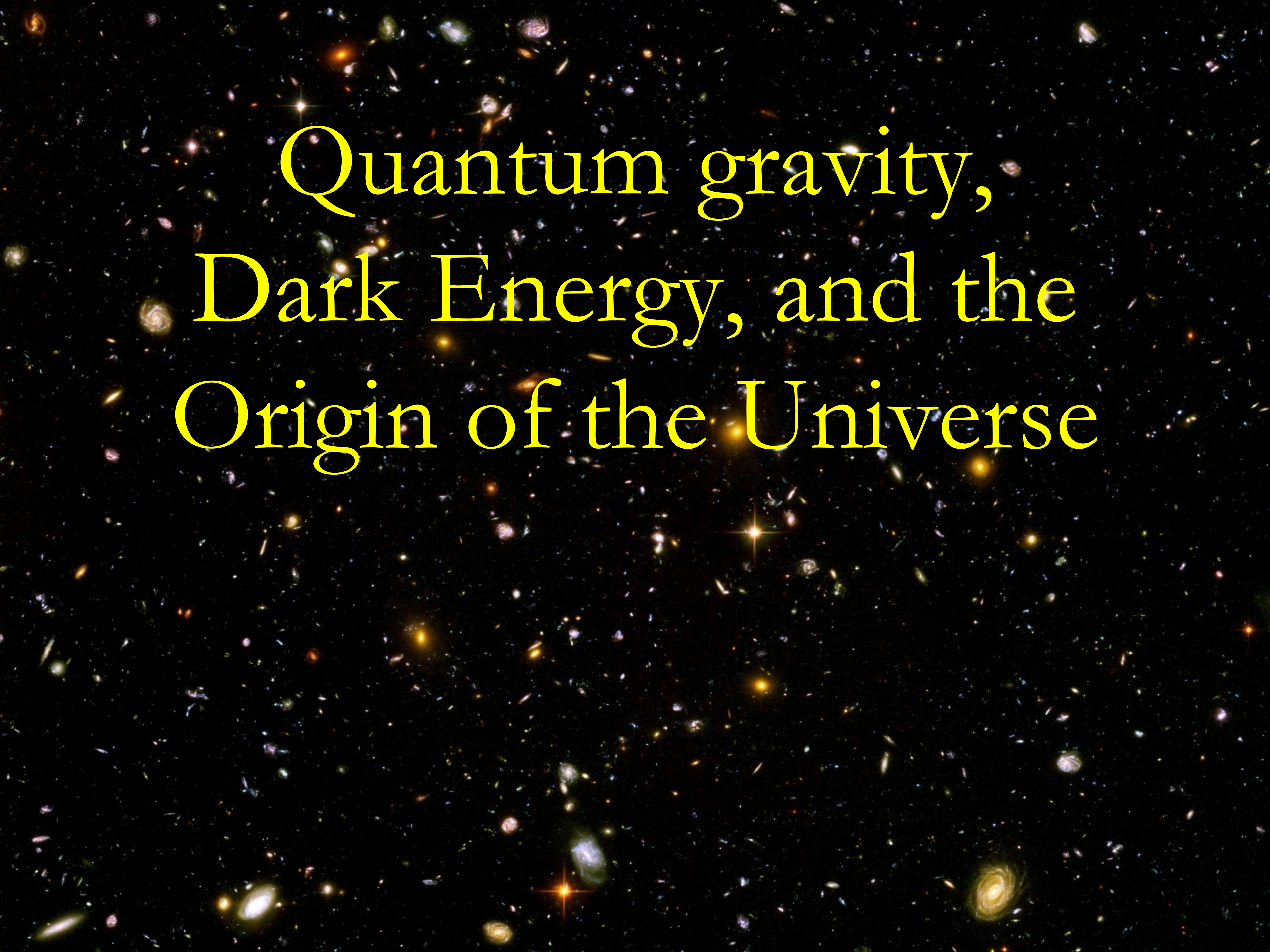
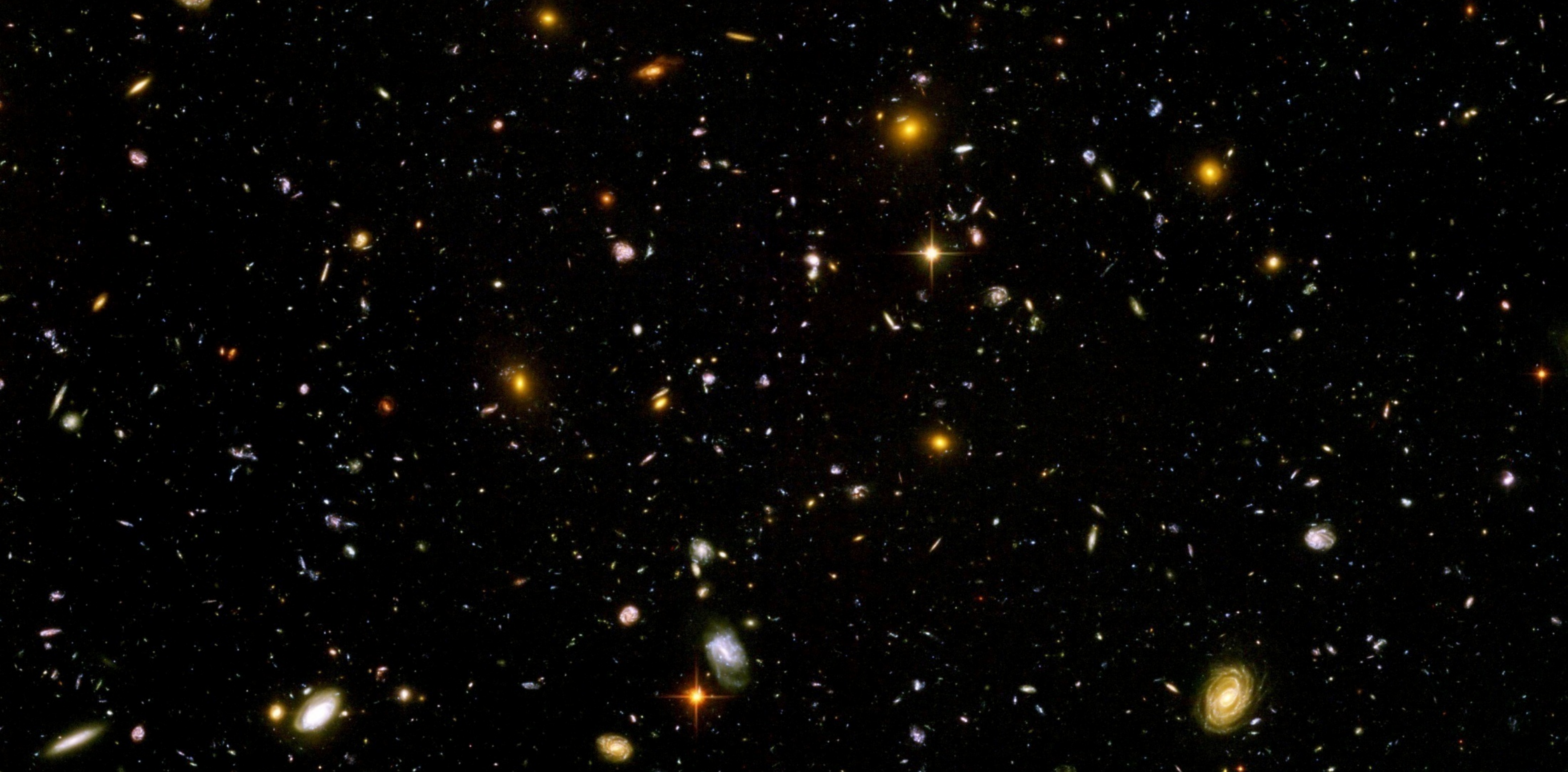
Quantum gravity, Dark Energy, and the Origin of the Universe



Expanding Universe or shrinking atoms ?

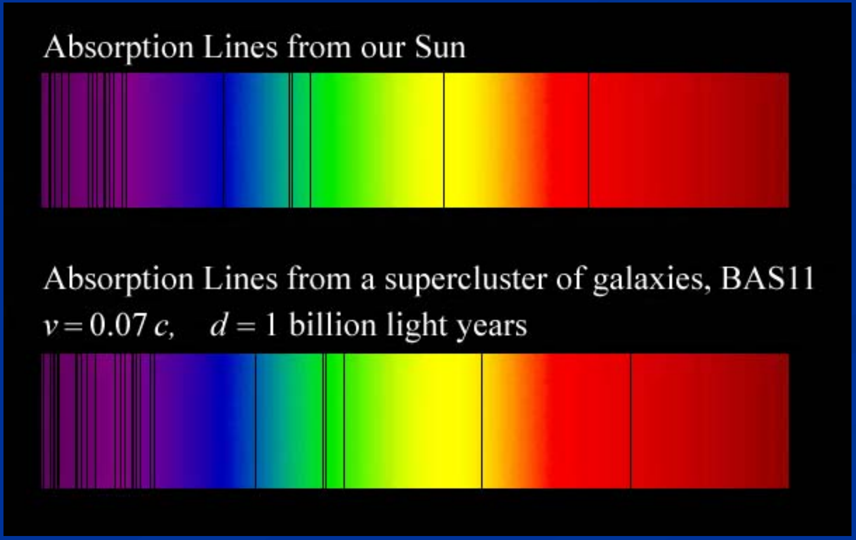


Hot big bang or freeze ?

Do we know that the Universe expands ?

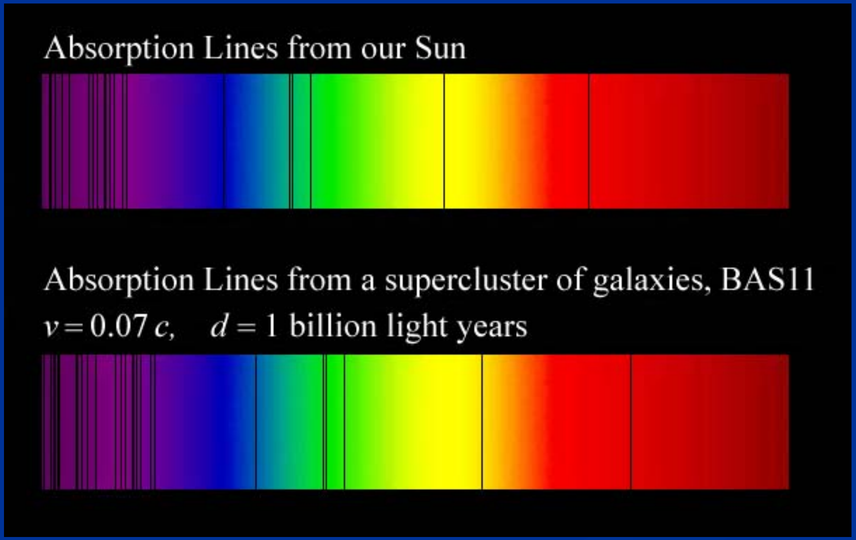
instead of redshift due to expansion :

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 .

