Time Evolution of the Electromagnetic Coupling in Accelerating Universes

- Variation of Couplings and Accelerated Expansion
- $N = 4$ Supergravity Model
- Breaking of Lorentz Symmetry
- Constraints on the Variation of the Electromagnetic Coupling
- Two-Field Quintessence Model
- Outlook

Orfeu Bertolami

Instituto Superior Técnico, Departamento de Física, Lisbon

O. B., R. Lehnert, R. Potting, A. Ribeiro

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Variation of Couplings and Accelerated Expansion

• Variation of couplings, masses and violation of fundamental symmetries arise in many effective low-energy models of unification theories

- Tree level 4-D string theory, masses and couplings run towards zero, unless the dilaton, Φ, acquires a potential with suitable minima
Dilaton runaway problem: $V(\Phi) = 0$ in all orders in string perturbation theory

Genus expansion model (Damour, Polyakov 1994)

Effective low-energy 4-D action, after dropping the antisymmetric second-order tensor and introducing fermions, $\hat{\psi}$, Yang-Mills fields, $\hat{A}^{\mu}$ in a space-time described by the metric, $\hat{g}_{\mu\nu}$:

$$S = \int_M d^4x\sqrt{-\hat{g}}B(\Phi)[\frac{1}{\alpha'}(\hat{R} + 4\hat{\nabla}_{\mu}\hat{\nabla}^{\mu}\Phi - 4(\hat{\nabla}\Phi)^2) - \frac{k_i}{4}\hat{F}_{\mu\nu}\hat{F}^{\mu\nu} - \overline{\hat{\psi}}\gamma^{\mu}\hat{D}_{\mu}\hat{\psi} + ...]$$

where the genus string expansion is contained in the function

$$B(\Phi) = e^{-2\Phi} + c_0 + c_1 e^{2\Phi} + c_2 e^{4\Phi} + \ldots$$

where α' is the inverse of the string tension, k_i is a gauge group constant and the constants c_0, c_1, ..., can be determined.
To recover Einstein gravity, a conformal transformation must be performed

$$g_{\mu\nu} = B(\Phi)\hat{g}_{\mu\nu}$$

leading to an action where the coupling constants and masses are functions of the rescaled dilaton, ϕ,

$$S = \int_M d^4x\sqrt{-g}\left[\frac{1}{4q}R - \frac{1}{2q}(\nabla\phi)^2 - \frac{k}{4}B(\phi)F_{\mu\nu}F^{\mu\nu} - \overline{\psi}\gamma^{\mu}D_{\mu}\psi + \ldots\right]$$

so that $4q = 16\pi G = \frac{1}{4}\alpha'$ and

$$g^{-2} = kB(\phi) \quad , \quad m_{\psi} = m_{\psi}(B(\phi))$$

This dependence implies that particles fall differently in a gravitational field and leads to a small violation of the Weak Equivalence Principle:

$$\frac{\Delta a}{a} \simeq 10^{-18}$$

This model also implies the electromagnetic coupling is a function of the redshift, z:

$$\frac{|\alpha(z) - \alpha(0)|}{\alpha(0)} \lesssim 0.7 \times 10^{-6} ln(1+z)$$

[Damour 2003]

- In scalar-tensor theories of gravity, the gravitational coupling has a dependence on the cosmic time. Bounds arise from the timing of the binary pulsar PSR1913+16, but varying-G solar models and measurements of masses and ages of neutron stars yield the most stringent limits:

$$\left(\frac{\dot{G}}{G}\right) = (-0.6 \pm 2.0) \times 10^{-12}\, y^{-1}$$

[O.B., Garcia-Bellido 1996; Gillies 1997; Chiba 2001]

• The acceleration of the expansion of the Universe inferred from Type Ia Supernovae ($z \gtrsim 0.3$) seems to be the only late time cosmological event to which the recent evidence on the variation the fine structure constant obtained from the observation of distant GSOs (($z \sim 0.2 - 3.7$) can be related with

[Olive, Pospelov 2002; Gardner 2003; Anchordoqui, Goldberg 2003]
[Khouri, Weltman 2003; Mota, Barrow 2003]
[Copeland, Nunes, Pospelov 2004]

$N = 4$ ($D = 4$) Supergravity Model

- Limit of $N = 1$ Supergravity in $D = 11$ (M-theory)
- Exhibits variation of couplings and violation of Lorentz symmetry

[Kostelecký, Lehnert, Perry 2003]

- Bosonic sector: A (axion), B (dilaton) coupled to $F_{\mu\nu}$:

$$\kappa\mathcal{L}_{\rm Sugra} = -\tfrac{1}{2}\sqrt{g}R + \sqrt{g}(\partial_\mu A\partial^\mu A + \partial_\mu B\partial^\mu B)/4B^2 - \tfrac{1}{4}\kappa\sqrt{g}MF_{\mu\nu}F^{\mu\nu}$$
$$-\tfrac{1}{4}\kappa\sqrt{g}NF_{\mu\nu}\tilde{F}^{\mu\nu}$$

where $\kappa = 8\pi G$, $\tilde{F}^{\mu\nu} = \varepsilon^{\mu\nu\rho\sigma}F_{\rho\sigma}/2$ and

$$M = \frac{B(A^2 + B^2 + 1)}{(1 + A^2 + B^2)^2 - 4A^2} \qquad N = \frac{A(A^2 + B^2 - 1)}{(1 + A^2 + B^2)^2 - 4A^2}$$

Potentials for the scalars are modelled by quadratic self-interactions, so that including the coupling with matter, the full Lagrangian density reads:

$$\mathcal{L} = \mathcal{L}_{\rm Sugra} - \tfrac{1}{2}\sqrt{g}(m_A^2A^2 + m_B^2B^2) + \mathcal{L}_{\rm Matter}$$

Evolution equations in a flat Friedmann-Robertson-Walker Universe ($F_{\mu\nu} = 0, \rho = c_n a^{-3}$)

$$6\frac{\dot{a}^2}{a^2} = m_A^2A^2 + m_B^2B^2 + \frac{\dot{A}^2 + \dot{B}^2}{2B^2} + 2\rho$$

$$4\frac{\ddot{a}}{a} + 2\frac{\dot{a}^2}{a^2} = m_A^2A^2 + m_B^2B^2 - \frac{\dot{A}^2 + \dot{B}^2}{2B^2}$$

$$\frac{d}{dt}\left(\frac{a^3\dot{A}}{B^2}\right) = -2a^3m_A^2A$$

$$\frac{d}{dt}\left(\frac{a^3\dot{B}}{B^2}\right) = -2a^3m_B^2B - \frac{a^3}{B^3}(\dot{A}^2 + \dot{B}^2)$$

From the Einstein equations:

$$6\frac{\ddot{a}}{a} = m_A^2 A^2 + m_B^2 B^2 - \frac{\dot{A}^2 + \dot{B}^2}{B^2} - \rho$$

Thus, in a realistic model, at least one of the parameters m_A or m_B must be non-vanishing in order to yield $\ddot{a}(t) > 0$

Numerical search has given a variety of parameter sets consistent with the observations. An example is the following set:

$$\begin{aligned}
m_A &= 2.7688 \times 10^{-42}\,\mathrm{GeV} \\
m_B &= 3.9765 \times 10^{-41}\,\mathrm{GeV} \\
c_{\mathrm{n}} &= 2.2790 \times 10^{-84} \\
a(t_{\mathrm{n}}) &= 1 \\
A(t_{\mathrm{n}}) &= 1.0220426 \\
\dot{A}(t_{\mathrm{n}}) &= -8.06401 \times 10^{-46}\,\mathrm{GeV} \\
B(t_{\mathrm{n}}) &= 0.016598 \\
\dot{B}(t_{\mathrm{n}}) &= -2.89477 \times 10^{-45}\,\mathrm{GeV}
\end{aligned}$$

The parameter values for the "canonical" model as inferred from the cosmological observations are taken to be

$$\begin{aligned}
\Omega_{\mathrm{M}} &= 0.30 \pm 0.04 \\
\Omega_{\Lambda} &= 0.70 \pm 0.04 \\
H_0 &= (70 \pm 4)\ km\ s^{-1}\ Mpc^{-1}
\end{aligned}$$

Breaking of Lorentz and CPT Symmetries

- Spontaneous Symmetry Breaking - String Theory

[Kostelecký, Samuel 1989]
[Kostelecký, Potting 1996, 2001]

