QUINTESSENCE AND VARYING ALPHA

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70% of energy density of the universe is composed of
DARK ENERGY

smooth, very weakly interacting, with negative pressure

can be modeled by a scalar field with a run-away potential
QUINTESSENCE

Want to study
effect of interactions of this field with rest of the world

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Cosmology with a scalar field

in a flat universe

$$\frac{\ddot{a}}{a} = -\frac{4\pi}{3M_p^2} \sum_i (1+3w_i)\rho_i$$

acceleration equation

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi}{3M_p^2} \sum \rho_i$$

Friedmann equation

$$\ddot{\phi} + 3H\dot{\phi} + \frac{dV}{d\phi} = 0$$

scalar field equation

a = scale factor of the universe
H = Hubble parameter
ρ_i = energy density for component *i*
w_i = equation of state for component *i*

scalar equation of state

$$w_\phi = \frac{\dot{\phi}^2/2 - V(\phi)}{\dot{\phi}^2/2 + V(\phi)}$$

Cosmology of scalar field admits attractor solutions

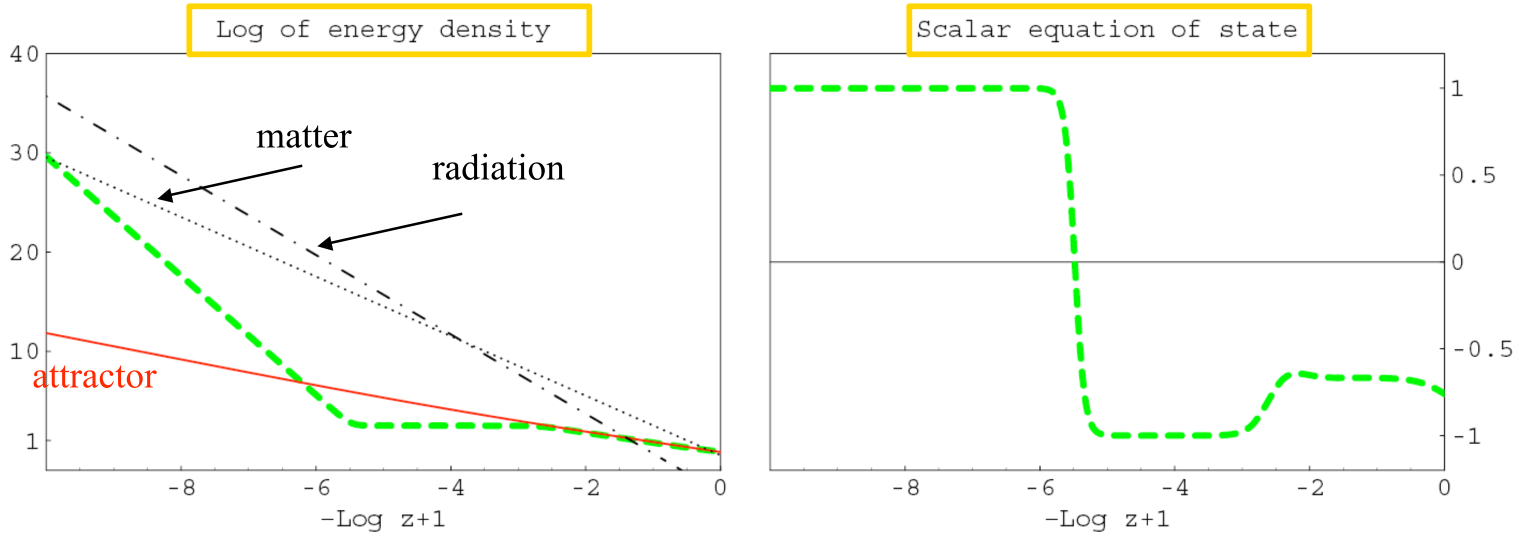

Figure 2. Evolution of the energy densities (left) and scalar equation of state (right) for a quintessence model with potential $V = 1/\phi$ and initial conditions $\rho_\phi^{in}/\rho_c^0 = 10^{30}$ at $z = 10^{10}$. The dot-dashed line represents the energy density of radiation, the dotted line the energy density of matter, the green dashed line the energy density of quintessence and the red solid line the attractor. All of the energy densities are expressed in units of the present critical energy density ρ_c^0.

