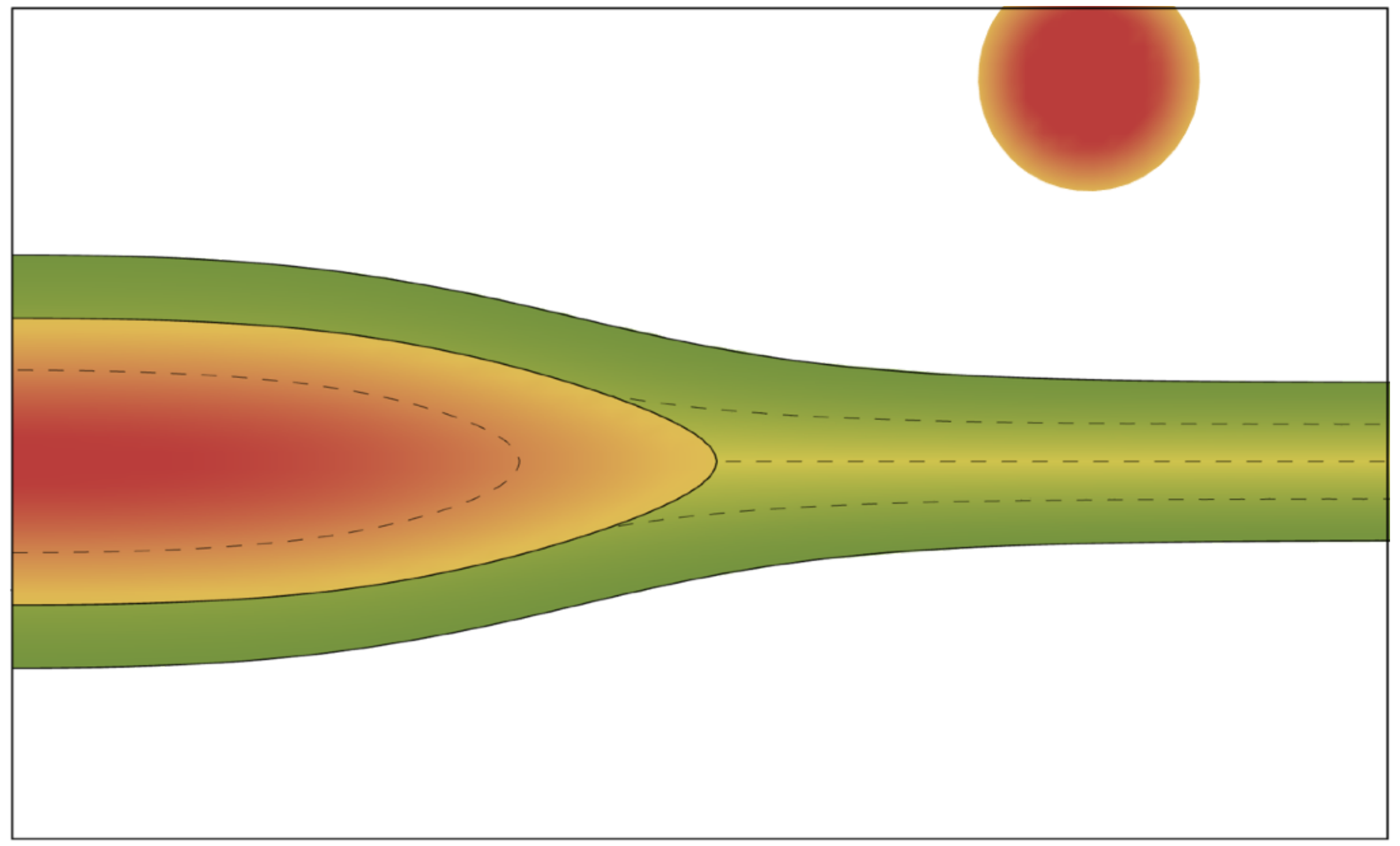


A seeded electroweak phase transition

Simone Blasi
DESY Hamburg

SB, Mariotti [2203.16450] PRL

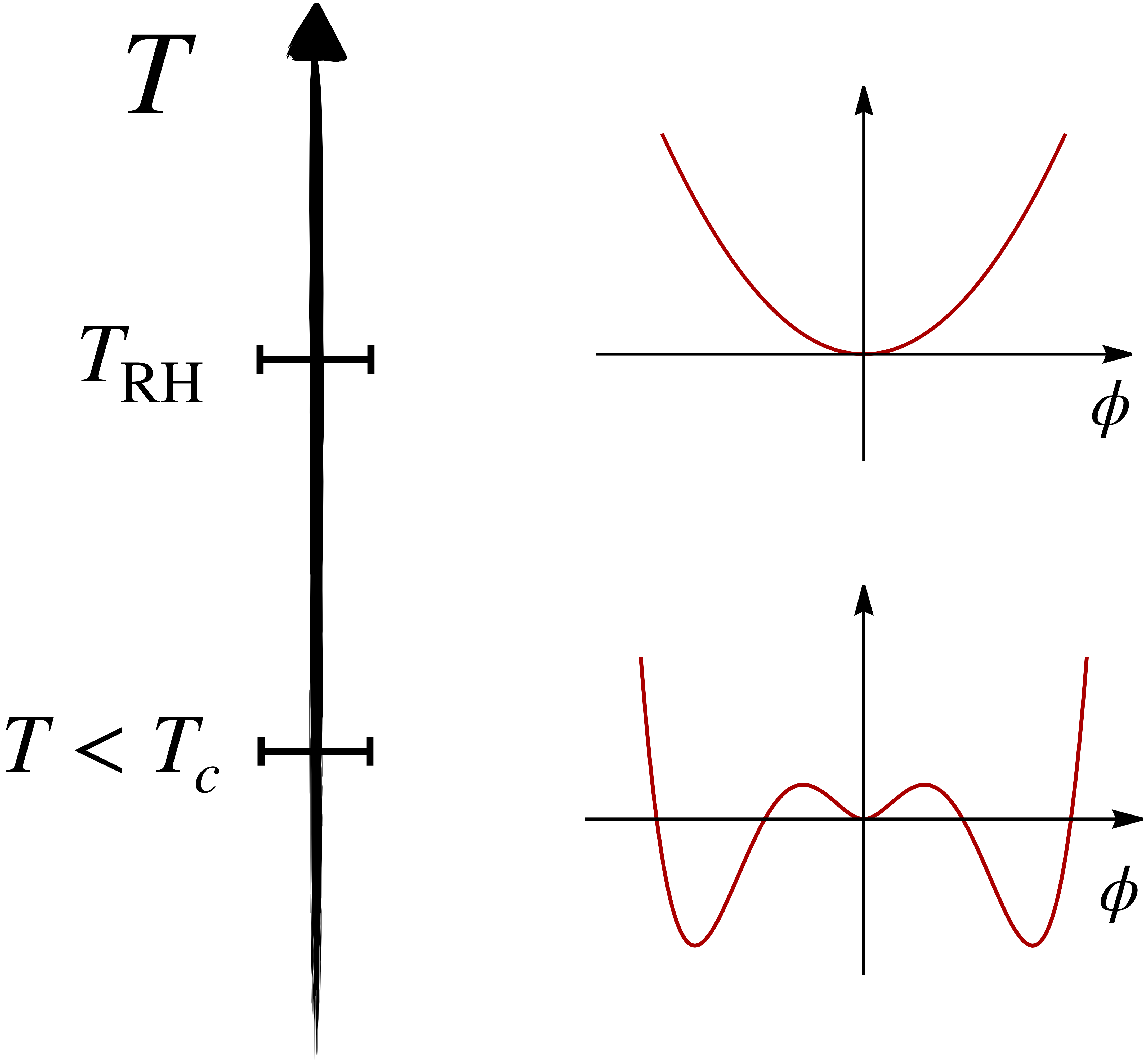
SB, Jinno, Konstandin, Rubira, Stomberg [2302.06952] JCAP

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

SB, Mariotti [2405.08060] SciPost

Asymptotic Safety meets Particle Physics & Friends - 18.12.2024

Introduction



Symmetries are **restored** at high temperatures/early times

Spontaneous breaking while the Universe expands and cools down

Introduction

$\Rightarrow$ Cosmological phase transitions

Key to address open questions: **baryogenesis**

Aftermath directly observable in **GWs**

Evidence for **new** fundamental **physics**

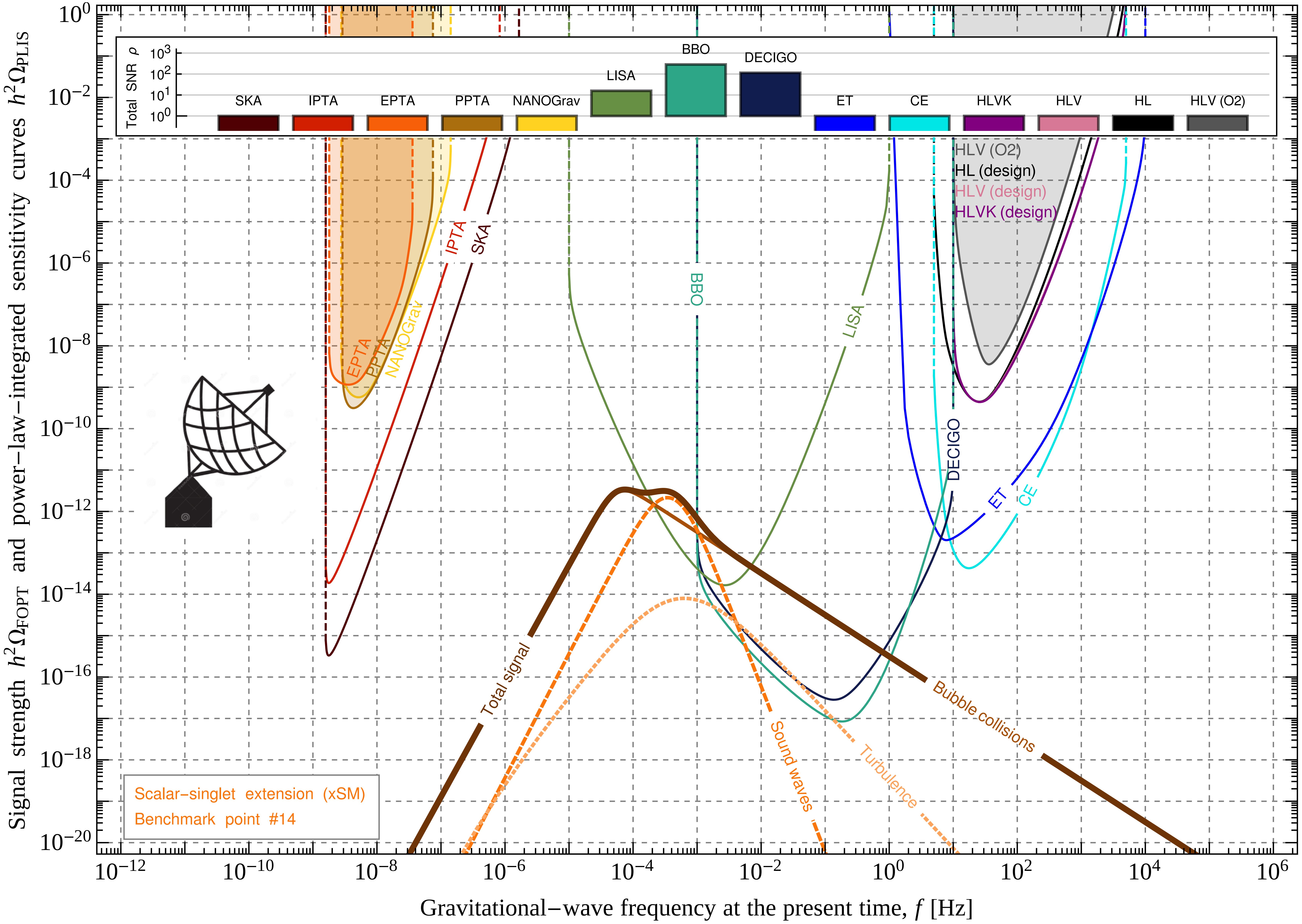


Fig. from Schmitz [2002.04615] JHEP

Nucleation theory

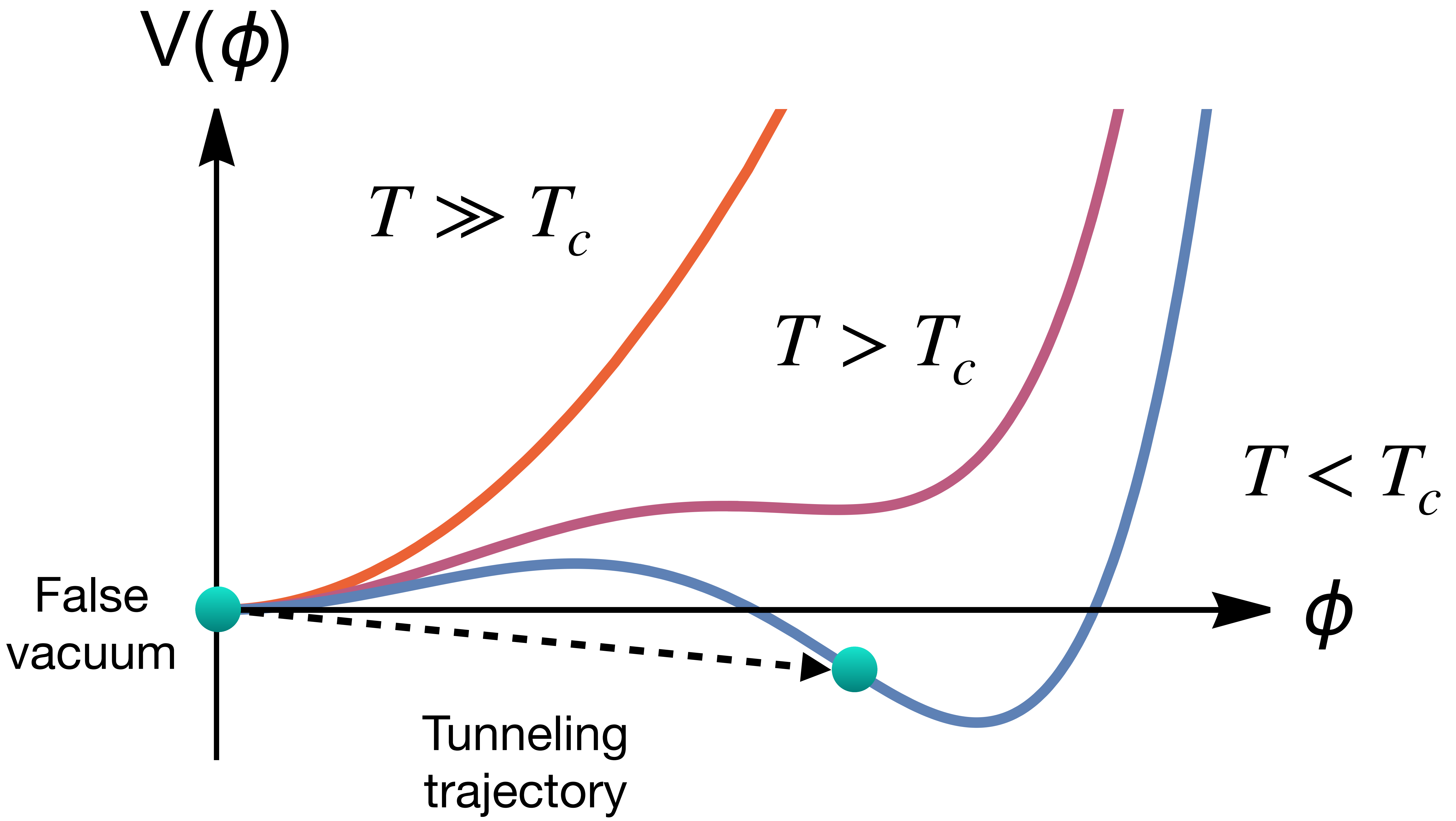
Coleman 1977 (PRD)
Callan, Coleman 1977 (PRD)
Linde 1983 (NPB)

- 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

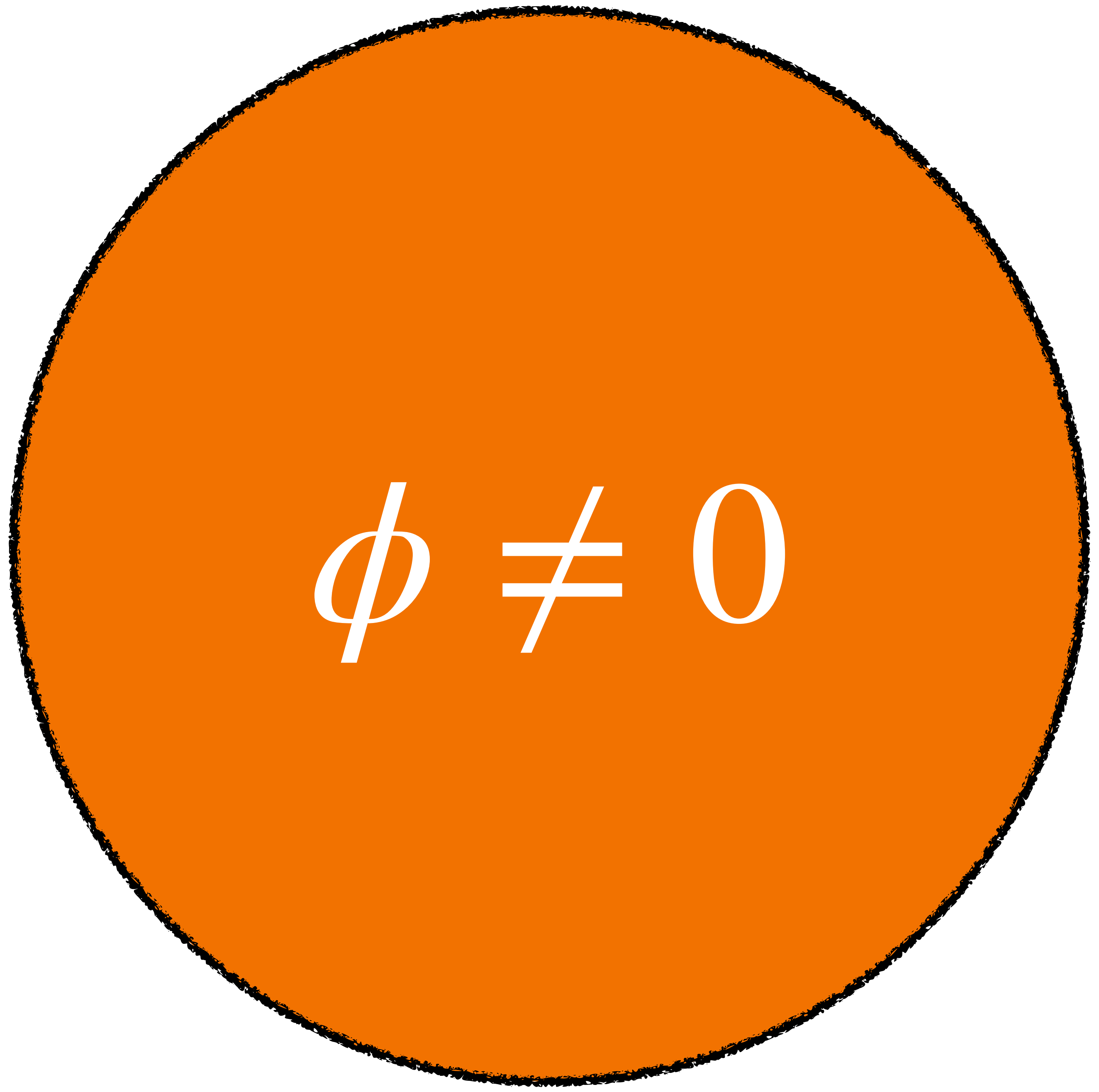
$$\gamma_V \sim T^4 \exp(-S_3/T)$$



Nucleation theory

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

$$\phi = 0$$



- False vacuum is homogeneous field configuration
- Critical bubble is a sphere
- Nucleation probability is the same everywhere

What about impurities?

