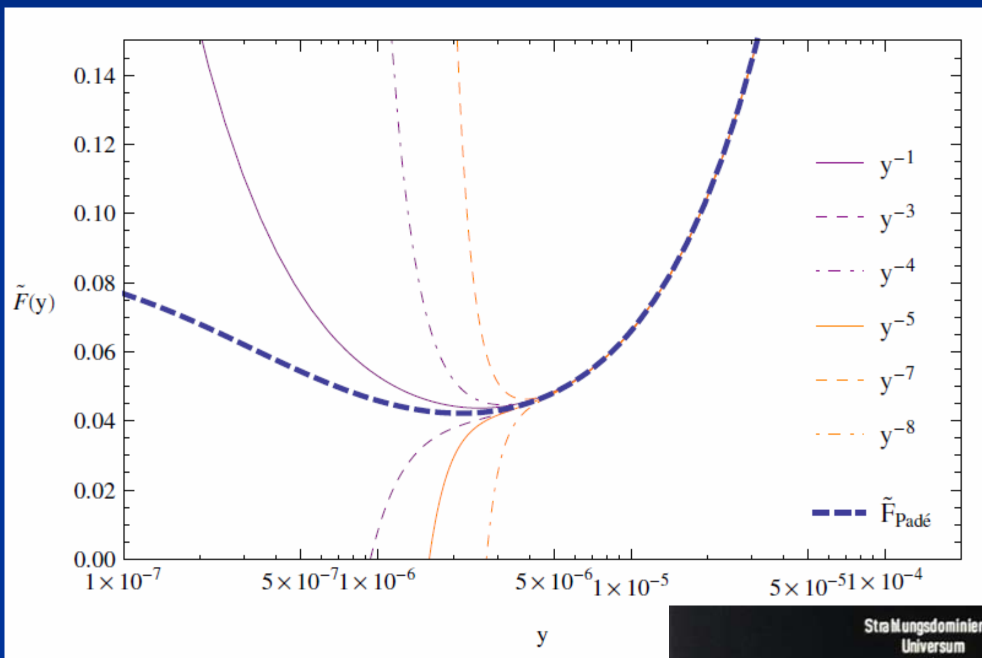
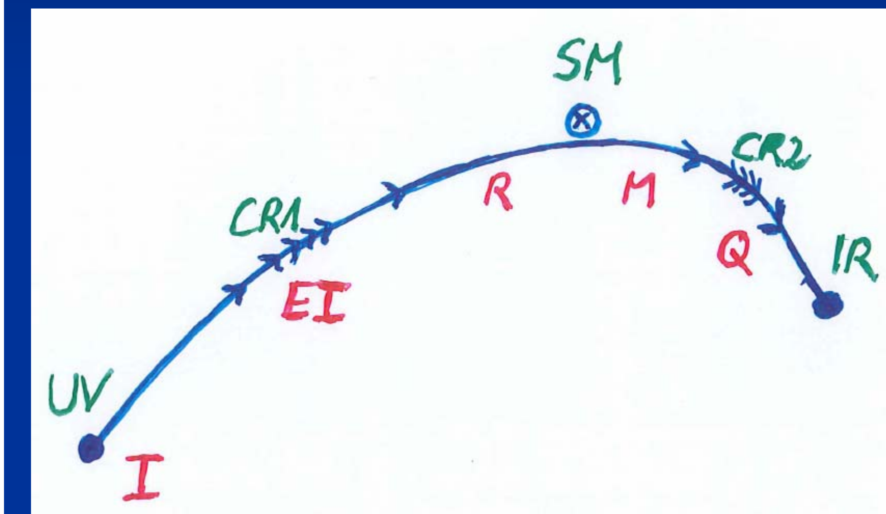
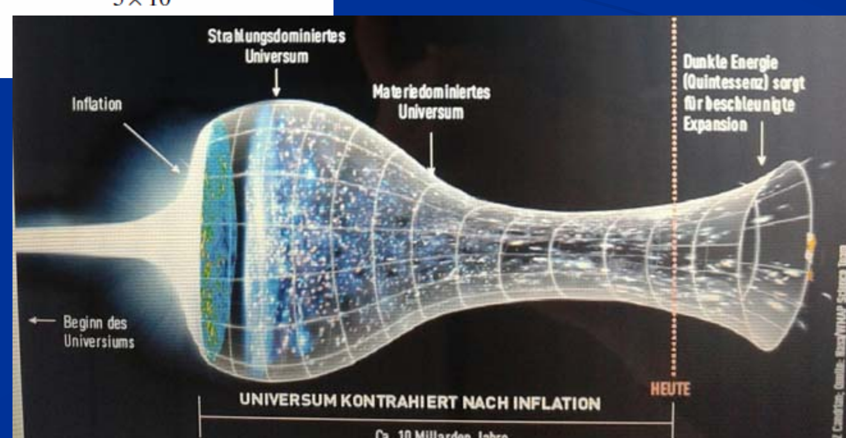
Dilaton quantum gravity and cosmology







Dilaton quantum gravity

Dilaton Quantum Gravity

T. Henz, J. M. Pawlowski, A. Rodigast, and C. Wetterich

Functional renormalization flow,

with truncation :

$$\Gamma_k = \int d^4x \sqrt{g} \left(V_k(\chi^2) - \frac{1}{2} F_k(\chi^2)\, R + \frac{1}{2} g^{\mu\nu} \partial_\mu \chi \partial_\nu \chi \right)$$

Functional renormalization equations

$$V_k = k^4\, y^2\, v_k(y), \;\; F_k = k^2\, y\, f_k(y)$$

$$y = \frac{\chi^2}{k^2}$$

$$\partial_t v_k(y) \;=\; 2\,y\,v_k'(y) + \frac{1}{y^2}\,\zeta_V$$

$$\partial_t f_k(y) \;=\; 2\,y\,f_k'(y) + \frac{1}{y}\,\zeta_F\,.$$

$$\zeta_V \;=\; \frac{1}{192\pi^2}\left\{6 + \frac{30\,\tilde V}{\Sigma_0} + \frac{3(2\Sigma_0 + 24\,y\,\tilde F'\,\Sigma_0' + \tilde F\Sigma_1)}{\Delta} + \delta_V\right\},$$

$$\begin{aligned}\zeta_F \;=\; \frac{1}{1152\pi^2}\Bigg\{&150 + \frac{30\,\tilde F\,(3\,\tilde F - 2\tilde V)}{\Sigma_0^2} \\ &-\frac{12}{\Delta}\left(24\,y\,\tilde F'\,\Sigma_0' + 2\Sigma_0 + \tilde F\Sigma_1\right) - 6y\,(3\,\tilde F'^2 + 2\Sigma_0'^2) \\ &-\frac{36}{\Delta^2}\Big[2y\,\Sigma_0\,\Sigma_0'\,(7\,\tilde F' - 2\tilde V')\,(\Sigma_1 - 1) + 2\,\Sigma_0^2\,\Sigma_2 \\ &+2\,y\Sigma_1\,(7\,\tilde F' - 2\tilde V')\,(2\,\Sigma_0\,\tilde V' - \tilde V\,\Sigma_0') \\ &+24\,y\,\tilde F'\,\Sigma_0\,\Sigma_0'\,\Sigma_2 - 12\,y\,\tilde F\,\Sigma_0'^2\,\Sigma_2\Big] + \delta_F\Bigg\}.\end{aligned} \qquad (10)$$

$$\tilde V = y^2\,v_k(y)\;,\;\; \tilde F \;=\; y\,f_k(y),$$

$$\Sigma_0 = \frac{1}{2}\tilde F - \tilde V\;,\;\; \Delta \;=\; (12\,y\,\Sigma_0'^2 + \Sigma_0\,\Sigma_1)$$

$$\Sigma_1 = 1 + 2\,\tilde V' + 4\,y\,\tilde V''\;,\;\; \Sigma_2 \;=\; \tilde F' + 2\,y\,\tilde F''.$$