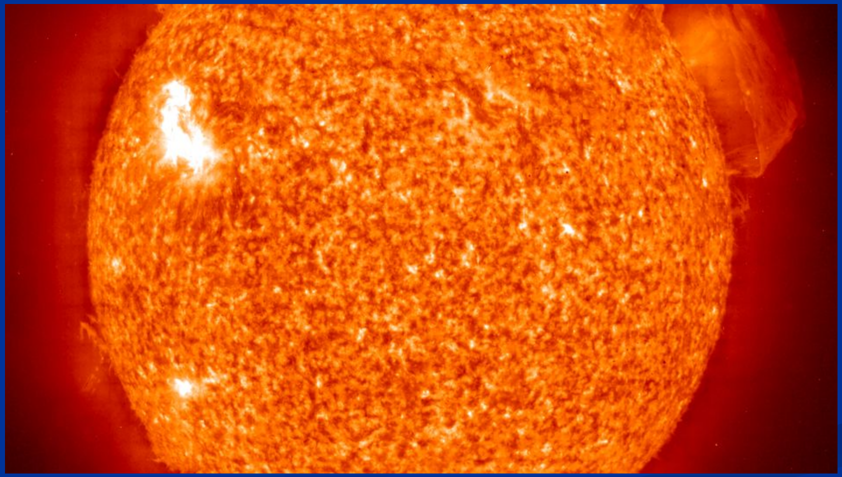
Do we know that the temperature was higher in the early Universe than now ?

Cosmic microwave radiation , nucleosynthesis

instead of

higher temperature :

smaller particle masses



Hot plasma ?

- Temperature in radiation dominated Universe :
  $T \sim \chi^{1/2}$ 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.

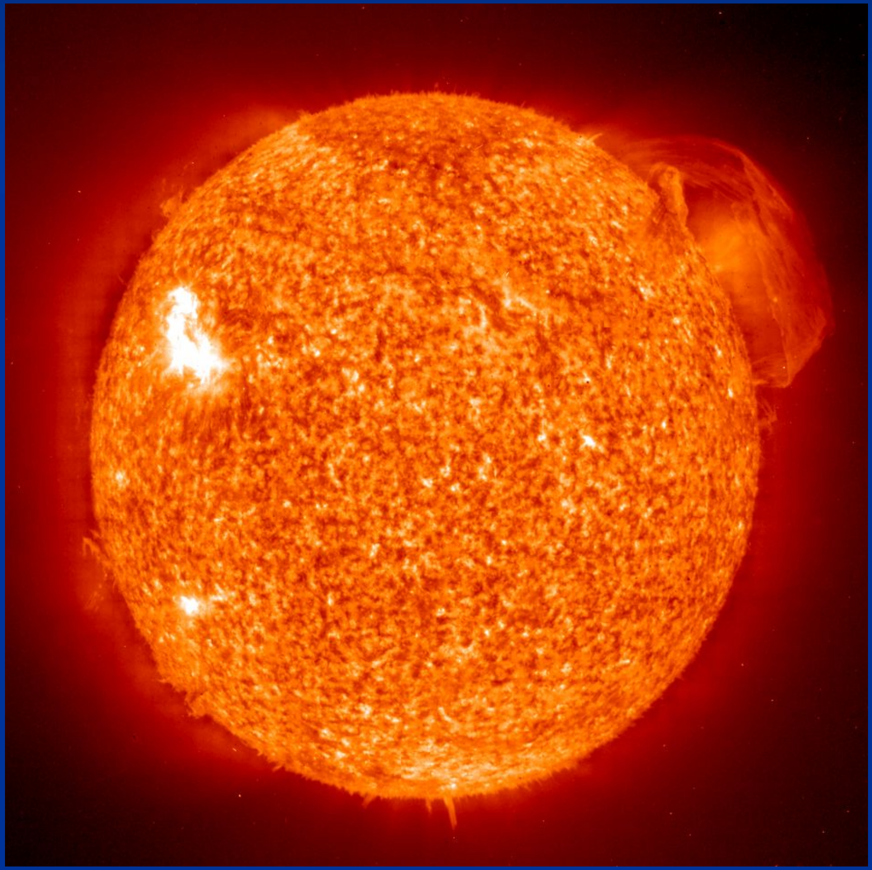
- Nucleosynthesis , CMB emission as in standard cosmology !

Freeze Universe

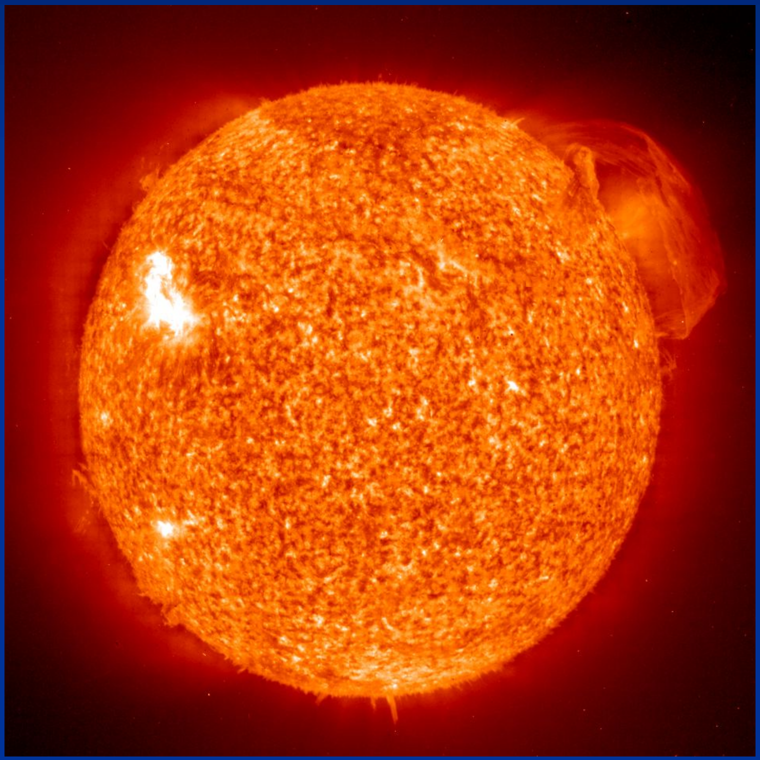
The Universe may have started very cold,
and only later heat up.

Freeze picture of the Universe

Big bang or freeze ?



Big bang or freeze ?



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

Big bang is not wrong,

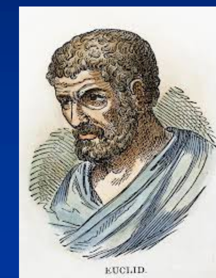
but alternative pictures exist !

Field relativity : different pictures of cosmology

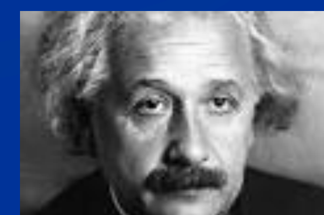
- same physical content can be described by different pictures
- related by field – redefinitions , e.g. Weyl scaling , conformal scaling of metric
- observables cannot depend on choice of fields
- metric is one of the fields
- which picture is usefull ?

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.

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

Some aspects are understood easier :

- Beginning of Universe
- Role of scale symmetry
- Range of impact of quantum gravity

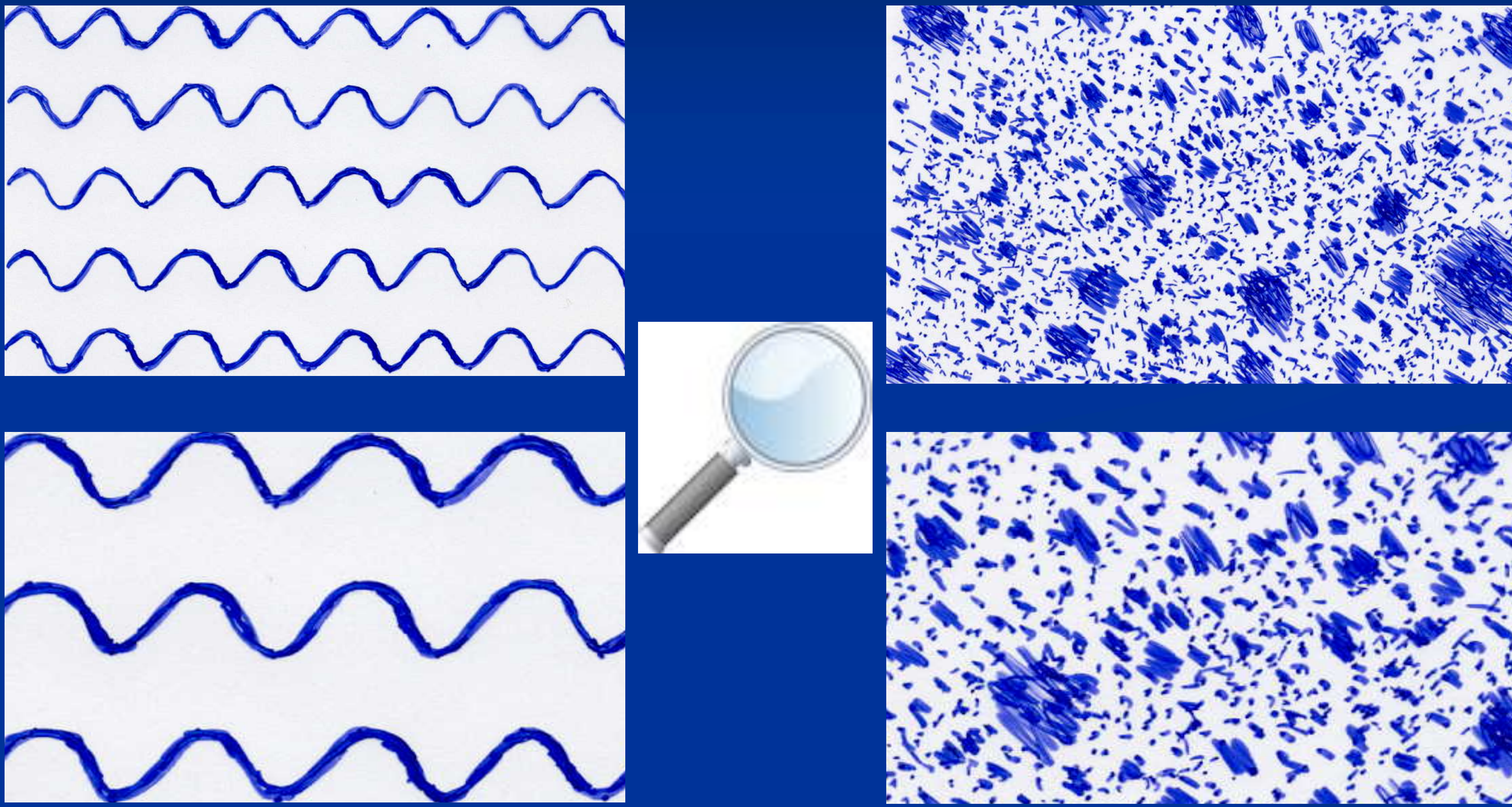
preview

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

- Quantum gravity may be observable in
  dynamics of present Universe

quantum gravity – the role of scale symmetry

Scale symmetry



no scale symmetry

scale symmetry

Scale symmetry

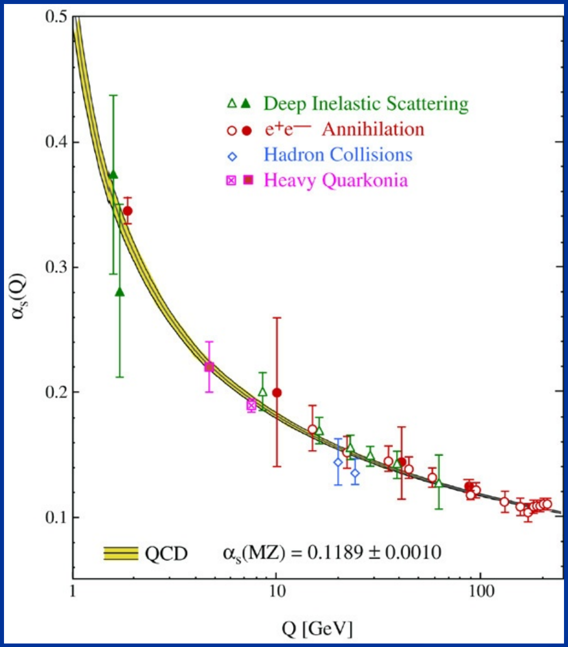
No parameter with dimension of length or mass is present.

