アクシオンのバブルミスアラインメント
Bubble Misalignment Mechanism for Axions

Aug 21, 2024
PPP2024, Kyoto

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Based on JCAP05(2024)122 arXiv:2402.09501 collaboration with Kai Murai, Fuminobu Takahashi, and Wen Yin

First-order phase transition

Bubble Misalignment Mechanism for Axions

Dark matter production

We study the dynamics of axion dark matter in the first-order phase transition.

Axions

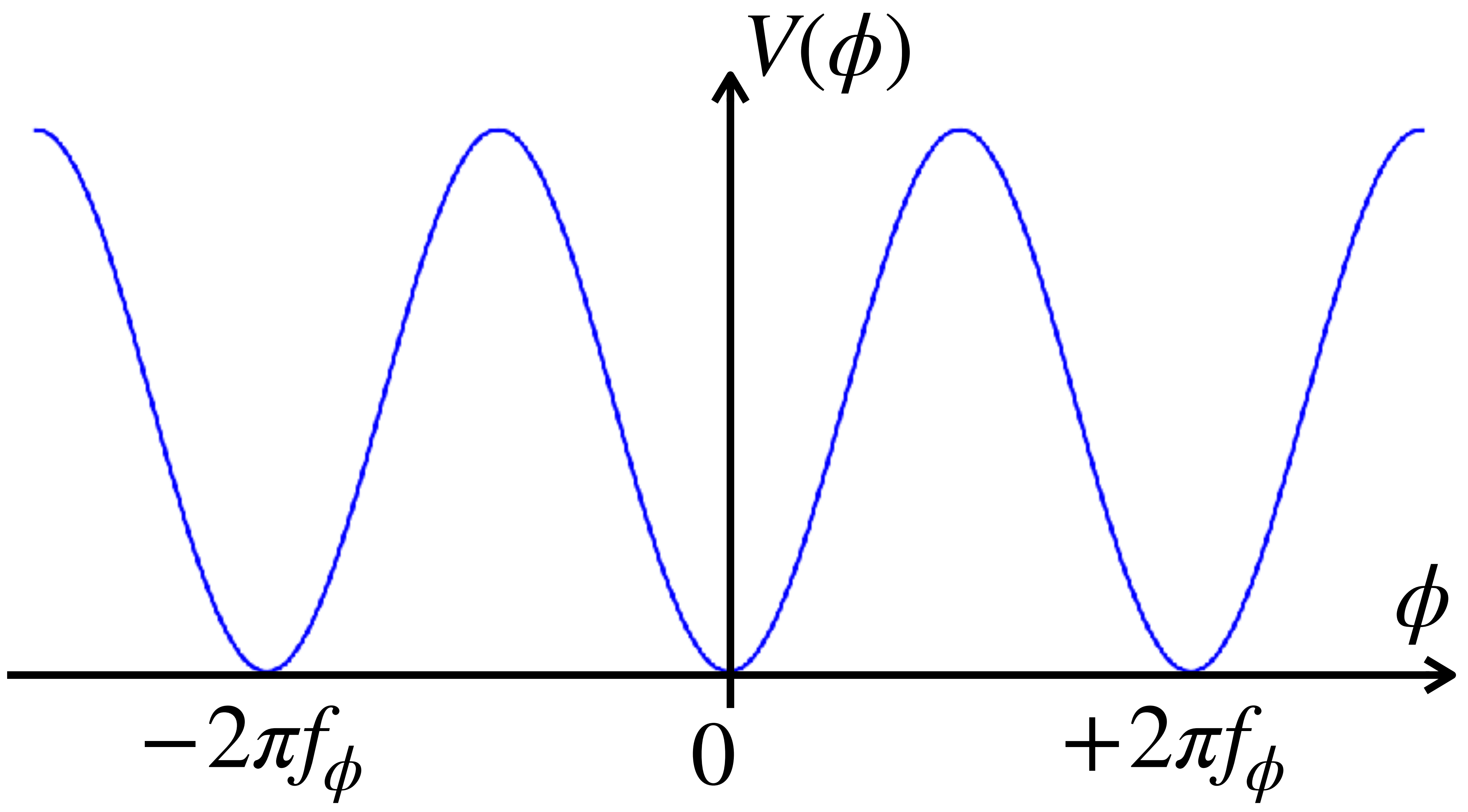
Axion is a scalar particle with shift symmetry.

$$\phi \to \phi + 2\pi f_\phi$$

Its decay constant f_ϕ suppresses its interactions.

Axion obtains tiny mass m_ϕ by the explicit breaking of shift symmetry.

Hawking `75, Banks and Dixon `88, Coleman `88, ⋯



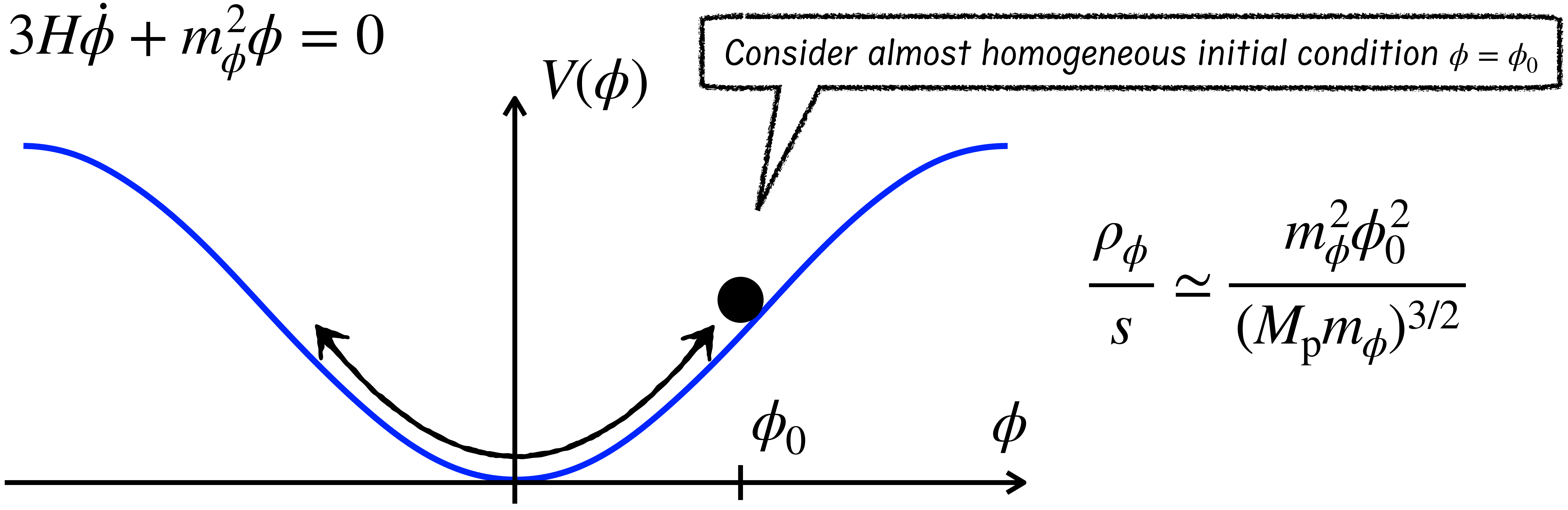
Misalignment Mechanism

Preskill, Wise, Wilczek `83, Abbott, Sikivie `83, Dine, Fischler `83

Axion starts to oscillate after the Hubble parameter H becomes smaller than its mass m_ϕ.

This coherent oscillation acts as dark matter.

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$



$$\frac{\rho_\phi}{s} \simeq \frac{m_\phi^2 \phi_0^2}{(M_\mathrm{p} m_\phi)^{3/2}}$$

First-Order Phase Transition

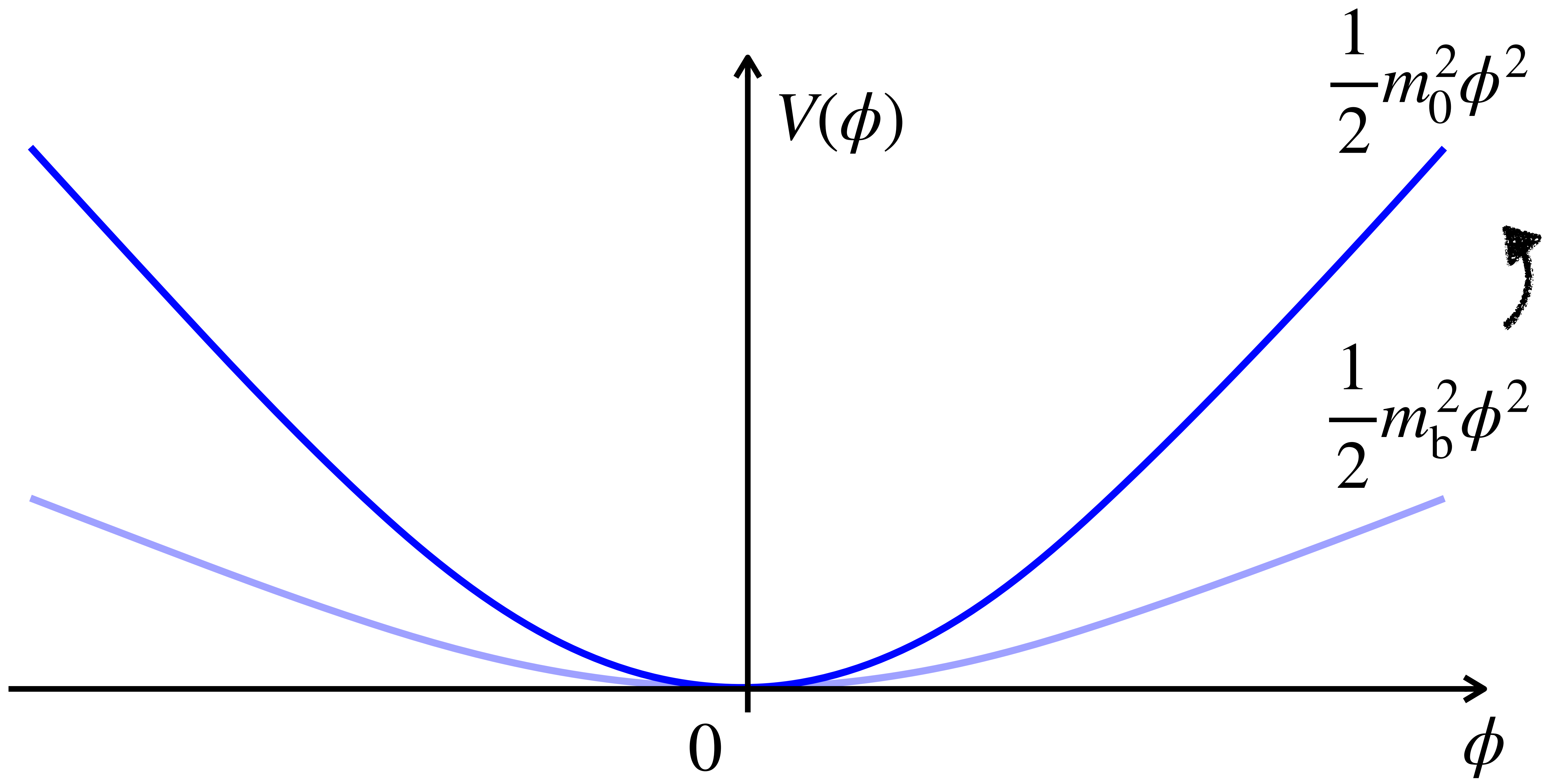
First-order phase transitions appear in the theories beyond the standard model.

