

A vast field of galaxies, including spirals, ellipticals, and irregular shapes, scattered across a dark cosmic background. The galaxies are in various colors, including yellow, blue, and purple, and are of different sizes and orientations. The text "Big bang or freeze ?" is centered in the upper half of the image in a yellow, serif font.

Big bang or freeze ?

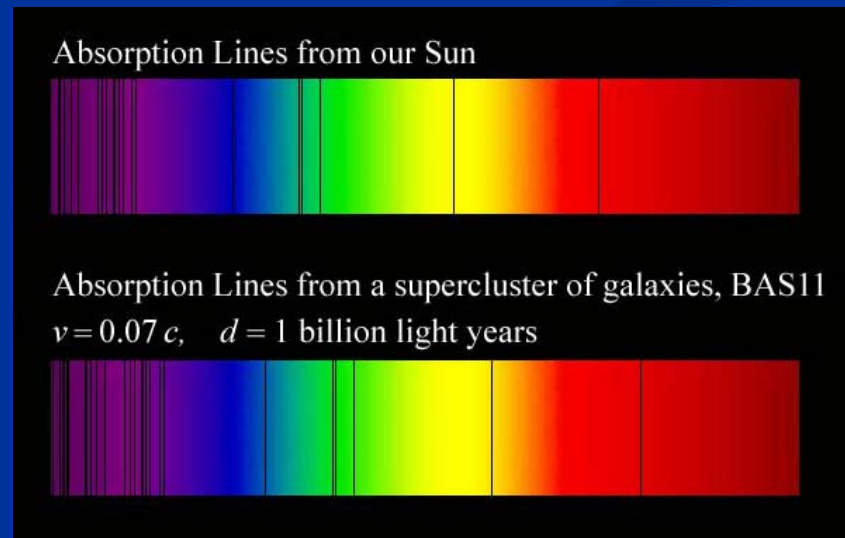
conclusions

- Big bang singularity is artefact of inappropriate choice of field variables – no physical singularity
- Quantum gravity is observable in dynamics of present Universe

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 !



What is increasing ?

Ratio of distance between galaxies
over size of atoms !

atom size constant : expanding geometry

alternative : shrinking size of atoms

Variable Gravity

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

quantum effective action,
variation yields field equations

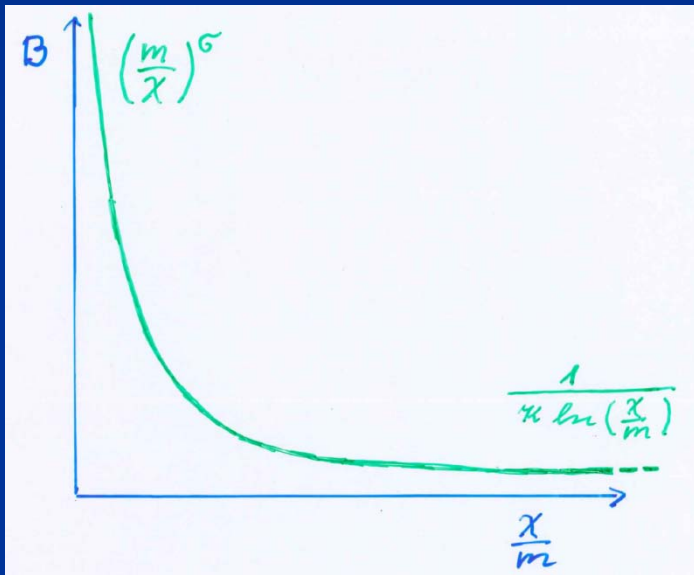
Variable Gravity

- 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

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

Kinetic B :

