Adiabatic conversion between the QCD axion and ALP dark matter at level crossing

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In preparation

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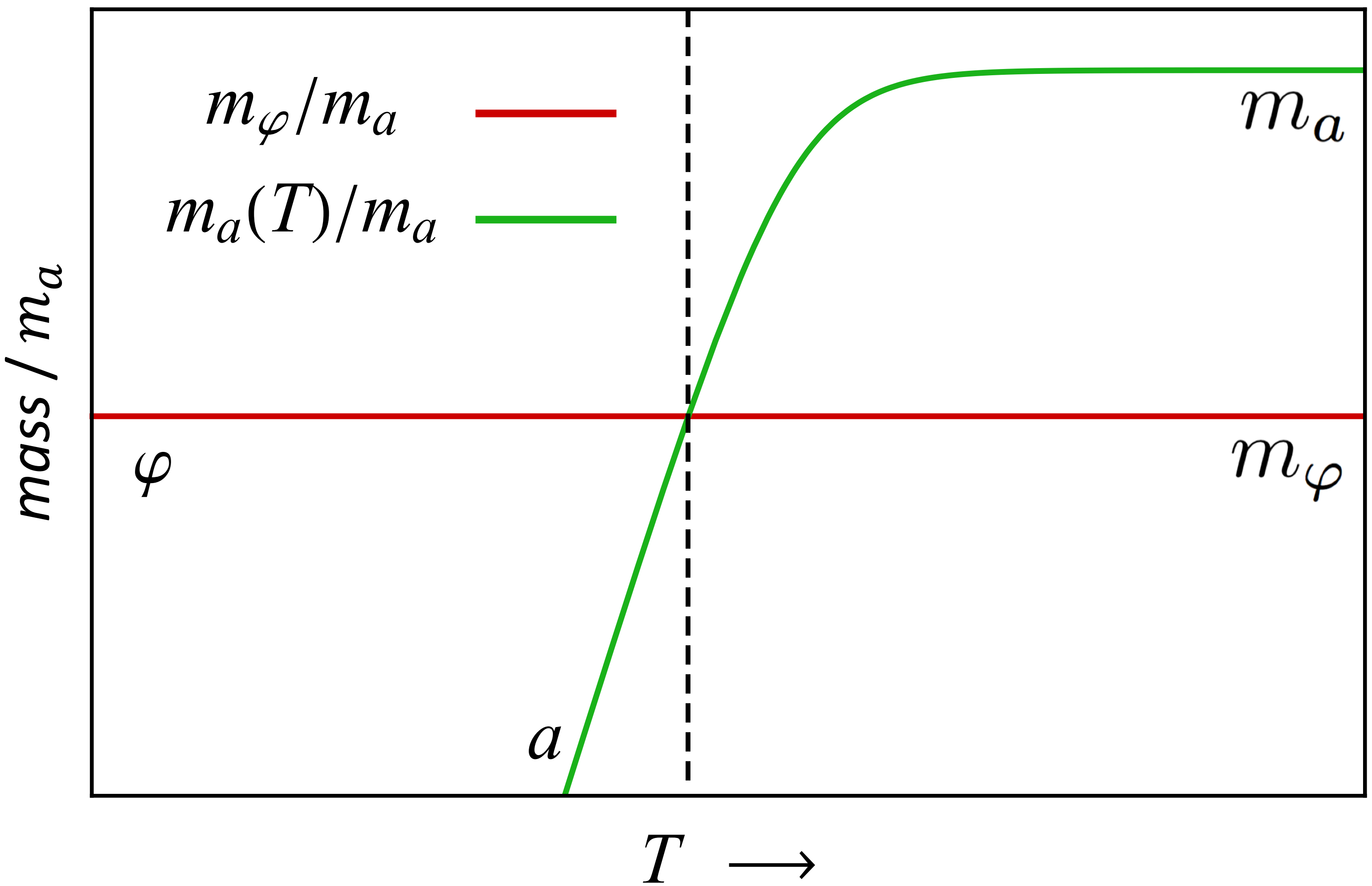
What if QCD axion a and ALP φ coexist in nature?

What happen if they have a mass mixing?

Level crossing

Without mass mixing

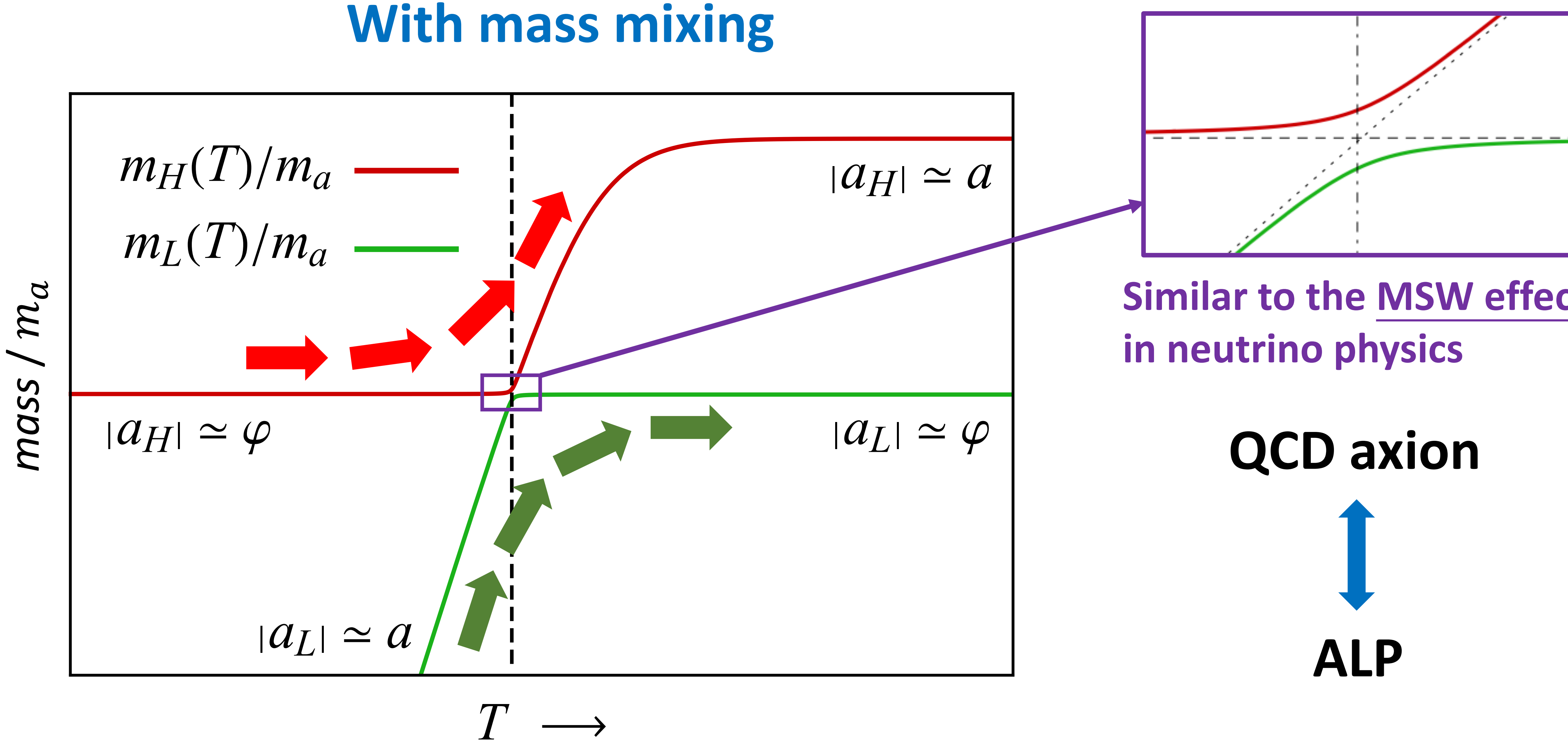


$$\begin{cases} m_a(T) \to 0 & T \gg \Lambda_{\rm QCD} \\ m_a(T) \to m_a & T \ll \Lambda_{\rm QCD} \end{cases}$$

ALPs do not acquire a mass from the effects of QCD.

Level crossing

With mass mixing



Similar to the MSW effect in neutrino physics

QCD axion

↕

ALP

What if QCD axion a and ALP φ coexist in nature?

What happen if they have a mass mixing?

Adiabatic conversion between the QCD axion and ALP could take place!

