Cosmology of models with spontaneous scalarization: instability and a cure

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Beyond General Relativity, Beyond Cosmological Standard Model

Motivation

- Testable gravity modifications: neutron stars and black holes
- Benchmarks for testing General Relativity:
  - **LIGO/Virgo**
  - **LISA**
  - **EHT**
  - **GRAVITY**
  - **...**

Original model of scalarization by Damour-Esposito-Farèse

Vanilla scalar-tensor theory:

$$S_{\mathrm{E}} = \int \mathrm{d}^4x \frac{\sqrt{-g}}{2\kappa} \left(-R + 2\partial_\mu\varphi\partial^\mu\varphi\right) + S_{\mathrm{m}}\left[A^2(\varphi)g_{\mu\nu}, \psi_{\mathrm{m}}\right]$$ (+---)

$$\kappa = 8\pi G$$

$$A(\varphi) = e^{\frac{1}{2}\beta\varphi^2}$$

β is a constant, which feeds into deviations from GR

φ is dimensionless

Original model of scalarization by Damour-Esposito-Farèse

[Damour&Esposito-Farese'93'96]

Essence of scalarization:

$$\Box\varphi + \frac{\kappa}{2}\alpha(\varphi)T^{\mathrm{m}} = 0$$

$$\alpha(\varphi) \equiv \frac{\mathrm{d}\ln A(\varphi)}{\mathrm{d}\varphi} = \beta\varphi$$

$$T^{\mathrm{m}}_{\mu\nu} = \frac{2}{\sqrt{-g}}\frac{\delta S_{\mathrm{m}}}{\delta g^{\mu\nu}}$$

- $\varphi = 0$ is the GR solution;
- For $\beta < 0$ and $T^{\mathrm{m}} > 0$, tachyonic mass $\Rightarrow$ other solutions?

This is indeed the case for $\beta \lesssim -4$ for neutron stars

Scalar-Gauss-Bonnet model of scalarization

[Doneva&Yazadjiev'17
Silva et al'17
Antoniou et al'17]

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + f(\phi)\hat{G}\right]$$

(-+++)

$$\hat{G} = R_{\mu\nu\sigma\alpha}R^{\mu\nu\sigma\alpha} - 4R_{\mu\nu}R^{\mu\nu} + R^2$$

$$\Box\phi + f'(\phi)\hat{G} = 0$$

f(phi)-GB model

$$\Leftrightarrow$$

$$\Box\varphi + \frac{\kappa}{2}\alpha(\varphi)T^{\mathrm{m}} = 0$$

Vanilla DEF model

When $f'(\phi_0) = 0$ and $f''(\phi_0) > 0$ then black holes and neutron stars are spontaneously scalarized

Instability of the GR solution

Trivial scalar $\phi_{\rm GR} = 0$ and background Schwarzschild metric

Perturbations: $$\left(\Box + f''(\phi_0)\hat{G}\right)\delta\phi = 0$$

Decomposition in spherical harmonics: $$\delta\phi = \frac{u(r)}{r}e^{-i\omega t}Y_{lm}(\theta,\varphi)$$

Schrödinger-like equation: $$\boxed{\frac{\mathrm{d}^2 u}{\mathrm{d}r_*^2} + \omega^2 u = V_{\rm eff}(r)u}$$

$$V_{\rm eff}(r) = \left(1 - \frac{r_g}{r}\right)\left(\frac{r_g}{r^3} - \frac{12 r_g^2}{r^6}f''(\phi_0)\right)$$

Instability of the GR solution

$$f(\phi) \;=\; \frac{1}{8}\lambda^2\phi^2 + \ldots$$

Scalarization happens for $\lambda \gtrsim r_g$, i.e. $\lambda \sim \frac{M_\odot}{M_P^2}$

Similarly in DEF model:

$$\Box\delta\varphi + \frac{\kappa}{2}\beta T^{\mathrm{m}}\,\delta\varphi = 0$$

For $\beta \lesssim -4$ the GR solution for neutron stars, $\varphi_{GR} = 0$, is unstable

There is a tachyonic instability in these models for GR solutions

Is this instability present in cosmology?

