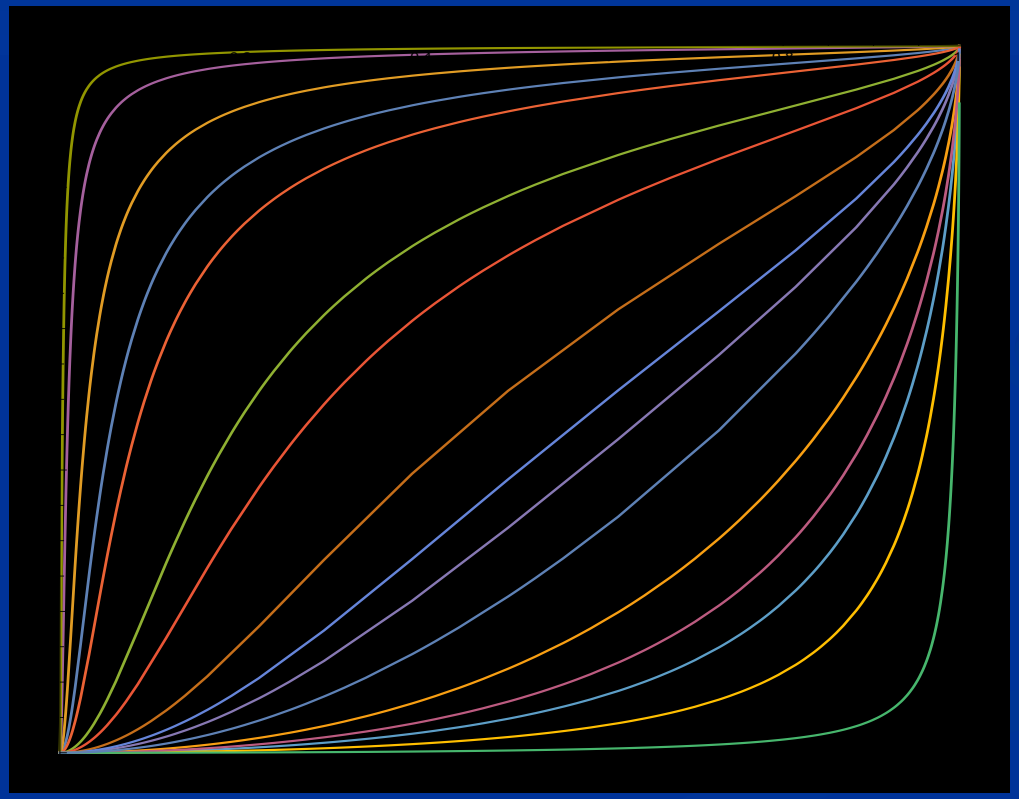
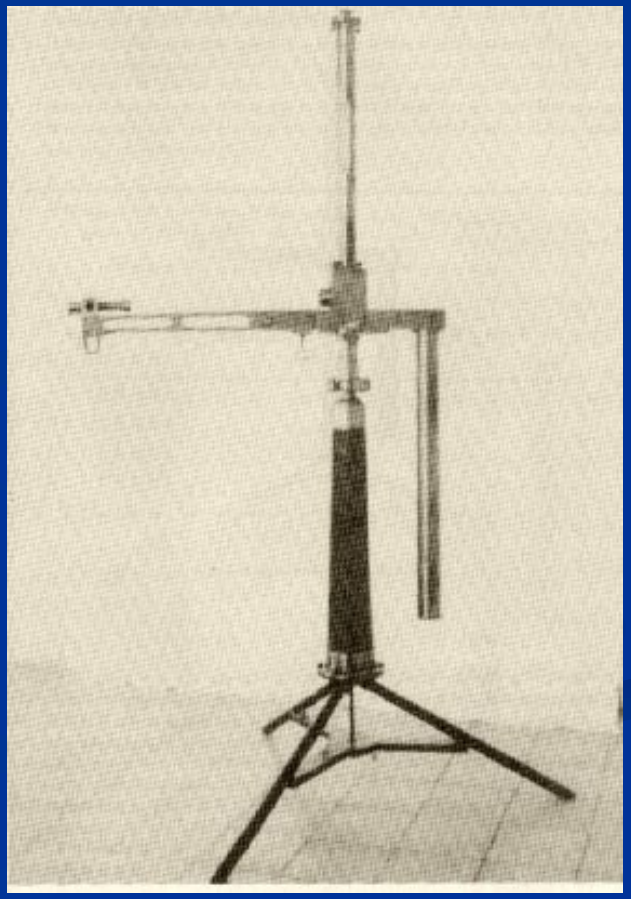
Quantum scale symmetry and the Equivalence principle