Crossover between two fixed points



running
coupling obeys
flow equation

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

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

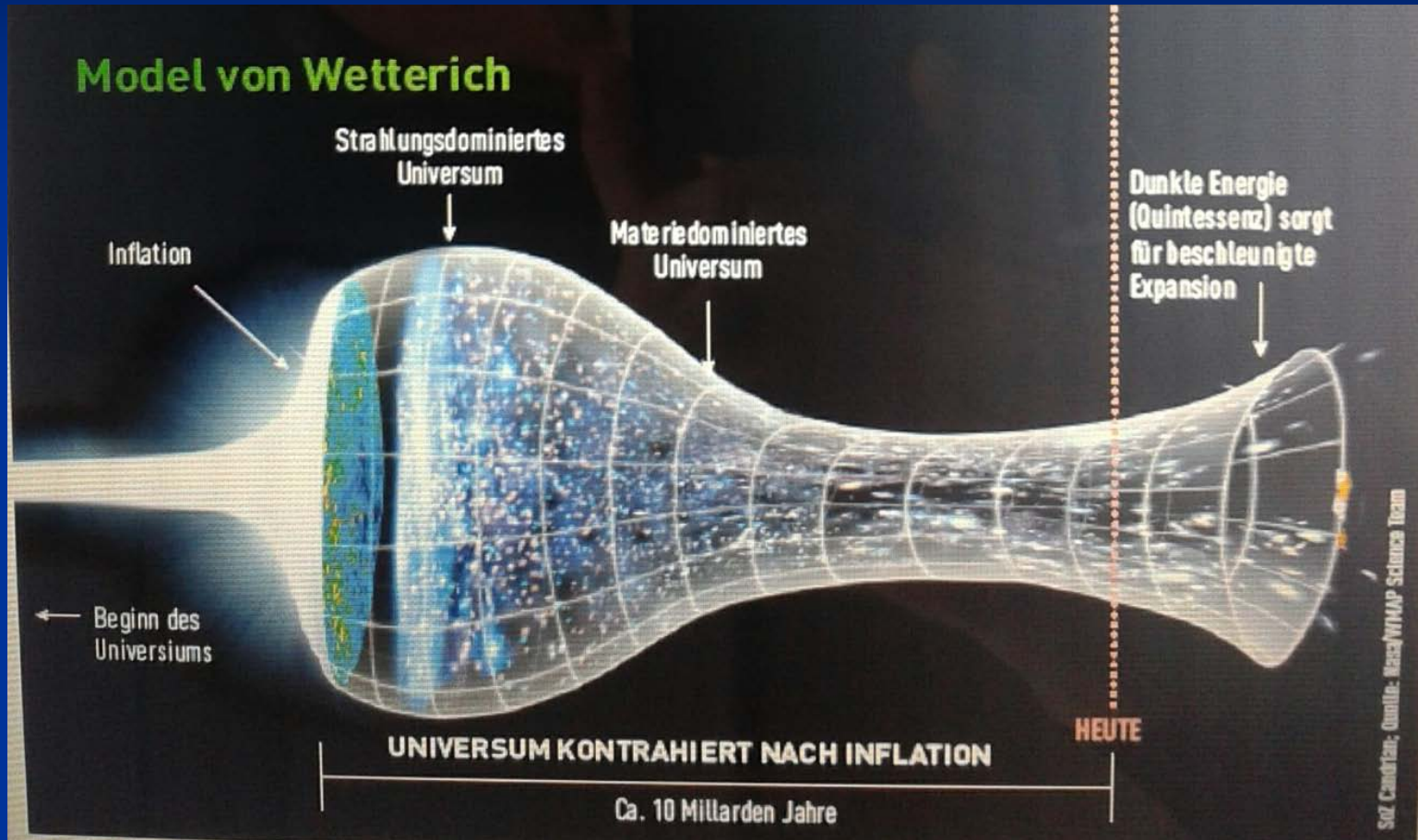
m : scale of crossover

can be exponentially larger than intrinsic scale μ

Cosmological solution

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

Strange evolution of Universe



Sonntagszeitung Zürich , Laukenmann

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

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

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

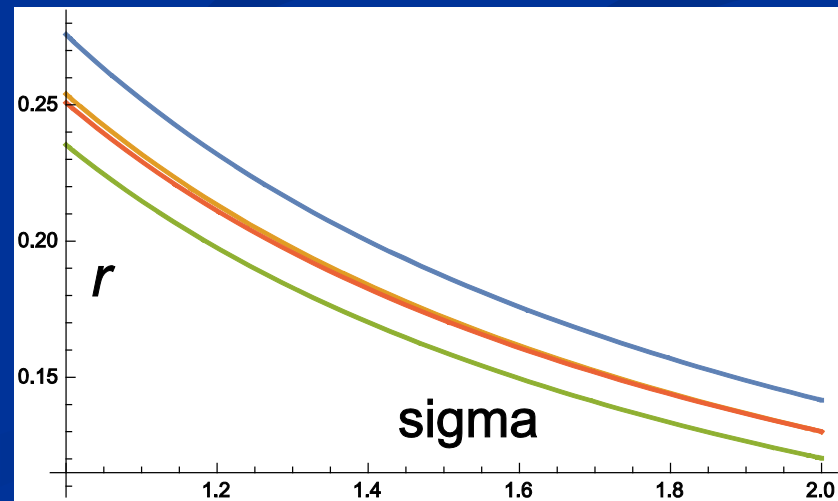
Anomalous dimension determines spectrum of primordial fluctuations

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

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

$$\sigma = 2$$

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



Amplitude of density fluctuations

small because of logarithmic running
near UV fixed point !

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

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

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

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

N : number of e – foldings at horizon crossing

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.

Einstein frame

Weyl scaling :

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

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 :

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 ?

Primordial flat frame

$$\Gamma = \int_x \sqrt{g} \left\{ -\frac{1}{2} \chi^2 R + \bar{\lambda} \chi^4 \ln \left(\frac{\bar{m}}{\chi} \right) + \left[\ln^{-1} \left(\frac{\bar{m}}{\chi} \right) - 3 \right] \partial^\mu \chi \partial_\mu \chi \right\}$$

$$a = a_\infty \exp \left\{ -\frac{\tilde{c}_H}{\ln \left(\frac{\bar{m}}{\chi} \right)} \right\}$$

