The QCD axion window and low-scale inflation

July 26@Brown University
Identification of Dark Matter 2018

Fumi Takahashi
(Tohoku/Kavli IPMU/MIT)

FT, Wen Yin, Alan H. Guth, arXiv:1805.08763 to appear in PRD

The upper bound of the QCD axion window can be relaxed in low-scale inflation with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$.

Peter W. Graham, Adam Scherlis, 1805.07362,
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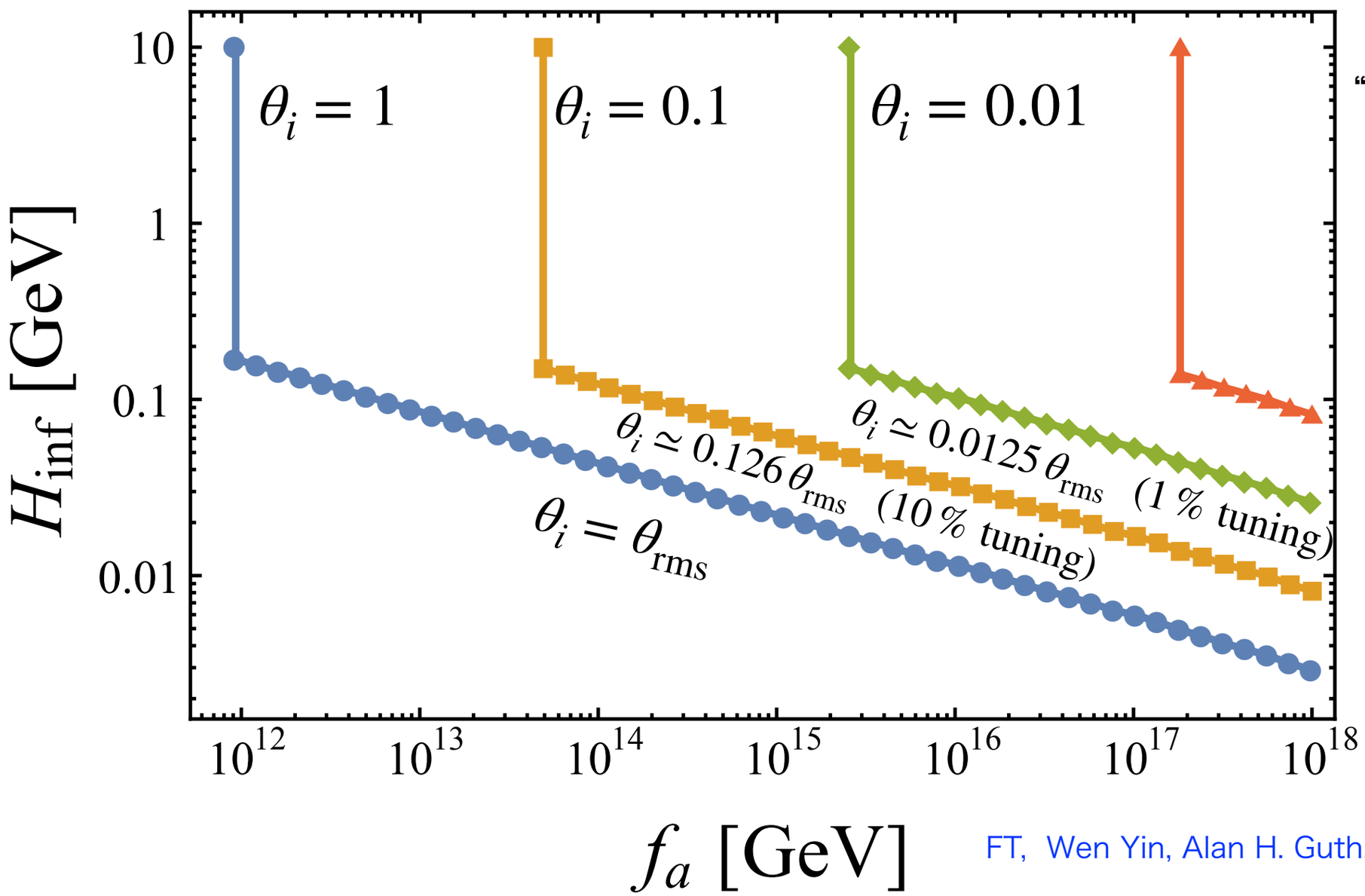
See the talk by Scherlis



"Bunch-Davis distribution"

$$\theta_{\rm rms} = \sqrt{\frac{3}{8\pi^2}}\frac{H_{\rm inf}^2}{f_a m_a(T_{\rm inf})}$$

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Conventional axion window, $f_a \lesssim 10^{12}\,\mathrm{GeV}$

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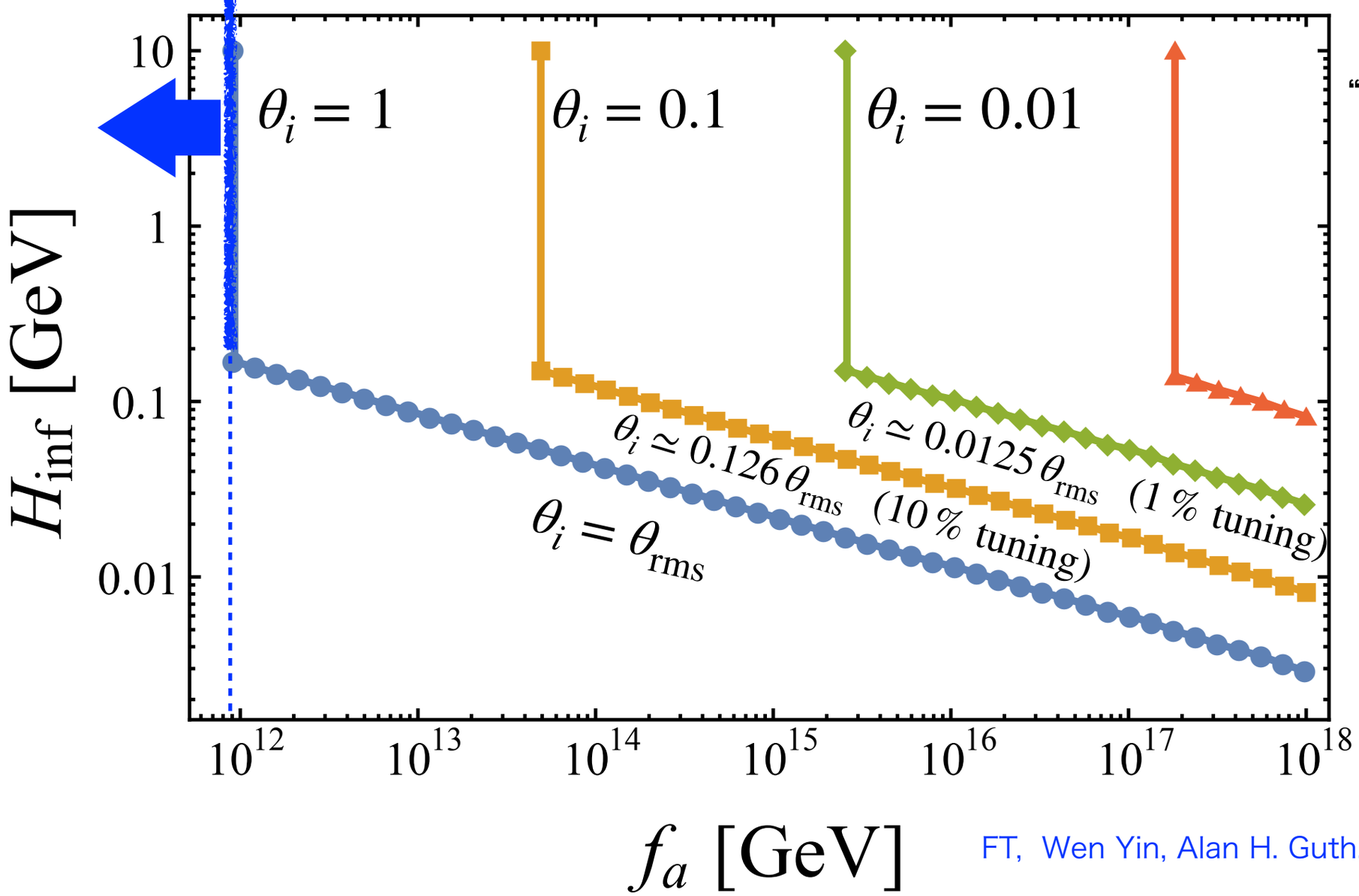

