A Graceful Exit for the Cosmological Constant Damping Scenario

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Hot Topics in Modern Cosmology 2019

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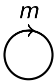
The cosmological constant fine-tuning problem

All forms of vacuum energy contribute to the cosmological constant Λ:

$$\rho_{vac} \sim$$



$$\sim m^4 \ln \frac{m^2}{\mu^2}$$

From the Standard Model of particle physics, we therefore expect

$$|\rho_{vac}| > (100 \text{ GeV})^4 \, .$$

Assuming the ΛCDM cosmological model, the measured vacuum energy density is

$$\rho_{vac}\big|_{obs} \approx \left(10^{-12} \text{ GeV}\right)^4 \, .$$

Possible theoretical resolution:

- Lagrangians fined-tuned in the ultra-violet
- Symmetry principle (SUSY,...) constraining ρ_{vac}
- Dynamical relaxation mechanism of the Hubble rate $H(t)$
- ?

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Dynamical damping scenarios

Scalar-tensor models studied in 1810.12336 (Phys. Rev. D) together with Oleg Evnin:

$$S = \frac{1}{16\pi G}\int d^4x\,\sqrt{-g}\,[R-2\Lambda]$$
$$-\frac{1}{2}\int d^4x\,\sqrt{-g}\left[(\partial_\mu\phi)^2 + m^2\phi^2 + \xi R\phi^2 + \lambda\phi^4 + G\lambda_R R\phi^4\right]$$

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- $\xi < 0$: unstable/growing solutions + negative energy component
- $\lambda, \lambda_R > 0$: potential bounded from below + stabilization of ϕ

$$\lim_{t\to\infty}\phi(t) = \phi_0$$

- $Gm^2, \lambda, \lambda_R \ll |\xi|$: unstable regime dominates until $\phi \gg 0$

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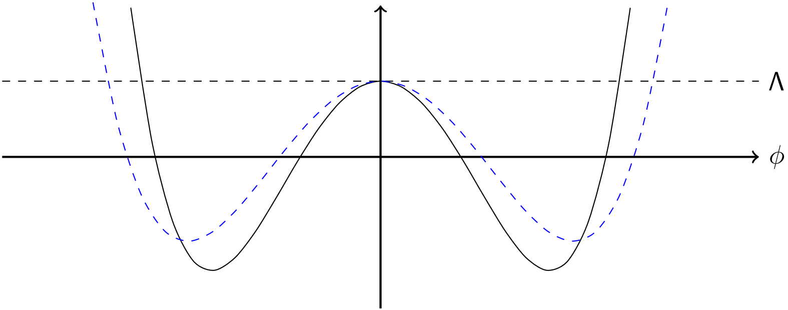
Dynamical damping of the Hubble rate

$$\lim_{t\to\infty} H(t) = H_0 \qquad \text{such that} \qquad G_{eff} H_0^2 \sim 10^{-120}.$$

Dynamical damping scenarios

$$V(\phi, R, \Lambda) = \Lambda + m^2\phi^2 + \xi R\phi^2 + \lambda\phi^4 + \lambda_R R\phi^4$$



Ansatz: $\phi(t), \qquad ds^2 = -dt^2 + a(t)^2 d\vec{x}^2, \qquad H(t) \equiv \frac{\dot{a}}{a}$

Friedmann equation (adiabatic approximation):

$$H^2\left(1 - \xi\phi^2 - G\lambda_R\phi^4\right) \approx H_\Lambda^2 + m^2\phi^2 + \lambda\phi^4, \qquad \Lambda \equiv 3H_\Lambda^2$$

Dynamical attractor solutions

Assuming $Gm^2, \lambda, \lambda_R \ll |\xi|$:

