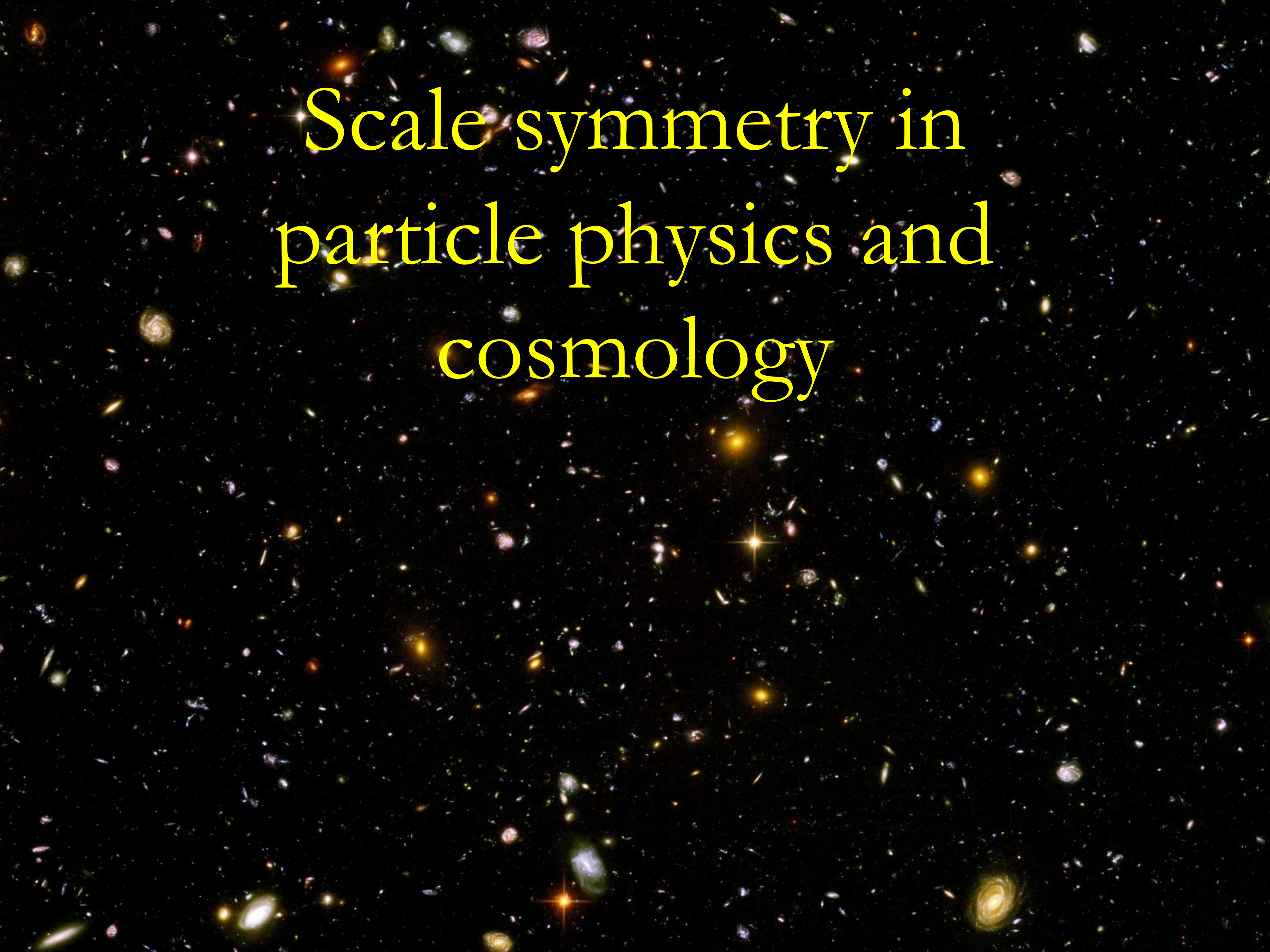
Scale symmetry in particle physics and cosmology



Scale symmetry

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

Scale symmetric classical gravity

Replace Planck mass by scalar field

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

$$g_{\mu\nu} \rightarrow \alpha^{-2} g_{\mu\nu}$$

$$\chi \rightarrow \alpha\,\chi$$

$$g^{\mu\nu} \rightarrow \alpha^{2} g^{\mu\nu}$$

$$\sqrt{g} \rightarrow \alpha^{-4}\sqrt{g}$$

Scale invariance of scalar kinetic term

$$\sqrt{g}\, \partial^{\mu}\chi\, \partial_{\mu}\chi$$

$$= \sqrt{g}\, g^{\mu\nu}\, \partial_{\mu}\chi\, \partial_{\nu}\chi$$

$$g_{\mu\nu} \to \alpha^{-2} g_{\mu\nu}$$

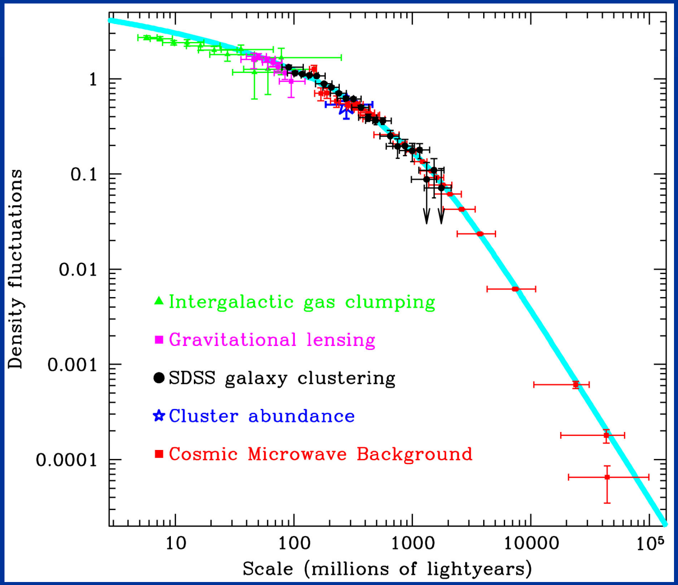
$$\chi \to \alpha\, \chi$$

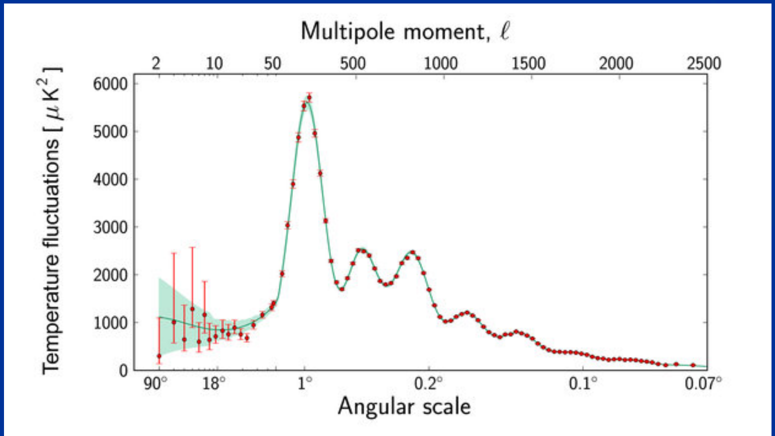
$$\sqrt{g} \to \alpha^{-4} \sqrt{g}$$

$$g^{\mu\nu} \to \alpha^{2} g^{\mu\nu}$$

Scale symmetry in cosmology ?

Almost scale invariant primordial fluctuation spectrum





scales are present in cosmology

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

Quantum scale symmetry

Quantum scale symmetry

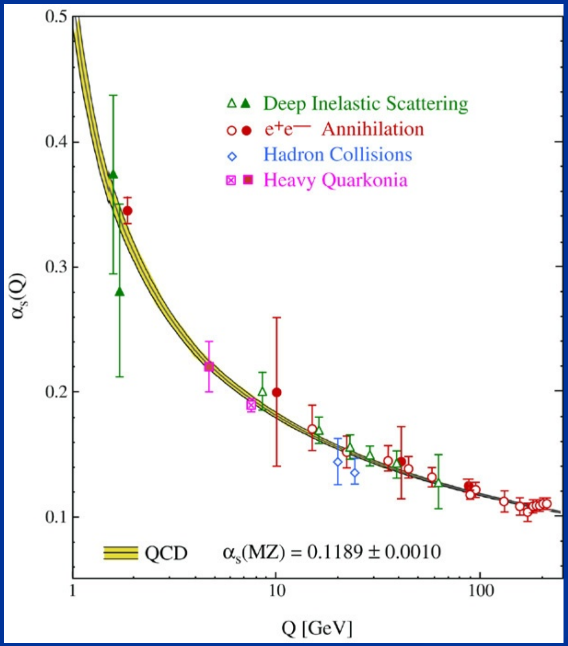
No parameter with dimension of length or mass is present in the quantum effective action.

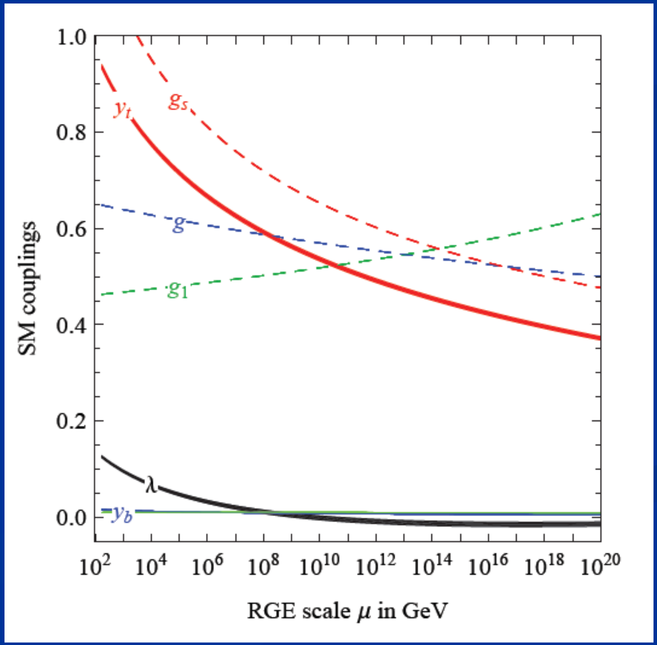
Then invariance under dilatations or global scale transformations is realized.

