VRIJE UNIVERSITEIT BRUSSEL

Domain walls seeding the electroweak phase transition

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work in collaboration with Alberto Mariotti

Based on 2203.16450 [hep-ph]

PASCOS 2022, MPIK Heidelberg 26.07.

Standard nucleation theory

- Thermal fluctuations in **homogeneous spacetime**
- $O(3)$ symmetric bubbles:

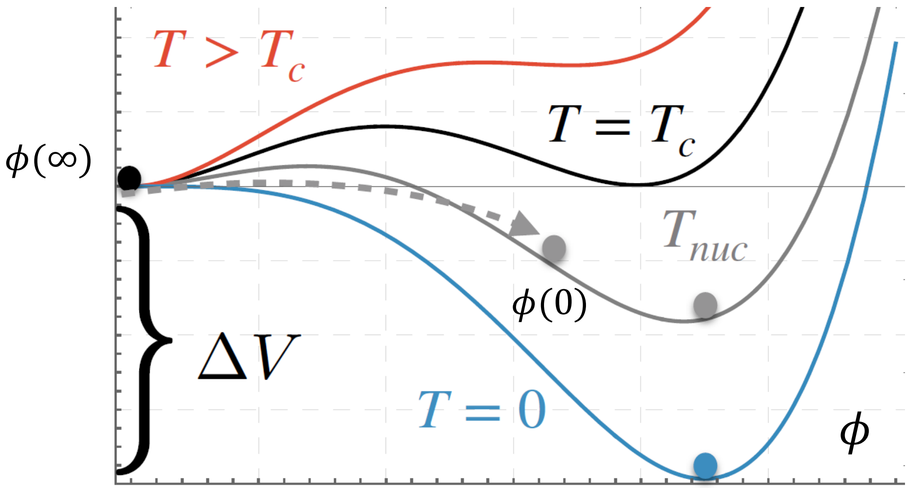
$$\phi''(r) + \frac{2}{r}\,\phi'(r) = \frac{\partial V}{\partial \phi}, \qquad \phi'(0) = 0, \quad \phi(\infty) = 0$$

- Nucleation rate/volume set by the bounce action

$$\gamma_V(T) \sim T^4 e^{-S_3(T)/T}$$

- Nucleation temperature $\gamma_V \sim \text{Hubble}^4$

Fig. adapted from N.Levi's talk



However…

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."

Impurities in the early universe

Yutaka Hosotani

Department of Physics, University of Pennsylvania, Philadelphia, Pennsylvania 19104

(Received 1 November 1982)

"Now one has to ask the following question: **Is the early universe really sufficiently pure in order for supercooling to take place**? The aim of this paper is to show that in most cases the early universe is very pure. […] In this paper we consider **ordinary particles as impurities**."

Cosmic separation of phases

Edward Witten*

Institute for Advanced Study, Princeton, New Jersey 08540

(Received 9 April 1984)

"In particle physics it is often assumed that phase transitions are nucleated by thermal fluctuations. In practice, […] except in very pure, homogeneous samples, **phase transitions are often nucleated by various forms of impurities and inhomogeneities of nonthermal origin**."

"What if the transition was nucleated by impurities? In this case **the mean spacing between bubbles has nothing to do with free energies** of nucleation and is simply the spacing between the relevant impurities. "

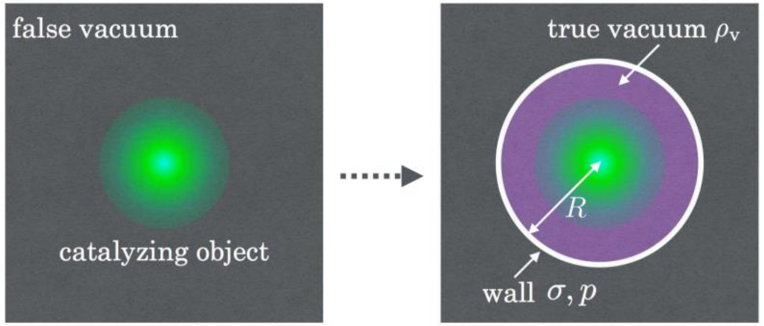
The nature of impurities

- Compact objects, (not only) gravitational effects

(Coleman-de Luccia, PRD, 1980)

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

Hiscock, PRD, 1987; Burda, Gregory, Moss [1501.04937], PRL



- Topological defects (strings and monopoles)

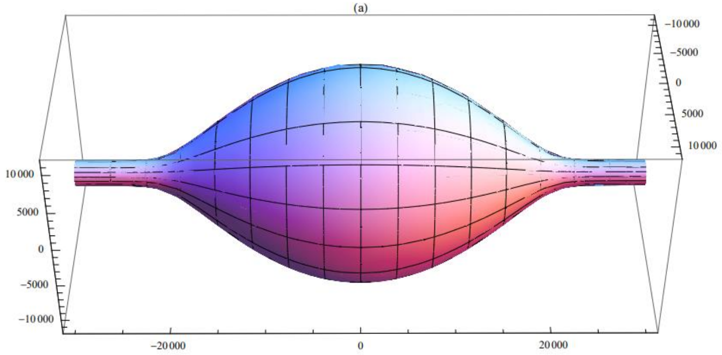


Fig. from Lee et al., [1310.3005], PRD

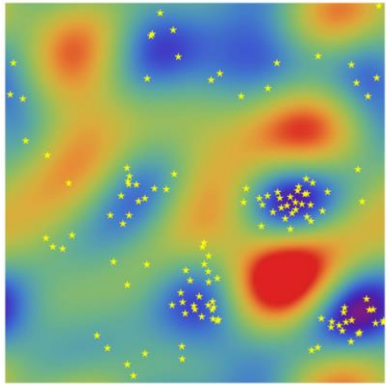
Yajnik, PRD, 1986

…

Agrawal and Nee, [2202.11102]

- Primordial density fluctuations

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



- What about **domain walls?**

This talk:

- ✓ Higgs + Singlet (xSM)
- ✓ Thermal history
- ✓ New method for bounce

SB & Mariotti, [2203.16450]

(Haberichterb et al. [1506.05838], Dupuis et al. [1506.05091])

