Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

DESY.

Particle Production after a first order phase transition: What happens when bubbles collide?

Henda Mansour †‡ , Supervisor: Bibhushan Shakya ‡

† Department of Physics, University of Hamburg

‡ Theory Group, Deutsches Elektronen Sychrotron (DESY)

27.11.2022 – Karlsruhe- Deutsche Physikerinnentagung 2022

First Order Phase Transitions

- A scalar field φ with a temperature-dependent effective potential

$$V_{\text{eff}}(\phi, T) = V_{\text{tree}}(\phi) + \Delta V(\phi, T)$$

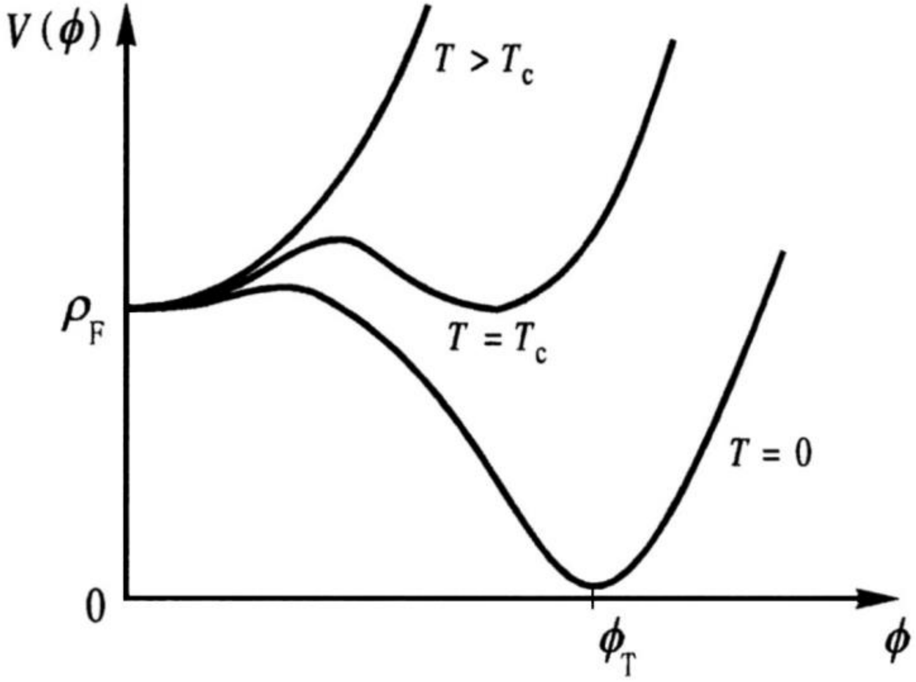
- Example: HT approximation of Higgs 1-loop effective potential

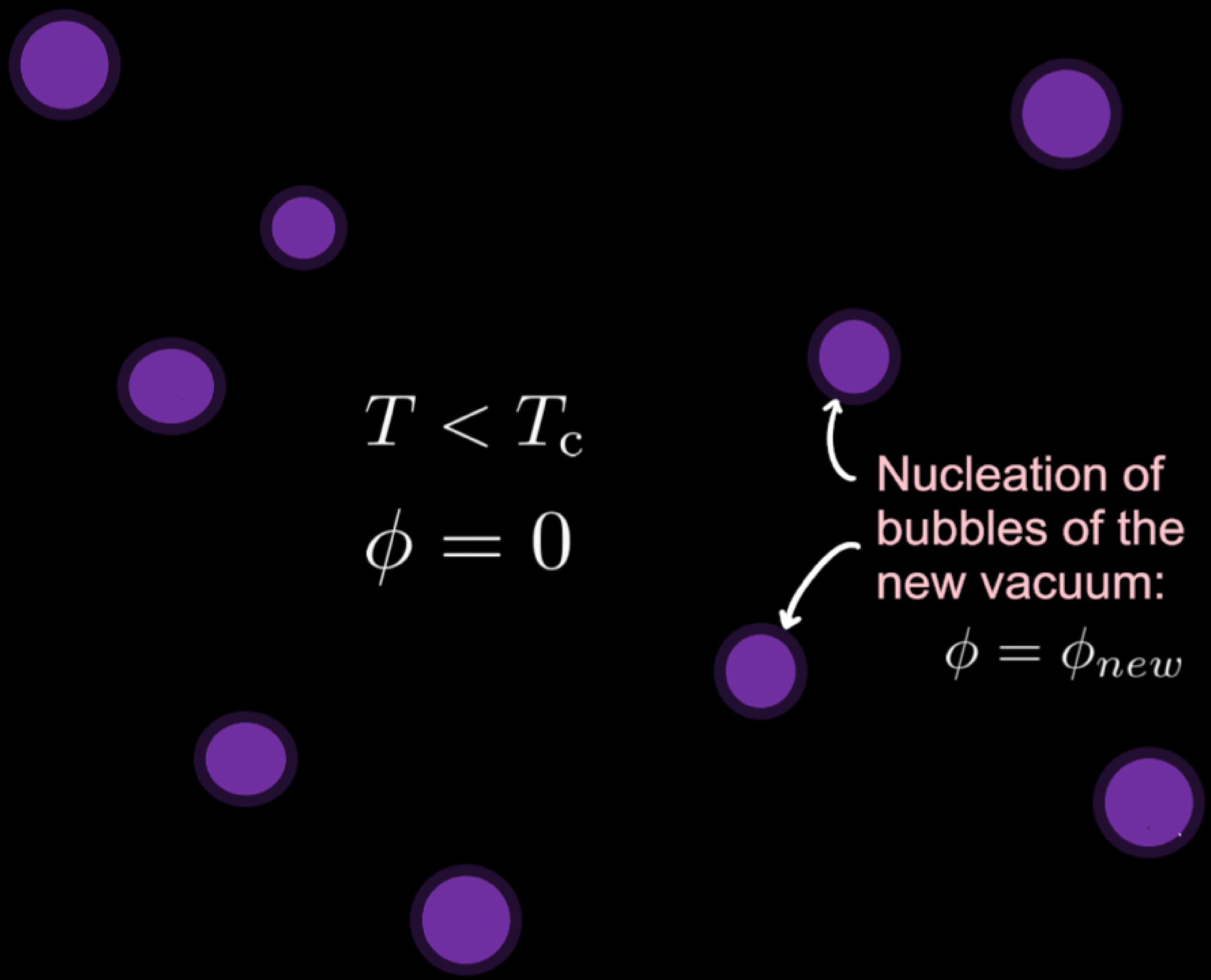
$$V(\phi, T) = \alpha(T^2 - T_0^2)\phi^2 - \beta T\phi^3 + \frac{\lambda(T)}{2}\phi^4$$

