Can the QCD axion feed a DE component?

[Can the QCD axion play a role in accelerating the expansion?]

KBFI NICPB HEP Group

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[arXiv:2405.00090] with: K. Müürsepp (NICPB, Tallinn) & C. Smarra (SISSA, Trieste)

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The axion defining interaction

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

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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]

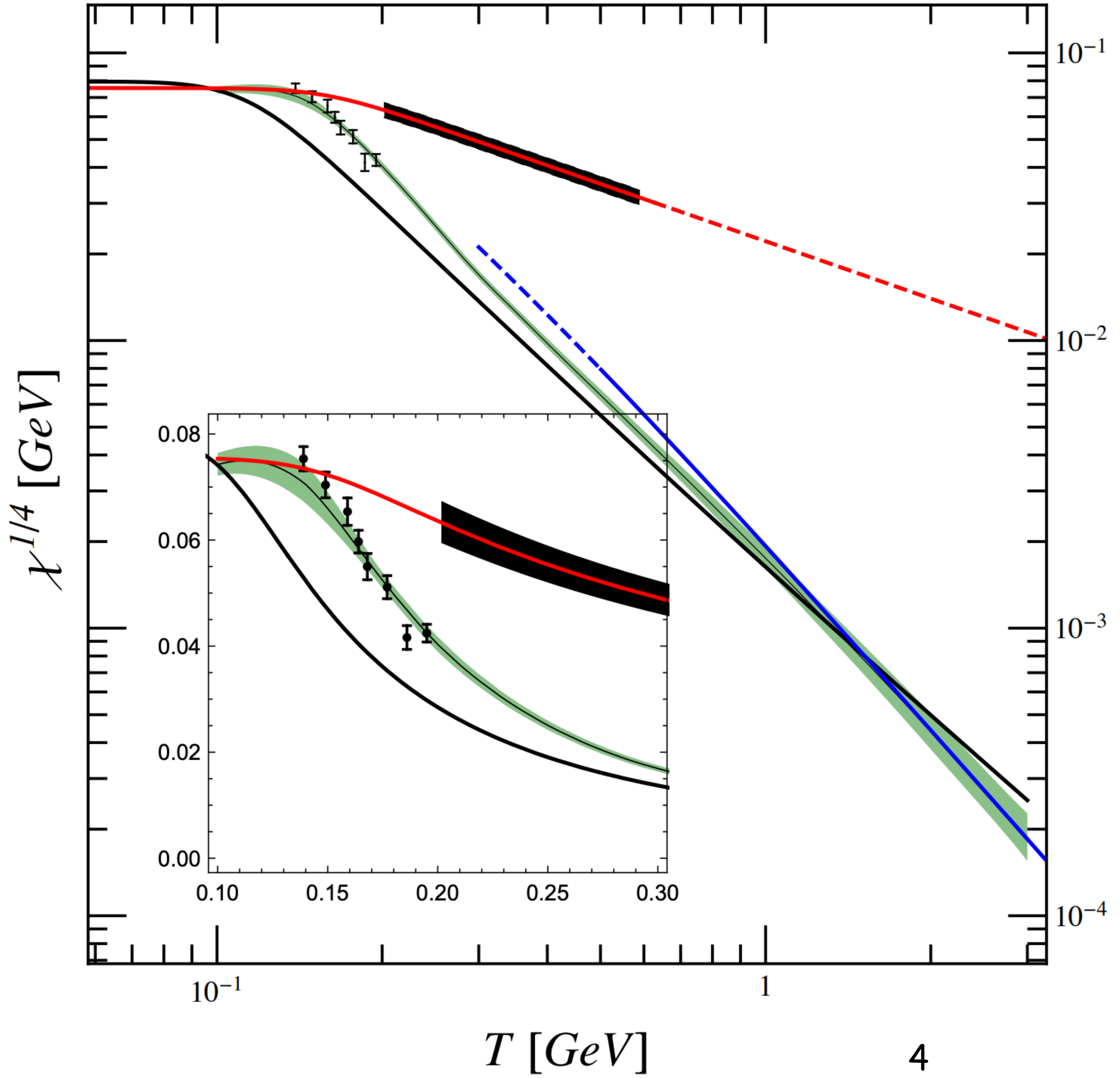
Effective mass, lattice calculations

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)

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



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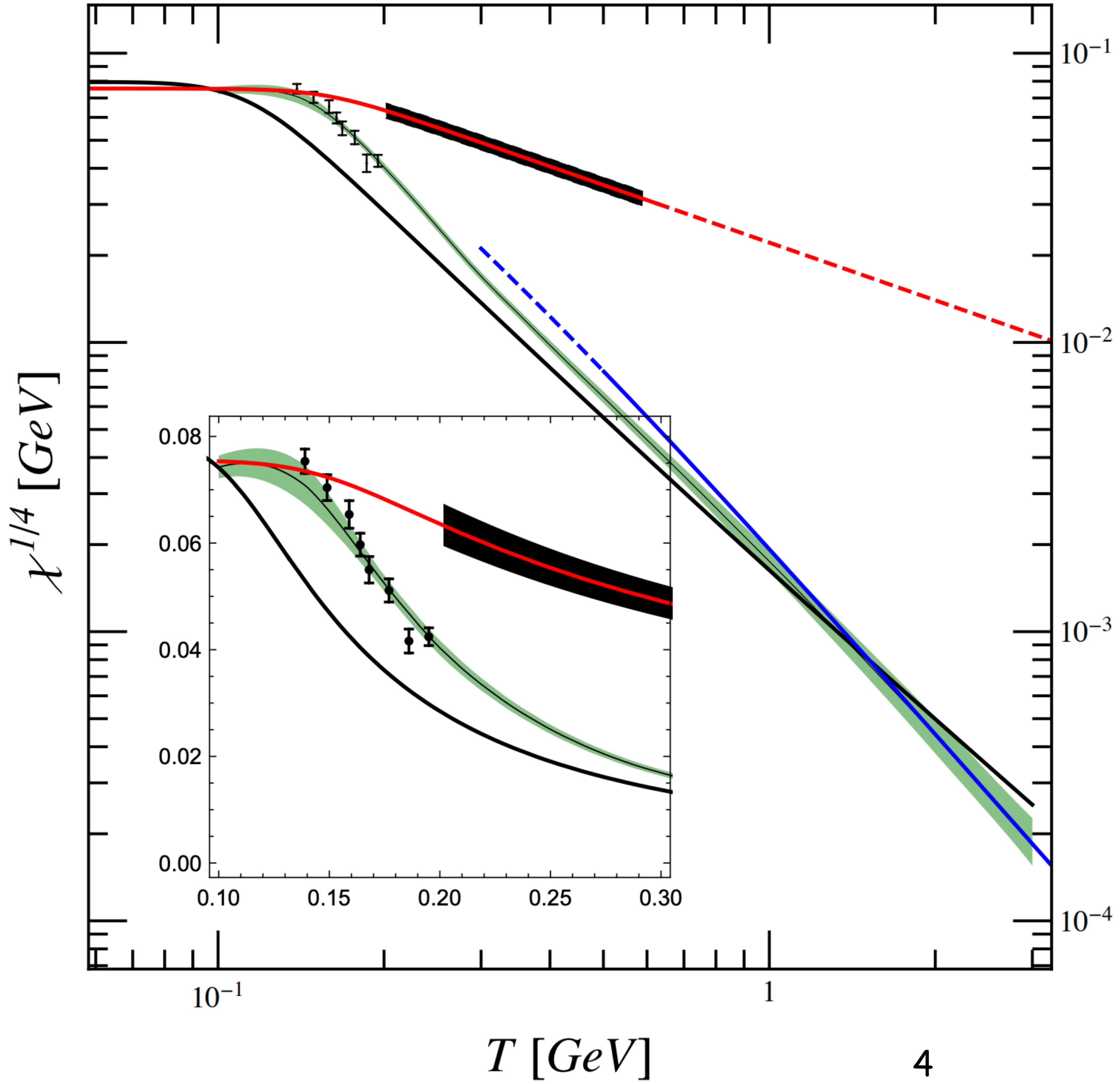

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Take away message:

Even in canonical QCD [SU(3), n_f=3]

$$m_a^2 \sim T^{-6}$$

is a reasonable T dependence, at least in some transient regime

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

undergoing a confining PT now ($\Lambda_b < T_0$) produce Cosmo accel.?

