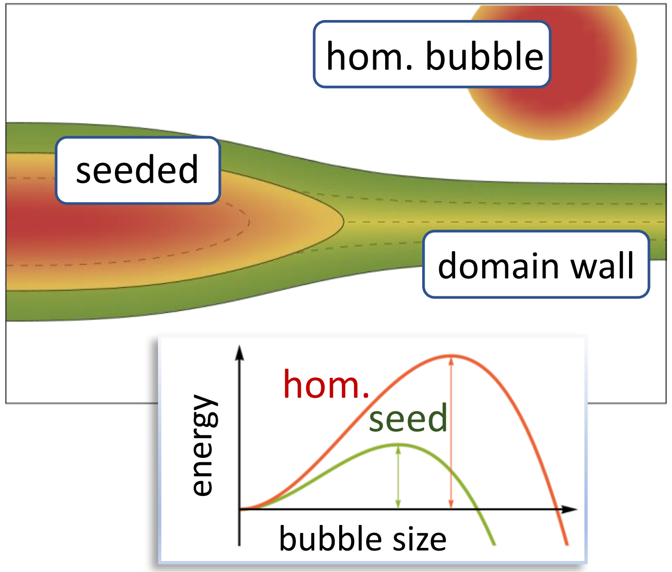
Domain walls seeding the electroweak phase transition in the xSM



Simone Blasi

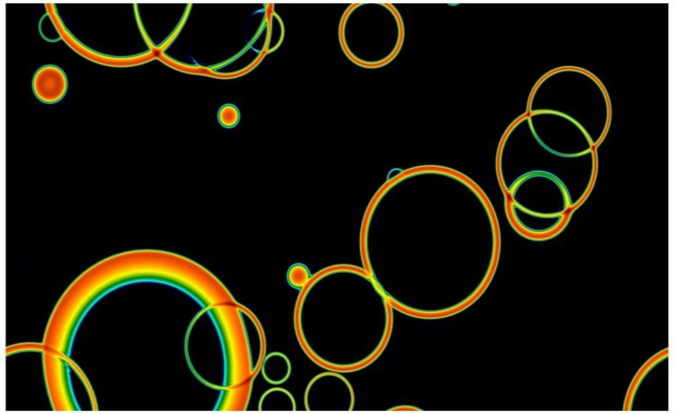
work in collaboration with A. Mariotti

Based on 2203.16450 [hep-ph]

Be.HEP Summer Solstice, 21.06.22

Introduction

Fig. from Weir's review [1705.01783]



- In the SM, QCD and electroweak phase transitions are not first-order (given measured m_h)

Departure from thermal equilibrium, **baryogenesis** ← Have there been any first order transitions in the early Universe? → Stochastic background of **gravitational waves**

New phase transitions, e.g. secluded sector

Breitbach, Kopp, Madge, Opferkuch, Schwaller [1811.11175] JCAP

Ertas, Kahlhoefer, Tasillo [2109.06208] JCAP

New physics can affect the expected SM transitions

- Electroweak
  extended scalar sectors, composite Higgs, SUSY…
- QCD
  1st order with $N_f = 6$ (active)

e.g. Ipek and Tait [1811.00559] PRL

The SM + Z_2-odd scalar singlet

h boson as the portal to new physics:

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

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

Curtin, Meade, Yu [1409.0005] JHEP

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

  Espinosa, Konstandin, Riva [1107.5441] NPB

- Minimal mechanism for EW baryogenesis when Z_2 = CP

  Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

- New confining group as natural UV completion, next-to-minimal Composite Higgs

  Gripaios, Pomarol, Riva, Serra [0902.1483] JHEP

- Standard benchmark for gravitational wave signals

  Caprini et al. [1512.06239] JCAP

The SM + Z_2-odd scalar singlet: into the nightmare

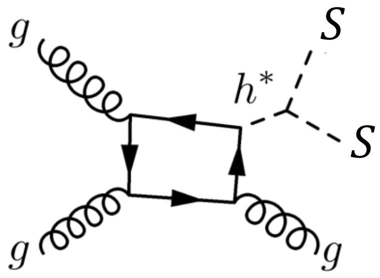
HL-LHC

$$V \supset +\frac{1}{2}\kappa\, h^2 S^2$$

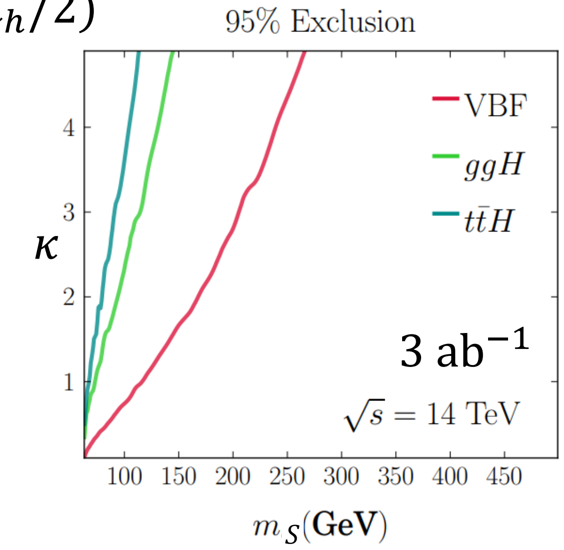
- No single production of S, missing energy
- $m_S < m_h/2$ strongly constrained by invisible Higgs decays

Englert, Jaeckel, Khoze, Spannowsky, [1111.1719], PRD

- Non-resonant pair production ($m_S > m_h/2$)