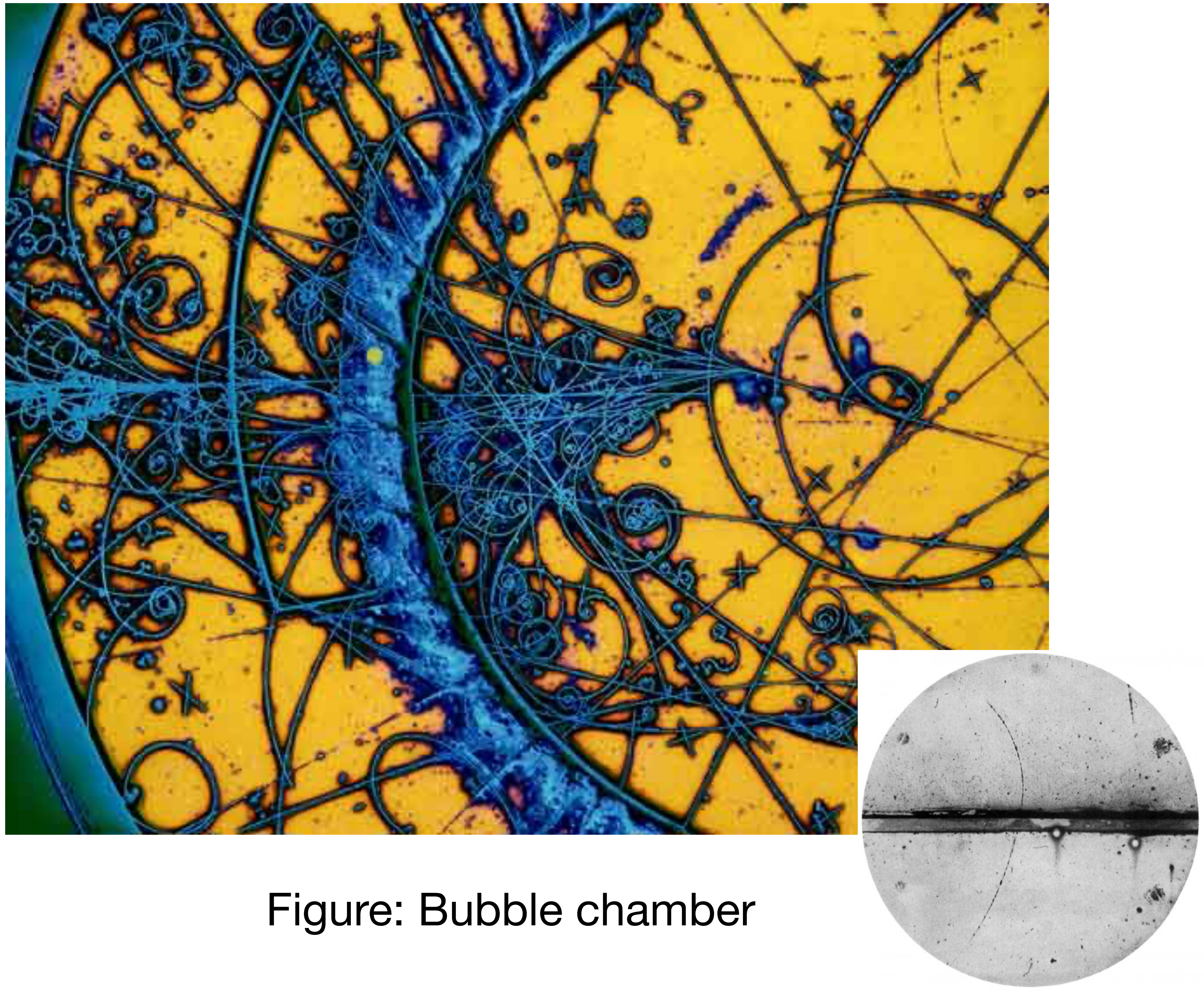


Figure: Bubble chamber

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 and gravitational effects

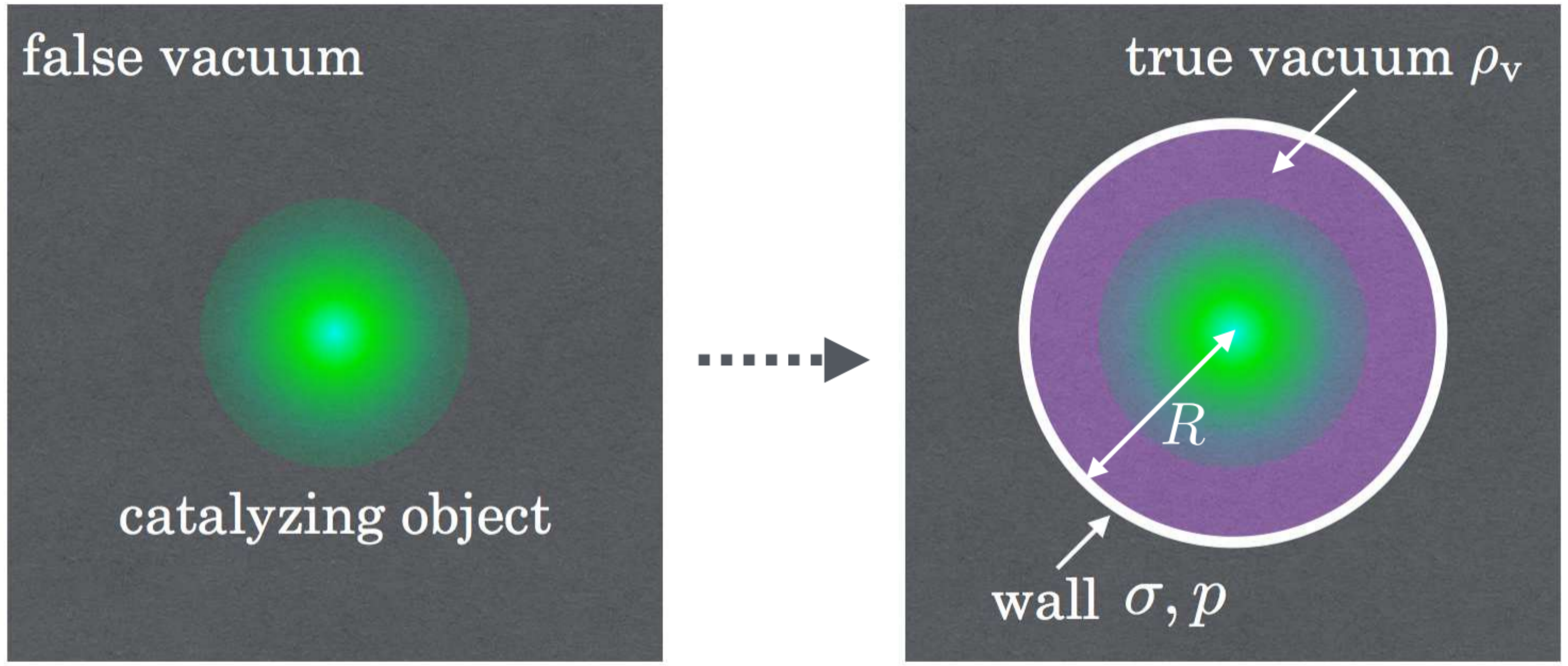


Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

- Primordial density fluctuations

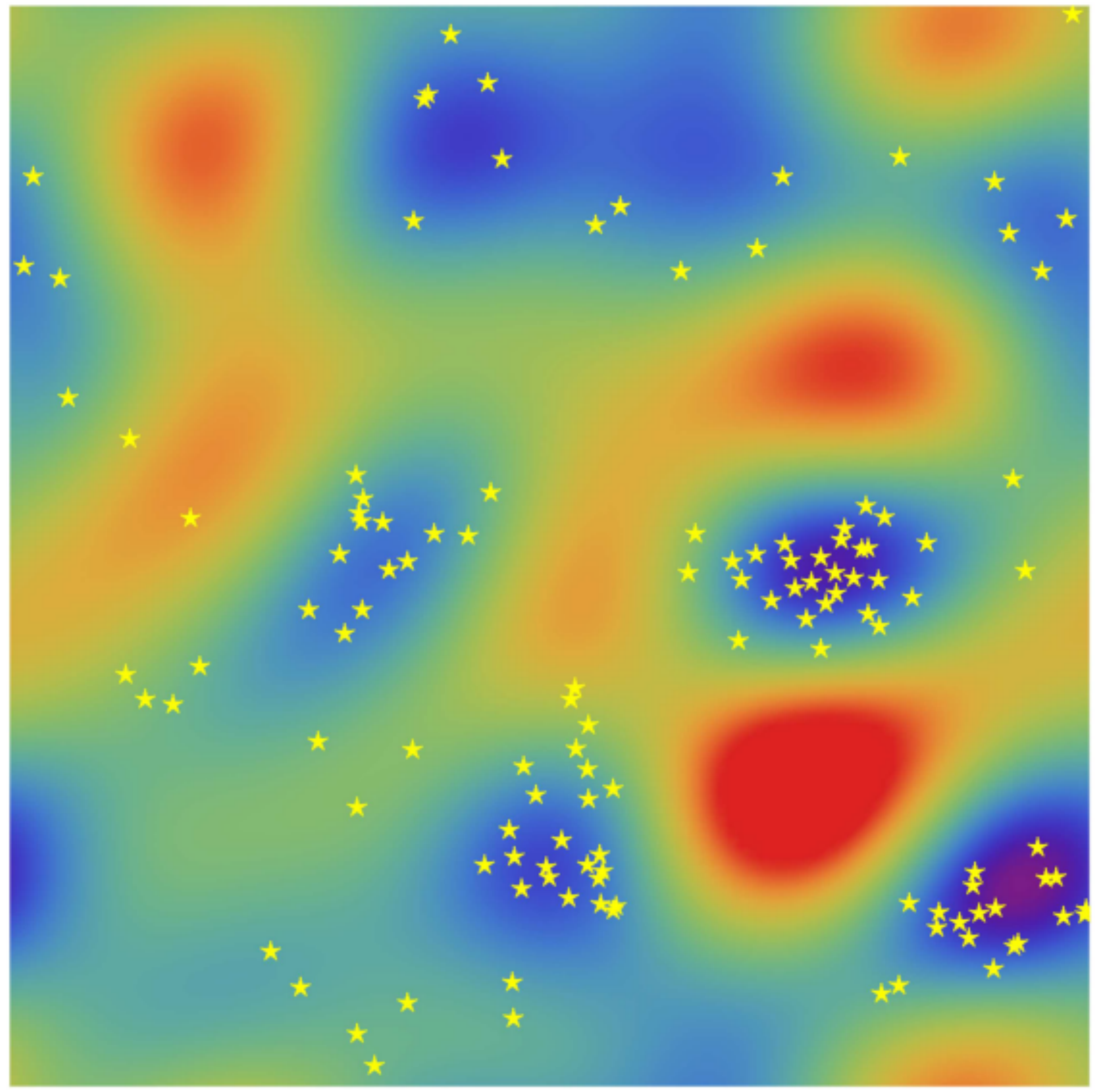


Fig. from Jinno, Konstandin, Rubira, van de Vis, [2108.11947], JCAP

The nature of impurities

- Topological defects

Strings

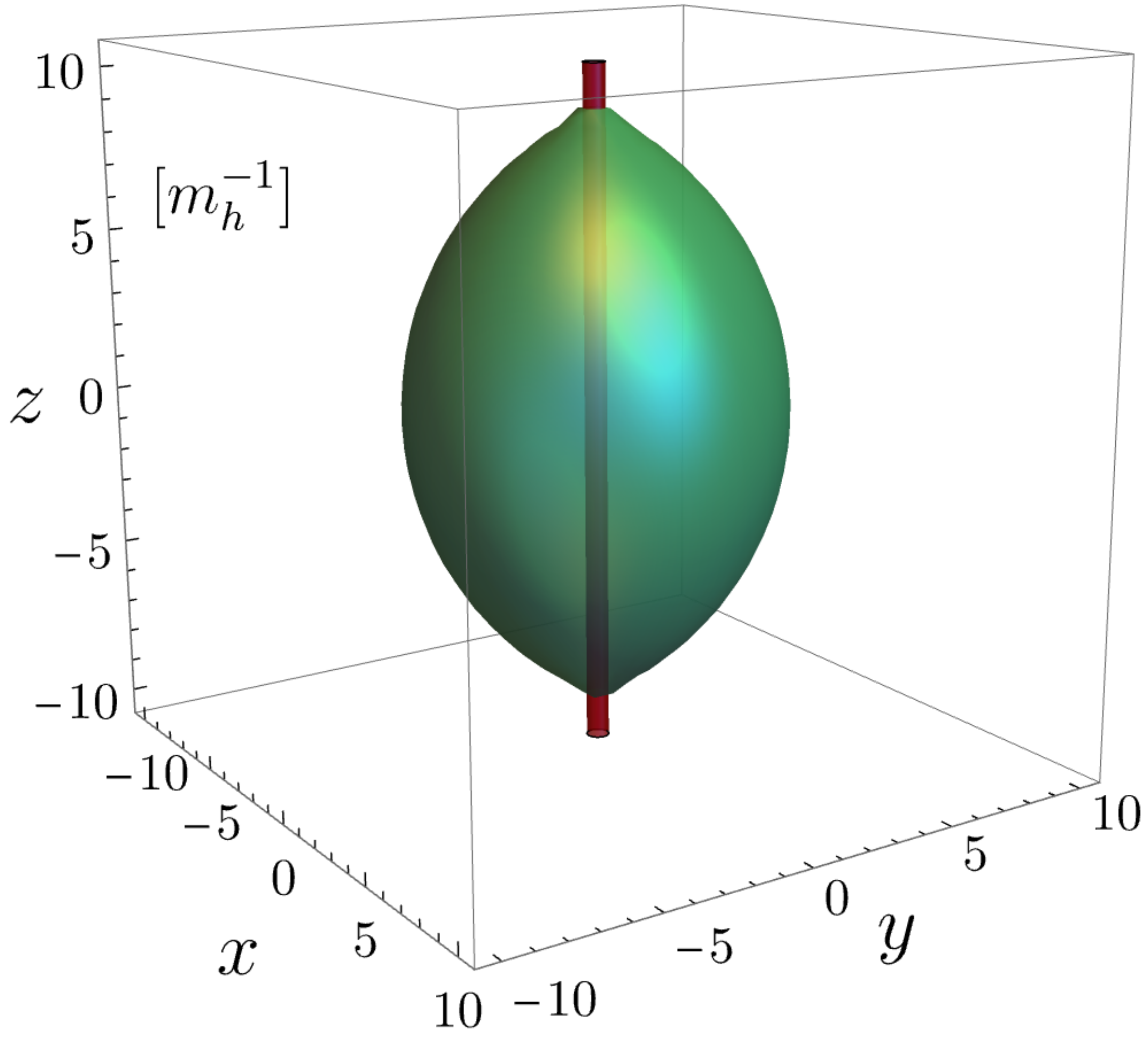


Fig. from **SB**, Mariotti, [2405.08060] SciPost

Domain walls

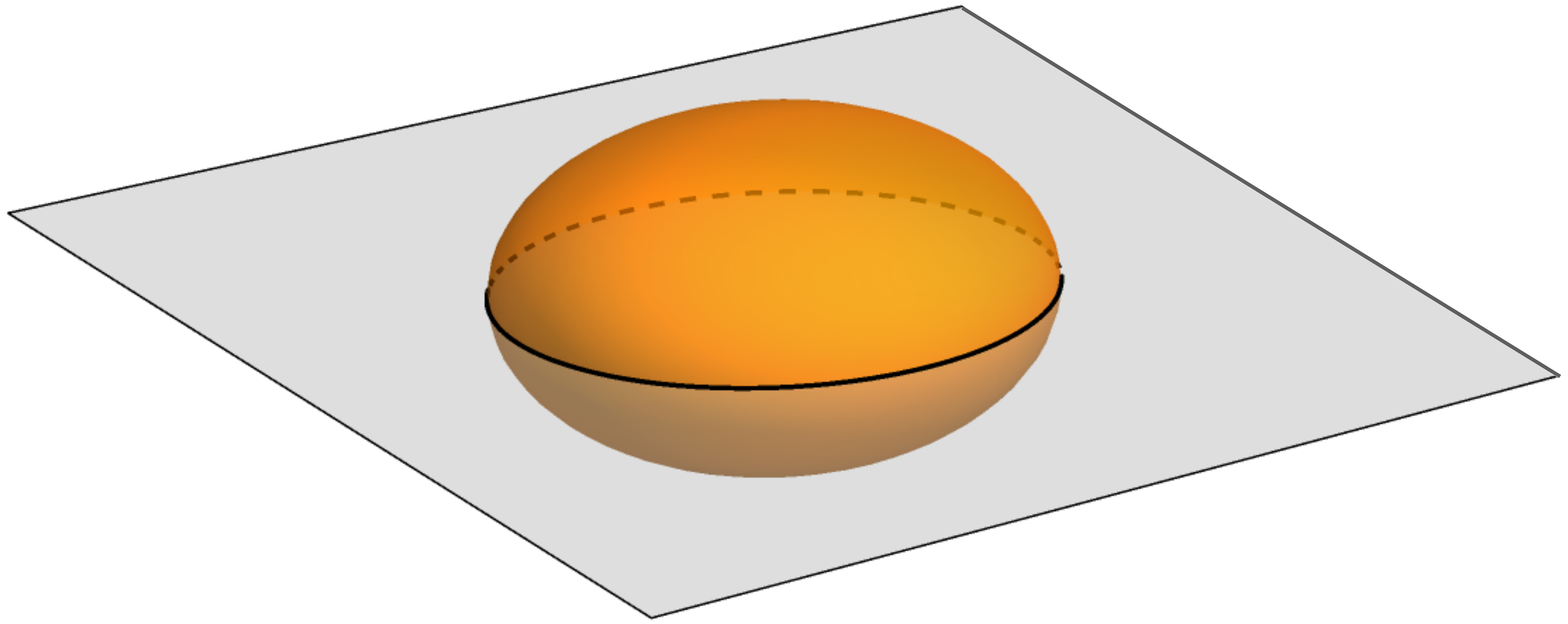
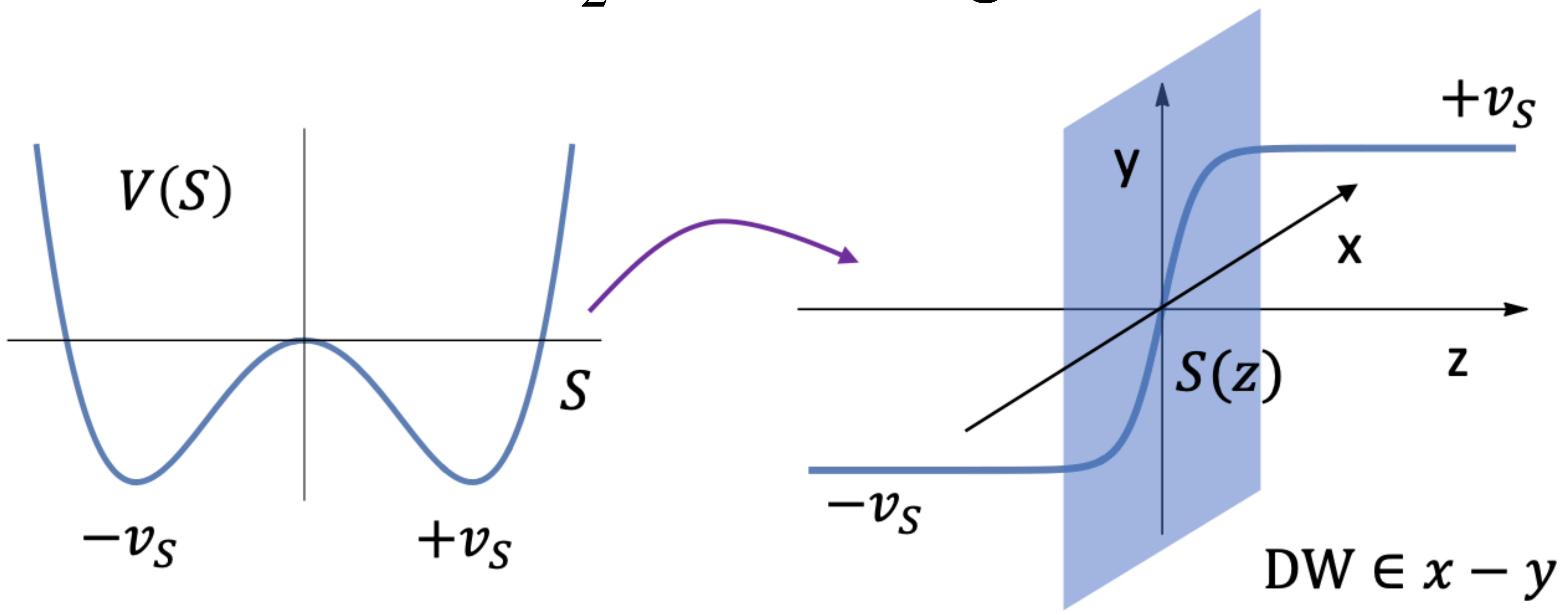


Fig. from Agrawal, **SB**, Mariotti, Nee [2312.06749] JHEP

Topological classification

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

$\mathbb{Z}_2 \rightarrow$ nothing



$\mathrm{U}(1) \rightarrow$ nothing

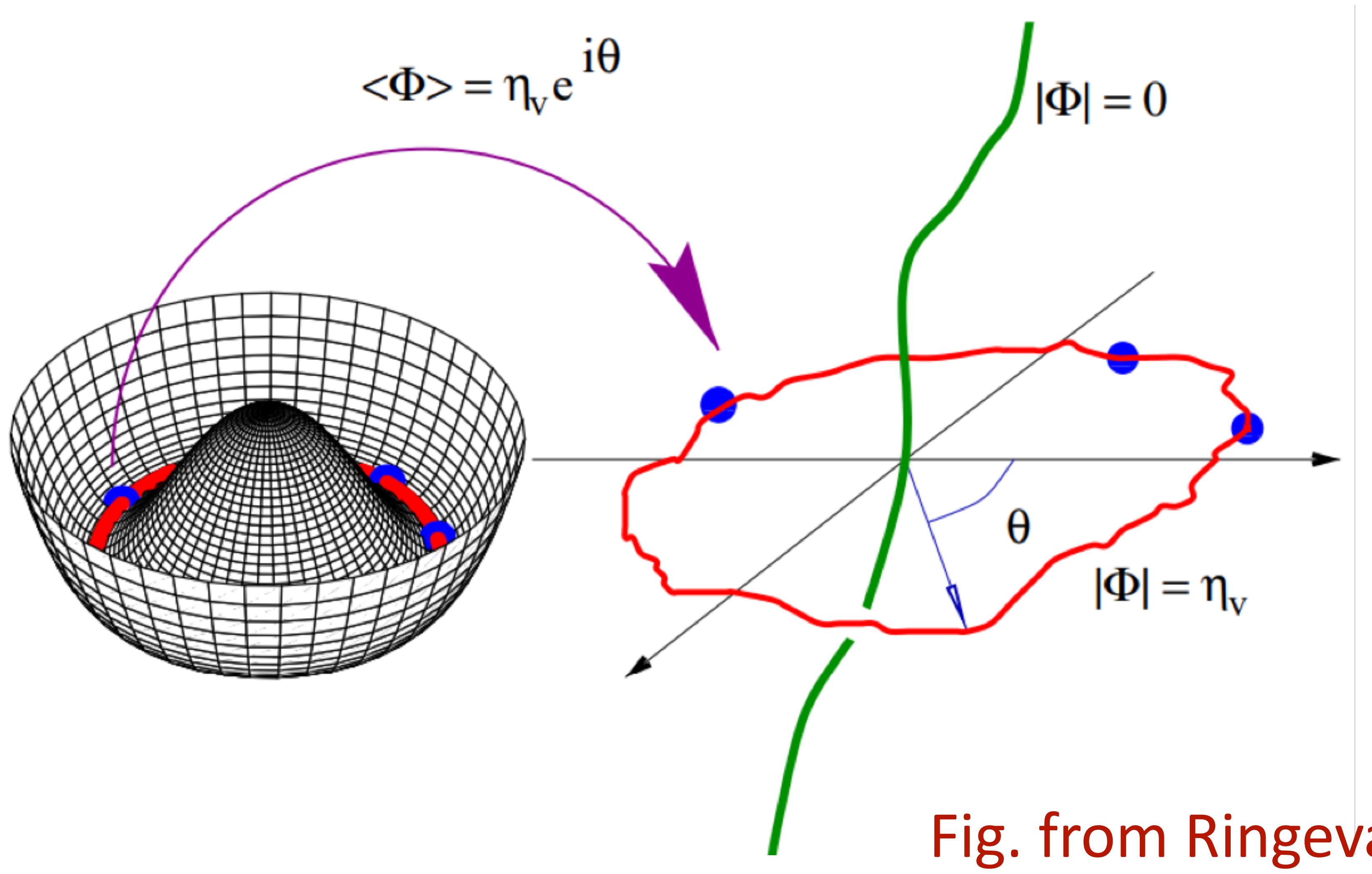


Fig. from Ringeval 2010

EWPT with a singlet

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

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

*$\mathbb{Z}_2$ breaking terms destabilize the wall network and are set to zero in the following

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

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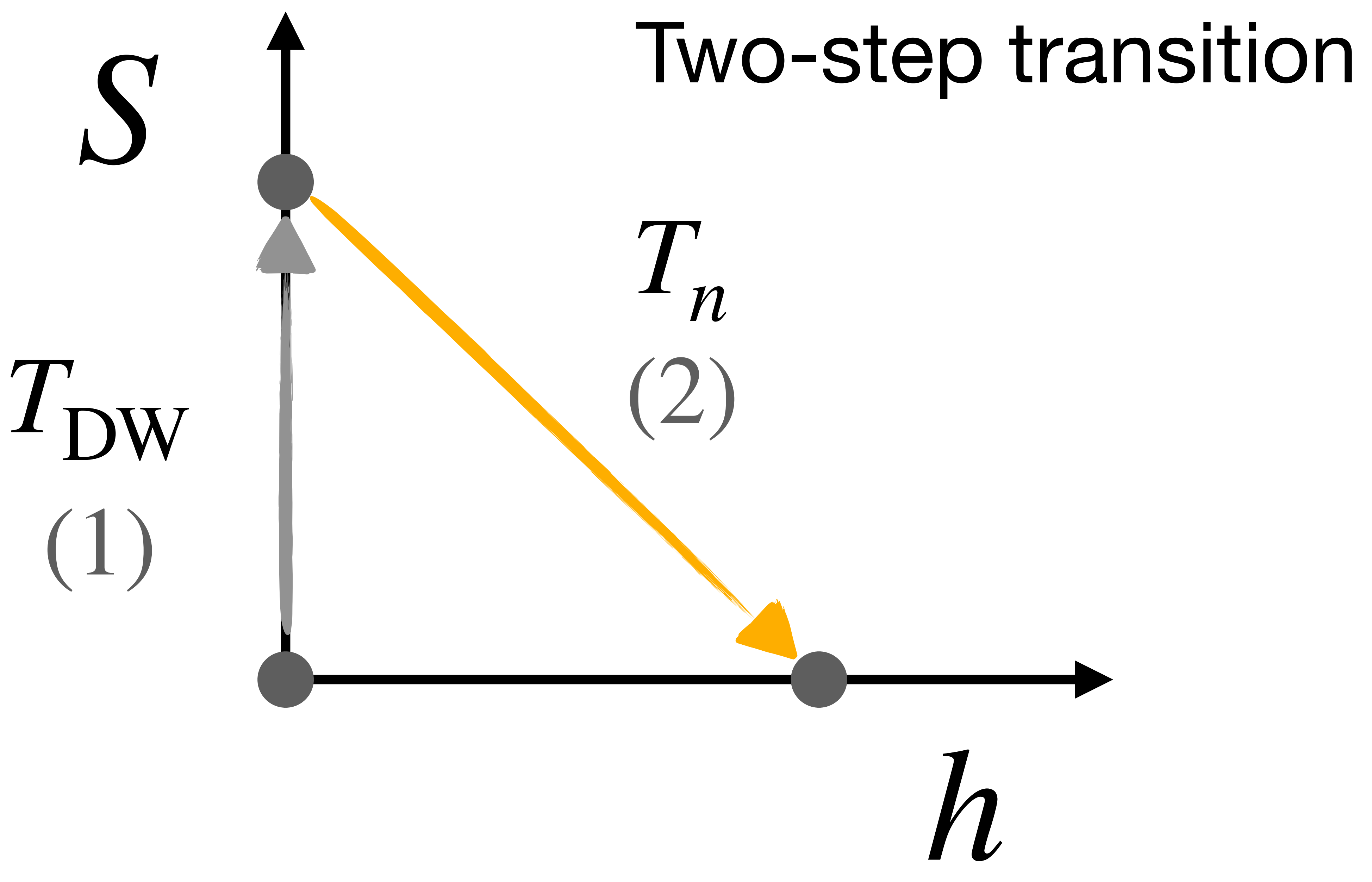