C. T. Hill and G. G. Ross (1988)
N. Kitajima & F. Takahashi (2014)

Content

- Level crossing & Adiabatic conversion
- Cosmological abundances
- Axion-photon coupling
- Summary

Mass mixing of the QCD axion and ALP

- The Model

Mass mixing

$$V_{\rm QCD}(a) = \underline{m_a^2(T)} f_a^2 \left[1 - \cos\left(\frac{a}{\underline{f_a}}\right)\right], \quad V_{\rm mix}(a,\varphi) = \underline{m_\varphi^2} f_\varphi^2 \left[1 - \cos\left(\frac{a}{f_a} + \frac{\varphi}{\underline{f_\varphi}}\right)\right]$$

QCD axion mass

QCD axion decay constant

ALP mass

ALP decay constant

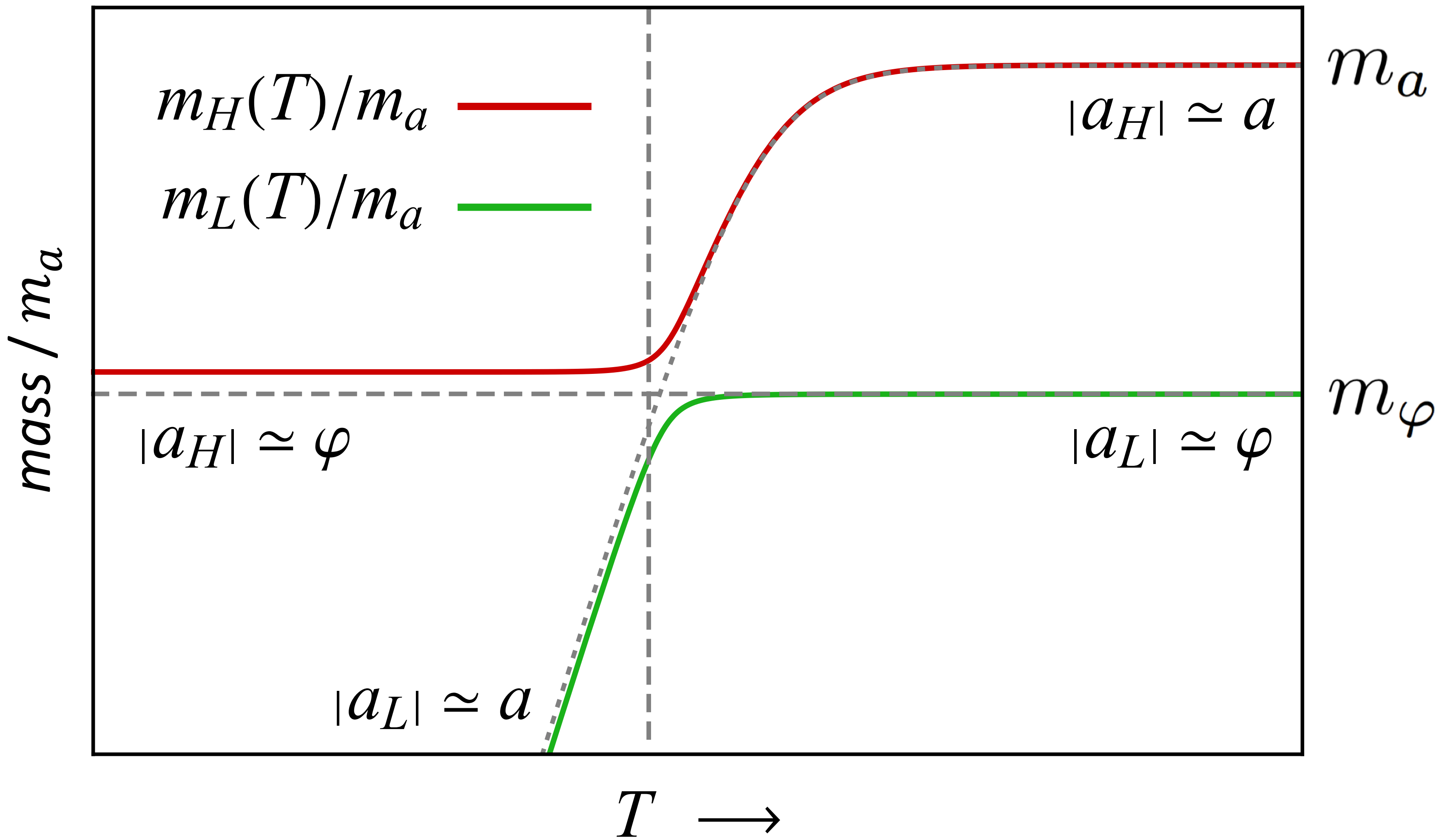
- Mass eigenstate $(\varphi, a) \to (a_H, a_L)$

$$m_{H,L}^2(T) = \frac{1}{2} m_a^2(T) \left\{1 + \mathcal{R}_m^2 \frac{m_a^2}{m_a^2(T)} \left[1 + \mathcal{R}_f^2 \pm \sqrt{\left(1 - \mathcal{R}_f^2 - \frac{1}{\mathcal{R}_m^2}\frac{m_a^2(T)}{m_a^2}\right)^2 + 4\mathcal{R}_f^2}\right]\right\}$$

$$a_H = \varphi \cos\xi + a \sin\xi \qquad a_L = -\varphi \sin\xi + a \cos\underline{\xi}$$

