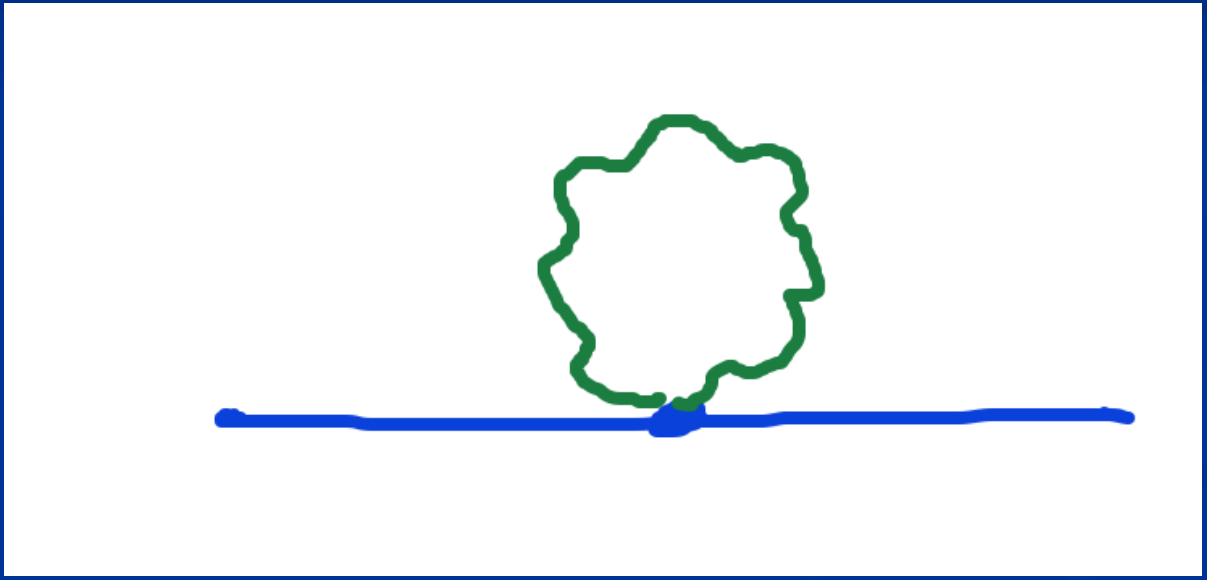
Quantum gravity predictions for particle physics and cosmology

quantum gravity

Graviton fluctuations matter



Quantum gravity needs method to take them into account

Fluctuations of metric, vierbein

- Near and beyond Planck scale
- Typically includes other (geometrical) fields

Completely new structure ?

around the Planck scale ?

Should not leave substantial trace in primordial cosmic fluctuations (isotropy,…)

Quantum gravity

- Gravity is field theory. Similar to electrodynamics. Metric field.
- Gravity is gauge theory. Similar to QED or QCD. Gauge symmetry: general coordinate transformations (diffeomorphisms)
- Quantum gravity: include metric fluctuations in functional integral

Quantum gravity

- Quantum gravity is similar to other quantum field theories
- Difference: metric is tensor, gauge bosons are vectors (vierbein, spin connection : vectors)
- Difference: Quantum (Einstein-) gravity is not perturbatively renormalizable
- no small dimensionless coupling constant, effective coupling q^2/M^2

Quantum gravity

Quantum gravity is

non-perturbatively renormalizable

Asymptotic safety : non-perturbative renormalizabilty

Weinberg, Reuter, …

Use functional renormalization !

Renormalizability

Theory can be extrapolated to infinitely small distances or infinitely large energies.

Flowing couplings

Couplings change with renormalization scale k due to (quantum) fluctuations.

Renormalization scale k : Only fluctuations with momenta larger k are included.

Flow of k to zero : all fluctuations included, IR-limit
Flow of k to infinity : UV-limit

k-dependence can differ from momentum dependence

Ultraviolet fixed point

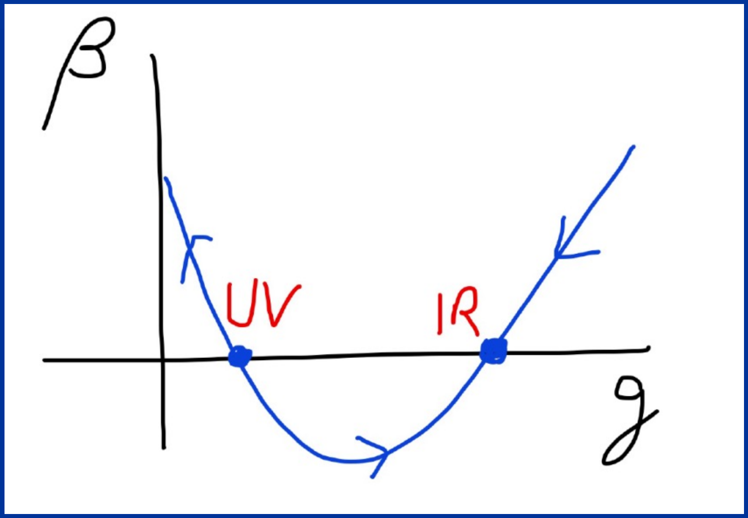
- Flow of dimensionless couplings stops as k increases towards infinity

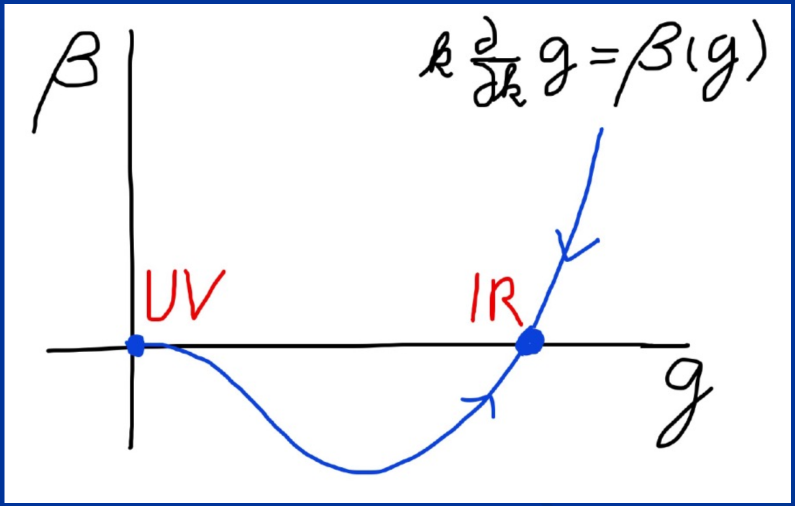
- Renormalizable theories have ultraviolet fixed point in the scale dependence of couplings
  (renormalization flow)

