Accelerated Cosmic Expansion, Mass Creation, and the QCD Axion

Enrico Nardi

with: K. Müürsepp (NICPB) & C. Smarra (SISSA)

KBFI NICPB HEP Group

INFN Istituto Nazionale di Fisica Nucleare Laboratori Nazionali di Frascati

FLASY 2025 - 11th Workshop - July 2, 2025 - Rome 3

This presentation is organized in two parts

Part 1: (Cosmology)

Mechanism for cosmic expansion acceleration
[triggered by specific initial conditions]

Part2: (Particle Physics)

Mechanism that sets the initial conditions
for triggering self-sustained acceleration

Accelerated expansion:

Accelerated expansion:

Requires a new energy component (DE) beyond usual matter and radiation

Accelerated expansion:

Requires a new energy component (DE) beyond usual matter and radiation

Most popular New Energy Component Solutions

- CC: $\Lambda \sim (2.25 \times 10^{-3}\ \mathrm{eV})^4$ ΛCDM model (tiny value explained anthropically [Weinberg 87])

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

Accelerated expansion:

Requires a new energy component (DE) beyond usual matter and radiation

Most popular New Energy Component Solutions

- CC: $\Lambda \sim (2.25 \times 10^{-3}\ \mathrm{eV})^4$ ΛCDM model (tiny value explained anthropically [Weinberg 87])

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

Acceleration is also possible with energy density creation: $\rho_{DE} = \rho_\varphi = m_\varphi n_\varphi \sim$ const.

Accelerated expansion:

Requires a new energy component (DE) beyond usual matter and radiation

Most popular New Energy Component Solutions

- CC: $\Lambda \sim (2.25 \times 10^{-3}\ \mathrm{eV})^4$ ΛCDM model (tiny value explained anthropically [Weinberg 87])

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

Acceleration is also possible with energy density creation: $\rho_{DE} = \rho_\varphi = m_\varphi n_\varphi \sim$ const.

- $n_\varphi \sim$ const (particle creation) [Bondi & Gold (1948); Hoyle (1948)] Steady State Univ.

Accelerated expansion:

Requires a new energy component (DE) beyond usual matter and radiation

Most popular New Energy Component Solutions

- CC: $\Lambda \sim (2.25 \times 10^{-3}\ \mathrm{eV})^4$ ΛCDM model (tiny value explained anthropically [Weinberg 87])
- $|V(\varphi)| \gg \dot{\varphi}^2$ (φ dynamical field)   wCDM models   ($w = p/\rho$ EoS parameter)

Acceleration is also possible with energy density creation: $\rho_{DE} = \rho_\varphi = m_\varphi\, n_\varphi \sim \mathrm{const.}$

- $n_\varphi \sim$ const (particle creation) [Bondi & Gold (1948); Hoyle (1948)] Steady State Univ.
- $m_\varphi \sim R^3$ (interpretation as varying mass, $n_\varphi \sim R^{-3}$)   [This talk]

Field theory: 

Historical Note

Theoretical Cosmology, first half of XX century: Two confirmed predictions

Historical Note

Theoretical Cosmology, first half of XX century: Two confirmed predictions

1. The Universe is expanding:	Observational confirmation
Friedmann (1922), Lemaitre (1927)	Hubble (1929)

Historical Note

Theoretical Cosmology, first half of XX century: Two confirmed predictions

1. The Universe is expanding: Observational confirmation

   Friedmann (1922), Lemaitre (1927) — Hubble (1929)

2. The expansion is accelerating: Observational confirmation

   Hoyle (1948); Bondi & Gold (1948) — Riess (1998) et al.; Perlmutter et al. (1999)

Historical Note

Theoretical Cosmology, first half of XX century: Two confirmed predictions

1. The Universe is expanding: Friedmann (1922), Lemaitre (1927) — Observational confirmation: Hubble (1929)

2. The expansion is accelerating: Hoyle (1948); Bondi & Gold (1948) — Observational confirmation: Riess (1998) et al.; Perlmutter et al. (1999)

1. Follows from Cosmological Principle: Universe homogeneous and isotropic on large scales
2. Follows from **Perfect** Cosmological Principle: Universe unchanging in time on large scales

Historical Note

Theoretical Cosmology, first half of XX century: Two confirmed predictions

1. The Universe is expanding: Friedmann (1922), Lemaitre (1927)
   Observational confirmation: Hubble (1929)

2. The expansion is accelerating: Hoyle (1948); Bondi & Gold (1948)
   Observational confirmation: Riess (1998) et al.; Perlmutter et al. (1999)

1. Follows from Cosmological Principle: Universe homogeneous and isotropic on large scales
2. Follows from **Perfect** Cosmological Principle: Universe unchanging in time on large scales

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."

"Physical laws cannot be assumed to be independent on the structure of the Universe. Conversely, the structure of the Universe depends upon the physical laws." Then there may be a stable, self-perpetuating state with constant physical laws"

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."

"Physical laws cannot be assumed to be independent on the structure of the Universe. Conversely, the structure of the Universe depends upon the physical laws." Then there may be a stable, self-perpetuating state with constant physical laws"

Steady State Universe (SSU): to counterbalance dilution from the expansion, matter is constantly created at the rate of 1 H atom (or 1 neutron)/cm^3/10^{12} yrs.

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.”

“Physical laws cannot be assumed to be independent on the structure of the Universe. Conversely, the structure of the Universe depends upon the physical laws.” Then there may be a stable, self-perpetuating state with constant physical laws”

Steady State Universe (SSU): to counterbalance dilution from the expansion, matter is constantly created at the rate of 1 H atom (or 1 neutron)/cm^3/10^{12} yrs.

[SSU disproven **directly** by quasars & radio galaxies observations (at large z) , and **indirectly** by BBN/CMB (hot early phase)]

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."

"Physical laws cannot be assumed to be independent on the structure of the Universe. Conversely, the structure of the Universe depends upon the physical laws." Then there may be a stable, self-perpetuating state with constant physical laws"

Steady State Universe (SSU): to counterbalance dilution from the expansion, matter is constantly created at the rate of 1 H atom (or 1 neutron)/$cm^3/10^{12}$ yrs.

[SSU disproven **directly** by quasars & radio galaxies observations (at large z) , and **indirectly** by BBN/CMB (hot early phase)]

I will discuss a construction that also involves energy density creation. But it does not imply a steady state cosmology. The standard cosmological history is unaltered until a certain "Level Crossing", occurring around redshift $z \sim 2 - 4$.

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."

"Physical laws cannot be assumed to be independent on the structure of the Universe. Conversely, the structure of the Universe depends upon the physical laws." Then there may be a stable, self-perpetuating state with constant physical laws"

Steady State Universe (SSU): to counterbalance dilution from the expansion, matter is constantly created at the rate of 1 H atom (or 1 neutron)/cm^3/10^{12} yrs.

[SSU disproven **directly** by quasars & radio galaxies observations (at large z) , and **indirectly** by BBN/CMB (hot early phase)]

I will discuss a construction that also involves energy density creation. But it does not imply a steady state cosmology. The standard cosmological history is unaltered until a certain "Level Crossing", occurring around redshift $z \sim 2 - 4$.

Locality of field eqs.: "Particle creation" => "Mass growth of a certain particle"

The acceleration mechanism

The acceleration mechanism

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:

$$C_{00} = \dot{\rho}_b \,, \quad C_{ii} = -\, R\dot{R}\,\rho_b$$

The acceleration mechanism

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:

$$C_{00} = \dot{\rho}_b\,, \quad C_{ii} = -R\dot{R}\,\rho_b$$

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

Geometry — Energy density — Cov. deriv. of "b" energy density

$$\mathscr{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathscr{R} = \frac{1}{m_P^2}T_{\mu\nu} + \frac{1}{\eta}C_{\mu\nu}$$

The acceleration mechanism

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:

$$C_{00} = \dot{\rho}_b \,, \quad C_{ii} = -R\dot{R}\,\rho_b$$

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

Geometry | Energy density | Cov. deriv. of "b" energy density

$$\mathscr{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathscr{R} = \frac{1}{m_P^2}T_{\mu\nu} + \frac{1}{\eta}C_{\mu\nu}$$

Matter/DE domination era

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

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

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

The acceleration mechanism

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:

$$C_{00} = \dot{\rho}_b\,, \quad C_{ii} = -\,R\dot{R}\,\rho_b$$

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

Geometry — Energy density — Cov. deriv. of "b" energy density

$$\mathscr{R}_{\mu\nu} - \frac{1}{2}g_{\mu\nu}\mathscr{R} = \frac{1}{m_P^2}T_{\mu\nu} + \frac{1}{\eta}C_{\mu\nu}$$

Matter/DE domination era

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

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

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

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

Modified Friedmann Equations

Modified Friedmann Equations

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

Modified Friedmann Equations

With C-term: $2R\ddot{R} + \dot{R}^2 = R\dot{R}\frac{\rho_b}{\eta}$; $3\frac{\dot{R}^2}{R^2} = \frac{\rho}{m_P^2} + \frac{\dot{\rho}_b}{\eta}$, $(\rho = \rho_m + \rho_b)$

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

Modified Friedmann Equations

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

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

$$\frac{\rho_b}{\eta} \approx 3\frac{\dot{R}}{R}$$

exponential acceleration

Modified Friedmann Equations

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

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

$$\frac{\rho_b}{\eta} \approx 3\frac{\dot{R}}{R}$$

exponential acceleration

This regime is reached around the present epoch for $\eta \approx H_0 m_P^2$

Numerical Integration

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

Numerical Integration

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

The two equations become:

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

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

Numerical Integration

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

The two equations become:

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

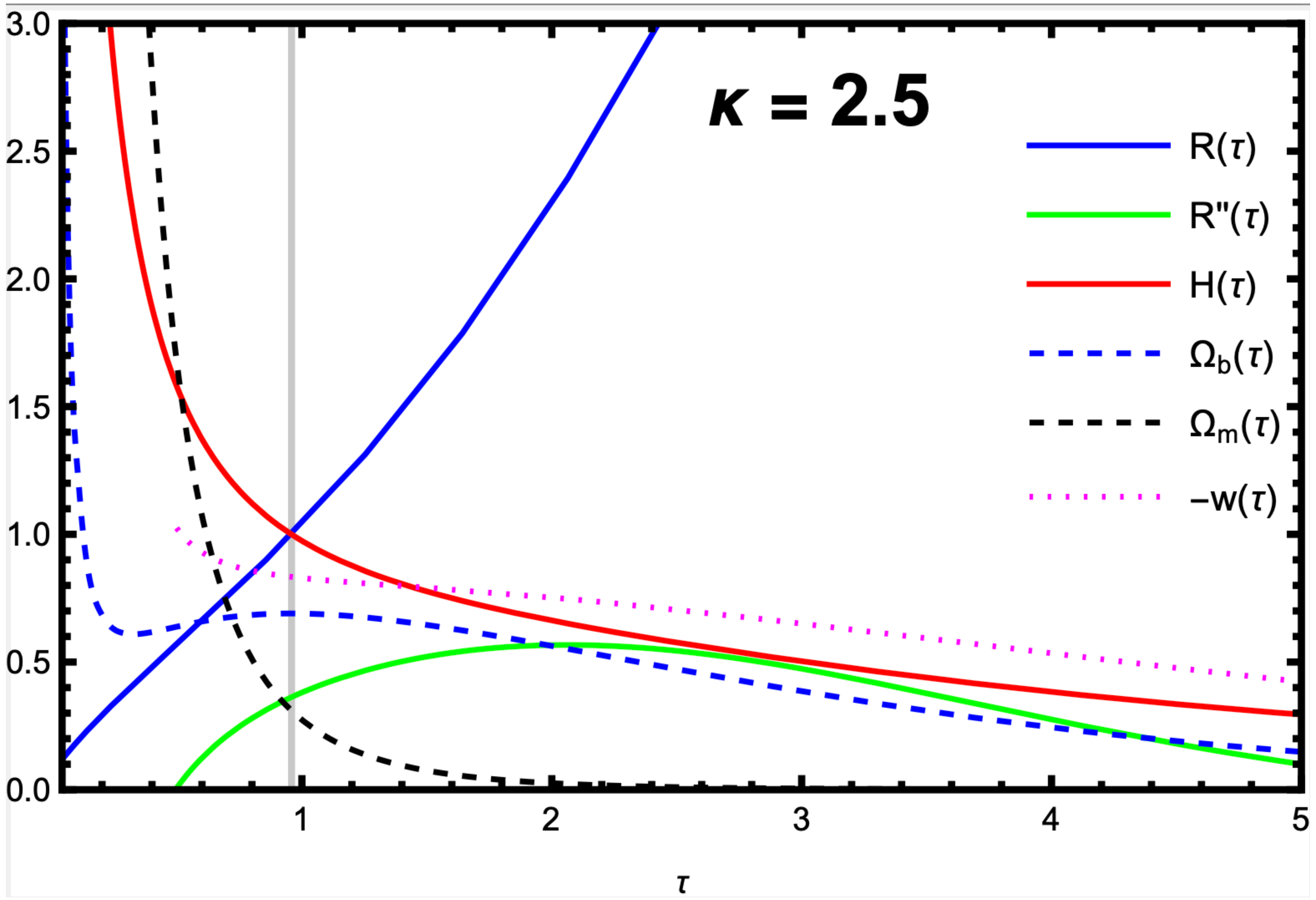
$$\frac{R'^2}{R^2} = \frac{\Omega_{m,0}}{R^3} + \Omega_{b,0}\left(\mathscr{F}_b + \frac{\kappa}{3}\mathscr{F}'_b\right)$$

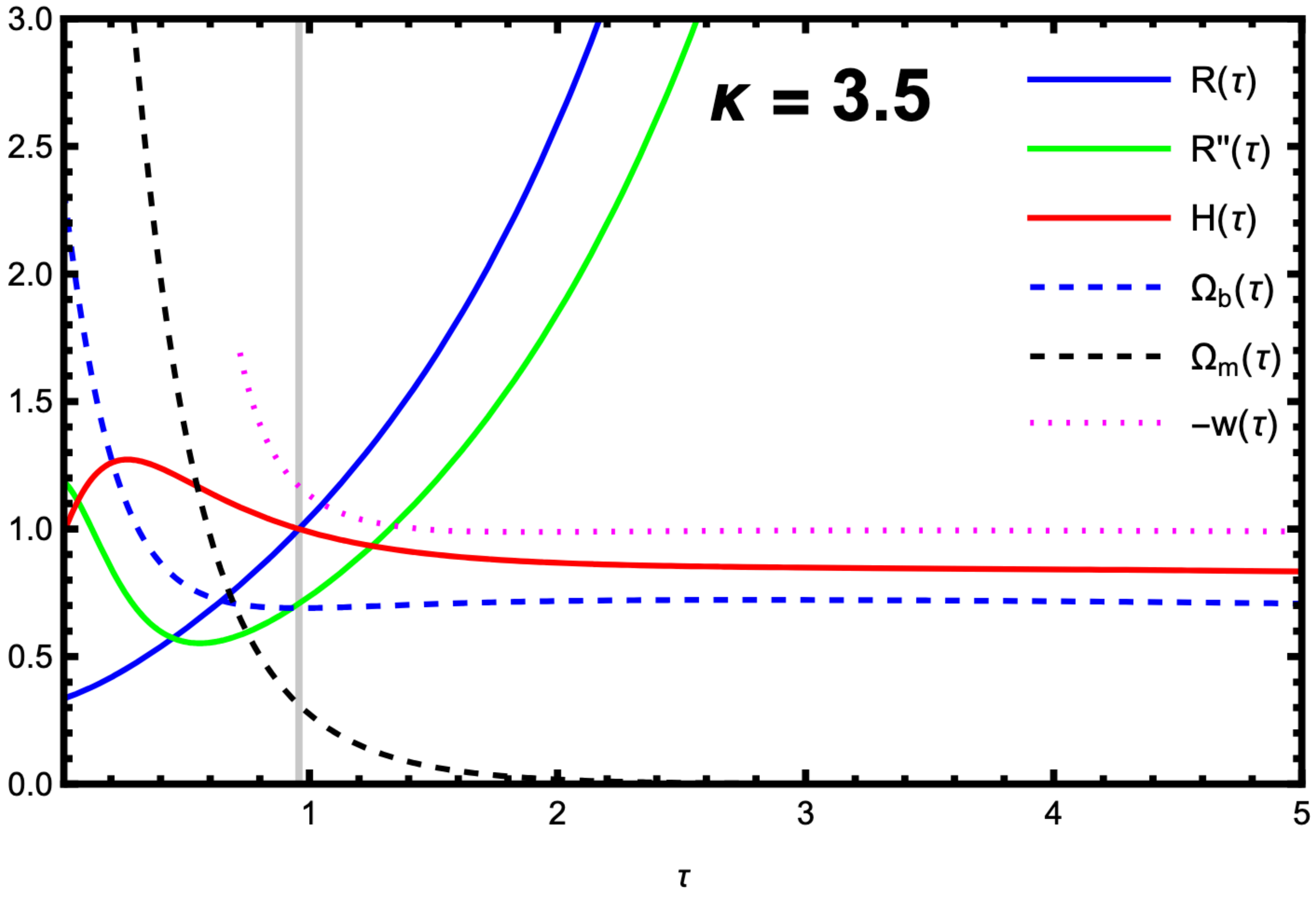
$$\kappa = \frac{\rho_c^0}{H_0\, \eta} = \frac{\rho_c^0}{H_0^2\, m_{\rm P}^2} \approx 3$$

Present epoch boundary conditions:

$$R(\tau_0) = R'(\tau_0) = \mathscr{F}_b(\tau_0) = 1; \;\; \rho_b'(\tau_0) = 0$$

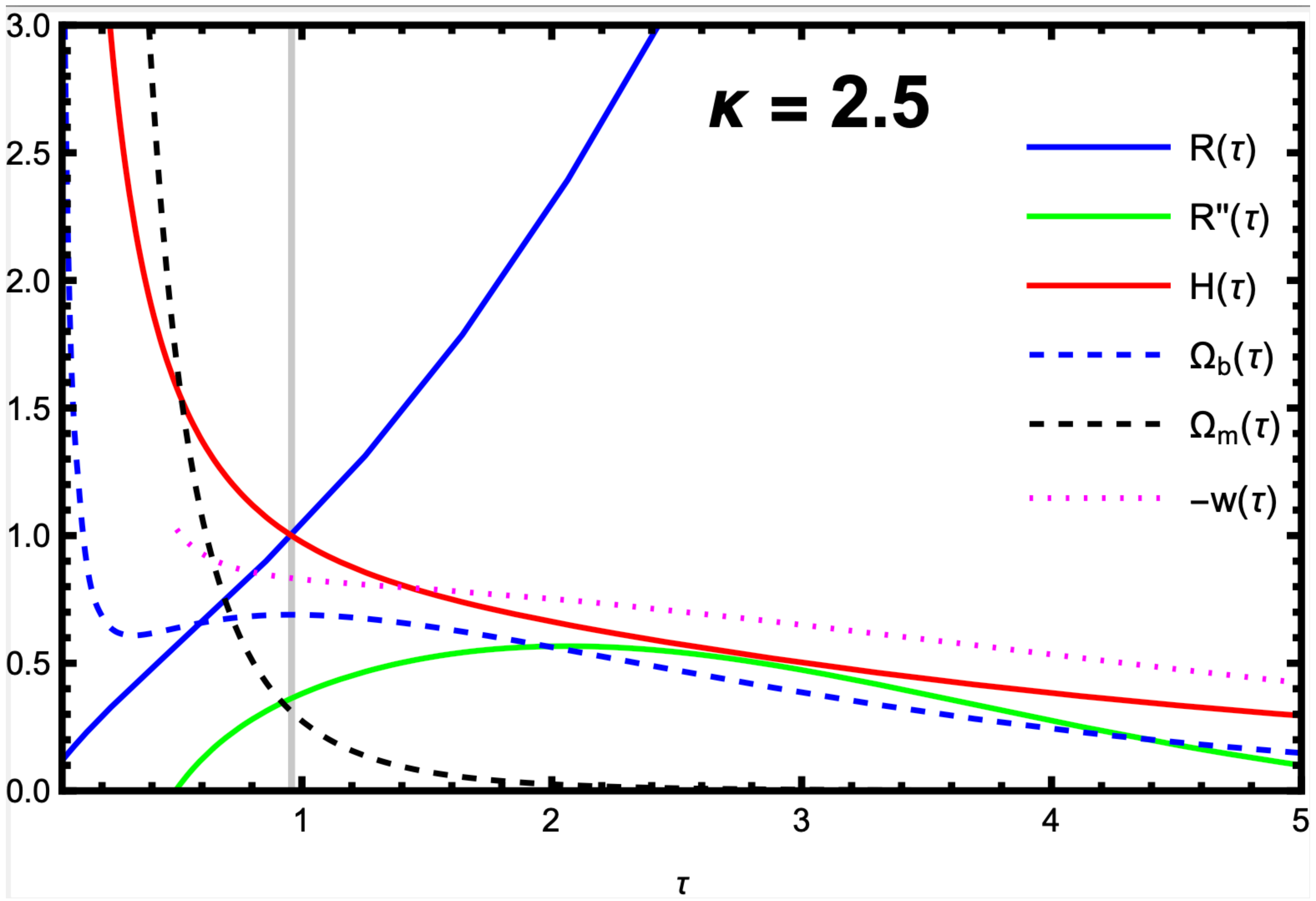
Two Examples: κ= 2.5 and κ = 3.5

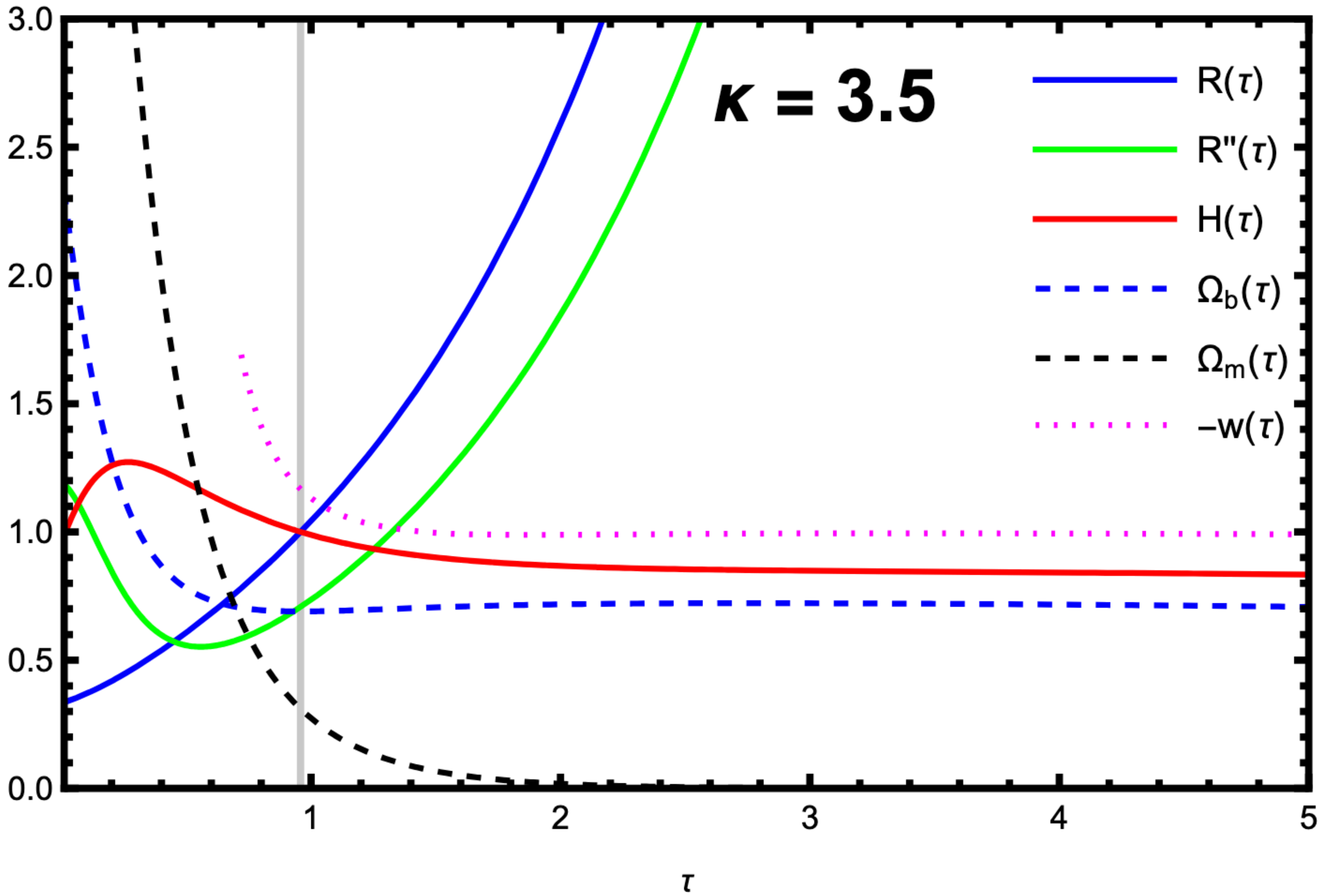




Evolution of $R(\tau)$, $R''(\tau)$, $H(\tau)$, w(τ) and of the normalised densities $\Omega_b(\tau)$, $\Omega_m(\tau)$