Possible couplings of Quintessence scalar THEORETICAL FRAMEWORK

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\ R + \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right]$$

COSMO

(Olive & Pospelov, 2002)

can introduce couplings by promoting to functions the constants in the other terms of the action

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COUPLINGS

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$$+\int d^4x\sqrt{-g}\ \sum_j\left[\bar{\psi}_j \not{D}\psi_j + \underline{iB_j(\phi)m_j}\bar{\psi}_j\psi_j\right]$$

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$$+\int d^4x\sqrt{-g}\ \sum_j\left[\bar{\psi}_j \not{D}\psi_j + \underline{iB_j(\phi)}m_j\bar{\psi}_j\psi_j\right]$$
$$+\int d^4x\sqrt{-g}\ \left[\bar{\chi}\not{\partial}\chi - \underline{B_\chi(\phi)}m_\chi\chi^T\chi\right]$$

COSMO

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We will limit ourselves to …

$$S = \frac{1}{16\pi G}\int d^4x\sqrt{-g}\; R + \int d^4x\sqrt{-g}\left[\frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)\right]$$
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Effective fine structure constant

$$\boxed{\alpha(t) = \frac{\alpha_0}{B_F(\phi(t))}}$$

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Cosmological time variation

$$\boxed{\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(t)-\alpha_0}{\alpha_0} = \frac{1-B_F(\phi(t))}{B_F(\phi(t))}}$$

Having in mind these definitions…

$$\alpha(t) = \frac{\alpha_0}{B_F(\phi(t))}$$

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(t) - \alpha_0}{\alpha_0} = \frac{1 - B_F(\phi(t))}{B_F(\phi(t))}$$

We:

- ✓choose a generic model for the Quintessence scalar with potential V(□) = 1/□
- ✓solved the equations for □
- ✓computed the cosmological evolution of □□/□ depending on the functional form of B_F(□)

➔ complementary to Copeland, Nunes & Pospelov (2004)
kept B_F(□) fixed and varied V(□)

Many other references …

starting from Beckenstein (1982)

- ✓complete list is on the paper

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Experimental constraints on log $\Delta\alpha/\alpha$