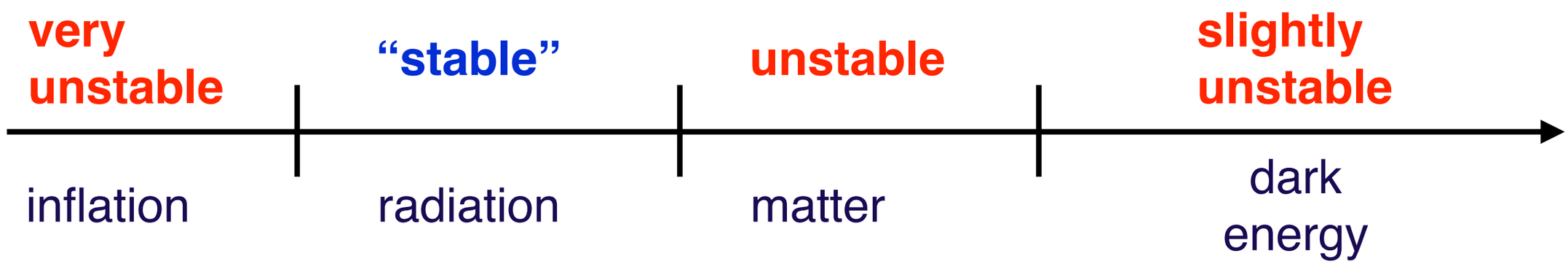
<u>Then there is a problem:</u>

- Unstable solutions

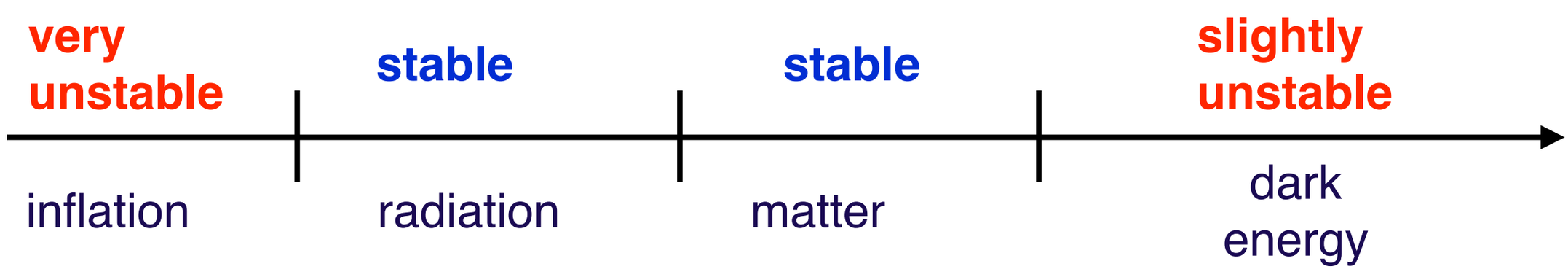
- Non-GR cosmology

instability in cosmology

DEF model:



Scalar-GB model:



constraint in DEF model

Shapiro time-delay measurement: $\gamma_{\rm PPN} = 1 \pm (2.1 \pm 2.3) \times 10^{-5}$

$$\varphi_0 \lesssim 10^{-3}$$

Can we "naturally" have a small value for the cosmological scalar field?

instability in DEF model

Matter domination:

$$\varphi_0 \lesssim 10^{-3} \quad \Rightarrow \quad \varphi_{\rm eq} \lesssim 10^{-10}$$

Radiation domination:

$$\frac{\varphi_{\rm eq}}{\varphi_{\rm i}} \simeq 10 \quad \Rightarrow \quad \varphi_{\rm i} \lesssim 10^{-11}$$

Inflation: Fine-tune $\varphi = 0$ in the beginning of inflation.
Perturbations:

$$\langle (\delta\varphi)^2 \rangle_{k \in \{k_{min}, k_{max}\}} = \frac{2^{2\nu}\Gamma^2(\nu)}{2(2\nu-3)\pi^2} \cdot \frac{H^2}{M_{Pl}^2} \cdot \left| \frac{\eta_*}{\eta} \right|^{2\nu-3} \gg 1$$

Curing DEF model

idea: Give large normal mass to the scalar responsible for scalalrization during inflation and kill the mass after inflation ends

$$\sim \varphi^2 \chi_{infl}^2$$

$$V(\varphi, \chi) = g^2 \varphi^2 \chi^2$$

We assume $m_{\rm eff} = g^2 \chi^2 \gg H^2$

For $\chi \simeq M_{Pl}$ and $H \simeq 10^{13}$ GeV, $g^2 > 10^{-12}$

Curing DEF model

The background:

