Time variation of „fundamental constants“ in quintessence cosmologies

Fundamental “constants” are not constant

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

Yes !

Fundamental couplings in quantum field theory

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

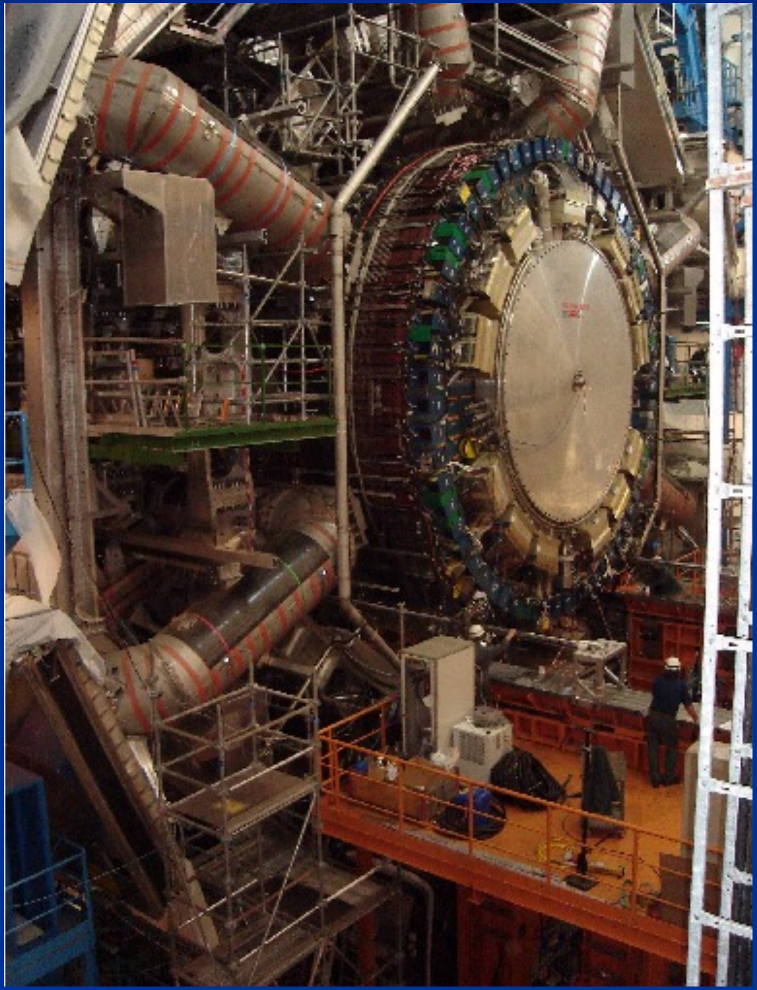
Similar to Maxwell – equations in matter

Standard model of particle physics :

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

Quark and lepton masses proportional to 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

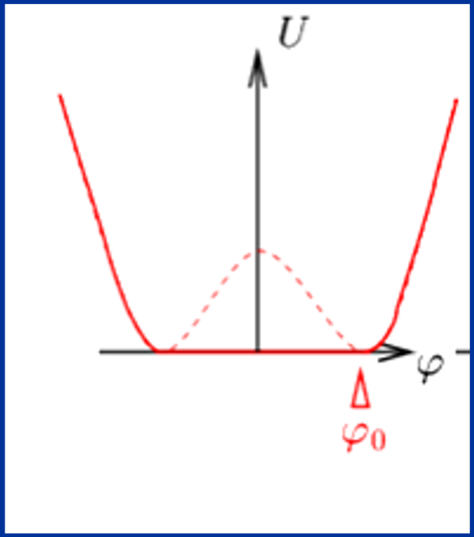
Restoration of symmetry at high temperature in the early Universe

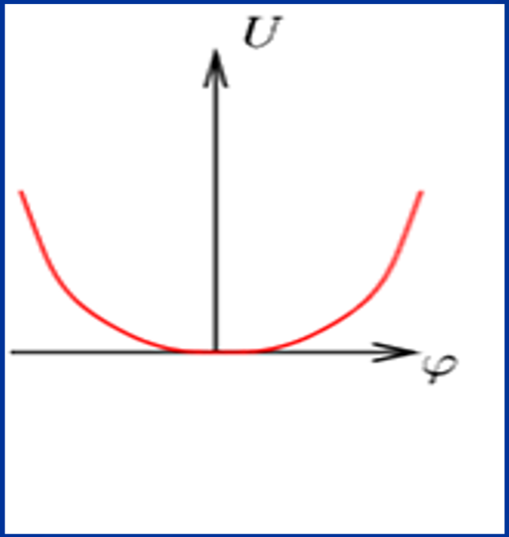
Low T
SSB
$\langle\varphi\rangle = \varphi_0 \neq 0$

High T
SYM
$\langle\varphi\rangle = 0$

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 scalar field : $\alpha(\varphi)$

- Time evolution of φ $\Rightarrow$

  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

$\Rightarrow$

Physics beyond Standard Model

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

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 :*

  $\rho_h(t)$ *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 $V(\varphi)$ determines details of the model

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

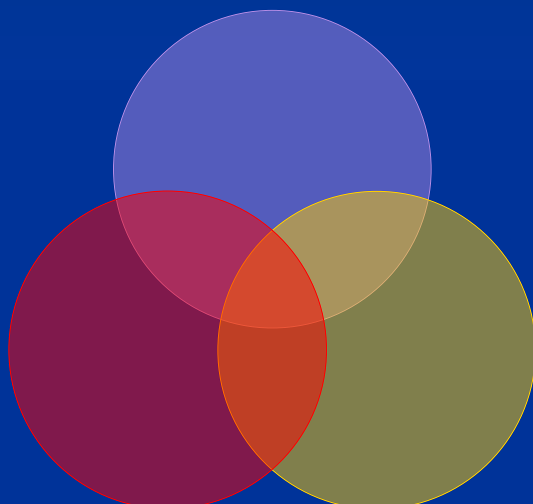
for increasing φ the potential decreases towards zero !