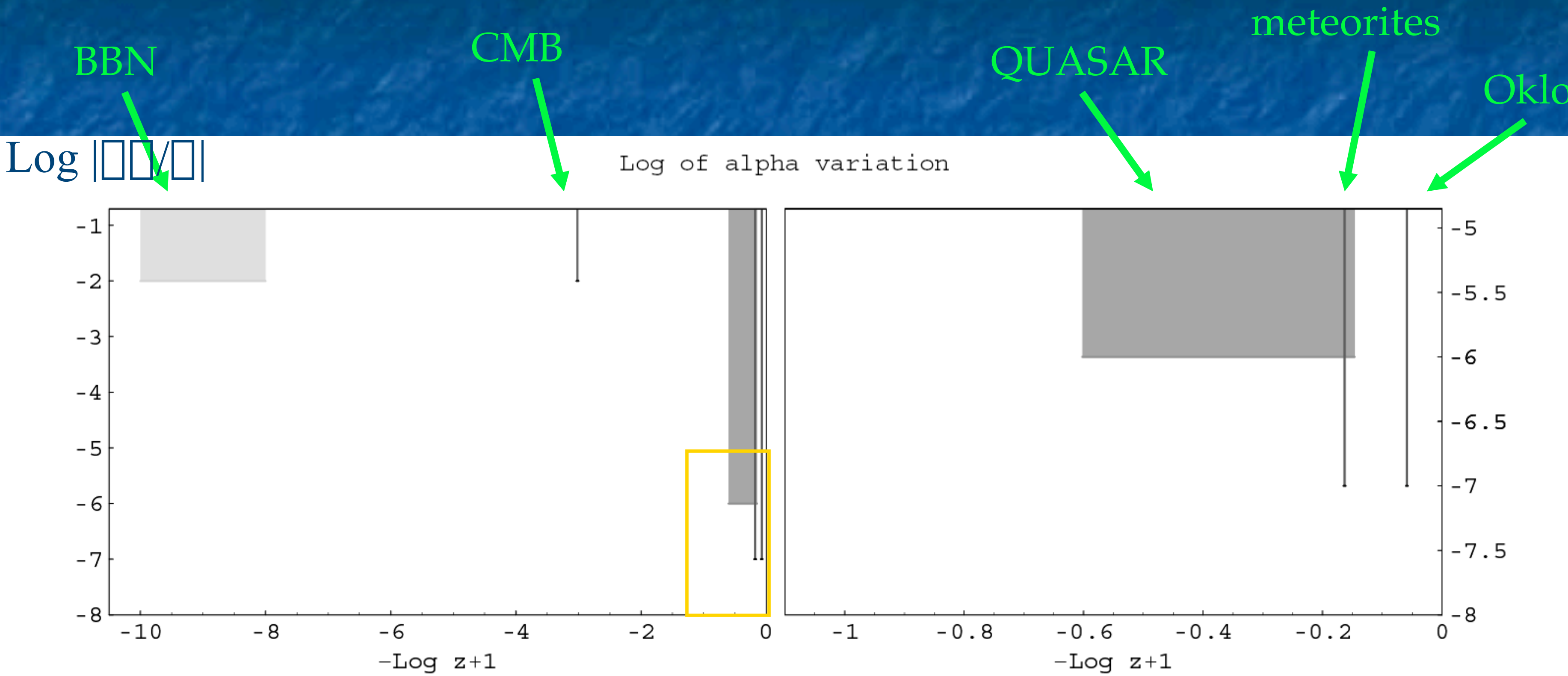
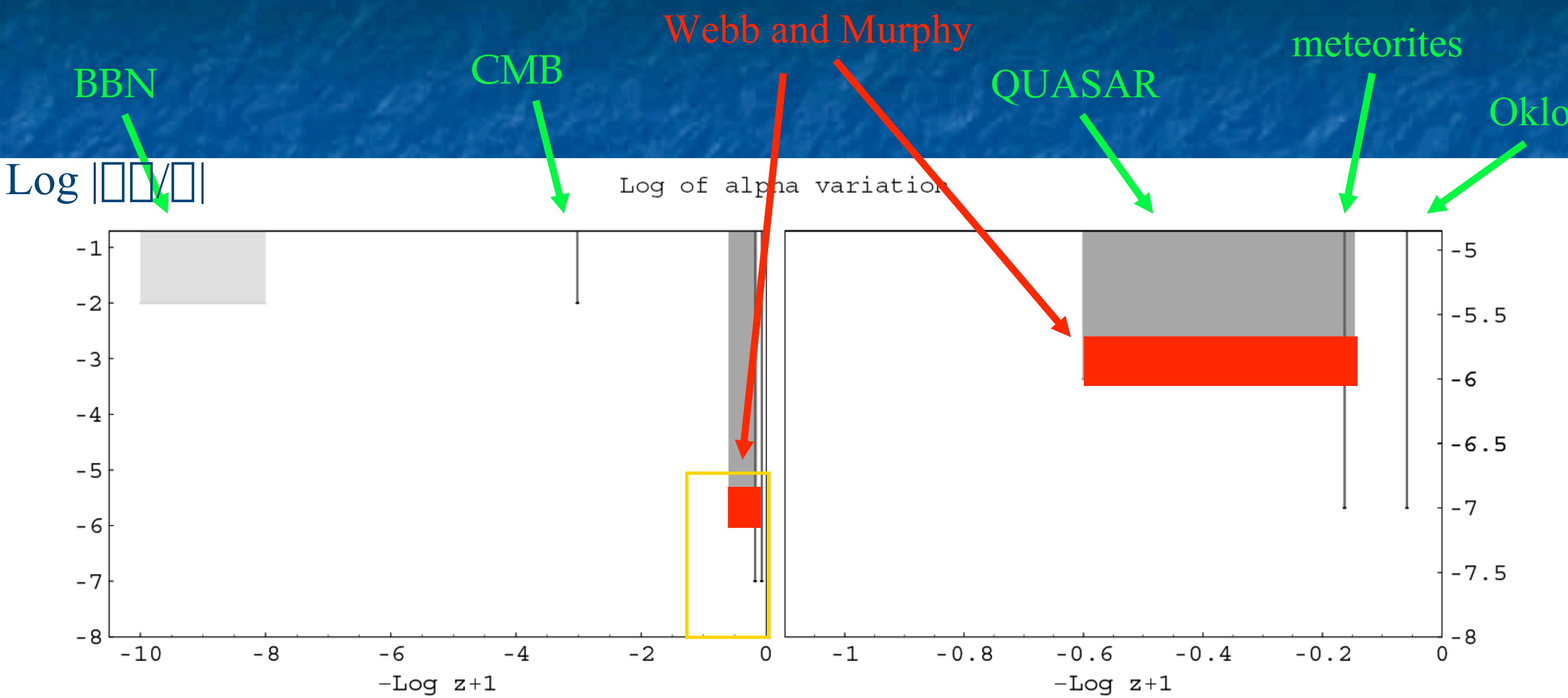


Figure 1. The experimental constraints (1)-(6) discussed above are summarized in the picture: $\log|\Delta\alpha/\alpha|$ is plotted as a function of the redshift z. On the right-hand side we zoom on $z \lesssim 10$. The grey areas are those excluded by present data.

