Bubble Misalignment Mechanism for Axions

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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

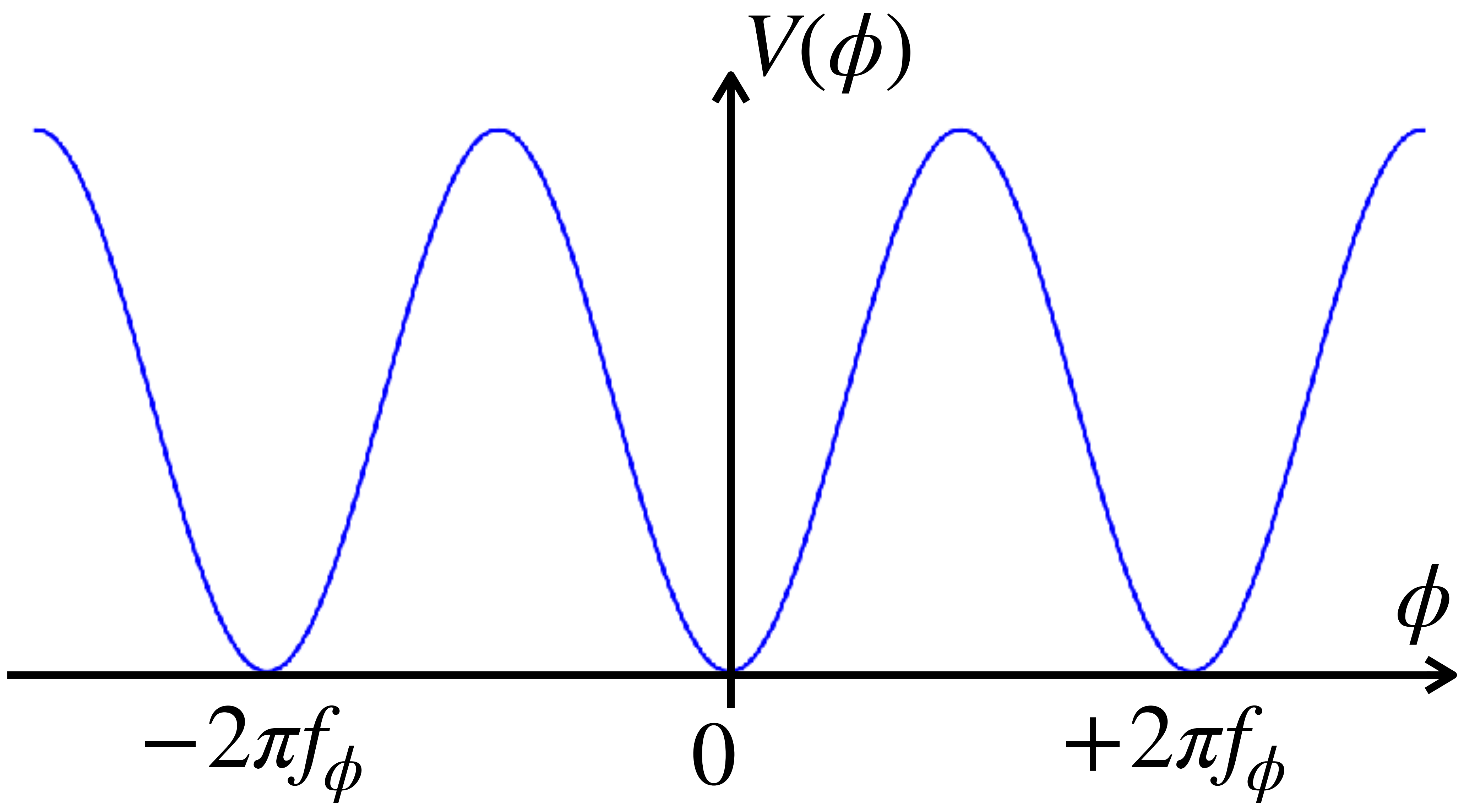
Axion is a scalar particle with shift symmetry.

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

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, ⋯



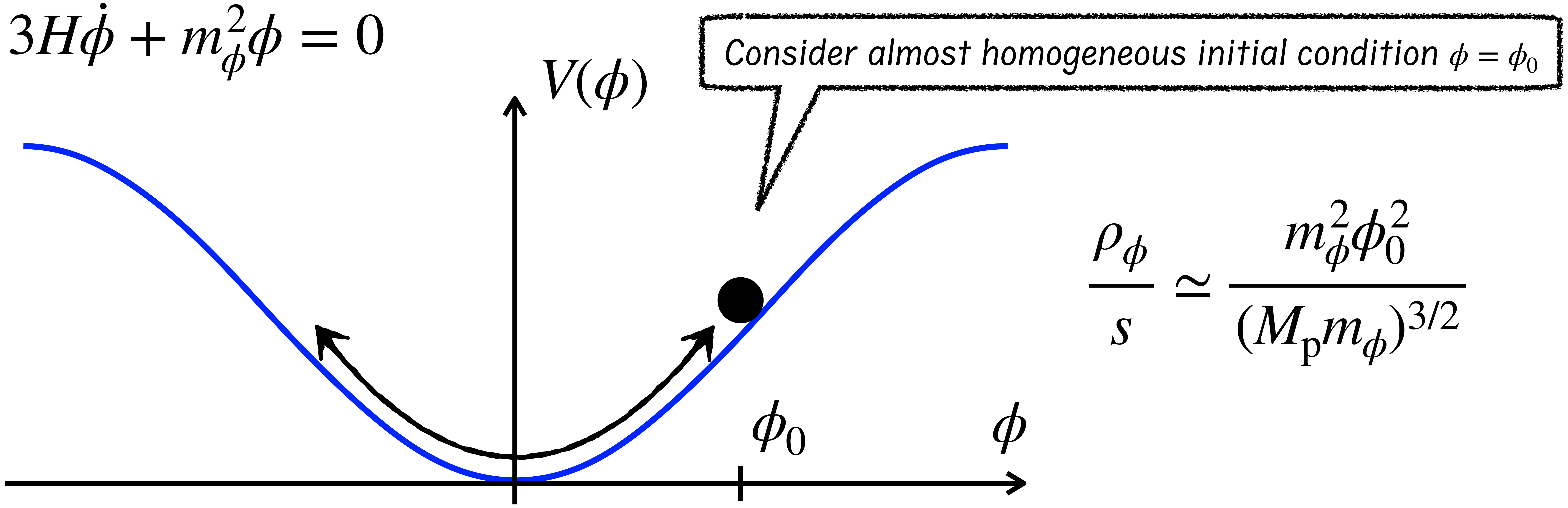
Misalignment Mechanism

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 and have various cosmological implications.

e.g.) baryogenesis, dark matter, and gravitational waves, ⋯

Let us consider the phase transition from the deconfined phase to the confined phase in non-Abelian gauge theory.

e.g.) phase transition in the pure $\mathrm{SU}(N)$ Yang-Mills theory where $N \geq 3$

B. Lucini, M. Teper and U. Wenger, `03, `05

First-Order Phase Transition

Assume that axion mass arises through the coupling to such a gauge field.

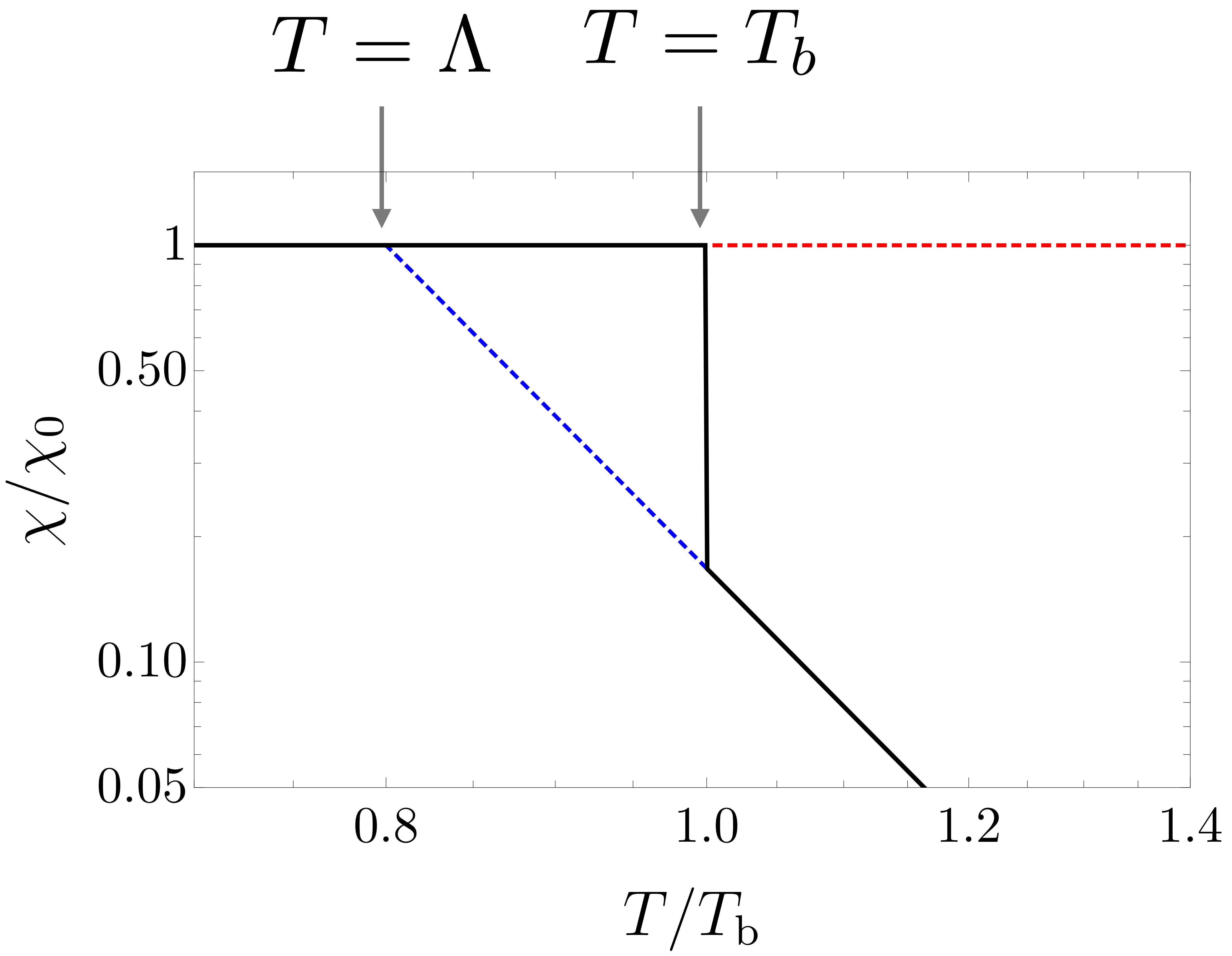
Topological susceptibility changes discontinuously during the transition.

potential: $$V(\phi) = \chi(T)\left[1 - \cos\left(\frac{\phi}{f_\phi}\right)\right]$$

