# Cosmological first-order phase transitions without bubbles

蒋贇

27th Mini-workshop on the frontier of LHC

Zhuhai · 2024.1.21

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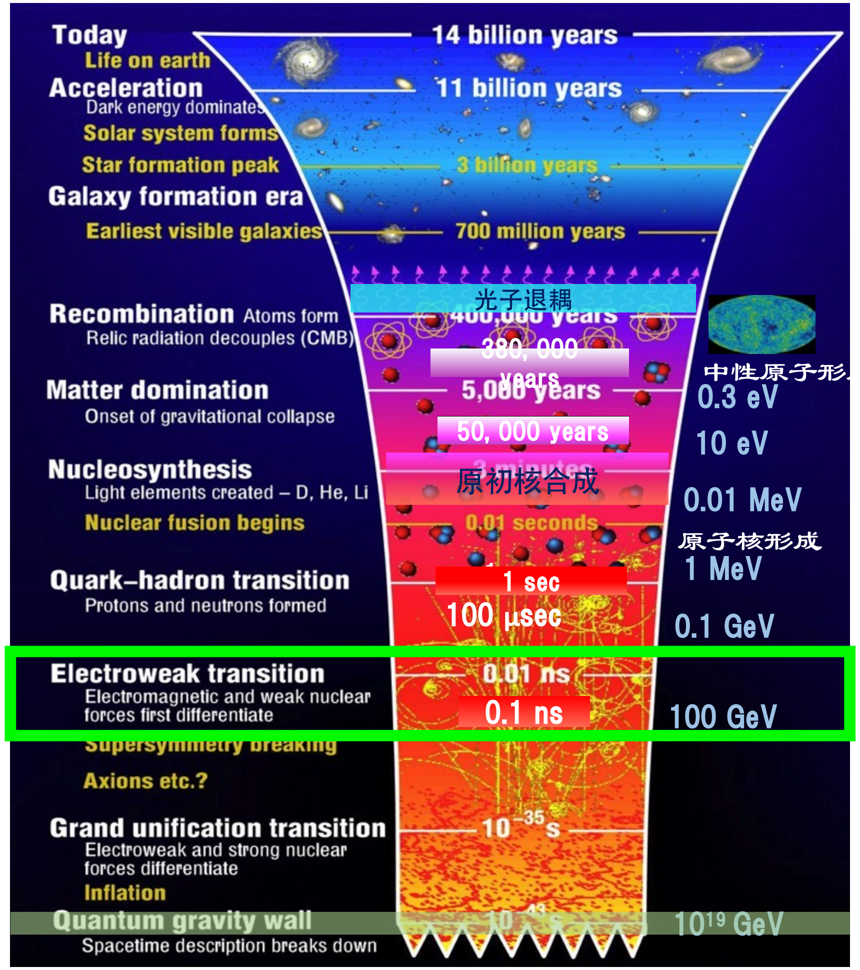
# Outline

- About the cosmological first-order phase transitions (cosFOPTs)
- Bubble-free cosFOPTs: motivation, modeling and result analysis
- GWs from domain wall seeded cosFOPTs
- Conclusions

This talk is based on:

- 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)
- Haibin Chen, Dongdong Wei, **YJ***, *Dynamics of electroweak phase transitions: from nucleation to percolation*, working in progress

# FOPT is of particular interest for cosmology.




- **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)]

- **弱电相变产生的引力波在空间引力波的探测频段上；**

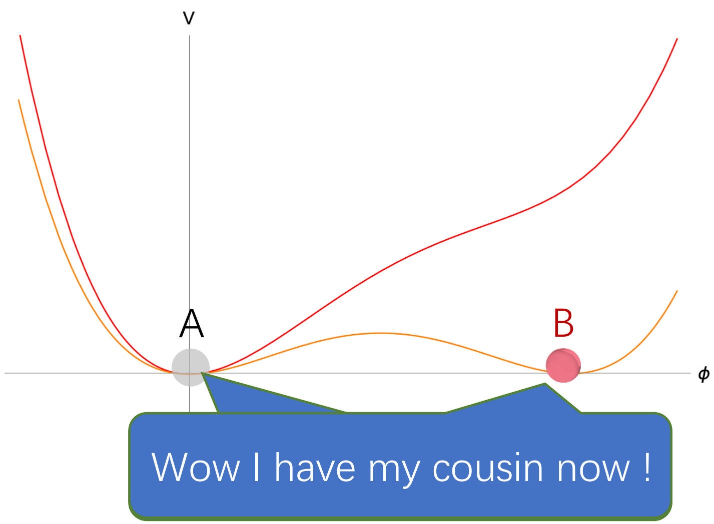
  i.e. Liang, Hu YJ, Cheng, Zhang, Mei, Phys. Rev. D 105, 022001 (2022)

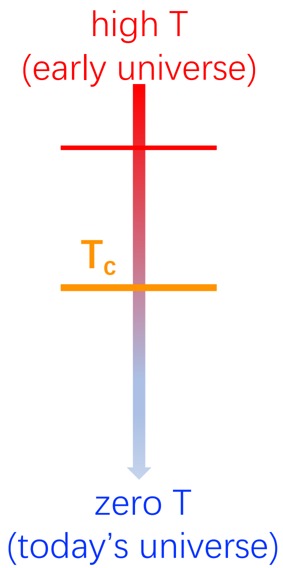
- **也可能影响暗物质的最初产生。**

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

# What is the cosFOPTs?

Suppose our universe is described by the scalar field $\Phi$




our universe

The sea of the A vacuum

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

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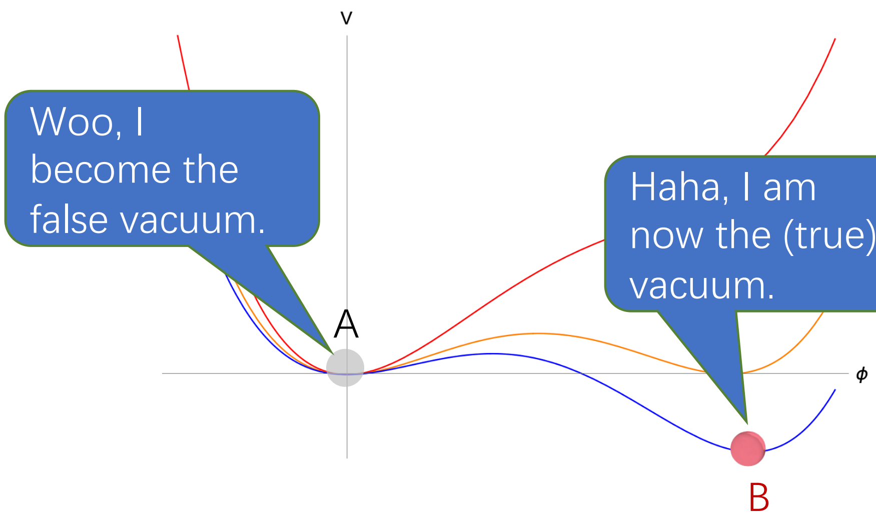
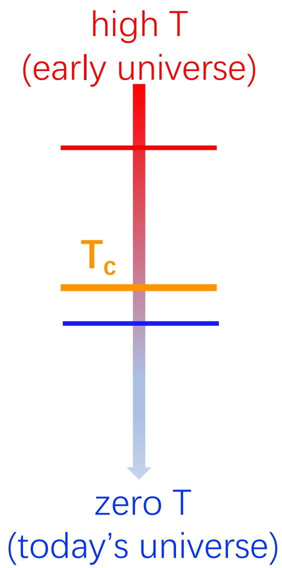
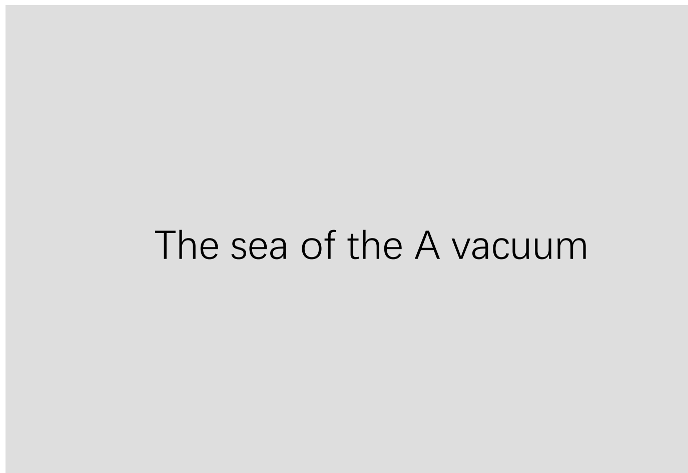