Continuous global symmetry

Quantum fluctuations induce running couplings

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

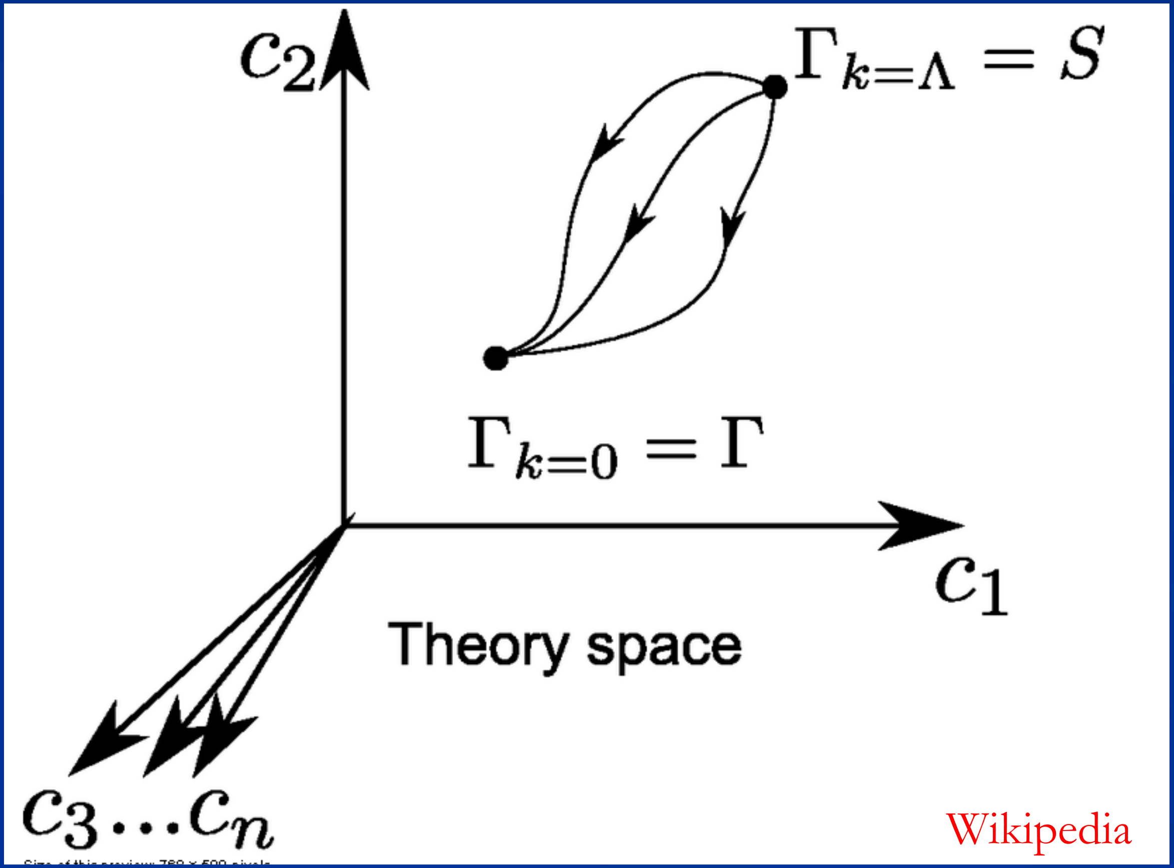




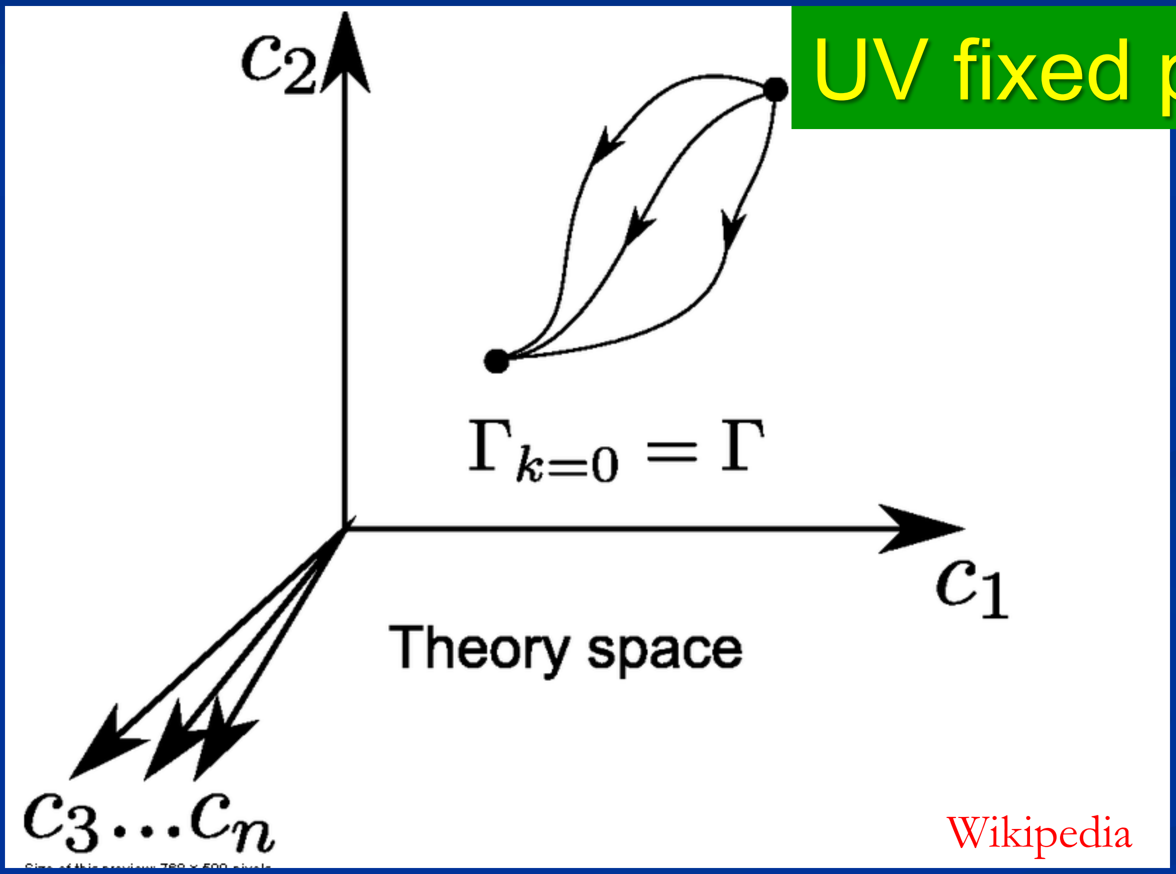
Quantum scale symmetry

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

Functional renormalization : flowing 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 for renormalized fields.

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

Continuous global symmetry

Two scale symmetries

- Gravity scale symmetry:

  includes transformation of metric and scalar singlet for variable Planck mass

- Particle scale symmetry:

  Symmetry of effective theory below Planck mass

  relative scaling of momenta with respect to Planck mass

  Violated by running couplings

Gravity scale symmetry

Gravity scale symmetry

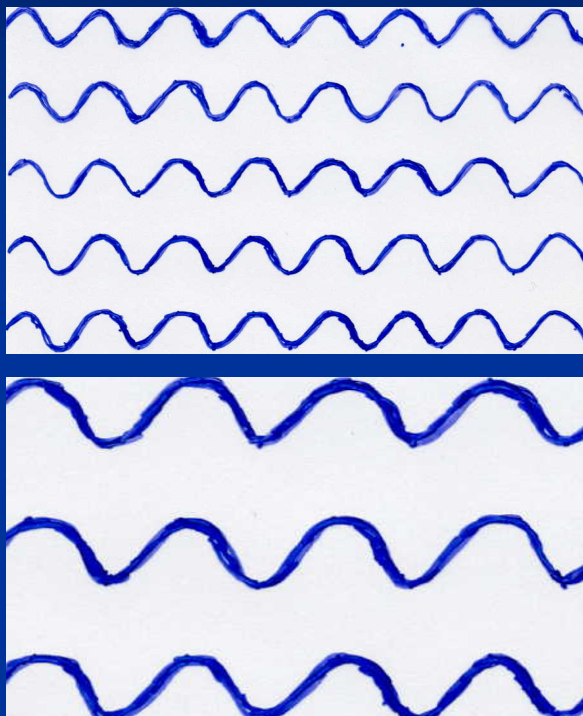
Replace Planck mass by scalar field

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

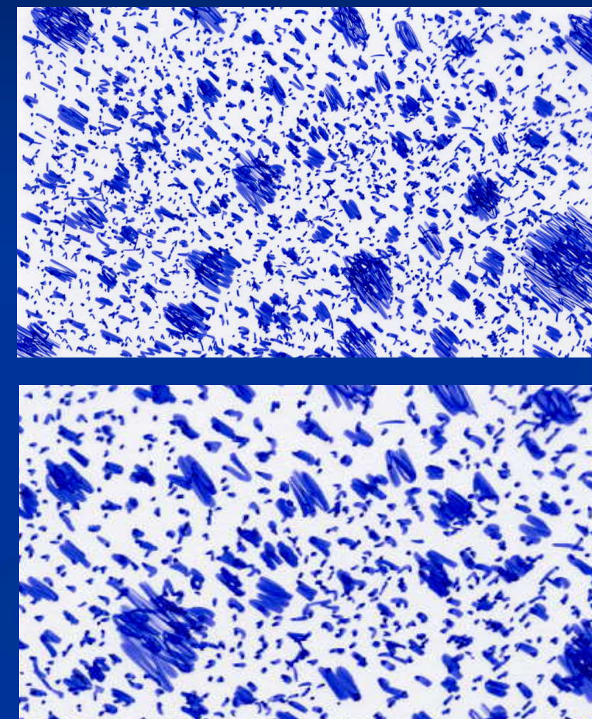
Spontaneous breaking of scale symmetry

- 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

Scale symmetry



no scale symmetry



scale symmetry

only if no spontaneous symmetry breaking!

Scale symmetric standard model

- Replace all mass scales by scalar field χ

(1) Higgs potential

$$U = \frac{\lambda_H}{2}(\varphi^\dagger\varphi - \epsilon\chi^2)^2 \quad \Rightarrow \quad \varphi_0^2 = \epsilon\chi^2$$

Fujii, Zee, CW

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

$$g(\chi) = \bar{g} \quad \Rightarrow \quad \Lambda_{\text{QCD}} = \chi \exp\left(-\frac{1}{b_0 \bar{g}^2}\right) \qquad b_0 = \frac{1}{16\pi^2}\left(22 - \frac{4}{3}N_f\right)$$

(3) Similar for all dimensionless couplings

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

Quantum scale symmetry

CW'87

For $\chi_0 \neq 0$ massless Goldstone boson

Particle scale symmetry

Second order

vacuum electroweak phase transition

➡

fixed point

➡

quantum scale symmetry

Scale symmetry and Fermi scale

- Vacuum electroweak phase transition is (almost) second order, **including all effects from quantum fluctuations**
- Critical surface of second order phase transition: exact fixed point, **quantum scale symmetry**
- Scale symmetry guarantees **"naturalness"** of gauge hierarchy

C. Wetterich, Phys. Lett.B140(1984)215,
W. A. Bardeen, FERMILAB-CONF-95-391-T(1995)

Scale symmetry and Fermi scale

- Vacuum electroweak phase transition is (almost) second order
- Critical surface of second order phase transition:
  exact fixed point, **quantum scale symmetry**
- Scale symmetry guarantees **"naturalness"** of small gauge hierarchy

- No fine tuning for renormalisation group improved perturbation theory for deviation from critical surface

$$\mu\frac{\partial}{\partial\mu}\delta = A\delta \qquad A = \frac{1}{16\pi^2}\left(2\lambda_H + 6h_t^2 - \frac{9}{2}g_2^2 - \frac{3}{2}g_1^2\right)$$

Fine tuning

- Need to understand small parameter
- Suitable renormalized parameter needs not to be tuned: take distance from second order vacuum electroweak phase transition as one of the relevant parameters
- If distance from phase transition is small:

Expression in terms of other large renormalized parameters necessarily involves cancellations

Technical fine tuning ?

