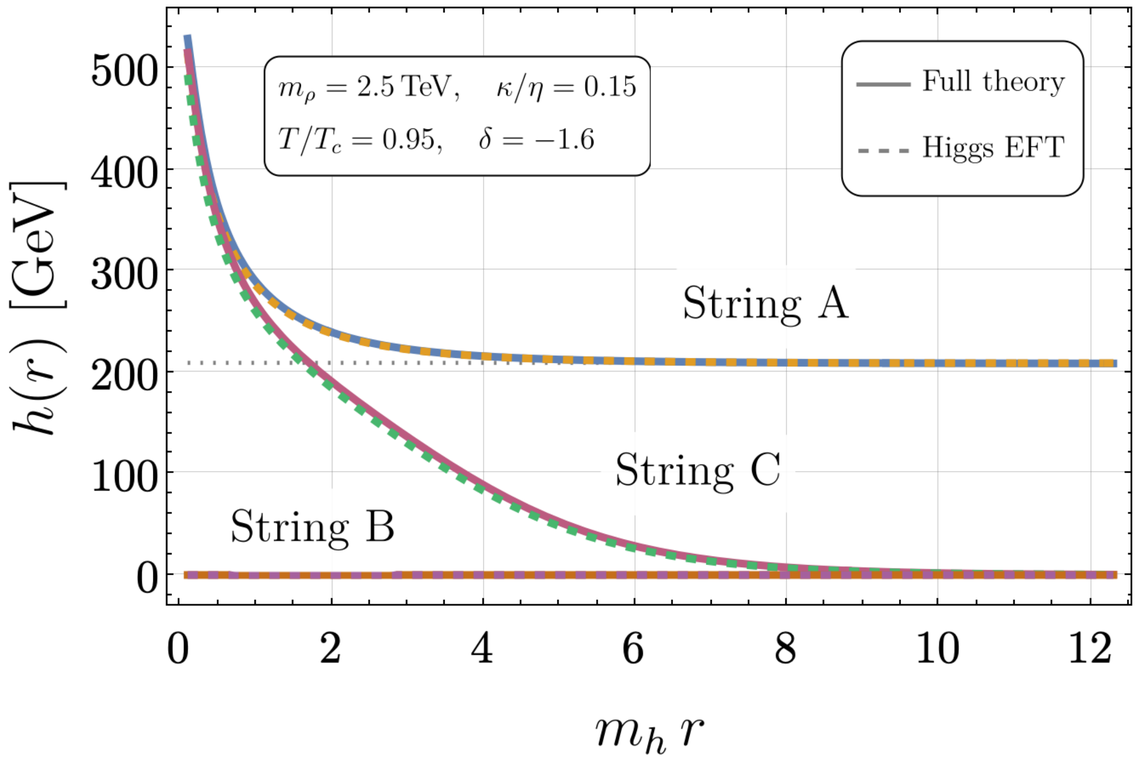

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Axion strings during the EWPT

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- Physics captured by electroweak-scale EFT (SM + axion or ALP):

$$S_{\rm EFT}[h] = \int d^4x \left\{ \frac{1}{2}(\partial_\mu h)^2 - V_{\rm EW}(h) - \frac{1}{2}\frac{\kappa}{\eta}(\partial_\mu \alpha)^2 h^2 + \pi \frac{\kappa}{\eta} C(\epsilon)\delta^{(2)}(r-\epsilon)h^2 \right\}$$

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- Explicit UV scale:

$$\epsilon \sim 1/m_\rho$$

- Axion-Higgs portal, in the string background:

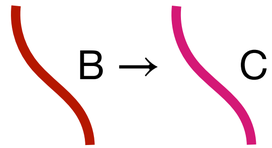
$$\alpha = \theta \;\Rightarrow\; \partial_\mu \alpha \sim 1/r$$

- δ-potential imposes UV matching condition:

$$\epsilon\, h'(\epsilon) = -C(\epsilon)\frac{\kappa}{\eta} h(\epsilon)$$

SM + PQ

- Consider the minimal Higgs potential of the SM
- Standard axion string develops a Higgs core at $T = T_r^B$:



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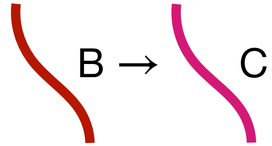

