Cosmodynamics

Quintessence and solution of cosmological constant problem should be related !

Cosmon and fundamental mass scales

- Assume all mass parameters are proportional to scalar field χ (GUTs, superstrings,…)
- $M_p \sim \chi$, $m_{proton} \sim \chi$, $\Lambda_{QCD} \sim \chi$, $M_W \sim \chi$,…
- χ may evolve with time
- m_n/M : (almost) constant - ***<u>observation</u>*** !

Only ratios of mass scales are observable

Dirac's hypothesis

The very small dimensionless numbers in physics are due to huge age of the universe .

(A)
may be true for
ratio of dark energy
over M^4

(B) nucleon mass $m_n / \bar{M}_p \approx 10^{-18}$

$$\left| \frac{d}{dt} \ln \left(\frac{m_n}{\bar{M}} \right) \right| < 3 \cdot 10^{-15} \, yr^{-1}$$

from Oklo + GUT
less stringent direct bounds

⇒ today essentially settled !
(perhaps more substantial evolution in very early cosmology)

Dilatation symmetry

- Lagrange density:

$$L = \sqrt{g}(-\frac{1}{2}\chi^2 R + \frac{1}{2}(\delta - 6)\partial^\mu \chi \partial_\mu \chi + V(\chi) + h\chi\overline{\psi}\psi)$$

- Dilatation symmetry for

$$V = \lambda\chi^4, \lambda = const., \delta = const., h = const.$$

- Conformal symmetry for $\delta=0$

Dilatation anomaly

- Quantum fluctuations responsible for dilatation anomaly
- Running couplings:

$$\partial\lambda/\partial \ln\chi = -A\lambda\,,\ \partial\delta/\partial \ln\chi = E\delta^2$$

- $V \sim \chi^{4-A}$, $M_p(\chi) \sim \chi$
- **$V/M_p^{\,4} \sim \chi^{-A}$: decreases for increasing χ !!**
- $E>0$: crossover quintessence

Cosmology

- Cosmology : χ increases with time !
- (due to coupling of χ to curvature scalar)
- " late time cosmology explores the ultraviolet"
- for large χ the ratio V/M^4 decreases to zero

→

- Effective cosmological constant vanishes asymptotically for large t !

Weyl scaling

Weyl scaling : $g_{\mu\nu} \rightarrow (M/\chi)^2 g_{\mu\nu}$,

$\varphi/M = \ln(\chi^4/V(\chi))$

$$L = \sqrt{g}\Big(-\frac{1}{2}M^2 R + \frac{1}{2}k^2(\phi)\partial^\mu\phi\partial_\mu\phi + V(\phi) + m(\phi)\overline{\psi}\psi\Big)$$

Exponential potential : $V = M^4 \exp(-\varphi/M)$

No additional constant !

Crossover Quintessence

$$\partial\delta/\partial \ln\chi = E\delta^2$$

(like QCD gauge coupling)

critical χ where δ grows large

critical φ where k grows large

$k^2(\varphi) = \delta(\chi)/4$

$k^2(\varphi) =$ "$1/(2E(\varphi_c - \varphi)/M)$"

if $\varphi_c \approx 276/M$ (tuning !)

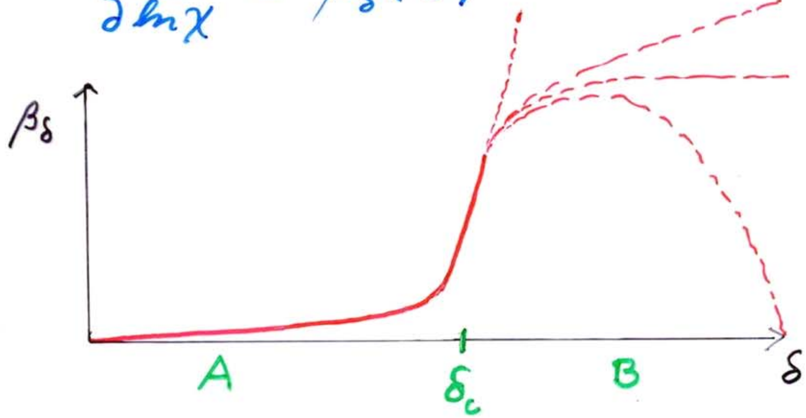
Relative increase of dark energy in present cosmological epoch

