Varying fundamental constants
-
a key property and key problem of quintessence

Fundamental “constants” are not constant

Have coupling constants in the early Universe other values than today ?

Yes !

Fundamental couplings in quantum field theory

Masses and coupling constants are determined by properties of ***vacuum*** *!*

Similar to Maxwell – equations in matter

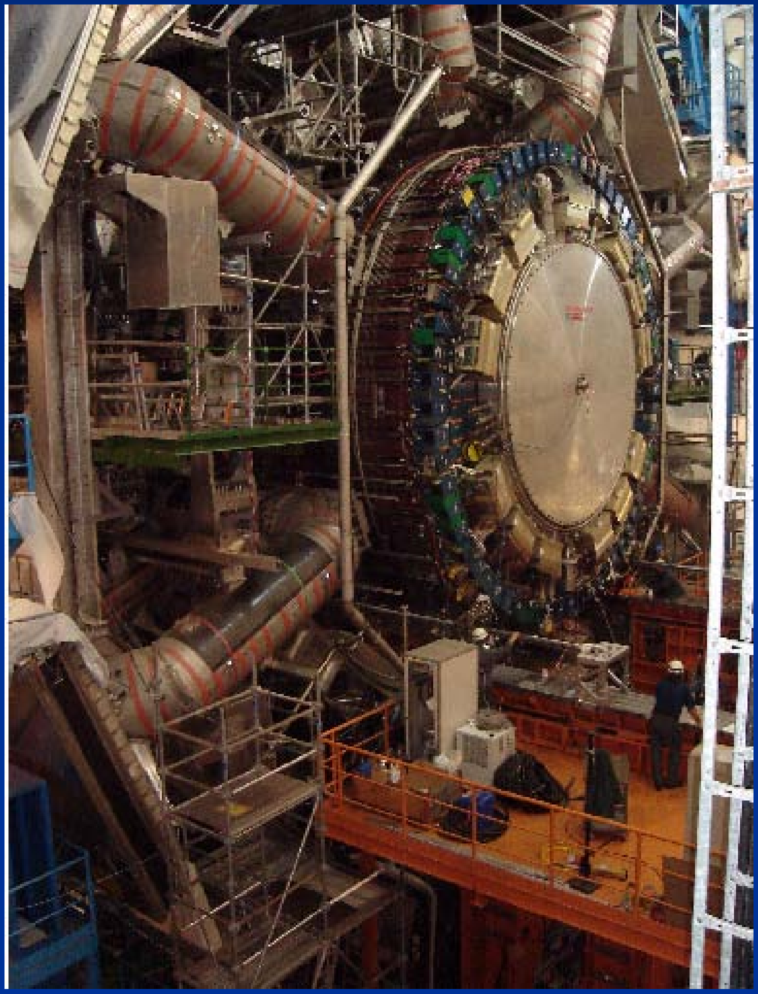
Condensed matter physics : laws depend on state of the system

- Ground state , thermal equilibrium state …
- Example : Laws of electromagnetism in superconductor are different from Maxwells' laws

Standard model of particle physics :

Electroweak gauge symmetry is spontaneously broken by expectation value of Higgs scalar

Spontaneous symmetry breaking confirmed at the LHC



Cosmology :

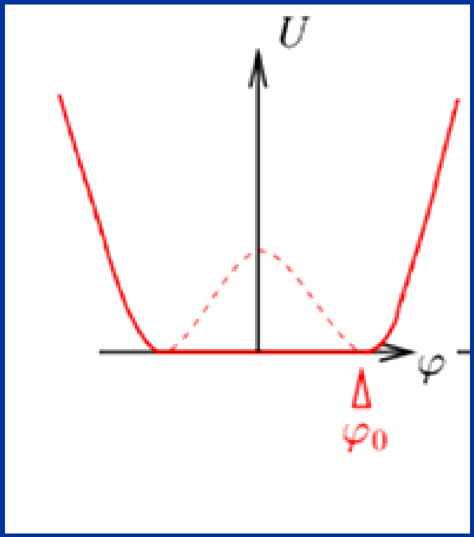
- Universe is not in one fixed state
- Dynamical evolution
- Laws are expected to depend on time

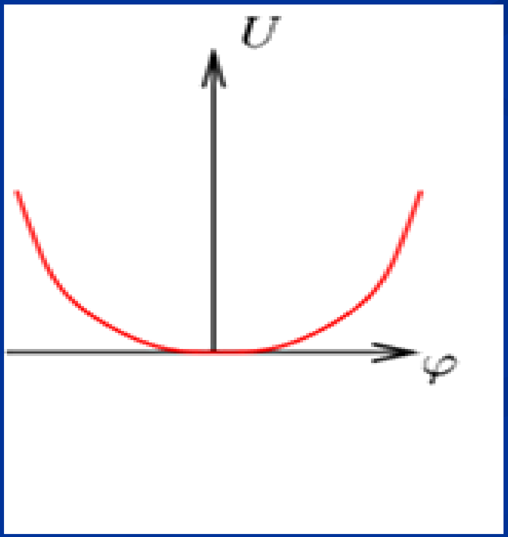
Restoration of symmetry at high temperature in the early Universe

Low T
SSB
$<\varphi>=\varphi_0 \neq 0$

High T
SYM
$<\varphi>=0$

high T :
Less order
More symmetry





Example:
Magnets

In hot plasma
of early Universe :

masses of electron und muon
not different!

similar strength of electromagnetic
and weak interaction

Varying couplings

only question :

How strong is **present** variation of couplings ?

