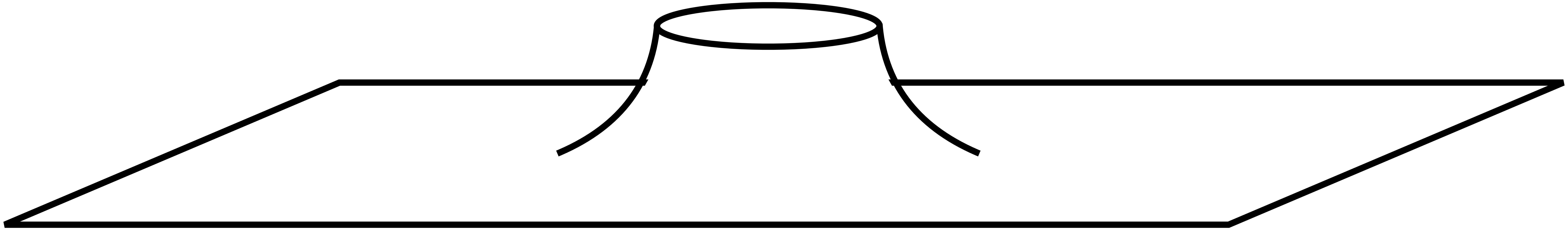
Wormhole-Induced ALP Dark Matter



(w/ K. Hamaguchi, Y. Kanazawa, S.M. Lee, N. Nagata, S.C. Park)

[2411.07713] —> Accepted in JHEP

Dhong Yeon Cheong (Yonsei U.)

(Related work : DYC, K. Hamaguchi, Y. Kanazawa, S.M. Lee, N. Nagata, S.C. Park, [2210.11330], / DYC, S.C. Park, C.S. Shin [2310.11260])

Feb. 24th. 2025

연세대학교
YONSEI UNIVERSITY

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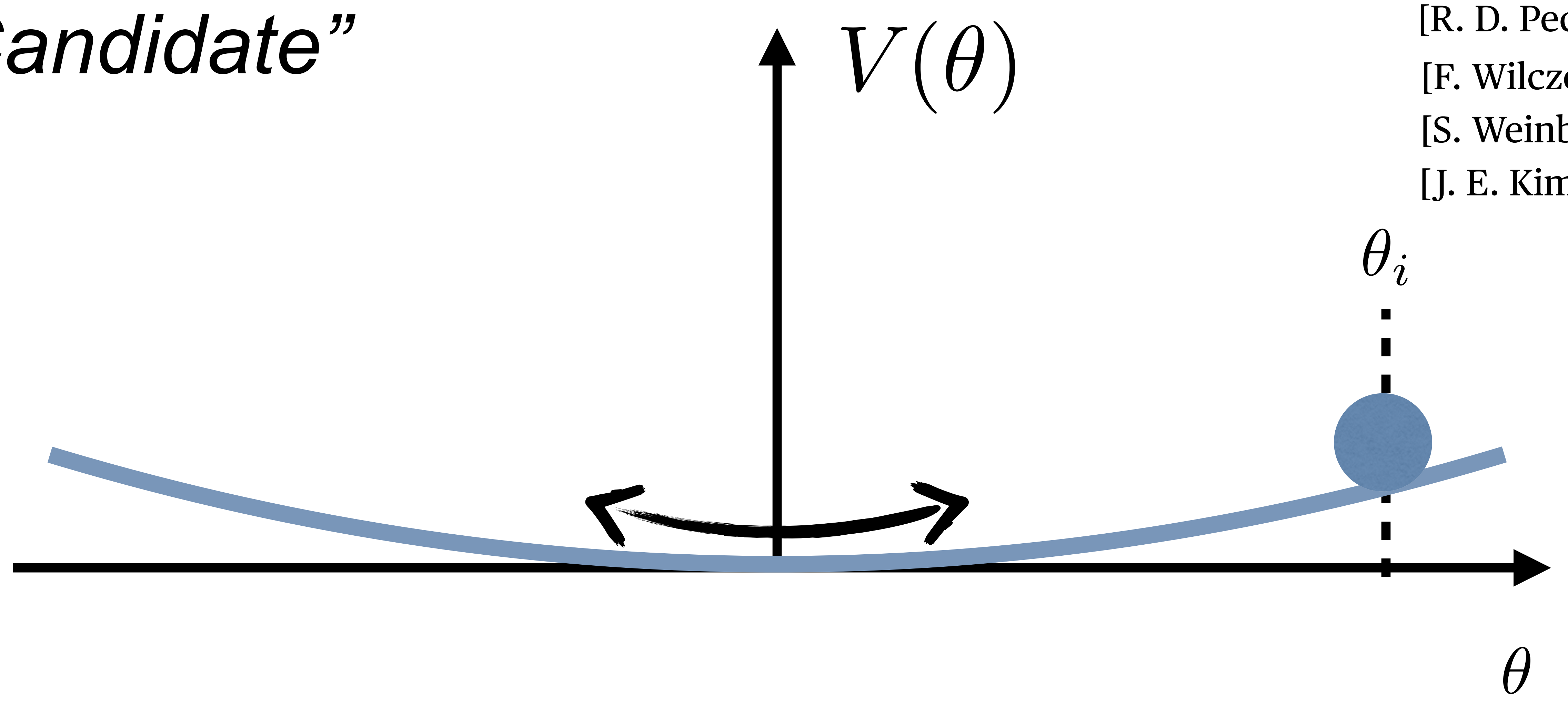

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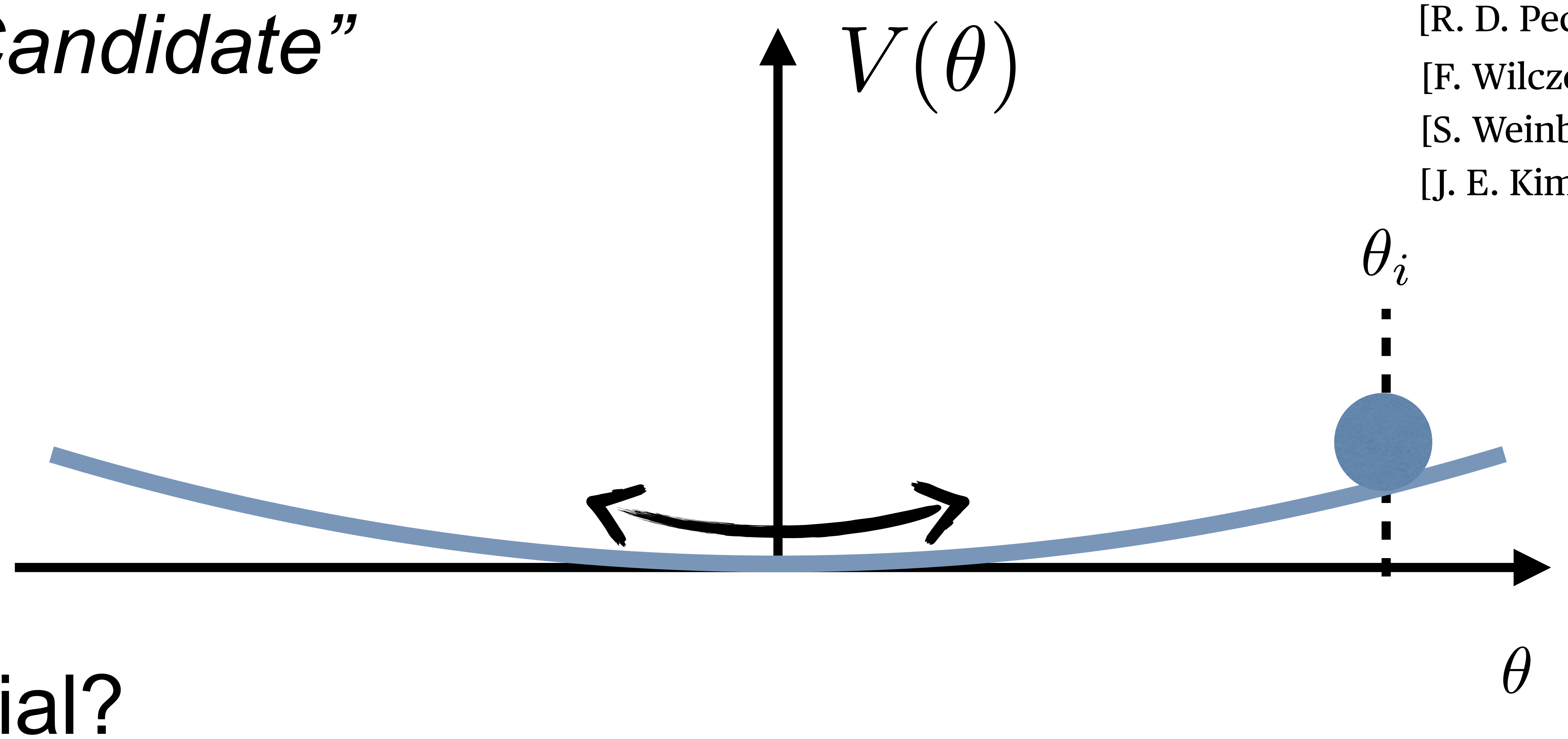

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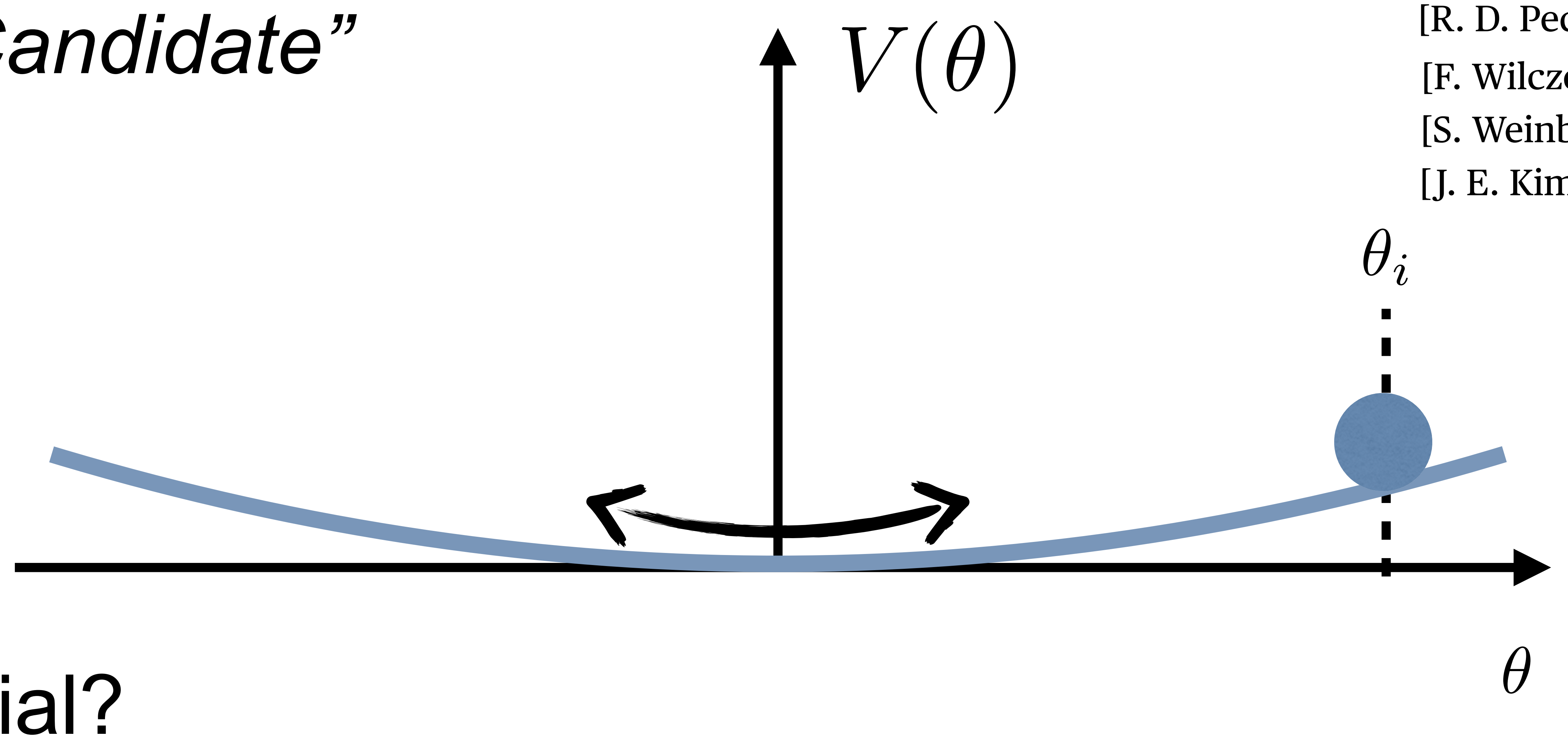

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$$\mathcal{L}(\mu > \Lambda_{\rm QCD}) = \frac{1}{2}(\partial_\mu a)^2 + \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G_{\mu\nu}\tilde{G}^{\mu\nu} + \dots$$

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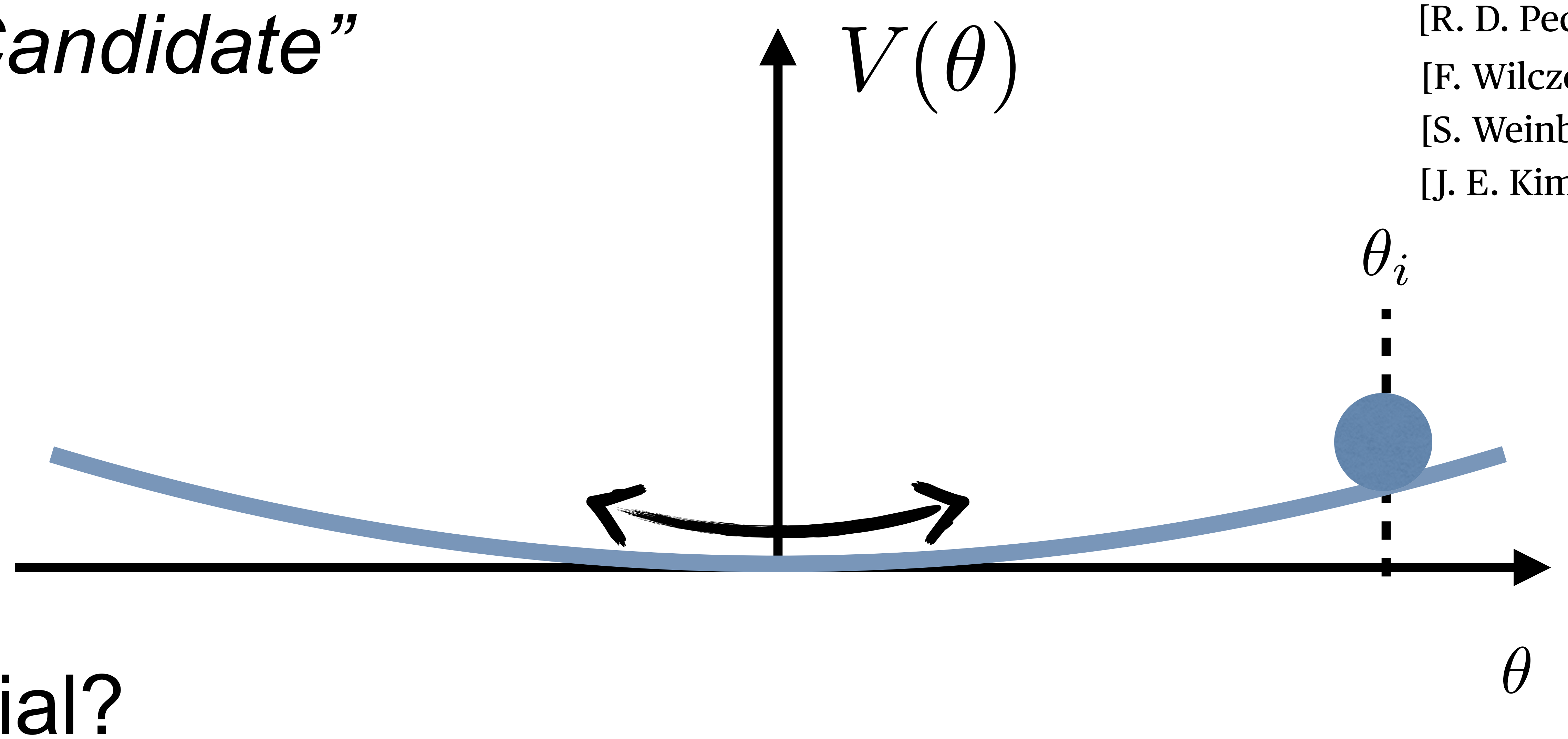

