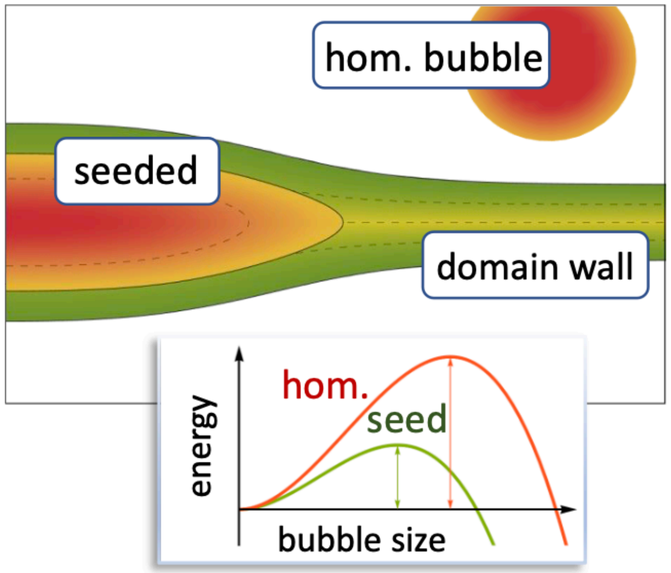
Exploring the electroweak phase transition at FCC

Simone Blasi

Vrije Universiteit Brussel (VUB)

In collaboration with Alberto Mariotti arXiv:2203.16450 [hep-ph]



FCC BSM Physics Programme Workshop, CERN 15-16 September 2022

Introduction

The EWPT beyond the SM

The EWPT is not first order in the SM according to lattice, but it could.

BSM physics can dramatically change this conclusion due to new particles at the electroweak scale: testable at colliders.

Connection with the mechanism underlying EWSB, baryogenesis, …

Exciting prospects for a detectable gravitational wave signal at LISA.

See talk by M. Ramsey-Musolf!

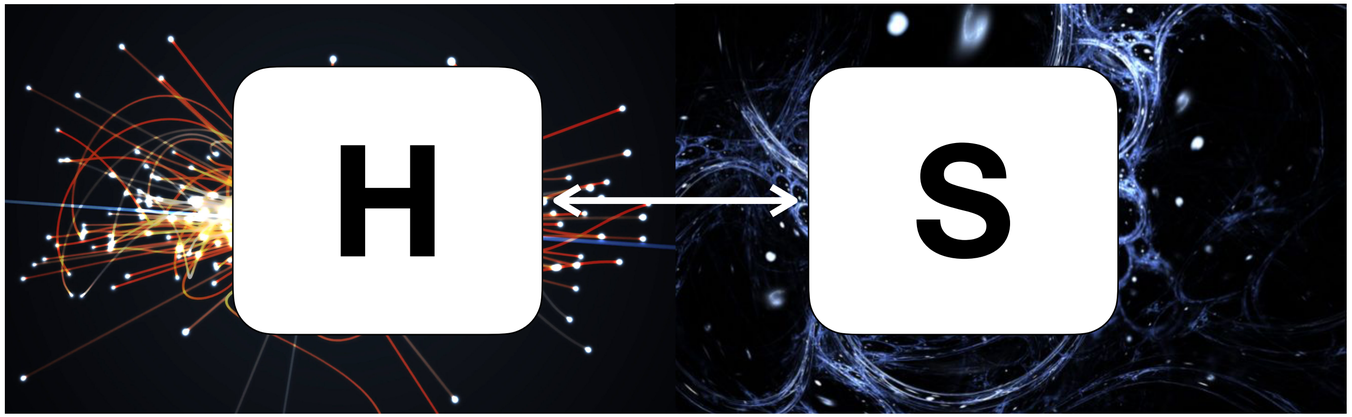
Introduction

The EWPT beyond the SM

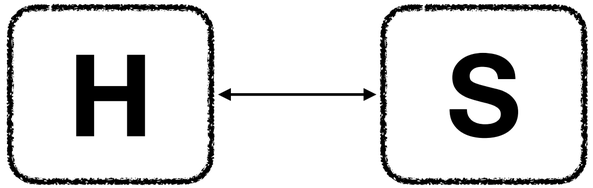
Benchmark models are useful to quantitatively explore the interplay between colliders and cosmological probes (GWs).

Requirements: pass present constraints and trigger strong first order EWPT.

A possibility: Higgs portal to a dark sector:



The extended SM (xSM)



Minimal renormalizable extension of the SM with real scalar singlet

$$V \supset -\frac{1}{2}m^2 S^2 + \eta S^4 + \kappa |H|^2 S^2 + \cancel{\text{odd terms}} \text{ in S}$$

Loryon!
see T. Cohen's talk

…not the ultimate BSM theory but:

- pheno controlled by portal coupling/singlet mass: minimal and predictive
- mixing angle with the Higgs naturally small or vanishing: hard to test at collider, nightmare scenario

Curtin, Meade, Yu [1409.0005] JHEP

- the EWPT is strongly first order at "tree level"

Espinosa, Konstandin, Riva [1107.5441] NPB

The extended SM (xSM)

Collider probes

FCC Physics Opportunities EPJC (2019)