Percacci, Narain

Fixed point for large scalar field

$$\lim_{y\to\infty} f(y) = \xi$$

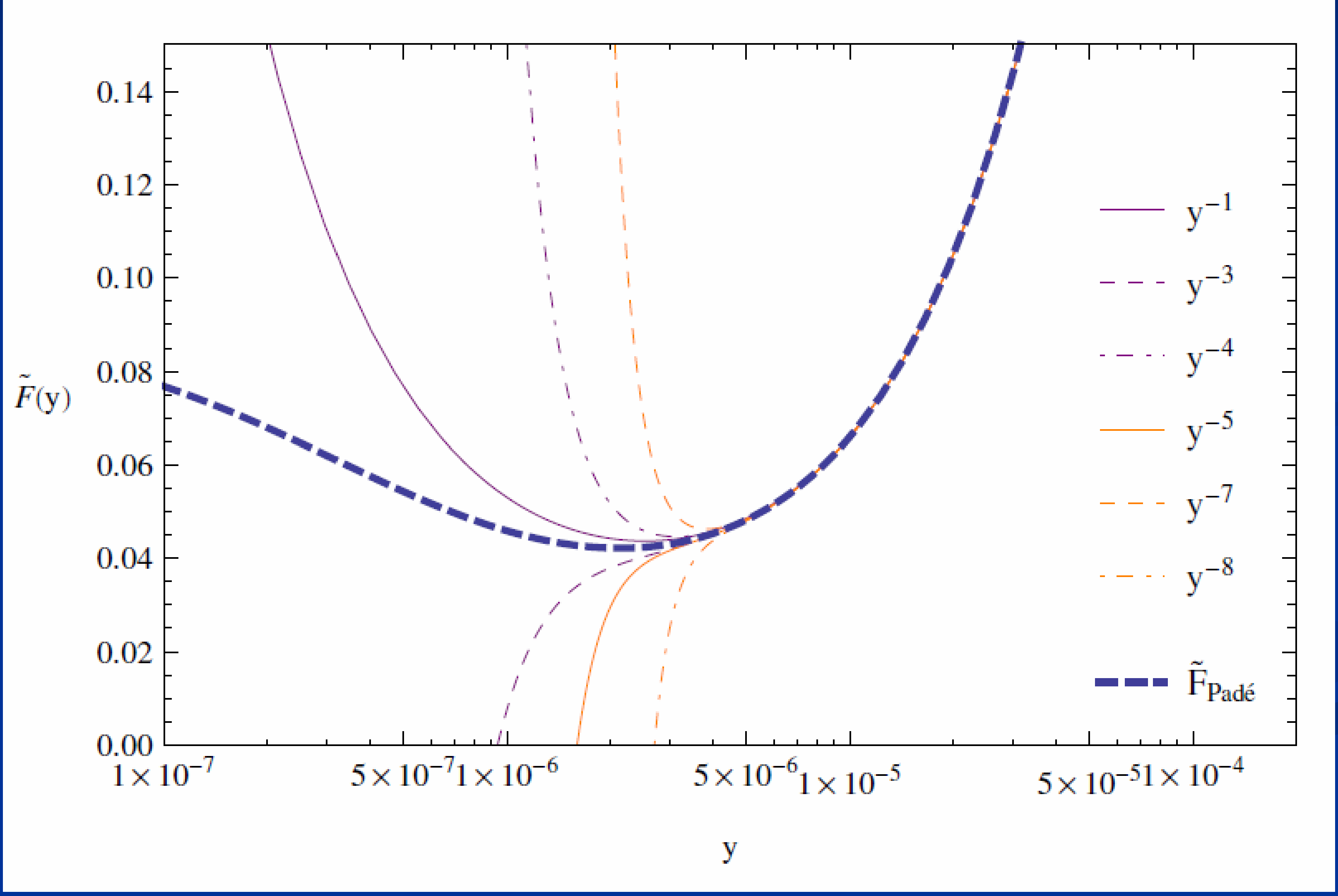
$$\lim_{y\to\infty} v(y) = 0$$

$$\Gamma = \int d^4x \sqrt{g} \left(\frac{1}{2} g^{\mu\nu} \partial_\mu \chi \, \partial_\nu \chi - \frac{1}{2} \xi \chi^2 R \right)$$

This fixed point describes already realistic gravity !

Limit k → 0 can be taken !

Fixed point for large scalar field



Vicinity of fixed point

$$\partial_t V = \bar{\zeta}_V k^4 \ , \ \partial_t F = \bar{\zeta}_F k^2$$

$$\bar{\zeta}_V = -\frac{1}{48\pi^2}\left(6 - \frac{\partial_t f_0}{f_0}\right),$$
$$\bar{\zeta}_F = \frac{1}{1728\pi^2}\left(249 - 41\frac{\partial_t f_0}{f_0}\right)$$

solution :

$$V = \frac{\bar{\zeta}_V}{4}k^4 + \bar{V},$$
$$F = \xi\chi^2 + \frac{\bar{\zeta}_F}{2}k^2 + \bar{F}$$

$$\Gamma = \int d^4x\sqrt{g}\left(\frac{1}{2}g^{\mu\nu}\partial_\mu\chi\partial_\nu\chi - \frac{1}{2}(\xi\chi^2 + \bar{F})R + \bar{V}\right)$$

Cosmology with dynamical dark energy !

