Enhanced photon coupling of ALP dark matter adiabatically converted from the QCD axion

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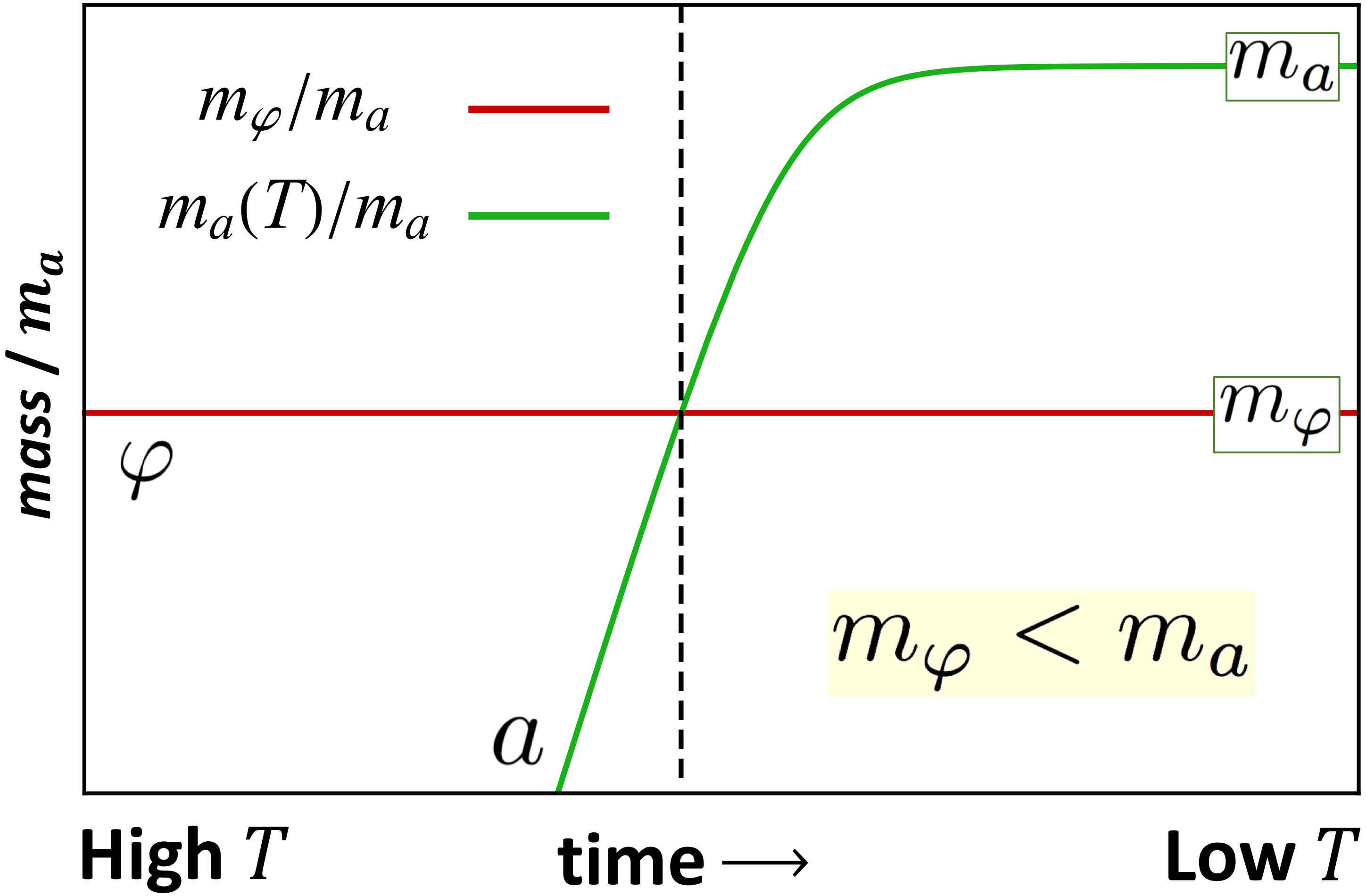
What if QCD axion a and ALP φ co-exist in nature?

