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AND FUNDAMENTAL CONSTANTS**

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COSMOLOGICAL ACCELERATION AND POSSIBLE OSCILLATORY TIME-DEPENDENCE OF THE FINE-STRUCTURE CONSTANT

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ICTP, September 2004

Cosmological acceleration and possible oscillatory time-dependence of the fine-structure constant

Yasunori Fujii

1. Theoretical motivations
2. Cosmological solutions
3. 3-parameter fit
4. Comparison with observed $\Delta\alpha/\alpha$
5. Meteorite constraint

1. Theoretical motivations

Linking Accelerating Universe and Time-dependent $\alpha(t)$

The same origin: Time-dependent scalar field, oscillating ?

- Accelerating universe: scalar field (σ, quintessence, dilaton, $\cdots$)
  $\rho_\sigma(t) \sim \text{const} \sim \Lambda$ term temporarily: scalar field trapped to a potential
  Gardner; Anchordoqui and Goldberg; Bertolami et al; Bento et al; Lee et al; Y.F.

Damped oscillation continued toward present epoch

- $\Delta\alpha/\alpha \propto \Delta\sigma \rightarrow$ also oscillating $\alpha(t)$? fractional lookback time $s = 1 - t/t_0$

  – Oscillation can be consistent with the measurement

  – Suspected large systematic errors, but accept the data as it is

  – Reconcile QSO and Oklo by oscillation?

$$\frac{\Delta\alpha}{\alpha} : \begin{cases} \textbf{QSO;} & \sim 10^{-5}, \quad s = 0.2 - 0.9 \\ \textbf{Oklo;} & \lesssim 10^{-7}, \quad s \approx 0.14(\pm 10^{-4}) \ (\sim 2 \times 10^9 \text{ys ago}) \end{cases}$$

Sharp fall-off by 2-3 orders of magnitude? A zero of oscillation ?

Spatial variation and Virialization needs more care

D.F. Mota and J.D. Barrow, PL B581(04)141; MNRAS 349(04)281

2. Cosmological solutions

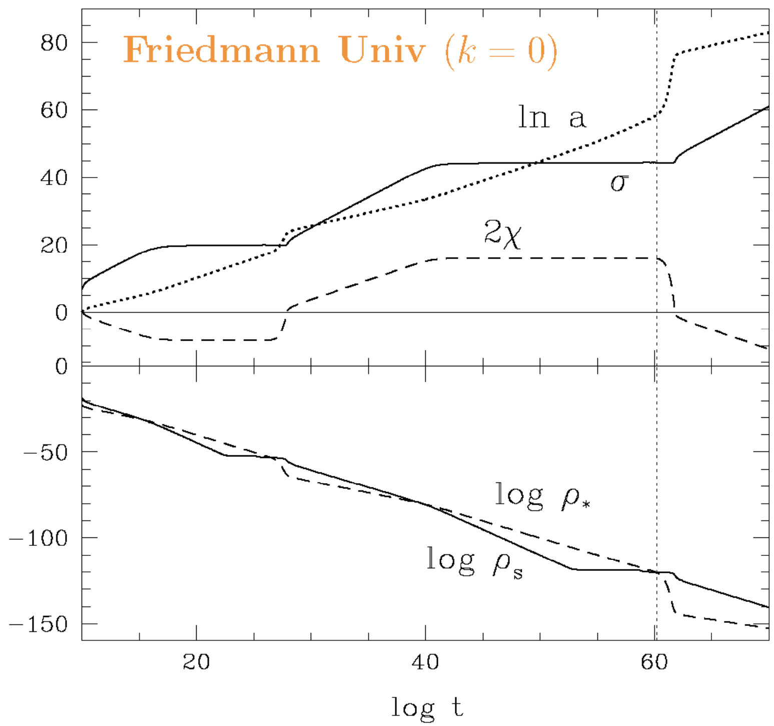
An example of damped oscillation of σ in accelerating universe