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

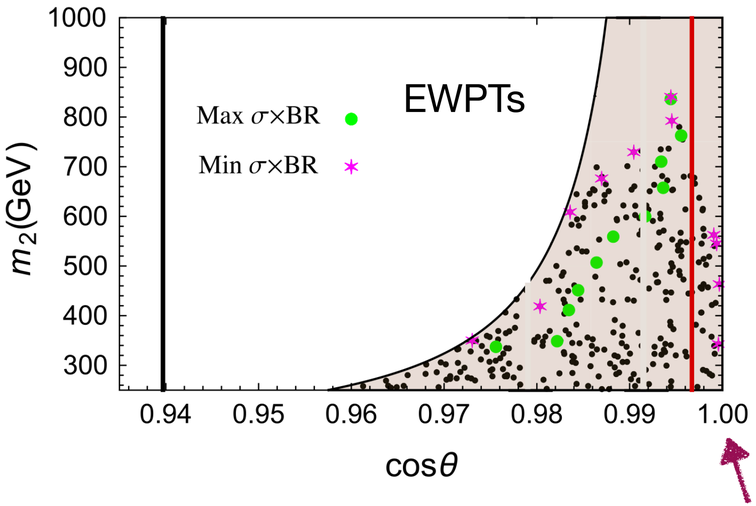


Fig. based on Kotwal, Ramsey-Musolf, No, Winslow [1605.06123] PRD

- Modifications of Higgs couplings

Z_2 limit

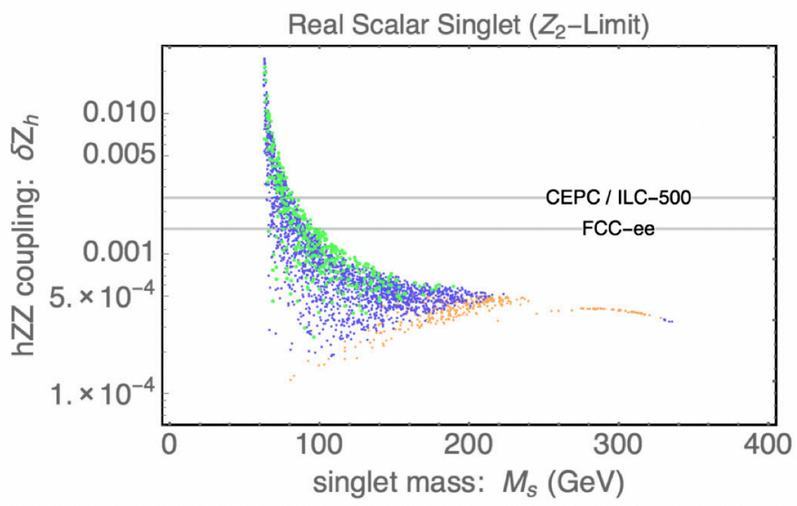


Fig. from Huang, Long, Wang [1608.06619] PRD

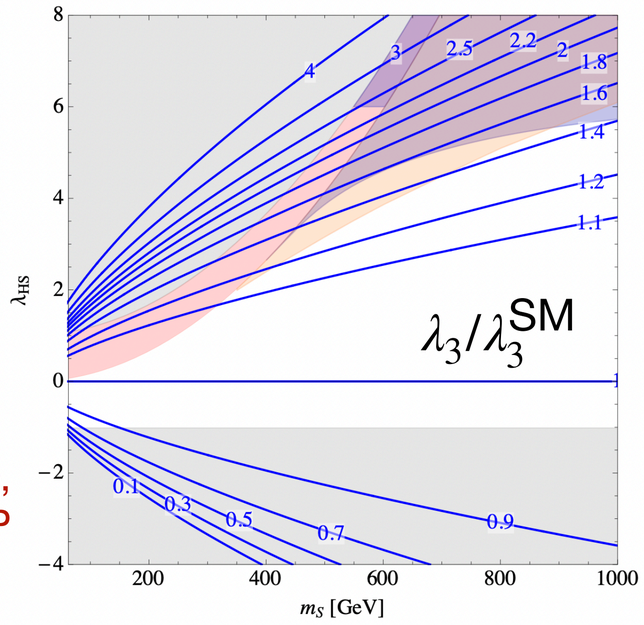


Fig. from from Curtin, Meade, Yu [1409.0005] JHEP

The extended SM (xSM)

Collider probes

FCC Physics Opportunities EPJC (2019)