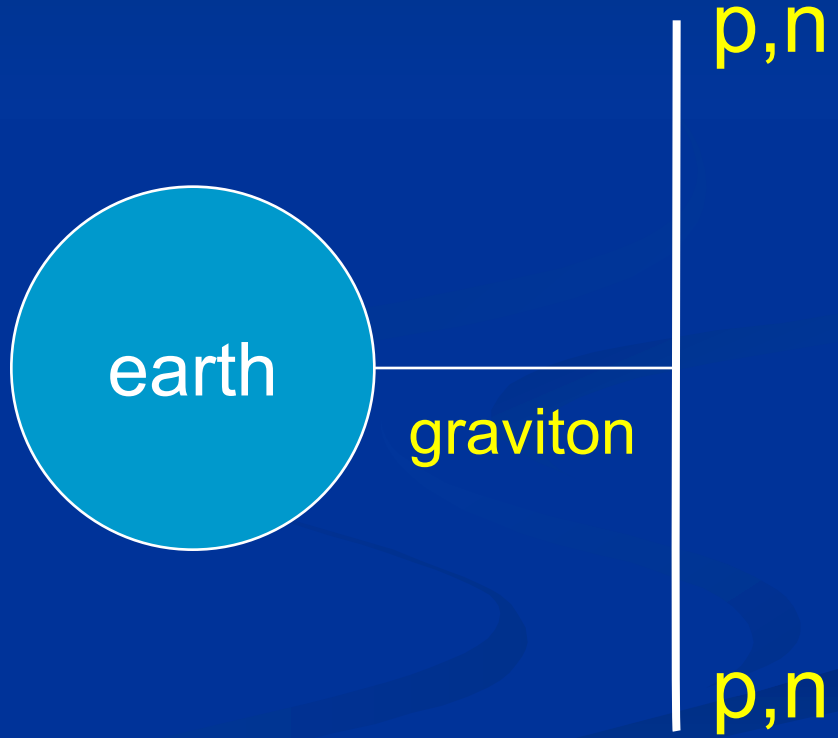


Equivalence principle

Coupling of graviton to proton and neutron proportional to mass

Same acceleration

Equivalence principle

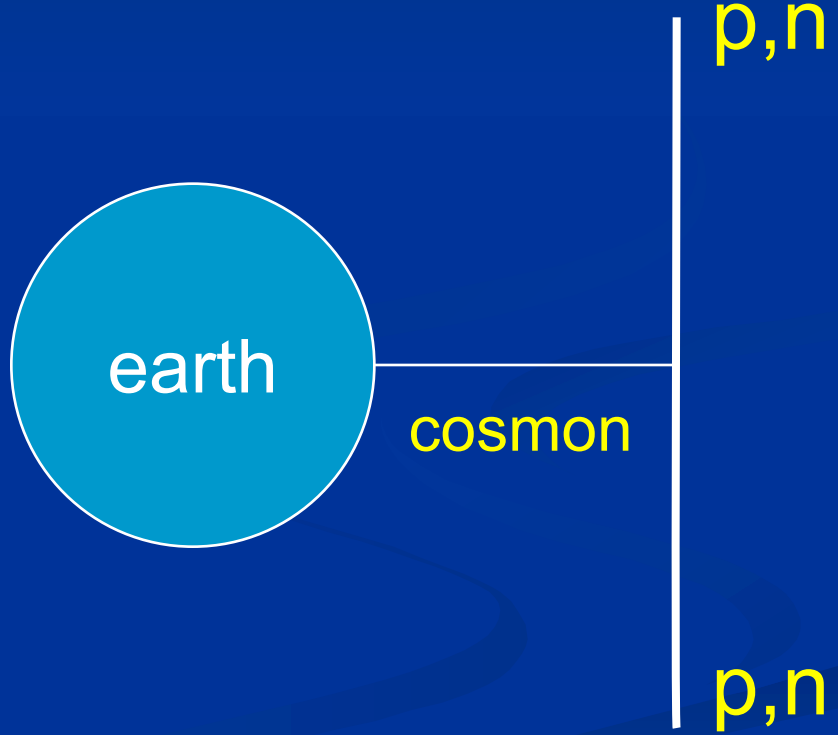


Violation of equivalence principle

Different couplings of cosmon to proton and neutron

Differential acceleration

"Violation of equivalence principle"



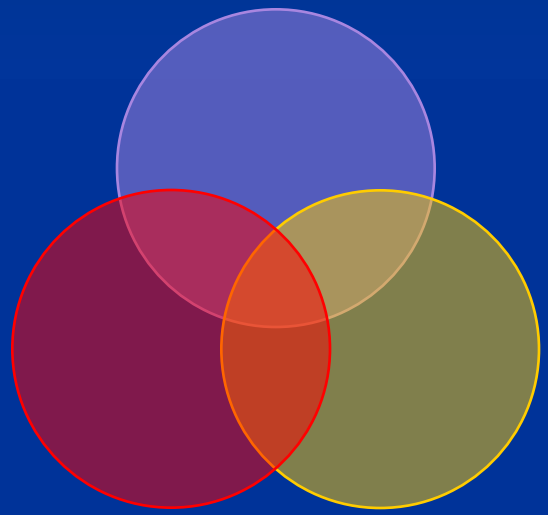
only apparent : new "fifth force" !

New scalar force

- Spontaneously broken quantum scale symmetry predicts massless scalar (cosmon)
- Only tiny violation of equivalence principle if scale symmetry is approximate

