New Perspectives on Axion Misalignment Mechanism

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arXiv: 1911.11885, C.-F. with Yanou Cui

R. T. Co, L. J. Hall, and K. Harigaya, (2019), arXiv:1910.14152 [hep-ph]

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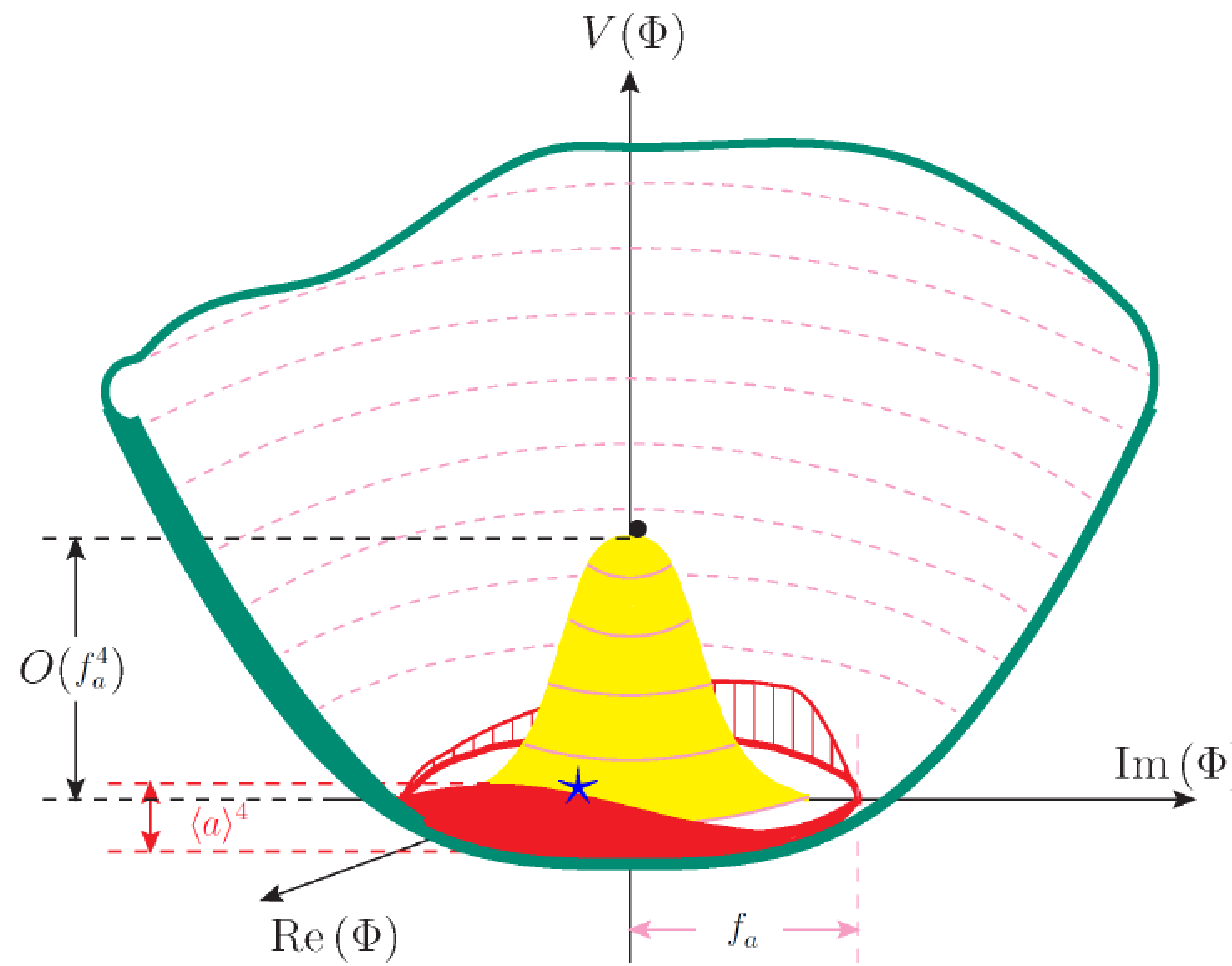
Outline

1. Briefly introduce axion evolution in universe
2. Kinetic misalignment mechanism
3. Conclusion and Discussion

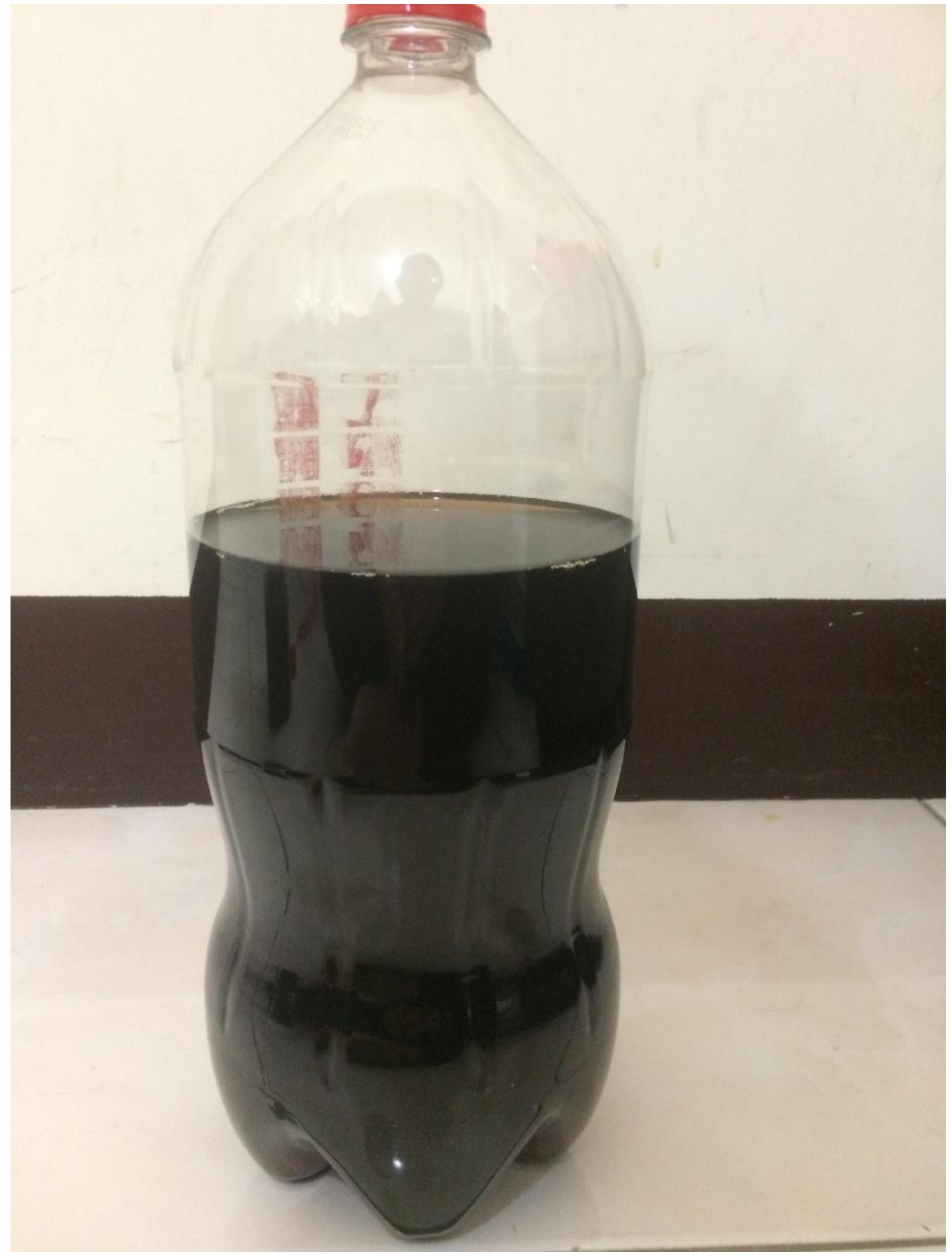
- Strong CP Problem & U(1)_A Problem

- Cosmological Problems

$$G \xrightarrow{f_a} H \times U(1)_a \xrightarrow{\Lambda_{\rm QCD}} H_0 \times Z_n$$

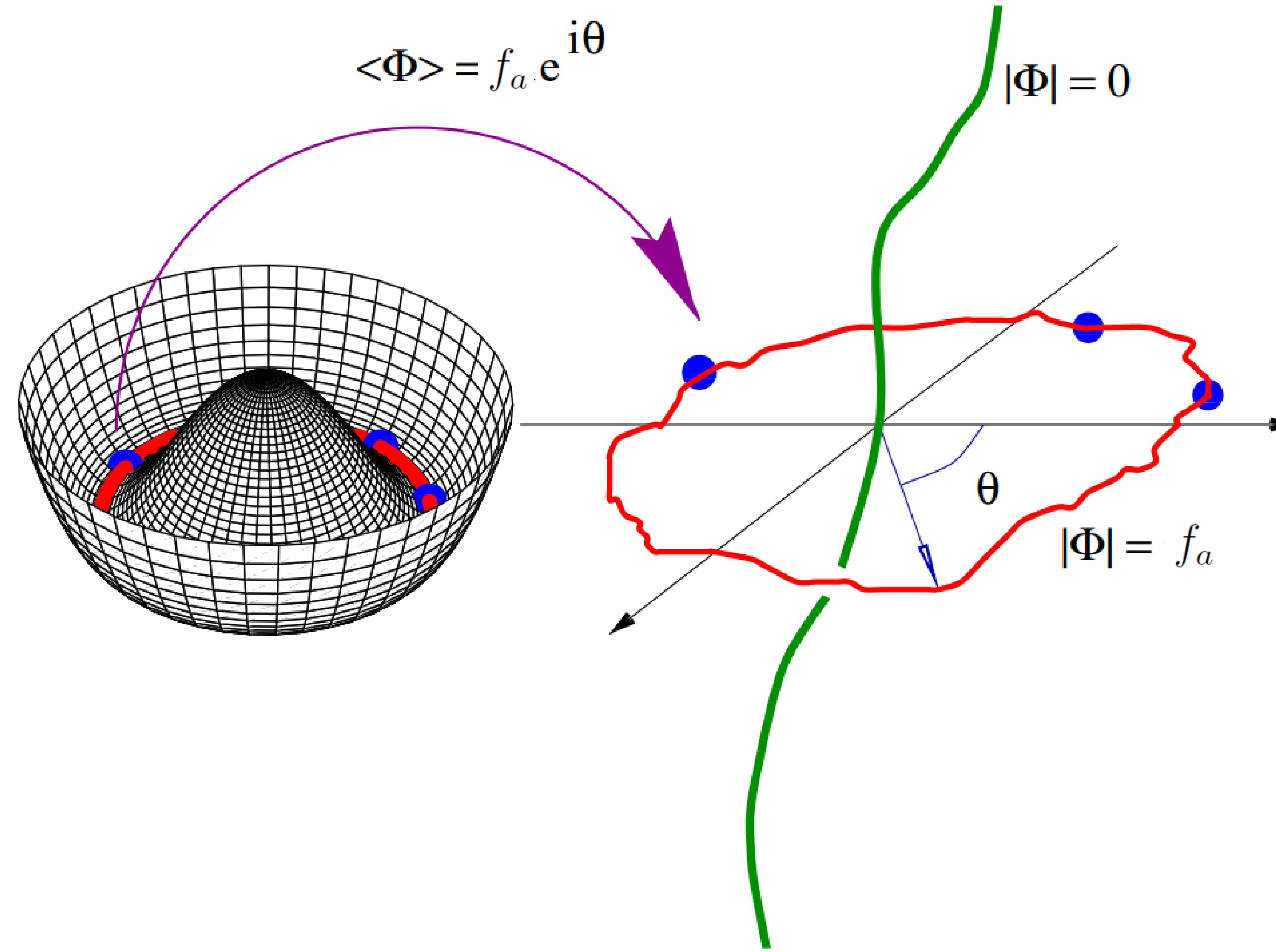


Jihn E. Kim



Cosmic String

f_a



$$e^{i\gamma_5 \frac{a}{f_a}}\psi \to e^{i\gamma_5\left(\frac{a}{f_a}+\alpha\right)}\psi,$$

