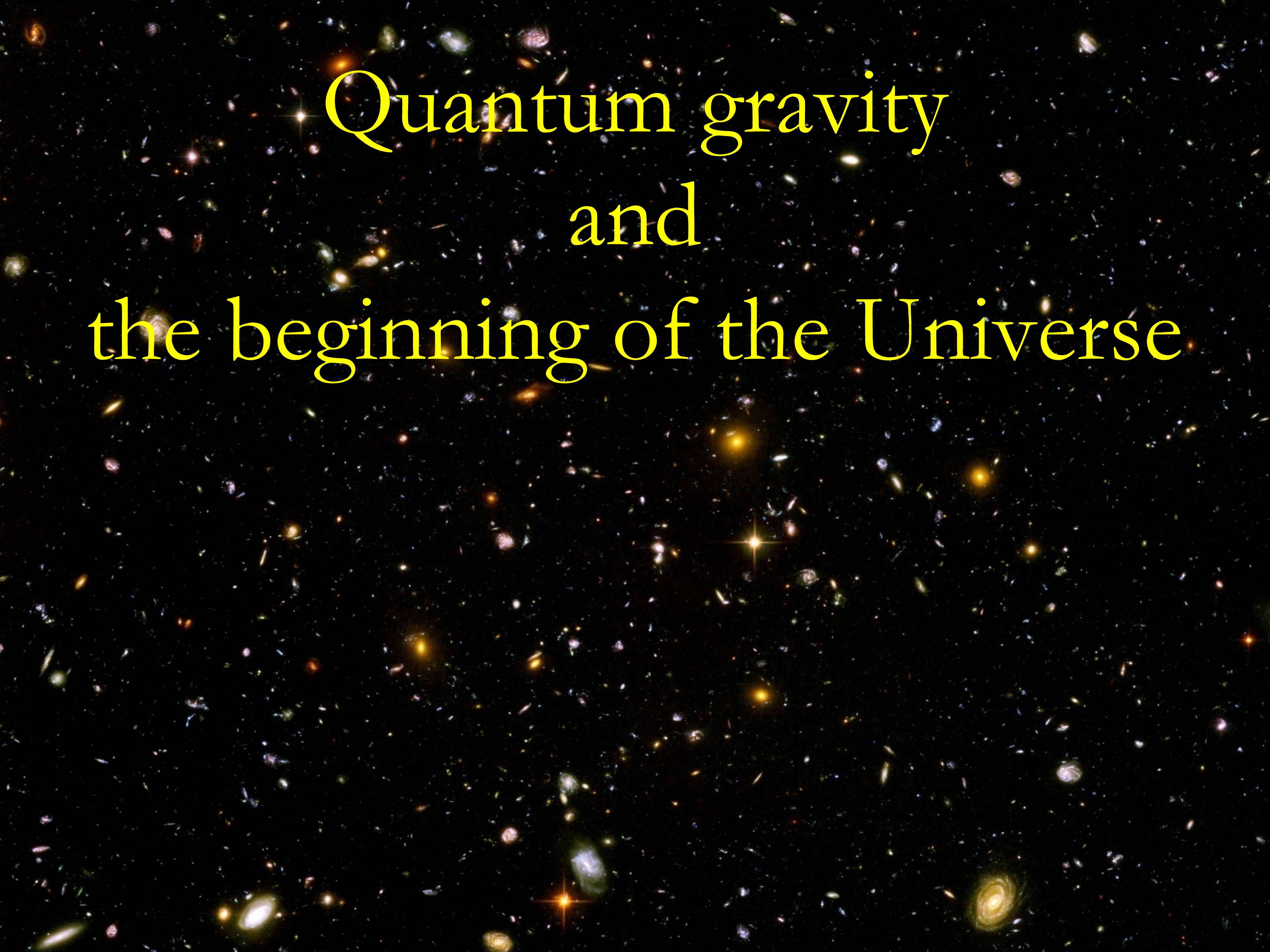
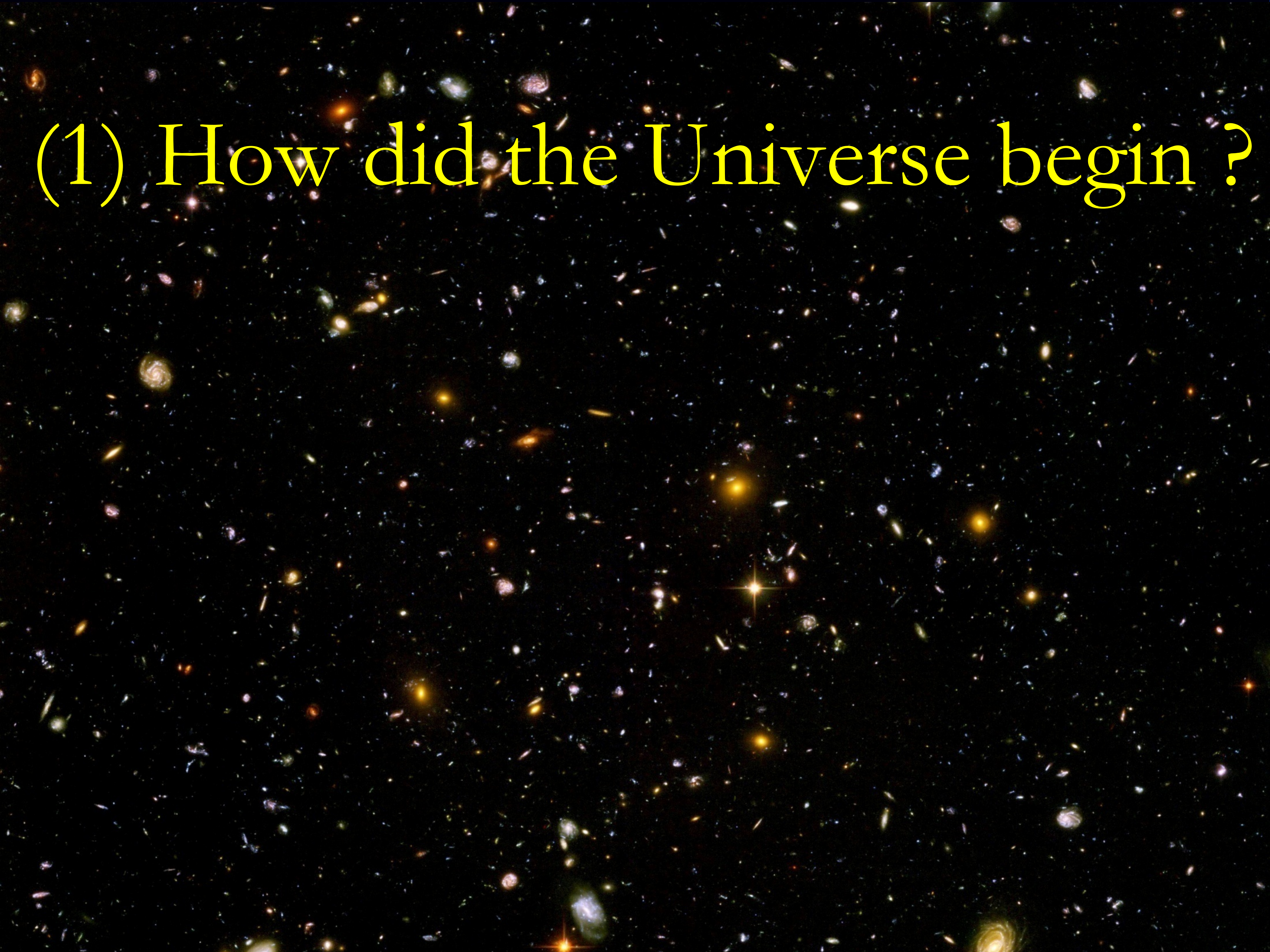
Quantum gravity and the beginning of the Universe



(1) How did the Universe begin ?



Beginning of Universe

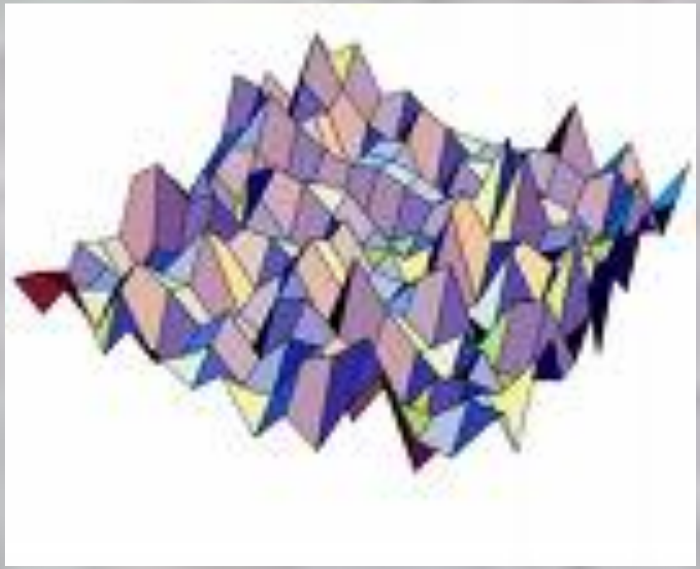
Zu Anfang war die Welt öd und leer und währte ewig.

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

Eternal light-vacuum

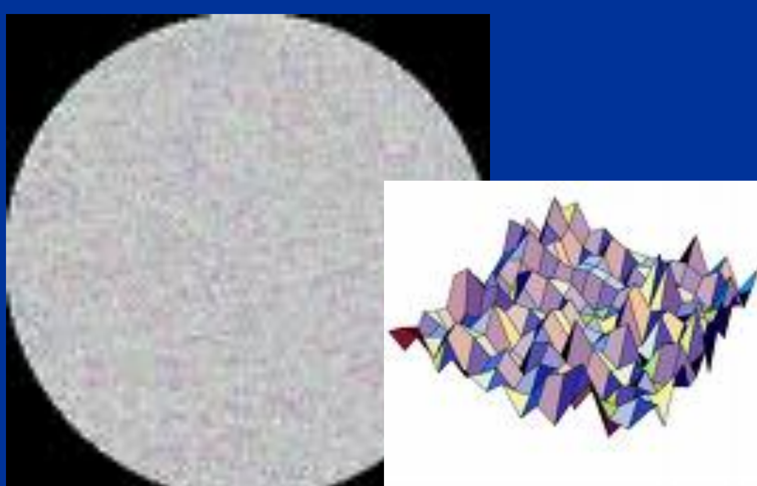
Everywhere almost nothing
only fields and their fluctuations

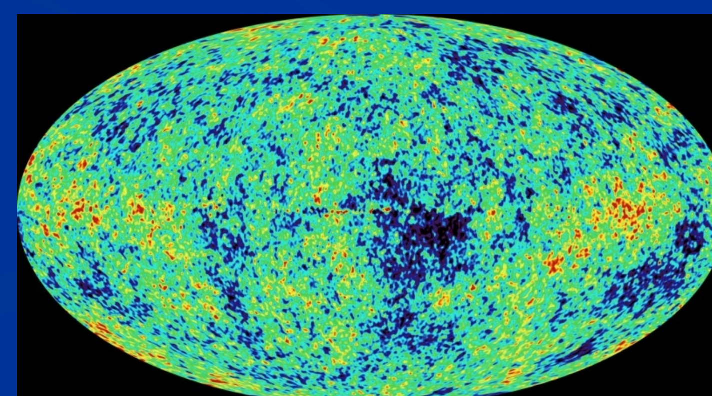
All particles move
with light velocity,
similar to photons