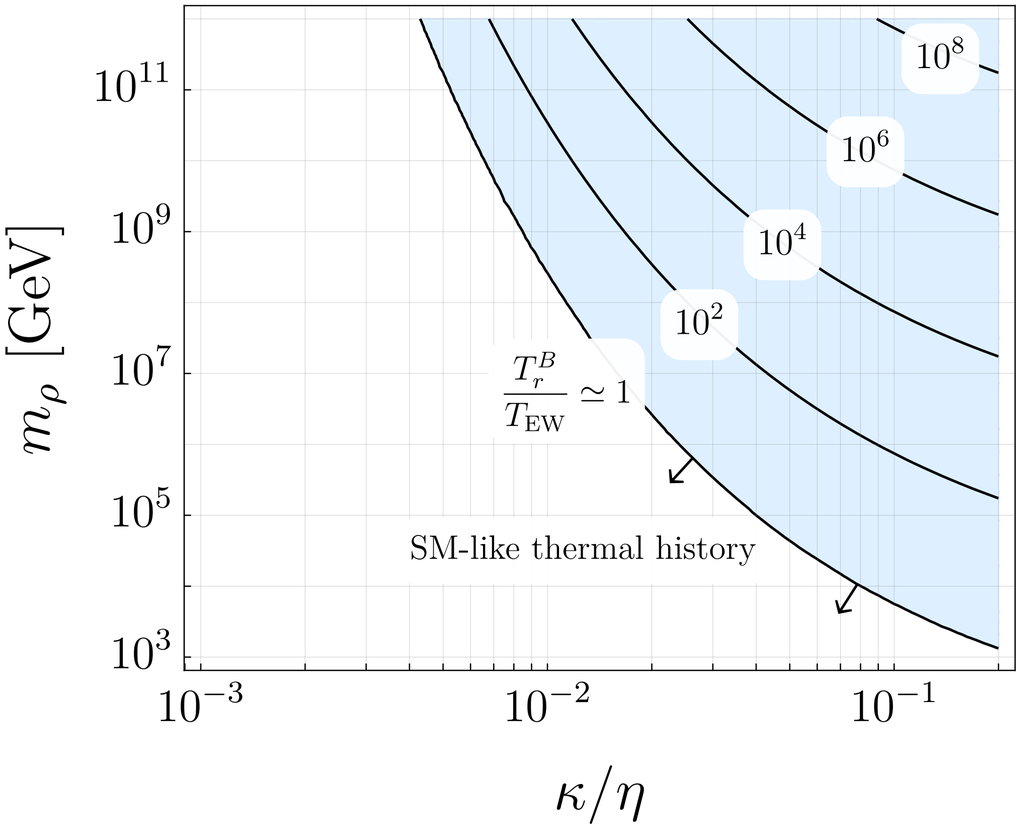

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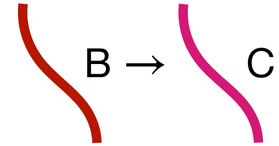

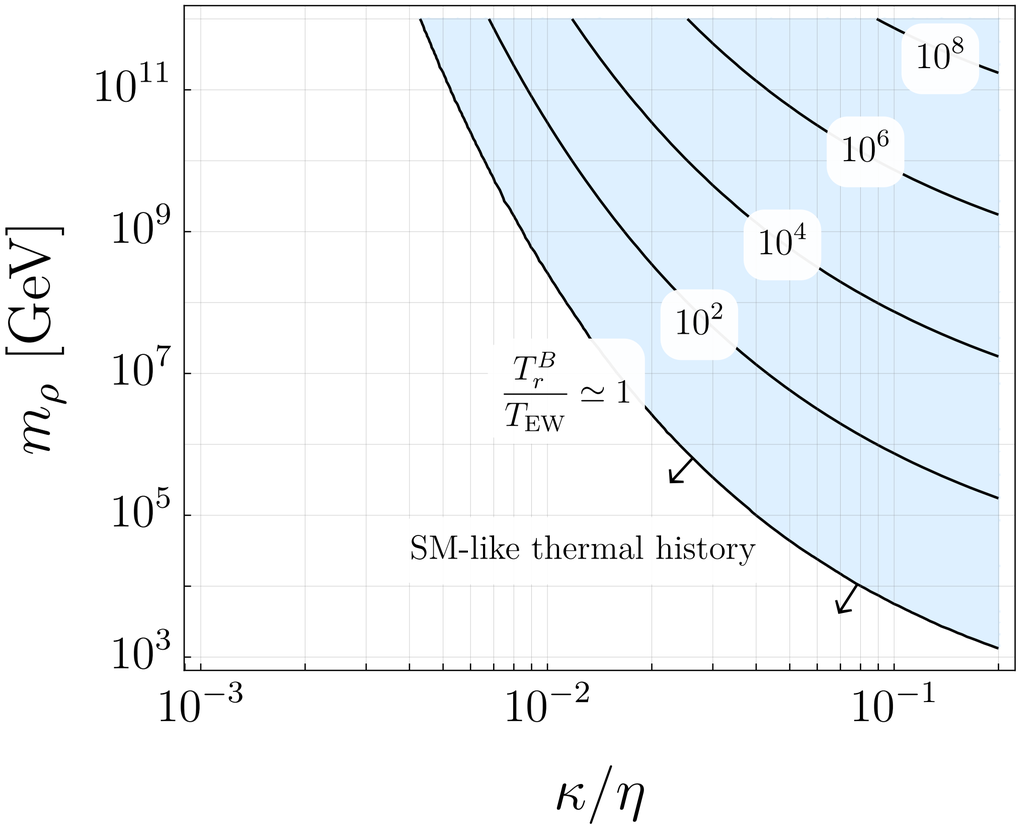

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2D mass — 4D mass — Δm_h^2

$$f(\kappa/\eta) = \exp\left\{ -\frac{\pi}{\sqrt{\kappa/\eta}} - \gamma_{\rm E} + 2C(\epsilon) \right\}$$

First order EWPT + PQ

- Consider BSM model with a first order (hom.) EWPT B → A which fails to nucleate: transition *still possible* around the axion strings