Two Examples: κ= 2.5 and κ = 3.5

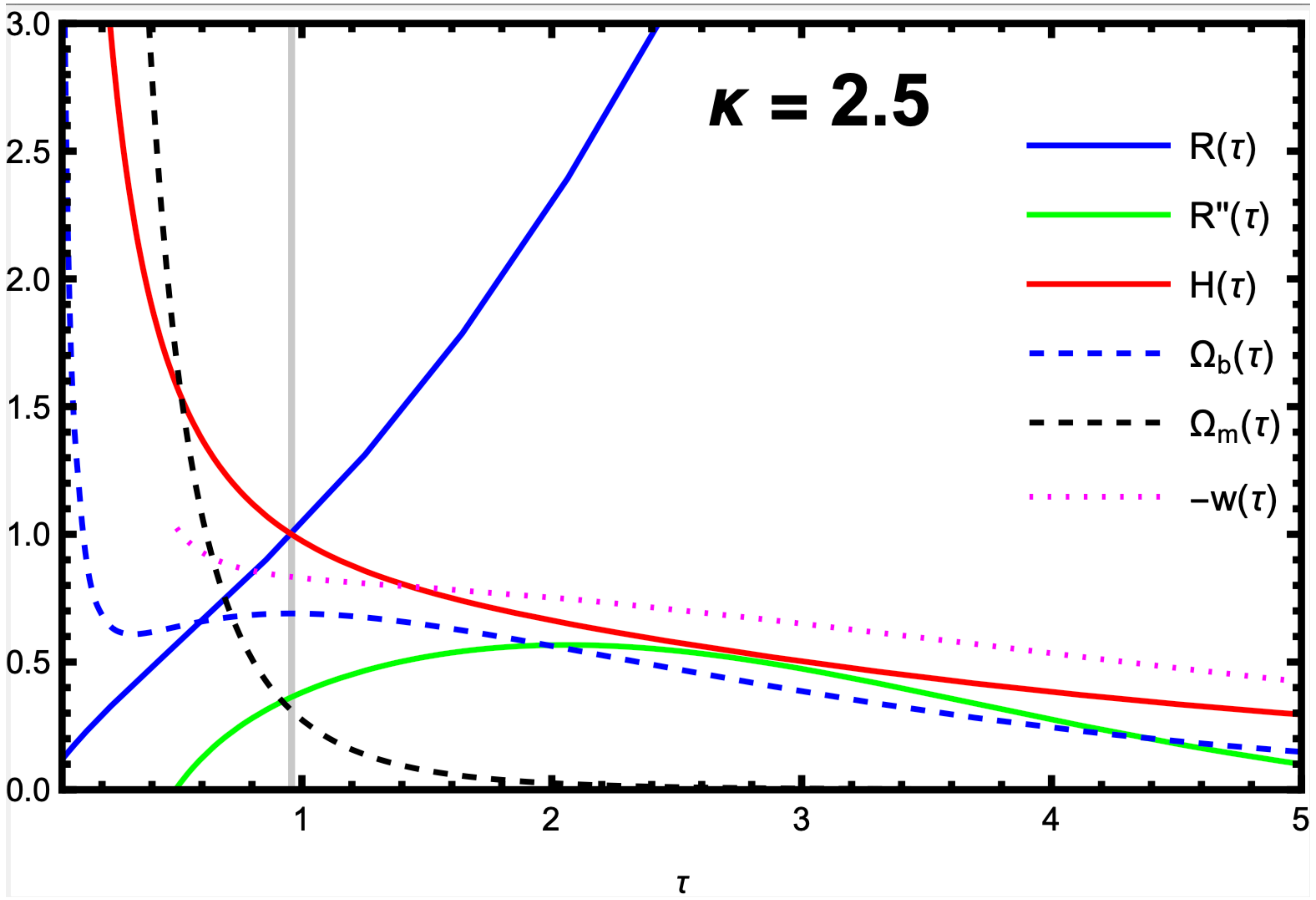


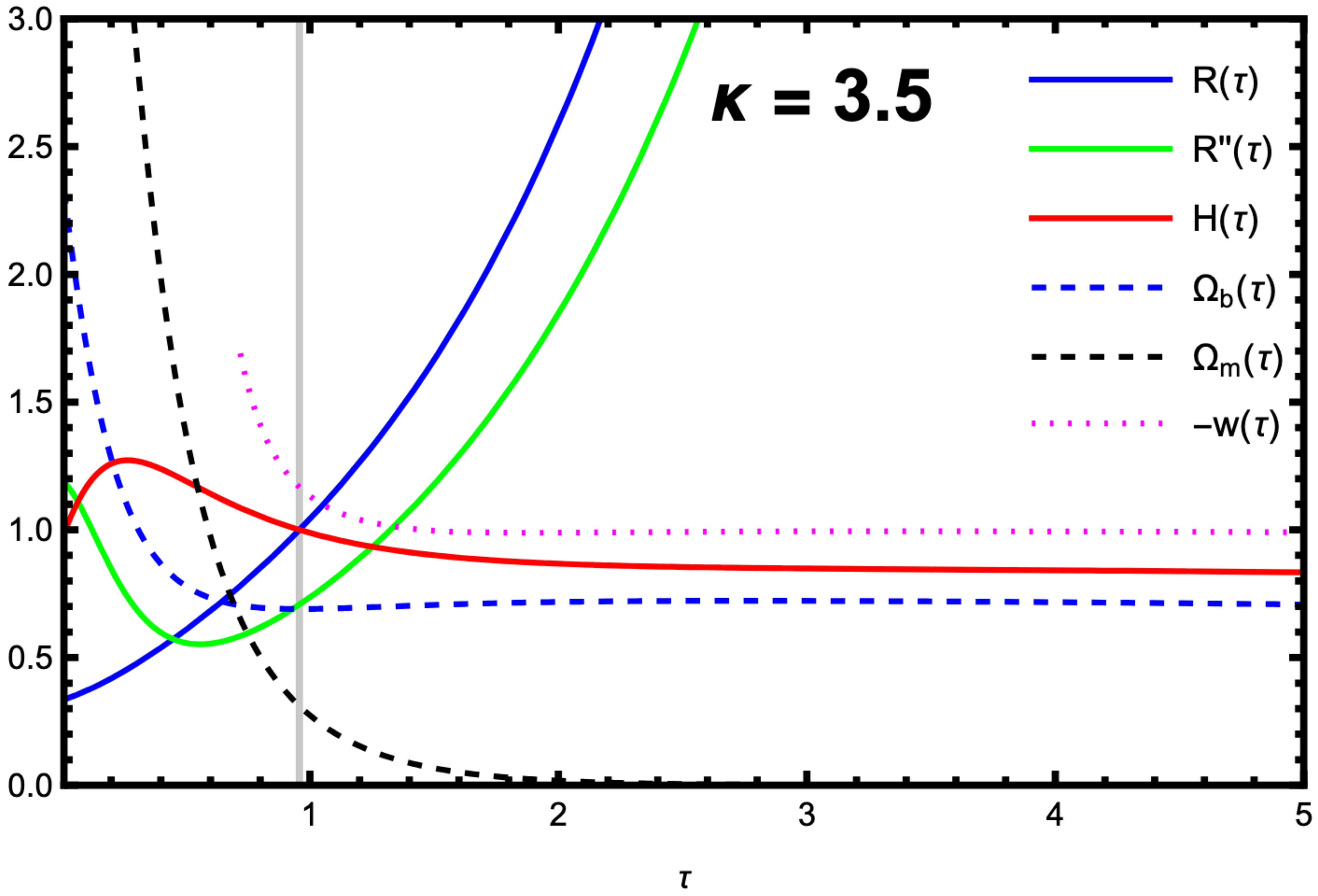


Evolution of $R(\tau)$, $R''(\tau)$, $H(\tau)$, w(τ) and of the normalised densities $\Omega_b(\tau)$, $\Omega_m(\tau)$

Evolving backwards: for $\tau \lesssim 0.1$, $\Omega_b/\Omega_m \sim$ [2% - 28 %] const. $\Rightarrow$ $\Omega_b \sim R^{-3}$

Two Examples: κ= 2.5 and κ = 3.5





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

Evolving backwards: for $\tau \lesssim 0.1$, $\Omega_b/\Omega_m \sim$ [2% - 28 %] const. $\Rightarrow$ $\Omega_b \sim R^{-3}$

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

Why the acceleration ?

Why the acceleration ?

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

and let us define: $$\widetilde{T}^b_{\mu\nu} = T^b_{\mu\nu} + \frac{m_P^2}{\eta} C_{\mu\nu}$$

Why the acceleration ?

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

and let us define: $$\tilde{T}^b_{\mu\nu} = T^b_{\mu\nu} + \frac{m_P^2}{\eta} C_{\mu\nu}$$

$$C_{ii} \approx -\frac{\eta}{m_P^2} R^2 \rho_b \quad \Longrightarrow \quad \boxed{\mathcal{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathcal{R} = \frac{1}{m_P^2} T^m_{\mu\nu} + \frac{\rho_b}{m_P^2} g_{\mu\nu}}$$

Why the acceleration ?

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

and let us define: $$\widetilde{T}^b_{\mu\nu} = T^b_{\mu\nu} + \frac{m_P^2}{\eta} C_{\mu\nu}$$

$$C_{ii} \approx -\frac{\eta}{m_P^2} R^2 \rho_b \quad \Longrightarrow \quad \boxed{\mathscr{R}_{\mu\nu} - \frac{1}{2} g_{\mu\nu} \mathscr{R} = \frac{1}{m_P^2} T^m_{\mu\nu} + \frac{\rho_b}{m_P^2} g_{\mu\nu}}$$

The field equations approximately reproduce Einstein equations with a cosmological constant : $\Lambda = \dfrac{\rho_b}{m_P^2}$

Some encouraging implications:

Some encouraging implications:

- Our construction predicts DE time-variance at a late epoch (cf. DESI results)

Some encouraging implications:

- Our construction predicts DE time-variance at a late epoch (cf. DESI results)

- For κ=2.5 the evolution of the normalised energy density $\rho_{DE}(z)/\rho_{DE,0}$ found in arXiv:2503.14743 is qualitatively reproduced: an initial increase with the scale factor, a broad peak around z_{DE}, a decrease as the Universe continues to expand

Some encouraging implications:

- Our construction predicts DE time-variance at a late epoch (cf. DESI results)

- For κ=2.5 the evolution of the normalised energy density $\rho_{DE}(z)/\rho_{DE,0}$ found in arXiv:2503.14743 is qualitatively reproduced: an initial increase with the scale factor, a broad peak around z_{DE}, a decrease as the Universe continues to expand

- 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)

Generating ρ_b around z ~ a few

Generating ρ_b around $z \sim$ a few

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

Generating ρ_b around z ~ a few

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

— NGBs appear during phase transitions when some global symmetry gets broken

Generating ρ_b around z ~ a few

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

— NGBs appear during phase transitions when some global symmetry gets broken

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

A quick overview of axion properties

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

A quick overview of axion properties

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

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:

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

Temperature dependent axion mass

Temperature dependent axion mass

$m_a^2 = \chi / F^2$ since $\chi = \chi(T)$ => $m_a^2 = m_a^2(T)$

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: $\chi = (160\ \mathrm{MeV})^4$

Temperature dependent axion mass

$m_a^2 = \chi / F^2$ since $\chi = \chi(T)$ => $m_a^2 = m_a^2(T)$

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: $\chi = (160\ \mathrm{MeV})^4$

What is the T dependence in QCD ? $m_a^2(T) \sim T^{-n}$, $[n \sim n(T)]$

Temperature dependent axion mass

$m_a^2 = \chi / F^2$ since $\chi = \chi(T)$ => $m_a^2 = m_a^2(T)$

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: $\chi = (160\ \text{MeV})^4$

What is the T dependence in QCD ? $m_a^2(T) \sim T^{-n}$, [$n \sim n(T)$]

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 instanton liquid model: Shellard & Wanz, 2010]

Generating ρ_b from QCD axion DM

Generating ρ_b from QCD axion DM

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

Generating ρ_b from QCD axion DM

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

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

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

Generating ρ_b from QCD axion DM

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

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

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

This generates the potential:

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

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

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

Equations of motion

Equations of motion

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

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

Equations of motion

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

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

Assumption: at T=0 $m_b \approx \Lambda_b^2 / f > m_a$ [f<<F, i.e. v_1 << v_2]

Equations of motion

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

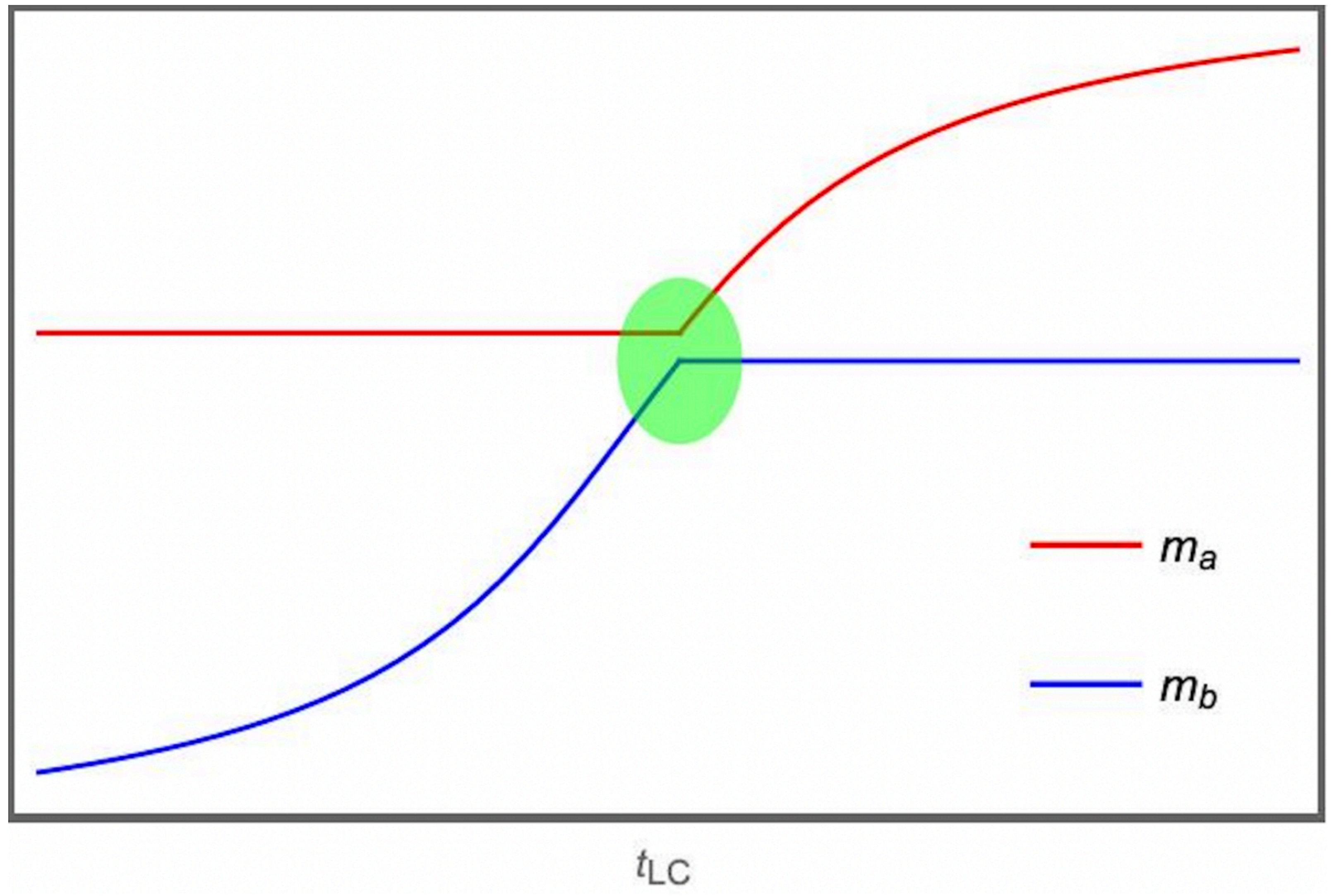
$$A = \begin{pmatrix} \varphi_a \\ \varphi_b \end{pmatrix}; \quad \mathscr{M}^2 = m_a^2 \begin{pmatrix} 1 & \epsilon\, r(T) \\ \epsilon\, r(T) & r(T) \end{pmatrix}; \quad m_a = \frac{\Lambda_a^2}{F}, \quad r(T) = \frac{m_b^2(T)}{m_a}, \quad \epsilon = \frac{f}{F'}$$