Quadratic divergences concern bare perturbation theory for location of critical surface in coupling constant space.

not relevant for observation,

not particularly interesting,

regularization dependent, not universal,

always depends on unknown microscopic details

bare perturbation theory is bad expansion

Quantum Gravity

Quantum Gravity can be a renormalisable quantum field theory

Asymptotic safety

Asymptotic safety of quantum gravity

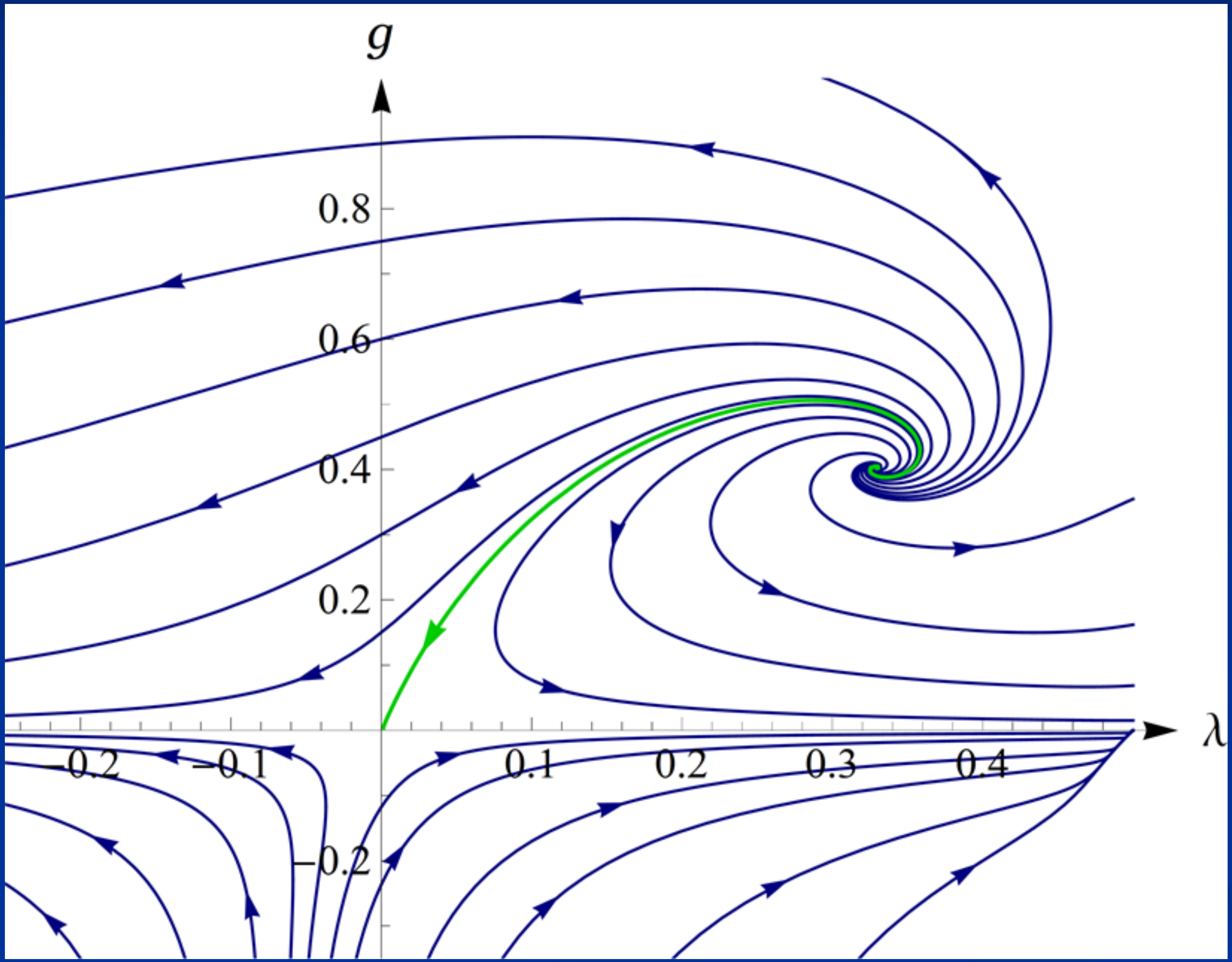
if UV fixed point exists :

quantum gravity is

non-perturbatively renormalizable !

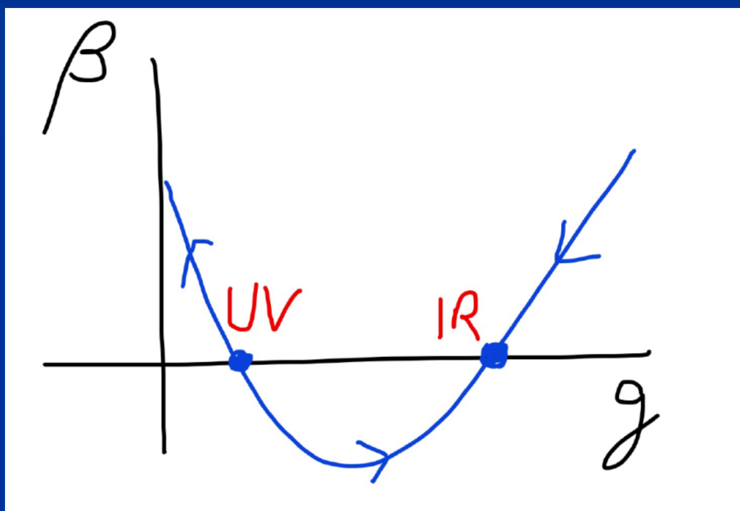
S. Weinberg , M. Reuter

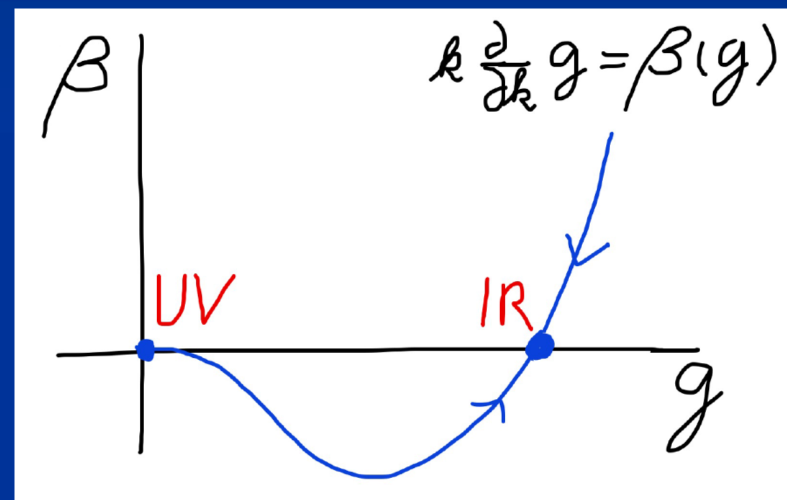
UV- fixed point for quantum gravity



Wikipedia

Asymptotic safety   Asymptotic freedom





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

a prediction…

Asymptotic safety of gravity and the Higgs boson mass

Mikhail Shaposhnikov

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Christof Wetterich

Institut für Theoretische Physik, Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany

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 contributions to running couplings in standard model

$$k\frac{dx_j}{dk} = \beta_j^{\text{SM}} + \beta_j^{grav}$$

$$\beta_j^{grav} = \frac{a_j}{8\pi}\frac{k^2}{M_P^2(k)}x_j$$

Running Planck mass :

$$M_P^2(k) = M_P^2 + 2\xi_0 k^2$$

$$k_{tr} = \frac{M_P}{\sqrt{2\xi_0}} \approx 10^{19}\ \text{GeV}$$

Large k :

$$x_j(k) \sim k^{A_j}$$

$$A_j = \frac{a_j}{16\pi\xi_0}$$

For quartic scalar coupling
(R.Percacci et al)

$$a_\lambda \approx 3.1\ ,\ A_\lambda \simeq 2.6$$

Add fermions
+…

$$\beta_\lambda = \frac{a_\lambda}{16\pi\xi_0}\lambda + \frac{1}{16\pi^2}(24\lambda^2 + 12\lambda h^2 - 6h^4)$$

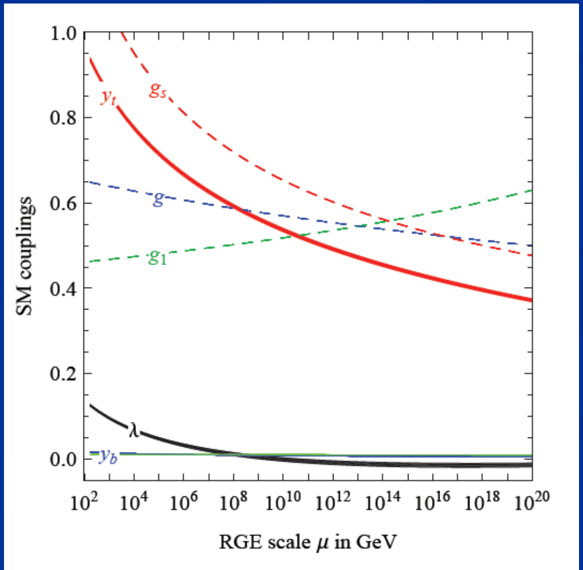
$$24\lambda_*^2 + 12\lambda h_*^2 - 6h_*^4 + \frac{\pi a_\lambda \lambda_*}{\xi_0} = 0$$

$$\lambda(k_{tr}) \approx 0\ ,\ \beta_\lambda(k_{tr}) \approx 0$$

Essential point for prediction of Higgs boson mass:

- More precisely : ratio Higgs boson mass over W-boson mass, or Higgs boson mass over top quark mass
- Initial value of quartic scalar coupling near Planck mass is predicted by UV- fixed point

Extrapolate perturbatively to Fermi scale :



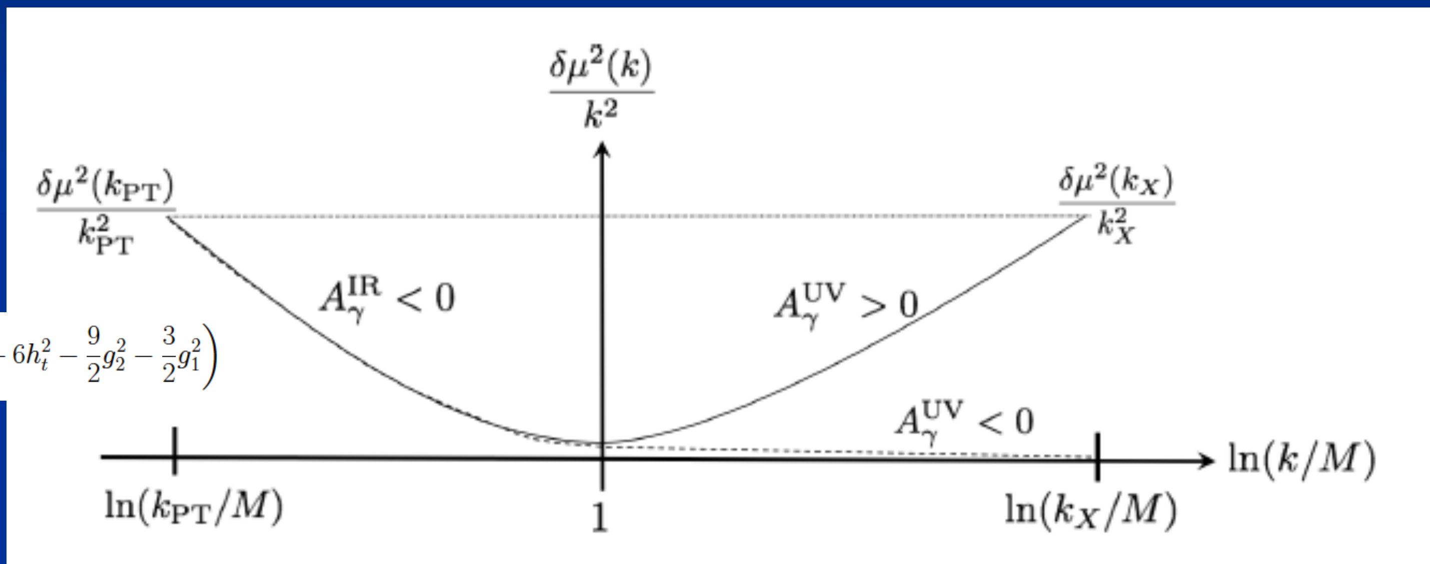
Gauge hierarchy

- Possible explanation of small parameter : distance from second order vacuum electroweak phase transition is **irrelevant parameter** at UV – fixed point

