QCD axion strings or seeds?

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], JHEP

SB, Mariotti, [2405.08060]

Crossroads between Theory and Phenomenology - CERN - 13.06.2024

The hydrodynamics of inverse phase transitions

2406.01596

Giulio Barni*[1,2], Simone Blasi,†[3,4] and Miguel Vanvlasselaer‡[4]

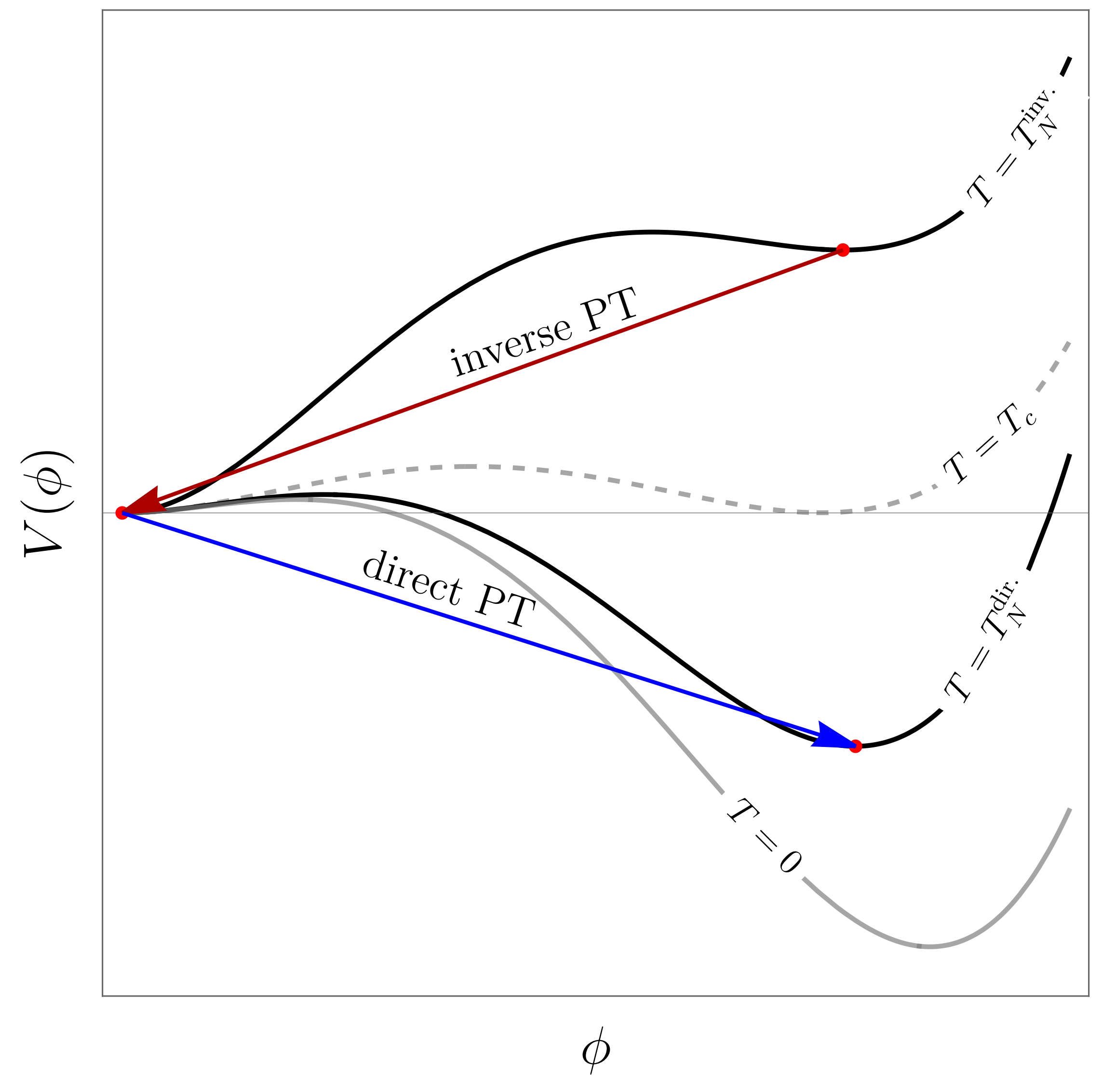
[1] *SISSA International School for Advanced Studies, Via Bonomea 265, 34136, Trieste, Italy*

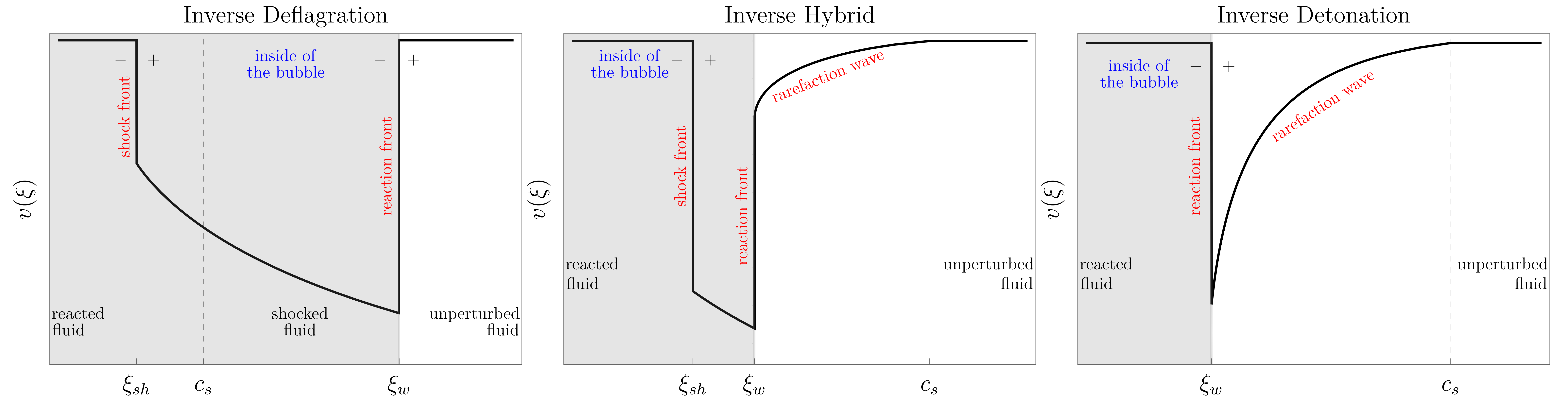
[2] *INFN - Sezione di Trieste, Via Bonomea 265, 34136, Trieste, Italy*

[3] *Deutsches Elektronen-Synchrotron DESY, Notkestr. 85, 22607 Hamburg, Germany*

[4] *Theoretische Natuurkunde and IIHE/ELEM, Vrije Universiteit Brussel, & The International Solvay Institutes, Pleinlaan 2, B-1050 Brussels, Belgium*

3 Jun 2024





See also Buen-Abad, Chang, Hook [2305.09712], PRD

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

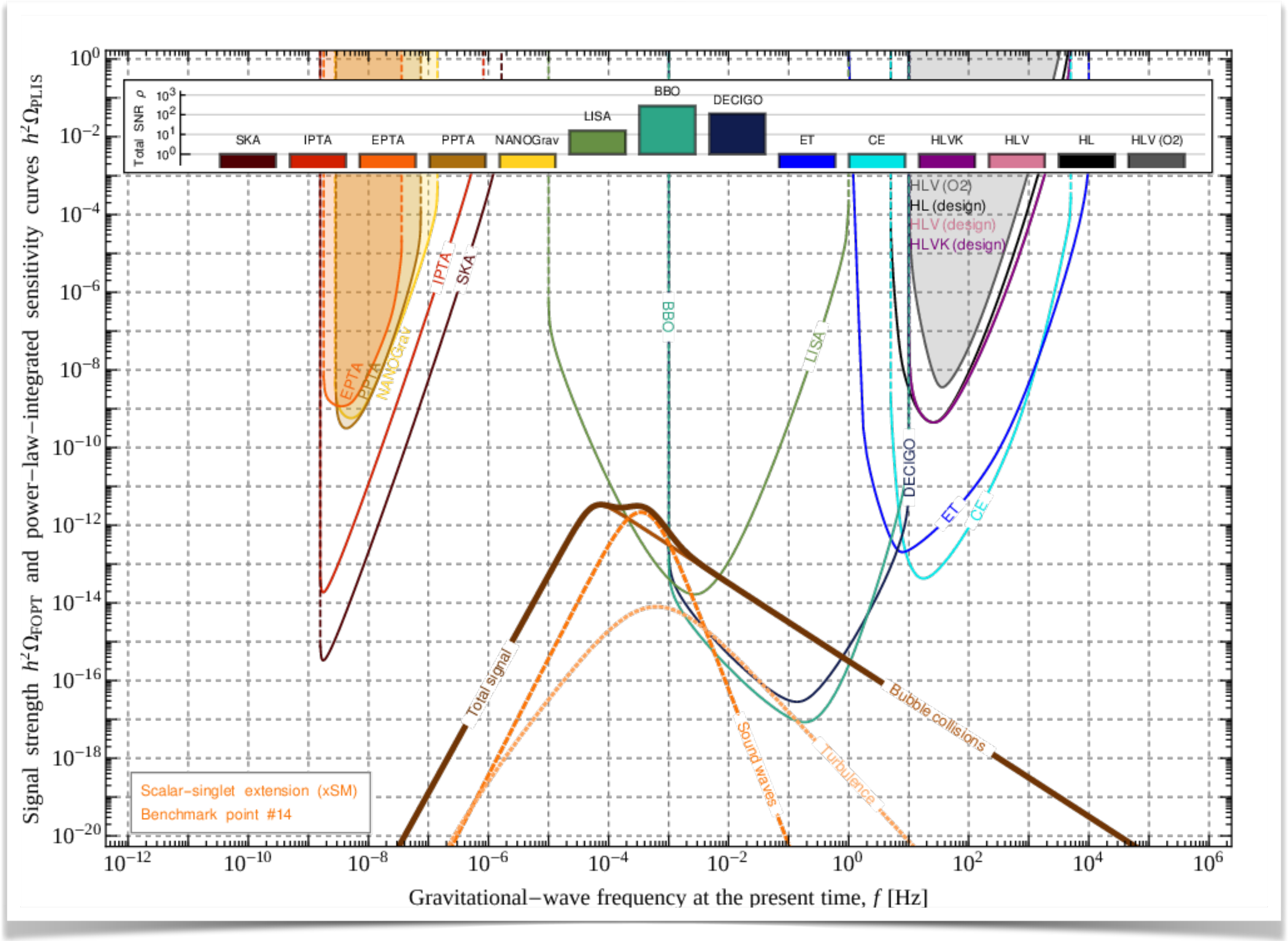


Fig. from Schmitz [2002.04615] JHEP

Nucleation theory

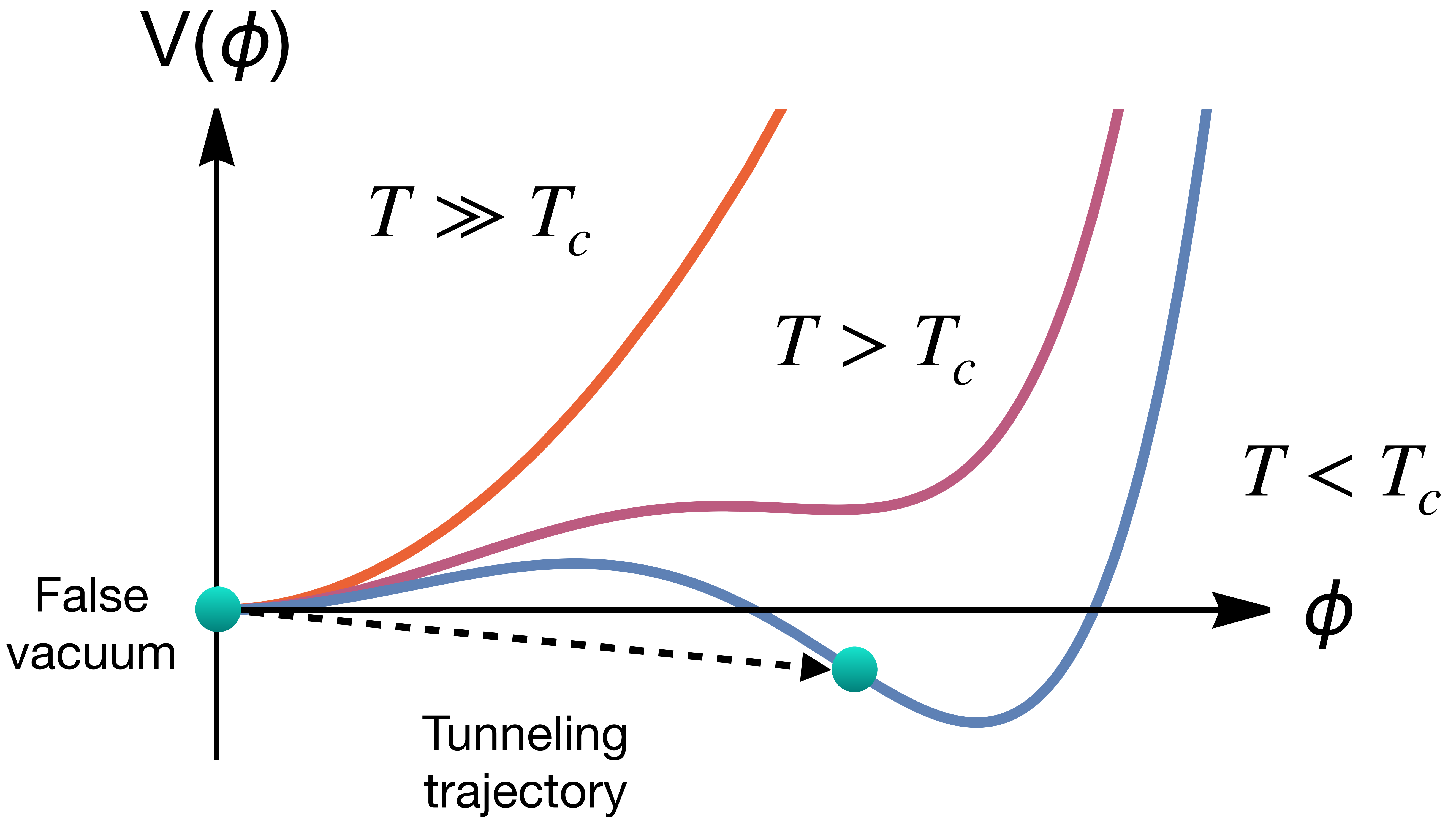
Coleman 1977 (PRD)
Callan, Coleman 1977 (PRD)
Linde 1983 (NPB)

- 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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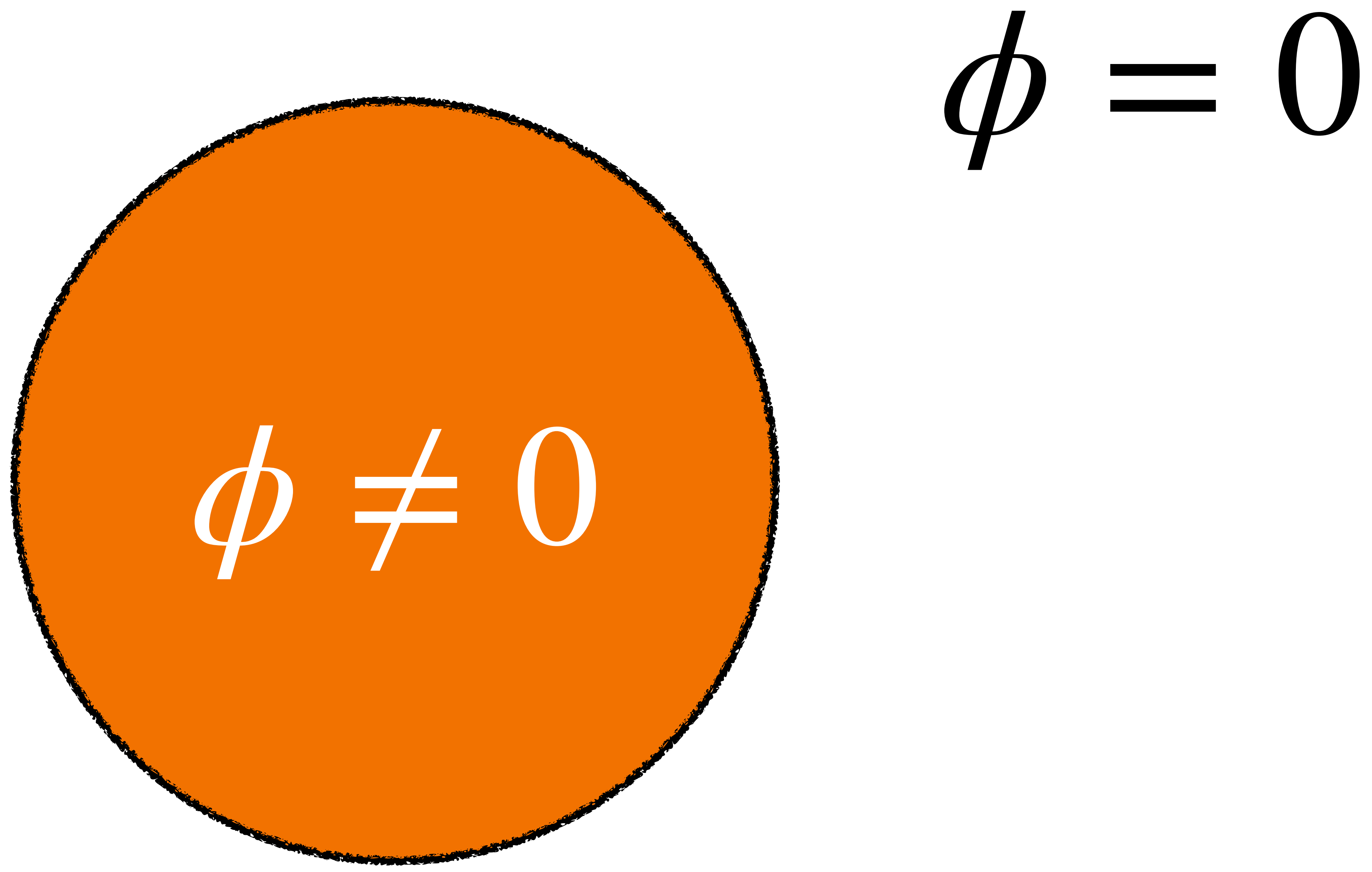


What about impurities?

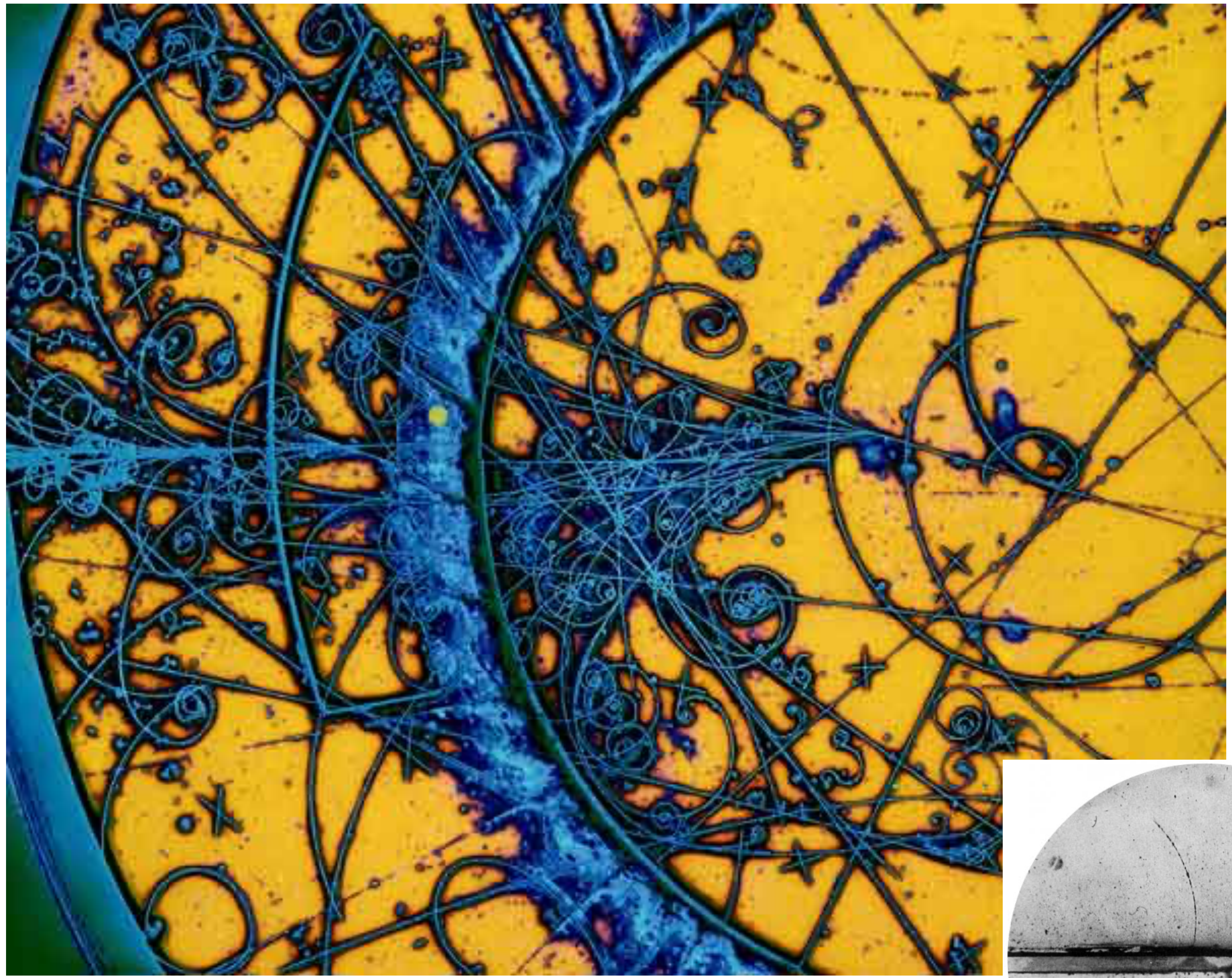
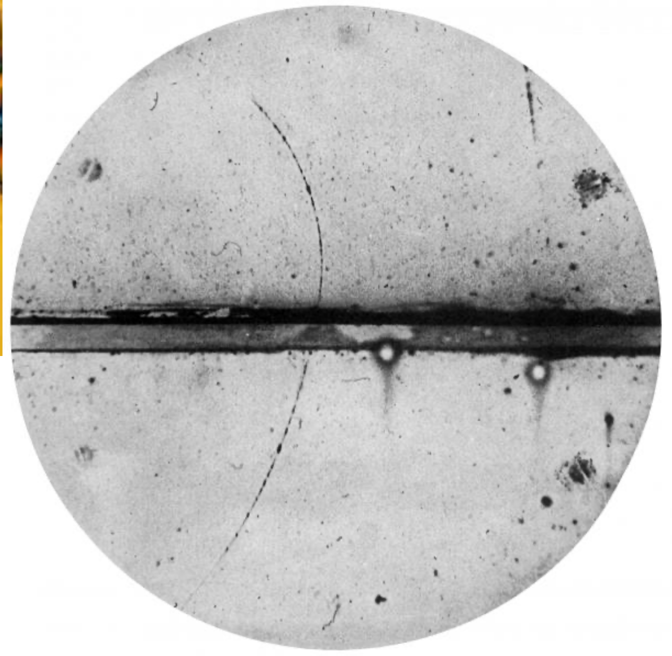



Figure: Bubble chamber

The nature of impurities

- Compact objects and gravitational effects

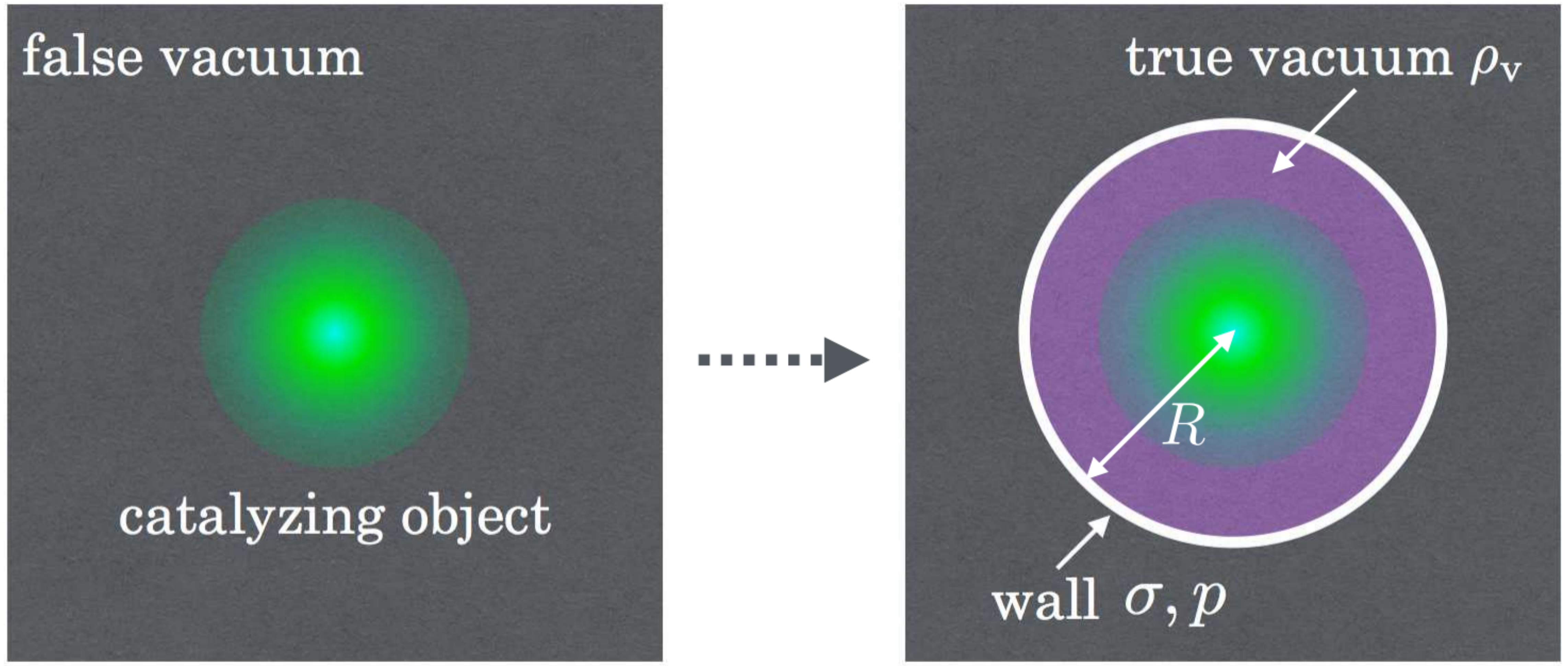


Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

- Primordial density fluctuations

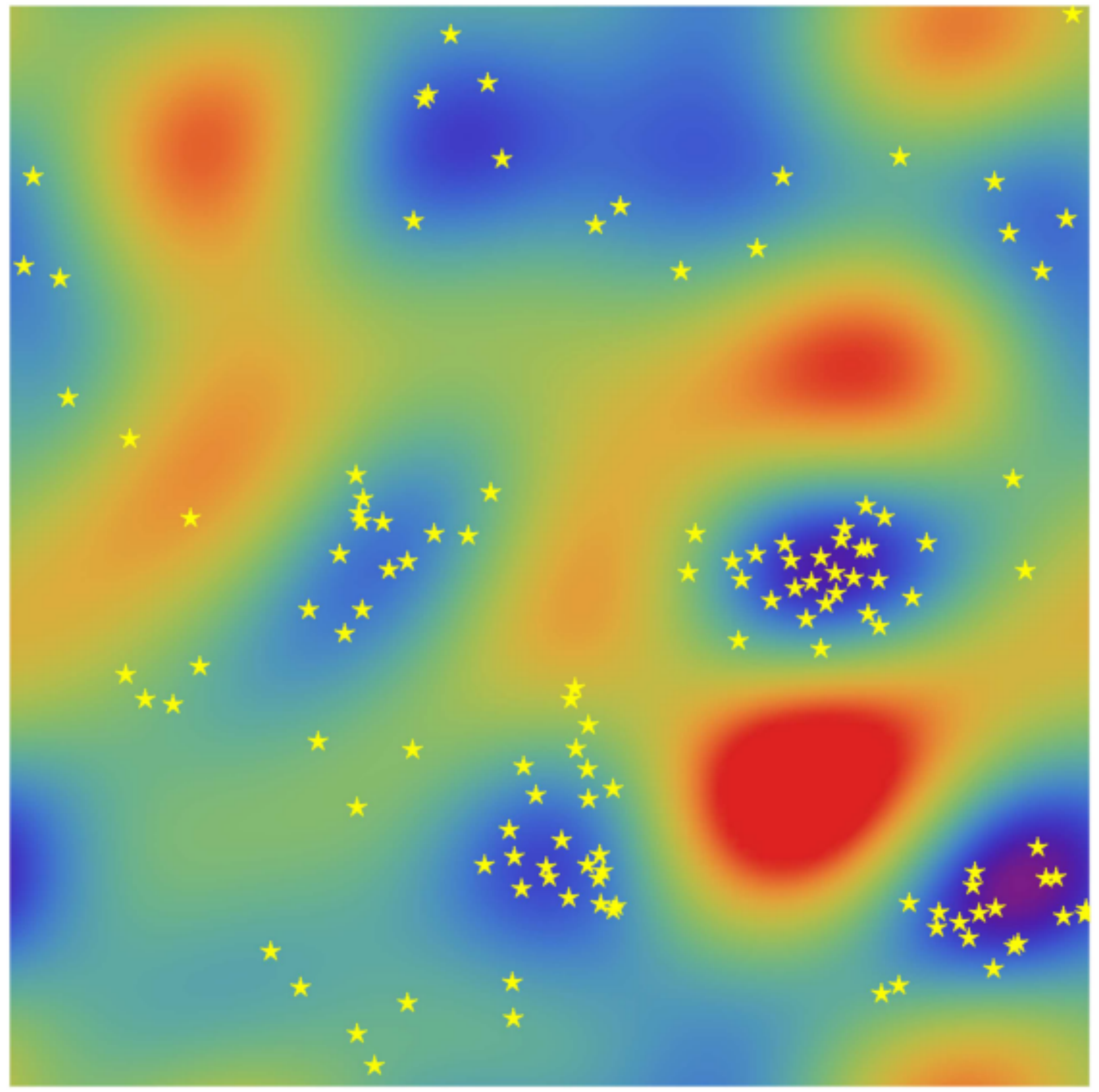


Fig. from Jinno, Konstandin, Rubira, van de Vis, [2108.11947], JCAP

The nature of impurities

- Topological defects

Domain walls

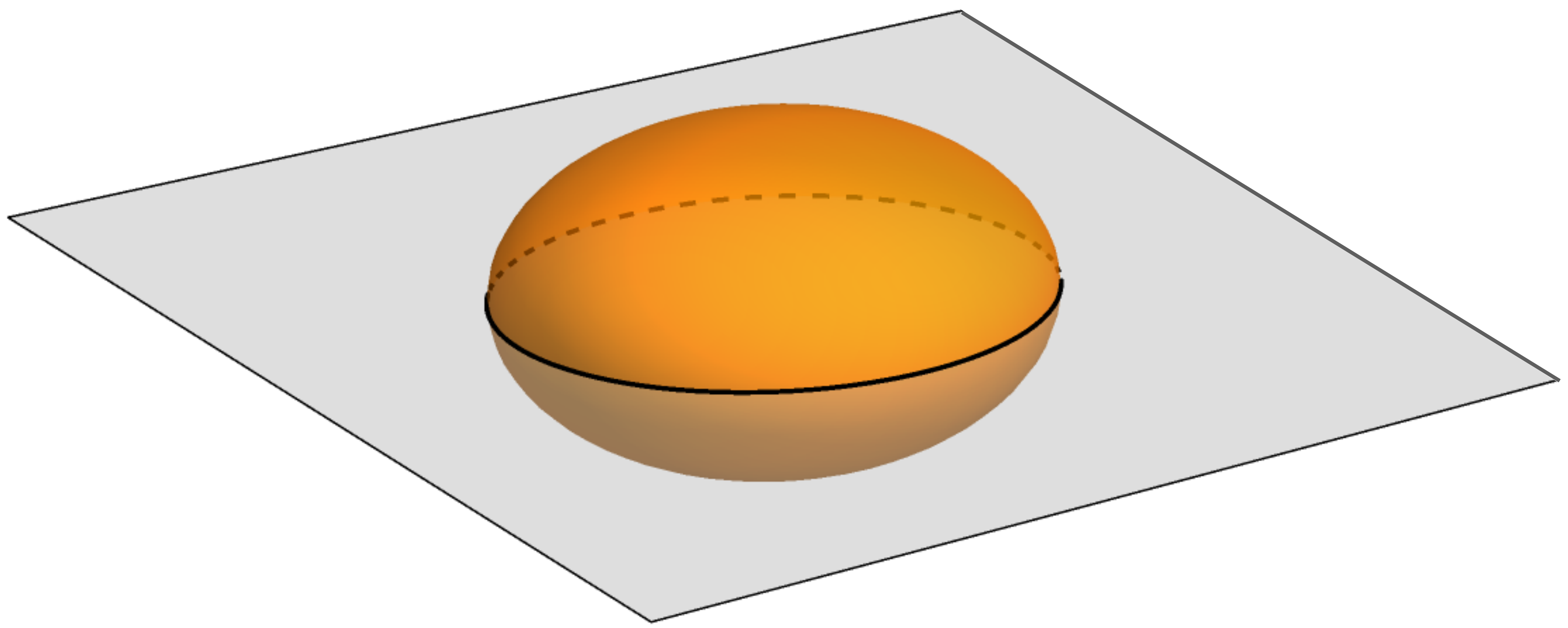


Fig. From Agrawal, **SB**, Mariotti, Nee [2312.06749]