Can variation of fundamental “constants” be observed ?

Fine structure constant α (electric charge)

Ratio electron mass to proton mass

Ratio nucleon mass to Planck mass

Time evolution of couplings and scalar fields

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

- Time evolution of φ

⟹ Time evolution of α

Jordan,…

Static scalar fields

In Standard Model of particle physics :

- Higgs scalar has settled to its present value around 10^{-12} seconds after big bang.
- Chiral condensate of QCD has settled at present value after quark-hadron phase transition around 10^{-6} seconds after big bang .
- No scalar with mass below pion mass.
- No substantial change of couplings after QCD phase transition.
- Coupling constants are frozen.

Observation of time- or space-variation of couplings

⟹

Physics beyond Standard Model

Particle masses in quintessence cosmology

can depend on value of cosmon field

similar to dependence on value of Higgs field

Time evolution of couplings and scalar fields

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

Cosmon field changes in present cosmological epoch

Time evolution of φ ⇒ Time evolution of α

Jordan,…

Dark Energy :
Energy density that does not clump

Photons , gravitons : insignificant

Matter

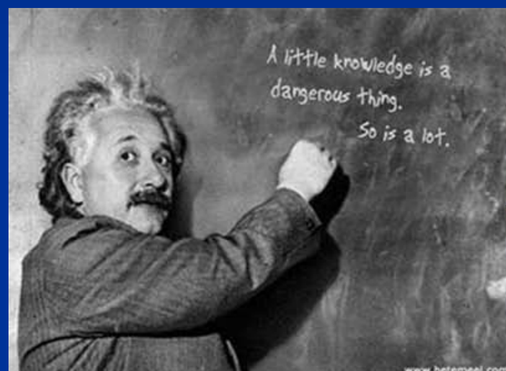

Gravitational Lens in Galaxy Cluster Abell 1689
HUBBLESITE.org

Space between clumps
is not empty :

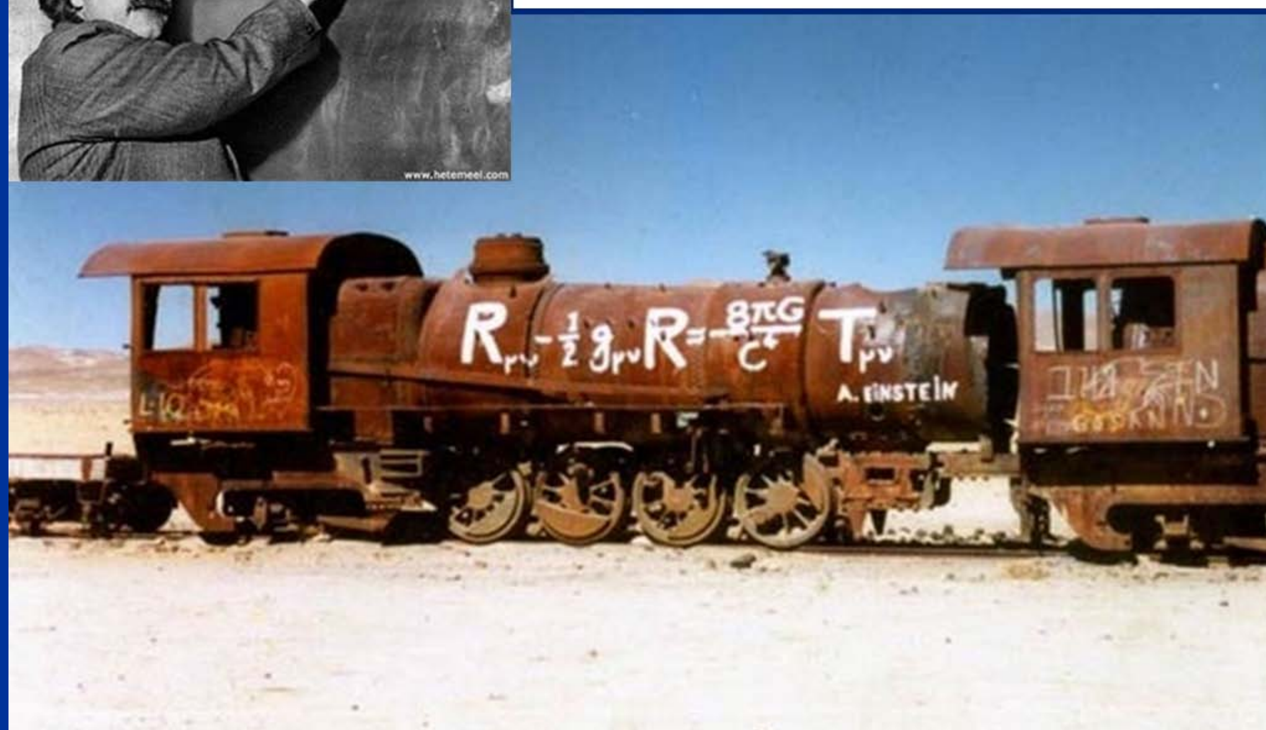
Dark Energy !