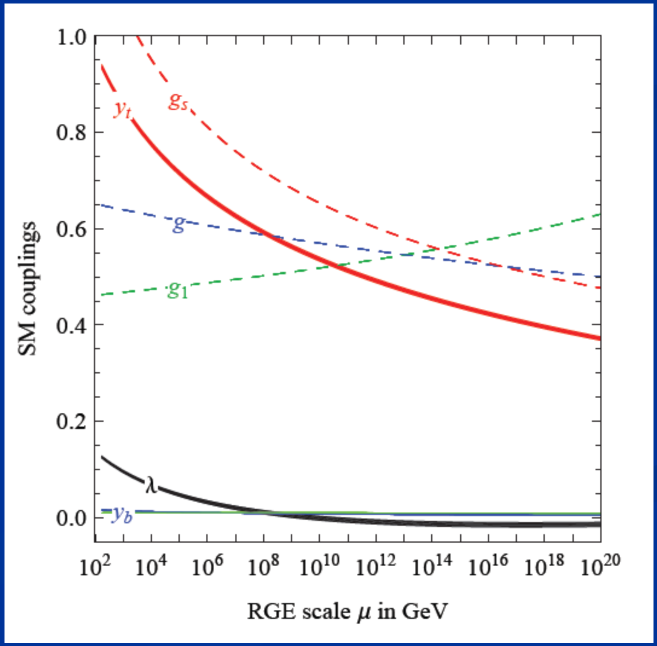
Then invariance under dilatations or global scale transformations is realized.

Continuous global symmetry

Fluctuations induce running couplings

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

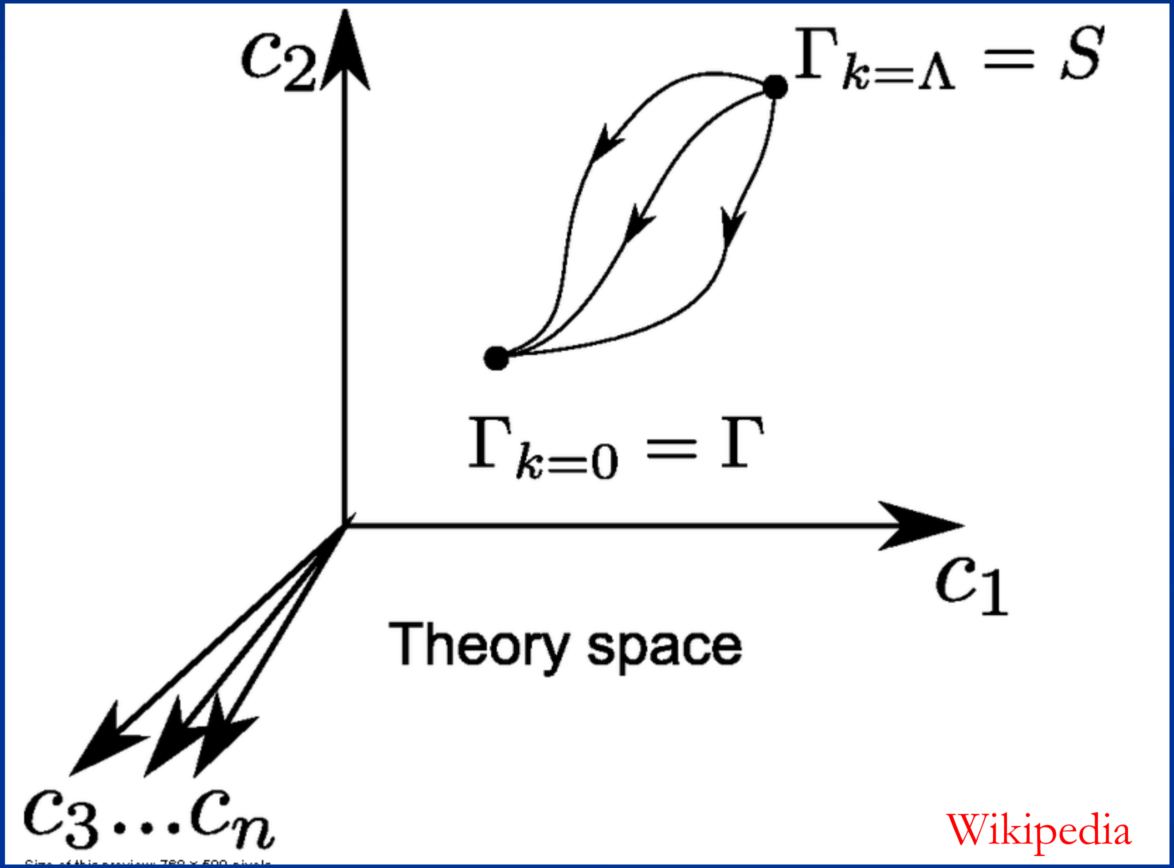




Quantum scale symmetry

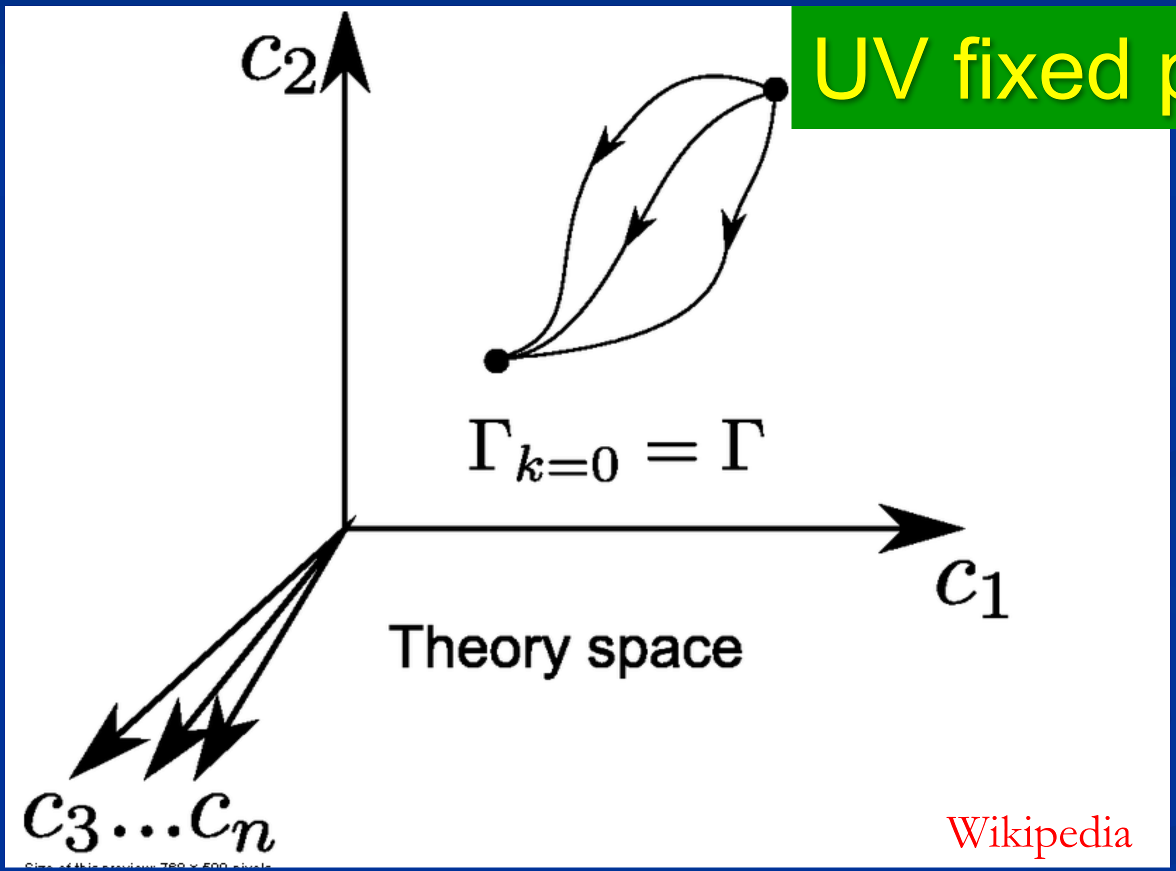
- quantum fluctuations violate scale symmetry
- running dimensionless couplings
- at fixed points , scale symmetry is exact !
- quantum fluctuations can generate scale symmetry !

