2024年紫金山暗物质研讨会——南京大学苏州校区 （2024.10.11-15）

Axion-like particle models and constraints

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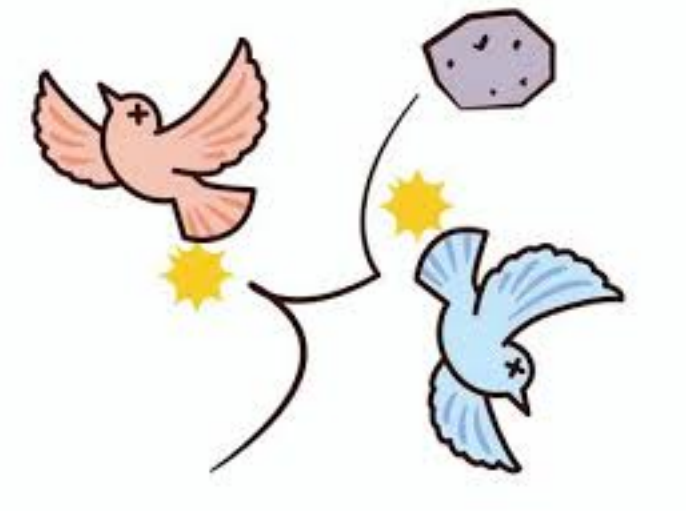
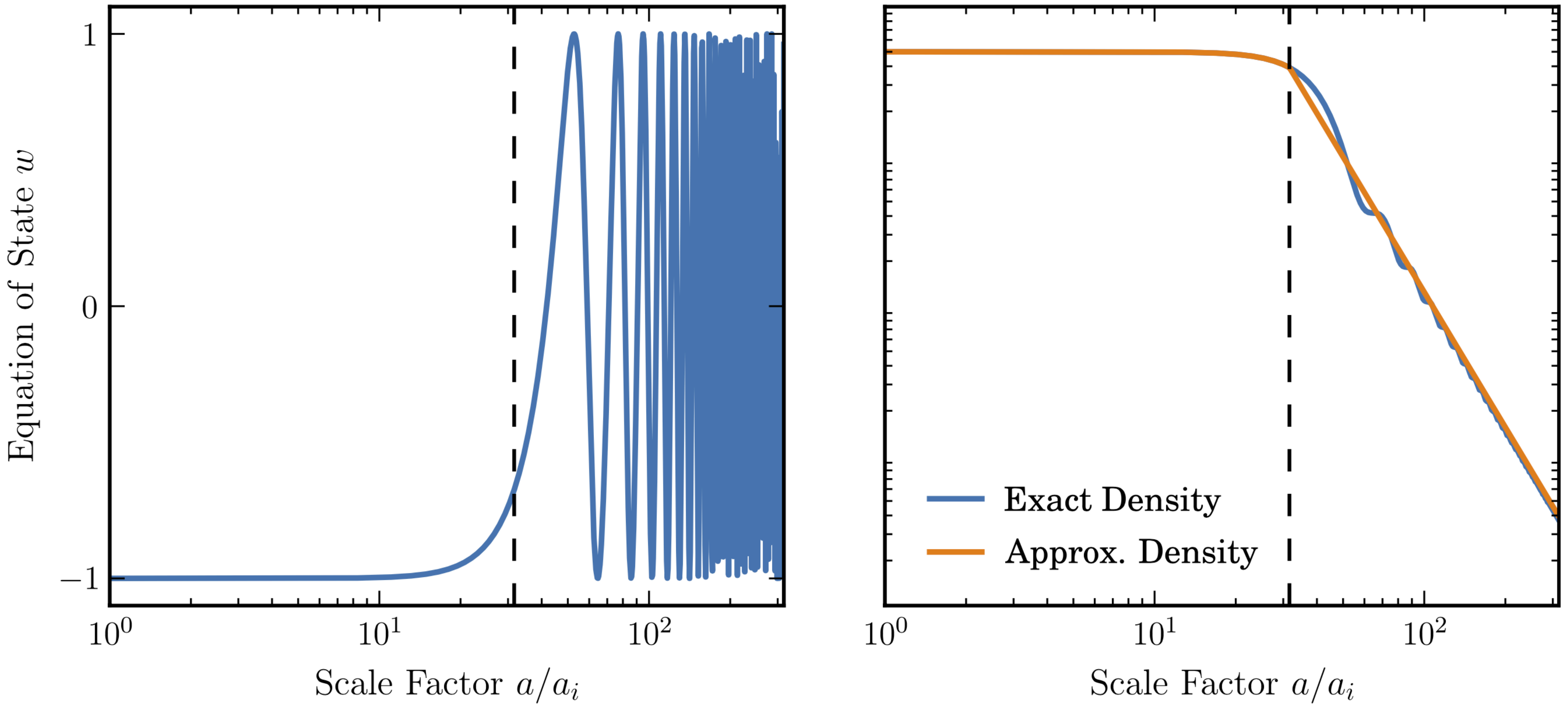
2024年10月14日

Axion-like particle as the DM candidate

Merits



Solving the strong CP problem and the dark matter problem.



Problems

- The UV origin of the Peccei-Quinn symmetry
- The PQ quality problem
- The mass generation mechanism of the ALP
- Overproduction of ALP from the axion cosmic string
- The ALP domain-wall problem
- Signal of the ALP in various experiments...

Outline

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- ○ ALP mass generation via the seesaw mechanisms

Axion-like dark matter from the type-II seesaw mechanism, Wei Chao, M.J. Jin, H.J. Li Y.Q. Peng, Phys.Rev.D

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- ○ ALP direct detections via the scattering off the electron

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ALP & neutrino mass via type-I seesaw

Type-I seesaw + spontaneous breaking $U(1)_L$ symmetry

$$\mathscr{L}_{\rm BSM} = \left(\partial_\mu \Phi\right)^\dagger (\partial^\mu \Phi) + \mu_\Phi^2 \Phi^\dagger \Phi - \lambda_1 (\Phi^\dagger \Phi)^2 - \lambda_2 (\Phi^\dagger \Phi)(H^\dagger H) - \left[Y_{\rm N} \overline{\ell_L} \tilde{H} N_R + \frac{1}{2} \overline{N_R^C} \left(Y_{\rm M} \Phi + m \right) N_R + {\rm h.c.} \right]$$

LNV term!

$$H = \begin{pmatrix} \phi^+ \\ \dfrac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Phi = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}} \qquad \tilde{a}:$$

ALP

Yukawa Interaction $-Y_{\rm N} \overline{\ell_L} \tilde{H} N_R \to M_D = Y_N v/\sqrt{2}$

Key term: $m \overline{N_R^C} N_R + h.c.$

Quantum Gravity effect!

ALP interactions and mass

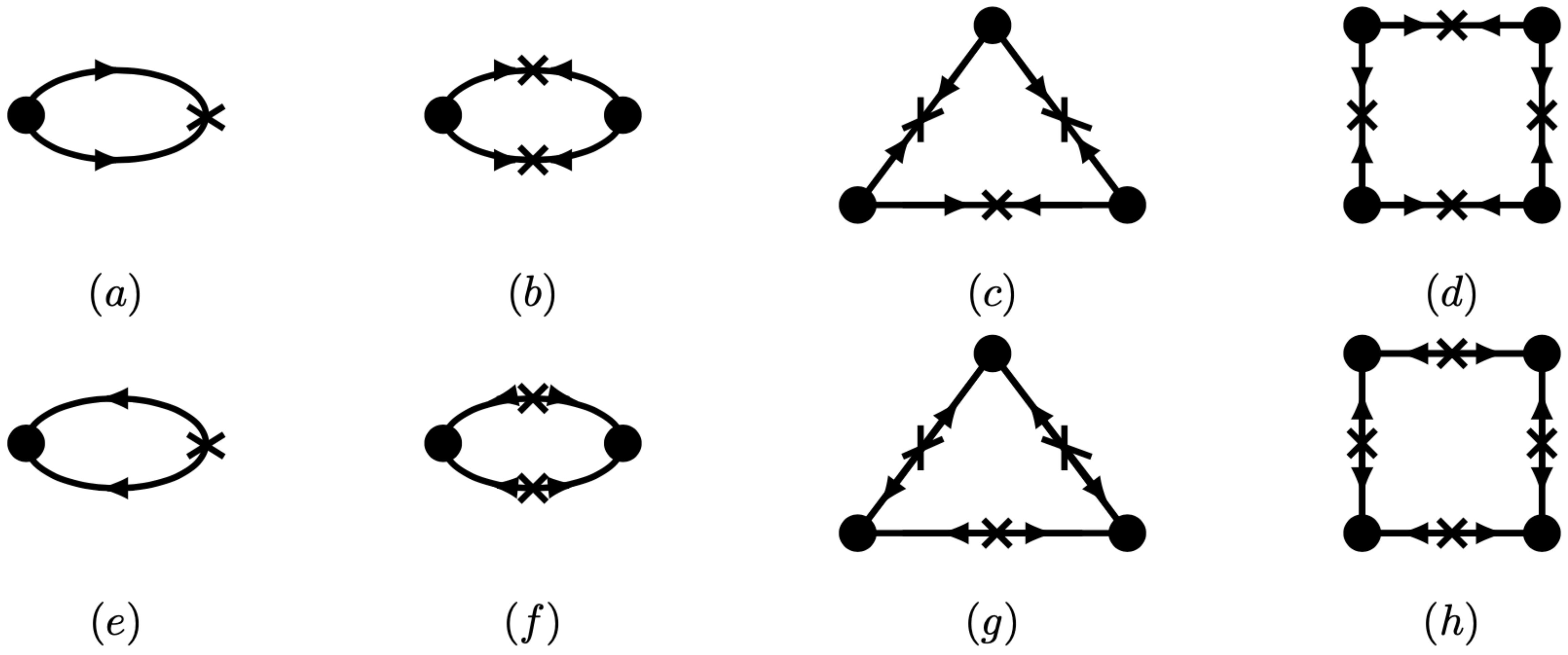
Field-dependent phase transformation

$$\left.\begin{array}{ll} \ell_L \to e^{-\frac{ia}{2f}}\ell_L & S \to e^{+\frac{ia}{f}}S \\ E_R \to e^{-\frac{ia}{2f}}E_R & H \to H \end{array}\right\} \begin{array}{l} \mathscr{L} \to \mathscr{L} - \frac{a}{2f}\partial_\mu\left(\overline{\ell_L}\gamma^\mu \ell_L + \overline{E_R}\gamma^\mu E_R\right) \\ = \mathscr{L} - \frac{a}{2f}\partial_\mu J^L_\mu \\ = \mathscr{L} + \frac{a}{2f}\frac{N_f}{32\pi^2}\left(g^2 W^a_{\mu\nu}\widetilde{W}^{\mu\nu,a} - g'^2 B_{\mu\nu}\widetilde{B}^{\mu\nu}\right) \end{array}$$

$$N_R \to e^{-\frac{ia}{2f}}N_R \quad \longrightarrow \quad \frac{1}{2}e^{-i\theta}\overline{N_R^C}mN_R + h.c.$$