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

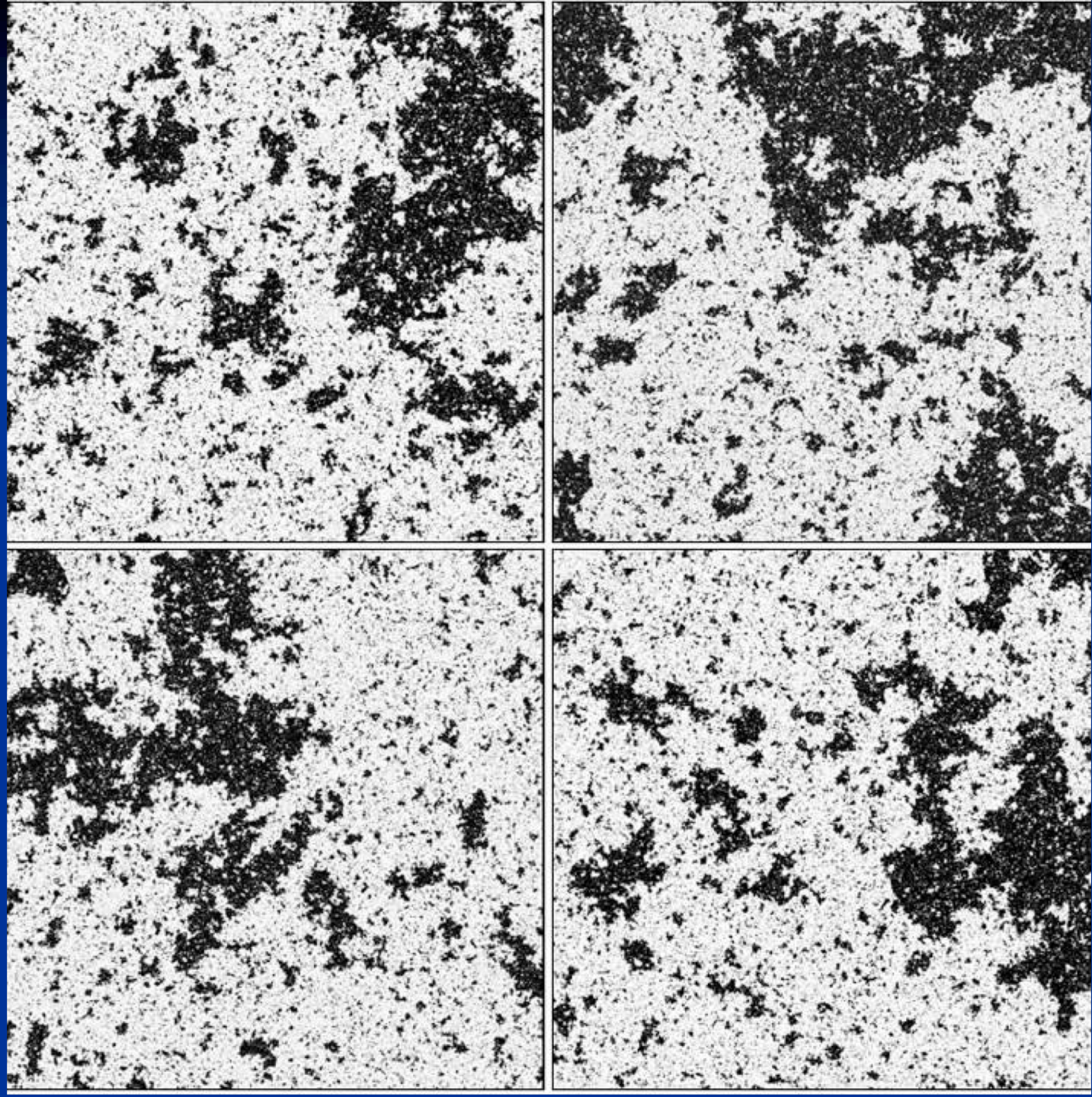
Scale symmetry

Scale transformation

- Scale all lengths with constant factor
- Scale all masses with inverse factor

Unbroken scale symmetry :

Physics looks the same on all scales



Scale transformation of renormalized fields

$$g'_{\mu\nu} = \alpha^{-2} g_{\mu\nu} \,, \quad \sqrt{g'} = \alpha^{-4} \sqrt{g}$$

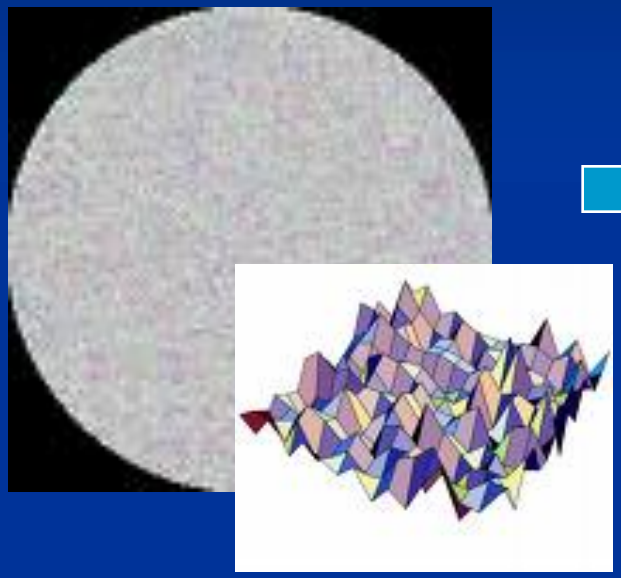
$$A'_\mu = A_\mu \,, \quad \psi' = \alpha^{3/2} \psi$$

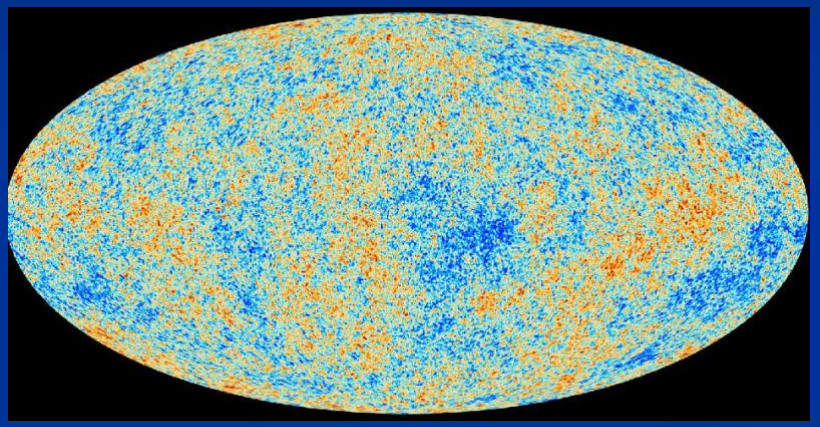
$$\chi' = \alpha \chi$$

$$\mathcal{L}_\chi = \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi + \tilde{\lambda} \chi^4$$

Have we observed
scale symmetry ?

