Seeded phase transitions

Simone Blasi
DESY Hamburg

SB, Mariotti [2203.16450] PRL

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

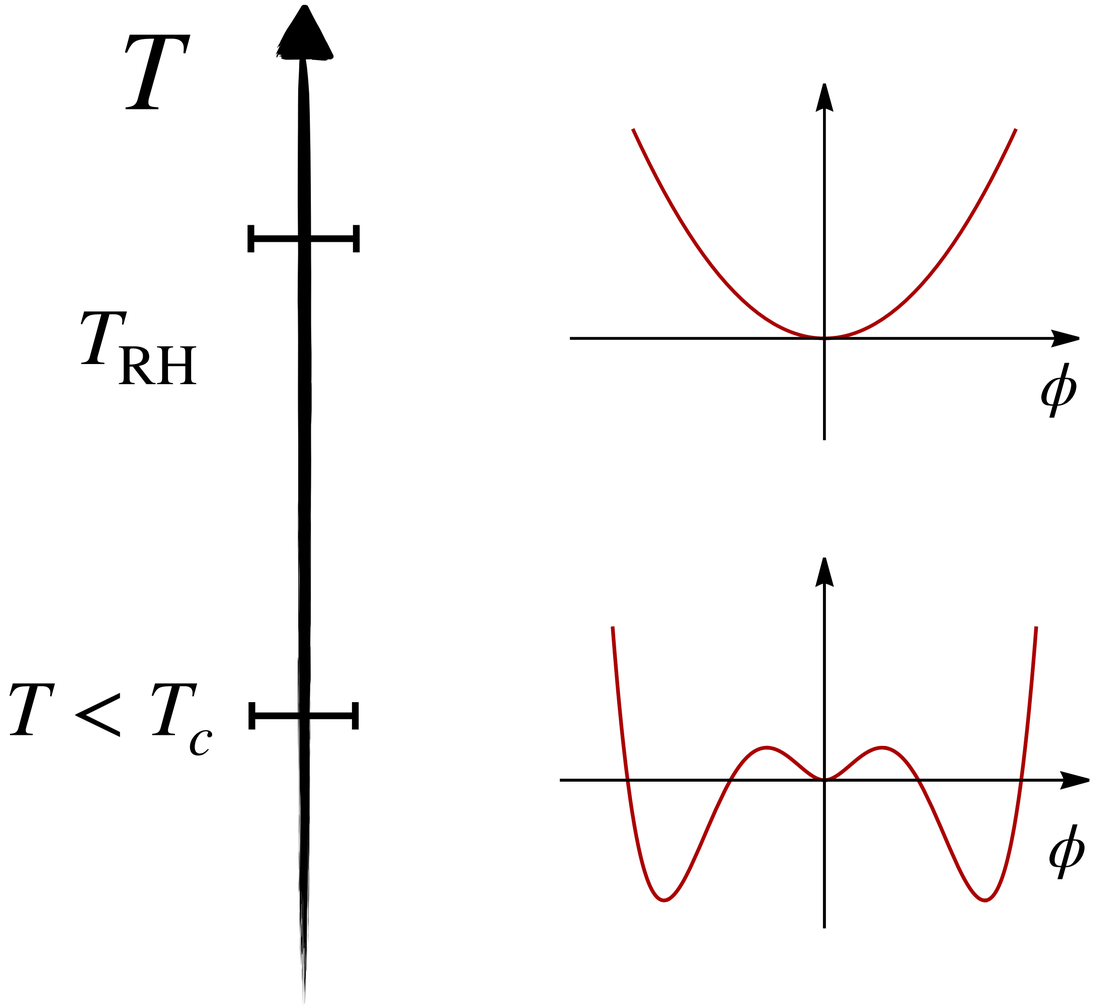
Agrawal, SB, Mariotti, Nee [2312.06749] JHEP

SB, Mariotti [2405.08060] SciPost Phys.

+ ongoing

DESY Theory Workshop 24.09.2025

Introduction



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

$$\langle \phi \rangle : G \to H$$

Spontaneous breaking while the Universe expands and cools down

Cosmological phase transitions

Key to address open questions: **baryogenesis**

Aftermath directly observable in **GWs**

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

Fig. from [2409.03651] JHEP

Phase transition dynamics

Phase transition at T_c

$\langle \phi \rangle : G \to H$

Phase transition dynamics

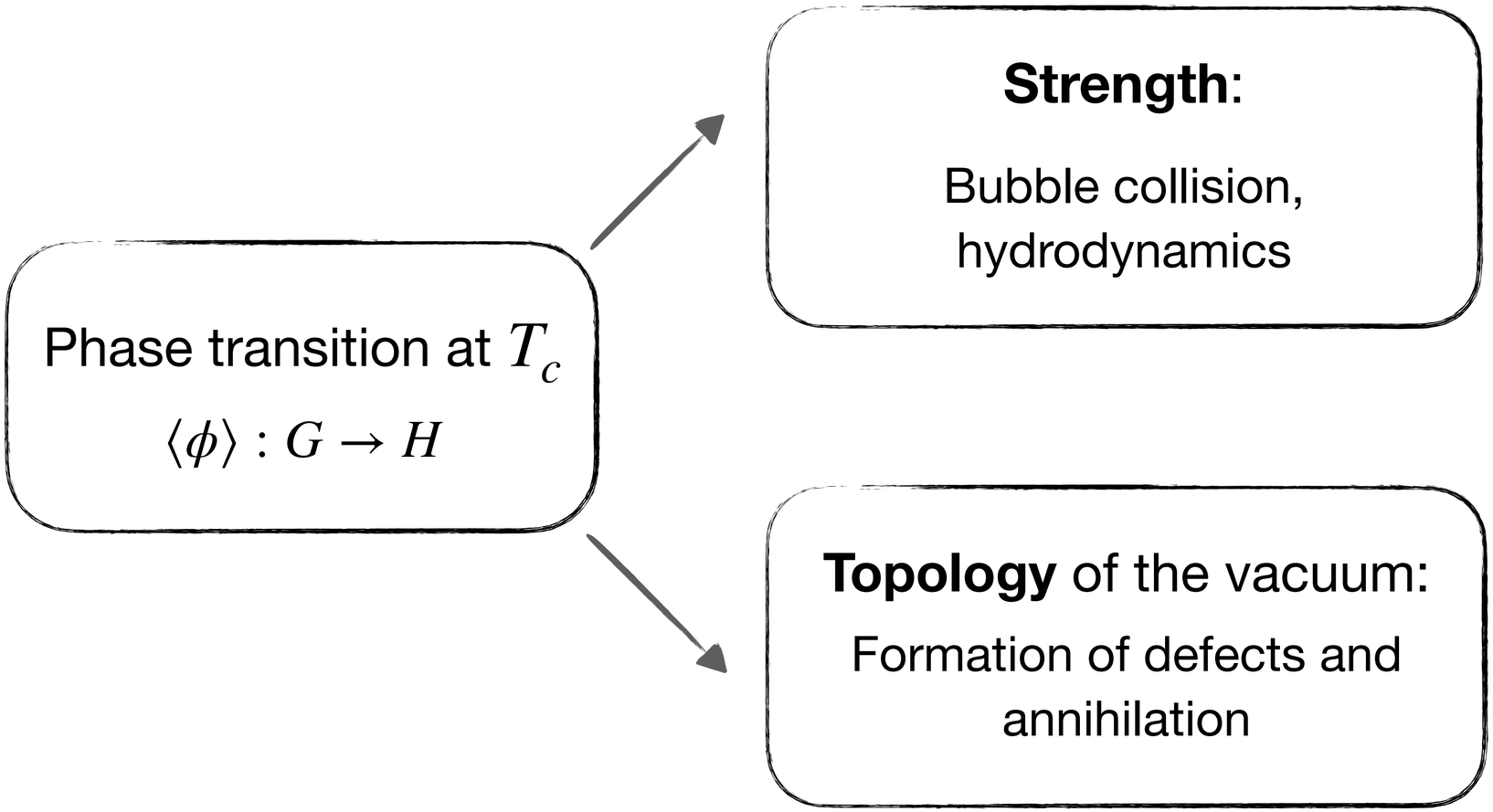
Phase transition at T_c

$\langle \phi \rangle : G \to H$

Strength:

Bubble collision,
hydrodynamics

Phase transition dynamics



Phase transition dynamics

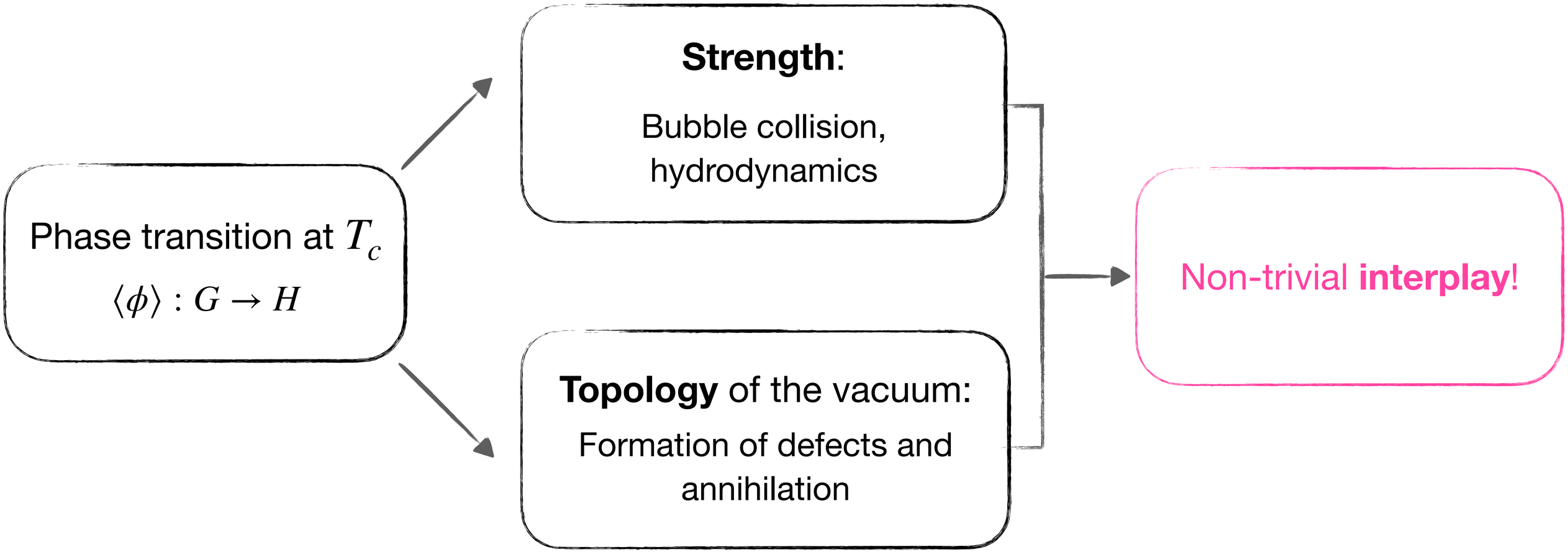
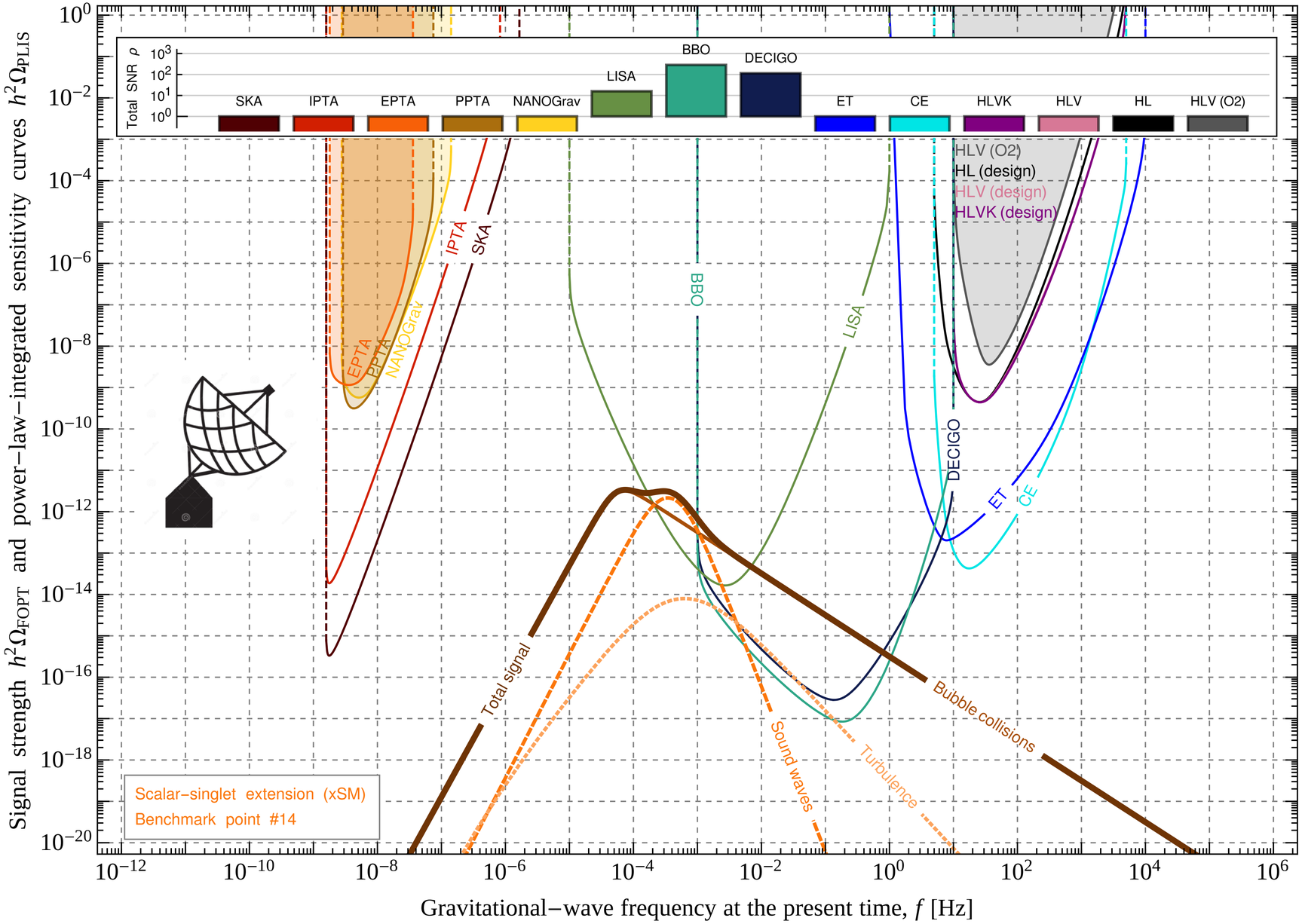


