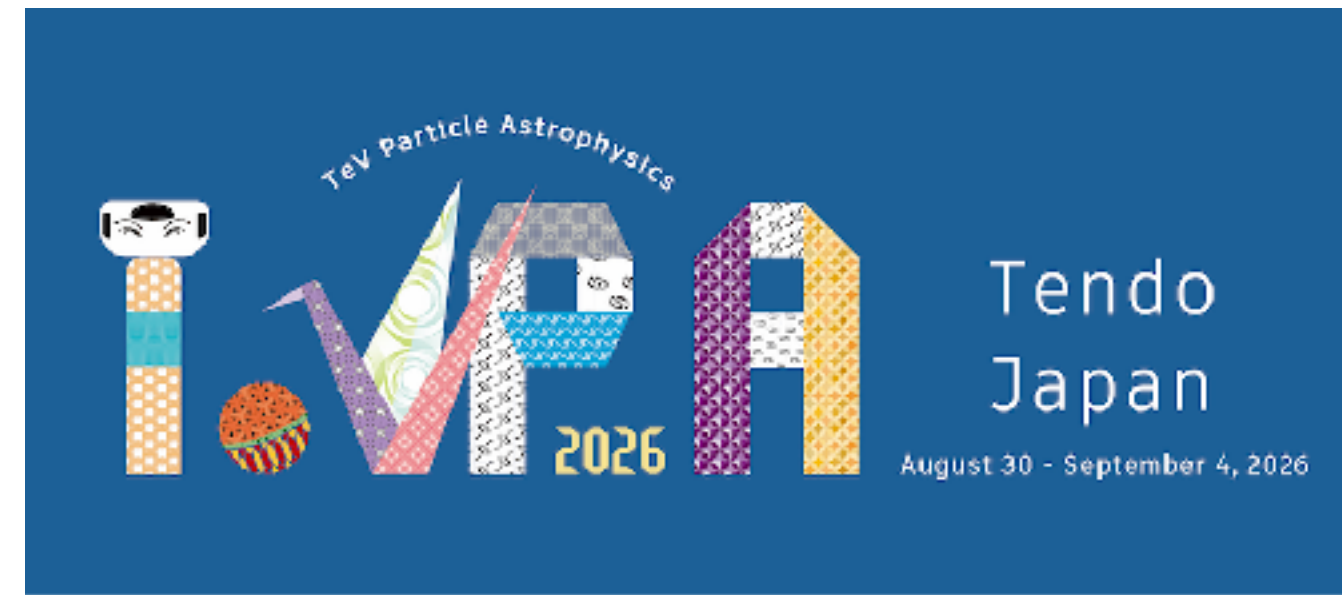
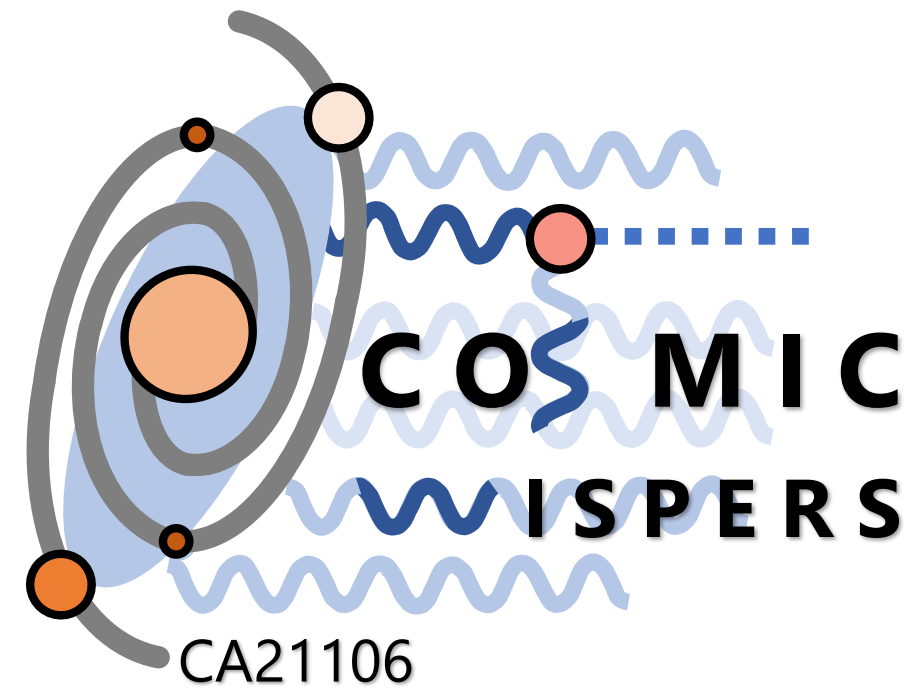




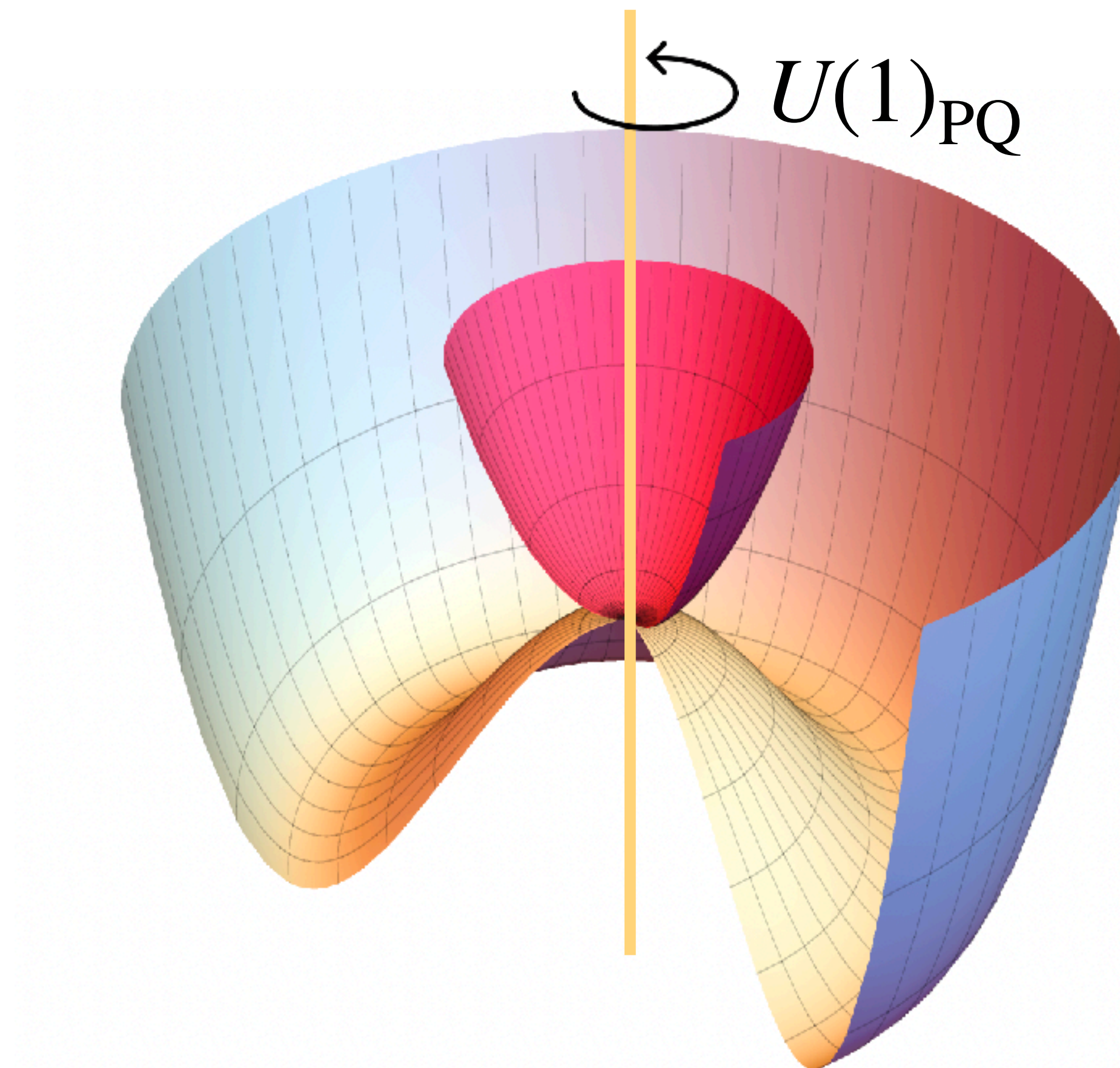
Beyond Standard Misalignment: Theory of Axion and ALP Dark Matter

Sep 4, 2026
@TeVPA 2026

Fumi Takahashi (Tohoku University)

Axion

The axion is a pseudo Nambu-Goldstone boson associated with SSB of $U(1)$ Peccei-Quinn symmetry.



Peccei, Quinn '77, Weinberg '78,
Wilczek '78

See also talks by Robert,
Schönfeld, Bhattacharjee,
Chen, and Terzić during this
conference.

QCD axion

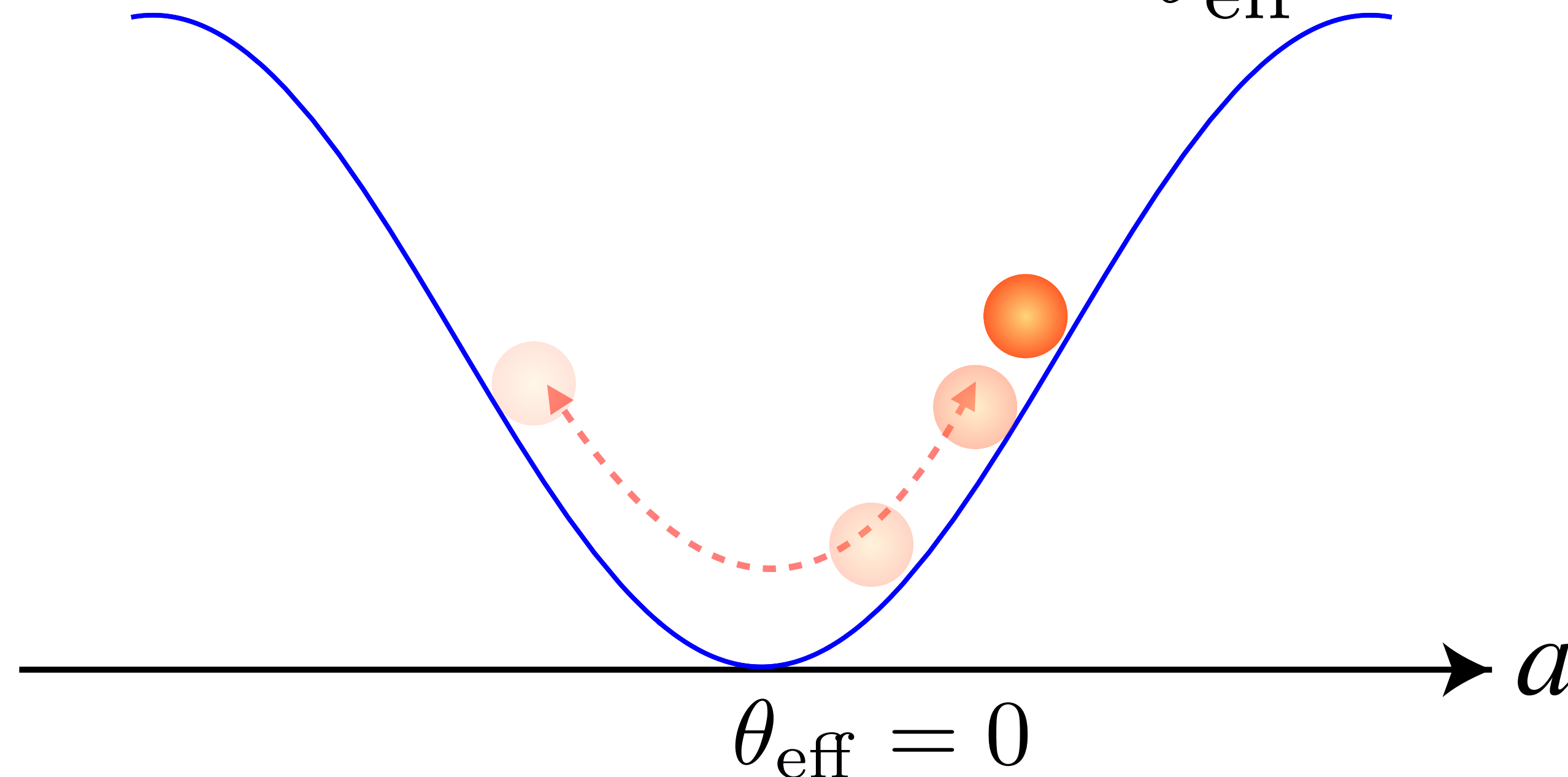
Peccei, Quinn '77, Weinberg '78, Wilczek '78

Dynamically solves the strong CP problem.

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a \rightarrow \mathcal{L}_\theta = \underbrace{\left(\theta + \frac{a}{f_a} \right)}_{\theta_{\text{eff}}} \frac{g_s^2}{32\pi^2} G^{a\mu\nu} \tilde{G}_{\mu\nu}^a$$

$|\bar{\theta}| \lesssim \mathcal{O}(10^{-10})$: strong CP problem

Neutron EDM,
Abel et al, 2001.11966



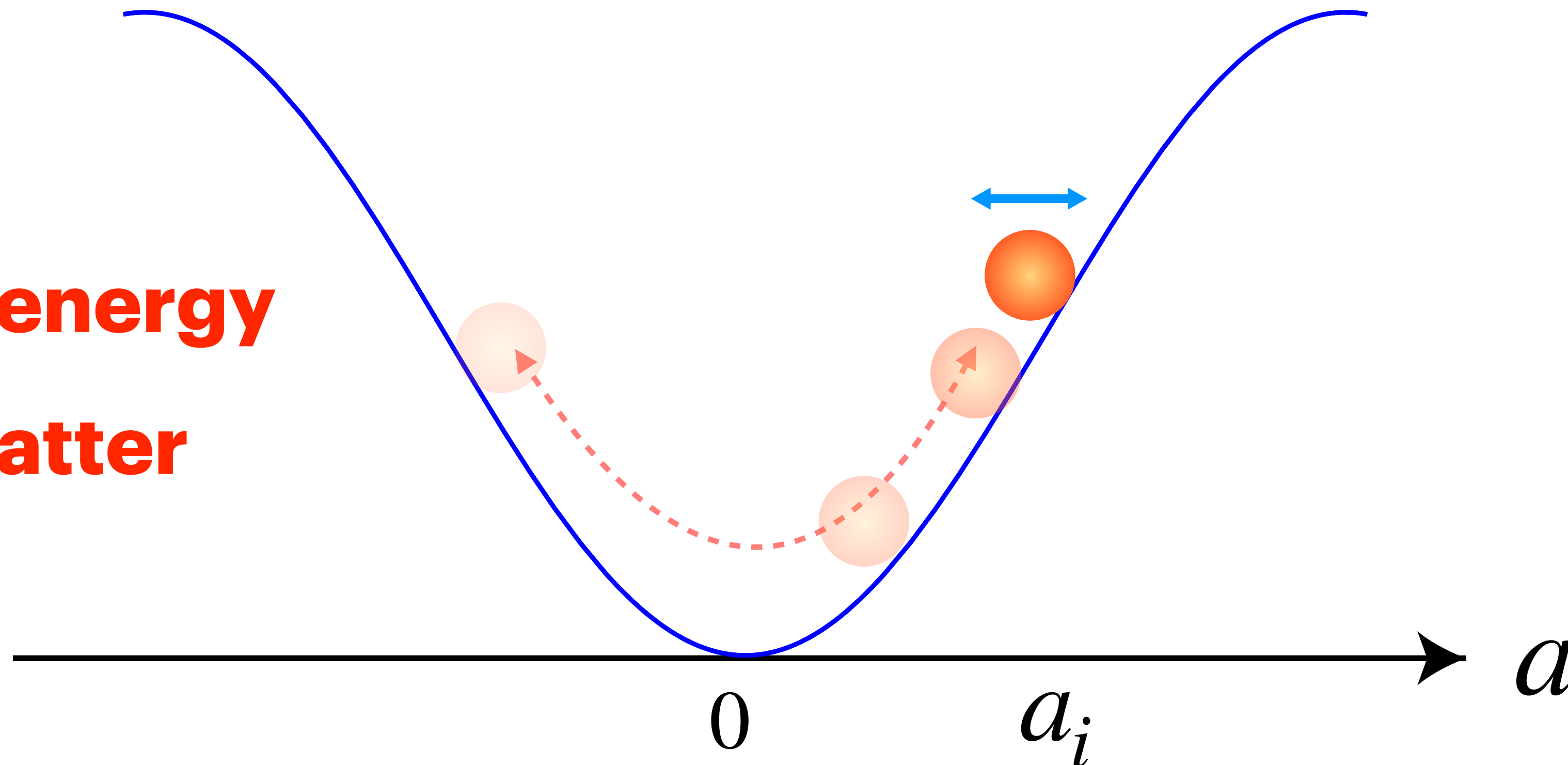
Misalignment mechanism

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

Axion starts to oscillate when the mass becomes comparable to the Hubble parameter, $H \sim m_a$.

$$\ddot{a} + 3H\dot{a} + m_a^2 a = 0$$

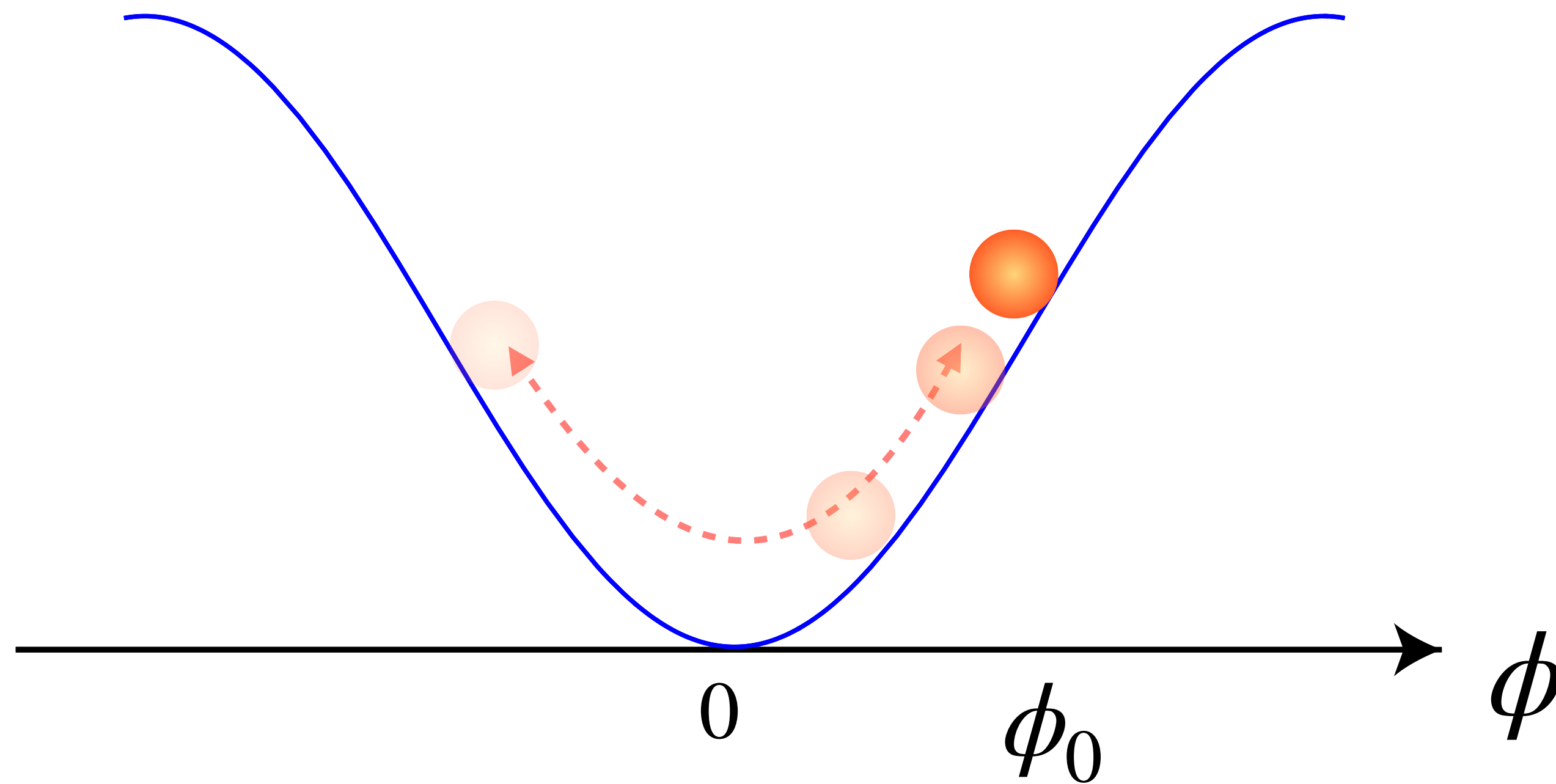
**Oscillation energy
= Dark matter**



Axion Dark Matter

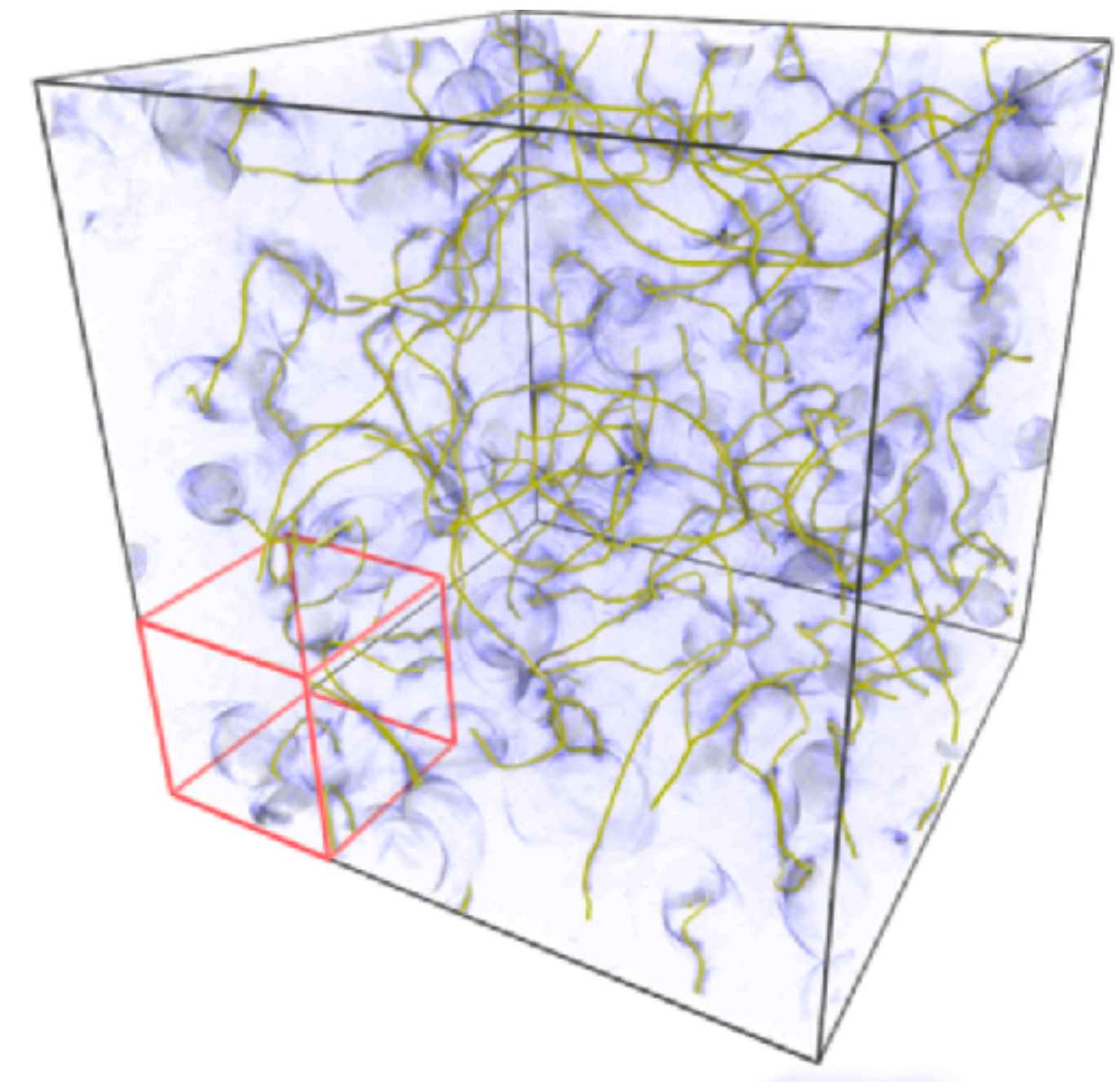
Axion cold dark matter can be produced by (i) misalignment mechanism, and (ii) decay of topological defects.

Pre-inflationary scenario



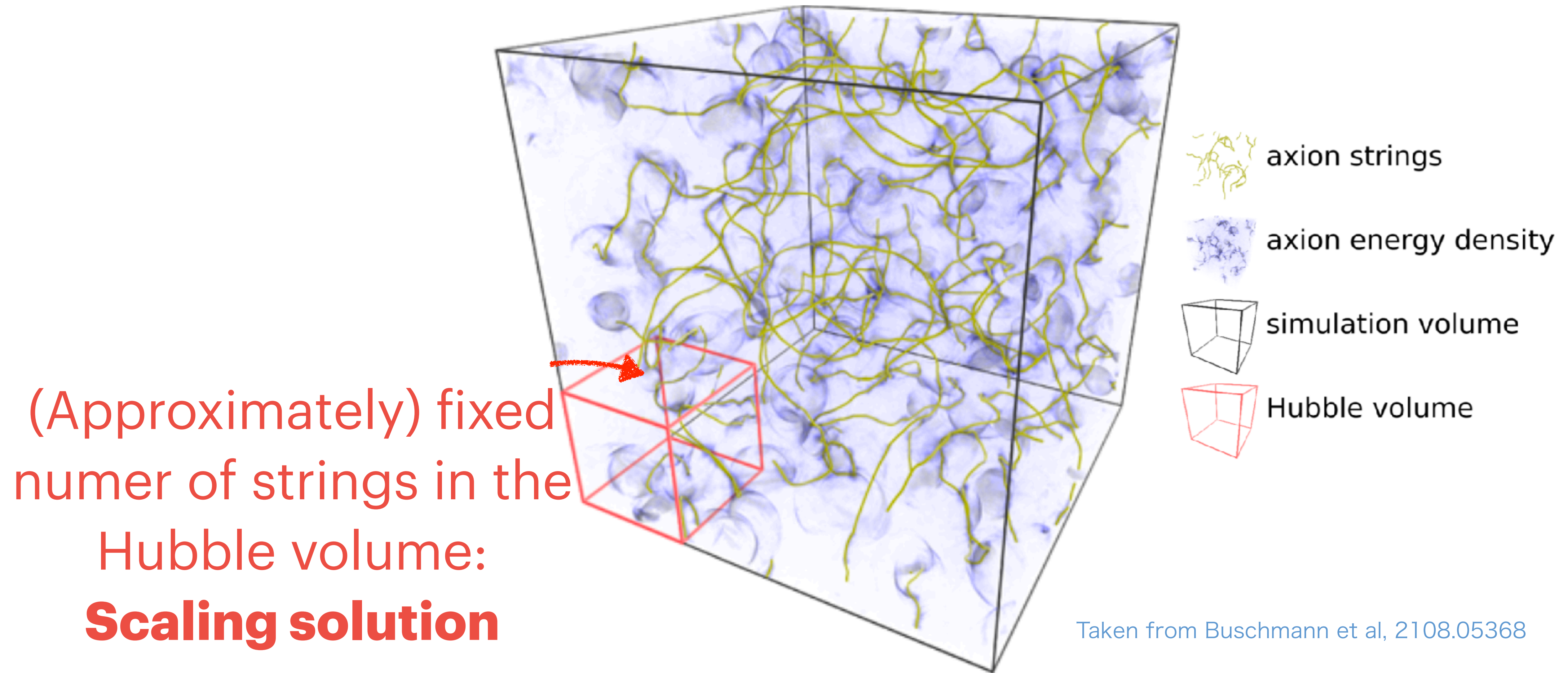
Preskill, Wise, Wilczek '83, Abbott, Sikivie '83, Dine, Fischler '83

Post-inflationary scenario

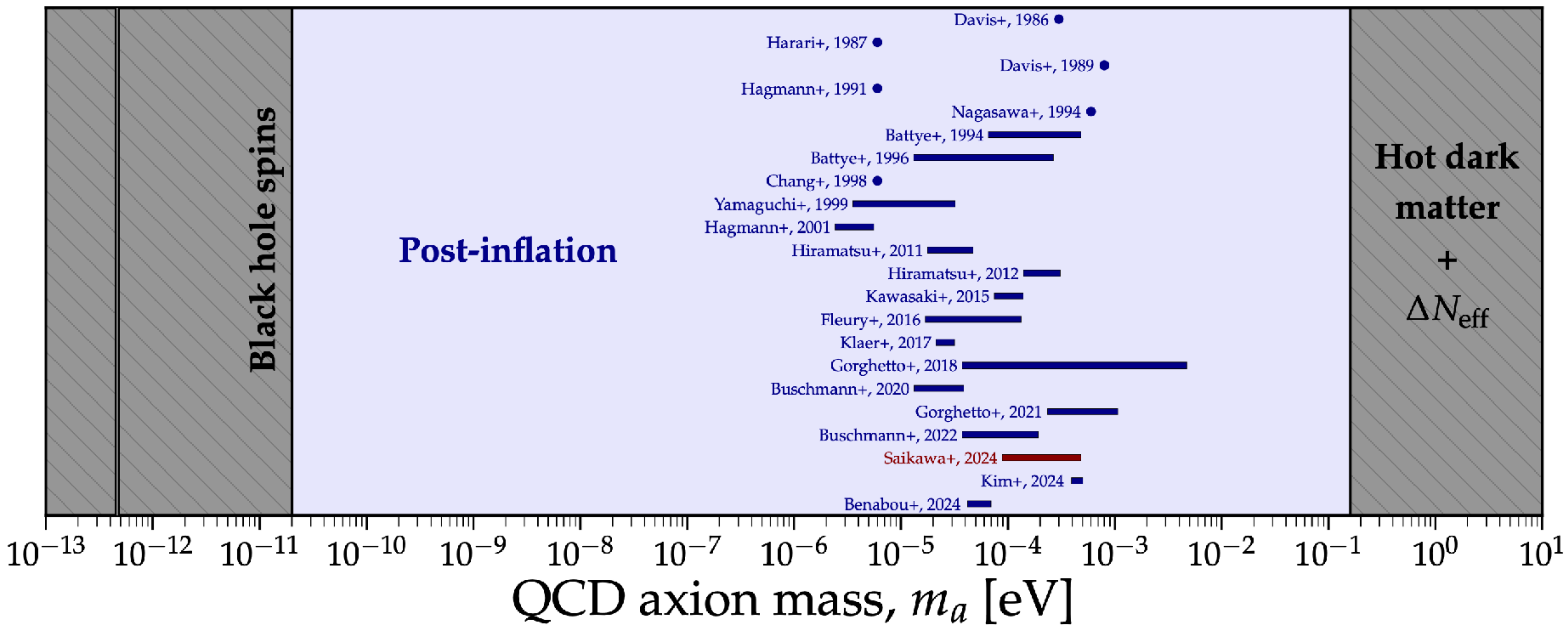


Buschmann et al, 2108.05368

Axion production from strings/walls



Prediction of post-inflationary scenario



Key assumption :