Dark Energy : Homogeneously distributed

Einstein's equations : almost static Dark Energy predicts accelerated expansion of Universe



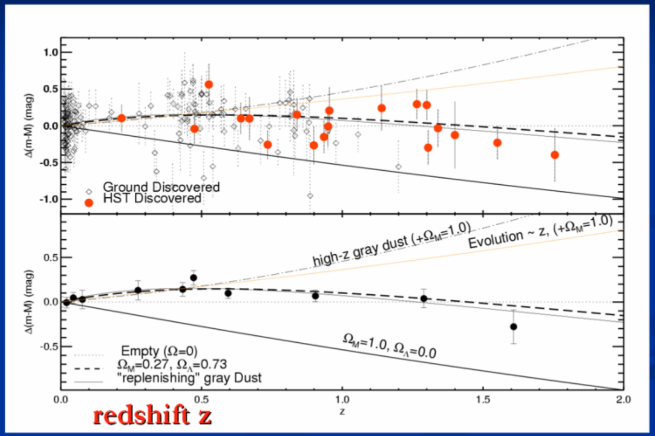
$$G_{\mu\nu} = 8\pi T_{\mu\nu}$$



Predictions for dark energy cosmologies

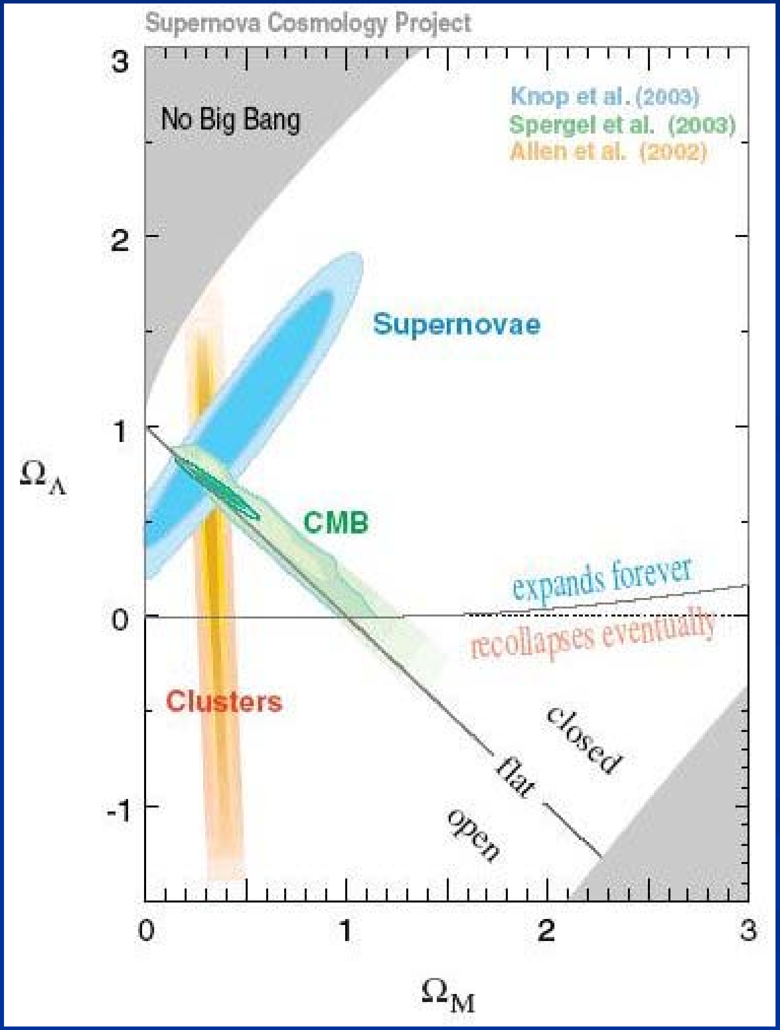
The expansion of the Universe
accelerates today !

Supernovae 1a Hubble diagram



Riess et al. 2004

Dark Energy : observations fit together !



Composition of the Universe

$\Omega_b = 0.045$	visible	clumping
$\Omega_{dm} = 0.25$	invisible	clumping
$\Omega_h = 0.7$	invisible	homogeneous

What is Dark Energy ?

Cosmological Constant

or

Quintessence ?

Cosmological Constant
- Einstein -

- Constant λ compatible with all symmetries
- No time variation in contribution to energy density

- Why so small ? $\lambda/M^4 = 10^{-120}$

- Why important just today ?