Fig. from Schmitz [2002.04615] JHEP

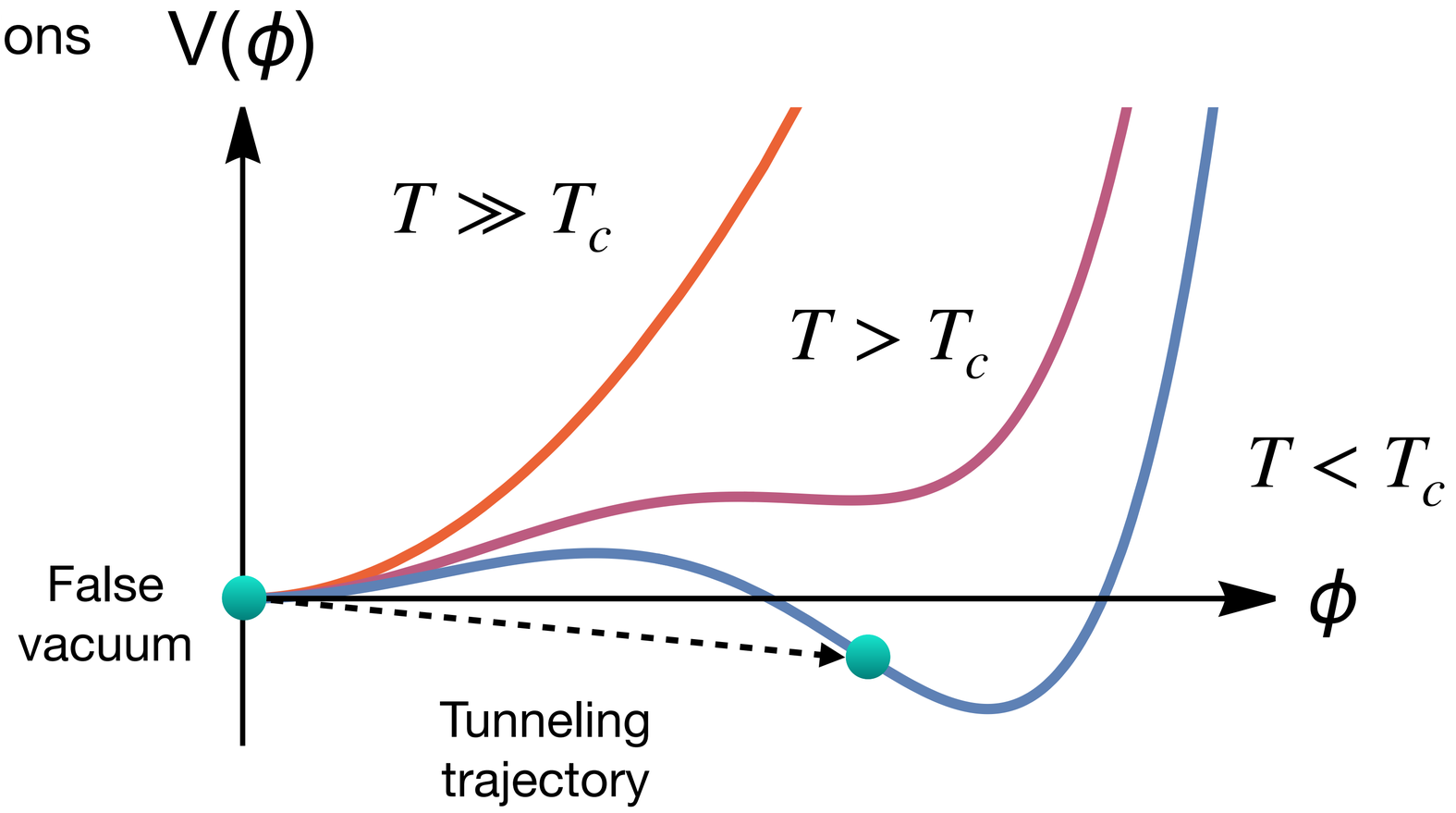


Nucleation theory

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

- Often assume thermal fluctuations in homogeneous spacetime

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

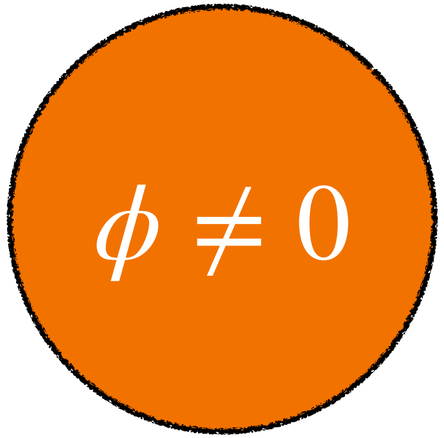


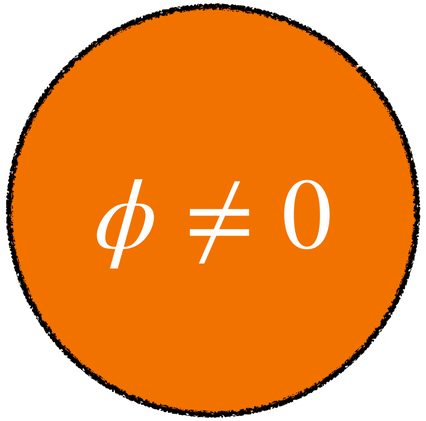
Nucleation theory

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

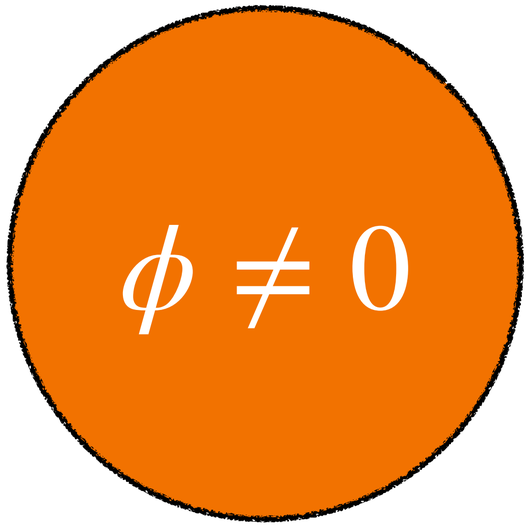
- Bubbles are nucleated with same probability everywhere

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





$\phi = 0$



What about impurities?

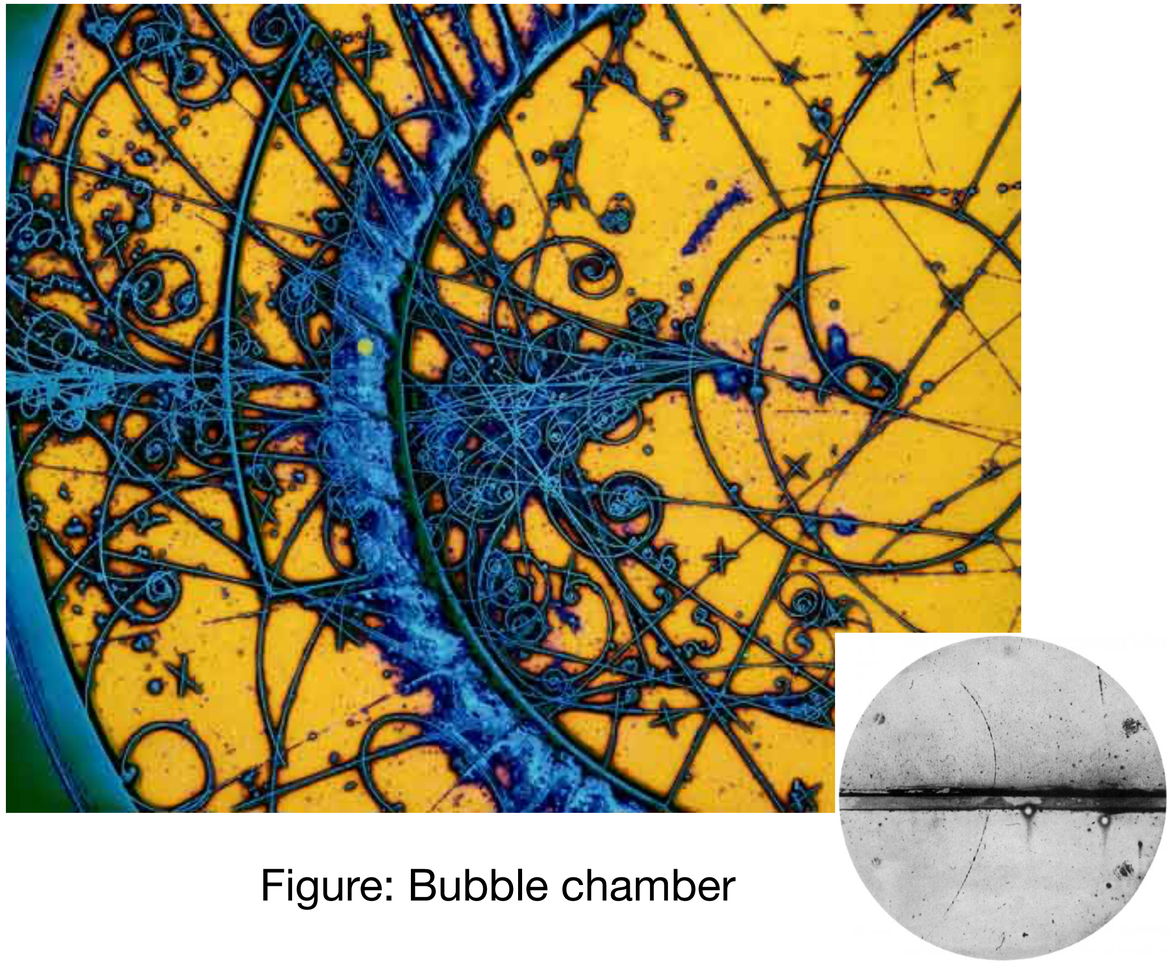


Figure: Bubble chamber

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

(Coleman-de Luccia, PRD, 1980)

