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.

We see how bubbles produce axions.

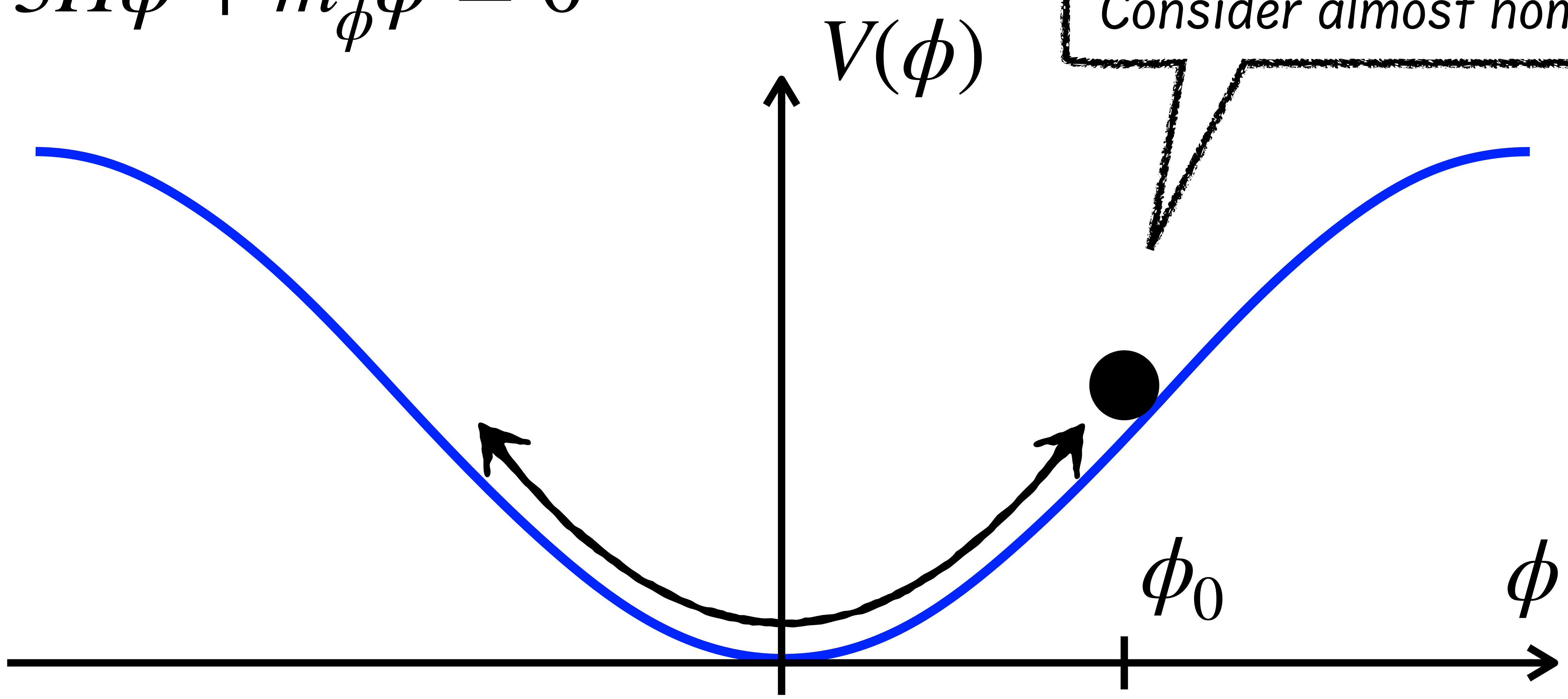
Misalignment Mechanism

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.

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



Consider almost homogeneous initial condition $\phi = \phi_0$

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

First-Order Phase Transition

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

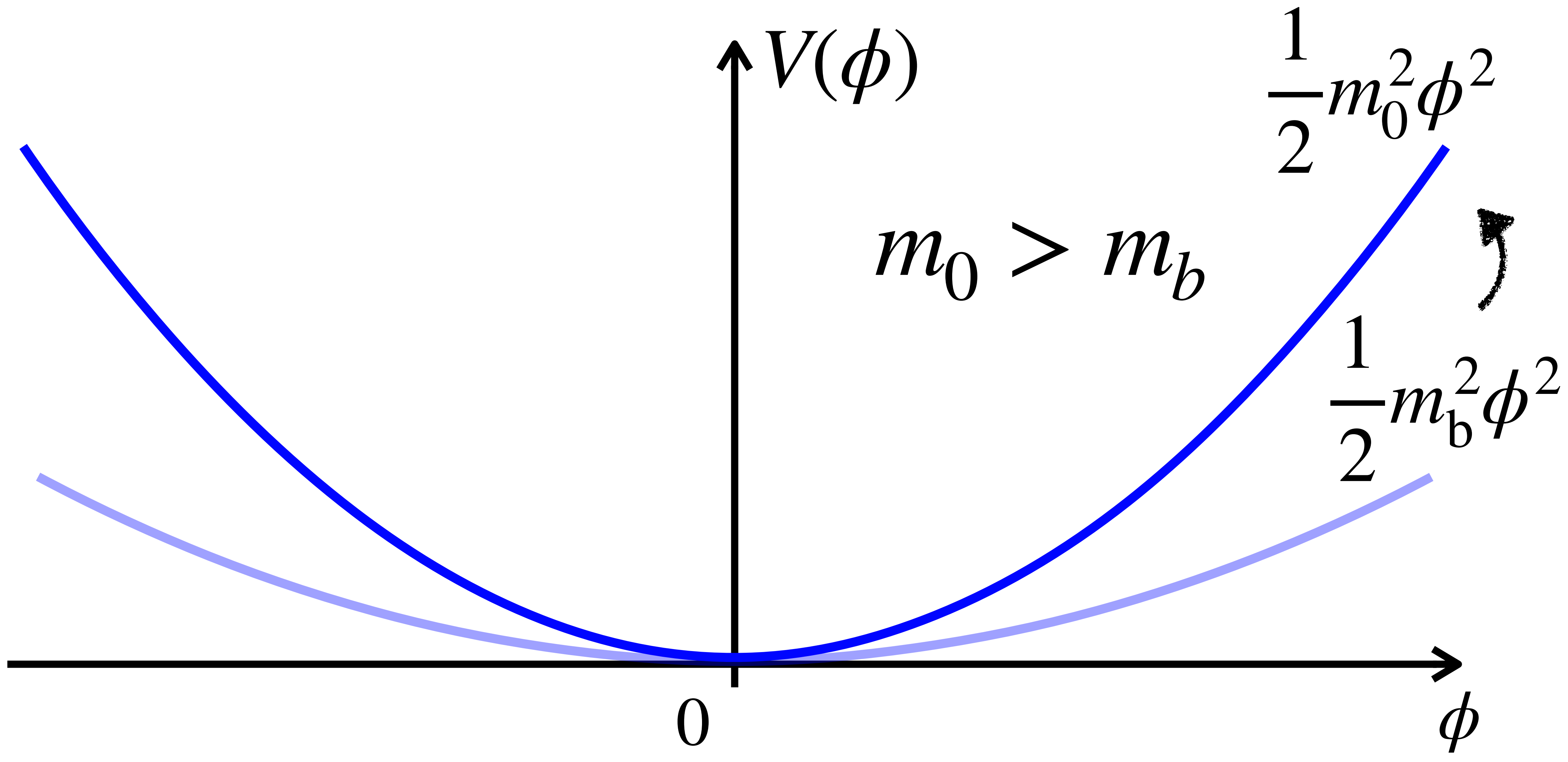
For example, the phase transition from the deconfined phase to the confined phase in the pure $SU(N)$ Yang-Mills theory where $N \geq 3$ is known to be a first-order phase transition. B. Lucini, M. Teper and U. Wenger, `03, `05

There are various cosmological implications.

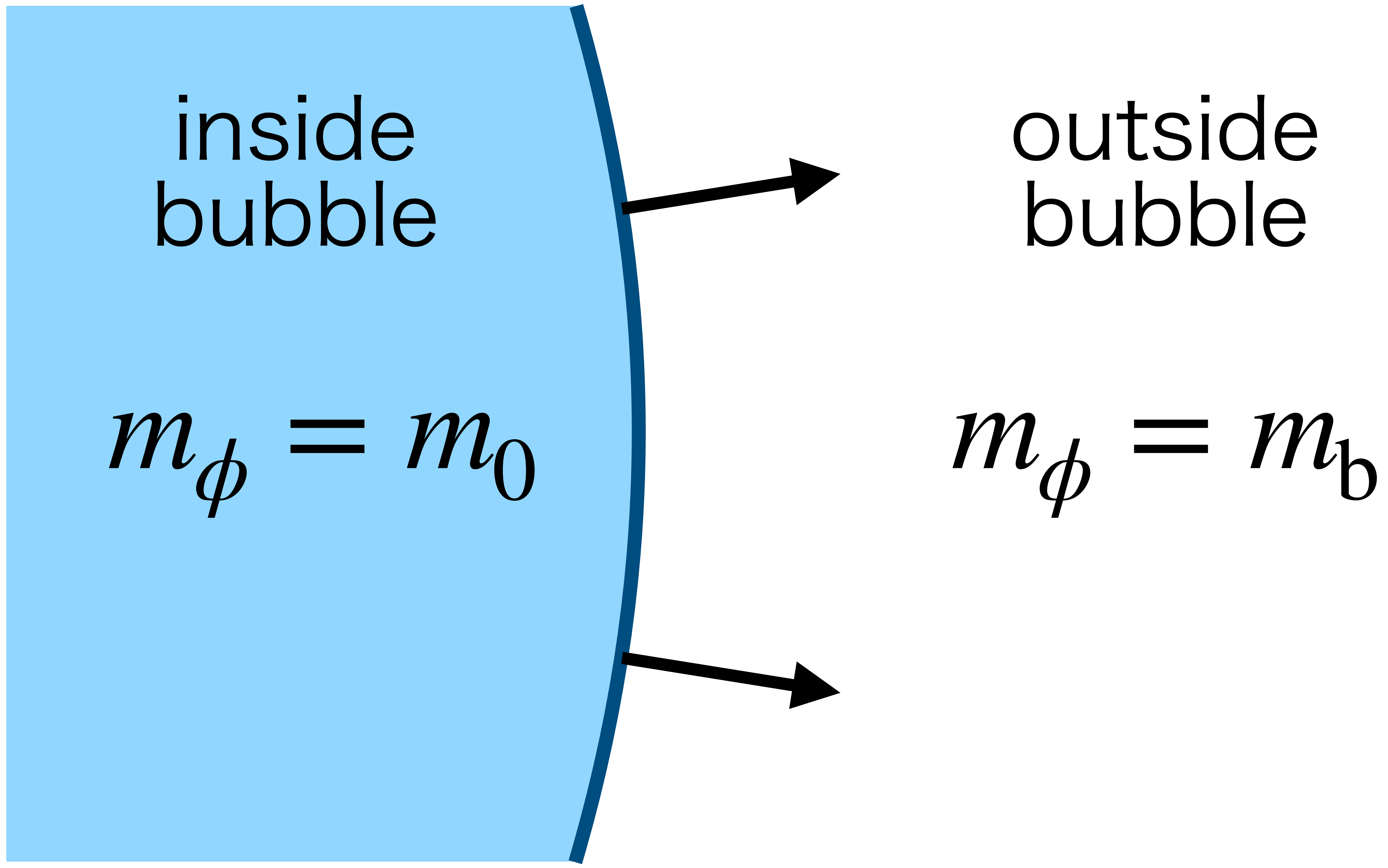
e.g.) baryogenesis, dark matter, and gravitational waves, $\cdots$

Discontinuous change of axion mass

We assume the axion mass arises from coupling to non-Abelian gauge fields that undergo a first-order phase transition from a deconfined to a confined phase.



