The role of impurities in first order phase transitions

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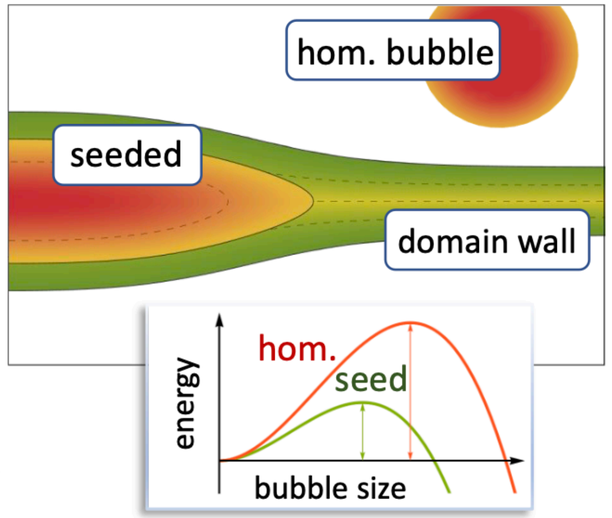
In collaboration with Alberto Mariotti arXiv:2203.16450 (to appear in PRL)



What the heck happens when the Universe boils? Kavli IPMU, 5-9 December 2022

The extended SM (xSM)

Collider probes

FCC Physics Opportunities EPJC (2019)

- Invisible Higgs decays: $m_h < 2m_S$
- Higgs-S mixing

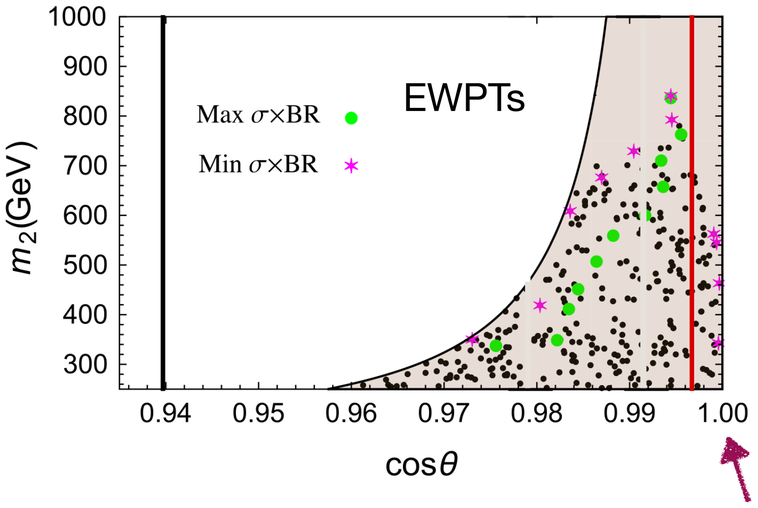


Fig. based on Kotwal, Ramsey-Musolf, No, Winslow [1605.06123] PRD

- Modifications of Higgs couplings

Z_2 limit

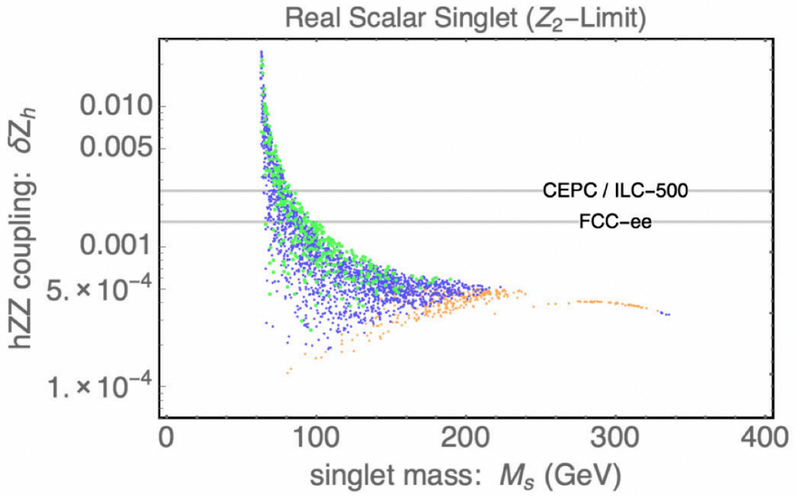


Fig. from Huang, Long, Wang [1608.06619] PRD

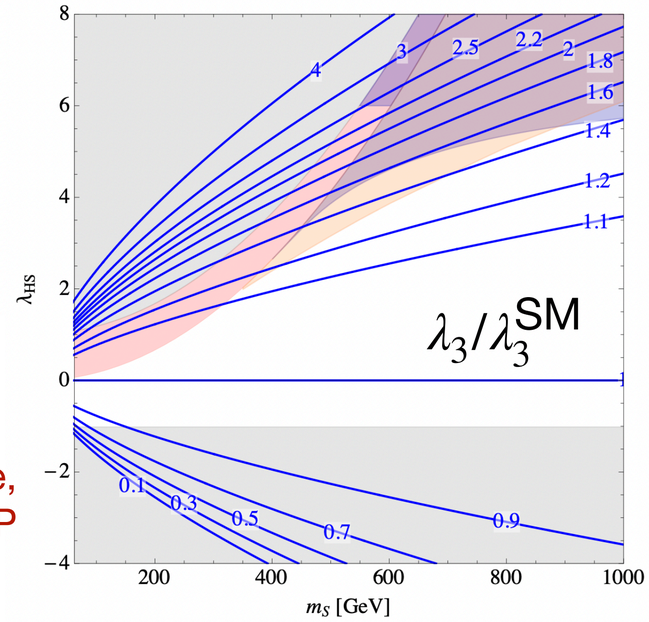


Fig. from from Curtin, Meade, Yu [1409.0005] JHEP

The extended SM (xSM)