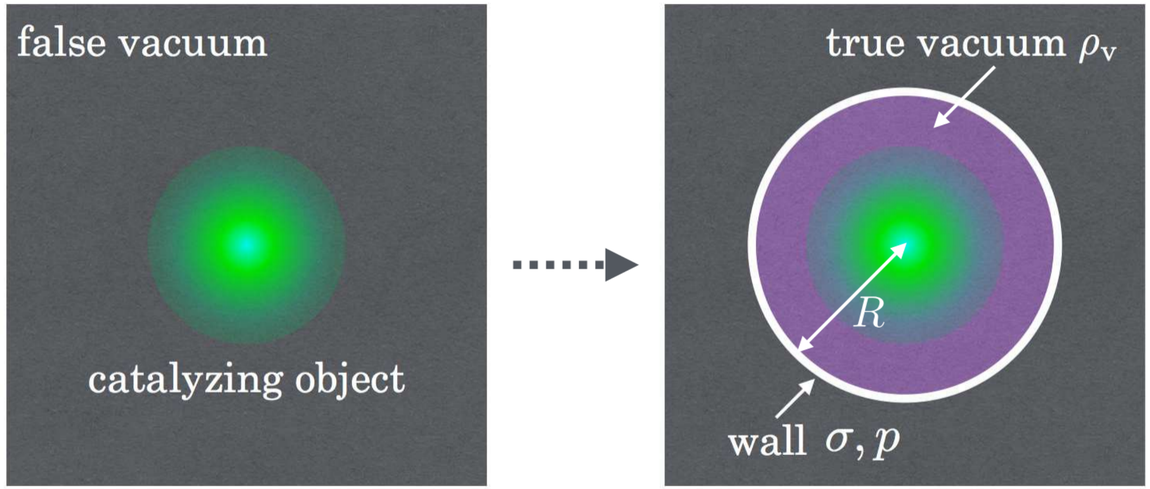


Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

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

The nature of impurities

- Compact objects and gravitational effects

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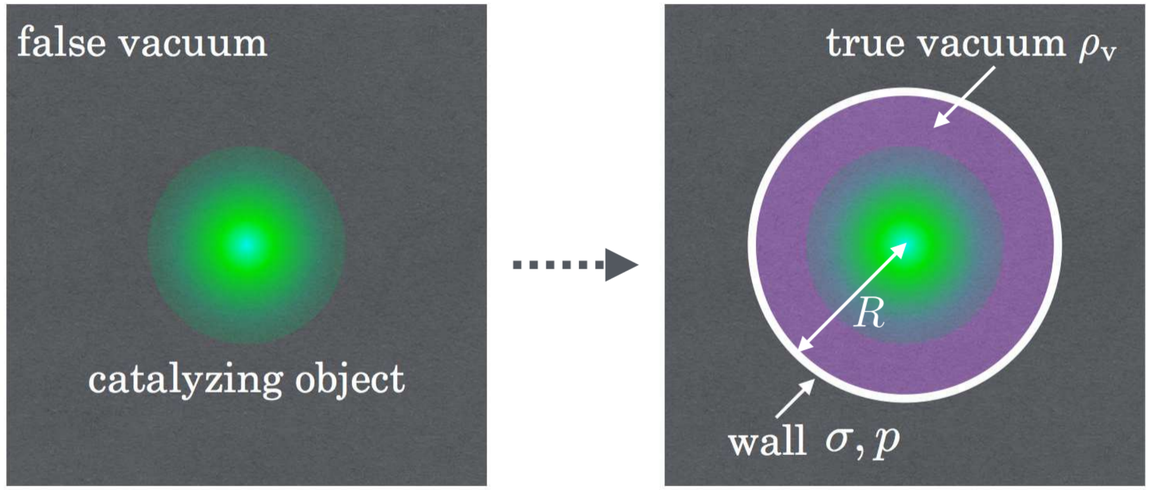


Fig. from Oshita, Yamada, Yamaguchi [1808.01382], PLB

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

- Primordial density fluctuations

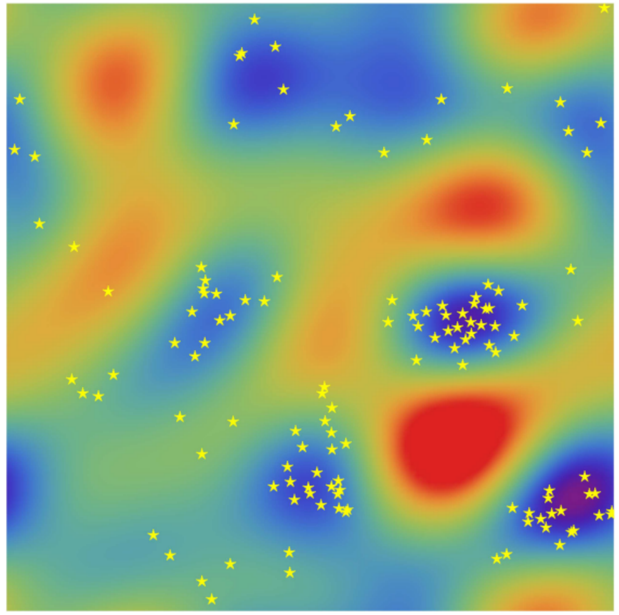
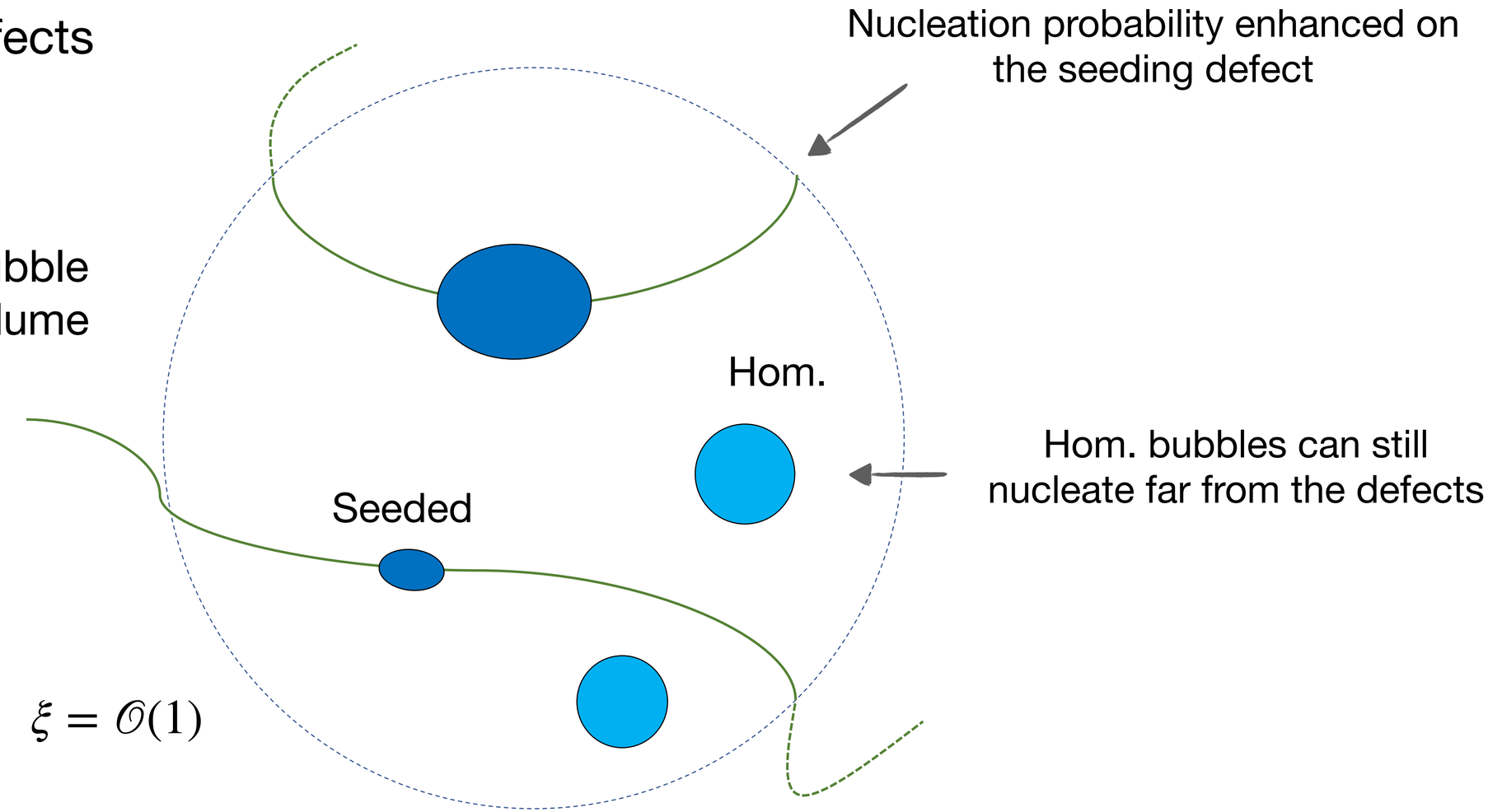


Fig. from Jinno, Konstandin, Rubira, van de Vis, [2108.11947], JCAP

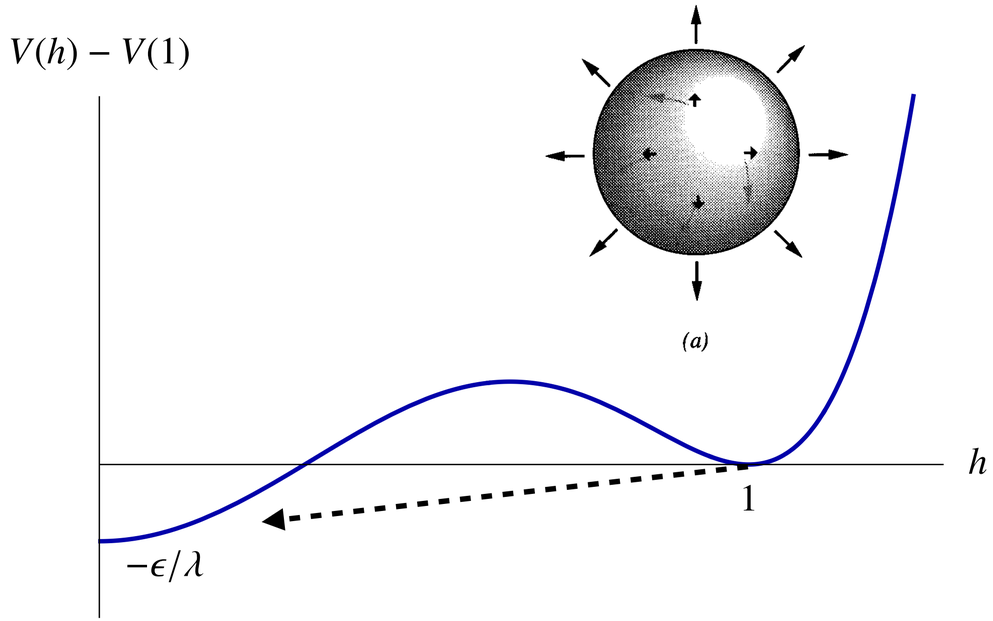
The nature of impurities

- Topological defects

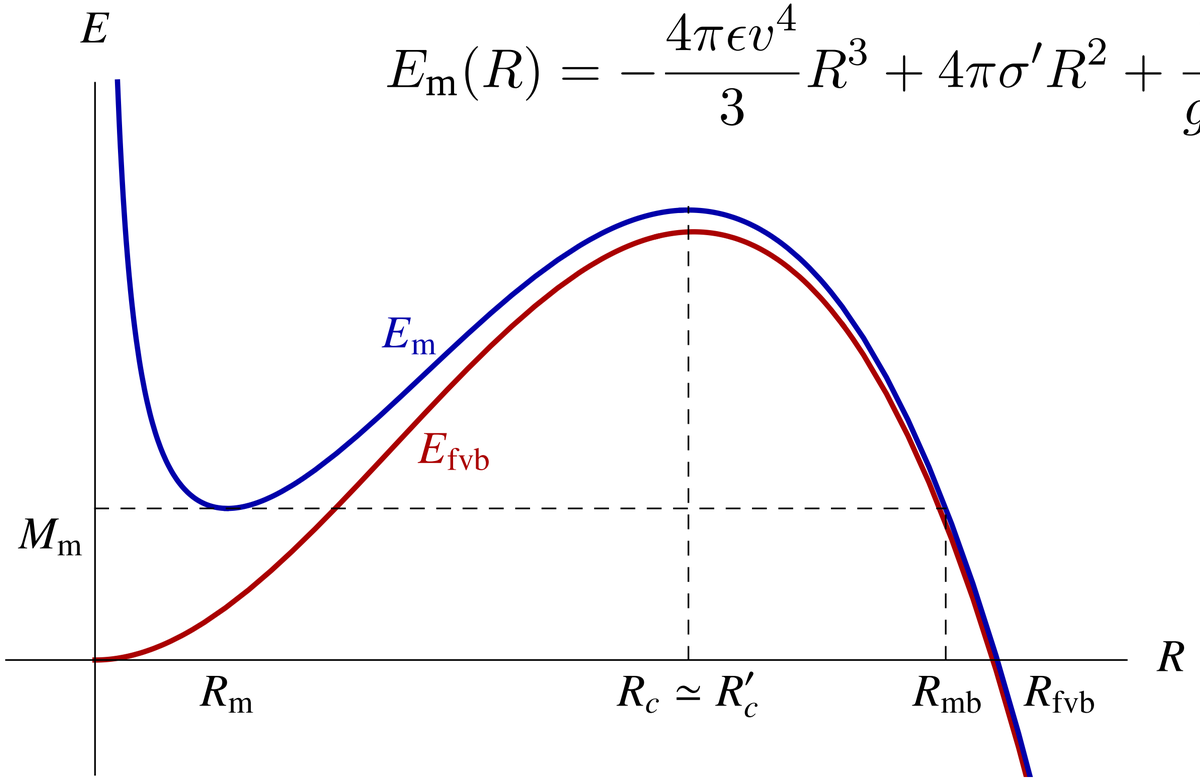


The nature of impurities

Monopoles



$$E_{\rm m}(R) = -\frac{4\pi\epsilon v^4}{3}R^3 + 4\pi\sigma' R^2 + \frac{2\pi}{g^2 R}$$



Figs. from Agrawal, Nee [2202.11102] SciPost Phys.