Possible explanation of gauge hierarchy

$A_\gamma^{\mathrm{IR}} = -2 + A,$

$$A = \frac{1}{16\pi^2}\left(2\lambda_H + 6h_t^2 - \frac{9}{2}g_2^2 - \frac{3}{2}g_1^2\right)$$



Gauge hierarchy problem in asymptotically safe gravity –the resurgence mechanism

Christof Wetterich[1] and Masatoshi Yamada[1]

Phys.Lett. B770 (2017) 268-271

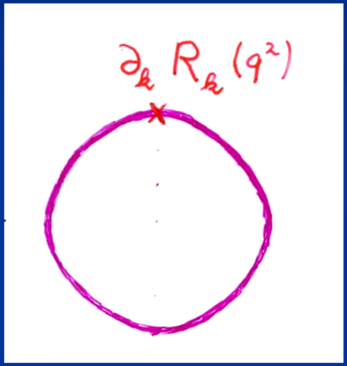
Infrared flow in gravity

for k much smaller than M

Graviton contribution to flow of scalar potential

$$\partial_t V = k\,\partial_k V = 5 I_k\left(-\tfrac{2V}{M^2}\right)$$

$$I_k(m^2) = \frac{1}{2}\int_q \left(q^2 + R_k(q) + m^2\right)^{-1} \partial_t R_k(q)$$



$$I_k(m^2) = \frac{1}{32\pi^2}\frac{k^6}{k^2+m^2}$$

$$m^2 = -\frac{2V}{M^2}$$

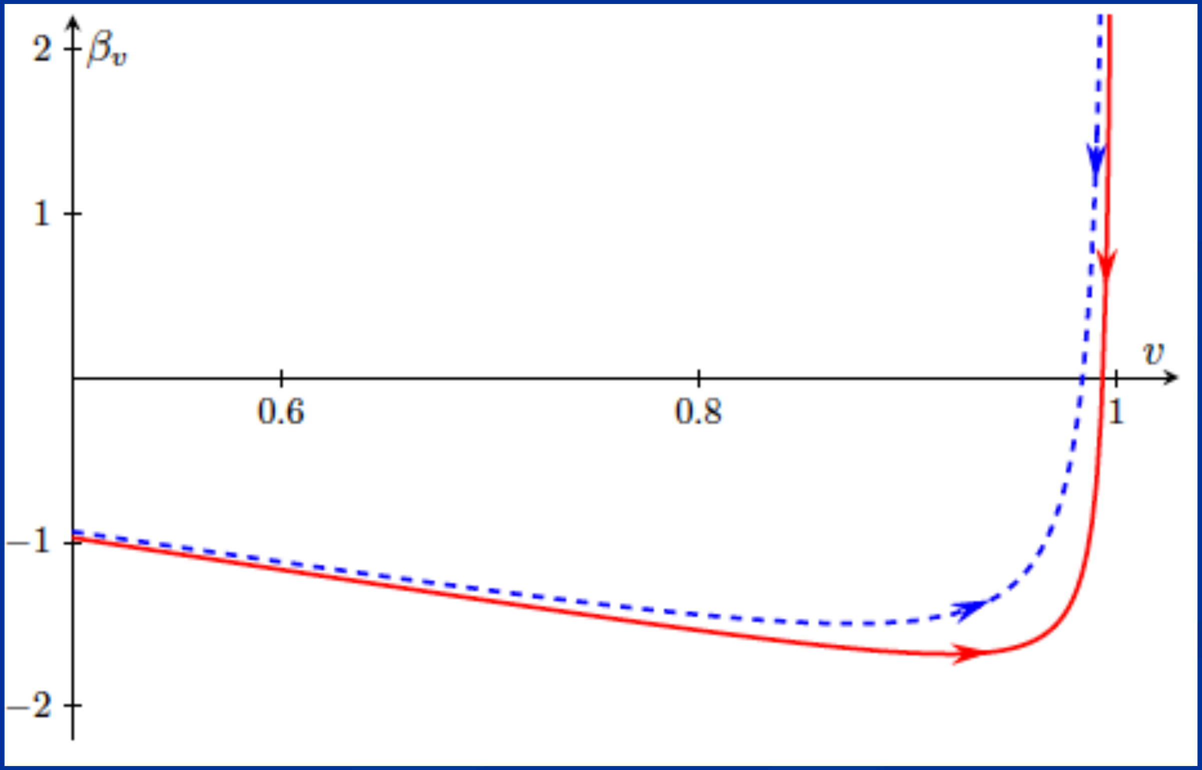
crucial dimensionless quantity

$$v = \frac{2V}{M^2 k^2}$$

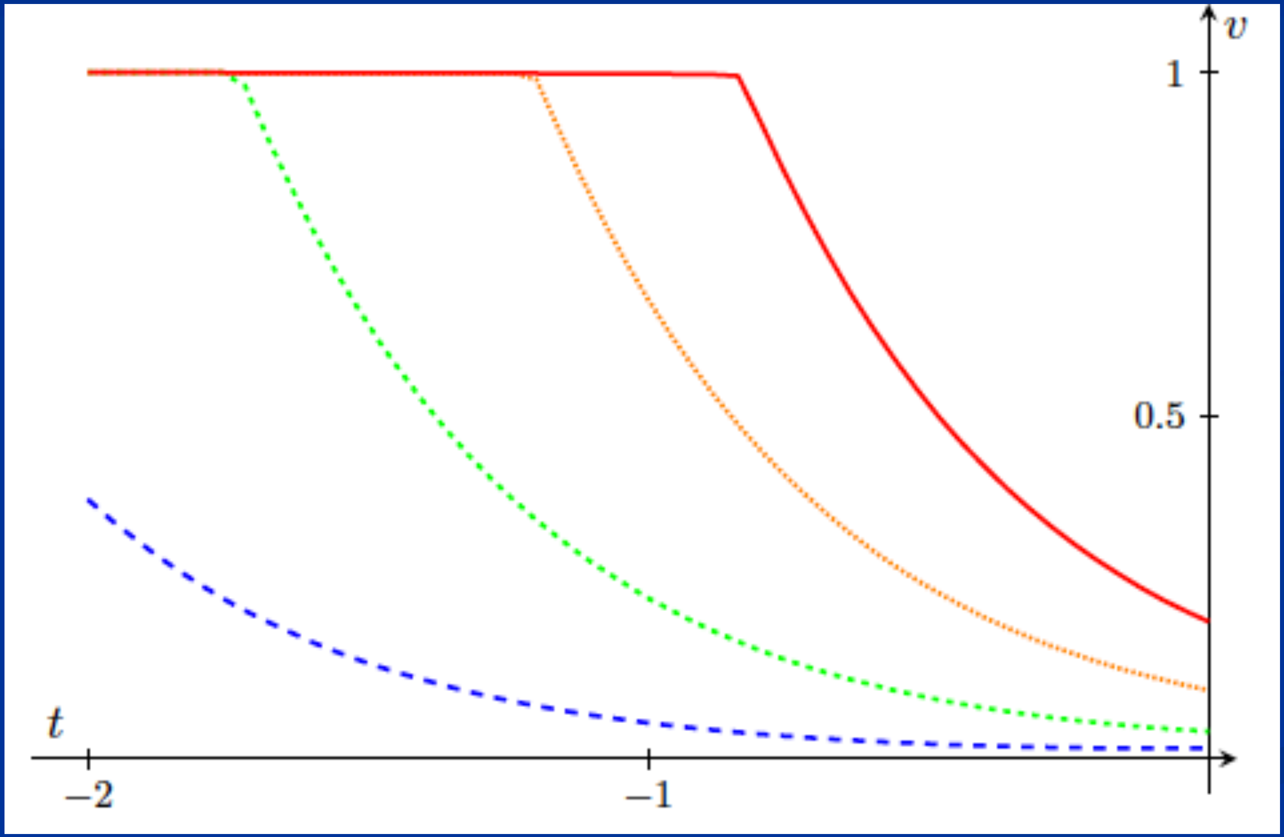
Flow equation for v

$$\partial_t v = \beta_v = -2v + \frac{5k^2}{16\pi^2 M^2}(1-v)^{-1}.$$

$$v = \frac{2V}{M^2 k^2}$$



Flow of v for different initial conditions



Infrared value of effective scalar potential for k/$\chi \to 0$

v=1

$$U = \frac{\bar{k}^2}{2} M^2(\chi)$$

graviton barrier !

Graviton fluctuations erase the cosmological constant

Graviton barrier and solution of the cosmological constant problem

V cannot increase stronger than M^2 !

If M increases with χ, and for cosmological solutions where χ asymptotically diverges for time going to infinity:

Effective cosmological constant vanishes in infinite future

Normalization of scalar field

If M increases monotonically with χ :

choose normalization of scalar

$$M = \chi$$

asymptotically vanishing cosmological „constant“

- What matters : Ratio of potential divided by fourth power of Planck mass

$$\frac{V}{\chi^4} = \frac{\mu^2 \chi^2}{\chi^4} = \frac{\mu^2}{\chi^2}$$

- vanishes for $\chi \to \infty$!

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)

Predictions of quantum gravity ?

Simple approximation for graviton contribution to scalar potential:

- Predicts mass of Higgs scalar
- Solves Gauge Hierarchy problem
- Solves cosmological constant problem

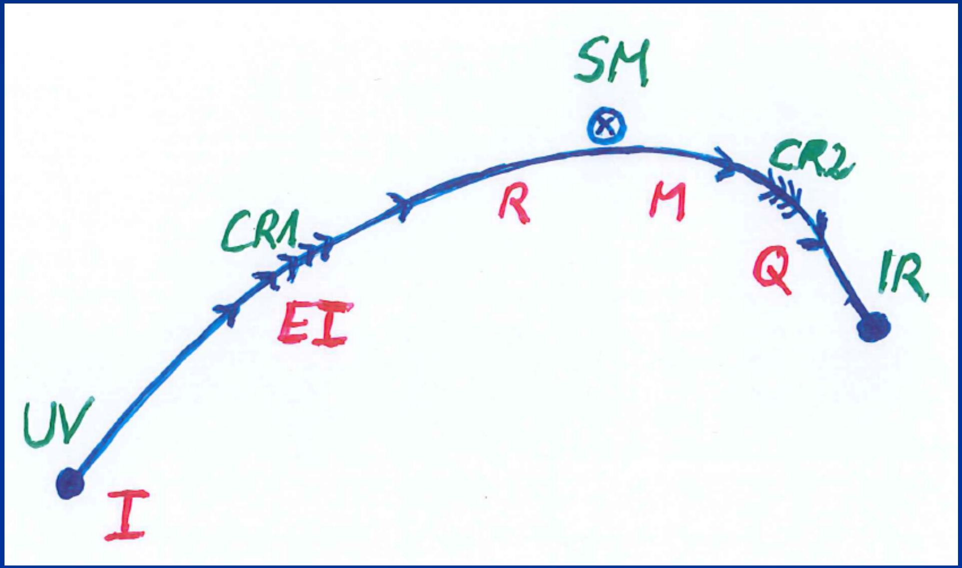
Quantum gravity with scalar field – the role of scale symmetry for cosmology