- Spacetime foam

[Ellis, Mavromatos, Nanopoulos 1999]

- Non-trivial spacetime topology

[Klinkhamer 2000]

- Loop quantum gravity

[Alfaro, Morales-Técotl, Urrutia 2000]

- Noncommutative Field Theory

[Carroll, Harvey, Kostelecký, Lane, Okamoto 2001]
[O.B., Guisado 2003]

- Spacetime-varying couplings ($\star$)

[Kostelecký, Lehnert, Perry 2003]
[O.B., Lehnert, Potting, Ribeiro 2004]

($\star$) Equations of Motion

$$\frac{1}{e^2}\partial_\mu F^{\mu\nu} - \frac{2}{e^3}(\partial_\mu e)F^{\mu\nu} + \frac{1}{4\pi^2}(\partial_\mu \theta)\tilde{F}^{\mu\nu} = J^\nu$$

Gradient terms in e and θ select a preferred direction in the local inertial frame

Constraints on the Variation of the Electromagnetic Coupling

- Observations of the spectra of 128 QSOs with $z = 0.2 - 3.7$ suggest that the fine structure constant was smaller in recent cosmological past ($4.7\,\sigma$):

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(z) - \alpha(0)}{\alpha(0)} = (-0.54 \pm 0.12) \times 10^{-5}$$

[Murphy et al. 2000-2003]

- Most recent data from Chand *et al.* obtained via a new sample of $Mg\ II$ systems from QSOs ($0.4 \leq z \leq 2.3$) yield ($3\,\sigma$) (terrestrial isotopic abundances):

$$\frac{\Delta\alpha}{\alpha} = (-0.06 \pm 0.06) \times 10^{-5}$$

If, instead, low-metalicity isotopic abundances are assumed

$$\frac{\Delta\alpha}{\alpha} = (-0.36 \pm 0.06) \times 10^{-5}$$

- Oklo natural reactor yields, at 95% CL ($z = 0.14$)

$$-0.9 \times 10^{-7} < \frac{\Delta\alpha}{\alpha} < 1.2 \times 10^{-7}$$

[Damour, Dyson 1996; Fujii 2003]

A lower bound over the last two billion years is given by

$$\frac{\Delta\alpha}{\alpha} \geq 4.5 \times 10^{-8}$$

[Lamoreaux 2003]

- Estimates of the age of iron meteorites ($z = 0.45$), combined with a measurement of the Os/Re ratio from the radioactive decay ^{187}Re $\rightarrow ^{187}$Os, gives ($2\,\sigma$)

$$-24 \times 10^{-7} < \frac{\Delta\alpha}{\alpha} < 8 \times 10^{-7}$$

[Olive et al. 2003; Fujii, Iwamoto 2003]

- Observations of the hyperfine frequencies of the ^{133}Cs and ^{87}Rb atoms in their electronic ground state, using several laser cooled atomic fountain clocks give at present ($z = 0$)

$$\left|\frac{1}{\alpha}\frac{d\alpha}{dt}\right| < 4.2 \times 10^{-15}\ \mathrm{yr}^{-1}$$

[Marion et al. 2002]

- Tigher bounds arise from the remeasurement of the $1s - 2s$ transition of the atomic hydrogen and comparison with respect to the ground state hyperfine splitting in ^{133}Cs and combination with the drift of an optical transition frequency in ^{199}Hg^{+}:

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = (-0.9 \pm 4.2) \times 10^{-15}\ \mathrm{yr}^{-1}$$

[Fischer et al. 2003]

- Constraints from Cosmic Microwave Background Radiation ($z = 10^{3}$)

$$|\Delta\alpha/\alpha| \leq 10^{-2}$$

[Battye, Crittenden, Weller 2001]

- Constraints from Big Bang nucleosynthesis ($z = 10^{8} - 10^{10}$)

$$-6 \times 10^{-4} < \Delta\alpha/\alpha < 1.5 \times 10^{-4}$$

[Kaplinghat, Scherrer, Turner 1999; Landau, Harari, Zaldarriaga 2001]

Two-Field Quintessence Model Minimally Coupled to Electromagnetism

• Scalar fields are ubiquitous in unification theories. In cosmology, coupled scalar fields are considered to model the reheating process after inflation and in the so-called hybrid inflationary models

Two-field quintessence models have interesting features: are "natural" in SUSY theories, allow for transient acceleration (no future horizons and no inconsistency with S-matrix of string theory)

[Masiero, Pietroni, Rosati 2000; Fujii 2000; Bento, O.B., Santos 2002]

- Effective action, in natural units ($M \equiv M_P/\sqrt{8\pi} = 1$)

$$S = \int d^4x\sqrt{-g}\ \left[-\tfrac{1}{2}R + \mathcal{L}_b + \mathcal{L}_Q + \mathcal{L}_{Q-em}\right]$$

where $\mathcal{L}_b$ represents the background matter (CDM, baryons and radiation), with the equation of state $p_b = w_b\ \rho_b$ ($-1 \leq w_b \leq 1$); $\mathcal{L}_Q$ is the Lagrangian density for the scalar fields

$$\mathcal{L}_Q = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi + \frac{1}{2}\partial^\mu\psi\partial_\mu\psi - V(\phi,\psi)$$

and

$$V(\phi,\psi) = e^{-\lambda\phi}P(\phi,\psi)$$

where

$$P(\phi,\psi) = A\ + (\phi-\phi_*)^2 + B\ (\psi-\psi_*)^2\ + C\ \phi(\psi-\psi_*)^2 + D\ \psi(\phi-\phi_*)^2$$

Evolution equations for a spatially-flat Friedmann-Robertson-Walker Universe ($H \equiv \dot{a}/a$):

$$\dot{H} = \frac{1}{2}\left(\rho_b + p_b + \dot{\phi}^2 + \dot{\psi}^2\right)$$

$$\dot{\rho}_\gamma = -3H(\rho_b + p_b)$$

$$\ddot{\phi} = -3H\dot{\phi} - \partial_\phi V$$

$$\ddot{\psi} = -3H\dot{\psi} - \partial_\psi V$$

subject to the Friedmann constraint

$$H^2 = \frac{1}{3}\left(\rho_b + \frac{1}{2}\dot{\phi}^2 + \frac{1}{2}\dot{\psi}^2 + V\right)$$

where $\partial_{\phi(\psi)}V \equiv \frac{\partial V}{\partial\phi(\psi)}$. The total energy density of the homogeneous scalar fields is given by $\rho_Q = \dot{\phi}^2/2 + \dot{\psi}^2/2 + V(\phi,\psi)$.

- The interaction term between the scalar fields and the electromagnetic field is given by

$$\mathcal{L}_{Q-em} = -\tfrac{1}{4}B_F(\phi,\psi)F_{\mu\nu}F^{\mu\nu}$$

[Bekenstein 1982]

Linearly expanding $B(\phi,\psi)$

$$B_F(\phi,\psi) = 1 - \zeta_1(\phi - \phi_0) - \zeta_2(\psi - \psi_0)$$

where ϕ_0 and ψ_0 are the present values of the scalar fields. Thus, the variation of the fine structure constant, $\alpha = \alpha_0/B_F(\phi,\psi)$, is given by

$$\frac{\Delta\alpha}{\alpha} = \zeta_1(\phi - \phi_0) + \zeta_2(\psi - \psi_0)$$

Searches of new forces mediated by new scalars yield

$$\zeta_F \leq 7 \times 10^{-4}$$

[Olive, Pospelov 2002]

Thus

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -\left(\zeta_1\frac{d\phi}{dy} + \zeta_2\frac{d\psi}{dy}\right)H_0$$

where $y \equiv 1 + z$ and $H_0 = (h/9.78) \times 10^{-9}\ \mathrm{yr}^{-1}$

Results

- Adopt priors: $h = 0.70$, $\Omega_m = 0.3$, $\Omega_Q = 0.70$, $\Omega_r = 4.15 \times 10^{-5} h^{-2}$ and adjust ζ_1 and ζ_2, so to satisfy the bounds on the evolution of α

These priors are consistent with a combination of WMAP data and other CMB experiments (ACBAR and CBI), 2dFGRS measurements and Lyman α forest data: $h = 0.71^{+0.04}_{-0.03}$, $\Omega_m = 0.27 \pm 0.04$, $\Omega_Q = 0.73 \pm 0.04$. $w_Q < -0.78$ (95% CL)