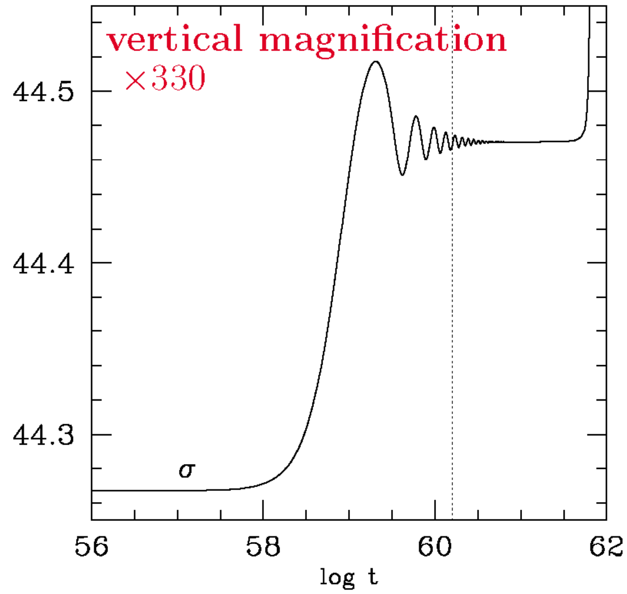
G.L.Gardner, PRD68(03)043513; L.Anchoridoqui and H.Goldberg, PRD68(03)083513; O.Bertolami, R.Lehnert, R.Potting and A.Ribeiro, PRD69(04)083513; M.Bento, O.Bertolami and N.Santos,astro-ph/0402159

Our 2-scalar model (σ, χ) with 4 goals, based on scalar-tensor theory

Y.F. and K.Maeda, *The scalar-tensor theory of gravitation,* Cambridge U Press. 03

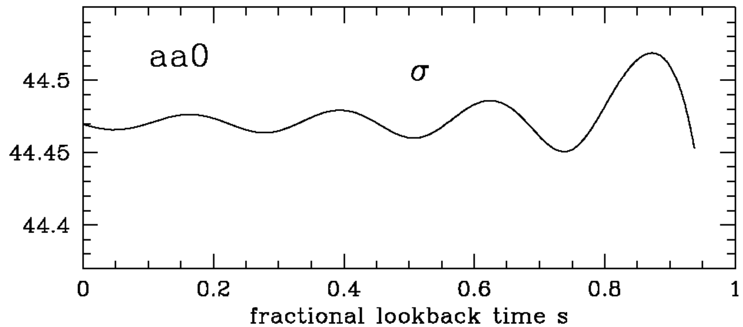
1. Derive exponential potential (conformal transformation, roles of different conformal frames; physical conformal frame; scale-invariant model)
2. Scenario of decaying $\Lambda \sim t^{-2}$ (why so small compared with $M_{\rm P}^4 \sim 1$ by 120 orders of magnitude?)
3. Reproduce acceleration (why still nonzero Λ? $(\Omega_\Lambda \sim 0.7)$)
4. Avoid coincidence problem (how lucky are we? repeated occurrence of mini-inflations)





$t_0 = 1.38 \times 10^{10}\text{y} = 10^{60.2}$ $((8\pi G)^{-1/2} = 1)$

Reduced Planckian Units

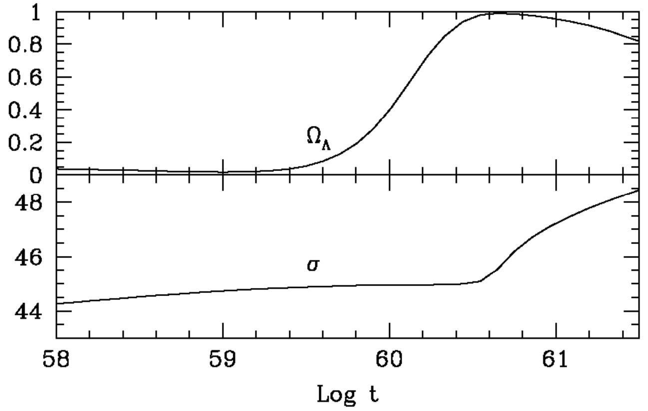


reference	T
Fujii and Maeda	**0.22**
Gardner	**26-18**
Anchoridoqui and Goldberg	**0.87, 1.94**
Bertolami et al	**~0.5**