- Resonant di-Higgs production

$$pp \to S \to hh$$

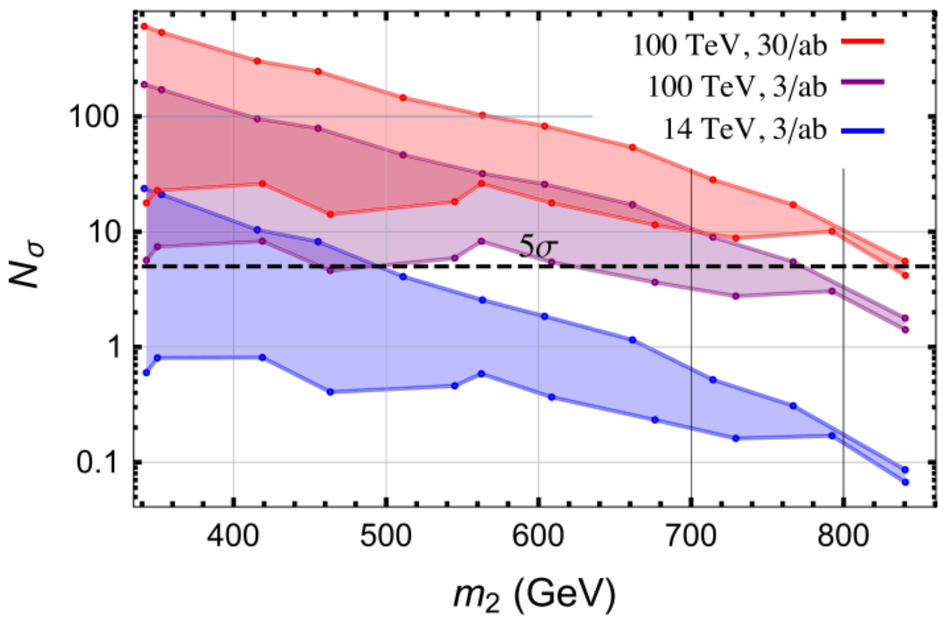


Fig. from Kotwal, Ramsey-Musolf, No, Winslow [1605.06123] PRD

- Non-resonant (invisible) pair production

$$pp \to SSjj$$

Z_2 limit

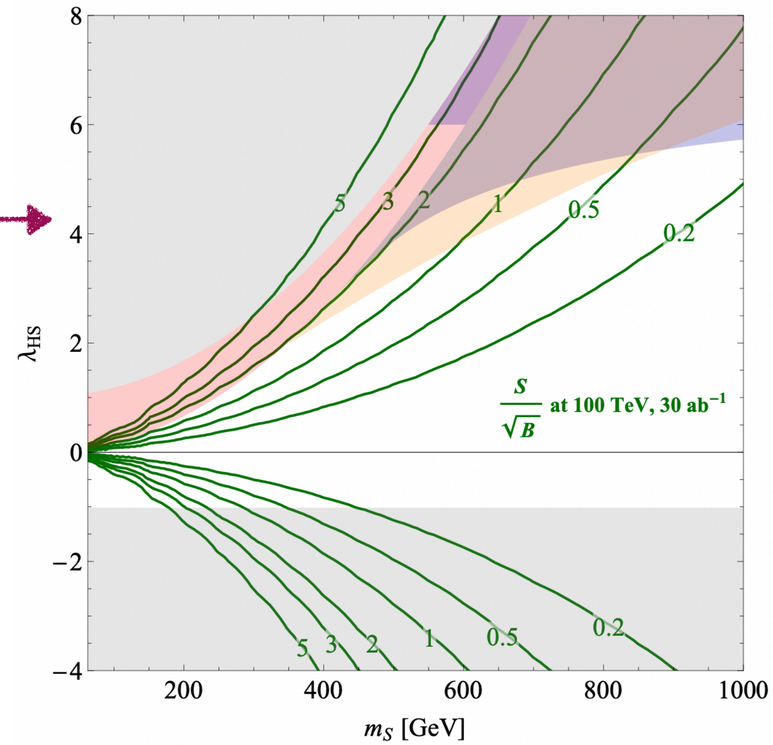
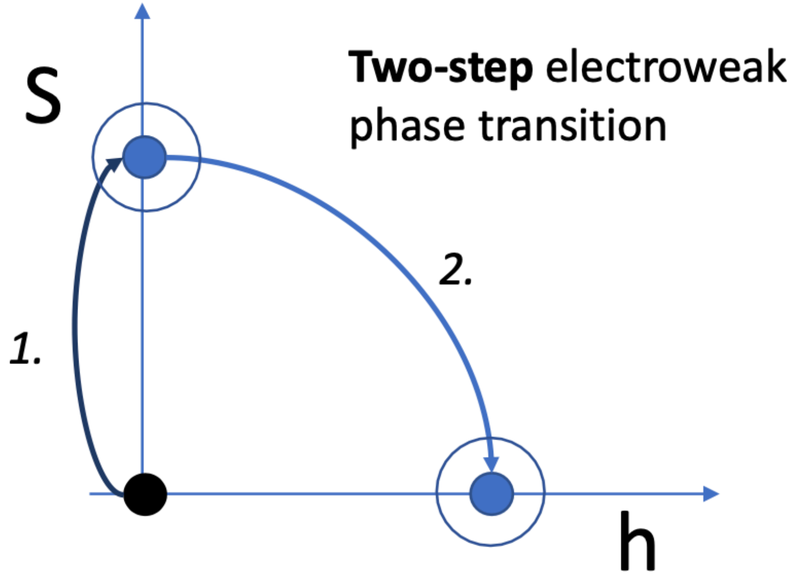


Fig. from Curtin, Meade, Yu [1409.0005] JHEP

The extended SM (xSM)