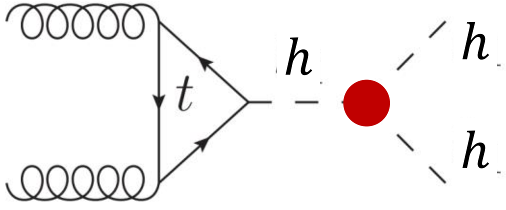


$$pp \to h^{(*)} + X \to SS + X$$



Figs. from Craig, Lou, McCullough, Thalapillild, [1412.0258], JHEP

- Loop corrections to trilinear h couplings



$$\frac{\kappa^2}{16\,\pi^2}\frac{v^2}{m_S^2} > 30\%\ \lambda_{\text{SM}}$$

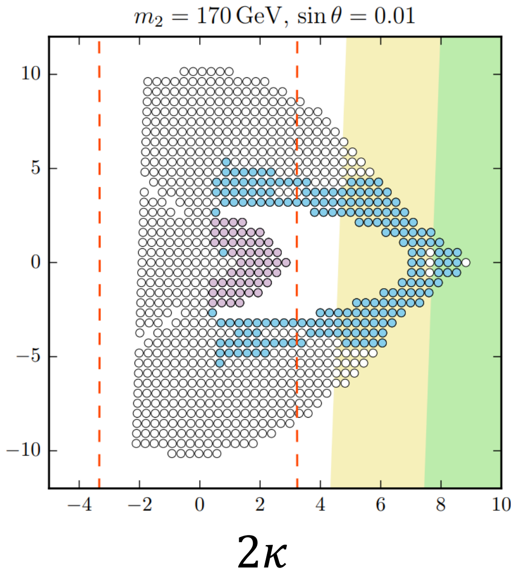
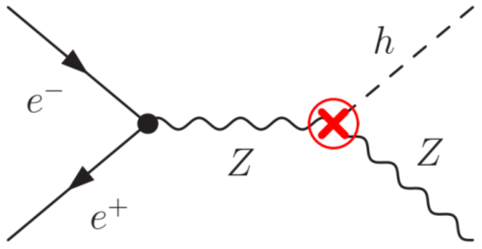


Fig. from Chen, Kozaczuk, Lewis, [1704.05844], JHEP

The SM + Z_2-odd scalar singlet: into the nightmare

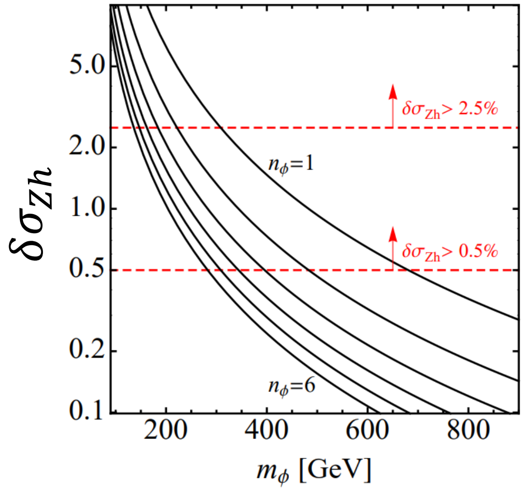
- Associated production at lepton colliders (Higgs-strahlung)

ILC,
FCC-ee



$$\frac{\delta\sigma_{Zh}}{\sigma_{Zh}} \sim \frac{\kappa^2}{16\pi^2}\frac{v^2}{m_S^2} \sim O(1\%)$$

peaks @ $\sqrt{s} \simeq 250$ GeV



Figs. from Craig, Englert, McCullough, [1305.5251], PRL

- Vector boson fusion at high-energy lepton colliders

CLIC,
muon collider

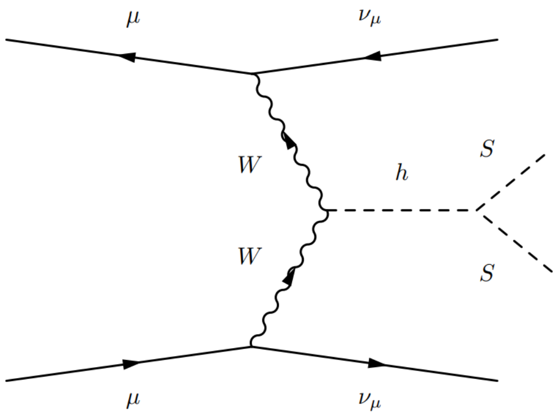


Fig. from Constantini, De Lillo, Maltoni, Mantani, Mattelaer, Ruiz, Zhao [2005.10289], JHEP