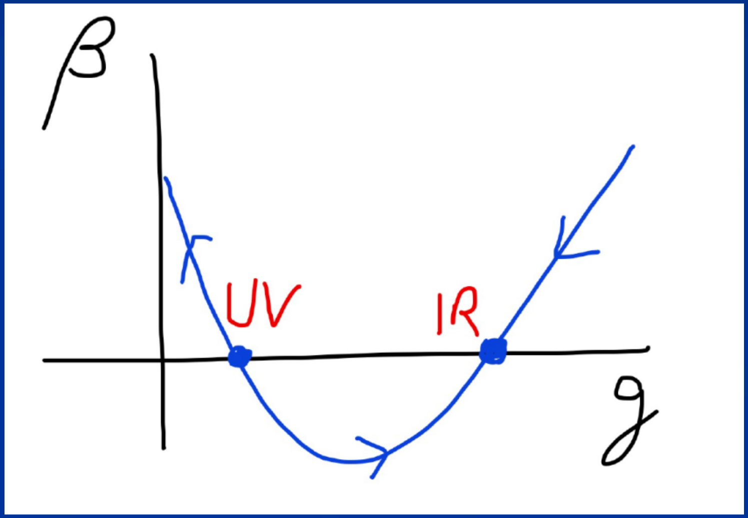
Approximate scale symmetry near fixed points

- 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

Possible consequences of crossover in quantum gravity





Realistic model for inflation and dark energy with single scalar field

variable gravity

“Newton’s constant is not constant –
and particle masses are not constant”


Πάντα ῥεῖ

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

+ scale symmetric standard model

- Replace all mass scales by scalar field χ

(1) Higgs potential $U = \frac{\lambda_H}{2}(\varphi^\dagger \varphi - \epsilon \chi^2)^2 \;\Rightarrow\; \varphi_0^2 = \epsilon \chi^2$

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

$$g(\chi) = \bar{g} \;\Rightarrow\; \Lambda_{QCD} = \chi \exp\left(-\frac{1}{b_0 \bar{g}^2}\right) \quad b_0 = \frac{1}{16\pi^2}\left(22 - \frac{4}{3}N_f\right)$$

+ scale invariant action for dark matter

Scale symmetry in variable gravity
(IR – fixed point)

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

quantum effective action,
variation yields field equations

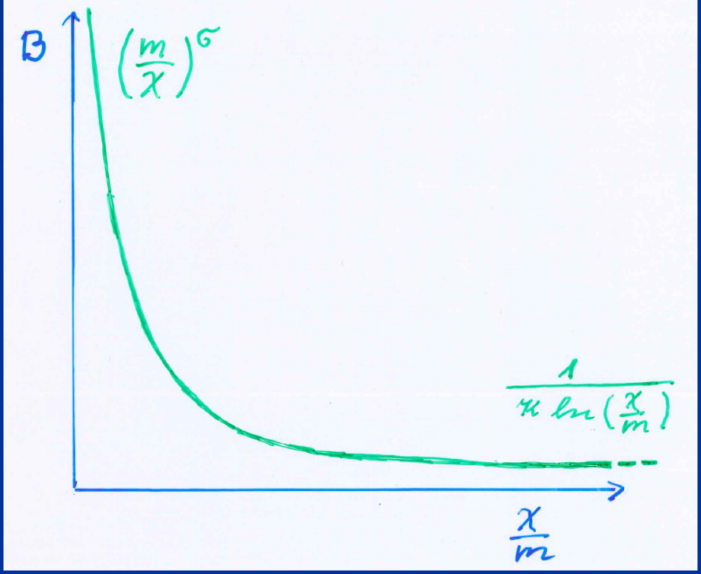
Einstein gravity : $\Gamma = \int_x \sqrt{g}\left\{-\frac{1}{2} M^2 R\right\}$

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

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

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

Cosmology

Add matter and radiation (standard model + dark matter)

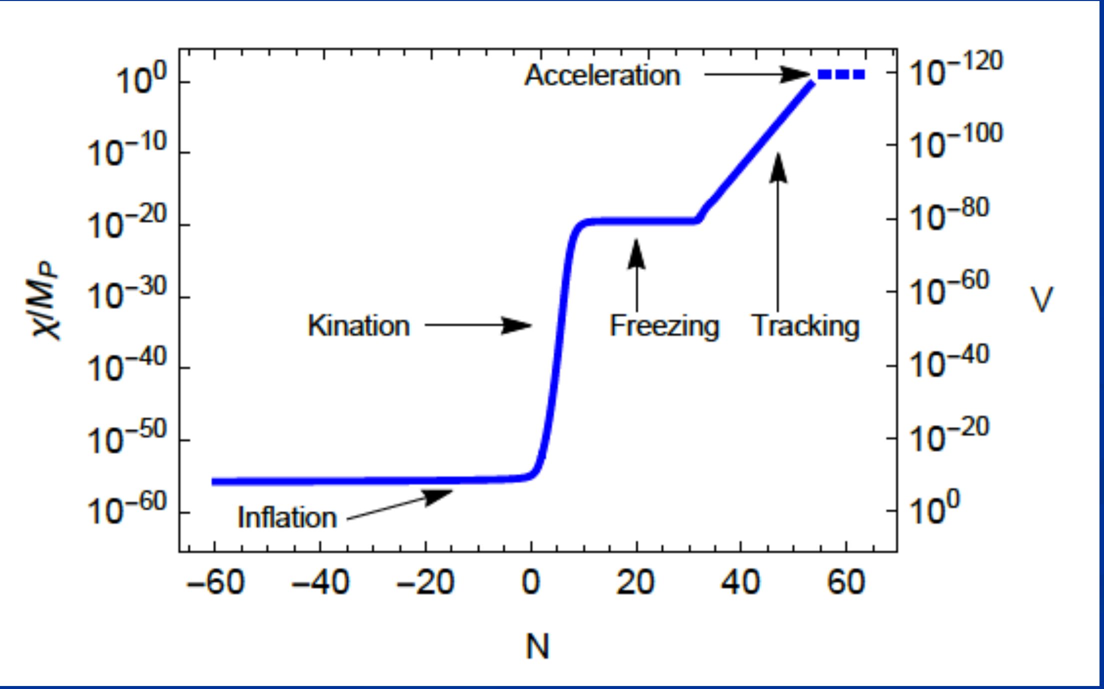
Solve field equations…

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

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

Cosmological solution

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



J.Rubio,…

Model is compatible with present observations

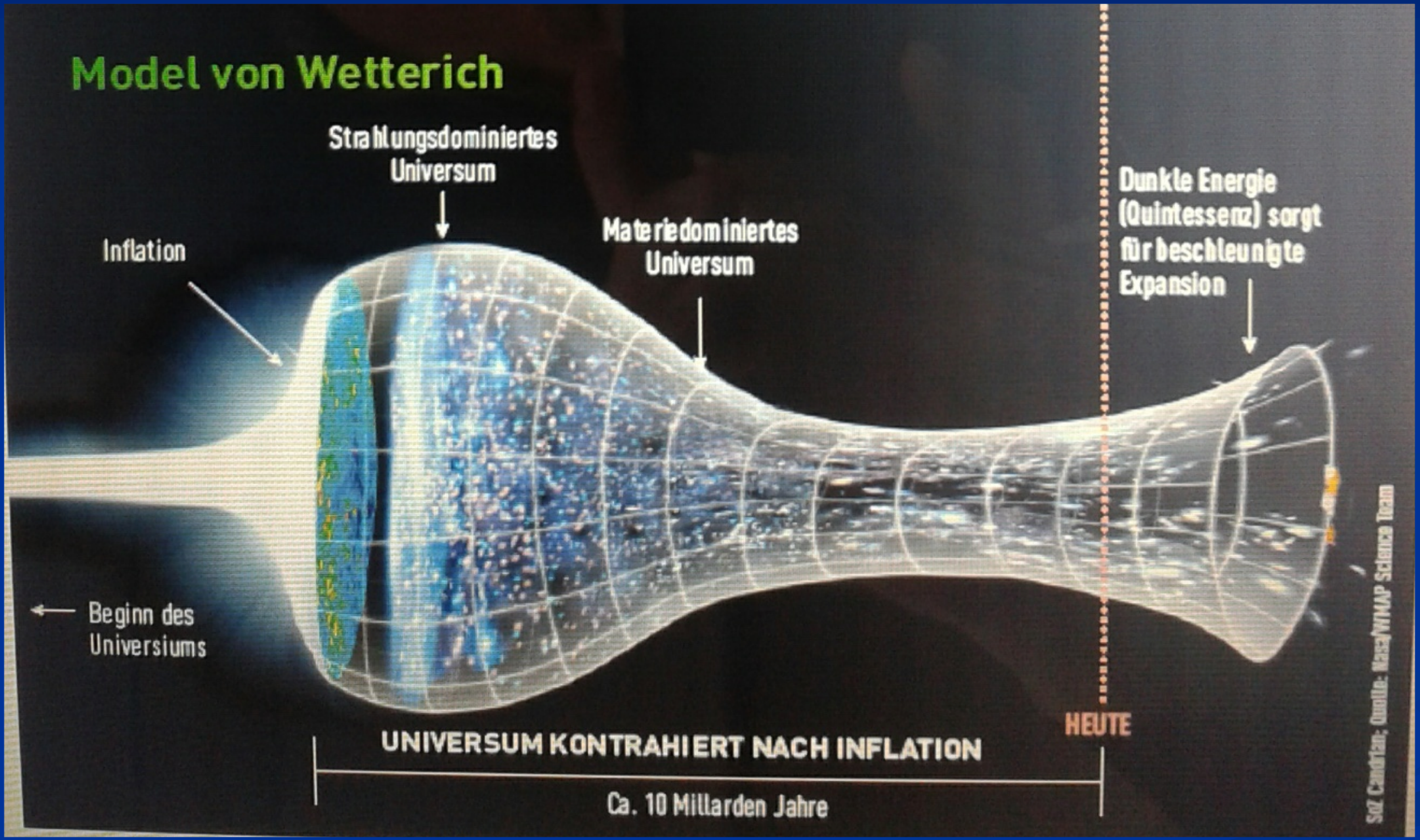
Together with variation of neutrino mass over electron mass in present cosmological epoch :