Running dimensionless coupling $\delta(\chi/m)$

local conformal symmetry for $\delta = 0$, $m = 0$

for $\chi \gg m$:

$$\frac{\partial \delta}{\partial \ln \chi} = \beta_\delta(\delta)$$



A: vicinity of conformal fixed point at $\delta = 0$

B: cosmon + metric interactions are pure derivative interactions

δ_c : characteristic coupling for crossover example :

$$\beta_\delta = E\,\delta^2 \qquad (\delta_c \approx 1/E)$$

$$\delta = \frac{1}{E \ln(\chi_c/\chi)}$$

characteristic crossover scale χ_c

define $\delta_i = \delta(\chi = m)$

$$\Rightarrow \frac{\chi_c}{m} = \exp \frac{1}{E\,\delta_i}$$

(„Landau pole")

$$\frac{\chi_c}{m} \gg 1$$

for $\delta_i \approx \frac{1}{138\,E}$:

$\Rightarrow$ realistic cosmology

scenario , where

a) „cosmological constant" vanishes for $t \to \infty$

$$V \sim \exp - \frac{\varphi}{\bar{M}_p} \text{ , } \underline{\text{not}} \quad \exp - \frac{\varphi}{\bar{M}_p} + c$$

b) before present epoch :

δ varies slowly

$$\Omega_h \approx \begin{cases} \delta & \text{radiation dom.} \\ \frac{3}{4}\delta & \text{matter dom.} \end{cases}$$

Ω_h small, but not tiny in the past !

c) „today" linked to small number in fundamental theory

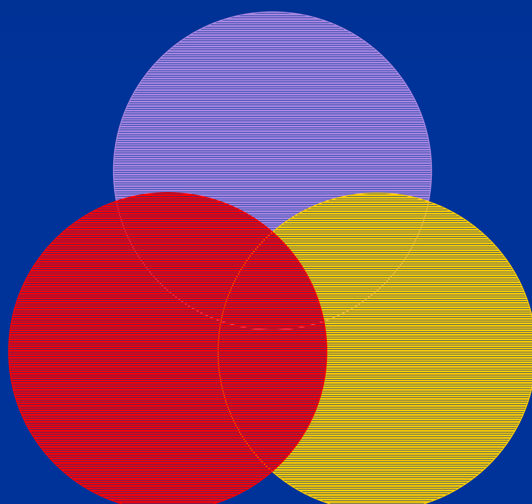
$E\delta_i \approx 1 / 138$

One could hope for explanation of „cosmic coincidences" that relate $H_0 / \bar{M}_p$ to fundamental parameters

$$\frac{H_0^2}{\bar{M}_p^2} \approx \frac{1}{3} \exp - \frac{1}{\delta_i E}$$

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Cosmon

- *Tiny mass*
- $m_c \sim H$
- *New long - range interaction*

cosmon mass

for standard kinetic term

- $m_c^2 = V''$

for standard exponential potential , k = const.

- $m_c^2 = V''/ k^2 = V/(k^2 M^2)$

  $= 3\, \Omega_h (1 - w_h)\, H^2 / (2\, k^2)$

Are fundamental "constants" time dependent ?

Fine structure constant α (electric charge)

Ratio nucleon mass to Planck mass

"Fifth Force"

- Mediated by scalar field

R.Peccei,J.Sola,C.Wetterich,Phys.Lett.B195,183(1987)

- Coupling strength: weaker than gravity

  (nonrenormalizable interactions ~ M^{-2})

- Composition dependence

  ⇨ violation of equivalence principle

- Quintessence: connected to time variation of fundamental couplings

C.Wetterich , Nucl.Phys.B302,645(1988)

Quintessence and Time dependence of "fundamental constants"