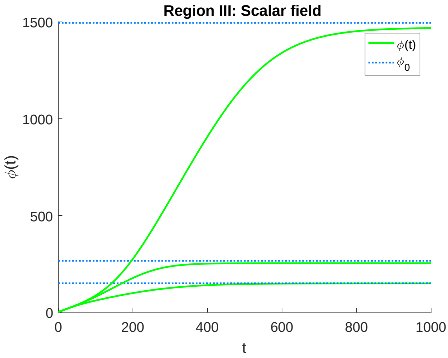
	I	II	III	IV	V
	$Gm^2, \lambda_R \ll \lambda$	$Gm^2 \lesssim \lambda_R \sim \lambda$	$0 < \lambda_R \lesssim \lambda \ll Gm^2$	$\lambda \ll \lambda_R \ll Gm^2$	$Gm^2, \lambda \ll \lambda_R$
$G_{eff} H_0^2$	$\frac{\lambda}{3\xi^2}$	$\frac{\lambda}{3\xi^2}$	$\frac{\lambda}{3\xi^2}$	$\frac{9Gm^2\lambda_R}{4\|\xi\|^3}$	$\frac{32GH_\Lambda^2\lambda_R^2}{\xi^4}$
H_0^2	H_Λ^2	$\left(\frac{3H_\Lambda^2\lambda^2}{108G^2\xi^2\lambda_R}\right)^{1/3}$	$\frac{1}{6}\sqrt{\frac{m^2\lambda}{2G\|\xi\|\lambda_R}}$	$\frac{m^2}{4\|\xi\|}$	$\frac{4H_\Lambda^2\lambda_R}{\xi^2}$
ϕ_0^2	$\frac{6\|\xi\|H_\Lambda^2}{\lambda}$	$\frac{6\|\xi\|H_0^2}{\lambda}$	$\sqrt{\frac{m^2\|\xi\|}{2G\lambda\lambda_R}}$	$\frac{\|\xi\|}{3G\lambda_R}$	$\frac{\|\xi\|}{2G\lambda_R}$
G_{eff}	$\frac{\lambda}{3\xi^2H_\Lambda^2}$	$\frac{\lambda}{3\xi^2H_0^2}$	$\sqrt{\frac{8G\lambda\lambda_R}{m^2\|\xi\|}}$	$\frac{9G\lambda_R}{\xi^2}$	$\frac{8G\lambda_R}{\xi^2}$

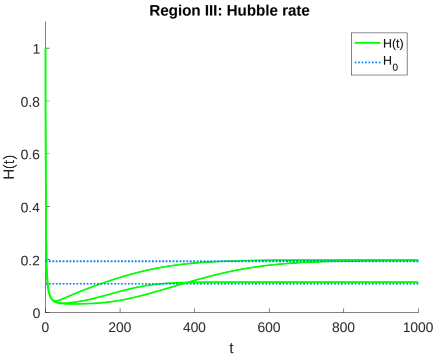
Table 1: Characteristic quantities of late-time constant attractor solutions in relevant regions of the parameter space.

Resolution of the cosmological constant problem

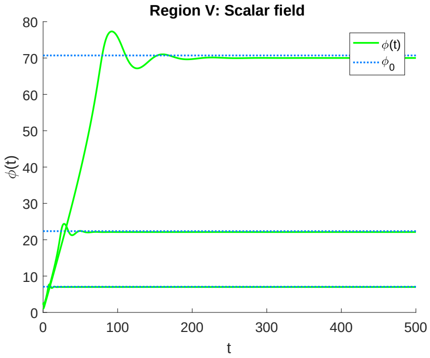
Fine-tuning of Λ $\longrightarrow$ hierarchy of couplings

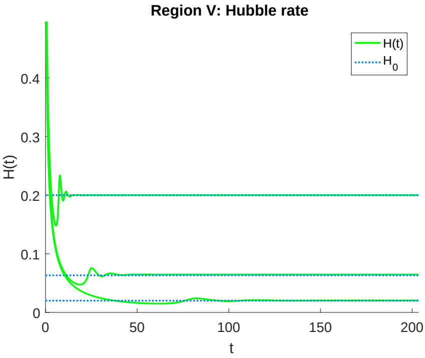
Examples of dynamical attractor solutions (III)





Examples of dynamical attractor solutions (V)





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Technical naturalness

't Hooft (1979):

"(...) the effective interactions at (...) a low energy scale μ_1*, should follow from the properties at a (...) much higher energy scale* μ_2*, without the requirements that various different parameters at the energy scale* μ_2 *match with an accuracy of the order of* μ_1/μ_2*. That would be unnatural."*