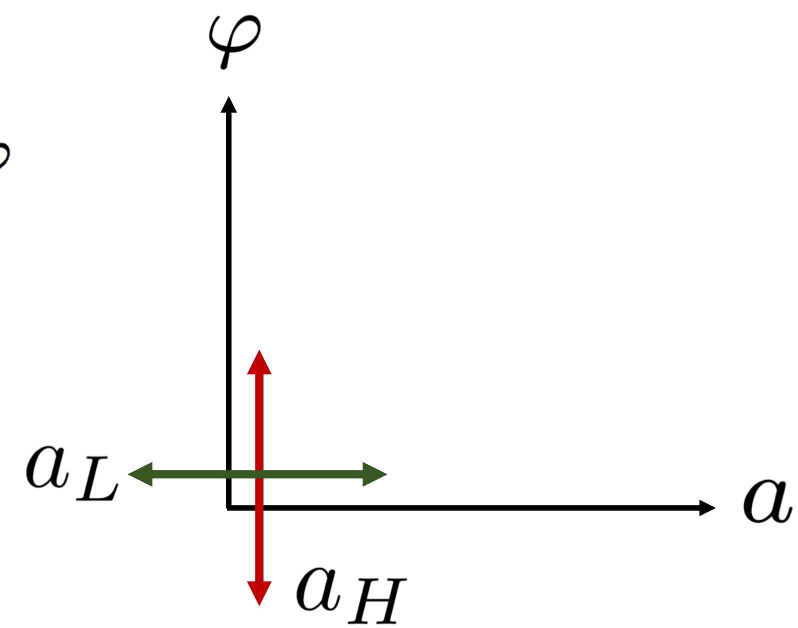
Mixing angle

Level crossing

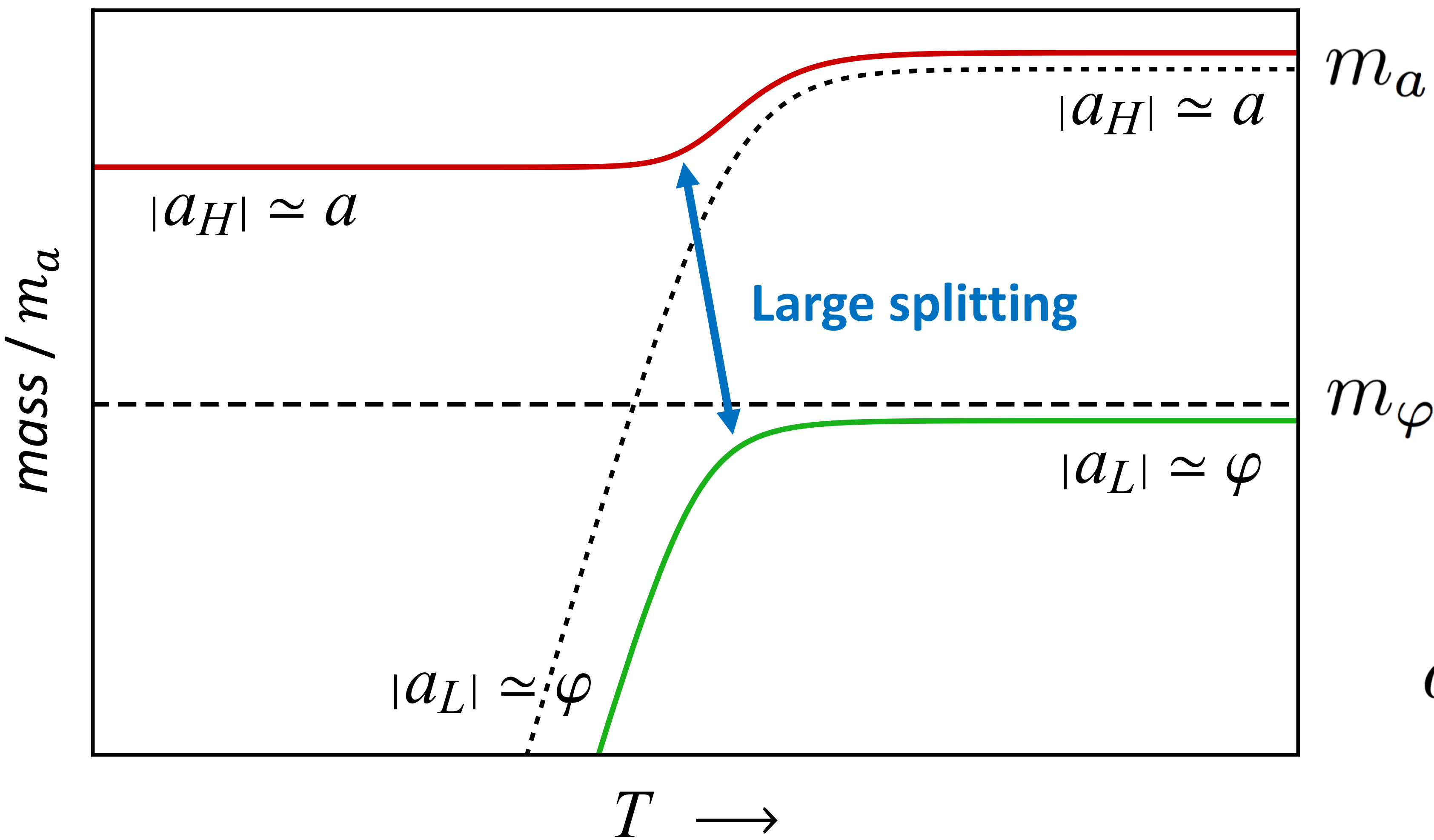


$$f_\varphi < f_a$$

$$m_\varphi < m_a$$

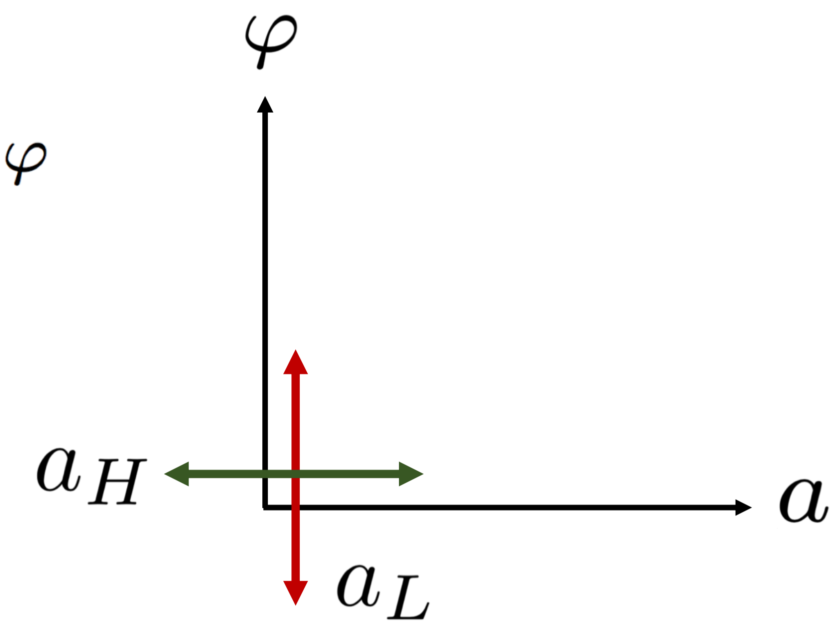


Level crossing



$$f_\varphi > f_a$$

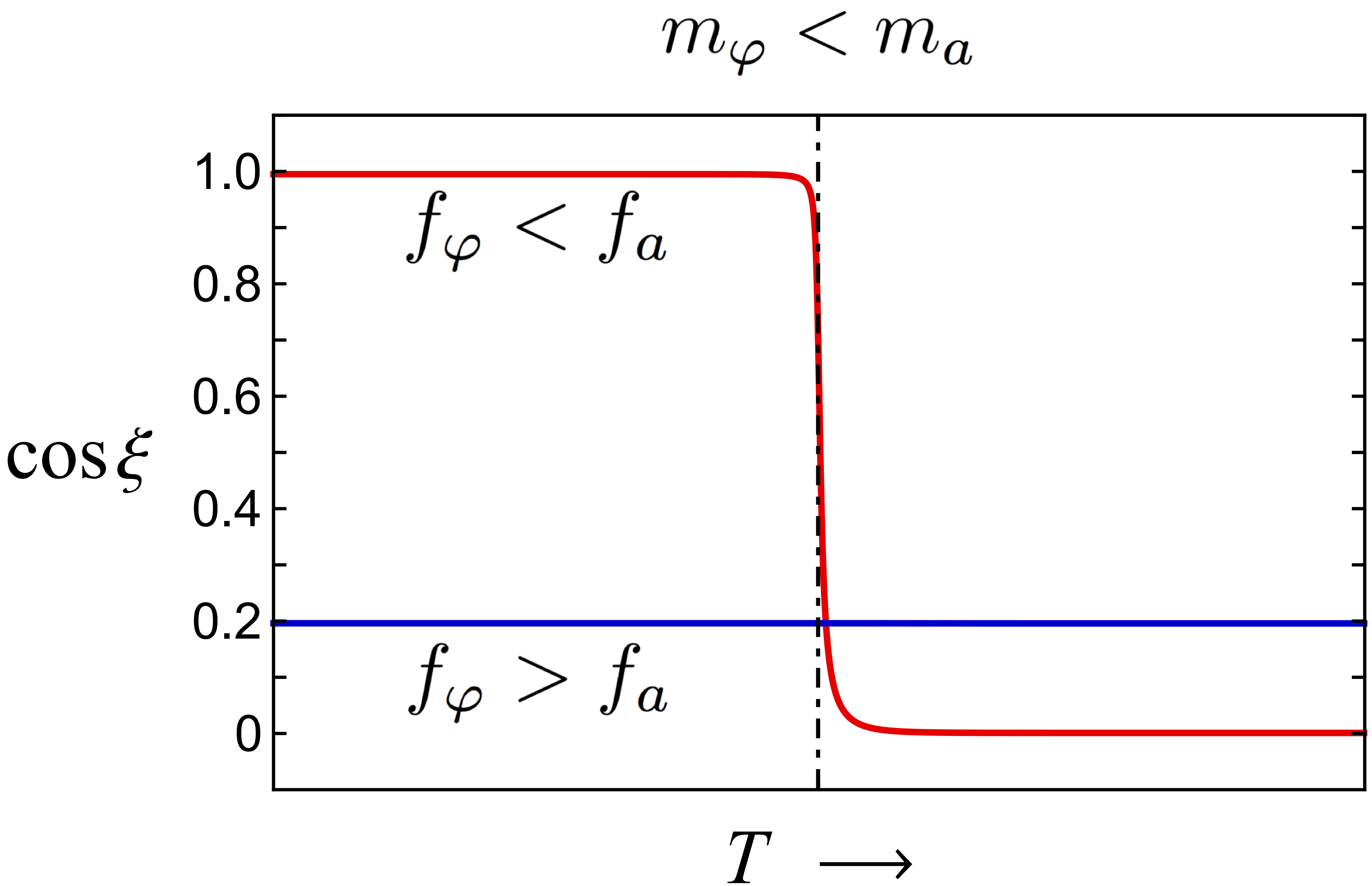
$$m_\varphi < m_a$$

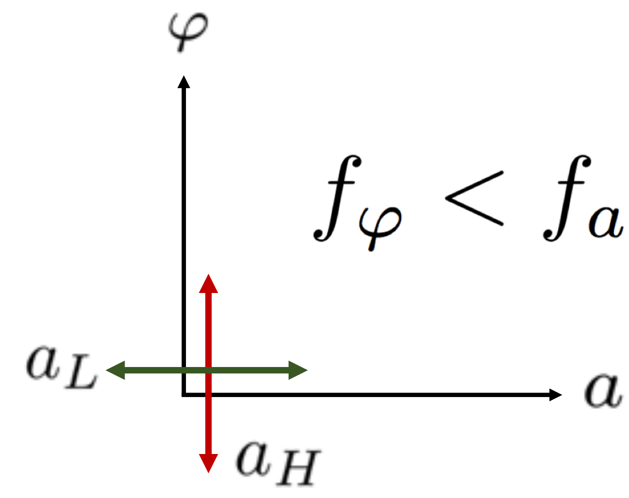


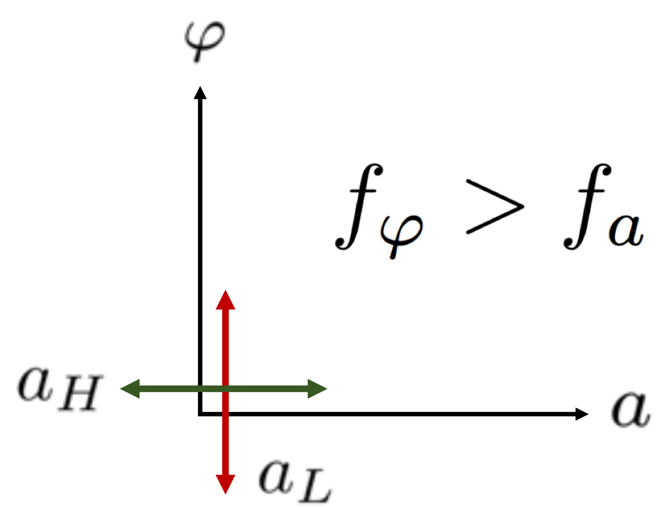
Level crossing

$$a_H = \varphi \cos\xi + a \sin\xi$$

$$a_L = -\varphi \sin\xi + a \cos\xi$$

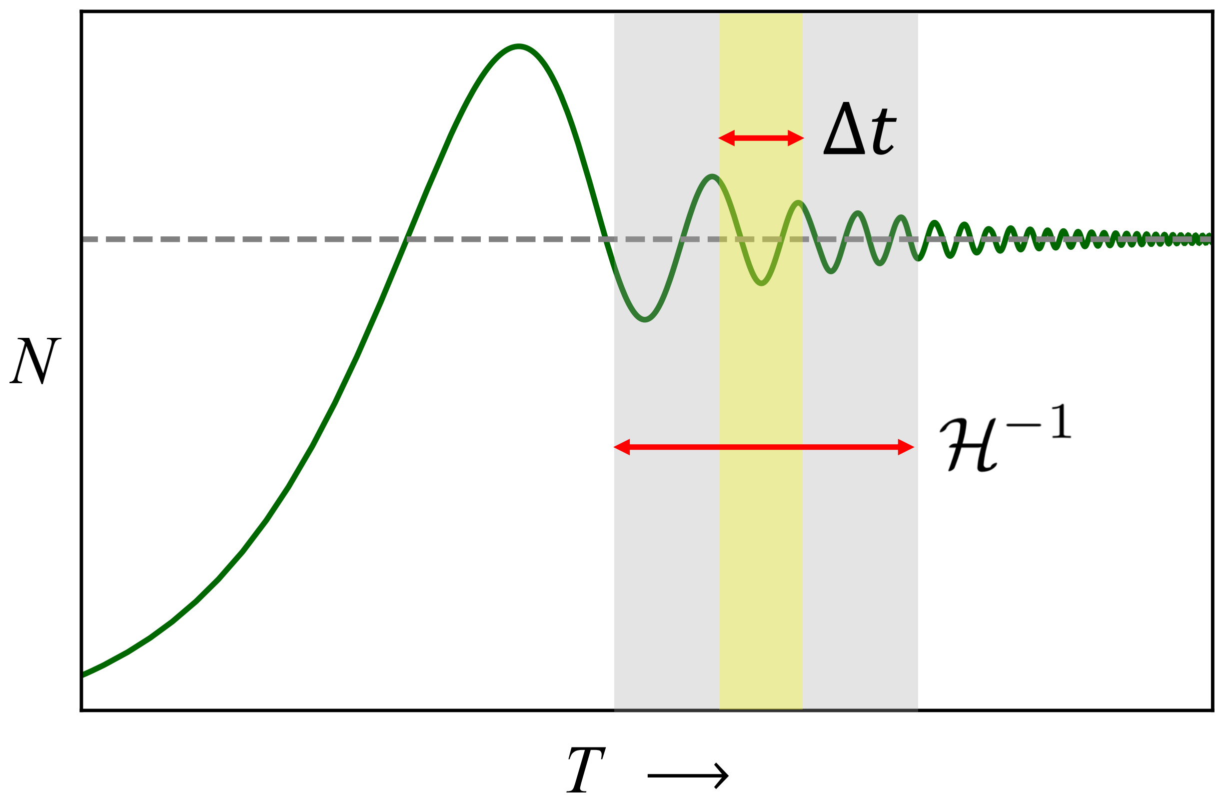






Adiabatic invariant in the case of a single axion

- Comoving axion number $N(T)$: **adiabatic invariant**



Adiabatic process

External time scale >> Internal time scale

$$\mathcal{H}^{-1} \gg \Delta t = \frac{2\pi}{m_a(T)}$$

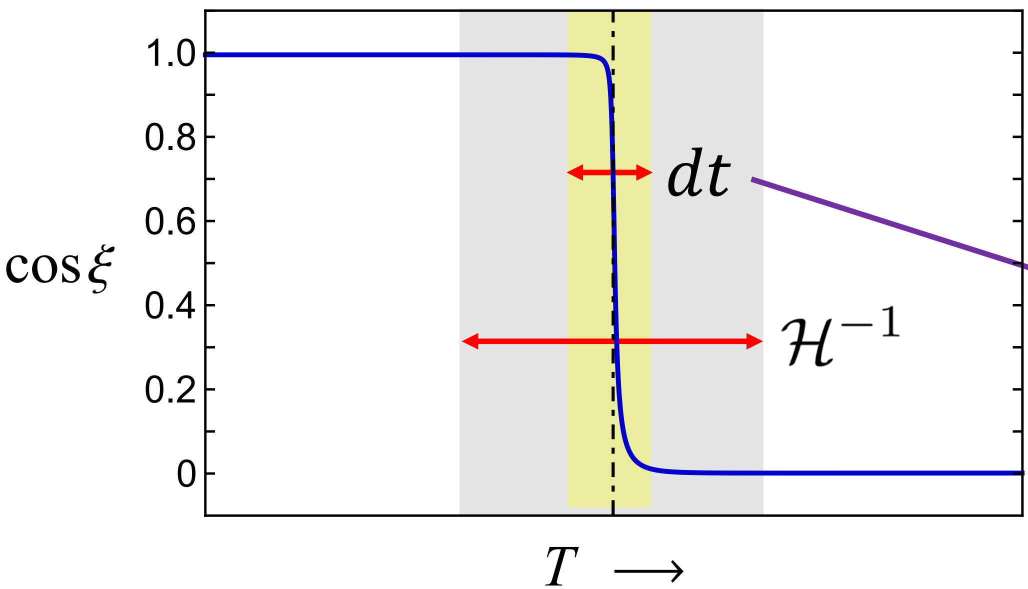
$$\downarrow$$

$$N(T < T_{\mathrm{osc}}) = \text{const.}$$

$\mathcal{H} = \mathcal{H}(T)$: Hubble parameter