Collider probes

FCC Physics Opportunities EPJC (2019)

- Resonant di-Higgs production

$$pp \to S \to hh$$

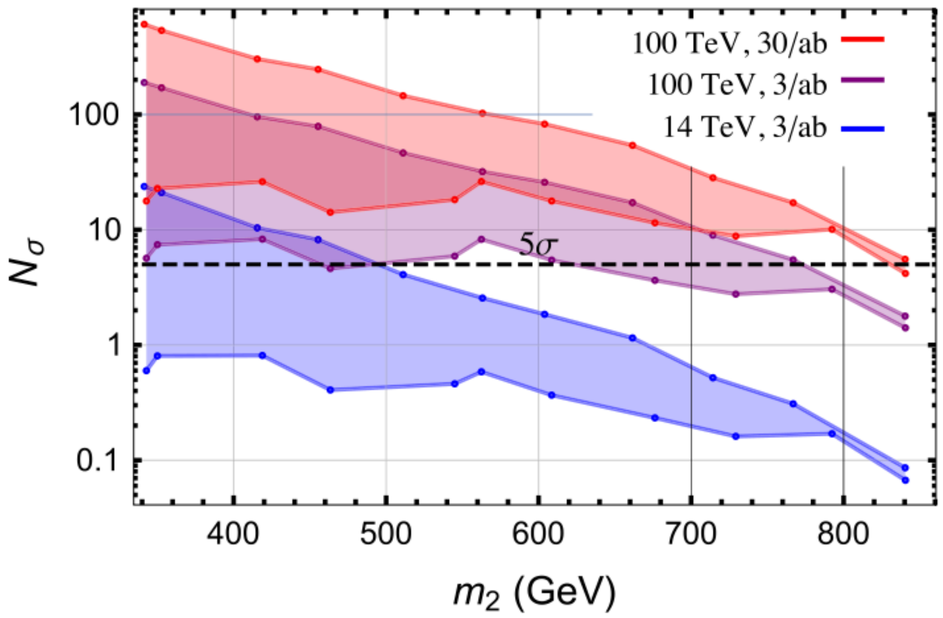


Fig. from Kotwal, Ramsey-Musolf, No, Winslow [1605.06123] PRD

- Non-resonant (invisible) pair production

$$pp \to SS\,jj$$

Z_2 limit

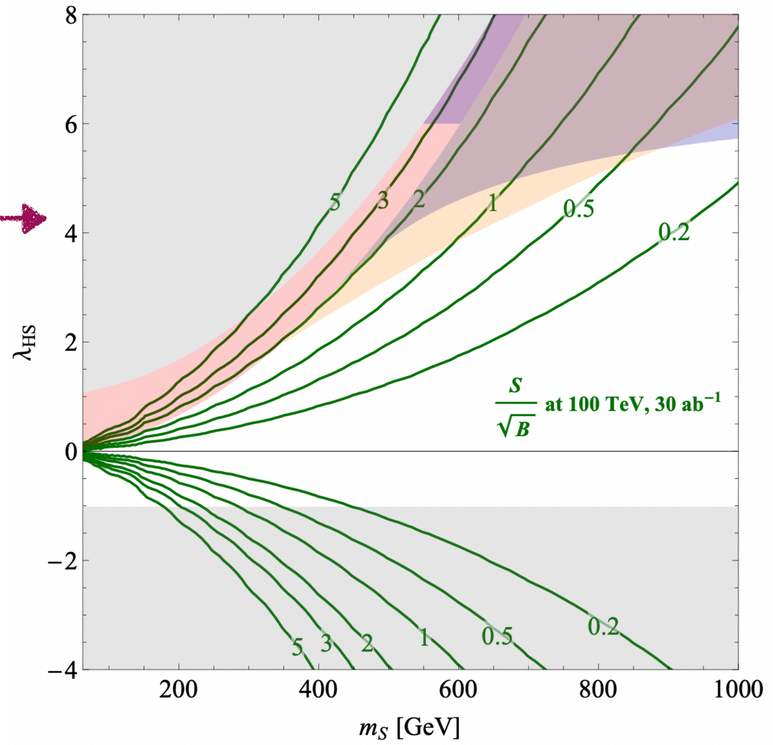
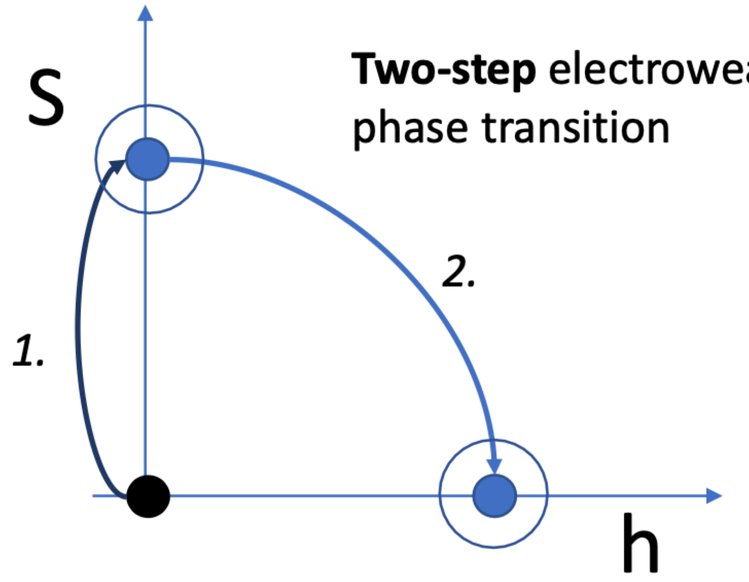