For example, the phase transition from the deconfined phase to the confined phase in the pure $SU(N)$ Yang-Mills theory where $N \geq 3$ is known to be a first-order phase transition. B. Lucini, M. Teper and U. Wenger, `03, `05

There are various cosmological implications.

e.g.) baryogenesis, dark matter, and gravitational waves, $\cdots$

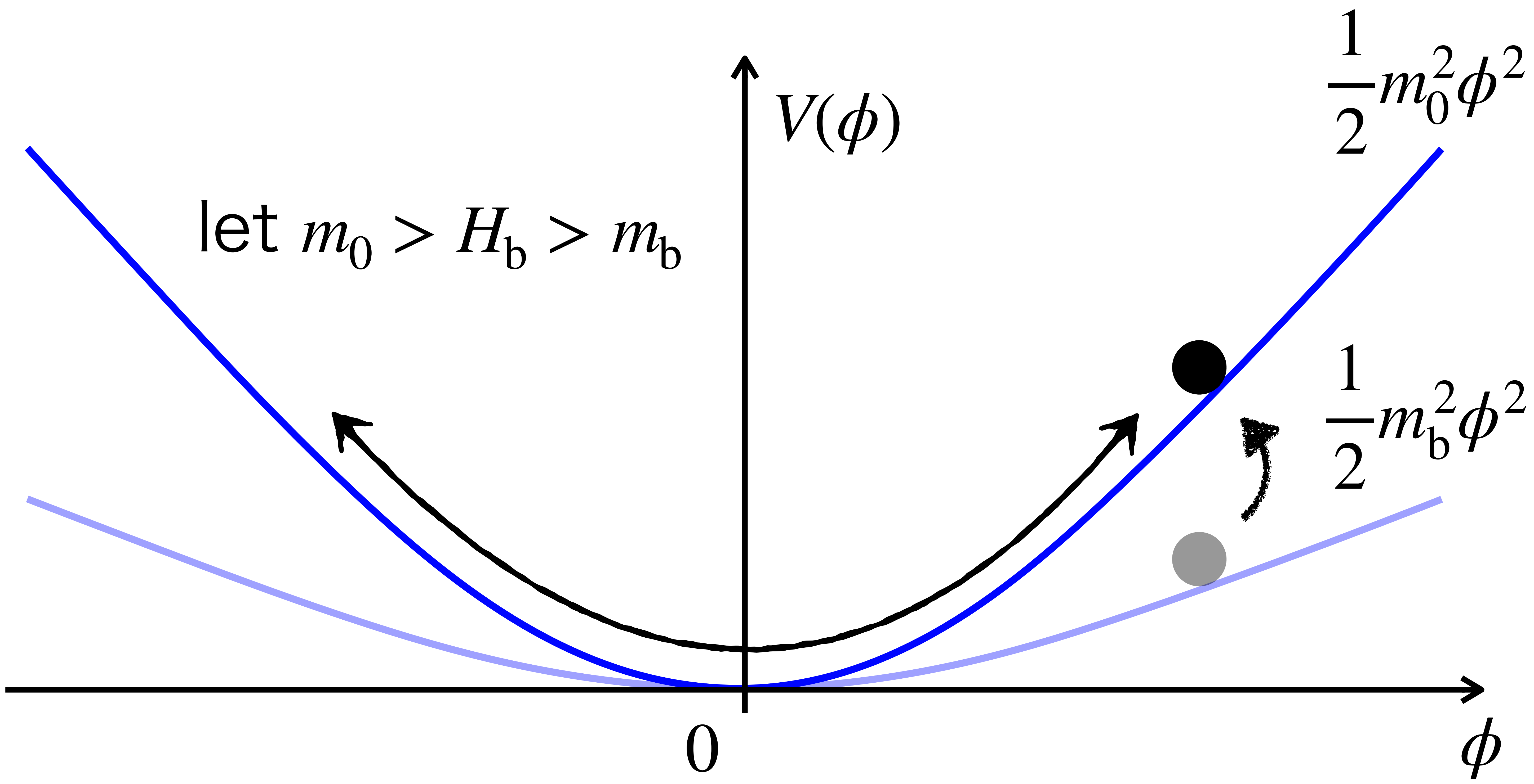
First-Order Phase Transition



@ $T = T_b$ (bubble nucleation temperature)

$m_0 > m_b$

When mass changes homogeneously



$$\frac{\rho_\phi}{s} \simeq \frac{m_0^2\phi_0^2}{T_\mathrm{b}^3}$$

This corresponds to the case where the duration of phase transition is enough shorter than m_0

How about the case where spatial inhomogeneity due to the bubbles becomes important?

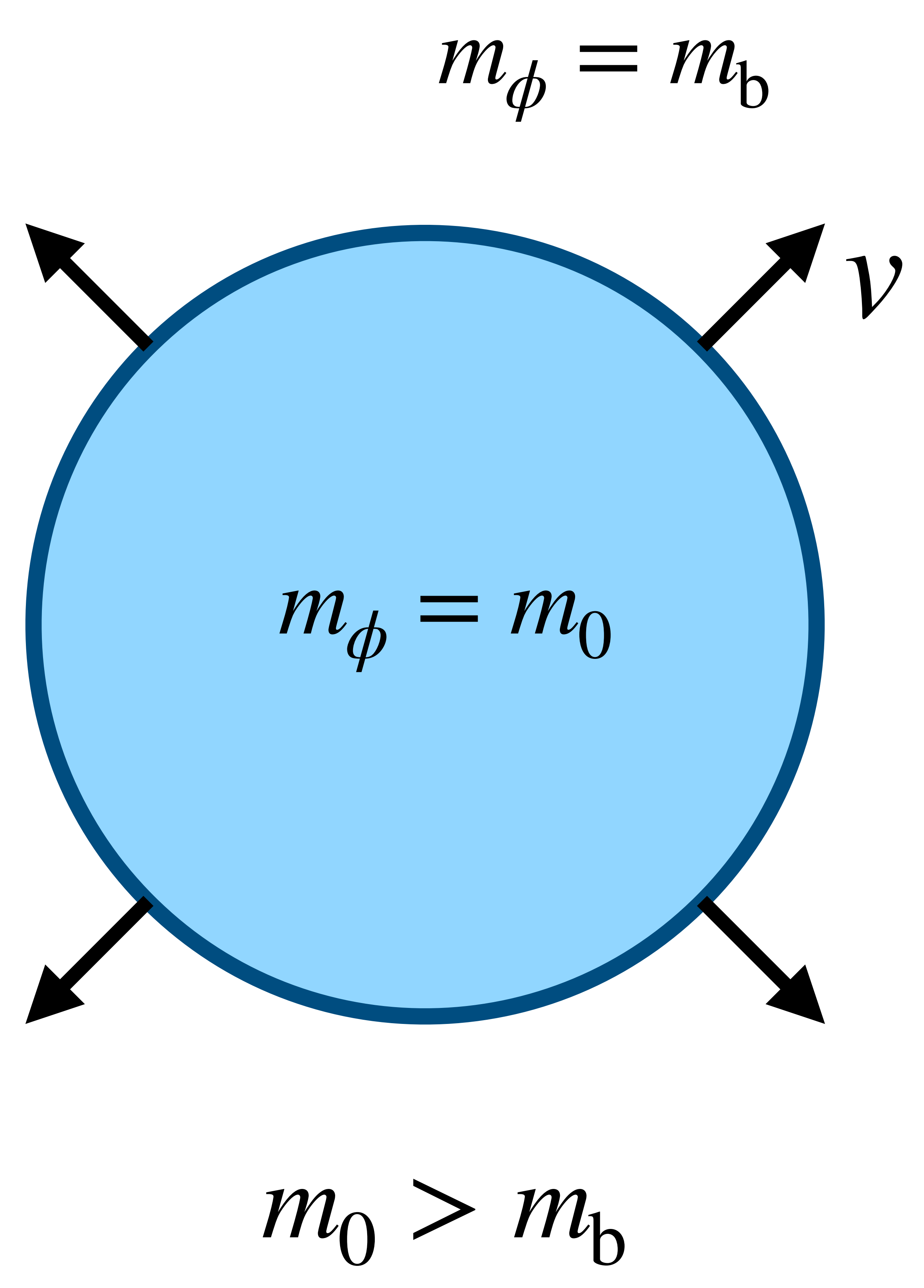
Bubble Nucleation

Bubble nucleation rate generically can be written in

$$\Gamma(t) \propto \exp[\beta(t - t_0) + \cdots]$$

Spherical bubbles nucleate at $T = T_b$, expand out with velocity v, and percolate with time scale β^{-1}.

Assume $\beta > H_b$ where H_b is the Hubble parameter at bubble nucleation.



Bubble Nucleation

Let us consider

Bubble dynamics plays an important role.

$$m_{\rm b}, H_{\rm b} < \beta < m_0$$

thus the axion oscillation is relevant inside bubbles during the phase transition, while it is not outside bubbles.

JL, Murai, Takahashi, and Yin 2402.09501

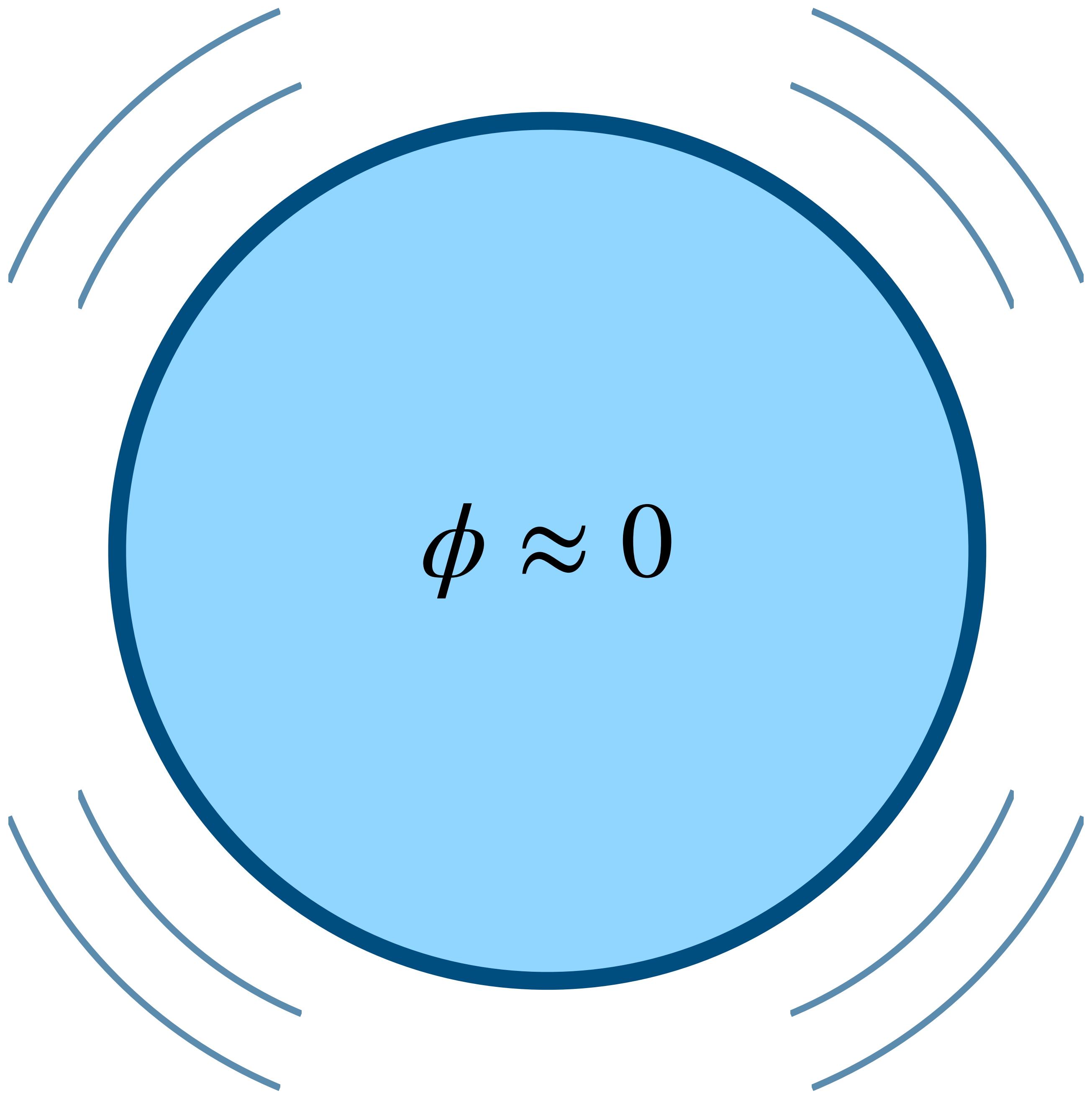
Then three remarkable phenomena take place:

1. Bubbles expel the axion waves producing "axion shock wave".
2. Axion waves accumulate between bubbles and are accelerated analogous to "Fermi acceleration".
3. Axions that obtain enough energy start to transmit into bubbles.

