Accelerated Cosmic Expansion, Mass Creation, and the QCD Axion

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This presentation is organised in two parts

Part 1: (Cosmology)

Mechanism for cosmic expansion acceleration

Part2: (Particle Physics)

Mechanism to trigger the mechanism for cosmic expansion acceleration

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- $|V(\varphi)| \gg \varphi^2$ (φ dynamical field) wCDM models ($w = p/\rho$ EoS parameter)

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- $m_\varphi \sim R^3$ (interpretation as varying mass, $n_\varphi \sim R^{-3}$) [This talk]

Field theory: 

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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) [Bondi & Gold (1948)]:

"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 constants applicable in a denser universe. But we have no determination for those."

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Because of locality: "Particle creation" => "Mass growth of a certain particle"

Assume a FLRW metric $ds^2 = g_{\mu\nu}dx^\mu dx^\nu = dt^2 - R^2(t)(dx_1^2 + dx_2^2 + dx_3^2)$

Introduce a 4-vector $C_\mu=(\rho_b,0,0,0)$ with ρ_b, a certain (pressurless) `substance'.

The non-vanishing components of the covariant derivative $C_{\mu\nu}=(C_\mu)_{;\nu}$ are:

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Add a C-tensor term to Einstein equation with η a new fundamental constant

$$\boxed{R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathscr{R} - \frac{1}{\eta}C_{\mu\nu} = \frac{1}{m_{\rm P}^2}T_{\mu\nu}}$$

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Matter/DE domination era

($\rho_{rad} \ll \rho_m, \rho_{DE}$)

$$T_{\mu\nu} = T^b_{\mu\nu} + T^m_{\mu\nu}; \qquad T^{rad}_{\mu\nu} \simeq 0$$

$$T^b_{\mu\nu} = \mathrm{diag}(\rho_b,0,0,0), \quad T^m_{\mu\nu} = \mathrm{diag}(\rho_m,0,0,0)$$

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$$\boxed{\text{Assuming } (T^{m\,\mu\nu})_{;\nu} = 0 \;\Rightarrow\; (T^{b\,\mu\nu})_{;\nu} = -\frac{m_{\mathrm{P}}^2}{\eta}(C^{\mu\nu})_{;\nu} \quad C_{\mu\nu} \neq 0 \;\Rightarrow\; \rho_b \text{ creation}}$$

With *C*-term: $2R\ddot{R} + \dot{R}^2 - R\dot{R}\frac{\rho_b}{\eta} = 0;\qquad 3\frac{\dot{R}^2}{R^2} = \frac{\rho}{m_{\rm P}^2} + \frac{\dot{\rho}_b}{\eta},\quad (\rho = \rho_b + \rho_m)$

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Rewrite 1st eq. as: $2\frac{d}{dt}\left(\frac{\dot{R}}{R}\right) + \underbrace{3\frac{\dot{R}^2}{R^2} - \frac{\dot{R}}{R}\frac{\rho_b}{\eta}}_{\text{if this} \approx 0 \Rightarrow \dot{R}/R \approx \text{const.}} = 0$

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exponential acceleration

For $\eta \approx H_0 m_P^2$ this regime is reached around the present epoch

Replace $t \;\rightarrow\; \tau = H_0\, t, \;\; (\tau_0 \simeq 0.958)$ and define $\rho_b(\tau) = \rho_c^0\, \Omega_{b,0}\, \mathscr{F}_b(\tau)$

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The two equations become:

$$2RR'' + R'^2 - \kappa\, RR'\, \Omega_{b,0}\, \mathscr{F}_b = 0,$$

$$\frac{R'^2}{R^2} = \frac{\Omega_{m,0}}{R^3} + \Omega_{b,0}\left(\mathscr{F}_b + \frac{\kappa}{3}\mathscr{F}'_b\right)$$

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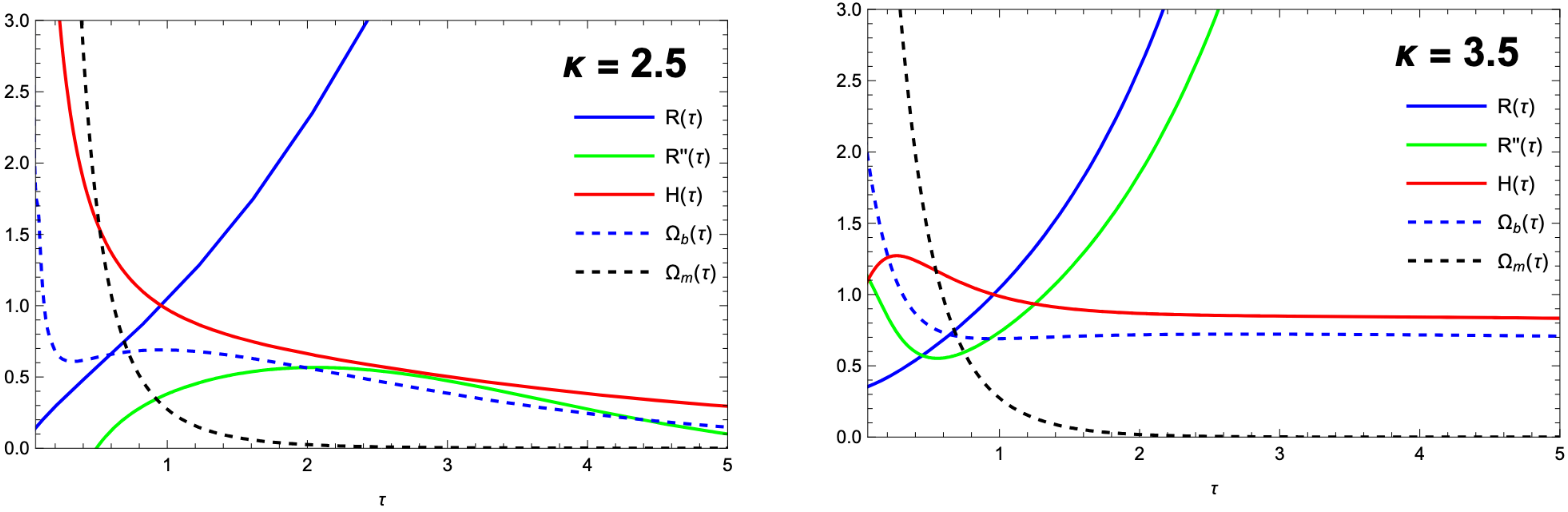
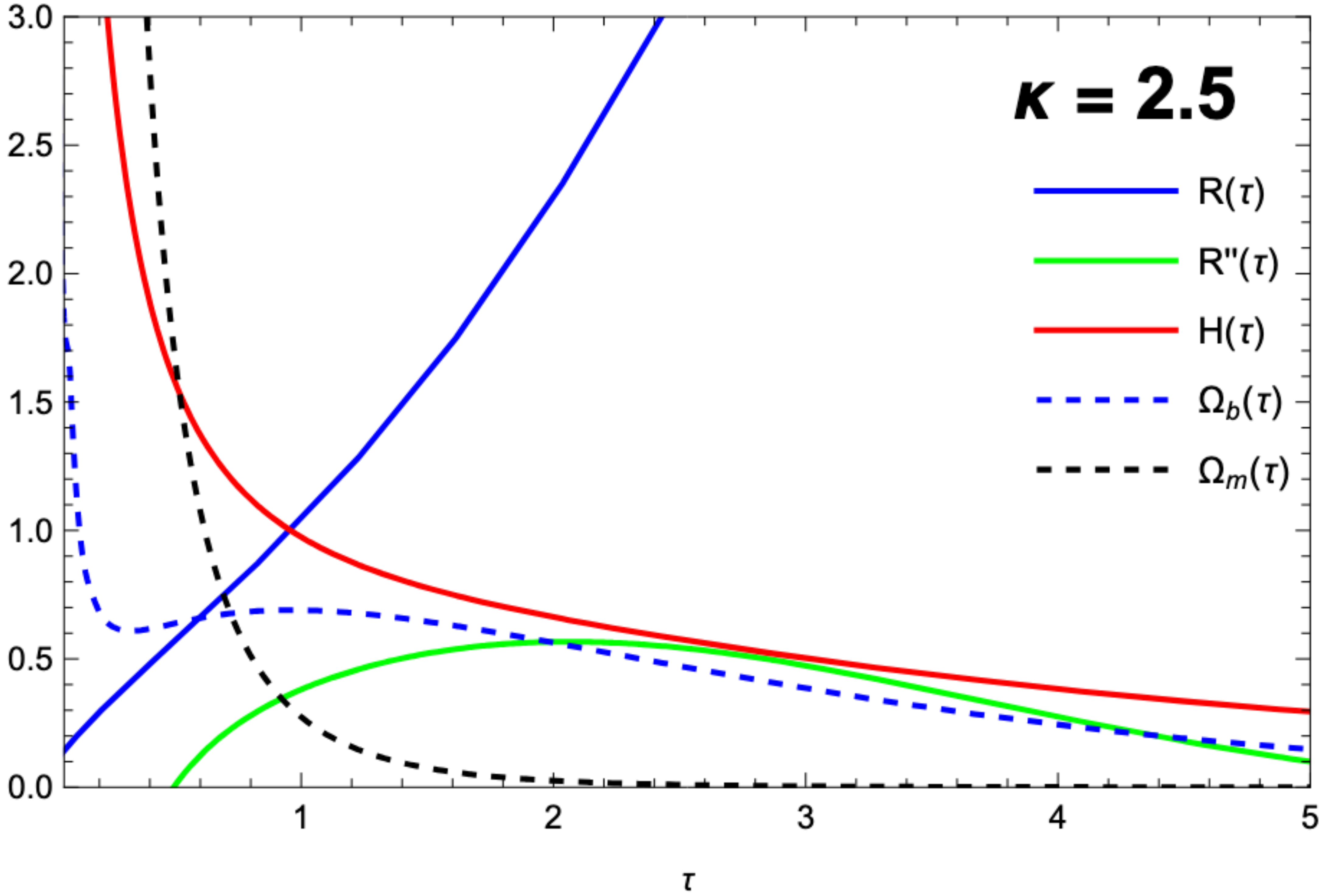
$$\kappa = \frac{\rho_c^0}{H_0\,\eta} = \frac{\rho_c^0}{H_0^2\, m_{\mathrm{P}}^2} \approx 3$$