Fig. from Curtin, Meade, Yu [1409.0005] JHEP

The extended SM (xSM)

Electroweak phase transition



The EWPT (2.) is first order already in the leading high-T approximation

$$m_\phi^2 \to m_\phi^2 - cT^2$$

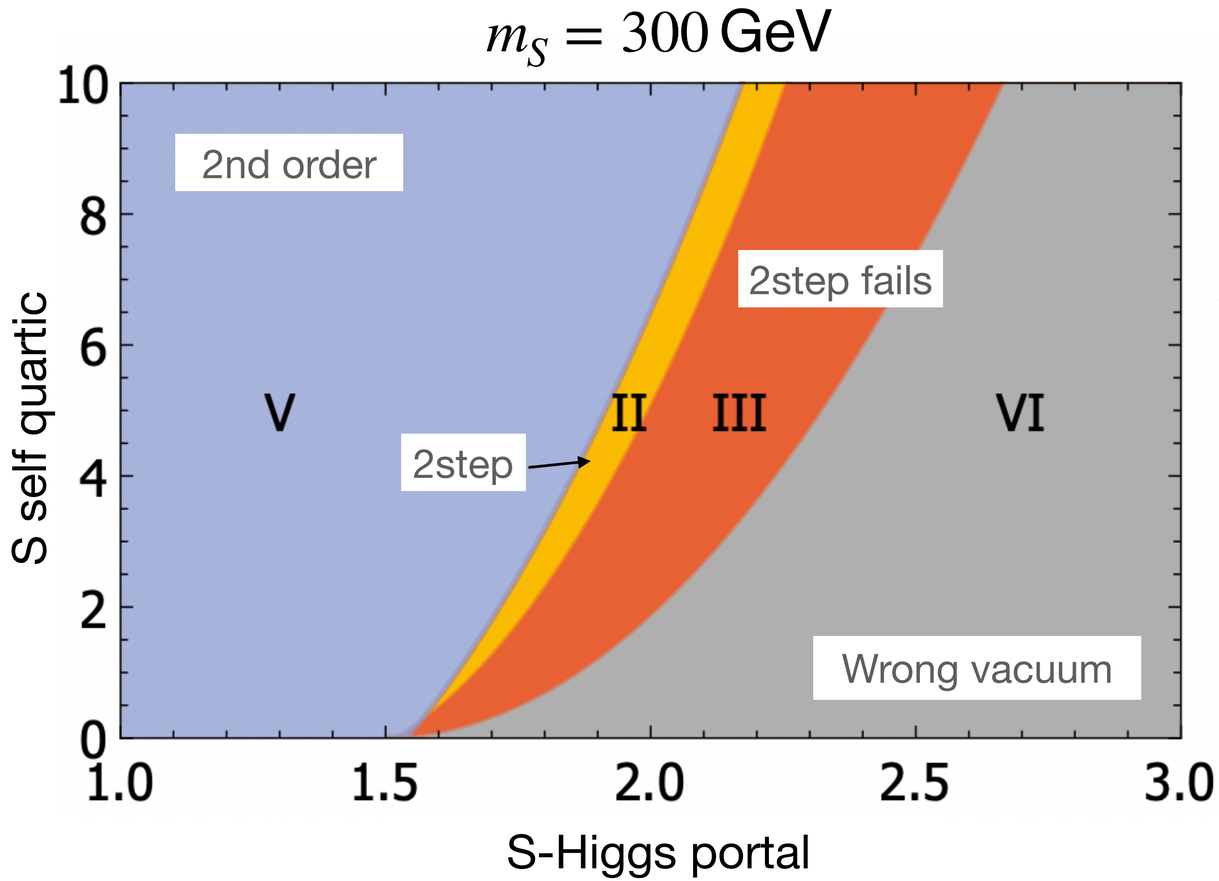


Fig. adapted from Kurup, Perelstein [1704.03381] PRD

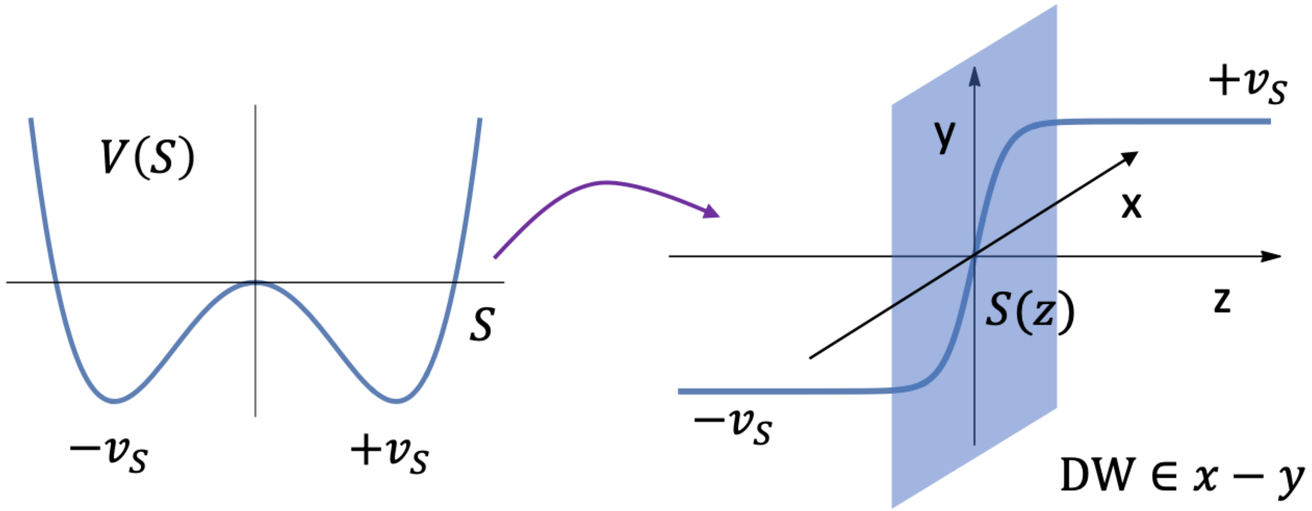
What about domain walls?

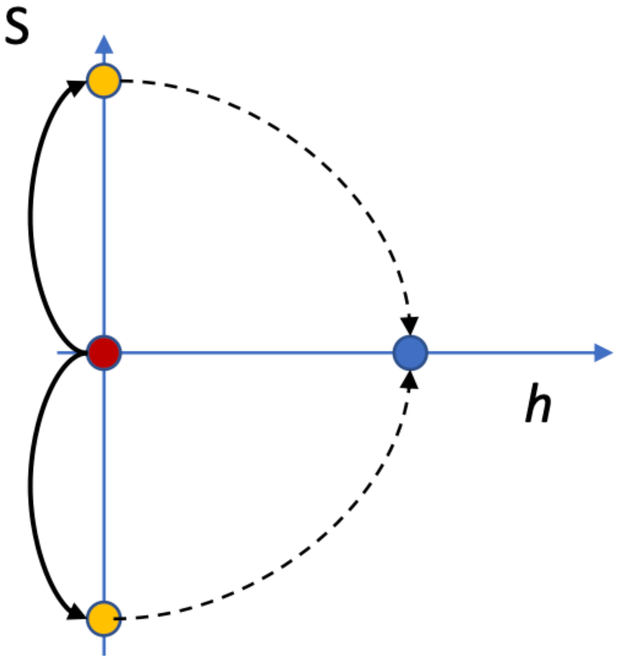
See e.g. Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

Vacuum manifold is disconnected after the first step: two vacua $\pm v_S$ related by $S \to -S$

Walls are formed at the boundaries between different domains, with tension $\sigma_{\mathrm{W}} \sim v_S^3$

After EWSB true vacuum has $\langle S \rangle = 0$, domain walls will eventually decay: no issue with cosmology