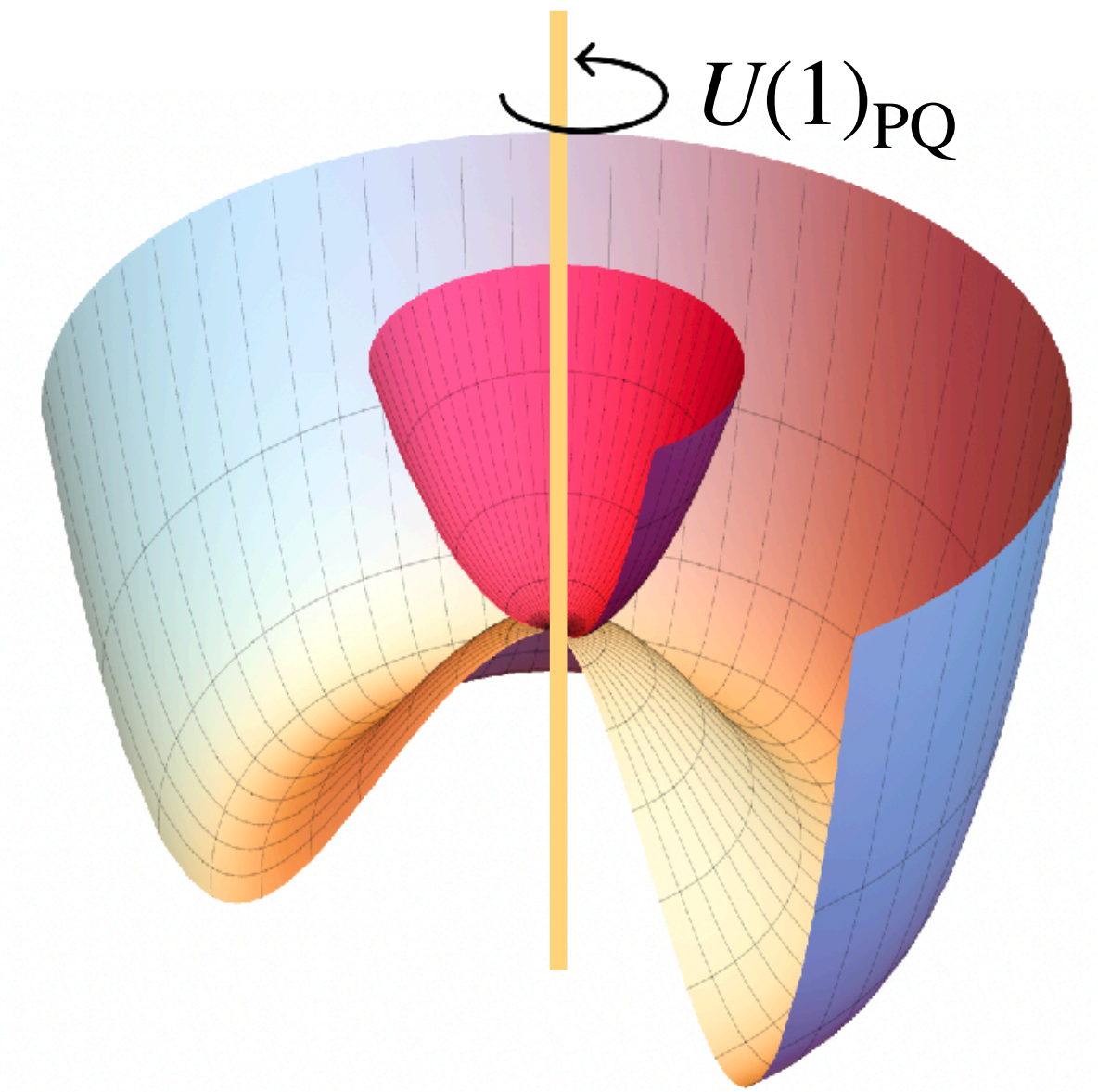
Single PQ scalar model

$$\Phi = \frac{f_a + s}{\sqrt{2}} e^{ia/f_a}$$

- Prevalent in high-precision lattice calculations.
- Simplifying assumption or crucial factor?



Origin and breaking of U(1) PQ are unknown!



Two axion system

We introduce two PQ scalars

$$\Phi_1 = \frac{f_1}{\sqrt{2}} e^{i \frac{\phi_1}{f_1}} \quad \text{and} \quad \Phi_2 = \frac{f_2}{\sqrt{2}} e^{i \frac{\phi_2}{f_2}}$$

and the potential for axions

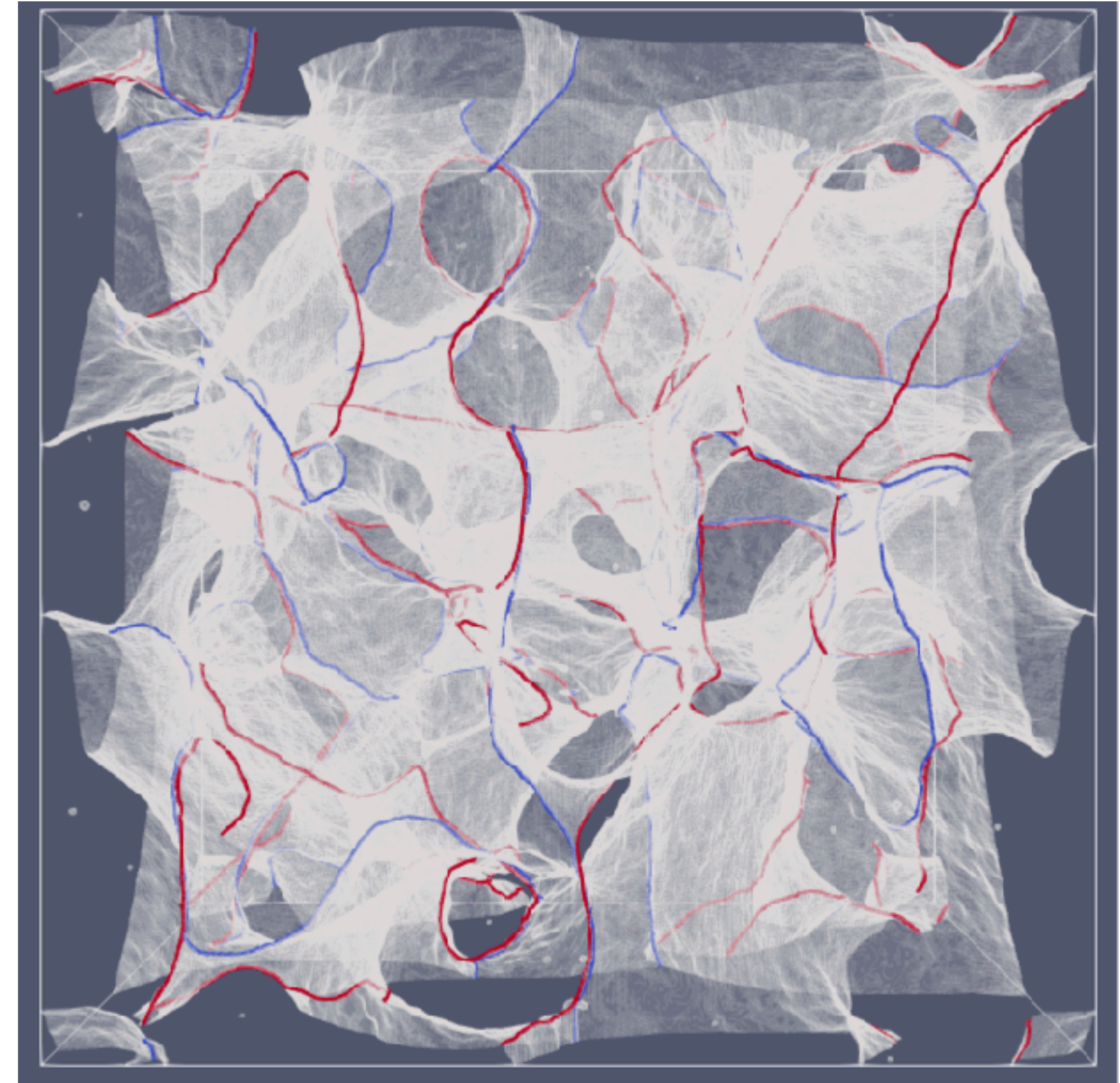
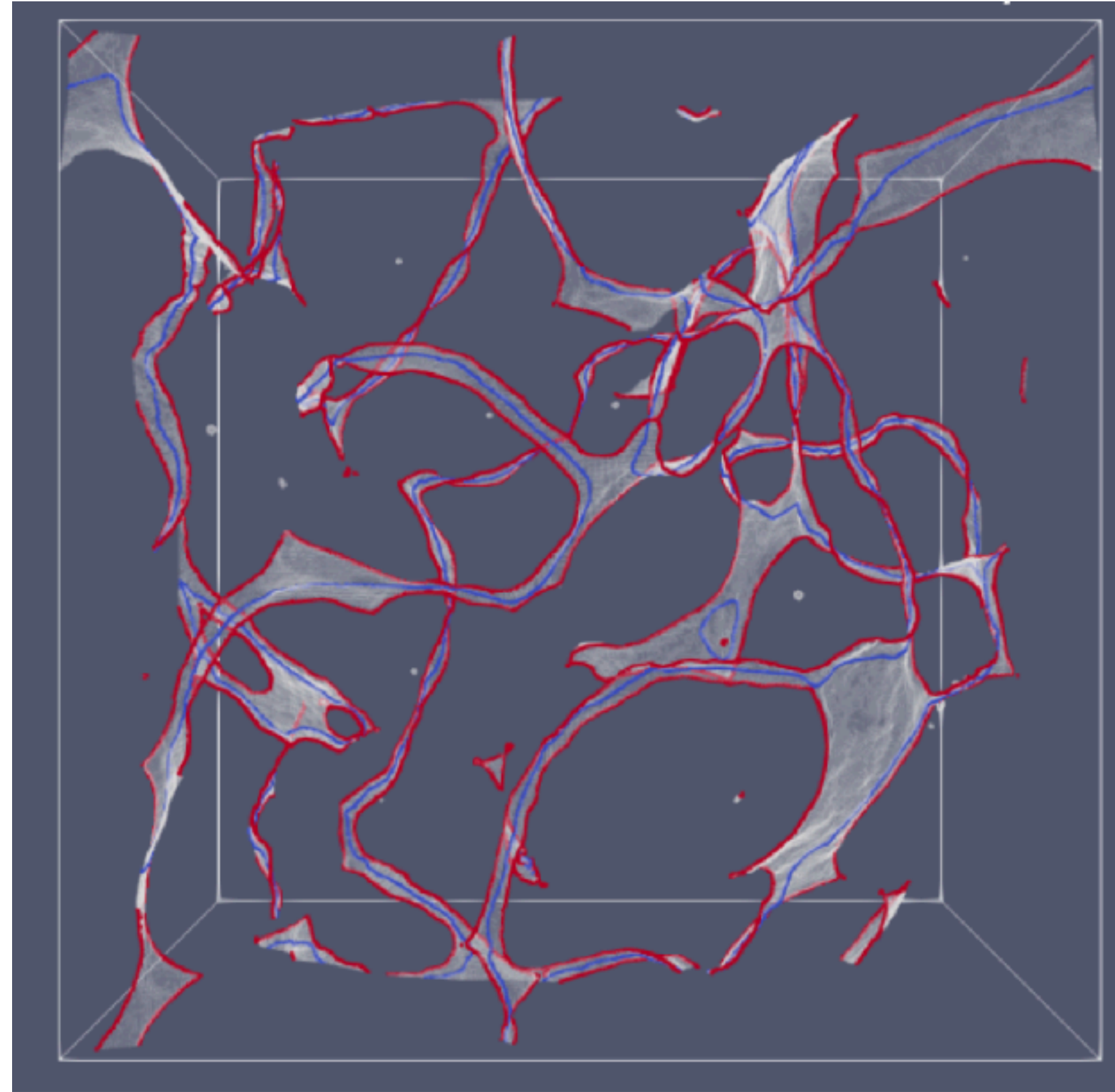
$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$

with the post-inflationary initial condition.



A minimal extension from one to two PQ scalars can lead to stable DWs with large tension, even if the vacuum is unique.

Higaki, Jeong, Kitajima, Sekiguchi and FT, 1606.05552 Lee, Murai, FT and Yin 2409.09749



$$|n_1| = 1 \quad \text{or} \quad |n_2| = 1$$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right] \quad |n_1|, |n_2| \geq 2.$$

Interactions of axions

• Photon

$$\begin{aligned}\mathcal{L}_{a\gamma\gamma} &= \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B} \\ &= c_\gamma \frac{\alpha}{4\pi} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}\end{aligned}$$

Axion-like particle (ALP)

c_γ : EM anomaly coefficient

cf. Meson mixings also contribute in the case of QCD axion

• Electron

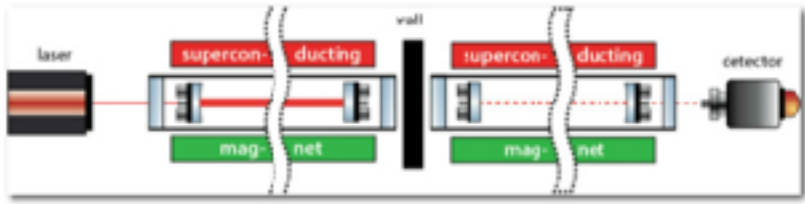
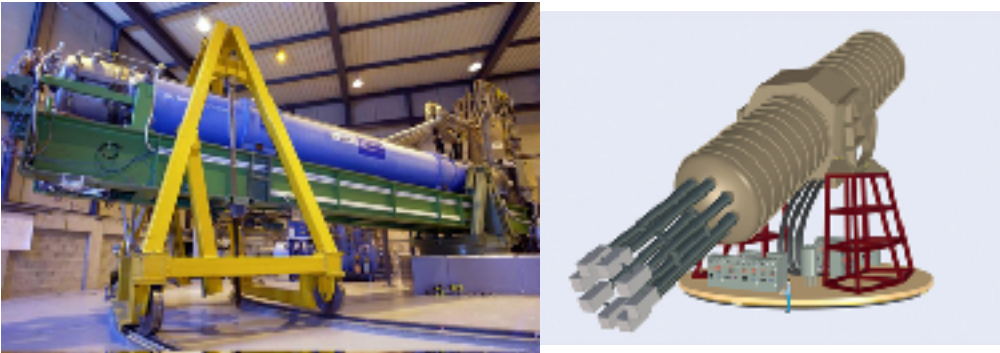
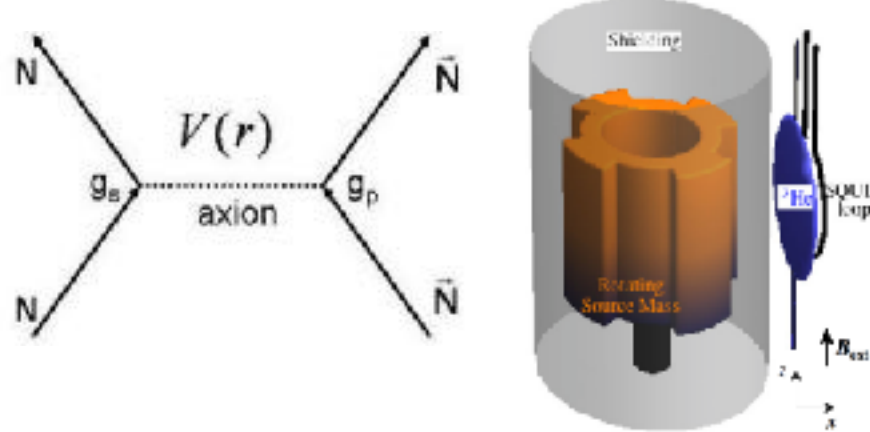
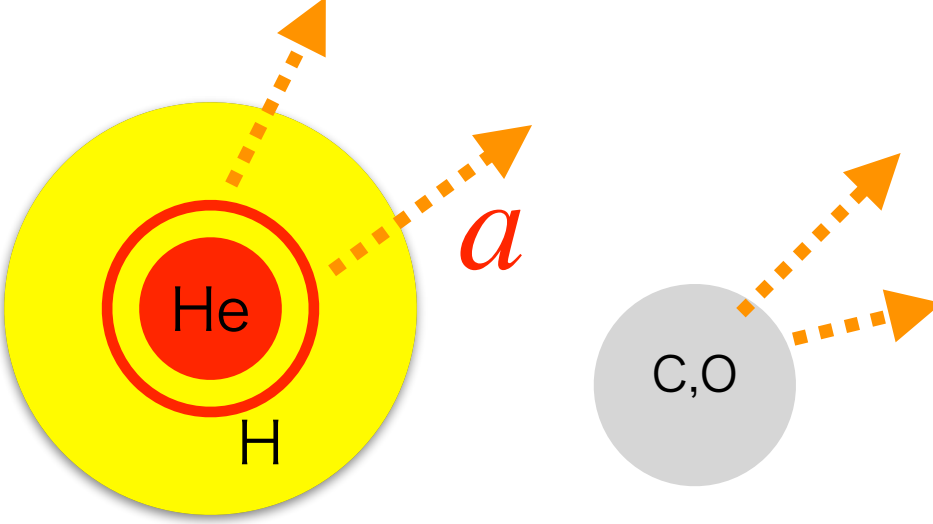
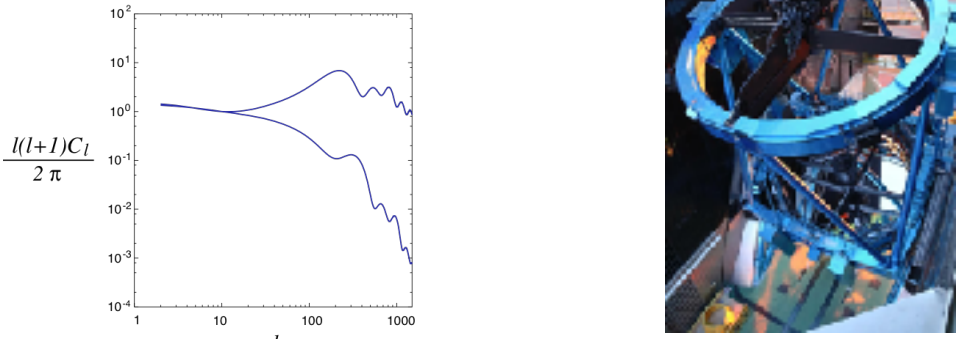
$$\begin{aligned}\mathcal{L}_{aee} &= \frac{C_e}{2f_a} \partial_\mu a \left(\bar{\Psi}_e \gamma^\mu \gamma_5 \Psi_e \right) = -ig_{aee} a \left(\bar{\Psi}_e \gamma_5 \Psi_e \right) + \dots \\ g_{aee} &\equiv \frac{C_e m_e}{f_a}\end{aligned}$$

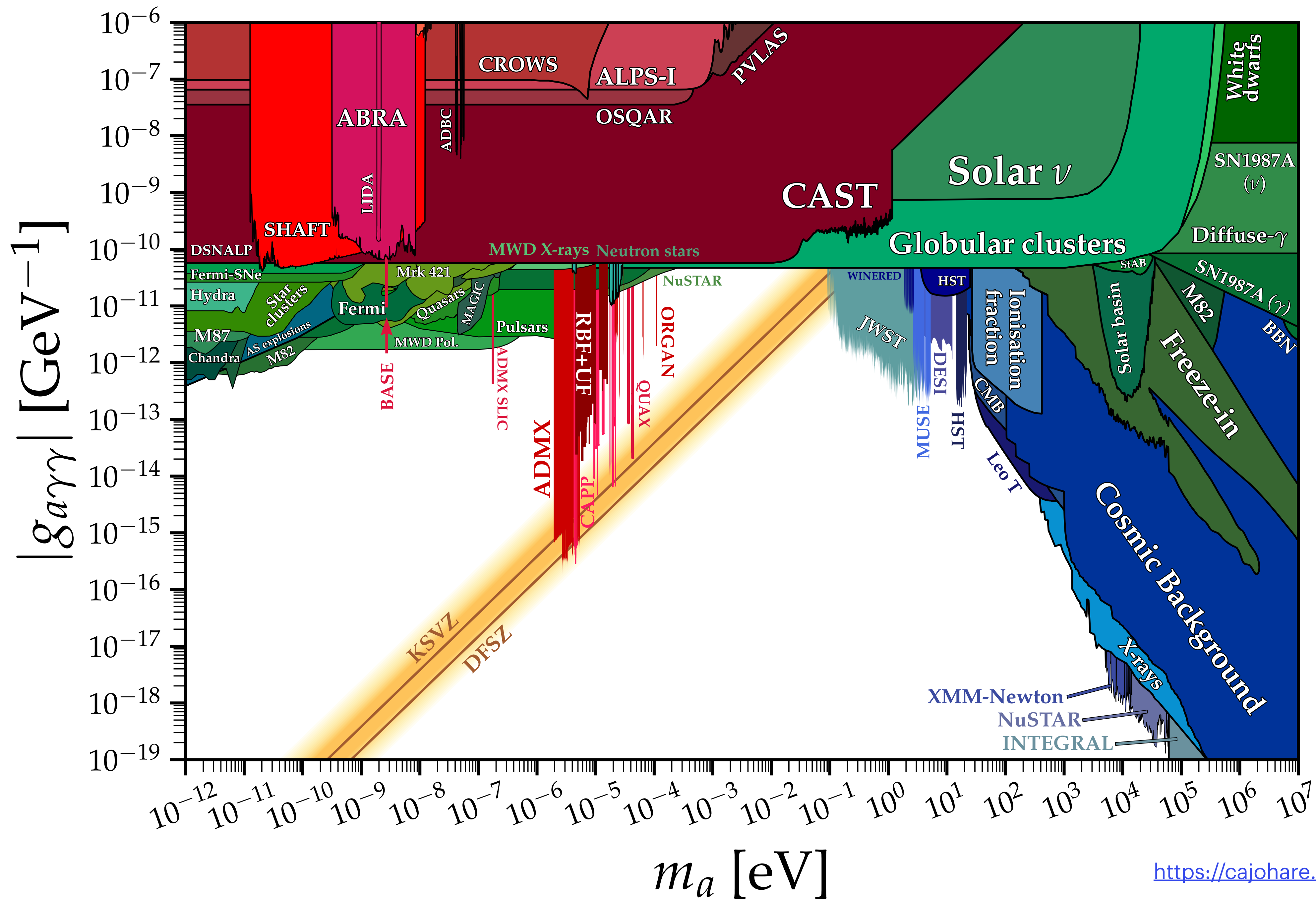
$$C_e = \frac{\cos^2 \beta}{3} \text{ for DFSZ axion.}$$

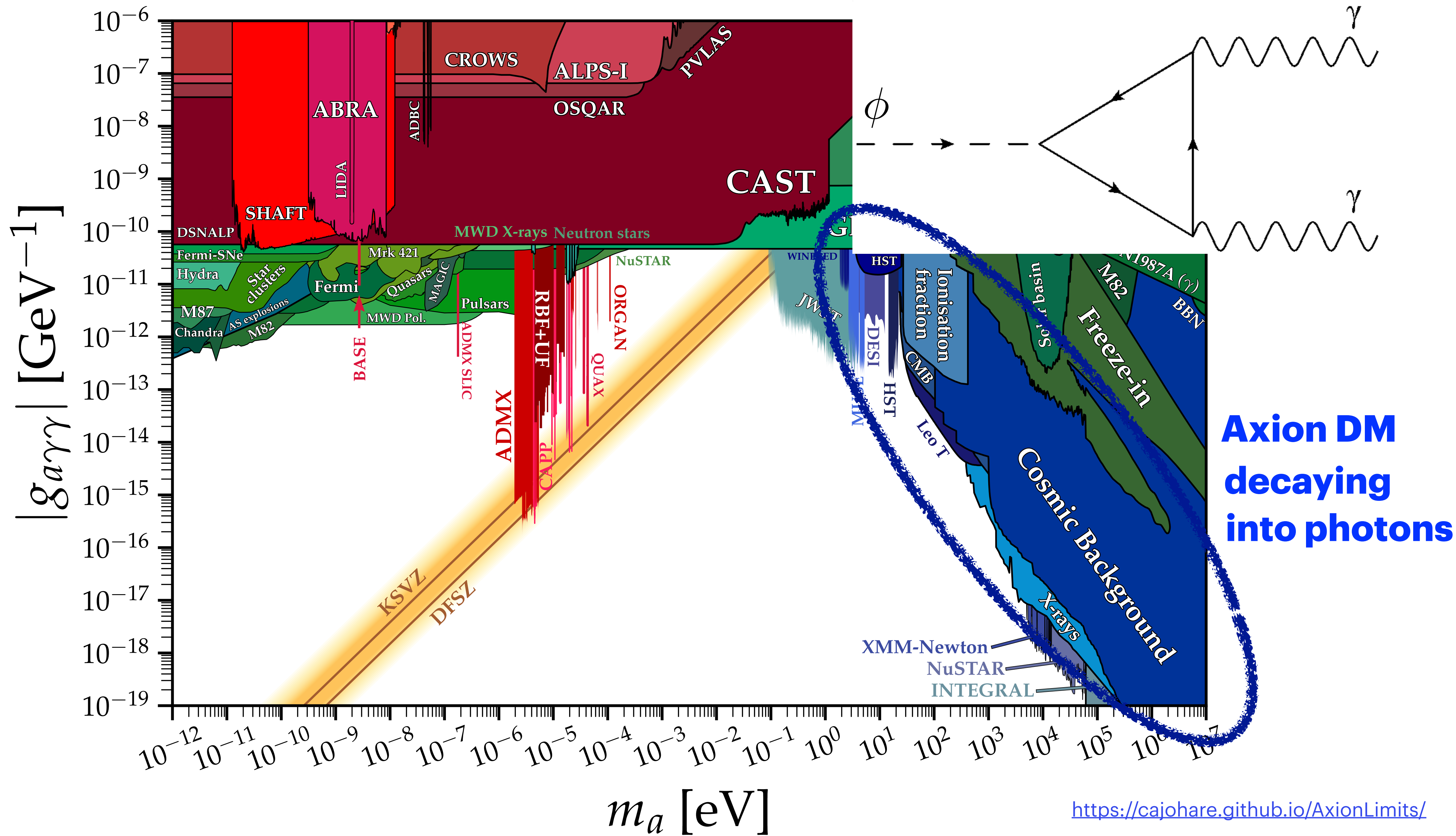
Model-dependent, and it appears at loop level in hadronic axions.

