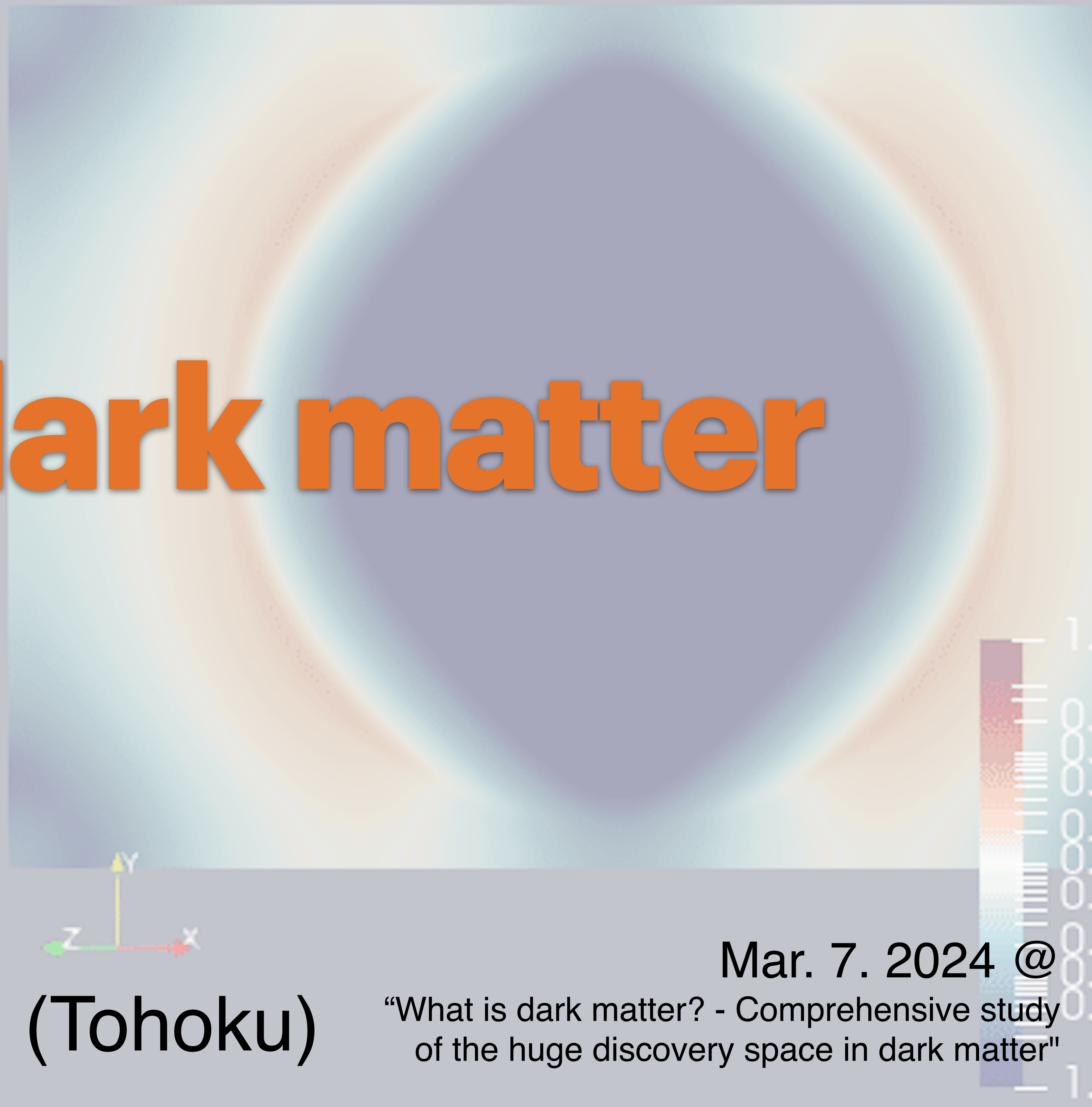
Axion shock wave



A01: Light dark matter

Fumi Takahashi (Tohoku)

Mar. 7. 2024 @
“What is dark matter? - Comprehensive study of the huge discovery space in dark matter"

Mass scale of light dark matter

Members

Masahiro Kawasaki

Naoya Kitajima

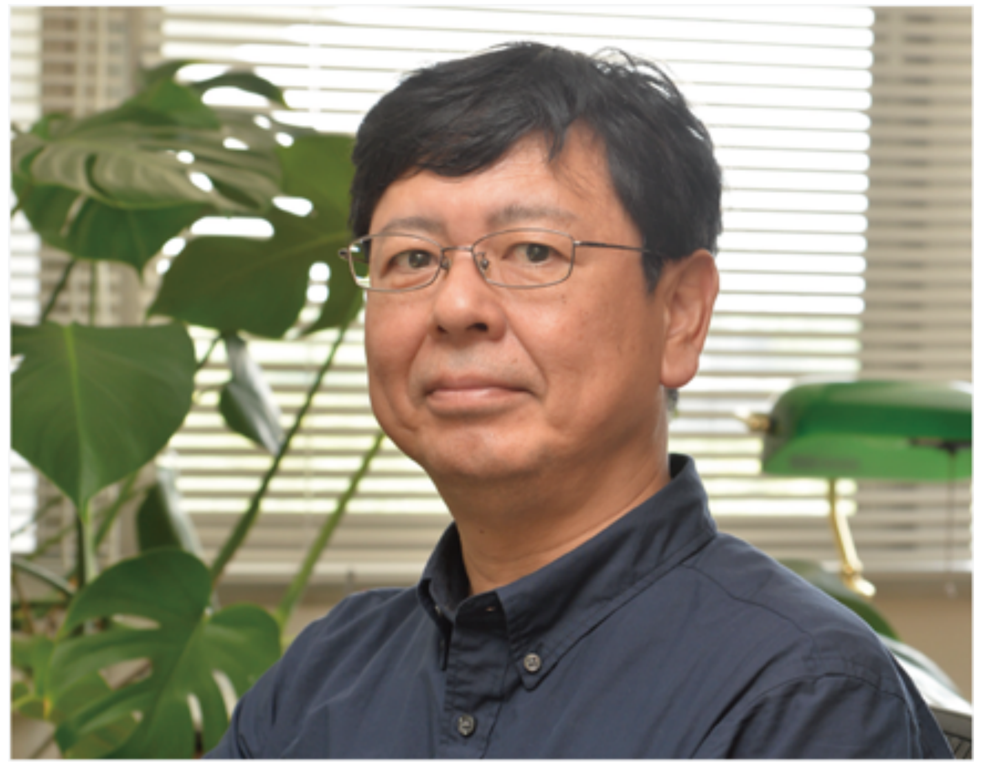
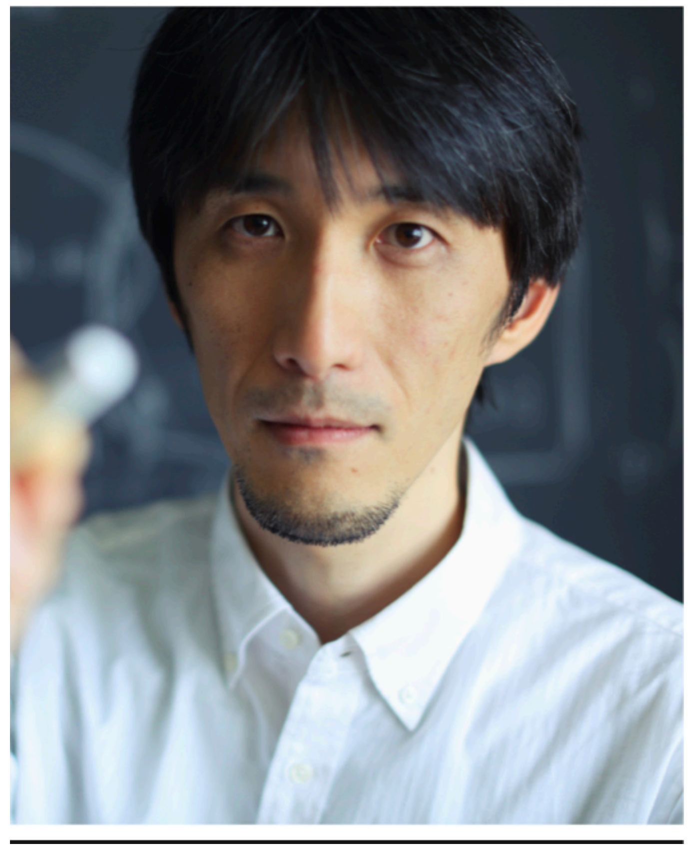
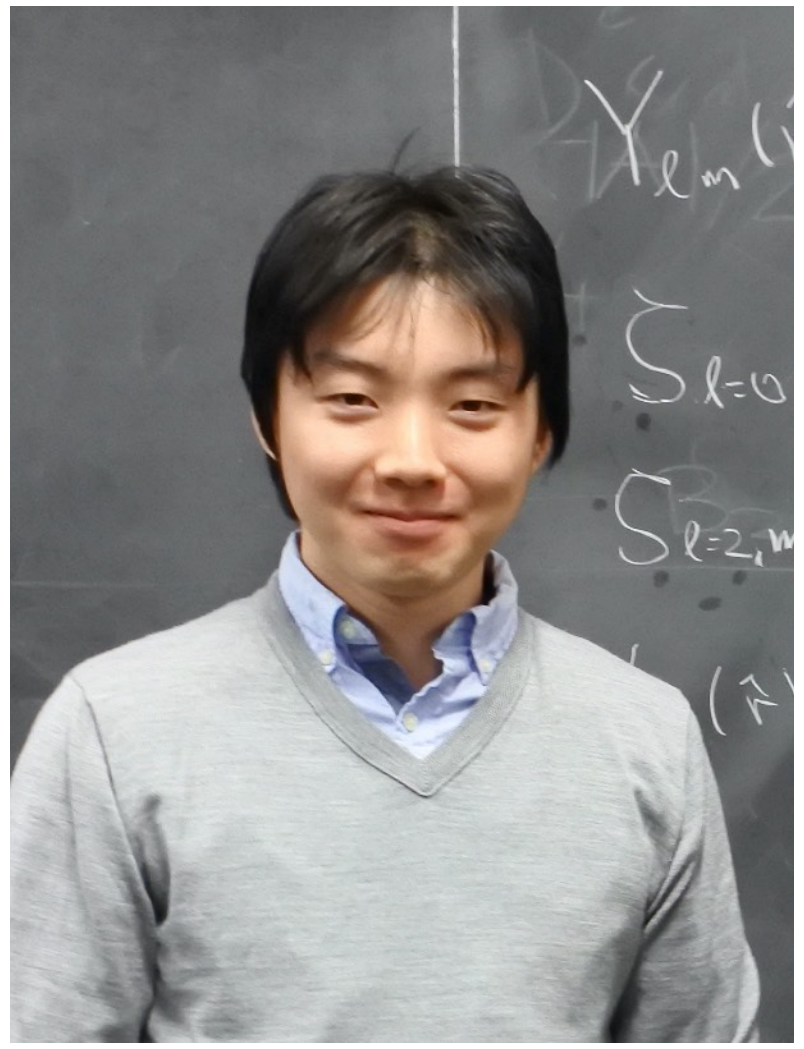
Fuminobu Takahashi