ALP interactions and Majoron mass

$$\frac{1}{2}e^{-i\theta}\overline{N_R^C}mN_R + h.c. \longrightarrow$$


(a) (b) (c) (d)

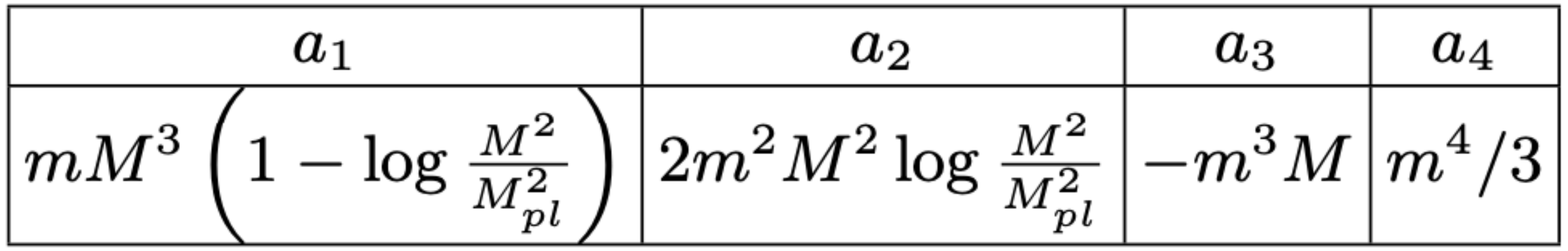
(e) (f) (g) (h)

Mass insertion of right-handed neutrino masses:

Before symmetry breaking: $M = m$

After symmetry breaking: $M = f_a Y_M/\sqrt{2} + m$

$$V_a \sim -\frac{1}{16\pi^2}\sum_{n=1}^{4} a_n \cos n\theta\,.$$

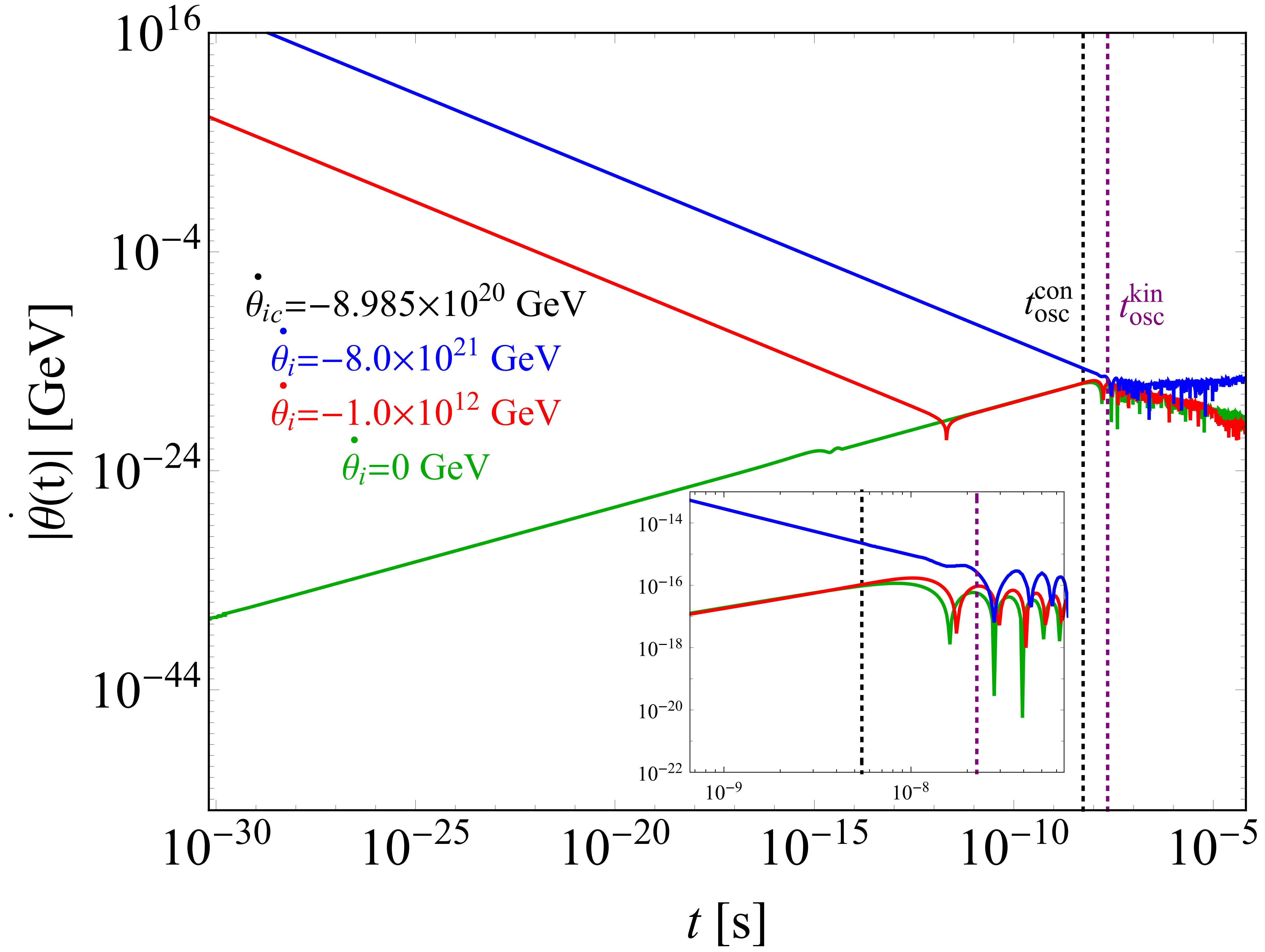


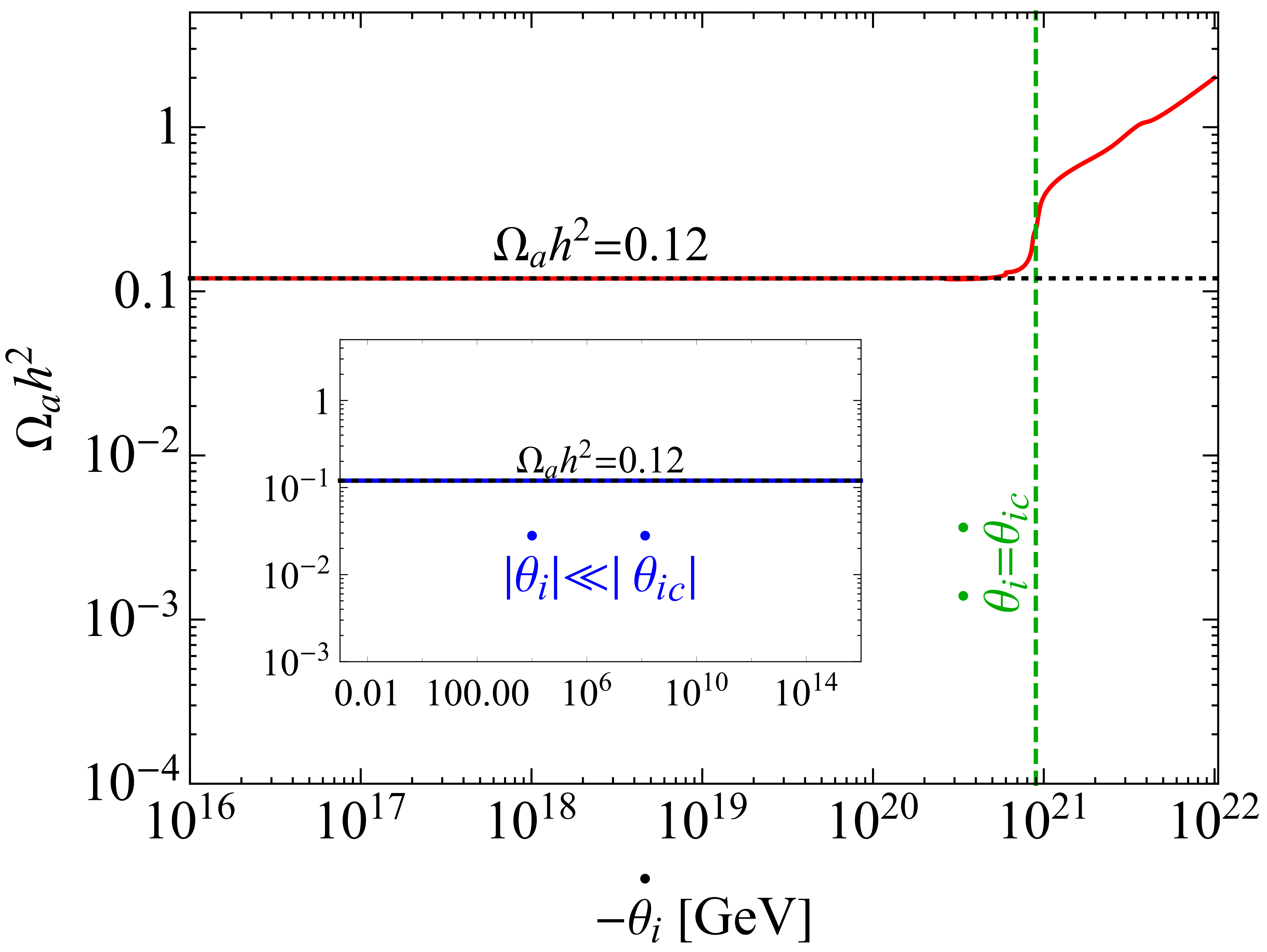
a_1	a_2	a_3	a_4
$mM^3\left(1-\log\frac{M^2}{M_{pl}^2}\right)$	$2m^2M^2\log\frac{M^2}{M_{pl}^2}$	$-m^3M$	$m^4/3$

ALP mass and its relic density

ALP mass:	$m_a^2 = \frac{1}{f_a^2}\frac{d^2V}{d\theta^2} = \frac{1}{16\pi^2 f_a^2}\left\| a_1 + 4a_2 + 9a_3 + 16a_4 \right\| .$	
Initial velocity: **(From Noether theorem)**	$\partial_\mu j^\mu = \left(\frac{\partial V}{\partial \phi}\right)\phi - \phi^\dagger \left(\frac{\partial V}{\partial \phi^\dagger}\right)$	**In the traditional misalignment mechanism** $\dot{\theta}_i = 0$
EOM	$\ddot{\theta} + 3H\dot{\theta} + \frac{1}{f_a^2}\frac{dV_a}{d\theta} = 0,$	**Different oscillation temperature**

ALP mass and its relic density





ALP & neutrino mass via type-II seesaw

Type-II seesaw + spontaneous breaking $U(1)_L$ symmetry

LNV term!

$$V(S,\Phi,\Delta) = V(\Phi,\Delta) - \mu_S^2(S^\dagger S) + \lambda_6(S^\dagger S)^2$$
$$+\lambda_7(S^\dagger S)(\Phi^\dagger\Phi) + \lambda_8(S^\dagger S)\mathrm{Tr}(\Delta^\dagger\Delta) + \mu\Phi^T i\tau_2\Delta^\dagger\Phi + \lambda S\Phi^T i\tau_2\Delta^\dagger\Phi + \mathrm{h.c.},$$

$$\Phi = \begin{pmatrix} \phi^+ \\ \frac{v_\phi + \phi + i\chi}{\sqrt{2}} \end{pmatrix} \qquad \Delta = \begin{pmatrix} \frac{\Delta^+}{\sqrt{2}} & \Delta^{++} \\ \frac{v_\Delta + \delta + i\xi}{\sqrt{2}} & \frac{\Delta^+}{\sqrt{2}} \end{pmatrix} \qquad S = \frac{v_s + \tilde{s} + i\tilde{a}}{\sqrt{2}}$$