Adiabatic invariant in the case of two axions

- If there is a mass mixing between the QCD axion and ALP



Adiabatic process

External time scale >> Internal time scale

$$\left|\frac{1}{\cos\xi(T)}\frac{d\cos\xi(T)}{dt}\right|^{-1} > \max\left[\frac{2\pi}{m_L(T)}, \frac{2\pi}{m_H(T)-m_L(T)}\right]$$

$$(\mathcal{H}^{-1} \gg dt)$$

Beat frequency

At the level crossing

$$f_\varphi < f_a$$

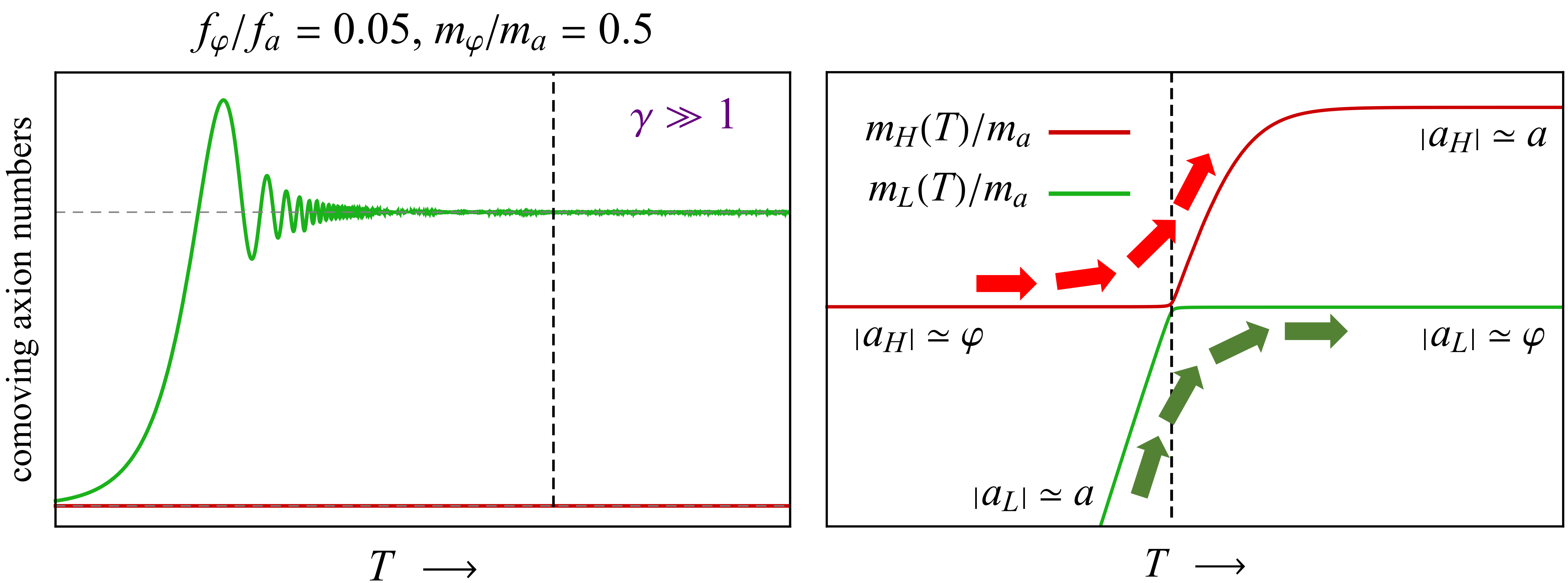
$$\gamma \equiv \beta\,\frac{f_\varphi}{f_a}\sqrt{\frac{m_\varphi}{\mathcal{H}(T_{\rm lc})}} \gg 1$$

If this inequality is satisfied, the conversion of the QCD axion and ALP is adiabatic, the comoving axion numbers are separately conserved.

Adiabatic conversion

$$\gamma = \beta \frac{f_\varphi}{f_a} \sqrt{\frac{m_\varphi}{\mathcal{H}(T_{\rm lc})}}$$

- Evolution of $N_{L,H}(T)$ — $N_L(T)$ (green line), $N_H(T)$ (red line)