Masaki Yamada

Wen Yin

Shota Nakagawa

Kai Murai



Papers

28 papers appeared on arXiv since Apr. 2023.

(104 papers since Oct. 2020)

Highlights

- First Result for Dark Matter Search by WINERED See talk by Yin

  Wen Yin, Taiki Bessho, Yuji Ikeda, Hitomi Kobayashi, Daisuke Taniguchi et al. 2402.07976

- Misalignment production of vector boson dark matter from axion-SU(2) inflation

  Tomohiro Fujita, Kai Murai, Kazunori Nakayama, Wen Yin, 2312.06889

  See talk by Murai

- Cosmic strings from pure Yang–Mills theory

  collaboration with B01

  Masaki Yamada, Kazuya Yonekura 2204.13123, 2204.13125, 2307.06586

- Dark photon dark matter production

  See talk by Kitajima

  Naoya Kitajima and Kazunori Nakayama 2303.04287, FT, Naoya Kitajima, 2303.05492

- Axion dark matter from FOPT

  Shota Nakagawa, FT, Masaki Yamada, and Wen Yin 2210.10022   Junseok Lee, Kai Miurai, FT, and Wen Yin 2402.09501

- Primordial black holes from QCD axion bubbles

  Kentaro Kasai, Masahiro Kawasaki, Naoya Kitajima, Kai Murai, Shunsuke Neda, FT 2305.13023, 2310.13333

- Gravitational waves from domain walls

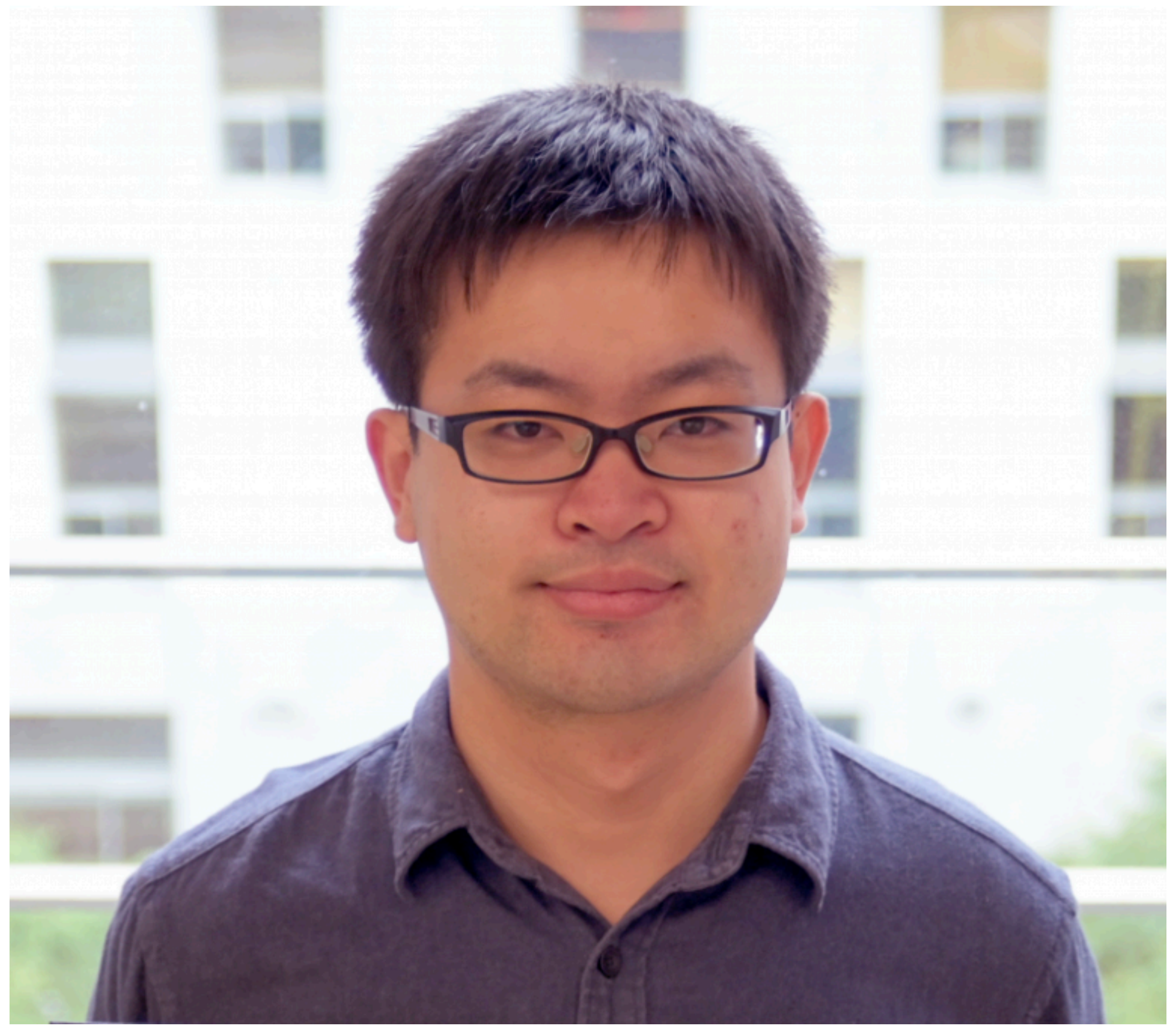
  Naoya Kitajima, Junseok Lee, Kai Murai, FT, and Wen Yin 2306.17146   Naoya Kitajima, Junseok Lee, FT, and Wen Yin 2311.14590