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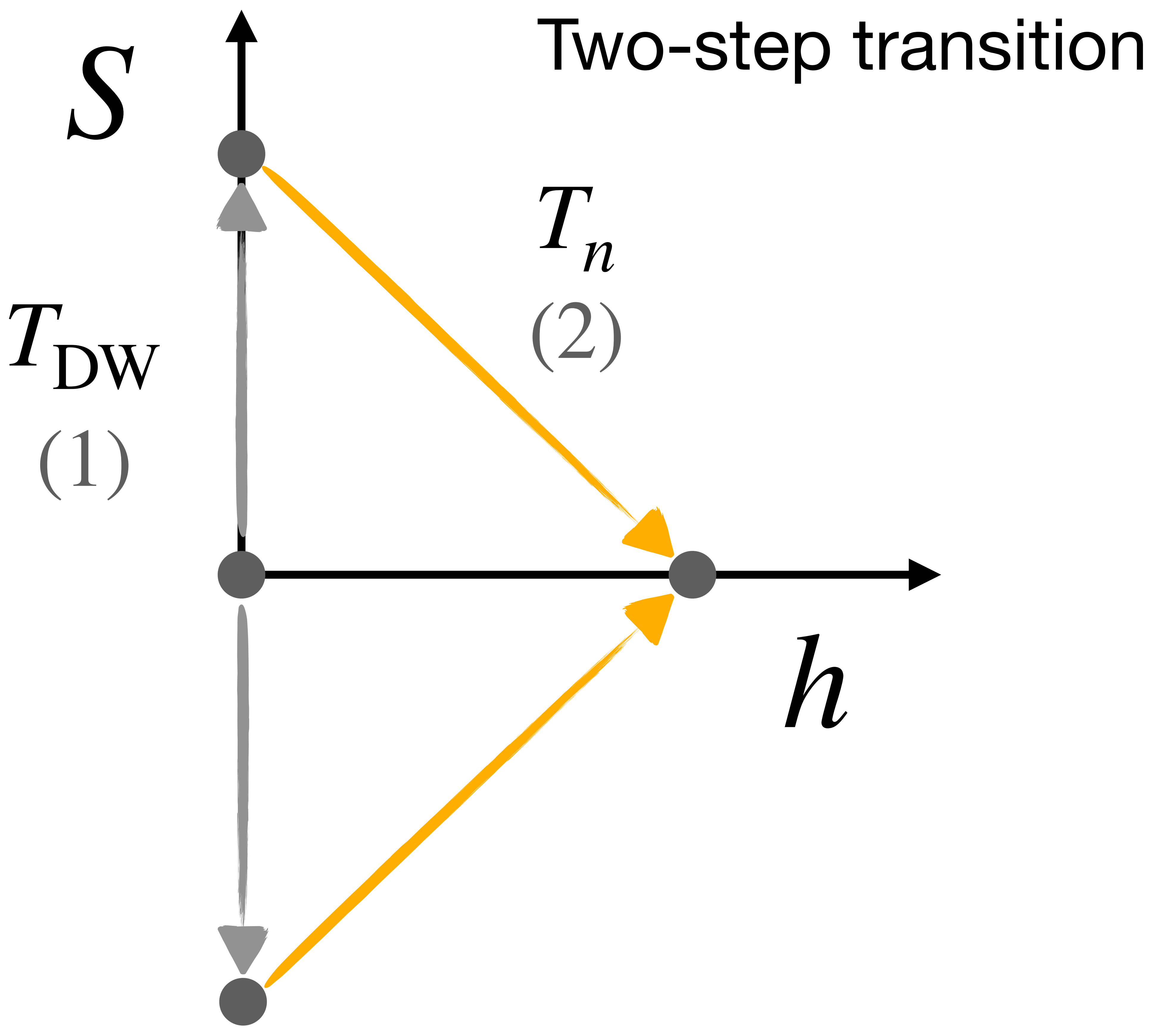

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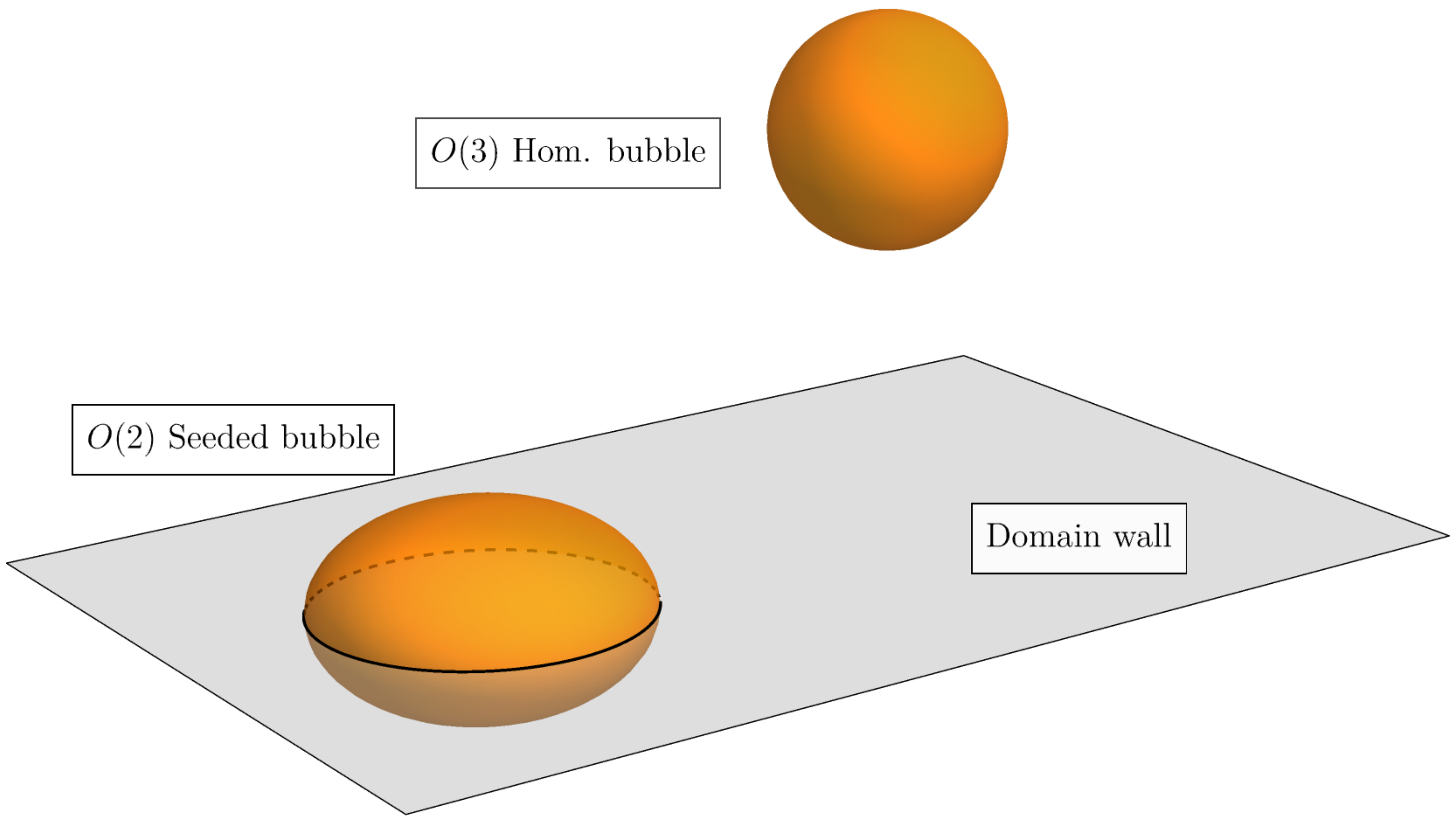
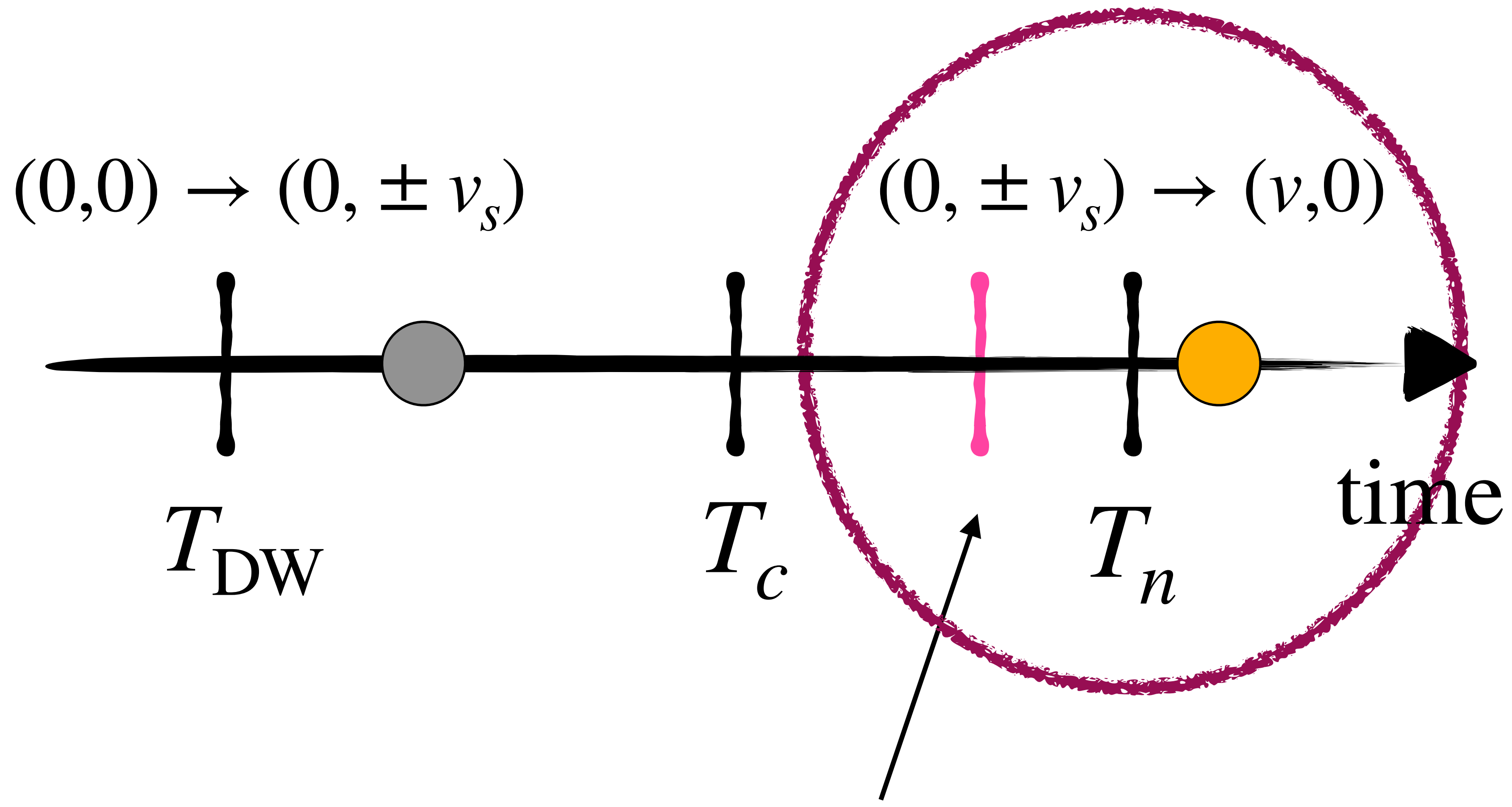
EWPT with a singlet

- Competition between homogenous and seeded nucleation for 2nd step

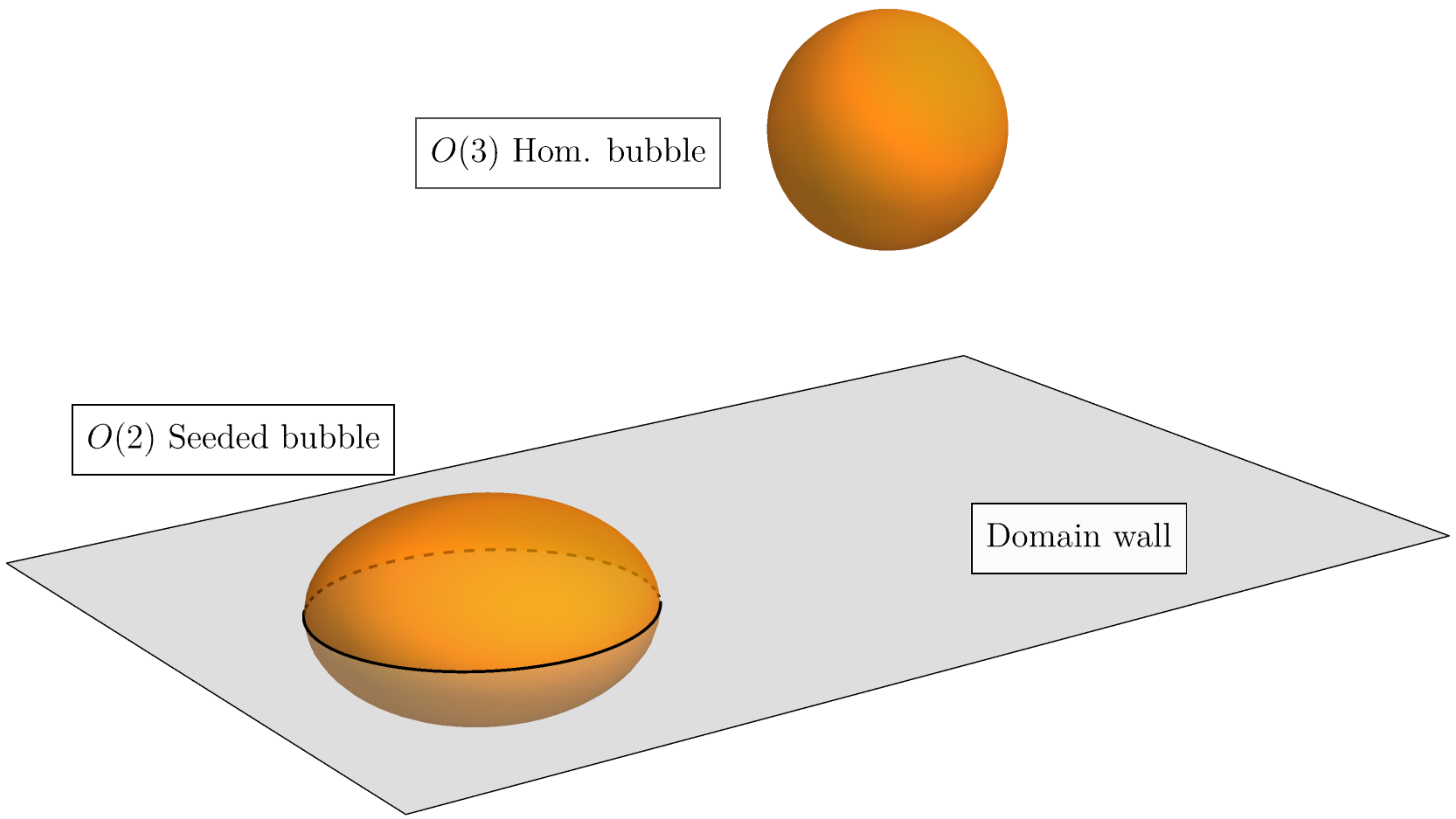


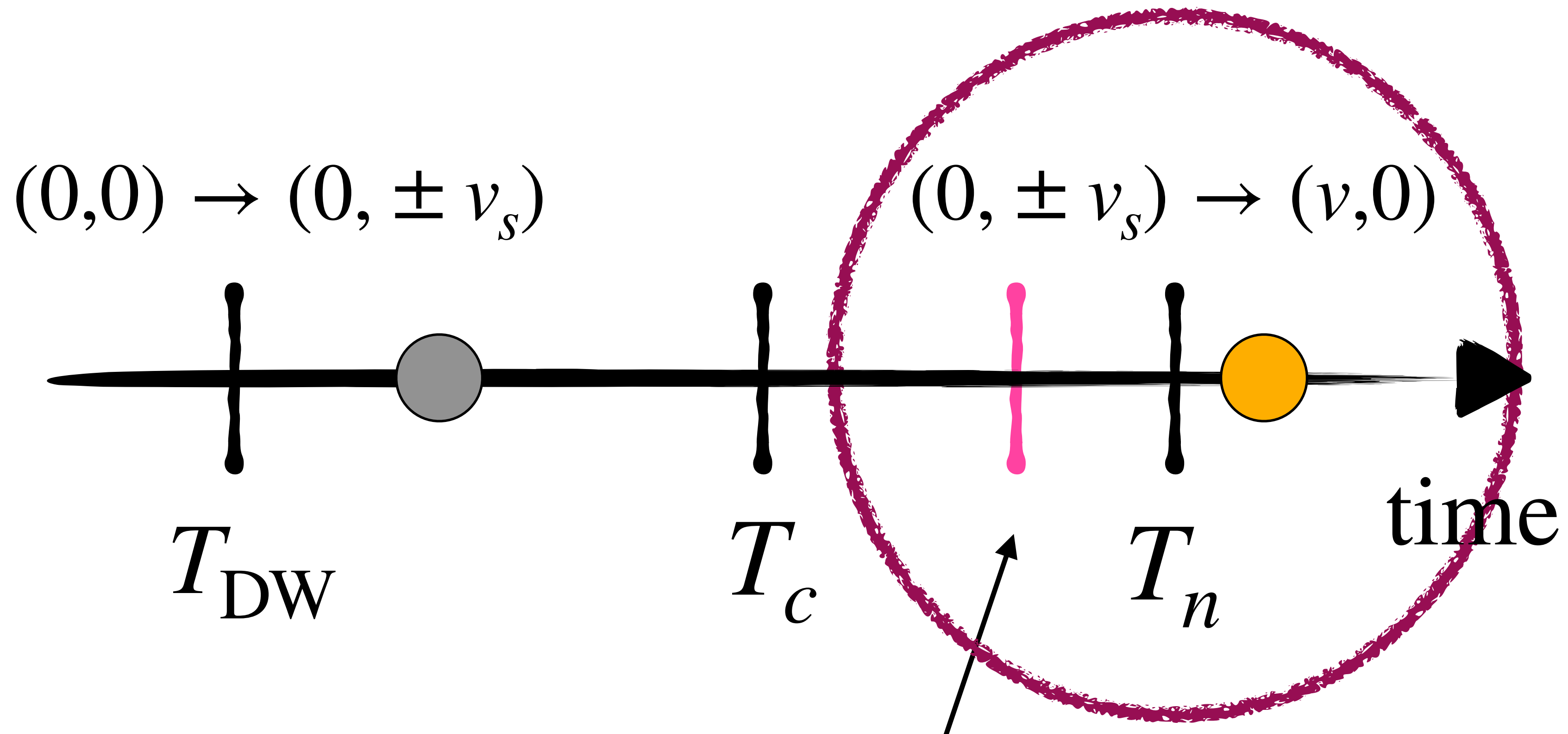


At T_n^{seed} bubbles may nucleate *on the walls*

EWPT with a singlet

- Competition between homogenous and seeded nucleation for 2nd step





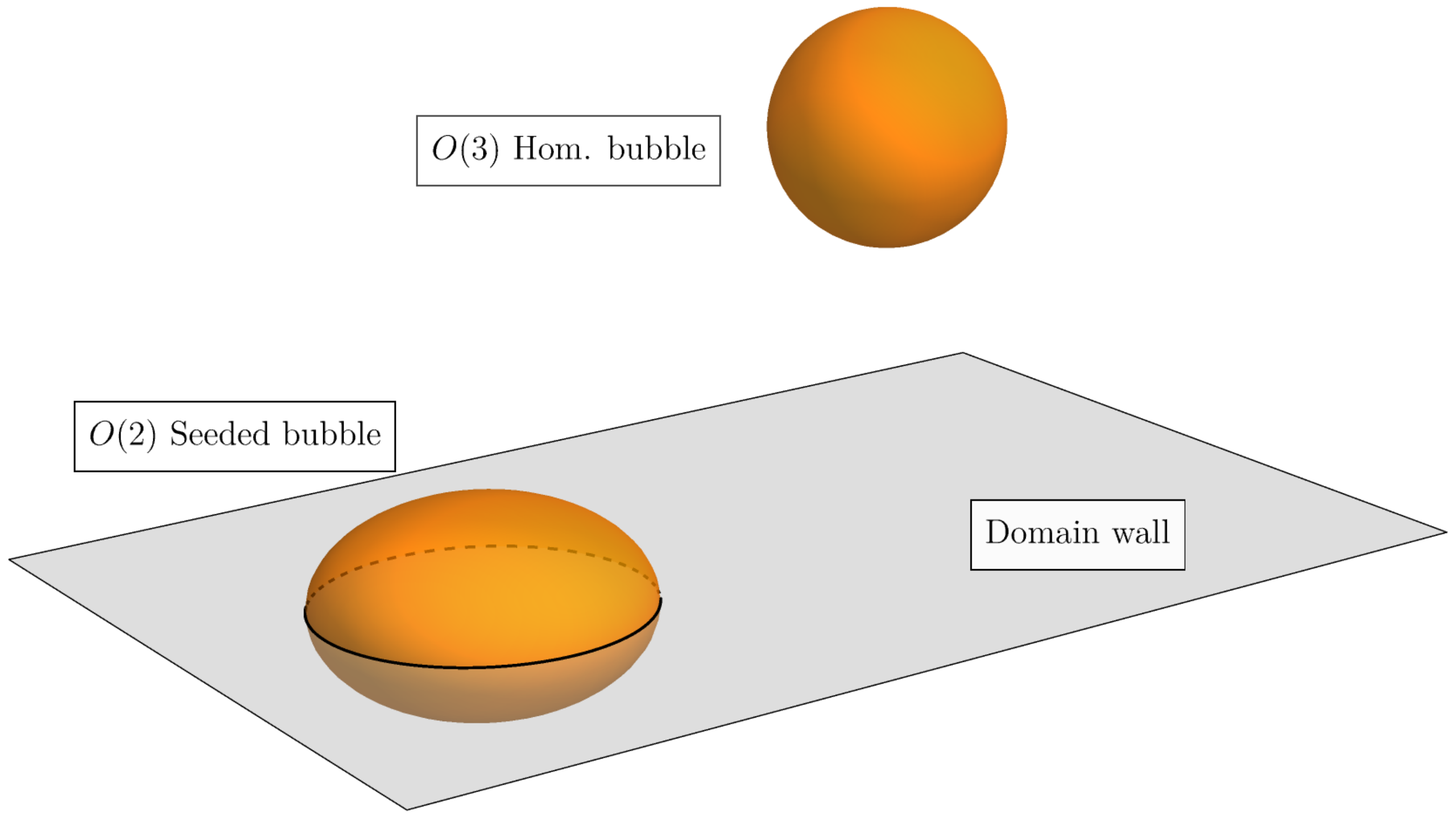
At T_n^{seed} bubbles may nucleate *on the walls*

- Define nucleation rate per unit surface
- Stricter nucleation condition (only on sub manifold)

Lazarides, Shafi, Kibble 1982, PRD
Perkins, Vilenkin 1992, PRD

EWPT with a singlet

Only O(2) symmetry



1. Solving coupled **system of PDEs**

- "Exact"
- Physical picture?
- Which initial conditions for the algorithm?

