Higgs-Dilaton Cosmology:
From the Early to the Late Universe

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КВАНТОВЫЕ ПОЛЯ

Допущено Министерством высшего и среднего специального образования СССР в качестве учебного пособия для студентов физических специальностей высших учебных заведений

First meeting with Dima: 1977

МОСКВА «НАУКА»
ГЛАВНАЯ РЕДАКЦИЯ
ФИЗИКО-МАТЕМАТИЧЕСКОЙ ЛИТЕРАТУРЫ
1980

Based on:

- M.S., Daniel Zenhäusern, Phys. Lett. B **671** (2009) 162
- M.S., Daniel Zenhäusern, Phys. Lett. B **671** (2009) 187
- Diego Blas, M.S., Daniel Zenhäusern, Phys. Rev. D84 (2011) 044001
- J. García-Bellido, J. Rubio, M.S., D. Zenhäusern, 1107.2163

Outline

- ETOE
- Dilaton-Higgs Cosmology
- Conclusions

An alternative to SUSY, large extra dimensions, technicolor, etc

Effective

Theory

Of

Everything

Definitions

"Effective": valid up to the Planck scale, quantum gravity problem is not addressed. No new particles heavier than the Higgs boson.

May be even fundamental, if gravity is "asymptotically safe" (S. Weinberg '79, M. Reuter '98)

"Everything": neutrino masses and oscillations, dark matter, baryon asymmetry of the Universe, inflation, and presence of dark energy.

Particle content of ETOE

Particles of the SM

+

graviton

+

dilaton

+

3 Majorana leptons

Symmetries of ETOE

- gauge: SU(3)$\times$SU(2)$\times$U(1) – the same as in the Standard Model

Symmetries of ETOE

- Restricted coordinate transformations: TDIFF, $det[-g] = 1$ (Unimodular Gravity).

Equations of motion for Unimodular Gravity:

$$R_{\mu\nu} - \frac{1}{4} g_{\mu\nu} R = 8\pi G_N (T_{\mu\nu} - \frac{1}{4} g_{\mu\nu} T)$$

Perfect example of “degravitation" - the “$g_{\mu\nu}$" part of energy-momentum tensor does not gravitate. Solution of the “technical part" of cosmological constant problem - quartically divergent matter loops do not change the geometry. But - no solution of the “main" cosmological constant problem - why $\Lambda \ll M_P^4$? Scale invariance can help!

Symmetries of ETOE

- Exact quantum scale invariance
  - No dimensionful parameters
  - Cosmological constant is zero
  - Higgs mass is zero
  - these parameters cannot be generated radiatively, if regularisation respects this symmetry
- Scale invariance must be spontaneously broken
  - Newton constant is nonzero
  - W-mass is nonzero
  - Λ_{QCD} is nonzero

Lagrangian of ETOE

Scale-invariant Lagrangian

$$\mathcal{L}_{\nu\mathrm{MSM}} = \mathcal{L}_{\mathrm{SM}[\mathrm{M}\to 0]} + \mathcal{L}_G + \frac{1}{2}(\partial_\mu \chi)^2 - V(\varphi,\chi)$$
$$+ \left(\bar{N}_I i\gamma^\mu \partial_\mu N_I - h_{\alpha I}\, \bar{L}_\alpha N_I \tilde{\varphi} - f_I \bar{N}_I{}^c N_I \chi + \mathrm{h.c.}\right) ,$$

Potential (χ - dilaton, φ - Higgs, $\varphi^\dagger\varphi = 2h^2$):

$$V(\varphi,\chi) = \lambda \left(\varphi^\dagger\varphi - \frac{\alpha}{2\lambda}\chi^2\right)^2 + \beta\chi^4,$$

Gravity part

$$\mathcal{L}_G = -\left(\xi_\chi \chi^2 + 2\xi_h \varphi^\dagger\varphi\right)\frac{R}{2} ,$$