Strings

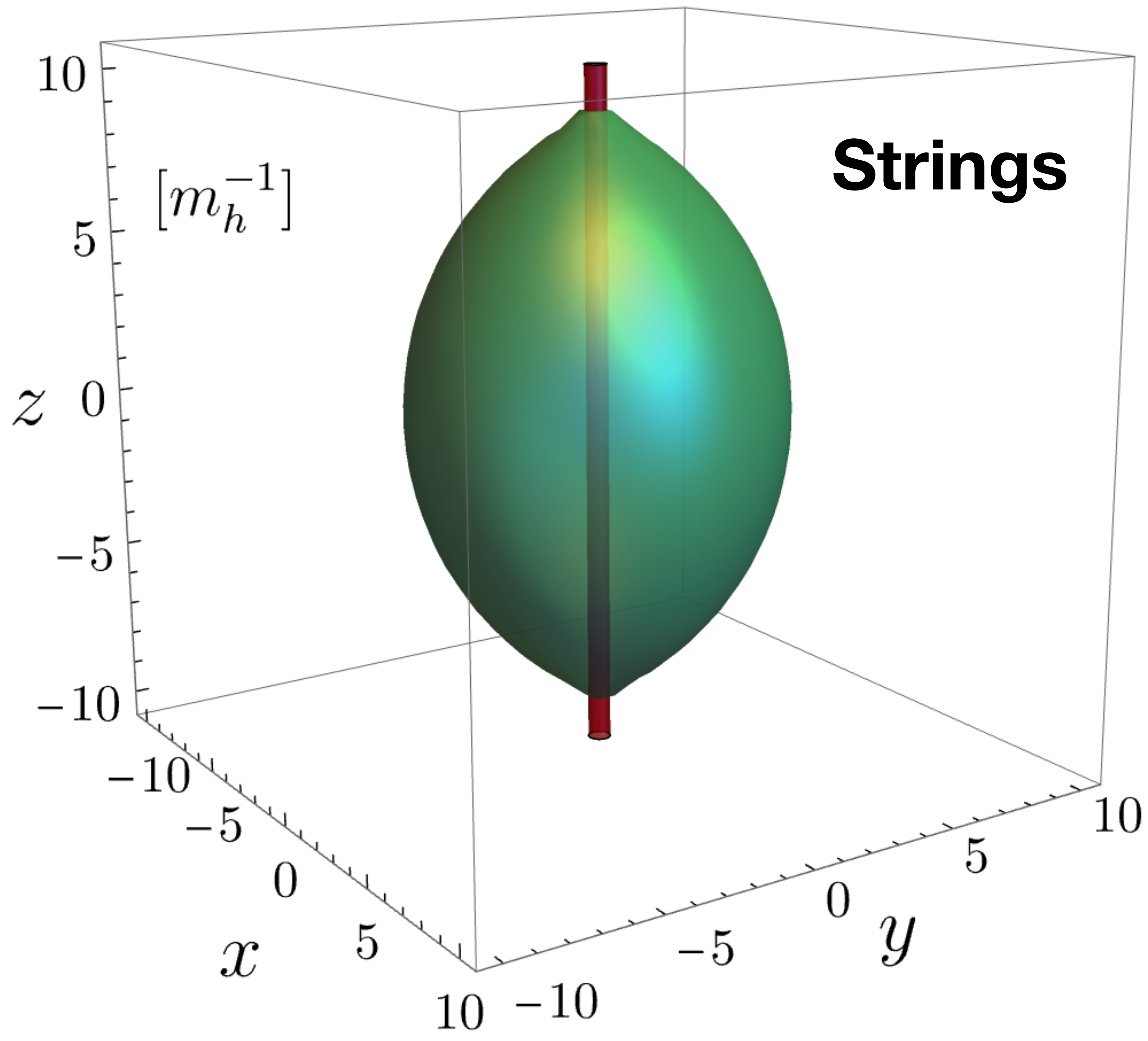
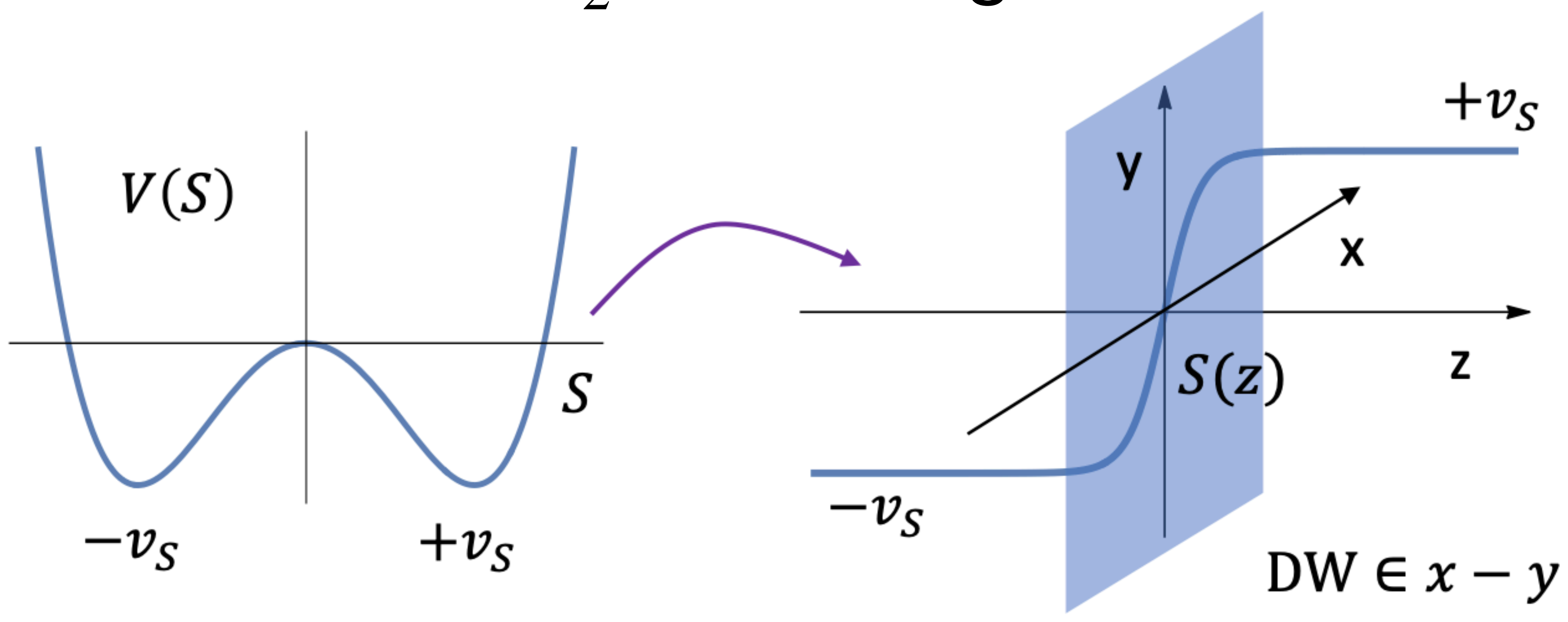


Fig. From **SB**, Mariotti, [2405.08060]

Topological classification

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

$\mathbb{Z}_2 \to$ nothing



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

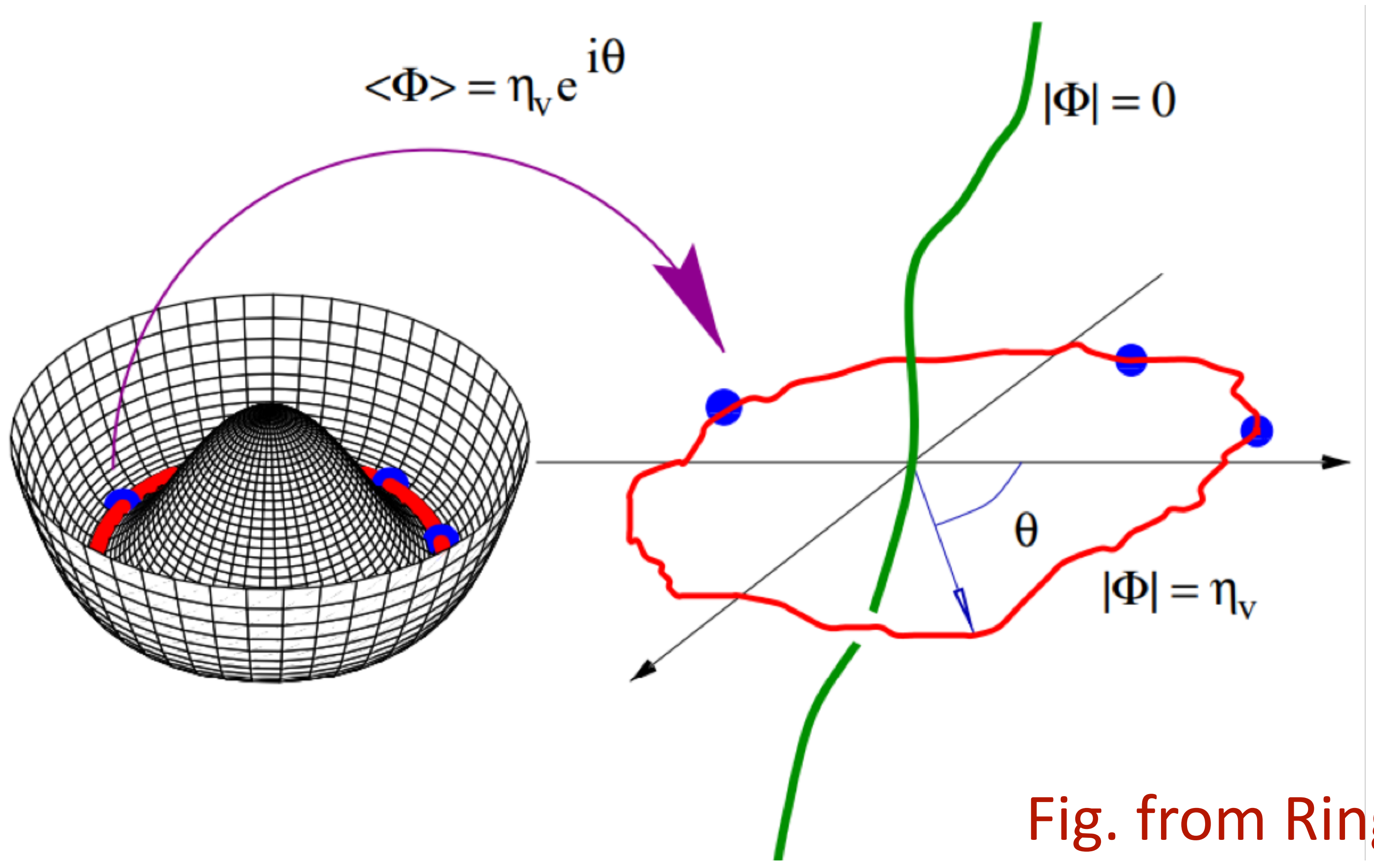
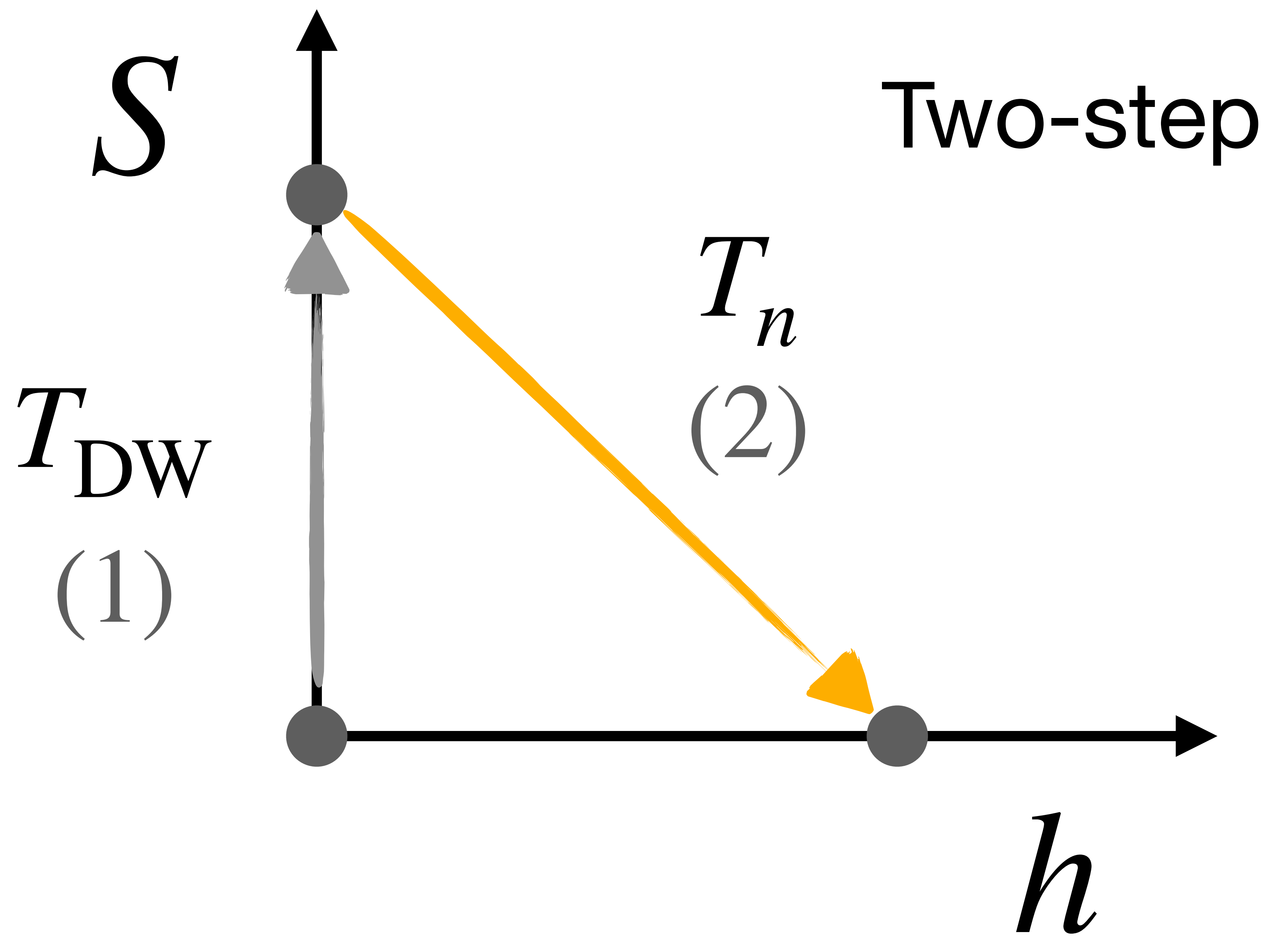


Fig. from Ringeval 2010

EWPT 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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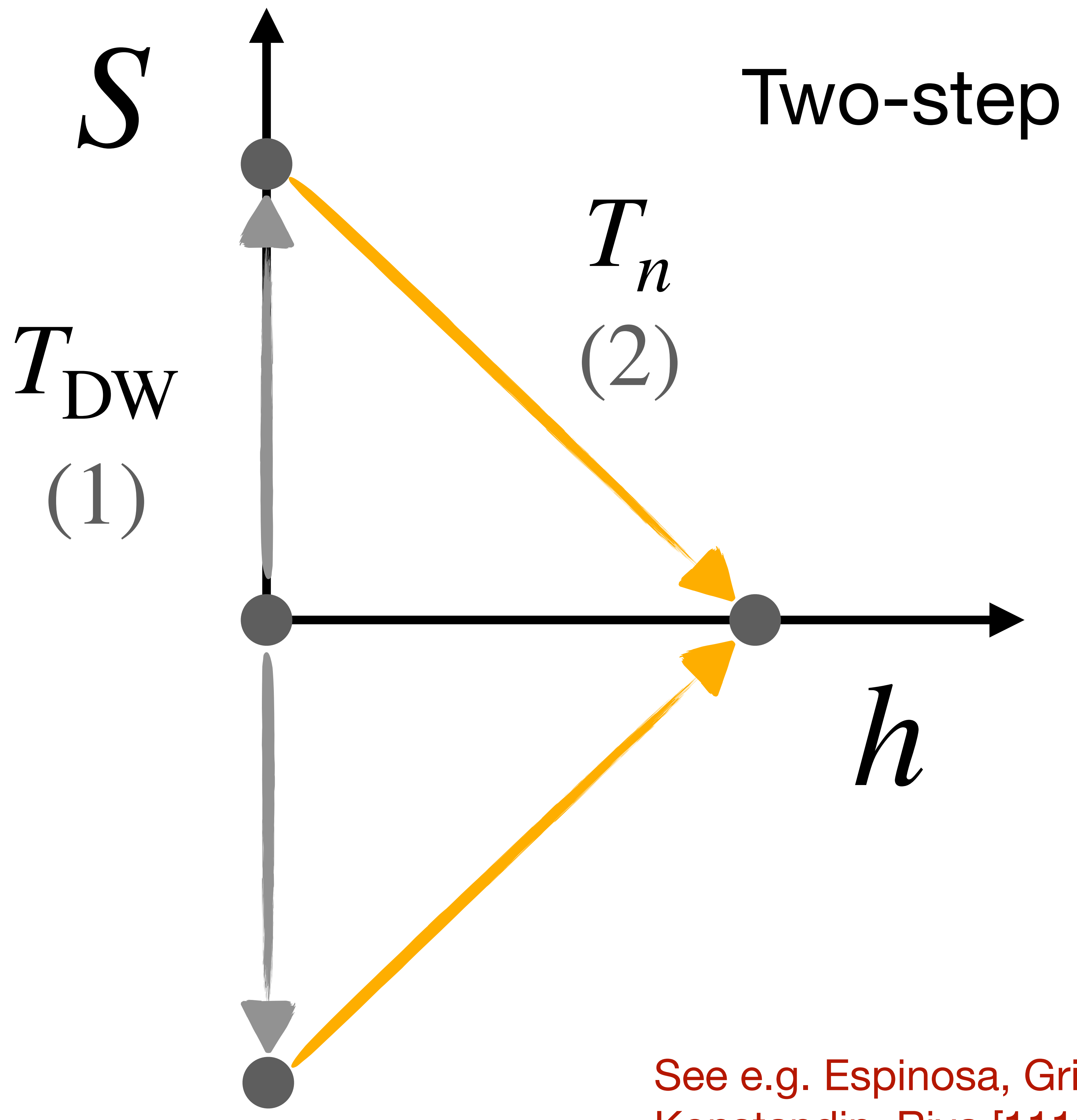

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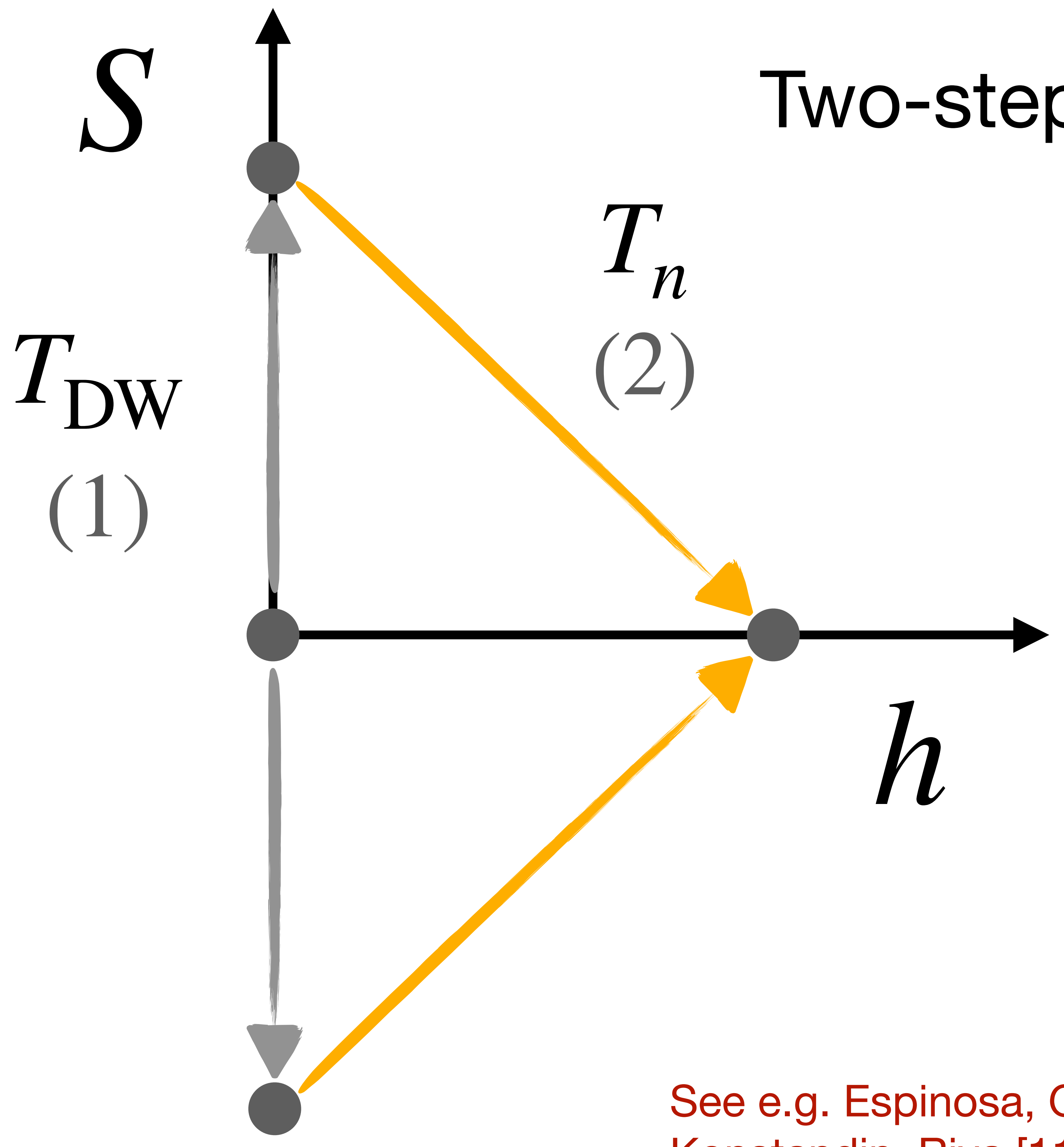
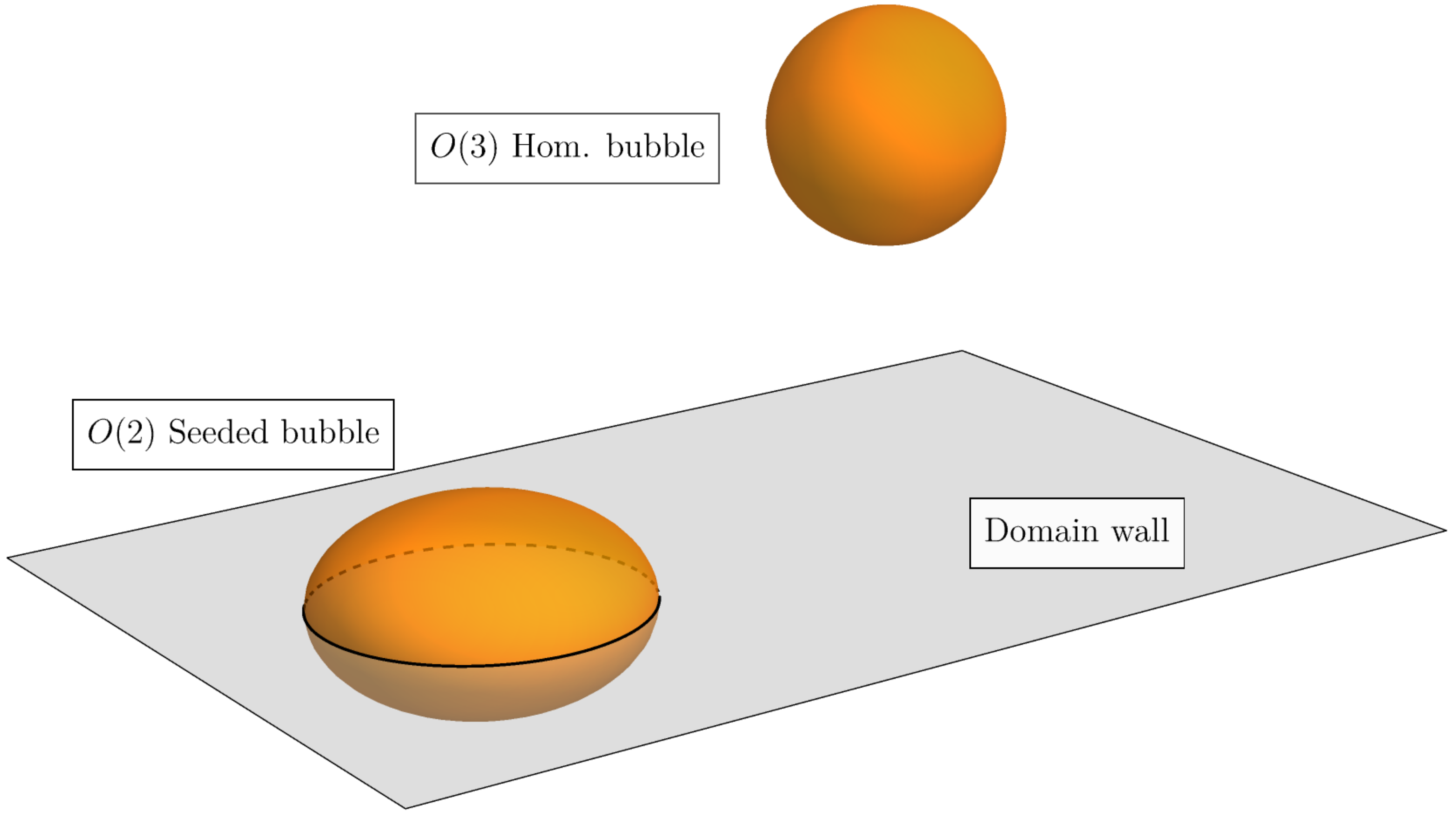