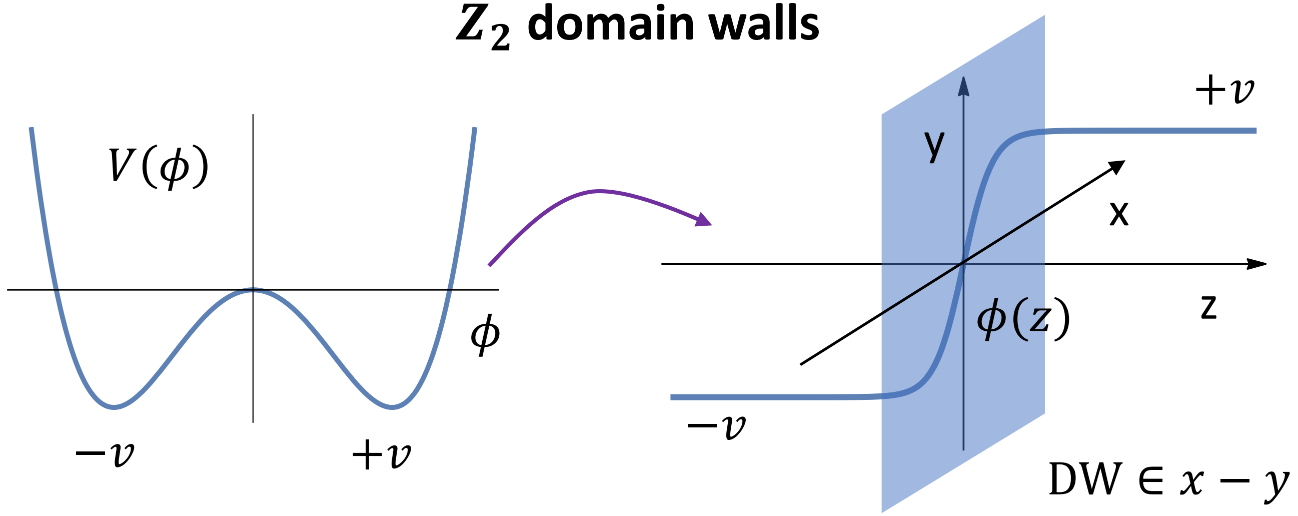
Topological defects

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

Relics of PTs depending on topology of vacuum manifold *M*, not on the strength

Defect	Dimension	Homotopy
Domain walls	2	$\pi_0(M)$
Strings	1	$\pi_1(M)$
Monopoles	Point-like	$\pi_2(M)$
Textures	-	$\pi_3(M)$

Z_2 domain walls



$U(1)$ strings

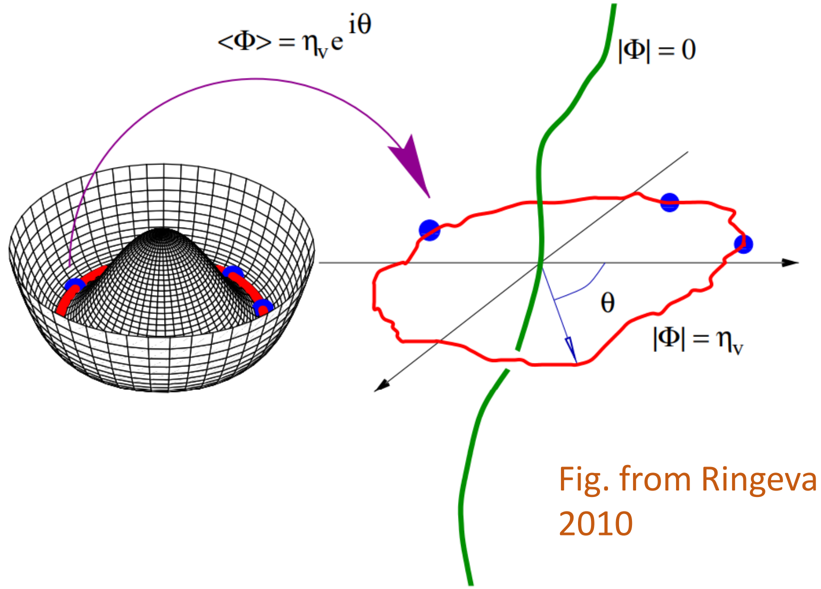
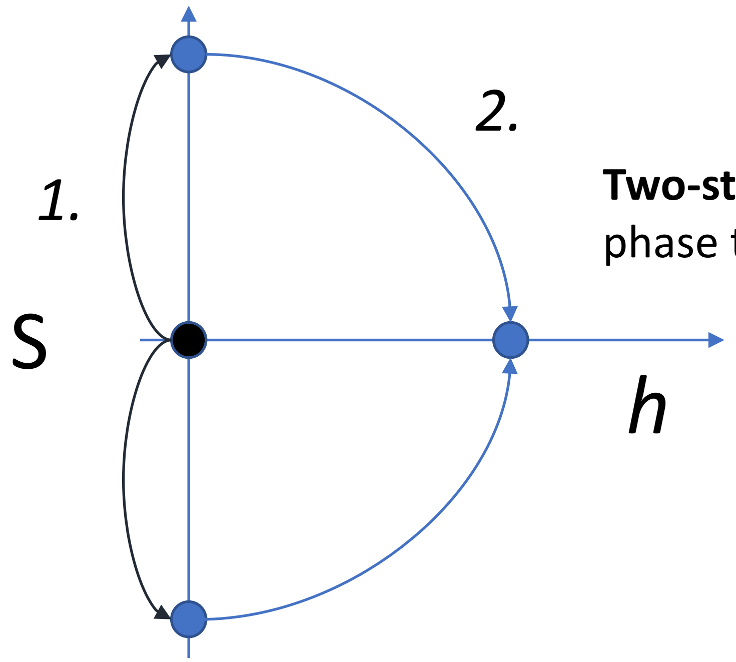


Fig. from Ringeval 2010

Cosmic strings and other topological defects,
Vilenkin & Shellard

The electroweak PT in the SM + scalar singlet

$$V = -\frac{1}{2}(\mu^2 - c_h T^2)h^2 + \frac{1}{4}\lambda\, h^4 - \frac{1}{2}(m^2 - c_s T^2)S^2 + \frac{1}{4}\eta\, S^4 + \frac{1}{2}\kappa\, h^2 S^2$$



Two-step electroweak phase transition

- Probably simplest new physics scenario with strong first order EWPT, tree-level barrier

Espinosa, Konstandin, Riva [1107.5441] NPB

- When Z_2 symmetry $S \to -S$ imposed difficult to test at colliders (nightmare scenario)

Curtin, Meade, Yu [1409.0005] JHEP

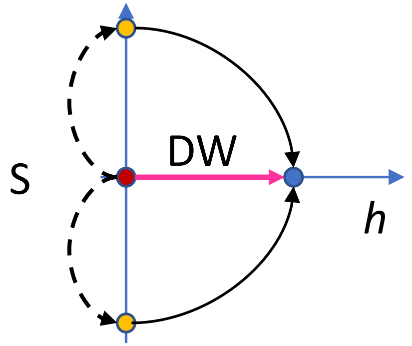
- Minimal mechanism for EW baryogenesis when Z_2 = CP

Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

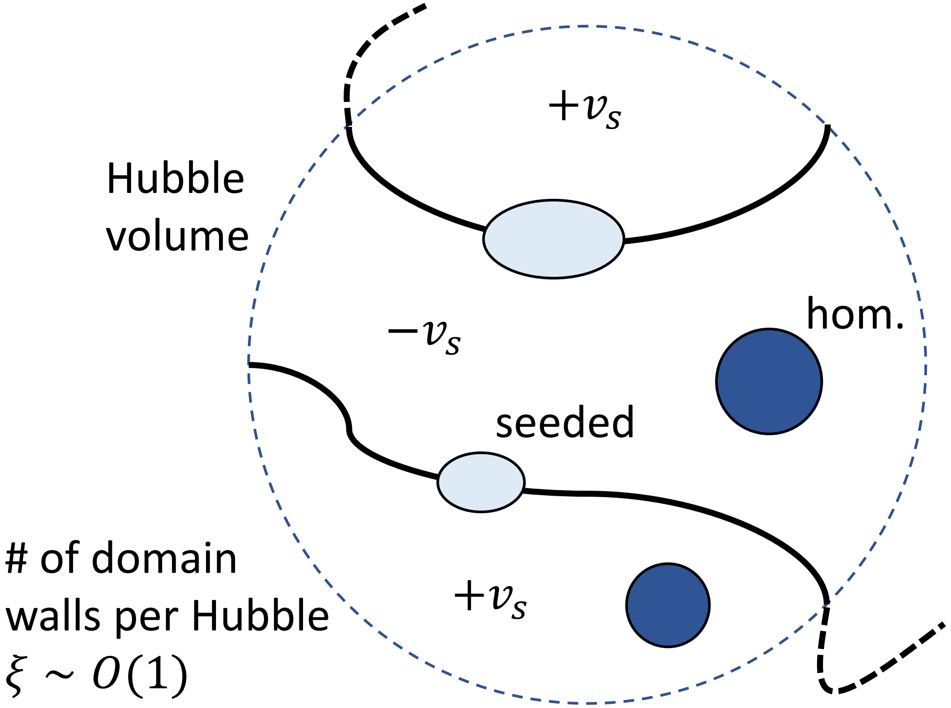
- New confining group as possible UV completion, next-to-miniml Composite Higgs

Gripaios, Pomarol, Riva, Serra [0902.1483] JHEP

Seeded vs homogeneous tunneling



- Nucleation prob. no longer the same everywhere, **enhanced at DW location**



- Seeded, or inhomogeneous, tunneling **probability per unit surface**:

Lazarides, Shafi, Kibble 1982, PRD

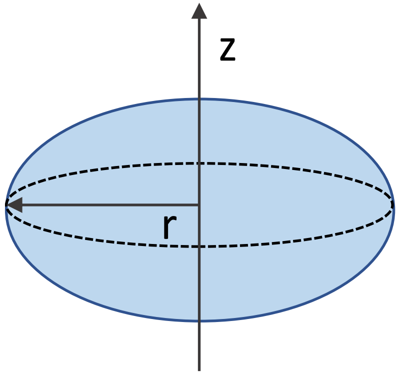
Perkins, Vilenkin 1992, PRD

$$\gamma_S \sim v_S^3 \exp(-S_2/T) \qquad [\gamma_V \sim T^4 \exp(-S_3/T)]$$

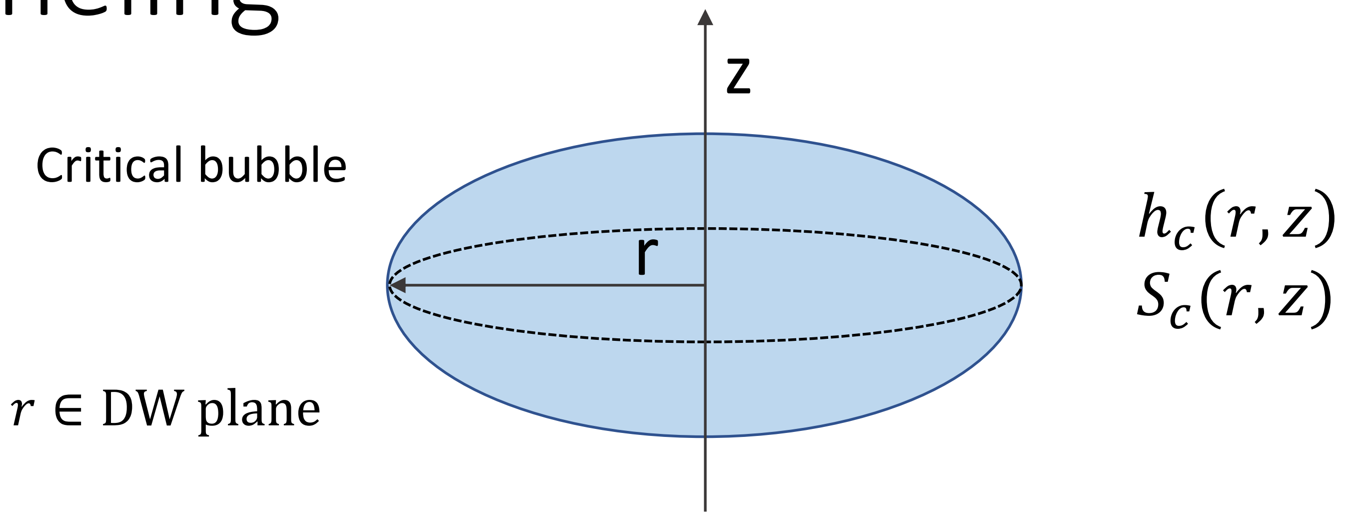
- **Stricter nucleation** condition (only on submanifold)

$$S_2/T \sim 100 + \log \xi \qquad [S_3/T \sim 140]$$

- **Critical bubble** will have only O(2) symmetry on the domain wall plane



Seeded tunneling



1. Solving coupled **system of PDEs**

- Exact
- physical understanding?
- Which initial conditions for the algorithm?

2. **Thin wall** approximation

- Limited validity
- Intuitive picture
- Simple calculation

3. **Kaluza-Klein** decomposition (**new**)

- Quantitative results
- Still intuitive
- Initial conditions for num. algorithms and cross-checks

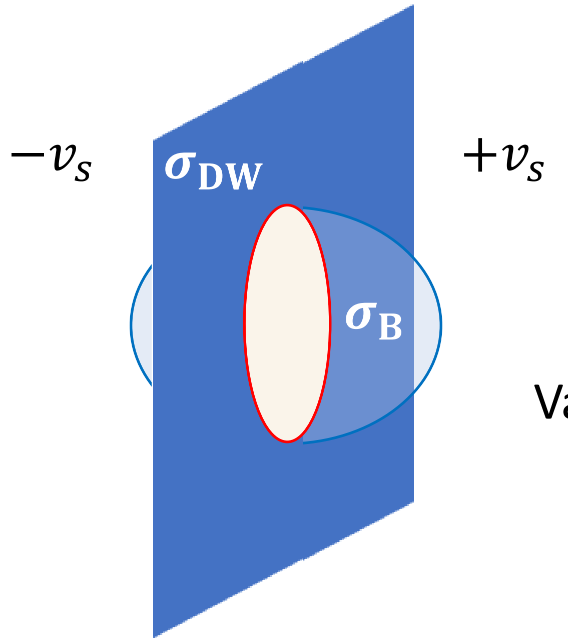
Seeded tunneling rate: thin wall limit

- Geometrical approach to estimate the energy of the critical bubble configuration