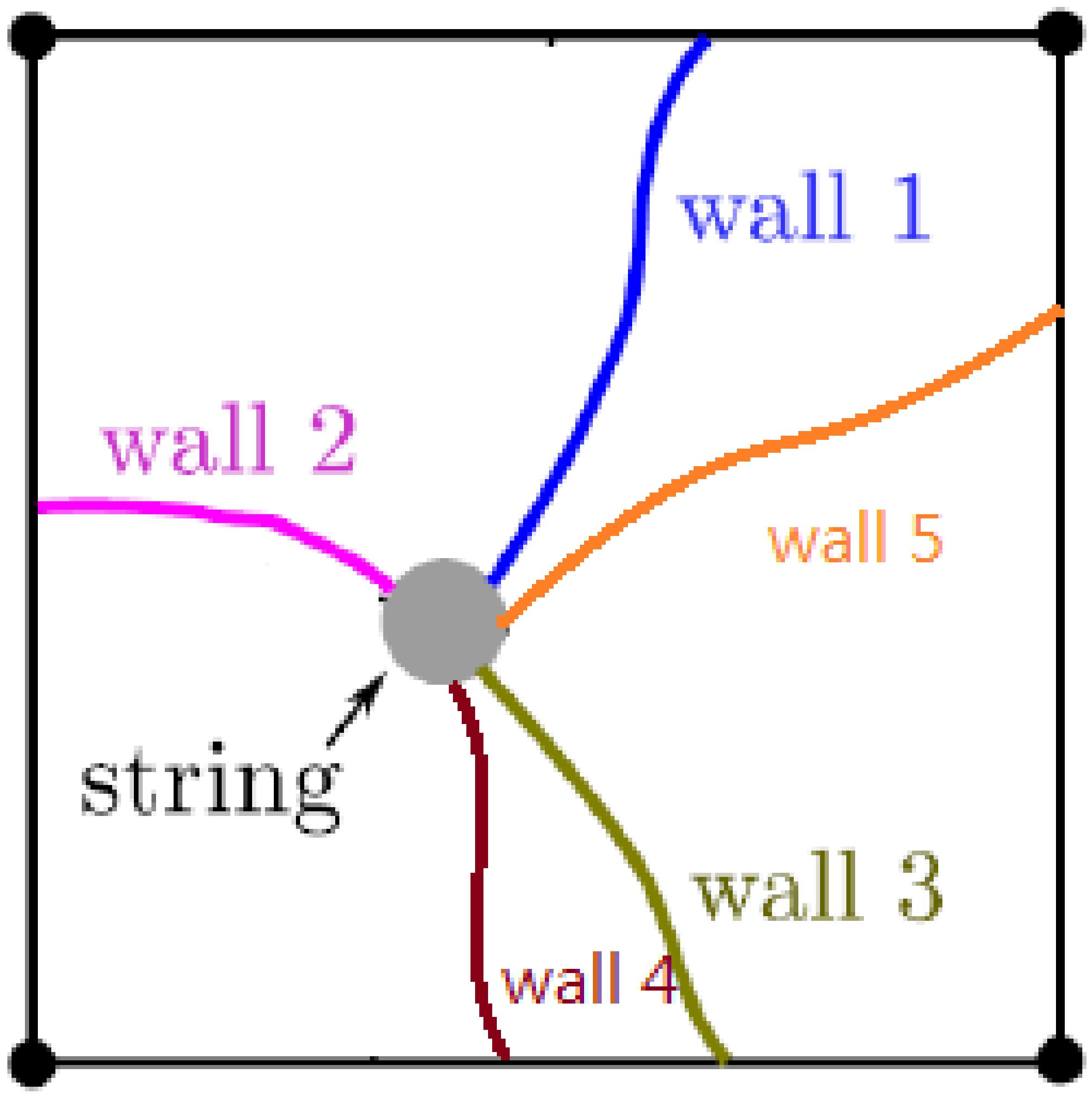
Christophe Ringeval 1005.4842

f_a

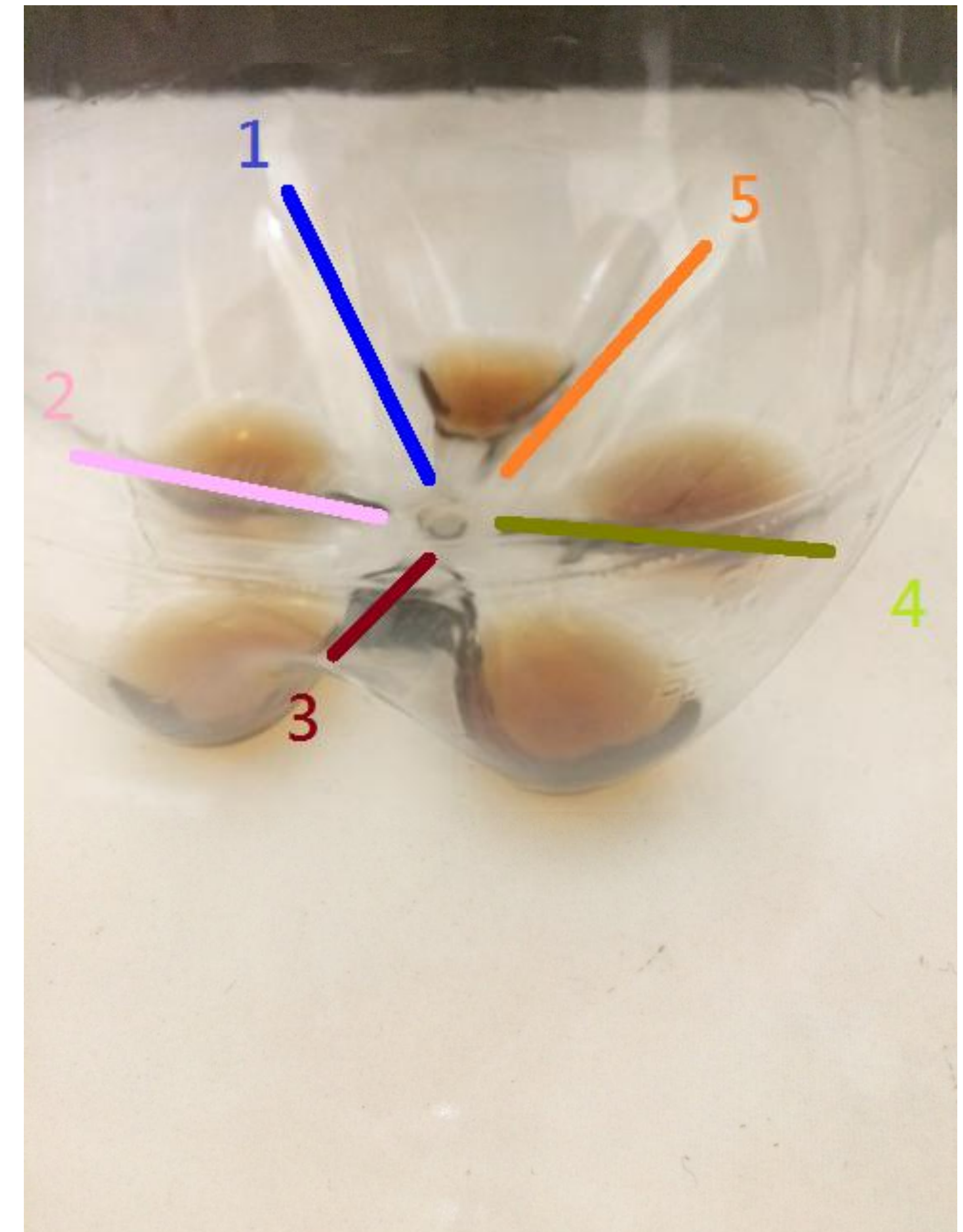
Λ_{QCD}

$$e^{i\gamma_5 \frac{a}{f_a}} \psi \rightarrow e^{i\gamma_5 \left(\frac{a}{f_a} + \alpha\right)} \psi,$$

real space



$\Lambda_{\rm QCD}$



Domain Wall

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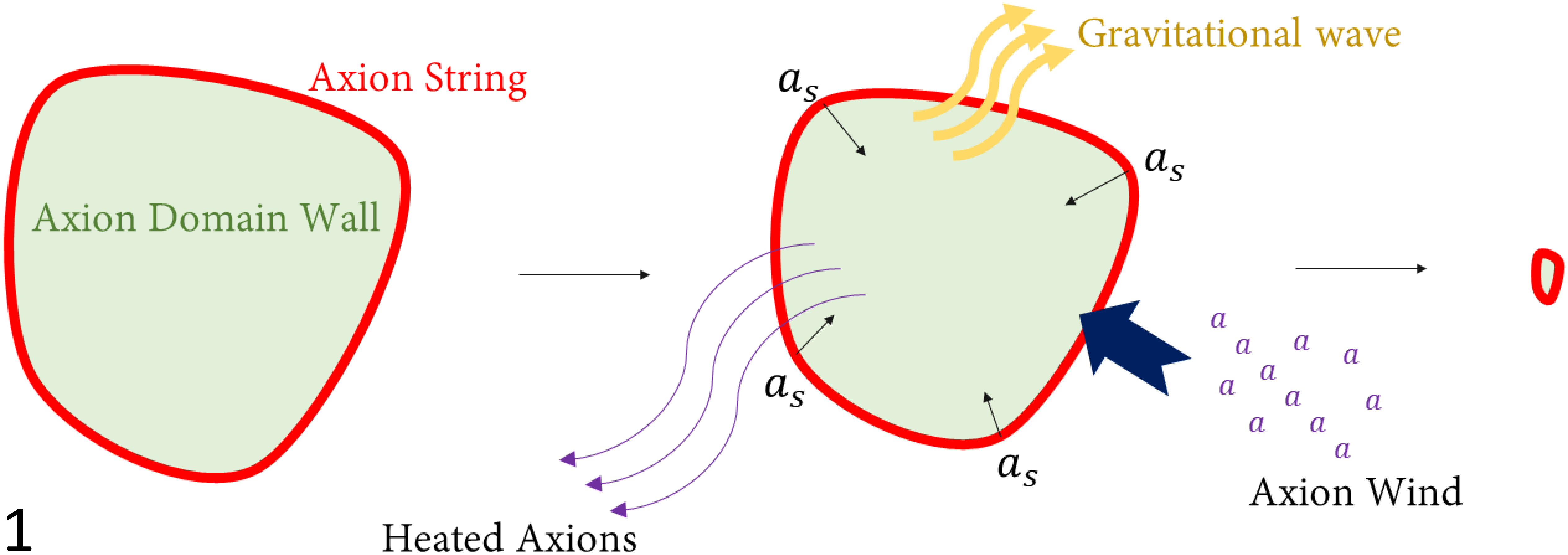
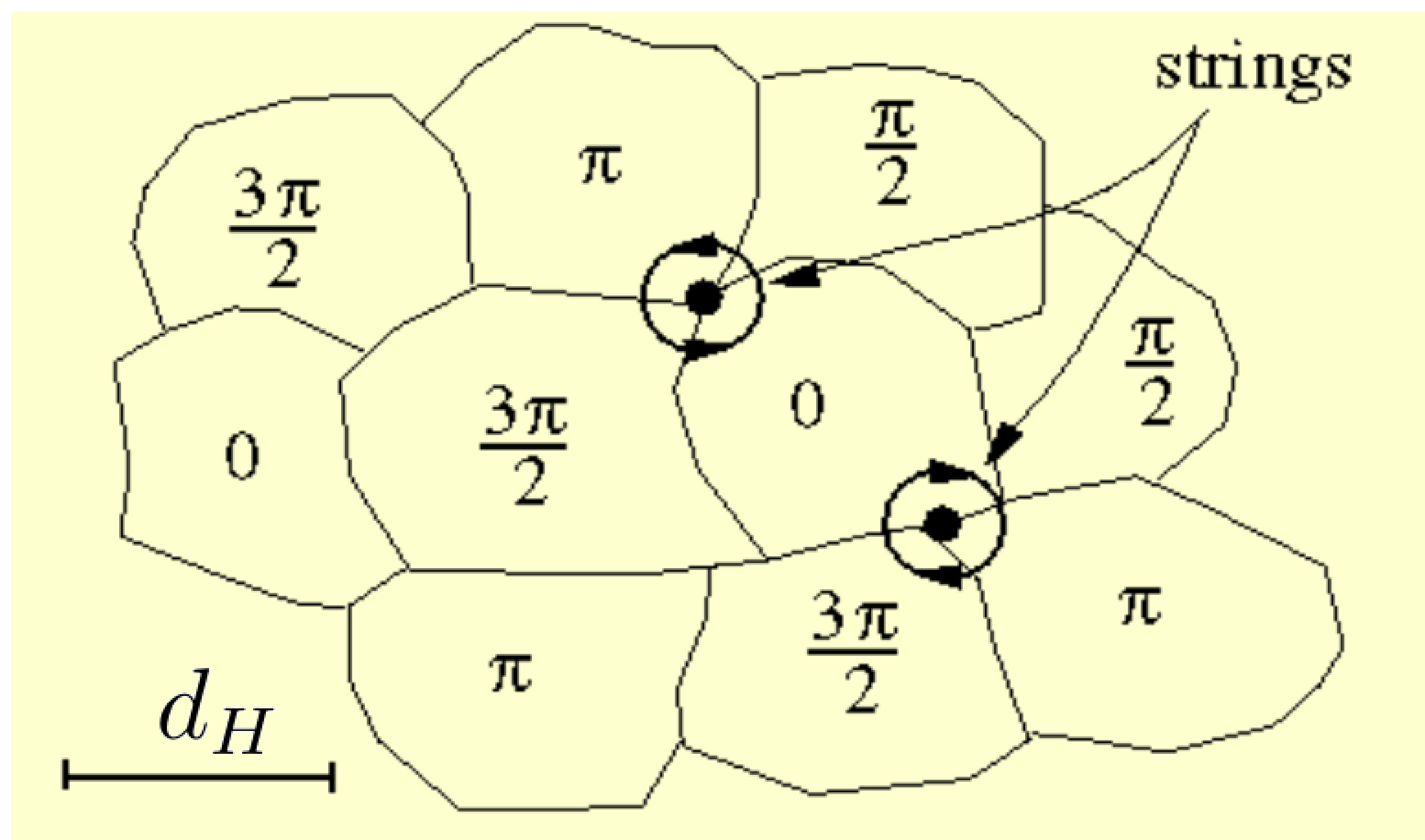


N=1



N=3

The Kibble mechanism for the formation of cosmic strings.

$$\Omega_{a,\mathrm{Mis}} \simeq 0.19\langle\theta_1^2\rangle \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19},$$

$$\Omega_{a,\mathrm{str}} \simeq (4.0 \pm 2.0) \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19},$$?

$$\Omega_{a,\mathrm{wall}} \simeq (11.8 \pm 5.7) \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19},$$?

