

QCD axion strings or seeds?

Simone Blasi DESY Hamburg

Crossroads between Theory and Phenomenology - CERN - 13.06.2024

SB, Mariotti [2203.16450], PRL

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

Agrawal, **SB**, Mariotti, Nee [2312.06749], JHEP

SB, Mariotti, [2405.08060]

Based on:

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See also Buen-Abad, Chang, Hook [2305.09712], PRD
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walls in inverse phase transitions. In inverse phase transitions, we have

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The hydrodynamics of inverse phase transitions 2406.01596

Giulio Barni^{*1,2}, Simone Blasi,^{†3,4} and Miguel Vanvlasselaer^{‡4}

Introduction

Higgs mechanism + Hot Big Bang = Cosmological phase transitions

Key to address SM open questions: e.g. matter/antimatter asymmetry, dark matter…

Aftermath of phase transitions directly observable in gravitational waves

QCD and EWPT are not first order in the SM: need for new particles or new symmetries

Fig. from Schmitz [2002.04615] JHEP

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

• Tunneling rate per unit volume given by O(3) action S_3/T

Nucleation theory Coleman 1977 (PRD)

• Assume thermal fluctuations in homogeneous spacetime:

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

$$
\gamma_V \sim T^4 \exp(-S_3/T)
$$

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What about impurities?

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A supercool experiment

82K views 3 yr ago ... more

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

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

The nature of impurities

• Compact objects and gravitational effects • Primordial density fluctuations

Fig. From Agrawal, **SB**, Mariotti, Nee [2312.06749]

• Topological defects

The nature of impurities

Domain walls

Fig. From **SB**, Mariotti, [2405.08060]

Topological classification

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

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

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

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SB, Mariotti [2203.16450], PRL Agrawal, **SB**, Mariotti, Nee [2312.06749]

• Competition between homogenous and seeded nucleation for 2nd step:

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• Homogenous vs seeded nucleation rate:

Agrawal, **SB**, Mariotti, Nee [2312.06749]

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• Real time bubble nucleation:

Crosscheck theoretical prediction for the nucleation rate/lifetime of FV

• Domain wall network mimicked by Ising model

• Spectrum shifted to IR with enhanced amplitude

GWs from seeded bubbles

Stomberg [2302.06952] JCAP

What about other defects?

SB, Mariotti [2405.08060]

QCD axion strings • Strings form at PQ phase transition String—wall network collapses Strings connected by axion domain walls *T f a* QCD

QCD axion strings Strings form at PQ phase transition String—wall network collapses Strings connected by axion domain walls ??? *T f a* QCD

QCD axion strings

• Global string solution

• Potential for PQ field

 $\Phi = \rho e^{i\alpha}$

 $V_{\text{PQ}}(\Phi)$

QCD axion strings and we have restricted our study of the west which we have restricted our study to KSV and we have restricted our stricted o

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

 $V = V_{PQ}(|\Phi|) + V_{EW}(|\mathcal{H}|;T)$

 $V_{\mathrm{PQ}}(|\Phi|) =$

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

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

EW(0; *^T*) ⇠ *^T*² *^T*²

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$$

$$
\mathcal{L}_{\text{Q}}(|\Phi|) = \eta \left(|\Phi|^2 - \frac{f_a^2}{2}\right)^2
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 $\mathcal{V} = V_{\text{PQ}}(|\Phi|) + V_{\text{EW}}(|\mathcal{H}|;T)$

$$
T)+\kappa\left(|\Phi|^2-\frac{f_a^2}{2}\right)\left(|\mathcal{H}|^2-\frac{v^2}{2}\right)
$$

How do strings affect electroweak 2*.*5 symmetry breaking?