Eternal light-vacuum is unstable

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



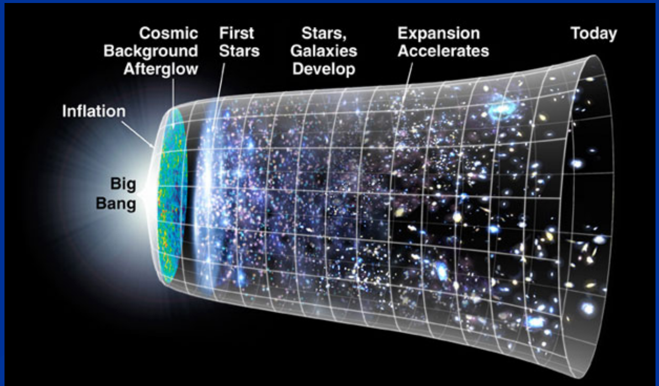


The great emptiness story

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

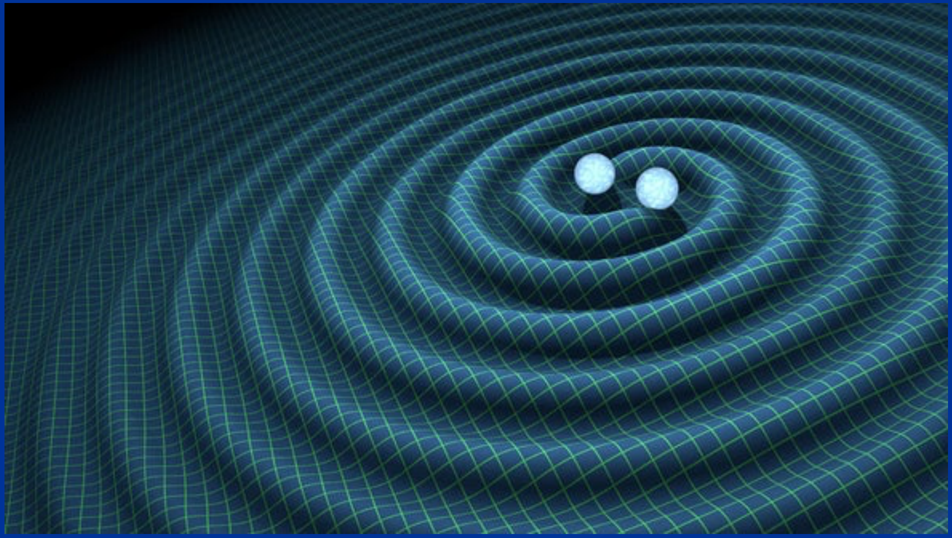
- Both stories are equivalent
- related by field transformation of the metric

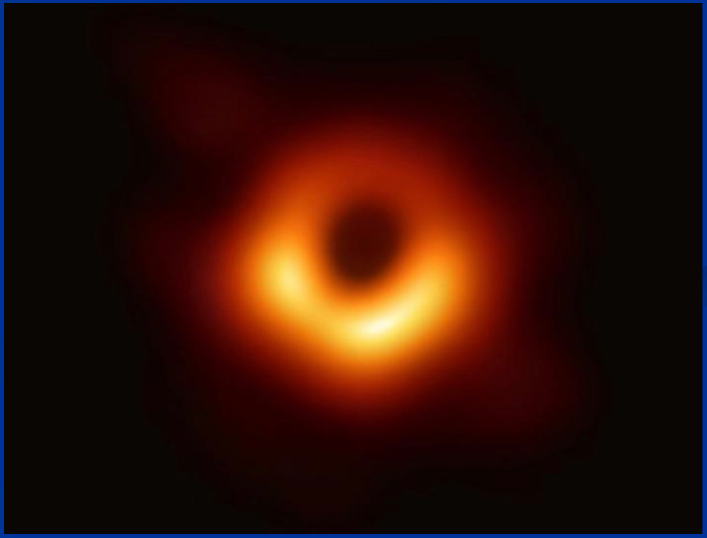
$$g'_{\mu\nu} = \frac{\chi^2}{M^2} g_{\mu\nu}$$

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

Metric $g_{\mu\nu}$

- Metric field **$g_{\mu\nu}$ (t , x)** is central ingredient for gravity
- similar to electric or magnetic fields
- generalizes gravitational field in Newtonian gravity





different possible choices for the metric field

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

Field relativity : different pictures of cosmology

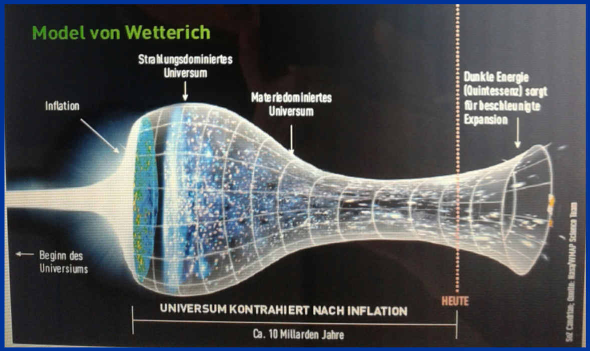
- same physical content can be described by different pictures
- related by field – redefinitions ,
- observables cannot depend on choice of fields
- different fields: different variables in differential equations
- metric is one of the fields

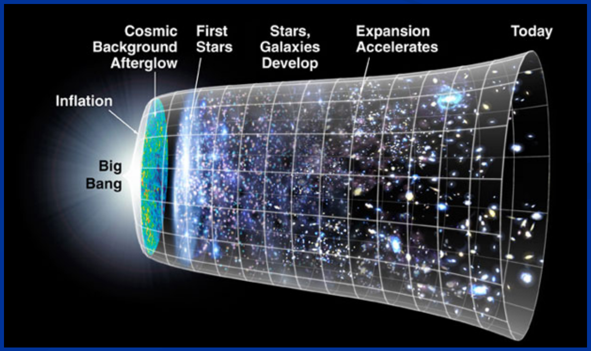
Field relativity

Weyl scaling :

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

changes geometry,
not a coordinate transformation





Expansion of the Universe

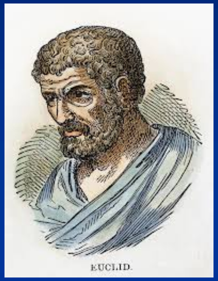
- What does expansion of space mean ?
- A field changes its value

that's all

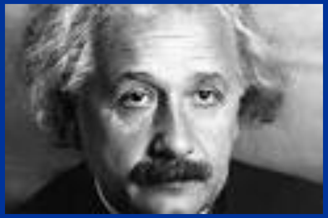
- Propagation of particles and photons depend on the value of the metric field

Relativity of geometry

- Euclid … Newton : space and time are absolute and observable



- 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.

Field - singularity

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

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

Do not always believe pictures

ask what is the physical content

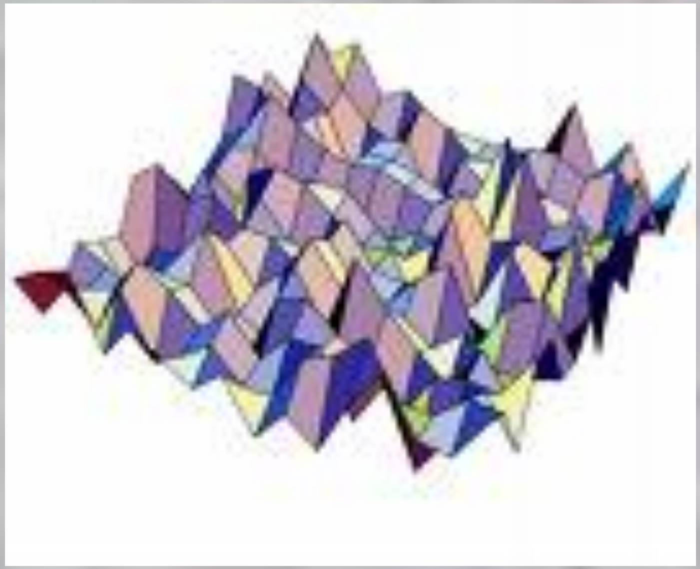
Physical properties during inflationary epoch

- All particles get effectively massless as singularity is approached
- Relevant quantity : mass /momentum
- Momentum diverges
- Ratio goes to zero

Eternal light-vacuum

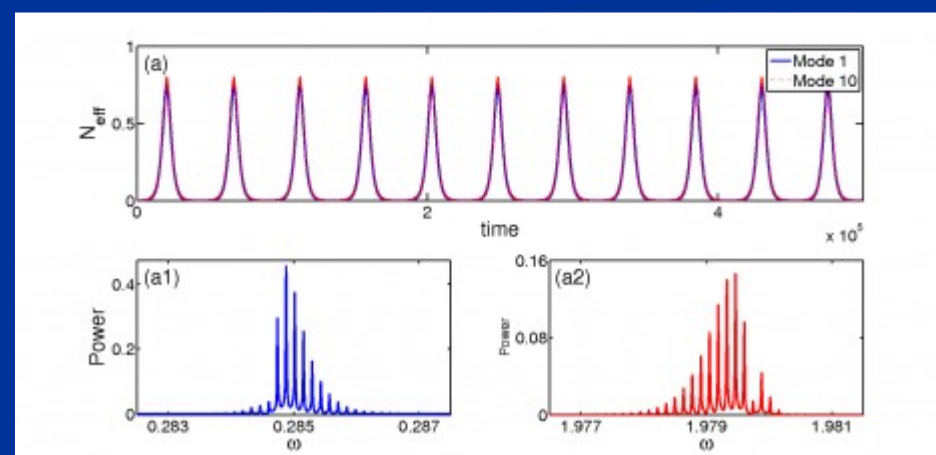
Everywhere almost nothing
only fields and their fluctuations

All particles move
with light velocity,
similar to photons



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
- physical time towards the past: infinite number of oscillations

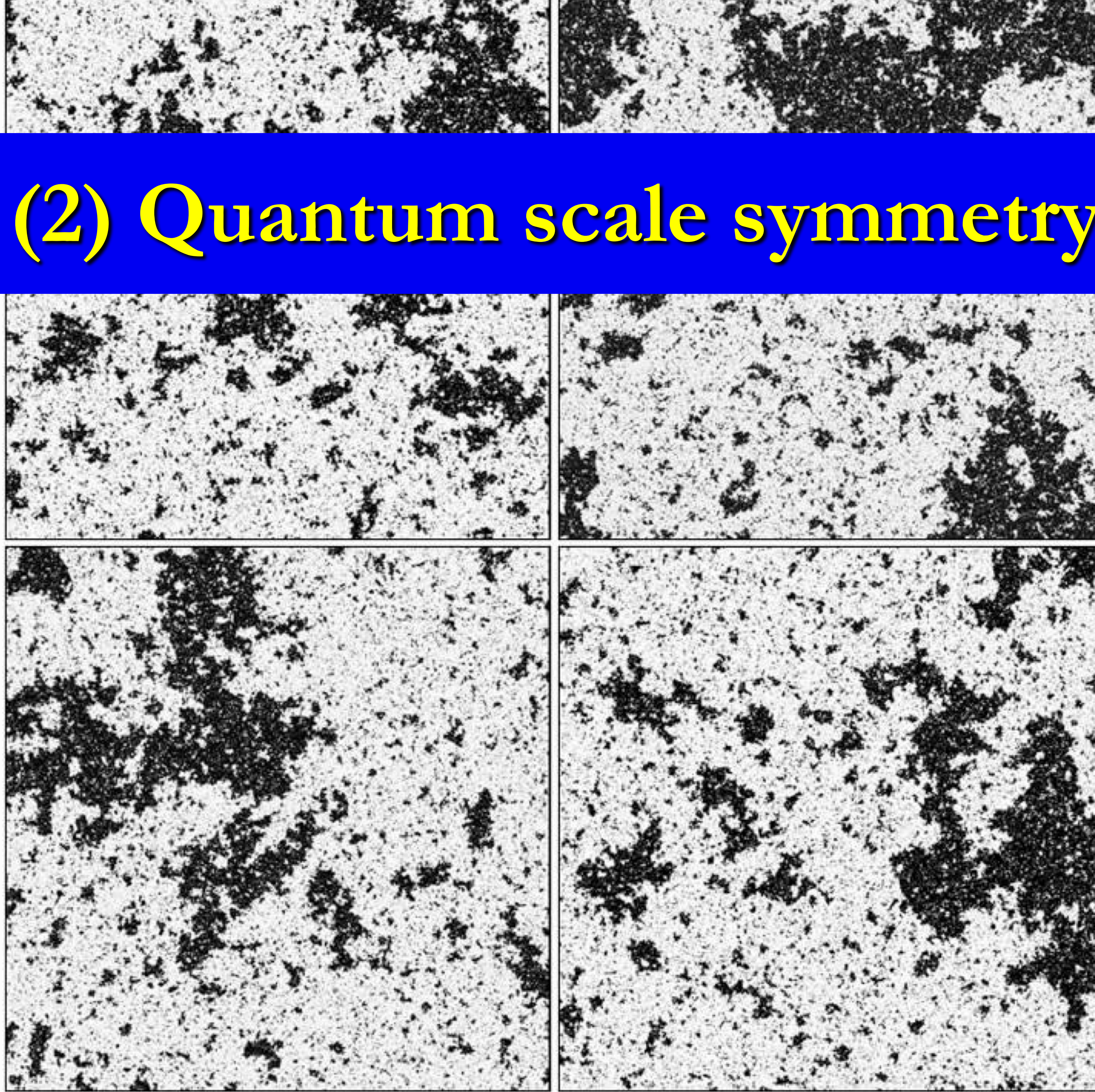
Conclusion (1)