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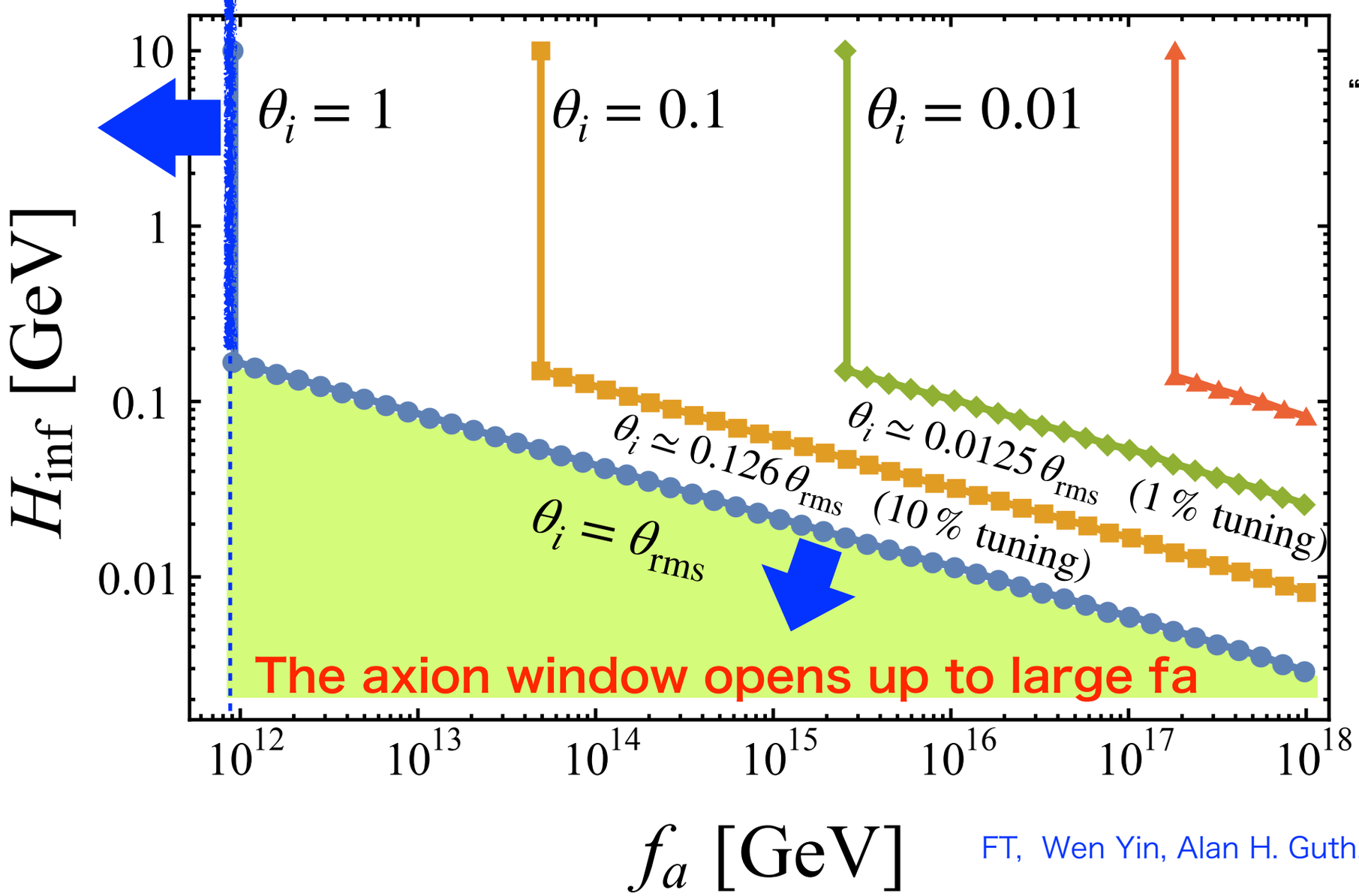

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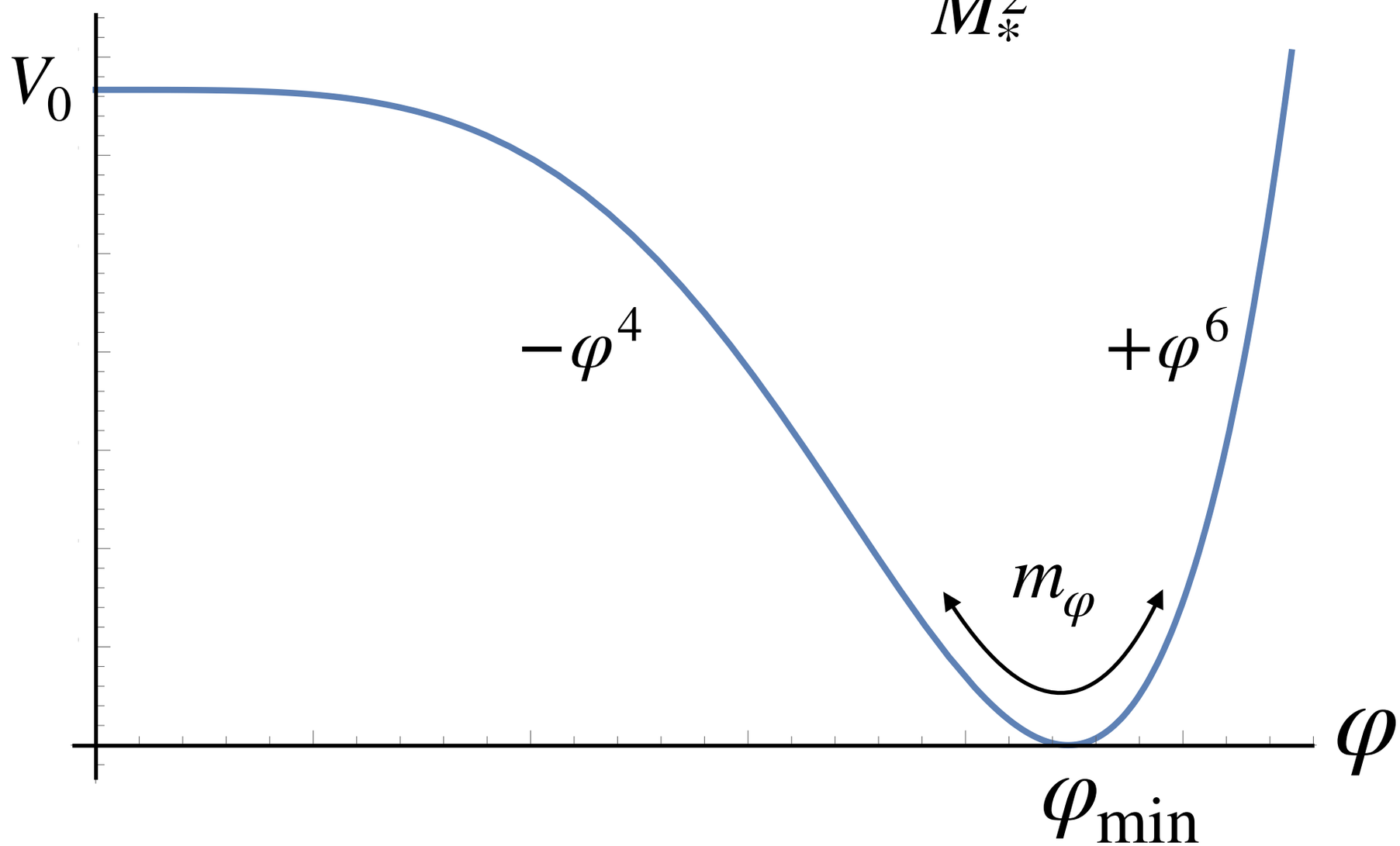
FT, Wen Yin, Alan H. Guth, 1805.08763

Low-scale inflation model with $H_{\rm inf} \lesssim \Lambda_{\rm QCD}$

$$V(\varphi) = V_0 - \kappa\varphi^4 + \lambda\frac{\varphi^6}{M_*^2}$$



$$H_{\rm inf} \sim 100\,{\rm MeV}, \quad m_\varphi \sim 10^6\,{\rm GeV}, \quad \varphi_{\rm min} \sim 10^{12}\,{\rm GeV}$$

FT, Wen Yin, Alan H. Guth, arXiv:1805.08763

Spectral index $n_s \simeq 0.96$ can be realized by including either a linear term or Coleman-Weinberg correction.

Nakayama, FT, 1108.0070, FT 1308.4212

Successful reheating is possible

We introduce a coupling to right-handed neutrinos,

$$\mathscr{L} = y_{N_i} \varphi \, \bar{\nu}^c_{Ri} \nu_{Ri}$$

with $y_N \sim 10^{-7}$.

The decay rate is $\Gamma_\varphi = \sum \frac{y_{N_i}^2}{8\pi} m_\varphi$ if kinematically allowed.

$$T_R \sim \left(\frac{90}{\pi^2 g_*}\right)^{\frac{1}{4}} \sqrt{M_{\rm pl}\Gamma_\varphi}$$

$$\simeq O(10)\text{TeV} \left(\frac{106.75}{g_*}\right)^{\frac{1}{4}} \left(\frac{y_N}{10^{-7}}\right) \left(\frac{m_\varphi}{10^6\text{GeV}}\right)^{\frac{1}{2}} \left(\frac{N_R^{\rm eff}}{2}\right)^{1/2}$$

cf. Even Inflation with $H_{\rm inf} = O(1)\,\text{eV}$ is possible. In this case the reheating proceeds through thermal dissipation. "ALP miracle", Daido, FT, Yin, 1702.03284, 1710.11107

