High precision data for fundamental constants – what do we learn about the Universe ?

Time variation of fundamental constants

- For cosmology : time variation of fundamental constants can give information on dynamics of the Universe
- Tiny effect, with important consequences
- High precision required !

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*** *!*

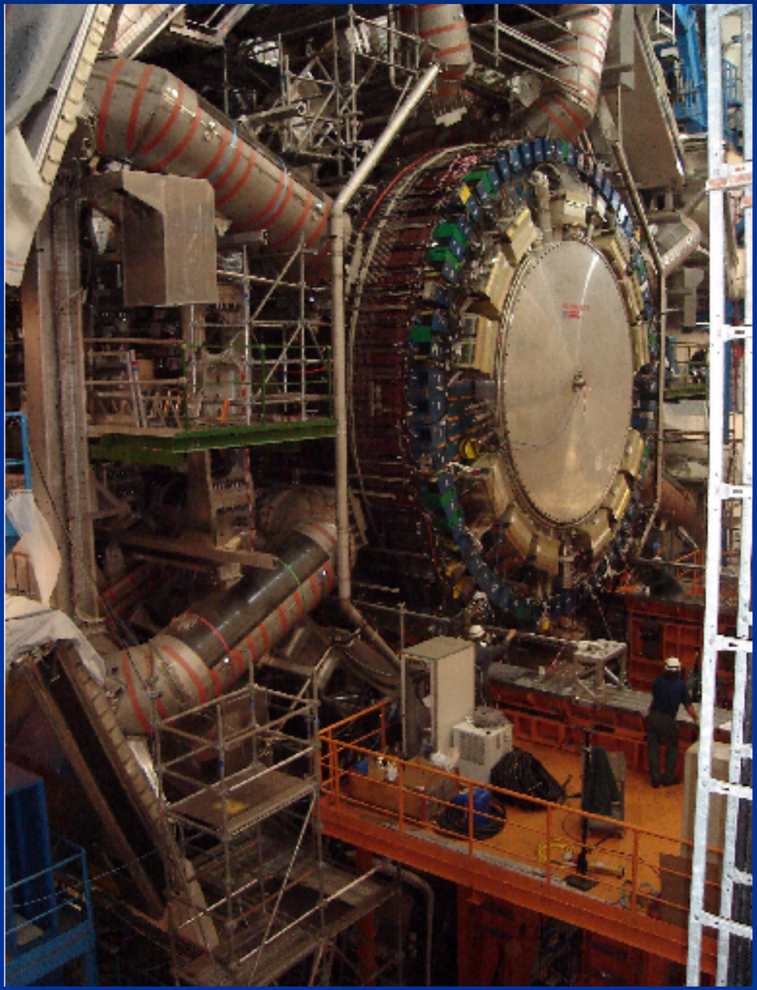
Similar to Maxwell – equations in matter

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 :

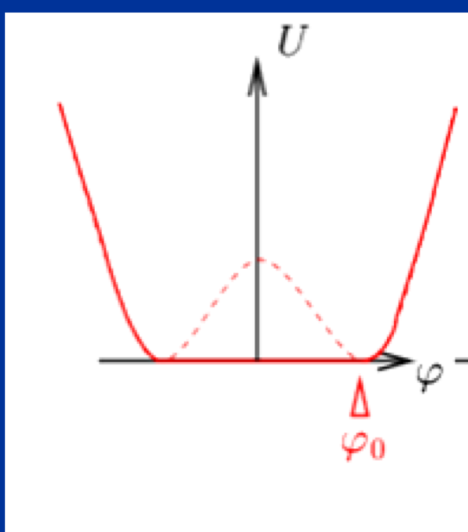
- Universe is not in one fixed state
- Dynamical evolution
- Laws are expected to depend on time

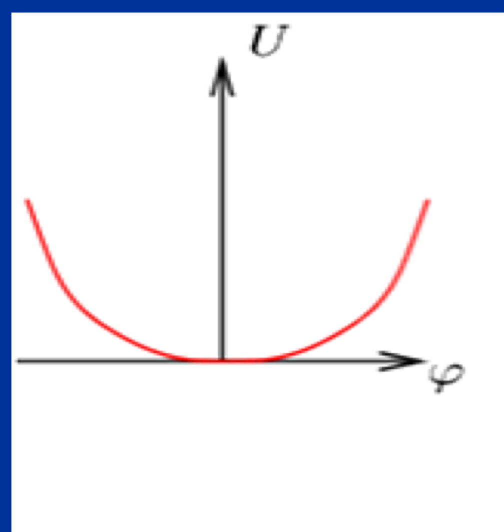
Restoration of symmetry at high temperature in the early Universe

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

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 scalar 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