@$T = T_b$ (bubble nucleation temperature)



inside bubble

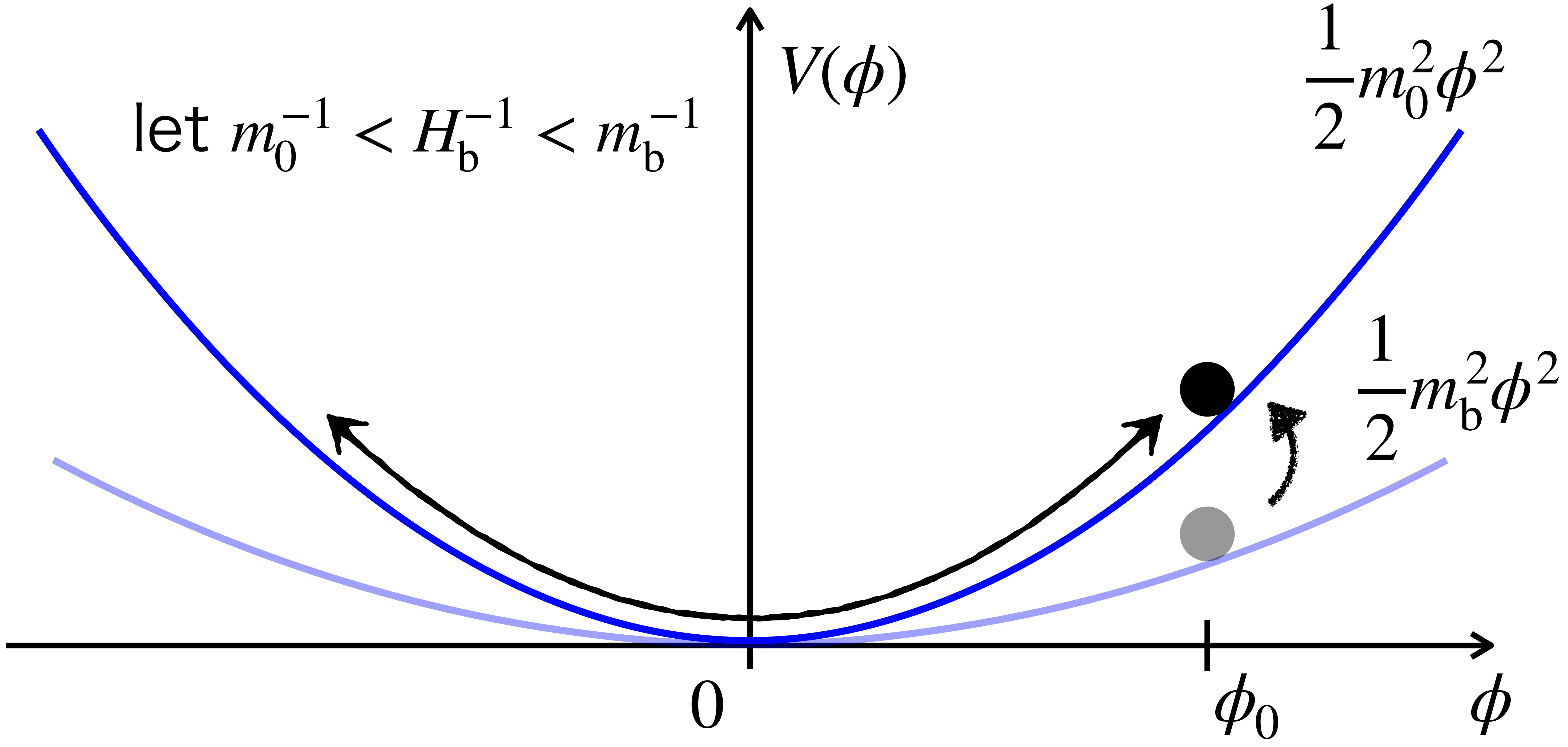
$m_\phi = m_0$

outside bubble

$m_\phi = m_b$

When mass changes homogeneously

Nakagawa, Takahashi, Yamada, Yin `22



$$\frac{\rho_\phi}{s} \simeq \frac{m_0^2\phi_0^2}{T_b^3}$$

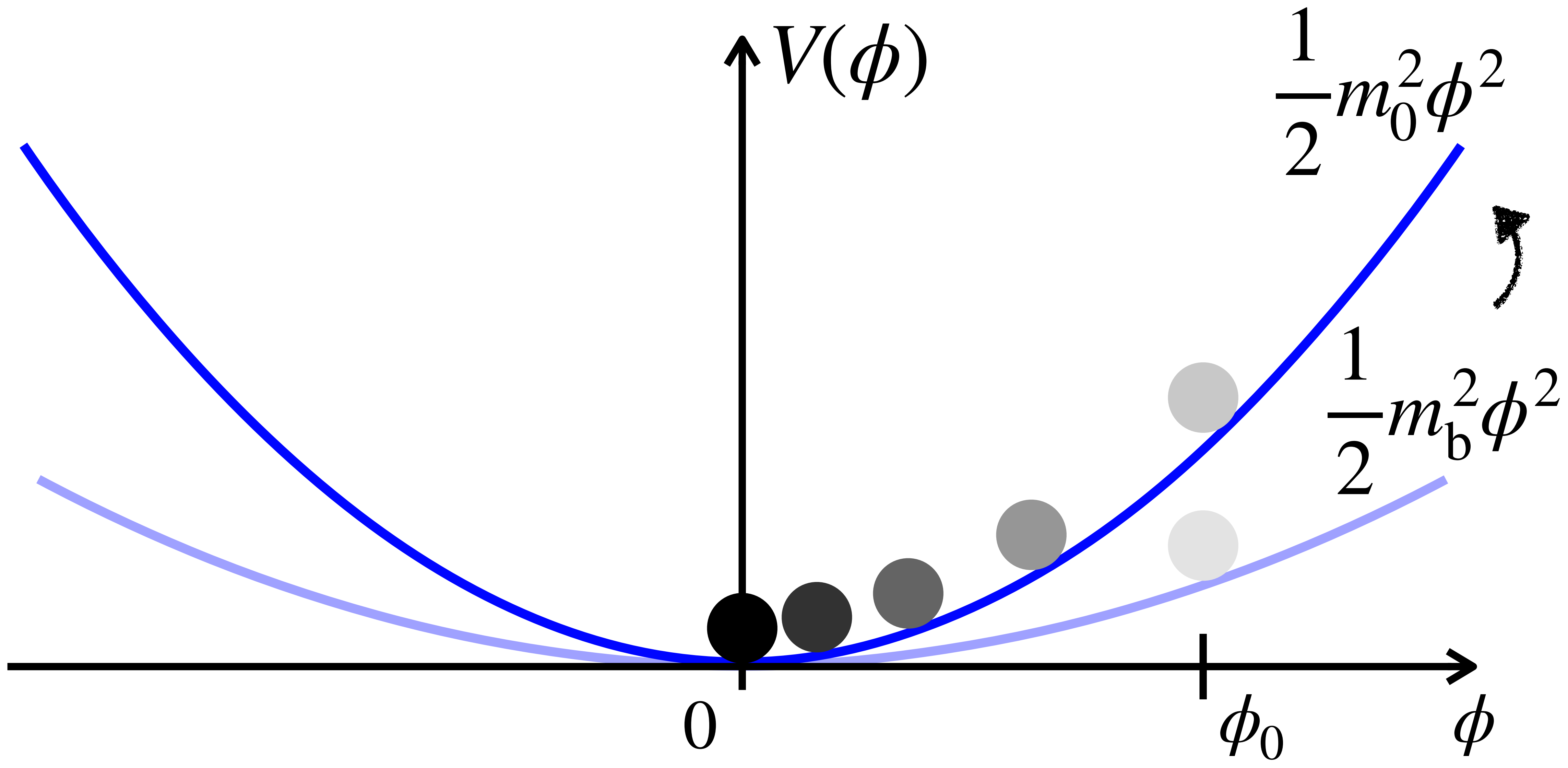
This corresponds to the case where the duration of phase transition is enough shorter than m_0^{-1}.

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

Focus on the case of $m_0^{-1} <$ duration of phase transition $< m_b^{-1}, H_b^{-1}$.

Bubbles expel axion waves

Axion inside the bubble wall settles down to $\phi = 0$ by mass and does not oscillate due to the gradient energy around the wall.



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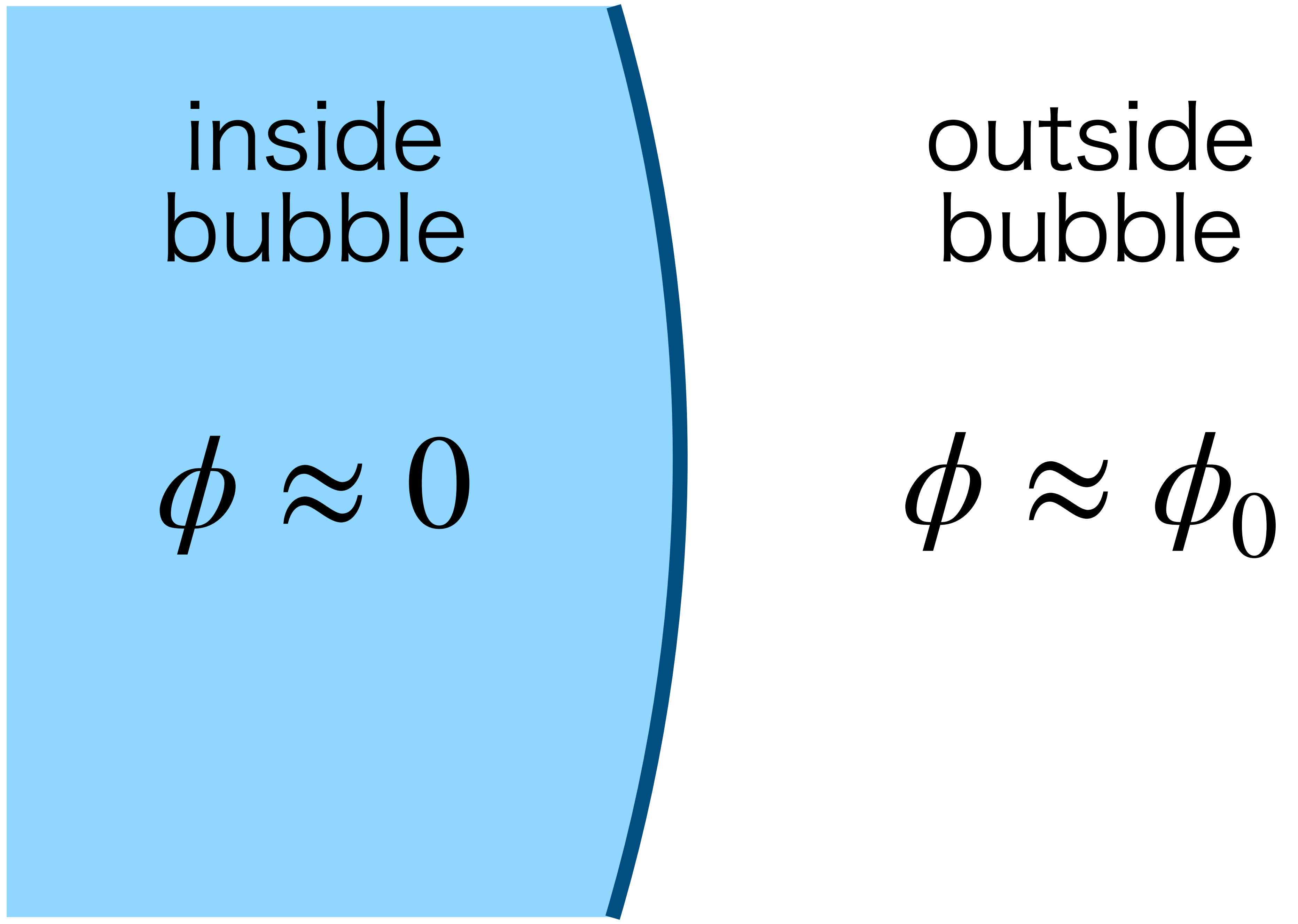