Two-step transition

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

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

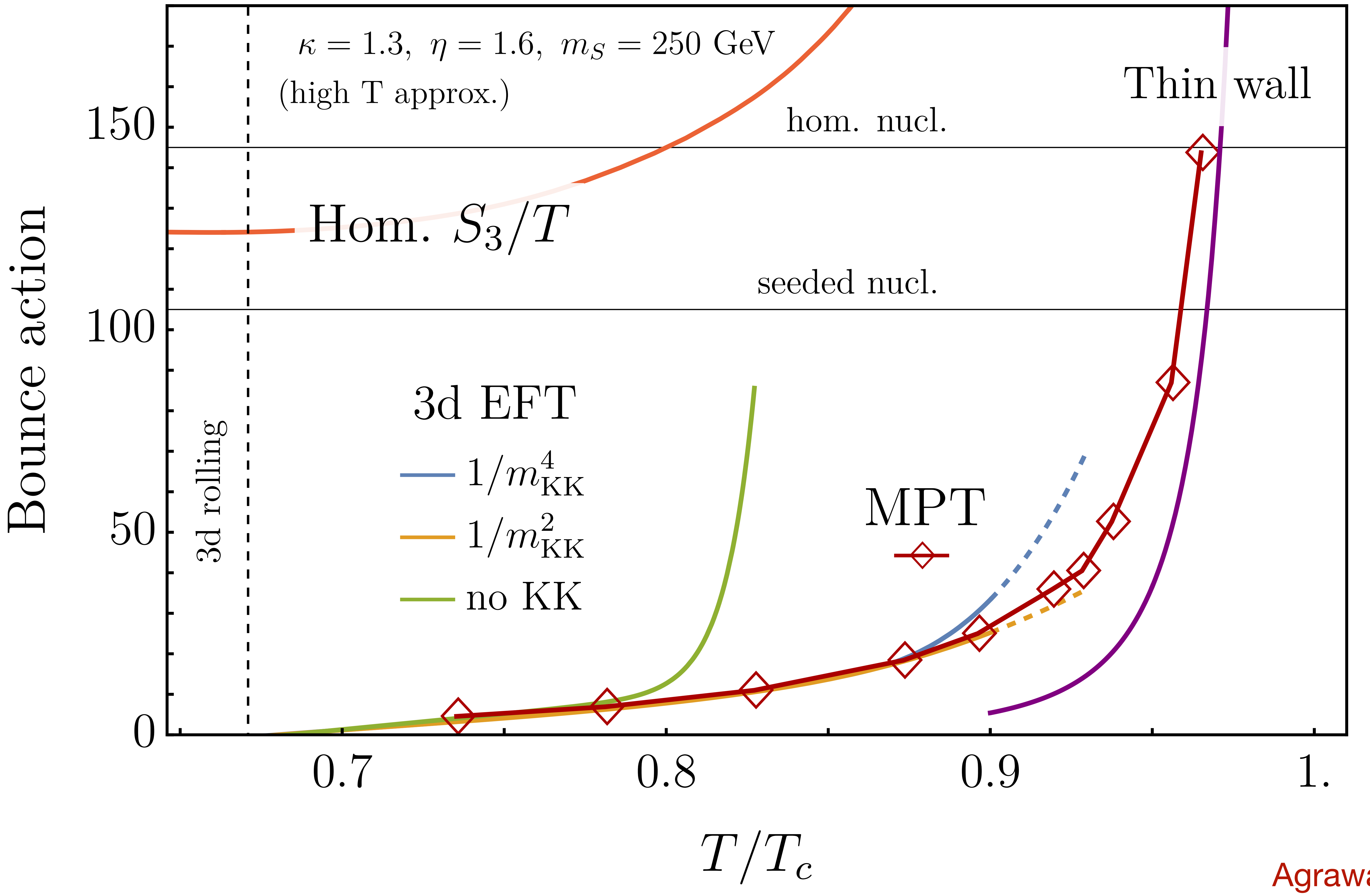


SB, Mariotti [2203.16450], PRL

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

EWPT with a singlet

- Homogenous vs seeded nucleation rate:

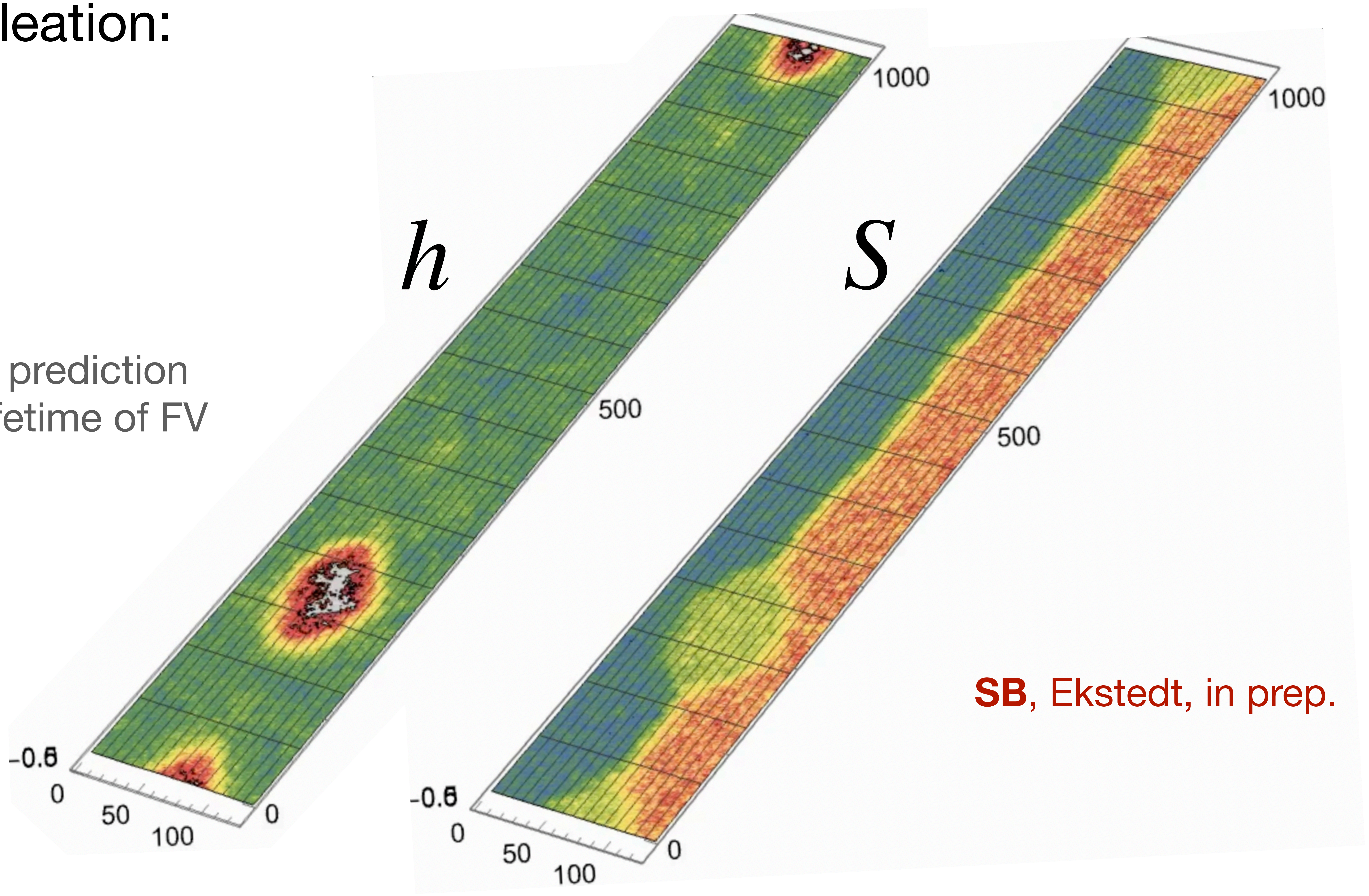


Agrawal, **SB**, Mariotti, Nee [2312.06749]

EWPT with a singlet

- Real time bubble nucleation:

Crosscheck theoretical prediction
for the nucleation rate/lifetime of FV

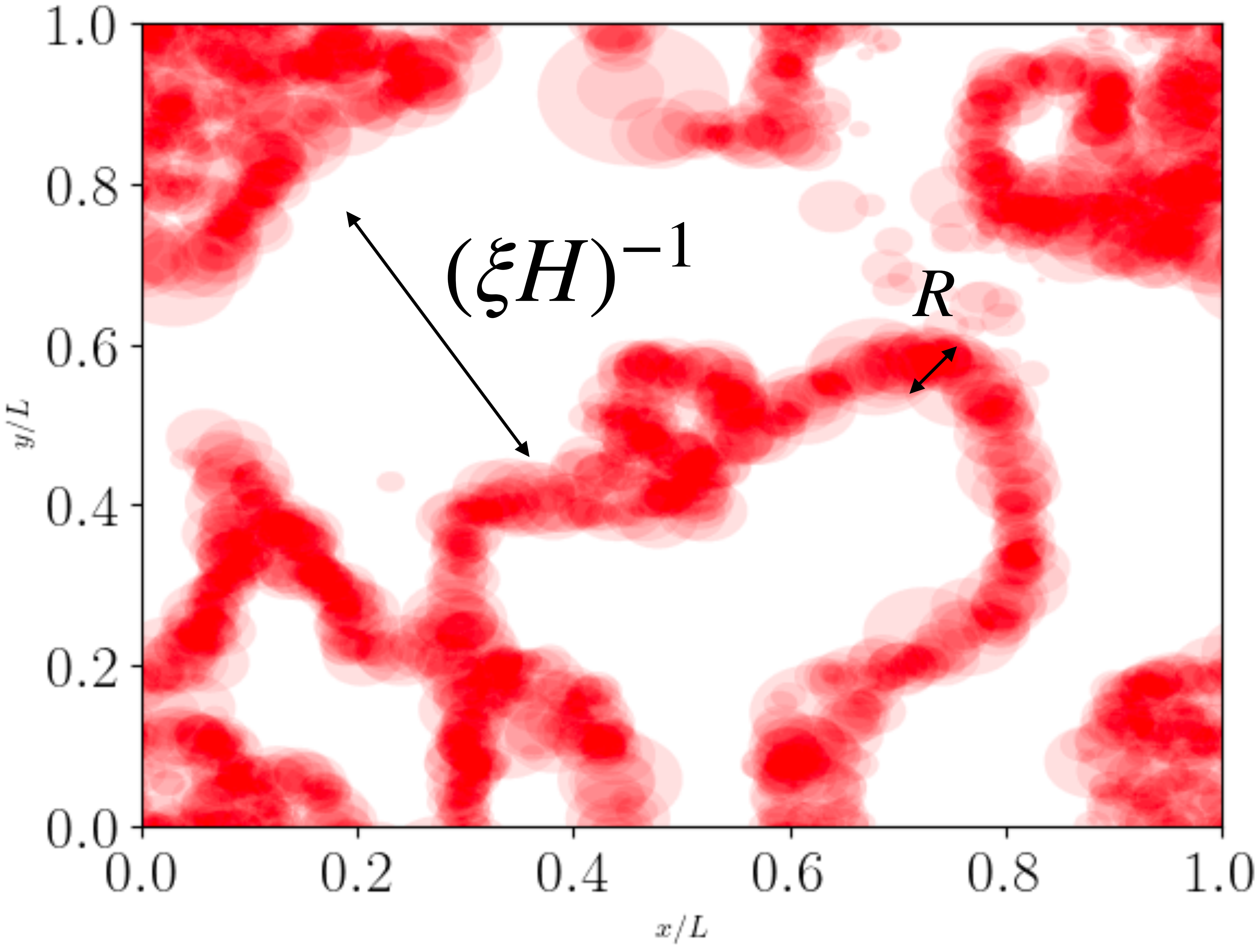


SB, Ekstedt, in prep.

GWs from seeded bubbles

- Domain wall network mimicked by Ising model

- Spectrum shifted to IR with enhanced amplitude



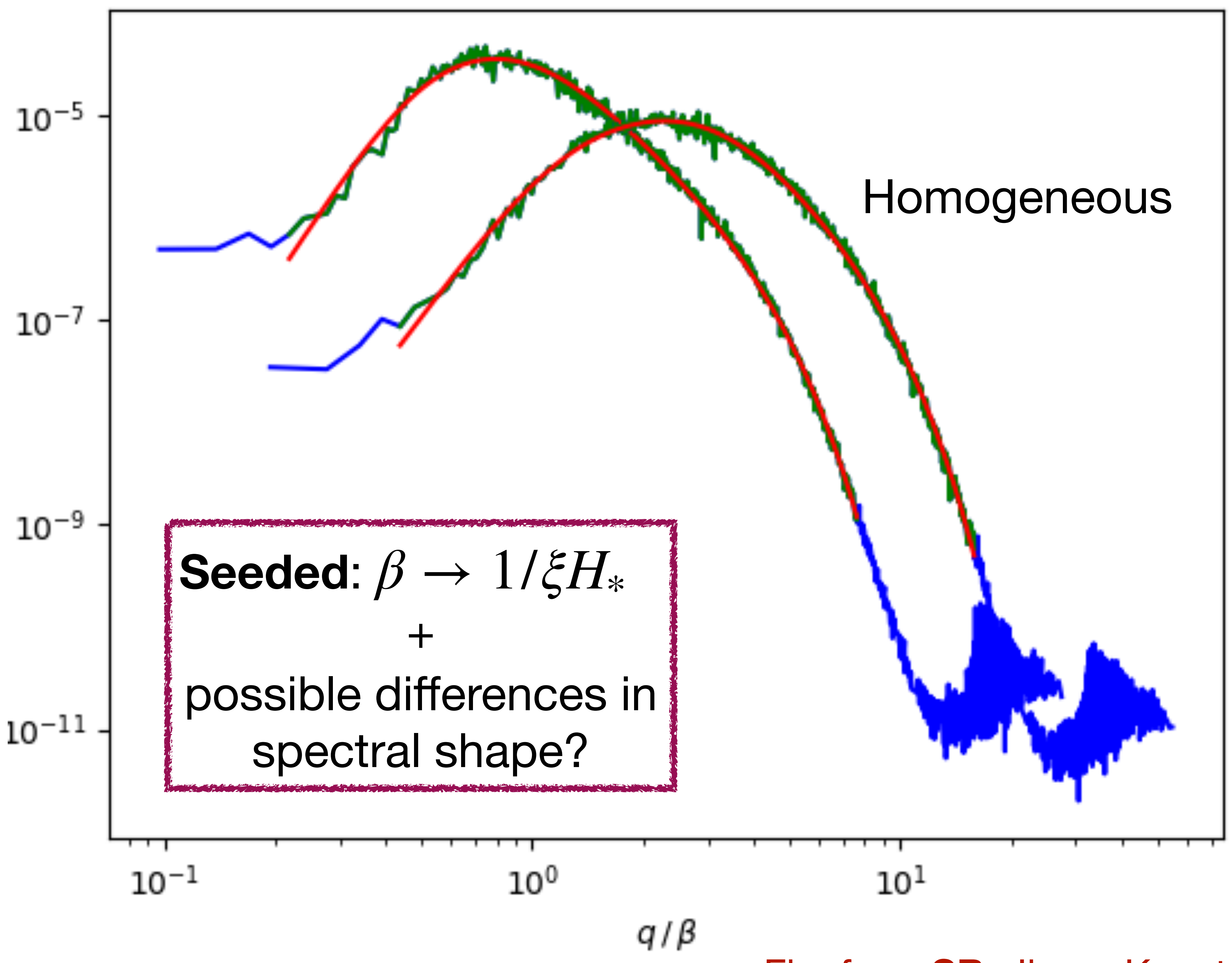


Fig. from **SB**, Jinno, Konstandin, Rubira, Stomberg [2302.06952] JCAP

What about other defects?

SB, Mariotti [2405.08060]

QCD axion strings

T

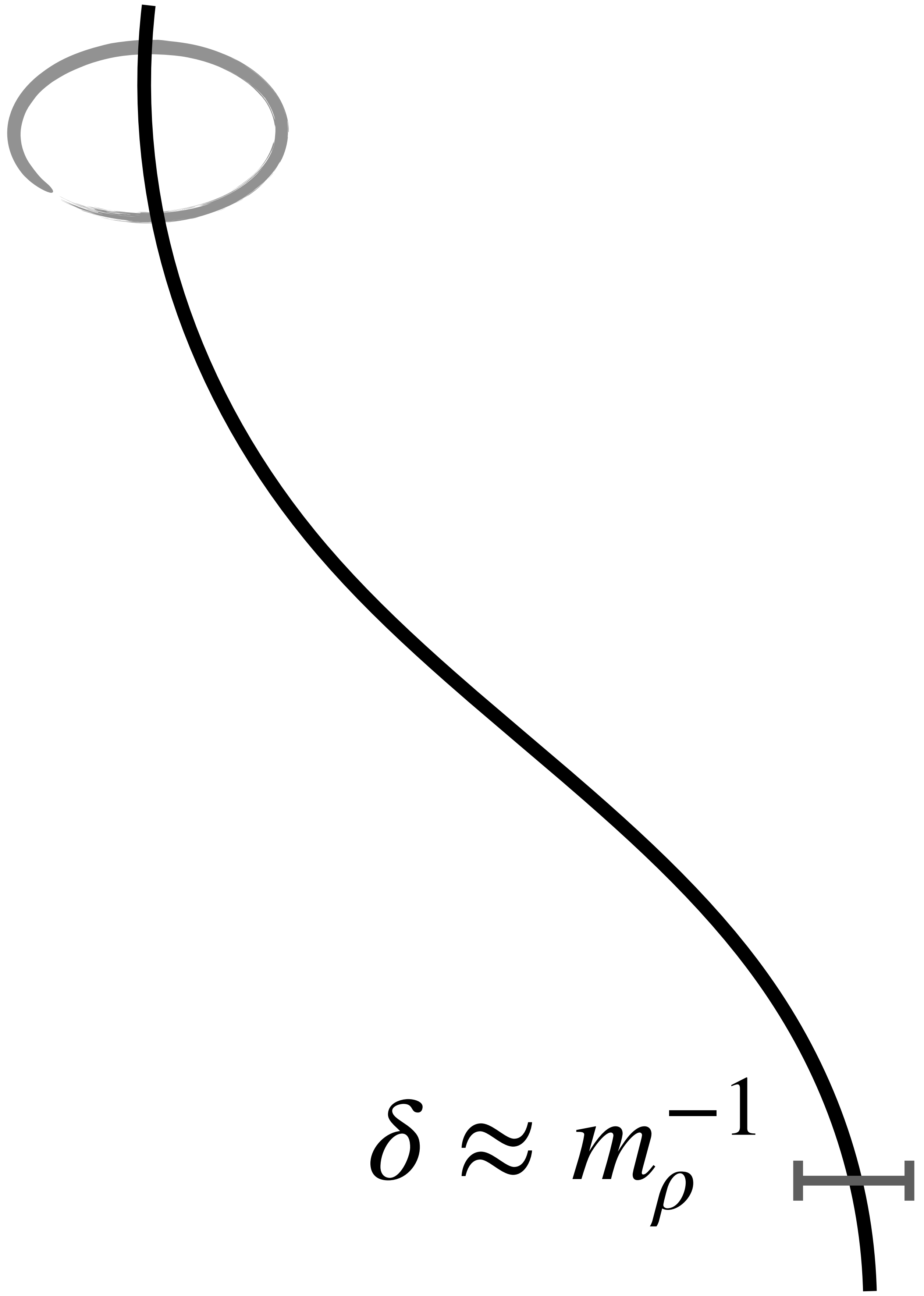
f_a

- Strings form at PQ phase transition

QCD

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

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



$\delta \approx m_\rho^{-1}$

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???

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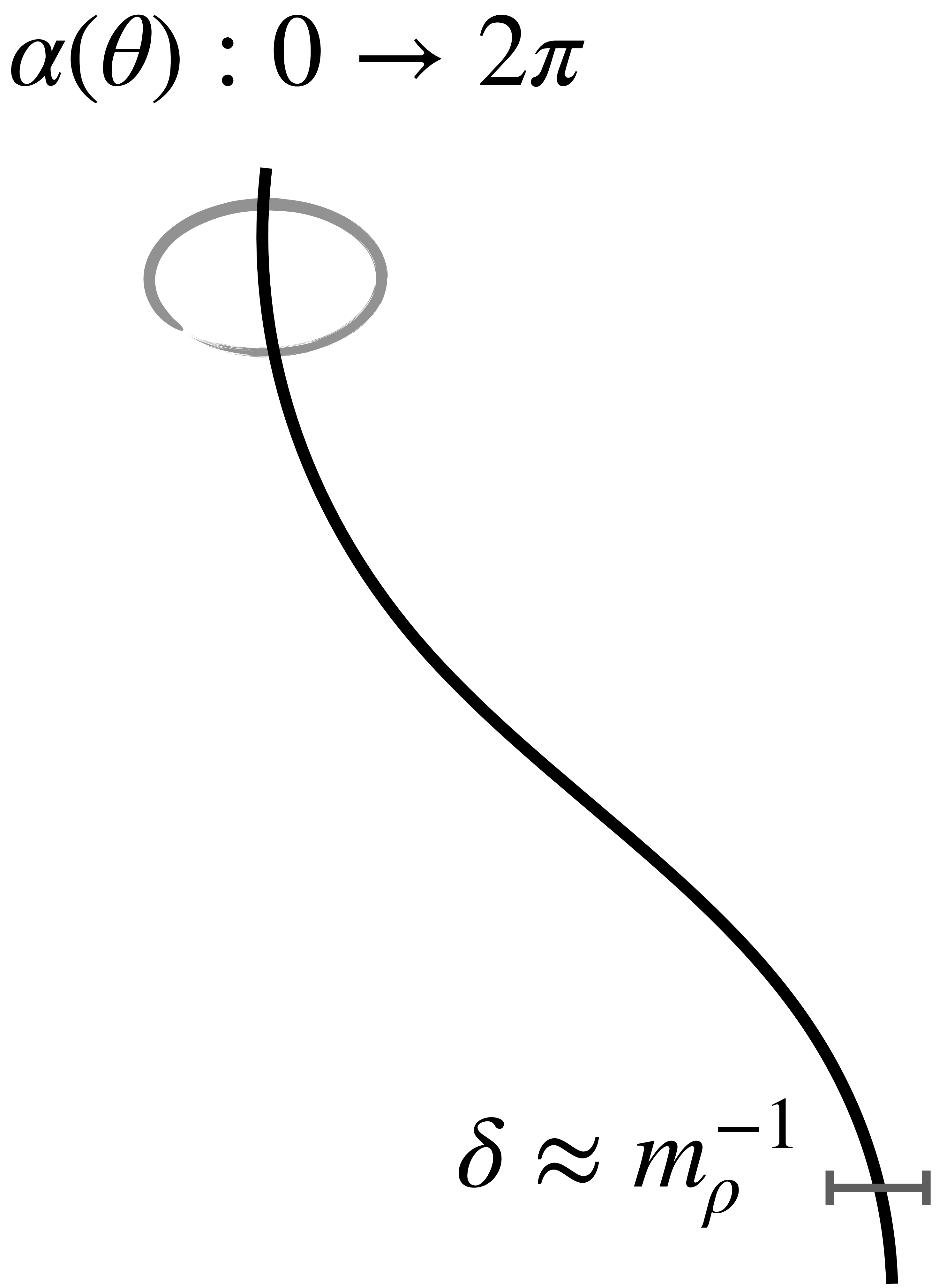
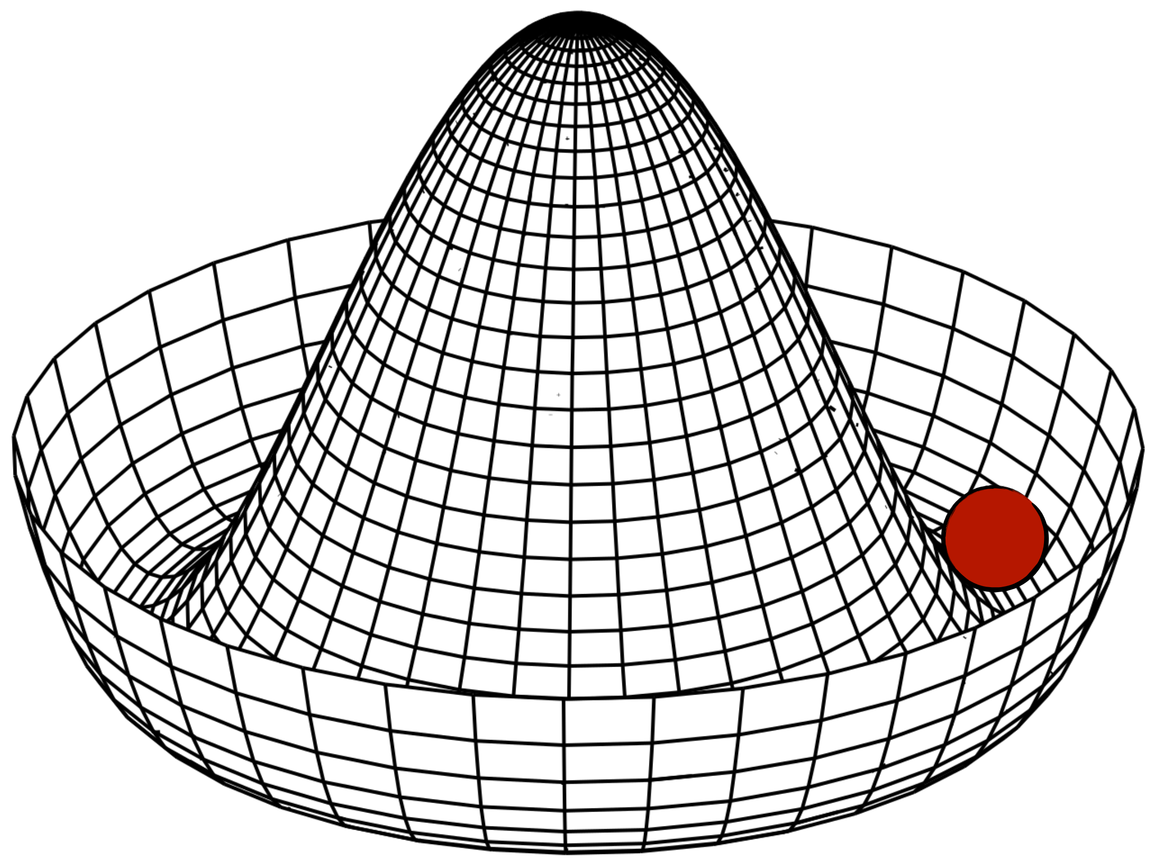