⇒

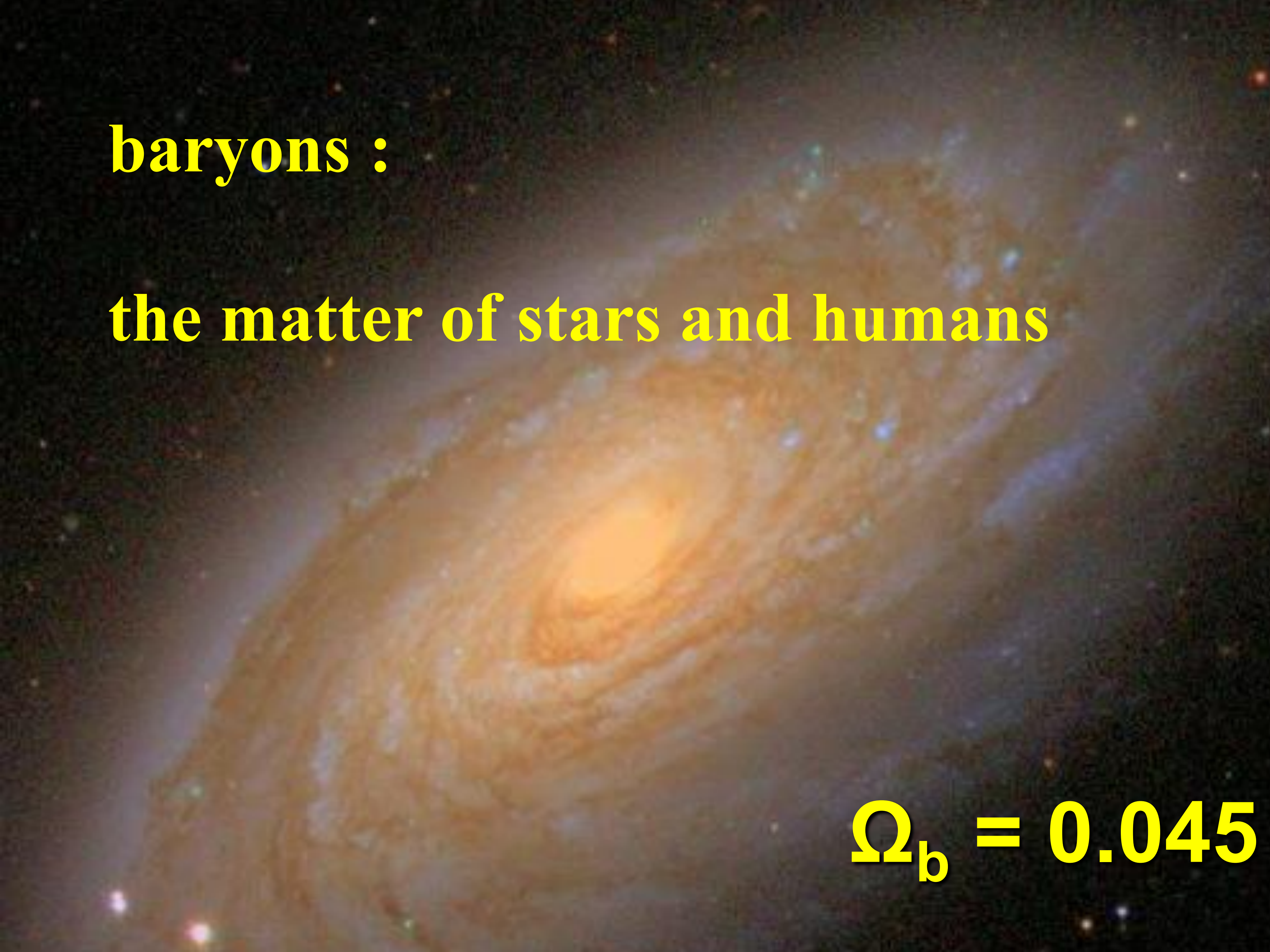
Physics beyond Standard Model

Particle mass ratios and dimensionless couplings in quintessence cosmology

can depend on value of cosmon field

similar to dependence on value of Higgs field

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

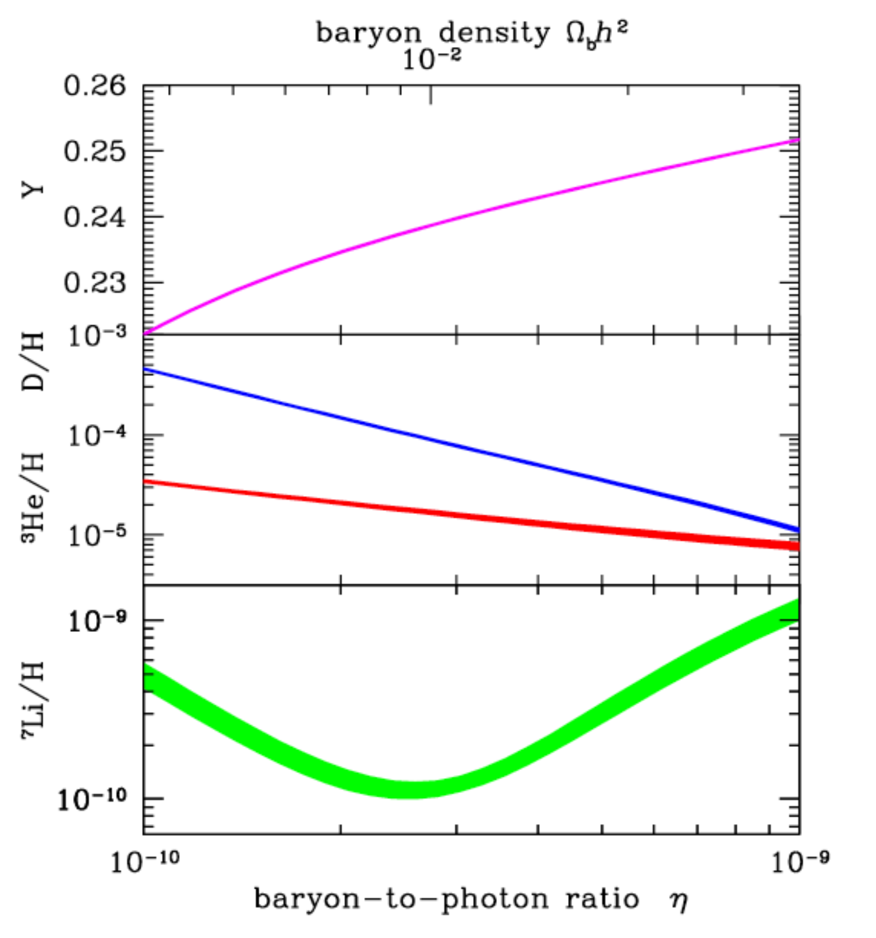
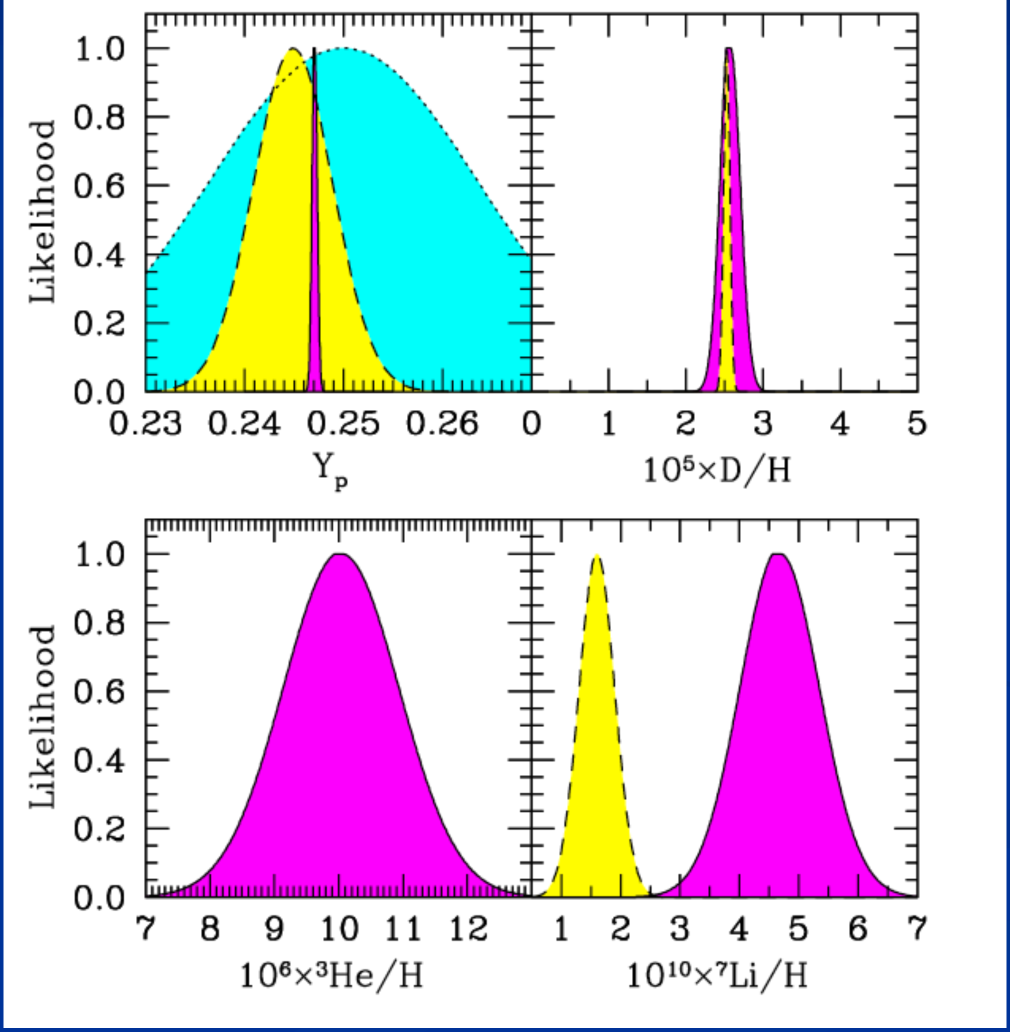