- Minkowski space in infinite past
- absence of any singularity
- geodesic completeness

Eternal Universe

Asymptotic solution in
freeze frame :

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

- solution valid back to the infinite past in physical time
- no singularity
- physical time to infinite past is infinite

Physical time

field equation for scalar field mode

$$(\partial_\eta^2 + 2Ha\partial_\eta + k^2 + a^2m^2)\varphi_k = 0$$

$$\varphi_k = \frac{\tilde{\varphi}_k}{a} \quad \left\{ \partial_\eta^2 + k^2 + a^2 \left(m^2 - \frac{R}{6} \right) \right\} \tilde{\varphi}_k = 0$$

determine **physical time** by counting number of oscillations

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

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

$$m=0$$

*Big bang singularity
in Einstein frame is
field singularity !*

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

choice of frame with constant particle masses is not well suited if physical masses go to zero !

No tiny dimensionless parameters (except gauge hierarchy)

- one mass scale $\mu = 2 \cdot 10^{-33} \text{ eV}$
- one time scale $\mu^{-1} = 10^{10} \text{ yr}$
- Planck mass does not appear as parameter
- Planck mass grows large dynamically

Slow Universe

Asymptotic solution in
freeze frame :

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

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

Expansion or shrinking always slow ,
characteristic time scale of the order of the age of the
Universe : $t_{\text{ch}} \sim \mu^{-1} \sim 10 \text{ billion years !}$

Hubble parameter of the order of **present** Hubble
parameter for all times , including inflation and big bang !
Slow increase of particle masses !

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 $\chi \rightarrow \infty$!

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)