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

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

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

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This generates the potential:

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

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

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

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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 $m_b(T_{\mathrm{LC}}) = m_a$ (width Γ_{LC} ~ 3ε) where QCD axions φ_a can partially convert into b-axions φ_b

Dynamics of Level Crossing

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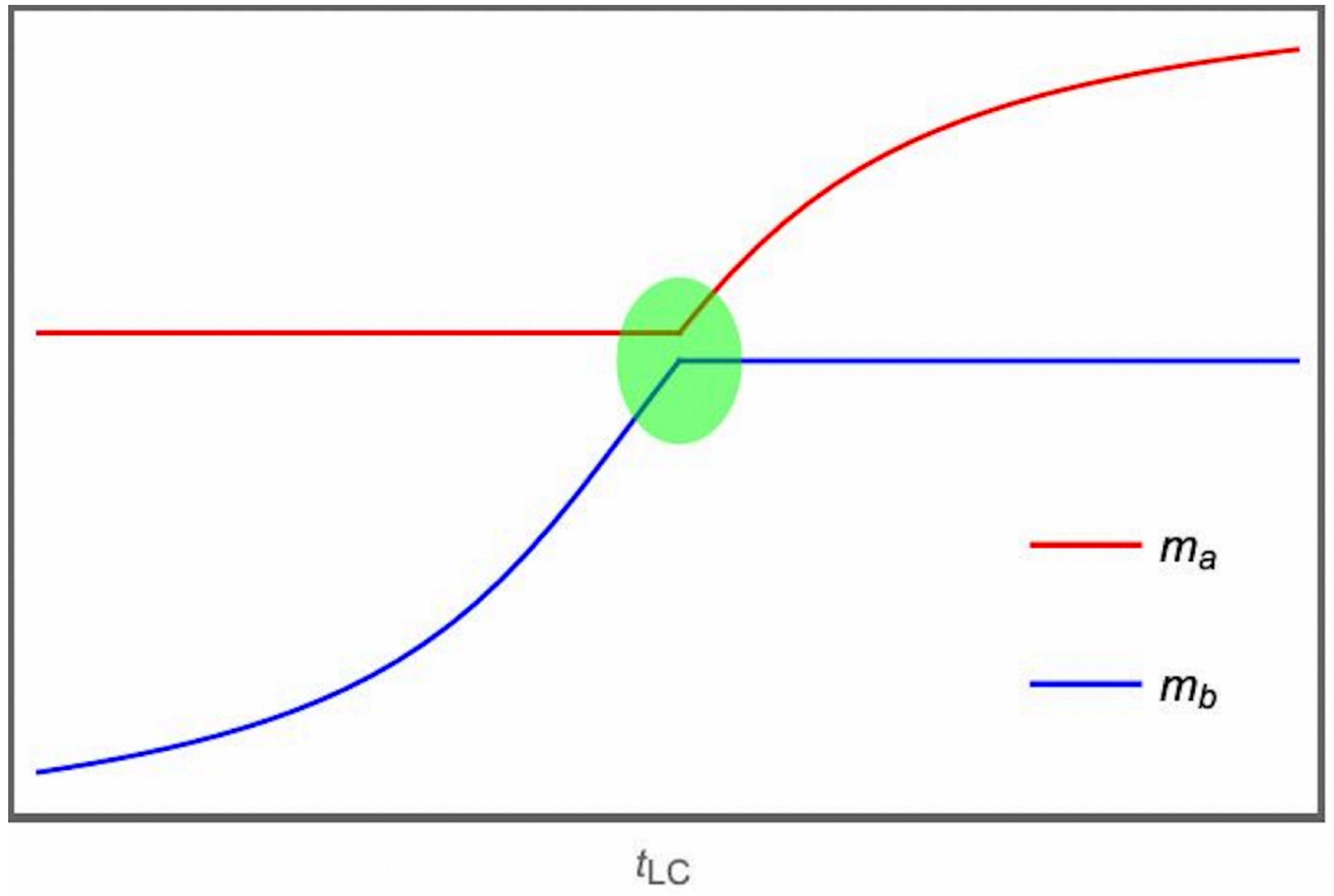

Adiabatic

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

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

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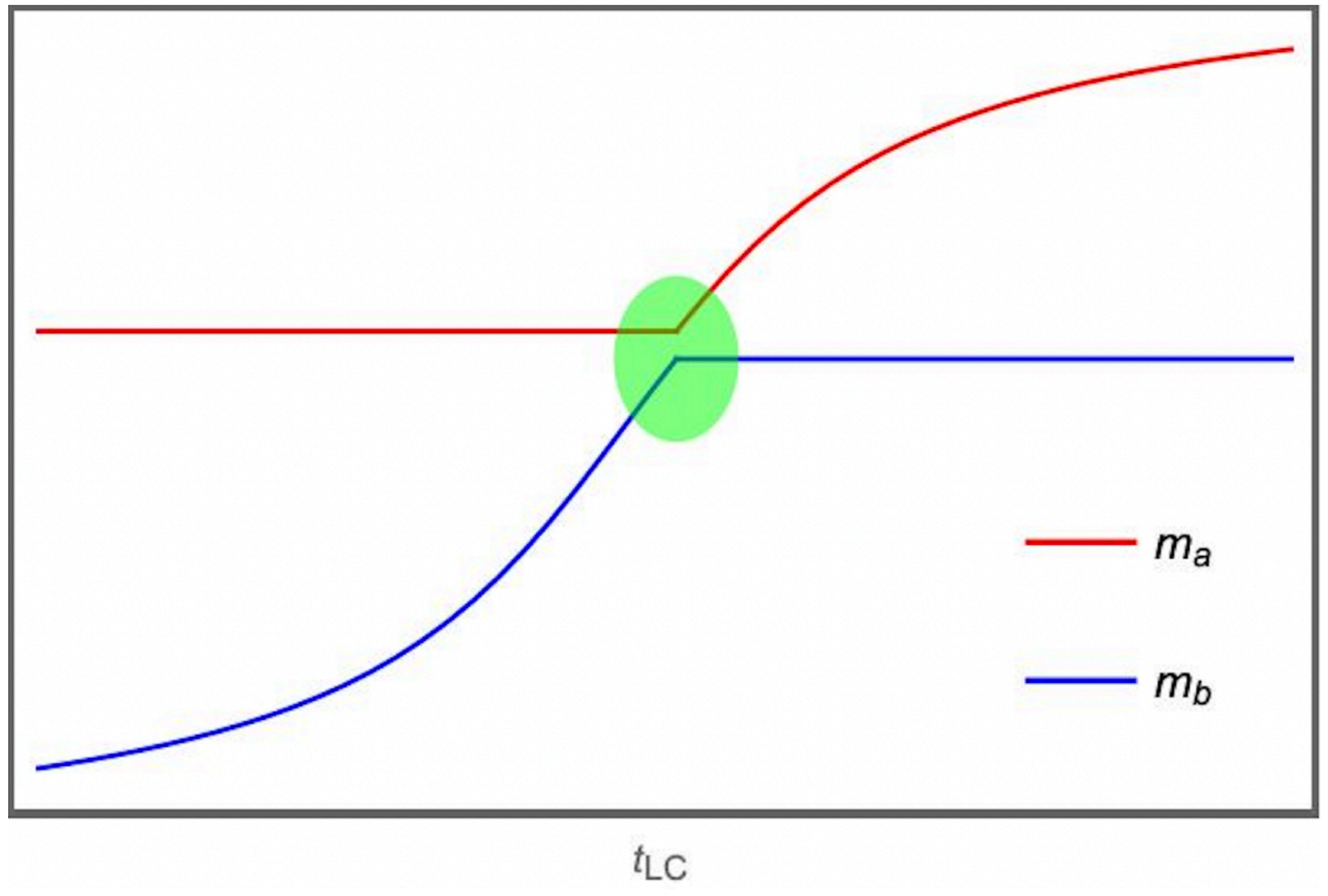