2. **Thin wall** approximation

- Limited validity
- Intuitive picture
- Simple calculation

3. **Kaluza-Klein** decomposition

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

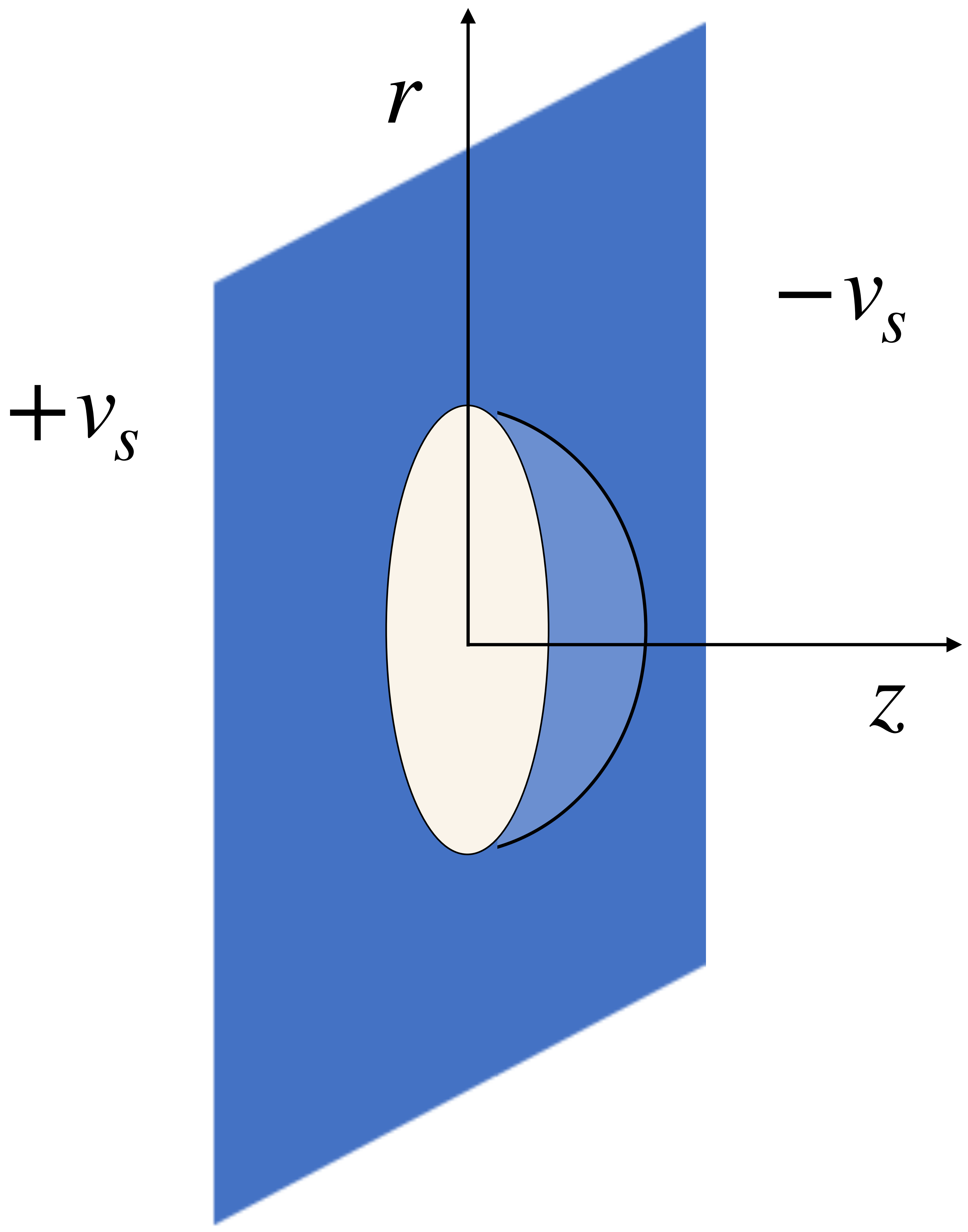
System of PDEs

False vacuum is non-trivial as it contains a domain wall (which depends on z)

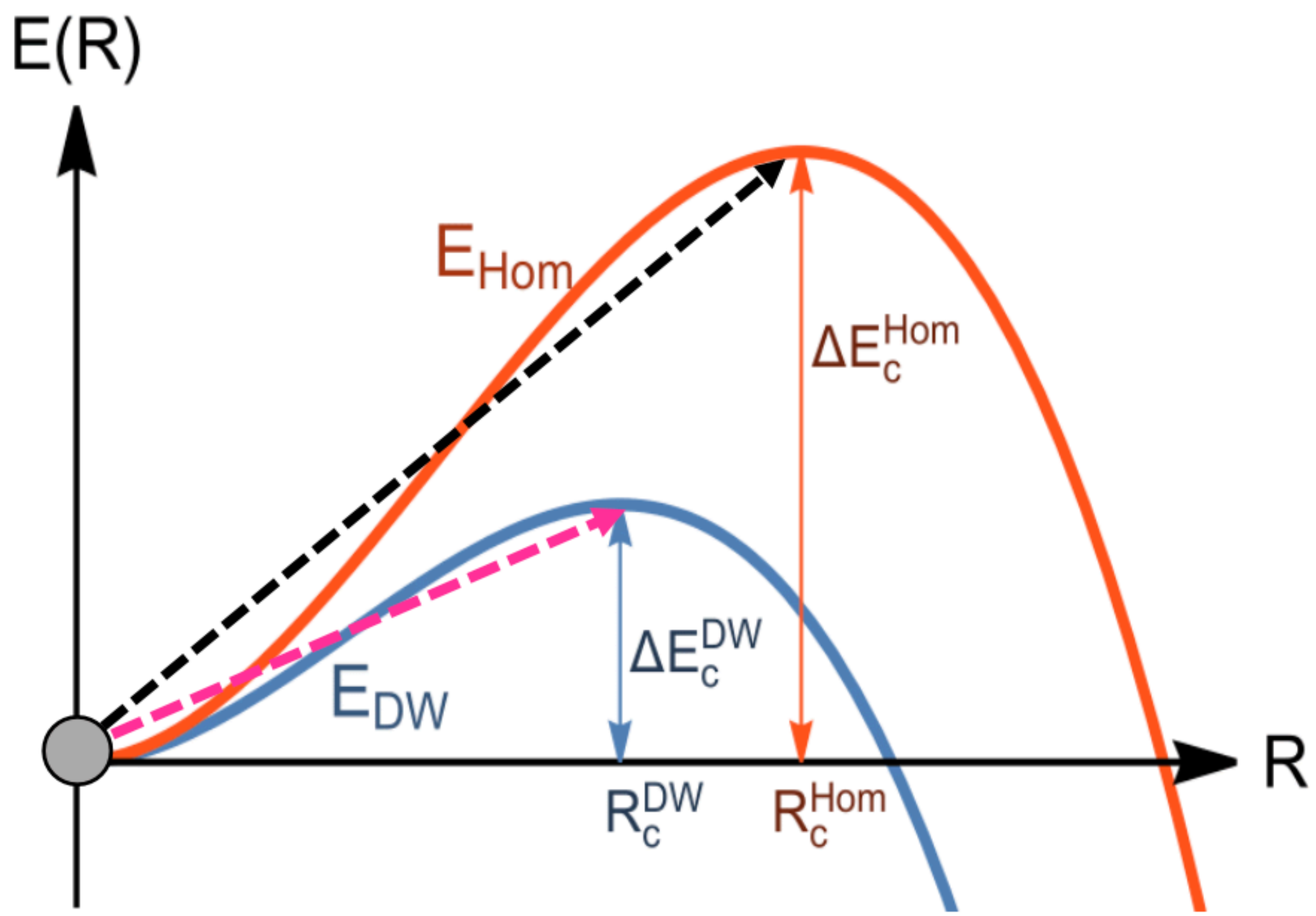
$$\frac{\partial^2\phi}{\partial r^2} + \frac{1}{r}\frac{\partial\phi}{\partial r} + \frac{\partial^2\phi}{\partial z^2} = \frac{\partial V}{\partial\phi}, \qquad \phi = h, S$$

$$S(\infty, z) = S_{DW}(z), \qquad S(r, \pm\infty) = \pm v_s,$$

$$h(\infty, z) = h(\rho, \pm\infty) = 0$$

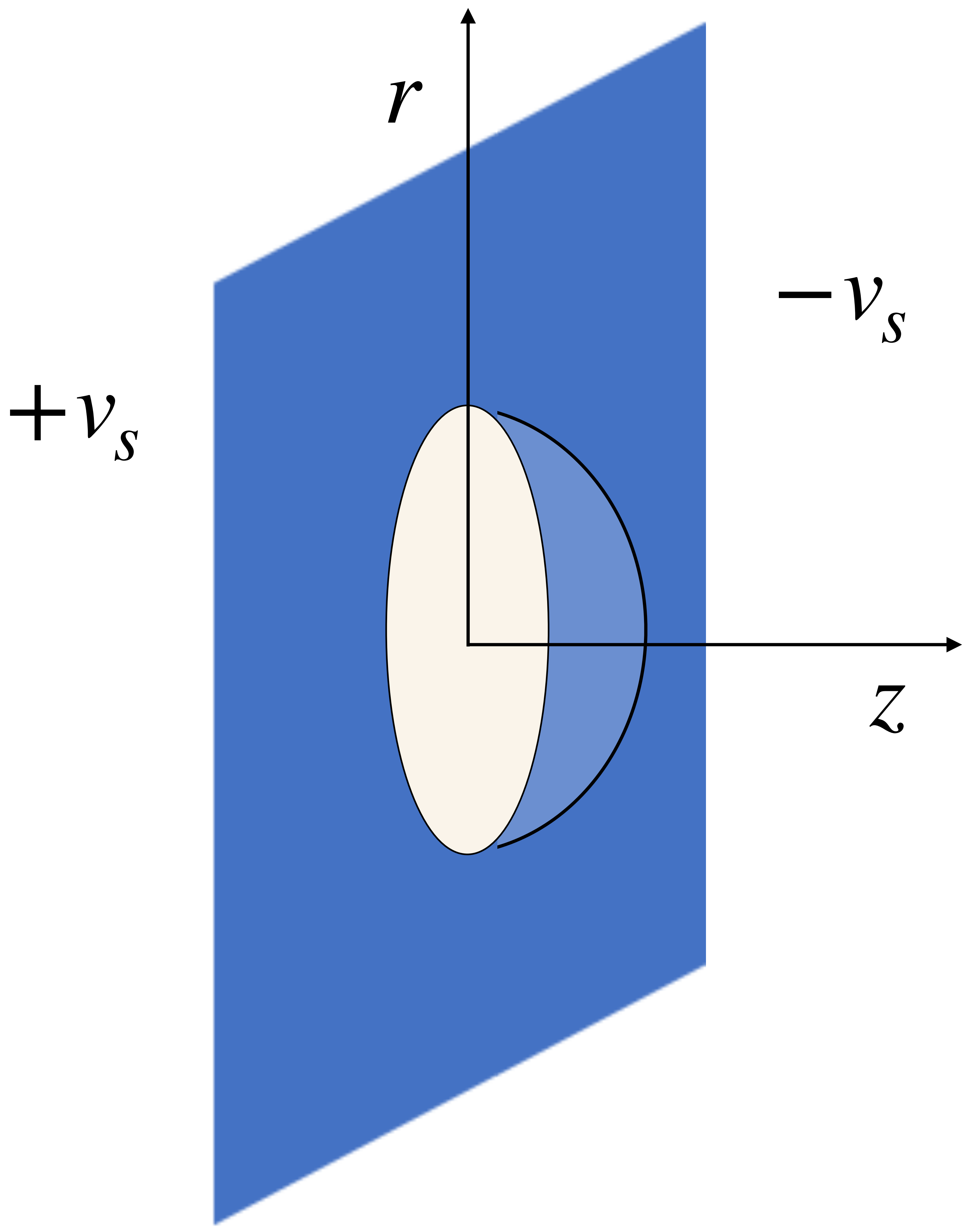


Thin wall approximation



$$E(R) = -\frac{4\pi}{3}\epsilon R^3 + 4\pi\left(\sigma_B - \frac{1}{4}\sigma_{DW}\right) R^2$$

Gain by eating up domain wall surface



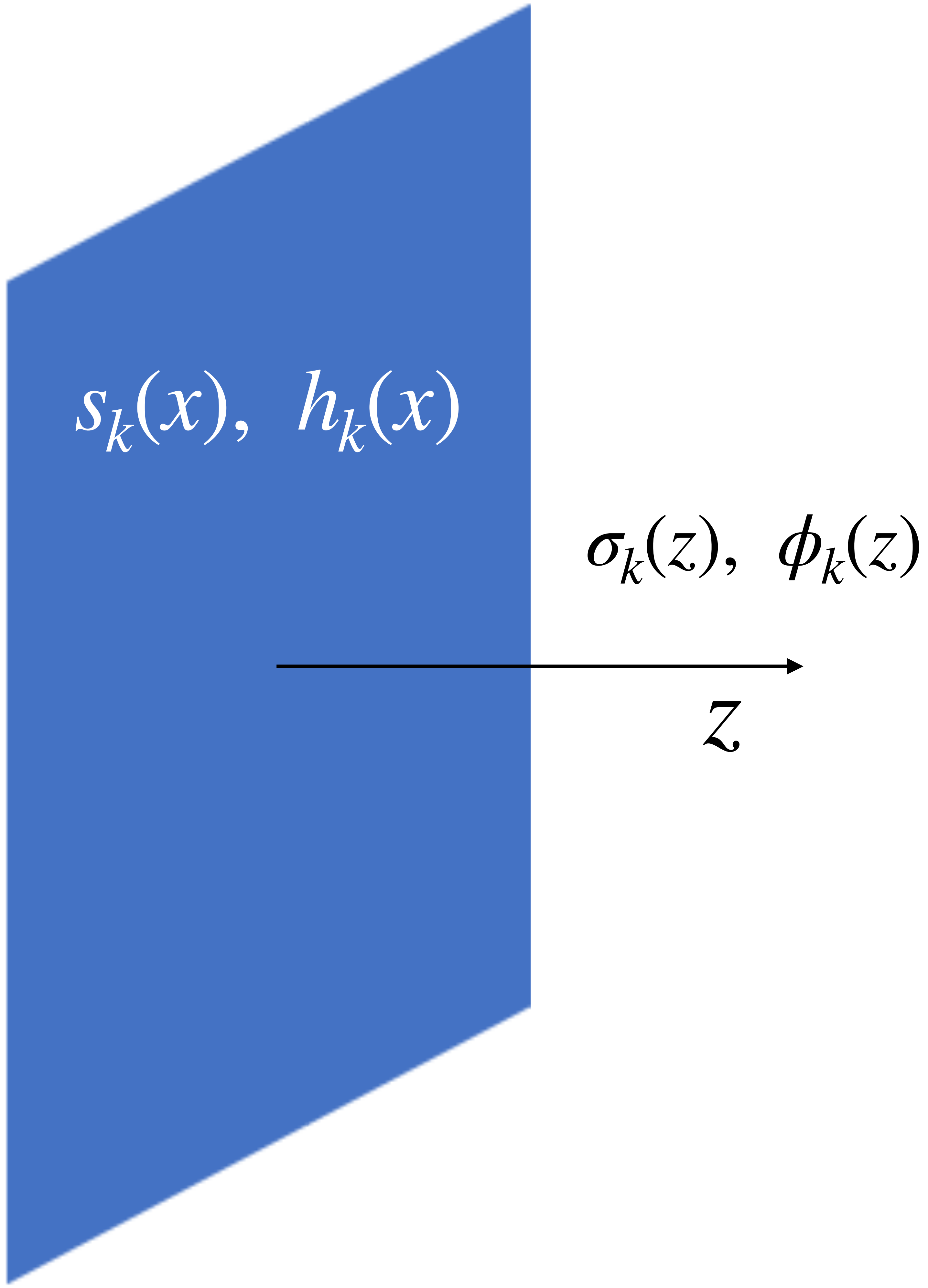
Kaluza-Klein decomposition

- Expand the fields around the domain wall background:

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

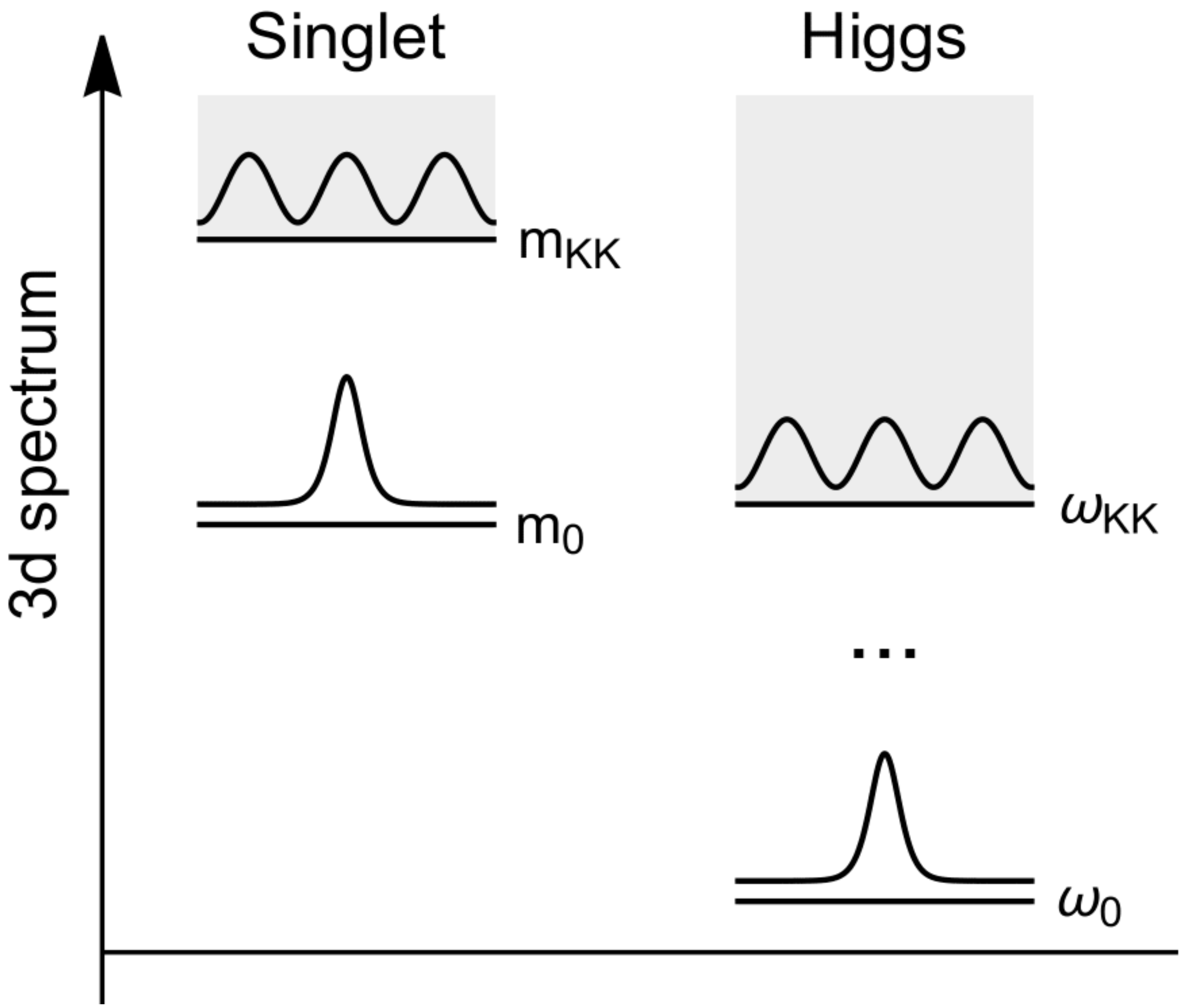
$$h = \sum_k h_k\left(x_\mu\right)\phi_k(z)$$

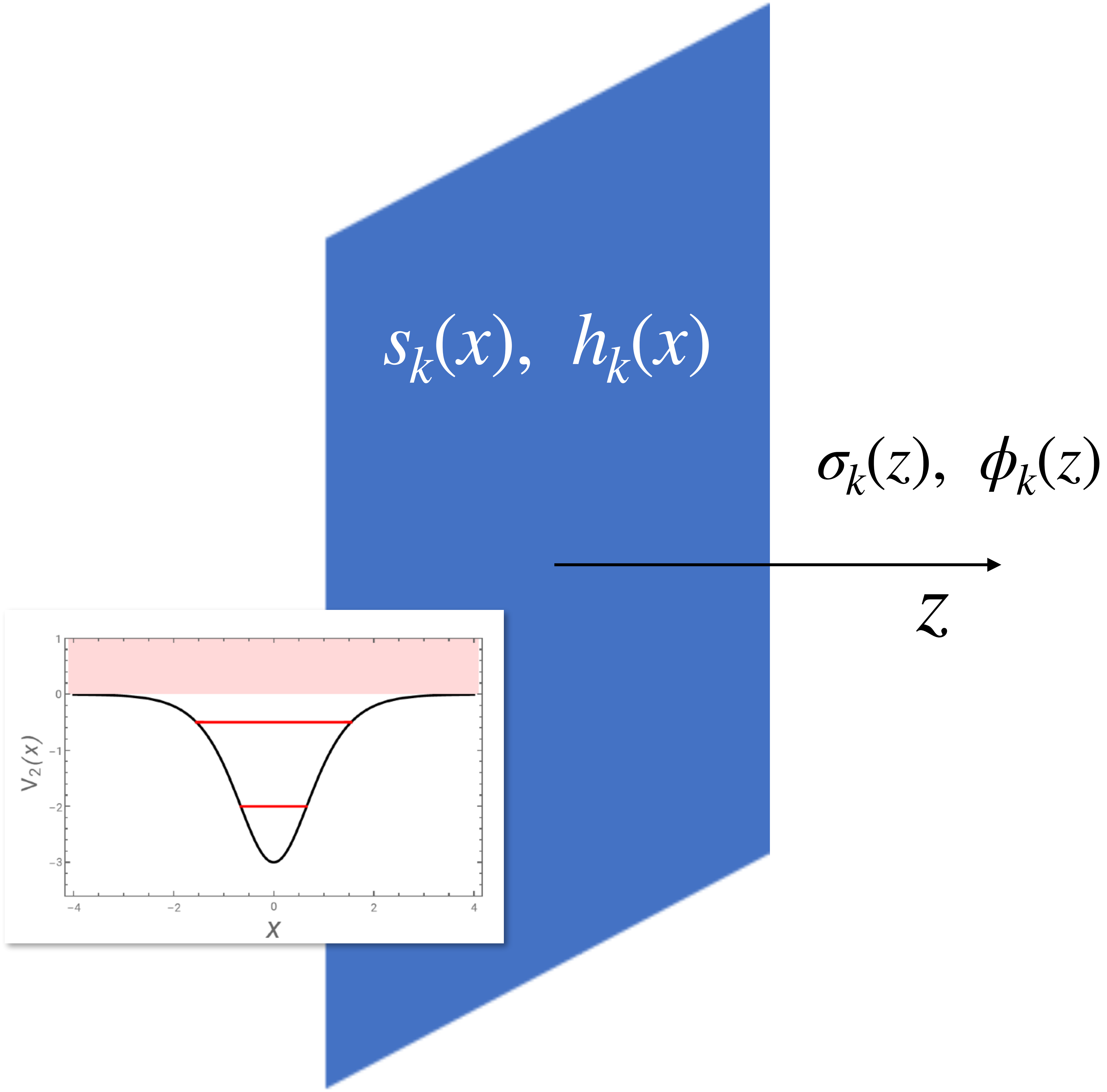
$$x_\mu = t, x, y$$



Kaluza-Klein decomposition

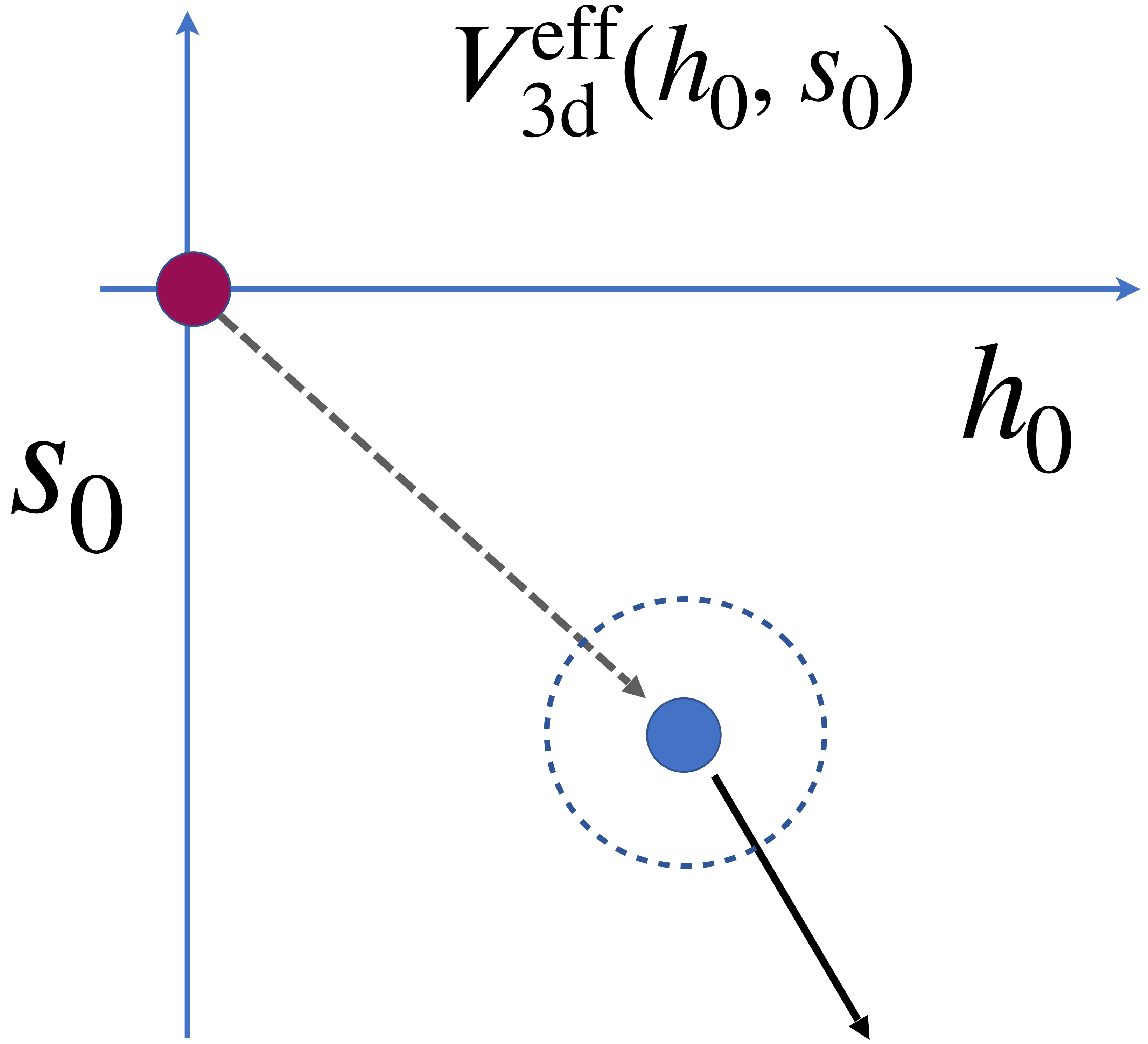
- Eigenspectrum of excitations on the wall:





Kaluza-Klein decomposition

- Seeded tunneling as homogenous nucleation in lower dimension



Kaluza-Klein decomposition

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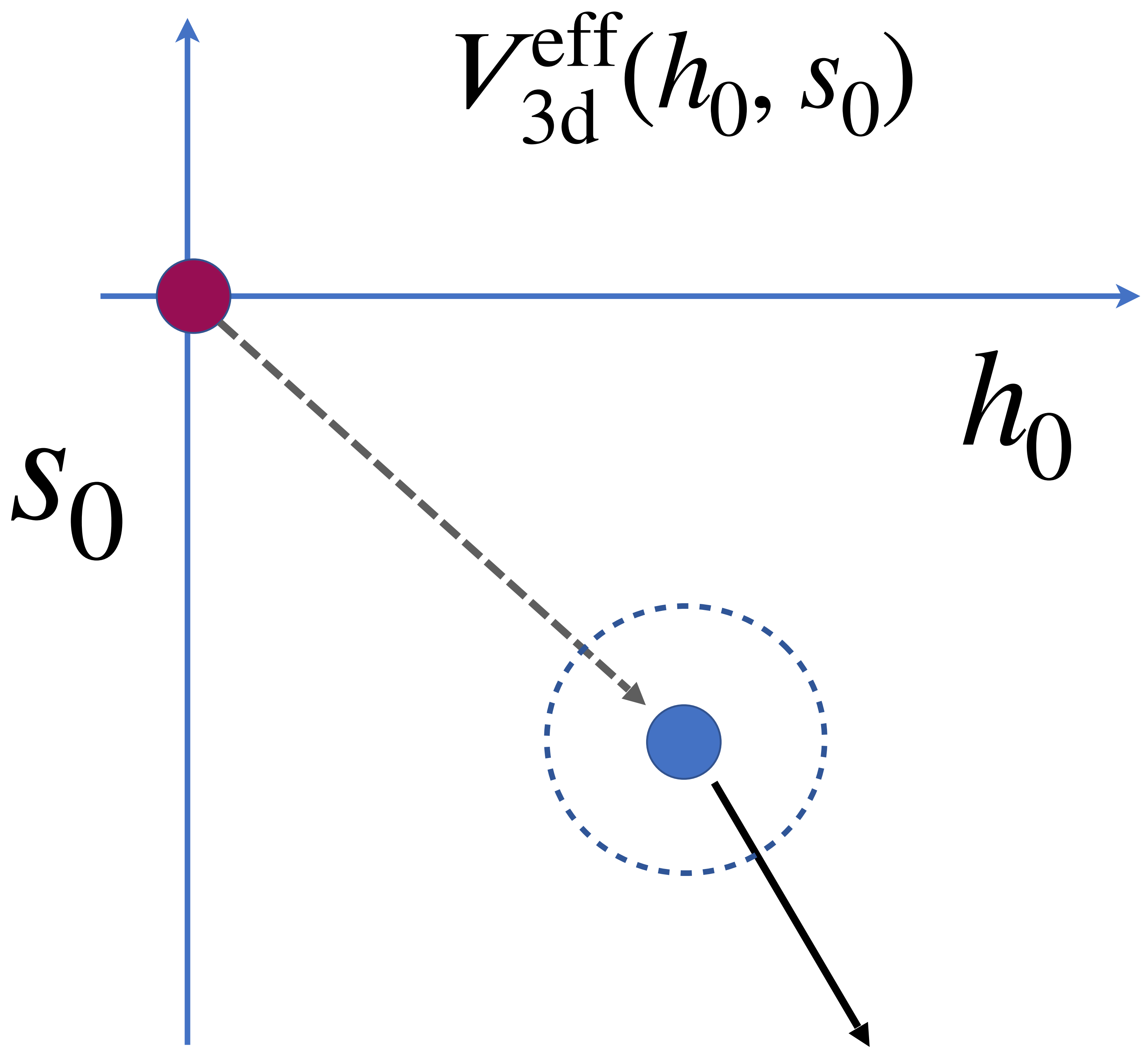
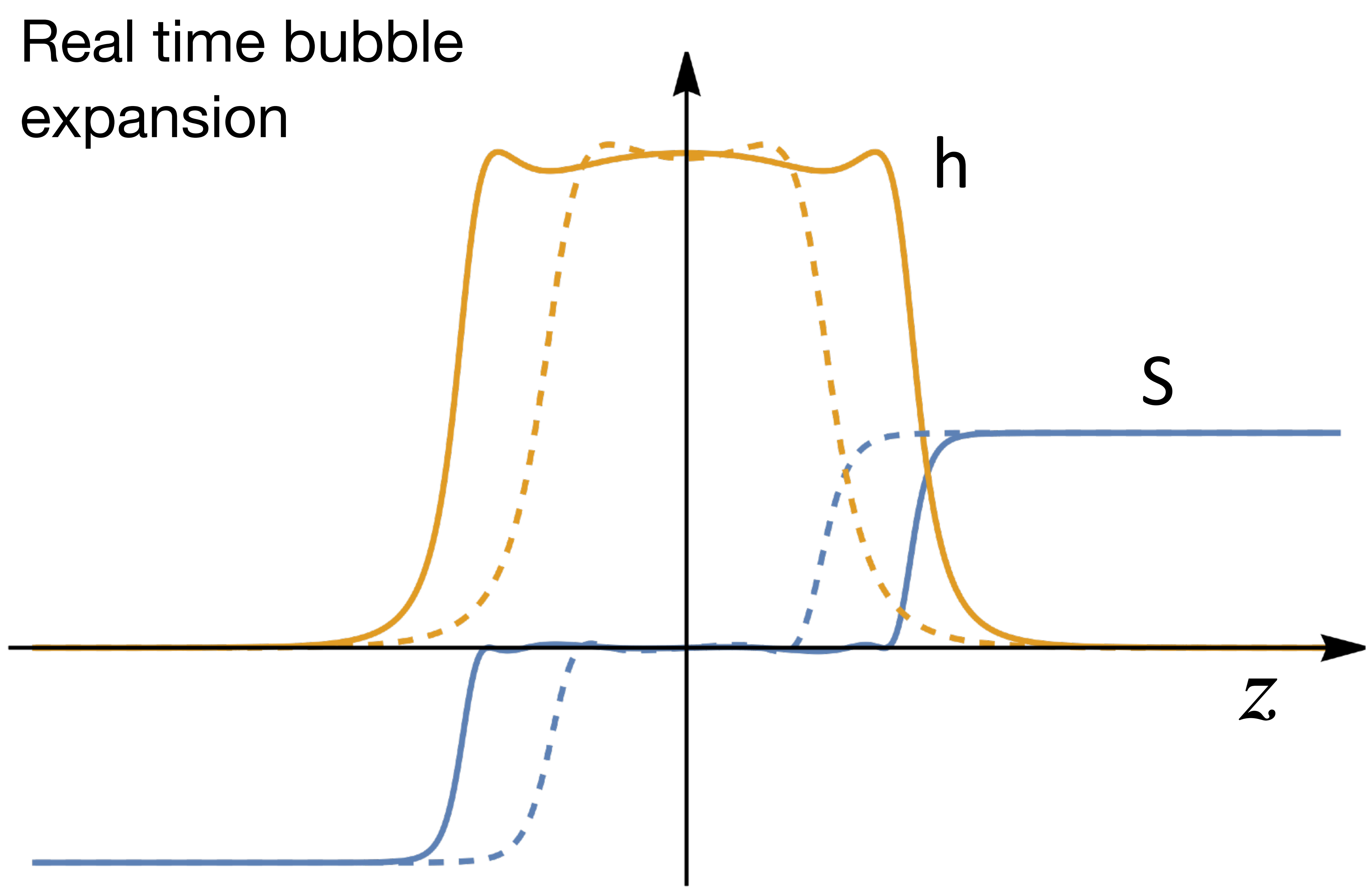
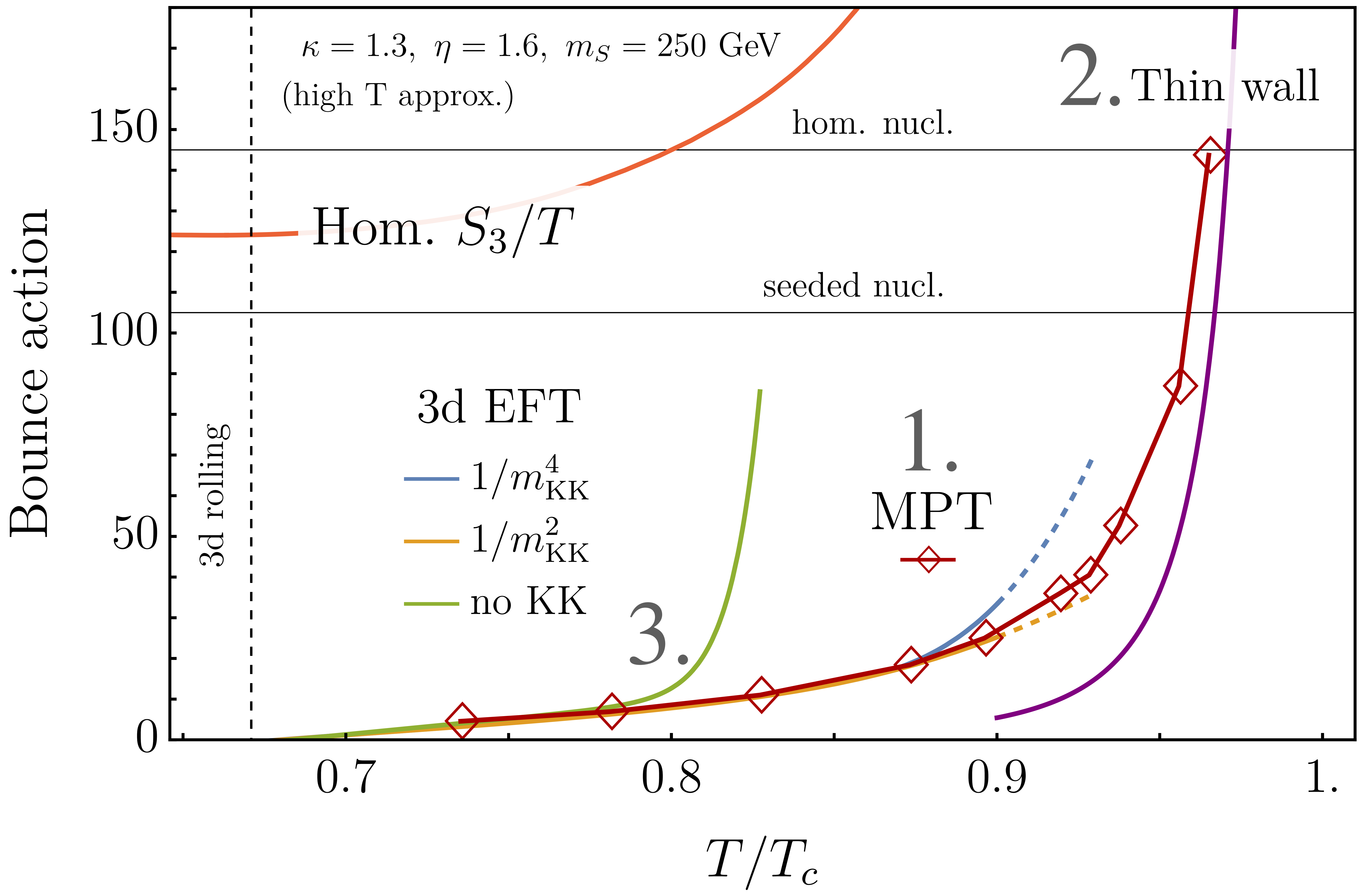




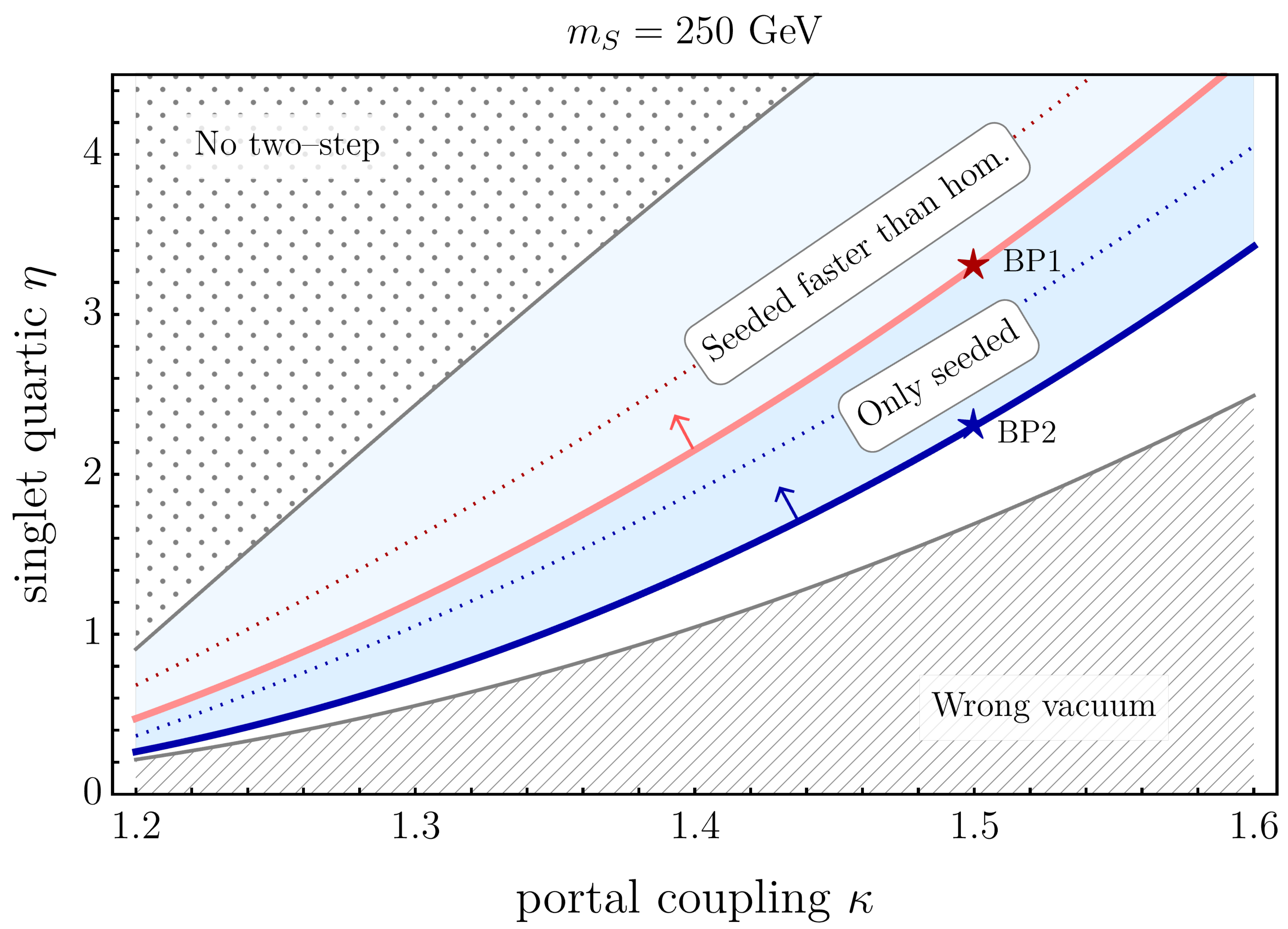
Comparison



$\kappa = 1.3,\ \eta = 1.6,\ m_S = 250$ GeV
(high T approx.)
2. Thin wall
hom. nucl.
Hom. S_3/T
seeded nucl.
3d EFT
$1/m_{\rm KK}^4$
$1/m_{\rm KK}^2$
no KK
1.
MPT
3.
3d rolling
Bounce action
150
100
50
0
0.7
0.8
0.9
1.
T/T_c

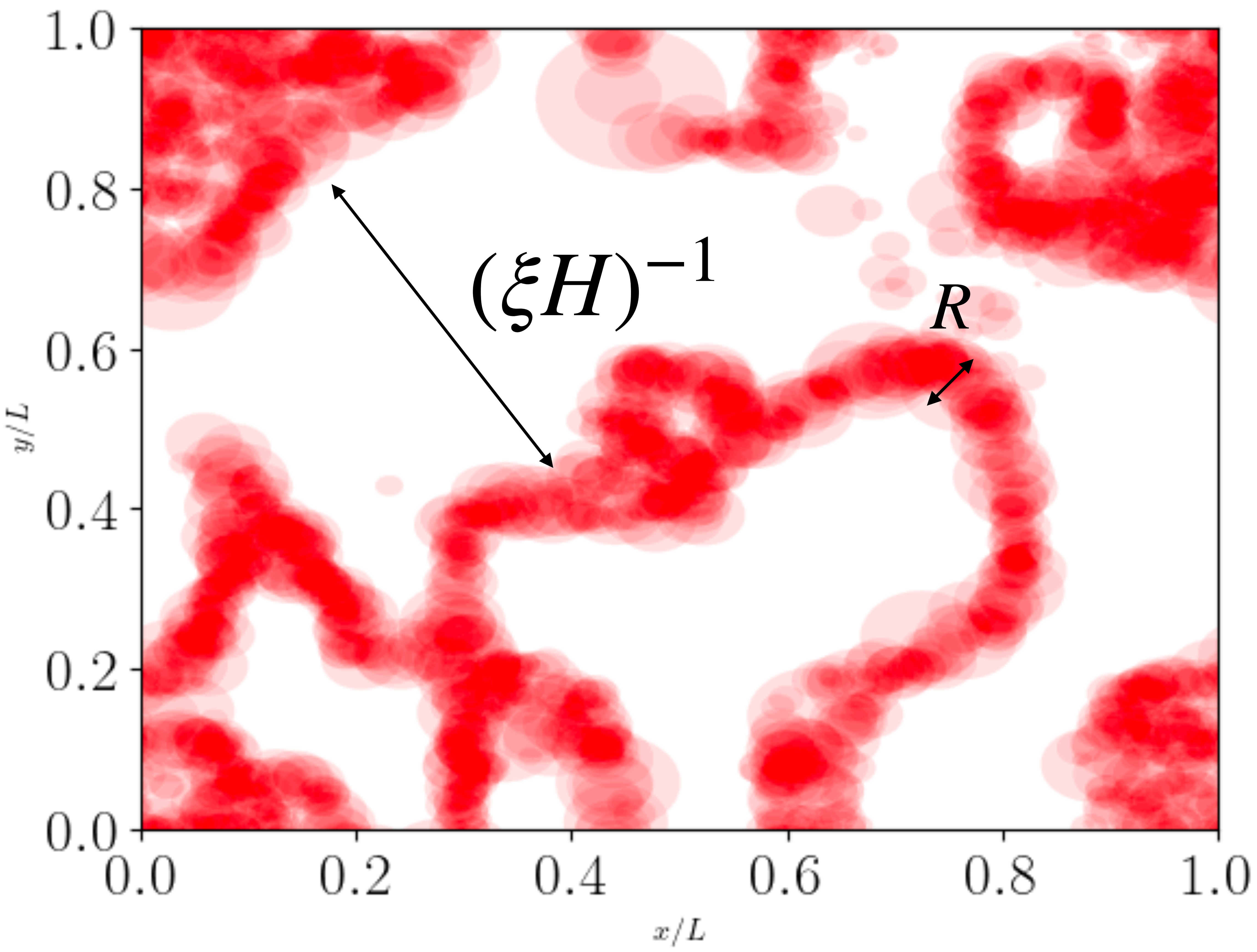
EWPT with a singlet

- Seeded transition is faster in all the two-step parameter space
- New parameter space becomes viable thanks to seeded tunneling

