Fudan University
Physics Department

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Bouncing cosmologies from Born–Infeld-type gravity

Yermek Aldabergenov
with Wei Lin, Rongjian Li, Ding Ding, and Yidun Wan

Introduction

Various attempts have been made so far to replicate the structure of the Born–Infeld (BI) electrodynamics theory in the gravitational sector, in order to remove singularities plaguing general relativity (GR). In this work we reconstruct a BI-type modified gravity based on the Kaluza–Klein (KK) approach of embedding electromagnetism in a 5D gravitational theory. The following two key results are obtained:

- By embedding the BI electrodynamics in 5D modified gravity, we reconstruct a ghost-free BI-type $f(R,\mathcal{G})$ gravity in 4D, where $\mathcal{G}$ is the Gauss–Bonnet (GB) term;
- We find and classify bouncing cosmological solutions, including multi-bounce solutions.

1 Born–Infeld from Kaluza–Klein

We take the following KK metric ansatz,

$$\hat{g}_{MN} = \begin{pmatrix} g_{\mu\nu} + 2\Phi^2 A_\mu A_\nu & \sqrt{2}\Phi^2 A_\mu \\ \sqrt{2}\Phi^2 A_\nu & \Phi^2 \end{pmatrix} , \tag{1}$$

where Φ is a scalar field controlling the size of the compact dimension (in this work, we set $\Phi = 1$), $A_{\mu\nu}$ is the KK gauge field, and $\hat{g}$ and g are the 5D and 4D metric tensors.

Demanding that after the dimensional reduction to 4D, and in flat spacetime, we get BI electrodynamics (up to field strength derivative corrections), leads to the 5D $f(R,\mathcal{G})$ gravity of the type

$$S_{5d} = \tfrac{1}{2}\hat{M}_P^3 \int d^5x \sqrt{-\hat{g}}\, f(\hat{R},\hat{\mathcal{G}}) , \quad f = \tfrac{2}{b^2}\Big(1 - \sqrt{1 - b^2\hat{R} - \tfrac{b^4}{24}\hat{\mathcal{G}}}\Big) , \tag{2}$$

where the "hatted" terms are derived from the 5D metric, and b is the BI parameter.

After using the KK ansatz (1), and flat 4D spacetime, $g_{\mu\nu} = \eta_{\mu\nu}$, we get the BI theory up to derivative corrections (in 4D):

$$\mathcal{L} = b^{-2}\left[1 - \sqrt{1 + \frac{b^2}{2}F^2 - \frac{b^4}{16}(F\tilde{F})^2 - \frac{b^4}{12}\big(\Box F^2 + 2\partial_\lambda\partial^\mu(F_{\mu\nu}F^{\nu\lambda})\big)}\,\right] . \tag{3}$$

Conversely, if we ignore the gauge field, we get a 4D BI-type gravity

$$\mathcal{L} = b^{-2}\sqrt{-g}\Big(1 - \sqrt{1 - b^2 R - \tfrac{b^4}{24}\mathcal{G}}\Big) , \tag{4}$$

which reduces to GR in the $b \to 0$ limit. The full Lagrangian also includes non-minimal coupling of the gauge field to curvature terms, but in this work we will focus on the gravitational sector only.