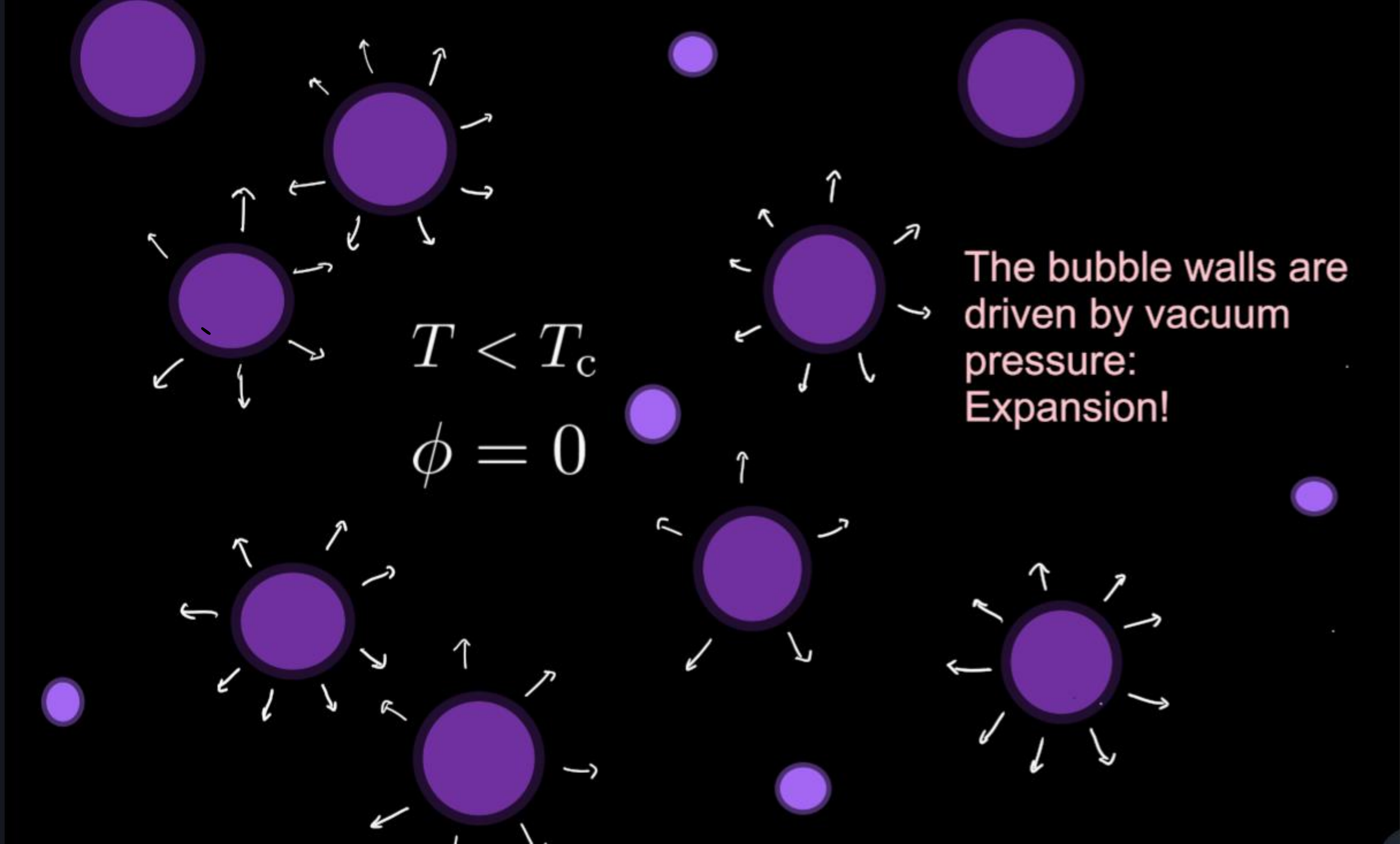
- New local minimum with decreasing temperature and at $T = T_c$ both minima are degenerate.