TABLE II. Comparison of BBN Results

	η_{10}	N_ν	Y_p	D/H	^{3}He/H	^{7}Li/H	^{6}Li/H
This Work	6.10	3	0.2470	2.579×10^{-5}	0.9996×10^{-5}	4.648×10^{-10}	1.288×10^{-14}
Iocco et al. [3] fit	6.10	3	0.2463	2.578×10^{-5}	0.9983×10^{-5}	4.646×10^{-10}	1.290×10^{-14}

Cyburt, Fields, Olive, Yeh, 2015

Nucleosynthesis + CMB

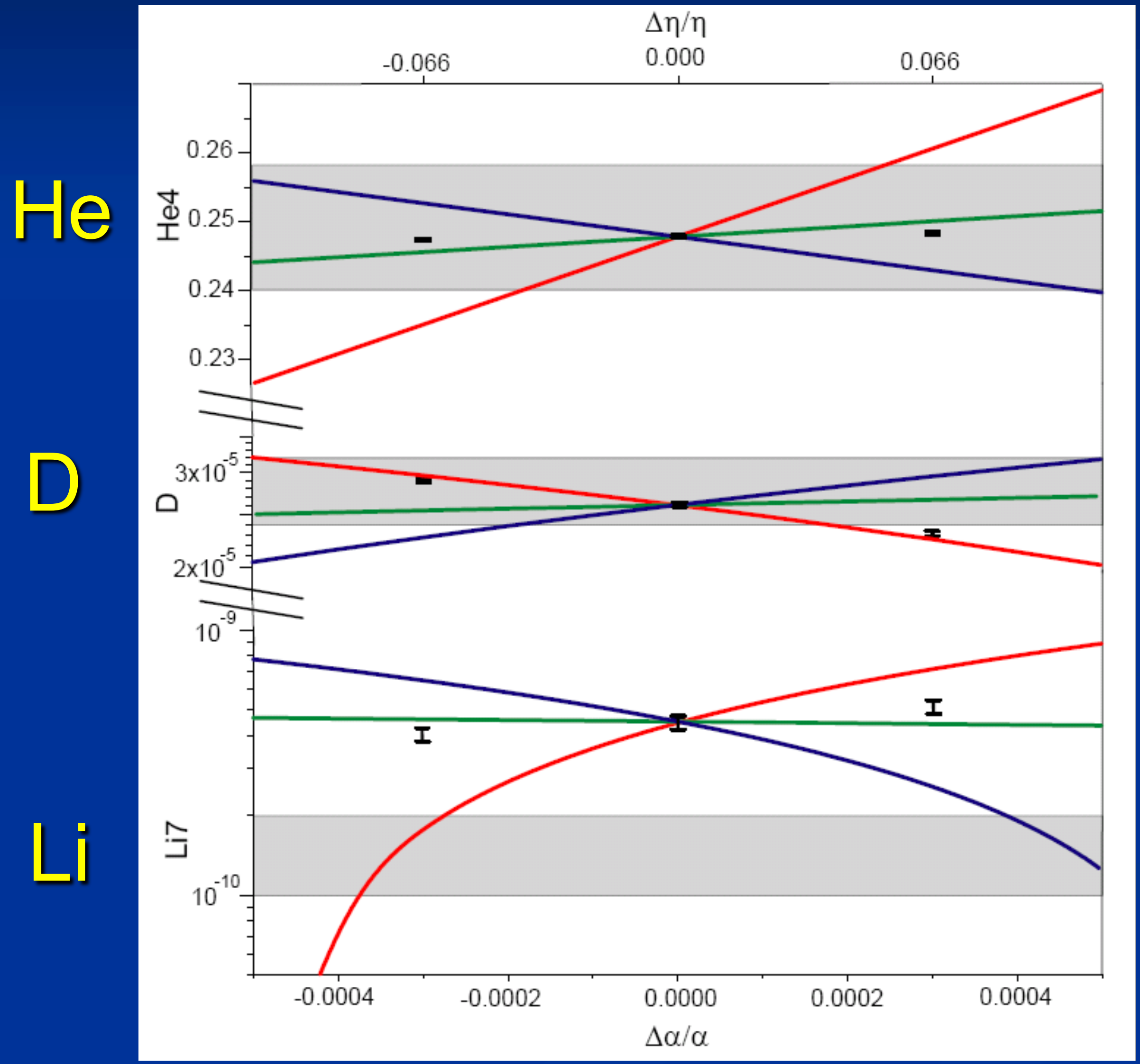


Cyburt, Fields, Olive, Yeh, 2015

purple: BBN+CMB

yellow: observation

primordial abundances for three GUT models



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

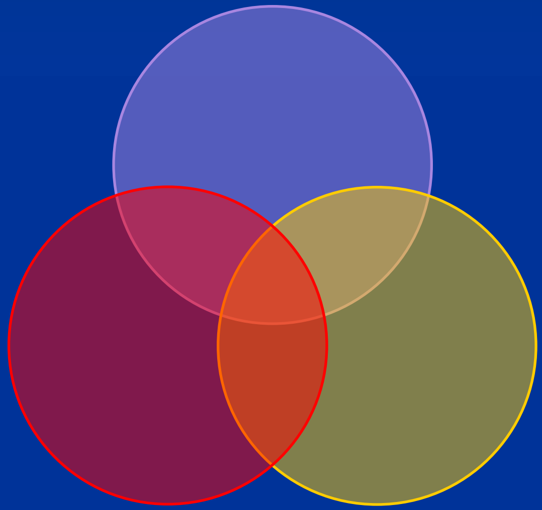
Time variation of coupling constants must be tiny –

would be of very high significance !