Almost scale invariant primordial fluctuation spectrum seeds all structure in the universe





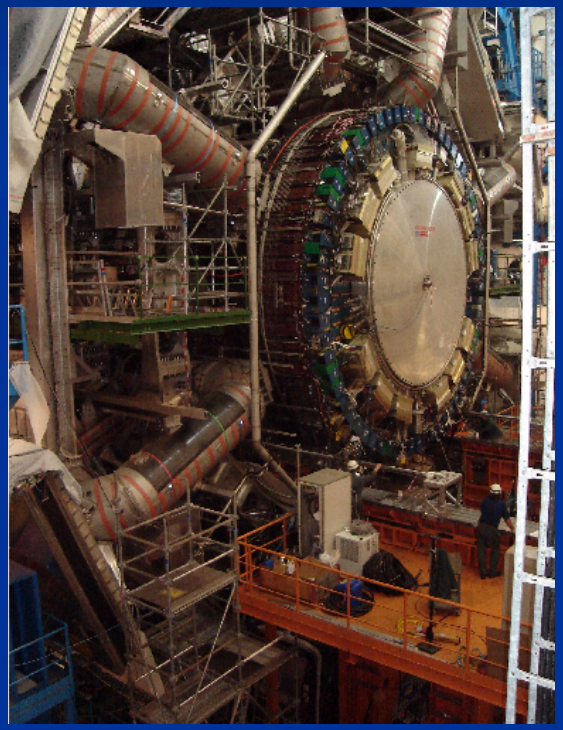
Scale symmetry in elementary particle physics ?

proton mass , electron mass

Scales are present in particle physics,
but very small as compared to Planck mass

High momentum scattering almost scale invariant

Approximate scale symmetry at highest energies at the LHC



and at the next collider ?

Quantum scale symmetry

Quantum scale symmetry

No parameter with dimension of length or mass is present in the quantum effective action.

Then invariance under dilatations or global scale transformations is realized.

Continuous global symmetry

Quantum fluctuations induce running (momentum dependent) couplings

Running fine structure constant

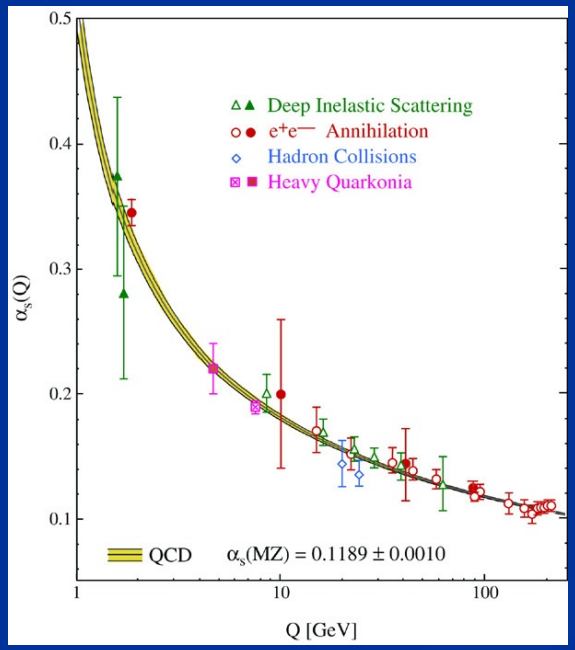
$\alpha = 1/137$ for atoms

$\alpha = 1/128$ at LEP

Induced by quantum fluctuations of electrons, muons, quarks etc.

Quantum fluctuations induce running couplings

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



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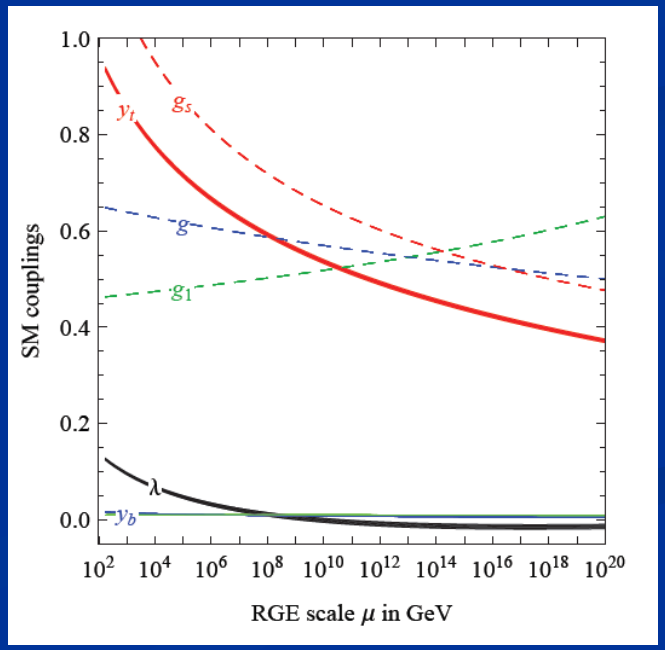


Degrassi et al

Quantum scale symmetry

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

Fixed points and scale symmetry

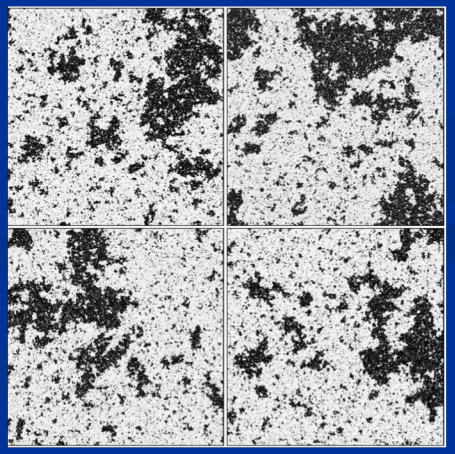
- At a fixed point, scale symmetry is exact in the presence of fluctuations (quantum scale symmetry)
- Well known in condensed matter physics :