inside bubble

$\phi \approx 0$

outside bubble

$\phi \approx \phi_0$

“Bubble” Misalignment Mechanism

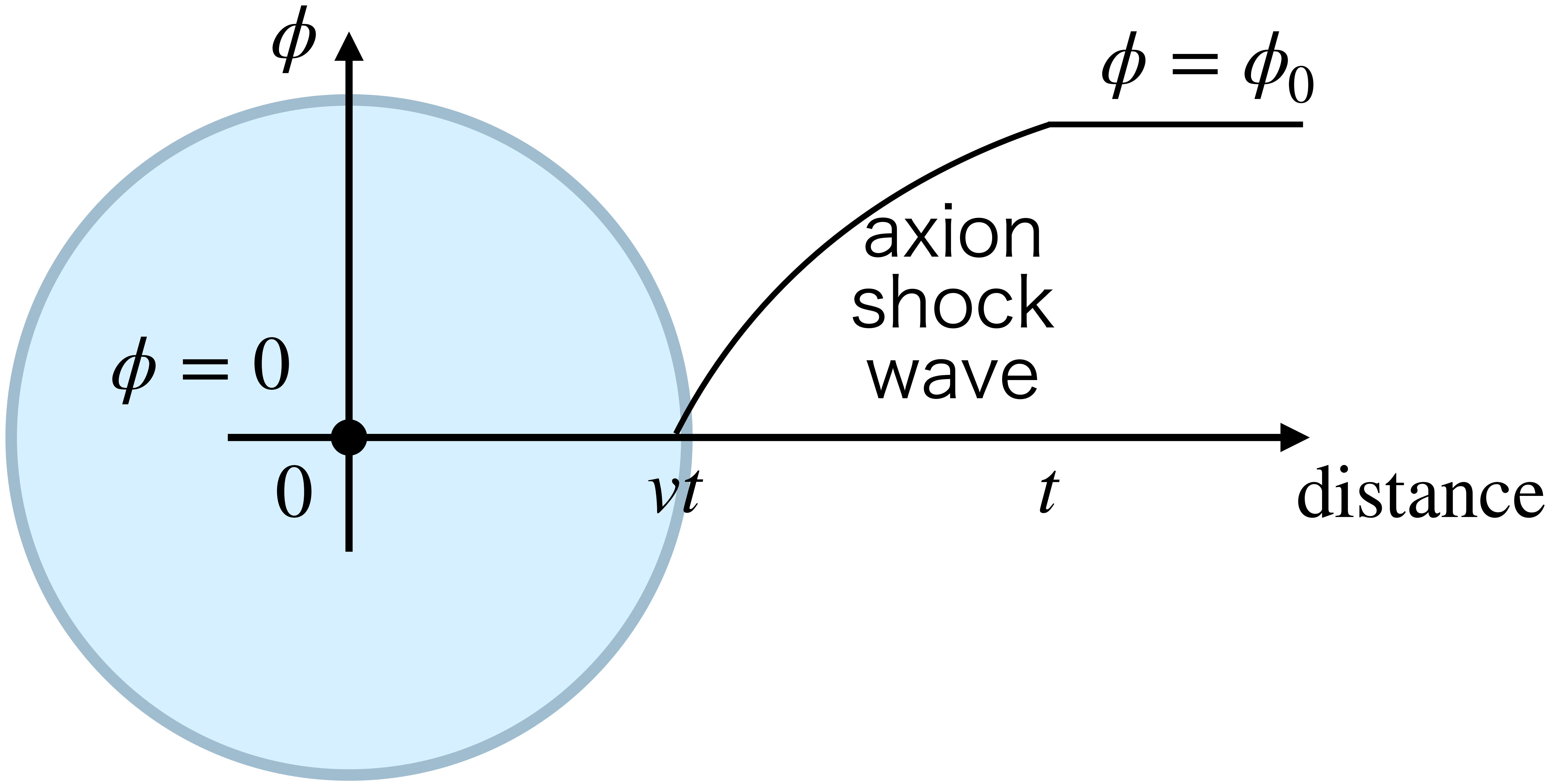
JL, Murai, Takahashi, and Yin 2402.09501

Three Steps

1. “Axion Shock Wave” (axion production)
2. “Fermi Acceleration” (energy enhancement)
3. Transmission into the Bubbles

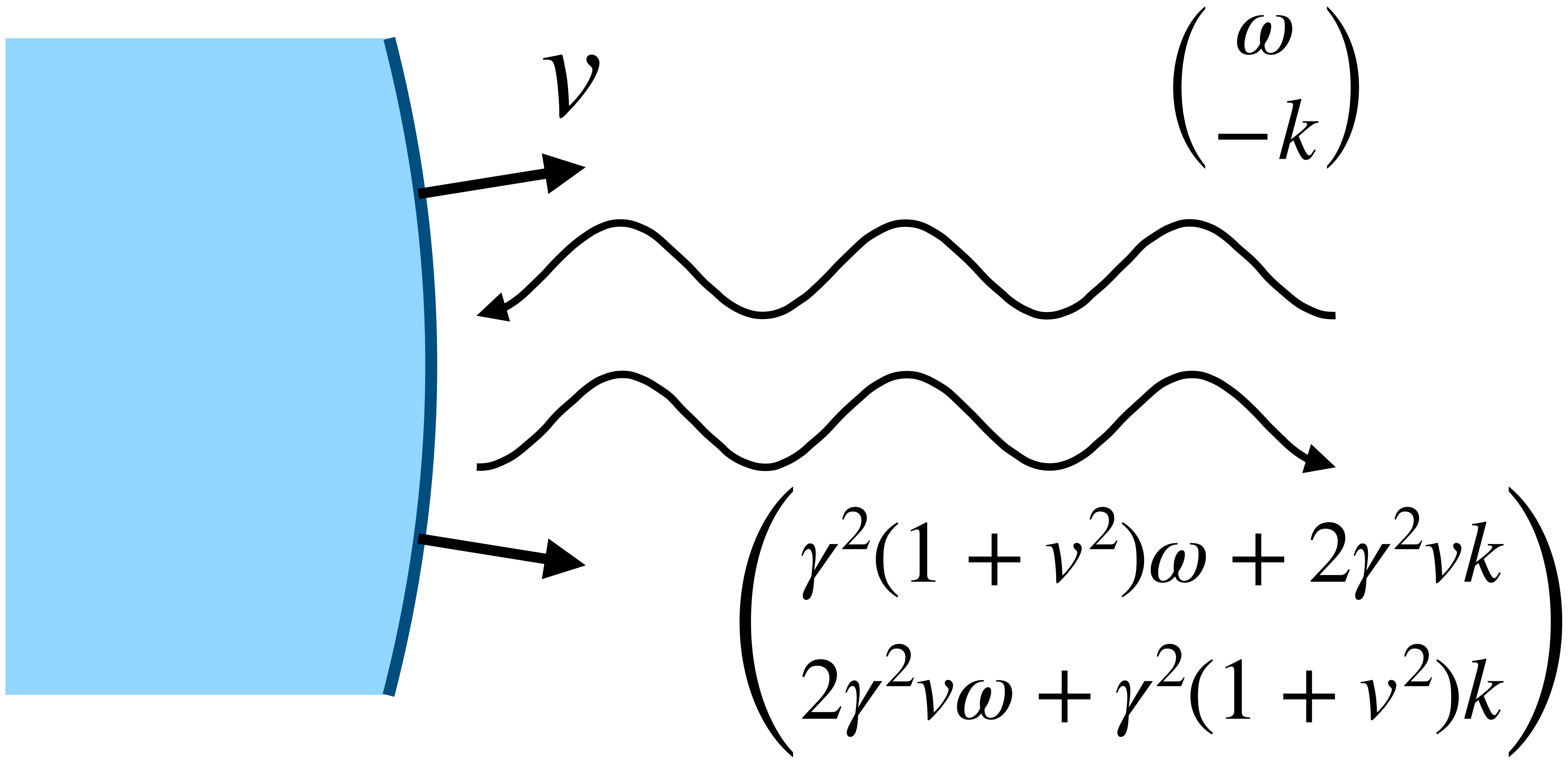
Axion Shock Wave

Axion settles down to $\phi = 0$ inside the bubble by mass. This produces energy excitations (axion shock wave) which result in the enhancement of the axion abundance.



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)

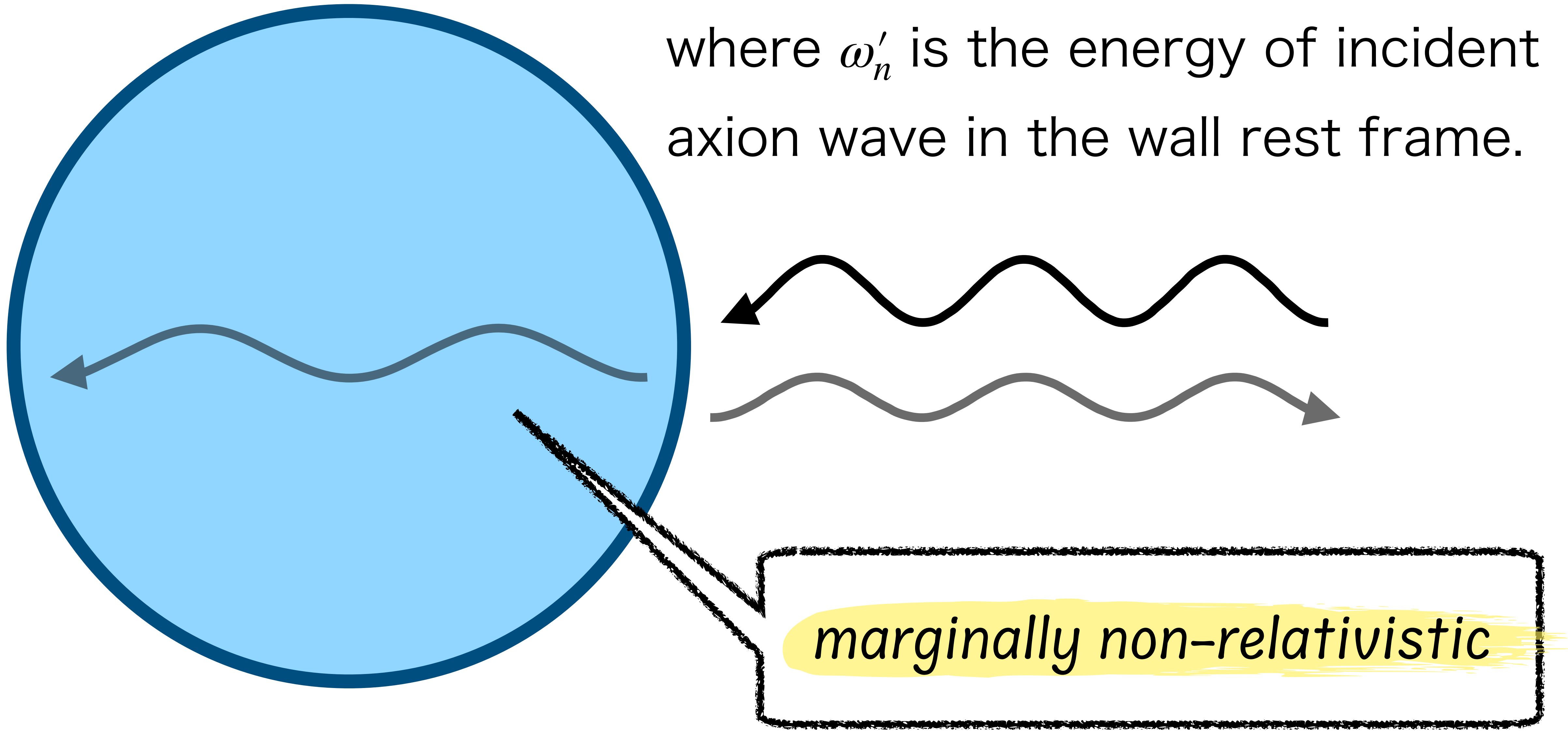


Axion waves transmit inside bubbles

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.