Cosmological mass scales

- Energy density

$\varrho \sim (\, 2.4 \times 10^{-3}\ \mathrm{eV}\,)^{-4}$

- Reduced Planck mass

$M = 2.44 \times 10^{27}\ \mathrm{eV}$

- Newton's constant

$G_N = (8\pi M^2)$

Only ratios of mass scales are observable !

homogeneous dark energy: $\rho_h / M^4 = 6.5\ 10^{-121}$

matter: $\rho_m / M^4 = 3.5\ 10^{-121}$

Time evolution

- $\varrho_m/M^4 \sim a^{-3} \sim$ t^{-2} matter dominated universe
  $t^{-3/2}$ radiation dominated universe

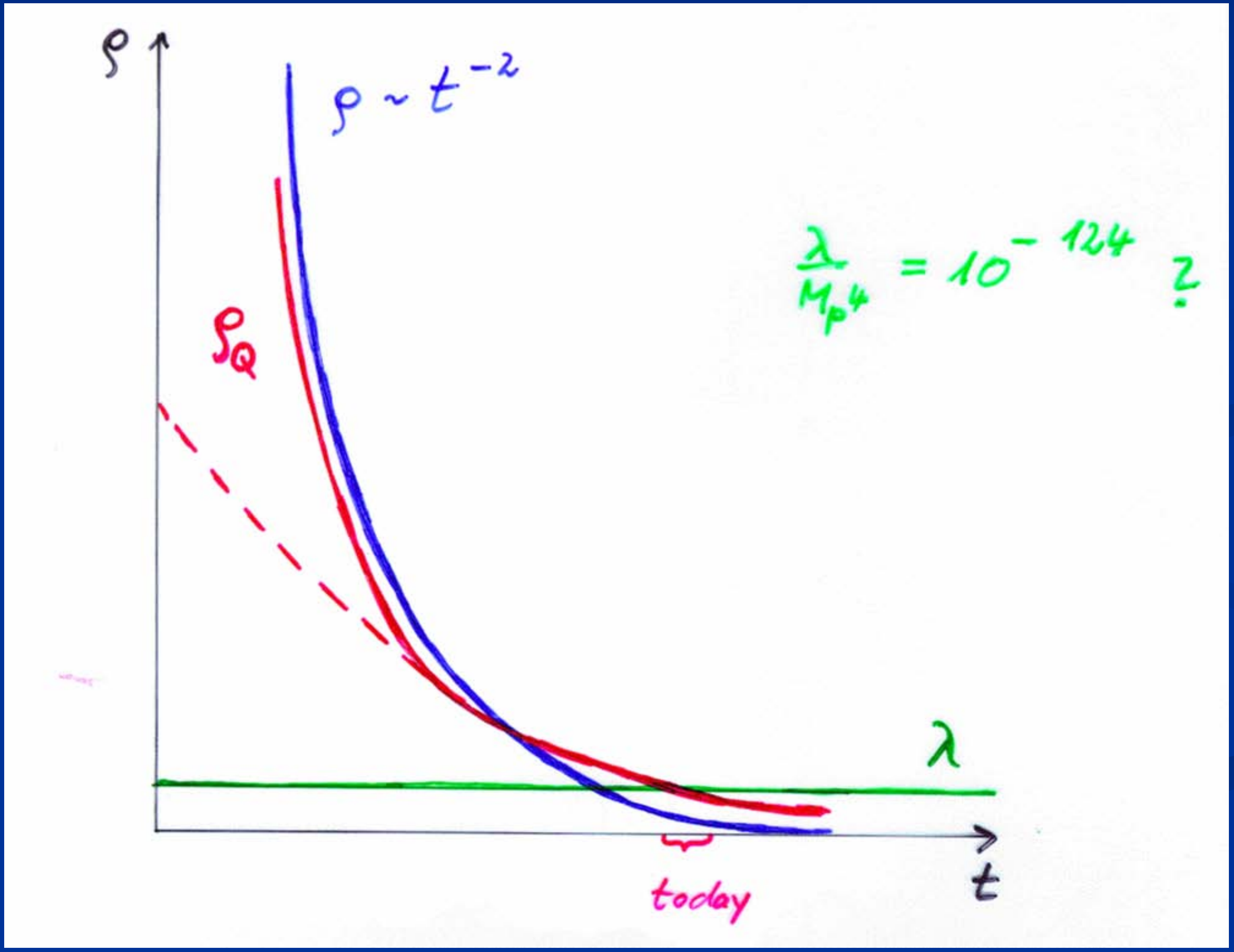
- $\varrho_r/M^4 \sim a^{-4} \sim t^{-2}$ radiation dominated universe

Huge age ⇨ small ratio

Same explanation for small dark energy?

Cosm. Const. | Quintessence

static | dynamical



Quintessence

Dynamical dark energy ,

generated by scalar field

(cosmon)

C.Wetterich,Nucl.Phys.B302(1988)668, 24.9.87

P.J.E.Peebles,B.Ratra,ApJ.Lett.325(1988)L17, 20.10.87

Prediction :

homogeneous dark energy influences recent cosmology

- of same order as dark matter -

Original models do not fit the present observations
…. modifications

Quintessence

Cosmon – Field $\varphi(x,y,z,t)$

similar to electric field , but no direction (scalar field)

Homogeneous und isotropic Universe : $\varphi(x,y,z,t)=\varphi(t)$

Potential und kinetic energy of the cosmon -field contribute to a dynamical energy density of the Universe !