The nature of impurities

Domain walls

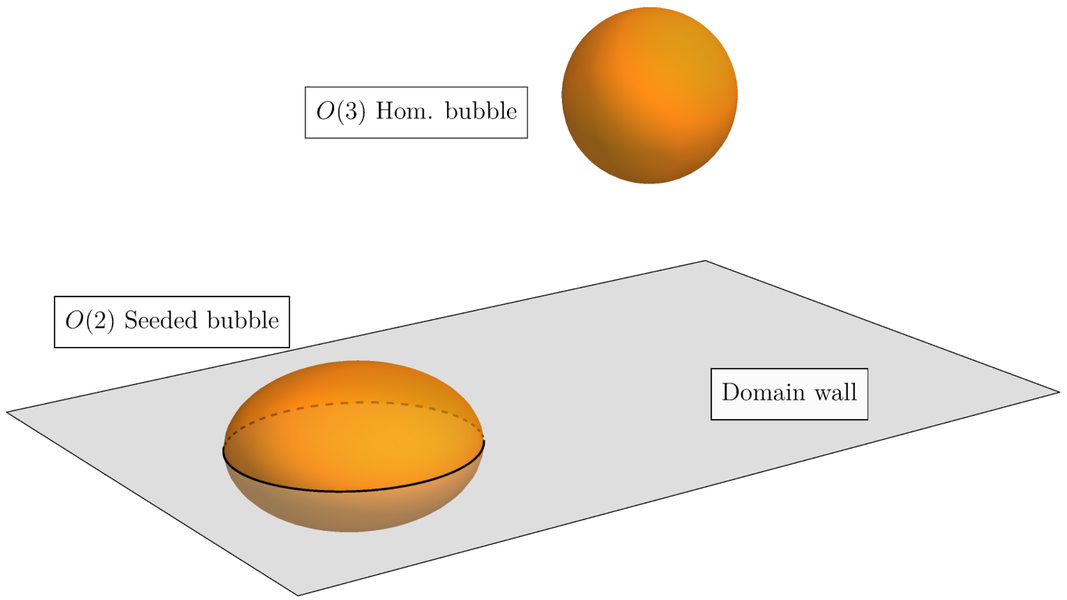


Fig. from Agrawal, SB, Mariotti, Nee [2312.06749] JHEP

SB, Mariotti [2203.16450] PRL

Sassi, Moortgat-Pick [2506.14880]

Cosmic strings

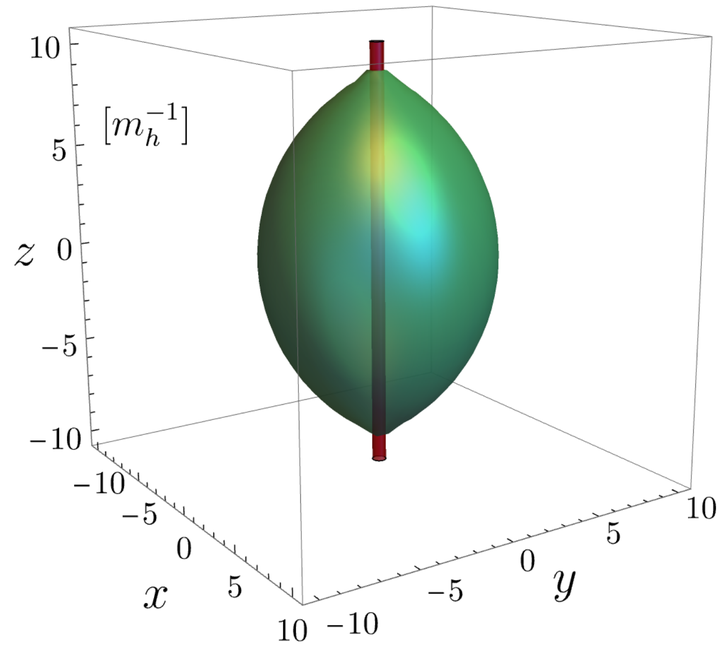


Fig. from SB, Mariotti, [2405.08060] SciPost Phys.

Lee et al., [1310.3005], PRD

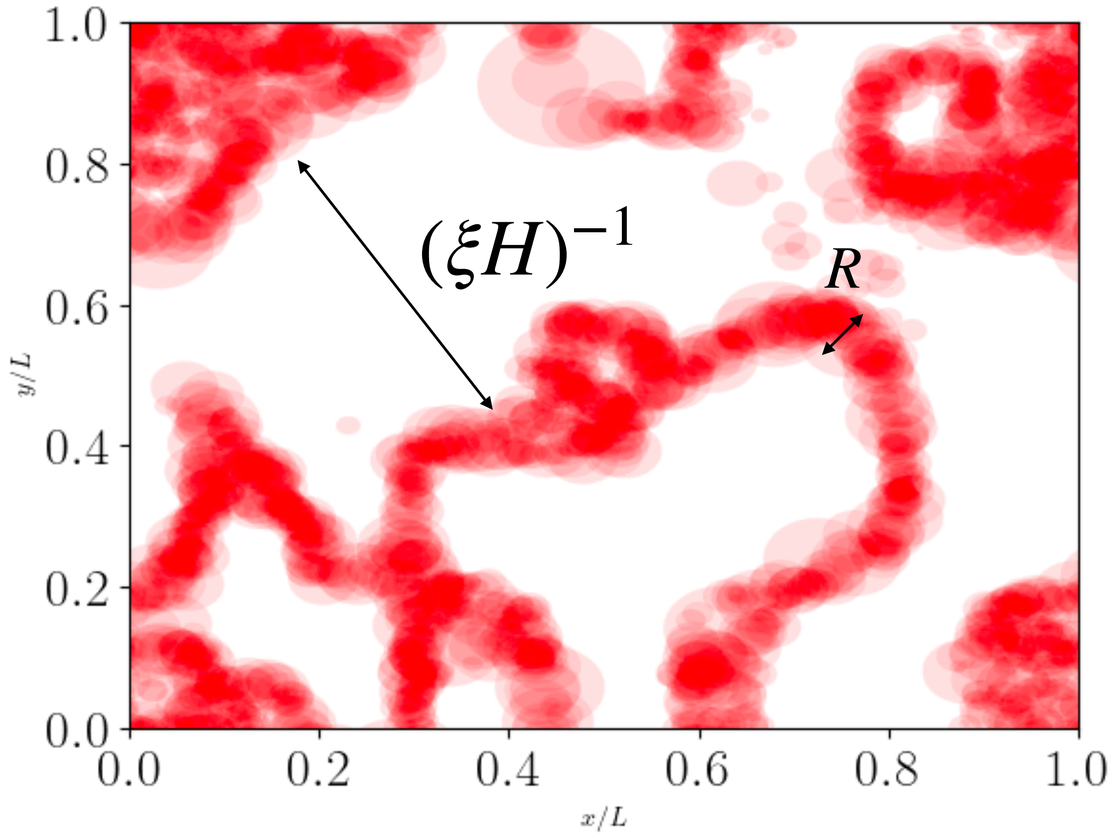
Yajnik, PRD, 1986

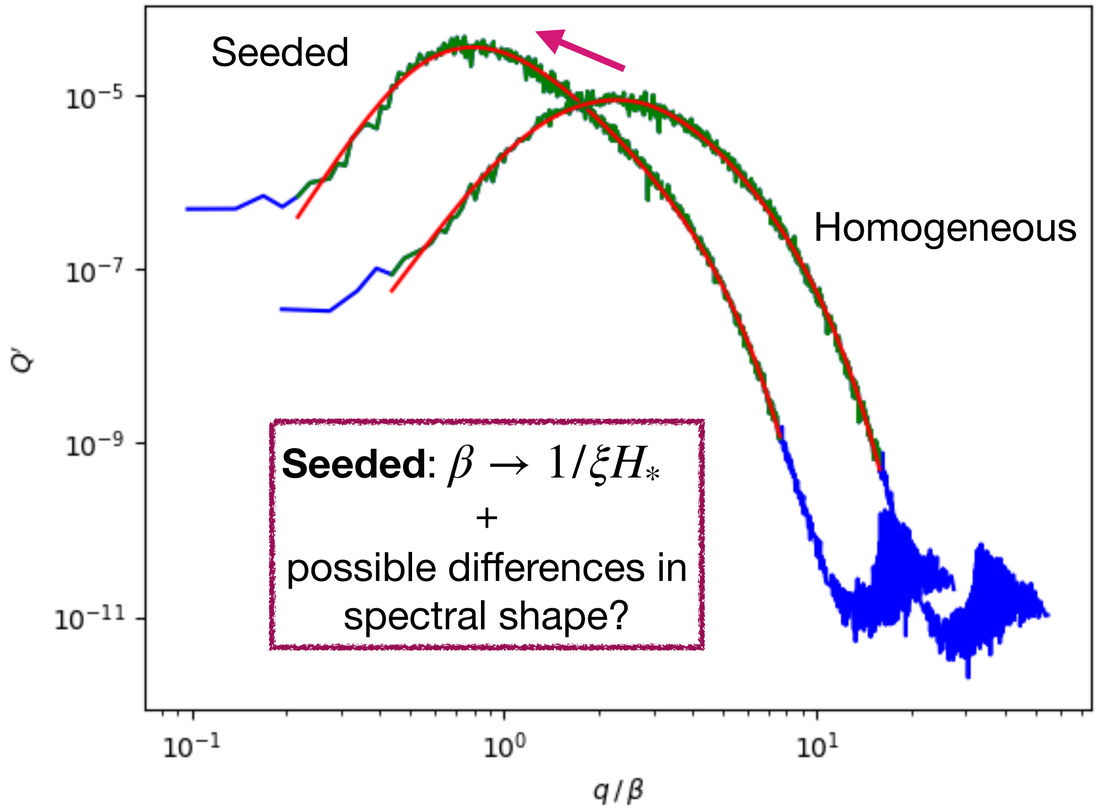
Motivation

- So far mostly used to constrain the existence of the seeds, e.g. pBH in the context of the SM metastability
- However, seeded nucleation can drastically change the dynamics of the phase transition: *observable consequences*
- General mechanism with a large range of applications: 1) singlet extension of the SM with a first order phase transition; 2) QCD axion strings
- New perspective on tunneling within quantum/thermal field theory

Gravitational waves from seeded transitions

- Numerical simulation of a domain-wall seeded electroweak phase transition





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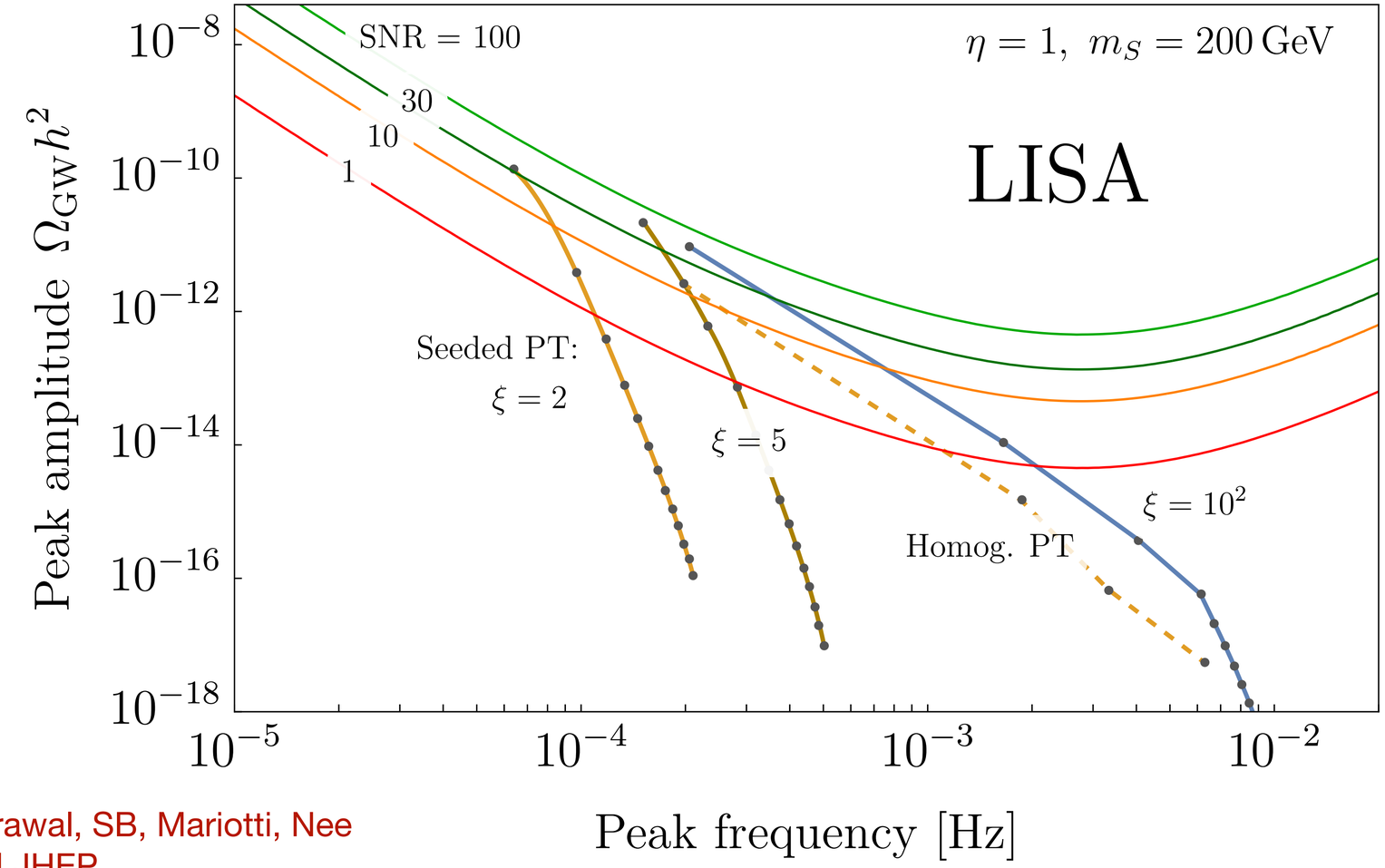
Gravitational waves from seeded transitions