Bubbles expel the axion waves

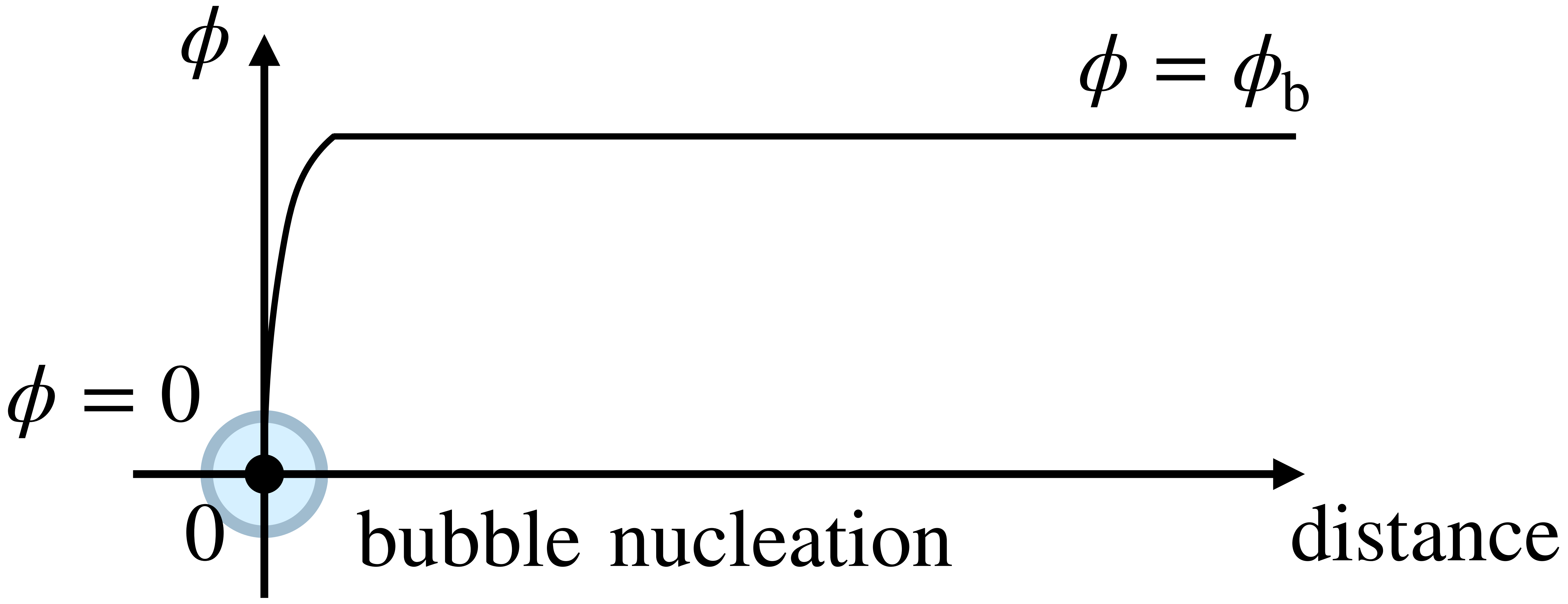
Unless $\frac{m_b}{\sqrt{1-v^2}} > m_0$, axion waves propagate outside bubbles.

Axion shock waves are induced near the bubble wall.



Axion Shock Wave

Axion settles down to $\phi = 0$ inside the bubble by mass. This information propagates with light speed making a gradient.



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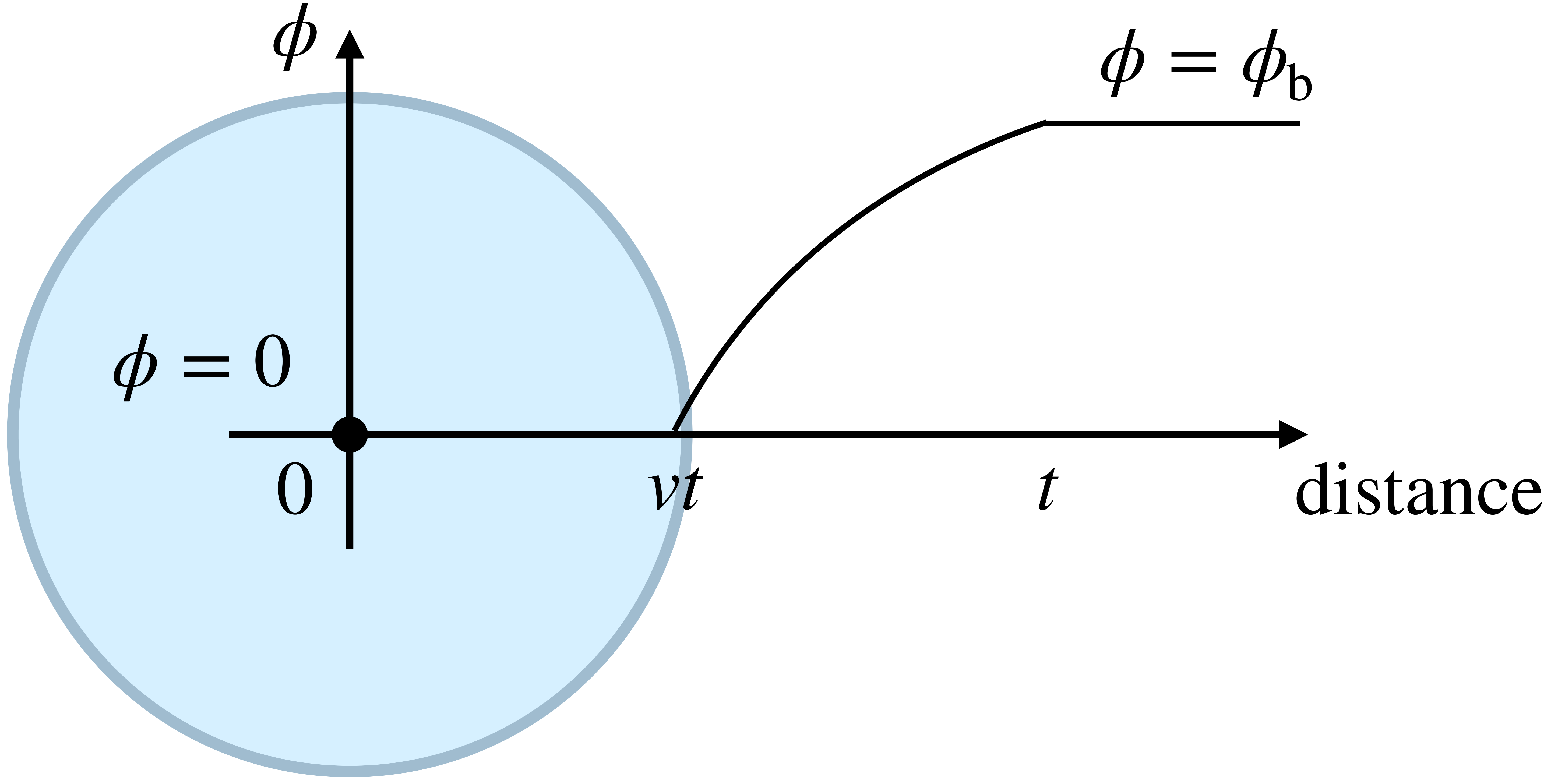


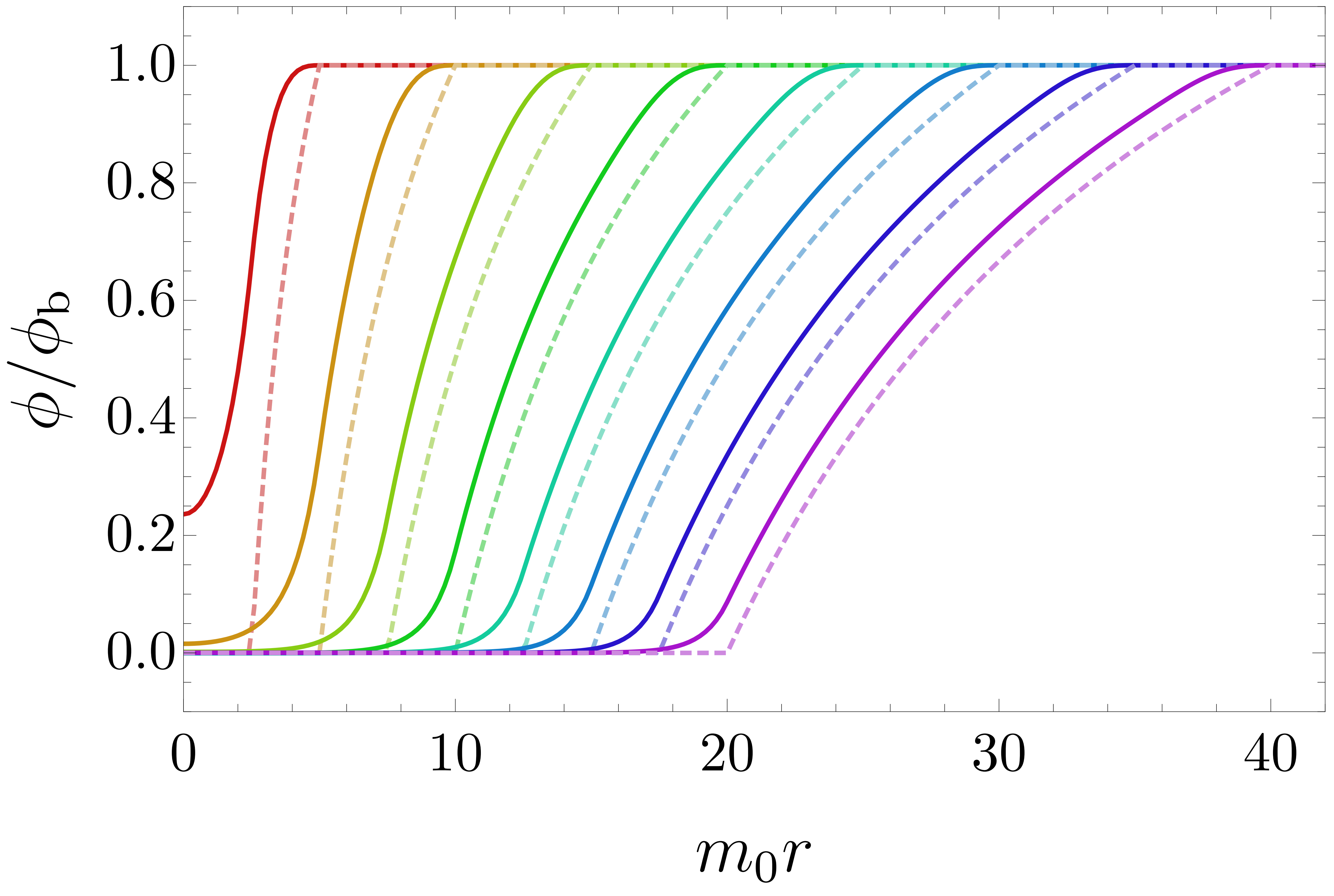
Axion Shock Wave

Axion settles down to $\phi = 0$ inside the bubble by mass. This information propagates with light speed making a gradient.