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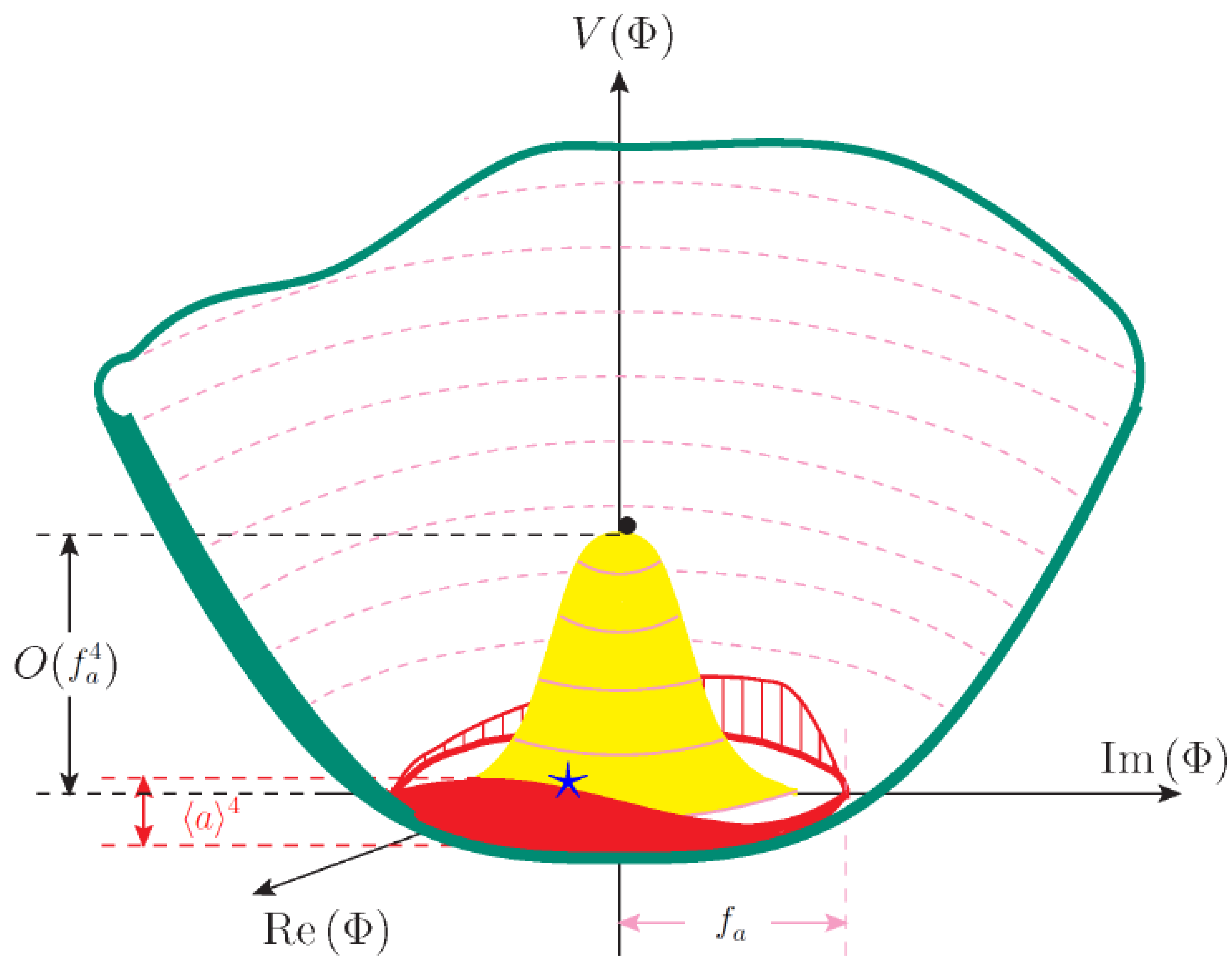
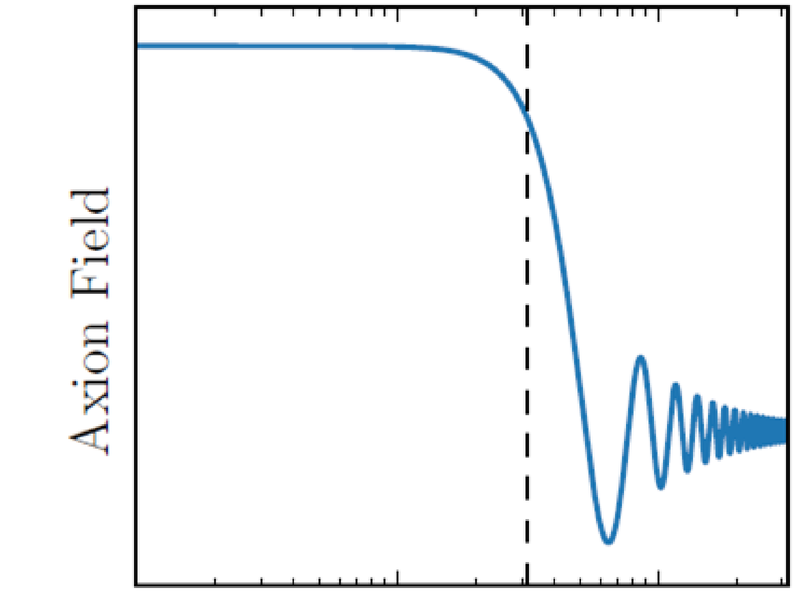
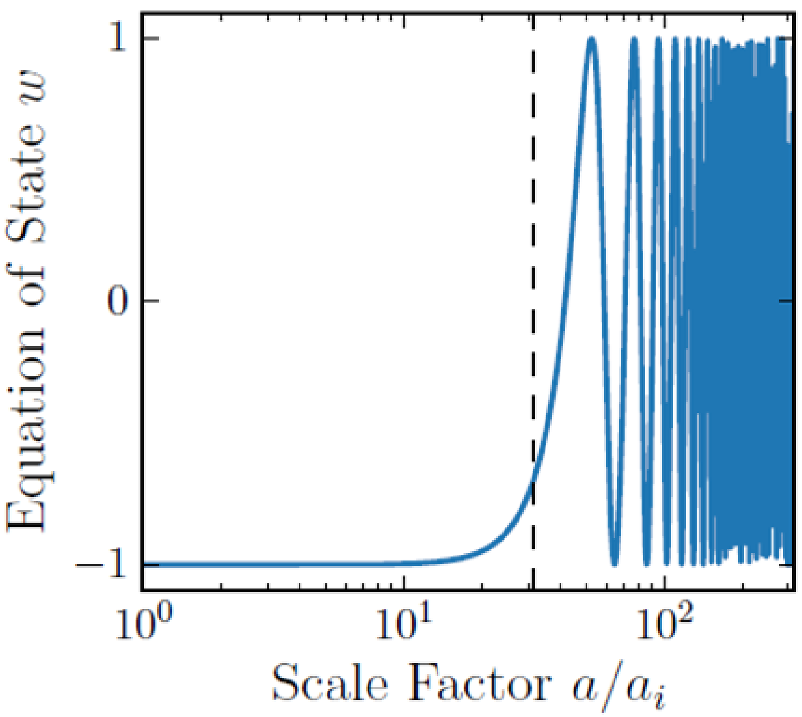
Misalignment Mechanism

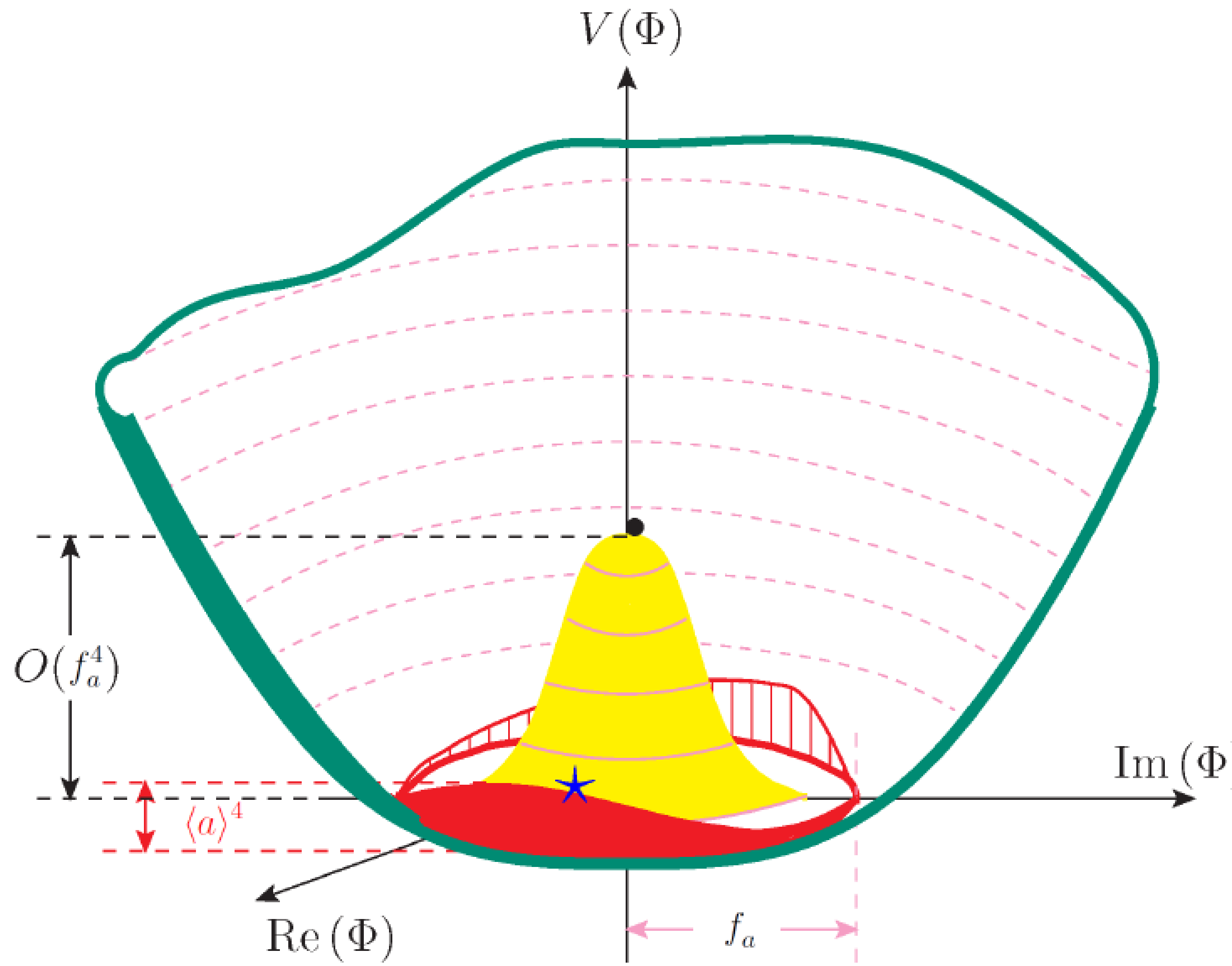


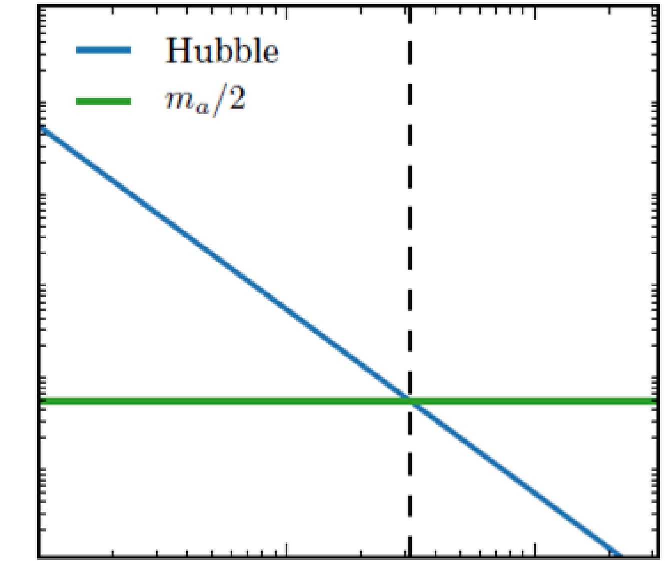
$$V(a) = m_a^2 f_a^2 \left[1 - \cos\left(\frac{a}{f_a}\right)\right] \simeq \frac{1}{2} m_a^2 a^2 + \cdots$$

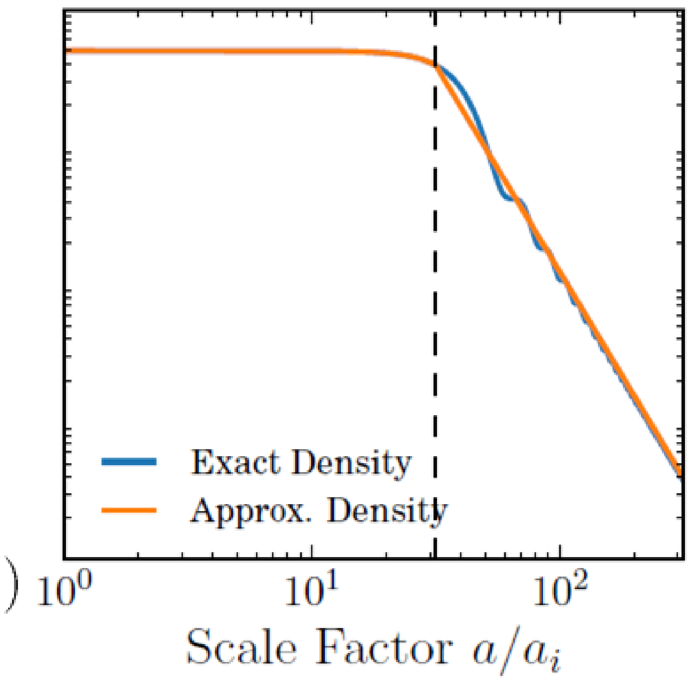
Misalignment Mechanism











$$\ddot{a} + 3H\dot{a} + V'(a) = 0 \quad \rightarrow \quad \ddot{a} + m_a^2 a \simeq 0 \quad \rightarrow \quad a(t) = A(t)\cos(m_a t + C)$$

$$a(t_i) = f_a\theta_{a,i}, \qquad \dot{a}(t_i) = 0, \qquad \rho_a = \frac{1}{2}\dot{a}^2 + \frac{1}{2}m_a^2 a^2, \qquad P_a = \frac{1}{2}\dot{a}^2 - \frac{1}{2}m_a^2 a^2.$$

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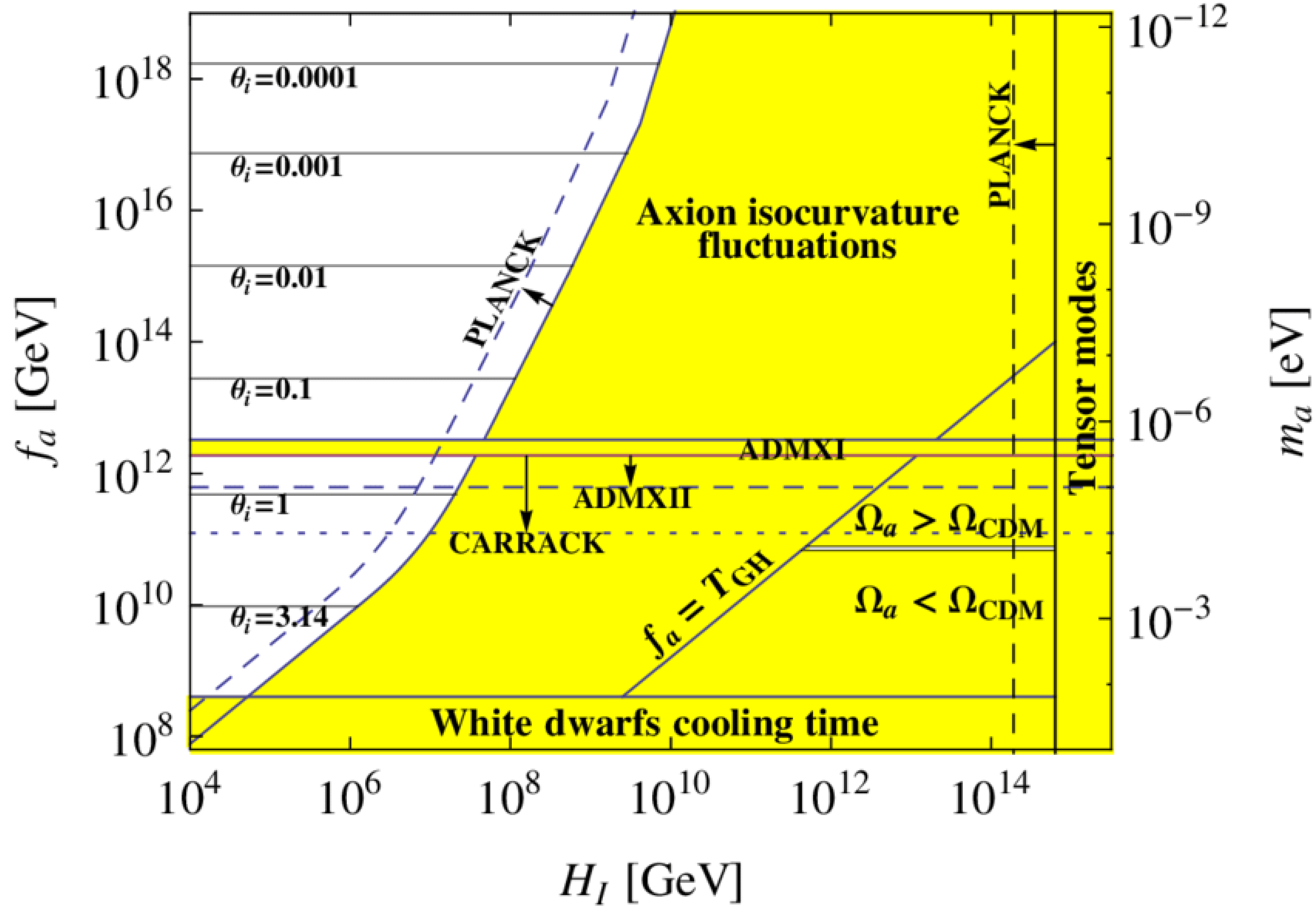
$$\Omega_a = 0.02\,\langle \theta_i^2 \rangle \left(\frac{f_a}{10^{11}\ \mathrm{GeV}} \right)^{7/6}$$



