

Particle productions during collisions of highly boosted bubble walls

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Haipeng An and H. Jiang, arXiv:2607.16398.

First-Order Phase Transitions in the Early Universe

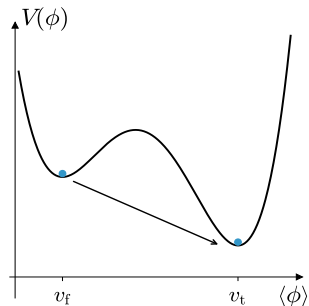
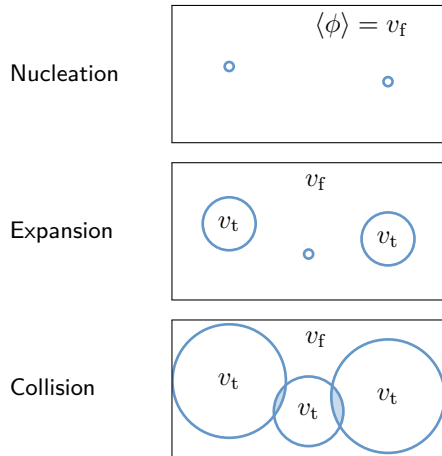
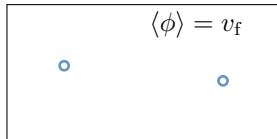


Figure: Potential profile of a first-order phase transition.

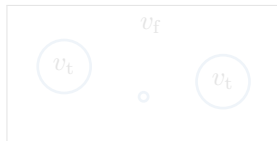
Figure: Three stages of bubble dynamics during a first-order phase transition: nucleation, expansion, and collision.

First-Order Phase Transitions in the Early Universe

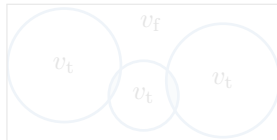
Nucleation



Expansion



Collision

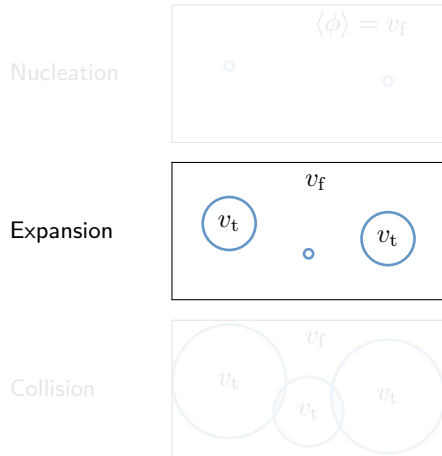


Spectrum: $E \lesssim 1/L_w$.

Number density: $n \propto L_w^{-3} (R_c/R_*)^3$.

Figure: Three stages of bubble dynamics during a first-order phase transition: nucleation, expansion, and collision.

First-Order Phase Transitions in the Early Universe



Expansion in vacuum

Spectrum: $E \lesssim 1/R_c \sim 1/L_w$.

Number density: $n \propto R_*^{-3}$.

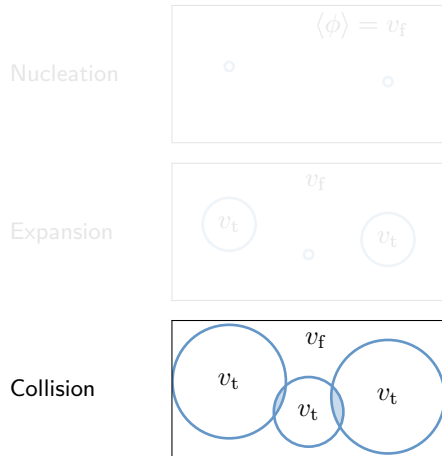
Expansion in thermal bath

Much more complicated.

Depends on the details.

Figure: Three stages of bubble dynamics during a first-order phase transition: nucleation, expansion, and collision.

First-Order Phase Transitions in the Early Universe



Runaway bubble (e.g., vacuum, supercool): $\gamma_w \gg 1$

high energy particles:
Baryogenesis/Leptogenesis!

Spectrum: $E \lesssim \gamma_w / L_w$.

Number density: $n \propto R_*^{-1}$.

Figure: Three stages of bubble dynamics during a first-order phase transition: nucleation, expansion, and collision.

