

Outline

- nAbout the cosmological first-order phase transitions (cosFOPTs)
- nBubble-free cosFOPTs: motivation, modeling and result analysis
- nGWs from domain wall seeded cosFOPTs
- n**Conclusions**

This talk is based on:

- ^l Dongdong Wei, Haibin Chen, Qiqi Fan, **YJ***, Cosmological first-order phase transitions without bubbles, arXiv: 2401.08801 [hep-ph] (submitted to PRL)
- Dongdong Wei, YJ^{*}, *Domain wall networks from first-order phase transitions and gravitational waves*, arXiv: 2208.07186 [hep-ph] (peer review under PRX)
- ^l Haibin Chen, Dongdong Wei, **YJ***, Dynamics of electroweak phase transitions: from nucleation to percolation, working in progress

FOPT is of particular interest for cosmology.

 \bullet 能够解释早期宇宙正反物质不对称问题; See review [Morrissey, Ramsey-Musolf, New J. Phys. 14, 125003 (2012)]

 \bullet 弱电相变产生的引力波在空间引力波的探测 频段上;

i.e. Liang, Hu YJ, Cheng, Zhang, Mei, Phys. Rev. D 105, 022001 (2022)

\bullet 也可能影响暗物质的最初产生。

i.e. Baker, Kopp, Phys. Rev. Lett. 119, 061801 (2017) Baker, Kopp, Long, Phys. Rev. Lett. 125, 151102 (2020)

Yun JIANG (SYSU) cosFOPTs without bubbles 3

What is the cosFOPTs?

Suppose our universe is described by the scalar field \varPhi

 \bullet At the critical temperature there exists degenerate vacuum separated by a potential barrier.

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Suppose our universe is described by the scalar field ϕ

- \bullet At the critical temperature there exists degenerate vacuum separated by a potential barrier.
- \bullet The false vacuum would be stable classically, but quantum mechanically metastable.
- \bullet Transition to the true vacuum state by tunnelling process occurs through the nucleation of bubbles of the true vacuum phase.

Yun JIANG (SYSU) $\overline{\mathsf{G}}$

Go beyond the standard picture

This is the standard picture of cosFOPTs that we have well understood so far. But the full theory of phase transitions is far more complicated.

- \bullet One step PT -> multi-step PT
- \bullet Involving a single field -> Involving multiple fields
- \bullet Bubbles only -> Bubbles + else

Implemented in PhaseTracer 2

Suppose our universe is described by the scalar field ϕ

If quantum tunneling probability is not efficient, the phase transition will **not** happen and the universe will be trapped in the false vacuum. This phenomenon is dubbed "vacuum trapping". Biekotter, Heinemeyer, No, Olea, Weiglein, JCAP 03, 031 (2023)

Yun JIANG (SYSU) $\begin{array}{ccc} & \text{cosFOPTs without bubbles} \end{array}$

Question #1: is the false vacuum trapping problem cosmologically acceptable?

cosFOPTs without bubbles

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Question #1: is the false vacuum trapping problem cosmologically acceptable?

The answer is: it is pretty much **dangerous** !

 \bullet induce a catastrophic inflation

Guth, Weinberg, Nucl. Phys. B 212, 321 (1983). Hawking, Moss, Stewart, Phys. Rev. D 26, 2681 (1982).

• if the true vacuum is the desired phase at $T < T_c$, (i.e., the EWbroken minimum accounting for a proper EW symmetry breaking)

Baum, Carena, Shah, Wagner, Wang, JHEP 03, 055 (2021) Biekotter, Heinemeyer, No, Olea, Weiglein, JCAP 06, 018 (2021), JCAP 03, 031 (2023),

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Question #2 : are there other new approaches to false vacuum decay so that the trapped vacuum can be rescued?

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The answer is **yes** !

- \bullet • The existence of Topological defects will give rise to a rich impact on the dynamics of the cosmological phase transition.
- **•** In this talk we focus on the **domain wall**, which arises from the spontaneous breaking of a discrete symmetry. Such discrete symmetries occur frequently in many particle physics models.

Formation of domain walls

Α phase transition consisting of two steps is the minimal realization.

 1 The 1st step is responsible for generating domain walls -> require the spontaneous breaking of the Z₂ symmetry

Neither of the s_\pm vacuum $^+$ is thermodynamically favorable.

Formation of domain walls Real scalar field φ (*^x*, *t*), symmetry L ¹ ² ∂φ · ∂φ

A phase transition consisting of two steps is the minimal realization.

 s ible for gen ϵ troweak scale *^v*EW and the observed Higgs mass 1) The 1 $^{\rm st}$ step is responsible for generating domain walls -> require the spontaneous breaking of the Z $_2$ symmetry

V \mathcal{L} φ), *V*

V (*h, s, ^T*) ⁼

 $\overline{}$

 \mathbf{u}

ī *µ*

4

(λφ

c T 2 *h*

v

Formation of domain walls

Α phase transition consisting of two steps is the minimal realization.