QCD axion strings

- Potential for PQ field

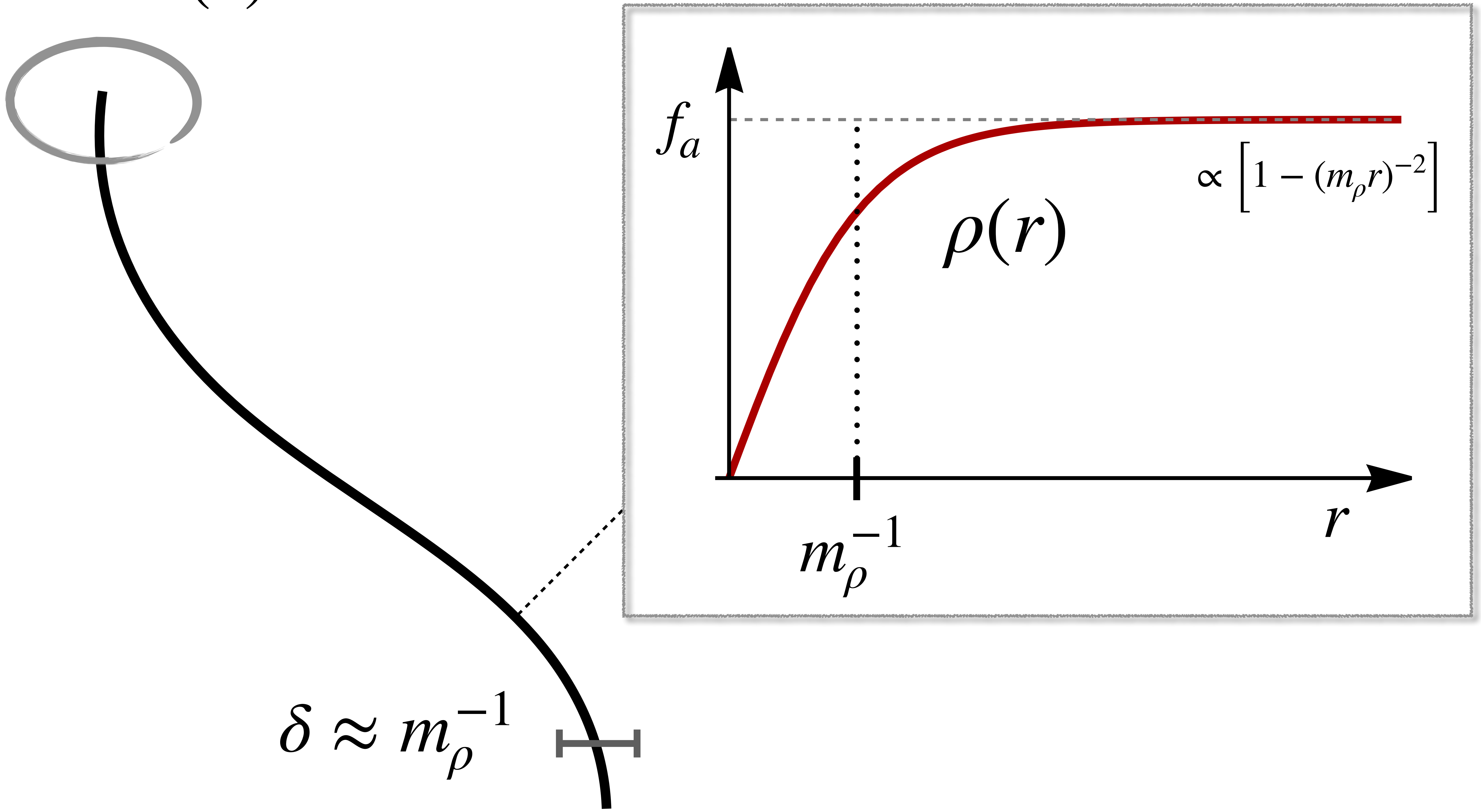
$$\Phi = \rho e^{i\alpha}$$



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

- Global string solution

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



QCD axion strings

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

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

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

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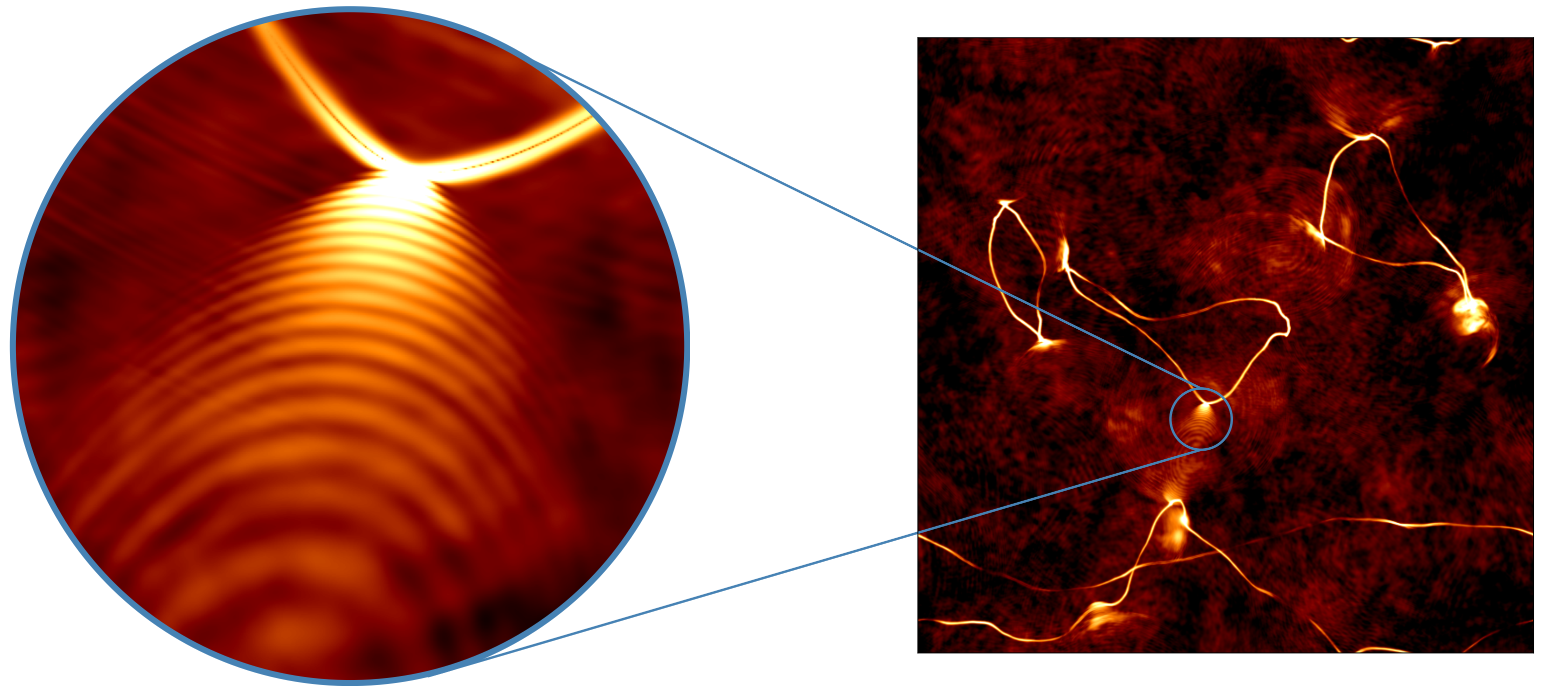
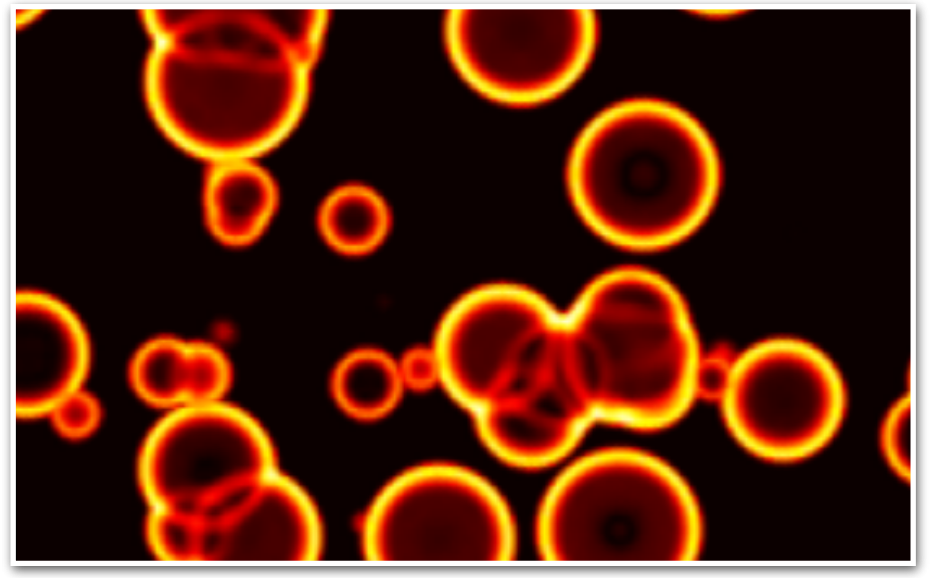
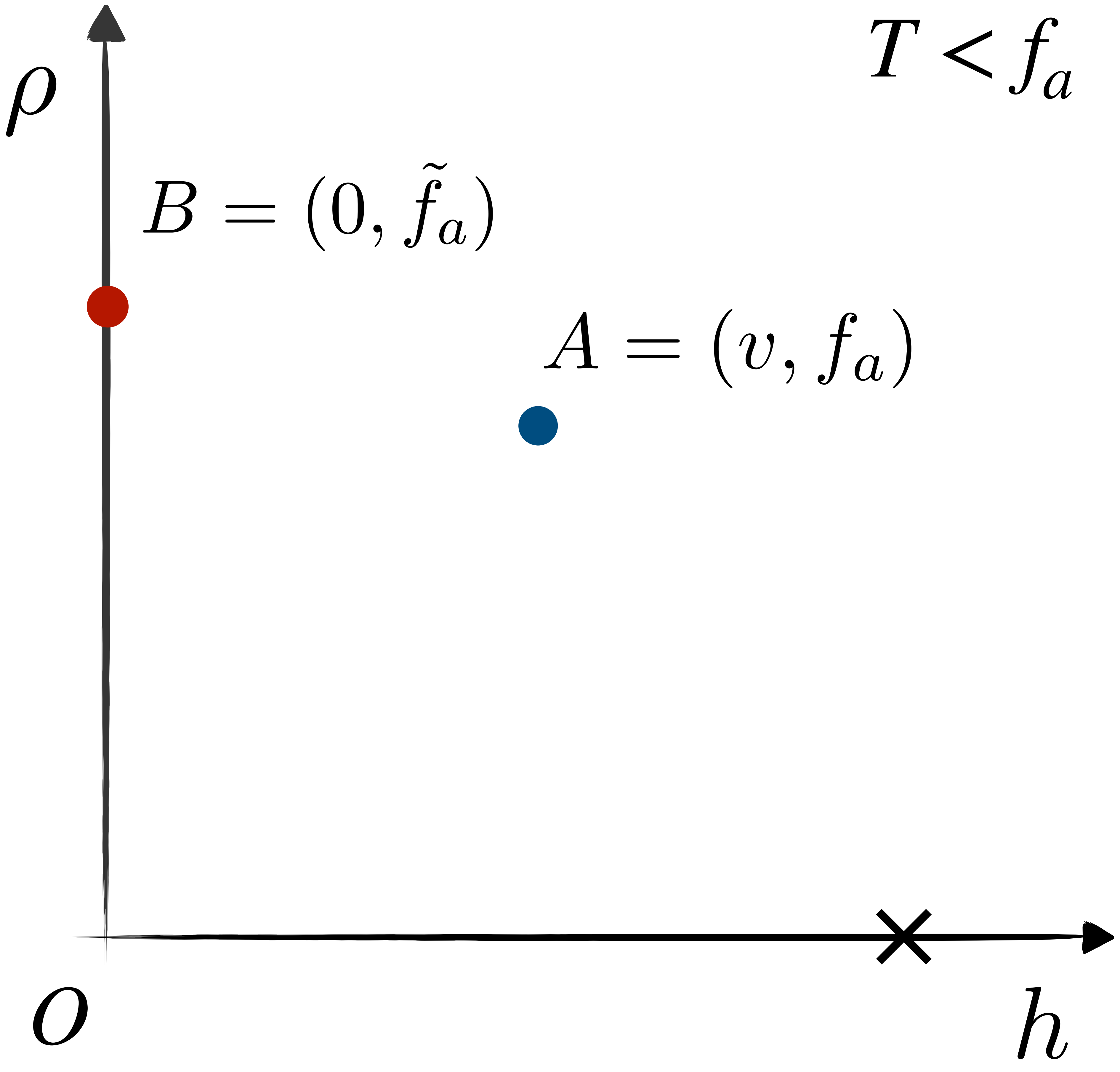


How do strings affect electroweak symmetry breaking?



String solutions

- Relevant points in field space:



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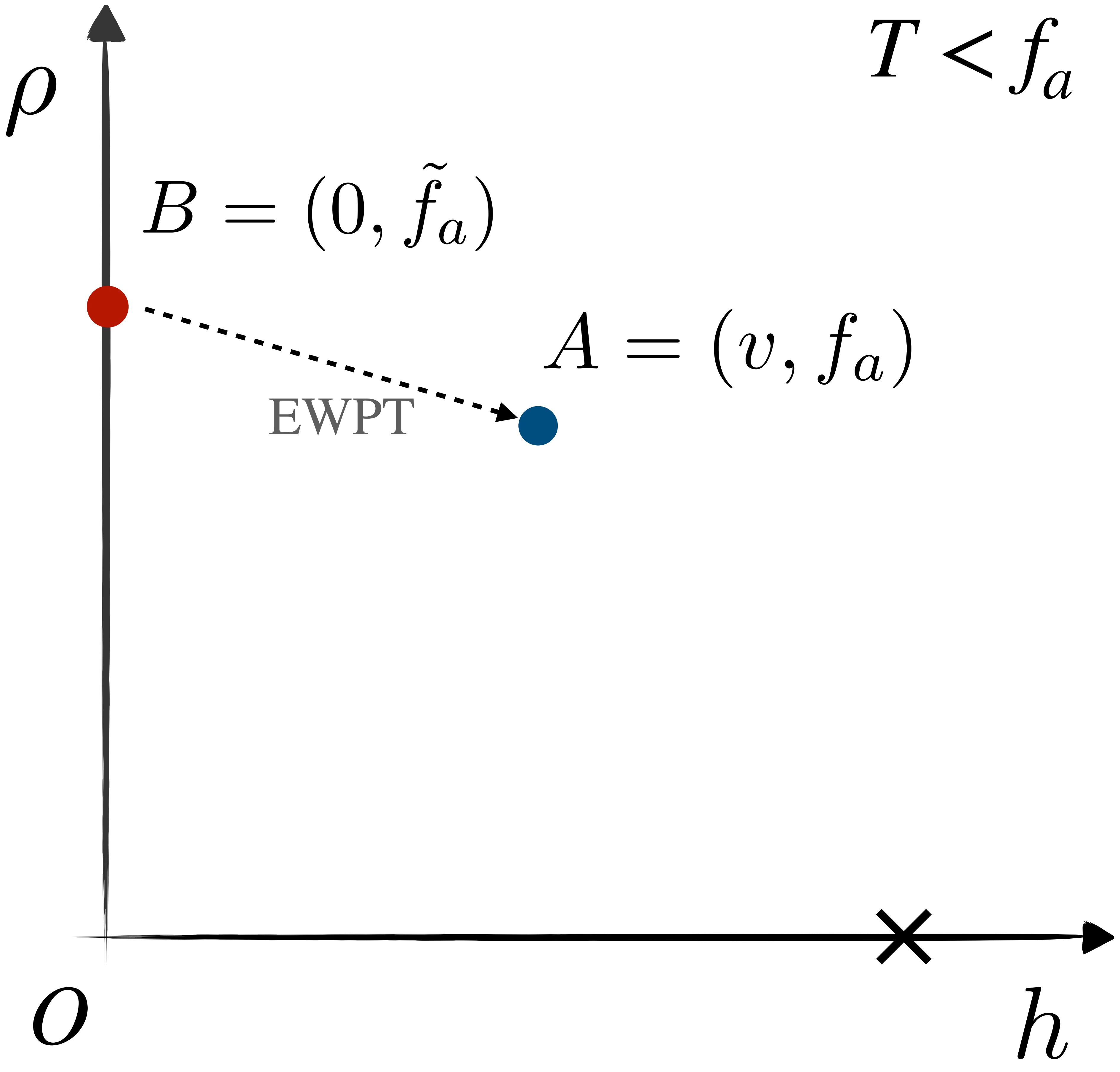

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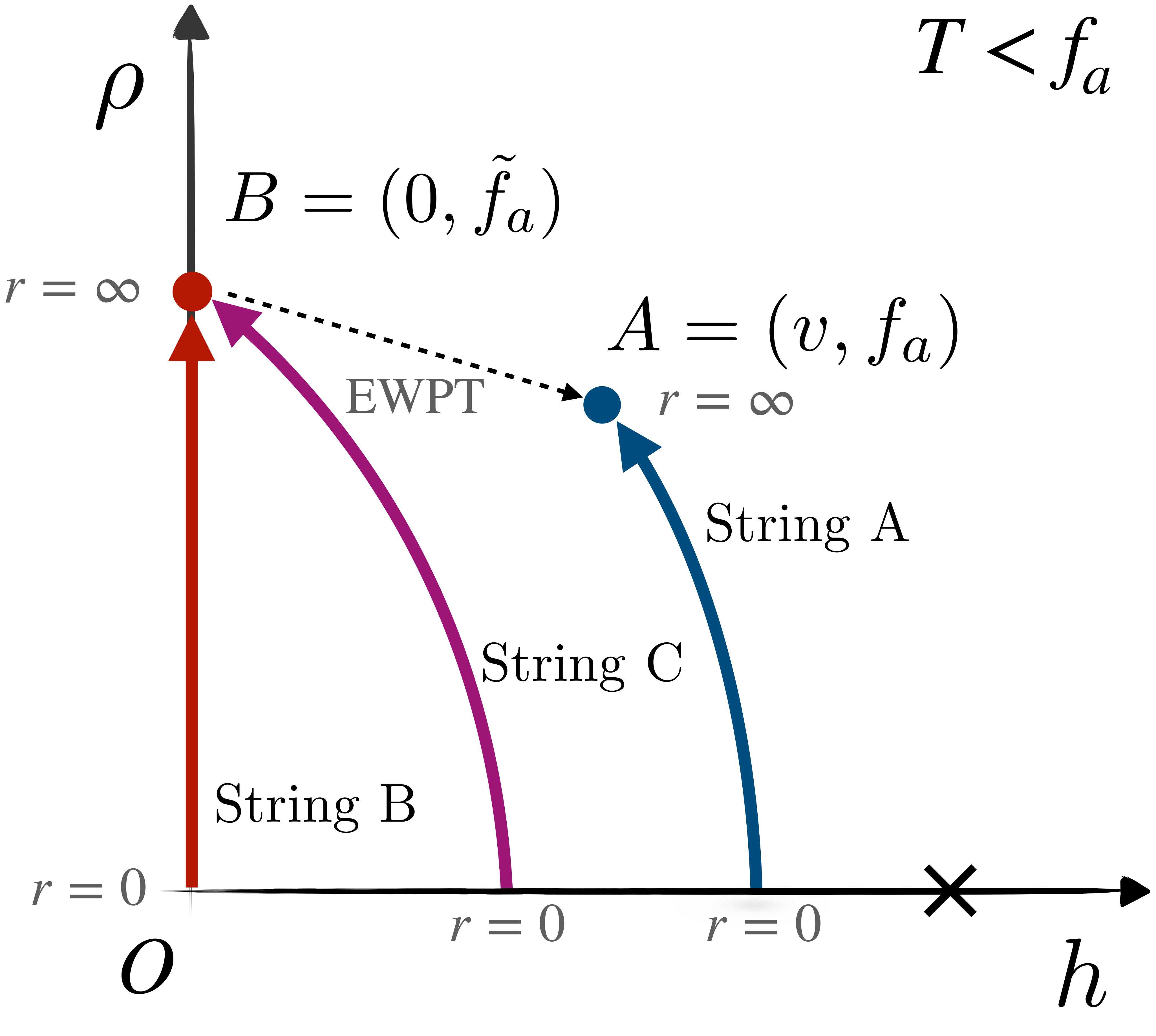
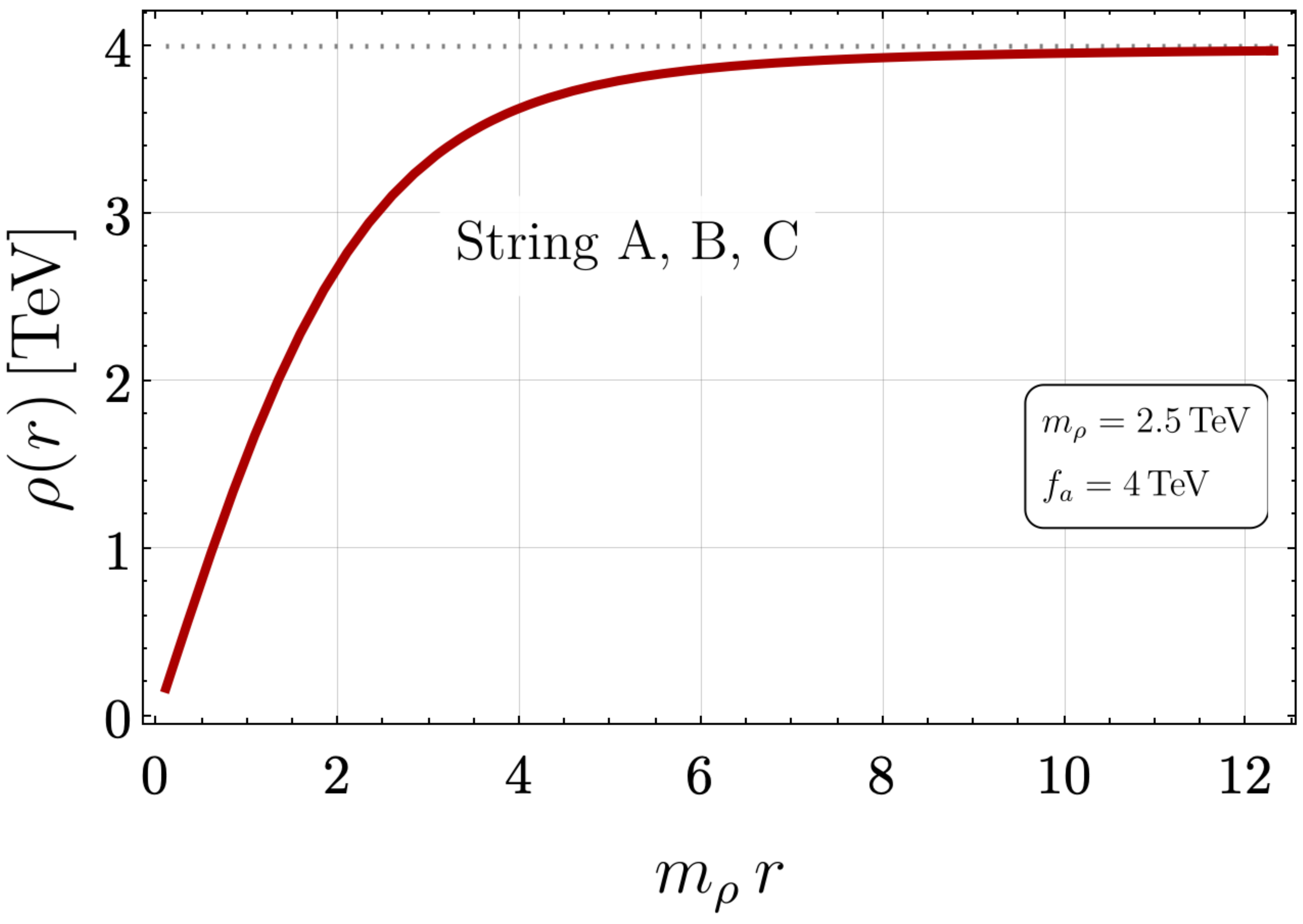
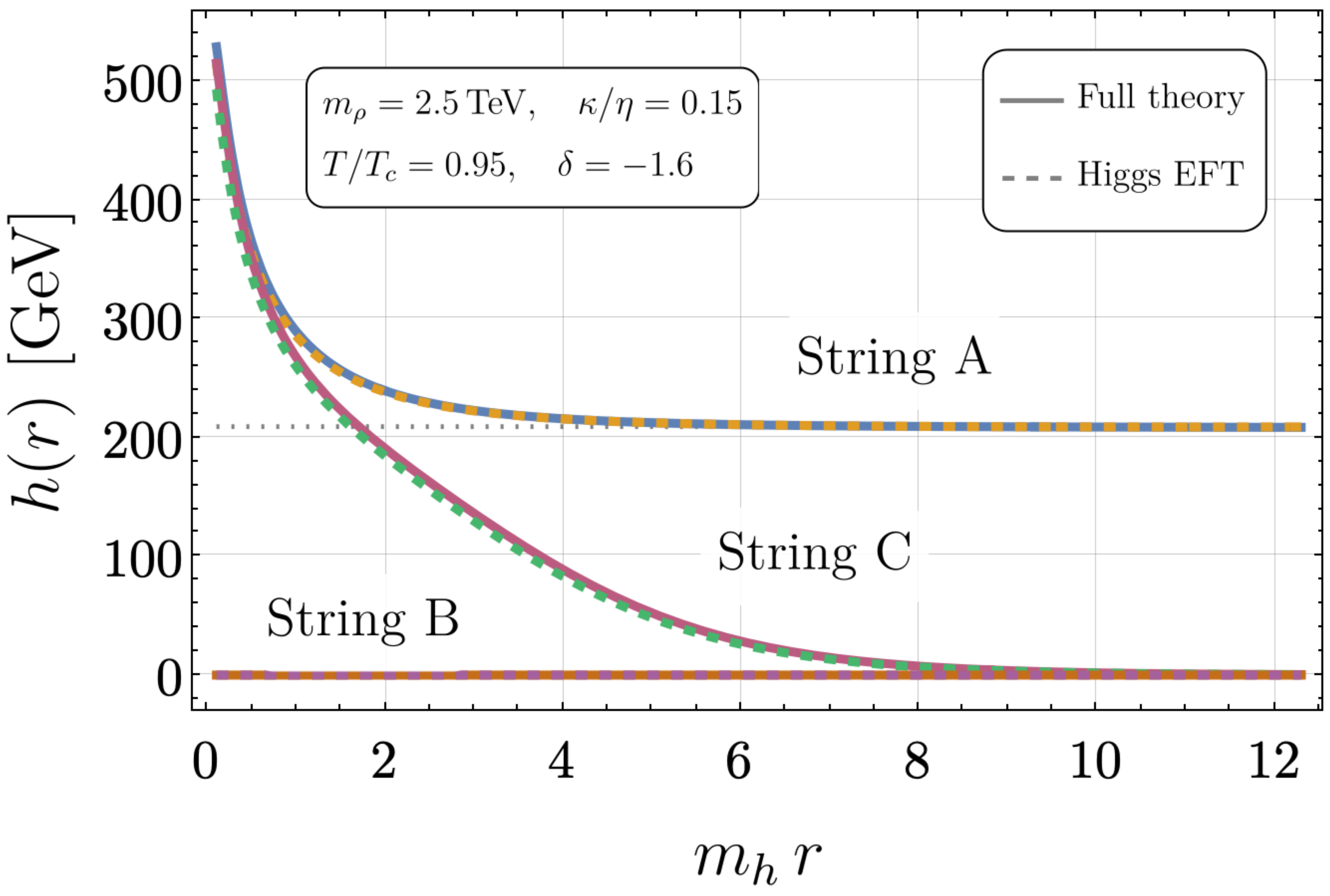


String solutions

- Typical string profiles:





EFT with heavy defects

- Large hierarchy between the mass of the Higgs and the PQ radial mode

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

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

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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:

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

Higgs mass along the string

- Solve eigenvalue equation for small perturbations + boundary condition :

$$\left[-\frac{d^2}{dr^2} - \frac{1}{r}\frac{d}{dr} - (\kappa/\eta)\frac{1}{r^2} + V''_{\rm EW}(0;T)\right] h(r) = \underbrace{\omega^2}_{\text{2D mass}} h(r)$$

$$\epsilon\, h'(\epsilon) = -C(\epsilon)\frac{\kappa}{\eta}h(\epsilon) \qquad\qquad \epsilon \sim 1/m_\rho$$

Higgs mass along the string

- Solve eigenvalue equation for small perturbations + boundary condition :

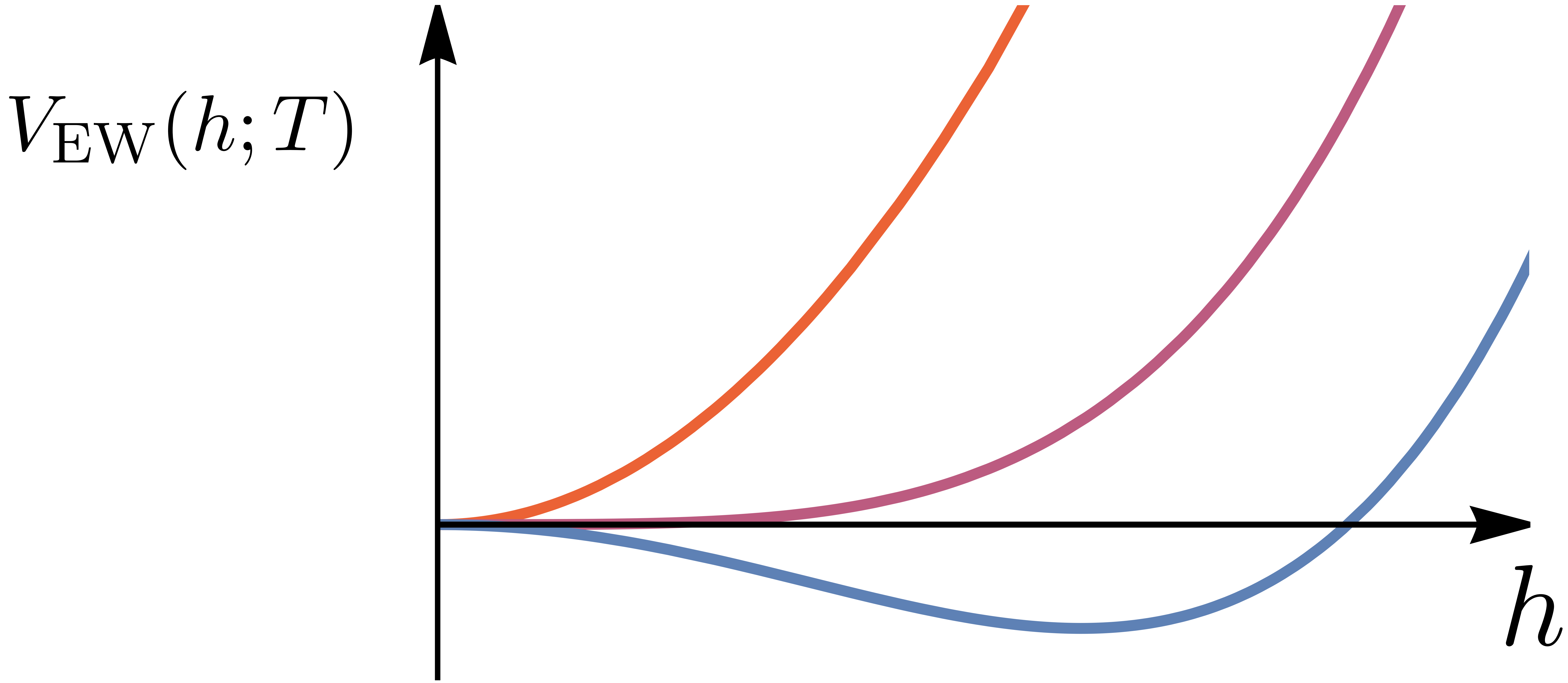
$$\omega^2 = \underbrace{V''_{\rm EW}(0;T)}_{\text{4D mass}} - \underbrace{\frac{1}{2}m_\rho^2 \exp\left\{-\frac{\pi}{\sqrt{\kappa/\eta}} - \gamma_{\rm E} + 2C(\epsilon)\right\}}_{\Delta m_h^2}$$