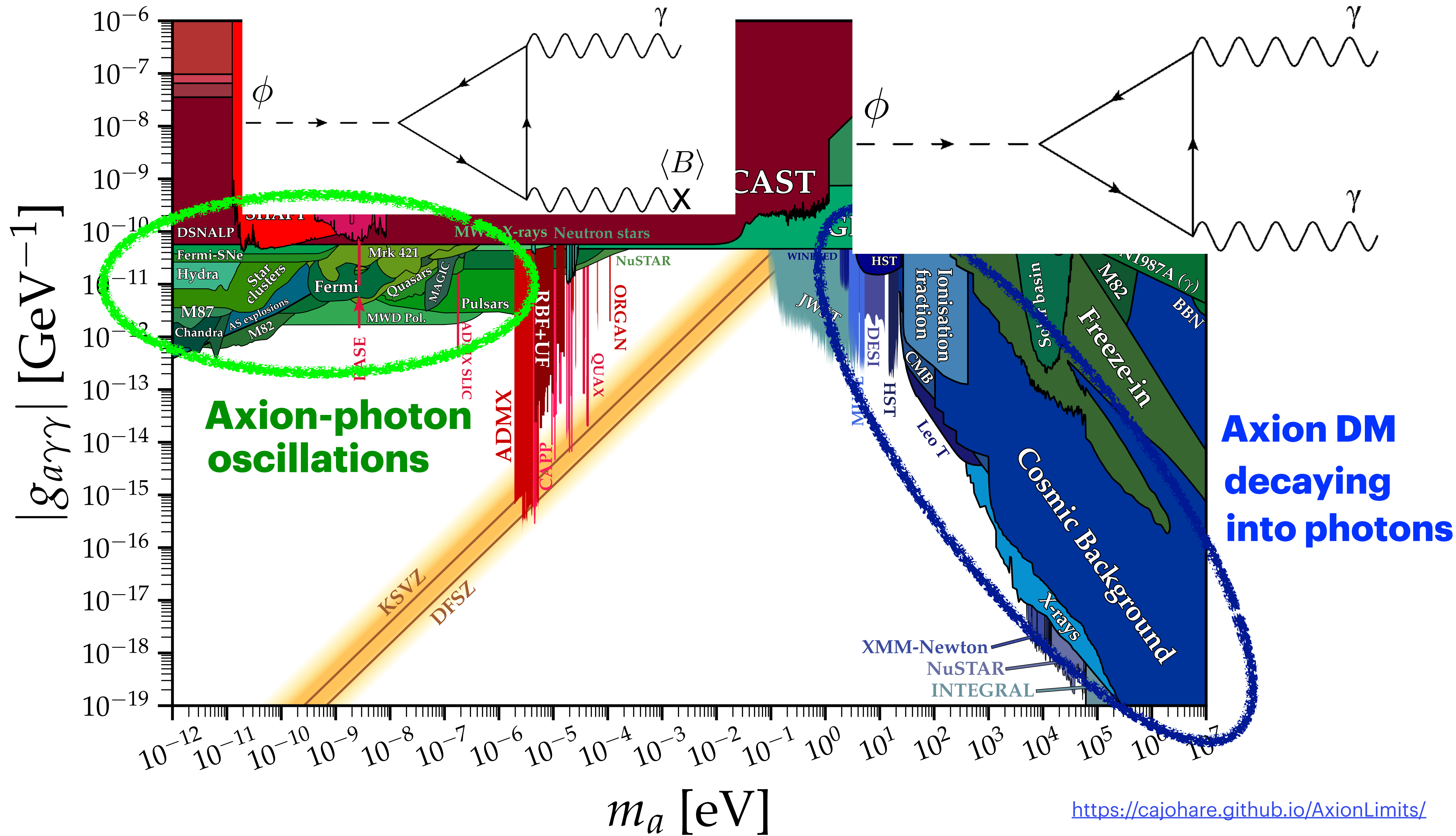
• Nucleon

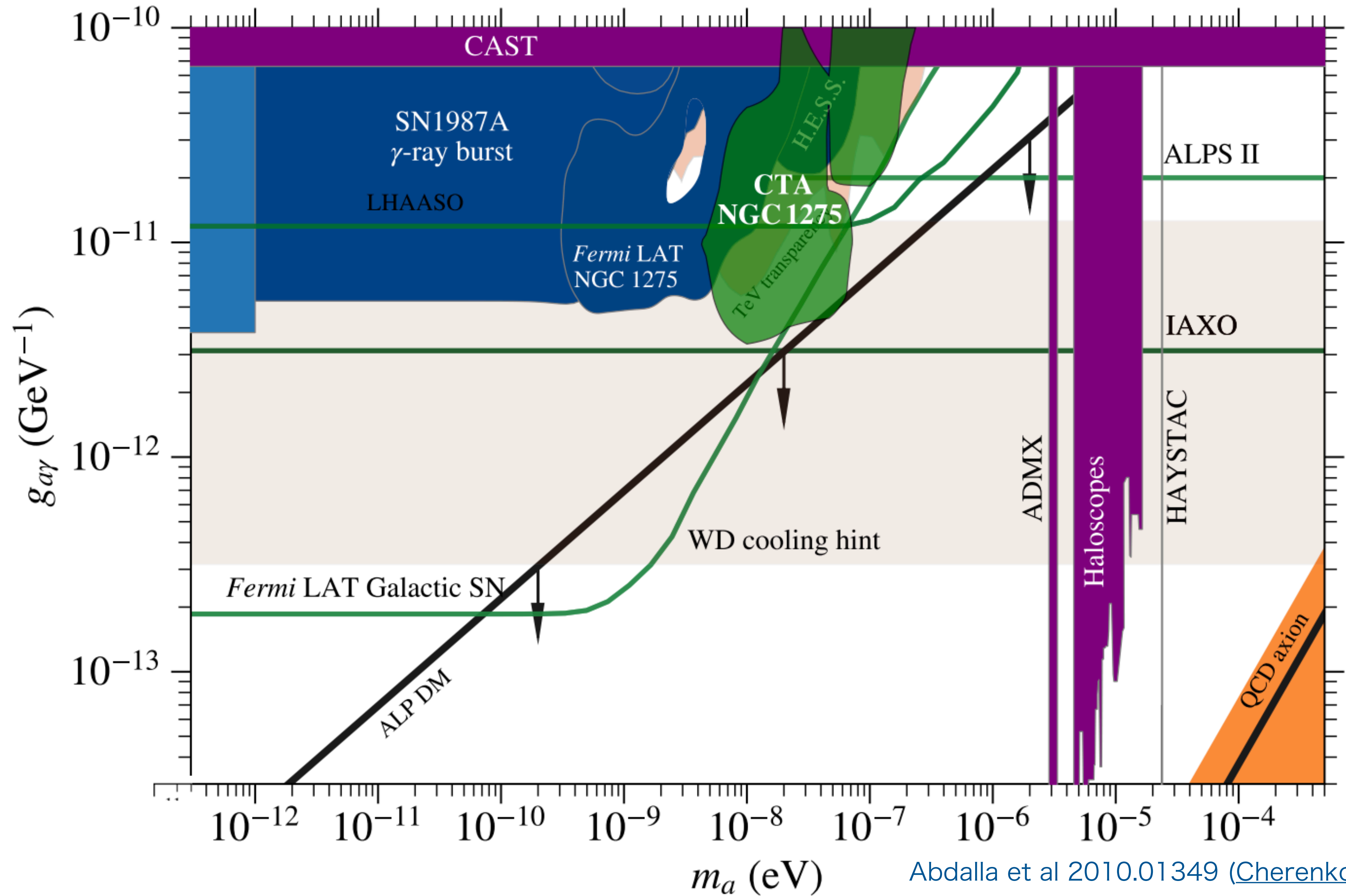
$$\mathcal{L}_{aNN} = \sum_{N=p,n} \frac{C_N}{2f_a} \partial_\mu a \left(\bar{\Psi}_N \gamma^\mu \gamma_5 \Psi_N \right)$$

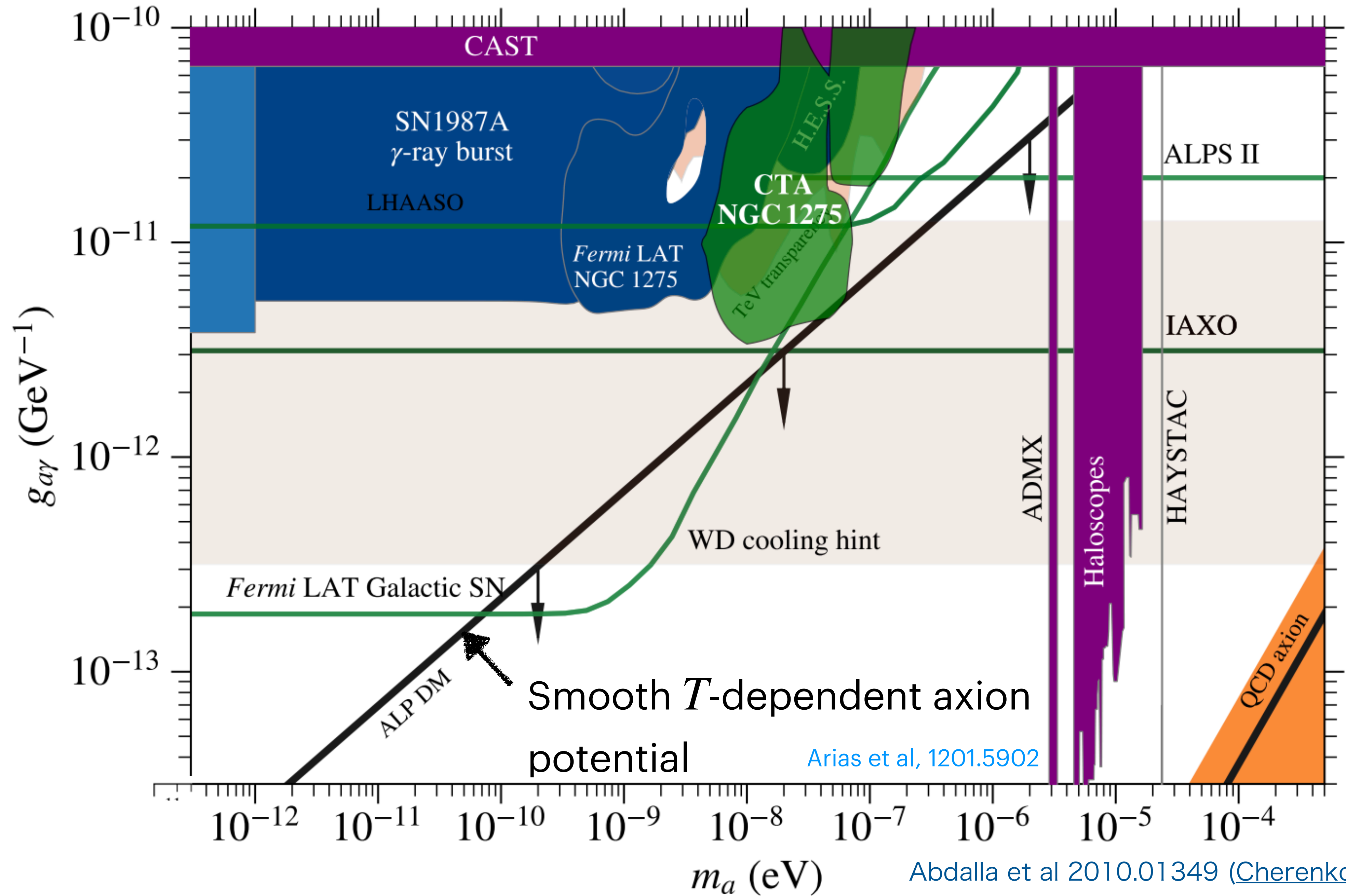
		Production		
		Ground	Inside stars	Early Universe
Detection	Direct	LSTW, Photon pol. ALPS II, SAPPHIRES 	Solar axion CAST, (Baby)IAXO, XENONnT, PandaX, LZ 	Axion DM ADMX, CAPP, HAYSTAC MADMAX, DMRadio, DANCE, LIDA, ADBC, EDAMAME, CASPEr, QUAX, XENONnT, PandaX, LZ 
	Indirect	Spin-dependent fifth force ARIADNE QUAX-gpgs Torsion pendulum 	Excessive cooling of WD, RGB, AGB, HB, and NS, BH superradiance 	Isocurvature, DR, HDM, spectral irreg. transparency, birefringence, axion decay PRIMA, Fermi-LAT, CTAO XRISM, Athena, CMB, lensing 





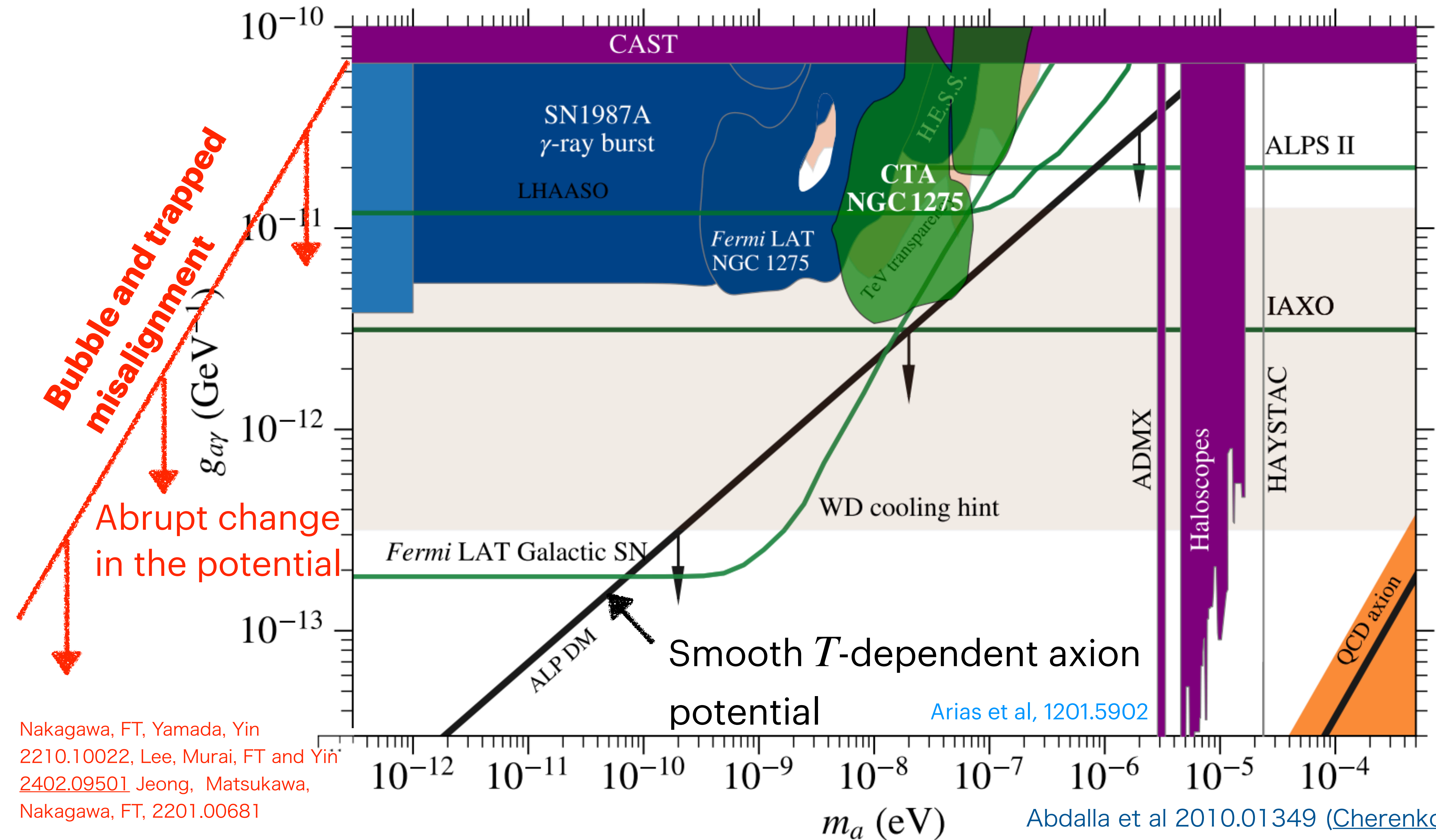






Arias et al, 1201.5902

Abdalla et al 2010.01349 ([Cherenkov Telescope Array Consortium](#).)



Nakagawa, FT, Yamada, Yin
 2210.10022, Lee, Murai, FT and Yin
 2402.09501 Jeong, Matsukawa,
 Nakagawa, FT, 2201.00681

Arias et al, 1201.5902

Abdalla et al 2010.01349 (Cherenkov Telescope
 Array Consortium.)

Beyond Standard Misalignment

Axion abundance depends on the initial amplitude θ_i and the properties of axion potential.

1. Constant axion potential

2. Axion mass as a continuous function of temperature cf. P. Arias et al, 1201.5902

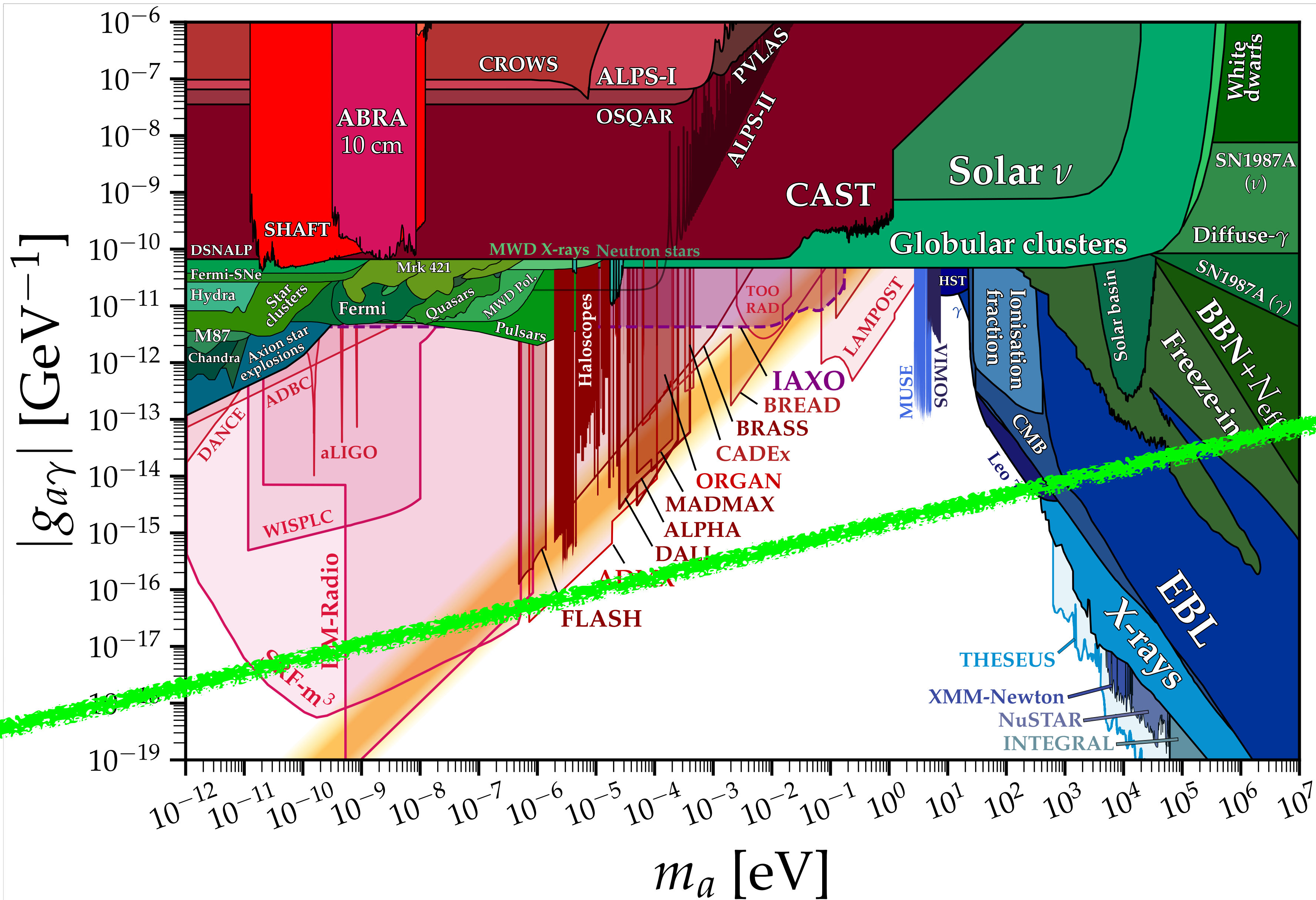
e.g. QCD axion: $m_a^2(T) \propto T^{-8.16}$ at $T > T_{\text{QCD}}$ S. Borsanyi et al., Nature 539 (2016) 69 [1606.07494].

3. Axion mass changing abruptly due to a first-order phase transition or trapping

e.g. FOPT for SU(N) with $N \geq 3$.

B. Lucini, M. Teper and U. Wenger, hep-lat/0307017, hep-lat/0502003

Nakagawa, FT, Yamada, and Yin 2210.10022, Lee, Murai, FT and Yin 2402.09501 K-S Jeong, K. Matsukawa, S. Nakagawa, FT, 2201.00681, cf. T. Higaki, K-S Jeong, N. Kitajima, and FT, 1603.02090, S. Nakagawa, FT, and M. Yamada 2012.13592, Luca Di Luzio, B. Gavela, and A. Ringwald, 2102.01082



$$\phi_0 = f_a$$

$$g_{a\gamma\gamma} = \frac{\alpha}{4\pi f_a}$$

(1) Constant axion mass

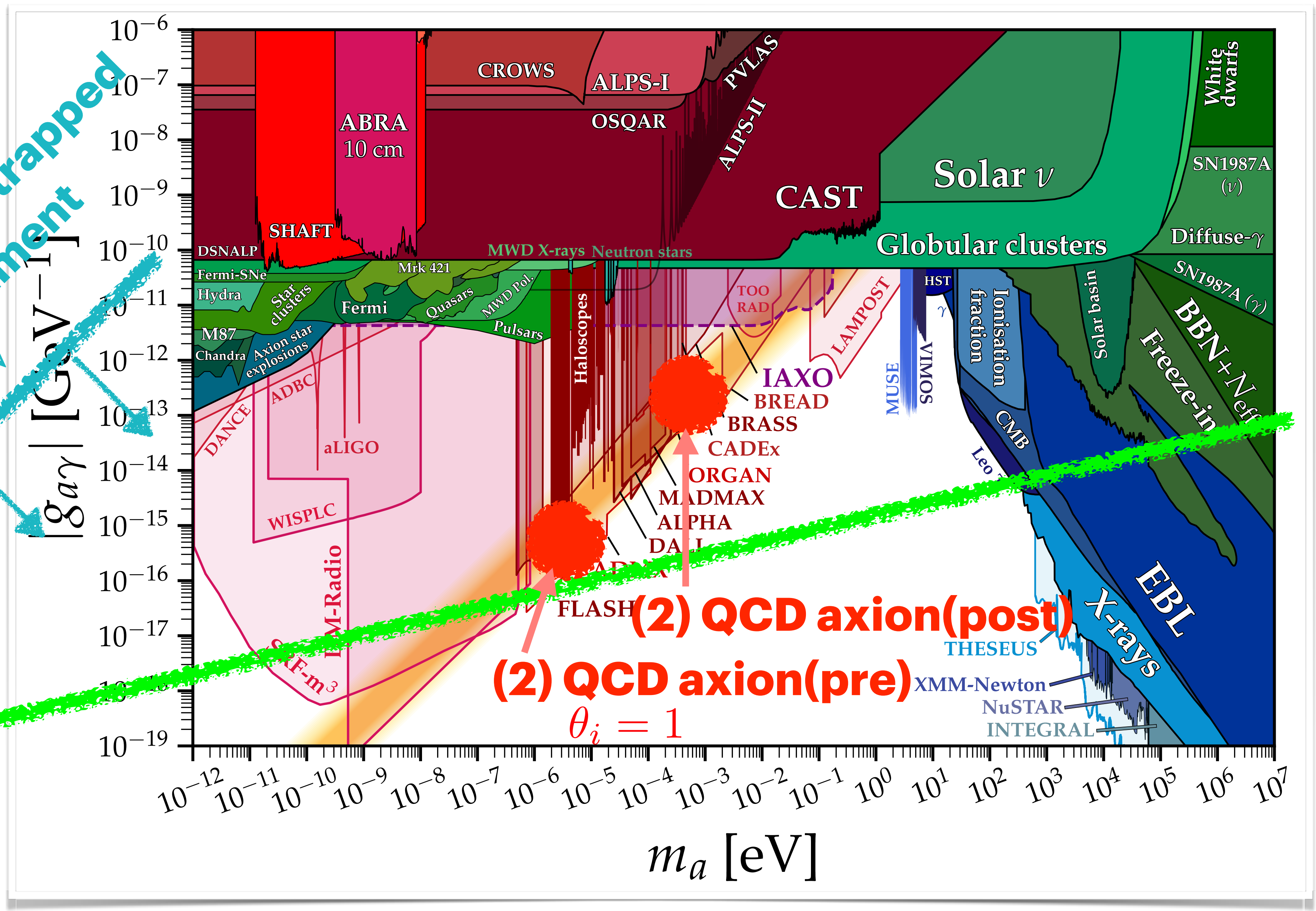
$$\theta_i = 1$$

$$g_{a\gamma\gamma} = \frac{\alpha}{4\pi f_a}$$



$$\theta_i = 1$$

(3) Bubble/trapped
misalignment
 $T_{\text{osc}} = 230 \text{ eV}$



$$\phi_0 = f_a$$

$$g_{a\gamma\gamma} = \frac{\alpha}{4\pi f_a}$$

(1) Constant
axion mass
 $\theta_i = 1$

Bubble misalignment mechanism

Lee, Murai, FT and Yin [2402.09501](#) , Nakagawa, FT, Yamada, and Yin 2210.10022

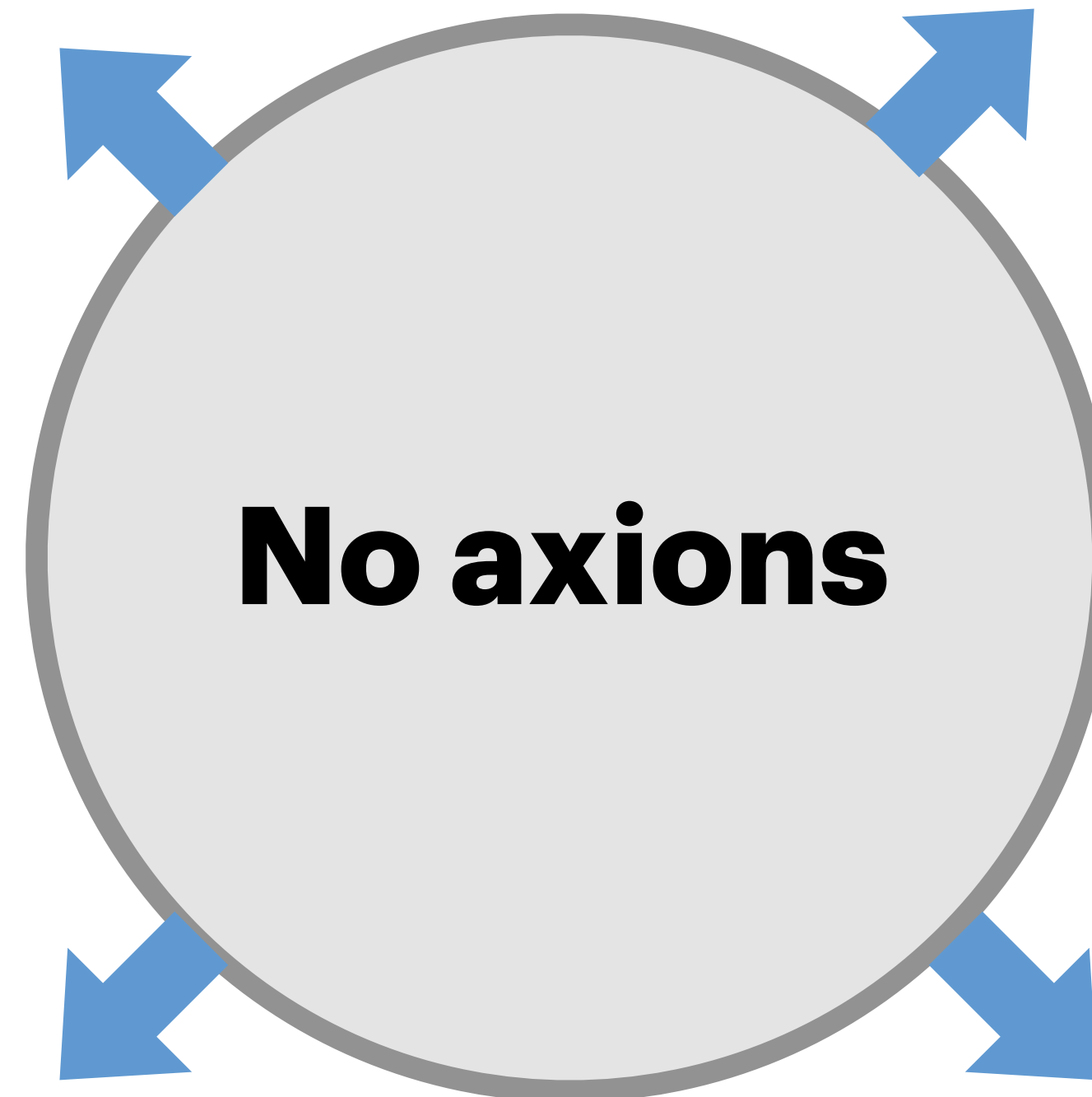


Bubble misalignment mechanism

Lee, Murai, FT and Yin [2402.09501](#) , Nakagawa, FT, Yamada, and Yin [2210.10022](#)

If the axion mass is generated by a first-order phase transition, it changes abruptly, leading to an enhanced axion abundance.

- ① Axions are expelled from the inside of bubbles.

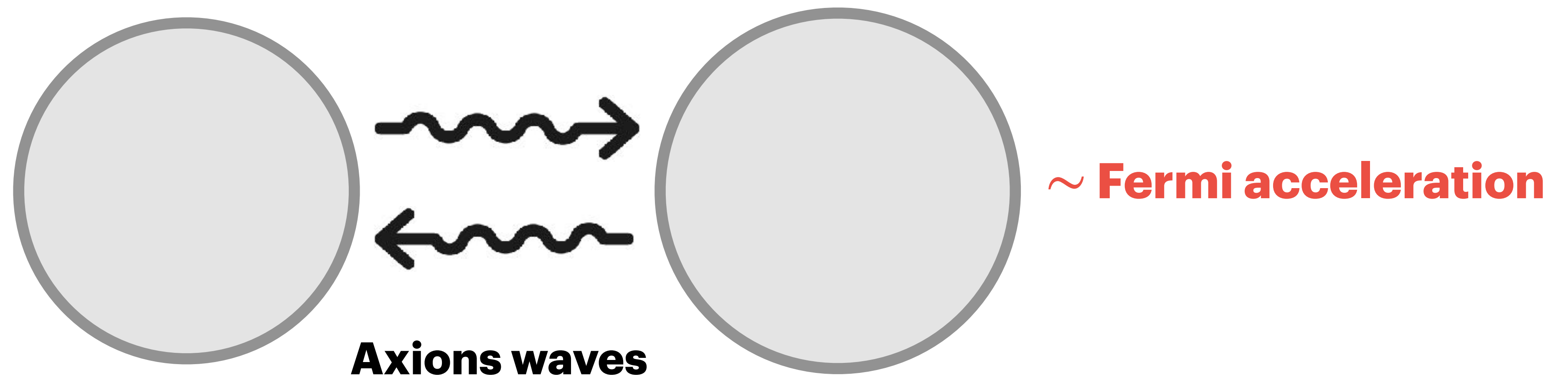


Bubble misalignment mechanism

Lee, Murai, FT and Yin [2402.09501](#) , Nakagawa, FT, Yamada, and Yin [2210.10022](#)

If the axion mass is generated by a first-order phase transition, it changes abruptly, leading to an enhanced axion abundance.