Cosmological adiabatic conversion btw. QCD axion and ALP DM

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Fumi Takahashi
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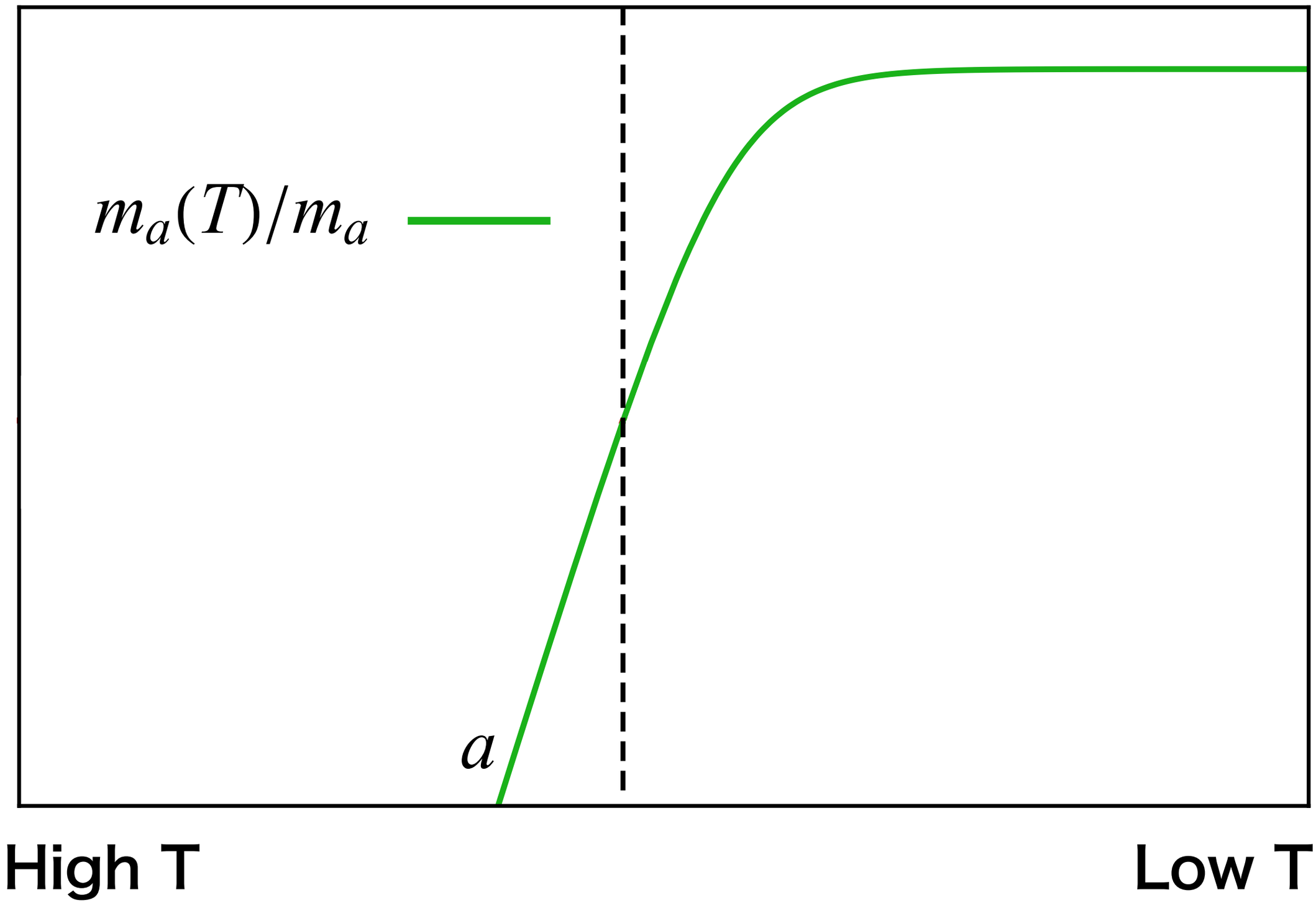
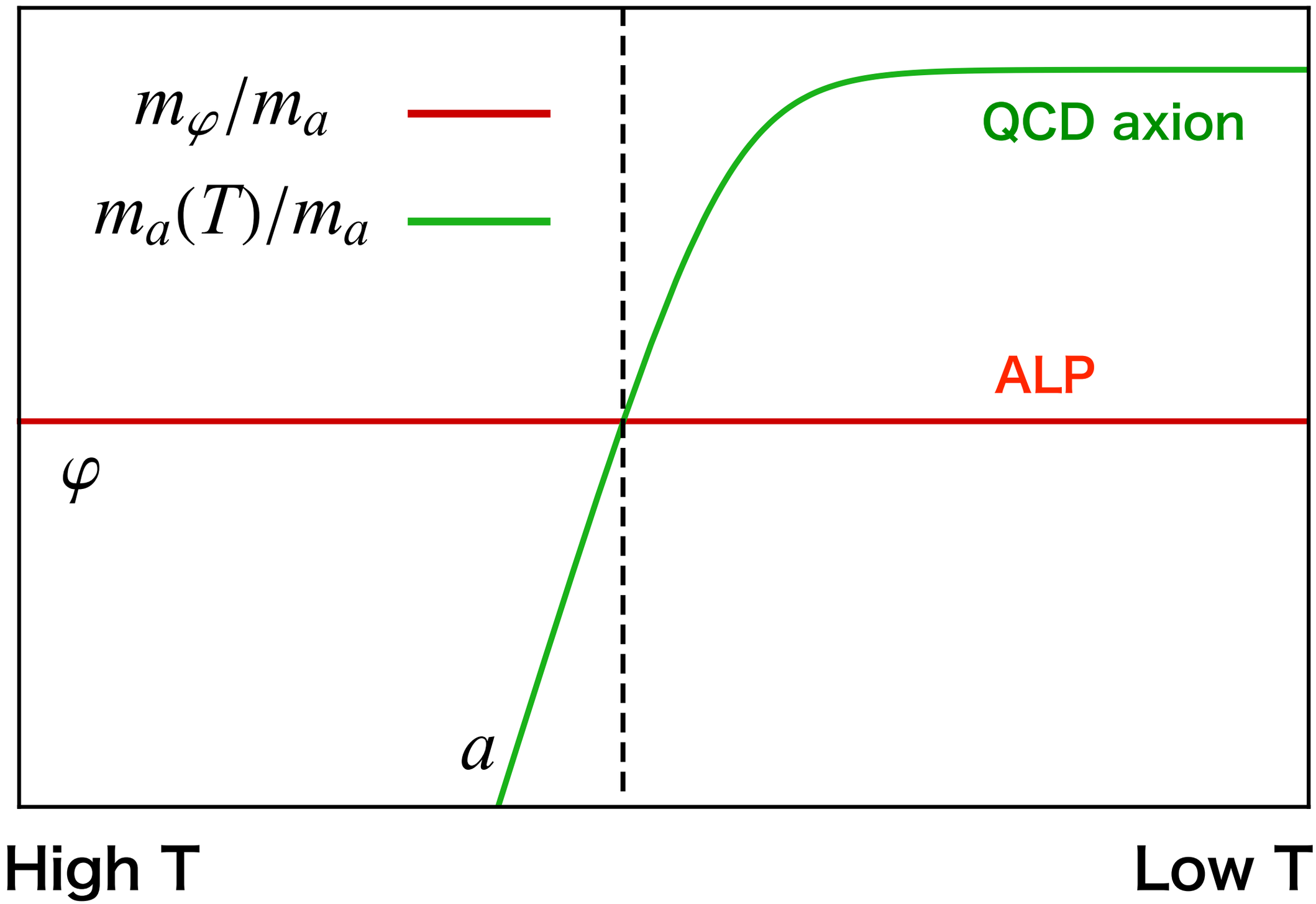
S-Y Ho, K. Saikawa, FT, 1806.09551 submitted to JCAP