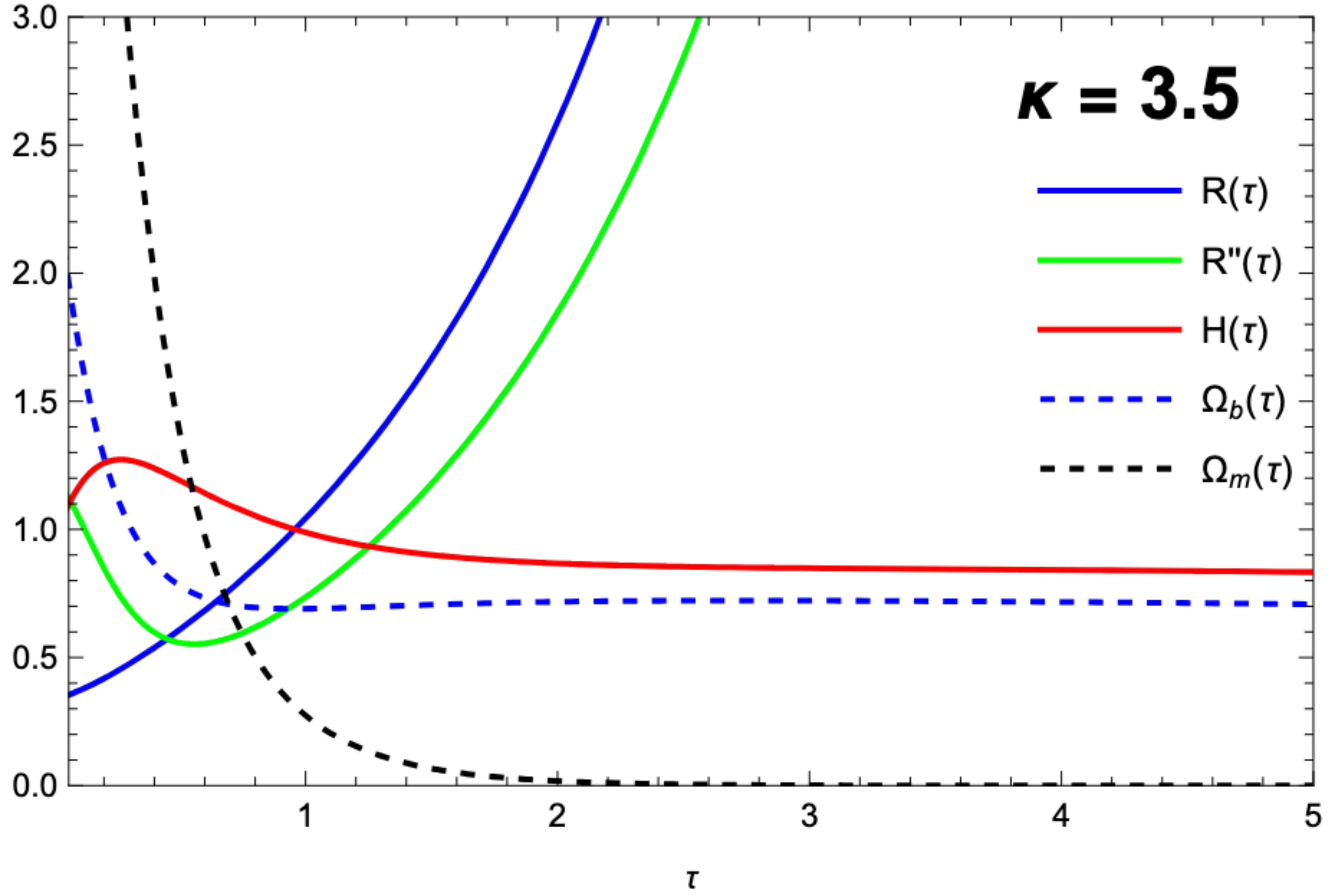
Present epoch boundary conditions

$$R(\tau_0) = \mathcal{F}_b(\tau_0) = 1; \quad R'(\tau_0) = 1$$



Evolution of $R(\tau)$, $R''(\tau)$, $H(\tau)$ and of the normalised densities $\Omega_b(\tau)$, $\Omega_m(\tau)$