our universe

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- The false vacuum would be stable classically, but quantum mechanically metastable

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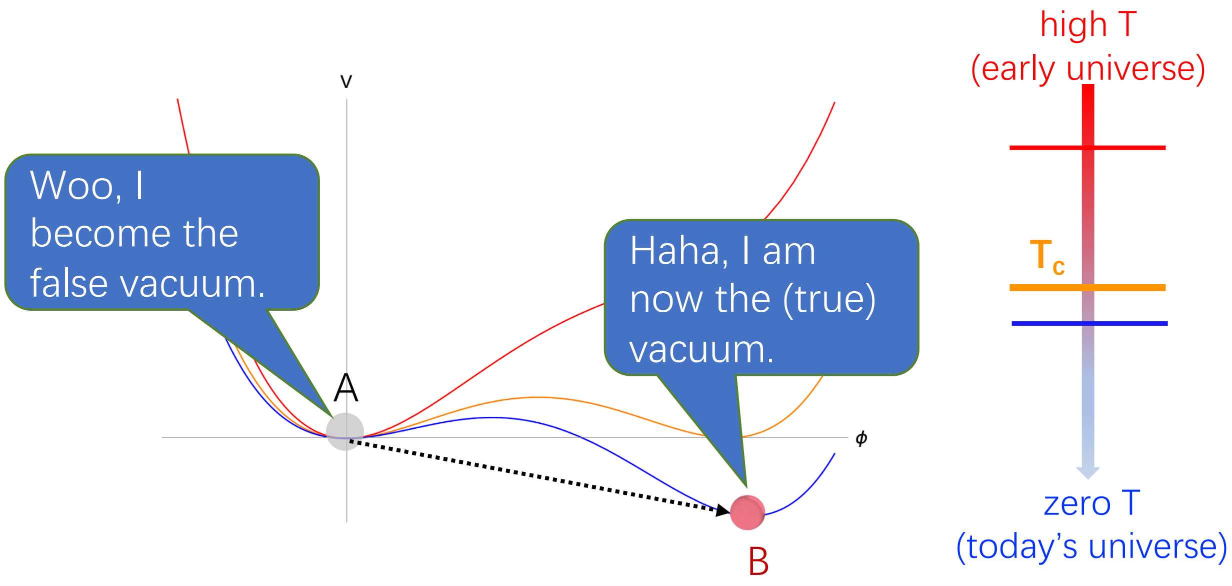
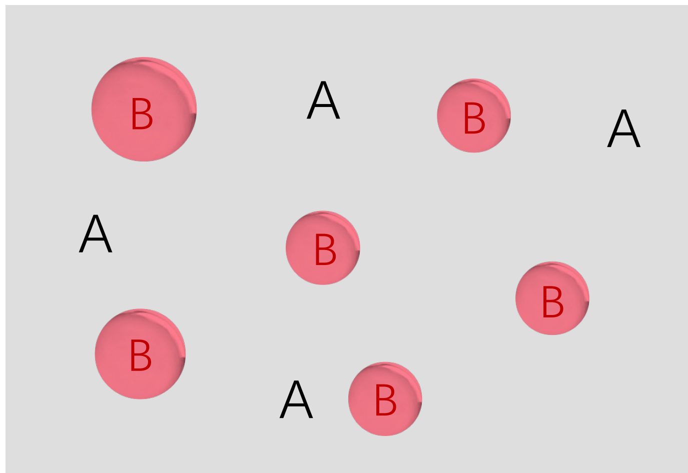



our universe




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

# Go beyond the standard picture

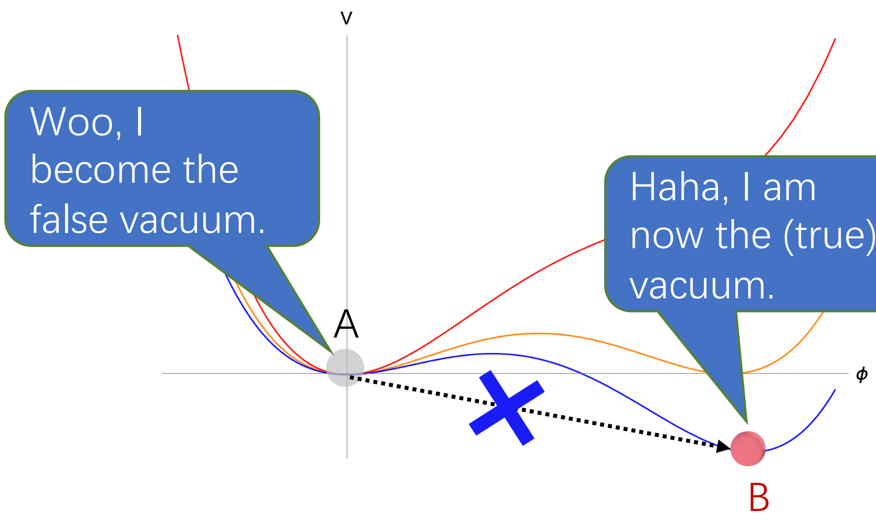
This is the standard picture of cosFOPTs that we have well understood so far. But the full theory of phase transitions is far more complicated.

