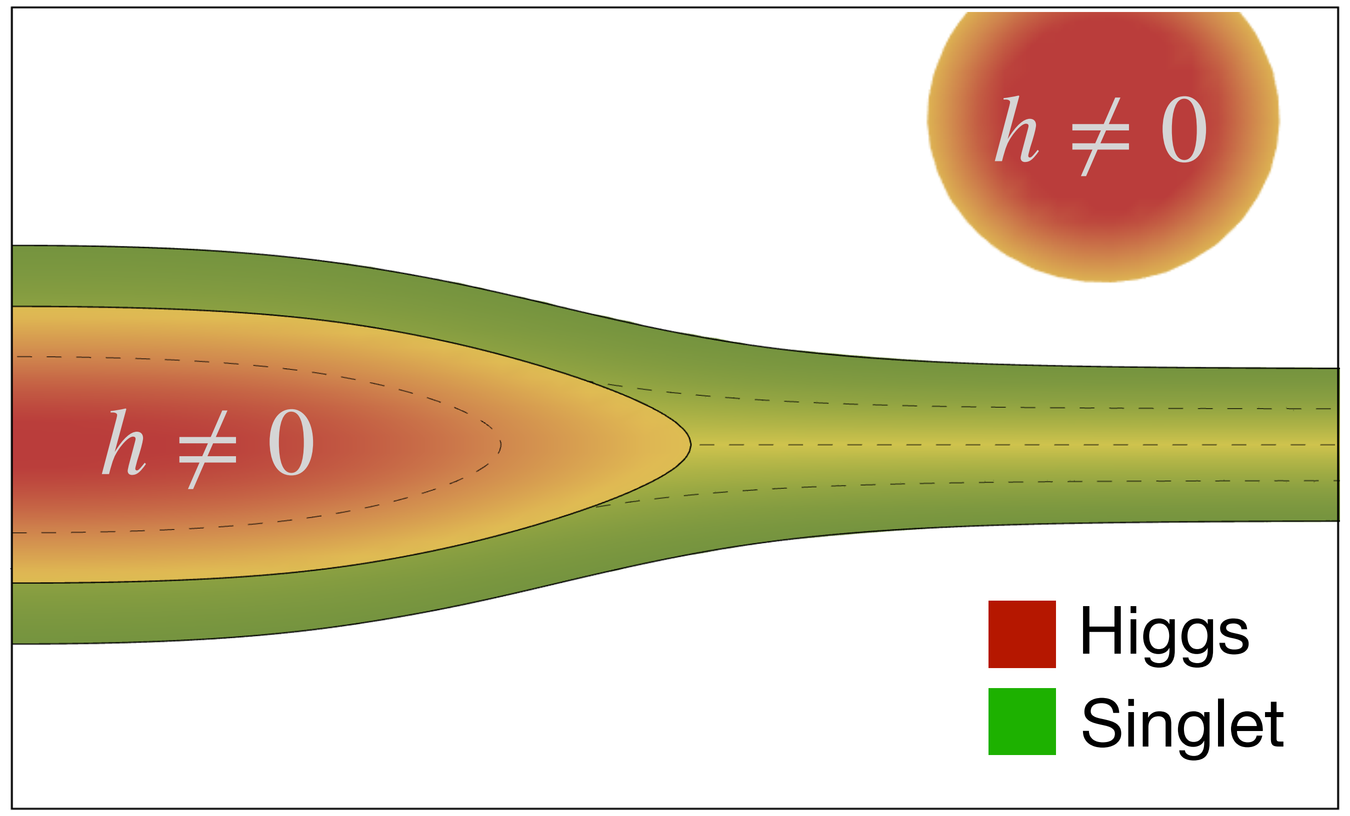


Cosmological defects

Simone Blasi
Vrije Universiteit Brussel (VUB)*

Based on:

SB, Mariotti [2203.16450], PRL

SB, Jinno, Konstandin, Rubira, Stomberg [2302.06952] (to appear in JCAP)

Agrawal, **SB**, Mariotti, Nee, in prep.

*On the way to DESY

COSMIC WISPers 1st General Meeting, 06.09.2023, Bari

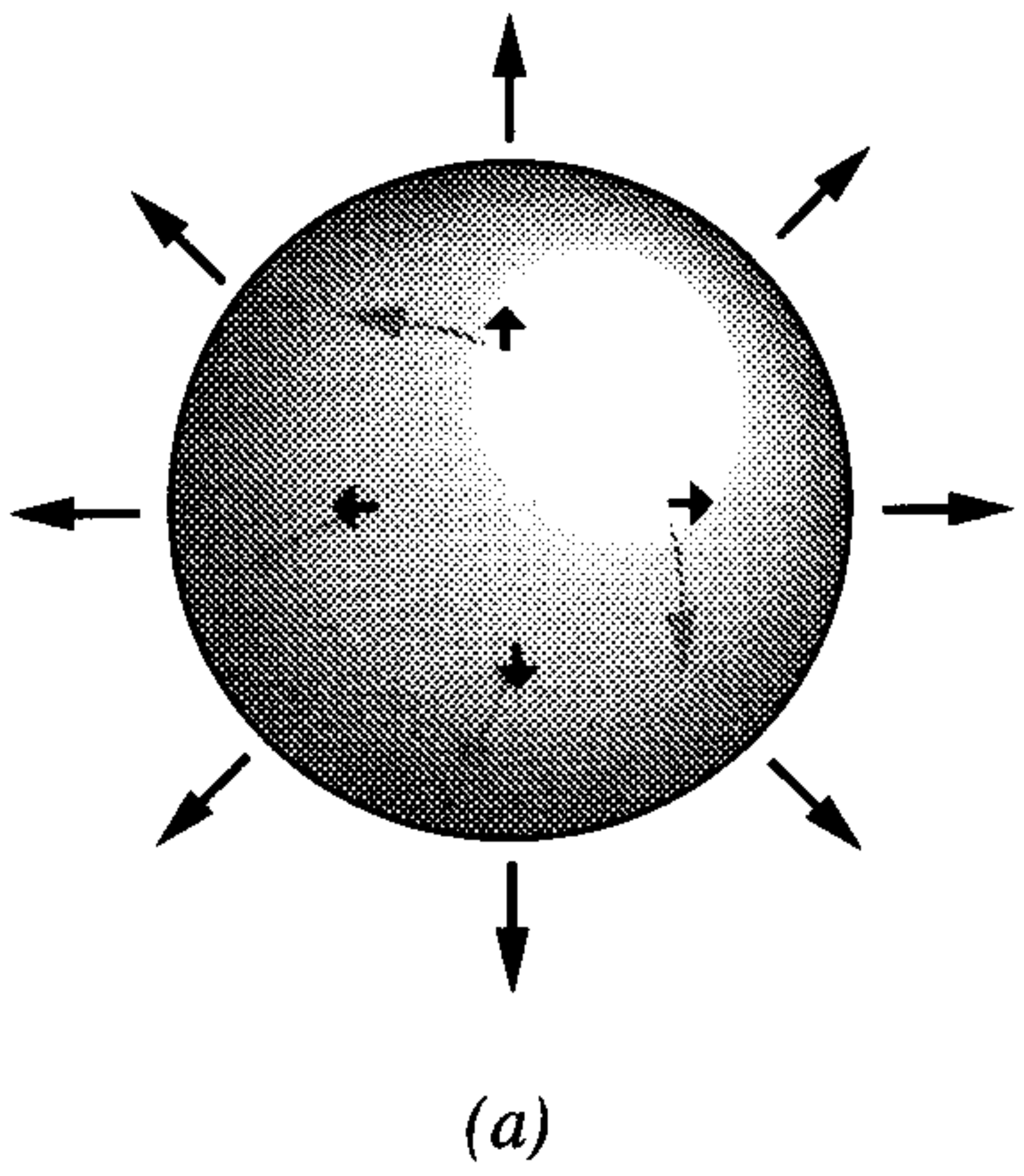
Topological defects

$\mathscr{M}$ **vacuum manifold**:

$$G \to H, \quad \mathscr{M} = G/H$$

Defect	Dimension	Homotopy	Mass
Domain walls	2	$\pi_0(\mathscr{M})$	σL^2
Strings	1	$\pi_1(\mathscr{M})$	μL
Monopoles	point-like	$\pi_2(\mathscr{M})$	v^2/α

Plus **hybrid defects** (walls bounded by strings, strings ending on monopoles etc.)



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

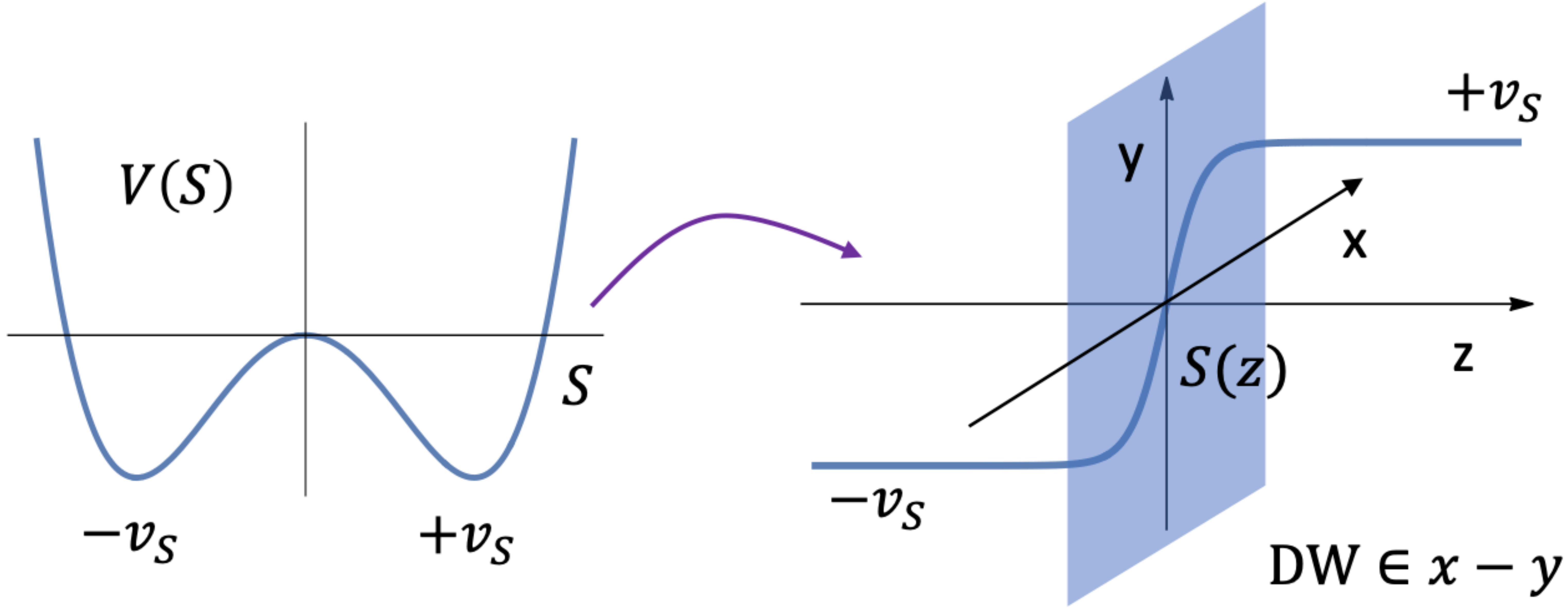
('t Hooft Polyakov Monopole)

Fig. from Vilenkin & Shellard 1994

Topological defects

Field theory: classical solutions to the EoM

$$\mathbb{Z}_2 \to \varnothing$$



Domain wall tension:

$$\sigma_{\rm DW} \sim v_s^3$$

Topological defects

Extended objects: Dirac action (world volume)

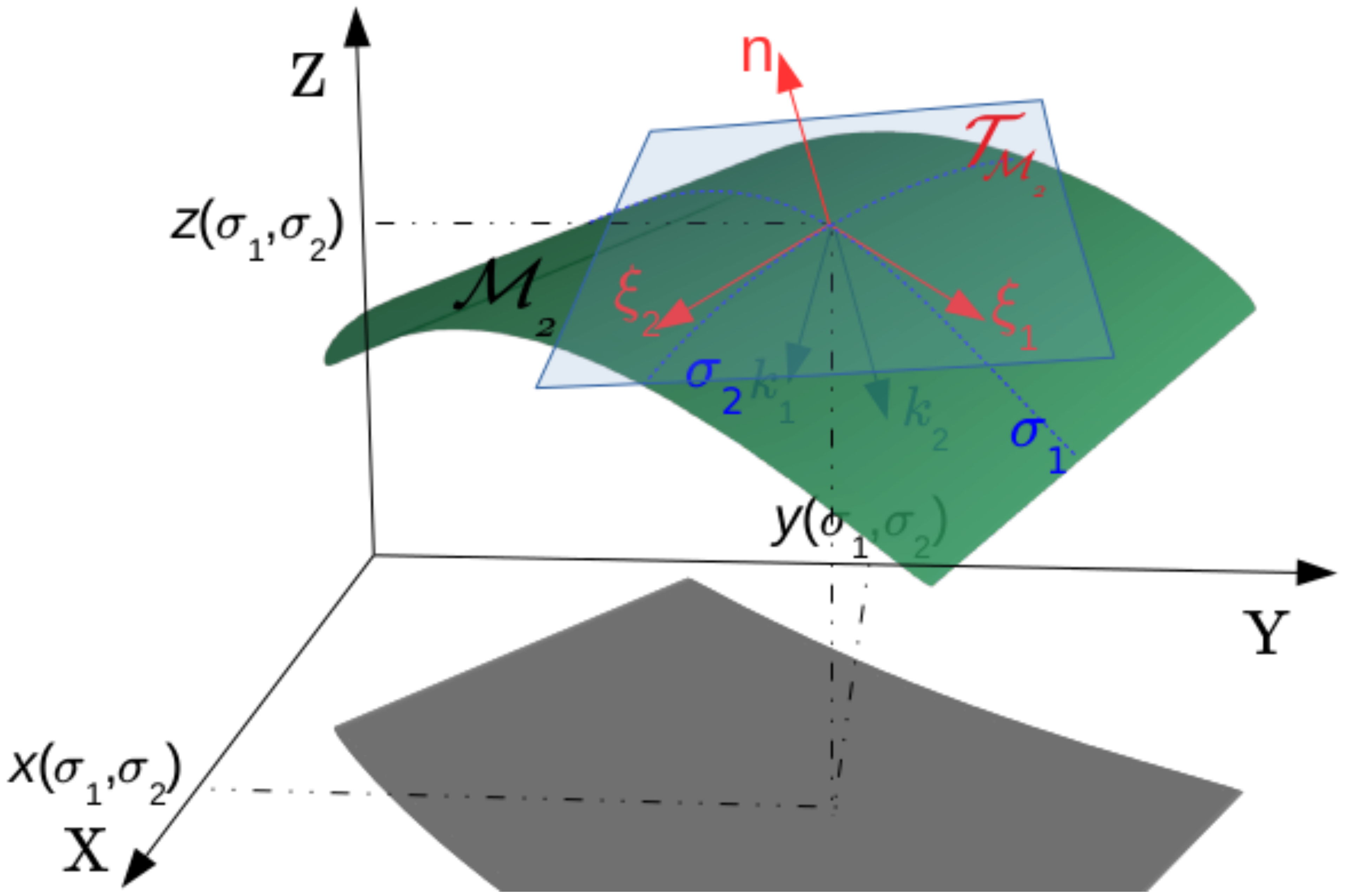


Fig. from Martins, Rybak, Avgoustidis, Shellard [1602.01322], PRD 2016

$$\mathcal{S} = -\,\sigma_{\rm DW} \int \sqrt{-\gamma}\; d^3\sigma$$

Tension

Induced metric

Point particle: $\mathcal{S} = -\,m \int \sqrt{1 - \dot{x}^2}\; dt$

Cosmological defects

- Monopole (and domain wall) problem in GUTs: inflation!

Guth, PRD 1981; Linde, PLB 1982
Albrecth, Steinhardt, PRL 1982

- Baryogenesis

Rubakov, JETP Lett. 1982
Cline, Espinosa, Moore, Riotto, PRD 1999
Daido, Kitajima, Takahashi [1504.07917] JCAP

- Contribution to dark matter relic abundance

Hiramatsu et al. [1012.5502] PRD
Gorghetto, Hardy, Villadoro
[1806.04677] JHEP; [2007.04990] SciPost

- Strong source of gravitational waves

Saikawa [1703.02576]
Blanco-Pillado, Olum [1703.02576] PRD

- Impact on cosmological phase transitions

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Nucleation sites

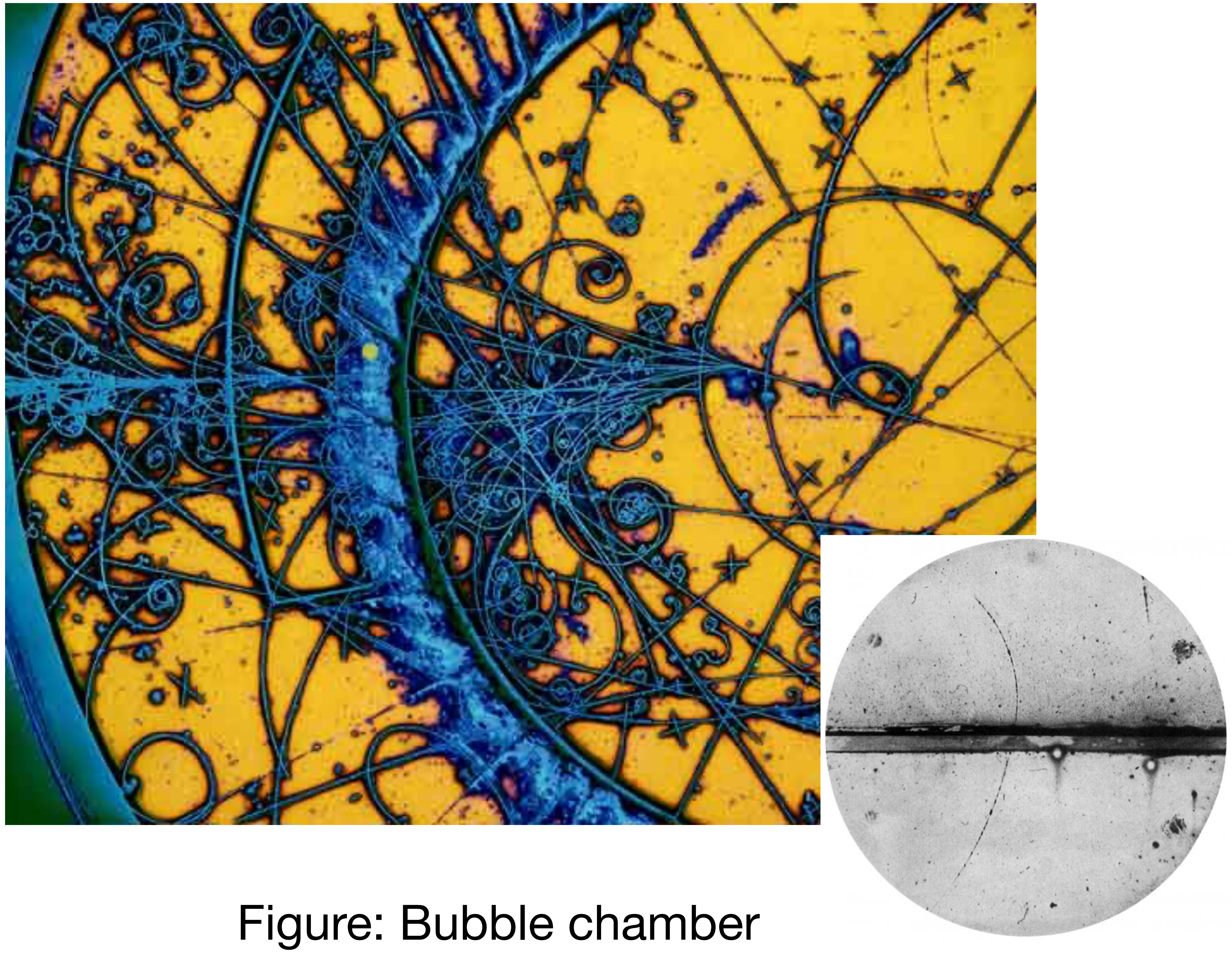


Figure: Bubble chamber

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

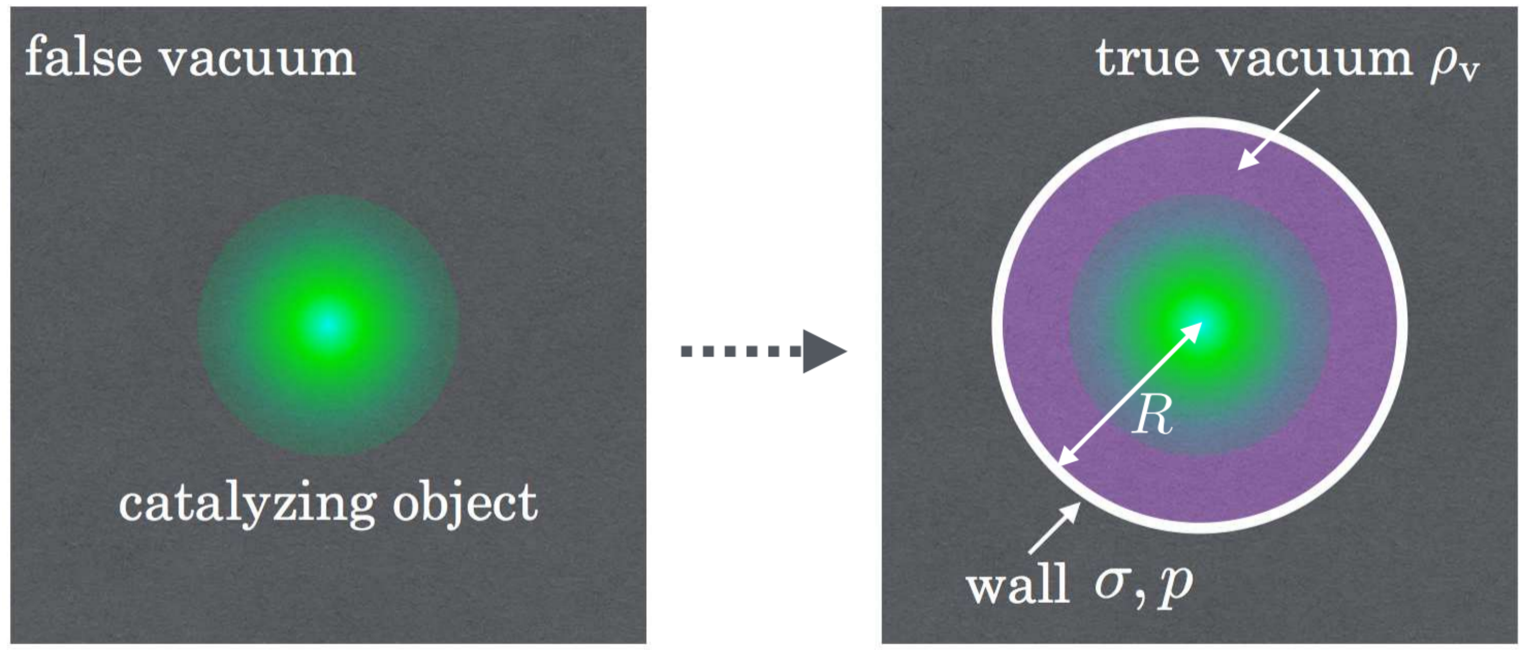
- Compact objects and gravitational effects

