Can the QCD axion feed a DE component?

with: K. Müürsepp & C. Smarra [arXiv:2405000090] .

Enrico Nardi

KBFI NICPB HEP Group

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

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The axion defining interaction

$$\mathscr{L}_a = \frac{\alpha_s}{8\pi}\underbrace{\left(\frac{a(x)}{F} + \bar{\theta}\right)}_{a \to a + \text{const.}} G\tilde{G} + \mathscr{L}\underbrace{\left(\partial_\mu a(x), \psi, \varphi, A_\mu\right)}_{\partial_\mu a \to \partial_\mu a \text{ invariant}} + \underbrace{\left[\delta\mathscr{L}_{\text{eff}}(a(x), \ldots)\right]}_{\substack{\text{Absent or suppressed} \\ \Lambda_{\text{eff}} \sim m_P \,\&\, d \geq 10}}$$

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1. $\bar{\theta}$ is removed via a shift of the axion field $a \to a - \bar{\theta} F$
2. Minimum of the vacuum energy occurs for $\langle a(x) \rangle \to 0$: solves strong CP problem
3. The $a\, G\tilde{G}$ interaction generates a mass term:

$$F^2 m_a^2 = i \int d^4x \langle \frac{\alpha_s}{8\pi} G\tilde{G}(x) \frac{\alpha_s}{8\pi} G\tilde{G}(0) \rangle \equiv \chi \leftarrow \text{"Topological susceptibility"}$$

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DIGA (lowest order): $n = \beta_0 - n_f - 4 = \frac{11}{3}N + \frac{1}{3}n_f - 4$ $n = 8$ (QCD)

IILM (more appropriate for $T \sim T_{osc}$): $n \sim 6.68$

[Interacting inst. liquid model: Shellard & Wanz, 2010]

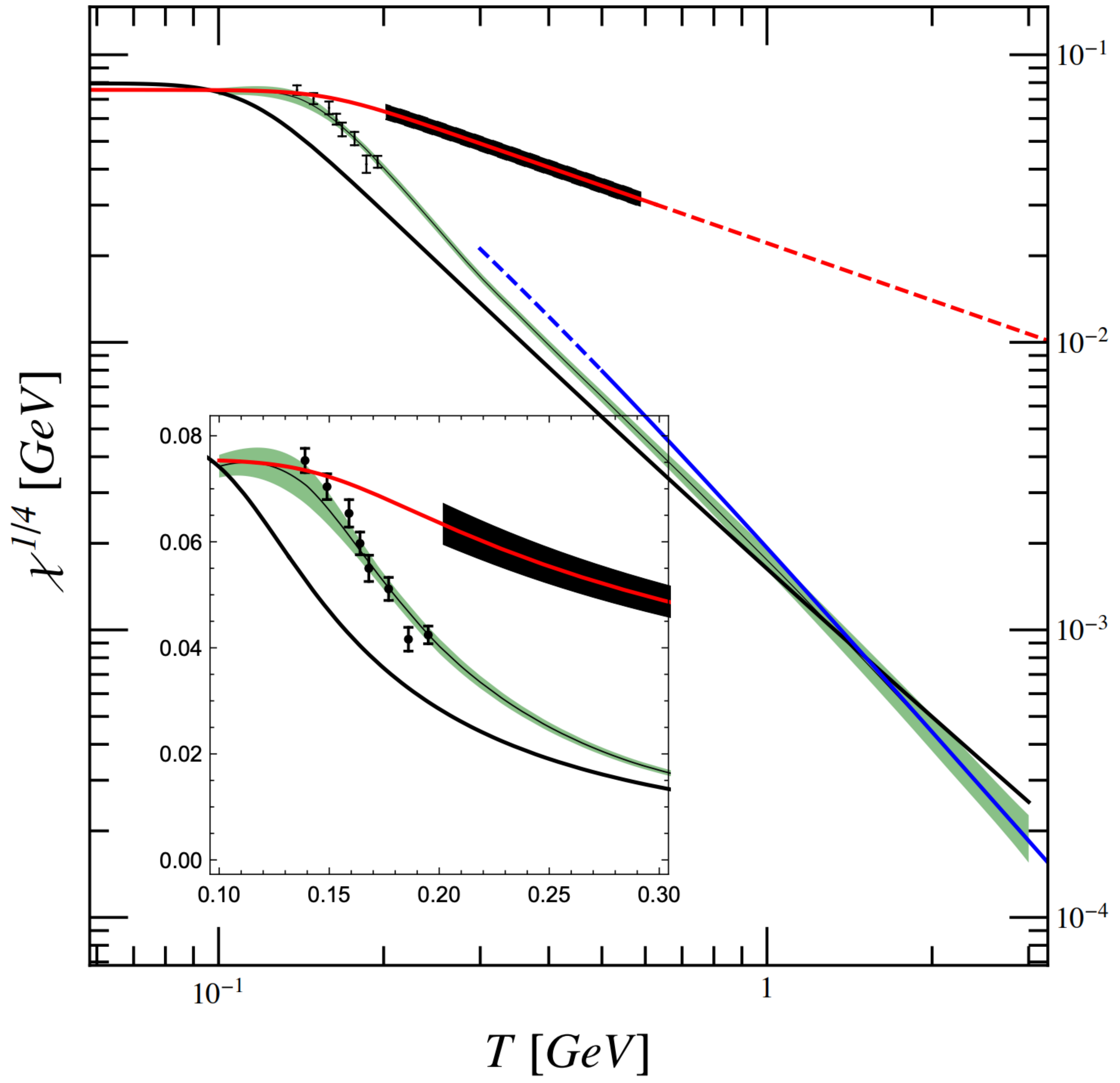
Effective mass, lattice calculations

Lattice QCD: we can compute axion mass

$$m_a^2 f_a^2 = \chi(T)$$

At high T (no mesons)
we can analytically compute potential (DIGA)

$$V(\theta) = -\chi(T)\cos\theta$$



Lattice QCD 2+1+1 [Borsanyi]
Lattice QCD 2+1 [Bonati]
Lattice QCD (DWF) 2+1 [Buchoff] (points)
DIGA (T>>Tc) [Borsanyi]
IILM [Wantz]

[A. Ringwald —>]

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Could a PNGB $b(x)$, coupled to a "dark" gauge group G_b that

is undergoing a confining PT now ($\Lambda_b < T_0$), explain the DE ?

No. Not enough energy density: $\rho_b \lesssim \Lambda_b^4 < T_0^4 \sim \rho_{rad} \ll \rho_{DE}$

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$$\mathscr{L}_Y \sim \bar{\psi}_L \psi_R \, \Phi_1 \; + \; \bar{\chi}_L \chi_R \, \Phi_2 \quad \to \quad \bar{\psi}_L \psi_R v_1 e^{i\frac{a_1}{v_1}} \; + \; \bar{\chi}_L \chi_R v_2 e^{i\frac{a_2}{v_2}}$$

$$\psi \sim (1,3), \quad \chi \sim (3,3)$$

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This generates the potential:

$$F, F' \propto v_2, \quad f \propto v_1$$

$$V = \Lambda_a^4 \left[1 - \cos\left(\frac{\varphi_a}{F} \right) \right] + \Lambda_b^4 \left[1 - \cos\left(\frac{\varphi_a}{F'} + \frac{\varphi_b}{f} \right) \right];$$

$$\begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

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$$\ddot{A} + 3H\dot{A} + \mathcal{M}^2 A = 0$$

$$A = \begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix}; \quad \mathcal{M}^2 = m_a^2 \begin{pmatrix} 1 & \epsilon\, r(T) \\ \epsilon\, r(T) & r(T) \end{pmatrix}; \qquad m_a = \frac{\Lambda_a^2}{F}, \quad r(T) = \frac{m_b^2(T)}{m_a}, \quad \epsilon = \frac{f}{F'}$$

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This implies a Level Crossing $m_b(T_{\rm LC}) = m_a$ (width $\Gamma_{LC} \sim 3\varepsilon$)
where QCD axions φ_a can partially convert into b-axions φ_b