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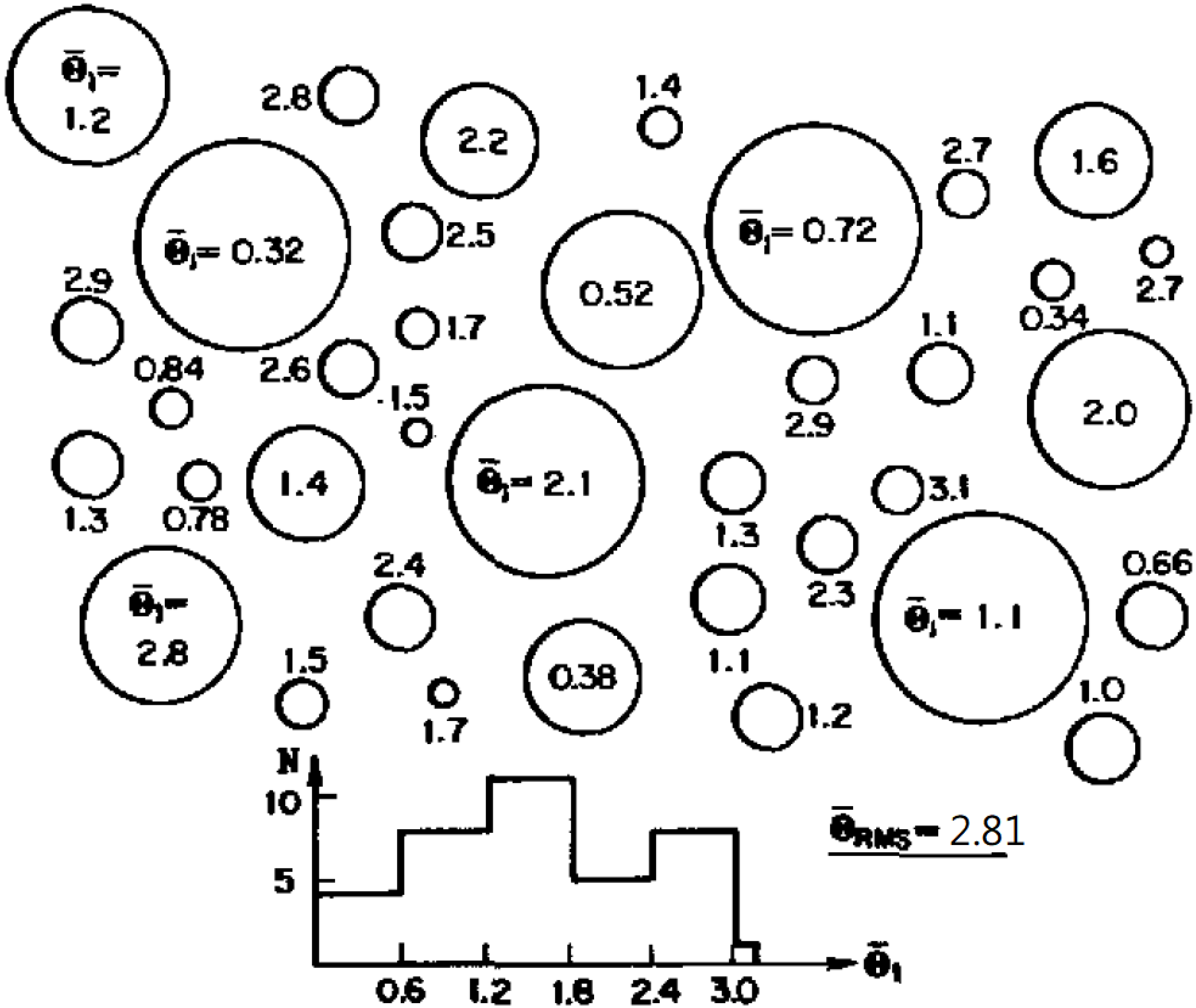
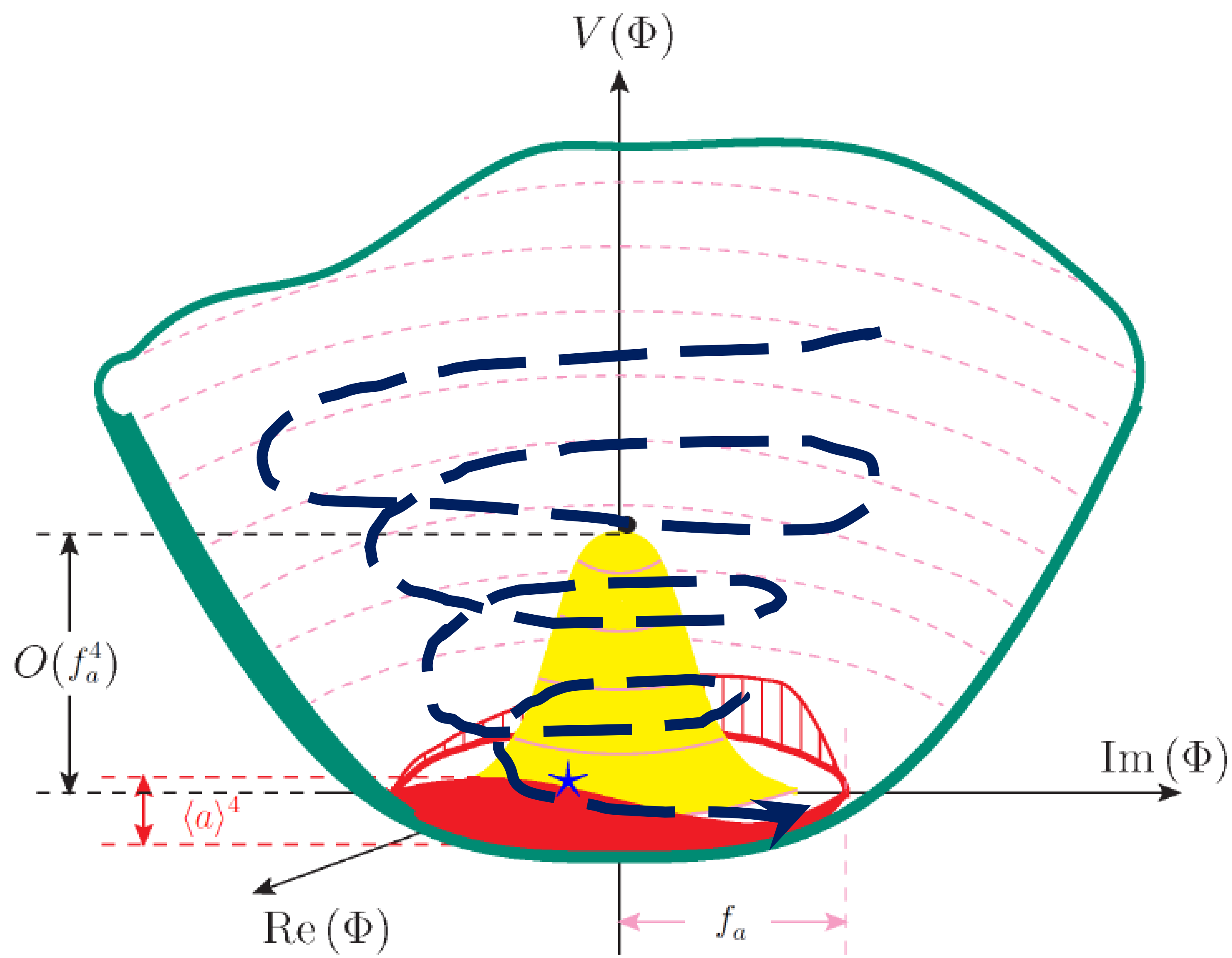

θ̄ᵢ= 1.2
2.8
2.2
1.4
1.6
2.7
θ̄ᵢ= 0.32
2.5
0.52
θ̄ᵢ= 0.72
2.9
1.7
2.7
1.1
0.34
0.84
2.6
1.5
2.9
2.0
1.4
θ̄ᵢ= 2.1
3.1
1.3
0.78
1.3
2.3
0.66
θ̄ᵢ= 2.8
2.4
θ̄ᵢ= 1.1
1.5
0.38
1.1
1.0
1.7
1.2
N
10
5
0.6
1.2
1.8
2.4
3.0
θ̄ᵢ
θ̄RMS= 2.81

Kinetic Misalignment

$$a(t_i) = f_a \theta_{a,i}, \qquad \dot{a}(t_i) \neq 0,$$

$$\ddot{a} + 3H\dot{a} + V'(a) = 0 \quad \rightarrow \quad \ddot{a} + m_a^2 a \simeq 0 \quad \rightarrow \quad a(t) = A(t)\cos(m_a t + C)$$