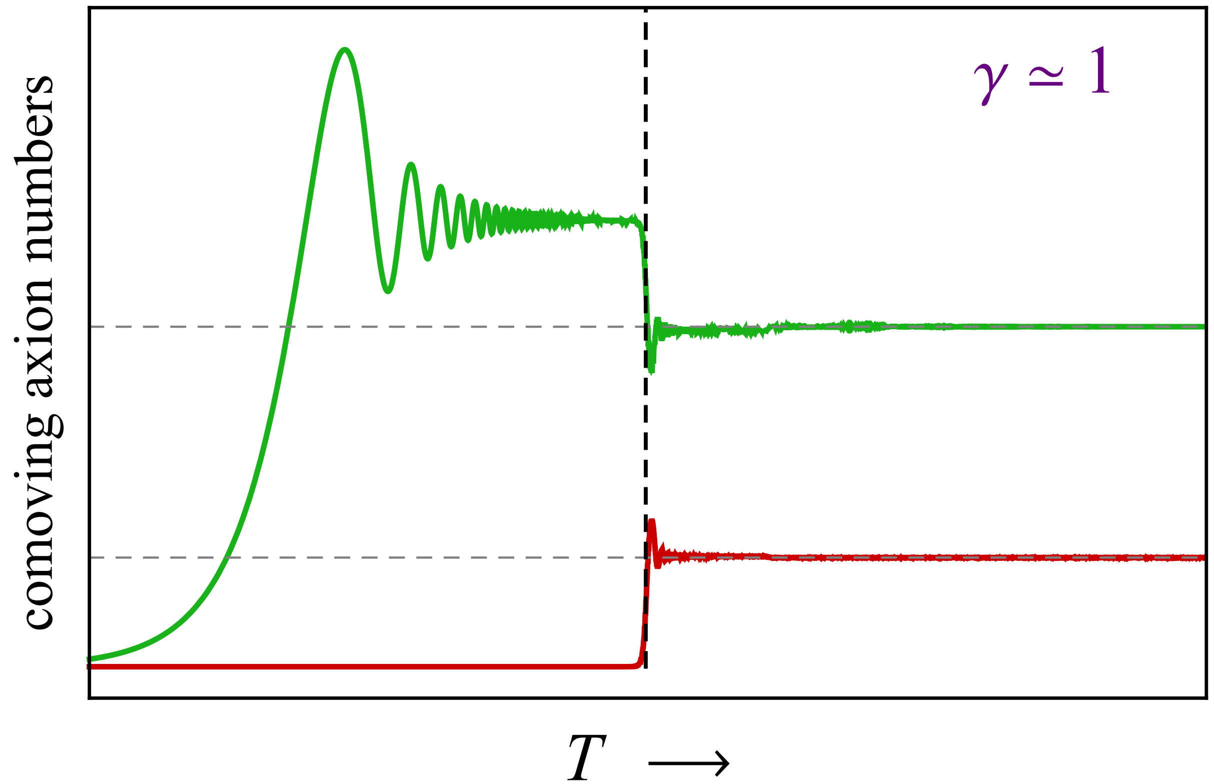


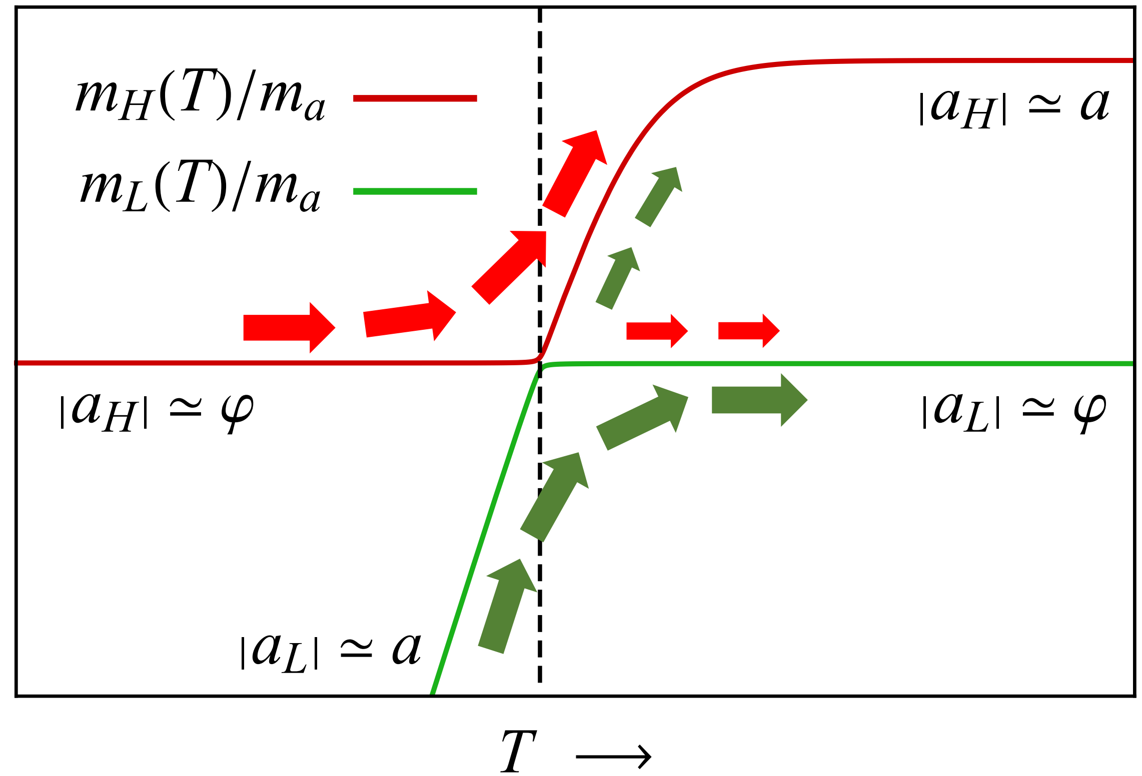
Adiabatic conversion

$$\gamma = \beta \frac{f_\varphi}{f_a} \sqrt{\frac{m_\varphi}{\mathcal{H}(T_{\rm lc})}}$$

- Evolution of $N_{L,H}(T)$ $\quad N_L(T)$ (green) $\quad N_H(T)$ (red)

$f_\varphi/f_a = 0.05,\ m_\varphi/m_a = 0.1$



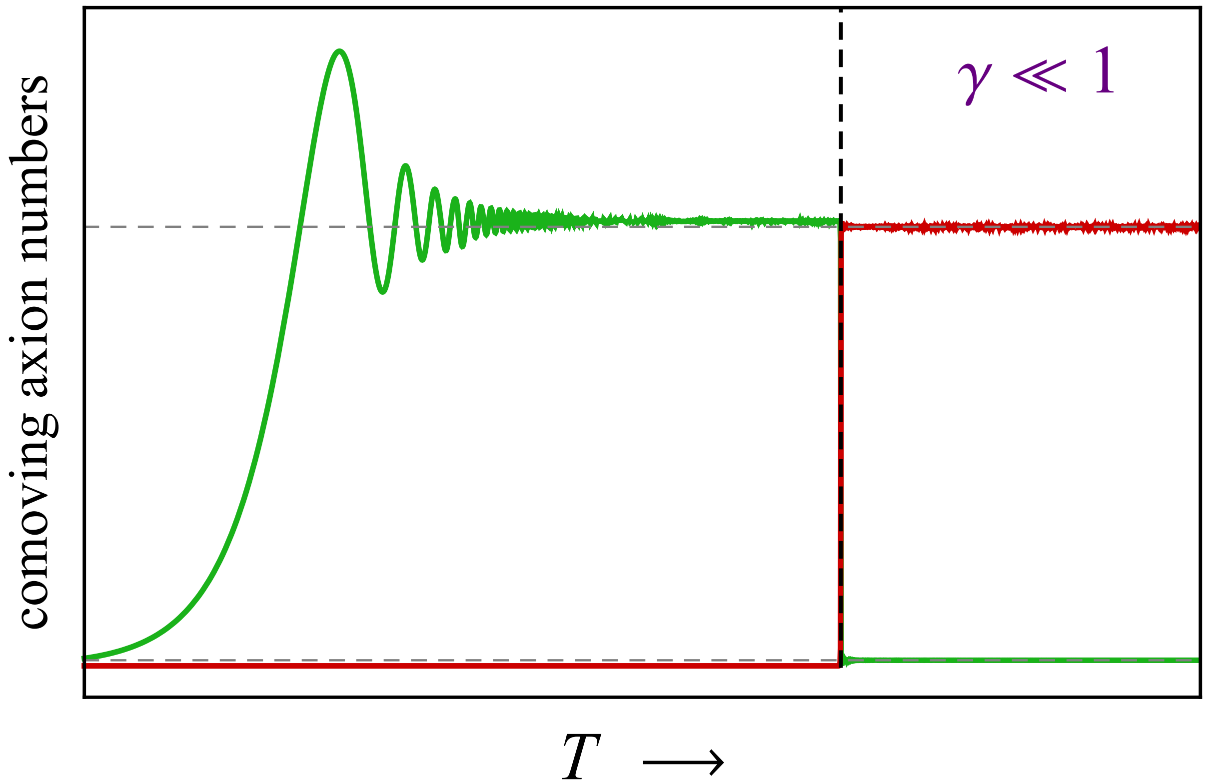


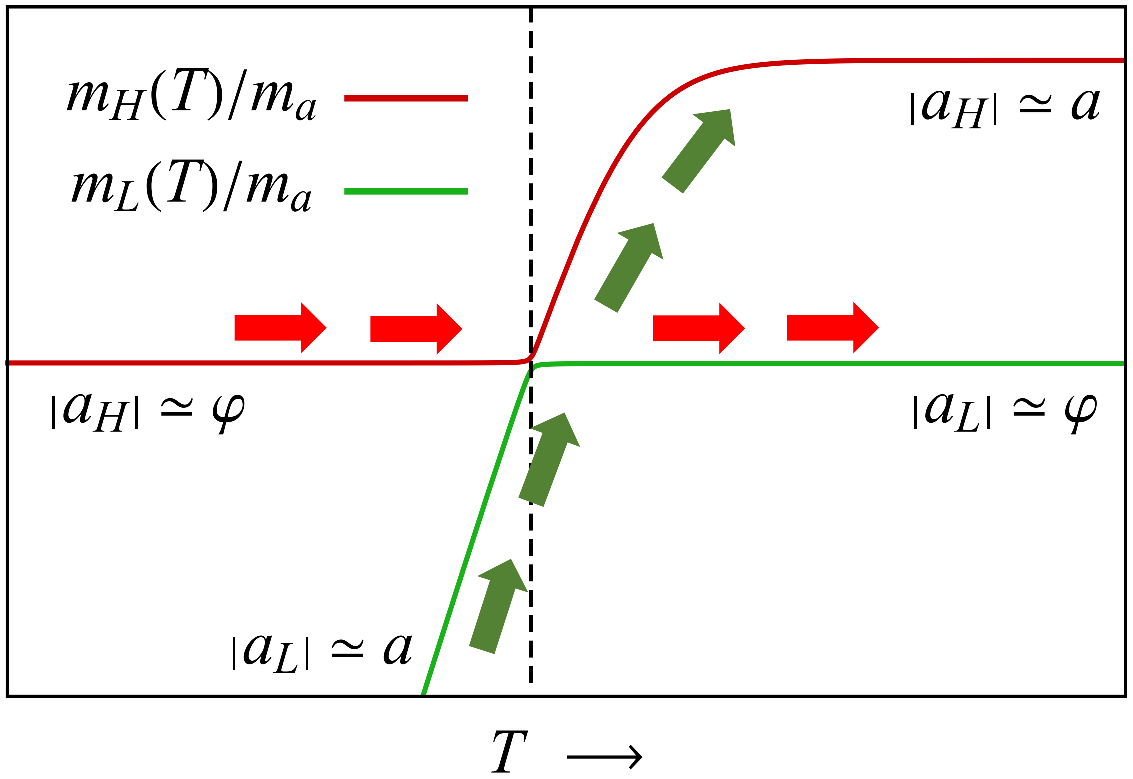
Adiabatic conversion

$$\gamma = \beta \frac{f_\varphi}{f_a} \sqrt{\frac{m_\varphi}{\mathcal{H}(T_{\rm lc})}}$$