Dynamics of Level Crossing

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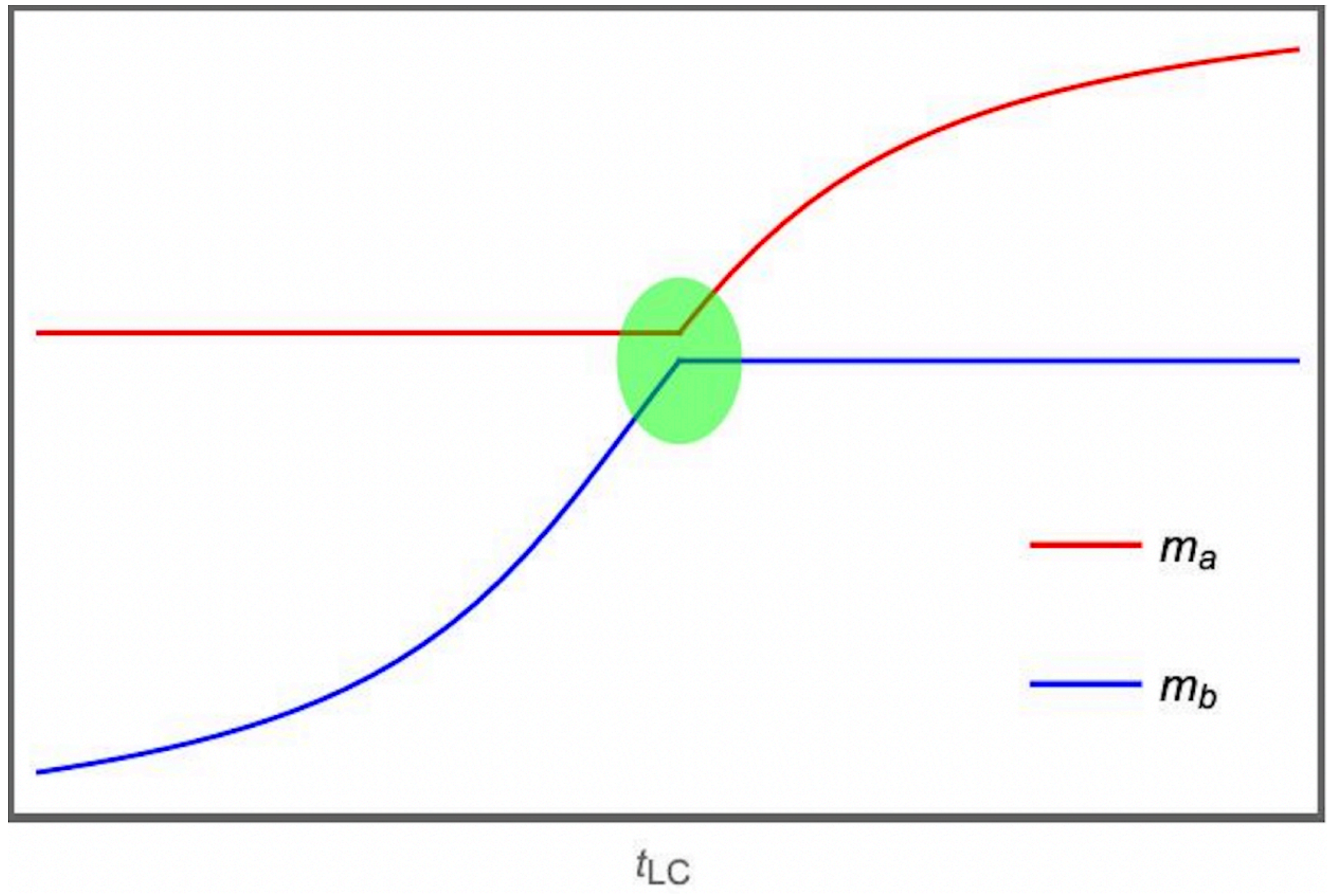

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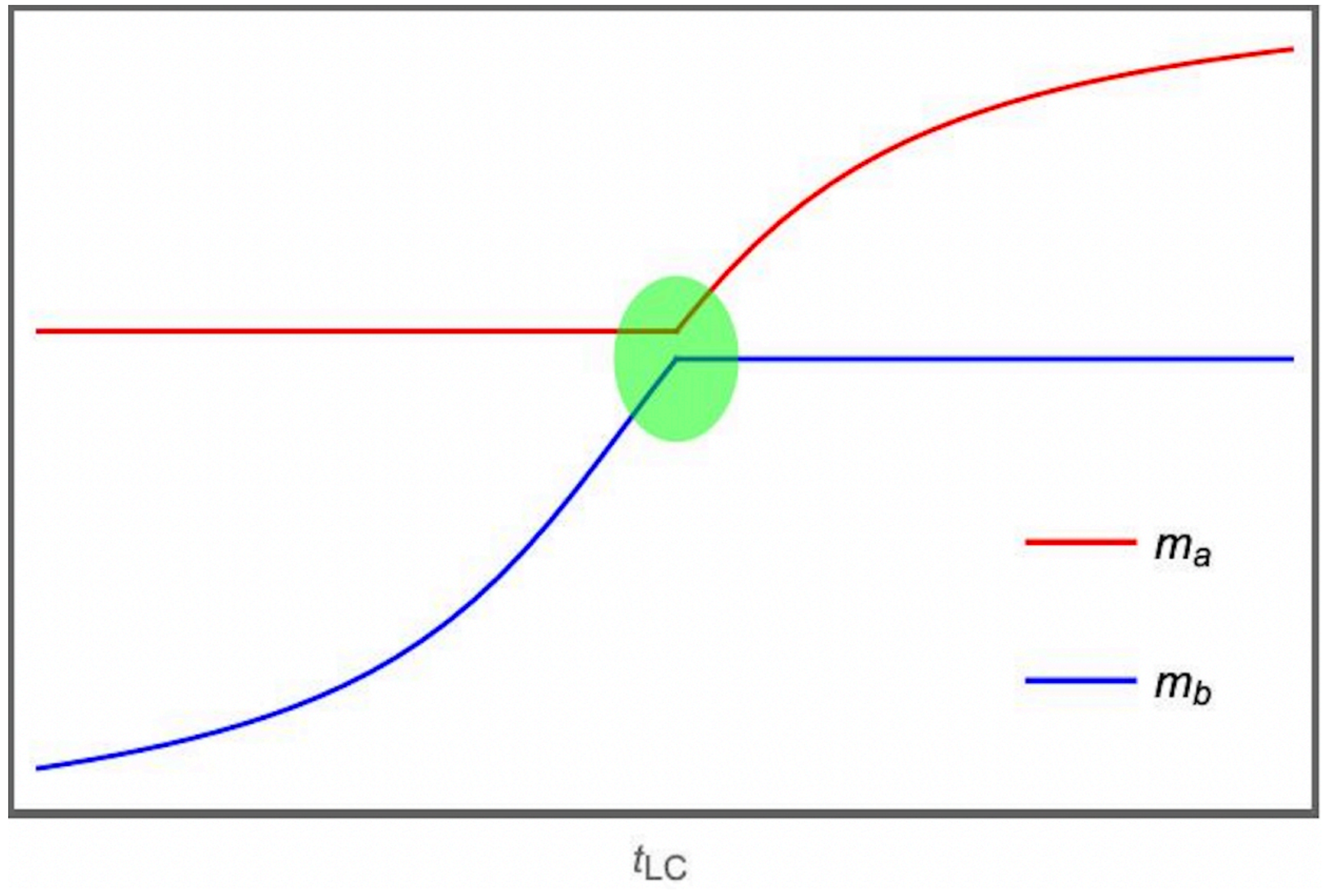