  second order phase transition ⟹

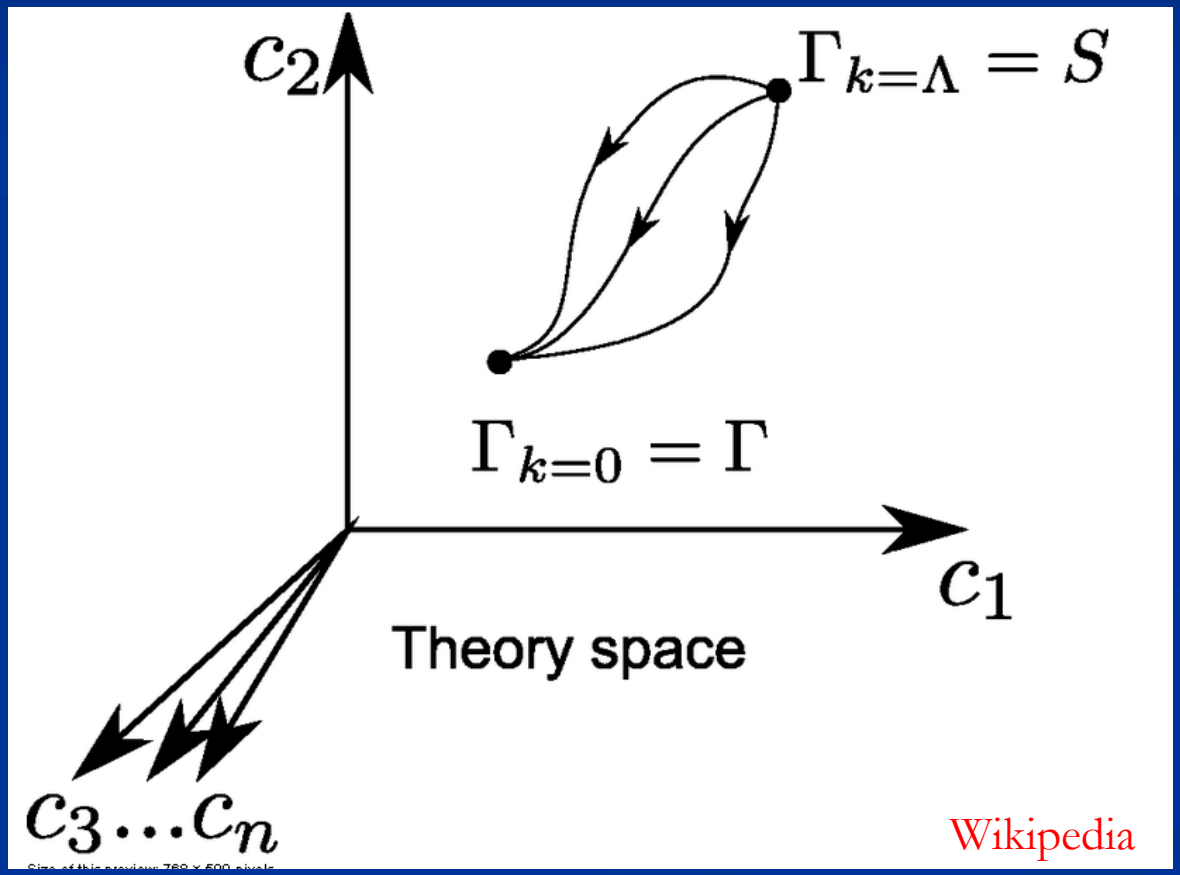
  fixed point or scaling solution ⟹

  exact scale symmetry ⟹

  critical phenomena
- Classical or quantum Ising model



Functional renormalization : flowing action



Wikipedia

From

Microscopic Laws

(Interactions, classical action)