Electroweak phase transition



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

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

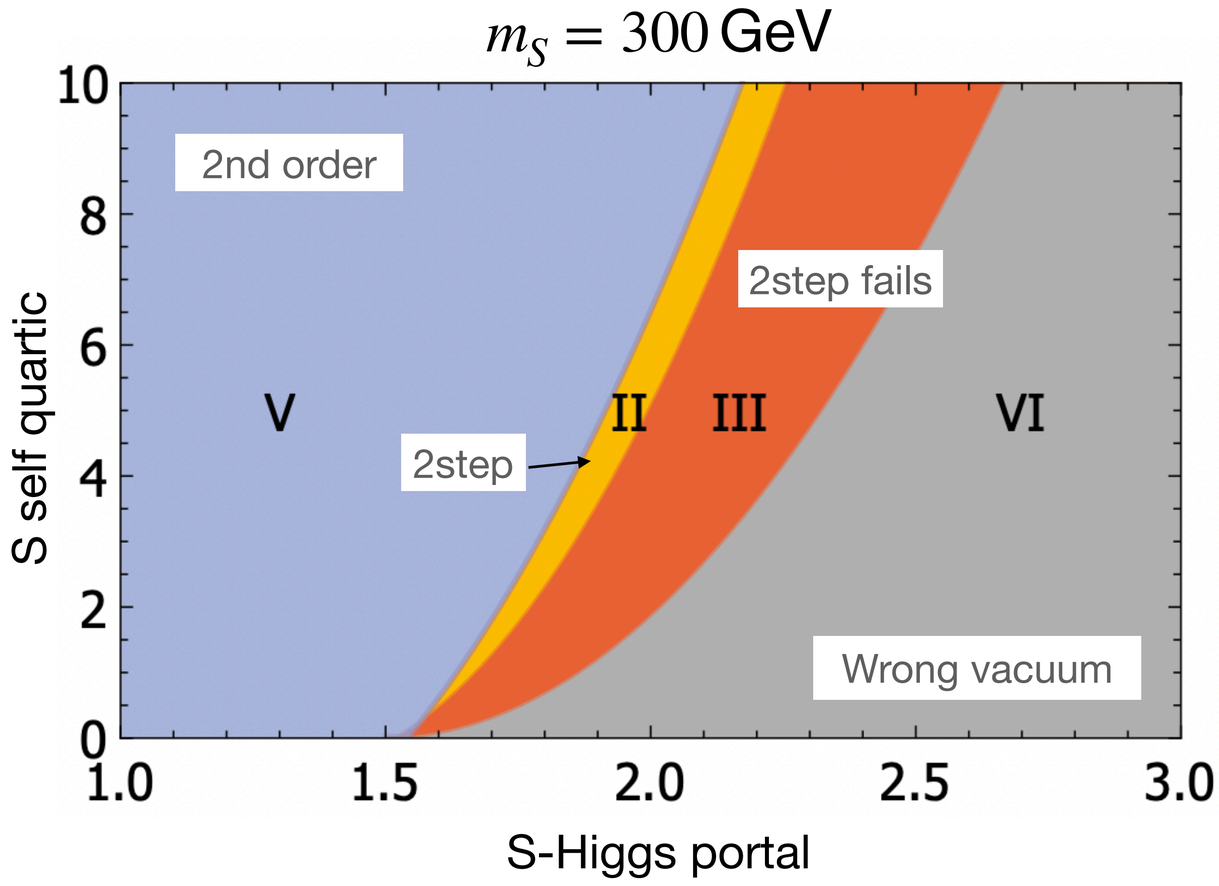


Fig. adapted from Kurup, Perelstein [1704.03381] PRD

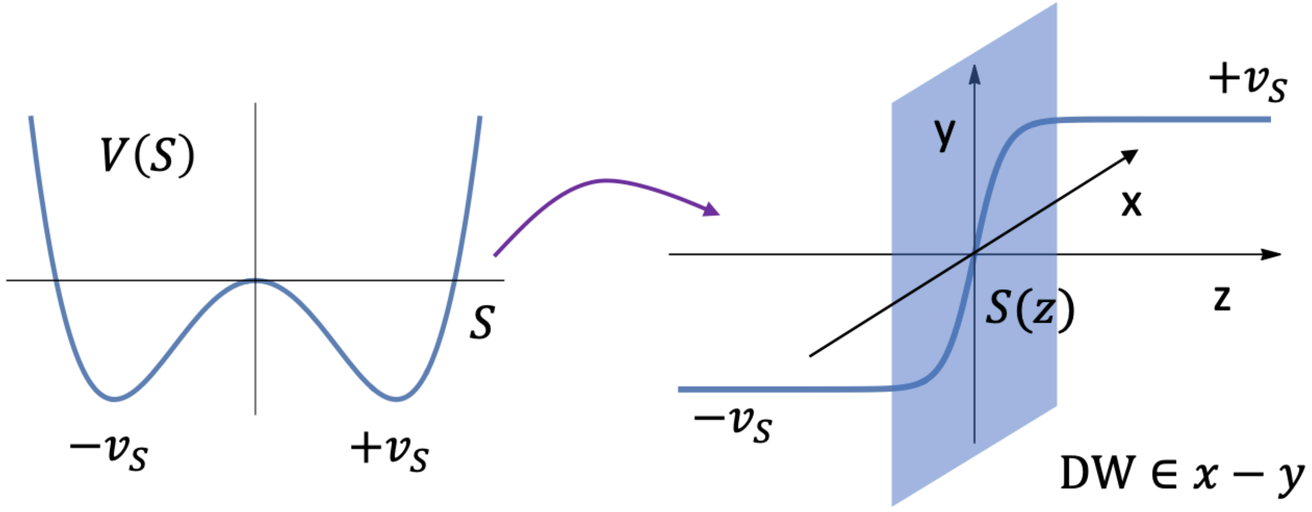
What about domain walls?

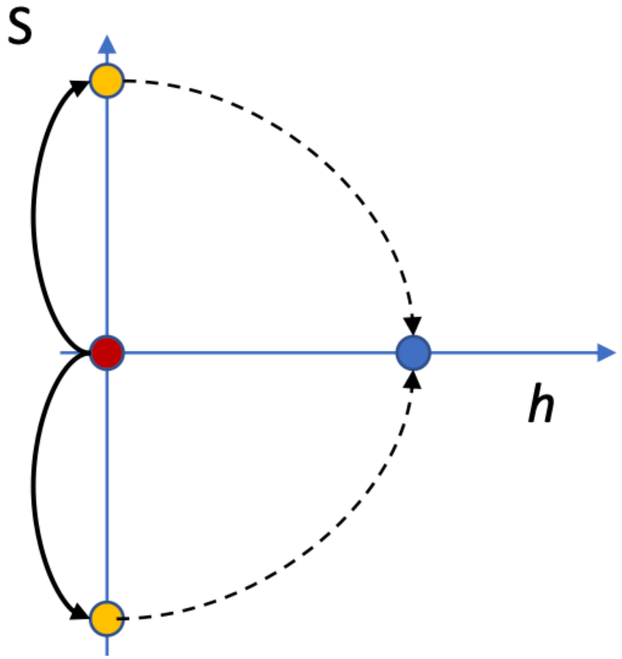
See e.g. Espinosa, Gripaios, Konstandin, Riva [1110.2876] JCAP