- There are equivalent pictures of the Universe with different geometry
- Singularity free choice of fields is preferable for the description of the beginning

No scales in the infinite past

- No time scale : time is infinite and no change of properties as time goes to minus infinity
- No length scale : Universe is homogeneous and infinite
- No mass scale : all particles are massless

(2) Quantum scale symmetry



Scale transformation

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

Quantum scale symmetry

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

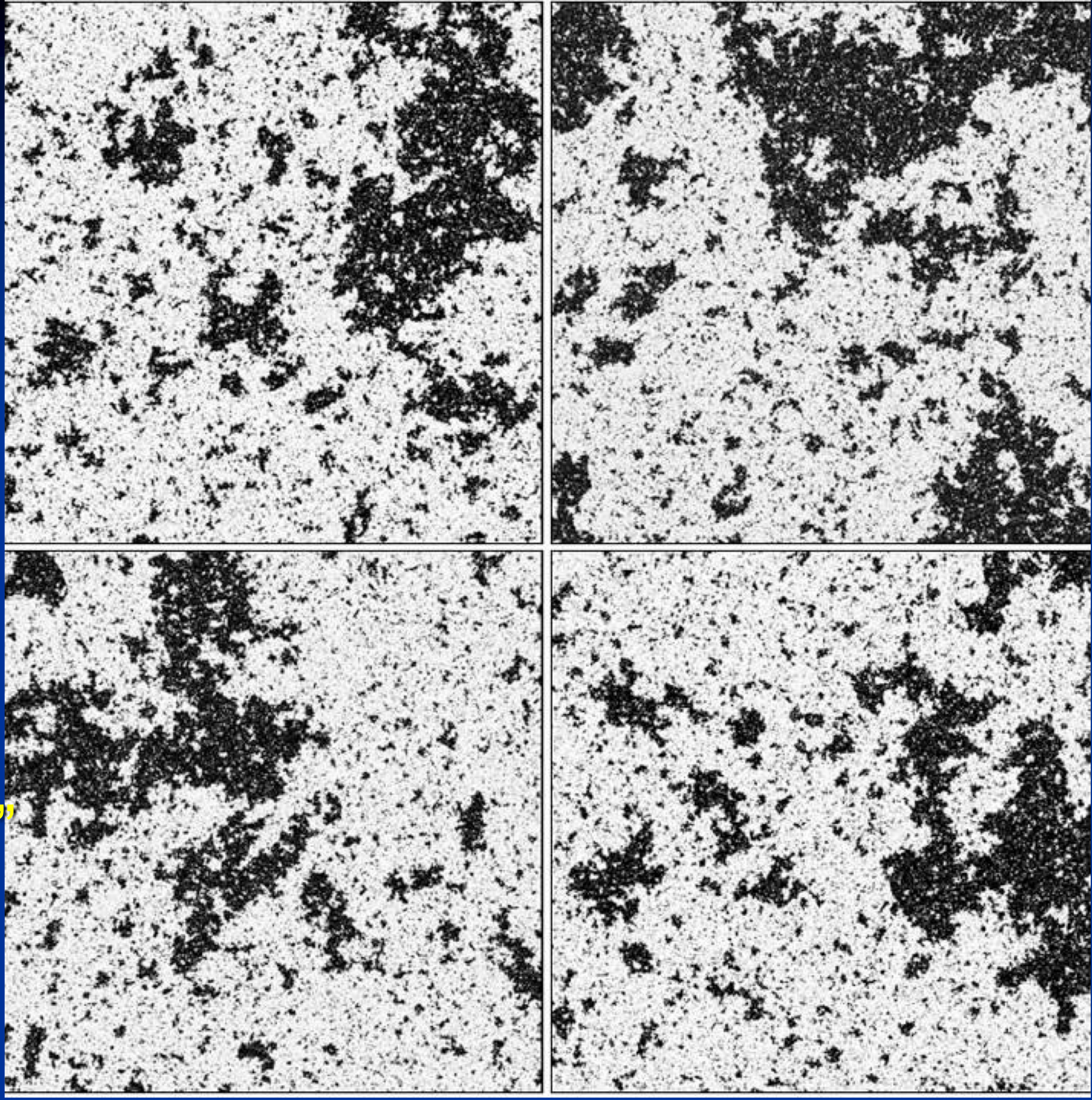
Then invariance under dilatations or global scale transformations is realized.

Continuous global symmetry

Unbroken scale symmetry :

Physics looks the same on all scales

All “particles” are massless



Running couplings : the physics of fluctuations

- The physical laws do not look the same on all length scales
- Effective macroscopic laws emerge
- Key concept in statistical physics / condensed matter physics

Quantum fluctuations induce running (momentum dependent) couplings

Running fine structure constant

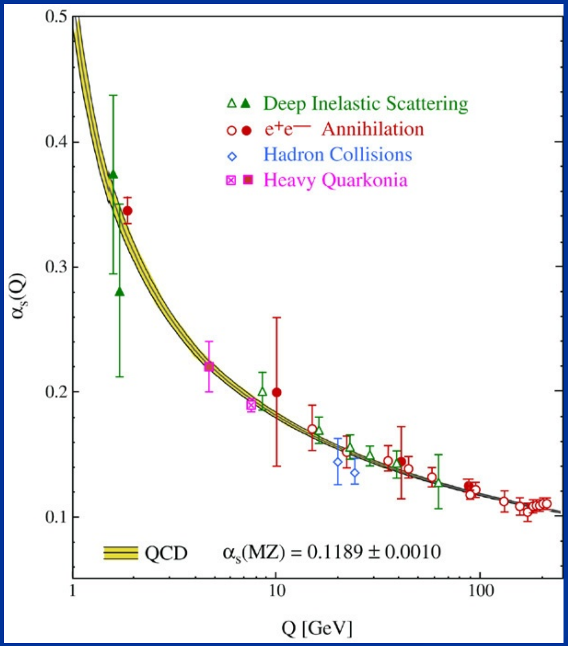
$\alpha = 1/137$ for atoms

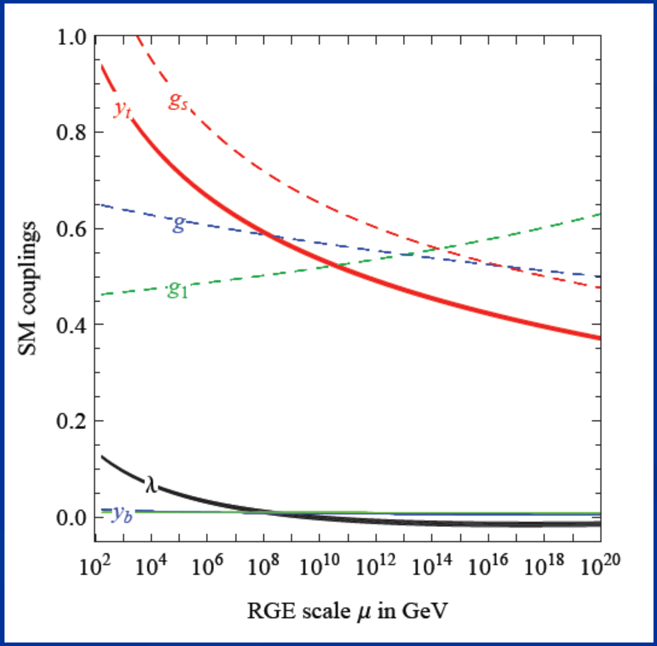
$\alpha = 1/128$ at LEP

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





Quantum scale symmetry

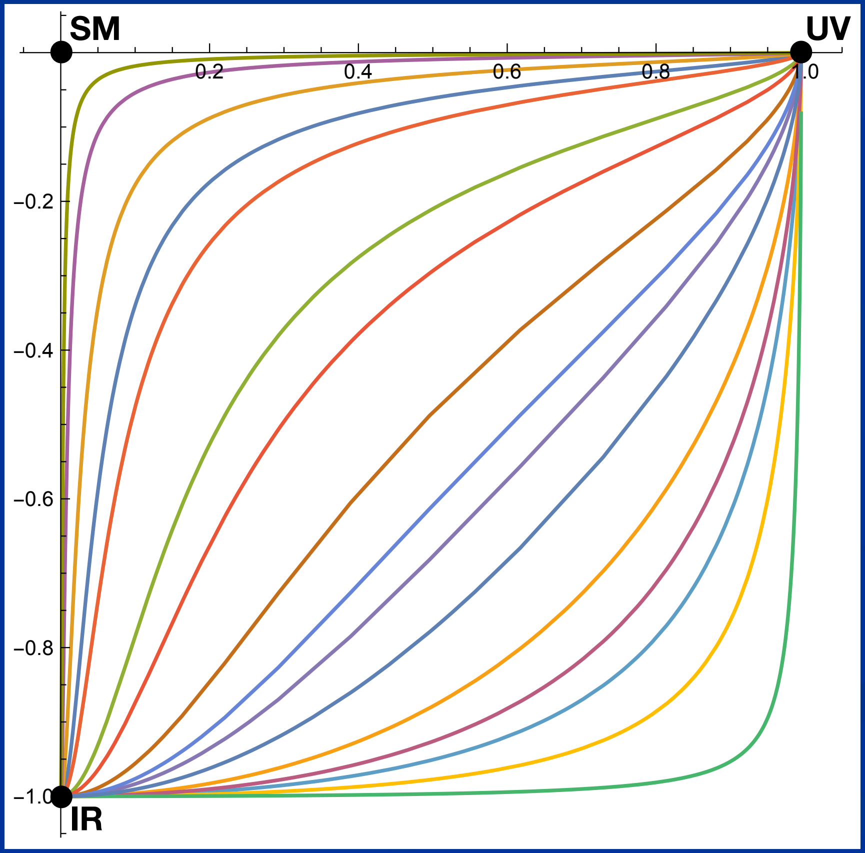
- quantum fluctuations can violate scale symmetry
- running dimensionless couplings
- fixed point : no running of couplings
- at fixed points , scale symmetry is exact !
- quantum fluctuations can generate scale symmetry !

Scale symmetry and fixed points

Relative strength of gravity

Particle scale symmetry

Cosmic scale symmetry



Gravity scale symmetry

Distance from electroweak phase transition

Fixed points and scale symmetry

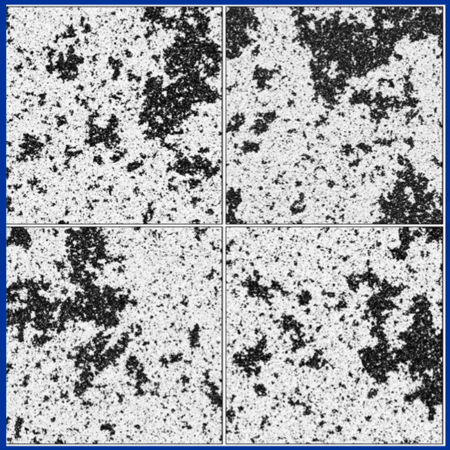
- At a fixed point, scale symmetry is exact in the presence of fluctuations (quantum scale symmetry)
- Well known in condensed matter physics :

  second order phase transition →

  fixed point or scaling solution →

  exact scale symmetry →

  critical phenomena
- Classical or quantum Ising model



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

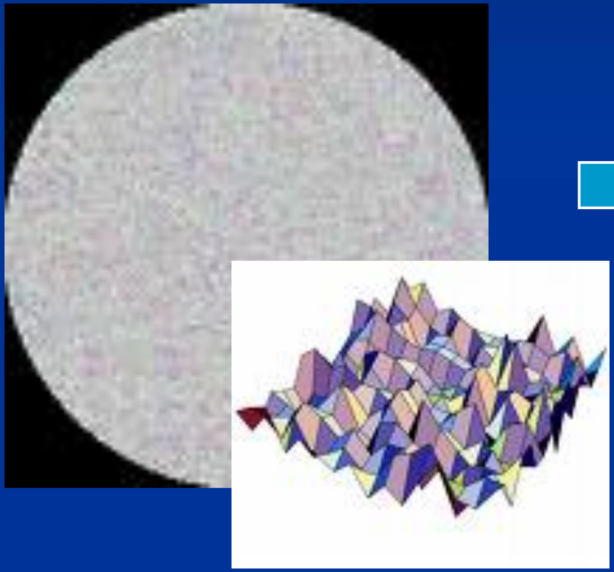
Have we observed scale symmetry in cosmology ?