Functional renormalization : flowing action



Ultraviolet fixed point

UV fixed point



Asymptotic safety of quantum gravity

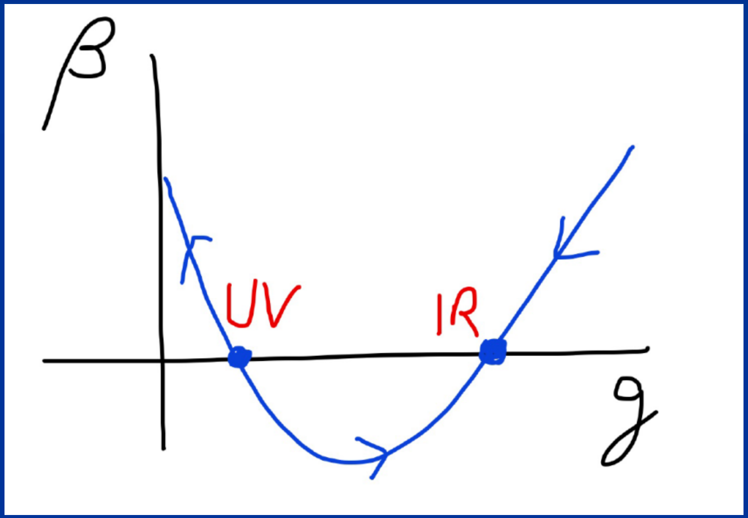
if UV fixed point exists :

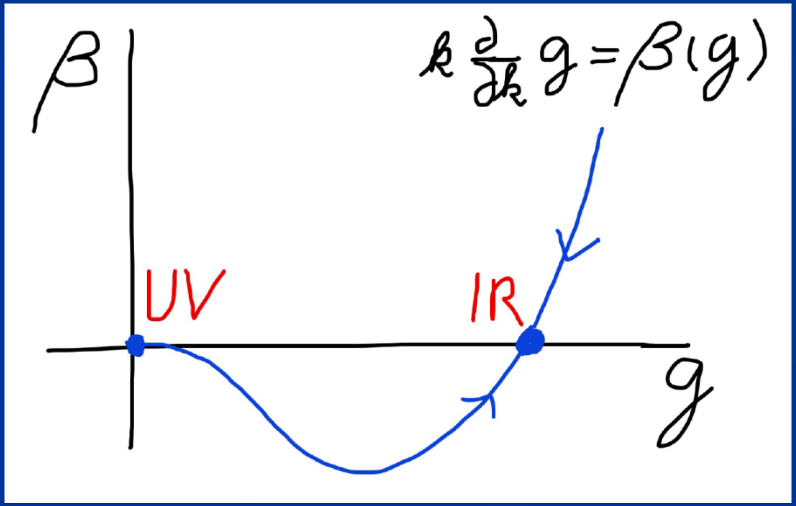
quantum gravity is

non-perturbatively renormalizable !

S. Weinberg , M. Reuter

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

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

Spontaneous breaking of scale symmetry

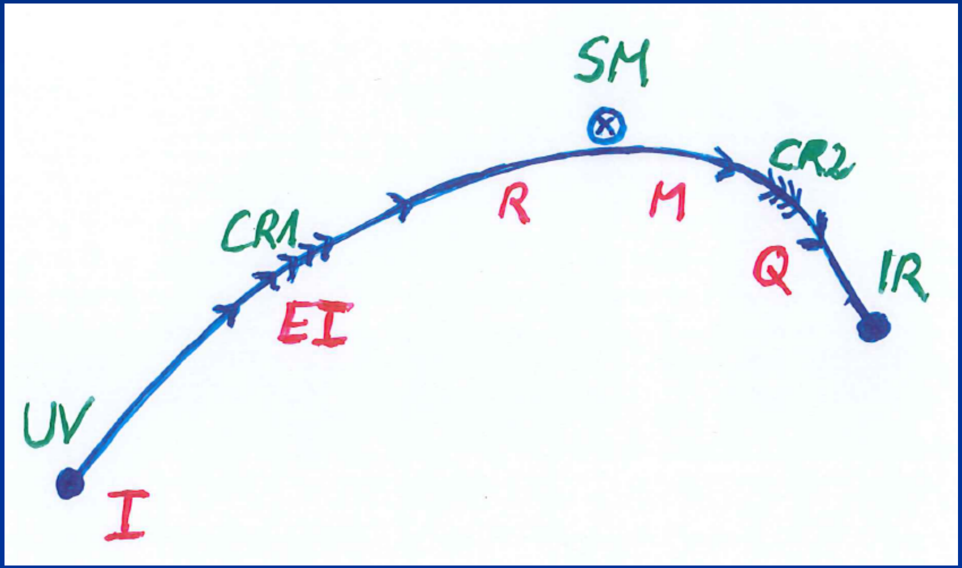
- expectation value of scalar field breaks scale symmetry spontaneously
- massive particles are compatible with scale symmetry
- in presence of massive particles : sign of exact scale symmetry is exactly massless Goldstone boson – the dilaton

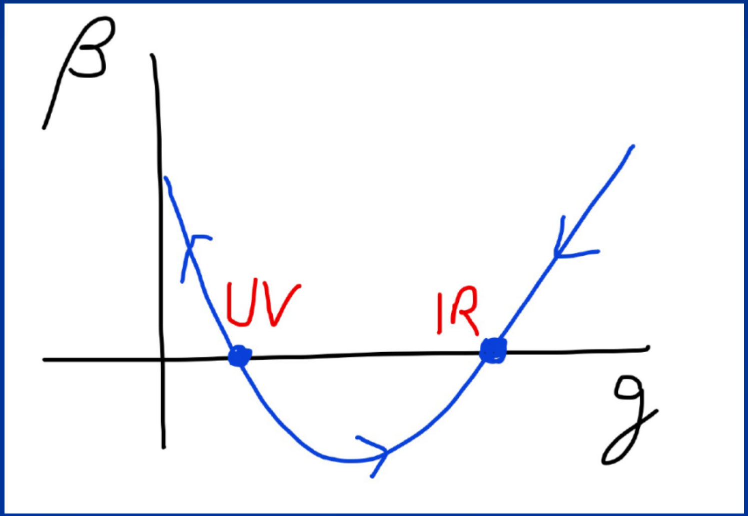
Approximate scale symmetry near fixed points

- 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"

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 symmetry in variable gravity
(IR – fixed point)

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

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

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

What is Dark Energy ?

Dark energy is energy density of scalar field χ

ρ = V + kinetic term

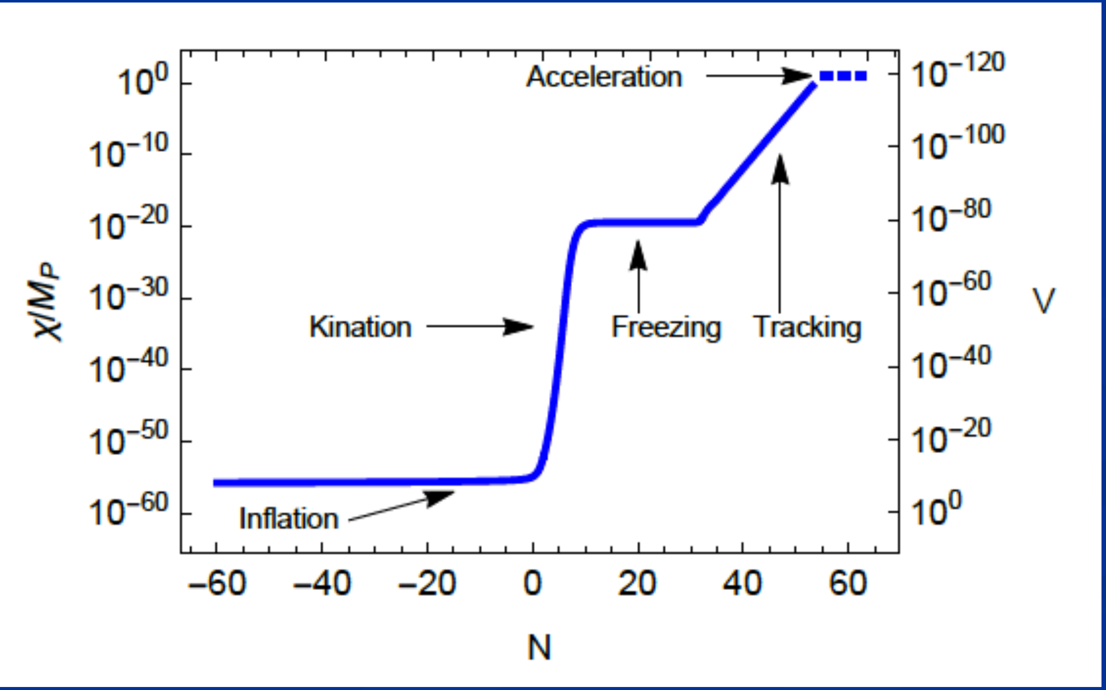
$$V = \mu^2 \chi^2$$

p = -V + kinetic term

Dark energy is dynamical if χ changes with time

Cosmological solution

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



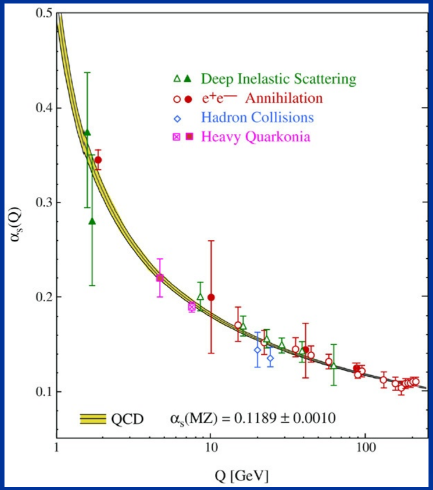
J.Rubio,…

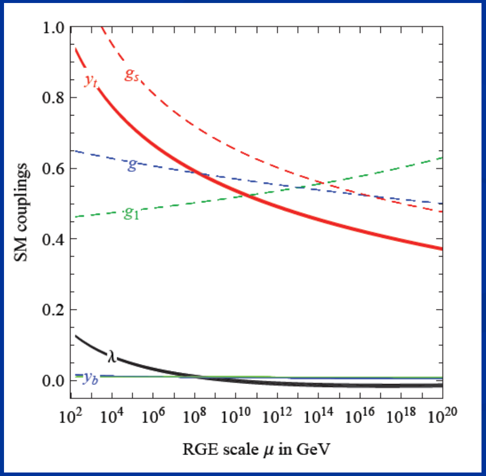
Kinetial B : running coupling

- B varies if intrinsic scale μ changes

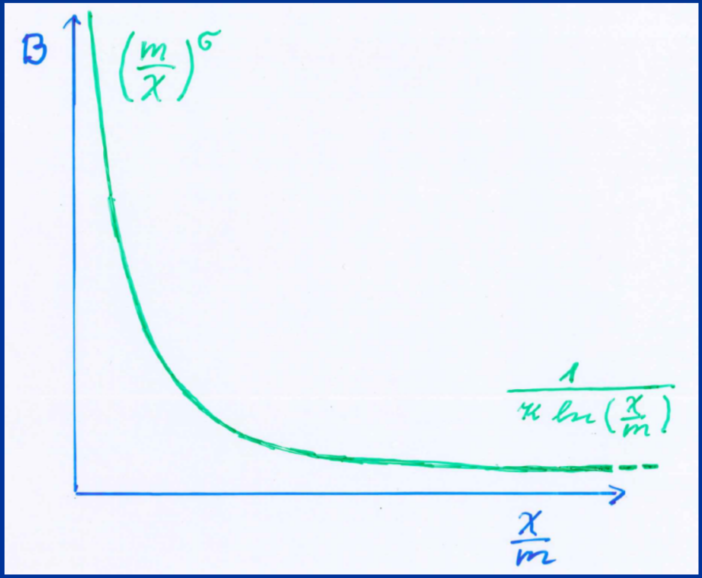
$$\Gamma = \int_x \sqrt{g} \left\{ -\frac{1}{2}\chi^2 R + \mu^2\chi^2 + \frac{1}{2}\left(B(\chi/\mu) - 6\right)\partial^\mu\chi\partial_\mu\chi \right\}$$