Roles of different particles

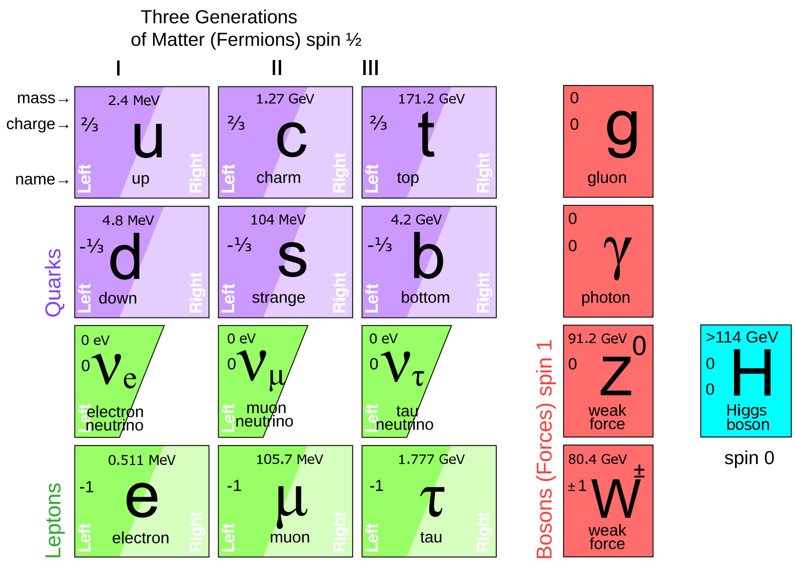
The roles of dilaton:

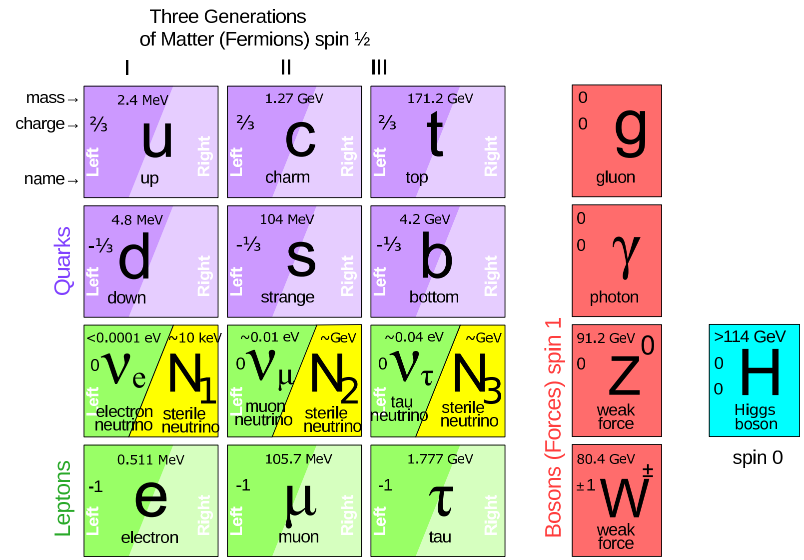
- determine the Planck mass
- give mass to the Higgs
- give masses to 3 Majorana leptons
- lead to dynamical dark energy
- Note: dilaton is a Goldstone boson of broken dilatation symmetry
  $\Longrightarrow$ only derivative couplings to matter, no fifth force!

Roles of the Higgs boson:

- give masses to fermions and vector bosons of the SM
- provide inflation

New fermions: the νMSM





Role of N_1 with mass in keV region: dark matter

Role of N_2, N_3 with mass in 100 MeV – GeV region: “give” masses to neutrinos and produce baryon asymmetry of the Universe

The couplings of the νMSM

Particle physics part, accessible to low energy experiments: the νMSM. Mass scales of the νMSM:

$M_I < M_W$ (No see-saw)

Consequence: small Yukawa couplings,

$$F_{\alpha I} \sim \frac{\sqrt{m_{atm} M_I}}{v} \sim (10^{-6} - 10^{-13}),$$

here $v \simeq 174$ GeV is the VEV of the Higgs field,

$m_{atm} \simeq 0.05$ eV is the atmospheric neutrino mass difference.

Small Yukawas are also necessary for stability of dark matter and baryogenesis (out of equilibrium at the EW temperature).

For $\lambda > 0, \ \ \beta = 0$ the scale invariance can be spontaneously broken.

The vacuum manifold:

$$h_0^2 = \frac{\alpha}{\lambda}\chi_0^2$$

Particles are massive, Planck constant is non-zero:

$$M_H^2 \sim M_W \sim M_t \sim M_N \propto \chi_0, \ \ M_{Pl} \sim \chi_0$$

Phenomenological requirement:

$$\alpha \sim \frac{v^2}{M_{Pl}^2} \sim 10^{-38} \lll 1$$

Scale invariance + unimodular gravity

Solutions of scale-invariant UG are the same as the solutions of scale-invariant GR with the action

$$S = -\int d^4x \sqrt{-g}\left[\left(\xi_\chi \chi^2 + 2\xi_h \varphi^\dagger \varphi\right)\frac{R}{2} + \Lambda + \dots\right] ,$$

Physical interpretation: Einstein frame

$$g_{\mu\nu} = \Omega(x)^2 \tilde{g}_{\mu\nu} \ , \ \ (\xi_\chi \chi^2 + \xi_h h^2)\Omega^2 = M_P^2$$

Λ is not a cosmological constant, it is the strength of a peculiar potential!