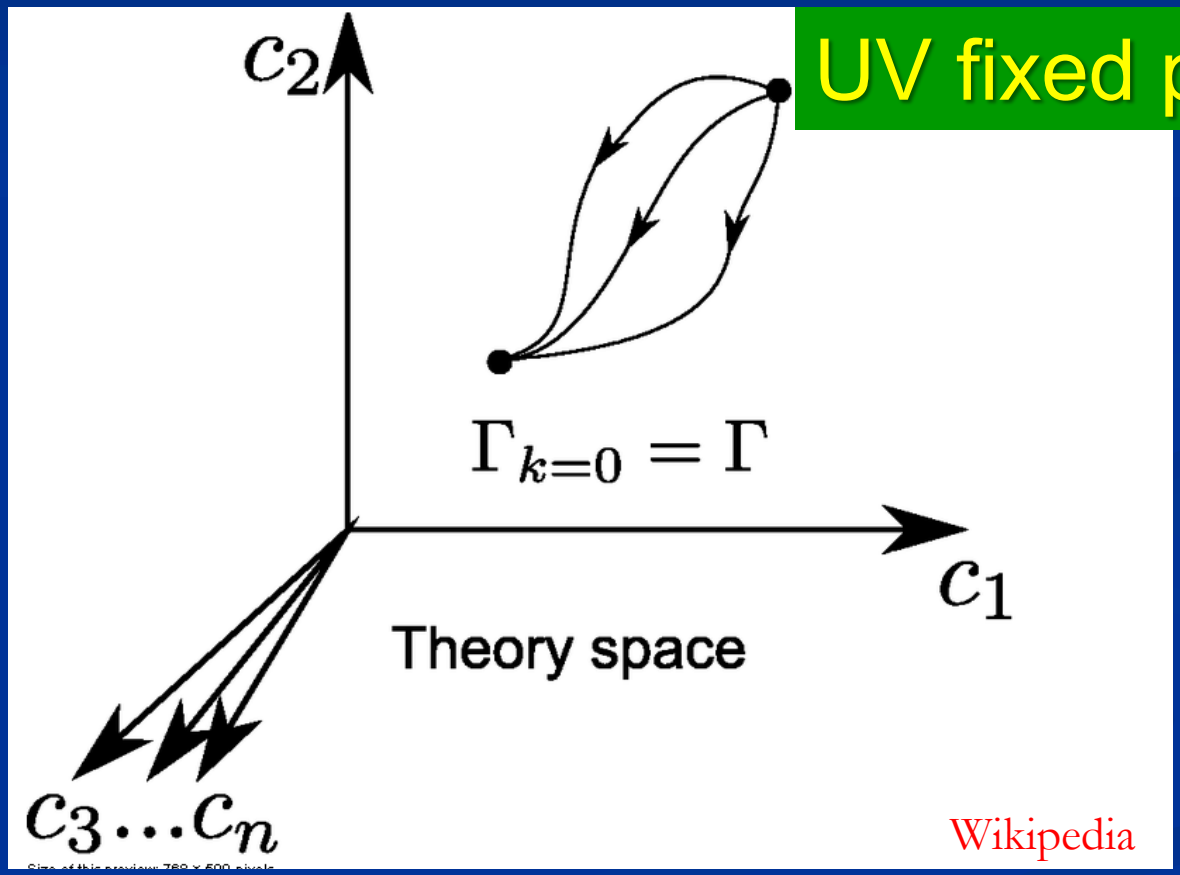
to

Fluctuations!

Macroscopic Observation

(Free energy functional, effective action)

Ultraviolet fixed point



Quantum scale symmetry

Exactly on fixed point:
No parameter with dimension of length or mass is present in the quantum effective action.

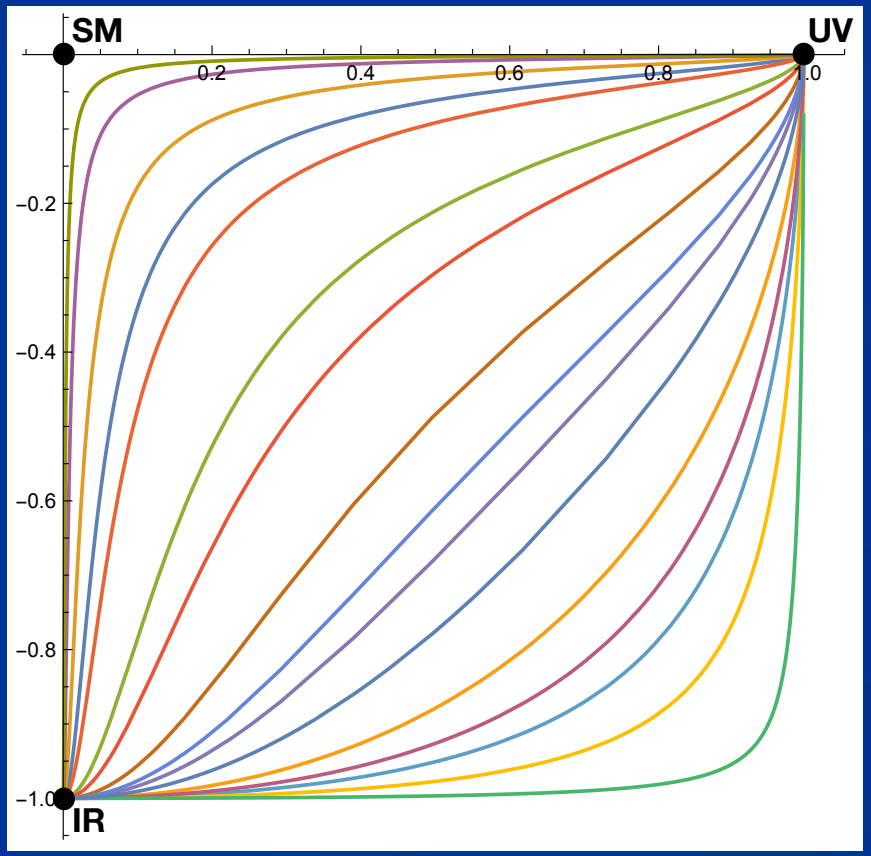
Then invariance under dilatations or global scale transformations is realized as a quantum symmetry.