(Coleman-de Luccia, PRD, 1980)

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

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

Strumia [2209.05504]



- Topological defects (strings and monopoles)

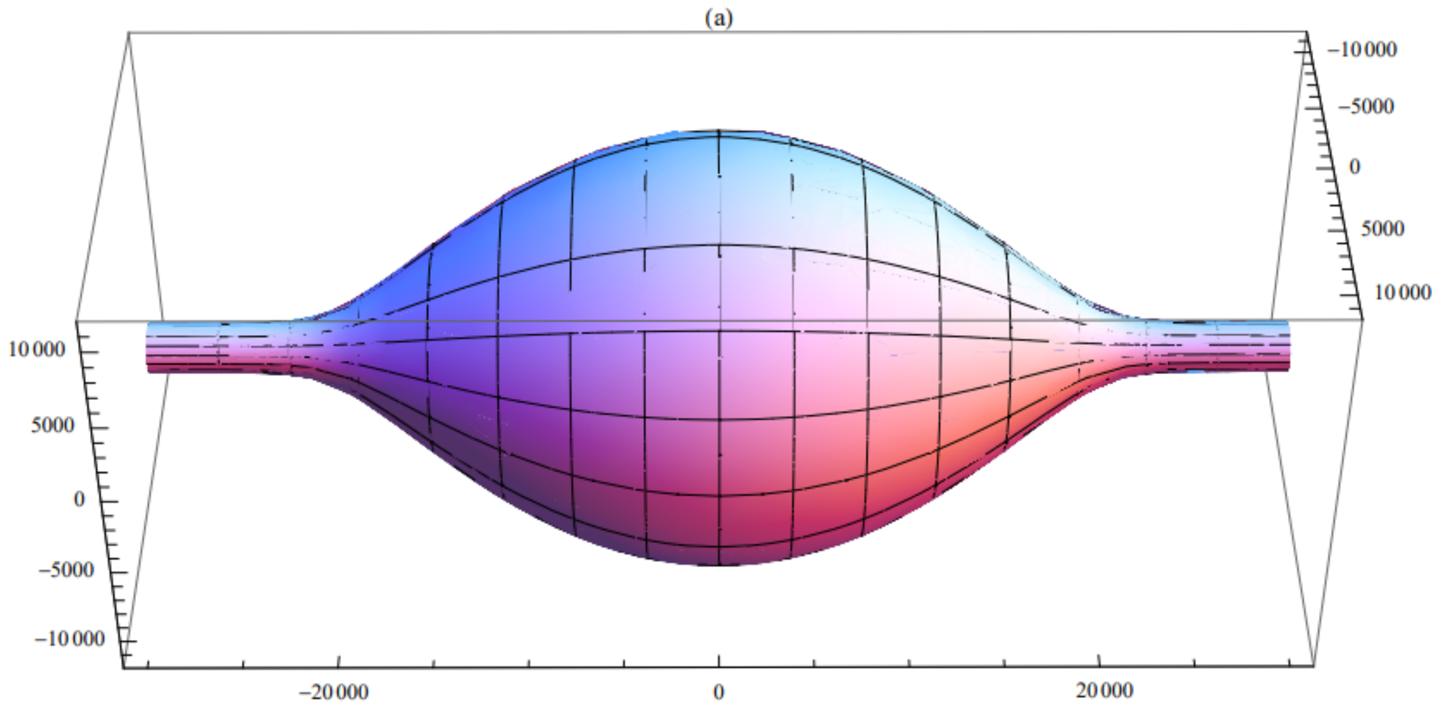


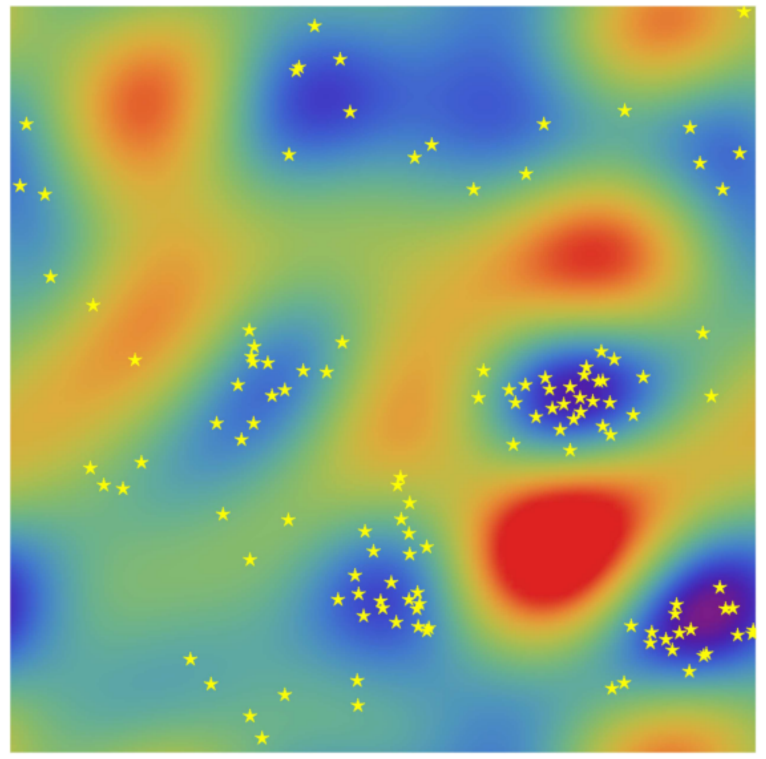
Fig. from Lee et al., [1310.3005], PRD

Yajnik, PRD, 1986 …

Agrawal and Nee, [2202.11102], SciPost

- Primordial density fluctuations

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



- **Domain walls**

This talk:

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

SB, Mariotti [2203.16450] PRL

Electroweak phase transition (xSM)

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

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

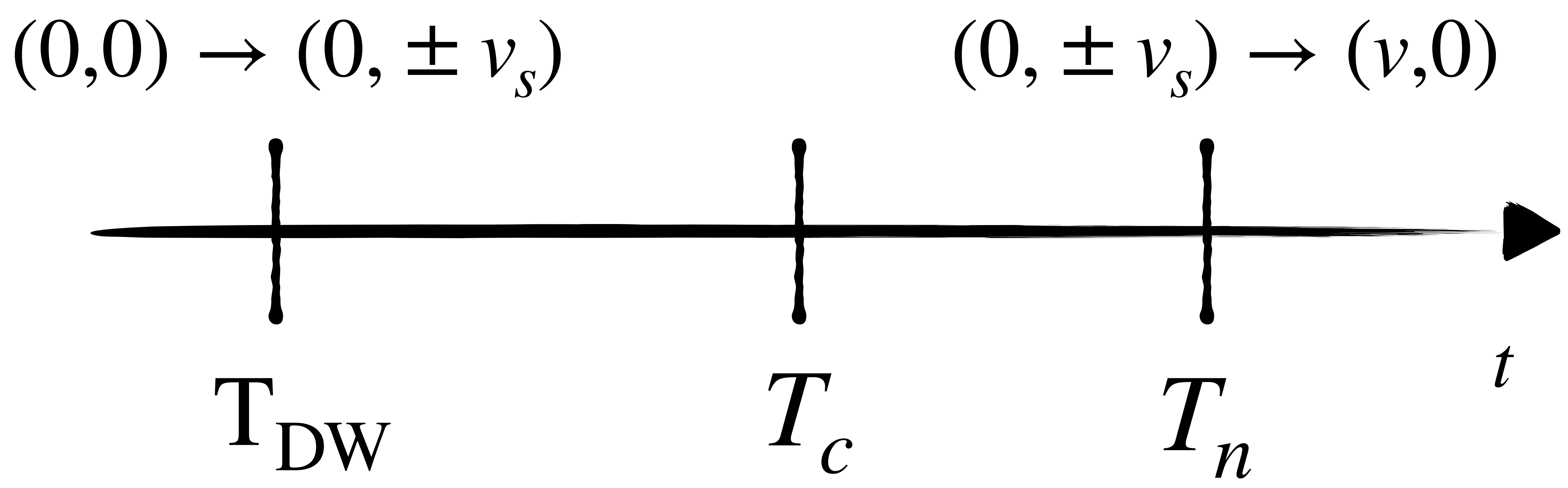
$$V = -\frac{1}{2}(\mu^2 - c_h T^2) h^2 + \frac{1}{4}\lambda\, h^4$$
$$-\frac{1}{2}(m^2 - c_s T^2) S^2 + \frac{1}{4}\eta\, S^4$$
$$+\frac{1}{2}\kappa\, h^2 S^2$$

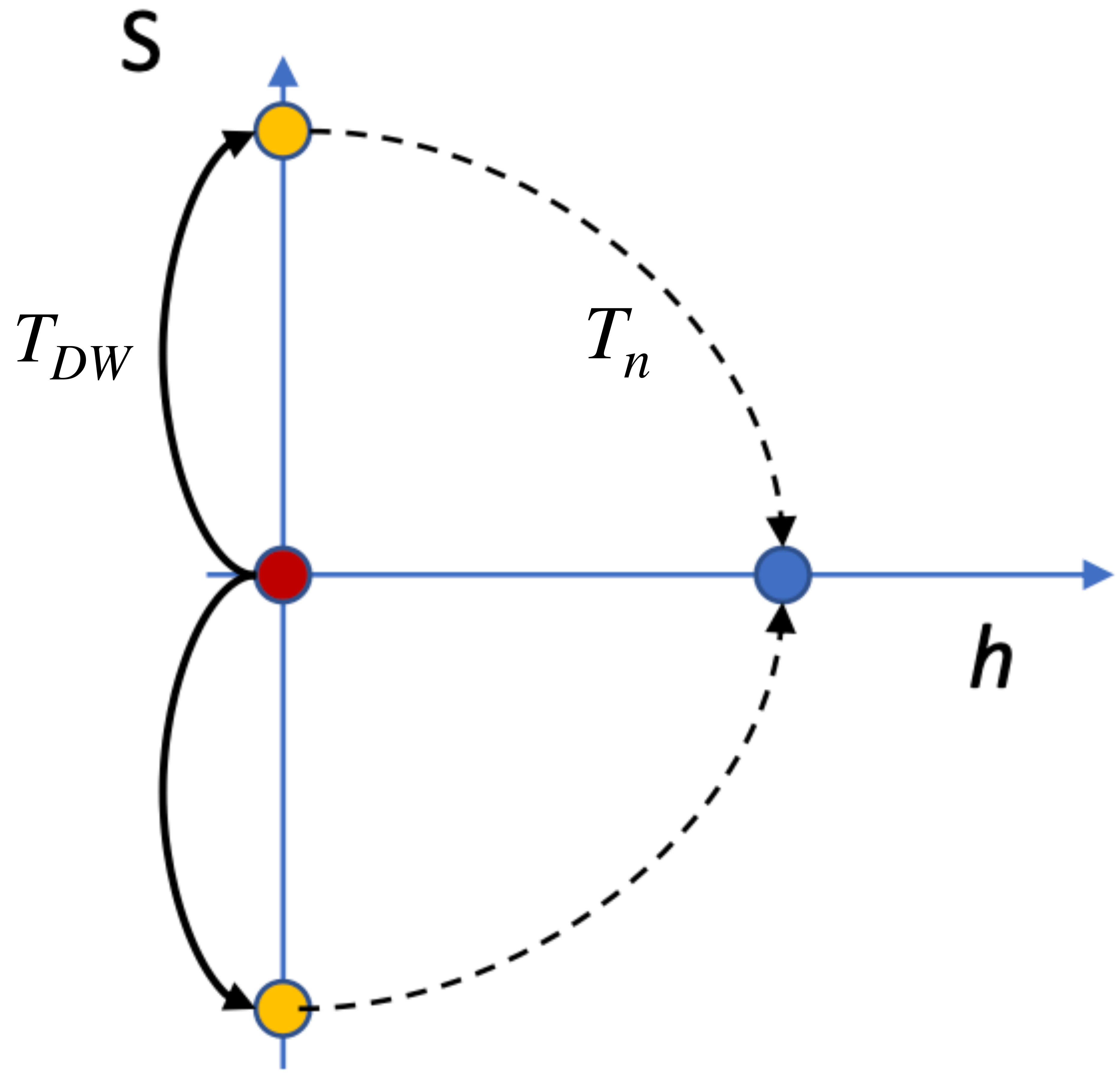
Electroweak phase transition (xSM)

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

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

Two step transition



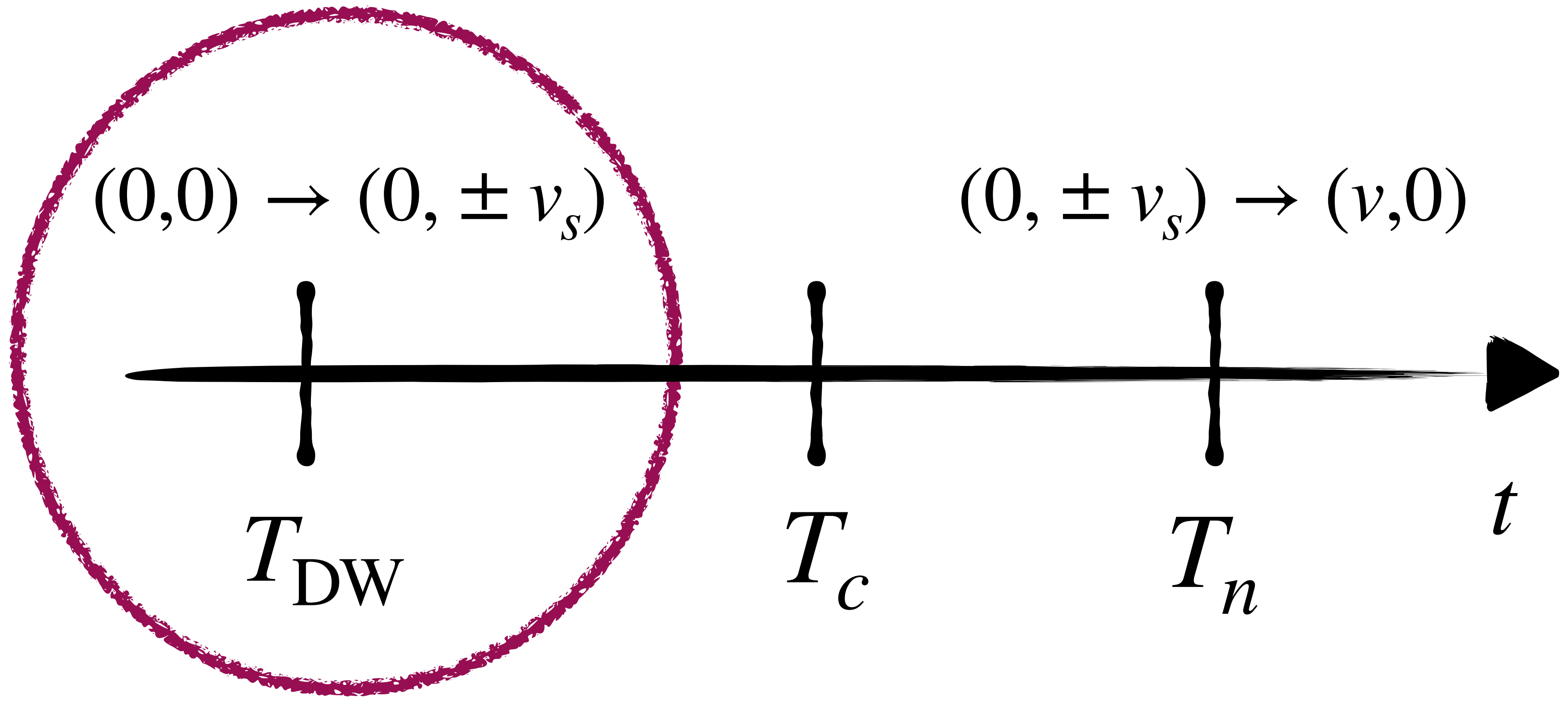


1st step: domain wall formation

Kibble mechanism:

Zeldovich et al. 1975, Kibble 1976

- Fluctuations have finite correlation length $\xi(T) < d_H$
- Uncorrelated patches will select different points of vacuum manifold $\mathscr{M}$