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

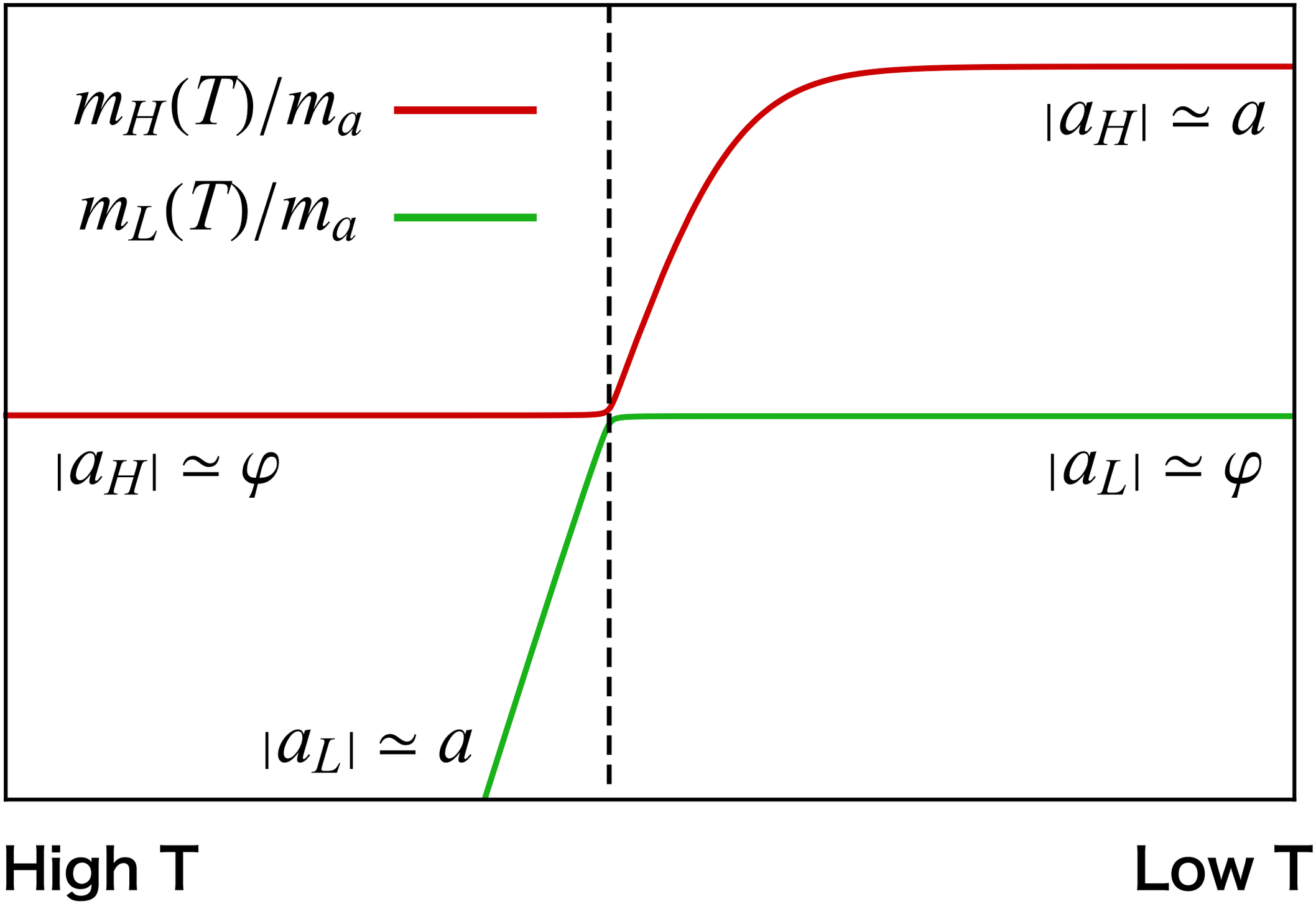
QCD axion



QCD axion + ALP with $m_\varphi < m_a(T=0)$



QCD axion + ALP with $m_\varphi < m_a(T=0)$ + mass mixing



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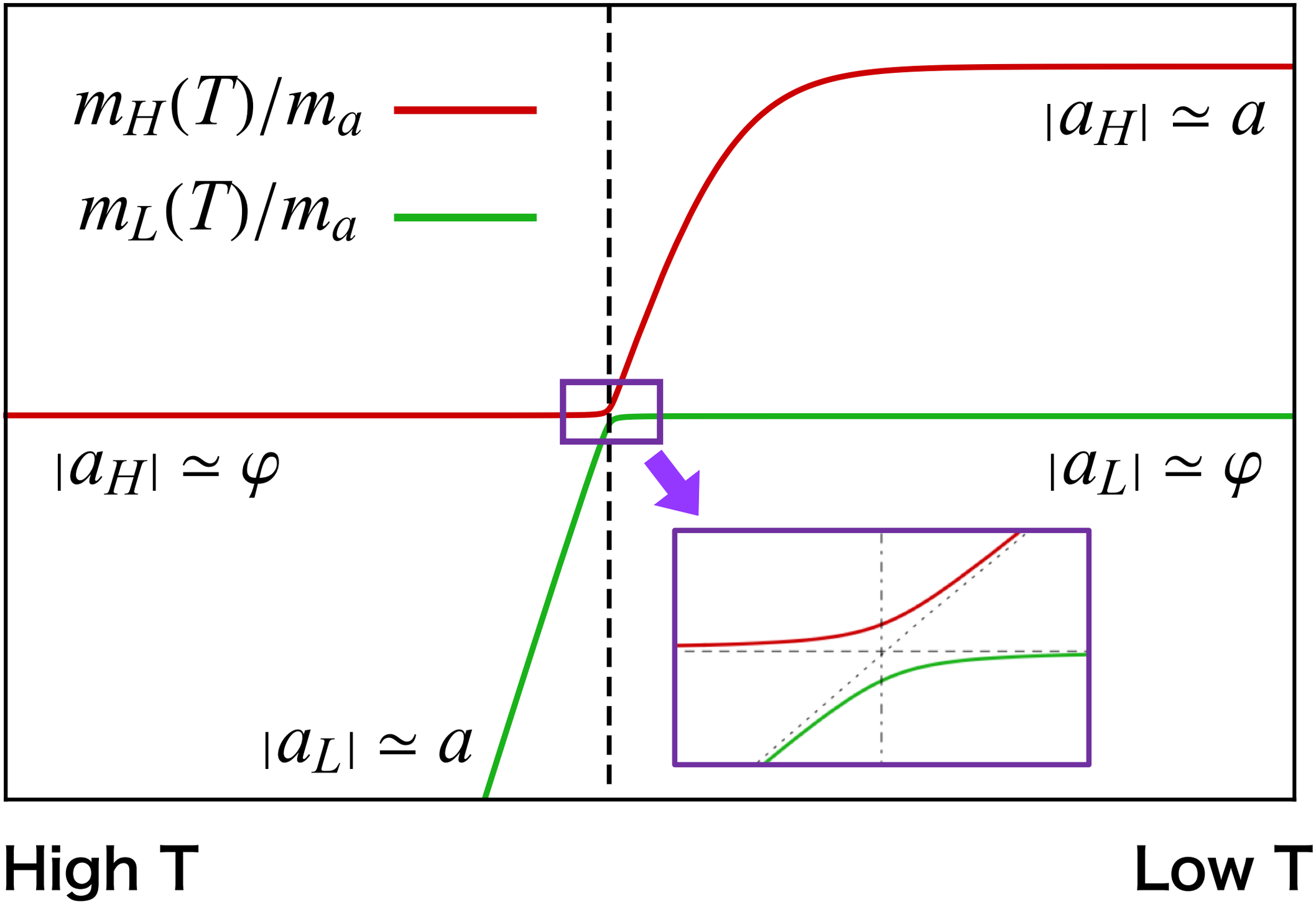

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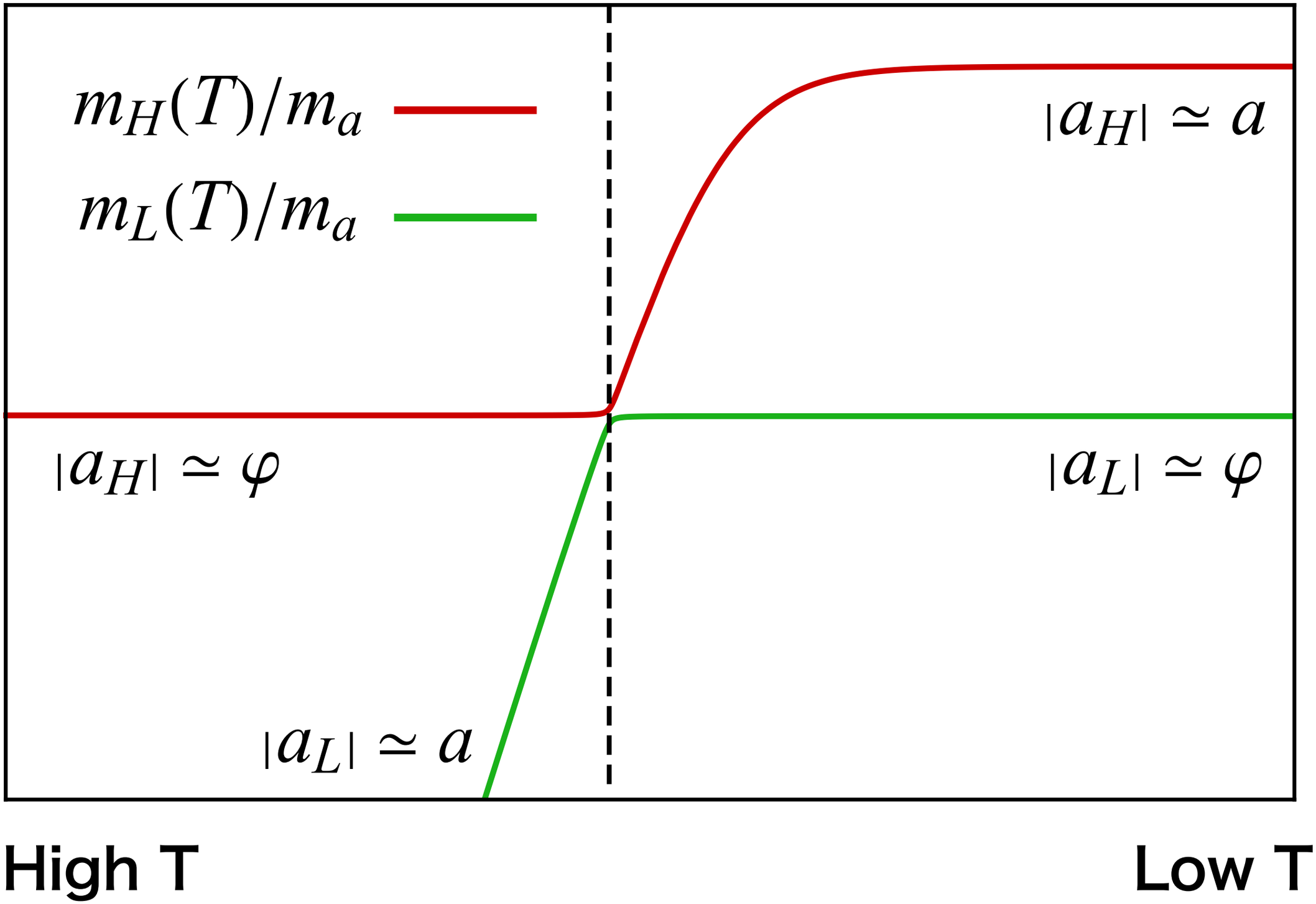