Efficiency Factor

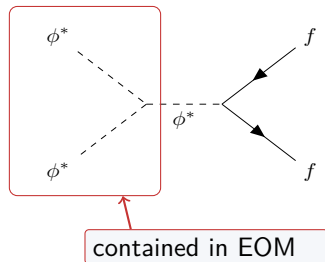
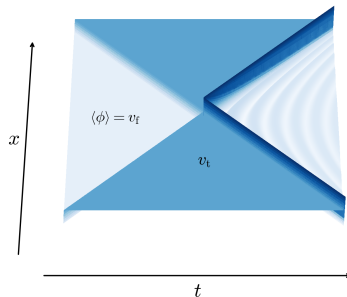
Particle production rate*:

$$\frac{N}{A} = \frac{1}{2\pi^2} \int \text{Im} \left[\tilde{\Gamma}^{(2)}(\chi) \right] f(\chi) d\chi.$$

Efficiency factor:

$$f(\chi) = \int \delta(\omega^2 - k_z^2 - \chi) |\tilde{\phi}(\omega, k_z)|^2 d\omega dk_z.$$

* R. Watkins and L. M. Widrow, Nucl. Phys. B 374 (1992) 446–468.



Previous Studies

Analytical*:

Elastic collision: $f(\chi) \sim v^2 \chi^{-2}$.

Inelastic collision: $f(\chi) \sim v^2 m^4 \chi^{-4}$.

Numerical**:

Both cases: $f(\chi) \sim v^2 \chi^{-2}$.

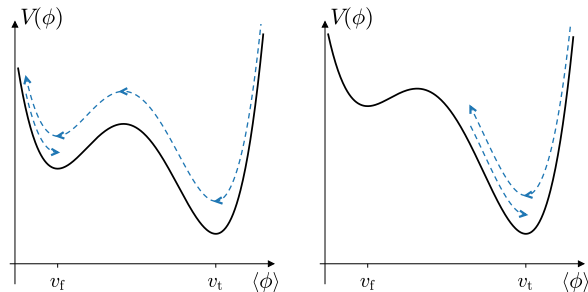
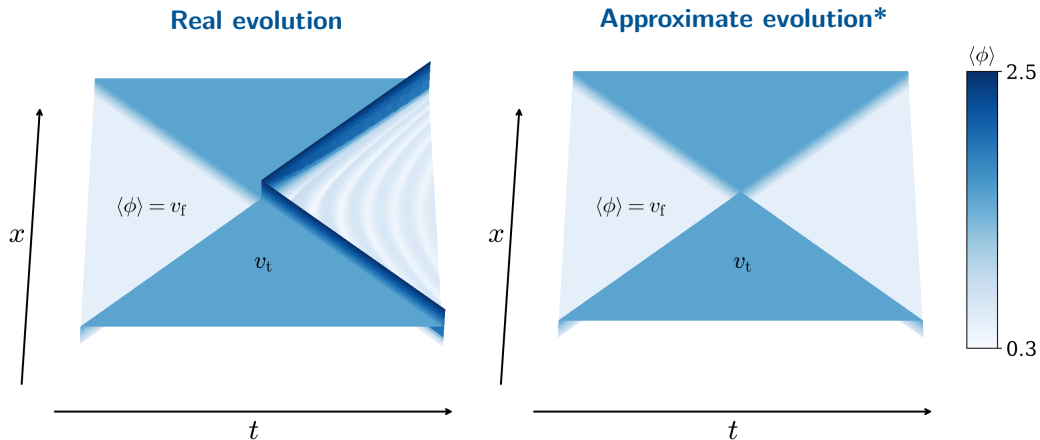


Figure: Elastic (left) and inelastic (right) collisions.