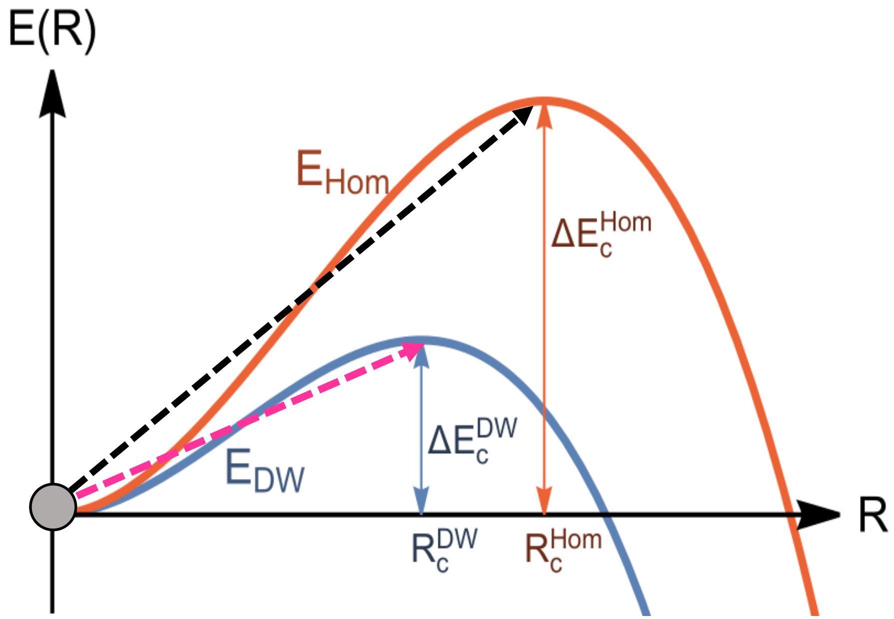
$S_2/T \sim \Delta E/T$ (Boltzmann)

$$E(R) \simeq 4\pi R^2\,\sigma_B - \frac{4}{3}\pi R^3 \epsilon - \pi R^2 \sigma_{DW}$$

Gain by eating up domain wall surface

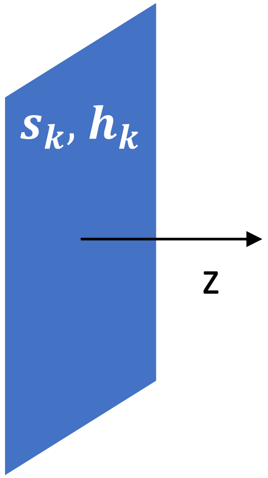


Valid at $T \sim T_c$



Seeded phase transition: Kaluza-Klein decomposition

- Expand the fields around the domain wall background, and integrate over the orthogonal direction



$$S = S_{\mathrm{DW}}(z) + \sum_k s_k(x_\mu)\sigma_k(z)$$

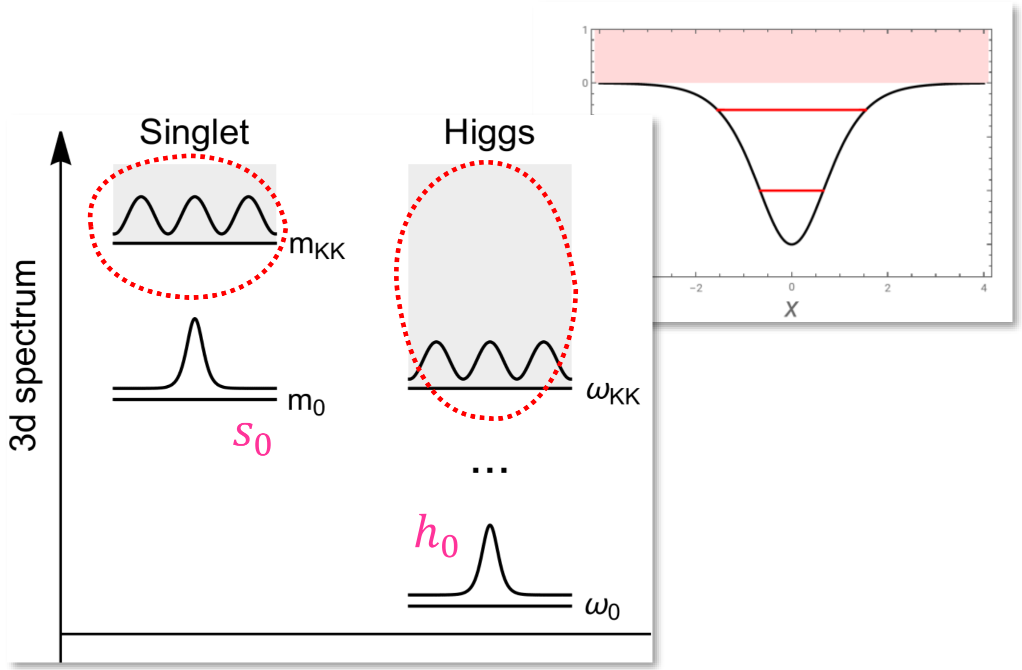
$$h = \sum_k h_k(x_\mu)\phi_k(z)$$

$$x_\mu = t, x, y$$

- Profiles are chosen in order to have canonical 3d fields:

$$-\sigma_k''(z) + \left(3\eta\, S_{\mathrm{DW}}^2(z) - m^2\right)\sigma_k(z) = m_k^2 \sigma_k(z)$$