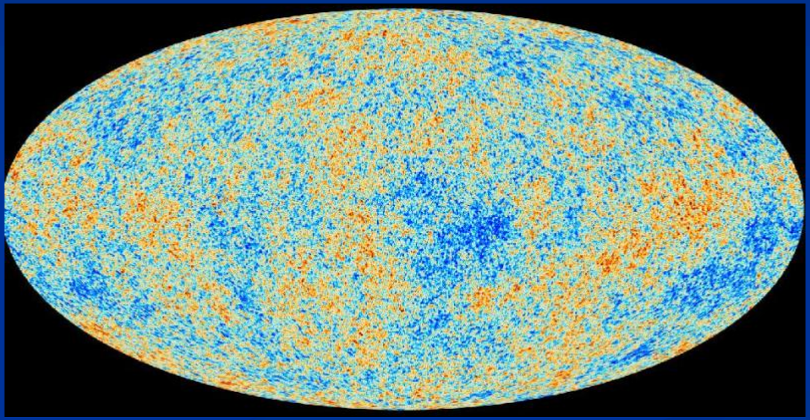
Approximate scale symmetry near fixed points

- 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

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

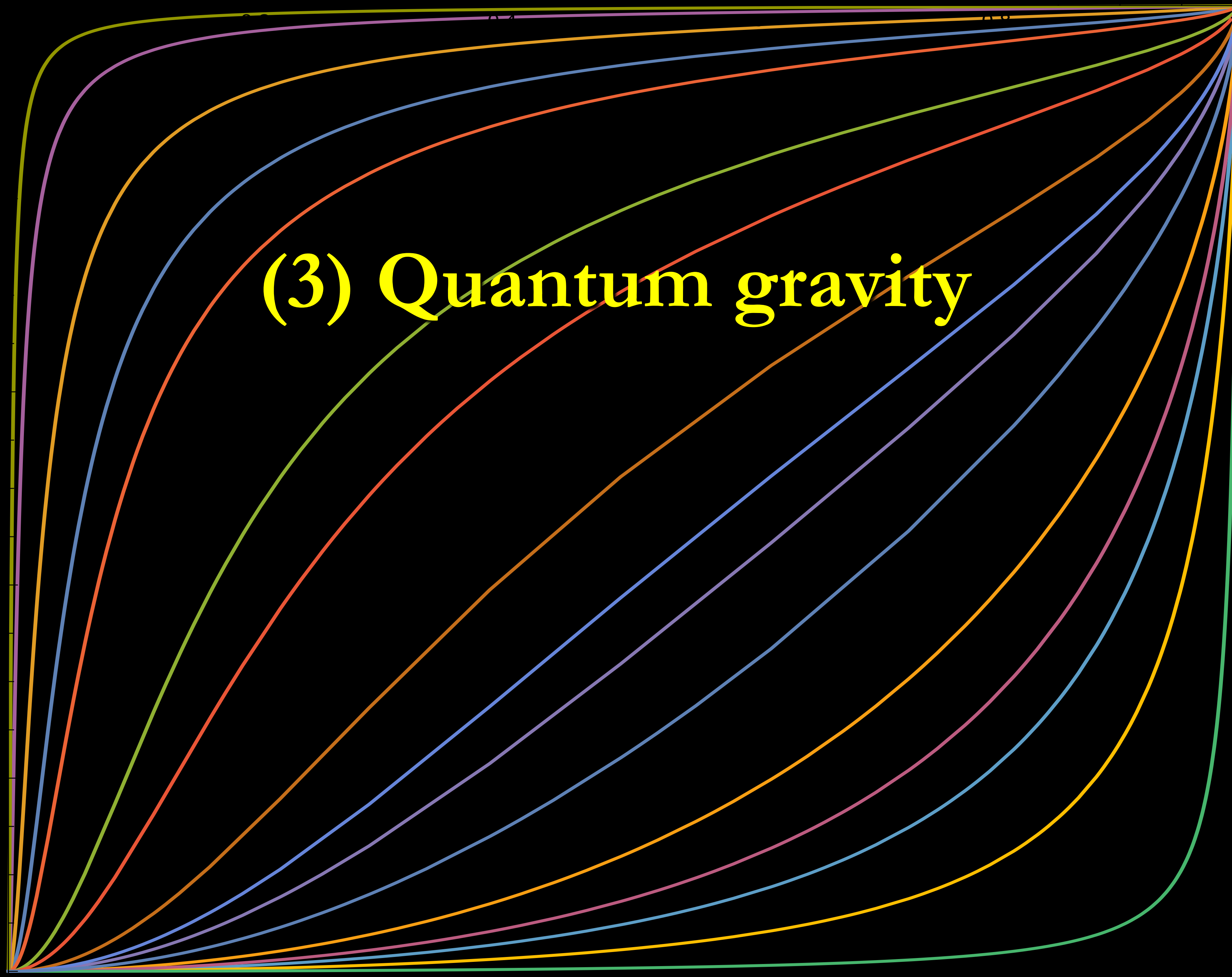




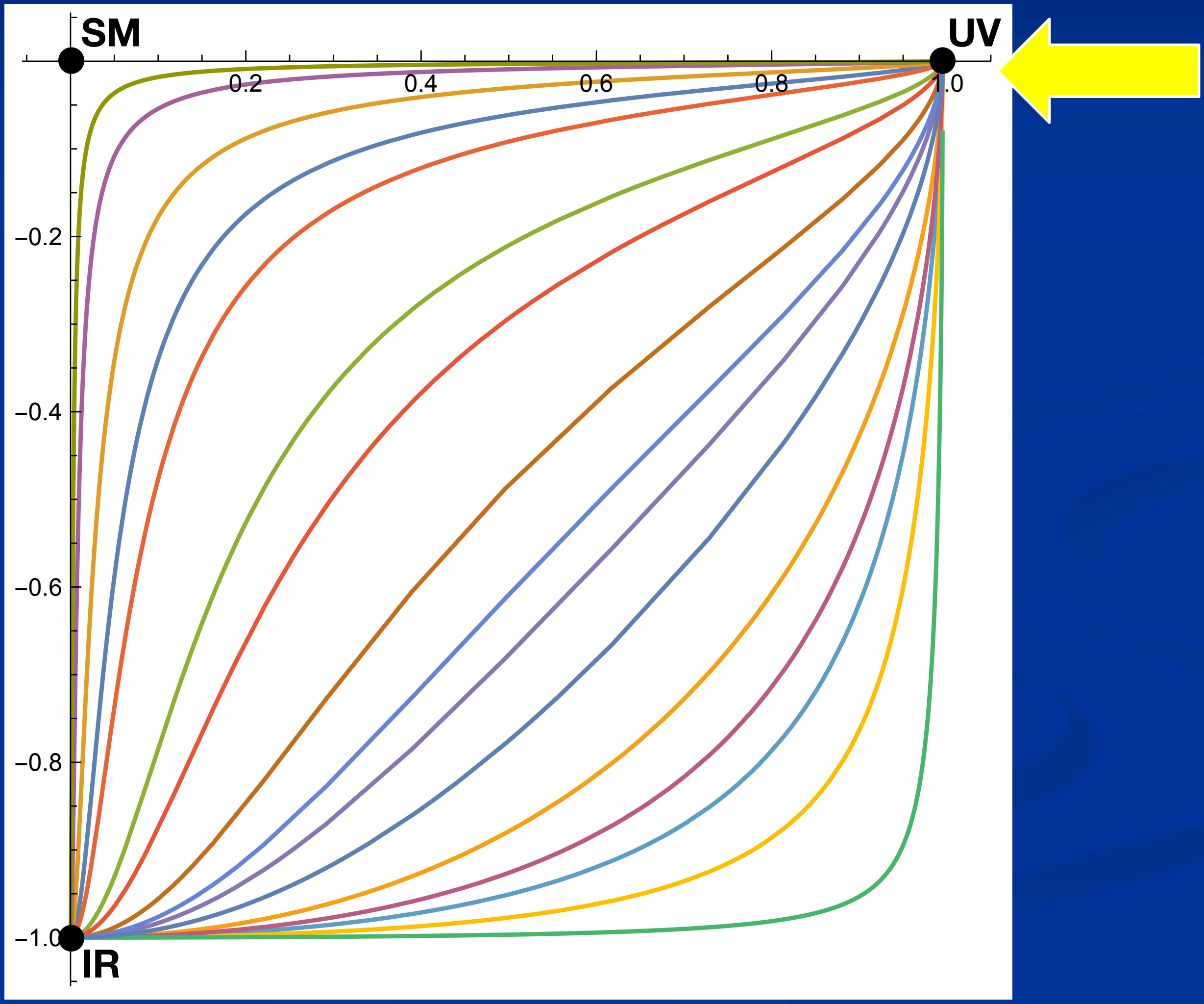
Conclusion (2)

The beginning of the Universe is the reign of quantum scale symmetry

(3) Quantum gravity



Quantum gravity



Quantum Gravity

Quantum Gravity can be a renormalisable quantum field theory

Asymptotic safety

Asymptotic safety of quantum gravity

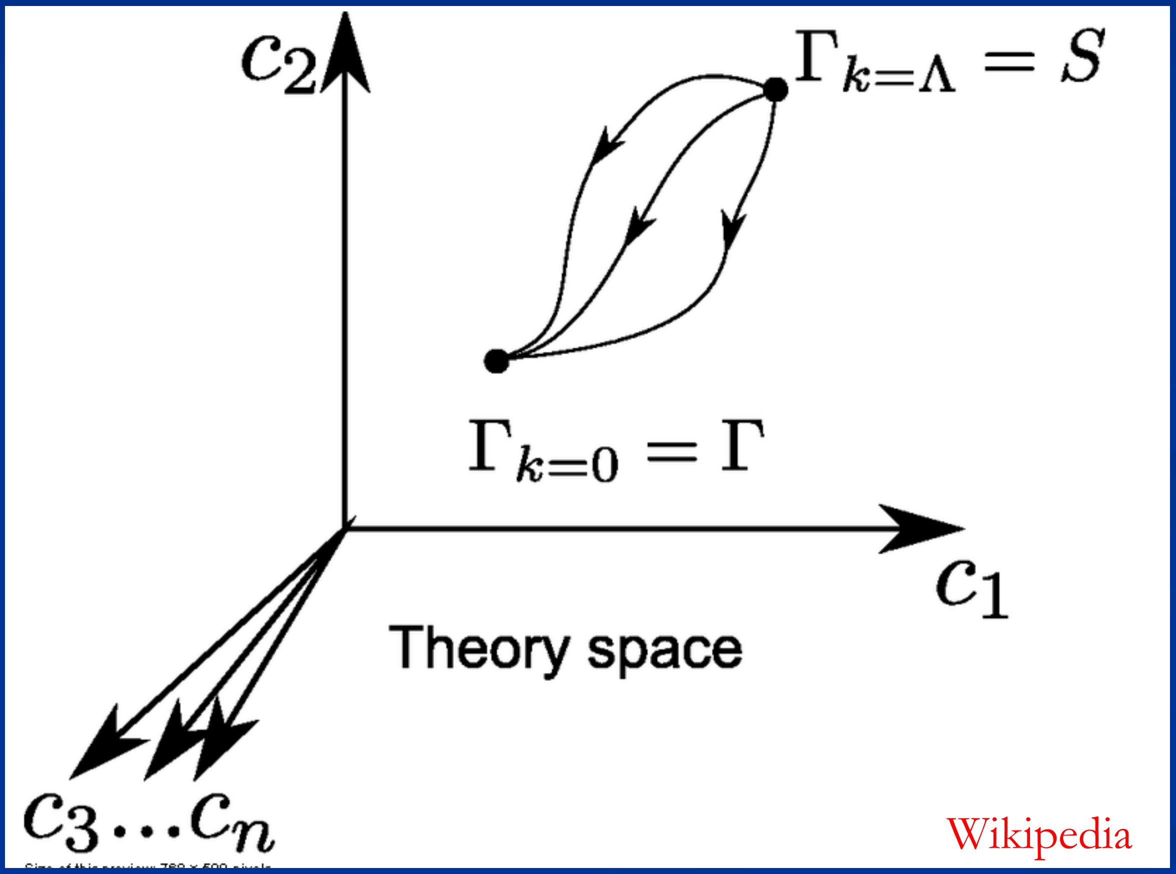
if UV fixed point exists :