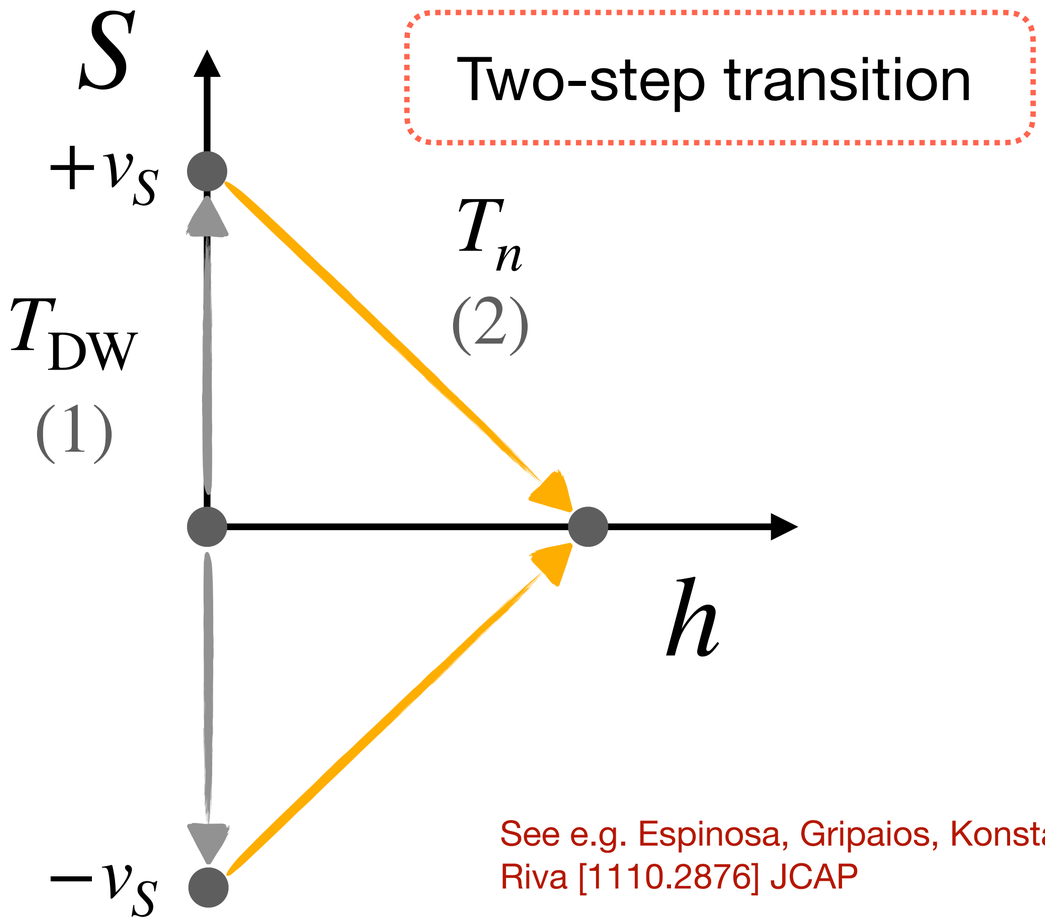


Dots: different benchmark points

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

Explicit realizations

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



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

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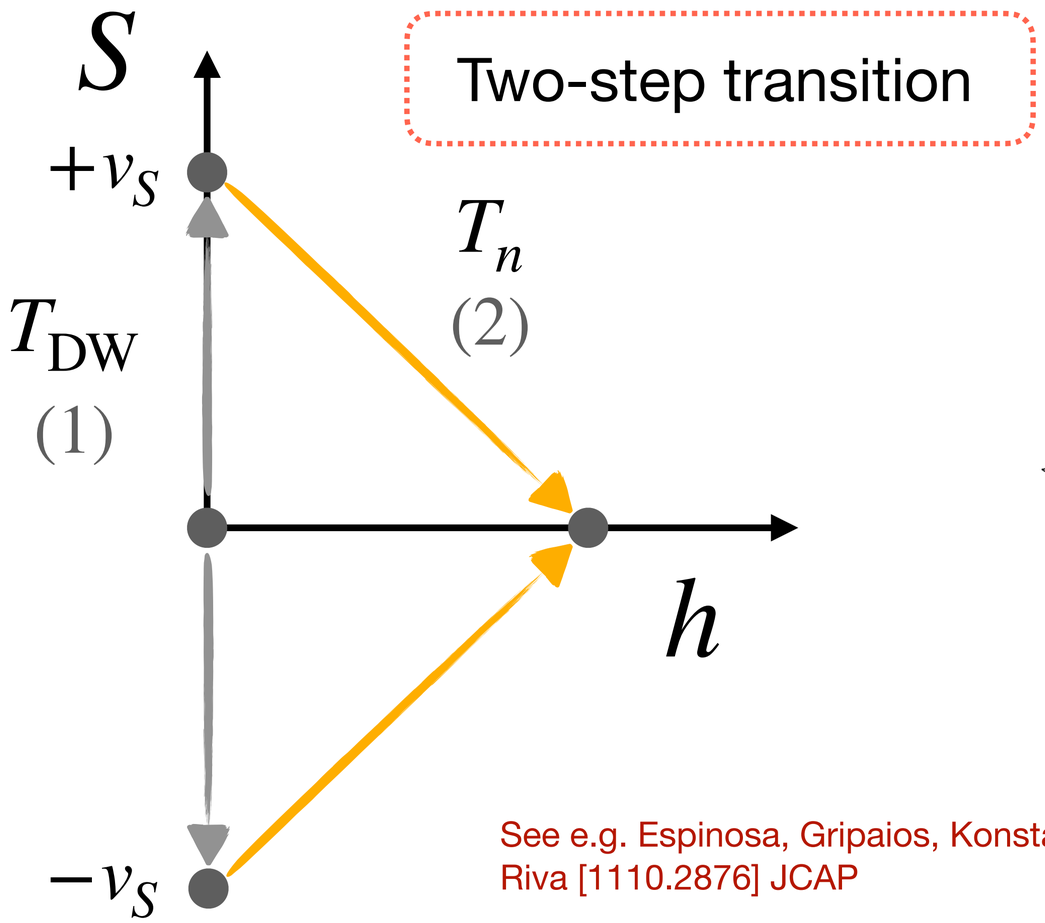
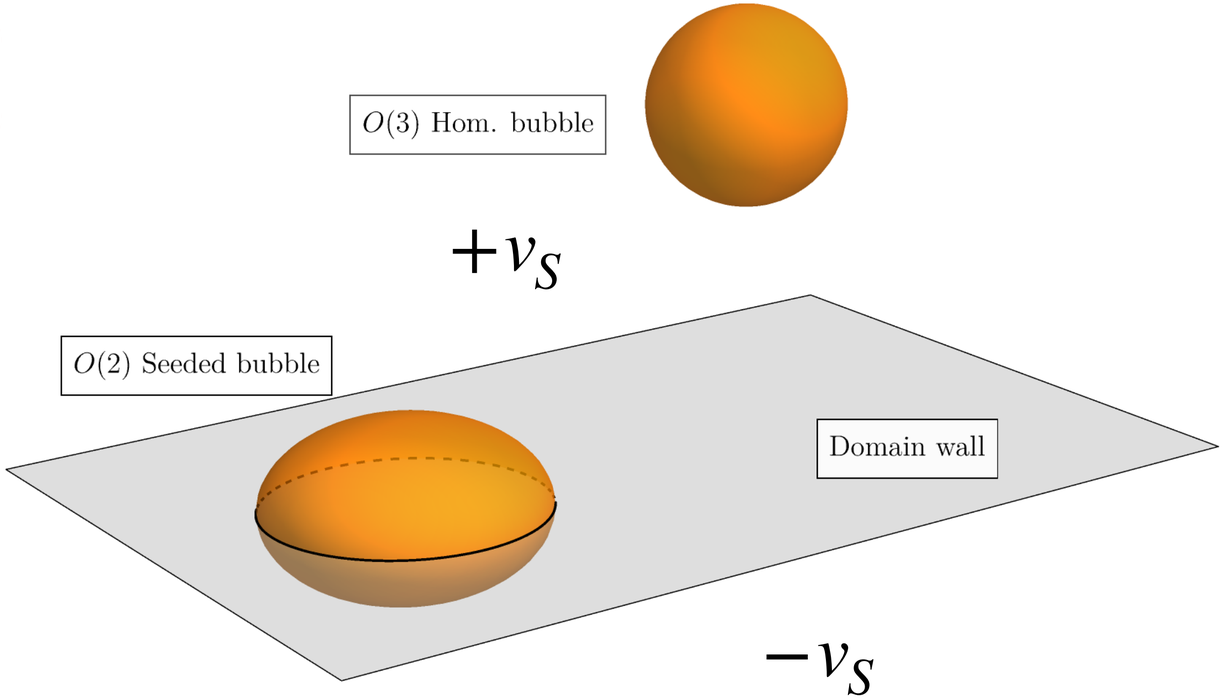


Two-step transition

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



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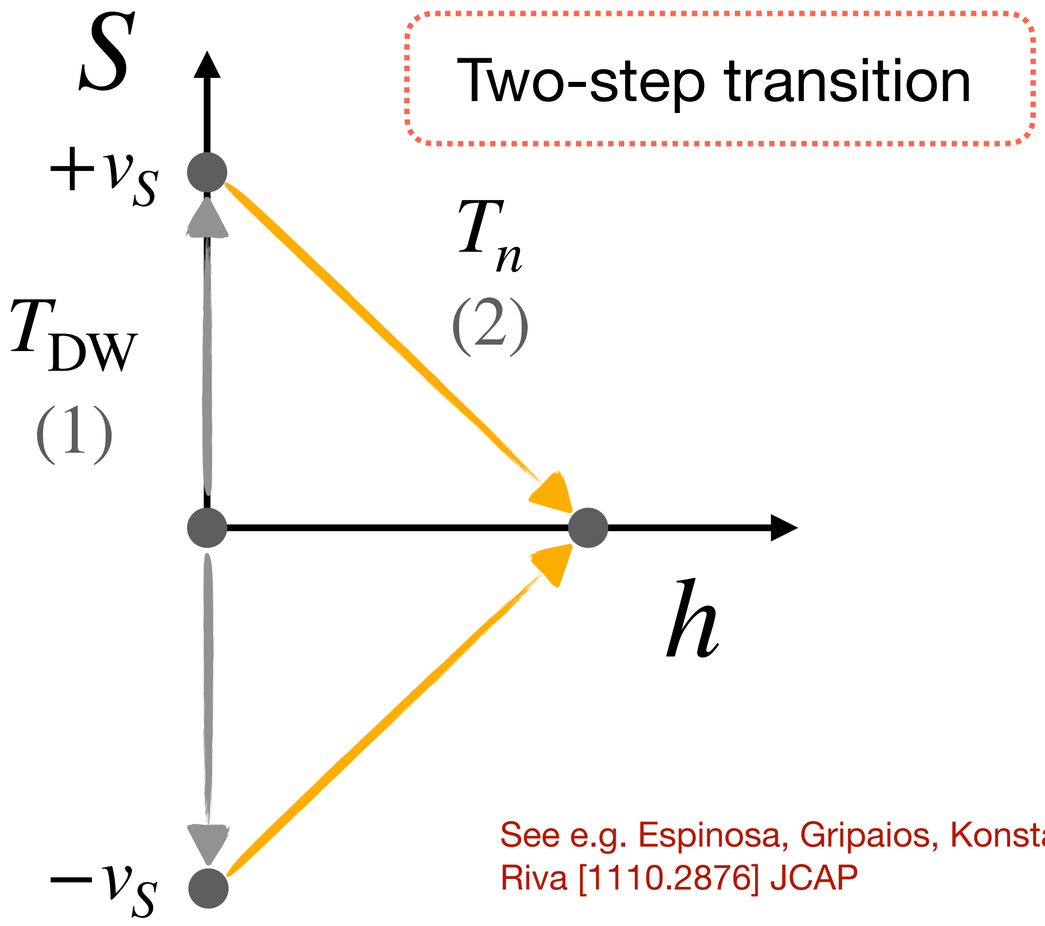