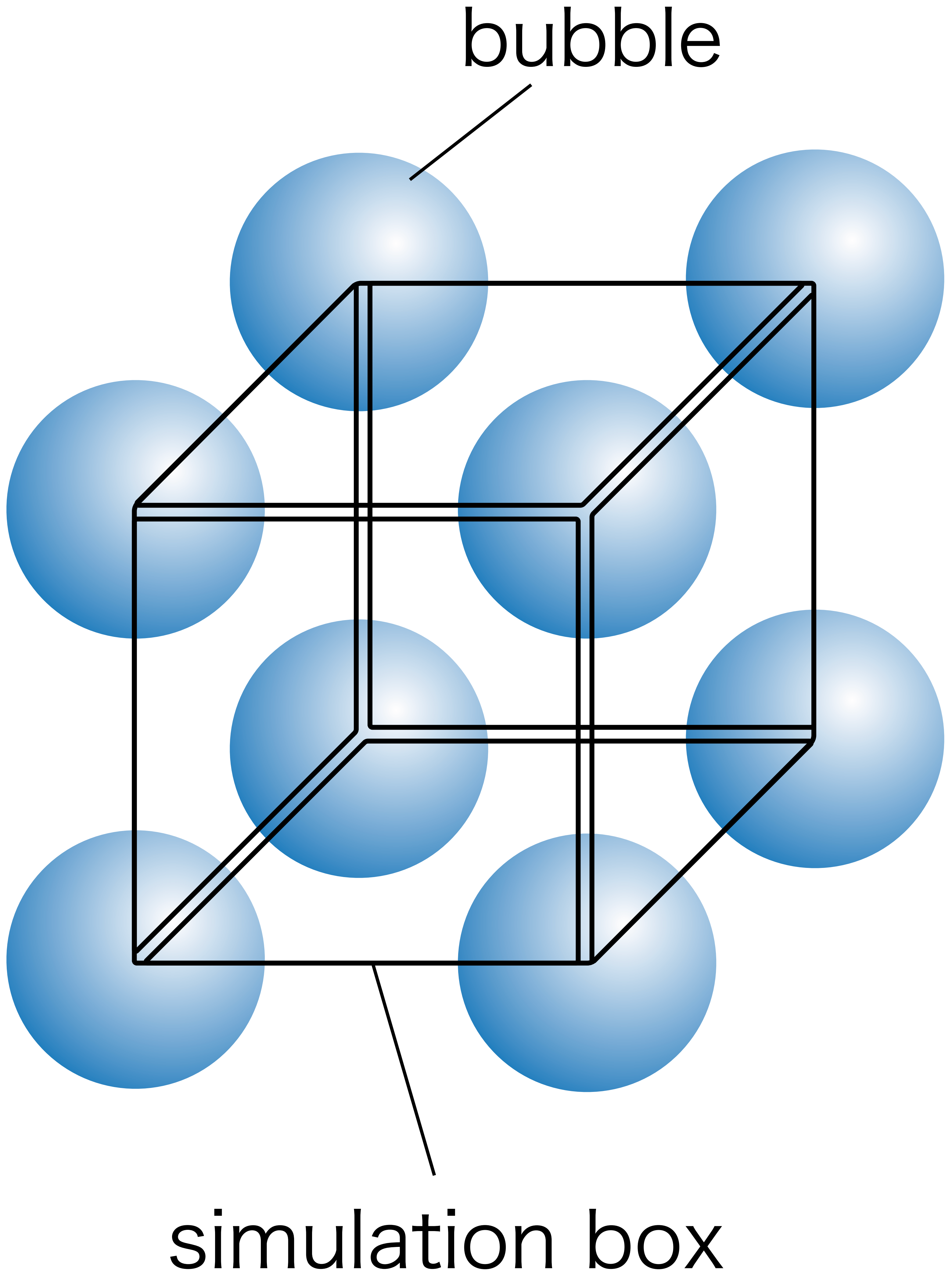
marginally non-relativistic

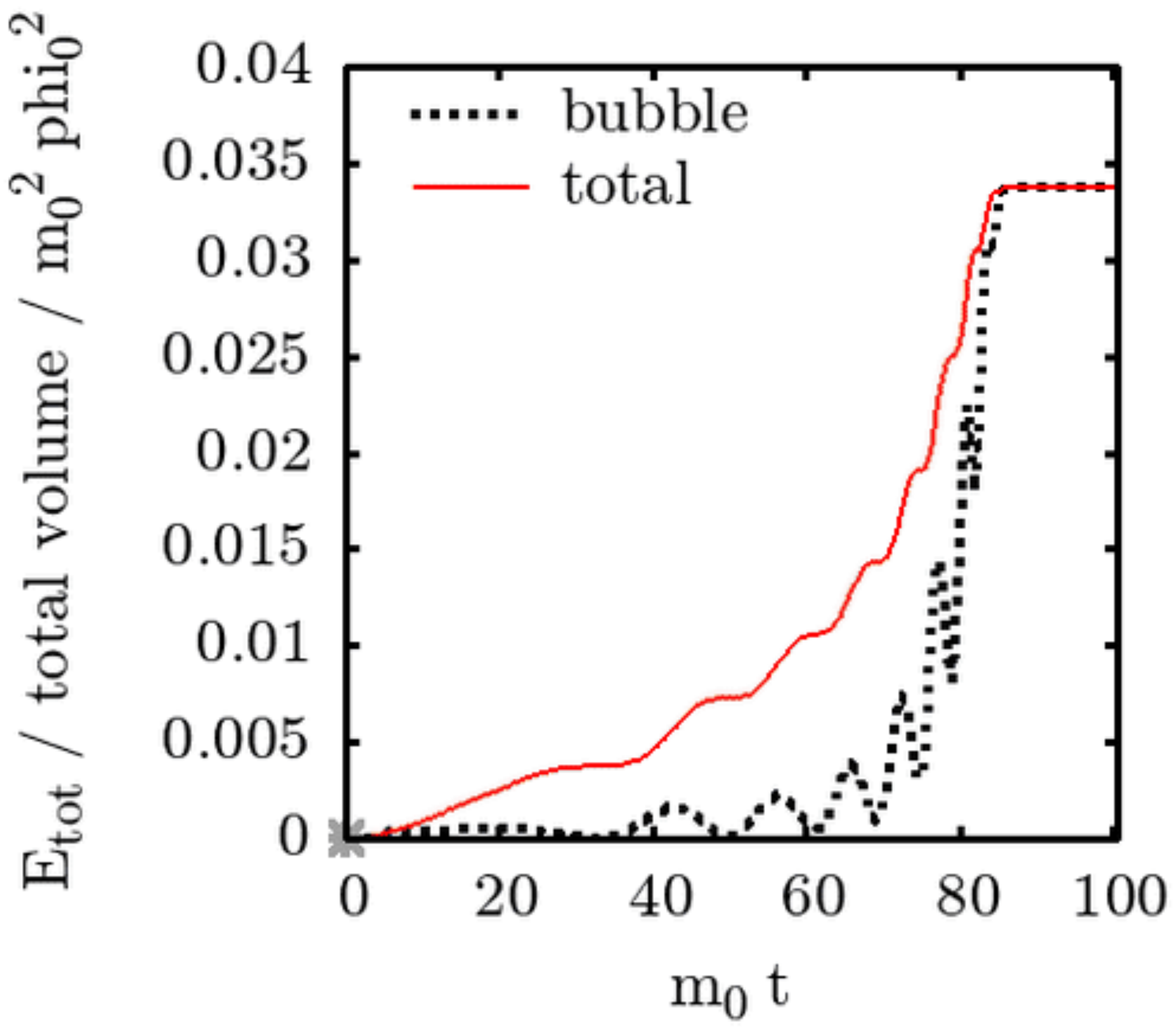
Numerical Simulation

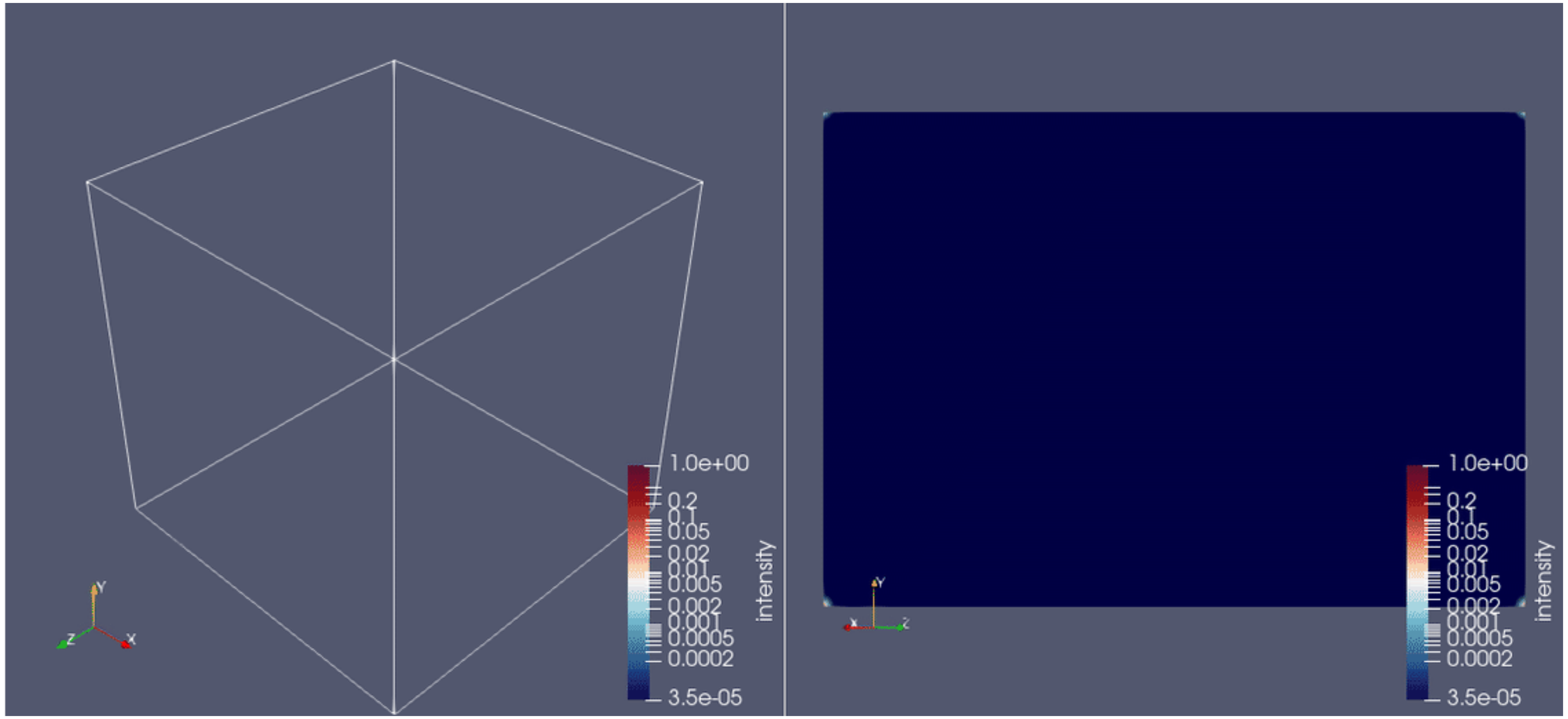
We performed the numerical simulations:

- 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.

$$m_0^{-1} < \text{duration of phase transition} \ll m_\mathrm{b}^{-1}, H_\mathrm{b}^{-1}\,.$$




E_{tot} / total volume / m_0^2 phi_0^2
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
bubble
total
0
20
40
60
80
100
m_0 t