2 The produced DWs are spontaneously destroyed in the 2nd step -> escape the DW problem

Yun JIANG (SYSU) **Superior Cost Contract System** Cost CPTs without bubbles **15**

Quantum tunneling vs. classical rolling

Question #3: What is the role do domain walls play?

 \bullet Domain walls can act as impurities to catalyze bubble nucleation, thereby enhancing the inhomogeneous tunneling to complete the seeded phase transition.

S. Blasi and A. Mariotti, Phys. Rev. Lett. (2022), arXiv:2203.16450 [hep-ph]

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However, this realization is based on the quantum tunneling effect and largely relies on the considerable area occupied by the domain walls, which is not yet verified in the entire parameter space.

• We observe that there exists a higher-energy vacuum state in the domain wall, which can be spontaneously destroyed by virtue of vacuum fluctuations and classically transform into the true vacuum. This is our work and we name it the **bubble -free FOPT**.

^s field direc*^s*, leading to $\overline{}$ actions involving the *^s*-field. Assuming that the relevant couplings, *^s* and *hs*, of our BMPs are su ciently weak, the domain walls will quickly reach the scaling regime and **Bubble-free FOPTs: simulation** *^s*, leading to the coexistence of two energetically equivalent domains: actions involving the *^s*-field. Assuming that the relevant couplings, *^s* and *hs*, of our BMPs are su ciently weak, the domain walls will quickly reach the scaling regime and

T^c depends on the strength of the inter-

 \overline{u} domains, \overline{u} ^a result of the smooth interpolation of the field configuerform the lattice simulation from T in a volume muc that the domain walls at $L - 1$ $(T \setminus$ \cdots then since simulation so that the simulation so that they can be described by the \cdots We perform the lattice simulation from $T_{\rm c}$ in a volume much smaller than the Hubble size, $\mathsf{H}^{-1}\left(\mathsf{T_c}\right)$. *^vs*). In the transition re-*[±]* domains, domain walls are generated as a result of the smooth interpolation of the smooth interpolation of the smooth interpolation of the field confi can be stretched to the curvature radius that is compaerform the lattice simulation from T_c in a volume muc

⁰, the field configurations interpolating between static field solution, $\mathcal{L}(\mathcal{A}) \cong \mathcal{L}(\mathcal{A})$ Initialization of the field configuration (t=0 @ T $_{\rm c})$ ⁰, the field configurations interpolating between

domain walls at

$$
s(\mathbf{x}, t = 0) = s_{\text{dw}}, \quad \dot{s}(\mathbf{x}, t = 0) = 0,
$$

$$
h(\mathbf{x},t=0)~= \delta h(\mathbf{x},\tau_\mathrm{ref}), \quad \dot{h}(\mathbf{x},t=0) = \delta \dot{h}(\mathbf{x},\tau_\mathrm{ref})
$$

^s/c^s, the minimum of the potential starts

Bubble-free FOPTs: simulation *^s* field direc- $\overline{}$ *^s*-field. Assuming that the relevant the domain walls will quickly reach the scaling regime and *^s* field direc*^s*, leading to the coexistence of two energetically equivalent domains: actions involving the *^s*-field. Assuming that the relevant couplings, *^s* and *hs*, of our BMPs are su ciently weak, the domain walls will quickly reach the scaling regime and

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- \bullet • Assuming that the relevant couplings are sufficiently weak, the domain walls will quickly reach the scaling regime and can be stretched to the curvature radius that is $\,$ comparable to $\mathsf{H}^{-1}(\mathsf{T}_{\mathrm{c}}).$ formally walls will quickly reach the scaling regime an \ddotsc where the thickness of the wall is characterized by 3 For the BMP-A in the Bang-A inhomogeneous buildings water seeded by domain walls are seen to do the seeded b ⁴ For the case of strong couplings, it is di
	- *^h*, indicating ^a FOPT in the second step. *^T^c* (as illustrated in $\frac{1}{2}$ • We introduce inhomogeneous perturbations that originate from the vacuum fluctuation. The planar solution to describe the domain walls may not l*^h*, indicating ^a FOPT in the second step. ritroquee imformogeneous pertunbations that origina

^s/c^s, the minimum of the potential starts

Bubble -free FOPTs: simulation

We set up a pair of domain walls at z $_0$ = \pm L/4.

 \rightarrow time

wider and eat the domains of the false vacuum (s $_{\pm}$ vacuum), making the entire volume eventually \pm transition to the true vacuum (h vacuum) state.
———————————————————————————————— *s* The domain wall destabilizes and quickly turns into the **domain trench**, which will subsequently grow

Yun JIANG (SYSU) **21**

Bubble-free FOPTs: Tres calculation

While the inhomogeneous fluctuations can be implemented in the simulations, we are *unable* to evaluate from which temperature the domain wall becomes the domain trench.

Define this critical temperature as the **rescue temperature**, Tres.

 T_{c}

 s_{SUS} , and s_{SUS} , the Fourier-transformed modes modes modes of θ

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Bubble-free FOPTs: Tres calculation

In addition to the lattice simulation, T_{res} can be alternatively estimated from the view of energy conservation.