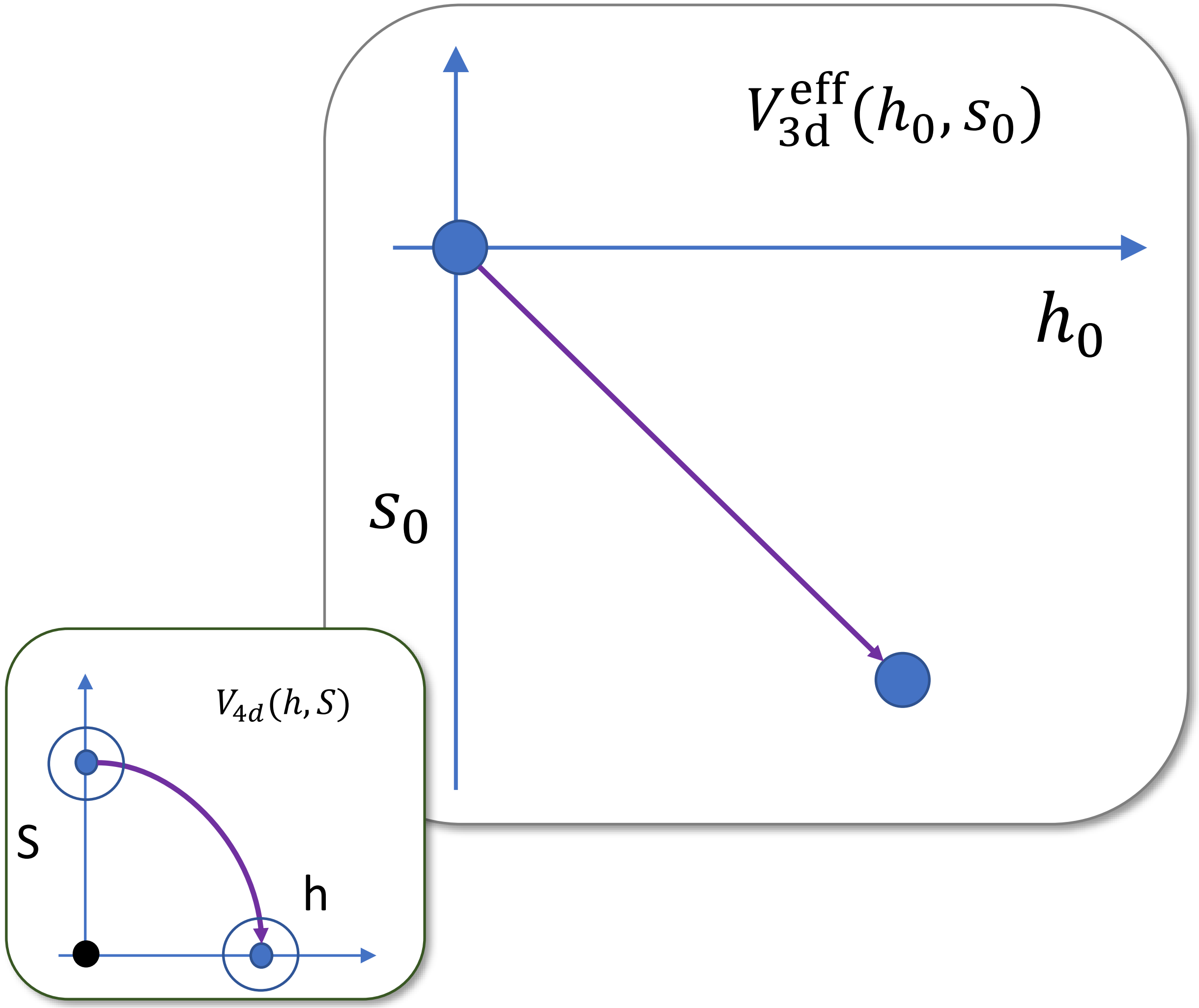
$$-\phi_k''(z) + \left(\kappa\, S_{\mathrm{DW}}^2(z) - \mu^2\right)\phi_k(z) = \omega_k^2\, \phi_k(z)$$



- Study the 3d theory on the DW plane, interaction from overlap integrals with $V(h, S)$

- Take advantage of the gap to integrate continuum states out in favor of EFT for h_0, s_0

Seeded phase transition: Kaluza-Klein decomposition

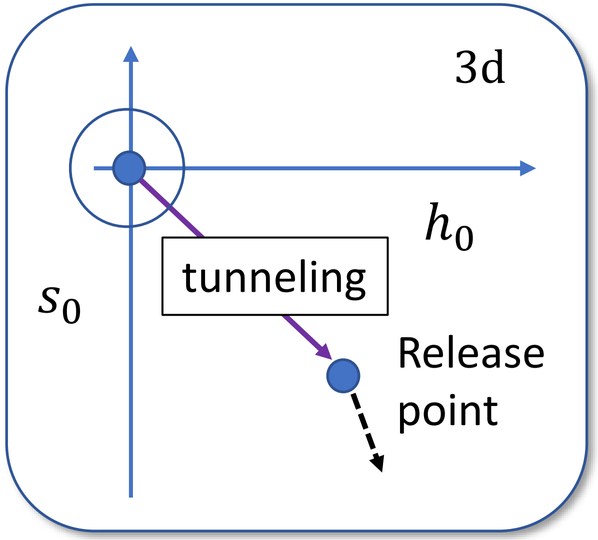


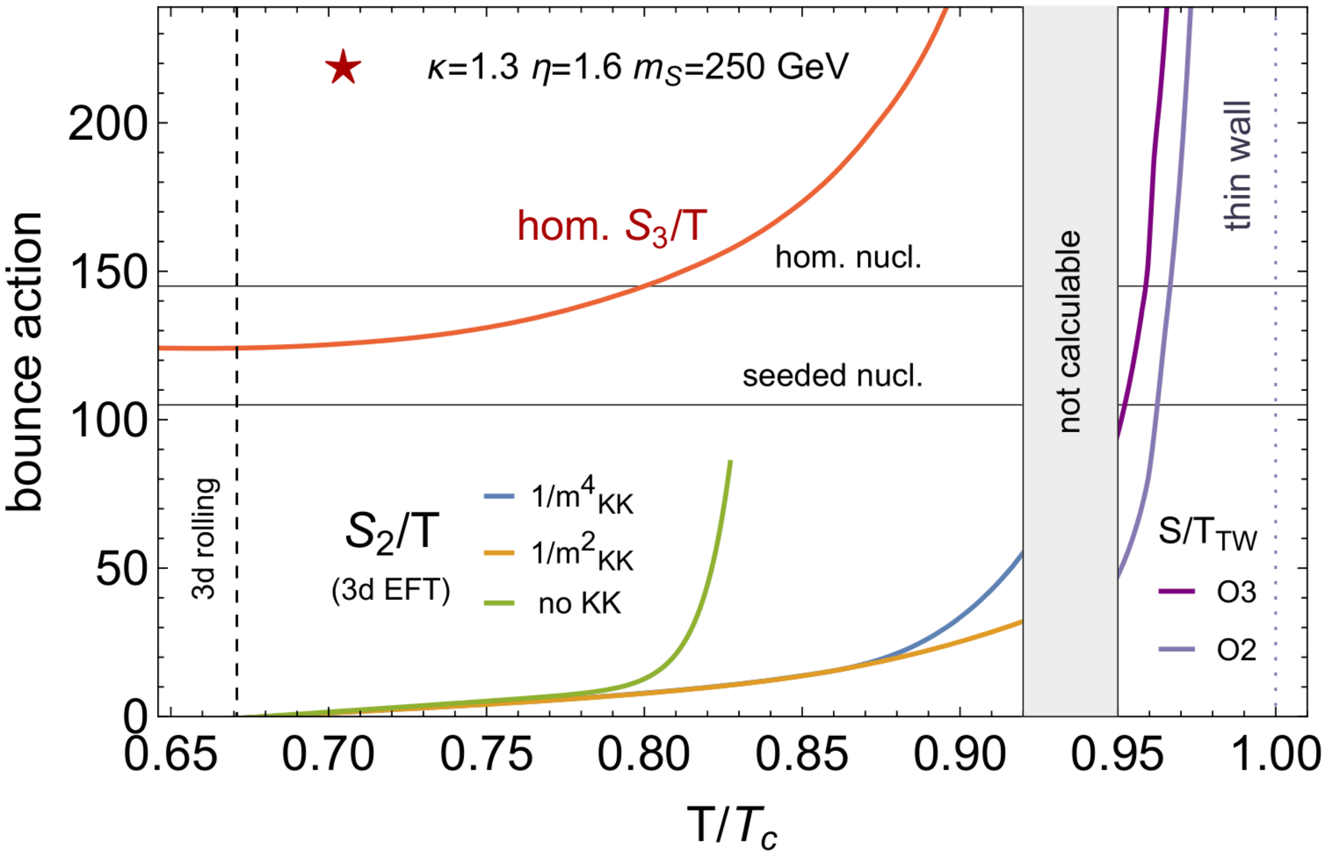
- Seeded phase transition reduced to homogeneous problem in 3d
- h_0 and s_0 taking a vev (and hence KK states) changes original DW profile
- Metastability of DW (= barrier at the origin) controlled by the **3d $\boldsymbol{h}$ mass, $\boldsymbol{\omega_0^2}$**:

$$\omega_0^2(T) = \frac{1}{2} p\, m^2 - \mu^2$$

1. $\omega_0^2 < 0$ for $T > T_c$: classical instability (origin is a saddle)
2. $\omega_0^2 > 0$ for $T < T_c$: seeded tunnelling (origin is a minimum)