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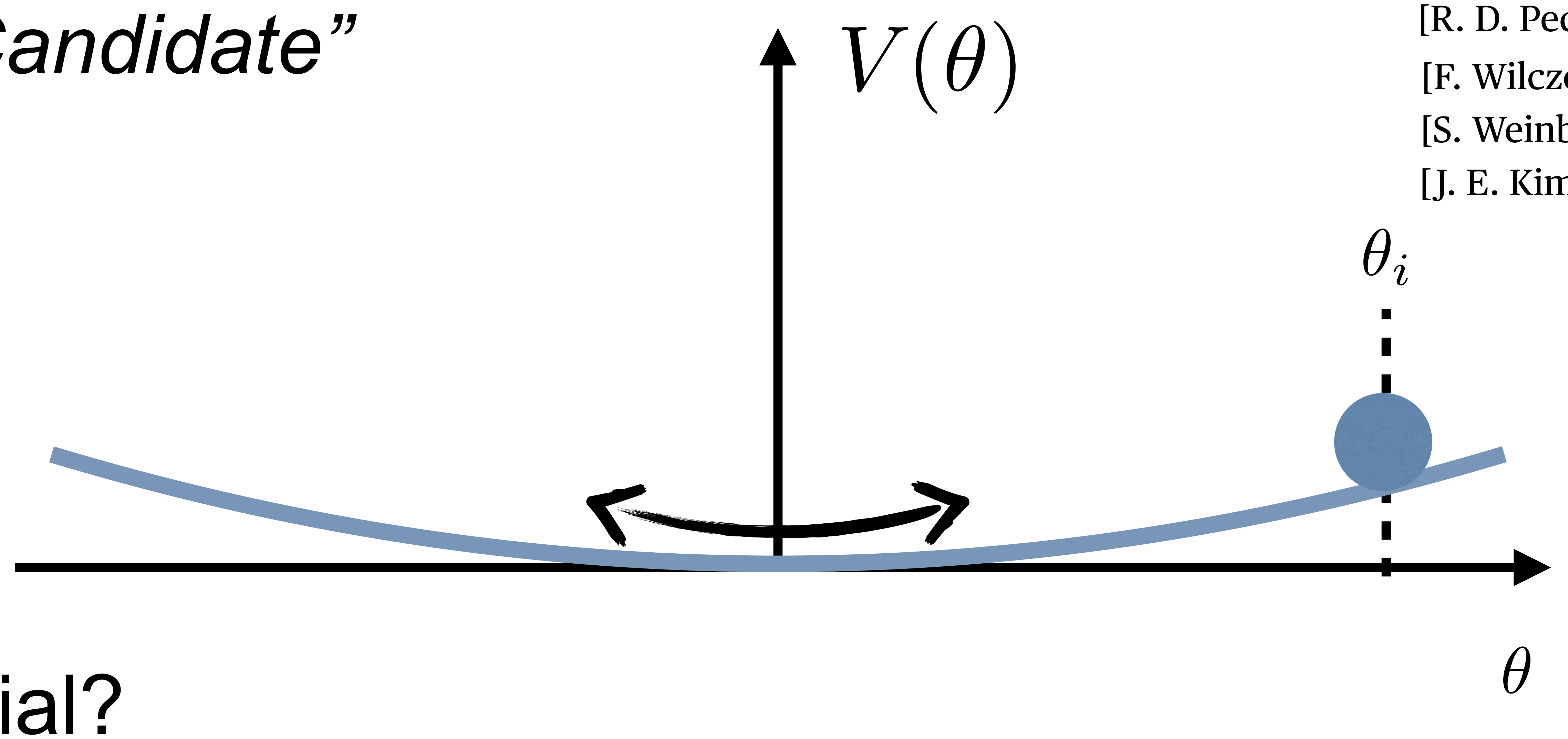

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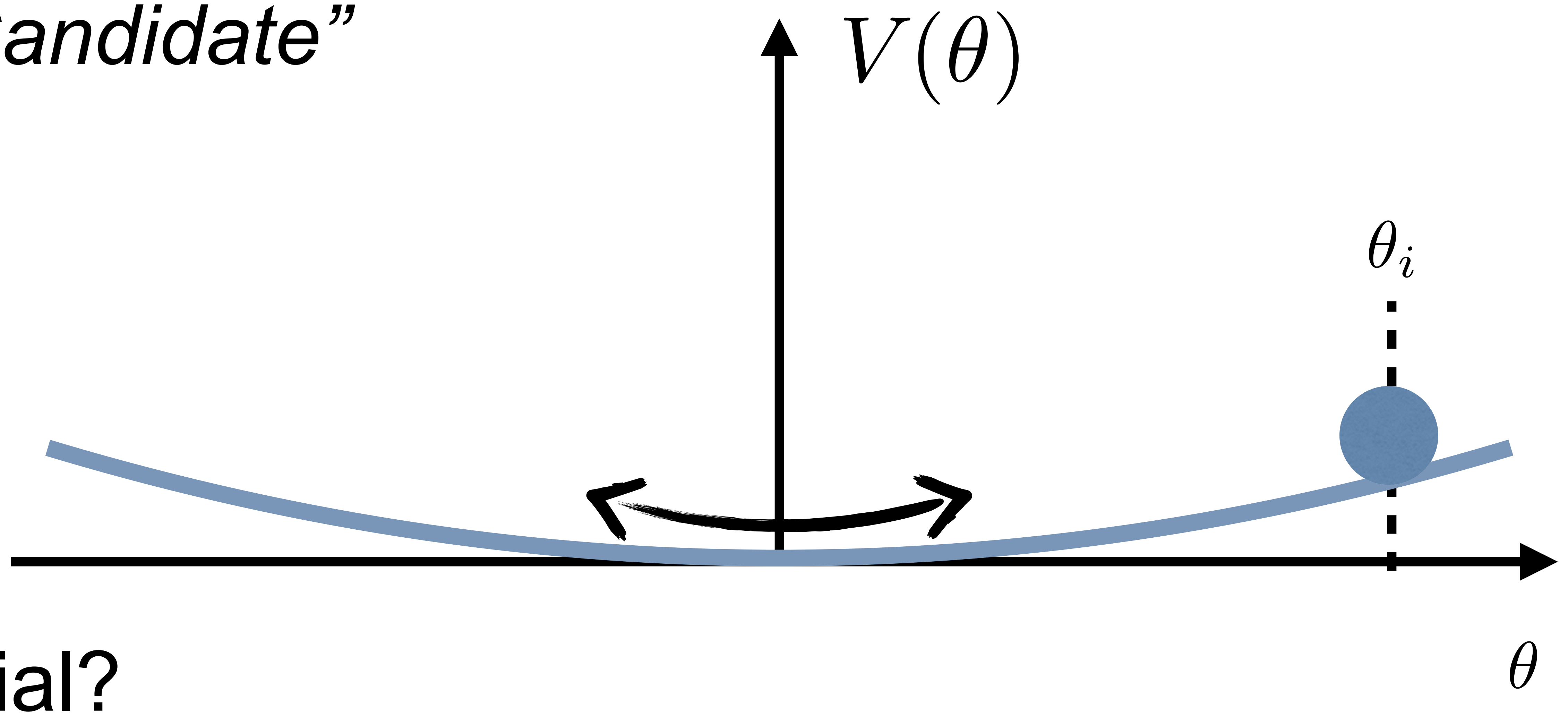

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Non-perturbative gravity effects explicitly break $U(1)$ *in ALP models*

↓

Origin for $V(\theta)$ *, Dark Matter Possibility!*

↓

Objects : Euclidean ALP Wormholes

ALP Wormholes

$U(1)$ complex scalar + non-minimal coupling to gravity $\Phi = \frac{1}{\sqrt{2}}\rho e^{i\theta}$

$$S = \int d^4x \sqrt{|g|} \left[-\frac{M_P^2}{2}\left(1 + \frac{\xi}{M_P^2}(\rho^2 - f_a^2)\right) R(\Gamma) + \frac{1}{2}(\partial_\mu \rho)^2 + \frac{1}{2}\rho^2 (\partial_\mu \theta)^2 + \frac{\lambda_\Phi}{4}\left(\rho^2 - f_a^2\right)^2 \right]$$

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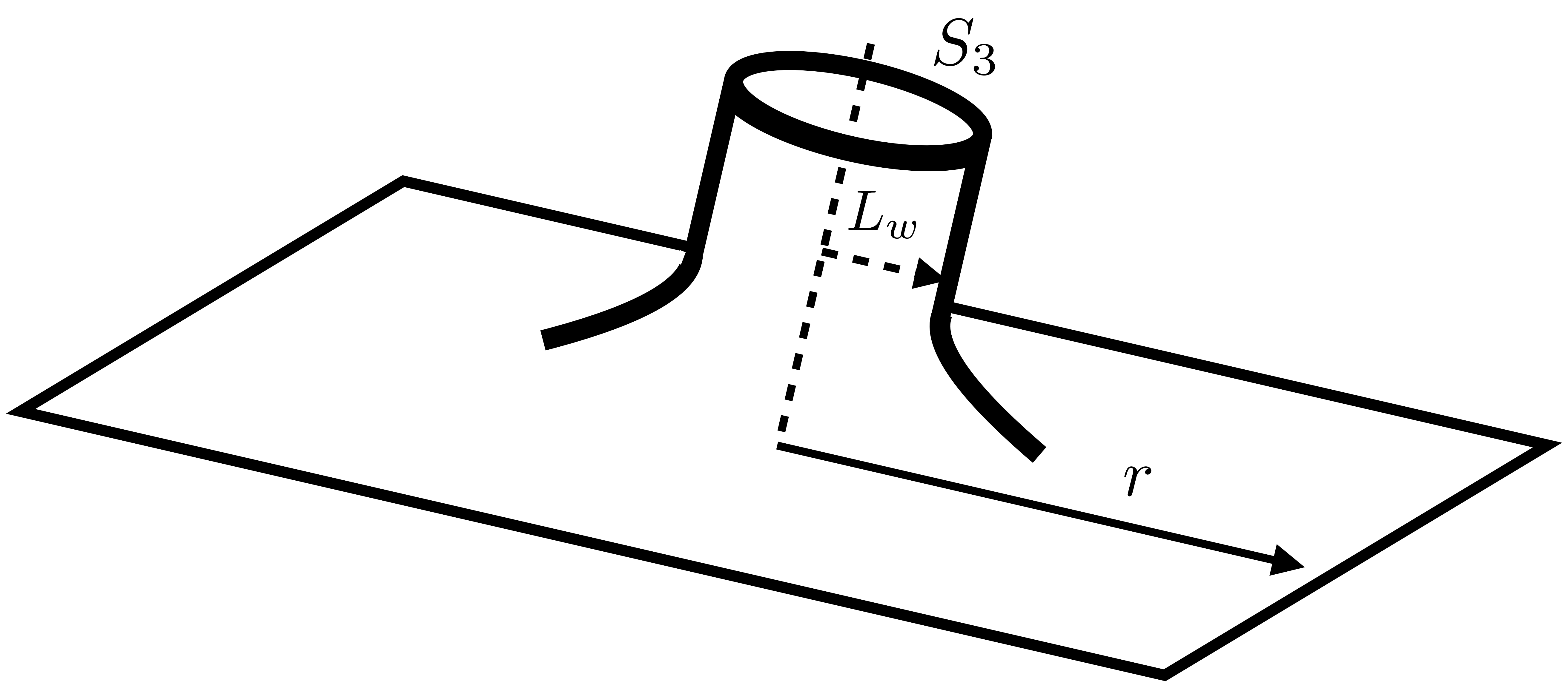

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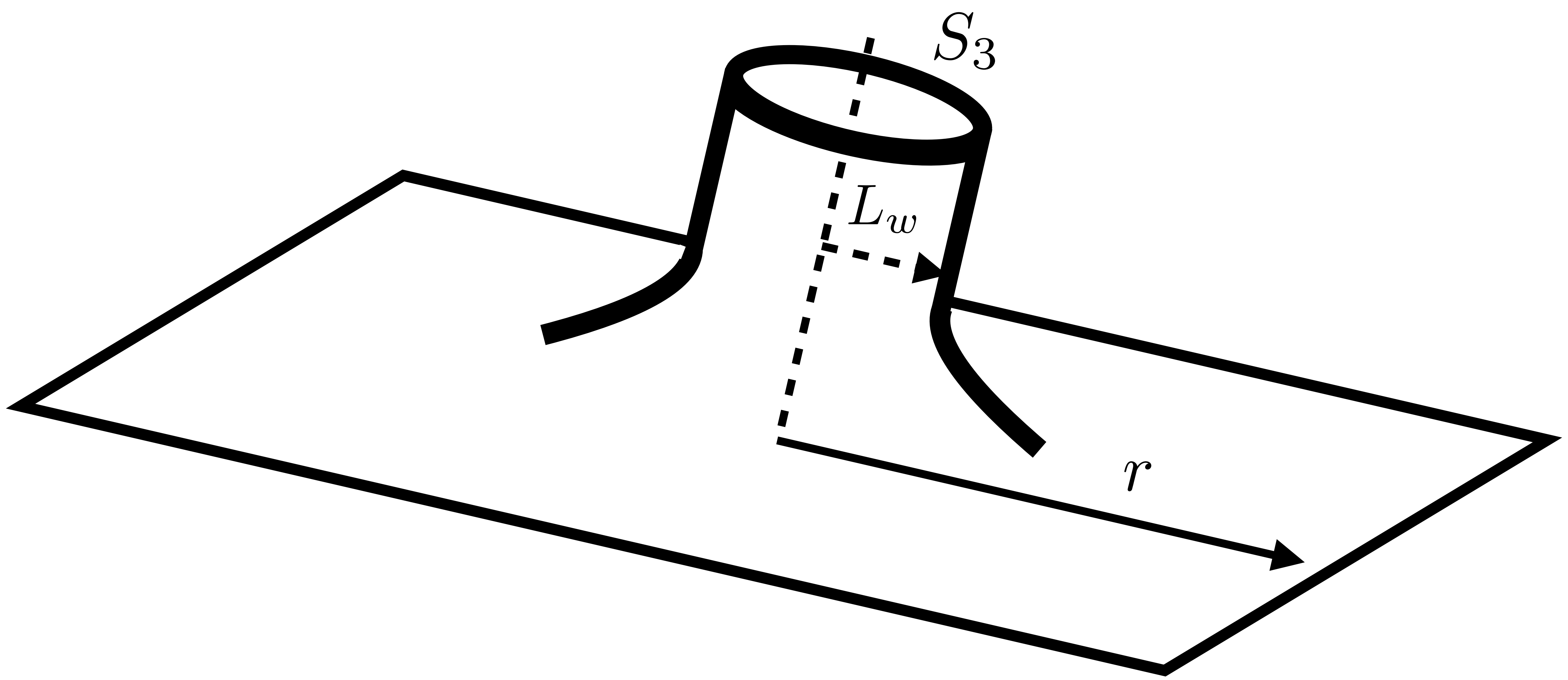
See e.g. [A. Hebecker, T. Mikhail, P. Soler, (2018)]