$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = 0$$

$$m^2 = g^2\chi^2 + 6\beta H^2$$

Starting from $\varphi \simeq 1$ by the end of inflation the field φ is relaxed to

$$\varphi \lesssim 10^{-39}$$

Perturbations:

$$\sqrt{\langle \delta\varphi^2 \rangle_{\rm unstable}(\eta_f)} \simeq 10^{-46}$$

No Cure for scalar-Gauss-Bonnet

Vanilla scalar-tensor theory:

$$S_{\mathrm{E}} = \int \mathrm{d}^4x \frac{\sqrt{-g}}{2\kappa} \left(-R + 2\partial_\mu\varphi\partial^\mu\varphi\right) + S_{\mathrm{m}}\left[A^2(\varphi)g_{\mu\nu}, \psi_{\mathrm{m}}\right]$$

$$A(\varphi) = e^{\frac{1}{2}\beta\varphi^2}$$

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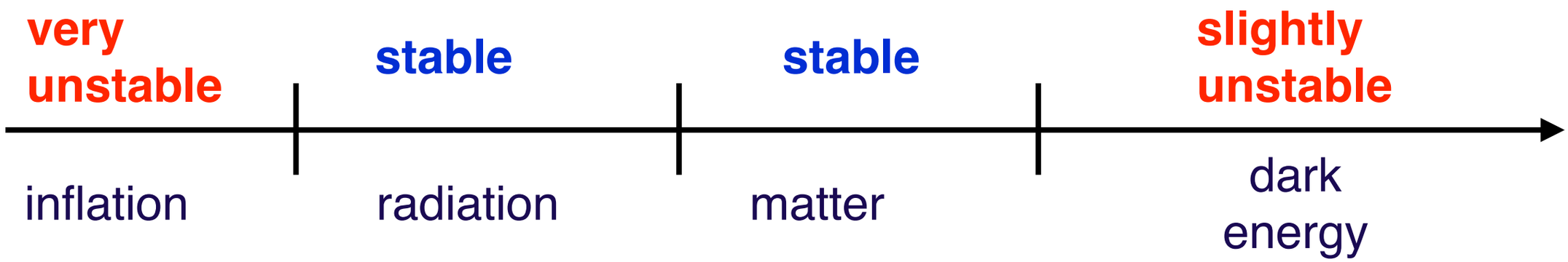
Scalar-Gauss-Bonnet theory

$$S = \int \mathrm{d}^4x\sqrt{-g}\left[\frac{M_P^2}{2}R - \frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi + f(\phi)\hat{G}\right]$$

$$f(\phi)\hat{G} = \frac{1}{8}\lambda^2\phi^2\hat{G} + \ldots$$

$$\lambda \sim \frac{M_\odot}{M_P^2} \sim 10^{19}\mathrm{GeV}^{-1}$$

No Cure for scalar-Gauss-Bonnet



$$\frac{t_{\rm inst}}{t_{\rm inf}} \sim \frac{1}{N\lambda H_{\rm inf}} \sim 10^{-34}$$

$$\frac{t_{\rm inst}}{t_0} \sim \frac{H_0}{m_{\rm eff}} \sim \frac{1}{\lambda H_0} \sim 10^{23}$$

for inflation with the scale
$H_{\rm inf} \sim 10^{13}$GeV and $N \sim 10^2$ e-foldings

Destabilisation occurs very quickly => no standard cosmological inflation

Trying to cure scalar-Gauss-Bonnet scalarization model

The same idea with coupling to inflaton? $\sim g^2\chi^2\phi^2$

However: $$g^2 \gtrsim \frac{6\lambda^2 H^4}{\chi^2} \simeq 10^{53}$$

$$\text{for } \chi \simeq M_P,\ \lambda H \simeq 10^{32},\ \text{and } H \simeq 10^{13}\ \text{GeV}$$

Extreme strong coupling !

Trying to cure scalar-Gauss-Bonnet scalarization model

[Macedo et al'19]

quartic self-interaction: $\sim g\phi^4$

the scalar field is in the minimum of the effective potential during inflation

However: $\phi_{min} \sim 10^{64} M_P$

Also extra potential energy: $\sim 10^{180} M_P^4$

Conclusions

- Vanilla DEF and modern scalar-Gauss-Bonnet models of scalarization gives interesting modifications of gravity, leading to different from GR neutron stars or/and black hole solutions.

- Both models do contain dangerous instabilities during inflation

- It is possible to `naturally' cure the original DEF model

- It seems however that the scalar-Gauss-Bonnet model cannot be cured