Assumption: at T=0 $m_b \approx \Lambda_b^2 / f > m_a$ [f<<F, i.e. $v_1 \ll v_2$]

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

Dynamics of Level Crossing

Dynamics of Level Crossing

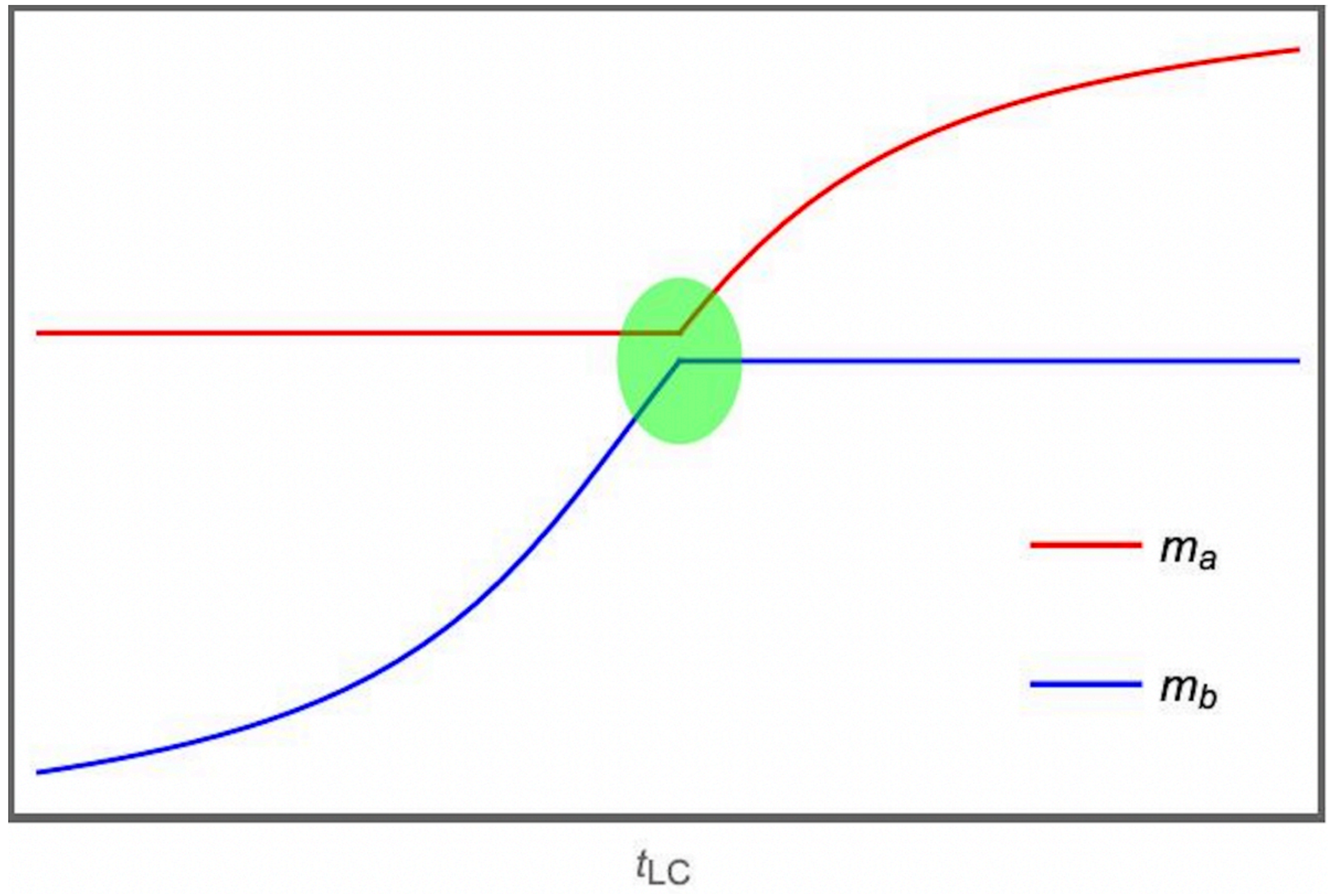


Adiabatic

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

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

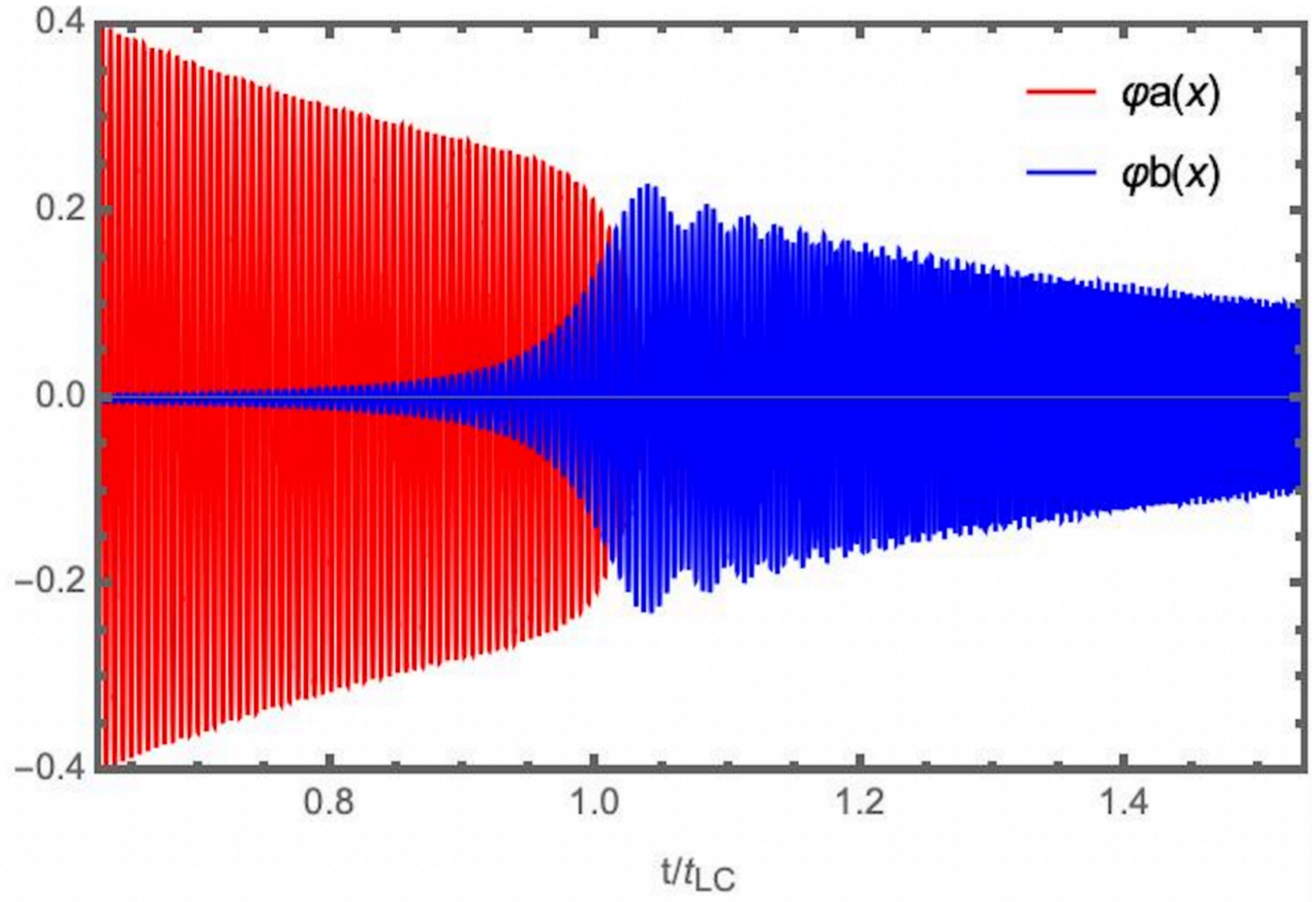
Dynamics of Level Crossing



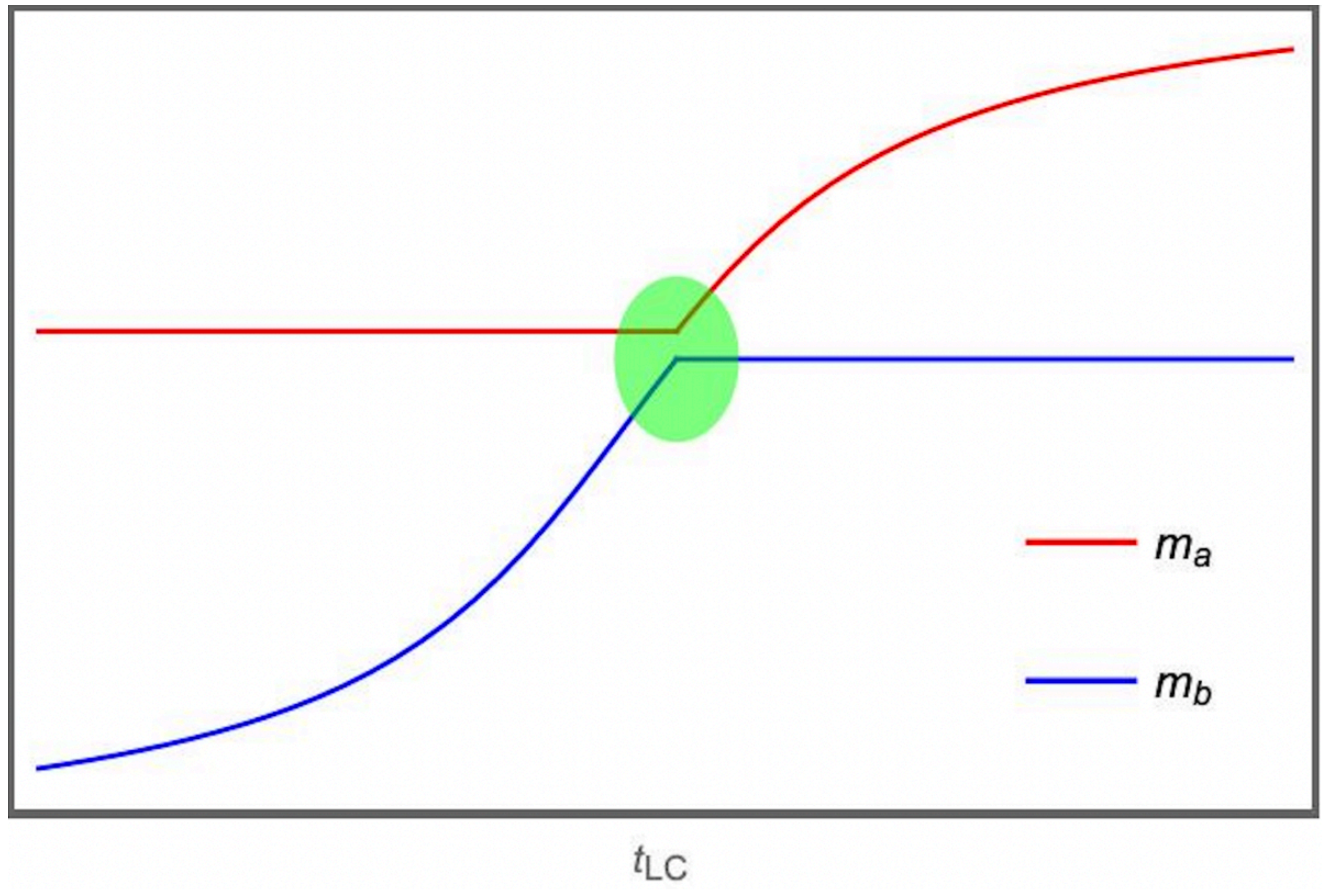
Adiabatic

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

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



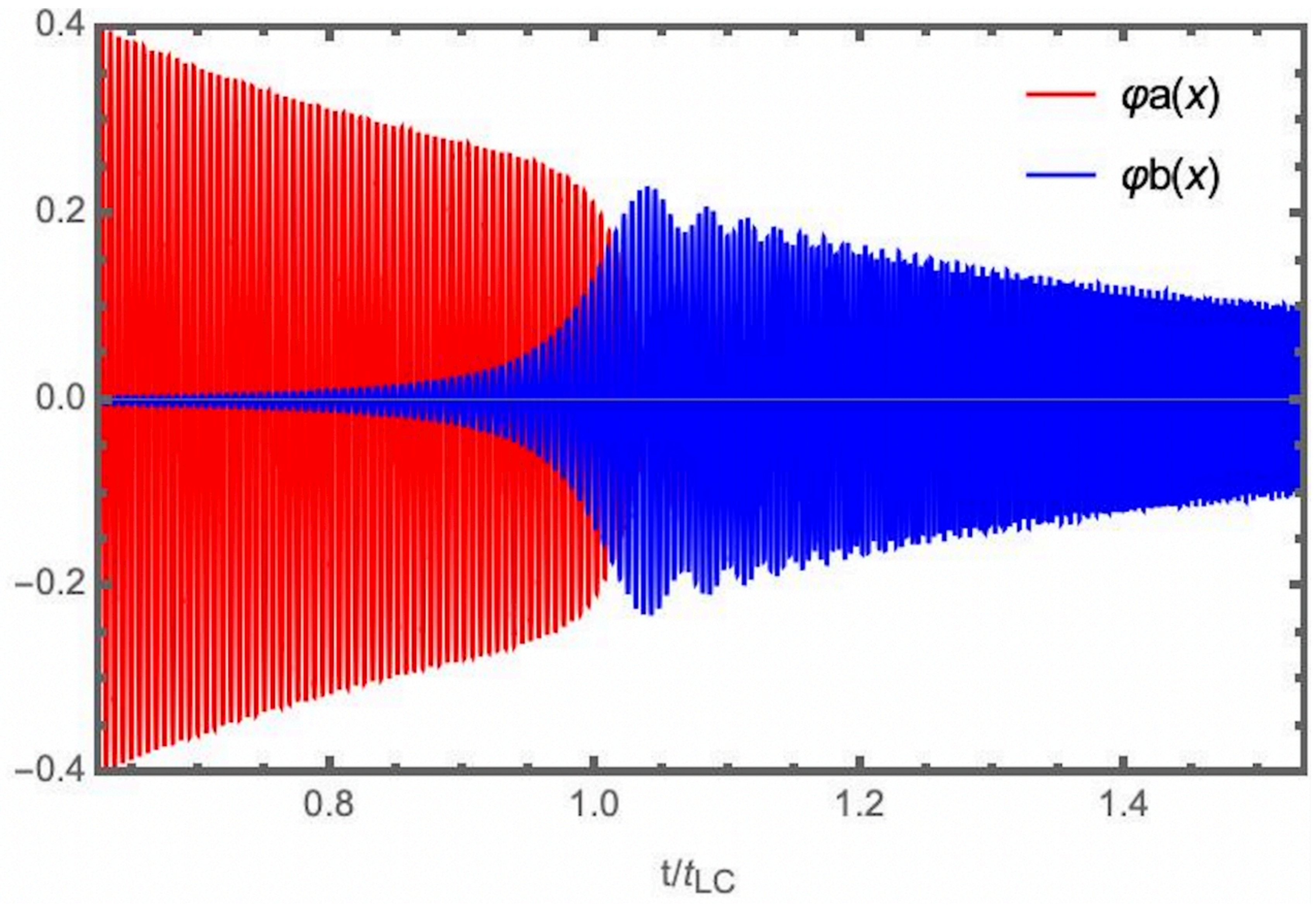
Dynamics of Level Crossing

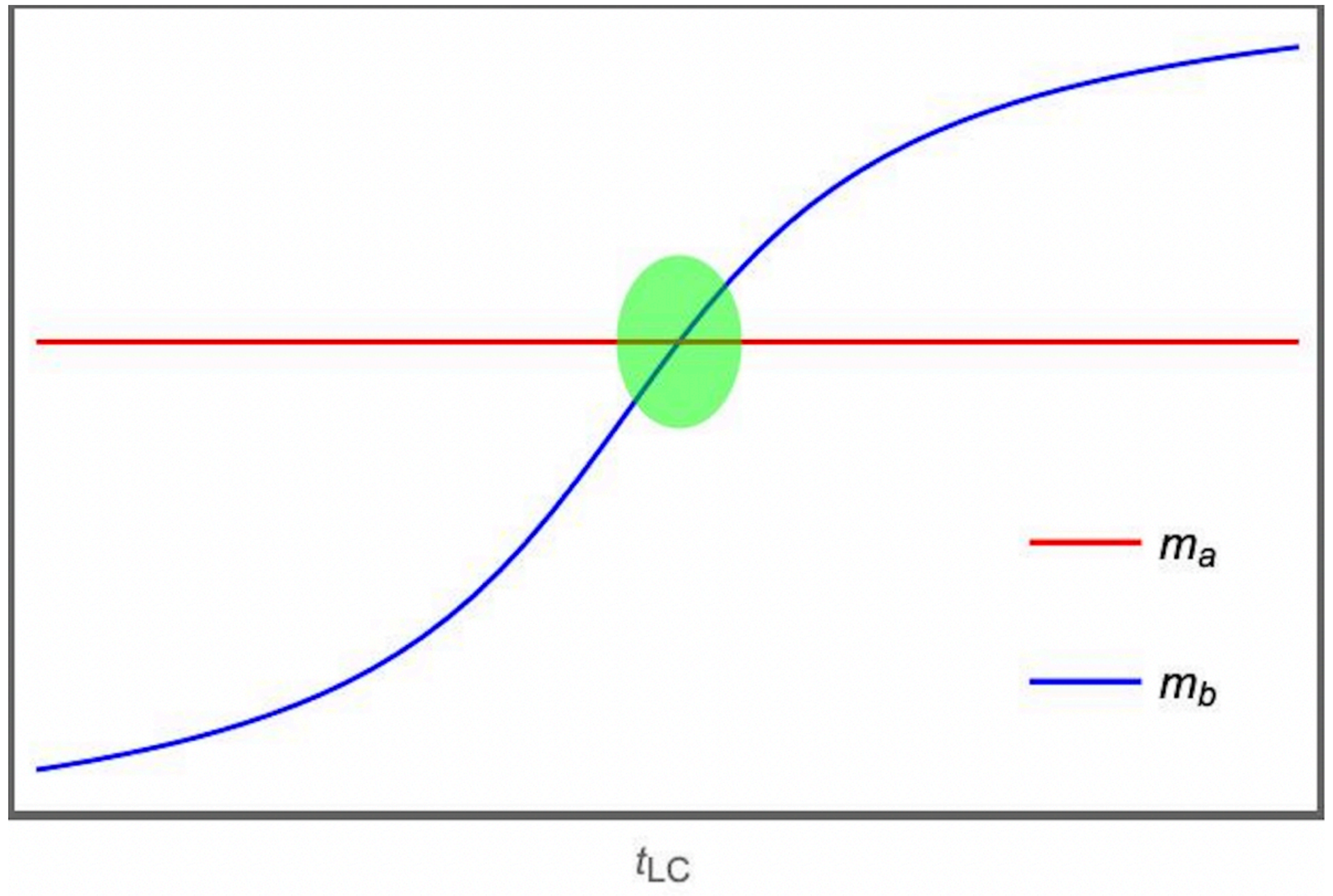


Adiabatic

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

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



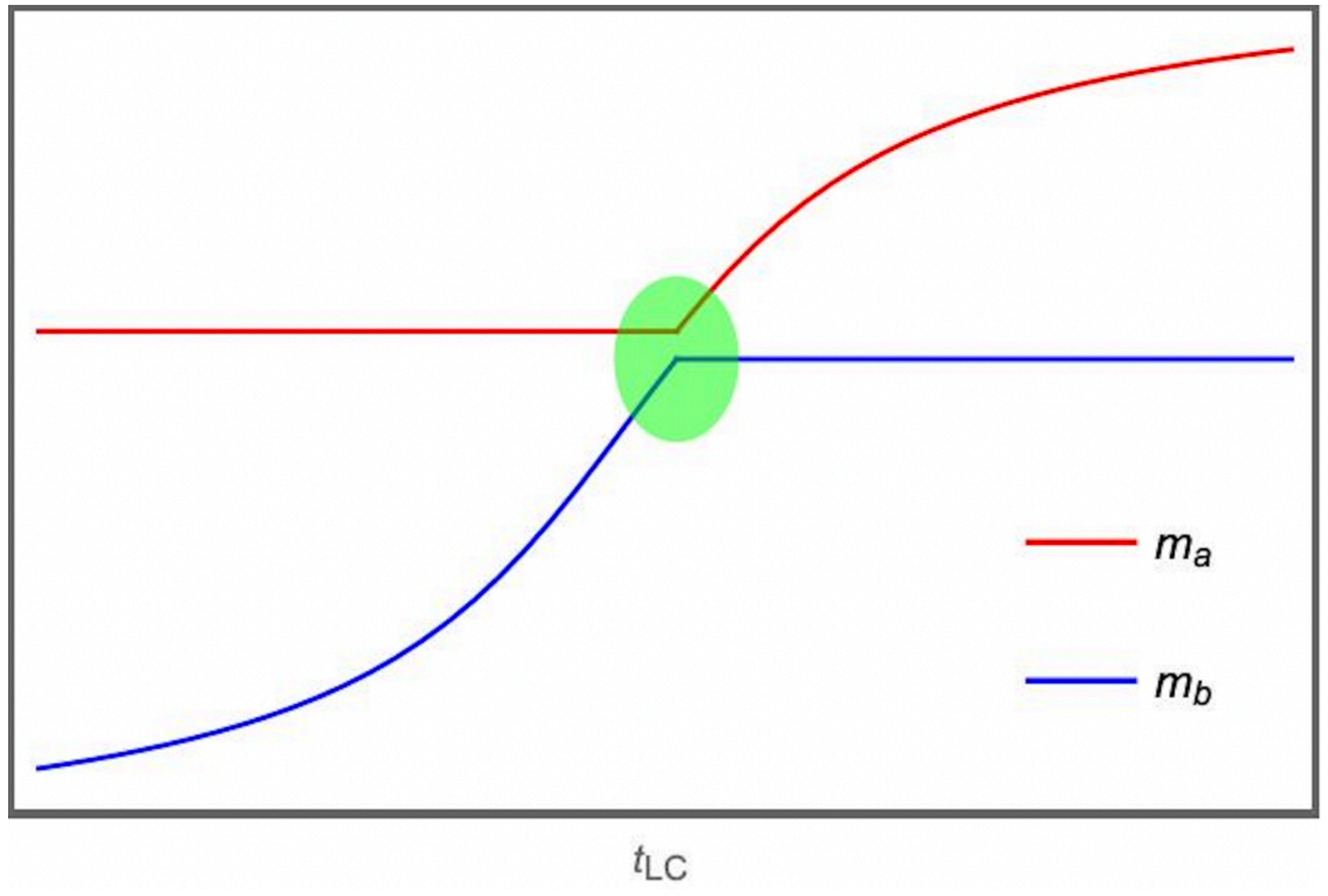


non-Adiabatic

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

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

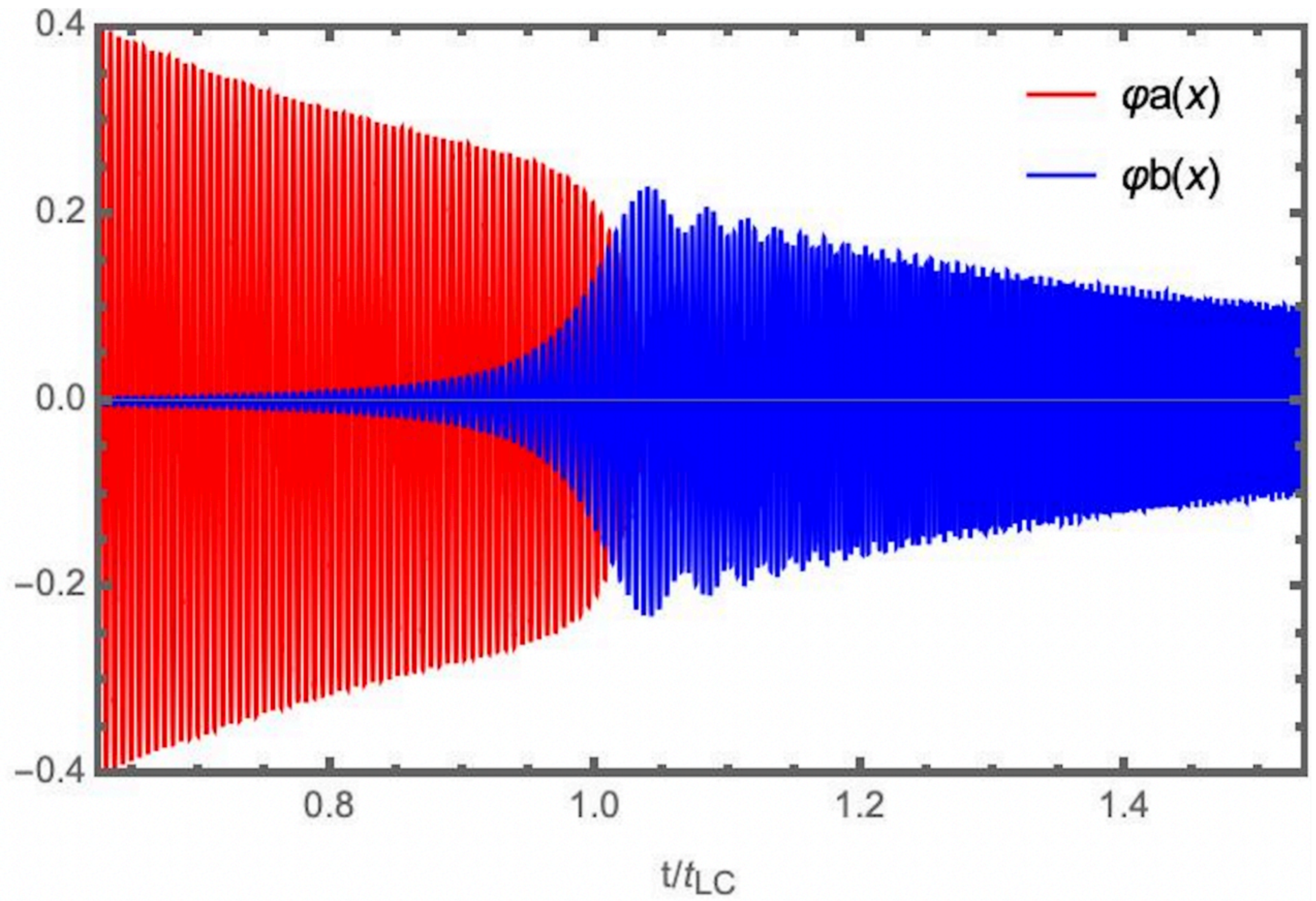
Dynamics of Level Crossing