2 Bouncing cosmology

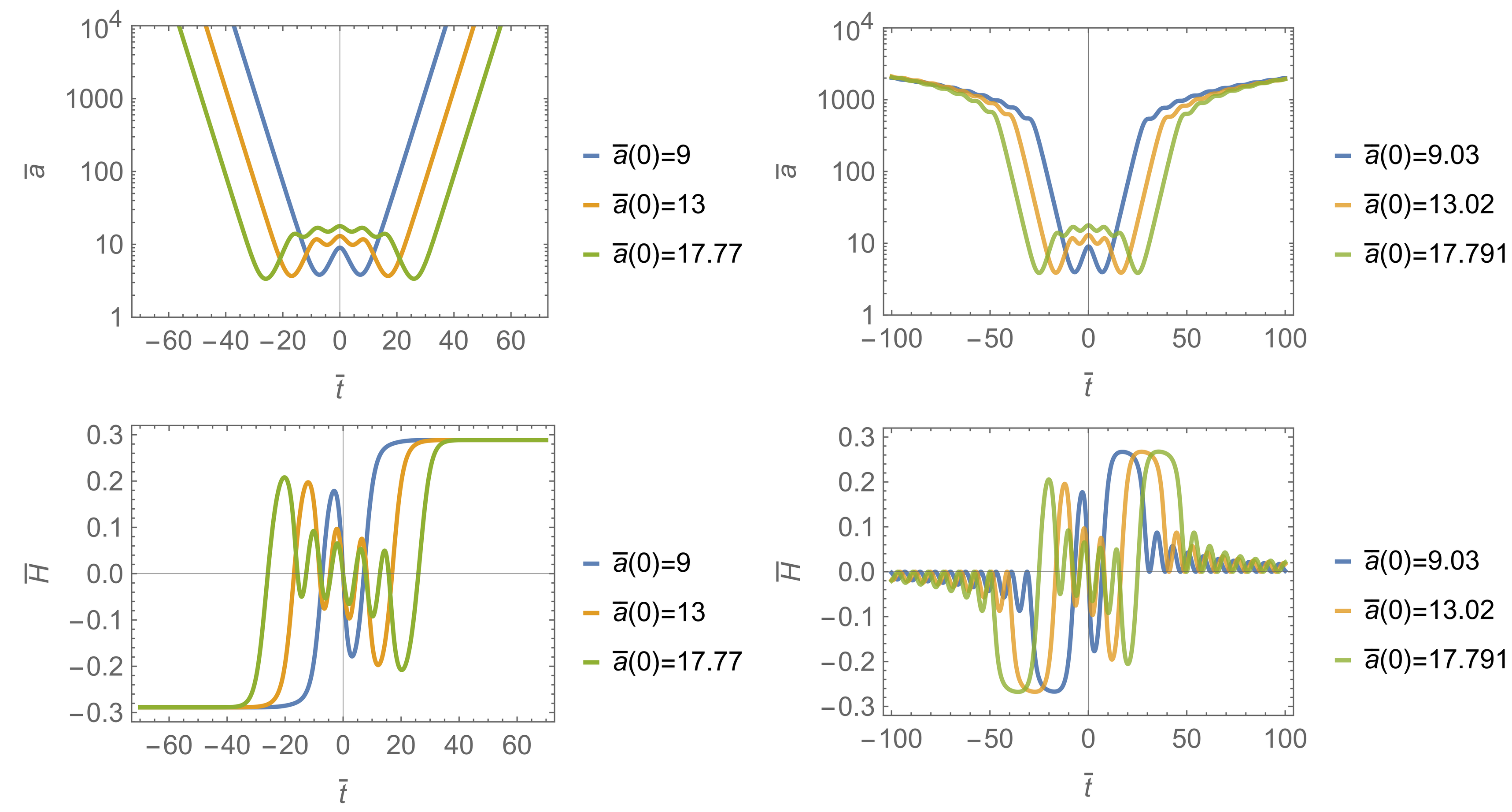
We take FLRW metric with spatial curvature K:

$$ds^2 = -dt^2 + a(t)^2\left[\frac{dr^2}{1 - Kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right] . \tag{5}$$

Main properties of the bouncing solutions are captured within the simplified model (without the GB term):

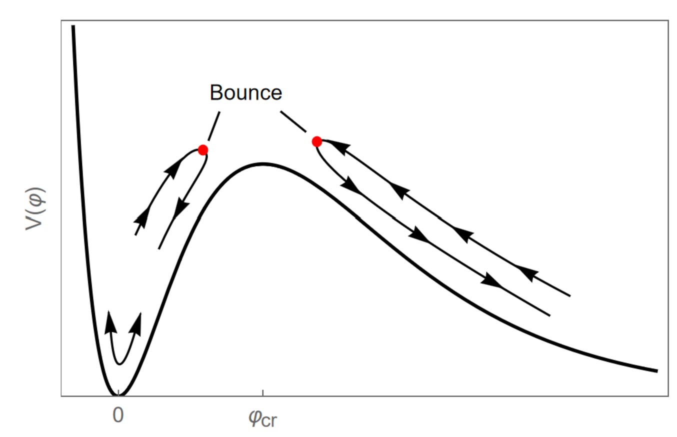
$$\mathcal{L} = b^{-2}\sqrt{-g}\Big(1 - \sqrt{1 - b^2 R}\Big) . \tag{6}$$

The corresponding 00 Einstein equation is a third-order equation (for the scale factor) which can be nondimensionalized to remove b (assuming $b \neq 0$). Its solutions can be fully classified by the choice of the initial conditions. We find that bouncing solutions require closed universe with $K = +1$.