- QCD axion hybrid inflation Yuma Narita, FT and Yin, 2308.12154

Bubble misalignment mechanism

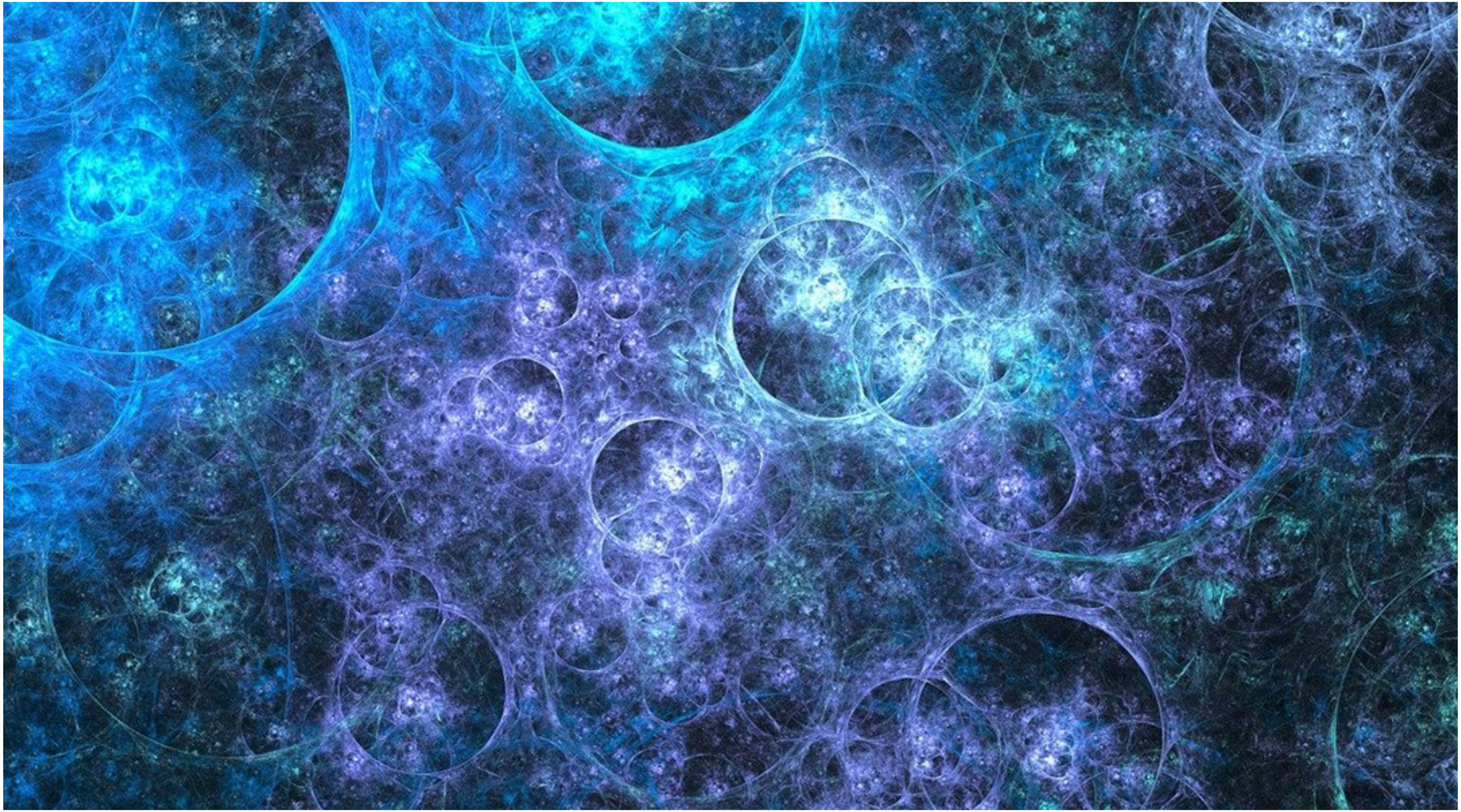
Junseok Lee, Kai Murai, FT and Wen Yin, 2402.09501

Junseok Lee



Kai Murai

Wen Yin



https://www.advancedsciencenews.com/footprints-of-phase-transitions-in-the-early-universe/

Bubble nucleation in FOPT

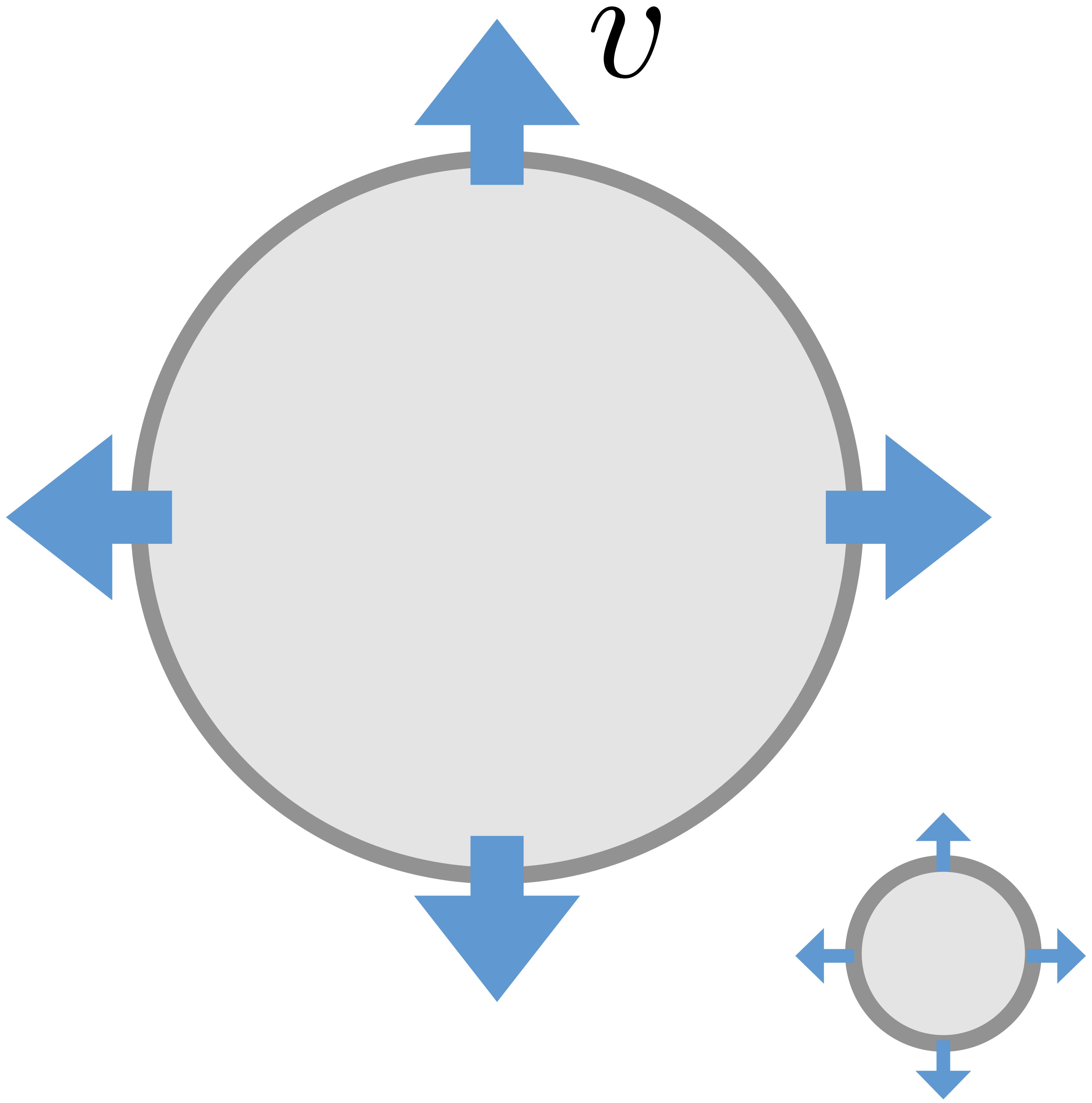
We introduce two parameters: v and β

- Once bubbles nucleate, they expand with velocity v.

- The bubble nucleation rate generically depends on temperature (or time);

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

β^{-1} defines the duration of FOPT.



We assume $\beta > H_\mathrm{b}$.

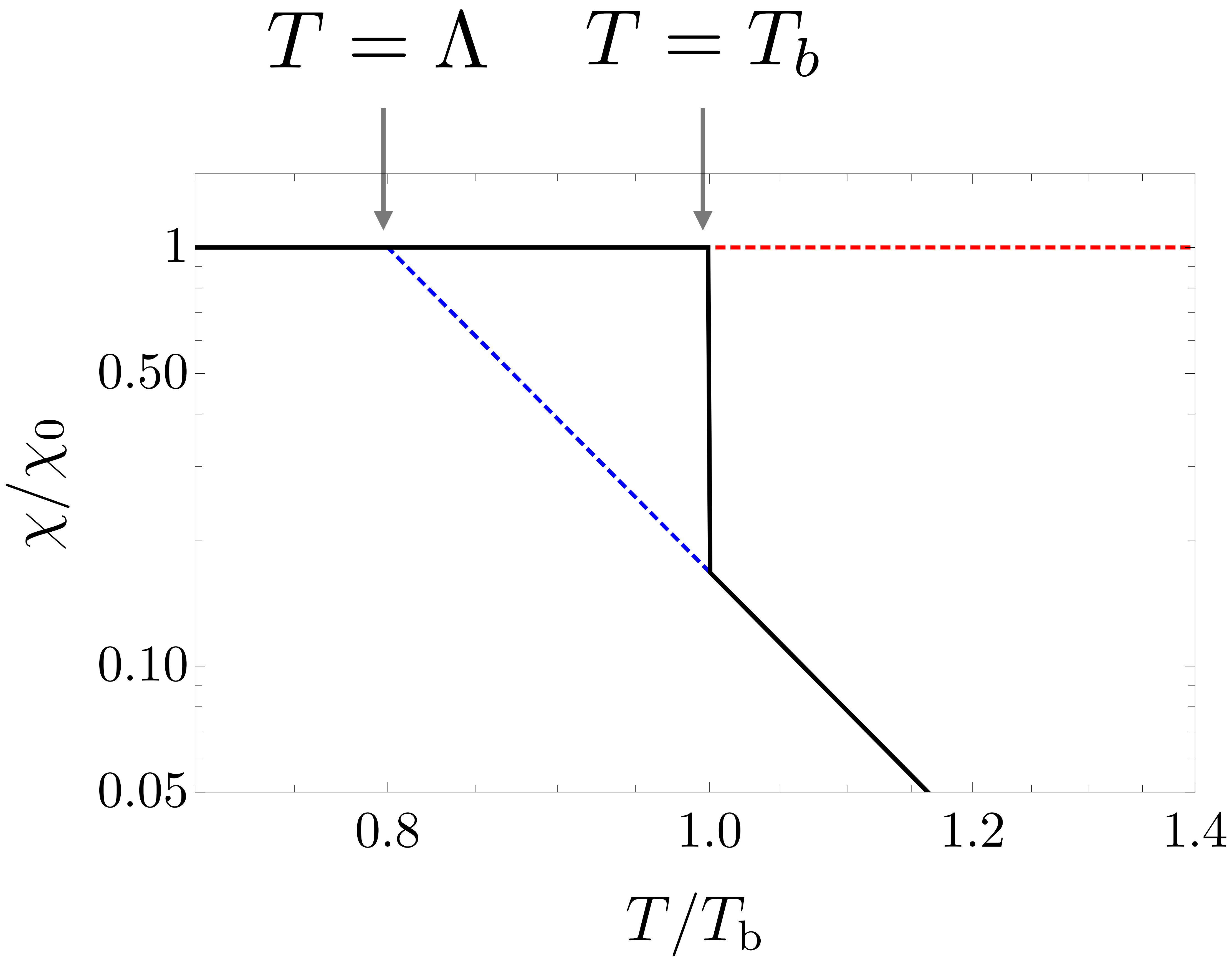
Axion mass in FOTP

The topological suceptibility changes discontinuously at the transition.