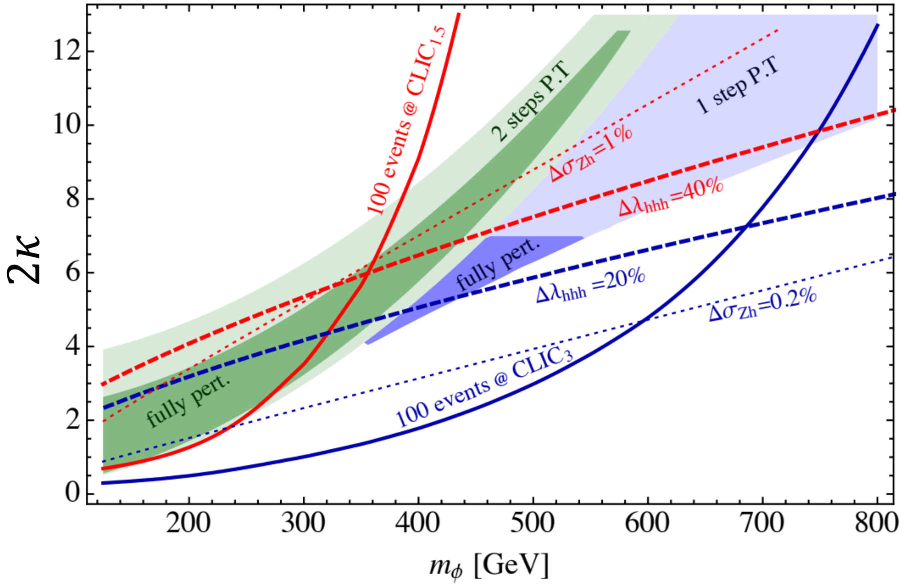
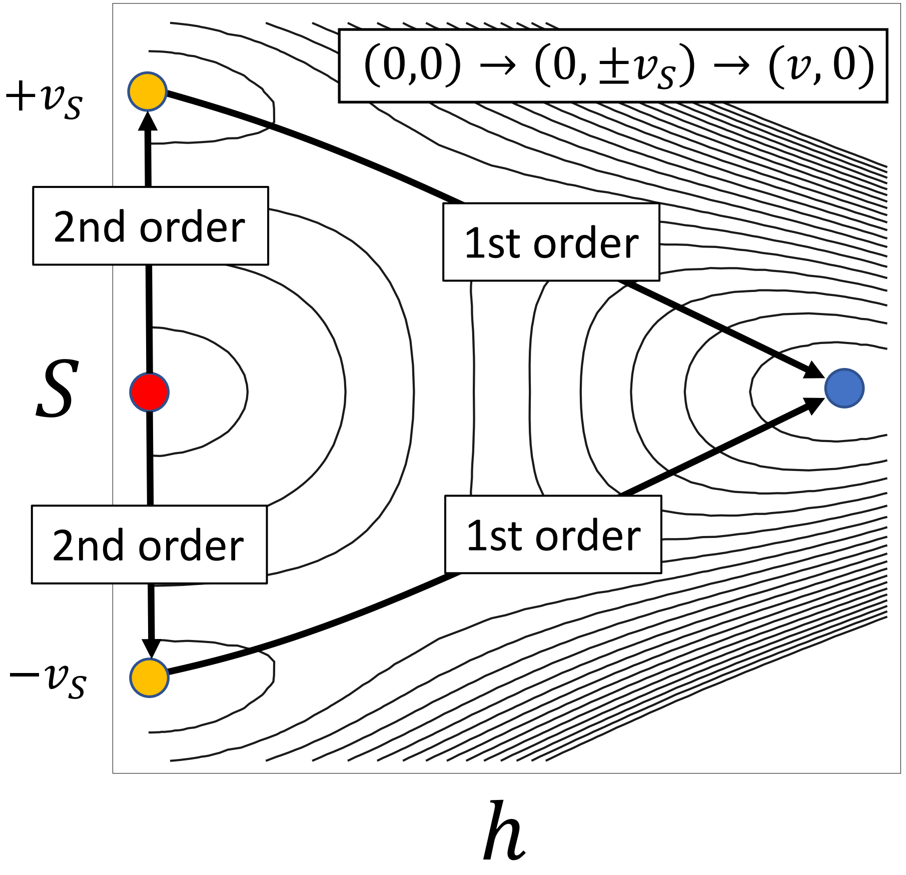


Fig. from Buttazzo, Redigolo, Sala, Tesi, [1807.04743], JHEP

The electroweak PT in the SM + scalar singlet

- Two-step electroweak phase transition



- The second step is 1st order owing to non-zero S vev

$$\gamma_{\mathrm{V}} \sim T^4 \exp(-S_3/T) \sim H^4$$

spherical bubbles,
homogeneous spacetime

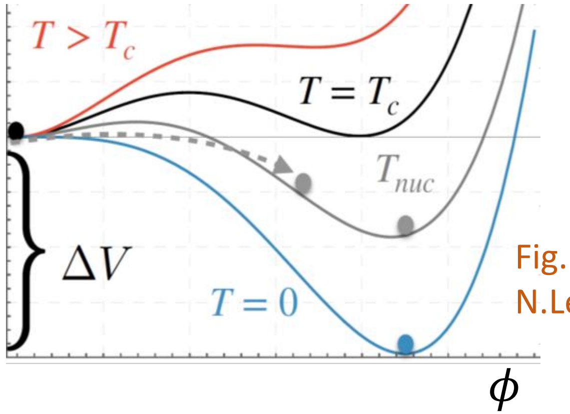


Fig. from N.Levi's talk

- Minimal EW baryogenesis

$$L \supset i \frac{1}{\Lambda} S\, H\, \bar{q}\, \gamma_5\, t$$

Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

- Detectable GW signal at LISA

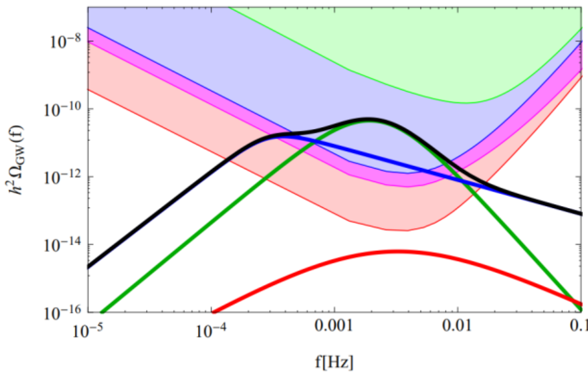


Fig. from Caprini et al. [1512.06239] JCAP

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)