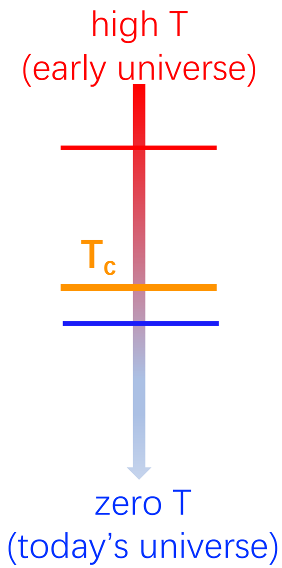
- One step PT -> multi-step PT
- Involving a single field -> Involving multiple fields
- Bubbles only -> Bubbles + else

} Implemented in PhaseTracer 2

# False vacuum trapping

Suppose our universe is described by the scalar field $\Phi$




our universe

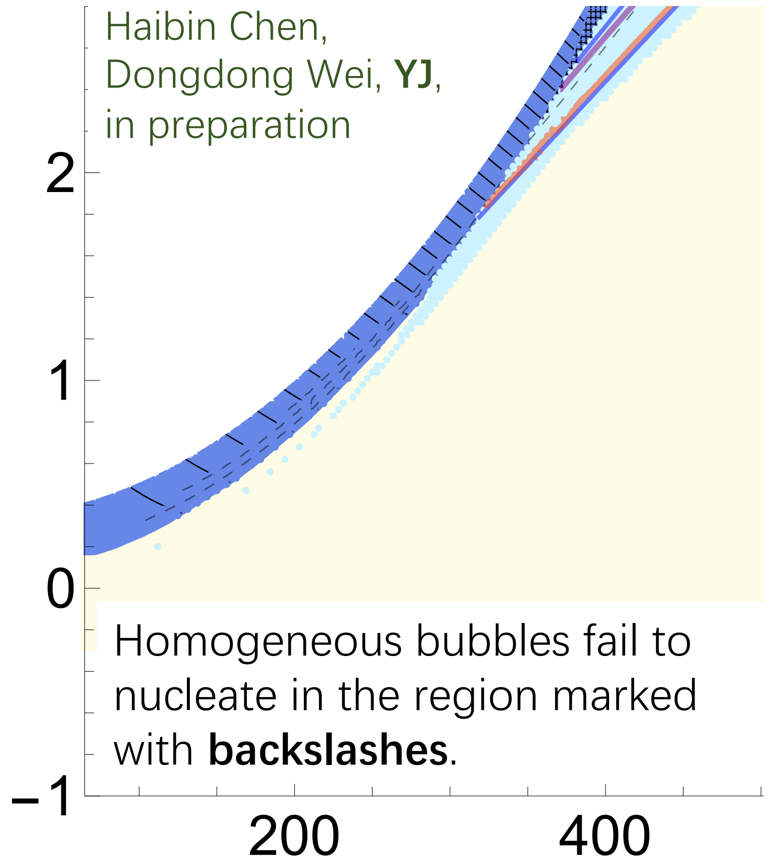
The sea of the A vacuum

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)

# False vacuum trapping

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



# False vacuum trapping

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

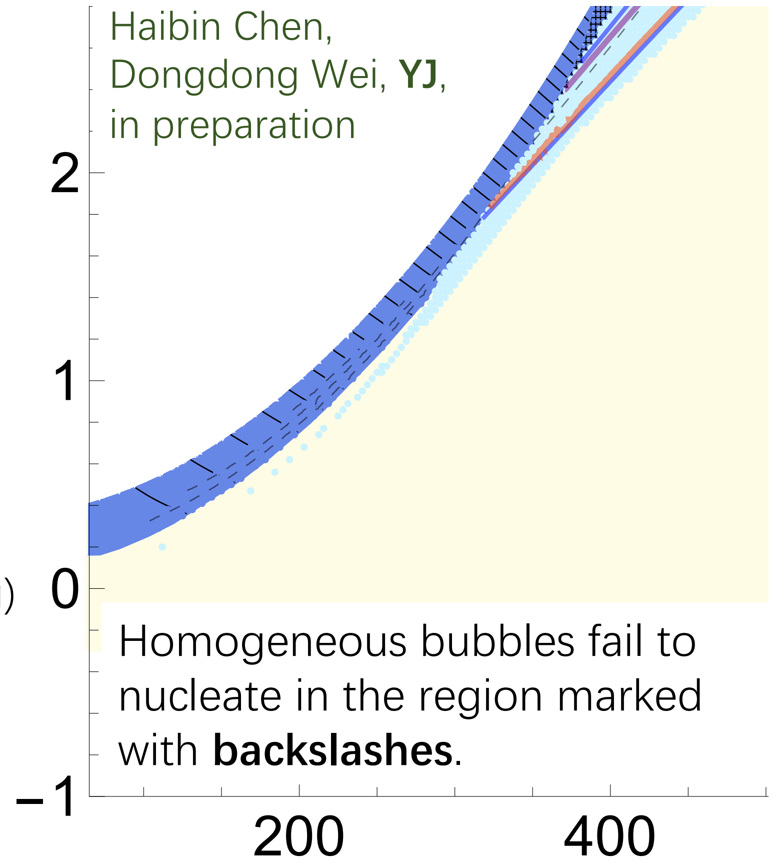
The answer is: it is pretty much **dangerous** !

- 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 EW-broken 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),



# False vacuum trapping

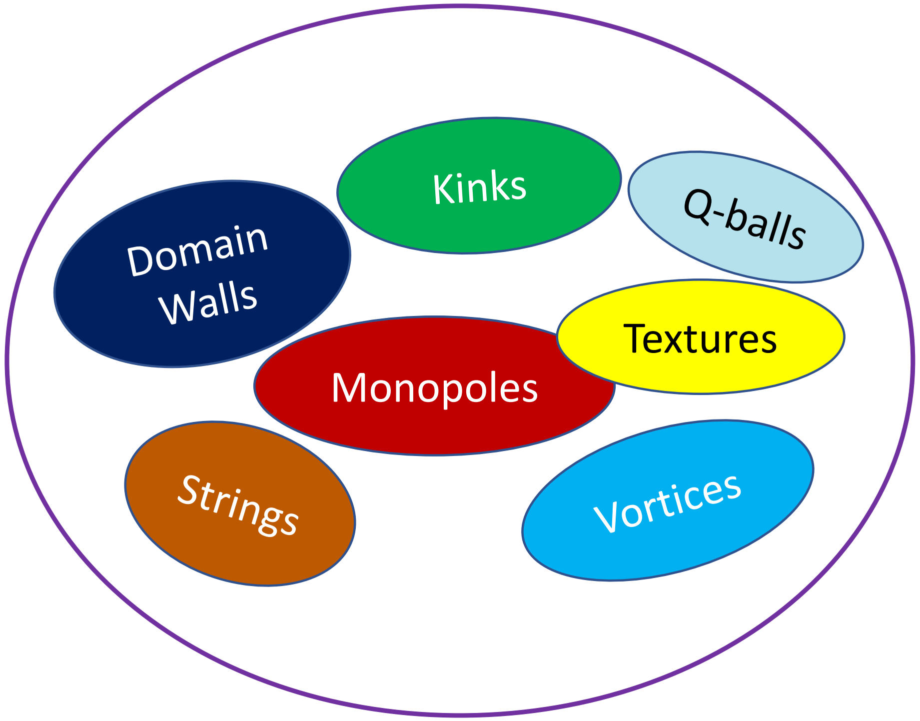
**Question #2** : are there other new approaches to false vacuum decay so that the trapped vacuum can be rescued?

# False vacuum trapping

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

The answer is **yes** !