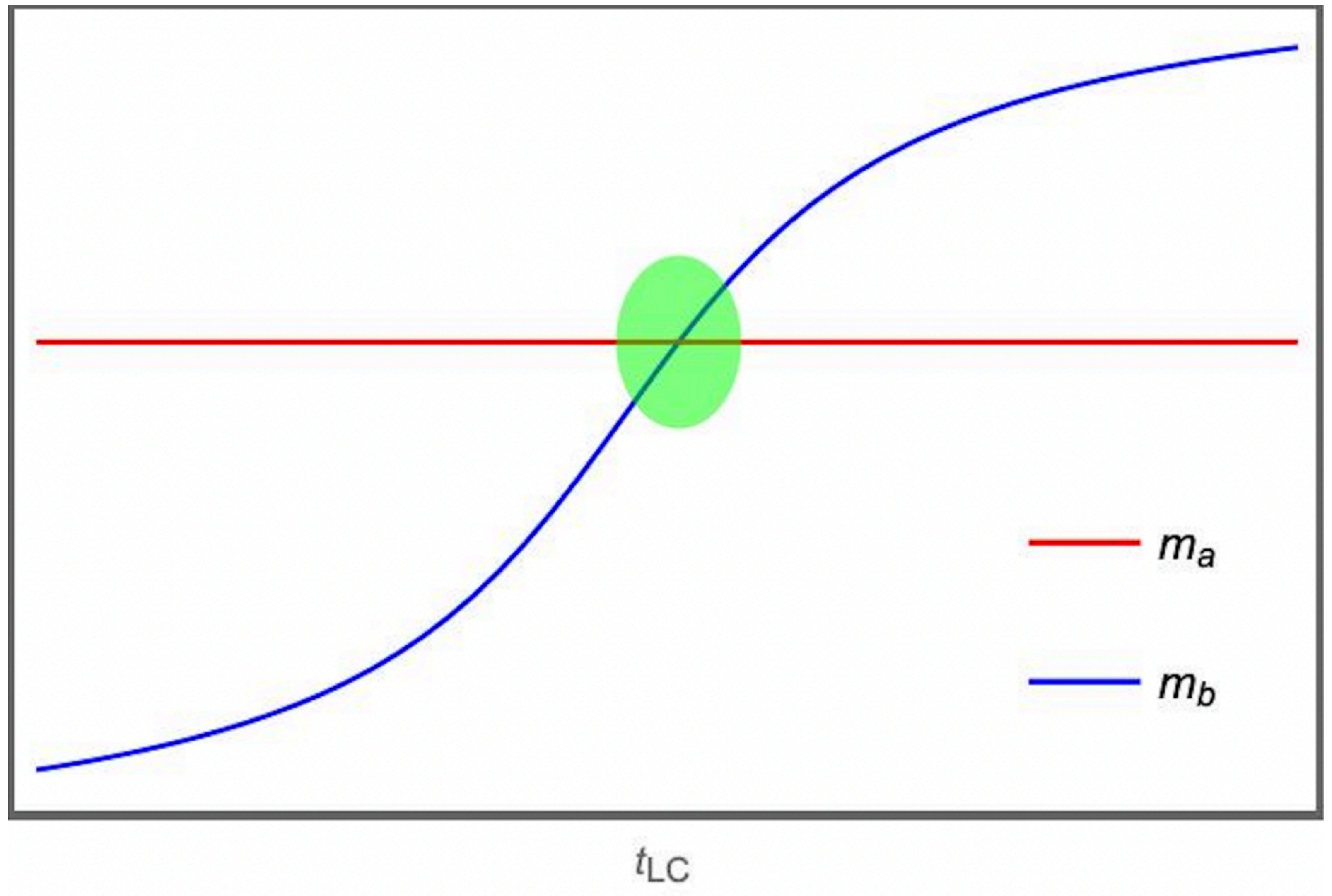


Adiabatic

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

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

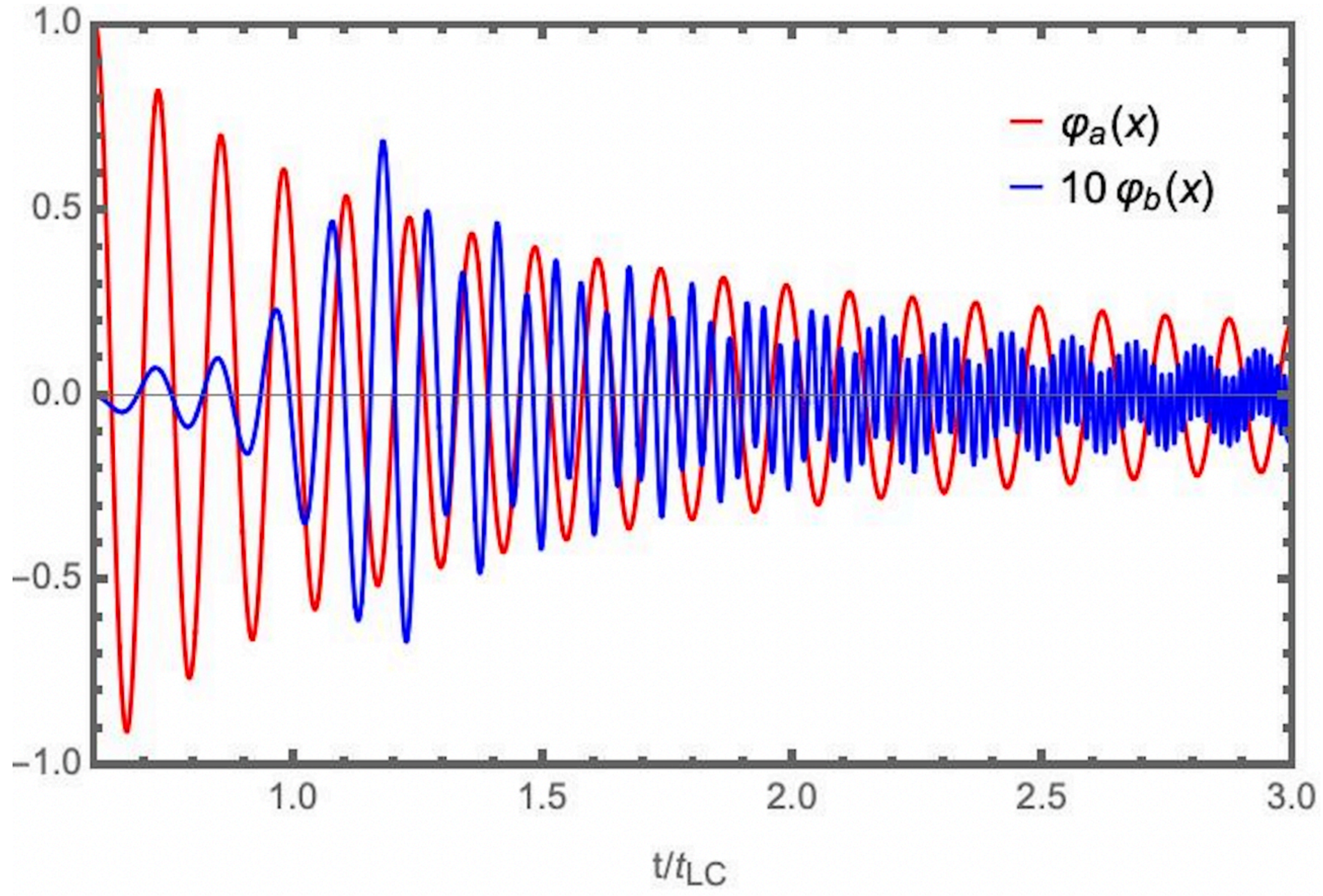




non-Adiabatic

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

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



QCD Axion DM —> DM+DE

QCD Axion DM —> DM+DE

Several constraining conditions, eg:

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

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

$$f > \Lambda_b\,; \qquad f \ll {\rm eV}$$

QCD Axion DM —> DM+DE

Several constraining conditions, eg:

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

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

$$f > \Lambda_b\,; \qquad f \ll {\rm eV}$$

Imply a **non-adiabatic** level crossing

$$\epsilon = \frac{f}{F} \lesssim 10^{-22}$$

QCD Axion DM —> DM+DE

Several constraining conditions, eg:

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

Imply a **non-adiabatic** level crossing

$$\epsilon = \frac{f}{F} \lesssim 10^{-22}$$