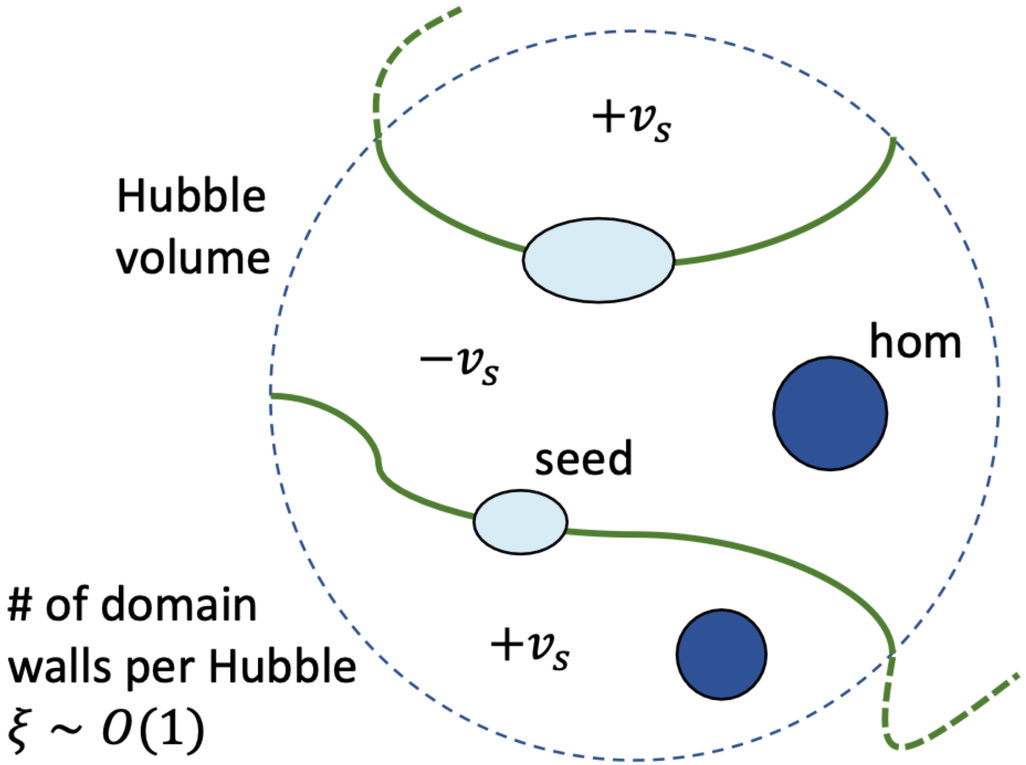
Transient defects

"Cosmic strings and other topological defects", Vilenkin and Shellard

Seeded vs homogeneous nucleation

SB, Mariotti [2203.16450]

Tunneling probability is no longer homogeneous, but it is enhanced in the vicinity of the defects.



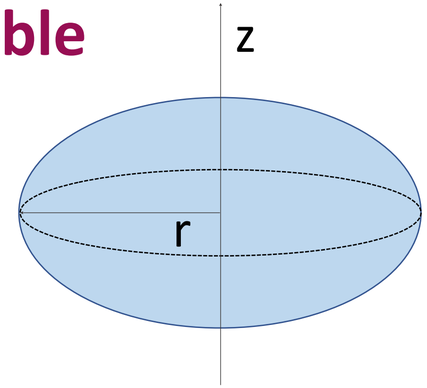
	Nucleation **probability**	Nucleation **condition**
x unit volume (standard)	$T^4 \exp(-S_3/T)$	$S_3/T = 145$
x unit surface (domain walls)	$T^3 \exp(-S_2/T)$	$S_2/T = 110$

O(2) symmetry

How to calculate the bounce action?

Critical bubble

$r \in$ DW plane



$h_c(r, z)$

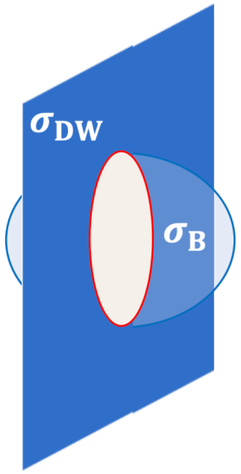
$S_c(r, z)$

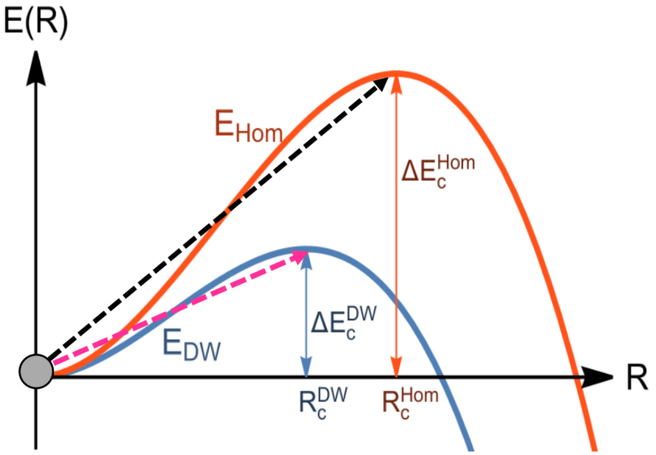
A. Coupled system of PDEs

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

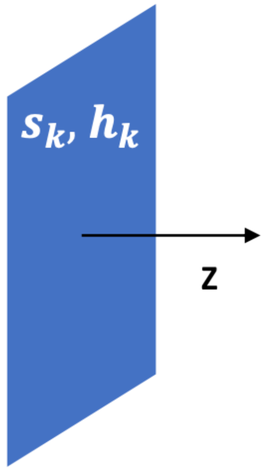
Domain wall profile as the “false vacuum”