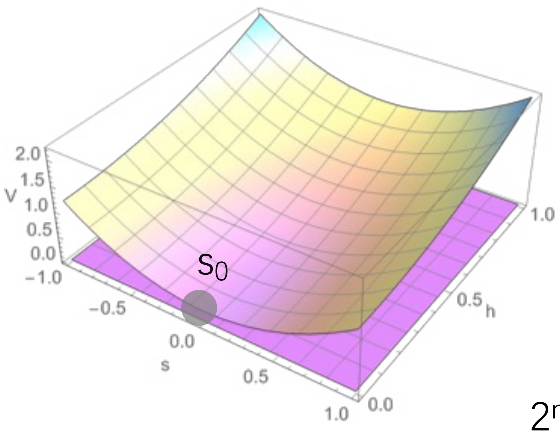
- The existence of Topological defects will give rise to a rich impact on the dynamics of the cosmological phase transition.
- In this talk we focus on the **domain wall**, which arises from the spontaneous breaking of a discrete symmetry. Such discrete symmetries occur frequently in many particle physics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



# Formation of domain walls

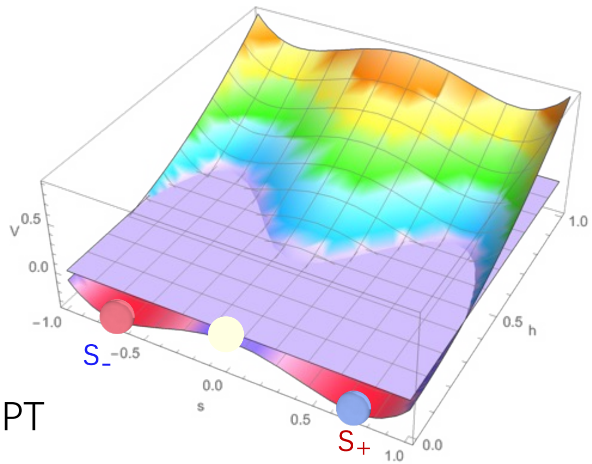
A phase transition consisting of two steps is the minimal realization.

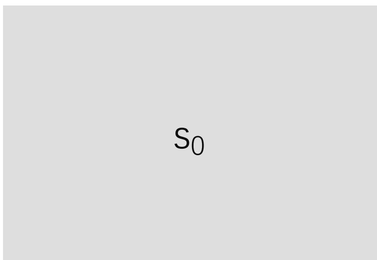
① The 1st step is responsible for generating domain walls -> require the spontaneous breaking of the $Z_2$ symmetry

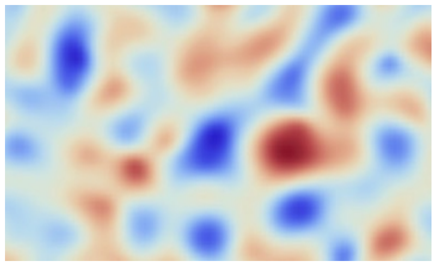



$1^{st}$ step

$2^{nd}$-order PT



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

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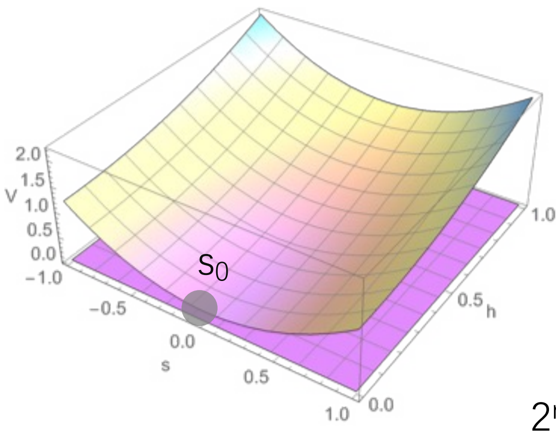
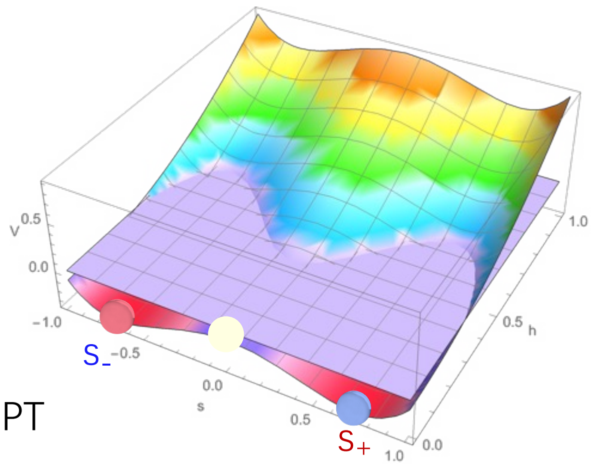
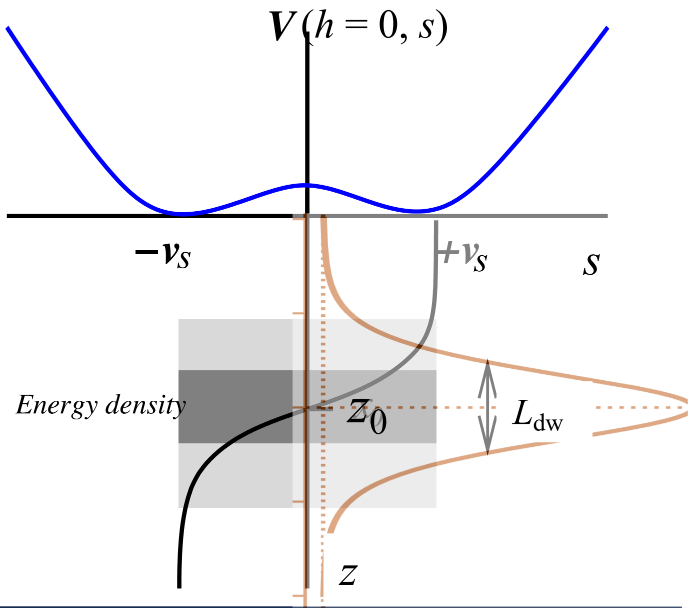
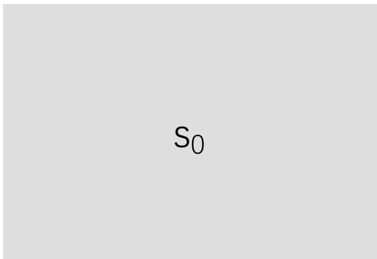


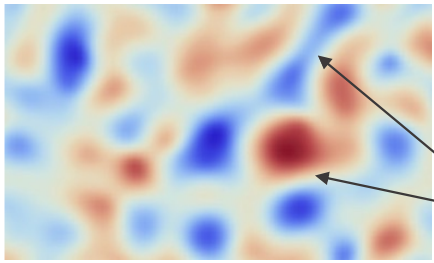

1st step

2nd-order PT



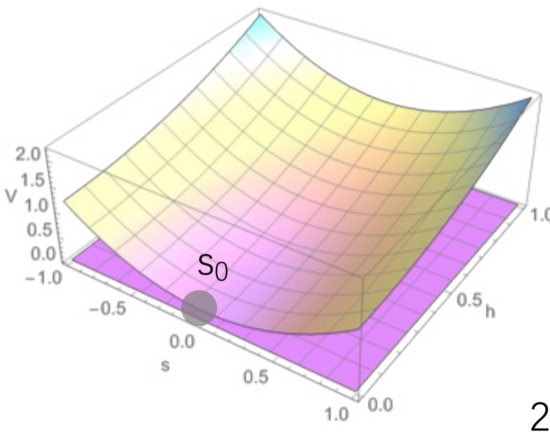
$$s_{\rm dw}(\mathbf{x}, z_0, T) = v_s(T)\tanh[(z - z_0)/L_{\rm dw}(T)],$$