* A. Falkowski and J. M. No, JHEP 02 (2013) 034, [arXiv:1211.5615]

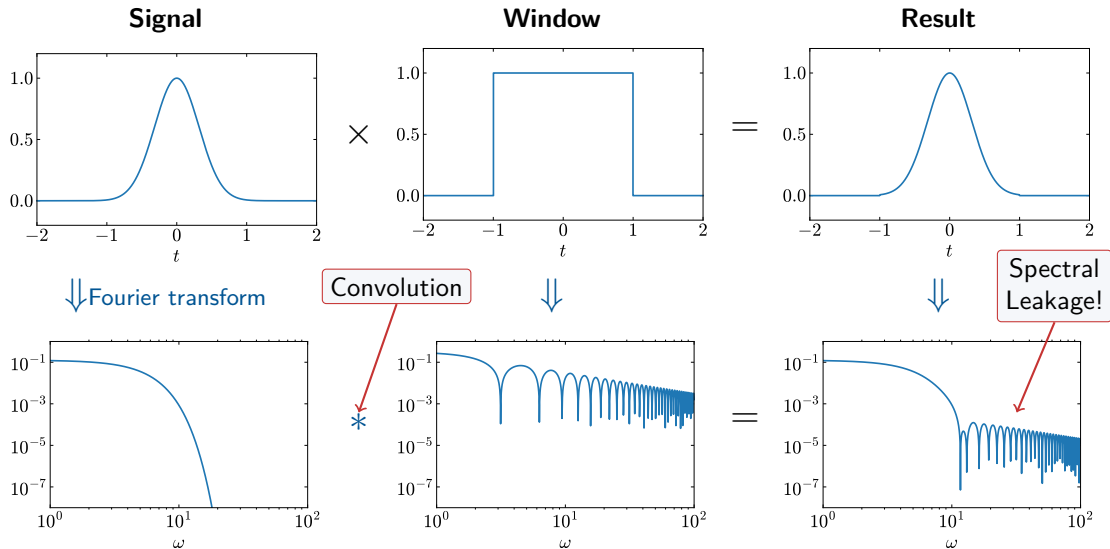
** H. Mansour and B. Shakya, Phys. Rev. D 111 (2025), no. 2 023520, [arXiv:2308.13070].

Why We Differ (Analytical)



* A. Falkowski and J. M. No, JHEP 02 (2013) 034, [arXiv:1211.5615]

Why We Differ (Numerical)



Origin of the χ^{-4} Scaling

Asymptotic expansion:

At large χ , the Fourier transform of the field profile can be expanded as:

$$\tilde{\phi}(\chi) = \frac{C_1}{\chi} + \frac{C_2}{\chi^2} + \frac{C_3}{\chi^3} + \dots$$

Coefficients:

By analyzing the field profile, we can determine the coefficients in the asymptotic expansion:

$$C_1 = 0, \quad C_2 = -2V'(\phi(0^+)), \quad \dots$$

Field value immediately after the collision

Leading order behavior:

At large χ , the efficiency factor behaves as:

$$f(\chi) \sim |\tilde{\phi}(\chi)|^2 \sim \frac{4[V'(\phi(0^+))]^2}{\chi^4} + O(\chi^{-5}).$$

How to Perform Numerical Simulation?

Trapping equation:

After highly-boosted collision, the field profile can be described by:

$$\partial_\tau^2 \phi + \frac{1}{\tau} \partial_\tau \phi + V'(\phi) = 0.$$

M_h : mass of ϕ around the VEV after collision.

$i\epsilon$ prescription:

To suppress the spectral leakage, we introduce an $i\epsilon$ -term in frequency:

$$\sqrt{\chi} = \sqrt{\omega^2 - k_z^2} \rightarrow \sqrt{(\omega + i\epsilon)^2 - k_z^2} \simeq \sqrt{\chi} + i\epsilon \frac{\omega}{\sqrt{\chi}}.$$

Constraints:

Shannon-Nyquist theorem: grid spacing $\ll \chi^{-1/2}$.

Negligible regulator effects: $\omega\epsilon \ll \chi$.

Window-signal separation: $\epsilon \times \text{total simulation time} \gg 1$.