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

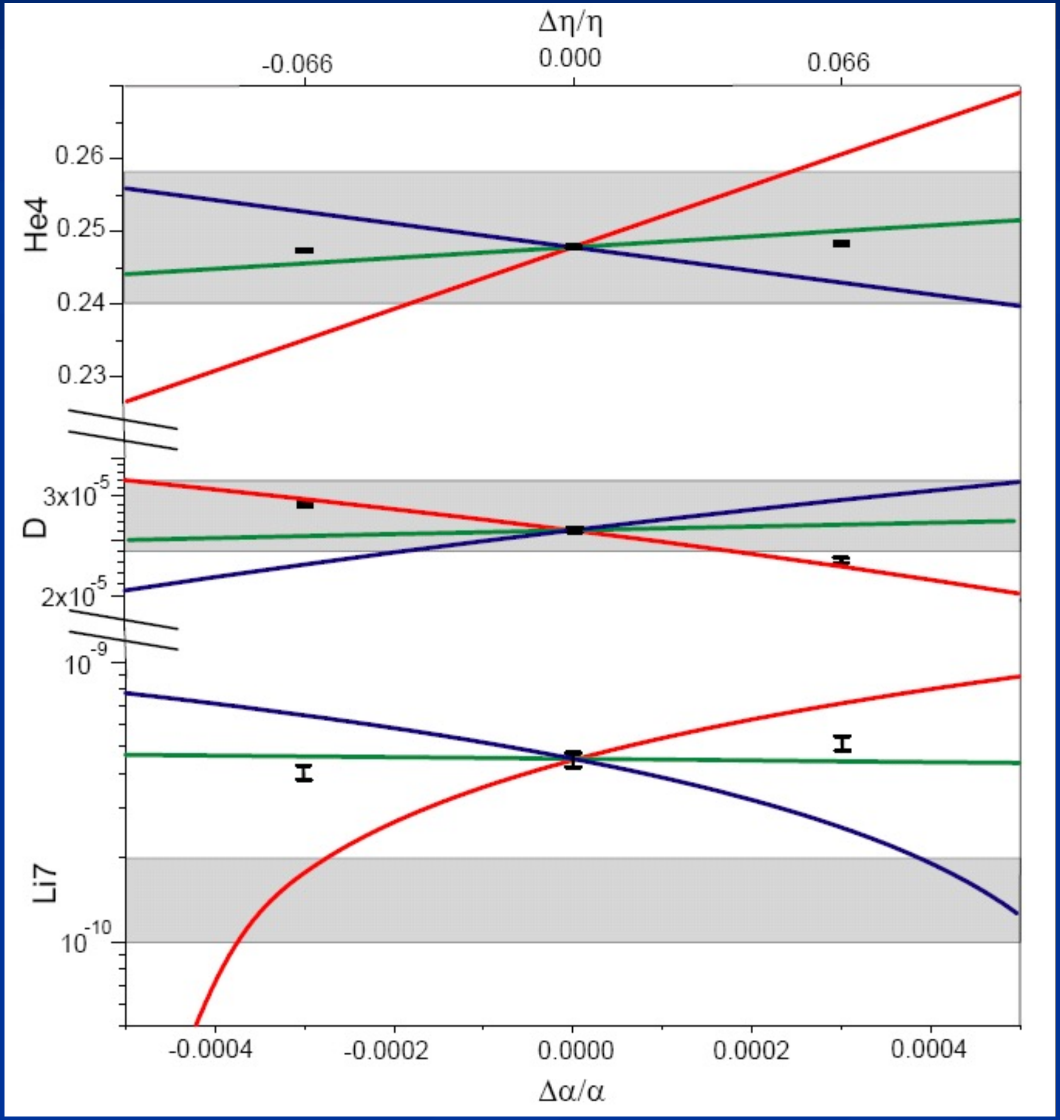
  (after Weyl scaling)
- But most models show too strong time dependence of fundamental constants !

primordial abundances for three GUT models

He

D

Li



present observations : 1σ

T.Dent, S.Stern,…

Time variation of coupling constants must be tiny –

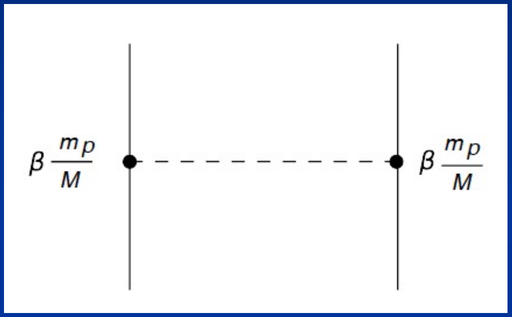
would be of very high significance !

Possible signal for Quintessence

Fifth force

Fifth force

- coupling strength $\beta \frac{m_p}{M}$
- range $\frac{1}{m}$



m ~ H : long range (dynamical dark energy)

m $\gg$ H : short range (dark matter)

concentrate on long range – effectively massless scalar for earth, solar system, galaxies, black holes, laboratory

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

(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 questions (1)

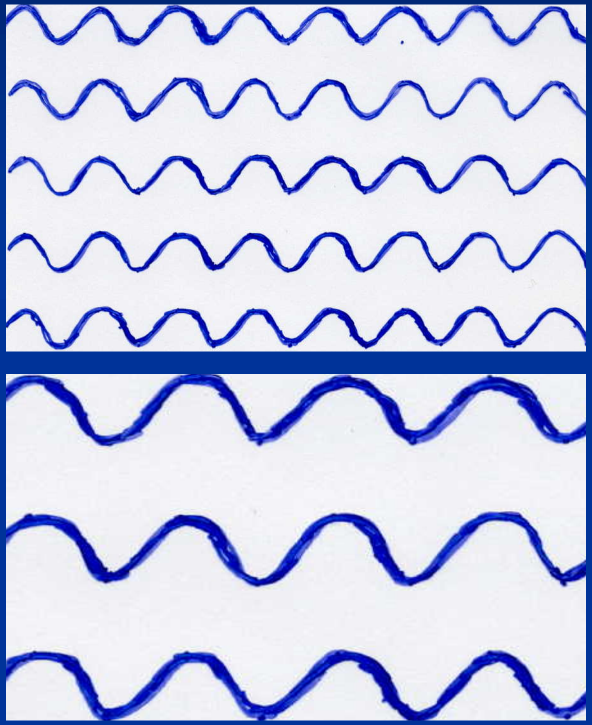
- Why is atom – scalar coupling much weaker than gravity?
- Why is scalar (almost) massless despite the presence of quantum fluctuations ?