Possible signal for Quintessence

“Fundamental” Interactions

Strong, electromagnetic, weak interactions



gravitation cosmodynamics

On astronomical length scales:

graviton

+

cosmon

Variation of fundamental couplings and apparent violation of equivalence principle

Coupling of cosmon to atoms needed : Standard model with non-renormalizable operators

$$\beta_m \frac{\varphi}{M} \bar{\psi} \psi h$$

φ - dependent masses

$$\beta_F \frac{\varphi}{M} F_{\mu\nu} F^{\mu\nu}$$

φ - dependent gauge couplings

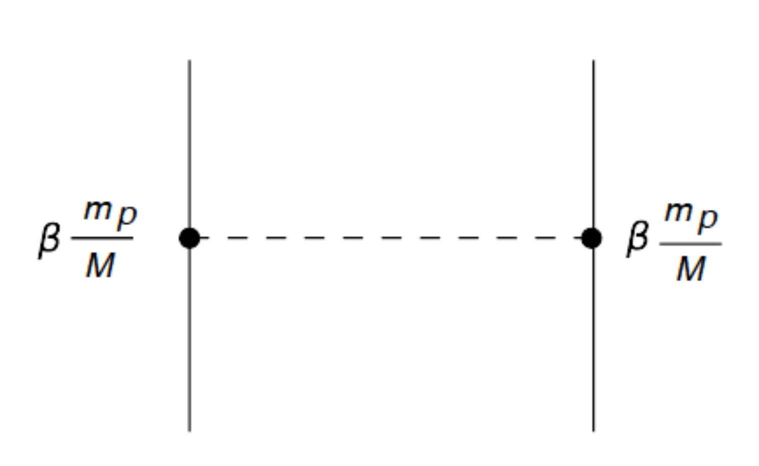
Fifth force

Scalar tensor theories

- Dirac's hypothesis
- Weyl scaling
- Brans-Dicke theory

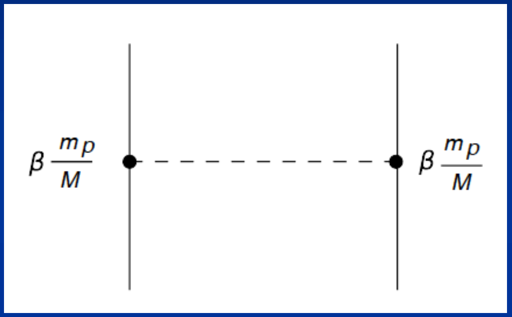
additional interaction :

$$\beta_m \frac{\varphi}{M} \bar{\psi}\psi h$$



Fifth force

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



m ~ H : long range (dynamical dark energy)

m ≫ H : short range (dark matter)

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

Models with massless scalar fields

- Higher dimensions : strings, Kaluza-Klein theories (moduli)
- Modified gravity (Brans-Dicke theory, f(R)-theories, ….)
- if scalar plays a role for late cosmology : “ cosmon “

Standard model with non-renormalizable operators

$$\beta_m \frac{\varphi}{M} \bar{\psi}\psi h$$

φ - dependent masses

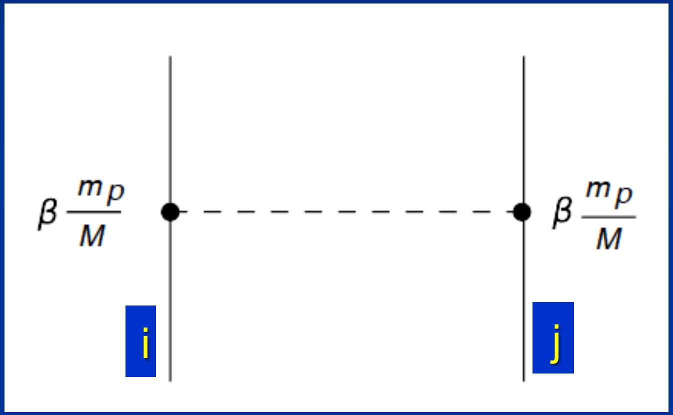
$$\beta_F \frac{\varphi}{M} F_{\mu\nu} F^{\mu\nu}$$

φ - dependent gauge couplings

Tests of GR : $|\beta_n| \ll 10^{-2}$

Tests of equivalence principle: $|\Delta\beta_i| \ll 10^{-5}$

Scalar force (fifth force)



attractive: $\beta_i \beta_j > 0$

repulsive: $\beta_i \beta_j < 0$

"Fifth Force"

- Mediated by scalar field

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

- Coupling strength: weaker than gravity

  (non-renormalizable interactions ~ M^{-2})

- Composition dependence

  ⇨ violation of equivalence principle

- Quintessence: connected to time variation of fundamental couplings

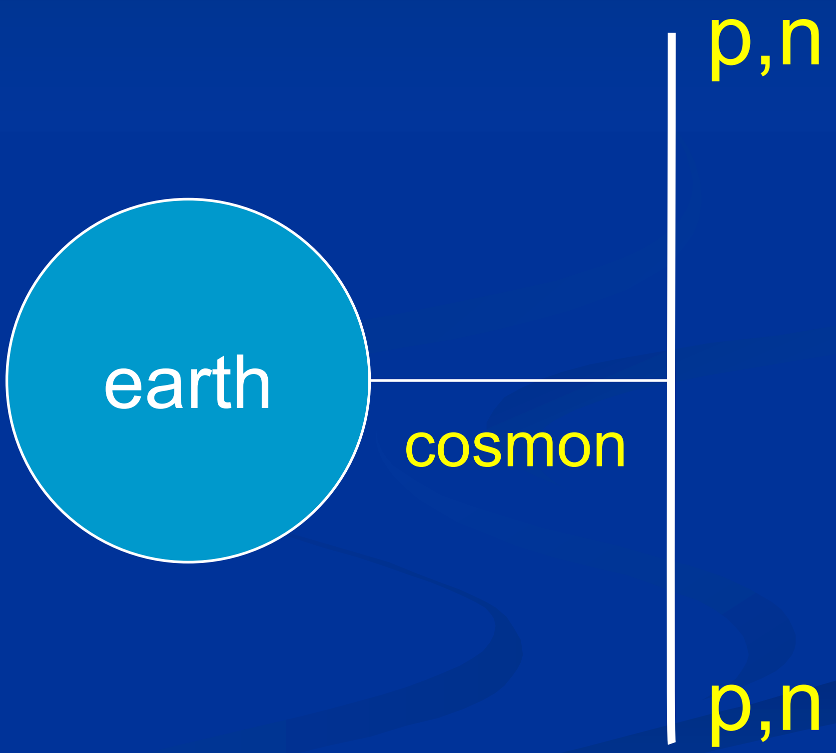
C.Wetterich , Nucl.Phys.B302,645(1988)

Violation of equivalence principle

Couplings of cosmon to proton and neutron not proportional to mass

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 : **$\eta < 10^{-14}$**

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

tested by 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)

Conclusion (1)
Time variation of couplings

- Find it , and you discover a new fundamental interaction.
- This interaction remains relevant at the largest length scales.
- Measure as precise as you can!