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

with $\chi(T) \simeq \begin{cases} \chi_0 & (T < \Lambda) \\ \chi_0\left(\dfrac{T}{\Lambda}\right)^{-p} & (T \geq \Lambda) \end{cases}$.

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



The axion mass changes from m_b to m_0 at $T = T_\mathrm{b}$.

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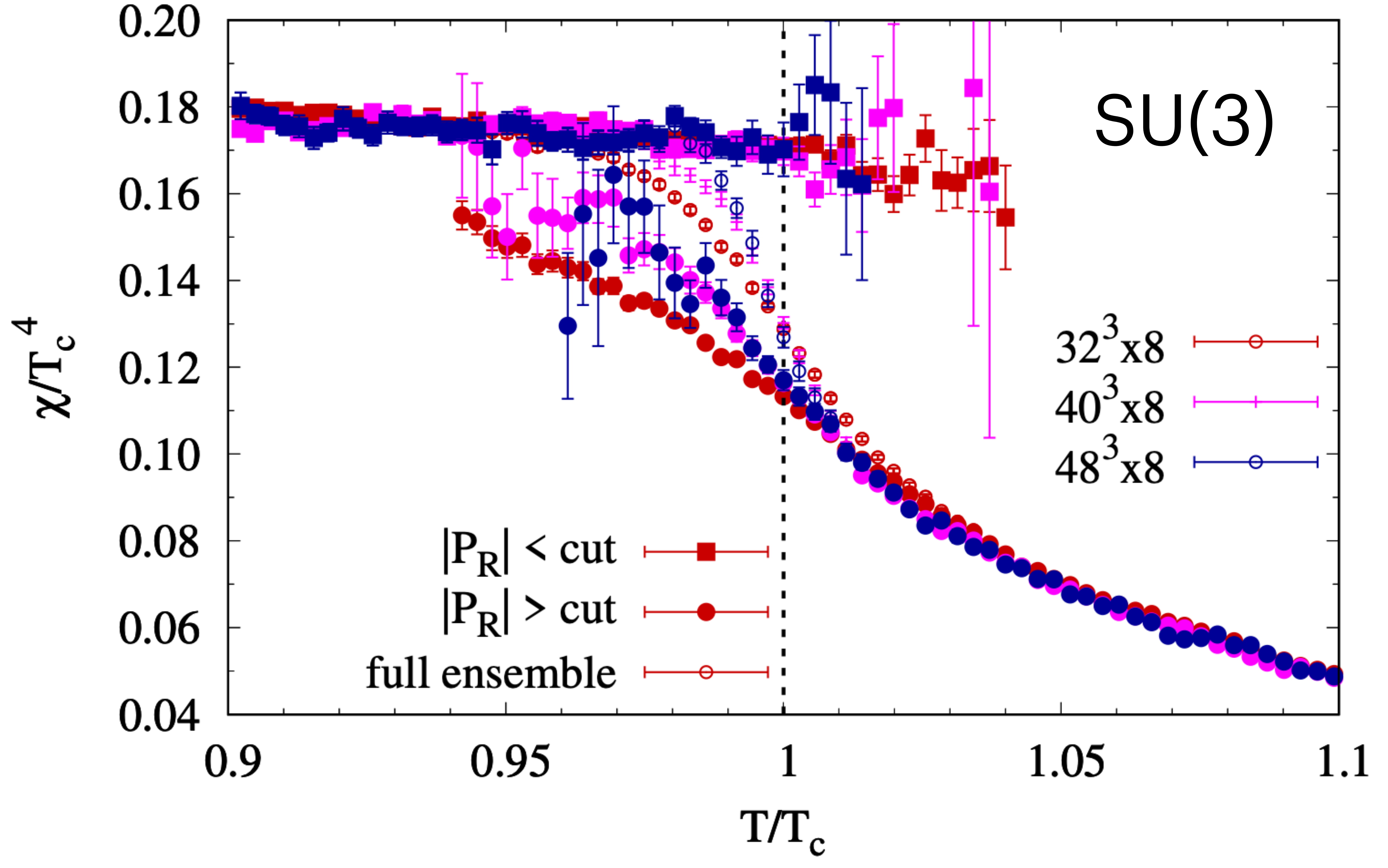

S. Borsányi et al, 2212.08684

The axion mass changes from m_b to m_0 at $T = T_b$.

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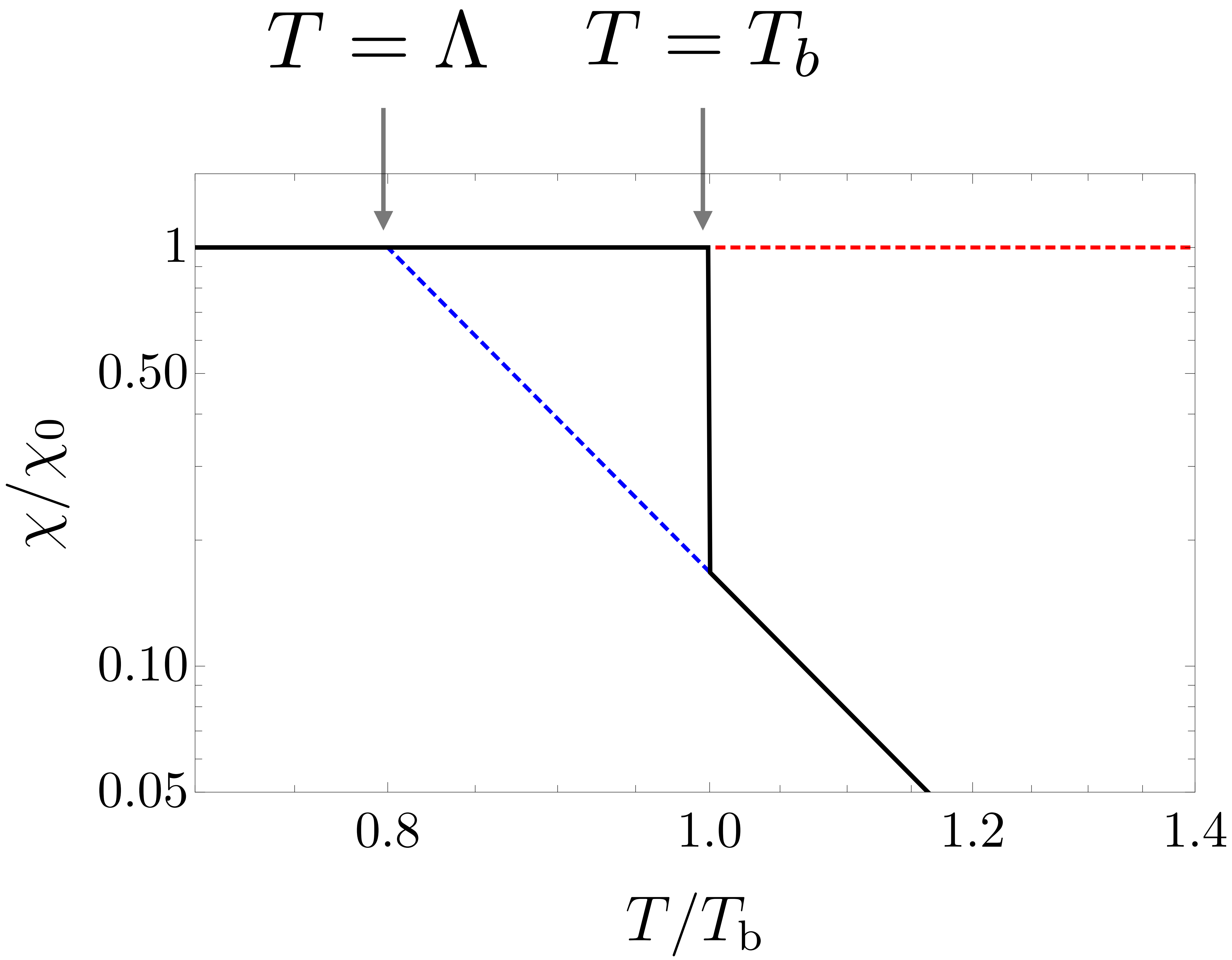