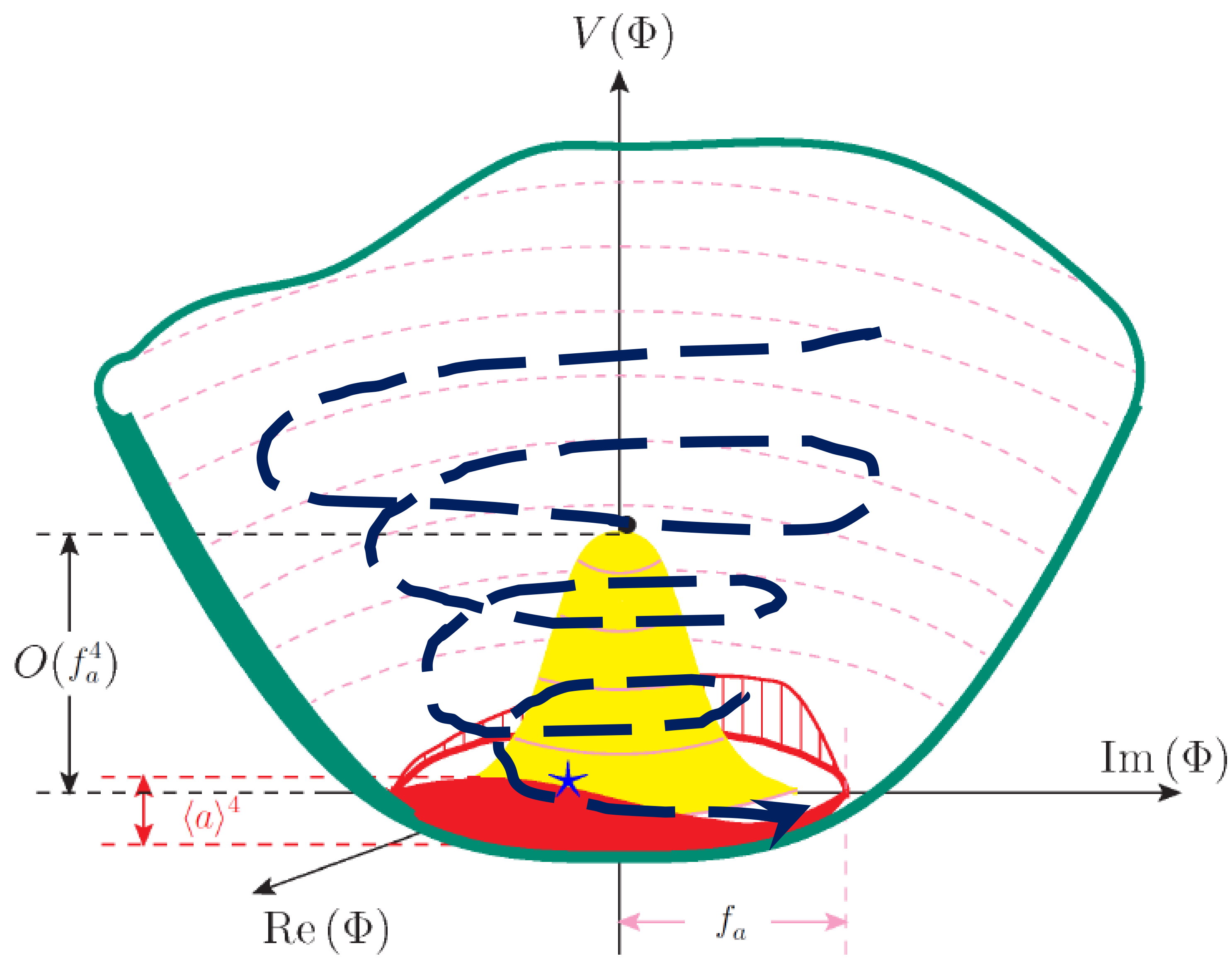


Kinetic Misalignment

$$a(t_i) = f_a\theta_{a,i}, \qquad \dot{a}(t_i) \neq 0,$$

$$\ddot{a} + 3H\dot{a} + V'(a) = 0$$

U(1): $R^3 f_a^2 \dot{\theta}$ = constant



Kinetic Misalignment

$$a(t_i) = f_a \theta_{a,i}, \qquad \dot{a}(t_i) \neq 0,$$

$$\ddot{a} + 3H\dot{a} + V'(a) = 0$$

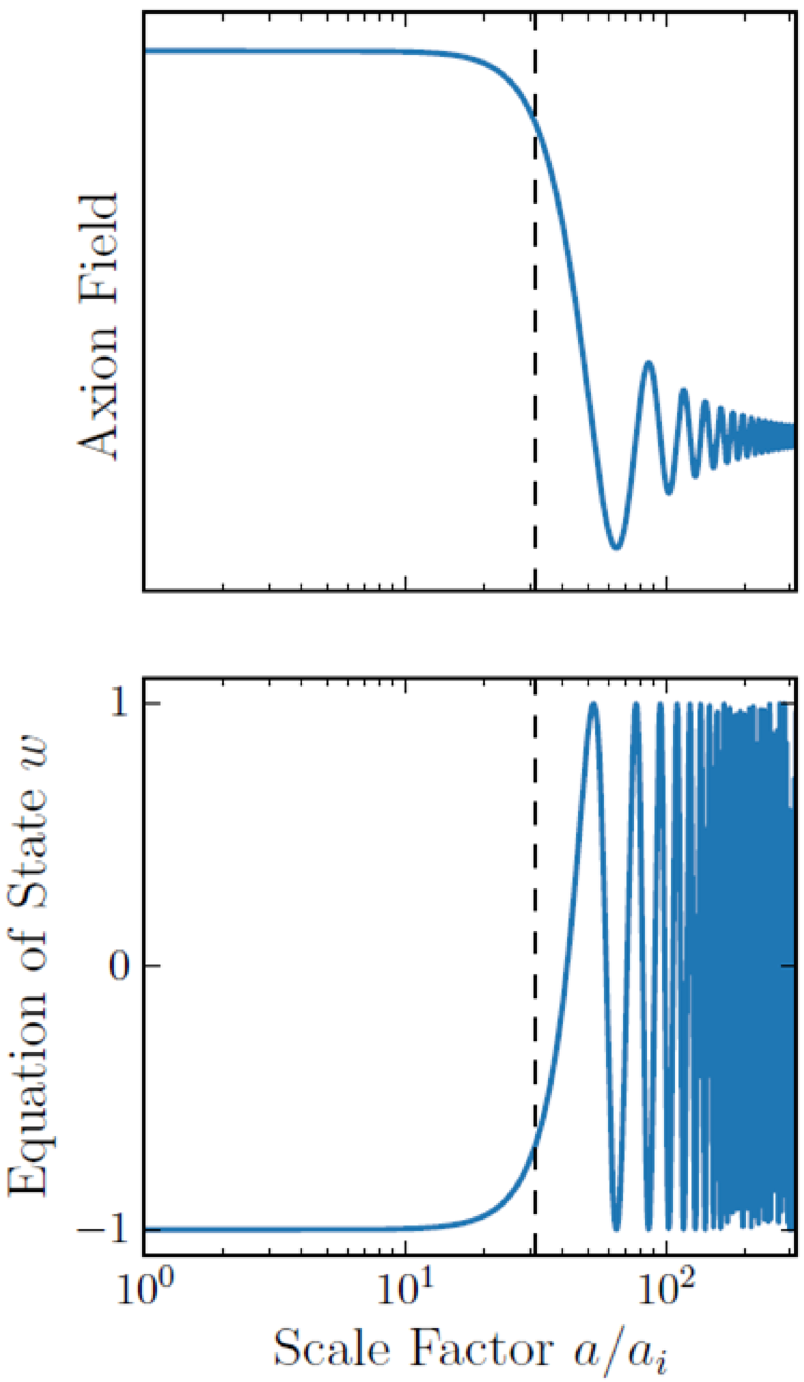
U(1): $R^3 f_a^2 \dot{\theta}$ = constant

$$\theta(t) \equiv a(t)/f_a \pmod{2\pi}$$

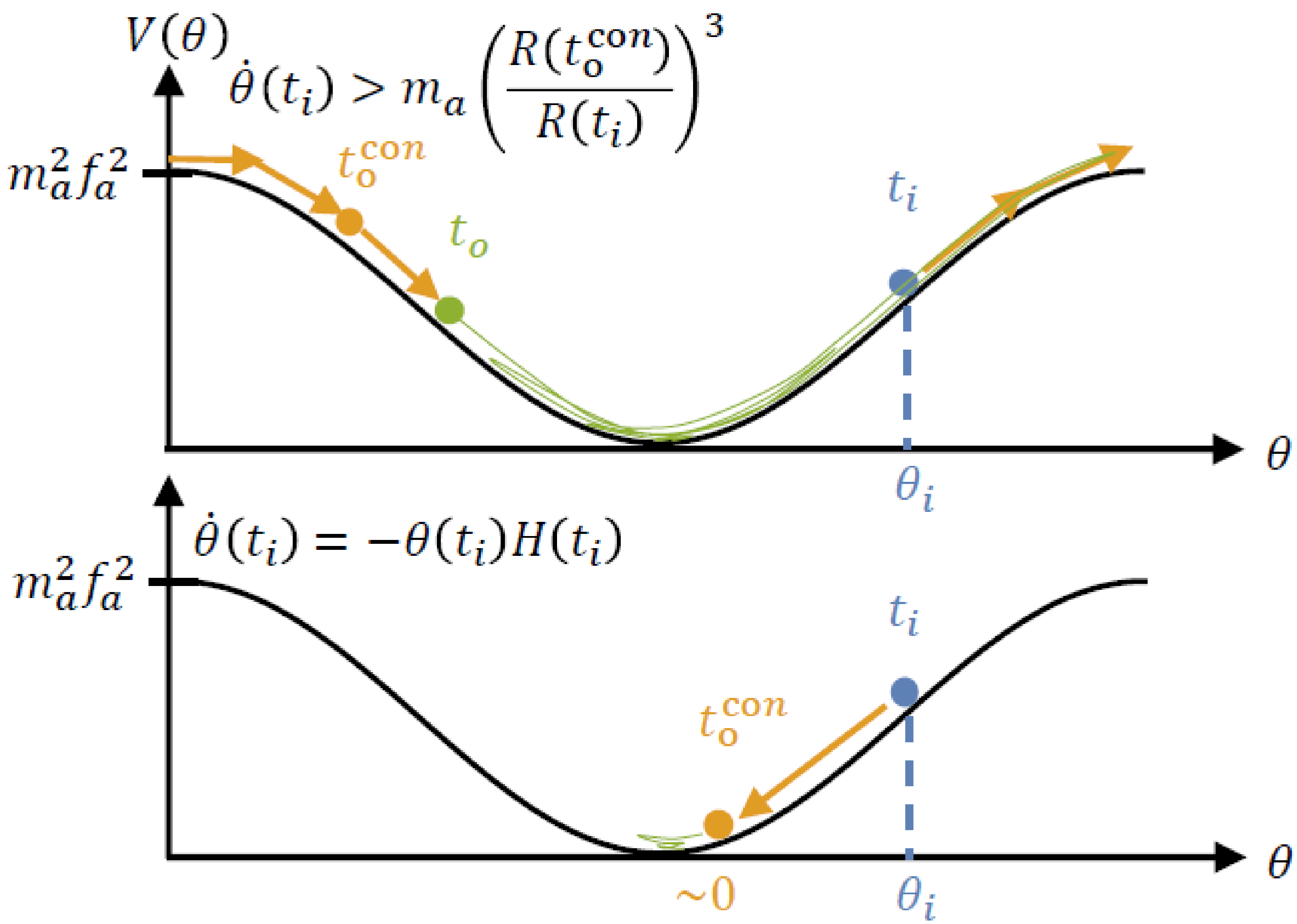
$$\theta(t) = \begin{cases} \theta_i + \frac{\dot{\theta}_i}{H_i}\left(\frac{2}{6-n}\right)\left[1 - \left(\frac{R(t)}{R(t_i)}\right)^{n/2-3}\right], & (n \neq 6) \\ \theta_i + \frac{\dot{\theta}_i}{3H_i}\ln\left[\frac{t}{t_i}\right], & (n = 6) \end{cases}$$

$$\dot{\theta}(t) = \dot{\theta}_i \left(\frac{R(t_i)}{R(t)}\right)^3.$$

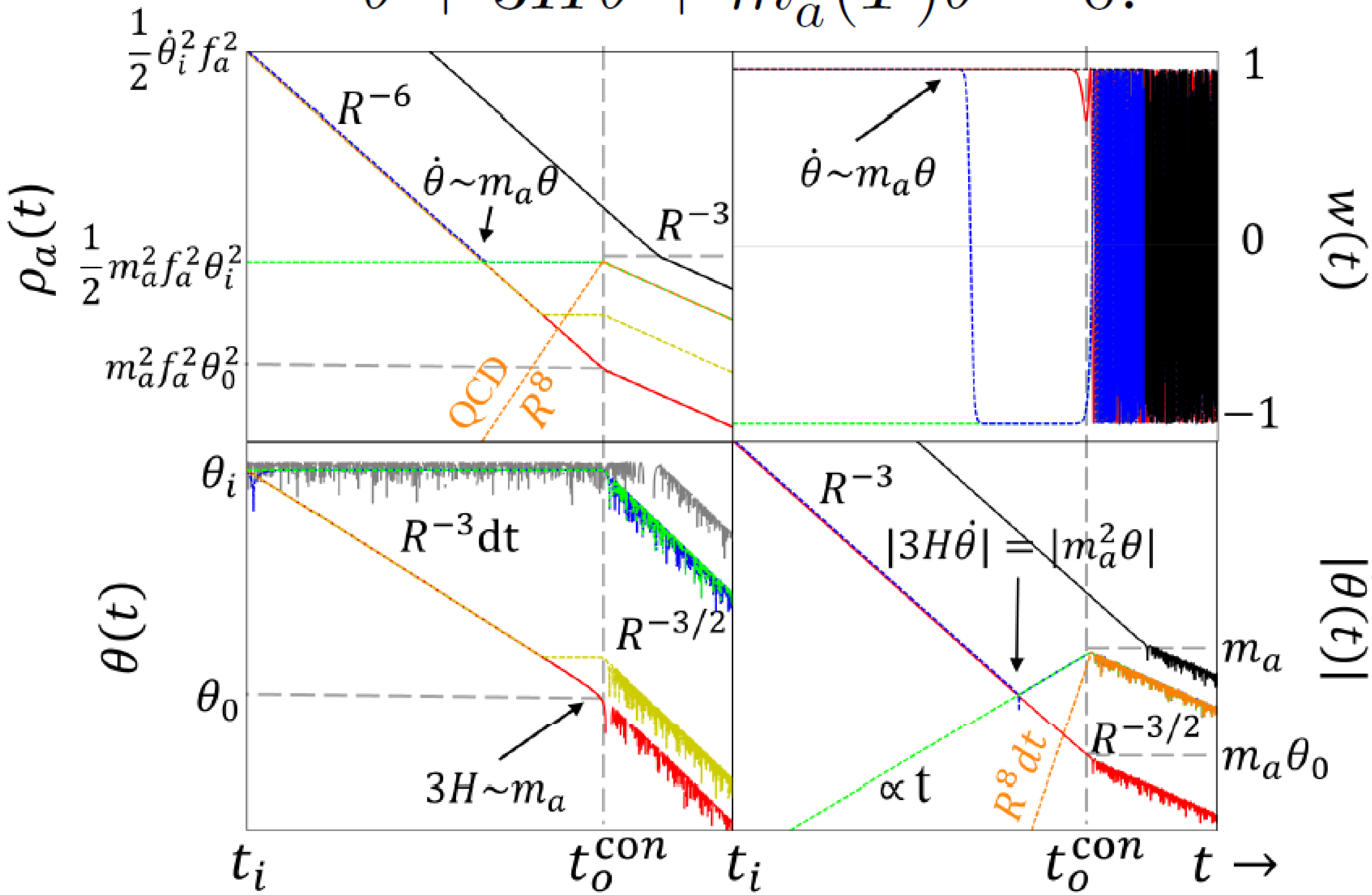
Conventional Misalignment



Kinetic Misalignment

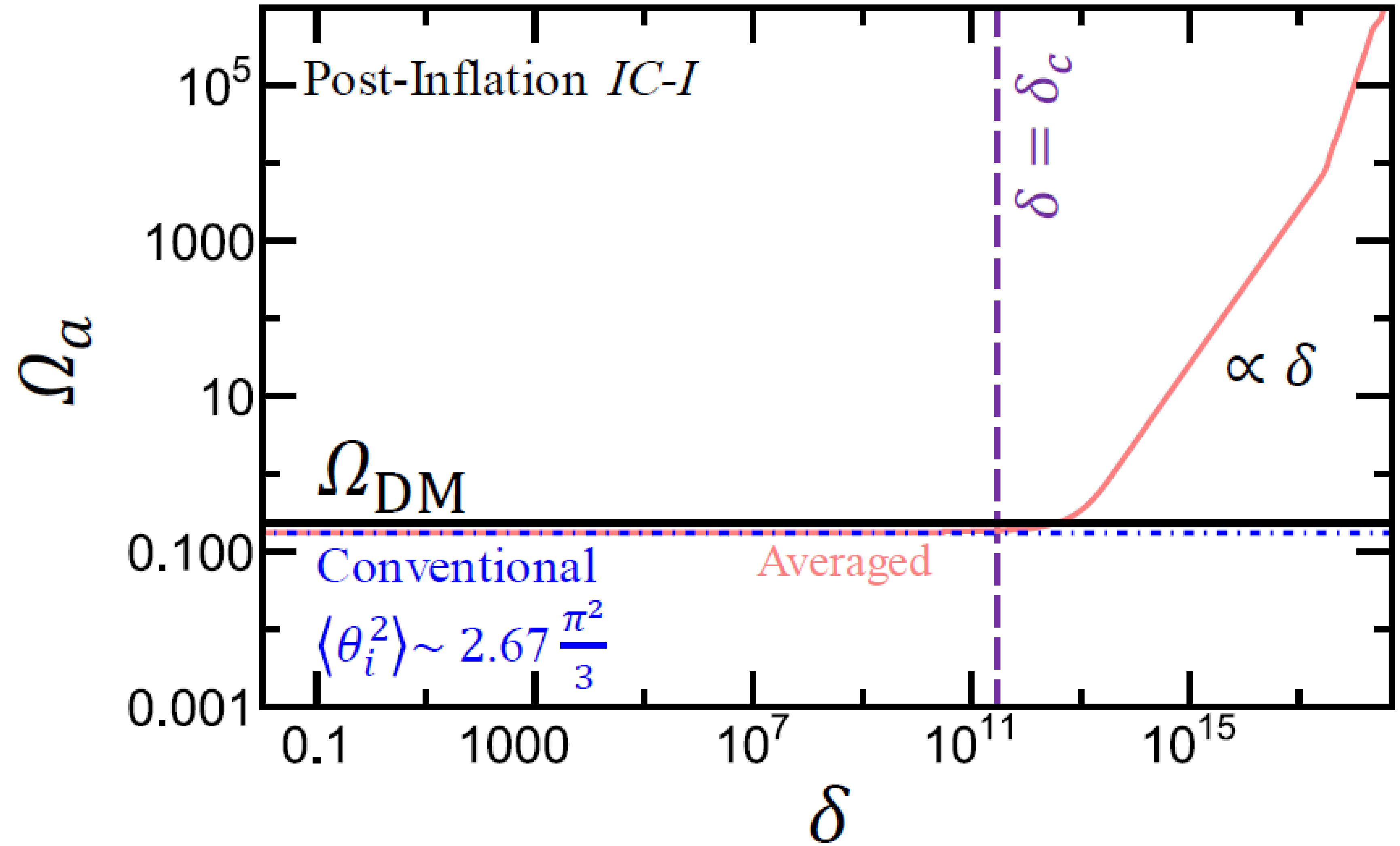


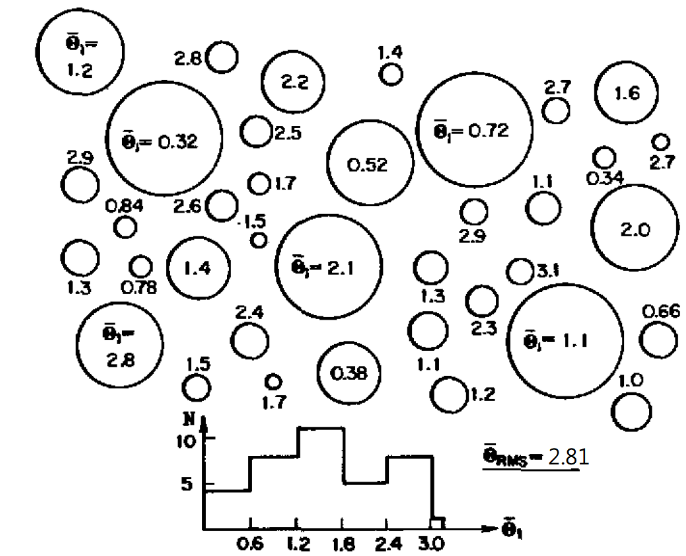
$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0.$$