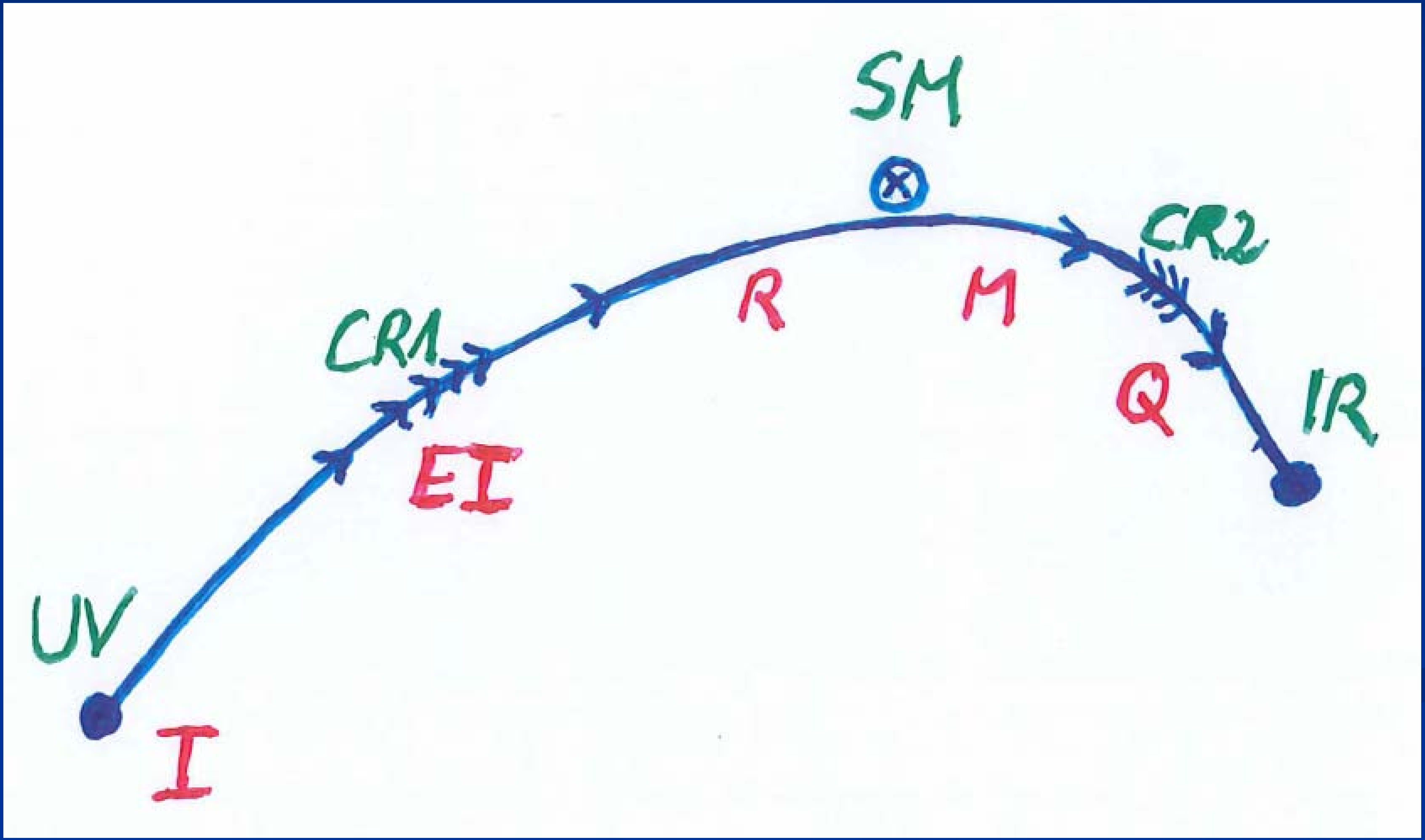
Cosmological constant vanishes asymptotically !

open …

- full scaling solution
- behavior for negative kinetic term close to conformal value

a guess for dilaton quantum gravity and its cosmological consequence

Crossover in quantum gravity



Approximate scale symmetry near fixed points

- UV : approximate scale invariance of primordial fluctuation spectrum from inflation

- IR : almost massless pseudo-Goldstone boson (cosmon) responsible for dynamical Dark Energy

Variable Gravity

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

scale invariant for $\mu = 0$ and B const.

quantum effects : flow equation for kinetial

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

Variable Gravity

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

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

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
- Planck mass grows large dynamically

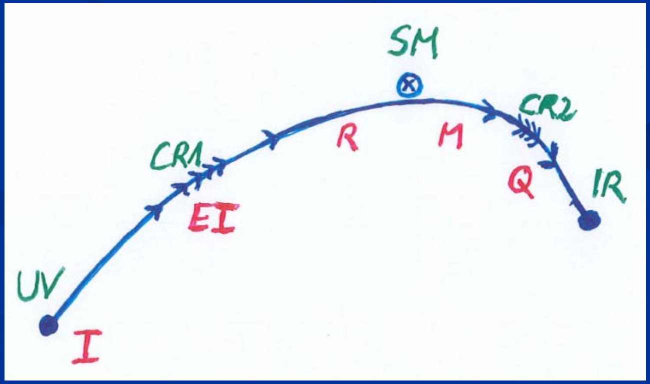
Infrared fixed point

- $\mu \to 0$
- $B \to 0$

$$\mu \partial_\mu B = \kappa B^2 \qquad \text{for} \qquad B \to 0$$

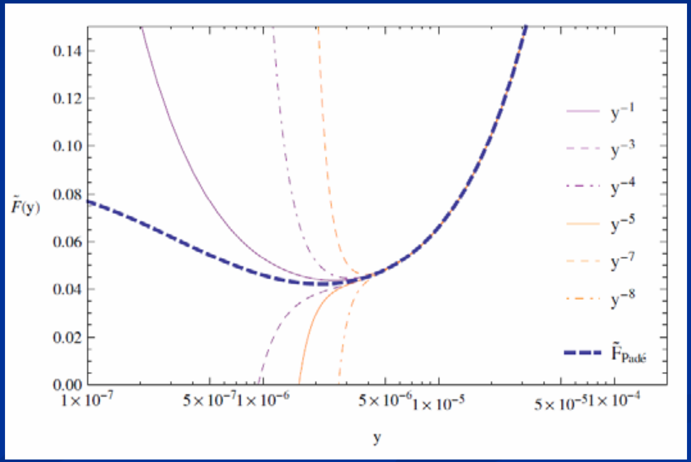
$$\Gamma = \int_x \sqrt{g} \left\{ -\frac{1}{2}\chi^2 R + \mu^2 \chi^2 + \frac{1}{2}\left(B(\chi/\mu) - 6\right)\partial^\mu \chi \partial_\mu \chi \right\}$$

- no intrinsic mass scale
- scale symmetry

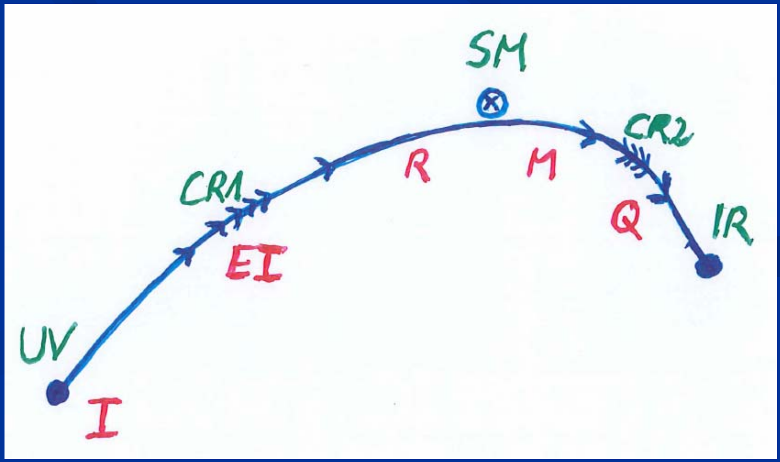


Fixed points and limits for sclar field

- Dimensionless functions as B depend only on ratio μ/χ .
- IR: μ→0 , χ→∞ / y →∞
- UV: μ→∞ , χ→0 / y →0

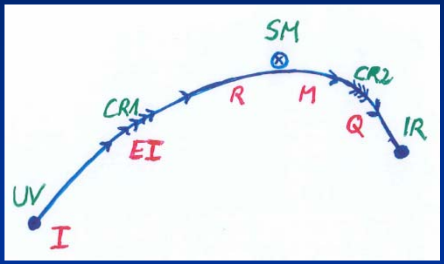


Cosmology makes crossover between fixed points by variation of χ .