- Evolution of $N_{L,H}(T)$ $N_L(T)$ $N_H(T)$

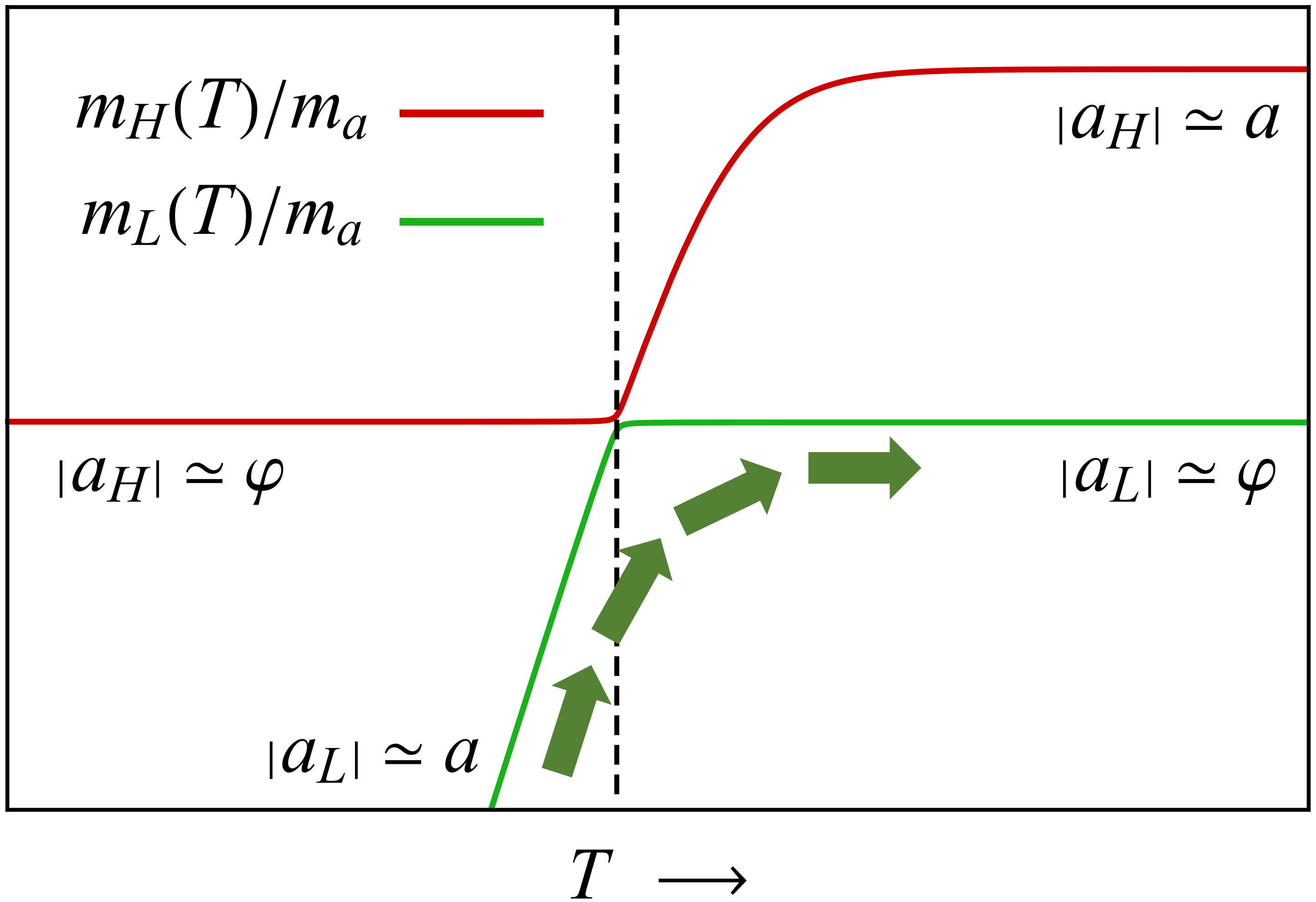
$f_\varphi / f_a = 0.001,\ m_\varphi / m_a = 0.5$





Dark matter abundance

- When adiabatic conversion occurs, the QCD axion becomes ALP



$$\Omega_a \propto m_a N_a$$

(w/o adiabatic conversion)

$$\Omega_L \propto m_\varphi N_L$$

(w/ adiabatic conversion)

The abundance is suppressed by the mass ratio m_φ / m_a

Dark matter abundance

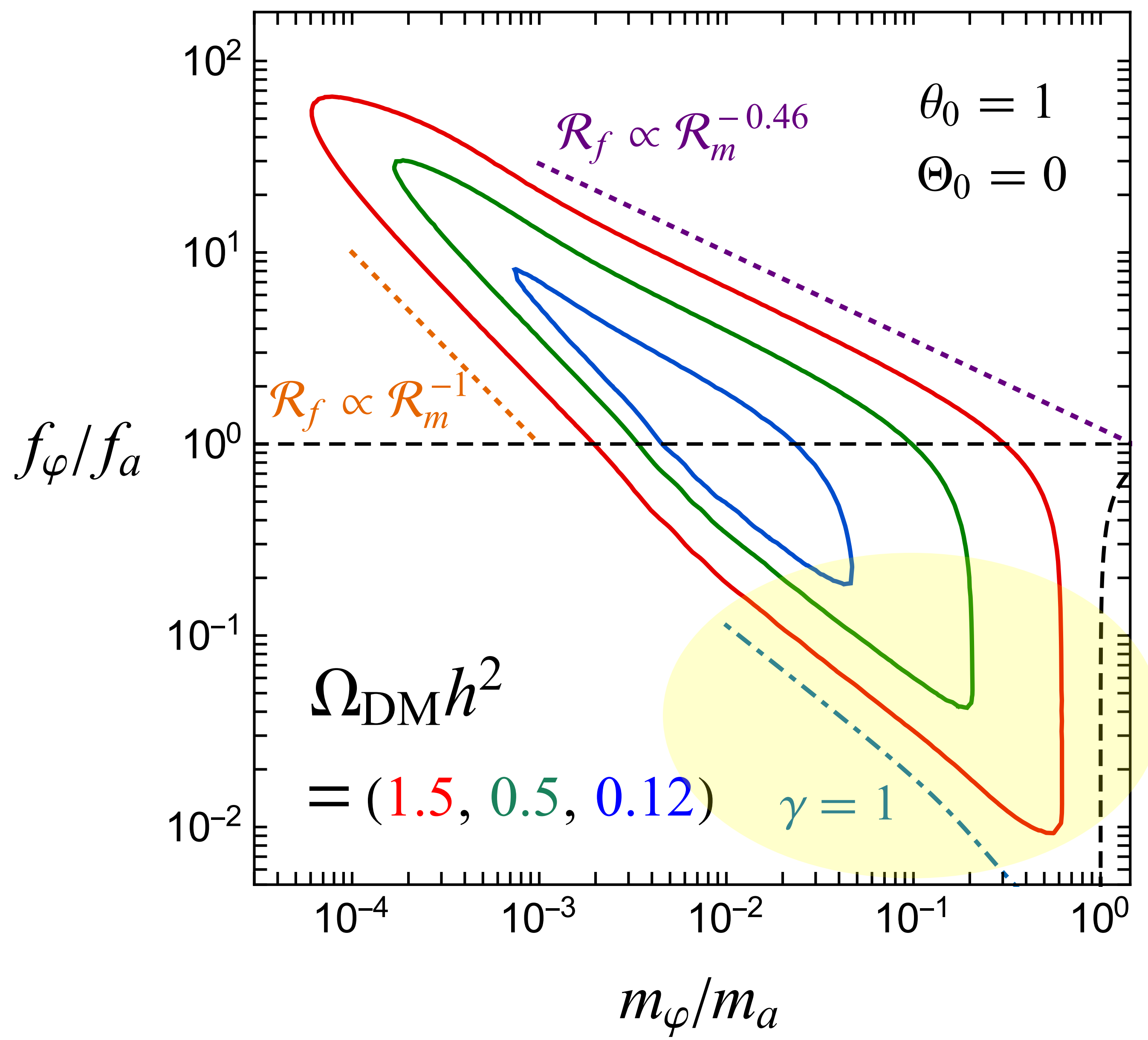
- Contours of $f_a = 10^{13}\,\mathrm{GeV}$