Cosmon

- *Scalar field changes its value even in the* **present** *cosmological epoch*
- *Potential und kinetic energy of cosmon contribute to the energy density of the Universe*
- *Time - variable dark energy :*

  $\varrho_h(t)$ *decreases with time !*

Evolution of cosmon field

Field equations

$$\ddot{\phi} + 3H\dot{\phi} = -dV/d\phi$$

$$3M^2H^2 = V + \frac{1}{2}\dot{\phi}^2 + \rho$$

Potential V(φ) determines details of the model

$$V(\varphi) = M^4 \exp(-\alpha\varphi/M)$$

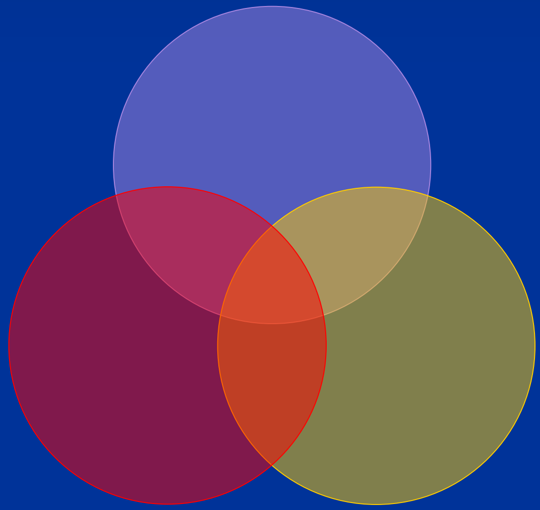
for increasing φ the potential decreases towards zero !

Cosmon

- *Tiny mass*
- $m_c \sim H$ *(depends on time !)*
- *New long - range interaction*

"Fundamental" Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Time varying constants

- It is not difficult to obtain quintessence potentials from higher dimensional or string theories
- Exponential form rather generic

  (after Weyl scaling)
- But most models show too strong time dependence of fundamental constants !

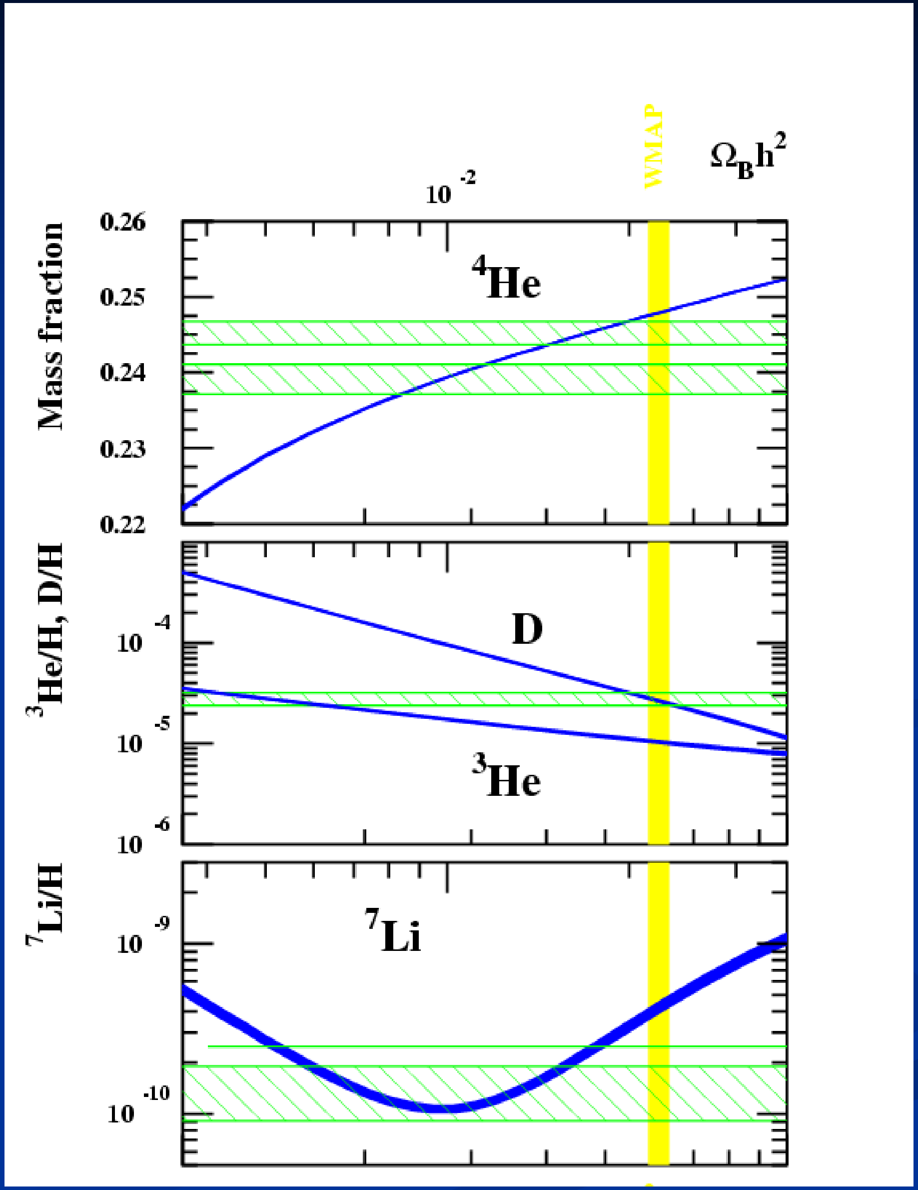
Bounds on time varying couplings from nucleosynthesis

baryons :