- Fine structure constant depends on value of cosmon field : $\alpha(\varphi)$

(similar in standard model: couplings depend on value of Higgs scalar field)

- Time evolution of φ → Time evolution of α

Jordan,…

Field dependent gauge coupling (gauge invariance maintained)

$$\mathcal{L}_g = \frac{1}{4} Z_F(\chi) F^{\mu\nu} F_{\mu\nu}$$

renormalized gauge coupling

$$g^2(\chi) = \bar{g}^2 Z_F^{-1}(\chi)$$

for GUT : C.Hill ; Q.Shafi , CW

GUT : running of electromagnetic and strong gauge coupling related

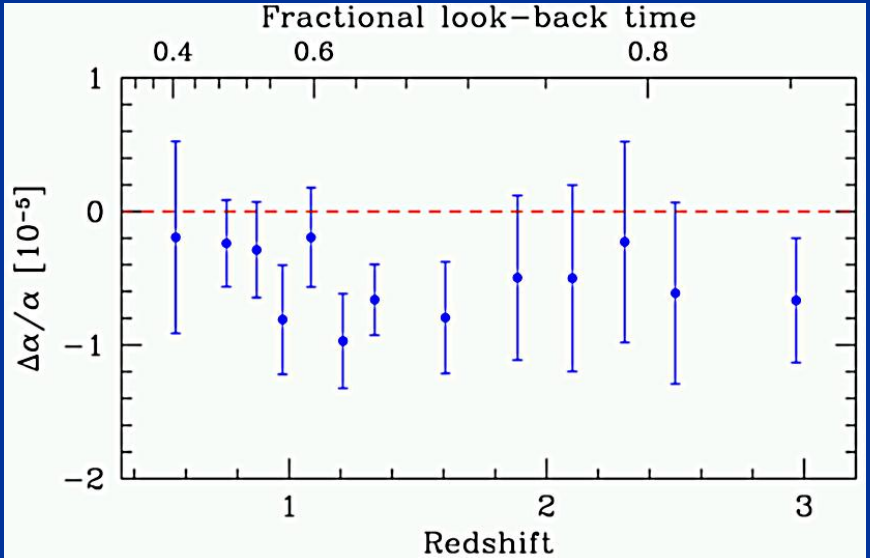
$$\alpha_{em}^{-1}(m_e) = \frac{32\pi Z_F(x)}{3\bar{g}^2} + \frac{5}{3\pi}\ln\frac{M_{GUT}}{M_W} + \frac{10}{3\pi}\ln\frac{M_W}{m_n} + \frac{2}{\pi}\ln\frac{m_n}{m_e}$$

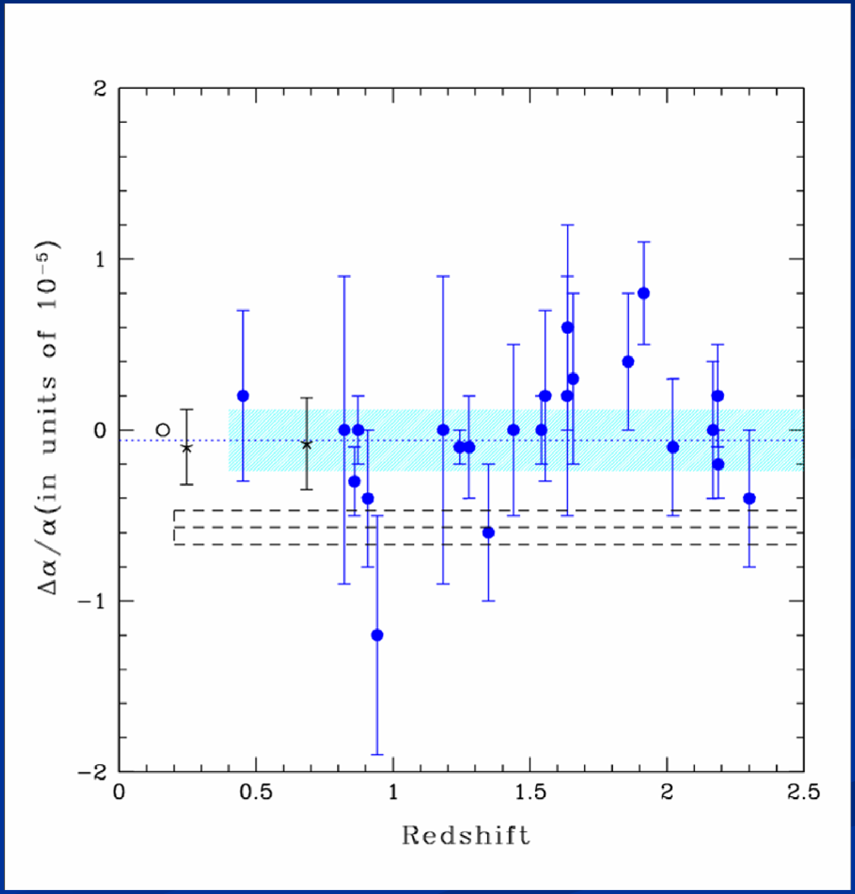
$$\frac{\Delta(m_n/M)}{(m_n/M)} = 39.1\,\frac{\Delta\alpha_{em}}{\alpha_{em}}$$