- For large z, the tightest bound on dark energy arises from nucleosynthesis, $\Omega_Q(z = 10^{10}) < 0.045$, implying that $\lambda > 9$

[Bean, Hansen, Melchiorri 2001]

$\star$ Set of parameters for transient acceleration models: $\lambda = 9.5$, $A = 0.1$, $B = 10^{-3}$, $C = 8 \times 10^{-5}$, $D = 2.8$, $\phi_* = 28.965$, $\psi_* = 20$, $\Omega_Q = 0.042$ with $\zeta_1 = 2 \times 10^{-6}$ and $\zeta_2 = 8 \times 10^{-5}$, yielding

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = -4.5 \times 10^{-17}\ \text{yr}^{-1}$$

and

$$\frac{\Delta\alpha}{\alpha}(CMBR) = -2.7 \times 10^{-6}$$

$$\frac{\Delta\alpha}{\alpha}(BBN) = -1.1 \times 10^{-6}$$

$\star$ Set of parameters for permanent acceleration models: $\lambda = 9.5$, $A = 0.02$, $B = 2 \times 10^{-3}$, $C = 6 \times 10^{-4}$, $D = 4.5$, $\phi_* = 28.9675$, $\psi_* = 15$ for $\zeta_1 = -4 \times 10^{-5}$ and $\zeta_2 = 1 \times 10^{-6}$, yielding:

$$\frac{1}{\alpha}\frac{d\alpha}{dt} = 5.2 \times 10^{-17}\ \text{yr}^{-1}$$

$$\frac{\Delta\alpha}{\alpha}(CMBR) = 4.5 \times 10^{-5}$$

$$\frac{\Delta\alpha}{\alpha}(BBN) = 2.9 \times 10^{-4}$$

Outlook

• Connection between the variation of the electromagnetic coupling and the accelerated expansion of the Universe is intriguing. Most appealling models do not quite manage to fit the observed variation of α. A few causes can be advanced:

- Evidence on the change of α is not yet consensual

- Models do not account for all aspects of the problem

- Bekenstein model for the coupling between fields and the electromagnetic field strength is an oversimplification

• More research is required:

- Observational case for a varying α is settled

- Models based on fundamental theories are further studied

- Connection with the violation of fundamental symmetries (Lorentz, Weak Equivalence Principle, Translation, ...) are further investigated

- Connection with the Cosmological Constant Problem ?

TABLE I. Input-parameter sets P1, P2, P3, and P4.

Parameter	P1	P2	P3	P4
m_A in 10^{-42} GeV	0	1.5	0	1
m_B in 10^{-42} GeV	10	0	100	100
c_n in 10^{-84} GeV^2	2	2	2	2
$a(t_\mathrm{n})$	1	1	1	1
$A(t_\mathrm{n})$	1.023	1.023	1.023	1.023
$\dot{A}(t_\mathrm{n})$ in 10^{-47} GeV	47	47	47	-100
$B(t_\mathrm{n})$	0.022	0.022	0.022	0.022
$\dot{B}(t_\mathrm{n})$ in 10^{-45} GeV	-25	-25	-25	-60
t_n in 10^{40} GeV^{-1}	56	51	54	51

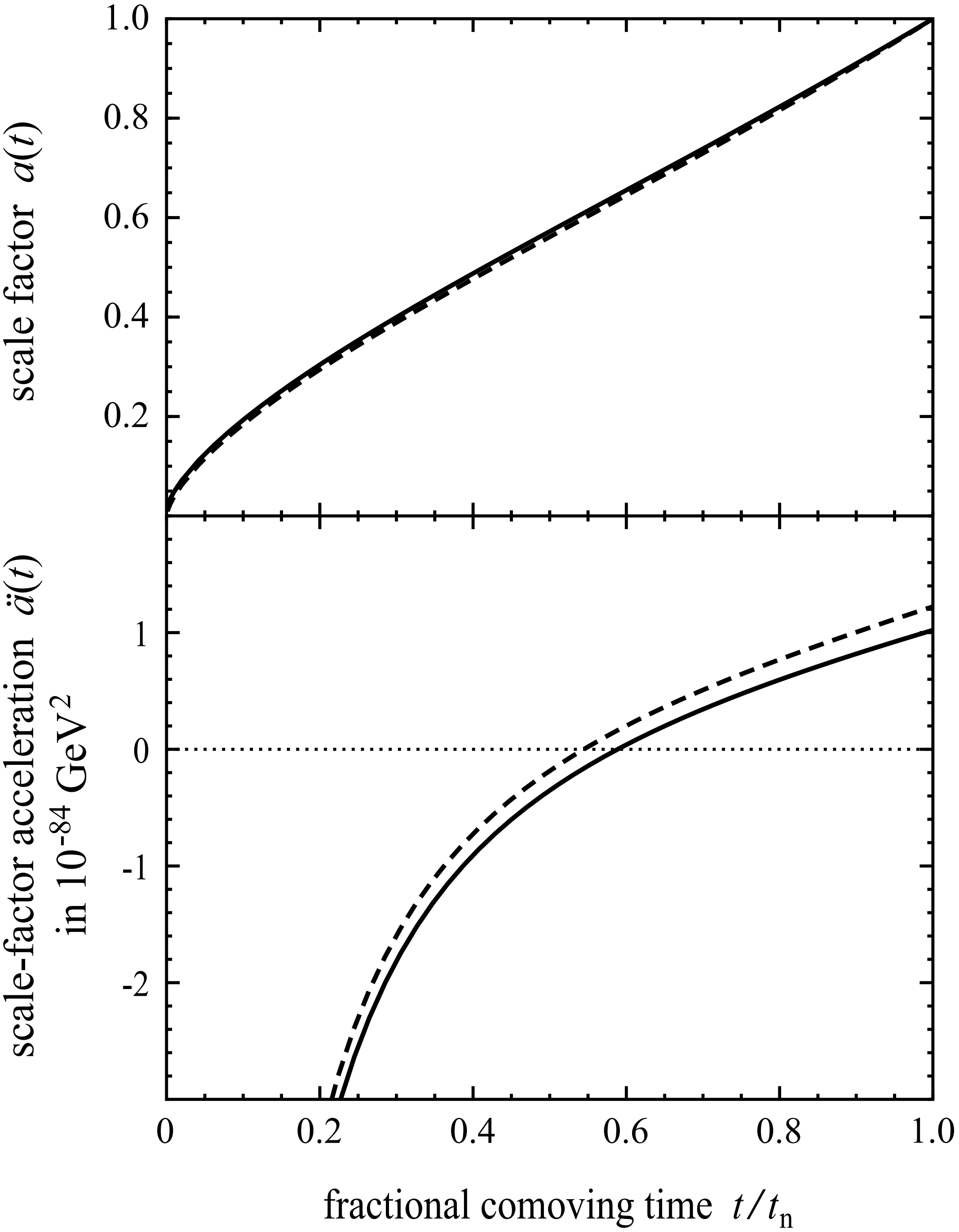

Figure 1: Time evolution of the scale factor $a(t)$ and its second derivative $\ddot{a}(t)$. The solid and dashed lines correspond to our supergravity universe and the canonical model, respectively. Note that for approximately the second half of its lifetime, the expansion of the Universe is speeding up in both models.