Two-step transition

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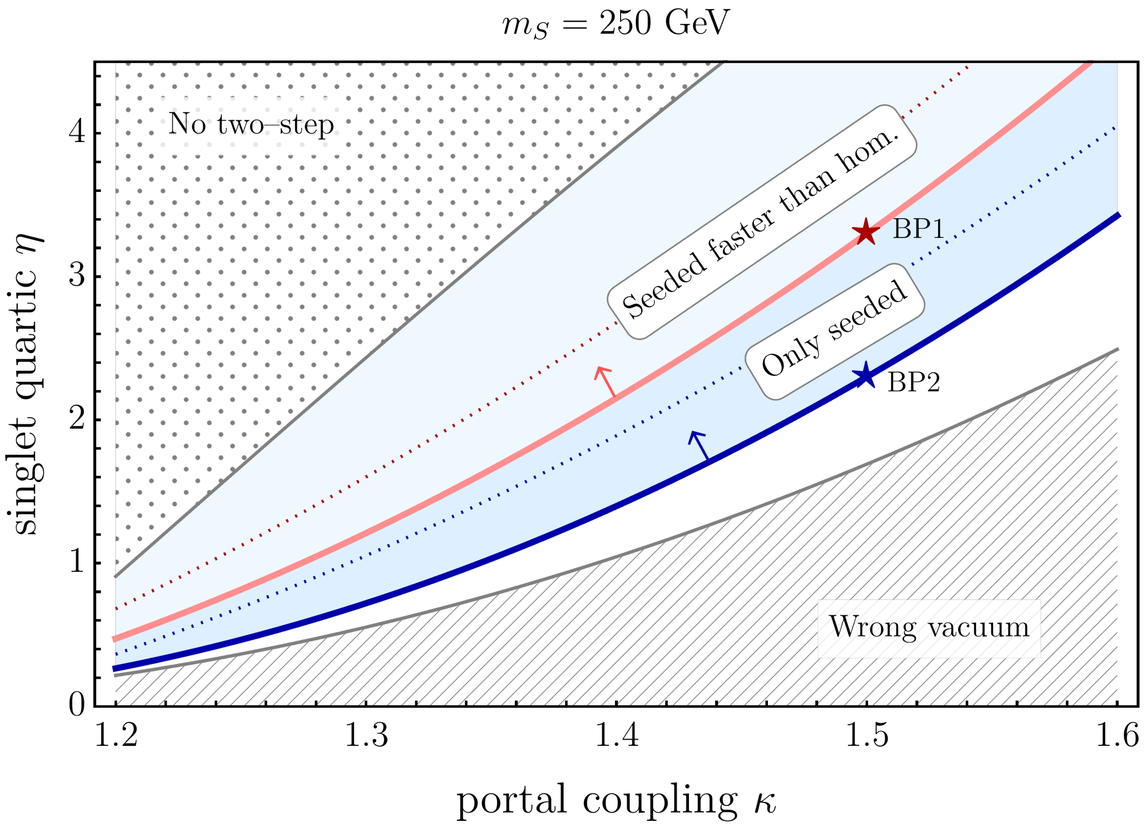
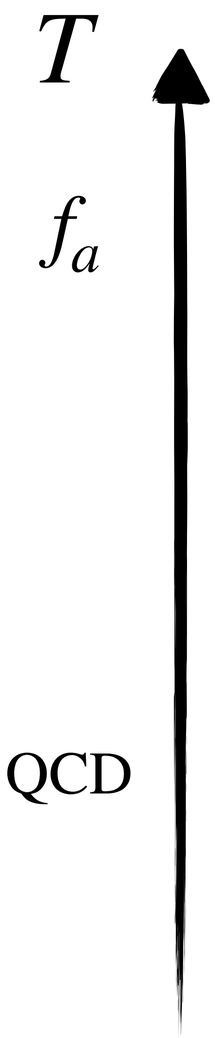
GW-collider interplay



SB, Mariotti [2203.16450] PRL

Agrawal, SB, Mariotti, Nee [2312.06749] JHEP

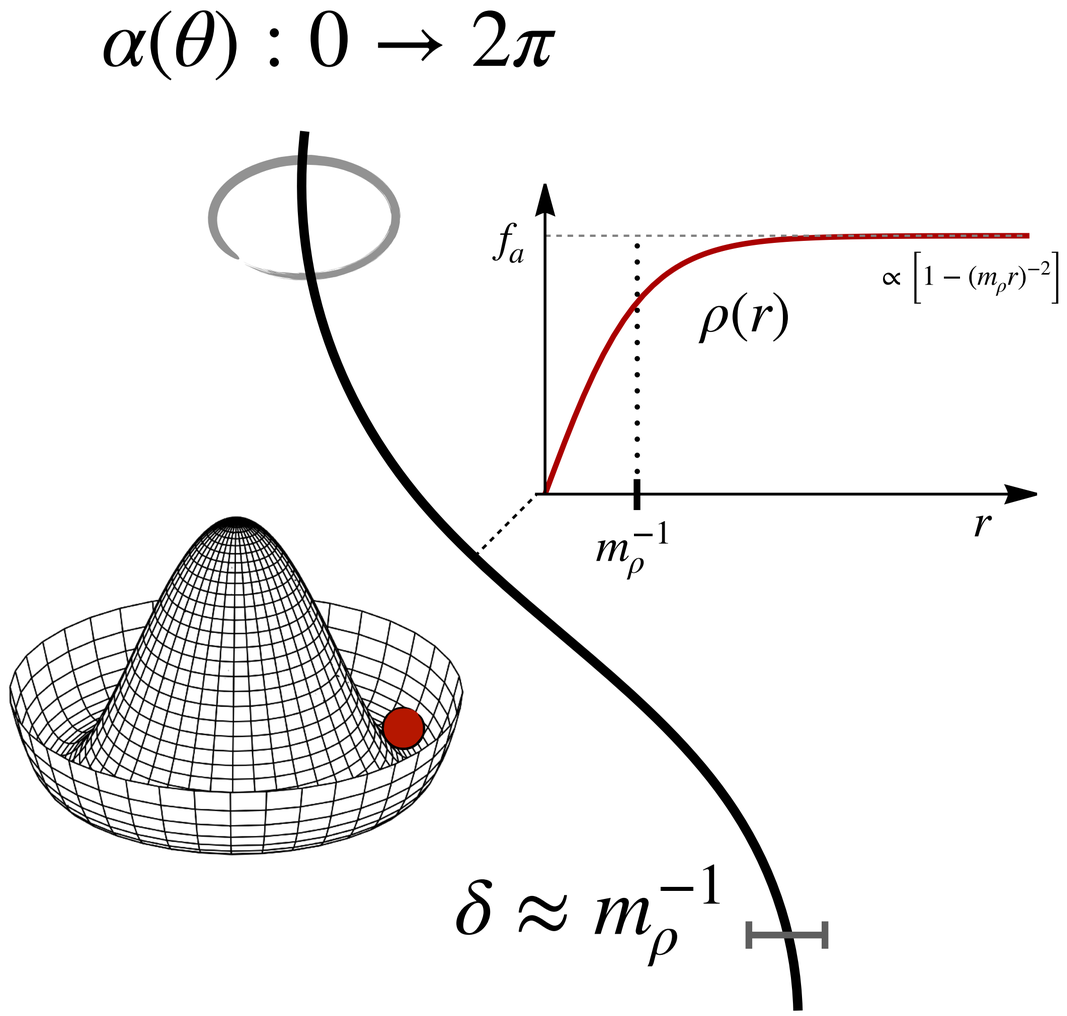
QCD axion strings



- Strings form at PQ phase transition

???

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

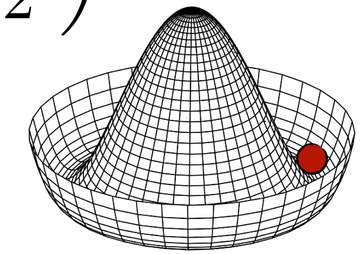


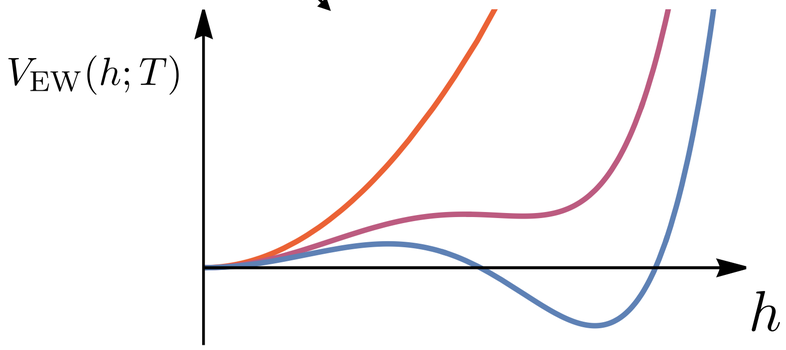
QCD axion strings

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

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

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





First order EWPT

QCD axion strings

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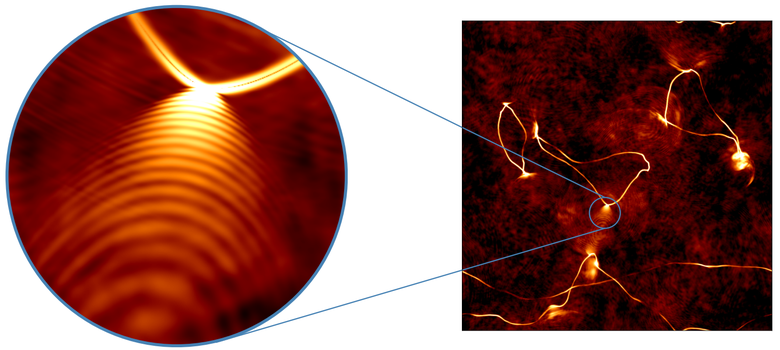


How do axion strings affect electroweak symmetry breaking?