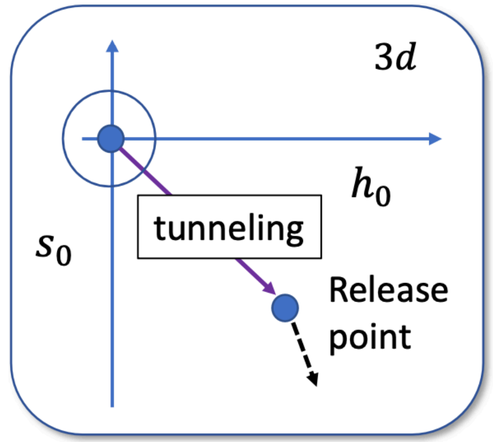
B. Thin wall approximation





C. Kaluza-Klein decomposition

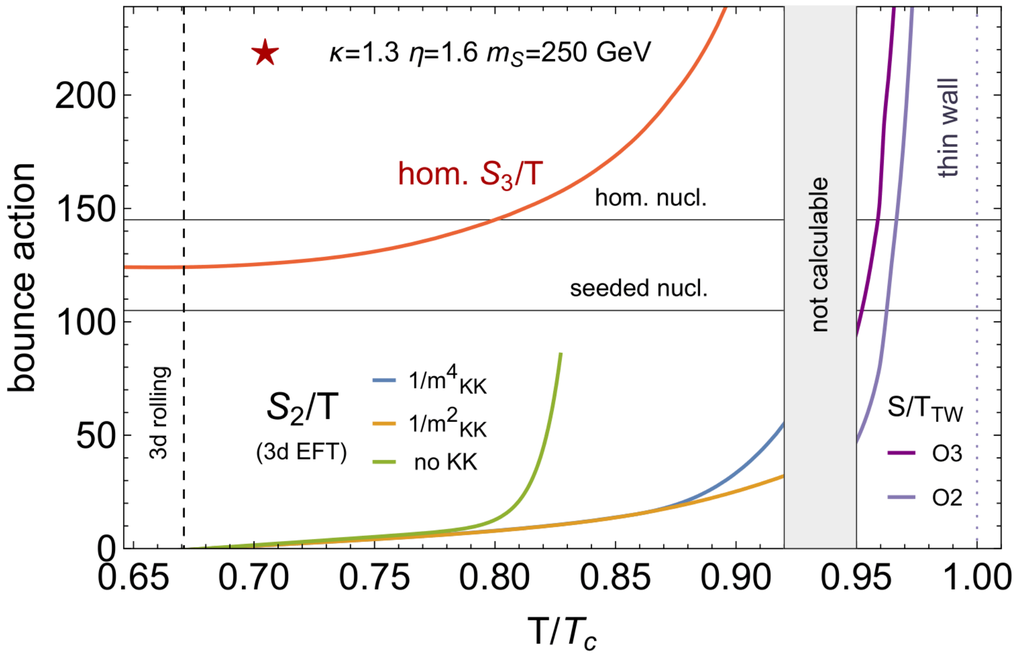




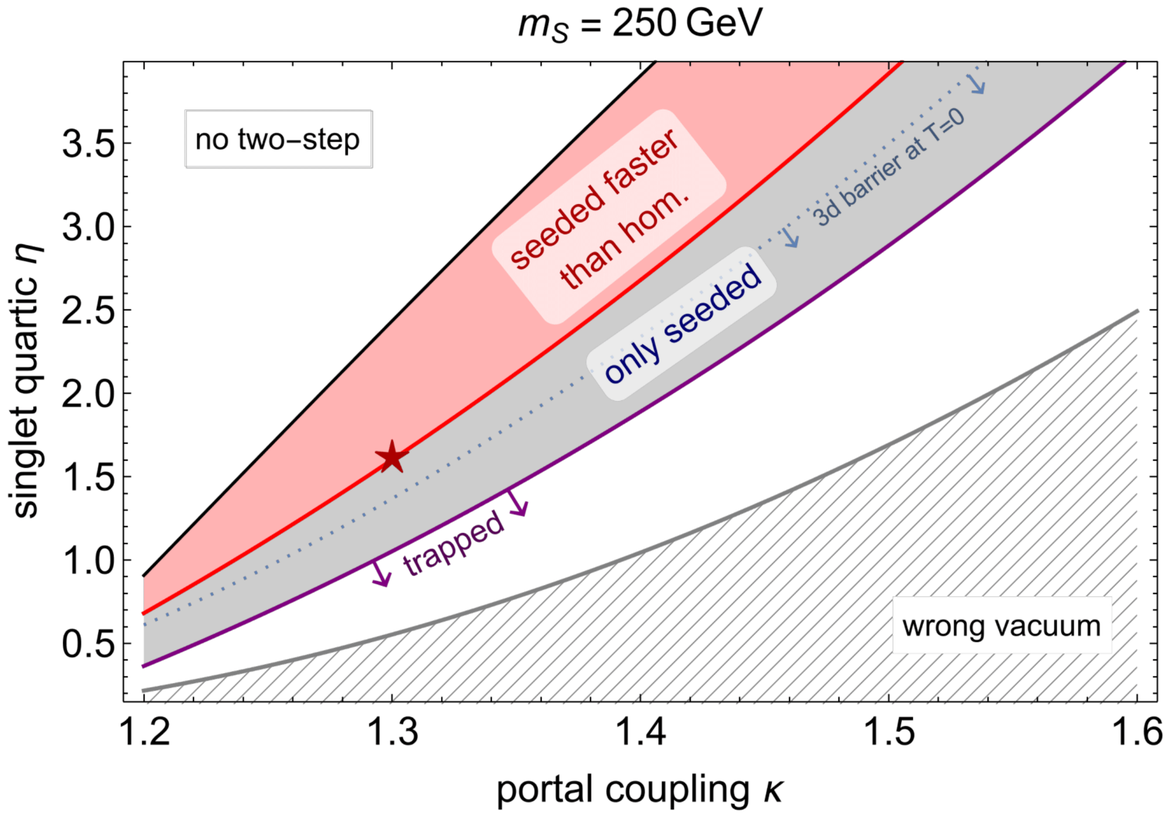
Impact

Seeded transition **faster** than homogeneous in all the two-step parameter space!