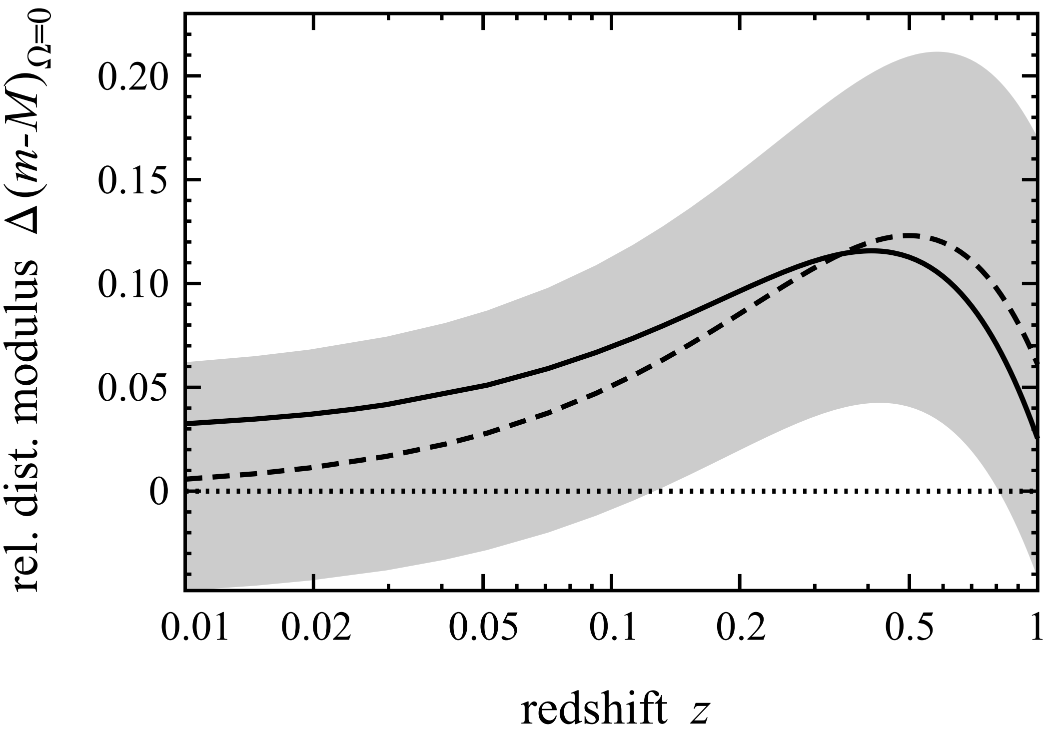

Figure 2: Distance modulus relative to an empty universe $\Delta(m - M)_{\Omega=0}$ versus redshift z. Our supergravity cosmology is represented by the solid line and the canonical model by the dashed line. The dotted line corresponds to the empty universe. The shaded region marks the canonical range of parameters.

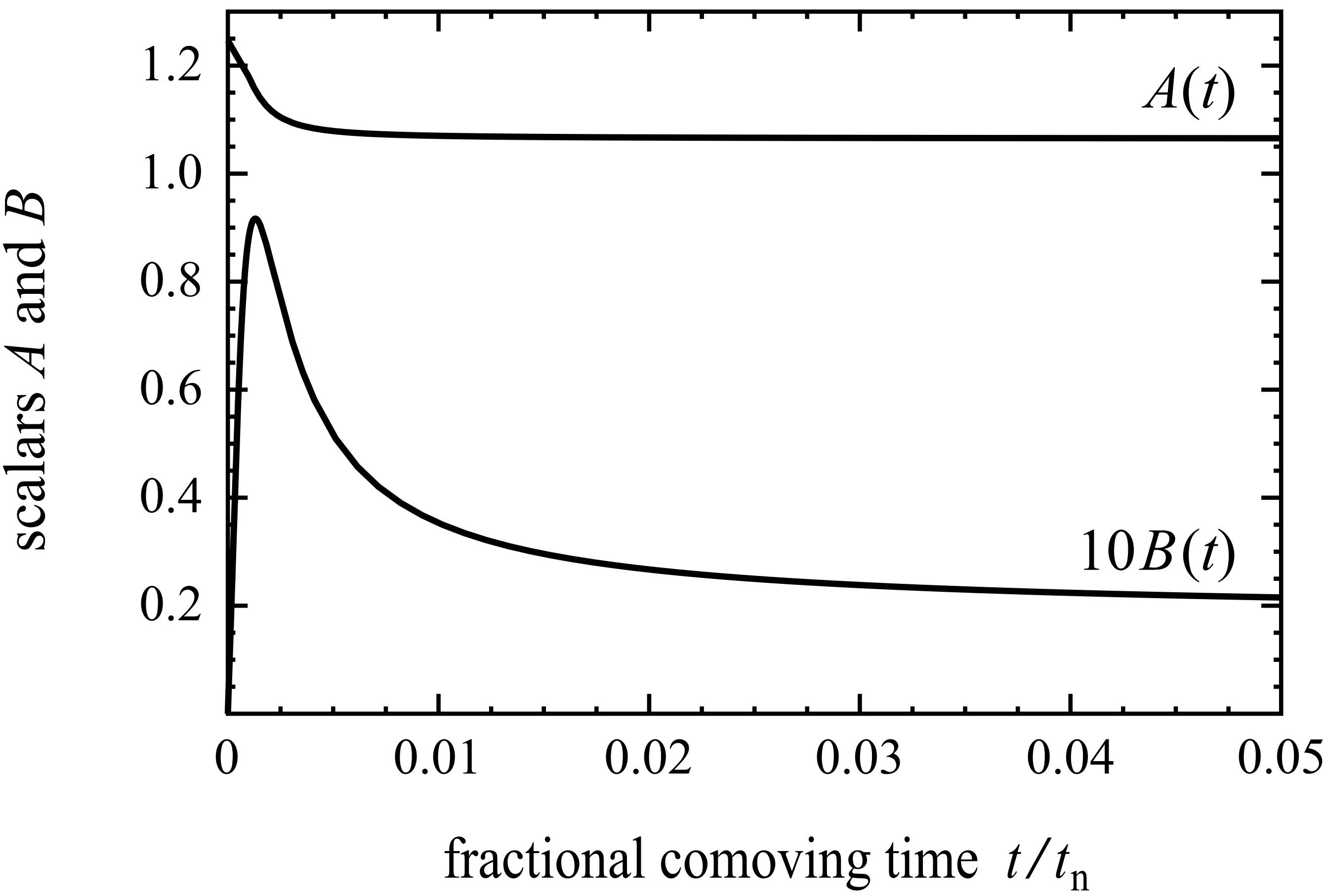

Figure 3: Time evolution of the scalars $A(t)$ and $B(t)$ at early cosmological times. In the recent past of our model universe, which is not shown here, $A(t)$ and $B(t)$ are essentially constant.