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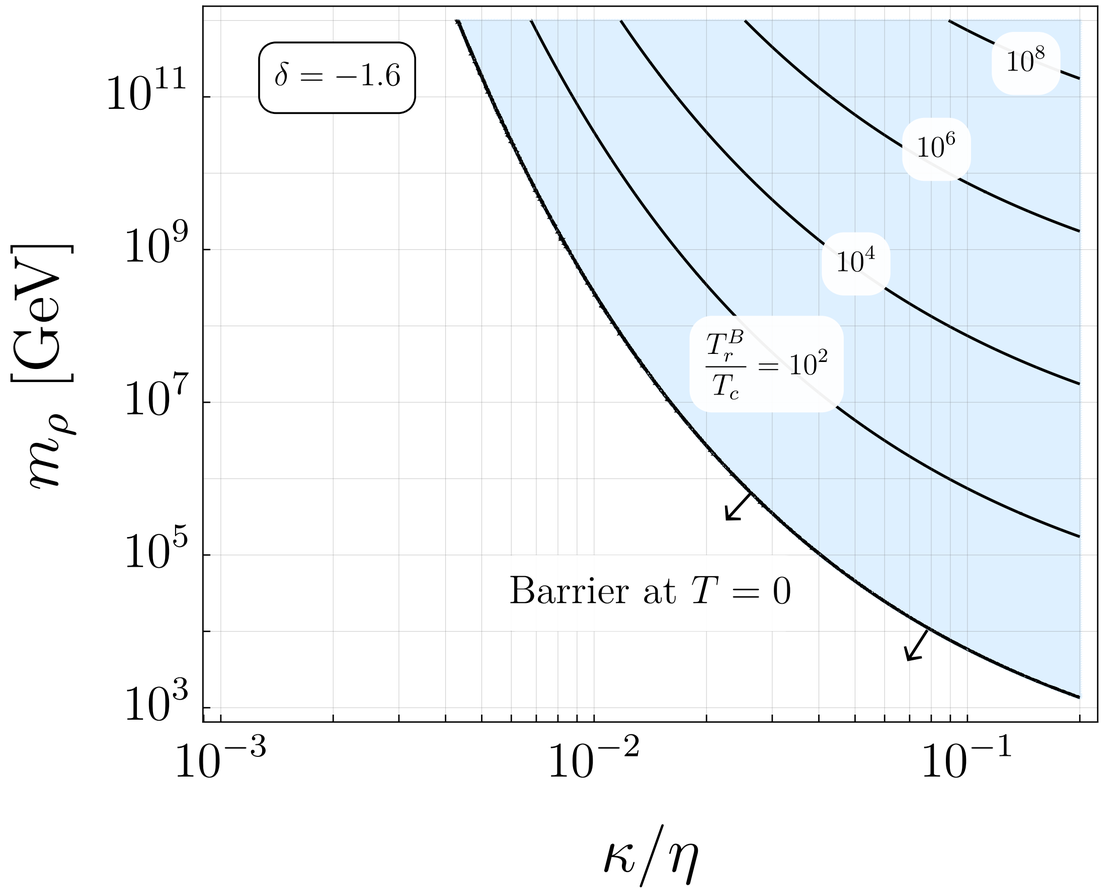

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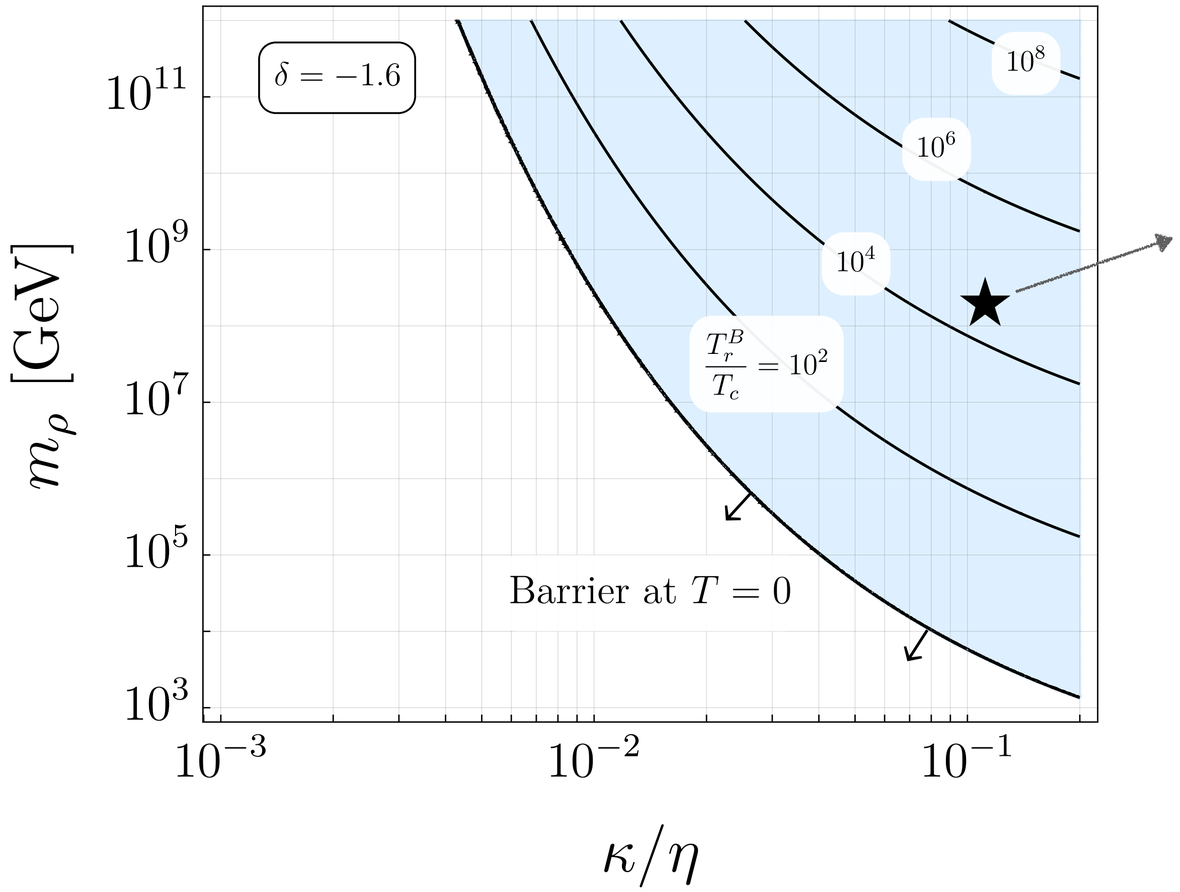