Ultraviolet fixed point

- μ→ ∞



- kinetial diverges

$$B = b\left(\frac{\mu}{\chi}\right)^{\sigma} = \left(\frac{m}{\chi}\right)^{\sigma}$$

- scale symmetry with anomalous dimension σ

$$g_{\mu\nu} \to \alpha^2 g_{\mu\nu} \ , \ \chi \to \alpha^{-\frac{2}{2-\sigma}}\chi$$

Renormalized field at UV fixed point

$$\chi_R = b^{\frac{1}{2}} \left(1 - \frac{\sigma}{2}\right)^{-1} \mu^{\frac{\sigma}{2}} \chi^{1-\frac{\sigma}{2}}$$

$1 < \sigma < 2$

$$\Gamma_{UV} = \int_x \sqrt{g} \left\{ \frac{1}{2} \partial^\mu \chi_R \partial_\mu \chi_R - \frac{1}{2} C R^2 + D R^{\mu\nu} R_{\mu\nu} \right\}$$

no mass scale

$$\Delta\Gamma_{UV} = \int_x \sqrt{g} E \left(\mu^2 - \frac{R}{2} \right) \mu^{-\frac{2\sigma}{2-\sigma}} \chi_R^{\frac{4}{2-\sigma}},$$

$$E = b^{-\frac{2}{2-\sigma}} \left(1 - \frac{\sigma}{2}\right)^{\frac{4}{2-\sigma}}$$

deviation from fixed point vanishes for $\mu \to \infty$

Asymptotic safety

if UV fixed point exists :

quantum gravity is

non-perturbatively renormalizable !

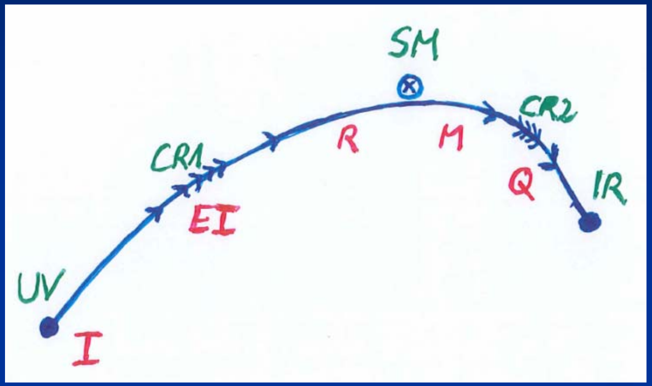
S. Weinberg , M. Reuter

Quantum scale symmetry

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

Crossover between two fixed points

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



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

m : scale of crossover

can be exponentially larger than intrinsic scale μ

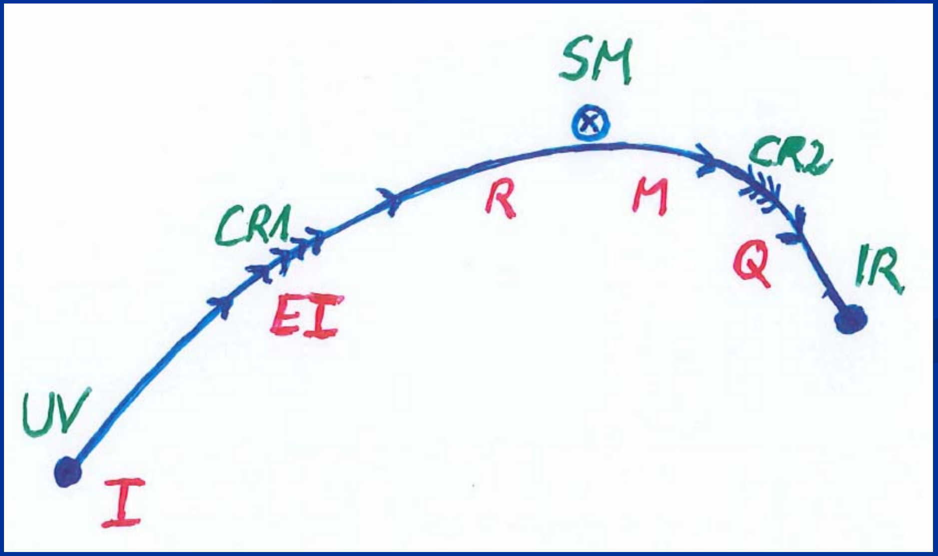
Origin of mass

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

Cosmological solution : crossover from UV to IR fixed point

- Dimensionless functions as B depend only on ratio μ/χ .
- IR: μ→0 , χ→∞
- UV: μ→∞ , χ→0

Cosmology makes crossover between fixed points by variation of χ .



Simplicity

simple description of all cosmological epochs

natural incorporation of Dark Energy :

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

Model is compatible with present observations

Together with variation of neutrino mass over electron mass during second stage of crossover :

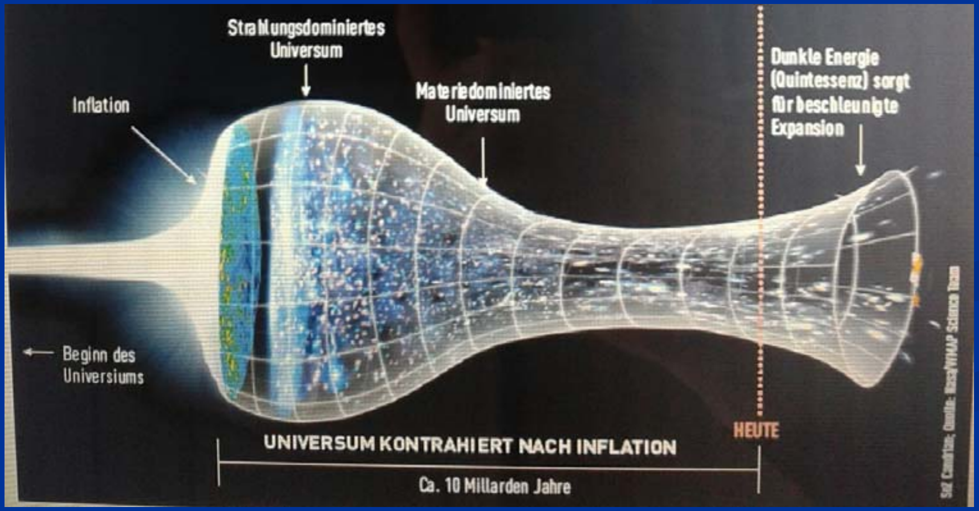
model is compatible with all present observations

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

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

Expansion

- Inflation : Universe expands
- Radiation : Universe shrinks
- Matter : Universe shrinks
- Dark Energy : Universe expands



Big bang or freeze ?