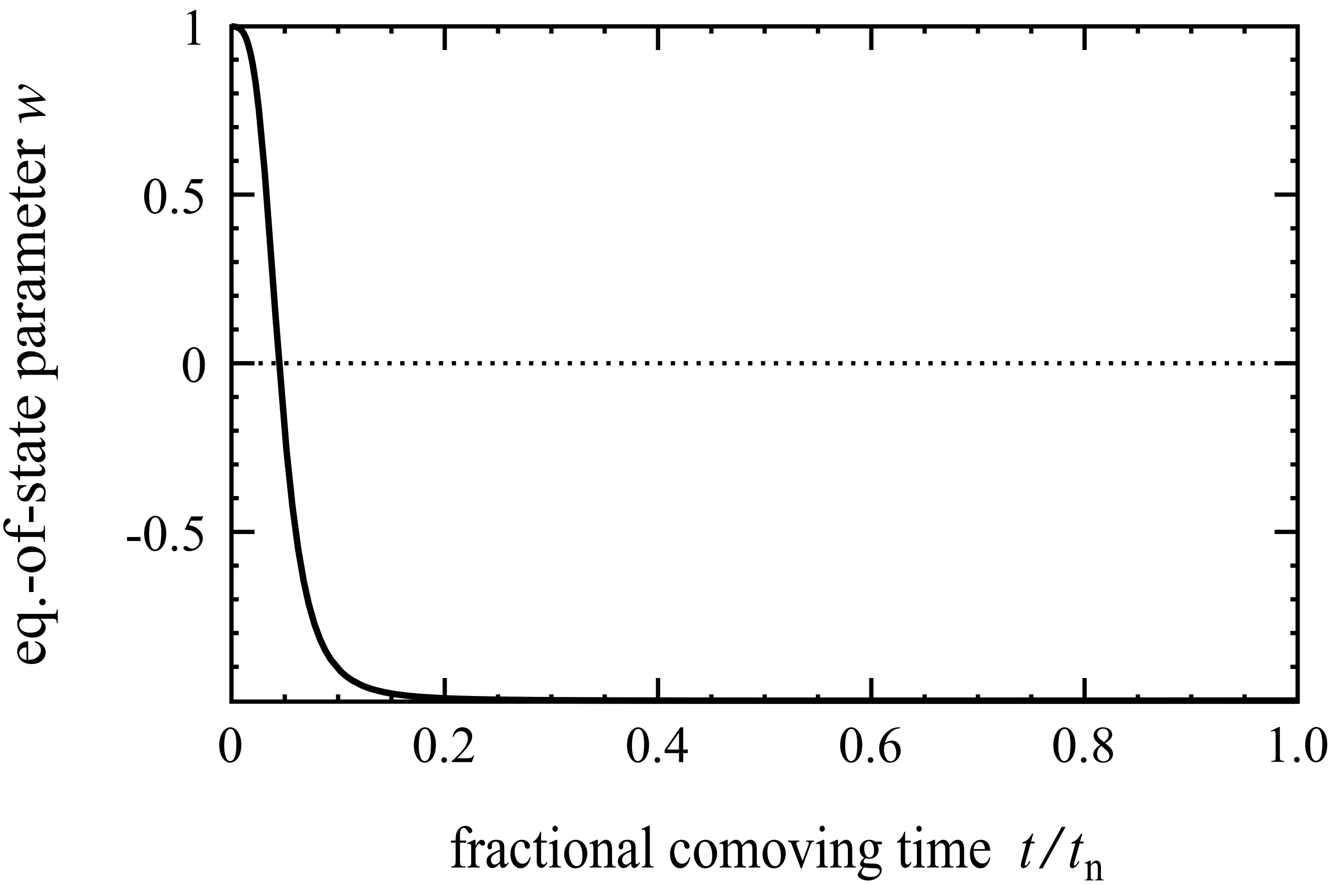

Figure 4: Time evolution of the equation-of state parameter w. At late times, $w \to -1$, so that the scalars essentially obey the cosmological-constant equation of state.

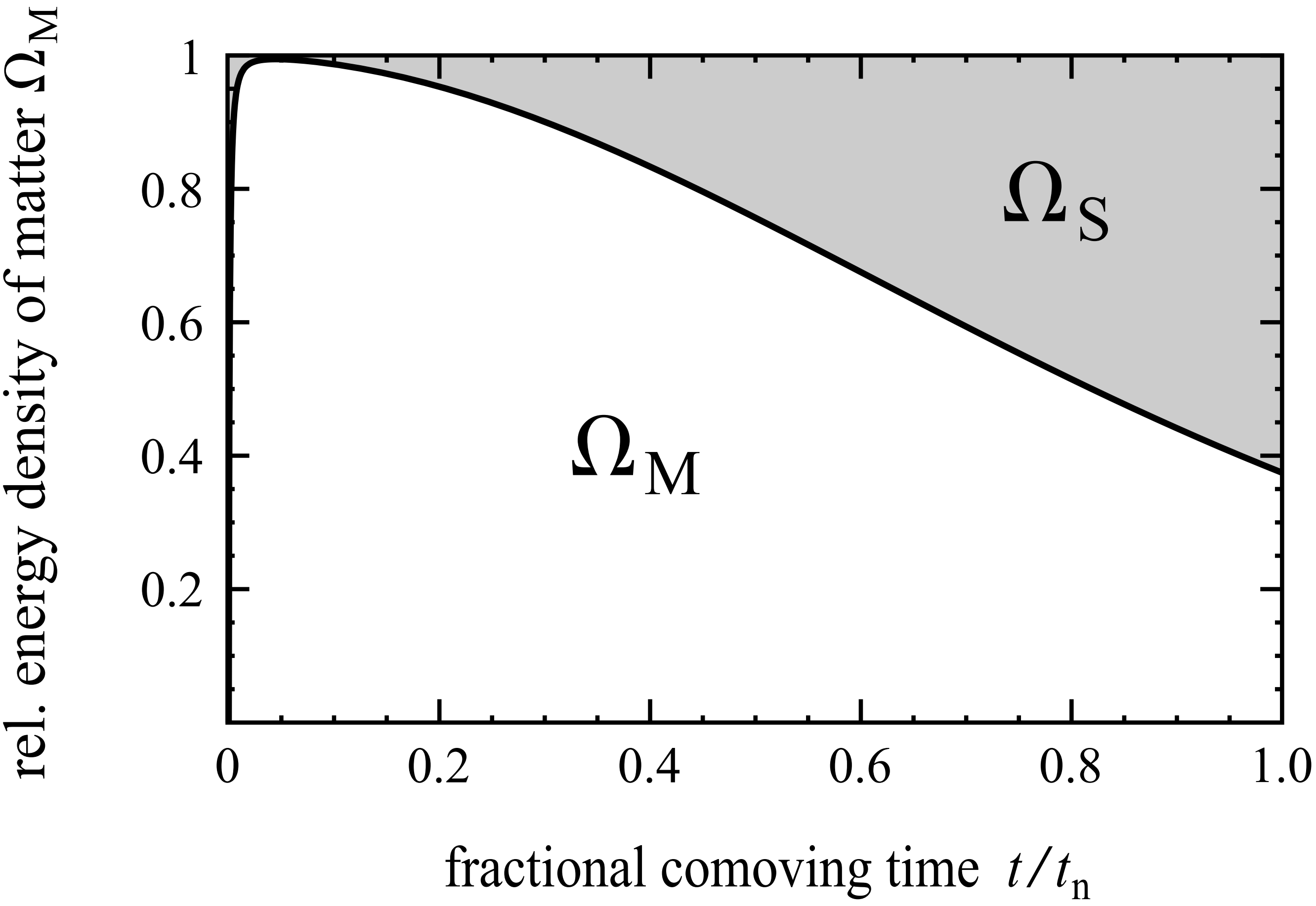

Figure 5: Relative energy density of matter Ω_M versus fractional comoving time. The shaded area shows Ω_S, which corresponds to the energy associated with the axion-dilaton background. At late times, Ω_S dominates, which parallels the cosmological-constant situation.

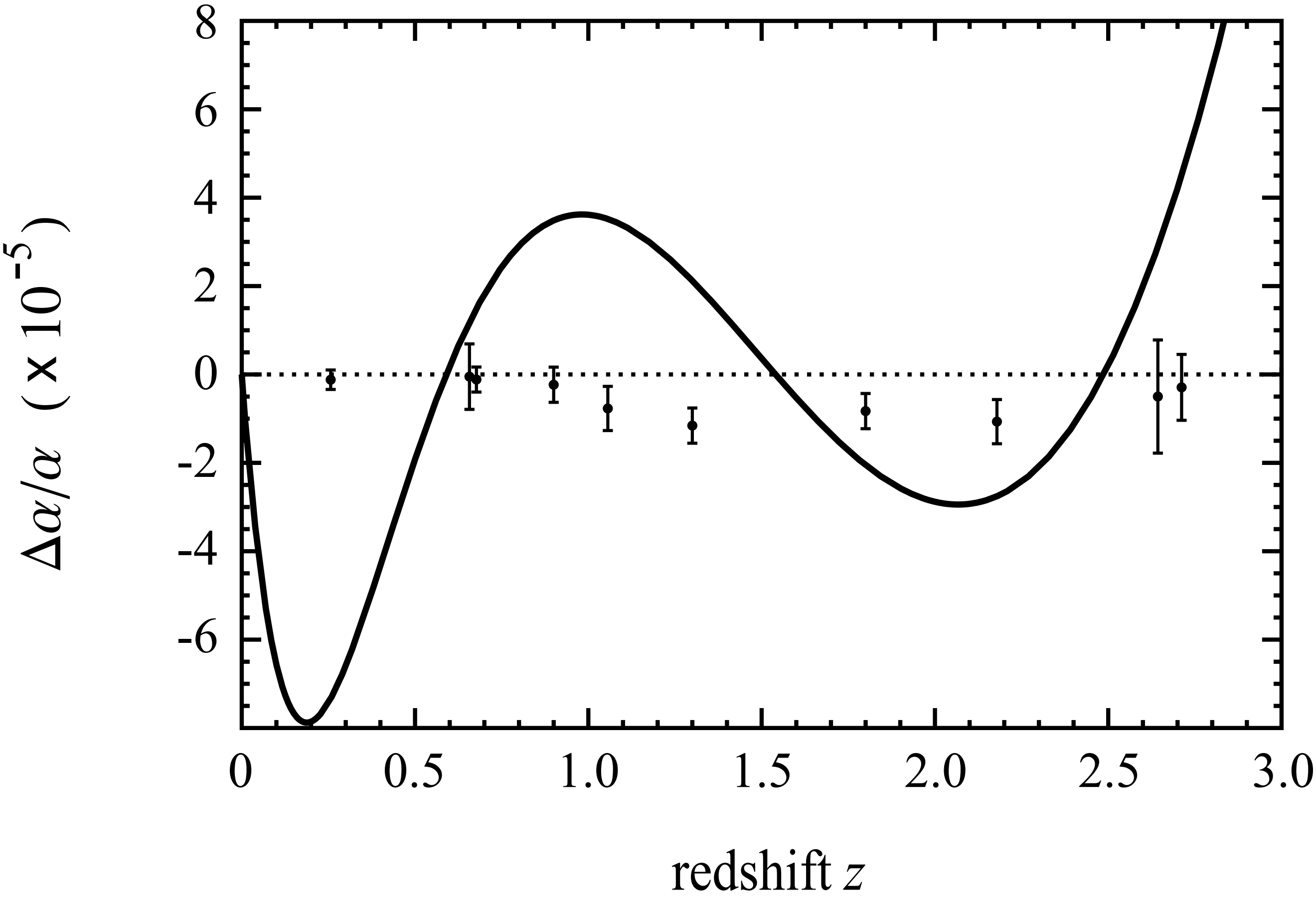

Figure 6: Relative time variation of the electromagnetic coupling versus fractional look-back time to the Big Bang. The present model with the specified parameters is represented by the solid line. Also shown is the Webb et al. dataset.