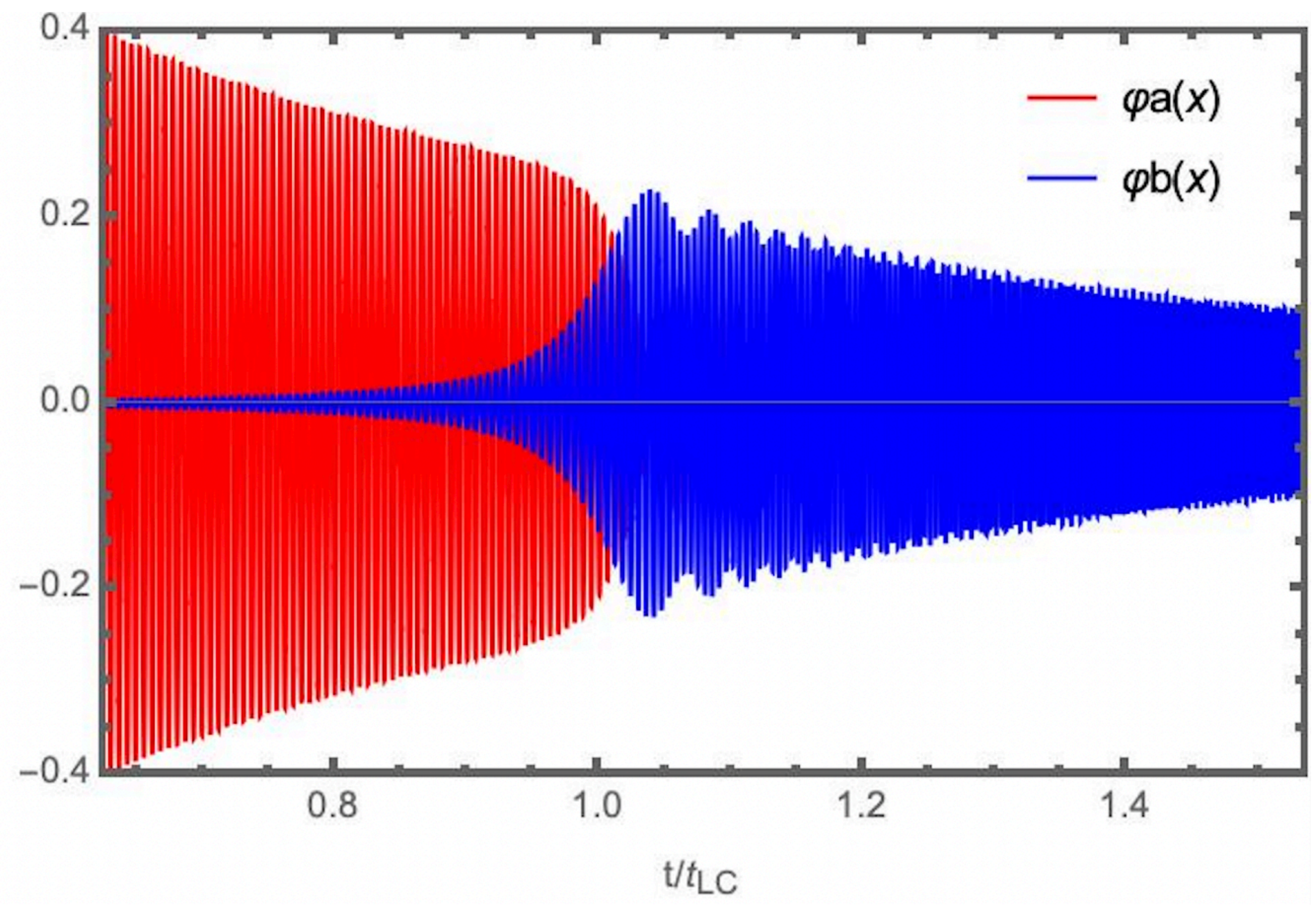

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$m_a\,(\varepsilon\, t_{LC}) \gg 1$

Plot: [$\varepsilon t_{LC}\, m_a = 50$]

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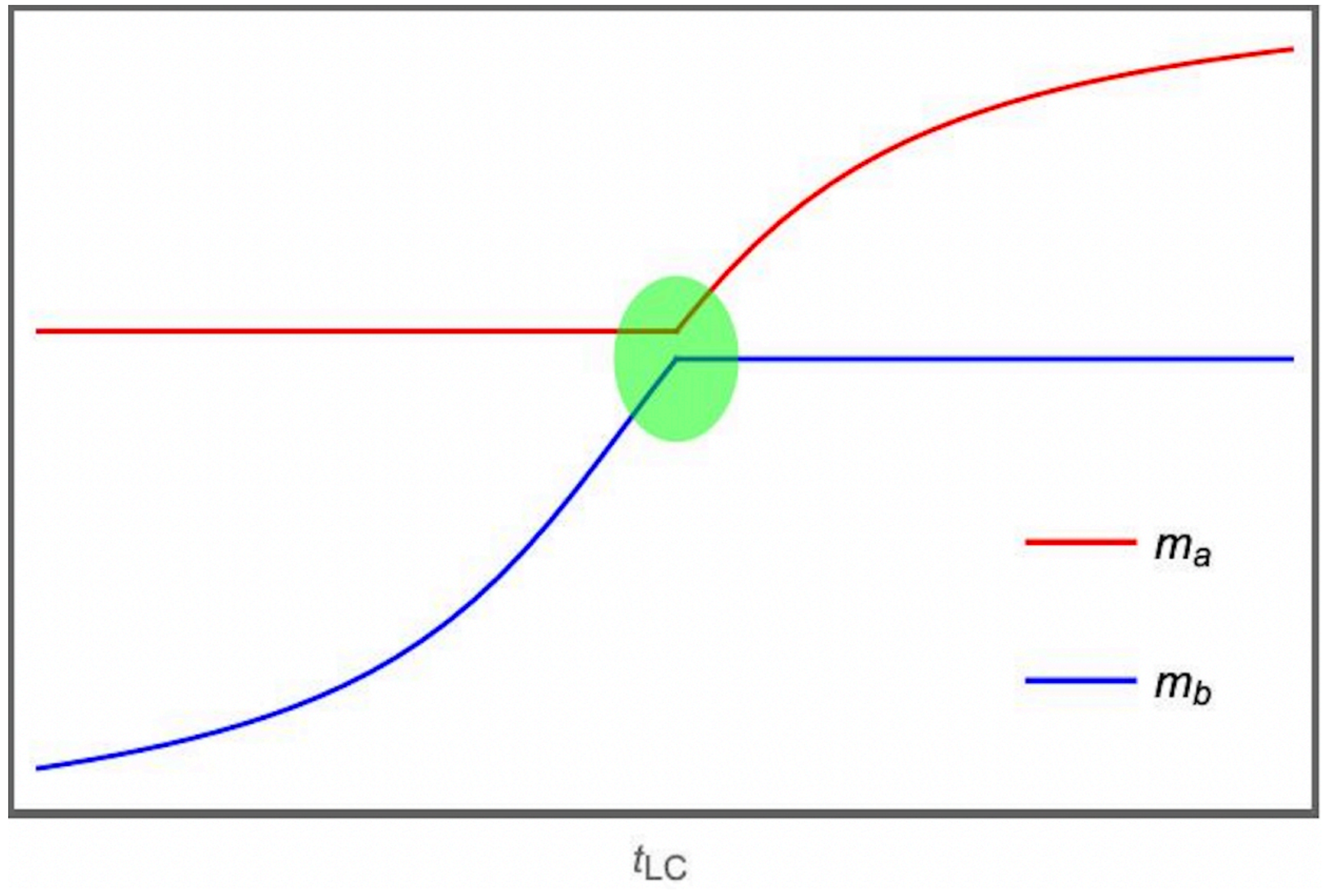