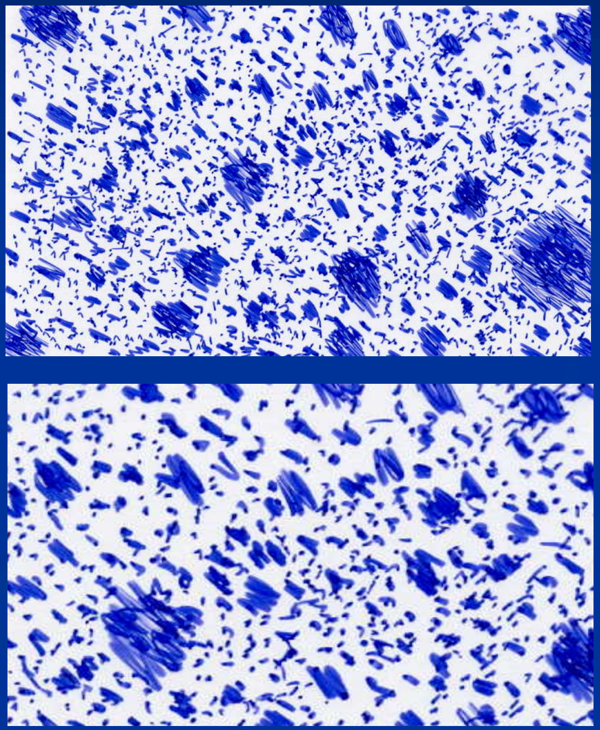
Spontaneously broken scale symmetry

scale symmetry

No intrinsic length or mass scale present

Scale symmetry





no scale symmetry

scale symmetry

only if no spontaneous symmetry breaking!

Scale symmetry

All parameters with mass are proportional to scalar field χ

- Dimensionless couplings are independent of χ.
- All particle masses are proportional to χ .
- Ratios of particle masses remain constant.
- Compatibility with observational bounds on time dependence of particle mass ratios even if χ changes with time.

Scale symmetry

All parameters with mass are proportional to scalar field χ

Classical scale symmetry with gravity:

$$\mathcal{L} = -\frac{1}{2}\chi^2 R + \frac{B-6}{2}\partial^\mu\chi\partial_\mu\chi + \lambda\chi^4$$

Fujii, Zee

Quantum scale symmetry

- quantum fluctuations violate scale symmetry
- running dimensionless couplings
- at fixed points , scale symmetry is exact !
- quantum scale symmetry

Quantum scale symmetry

In the quantum effective action
all parameters with mass are
proportional to scalar field χ

gravity:

$$\mathcal{L} = -\frac{1}{2}\chi^2 R + \frac{B-6}{2}\partial^\mu\chi\partial_\mu\chi$$

Higgs vev,

electron mass

$$\langle h \rangle \sim \chi \qquad m_e \sim \chi$$

QCD,

proton mass

$$\Lambda_{QDC} \sim \chi \qquad m_p \sim \chi$$

Spontaneous breaking of scale symmetry

- expectation value of scalar field breaks scale symmetry spontaneously
- massive particles are compatible with scale symmetry
- in presence of massive particles : sign of exact scale symmetry is exactly massless Goldstone boson – the dilaton

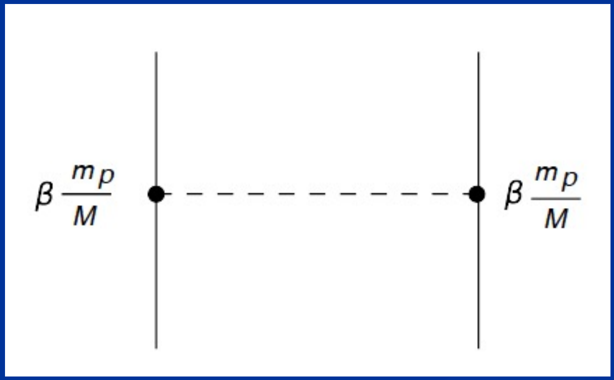
Einstein frame

Weyl scaling :

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu} \ , \ \varphi = \frac{2M}{\alpha} \ln\left(\frac{\chi}{\mu}\right)$$

scale transformation :

$$\varphi \to \varphi + \mathrm{const.}$$



$$m = 0, \ \beta_i = 0$$

Key questions (1)

- Why is atom – scalar coupling much weaker than gravity?
- Why is scalar (almost) massless despite the presence of quantum fluctuations ?

answer

Scale symmetry explains both massless scalar field and vanishing couplings

Approximate scale symmetry

Slowly running couplings close to fixed points

$$\frac{\partial g_i}{\partial \ln \chi} = A_i(g_i - g_{i*})$$

Simple 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 ?