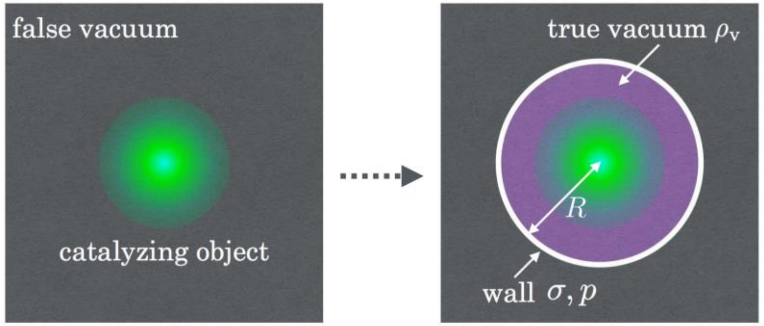
"In particle physics it is often assumed that phase transitions are nucleated by thermal fluctuations. In practice, […] except in very pure, homogeneous samples, **phase transitions are often nucleated by various forms of impurities and inhomogeneities of nonthermal origin**."

"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

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



- Topological defects (strings and monopoles)

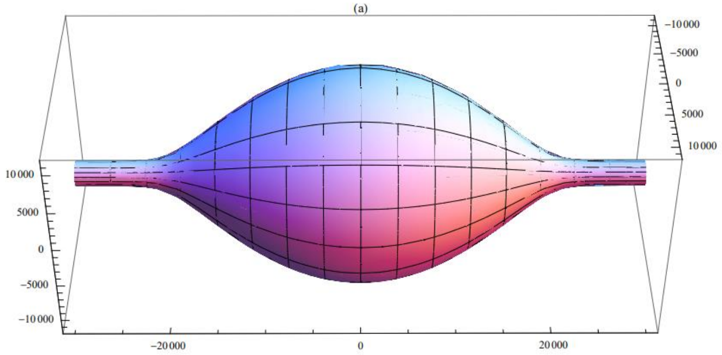
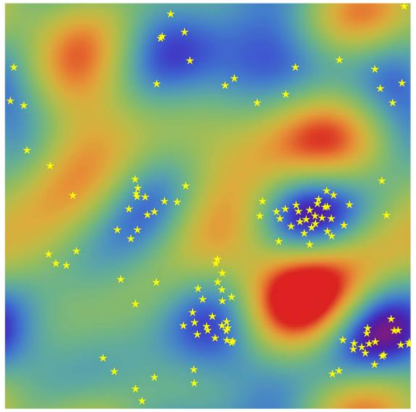


Fig. from Lee et al., [1310.3005] PRD

- Primordial density fluctuations

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



- What about domain walls?

This talk:

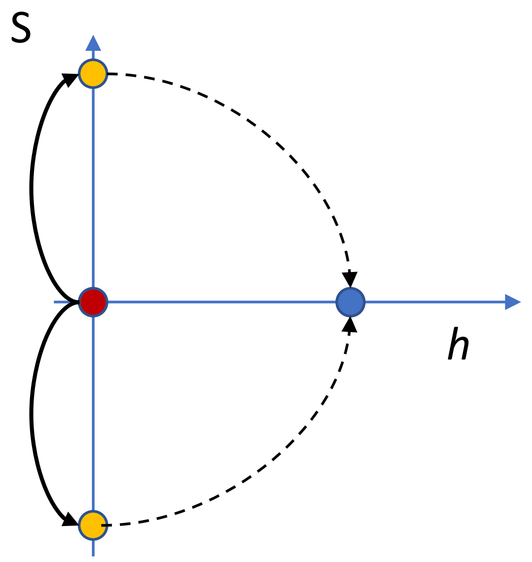
- Higgs + Singlet (xSM)
- Thermal history
- New method for bounce

SB & Mariotti, [2203.16450]

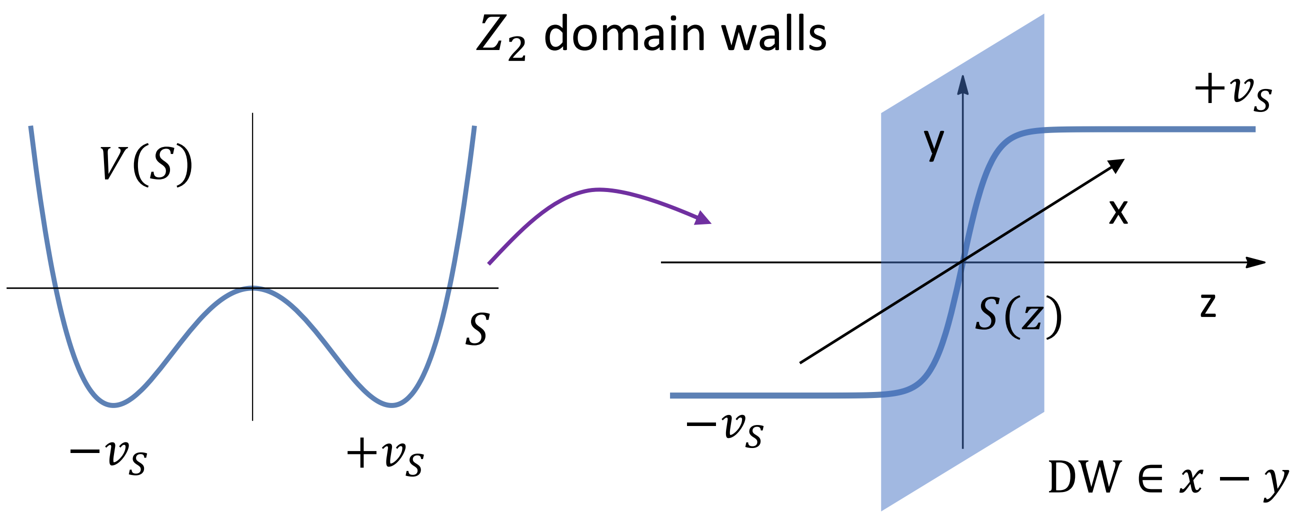
Topological defects

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

- Defects as relics of phase transitions depending on topology of vacuum manifold *M*, *not* on the strength of transition