- ① Axions are expelled from the inside of bubbles.
- ② Axions waves are accumulated outside the bubbles and repeatedly scatter off bubble walls.

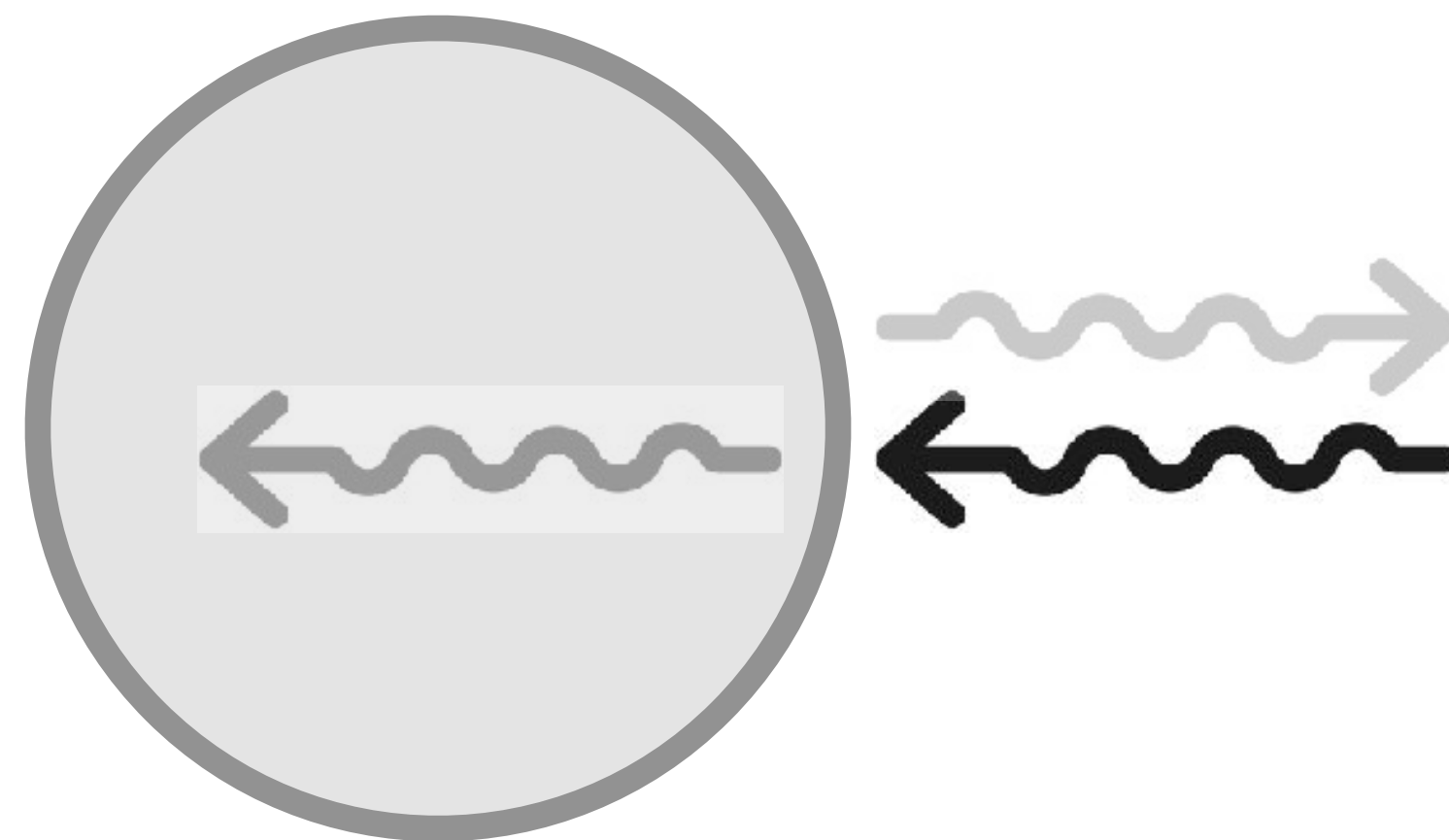


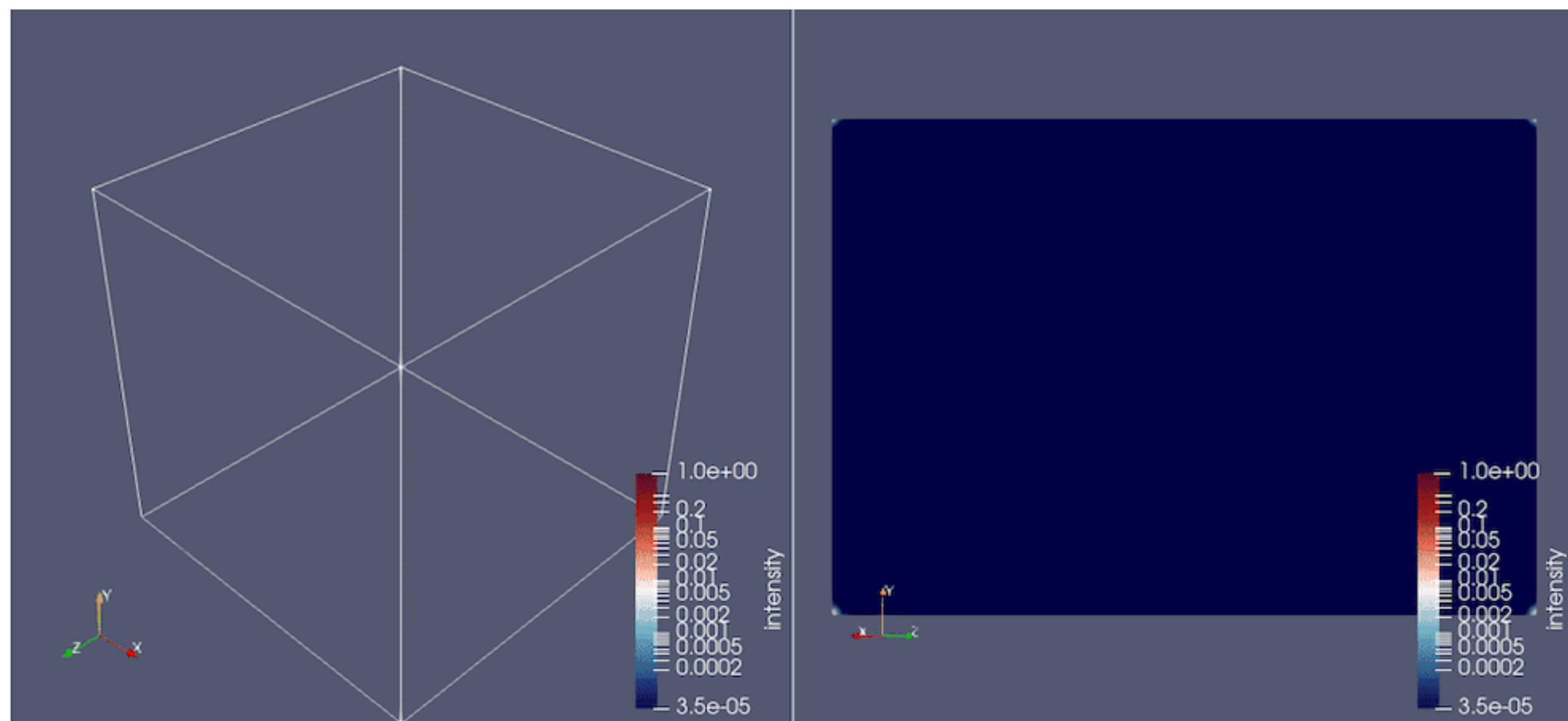
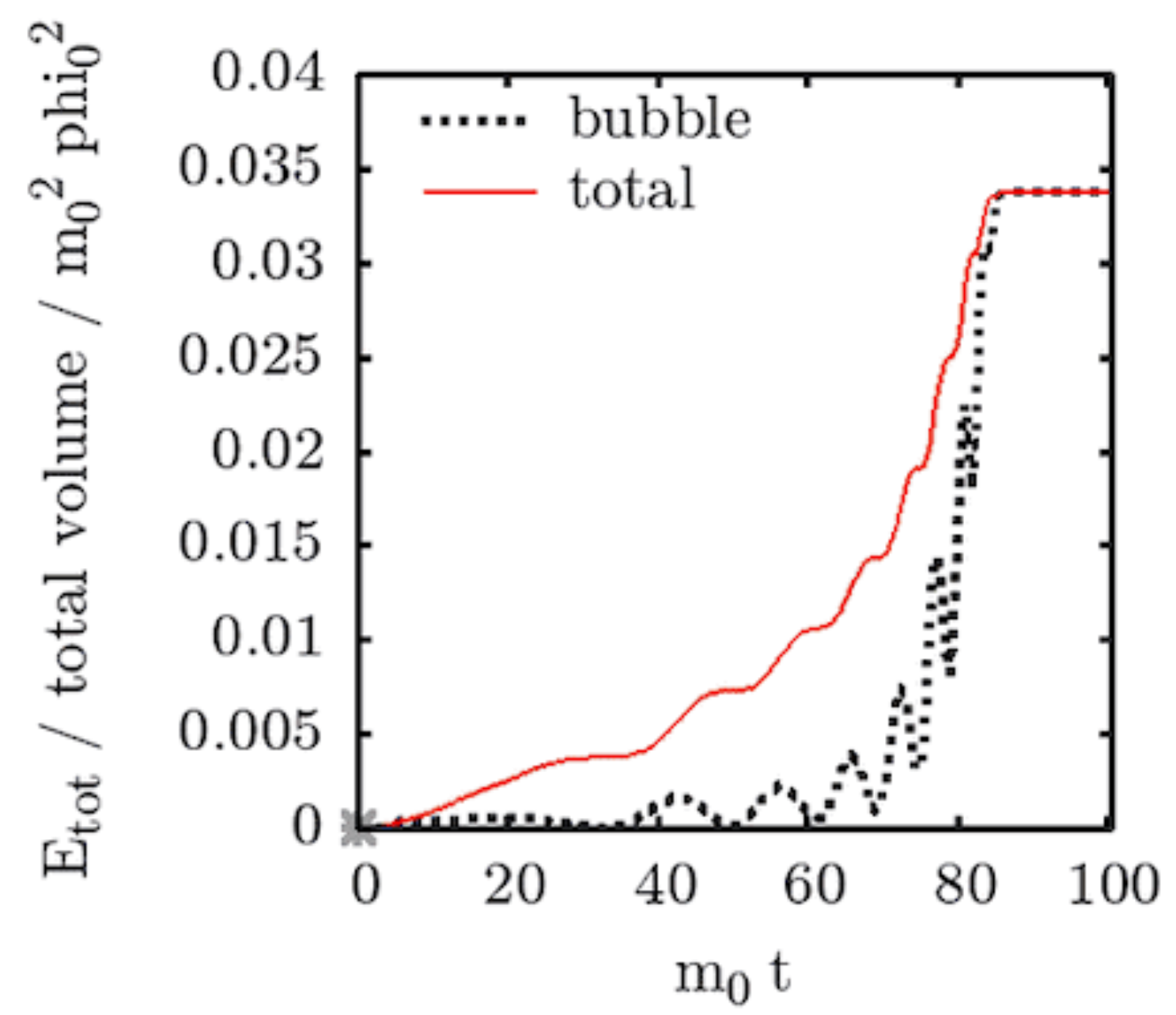
Bubble misalignment mechanism

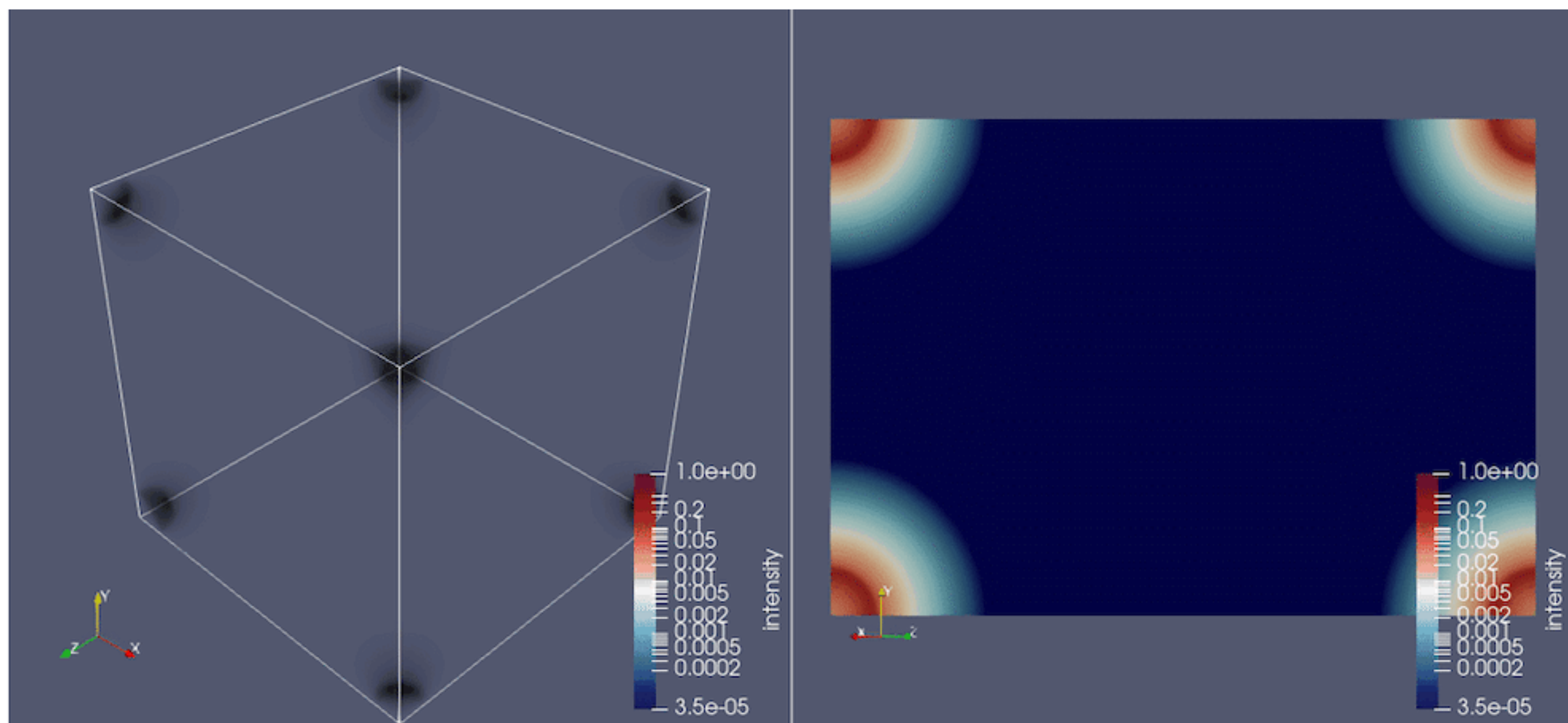
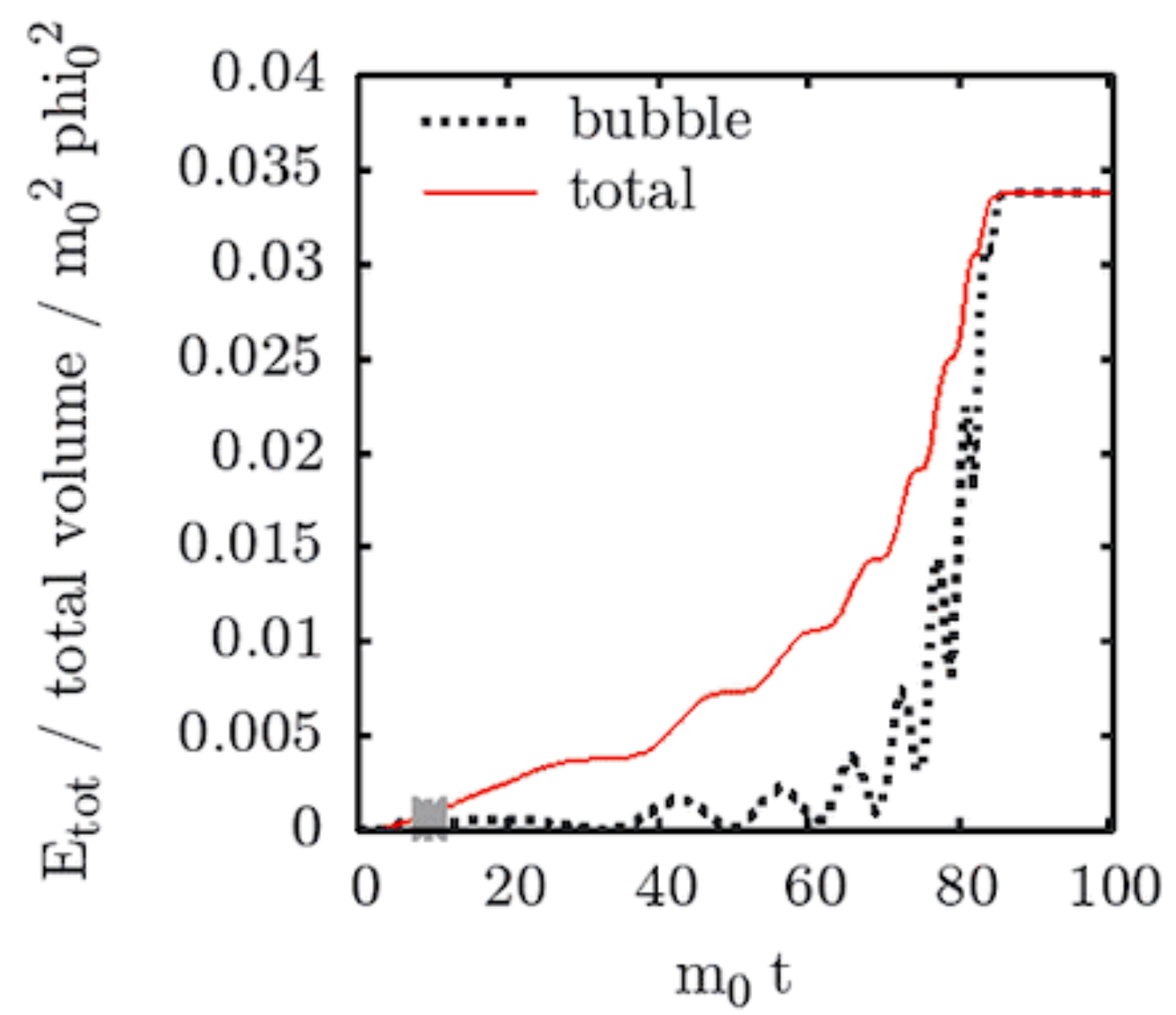
Lee, Murai, FT and Yin [2402.09501](#) , Nakagawa, FT, Yamada, and Yin [2210.10022](#)

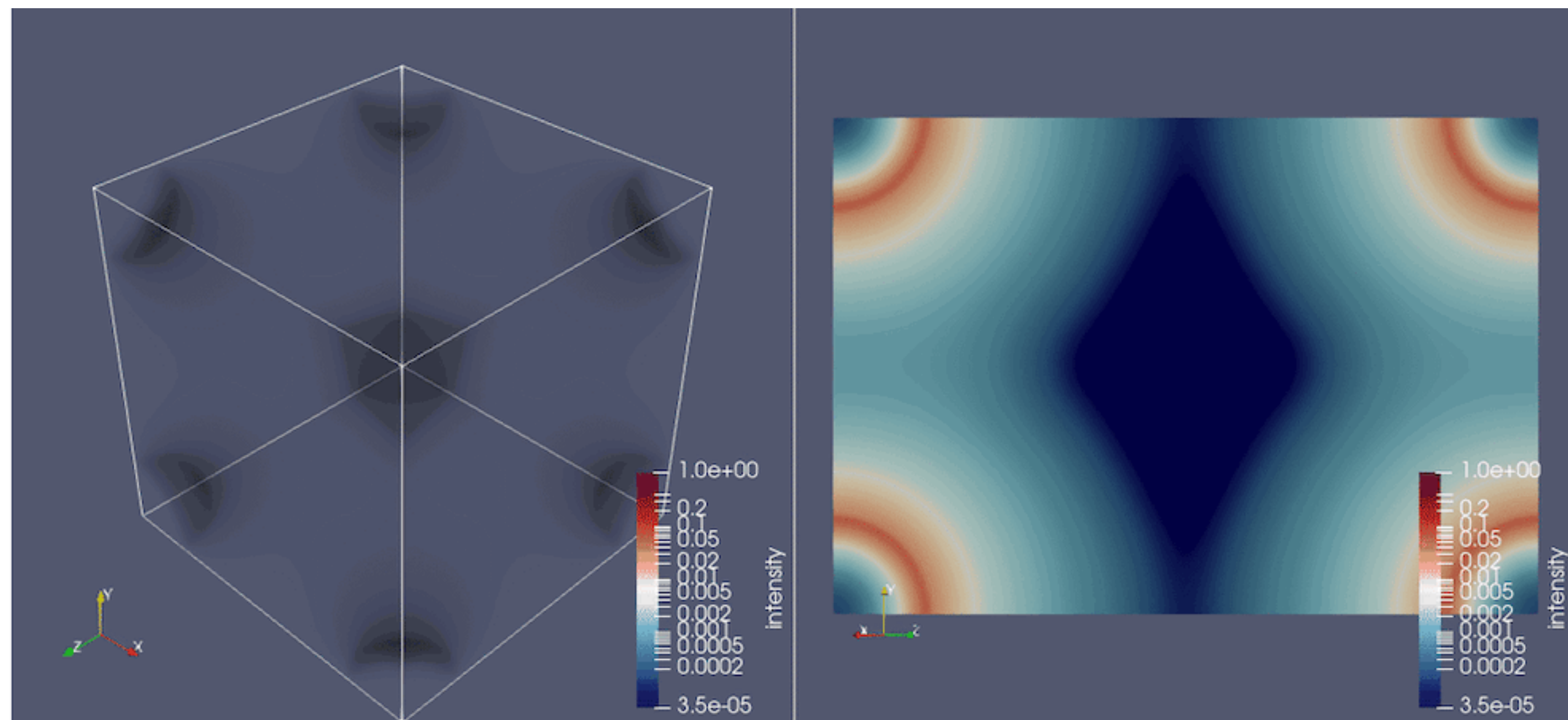
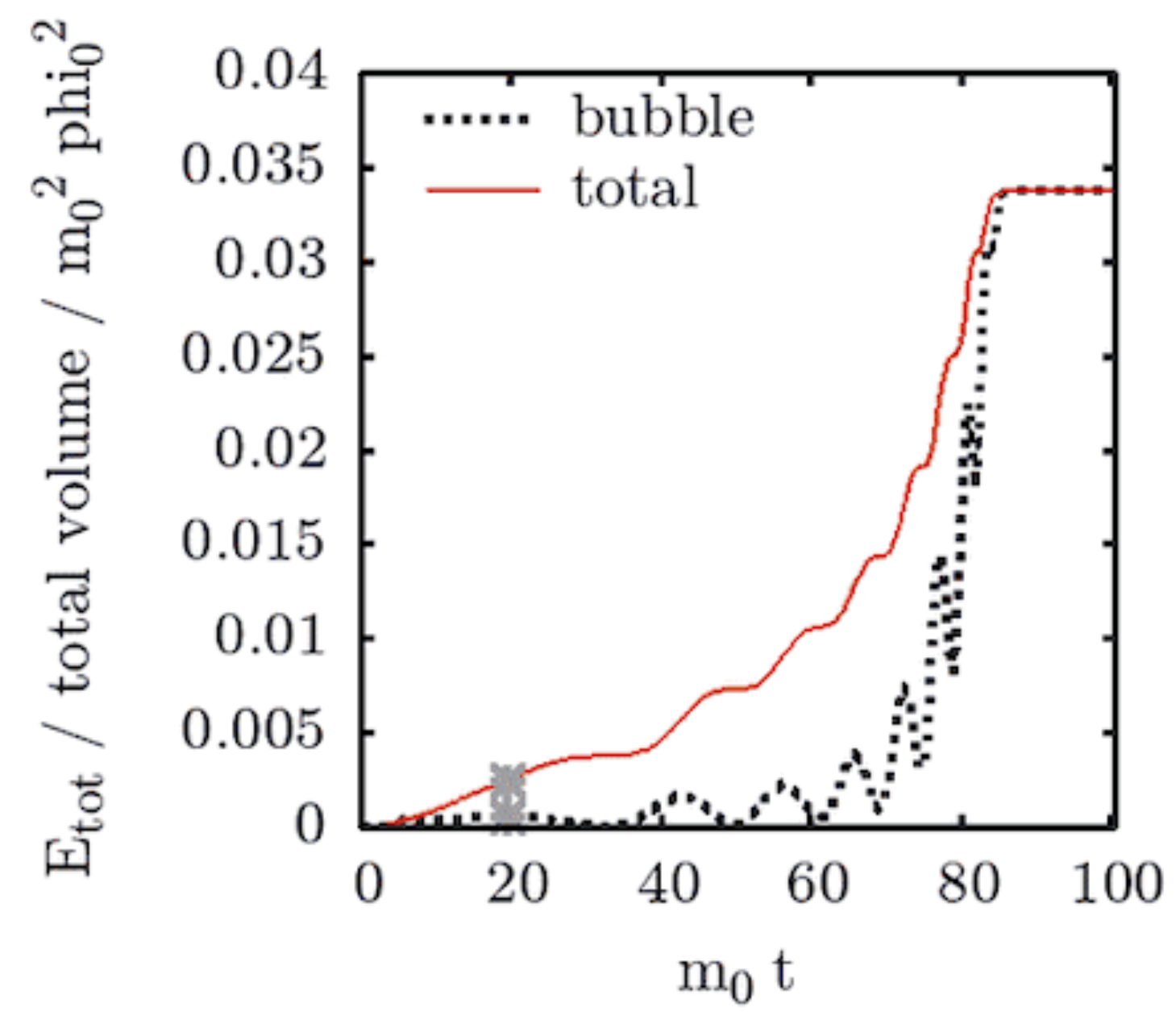
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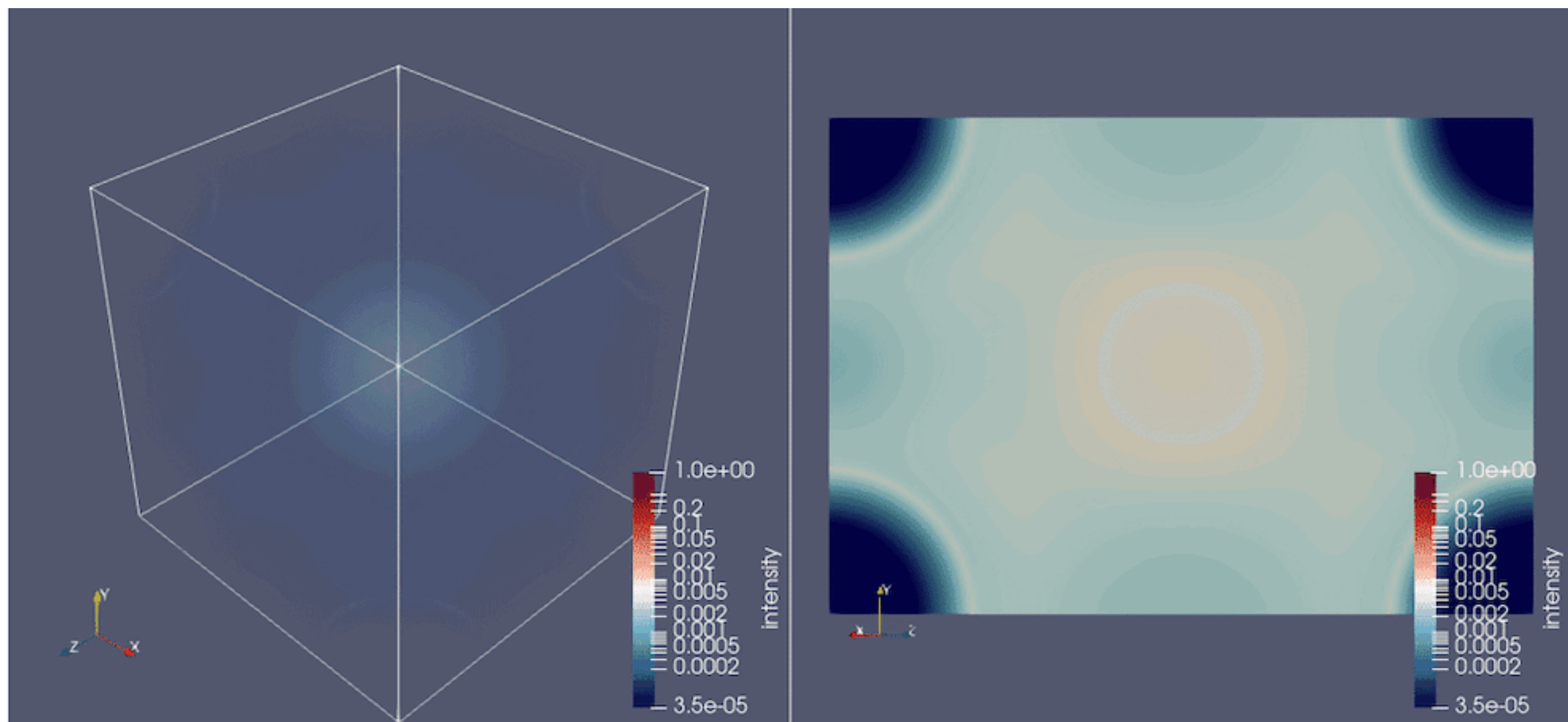
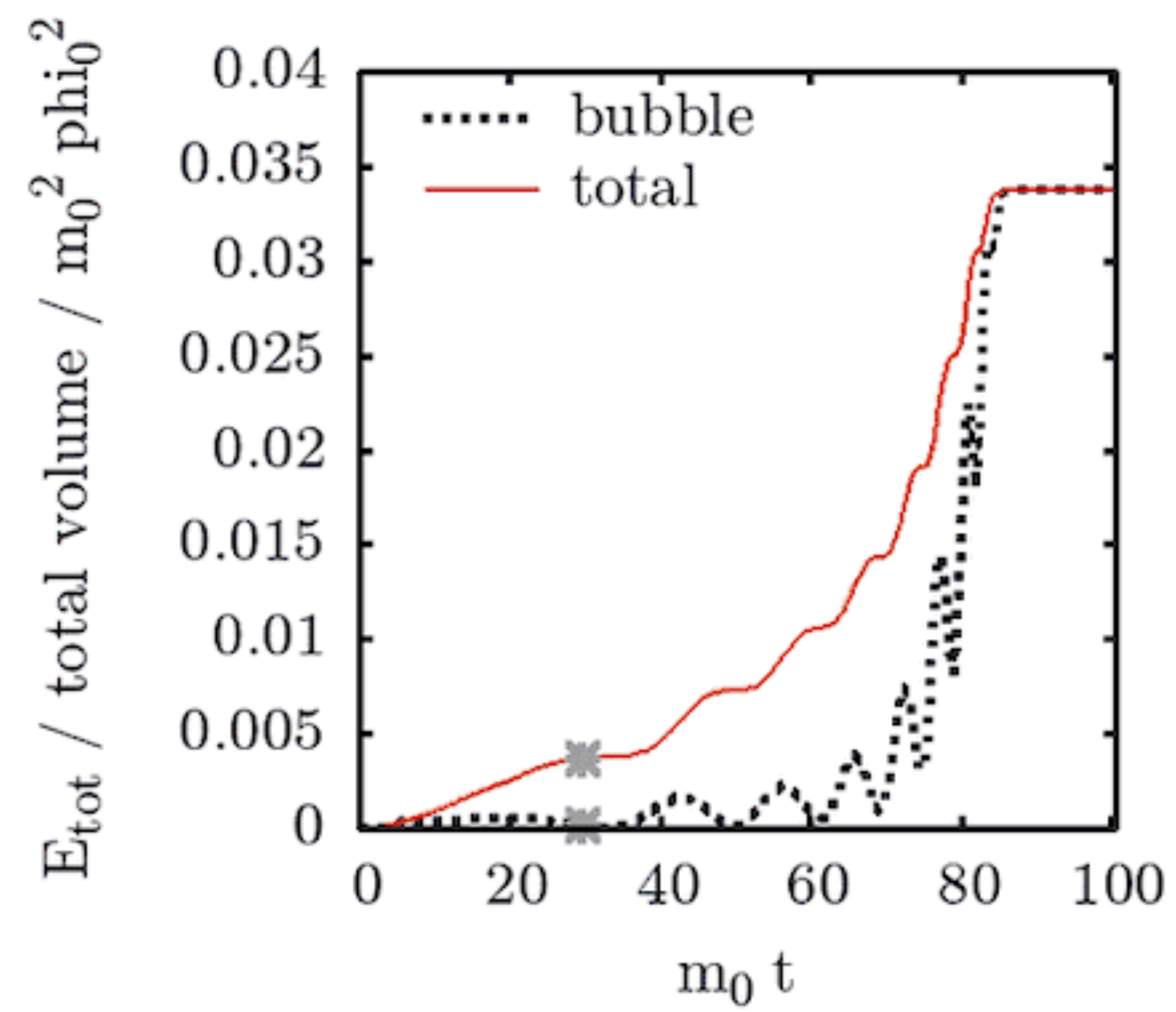
- ① Axions are expelled from the inside of bubbles.
- ② Axions waves are accumulated outside the bubbles and repeatedly scatter off bubble walls.
- ③ Axions waves enter the bubbles once they acquire enough energy.