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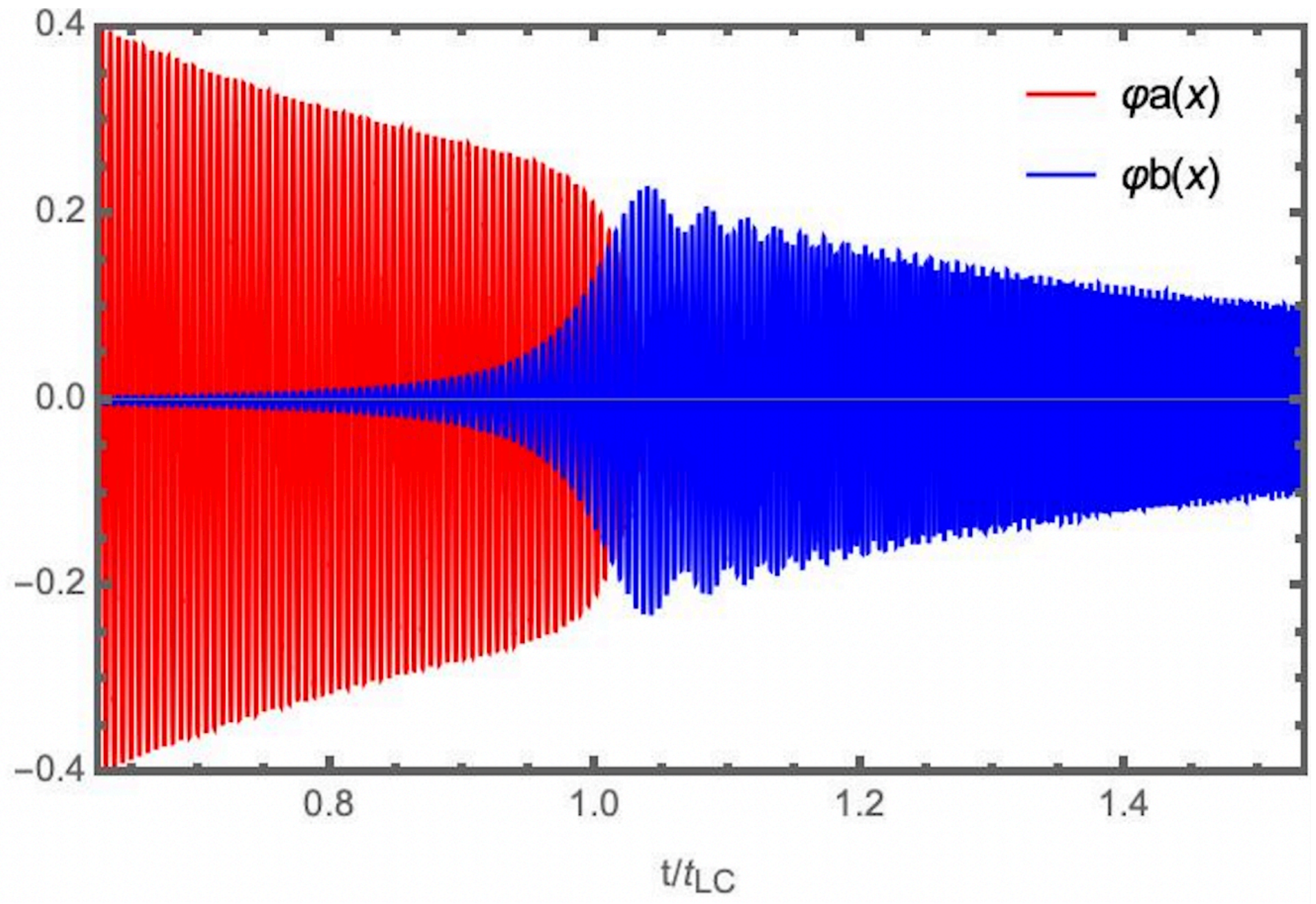

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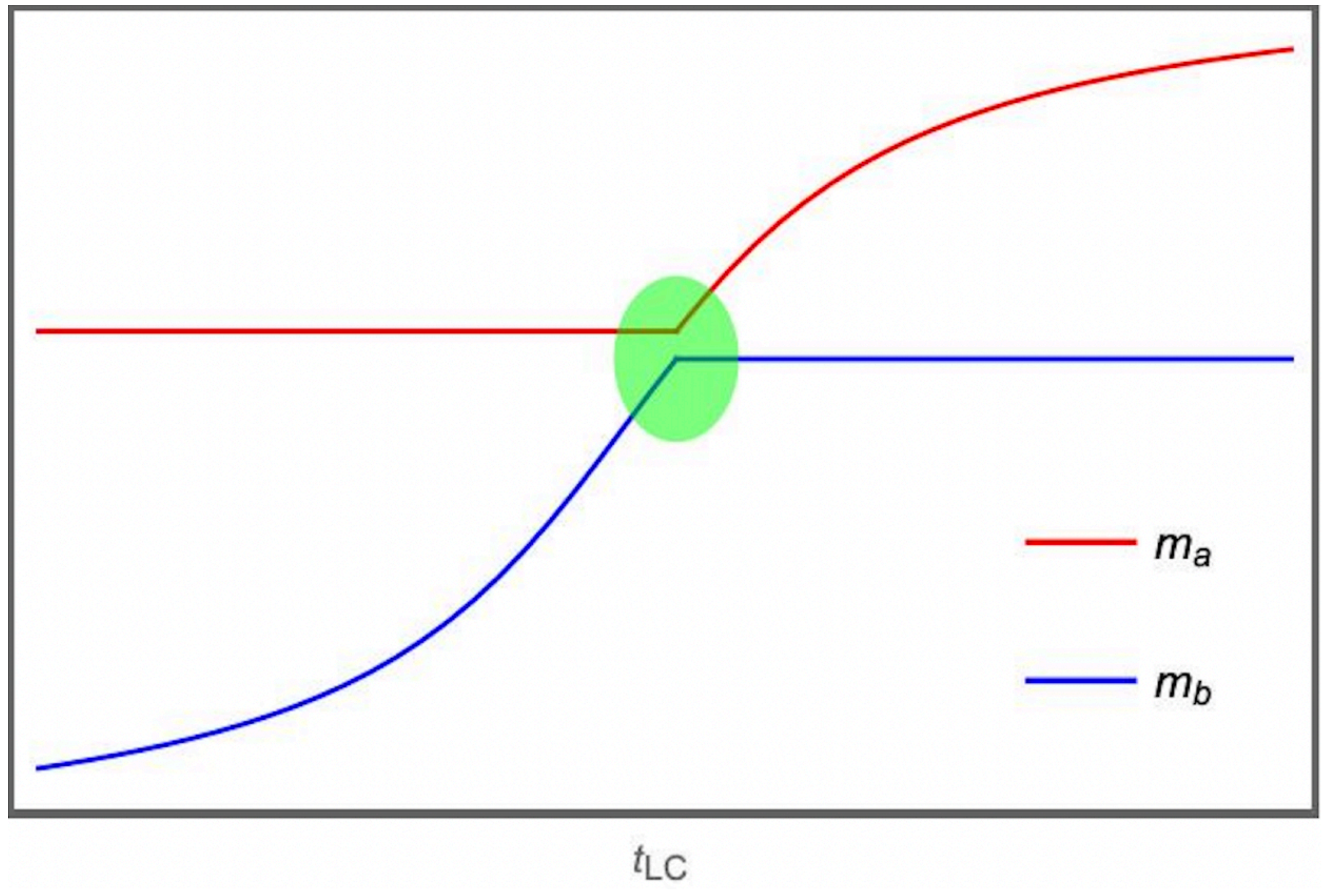