- The first step entails the formation of a domain wall network

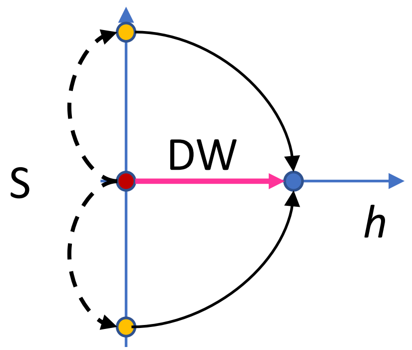


- Vacuum manifold is disconnected

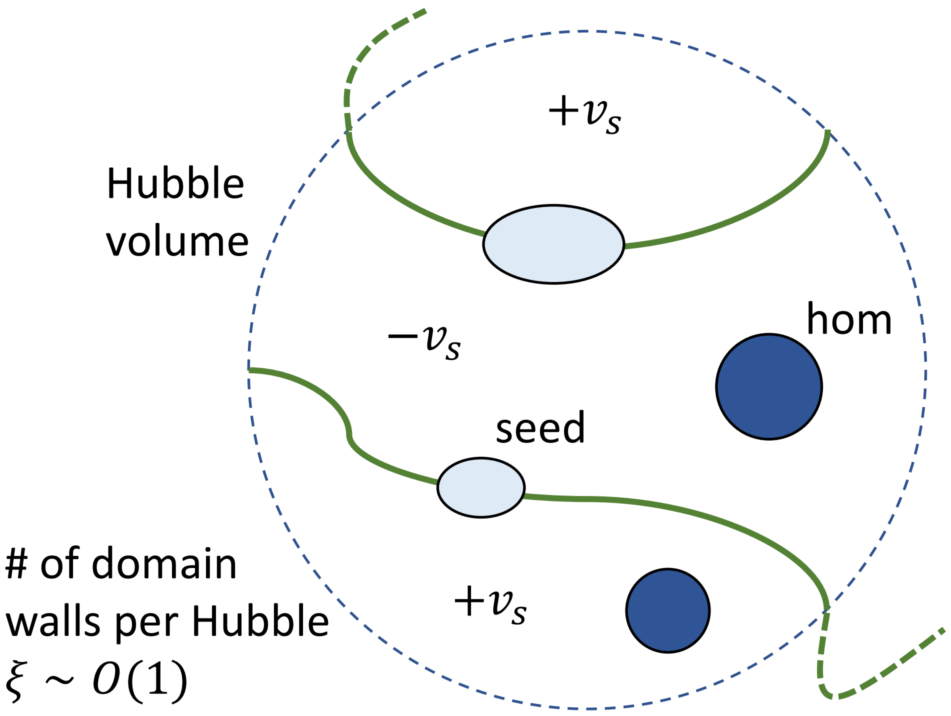
$$\pi_0(M) \neq I$$

Cosmic strings and other topological defects, Vilenkin and Shellard '94

Seeded vs homogeneous tunneling



- Nucleation prob. no longer the same everywhere, enhanced at DW location ($S = 0$)