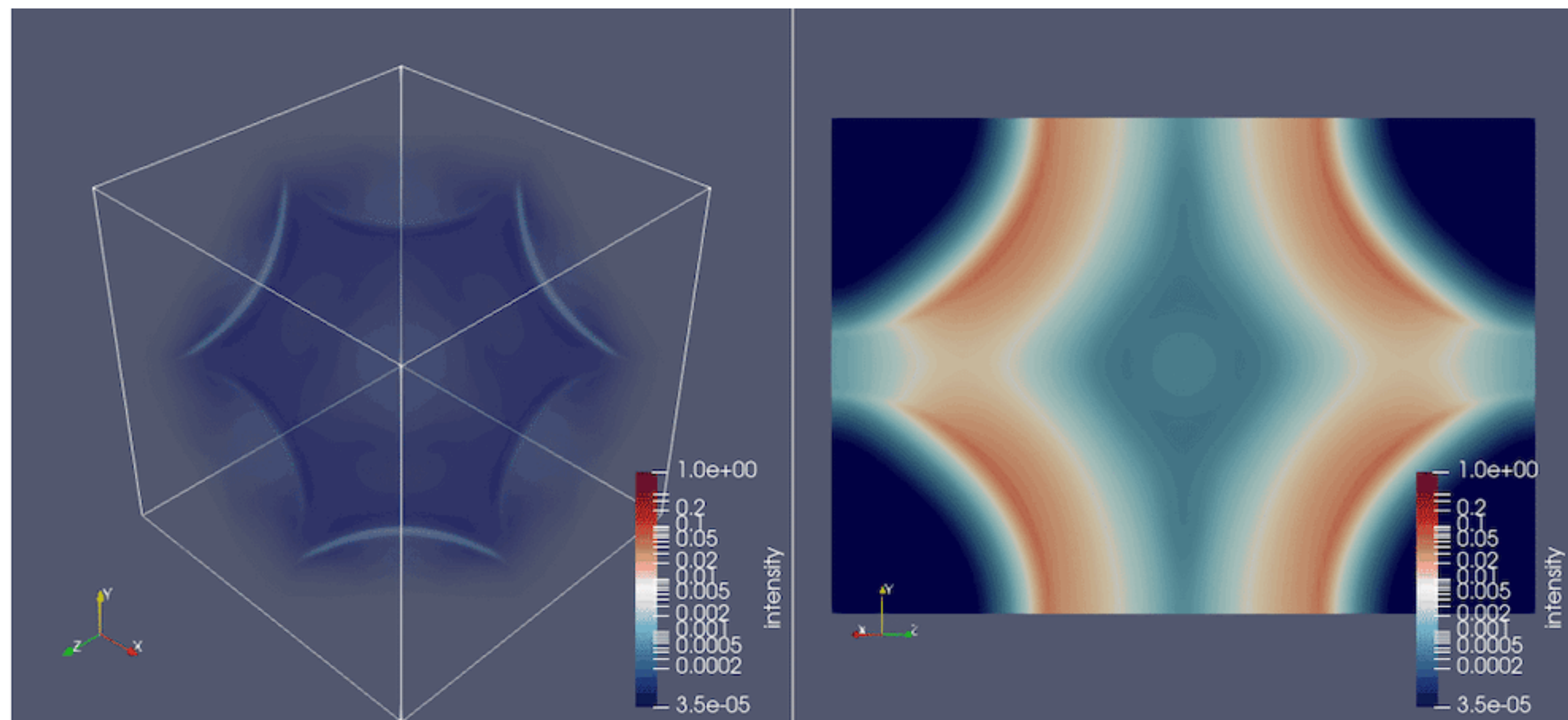
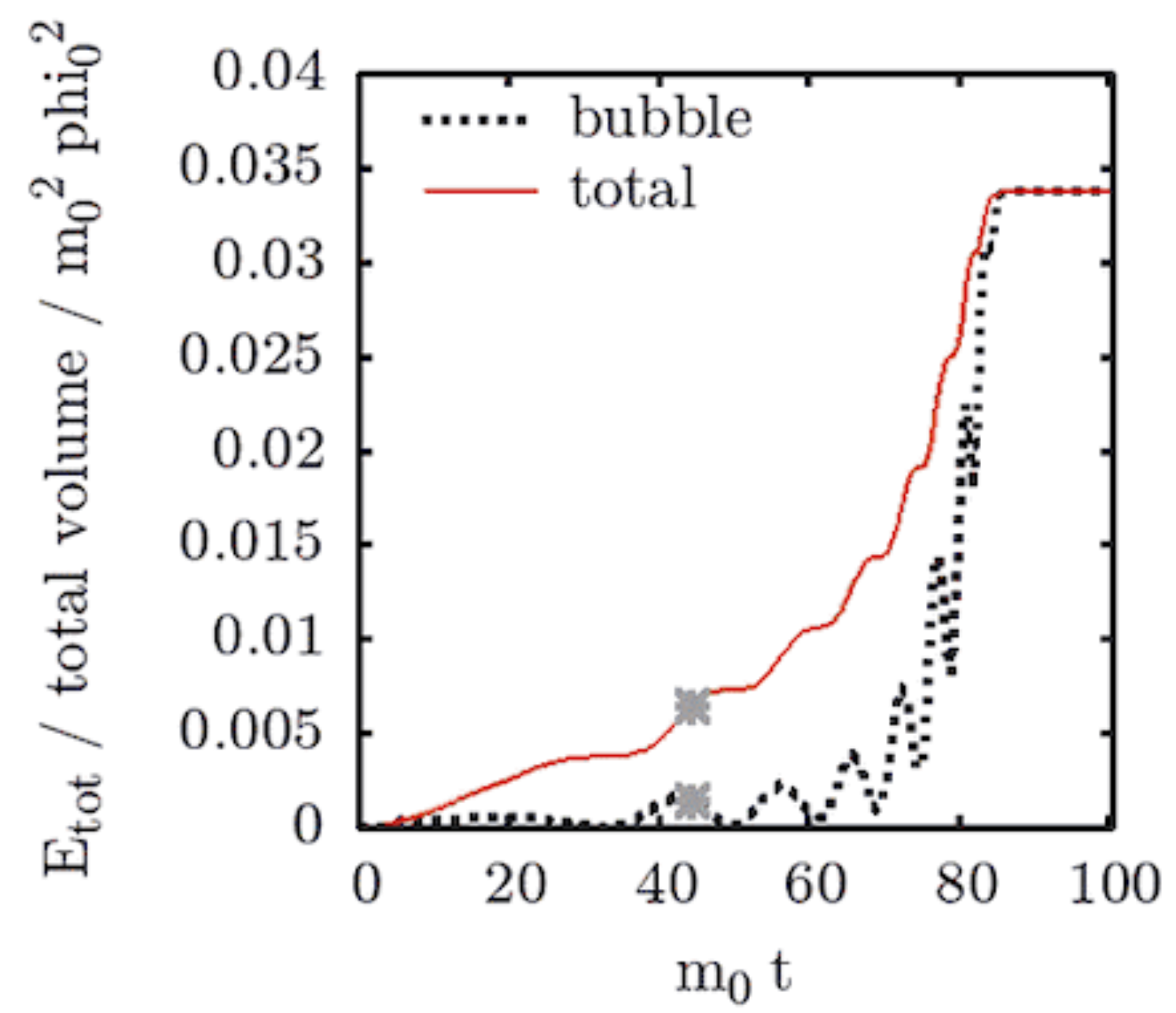


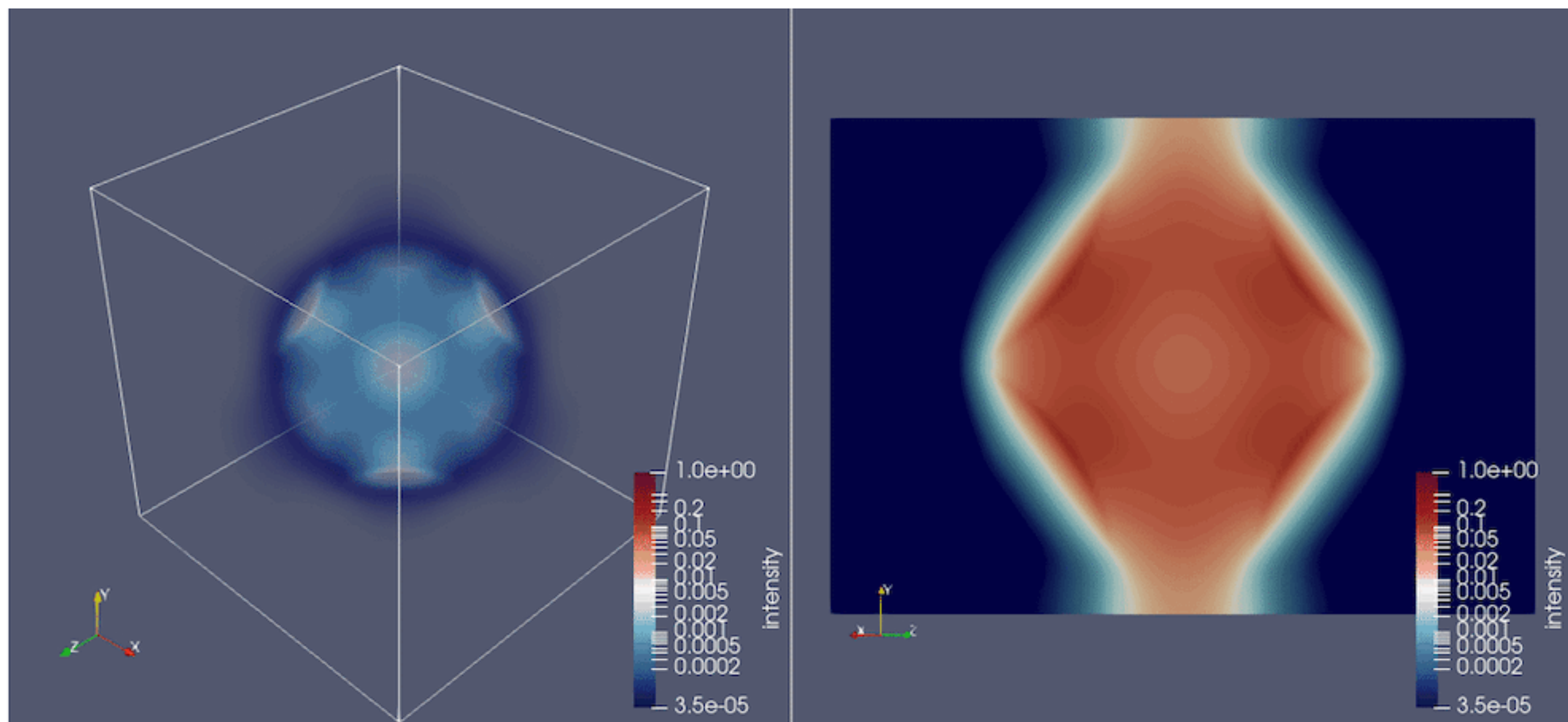
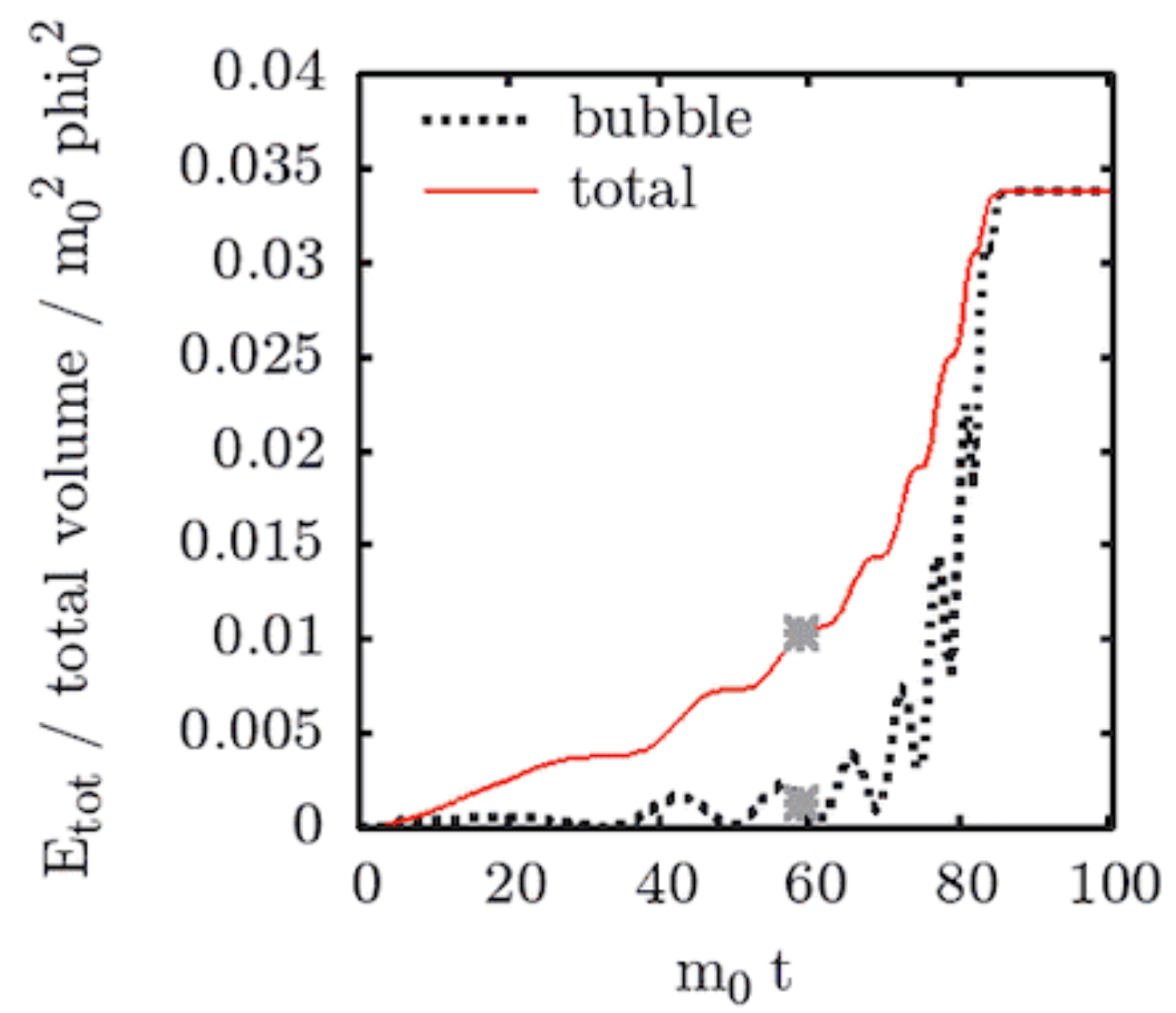


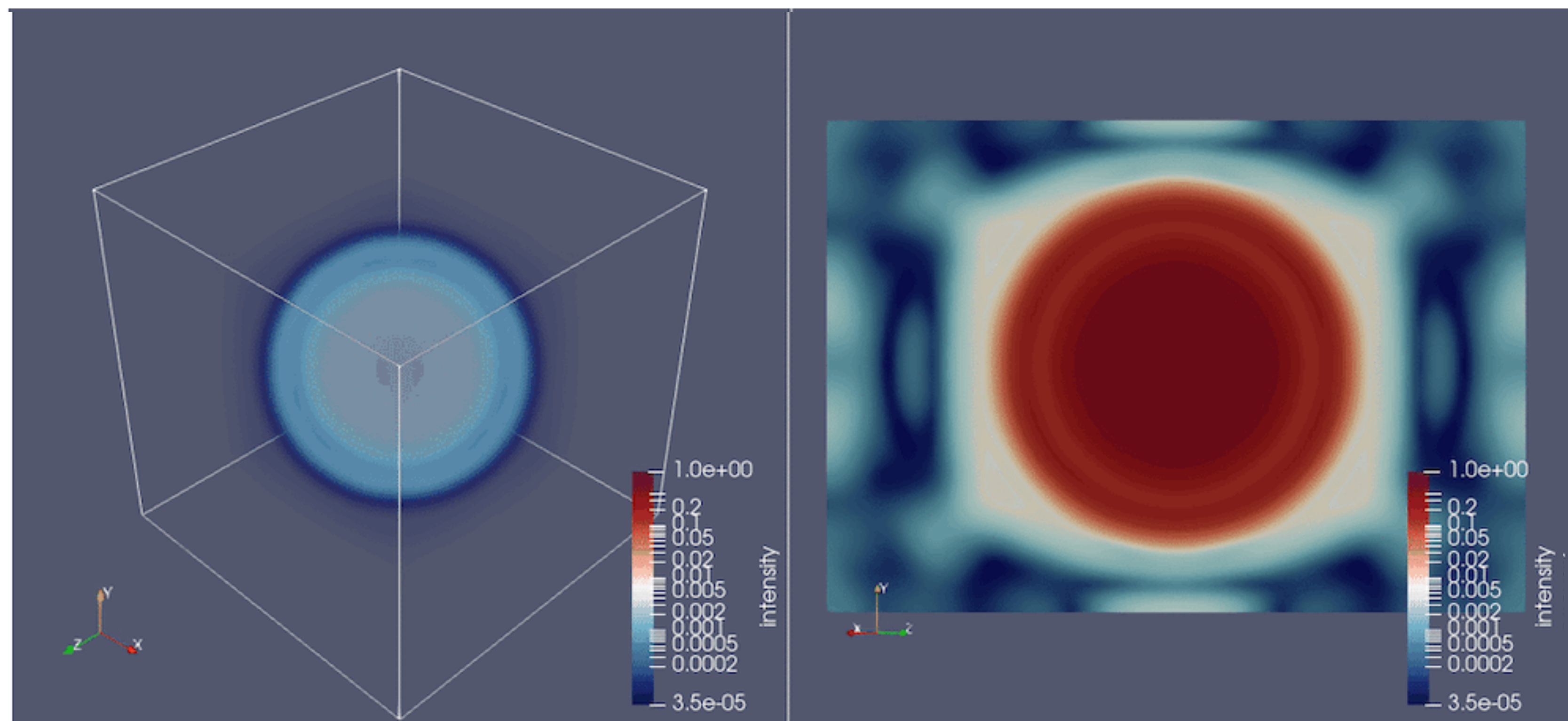
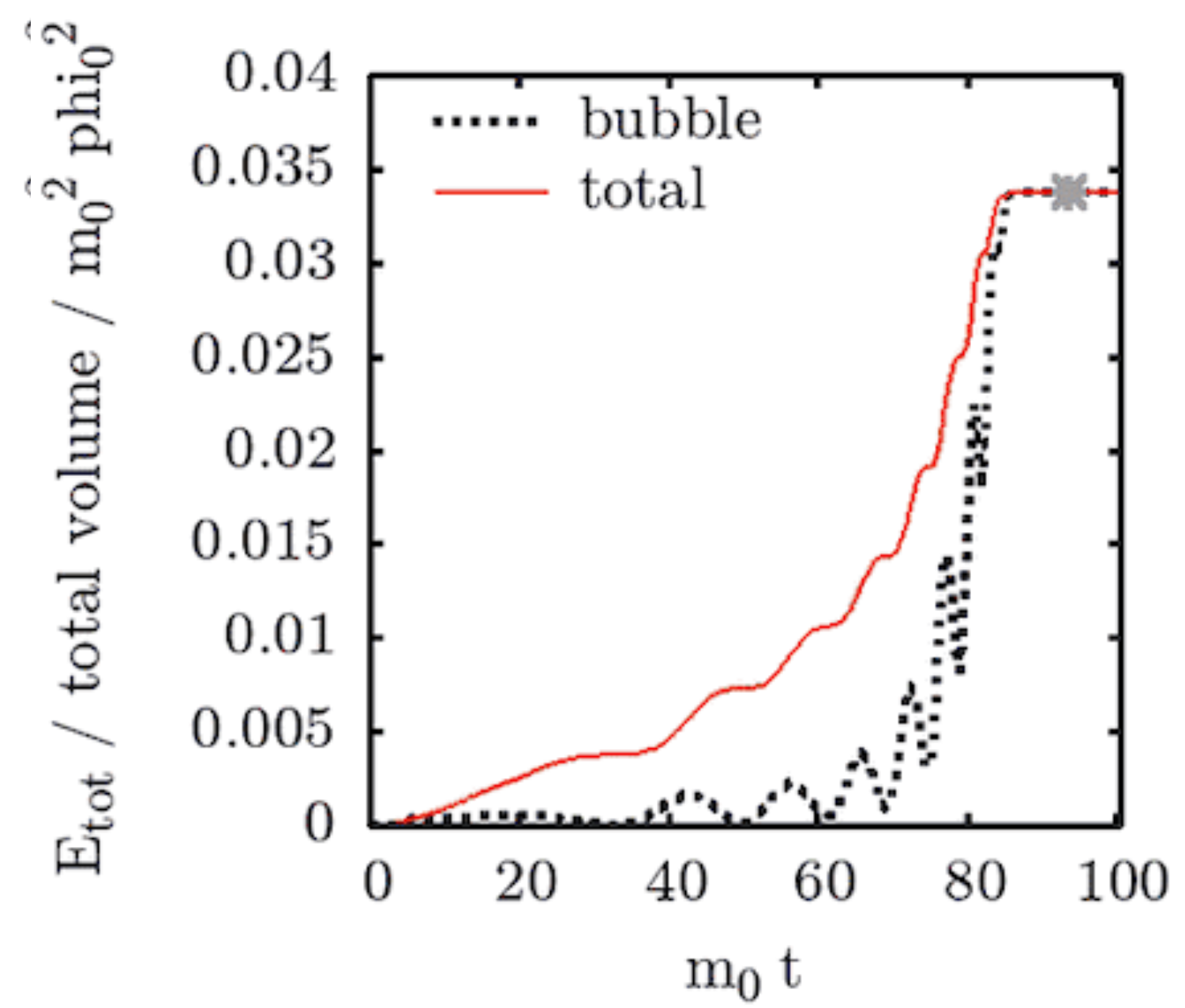