What is a consequence if they have a mass mixing?

Level Crossing between the QCD axion and ALP

QCD axion + ALP ("**without**" mass mixing)

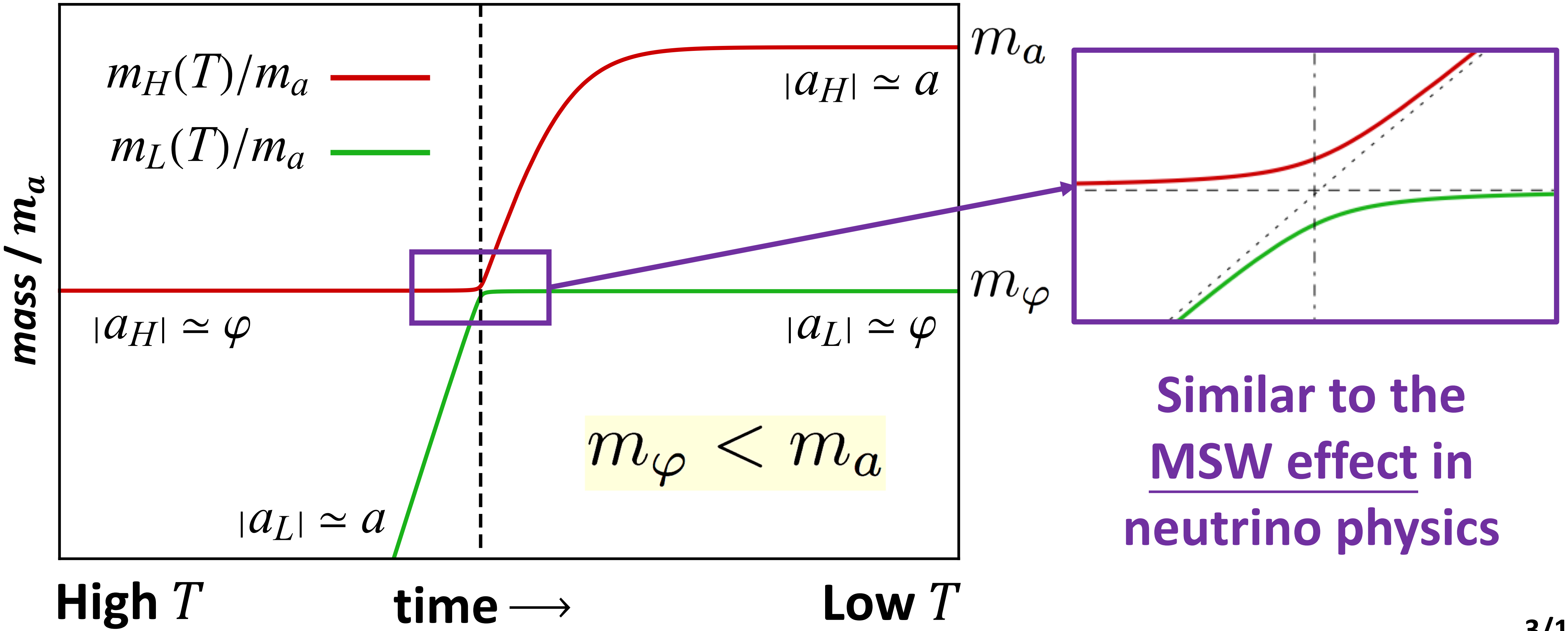


$$\begin{cases} m_a(T \gg \Lambda_{\rm QCD}) \to 0 \\ m_a(T \ll \Lambda_{\rm QCD}) \to m_a \end{cases}$$