- Axion strings classically develop a Higgs core if $\omega^2(T_r) < 0$

SM + PQ

- Higgs potential in the SM:

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



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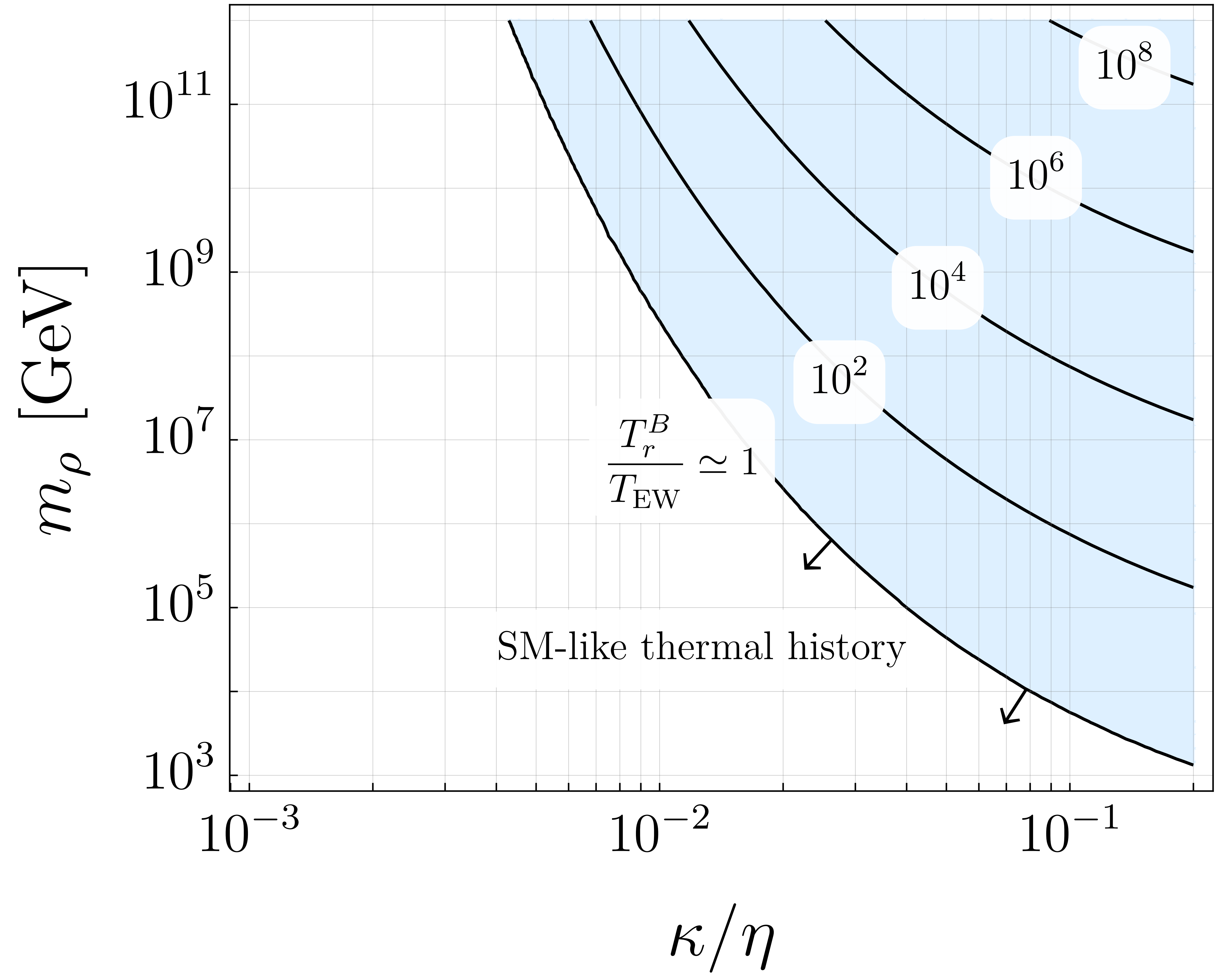

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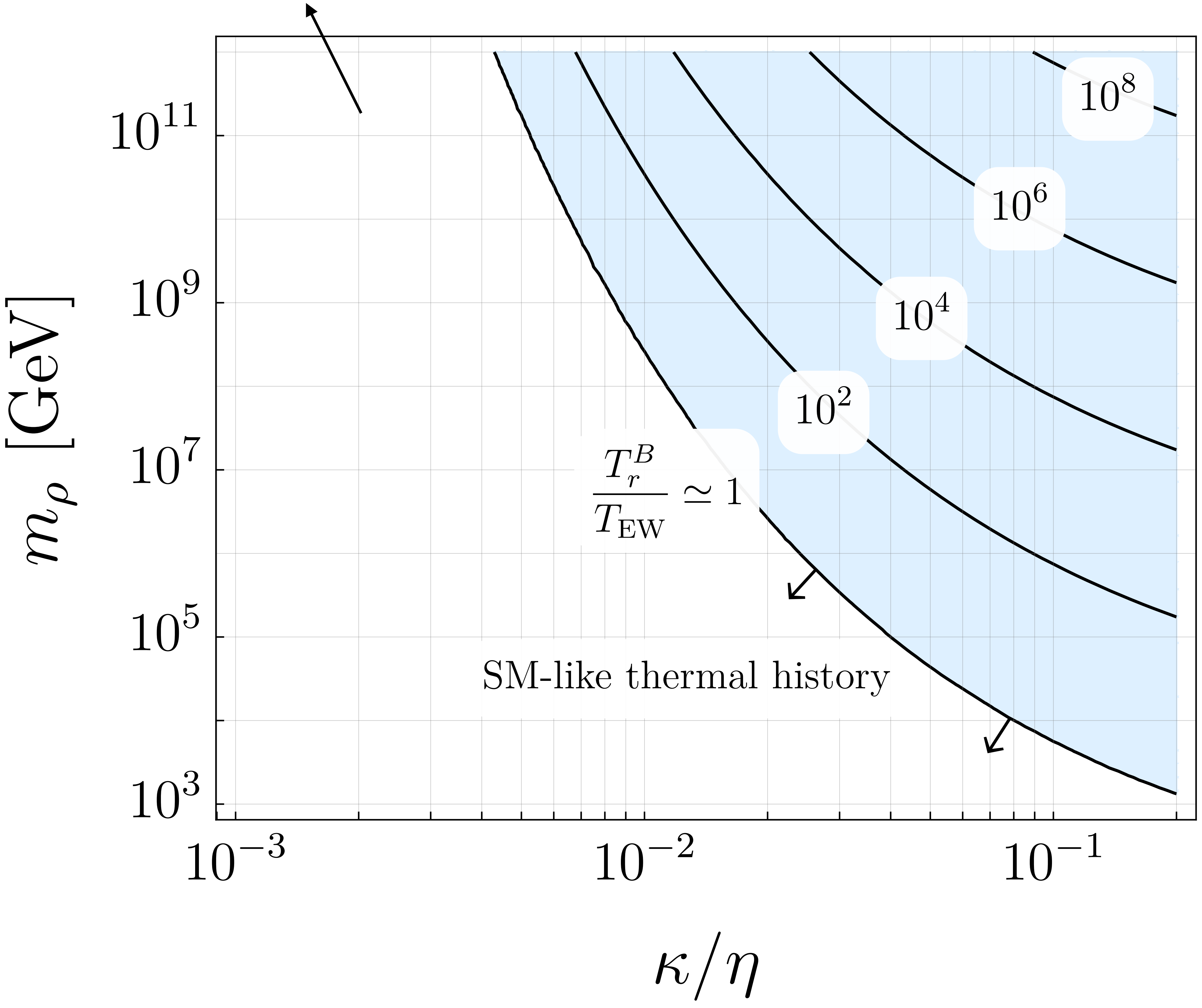
Higgs gets a vev $h \sim v$ in the string and in the bulk at same T



SM + PQ

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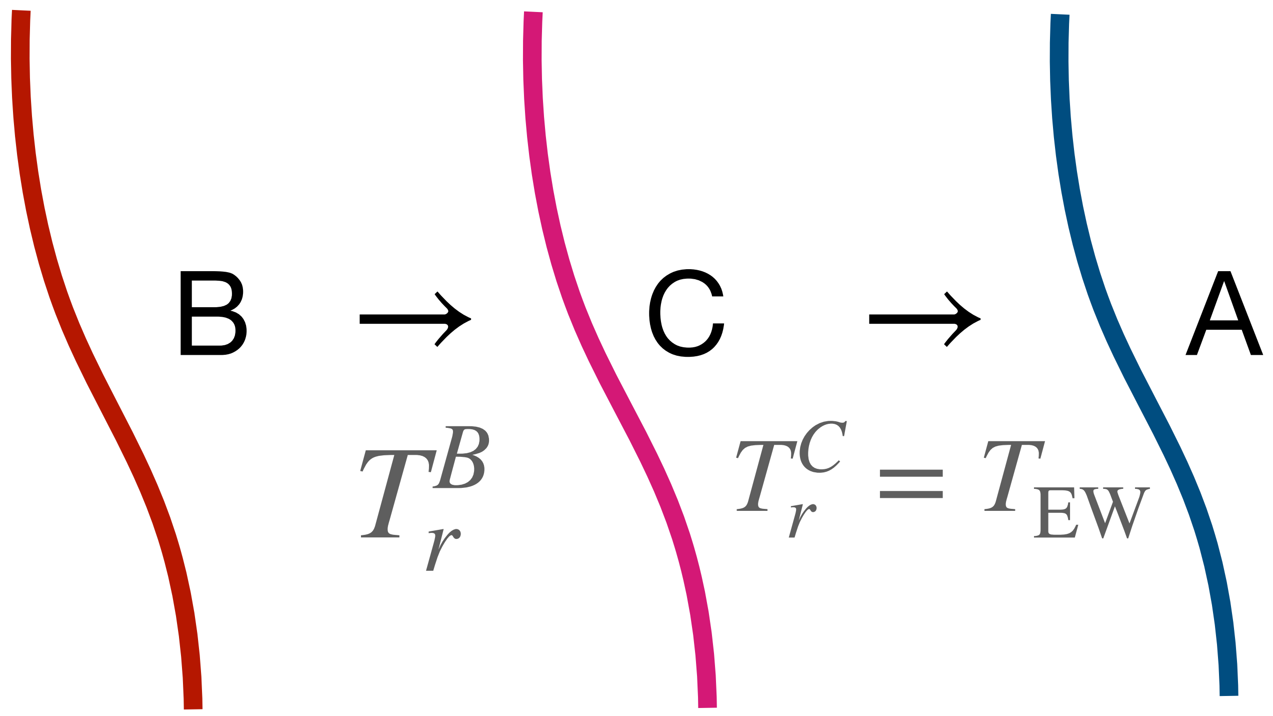
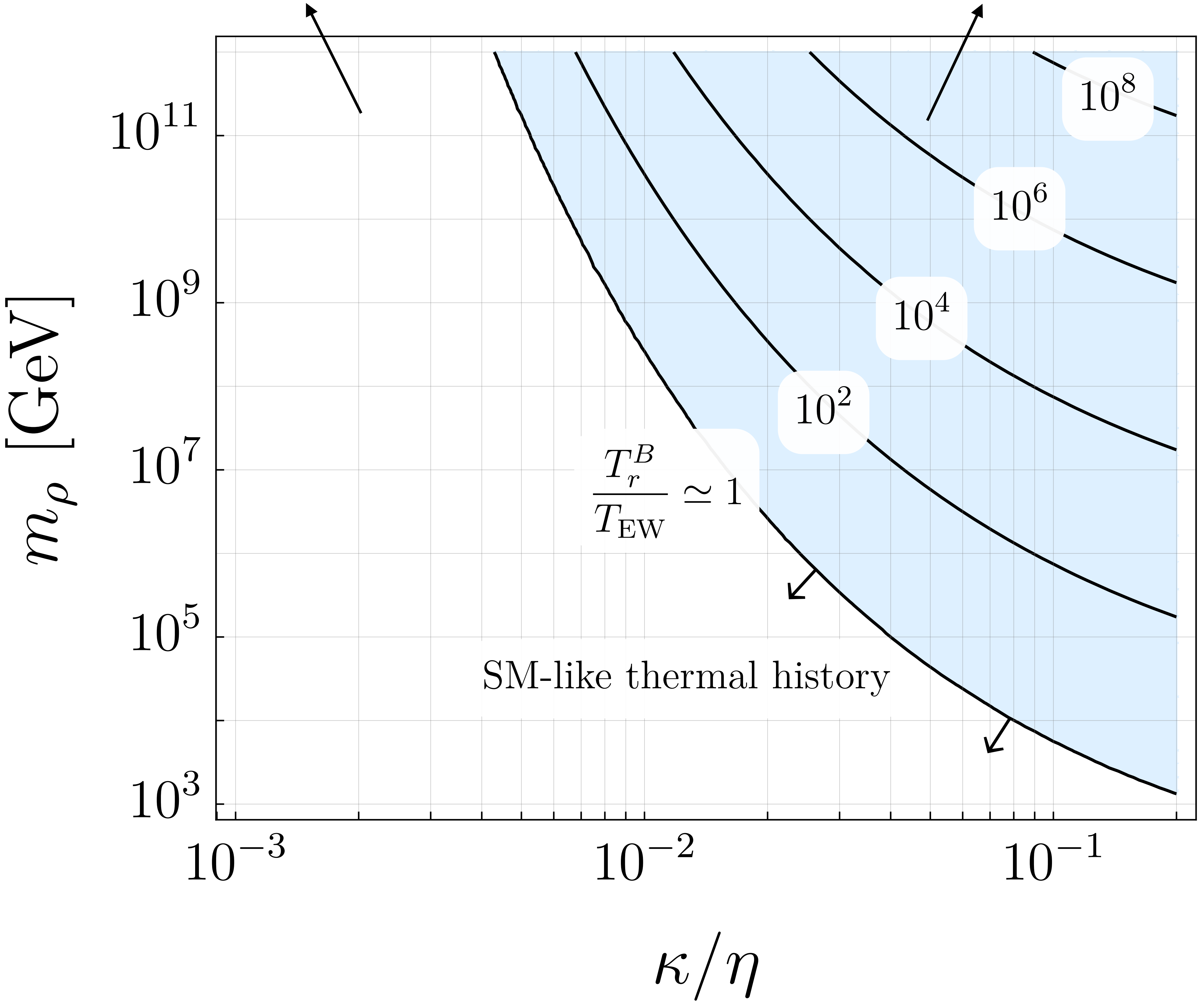
- Thermal history (blue region):



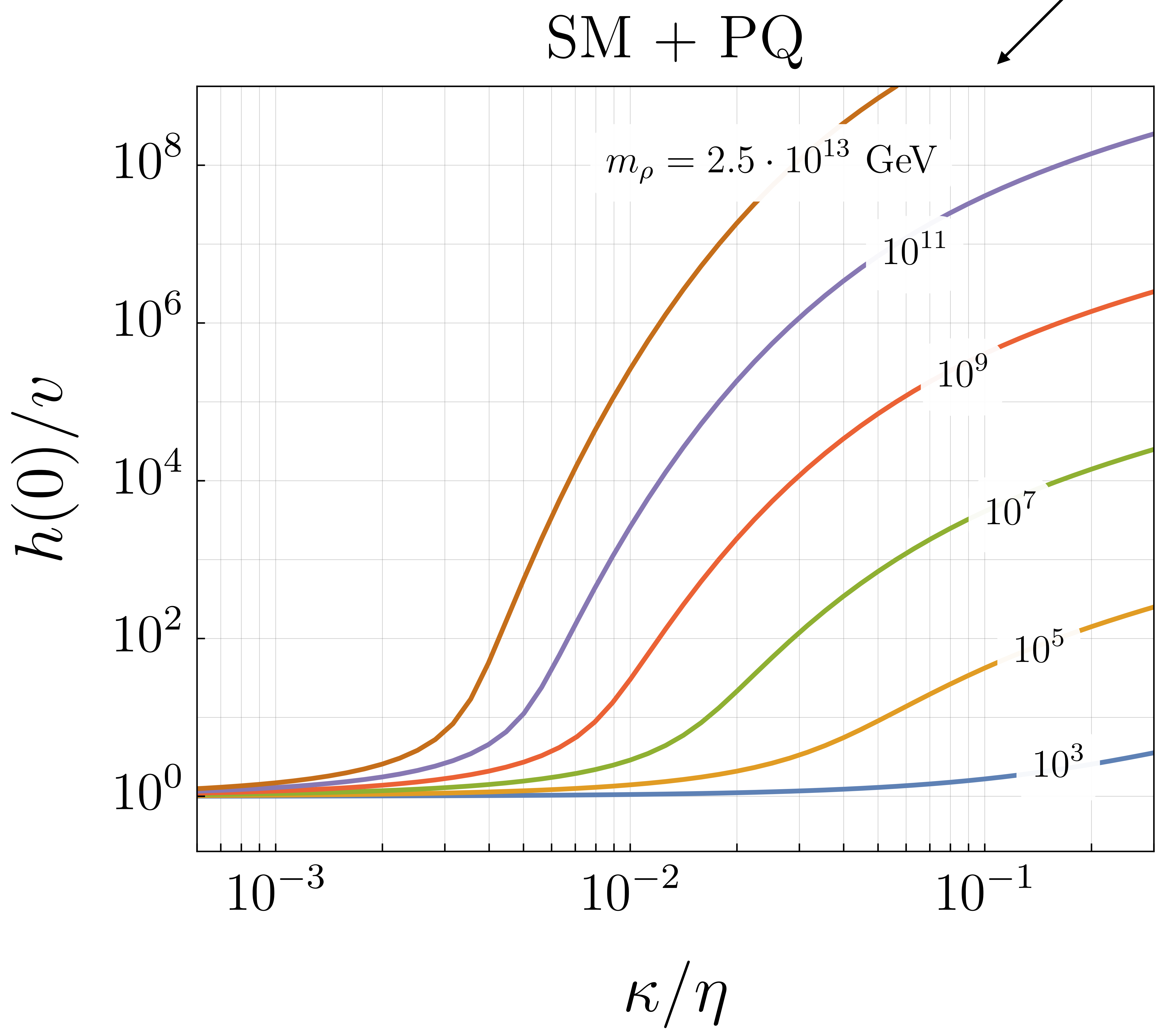
Higgs gets a vev $h \sim v$ in the string and in the bulk at same T

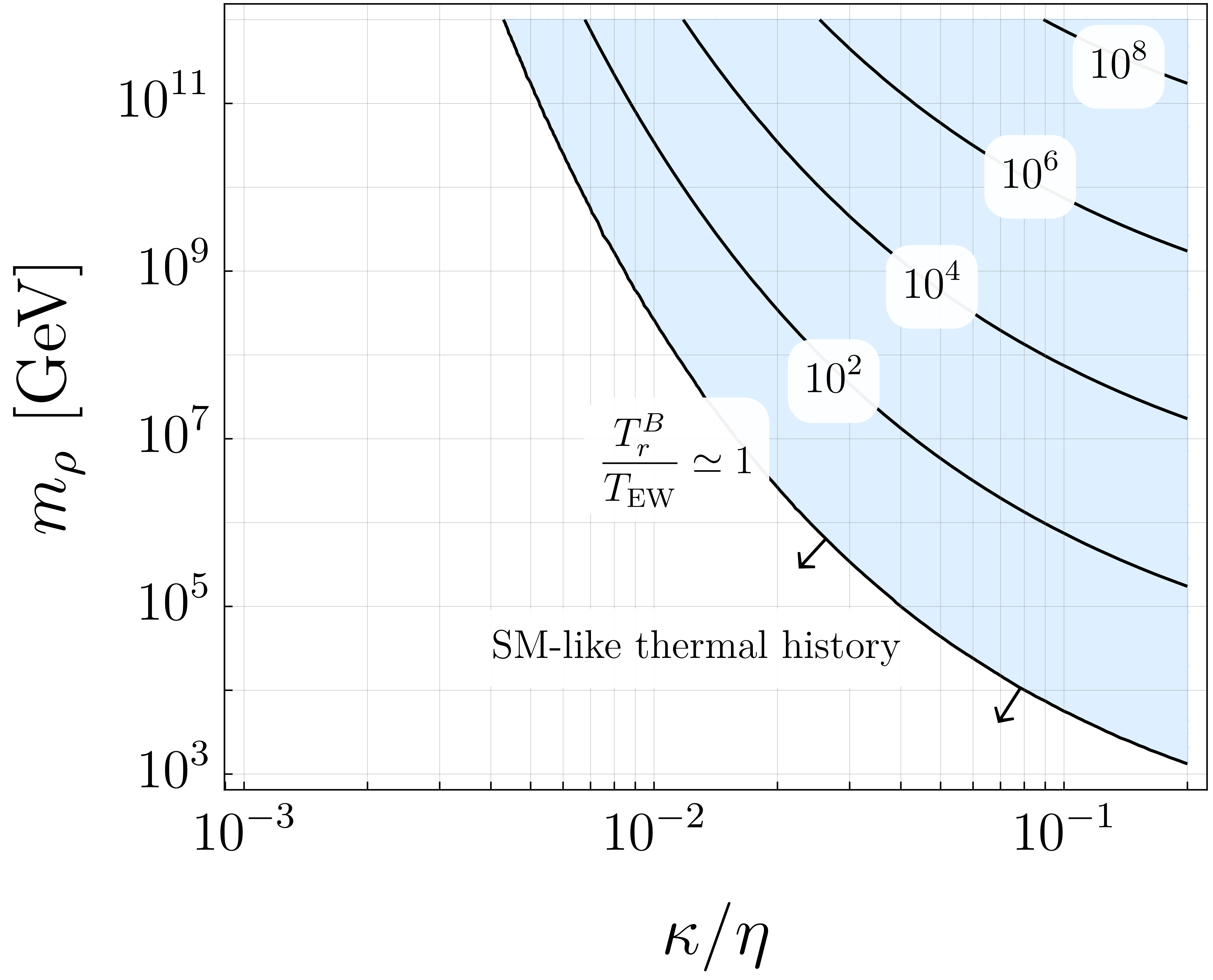
Higgs gets $h \gg v$ in the strings at $T \gg T_{\mathrm{EW}}$



SM + PQ

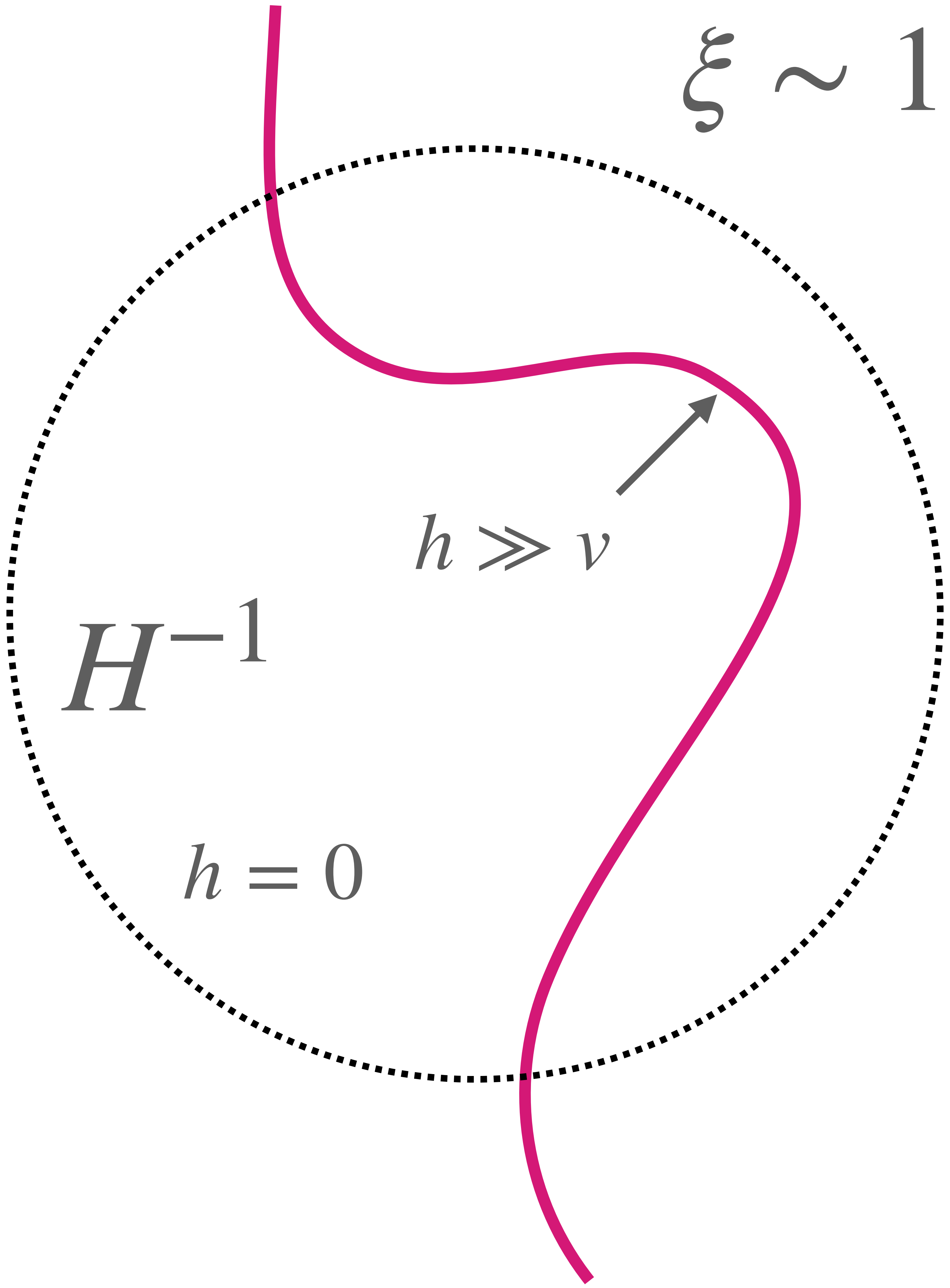
Size of the Higgs field at the string core