This energy excitation enhances the axion abundance.

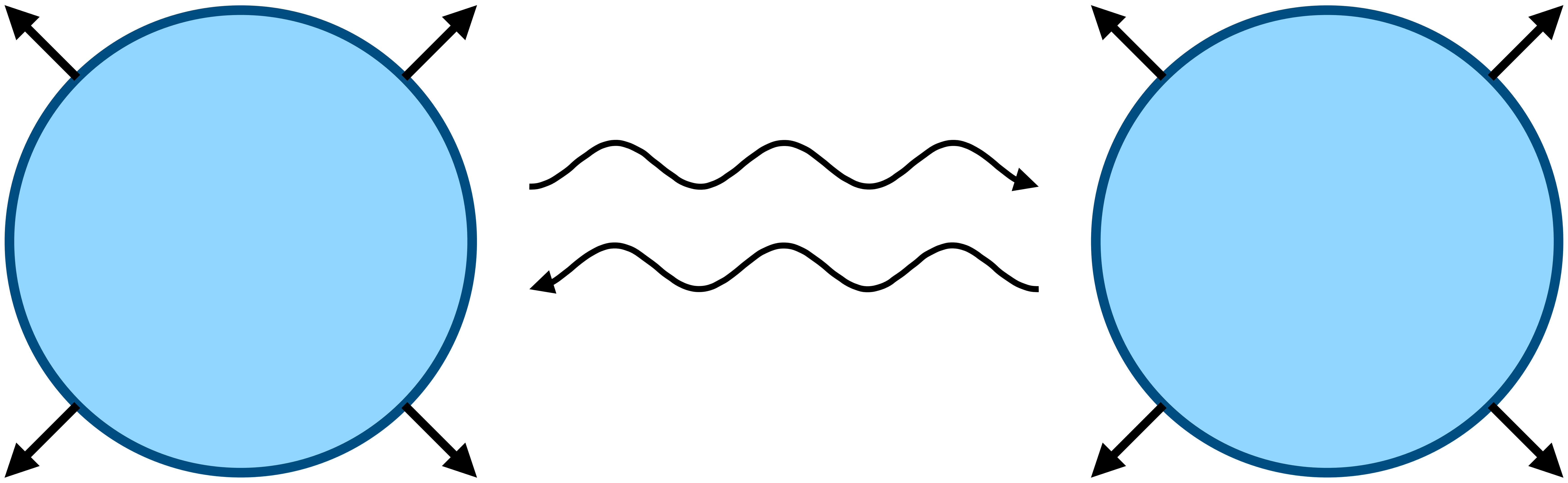
Axion number associated with a single bubble before collision is

$$N_\phi \simeq \frac{\pi \phi_b^2}{2}(1+v)^2 t^2$$



Repeating scatterings accelerate axions

Expelled waves propagate outside the bubble and are scattered by another bubble. They obtain energy through repeating scatterings. (analogous to Fermi acceleration)

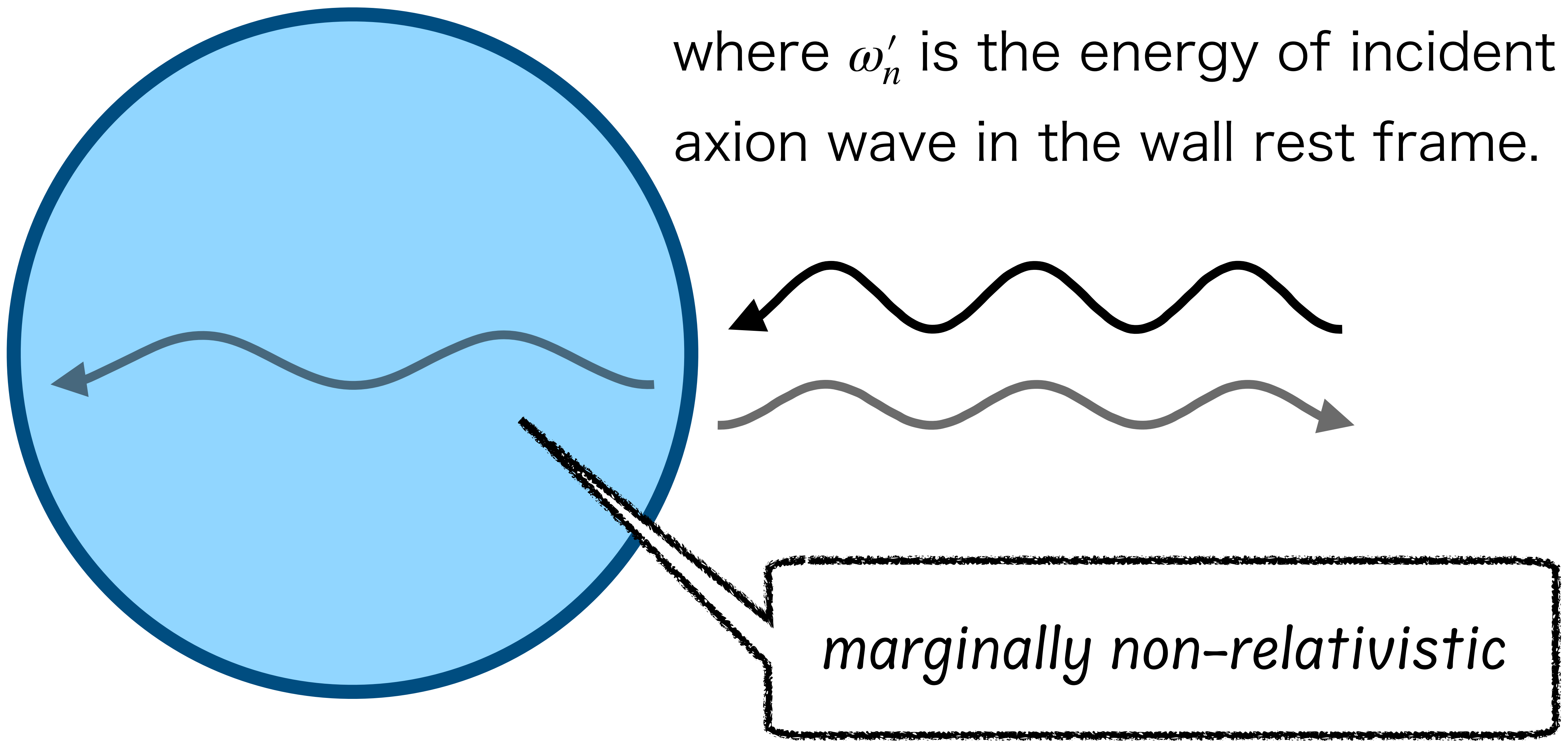


Axion waves transmit inside the bubble

When axion waves obtain sufficient energy by being accelerated, the wave can transmit bubble walls.

transmit when $\omega'_n > m_0$

where ω'_n is the energy of incident axion wave in the wall rest frame.