- Theory can be extrapolated to arbitrarily short distances

- Completeness

Asymptotic safety   Asymptotic freedom



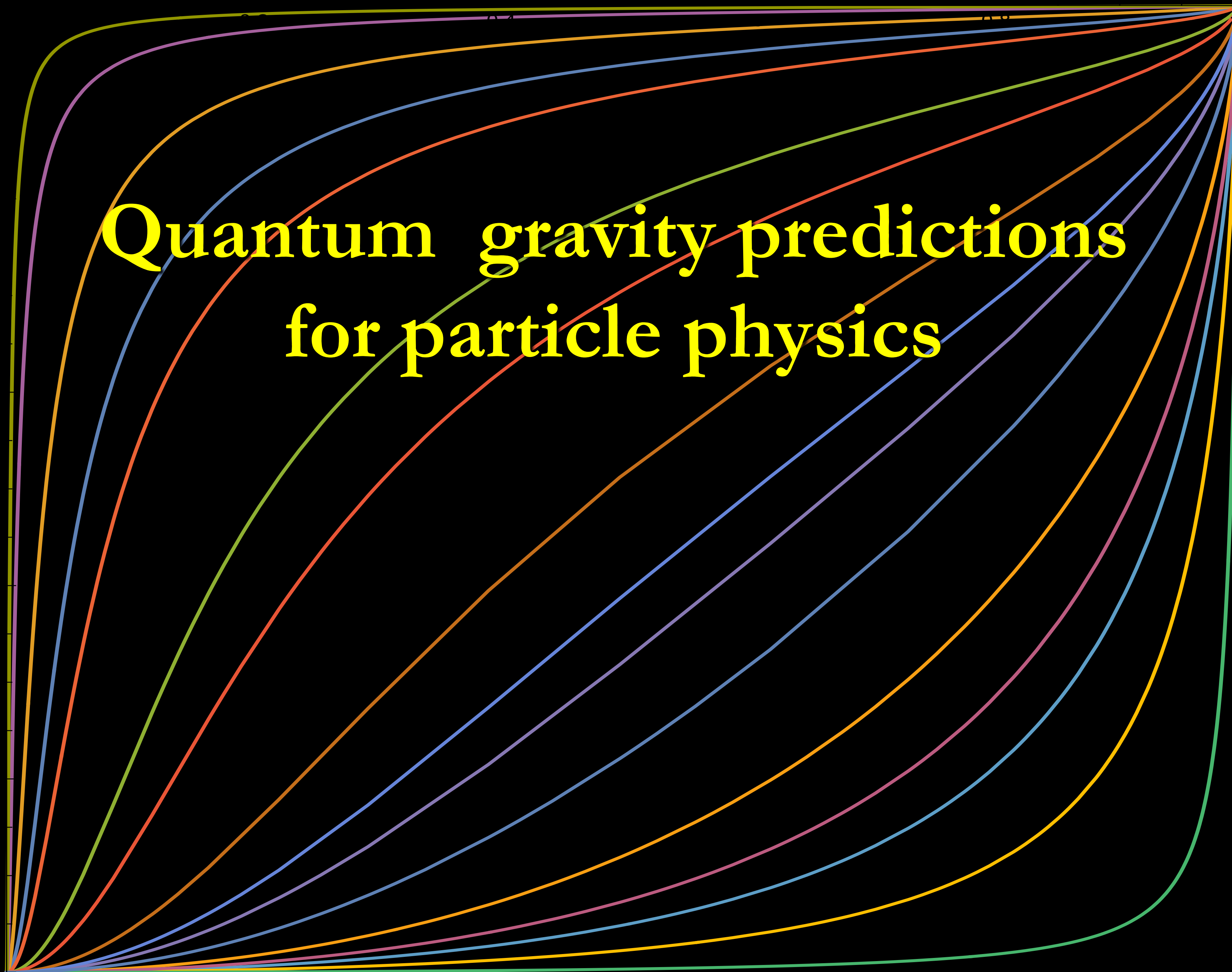


Asymptotically safe gravity

Ultraviolet fixed point exists for

quantum field theory for metric (or vierbein).

Quantum gravity predictions for particle physics



Prediction of mass of Higgs boson

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

Why can quantum gravity make predictions for particle physics ?