strong effect from variation of nucleon mass for time dependent couplings !

X.Calmet , H.Fritzsch

Variation of fine structure constant as function of redshift





Webb et al

Srianand et al

Variation of fine structure constant

Three independent data sets from Keck/HIRES

$$\Delta\alpha/\alpha = -0.54\ (12)\ 10^{-5}$$

Murphy,Webb,Flammbaum, june 2003

VLT

$$\Delta\alpha/\alpha = -0.06\ (6)\ 10^{-5}$$

Srianand,Chand,Petitjean,Aracil, feb.2004

$z \approx 2$

Crossover quintessence and time variation of fundamental "constants"

Upper bounds for relative variation of the fine structure constant

- Oklo natural reactor $\Delta\alpha/\alpha < 10^{-7}$ z=0.13
- Meteorites (Re-decay) $\Delta\alpha/\alpha < 3\ 10^{-7}$ z=0.45

- **Crossover Quintessence leads to small variation of couplings at low z as compared to z ≈ 2 !**

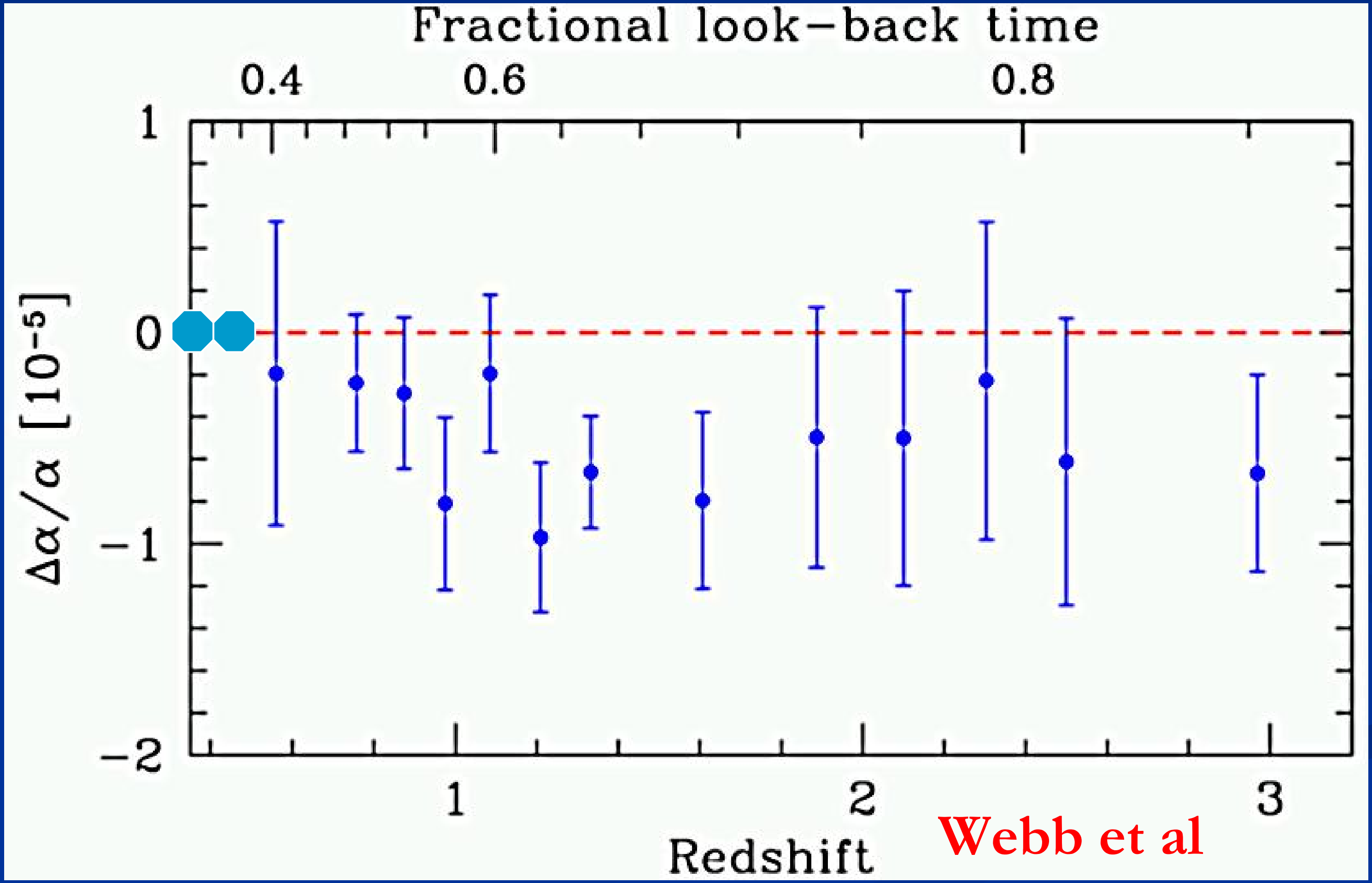
Time evolution of fundamental couplings traces time evolution of quintessence

today w_h close to -1 :

- Small kinetic energy
- Slow change of φ
- Slow change of α

Very small $\Delta\alpha/\alpha$ for low z !