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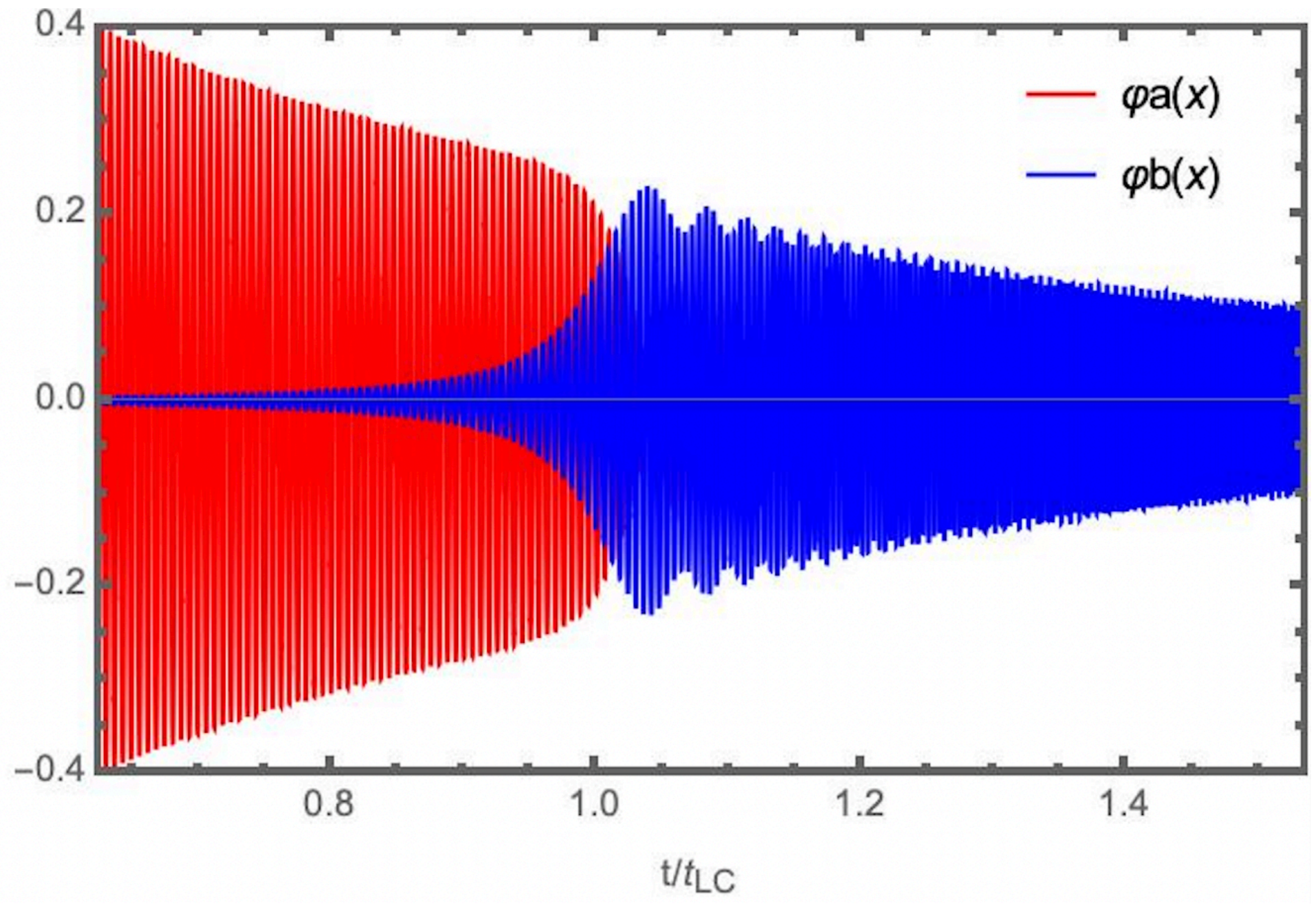

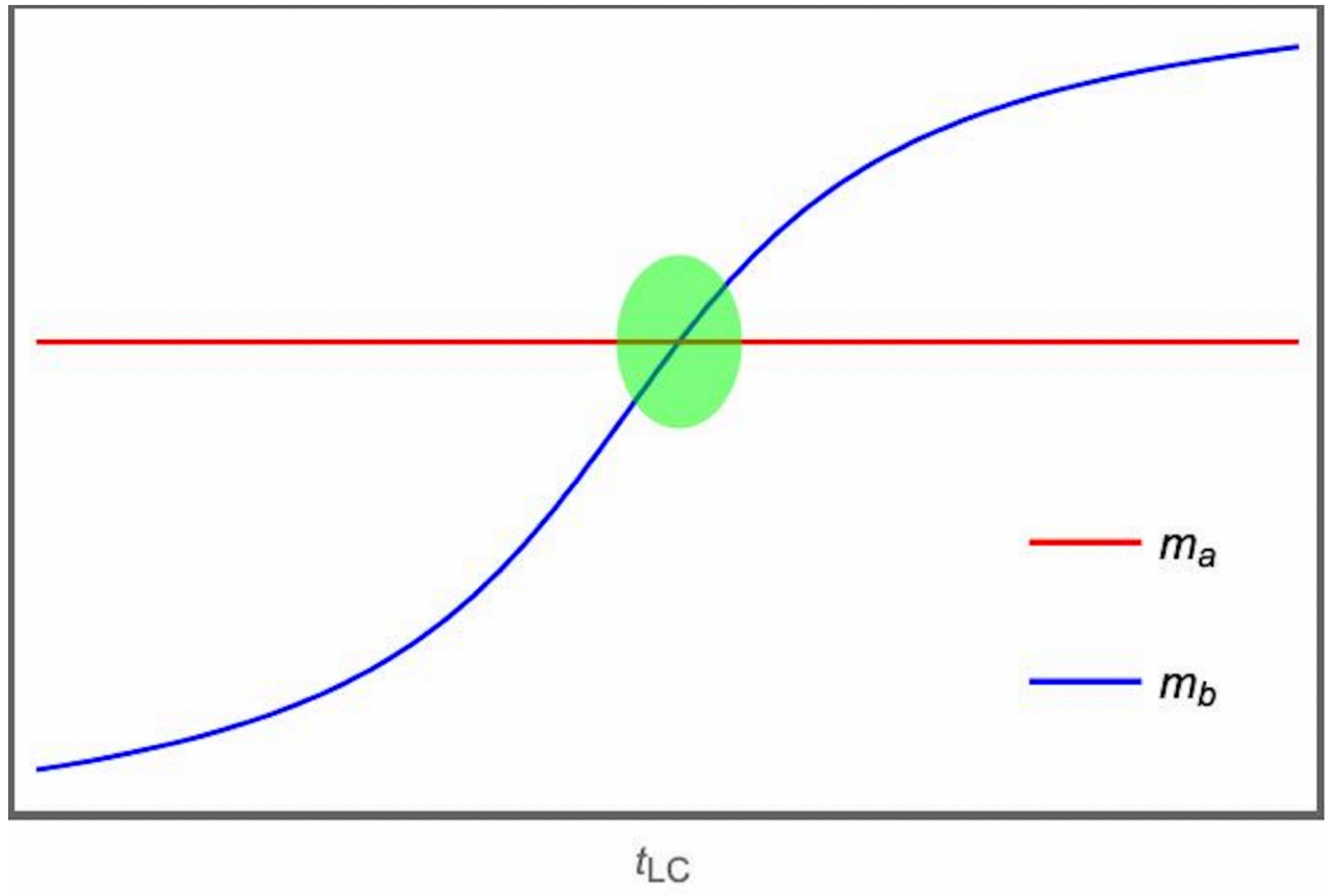

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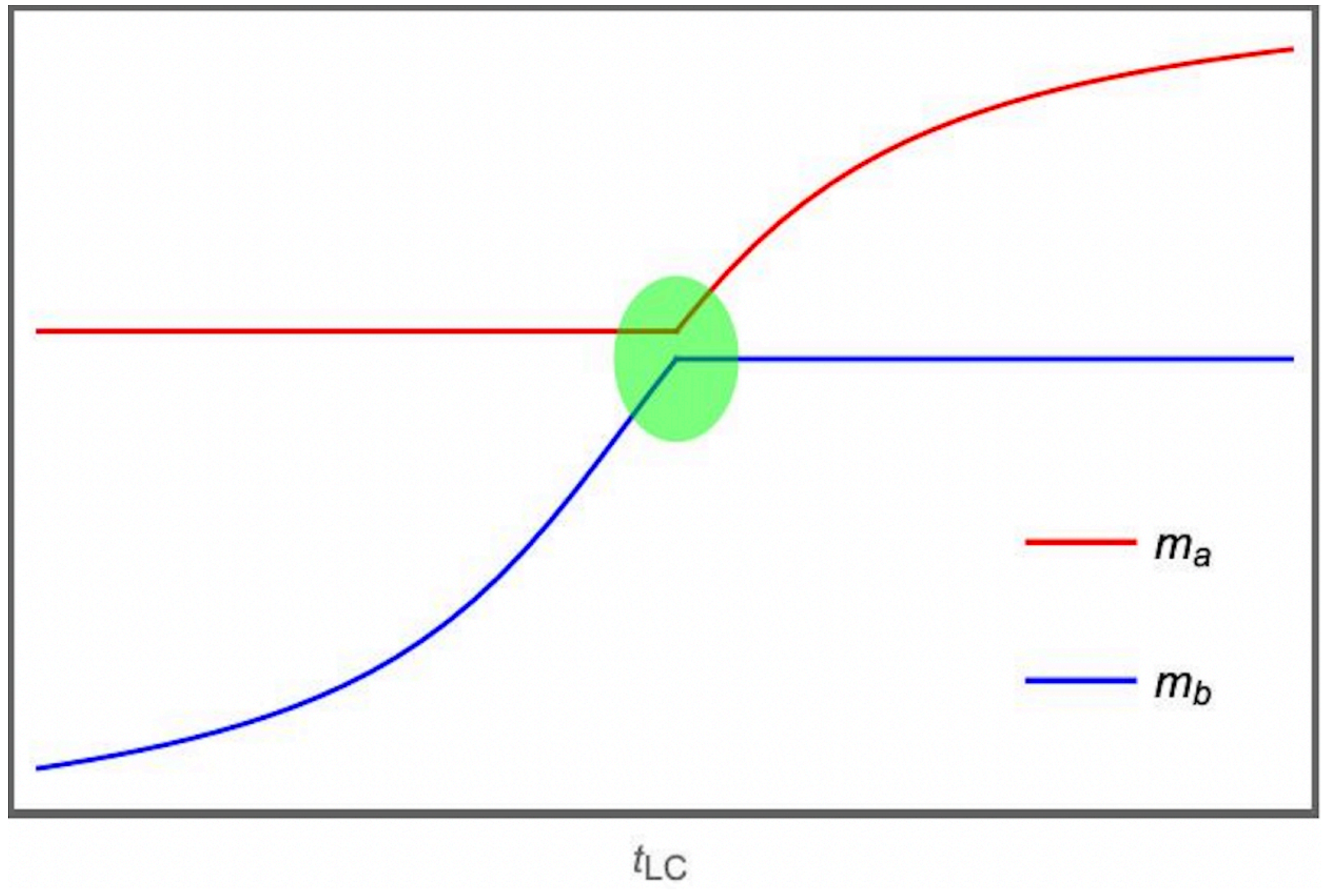