Finite-action solutions

$$ds^2 = \frac{dr^2}{(1 - L_w^4/r^4)} + r^2 d\Omega_3^2$$



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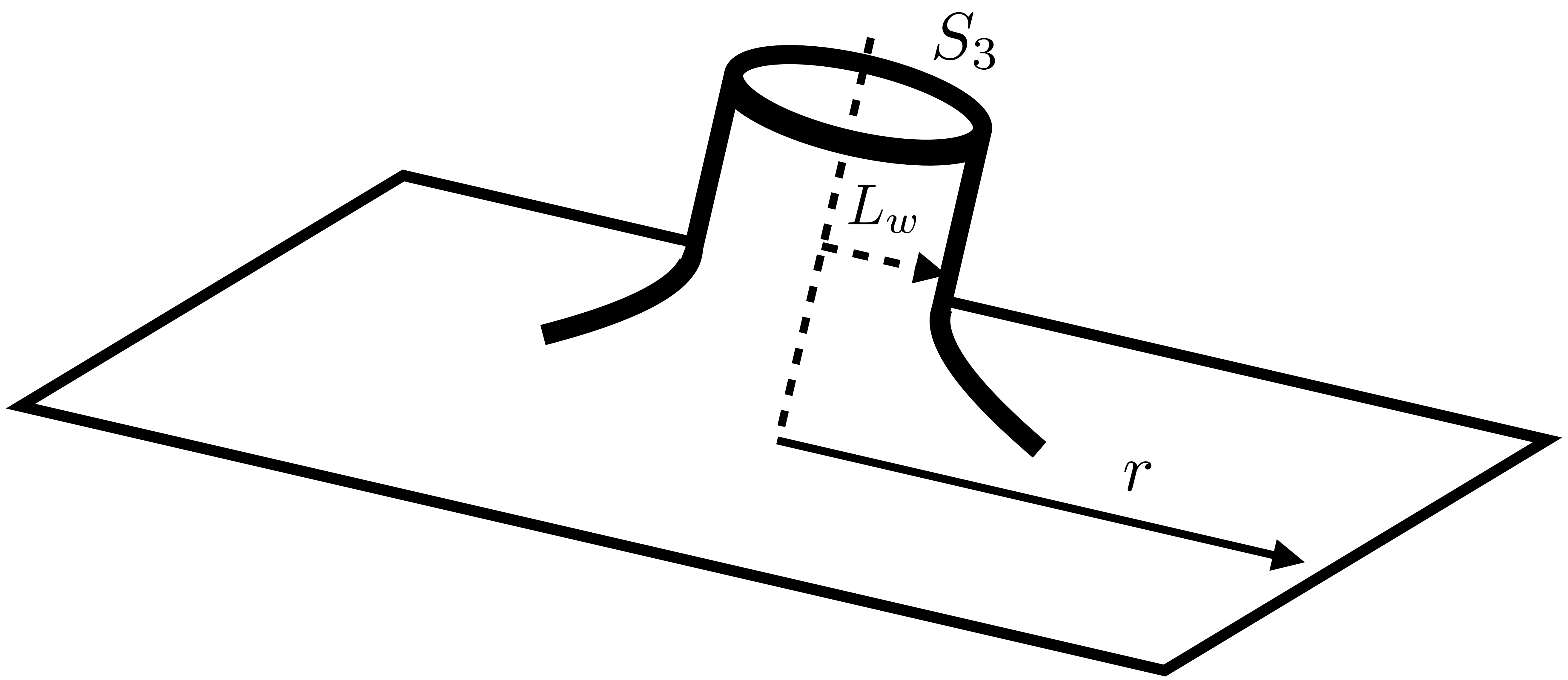

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PQ Charge of the wormhole

$$\int_{S_3} H_{E3} = q_e \qquad q_e = n_I \in \mathbb{N}$$

H_{E_3} : 3-form field strength, axion dual

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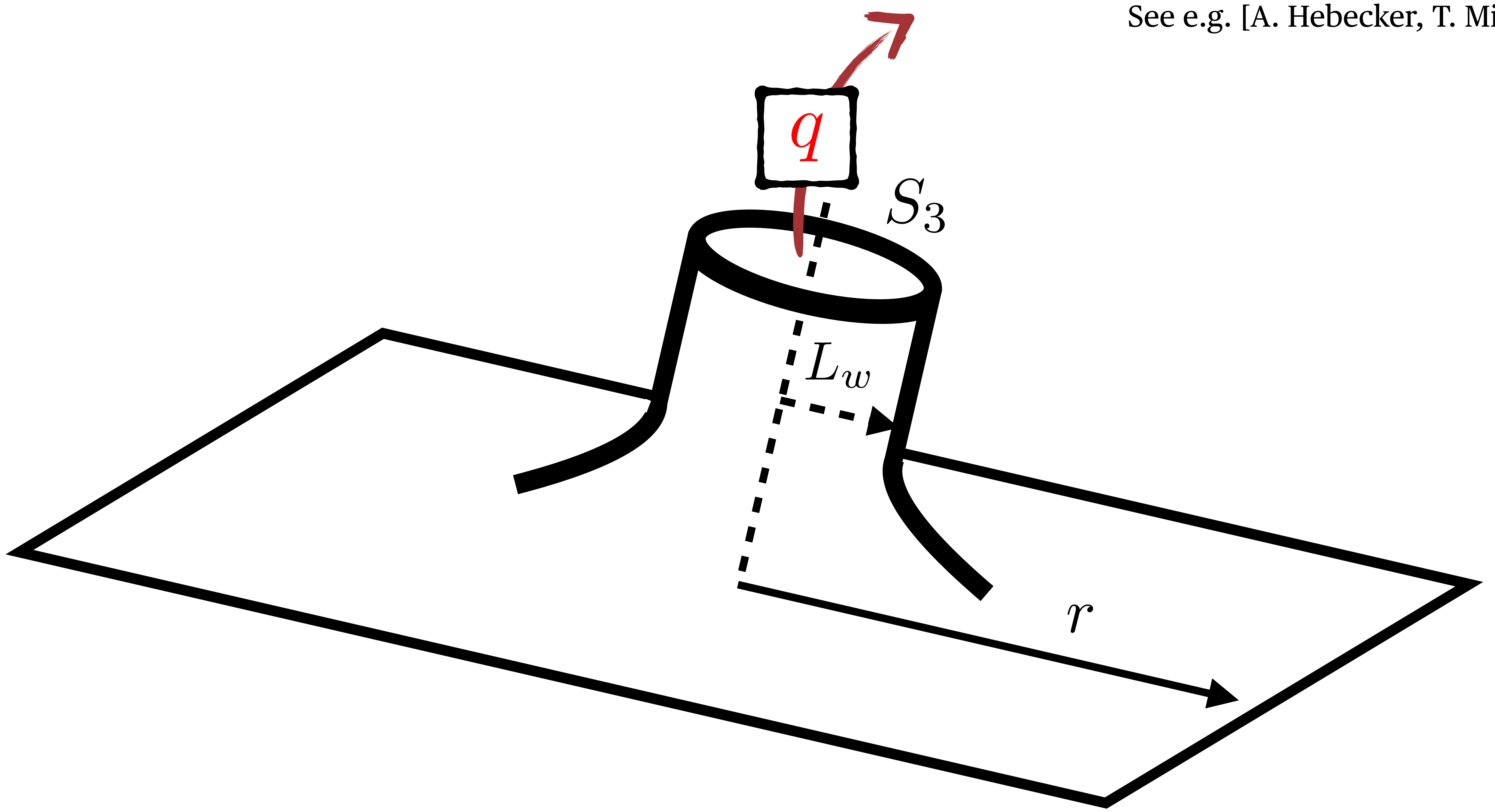

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[DYC, S.C. Park, C.S. Shin, 2310.11260] [DYC, et.al., 2411.07713]

Wormhole Action

Wormhole Throat

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$$S_w^{\xi\ll 1} \simeq \ln\left(\frac{M_P}{f_a}\right)$$

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Wormhole Induced ALP DM - Production

[DYC, et.al., 2411.07713]

Pre-Inflationary

Post-Inflationary

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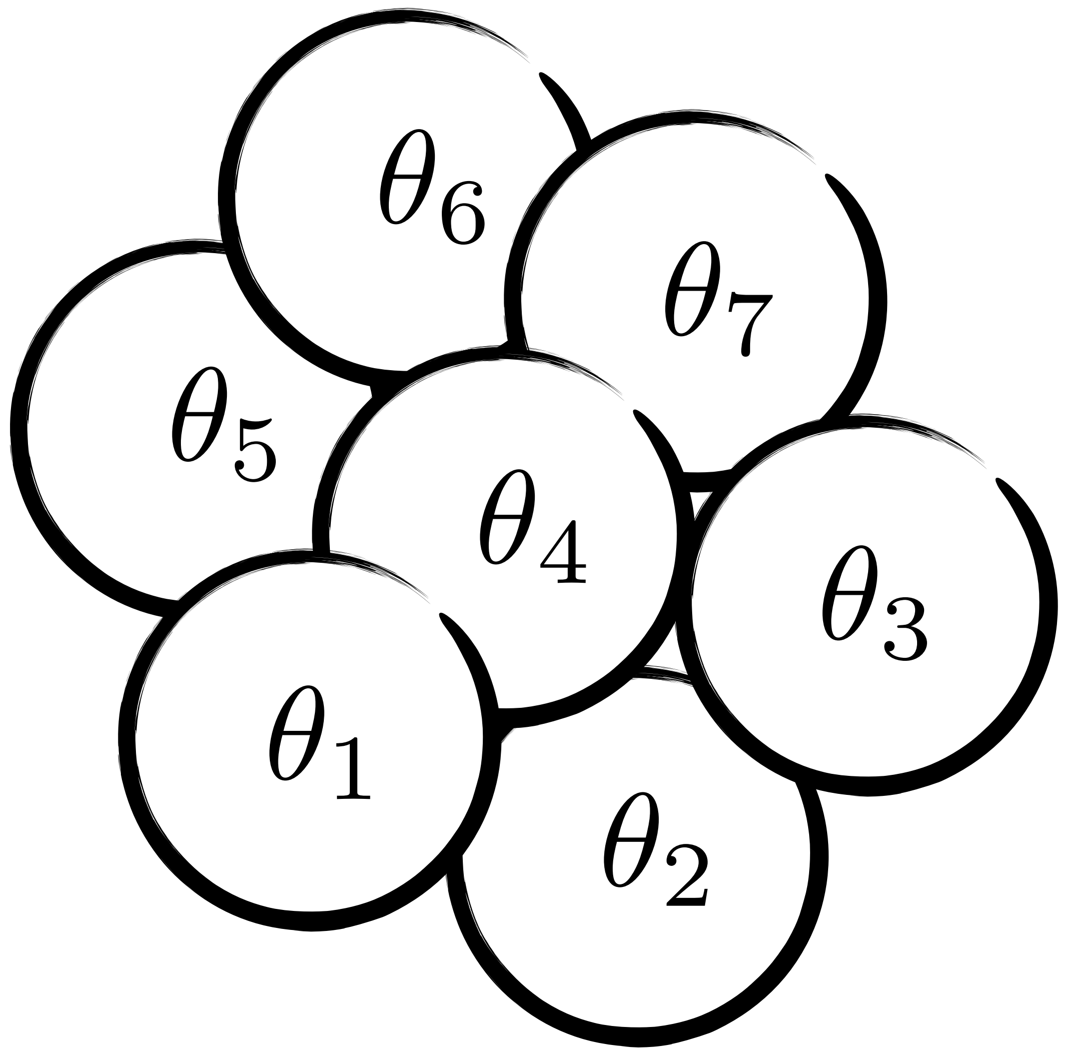

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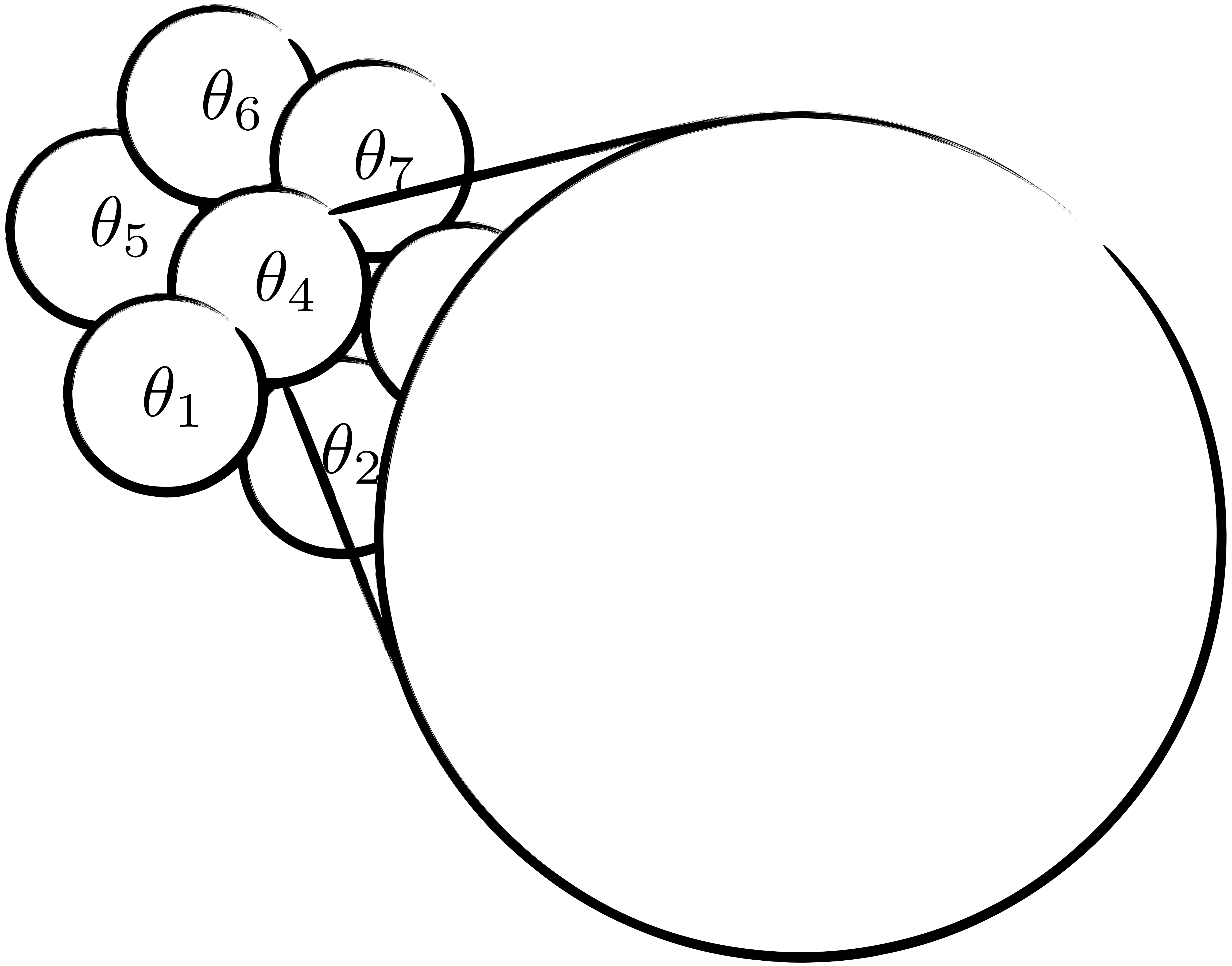