Here we assume ALP does not acquire a mass from QCD effects

Level Crossing between the QCD axion and ALP

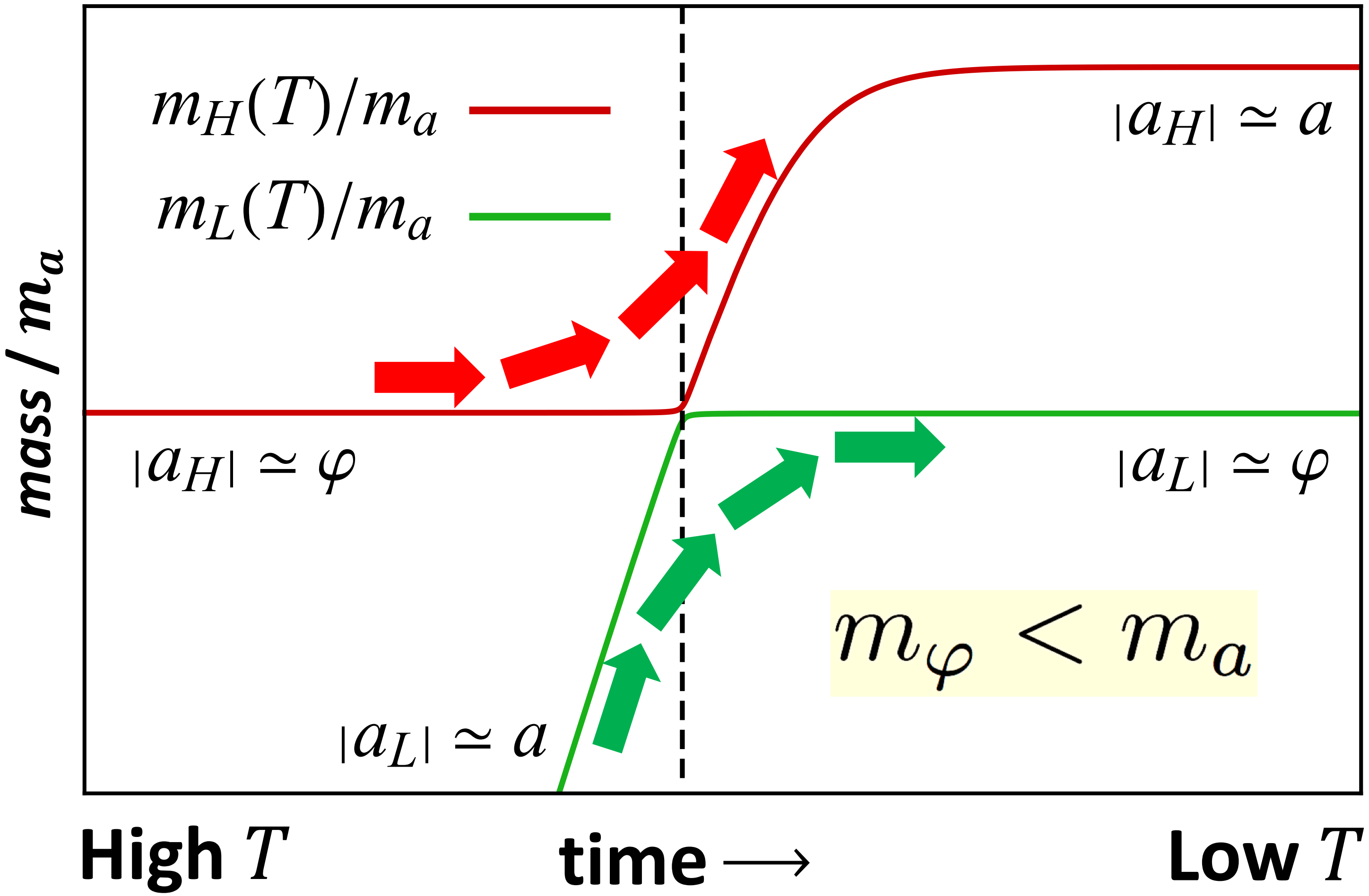
QCD axion + ALP ("with" mass mixing)



Similar to the MSW effect in neutrino physics

Level Crossing between the QCD axion and ALP

QCD axion + ALP ("with" mass mixing)



Adiabatic conversion could take place!!

$a \longleftrightarrow \varphi$

Then, the comoving number densities of the axions are conserved during the level crossing.

What if QCD axion a and ALP φ co-exist in nature?

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

Then, the axion abundance is suppressed by the mass ratio m_φ / m_a.

(Since the comoving number density is conserved)

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

What is new?