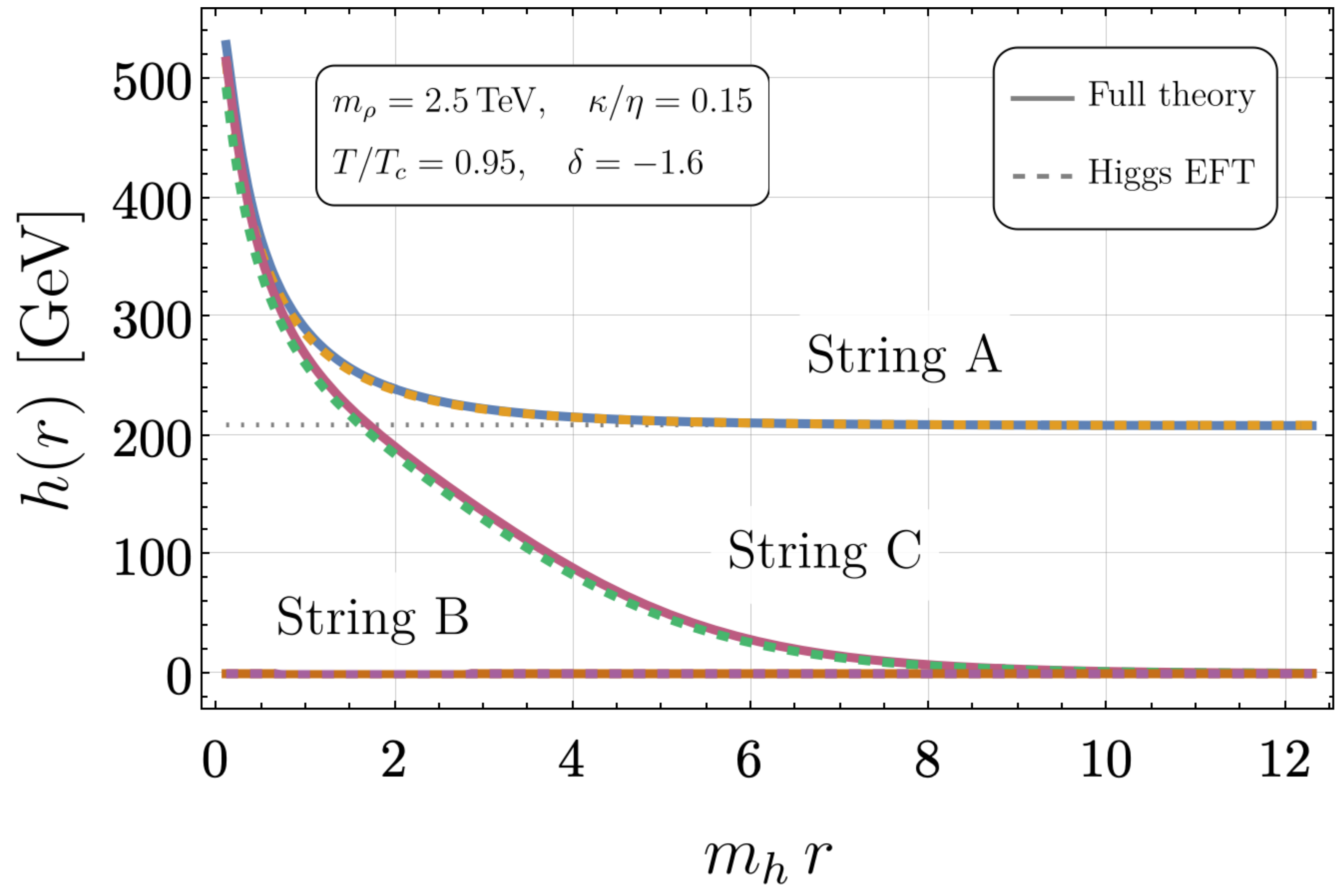
SM + PQ

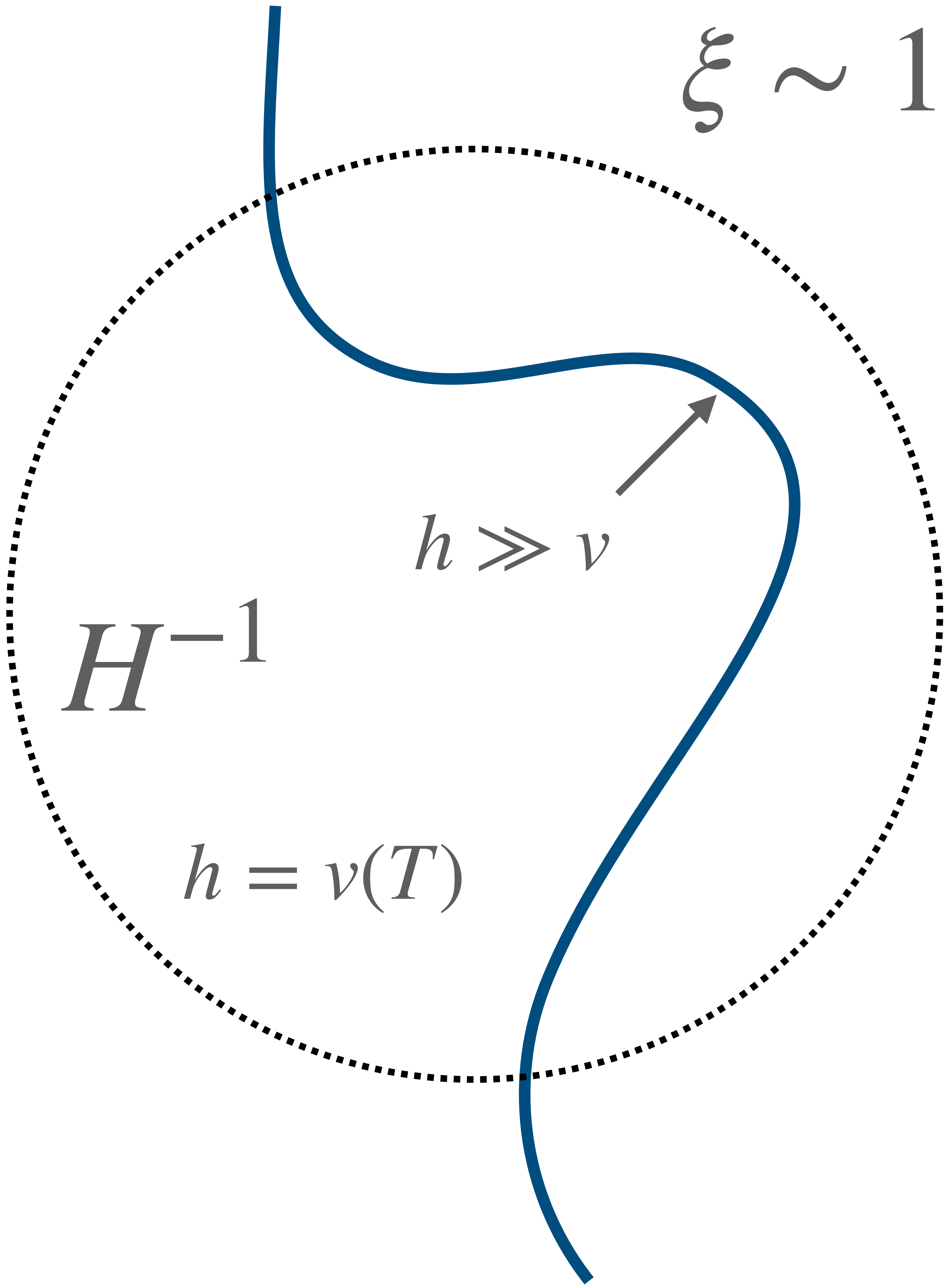
- At $T \gg T_{\rm EW}$ strings are of type C with a (potentially large) Higgs core



SM + PQ

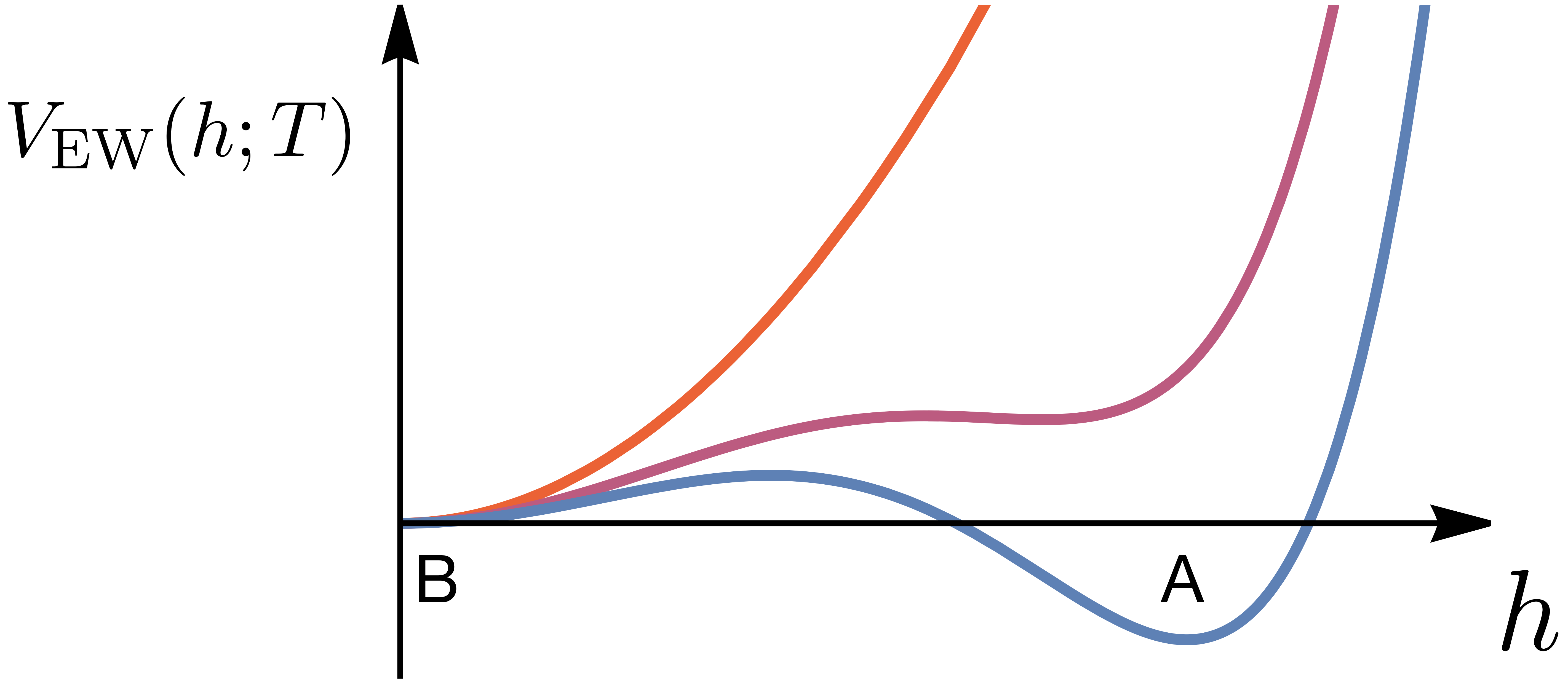
- At $T \gg T_{\mathrm{EW}}$ strings are of type C with a (potentially large) Higgs core
- At $T \leq T_{\mathrm{EW}}$ string C solution merges smoothly with the bulk and becomes type A





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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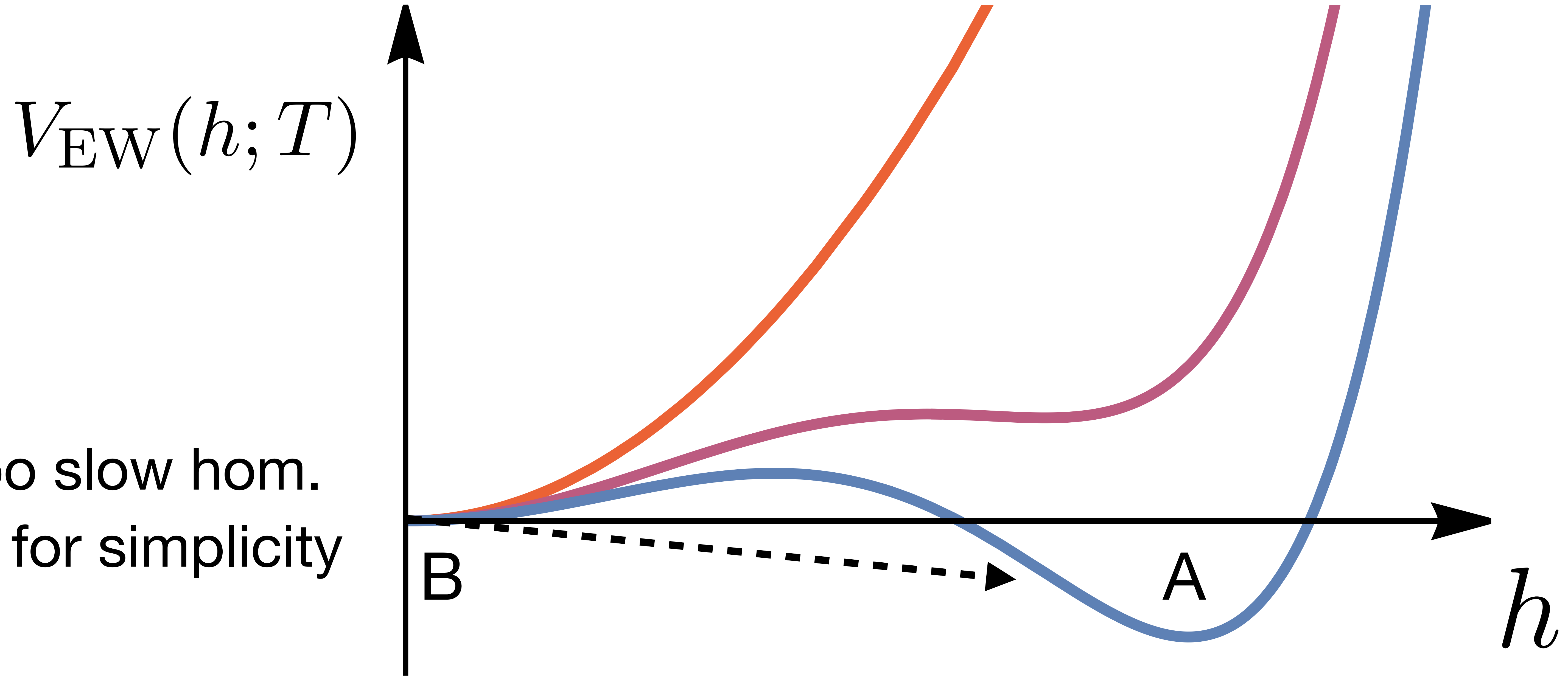
Assume too slow hom. nucleation for simplicity



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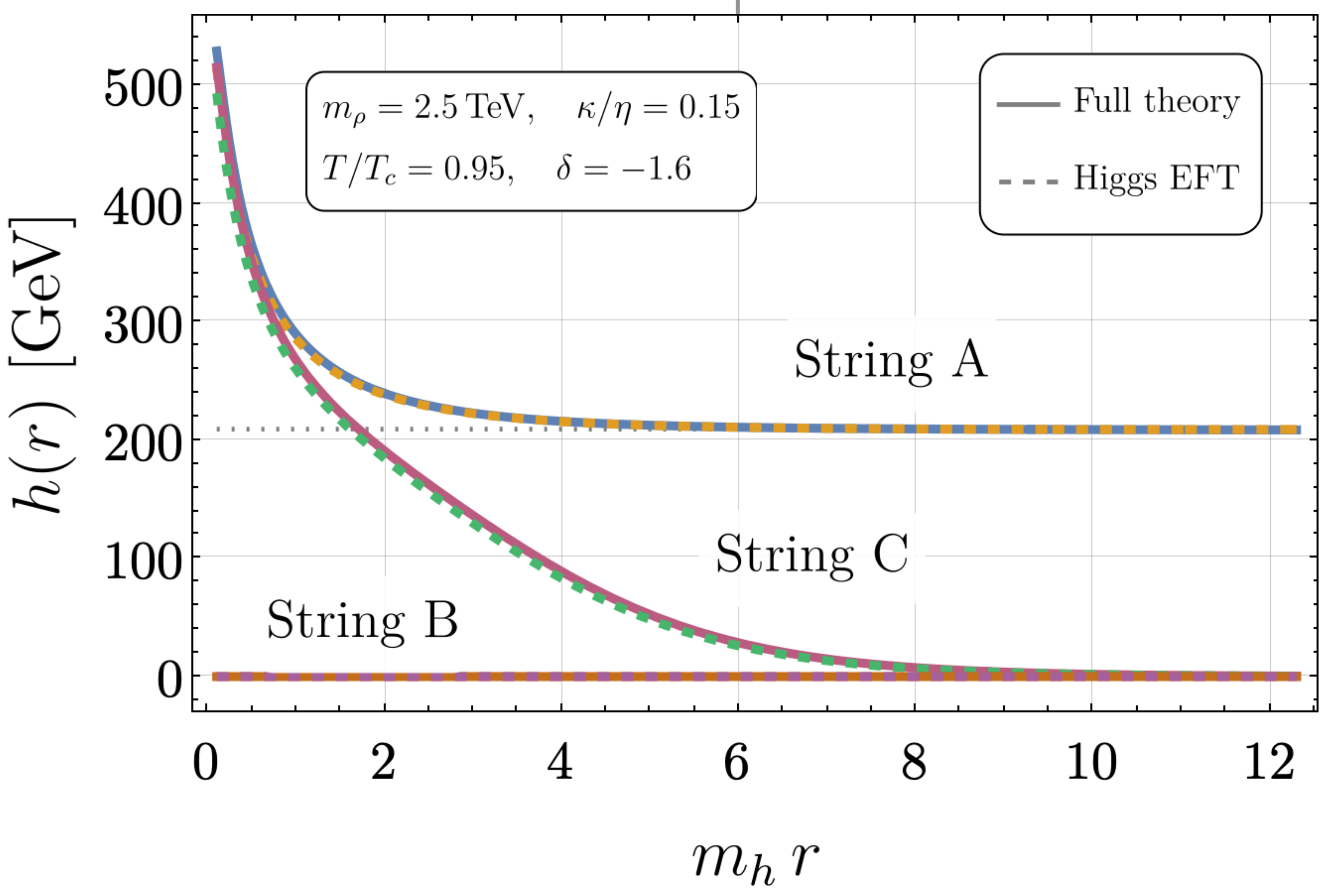
FOPT + PQ

- EWPT can still complete by catalyzed vacuum decay: strings as initial & final states



FOPT + PQ

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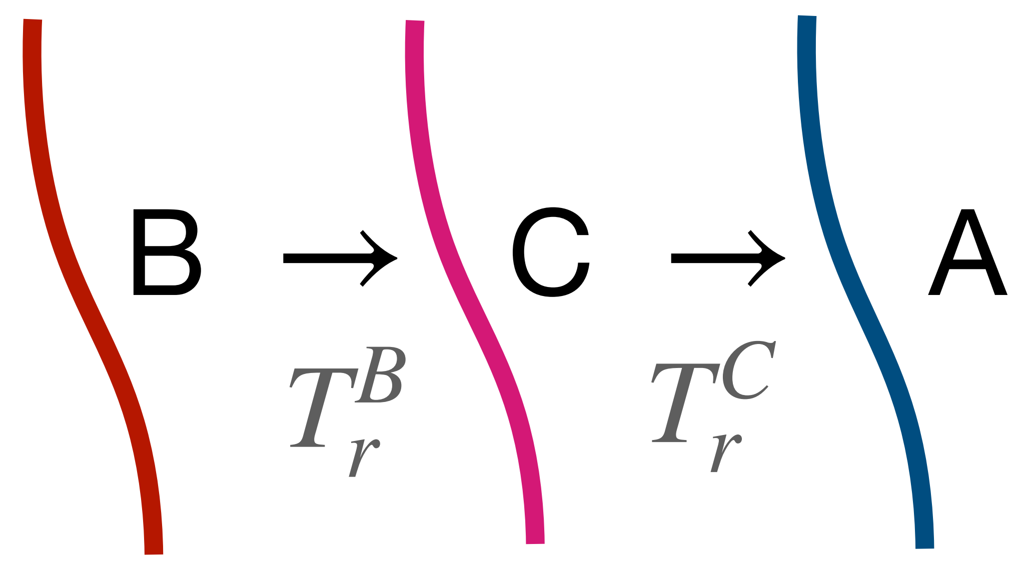
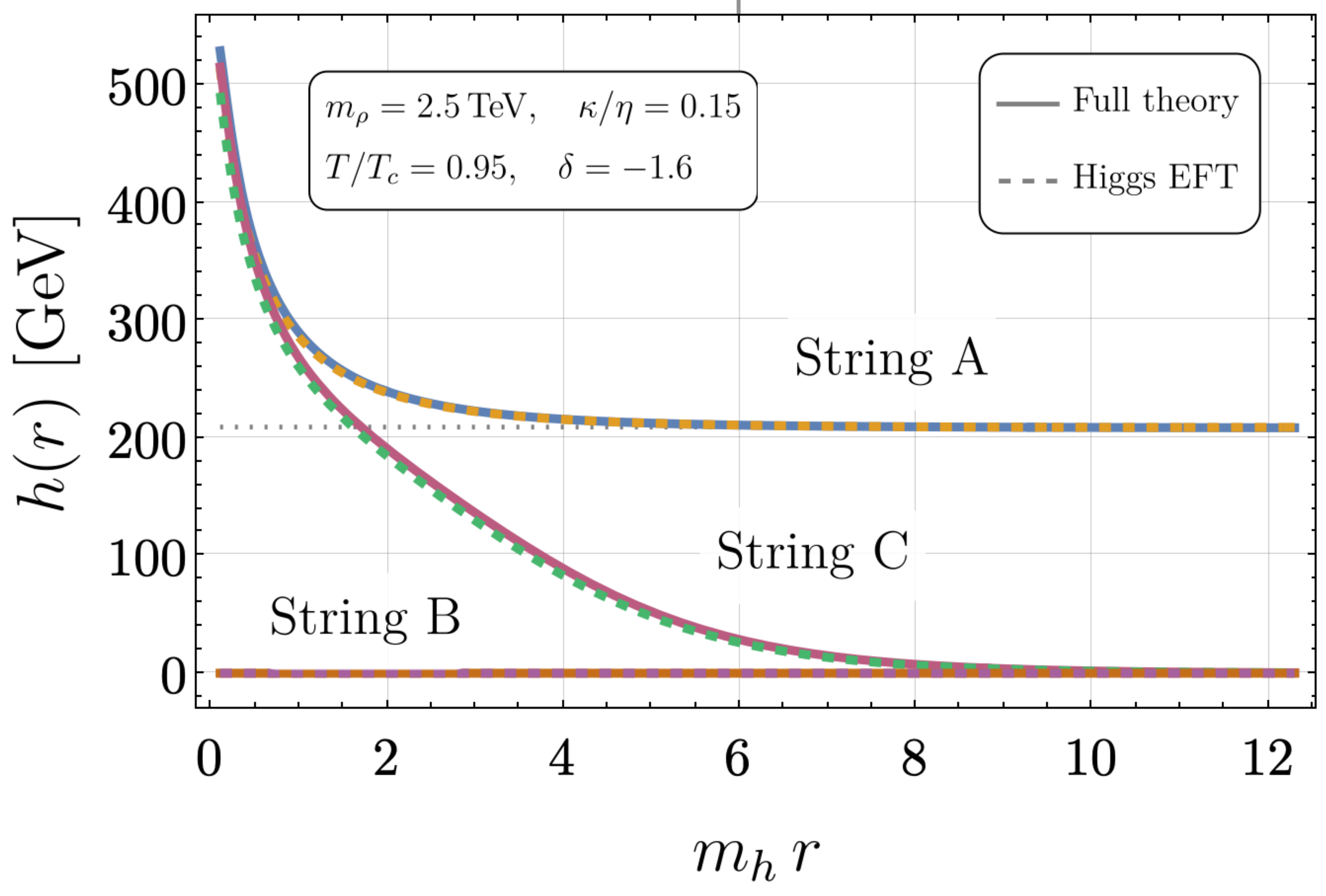
Axion strings *B* & *C* unstable at some finite T

Rolling



EWPT guaranteed to complete

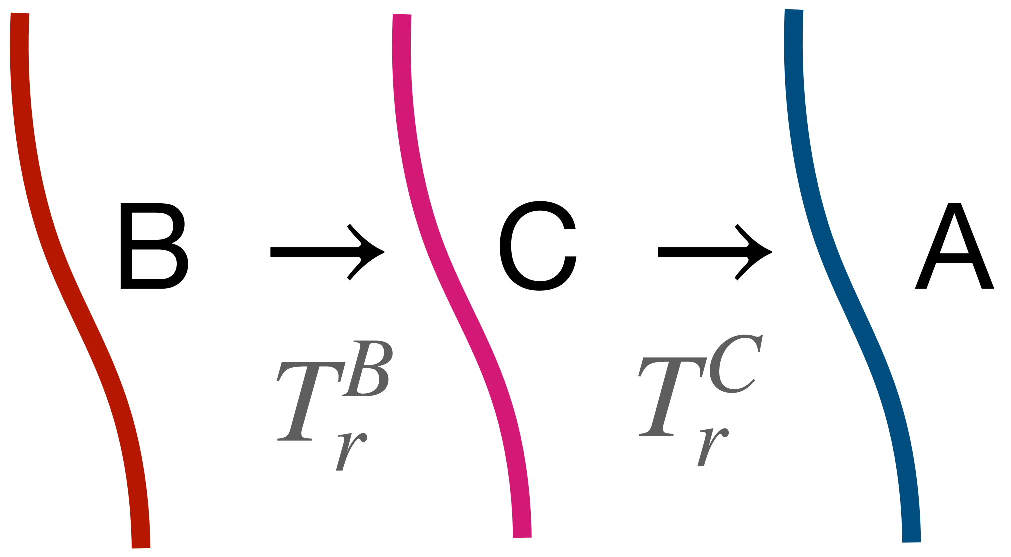


FOPT + PQ

- EWPT can still complete by catalyzed vacuum decay: strings as initial & final states

Axion strings *B* & *C* unstable at some finite T

Rolling



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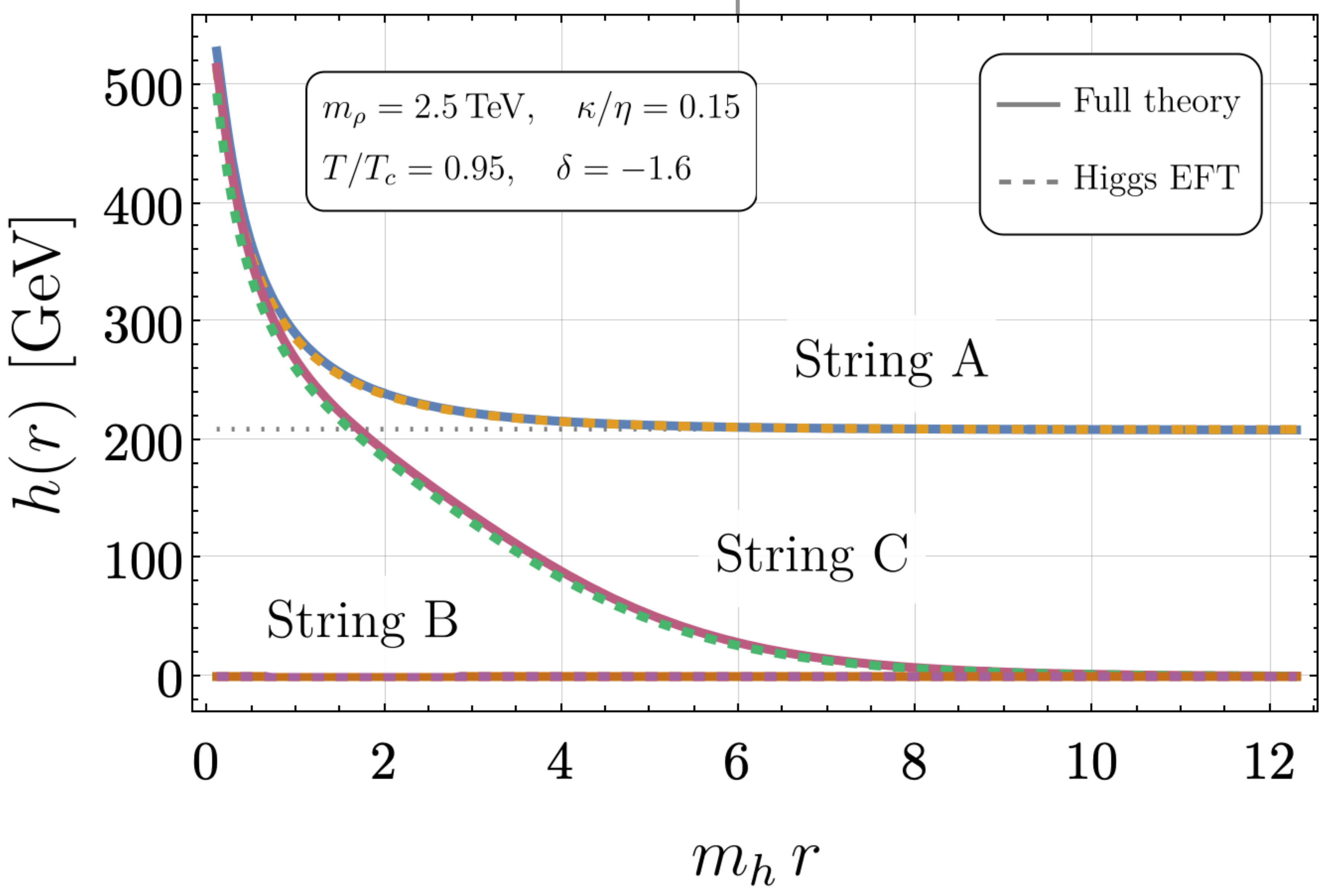
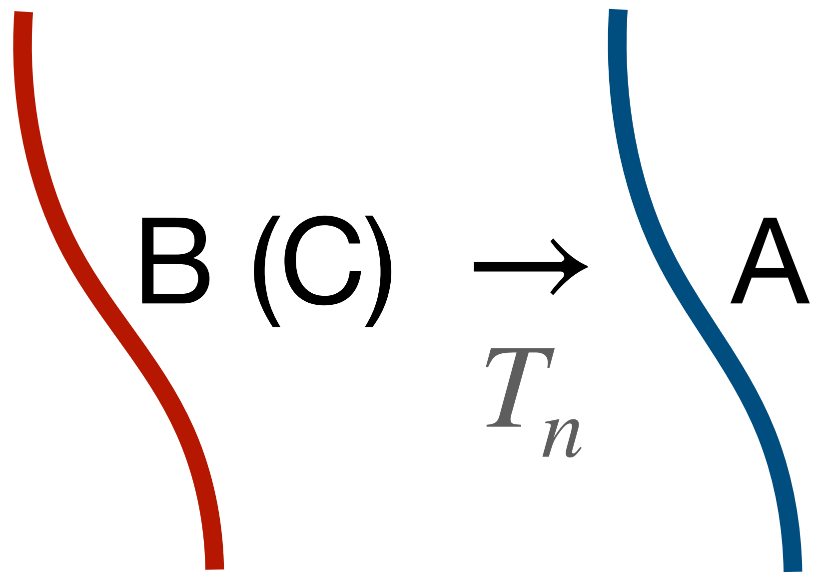