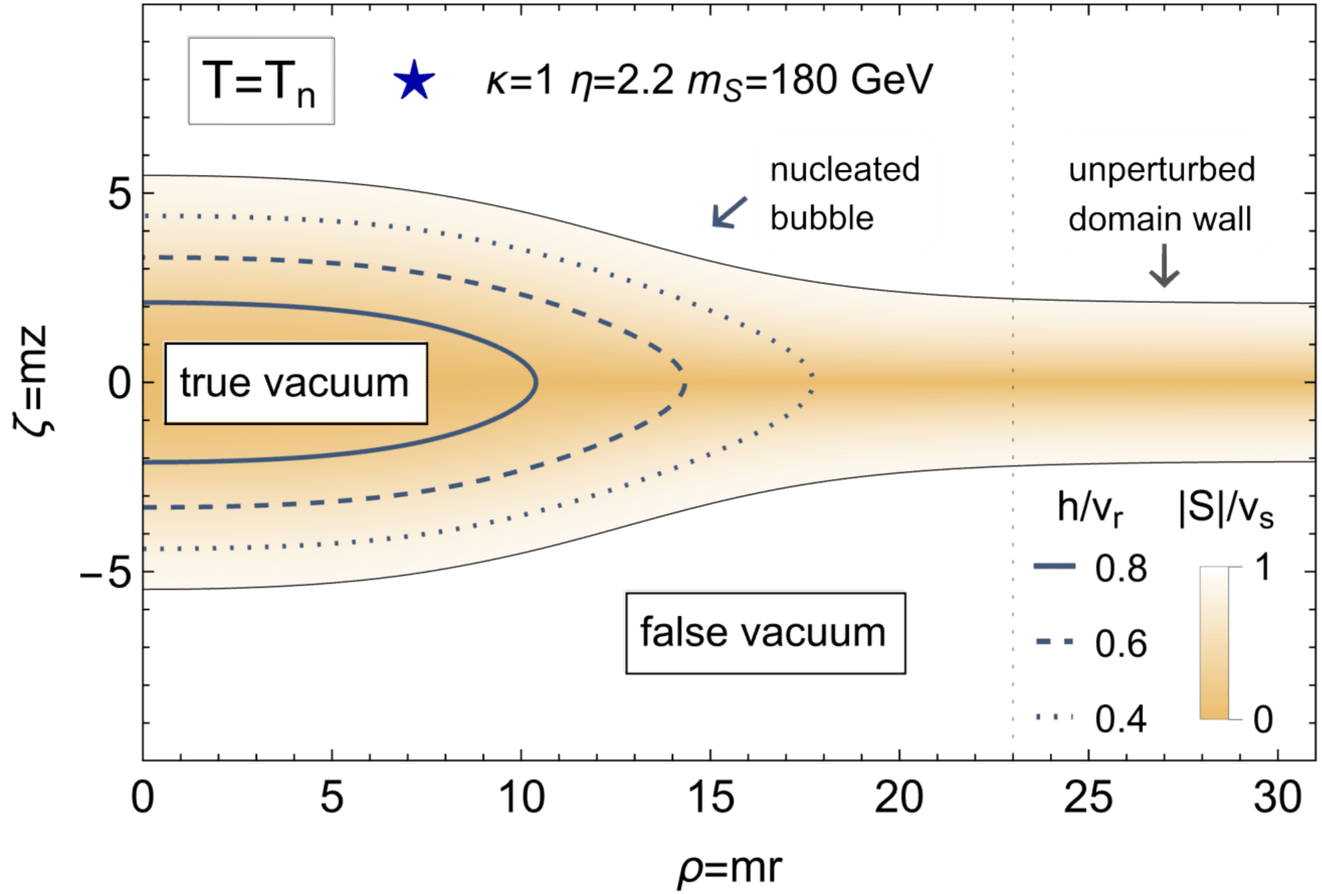
Seeded tunneling



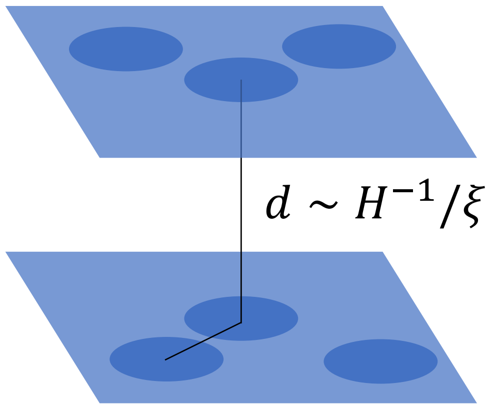


- Tunneling occurs before the would-be classical instability
- Seeded bounce action from CosmoTransition (adjusting for 3d)