the matter of stars and humans

$$\Omega_b = 0.045$$

Abundancies of primordial light elements from nucleosynthesis



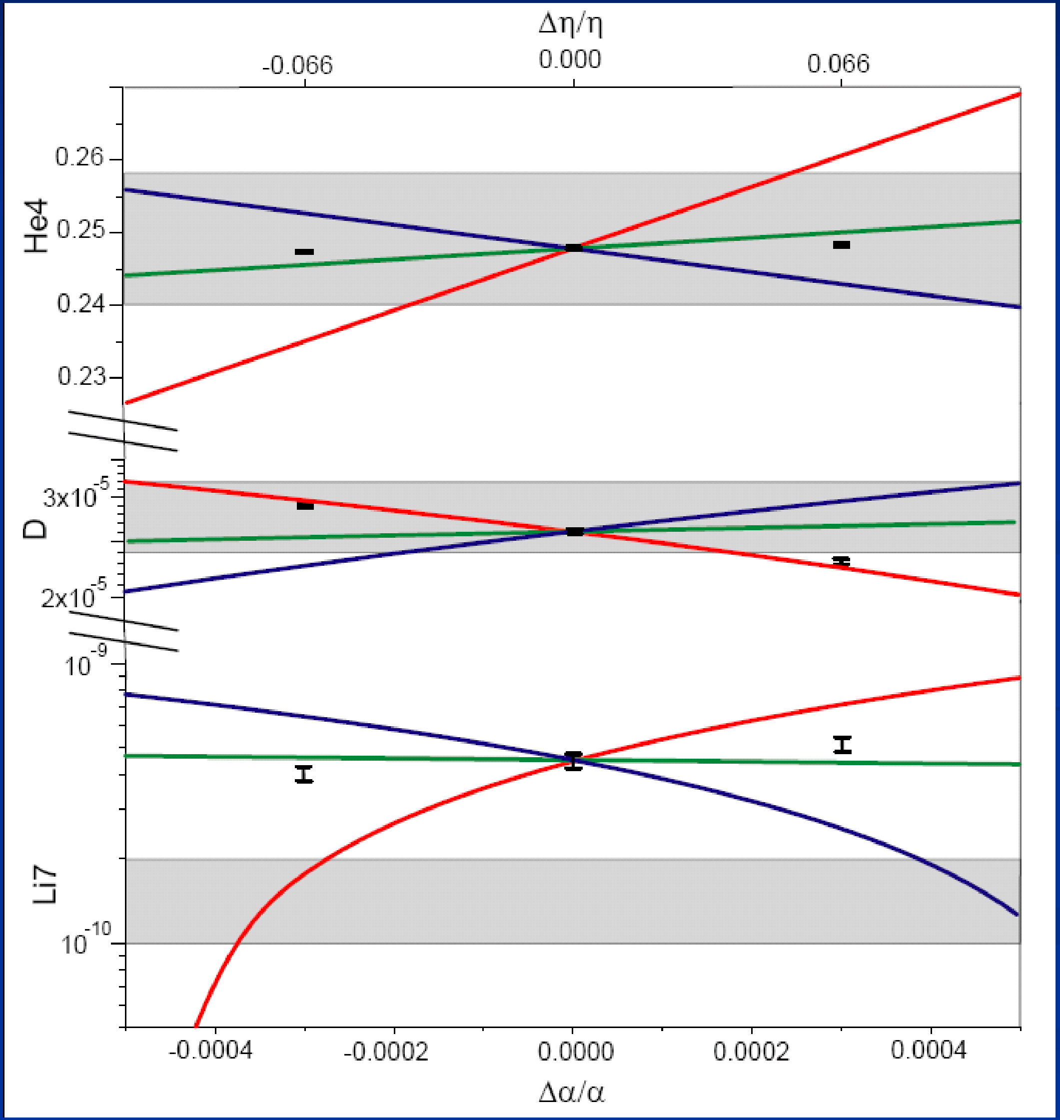
A.Coc

primordial abundances for three GUT models

He

D

Li



present observations : 1σ

T.Dent, S.Stern,…

three GUT models

- unification scale ~ Planck scale
- 1) All particle physics scales $\sim\Lambda_{QCD}$
- 2) Fermi scale and fermion masses ~ unification scale
- 3) Fermi scale varies more rapidly than Λ_{QCD}

$\Delta\alpha/\alpha \approx 4\ 10^{-4}$ allowed for GUT 2 and 3 , larger for GUT 1

$\Delta\ln(M_n/M_P) \approx 40\ \Delta\alpha/\alpha \approx 0.015$ allowed

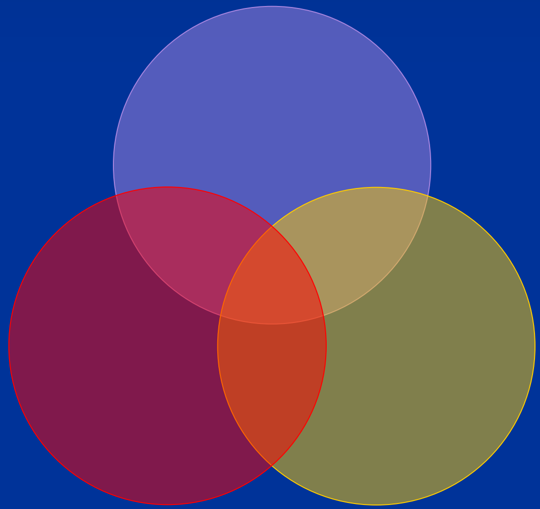
Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