- Strength of the transition α, amount of energy released compared to the energy density of the plasma

$$\alpha = \frac{\rho_v}{\rho_{\text{plasma}}} \propto \frac{\Delta V}{T^4}$$



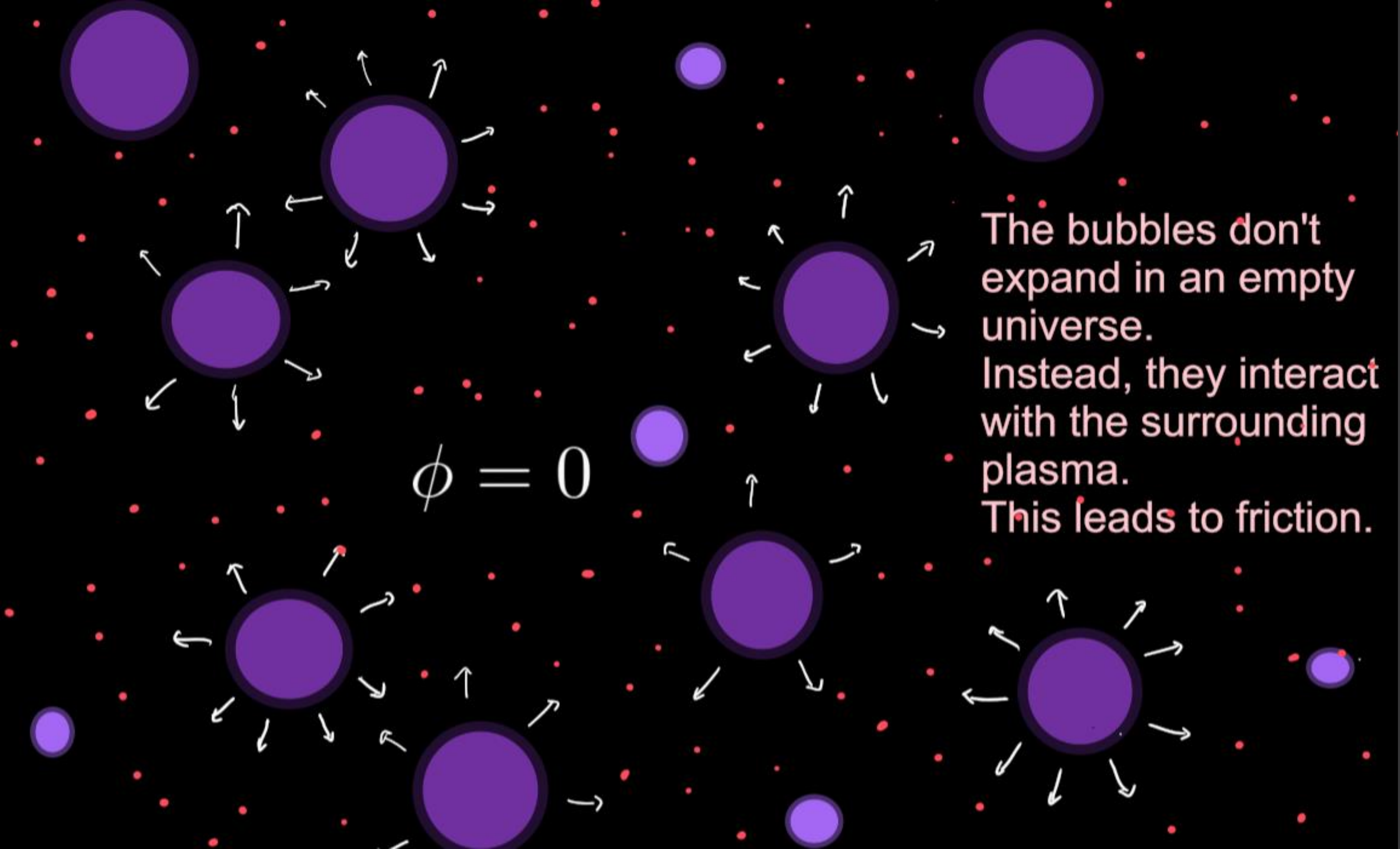

$T < T_c$
$\phi = 0$
Nucleation of bubbles of the new vacuum:
$\phi = \phi_{new}$