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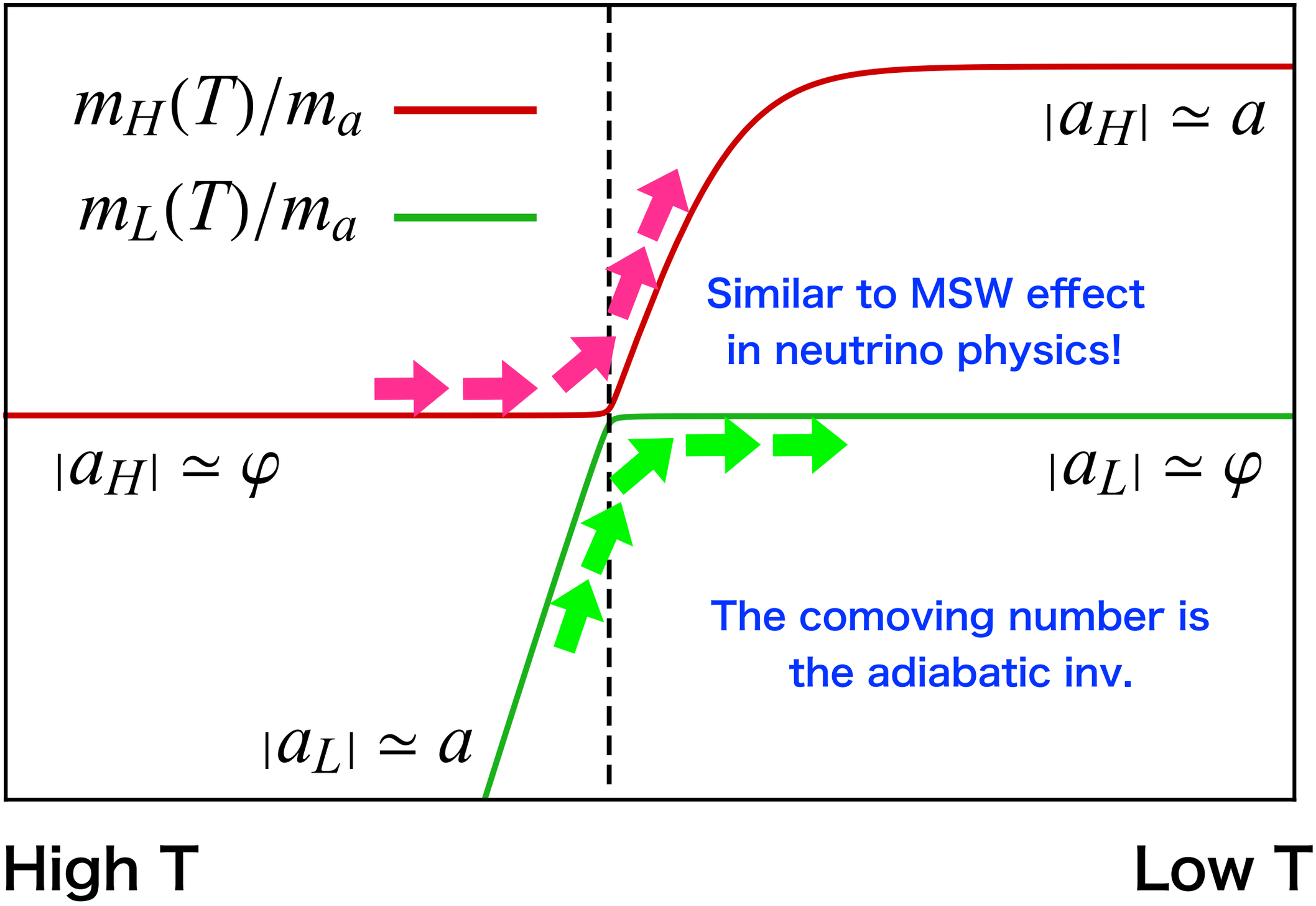


What if QCD axion a and ALP φ coexist in nature?

Adiabatic conversion can take place!

$$a \longleftrightarrow \varphi$$

Then, the axion abundance is suppressed by the mass ratio.

Kitajima and FT, 1411.2011
cf. Hill and Ross, `88

Set-up

- Axion potential

Mass mixing

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

Mass matrix: $$M^2 = \begin{pmatrix} 0 & 0 \\ 0 & m_a^2(T) \end{pmatrix} + m_\varphi^2 \begin{pmatrix} 1 & f_\varphi/f_a \\ f_\varphi/f_a & (f_\varphi/f_a)^2 \end{pmatrix}$$

Mass eigenstates and mixing angle:

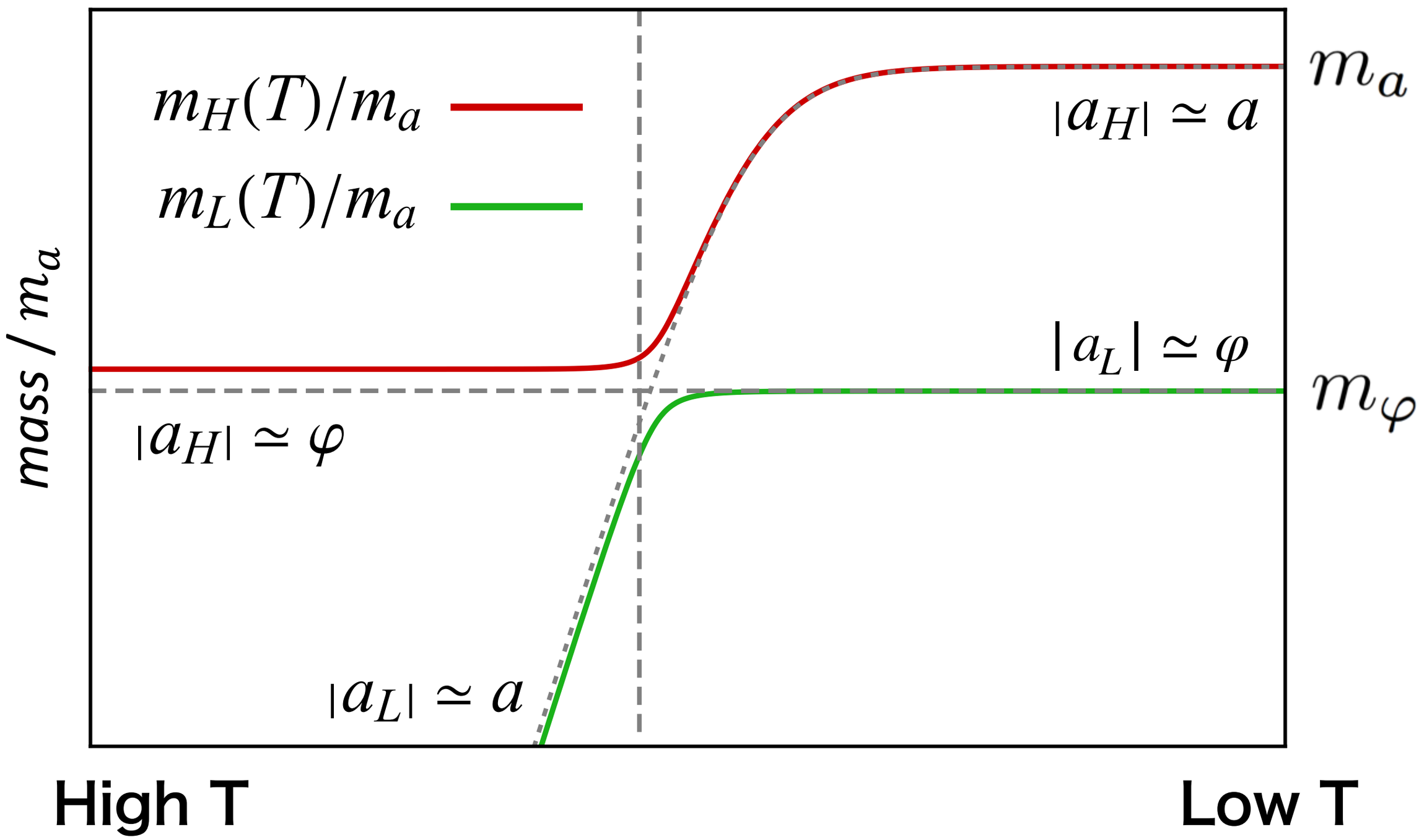
$$\begin{pmatrix} a_H \\ a_L \end{pmatrix} = \begin{pmatrix} \cos\xi & \sin\xi \\ -\sin\xi & \cos\xi \end{pmatrix} \begin{pmatrix} \varphi \\ a \end{pmatrix}$$

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

Level crossing

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

Level crossing takes place if $m_\varphi < m_a$ and $f_\varphi < f_a$



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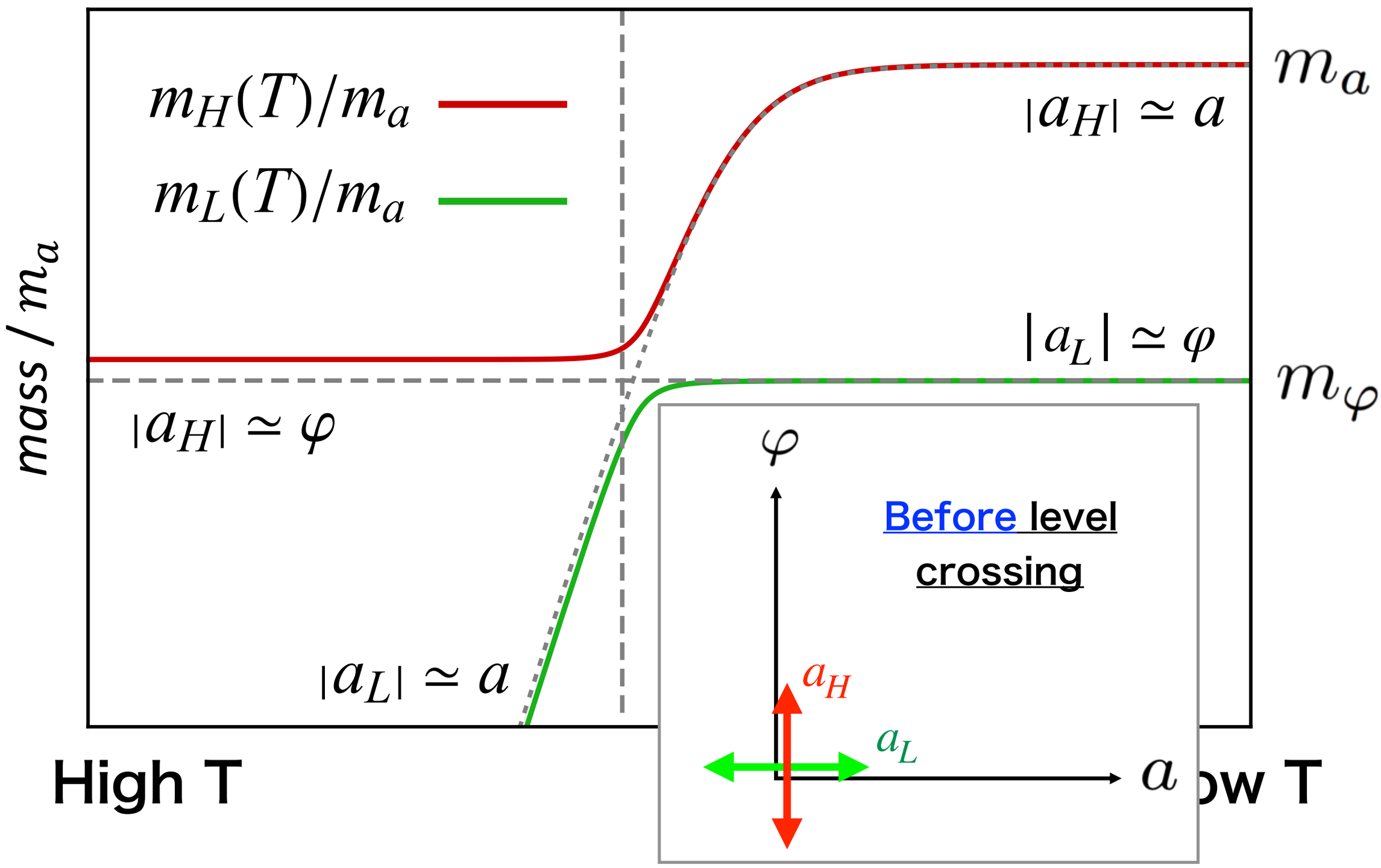