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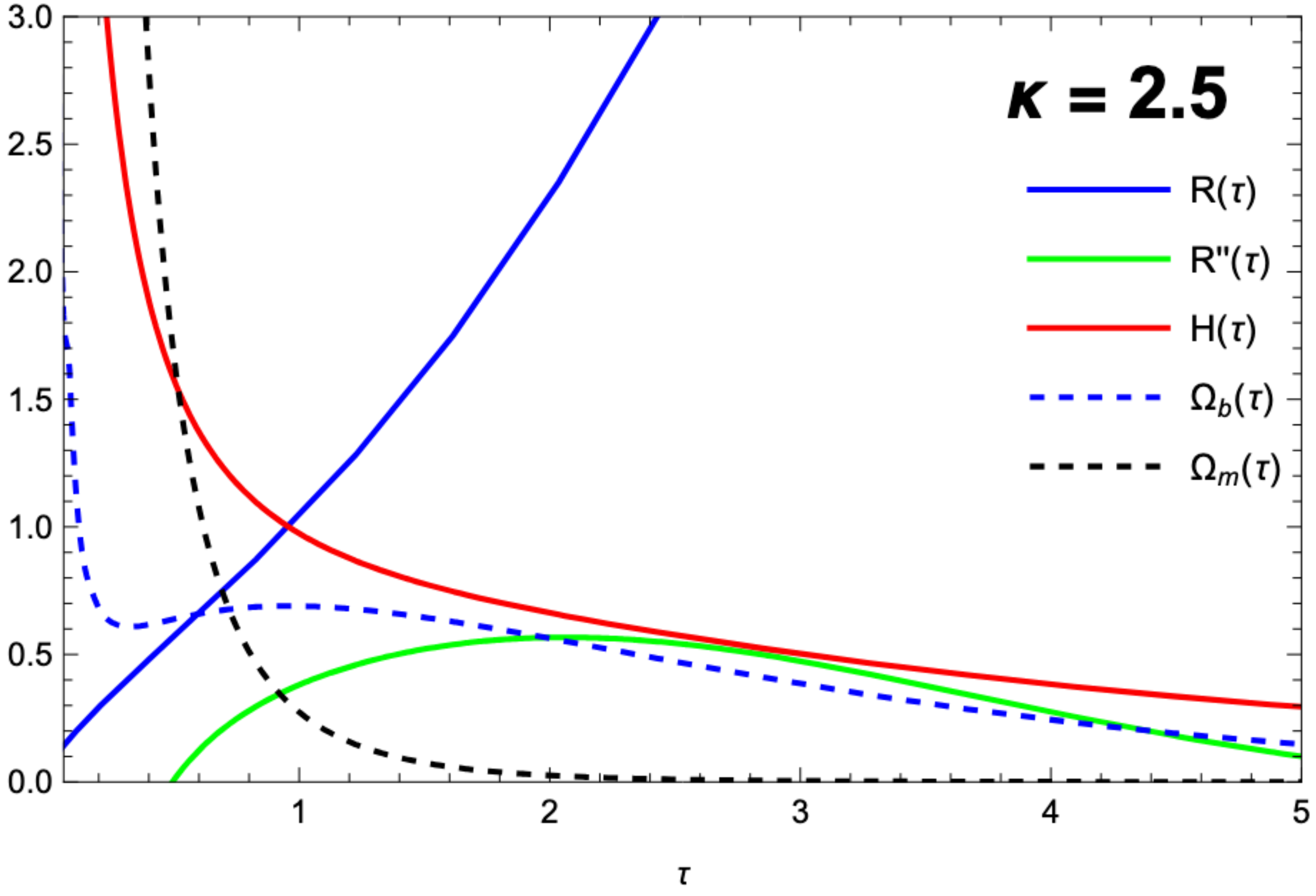

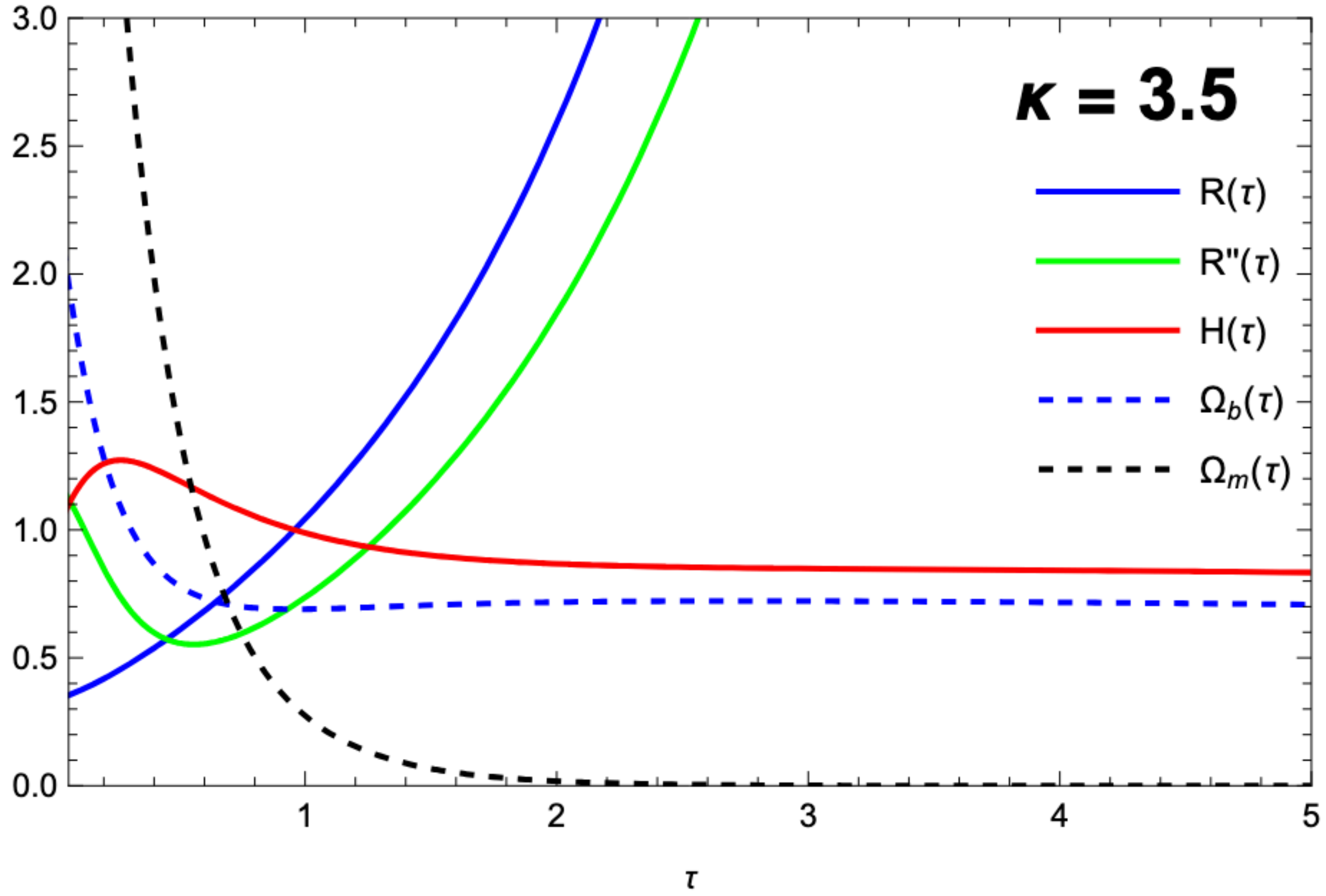

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Further backwards: $\tau \ll 10^{-4}$, a new (untenable) acceleration phase appears

Let us use the following approximations: $\rho_b \sim$ const. ; $\rho_b \gg \rho_m$

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The field equation reproduces Einstein equation with a cosmological constant : $\Lambda = \frac{\rho_b}{m_P^2}$

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- It solves a ~5σ tension with ΛCDM model recently reported in arXiv:2503.02880

The Universe's expansion rate was reconstructed, using cosmological datasets, at two different redshifts: $z_1 = 1.646$ (where the angular diameter distance D_A reaches its maximum) and $z_2 = 0.512$ (where $dD_A/dz = D_A$).
The ΛCDM model predicted value of $H(z_2)$ deviates from the reconstructed one at the level of 5σ.

In our model, for $\kappa = 2.5$, the values of $H(z_1)$ and $H(z_2)$ both agree within 1σ with the reconstructed values.