Quartic scalar coupling

prediction of mass of Higgs boson

=

prediction of value of quartic scalar coupling λ

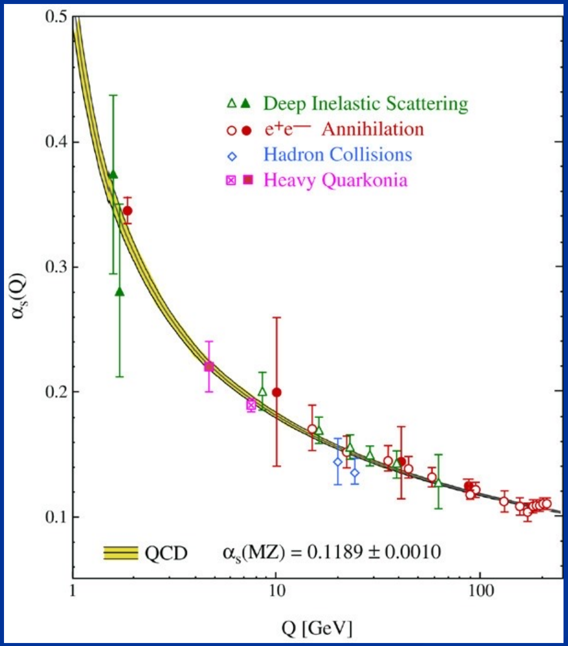
at Fermi scale

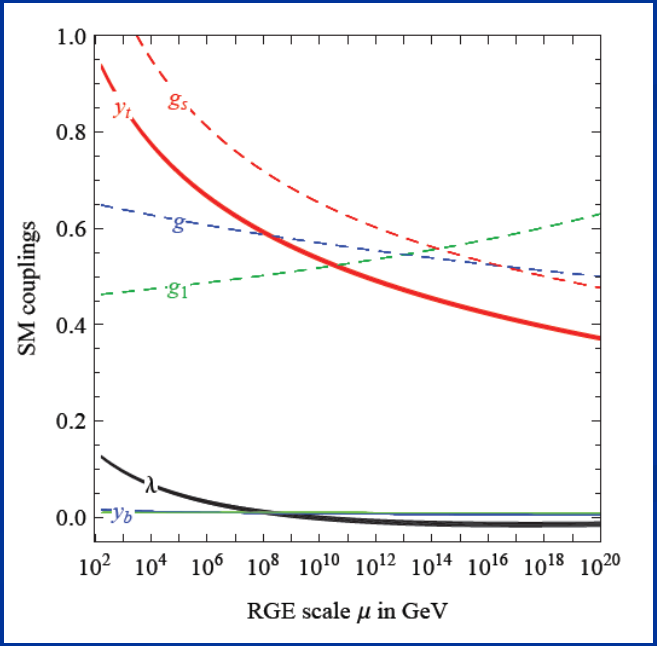
$$m^2 = 2\lambda\varphi_0^2$$

Quantum fluctuations induce running couplings

- running quartic scalar coupling, gauge couplings and Yukawa couplings

Bethke

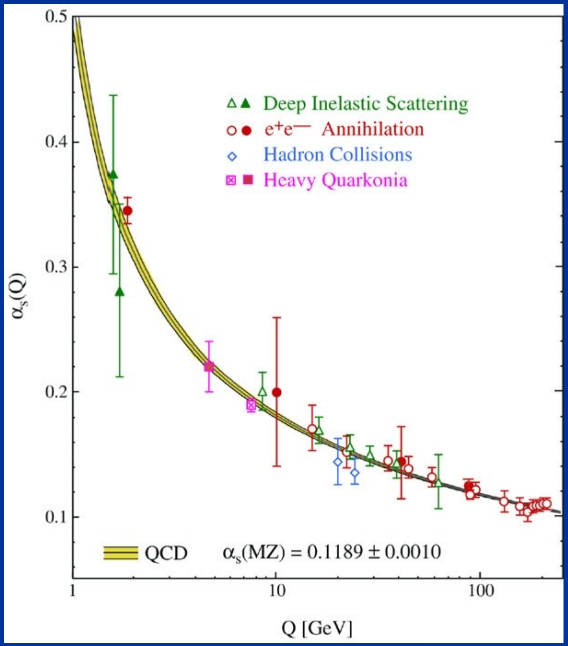


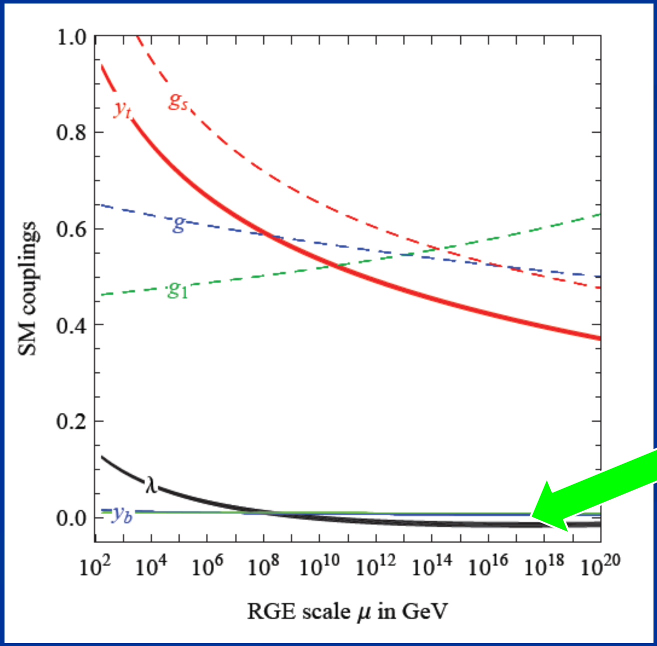


Degrassi et al

Quantum fluctuations induce running couplings

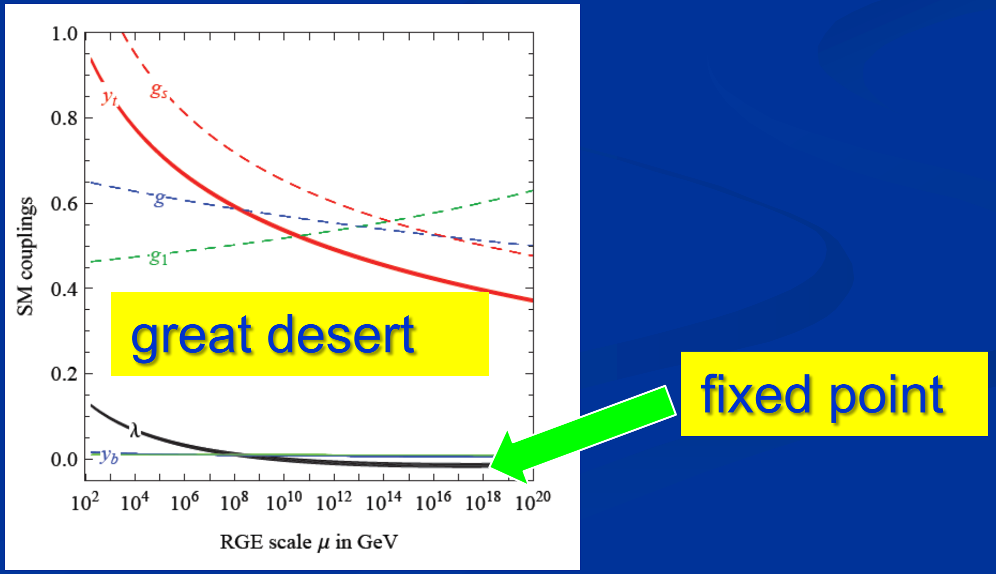
- connect Planck scale and Fermi scale

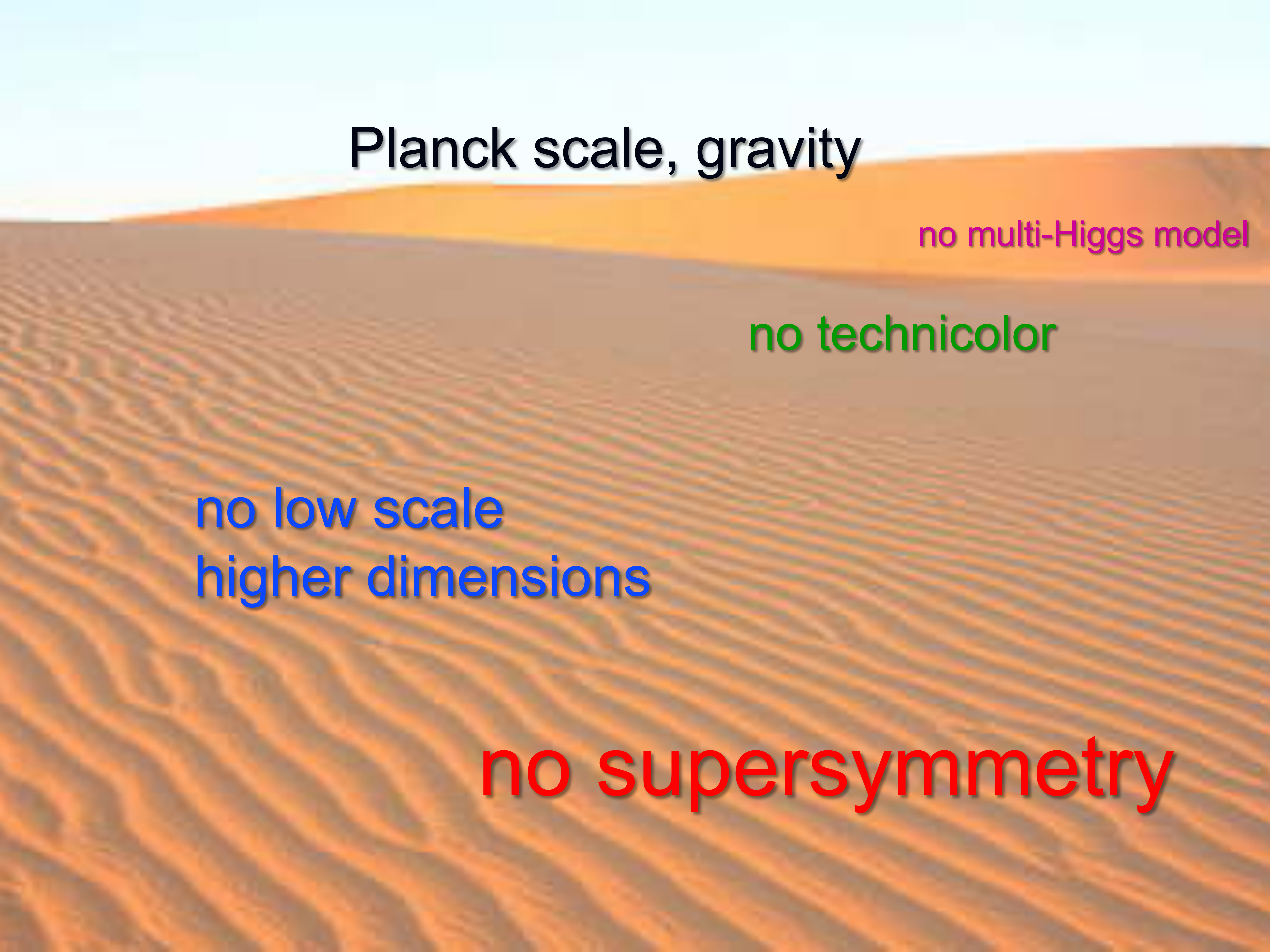




key points

- great desert
  (solution of hierarchy problem at high scale)
- high scale fixed point
- vanishing scalar coupling at fixed point




Planck scale, gravity
no multi-Higgs model
no technicolor
no low scale
higher dimensions
no supersymmetry

Oasis in the desert ?

- Possible
- Mass generation for neutrinos
- Dark matter particles
- Axions
- Beyond standard model physics

Should not strongly affect the running of the ratio between quartic scalar coupling and top Yukawa coupling

Near Planck mass gravity is not weak !

Predictive power !

Graviton fluctuations erase quartic scalar coupling

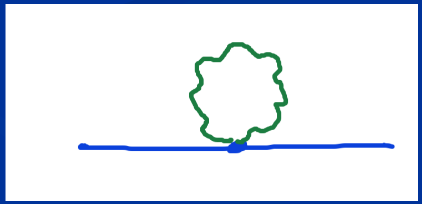
Renormalization scale k : Only fluctuations with momenta larger k are included.

Consider first only fluctuations of metric or graviton :

$$k \frac{\partial \lambda}{\partial k} = A \lambda$$

gravity induced anomalous dimension

A > 0



for constant A :

$$\lambda(k) = \lambda(\mu)\left(\frac{k}{\mu}\right)^A$$

$$k \to 0 \quad \Rightarrow \quad \lambda \to 0$$

Fixed point

$$k \frac{\partial \lambda}{\partial k} = A \lambda$$

$$\lambda(k) = \lambda(\mu) \left(\frac{k}{\mu} \right)^A$$

The quartic scalar coupling λ has a
fixed point at λ=0

For A>0 it flows towards the fixed point as k is lowered:
irrelevant coupling Narain, Percacci

For a UV – complete theory irrelevant couplings are predicted to assume the fixed point value