“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

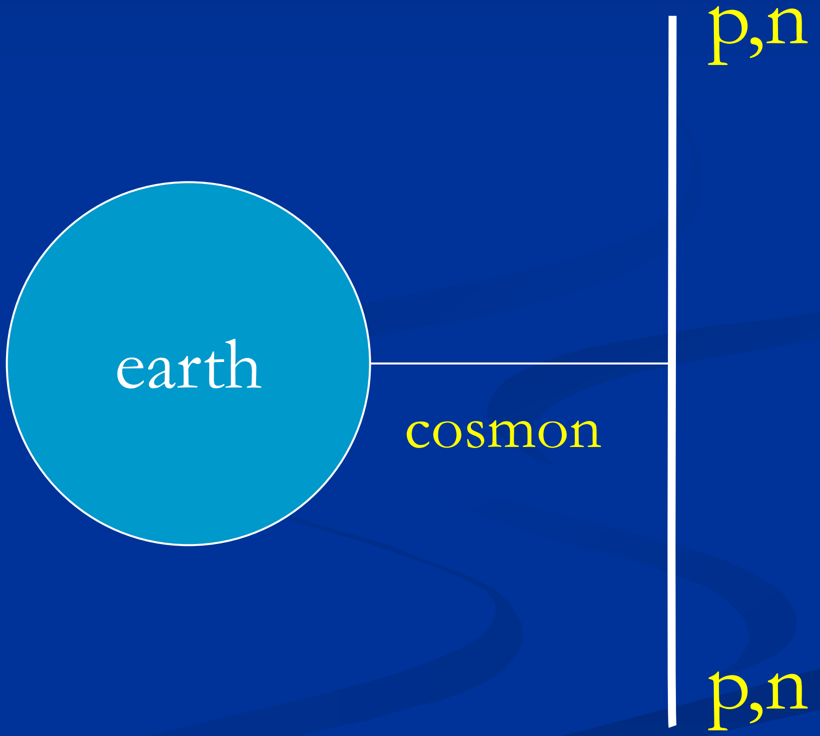
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

- Different couplings of cosmon to proton and neutron

- Differential acceleration

- "Violation of equivalence principle"



only apparent : new "fifth force" !

Differential acceleration

Two bodies with equal mass experience
a different acceleration !

$$\eta = (a_1 - a_2) / (a_1 + a_2)$$

bound : $\eta < 3 \; 10^{-14}$

Apparent violation of equivalence principle

and

time variation of fundamental couplings

measure both the

cosmon – coupling to ordinary matter

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 (MICROSCOPE , …)

Cosmon coupling to atoms

- Tiny !!!
- Substantially weaker than gravity.
- Non-universal couplings bounded by tests of equivalence principle.
- Universal coupling bounded by tests of Brans-Dicke parameter ω in solar system.
- Only very small influence on cosmology.

(All this assumes validity of linear approximation)

key problem for realistic quintessence

tiny cosmon - atom coupling

Planck mass may increase, but particle masses must be (almost) proportional to it

C.Wetterich , Nucl.Phys.B302, 645 and 668 (1988)

Possible mechanism for tiny cosmon-atom couplings

- asymptotic approach to fixed point for dimensionless couplings and mass ratios
- at fixed point : no cosmon coupling to atoms – no time variation of fundamental constants
- very near fixed point : tiny coupling
- how small ?

Approach to fixed point for φ → ∞

$$V = M^4 \exp\left(-\alpha \frac{\varphi}{M}\right)$$

$$\frac{m_n}{M} = f_0 + c_n \exp\left(-\beta_n \frac{\varphi}{M}\right)$$

requires for small time variation of couplings : $f_0 \neq 0$ or $\beta_n \ll \alpha$

similar for fine structure constant

$$\mathcal{L}_F = \frac{1}{4}\left[\frac{1}{e_0^2} + c_\alpha \exp\left(-\beta_\alpha \frac{\varphi}{M}\right)\right] F_{\mu\nu}F^{\mu\nu}$$

$$\frac{1}{e^2} = \frac{1}{e_0^2} + c_\alpha \exp\left(-\beta_\alpha \frac{\varphi}{M}\right) = \frac{1}{4\pi\alpha}$$

Neutrino cosmon coupling

- Strong bounds on atom-cosmon coupling from tests of equivalence principle or time variation of couplings.
- No such bounds for neutrino-cosmon coupling.
- In particle physics : Mass generation mechanism for neutrinos differs from charged fermions. Seesaw mechanism involves heavy particles whose mass may depend on the value of the cosmon field.

neutrino mass

$$M_\nu = M_D M_R^{-1} M_D^T + M_L$$

$$M_L = h_L \gamma \frac{d^2}{M_t^2}$$

seesaw and cascade mechanism

triplet expectation value ~ doublet squared

$$m_\nu = \frac{h_\nu^2 d^2}{m_R} + \frac{h_L \gamma d^2}{M_t^2}$$

omit generation structure

neutrino mass

$$M_\nu = M_D M_R^{-1} M_D^T + M_L$$

(?) ….