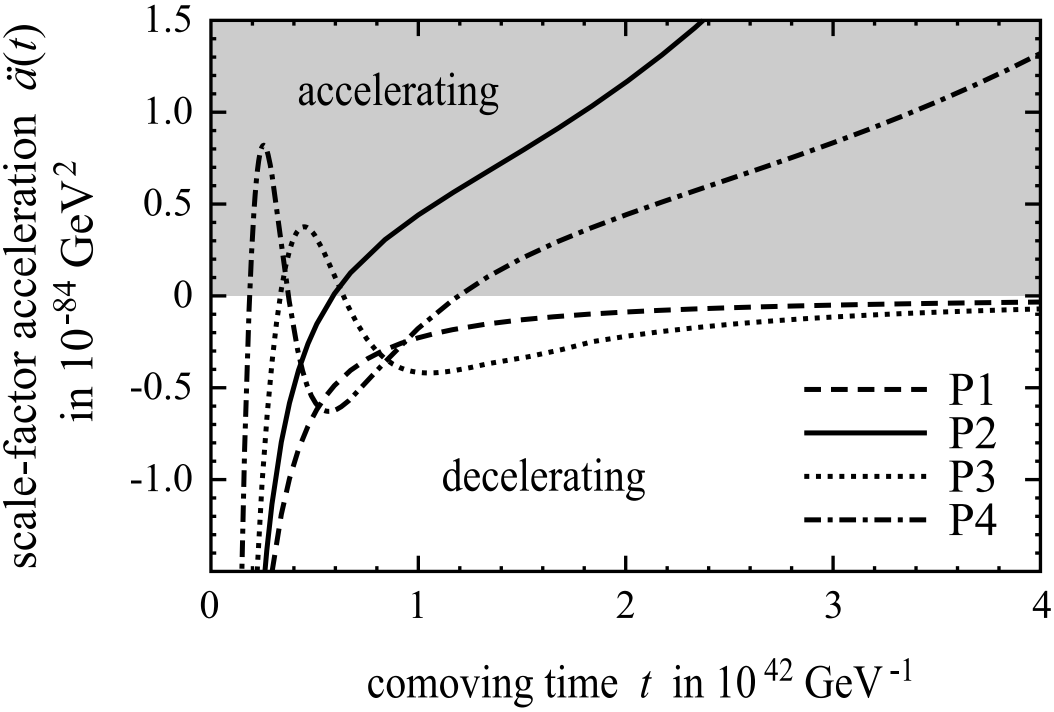

Figure 7: Acceleration $\ddot{a}(t)$ of the scale factor versus comoving time t for the various input values given in Table I. The shaded region corresponds to accelerated expansion.

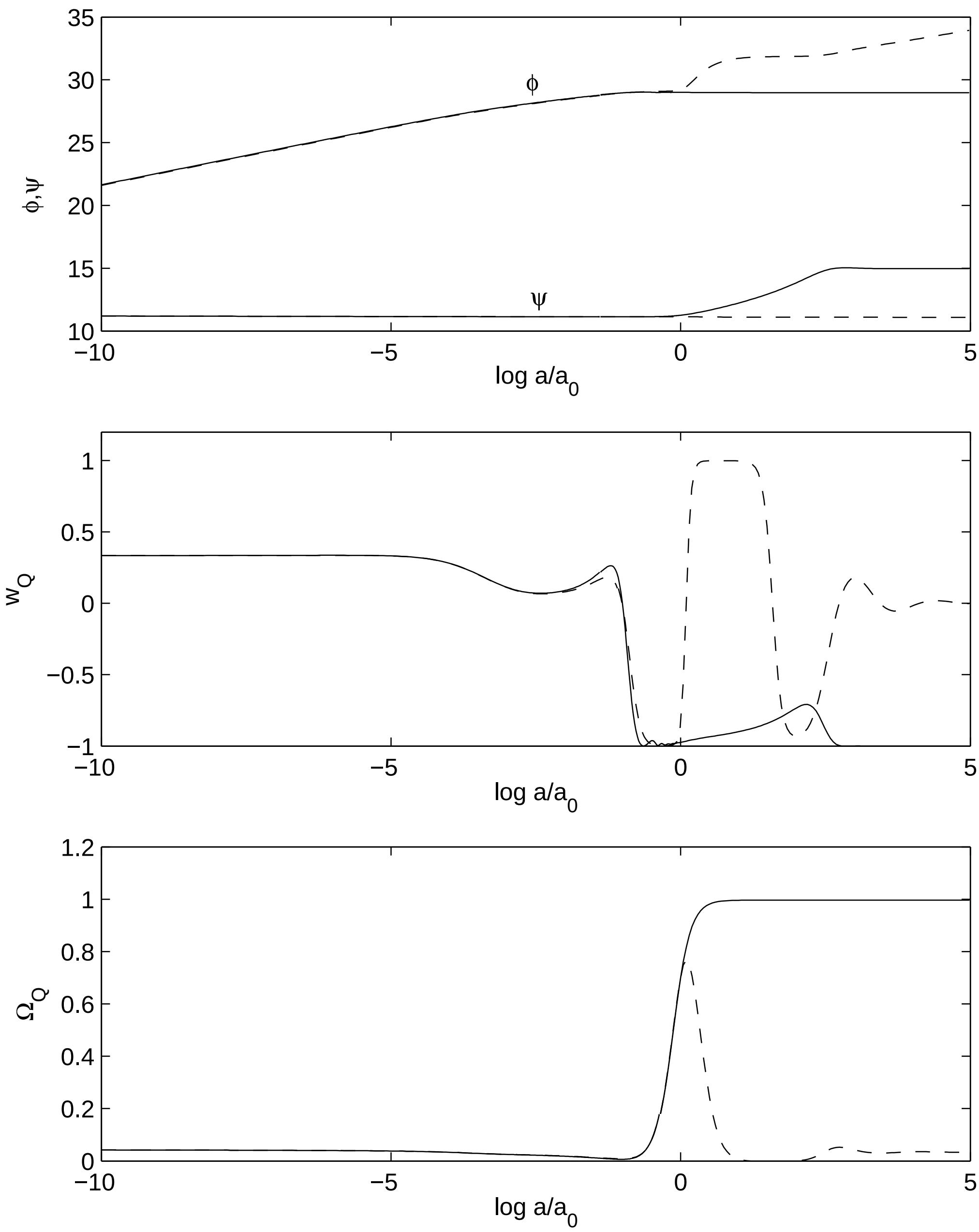

Figure 8: Evolution of the quintessence fields (upper panel), the equation of state parameter (middle panel) and the quintessence fractional energy density (lower panel), for transient (dashed) and permanent (full) acceleration solutions.