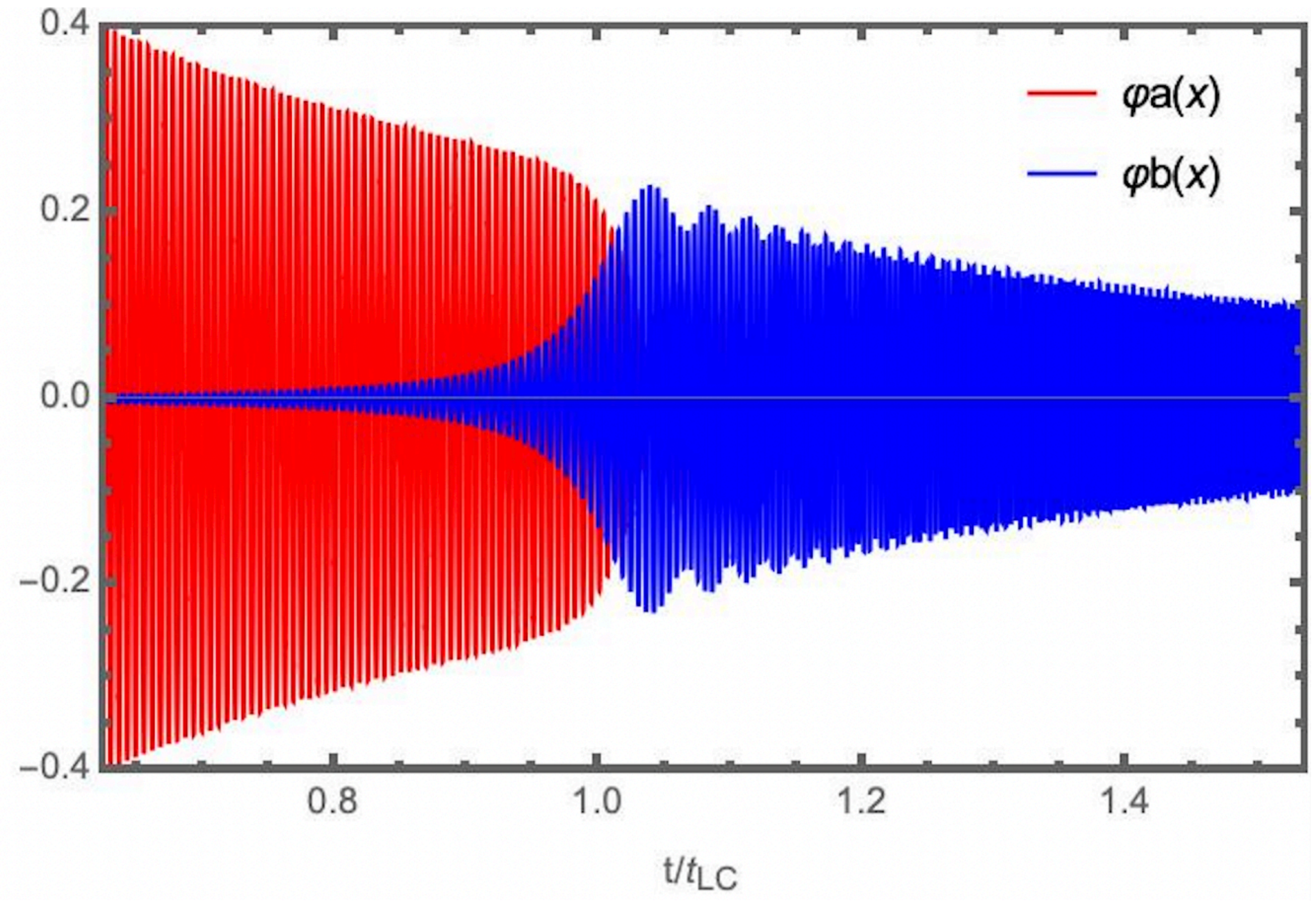

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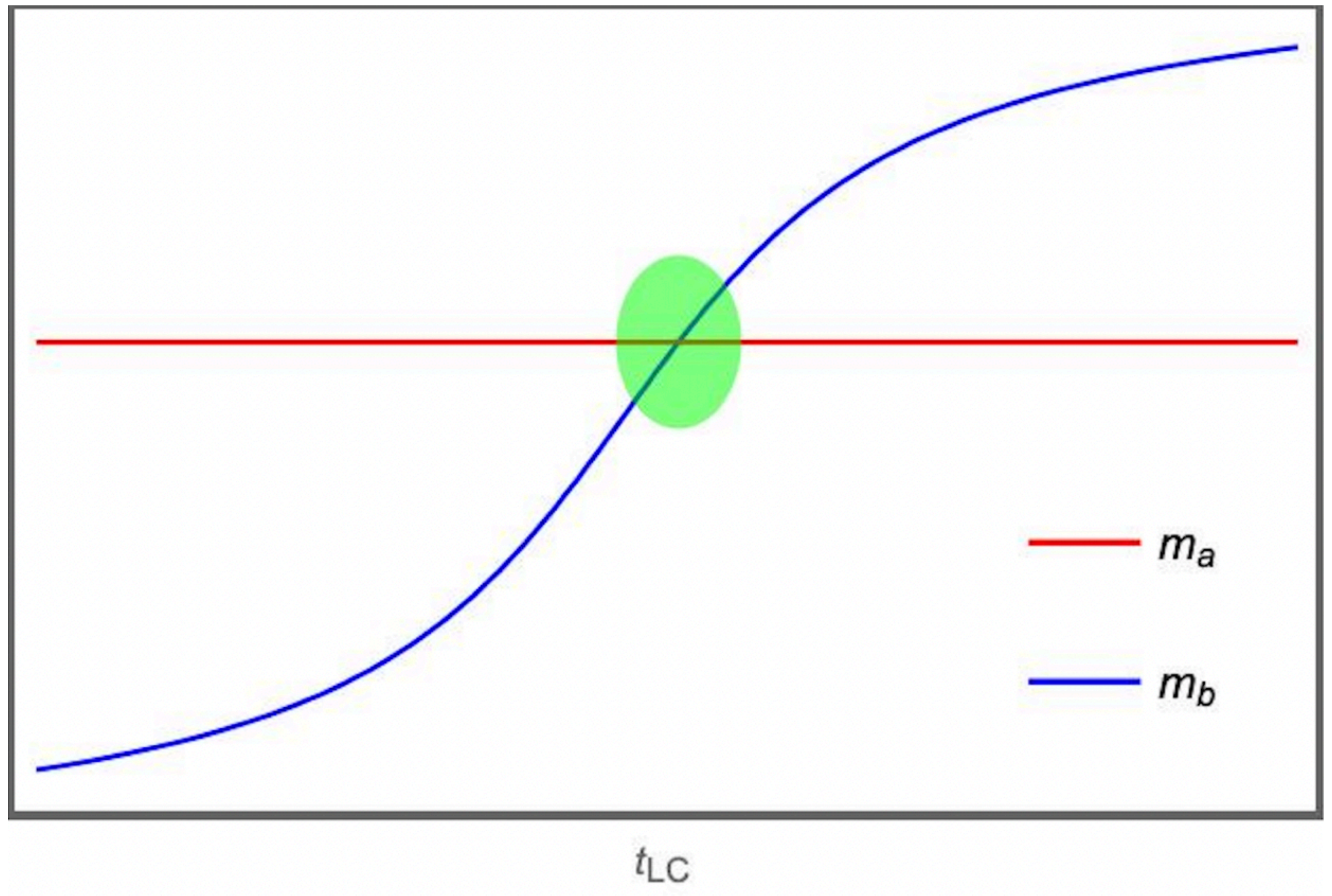

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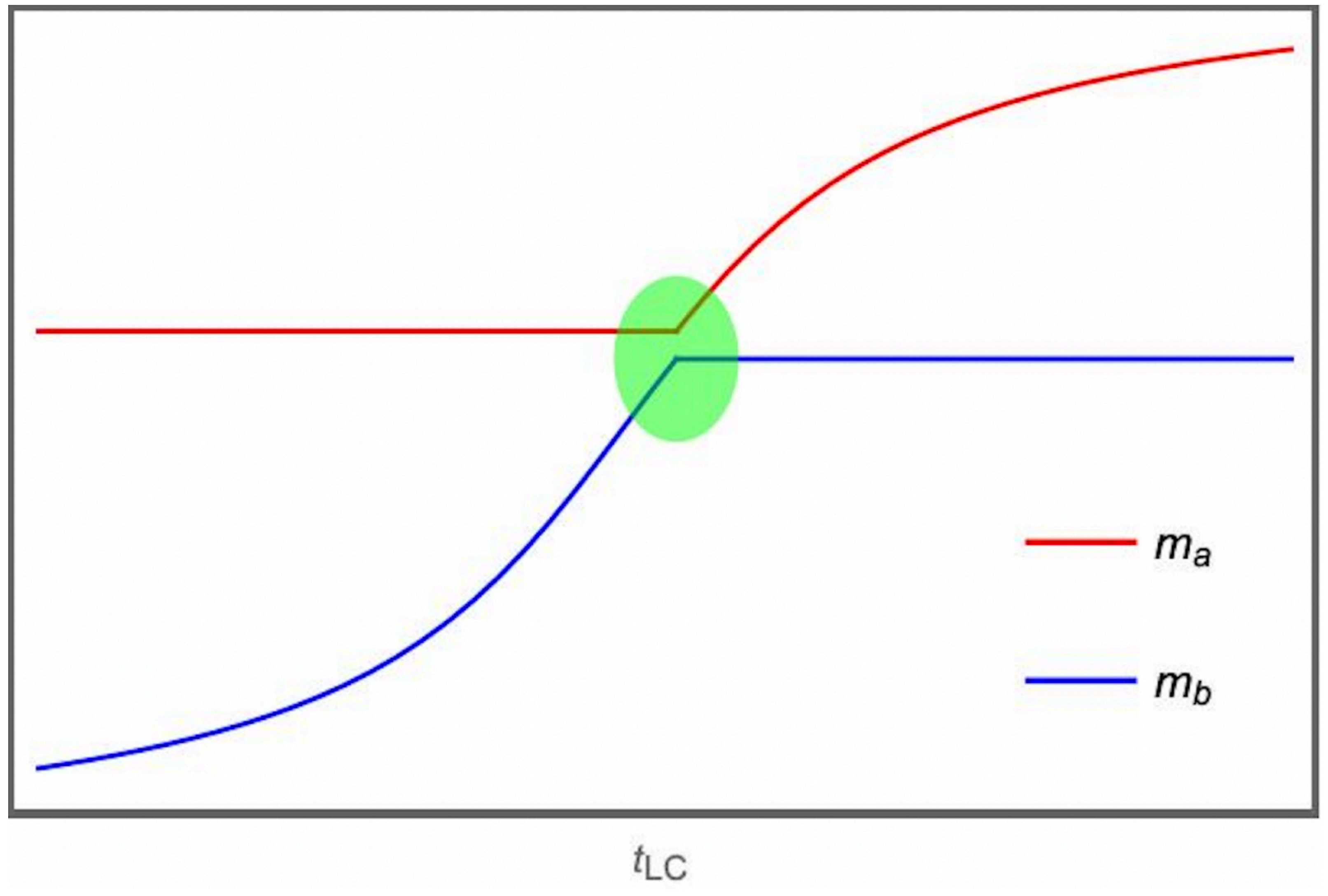