***NATURE* | NEWS**

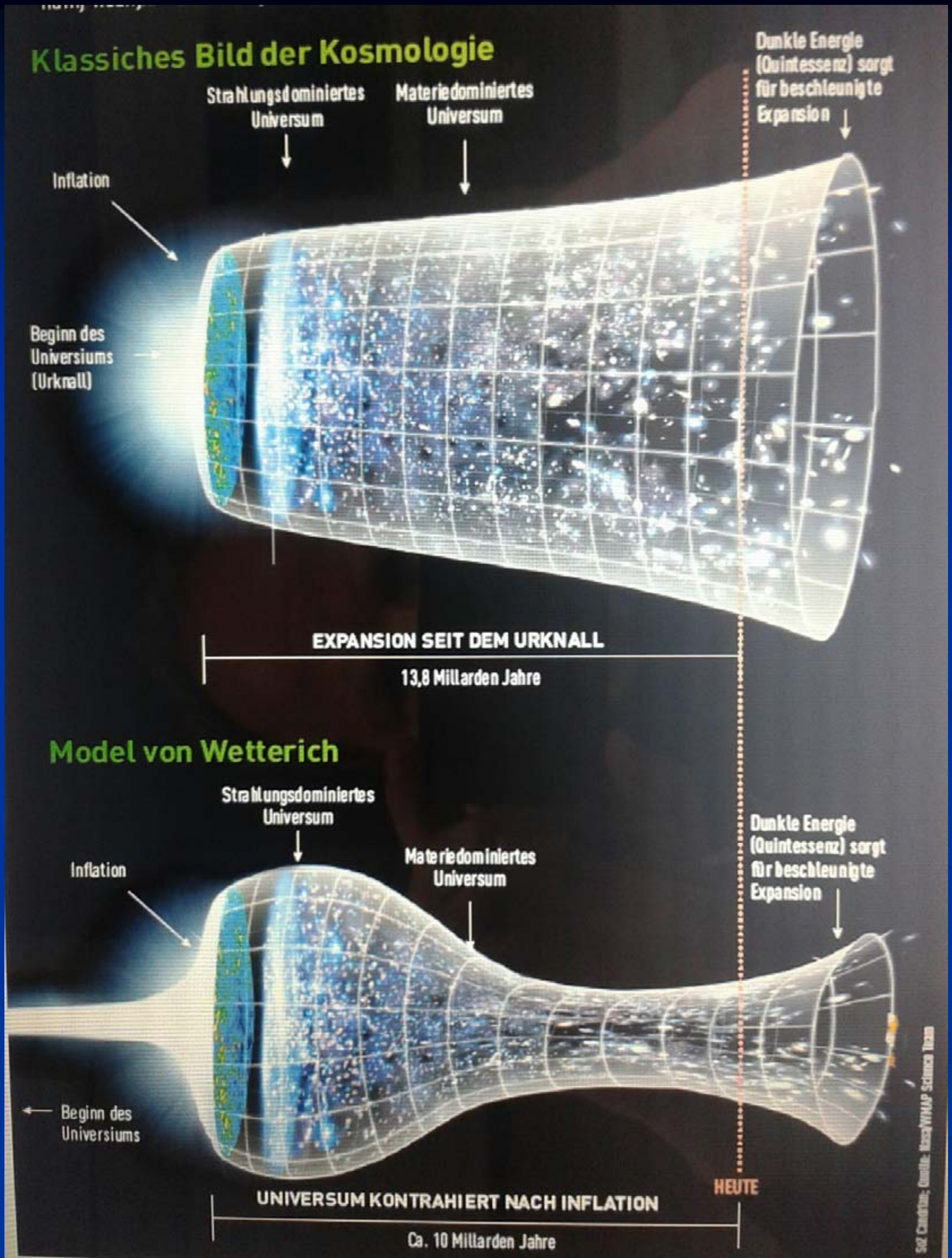
Cosmologist claims Universe may not be expanding

Particles' changing masses could explain why distant galaxies appear to be rushing away.

Jon Cartwright 16 July 2013

German physicist stops Universe

25.07.2013



Sonntagszeitung
Zürich
Laukenmann

The Universe is shrinking

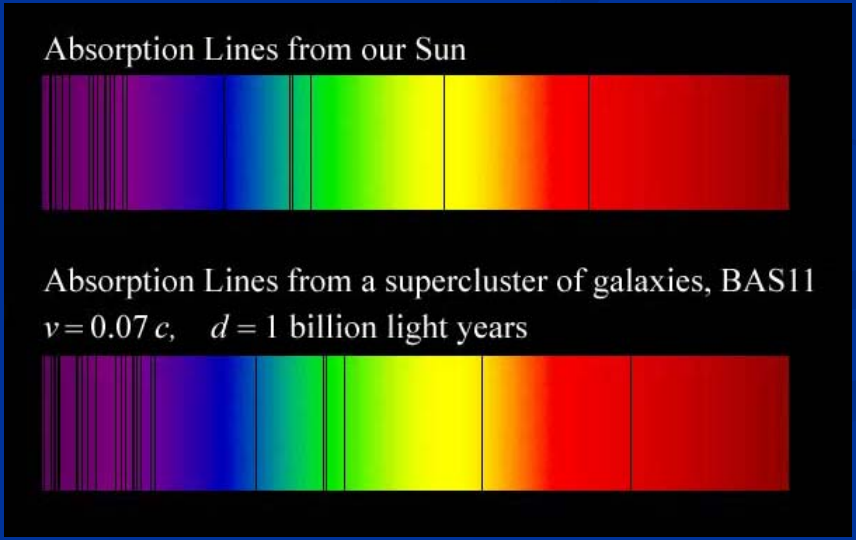
The Universe is shrinking …

while Planck mass and particle masses are increasing

Redshift

instead of redshift due to expansion :

smaller frequencies have been emitted in the past, because electron mass was smaller !



What is increasing ?

Ratio of distance between galaxies
over size of atoms !

atom size constant : expanding geometry

alternative : shrinking size of atoms

general idea not new : Hoyle, Narlikar,…

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
- which picture is usefull ?

Cosmological scalar field (cosmon)

- scalar field is crucial ingredient
- particle masses proportional to scalar field – similar to Higgs field
- particle masses increase because value of scalar field increases
- scalar field plays important role in cosmology
- cosmon : pseudo Goldstone boson of spontaneously broken scale symmetry

Cosmon inflation

Unified picture of inflation and dynamical dark energy

Cosmon and inflaton are the same scalar field

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)

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 !