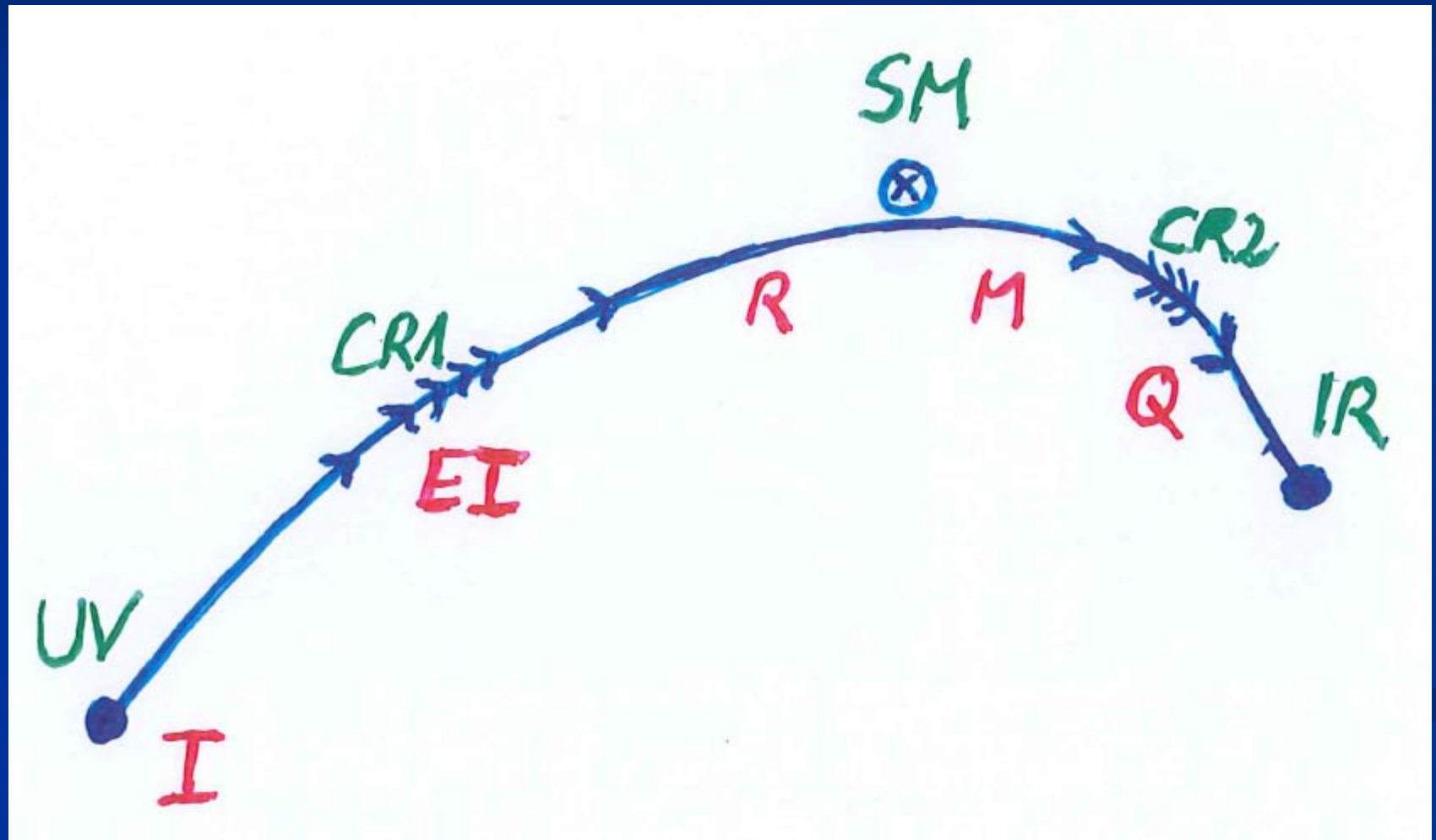
Cosmon inflation

Unified picture of inflation and
dynamical dark energy

Cosmon and inflaton are the same
scalar field

scalar field may be
important feature of
quantum gravity

Crossover in quantum gravity



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

Asymptotic safety

if UV fixed point exists :