Part 2: How to trigger the creation mechanism (particle physics)

— **b**-substance must appear before $z_{DE} \sim 0.3$ but not earlier than $z \sim$ a few

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— We identify **b**-substance with an axion (PNGB) φ_b coupled to a dark gauge group, that underwent confinement in a recent cosmological time

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

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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:

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

$$m_a^2 = \chi / F^2 \qquad \text{since} \qquad \chi = \chi(T) \qquad \Rightarrow \qquad m_a^2 = m_a^2(T)$$

In a hot plasma, at $T \gg T_c$, free color charges screen the correlator: $\chi = 0$

At $T < T_c$ color charges are confined in SU(3) singlets, no screening: $\chi = (160\ \text{MeV})^4$

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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]

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

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

Take $G_a \times G_b$, G_a = $SU(3)_{QCD}$; G_b = $SU(3)$ or $SU(2)$; $\Lambda_a \gg \Lambda_b$

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

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

This generates the potential:

$$\Lambda_b \ll \Lambda_a \quad F, F' \propto v_2 \; \gg \; f \propto v_1$$

$$V = \Lambda_a^4 \left[1 - \cos\left(\frac{\varphi_a}{F}\right)\right] + \Lambda_b^4 \left[1 - \cos\left(\frac{\varphi_a}{F'} + \frac{\varphi_b}{f}\right)\right]; \qquad \begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix} = \begin{pmatrix} \cos\beta & \sin\beta \\ -\sin\beta & \cos\beta \end{pmatrix} \begin{pmatrix} a_1 \\ a_2 \end{pmatrix}$$

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

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

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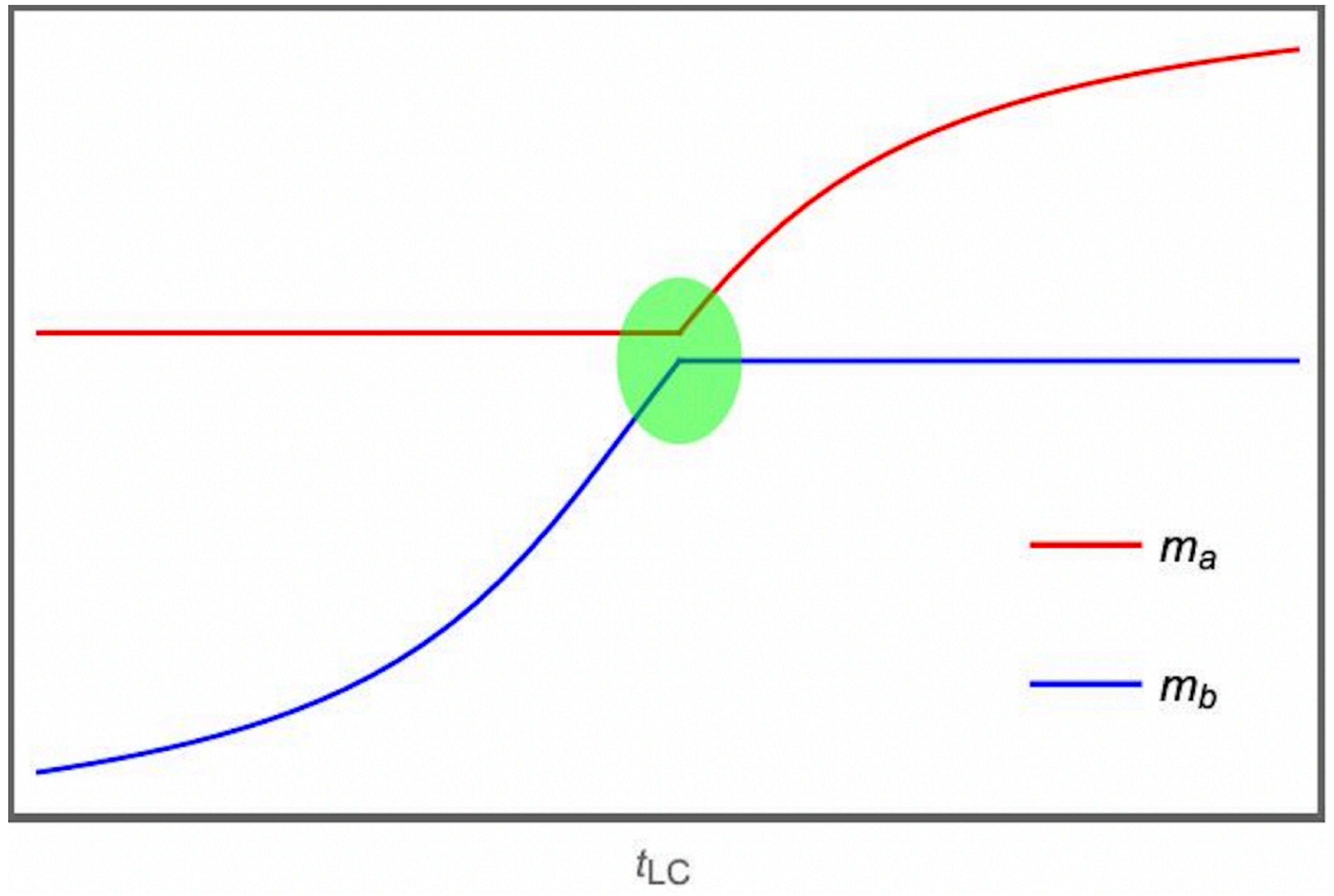
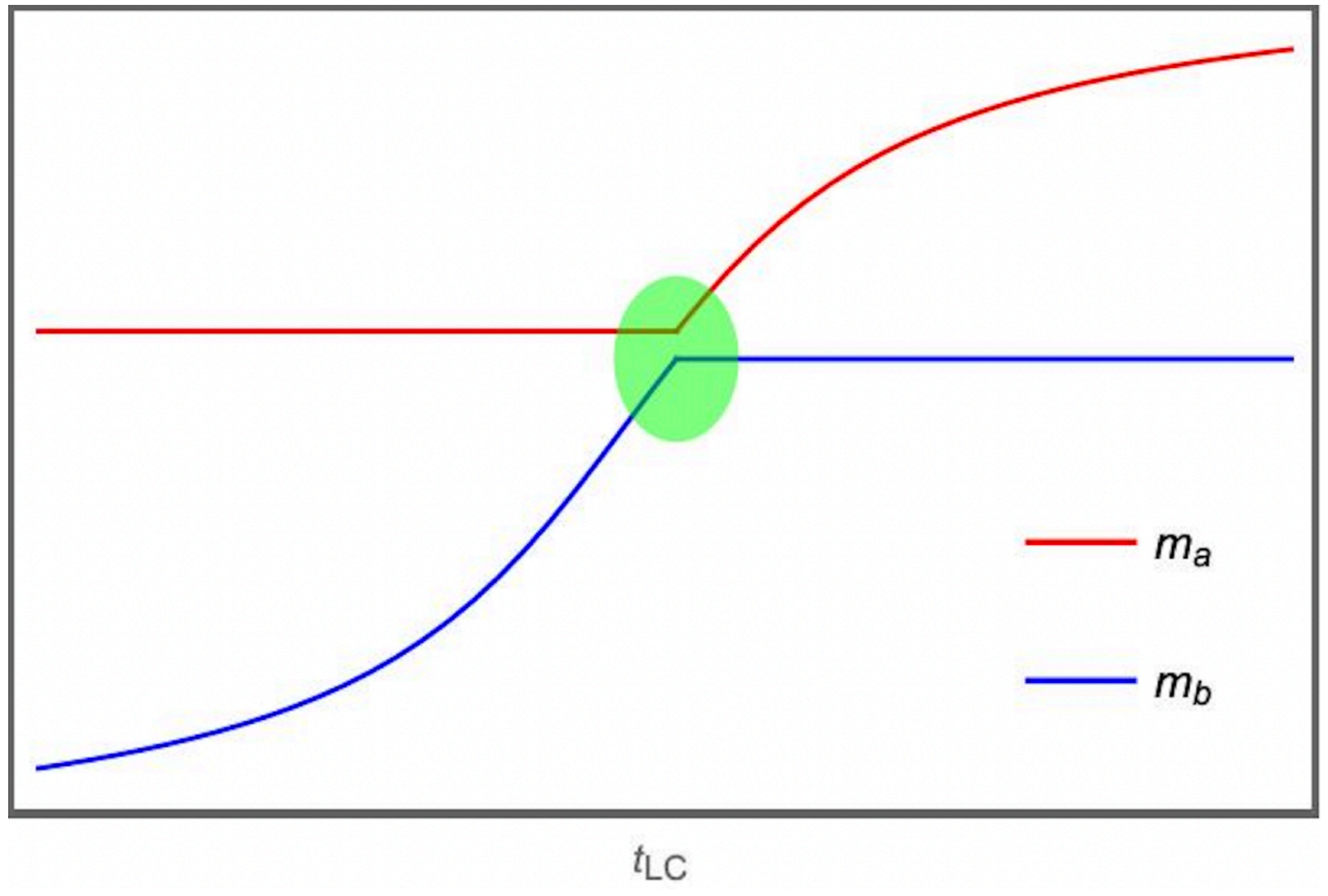
This implies a Level Crossing $m_b(T_{\rm LC}) = m_a$ (width $\Gamma_{LC} \sim 3\varepsilon$)
where QCD axions φ_a partially convert into b-axions φ_b