**Domain walls** exist in the transition region between two different domains ($s_\pm$ domains)

# Formation of domain walls

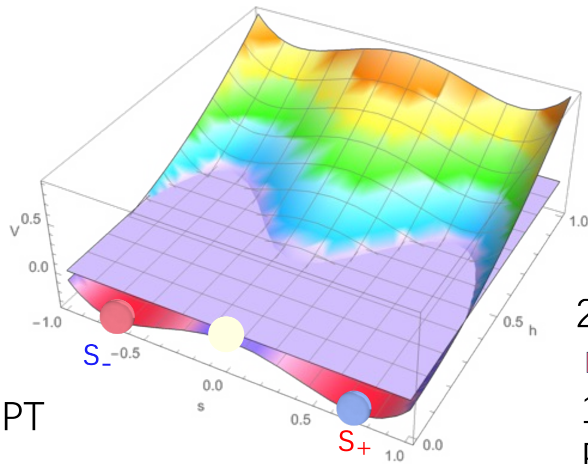
A phase transition consisting of two steps is the minimal realization.

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



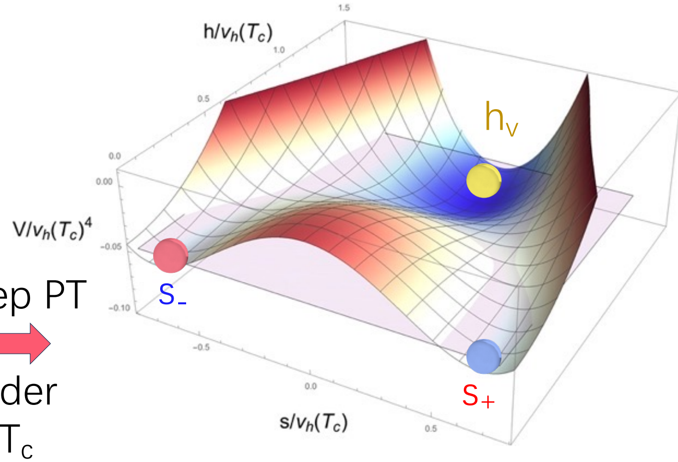

1st step

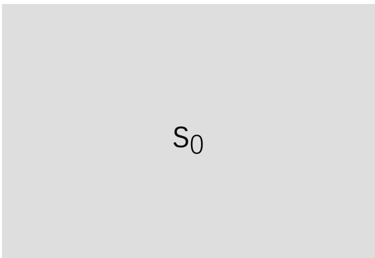
2nd-order PT

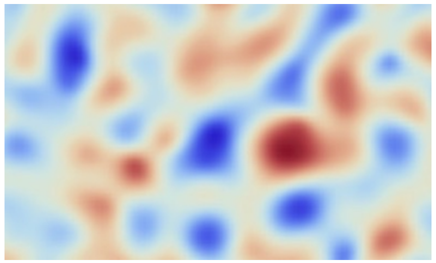



2nd step PT

1st-order PT at $T_c$



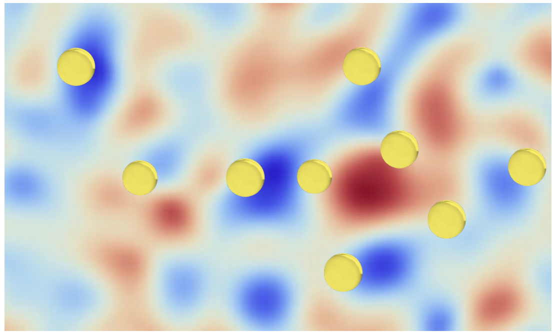
A new true vacuum ($h_v$ vacuum) develops, whereas the $s_\pm$ vacuum becomes the false vacuum.

# Quantum tunneling vs. classical rolling

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

- 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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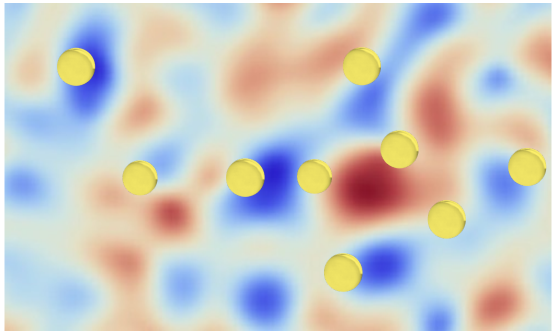

However, this realization is based on the quantum tunneling effect and largely relies on the considerable area occupied by the domain walls, which is not yet verified in the entire parameter space.

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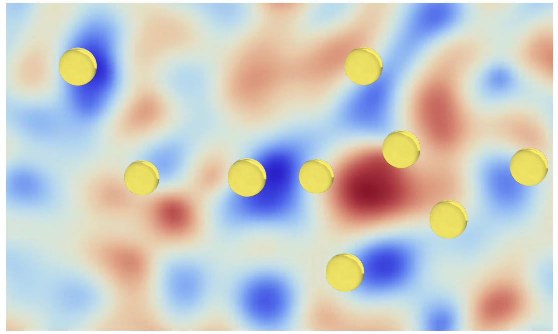

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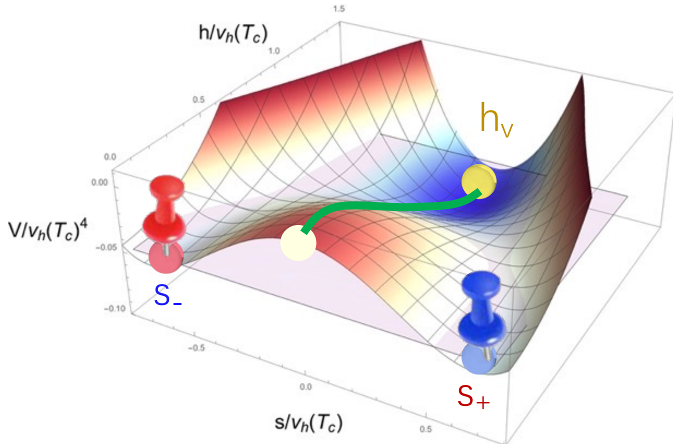



- We observe that there exists a higher-energy vacuum state in the domain wall, which can be spontaneously destroyed by virtue of vacuum fluctuations and classically transform into the true vacuum. This is our work and we name it the **bubble-free FOPT**.