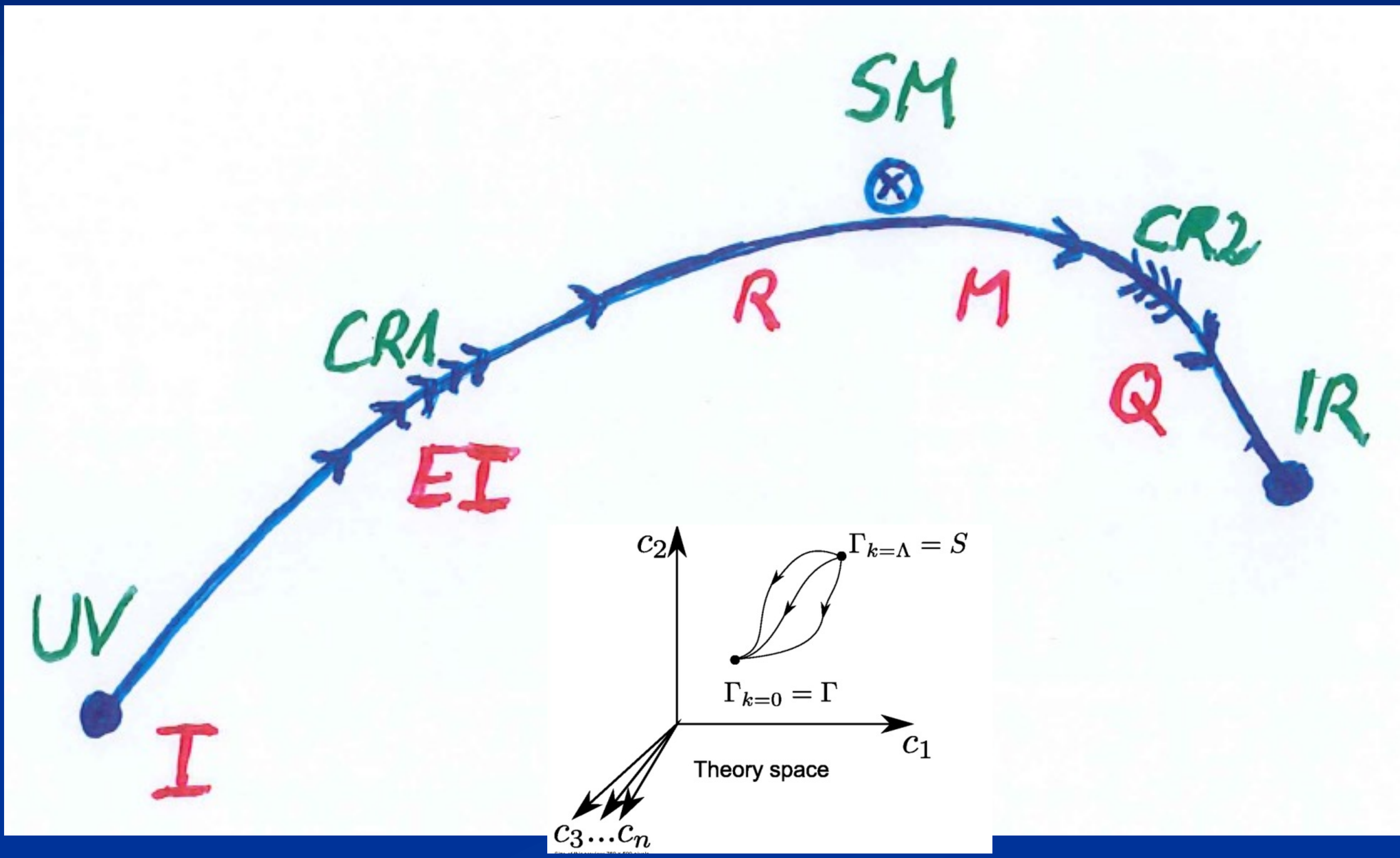
Simple mechanism for very light scalar field

- Exact scale symmetry :
  massless Goldstone boson
- Approximate scale symmetry :
  very light pseudo-Goldstone boson

Key question (2)

- Do fixed points play a role for cosmology ?

Crossover in quantum gravity



Approximate scale symmetry near fixed points

- UV : approximate scale invariance of primordial fluctuation spectrum from inflation
- IR : cosmon is pseudo Goldstone boson of
  spontaneously broken scale symmetry,
  tiny mass,
  responsible for dynamical Dark Energy

Asymptotic safety

if UV fixed point exists :

quantum gravity is

non-perturbatively renormalizable !

S. Weinberg , M. Reuter

a prediction…

Asymptotic safety of gravity and the Higgs boson mass

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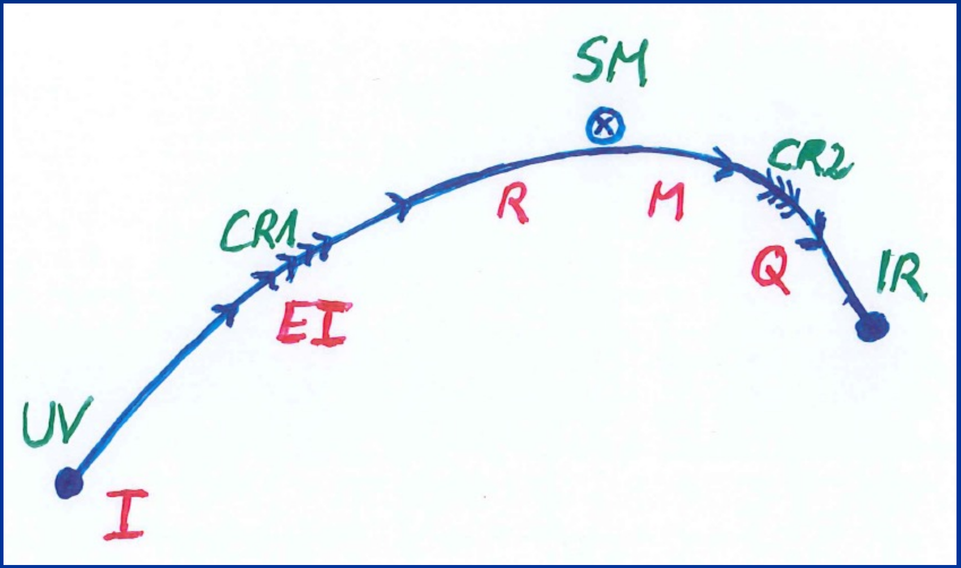
12 January 2010

Abstract

There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question of whether the mass of the Higgs boson m_H can be predicted. For a positive gravity induced anomalous dimension $A_\lambda > 0$ the running of the quartic scalar self interaction λ at scales beyond the Planck mass is determined by a fixed point at zero. This results in $m_H = m_{\min} = 126$ GeV, with only a few GeV uncertainty. This prediction is independent of the details of the short distance running and holds for a wide class of extensions of the SM as well.