- The condition of the adiabatic conversion

In previous study : $f_\varphi \simeq f_a$

$$\frac{m_\varphi}{H(T_{\rm lc})} \gg 1$$

N. Kitajima & F. Takahashi (2014)

In our study : $f_\varphi < f_a$

$$\frac{f_\varphi}{f_a}\sqrt{\frac{m_\varphi}{H(T_{\rm lc})}} \gg 1$$

SY. Ho, K. Saikawa & F. Takahashi (2018)

- Since we consider the case including $f_\varphi \ll f_a$, we expect that the **ALP-photon coupling is enhanced**, compared to a single ALP DM without mass mixing.

Mass Mixing of the QCD axion and ALP

- **The Model**

Mass mixing

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

QCD axion decay constant   ALP decay constant

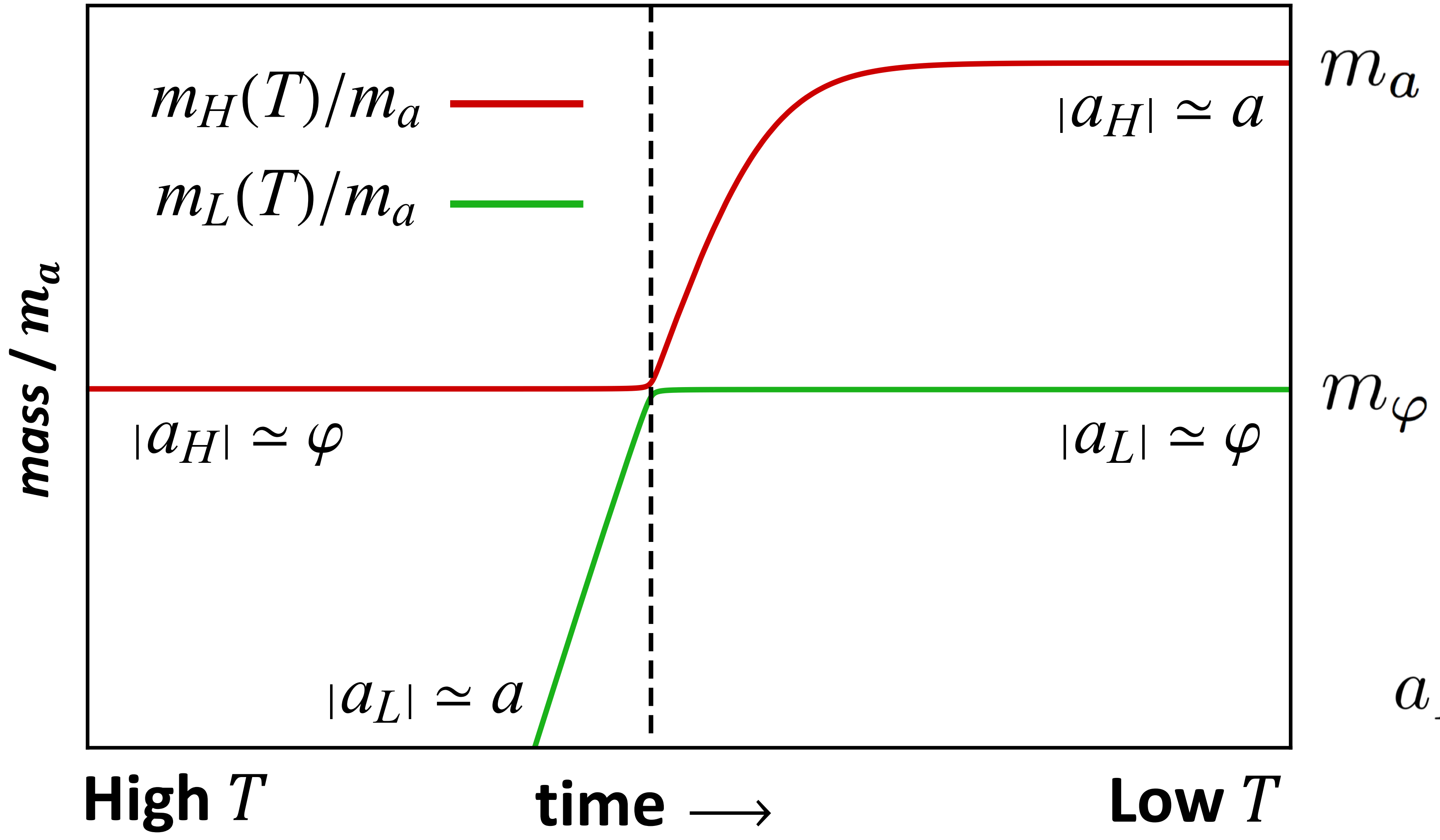
- **Mixing angle ξ :**

$$\begin{pmatrix} a_H \\ a_L \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \varphi \\ a \end{pmatrix}$$

- **Mass eigenvalues :**

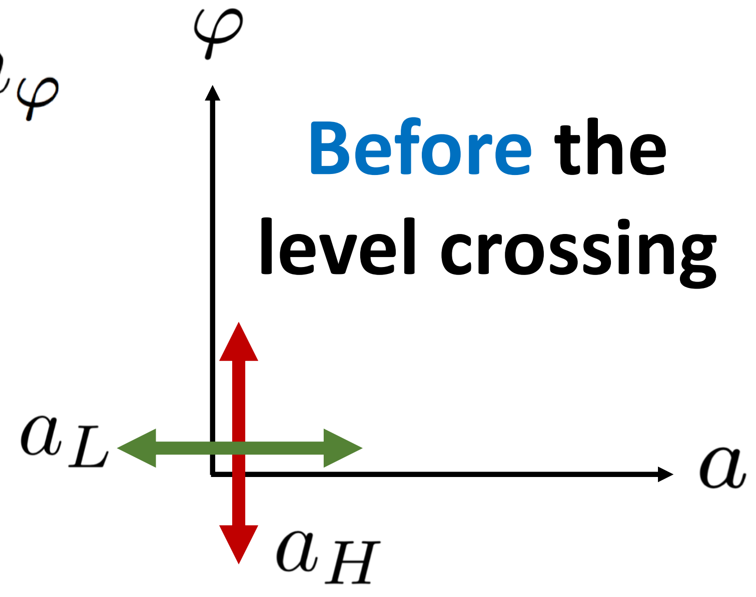
$$m_{H,L}^2(T) = \frac{1}{2} m_a^2(T) \left\{ 1 + \frac{m_\varphi^2}{m_a^2(T)} \left[1 + \frac{f_\varphi^2}{f_a^2} \pm \sqrt{\left(1 - \frac{f_\varphi^2}{f_a^2} - \frac{m_a^2(T)}{m_\varphi^2}\right)^2 + 4\frac{f_\varphi^2}{f_a^2}} \right] \right\}$$