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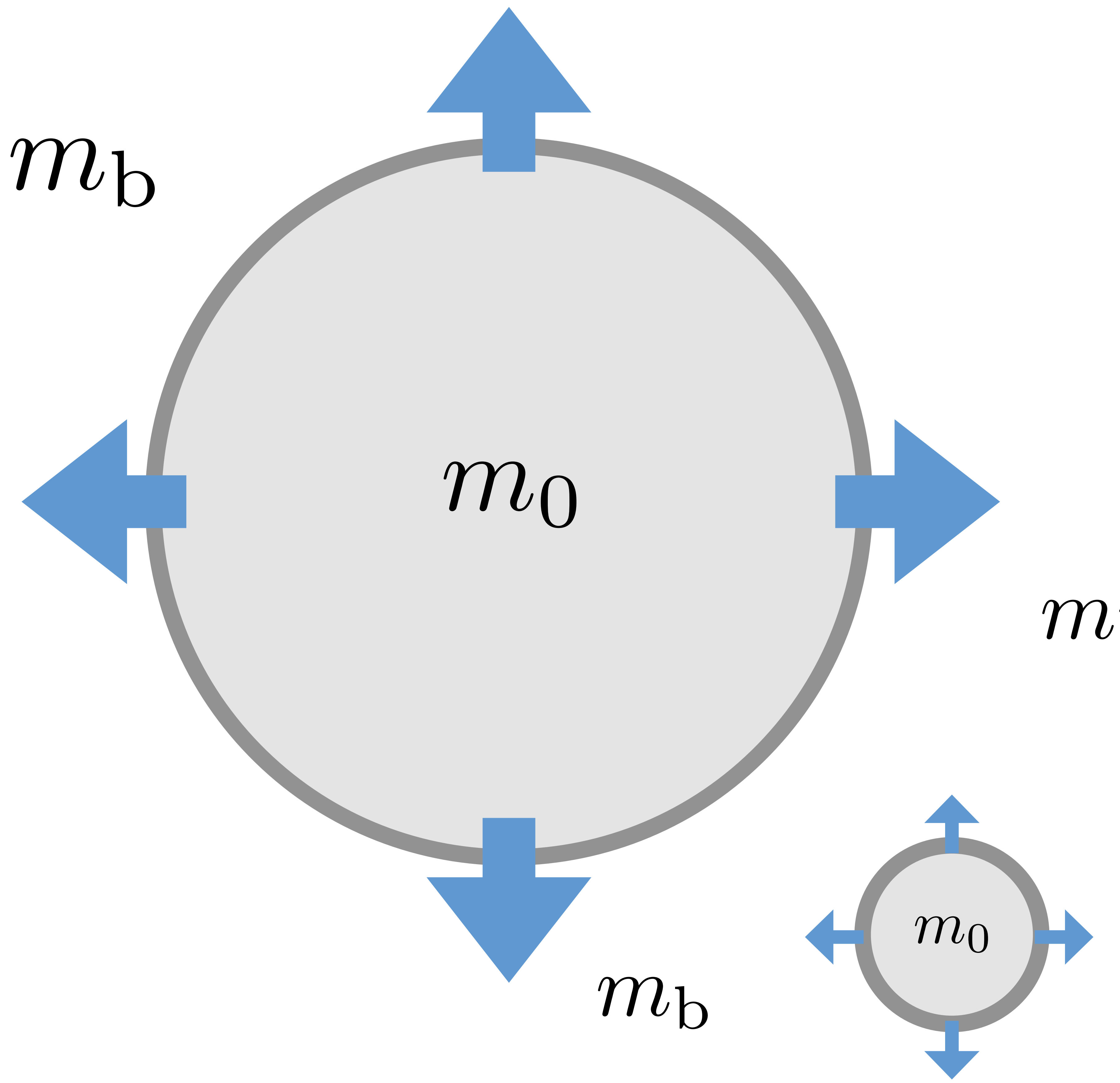

$m_0 > m_{\rm b}$

The axion mass changes from $m_{\rm b}$ to m_0 at $T = T_{\rm b}$.

Classification of the axion dynamics

Lee, Murai, FT and Yin 2402.09501

The most important criterion is whether the axion can move inside the bubble during the FOPT.

$\beta > m_0$ Axion does not move during FOPT.

Bubbles are irrelevant.

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Lee, Murai, FT and Yin 2402.09501

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$\beta > H_{\rm b}$

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Bubbles are irrelevant.

- $H_{\rm b} > m_0$: Axion begins to oscillate some time after FOPT.
  → Constant axion mass.
- $m_0 > H_{\rm b}$: Axion begins to oscillate right after FOPT.
  → Sudden change in axion mass.

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$m_0 > \beta$ Axion inside bubbles moves during FOPT.

Bubbles significantly influence the axion dynamics!

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Lee, Murai, FT and Yin 2402.09501

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$m_0 > \beta$ Axion inside bubbles moves during FOPT.

$m_b > \beta$

$\beta > m_b$

Axions may or may not oscillate outside bubbles during FOPT.

Bubbles significantly influence the axion dynamics!

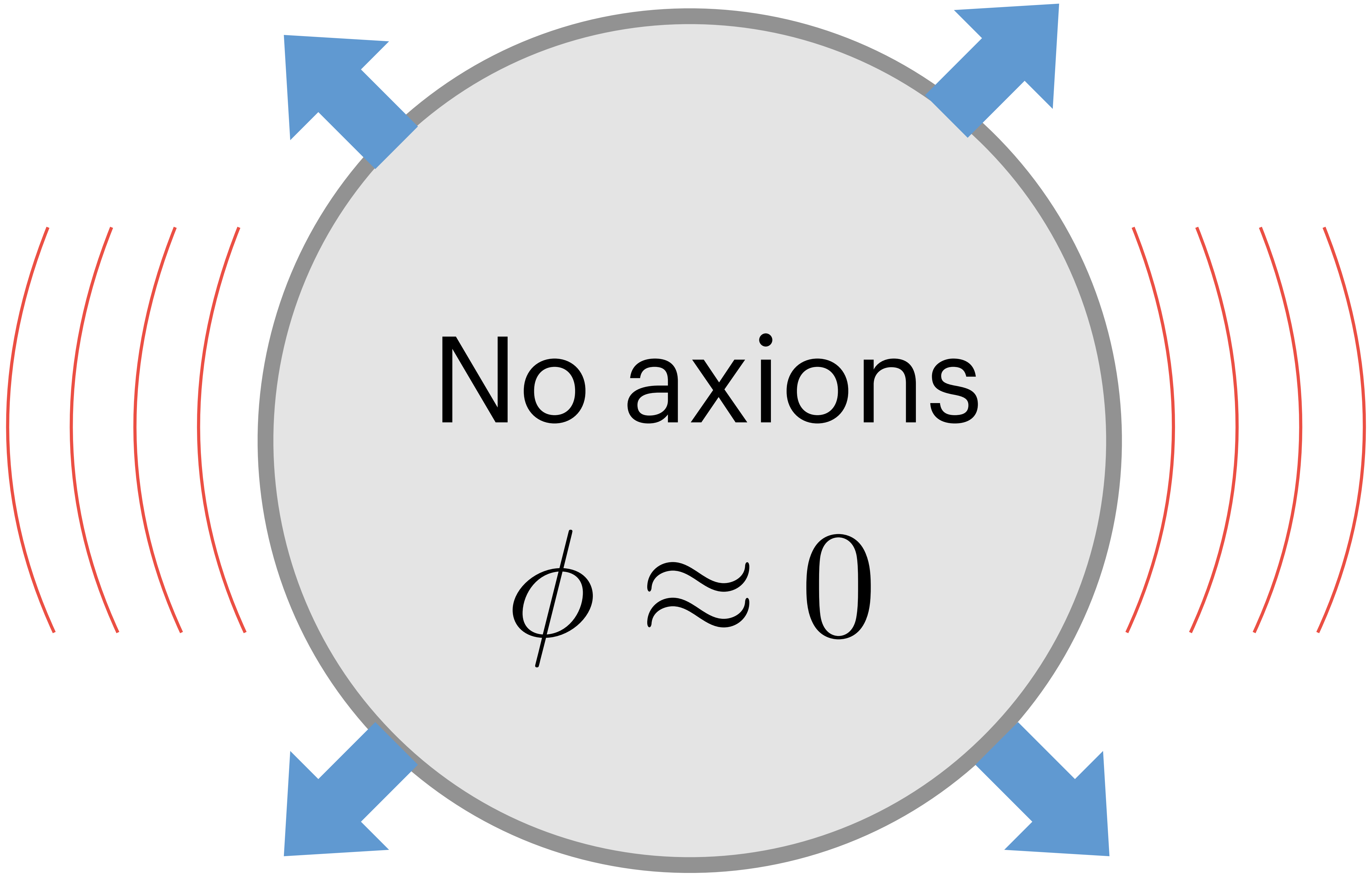
Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

① Axions are expelled from the inside of bubbles.



Axion waves propagate outside the bubbles.

For $m_b > \beta$, axion oscillates in the entire space during FOPT.

For $m_b < \beta$, axion shock wave is induced near the wall.

Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

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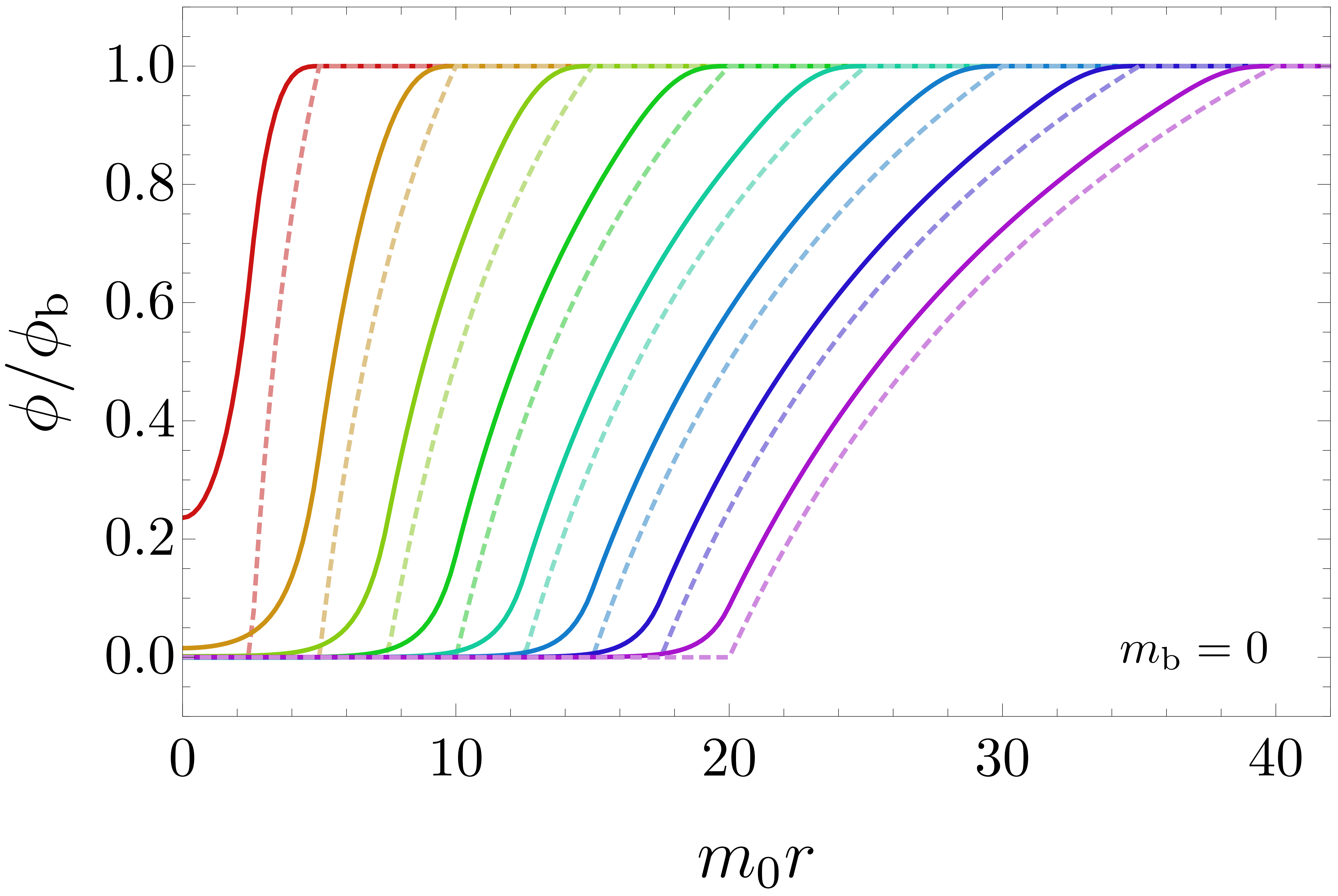
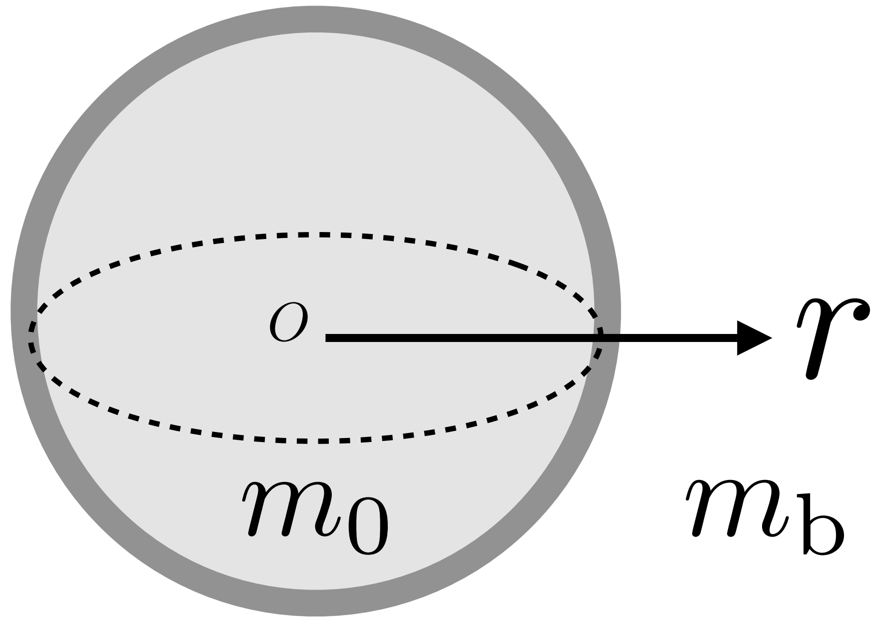




$m_0 > m_{\rm b}$

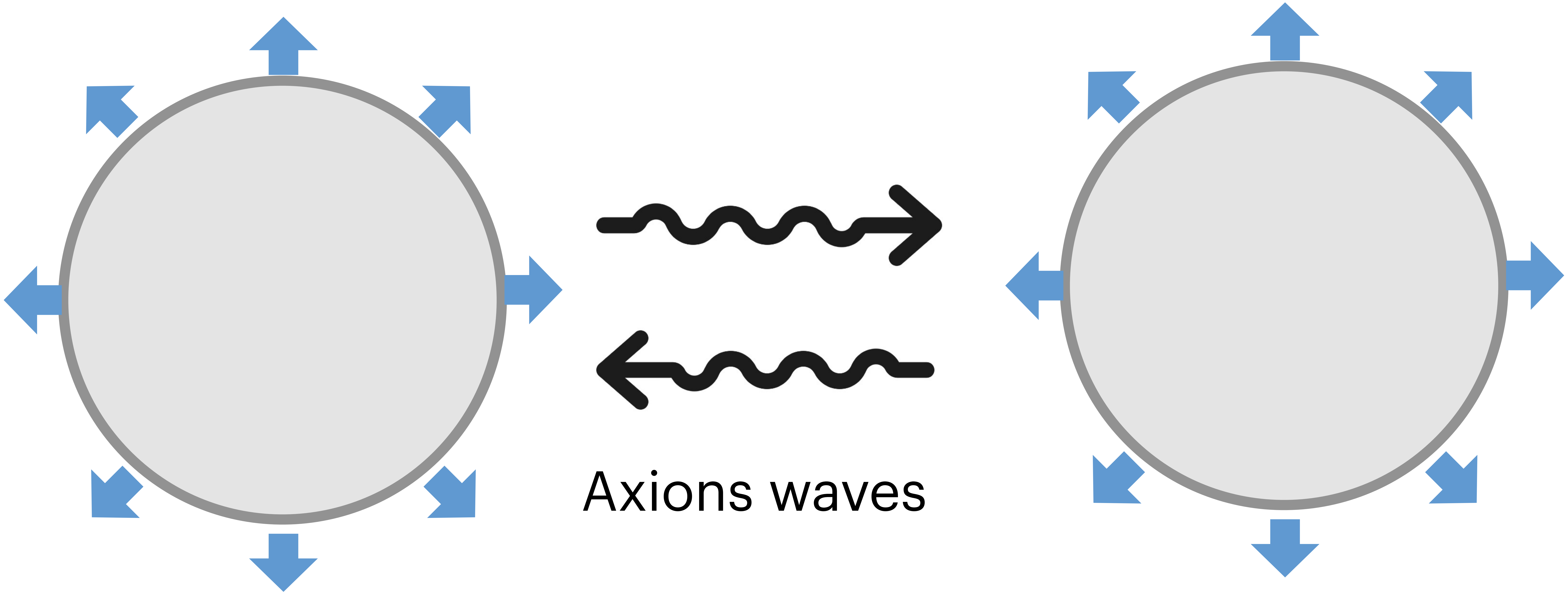
For $m_{\rm b} < H_{\rm b}$, axion shock wave is induced outside the wall.

Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

② Axion waves accumulate outside the bubbles and repeatedly scatter off the bubble walls. They are accelerated with each scattering.