Continuous global symmetry

Scale symmetry and fixed points

Relative strength of gravity

Particle scale symmetry

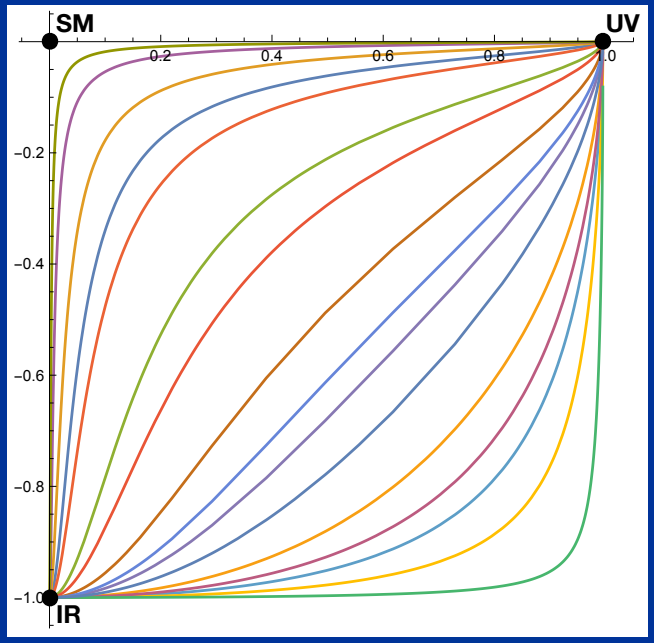


Gravity scale symmetry

Distance from electroweak phase transition

Cosmic scale symmetry

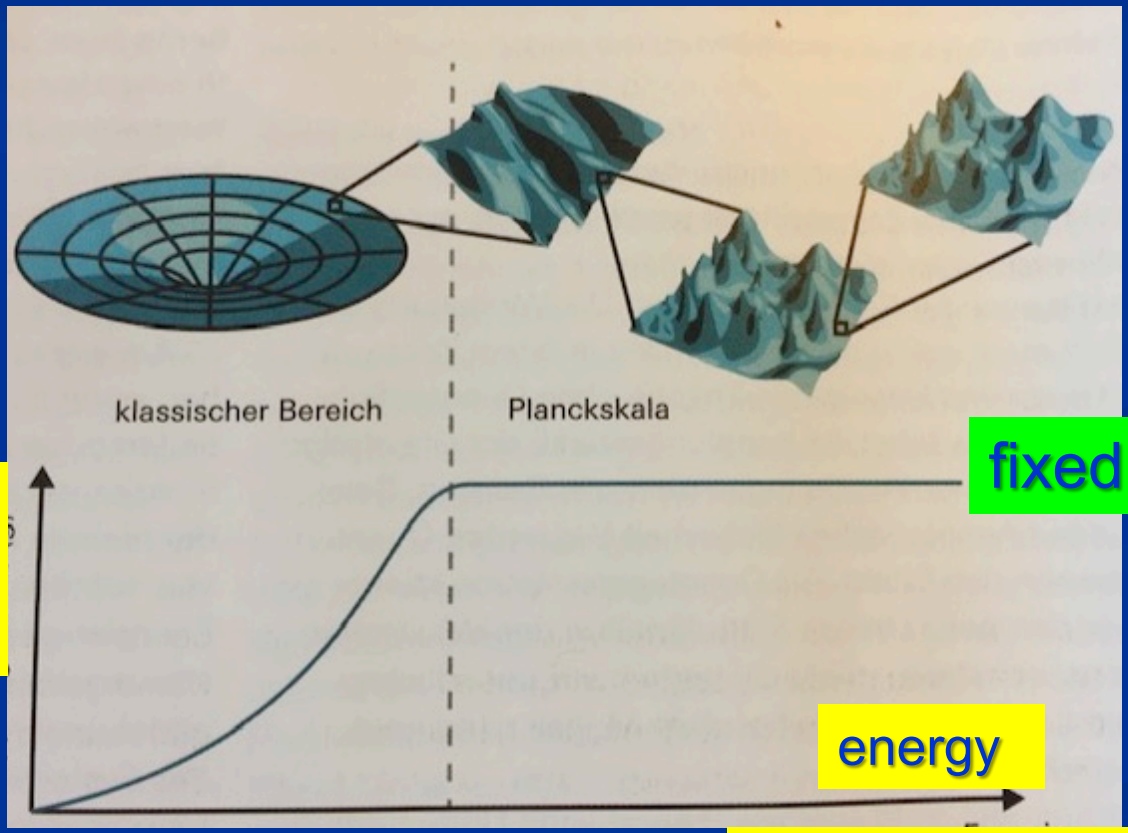
Gravity scale symmetry



Strength of gravity

classical gravity

quantum gravity



A. Eichhorn, CW, Spektrum der Wissenschaft

Asymptotic safety of quantum gravity

if UV fixed point exists :

quantum gravity is
non-perturbatively renormalizable
quantum field theory !

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

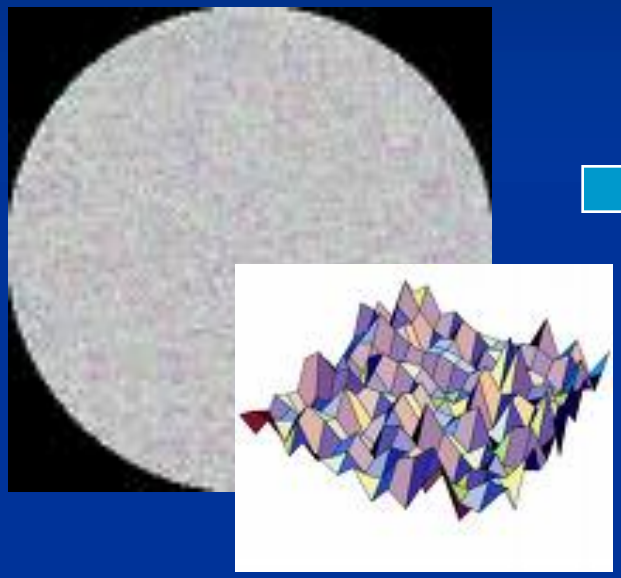
Gravity scale symmetry

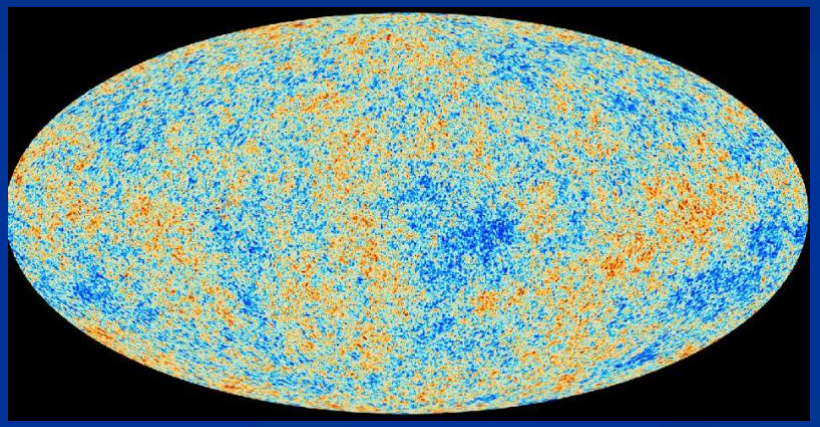
Replace Planck mass by scalar field χ

$$\Gamma = \int_x \sqrt{g} \left\{ -\frac{1}{2}\chi^2 R + \ldots \right\}$$

"Modified gravity" :
solve modified cosmological field equations

Almost scale invariant primordial fluctuation spectrum seeds all structure in the Universe





In the infinite past
Universe "begins"
at the fixed point

Gravity scale symmetry

Replace Planck mass by scalar field

$$\Gamma = \int_x \sqrt{g} \left\{ -\frac{1}{2}\chi^2 R + \right\}$$

Cosmological solution : $\chi(t)$ differs from zero, equals zero only in the infinite past

Spontaneous breaking of scale symmetry

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.