s in $m_H = m_{\min} = 126$ GeV, with o

Possible consequences of crossover in quantum gravity



Realistic model for inflation and dark energy with single scalar field

Variable Gravity

$$\Gamma = \int_x \sqrt{g}\left\{-\frac{1}{2}\chi^2 R + \mu^2\chi^2 + \frac{1}{2}\left(B(\chi/\mu) - 6\right)\partial^\mu\chi\partial_\mu\chi\right\}$$

quantum effective action,
variation yields field equations

Einstein gravity : $\Gamma = \int_x \sqrt{g}\left\{-\frac{1}{2} M^2 R \right\}$

Variable Gravity

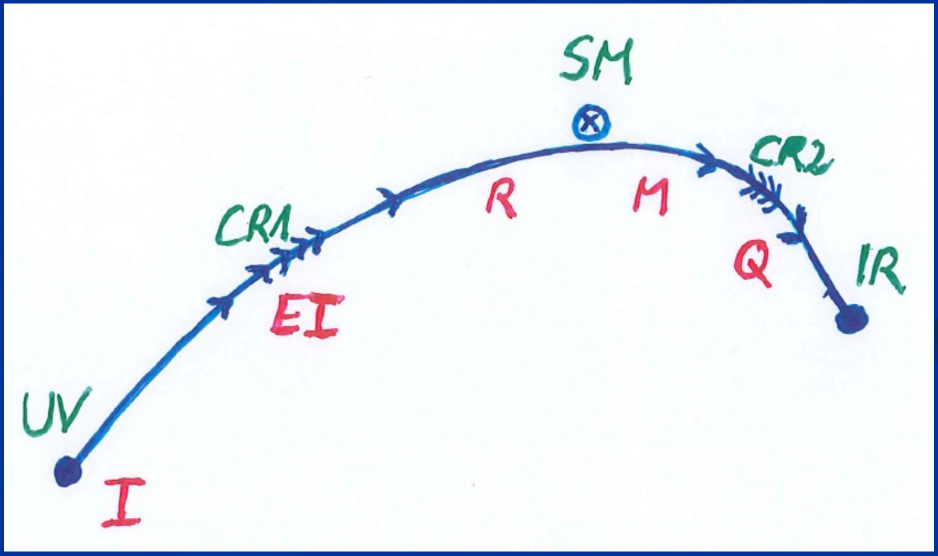
- Scalar field coupled to gravity
- Effective Planck mass depends on scalar field
- Simple quadratic scalar potential involves intrinsic mass μ
- Nucleon and electron mass proportional to dynamical Planck mass
- Neutrino mass has different dependence on scalar field

$$\Gamma = \int_x \sqrt{g}\left\{-\frac{1}{2}\chi^2 R + \mu^2\chi^2 + \frac{1}{2}\left(B(\chi/\mu) - 6\right)\partial^\mu\chi\partial_\mu\chi\right\}$$

Cosmological solution : crossover from UV to IR fixed point

- Dimensionless functions as B depend only on ratio μ/χ .
- IR: $\mu \to 0$, $\chi \to \infty$
- UV: $\mu \to \infty$, $\chi \to 0$

Cosmology makes crossover between fixed points by variation of χ .



Key question (2)

- Do fixed points play a role for cosmology ?

answer

likely

Conclusions

- Scalar force in cosmology can arise from quantum scale symmetry
- Realistic cosmology

Look for

- time variation of fundamental constants, violation of equivalence principle,
- huge lumps in cosmic neutrino background,
- dynamical dark energy

end

Slow Universe

Asymptotic solution in freeze frame :

$$H = \frac{\mu}{\sqrt{3}} \; , \; \chi = \frac{3^{\frac{1}{4}} m}{2\sqrt{\mu}} (t_c - t)^{-\frac{1}{2}}$$

$$\mu = 2 \cdot 10^{-33} \, \mathrm{eV}$$

Expansion or shrinking always slow , characteristic time scale of the order of the age of the Universe : $t_{ch} \sim \mu^{-1} \sim$ 10 billion years !

Hubble parameter of the order of present Hubble parameter for all times , including inflation and big bang !

Slow increase of particle masses !

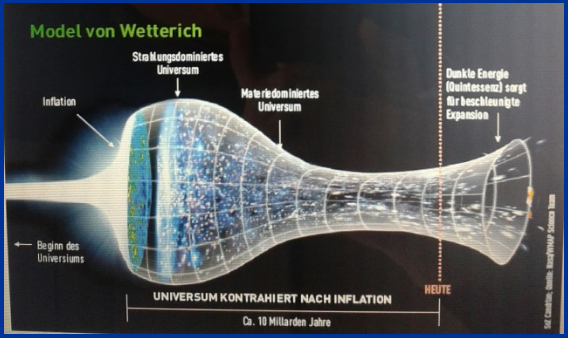
infinite past

Eternal Universe

Asymptotic solution in freeze frame :

$$H = \frac{\mu}{\sqrt{3}} \ , \ \chi = \frac{3^{\frac{1}{4}} m}{2\sqrt{\mu}} (t_c - t)^{-\frac{1}{2}}$$

- solution valid back to the infinite past in physical time

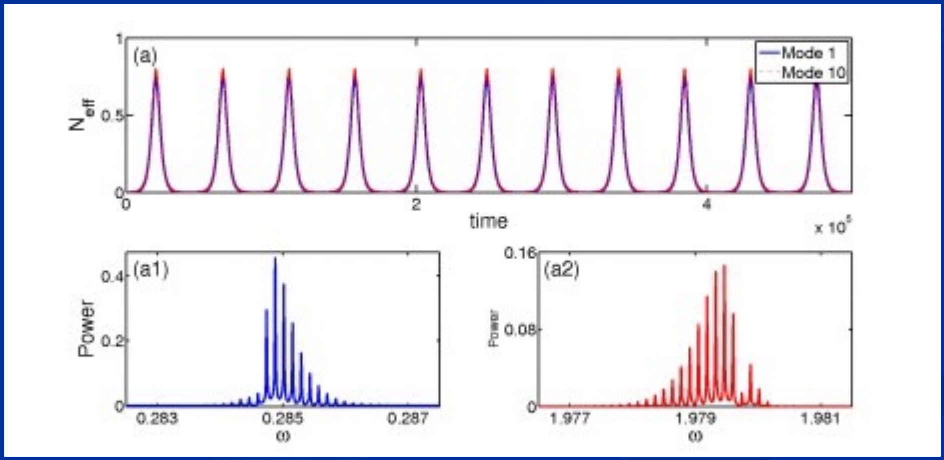


- no singularity

- physical time to infinite past is infinite

Physical time

count oscillations ….