Rolling

Axion string unstable at finite T_r^B, EWPT guaranteed to complete

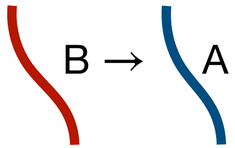
B → C → A

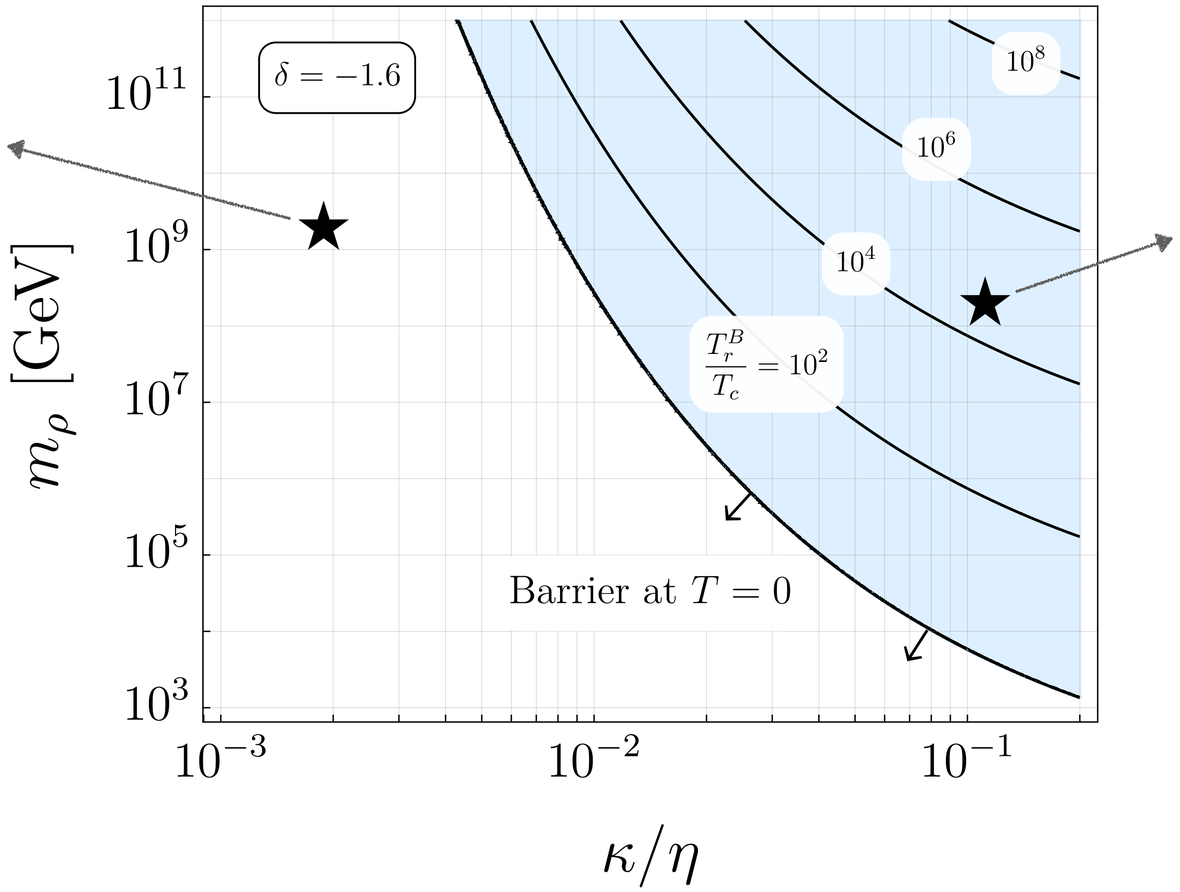
First order EWPT + PQ

- Consider BSM model with a first order (hom.) EWPT B → A which fails to nucleate: transition *still possible* around the axion strings