Adiabatic

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

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



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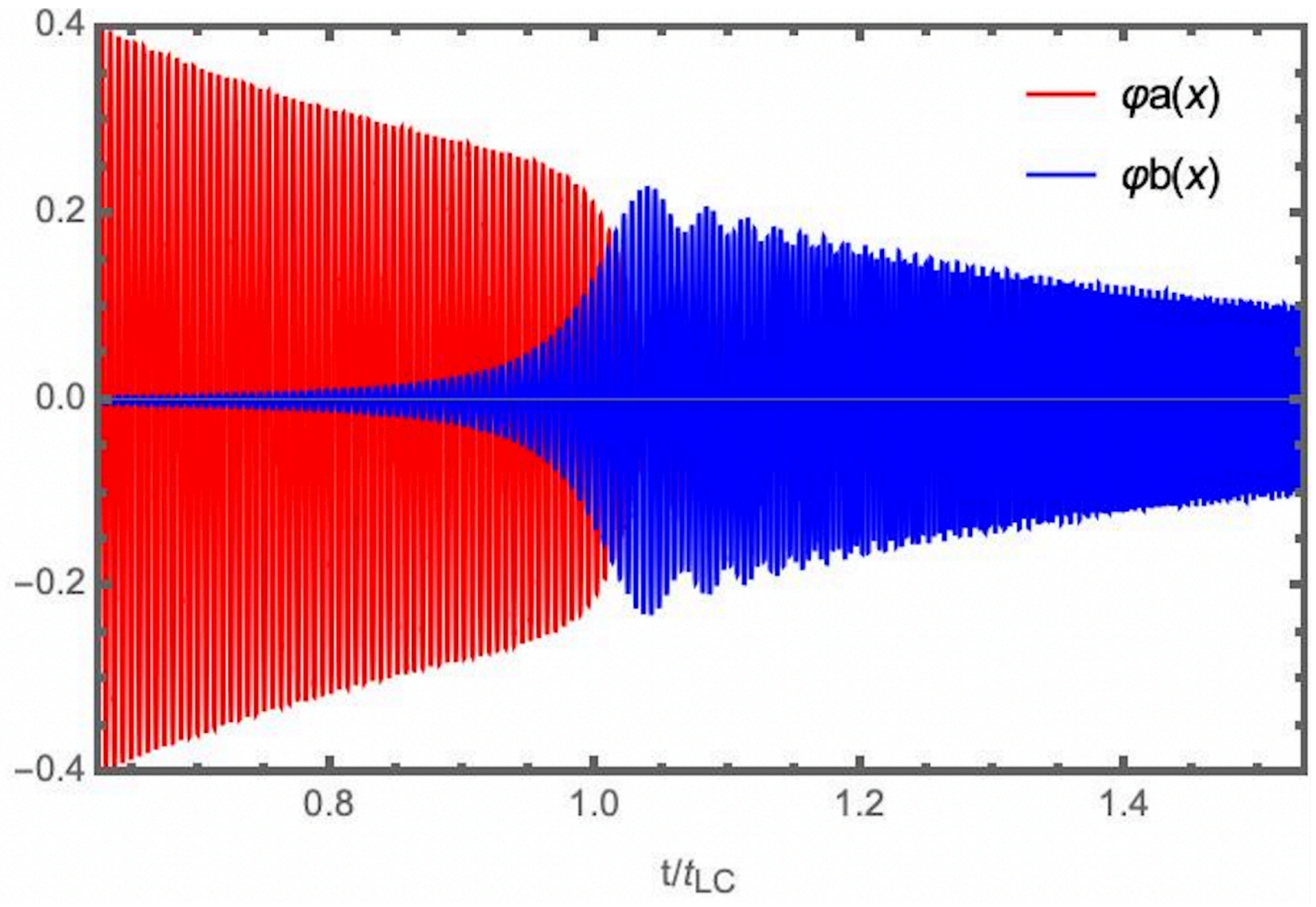