Should one expect a fifth force ?

Key questions (1)

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

Answer (1)

- Quantum scale symmetry predicts massless scalar field with vanishing couplings

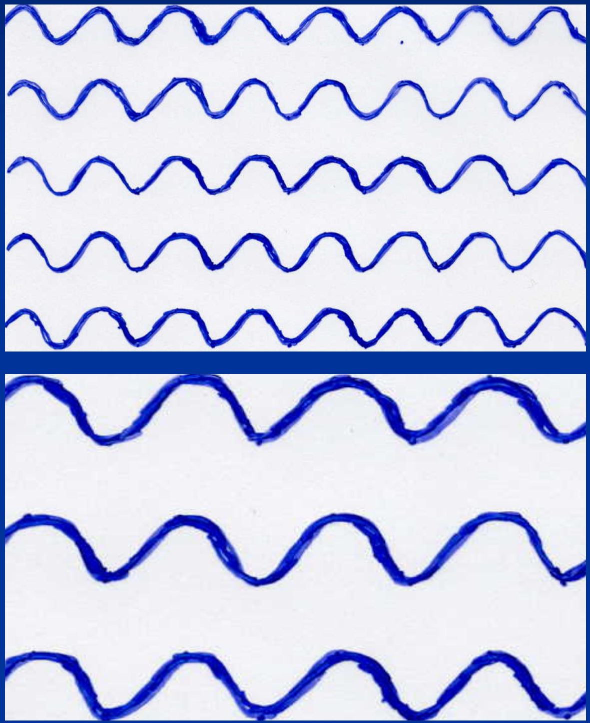
- Approximate quantum scale symmetry predicts very light scalar field with tiny couplings

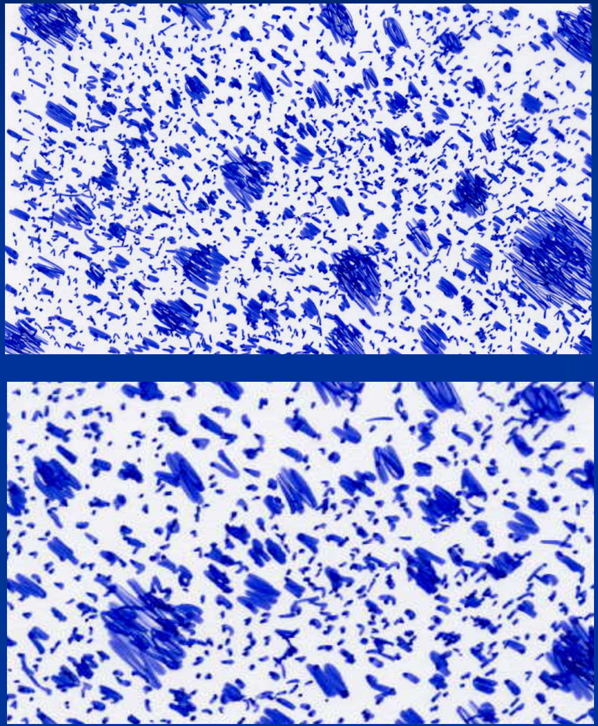
Spontaneously broken quantum scale symmetry

scale symmetry

No intrinsic length or mass scale present

Scale symmetry





no scale symmetry

scale symmetry

only if no spontaneous symmetry breaking!

Quantum 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.

Quantum scale symmetry

All parameters with mass are proportional to scalar field χ.

Generalized Higgs mechanism

gravity:

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

Higgs vev,

electron mass

$$\langle h \rangle \sim \chi$$

$$m_e \sim \chi$$

QCD,

proton mass

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

$$m_p \sim \chi$$

Quantum scale symmetric standard model

- Replace all mass scales by scalar field χ

(1) Higgs potential $U = \frac{\lambda_H}{2}(\varphi^\dagger\varphi - \epsilon\chi^2)^2$ → $\varphi_0^2 = \epsilon\chi^2$ Fujii Englert Zee

(2) Strong gauge coupling, normalized at $\mu = \chi$, is independent of χ

$g(\chi) = \bar{g}$ → $\Lambda_{QCD} = \chi \exp\left(-\frac{1}{b_0 \bar{g}^2}\right)$ $b_0 = \frac{1}{16\pi^2}\left(22 - \frac{4}{3}N_f\right)$ CW'87

(3) Similar for all dimensionless couplings

Quantum effective action for standard model does not involve intrinsic mass or length

Quantum scale symmetric standard model CW'87

For $\chi_0 \neq 0$: massless Goldstone boson

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

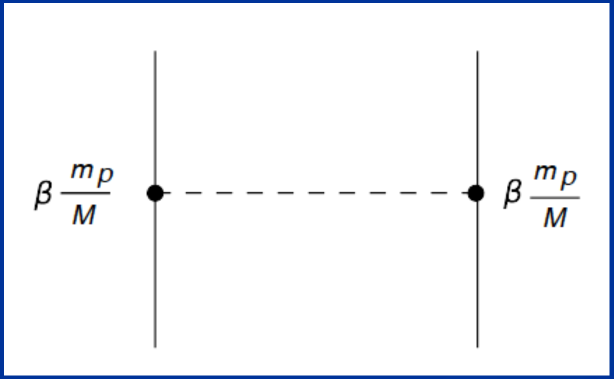
Einstein frame

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 :

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



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

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 ?