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

$$f > \Lambda_b\,; \qquad f \ll {\rm eV}$$

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

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

Conclusions of Part 2

Conclusions of Part 2

- A coupled 2 axions system can generate ρ_b from axion DM via φ_a -> φ_b conversion

Conclusions of Part 2

- A coupled 2 axions system can generate ρ_b from axion DM via φ_a -> φ_b conversion

- If the QCD axion constitutes the DM, there is not much freedom for model building. In particular, a non-adiabatic (partial) conversion is strongly favoured.

Conclusions of Part 2

- A coupled 2 axions system can generate ρ_b from axion DM via $\varphi_a \to \varphi_b$ conversion

- If the QCD axion constitutes the DM, there is not much freedom for model building. In particular, a non-adiabatic (partial) conversion is strongly favoured.

- The LC mechanism can shed light on the “why now ?” puzzle: why $z_{DE} \sim 0.3$

Conclusions of Part 2

- A coupled 2 axions system can generate ρ_b from axion DM via φ_a -> φ_b conversion

- If the QCD axion constitutes the DM, there is not much freedom for model building.
  In particular, a non-adiabatic (partial) conversion is strongly favoured.

- The LC mechanism can shed light on the "why now ?" puzzle: why $z_{DE} \sim 0.3$

Thanks for your attention !

arXiv:2503.14743

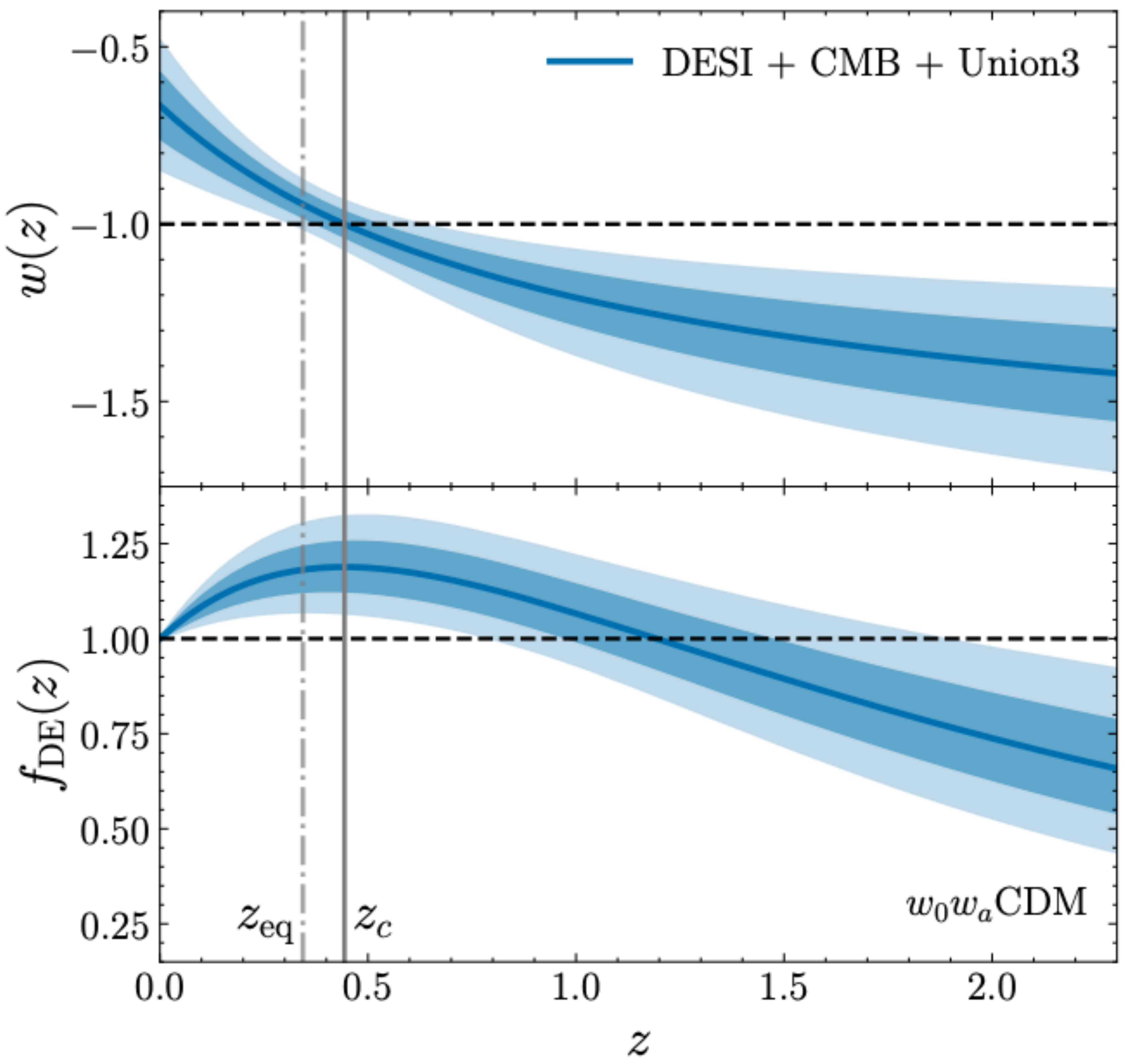


FIG. 2. Equation of state parameter, $w(z) = P/\rho c^2$, and corresponding normalized dark energy density, $f_{\rm DE}(z) \equiv \rho_{\rm DE}(z)/\rho_{\rm DE,0}$, as a function of redshift using the $w_0 w_a$ parametrization. The solid and dashed-dotted vertical lines indicate the phantom-crossing ($z_{\rm c}$) and dark energy-matter equality ($z_{\rm eq}$) redshifts, respectively. The horizontal dashed line represents ΛCDM.

Accelerated Cosmic Expansion, Mass Creation, and the QCD Axion

Enrico Nardi

with: K. Müürsepp (NICPB) & C. Smarra (SISSA)

KBFI NICPB HEP Group

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

LIO Int. Conference 2025 - May 23, 2025 - IP2I Lyon