New viable regions of parameter space thanks to the seeded nucleation



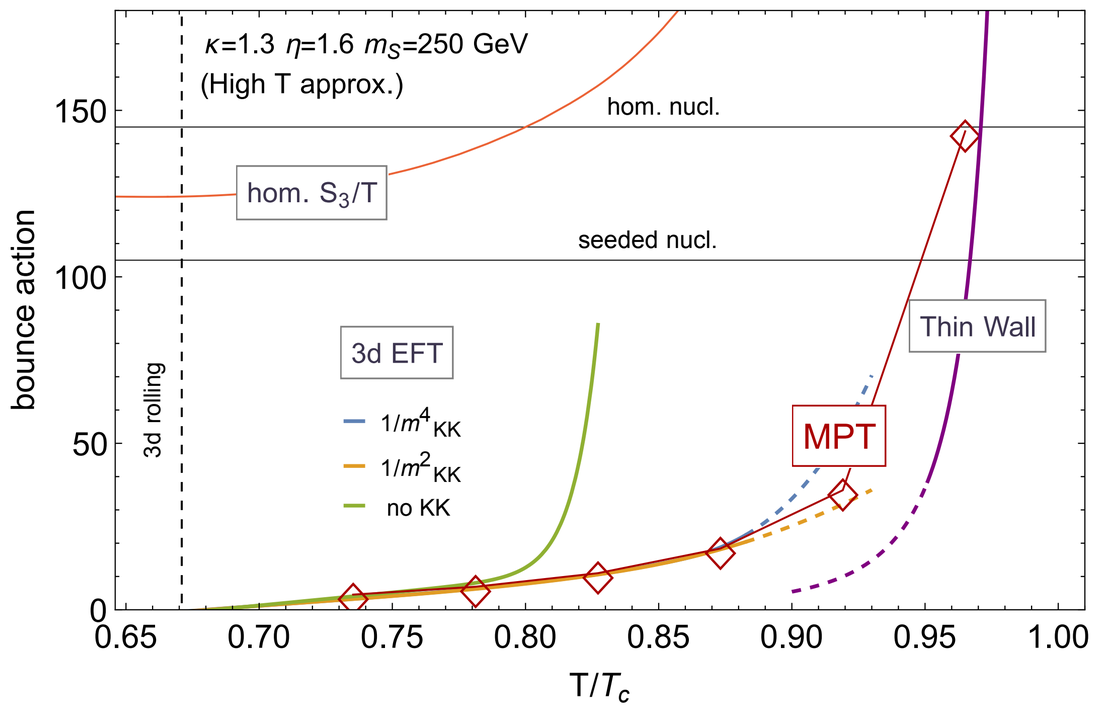
high-T approximation



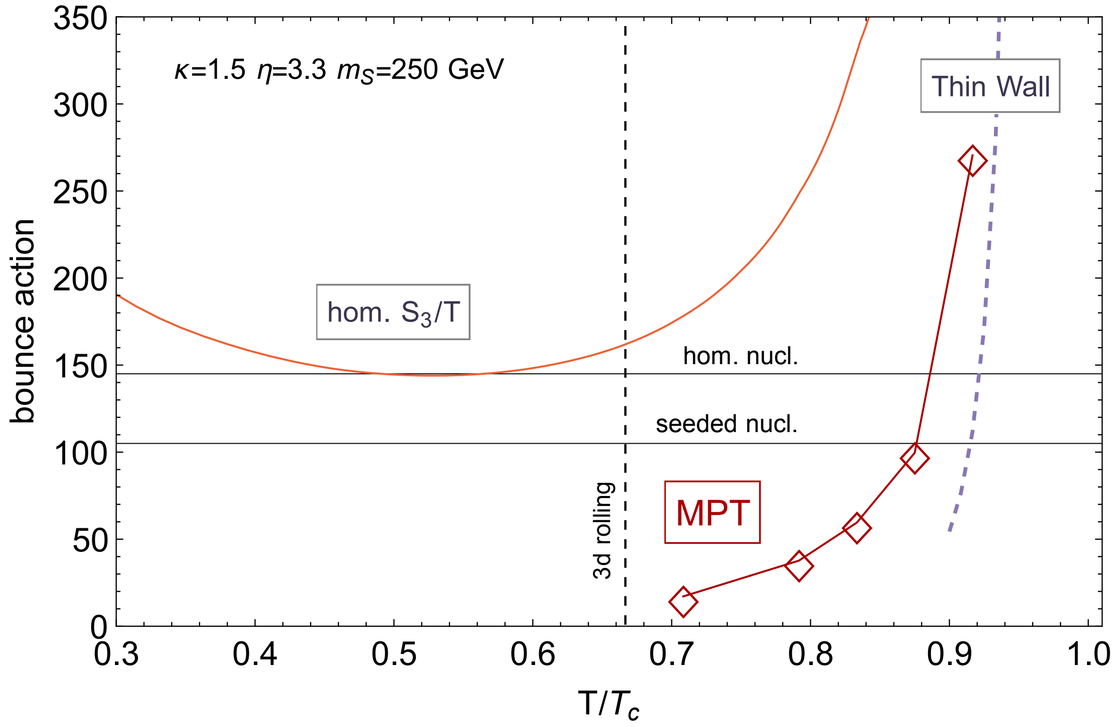
Ongoing projects

Agrawal, SB, Mariotti, Nee, in prep.