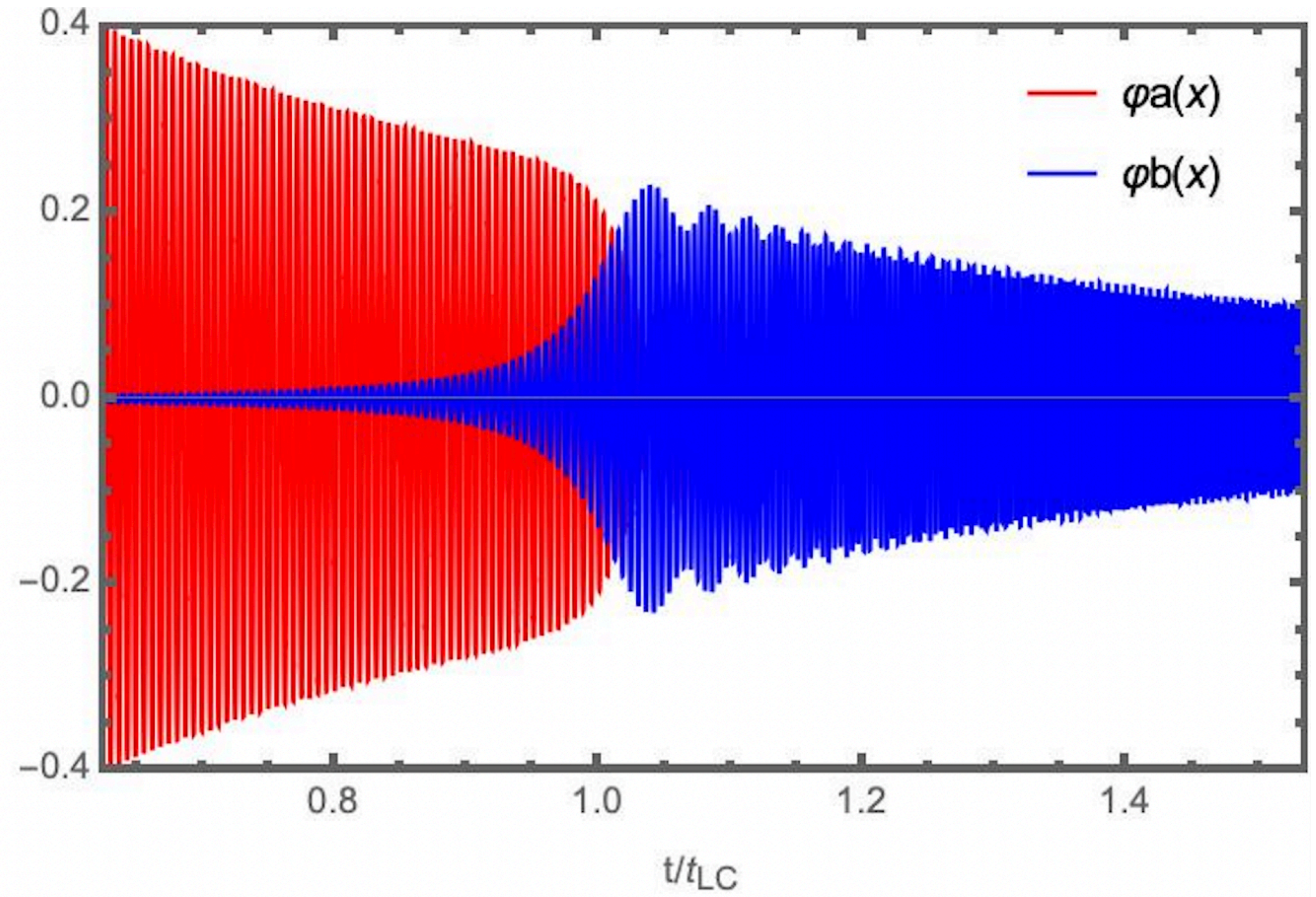

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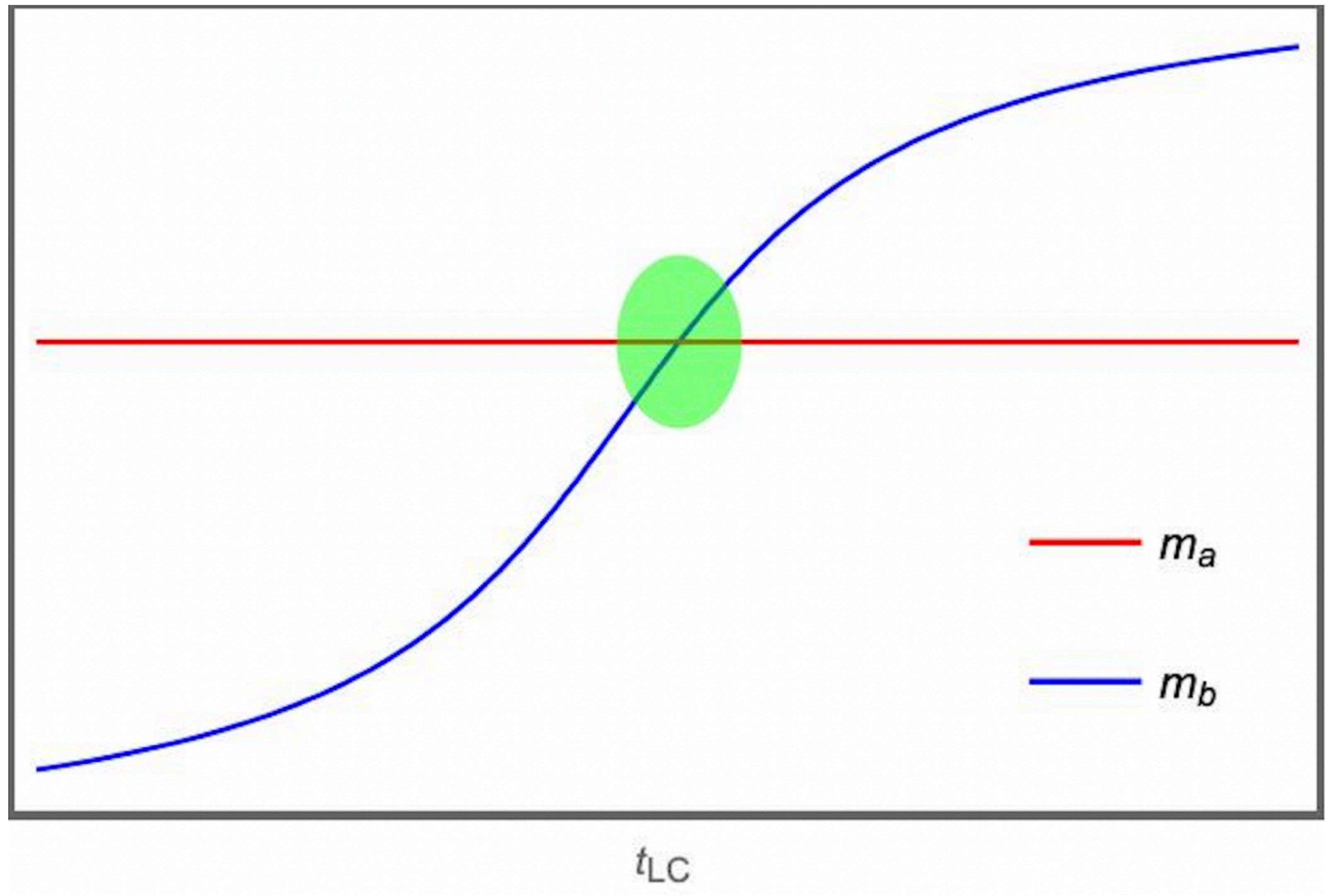