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





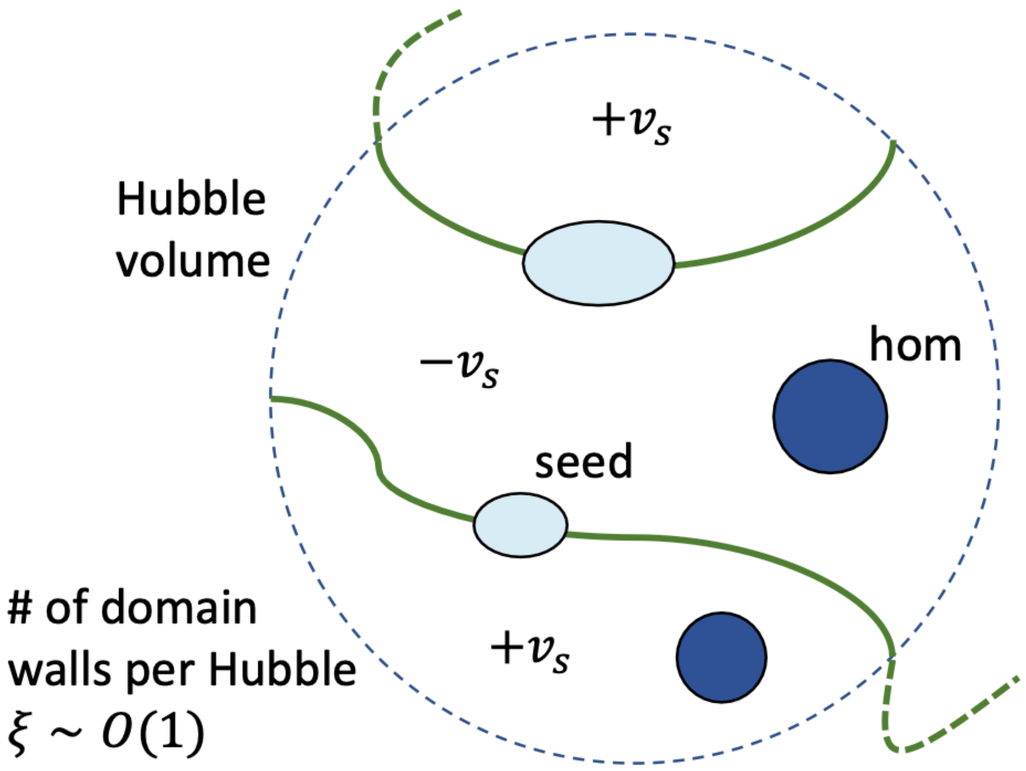
Transient defects

"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.



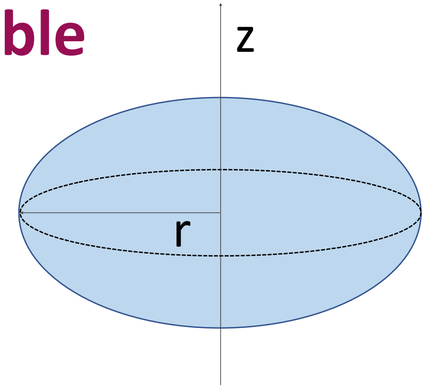
	Nucleation **probability**	Nucleation **condition**
x unit volume (standard)	$T^4 \exp(-S_3/T)$	$S_3/T = 145$
x unit surface (domain walls)	$T^3 \exp(-S_2/T)$	$S_2/T = 110$

O(2) symmetry

How to calculate the bounce action?

Critical bubble

$r \in$ DW plane



$h_c(r, z)$

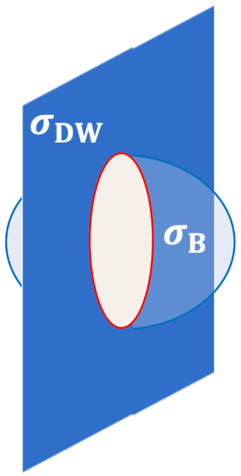
$S_c(r, z)$

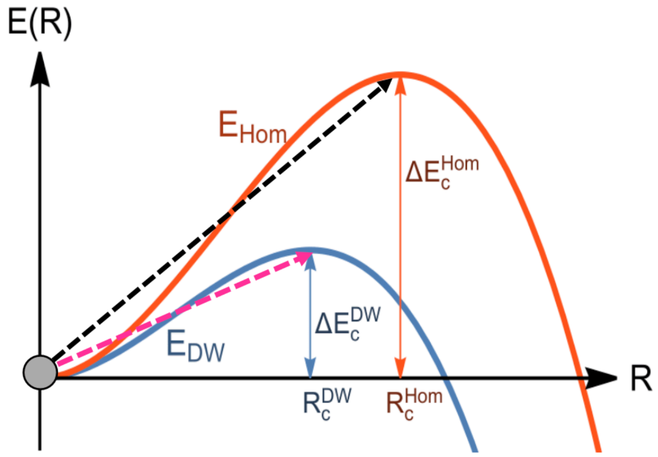
A. Coupled system of PDEs

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

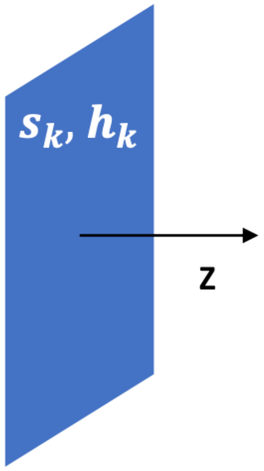
Domain wall profile as the “false vacuum”