Particle masses from spontaneous scale symmetry breaking

- Electron mass proportional to χ

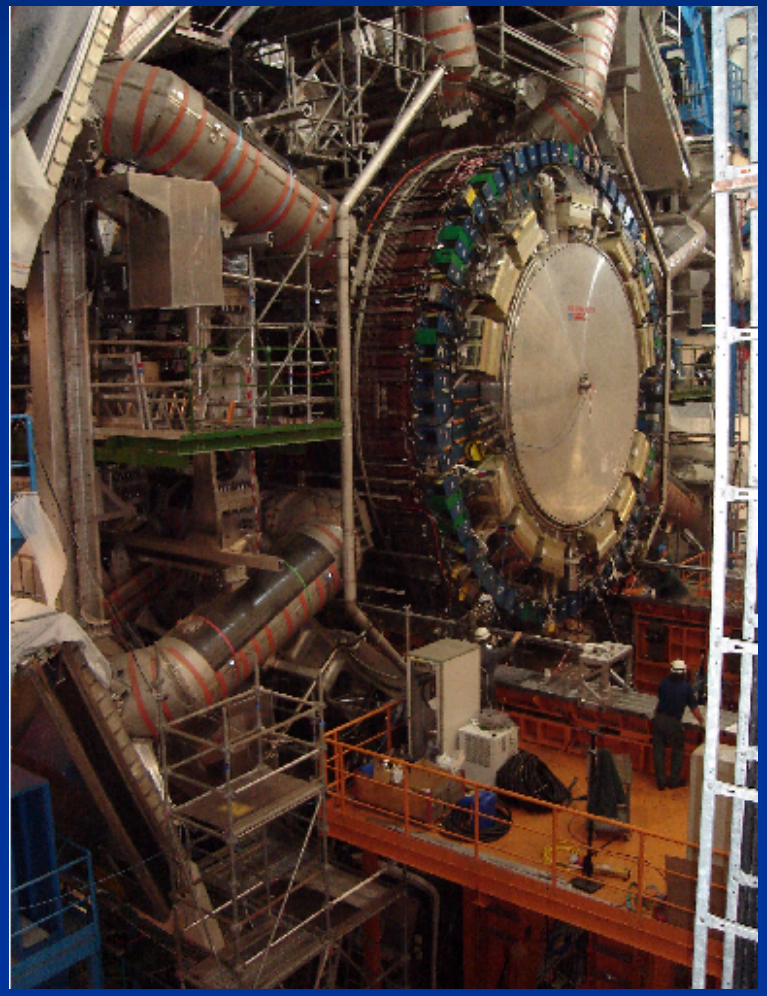
- $m_e \sim \varphi_0$ (expectation value of Higgs scalar)
- $\varphi_0 \sim \chi$

- $m_e = y_e \varphi_0$ (Yukawa coupling)

Spontaneous breaking of scale symmetry

- expectation value of scalar field breaks scale symmetry spontaneously
- particle masses can be proportional to scalar field χ
- massive particles are compatible with scale symmetry
- in presence of massive particles : sign of exact scale symmetry is exactly massless Goldstone boson – the dilaton or cosmon

Spontaneous symmetry breaking confirmed at the LHC



Variable Gravity

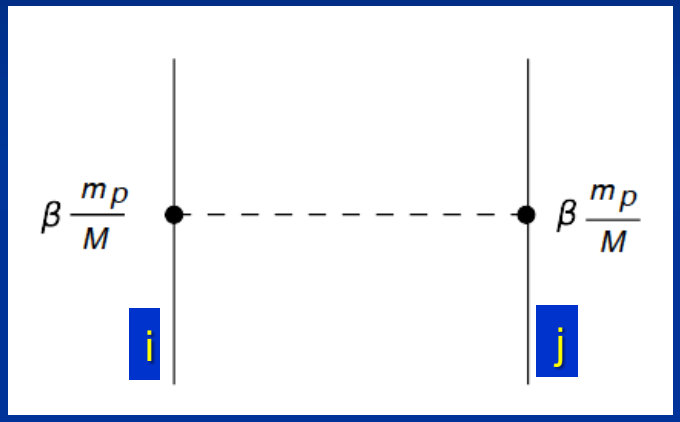
- Scalar field coupled to gravity
- Effective Planck mass depends on scalar field
- Simple quadratic scalar potential involves intrinsic mass μ
- Nucleon and electron mass proportional to dynamical Planck mass

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


Πάντα ῥεῖ

Fifth force

Scalar force (fifth force)



attractive: $\beta_i \beta_j > 0$

repulsive: $\beta_i \beta_j < 0$

Simple mechanism for very light scalar field

- Exact scale symmetry :
  massless Goldstone boson
- Approximate scale symmetry :
  very light pseudo-Goldstone boson
- Candidate for scalar fifth force

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 ?

Conclusions

- Quantum gravity makes predictions that can be tested by present observations and experiments
- Eötvös - type experiments remain very relevant today: test of tiny violations of quantum scale symmetry

end

Slowly running couplings close to fixed points

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

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

(different growth of neutrino mass)

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) :

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

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

η=Δa/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)