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

Lazarides, Shafi, Kibble 1982, PRD

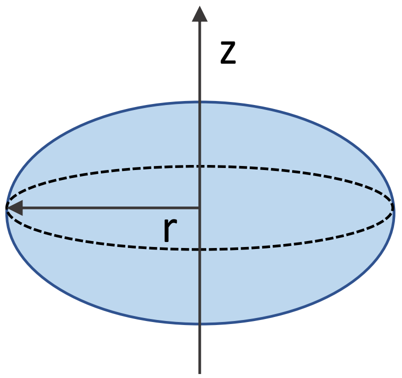
Perkins, Vilenkin 1992, PRD

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

- 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

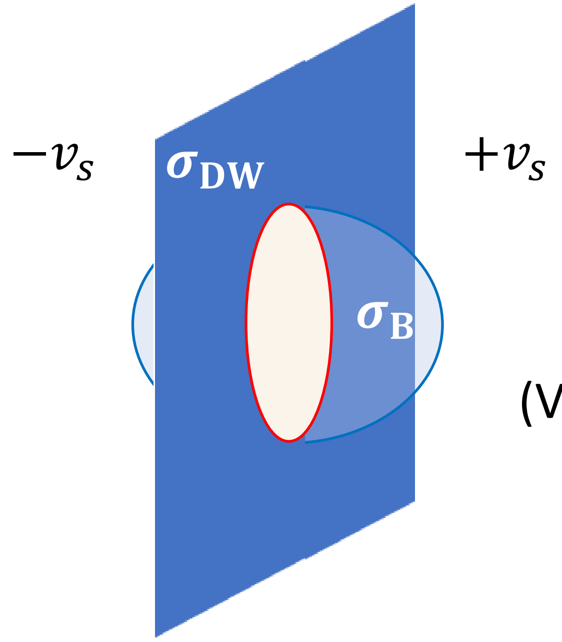


Seeded tunneling rate: thin wall limit

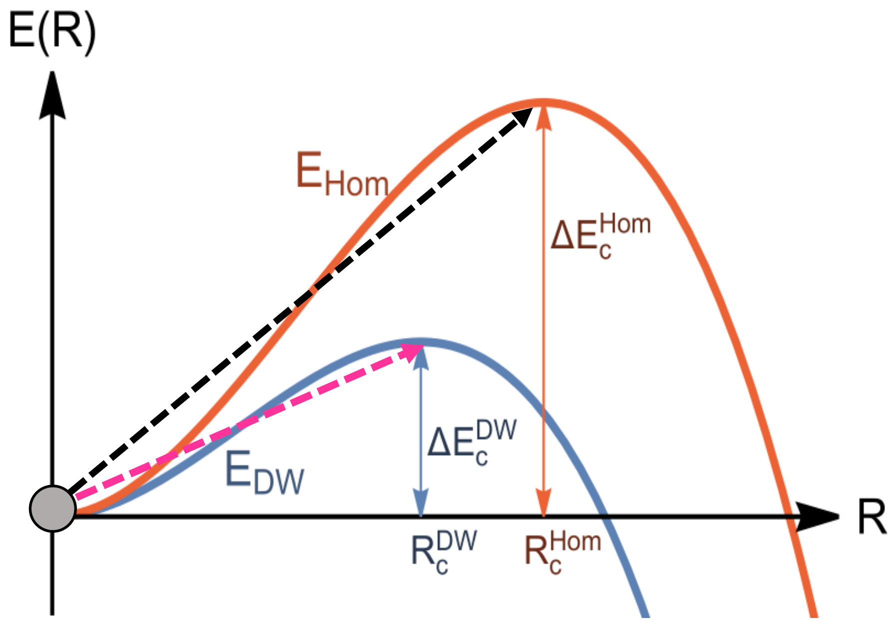
- Geometrical approach to estimate the energy of the critical bubble configuration

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

Gain by eating up domain wall surface



(Valid at $T \sim T_c$)



- Domain walls do catalyze the phase transition
  $S_2/T \sim \Delta E/T$

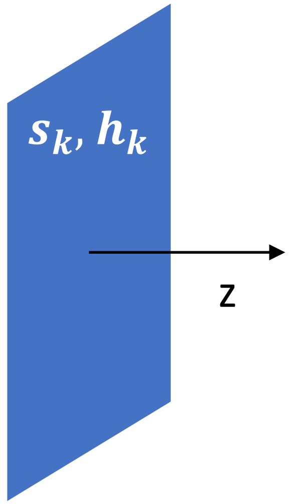
Seeded tunneling rate: Kaluza-Klein decomposition

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

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

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

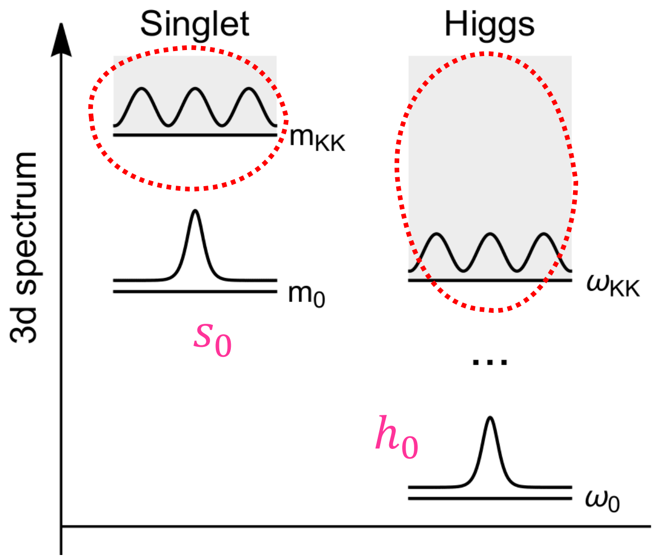
$$x_\mu = t, x, y$$



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

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

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



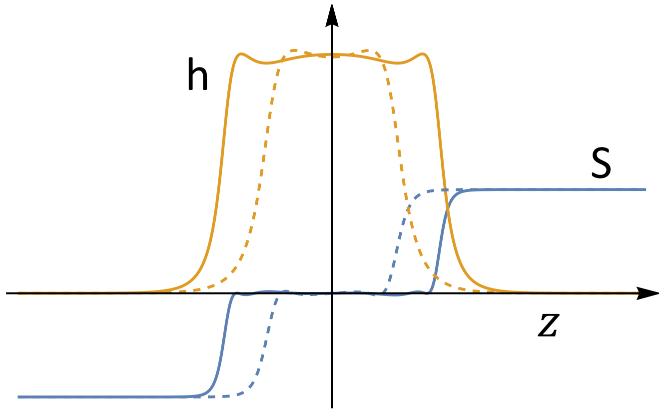
- Study the 3d theory on the DW plane, interaction from overlap integrals with $V(h, S)$