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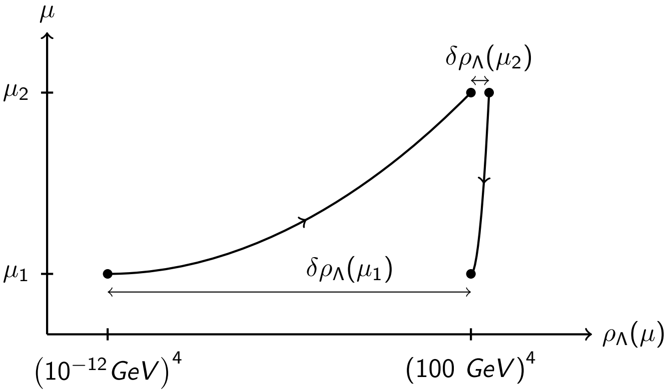
A small vacuum energy at the measured energy scale is NOT technically natural, since it requires fine-tuning of couplings at higher energy scales. This can be seen from the β-function:

$$\beta_{\rho_\Lambda} \approx \sum_{all} M_i^4$$

Technical naturalness

Unstability under perturbations of couplings at higher energy scales
= sensitivity to UV physics



Technical naturalness

Consistent low-energy EFT

The hierarchy pattern is stable under perturbations of couplings at higher energy scales, and is therefore technically natural.

This can be seen from the β-functions (assuming $\lambda_R = 0$):

$$\beta_{m^2} \approx m^2 \lambda$$
$$\beta_{\xi} \approx \left(\xi - \frac{1}{6} \right) \lambda$$
$$\beta_{\lambda} \approx \lambda^2$$

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Softly broken shift symmetry

The couplings $m^2\phi^2,\ \xi R\phi^2,\ \lambda\phi^4,\ \lambda_R R\phi^4$ break the shift symmetry $\phi \to \phi + a$. This guarantees that other interaction terms do not induce radiative corrections to these couplings.

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Summary

- Scalar-tensor theories achieving *dynamical damping* of the Hubble rate

  Initial instability period due to nonminimal coupling $\xi < 0$
  Stabilization through quartic couplings $\lambda, \lambda_R > 0$

- General Relativity recovered once the attractor solution is reached
- Conversion of the cosmological constant fine-tuning to a hierarchy of couplings
- Technically natural (softly broken shift symmetry)

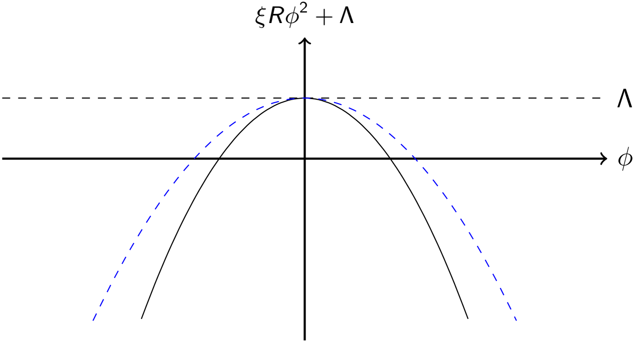
Future directions

- Rigorous proof of the attractor behavior
- Phenomenological robustness? (post-Newtonian parameters,...)
- Include radiation- and matter-dominated eras
- Include inflation
- Construct generalizations (multi-fields, spins, higher-dimension operators,...)
- ...

Thanks!

Dynamical cancellation of H_0: First attempt

First attempt by A. Dolgov and L. Ford in the 80s:



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Vanishing of Newton's constant and Weinberg's no-go

The model has an attractor solution at late-time $t \to \infty$:

$$\phi(t) \sim t,$$
$$a(t) \sim t^{\alpha}, \qquad \alpha \equiv \frac{2|\xi| + 1}{4|\xi|}.$$

In particular,

$$H(t) \sim t^{-1} \to 0$$

Vanishing of the effective Newton constant

$$G_{eff} \sim t^{-2} \to 0, \qquad \frac{1}{16\pi G_{eff}} \equiv \frac{1}{16\pi G} - \frac{\xi \phi^2}{2}$$

Weinberg's no-go theorem

Scalar-tensor theories do no admit flat solutions with nonvanishing G_{eff}, unless the Lagrangian is fine-tuned.