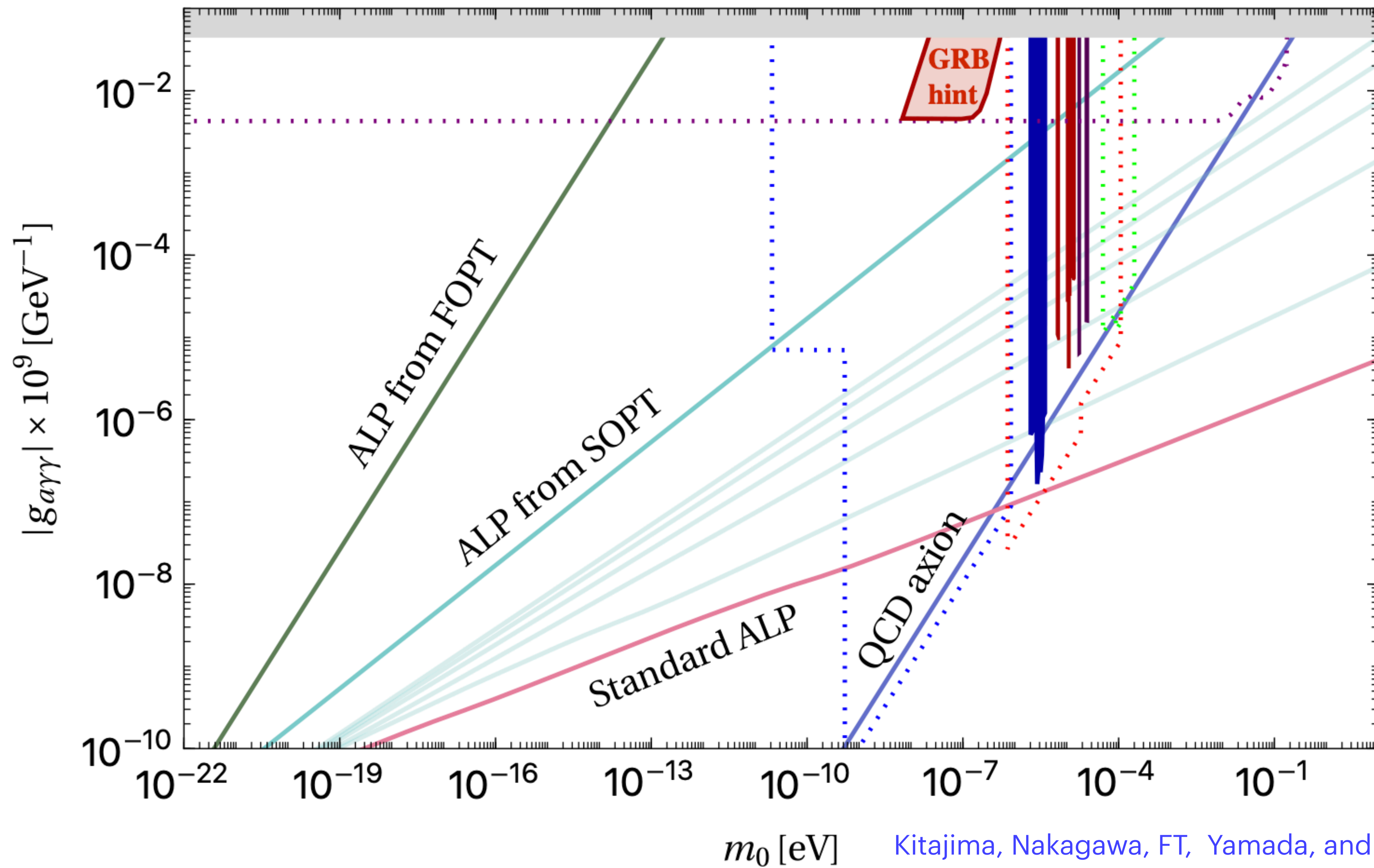






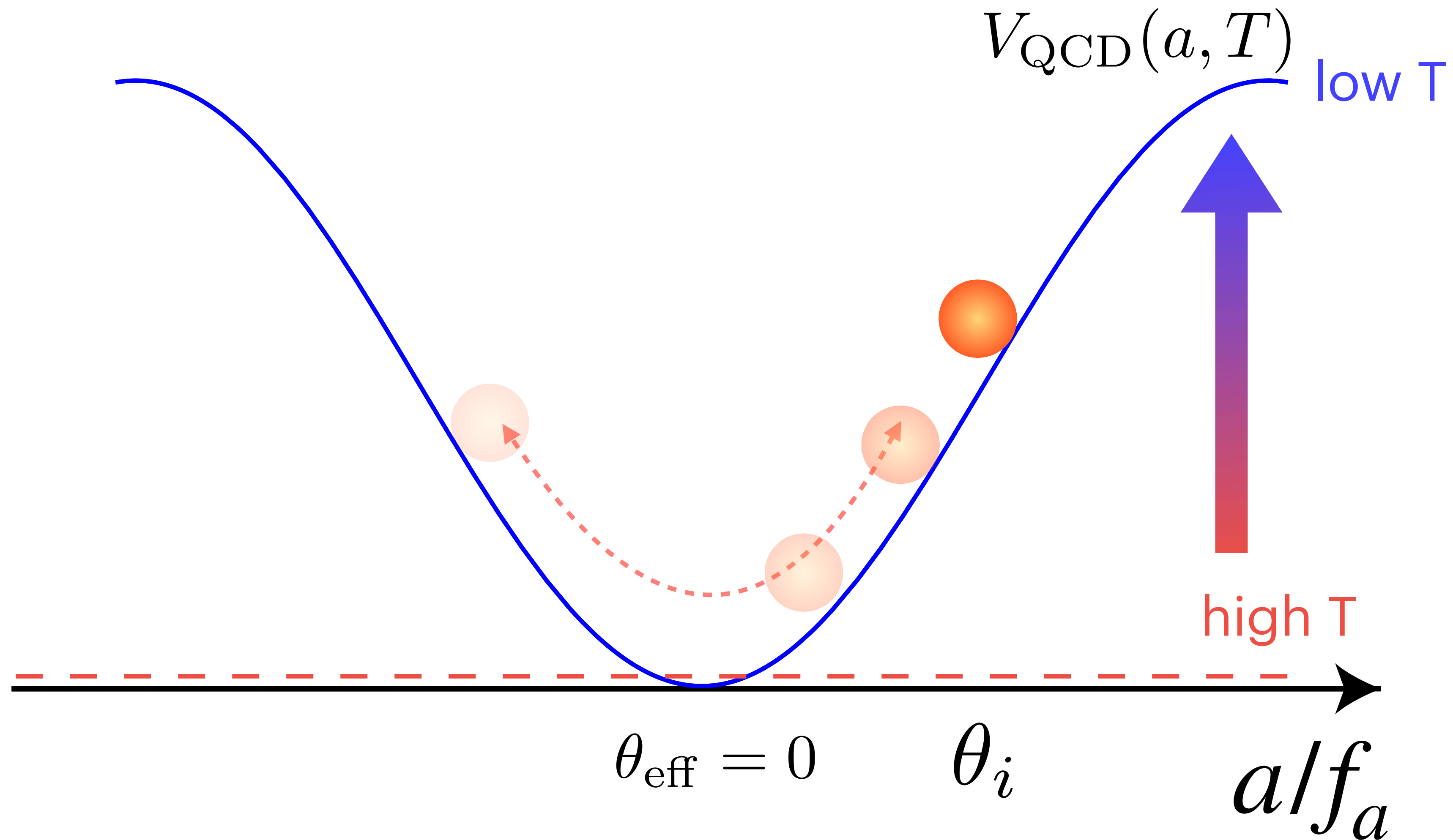






Trapped misalignment mechanism

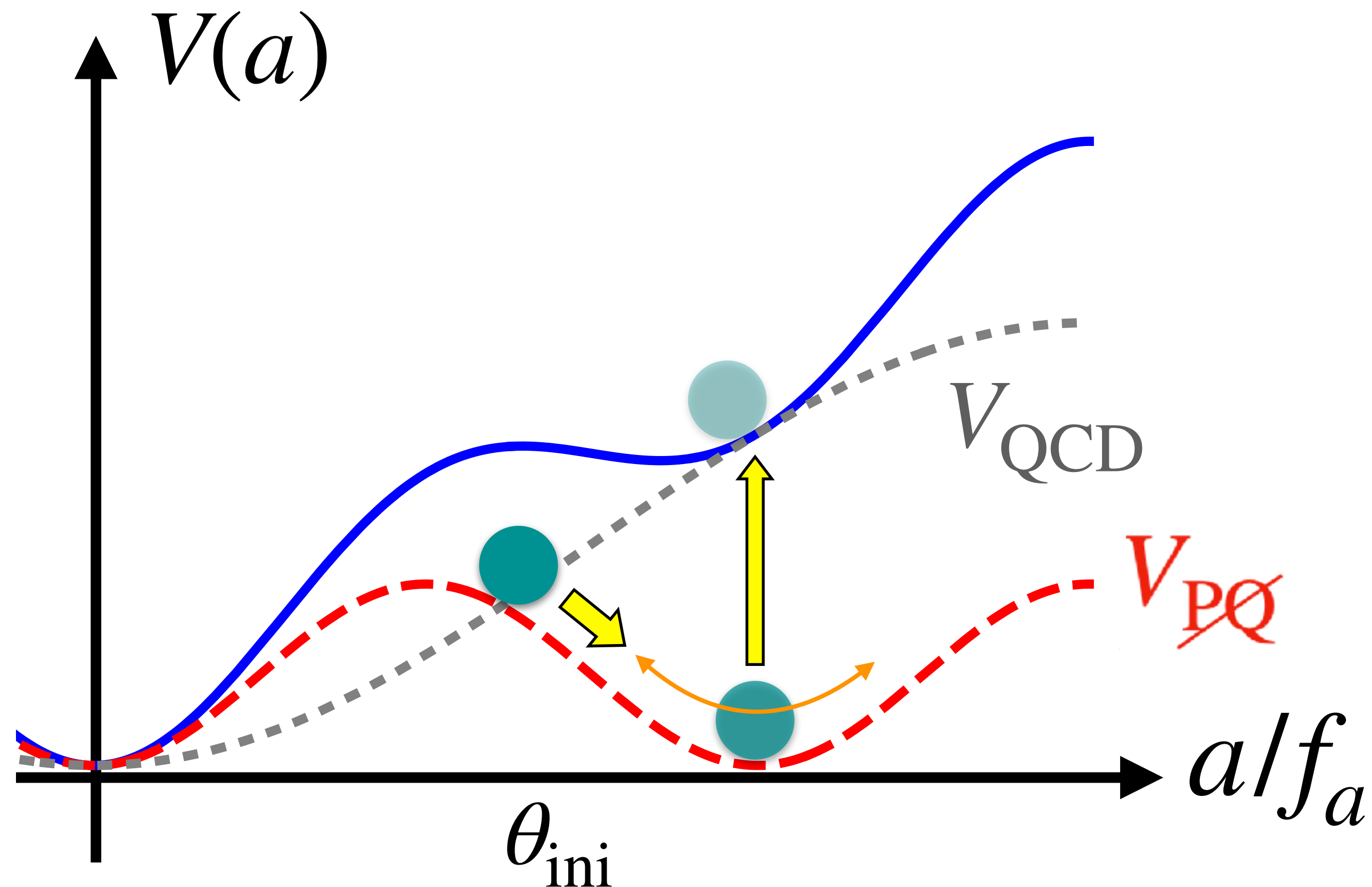
Higaki, Jeong, Kitajima, and FT, 1603.02090, Nakagawa, FT, and Yamada, 2012.13592, Di Luzio, Gavela, Quilez, and Ringwald 2102.01082, Jeong, Nakagawa, Matsukawa, and FT, 2201.00681



Trapped misalignment mechanism

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In the presence of extra PQ breaking, the axion could get trapped in a false vacuum until V_{QCD} becomes large.



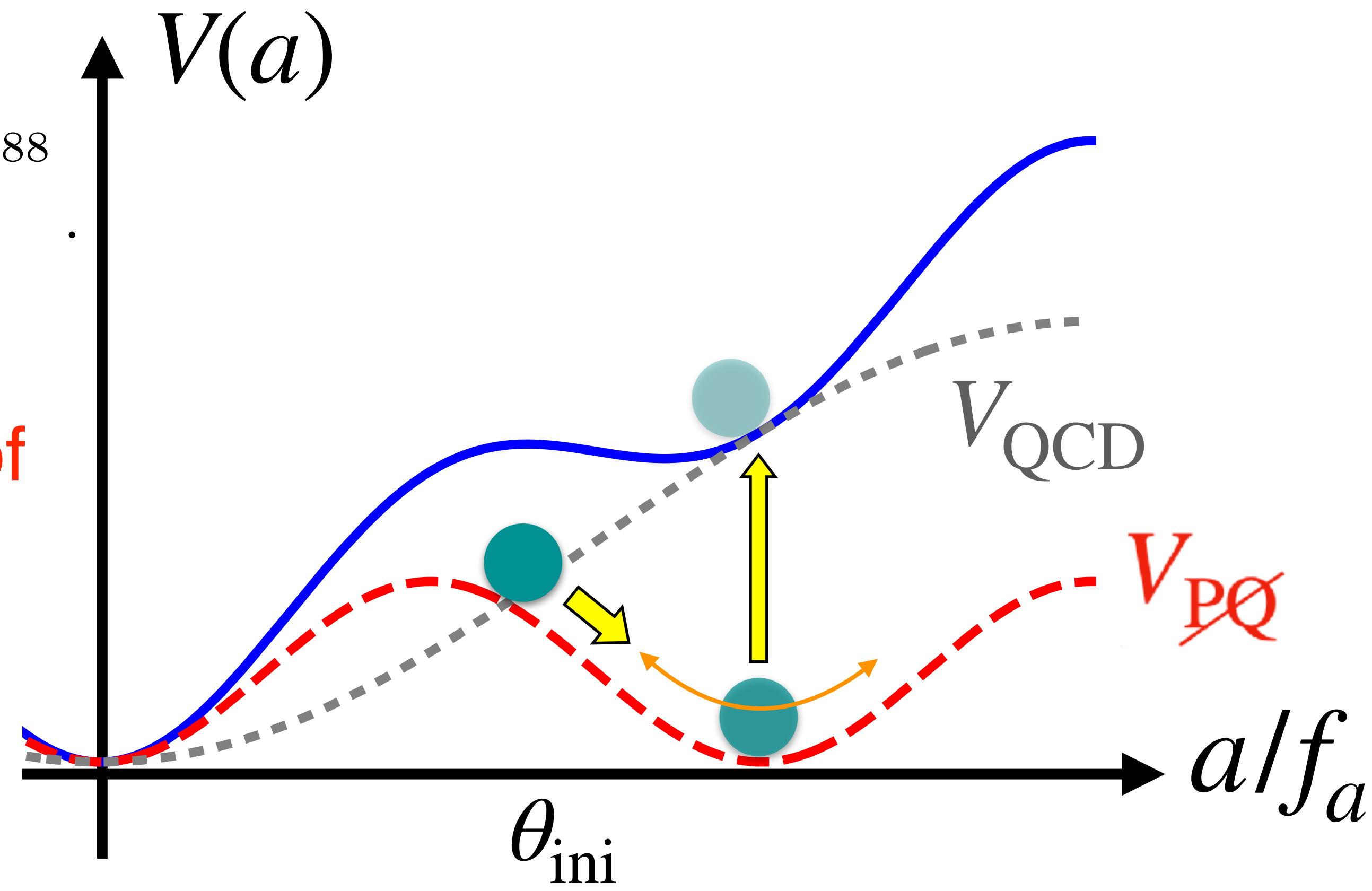
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In the presence of extra PQ breaking, the axion could get trapped in a false vacuum until V_{QCD} becomes large.

$$\Omega_a^{(\text{trap})} h^2 \simeq 0.25 \theta_{\text{osc}2}^2 \left(\frac{g_*(T_{\text{osc}2})}{60} \right)^{-1} \left(\frac{Nr^4}{10^{-6}} \right)^{0.88}.$$

The axion abundance is independent of f_a and θ_{ini} !



Summary

- Misalignment is a built-in production mechanism, but its prediction is not universal: it depends on the time evolution of the axion potential.
- Topological defects depend sensitively on the UV completion of the PQ sector.
- Bubble and trapped misalignment illustrate how hidden-sector dynamics can qualitatively reshape the axion dark-matter target.

Outlook: The next frontier is to connect the mass–coupling plane to the cosmological history of the axion field.

UV completion / phase transition → abundance and spatial distribution → laboratory, astrophysical, and cosmological signals

Back-up slides



Two axion system

We introduce two PQ scalars

$$\Phi_1 = \frac{f_1}{\sqrt{2}} e^{i \frac{\phi_1}{f_1}} \quad \text{and} \quad \Phi_2 = \frac{f_2}{\sqrt{2}} e^{i \frac{\phi_2}{f_2}}$$

$$\theta_1 \equiv \phi_1/f_1 \quad \text{and} \quad \theta_2 \equiv \phi_2/f_2$$

and the potential for axions

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$

$$V_2(\phi_1, \phi_2) = \Lambda'^4 \left[1 - \cos \left(n'_1 \frac{\phi_1}{f_1} + n'_2 \frac{\phi_2}{f_2} + \alpha \right) \right]$$

$$\Lambda \gg \Lambda'$$

$$n_1, n_2, n'_1, n'_2 \in \mathbf{Z}$$

with the post-inflationary initial condition.



Is the vacuum unique?

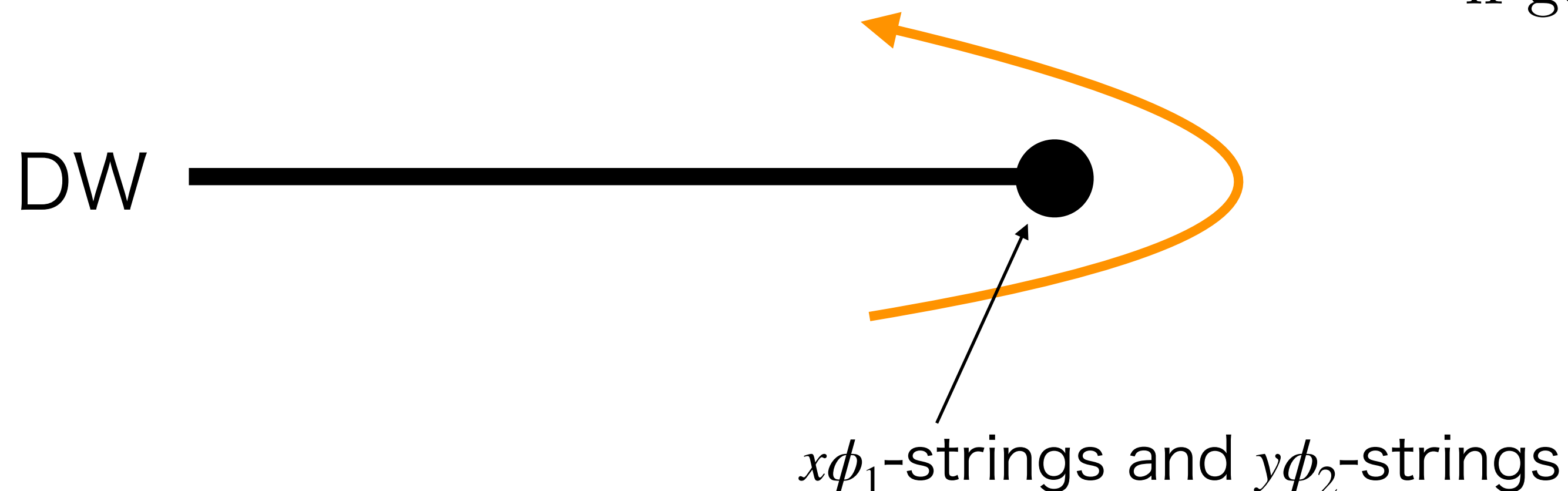
$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$

In the case of $\gcd[|n_1|, |n_2|] = 1$, the vacua separated by a DW is equivalent up to flat directions.

So, for a certain boundary, one could go one from the other continuously.

$$\exists x, y \in \mathbb{Z} \text{ s.t. } xn_1 + yn_2 = 1$$

if $\gcd[|n_1|, |n_2|] = 1$



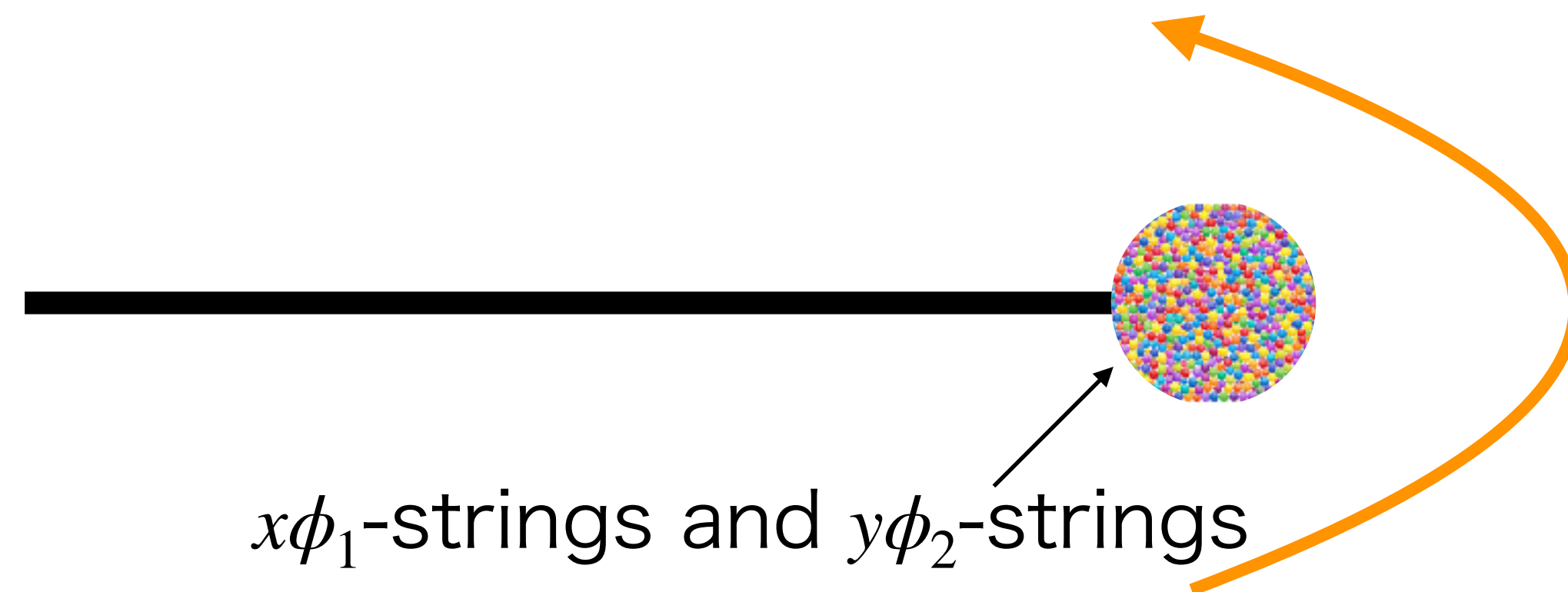
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However, if the required boundary is too complicated, it is never formed in the evolution of the universe.



Higaki, Jeong, Kitajima, Sekiguchi
and FT, 1606.05552

Is the vacuum unique?

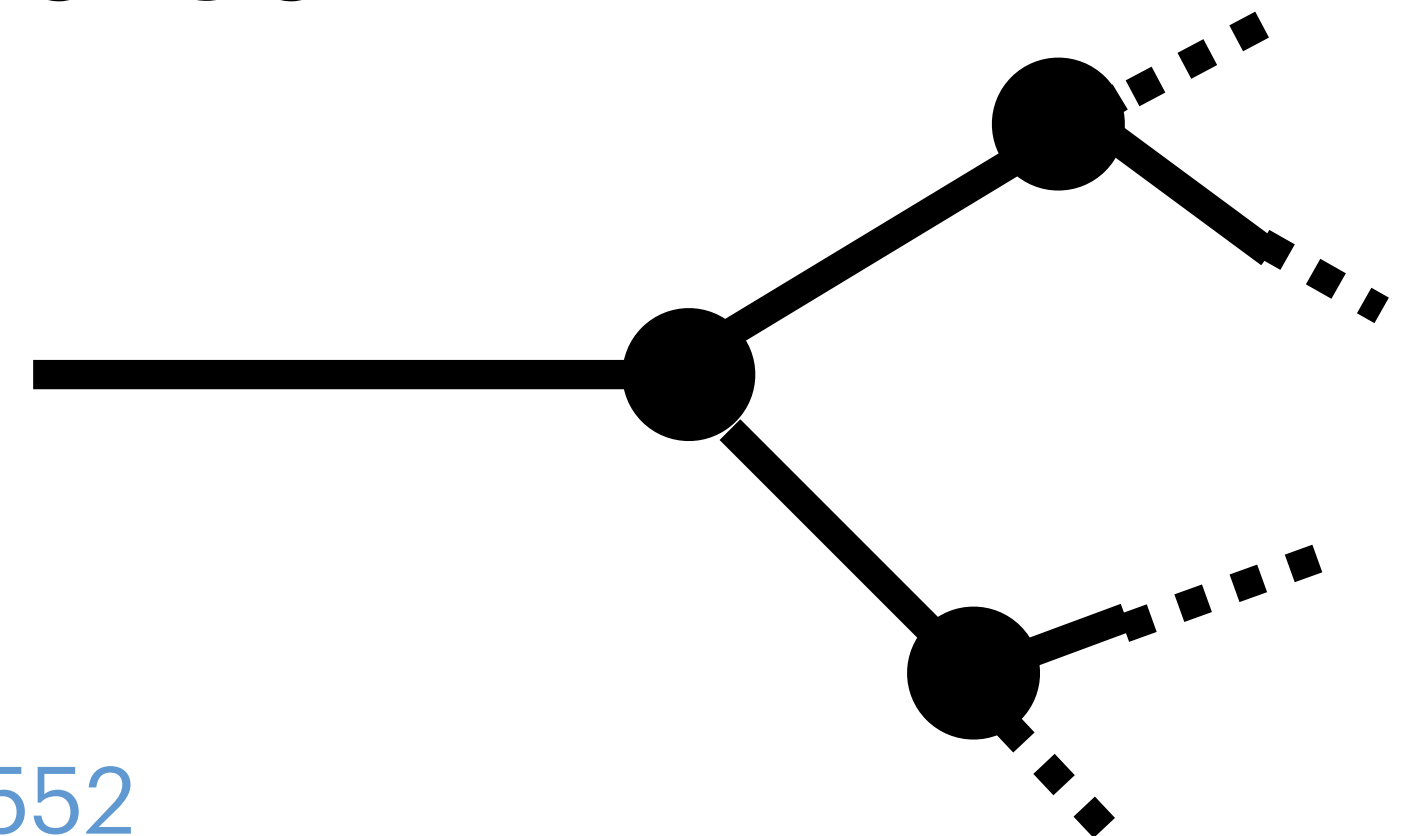
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In the case of $\gcd[|n_1|, |n_2|] = 1$, the vacua separated by a DW is equivalent up to flat directions.

So, for a certain boundary, one could go one from the other continuously.

However, if the required boundary is too complicated, it is never formed in the evolution of the universe.

Thus, we are left with DWs, even if the vacuum is unique up to flat directions.

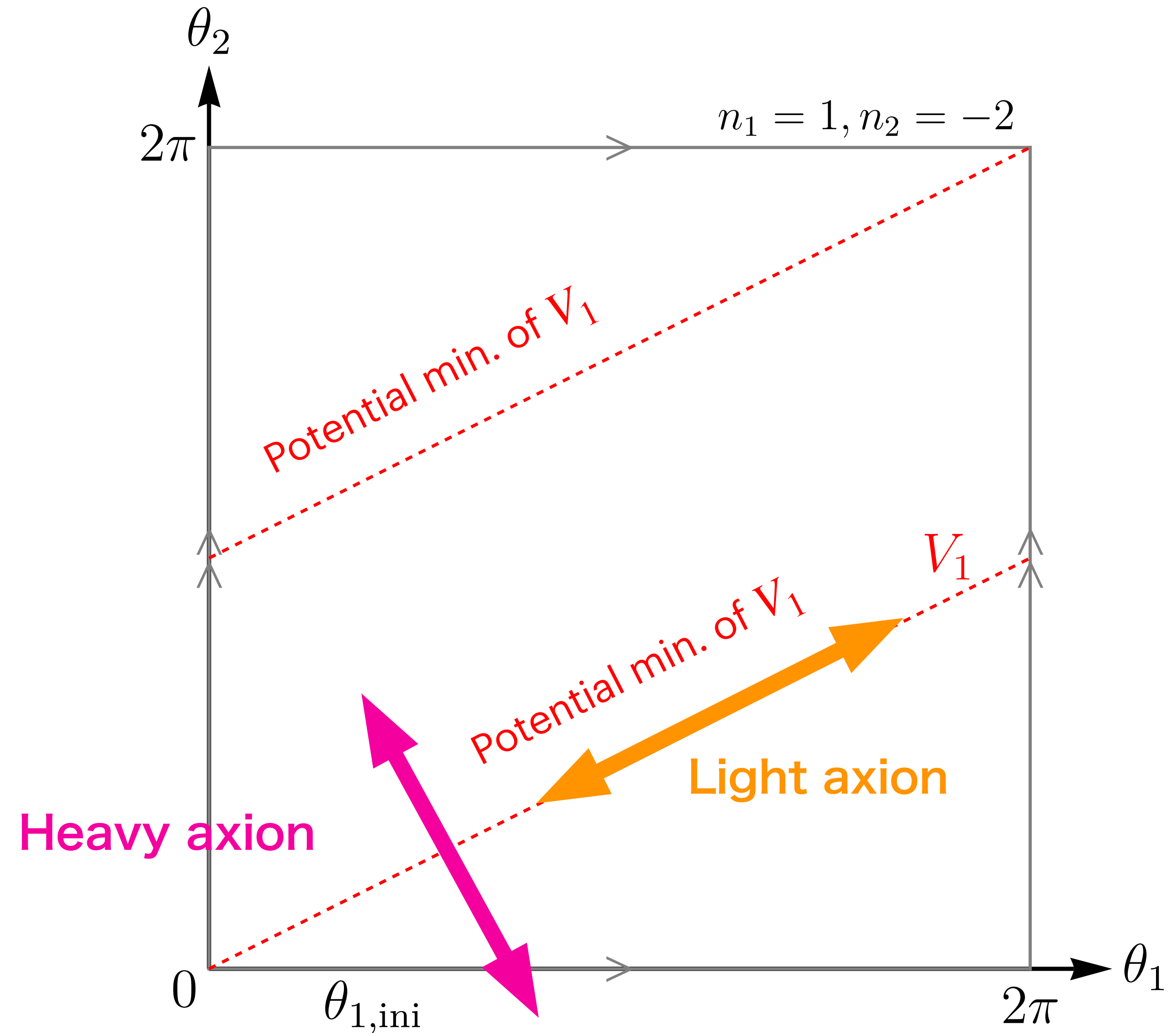


Two axion system

One linear combination of two axions becomes heavy, leaving the orthogonal one (nearly) massless.

$$\phi_{\text{heavy}} \propto n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2}$$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$



Two types of strings and multiple DWs

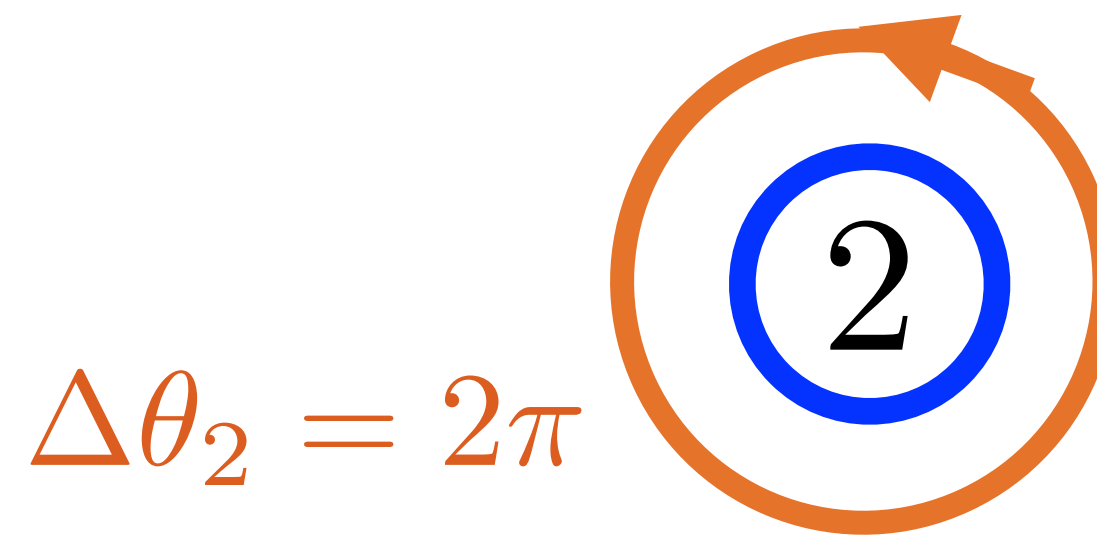
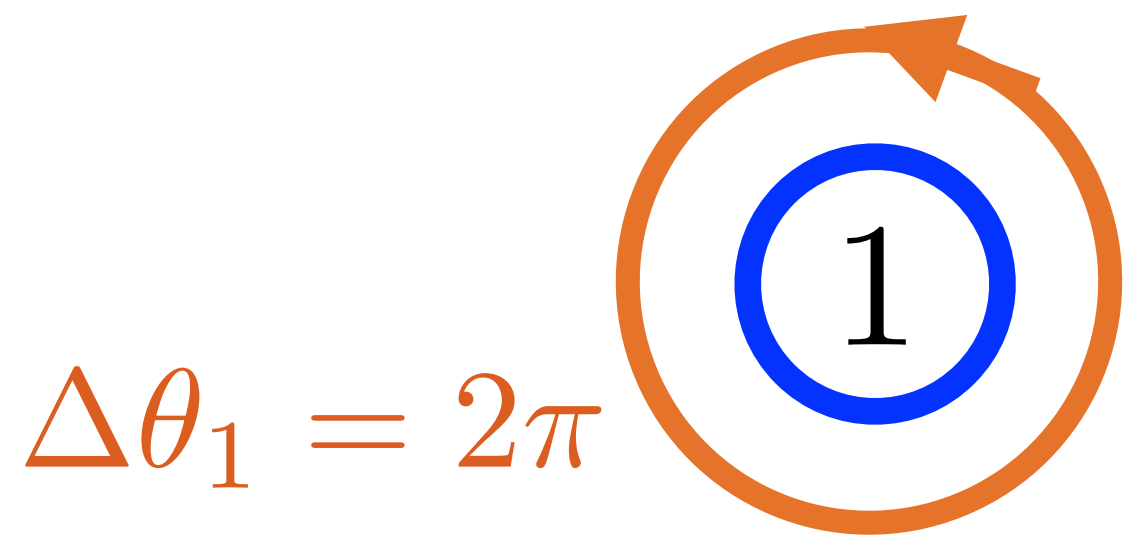
Both ϕ_1, ϕ_2 -strings quickly reach the scaling solution, and when V_1 becomes relevant, n_1 (n_2) domain walls appear, attached to the $\phi_1(\phi_2)$ -string.