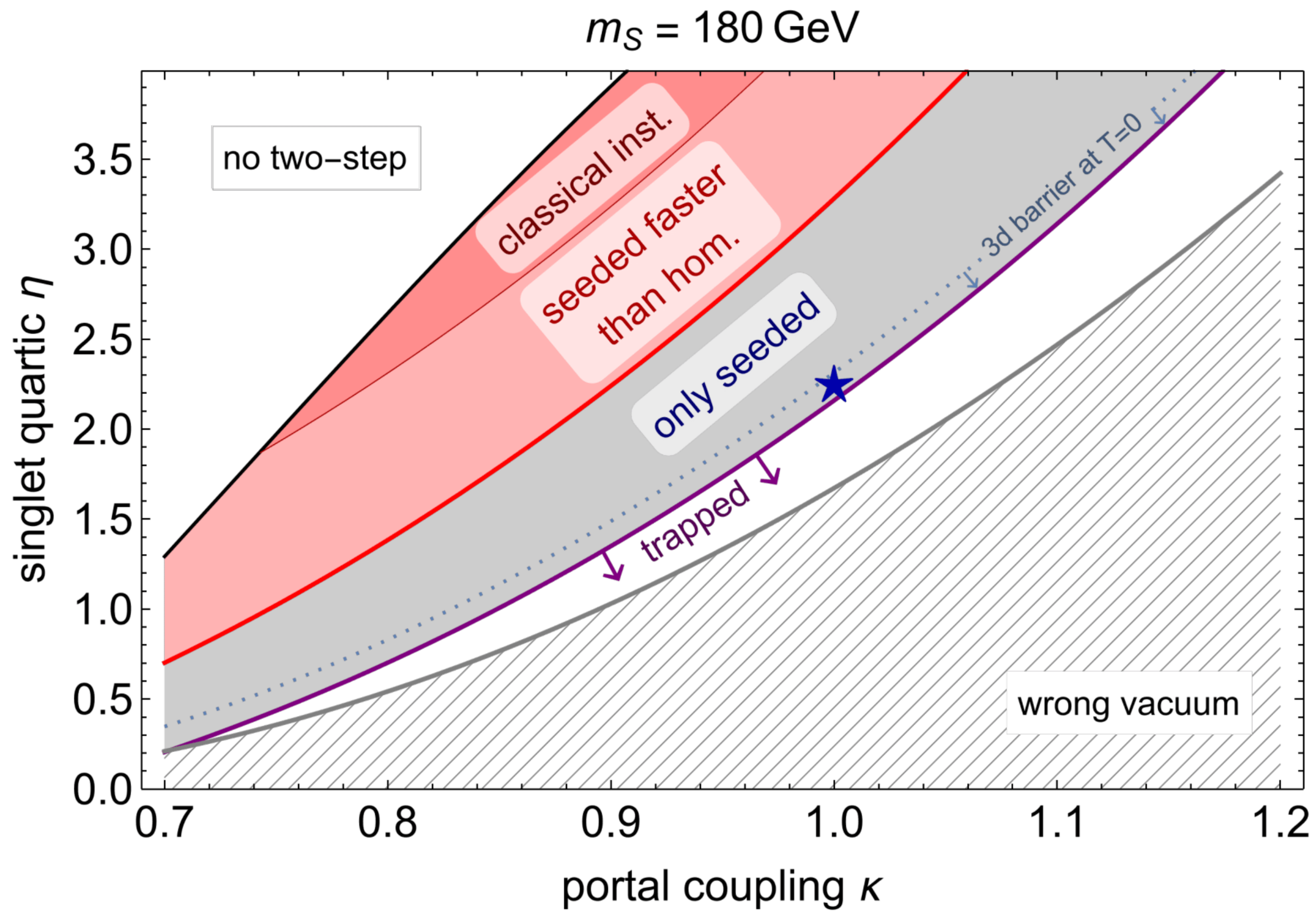
Shape of the bubbles



- Bubbles of true vacuum are nucleated inside the domain wall with only O(2) symmetry
- Nucleation rate on *same* DW is fast, but collisions among bubbles from *different* walls set by separation

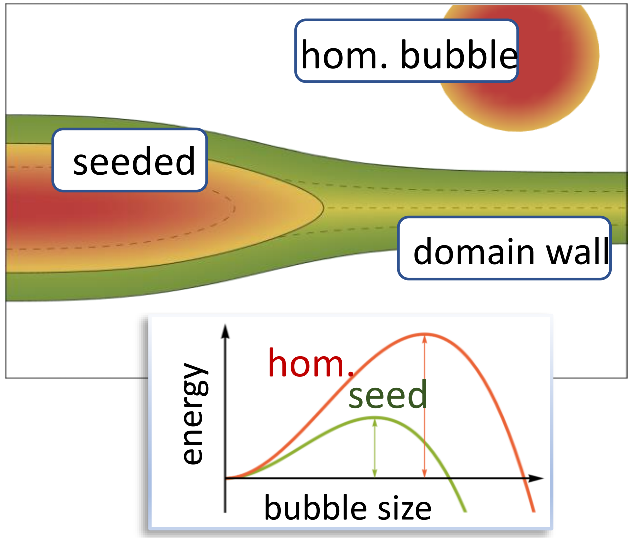


Results for the xSM parameter space



- Depending on m_S there can be a region of classical instability
- The seeded phase transition supersedes the homogeneous transition in all the (2-step) parameter space
- Domain walls make viable regions of parameter space where standard bubbles fail to nucleate

Conclusion

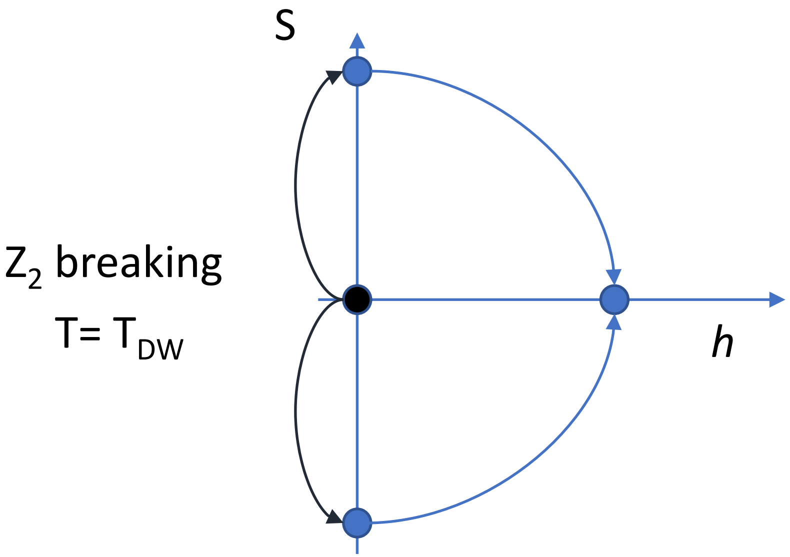


- Formation of defects during multi-step phase transition can dramatically affect the dynamics of the subsequent steps by providing new vacuum decay channels.
- In the xSM with *exact* Z_2 symmetry, the homogeneous transition does actually not occur, as the seeded phase transition is always faster.
- The phenomenology of the seeded transition yet to be explored, e.g. in terms of gravitational waves and baryogenesis + new available parameter space.
- Applications to other scalar sectors, e.g. two Higgs doublet models, and other defects such as cosmic strings.
- Further study on lower dimensional PT, e.g. can it be supercooled?

Thank you!