String solutions

• Relevant points in field space: As we can see, seeded tunneling is e↵ective in a small range around */*⌘ ⇠ *mh/m*⇢. As we can see the upper end in a small range around the onset of range around α and α around α around α around α around α are pointed in a small coupling for which is given by the portal coupling for whic B_{a} the contractive the thin C_{a} and

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 $B = (0, \tilde{f}_a)$ 1 *h*2 *,z* + 1
1
1 *h*2 *,r* ⁺ *^V* (⇢) + *^V* (*h*) + ¹ $A=(v,f_a)$ *,r* ⁺ *^V* (⇢) + *^V* (*h*) + ¹ $\overline{\textbf{X}}$ *,r ^V* (⇢) *^V* (*h*) ¹ *,r* ⁺ *^V* (⇢) + *^V* (*h*) + ¹ \boldsymbol{f} \boldsymbol{a} and \boldsymbol{b} string \boldsymbol{b} string \boldsymbol{b} *T* < *f a*

Simone Blasi - Crossroads TH and PH Simone Blasi - Crossroads TH and PH As we can see Simone Blasi - Crossroads TH and PH \overline{a}

$$
(\tilde{f}_a)
$$
\n
$$
A = (v, f_a)
$$
\n
$$
\tilde{f}_a
$$

String solutions

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@*h*⁰ Due to the friction term this bounce can only be obtained numerically. Let us now estimate the range of portal couplings that can sensibly a↵ect the homogeseeded tunneling becomes e↵ective when Let us now estimate the range of portal couplings that can sensibly a↵ect the homoge**netwich solutions**

As we can see, seeded tunneling is e↵ective in a small range around */*⌘ ⇠ *mh/m*⇢. B_{a} the contractive the thin C_{a} and neous tunneling. On the lower end of this range, the thin wall approximation is valid and $\overline{\mathsf{S}}$ • Relevant points in field space:

• Typical string profiles:

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 $m_h r$

String solutions

• Large hierarchy between the mass of the Higgs and the PQ radial mode

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EFT with heavy defects

EFT with heavy defects CO ✏ = 2p2*/m*⇢. As we can see, the precise shape of the string profile at scales *^m*⇢ does

- \bullet Large hierarchy between the mass of the Higgs and the PQ radial mode • Large hierarchy between the mass of the Higgs and the PQ radial mode
- Physics captured by electroweak scale EFT, SM + axion or ALP: Dirac– potential. I Hydrog captured by electroweak scale LI I, OM τ axion of π LI.

$$
S_{\text{EFT}}[h] = \int d^4x \left\{ \frac{1}{2} (\partial_\mu h)^2 - V_{\text{EW}}(h) - \frac{1}{2} \frac{\kappa}{\eta} (\partial_\mu \alpha)^2 h^2 + \pi \frac{\kappa}{\eta} C(\epsilon) \delta^{(2)}(r - \epsilon) h^2 \right\}
$$

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- Dirac– potential. I Hydrog captured by electroweak scale LI I, OM τ axion of π LI. • Physics captured by electroweak scale EFT, SM + axion or ALP:

✏ *h*0 background: • Explicit UV scale: $\epsilon \sim 1/m_\rho$

The function *C*(✏) can be evaluated numerically. One finds for instance *C* ' 1*.*2 for rass of the Higgs and the PQ radial mode • Large nierarchy between the mass of the Higgs and the PQ radial

$$
\epsilon\,h'(\epsilon)=-C(\epsilon)\frac{\kappa}{\eta}h(\epsilon)
$$

$$
S_{\text{EFT}}[h] = \int d^4x \left\{ \frac{1}{2} (\partial_\mu h)^2 - V_{\text{EW}}(h) - \frac{1}{2} \frac{\kappa}{\eta} (\partial_\mu \alpha)^2 h^2 + \pi \frac{\kappa}{\eta} C(\epsilon) \delta^{(2)}(r - \epsilon) h^2 \right\}
$$

• Explicit UV scale: • Axion-Higgs portal, in the string • δ -potential imposes UV

EFT with heavy defects CO ✏ = 2p2*/m*⇢. As we can see, the precise shape of the string profile at scales *^m*⇢ does the simple deformation of the SM potential considered here, thus paving the way to new phenomenological applications and interesting revisitations of (extensions of) the SM when \blacksquare framework can be straightforwardly generalized to a richer electroweak scalar sector beyond beyond beyond beyond

- \bullet Large hierarchy between the mass of the Higgs and the PQ radial mode • Large hierarchy between the mass of the Higgs and the PQ radial mode \bullet Large hierarchy between the mass of the Higgs and the PQ radial mode
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$$
\alpha = \theta \Rightarrow \partial_{\mu} \alpha \sim 1/r \qquad \qquad \epsilon h'(\epsilon) = -C(\epsilon)
$$

a 2

iggs portal, in the string $\qquad \bullet \ \ \delta\text{-potential imposes UV}$ und: $r = 0$ atching condition:

• Solve eigenvalue equation for small perturbations + boundary condition : σ do so, we consider the EFT (3.8) and study the eigenvalue problem for the simplest problem configuration with *h*(*r,* ✓) = *h*(*r*): • Solve eigenvalue equation for small perturbations + boundary condition:

 t

Higgs mass along the string is stable once the Higgs fluctuations around the Higgs fluctuations around around around are taken into account
Into account 4 and 20 and When the KSVZ fermions are taken into account, additional operators need to be considered in combination with the axion solution to the strong CP problem. Let us finally mention that while we have restricted our study to KSVZ–like models

$$
\left[-\frac{d^2}{dr^2} - \frac{1}{r}\frac{d}{dr} - (\kappa/\eta)\frac{1}{r^2} + V_{\text{EW}}''(0;T)\right]h(r) = \omega^2 h(r)
$$

\n
$$
\epsilon h'(\epsilon) = -C(\epsilon)\frac{\kappa}{\eta}h(\epsilon) \qquad \epsilon \sim 1/m_\rho
$$

\n2D mass

 $(T_r) < 0$

Higgs mass along the string this relation and the energy dividend in the barrier and \mathbf{F} the variation in the string tension is given by (??). In fact, as *h*(✏) ' *v* in the expression for

• Solve eigenvalue equation for small perturbations + boundary condition :

$$
\omega^2 = V''_{\text{EW}}(0;T) - \frac{1}{2}m_\rho^2 \exp\left\{-\frac{\pi}{\sqrt{\kappa/\eta}} - \gamma_{\text{E}} + 2C(\epsilon)\right\}
$$

4D mass
$$
\Delta m_h^2
$$

• Axion strings classically develop a Higgs core if $ω^2$

$SM + PQ$ $\mathbf{P} = \mathbf{P} \mathbf$ Our setup consists of a complex scalar field charged under a global *U*(1) Peccei–Quinn

SM + PQ transition is *hh*(0) ' *v*, namely when the homogenous bubble is thin walled.

• Higgs potential in the SM: \bullet Hinne noter \overline{e} *m*² ⇢ exp (⇡

$V_{\rm E'}''$ $T''_{\rm EW}(0;T)\sim T^2-T_{\rm E}^2$

SM + PQ transition is *hh*(0) ' *v*, namely when the homogenous bubble is thin walled.

;v /
a h Higgs gets a vev $h \sim v$ in the string and in the bulk at same *T*

• Higgs potential in the SM: \bullet Hinne noter \overline{e} *m*² ⇢ exp (⇡

 $V_{\rm E'}''$ $T''_{\rm EW}(0;T)\sim T^2-T_{\rm E}^2$

SM + PQ transition is *hh*(0) ' *v*, namely when the homogenous bubble is thin walled.

• Thermal history (blue region):

• Higgs potential in the SM: \bullet Hinne noter \overline{e} *m*² ⇢ exp (⇡

$$
V''_{\rm EW}(0;T)\sim T^2-T_{\rm EW}^2
$$

SM + PQ

• At $T \gg T_{\text{EW}}$ strings are of type C with a (potentially large) Higgs core

SM + PQ

- At $T \gg T_{\text{EW}}$ strings are of type C with a (potentially large) Higgs core
- At $T \leq T_{\text{EW}}$ string C solution merges smoothly with the bulk and becomes type A

FOPT + PQ $\tt\textrm{S/N}$. Do coupling strength . This point is portal may be thought of as being e α ectively generated from the strength of as $\begin{array}{c} \n \text{FOP} + \text{PQ} \\
\text{FOP} + \text{PQ}\n \end{array}$ to the coupling. In the following we will treat the fo 2.1 Scalar potential and its extrema potential and its extrema potential and its extrema potential and its extrema
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• Consider first order EWPT with false vacuum B metastable at $T=0$ • Consider first order EWPT with false vacuum B metastable at $T=0$ The Lagrangian of the theory reads Ω espaieles fisch cooles Γ W Γ with foles vecesses Γ sectories

Simone Blasi - Crossroads TH and PH not needed a Depending on the specific UV completion, the specific UV completion, the specific UV contribution of C