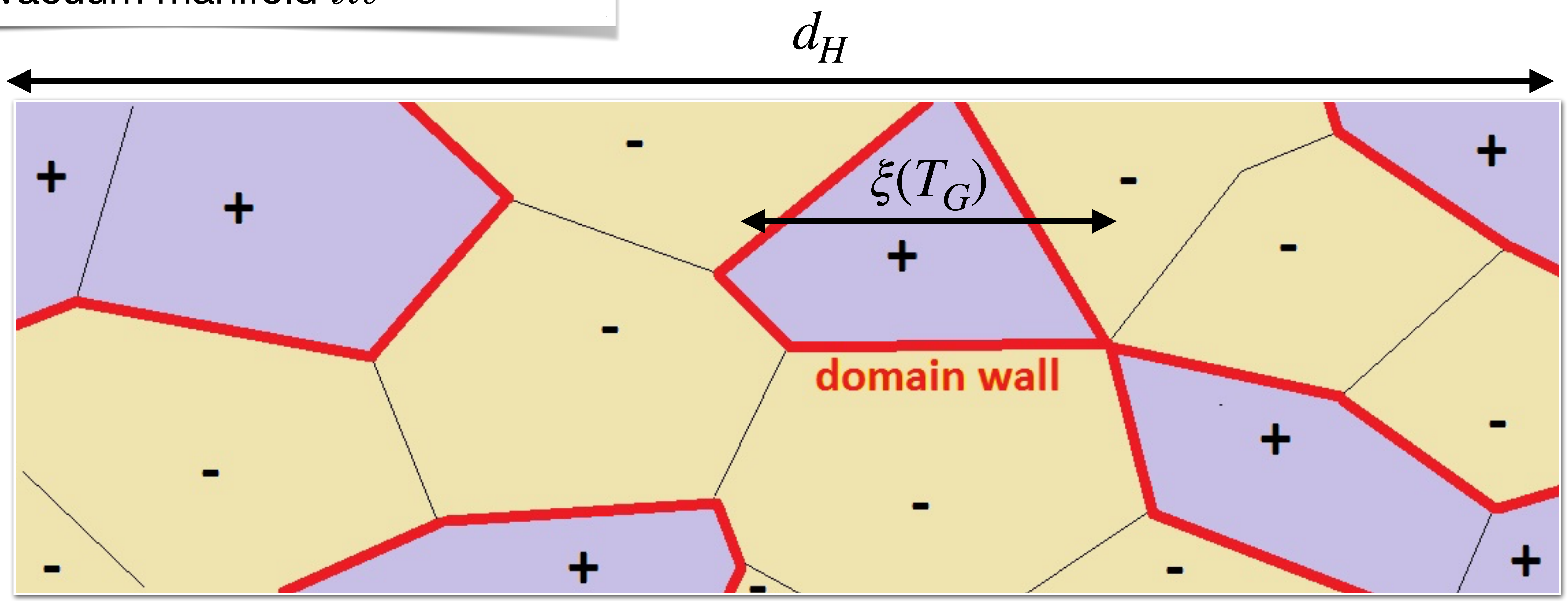
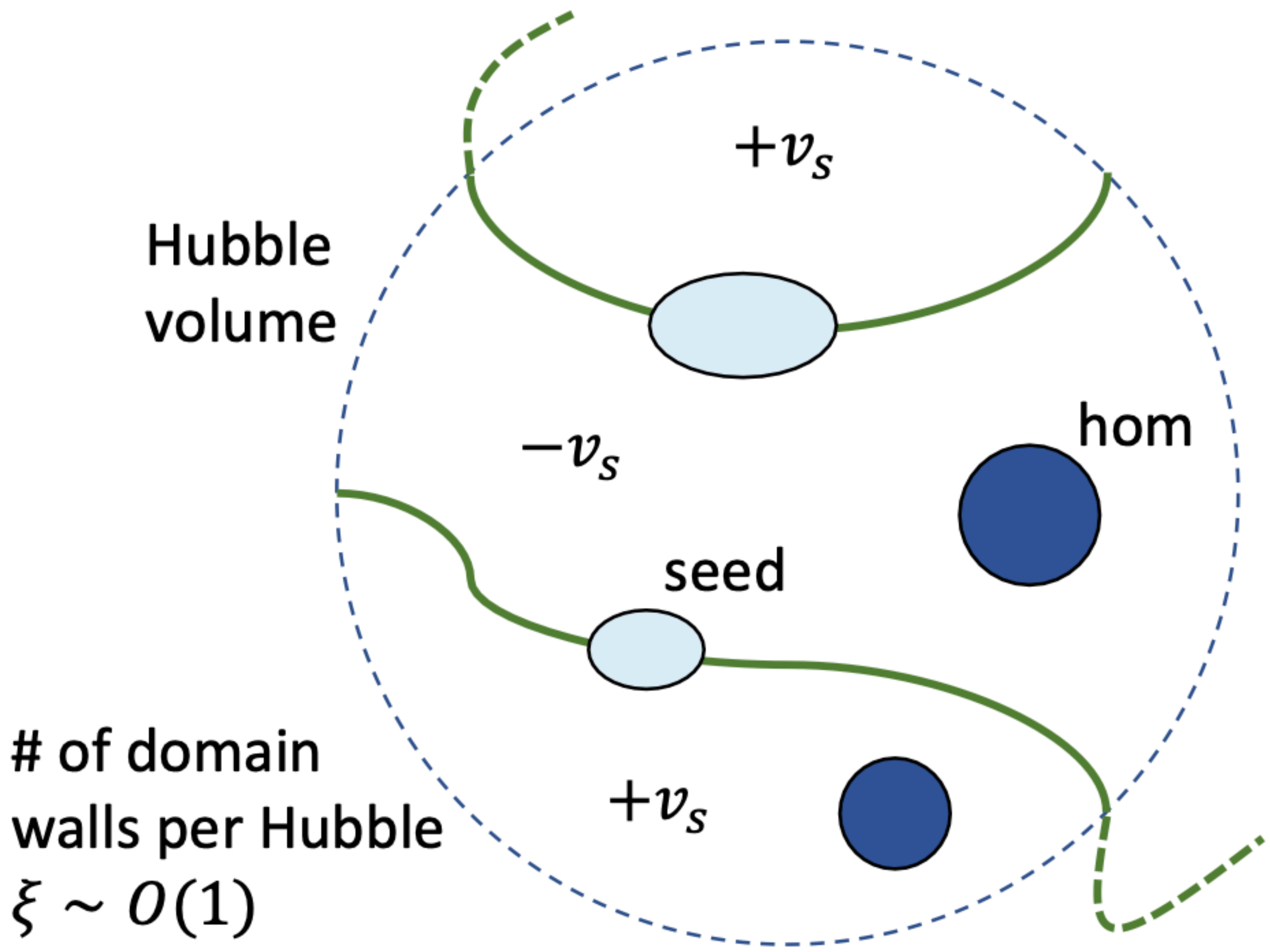
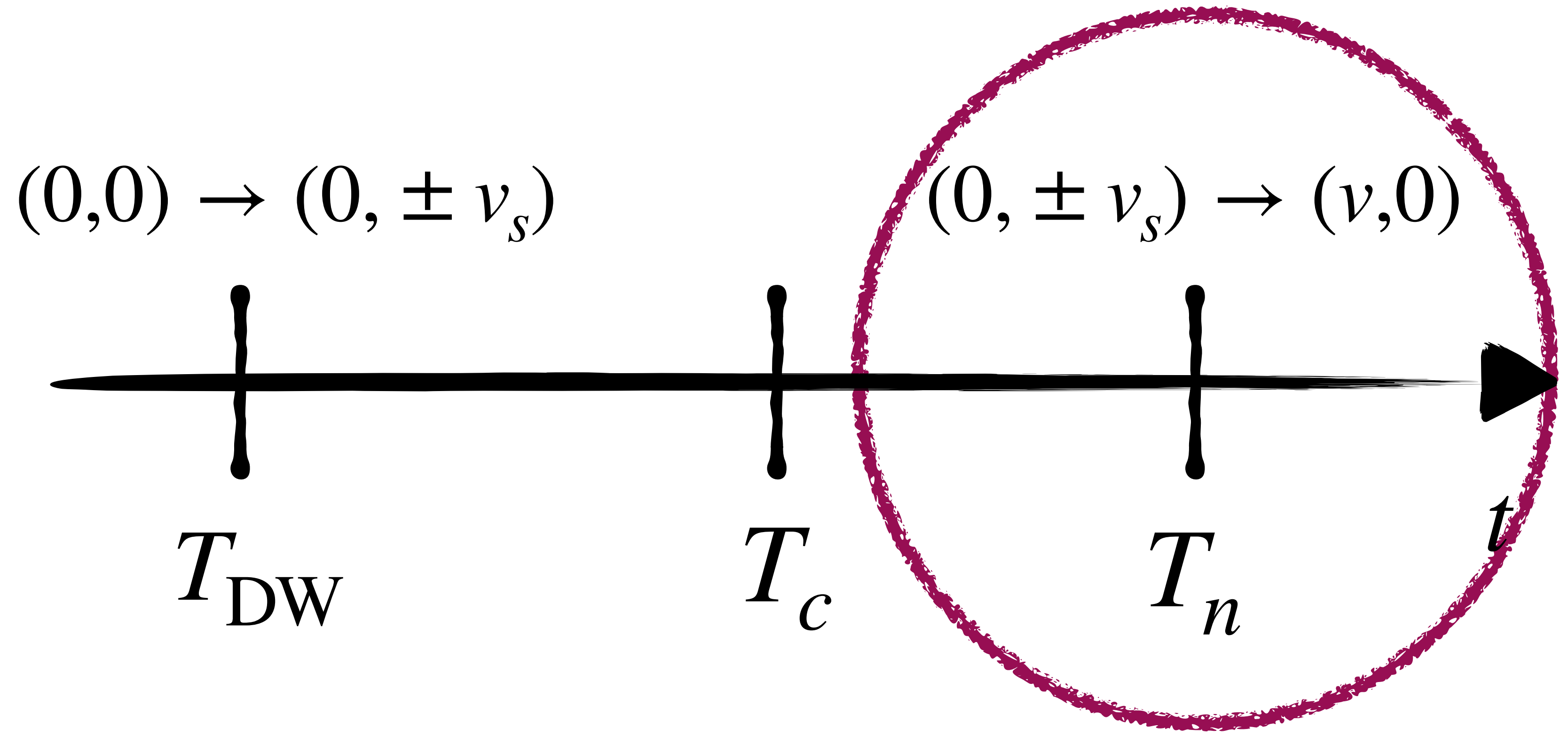


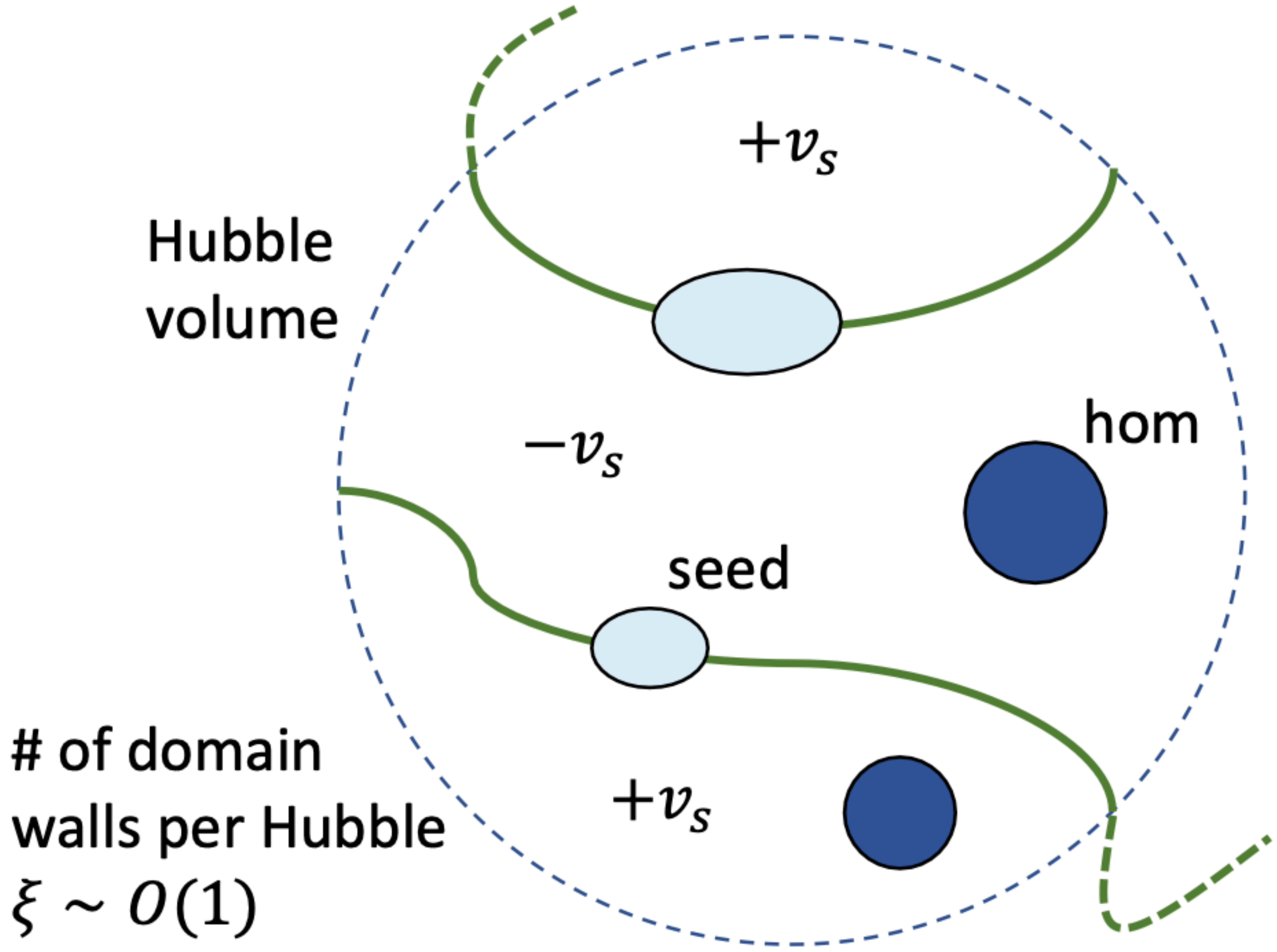
Fig. From MIT edu

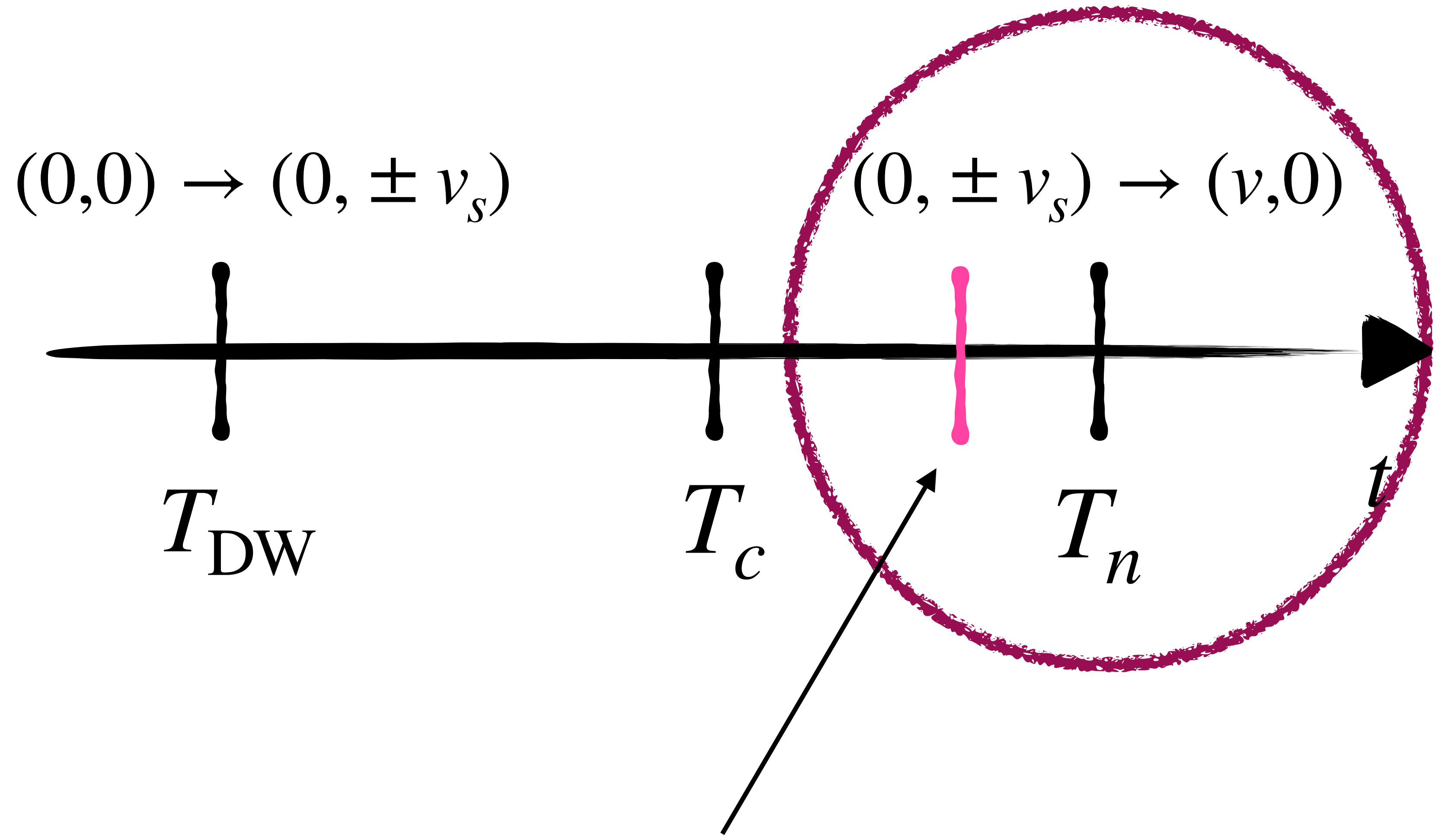
2nd step: tunneling to the EW vacuum





2nd step: tunneling to the EW vacuum



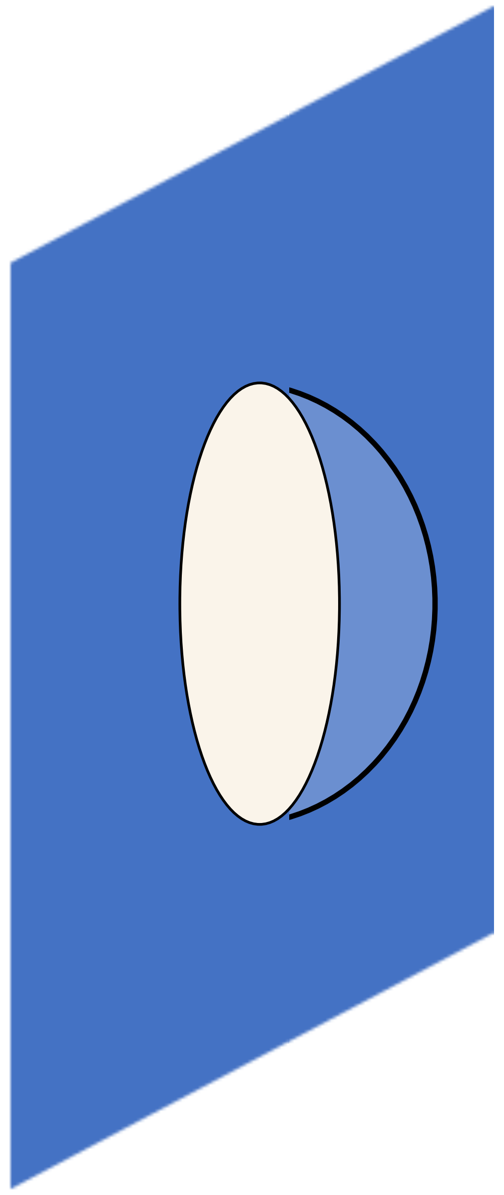


At T_n^{seed} bubbles nucleate on the walls

- Nucleation probability no longer the same everywhere, enhanced around the impurities

Seeded tunneling

Only O(2) symmetry



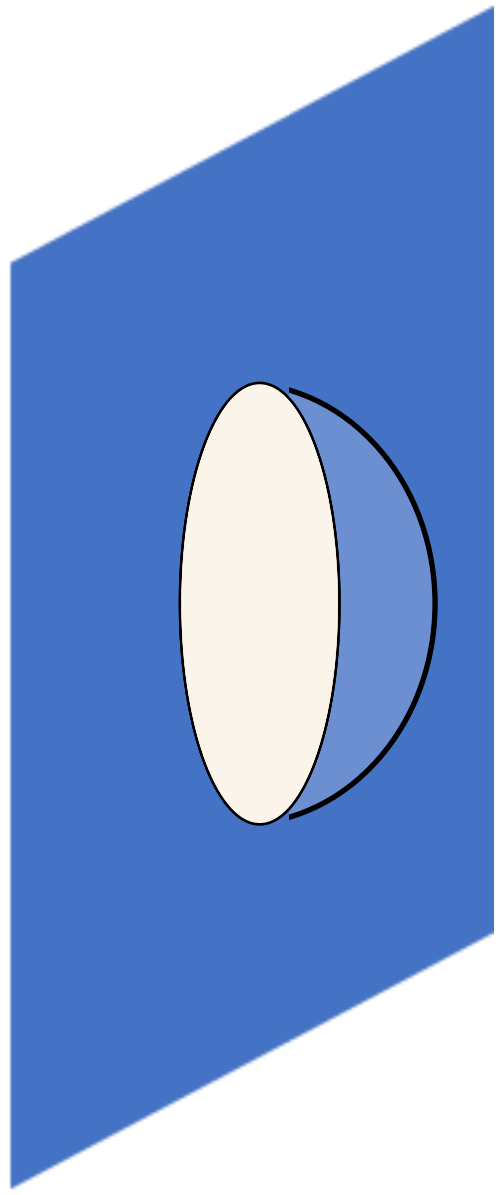
What is the action corresponding to the critical bubble?