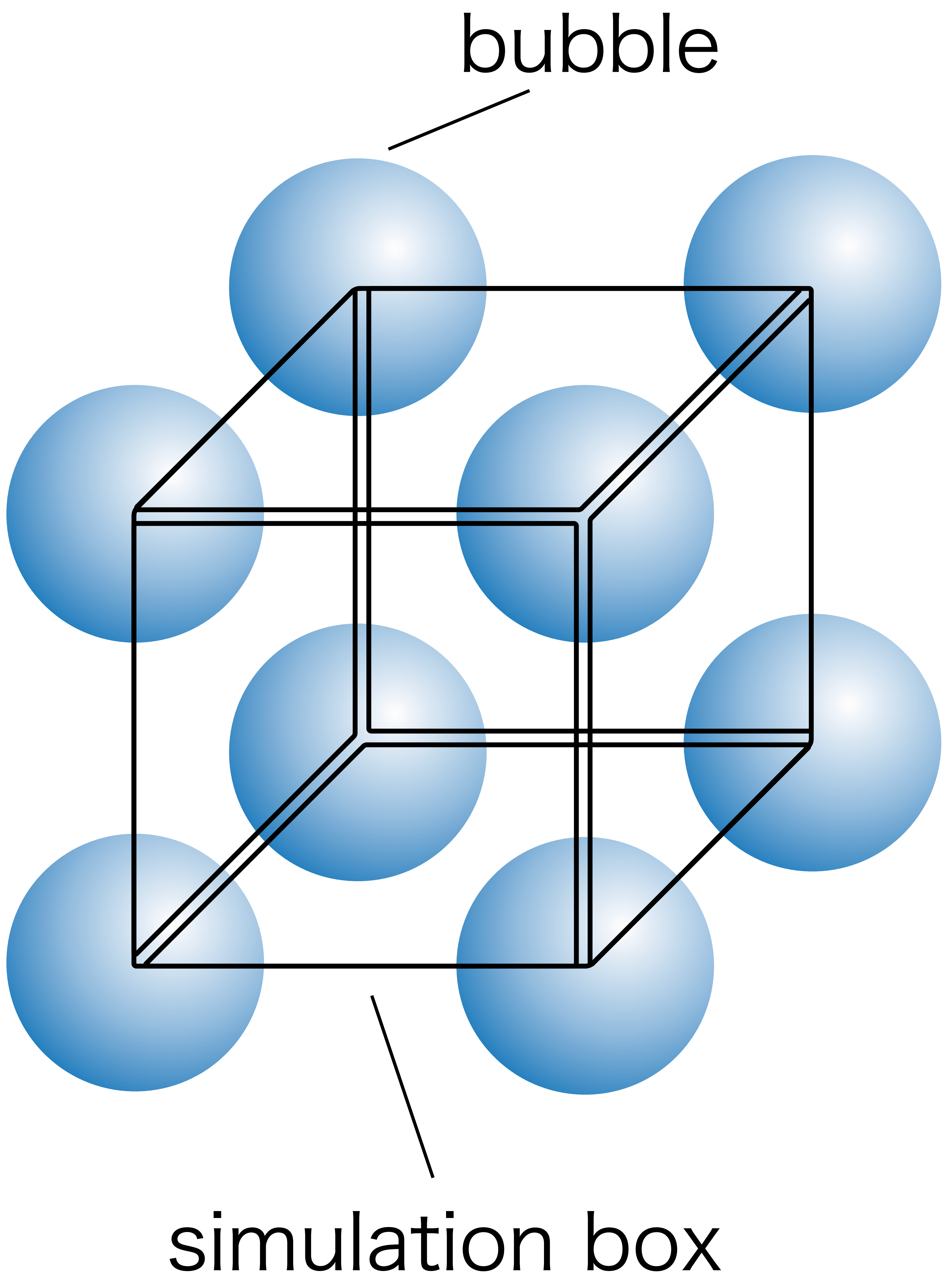


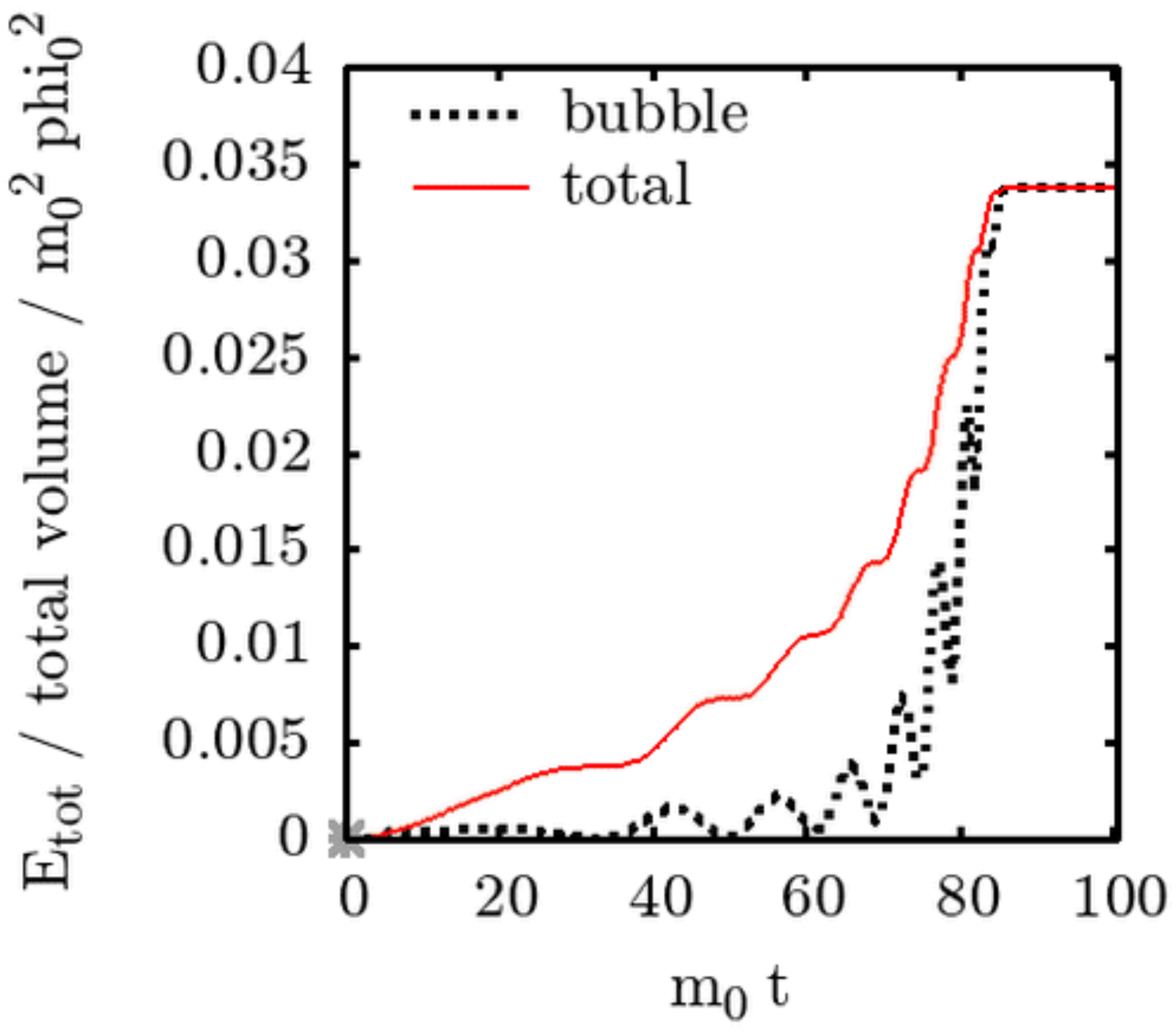
Numerical Simulation

We performed the numerical simulations:

- Three-dimensional lattice simulation.
- The bubble is nucleated at each corner of the simulation box.
- For simplicity, we neglect the expansion of the universe as well as the axion mass before the phase transition.

$$m_{\mathrm{b}}, H_{\mathrm{b}} \ll \beta < m_0$$





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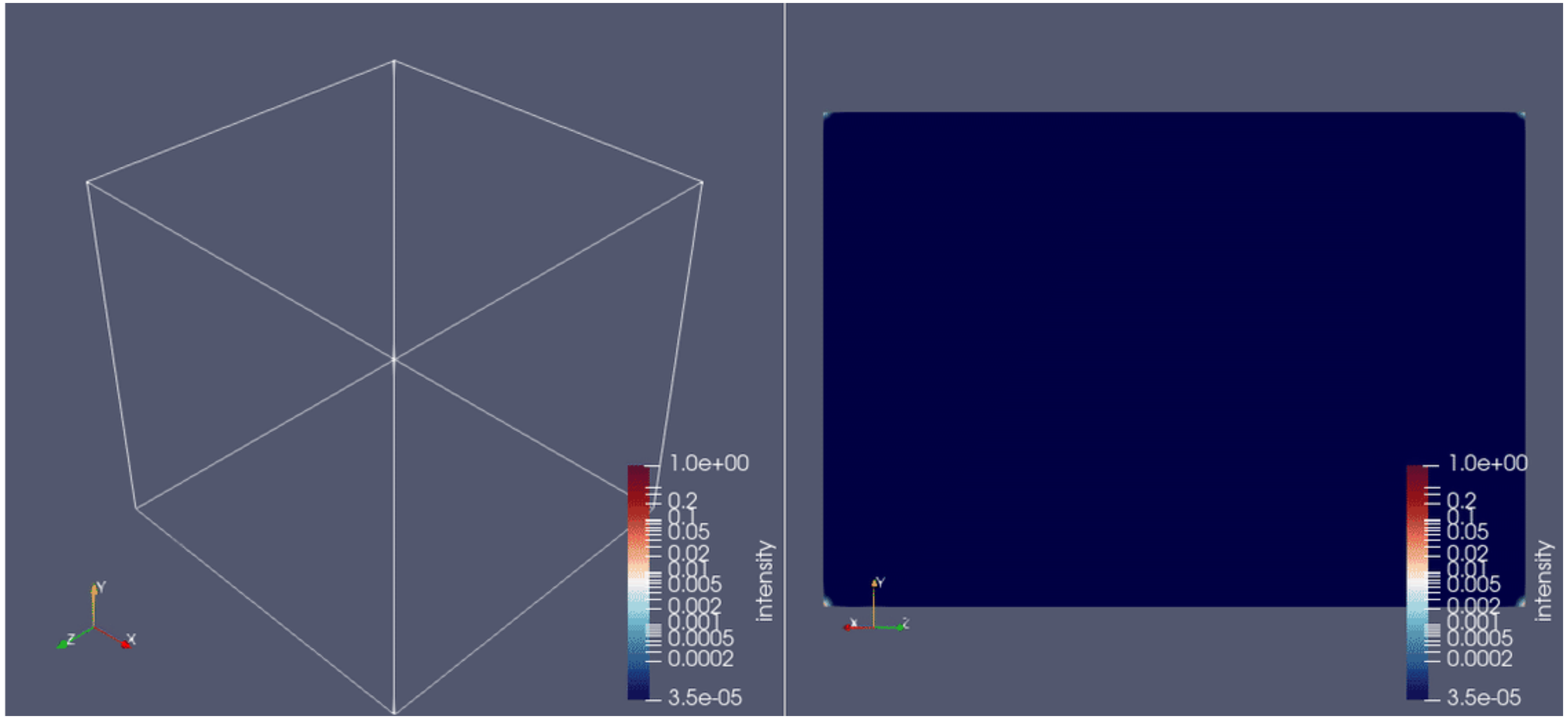
m_0 t
E_{tot} / total volume / m_0^2 phi_0^2



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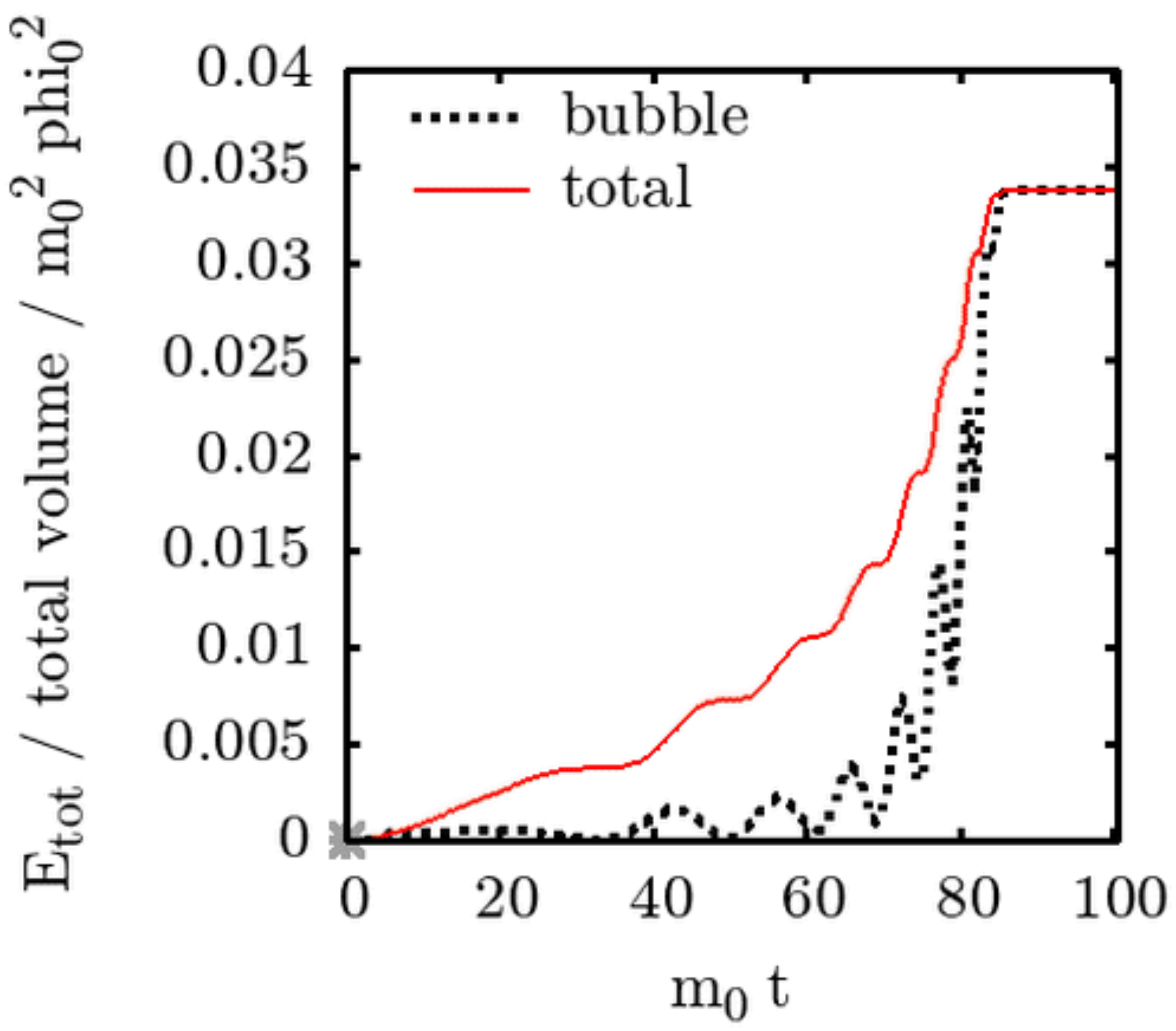