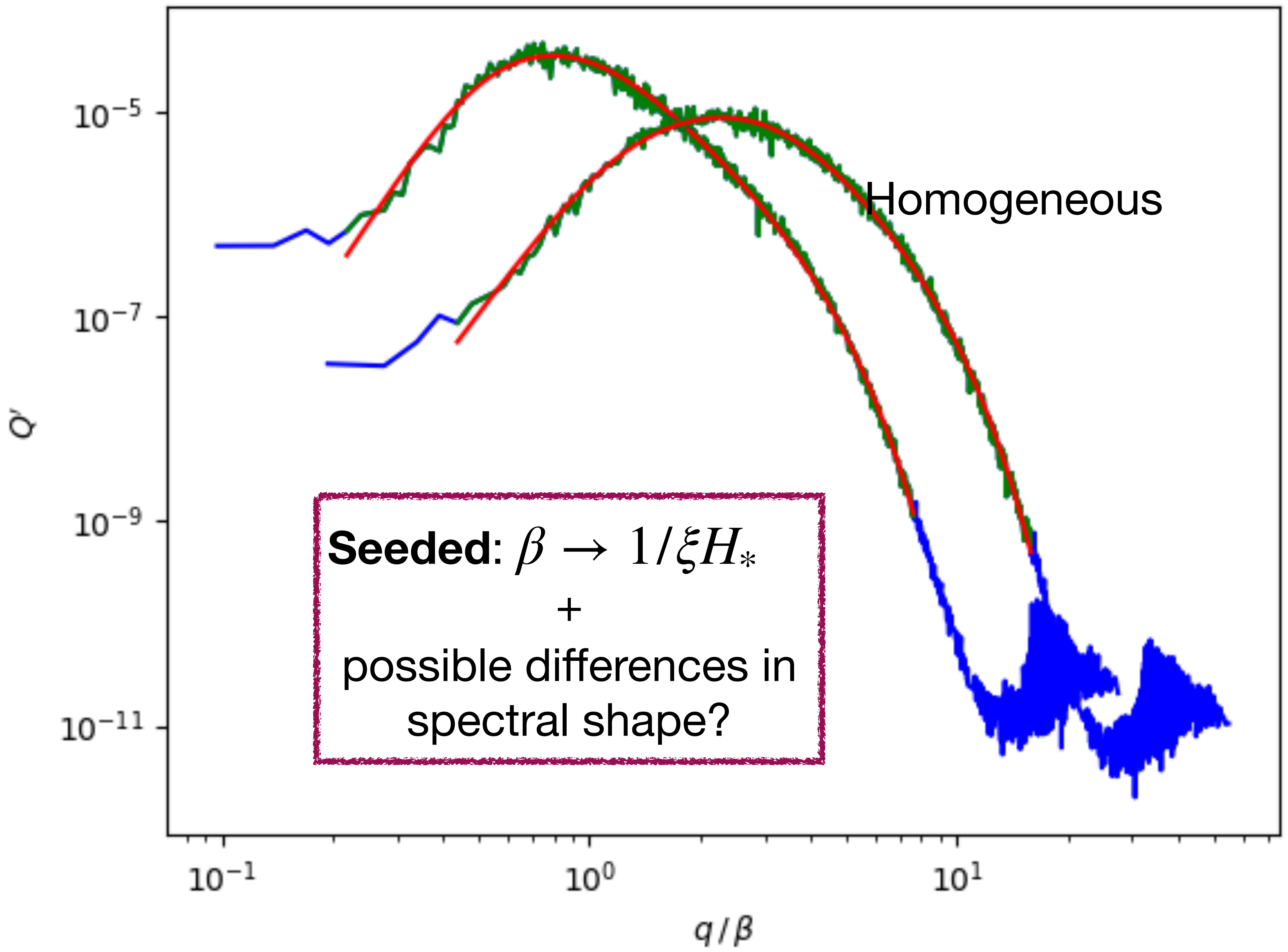


EWPT with a singlet

- Domain wall network mimicked by Ising model

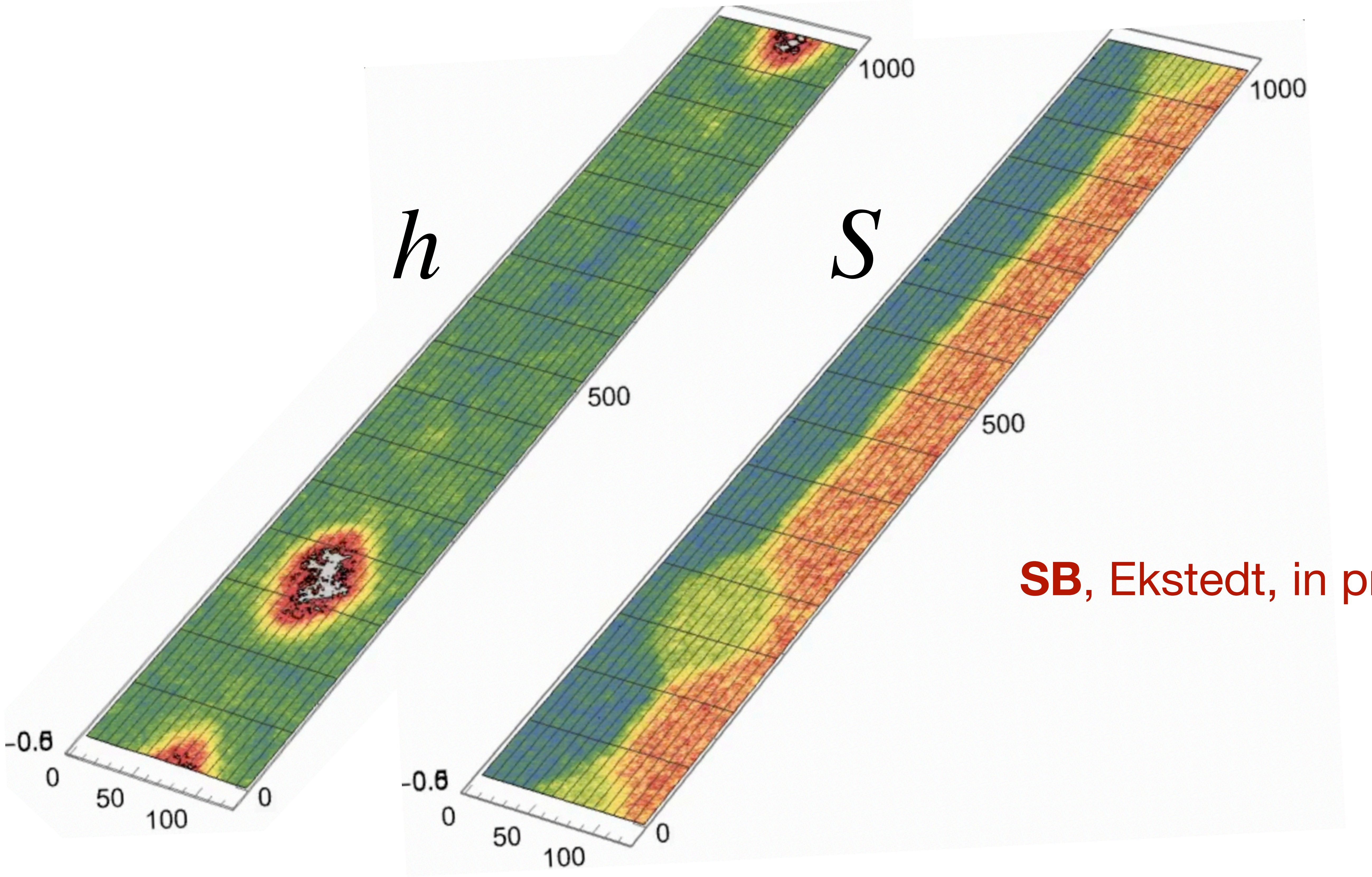


- Spectrum shifted to IR with enhanced amplitude



EWPT with a singlet

- Numerical simulation (Langevin equation)



SB, Ekstedt, in prep.

What about other defects?

SB, Mariotti [2405.08060] SciPost

QCD axion strings

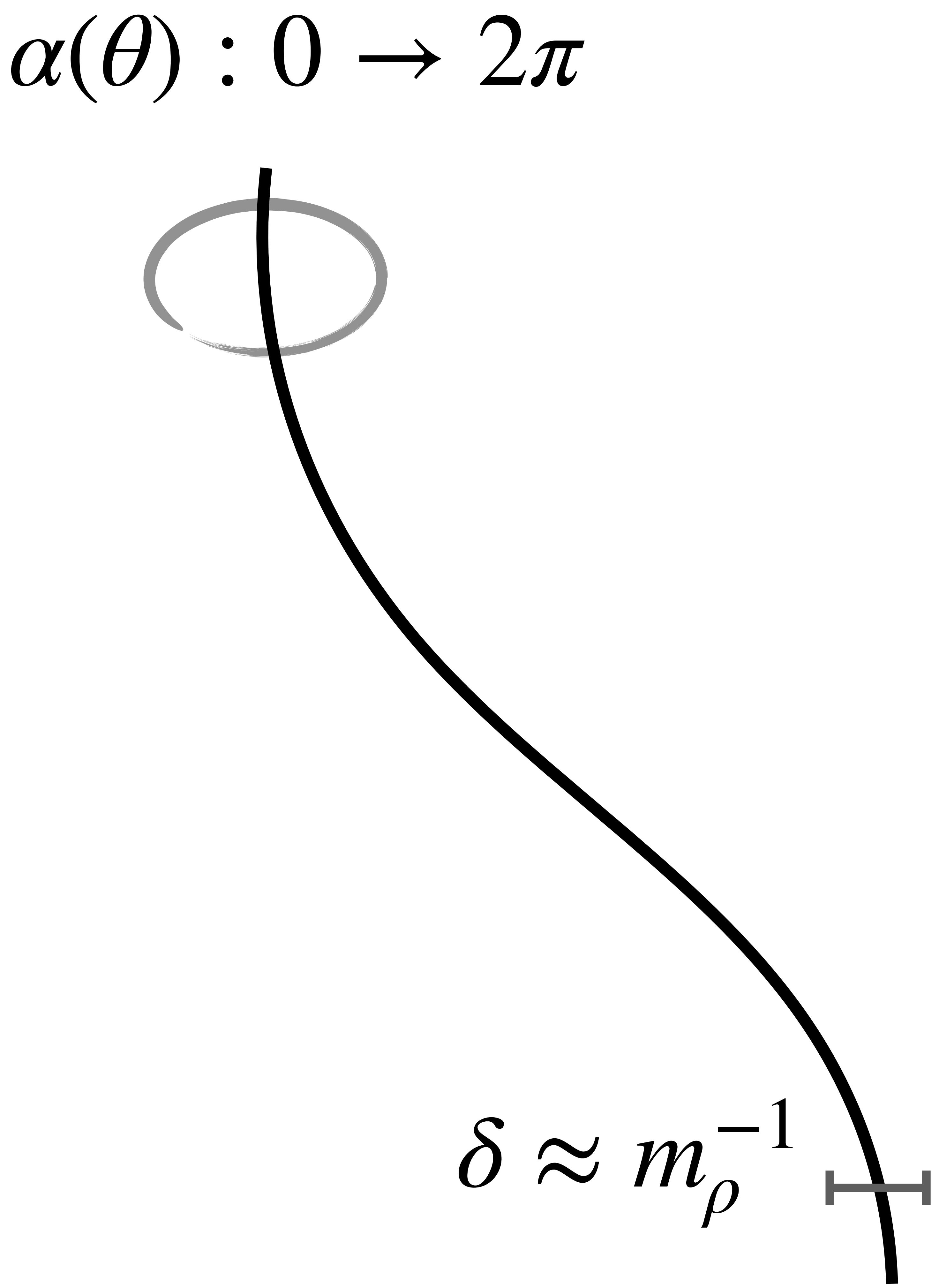
T

f_a

- Strings form at PQ phase transition

QCD

- Strings connected by axion domain walls
- String—wall network collapses



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T

f_a

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???

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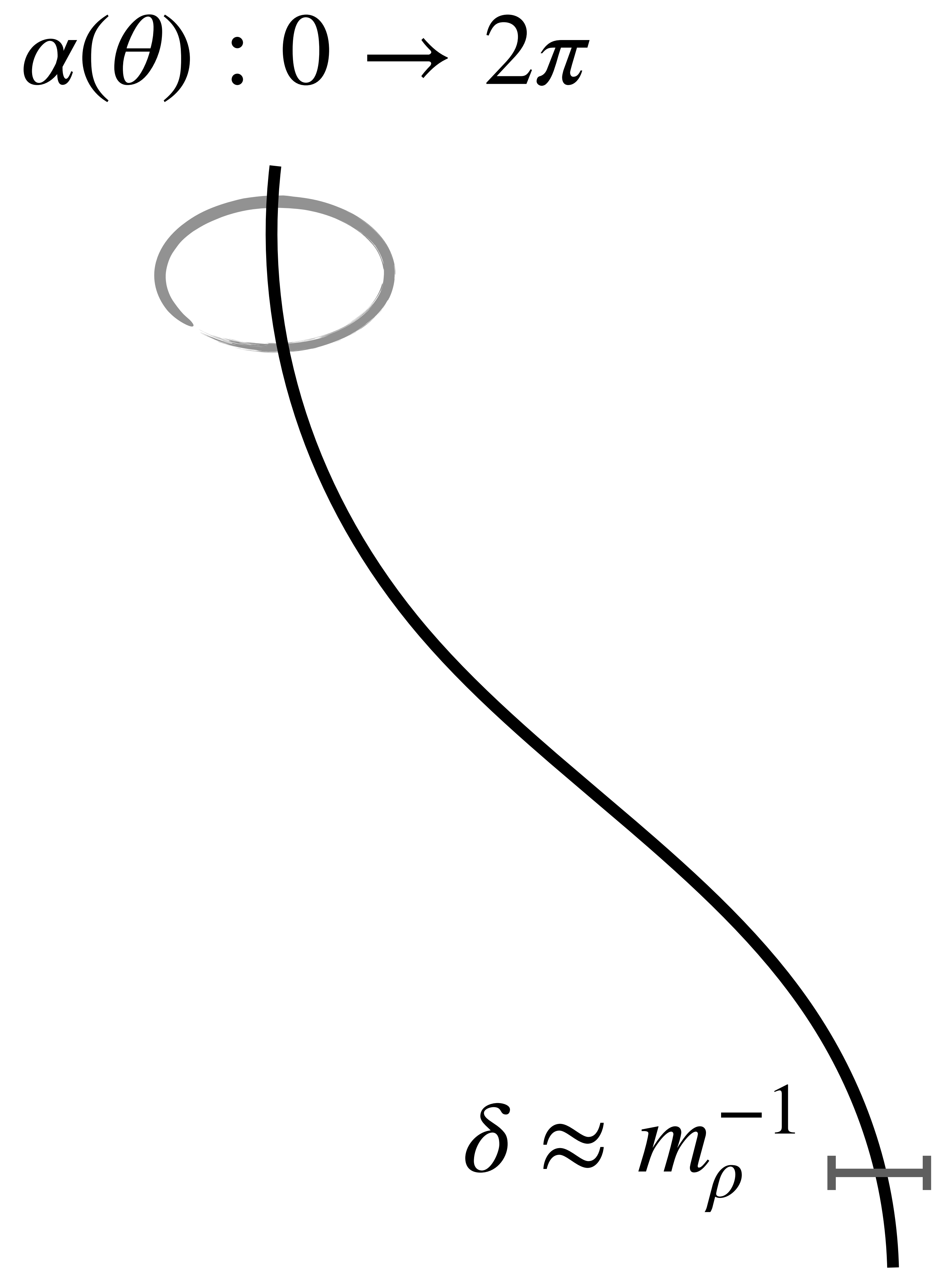
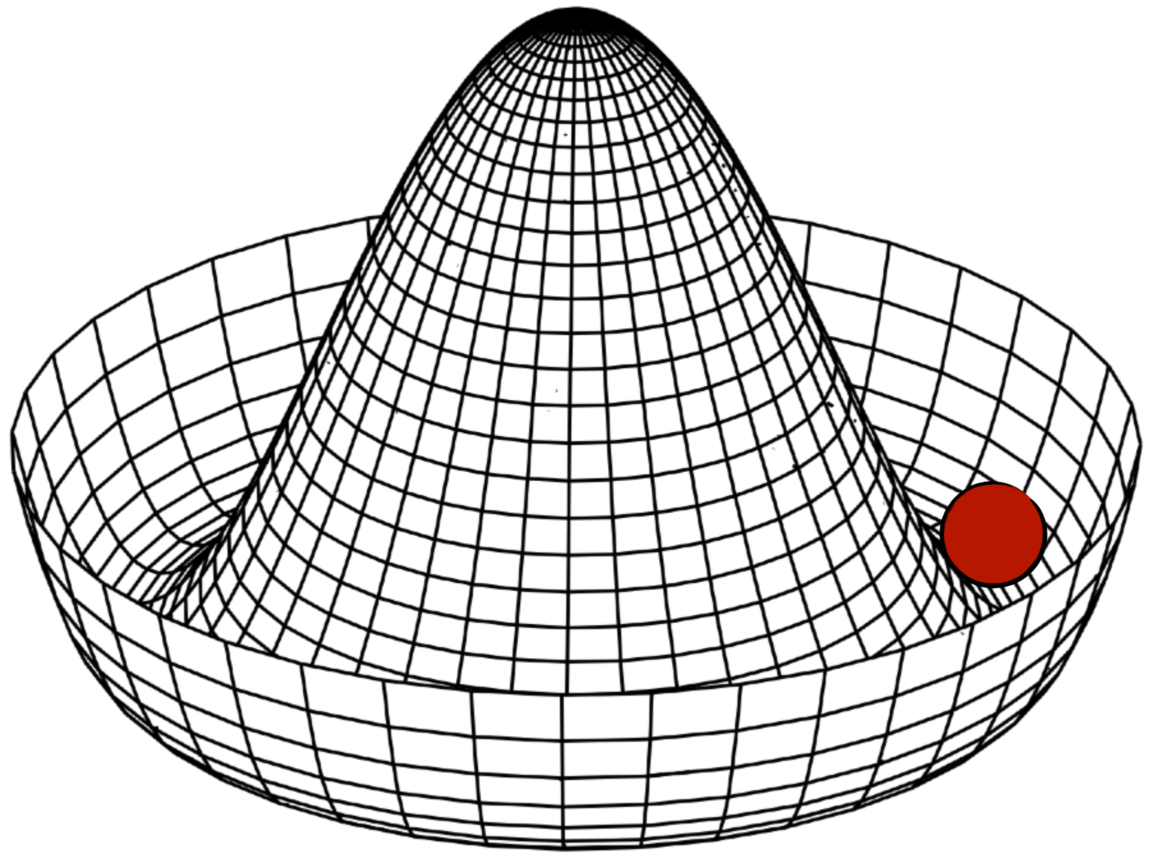
- String—wall network collapses



QCD axion strings

- Potential for PQ field

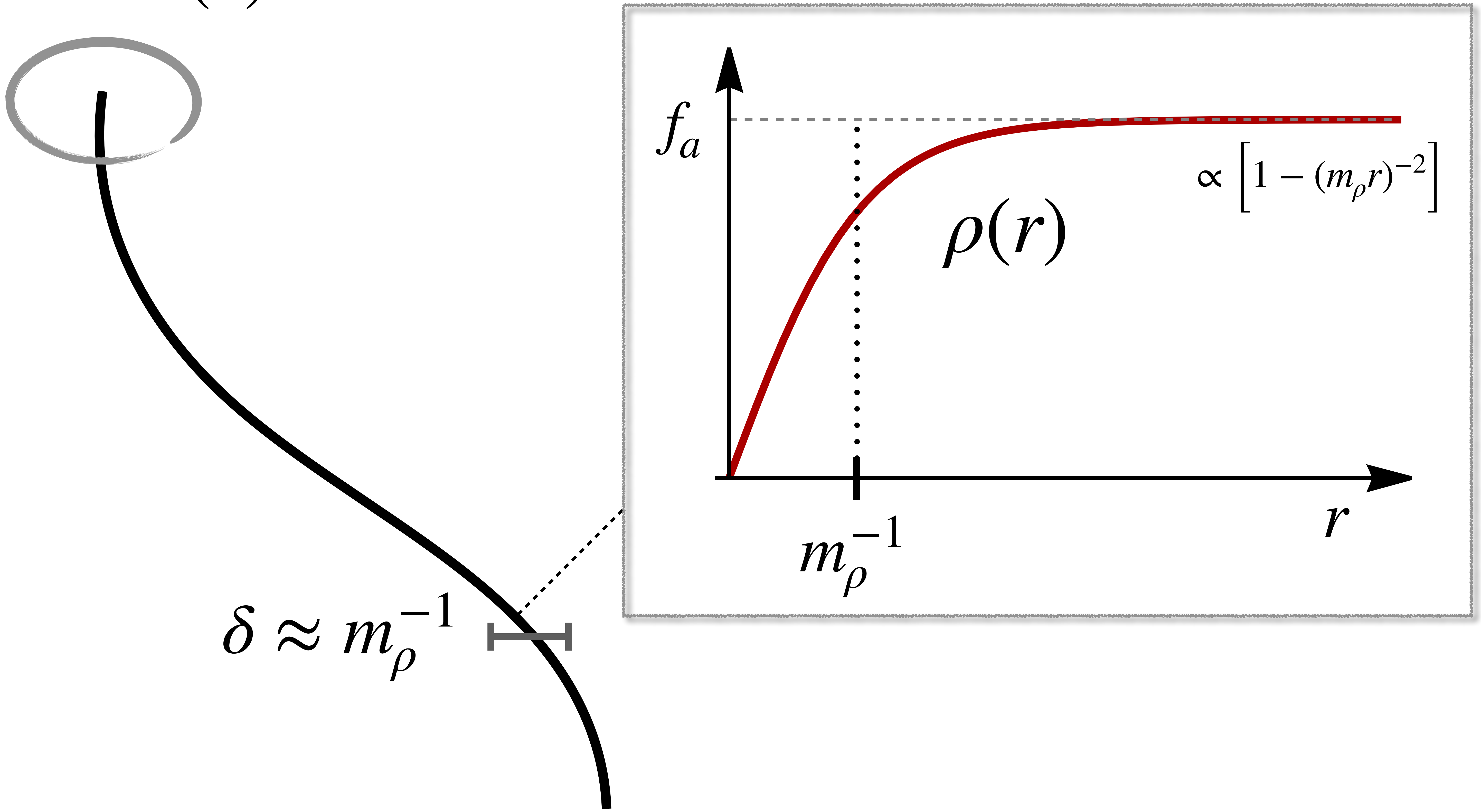
$$\Phi = \rho e^{i\alpha}$$



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

- Global string solution

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



QCD axion strings

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

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

$$V_{\rm PQ}(|\Phi|) = \eta \left(|\Phi|^2 - \frac{f_a^2}{2}\right)^2$$

QCD axion strings

- 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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QCD axion strings

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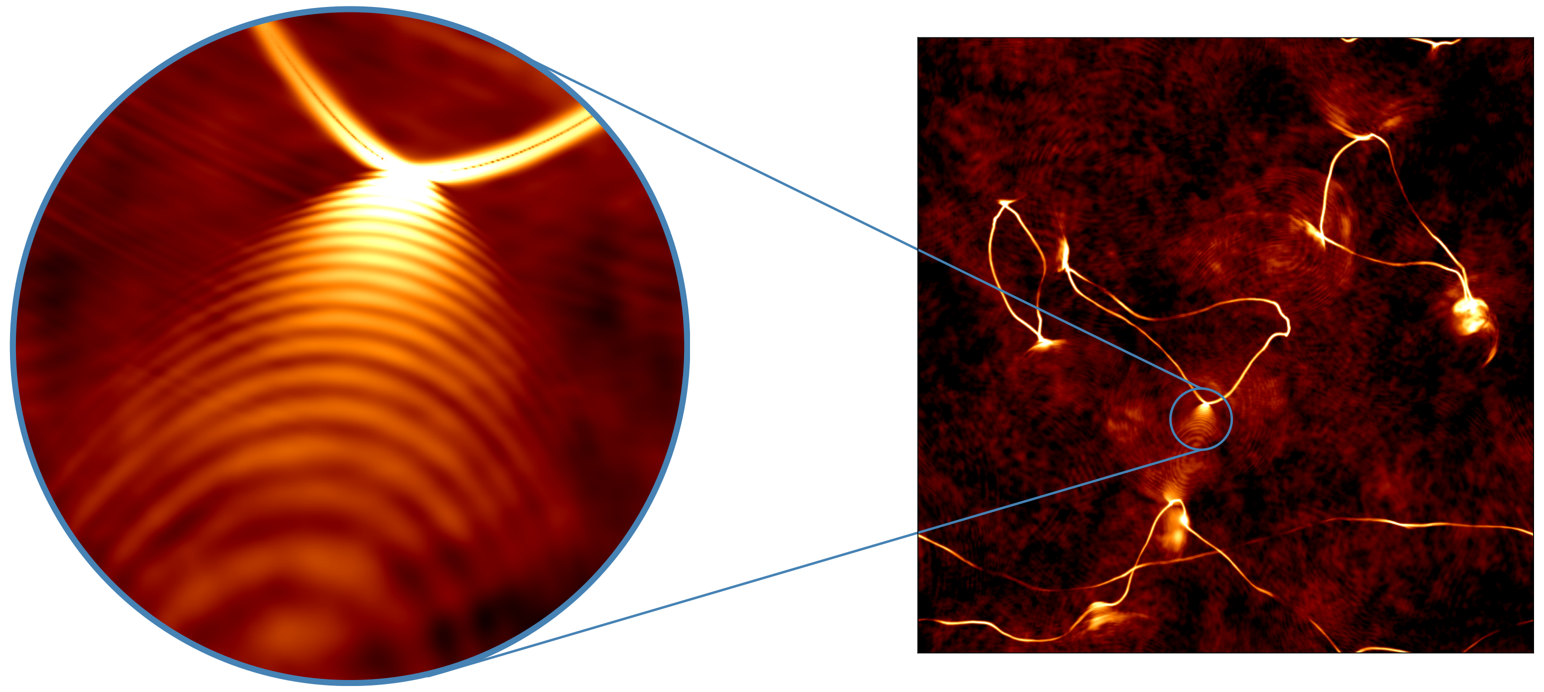
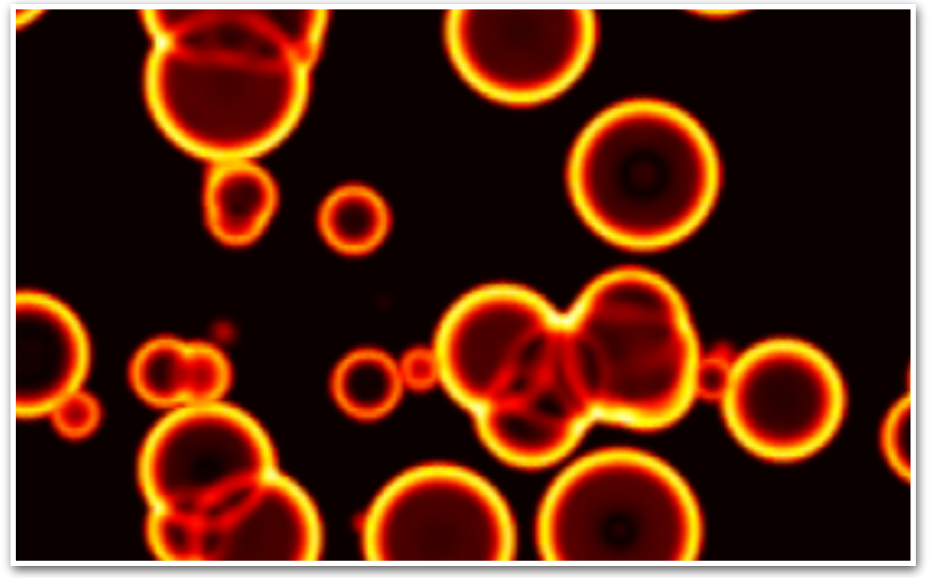
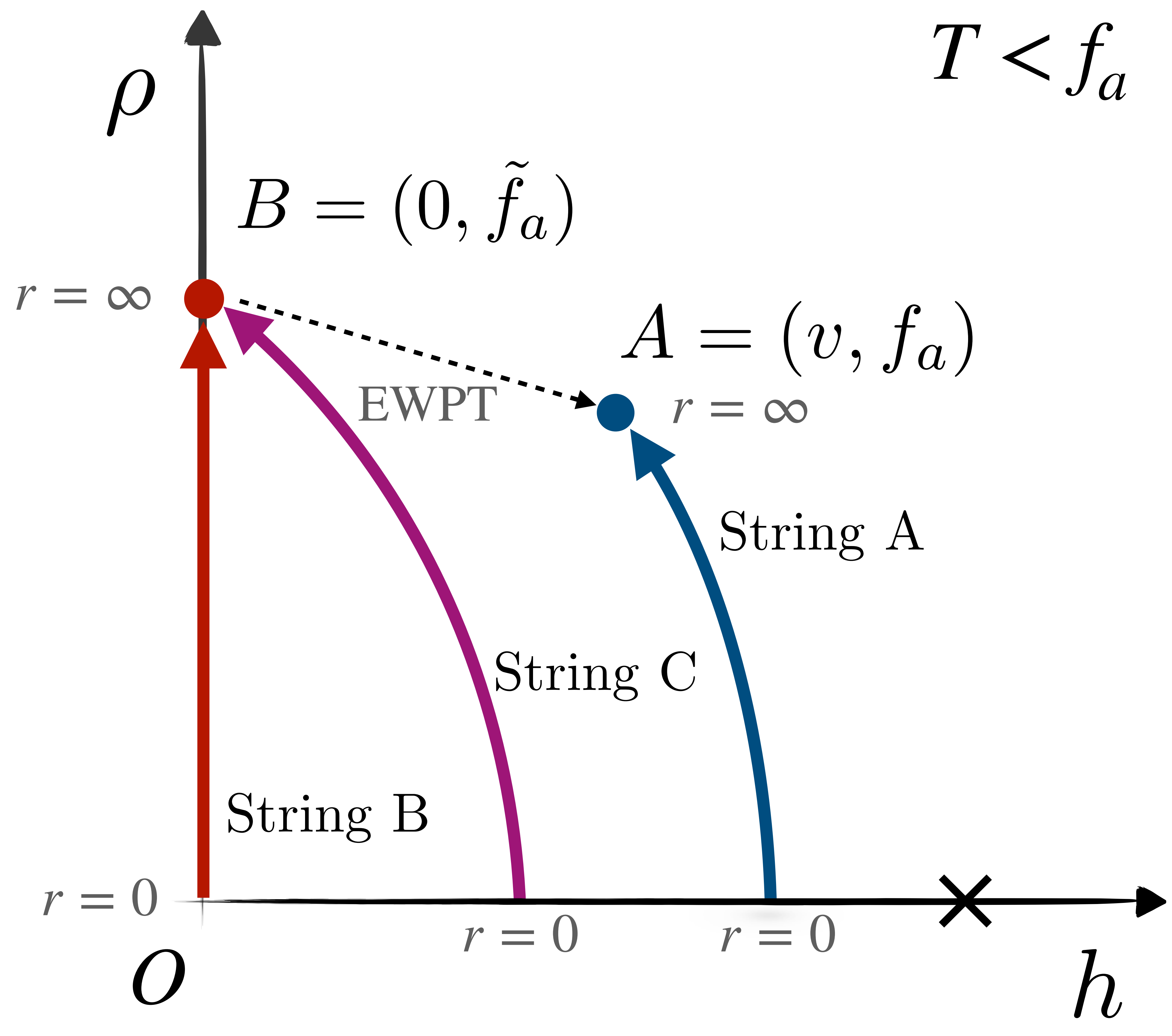