Gravitational contribution to running quartic coupling

$$\partial_t \lambda = A_\lambda \lambda$$

$$A = \frac{1}{48\pi^2 \tilde{M}_{\rm p}^2}\left[\frac{20}{(1-v_0)^2} + \frac{1}{(1-v_0/4)^2}\right]$$

$$\partial_t = k\partial_k$$

running Planck mass :

$$M_{\rm p}^2(k) = M^2 + \tilde{M}_{\rm p*}^2 k^2$$

dimensionless
squared Planck mass

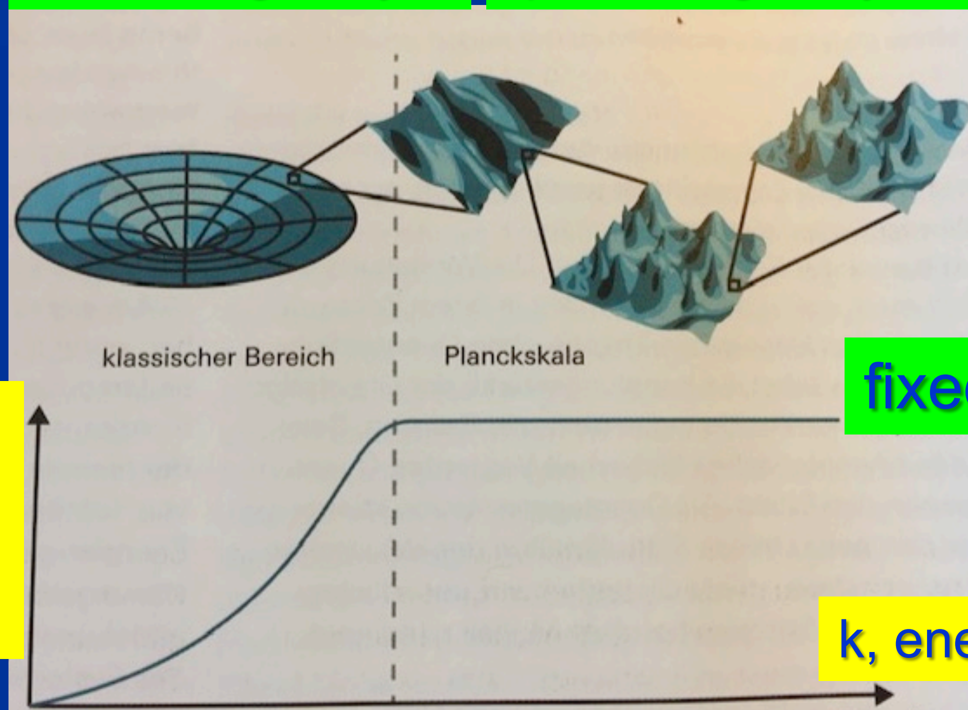
$$\tilde{M}_{\rm p}^2 = \frac{M_{\rm p}^2}{k^2}$$

Strength of gravity

$$g_{grav} = \frac{k^2}{2M^2(k)}$$

classical gravity

quantum gravity



fixed point

strength of gravity g_{grav}

k, energy scale

inverse distance

A. Eichhorn, CW, Spektrum der Wissenschaft

Flowing Planck mass

- Renormalization scale k : Only fluctuations with momenta larger k are included

Flowing Planck mass $M^2(k)$

$$\partial_t M^2 = 4ck^2$$

$$\partial_t = k\partial_k$$

M. Reuter

matter contribution

$$c_M = \frac{\mathcal{N}_M}{192\pi^2}.$$

$$\mathcal{N}_M = 4\, N_V - N_S - N_F$$

with graviton contribution

$$c_M = \frac{1}{192\pi^2}\left(\mathcal{N}_M + \frac{43}{6} + \frac{75(1-\eta_g/6)}{2(1-v)}\right)$$

Flowing Planck mass

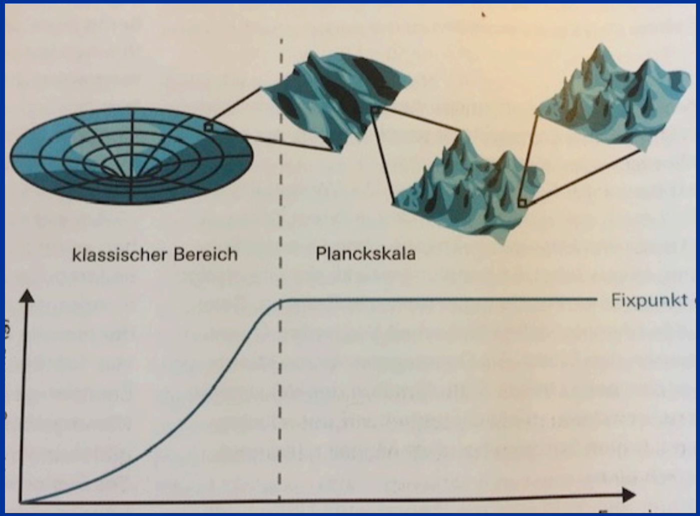
Flowing
Planck mass $M^2(k)$

$$\partial_t M^2 = 4ck^2$$

$$\partial_t = k\partial_k$$

solution :

$$M^2(k) = M^2 + 2c_M k^2$$



Enhanced predictivity for UV – fixed point

- Free parameters of a theory correspond to relevant parameters for small deviations from fixed point.
- If the number of relevant parameters at the UV-fixed point is smaller than the number of free parameters (renormalizable couplings) in the standard model:
- Relations between standard model parameters become predictable !

Asymptotically safe standard model

- Standard model seems compatible with asymptotic safety of gravity
- There exists a suitable UV-fixed point for which all observed couplings can be realized
- Non – trivial statement

Dou, Percacci, Daum, Reuter, Eichhorn, Dona, Perrini, Held, Pawlowski, Reichert, Yamada, Oda, Saueressig, Hamada, Lumma, Pauly, Pastor-Gutierrez   and many more

FRG landscape

- Beyond Standard Model physics
- similar predictions or restrictions for particles beyond standard model
- not everything goes !

Eichhorn, Yamada, Oda, Reichert, Pauly, De Brito, Lino dos Santos, Kowalska, Sessolo, Hamada, Pereira, Miqueleto…

Conclusion (1)

- Quantum gravity is a renormalizable quantum field theory, realized by UV - fixed point of running couplings or flowing effective action

- Quantum gravity is predictive :

  Mass of the Higgs boson

  Constraints on mass of t - quark (Eichhorn, Held)

  Scalar potential in GUT model

  Restrictions for Beyond-SM Particles

Quantum gravity predictions for cosmology

Inflation

minimal setting for standard model + gravity :

- coefficient of R^2 term α is relevant parameter
- can be chosen freely
- large α : Starobinski inflation