Relevant part of the Lagrangian (scalars + gravity) in Einstein frame:

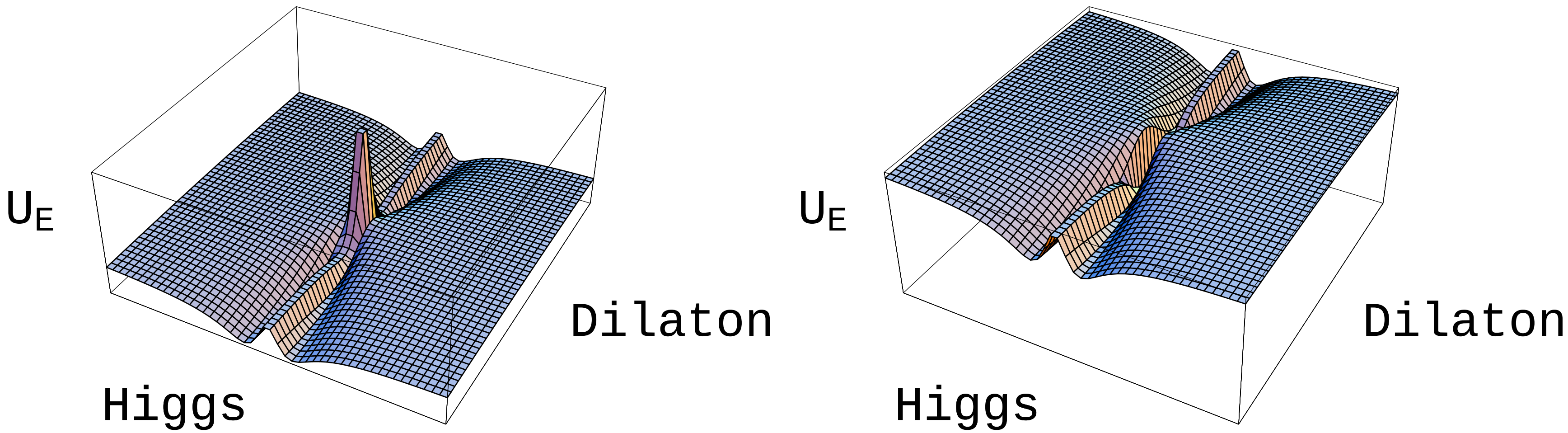
$$\mathcal{L}_E = \sqrt{-\tilde{g}}\left(-M_P^2\frac{\tilde{R}}{2} + K - U_E(h,\chi)\right) ,$$

K - complicated non-linear kinetic term for the scalar fields,

$$K = \Omega^2\left(\frac{1}{2}(\partial_\mu\chi)^2 + \frac{1}{2}(\partial_\mu h)^2\right) - 3M_P^2(\partial_\mu\Omega)^2 .$$

The Einstein-frame potential $U_E(h,\chi)$:

$$U_E(h,\chi) = M_P^4\left[\frac{\lambda\left(h^2 - \frac{\alpha}{\lambda}\chi^2\right)^2}{4(\xi_\chi\chi^2 + \xi_h h^2)^2} + \frac{\Lambda}{(\xi_\chi\chi^2 + \xi_h h^2)^2}\right] ,$$



Potential for the Higgs field and dilaton in the Einstein frame.

Left: $\mathbf{\Lambda > 0}$, right $\mathbf{\Lambda < 0}$.