①

②

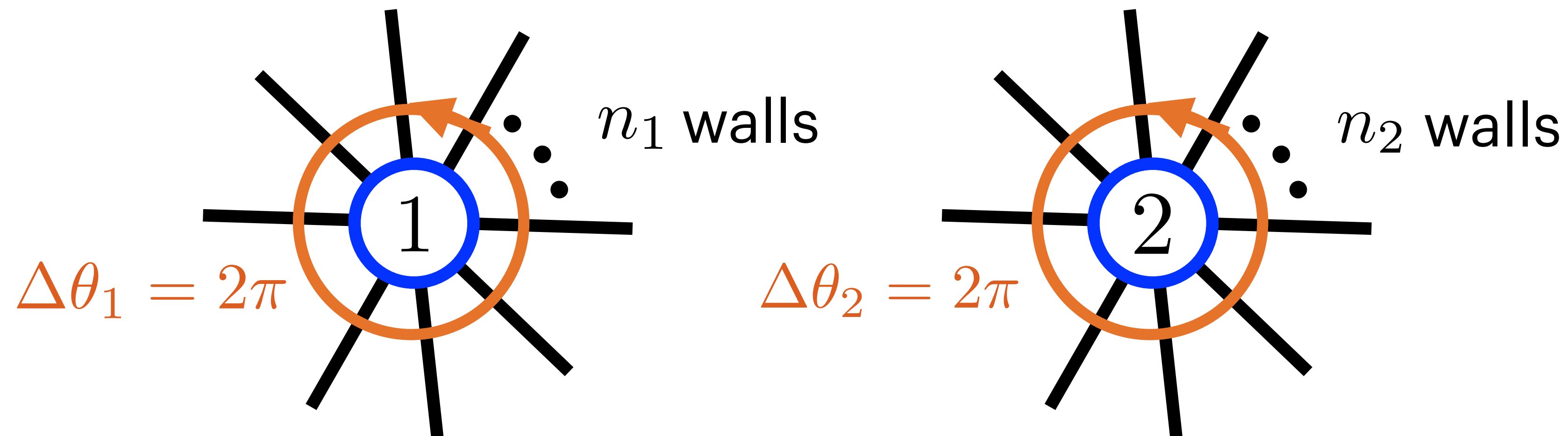
Two types of strings and multiple DWs

Both ϕ_1, ϕ_2 -strings quickly reach the scaling solution, and when V_1 becomes relevant, n_1 (n_2) domain walls appear, attached to the $\phi_1(\phi_2)$ -string.



Two types of strings and multiple DWs

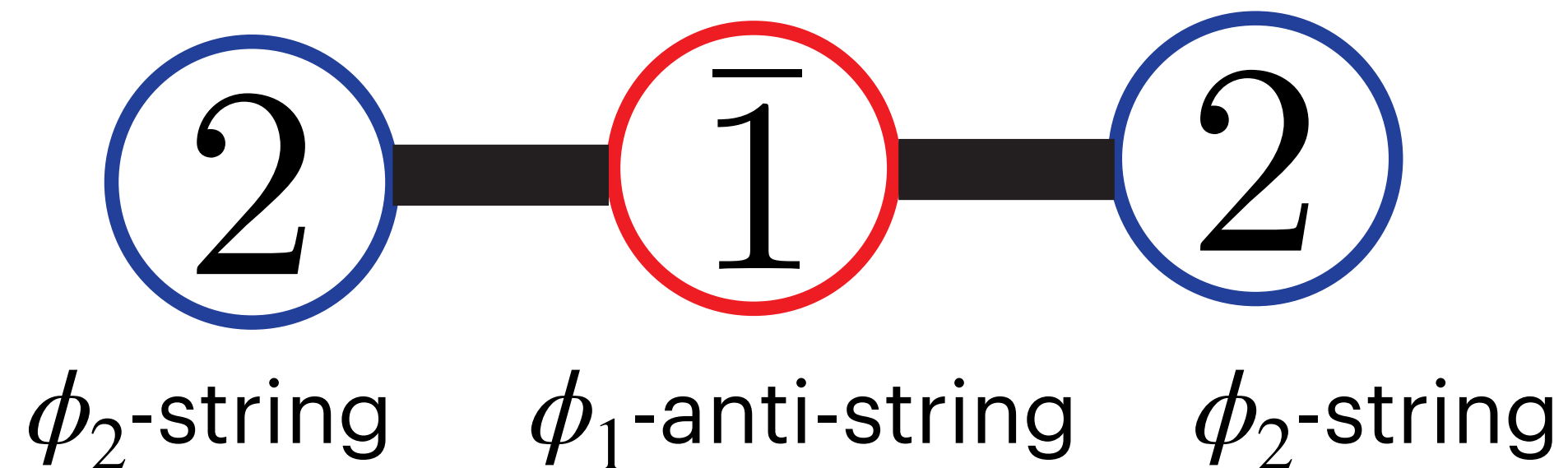
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$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right] \quad n_1, n_2 \in \mathbf{Z}$$

Case of $(n_1, n_2) = (2, 1)$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$

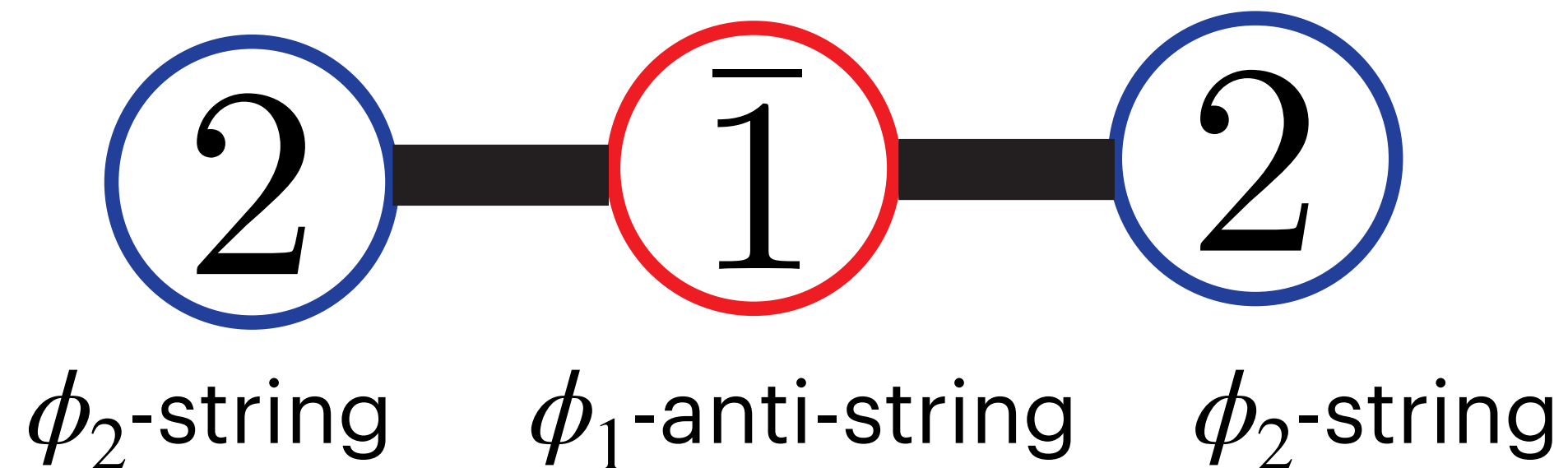


String bundle
(= ordinary cosmic string)

cf. Higaki, Jeong, Kitajima, Sekiguchi and FT, 1606.05552,
See also Eto, Hiramatsu, Saito and Sakakihara, 2309.04248

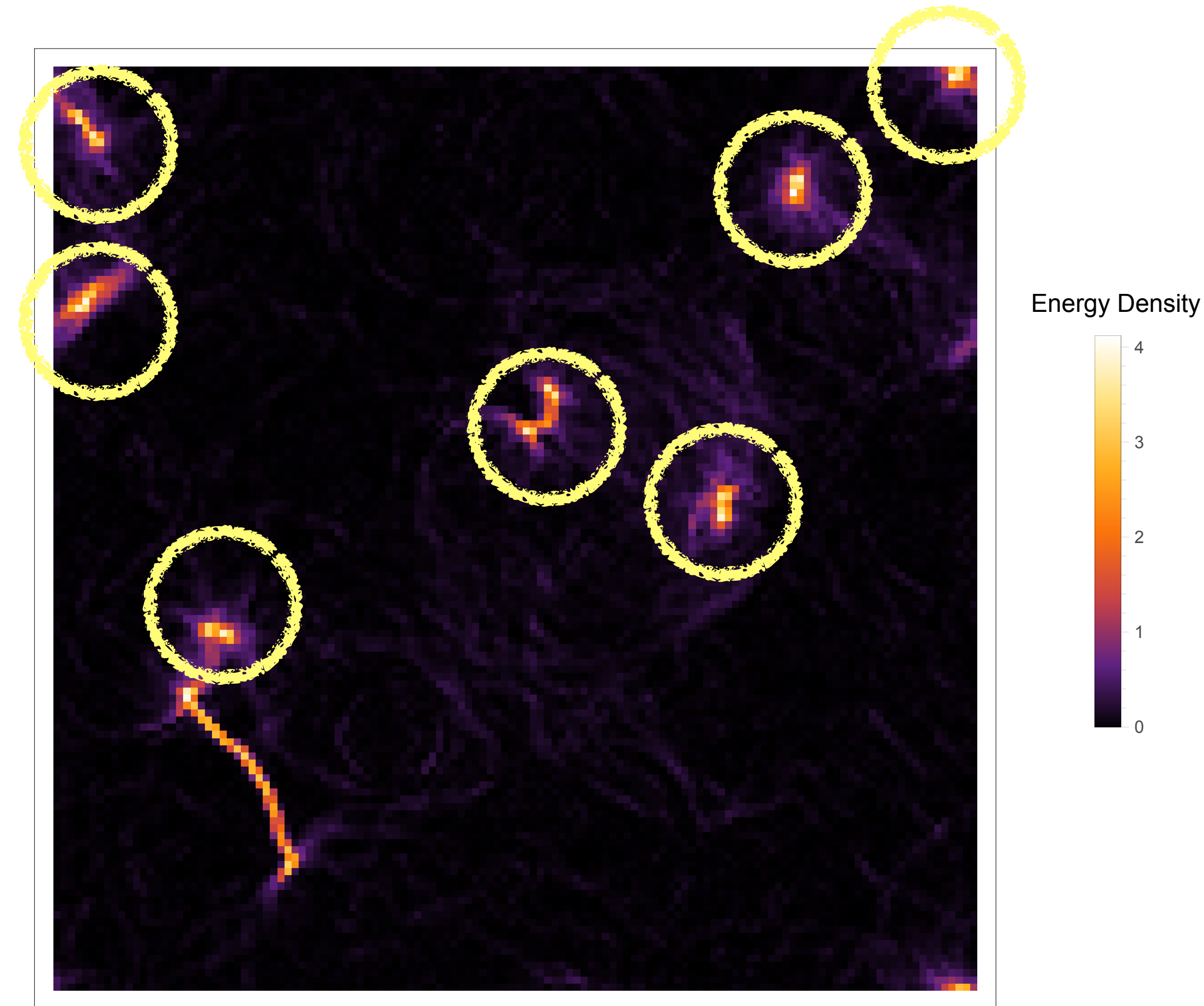
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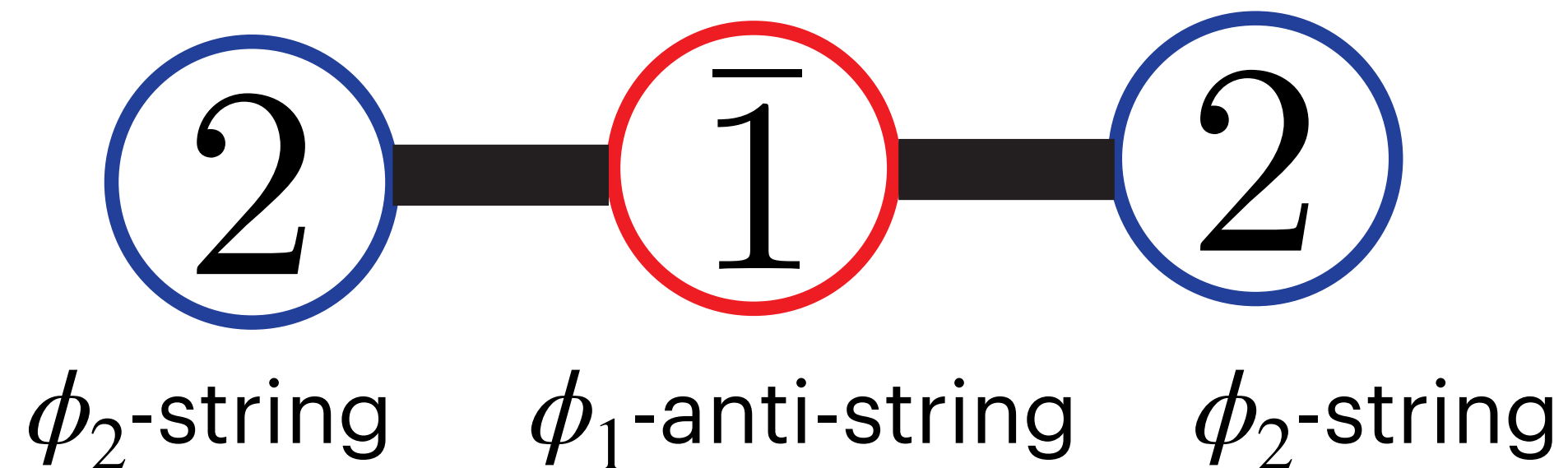


Numerical results (2D)

Lee, Murai, FT and Yin 2409.09749

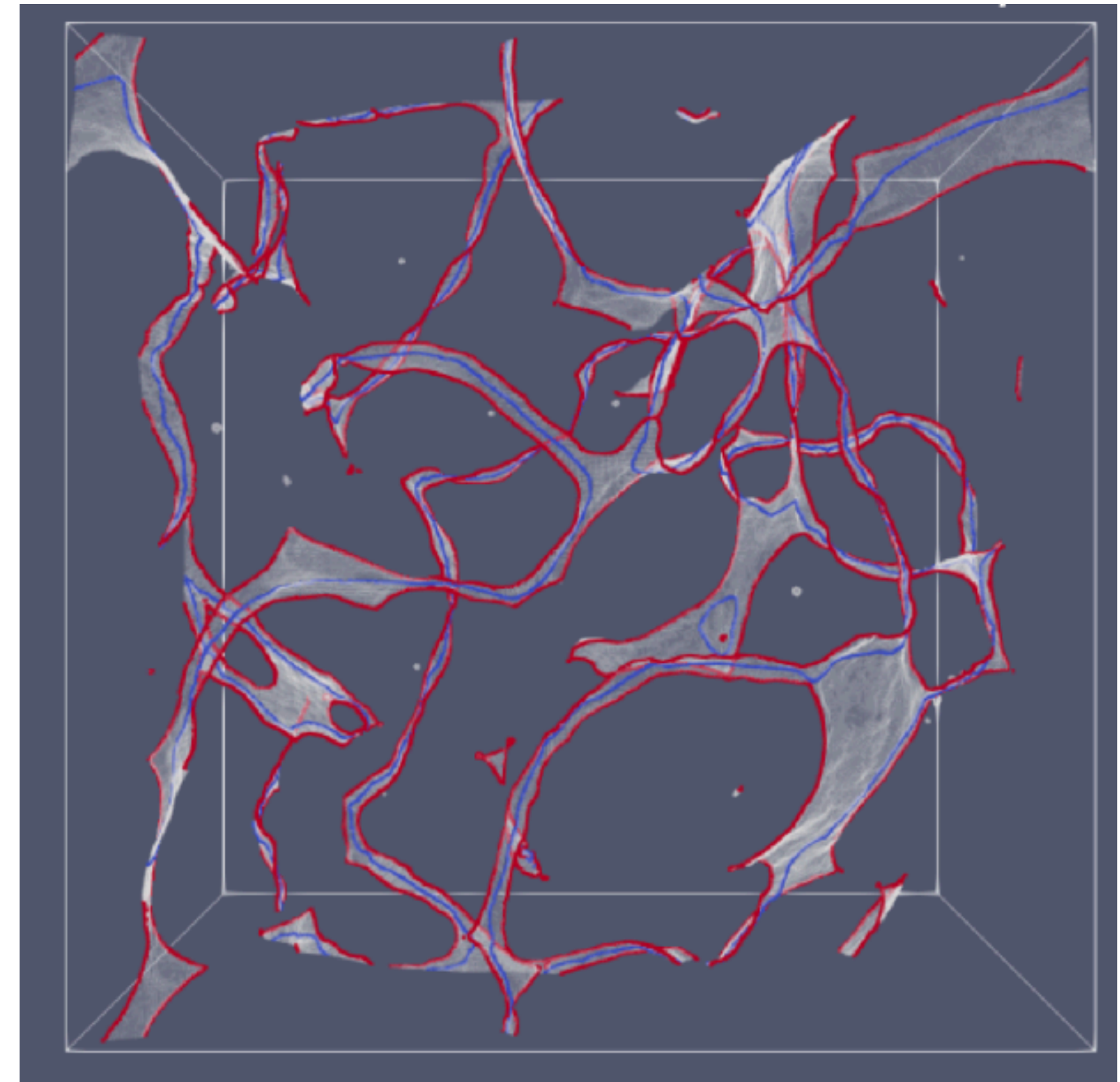
Case of $(n_1, n_2) = (2, 1)$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$



String bundle
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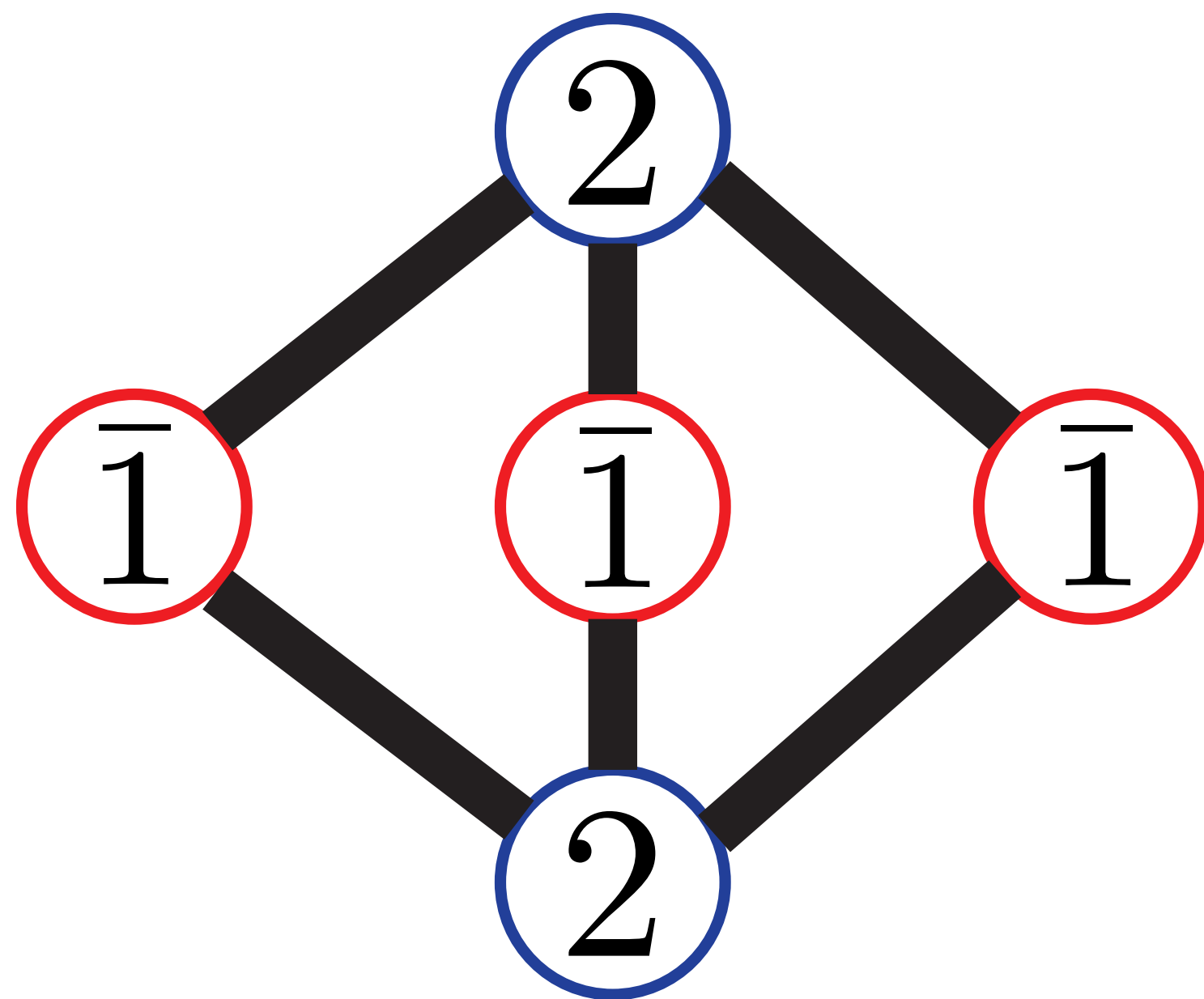


Numerical results (3D)

Lee, Murai, FT and Yin 2409.09749

Case of $(n_1, n_2) = (2, 3)$

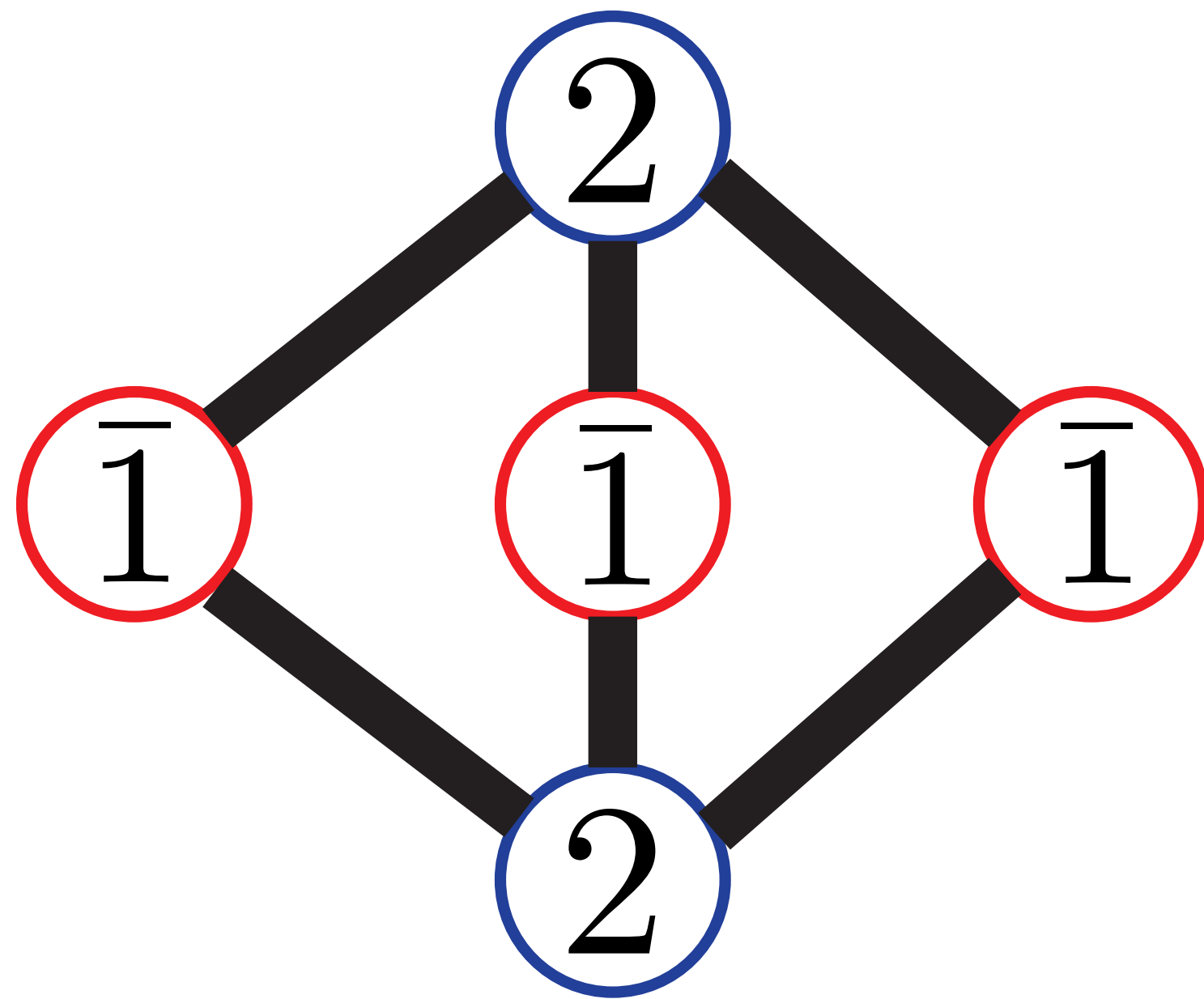
$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$



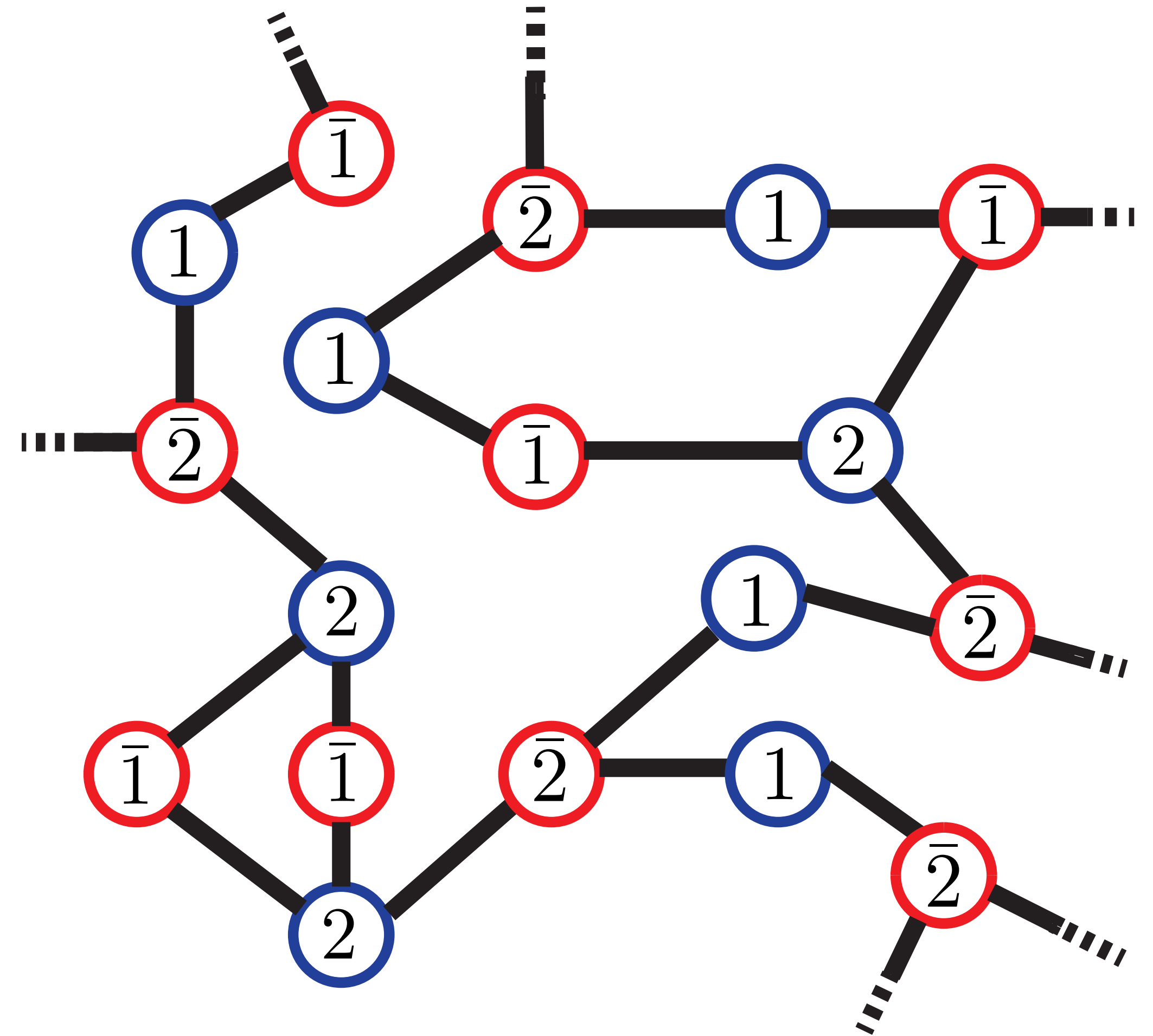
String bundle
(= ordinary cosmic string)

Case of $(n_1, n_2) = (2, 3)$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$