$$\Omega_{\rm DM} h^2 = \Omega_H h^2 + \Omega_L h^2$$

$$\Omega_H h^2 = \frac{m_H s_0}{\rho_{c,0}} N_H$$

$$\Omega_L h^2 = \frac{m_L s_0}{\rho_{c,0}} N_L$$

Preliminary



Dark matter abundance

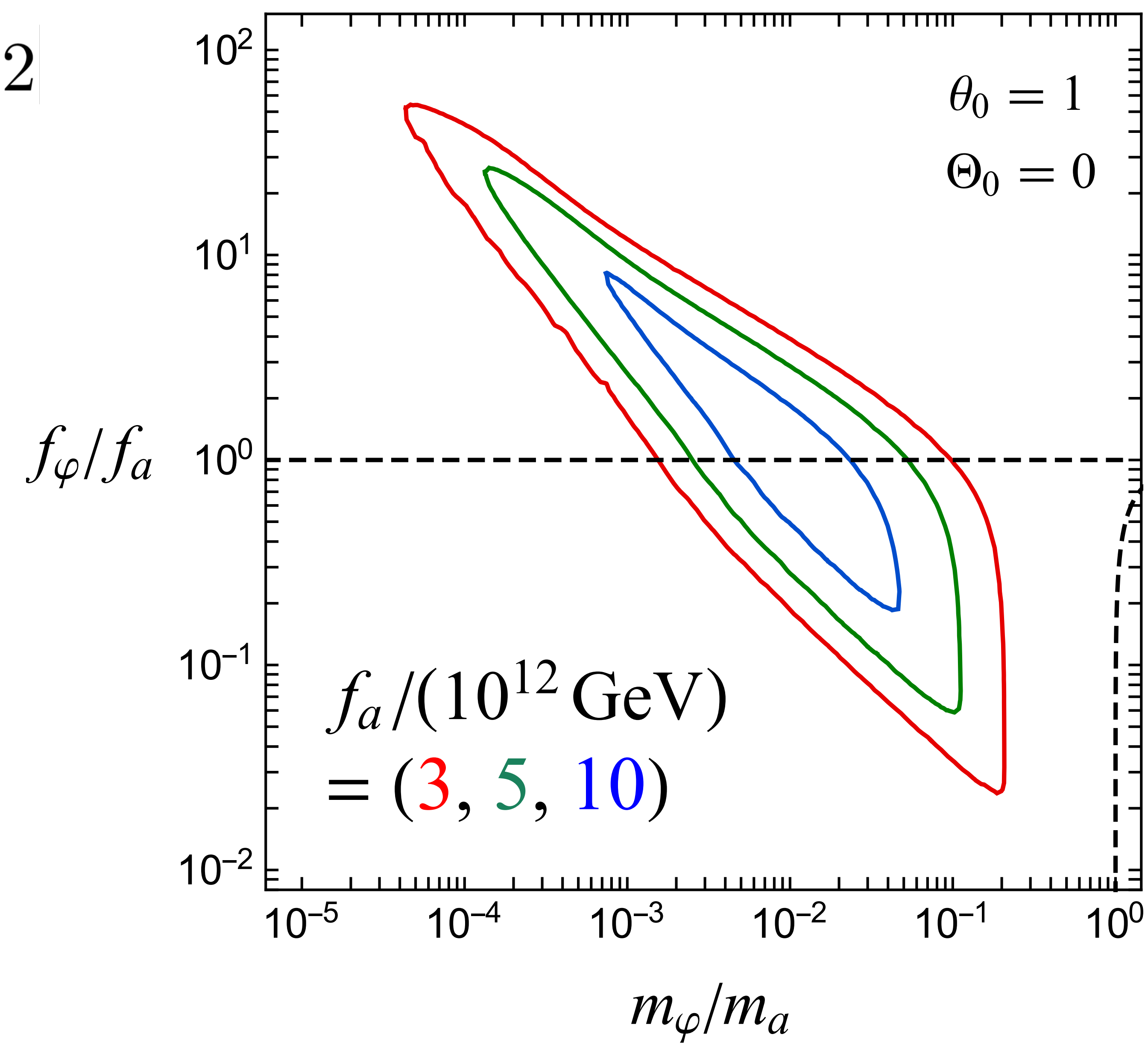
- Contours of $\Omega_{\rm DM}h^2 = 0.12$

$$\Omega_{\rm DM}h^2 = \Omega_H h^2 + \Omega_L h^2$$

$$\Omega_H h^2 = \frac{m_H s_0}{\rho_{c,0}} N_H$$

$$\Omega_L h^2 = \frac{m_L s_0}{\rho_{c,0}} N_L$$

Preliminary



Implications for the axion search experiments

- Axion-photon couplings

$$\mathcal{L}_{\text{axion-}\gamma\text{-}\gamma} = -\frac{\alpha}{8\pi}\left(C_{a\gamma}\frac{a}{f_a} + C_{\varphi\gamma}\frac{\varphi}{f_\varphi}\right)F_{\mu\nu}\widetilde{F}^{\mu\nu}$$
$$= -\frac{1}{4}\left(\underline{g_{L\gamma\gamma}}\,a_L + \underline{g_{H\gamma\gamma}}\,a_H\right)F_{\mu\nu}\widetilde{F}^{\mu\nu}$$

Couplings of the light (heavy) axion mode to photons

where

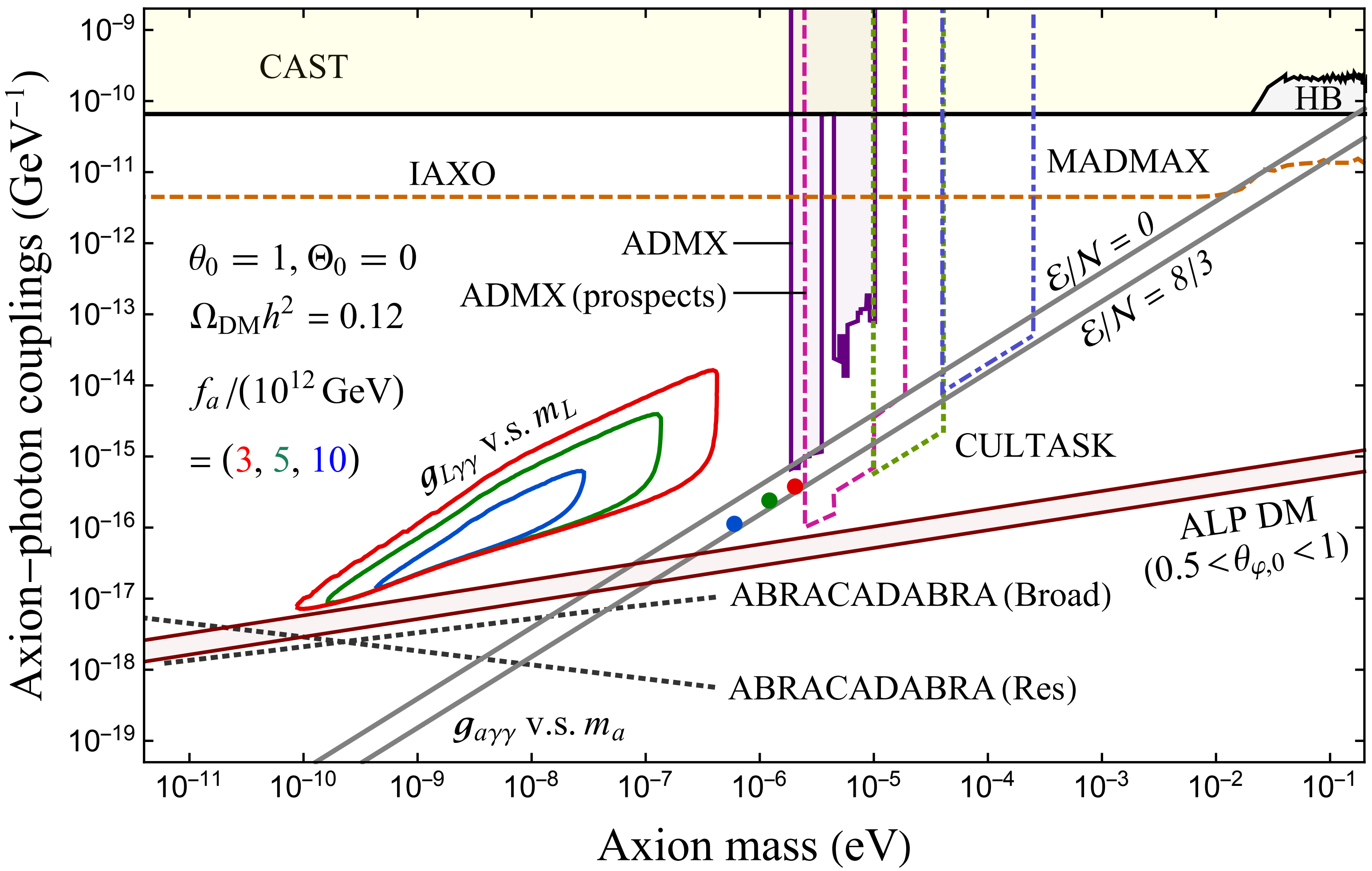
$$g_{L\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma}\cos\xi_0 - C_{\varphi\gamma}\frac{\sin\xi_0}{\mathcal{R}_f}\right), \quad g_{H\gamma\gamma} = \frac{\alpha}{2\pi f_a}\left(C_{a\gamma}\sin\xi_0 + C_{\varphi\gamma}\frac{\cos\xi_0}{\mathcal{R}_f}\right)$$

$$\xi_0 \equiv \xi(T \to 0)$$

Fiducial values : $C_{a\gamma} = C_{\varphi\gamma} = 1$

Implications for the axion search experiments

- Our result : ALP-photon coupling is enhanced by a factor of 10-1000 compared with the ALP DM without mass mixing.