$\mathbf{50\%}$ chance ($\mathbf{\Lambda < 0}$): inflation + late collapse

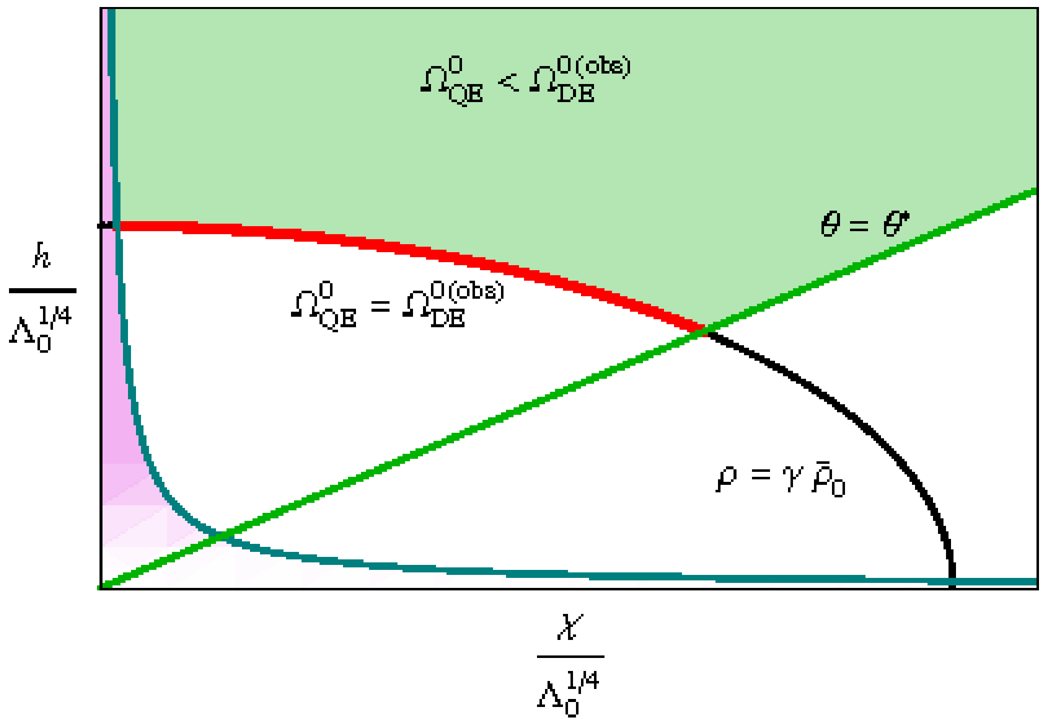
$\mathbf{50\%}$ chance ($\mathbf{\Lambda > 0}$): inflation + late acceleration

Strategy

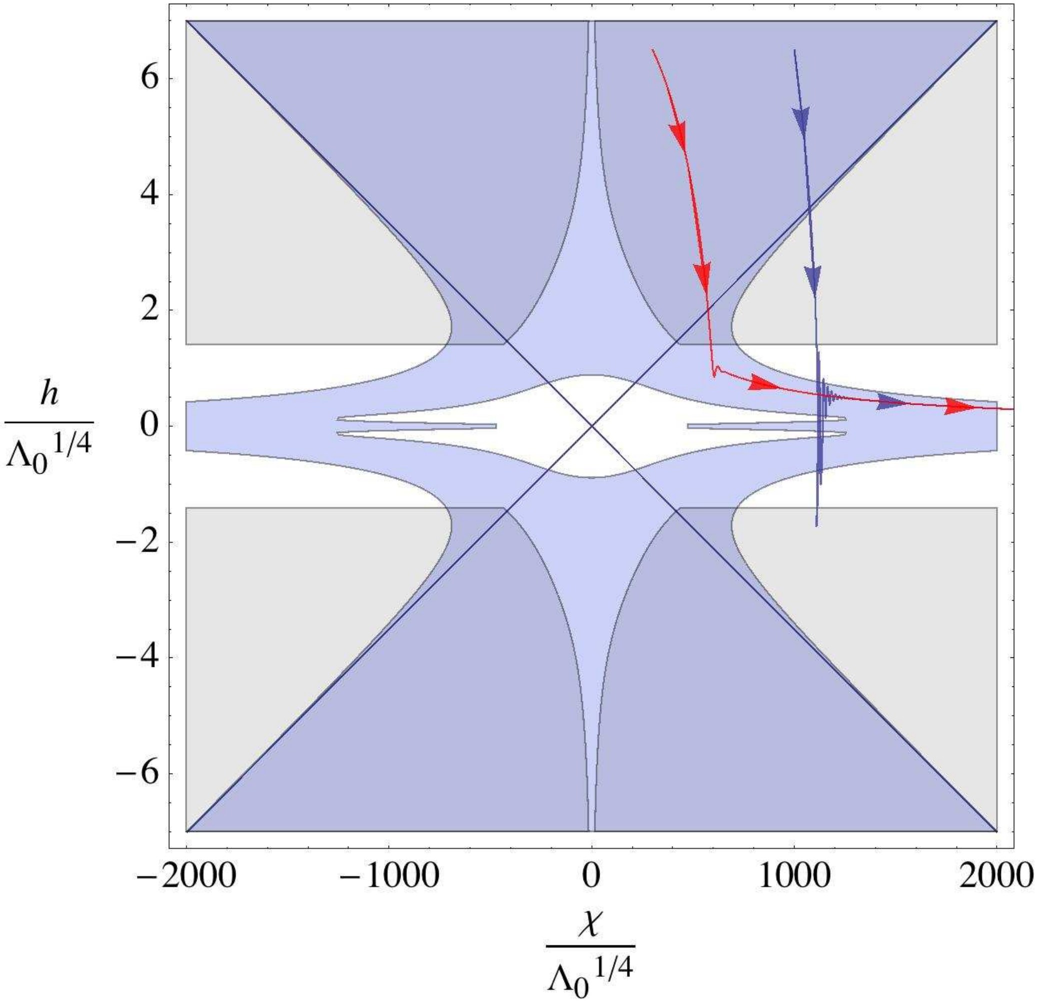
Juan García-Bellido, Javier Rubio, M.S., Daniel Zenhäusern