Post-Inflation

$$\dot{\theta}_i = -\delta H_i$$

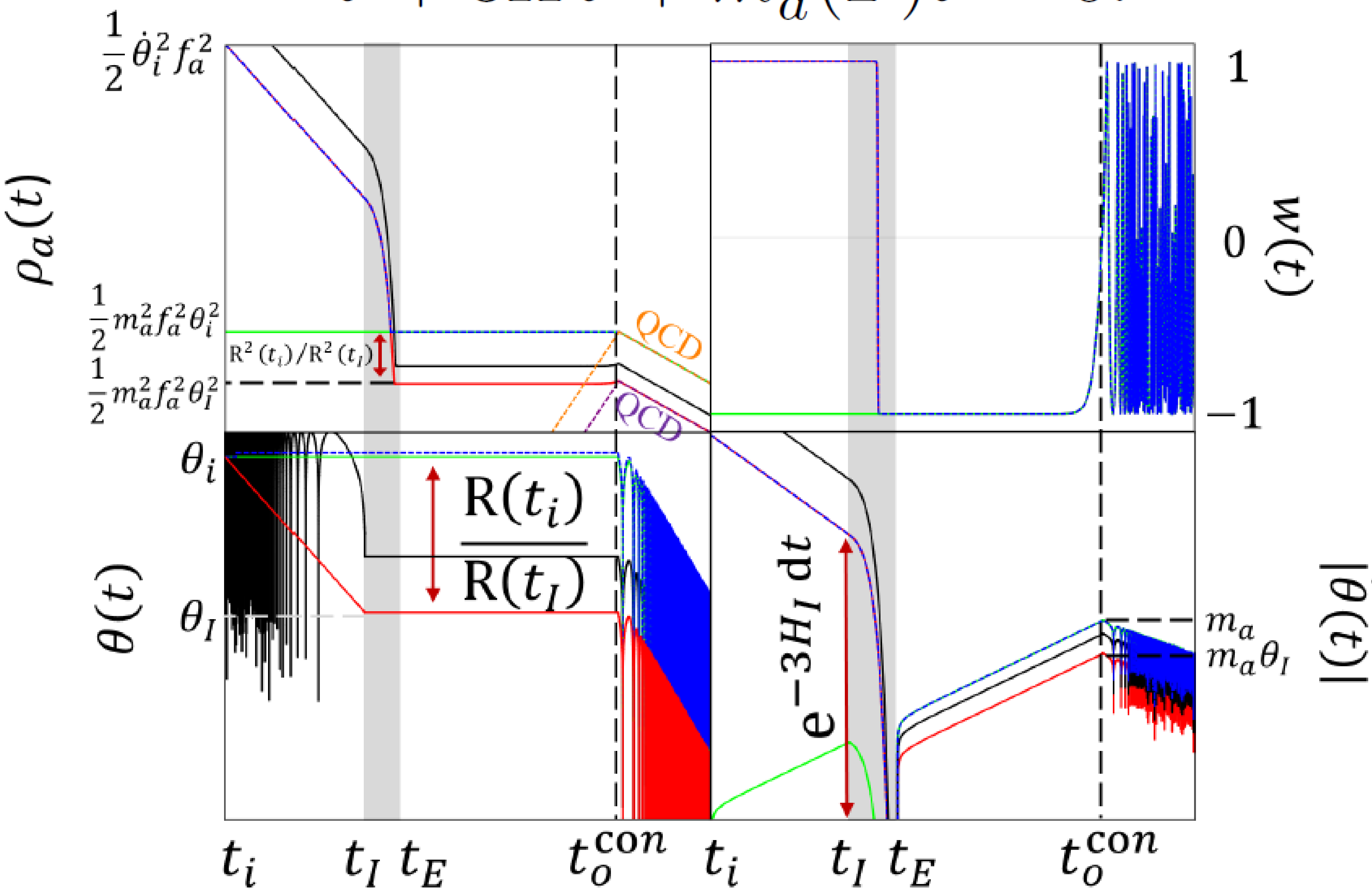




Post-Inflation

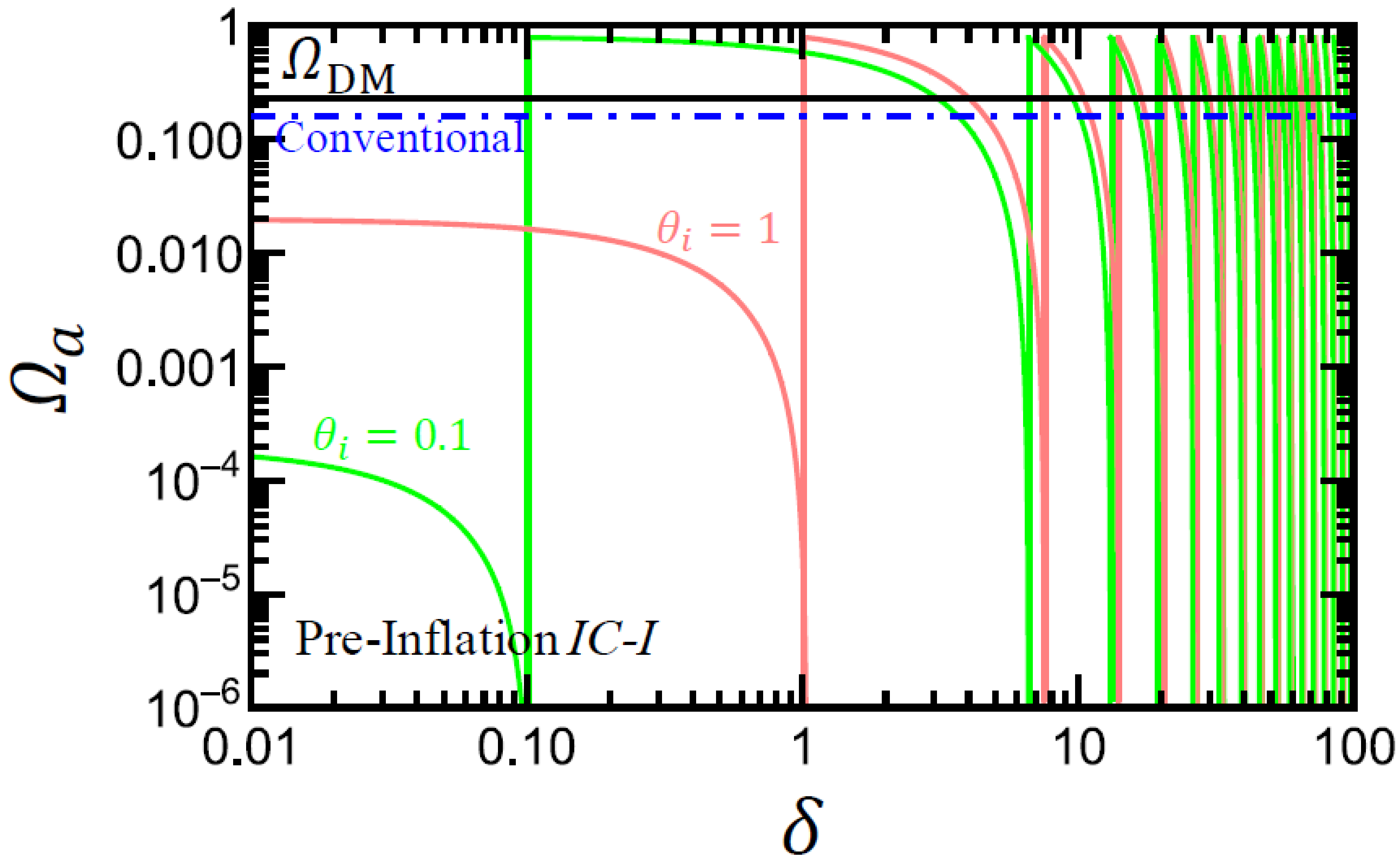
$$\Omega_a^{\rm post-I} \simeq \begin{cases} \Omega_a^{con} = 0.02\,\langle\theta_o^2\rangle \left(\dfrac{f_a}{10^{11}\,{\rm GeV}}\right)^{7/6}, & \delta < \delta_c \\ \Omega_a^{con}\dfrac{\delta}{\delta_c} \simeq 0.01\,\langle\theta_o^2\rangle \left(\dfrac{\delta}{10^{11}}\right), & \delta \geq \delta_c, \end{cases}$$

$$\ddot{\theta} + 3H\dot{\theta} + m_a^2(T)\theta = 0.$$



Pre-Inflation

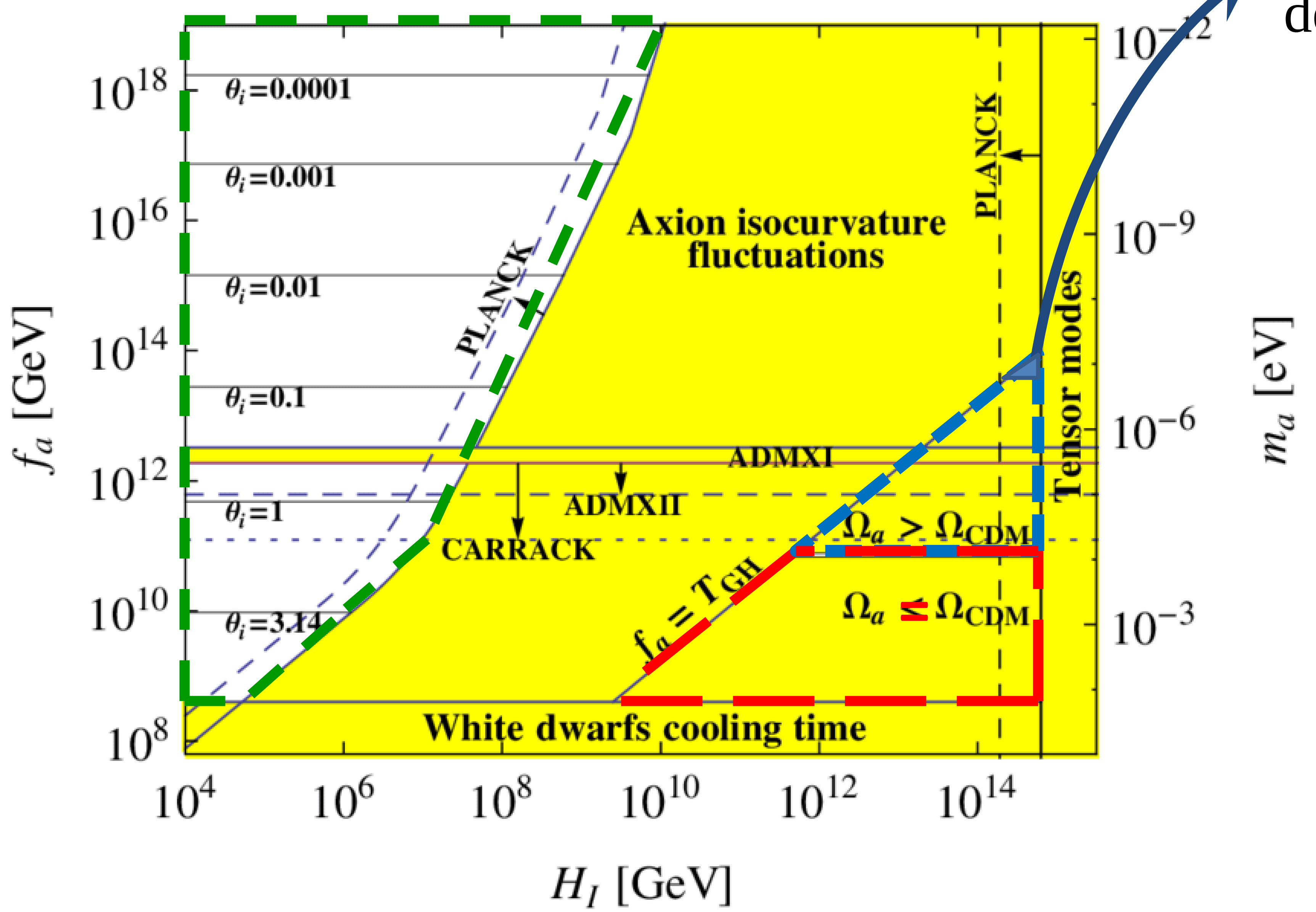
$$\dot{\theta}_i = -\delta H_i$$



$$\Omega_a^{\rm pre-I} = \Omega_a^{con} \frac{\theta_I^2}{\langle \theta_o^2 \rangle},$$

Pre-Inflation

$$\Omega_a = 0.02 \langle \theta_o^2 \rangle \left(\frac{f_a}{10^{11}\,\text{GeV}} \right)^{7/6}$$