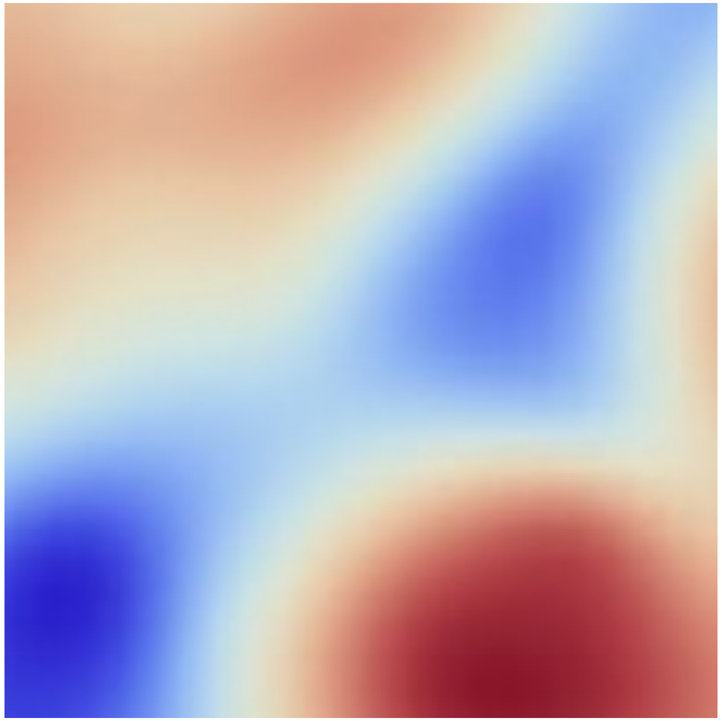
# Bubble-free FOPTs: simulation

We perform the lattice simulation from $T_c$ in a volume much smaller than the Hubble size, $H^{-1}(T_c)$.

Initialization of the field configuration (t=0 @ $T_c$)

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

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



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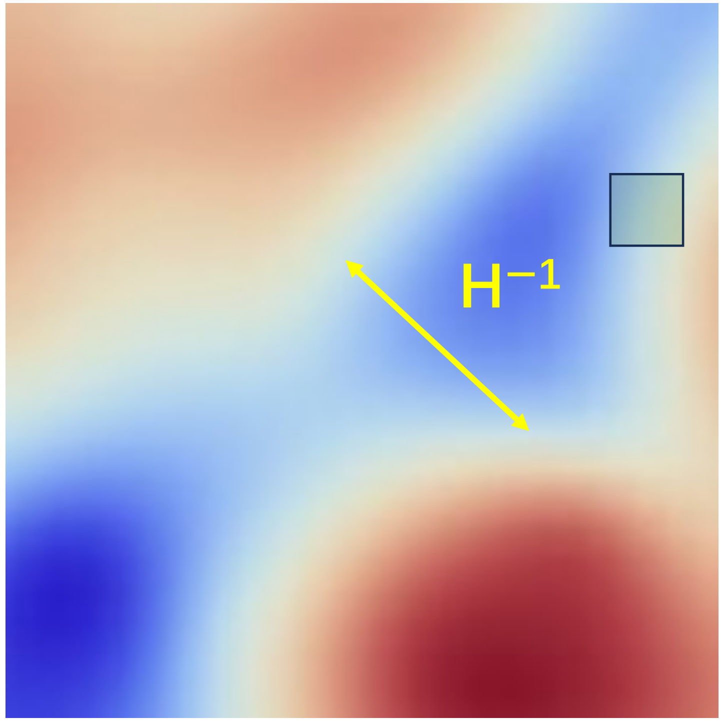
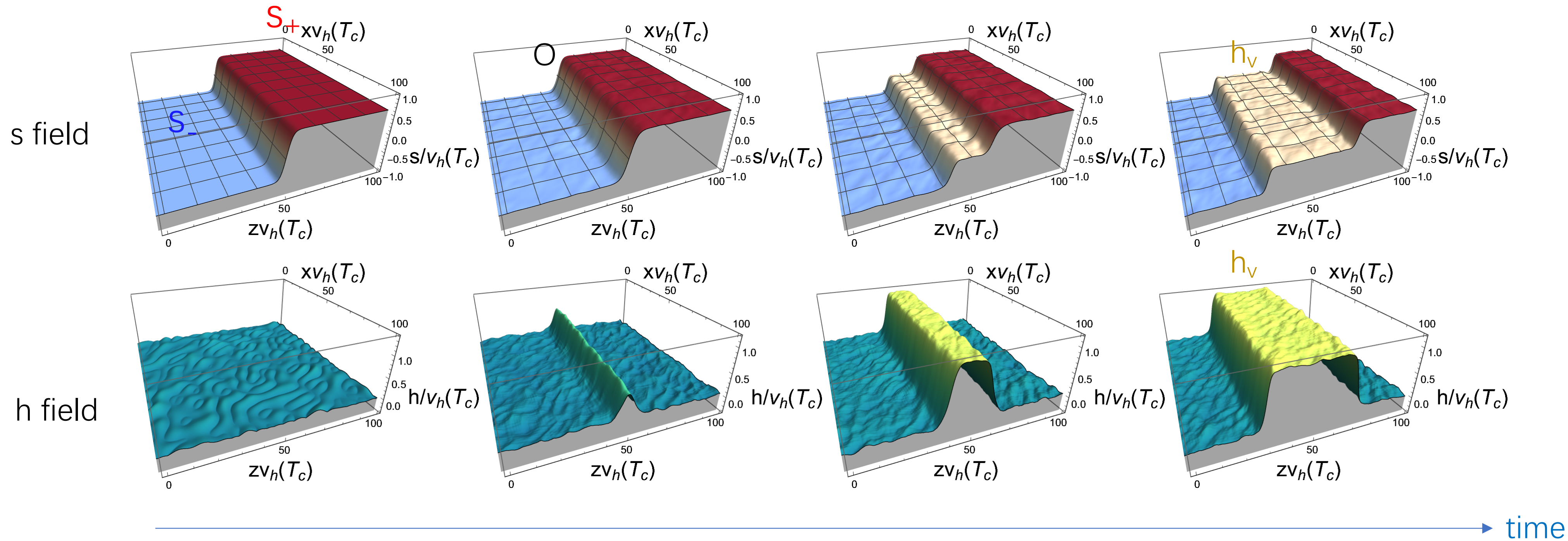
- Assuming that the relevant couplings are sufficiently weak, the domain walls will quickly reach the scaling regime and can be stretched to the curvature radius that is comparable to $H^{-1}(T_c)$.
- We introduce inhomogeneous perturbations that originate from the vacuum fluctuation.



# Bubble-free FOPTs: simulation

We set up a pair of domain walls at $z_0 = \pm L/4$.