*quantum gravity is
non-perturbatively renormalizable !*

S. Weinberg , M. Reuter

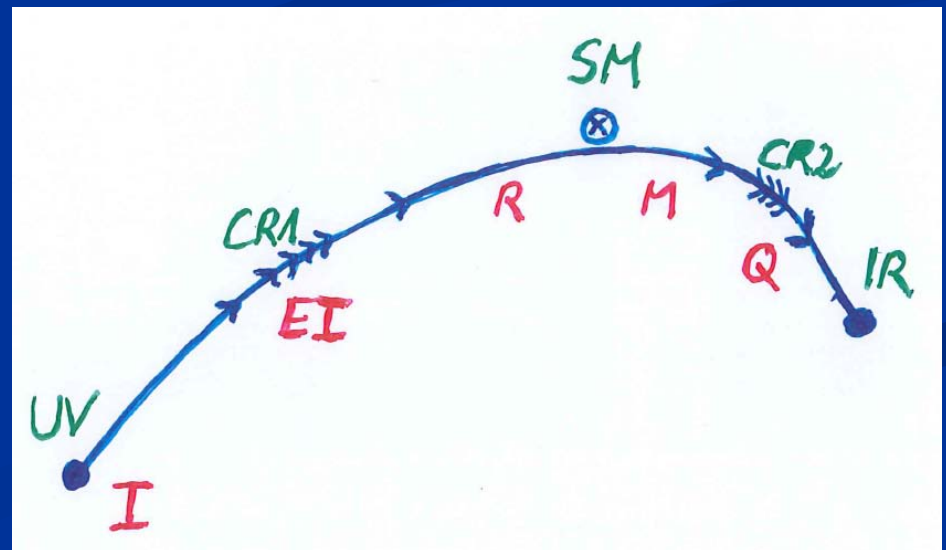
Quantum scale symmetry

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

Cosmological solution : crossover from UV to IR fixed point

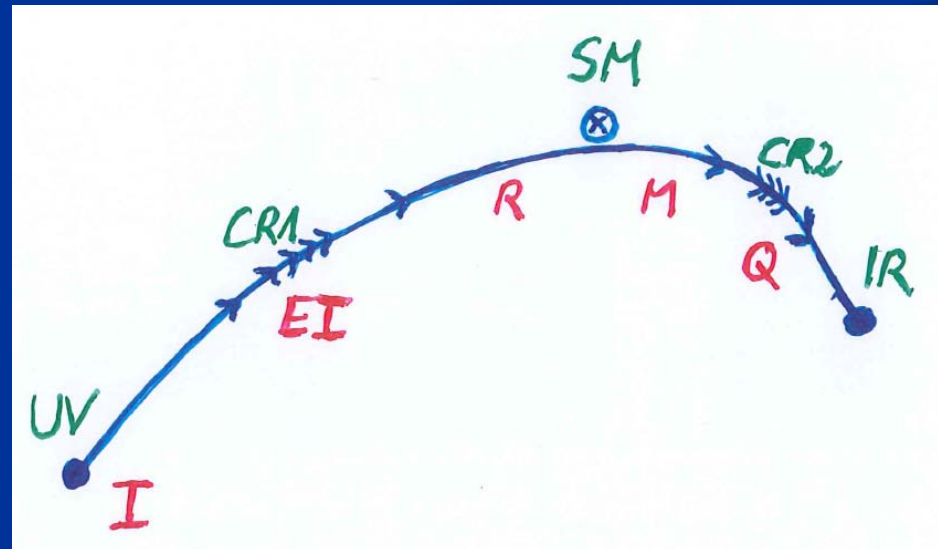
- Dimensionless functions as B depend only on ratio μ/χ .
- IR: $\mu \rightarrow 0$, $\chi \rightarrow \infty$
- UV: $\mu \rightarrow \infty$, $\chi \rightarrow 0$

**Cosmology makes
crossover between
fixed points by
variation of χ .**



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

- All particle masses **except for 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**.

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, ...

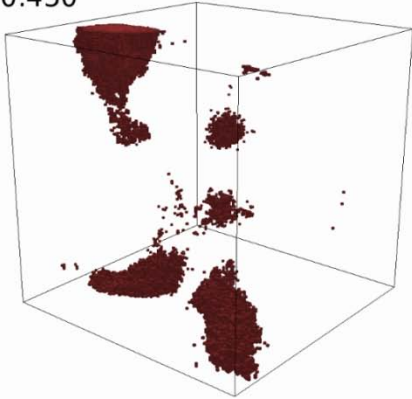
present dark energy density given by neutrino mass

present equation
of state given by
neutrino mass !