Stochastic GW from axion Strings are within future GW detector sensitivities

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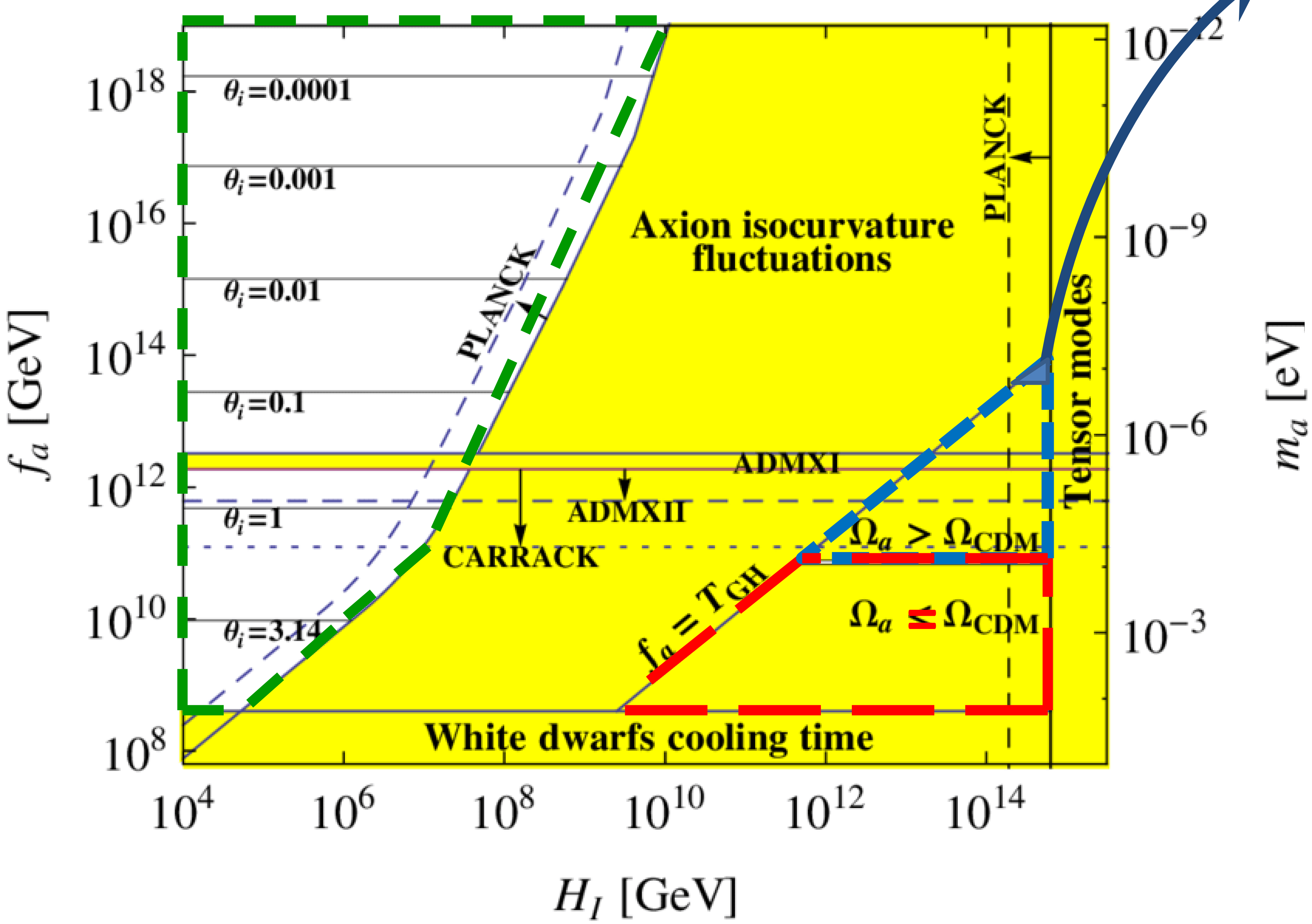
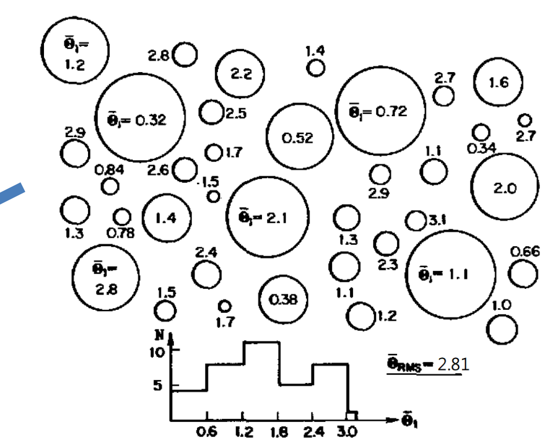
$$\Omega_a = 0.02\,\langle\theta_o^2\rangle \left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^{7/6}$$



Hints for Model Building ?

$$\dot{\theta}_i = -(1-\gamma)\theta_i H_i$$

$$\theta(t) = \theta_i \left[\gamma + (1-\gamma)\left(\frac{R(t_i)}{R(t)}\right)\right]$$



$$\theta_i \to \theta_i + \epsilon(x),$$

$$\Omega_a = 0.02\,\langle\theta_o^2\rangle \left(\frac{f_a}{10^{11}\,\text{GeV}}\right)^{7/6}$$

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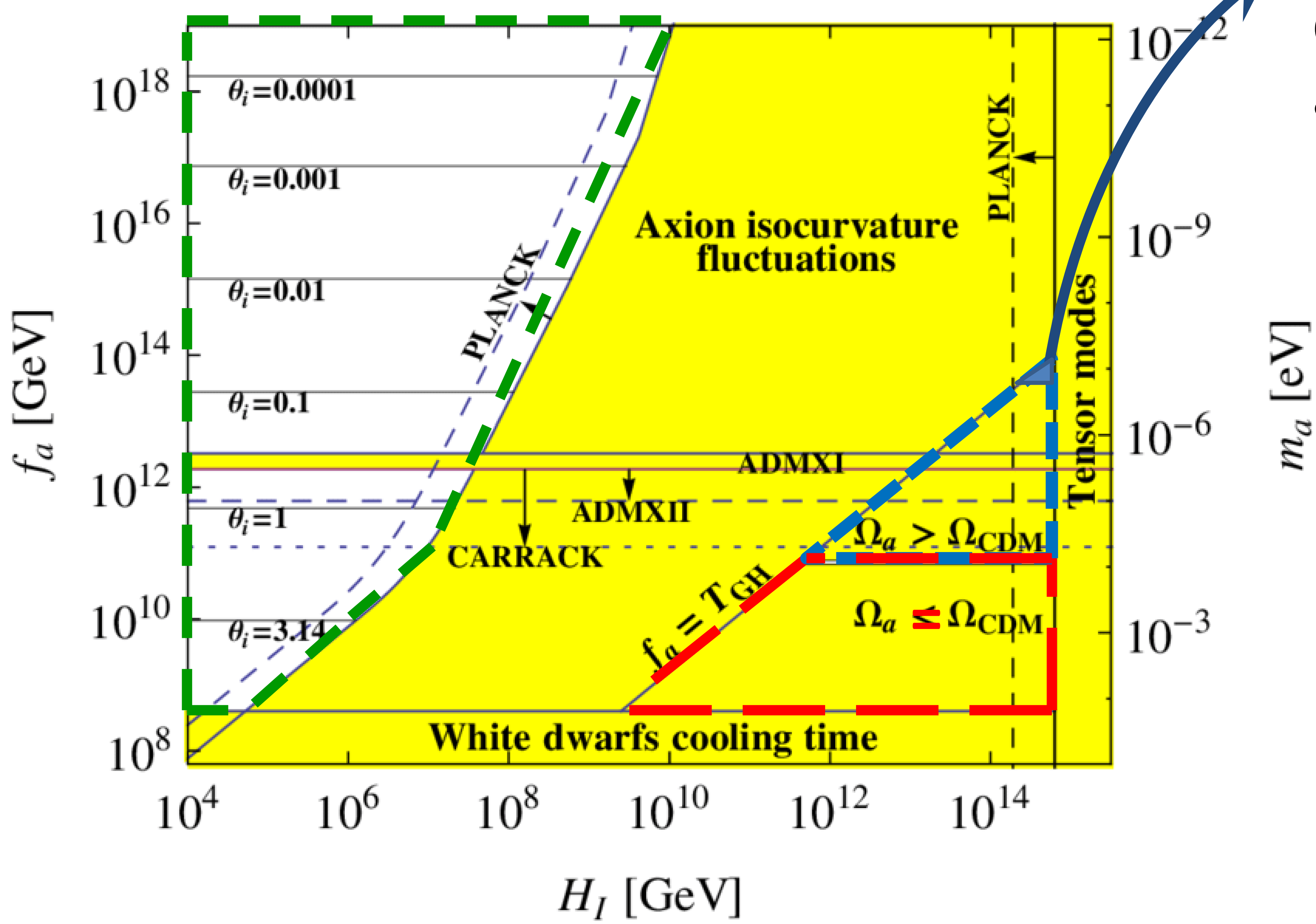
$$\Omega_a = 0.02\,\langle\theta_o^2\rangle \left(\frac{f_a}{10^{11}\,\mathrm{GeV}}\right)^{7/6}$$



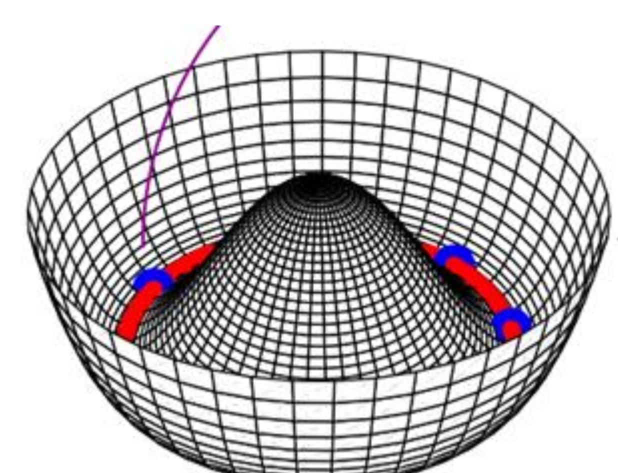
Hints for Model Building ?

Condition for the strongly suppressed axion energy density:

$$\dot{\theta}_i \propto \theta_i$$

$$\downarrow$$

$$U(1)_a$$



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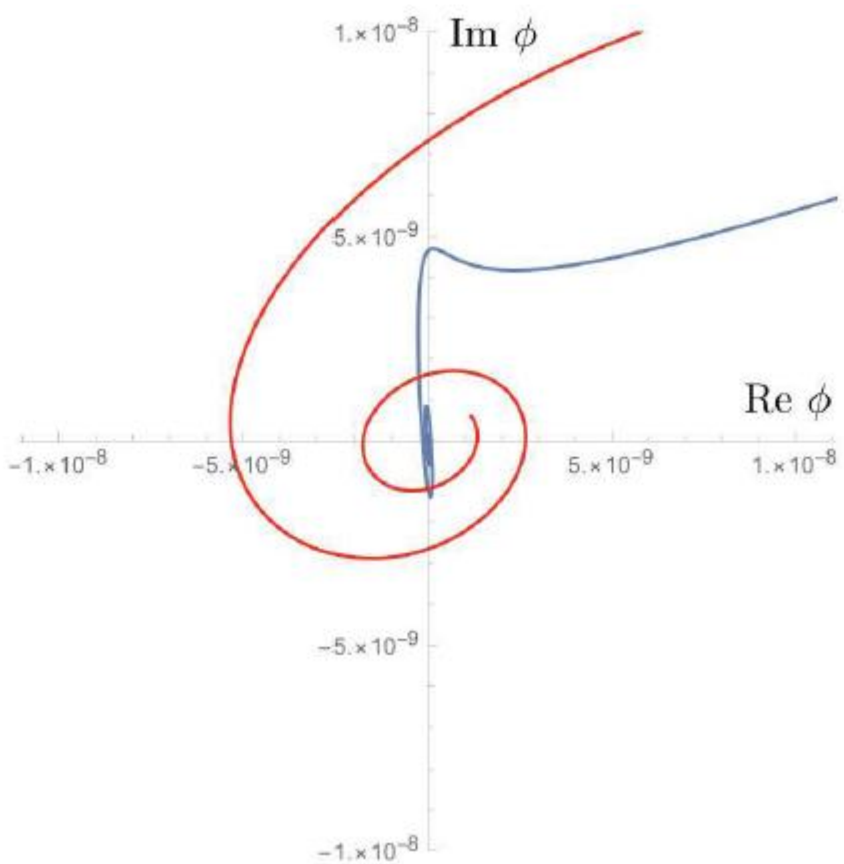
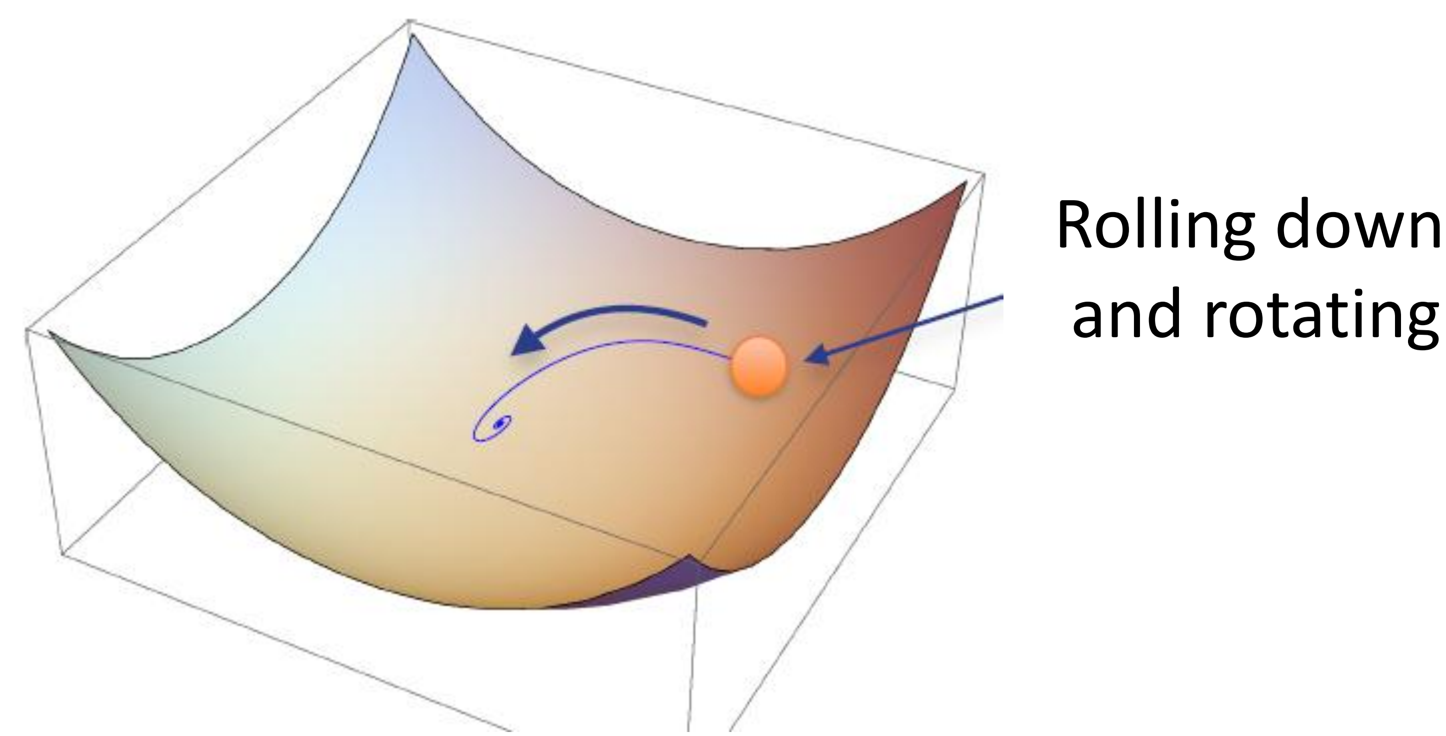
1. Example for the non-zero initial velocity: Affleck-Dine Mechanism

$$\mathcal{L} \supset c_0 \chi^\dagger \chi \phi^\dagger \phi. \qquad \rho \propto \langle \chi^\dagger \chi \rangle. \qquad \mathcal{L} \supset c_0' \langle \chi^\dagger \chi \rangle \phi^\dagger \phi = -cH^2 \phi^\dagger \phi,$$

$$\rho = 3H^2 M_{\rm Pl}^2$$

$$\left[\partial_t^2 |\psi| - |\psi| \left(\partial_t \theta\right)^2\right] + 3H\partial_t |\psi| + m^2 |\psi| - cH^2(t)|\psi| + \mathcal{O}(\phi^3) = 0$$