Mass Eigenvalues of the Axions



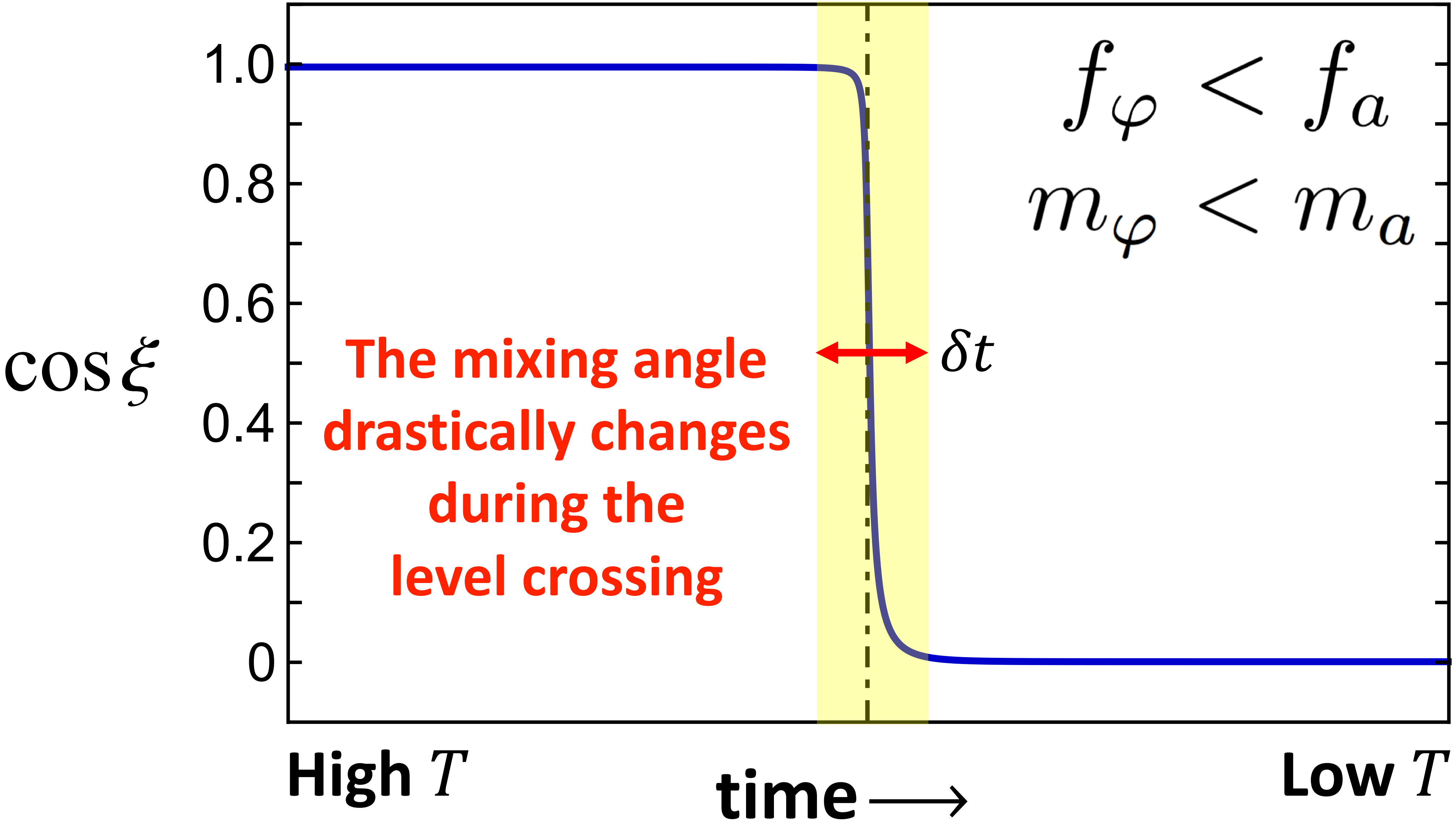
$f_\varphi < f_a$

$m_\varphi < m_a$



Before the level crossing

Mixing Angle



The Condition of the Adiabatic Conversion

Min[External time scales] >> Max[Internal time scales]

$$\delta t \sim \left| \left| \frac{d \ln \cos \xi(T)}{dt} \right|^{-1} \right|_{\rm lc} \gg \mathrm{Max} \left[\frac{2\pi}{m_H(T_{\rm lc})}, \frac{2\pi}{m_L(T_{\rm lc})}, \frac{2\pi}{m_H(T_{\rm lc}) - m_L(T_{\rm lc})} \right]$$