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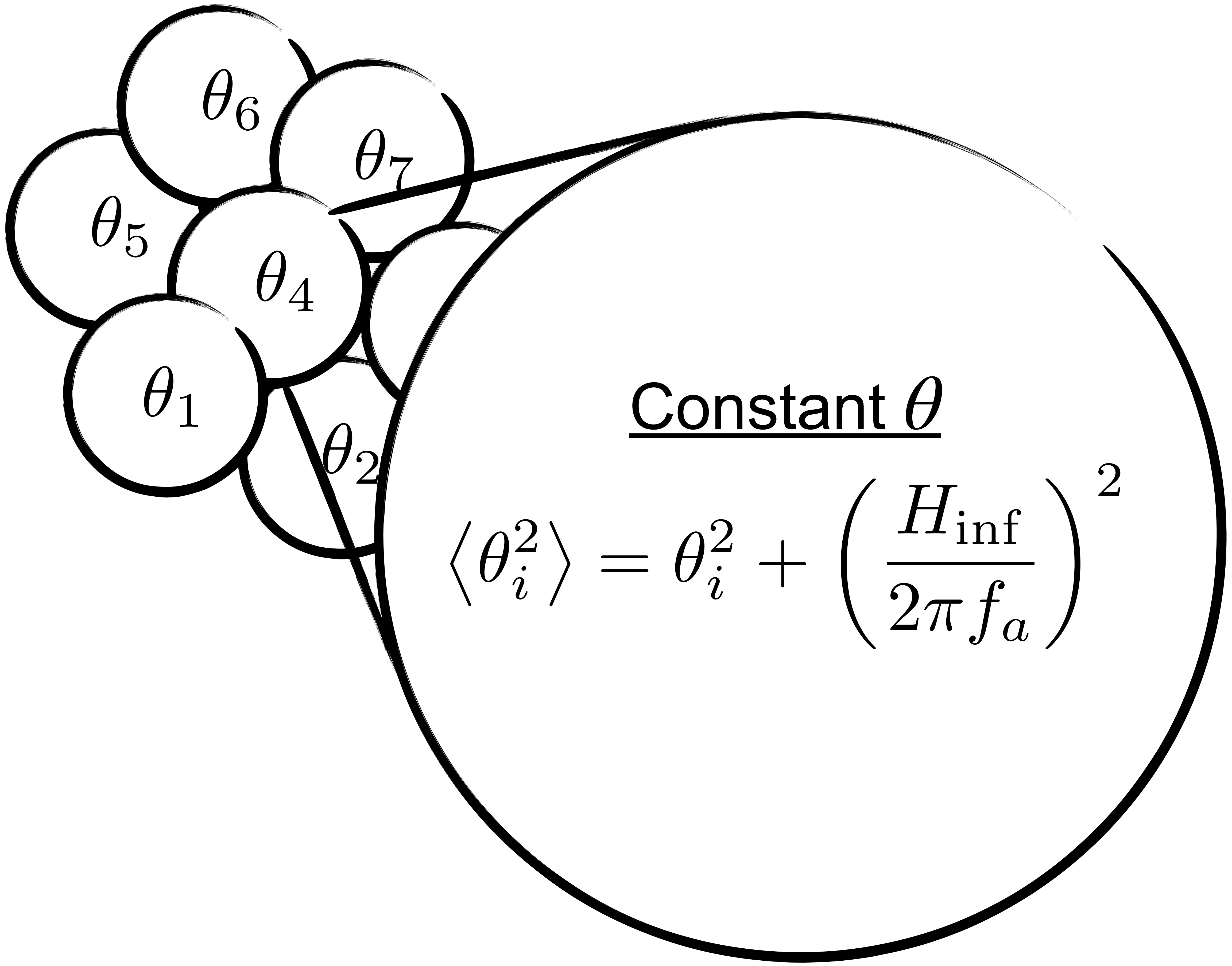

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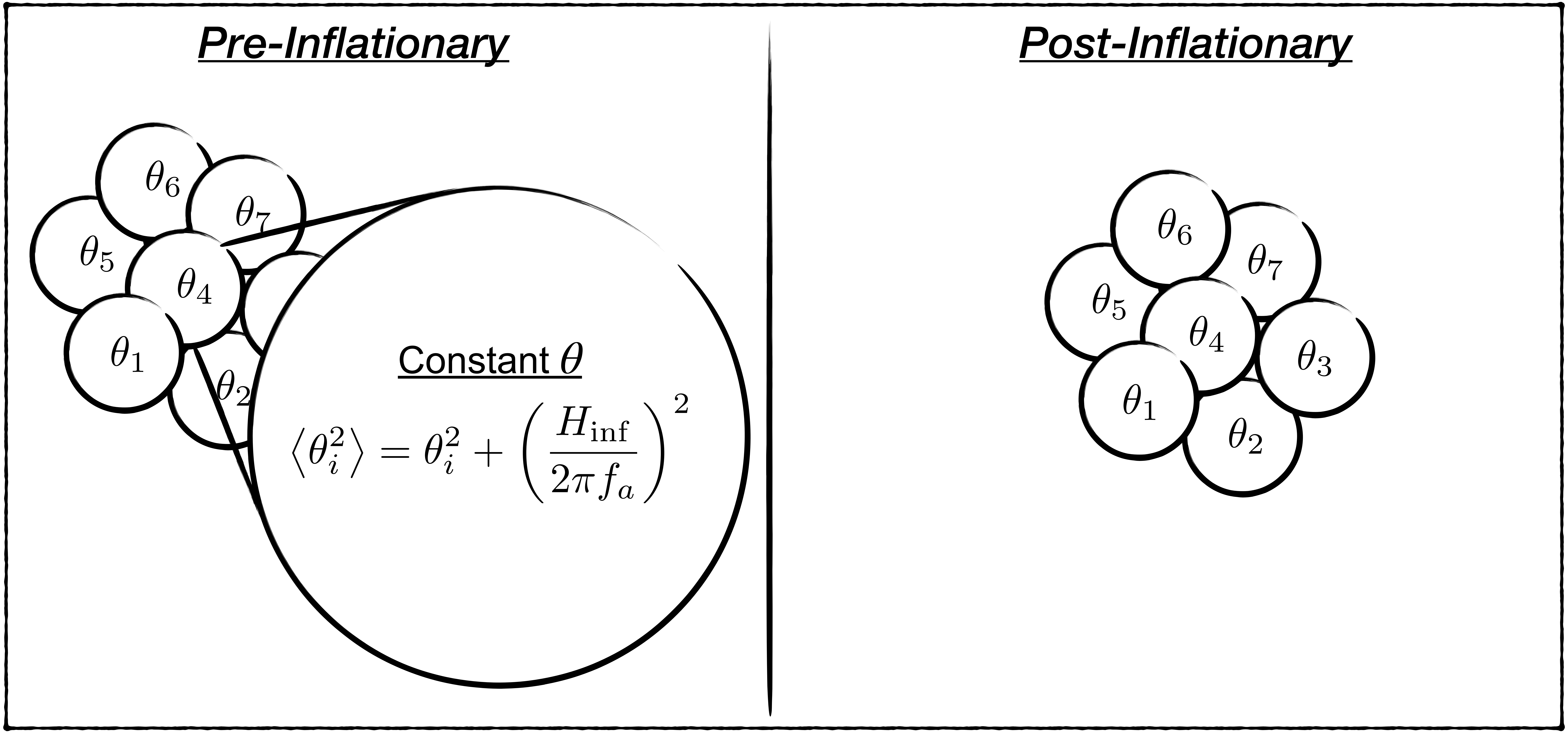

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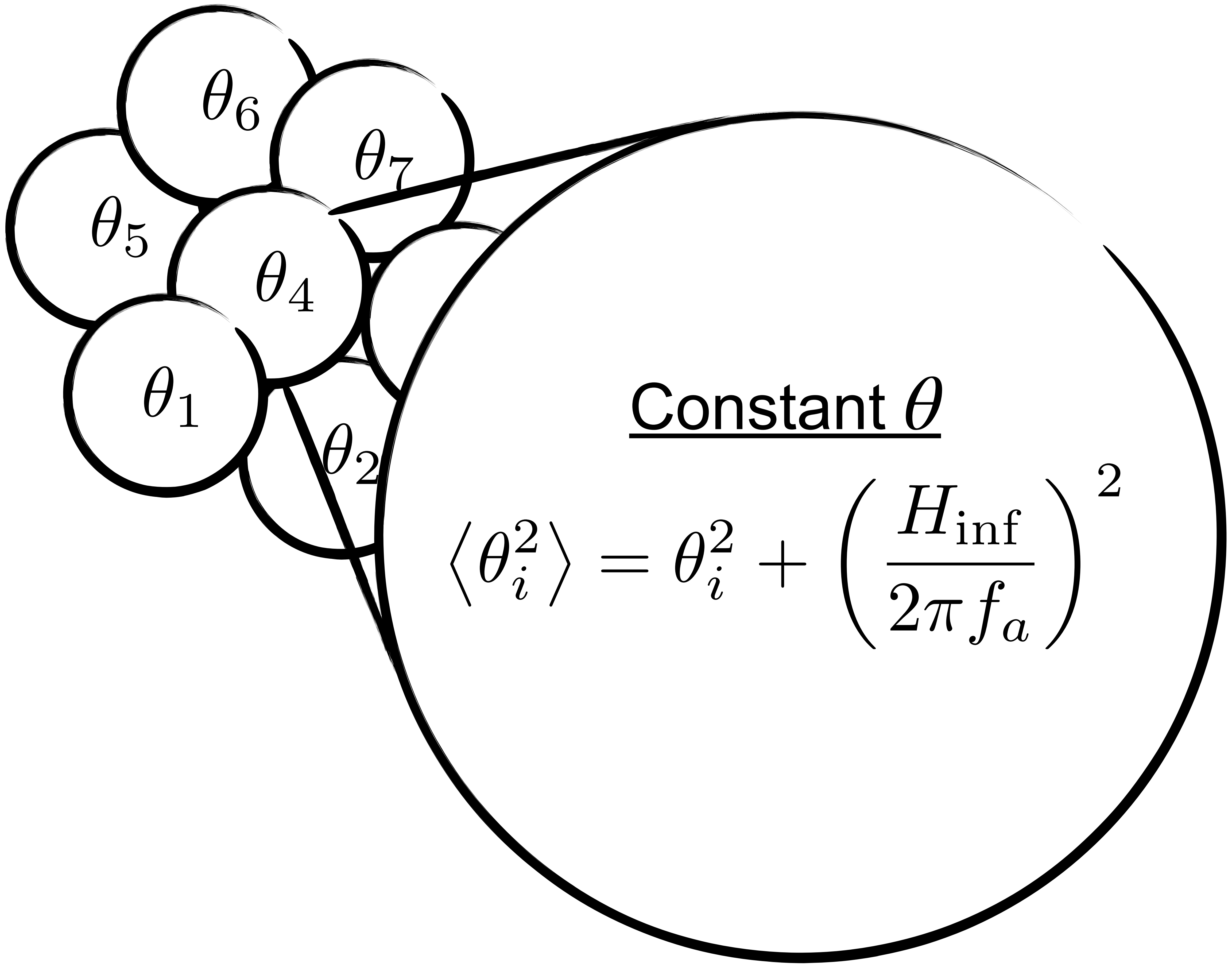

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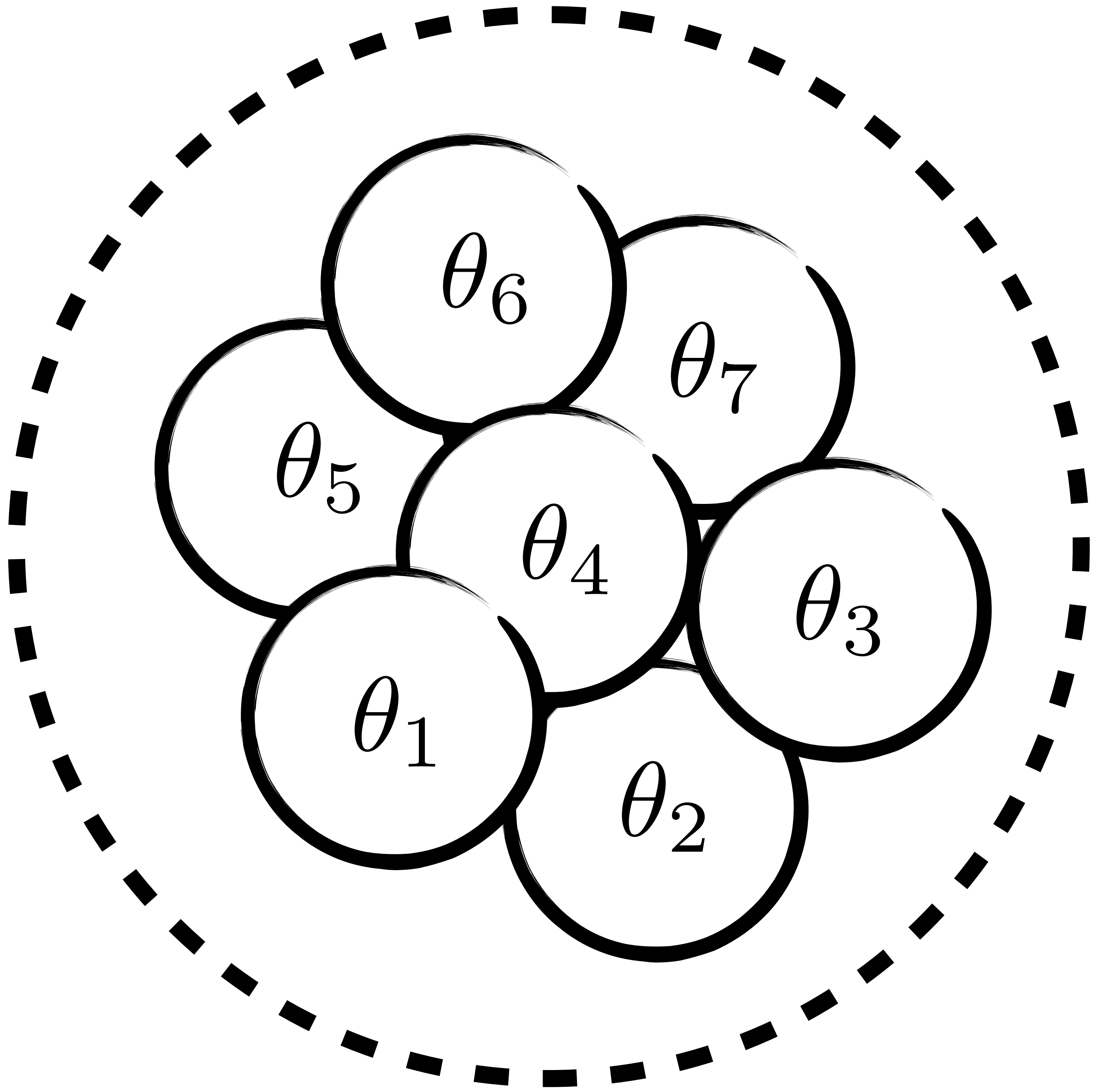

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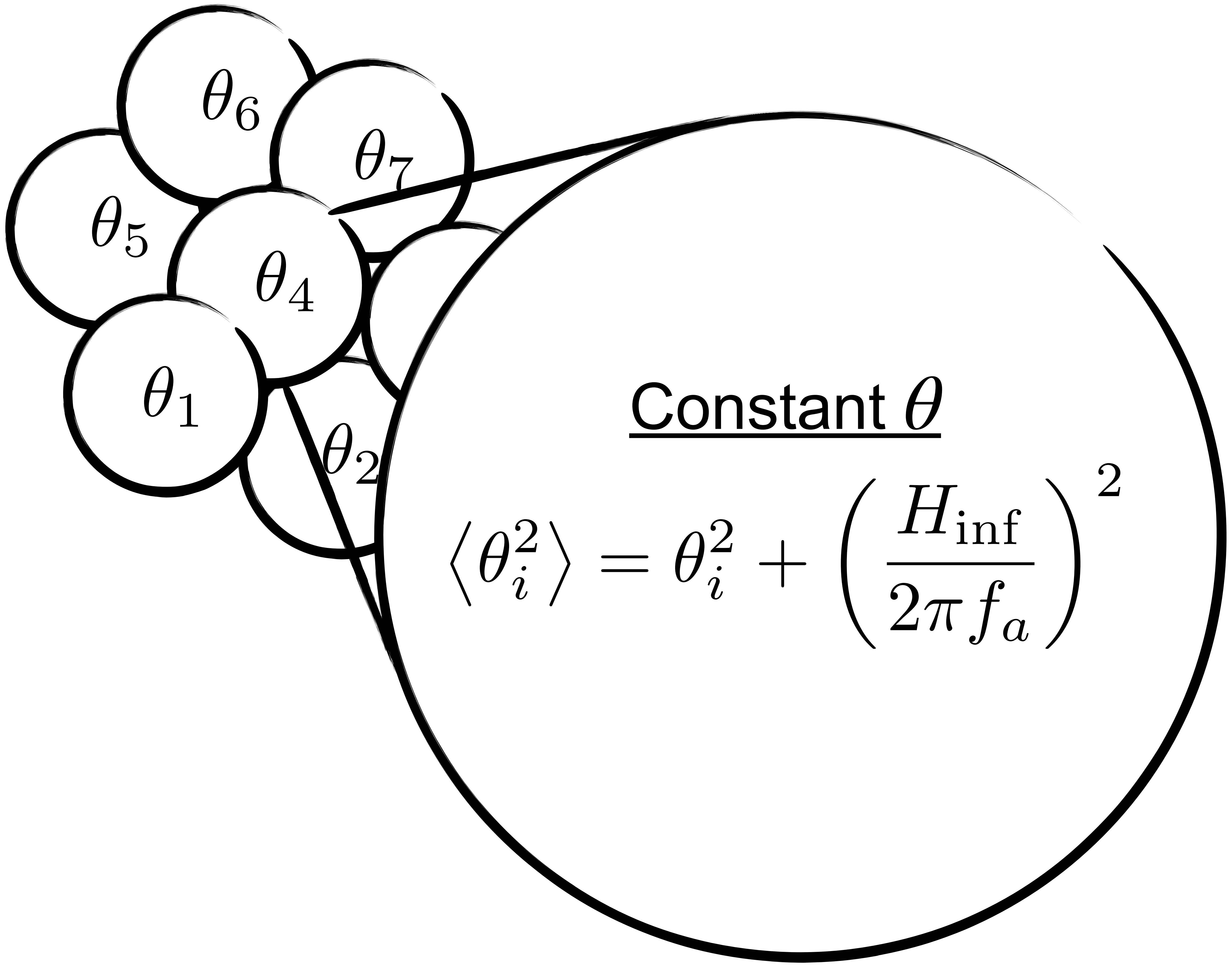