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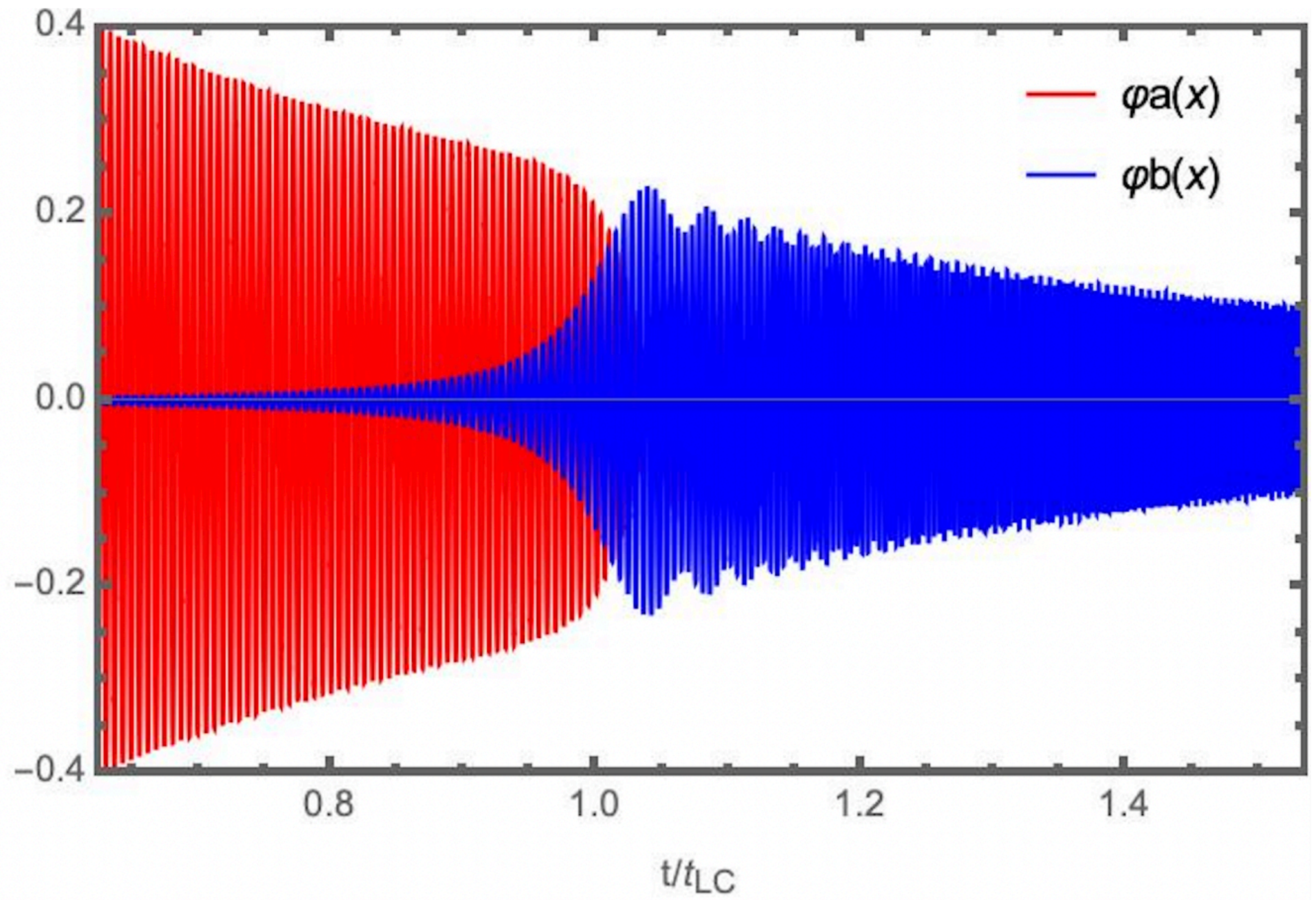