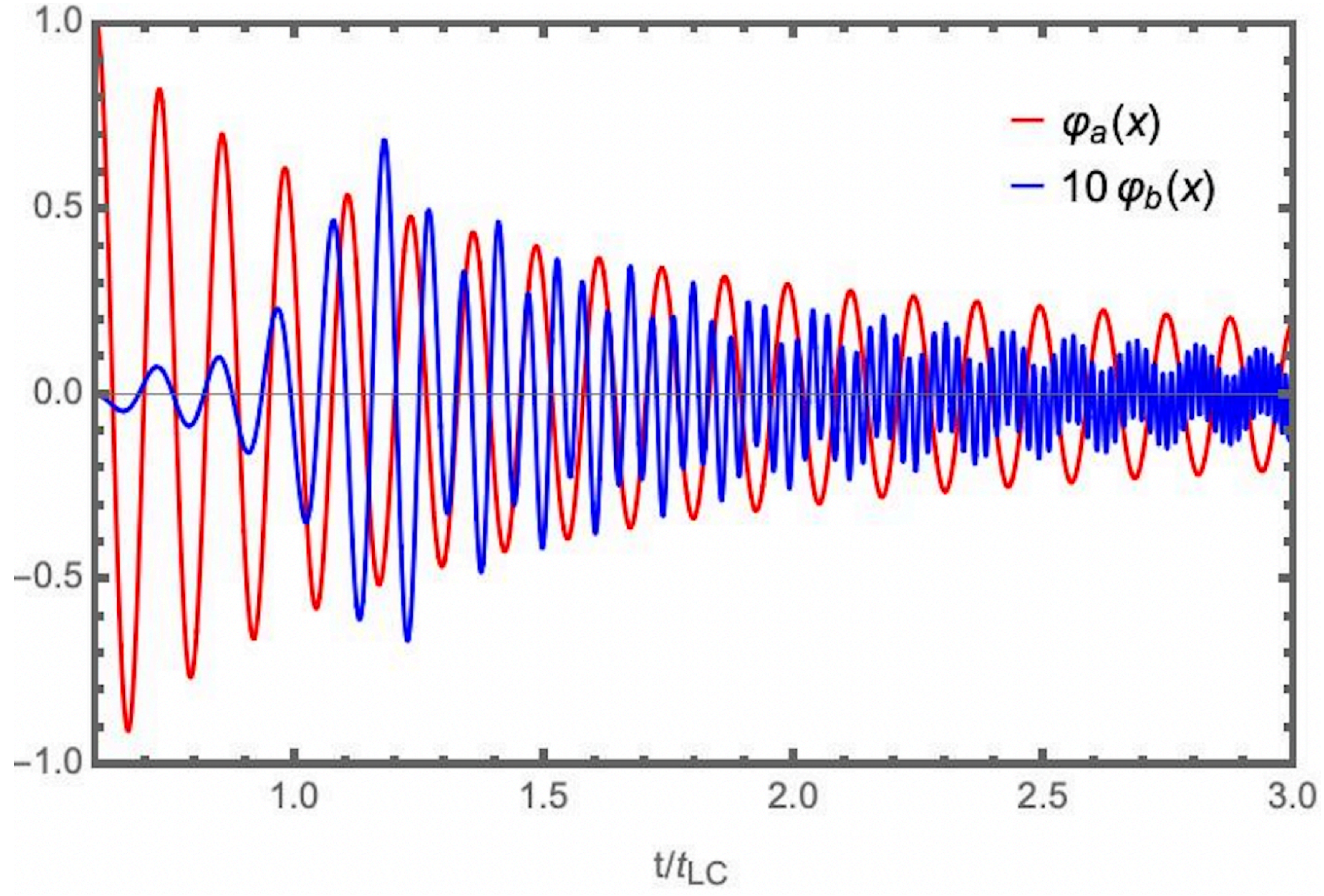

Diabatic

$m_a\,(\varepsilon\, t_{LC}) \lesssim 1$

Plot: [$\varepsilon t_{LC}\, m_a = 1$]

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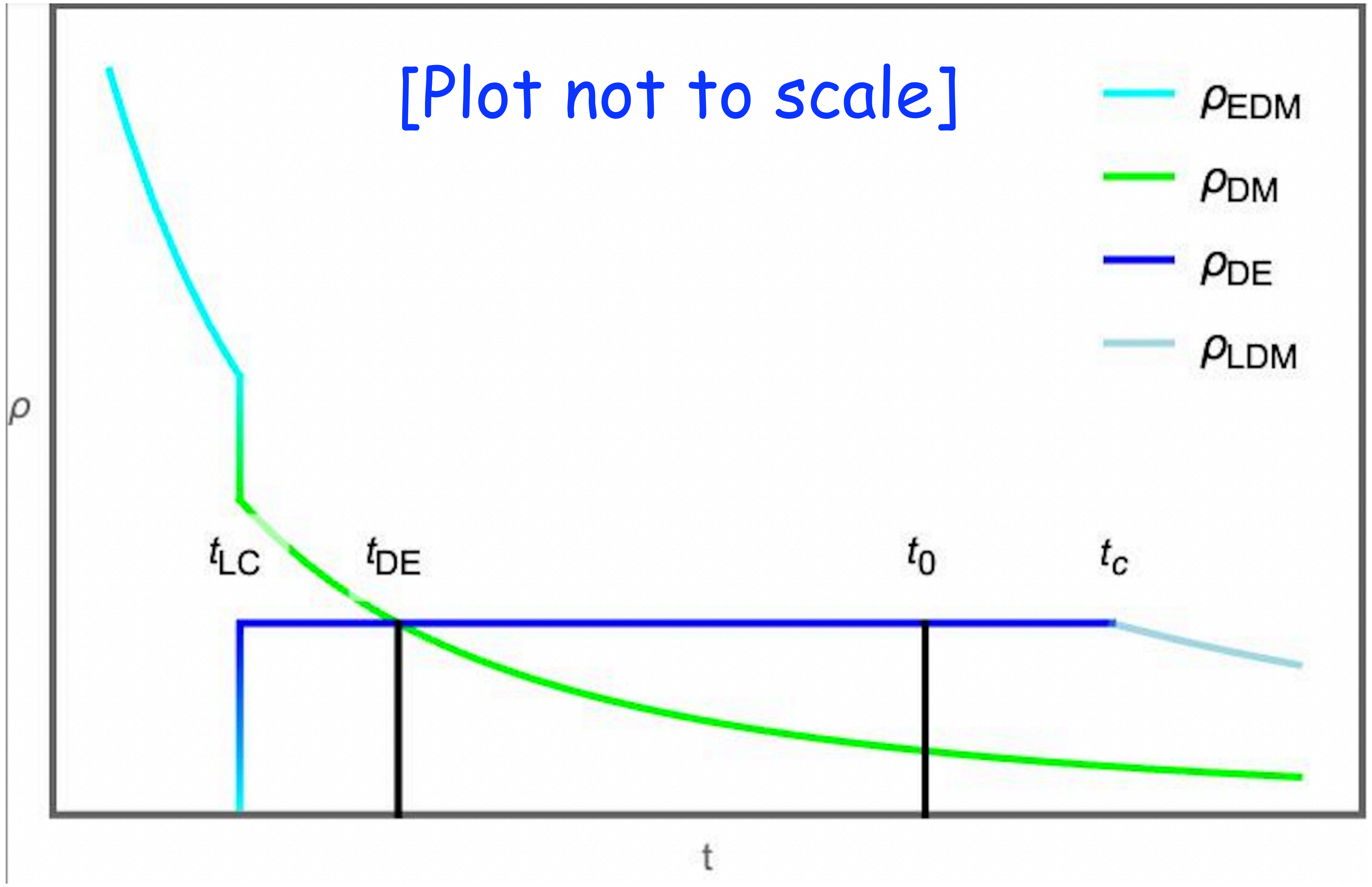