Variation of fine structure constant as function of redshift



Cosmon and time variation of couplings

- small coupling of cosmon to matter due to fixed points behavior

Dimensional transmutation

α_X : unified gauge coupling at unification scale $M_X \sim \chi$

running $\alpha_X(\chi)$:

$$\frac{\partial \alpha_X}{\partial \ln \chi} = b_2 \alpha_X - b_4 \alpha_X^2$$

$b_2, b_4 > 0$

IR - scale where α_X grows large : m

UV - fixed point reached for $\chi \gg m$

$$\alpha_{X*} = \frac{b_2}{b_4} \approx \frac{1}{40}$$

close to fixed point :
small time evolution of couplings
coupling to matter weaker
than gravitational strength

dependence of fixed point on δ could induce observable effect

$$\frac{\partial \alpha_X}{\partial \ln \chi} = 0.2\,\alpha_X - 8\alpha_X^2 - b_6\,\alpha_X^3\left(6 - \frac{\delta}{1+6\delta}\right)$$

adjusting b_6 to reproduce results by Webb et al:

$\Delta\alpha_{em} / \alpha_{em}$ for various z

z:	0.13	0.45	2	10^{10}
$\frac{\Delta\alpha}{\alpha}$	$-1.7\cdot10^{-7}$	$-8.2\cdot10^{-7}$	$-7\cdot10^{-6}$	$-7.8\cdot10^{-5}$

differential acceleration : $\eta = 4.4\cdot10^{-14}$

smaller for Srianand et al !