Infinite past : slow inflation

σ = 2 : field equations

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

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

solution

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

Slow Universe

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

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

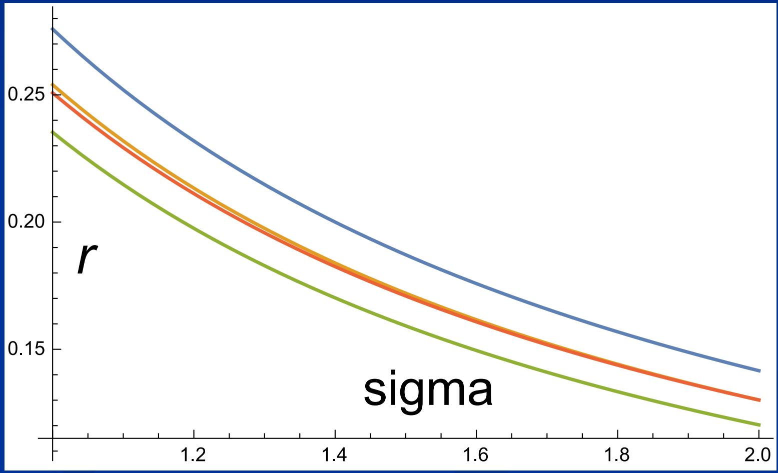
Slow increase of particle masses !

Spectrum of primordial density fluctuations

tensor amplitude

$$r = \frac{32}{B(N)}$$

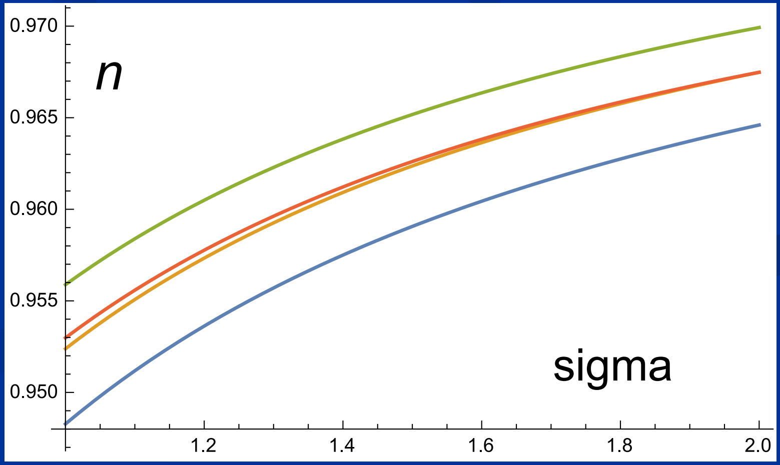
rather large !



spectral index

$$1 - n = \frac{r}{8}\left(1 + \frac{1}{2}\sigma(N)\right)$$

$$\sigma = -\frac{\partial \ln B}{\partial \ln \chi}\Big|_{B=2\sigma N+6}$$



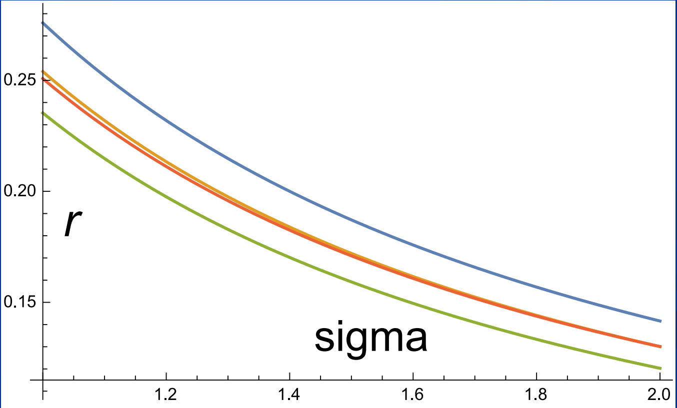
Anomalous dimension determines spectrum of primordial fluctuations

$$r = \frac{0.26}{\sigma}$$

$$n = 1 - \frac{0.065}{\sigma} \cdot \left(1 + \frac{\sigma - 2}{4}\right)$$

$$\sigma = 2$$

$$r = 0.13 \ , \ n = 0.967$$



Amplitude of density fluctuations

small because of logarithmic running near UV fixed point !

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

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

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

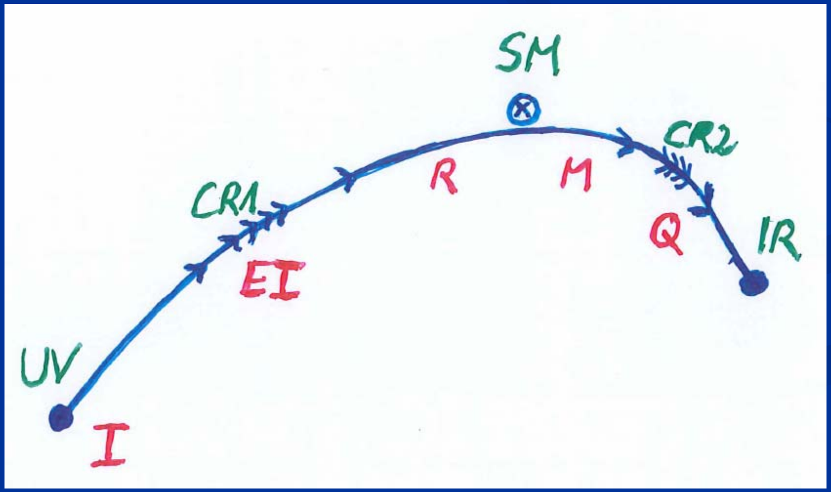
N : number of e – foldings at horizon crossing

First step of crossover ends inflation

- induced by crossover in B

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

- after crossover B changes only very slowly



Scaling solutions near SM fixed point

(approximation for constant B)

$$H = b\mu \ , \ \chi = \chi_0 \exp(c\mu t).$$

Different scaling solutions for radiation domination and matter domination

conclusions

- crossover in quantum gravity is reflected in crossover in cosmology
- quantum gravity becomes testable by cosmology
- quantum gravity plays a role not only for primordial cosmology
- crossover scenario explains different cosmological epochs
- simple model is compatible with present observations
- no more parameters than ΛCDM : tests possible

end

Radiation domination

$$c = \frac{2}{\sqrt{K+6}}$$ $$b = -\frac{c}{2}.$$

Universe shrinks !

$$T_{00} = \rho = \bar{\rho}\mu^2\chi^2.$$ $$\bar{\rho}_r = -3\frac{K+5}{K+6}.$$

K = B - 6

solution exists for B < 1 or K< -5

$$S = \int_x \sqrt{g}\left\{-\frac{1}{2}\chi^2 R + \frac{1}{2}K(\chi)\partial^\mu\chi\partial_\mu\chi + V(\chi)\right\}$$

$$H = b\mu \ , \ \chi = \chi_0 \exp(c\mu t).$$

Varying particle masses near SM fixed point

- All particle masses are proportional to χ .
  (scale symmetry)
- Ratios of particle masses remain constant.
- Compatibility with observational bounds on time dependence of particle mass ratios.

