A Non-Singular Cyclic Universe from Modified Gravity

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A phenomenological route to a finite-size bounce and a future turnaround

Outline

1. Motivation
2. From a modified potential to a modified Friedmann equation
3. The minimal cyclic background
4. Observational constraints and results
5. Connections to other bounce scenarios (unifying view)
6. Conclusions and future work

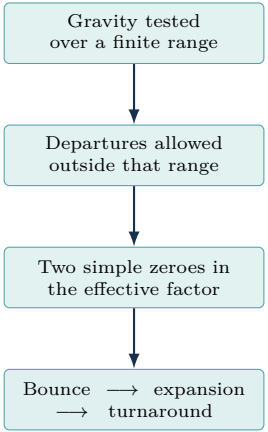
Reference: S. Das, M. Fridman, D. Kuniyal, S. Sur, arXiv:2609.16015 [physics.gen-ph].

Motivation: can classical modified gravity yield a cyclic universe?

- The concordance model, ΛCDM, describes the observed expansion history with considerable success.
- Its classical backward extrapolation reaches a Big-Bang singularity, where geodesic completeness fails and classical GR ceases to be predictive.
- Many proposed bounces invoke specific quantum-gravity ingredients. Their observational signatures are often model-dependent.

Question addressed

Can a non-singular (even cyclic) cosmology arise from a minimal, classical, phenomenological modification of gravity?



A phenomenological modification of the Newtonian potential

For a point mass M, consider

$$V(r) = -\frac{GM}{r}F(r), \qquad F(r) = 1 \quad \text{for } r \in (L_1, L_2),$$

where $L_1 \sim 10^{-4}$ m and $L_2 \sim 10^{26}$ m denote the approximate observational limits.

We factorize the modification as

$$\boxed{F(r) = F_1(r)F_2(r)F_3(r).}$$

$F_1(r)$: Regularization

$$F_1(r) = e^{-\ell_1/r}\frac{(r/\ell_2)^\alpha}{1+(r/\ell_2)^\alpha}.$$

Smooths the short-distance behaviour of the potential and removes the $r = 0$ singularity.

$\alpha > 0, \qquad \ell_1, \ell_2 < L_1.$

$F_2(r)$: Deformation

$$F_2(r) = \left[1 + \sum_{\ell=1}^{s}\left(\frac{r_{0\ell}}{r}\right)^{\ell}\right] \times \left[1 + \sum_{\ell'=1}^{s'}\left(\frac{r}{r'_{0\ell'}}\right)^{\ell'}\right].$$

Modifies the potential at short and large distances without introducing additional zeroes.

$F_3(r)$: Zero-generating

$$F_3(r) = \prod_{i=1}^{n}\left(1 - \frac{r_i}{r}\right)^{\nu_i} \times \prod_{j=1}^{n'}\left(1 - \frac{r}{r'_j}\right)^{\nu'_j}.$$

Introduces short- and large-distance zeroes, responsible for the bounce and turnaround.

The minimal zero structure: one bounce and one turnaround

Minimal cyclic configuration

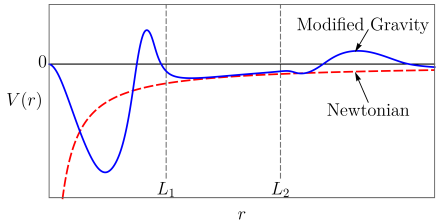
From the choice adopted in the previous slide,

$$F(r) = F_3(r).$$

We retain a single pair of simple zeroes:

$$\boxed{n = n' = \nu_1 = \nu_1' = 1.}$$

Figure 1: Schematic modified potential $V(r)$ illustrating the short- and large-distance zeroes.



- **Short-distance zero:** $r_1 \ll L_1$, corresponding to the cosmological bounce at $a = a_1$.
- **Large-distance zero:** $r_1' \gg L_2$, corresponding to the future turnaround at $a = a_1'$.
- Using $r = \ell_0 a$, the corresponding scale-factor zeroes are $a_1 = r_1/\ell_0$ and $a_1' = r_1'/\ell_0$.

Physical requirement

Simple zeroes (unit multiplicity) allow the bounce and turnaround to occur in finite cosmic time.