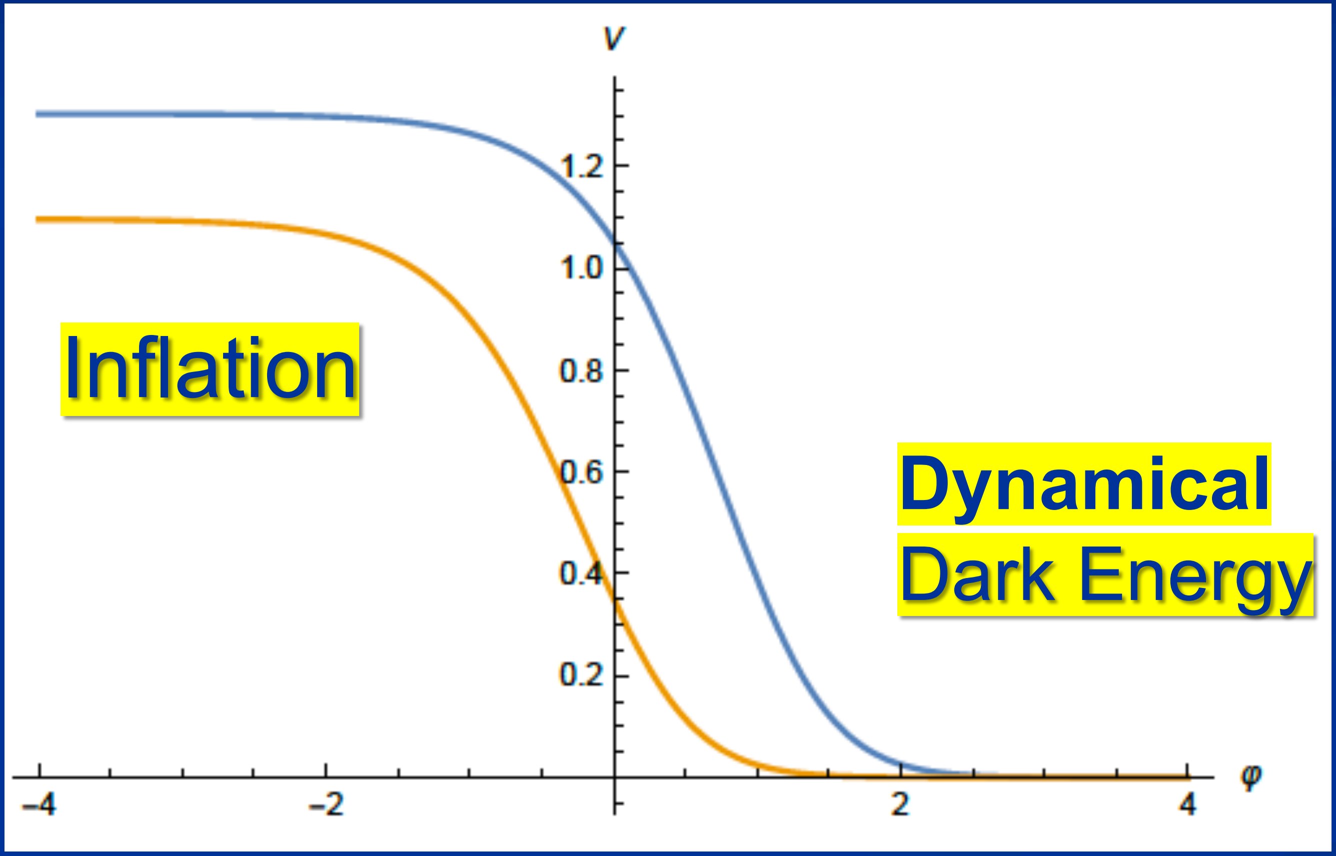
Gubitosi, Ooijer, Ripken, Saueressig,

Platania, Vacca, Laporte, Perreira, Wang, Knorr, Bonanno, Falls,…

Inflation and dynamical dark energy

Quantum gravity with singlet scalar field

Quintessential inflation



Spokoiny, Peebles, Vilenkin, Peloso, Rosati, Dimopoulos, Valle, Giovannini,
Brax, Martin, Hossain, Myrzakulov, Sami, Saridakis, de Haro, Salo, Bettoni, Rubio…

Scaling solutions

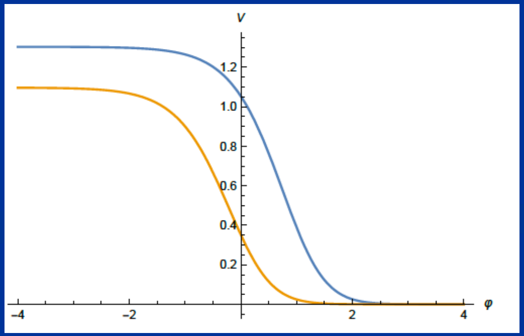
- At fixed point: all (infinitely many) dimensionless couplings take fixed values
- Whole scalar potential is fixed, for arbitrary values of scalar field
- Functional flow equations are needed

Scaling solutions are restrictive

- Scaling solutions are particular solutions of non-linear differential equations
- In presence of gravitational fluctuations: scalar effective potential no longer approximated by polynomial

Scaling solutions and cosmology

- Cosmology involves scalar potentials over large range of field values



- Inflaton potential
- Higgs potential for Higgs inflation
- Cosmon potential for dynamical dark energy or quintessence

Quantum gravity :

these potentials are not arbitrary

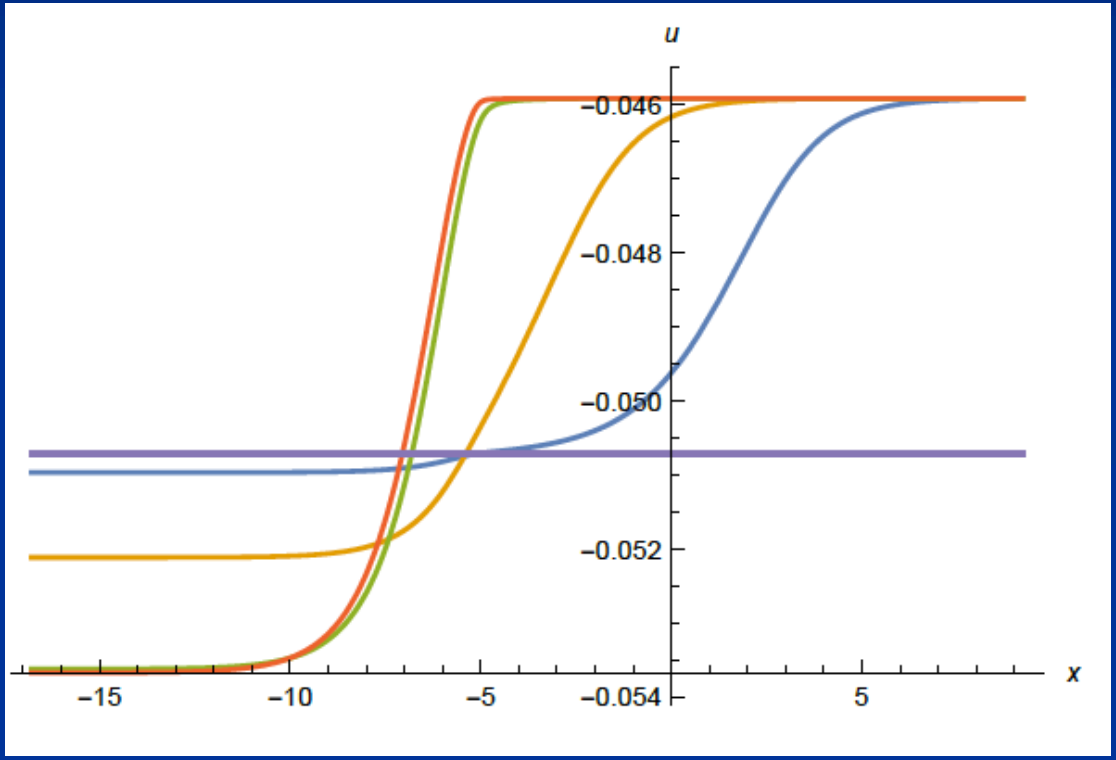
Dilaton quantum gravity

quantum gravity coupled to a scalar field

Henz, Pawlowski, Rodigast, Yamada, Reichert, Eichhorn, Pauly, Laporte, Pereira, Saueressig, Wang, Knorr, …

for low order polynomial expansion of potential : Percacci, Narain, …

Scaling potential in standard model



u : dimensionless scalar potential

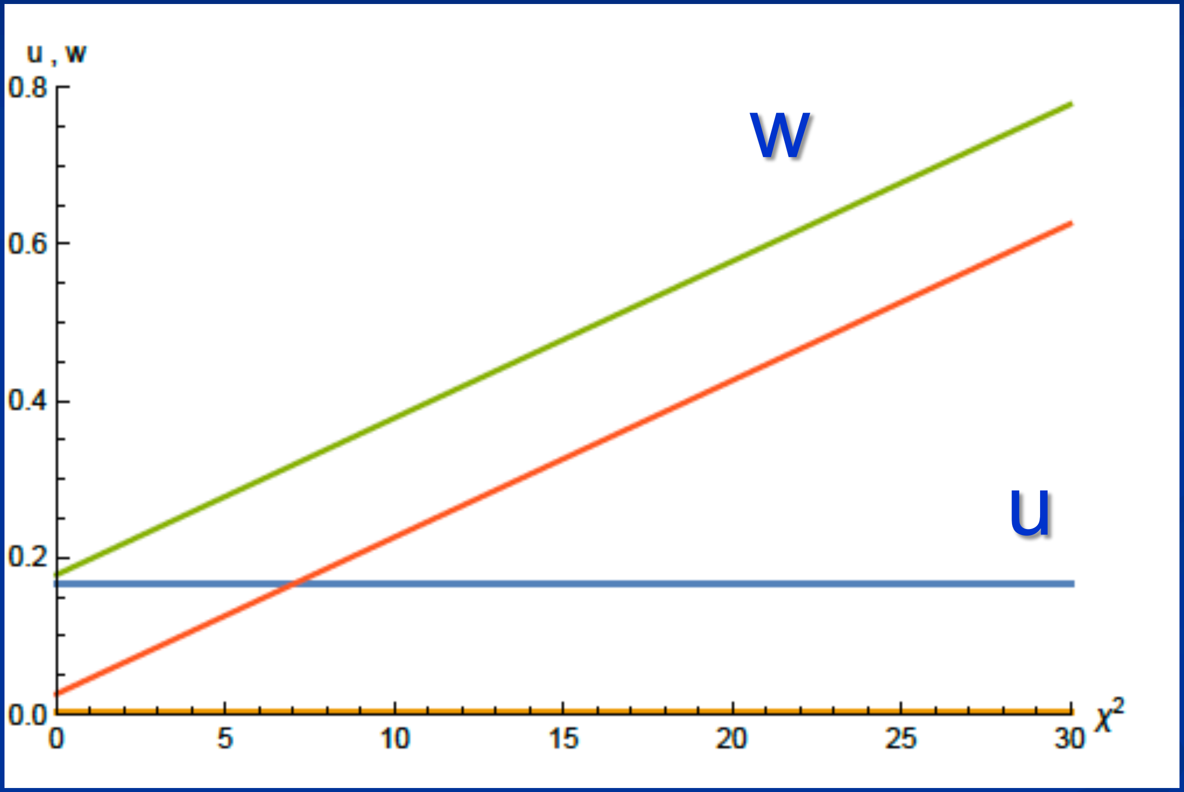
$u = U/k^4$

x : logarithm of scalar field value

Generic form of scaling potential

- Interpolates between two plateaus
- Scalar potential =
  field dependent "cosmological constant"
- Effectively massless particles contribute to flow
- Different numbers of massless particles in different regions of field space
- Gravity induced anomalous dimension A describes approach to scaling solution