Physical time

field equation for scalar field mode

$$(\partial_\eta^2 + 2Ha\partial_\eta + k^2 + a^2m^2)\varphi_k = 0$$

$$\varphi_k = \frac{\tilde{\varphi}_k}{a} \qquad \left\{\partial_\eta^2 + k^2 + a^2\left(m^2 - \frac{R}{6}\right)\right\}\tilde{\varphi}_k = 0$$

determine physical time by counting number of oscillations

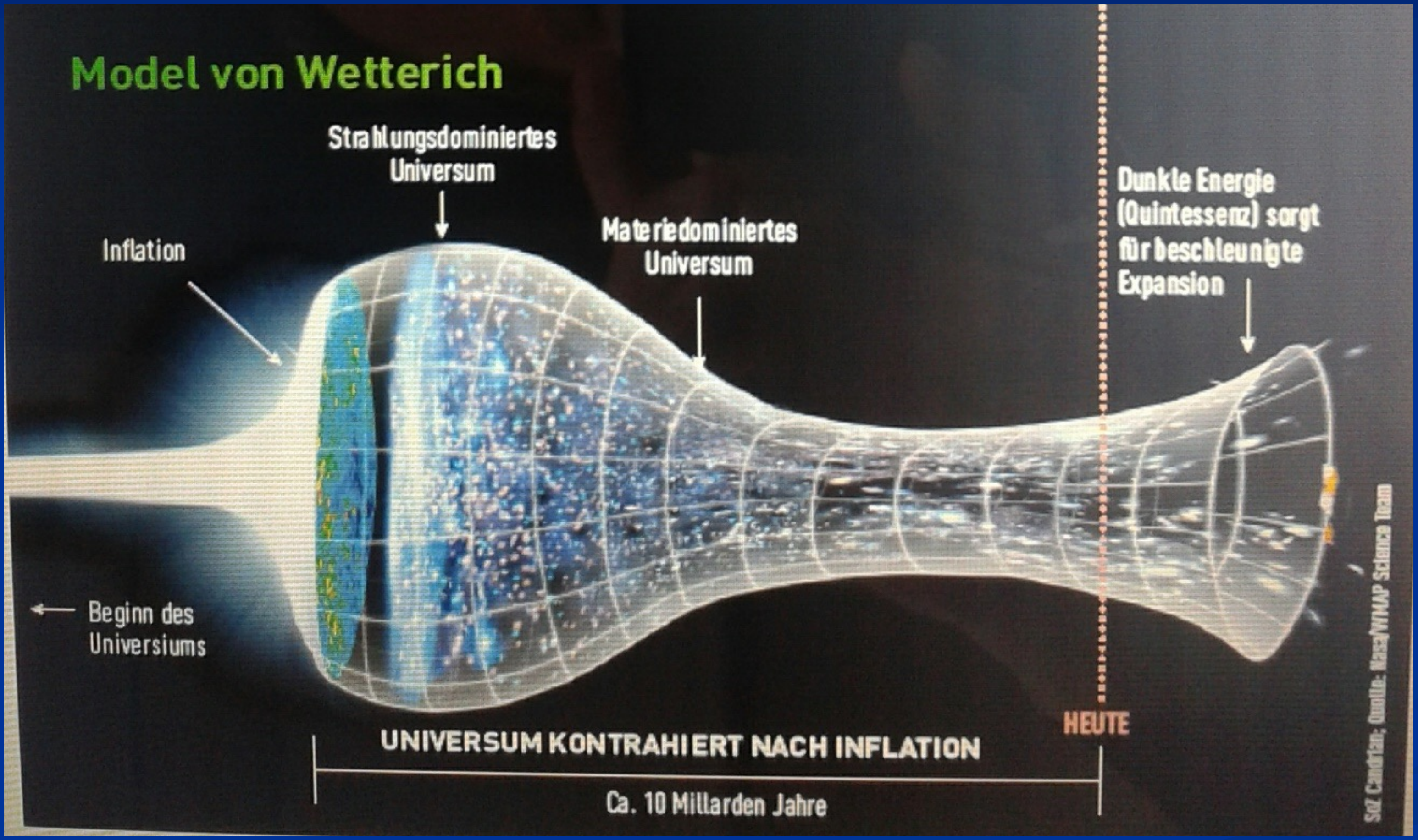
$$\tilde{t}_p = n_k \qquad n_k = \frac{k\eta}{\pi}$$

(m=0)

Physical time

- counting : discrete
- invariant under field transformations
- same in all frames

Strange evolution of Universe



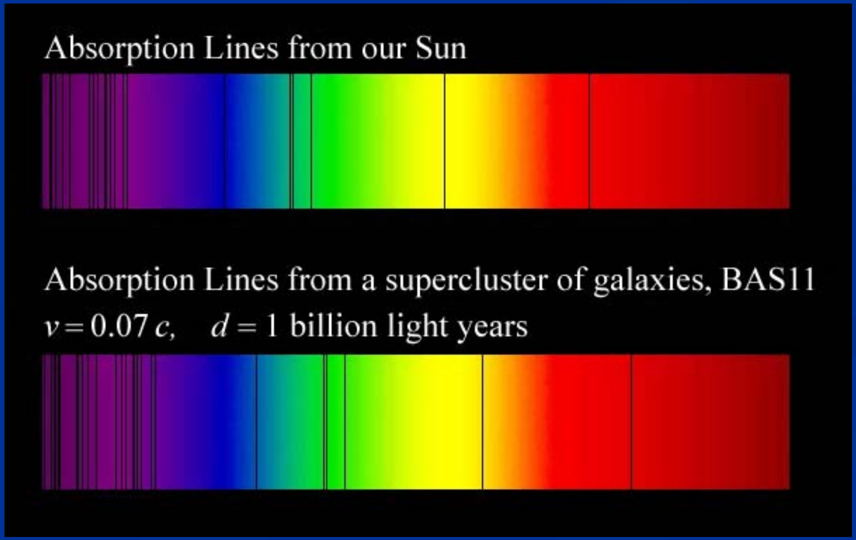
Sonntagszeitung Zürich , Laukenmann


Big bang or freeze ?