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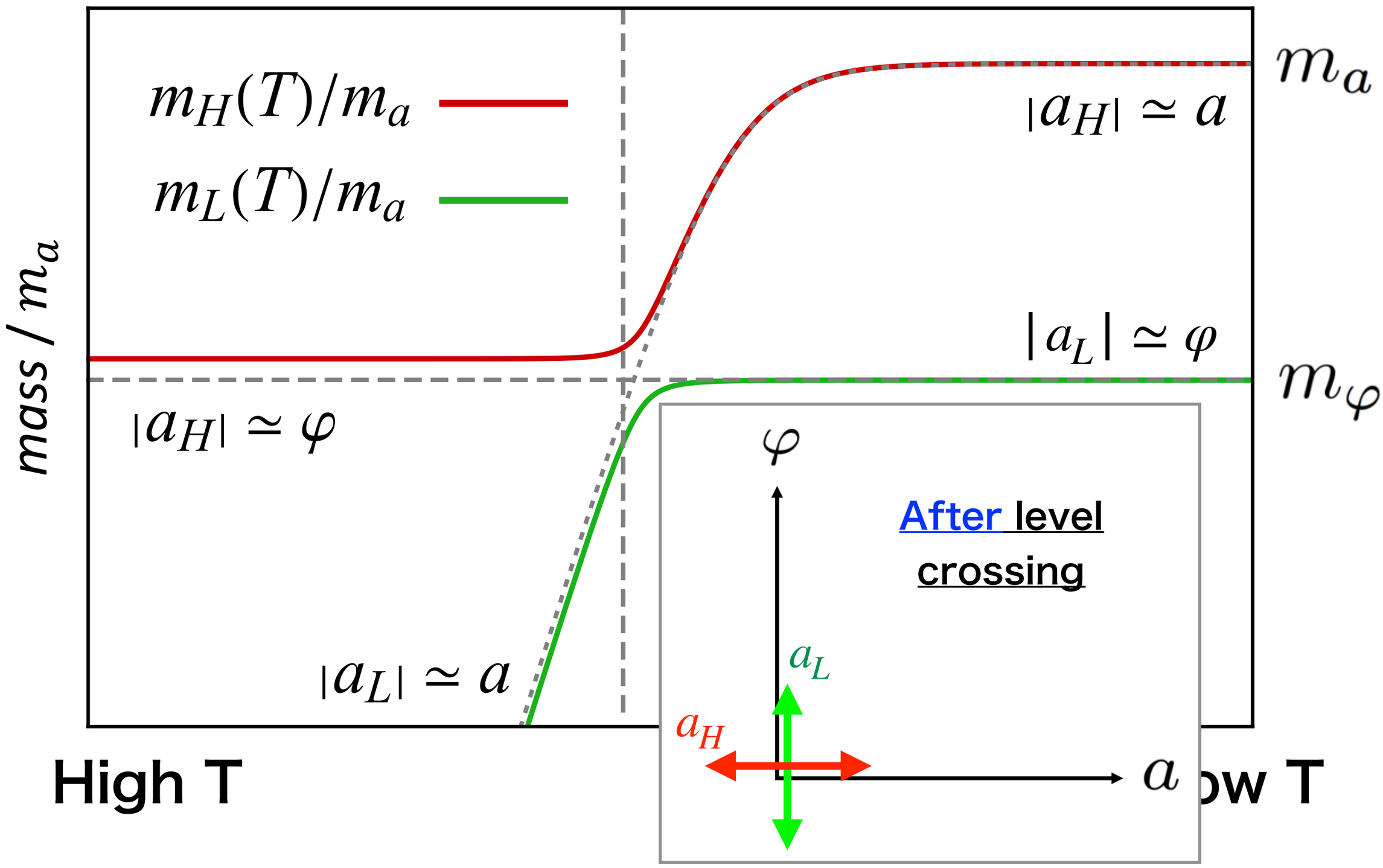

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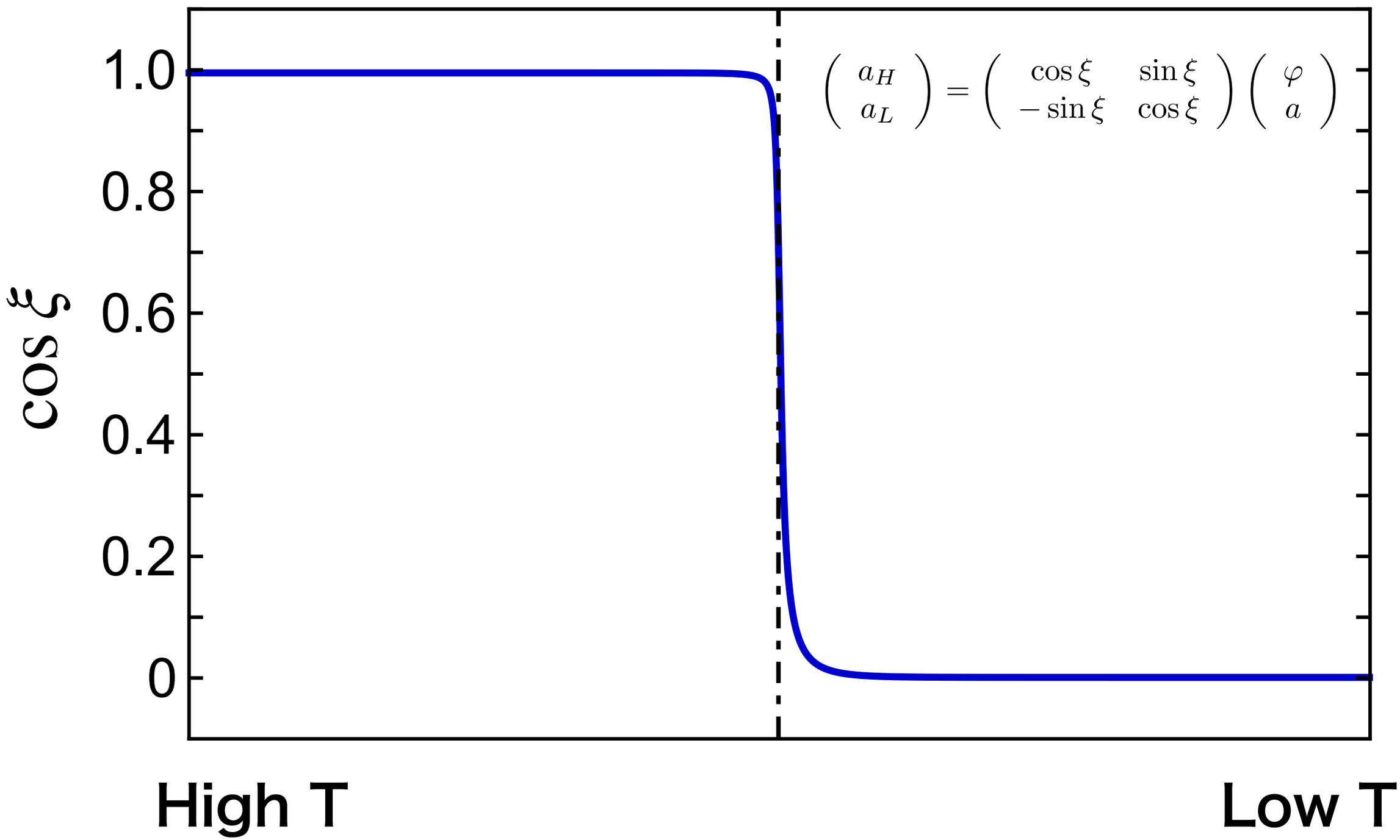