quantum gravity is

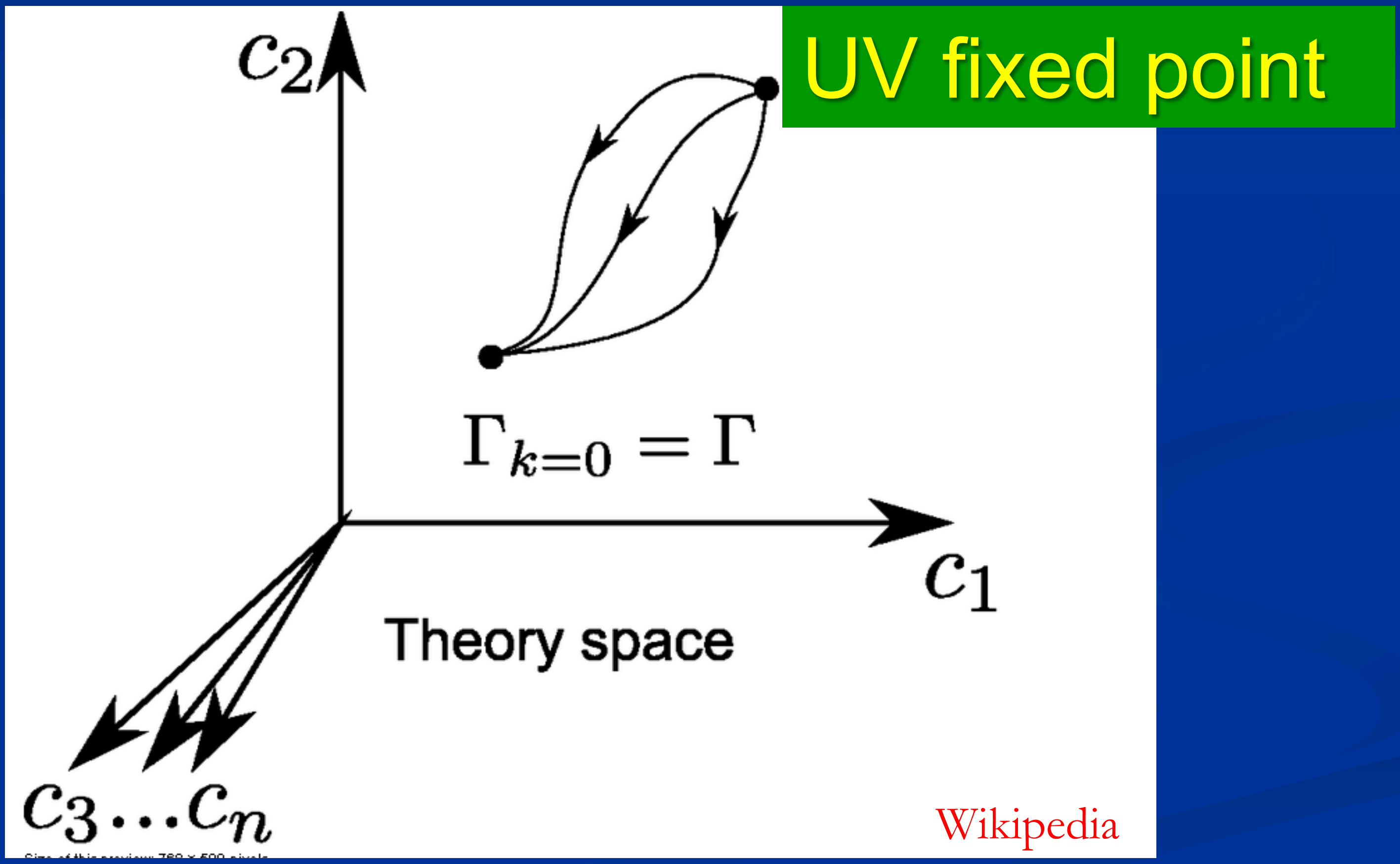
non-perturbatively renormalizable !

S. Weinberg , M. Reuter

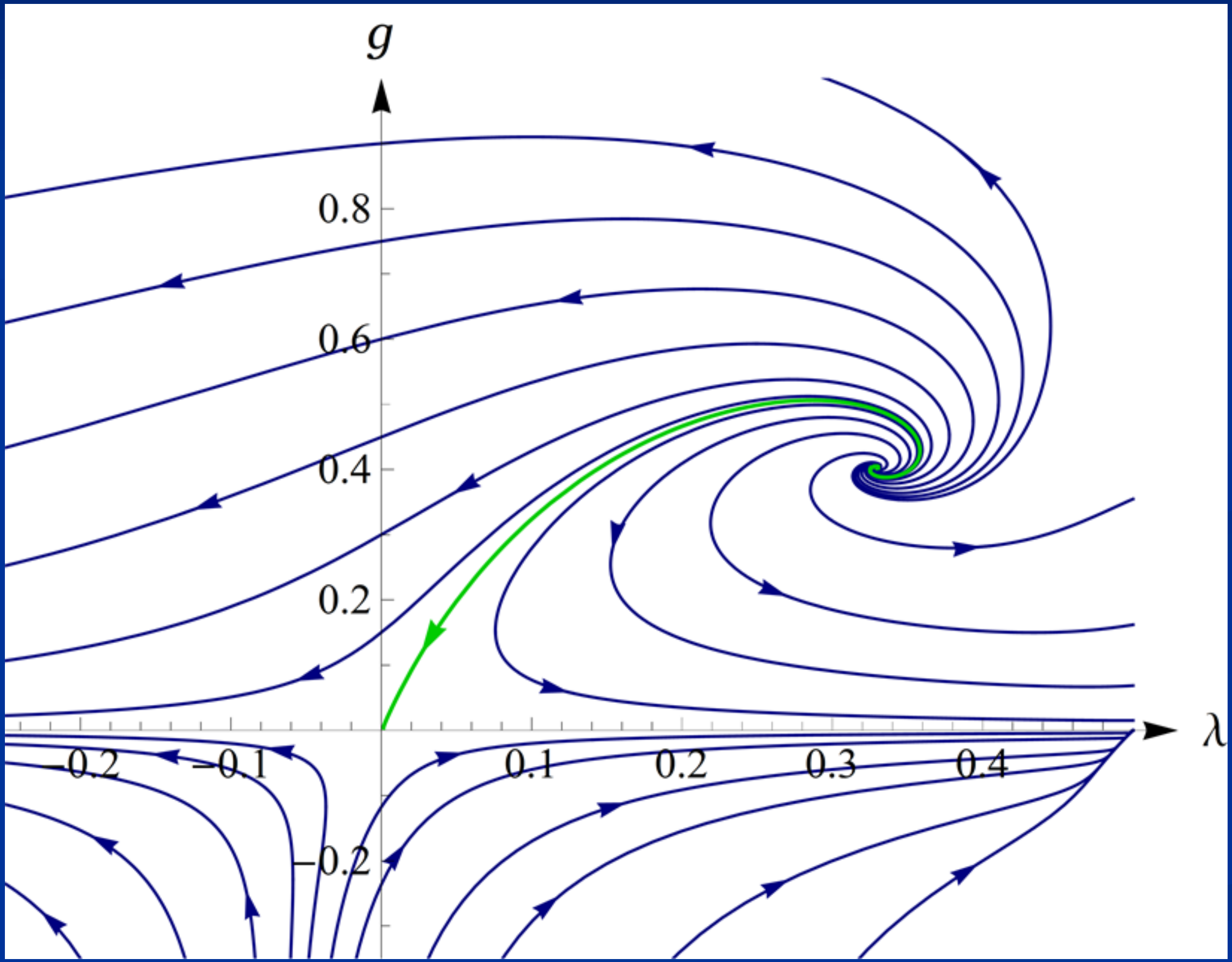
Functional renormalization : flowing action



Ultraviolet fixed point

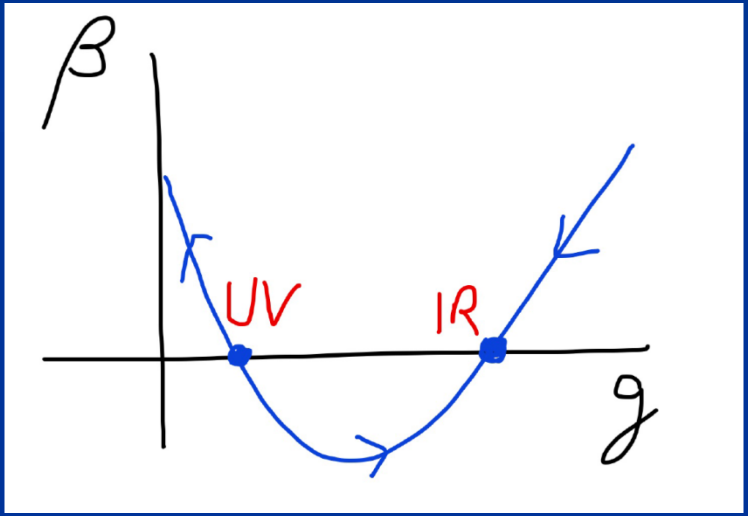


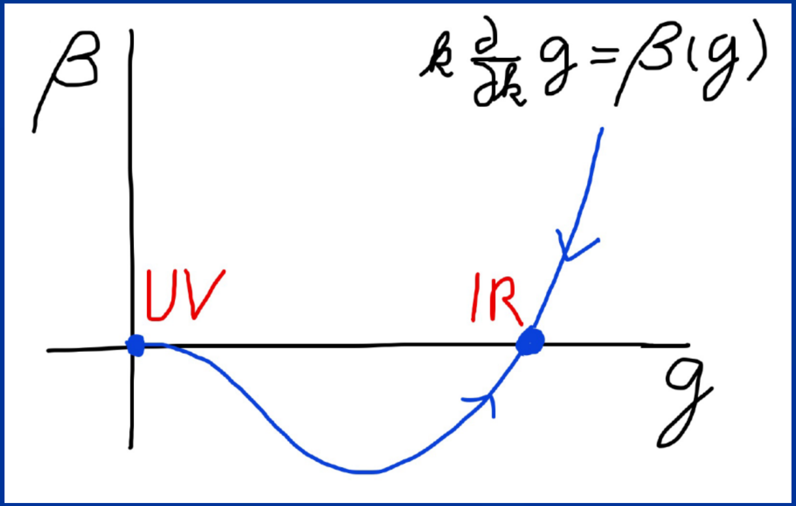
UV- fixed point for quantum gravity



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

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12 January 2010

Abstract

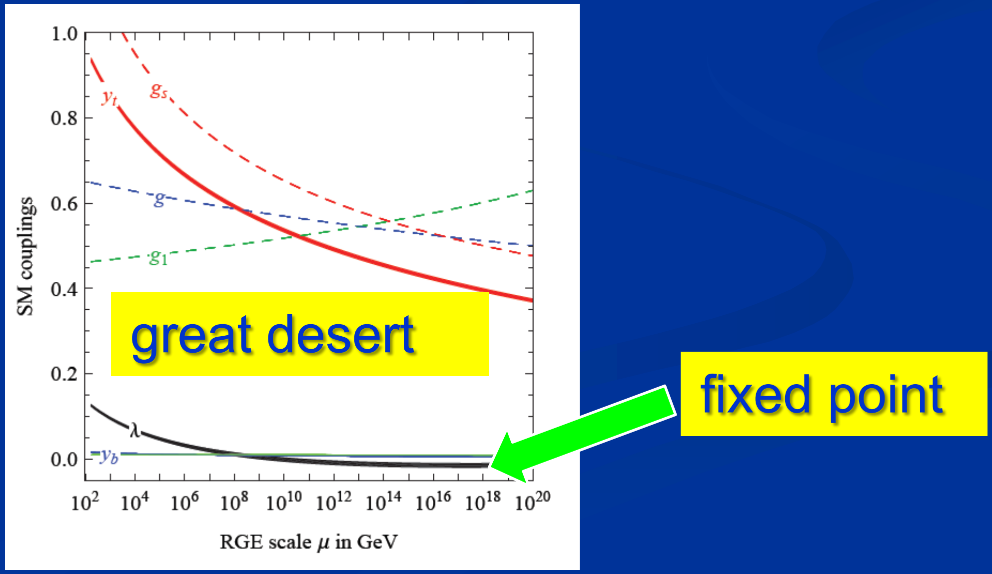
There are indications that gravity is asymptotically safe. The Standard Model (SM) plus gravity could be valid up to arbitrarily high energies. Supposing that this is indeed the case and assuming that there are no intermediate energy scales between the Fermi and Planck scales we address the question 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.