Realistic example, crossover quintessence

$E = 5 \qquad \left(\frac{\partial \delta}{\partial \ln \chi} = 5\delta^2\right)$

$h = 0.66\,, \qquad \Omega_h^{(0)} = 0.7$

$w_h^{(0)} = -0.93$

$t^{(0)} = 13.7\cdot10^9\,\mathrm{yr}$

$\Omega_h^{(ls)} = 0.02$

$l_3 = 796\,, \qquad \sigma_8/\sigma_8^{(\Lambda)} = 0.7$

Time variation of coupling constants
is tiny –

would be of very high significance !

Possible signal for Quintessence

Παντα ρει

Cosmodynamics

Cosmon mediates new long-range interaction

Range : size of the Universe – horizon

Strength : weaker than gravity

photon	electrodynamics
graviton	gravity
cosmon	cosmodynamics

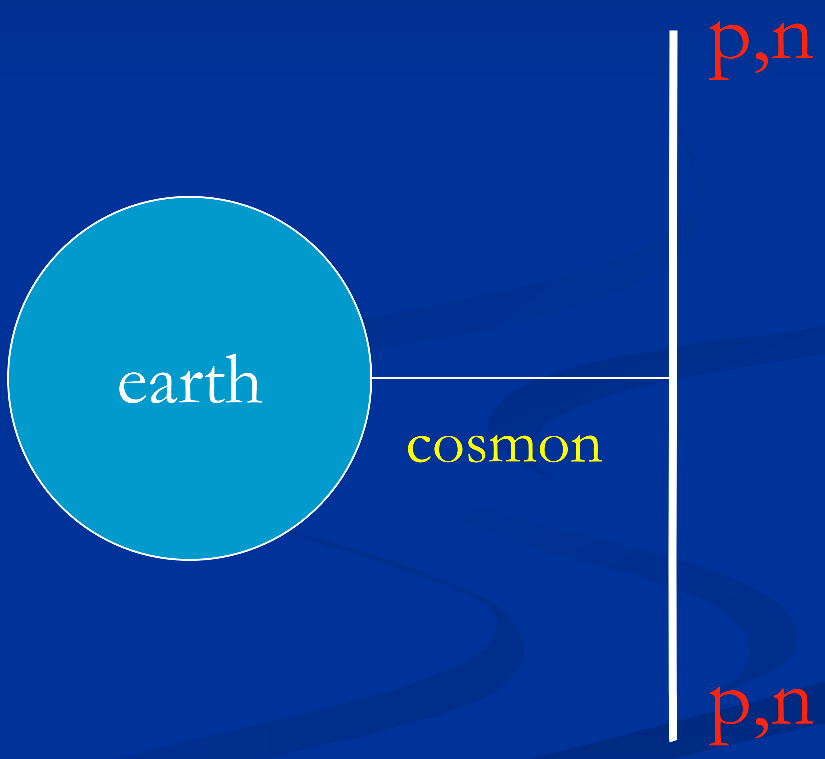
Small correction to Newton's law

Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

Violation of equivalence principle



Differential acceleration η

For unified theories (GUT) :

$$\eta = -1.75\ 10^{-2} \Delta R_z \left(\frac{\partial \ln \alpha}{\partial z}\right)^2 \frac{1+\tilde{Q}}{\Omega_h(1+w_h)}$$

$$\Delta R_z = \frac{\Delta Z}{Z+N} \approx 0.1$$

$\eta = \Delta a / 2a$

Q : time dependence of other parameters

Link between time variation of α

and violation of equivalence principle

typically : $\eta = 10^{-14}$

if time variation of α near Oklo upper bound

to be tested by MICROSCOPE

(1) $\alpha_X(\varphi) \rightarrow \Lambda_{QCD}(\varphi) \rightarrow m_n(\varphi)$

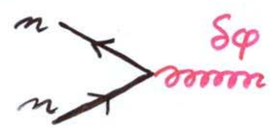
nucleon mass depends on value of the cosmon field (and therefore on time)

(2) expand around cosmological value $\varphi_0(t)$:

$$\varphi(\vec{x}, t) = \varphi_0(t) + \delta\varphi(\vec{x}, t)$$

$$m_n = m_n(\varphi_0) + \frac{\partial m_n}{\partial \varphi}\Big|_{\varphi_0} \delta\varphi$$