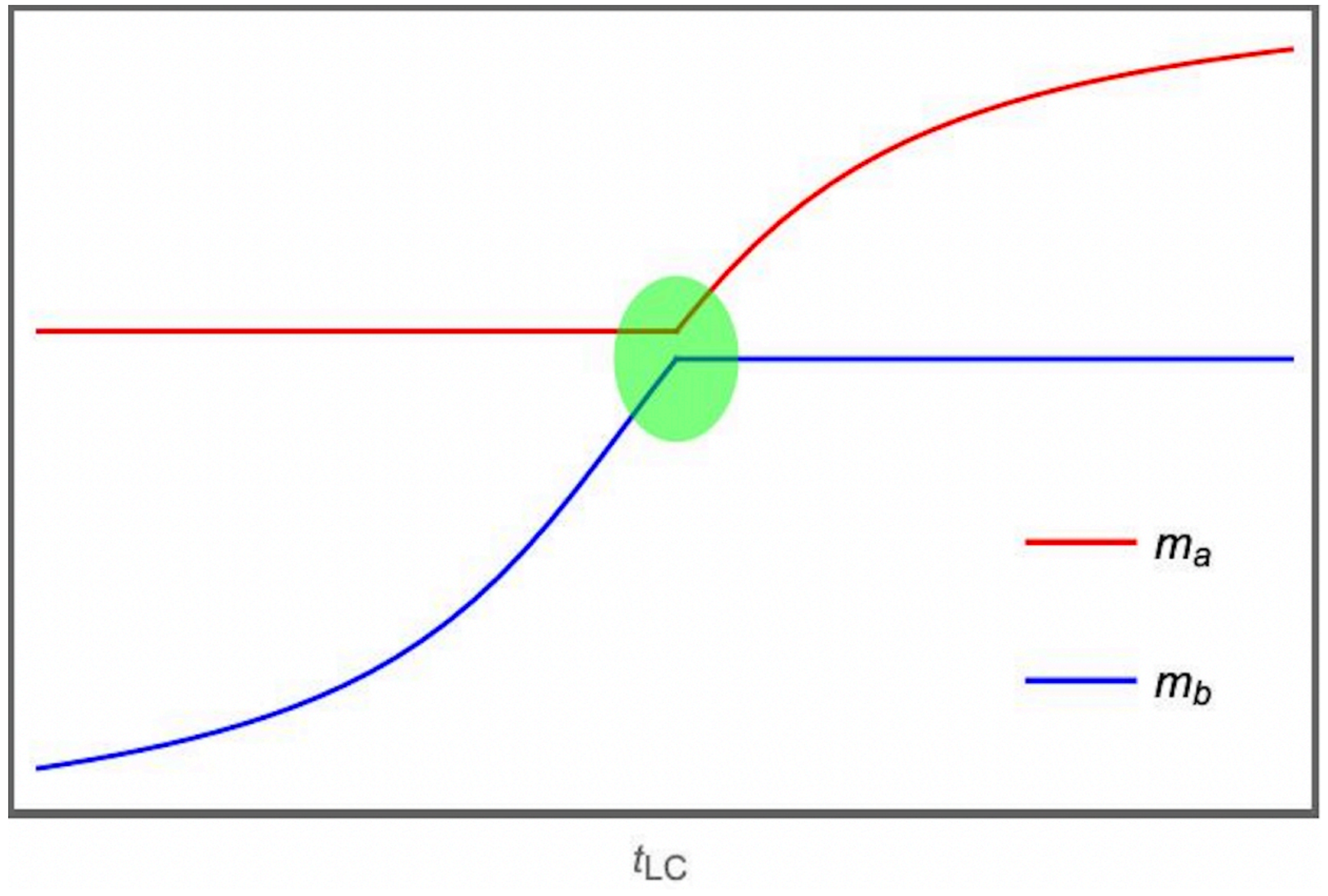

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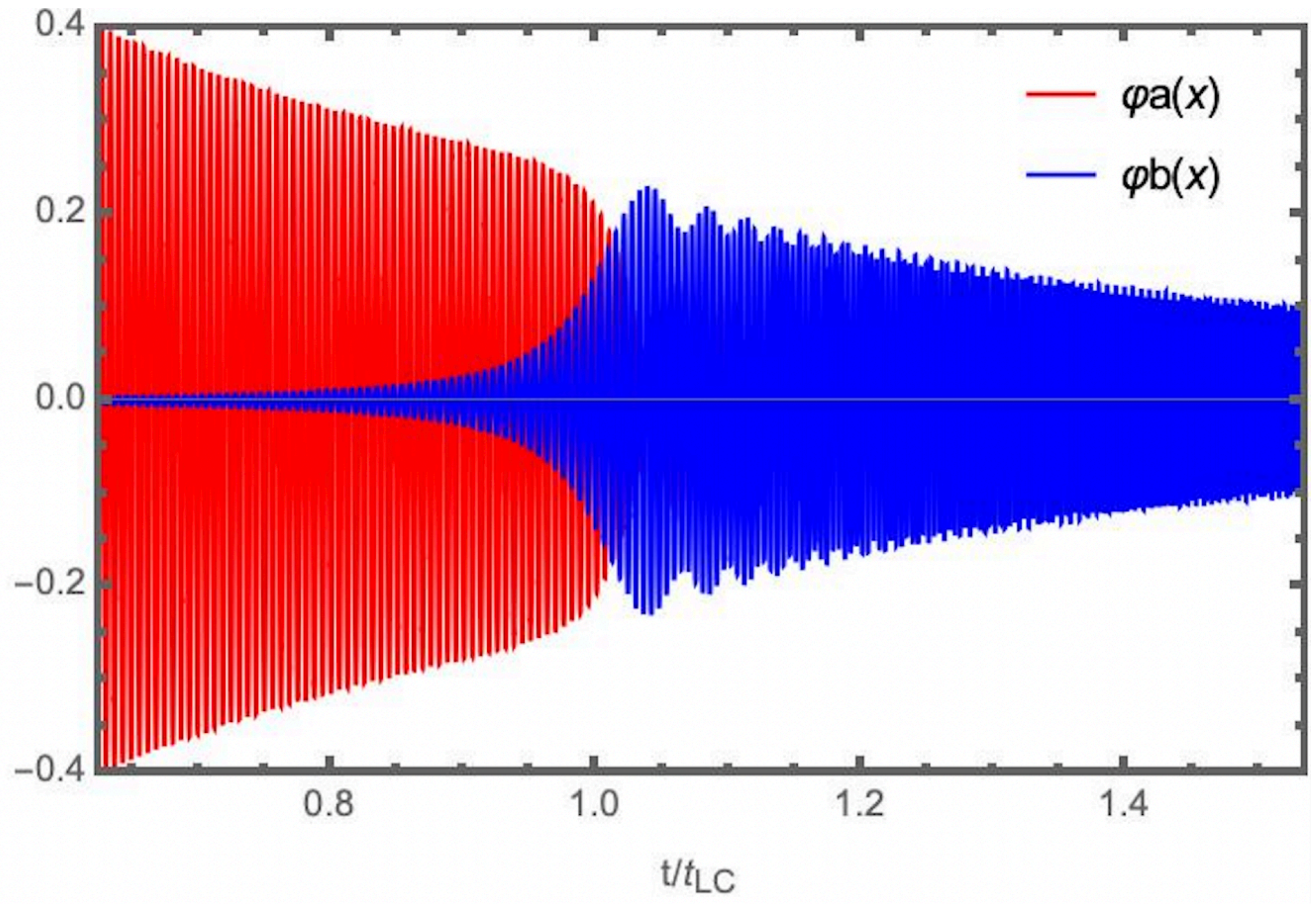
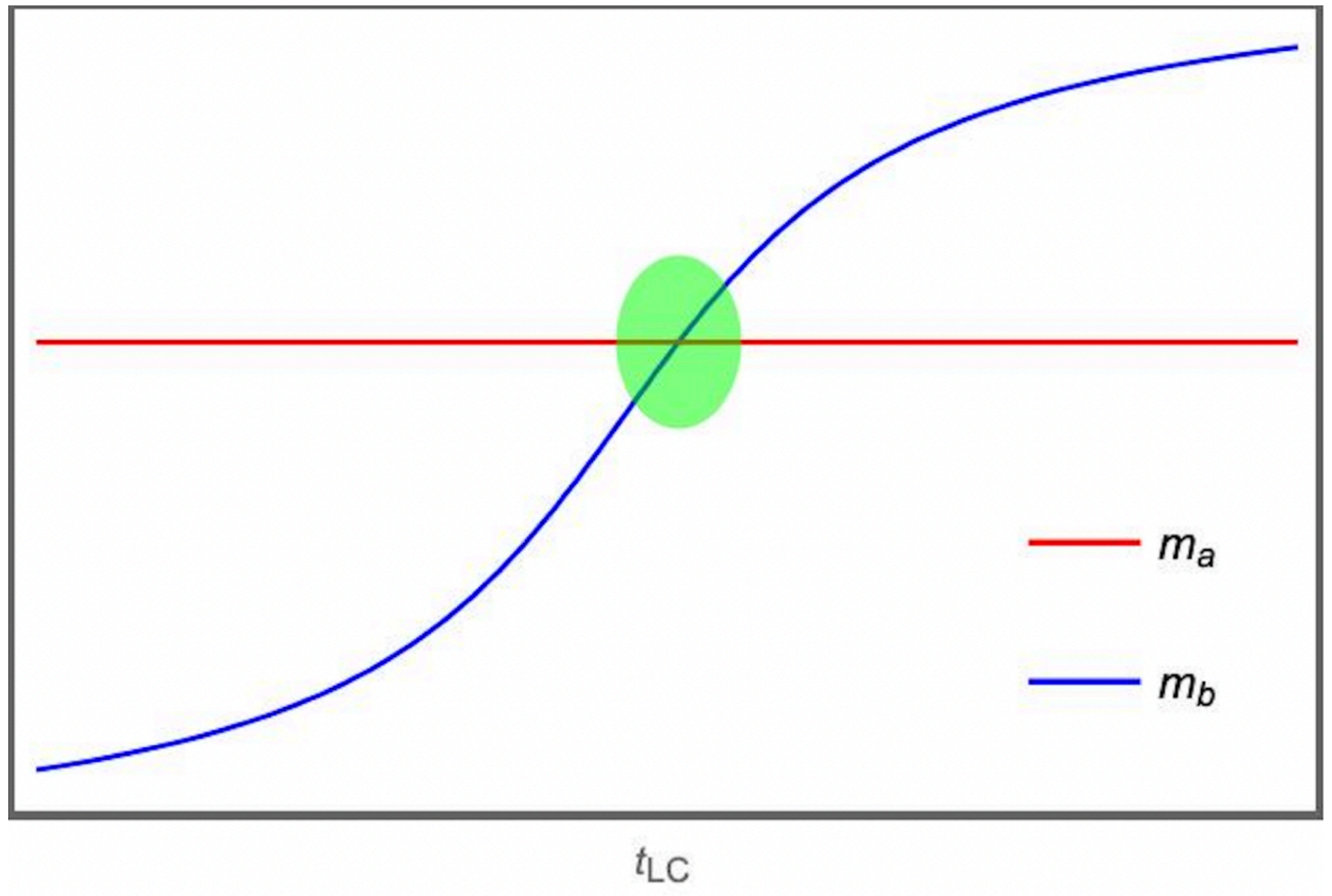
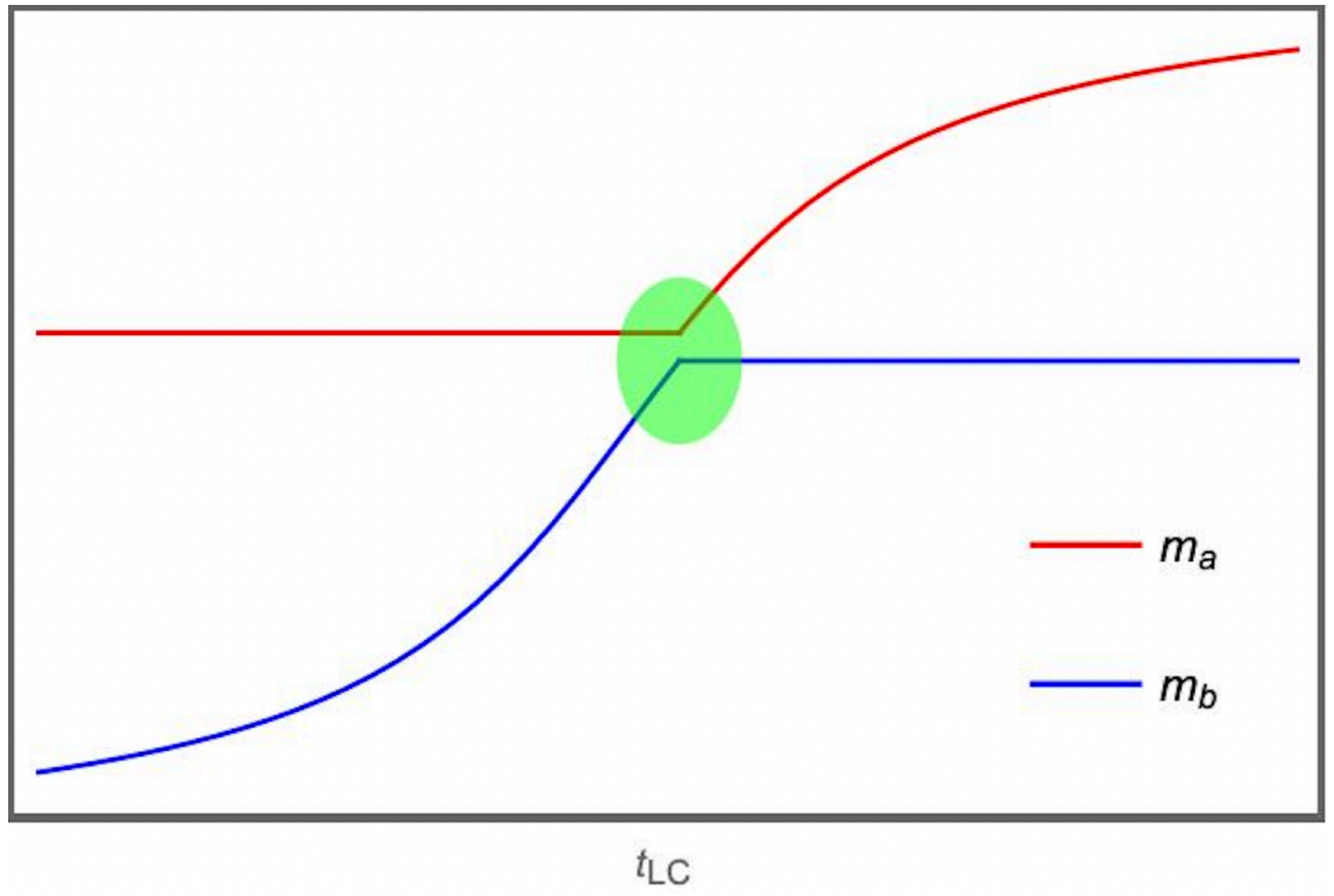