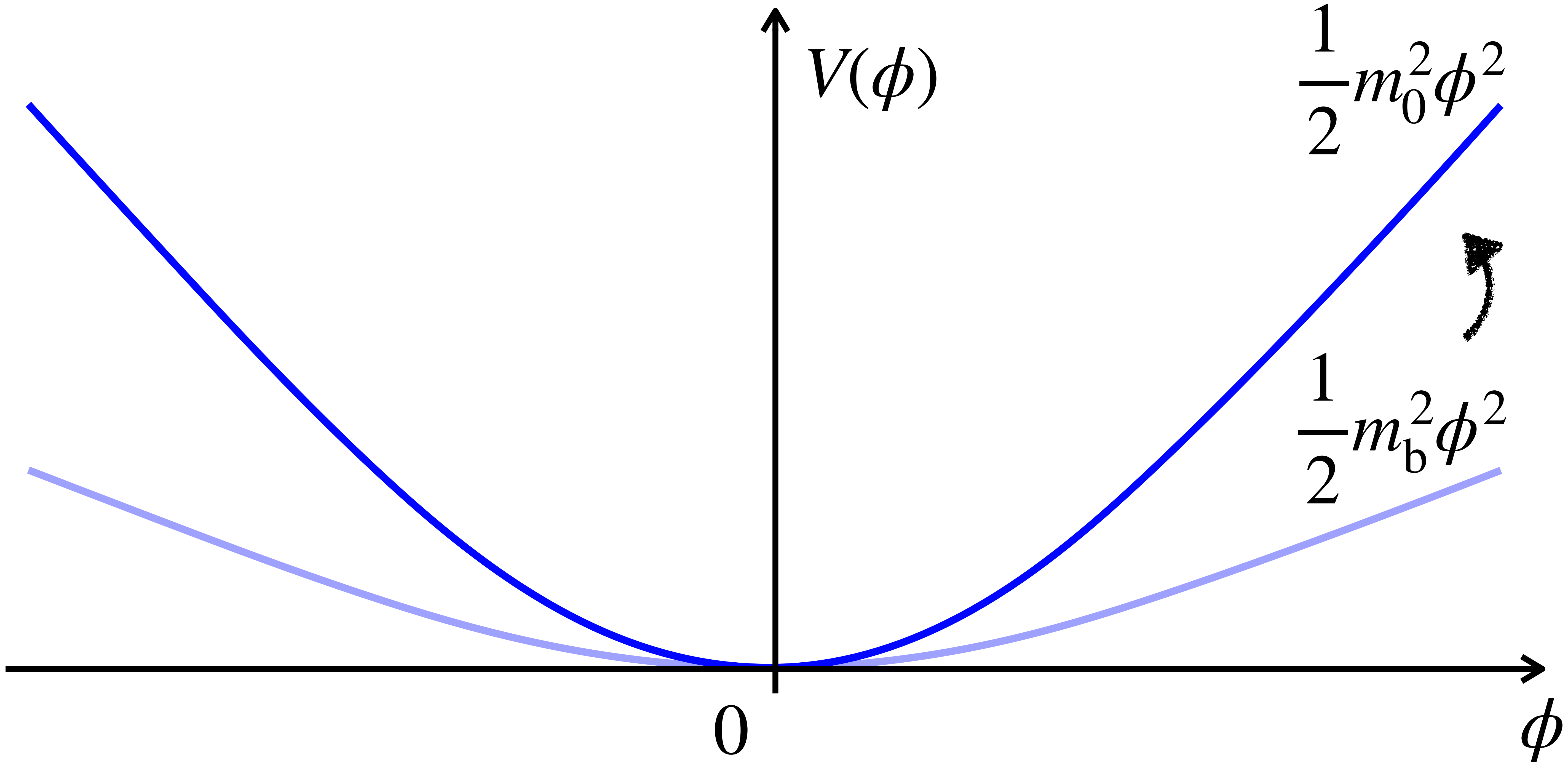
topological suceptibility

$$\chi(T) = \begin{cases} \chi_0 & (T < \Lambda) \\ \chi_0 \left(\dfrac{T}{T_{\rm QCD}}\right)^{-p} & (T \geq \Lambda) \end{cases}$$

$$m_{\rm b} \equiv \frac{\sqrt{\chi(T_{\rm b})}}{f_\phi} < m_0 \equiv \frac{\sqrt{\chi_0}}{f_\phi}$$



First-Order Phase Transition



@ $T = T_b$ (bubble nucleation temperature)

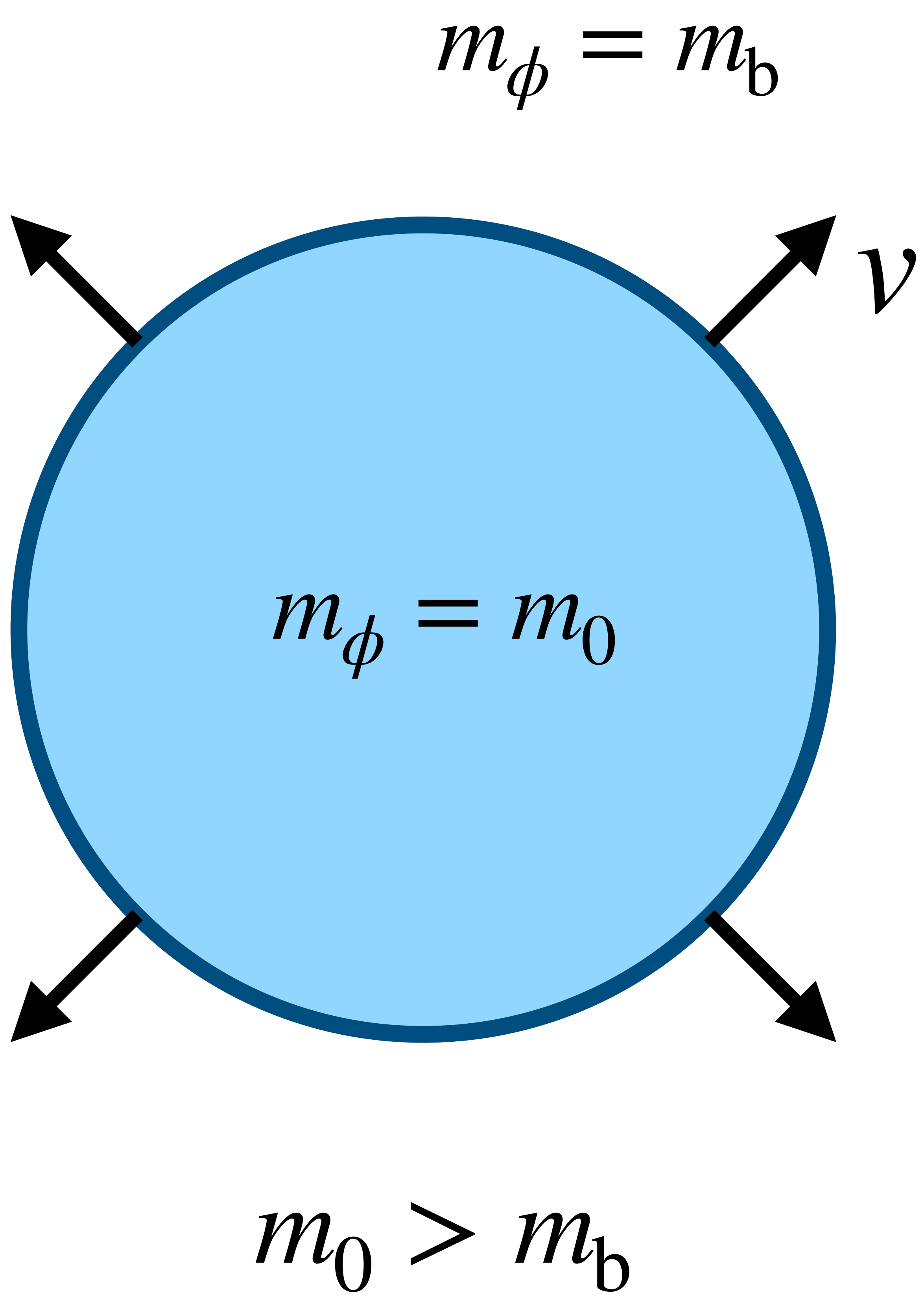
Bubble Nucleation

Bubble nucleation rate generically can be written in

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

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

Assume $\beta > H_\mathrm{b}$ where H_b is the Hubble parameter at bubble nucleation.



Bubble Nucleation

Bubble dynamics plays an important role.

Let us consider

$$m_b, H_b < \beta < m_0$$

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

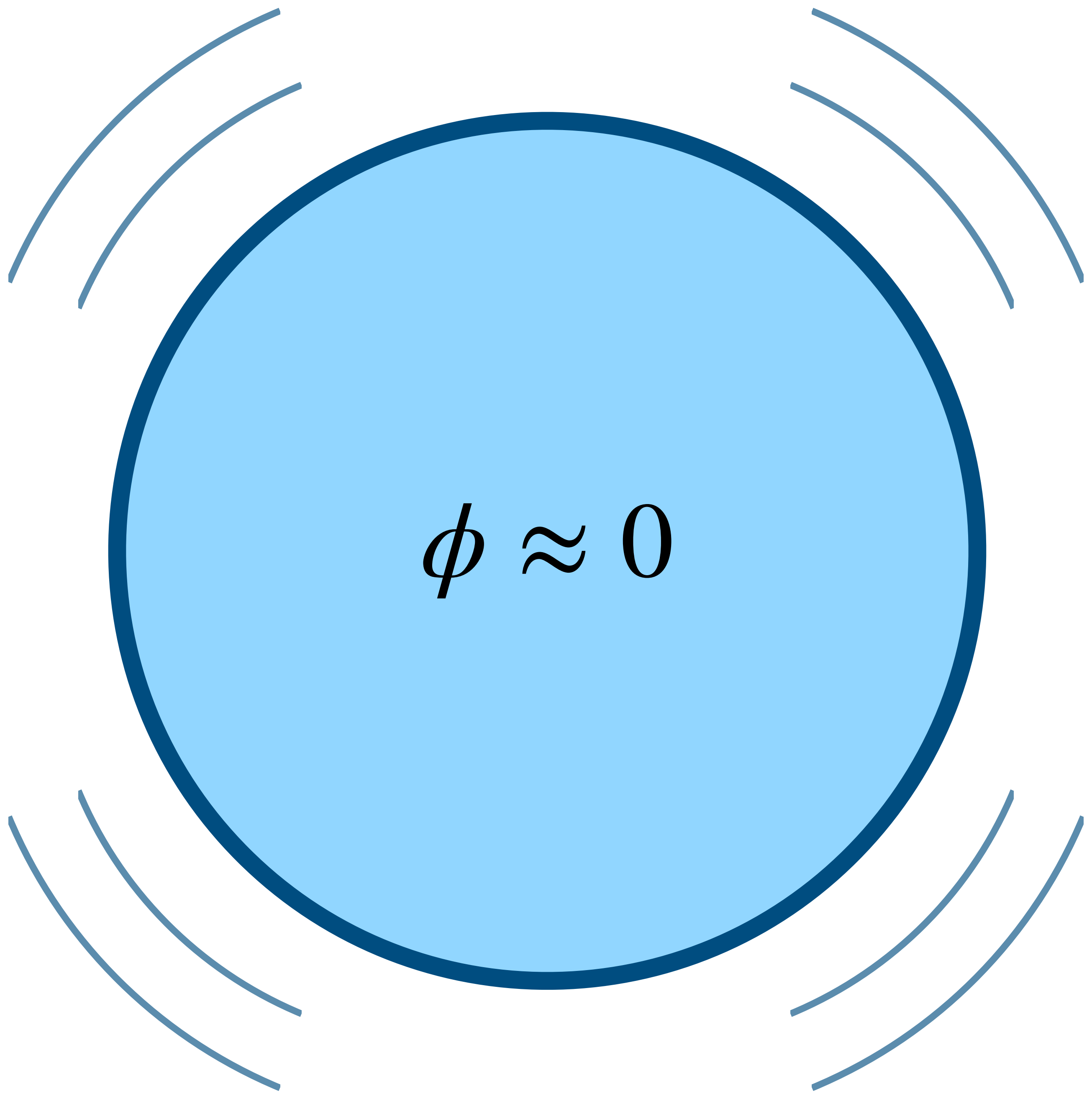
Then three remarkable phenomena take place:

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

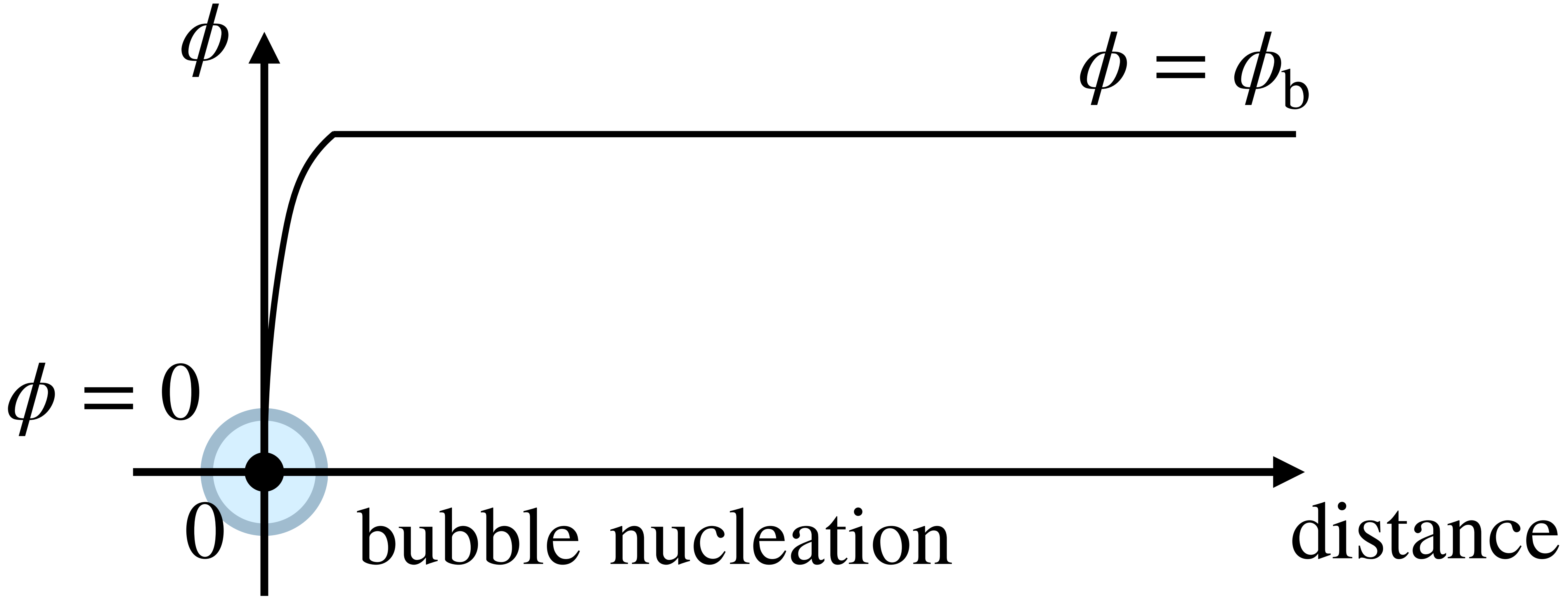
Unless $\frac{m_{\mathrm{b}}}{\sqrt{1-v^2}} > m_0$, axion waves propagate outside bubbles.

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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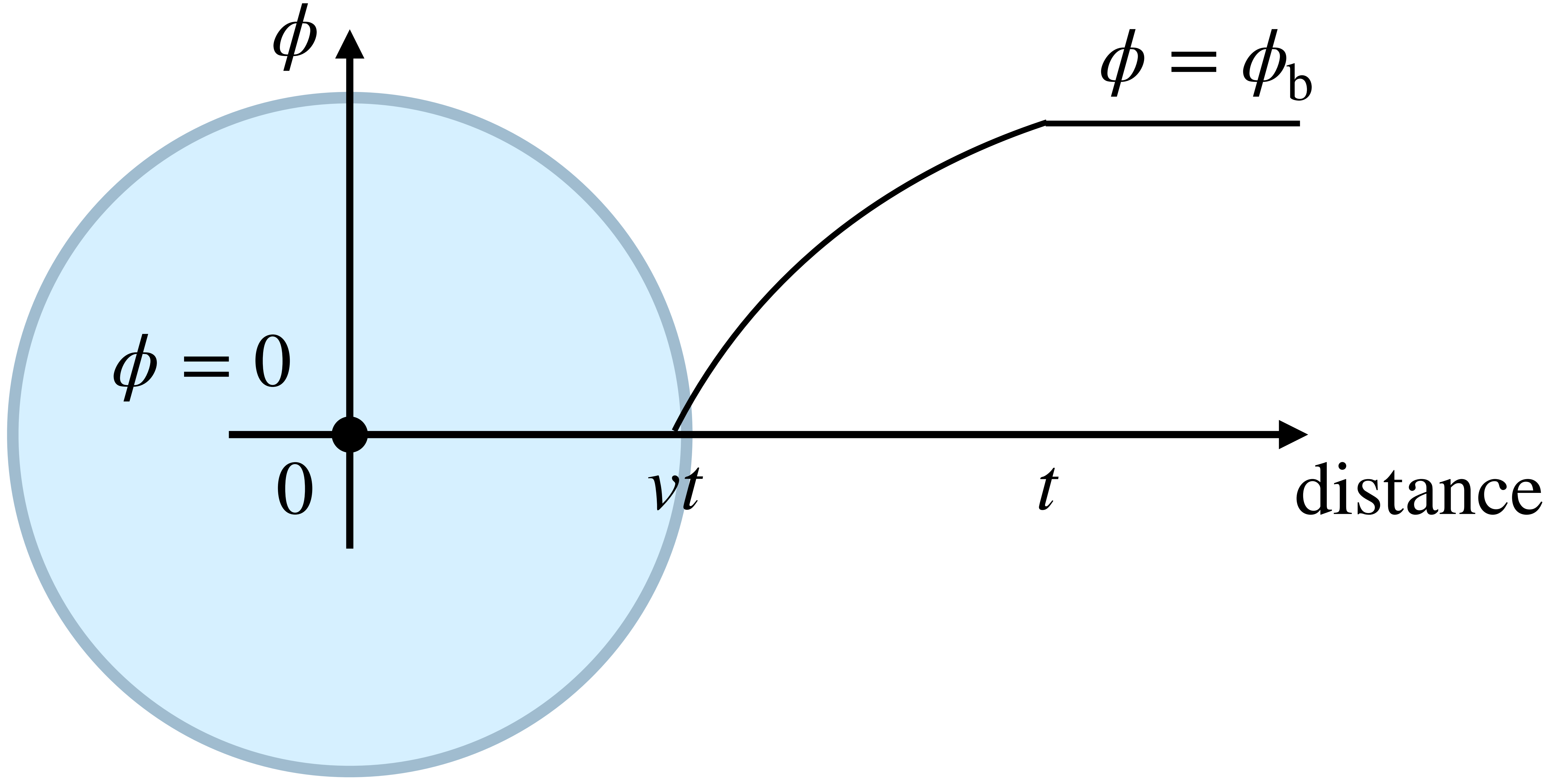


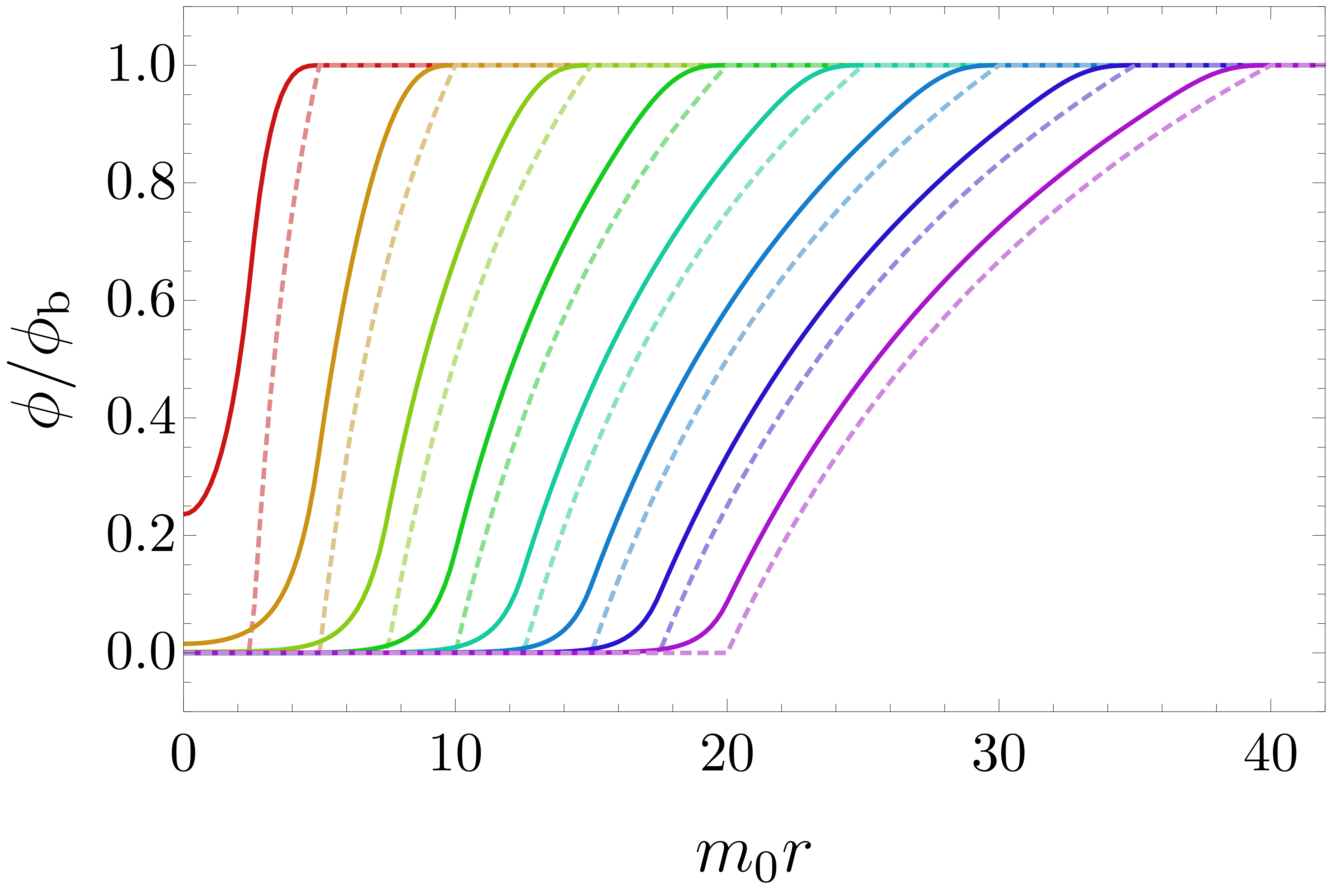
Axion Shock Wave

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.