$\tilde{a}$: **Majoron**

Yukawa Interaction $\quad -\mathscr{L}_\Delta = Y_{\alpha\beta}\overline{\ell_L^{\alpha C}} i\sigma^2\Delta\ell_L^\beta + h.c.$

Key term: $\quad \mu\Phi^T i\sigma^2\Delta\Phi + h.c.$

ALP & neutrino mass via type-II seesaw

Gauge boson masses

$$m_W^2 = \frac{g^2}{4}\left(v_\phi^2 + 2v_\Delta^2\right), \quad m_Z^2 = \frac{g^2}{4\cos^2\theta_W}\left(v_\phi^2 + 4v_\Delta^2\right). \qquad \rho \equiv \frac{m_W^2}{m_Z^2\cos^2\theta_W} = \frac{1 + \frac{2v_\Delta^2}{v_\phi^2}}{1 + \frac{4v_\Delta^2}{v_\phi^2}}.$$

Scalar mixings and masses

$$\begin{pmatrix} G^\pm \\ H^\pm \end{pmatrix} = \mathscr{R}(\beta)\begin{pmatrix} \phi^\pm \\ \Delta^\pm \end{pmatrix}, \quad \begin{pmatrix} G \\ A \\ a \end{pmatrix} = \mathscr{V}(\beta_1', \beta_2', \beta_3')\begin{pmatrix} \chi \\ \xi \\ \tilde{a} \end{pmatrix}, \quad \begin{pmatrix} h \\ H \\ s \end{pmatrix} = \mathscr{U}(\alpha_1, \alpha_2, \alpha_3)\begin{pmatrix} \phi \\ \delta \\ \tilde{s} \end{pmatrix},$$

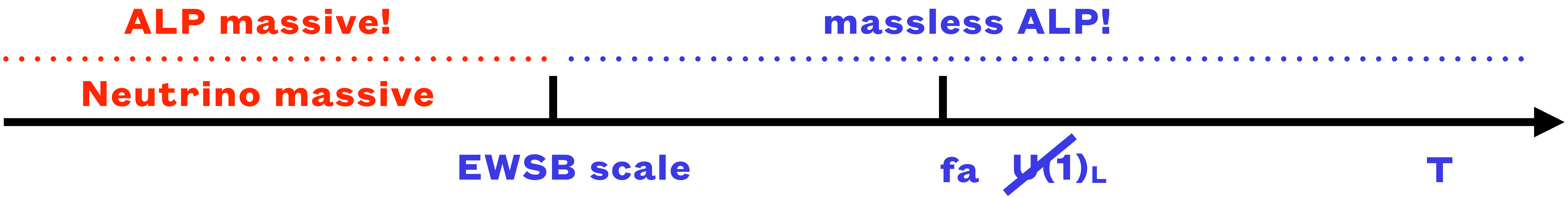
Mixing angle for pseudo-scalars

Majoron gets non-zero mass from the mixing!

$$\tan\beta = \frac{\sqrt{2}v_\Delta}{v_\phi}, \quad \tan\beta_1' = \frac{2v_\Delta}{v_\phi}, \quad \tan\beta_2' = 0, \quad \tan 2\beta_3' = \frac{-2\lambda v_\Delta v_s v_\phi\sqrt{v_\phi^2 + 4v_\Delta^2}}{v_\phi^2\left(-\lambda v_\Delta^2 + \lambda v_s^2 + \sqrt{2}\mu v_s\right) + 4v_\Delta^2 v_s\left(\sqrt{2}\mu + \lambda v_s\right)}.$$

ALP & neutrino mass via type-II seesaw

Sequential breaking of various symmetries



ALP massive!

massless ALP!

Neutrino massive

EWSB scale

fa $\cancel{U}(1)_L$

T

Temperature of Universe

$$(m_\nu)_{\alpha\beta} = y_{\alpha\beta} v_\Delta / \sqrt{2}\,.$$

$$m_a^2 = \frac{\sqrt{2}\mu v_\phi^2 v_\Delta (v_\phi^2 + 4 v_\Delta^2)}{2 v_\phi^2 (v_\Delta^2 + v_s^2) + 8 v_\Delta^2 v_s^2} \simeq \frac{\mu v_\phi^2 v_\Delta}{\sqrt{2} v_s^2}\,,$$

For experts of axion physics

Majoron mass should arise from cosine like potential!

$$\left.\begin{array}{ll} \ell_L \to e^{-\frac{ia}{2f}} \ell_L & S \to e^{+\frac{ia}{f}} S \\ E_R \to e^{-\frac{ia}{2f}} E_R & \Delta \to e^{-\frac{ia}{f}} \Delta \\ & \\ H \to H & \end{array}\right\} \quad -\mathscr{L}_{\rm int} \supset \mu e^{i\frac{a}{f_a}} \Phi^T i\tau_2 \Delta^\dagger \Phi + \mathrm{h.c.}..$$

After electroweak symmetry breaking

$$-\mathscr{L}_{\rm int} \supset \frac{\mu v_\Phi^2 v_\Delta}{\sqrt{2}} \cos\left(\frac{a}{f_a}\right)$$