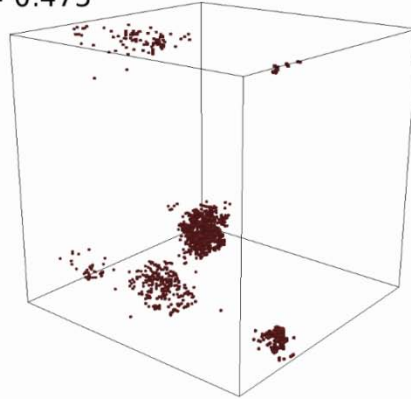
$$w_0 \approx -1 + \frac{m_\nu(t_0)}{12eV}$$

Oscillating neutrino lumps

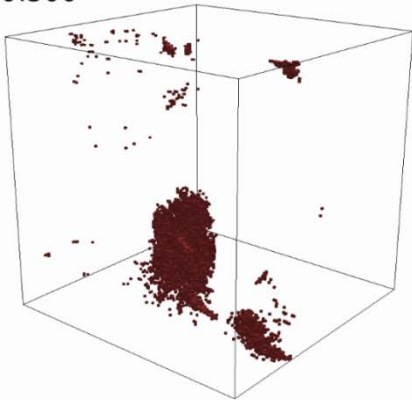
$a = 0.450$



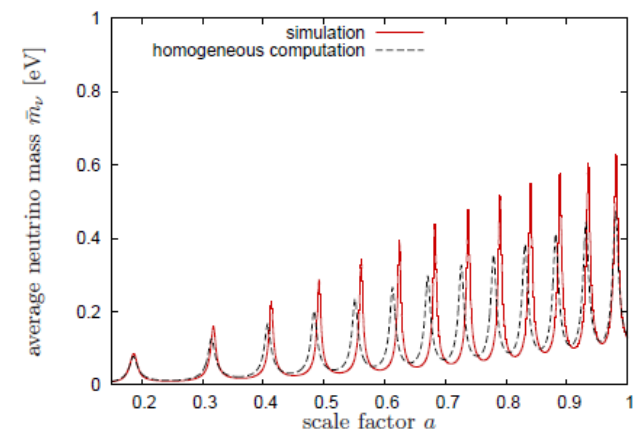
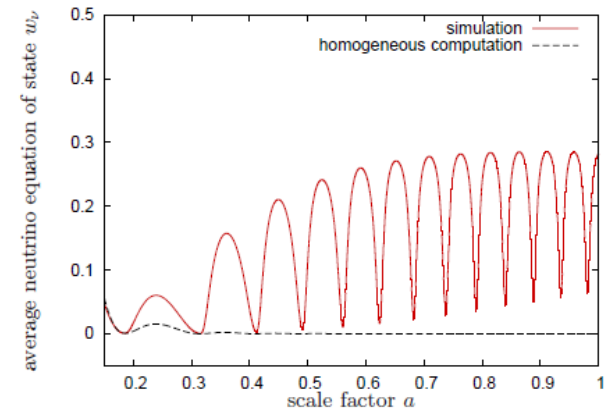
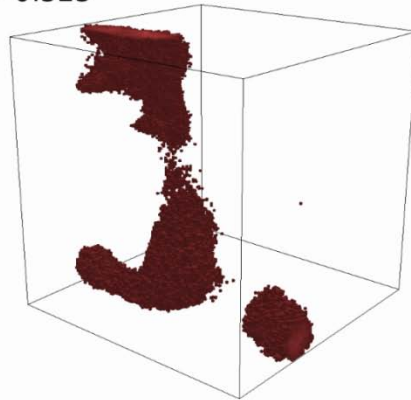
$a = 0.475$