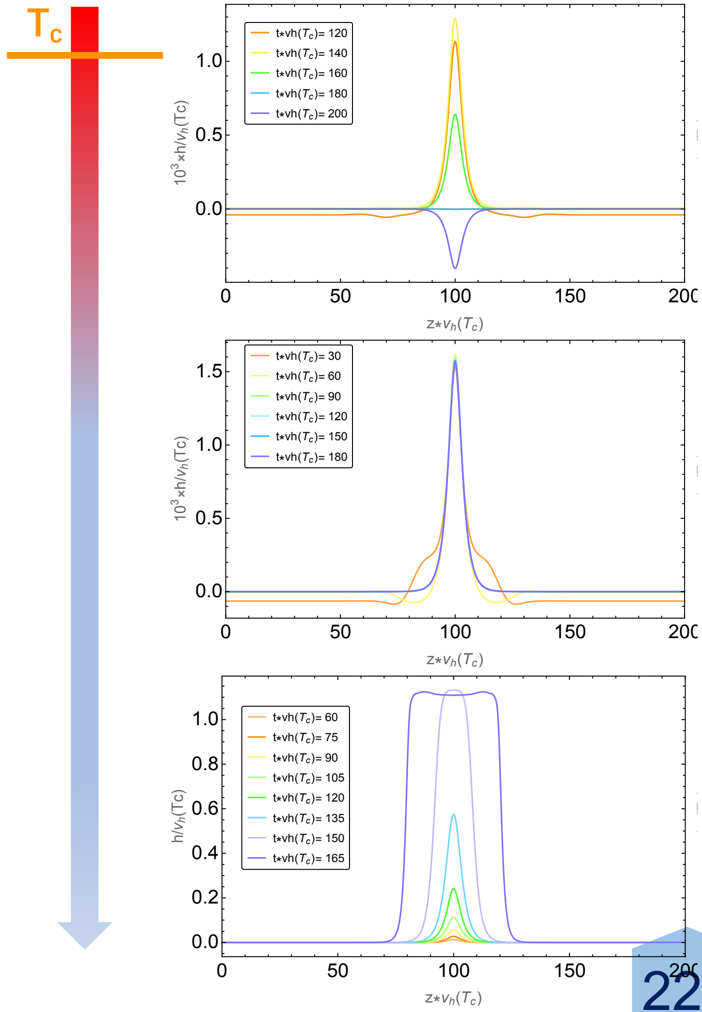



The domain wall destabilizes and quickly turns into the ***domain trench***, which will subsequently grow wider and eat the domains of the false vacuum ($s_\pm$ vacuum), making the entire volume eventually transition to the true vacuum (h vacuum) state.

# Bubble-free FOPTs: $T_{res}$ 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**, $T_{res}$.



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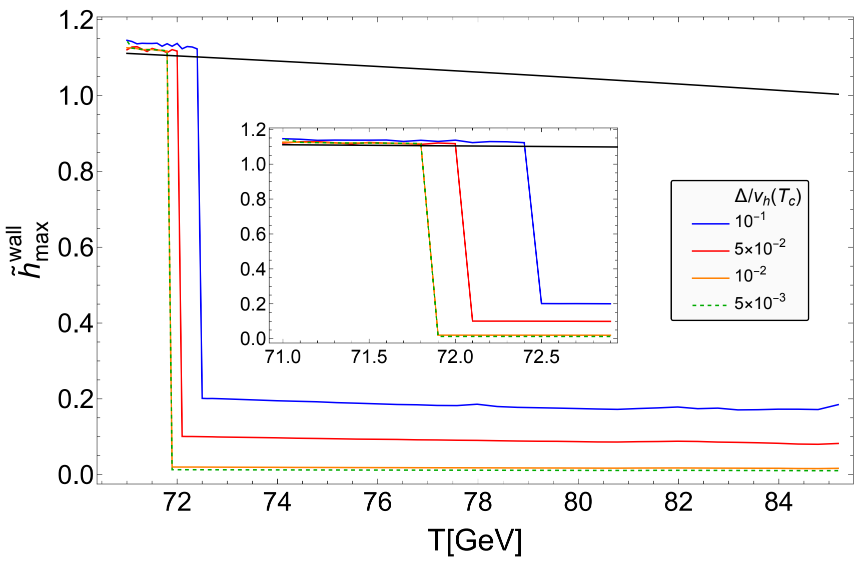
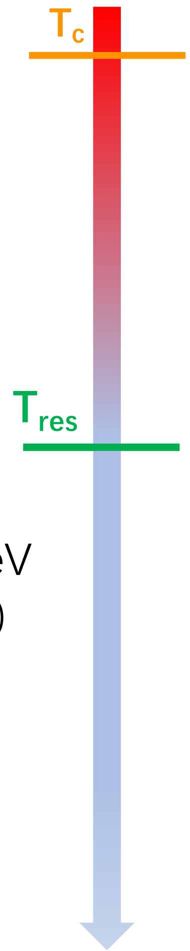
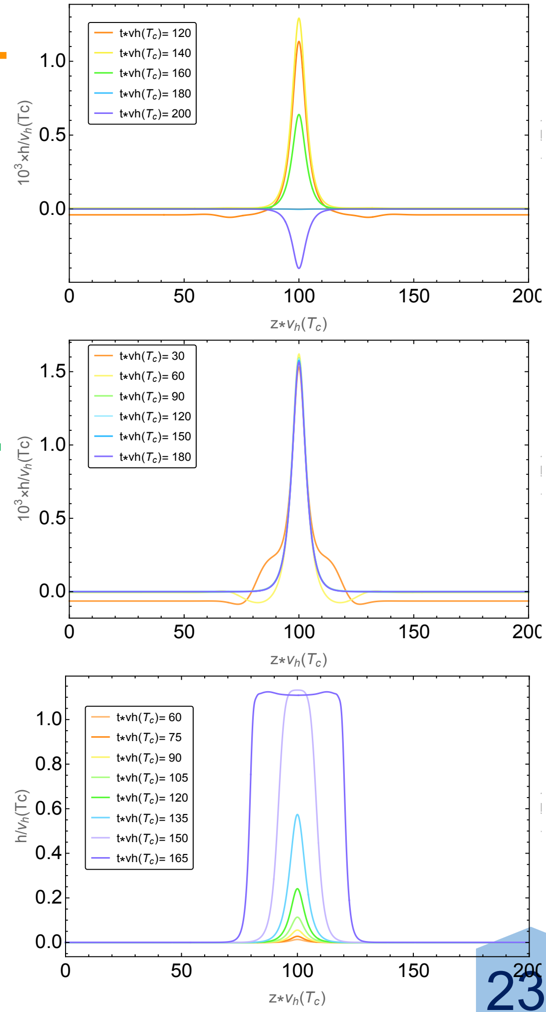



$T_{res}$ = 71.8 GeV (simulation)



# Bubble-free FOPTs: $T_{res}$ 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),

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

- the energy per area deposited into the domain wall, relative to the initial stable wall
- the wall tension characterized by the gradient energy

Therefore, $T_{res}$ is the highest temperature T satisfying $g(h_r, T) = 0 \quad \text{for} \quad T < T_c$

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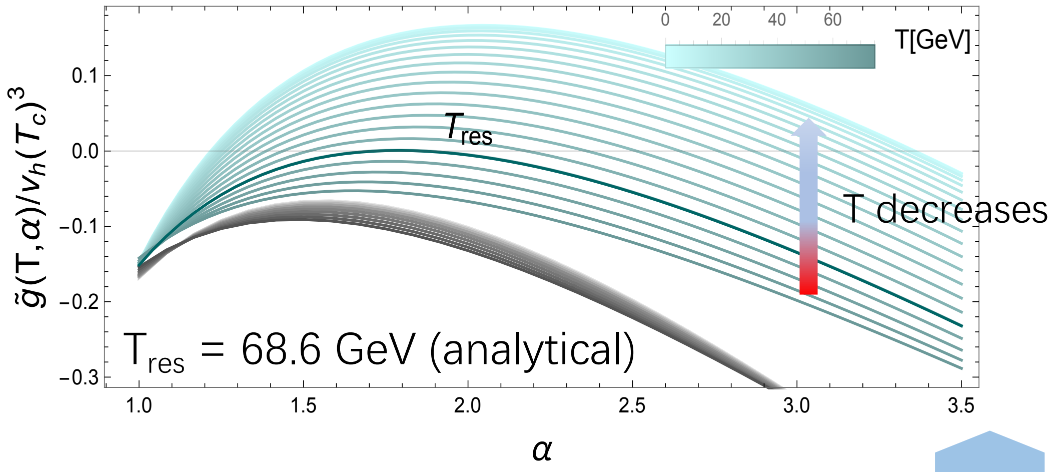
Therefore, $T_{res}$ is the highest temperature T satisfying $g(h_r, T) = 0 \quad \text{for} \quad T < T_c$

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

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

It is equivalent to the lowest Kaluza-Klein state.