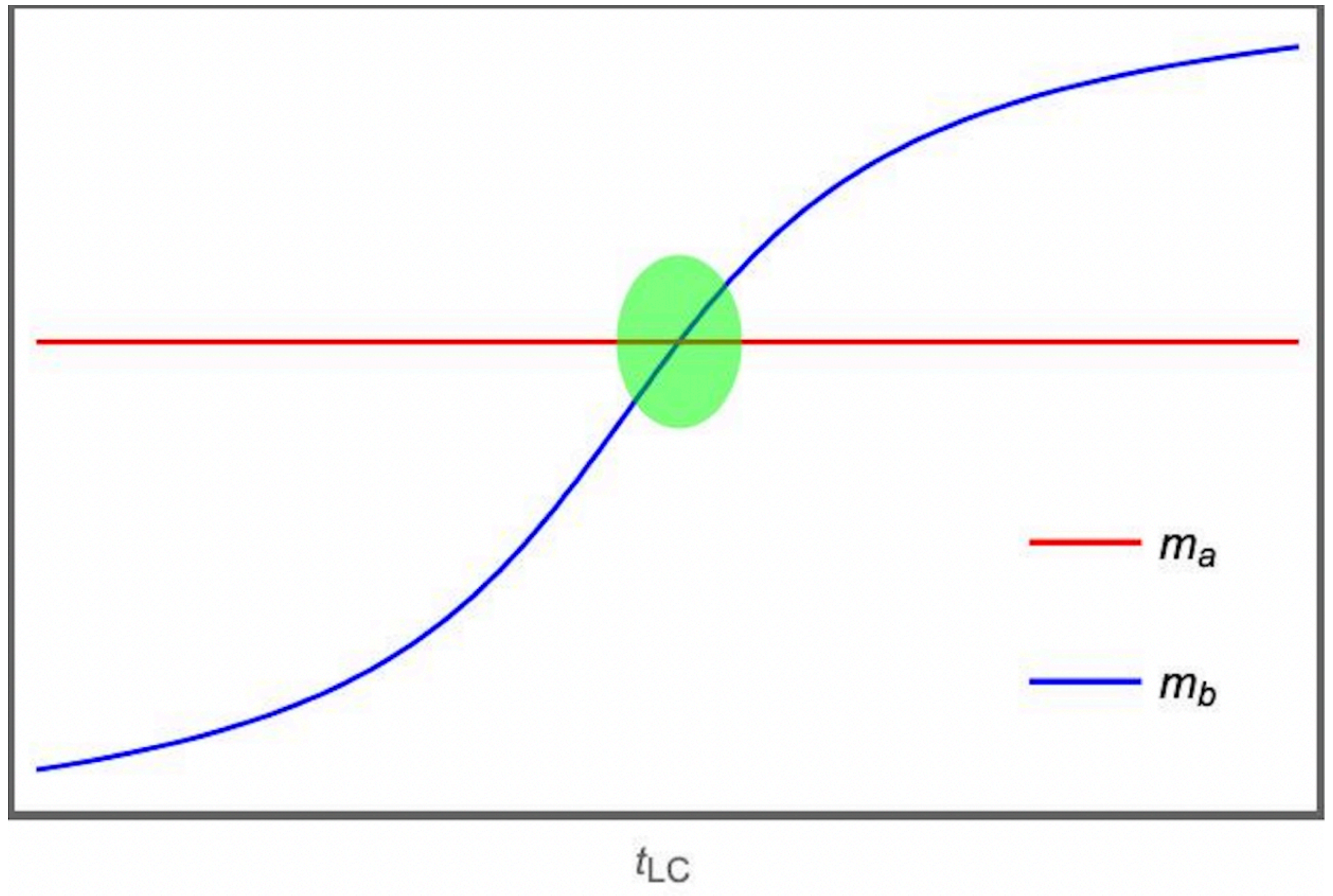

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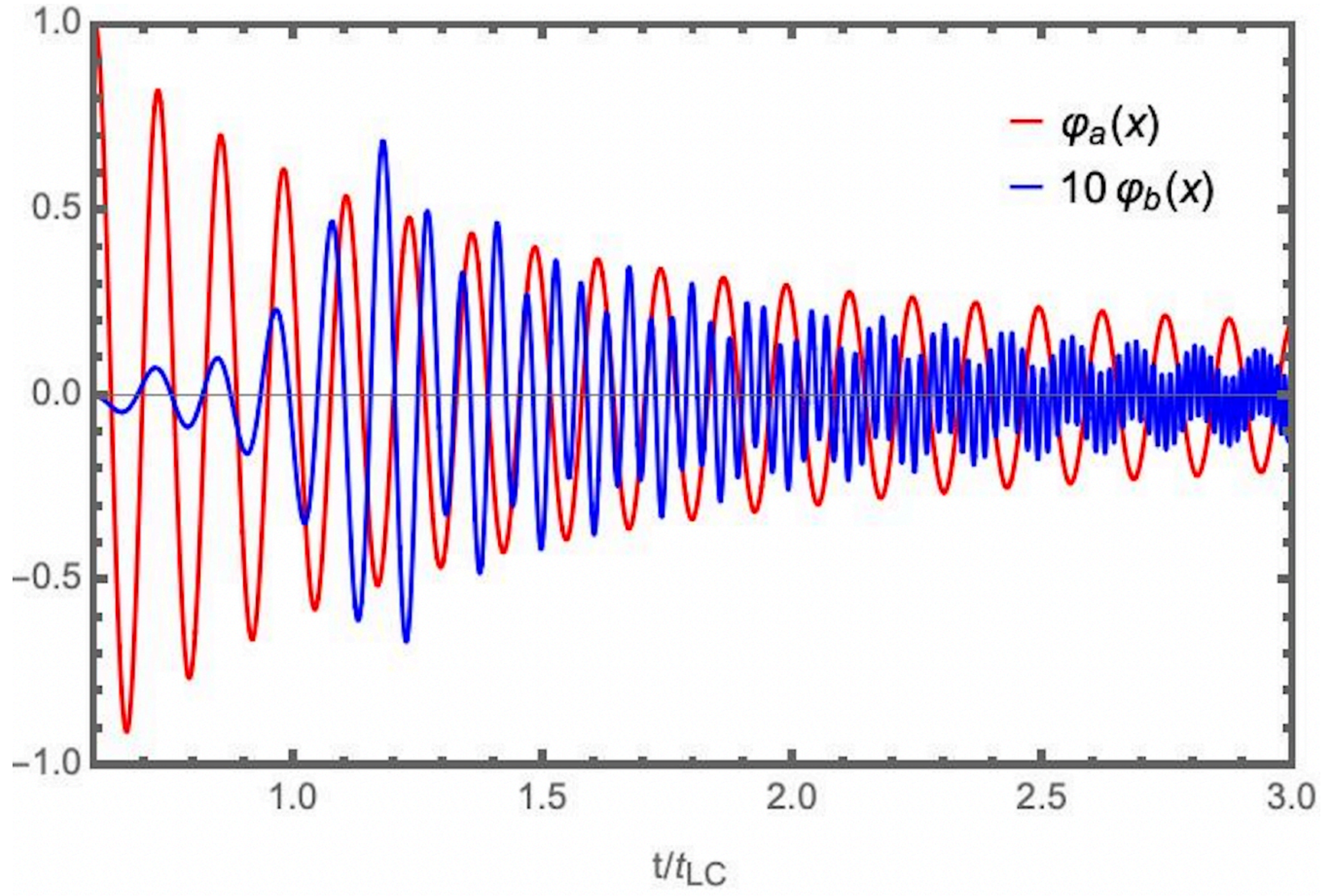

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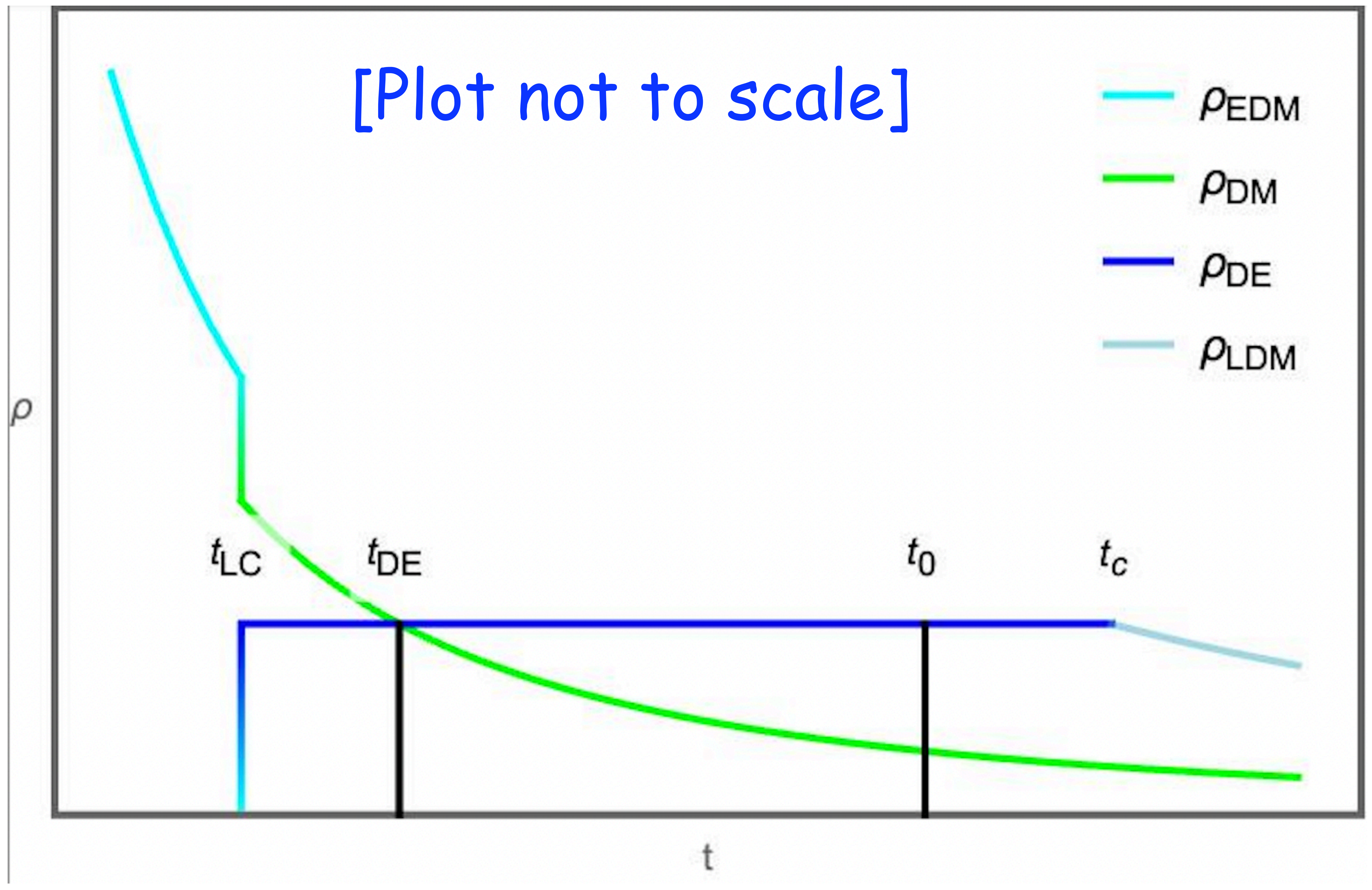