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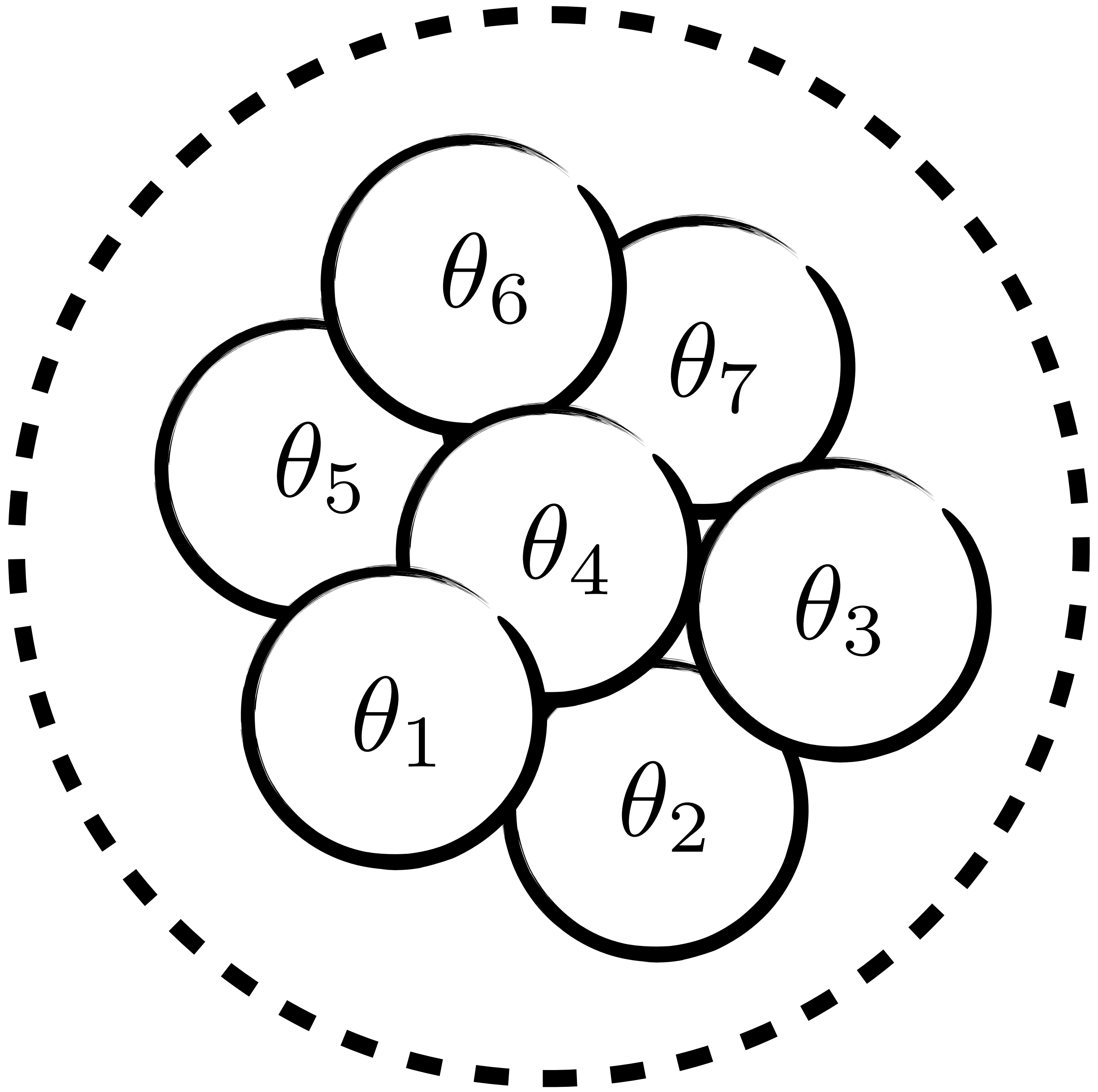
Post-Inflationary



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$$T_{\rm reh} = \epsilon_{\rm eff}\sqrt{H_{\rm inf} M_P}$$

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Dependence

epoch of ALP oscillation

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$$\langle\theta_i^2\rangle = \theta_i^2 + \left(\frac{H_{\rm inf}}{2\pi f_a}\right)^2$$

Dependence

epoch of ALP oscillation

Post-Inflationary

$$f_a < \max\{T_{\rm reh}, T_{\rm dS}\}$$

$$\langle\theta_i^2\rangle = \frac{1}{2\pi}\int_{-\pi}^{\pi} d\theta\theta^2 = \frac{\pi^2}{3}$$

Dependence

start of ALP oscillation

$$\Omega_a = \frac{\rho_a/s}{(\rho_{\rm crit}/s)_0} \sim f_a^2\langle\theta_i^2\rangle m_a^2$$

Wormhole Induced ALP DM - Production

[DYC, et.al., 2411.07713]

$$T_{\rm reh} = \epsilon_{\rm eff}\sqrt{H_{\rm inf} M_P}$$

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[PDG, 2022]

$$\beta_{\rm iso} \simeq \left(\frac{\Omega_a}{\Omega_{\rm CDM}}\right)^2 \frac{H_{\rm inf}^2}{8\pi^3 A_s f_a^2 \langle \theta_i^2 \rangle} < 0.038$$

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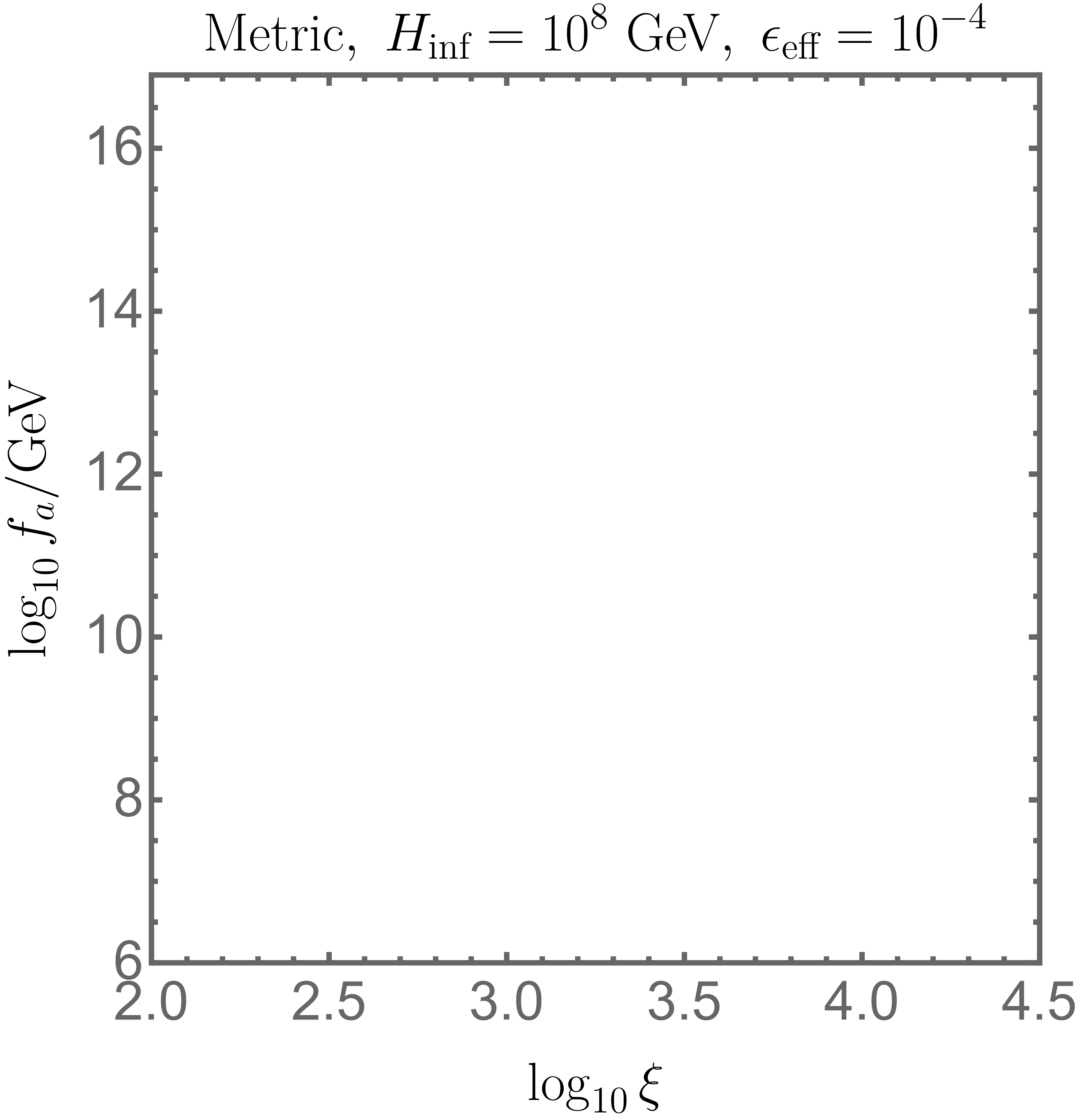
Contributions from cosmic string decays

$$\Omega_a^{\rm str} = \delta_{\rm dec}\Omega_a^{\rm mis}$$

Wormhole Induced ALP DM - Benchmark

[DYC, et.al., 2411.07713]



Wormhole Induced ALP DM - Benchmark

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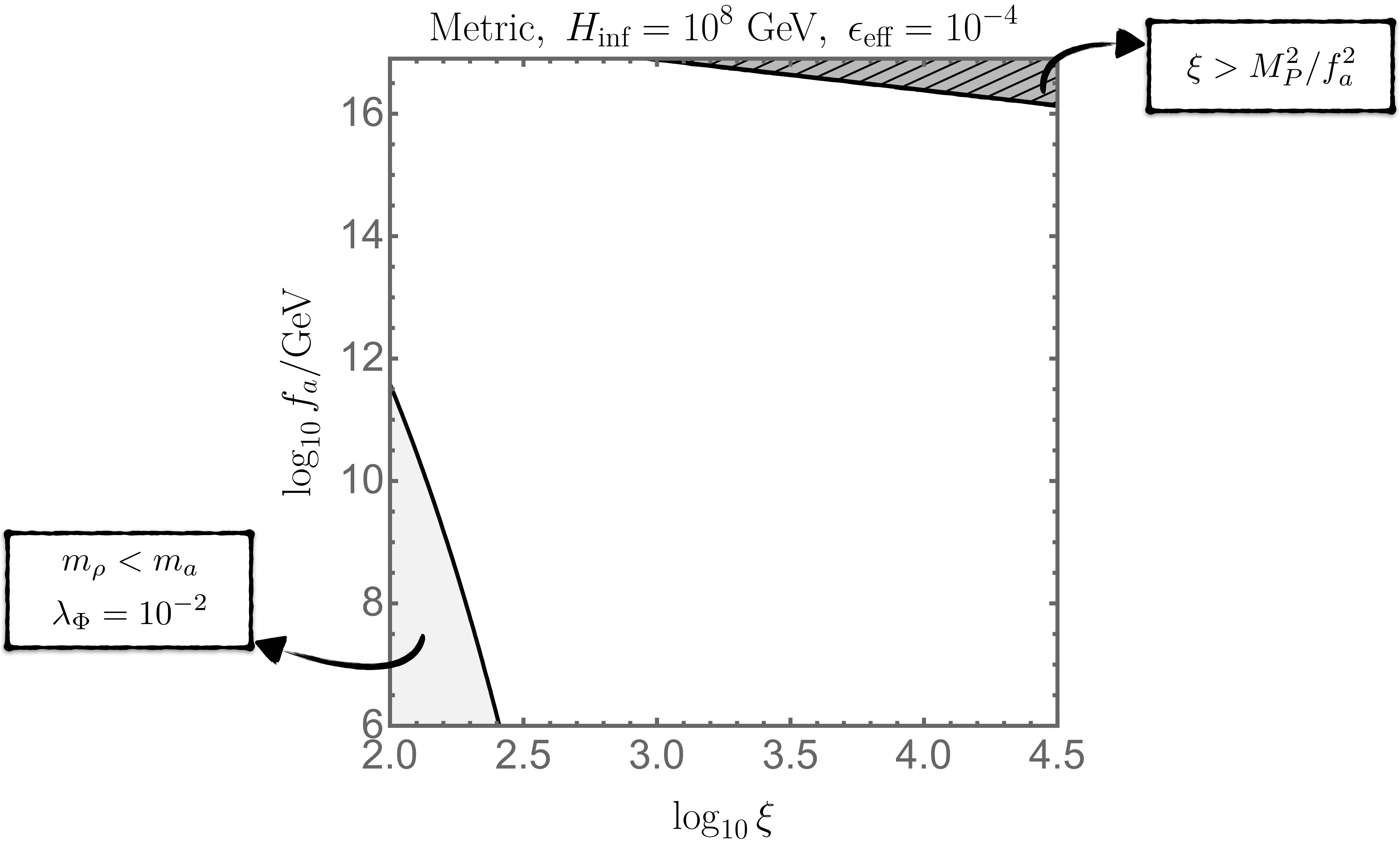
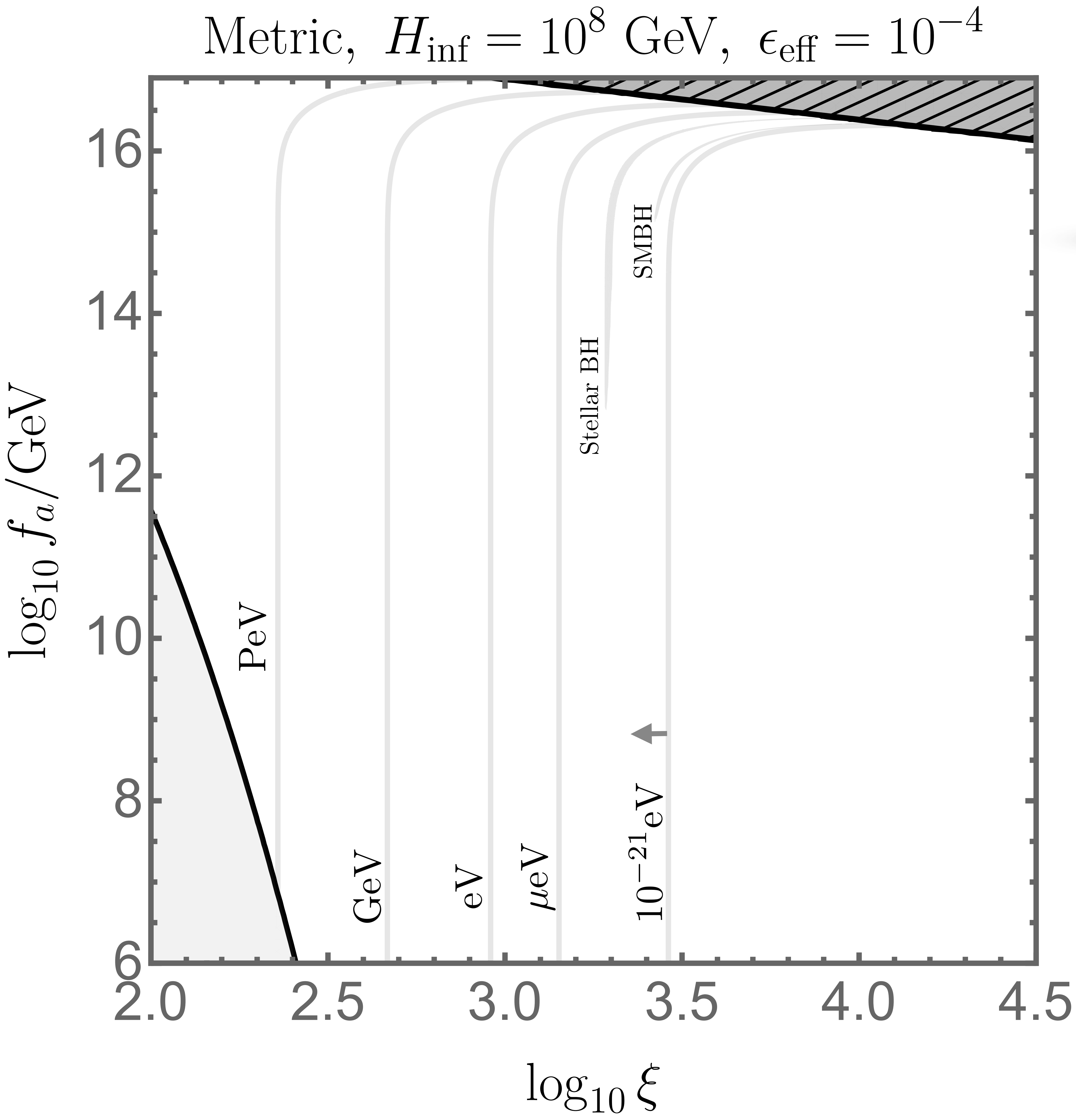