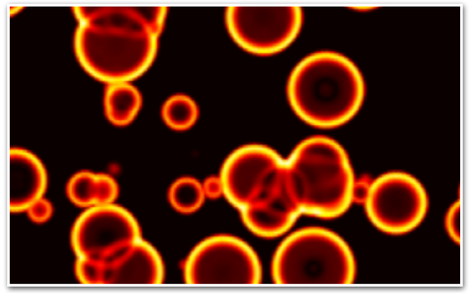
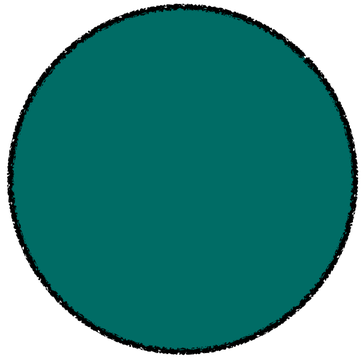


Fig. from 2308.01334

FOPT + PQ

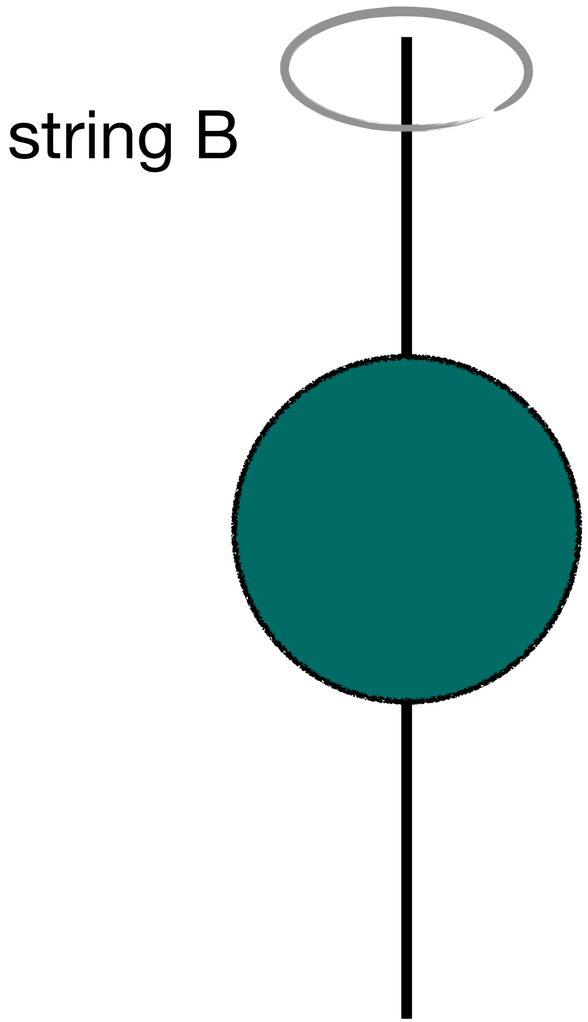
B → A



$= E_{\text{hom}}$

Critical bubble

FOPT + PQ

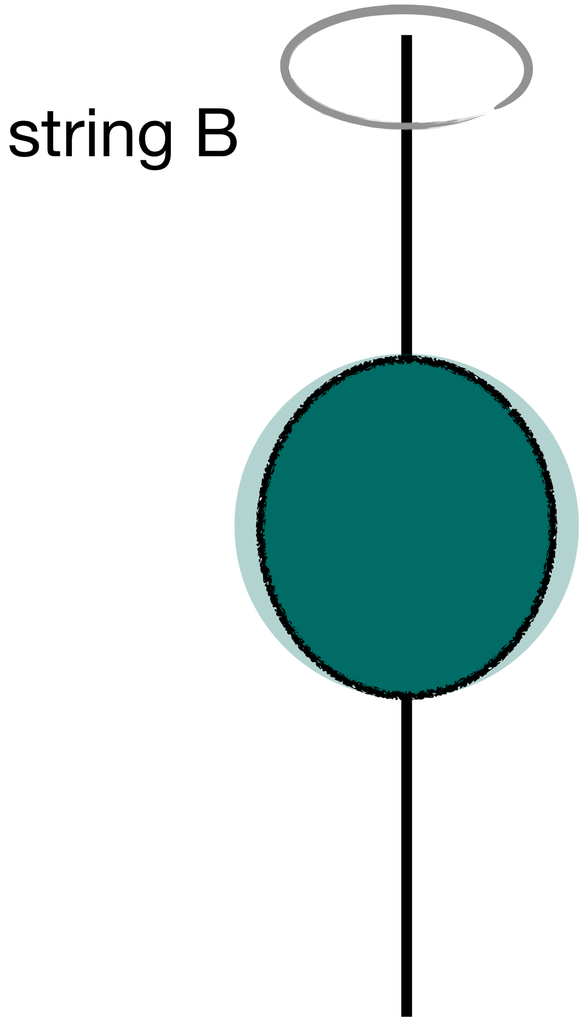


B → A

$$= E_{\text{hom}} \quad (\kappa = 0)$$

Critical bubble

FOPT + PQ

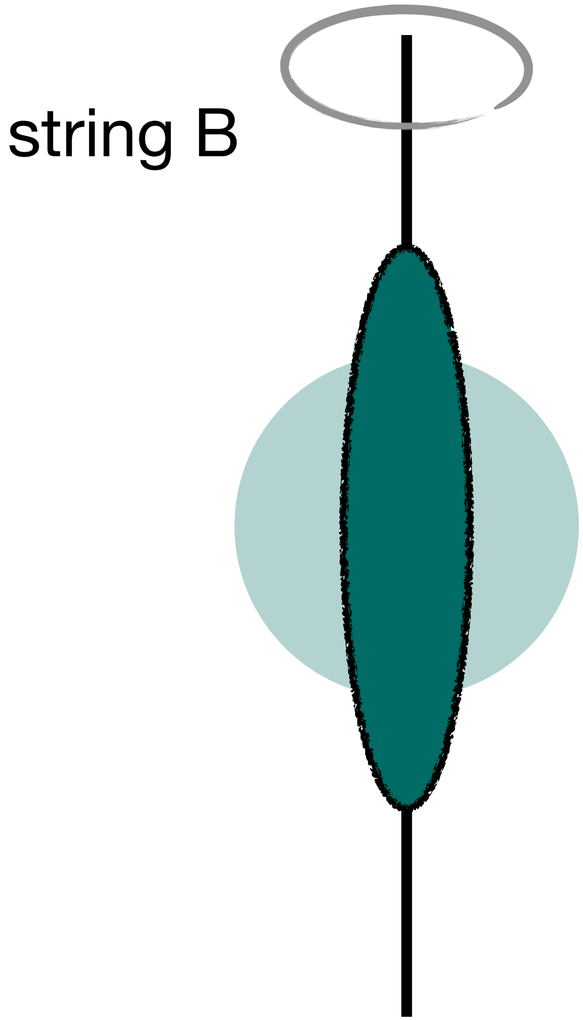


String B → String A

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

Critical bubble

FOPT + PQ

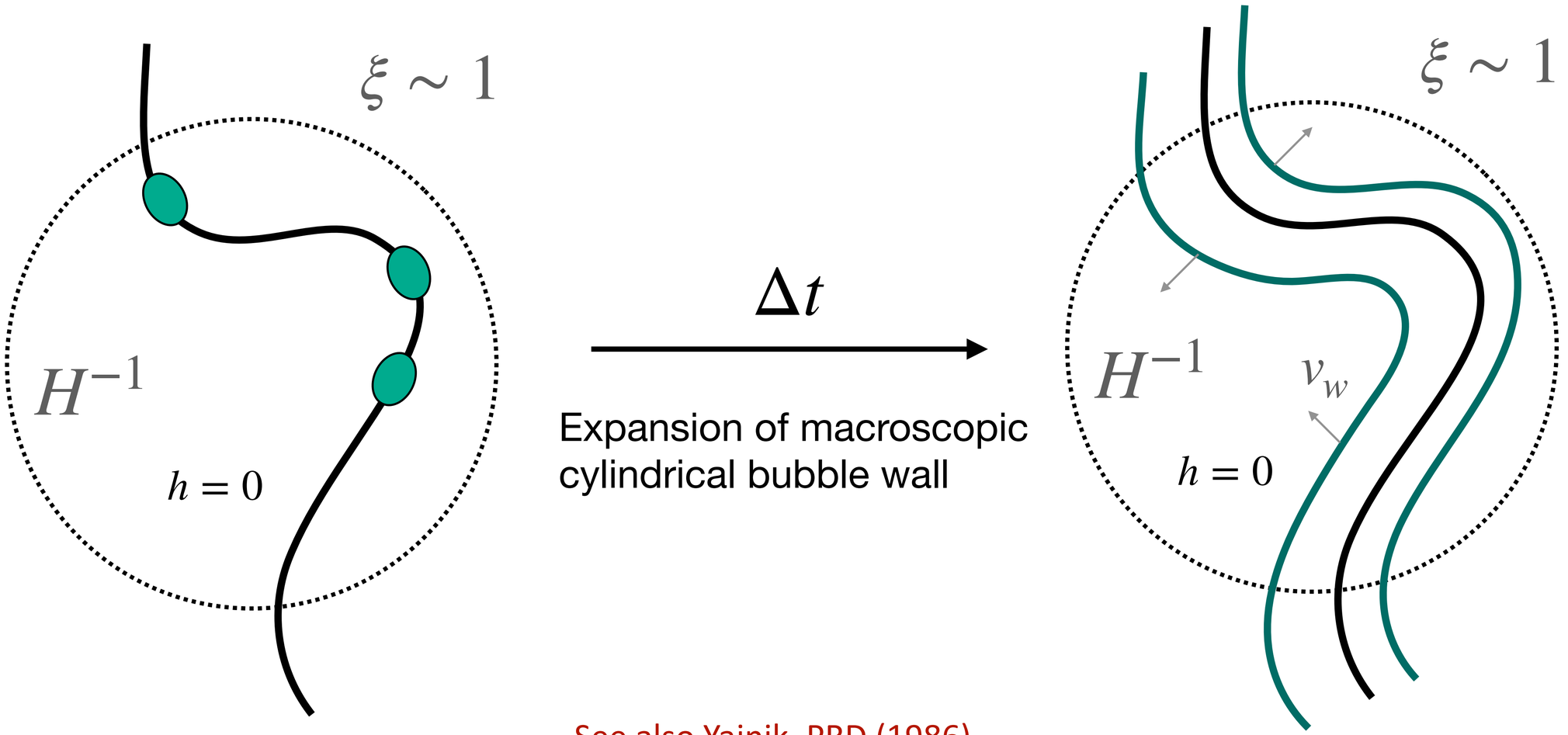


String B → String A

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

Critical bubble

FOPT + PQ



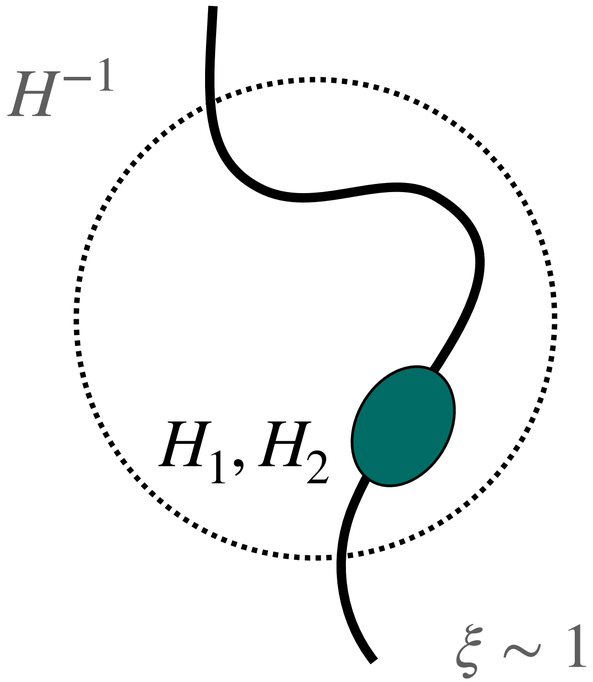
See also Yajnik, PRD (1986)

DFSZ axion strings

- DFSZ model where two Higgs doublets share a PQ charge:

$$\mathcal{L} = |\partial_\mu S|^2 + |D_\mu H_1|^2 + |D_\mu H_2|^2 - V_S(|S|) - V_{\rm EW}(H_1, H_2) - \left(\kappa S^2 H_1^\dagger H_2 + \text{h.c.}\right)$$

U(1) symmetry with massless A^0



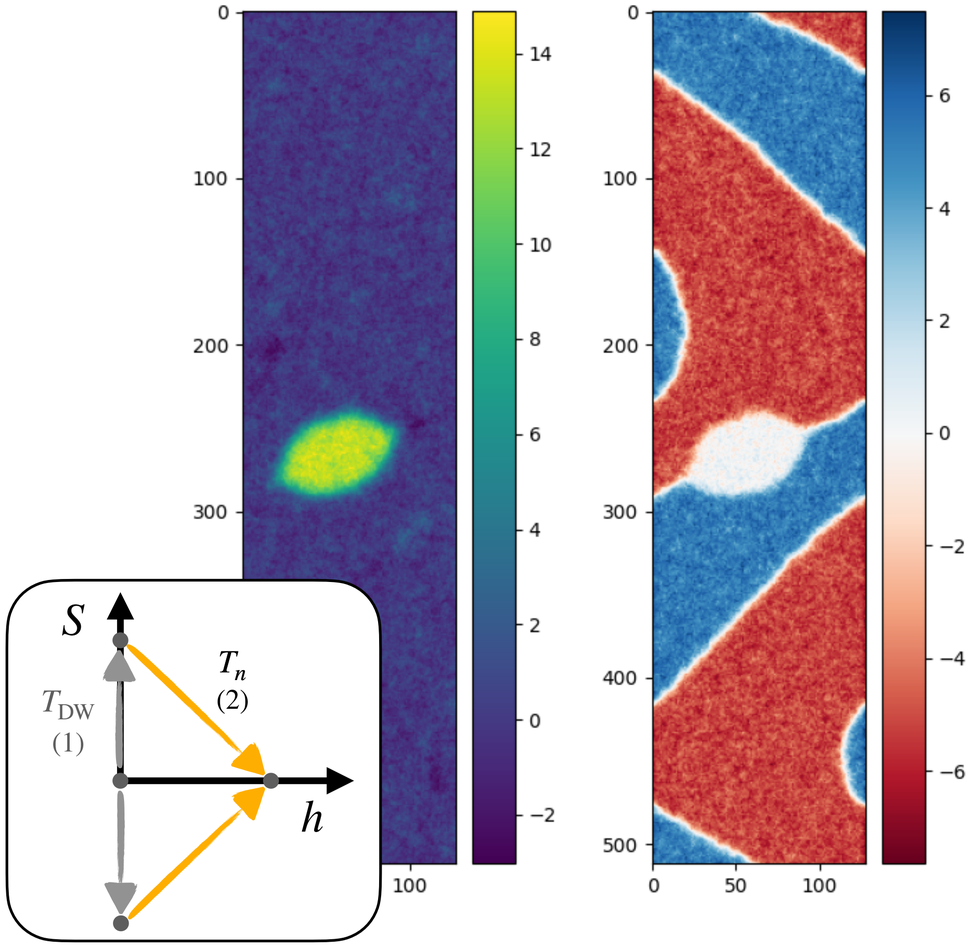
How does a non-zero κ affect EWSB?