Experimental constraints on log Δα/α



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Have also limit from atomic clocks

$$\left|\frac{\dot{\alpha}}{\alpha}\right| \lesssim 10^{-15}\ \mathrm{yr}^{-1} \qquad\qquad z = 0$$

…and from Weak Equivalence Principle

The coupling $B_F(\phi) F^{\mu\nu} F_{\mu\nu}$ also induces indirect violation of the Weak Equivalence Principle

due to the e.m. contribution to proton and neutron masses

Two test bodies having equal mass but different composition will fall with different accelerations

Eötvös ratio

$$\eta = 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

differential acceleration of two test bodies

current limit is $\eta < 10^{-13}$

Violation of WEP depends on derivative of □

$$\eta \simeq \frac{M_{Pl}^2}{4\pi\bar{m}^2}\left(R_n^E g_n + R_p^E g_p\right)\left(\Delta R_n g_n + \Delta R_p g_p\right)$$

$$\boxed{g_i = \frac{\partial m_i}{\partial \phi} = \frac{\partial \alpha}{\partial \phi} B_i}$$

$$m_p = m + \alpha\, B_p$$
$$m_n = m + \alpha\, B_n$$

$$B_p \equiv 0.63\mathrm{MeV}/\alpha_0,\ B_n \equiv -0.13\mathrm{MeV}/\alpha_0.$$

$$R_i^E \equiv \frac{n_i^E}{n_n^E + n_p^E} \simeq 0.5 \qquad \Delta R_i \equiv \frac{|n_{i,\,1} - n_{i,\,2}|}{n_n + n_p} \simeq 0.06 - 0.1$$

□ $\neq 0$ even if today □ $=$ □$_0$

Model building

Pick the most general function you can imagine …..

$$B_F(\phi) = \left(\frac{\phi}{\phi_0}\right)^{\epsilon} \left[1 - \zeta(\phi - \phi_0)^q\right] \; e^{\tau(\phi - \phi_0)}$$

Model building

Pick the most general function you can imagine …..

power-law

polynomial

exponential

$$B_F(\phi) = \left(\frac{\phi}{\phi_0}\right)^{\epsilon} \left[1 - \zeta(\phi - \phi_0)^{q}\right] \; e^{\tau(\phi - \phi_0)}$$