$\Rightarrow$ cosmon - nucleon vertex $\sim \bar{n} n \, \delta\varphi$



$\Rightarrow$ earth is source for surrounding local cosmon field $\delta\varphi(|\vec{r}|)$

(3) Test body carries effective „cosmon charge"

$$Q_c = k^{-1} \frac{\partial m_t}{\partial \varphi}$$

to be compared with „gravitational charge"

$$Q_g = \frac{m_t}{\sqrt{2}\,\bar{M}_p}$$

⇒ Correction to Newtonian potential

$$V_N = -\frac{G_N M m_t}{r}\left(1 + \alpha_t\right)$$

$$\alpha_t = \frac{2\bar{M}_p^2}{k^2} \frac{\partial \ln M}{\partial \varphi} \frac{\partial \ln m_t}{\partial \varphi}$$

(4) Protons and neutrons have different cosmon charges, $\frac{\partial m_p}{\partial \varphi} \neq \frac{\partial m_n}{\partial \varphi}$

This leads to differential acceleration !

observation

$$|\eta| < 3 \cdot 10^{-13}$$

Baessler et al.

Atomic clocks and OKLO

* Atomic clocks:

$$\frac{\dot{\alpha}_{em}}{\alpha_{em}} = -5.4 \cdot 10^{-10} \, \frac{\Delta\alpha_{em}}{\alpha_{em}}(z=0.13) \, yr^{-1}$$

observation $\frac{\dot{\alpha}_{em}}{\alpha_{em}} = (4.2 \pm 6.9) \cdot 10^{-15} \, yr^{-1}$

Sortais et al.

assumes that both effects are dominated by change of fine structure constant

small change of couplings in space

- Fine structure constant depends on location in space (satellites!)

$$r = 2R : \quad \frac{\delta\alpha_{em}}{\alpha_{em}} = 3 \cdot 10^{-19}\, k^{-2}$$

Summary

- $\Omega_h = 0.7$

- Q/Λ : dynamical und static dark energy
  will be distinguishable

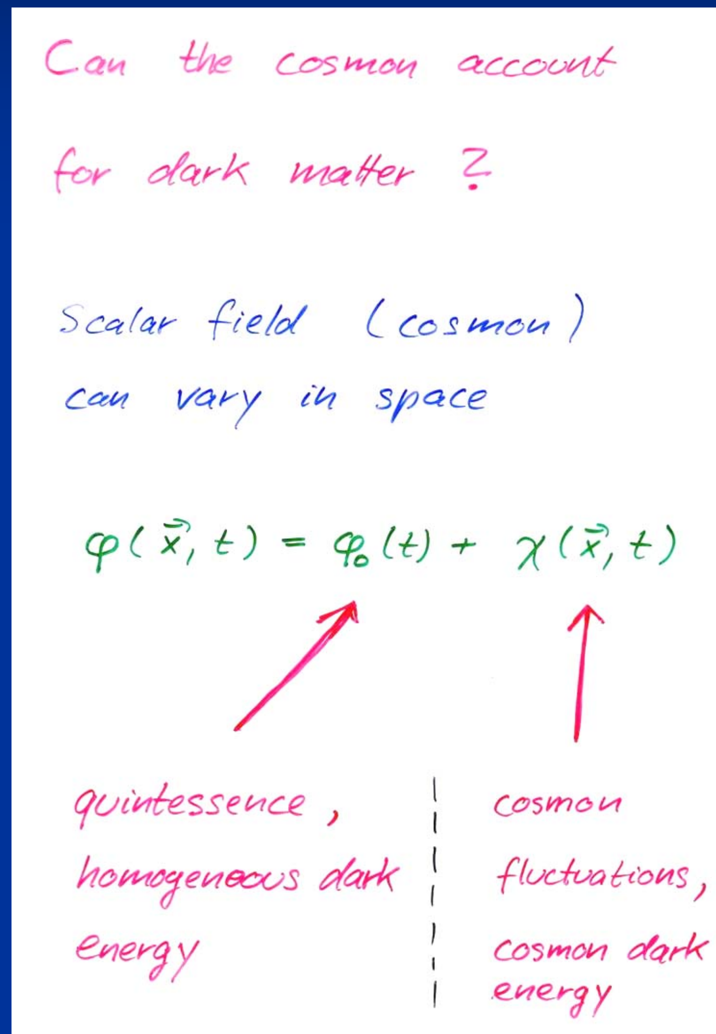
- Q : time varying fundamental coupling “constants”

  violation of equivalence principle

????????????????????????