non-Adiabatic

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

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



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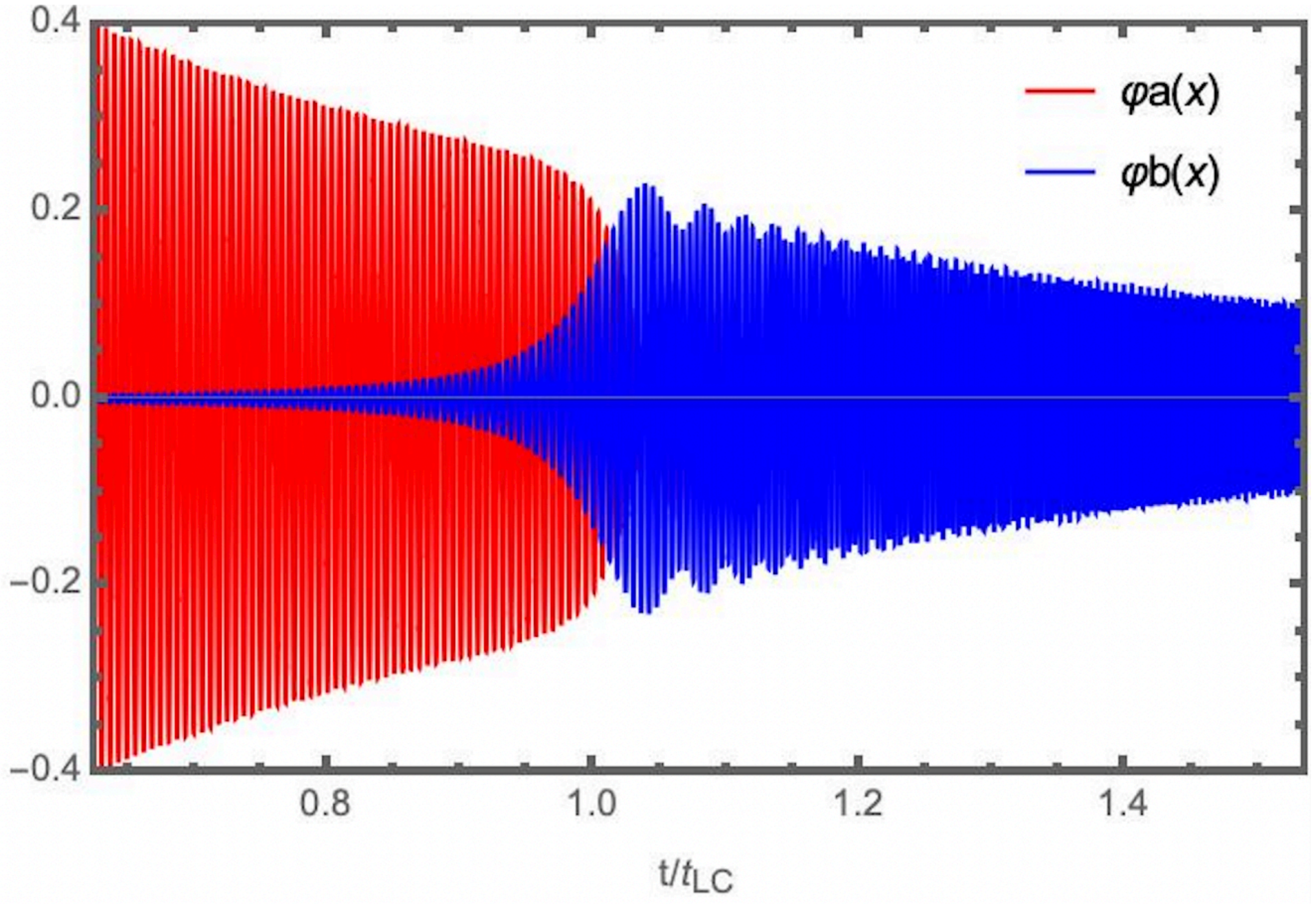