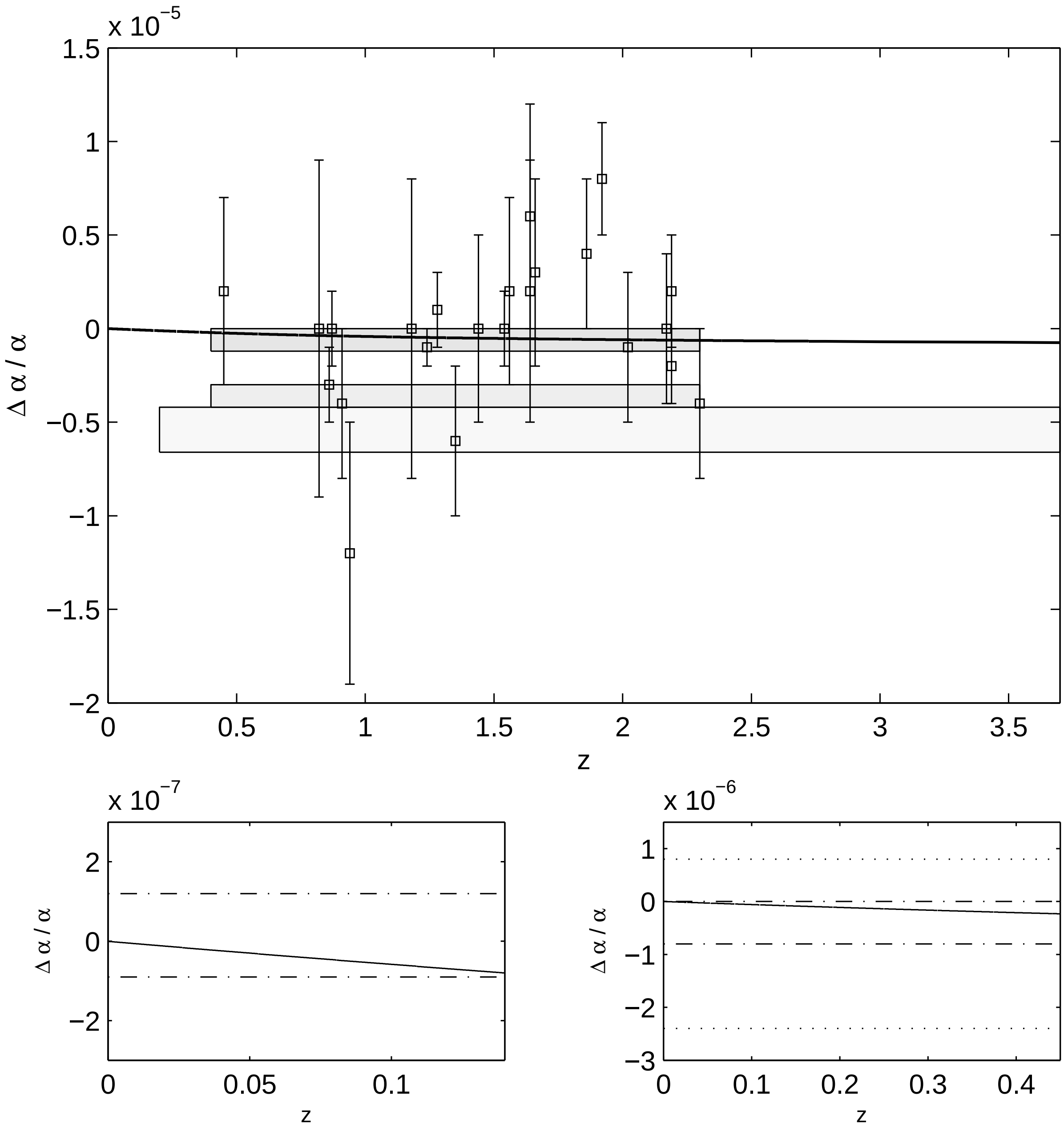

Figure 9: Evolution of α for a transient acceleration model with $\zeta_1 = 2 \times 10^{-6}$ and $\zeta_2 = 8 \times 10^{-5}$. In the upper panel, the boxes represent the QSO bounds given first and second Chand et al. bounds (top box), (middle box) and Murphy et al. (lower box). Also shown is the QSO absorption systems dataset of Chand et al.. The lower panel details the behaviour of α for small values of z. The lower left plot shows the Oklo bound (dash-dotted lines) and the right one the meteorite bounds (dash-dotted and dotted lines correspond to 1 σ and 2 σ, respectively).

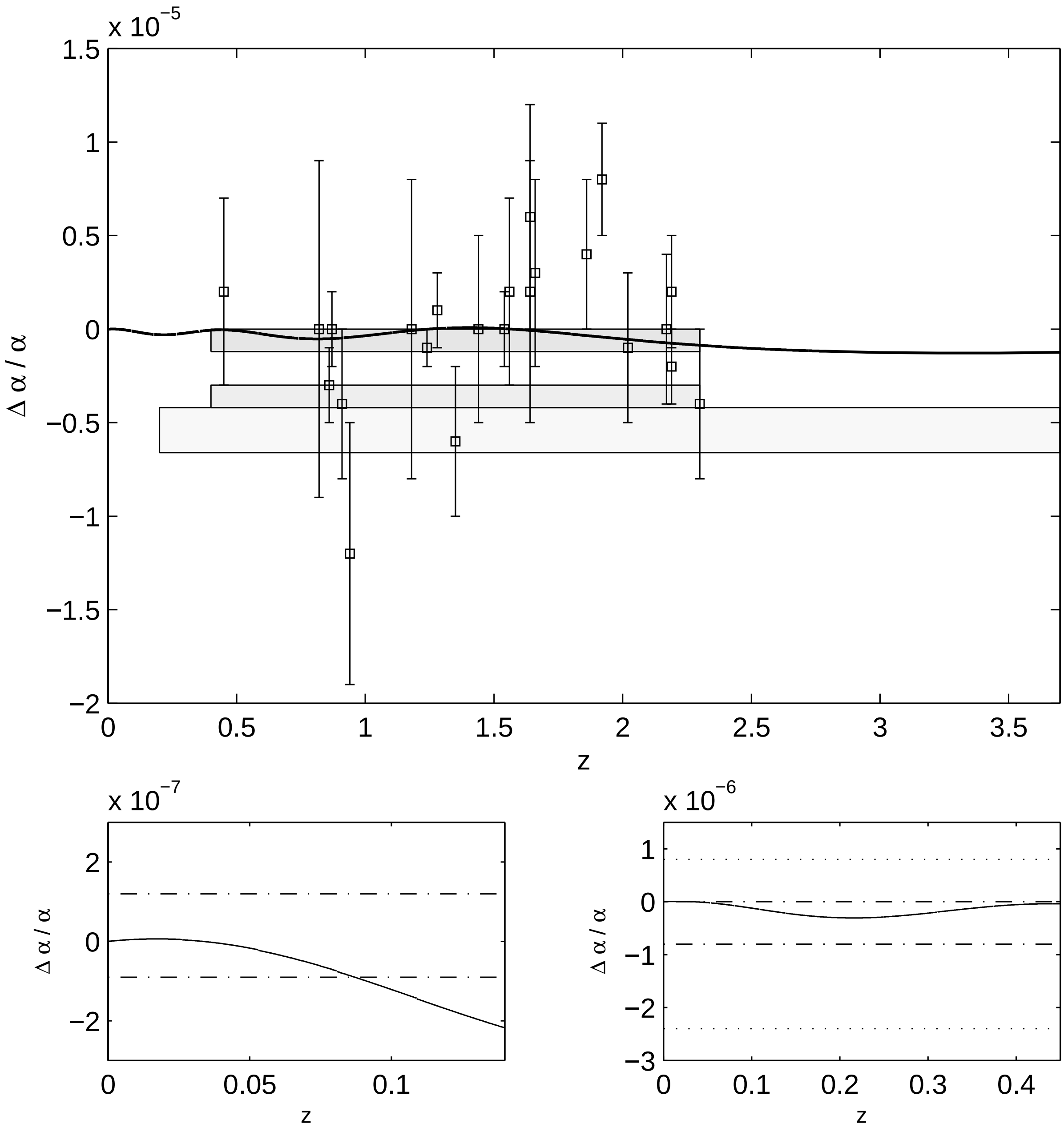

Figure 10: As above, but for a permanent acceleration model with $\zeta_1 = -4 \times 10^{-5}$ and $\zeta_2 = 1 \times 10^{-6}$.