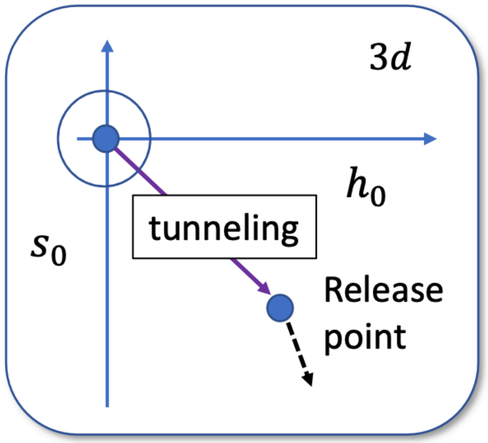
B. Thin wall approximation





C. Kaluza-Klein decomposition



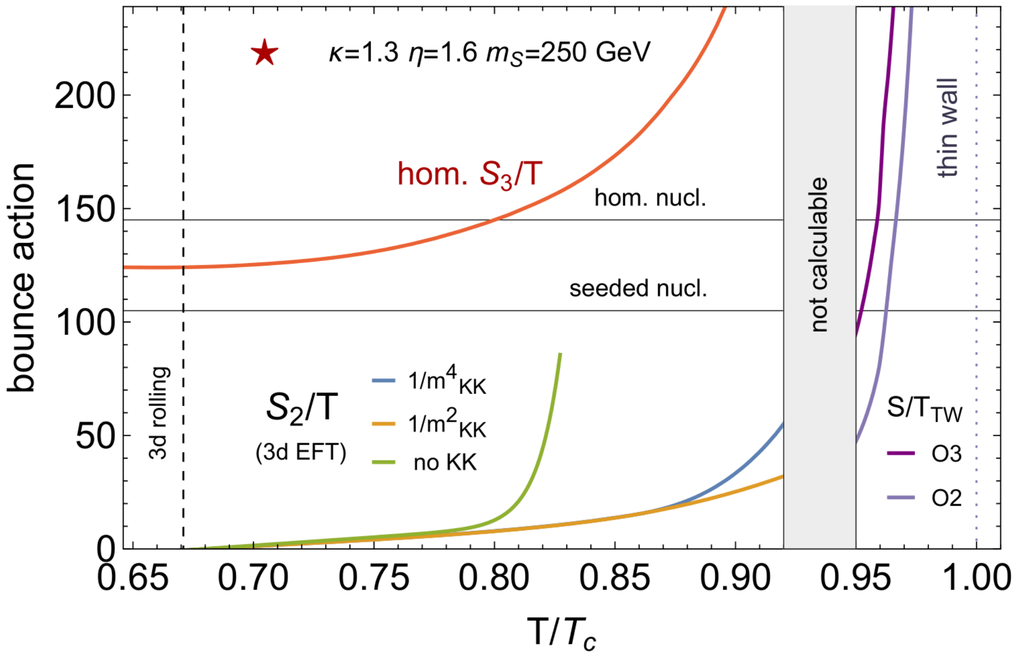


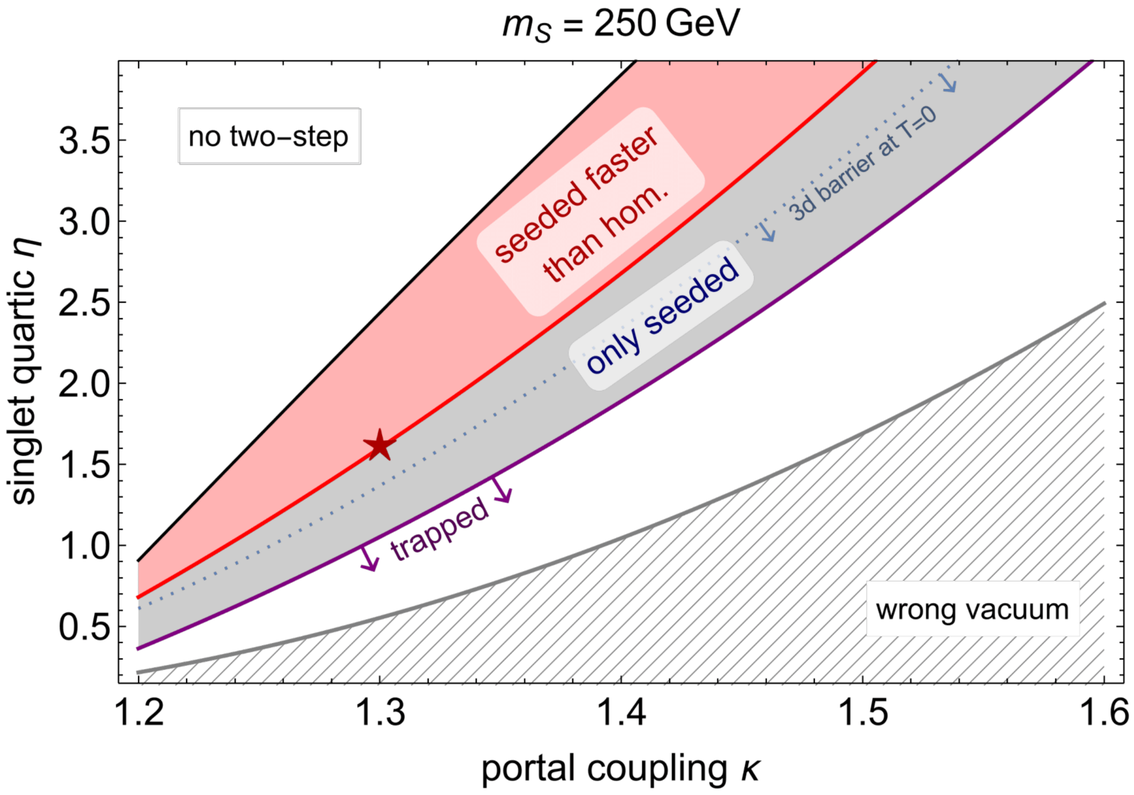
Impact

high-T approximation

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