Ignoring the kinetic energy associated with the domain wall (based on the observation),

 $g(h, T) = \tau(h, T)$ $\tau(h, T)$ $g\left(h_r,T\right)=\sigma_V\left(h_r,T\right)-\sigma_g\left(h_r,T\right)$

- \bullet • the energy per area deposited into the domain wall, relative to the initial stable wall solution for *T*res indicated in dark line. This results in an oscillatory state in the *h* field. As *T*
- \bullet • the wall tension characterized by the gradient energy **gradient** was a gradient wall. If α

Therefore, T_{res} **is the highest temperature T**

possible the destruction of the domain wall. Therefore,

 $g(h_r,T)=0 \,\,\,\text{ for }\,\, T < T_c$

Bubble-free FOPTs: T_{res} calculation $\sqrt{5}$ field $\sqrt{5}$ \blacksquare DUDDIE-ITEE FOP IS. The *T^c*. The result normalizing to the value of *^h*(*^Tc*), *v* where the function *g* is given by *^g*(*h ^r, ^T*) ⁼ *^V* (*h*

In addition to the lattice simulation, T_{res} can be alternatively estimated from <u>the view of energy</u> conservation. ce simulation, r_{res} can be alternatively estimated from <u>the view of energy</u> in this analysis we are most interested in the most interested in how small experiments are most interested in

h

Ignoring the kinetic energy associated with the domain wall (based on the observation),

successful or not strongly depends on the behavior of

 $g(h_x, T) = \sigma_V(h_x, T) - \sigma_g(h_x, T)$ $\frac{3}{2}$ used in Fig. $\frac{3}{2}$ is an optimized by $\frac{3}{2}$ $g\left(h_{r},T\right)=\sigma_{V}\left(h_{r},T\right)-\sigma_{g}\left(h_{r},T\right)$

- $\bullet\;$ the energy per area deposited into the domain wall, relative to the initial stable wall lwall solution for *T*res indicated in dark line. $\frac{1}{\sqrt{2}}$
	- the wall tension characterized by the α gradient energy \bullet *^g*, this would make

ternatively estimated from the view of energy conservative conservative conservative conservative conservative

energy associated with the domain wall is negligible. Letters associated with the domain wall is negligible. L

Therefore, T_{res} is the highest temperature T **T** *^s*-field configuration is well

h field configuration of the domain wall,

just becomes unstable, the $g(h_r, T) = 0 \text{ for } T < T_c$

To find Tres using, the field profile, $h_r(z)$ at T \simeq Tres must be known, which can be described by a Gaussian wave-packet

^r, ^T)

<u>e</u> *^g*(*^h*

$$
h_r(z) = Av_h e^{-\frac{(z-z_0)^2}{(\alpha L_{\rm dw})^2}}
$$

It is equivalent to the lowest Kaluza-Klein state.

the theory per area deposited into the energy per area deposited in the domain wall, ϵ of ϵ or ϵ or relative to the initial stable wall, is *^g*(*h ^r, ^T*) ⁼

^r(*z*) be the

An application

An application: the Z_2 -odd singlet model (no mixing)

$$
V_{\text{eff}}(s, h, T) = -\frac{1}{2} \left(\mu_H^2 - c_h T^2 \right) h^2 + \frac{1}{4} \lambda_H h^4
$$

- $\frac{1}{2} \left(\mu_S^2 - c_s T^2 \right) s^2 + \frac{1}{4} \lambda_S s^4 + \frac{1}{2} \lambda_H s h^2 s^2.$

The significant change due to our work occurs in the **cyan** and **blue** regions, where the transition proceeds only with the production of domain trenches from domain walls (bubble-free PT), opening up the new viable parameter region. **Outside** the backslashed region this mechanism can complete the transition before the onset of nucleation.

Red: phase transition proceeds with nucleating DWseeded bubbles (seeded PT)

Gray: phase transition is unsuccessful

Produced GWs

We have generated the power spectrum of the GWs from bubble-seeded domain wall network.

- structure is completely buried, which is very different from the one sourced $\overline{}$ by the bubbles only.
-

decay. With the bias term, although very small, the area

0.01 0.05 0.05 0.05 0.05 0.05

of the wall network decreases exponentially in time. Typ-Yun JIANG (SYSU) cosFOPTs without bubbles

Conclusions

- n The presence of domain walls, although no incontrovertible evidence found in our universe to date, can greatly enrich the ways phase transitions are completed.
- n The inhomogeneous vacuum fluctuations can cause the instability of the domain wall and the production of the domain trench to complete the FOPT without bubble nucleation. This bubble-free mechanism constitutes a competing way against with quantum tunneling in completing the FOPT, opening up the new viable parameter space of the phase transition models.
- n In the bubble-free FOPT, the collision between domain trenches can generate GWs, which may have a different power spectrum from those from the traditional FOPT. If it is true, this would allow us to determine how the phase transition is accomplished through GW detection.