Scaling solution : flat potential



squared scalar field value χ^2

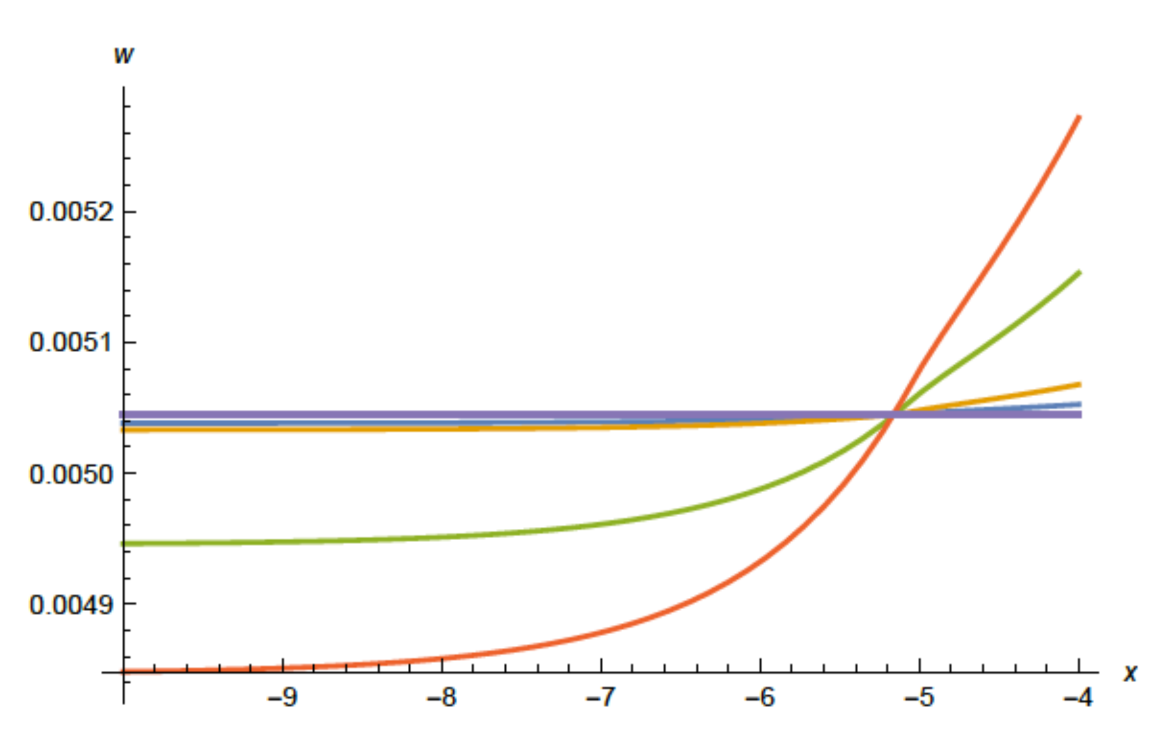
Derivative expansion of effective action

$$\Gamma = \int_x \sqrt{g}\Big\{ -\frac{1}{2}F(\chi)R + \frac{1}{2}K(\chi)\partial^\mu\chi\partial_\mu\chi + U(\chi)\Big\}$$

variable gravity

F : field dependent squared Planck mass

Coefficient of curvature scalar in standard model



x : logarithm of scalar field value

w : dimensionless field dependent squared Planck mass

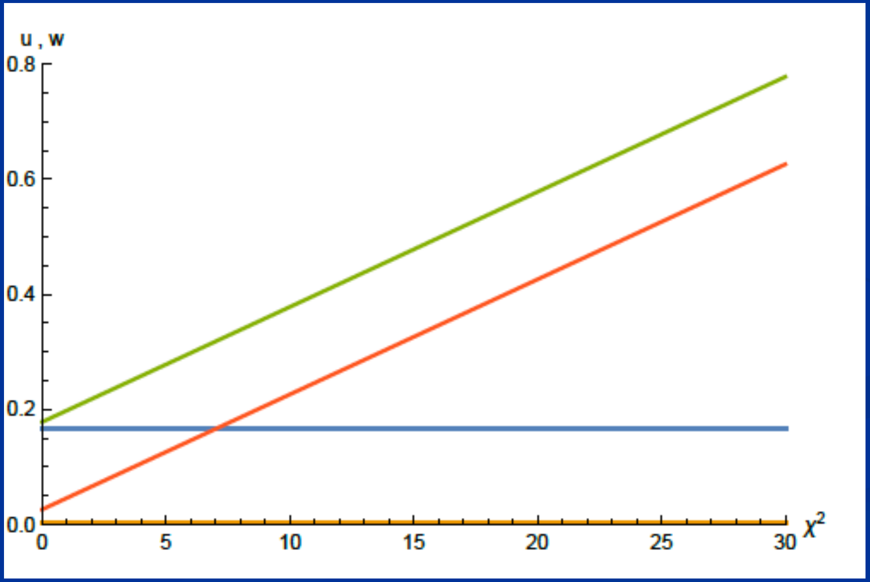
$w = 2\ F/\ k^2$

non-minimal coupling of scalar field to gravity: $\xi\chi^2 R$

Approximate scaling solution

- flat potential: u constant
- non-minimal scalar- gravity coupling:

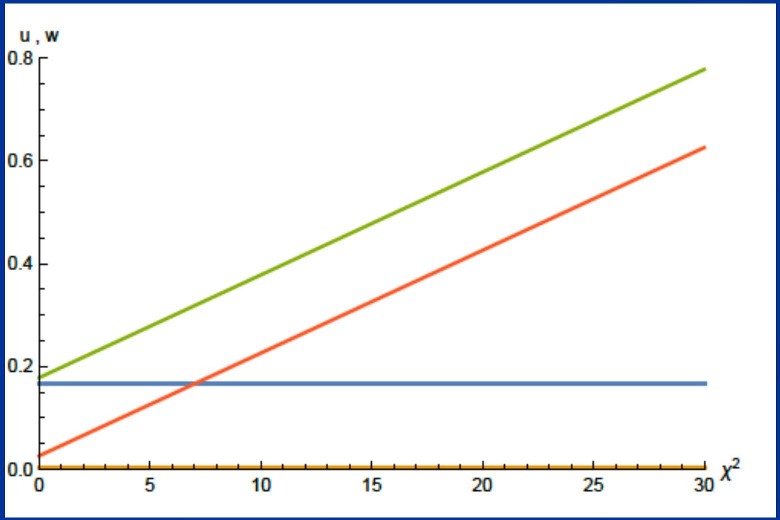
  for large scalar field w increases proportional χ^2