Y
Z
X
1.0e+00
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3.5e-05
intensity
Y
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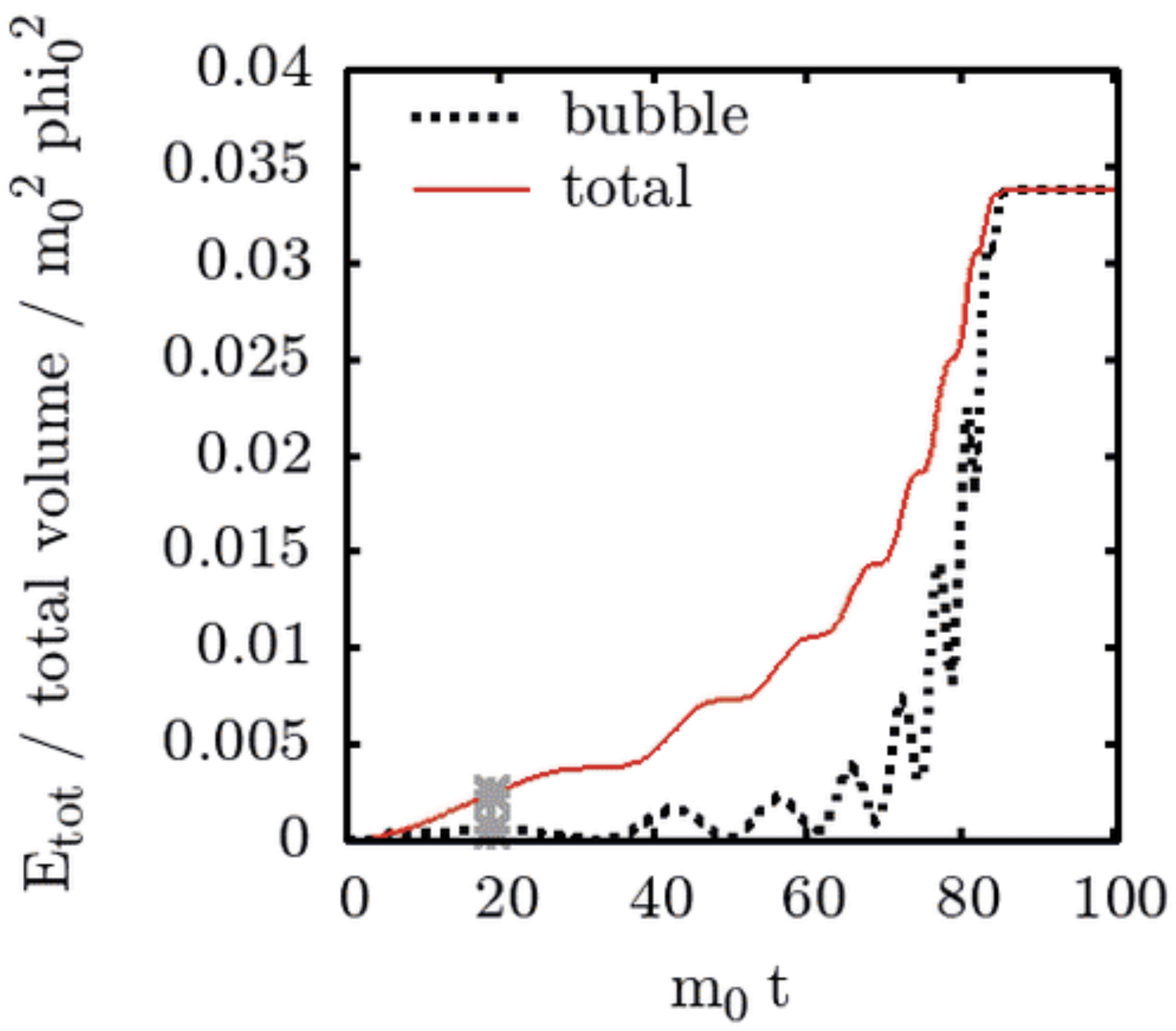
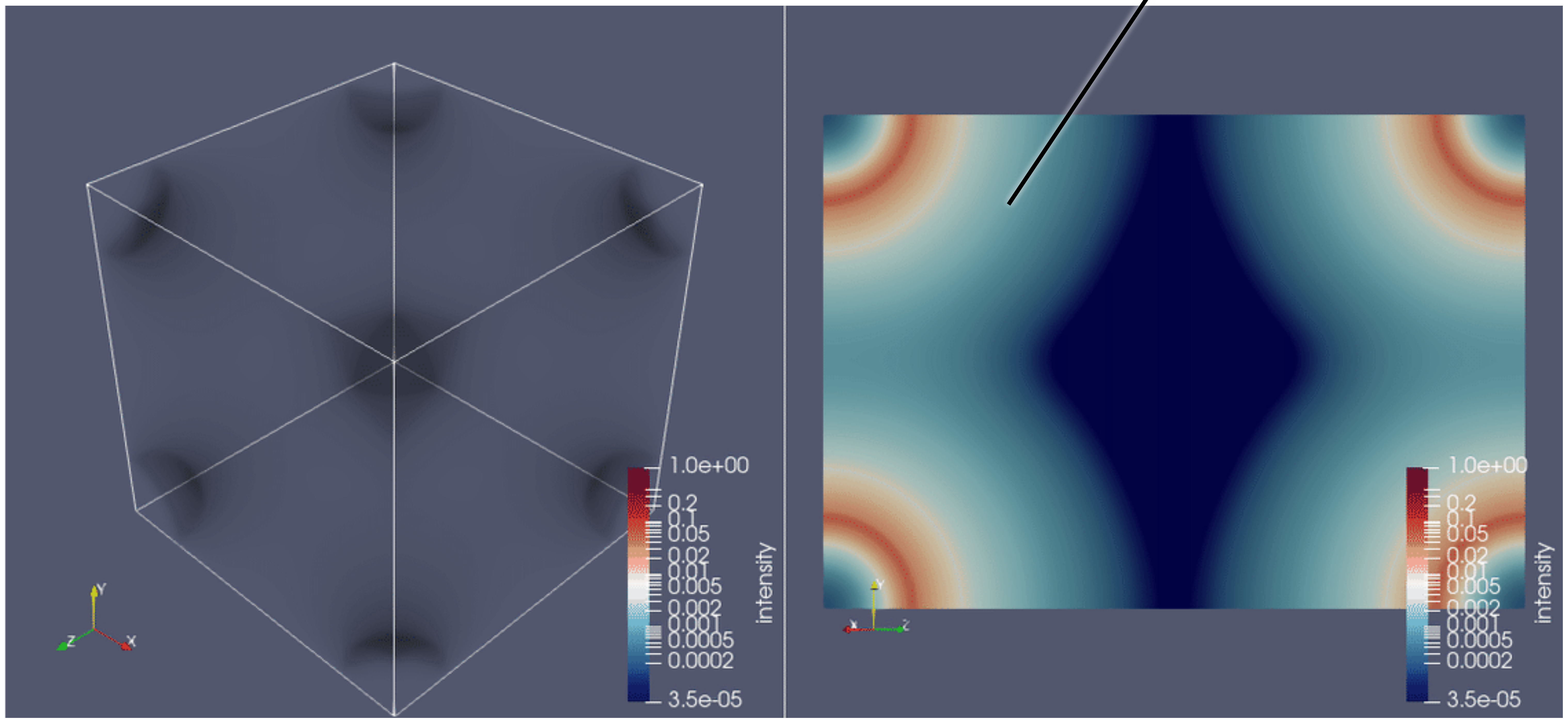
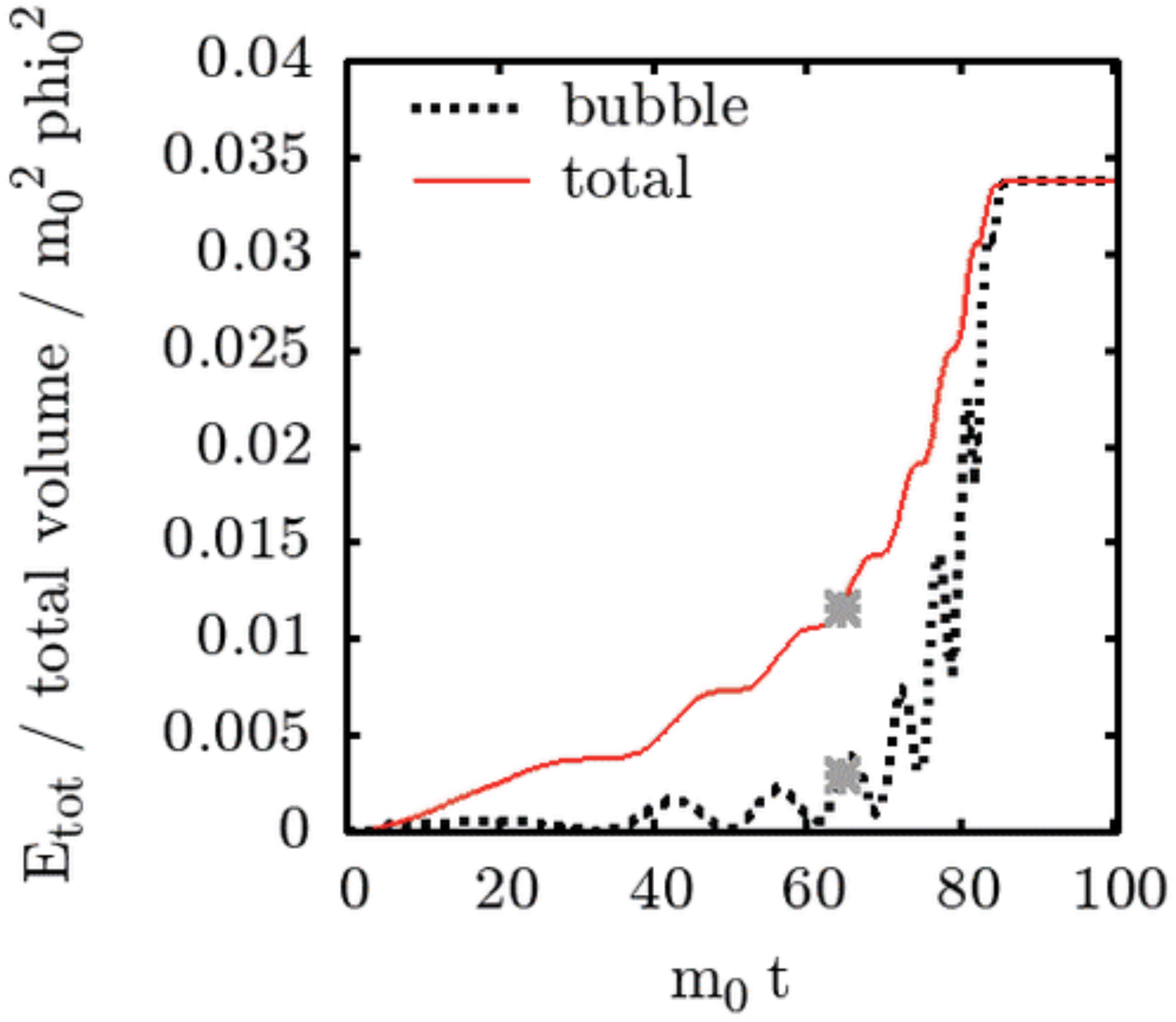
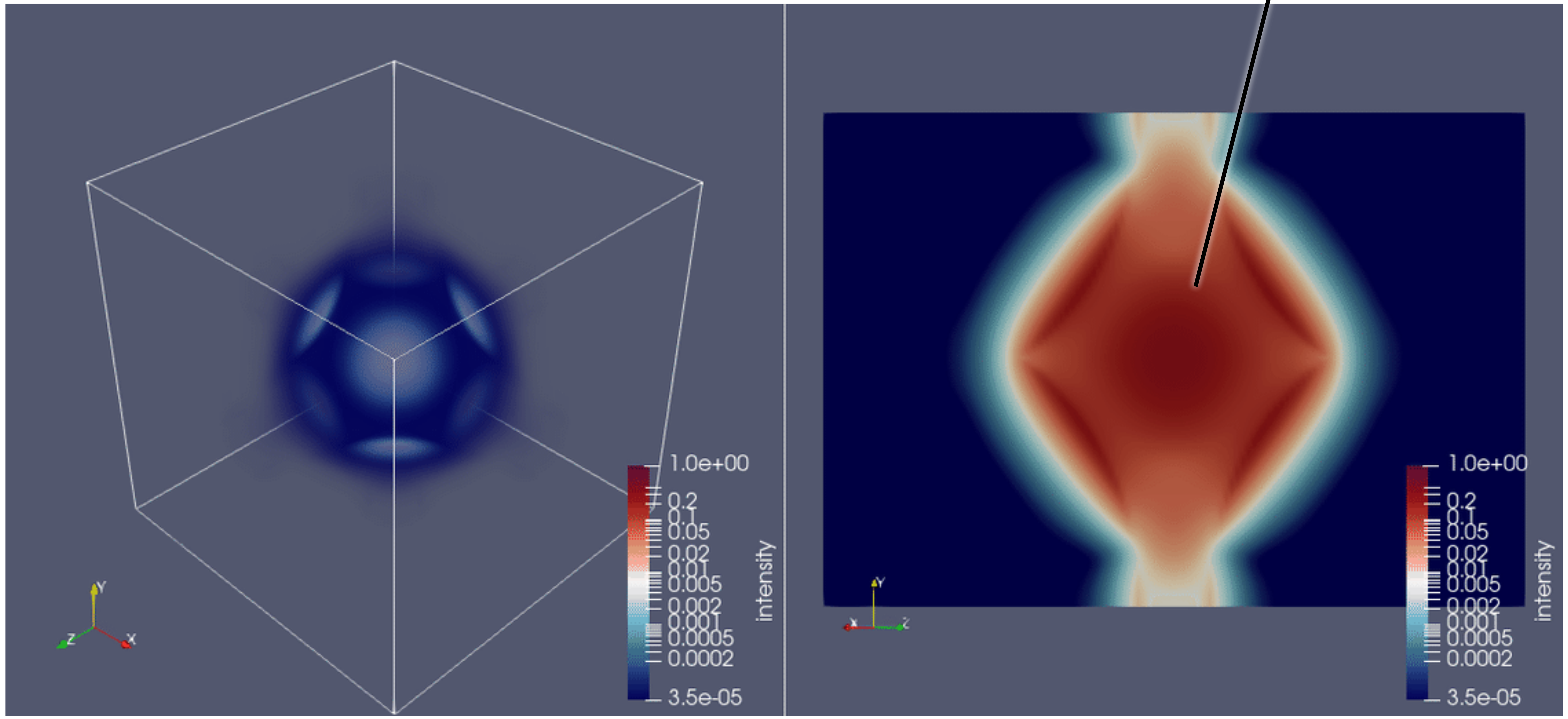