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Severe Constraining Conditions

$$m_b(T_{\rm LC}) \sim \frac{\Lambda_b^2}{f}\left(\frac{T_b}{T_{\rm LC}}\right)^3 = m_a = \frac{\Lambda_a^2}{F}$$

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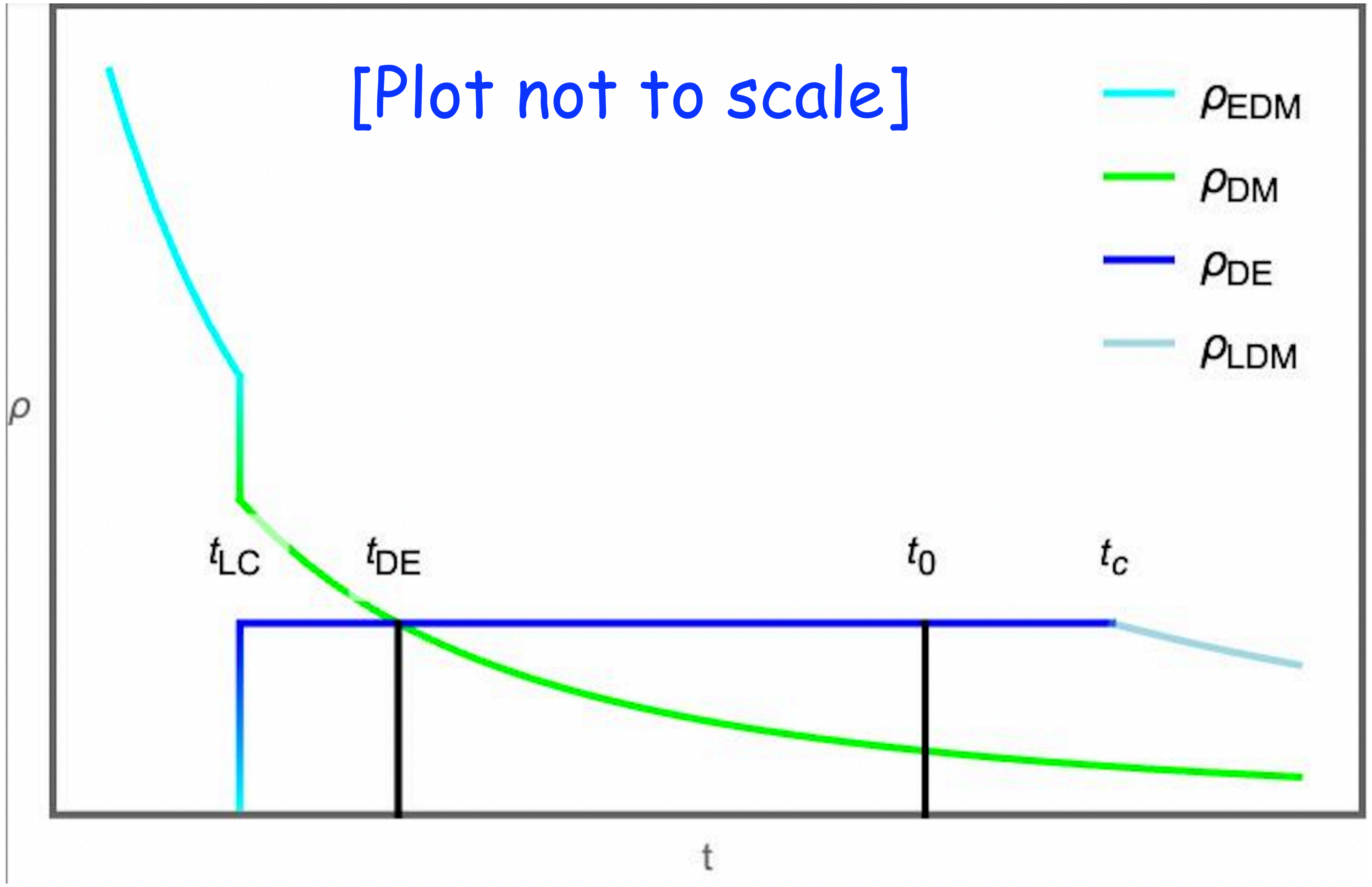

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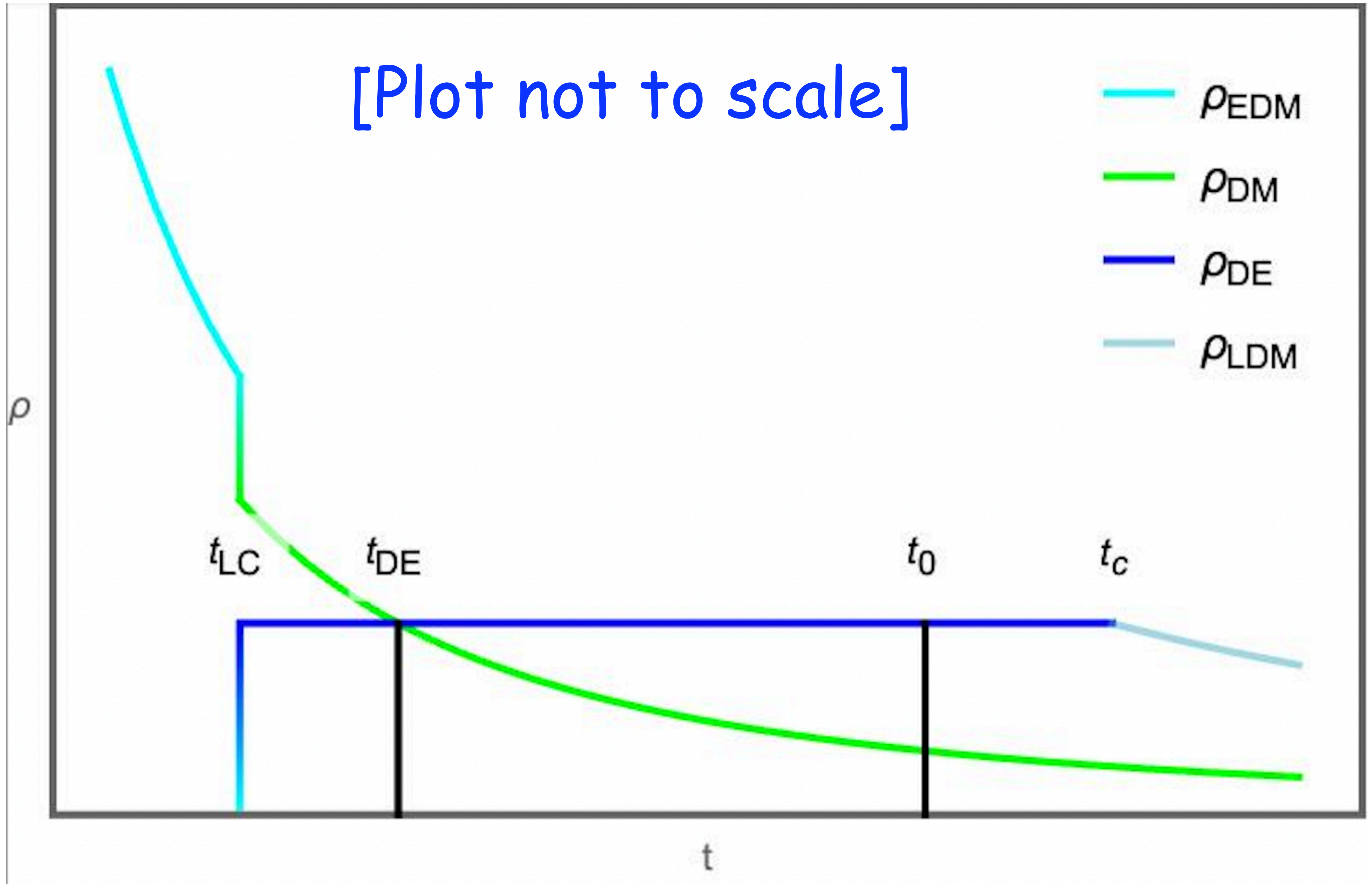