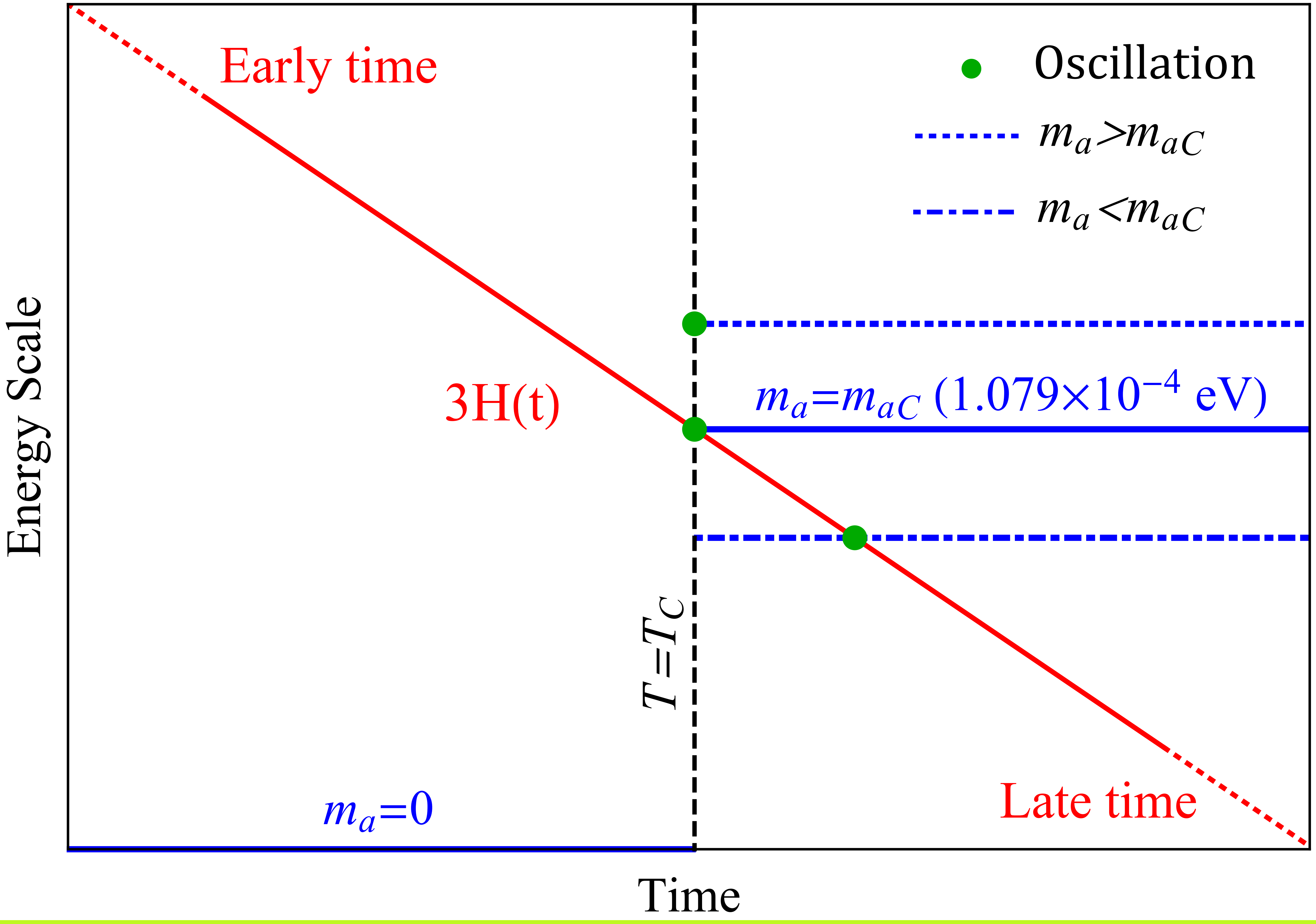
Non-zero Majoron mass

ALP DM—oscillation time

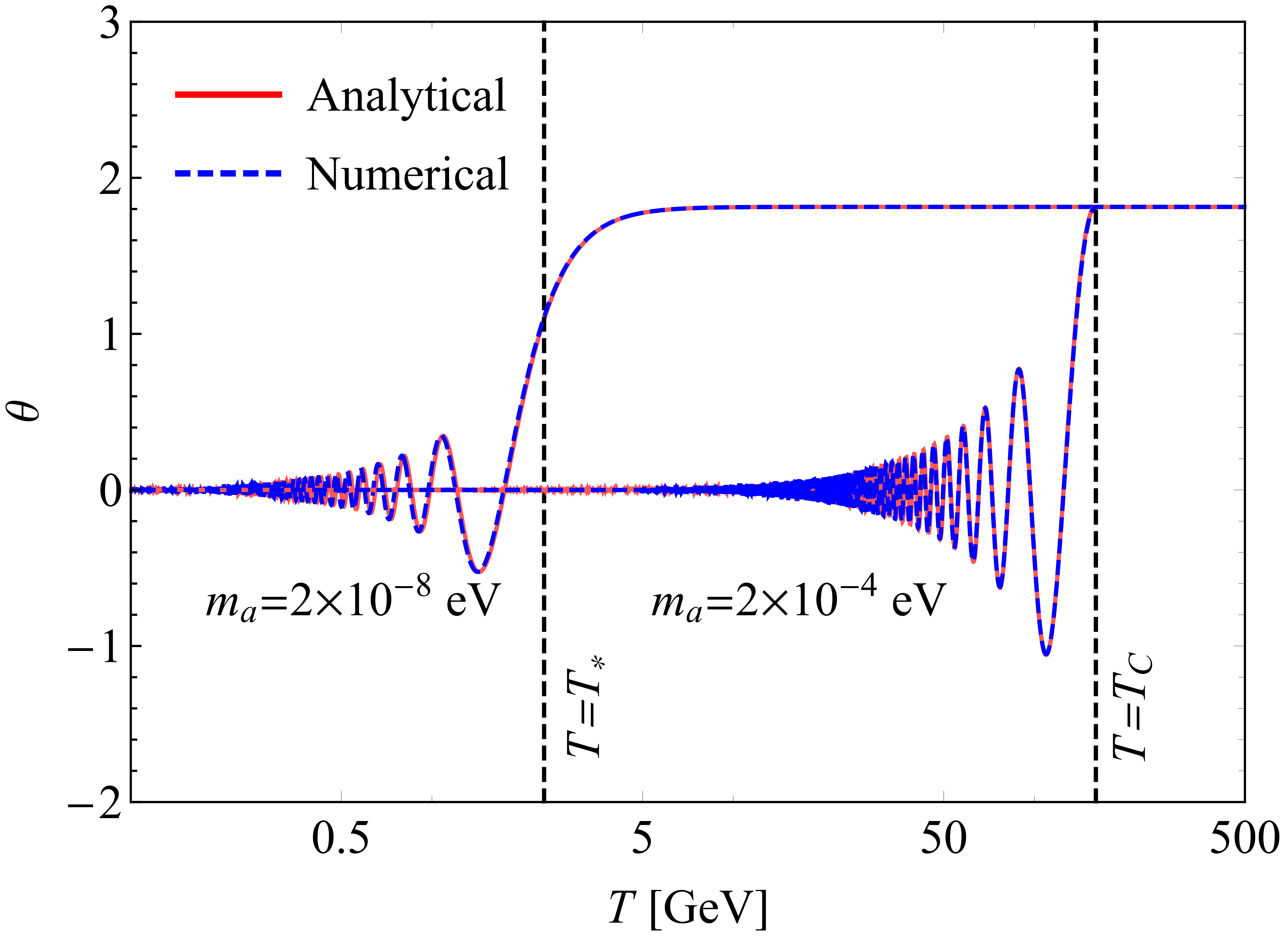
$$m_a^2(T) = \begin{cases} \dfrac{\mu v_\phi^2(T) v_\Delta(T)}{\sqrt{2} f_a^2}, & T \leq T_C \\ 0\,, & T > T_C \end{cases}$$

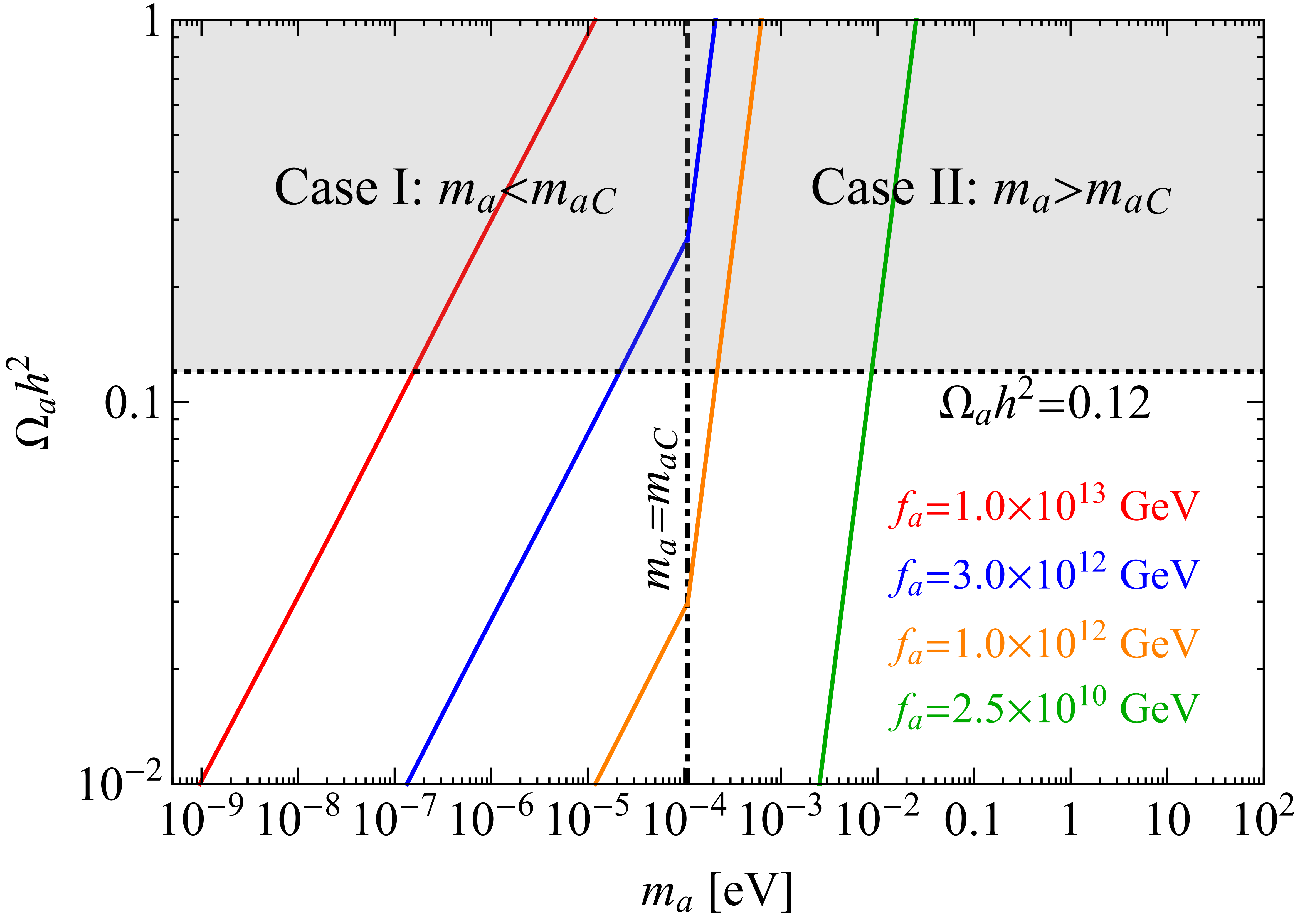
$$T_{\rm osc} = \begin{cases} T_*\,, & m_a < m_{aC} \\ T_C\,, & m_a \geq m_{aC} \end{cases}$$

$$m_{aC} = 1.079 \times 10^{-4}\,\mathrm{eV}$$



ALP DM—Relic Density





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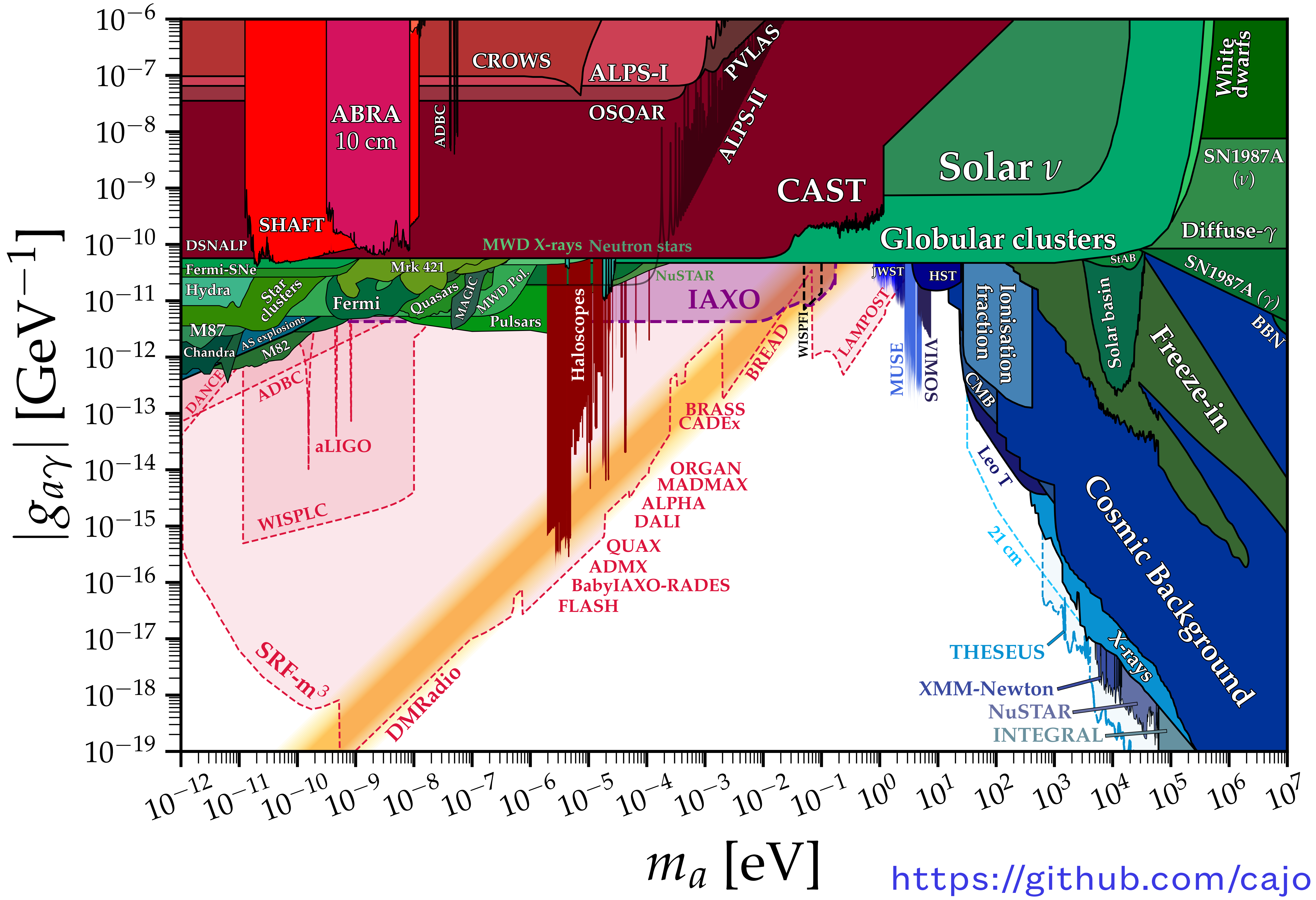
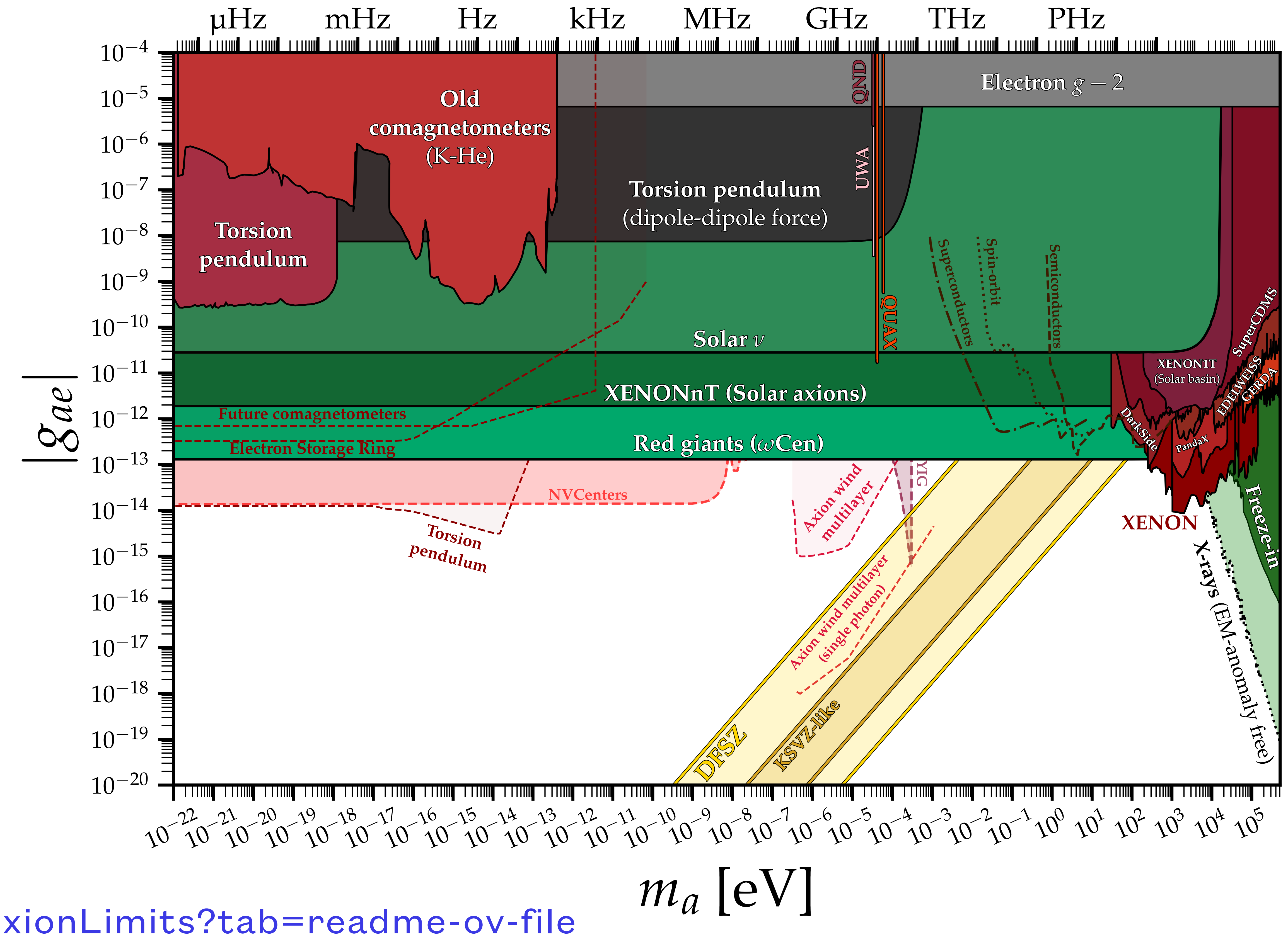
Detection of the ALP