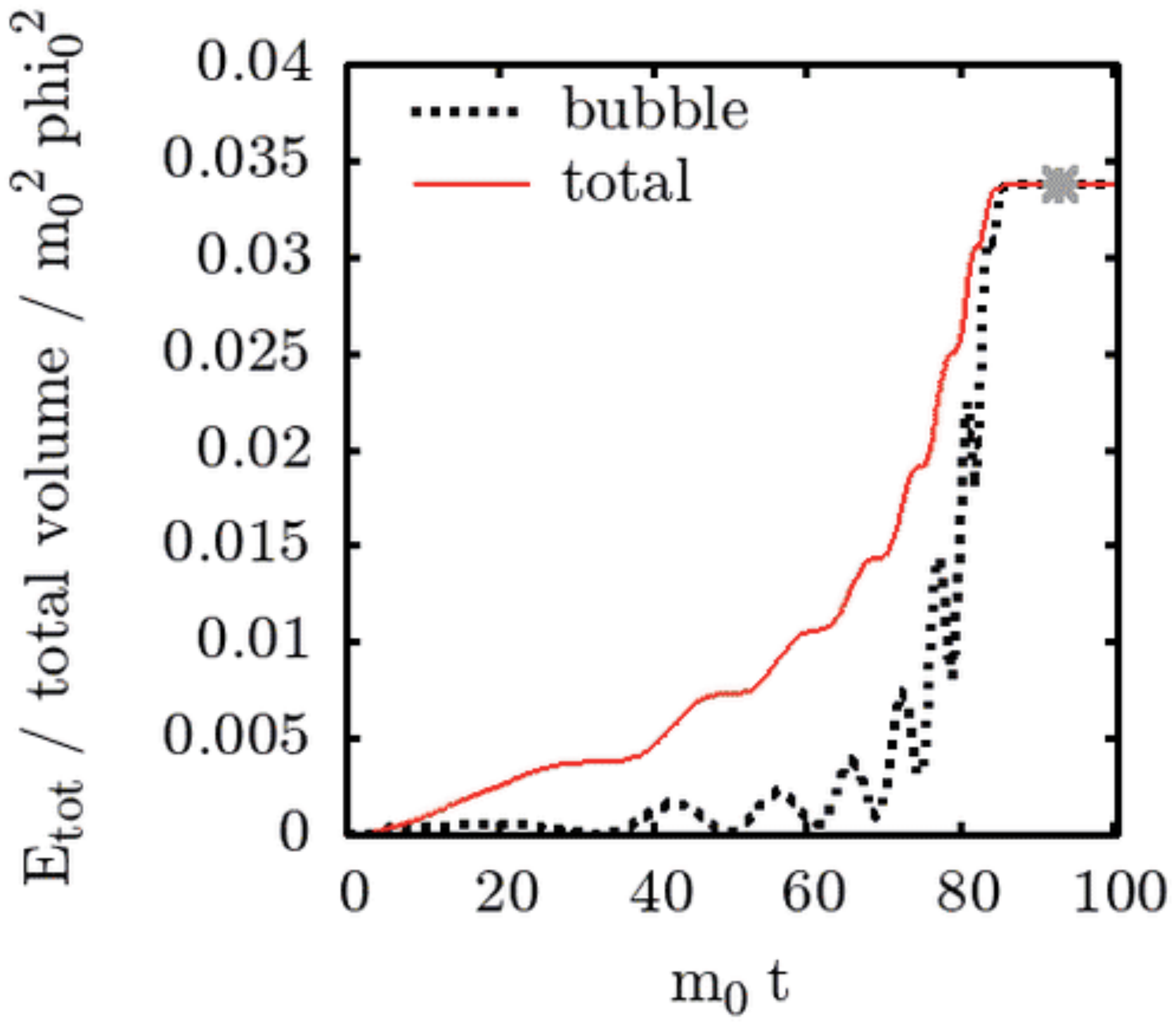


axion shock waves



accelerated axions

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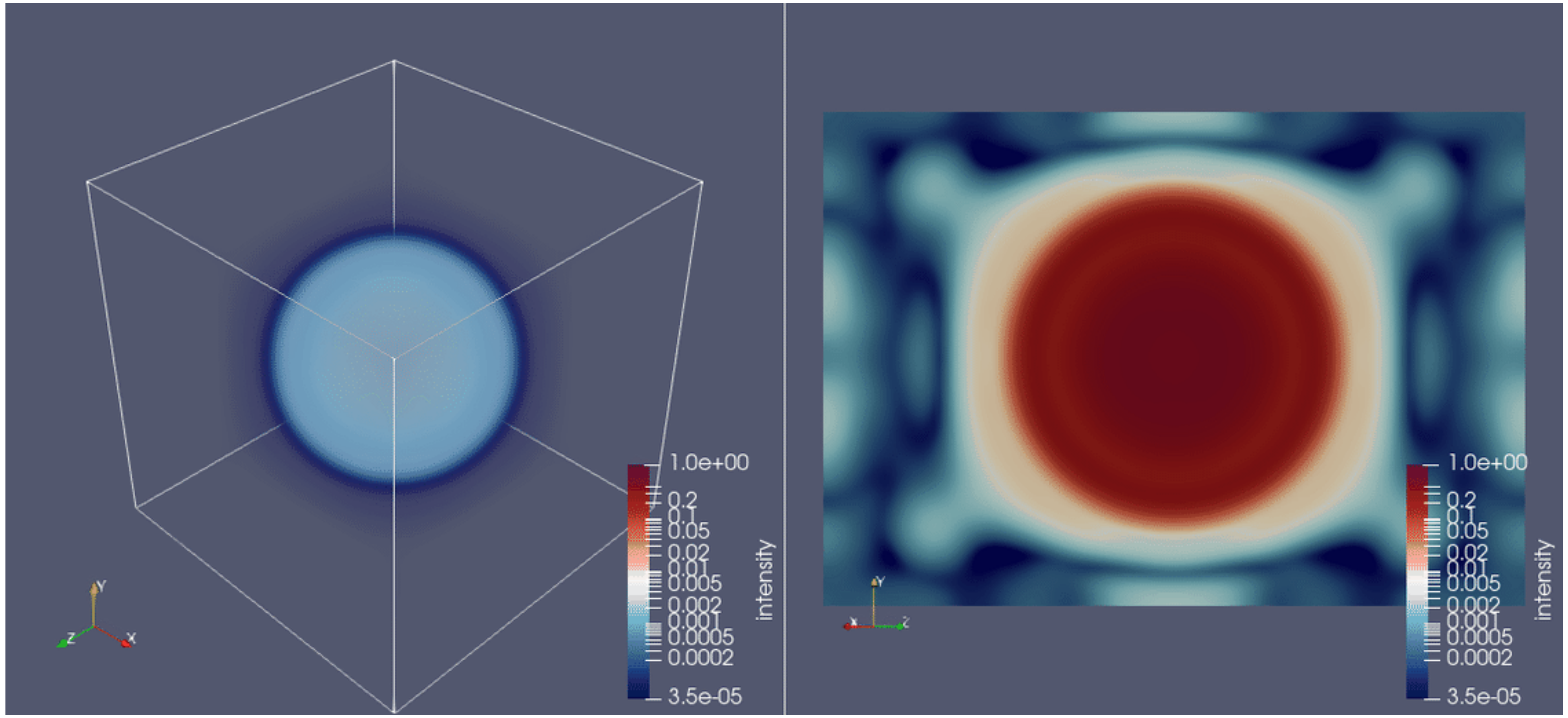
m_0 t


Y
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1.0e+00
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0.0002
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intensity
Y
X
Z
1.0e+00
0.2
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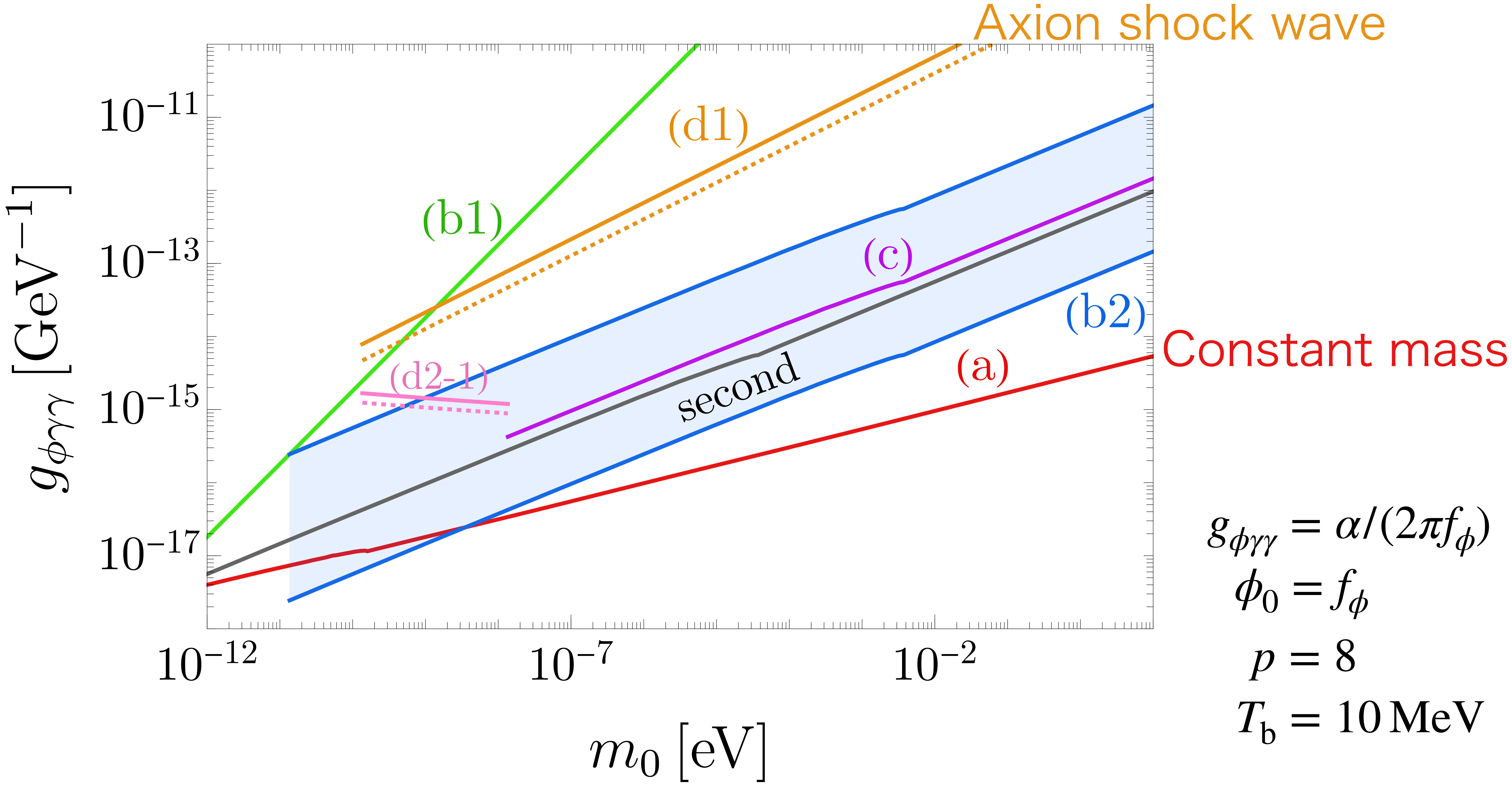
0.005
0.002
0.001
0.0005
0.0002
3.5e-05
intensity