New viable regions of parameter space thanks to the seeded nucleation





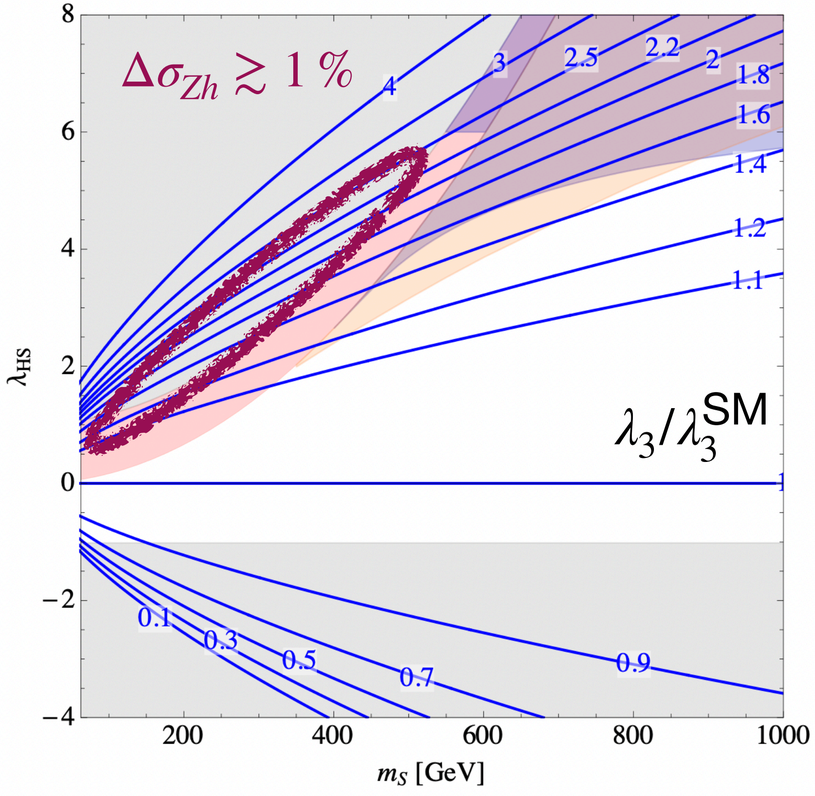
Caveat: Z_2 explicit breaking can make DWs collapse before they can trigger the EWPT (but difficult to quantify)