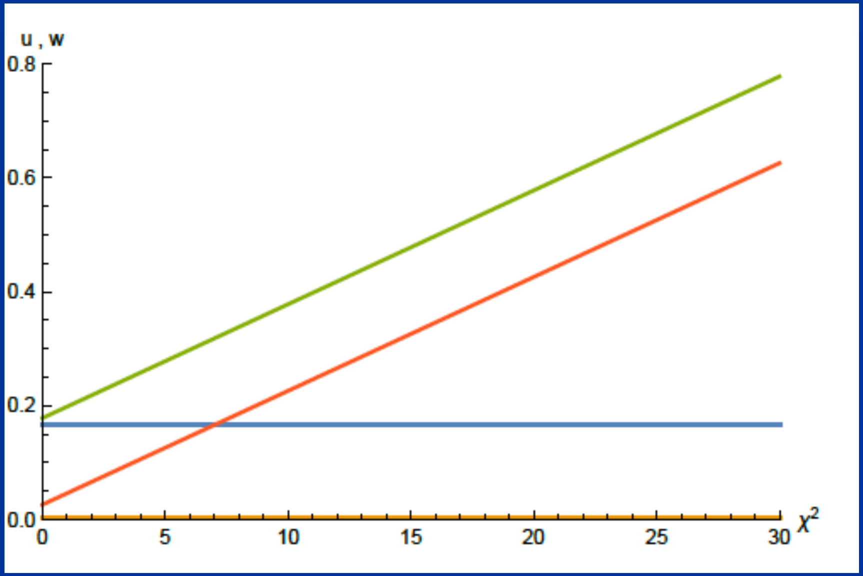
looks natural

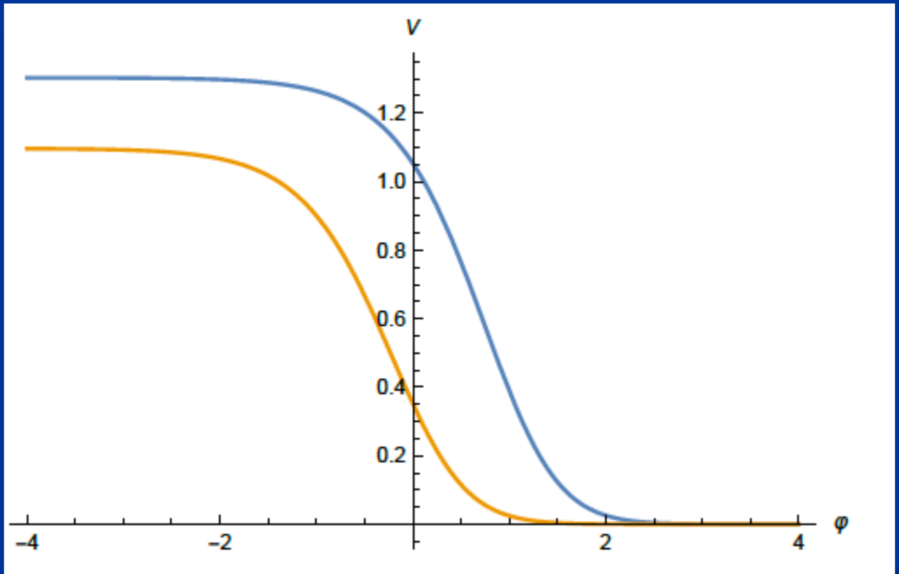
no small parameter

no tuning



Scaling solution in Einstein frame





Weyl transformation for variable gravity

$$g_{\mu\nu} = (M^2/F)g'_{\mu\nu}$$

$$\varphi = 4M\ln(\chi/k)$$

$$\Gamma = \int_x \sqrt{g}\Big\{-\frac{1}{2}F(\chi)R + \frac{1}{2}K(\chi)\partial^\mu\chi\partial_\mu\chi + U(\chi)\Big\}$$

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

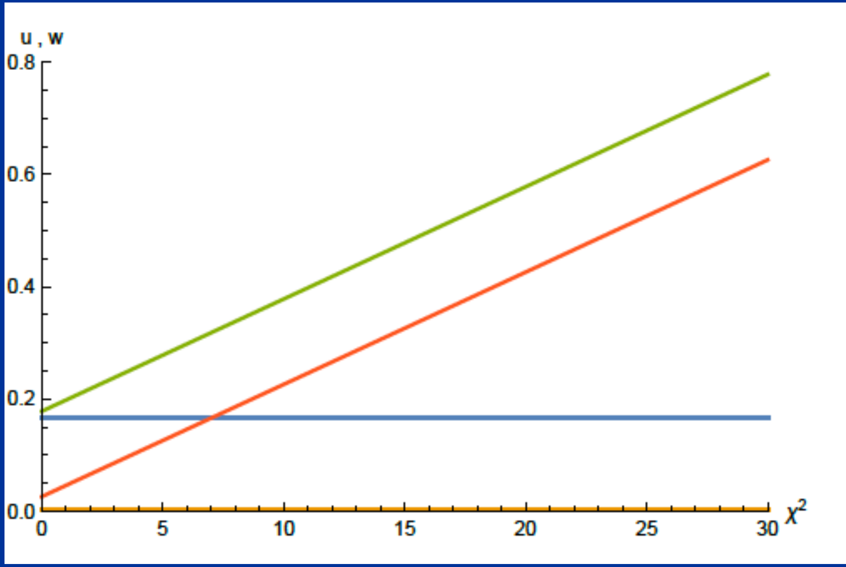
$$V(\varphi) = \frac{UM^4}{F^2}$$

$$Z(\varphi) = \frac{1}{16}\Big\{\frac{\chi^2 K}{F} + \frac{3}{2}\Big(\frac{\partial\ln F}{\partial\ln\chi}\Big)^2\Big\}$$

Scaling solution

$$U = u_0 k^4$$

$$F = 2 w_0 k^2 + \xi \chi^2$$



For low energy

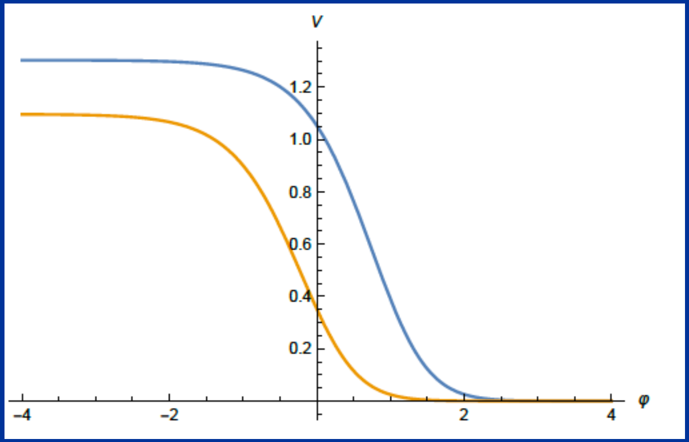
standard model :

$$u_\infty = \frac{7}{256\pi^2}$$

Asymptotic solution of cosmological constant problem

$$V = \frac{u_0 M^4}{\left(2w_0 + \xi \exp\left(\frac{\varphi}{2M}\right)\right)^2}$$

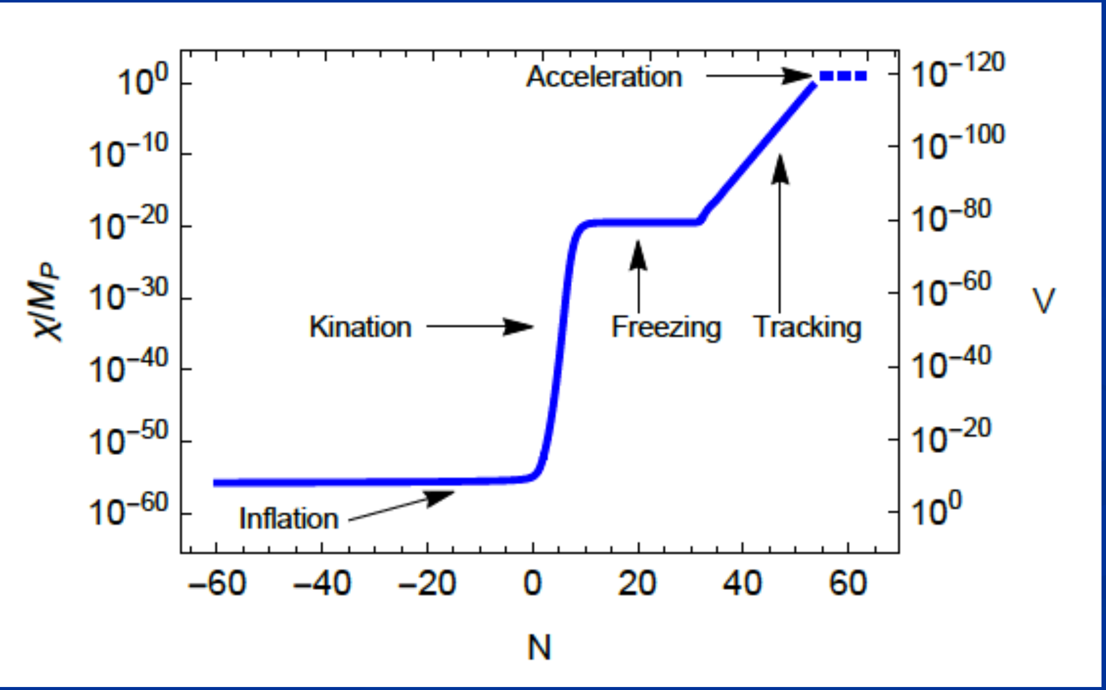
$$= \frac{u_0 M^4}{\xi^2}\left[1 + \frac{2w_0}{\xi}\exp\left(-\frac{\varphi}{2M}\right)\right]^{-2}\exp\left(-\frac{\varphi}{M}\right)$$



no tiny parameter !