HAVE 4 PARAMETERS

$B_F\,(\phi=\phi_0) = 1$

Now let’s see behaviour of □□

for different choices of

the parameters in the function B_F

EXPONENTIAL

$$B_F(\square) = e^{\square(\square\square\square_0)}$$

$\square \geq 1$ do not satisfy the experimental constraints

Need $\square \ll 1$ ➔ equivalent to linear coupling

LINEAR

$$B_F(\phi) = \left[1 - \zeta(\phi - \phi_0)\right]$$

Log $|\Delta\alpha/\alpha|$

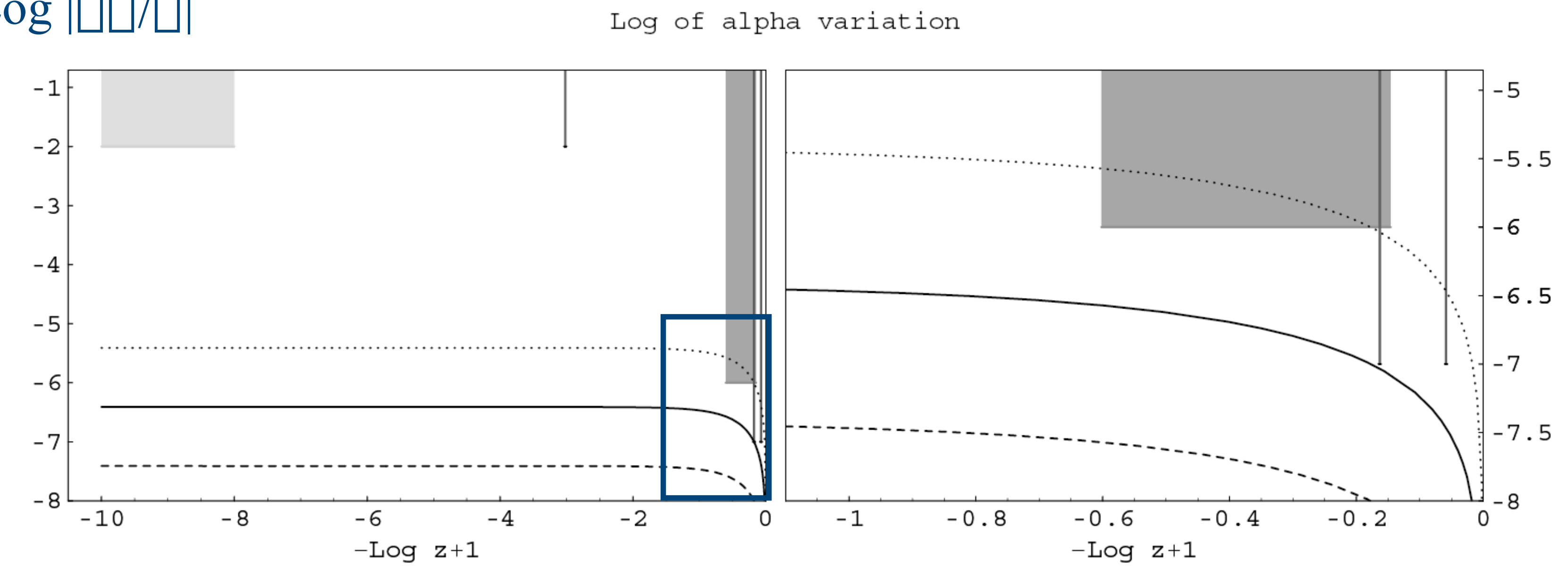

Figure 3. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = 1 - \zeta(\phi - \phi_0)$ with $\zeta = 0.6 \cdot 10^{-5}$ (dotted line), $\zeta = 0.6 \cdot 10^{-6}$ (solid line) and $\zeta = 0.6 \cdot 10^{-7}$ (dashed line). On the right-hand side we zoom on $z \lesssim 10$. Only the curves not overlapping the grey areas are phenomenologically viable.

POLYNOMIAL

$$B_F(\phi) = \left[1 - \zeta(\phi - \phi_0)^q\right]$$

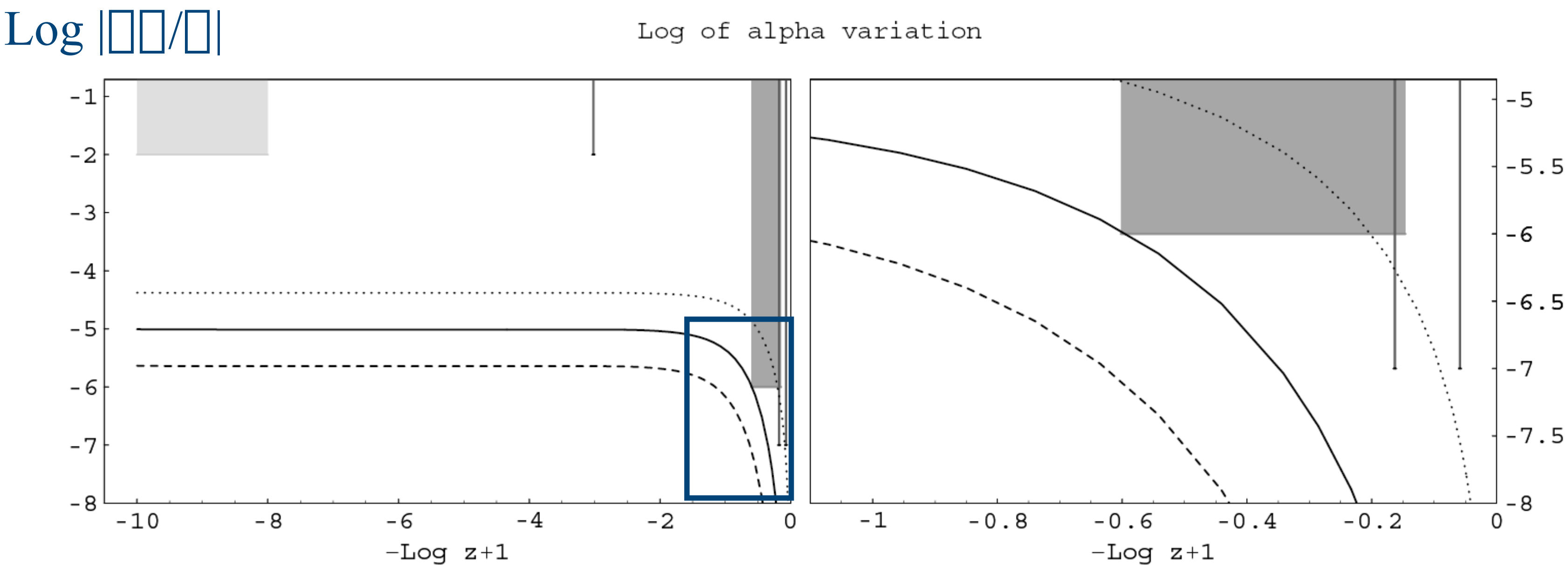

Figure 4. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = 1 - \zeta(\phi - \phi_0)^q$ with $\zeta = 10^{-4}$ and $q = 3$ (dotted line), $q = 6$ (solid line) and $q = 9$ (dashed line). On the right-hand side we zoom on $z \lesssim 10$. Only the curves not overlapping the grey areas are phenomenologically viable.