$a = 0.500$



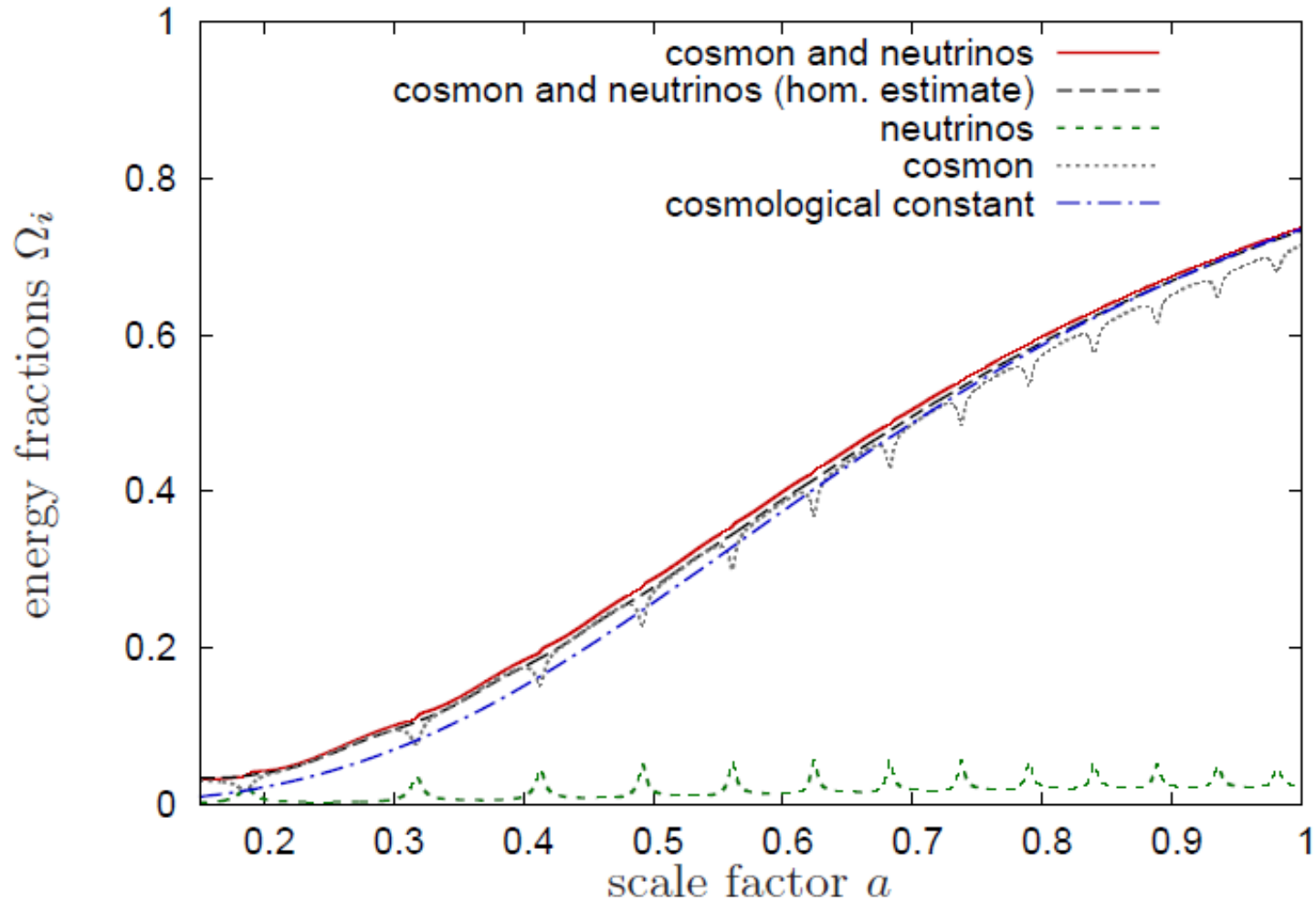
$a = 0.525$



Y.Ayaita, M.Weber,...

Ayaita, Baldi, Fuehrer,
Puchwein,...

Evolution of dark energy similar to Λ CDM



Compatibility with observations and possible tests

- Realistic inflation model:

$$n = 0.976, r = 0.13$$

- Almost same prediction for radiation, matter, and Dark Energy domination as Λ CDM
- 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

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 Λ CDM : tests possible



end

conclusions (2)

- Variable gravity cosmologies can give a simple and realistic description of Universe
- Compatible with tests of equivalence principle and bounds on variation of fundamental couplings if nucleon and electron masses are proportional to variable Planck mass
- Different cosmological dependence of neutrino mass can explain why Universe makes a transition to Dark Energy domination **now**
- **characteristic signal : neutrino lumps**