八仙过海、各显神通

$g_{a\gamma\gamma}$



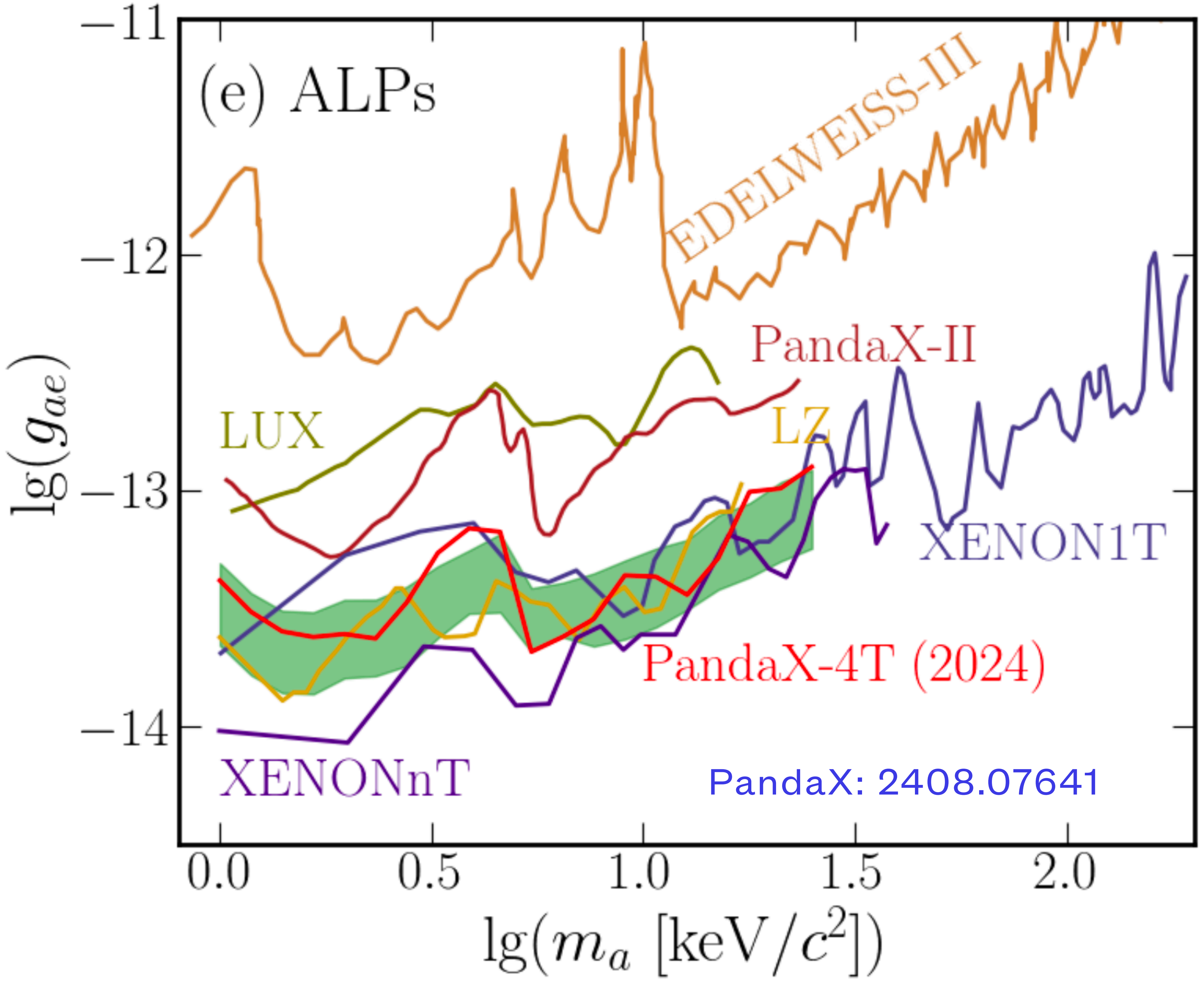
g_{aee}



https://github.com/cajohare/AxionLimits?tab=readme-ov-file

Detection of the ALP—direct detection

Axio-electric absorption of ALPs



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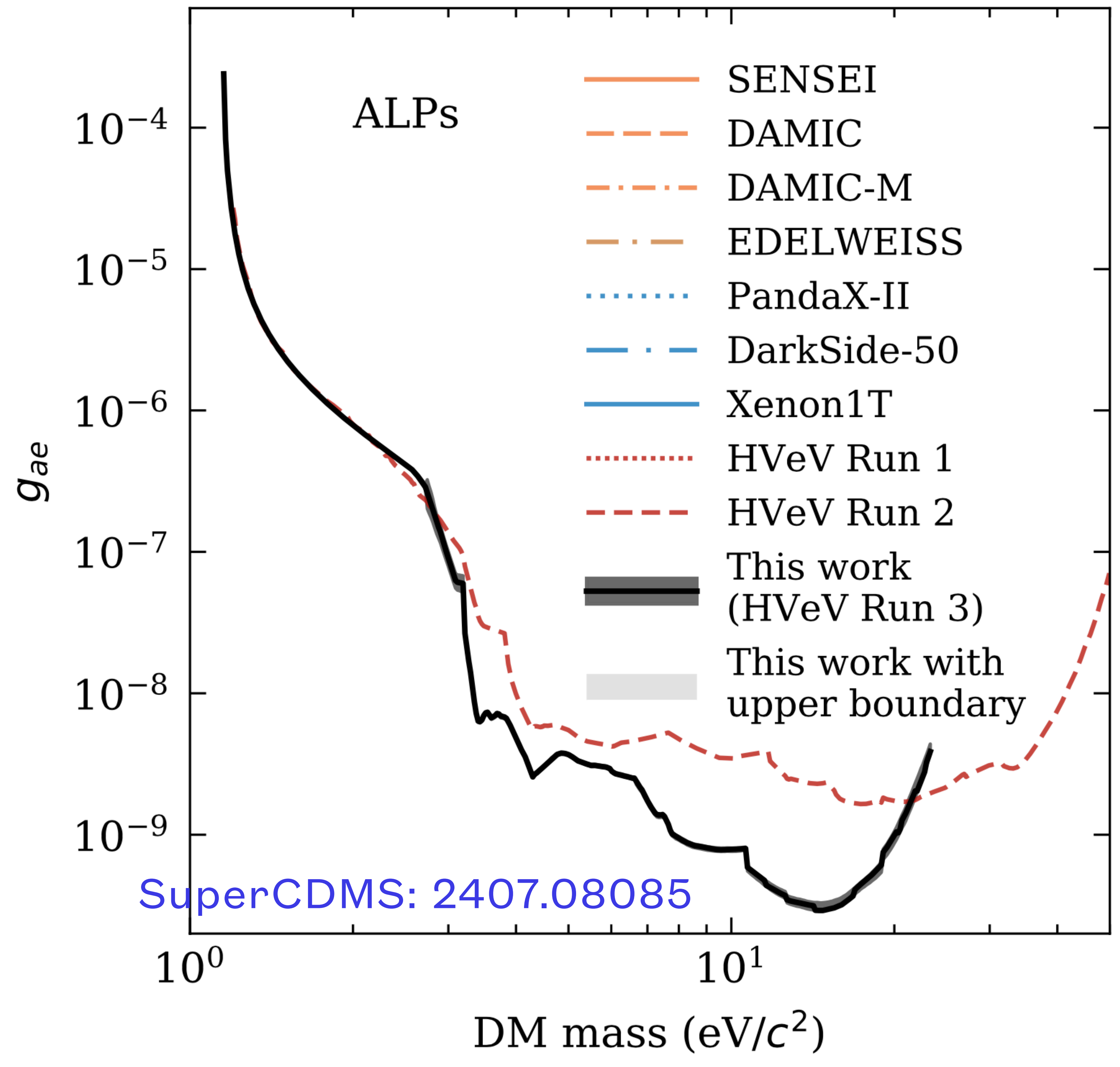
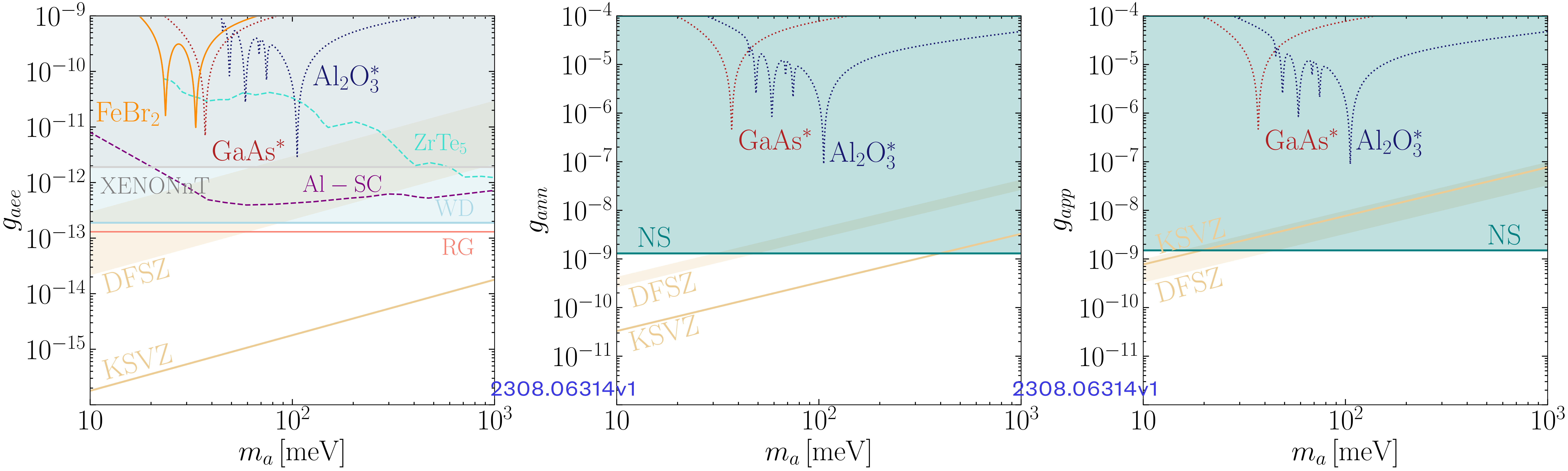