POLYNOMIAL

$$B_F(\phi) = \left[1 - \zeta(\phi - \phi_0)^q\right]$$

Log $|\Delta\alpha/\alpha|$

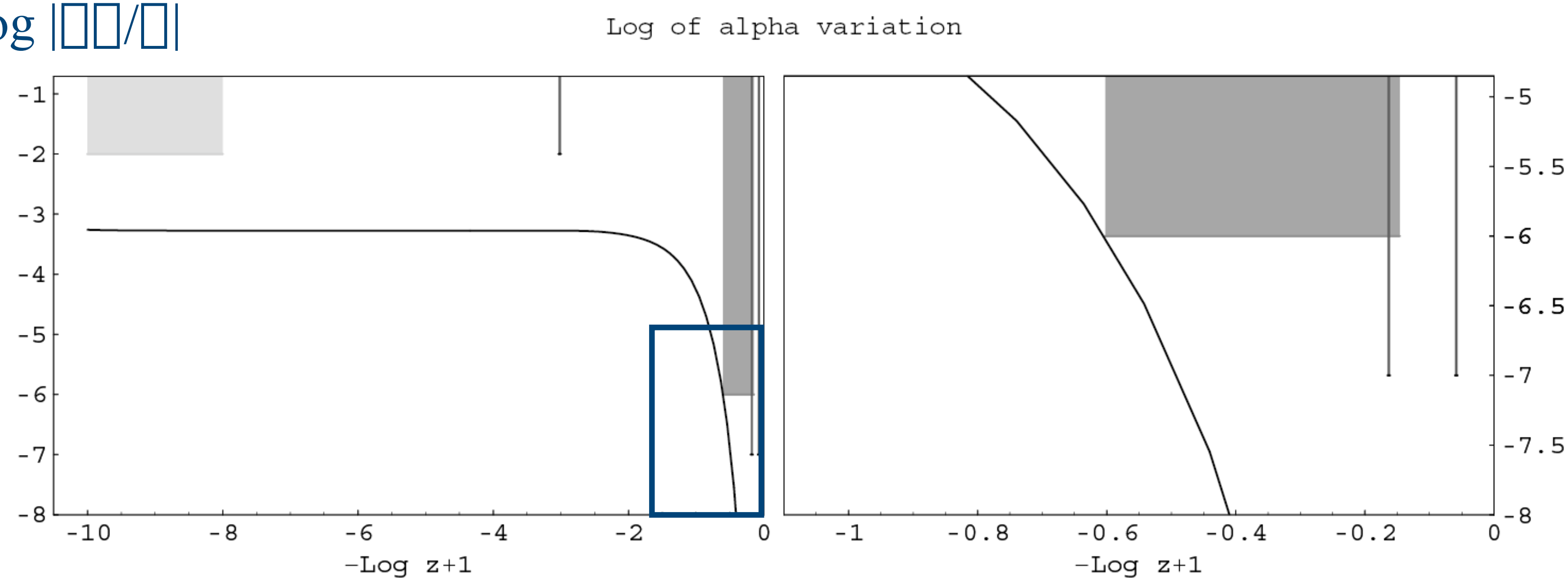

Figure 5. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = 1 - \zeta(\phi - \phi_0)^q$ with $\zeta = 1$ and $q = 17$ (solid line). On the right-hand side we zoom on $z \lesssim 10$. Note that all the experimental limits are satisfied without any fine–tuning in the parameters of the function $B_F(\phi)$.