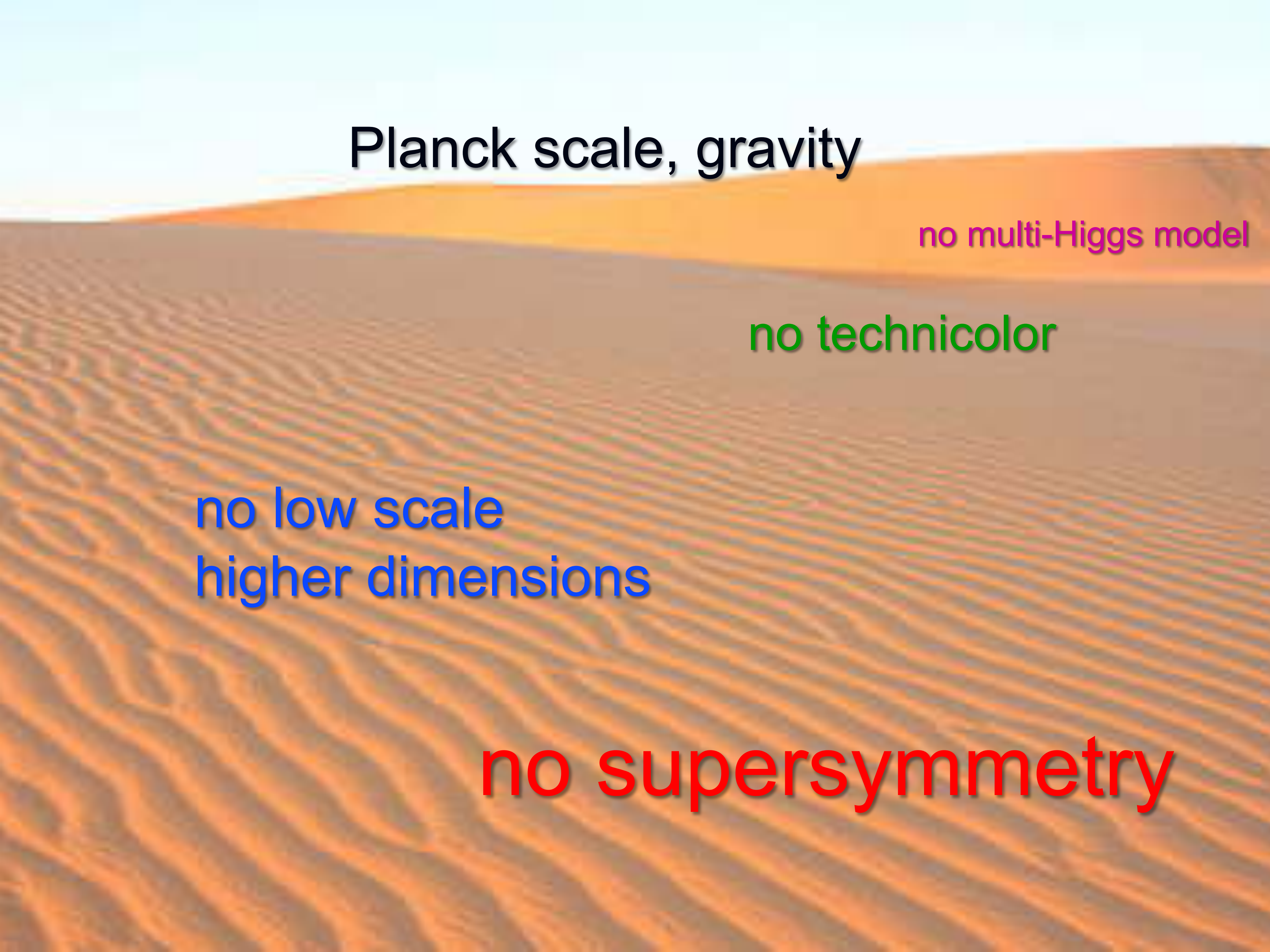
s in $m_H = m_{\rm min} = 126$ GeV, with o

The mass of the Higgs boson, the great desert, and asymptotic safety of gravity

key points

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

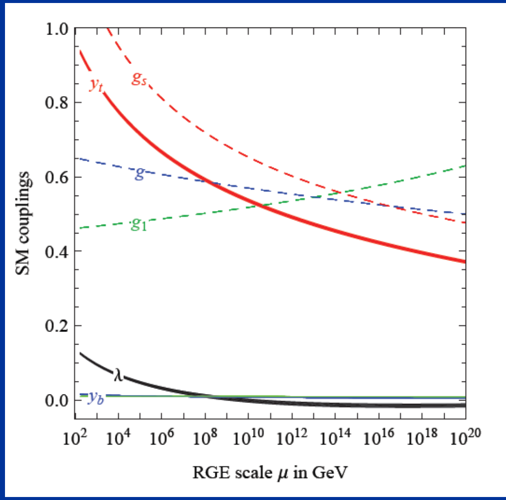



Planck scale, gravity
no multi-Higgs model
no technicolor
no low scale
higher dimensions
no supersymmetry

Essential point for prediction of Higgs boson mass:

Initial value of quartic scalar coupling near Planck mass is predicted by quantum gravity

Extrapolate perturbatively to Fermi scale



Results in prediction for ratio Higgs boson mass over W- boson mass, or Higgs boson mass over top quark mass

Near Planck mass gravity is not weak !

Predictive power !

Flowing couplings

Couplings change with momentum scale due to quantum fluctuations.

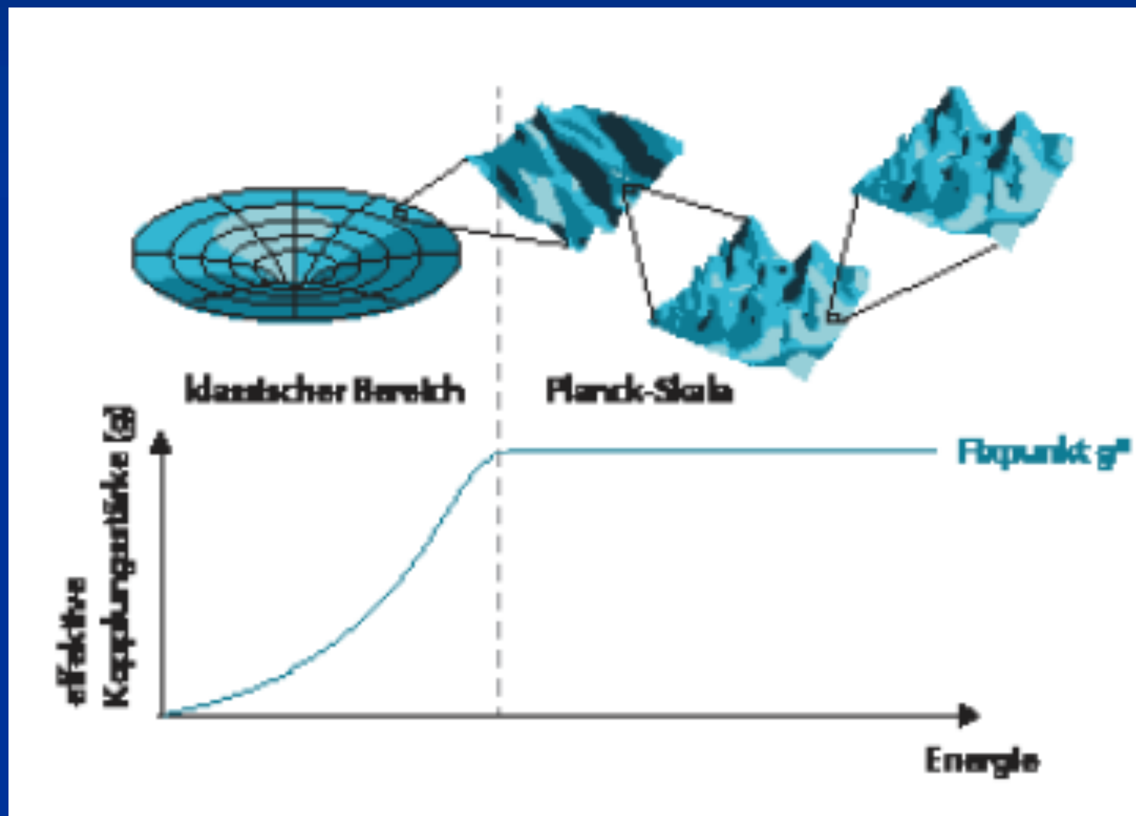
Renormalization scale k : Only fluctuations with momenta larger k are included. The scale k can be momenta, geometric quantities, or just be introduced "by hand".

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

Renormalization group

How do couplings or physical laws change with scale k ?

Strength of gravity



A.Eichhorn, CW, Spektrum der Wissenschaft

Graviton fluctuations erase quartic scalar coupling

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

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

gravity induced anomalous dimension

A > 0

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

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

Fixed point

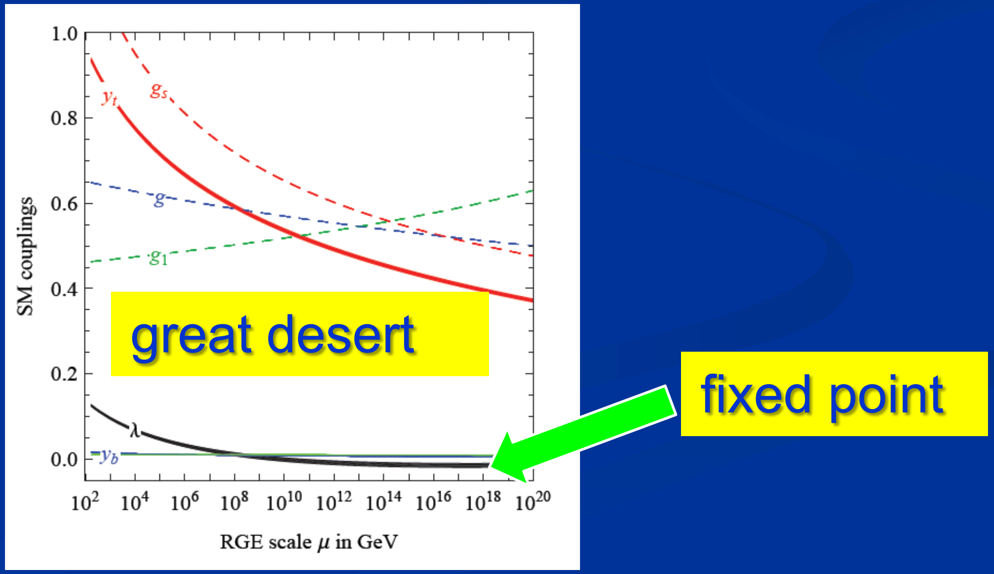
$$k \frac{\partial \lambda}{\partial k} = A \lambda$$