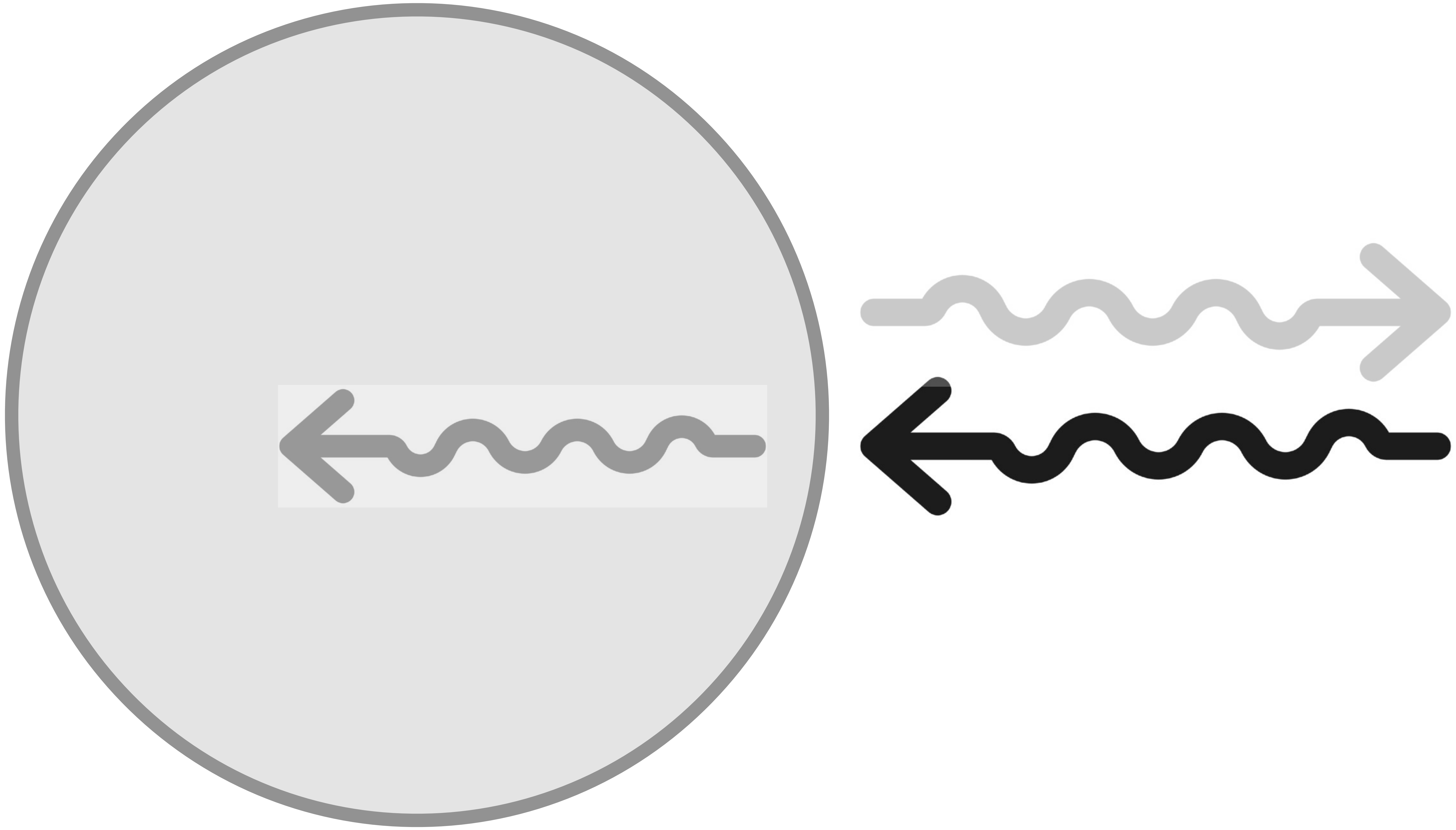
This is analogous to Fermi acceleration！



Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

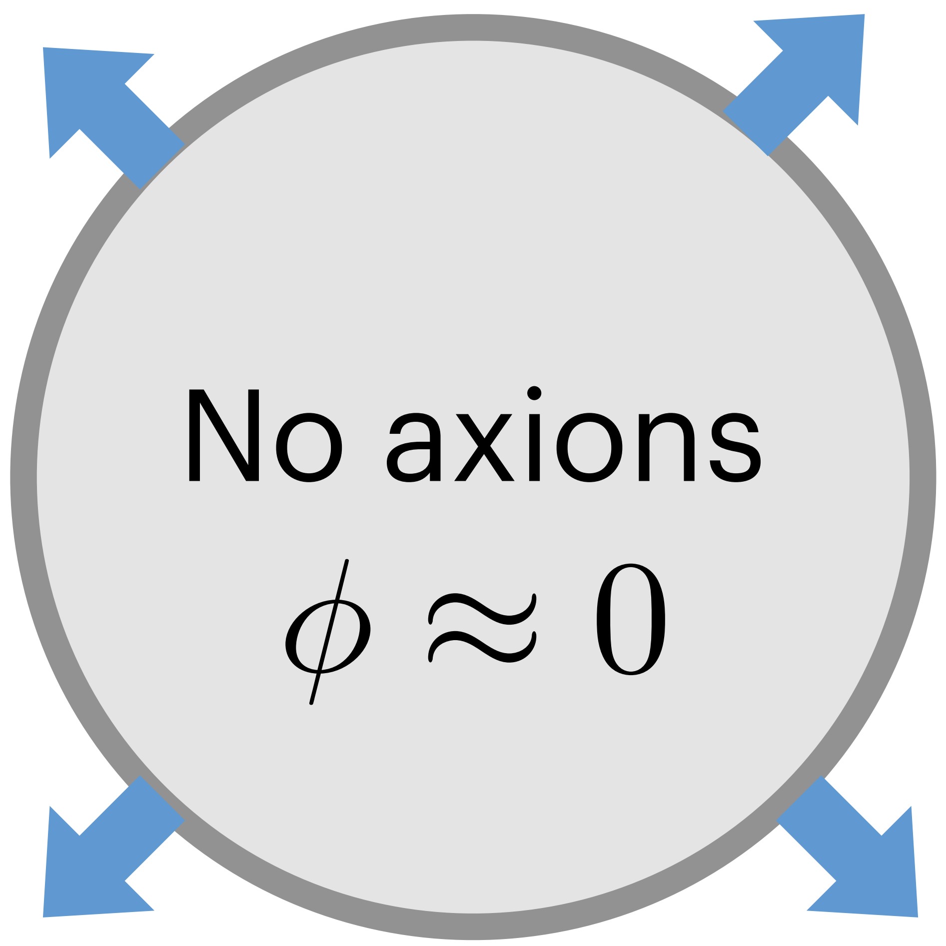
③ Axion waves enter the bubbles when they gain enough energy.
The axion number increases at the transmission.



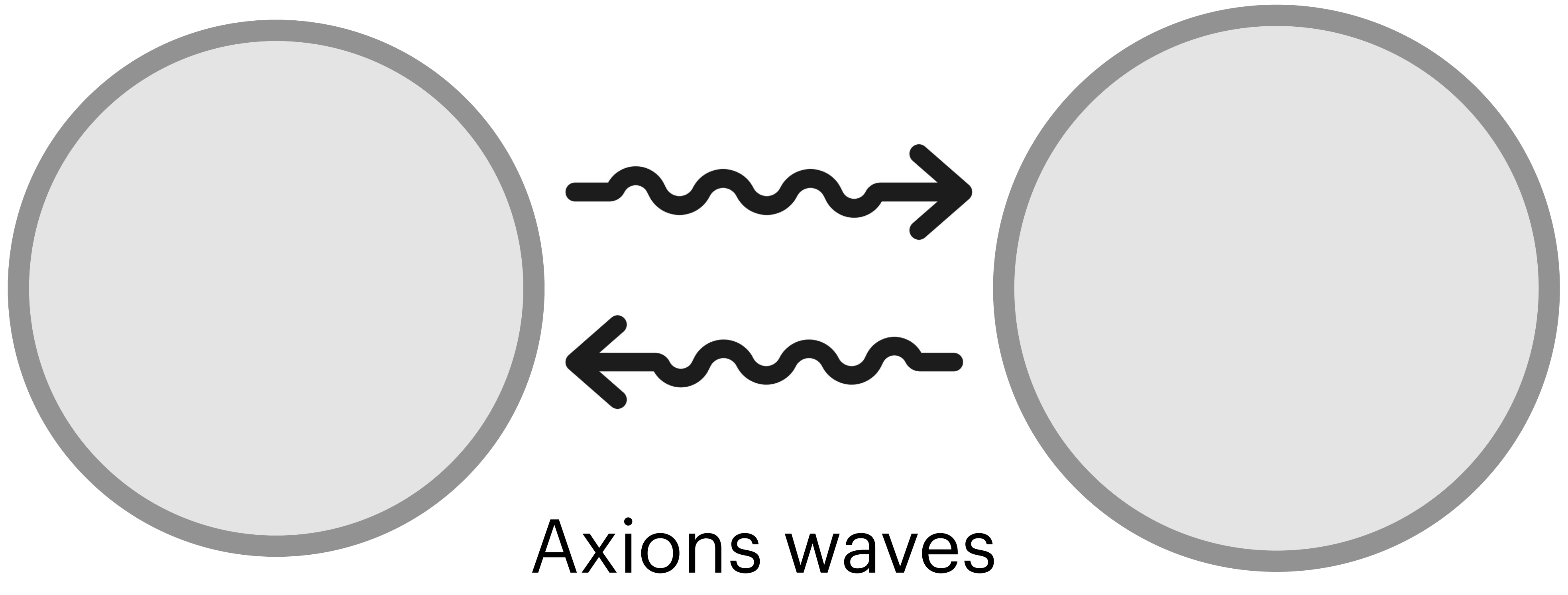
Bubble-induced axion dynamics

Lee, Murai, FT and Yin 2402.09501

① Axions are expelled from the inside of bubbles.