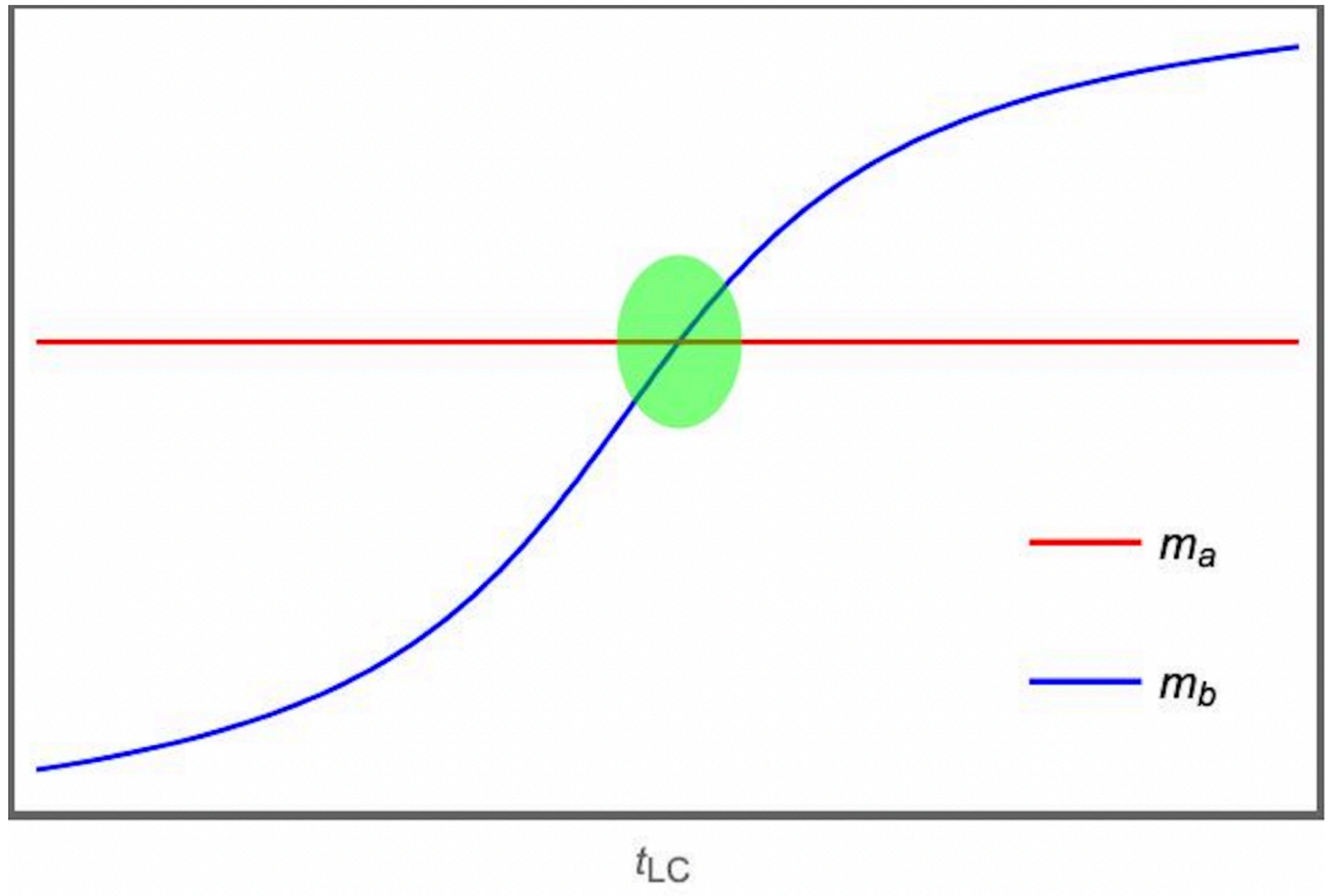

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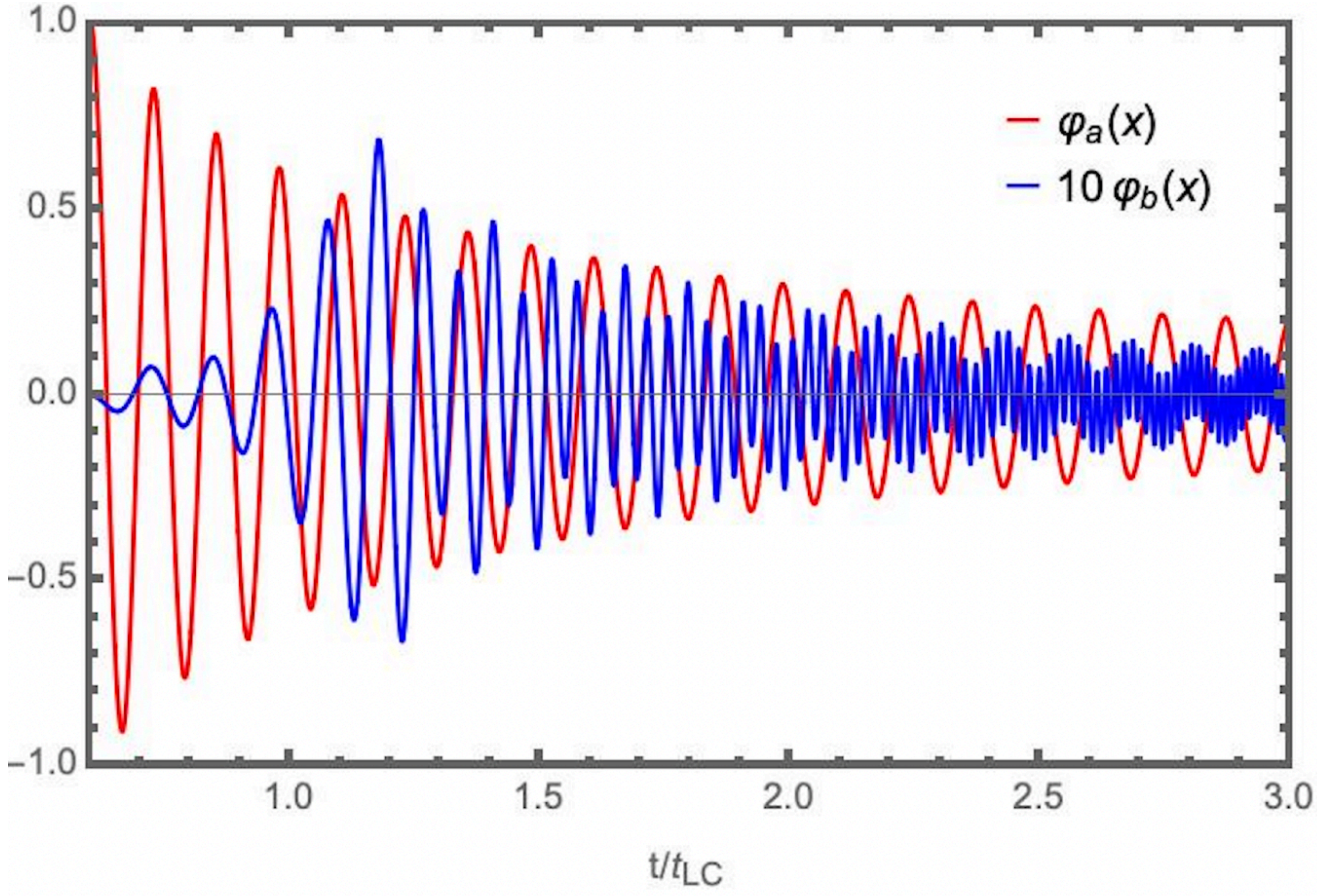

Several constraining conditions, eg:

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

$$f > T_{\rm LC} > T_{\rm DE} > T_0$$

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Because of the different evolution of $\rho_m(T)$ and $\rho_b(T)$, a non-adiabatic LC is what is required by cosmology

$$\left.\frac{\rho_{\rm DE}}{\rho_m}\right|_{\rm LC} = \left(\frac{1+z_{\rm DE}}{1+z_{\rm LC}}\right)^3 \sim 2\% - 20\,\%$$

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Thanks for your attention !