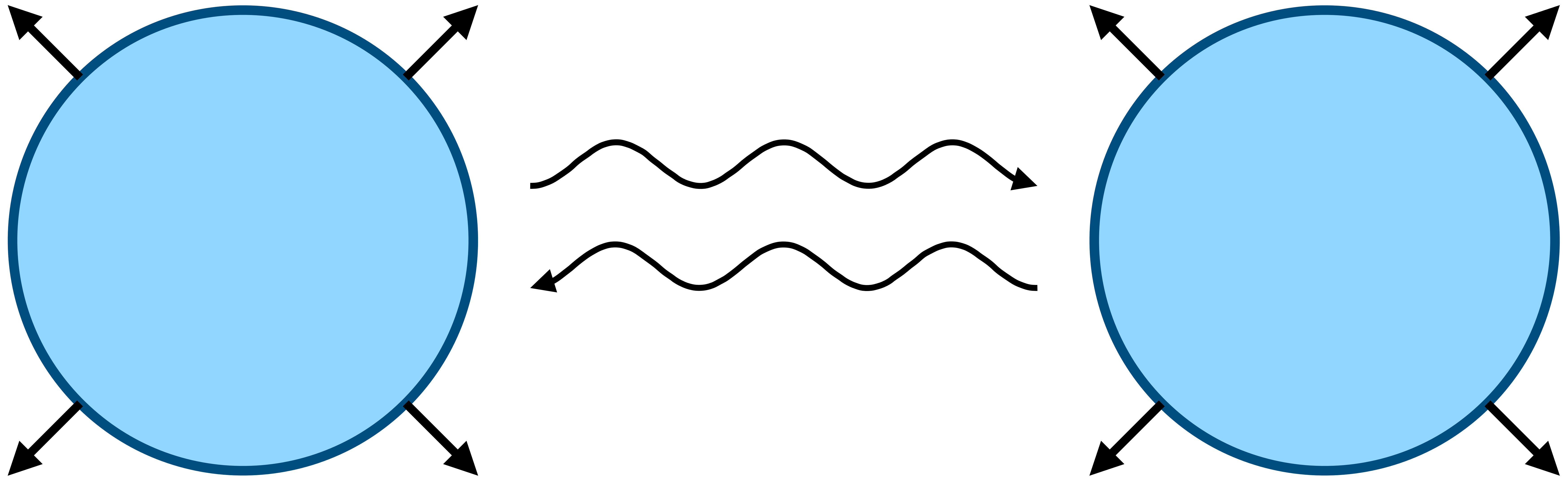
Axion number associated with a single bubble before collision is

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



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)

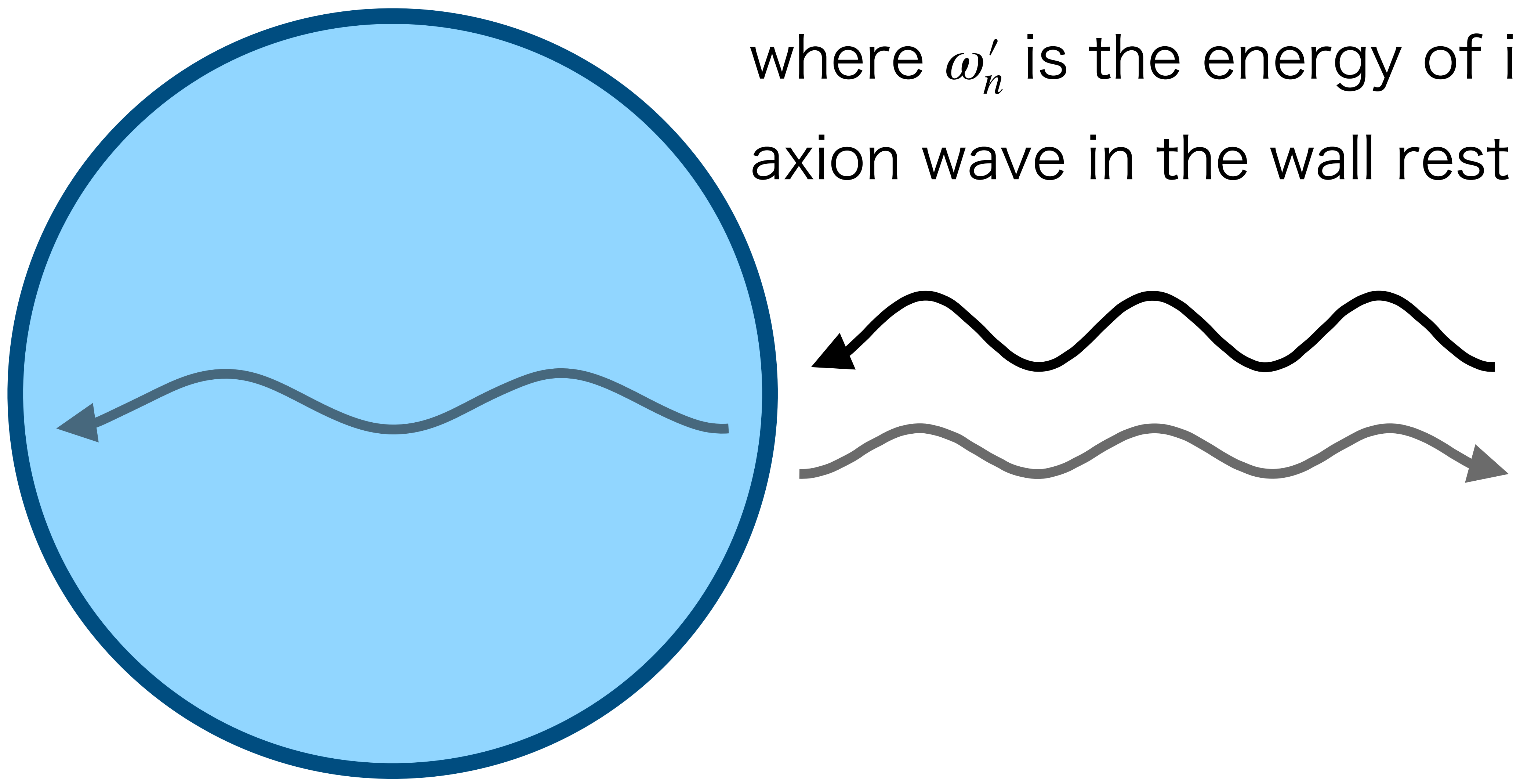


Axion waves transmit inside the bubble

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

transmit when $\omega'_n > m_0$

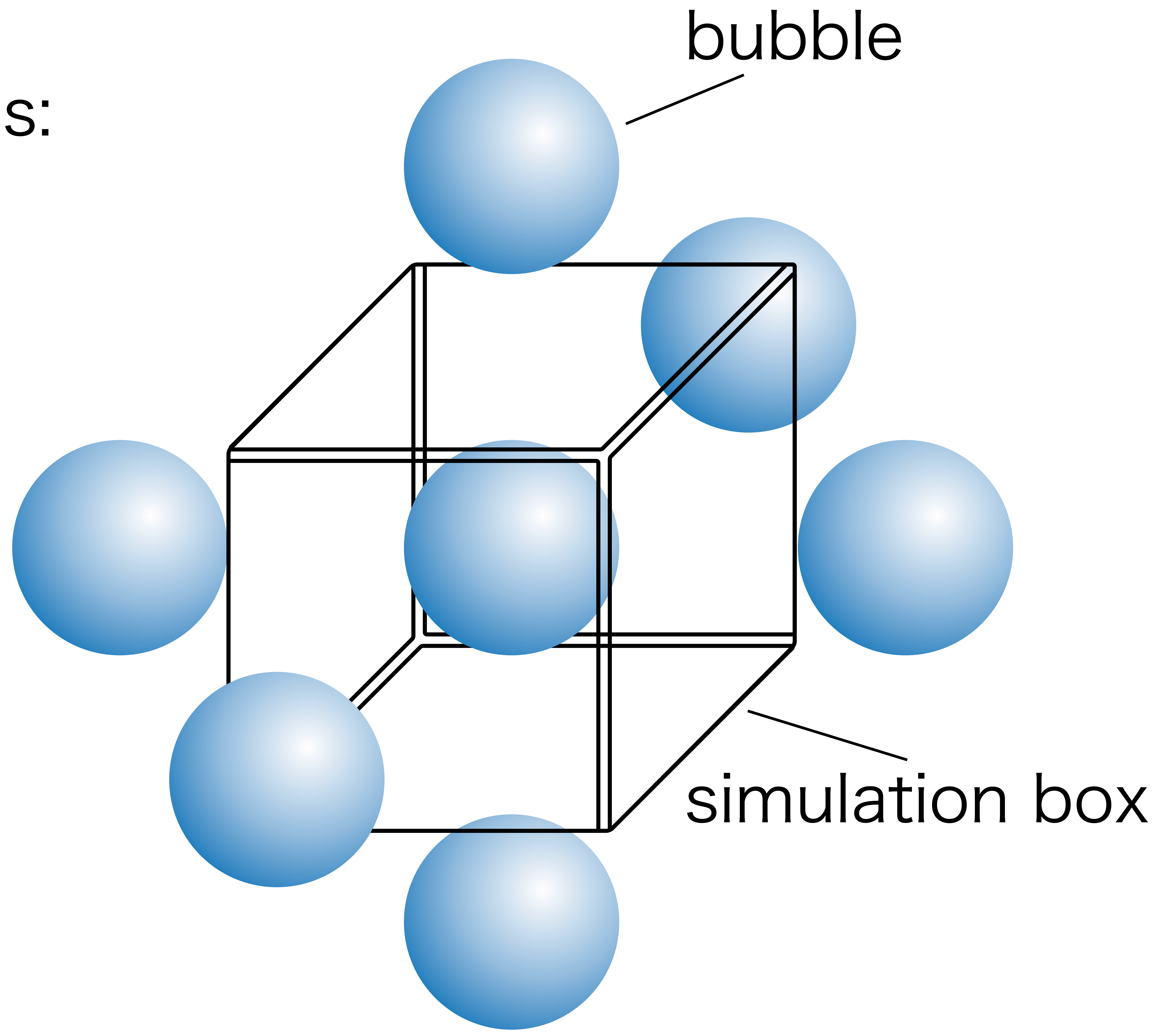
where ω'_n is the energy of incident axion wave in the wall rest frame.