Axion string (*B* or *C*) metastable at $T = 0$

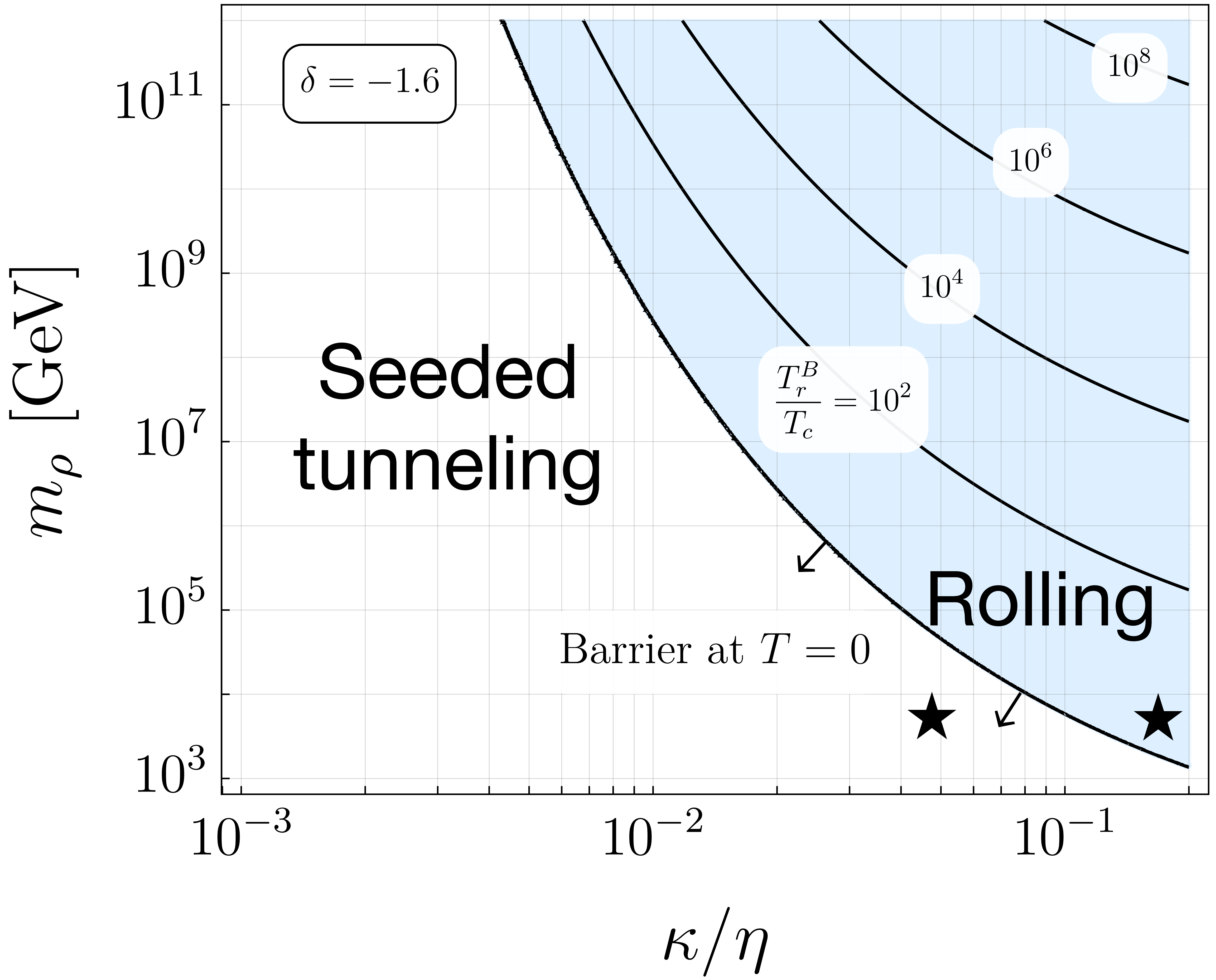
Seeded tunneling



EWPT may complete if fast enough rate

FOPT + PQ

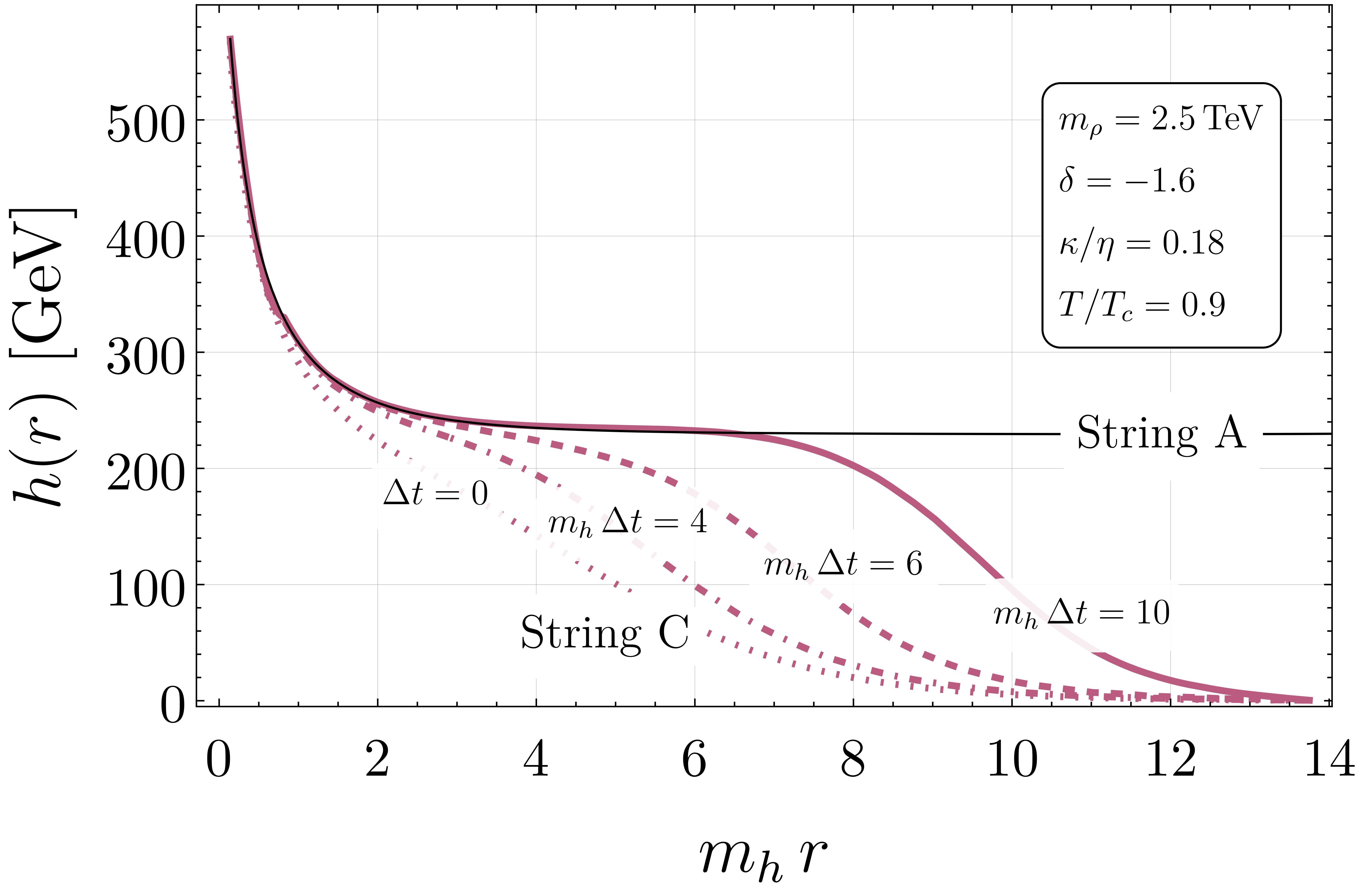
- EWPT can still complete by catalyzed vacuum decay: strings as initial & final states



Rolling

See also Yajnik, PRD (1986)

- String *C* becomes unstable and evolves towards string *A* at $T = T_r^C$



Rolling

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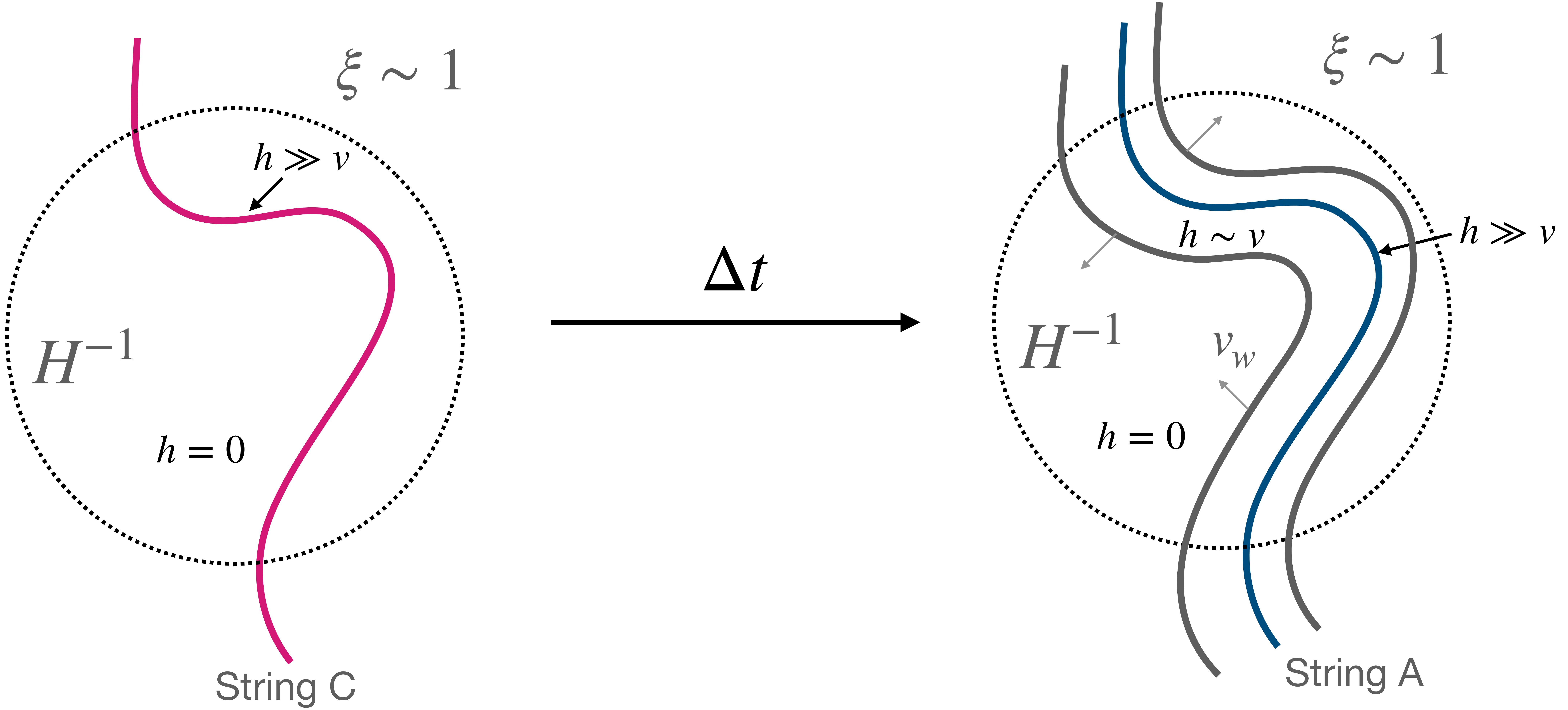

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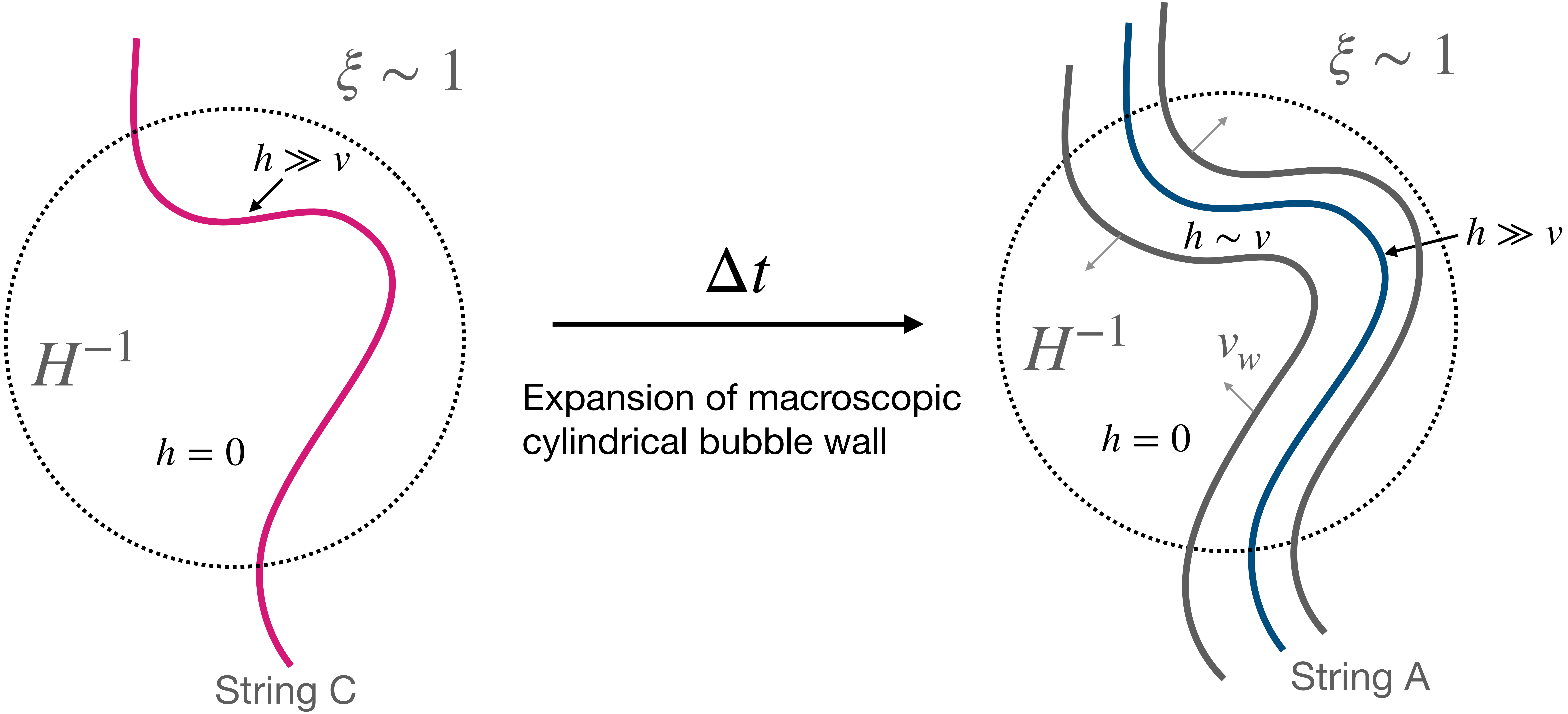


Seeded tunneling

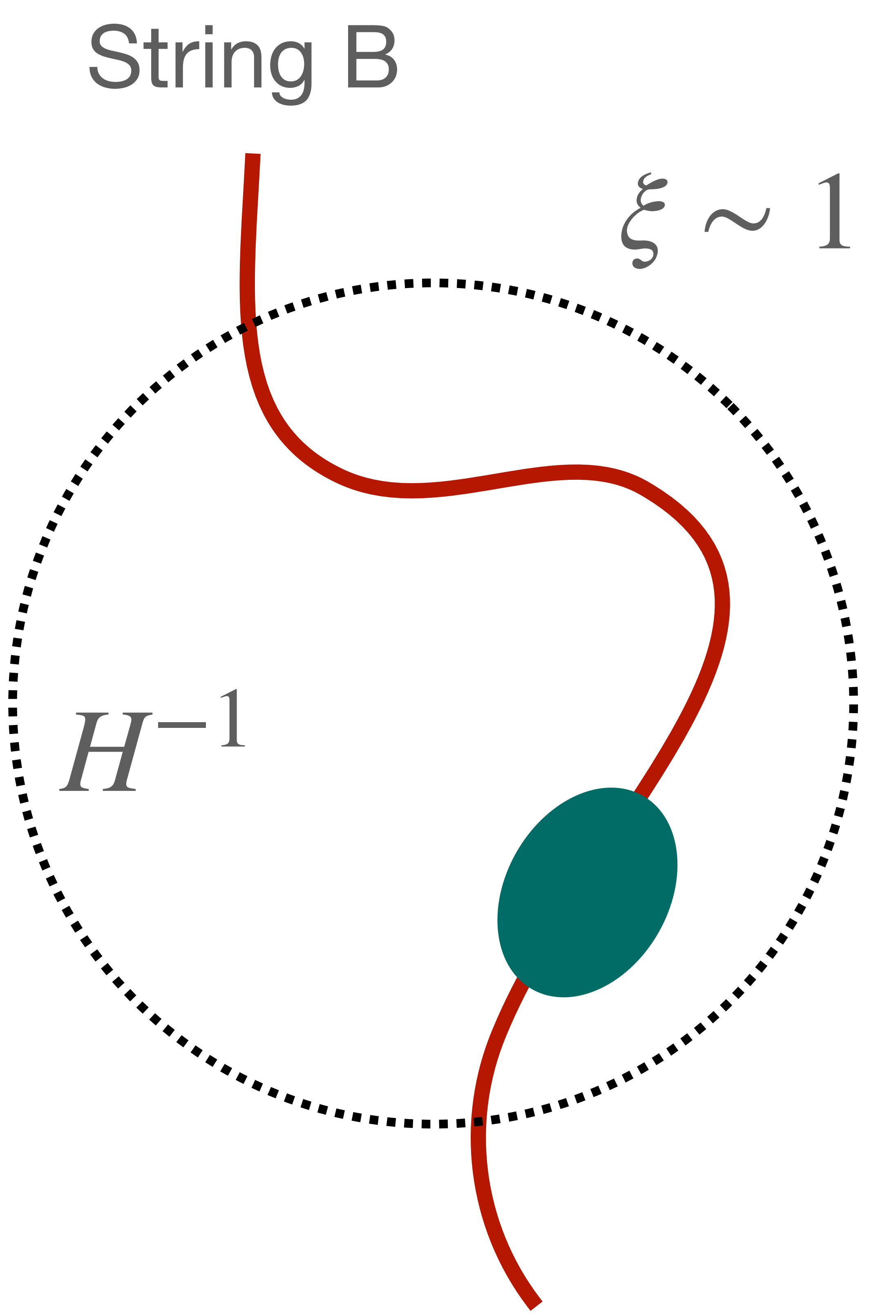
- Nucleation rate per unit time per unit string length:

$$\gamma_{\rm s} \simeq T^2 \exp(-S_{\rm string}/T)$$

- Nucleation condition:

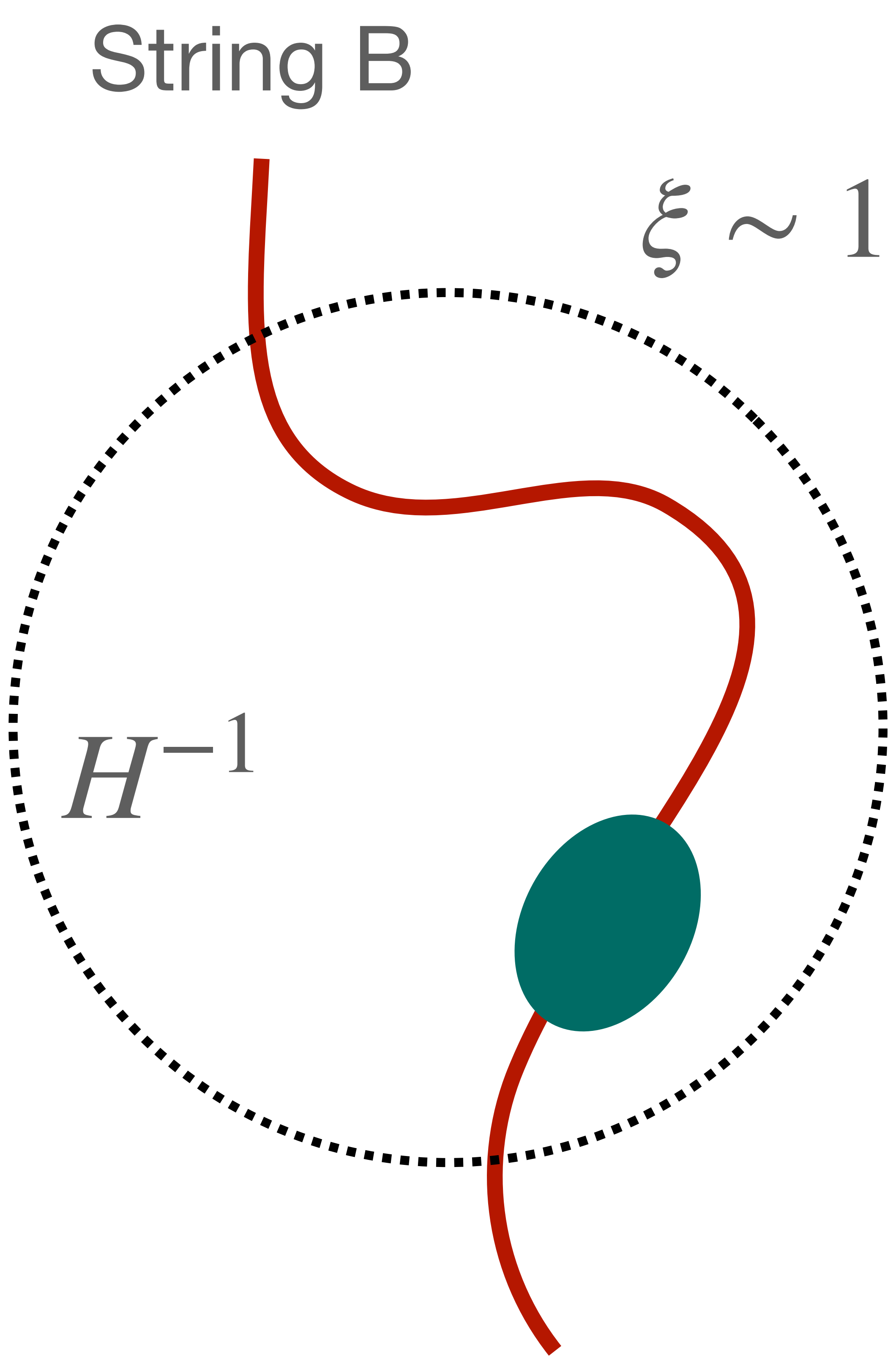
$$\mathcal{N}(T_n) = \int_{T_n}^{T_c} \xi \frac{\gamma_{\rm s}}{H^2} \frac{dT}{T} \simeq 1$$

$$\frac{S_{\rm string}}{T} \simeq 2\log(M_{\rm Pl}/T_n) + \log\xi - 2.4 \approx 73$$



Seeded tunneling

- How to evaluate the seeded action?

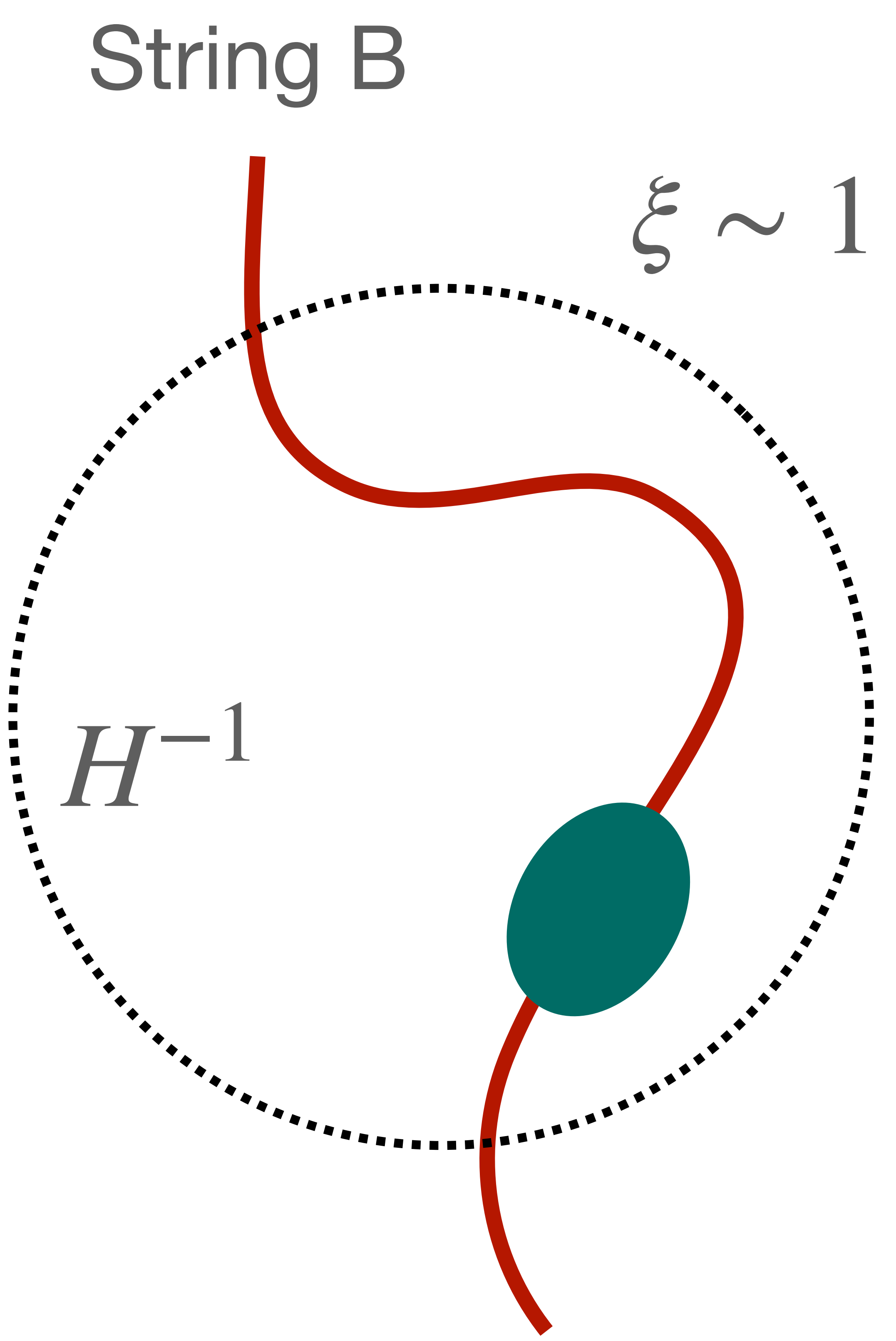


Seeded tunneling

- How to evaluate the seeded action?
  - **PDE** solution obtained numerically

$$\partial_z^2 h + \partial_r^2 h + \frac{1}{r}\partial_r h + (\kappa/\eta)\frac{h}{r^2} = V'_{\mathrm{EW}}(h)$$

$$\left.\begin{aligned} &\epsilon\,\partial_r h|_{r=\epsilon} = -\frac{\kappa}{\eta}C(\epsilon)h|_{r=\epsilon}, \quad \partial_z h|_{z=0} = 0 \\ &h|_{|z|=\infty} = 0, \quad h|_{r=\infty} = 0 \end{aligned}\right\} \text{Boundary conditions}$$



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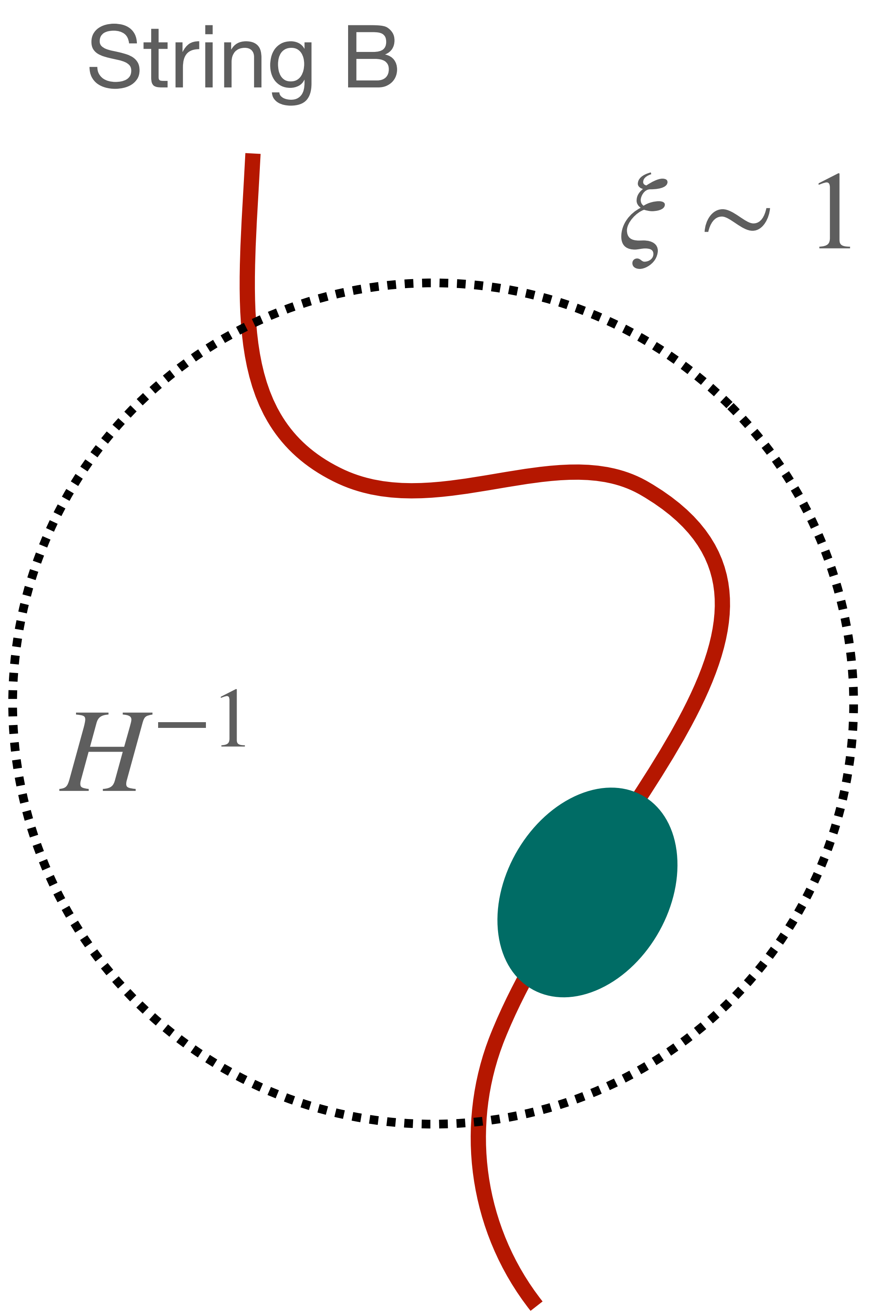
Boundary conditions