Some examples of multi-bounce solutions in the simplified case (6) ($\bar{a}$ = rescaled scale factor, $\bar{H}$ = rescaled Hubble rate). Left column: solutions with asymptotically constant Hubble rate. Right columnt: solutions with oscillating Hubble rate (with damped amplitude).

In the Einstein frame, the model (6) describes a canonical scalaron with the potential below, which shows the origin of the oscillations of the Hubble rate for one class of bouncing solutions, and runaway behavior for the other: oscillations happen around the Minkowski minimum, while the runaway behavior corresponds to the runaway minimum of the potential. Bounces happen around the local maximum of the potential.

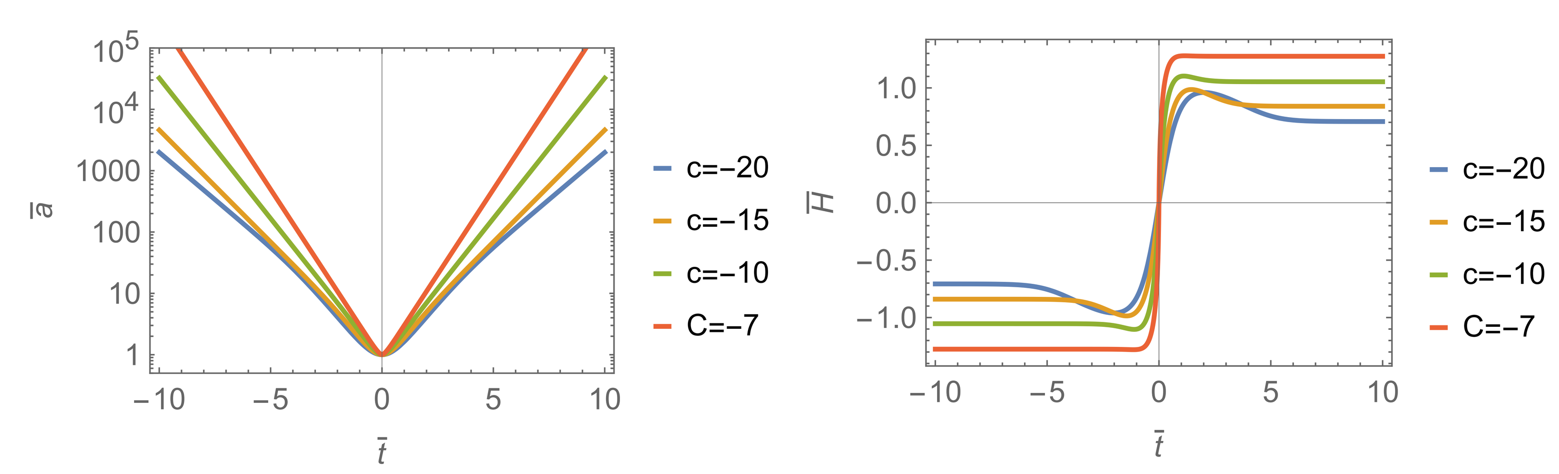


Einstein-frame representation of single-bounce solutions with the scalaron potential $V(\varphi)$.

With the GB term, the Lagrangian is

$$\mathcal{L} = b^{-2}\sqrt{-g}\Big(1 - \sqrt{1 - b^2 L}\Big) , \qquad L = R + \frac{c\,b^2}{24}\mathcal{G} , \tag{7}$$

with a new parameter c which generalizes the model. The BI-type theory (4) is recovered for $c = 1$. When $c \sim \mathcal{O}(1)$ or smaller, the GB term mildly deforms the solutions of the simplified case. For larger negative c, new bouncing solutions are found.



Gauss–Bonnet-supported bouncing solutions.

3 Summary

- We derived BI-type gravity from 5D embedding of the BI electrodynamics.
- We found bouncing cosmological solutions (single- and multi-bounce) in a closed universe, avoiding the Big Bang singularity.
- The runaway solutions are found to be stable future and past attractors. Oscillatory solutions are stabilized around the beginning of the oscillations.
- Future directions include embedding inflation in this model, and effects of the multi-bounce on CMB and gravitational wave background.

For more details see arXiv:2604.24860