- similar to QCD or standard model





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

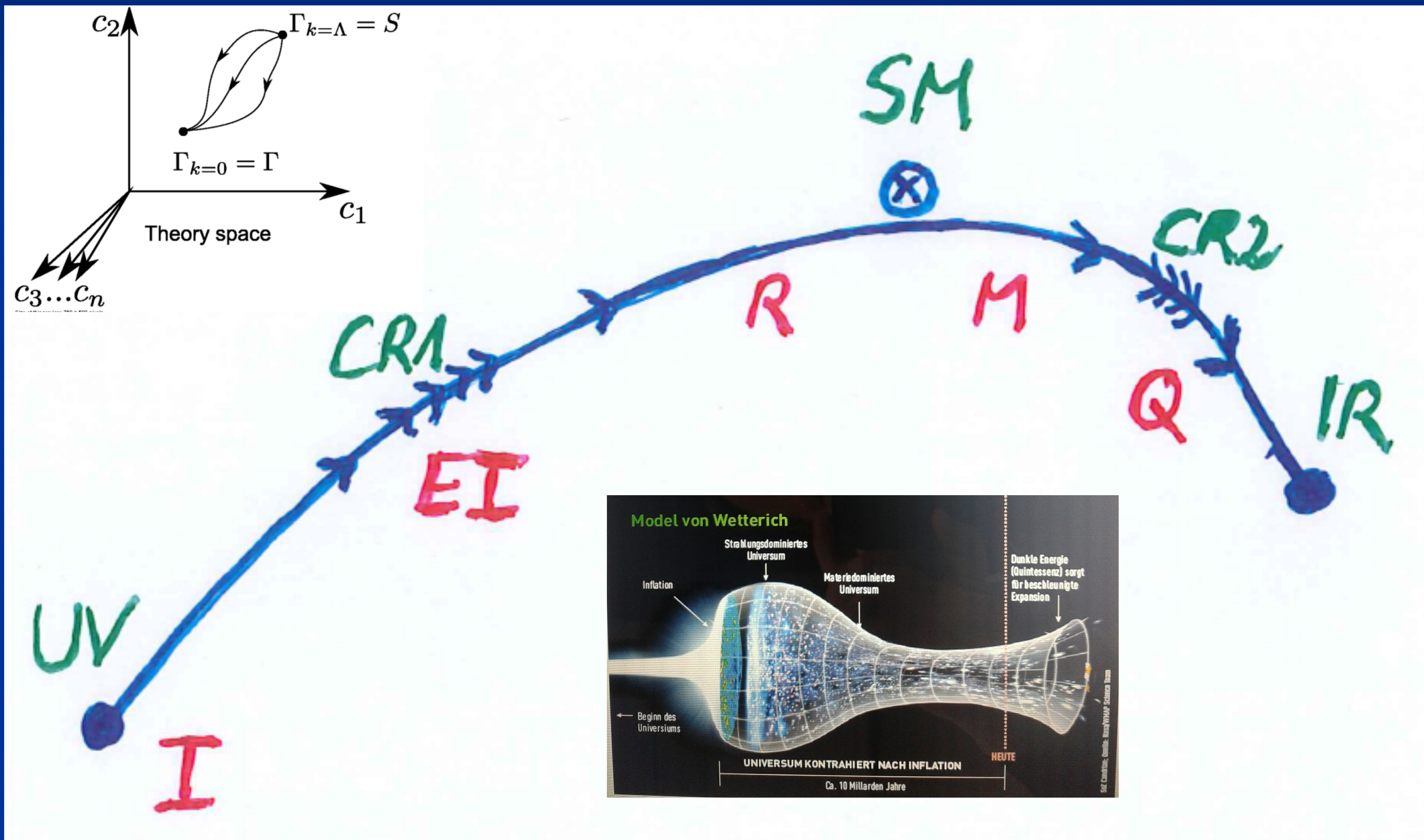
Together with variation of neutrino mass over electron mass in present cosmological epoch :

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

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

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

Crossover in quantum gravity and cosmology

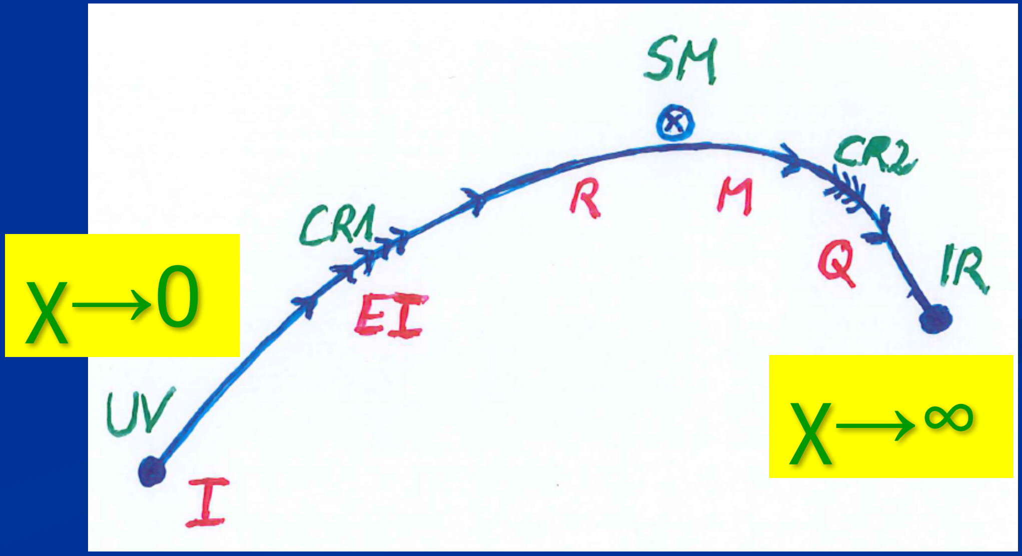


Cosmological solution : crossover from UV to IR fixed point

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

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

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

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 :

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

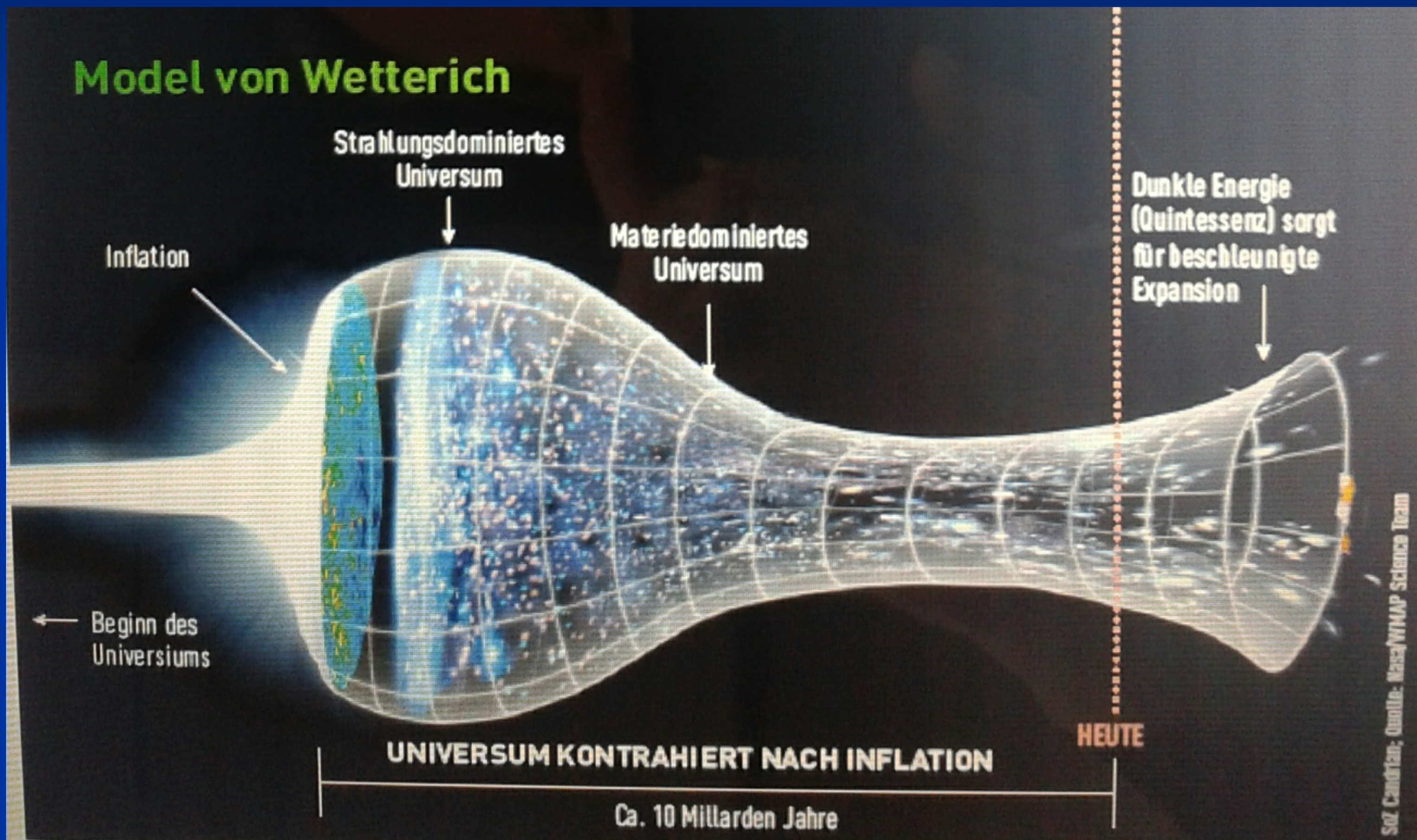
$$\mu = 2 \cdot 10^{-33} \, \text{eV}$$

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

- "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 :

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

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

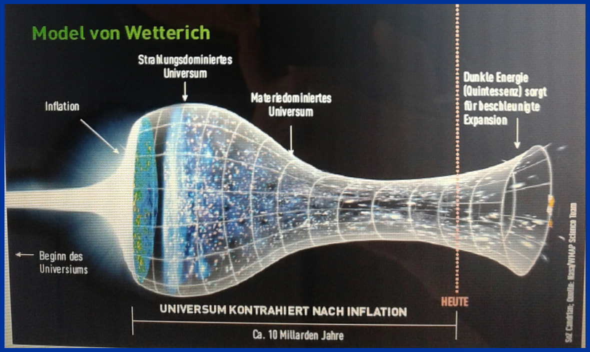
$$k^2 = \frac{\alpha^2 B}{4}$$

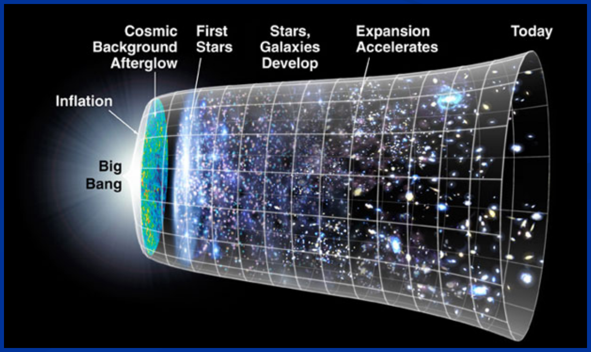
Field relativity

Weyl scaling :

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

changes geometry,
not a coordinate transformation





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

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

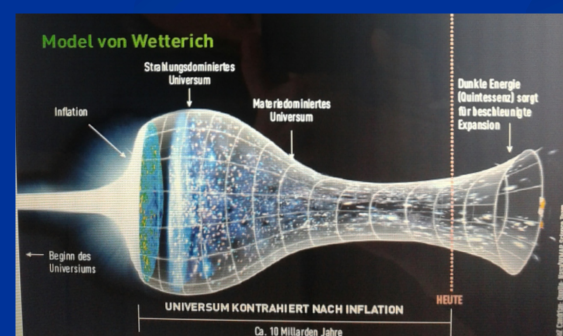
particles become massless in infinite past !