cosmon coupling to matter

$$K(\ddot{\chi} + 3H\dot{\chi}) + \frac{1}{2}\frac{\partial K}{\partial \chi}\dot{\chi}^2 = -\frac{\partial V}{\partial \chi} + \frac{1}{2}\frac{\partial F}{\partial \chi}R + q_\chi$$

$q_\chi = -(\rho - 3p)/\chi$

$F = \chi^2$

Matter domination

$$c = \sqrt{\frac{2}{K+6}},$$

$$b = -\frac{1}{3}\sqrt{\frac{2}{K+6}} = -\frac{1}{3}c,$$

$$T_{00} = \rho = \bar{\rho}\mu^2\chi^2,$$

$$\bar{\rho}_m = -\frac{2(3K+14)}{3(K+6)}$$

Universe shrinks !

$$K < -14/3$$

B < 4/3

Early Dark Energy

Energy density in radiation increases , proportional to cosmon potential

$$T_{00} = \rho = \bar{\rho}\mu^2\chi^2$$

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

fraction in early dark energy

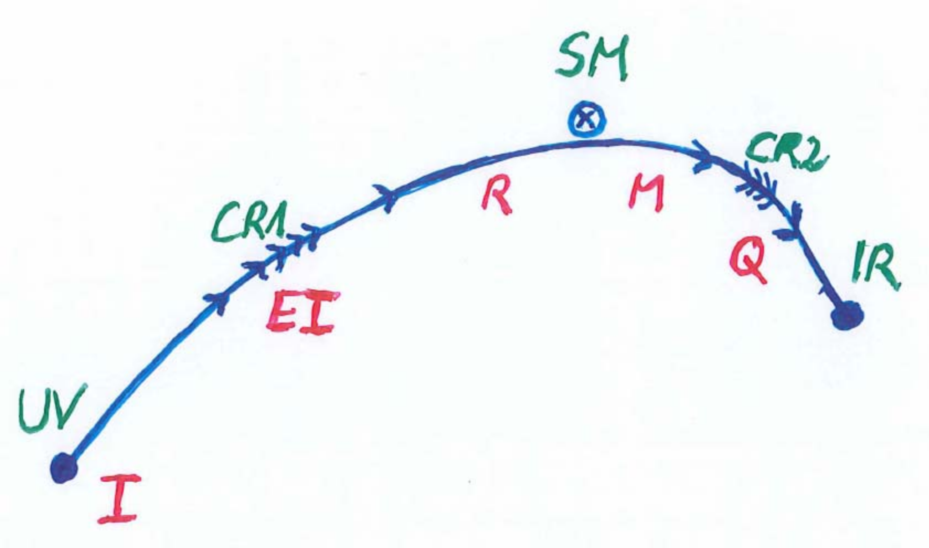
$$\Omega_h = \frac{\rho_h}{\rho_r + \rho_h} = \frac{nB(\chi)}{4}$$

or m

observation requires B < 0.02

Second crossover

- from SM to IR
- in sector of SM-singlets
- affects neutrino masses first



Varying particle masses at onset of second crossover

- All particle masses **except neutrinos** 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** .

Dark Energy domination

neutrino masses scale differently from electron mass

$$\frac{\partial \ln m_\nu}{\partial \ln \chi}\Big|_{\text{today}} = 2\tilde{\gamma} + 1$$

$$m_\nu = \bar{c}_\nu \chi^{2\tilde{\gamma}+1}$$

$$\chi q_\chi = -(2\tilde{\gamma} + 1)(\rho_\nu - 3p_\nu)$$

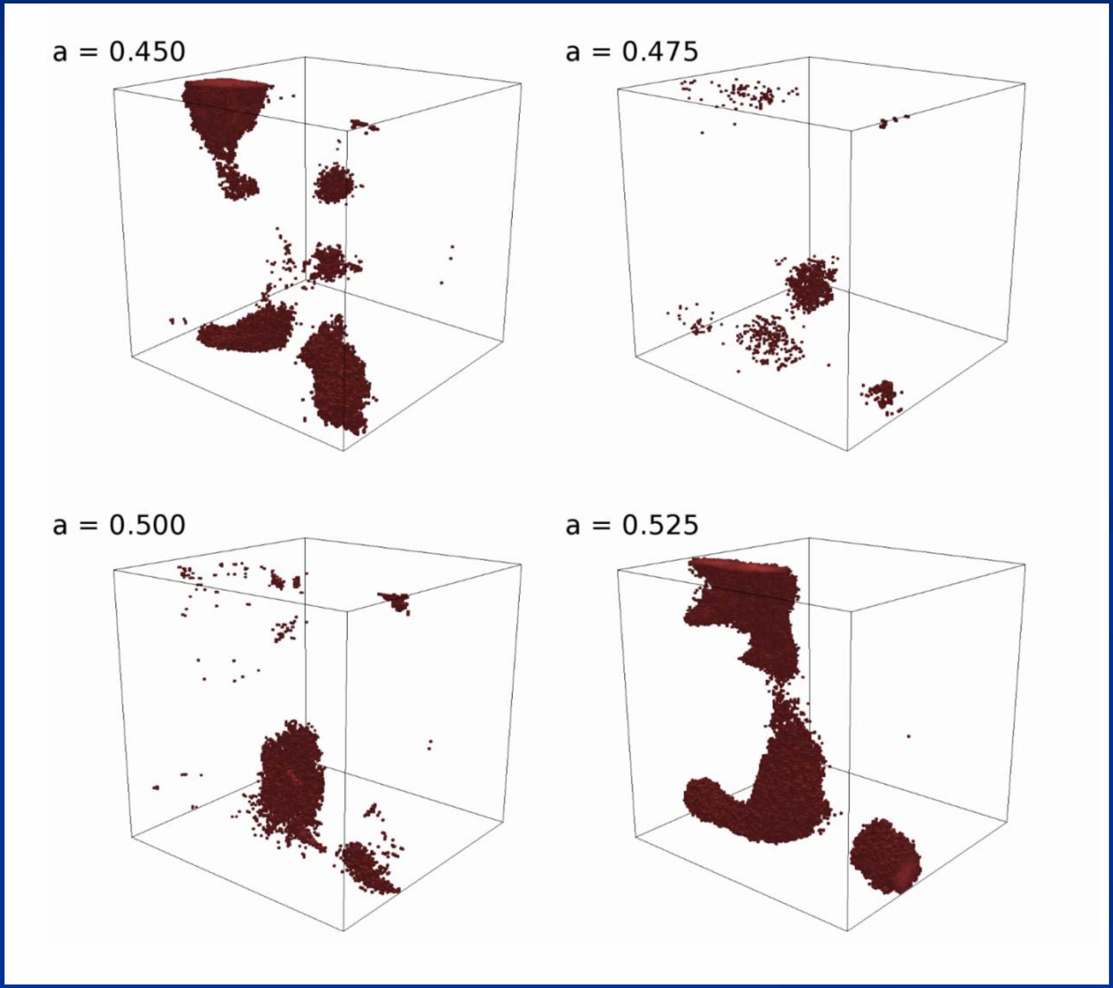
new scaling solution. not yet reached.