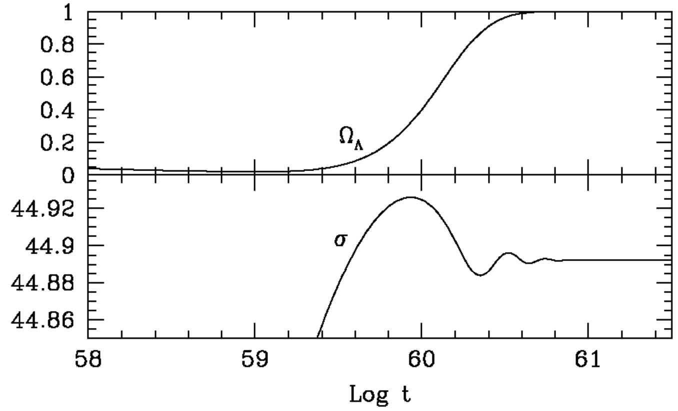
cosmological reference value

An exception of no oscillation of (2-1=)1-scalar model

S.Dodelson, M.Kaplinghat, E.Stewart, PRL 85(00)5276



No oscillation in one of the repeated, transient mini-inflations



Oscillation in final eternal inflation, shown 45 times magnified vertically in the lower panel

3. 3-parameter fit

Try to fit the data by an offset damped oscillation

$$\frac{\Delta\alpha}{\alpha}\times 10^5 \equiv y(s) = a\left(e^{bs}\cos\left(v-v_1\right)-\cos\left(v_1\right)\right), \quad \frac{v}{s}=\frac{v_1}{s_1}=\frac{2\pi}{T}$$

such that $y(0)=0$, becasue $\Delta\alpha \equiv \alpha(s)-\alpha(0)$

Also demand $y(s_{\rm oklo}\approx 0.142)=0$, becasue $|y|\sim\Delta y \lesssim 10^{-2}$

$\uparrow$ 1.9×10^9y ago

Choose

$$v_1 = \tan^{-1}\left(\frac{e^{-bs_{\rm oklo}}-\cos(v_{\rm oklo})}{\sin(v_{\rm oklo})}\right), \quad \frac{v_{\rm oklo}}{s_{\rm oklo}}=\frac{2\pi}{T}$$

3-parameter fit:

a, b, T to be determined to best fit the data of $\Delta\alpha/\alpha$ from QSO

Y.F. PL B573(03)39; hep-ph/0311026; Y.F. and S. Mizuno, astro-ph/0404222

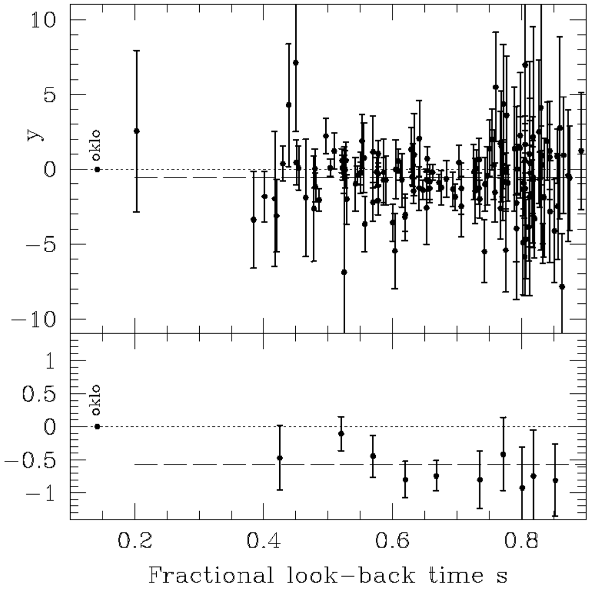
Weighted mean: 1-parameter fit by a horizontal straight line

- Ignoring "meteorite constraint" (Section 5)
- $\left(\frac{\dot\alpha}{\alpha}\right)_{t_0} = -\frac{1}{t_0}y'(0)\times 10^{-5}$ to be compared with laboratory experiment

4. Comparison with observed $\Delta\alpha/\alpha$

Keck/HIRES (143 data points)