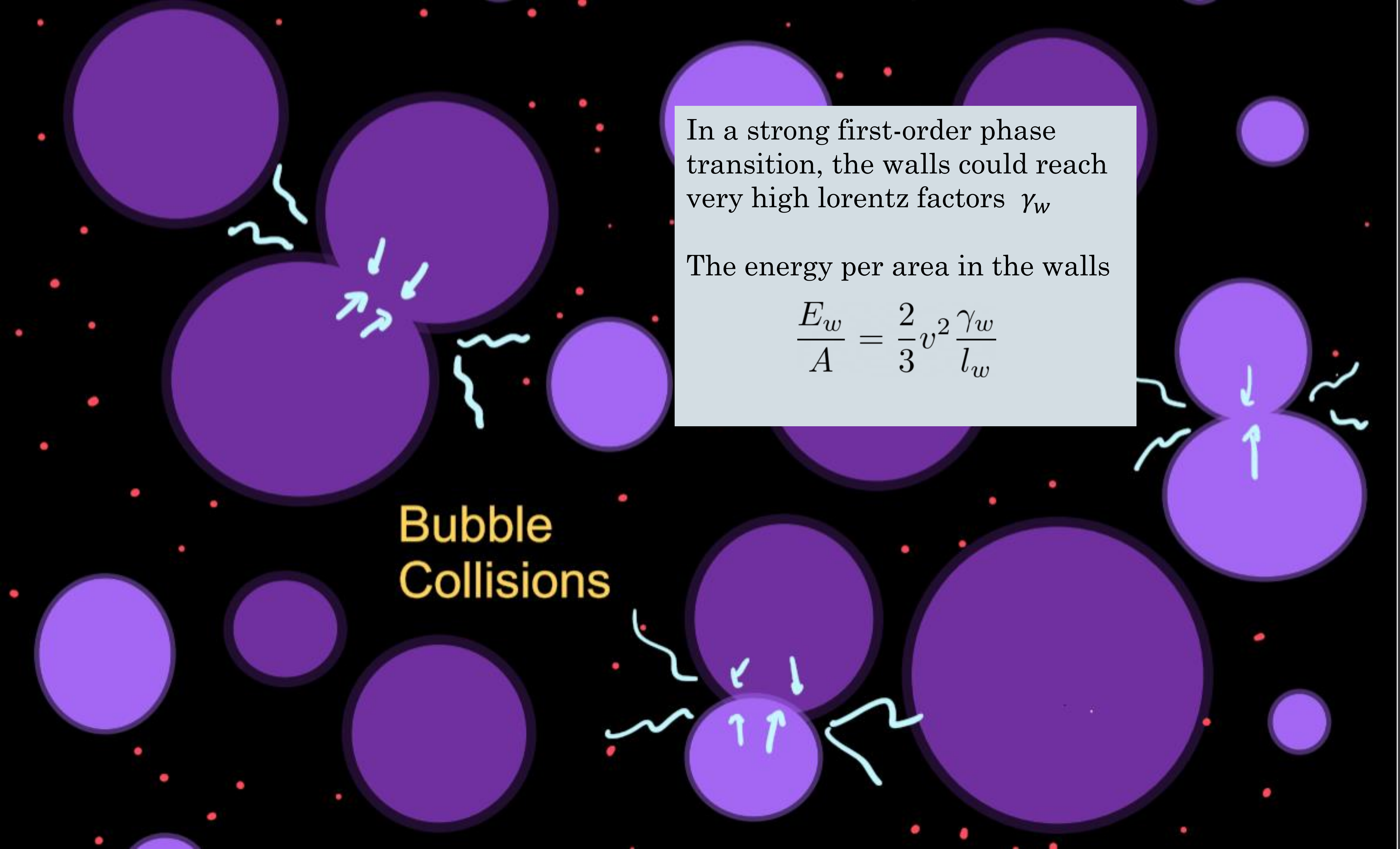
$T < T_c$

$\phi = 0$

The bubble walls are driven by vacuum pressure: Expansion!



The bubbles don't expand in an empty universe.
Instead, they interact with the surrounding plasma.
This leads to friction.