Seeded tunneling

Axion string metastable at $T = 0$: EWPT may complete if fast enough rate





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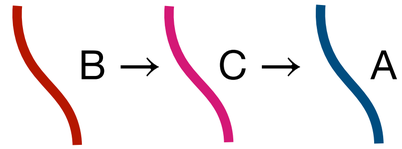
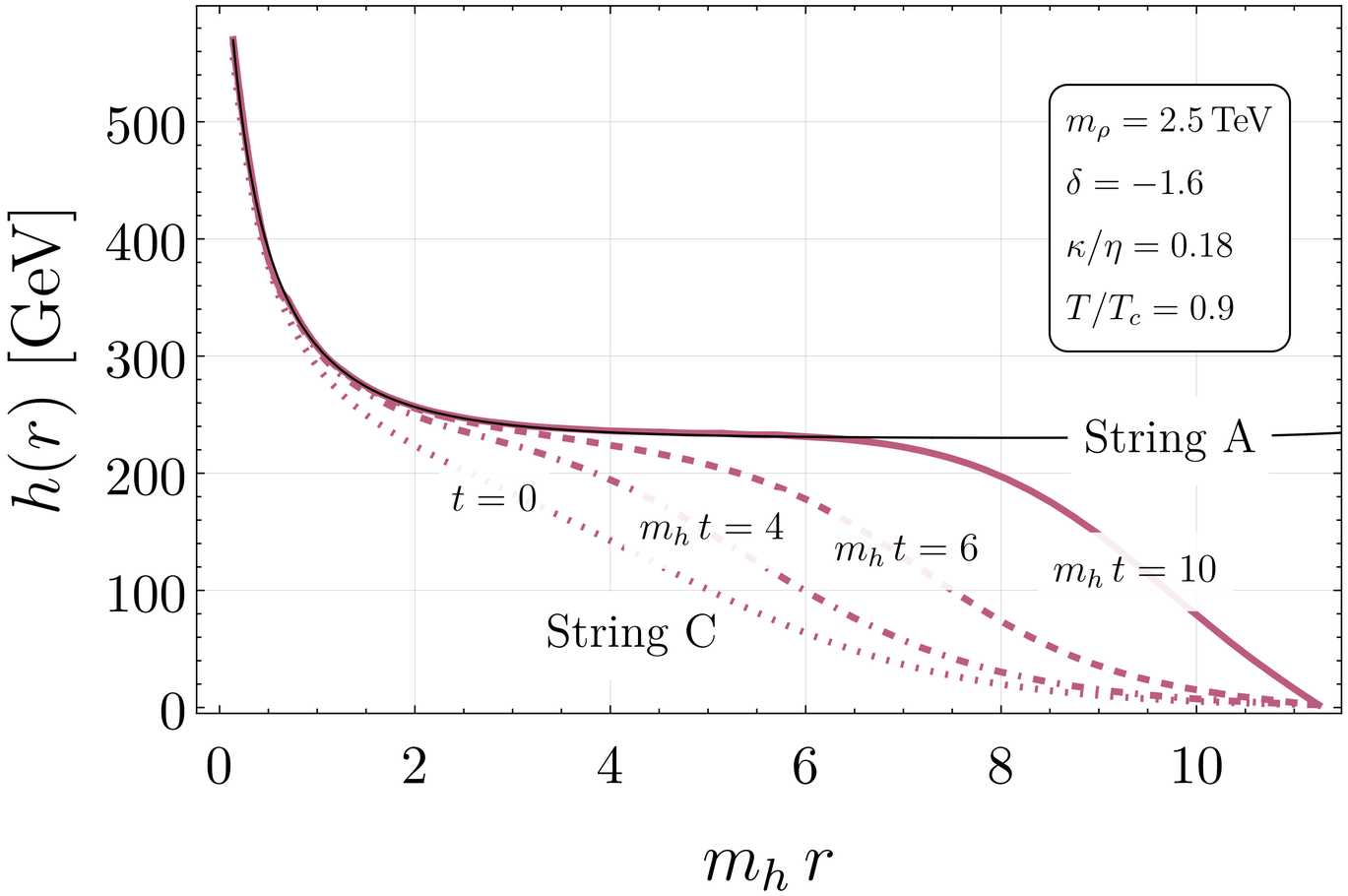
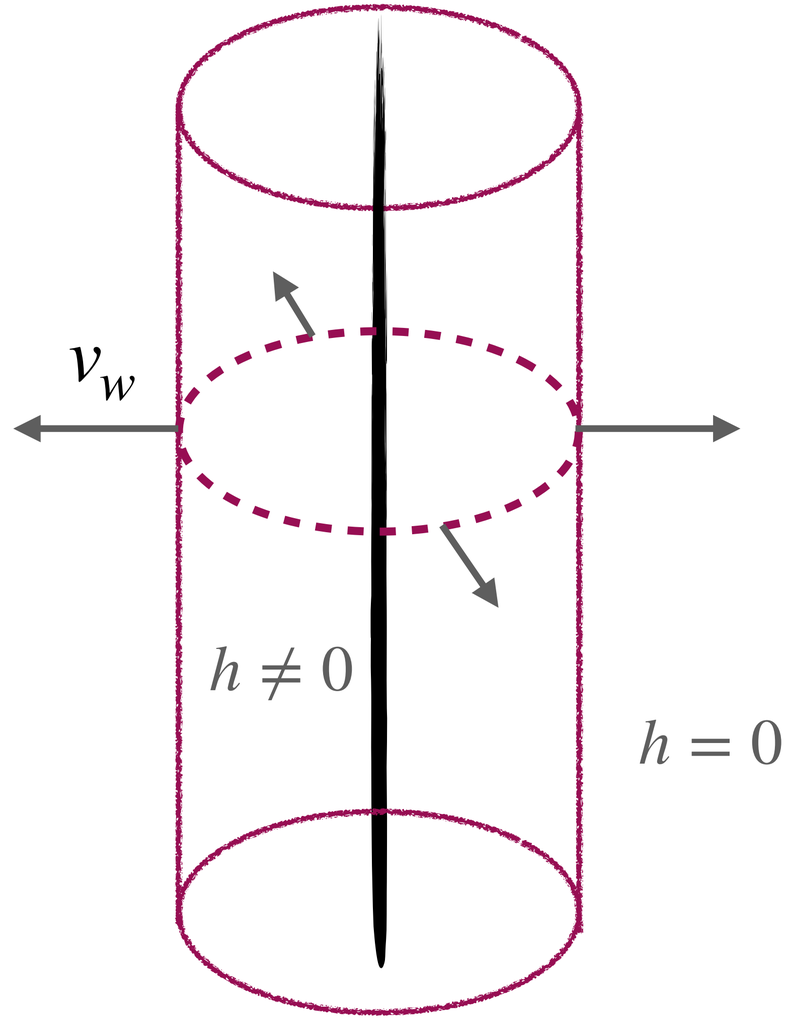