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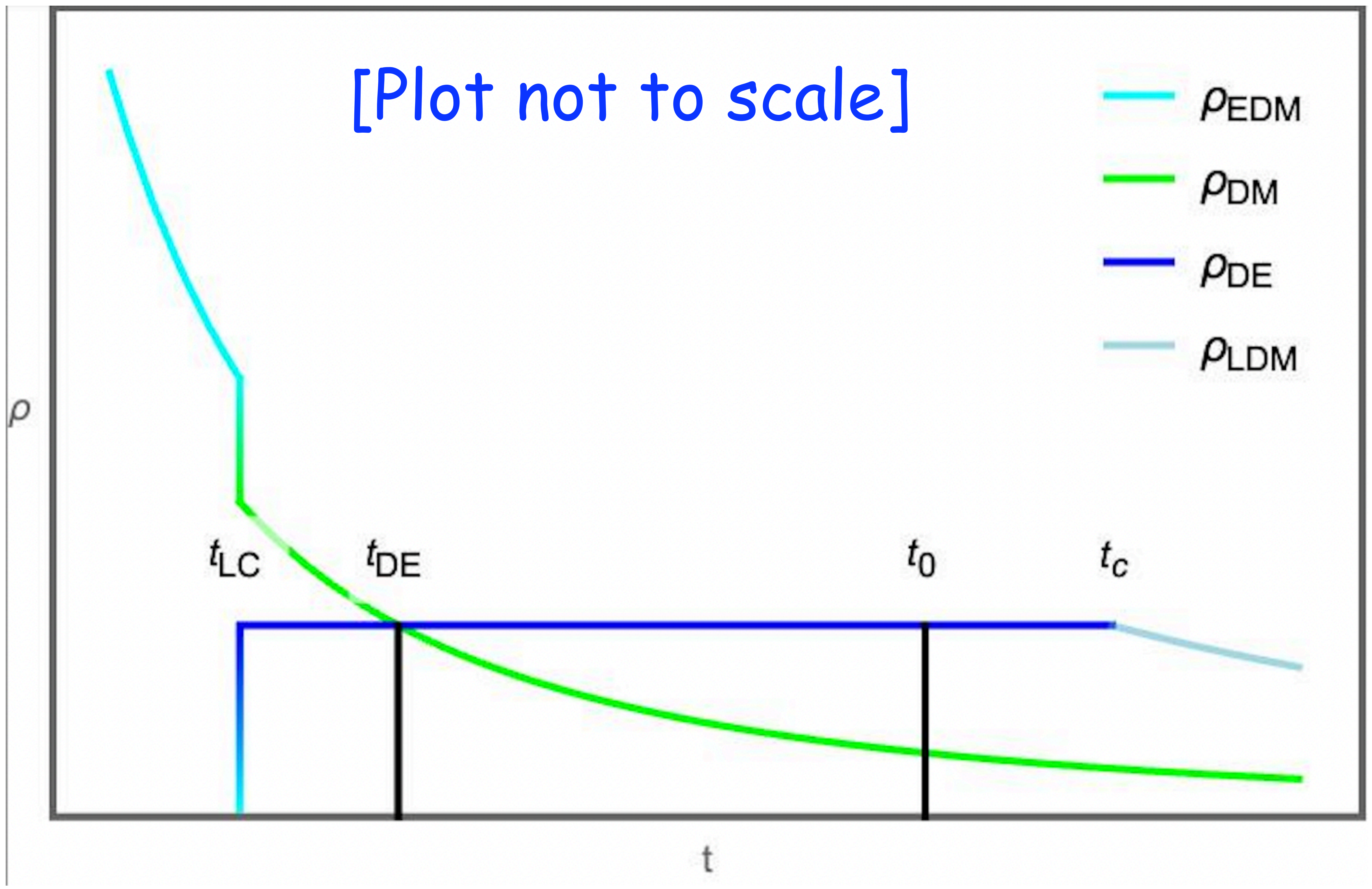

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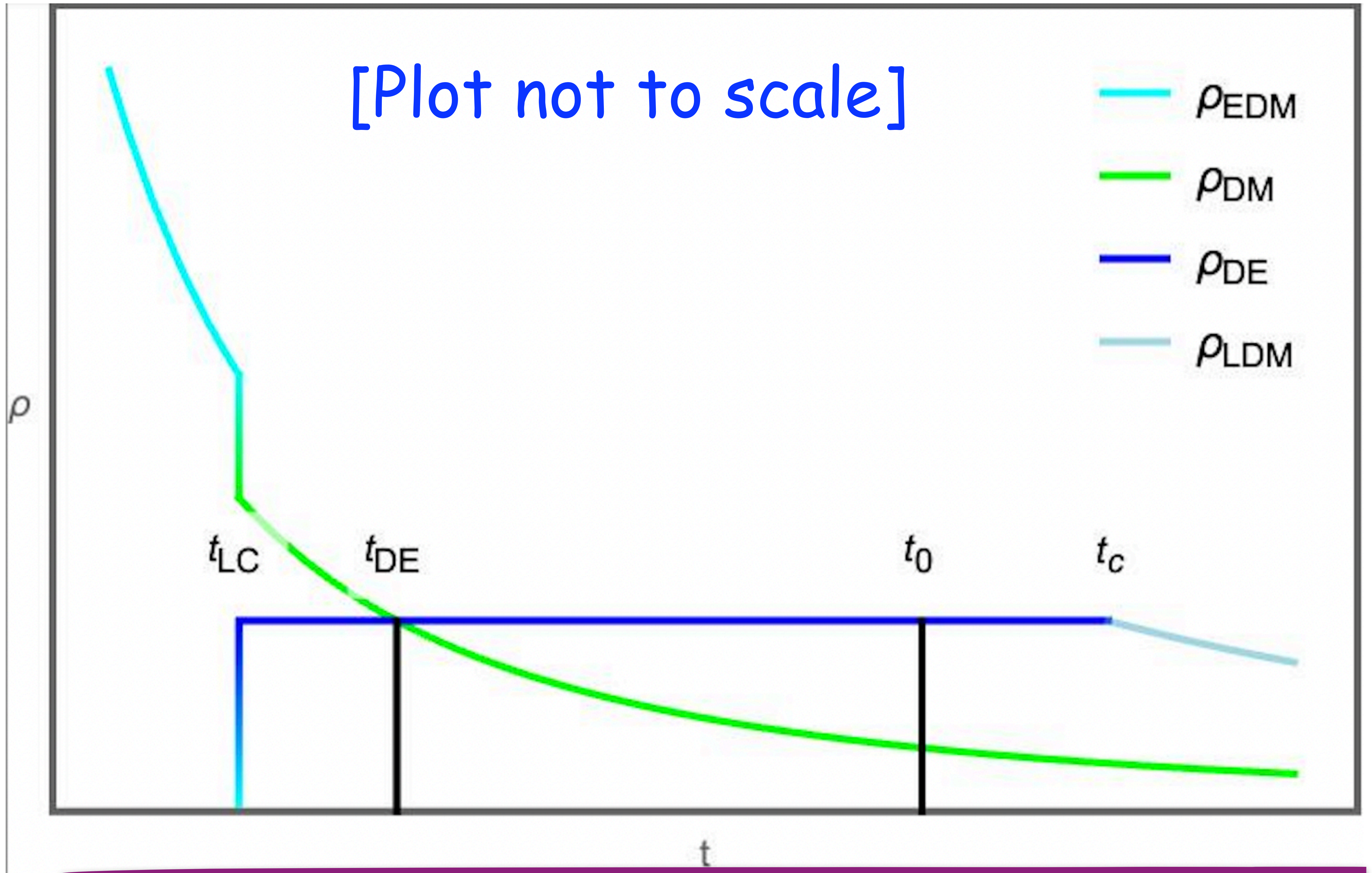

Non-adiabatic LC is in fact required !

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

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Perfect Cosmological Principle (Bondi & Gold, 1948): Cosmological principle **extended** by assuming the Universe to be homogeneous in space **and in time** (i.e. stationary).

Motivation (epistemological):

"Present observations indicate that the universe is expanding. This suggests that the mean density in the past has been greater than it is now. If we are now to make any statement regarding the behaviour of such a denser universe [...] then we have to know the physical laws and constant applicable in a denser universe. But we have no determination for those."

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Our construction also yields ρ_b = const. but is not "steady state".
Standard cosmological history unaltered until LC at $z \sim 2 - 10$.
"matter creation" => "mass generation from phase transition in a dark plasma"

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CATCH22+2 DIAS, Dublin, May 1-5 2024

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arXiv:2405.00090

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LPTHE, Paris, 10 June 2024