In a strong first-order phase transition, the walls could reach very high lorentz factors γ_w

The energy per area in the walls

$$\frac{E_w}{A} = \frac{2}{3} v^2 \frac{\gamma_w}{l_w}$$

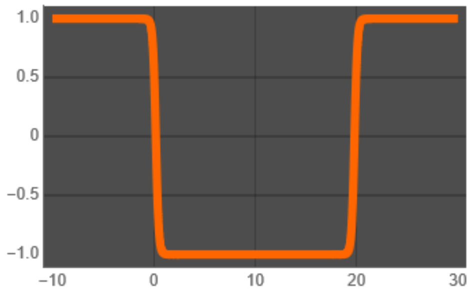
Investigating The Dynamics

To study the dynamics, we consider planar waves and the following potential

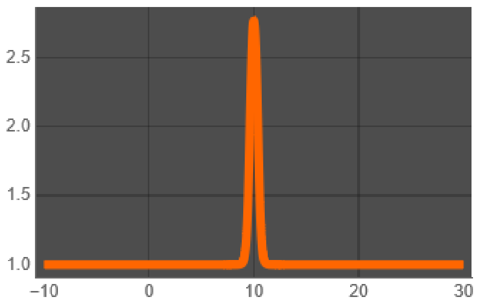
$$V(\phi) = av^2\phi^2 - (2a+4)v\phi^3 + (a+3)\phi^4 \quad \text{with a coupling} \quad \mathcal{L}_\chi = \frac{1}{2}m_\chi^2\chi^2 + \lambda\phi^2\chi^2$$

In the ultra-relativistic limit, the equation of motion can be simplified to:

$$\partial_s^2\phi + \frac{1}{s}\partial_s\phi + \frac{\mathrm{d}V}{\mathrm{d}\phi} = 0 \qquad s = \sqrt{t^2 - x^2}$$

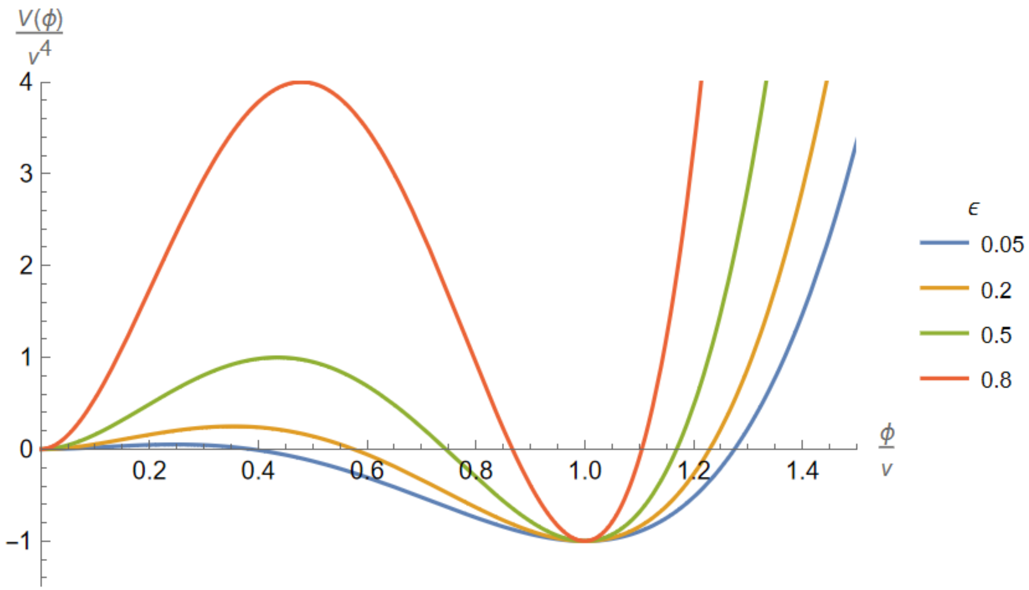


Before the collision:
Two planar walls approaching each other.



At collision:
The two walls superpose and the field experiences a jump.