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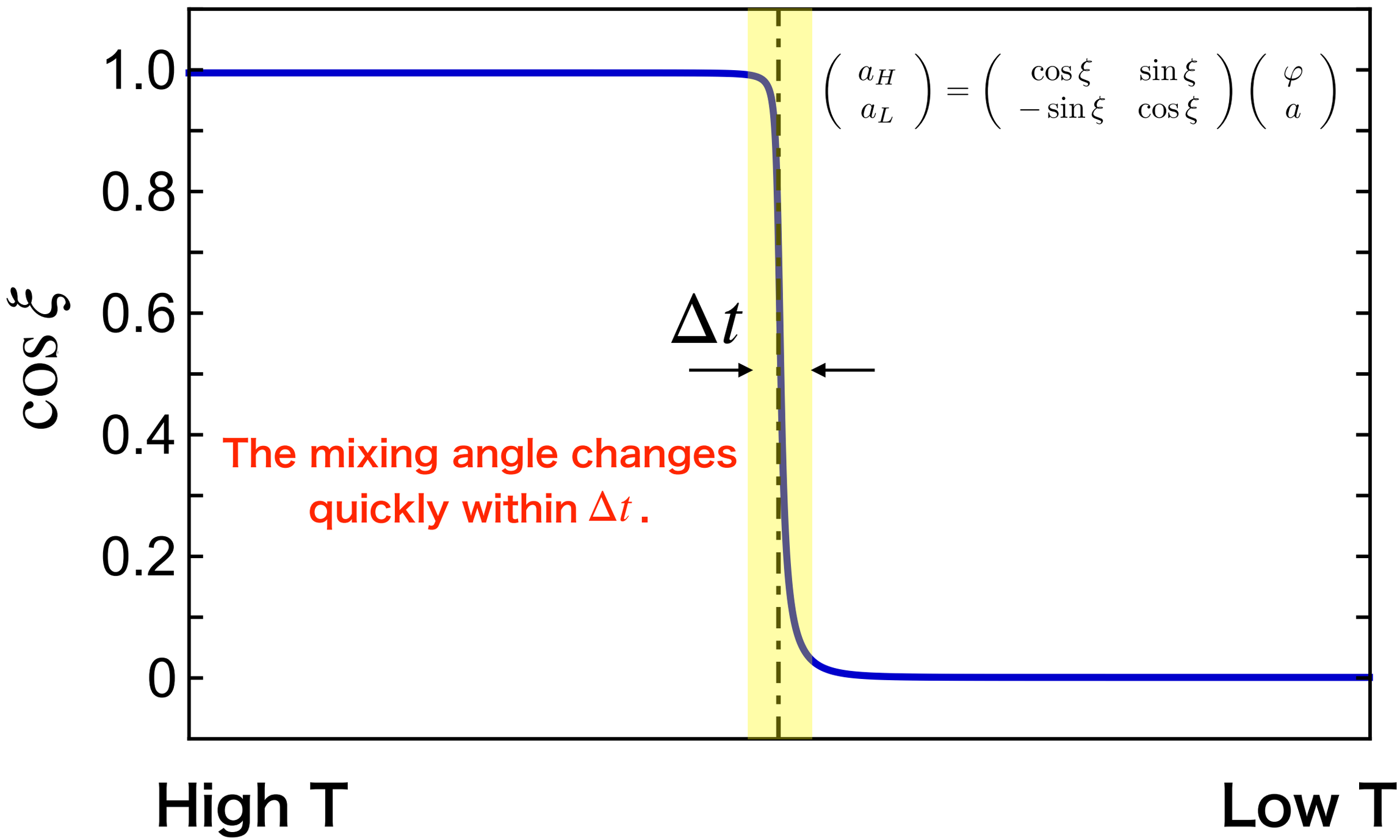


Adiabatic condition

The adiabatic invariants are the (comoving) number of the two massive scalars. For the adiabatic invariant to be conserved, one needs

External time scale >> Intrinsic time scale

$$\Delta t = \left(\frac{d \ln \cos \xi}{dt} \right)^{-1} \Bigg|_{\text{l.c.}} \gg \text{Max} \left[\frac{2\pi}{m_H}, \frac{2\pi}{m_L}, \frac{2\pi}{m_H - m_L} \right]$$

Beat frequency

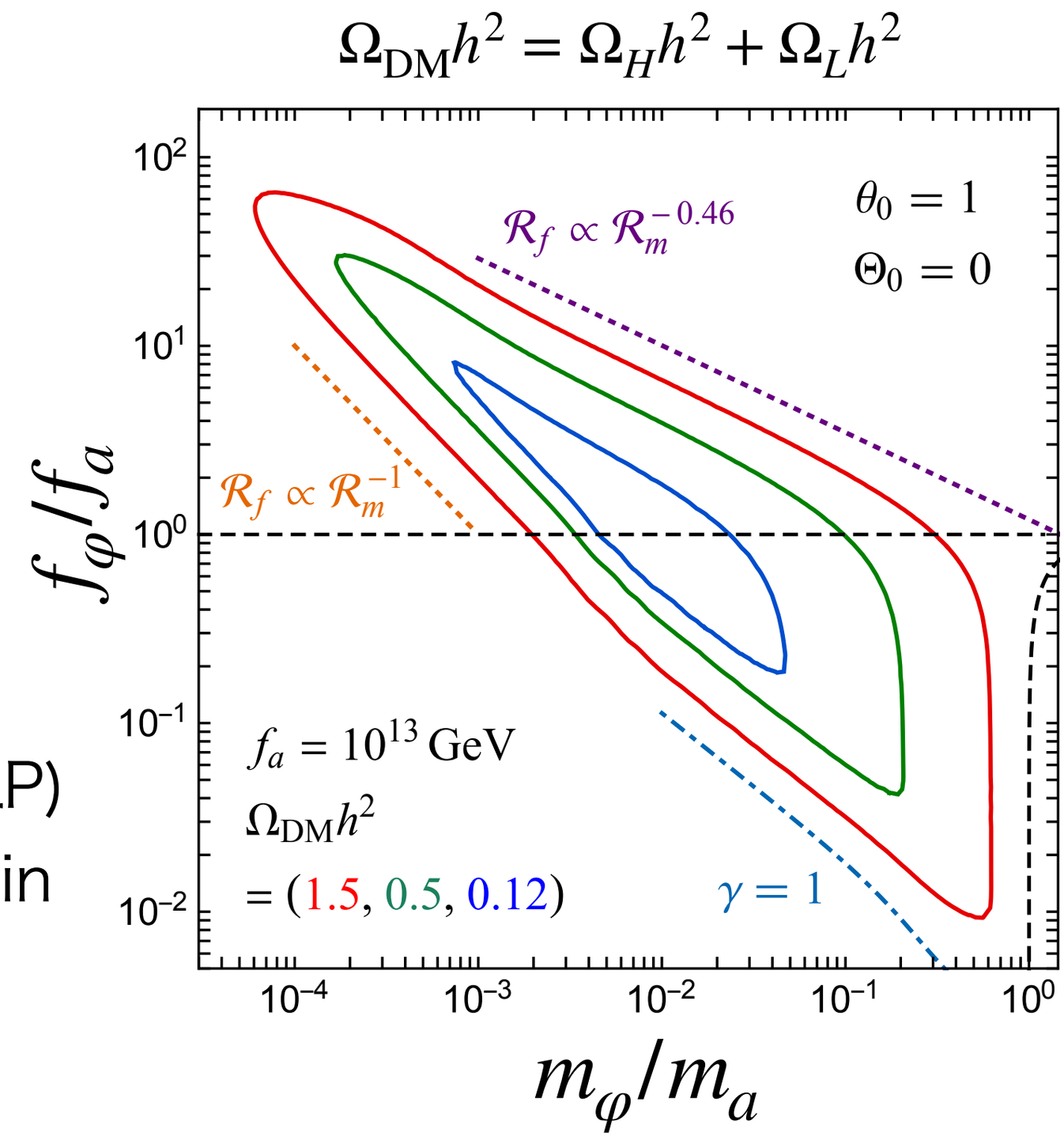
$$\gamma \equiv \beta \frac{f_\varphi}{f_a} \sqrt{\frac{m_\varphi}{H\left(T_{\text{lc}}\right)}} \gg 1$$

$$\beta \equiv \sqrt{\frac{1}{n\pi} \left[1 + \frac{1}{3} \frac{d \ln g_s(T)}{d \ln T} \right]} \Bigg|_{T=T_{\text{lc}}}$$