SuperCDMS: 2407.08085

Detection of the ALP—Condense matter material

$$R \approx \frac{1}{4}\frac{g_{aee}}{e}\frac{\omega}{m_e}\rho_a\rho_T\,\mathrm{Im}\left[-\frac{1}{\varepsilon(\omega)}\right]$$



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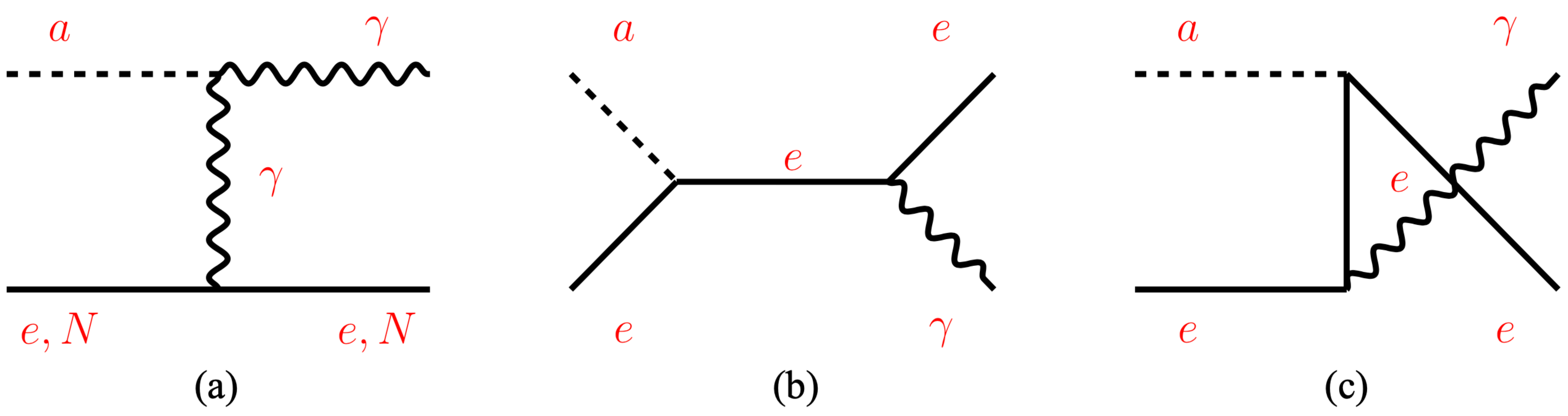
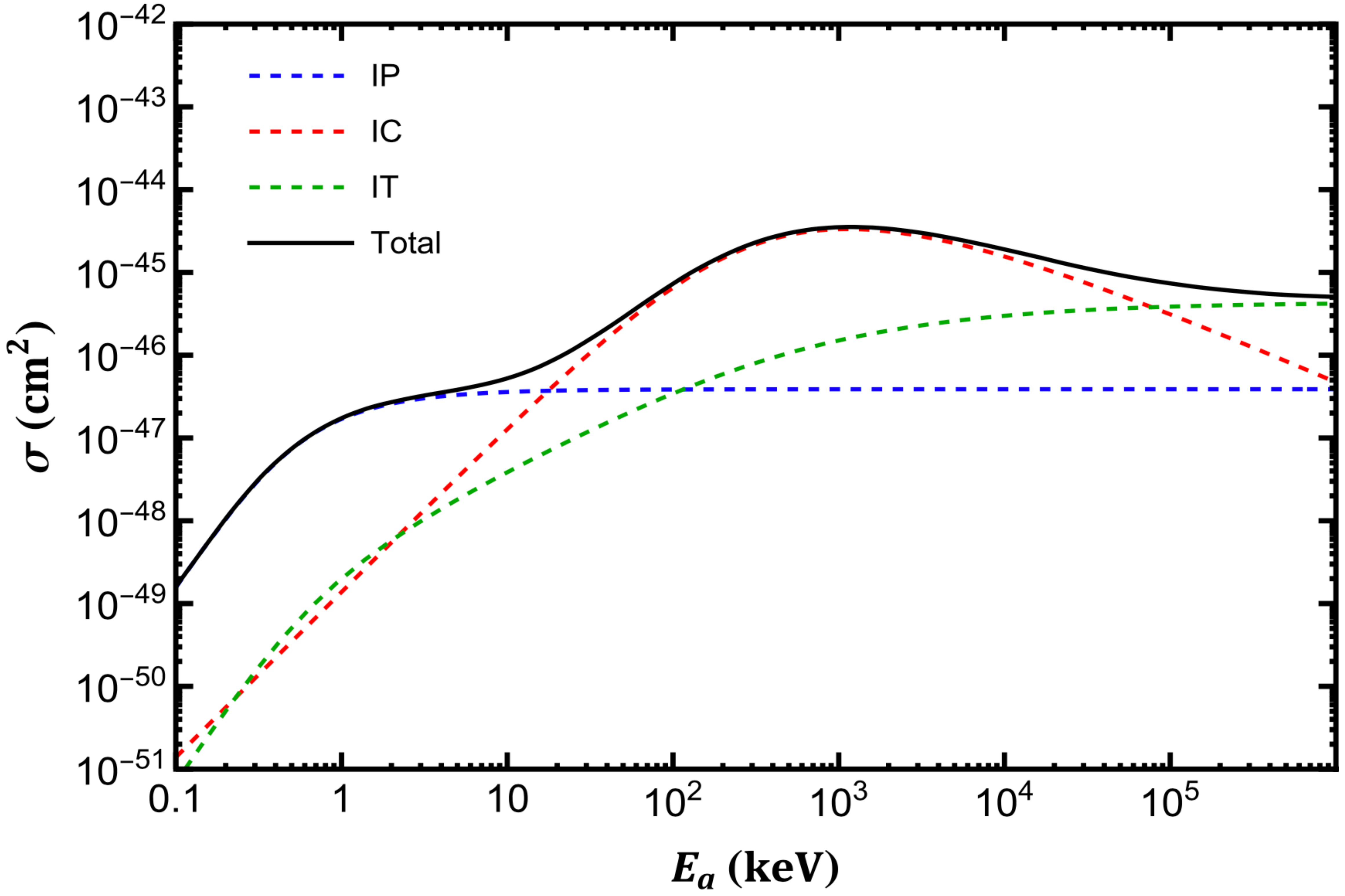
What we concern (1):Enhanced signal?

Is there an enhanced signal of ALP in direct detections when consider both $g_{a\gamma\gamma}$ and g_{aee} couplings?