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



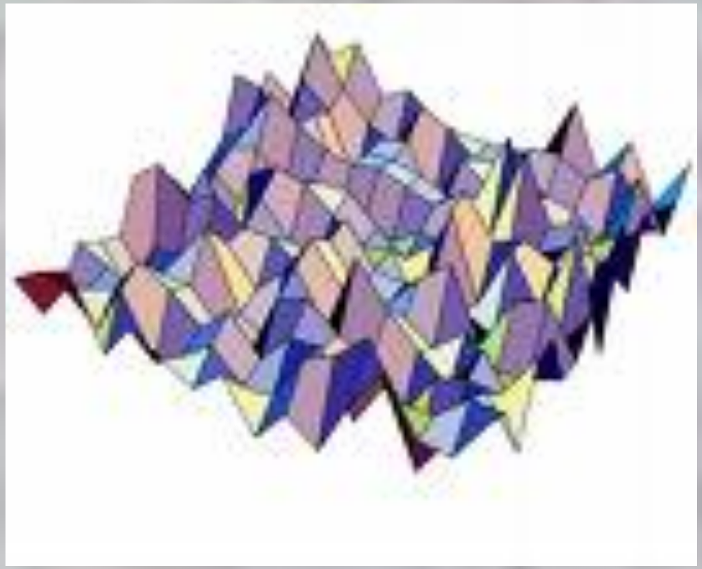
- physical time to infinite past is infinite

Eternal light-vacuum

Everywhere almost nothing
only fluctuations

All particles move
with light velocity,
similar to photons

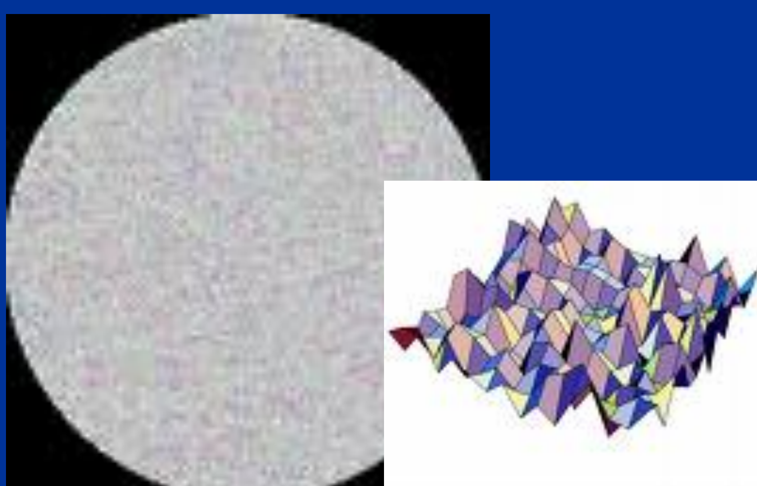
strength of gravity
much stronger than today

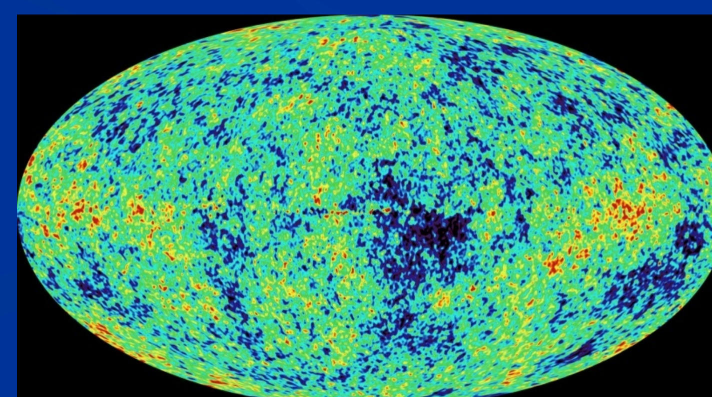


In the beginning was light-like emptiness.

Eternal light-vacuum is unstable

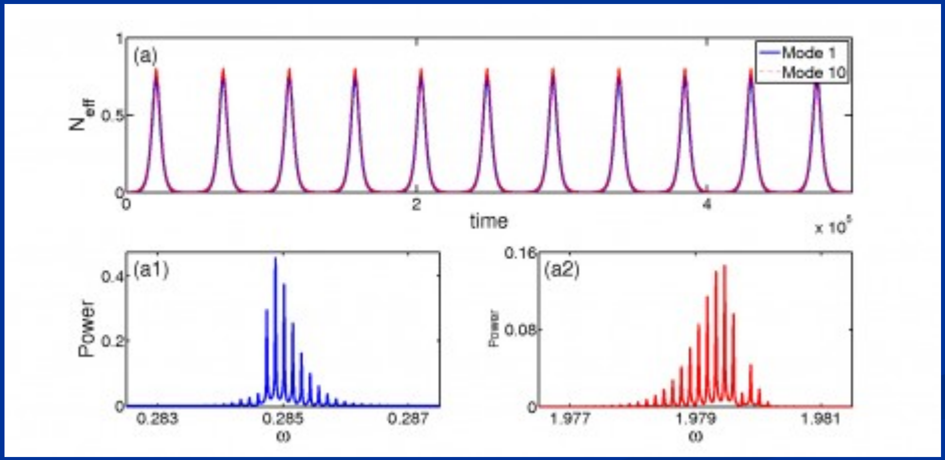
- Slow increase of particle masses and weakening of gravity
- Only slow change of space-time geometry
- Consequence for observation : primordial fluctuations become visible in cosmic background radiation
- We see fluctuations in a stage 5000 billion years ago.





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

$$\tilde{t}_p = n_k \qquad n_k = \frac{k\eta}{\pi}$$

(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 !