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 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.

back up

Axions

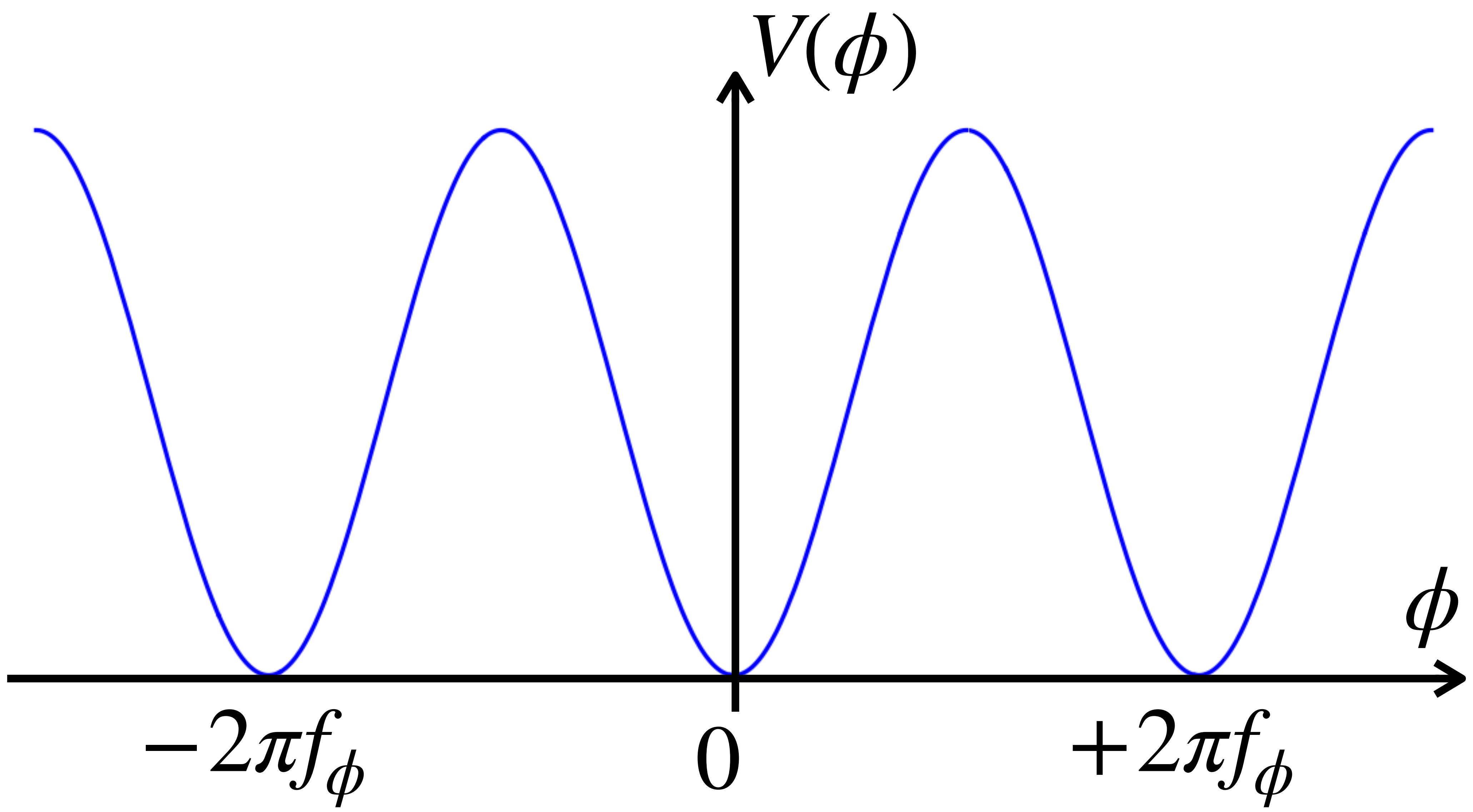
Axion is a scalar particle with shift symmetry,

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

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, ⋯



First-Order Phase Transition

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

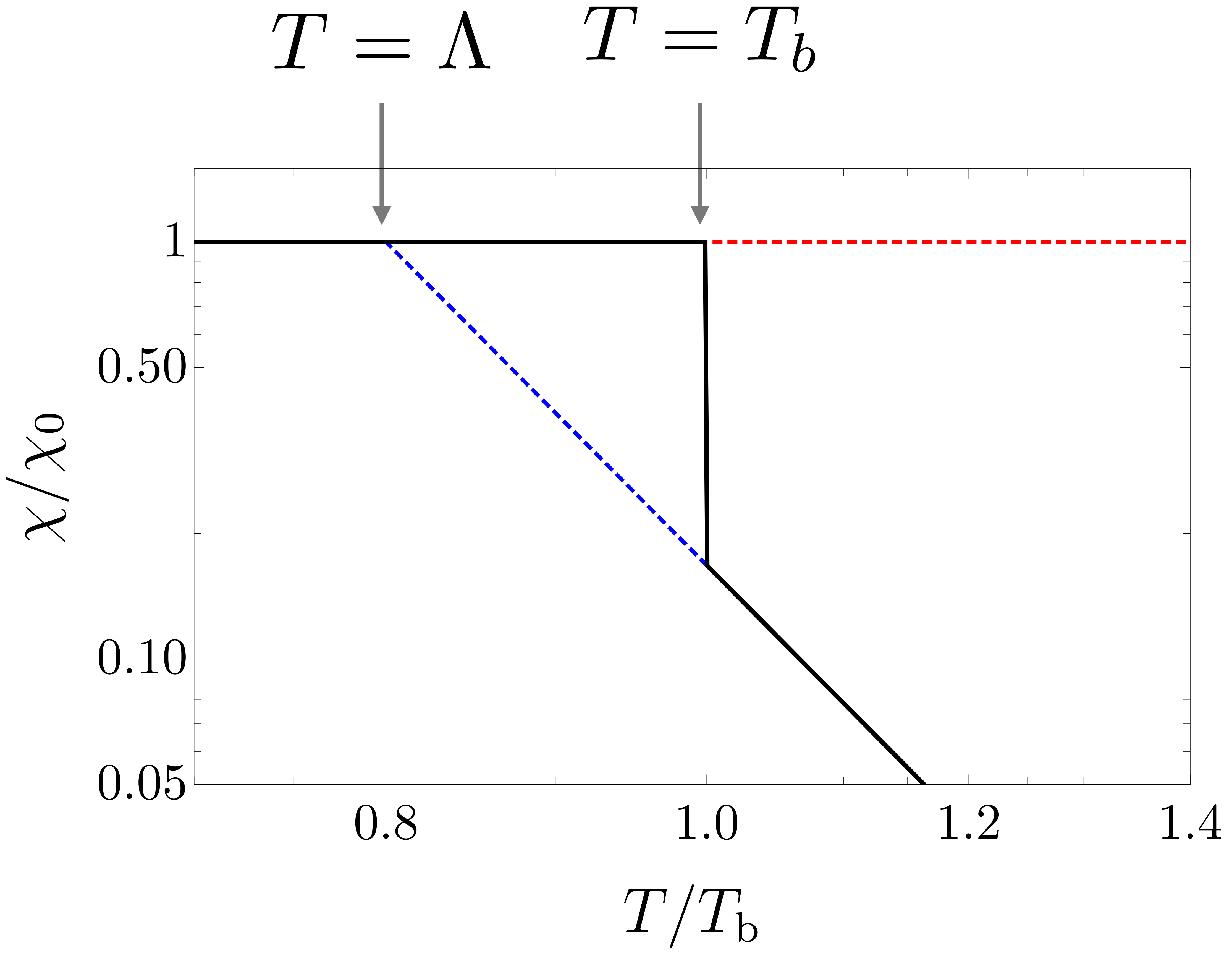
Topological susceptibility changes discontinuously during the transition.

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

topological suceptibility

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

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



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

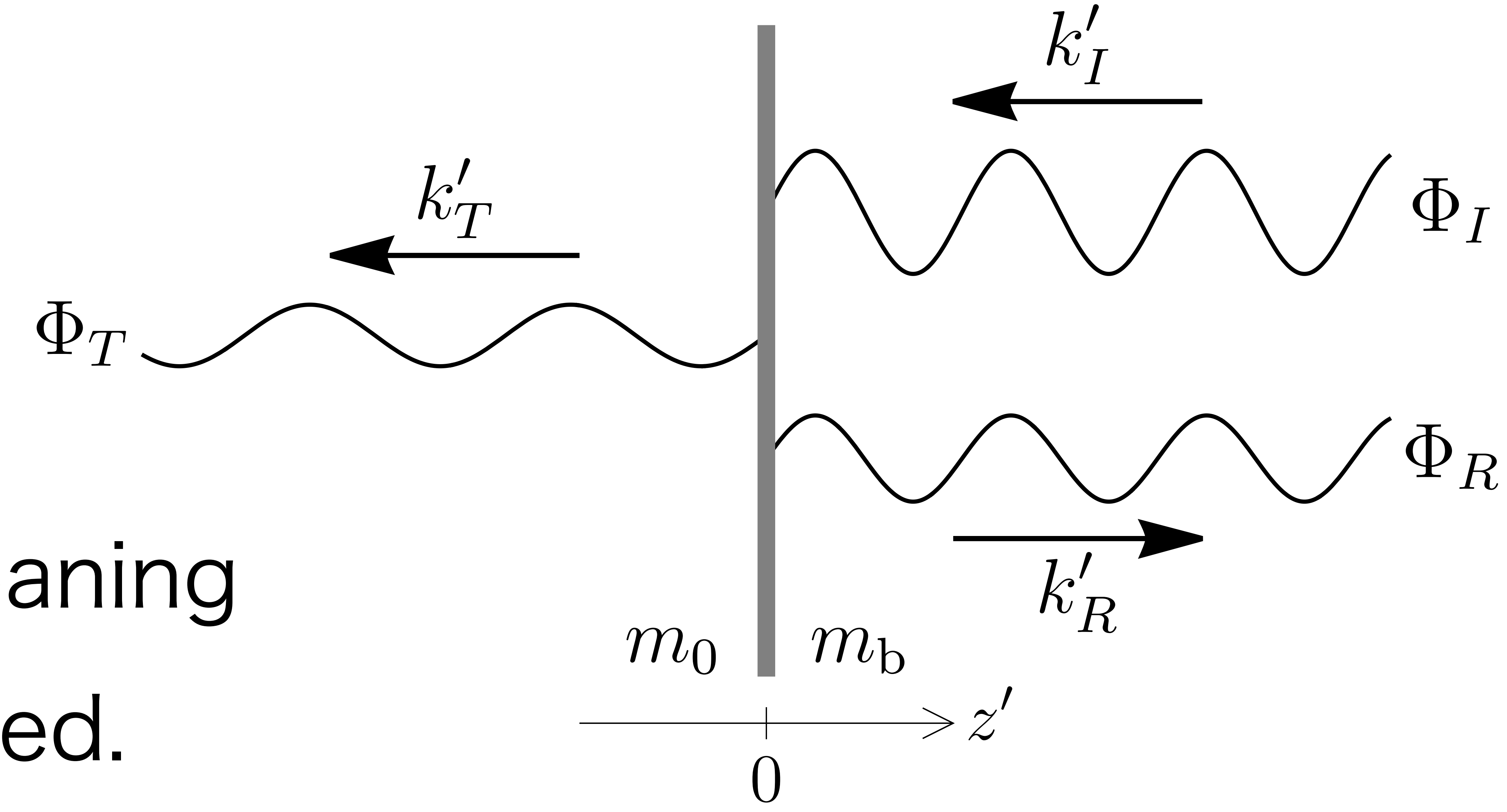
Consider the planar bubble wall at $z' = 0$ (wall-rest frame) and the plane wave propagating as