Rolling

See also Yajnik, PRD (1986)

- Classical evolution from string C to string A at $T \approx T_c$

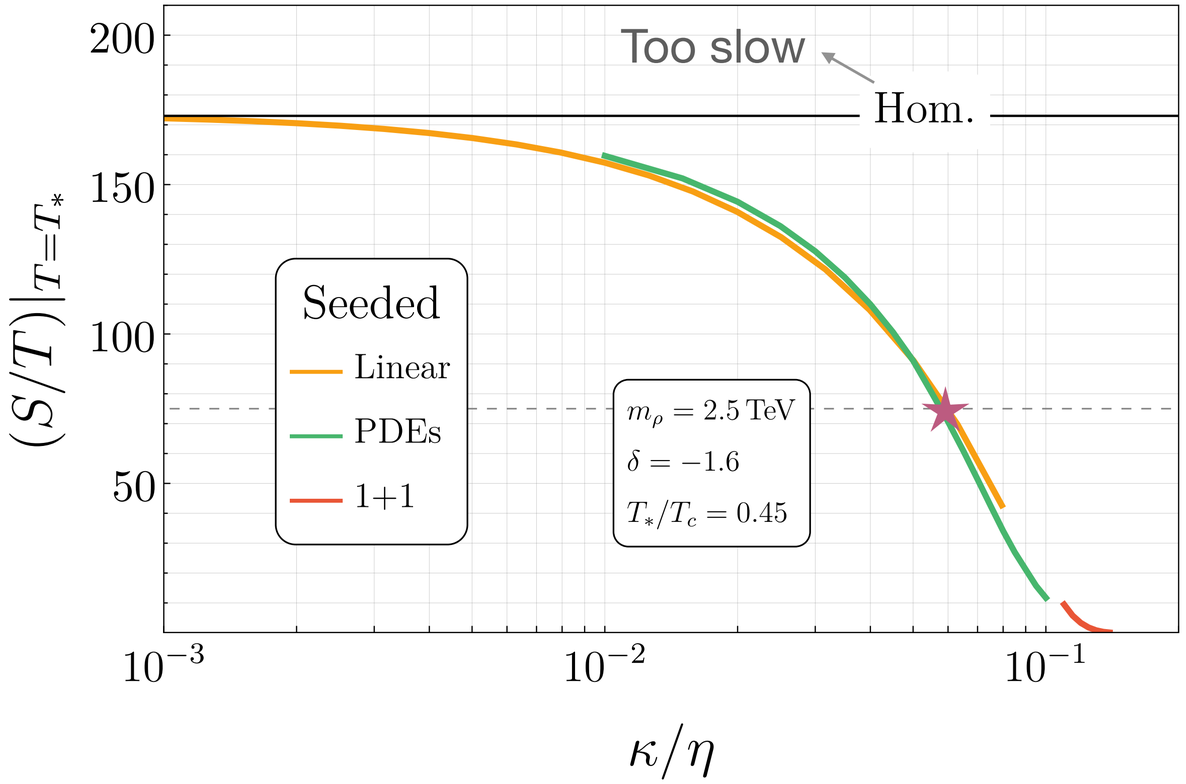




Cylindrical bubble wall expanding radially from the axion string

Seeded tunneling

- Bubble of broken electroweak symmetry nucleated around the axion string with a certain (exponential) rate S/T:



- **Linear** $\sim$ thin wall approximation:

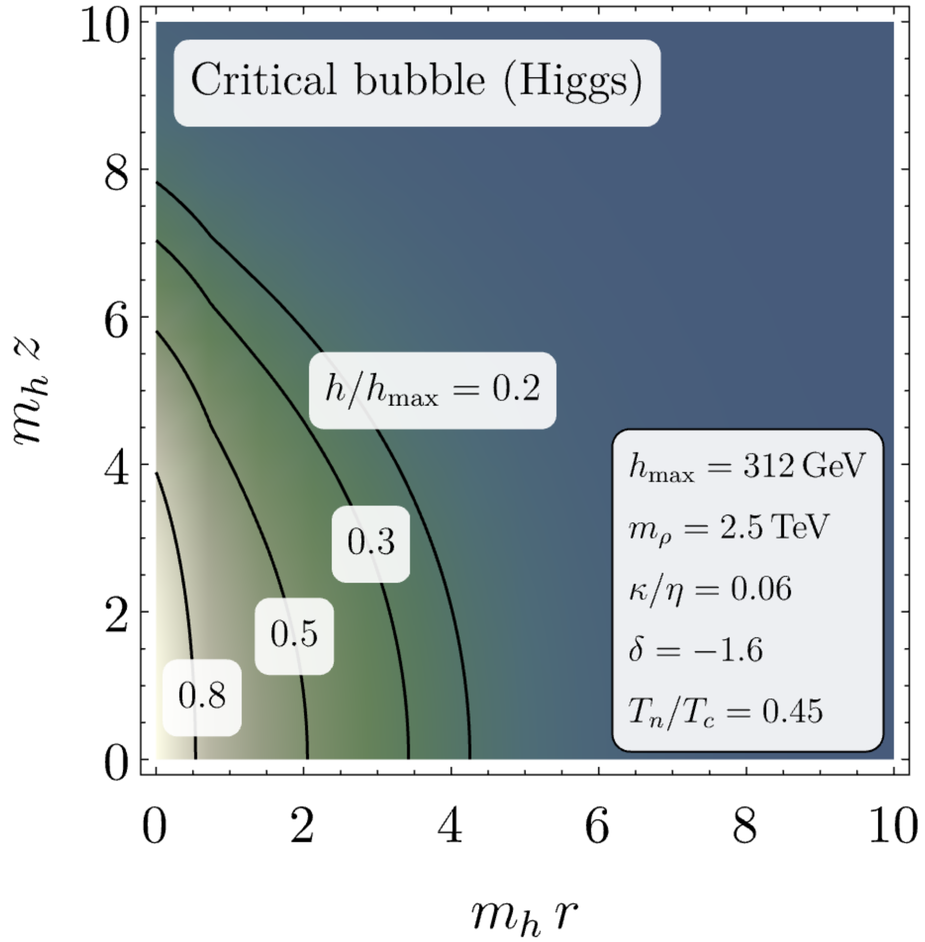
$$\delta S_{\rm TW} = -2\pi R\,\frac{\kappa}{\eta}\log\left(R\,m_\rho\right)\,h_{\rm r}^2(0) \equiv 2\pi R\,\Delta\mu_{\rm eff}$$