# An application

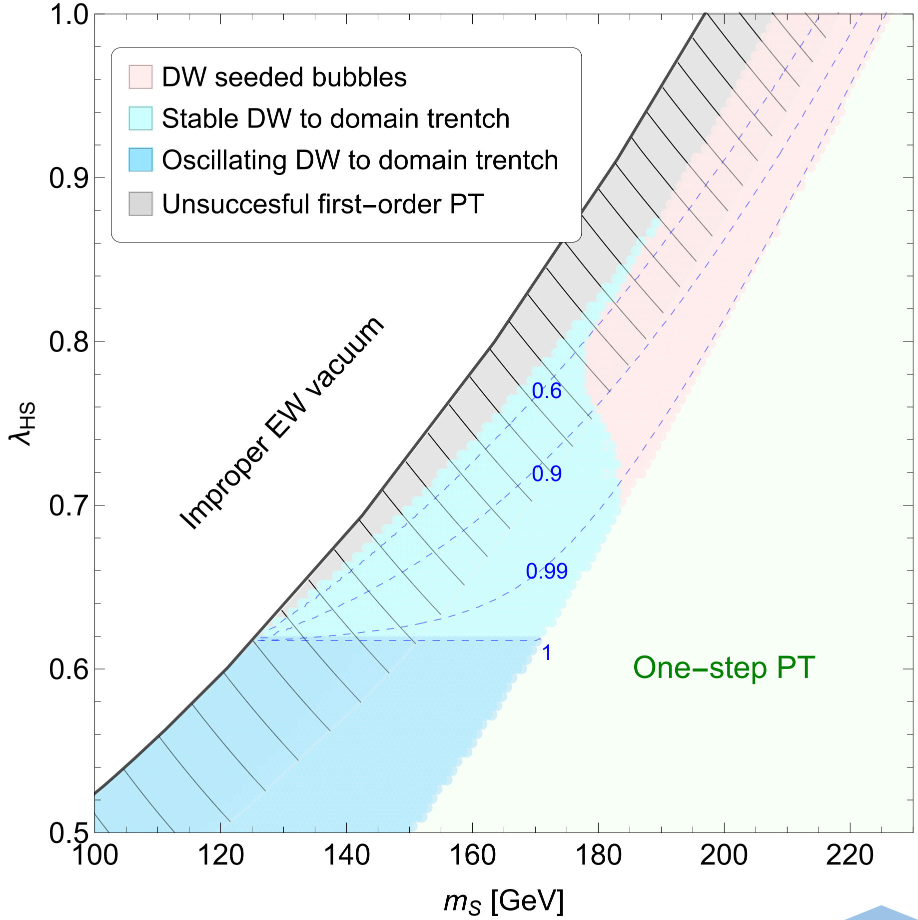
An application: the $Z_2$-odd singlet model (no mixing)

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

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.

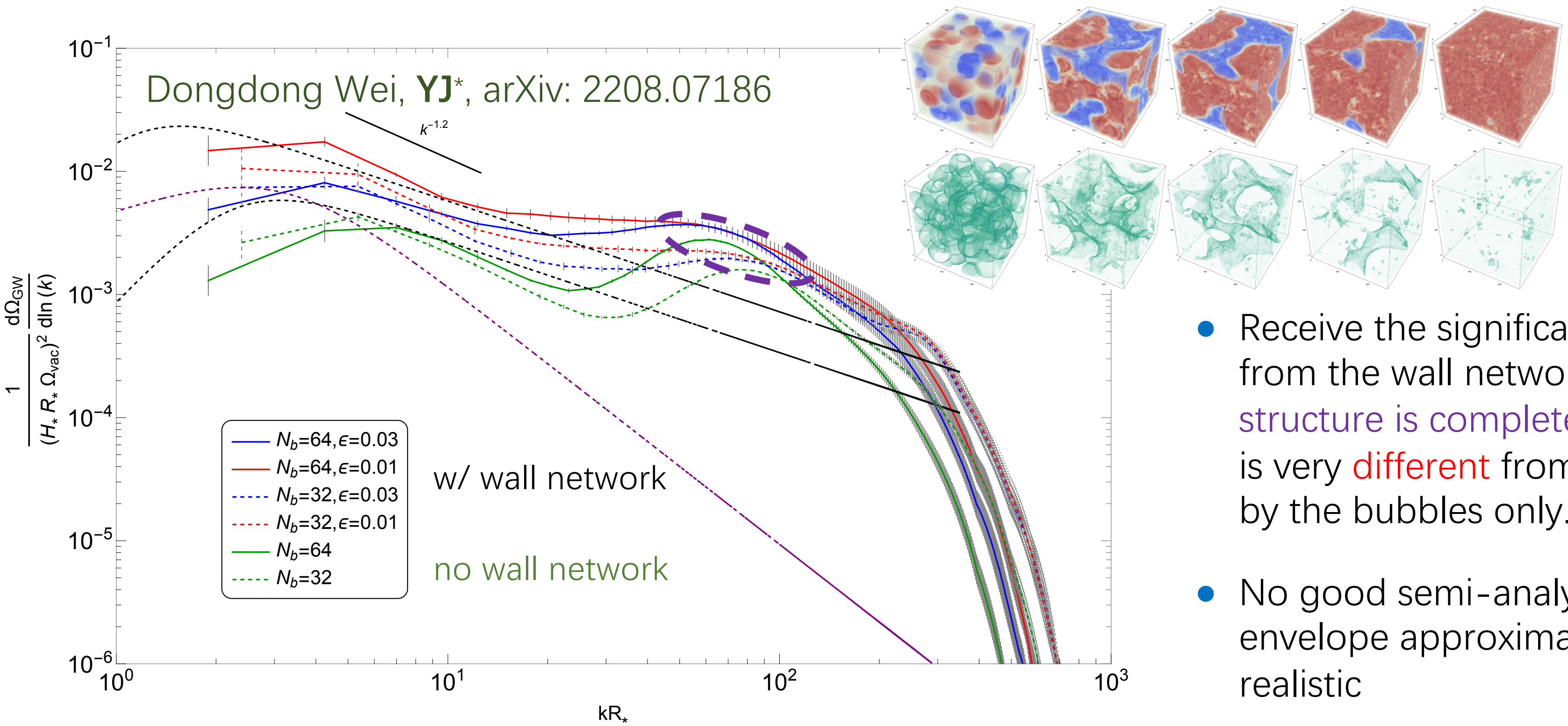
**Red**: phase transition proceeds with nucleating DW-seeded bubbles (seeded PT)

Gray: phase transition is unsuccessful



# Produced GWs

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




- Receive the significant contribution from the wall networks: double-pear structure is completely buried, which is very different from the one sourced by the bubbles only.
- No good semi-analytic model, envelope approximation is too realistic

# Conclusions

- The presence of domain walls, although no incontrovertible evidence found in our universe to date, can greatly enrich the ways phase transitions are completed.

- 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.

- 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.


Thank you