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Severe Constraining Conditions

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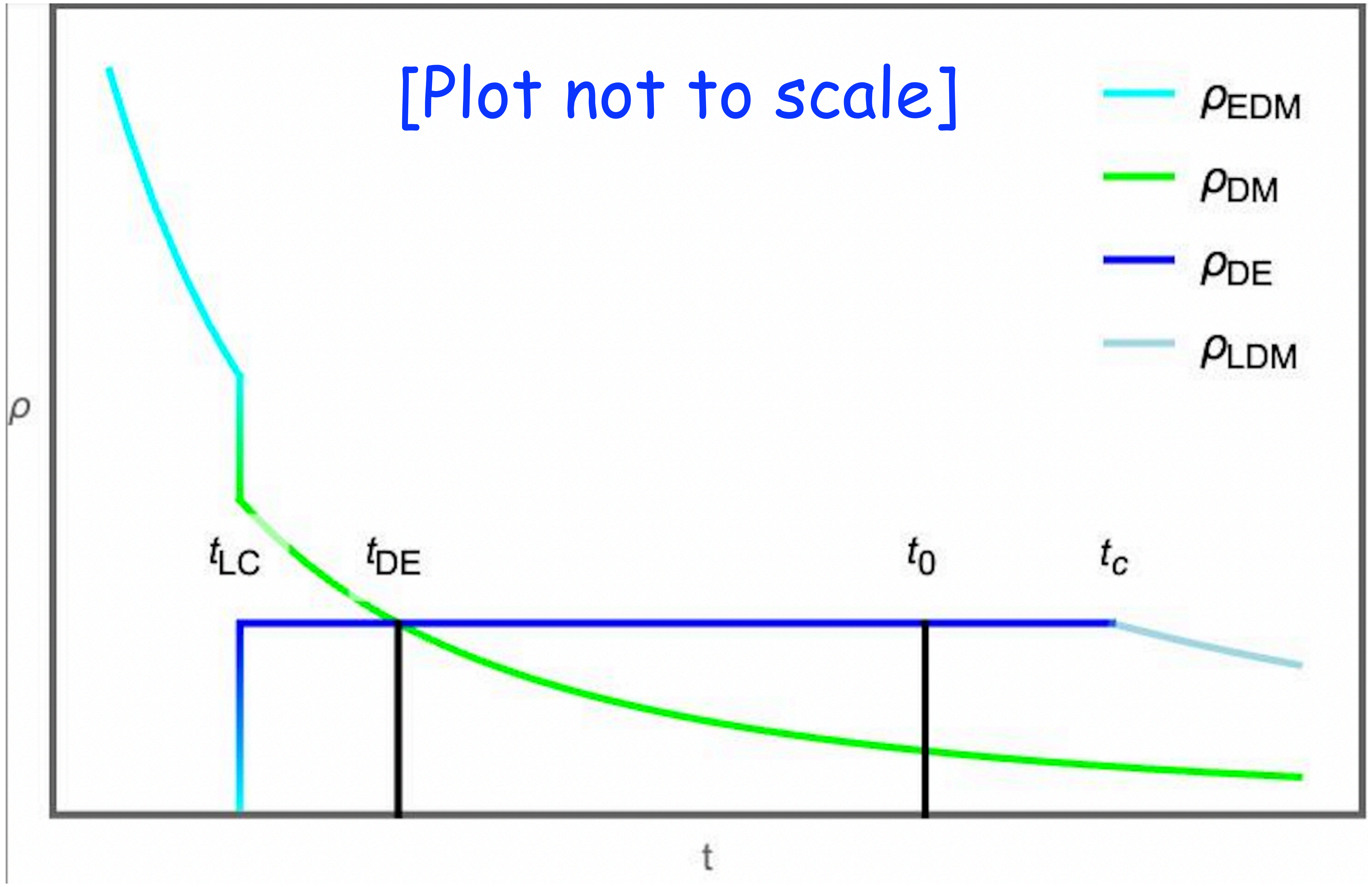

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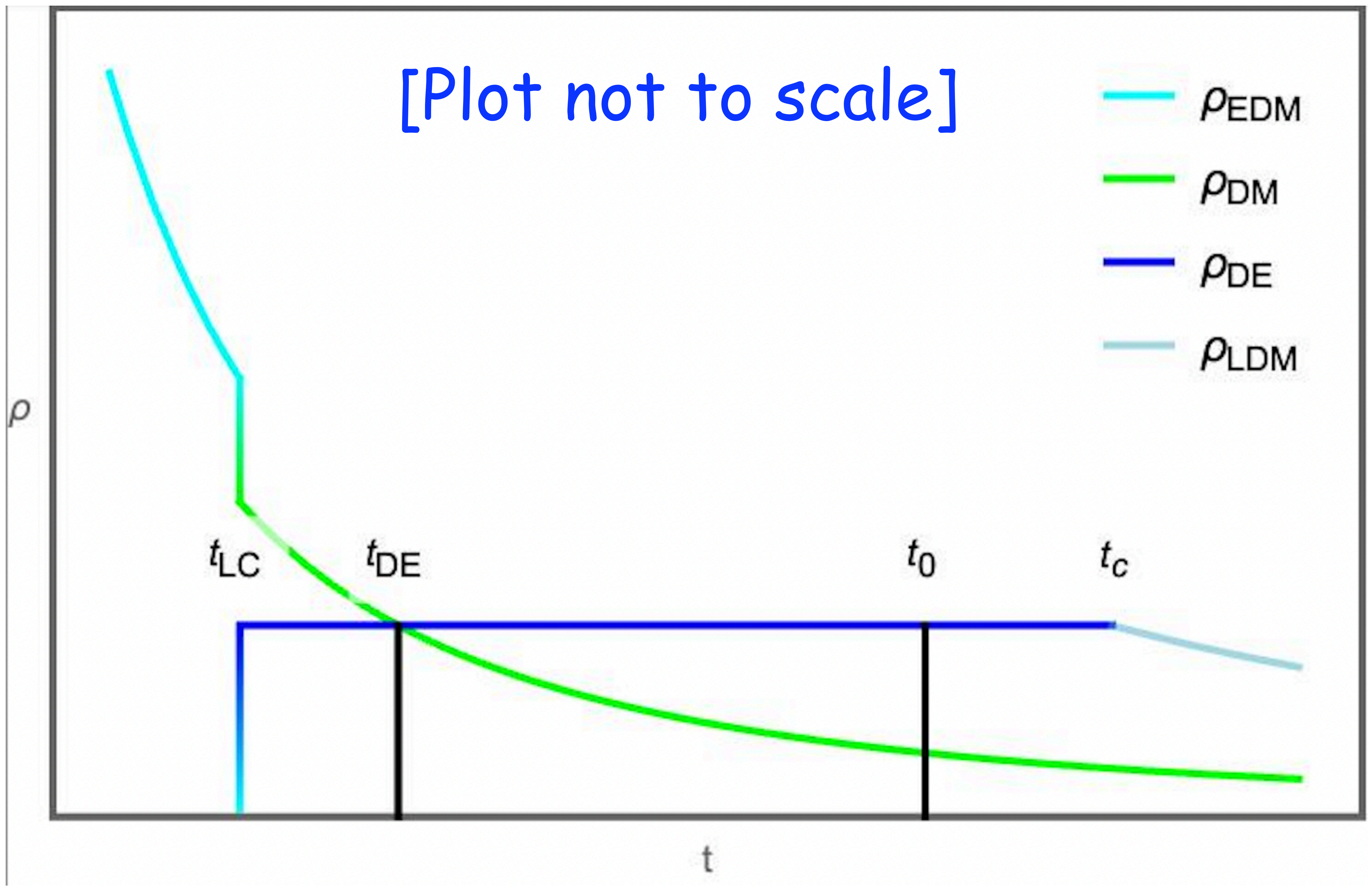