- **EFT** on the string for the lightest mode:

$$S_{1+1}[h_0] = \int dzdt\left\{\frac{1}{2}(\partial_\mu h_0)^2 - \tilde{V}(h_0)\right\}$$

Seeded tunneling

- Profile of the critical bubble: ★



Seeded tunneling

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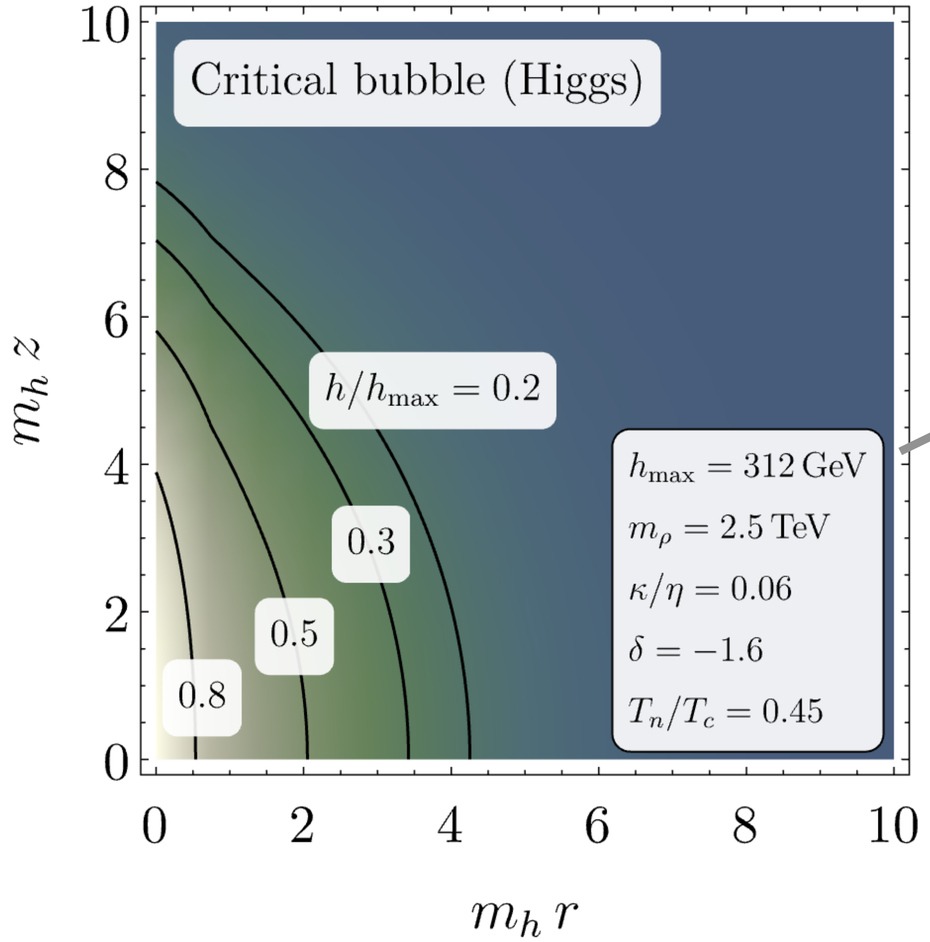
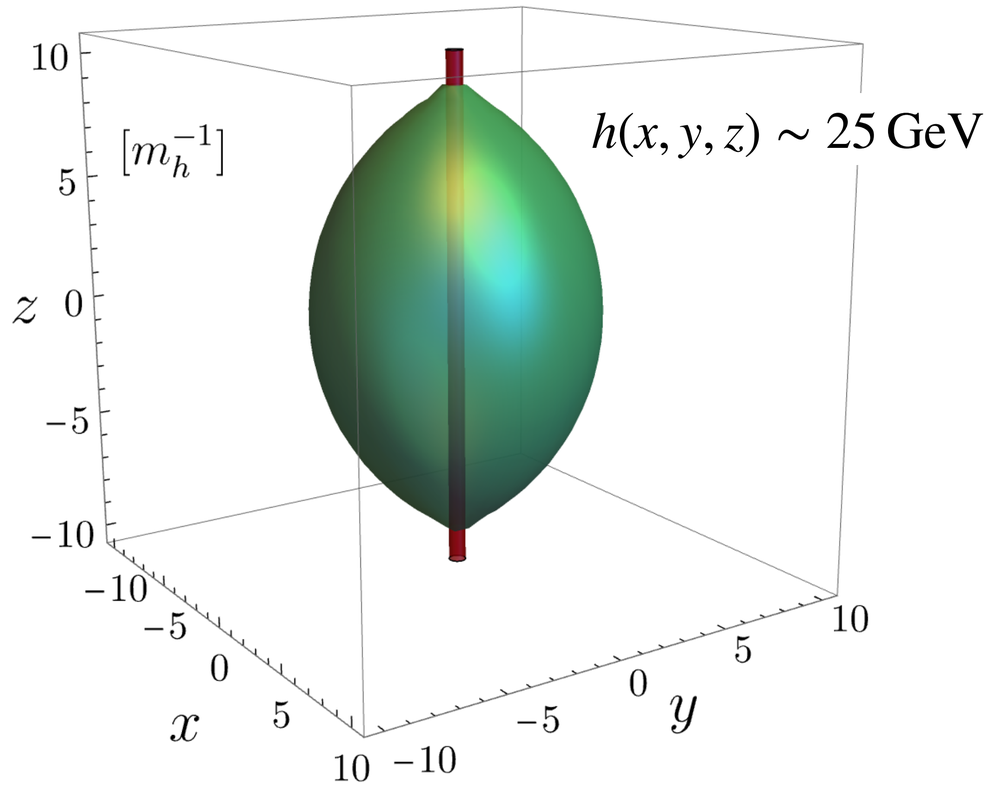