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

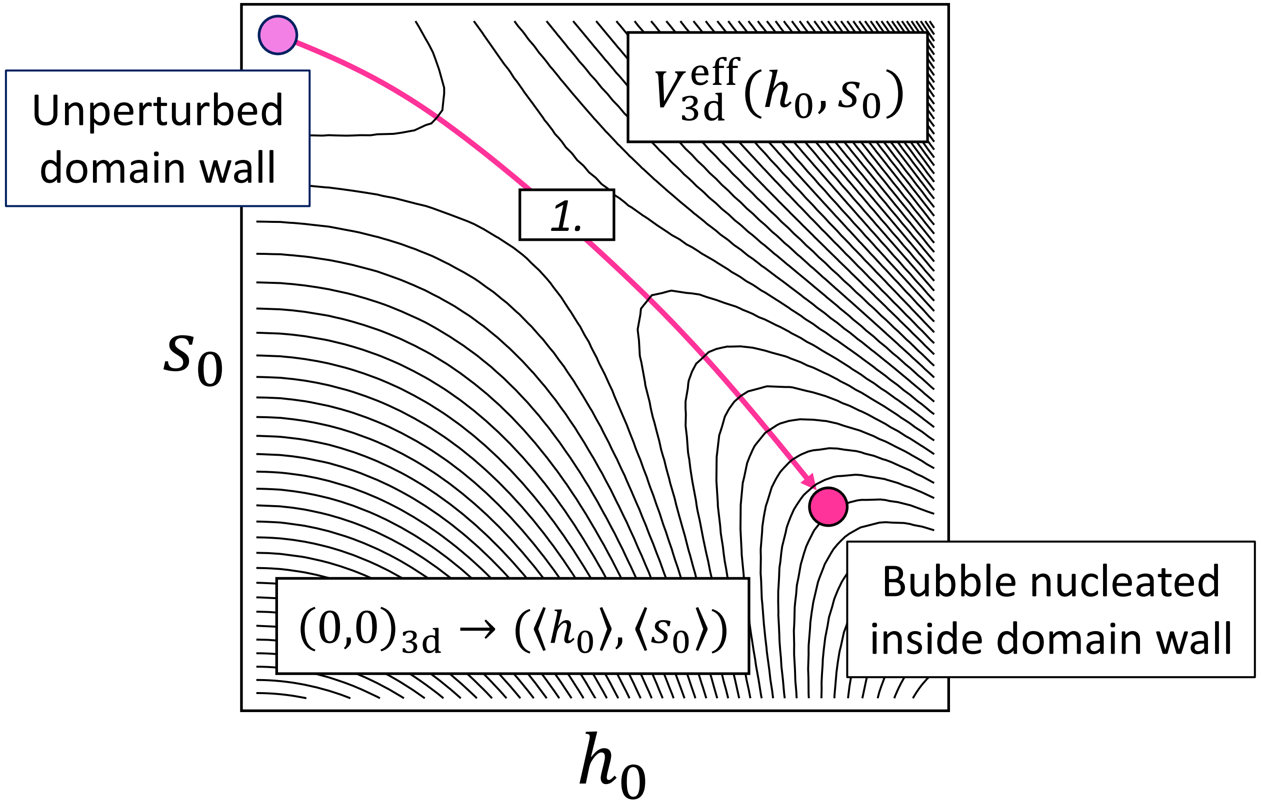
Seeded tunneling rate: Kaluza-Klein decomposition

- Metastability of DW (= barrier at the origin) controlled by the 3d h mass, ω_0^2:

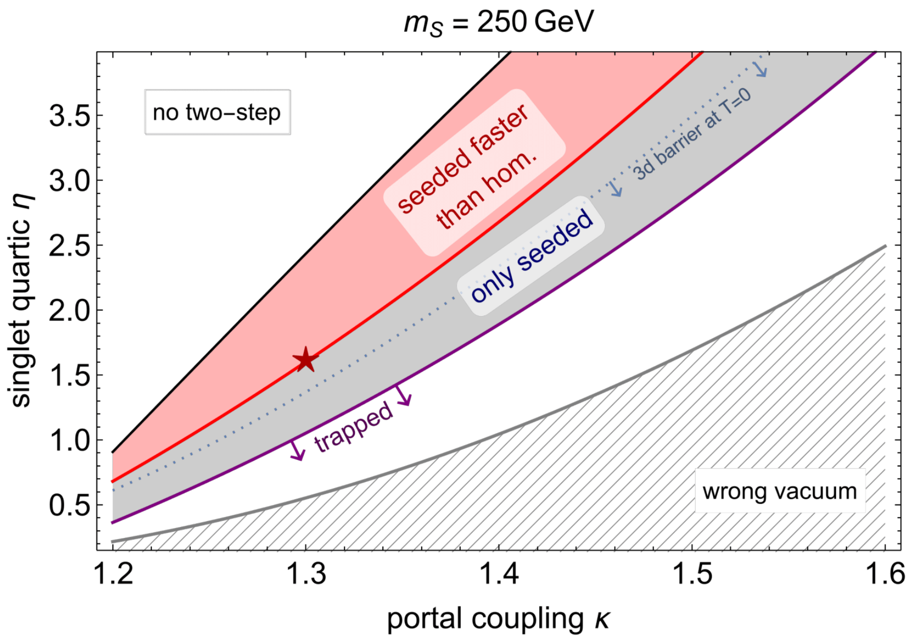
1. $\omega_0^2 > 0$ for $T < T_c$: seeded tunnelling (origin is a minimum)
2. $\omega_0^2 < 0$ for $T > T_c$: classical instability (origin is a saddle)