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

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

$\sigma = 2$: field equations

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

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

solution

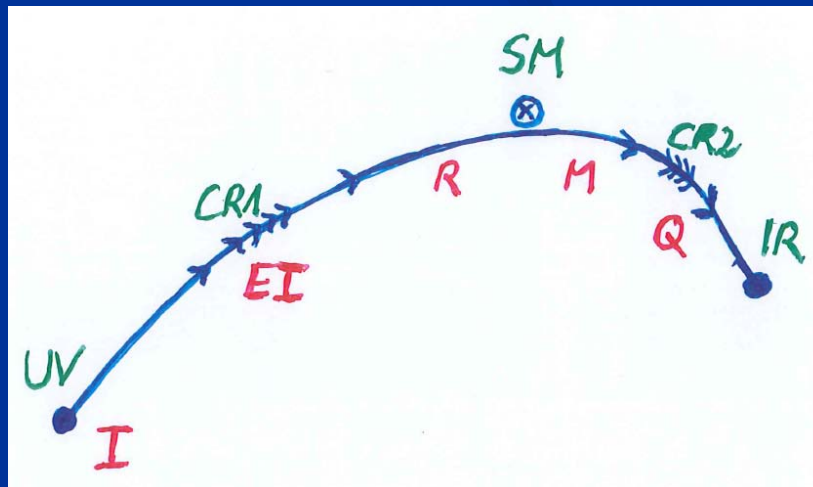
$$H = \frac{\mu}{\sqrt{3}}, \quad \chi = \frac{3^{\frac{1}{4}} m}{2\sqrt{\mu}} (t_c - t)^{-\frac{1}{2}}$$

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)

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

Different scaling solutions for
radiation domination and
matter domination

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 $K < -5$

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

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

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.

Scaling of particle masses

mass of electron or nucleon is proportional to variable Planck mass χ !

effective potential for Higgs doublet h

$$\tilde{V}_h = \frac{1}{2} \lambda_h (\tilde{h}^\dagger \tilde{h} - \epsilon_h \chi^2)^2$$

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

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

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

Universe shrinks !

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

solution exists for

$$B < 4/3, \quad K < -14/3$$

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

$$K = B - 6$$

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** (at CMB emission)

Dark Energy domination

neutrino masses scale
differently from electron mass

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



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

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

new scaling solution. not yet reached.
at present : transition period

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

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

Infrared fixed point

■ $\mu \rightarrow 0$

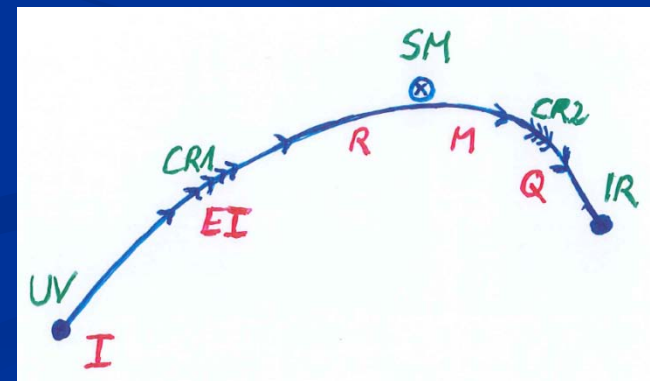
■ $B \rightarrow 0$

$$\mu \partial_\mu B = \kappa B^2 \quad \text{for} \quad B \rightarrow 0$$

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

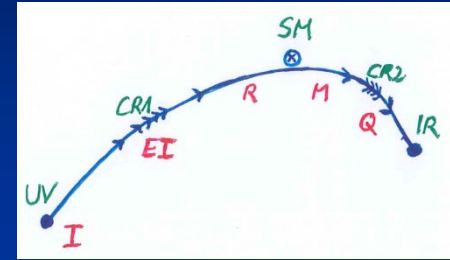
■ no intrinsic mass scale

■ scale symmetry



Ultraviolet fixed point

■ $\mu \rightarrow \infty$



■ kinetic diverges

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

■ scale symmetry with anomalous dimension σ

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

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

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

deviation from
fixed point
vanishes for

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

$$\mu \rightarrow \infty$$