POWER-LAW

$$B_F(\phi) = (\phi/\phi_0)^{\epsilon}$$

Log $|\Delta\alpha/\alpha|$

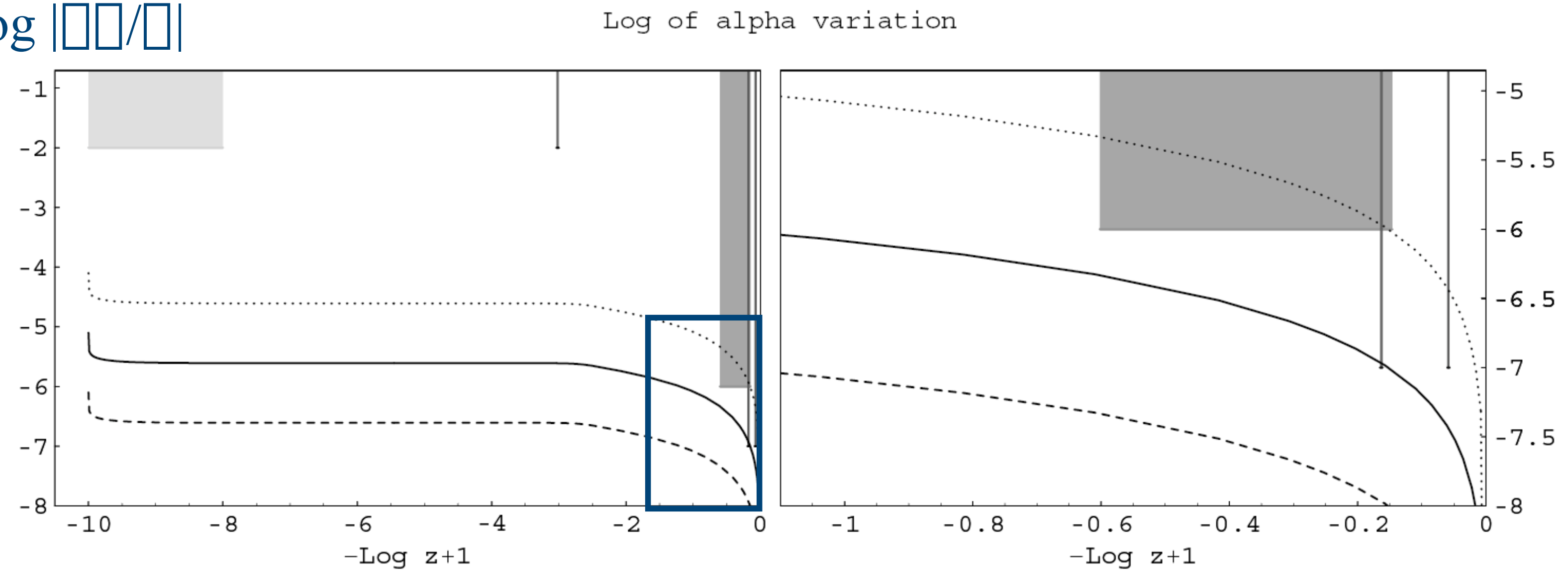

Figure 6. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = \left(\frac{\phi}{\phi_0}\right)^{\epsilon}$ with $\epsilon = 4 \cdot 10^{-6}$ (dotted line), $\epsilon = 4 \cdot 10^{-7}$ (solid line) and $\epsilon = 4 \cdot 10^{-8}$ (dashed line). On the right-hand side we zoom on $z \lesssim 10$. Only the curves not overlapping the grey areas are phenomenologically viable.

$$B_F(\phi) = (\phi/\phi_0)^{\epsilon}[1 - \gamma\epsilon(\phi - \phi_0)]; \quad \gamma = \ldots$$

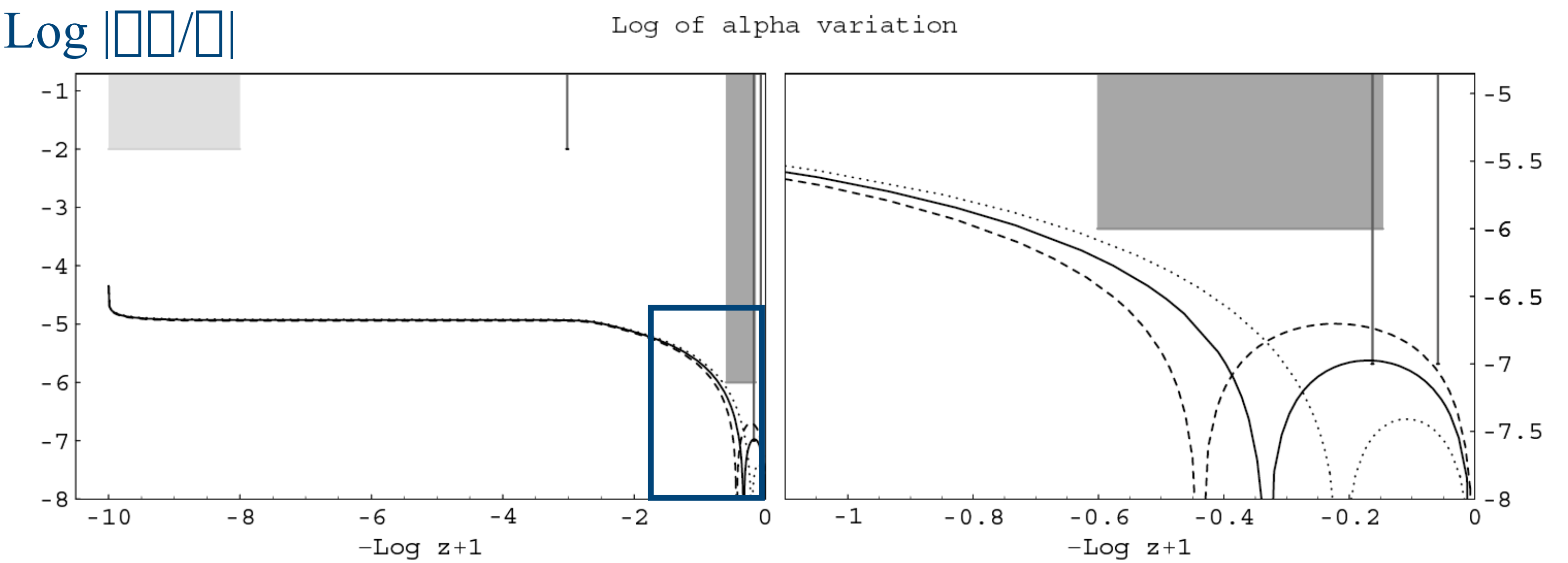

Figure 7. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = \left(\frac{\phi}{\phi_0}\right)^{\epsilon}(1 - \gamma\,\epsilon\,(\phi - \phi_0))$ with $\epsilon = 2.4 \cdot 10^{-6}$, $\gamma = 2.2$ (solid line) and $\gamma = 2.2 \pm 10\%$ (dashed and dotted respectively). On the right-hand side we zoom on $z \lesssim 10$. Only the curves not overlapping the grey areas are phenomenologically viable.