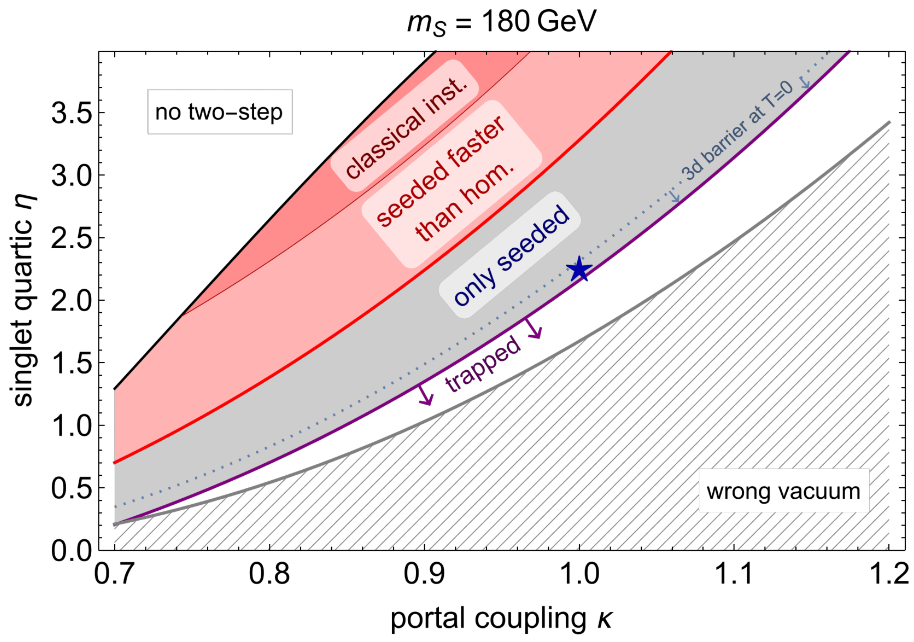


- Seeded tunneling as standard homogeneous problem in lower dimension, S_2/T from **CosmoTransition**

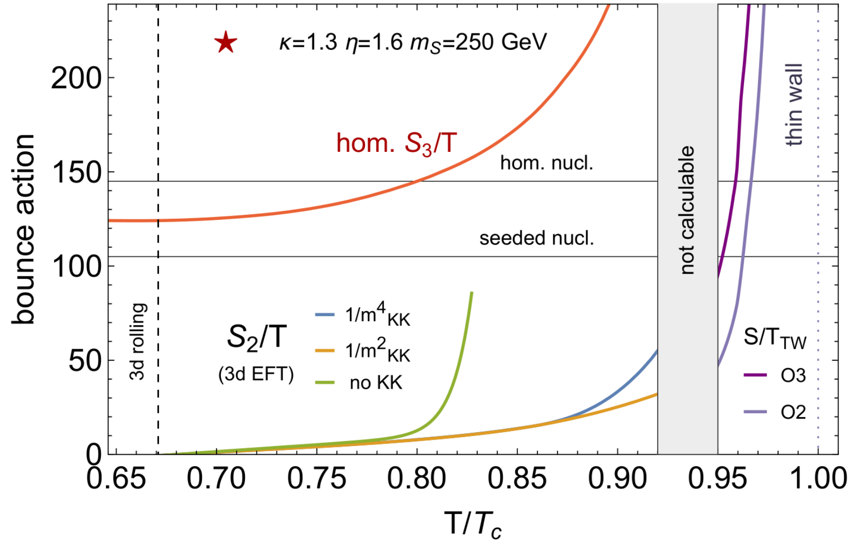


Results

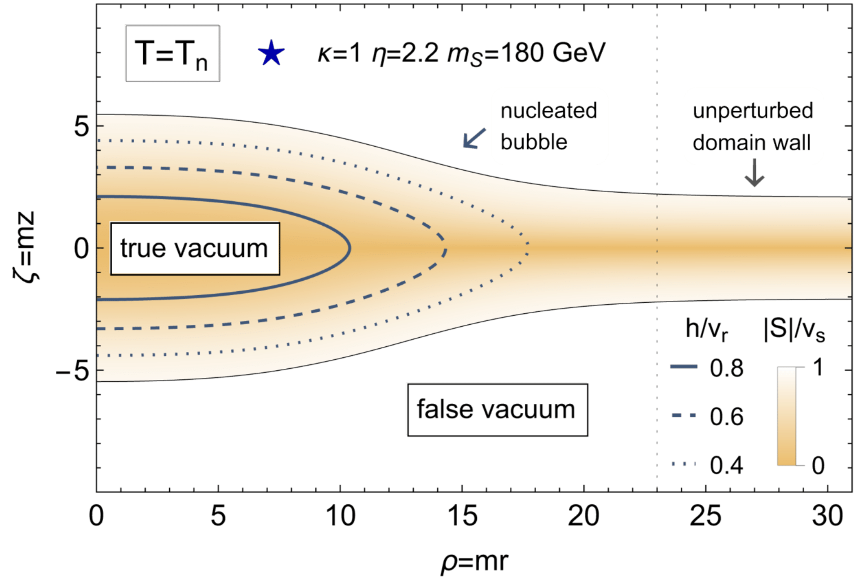




Nucleation rate: homogeneous vs seeded



Seeded critical bubble



Conclusion

- The xSM is a compelling model for new physics with interesting properties and challenges at colliders
- The electroweak phase transition in the xSM is typically first order and proceeds as a two-step process
- In the Z_2 limit, the first step entails the formation of domain walls: these act as local impurities which supersede the homogeneous nucleation
- The phenomenology of the seeded phase transition is a new target of study, e.g. for gravitational waves
- General ideas for multi-step phase transitions, possibly involving other types of defects