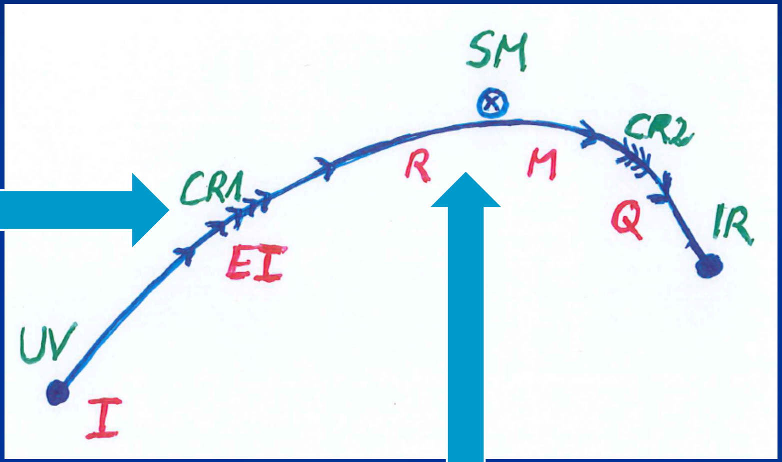
Field - singularity

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

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

Scaling solution

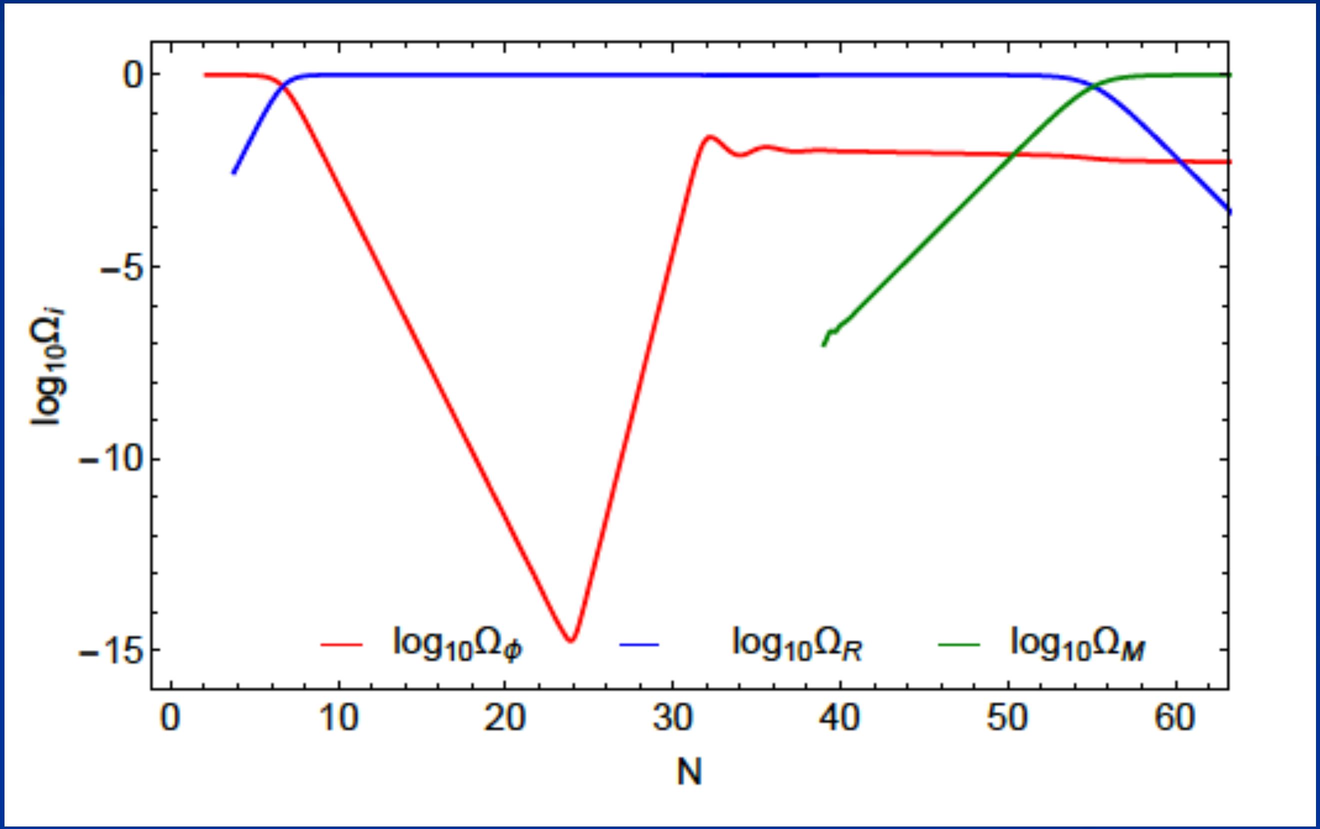
after end of inflation



scaling solution with
few percent
of Early Dark Energy

Dark Energy decreases similar to radiation and matter

Evolution of dark energy fraction

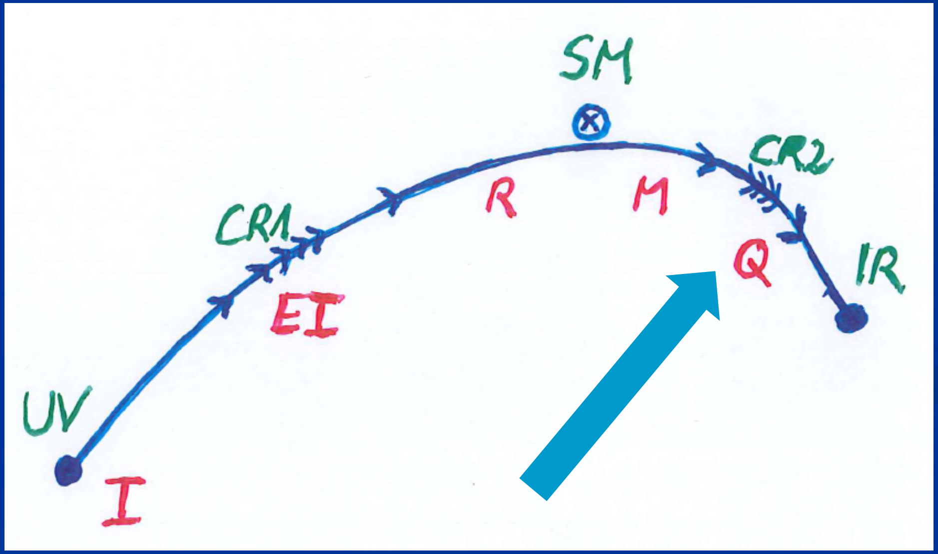


J. Rubio,…

Growing neutrino masses
and
quintessence

Second stage of crossover

- from SM to IR
- in sector Beyond Standard Model
- affects neutrino masses first (seesaw or cascade mechanism)



Varying particle masses at onset of second crossover

- **Except for neutrinos** all particle masses are proportional to χ .
- Ratios of particle masses remain constant.
- Compatibility with observational bounds on time dependence of particle mass ratios.
- Neutrino masses show stronger increase with χ , such that **ratio neutrino mass over electron mass grows** .

Cosmic trigger

- Stop of evolution of scalar field when neutrinos become non-relativistic
- Transition from scaling solution to (almost) cosmological constant

connection between dark energy and neutrino properties

$$[\rho_h(t_0)]^{\frac{1}{4}} = 1.27 \left(\frac{\gamma m_\nu(t_0)}{eV}\right)^{\frac{1}{4}} 10^{-3} eV$$

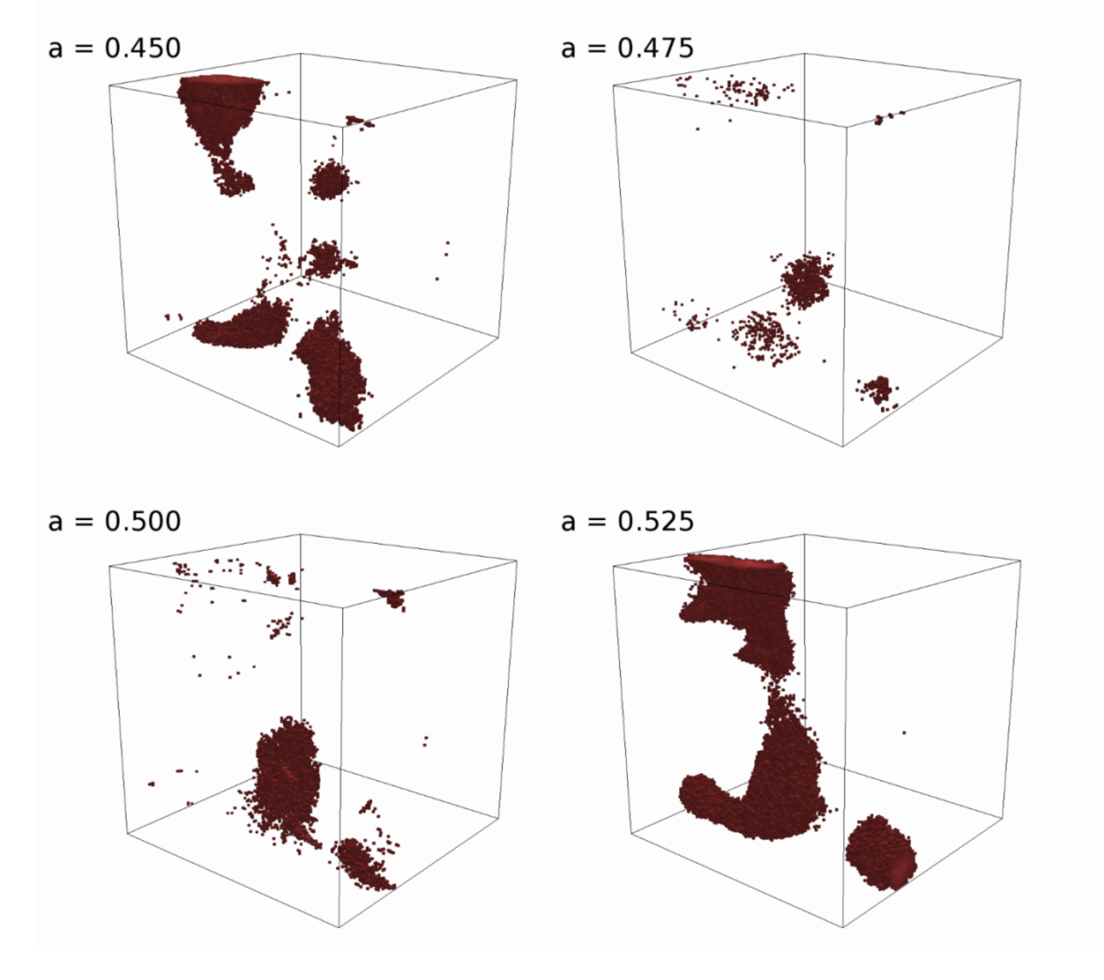
L.Amendola, M.Baldi, …

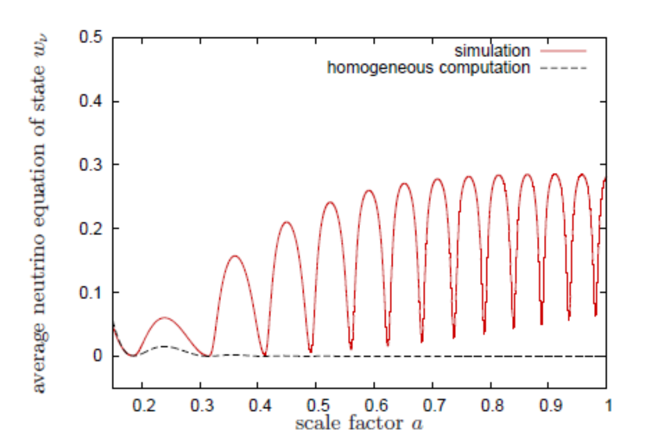
present dark energy density given by neutrino mass

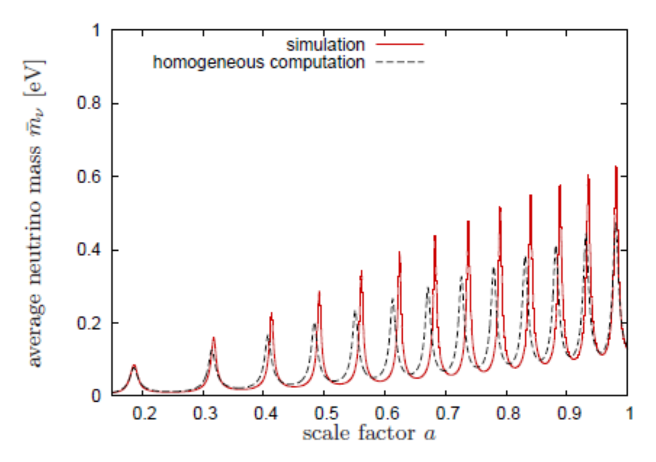
present equation of state given by neutrino mass !