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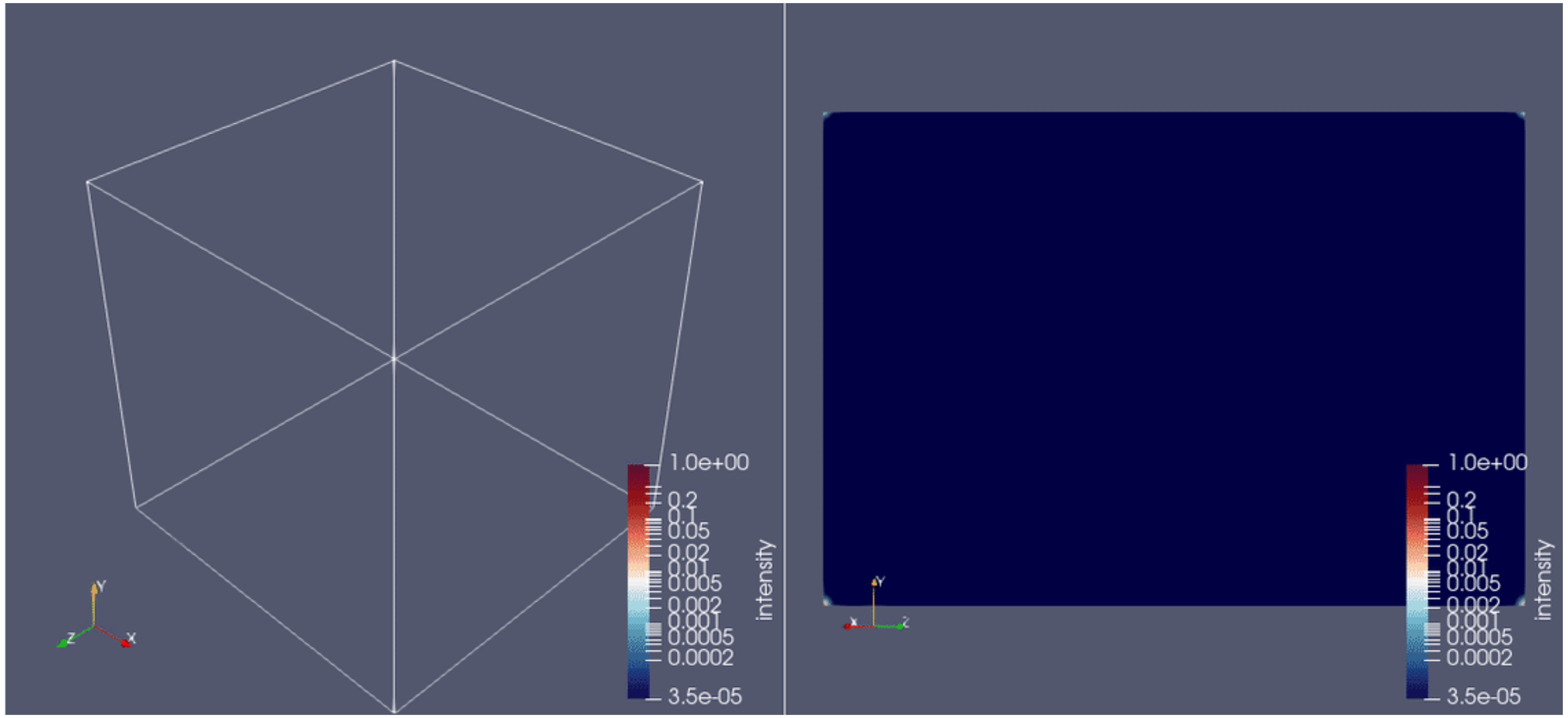