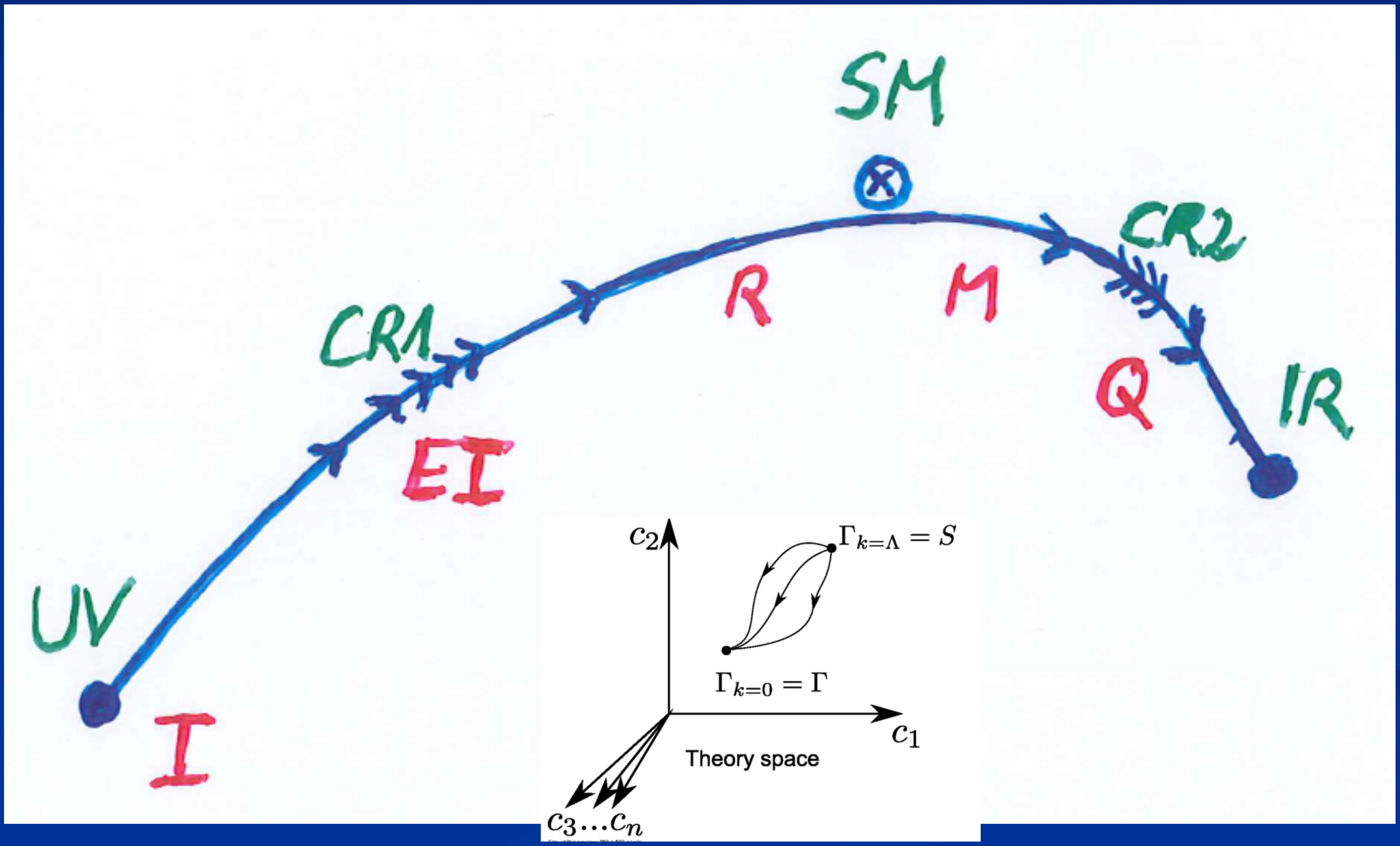
Simple mechanism for very light scalar field

- 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

Mikhail Shaposhnikov

Institut de Théorie des Phénomènes Physiques, École Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

Christof Wetterich

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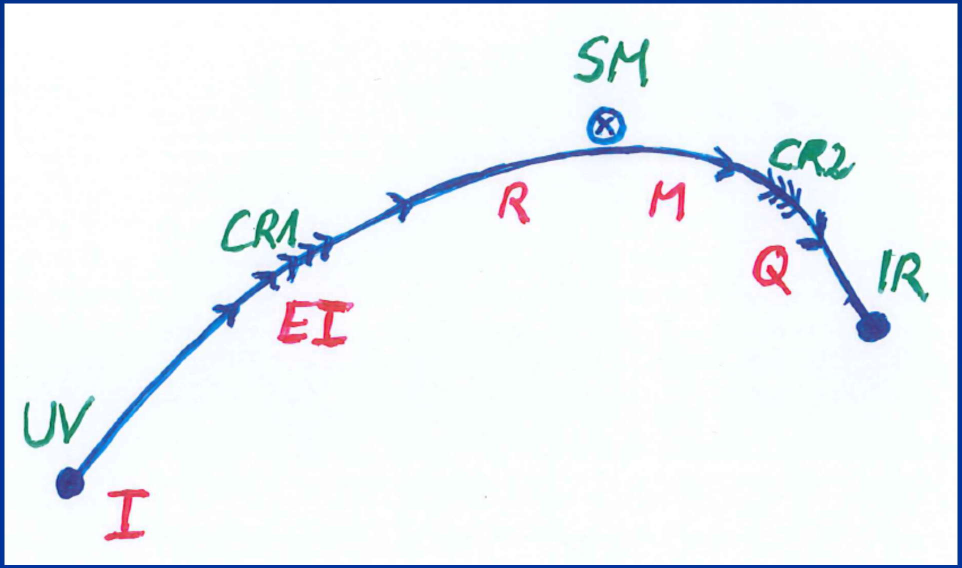
12 January 2010

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

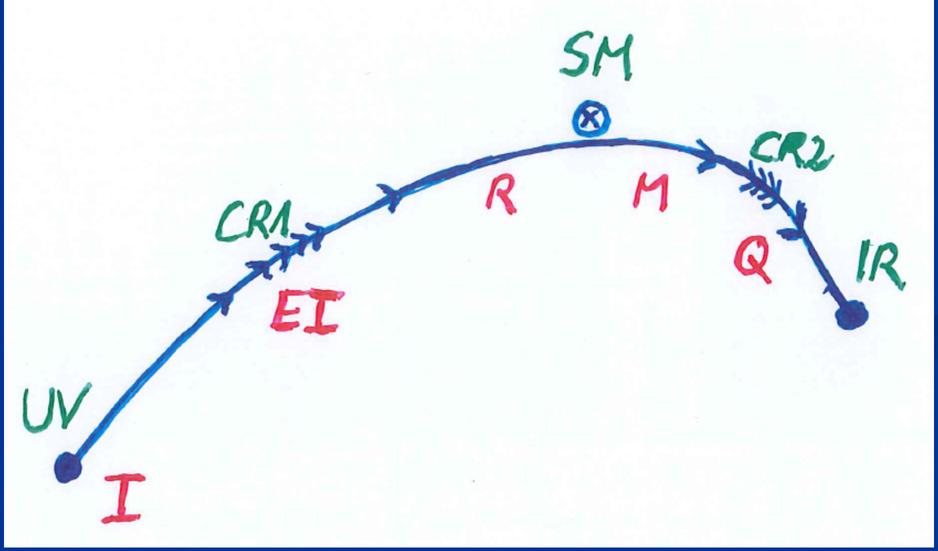
- Scalar field coupled to gravity
- Effective Planck mass depends on scalar field
- Simple quadratic scalar potential involves intrinsic mass μ
- Nucleon and electron mass proportional to dynamical Planck mass
- Neutrino mass has different dependence on scalar field