Cross check of EFT and TW (high T) with PDE solution (MPT)



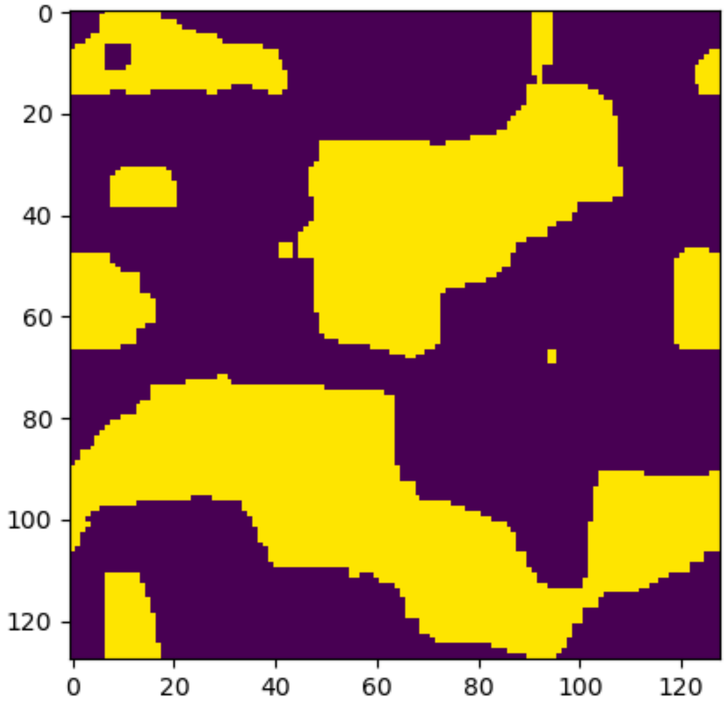
PDE solution (MPT) with truncated full dressing



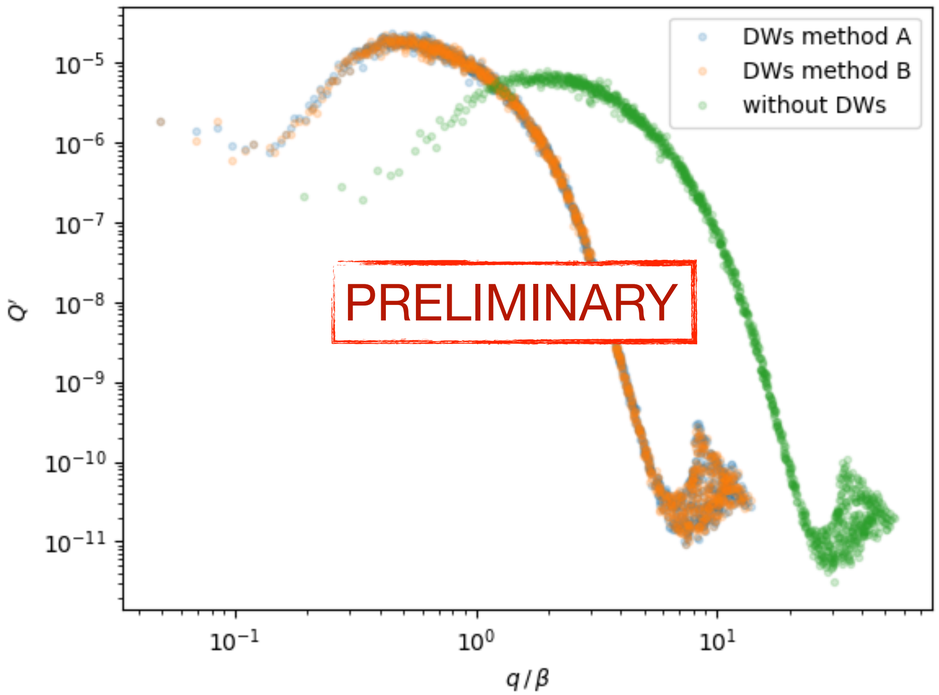
Ongoing projects

SB, Jinno, Konstandin, Rubira, Stomberg, in prep.

Simple Ising modeling of domain walls



GWs from sound waves:



Summary

Seeded nucleation is found to be always faster than homogeneous nucleation, and therefore it determines the phenomenology of the phase transition.

Pheno implications still largely unexplored in terms of GWs and baryogenesis!

Z_2 breaking terms make domain walls unstable: depending on their size, the PT can be either seeded or homogeneous. Both options should be taken into account when addressing e.g. collider pheno (as seeded PT makes new parameter space available)

Generalization to multi step PTs entailing e.g. the breakdown of global or gauge symmetries. When no bias term is allowed (either for pheno constraints or consistency) seeded transition likely to be the only outcome.