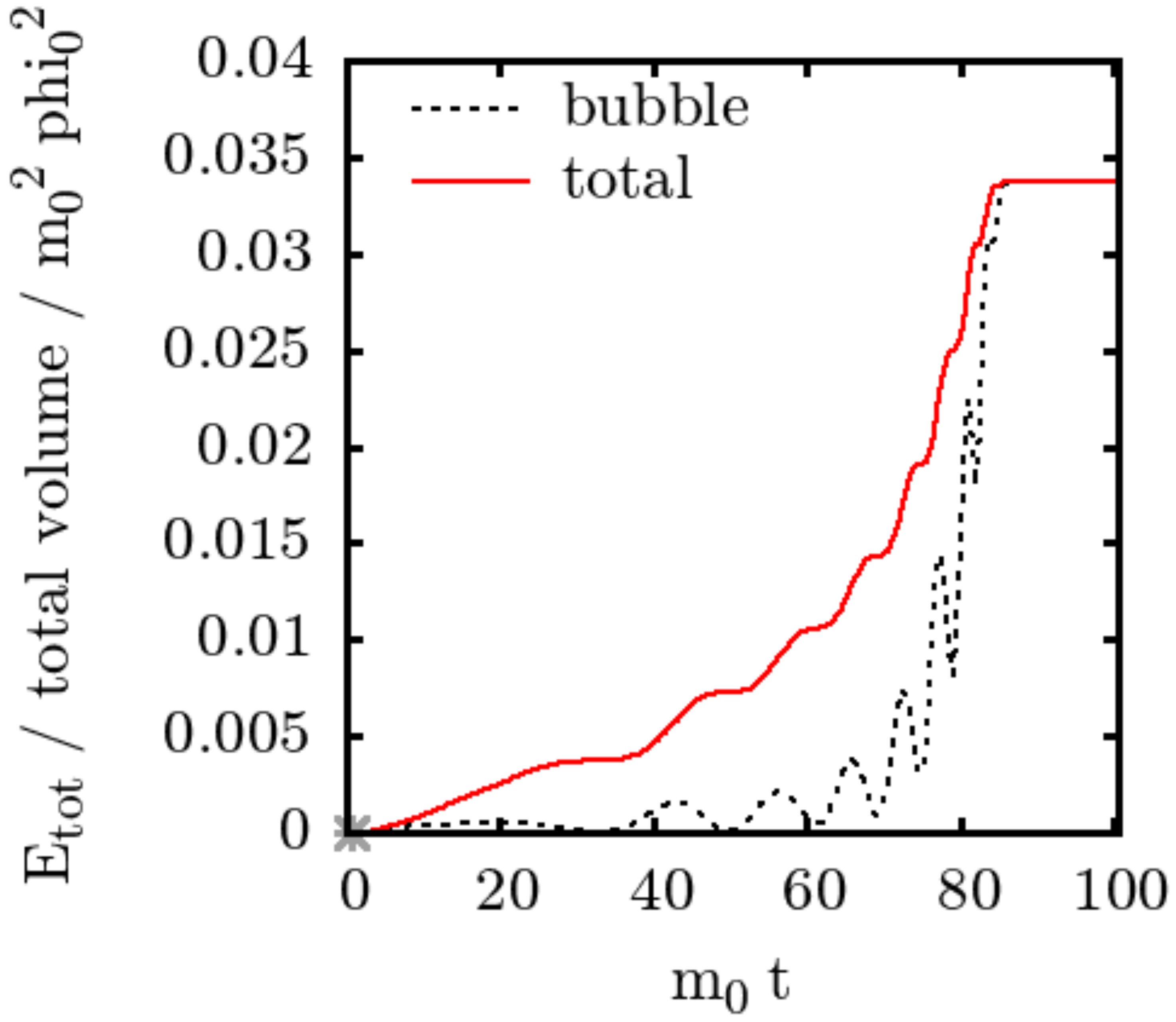


Numerical Simulation

We performed the numerical simulations:

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





0.04
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0.02
0.015
0.01
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bubble
total
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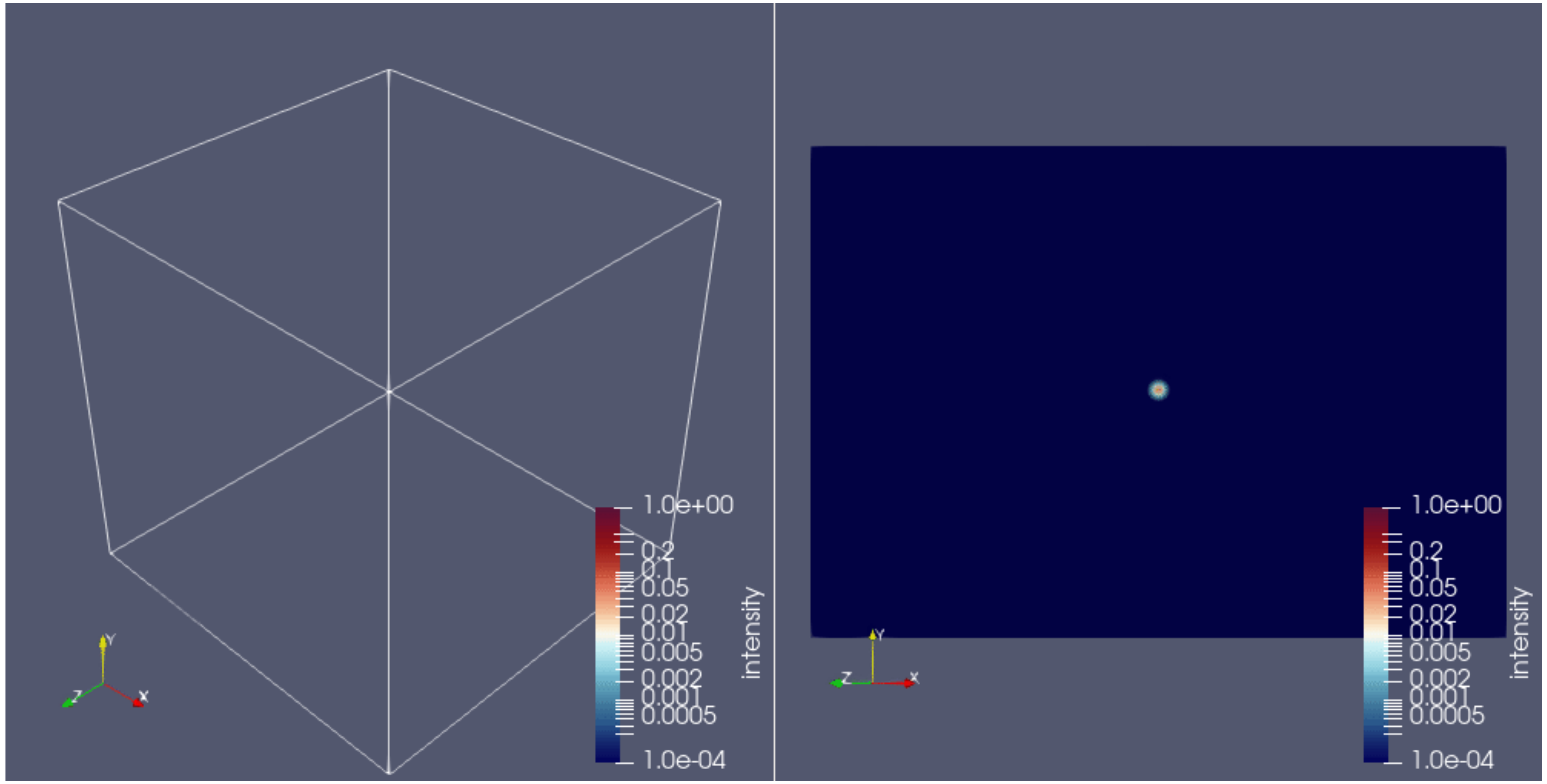
80
100
E_{tot} / total volume / m_0^2 phi_0^2
m_0 t



1.0e+00
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1.0e-04
intensity
1.0e+00
0.2
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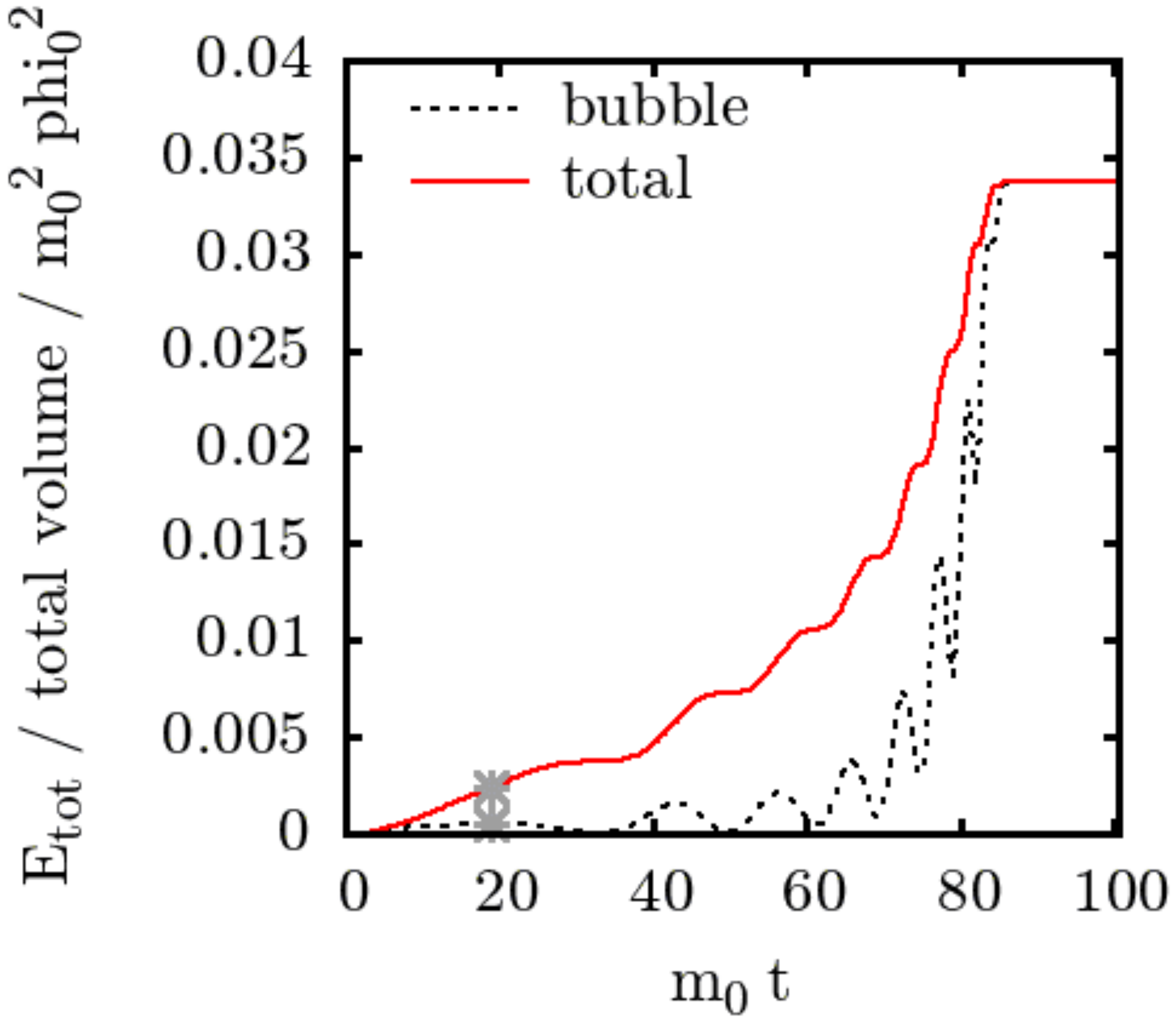