= O(3) breaking



Seeded tunneling

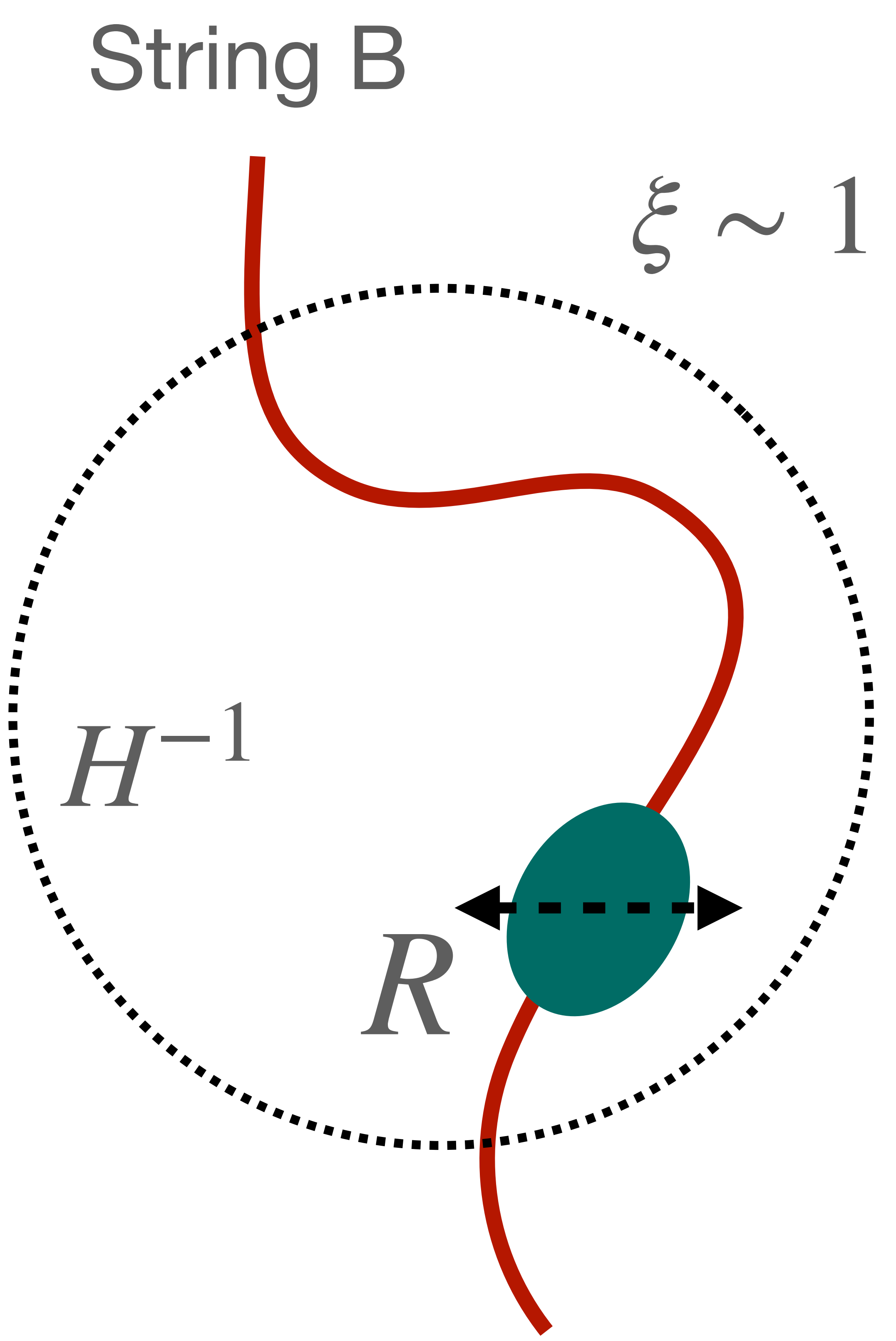
- How to evaluate the seeded action?
  - **Linear**: seeded bubble as small perturbation of homogeneous (spherical) bubble:

$$S_{\text{string}} = S_{\text{hom}} + \delta S_{\text{TW}}$$

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

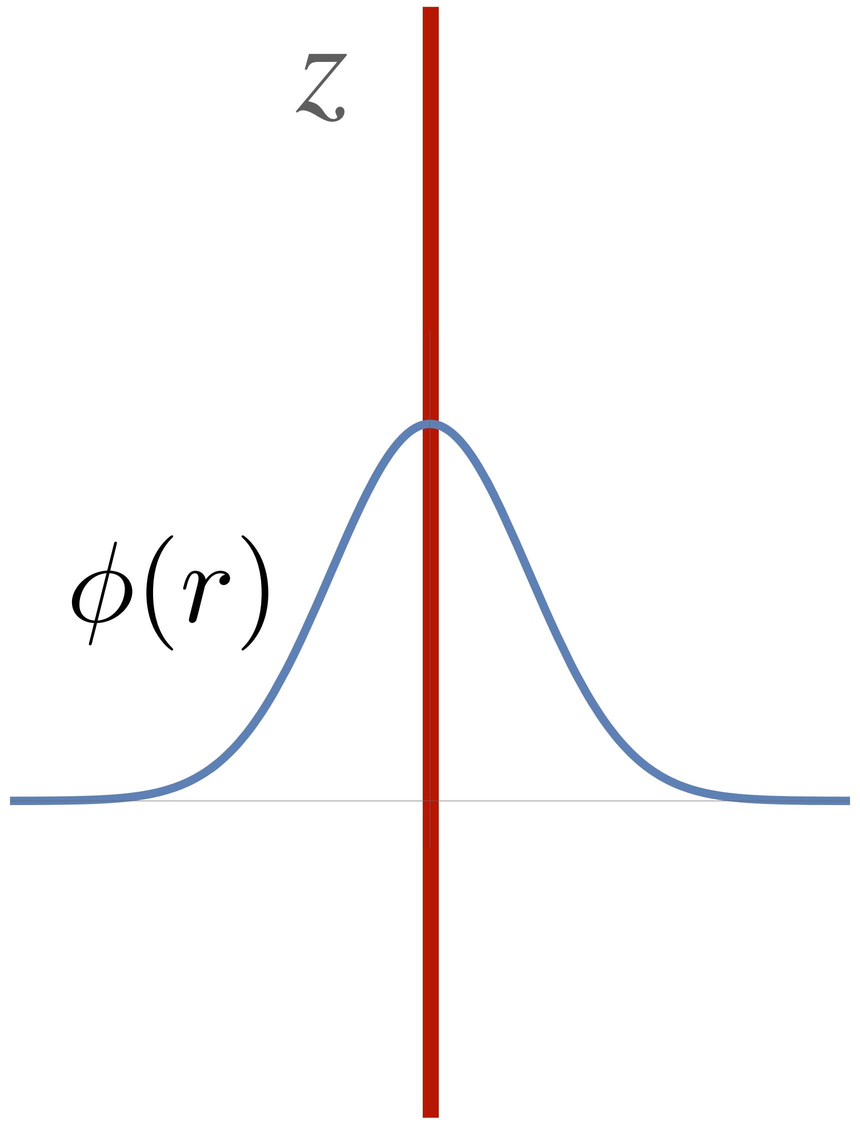
Radius hom. bubble

Release point hom. bubble



Seeded tunneling

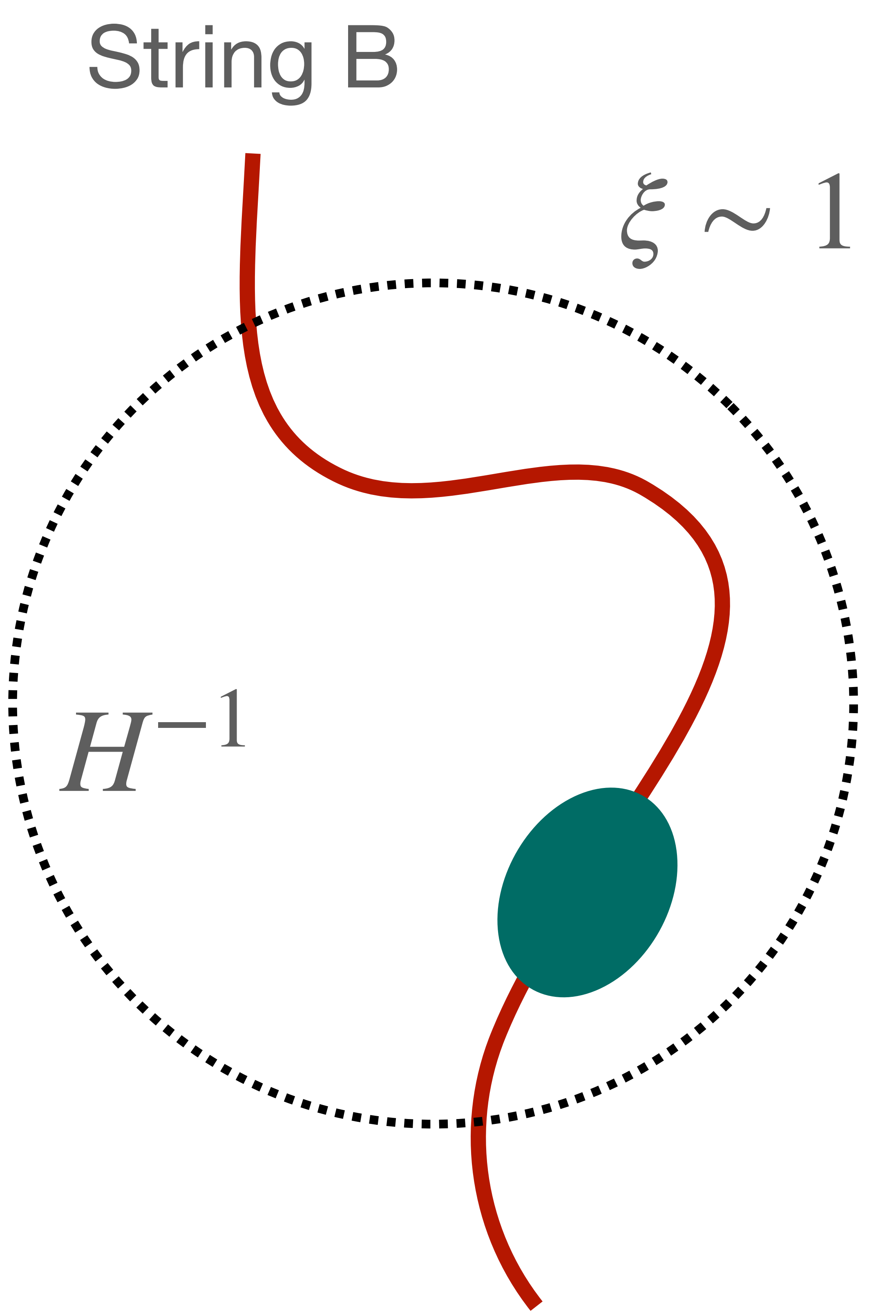
- How to evaluate the seeded action?
  - **EFT** on the string for the lightest Higgs mode



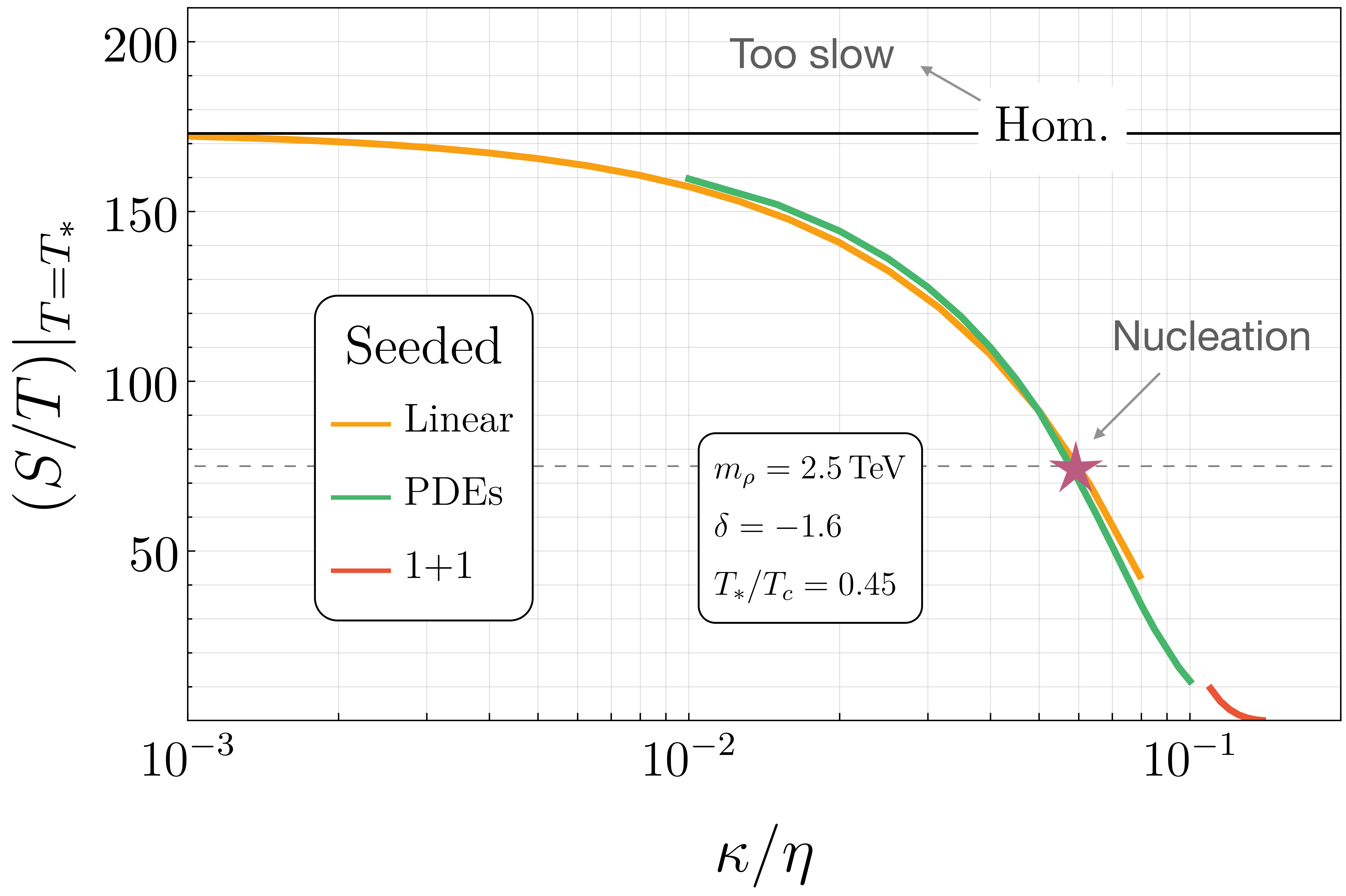
$$h(x^\mu) = \phi(r) h_0(z,t)$$

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

$$\tilde{V}(h_0) = \frac{1}{2}\omega^2 h_0^2 - \frac{1}{3!} c_3 h_0^3 + \frac{1}{4!} c_4 h_0^4$$

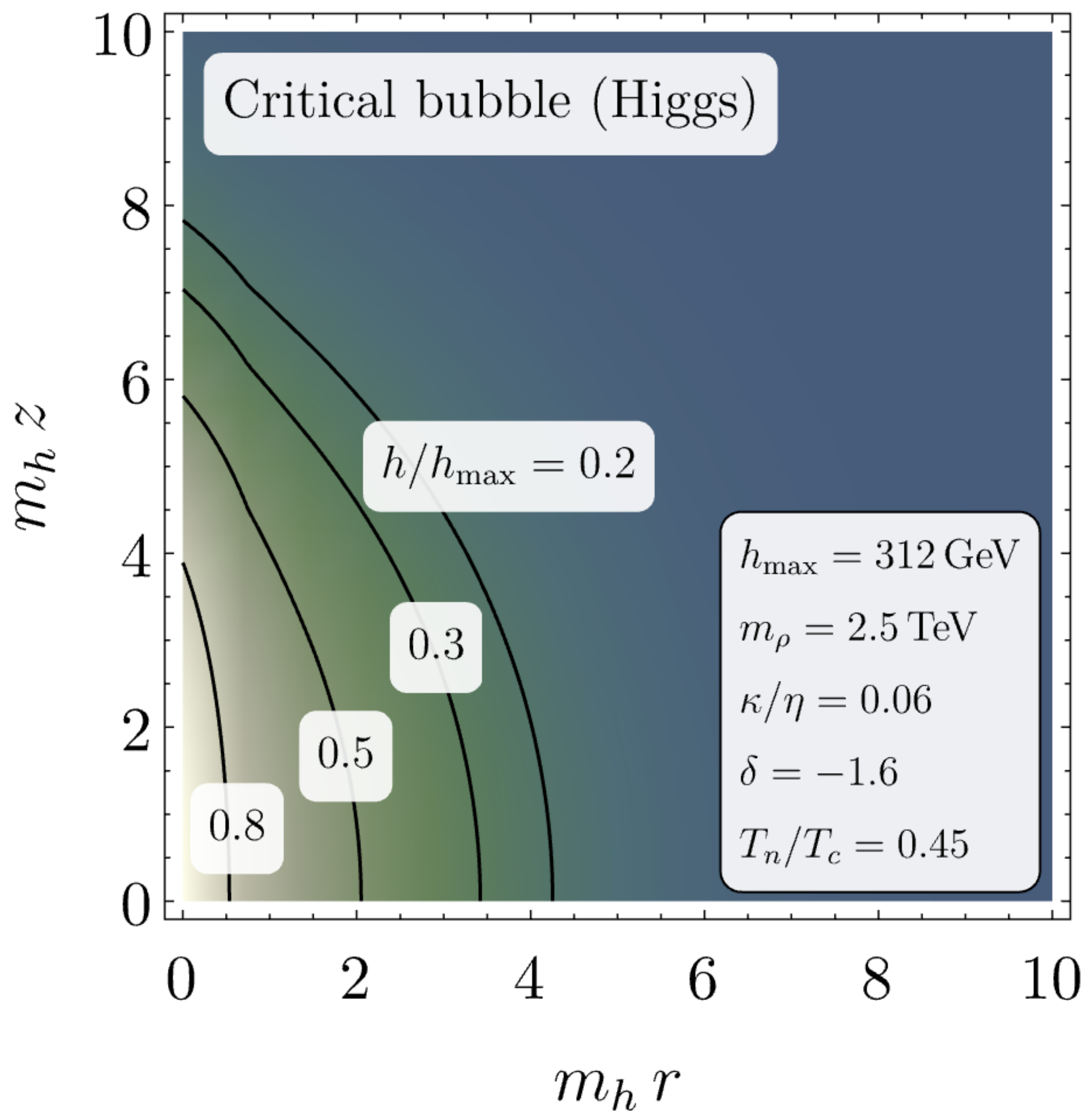


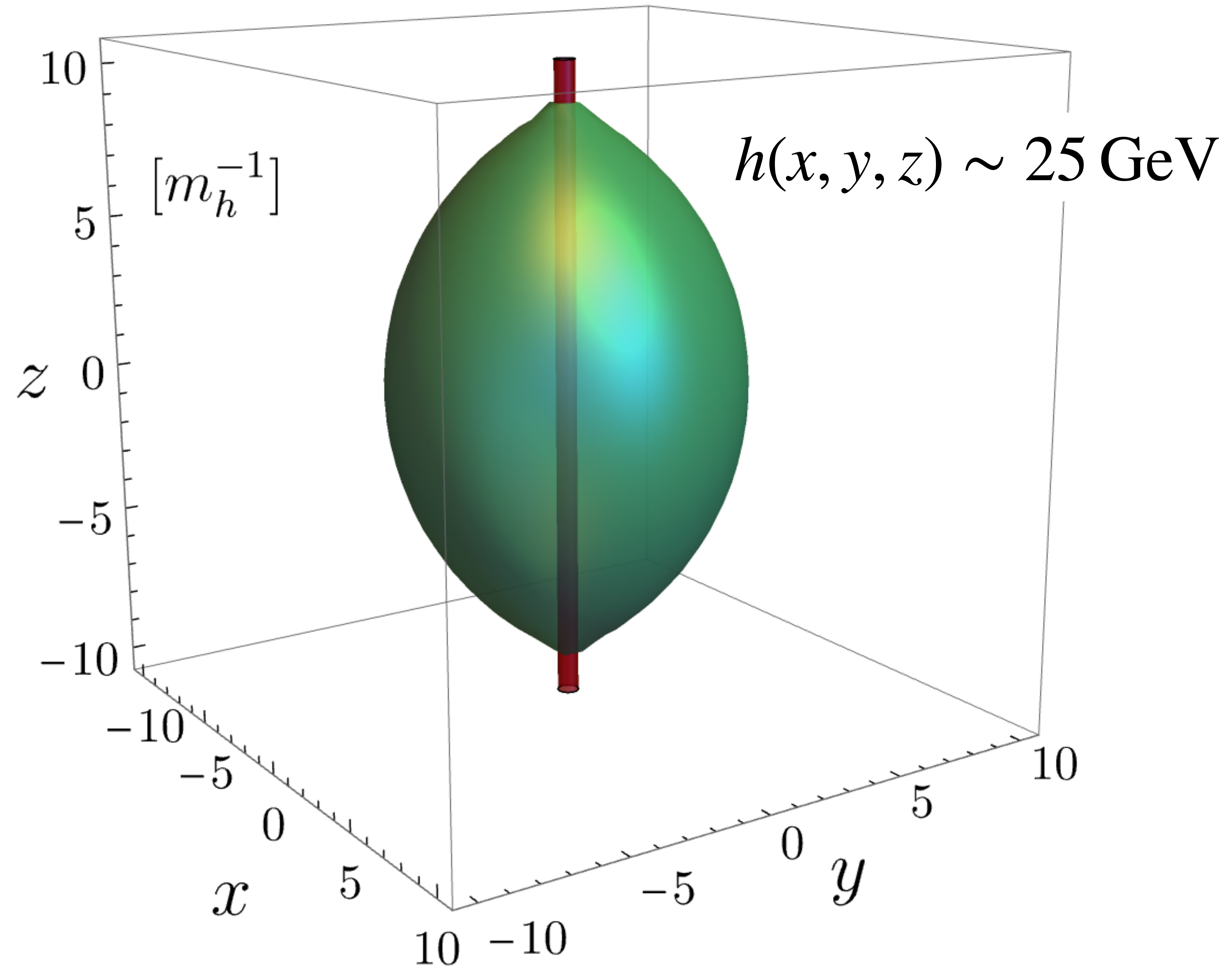
Seeded tunneling



Seeded tunneling

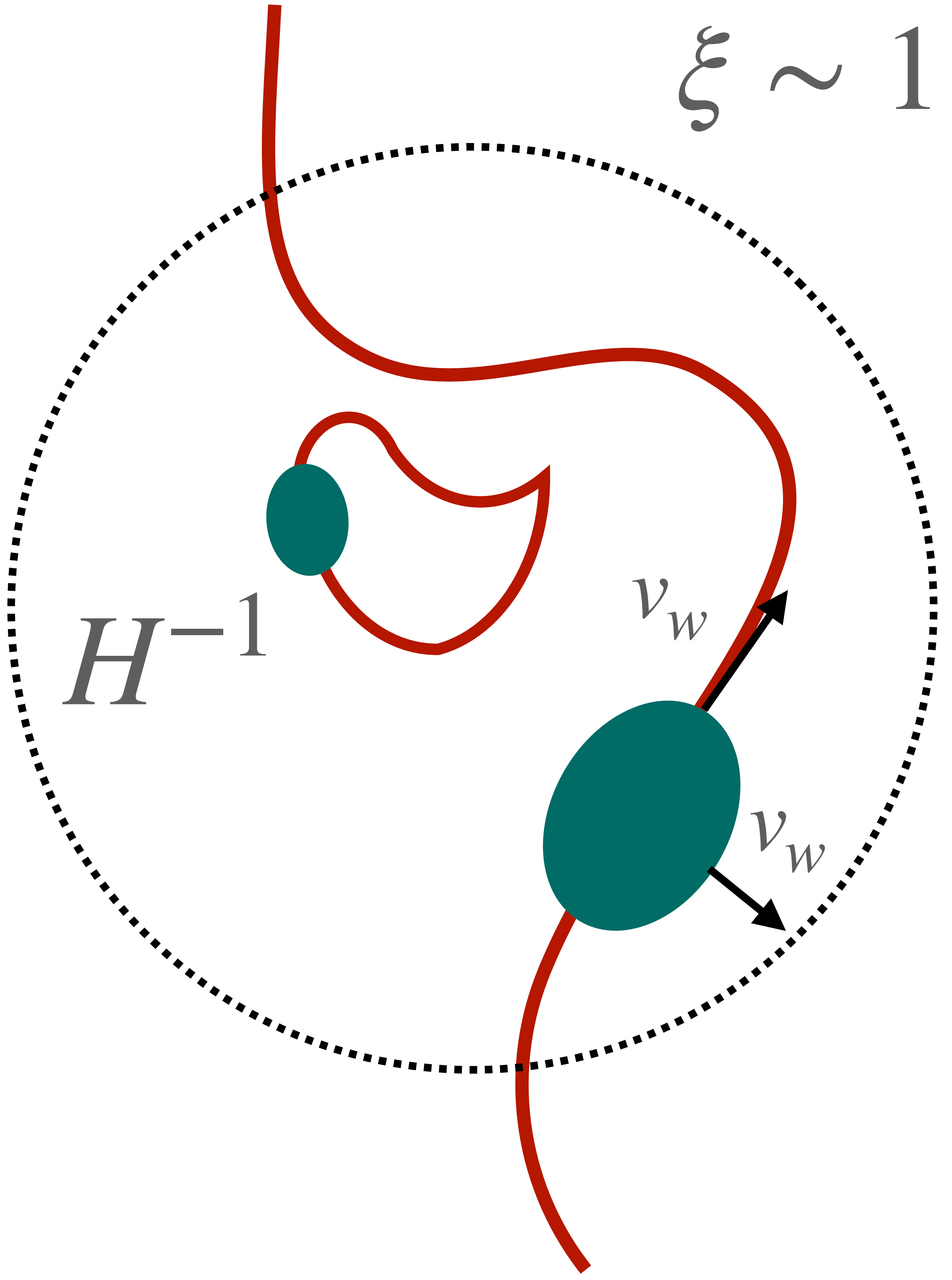
- Profile of the critical bubble: ★





Phenomenology

- 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 (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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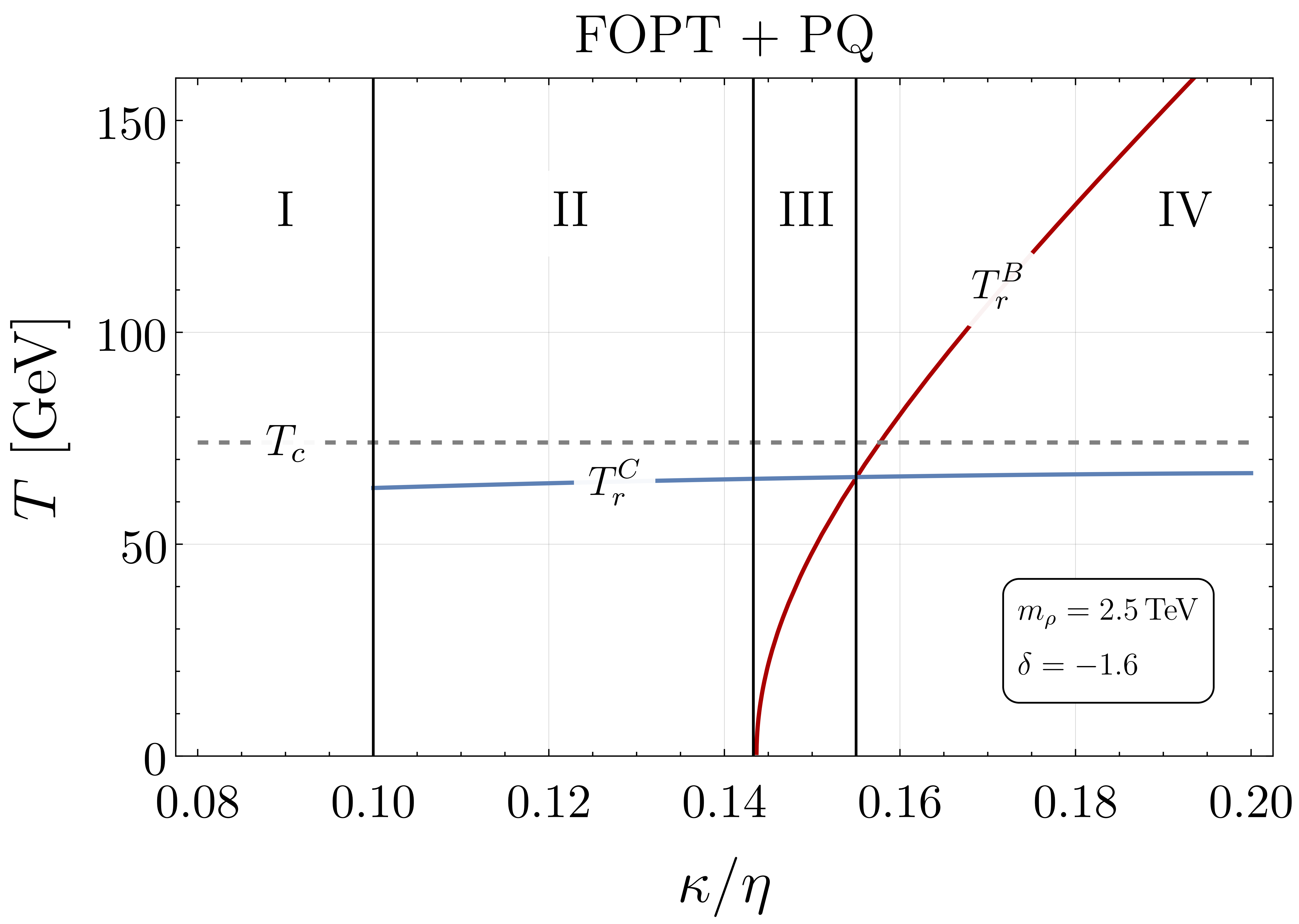
Thank you!

Backup


FOPT + PQ
I
II
III
IV
T_r^B
T_c
T_r^C
$m_\rho = 2.5\,\mathrm{TeV}$
$\delta = -1.6$
150
100
50
0
0.08
0.10
0.12
0.14
0.16
0.18
0.20
T [GeV]
κ/η