

A Graceful Exit for the Cosmological Constant Damping Scenario

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1. The cosmological constant fine-tuning problem
2. Dynamical damping scenarios
3. Technical naturalness
4. Summary and future directions

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The cosmological constant fine-tuning problem

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

$$\rho_{vac} \sim \text{loop with mass } m \sim m^4 \ln \frac{m^2}{\mu^2}$$

From the Standard Model of particle physics, we therefore expect

$$|\rho_{vac}| > 10^8 \text{ GeV}^4.$$

Assuming the Λ CDM cosmological model, the measured vacuum energy density is

$$\rho_{vac}|_{obs} \approx 10^{-47} \text{ GeV}^4.$$

Possible theoretical resolution:

- ▶ Fine-tuned Lagrangians
- ▶ 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:

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

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

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

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

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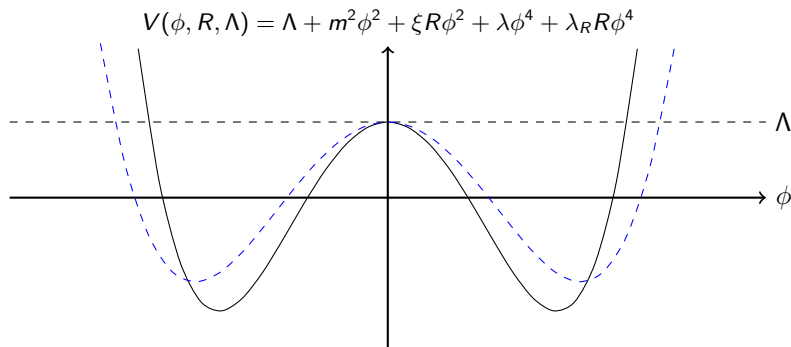
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Dynamical damping of the Hubble rate

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

Dynamical damping scenarios



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

Friedmann equation (adiabatic approximation):

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

Dynamical attractor solutions

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

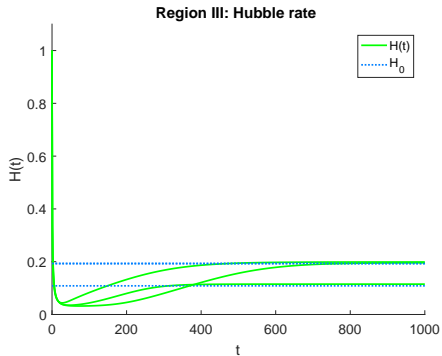
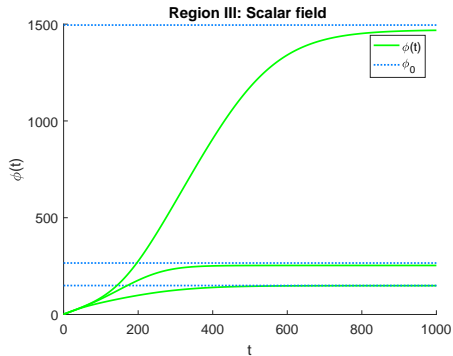
	I	II	III	IV	V
	$Gm^2, \lambda_R \ll \lambda$	$Gm^2 \lesssim \lambda_R \sim \lambda$	$0 < \lambda_R \lesssim \lambda \ll Gm^2$	$\lambda \ll \lambda_R \ll Gm^2$	$Gm^2, \lambda \ll \lambda_R$
$G_{eff} H_0^2$	$\frac{\lambda}{3\xi^2}$	$\frac{\lambda}{3\xi^2}$	$\frac{\lambda}{3\xi^2}$	$\frac{9Gm^2\lambda_R}{4 \xi ^3}$	$\frac{32GH_\Lambda^2\lambda_R^2}{\xi^4}$
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.

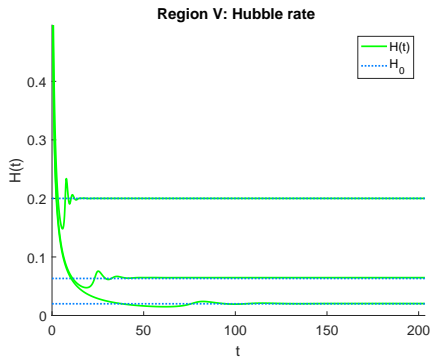
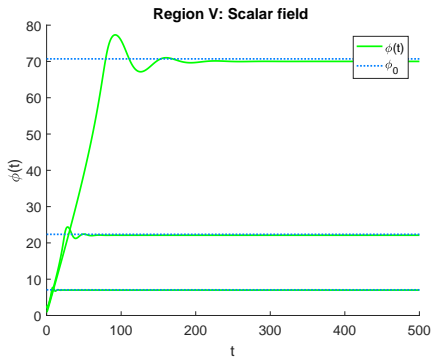
Resolution of the cosmological constant problem

Fine-tuning of $\Lambda \longrightarrow$ 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.”

Technical naturalness

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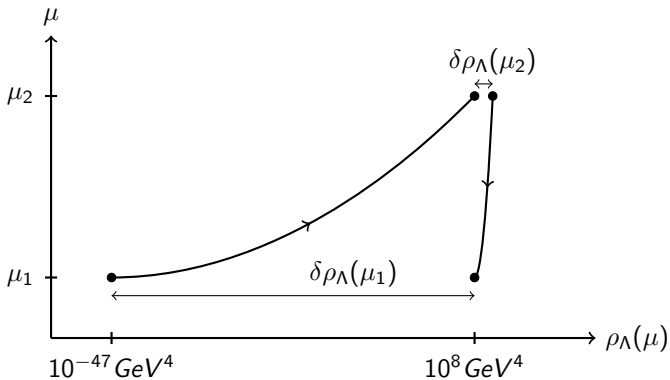
“(...) the effective interactions at (...) a low energy scale μ_1 , should follow from the properties at a (...) much higher energy scale μ_2 , without the requirements that various different parameters at the energy scale μ_2 match with an accuracy of the order of μ_1/μ_2 . That would be unnatural.”

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:

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

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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Note: the couplings

$$m^2 \phi^2, \quad \xi R \phi^2, \quad \lambda \phi^4, \quad \lambda_R R \phi^4,$$

break the shift symmetry $\phi \rightarrow \phi + a$. 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

Future directions

- ▶ Rigorous proof of the attractor behavior
- ▶ Include radiation- and matter-dominated eras
- ▶ Include inflation
- ▶ Construct generalizations (multi-fields, spins, higher-dimension operators,...)
- ▶ ...

Thanks!