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

The quartic scalar coupling λ has a
fixed point at λ=0
It flows towards the fixed point as k is lowered :
irrelevant coupling
For a UV – complete theory it is predicted to assume the fixed point value

Quantum gravity prediction of mass of the Higgs boson

- great desert
- high scale fixed point
- vanishing scalar coupling at fixed point

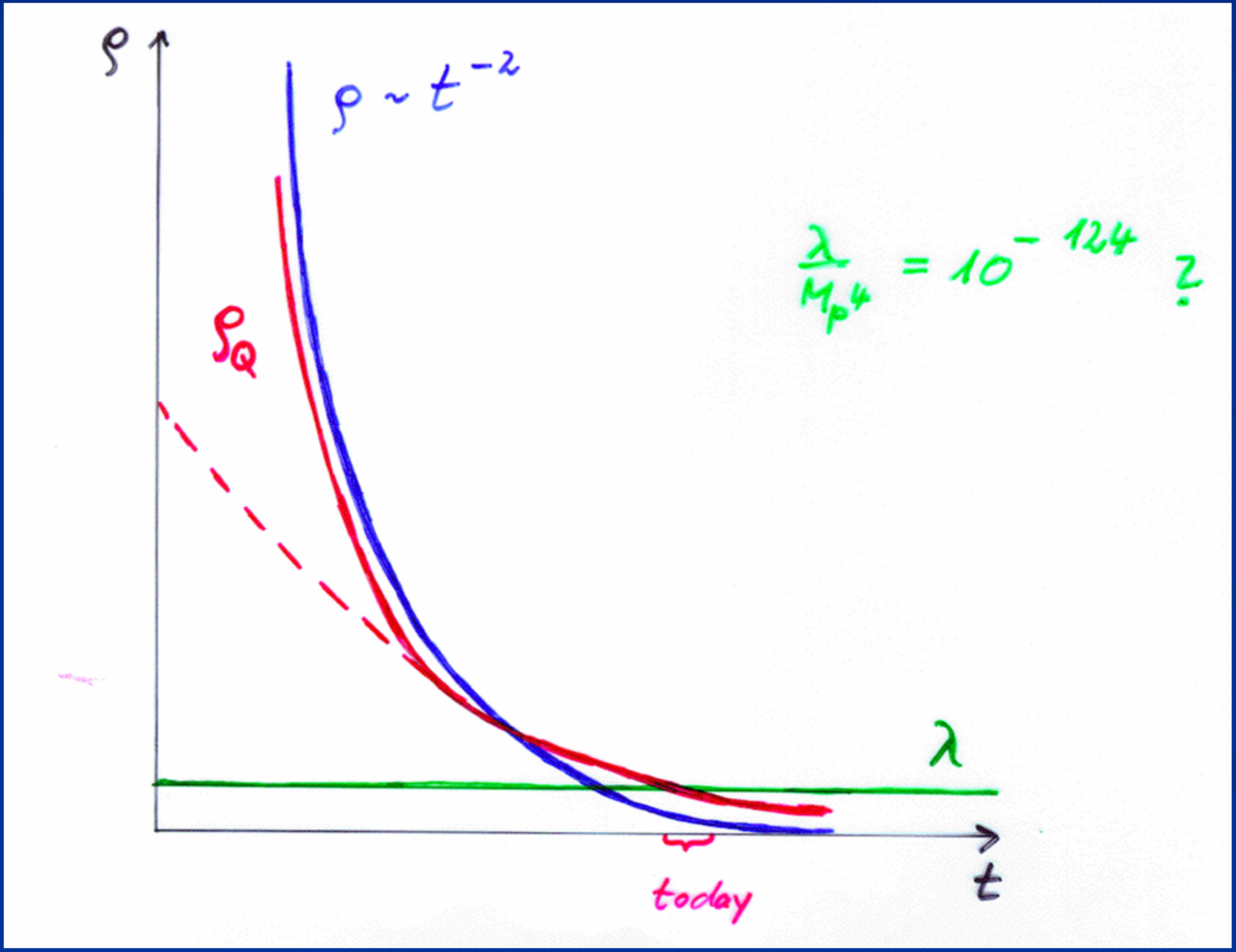


Conclusions (3)
Predictions of quantum gravity

Simple approximation for graviton contribution to scalar potential:

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

(4) Dark Energy



variable gravity

"Newton's constant is not constant – and particle masses are not constant"

"modified gravity"

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

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


Πάντα ῥεῖ

Cosmic scale symmetry and the cosmological constant problem

- IR – fixed point reached for $\chi \to \infty$
- Impact of intrinsic mass scale disappears

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

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)

Model is compatible with present observations

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

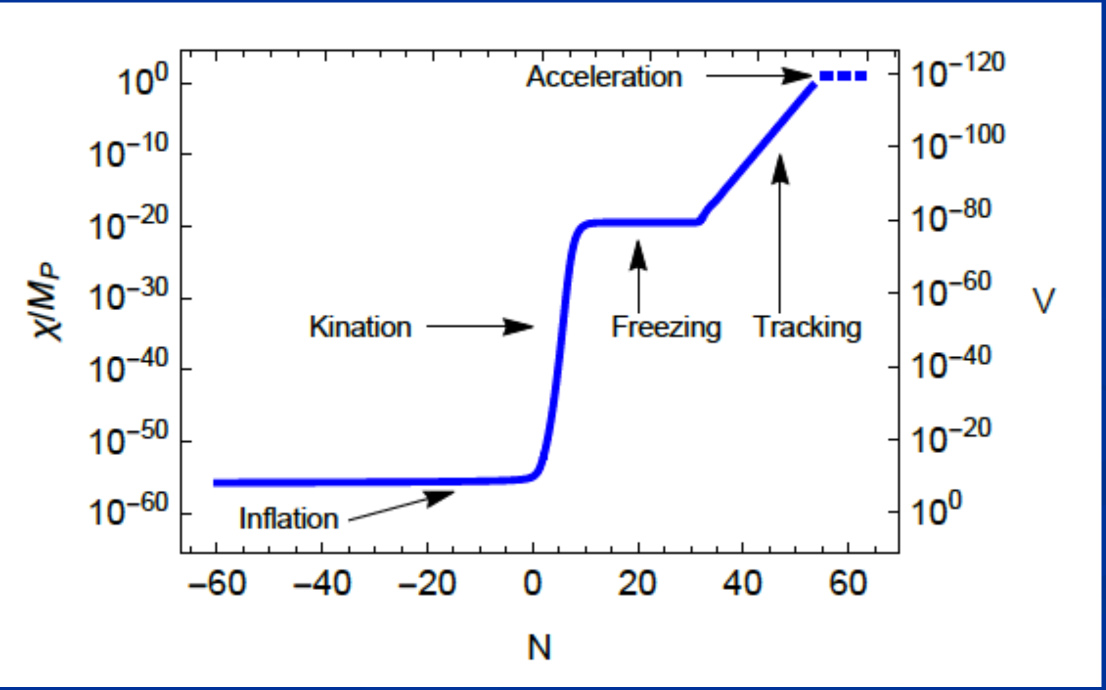
model is compatible with all present observations, including inflation and dark energy