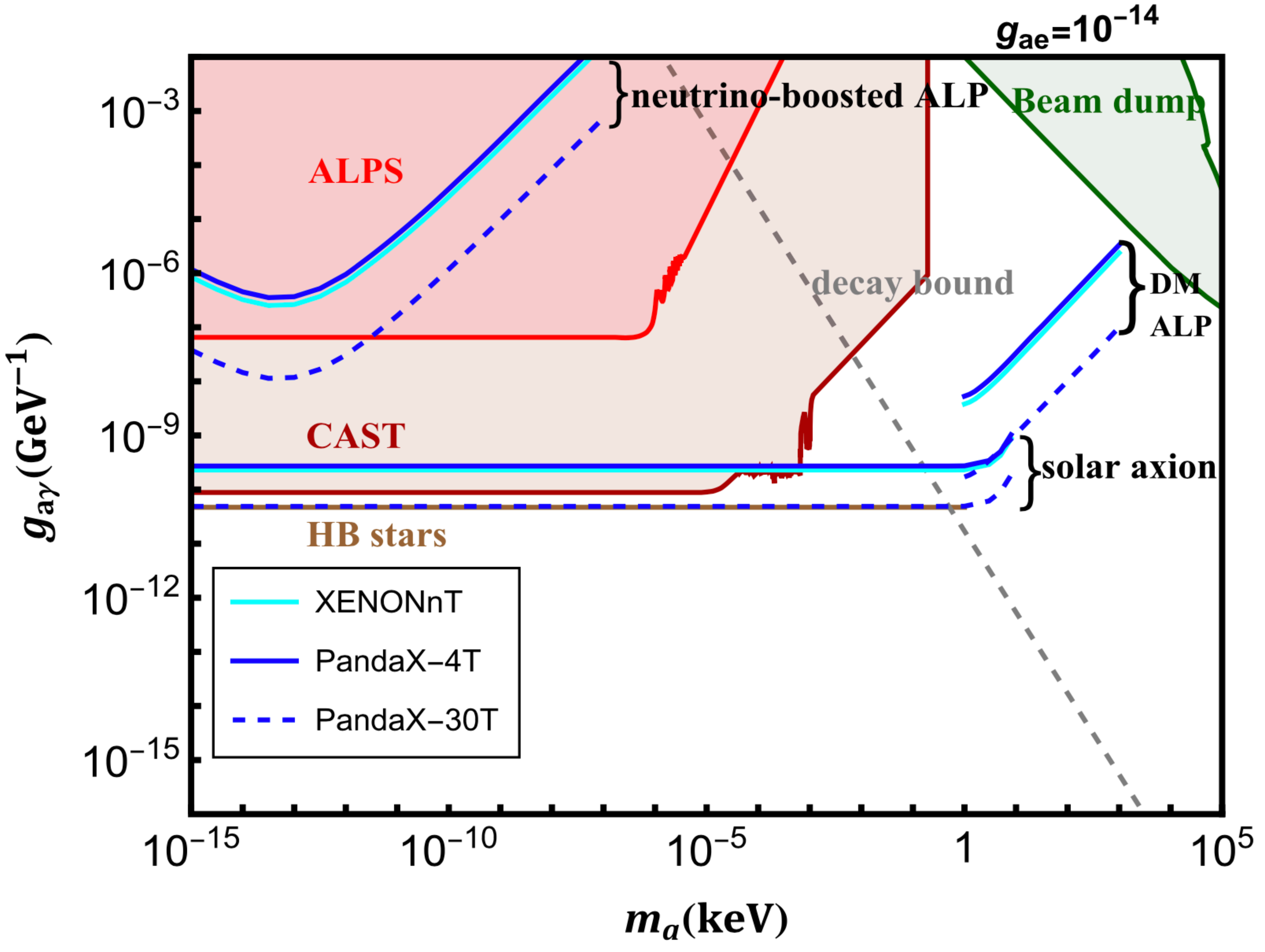
W. Chao, J. Feng, M.Jin, Phys.Rev.D

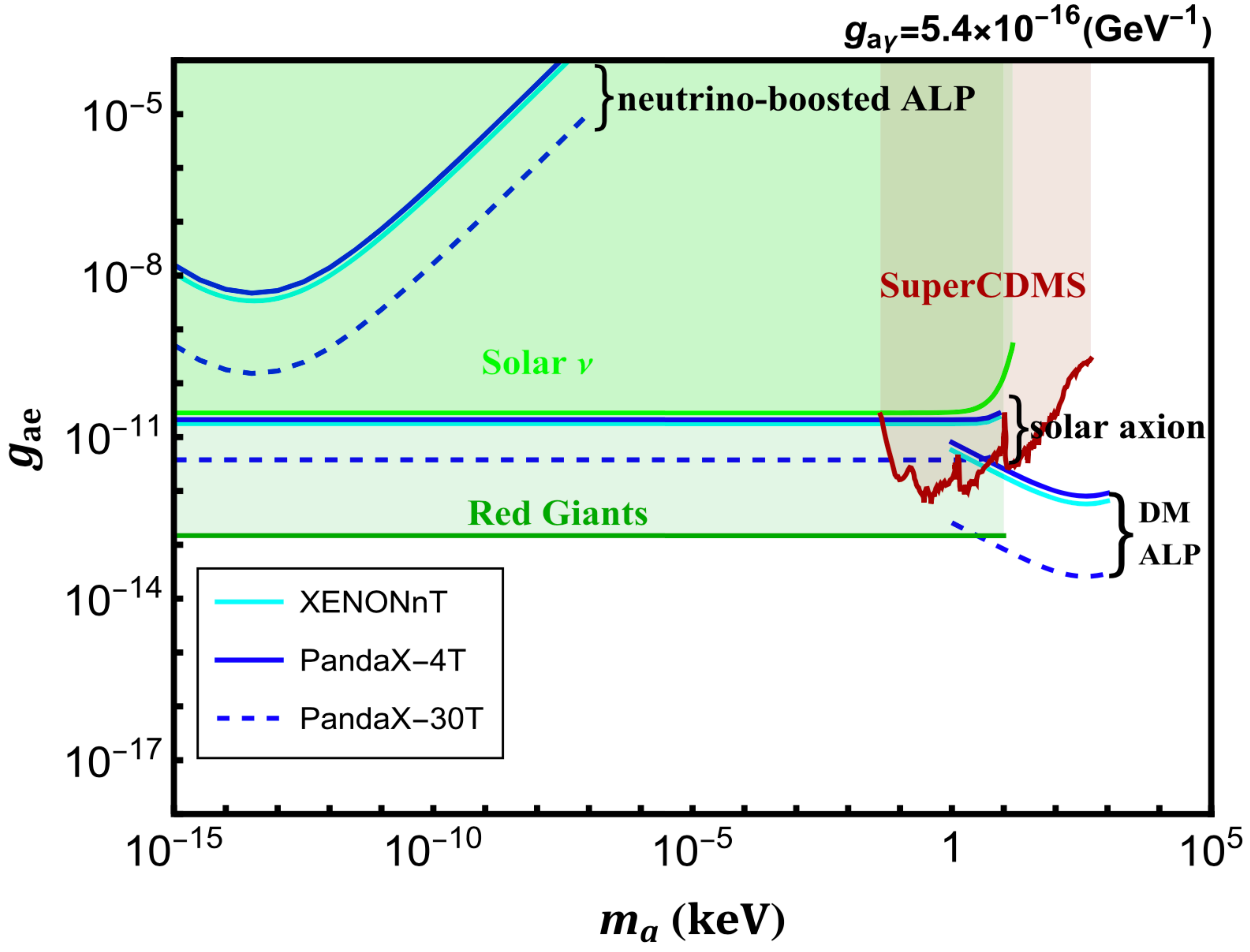
$$\mathscr{L} \sim -\frac{1}{4} g_{a\gamma\gamma} a F \tilde{F} + g_{aee} a \bar{e} i \gamma_5 e$$