How do axion strings affect electroweak symmetry breaking?



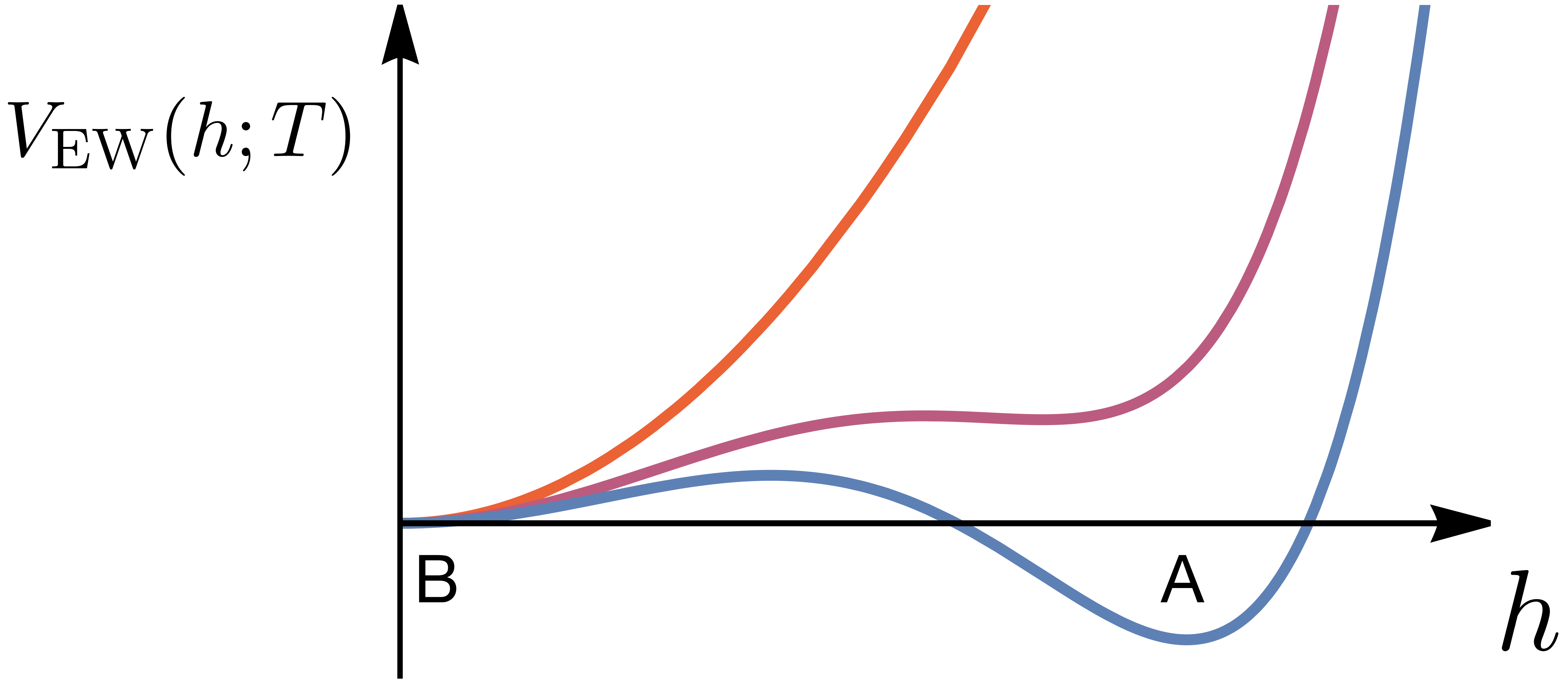
String solutions

- Relevant points in field space:



FOPT + PQ

- Consider first order EWPT with false vacuum B metastable at $T = 0$



$$V_{\rm EW}(h;T) = -\frac{1}{2}\left(\mu^2 - c_h T^2\right) h^2 + \frac{\delta}{3}\frac{m_h^2}{v^2} h^3 + \frac{1}{4}\lambda h^4$$

FOPT + PQ

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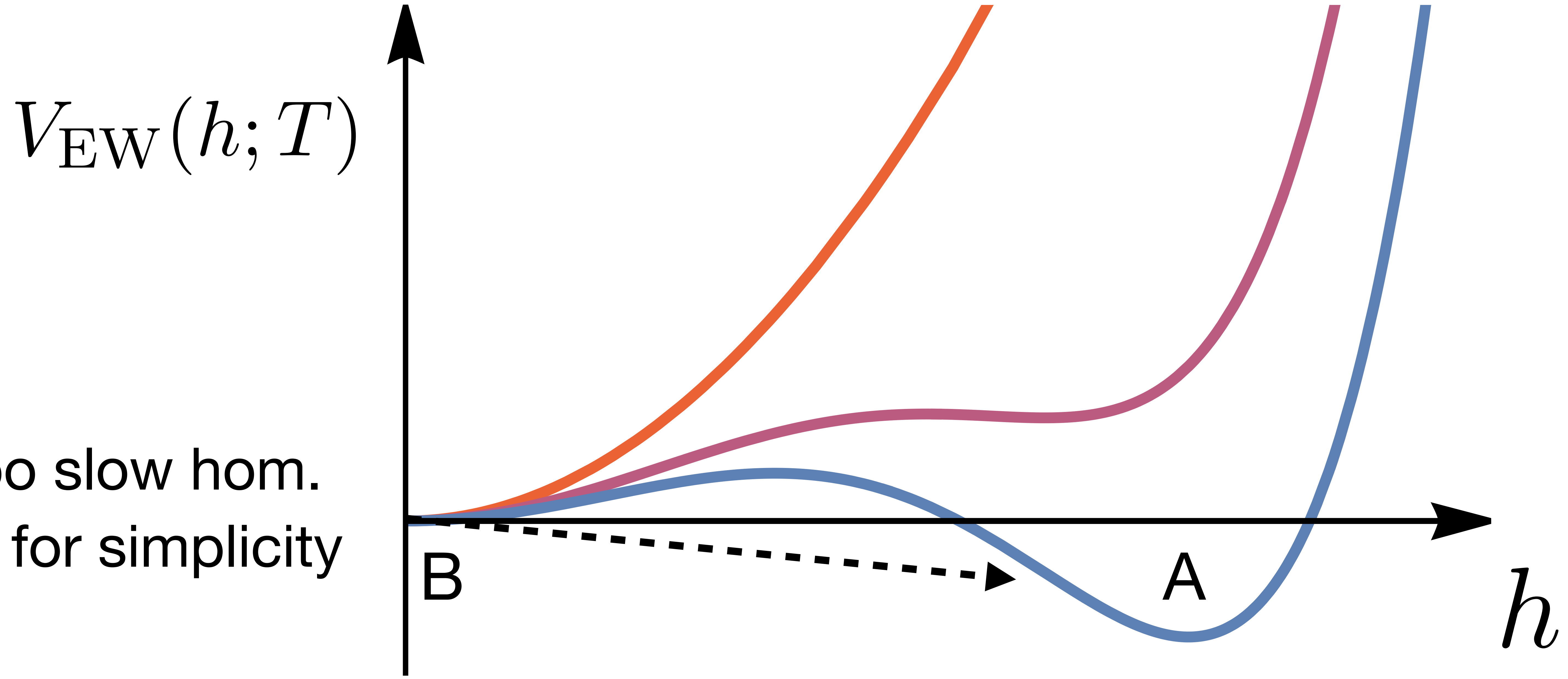
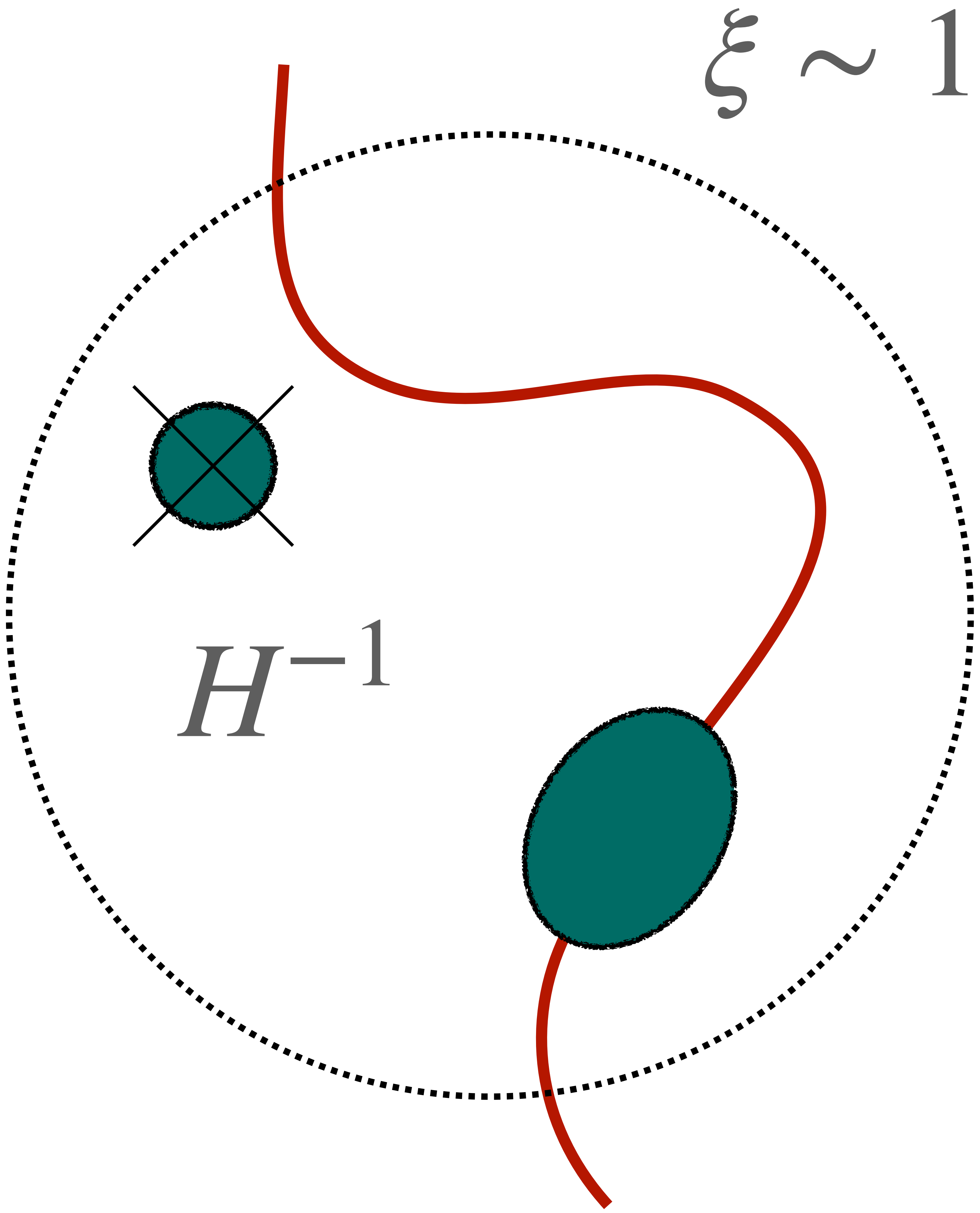


Assume too slow hom. nucleation for simplicity

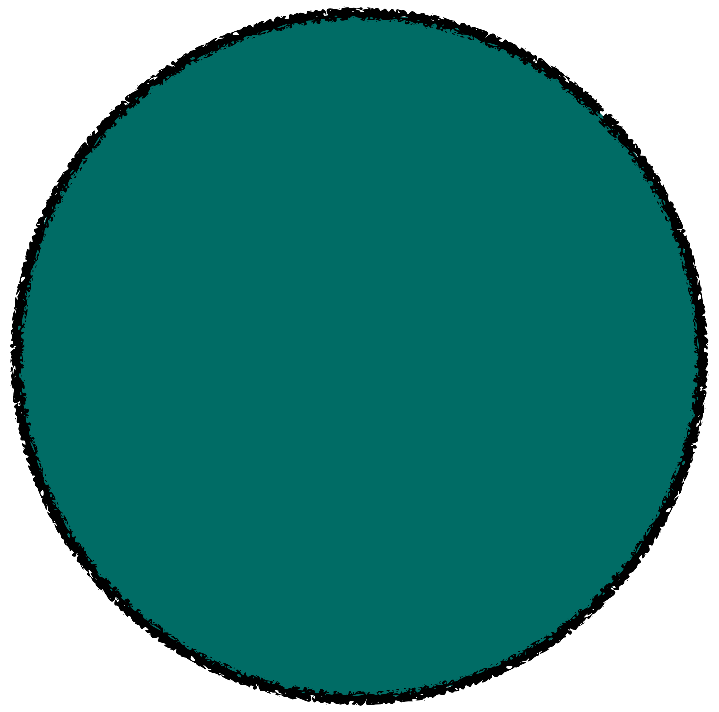
$$V_{\rm EW}(h;T) = -\frac{1}{2}\left(\mu^2 - c_h T^2\right) h^2 + \frac{\delta}{3}\frac{m_h^2}{v^2} h^3 + \frac{1}{4}\lambda h^4$$