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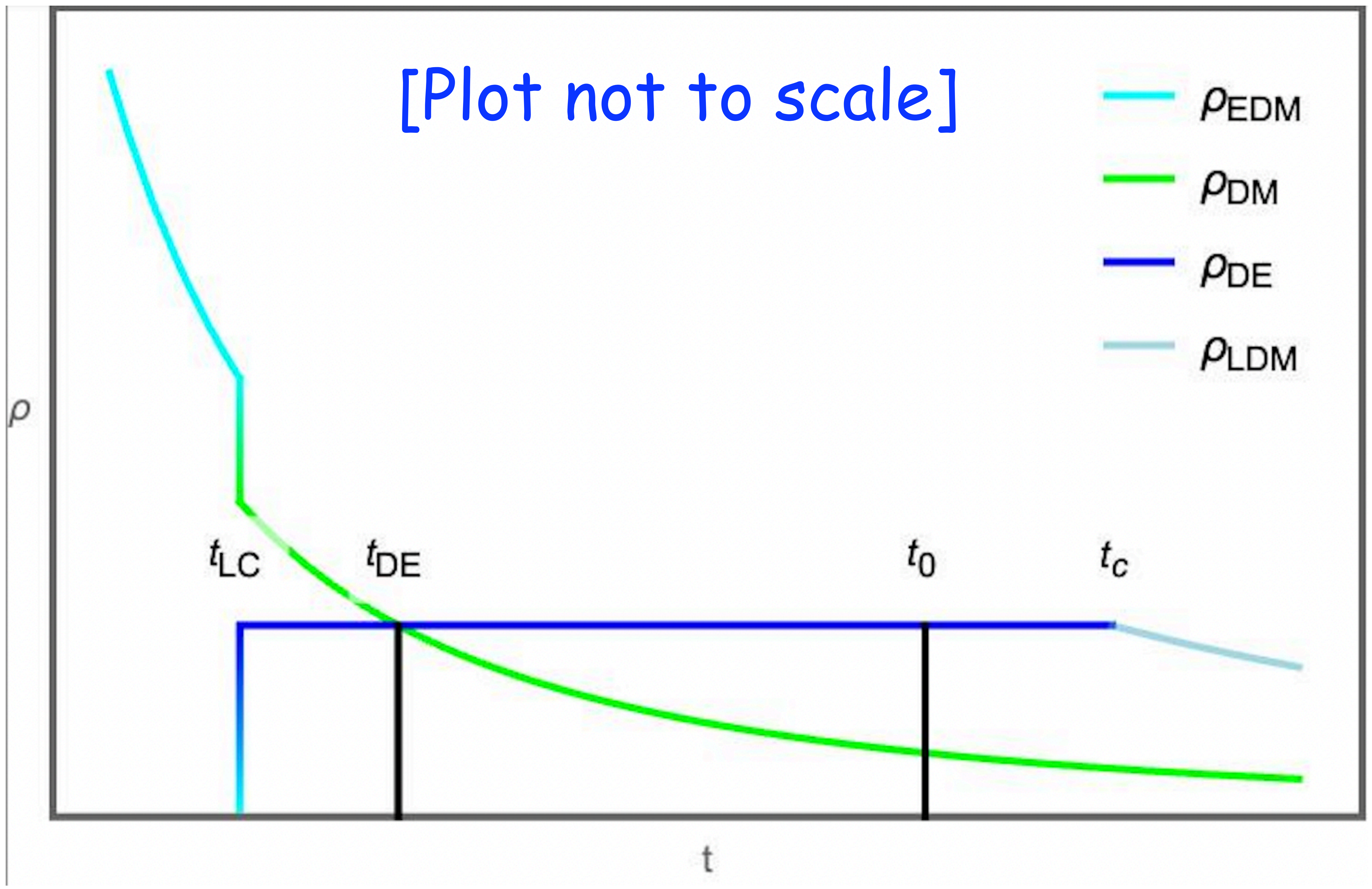

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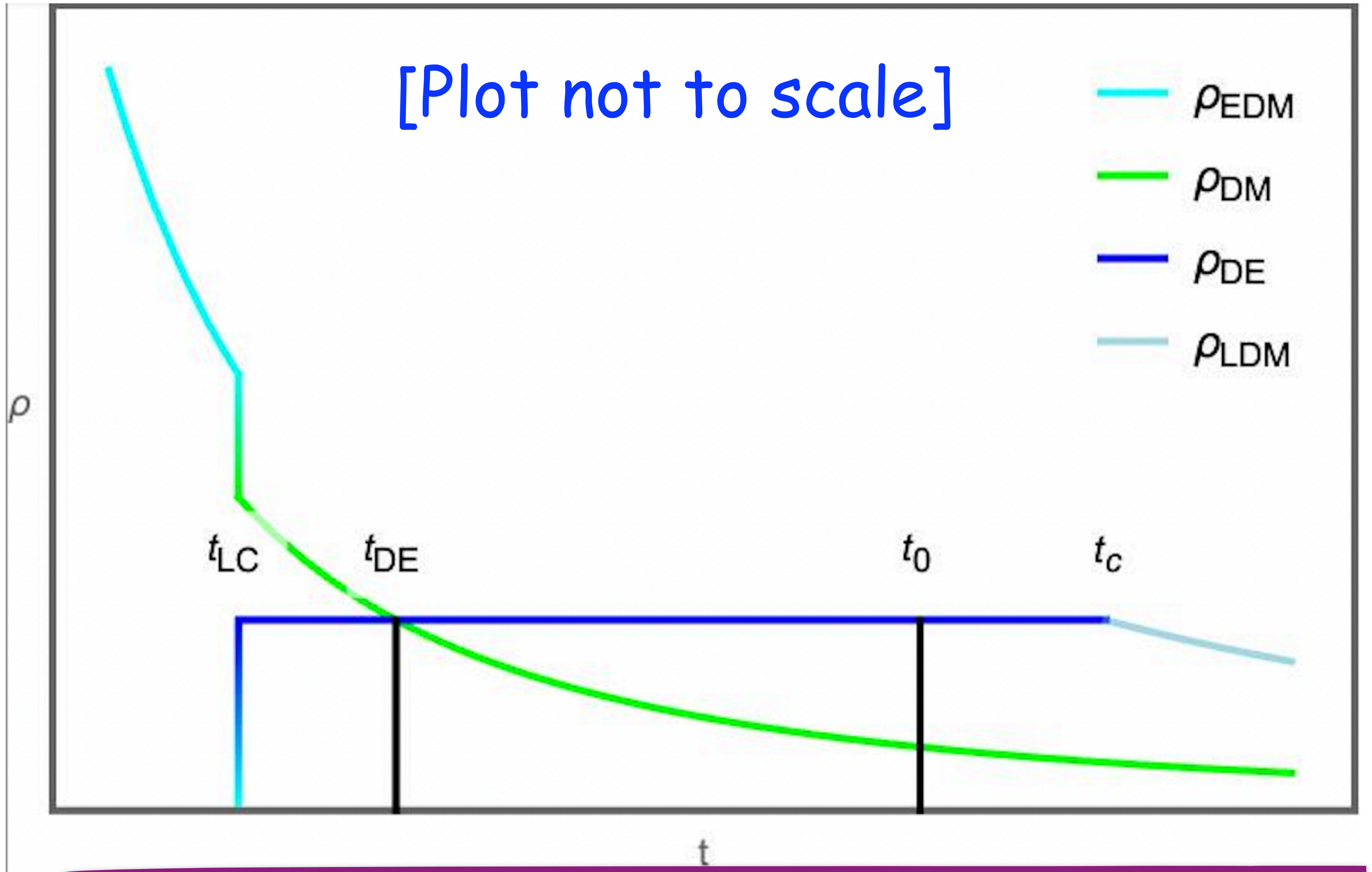

Non-adiabatic LC is in fact required !

$$\left.\frac{\rho_{\rm DE}}{\rho_m}\right|_{\rm LC} = \left(\frac{1+z_{\rm DE}}{1+z_{\rm LC}}\right)^3 \sim 1\% - 2\,\%$$

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Thanks for your attention !