- Take arbitrary initial conditions for the Higgs and the dilaton
- Find the region on the $\{\chi, h\}$ plane that lead to inflation
- Find the region on the $\{\chi, h\}$ plane that lead to exit from inflation
- Find the region on the $\{\chi, h\}$ plane that lead to observed abundance of Dark Energy

Initial conditions



Trajectories



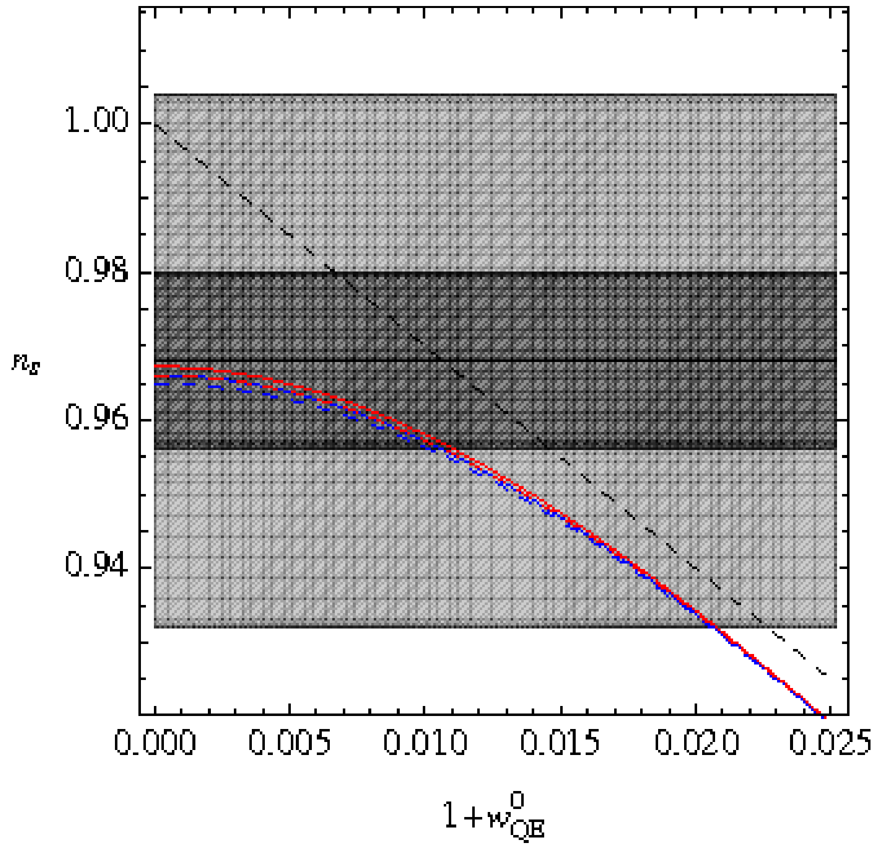
Generic semiclassical initial conditions lead to:

- the Universe, which was inflating in the past
- the Universe with the Dark Energy abundance smaller, than observed

Quantum initial state to explain the DM-DE coincidence problem?

Inflation-dark energy relation

Value of n_s is determined by ξ_h and ξ_χ, and equation of state of DE ω by $\xi_\chi \Longrightarrow n_s - \omega$ relation:



Conclusions

ETOE gives:

- Dynamical origin of all mass scales
- Hierarchy problem gets a different meaning - an alternative (to SUSY, techicolor, little Higgs or large extra dimensions) solution of it may be possible.
- Cosmological constant problem acquires another formulation.
- Natural chaotic cosmological inflation
- Low energy sector contains a massless dilaton
- There is Dark Energy even without cosmological constant
- There is direct relation between inflation and DE equation of state

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- Though the stability of the electroweak scale against quantum corrections may be achieved, it is unclear *why* the electroweak scale is so much smaller than the Planck scale (or why $\zeta \lll 1$).

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- Unitarity
- High energy limit

Happy birthday, Dima!