Do we know that the Universe expands ?

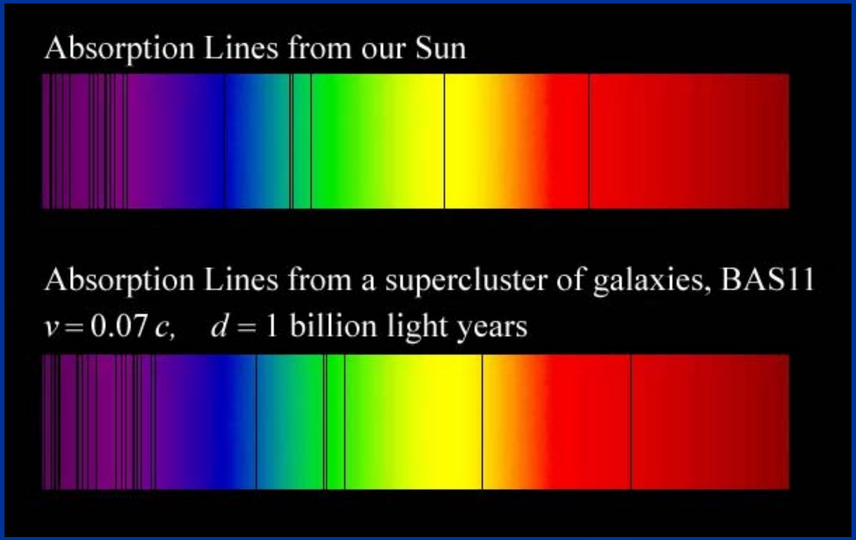
instead of redshift due to expansion :

smaller frequencies have been emitted in the past, because electron mass was smaller !



Why do we see redshift of photons emitted in the distant past ?

photons are more red because they have been emitted with longer wavelength



frequency ~ mass

wavelength ~ atomsize

What is increasing ?

Ratio of distance between galaxies
over size of atoms !

atom size constant : expanding geometry

alternative : shrinking size of atoms

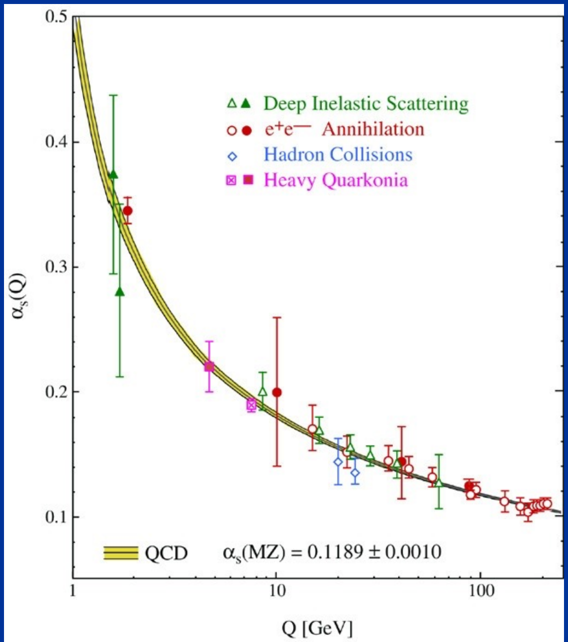
Key question (3)

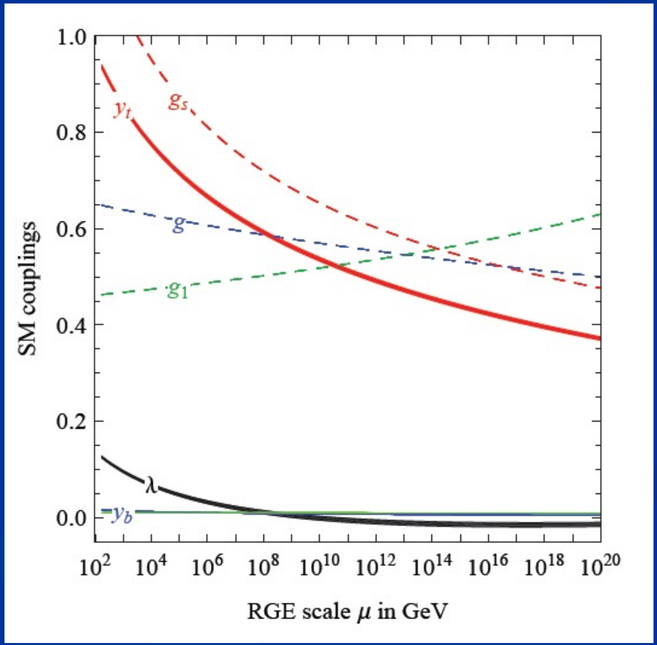
- Why does scale symmetry play a role even though it is violated by quantum fluctuations ?