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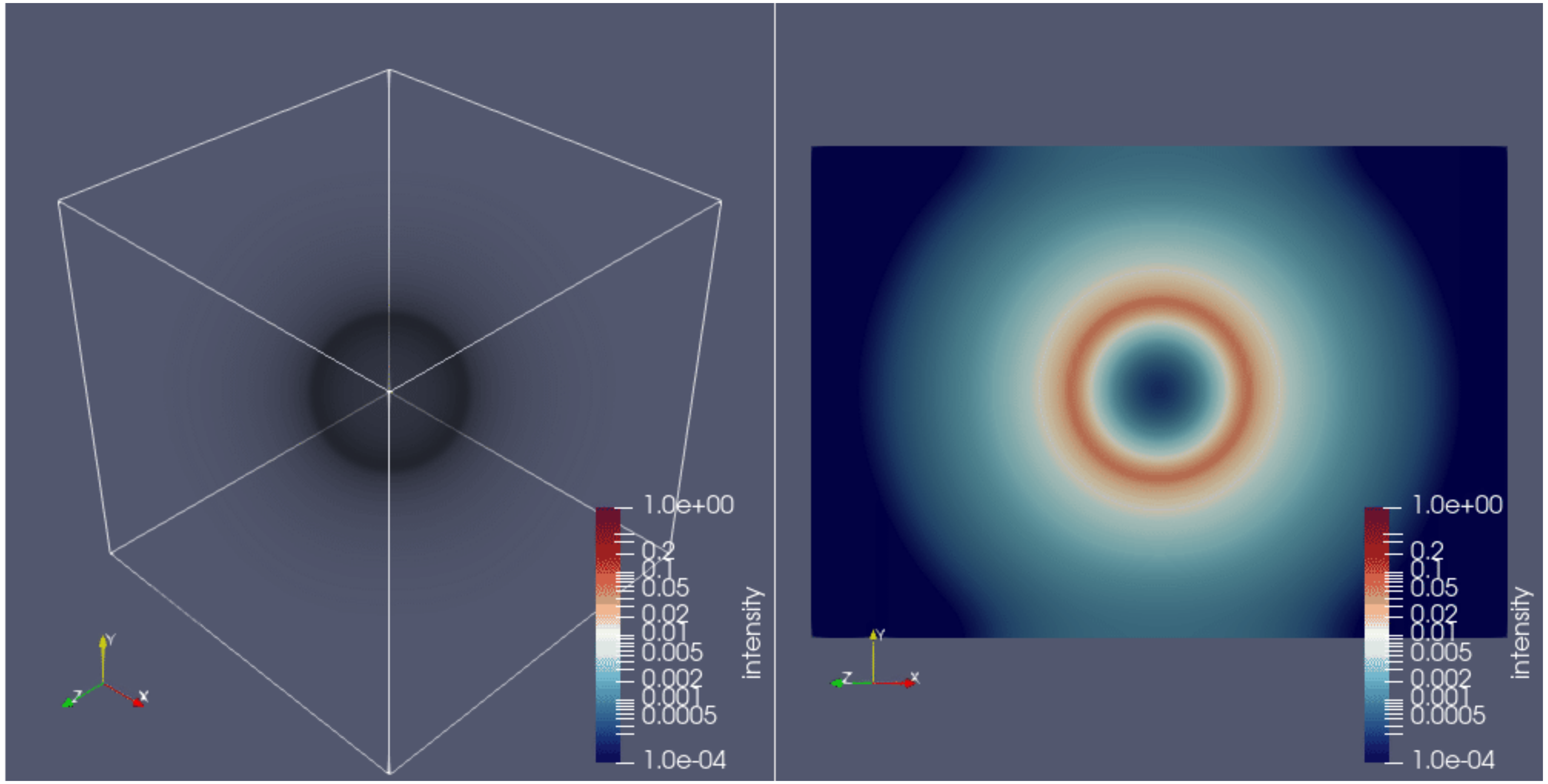

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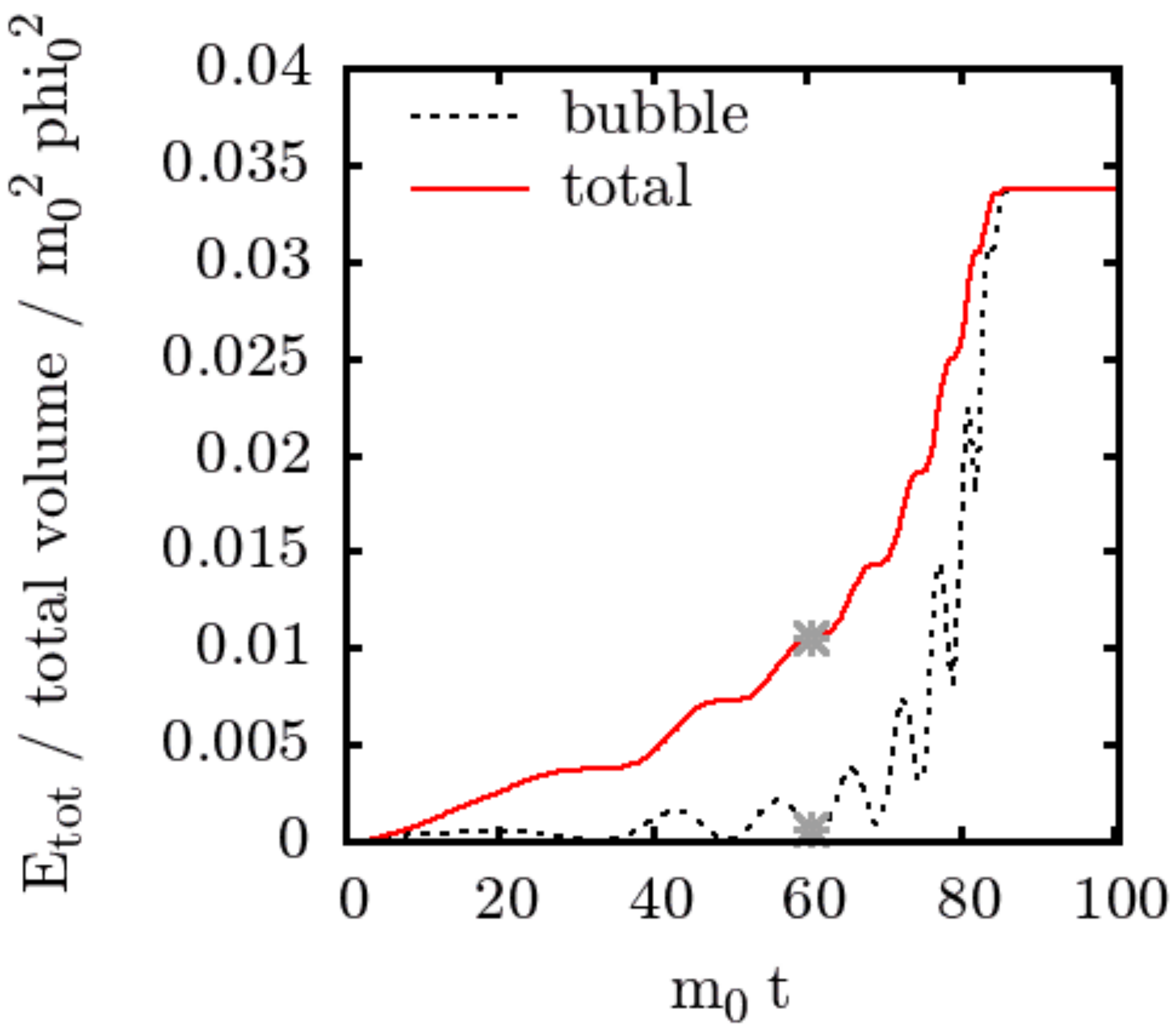

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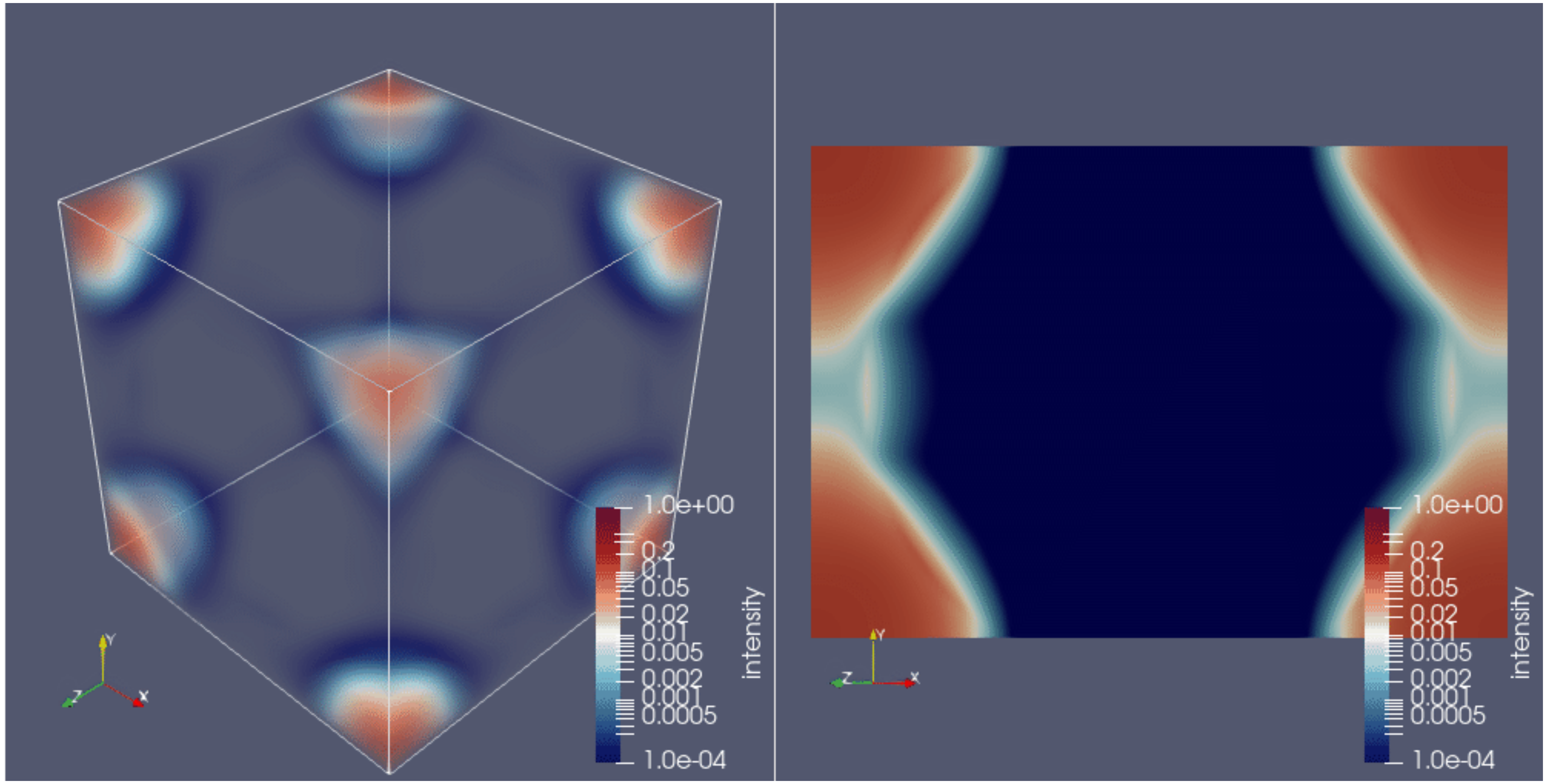