1. Solving coupled **system of PDEs**

- “Exact”
- Physical picture?
- Which initial conditions for the algorithm?

Seeded tunneling

Only O(2) symmetry



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- Limited validity
- Intuitive picture
- Simple calculation

Seeded tunneling

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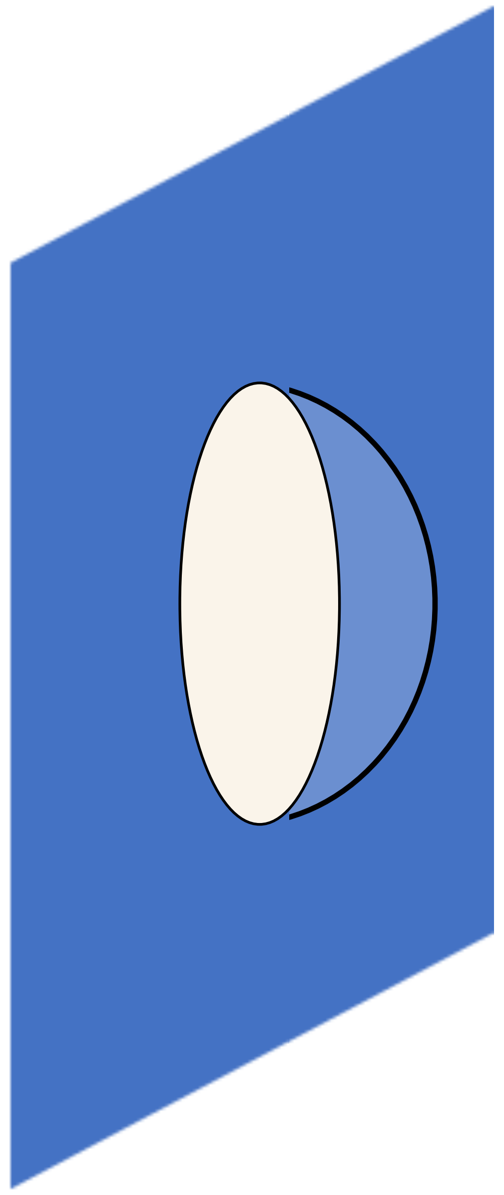


What is the action corresponding to the critical bubble?

1. Solving coupled **system of PDEs**
   - "Exact"
   - Physical picture?
   - Which initial conditions for the algorithm?

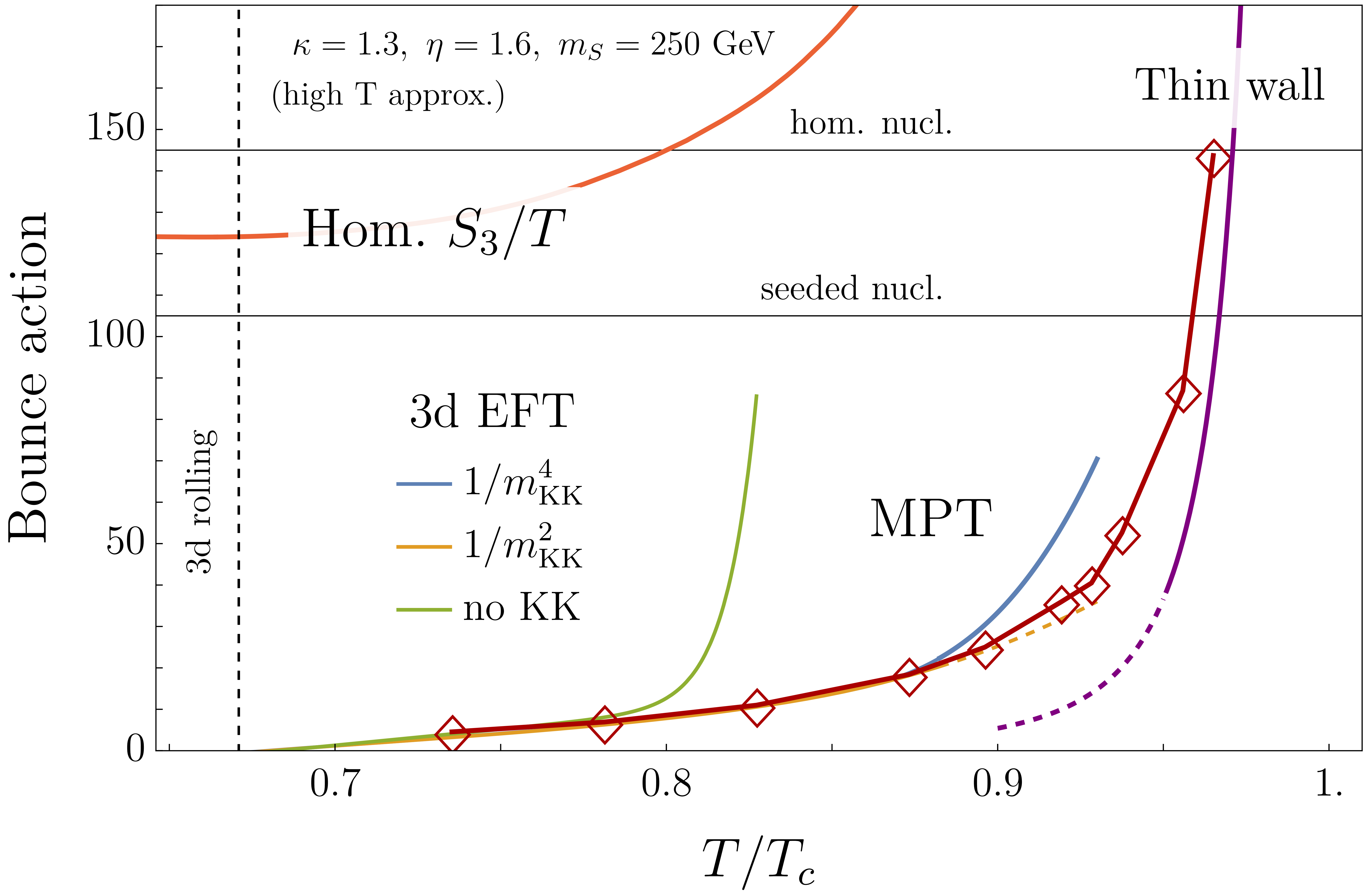
2. **Thin wall** approximation
   - Limited validity
   - Intuitive picture
   - Simple calculation

3. **Kaluza-Klein** decomposition
   - Quantitative results
   - Still intuitive
   - Initial conditions for num. algorithms and cross-checks

Comparison of 1, 2, 3

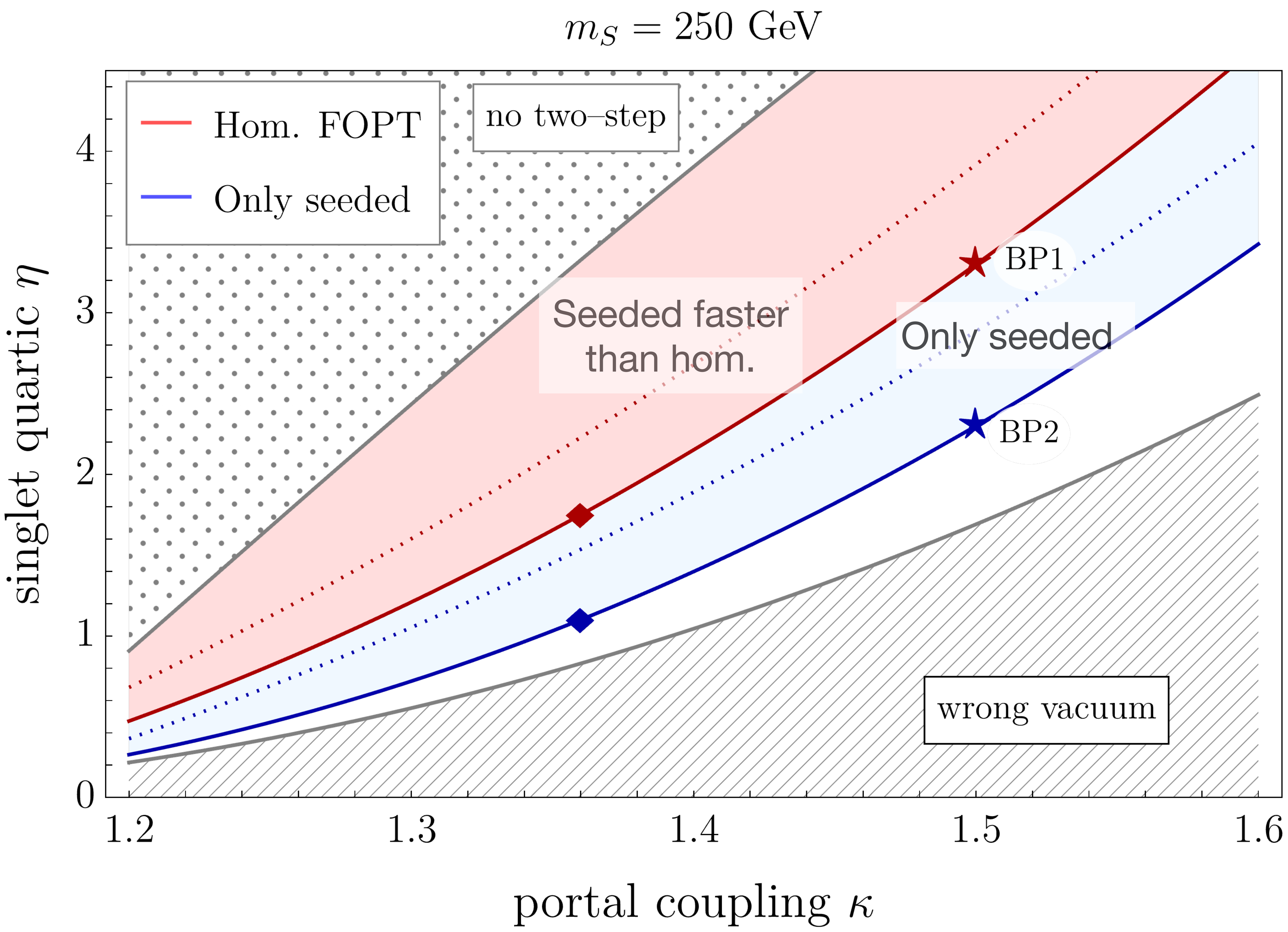
SB, Mariotti [2203.16450], PRL
Agrawal, **SB**, Mariotti, Nee, in prep.

$$\Gamma \sim e^{-S/T}$$



Parameter space of the xSM

SB, Mariotti [2203.16450], PRL
Agrawal, **SB**, Mariotti, Nee, in prep.

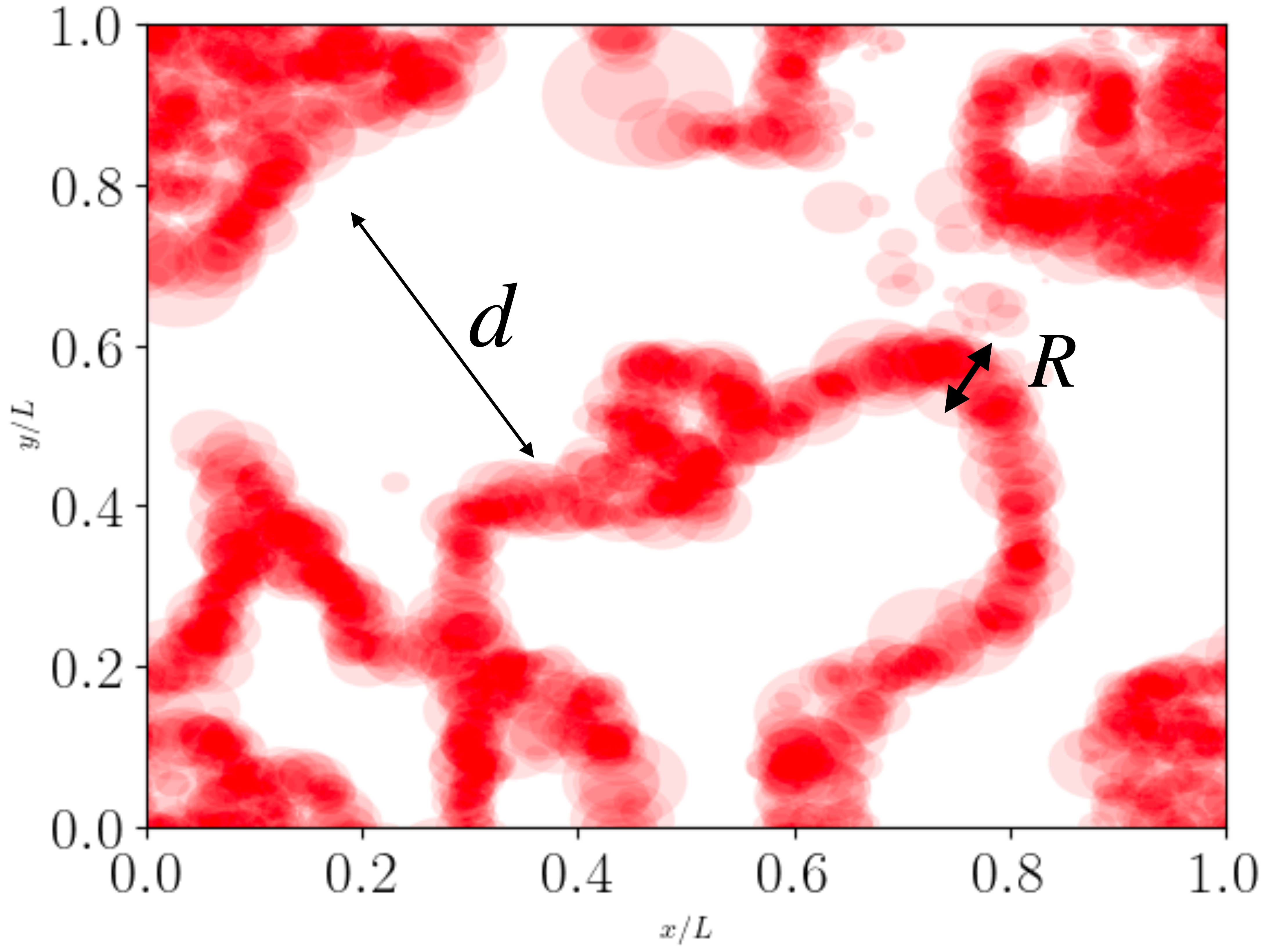


*In terms of nucleation temperature

Gravity waves from sound waves

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

Domain wall network
mimicked by Ising model



- Bubble size R controlled by the nucleation rate *on the wall* $R \sim \beta_{\rm DW}^{-1}$
- $R \ll d$: Bubbles grow out of the walls and will collide with typical size d

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

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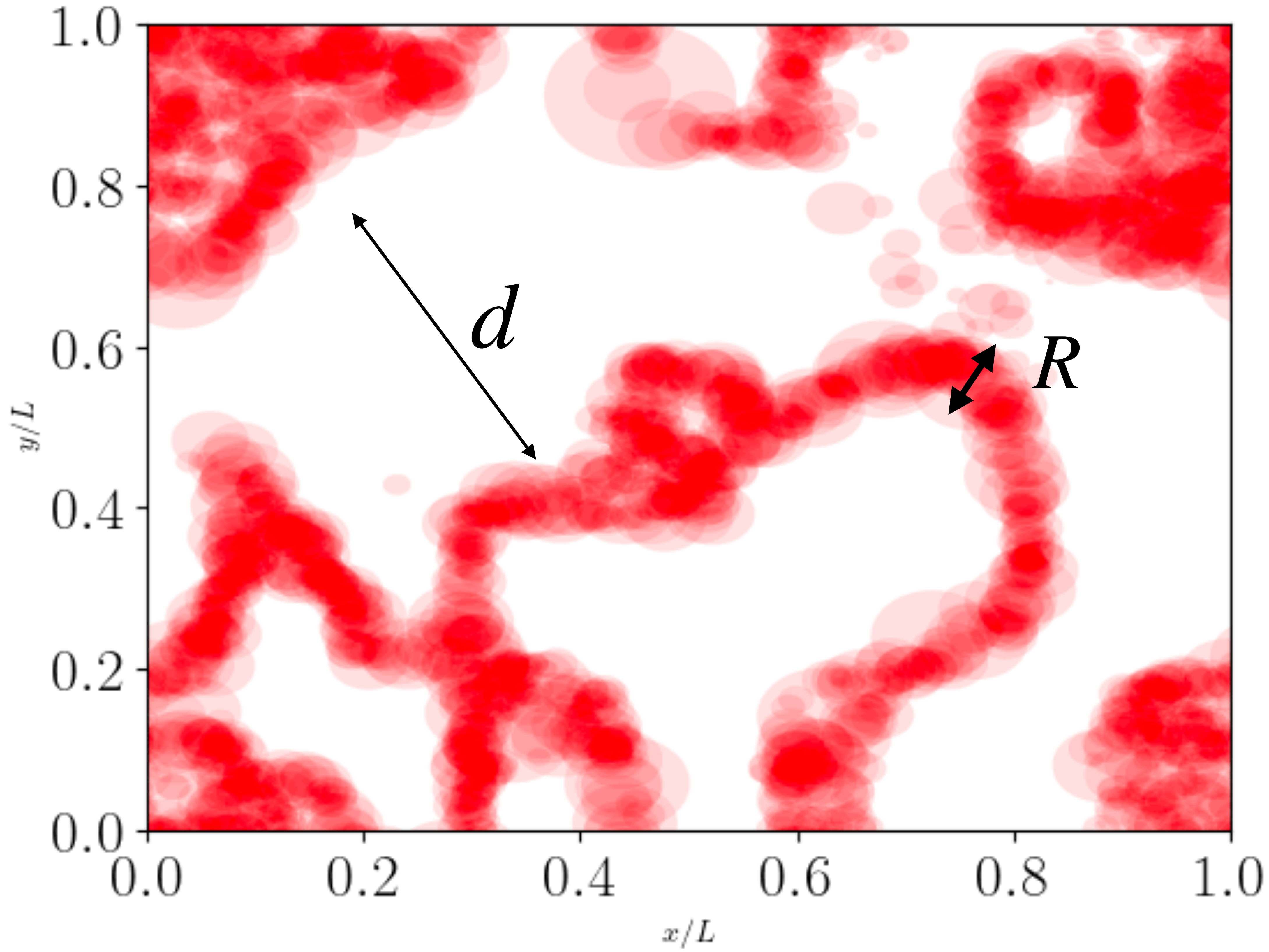
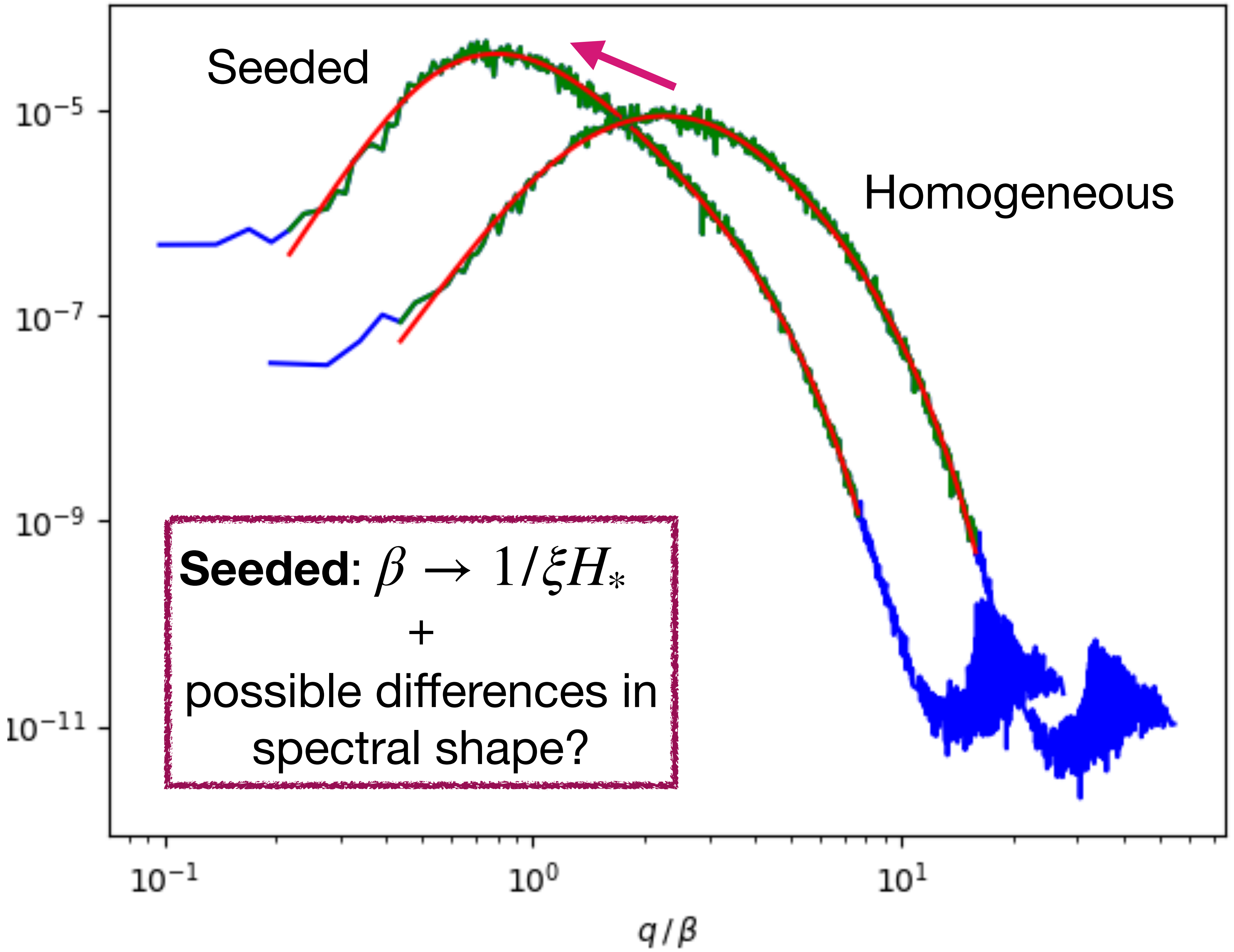