$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12\mathrm{eV}}$$

Oscillating neutrino lumps



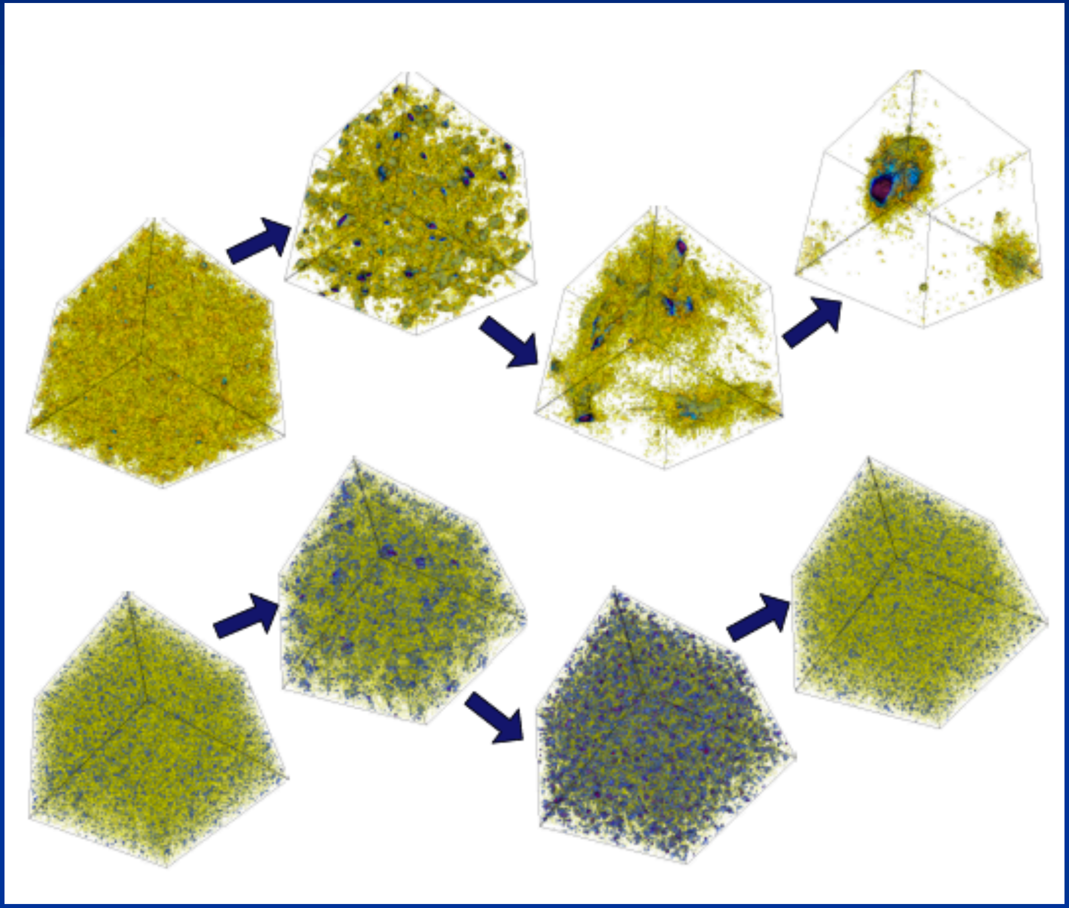




Y.Ayaita, M.Weber,…

Ayaita, Baldi, Fuehrer, Puchwein,…

Neutrino lumps

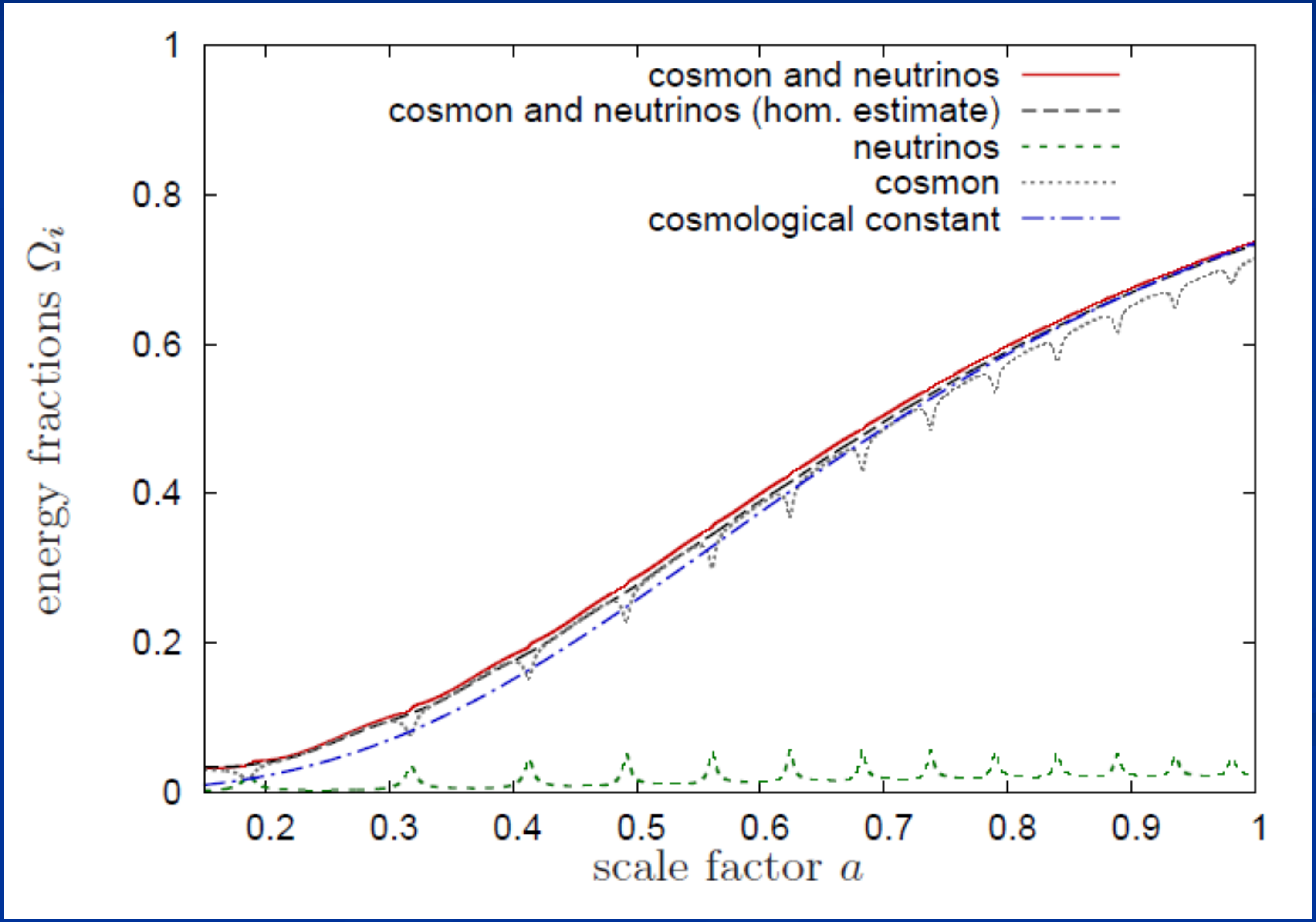


large m_ν

small m_ν

Casas, Pettorino,…

Evolution of dark energy similar to ΛCDM



Conclusions

Quantum gravity may be observable in dynamics of present Universe

Fixed points and scale symmetry crucial

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

Compatibility with observations and possible tests

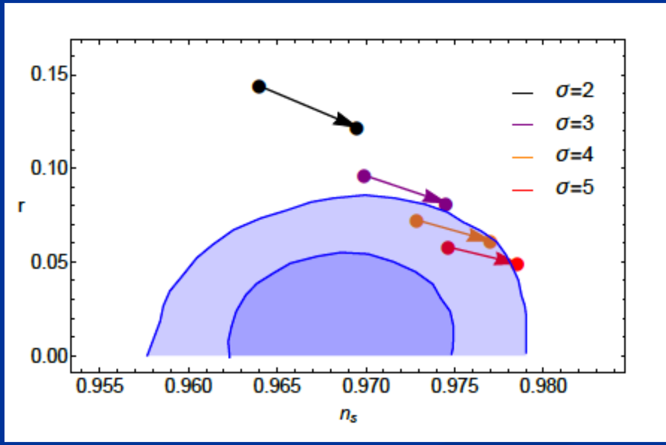
- Realistic inflation model
- Almost same prediction for radiation, matter, and Dark Energy domination as ΛCDM
- Presence of small fraction of Early Dark Energy
- Large neutrino lumps

Simplicity

simple description of all cosmological epochs

natural incorporation of Dark Energy :

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



J.Rubio…

end

No small parameter for dark energy

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

asymptotically vanishing cosmological „constant“

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

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

$V = \mu^2 \chi^2$

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

small dimensionless number ?

- needs two intrinsic mass scales
- standard approach :V and M (cosmological constant and Planck mass)
- variable gravity : Planck mass moving to infinity , with fixed V ➡ ratio vanishes asymptotically !

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 :

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

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

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

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)

In quantum gravity,
the graviton fluctuations can
play an important role on
distances as large as the
size of the Universe

- for long range scalar fields and dynamical dark energy
- not for all quantities

Instability of graviton propagator

effective action $$\Gamma = \int_x \sqrt{g}\left(-\frac{M^2}{2}R + V\right)$$

flat space: $$G^{-1} = \frac{M^2 q^2}{4} - \frac{V}{2}$$

Instability for V>0 : "tachyonic mass term" $-\frac{2V}{M^2}$

curved space: $$G^{-1} = \sqrt{g}\left\{\frac{M^2}{4}\left(-D^2 + \frac{2R}{3}\right) - \frac{V}{2}\right\}$$

Graviton barrier

Quantum gravity computation :

For $\chi \to \infty$

V cannot increase stronger than M^2 !

Instability of graviton propagator is avoided

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

$$\mathbf{M} = \chi \quad : \quad \mathbf{V} = \mu^2 \chi^2$$

end

Amplitude of density fluctuations

small because of logarithmic running near UV fixed point !

$$\mathcal{A} = \frac{(N+3)^3}{4} e^{-2c_t}$$

$$c_t = \ln\left(\frac{m}{\mu}\right) = 14.1.$$

σ=1

$$\frac{m}{\mu} = \frac{(N+3)^{\frac{3}{2}}}{2\sqrt{\mathcal{A}}} = 1.32 \cdot 10^6 \left(\frac{N}{60}\right)^{\frac{3}{2}}$$

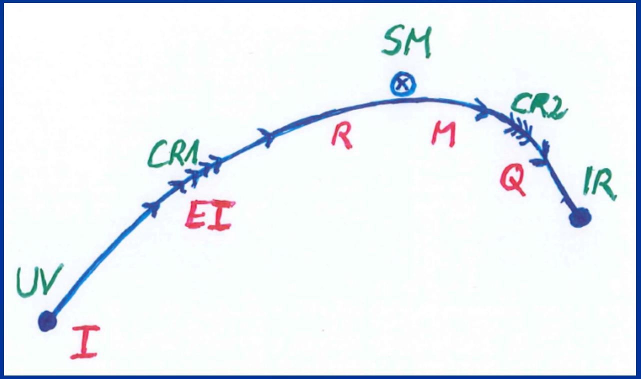
$$B^{-1} - \frac{\kappa}{\sigma} \ln B = \kappa \left[\ln\left(\frac{\chi}{\mu}\right) - c_t \right] = \kappa \ln\left(\frac{\chi}{m}\right)$$

N : number of e – foldings at horizon crossing

Origin of mass

- UV fixed point : scale symmetry unbroken

  all particles are massless



- IR fixed point :

  scale symmetry spontaneously broken,

  massive particles , massless dilaton

- crossover : explicit mass scale μ important

- approximate SM fixed point : approximate scale symmetry spontaneously broken, massive particles , almost massless cosmon, tiny cosmon potential

On shell graviton propagator

$$G^{-1} = \sqrt{g}\left\{\frac{M^2}{4}\left(-D^2 + \frac{2R}{3}\right) - \frac{V}{2}\right\}$$

on shell :
(for solution of field equations)

$$R = \frac{4V}{M^2}$$

homogenous isotropic metric,
conformal time

$$g_{\mu\nu} = a^2(\eta)\,\delta_{\mu\nu} \qquad \mathcal{H} = \frac{\partial \ln a}{\partial \eta}$$

inverse graviton
propagator in
de Sitter space

$$a^{-2}\left(-D^2 + \frac{R}{6}\right)a^2 = \frac{1}{a^2}\left(\partial_\eta^2 + 2\mathcal{H}\partial_\eta + \vec{q}^{\,2}\right)$$

milder instability, not tachyonic, absent for
cosmologies close to de Sitter space

IR – instability for graviton fluctuations

problem solved ?

- yes for primordial cosmic fluctuations (on shell)
- no for quantum gravity (off shell)
- Computation of effective action is an off-shell problem.
- example : one needs the effective potential for the Higgs field in the vicinity of its minimum (off shell), not only at the minimum (on shell)

Quantum gravity with scalar field

M² and V depend on scalar field χ

$$M^2 = c_1 + c_2\,\chi^2 \qquad V = d_1 + d_2\,\chi^2 + d_3\,\chi^4$$

question : behavior of V for $\chi \to \infty$

- $d_3 \neq 0$ excluded!
- $d_3 < 0$ unstable potential
- $d_3 > 0$ instability of graviton propagator