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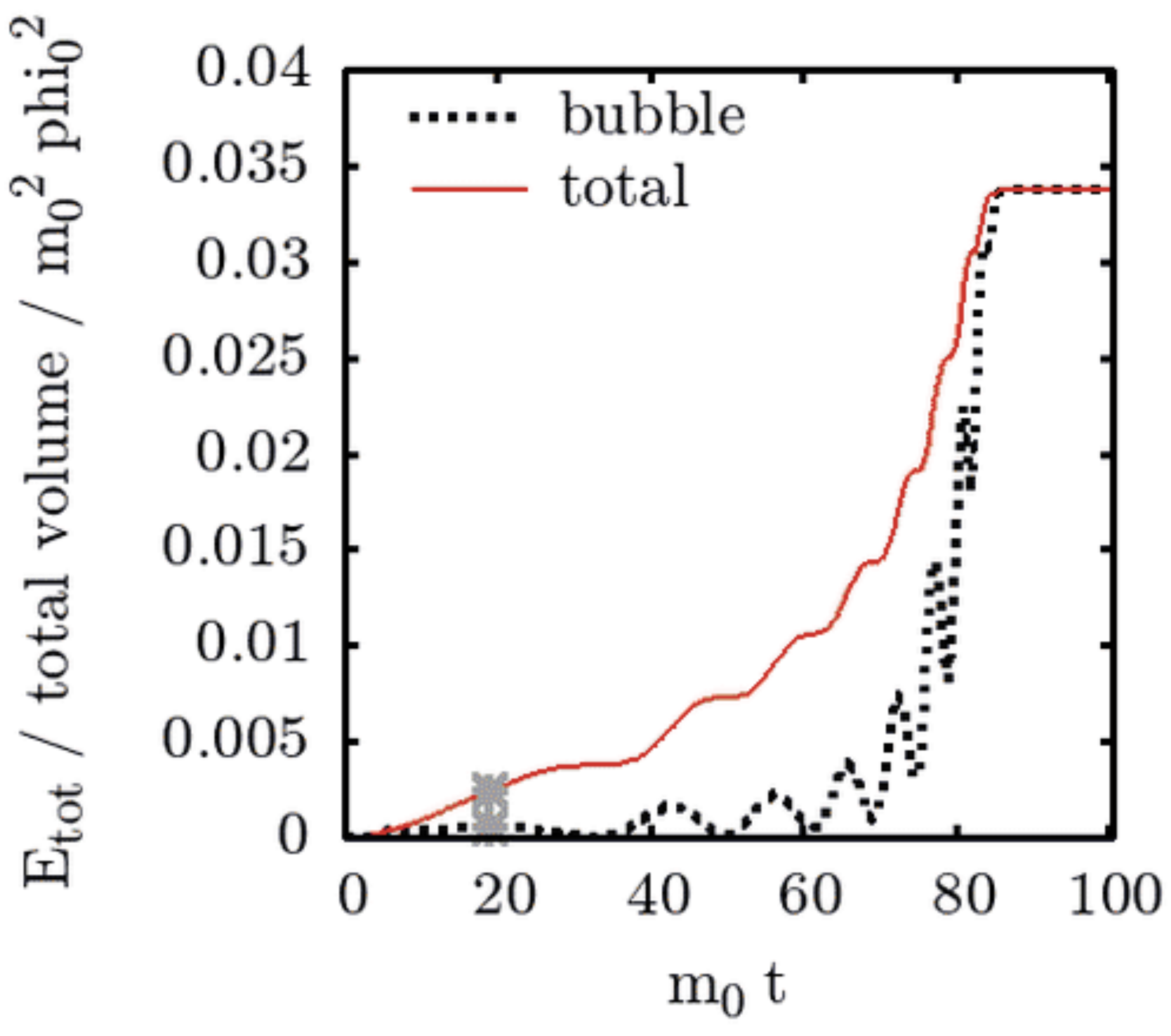
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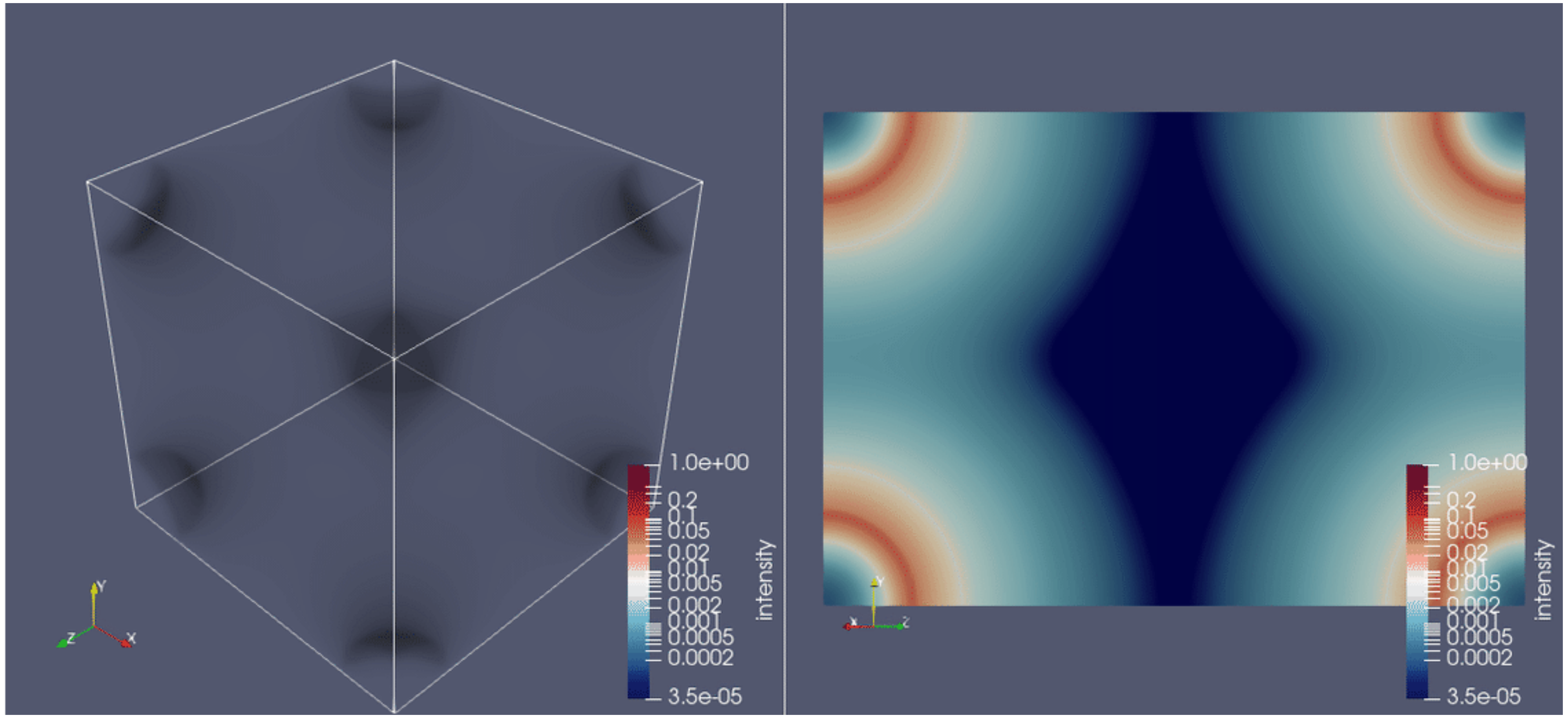
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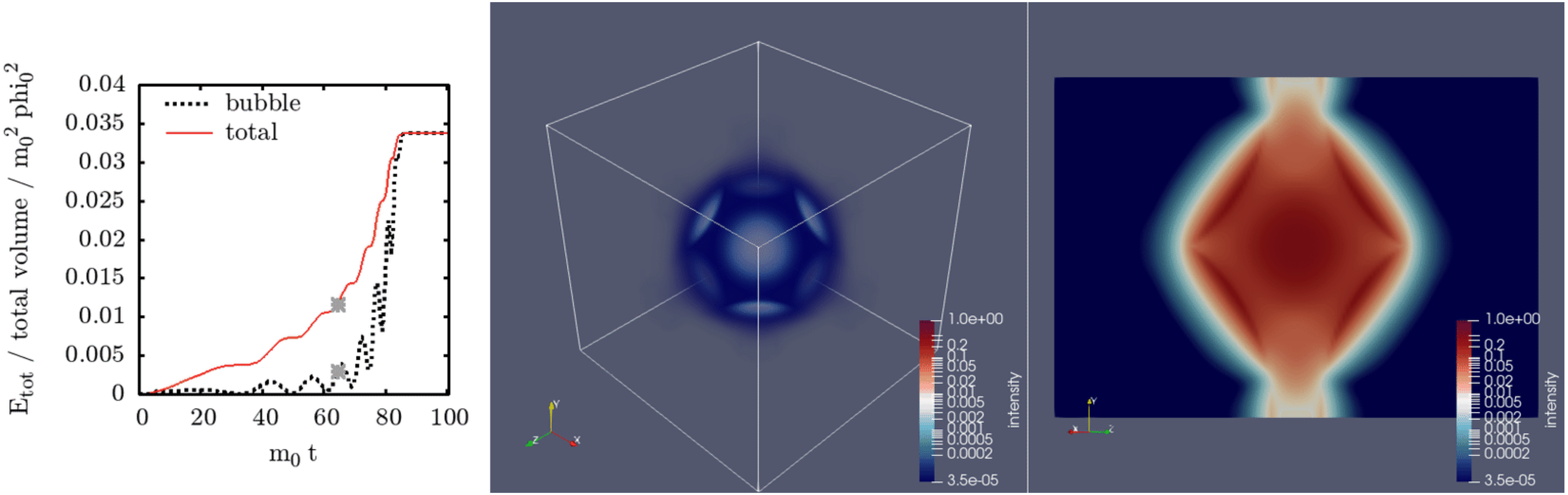
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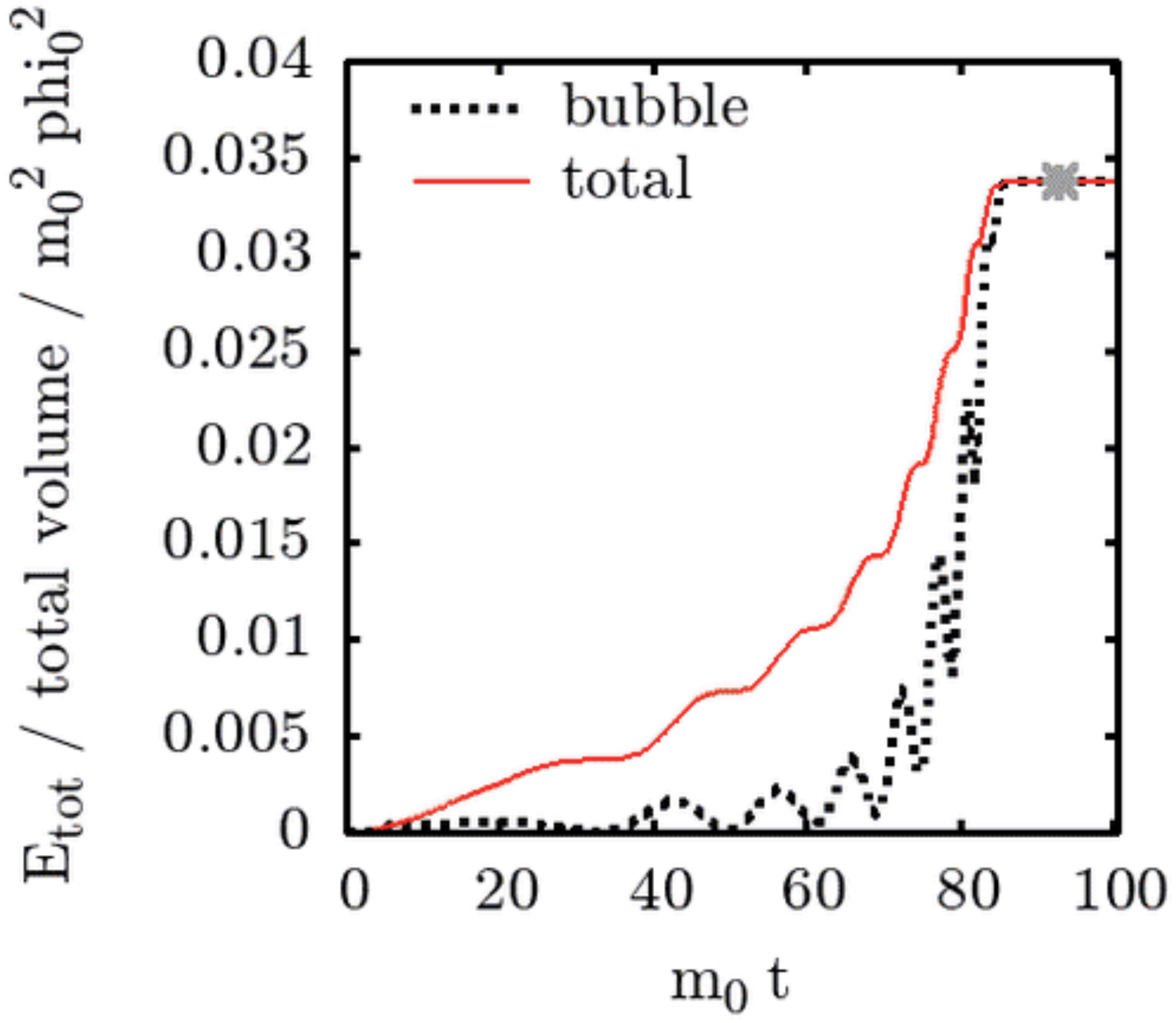
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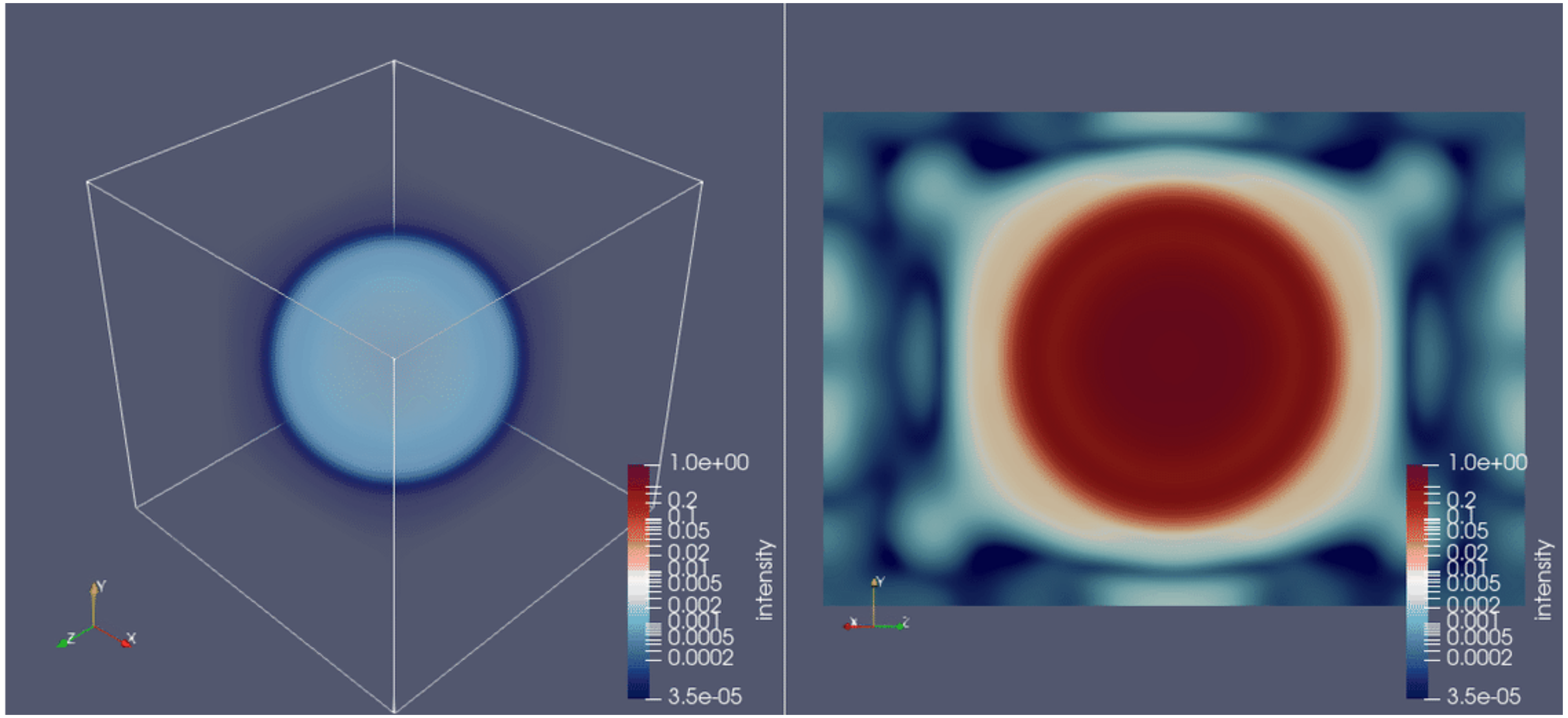
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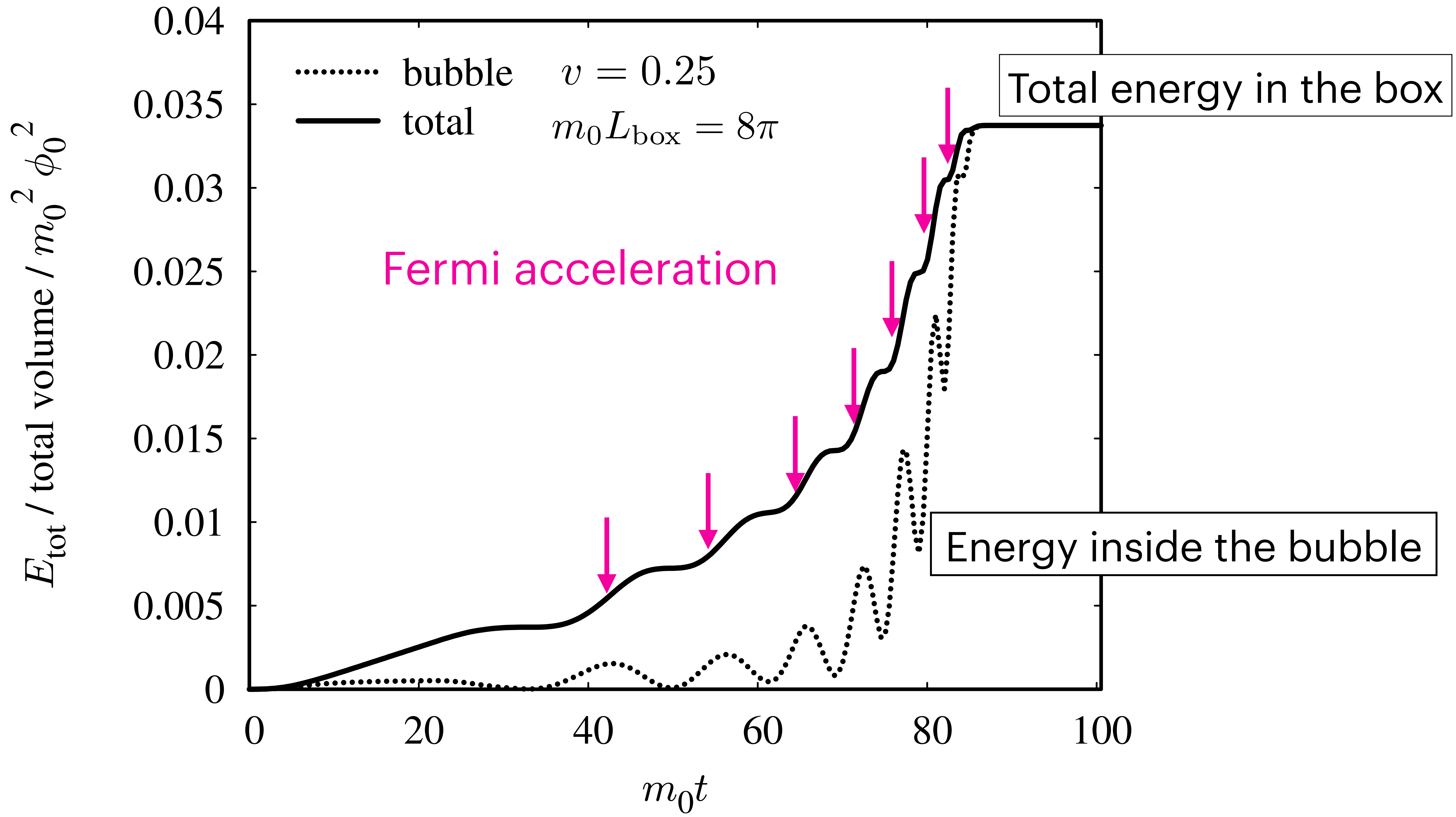
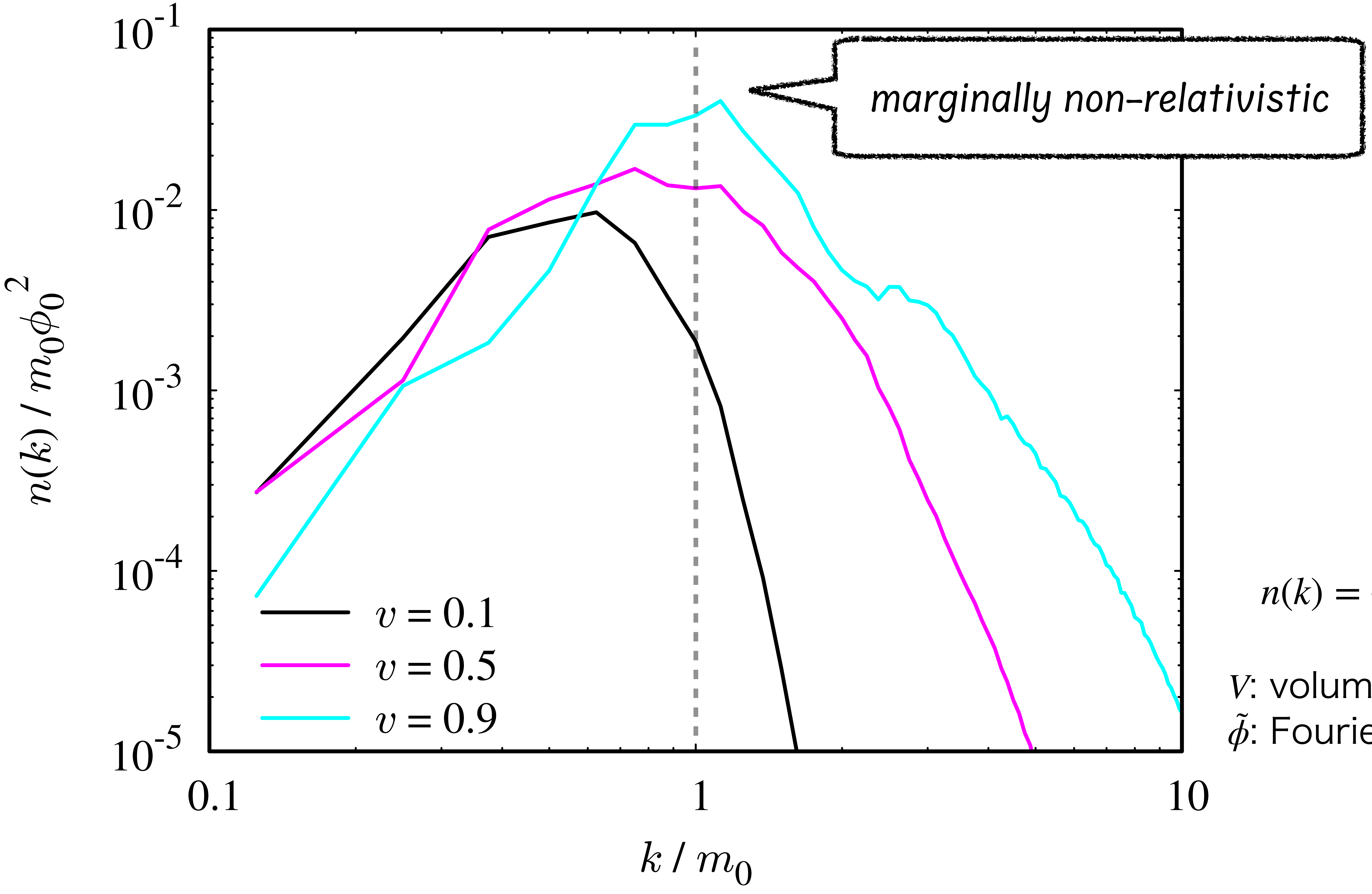
The evolution of the axion energy