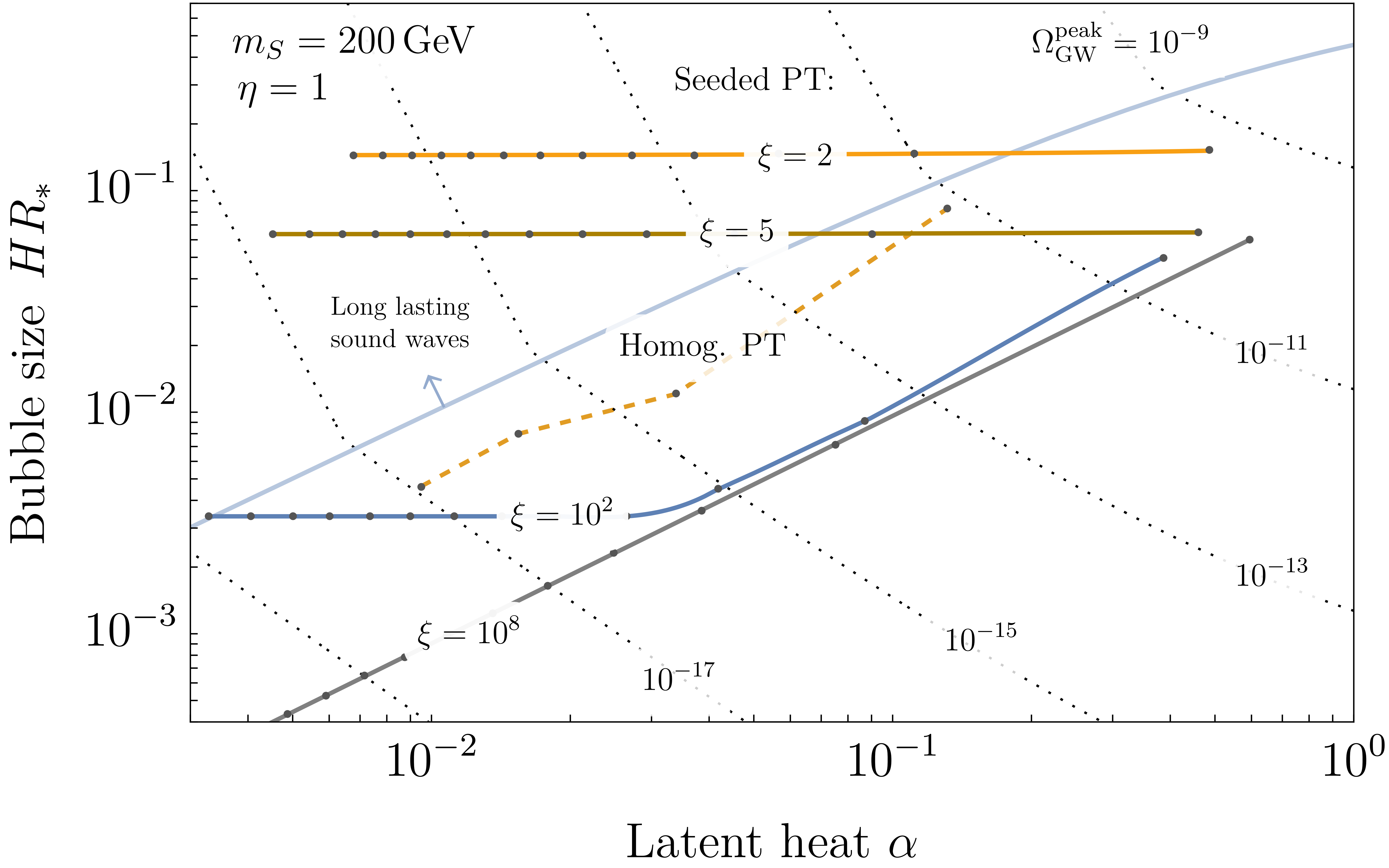
Spectrum shifted to IR with enhanced amplitude



Seeded: $\beta \to 1/\xi H_*$
+
possible differences in spectral shape?

Gravitational wave amplitude (xSM)

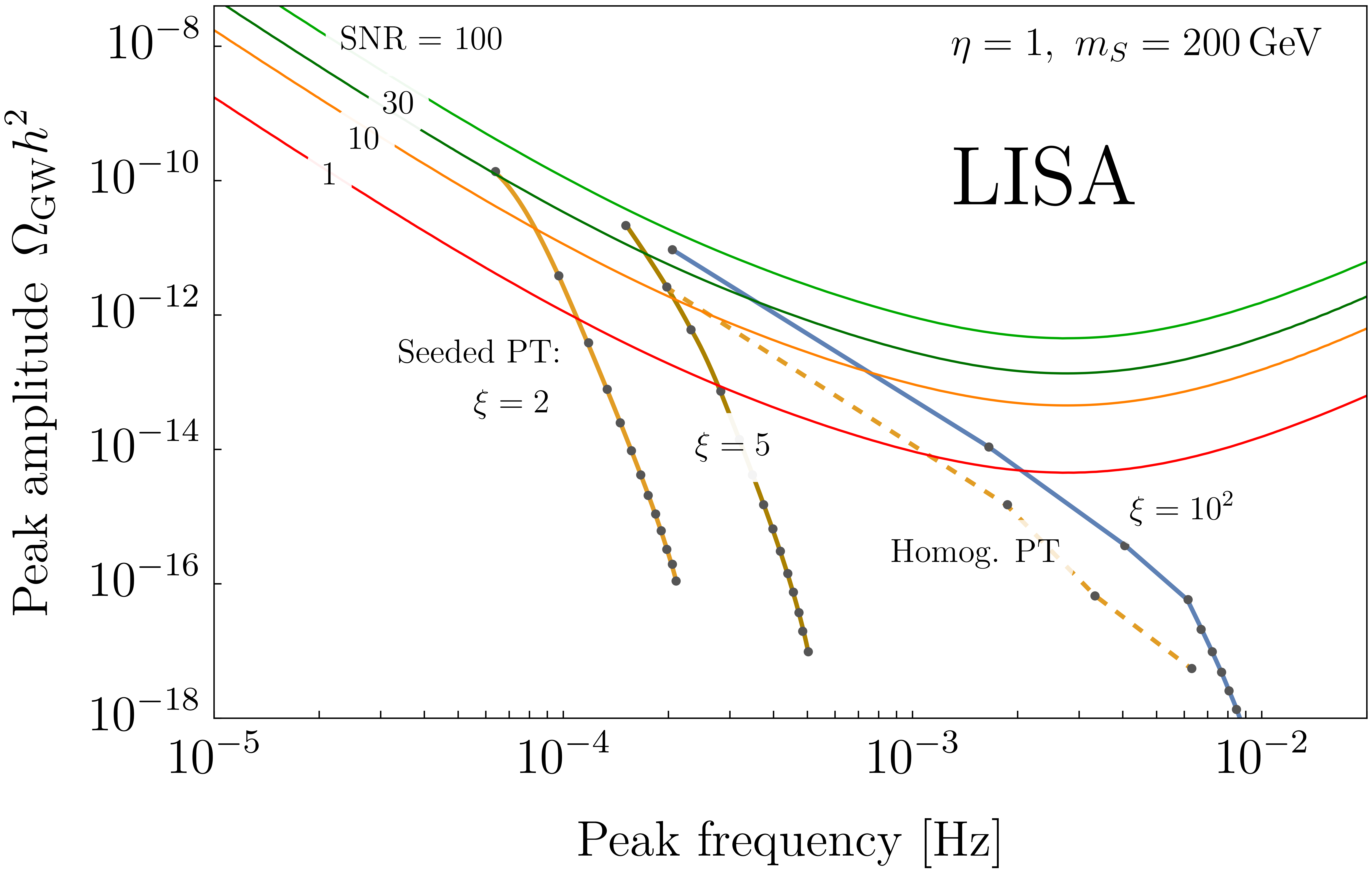
Agrawal, **SB**, Mariotti, Nee, in prep.



Break of the strong (R_*, α) correlation for $\xi \lesssim 10^2 - 10^3$

Prospects for the EWPT

Agrawal, **SB**, Mariotti, Nee, in prep.



Summary

- Formation of defects during multi-step phase transitions can dramatically affect the dynamics of bubble nucleation by providing new channels for vacuum decay.
- We have presented a minimal working example for a seeded electroweak phase transition in the xSM due to the presence of $\mathbb{Z}_2$ domain walls. As a result, the parameter space leading to successful nucleation is enlarged.
- Implications of seeded phase transitions in terms of gravitational waves (and possibly other relics) still largely unexplored.
- Different extensions of the SM may involve other types of defects such as strings or monopoles, with possibly different phenomenology.

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- Formation of defects during multi-step phase transitions can dramatically affect the dynamics of bubble nucleation by providing new channels for vacuum decay.
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Thank you!

Backup

1. Equations of motion

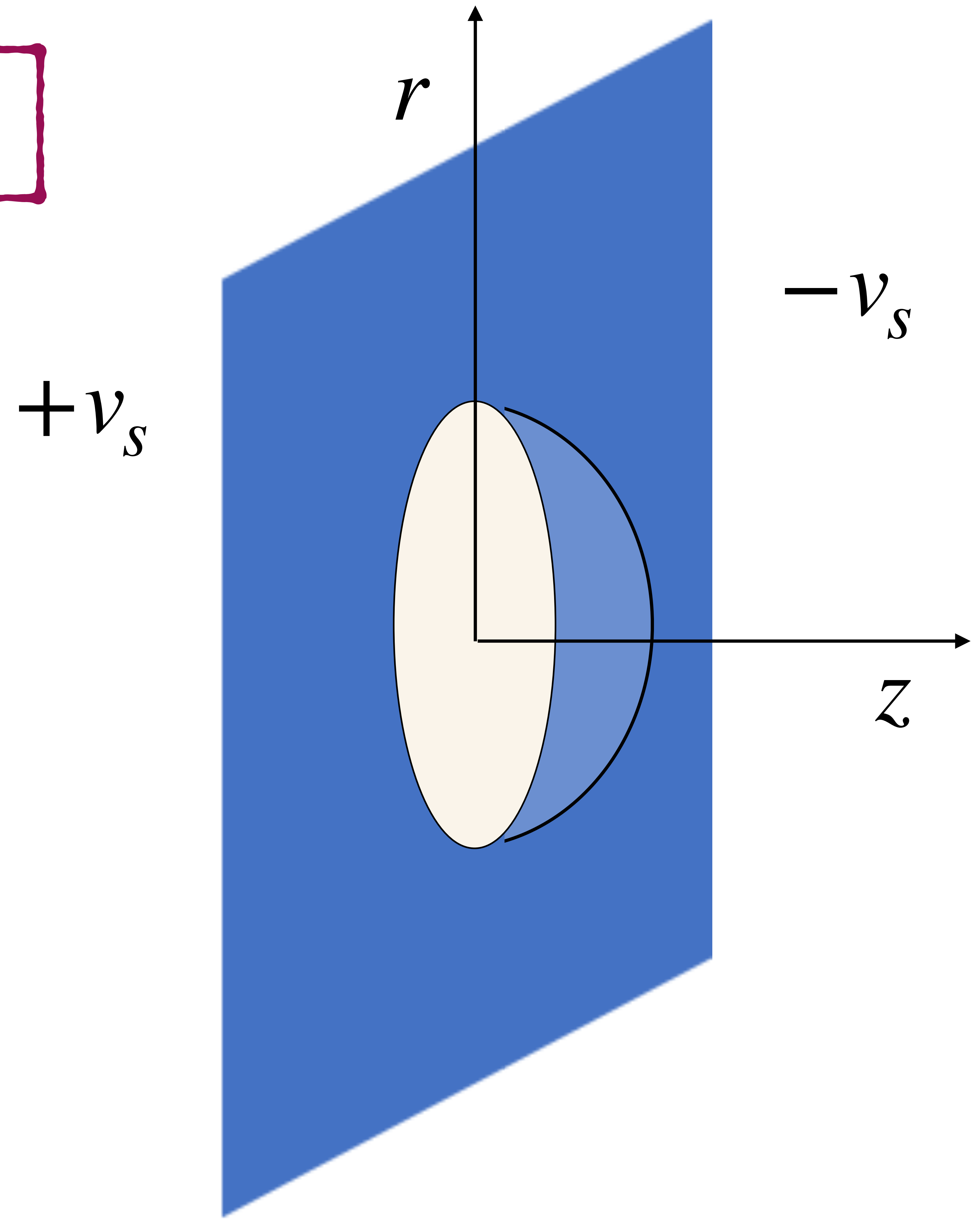
Agrawal, **SB**, Mariotti, Nee, in prep.

False vacuum is non-trivial as it depends on z

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

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

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



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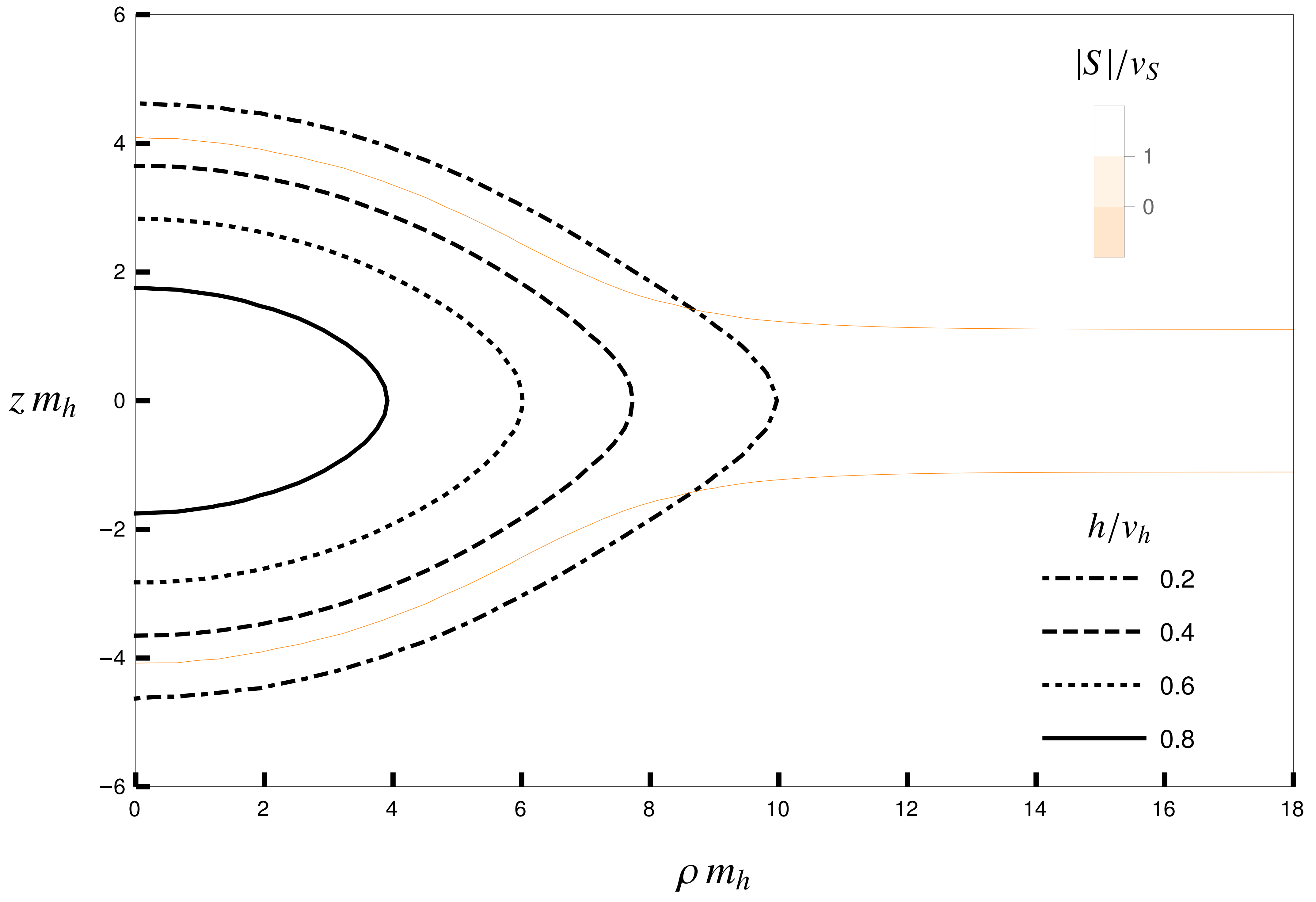
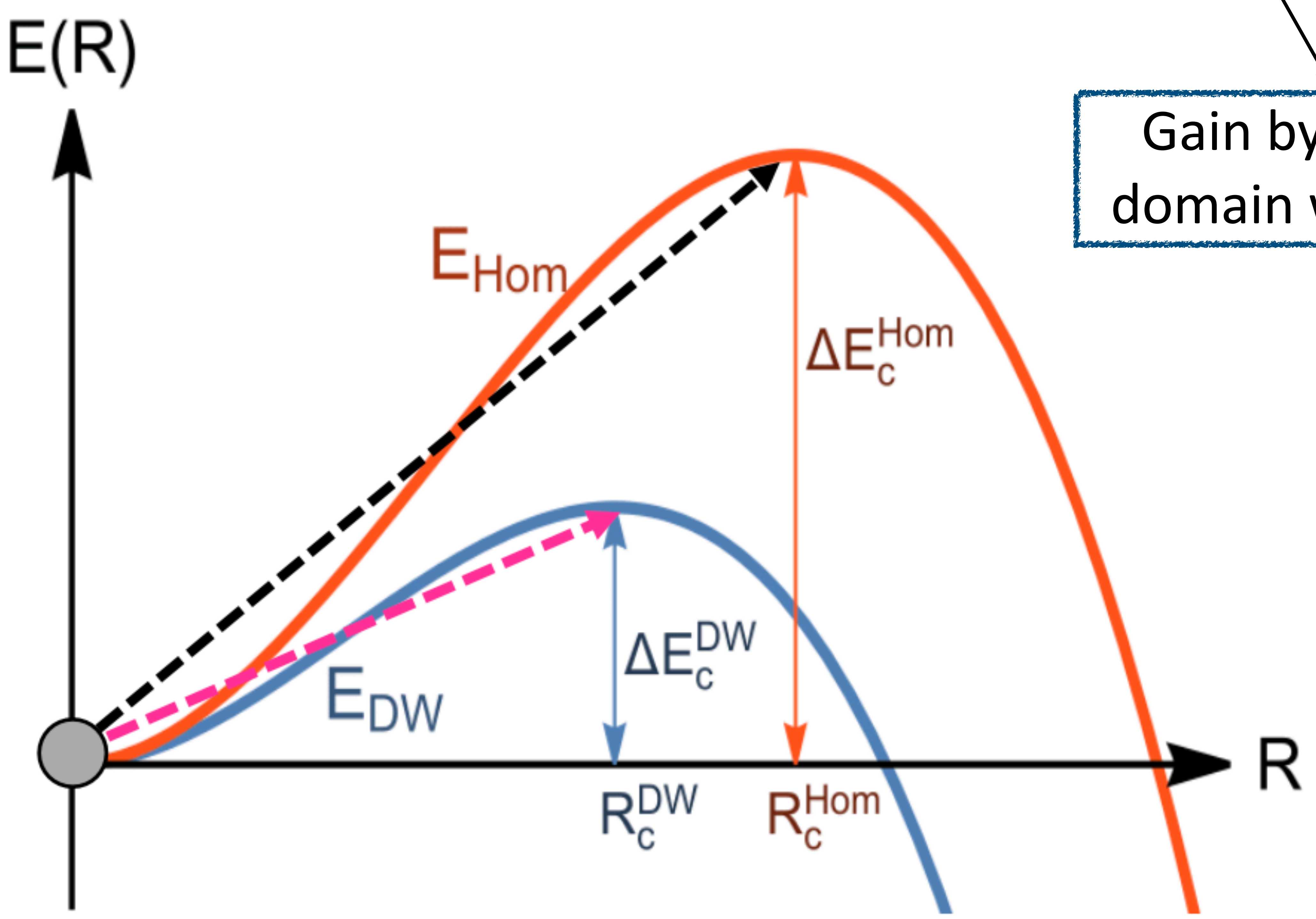