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

where $\omega' = \sqrt{k'^2_I + m_{\mathrm{b}}^2}$

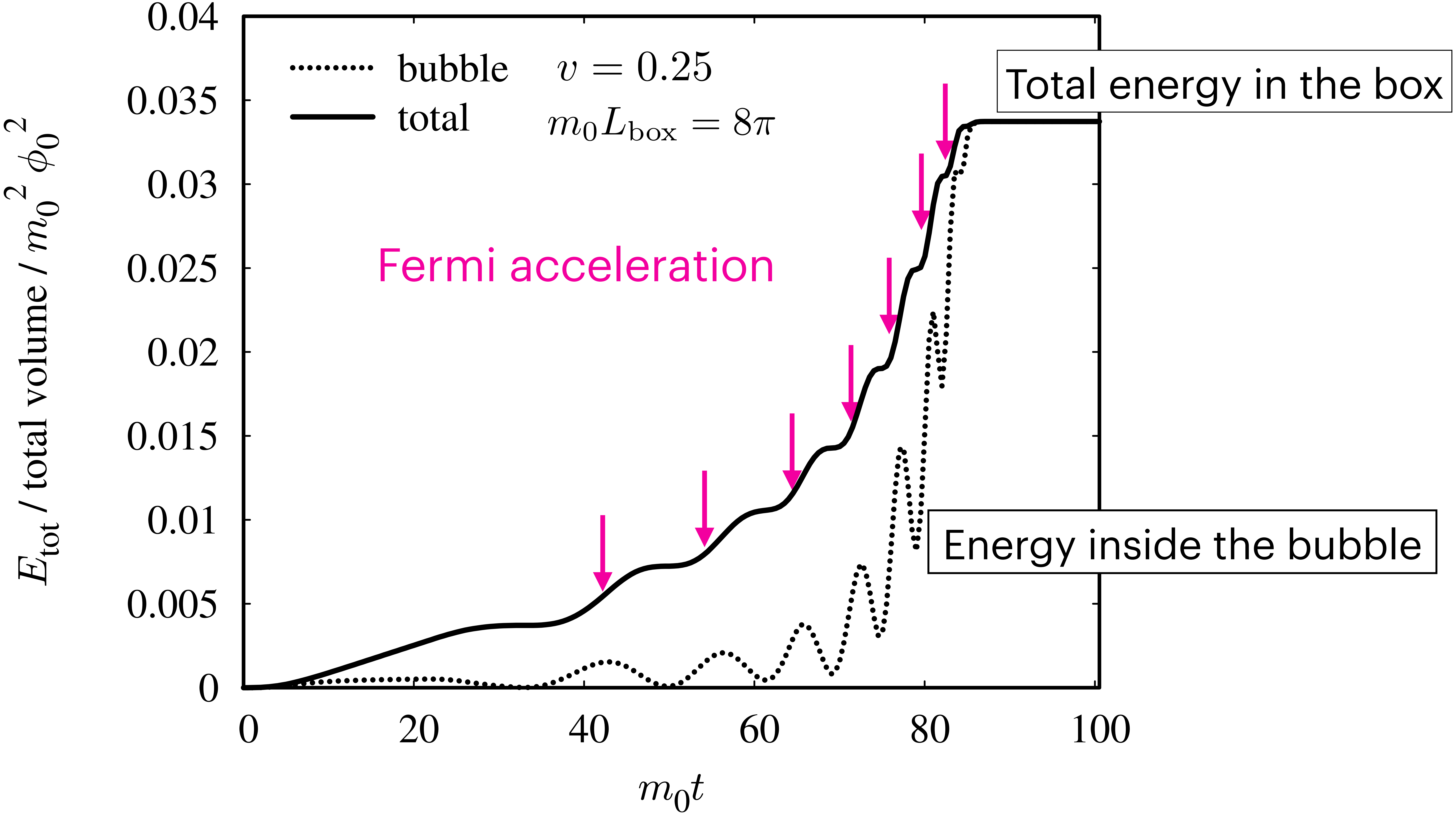
$'$ means it is evaluated in the wall-rest frame

Bubble wall



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

The evolution of the axion energy

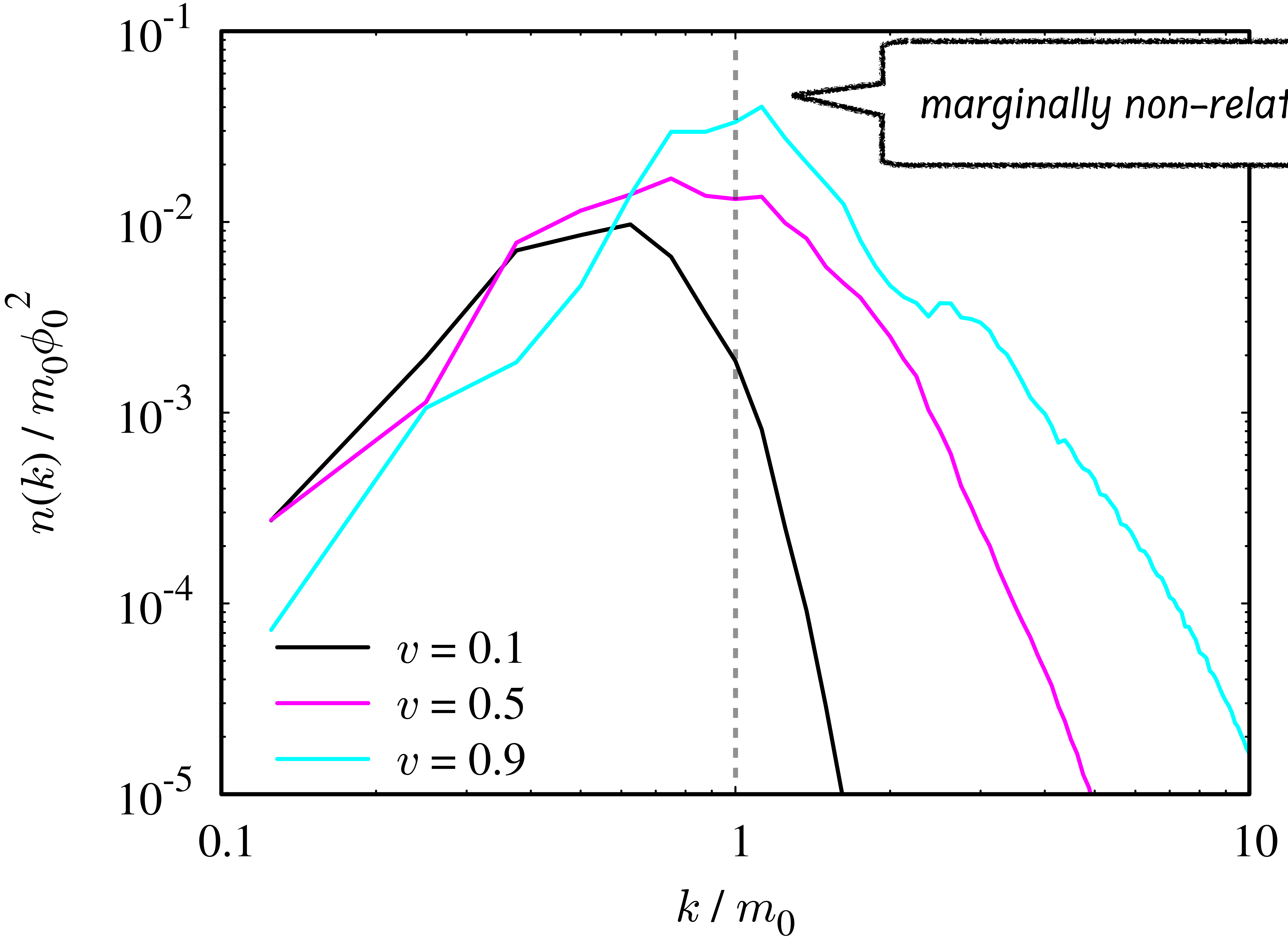


Fermi acceleration

Total energy in the box

Energy inside the bubble

The momentum distribution



marginally non-relativistic

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

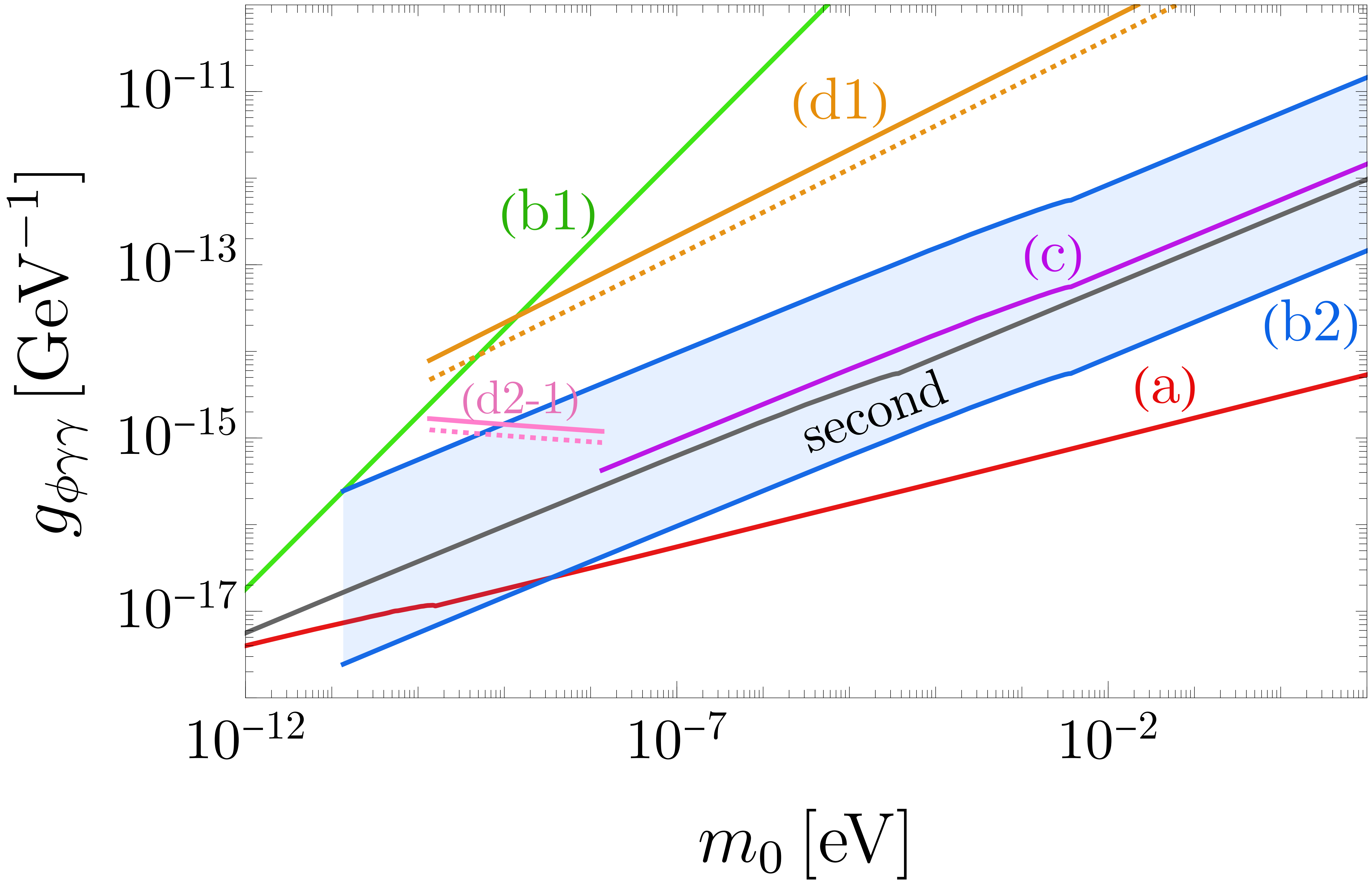
V: volume of the simulation box

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

Axion shock wave

$m_b < 3H_b < m_0 < \beta$

$m_b < 3H_b < \beta < m_0$



$3H_b < m_b < \beta < m_0$

$\beta < m_b$

Constant mass

$g_{\phi\gamma\gamma} = \alpha/(2\pi f_\phi)$
$\phi_0 = f_\phi$
$p = 8$
$T_b = 10\,\mathrm{MeV}$