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

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

Crossover cosmology

- Realistic cosmology can arise from crossover between two fixed points
- Universe exists since infinite past
- No big bang singularity

Conclusions

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

Look for

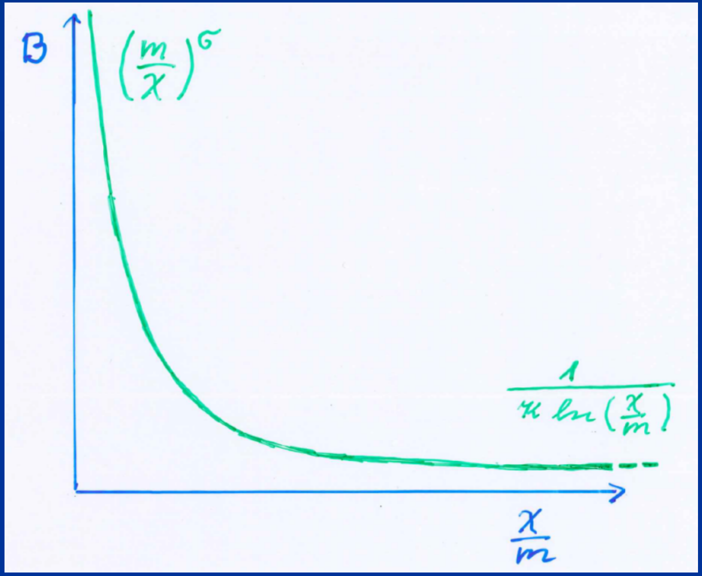
- time variation of fundamental constants, violation of equivalence principle,
- huge lumps in cosmic neutrino background,
- dynamical dark energy

end

Crossover cosmology

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

Kinetial B : Crossover between two fixed points



assumption: running coupling obeys flow equation

$$\mu \frac{\partial B}{\partial \mu} = \frac{\kappa \sigma B^2}{\sigma + \kappa B}$$

$$B^{-1} - \frac{\kappa}{\sigma} \ln B = \kappa \left[\ln \left(\frac{\chi}{\mu} \right) - c_t \right] = \kappa \ln \left(\frac{\chi}{m} \right)$$

m : scale of crossover

can be exponentially larger than intrinsic scale μ

Four-parameter model

- model has four dimensionless parameters
- three in kinetial :

  $\sigma \sim 2.5$

  $\varkappa \sim 0.5$

  $c_t \sim 14$ (or m/μ)
- one parameter for growth rate of neutrino mass over electron mass : $\gamma \sim 8$
- + standard model particles and dark matter : sufficient for realistic cosmology from inflation to dark energy
- no more free parameters than ΛCDM

Model is compatible with present observations

Together with variation of neutrino mass over electron mass in present cosmological epoch :

model is compatible with all present observations, including inflation and dark energy

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

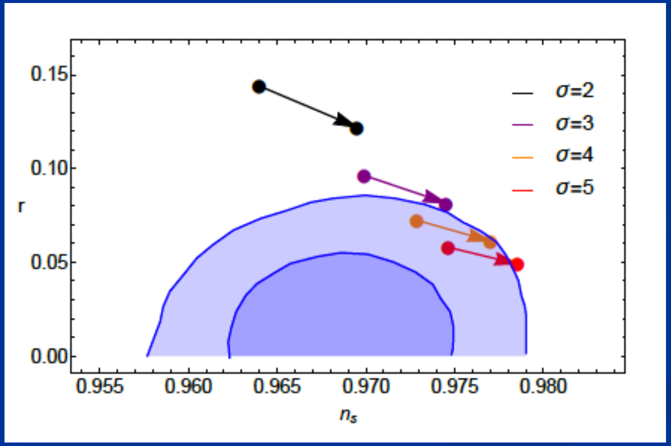
$$B^{-1} - \frac{\kappa}{\sigma}\ln B = \kappa\left[\ln\left(\frac{\chi}{\mu}\right) - c_t\right] = \kappa\ln\left(\frac{\chi}{m}\right)$$

Simplicity

simple description of all cosmological epochs

natural incorporation of Dark Energy :

- inflation
- Early Dark Energy
- present Dark Energy dominated epoch



J.Rubio…

Cosmological solution

- scalar field χ vanishes in the infinite past
- scalar field χ diverges in the infinite future

No tiny dimensionless parameters
(except gauge hierarchy)

- one mass scale $\mu = 2 \cdot 10^{-33}$ eV
- one time scale $\mu^{-1} = 10^{10}$ yr
- Planck mass does not appear as parameter
- Planck mass grows large dynamically

Slow Universe

Asymptotic solution in freeze frame :