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

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

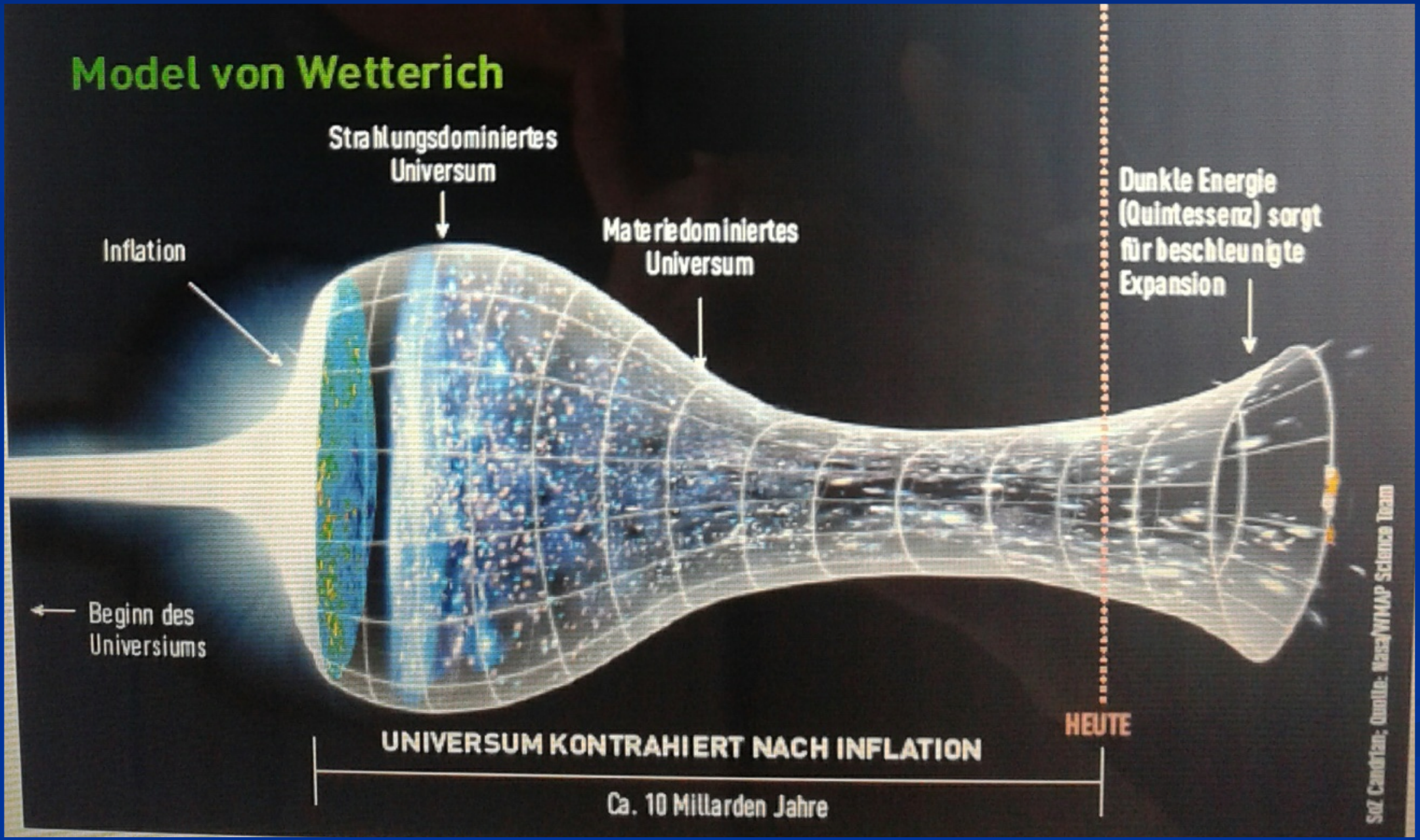
Cosmological solution

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



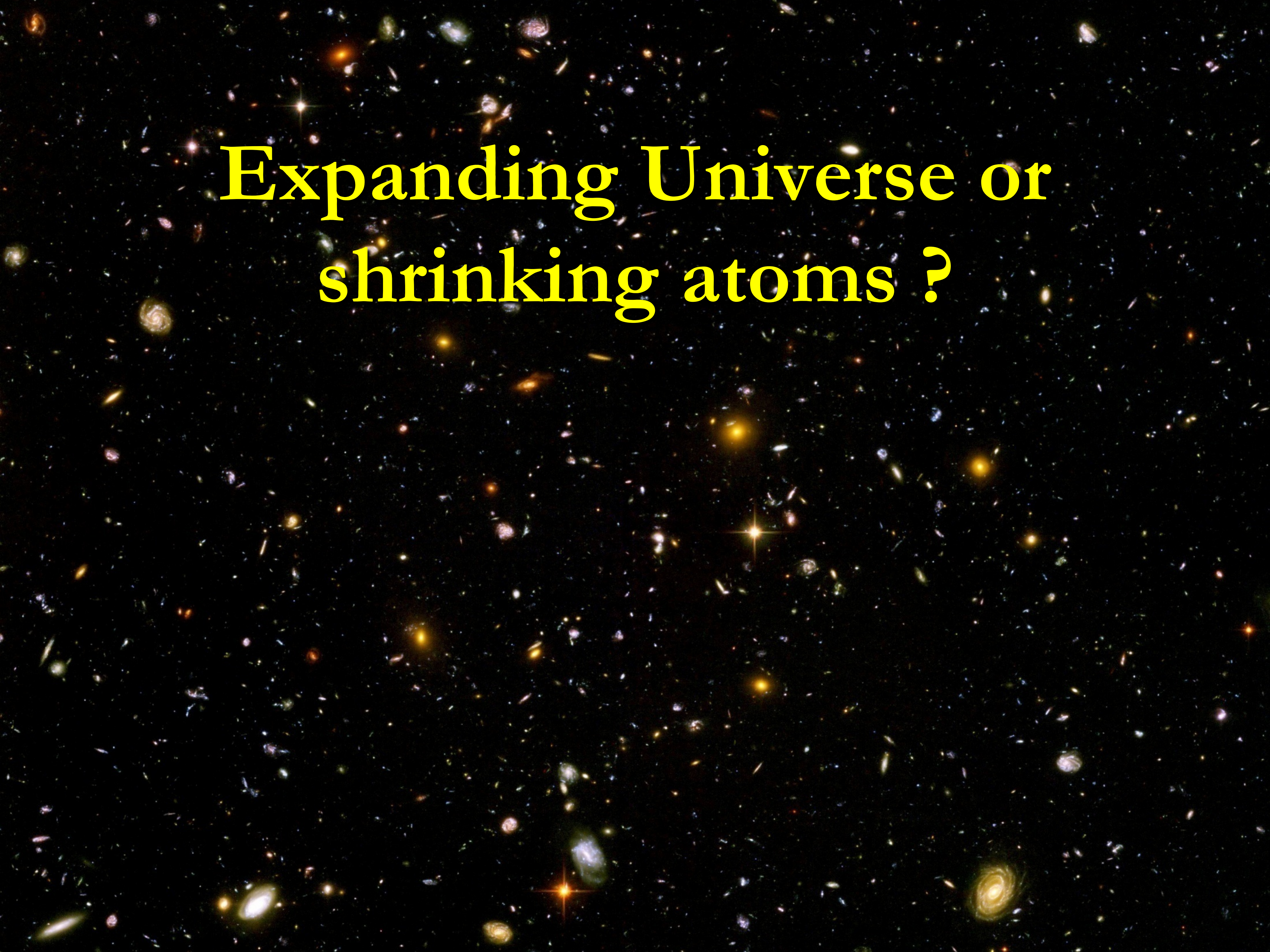
J.Rubio,…

In scaling frame: strange evolution of Universe



Sonntagszeitung Zürich , Laukenmann

Expanding Universe or shrinking atoms ?

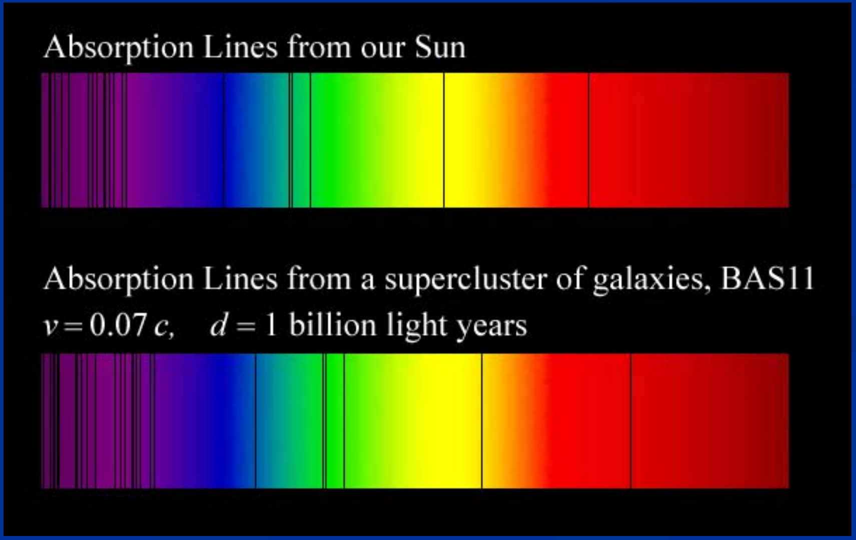


Hot big bang or freeze ?

Do we know that the Universe expands ?

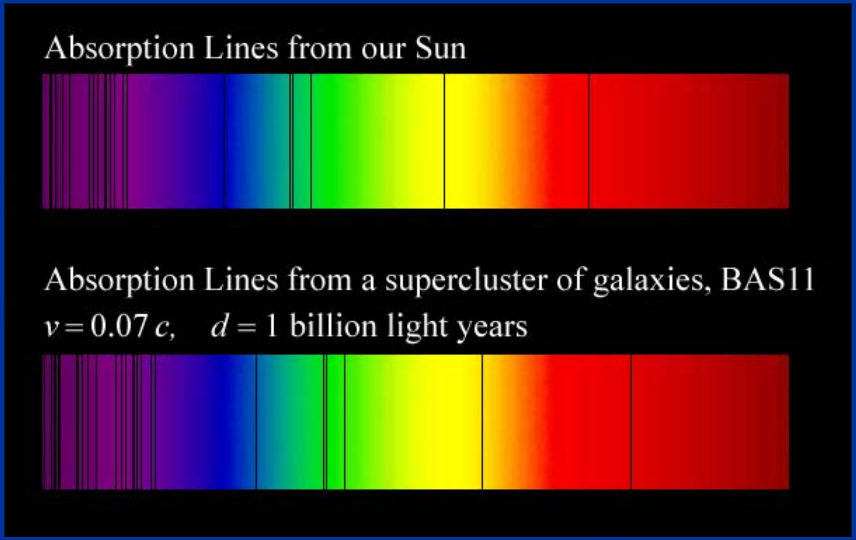
instead of redshift due to expansion :

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

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 .

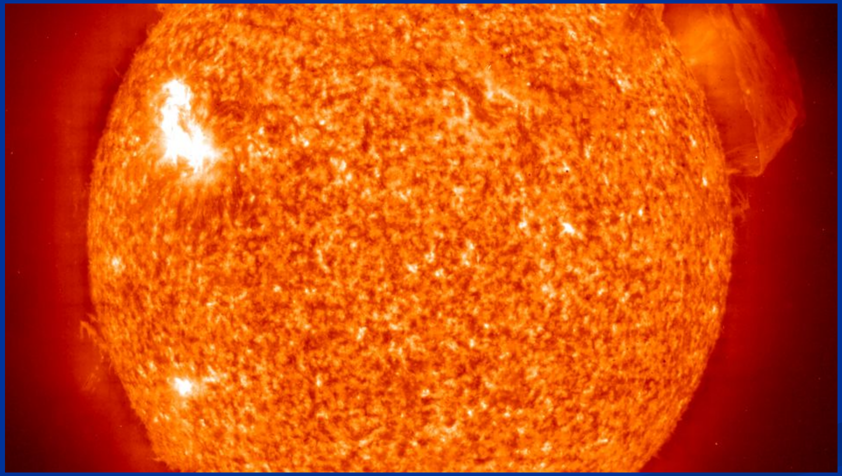
Do we know that the temperature was higher in the early Universe than now ?

Cosmic microwave radiation , nucleosynthesis

instead of

higher temperature :

smaller particle masses



Hot plasma ?

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

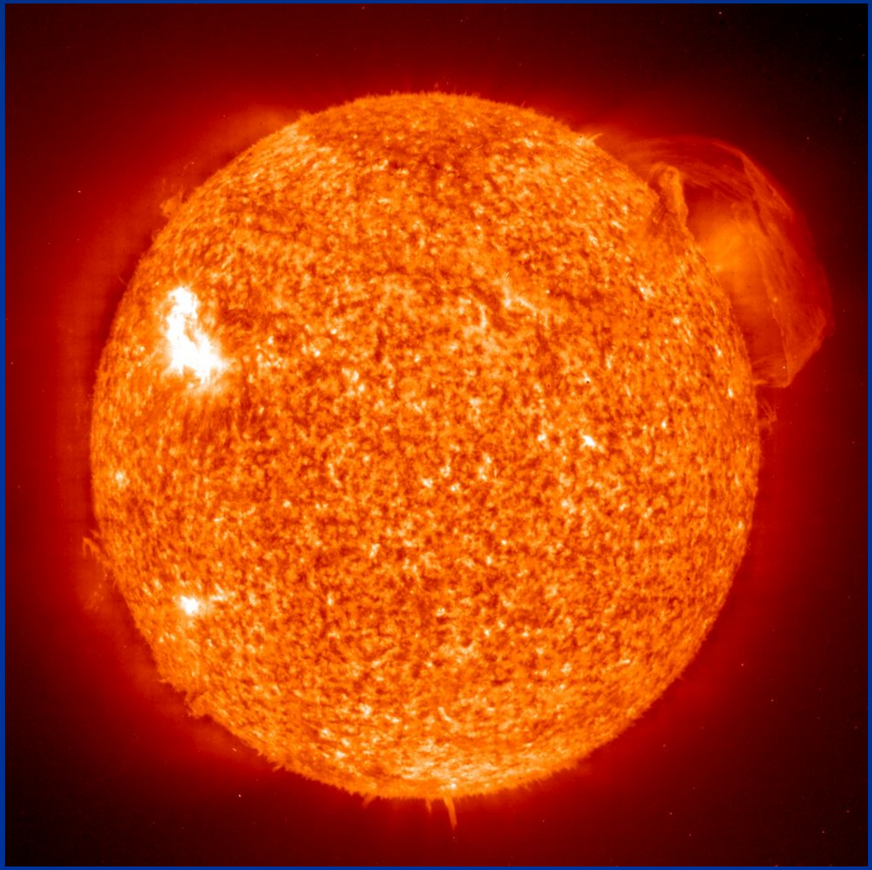
- Nucleosynthesis , CMB emission as in standard cosmology !

Freeze Universe

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

Freeze picture of the Universe

Big bang or freeze ?



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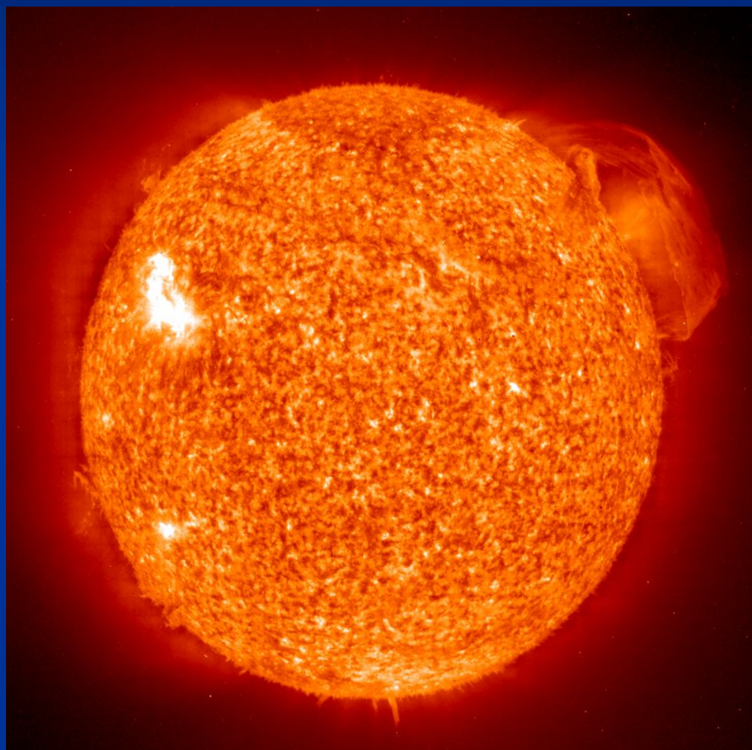

freeze picture :
only rods for measurements
(masses) are different !

Big bang is not wrong,

but alternative pictures exist !

Conclusions

- Quantum gravity is predictive renormalizable quantum field theory
- Quantum scale symmetry crucial for understanding the beginning of the Universe
- Simple ”scaling frame” for the choice of the metric field gives simple description without any singularities
- Big bang singularity is a field singularity
- Universe can be eternal in the past

end