Cosmological solution

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



J.Rubio,…

Predictions for primordial cosmic fluctuations

- Depend on form of kinetial K

$$\Gamma = \int_x \sqrt{g}\Big\{ -\frac{1}{2}F(\chi)R + \frac{1}{2}K(\chi)\partial^\mu\chi\partial_\mu\chi + U(\chi)\Big\}$$

- so far form of K assumed assumed :

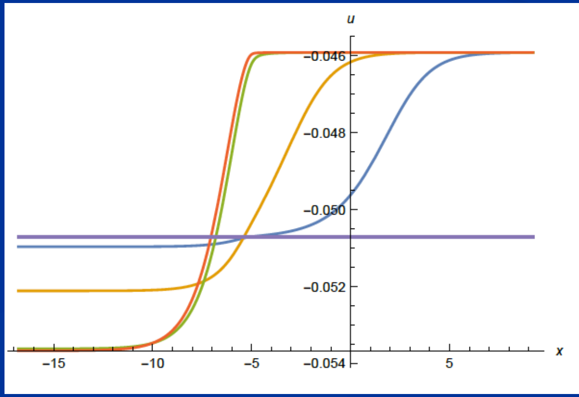
  realistic cosmology possible for suitable K
- K needs to be computed!

Alternatives for inflation in asymptotically safe quantum gravity

- use flow away from the scaling solution
- relevant parameters
- coefficient of R^2 term α
- large α : Starobinski inflation

Saueressig, Platania, Vacca, Laporte, Perreira, Wang

- Higgs inflation?



Conclusion (2)

Fixed points of quantum gravity
and associated quantum scale symmetry
are crucial for understanding the
evolution of our Universe

Quantum gravity
and
the beginning of the Universe

Beginning of Universe

Zu Anfang war die Welt öd und leer und währte ewig.

In the beginning the Universe was empty and lasted since ever.

Beginning close to ultraviolet fixed point for vanishing scalar field

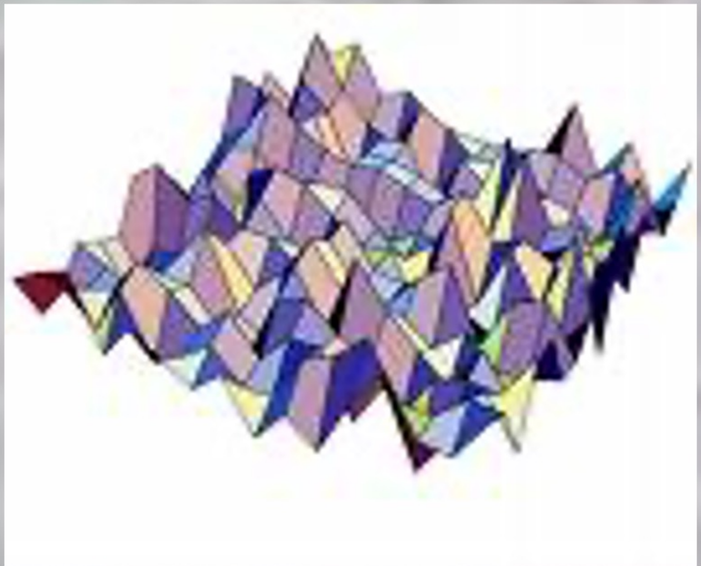
- all particles massless for $\chi = 0$
- fluctuations dominate
- metric field vanishes
- quantum scale symmetry

(equivalent primordial flat frame: initial flat Minkowski space)

Eternal light-vacuum

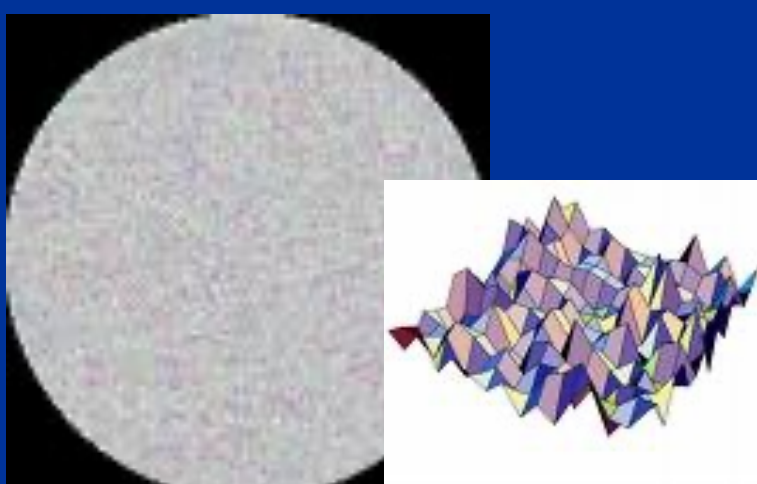
Everywhere almost nothing
only fields and their fluctuations

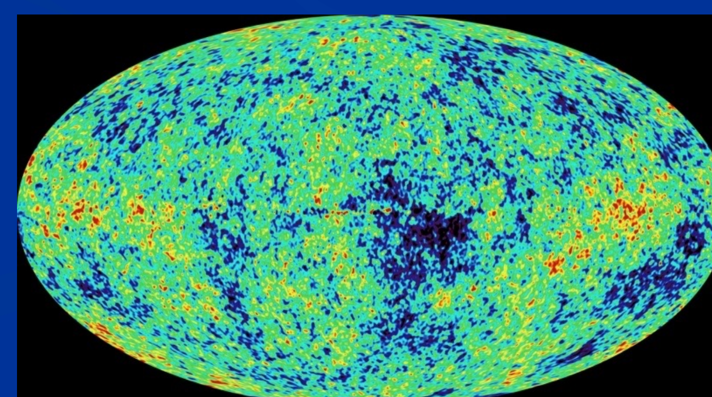
All particles move
with light velocity,
similar to photons



Eternal light-vacuum is unstable

- Slow increase of particle masses
- Only slow change of space-time geometry
- Creation of particles and entropy at crossover away from UV-fixed point
- Consequence for observation : primordial fluctuations become visible in cosmic background radiation
- We see fluctuations in a stage more than 1000 billion years ago.



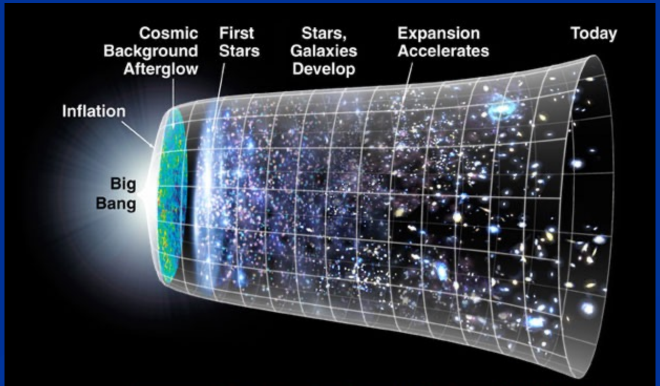


The great emptiness story

In the beginning was light-like emptiness.

The big bang story

- dramatic hot big bang
- started 13.7 billion years ago
- at the beginning extremely short period of cosmic inflation with almost exponential expansion of the Universe, duration around 10^{-40} seconds
- start with singularity : our whole observable Universe evolves from one point



Field relativity

- Both stories are equivalent
- related by field transformation of the metric

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

- different metrics related by Weyl transformation, which depends on scalar field (inflaton)

Field - singularity

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

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

end