$$B_F(\phi) = \left[1 - \zeta(\phi - \phi_0)^q\right] e^{-\tau(\phi - \phi_0)}$$

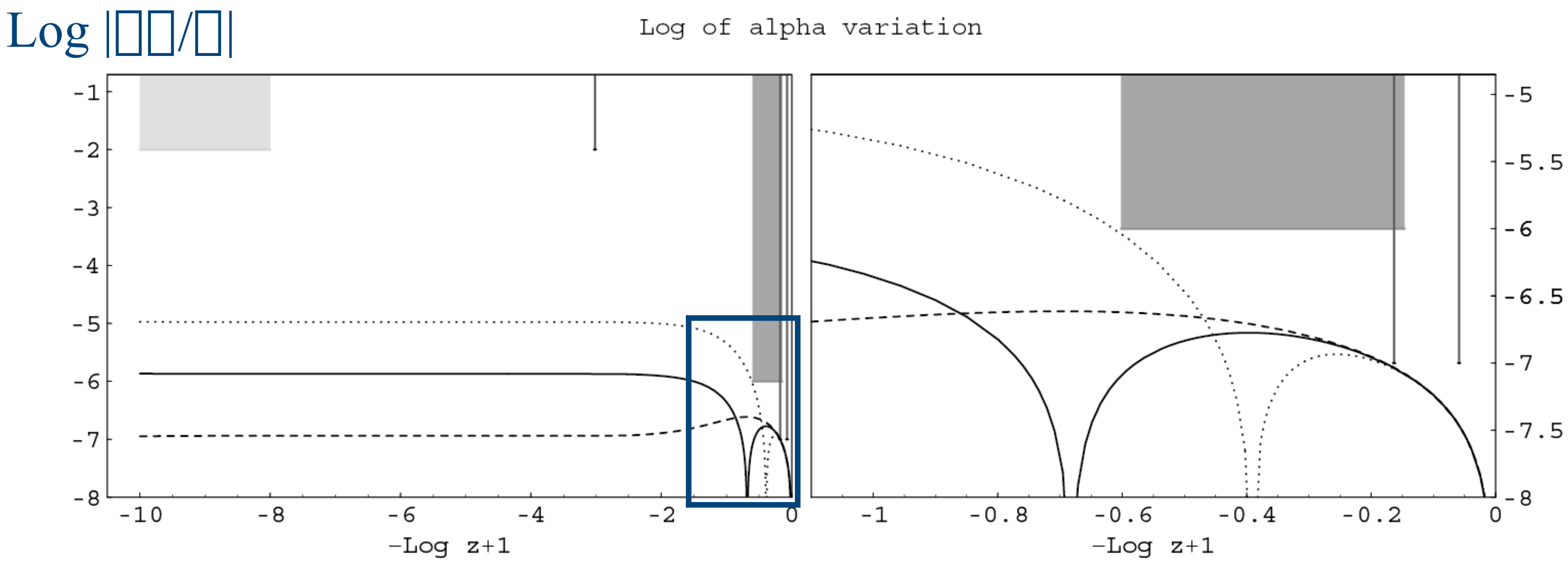

Figure 8. The logarithm of $|\Delta\alpha/\alpha|$ is plotted as a function of $\mathrm{Log}(z+1)$ for $B_F(\phi) = (1 - \zeta\,(\phi - \phi_0)^6)\; e^{-\tau(\phi-\phi_0)}$ with $\tau = 0.6 \cdot 10^{-6}$ and $\zeta = 2 \cdot 10^{-4}$ (dotted line), $\zeta = 3.2 \cdot 10^{-5}$ (solid line) and $\zeta = 5 \cdot 10^{-6}$ (dashed line). On the right-hand side we zoom on $z \lesssim 10$. Only the curves not overlapping the grey areas are phenomenologically viable.

Conclusions

- ✓Can get a variety of behaviours for □□(t)
- ✓ Parameters in B_F are not necessarily fine tuned
- ✓All models we have presented satisfy atomic clocks and WEP bounds
- ✓In principle, Quasars are not incompatible with Oklo
- ✓□□ can challenge WEP

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Cosmological evolution oh alpha driven by a general coupling with quintessence

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