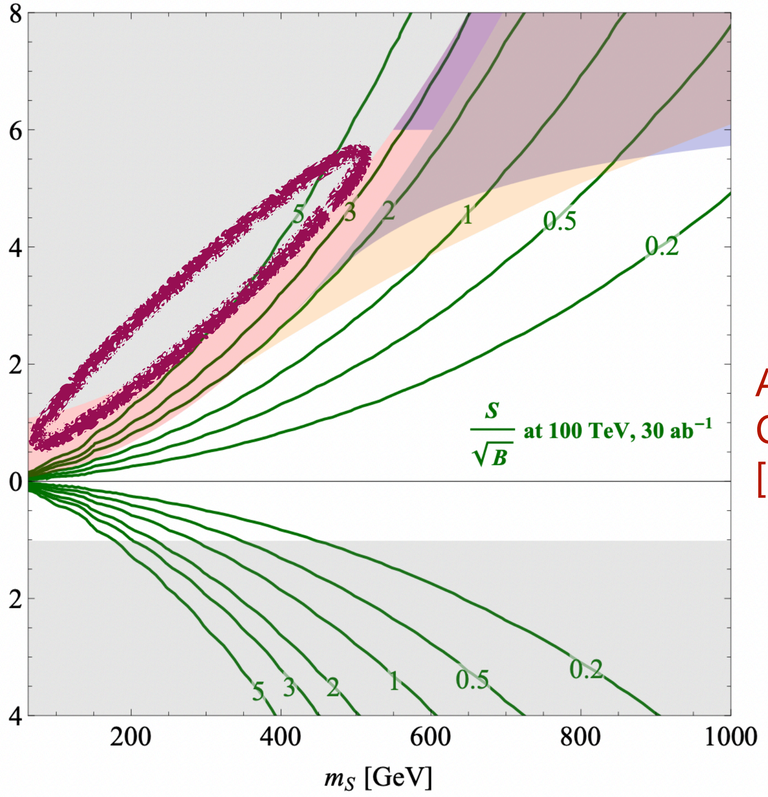
Implications of a seeded EWPT

Collider signatures

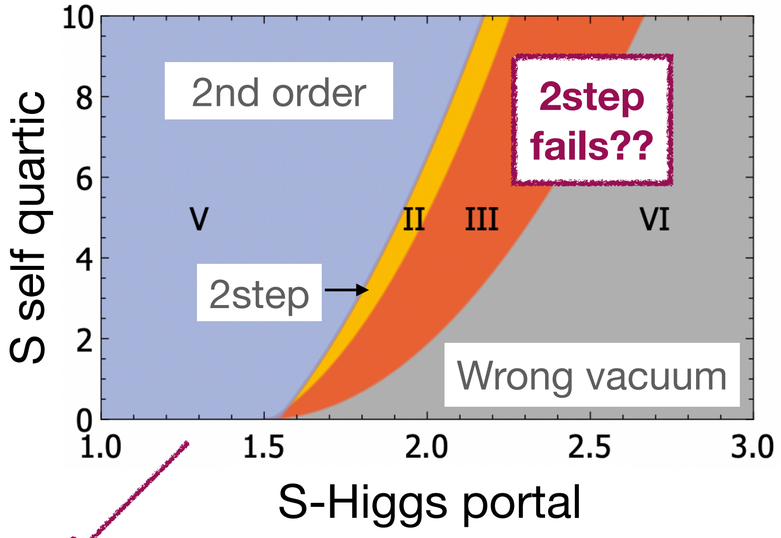
Adapted from Kurup, Perelstein [1704.03381] PRD

For a certain singlet mass, a **larger portal** is allowed as 2step may actually give successful nucleation: **stronger signals** are possible





$m_S = 300$ GeV



Adapted from from Curtin, Meade, Yu [1409.0005] JHEP

On the other hand, **evidence** for h-S **mixing disfavors** a seeded transition (e.g. S decaying visibly)

Implications of a seeded EWPT

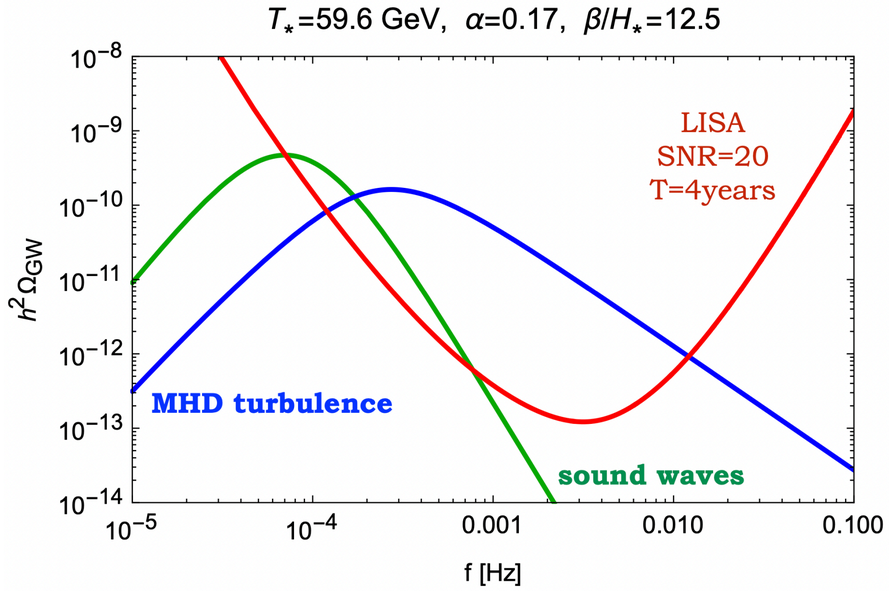
Gravitational waves

BP C: $m_S = 250\,\text{GeV} \quad \kappa = 1.5, \quad \eta = 3.3$

From [1512.06239] (LISA)

Approximate Z_2

Homogeneous phase transition



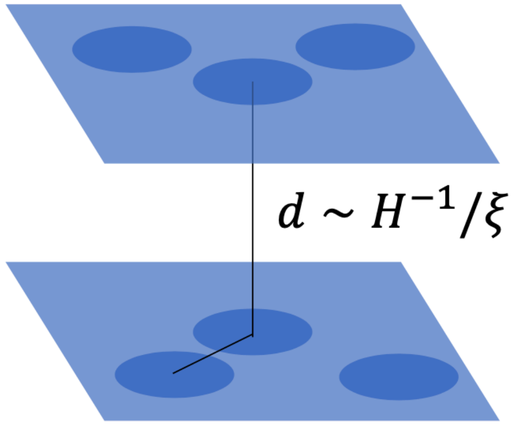
Credit: C. Caprini's talk

Good Z_2 → **Seeded phase transition**

Checked that it is **faster also with full-fledged thermal corrections** by numerically solving PDEs

with P. Agrawal and M. Nee,

(see also Agrawal, Nee [2202.11102] SciPost)



Gravitational wave spectrum is **unknown**.

# of domain walls ξ per Hubble patch as β_{eff}??

Summary

FCC has the capability to probe new physics connected to a first order electroweak phase transition also within the “nightmare” xSM scenario with no scalar mixing.

The region in the parameter space which would lead to the strongest signals (for a given value of S quartic coupling and mass) is however not viable as bubbles fail to nucleate.

However, the formation of defects during a multi—step electroweak phase transition (also beyond the xSM!) can make these regions viable thanks to a “seeded tunneling”.

By combining results from HL-LHC and FCC-ee(hh) we could find evidence for an impurity—driven phase transition in cosmology, or exclude it. (TO DO)

In addition, gravitational wave detection at LISA could directly probe the nature of the transition: homogeneous vs seeded. (TO DO)