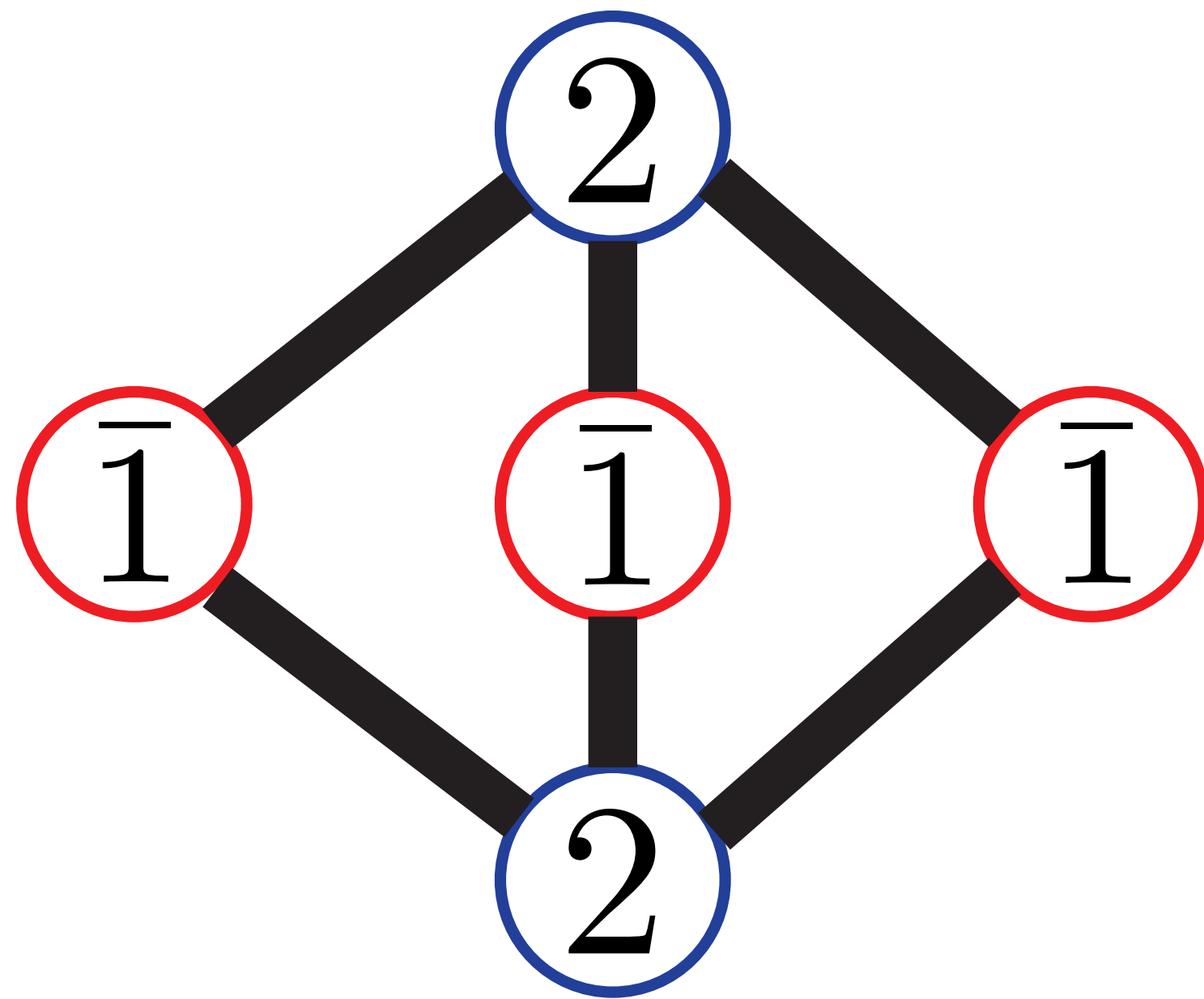
String bundle
(= ordinary cosmic string)



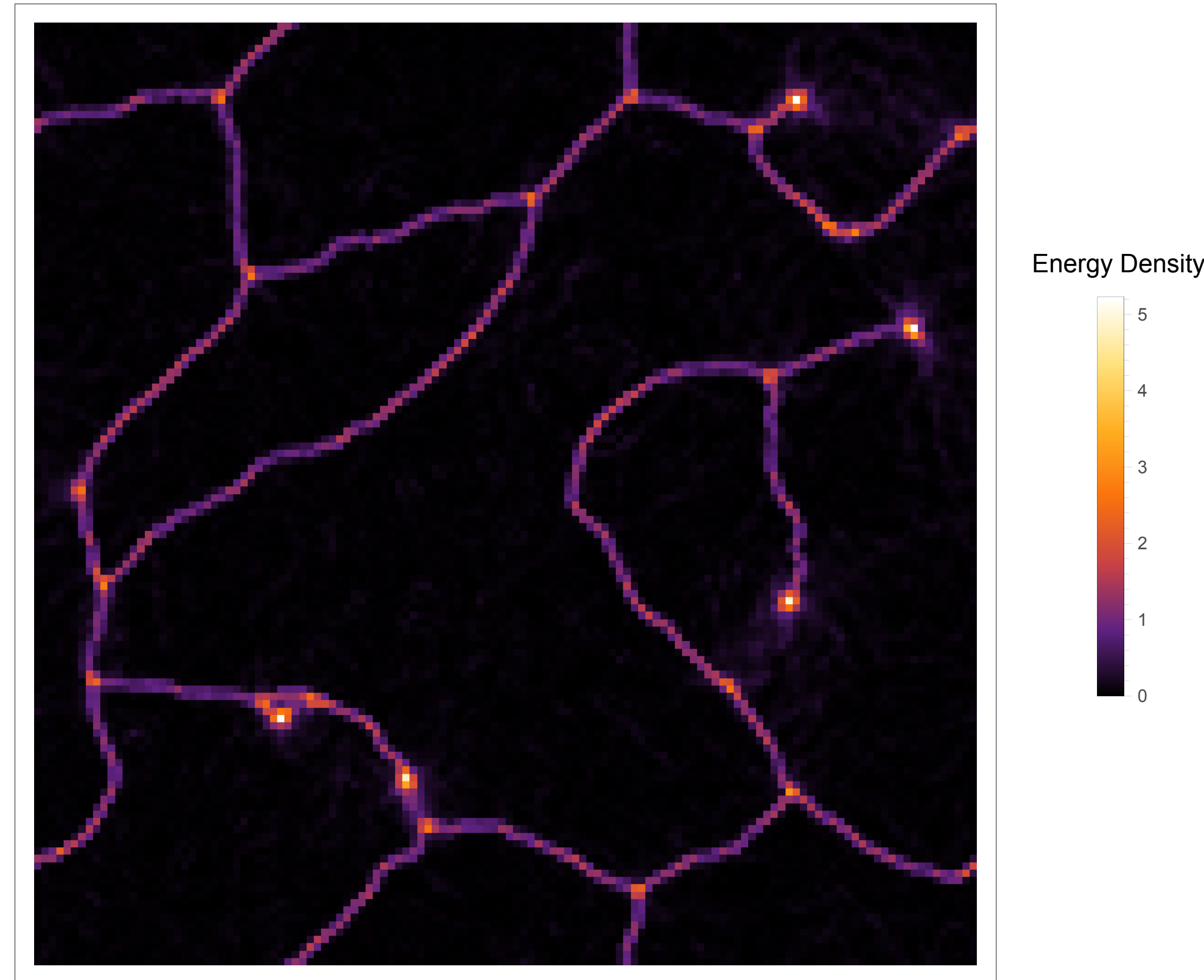
String-wall network

Case of $(n_1, n_2) = (2, 3)$

**String-wall network forms in
stead of string bundles.**



String bundle
(= ordinary cosmic string)

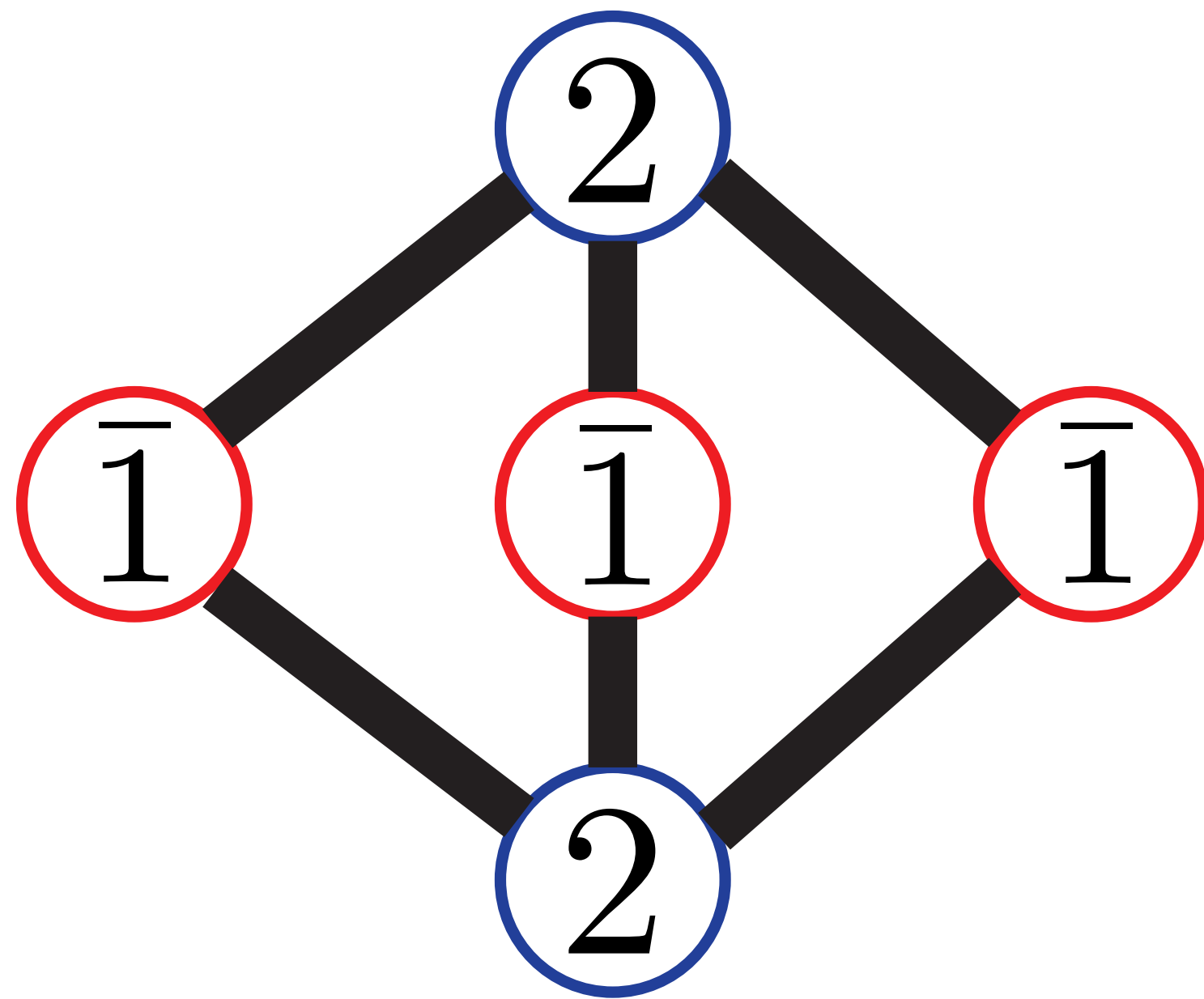


Numerical results (2D)

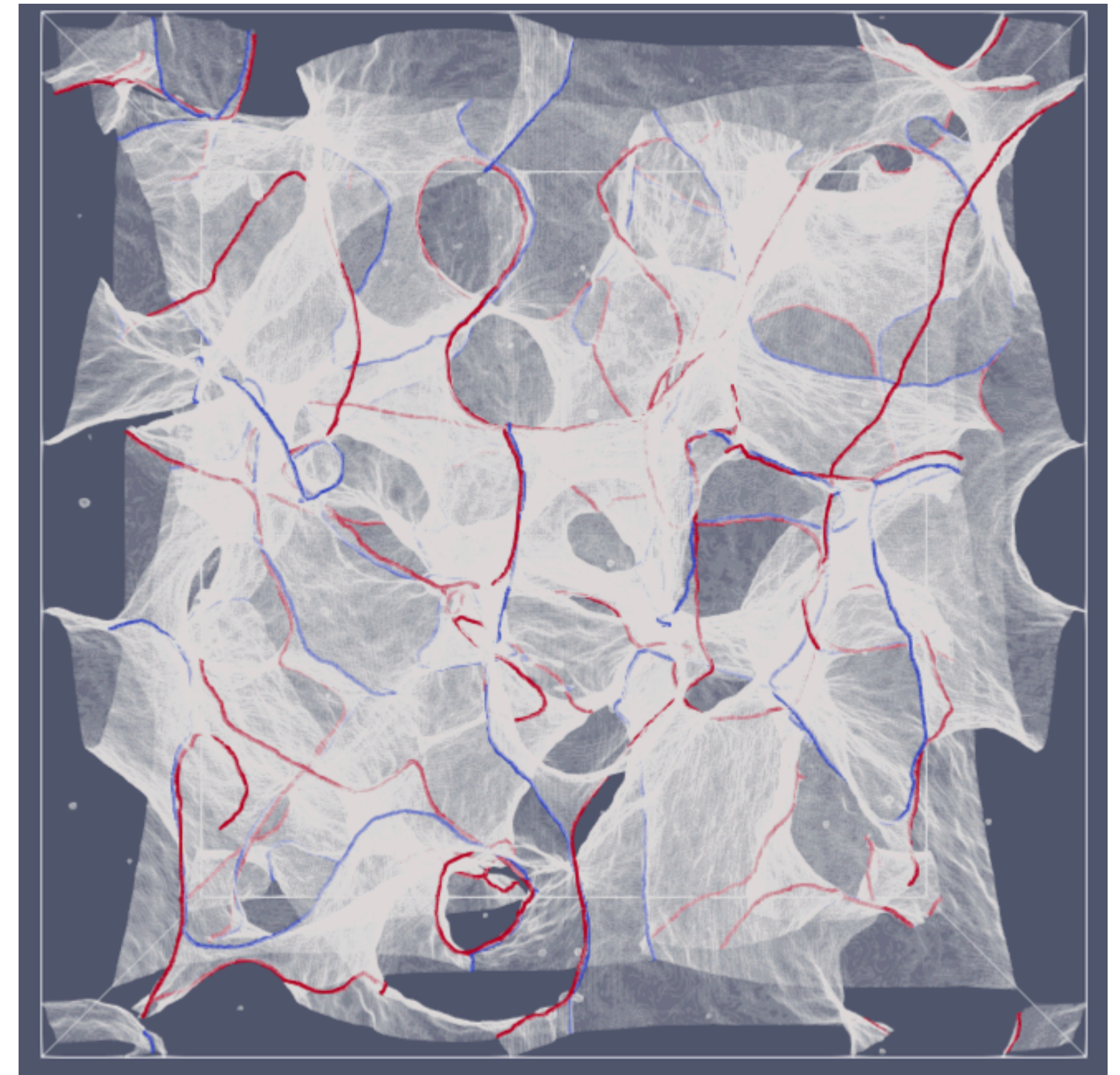
Lee, Murai, FT and Yin 2409.09749

Case of $(n_1, n_2) = (2, 3)$

**String-wall network forms in
stead of string bundles.**



String bundle
(= ordinary cosmic string)



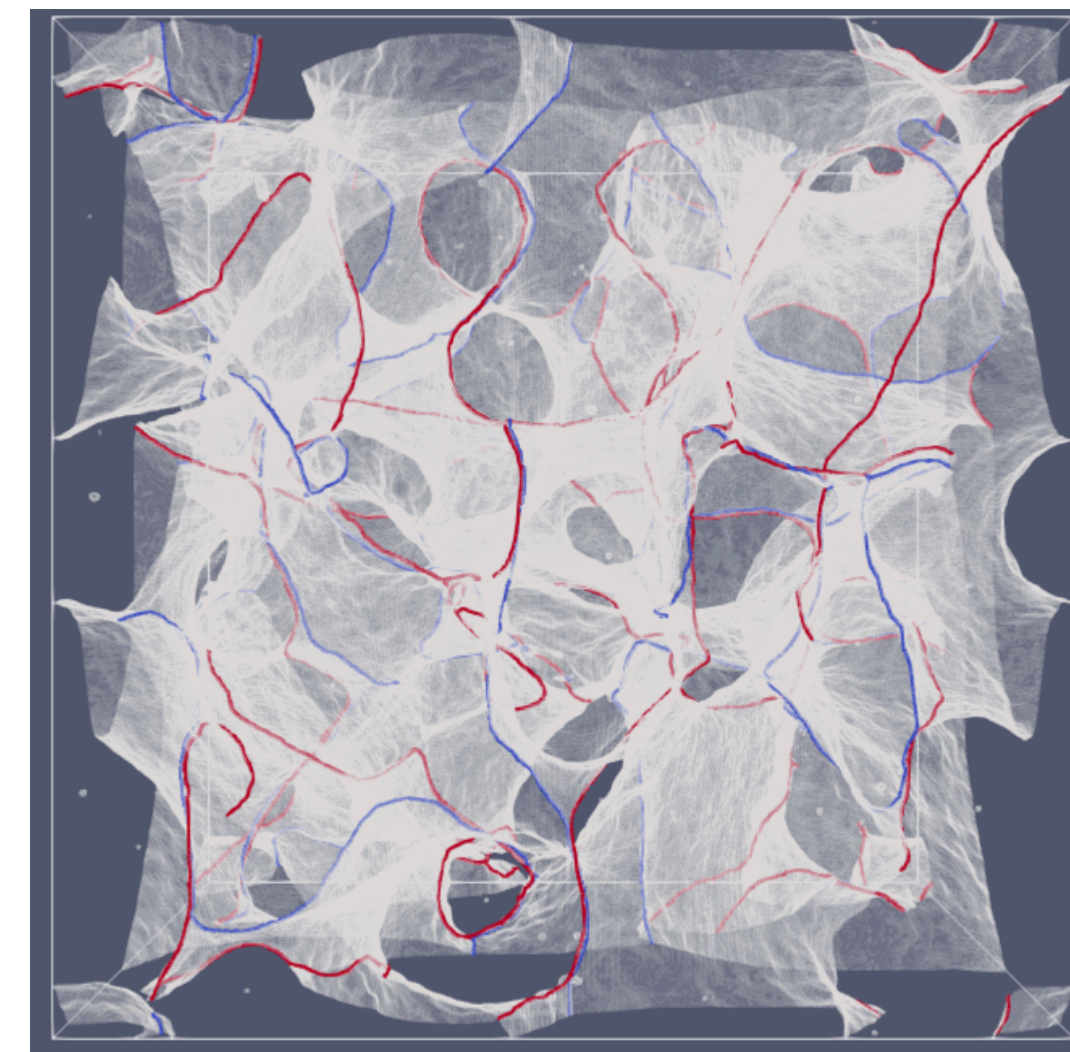
Numerical results (3D)

Courtesy of Junseok Lee

$$\gcd[|n_1|, |n_2|] > 1$$

$$V_1(\phi_1, \phi_2) = \Lambda^4 \left[1 - \cos \left(n_1 \frac{\phi_1}{f_1} + n_2 \frac{\phi_2}{f_2} \right) \right]$$

Domain walls



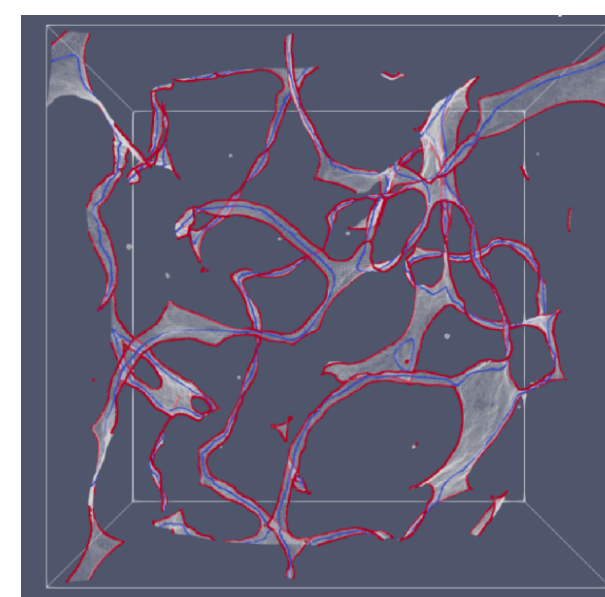
$$|n_1|, |n_2| \geq 2$$

$$\gcd[|n_1|, |n_2|] = 1$$

$$N_{\text{DW}} \geq 2$$

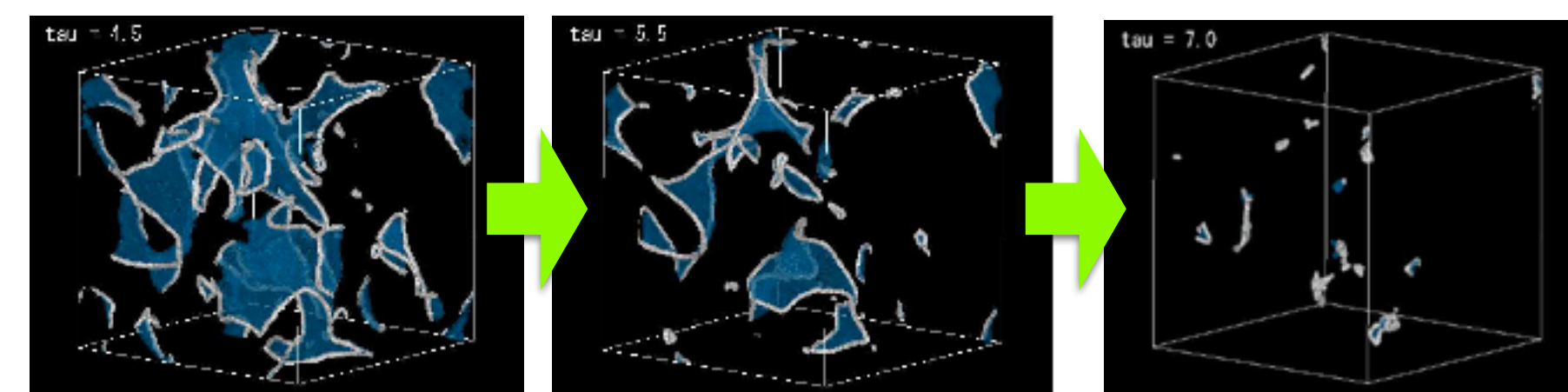
String bundles

$$|n_1| = 1 \text{ or } |n_2| = 1$$



$$N_{\text{DW}} = 1$$

String-wall network collapses

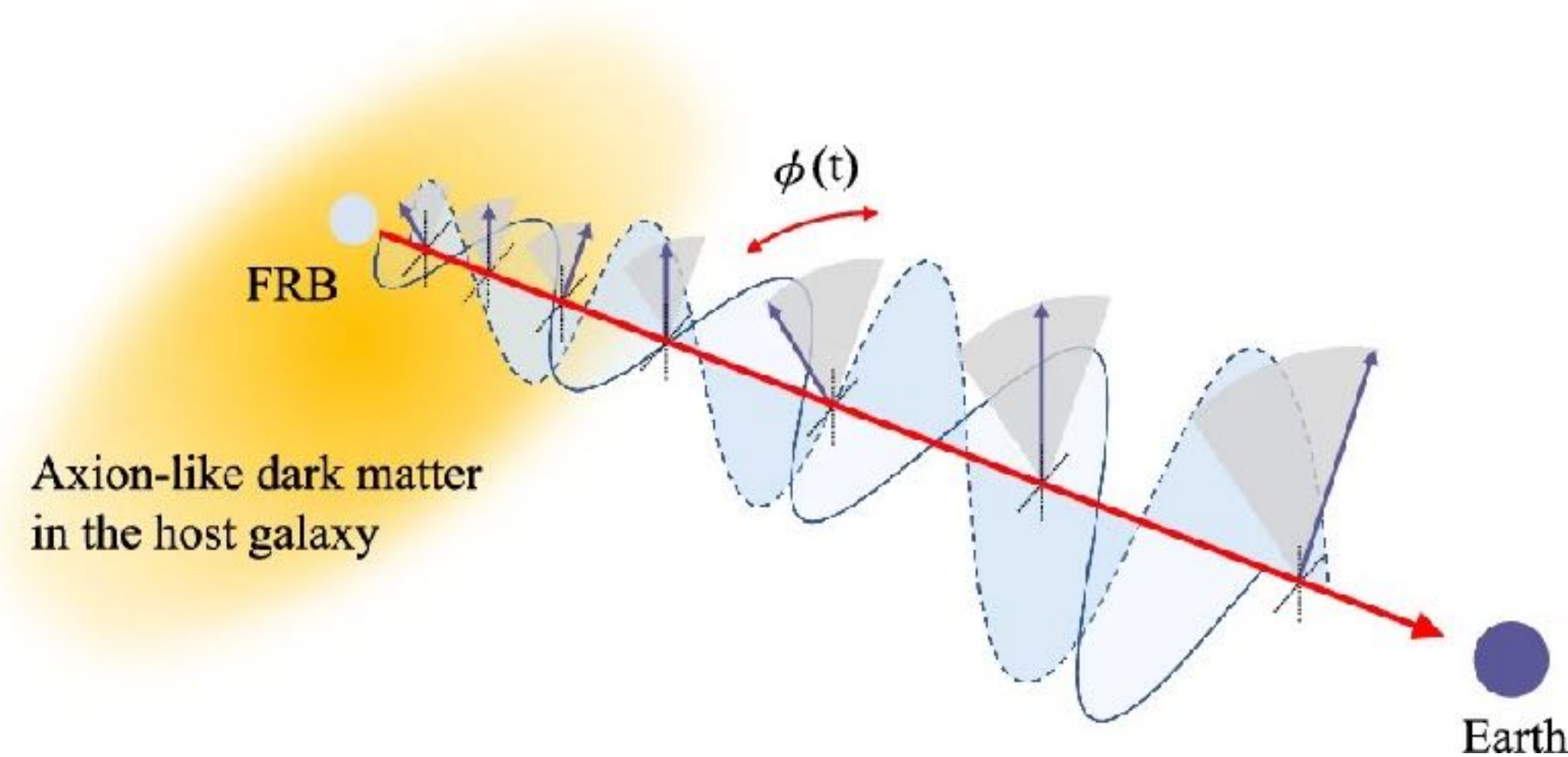


Axion-photon conversion

$$\mathcal{L}_{a\gamma\gamma} = \frac{g_{a\gamma\gamma}}{4} a F_{\mu\nu} \tilde{F}_{\mu\nu} = -g_{a\gamma\gamma} a \vec{E} \cdot \vec{B}$$

Axion-induced birefringence

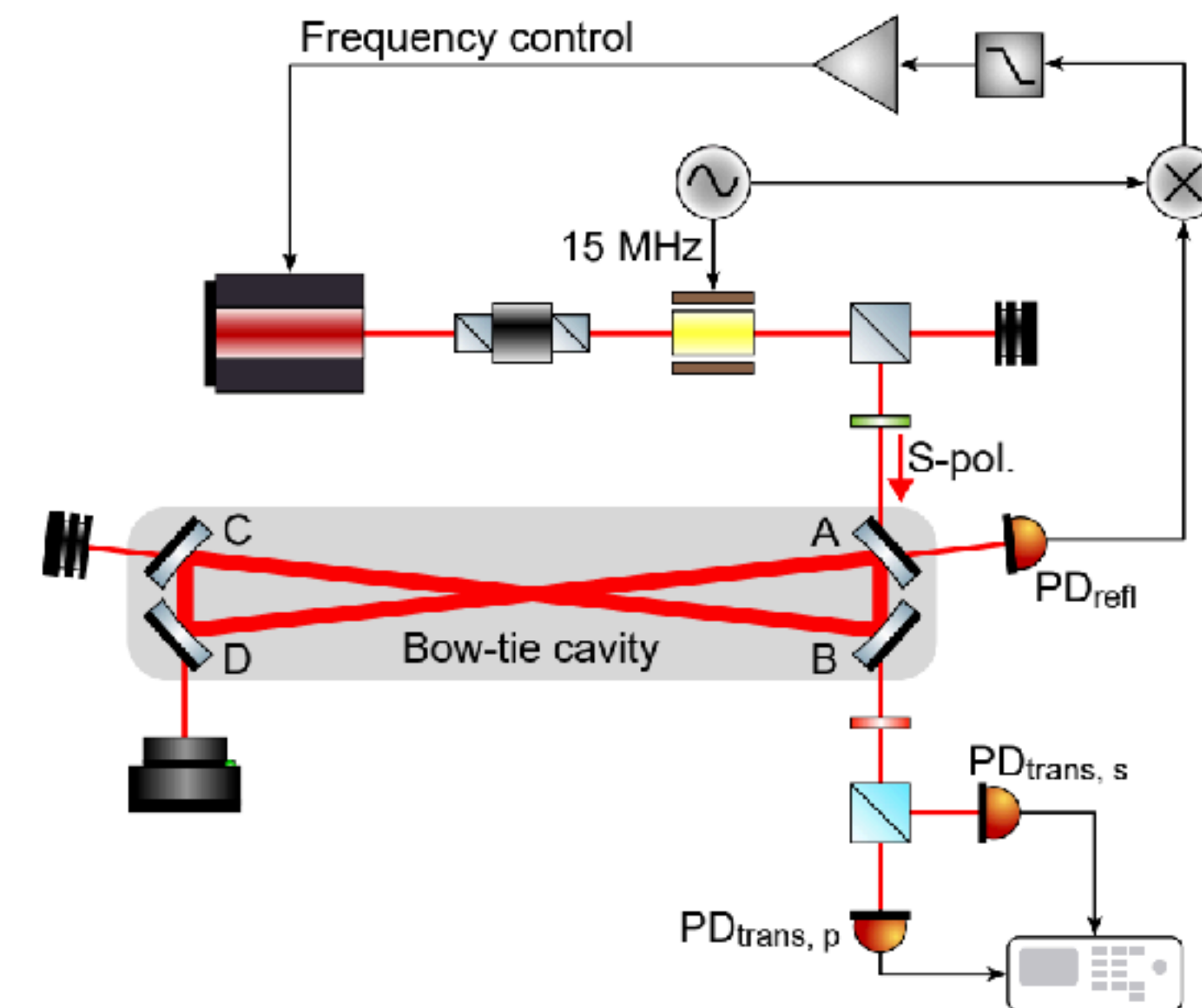
Cosmo/astro



B. Wang et al, arXiv:2402.00473

See also Fedderke, Graham, Rajendran, 1903.02666.

e.g. DANCE, LIDA, ADBC



from Y. Oshima et al, 2303.03594 (DANCE collab.)

See also K. Nagano et al 1903.02017