M.T.Murphy, V.V.Flambaum, J.K.Webb, V.V. Dzuba and A.M. Wolfe,
astro-ph/0310318

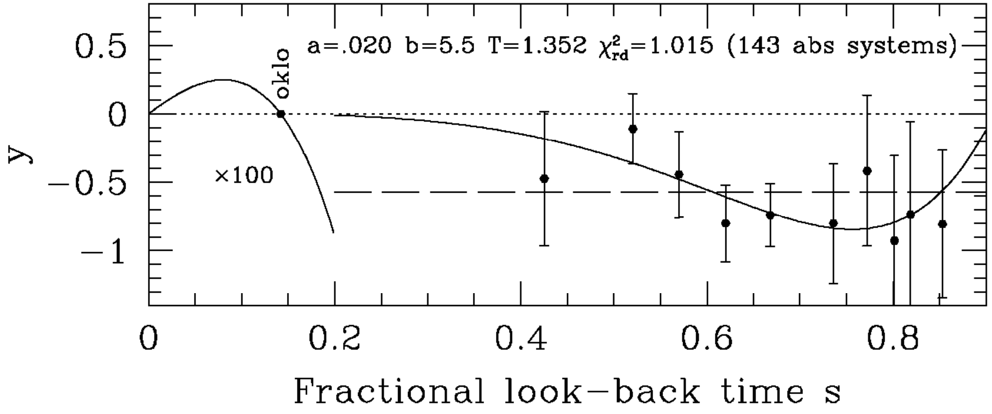


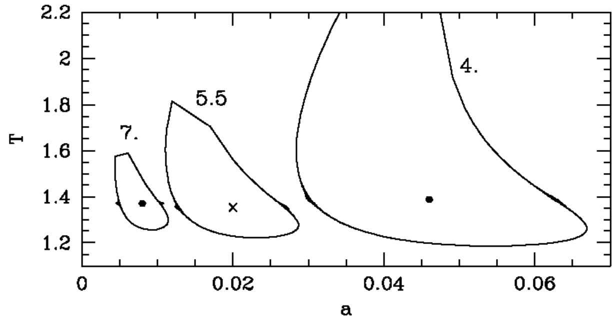
Weighted mean:

$y = -0.573 \pm 0.113$ **with** $\chi^2_{\rm rd} = 1.023$

- **Nonzero y beyond 5σ**
- **Binned data for easier inspection**
- **Horizontal line $y = -0.573$ if extended to the Oklo time, would have produced too large χ^2 to be acceptable**

3-parameter-fit: $a = 0.020, \quad b = 5.5, \quad T = 1.352, \quad \chi^2_{\rm rd} = 1.015$



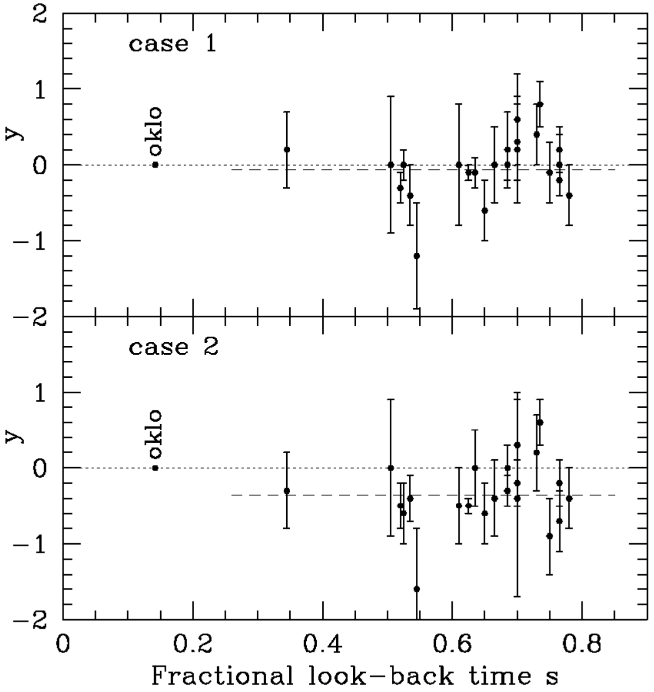


Nearly as good fit as the weighted mean fit, but worthy of increased number of parameters?