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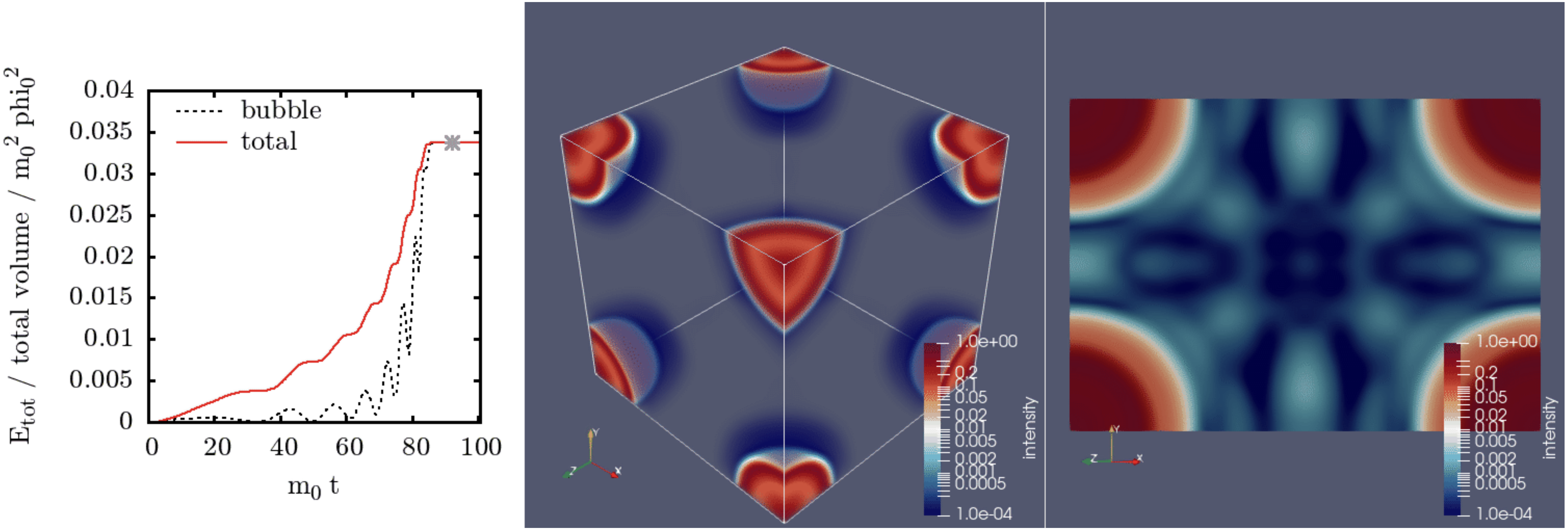

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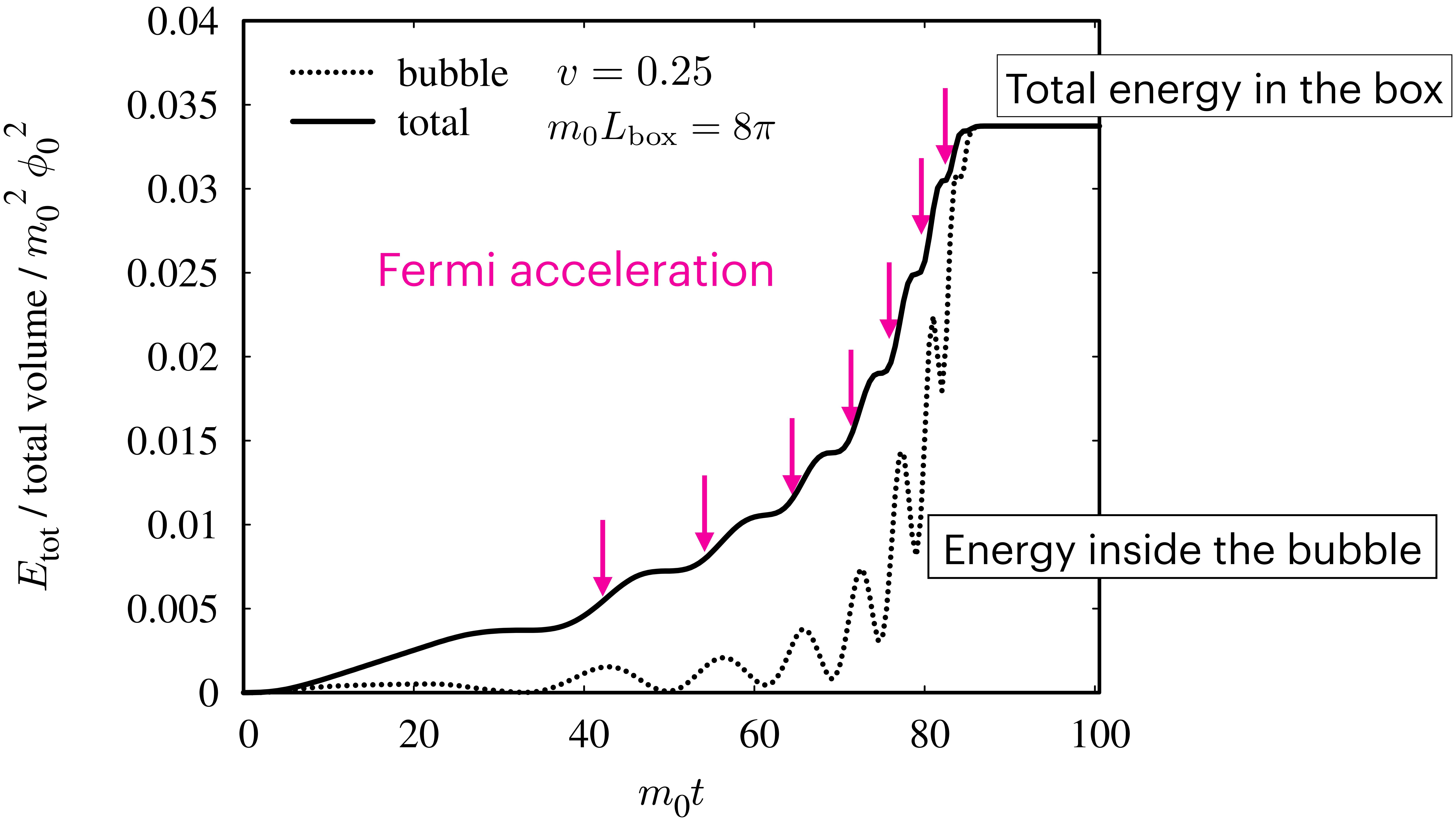
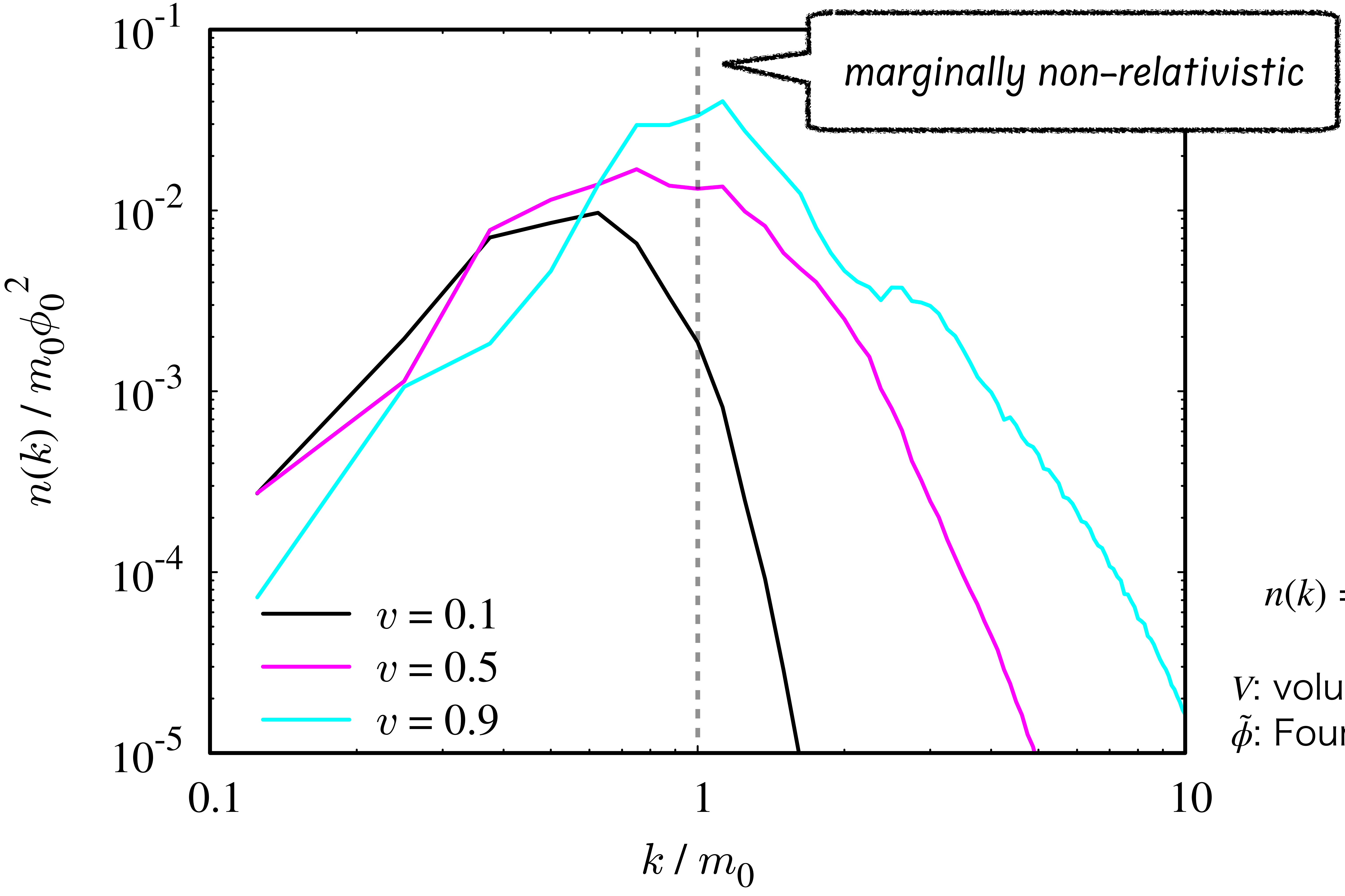
1.0e-04
intensity