beat frequency

$$f_\varphi \ll f_a$$

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

$$\beta \sim 0.3$$

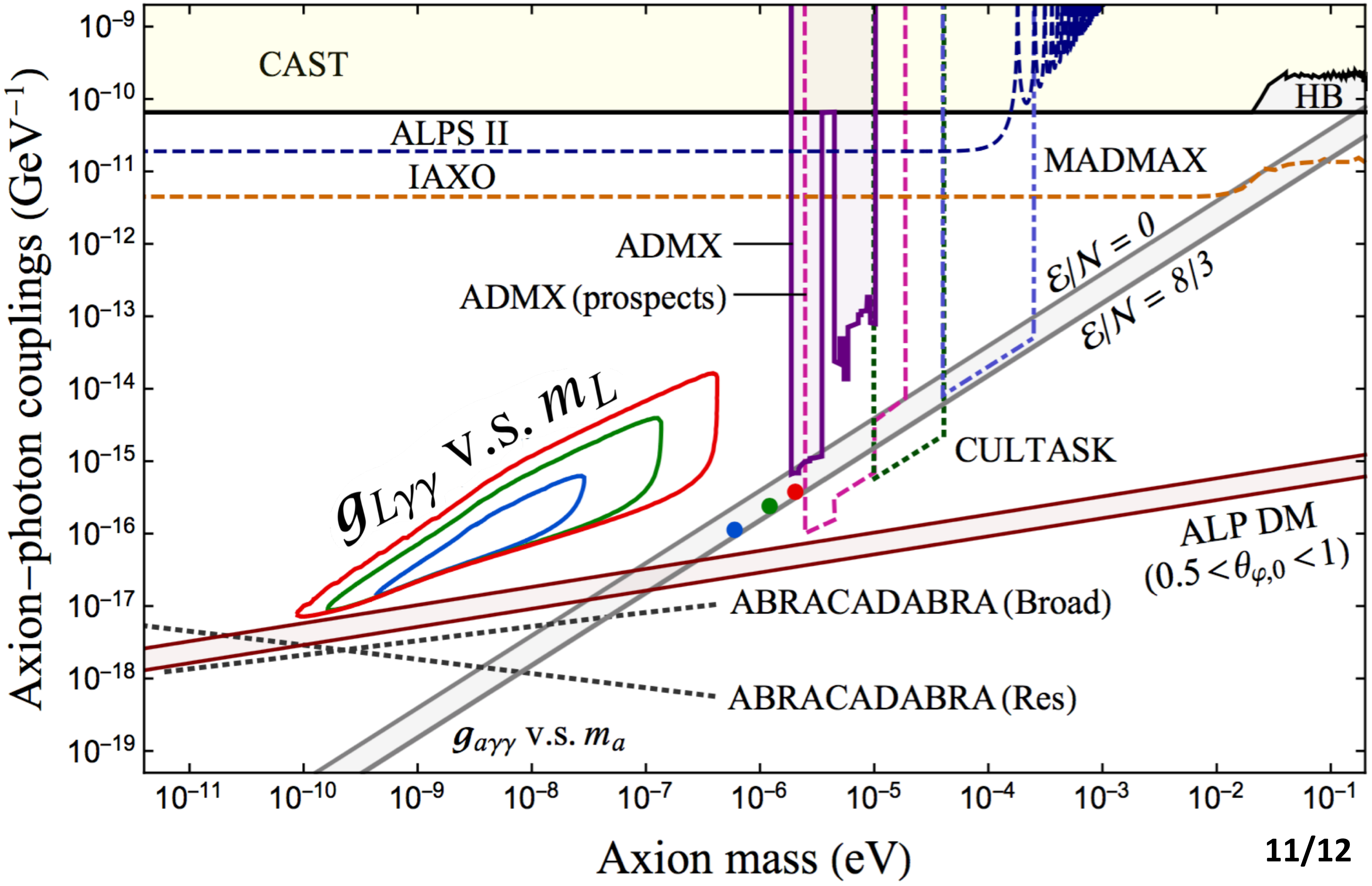
ALP-photon coupling

$$\Omega_{\rm DM} h^2 \simeq 0.12$$

$f_a = 3 \times 10^{12}$ GeV

$f_a = 5 \times 10^{12}$ GeV

$f_a = 10^{13}$ GeV

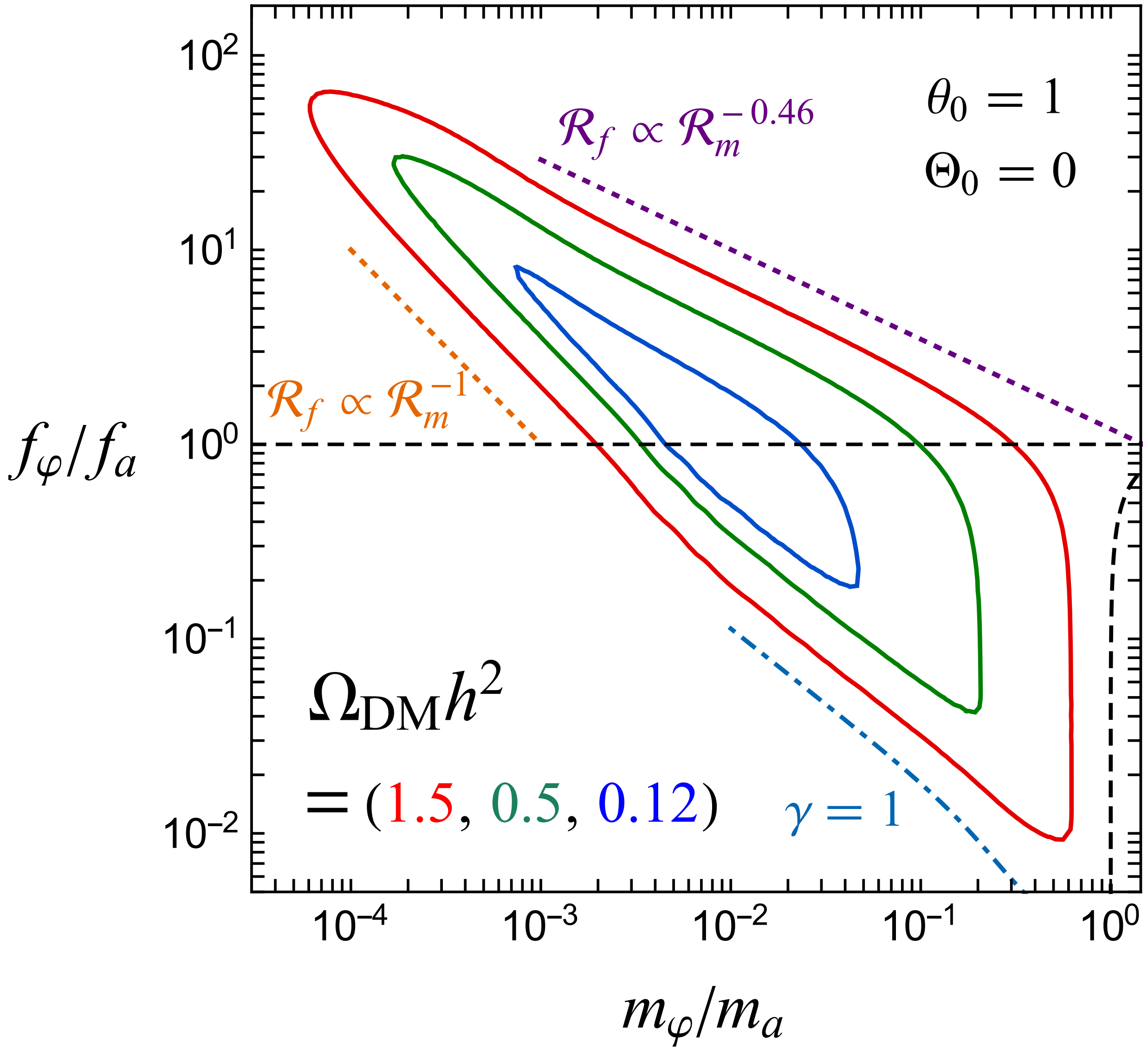


Summary

- **We refined the condition of the adiabatic conversion between the QCD axion and ALP, which is valid in a more general case.**
- **We showed that the ALP produced by the adiabatic conversion of the QCD axion can explain the observed DM abundance.**
- **In our scenario, the ALP-photon coupling is enhanced by a few orders of magnitude compared to a single ALP DM without mass mixing.**

Thank you for your attention!!

Back up



$\theta_0 = 1$
$\Theta_0 = 0$
$\mathcal{R}_f \propto \mathcal{R}_m^{-0.46}$
$\mathcal{R}_f \propto \mathcal{R}_m^{-1}$
$\Omega_{\rm DM} h^2$
$= (1.5, 0.5, 0.12)$
$\gamma = 1$
f_φ / f_a
m_φ / m_a
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
10^0