- Theoretically motivated, not simply for a better fit
- Consistent with Oklo
- $T \gg 0.22$ (cosmological reference value). Broad or flat distribution is a unique feature
- $$\left(\frac{\dot{\alpha}}{\alpha}\right)_{t_0} \approx -3.8 \times 10^{-17}{\rm y}^{-1} \ll 0.6 \times 10^{-15}{\rm y}^{-1} \sim \text{weighted mean}/(\bar{s}t_0)$$

VLT-UVES (23 data points)

H.Chand, R.Srianand, P.Petijean, B.Aracil, Astron.Astrophys. 417(04)853;
R.Srianand, H.Chand, P.Petijean, B.Aracil, PRL 92(04)121302



Weighted mean:

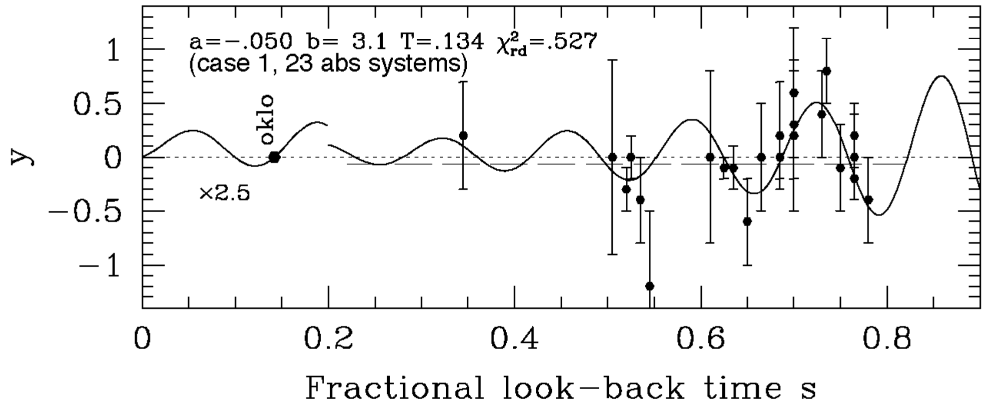
$y = -0.06 \pm 0.06,\ \chi^2_{\rm rd} = 0.95,$ (case **1**)

No time variation

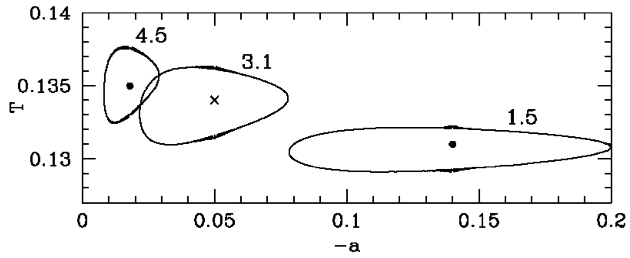
$y = -0.36 \pm 0.06,\ \chi^2_{\rm rd} = 1.03,$ (case **2**)

Negative beyond 6σ

Case 1 **3-parameter-fit:** $a = -0.050, \; b = 3.1, \; T = 0.134, \; \chi^2_{\rm rd} = 0.53$



Y.F. and S.Mizuno, astro-ph/0404222



$\chi^2_{\rm rd} \ll 1 \quad \Rightarrow$ faulty data as statistical ensemble?

Still the fit is away from null result $(a = 0)$ by **2.6**σ

Information Criterion; how rewarded is it to have more parameters?

k = # of parameters, N =# of data points

	(minus)gain and penalty	less than weighted mean by	critical $\chi^2_{\rm rd}$
Akaike IC	$\chi^2 + 2k$	**6.3**	**0.85**
Bayesian IC	$\chi^2 + k \ln N$	**4.0**	**0.73**

(over)rewarded

This data set allows nonzero oscillation despite preferred null result derived by assuming uniform time-dependence

Supported by theoretical ideas

- Consistency with Oklo
- $T \approx 0.13$ is close to ~ 0.22 (cosmological reference value): no feature of broad distribution in Keck/HIRES $(T \approx 1.35)$
- $b \approx 3.1$ is also close to ~ 2.5 in the same sense
- Overall amplitude in agreement with quantum-anomaly type estimate (fully exploiting scalar-tensor theoretical details)

$$\frac{\Delta\alpha}{\alpha} = \mathcal{Z}\frac{\alpha}{2\pi}\zeta\Delta\sigma \sim 1.2\mathcal{Z} \times 10^{-3}\Delta\sigma, \quad \mathcal{Z} \approx 5$$

within an order of magnitude. First successful understanding of the size of $\Delta\alpha/\alpha$?