Backup

Domain walls in the standard two-step scenario

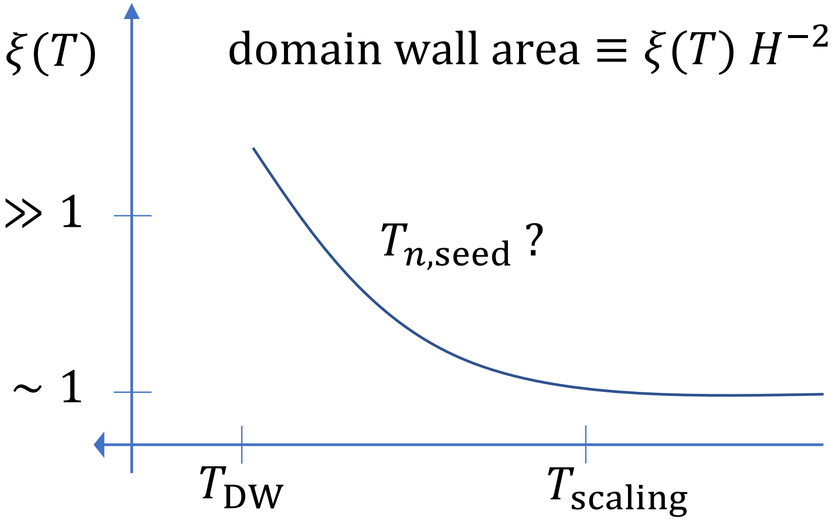


- Domain wall motion controlled by

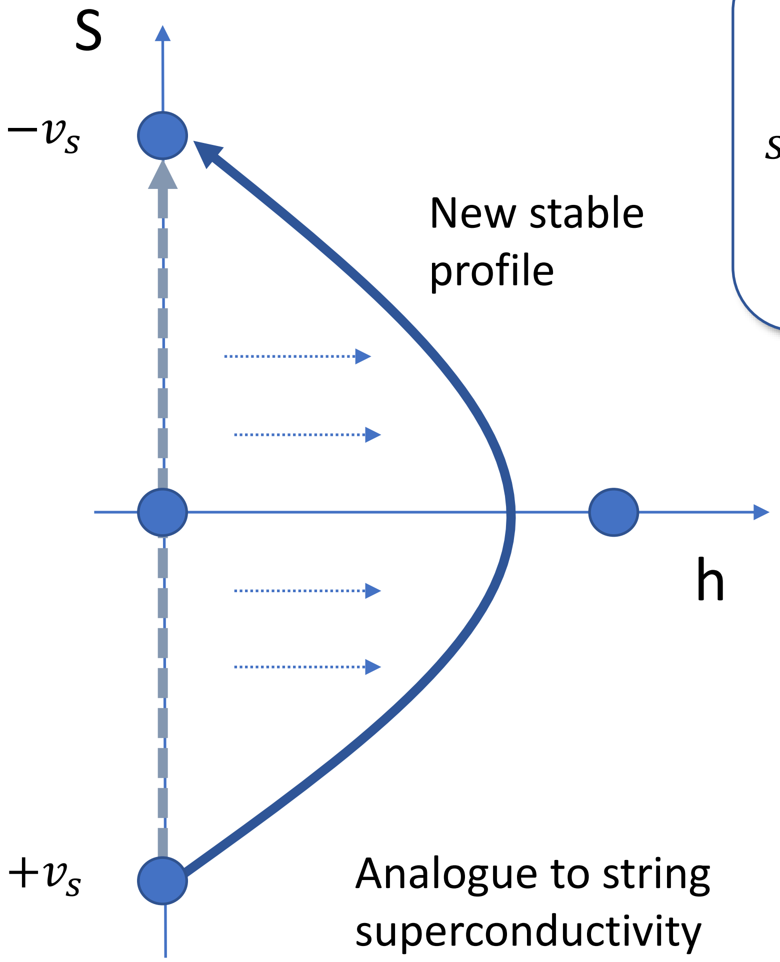
Domain wall tension	Wall collisions
Universe expansion	Particle production
Pressure from bias	Particle friction

Z_2 explicit breaking terms

- Deeper minimum expands against the other
- Impact on the domain wall life time
- Planck suppr. operators in general allow for DWs around the EWPT

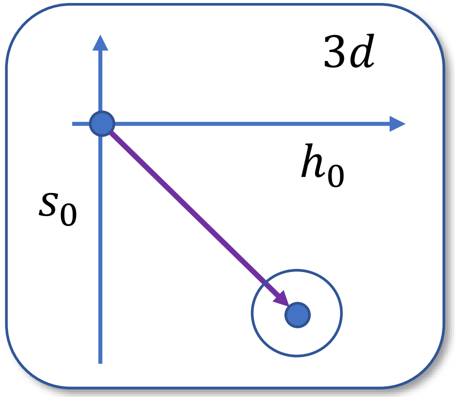


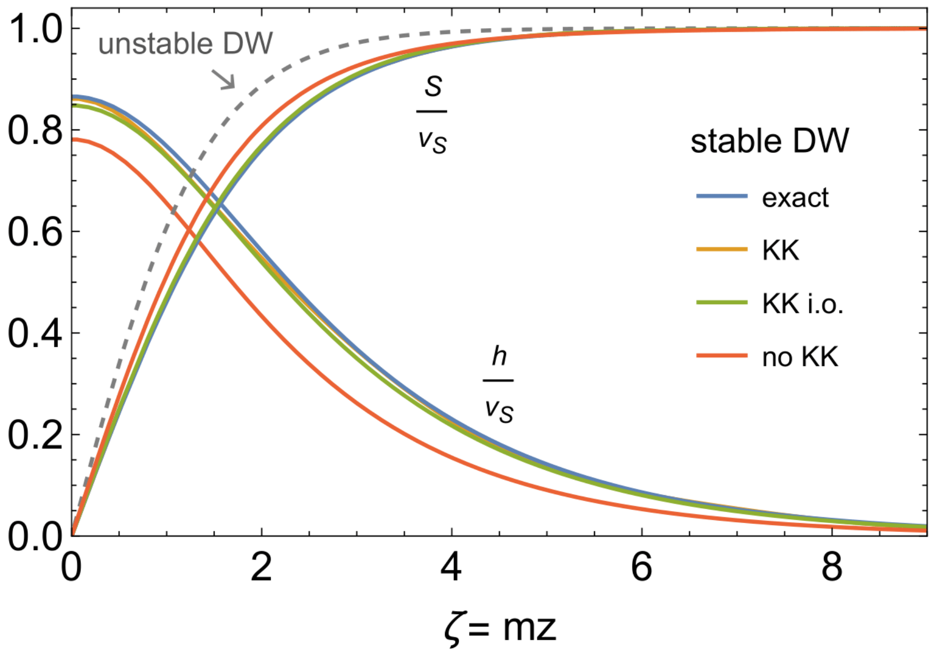
Classical instability: $\omega_0^2 < 0$ at $T > T_c$



Analogue to string superconductivity

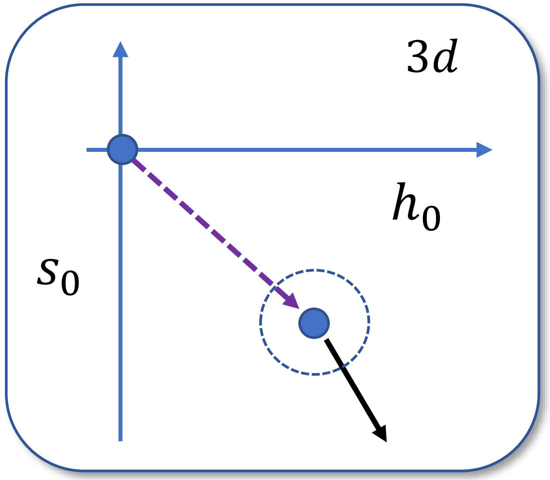
Witten 1985, NPB





- New stable profile for $h(z), S(z)$ obtained by minimizing 3d potential above T_c

… followed by dissociation at $T \approx T_c$



- For $T < T_c$ the minimum turns into a saddle and domain walls dissociate
- Effectively resembles weakly first order PT