FOPT + PQ



FOPT + PQ

B → A

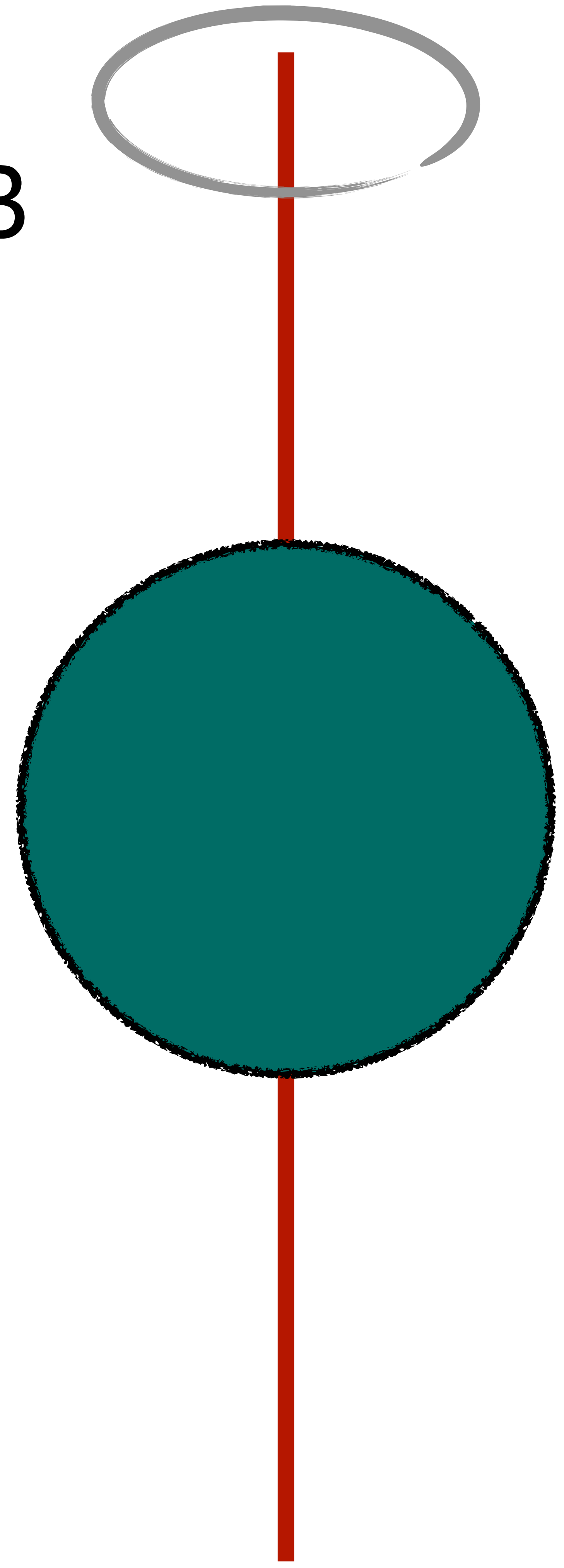


$= E_{\text{hom}}$

Critical bubble

FOPT + PQ

string B



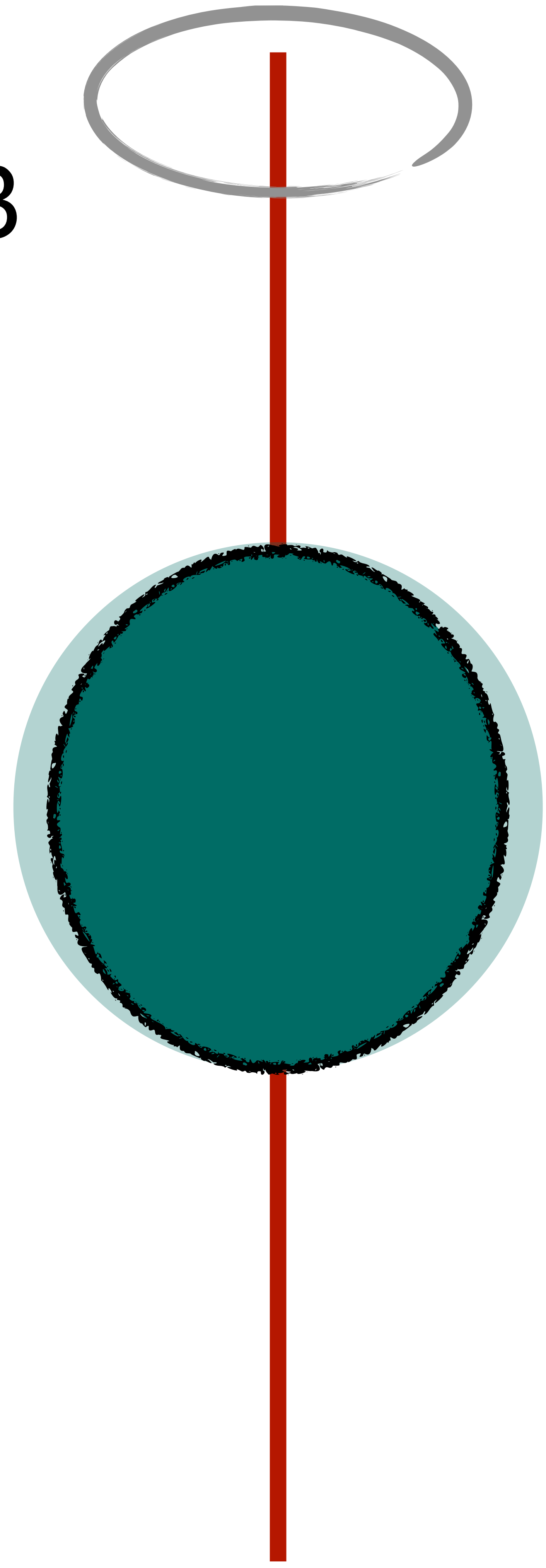
B → A

$$= E_{\rm hom} \qquad (\kappa = 0)$$

Critical bubble

FOPT + PQ

string B



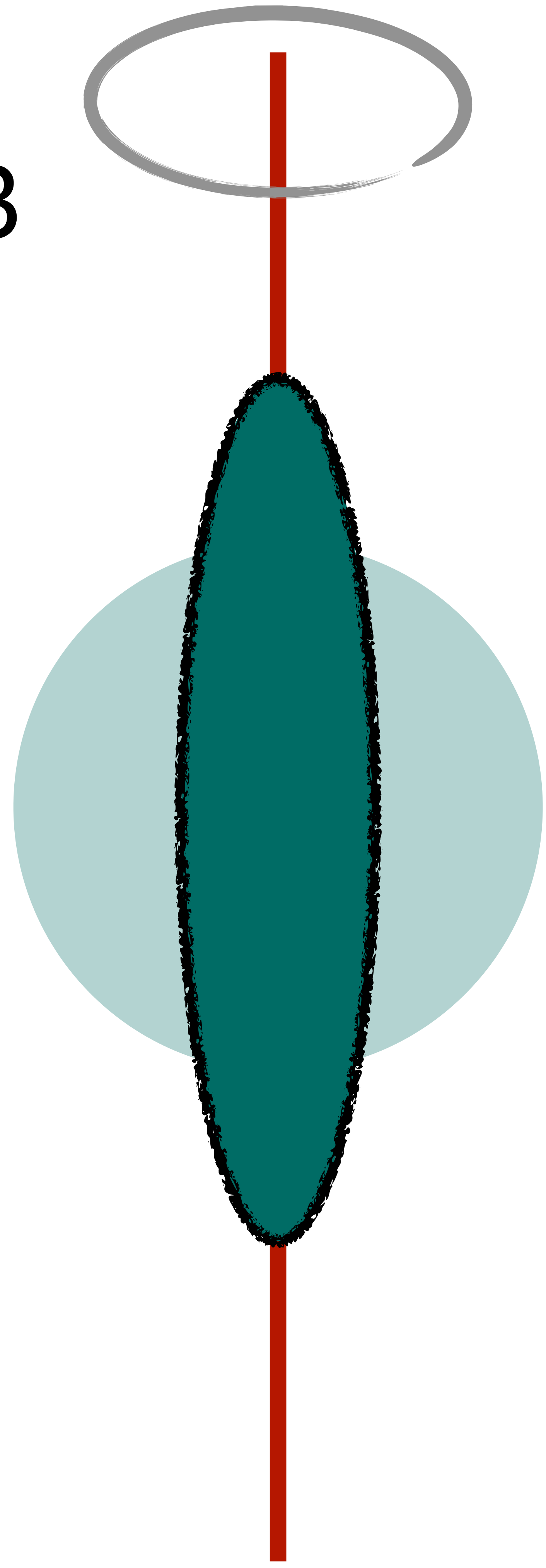
String B → String A

$$\lesssim E_{\rm hom} \quad (\kappa/\eta \ll 1)$$

Critical bubble

FOPT + PQ

string B

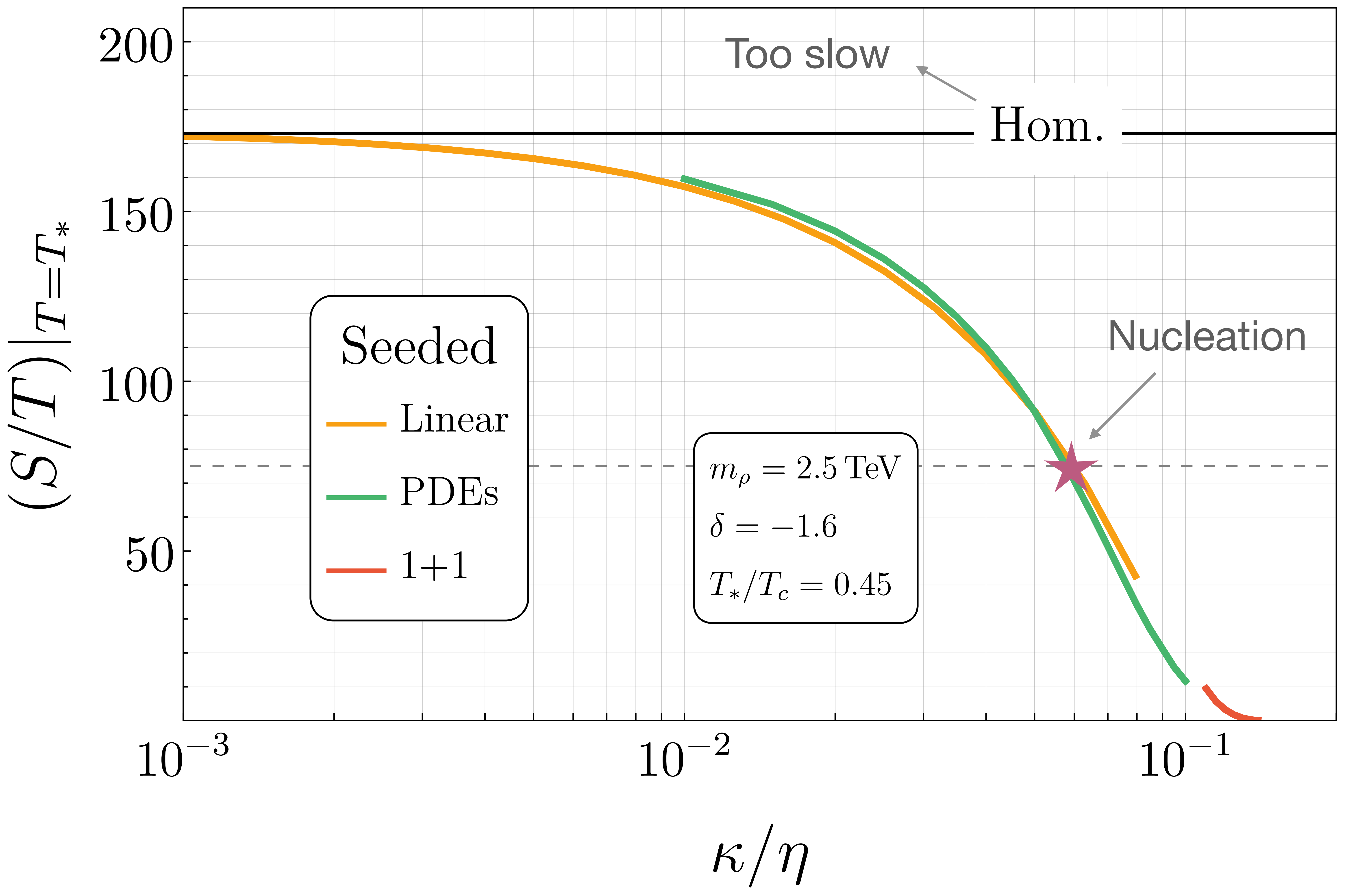


String B → String A

$$\ll E_{\rm hom} \quad (\kappa/\eta \sim \text{crit.})$$

Critical bubble

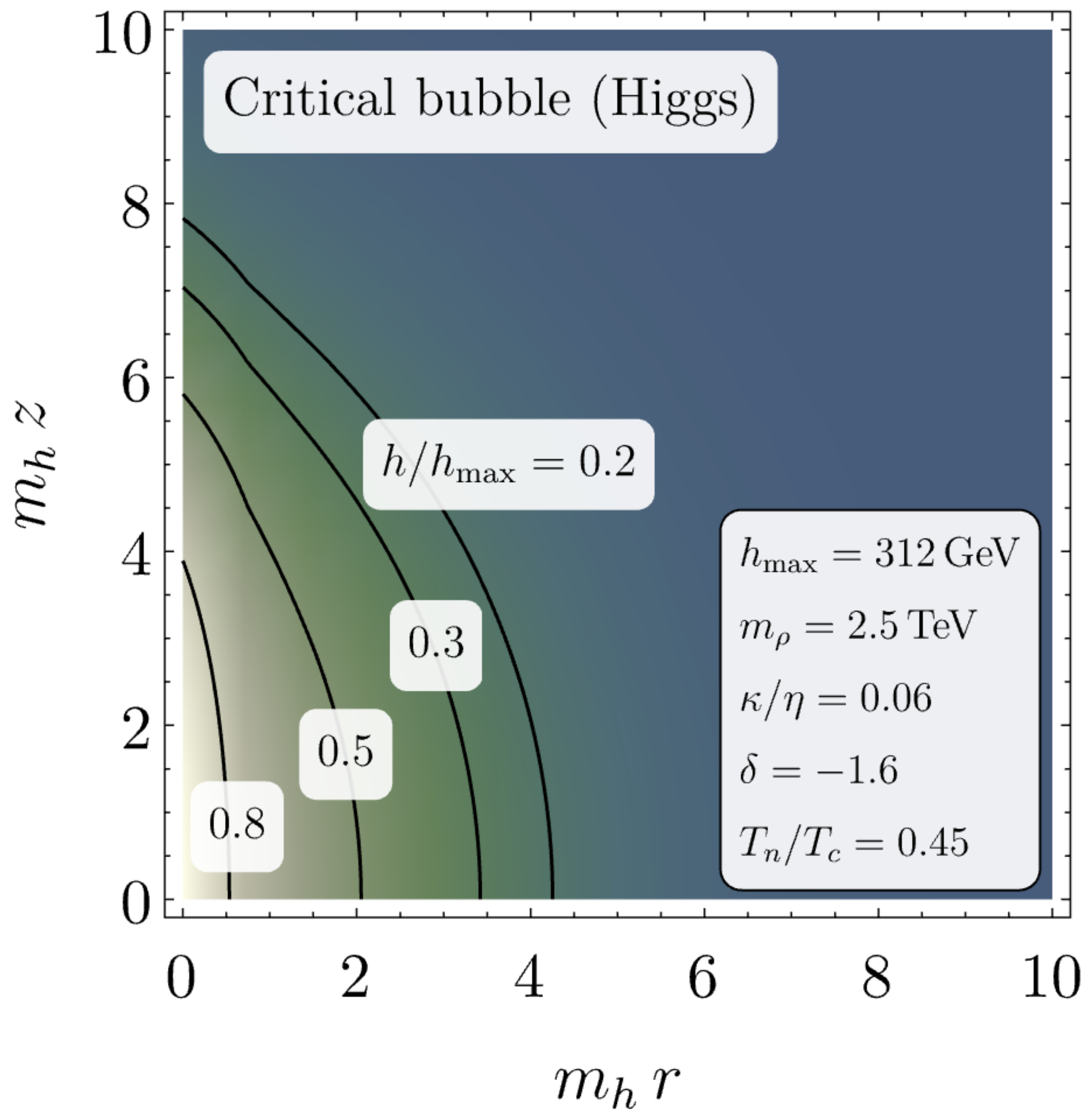
FOPT + PQ

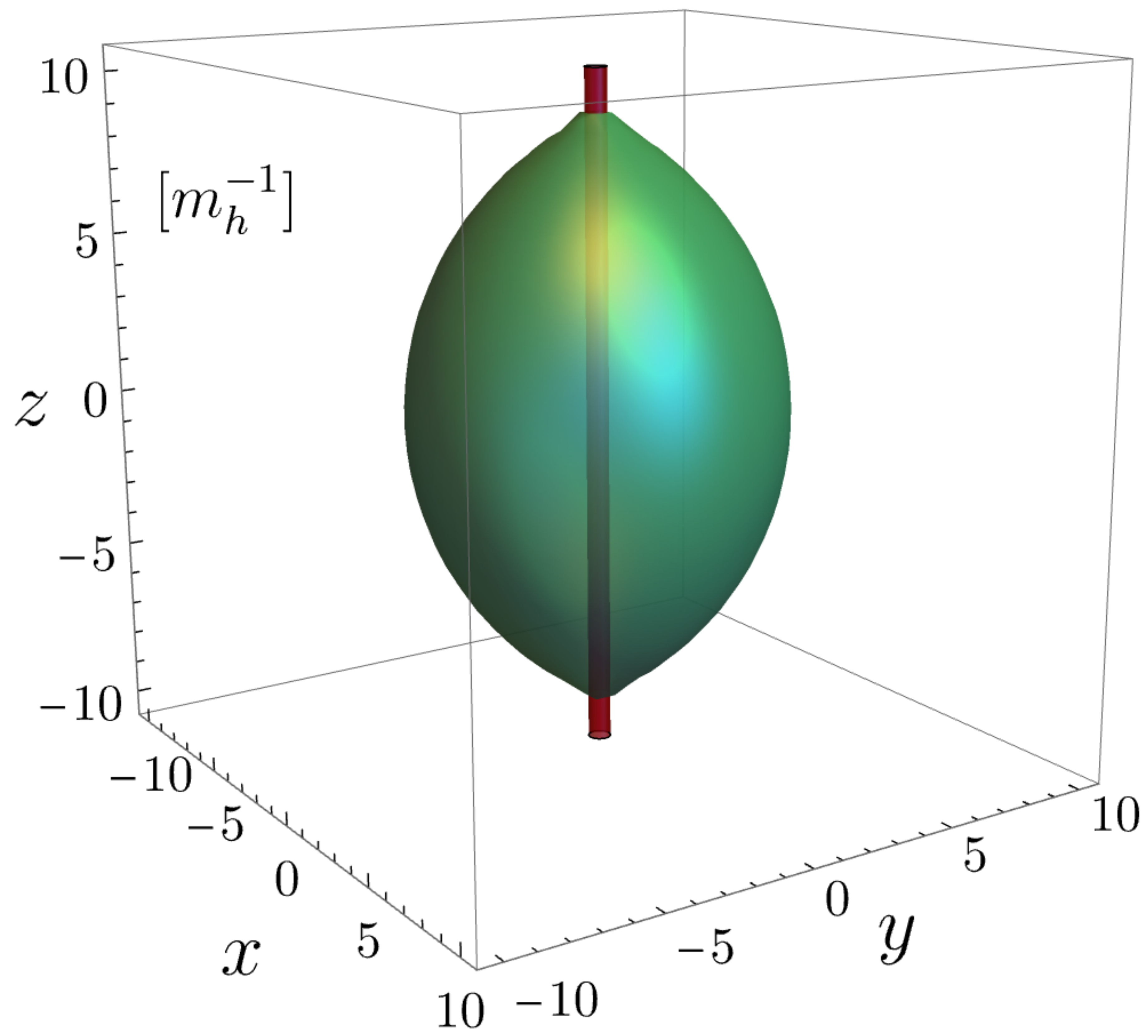


Too slow
Hom.
Nucleation
Seeded
Linear
PDEs
1+1
$m_\rho = 2.5\,\text{TeV}$
$\delta = -1.6$
$T_*/T_c = 0.45$
200
150
100
50
$(S/T)|_{T=T_*}$
10^{-3}
10^{-2}
10^{-1}
κ/η

FOPT + PQ

- Profile of the critical bubble: ★





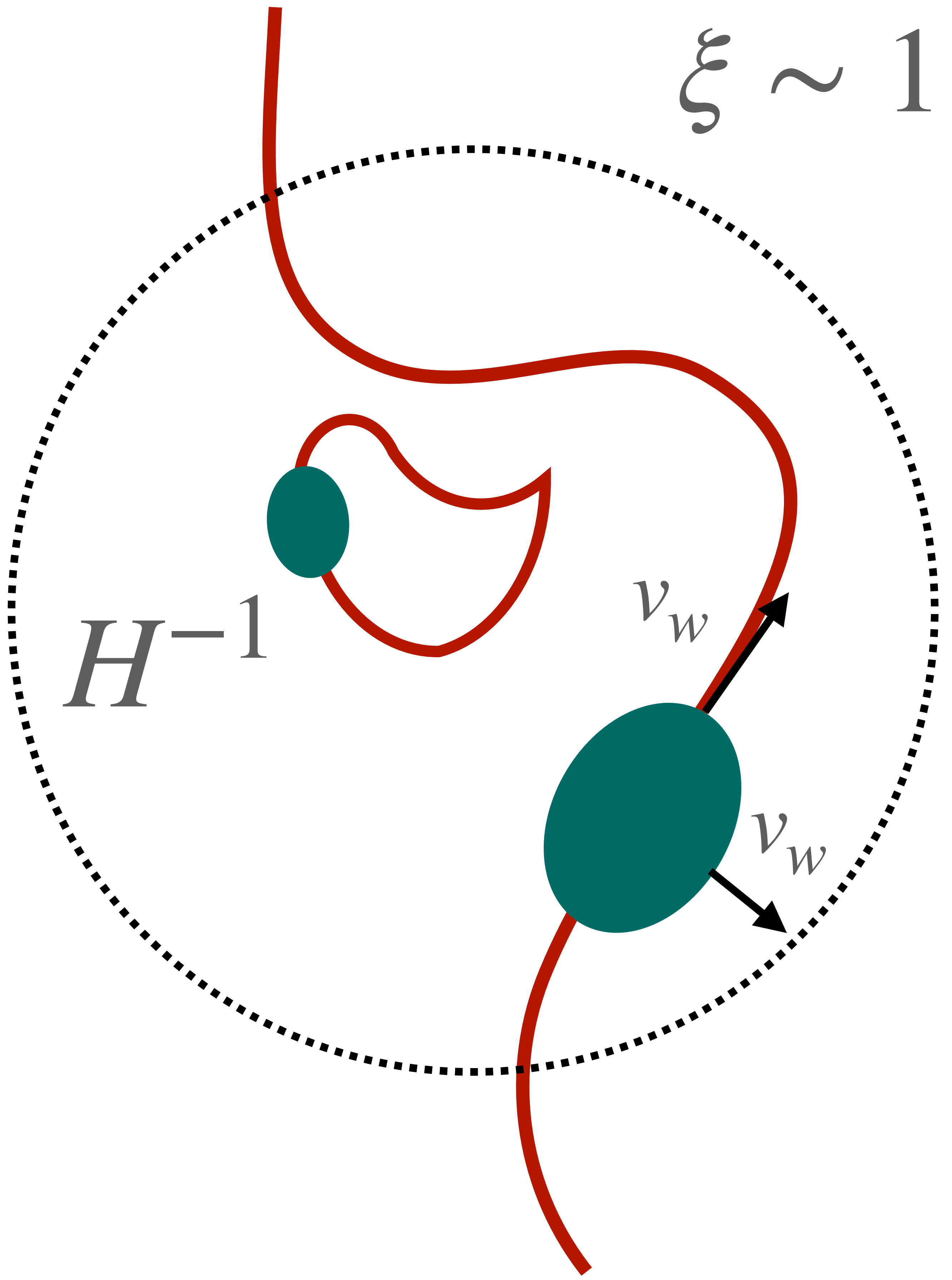
FOPT + PQ

- Percolation as interplay between seeded nucleation rate and density of defects

- Axion—seeded EWPT effectively $\beta/H \sim \xi \sim 10$

- Different velocities parallel or orthogonal to the string?

- Gravitational wave emission before collision (non-spherical bubbles)?



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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- The presence of impurities in the early Universe can strongly affect the way a phase transition proceeds
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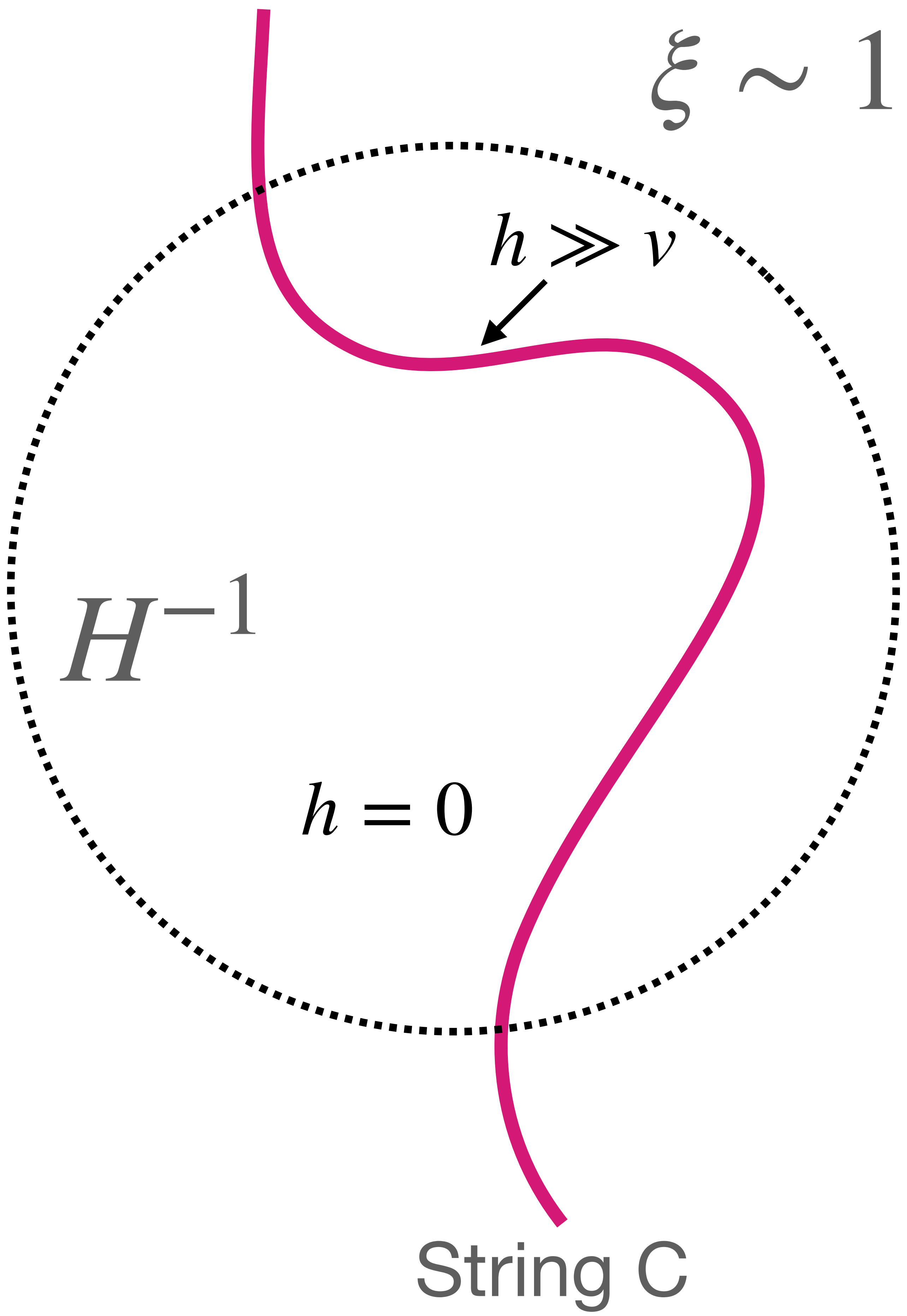
Thank you!

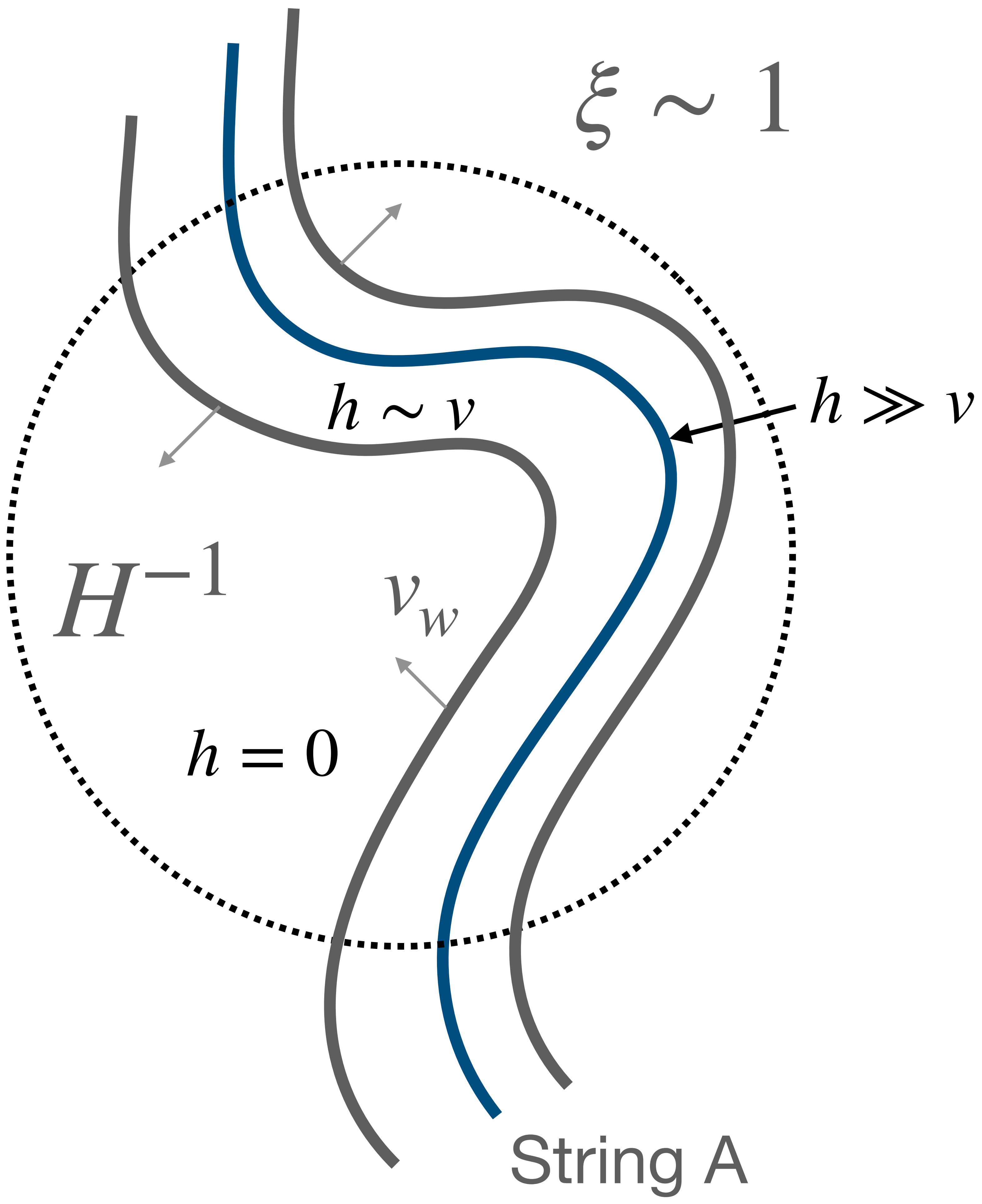
FOPT + PQ

See also Yajnik, PRD (1986)



Δt

Expansion of macroscopic cylindrical bubble wall



Seeded EWPT at LISA