How much is T? $\Rightarrow$ { difference between Keck/HIRES and VLT-UVES; provide a new clue on acceleration of universe }

$$\left(\frac{\dot{\alpha}}{\alpha}\right)_{t_0} \approx -0.96 \times 10^{-15}\mathrm{y}^{-1}$$ close to lab upper bound $\sim 2 \times 10^{-15}\mathrm{y}^{-1}$

E. Peik et al, physics/0402132

5. Meteorite constraint

Very slow β decay $\quad {}^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os}, \quad \lambda^{-1} \approx 6 \times 10^{10}\mathrm{y}$

Mass difference $2.6\mathrm{keV} \ll 16\mathrm{MeV}$**; near cancellation between Coulomb and strong interactions** $\Rightarrow$ **amplification**

$$\frac{\Delta\lambda}{\lambda} \approx -2 \times 10^4 \frac{\Delta\alpha}{\alpha} \quad \textbf{or} \quad \frac{\Delta\alpha}{\alpha} \approx -5 \times 10^{-4} \frac{\Delta\lambda}{\lambda}$$

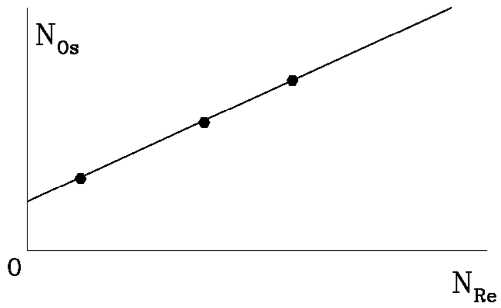
$$\textbf{If} \left|\frac{\Delta\lambda}{\lambda}\right| \sim 200 \ (\textbf{4.6 Gys ago}), \ \textbf{then} \left|\frac{\Delta\alpha}{\alpha}\right| \lesssim 10^{-2}$$

Dyson, PRL19(67)1291

Recent dating analysis in iron meteorites

$$N_{\mathrm{Os}}(t_0) = \left(e^{\lambda(t_0 - t_1)} - 1\right) N_{\mathrm{Re}}(t_0) + B,$$

isochron



with age $t_0 - t_1 \sim 4.6\mathrm{Gy}$ **better determined from** ${}^{235}\mathrm{U}$ **and Pb**

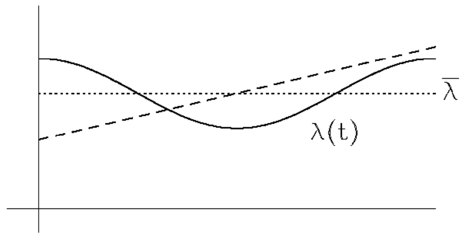
$$\left|\frac{\Delta\lambda}{\lambda}\right| \lesssim 0.5\% \quad \Rightarrow \quad \left|\frac{\Delta\alpha}{\alpha}\right| \lesssim 2.5 \times 10^{-7}, \quad \textbf{at} \quad s \approx 0.33$$

Smoliar, et al, Science 271(96)1099
Olive et al, PRD66(02)045022

If λ depends on time

$$(t_0 - t_1)\,\lambda \to \int_{t_1}^{t_0} \lambda(t)dt$$

$$\lambda \to \bar{\lambda} \equiv \frac{1}{t_0 - t_1}\int_{t_1}^{t_0} \lambda(t)dt, \quad \textbf{average}$$



Isochron analysis determines $\bar{\lambda}$, but generally

$$\frac{\Delta\bar{\lambda}}{\bar{\lambda}} \neq \frac{\Delta\lambda}{\lambda}$$

Replacing inequality by equality $\Rightarrow$ "meteorite constraint," but not always justifiable

Y.F. and A.Iwamoto, PRL26(03)261101; K.Olive, et al, PRD69(04)027701

Examples of difficulty to maintain consistency among Oklo constraint, meteorite constraint and Keck/HIRES

Wetterich, PLB B561(03)10; Anchordoqui and Goldberg, PRD68(03)083513; Gardner, PRD68(03)043513; Lee, et al,astro-ph/0406039

Decided not to use this constraint in our analysis