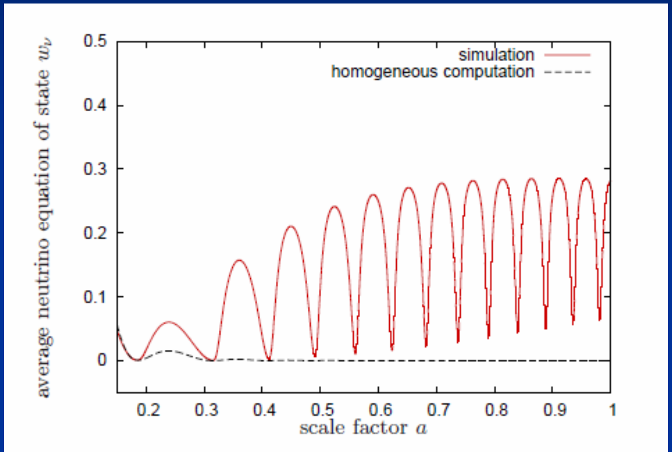
at present : transition period

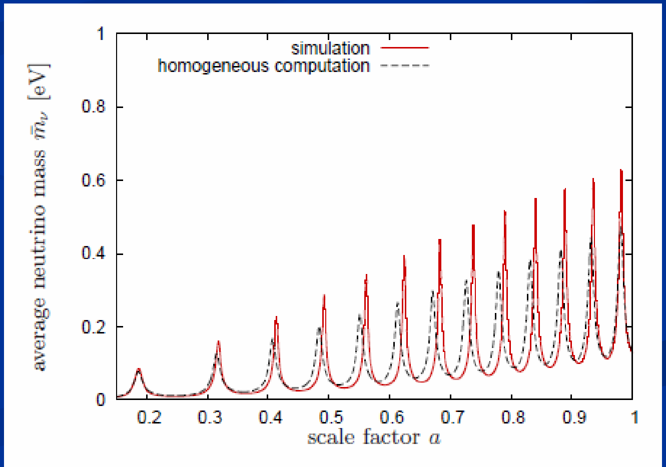
$$\frac{\rho_\nu}{\chi^2} = \bar{\rho}_\nu \mu^2$$

$$b = \frac{1}{3}(2\tilde{\gamma} - 1)c.$$

Oscillating neutrino lumps



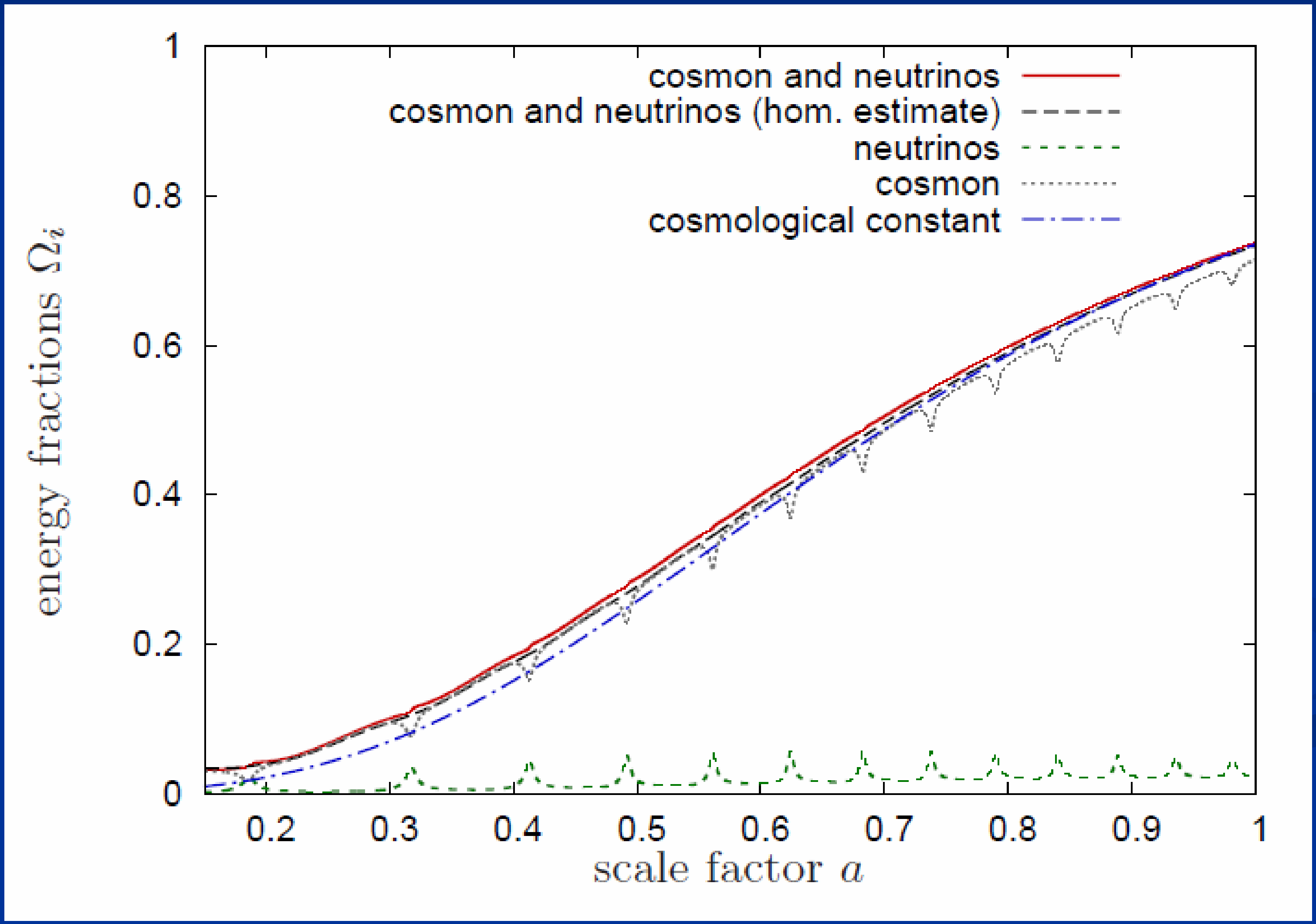




Y.Ayaita,M.Weber,…

Ayaita, Baldi, Fuehrer, Puchwein,…

Evolution of dark energy similar to ΛCDM



Compatibility with observations

- Realistic inflation model:

  $n=0.976$, $r=0.13$

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

Einstein frame

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

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

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

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

Einstein frame

- Weyl scaling maps variable gravity model to Universe with fixed masses and standard expansion history.
- Standard gravity coupled to scalar field.
- Only neutrino masses are growing.