The **CASPEr** experiment will be sensitive to our mass region.
See talks by
Antoine GARCON
John BLANCHARD
Nataniel FIGUEROA

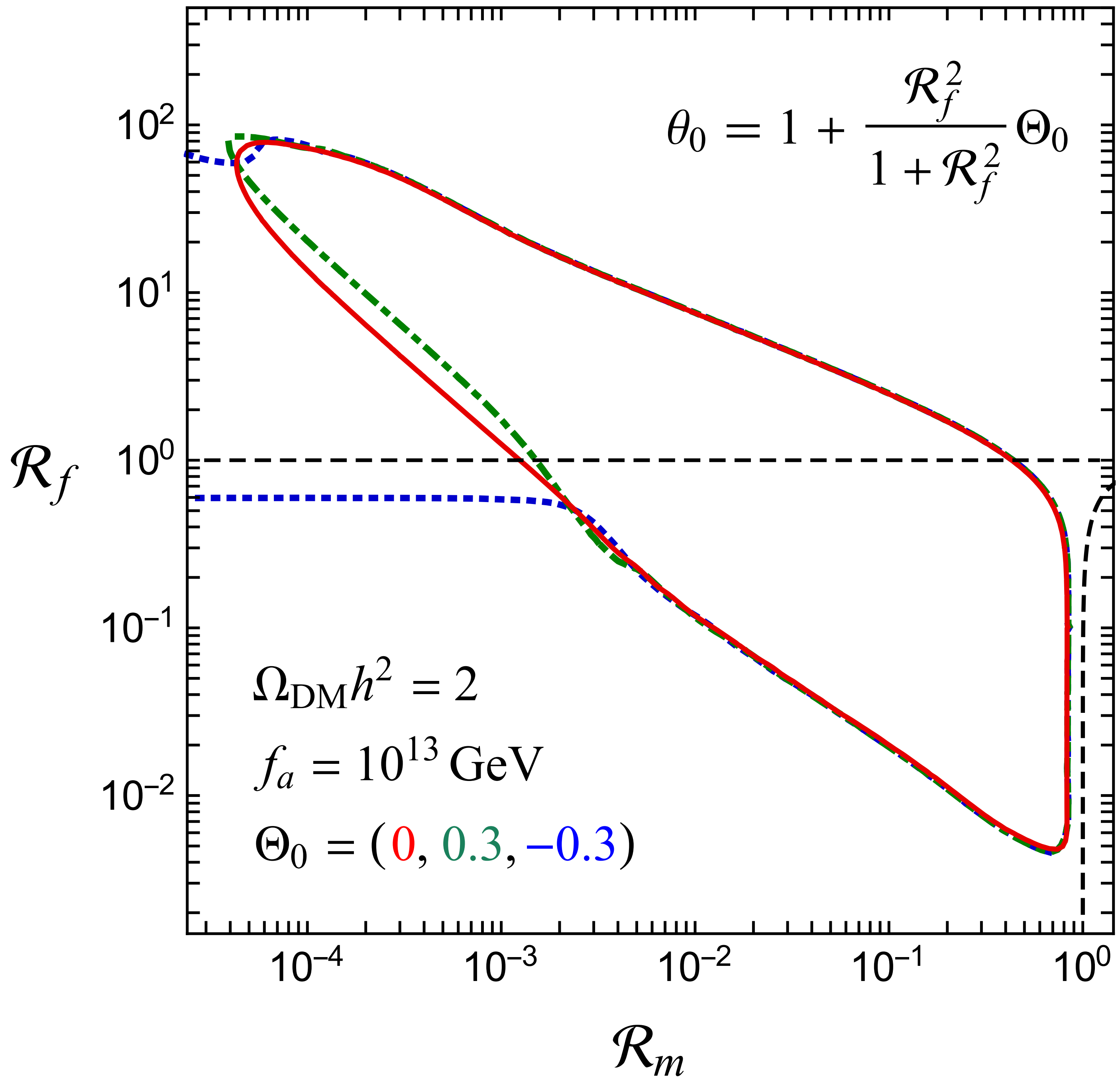
Preliminary

Summary

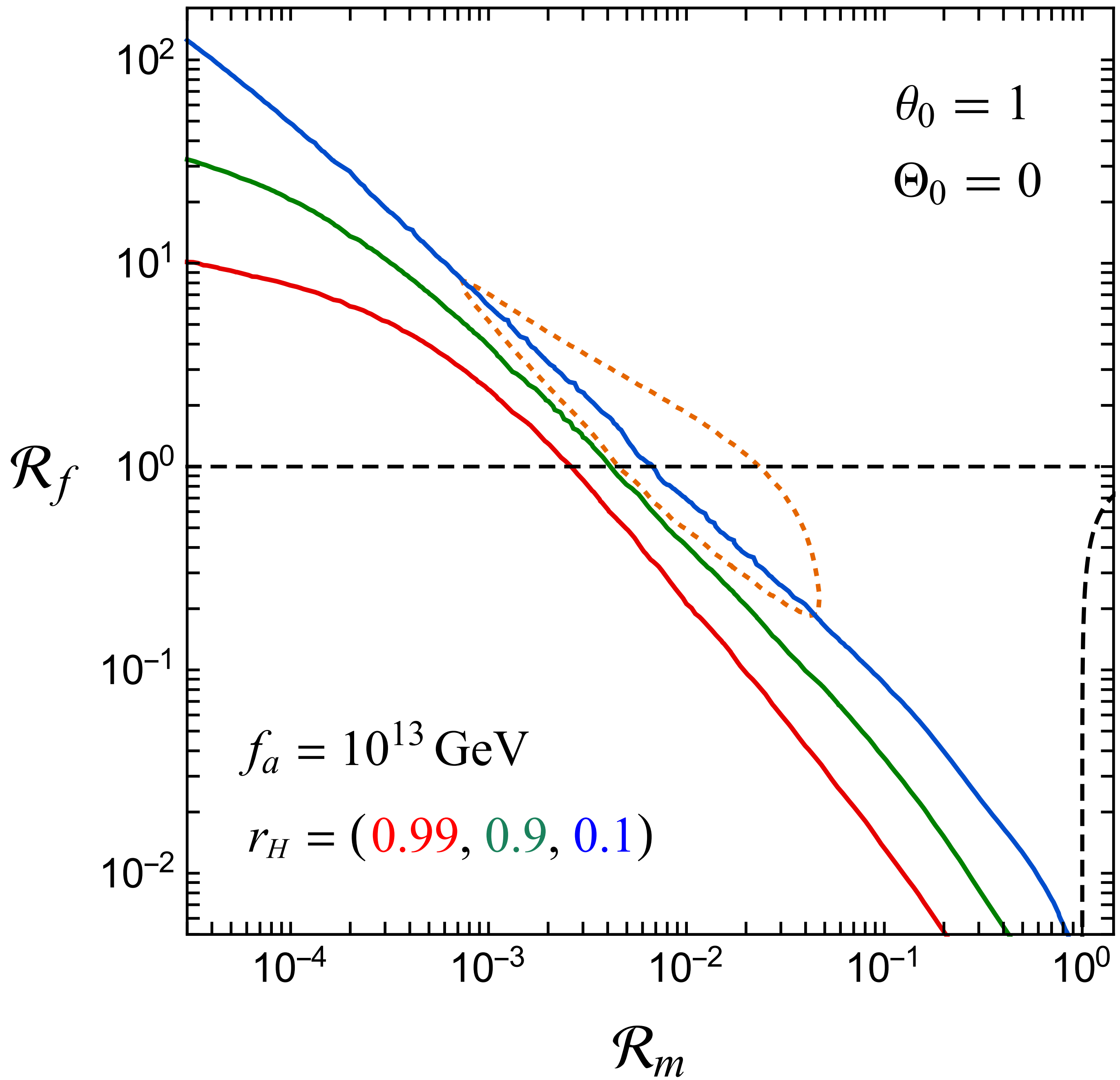
- We studied the scenario where the QCD axion and ALP have a nonzero mass mixing.
- We clarified when the adiabatic conversion takes place.
- We showed that the ALP produced by the adiabatic conversion of the QCD axion can explain the observed DM abundance.
- In this scenario, the ALP-photon coupling is enhanced by a few orders of magnitude, which is advantageous for the future axion search experiments using the axion-photon coupling.

Thank you for your attention!!

Back up



$\theta_0 = 1 + \frac{\mathcal{R}_f^2}{1+\mathcal{R}_f^2}\Theta_0$
$\Omega_{\rm DM}h^2 = 2$
$f_a = 10^{13}$ GeV
$\Theta_0 = (0, 0.3, -0.3)$
$\mathcal{R}_f$
$\mathcal{R}_m$
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^{0}



$$r_H = \frac{\Omega_H}{\Omega_L + \Omega_H}$$

- Equations of motion for the axions

$$\ddot{a} + 3\mathcal{H}\dot{a} + m_a^2(T) f_a \sin\left(\frac{a}{f_a}\right) + \frac{m_\varphi^2 f_\varphi^2}{f_a} \sin\left(\frac{a}{f_a} + \frac{\varphi}{f_\varphi}\right) = 0$$

$$\ddot{\varphi} + 3\mathcal{H}\dot{\varphi} + m_\varphi^2 f_\varphi \sin\left(\frac{a}{f_a} + \frac{\varphi}{f_\varphi}\right) = 0$$

$\mathcal{H} = \mathcal{H}(T)$: Hubble parameter

- Effective angles

$$\theta = \frac{a}{f_a}\,, \quad \Theta = \frac{a}{f_a} + \frac{\varphi}{f_\varphi}$$

$$\ddot{\theta} + 3\mathcal{H}\dot{\theta} + m_a^2(T)\sin\theta + m_\varphi^2 \mathcal{R}_f^2 \sin\Theta = 0$$

$$\ddot{\Theta} + 3\mathcal{H}\dot{\Theta} + m_a^2(T)\sin\theta + m_\varphi^2\left(1 + \mathcal{R}_f^2\right)\sin\Theta = 0$$

$$\theta(t_0) = \underline{\theta_0}\,,\ \Theta(t_0) = \underline{\Theta_0}\,,\ \dot{\theta}(t_0) = \dot{\Theta}(t_0) = 0$$

Initial (misalignment) angles

$$t_0 \ll t_{a,\varphi}^{\rm osc}$$