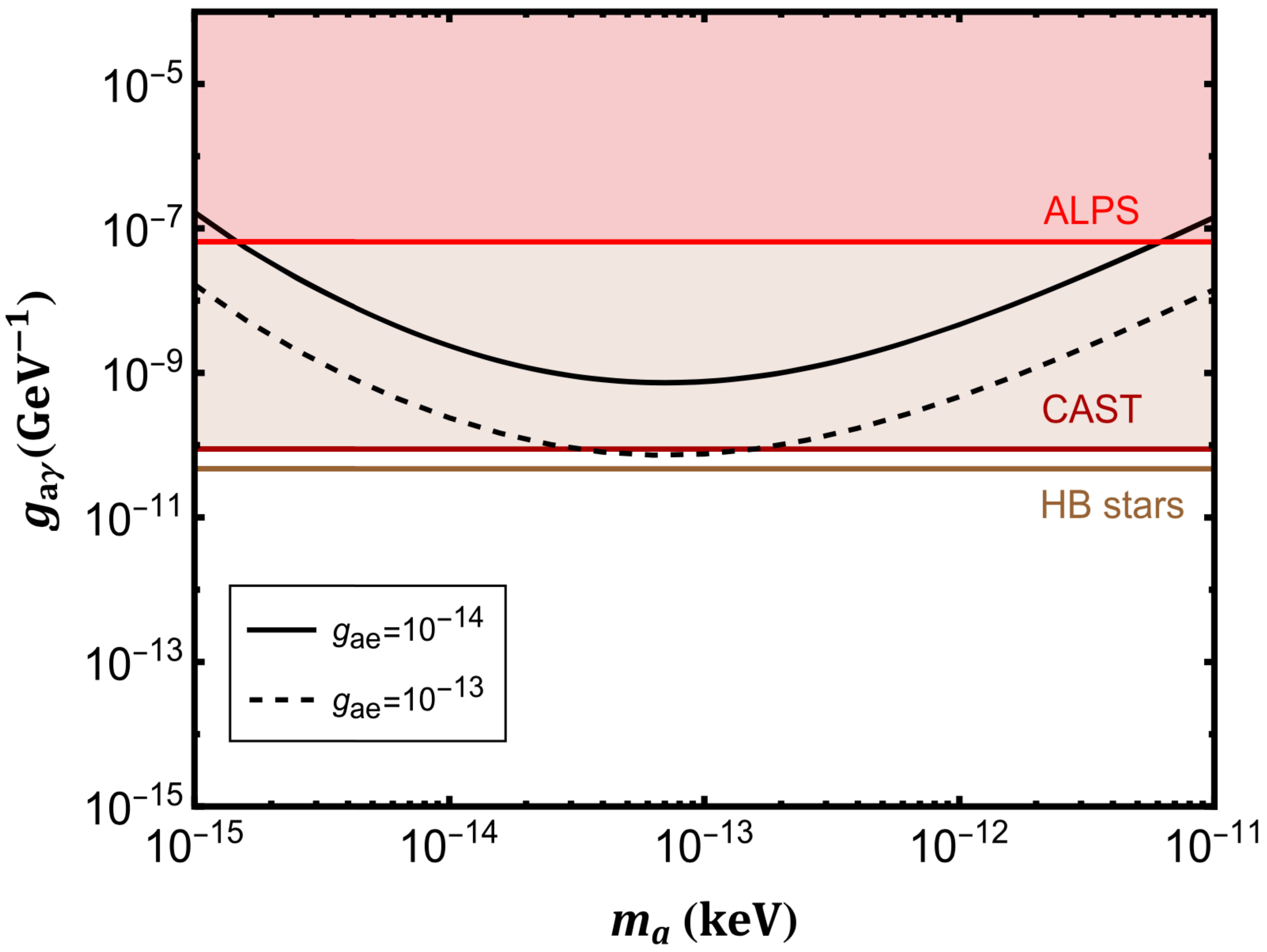
Constraint of DD

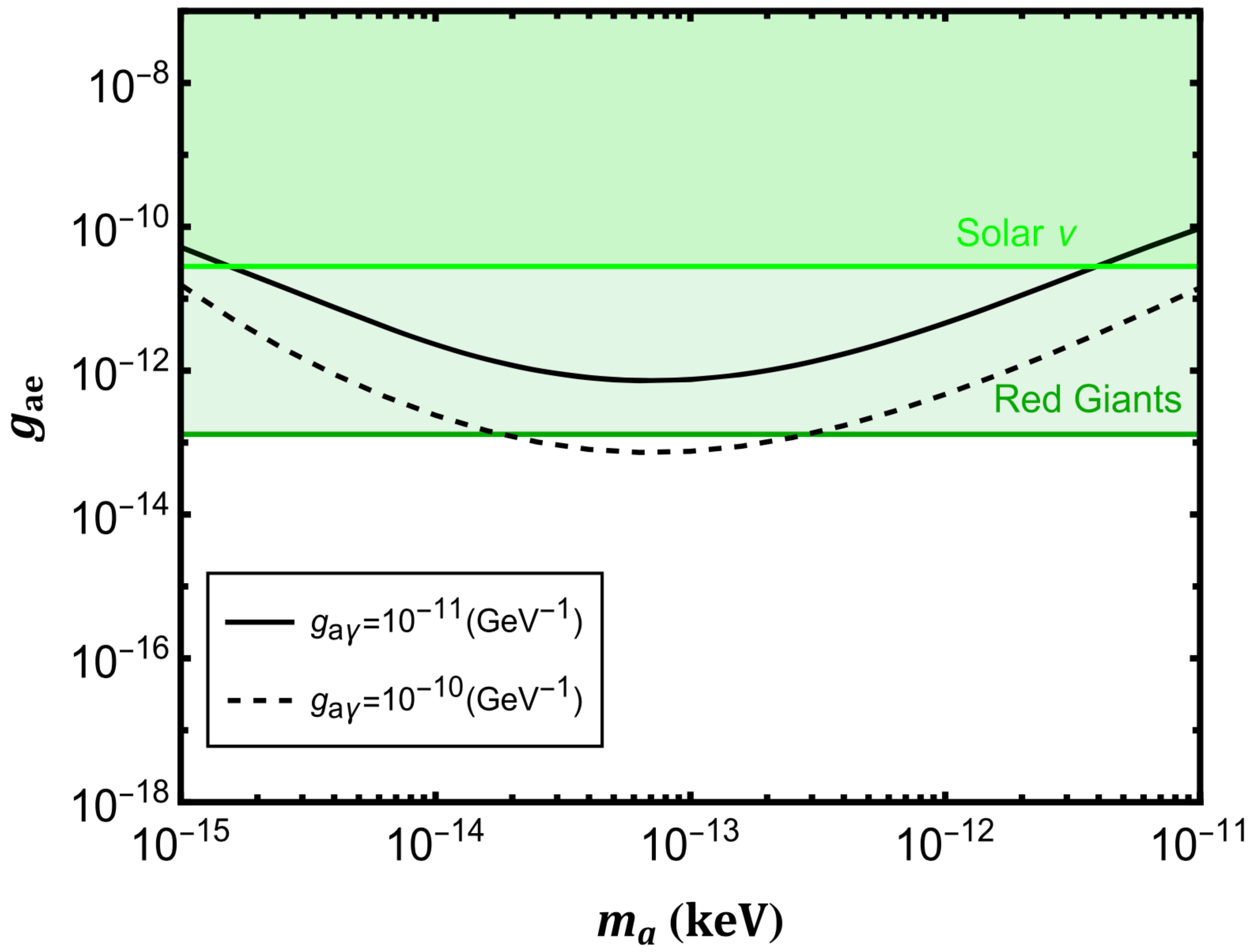




JUNO Constraint

$$N_{\text{event}} = N_e \cdot \Phi_a \cdot (\sigma^{\text{IP}} + \sigma^{\text{IC}} + \sigma^{\text{IT}}) \cdot \mathcal{R} \cdot \epsilon,$$





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✓

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What we concern (2):New DD strategy

Is there any new constraint on the ALP coupling from the superfluid?

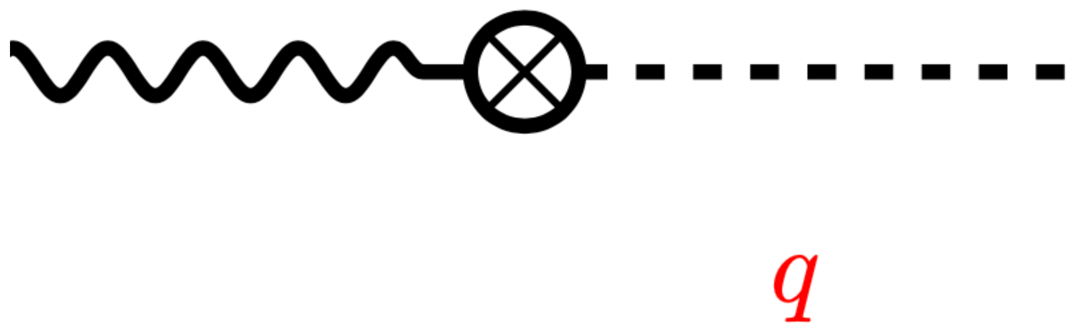
W Chao, S. Sun, X.Wang, C. Xie, Phys.Rev.D

Phonon (quasiparticle) in Superfluid Helium-4： **A Goldstone-like particle from the spontaneous breaking of the U(1) symmetry as well as the breaking of the boosts and the time translations in the superfluid He-4**

Action of phonon field

$$S_{int} \sim \int d^4x \sqrt{\frac{\mu}{\bar{n}}} c_s \left[\left(\frac{\mu^2}{2} \frac{db}{d\mu} + \mu b \right) \dot{\pi} F^{0\rho} F^0{}_\rho - \mu b \partial_j \pi F^{ij} F_{0i} + \frac{b}{2} \sqrt{\frac{\mu}{\bar{n}}} c_s \partial_\mu \pi \partial_\nu \pi F^{\mu\rho} F^\nu{}_\rho \right]$$

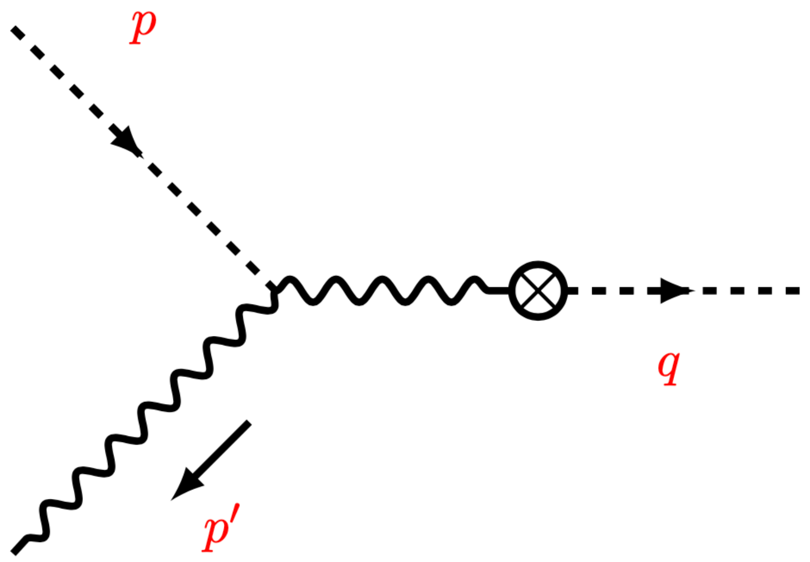
Phonon-photon conversion in external electric field



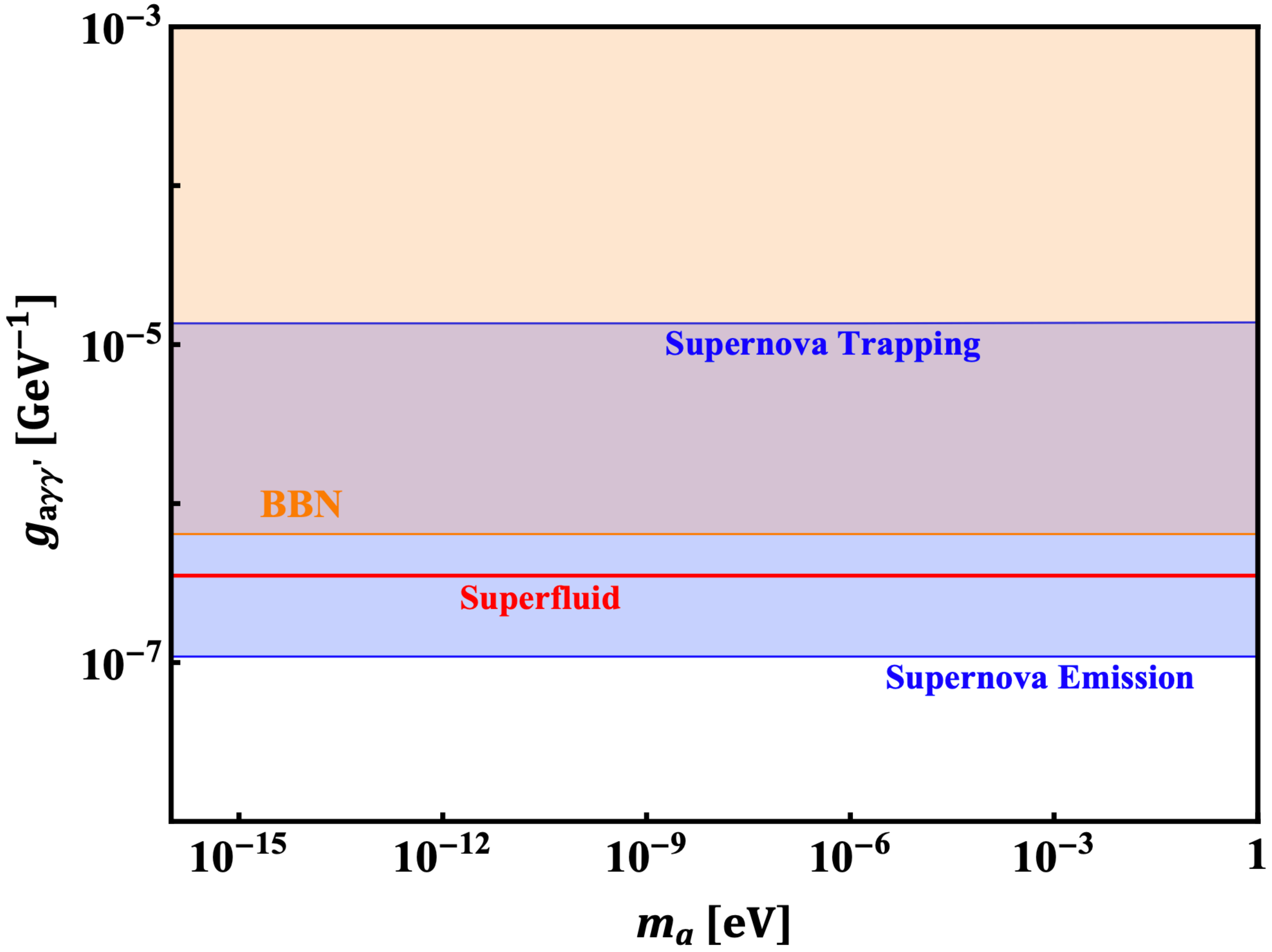
$$= i \frac{\alpha_E \bar{n}}{m_{He} c_s} \sqrt{\frac{m_{He}}{\bar{n}}} E_i \omega_q (\omega_q \delta_i^\mu + q_i \delta_0^\mu),$$

Constraints on $g_{a\gamma\gamma'}$

Why? (1) No DD constraint on this coupling ; (2) There are already strong constraint on $g_{a\gamma\gamma}$.



$$\frac{d\Gamma}{d\omega} = \frac{g^2_{a\gamma\gamma'}\bar{n}\alpha_E^2}{16\pi m_a \omega^2 m_{He} E v_a}\frac{|\mathbf{E}|^2\omega^2}{c_s^2}\left\{(\cos^2\theta_E - c_s^2)\omega^2\left(1-\frac{1}{c_s^2}\right)\left[E^2(1-v_a^2)\right.\right.$$
$$\left. + 2E\omega\left(\frac{v_a}{c_s}\cos\theta - 1\right) + \omega^2\left(1-\frac{1}{c_s^2}\right)\right] - \omega^2\left(1-\frac{1}{c_s^2}\right)(E\cos\theta_E - |\mathbf{p}|^2 c_s\cos\theta_a)^2$$
$$\left. - (\cos^2\theta_E - c_s^2)\left[\omega\left(E - \frac{|\mathbf{p}|}{c_s}\cos\theta\right) - \omega^2\left(1-\frac{1}{c_s^2}\right)\right]^2\right\}.$$



Summary

(1) A new ALP mass generation mechanism is discussed.

(2) The Direct detection of ALP is revisited.

(3) New strategy for the DD of ALP is considered.

Thank you for your attention!