The evolution of the axion energy



The momentum distribution

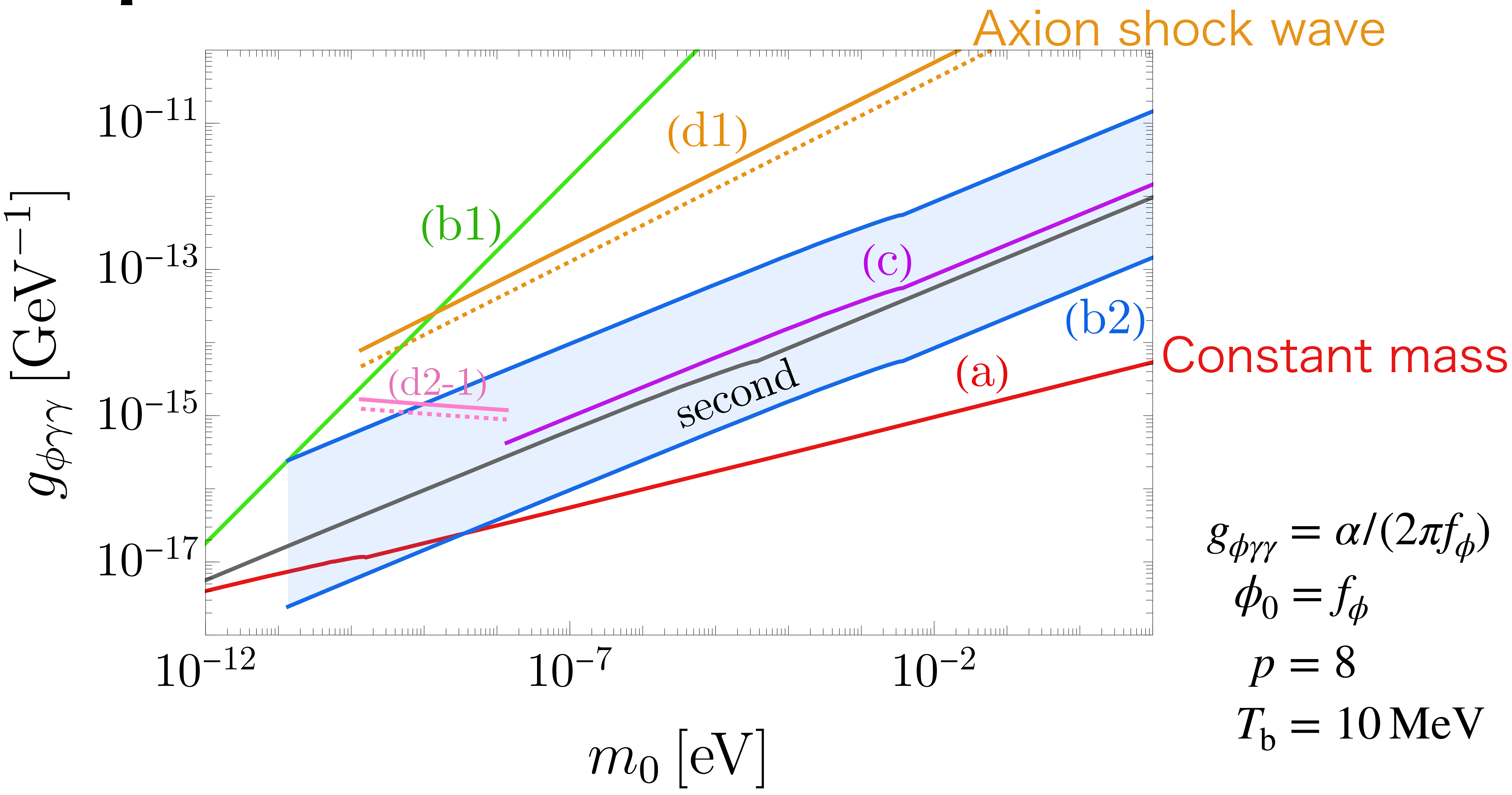


$$n(k) = \frac{k^3}{2\pi^2 \cdot 2\omega_k V}\left[\dot{\tilde{\phi}}^2 + \omega_k^2 \tilde{\phi}^2\right]$$

V: volume of the simulation box

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

Viable parameters for axions



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

$\phi_0 = f_\phi$

$p = 8$

$T_\mathrm{b} = 10\,\mathrm{MeV}$

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 and that **Fermi acceleration** occurs.
- If the axion 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.

back up

N.B.) flux conserves during transmission

Boundary condition,

$$\Phi_I[t',0] + \Phi_R[t',0] = \Phi_T[t',0] \ ,$$

$$\partial_{z'}\Phi_I[t',0] + \partial_{z'}\Phi_R[t',0] = \partial_{z'}\Phi_T[t',0]$$

has solution,

$$\Phi_R[t',z'] = \frac{k'_I - k'_T}{k'_I + k'_T}\phi_0 \exp[i(\omega' t' - k'_R z')] \ ,$$

$$\Phi_T[t',z'] = \frac{2k'_I}{k'_I + k'_T}\phi_0 \exp[i(\omega' t' + k'_T z')] \ ,$$

which satisfies

$$k'_I |\Phi_I[t',0]|^2 = k'_R |\Phi_R[t',0]|^2 + k'_T |\Phi_T[t',0]|^2 \, .$$

This implies the conservation of flux,

$$\text{flux} = \text{number density} \times \text{group speed}$$

$$= \omega' |\Phi|^2 \times (k'/\omega') \, .$$

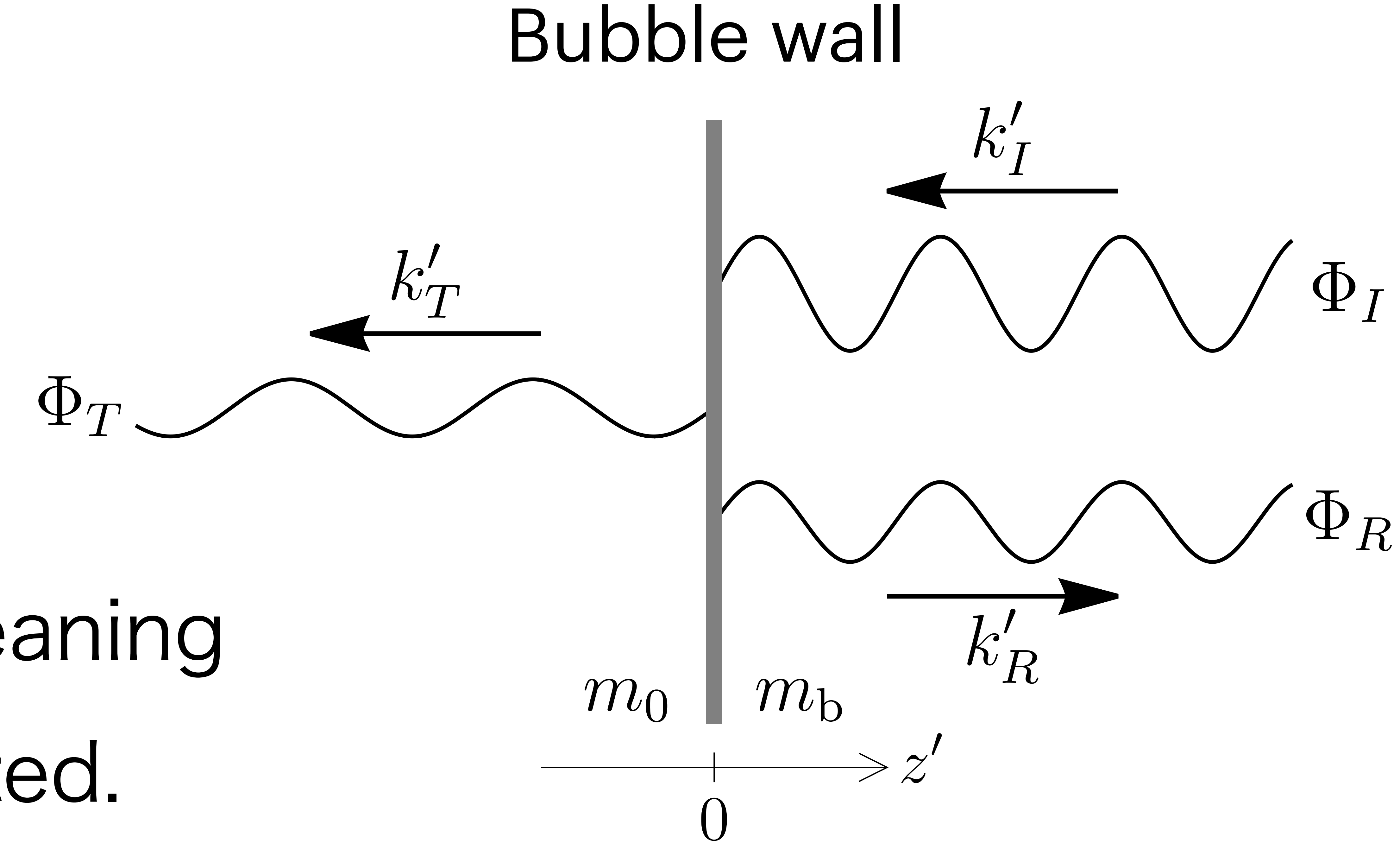
Bubbles expel the axion waves

Consider the planar bubble wall at $z' = 0$ (wall-rest frame) and the plane wave propagating as

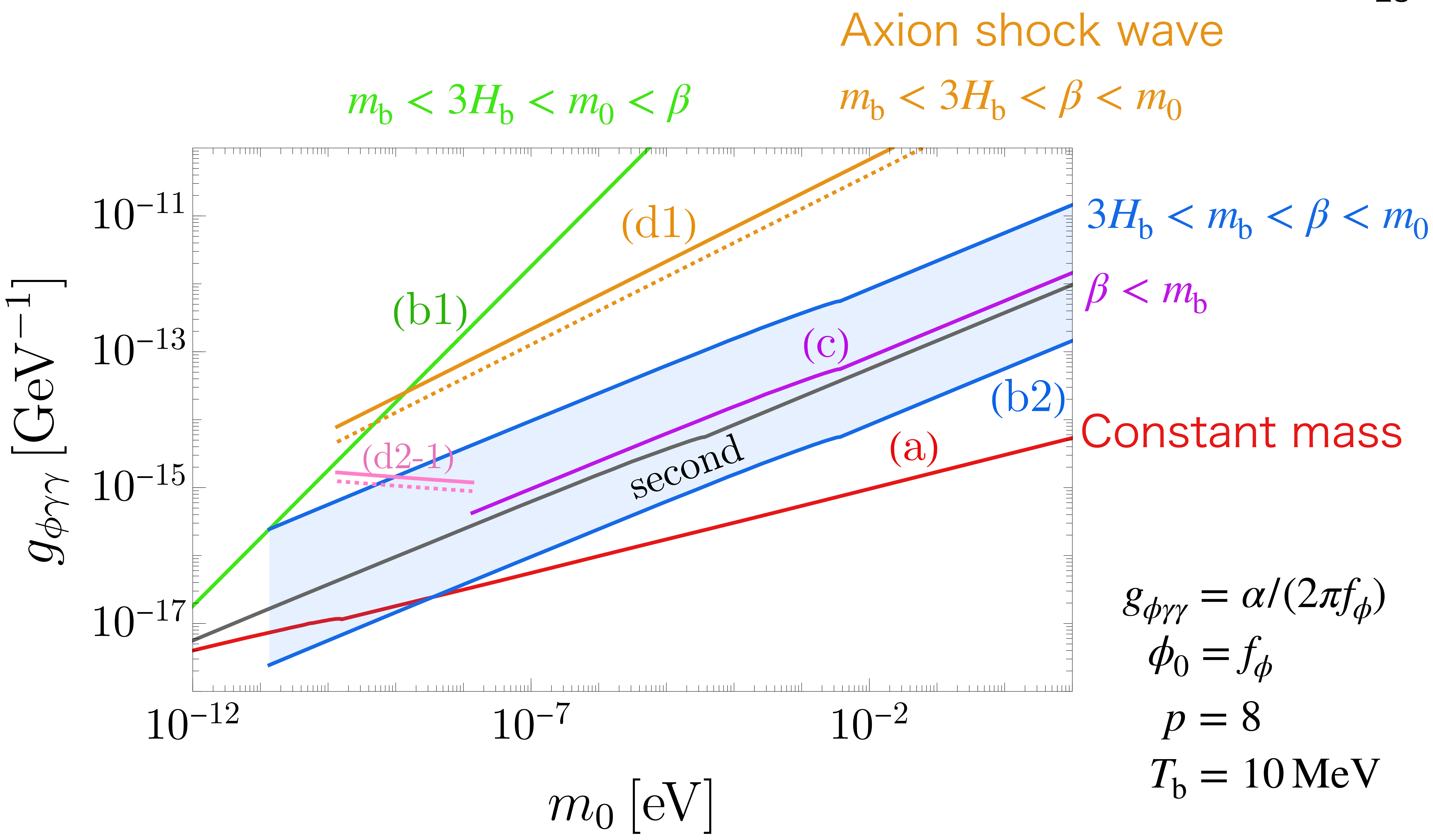
$$\Phi_I = \phi_0 \exp[i(\omega' t' + k_I' z')]$$

where $\omega' = \sqrt{k_I'^2 + m_b^2}$

$'$ means it is evaluated in the wall-rest frame



k_T' becomes imaginary when $\omega' < m_0$ meaning that the axion waves are totally reflected.



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