quantum gravity with scalar field – the role of scale symmetry

fluctuations induce running couplings

- violation of scale symmetry
- well known in QCD or standard model

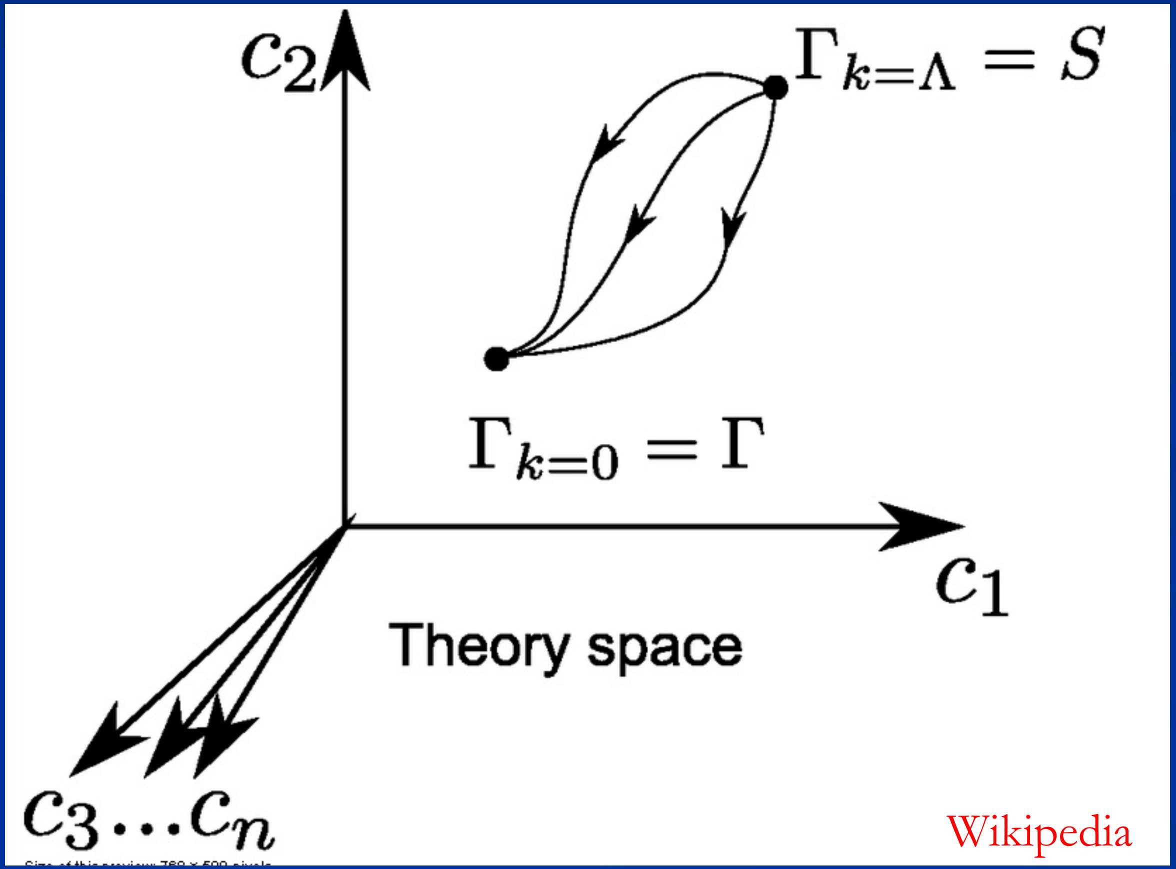




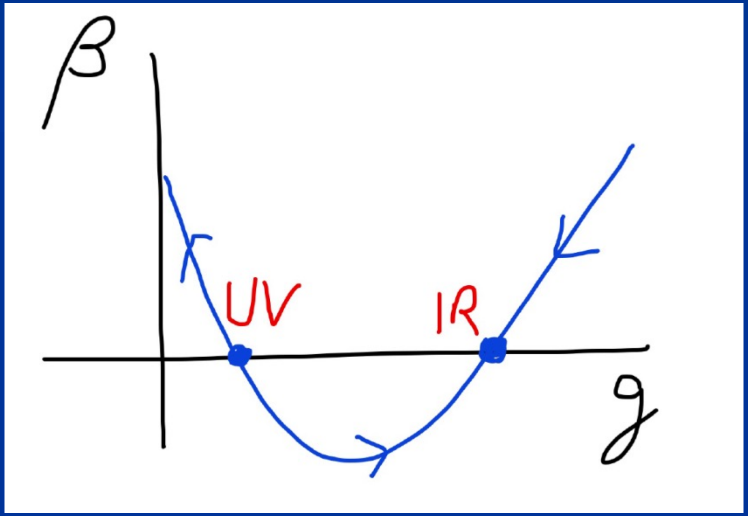
Quantum scale symmetry

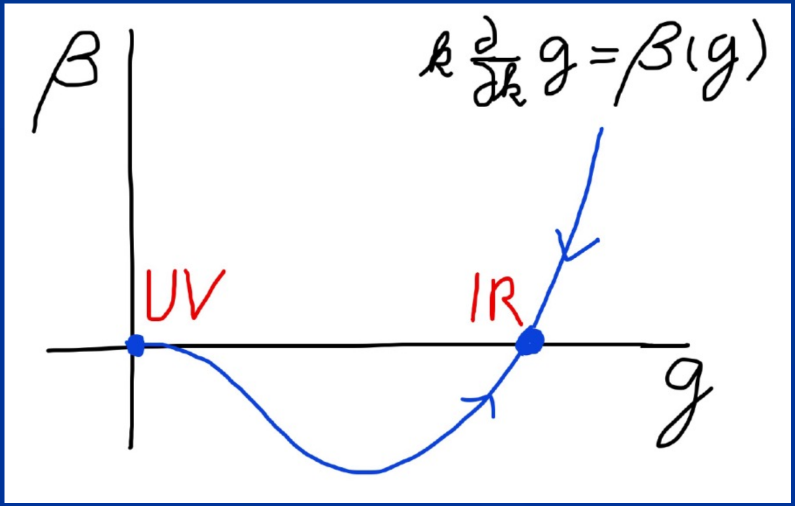
- quantum fluctuations violate scale symmetry
- running dimensionless couplings
- at fixed points , scale symmetry is exact !

functional renormalization : flowing action



Asymptotic safety   Asymptotic freedom





Relevant parameters yield undetermined couplings. Quartic scalar coupling is not relevant and can therefore be predicted.

Key question (3)

- Why does scale symmetry play a role even though it is violated by quantum fluctuations ?

answer

Fixed points
always realize scale symmetry

Big bang singularity in Einstein frame is field singularity !

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu} \; , \; \varphi = \frac{2M}{\alpha} \ln\left(\frac{\chi}{\mu}\right)$$

choice of frame with constant particle masses is not well suited if physical masses go to zero !