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

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

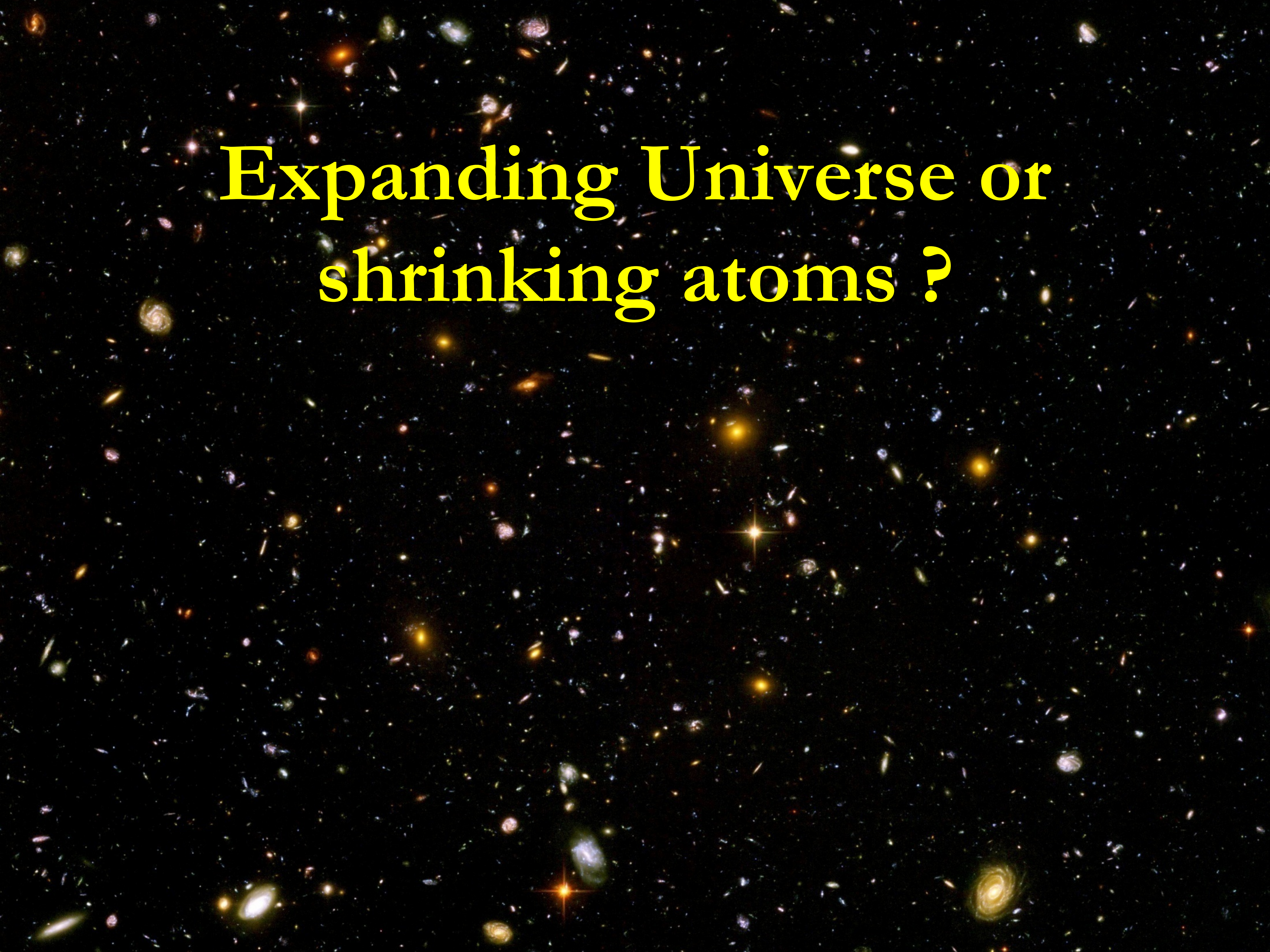
$$B^{-1} - \frac{\kappa}{\sigma}\ln B = \kappa\left[\ln\left(\frac{\chi}{\mu}\right) - c_t\right] = \kappa\ln\left(\frac{\chi}{m}\right)$$

Strange evolution of Universe



Sonntagszeitung Zürich , Laukenmann

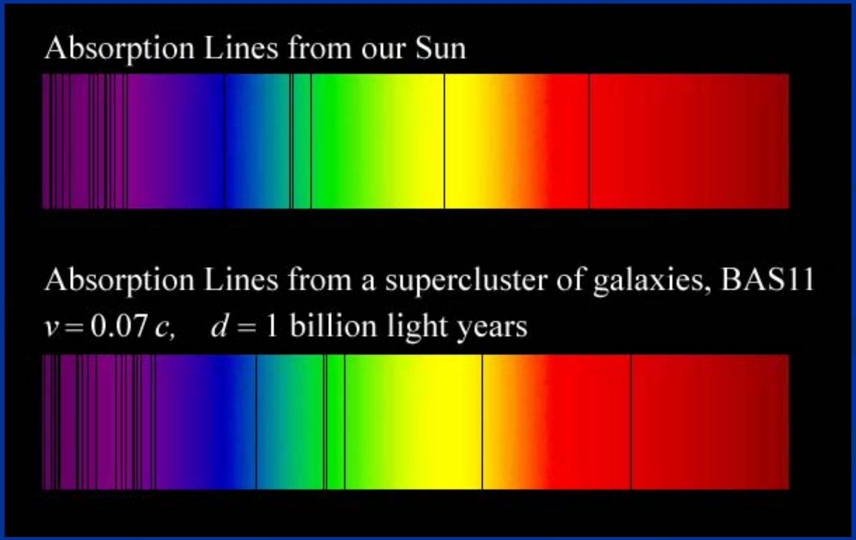
Expanding Universe or shrinking atoms ?



Do we know that the Universe expands ?

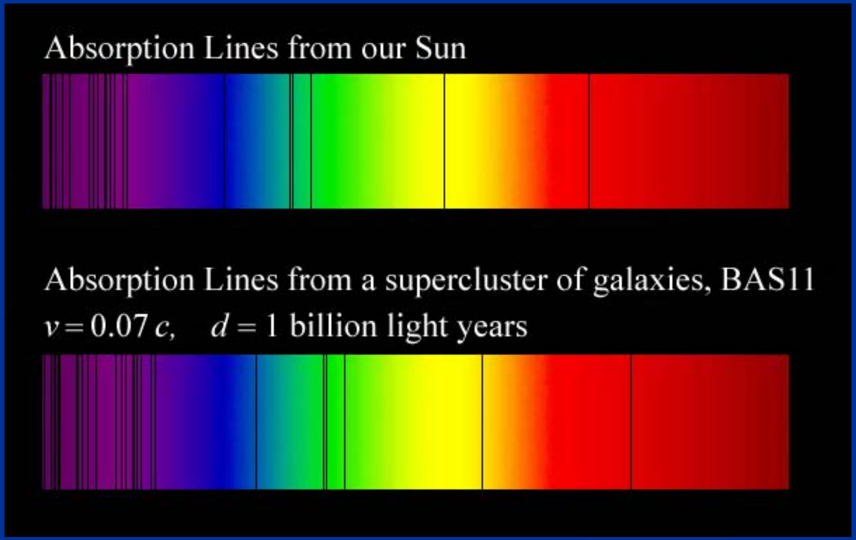
instead of redshift due to expansion :

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

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 !

  " different pictures"

- Standard gravity coupled to scalar field.

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 :

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

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

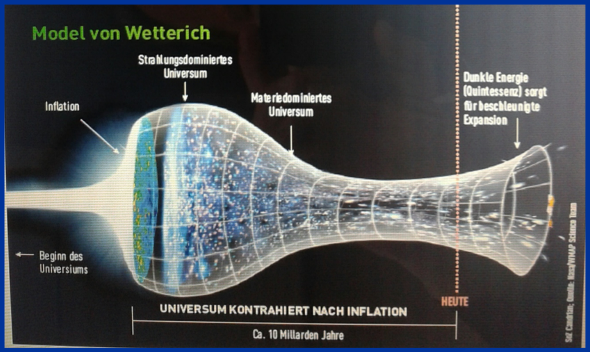
$$k^2 = \frac{\alpha^2 B}{4}$$

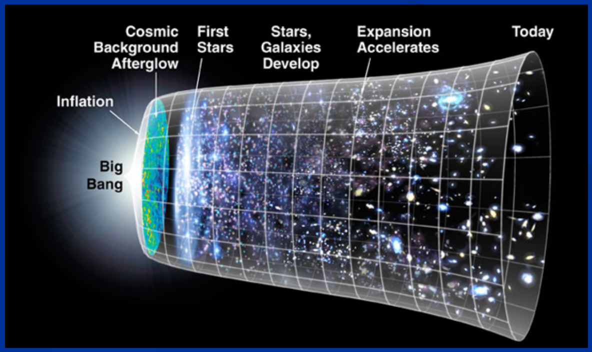
Field relativity

Weyl scaling :

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

changes geometry,
not a coordinate transformation



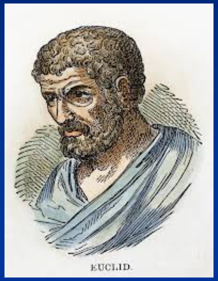


Field relativity : different pictures of cosmology

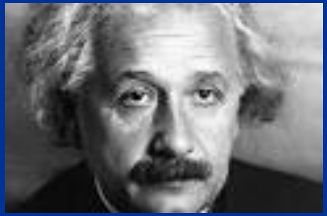
- same physical content can be described by different pictures
- related by field – redefinitions , e.g. Weyl scaling , conformal scaling of metric
- observables cannot depend on choice of fields
- metric is one of the fields
- which picture is usefull ?

Relativity of geometry

- Euclid … Newton : space and time are absolute



- Special relativity : space and time depend on observer
- General relativity : space-time is influenced by matter (including radiation)



  geometry is independent of coordinates
  geometry is observable
- Field relativity : geometry is relative

Space-time is a description of correlations between "matter".

Observables cannot depend on choice of fields used to describe them.

Different pictures for geometry exist.

How can particle masses change with time ?

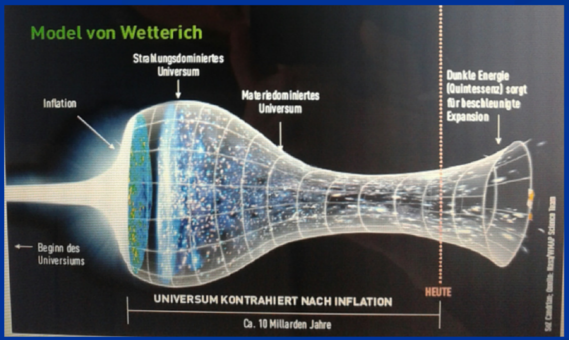
- Particle masses are proportional to scalar field χ . Similar to Higgs field.
- Scalar field varies with time.
- Ratios of particle masses are independent of χ and therefore remain constant.
- Compatibility with observational bounds on time dependence of particle mass ratios.
- Dimensionless couplings are independent of χ .

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

Field - singularity

- Big Bang is field - singularity
- similar (but not identical with) coordinate - singularity

$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

Conclusions

Quantum gravity may be observable in dynamics of early and present Universe

Predictions for parameters of standard model of particle physics

Fixed points and scale symmetry crucial

Big bang singularity is artefact of inappropriate choice of field variables – no physical singularity end

Hot big bang or freeze ?

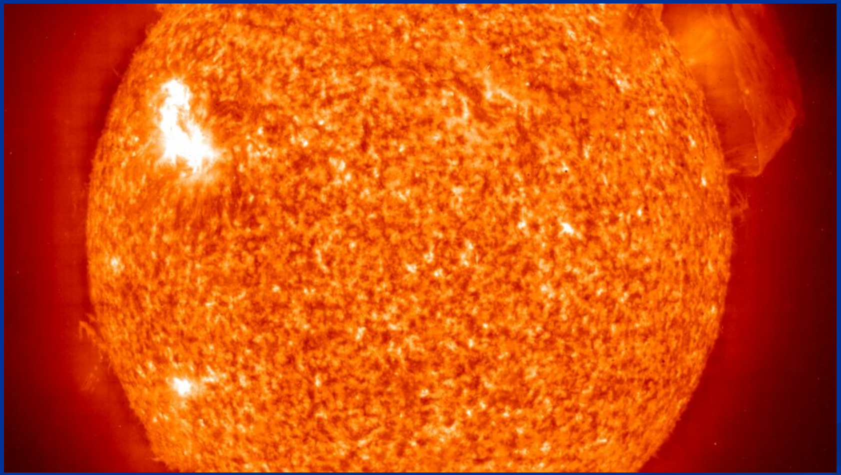
Do we know that the temperature was higher in the early Universe than now ?