C.Wetterich, Nucl.Phys.B187 (1981) 343

$$M_L = h_L \gamma \frac{d^2}{M_t^2}$$

cascade (seesaw II) mechanism

M.Magg, C.W. 1980

Neutrino cosmon coupling

- realized by dependence of neutrino mass on value of cosmon field

$$\beta(\varphi) = -M \frac{\partial}{\partial \varphi} \ln m_\nu(\varphi)$$

- β ≈ 1 : cosmon mediated attractive force between neutrinos has similar strength as gravity

growing neutrino quintessence

growing neutrinos change cosmon evolution

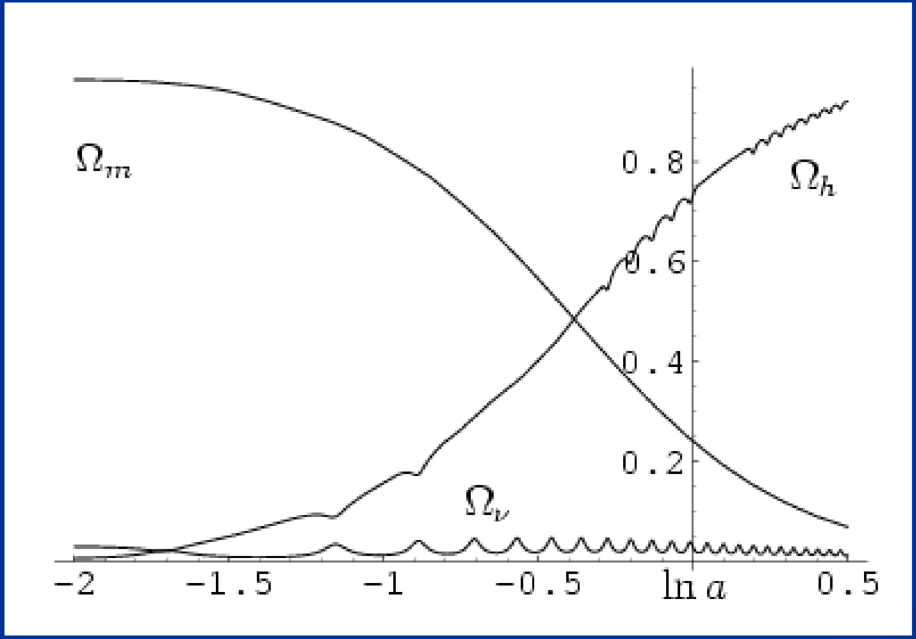
$$\ddot{\varphi} + 3H\dot{\varphi} = -\frac{\partial V}{\partial \varphi} + \frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu),$$

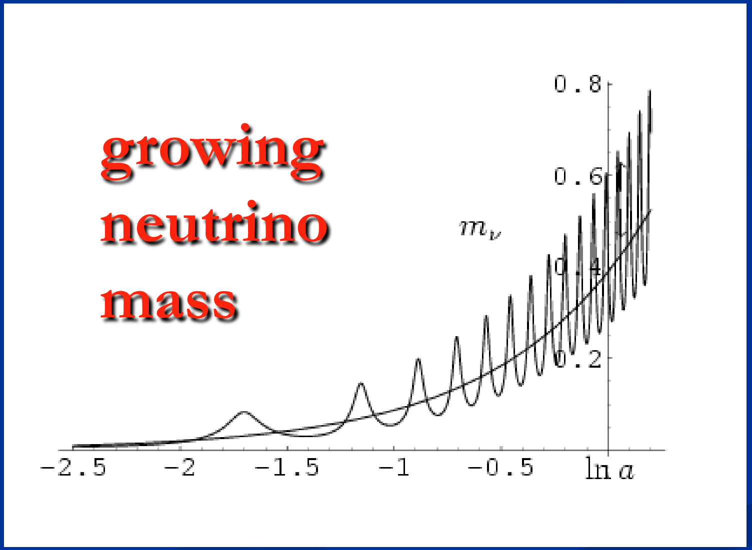
$$\beta(\varphi) = -M\frac{\partial}{\partial \varphi}\ln m_\nu(\varphi) = \frac{M}{\varphi - \varphi_t}$$

modification of conservation equation for neutrinos

$$\dot{\rho}_\nu + 3H(\rho_\nu + p_\nu) = -\frac{\beta(\varphi)}{M}(\rho_\nu - 3p_\nu)\dot{\varphi}$$
$$= -\frac{\dot{\varphi}}{\varphi - \varphi_t}(\rho_\nu - 3p_\nu)$$

growing neutrino mass triggers transition to almost static dark energy





L.Amendola, M.Baldi,…

effective cosmological trigger for stop of cosmon evolution : neutrinos get non-relativistic

- this has happened recently !
- sets scales for dark energy !

connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

present dark energy density given by neutrino mass

present equation of state given by neutrino mass !

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\text{eV}}$$

Induced small cosmon-atom coupling

- change of triplet expectation value induces tiny change of doublet expectation value

- change of Fermi scale
- change of ratio electron to proton mass
- change of fine structure constant

Time variation of coupling constants is tiny , but would be of very high significance !

Size not predicted

Possible signal for Quintessence

End