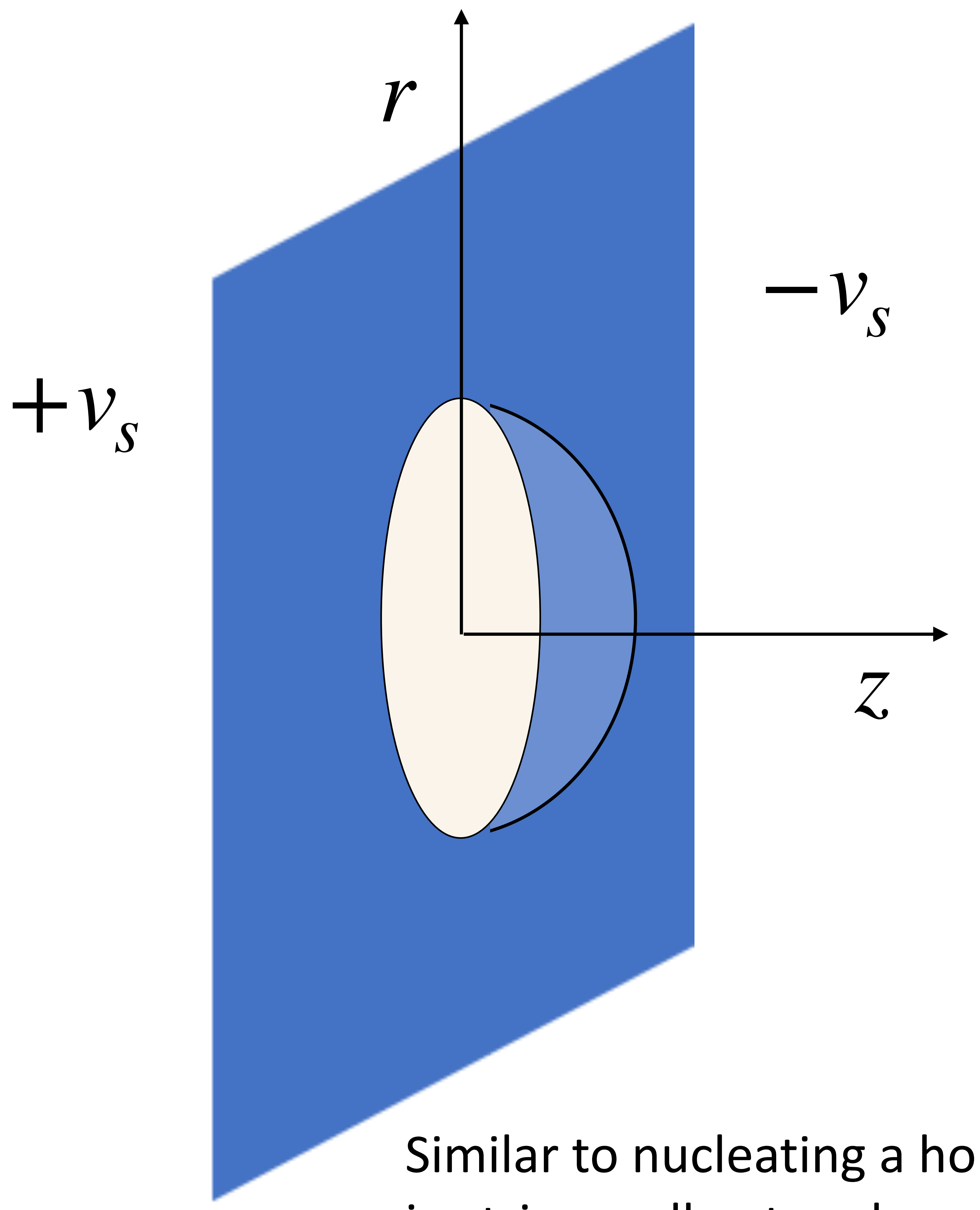
2. Thin wall approximation

SB, Mariotti [2203.16450], PRL

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

Gain by eating up domain wall surface





Similar to nucleating a hole in string-wall networks

3. Kaluza-Klein decomposition

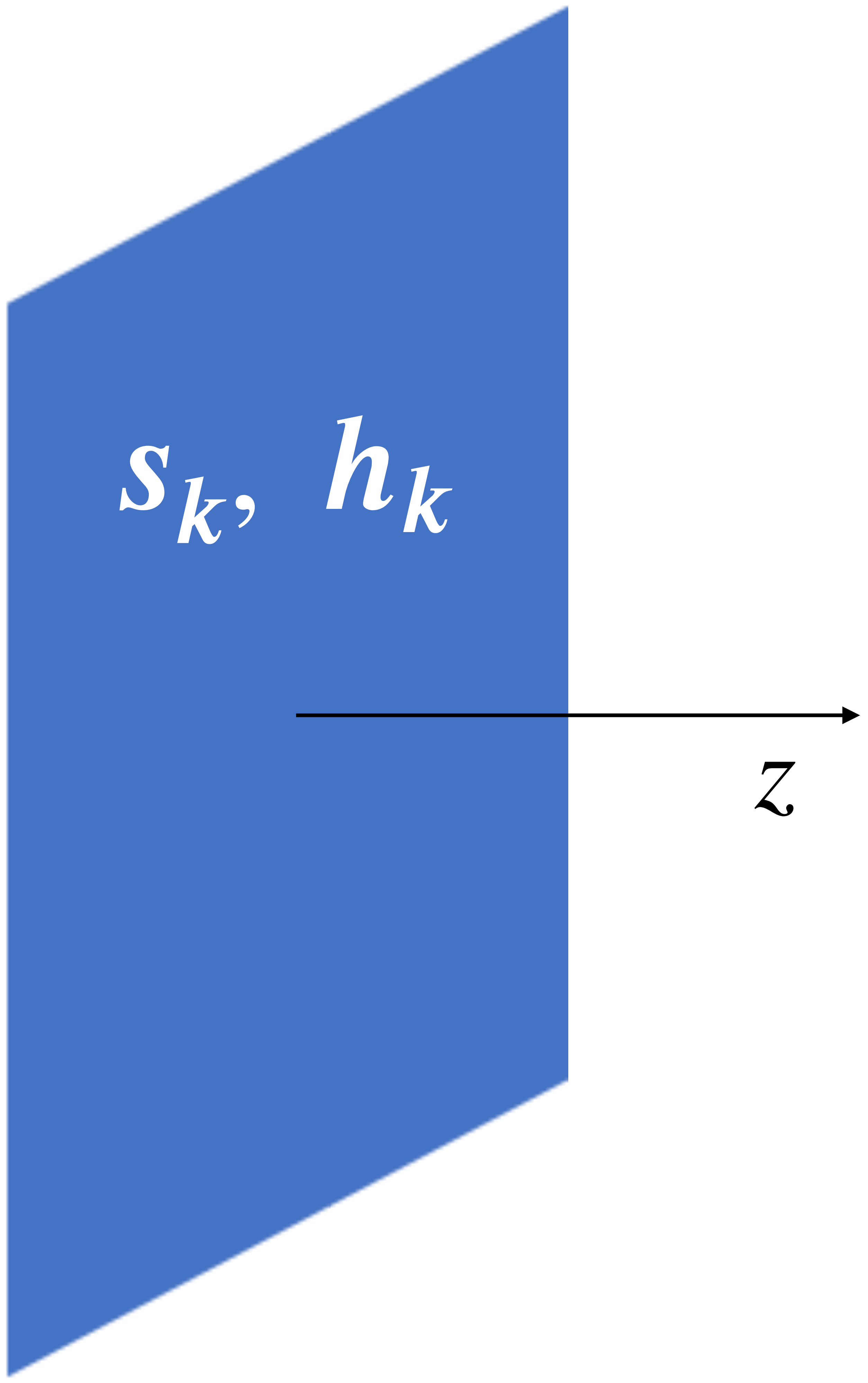
SB, Mariotti [2203.16450], PRL

- Expand the fields around the domain wall background:

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

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

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



3. Kaluza-Klein decomposition

SB, Mariotti [2203.16450], PRL

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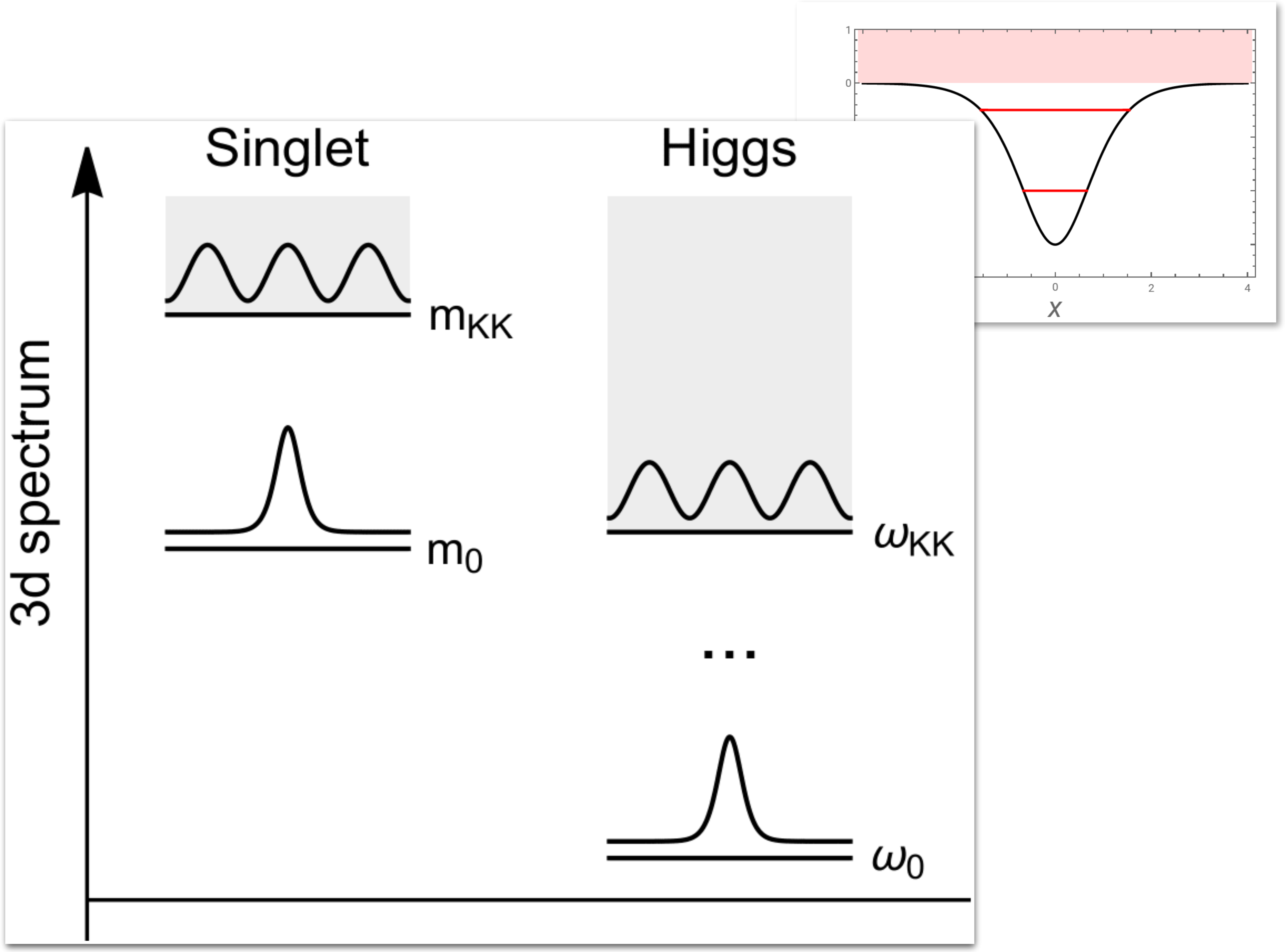
$$x_\mu = t, x, y$$

- Eigenspectrum of excitations:



3. Kaluza-Klein decomposition

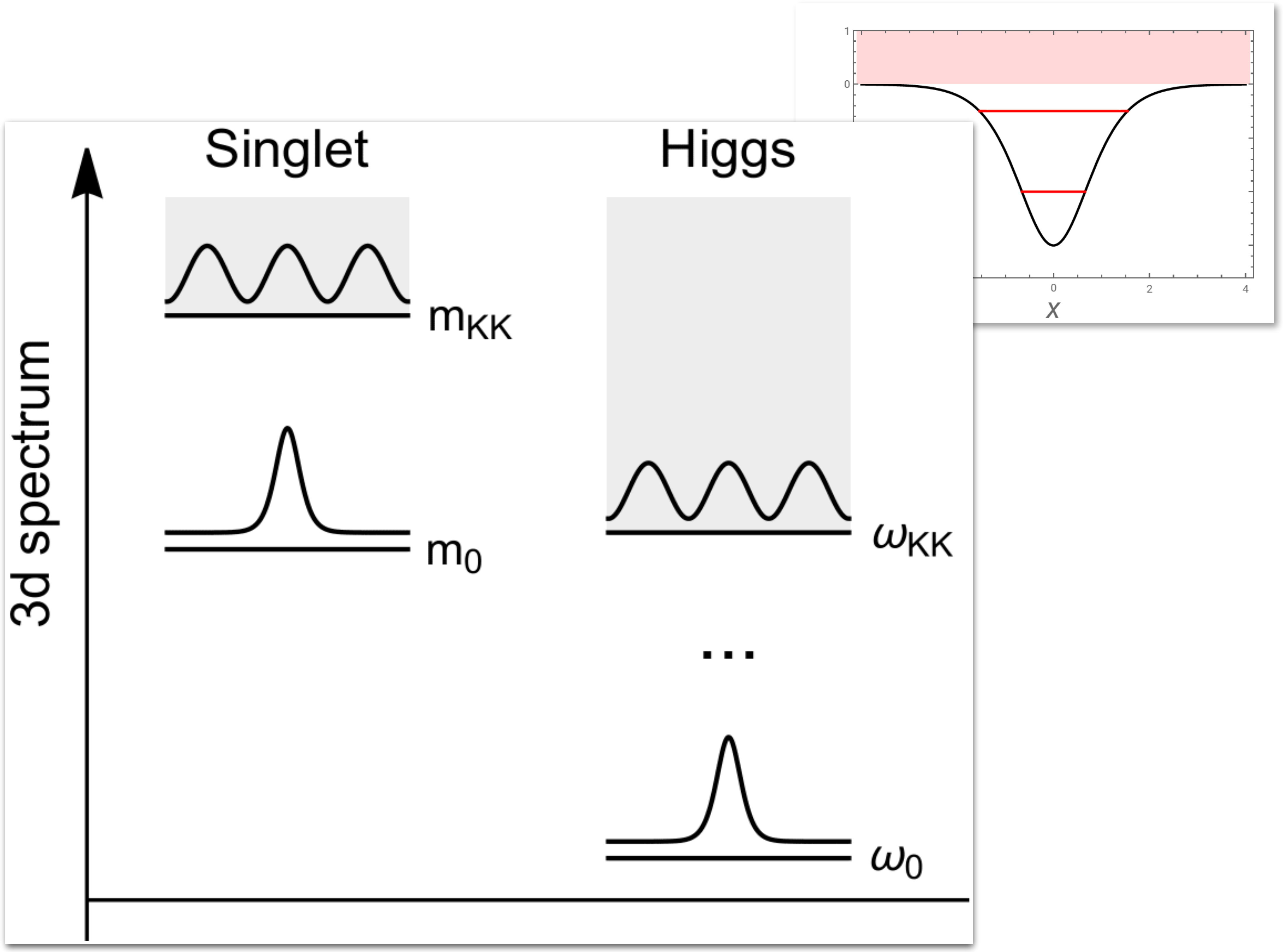
SB, Mariotti [2203.16450], PRL

- Integrate along z to obtain 3d action *and* integrate out continuum excitations:

$$S_{3d} = \int d^3x \; \frac{1}{2}(\partial_\mu h_0)^2 + \frac{1}{2}(\partial_\mu s_0)^2 - V_{3d}^{eff}(h_0, s_0)$$

Seeded tunneling as homogeneous problem in lower dimension!