The momentum distribution

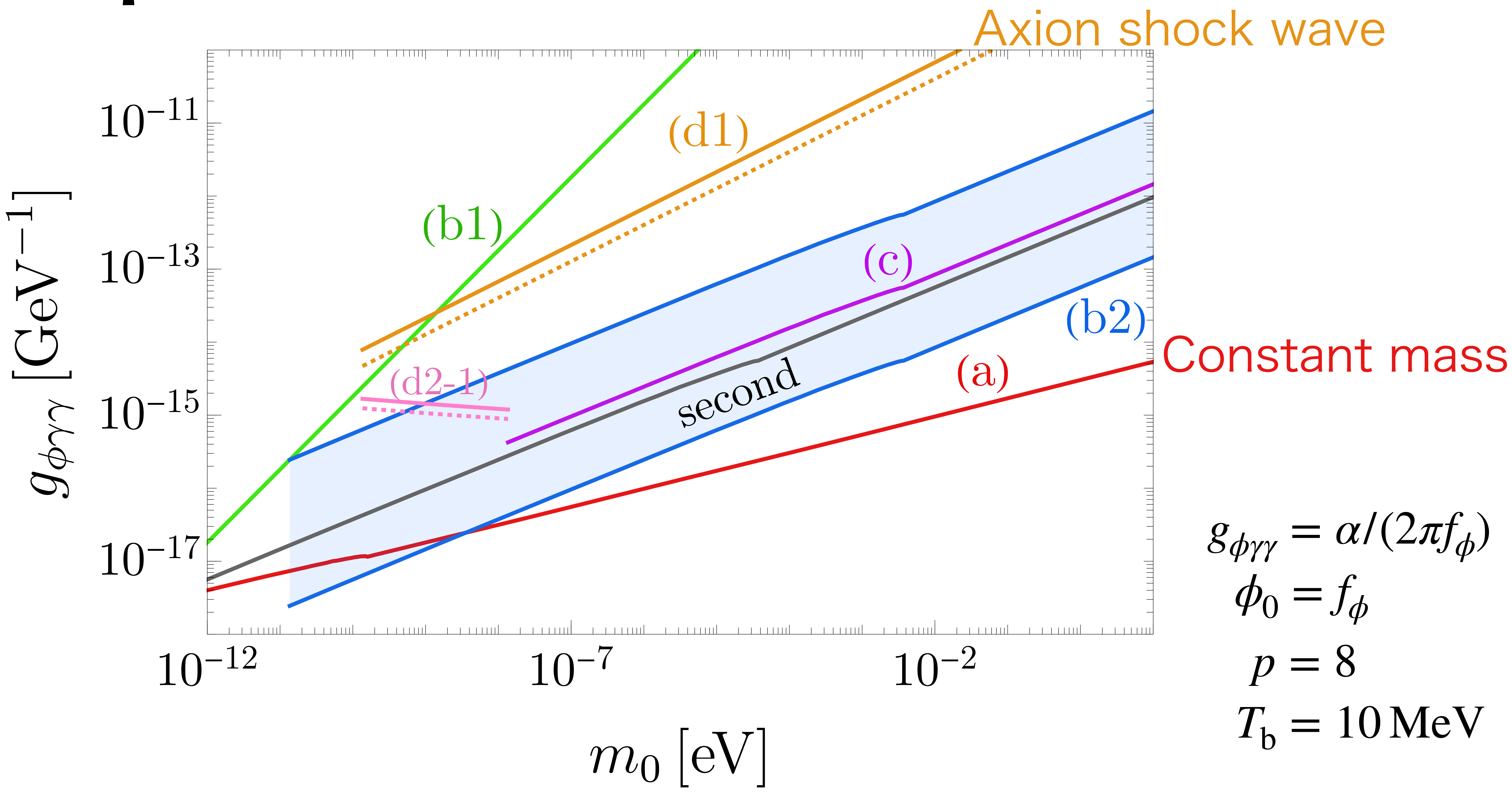


$$n(k) = \frac{k^3}{2\pi^2 \cdot 2\omega_k V}\left[\dot{\tilde{\phi}}^2 + \omega_k^2 \tilde{\phi}^2\right]$$

V: volume of the simulation box

$\tilde{\phi}$: Fourier transformation of ϕ

Viable parameters for axions



$g_{\phi\gamma\gamma} = \alpha/(2\pi f_\phi)$

$\phi_0 = f_\phi$

$p = 8$

$T_b = 10\,\mathrm{MeV}$

Summary

- We studied the axion evolution in the FOPT, taking account of the bubble dynamics; **“Bubble misalignment mechanism”**
- We find that axion is expelled from the interior of the bubbles producing an **axion shock wave** and that **Fermi acceleration** occurs.
- If the axion oscillations are relevant only inside the bubbles during the phase transition, **the axion abundance can be significantly increased** compared to the case of constant axion mass.
- Much to be done: analysis of realistic bubble nucleation, oscillon/I-ball formation, axion minicluster, production of dark photon dark matter, etc.