Cosmic microwave radiation , nucleosynthesis

instead of

higher temperature :

smaller particle masses



Hot plasma ?

- Temperature in radiation dominated Universe : $T \sim \chi^{1/2}$ smaller than today
- Ratio temperature / particle mass : $T/m_p \sim \chi^{-1/2}$ larger than today
- T/m_p counts ! This ratio decreases with time.

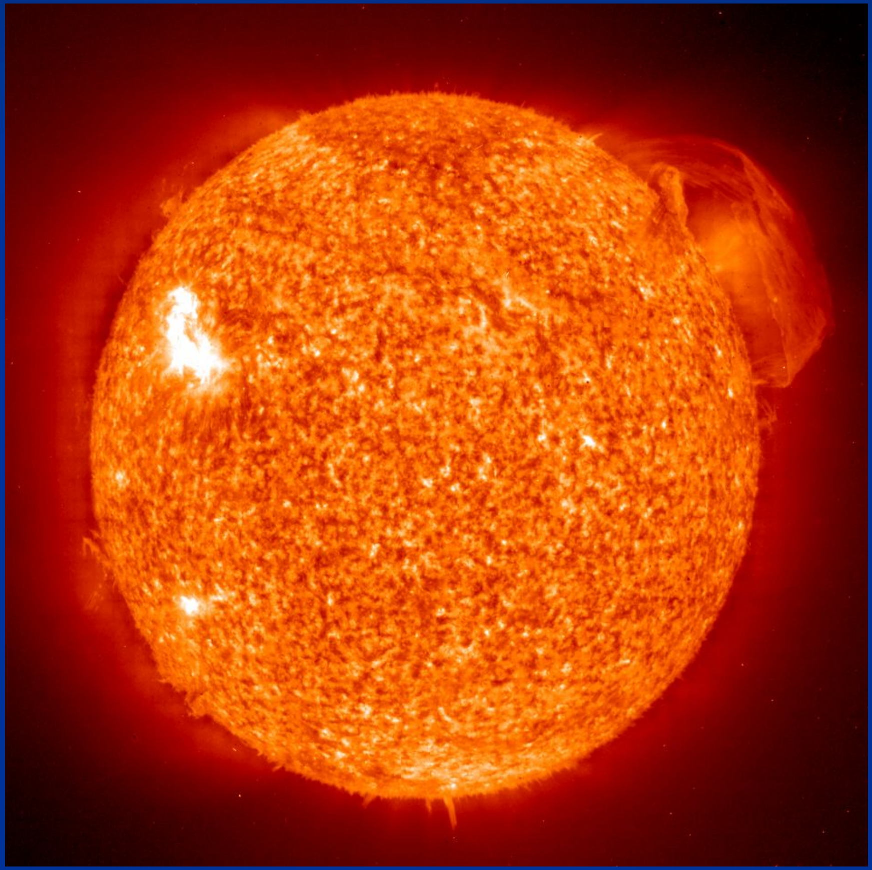
- Nucleosynthesis , CMB emission as in standard cosmology !

Freeze Universe

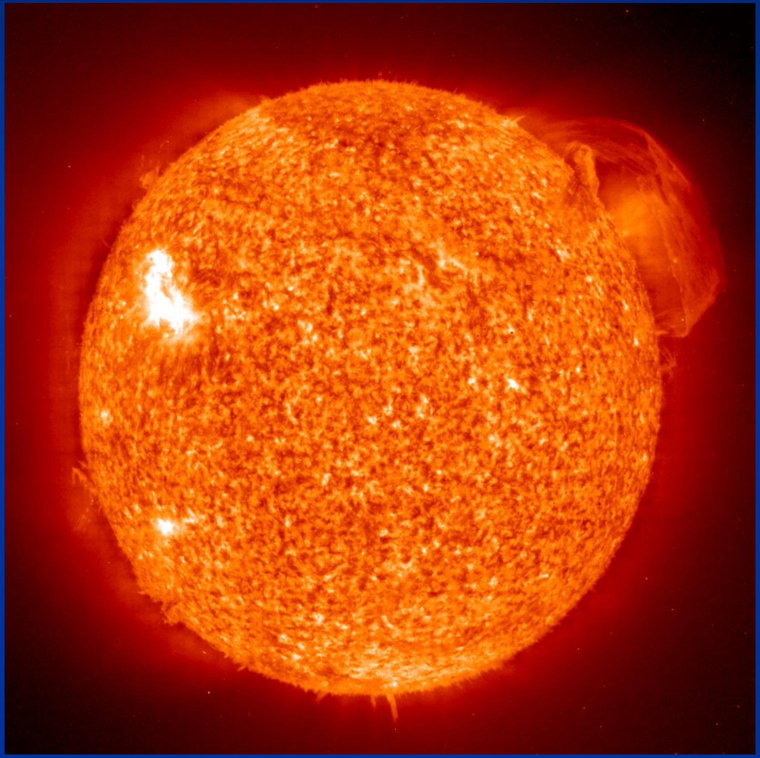
The Universe may have started very cold, and only later heat up.

Freeze picture of the Universe

Big bang or freeze ?



Big bang or freeze ?



freeze picture :
only rods for measurements
(masses) are different !

Why should you care about the freeze picture of the Universe ?

Some aspects are understood easier :

- Natural tiny present dark energy
- Beginning of Universe
- Role of scale symmetry
- Range of impact of quantum gravity

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
- Dark energy is tiny because Universe is old

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

Infinite past : slow inflation

$\sigma = 2$: field equations

$$\ddot{\chi} + \left(3H + \frac{1}{2}\frac{\dot{\chi}}{\chi}\right)\dot{\chi} = \frac{2\mu^2\chi^2}{m}$$

$$H = \sqrt{\frac{\mu^2}{3} + \frac{m\dot{\chi}^2}{6\chi^3}} - \frac{\dot{\chi}}{\chi}$$

approximative solution

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

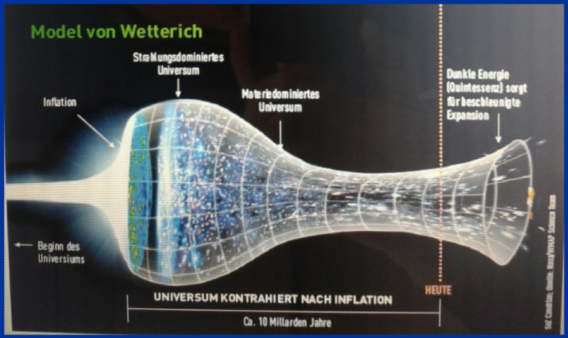
particles become massless in infinite past !

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



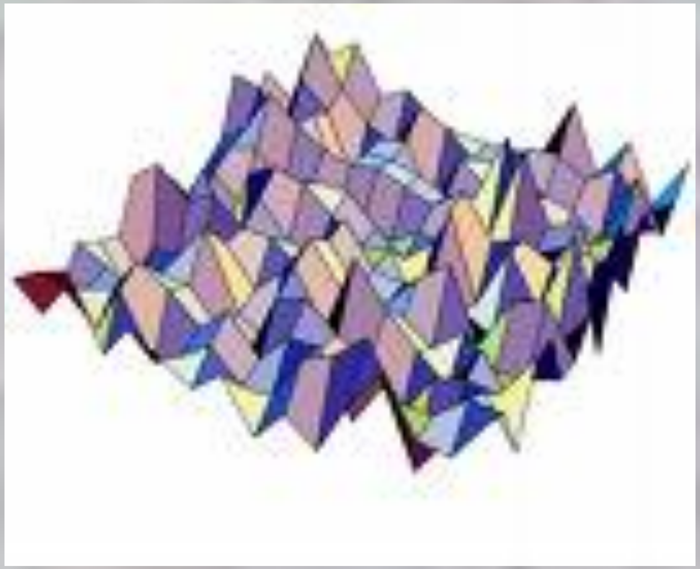
- physical time to infinite past is infinite

Eternal light-vacuum

Everywhere almost nothing
only fluctuations

All particles move
with light velocity,
similar to photons

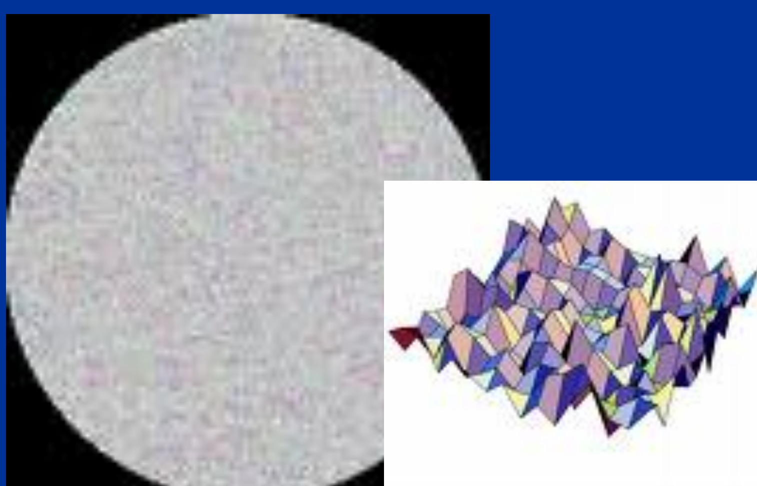
strength of gravity
much stronger than today

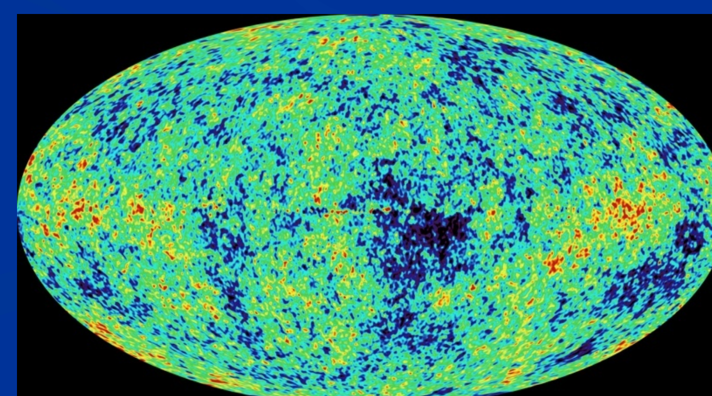


In the beginning was light-like emptiness.

Eternal light-vacuum is unstable

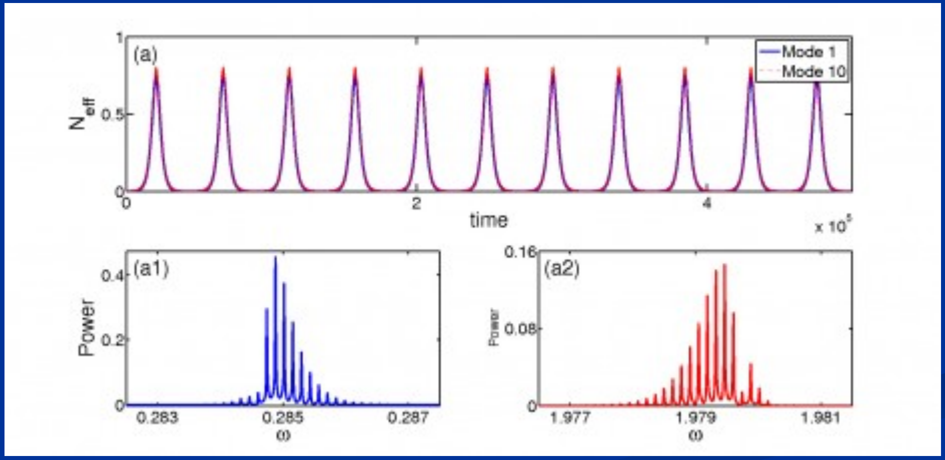
- Slow increase of particle masses and weakening of gravity
- Only slow change of space-time geometry
- Consequence for observation : primordial fluctuations become visible in cosmic background radiation
- We see fluctuations in a stage 5000 billion years ago.