From the modified potential to the modified Friedmann equation

In the quasi-Newtonian (QN) cosmological formulation, the resulting background equation is

$$H^2 = \frac{8\pi G}{3c^2} \sum_{I=1}^{N} \frac{\rho_{I0}}{a^{3(1+w_I)}} \left(1 - \frac{a_1}{a}\right) \left(1 - \frac{a}{a_1'}\right) - \frac{kc^2}{a^2}$$

The two turning points

For spatially flat Universe $k = 0$,

$$H(a_1) = 0, \qquad H(a_1') = 0.$$

For a positive total fluid density:

- Bounce: $\dot{H} > 0$ at $a = a_1$.
- Turnaround: $\dot{H} < 0$ at $a = a_1'$.

Scope of the equation

The QN construction reproduces the standard Friedmann-equation form at the homogeneous background level. It is not, by itself, a covariant perturbation theory.

Reference: S. Das, S. Sur, Eur. Phys. J. Plus 139 (2024) 1049.

Why must the zeroes be simple?

Near a zero $a = a_z$ of multiplicity ν, with the remaining factors finite and nonzero,

$$H^2 \propto (a - a_z)^\nu \quad \Longrightarrow \quad \dot{a} = aH \propto (a - a_z)^{\nu/2}.$$

The time required to reach the zero is therefore governed by

$$\Delta t \propto \int_{a_z}^{a_z+\epsilon} \frac{\mathrm{d}a}{(a - a_z)^{\nu/2}}.$$

Finite-time criterion

This integral converges only for $\nu < 2$. Since the multiplicity is a positive integer, the only allowed value is

$$\boxed{\nu = 1 \quad \text{(a simple zero).}}$$

A single simple zero at small a and one at large a are sufficient to confine the evolution to $a_1 \leq a \leq a_1'$ and generate repeated cycles.

Cosmic History: a finite-size bounce and a future turnaround

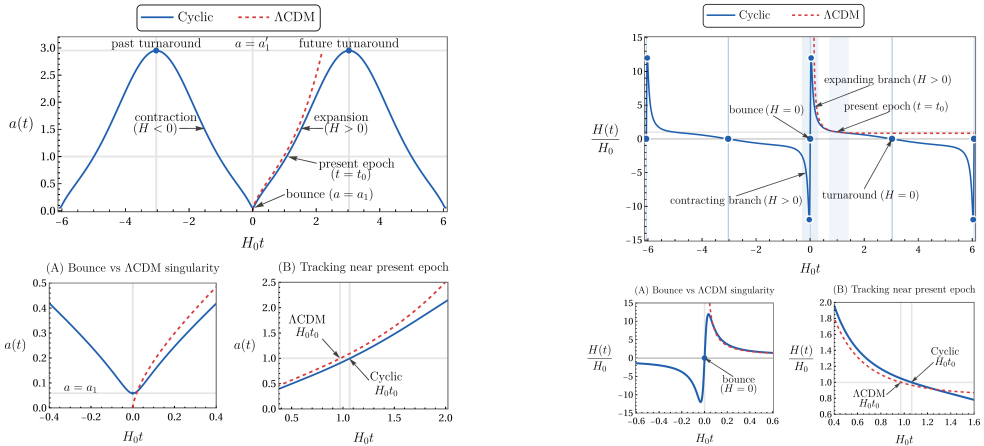


Figure 2: Cosmic evolution in the cyclic scenario and ΛCDM: (left) scale-factor evolution $a(t)$; (right) evolution of the dimensionless Hubble parameter $H(t)/H_0$. **Note:** The bounce scale is enhanced by a factor of 10^{12} in the plots for visual clarity.