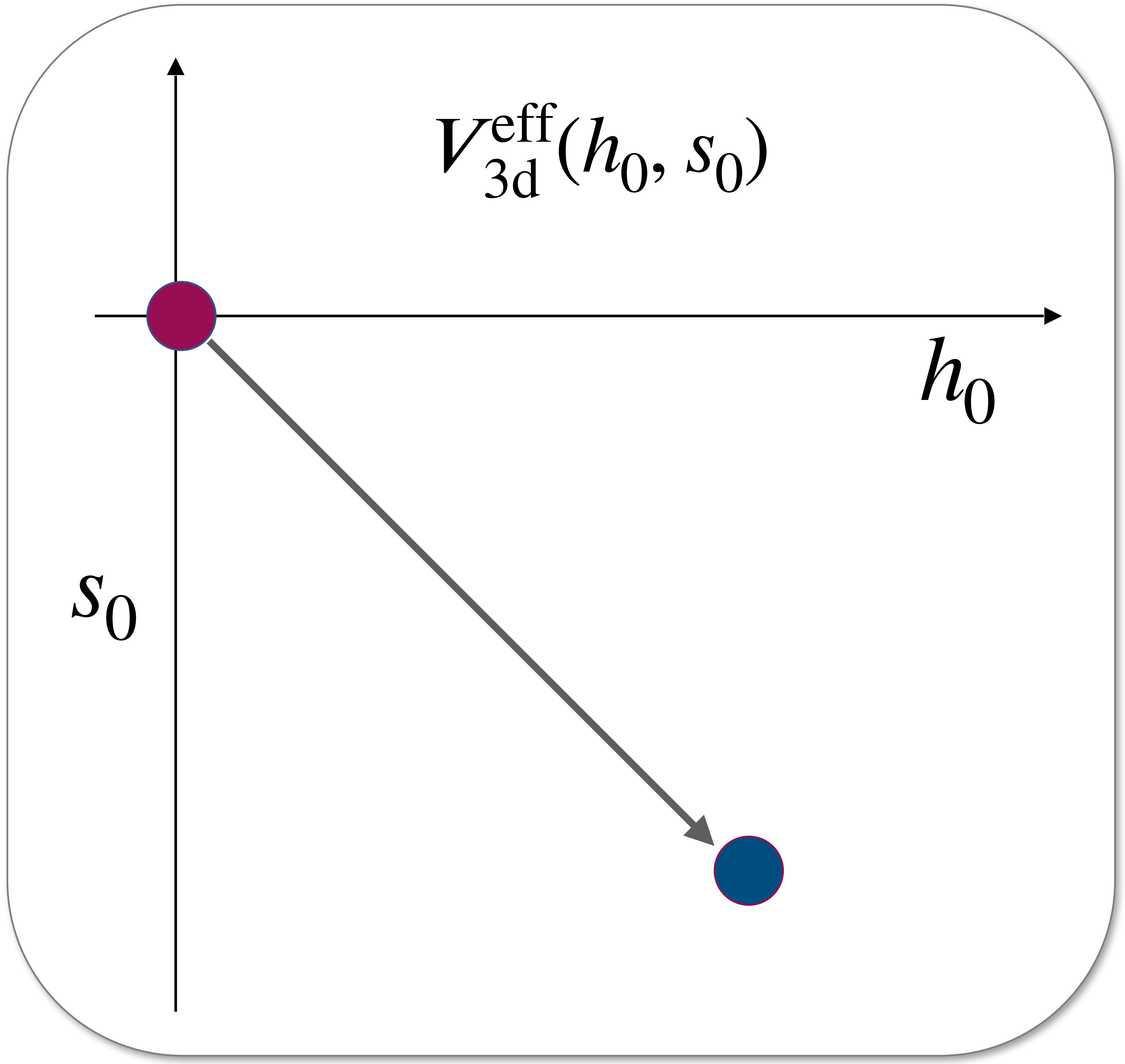
- Eigenspectrum of excitations:



3. Kaluza-Klein decomposition

SB, Mariotti [2203.16450], PRL

$$(0,0) \to (\langle h_0 \rangle, \langle s_0 \rangle)$$



- **Origin** = domain wall (before nucleation)
- **3d modes taking vev** deform the original domain wall profile
- Domain wall metastability controlled by the (temperature dep.) mass of s_0 and h_0

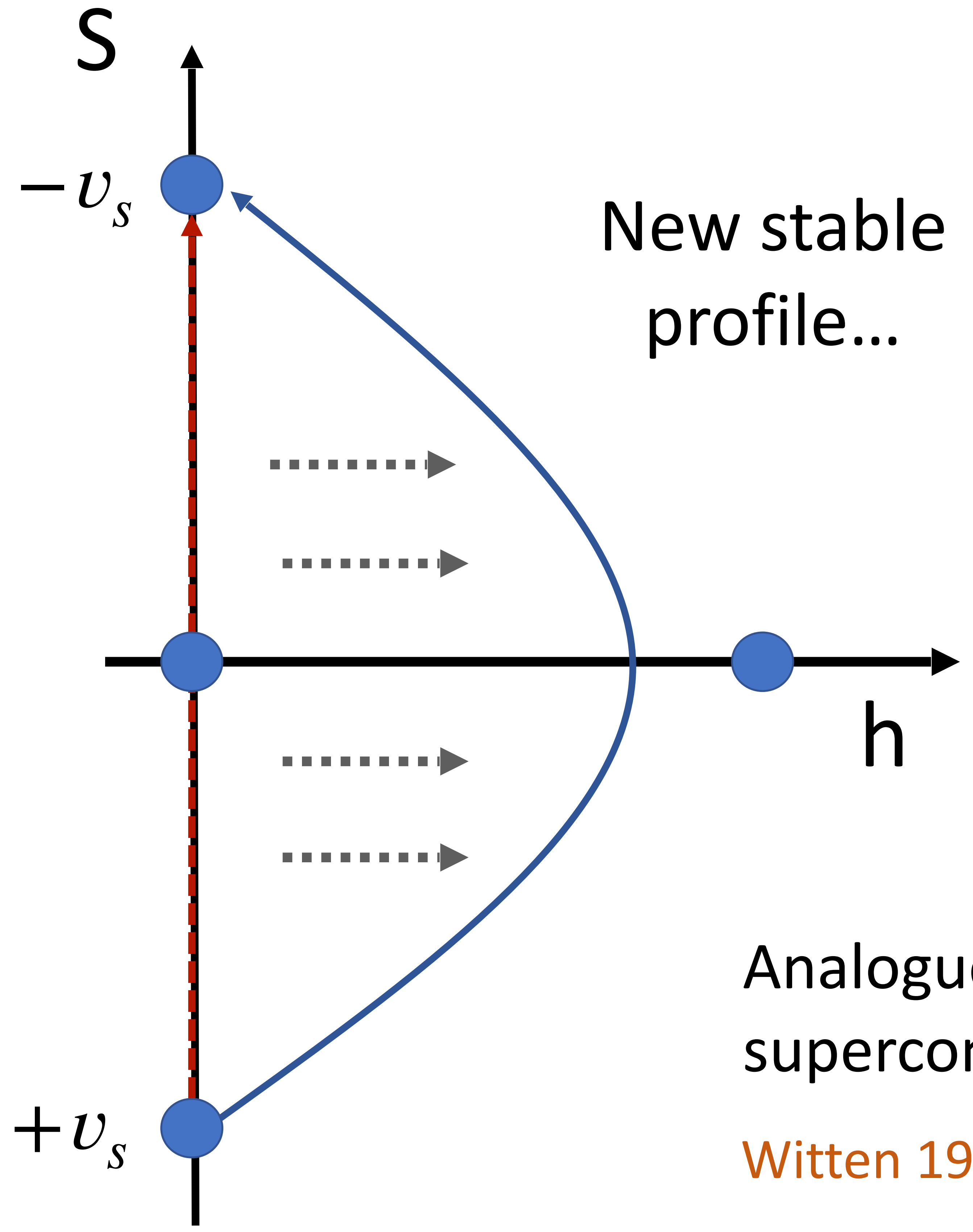
$$\omega_0^2(T) = \frac{1}{2} p\, m^2(T) - \mu^2(T)$$

$$m_0^2(T) = \frac{3}{2} m^2(T) > 0$$

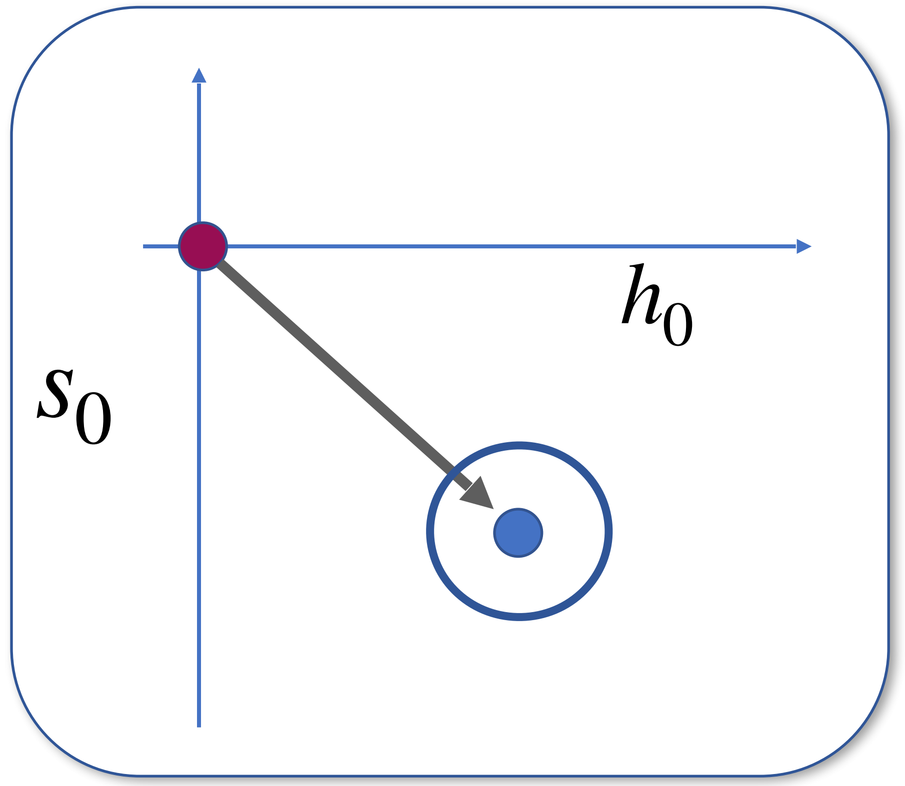
3. Kaluza-Klein decomposition

SB, Mariotti [2203.16450], PRL

- **Case I**: $\omega_0^2 < 0$ above T_c



New stable profile…



… can be obtained minimizing V_{3d}^{eff}

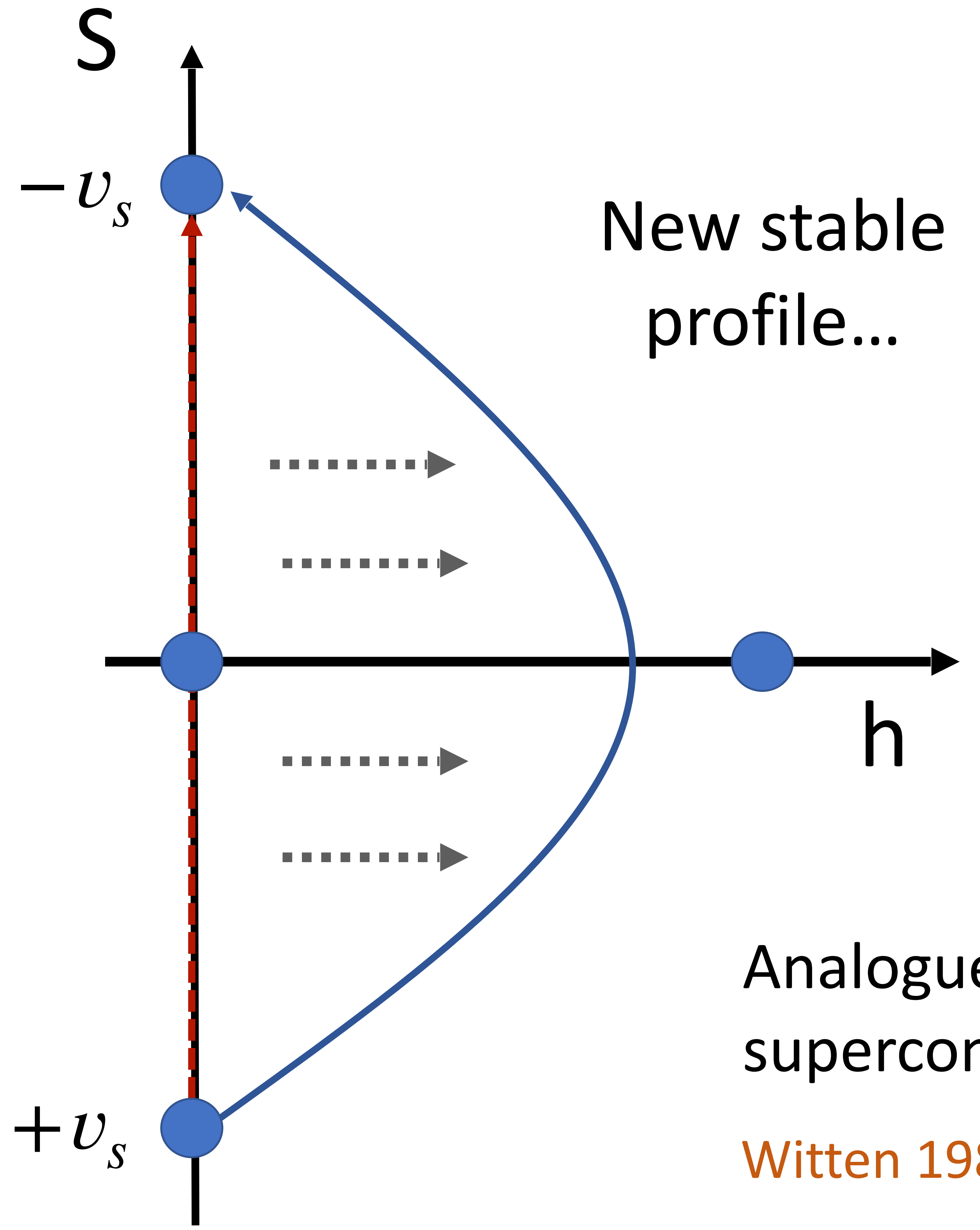
Analogue to string superconductivity

Witten 1985, NPB

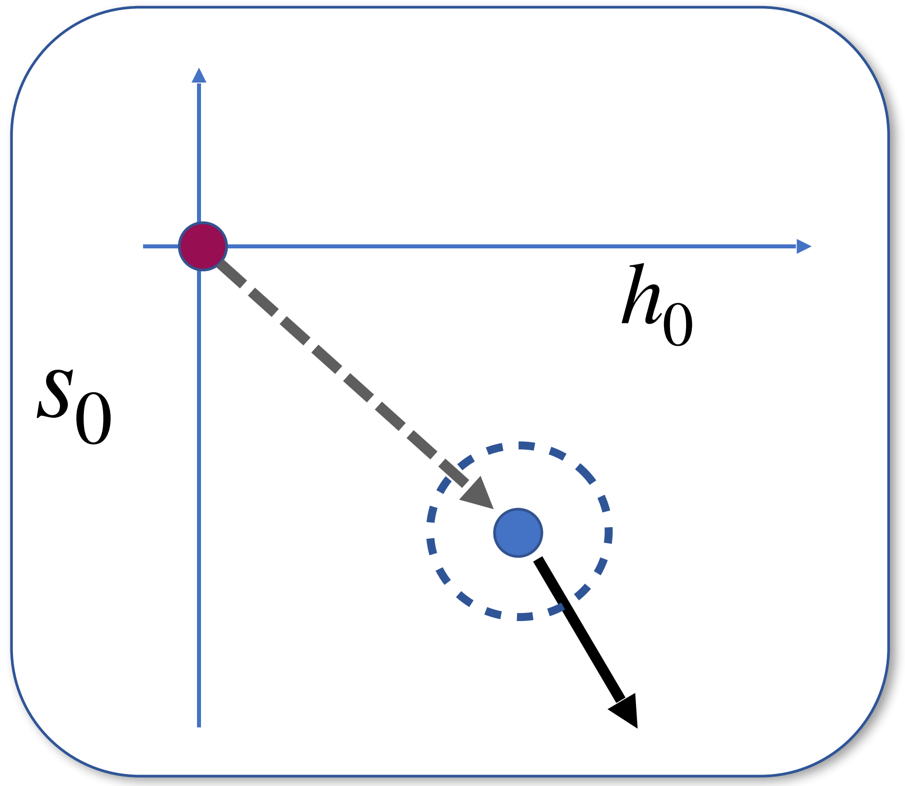
3. Kaluza-Klein decomposition

SB, Mariotti [2203.16450], PRL

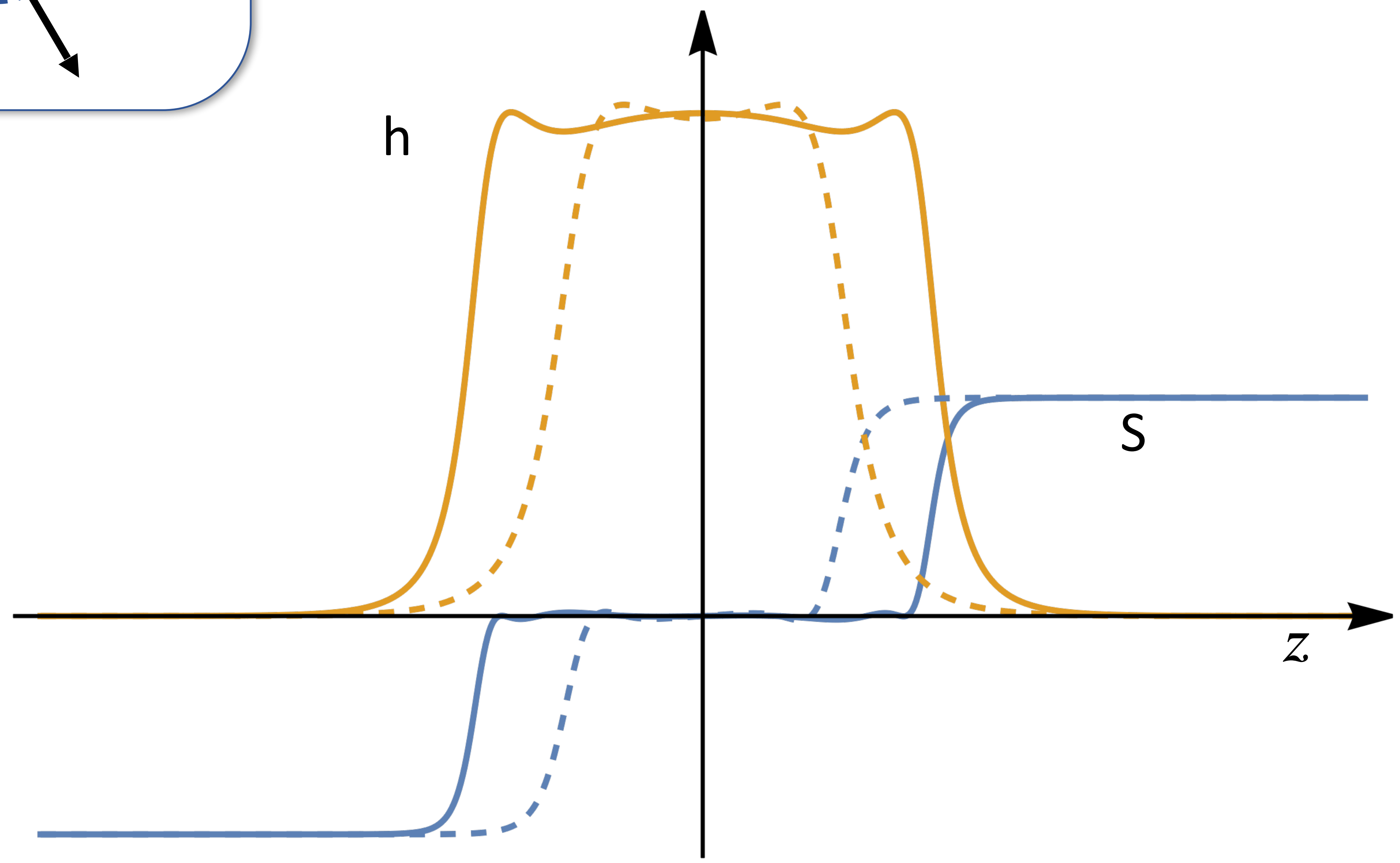
- **Case I**: $\omega_0^2 < 0$ above T_c



New stable profile...



...dissociates at $T \approx T_c$



Analogue to string superconductivity

Witten 1985, NPB

3. Kaluza-Klein decomposition

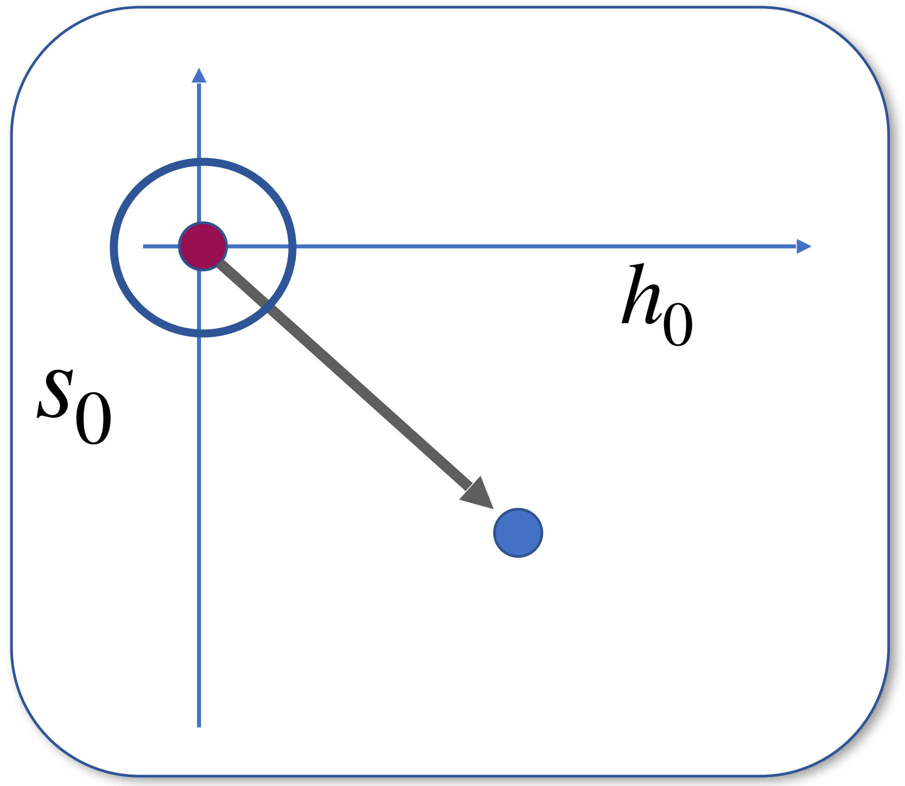
SB, Mariotti [2203.16450], PRL

- **Case II**: $\omega_0^2 > 0$

For $T < T_c$ the origin cannot be absolutely stable.