Release point is larger than the VEV: the bubble is partially reconstructing string A

Seeded tunneling

- Profile of the critical bubble: ★



Seeded tunneling

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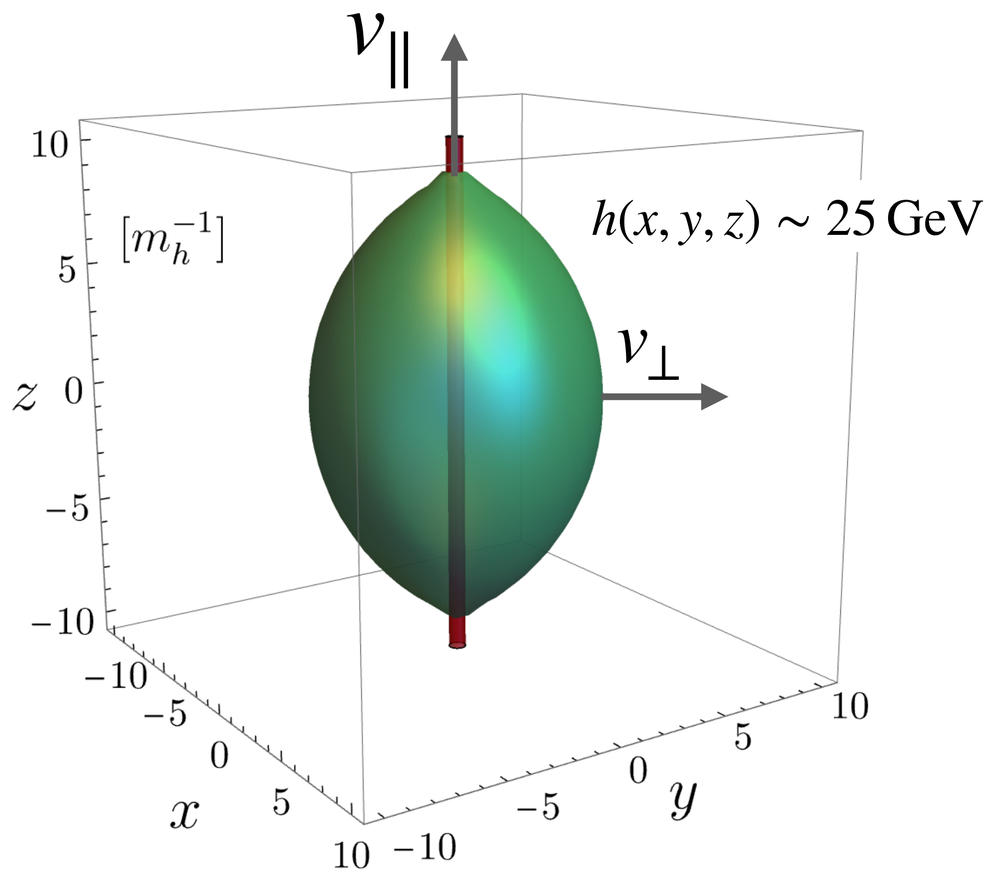

- Percolation as interplay between seeded nucleation rate and density of defects
- Is nucleation rate the same on loops?
- Different velocities parallel or orthogonal to the string?
- Gravitational wave emission before collision (non-spherical bubbles, same for *rolling* case)

Summary

- The presence of impurities in the early Universe can strongly affect the way a phase transition proceeds
- The xSM with Z_2 symmetry is arguably the simplest (and complete) example for a seeded EWPT
- Other defects can exist at the time of the EWPT: dedicated study of QCD axion strings in KSVZ model with Higgs portal
- Pheno aspects of seeded phase transitions: percolation, slow transitions, expansion of non—spherical bubbles, features in the GW signal?

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Thank you!