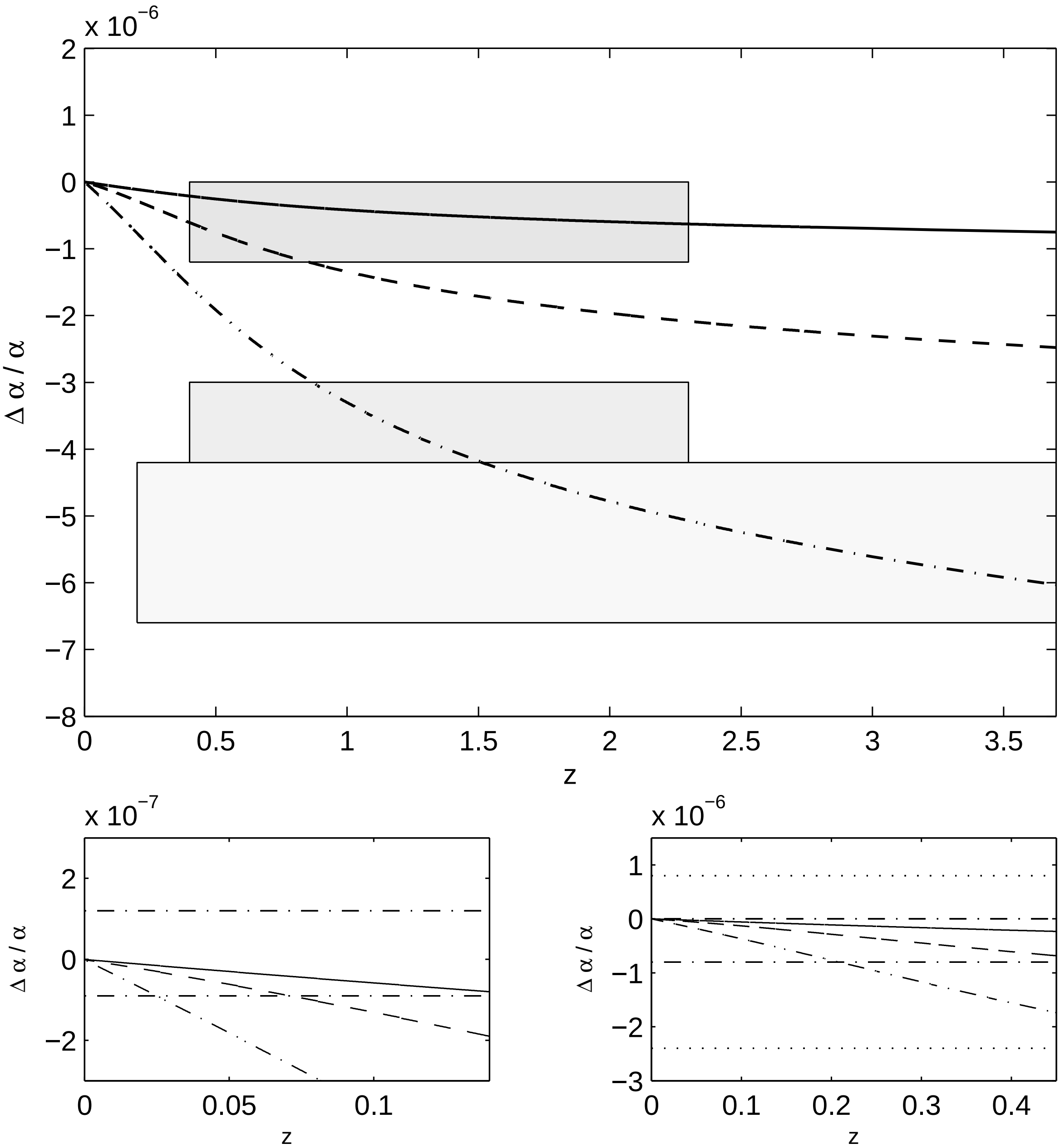

Figure 11: Evolution of α for a transient acceleration model with $\zeta_1 = 2 \times 10^{-6}$ and $\zeta_2 = 8 \times 10^{-5}$ (full line), $\zeta_1 = 5.3 \times 10^{-6}$ and $\zeta_2 = 3 \times 10^{-5}$ (dashed line), $\zeta_1 = 1.4 \times 10^{-5}$ and $\zeta_2 = 7 \times 10^{-4}$ (dash-dotted line). Line and box conventions are as above

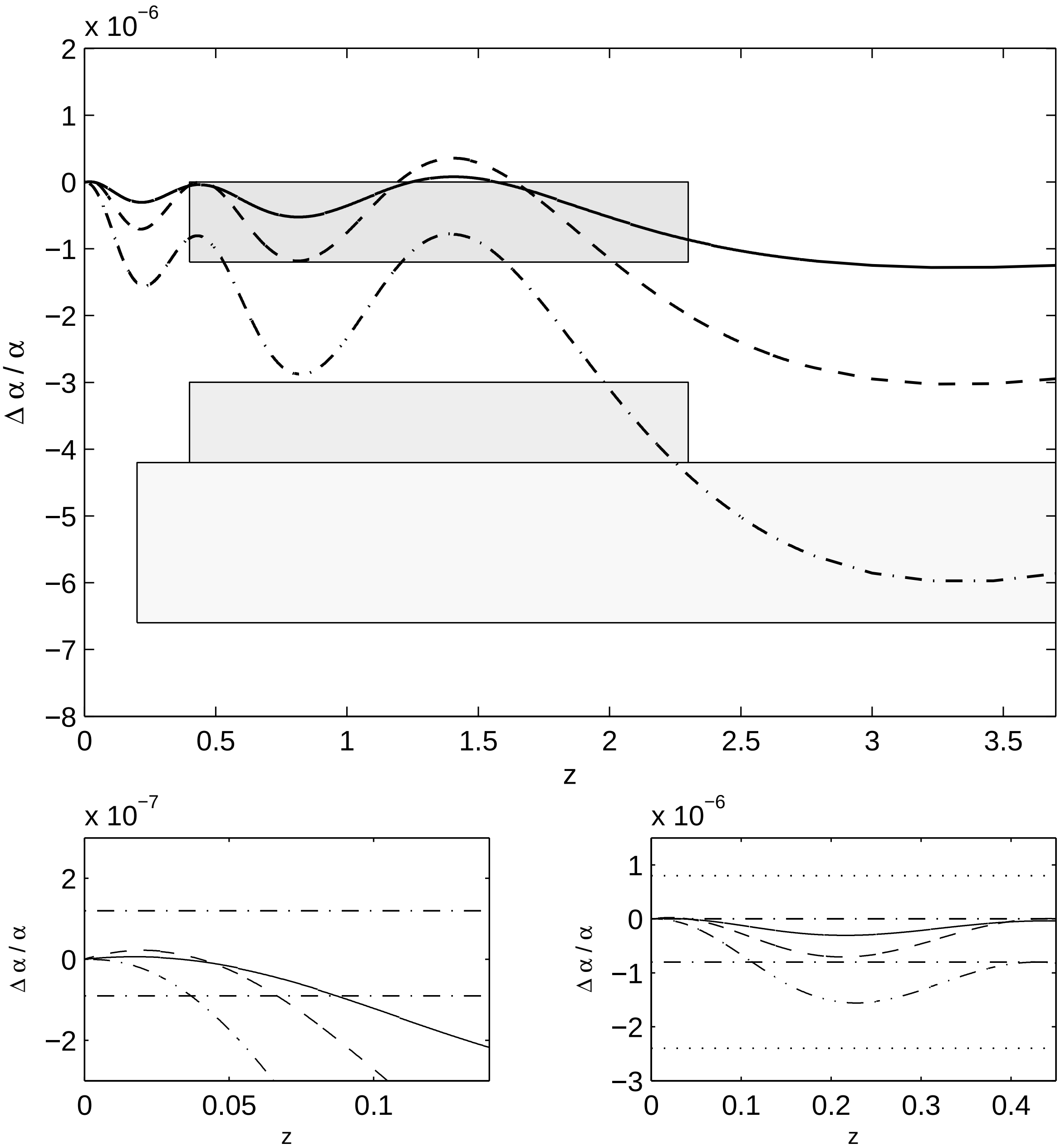

Figure 12: As above, but for a permanent acceleration model with $\zeta_1 = -4\times10^{-5}$ and $\zeta_2 = 1\times10^{-6}$ (full line), $\zeta_1 = -1\times10^{-4}$ and $\zeta_2 = 1\times10^{-6}$ (dashed line), $\zeta_1 = -1.5\times10^{-4}$ and $\zeta_2 = 1.4\times10^{-5}$ (dash-dotted line).