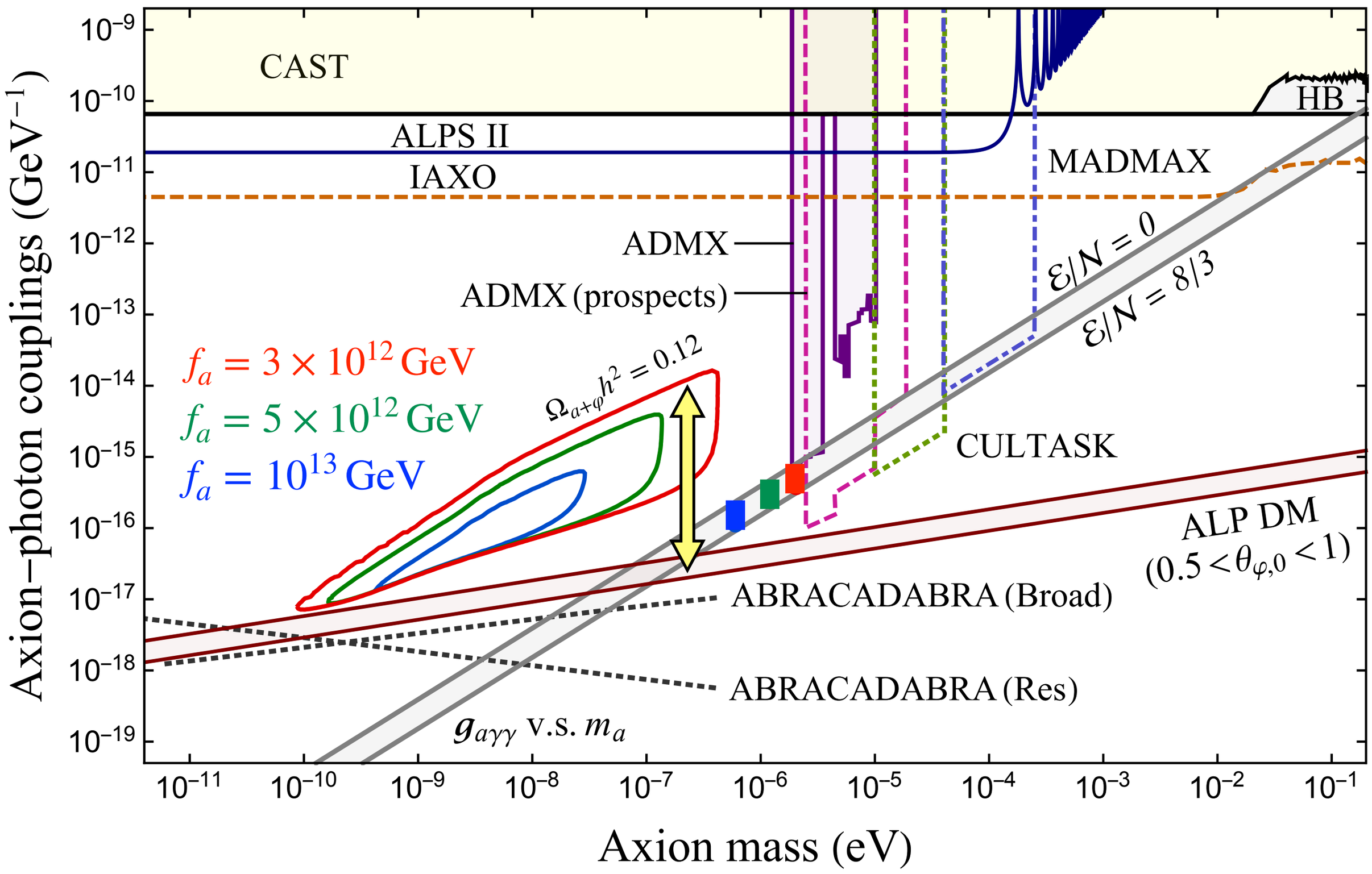
Axion DM abundance

We consider $f_a = 10^{13}\,\mathrm{GeV}$ for which the QCD axion abundance would exceed the obs. DM abundance, if there were not for adiabatic conversion.

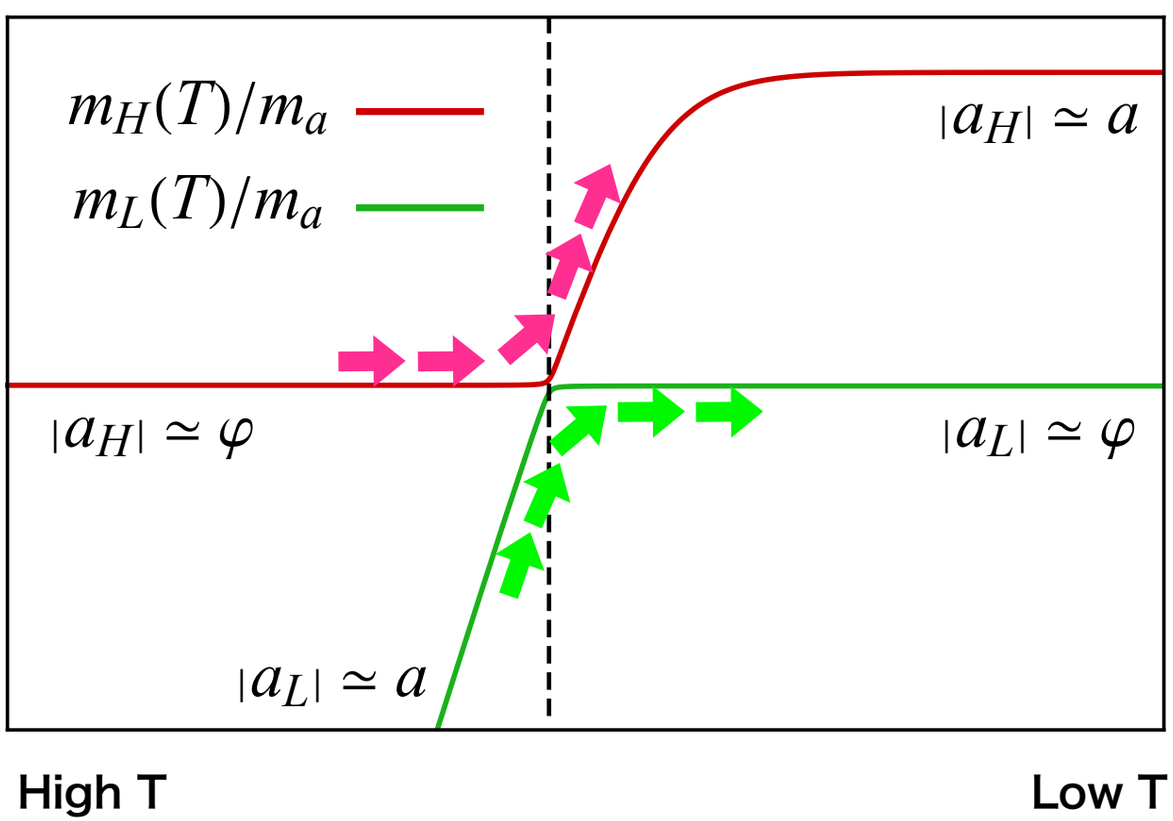
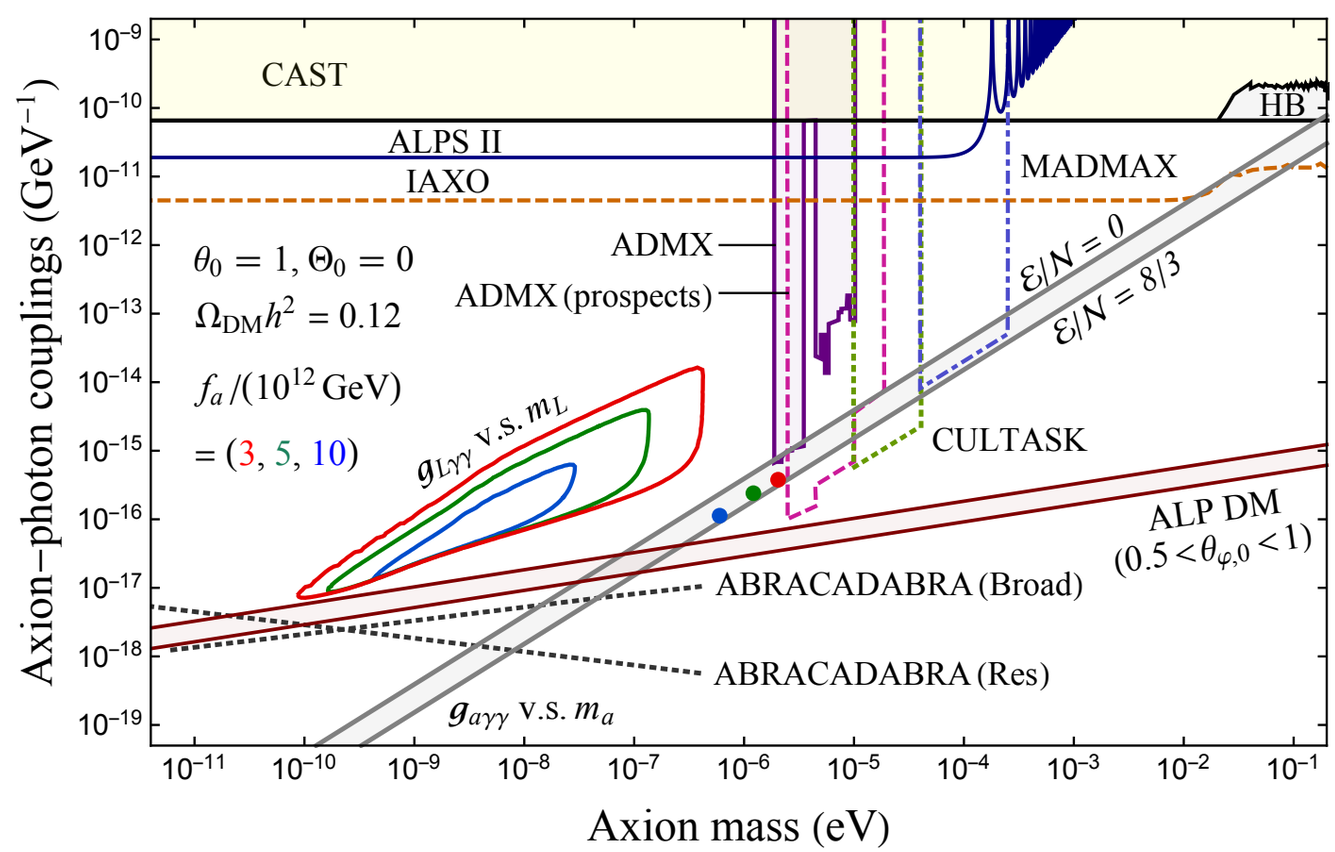
The lighter axion (mainly ALP) is the main DM component in the allowed region.



Axion coupling to photons



ALP coupling to photons can be enhanced by a few orders of magnitude.

Summary

- If the adiabatic conv btw QCD axion and ALP takes place, the axion abundance gets suppressed by the mass ratio, $m_\varphi/m_a < 1$.
- The ALP produced by the adiabatic conv of the QCD axion can explain DM, and the ALP-photon coupling can be enhanced by a few orders of magnitude, compared to a single ALP DM scenario.