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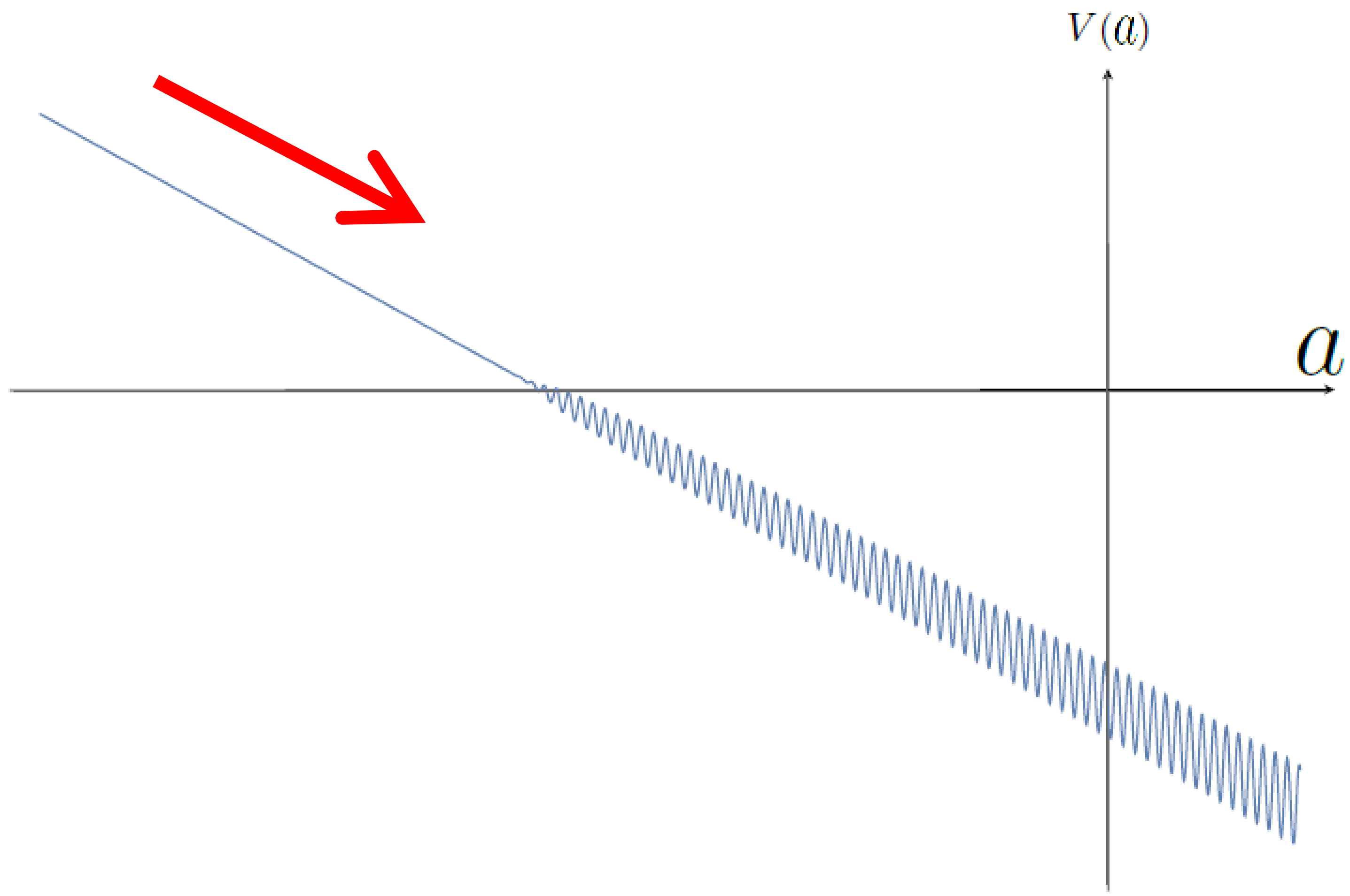
2. Example for the PQ U(1) symmetry breaking before QCD scale: Relaxion

$$(-M^2 + ga)|h|^2 + \frac{1}{32\pi^2}\frac{a}{f}\tilde{G}^{\mu\nu}G_{\mu\nu} + (gM^2 a + g^2 a^2 + \cdots) + \Lambda^4 \cos(a/f)$$



$$a(x) \to a(x) + \alpha f_a$$

$$U(1)_a$$

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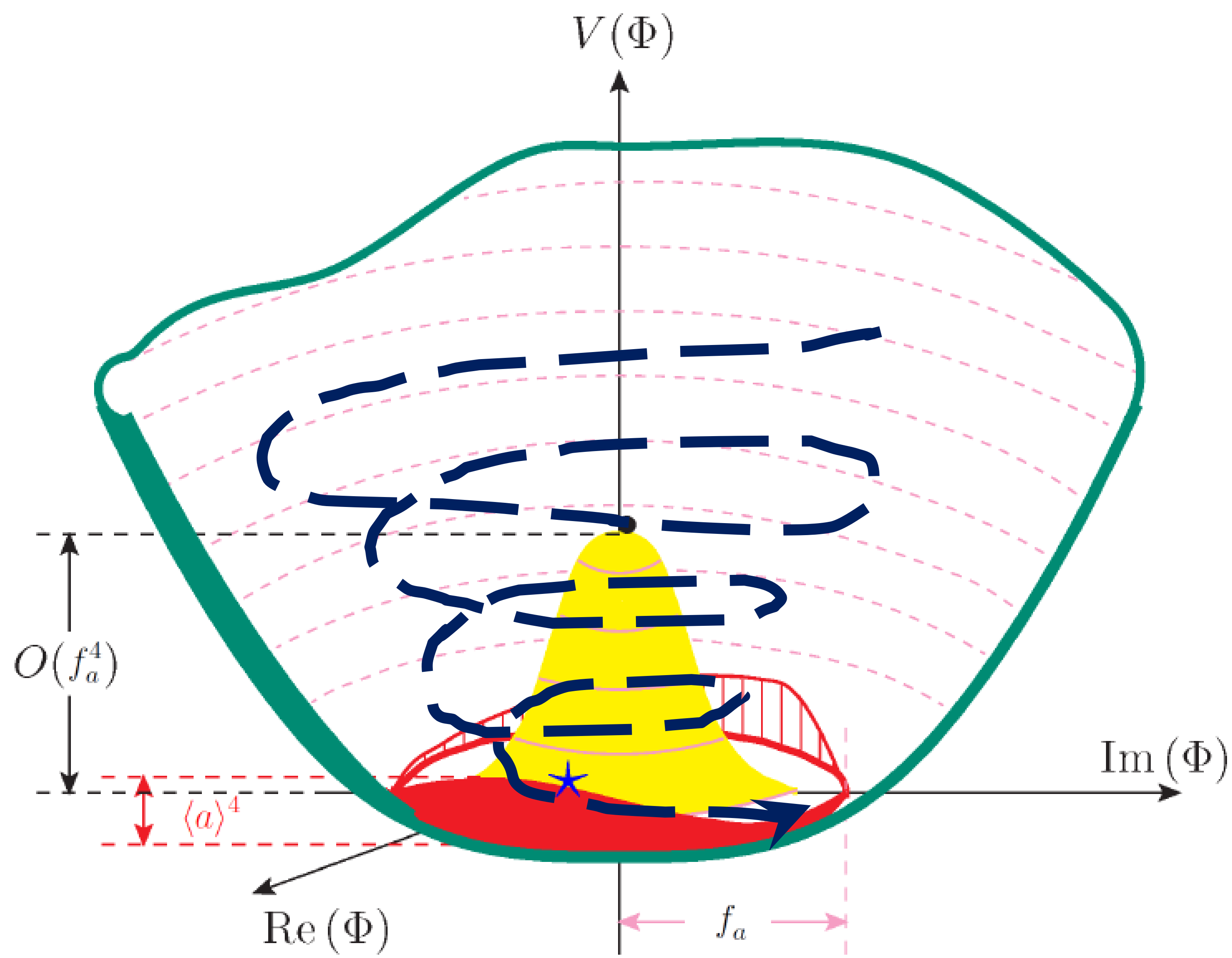
Conclusion and Discussion

1. The high initial velocities are able to generate a higher axion relic density in post-inflation scenario, by delaying the axion oscillation time.

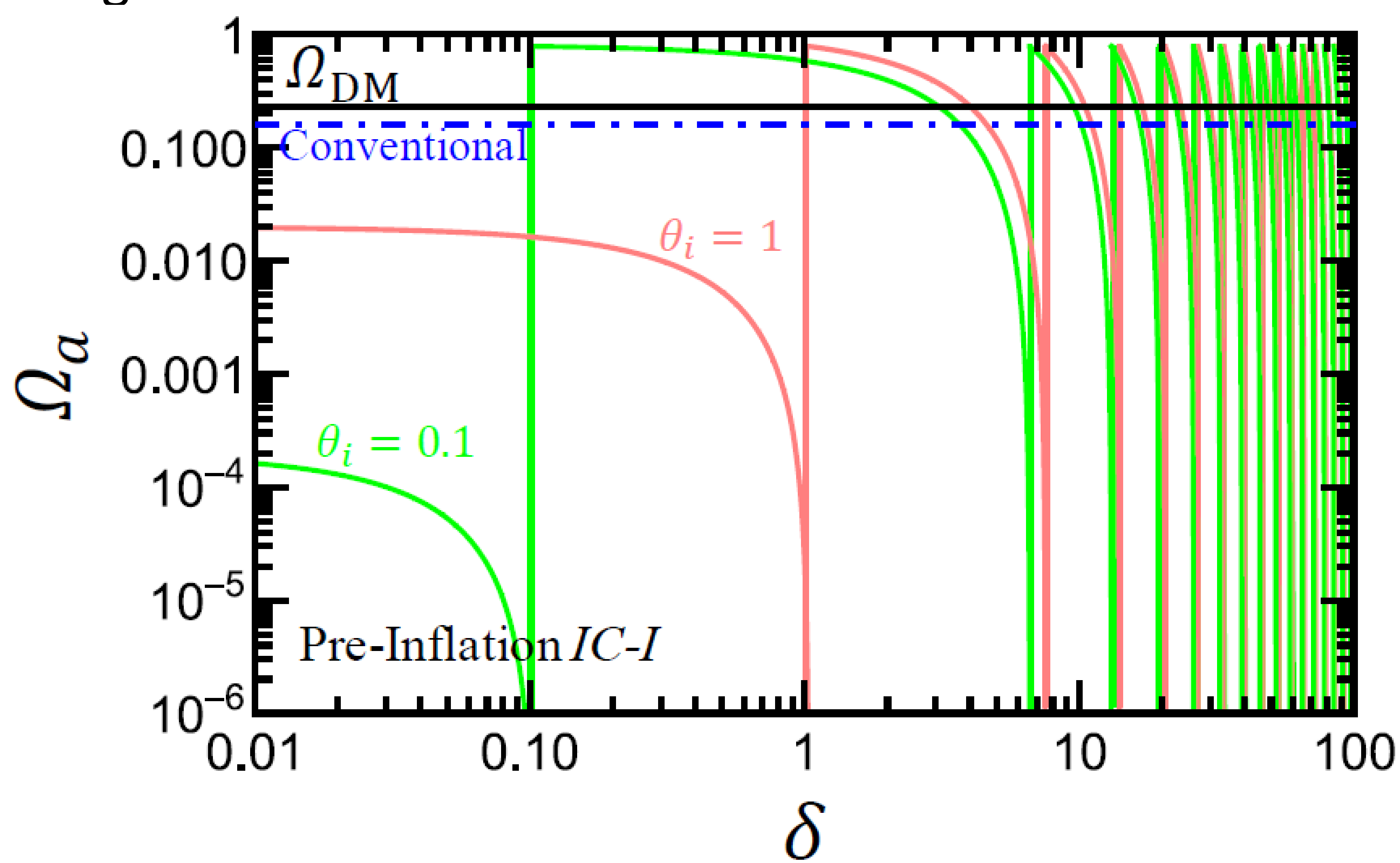


Conclusion and Discussion

1. The high initial velocities are able to generate a higher axion relic density in post-inflation scenario, by delaying the axion oscillation time.

2. The kinetic misalignment for a suppressed axion relic density in pre-inflation scenario is just another fine-tuning.

$$\dot{\theta}_i = -\delta H_i$$



Conclusion and Discussion

1. The high initial velocities are able to generate a higher axion relic density in post-inflation scenario, by delaying the axion oscillation time.

2. The kinetic misalignment for a suppressed axion relic density in pre-inflation scenario is just another fine-tuning.

3. The random distribution of axion field value in post-inflation scenario do wash out its suppression (not small axion relic density). There should be other new mechanism (~~U(1)~~) to generate the suppressed field value.

$$\dot{\theta}_i \propto \theta_i \longrightarrow \cancel{U(1)_a}$$

Thank you