 $V_{\rm EW}(h;T) = -\frac{1}{2} \left(\mu^2 - c_h T^2 \right) h^2 + \frac{\delta}{2} \frac{m_h^2}{2} h^3 + \frac{1}{4} \lambda h^4$ and we only consider scenarios with *>* 0. Here *V*PQ is the potential responsible for the $(\mu^2 - c_h T^2) h^2 +$ δ 3 m_h^2 $\frac{n_h}{v^2}h^3 +$ 1 4 λh^4

$$
V_{\rm EW}(h;T)
$$

2

FOPT + PQ $\tt\textrm{S/N}$. Do coupling strength . This point is portal may be thought of as being e α ectively generated from the strength of as $\begin{array}{c} \n \text{FOP} + \text{PQ} \\
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Simone Blasi - Crossroads TH and PH not needed a Depending on the specific UV completion, the specific UV completion, the specific UV contribution of C

$$
V_{\rm EW}(h;T)\Bigg\lvert
$$

 P - mucleation for simplicity *L* = *L* = *DUCLEATION*
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L = *DUCLEATION* Assume too slow hom.

 $V_{\rm EW}(h;T) = -\frac{1}{2} \left(\mu^2 - c_h T^2 \right) h^2 + \frac{\delta}{2} \frac{m_h^2}{2} h^3 + \frac{1}{4} \lambda h^4$ and we only consider scenarios with *>* 0. Here *V*PQ is the potential responsible for the $V_{\rm EW}(h;T) = -\frac{1}{2}$ 2 $(\mu^2 - c_h T^2) h^2 +$ δ 3 m_h^2 $\frac{n_h}{v^2}h^3 +$ 1 4 λh^4

preserving minimum and the EW breaking vacuum at all temperatures:

• EWPT can still complete by catalyzed vacuum decay: strings as initial & final states

Figure 3: Left: Profile of the PQ field along the radial direction perpendicular to the

string for the string B, as well as for string C and A as they di↵er by negligible EW scale

• EWPT can still complete by catalyzed vacuum decay: strings as initial & final states

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• EWPT can still complete by catalyzed vacuum decay: strings as initial & final states

Axion string (*B* or *C*) metastable at $T=0$

Seeded tunneling EWPT may complete if fast enough rate B (C) T_n

• EWPT can still complete by catalyzed vacuum decay: strings as initial & final states

 κ/η

Rolling See also Yajnik, PRD (1986)

• String C becomes unstable and evolves towards string A at $T=T_r^C$

r

 $m_h r$

Rolling

r ξ ∼ 1 *h* ∼ *v* $h \gg v$ Δ*t H*−¹ $\mathcal{V}_\mathcal{W}^$ $h = 0$ **String A**

See also Yajnik, PRD (1986)

• String C becomes unstable and evolves towards string A at $T=T_r^C$

Rolling

r ξ ∼ 1 *h* ∼ *v h* ≫ *v* Δ*t H*−¹ *vw* Expansion of macroscopic $h = 0$ cylindrical bubble wall**String A**

See also Yajnik, PRD (1986)

• String C becomes unstable and evolves towards string A at $T=T_r^C$

• Nucleation rate per unit time per unit string length: We define the tunneling per unit string rength. Simone Blasi - Crossroads TH and PH

• Nucleation condition:

Seeded tunneling 5.3.1 Nucleation condition We define the thermal tunneling rate per unit length as We define the thermal tunneling rate per unit length as ^s ' *^T*² exp(*S*string*/T*) (5.5)

 $\mathcal{N}(T_n) = \int_{T_n}^{T_c}$

$$
\frac{S_{\text{string}}}{T} \simeq 2 \log(M_{\text{Pl}}/T_n)
$$

Seeded tunneling

• How to evaluate the seeded action?