Wormhole Induced ALP DM - Benchmark

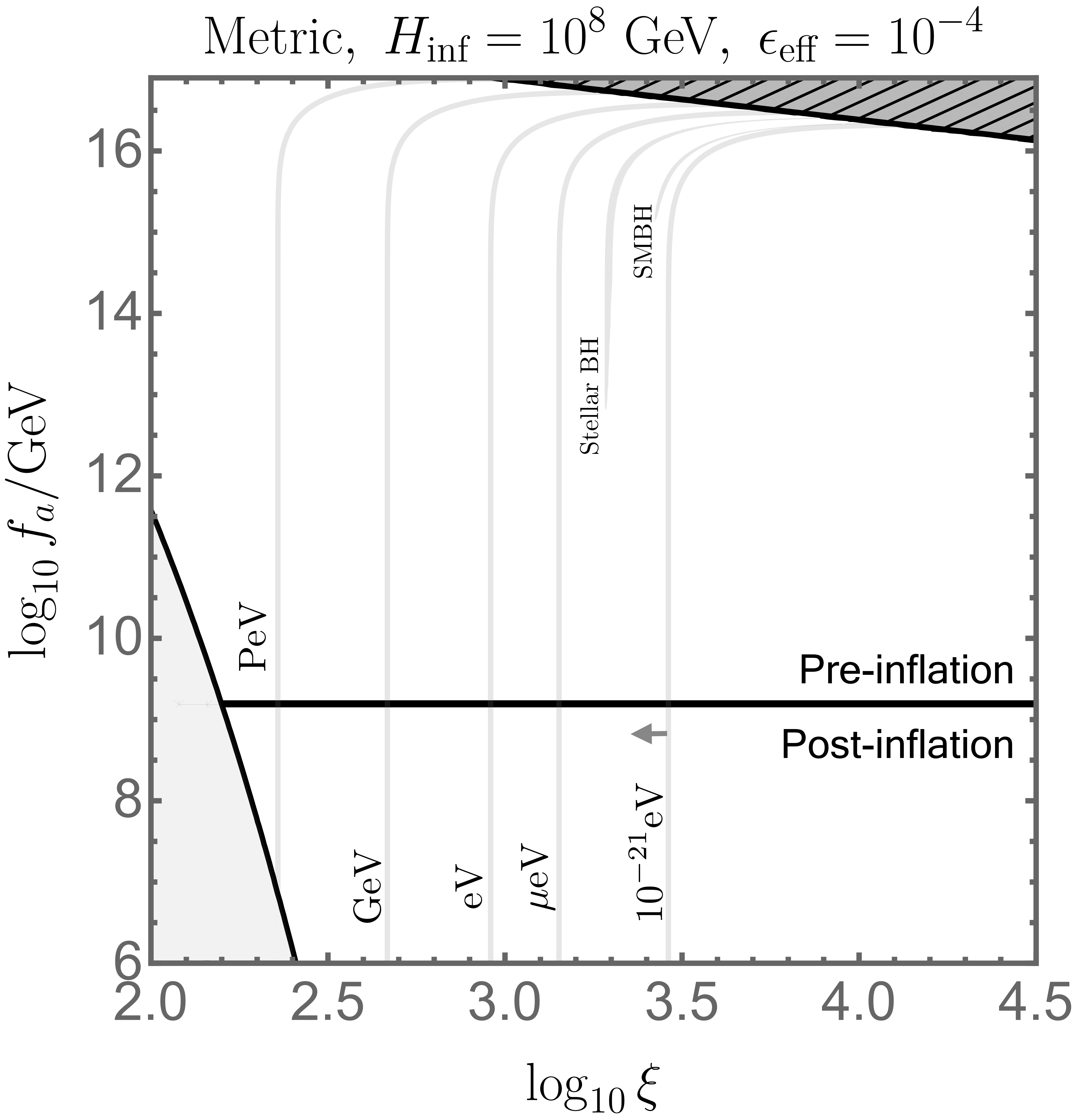
[DYC, et.al., 2411.07713]



$$m_a^2 \sim \frac{1}{f_a L_w^3} e^{-S_w}$$

Wormhole Induced ALP DM - Benchmark

[DYC, et.al., 2411.07713]



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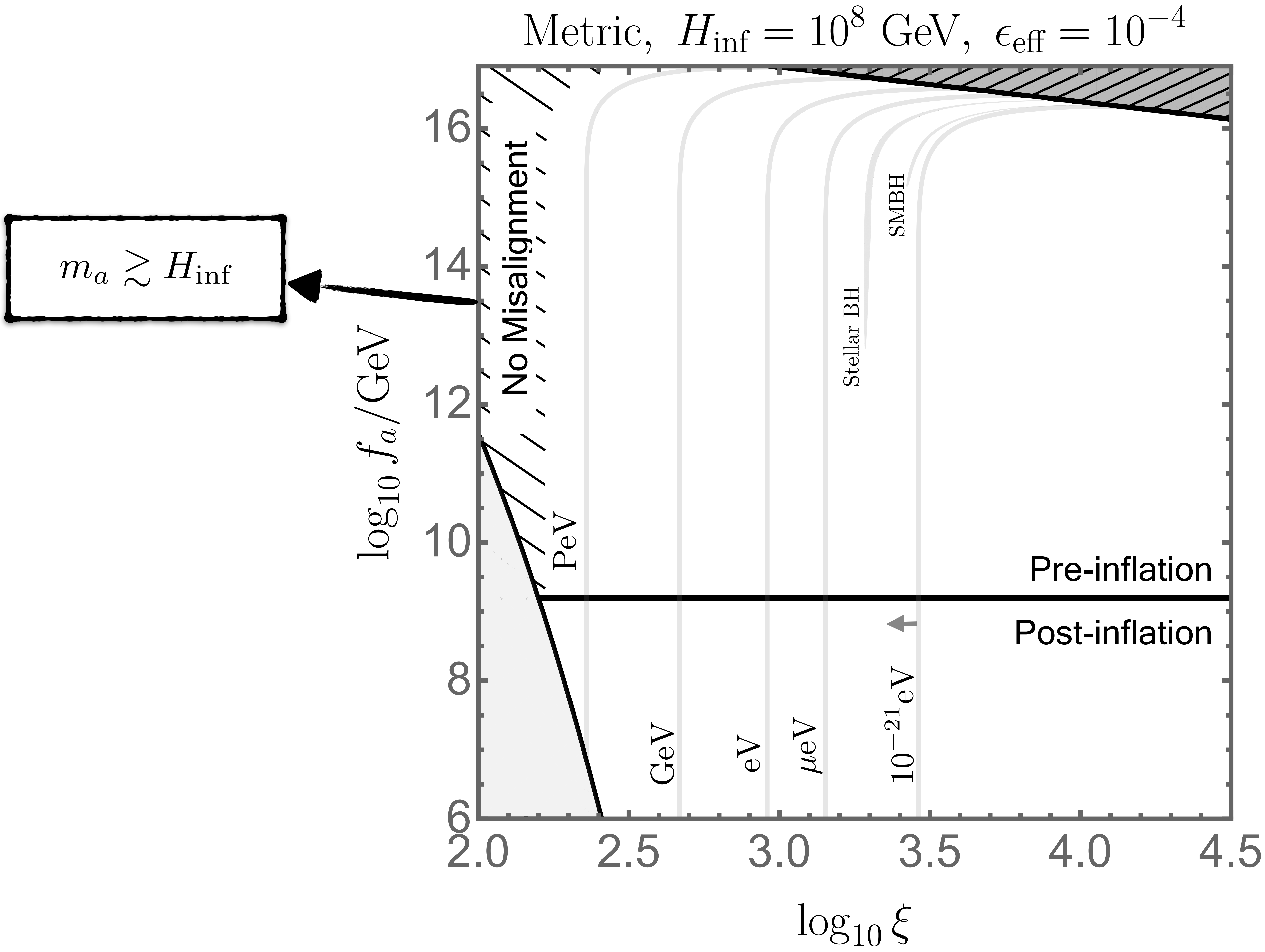

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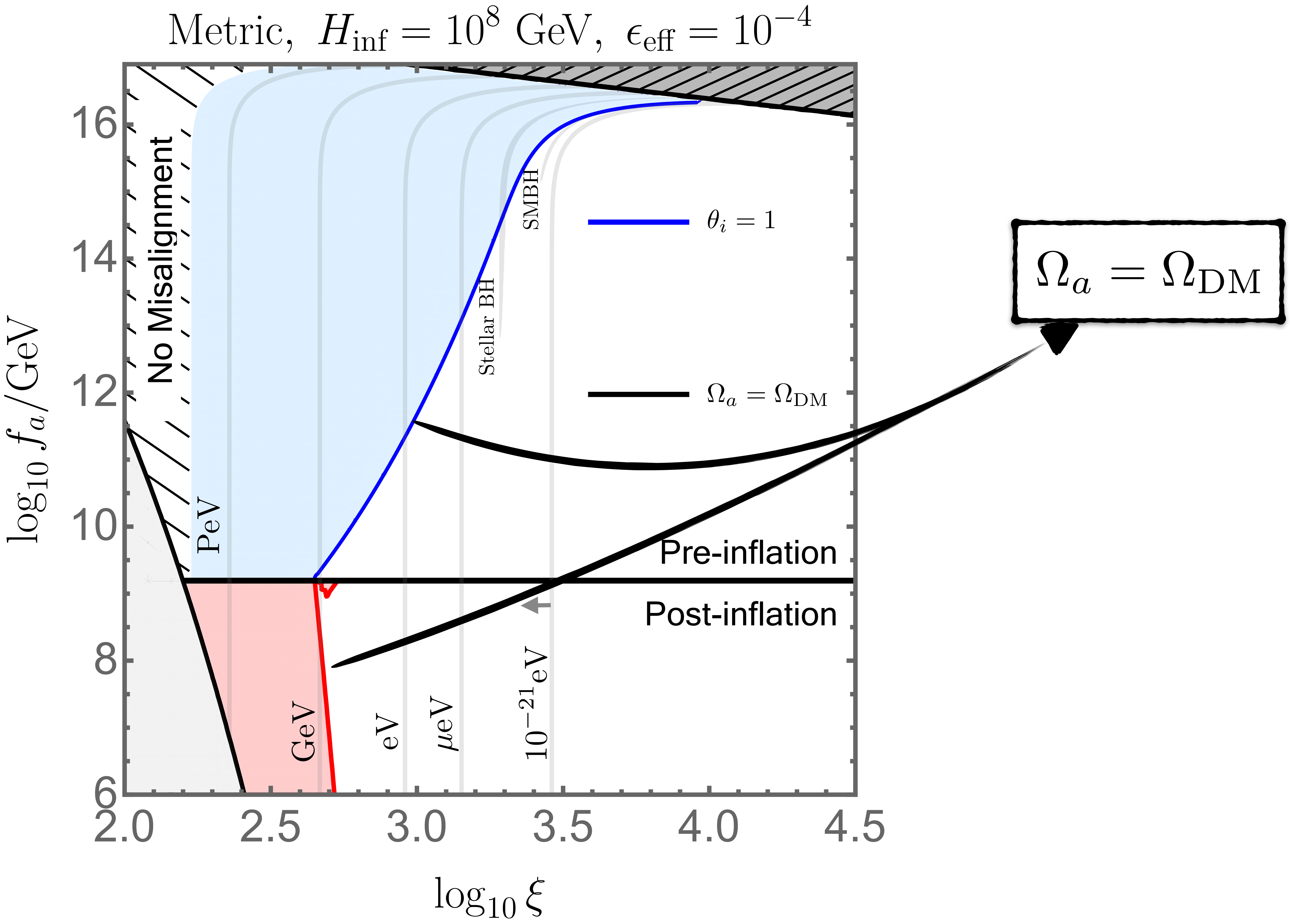

Wormhole Induced ALP DM - Benchmark

[DYC, et.al., 2411.07713]

$$H_{\rm osc} \lesssim H_c$$

$$\langle\theta_i^2\rangle = \pi^2/3$$

$$\left.\frac{\rho_a}{s}\right|_{\rm osc} \simeq \frac{3}{4}T_{\rm osc}\frac{g_*(T_{\rm osc})}{g_{*,s}(T_{\rm osc})}\cdot\frac{\langle\theta_i^2\rangle f_a^2 m_a^2/2}{3M_P^2H_{\rm osc}^2}$$