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

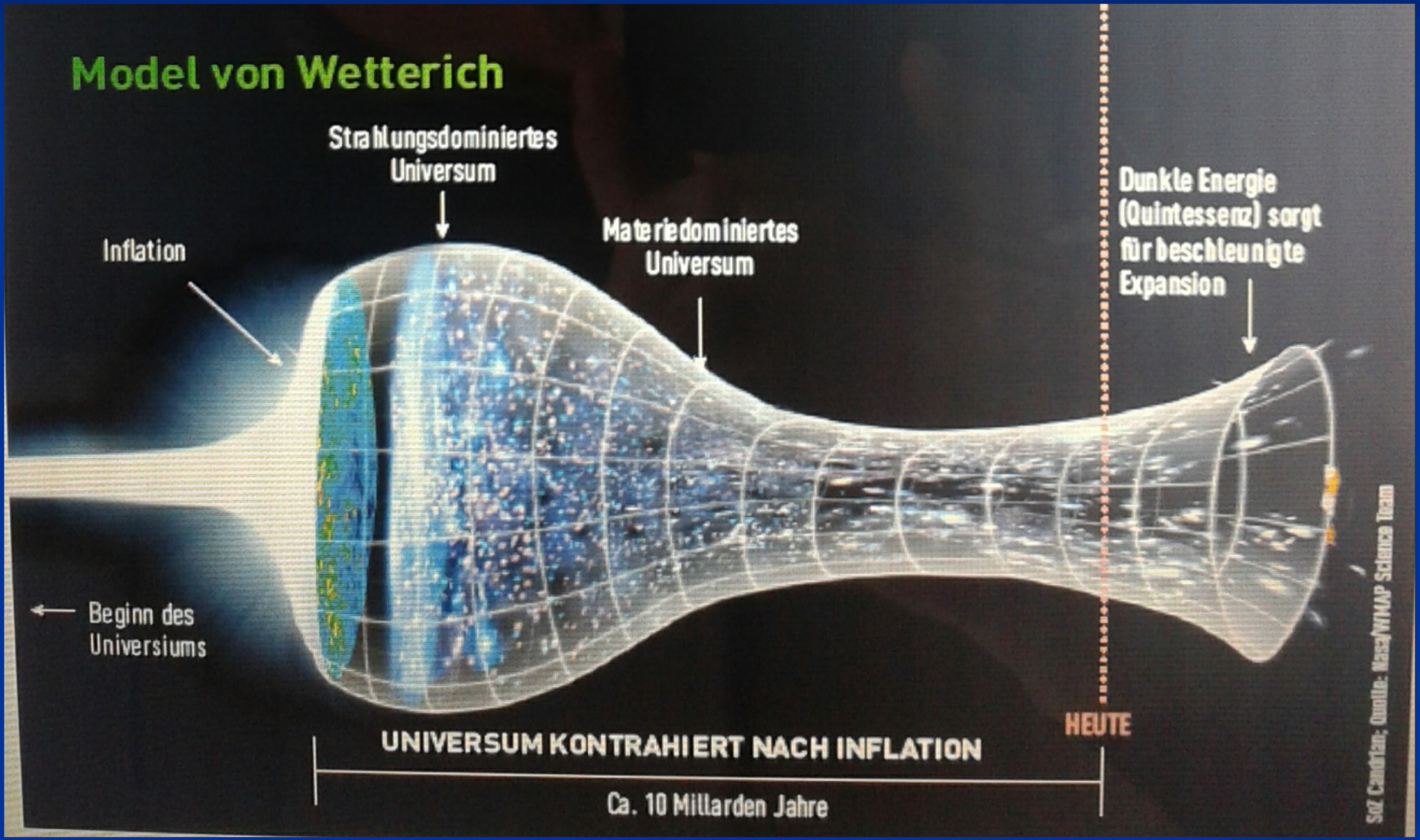
$$\mu = 2 \cdot 10^{-33} \text{ eV}$$

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 !

Strange evolution of Universe



Sonntagszeitung Zürich , Laukenmann

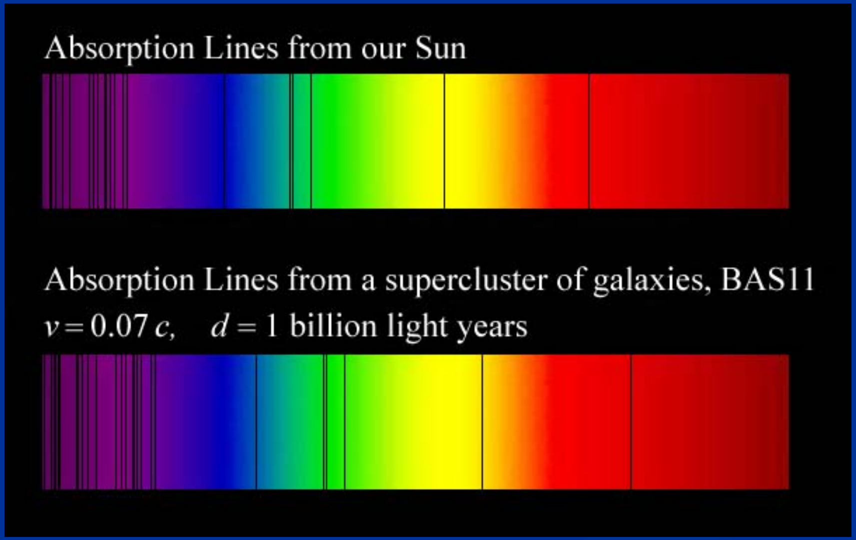
Einstein frame

Different choice of metric field :

- Big bang cosmology with inflation and dynamical dark energy
- Different frames are equivalent

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

Big bang is not wrong,

but alternative pictures exist !

Einstein frame

- "Weyl scaling" maps variable gravity model to Universe with fixed masses and standard expansion history.
- Exact equivalence of different frames !
- Standard gravity coupled to scalar field.
- Only neutrino masses are growing.

Einstein frame

Weyl scaling :

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

effective action in Einstein frame :

$$\Gamma = \int_x \sqrt{g'} \left\{ -\frac{1}{2} M^2 R' + V'(\varphi) + \frac{1}{2} k^2(\varphi) \partial^\mu \varphi \partial_\mu \varphi \right\}$$

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

$$k^2 = \frac{\alpha^2 B}{4}$$

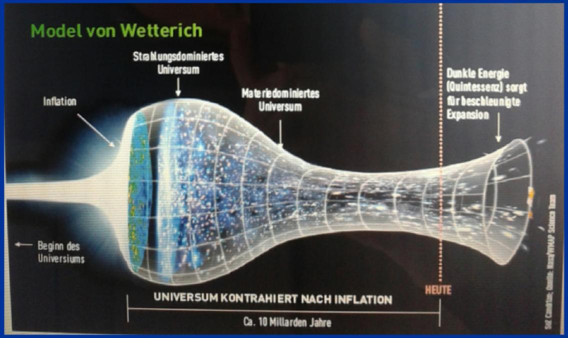
infinite past

Eternal Universe

Asymptotic solution in freeze frame :

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

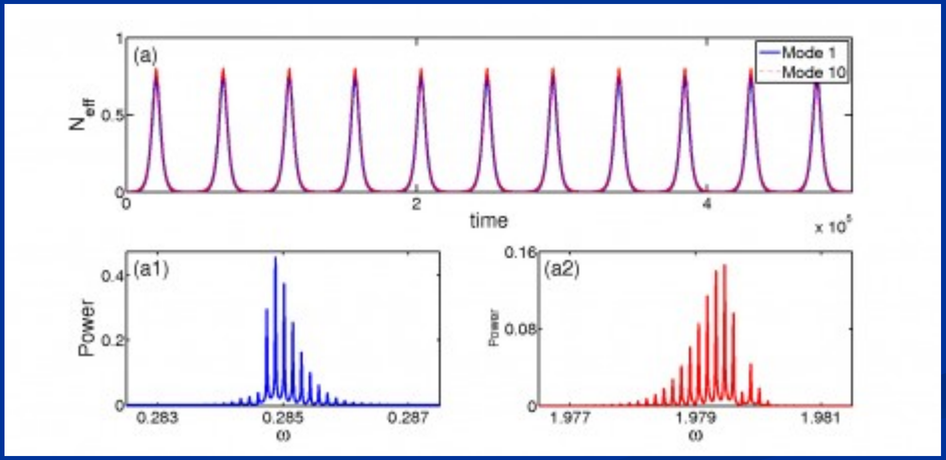
- solution valid back to the infinite past in physical time
- no singularity



- physical time to infinite past is infinite

Physical time

count oscillations ….



Physical time

field equation for scalar field mode

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

$$\varphi_k = \frac{\tilde{\varphi}_k}{a}$$

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

determine physical time by counting number of oscillations

$$\tilde{t}_p = n_k$$

$$n_k = \frac{k\eta}{\pi}$$

(m=0)

Physical time

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