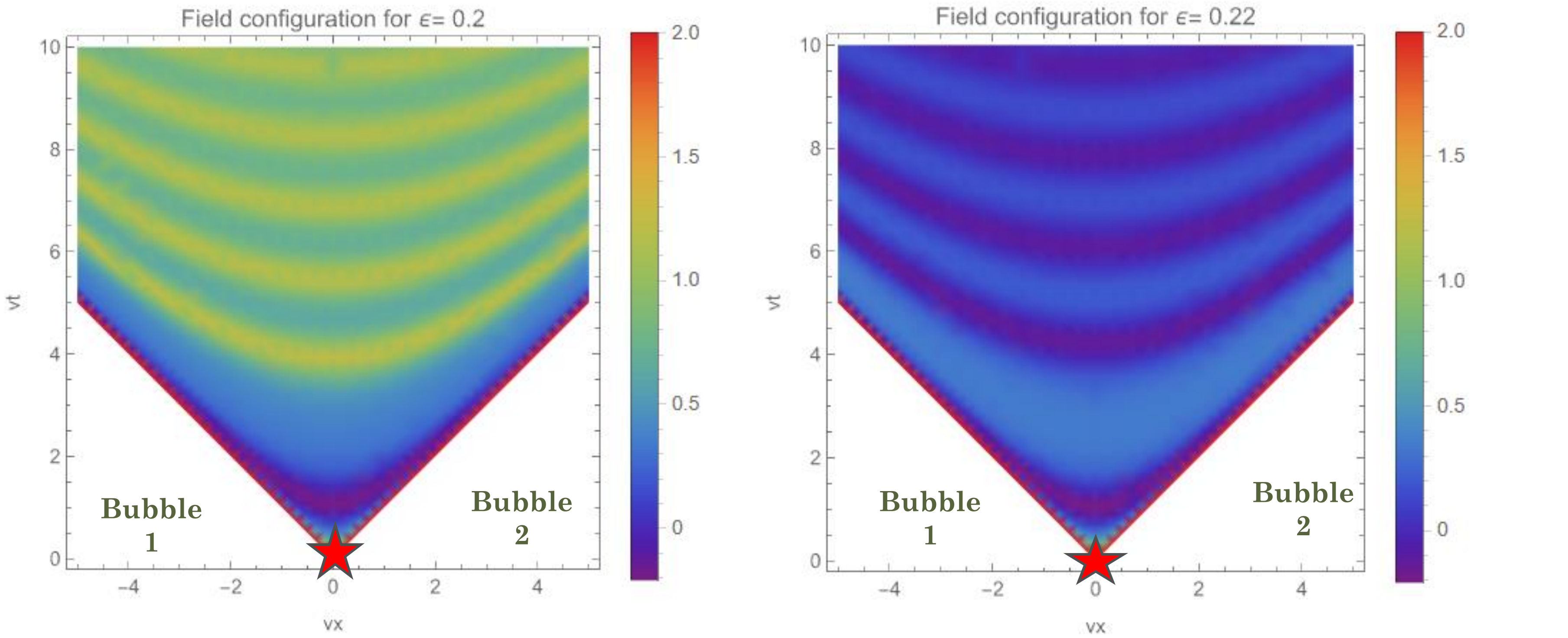
$$\phi_{\text{after}} = 2\phi_{\text{inside}} - \phi_{\text{outside}}$$



$$\epsilon = \frac{V_m - V_-}{V_m - V_+} = \frac{a^3(a+4)}{a^3(a+4) + 16(a+3)^3}$$

[Ryusuke Jinno, Thomas Konstandin, and Masahiro Takimoto. sep 2019, ArXiv: 1906.02588]

Field Configuration After Collision



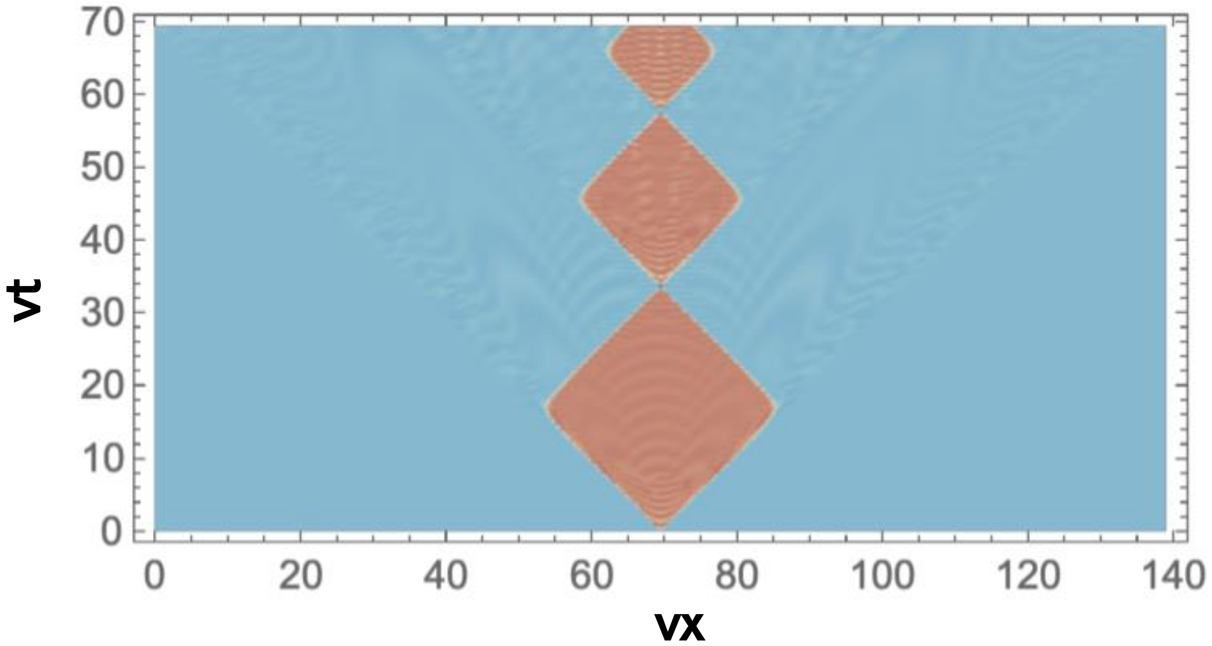
Inelastic collision: the field oscillates around the new minimum at $\varphi = 1$.

Elastic collision: the field oscillates back around the old minimum at $\varphi = 0$.

★ Marks the collision point.