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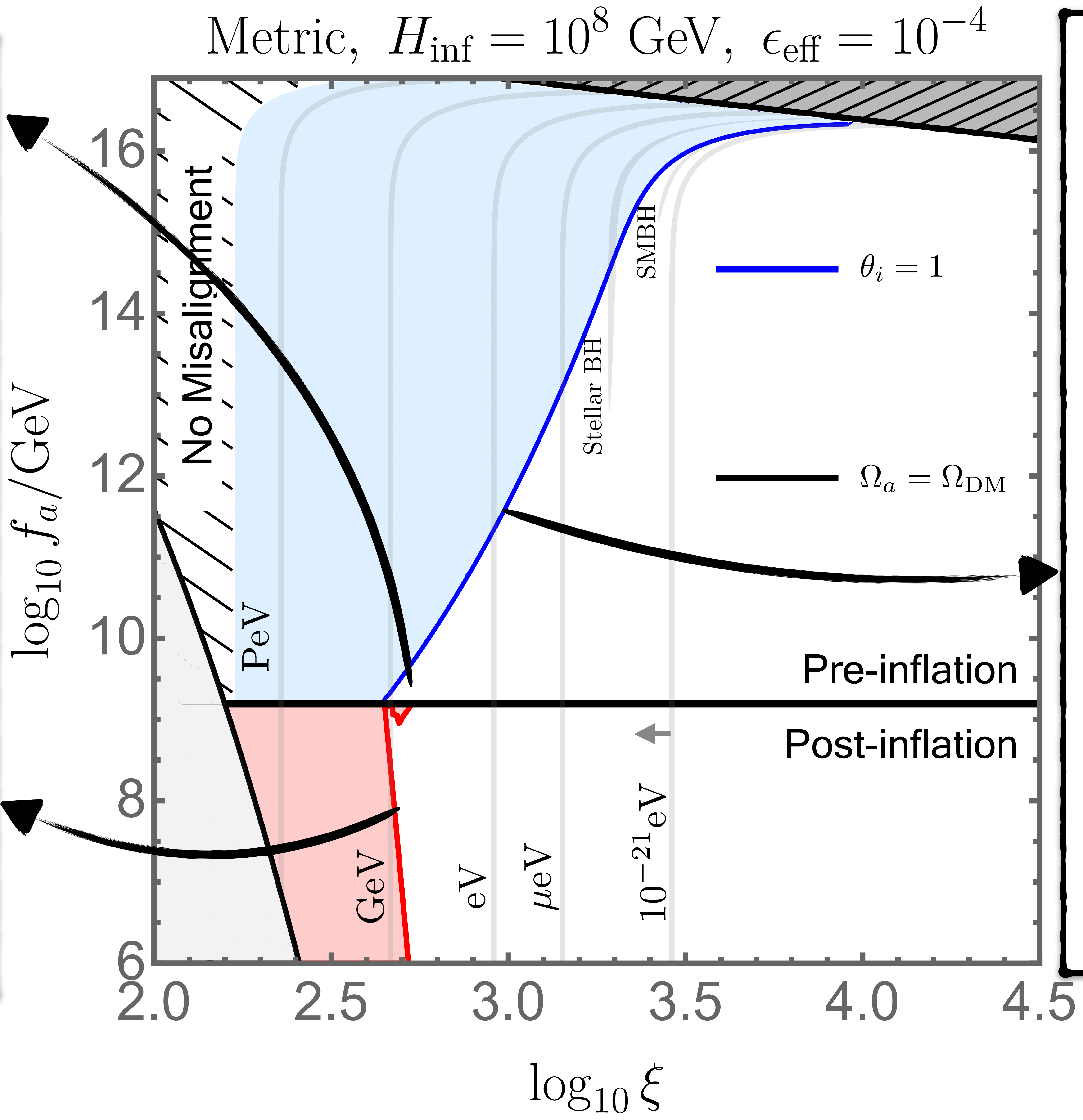
$$\left.\frac{\rho_a}{s}\right|_c = \frac{\langle\theta_i^2\rangle f_a^2 m_a^2/2}{2\pi^2 g_{*,s}(T_c)T_c^3/45}$$

osc. right after PT



$$H_{\rm osc} \lesssim H_{\rm reh}$$

osc. during RD

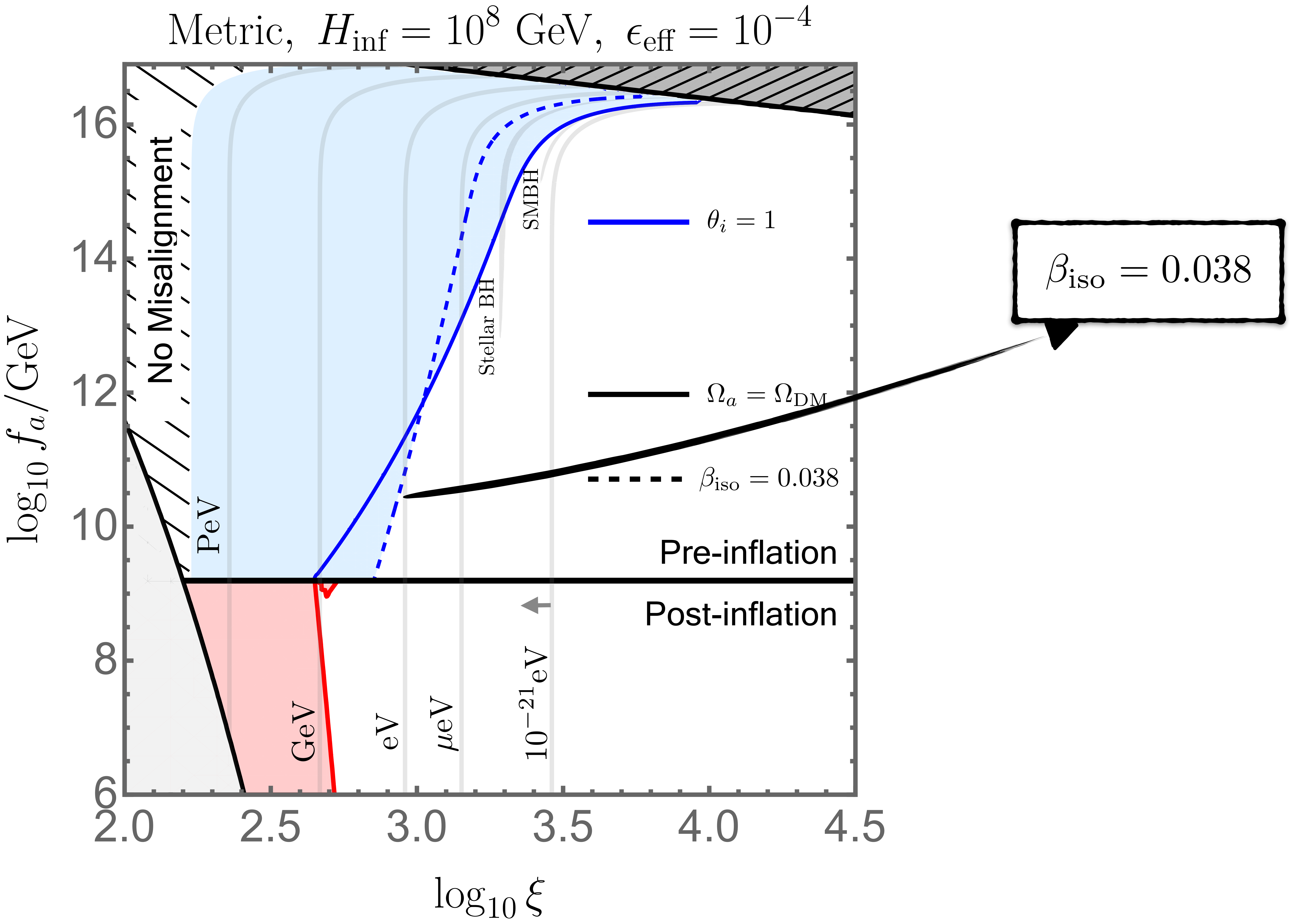
$$\left.\frac{\rho_a}{s}\right|_{\rm osc} = \left.\frac{\rho_{\rm rad}}{s}\right|_{\rm osc}\cdot\left.\frac{\rho_a}{\rho_{\rm rad}}\right|_{\rm osc}$$

$$\simeq \frac{3}{4}T_{\rm osc}\frac{g_*(T_{\rm osc})}{g_{*,s}(T_{\rm osc})}\cdot\frac{\langle\theta_i^2\rangle f_a^2 m_a^2/2}{3M_P^2H_{\rm osc}^2}$$

$$H = H_{\rm osc} \simeq m_a/3$$

Wormhole Induced ALP DM - Benchmark

[DYC, et.al., 2411.07713]



Wormhole Induced ALP DM - Benchmark

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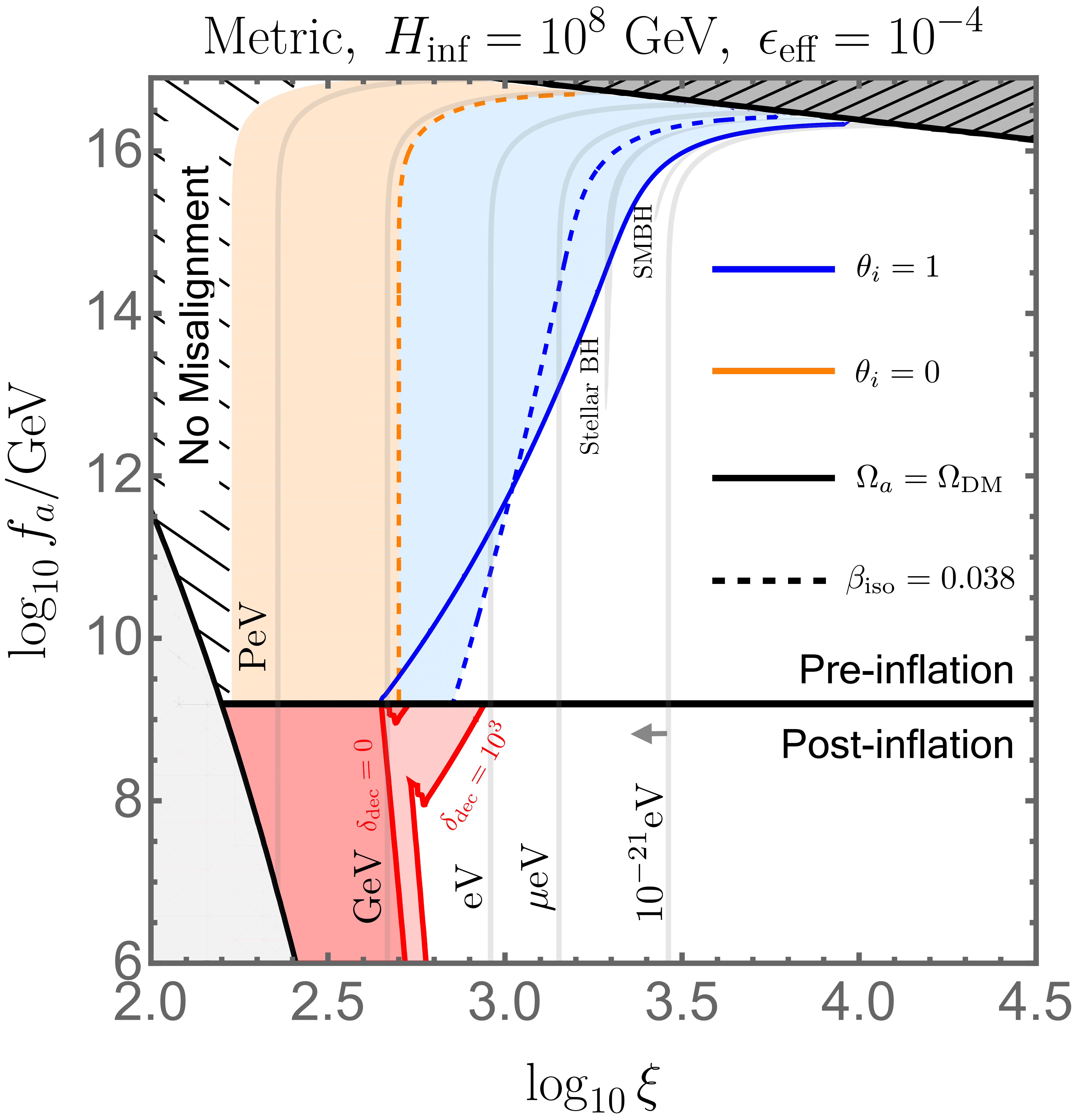
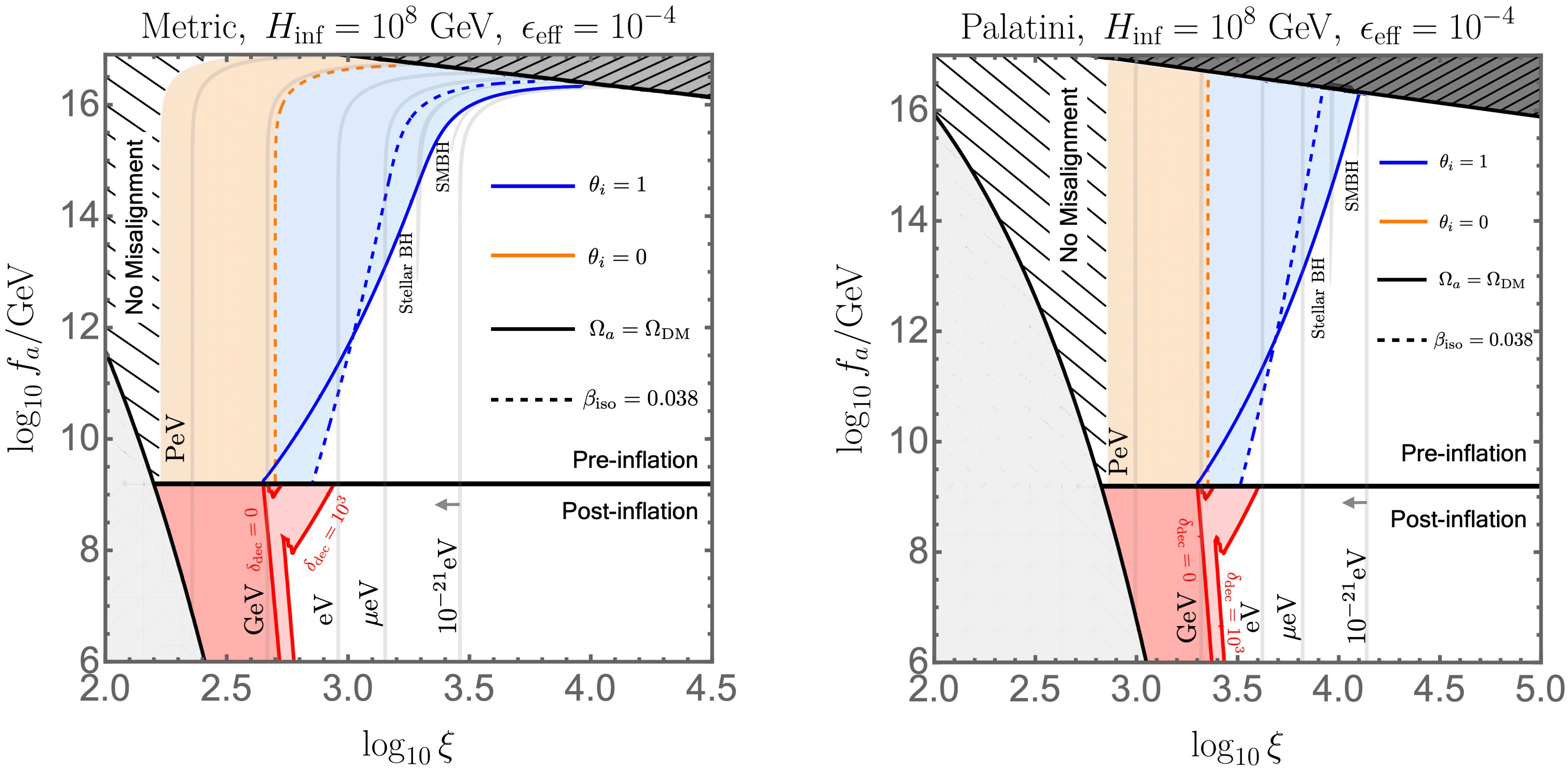


Wormhole Induced ALP DM - Metric vs Palatini

[DYC, et.al., 2411.07713]



Radial Mode Inflation?

[DYC, et.al., 2411.07713]

$$S=\int d^4x\sqrt{|g|}\left[-\frac{M_P^2}{2}\left(1+\frac{\xi}{M_P^2}(\rho^2-f_a^2)\right)R(\Gamma)+\frac{1}{2}\left(\partial_\mu\rho\right)^2+\frac{1}{2}\rho^2\left(\partial_\mu\theta\right)^2+\frac{\lambda_\Phi}{4}\left(\rho^2-f_a^2\right)^2\right]$$

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Large ξ values : ρ can act as an inflaton!