- Why becomes Quintessence dominant in the present cosmological epoch ?
- Are dark energy and dark matter related ?
- Can Quintessence be explained in a fundamental unified theory ?

Cosmon dark matter



$$\varphi_0(t) = \frac{1}{V}\int d^3x\, \varphi(\vec{x}, t)$$

cosmological expectation value

* similar to gravity
* different for gauge bosons, fermions

energy density in cosmon fluctuations ρ_c

$$\rho_c = \frac{1}{2}\int \frac{d^3k}{(2\pi)^3}\Big\{ |\dot{\chi}_k|^2 + \Big(\frac{k^2}{a^2} + V''(\varphi_0)\Big)|\chi_k|^2$$

$$+ \text{higher order terms} \Big\}$$

quintessence ρ_q

$$\rho_q = \frac{1}{2}\dot{\varphi}_0^2 + V(\varphi_0) = T + V$$

Different equation of state

for ρ_c, ρ_q ?

$$w = p / \rho$$

Well possible !

e.g. • ρ_c dominated by modes inside the horizon , $\frac{k^2}{a^2} \gg H^2$

• neglect higher order terms

a) $\frac{k^2}{a^2} \gg V'' \Rightarrow \frac{p_c}{\rho_c} = \frac{1}{3}$, radiation

b) $\frac{k^2}{a^2} \ll V'' \Rightarrow \frac{p_c}{\rho_c} = 0$, matter

but

$$\frac{p_q}{\rho_q} = \frac{T - V}{T + V}$$, can be negativ !

- most quintessence models :

$$V'' \approx H^2$$

$$\Rightarrow \frac{p_c}{\rho_c} = \frac{1}{3}$$ or

nonlinear terms play a role !

- one can construct models with $V'' \gg H^2$ (Matos et al)

$\Rightarrow$ cosmon dark matter

$(H \approx 10^{-33} eV)$

Can nonlinear effects induce an effective dynamical mass term ?

Why has quintessence become important now ?

$$\frac{d\Omega_h}{d\ln a} = -3 w_h \Omega_h (1 - \Omega_h)$$

$(a \gg a_{eq})$

a) properties of cosmon potential or kinetic term

(i) Late quintessence

$w_h \approx \text{const}$, $(w_h < -\frac{1}{3})$

Ω_h negligible in early cosmology

needs tiny parameter like cosmological constant , $V(a_p)/M_p^4 = 10^{-\text{many}}$

(ii) early quintessence

Ω_h changes only modestly

w_h changes with time

special feature in cosmon potential or kinetic term becomes important „now" , „tuning" at ‰ level

b) quintessence reacts to „special event" in cosmology

* onset of Matter dominance

  k - essence

  Amendariz-Picon, Mukhanov, Steinhardt

  needs higher derivative kinetic term

* appearance of non-linear structure

  „backreaction effect"

scalar evolution equation

$$\langle \ddot{\varphi} + 3H\dot{\varphi} + V'(\varphi) \rangle = 0$$

$$0 = \ddot{\varphi}_0 + 3H\dot{\varphi}_0 + V'(\varphi_0) + V''(\varphi_0)\langle\chi\rangle + \frac{1}{2}V'''(\varphi_0)\langle\chi^2\rangle$$

fluctuation effect

backreaction

(In principle, same for metric, but small effect)

* Needs large inhomogeneities in cosmon field <u>after</u> structure has formed

* Local cosmon field participates in structure

Need for understanding of

fluctuations on nonlinear level

Non - equilibrium QFT

?

end