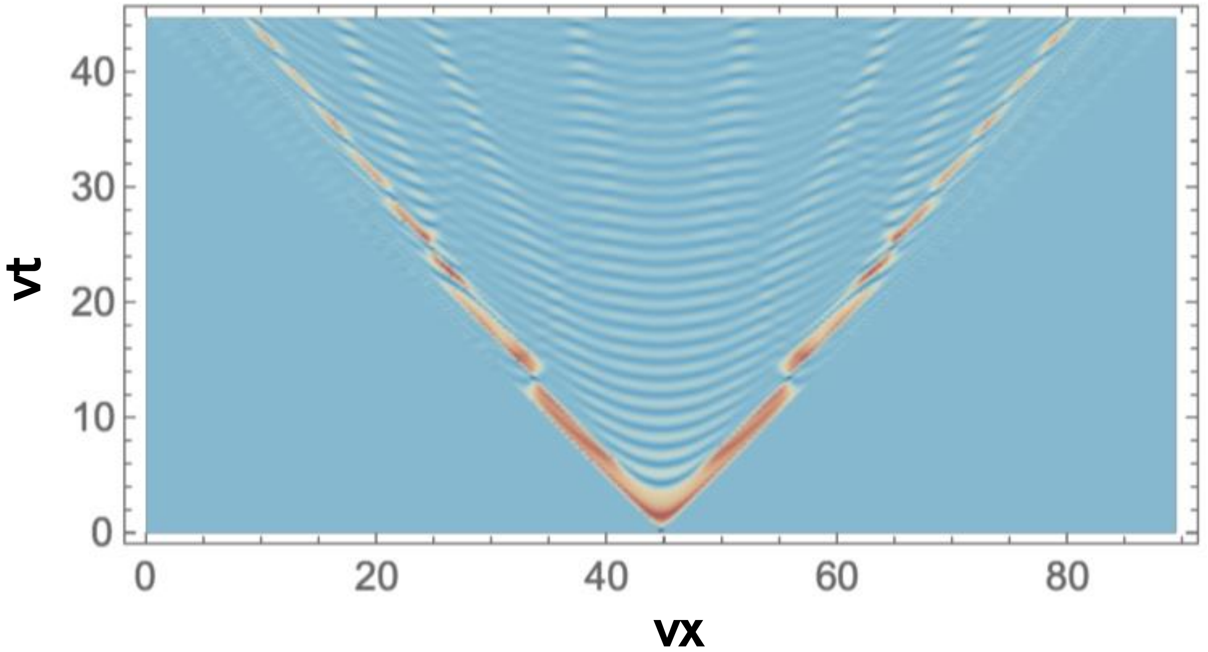
The behaviour of the field strongly depends on the potential shape!

[Thomas Konstandin and Géraldine Servant. Apr 2011, ArXiv:1104.4793]



Results from simulations of bubble collisions

(almost) elastic collisions:
Multiple cycles of collisions before establishment of the true vacuum. Re-establishment of the false vacuum in the regions between the walls.



Inelastic collisions:
The true vacuum is established after one collision

[Ryusuke Jinno, Thomas Konstandin, and Masahiro Takimoto. sep 2019 , ArXiv: 1906.02588]

Particle Production: A First Approach

Treat $\varphi(x,t)$ as an external background field to which the other quantum fields couple

$$\frac{N}{A} = 2\int \frac{dp_z\,dw}{(2\pi)^2} \underbrace{|\tilde{\phi}(p_z,w)|^2}_{\text{Fourier transformation of scalar field configuration}} \ \mathrm{Im}\ \underbrace{\left(\tilde{\Gamma}^{(2)}(w^2-p_z^2)\right)}_{\text{Fourier transformation of the effective action}}$$

Decompose the scalar configuration in Fourier modes and interpret each mode as a particle.
The integral over all „particles" multiplied with the decay rate gives the number of particles produced.

[R. Watkins, L. Widrow. Aspects of reheating in first order inflation. Nucl. Phys. B, 374:446–468, 1992]

Other non-perturbative effects

- Other mechanisms could play a role, so the Fourier decomposition approach might not be enough.

- Parametric resonance: exponential growth due to bose enhancement [1]

$$\ddot{\chi}_k + \left(k^2 + m_\chi^2(0) + 2\lambda\phi(t)^2\right)\chi_k = 0$$
$$\ddot{\chi}_k + \omega_k^2(t)\chi_k = 0$$