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$$\xi \simeq \begin{cases} 4.9 \times 10^4 \sqrt{\lambda_\Phi} & \text{(metric)} \\ 1.4 \times 10^{10} \lambda_\Phi & \text{(Palatini)} \end{cases}$$

$$\rho_* \simeq \begin{cases} \left(\frac{4N_e}{3\xi} \right)^{1/2} M_P & \text{(metric)} \\ 2\sqrt{2N_e} M_P & \text{(Palatini)} \end{cases}$$

$$H_{\text{inf}} \simeq \begin{cases} 1.4 \times 10^{13} \text{GeV} & \text{(metric)} \\ \frac{5.9 \times 10^{12}}{\sqrt{\xi}} \text{GeV} & \text{(Palatini)} \end{cases}$$

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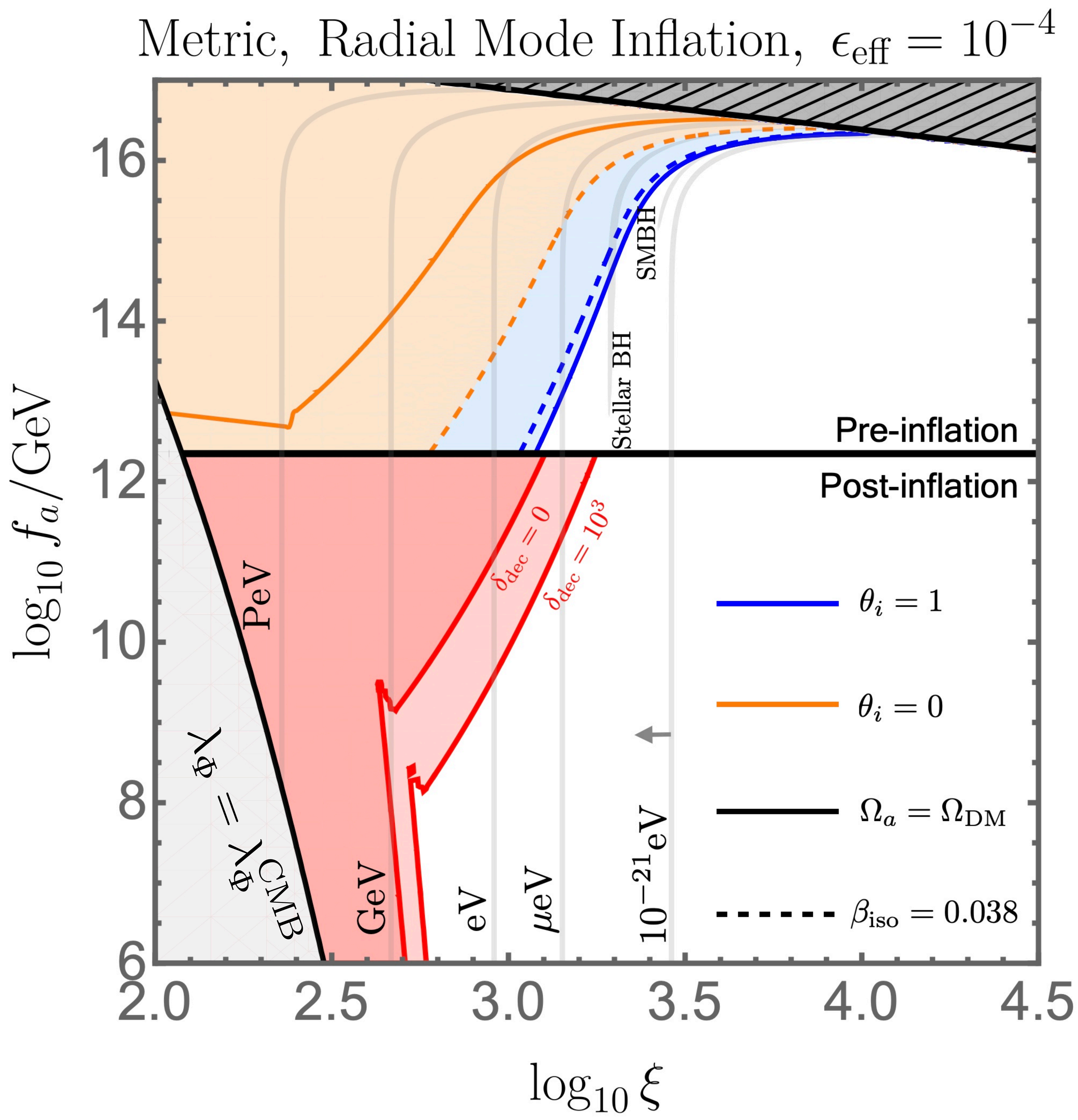
→

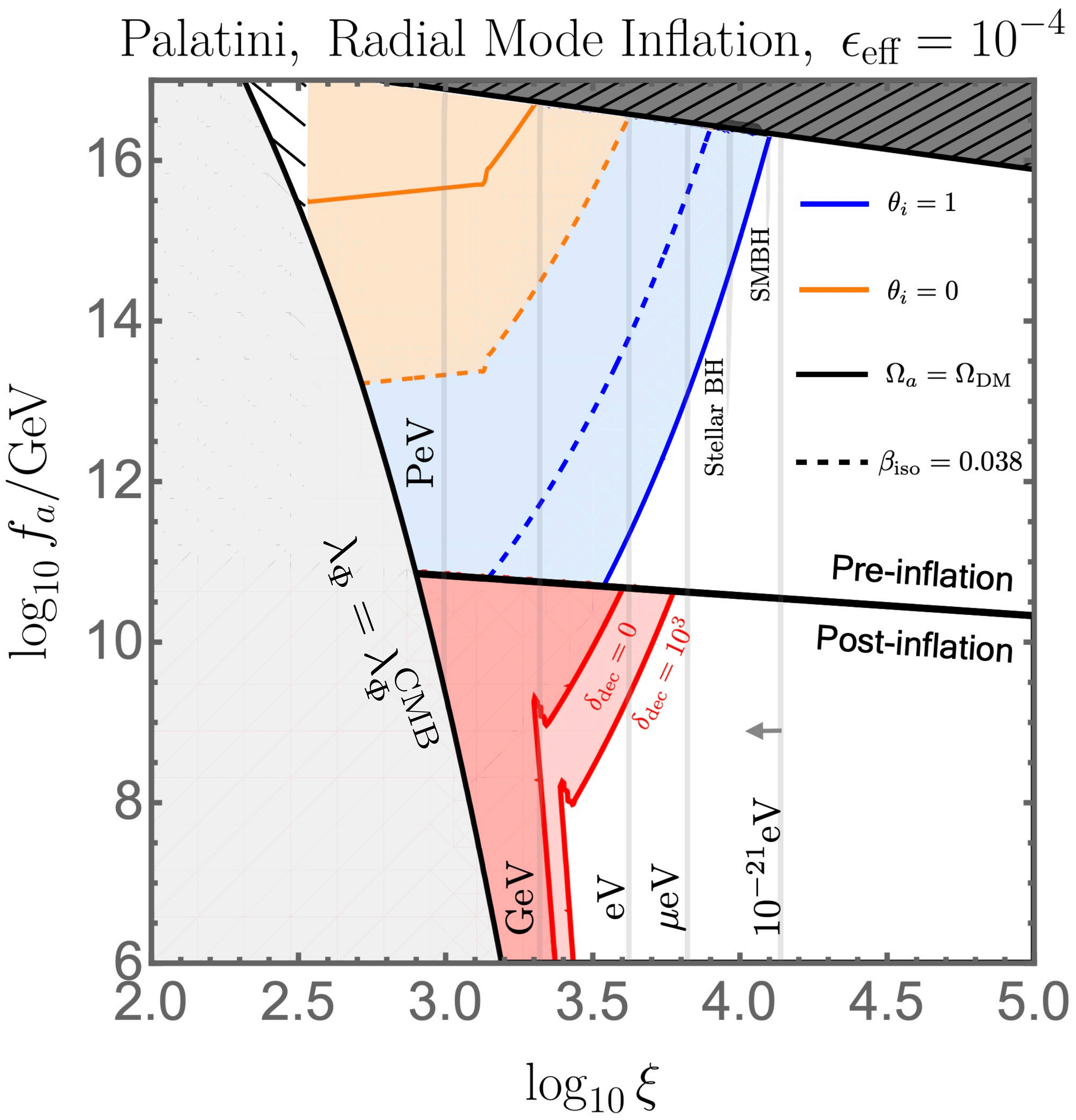
Different ρ value for β_{iso}!

$$\langle \theta^2_{\text{mis},*} \rangle = \theta_i^2 + \left(\frac{H_{\rm inf}}{2\pi \rho_*} \right)^2$$

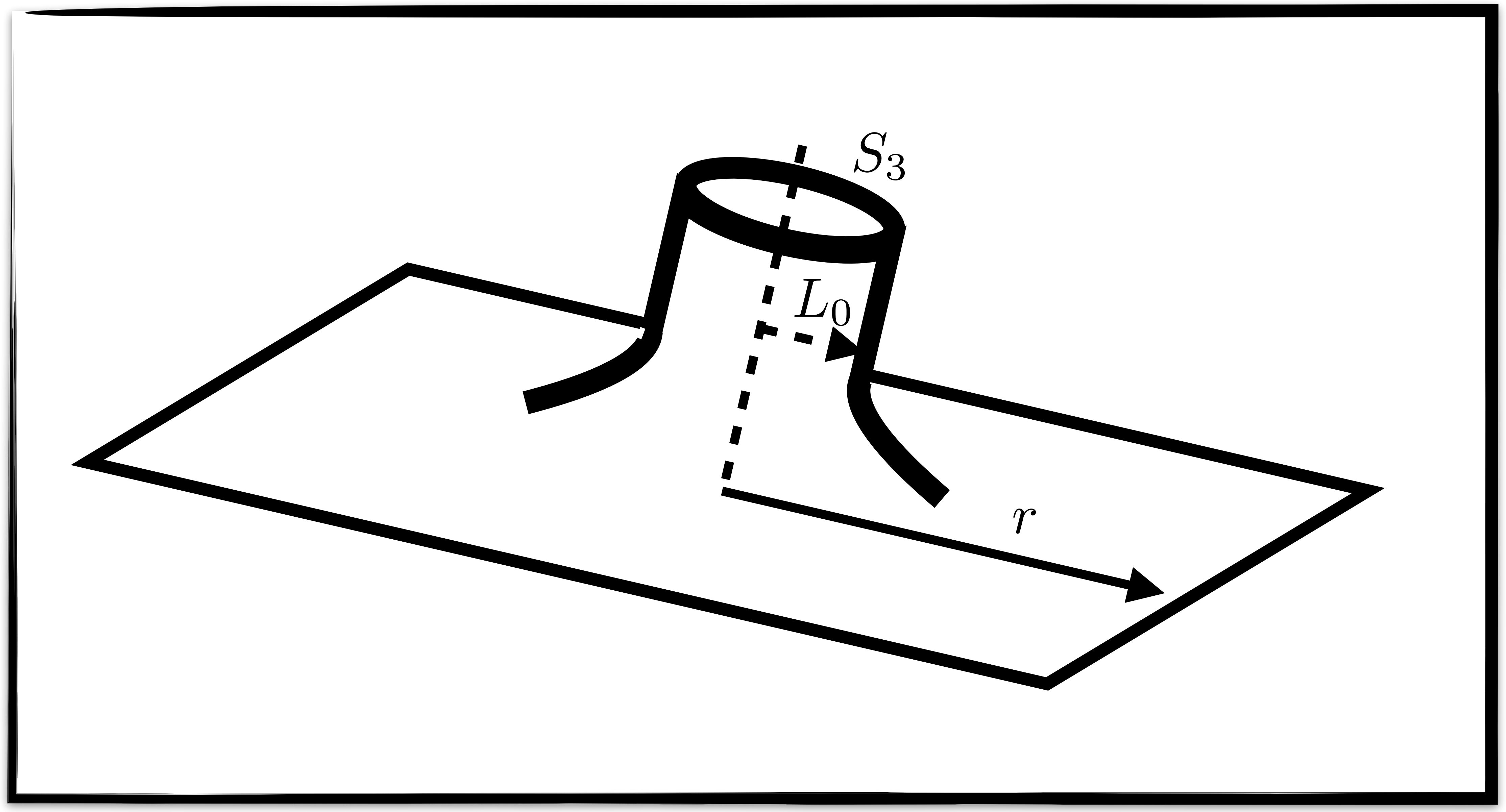
Wormhole ALP DM - Radial Mode Inflation

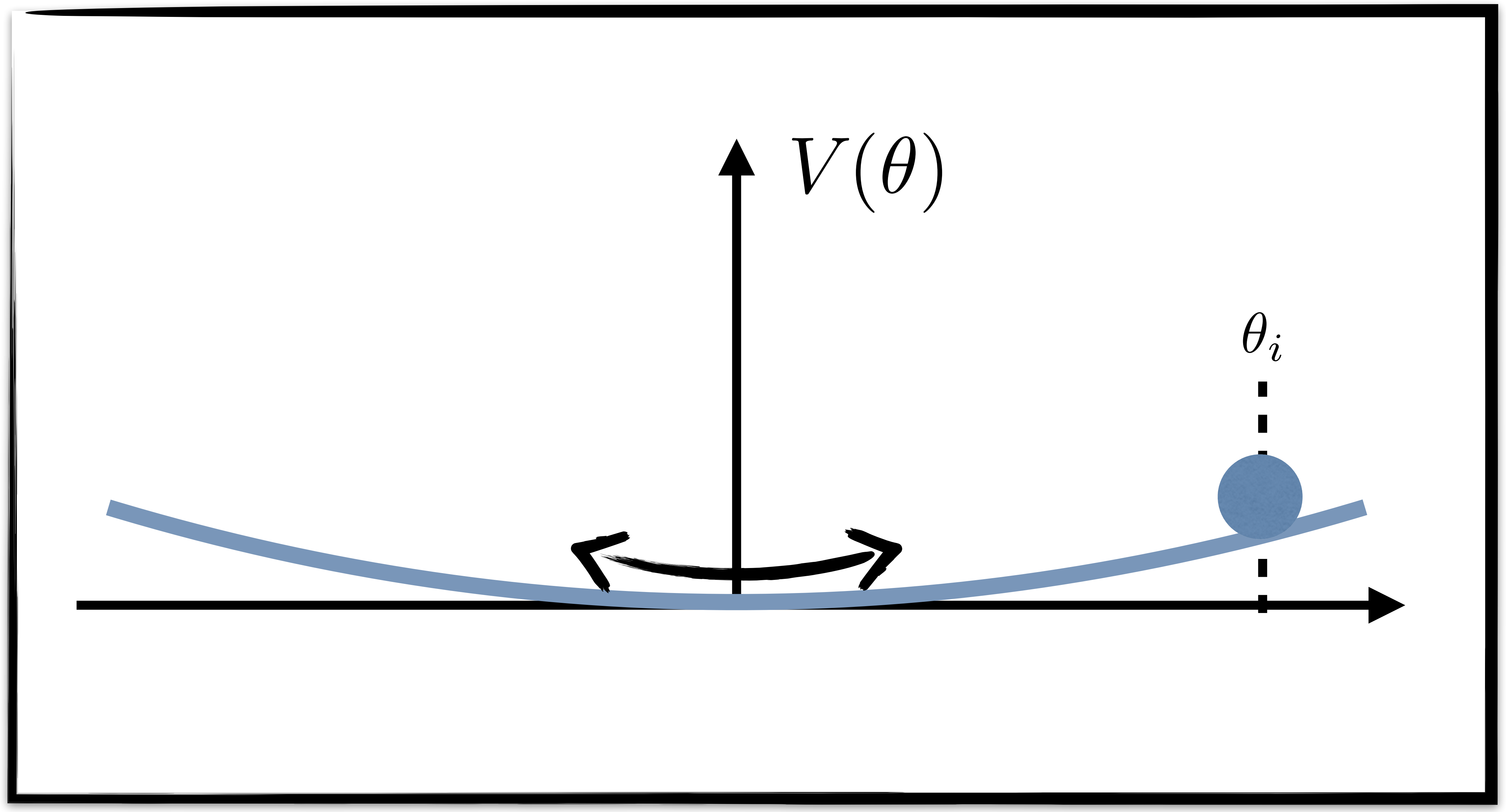
[DYC, et.al., 2411.07713]





Summary





Wormhole-Induced ALP Dark Matter!