A new minimum must appear with non-zero Higgs vev.

Transition involves a tunneling process (origin is local minimum).



3. Kaluza-Klein decomposition

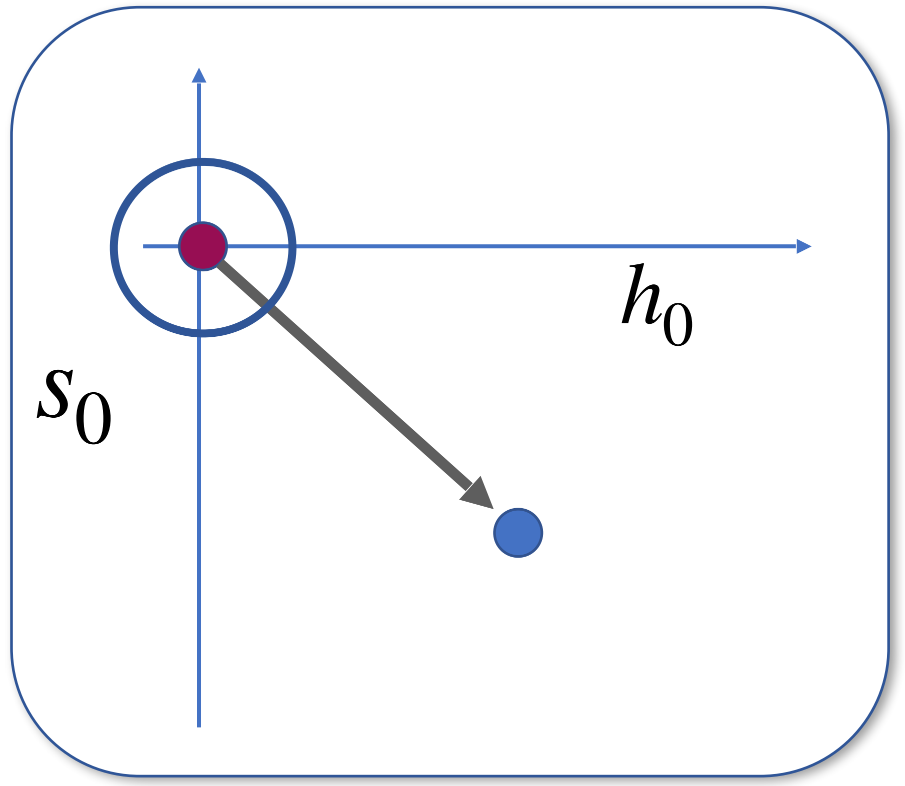
SB, Mariotti [2203.16450], PRL

- **Case II**: $\omega_0^2 > 0$

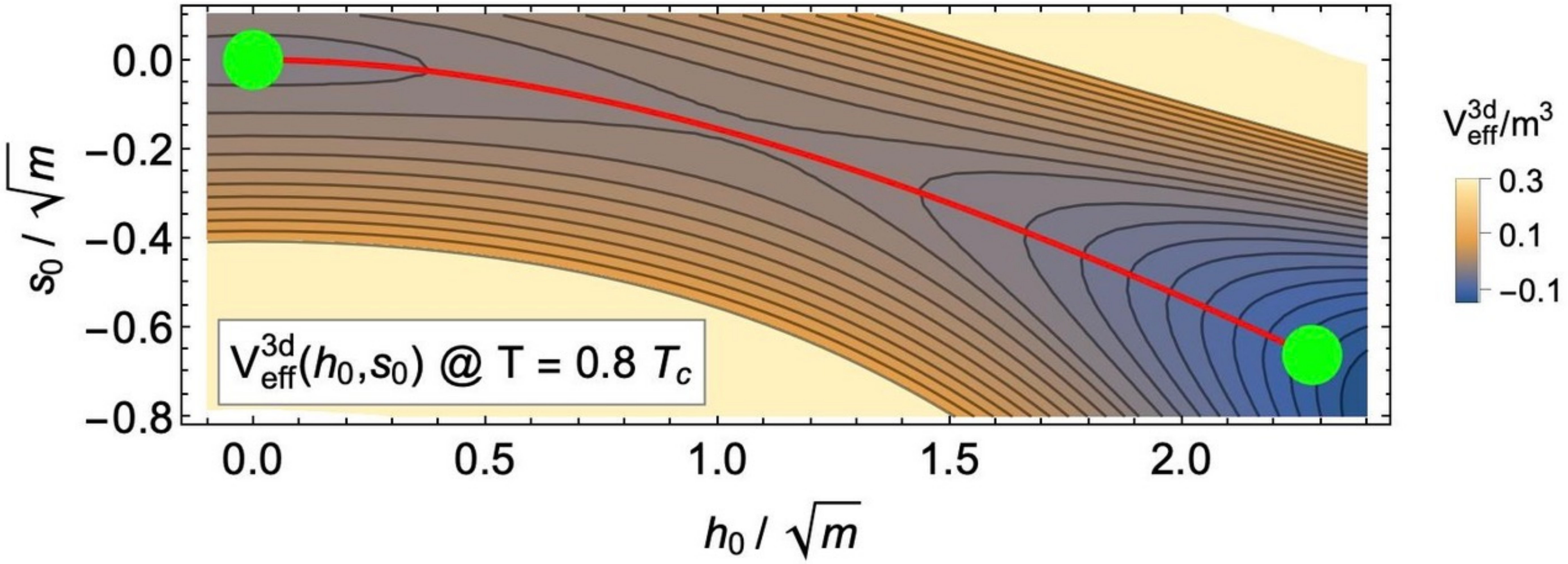
For $T < T_c$ the origin cannot be absolutely stable.

A new minimum must appear with non-zero Higgs vev.

Transition involves a tunneling process (origin is local minimum).



Tunneling trajectory obtained with `CosmoTransitions`:



Energy budget of the phase transition

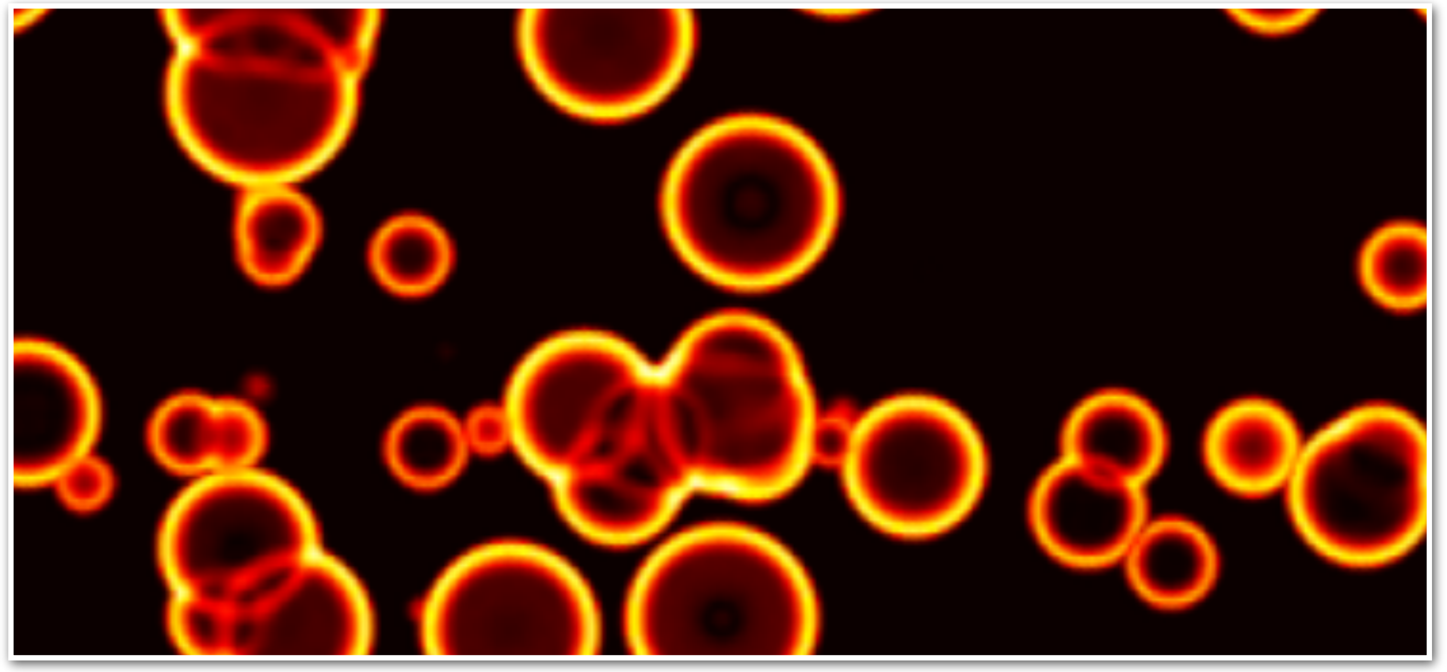
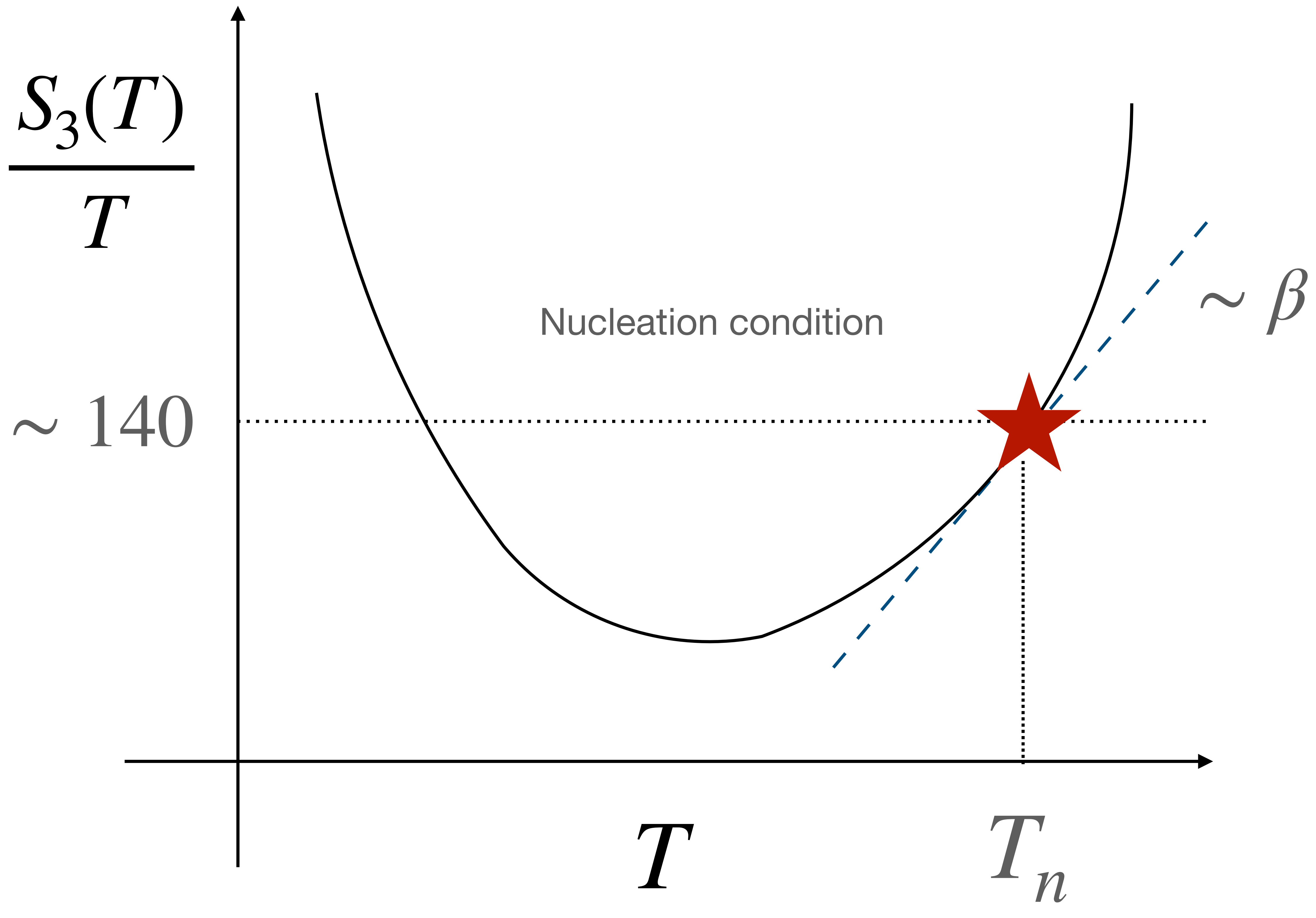


Fig. from Jinno, Konstandin, Rubira, Stomberg 2209.04369



- Energy released in the plasma:

$$\alpha_\star \simeq \frac{\Delta V(T_\star)}{\rho_{rad}(T_\star)}$$

- Duration of the transition:

$$\frac{\beta}{H_\star} = T\frac{d}{dT}(S_3/T)\Big|_{T_\star} \sim 100$$

Gravity wave spectrum

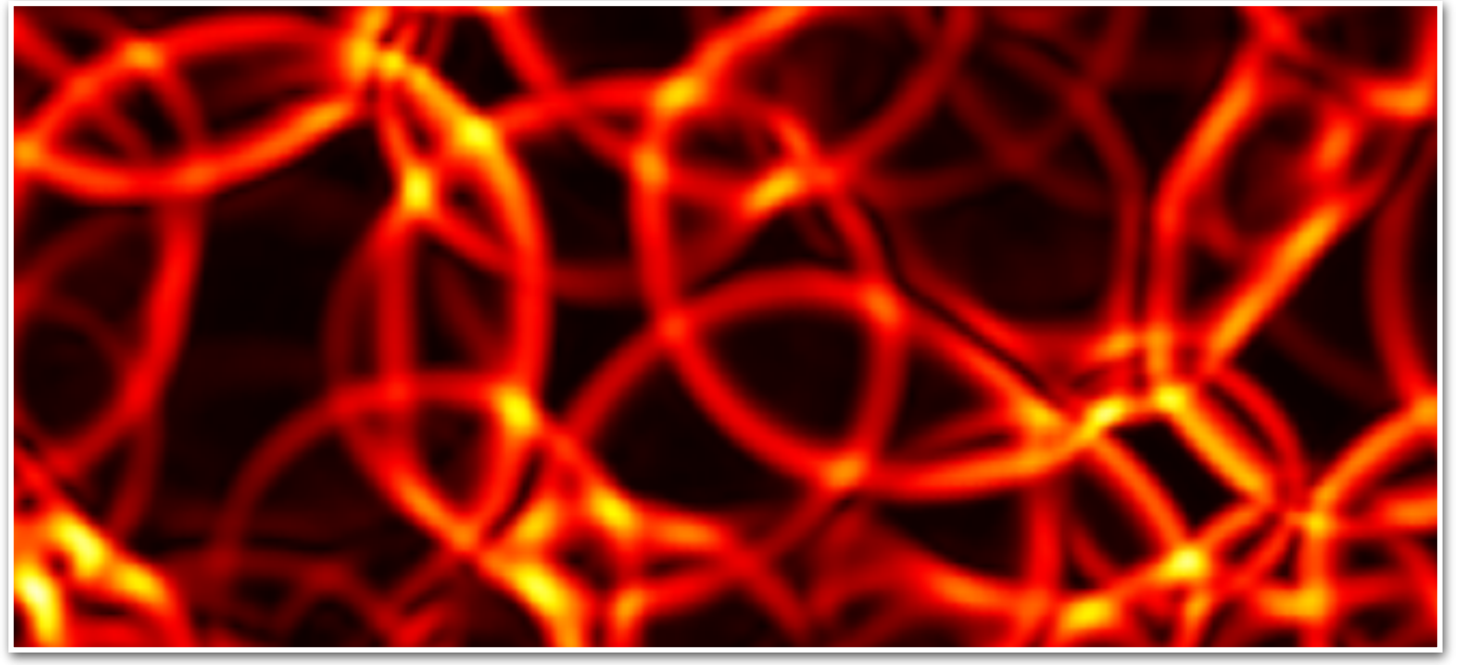


Fig. from Jinno, Konstandin, Rubira, Stomberg 2209.04369

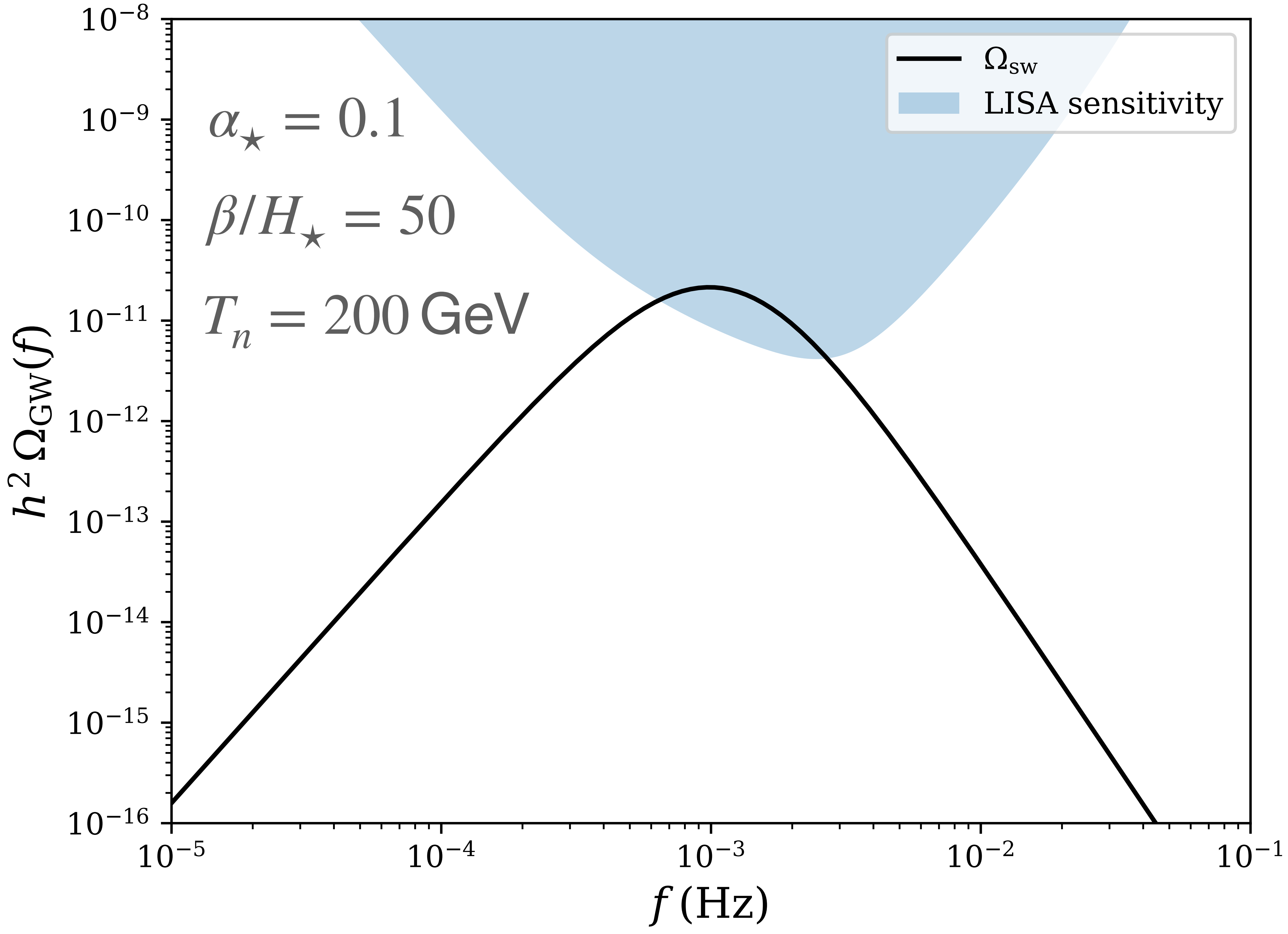


Fig. from LISA cosmology working group

- Spectrum from **sound waves**:

$$f|_{peak} \sim 10^{-5}\,\text{Hz}\left(\frac{\beta}{H_\star}\right)\left(\frac{T_\star}{100\,\text{GeV}}\right),$$

$$h^2\,\Omega_{sw}|_{peak} \sim 10^{-6}\left(\frac{H_\star}{\beta}\right)\left(\kappa_v\,\alpha_\star\right)^2$$

Other contributions: **bubble collisions** and **turbulence**