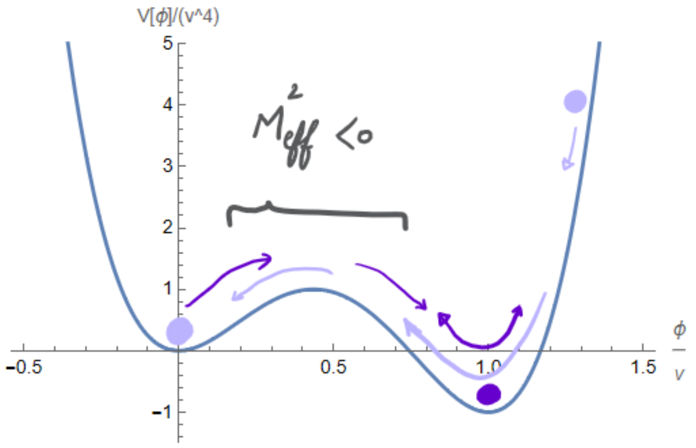
- Tachyonic preheating: when the φ field is over the potential barrier, the effective mass squared is negative, this leads to exponential growth of modes with $k < m_\varphi$

$$\phi_k(t) \propto \exp\left(it\sqrt{k^2 + M_\phi^2}\right) \quad \rightarrow \quad \phi_k(t) \propto \exp\left(t\sqrt{M_\phi^2 - k^2}\right)$$

- Since the field is spatially inhomogeneous in the case of

Bubble collisions, estimates of these effects need to be

Computed more carefully.



[1] Y. Shtanov, J. Traschen, and R. Brandenberger. Universe reheating after inflation. Physical Review D, 51(10):5438–5455, may 1995
[2] Lev Kofman. Tachyonic preheating, 2001

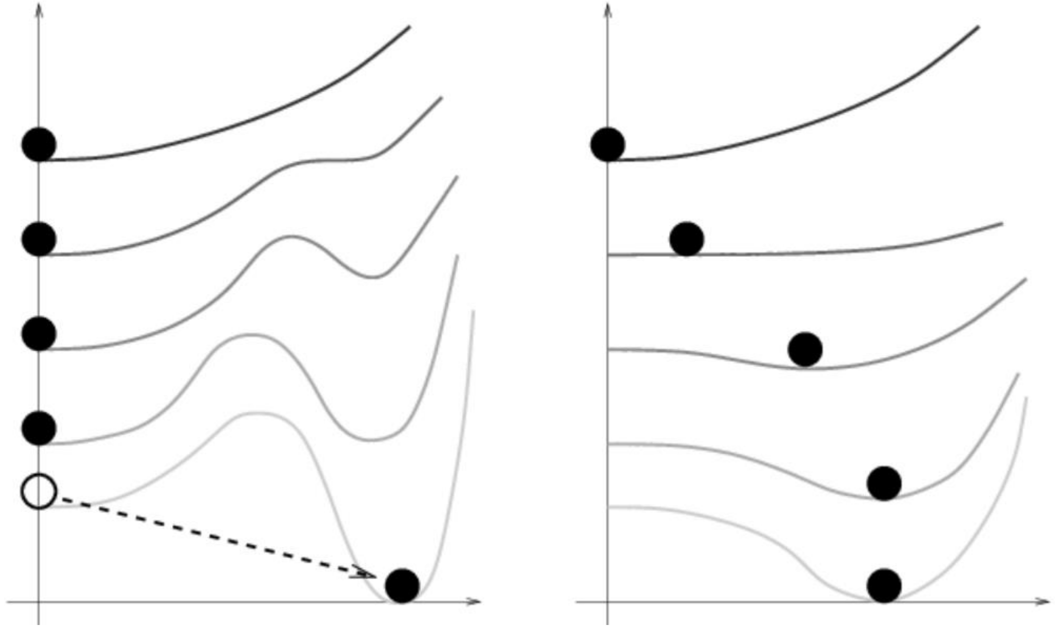
Conclusions and further questions

- Bubbles are cool!
- Research on the topic has until now over-simplified aspects of the field dynamics as well as other possibly very relevant mechanisms of particle production.
- To get the full picture in such scenarios, we will need to further investigate the interplay of different mechanisms.
- The importance of each mechanism depends on the dynamics of the field (i.e. Elastic vs. Inelastic collisions) , but also on the wall velocity.

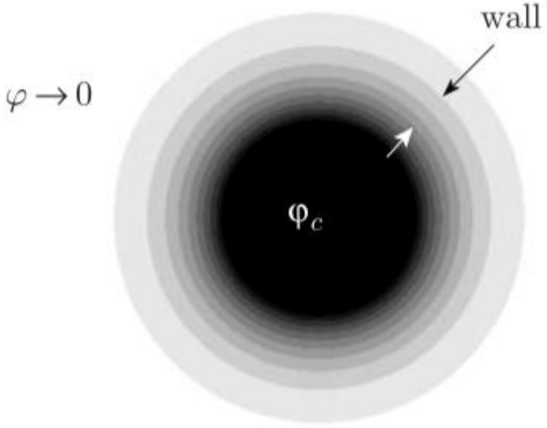
Thank you for your attention!

Lisa Website.
Credit: D. Weir, University of Helsinki

First-Order Vs. Second-Order PT



Effective potential as function of the scalar field for different temperatures. **Right:** The field rolls down continously to the new vacuum (second order phase transition). **Left:** Abrupt change of the field value (first order phase transition)



Bubble nucleation in the case of first-order PT.