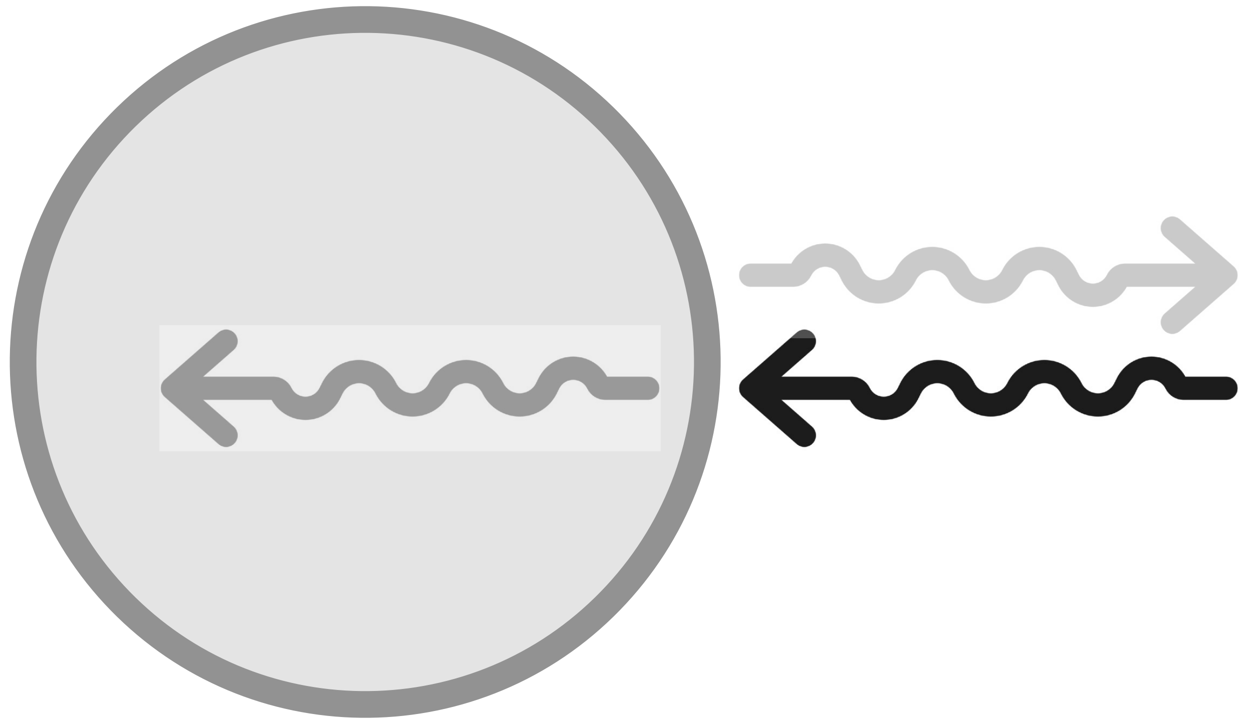


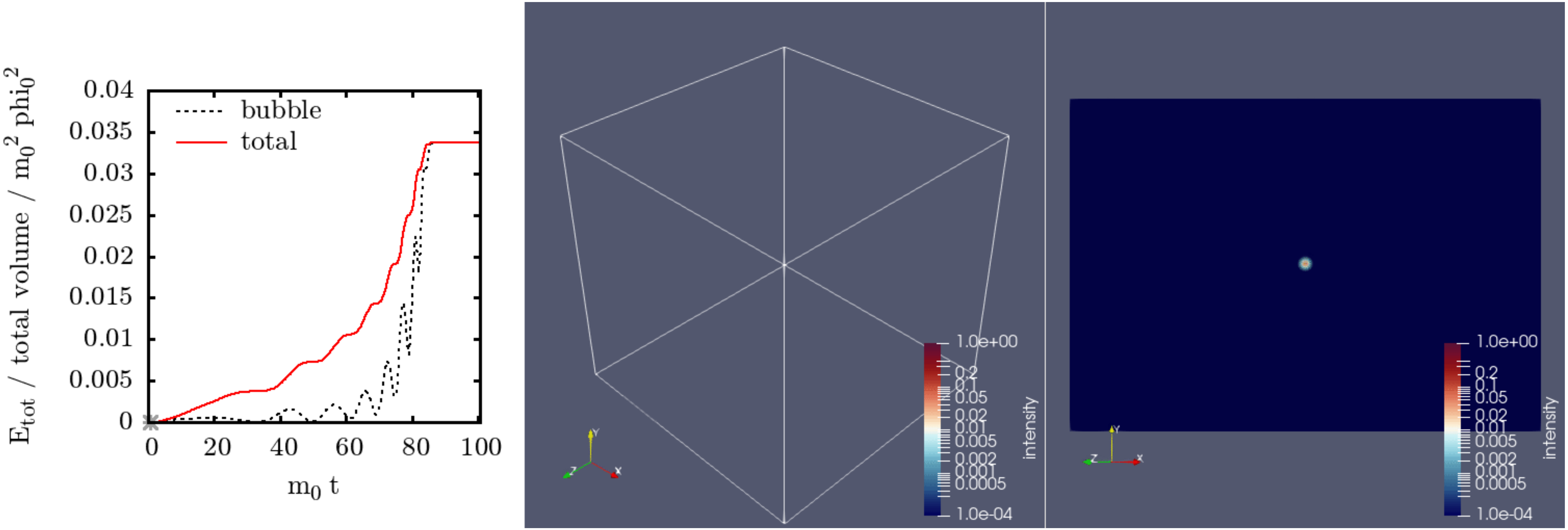
② Axions waves are accumulated outside the bubbles and repeatedly scatter off bubble walls.



~ **Fermi acceleration**

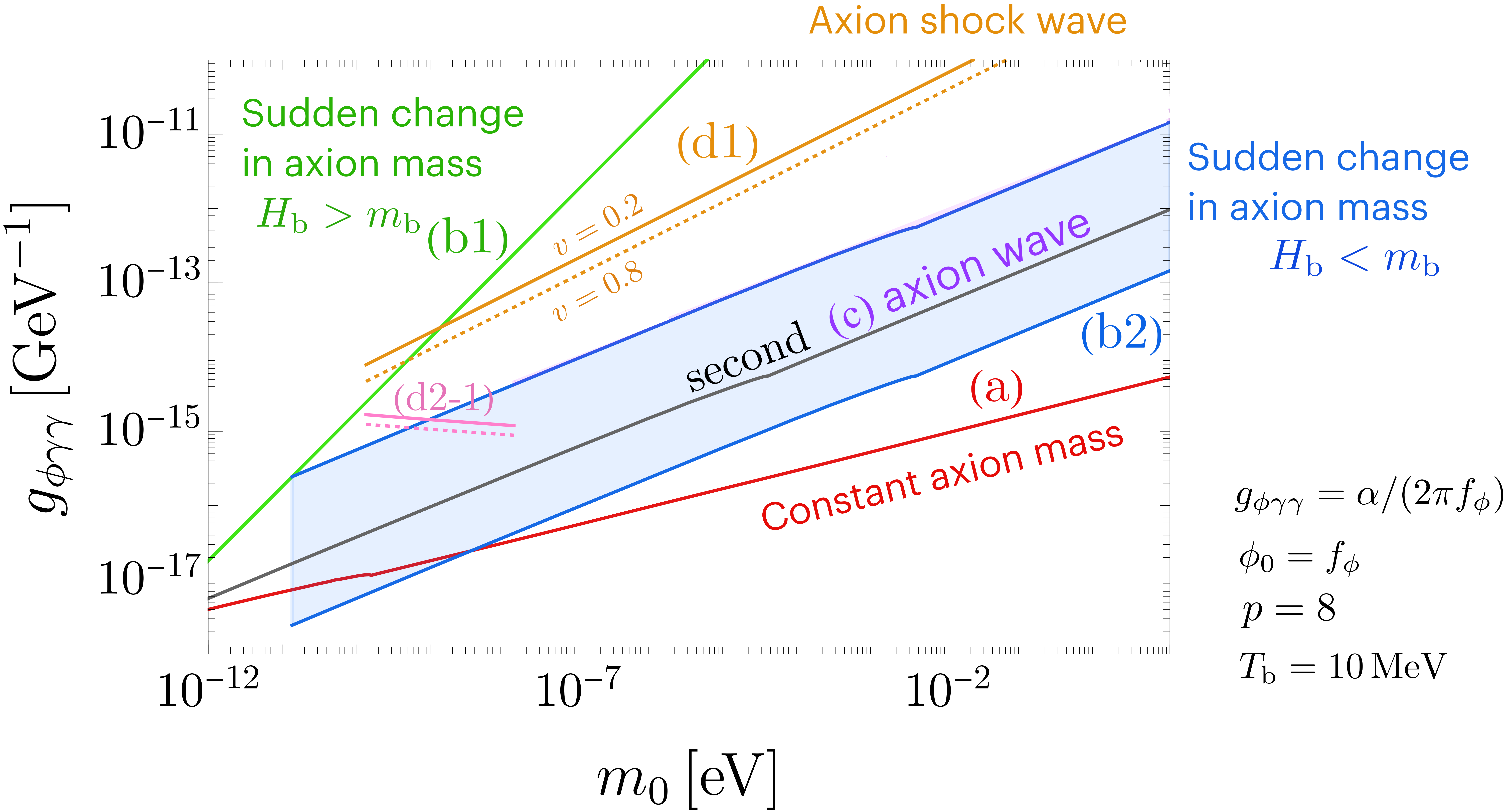
③ Axions waves enter the bubbles if they acquire enough energy.





bubble
total
0.04
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
0
20
40
60
80
100
E_{tot} / total volume / m_0^2 phi_0^2
m_0 t
1.0e+00
0.2
0.1
0.05
0.02
0.01
0.005
0.002
0.001
0.0005
1.0e-04
intensity
Y
Z
X

Viable region for axion dark matter



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.
- 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.