Numerical Simulation (Elastic)

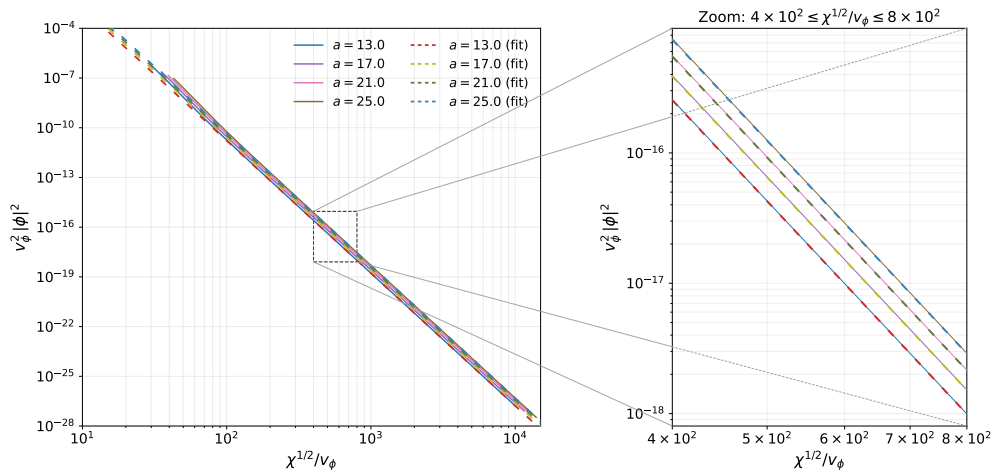


Figure: Elastic case. Dashed line: theoretical result $f(\chi) \propto \chi^{-4}$.

Numerical Simulation (Inelastic)

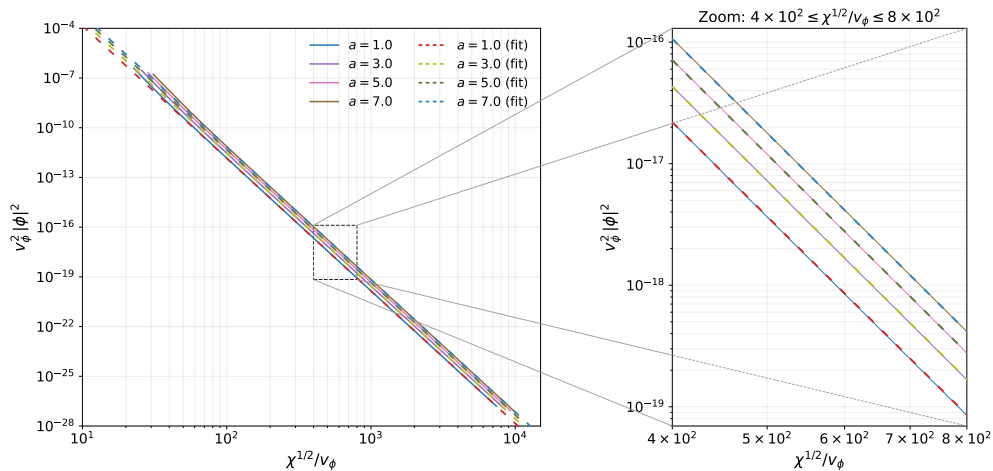


Figure: Inelastic case. Dashed line: theoretical result $f(\chi) \propto \chi^{-4}$.

Example: Yukawa Coupling

Lagrangian: $\mathcal{L} \supset y_\psi \phi \bar{\psi} \psi$.

First-order phase transition

Particle production rate in $(1+1)$ -dim:

Spectrum: $E_\psi \sim m_\psi$.

$$\text{Number density: } \frac{N_\psi}{A} \simeq \frac{y_\psi^2}{35\pi^3} \left(\frac{V'(2v_t - v_f)}{(v_t - v_f)^2} \right)^2 \left(\frac{(v_t - v_f)^2}{4m_\psi^2} \right)^2 \log \left(\frac{\gamma_w}{m_\psi L_w} \right)$$

$(3+1)$ -dim correction:

$$n_{3+1} \sim \frac{2R_{\text{coll}}}{R_{\text{coll}} + \sqrt{R_{\text{coll}}^2 + R_{\text{final}}^2}} n_{1+1}.$$

Conclusion and Outlook

Conclusions:

The efficiency factor is $f(\chi) \sim \chi^{-4}$.

The typical energy is $E \sim m$.

In $3 + 1$ dimensions, the particle number density is suppressed by an $O(1)$ factor which depends on the geometry of the bubbles.

Outlook:

Baryogenesis/leptogenesis: heavy particles $\rightarrow$ baryon/lepton asymmetry.

Dark matter: heavy particles $\rightarrow$ dark matter relic abundance.