SB, Yu Hamada, in prep.

Real-time simulations

- Bubble nucleation with a defect in the simulation box:

SB, Ekstedt, Hällfors, Rummukainen, in prep.



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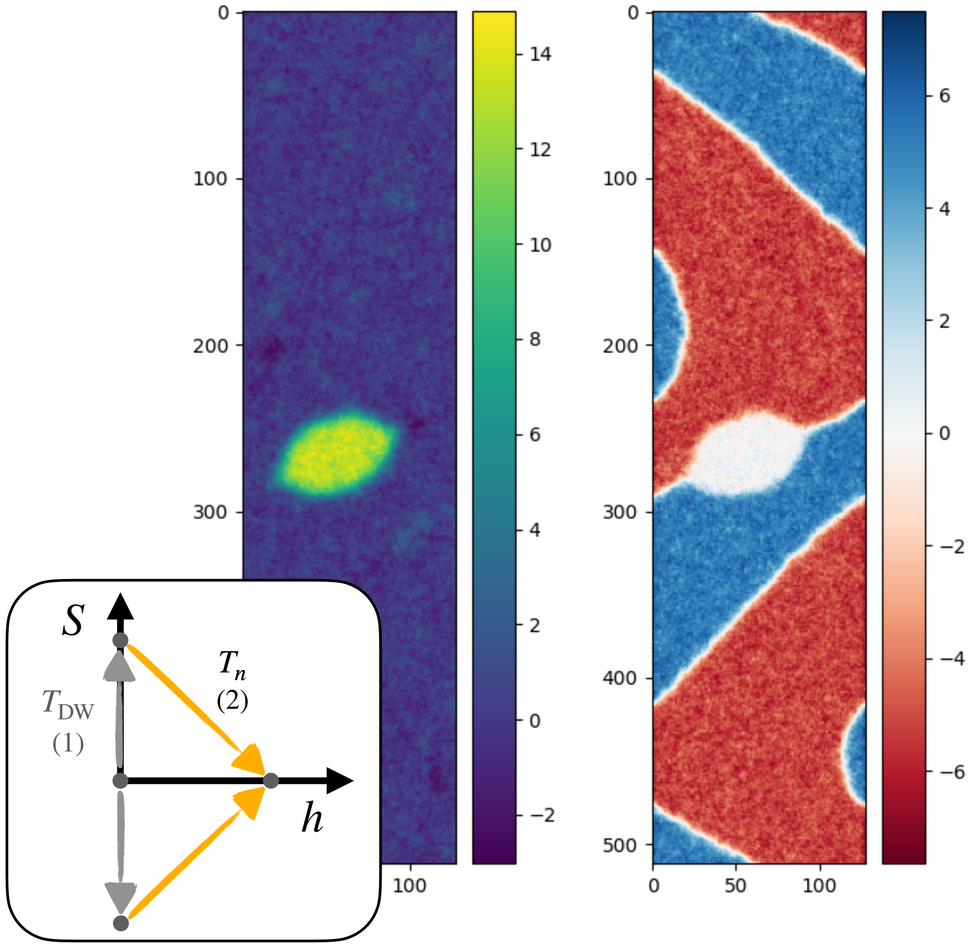

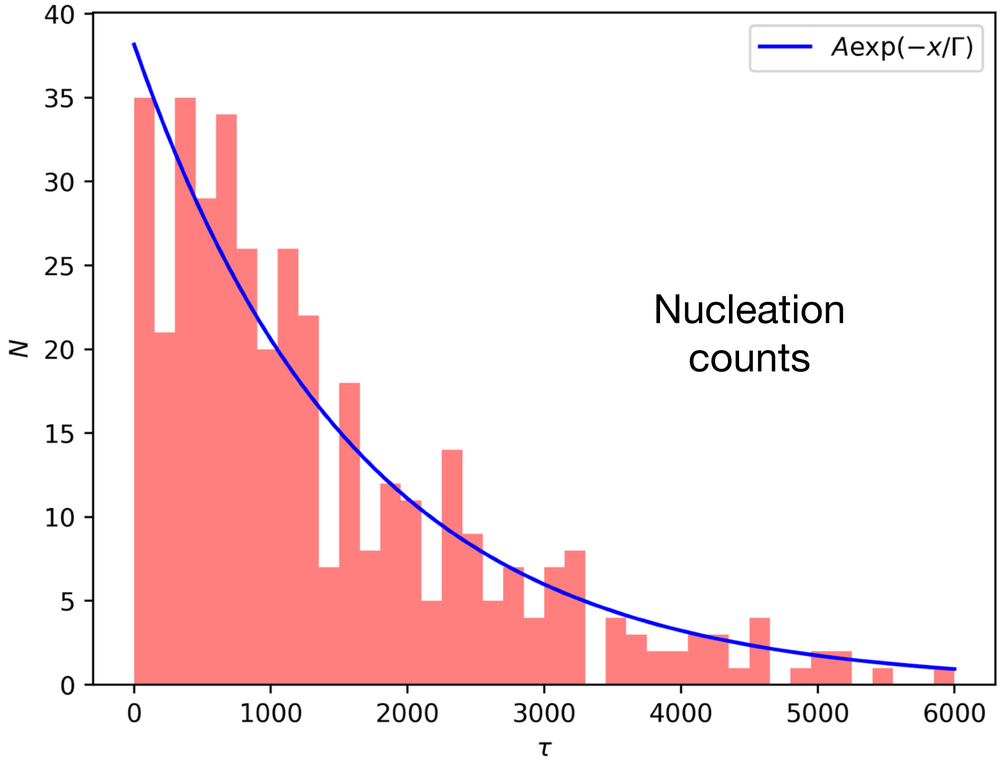

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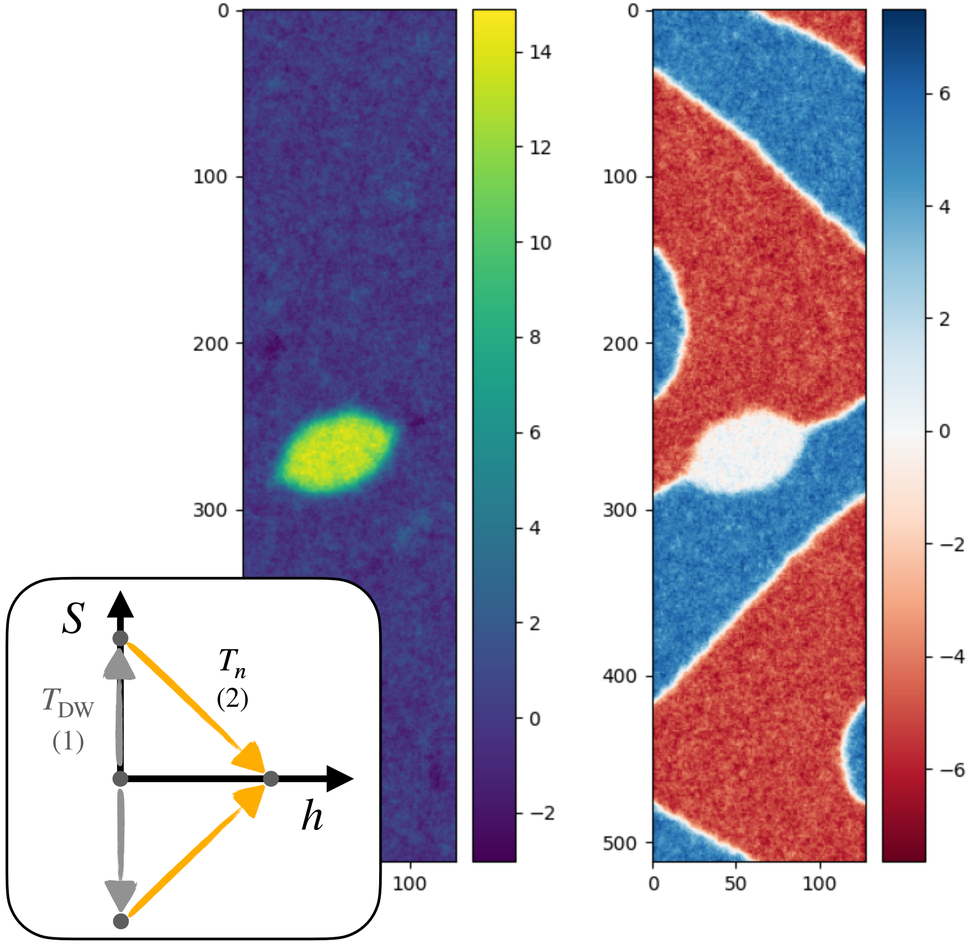
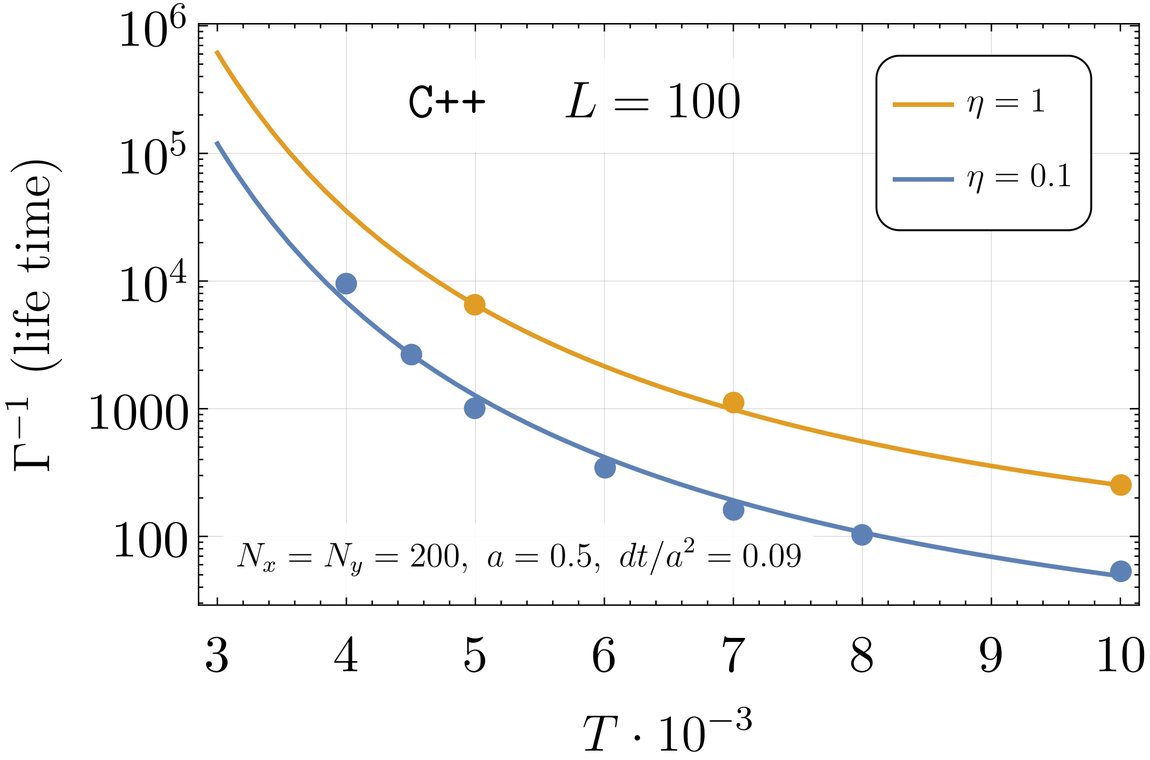


$$\Gamma = \sigma_{\mathrm{DW}} e^{-B/T}$$



Summary and outlook

- The presence of impurities in the early Universe can strongly affect the way a phase transition proceeds, with dramatic consequences for the phenomenology
- The xSM with Z_2 symmetry is arguably the simplest and complete example for an EWPT seeded by domain walls
- Other defects can exist at the time of the EWPT: dedicated study of QCD axion strings in KSVZ model with Higgs portal, and extension to DFSZ
- Pheno aspects of seeded phase transitions: percolation, slow transitions, expansion of non—spherical bubbles, features in the GW signal?
- New opportunities to study tunneling in quantum/thermal field theory including real-time lattice simulations

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Thank you!