⇢(*r* = 0*, z*)=0*,* @*z*⇢*|z*=0 = 0*,* @*rh|r*=0 = 0*,* @*zh|z*=0 = 0*.* (5.10)

$$
\partial_z^2 h + \partial_r^2 h + \frac{1}{r} \partial_r h + (\kappa/\eta) \frac{h}{r^2} =
$$

$$
\epsilon \,\partial_r h|_{r=\epsilon} = -\frac{\kappa}{\eta} C(\epsilon) h|_{r=\epsilon}, \quad \partial_z h|_{z=0} = 0
$$

Seeded tunneling S eeded tunneling

- How to evaluate the seeded action?
- PDE solution obtained numerically

symmetry. On the other hand a non–vanishing portal implies asymmetric motion due to the centrifugal term in (5.11) as well as asymmetric boundary conditions with possibly $C(2)$ broaking spherically symmetric, and seeded tunneling reduces to homogenous tunneling with *O*(3) $=$ O(3) breaking

⇢(*r* = 0*, z*)=0*,* @*z*⇢*|z*=0 = 0*,* @*rh|r*=0 = 0*,* @*zh|z*=0 = 0*.* (5.10)

$$
\partial_z^2 h + \partial_r^2 h + \frac{1}{r} \partial_r h + (\kappa/\eta) \frac{h}{r^2} = V_{\text{EW}}'(h)
$$

$$
\epsilon \partial_r h|_{r=\epsilon} = -\frac{\kappa}{\eta} C(\epsilon) h|_{r=\epsilon}, \quad \partial_z h|_{z=0} = 0
$$

Seeded tunneling S eeded tunneling

- How to evaluate the seeded action?
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Simone Blasi - Crossroads TH and PH *N* at α at α at α at α at α of the release point α of the release point α of the α

Seeded tunneling of **h**, and tunneling due to the string due to the string can be evaluated tunneling can be evaluated to the string can be evalua straightforwardly from (5.15) once the *O*(3) symmetric bounce profile is known. transition is *hh*(0) ' *v*, namely when the homogenous bubble is thin walled. \blacksquare

- e mow to evaluate the seeded action, namely a thing-wall a thin–wall spherical bubble of radius β $\overline{2}$ • How to evaluate the seeded action?
- Linear: seeded bubble as small perturbation of homogeneous (spherical) bubble:

$$
S_{\text{string}} = S_{\text{hom}} + \delta
$$

$$
\delta S_{\text{TW}} = -2\pi R \frac{\kappa}{\eta} \log(R m_{\rho}) h_{\text{r}}^2
$$

Release point hom. bubble

Radius hom. bubble

Seeded tunneling It can be useful to make a further step and derive a lower dimensional EFT for the Higgs \blacksquare 3.3 The 1+1 theory on the axion string if the EW potential has a barrier at the origin. An example of the Higgs profile for this string solution is shown in the left panel of S as we can see a structure 2. As we can see at S trivial. For the EW potential as in the SM, this is naturally realized when the string B \sim becomes university of the European space is the point B in fig.

- HOW TO EVAIUATE THE SEE GEQ ACTION ? • How to evaluate the seeded action?
- all scales between 1/_m and 1*/m*
A **FFT** on the string for the lightest Higgs mode

Simone Blasi - Crossroads TH and PH still the global minimum (*T* \overline{S} *T* \overline{S} \overline{S}

$$
h(x^{\mu}) = \phi(r)h_0(z)
$$

$$
S_{1+1}[h_0] = \int dzdt
$$

$$
\tilde{V}(h_0) = \frac{1}{2}\omega^2h_0^2 - \frac{1}{3!}
$$

Seeded tunneling transition into the EW breaking vacuum at *T /T^c* ' 0*.*45.

is a sign to satisfy the same to satisfy the nucleation condition in (Simone Blasi - Crossroads TH and PH Simone Blasi - Crossroads TH and PH

 κ/η

Seeded tunneling

• Profile of the critical bubble: \bigstar

 $m_h r$

Phenomenology

- Percolation as interplay between seeded nucleation rate and density of defects
- Axion—seeded EWPT effectively *β*/*H* ∼ *ξ* ∼ 10
- Different velocities parallel or orthogonal to the string?
- Gravitational wave emission before collision (non-spherical bubbles)?

vw

Summary

- The presence of impurities in the early Universe can strongly affect the way a phase transition proceeds
- The xSM with Z_2 symmetry is arguably the simplest (complete) example for a seeded EWPT
- Other defects can exist at the time of the EWPT: dedicated study of QCD axion strings in KSVZ model with Higgs portal
- Pheno aspects of seeded phase transitions: percolation, slow transitions, expansion of non—spherical bubbles, features in the GW signal?

Summary

- The presence of impurities in the early Universe can strongly affect the way a phase transition proceeds
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Thank you!

Backup