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

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

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

(m=0)

Physical time

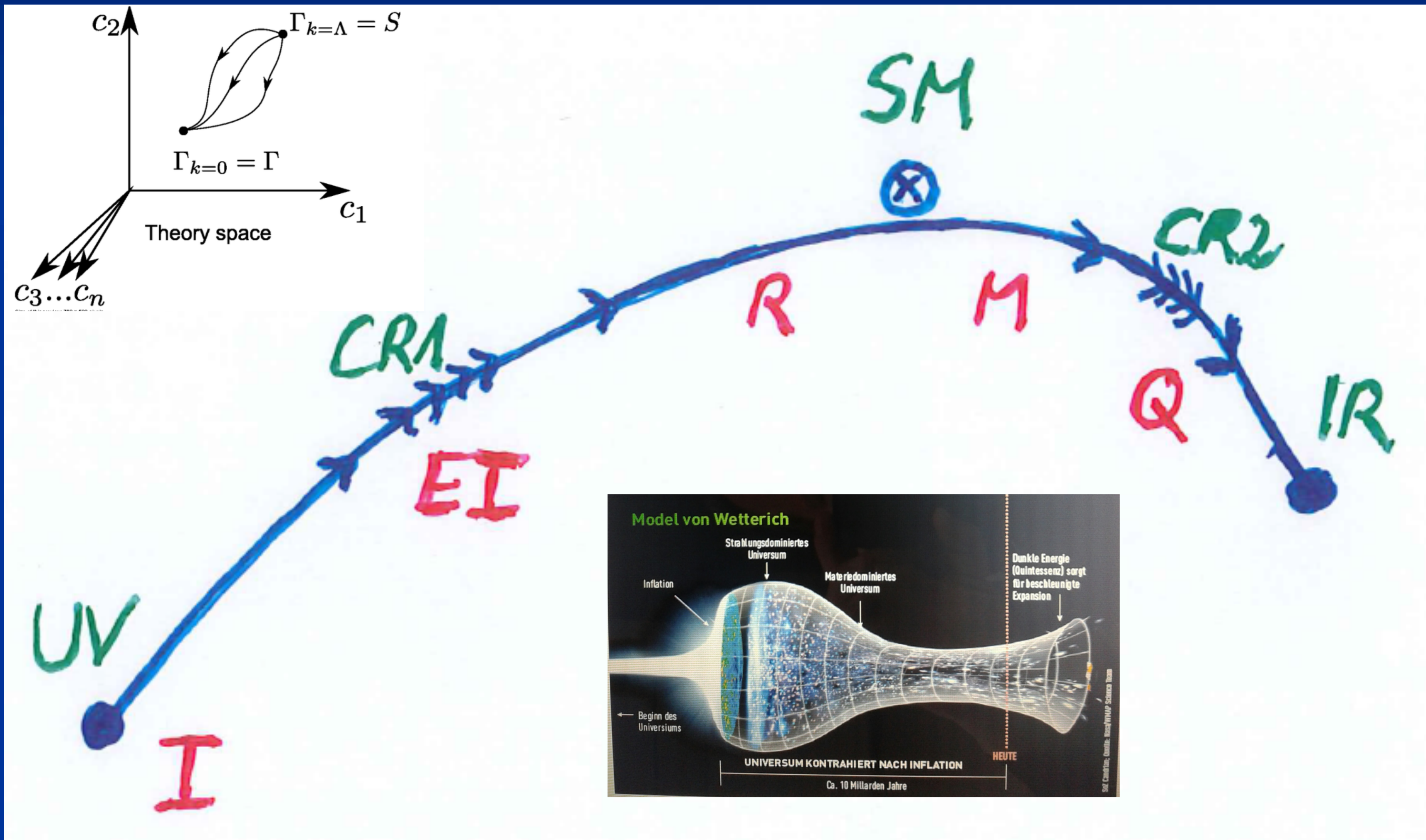
- counting : discrete
- invariant under field transformations
- same in all frames

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 !

Crossover in quantum gravity and cosmology

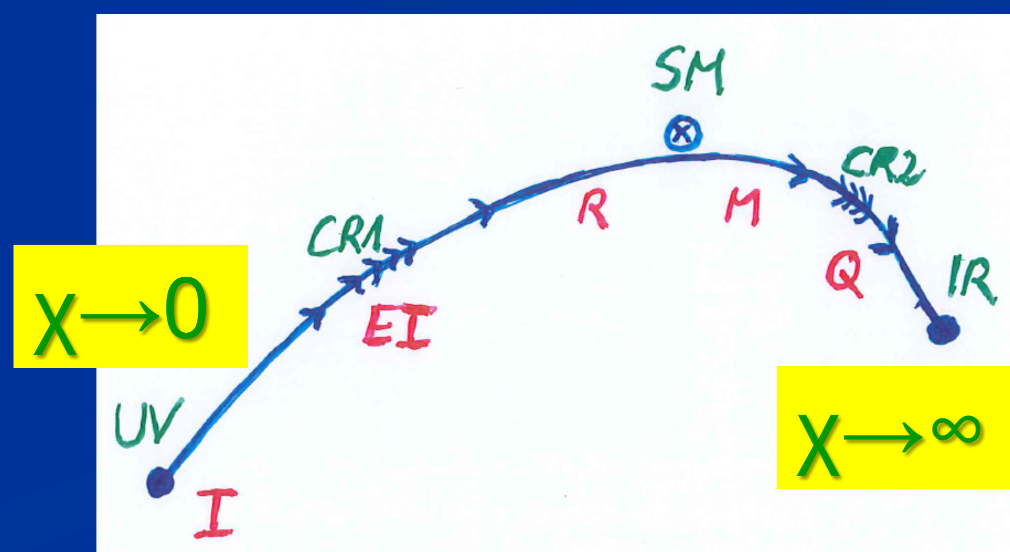


Cosmological solution : crossover from UV to IR fixed point

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

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

Cosmology makes crossover between fixed points by variation of χ .



Renormalization flow and cosmological evolution

- renormalization flow as function of μ

  is mapped by dimensionless functions to

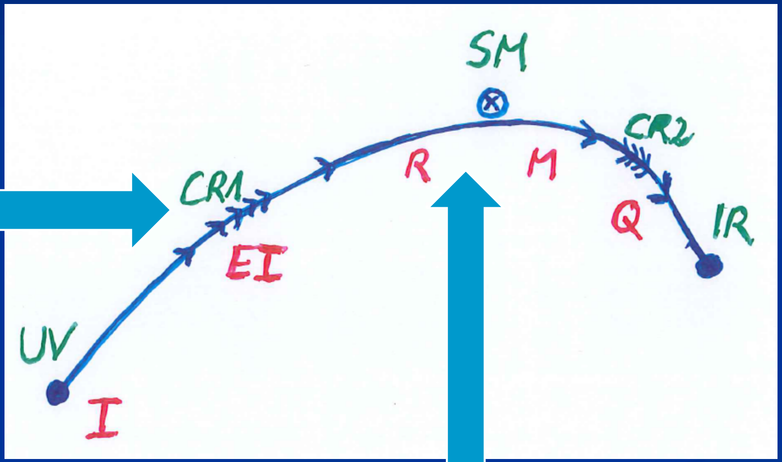
- field dependence of effective action on scalar field χ

  translates by solution of field equation to

- dependence of cosmology an time t or η

Scaling solution

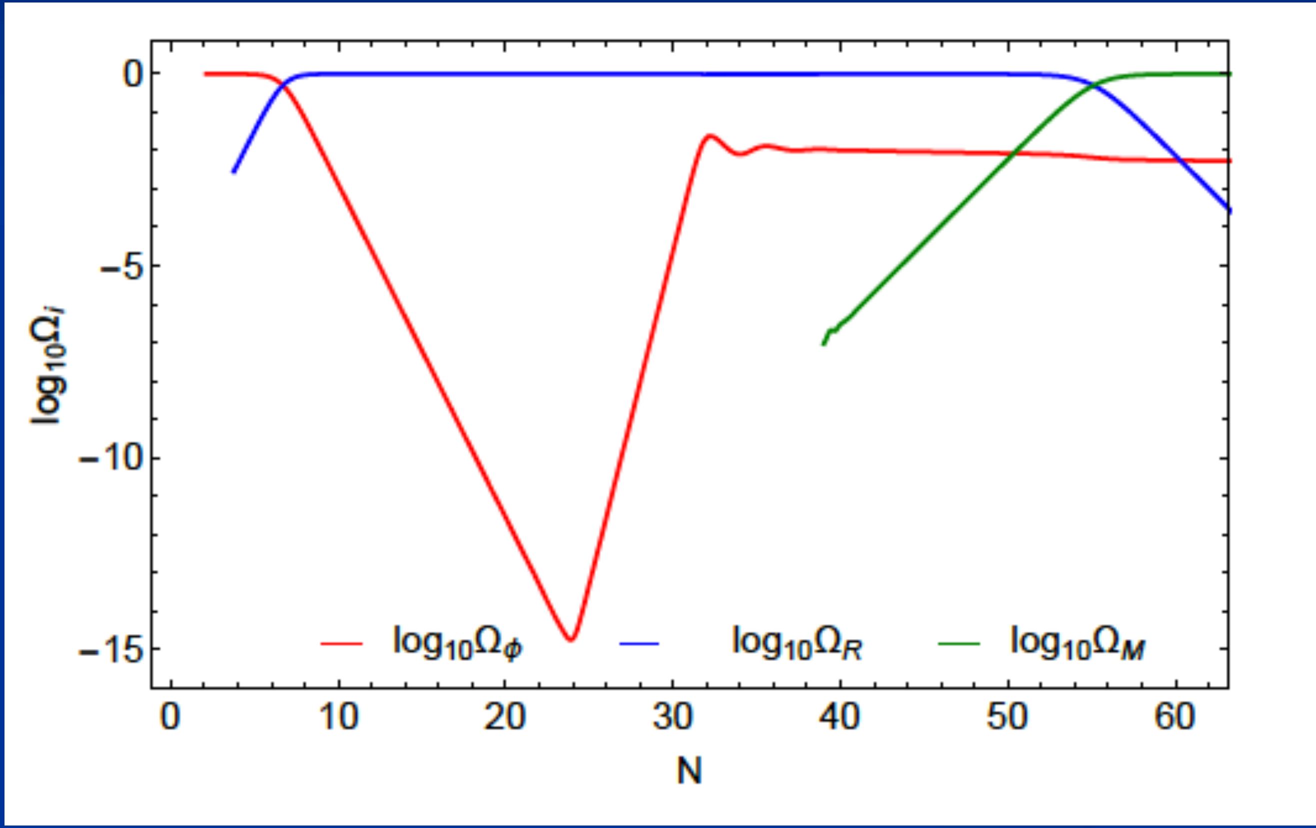
after end of inflation



scaling solution with
few percent
of Early Dark Energy

Dark Energy decreases similar to radiation and matter

Evolution of dark energy fraction



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