Density-parameter form and late-time background model

With $a_0 = 1$ and $H_0 \equiv H(a_0)$, define the critical density $\rho_{c0} \equiv 3c^2 H_0^2/8\pi G$ and the present-day density parameters

$$\Omega_{r0} \equiv \frac{\rho_{r0}}{\rho_{c0}}, \qquad \Omega_{m0} \equiv \frac{\rho_{m0}}{\rho_{c0}}, \qquad \Omega_{\Lambda 0} \equiv \frac{\rho_\Lambda}{\rho_{c0}} = \frac{\Lambda c^2}{3H_0^2}, \qquad \Omega_{k0} \equiv -\frac{kc^2}{H_0^2}.$$

Introducing $E(a) \equiv H(a)/H_0$, the modified Friedmann equation becomes

$$E^2(a) = \left(\Omega_{r0} a^{-4} + \Omega_{m0} a^{-3} + \Omega_{\Lambda 0}\right) \times \left(1 - \frac{a_1}{a}\right)\left(1 - \frac{a}{a_1'}\right) + \Omega_{k0} a^{-2}.$$

Working equation: flat, late-time universe

Spatial flatness and a negligible radiation at the present epoch is assumed: $\Omega_{k0} = 0$ and $\Omega_{r0} \simeq 0$. Using the normalization condition $E^2(1) = 1$, the background equation reduces to

$$E^2(a) = \left[\Omega_{m0}\left(\frac{1}{a^3} - 1\right) + \frac{1}{(1-a_1)(1-a_1'^{-1})}\right]\left(1 - \frac{a_1}{a}\right)\left(1 - \frac{a}{a_1'}\right).$$

Observational Data and Parameter Estimation

Probe	Data points
Cosmic Chronometers (CC)	51
Pantheon$^+$ Type-Ia supernovae	1701
BAO (SDSS/eBOSS/DESI)	15
Planck 2018 compressed CMB priors	4
BBN light-element abundances	2
Total	**1773**

Inference

- Joint maximum-likelihood analysis.
- MCMC with the affine-invariant `emcee` sampler.
- Flat priors; constraints reported at 68% C.L.
- Convergence: $\widehat{R} = 1.011$ (cyclic), 1.0025 (ΛCDM).

Seven sampled parameters in the cyclic model

$$\boldsymbol{\theta} = \{H_0, \Omega_{m0}, \Delta M, r_d, \omega_b, N_1, N_1'\}, \quad N_1 = \log_{10} a_1, \; N_1' = \log_{10} a_1'.$$

Data references in the manuscript: Moresco et al. (2016), Monjo (2024), Brout et al. (2022), SDSS/eBOSS/DESI, Arendse et al. (2020), and Pitrou et al. (2021).

Posterior Constraints: Cyclic Scenario vs. ΛCDM

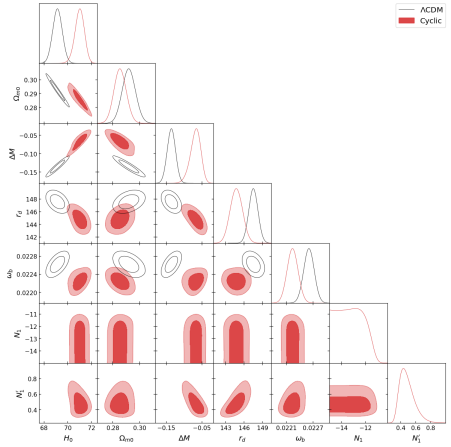


Figure 3: Marginalized 1D and 2D posterior distributions with 1σ and 2σ credible regions for $\boldsymbol{\theta}$s. Constraints are obtained from the joint CC + Pantheon$^+$ + BAO + CMB + BBN analysis.

Parameter Constraints: the bounce and turnaround are data-constrained

Parameter	**Cyclic scenario**	ΛCDM
$H_0\,[\mathrm{km\,s^{-1}\,Mpc^{-1}}]$	$71.0267^{+0.3821}_{-0.4031}$	$69.1491^{+0.4026}_{-0.3997}$
Ω_{m0}	$0.2855^{+0.0046}_{-0.0045}$	$0.2921^{+0.0050}_{-0.0049}$
$r_d\,[\mathrm{Mpc}]$	$144.7630^{+1.0090}_{-0.9923}$	$147.5370^{+0.7463}_{-0.7384}$
$N_1 = \log_{10} a_1$	$-13.2296^{+1.1910}_{-1.2030}$	—
$N_1' = \log_{10} a_1'$	$0.4703^{+0.1122}_{-0.0797}$	—

Past bounce

$$a_1 = 5.8939 \times 10^{-14}$$

Far earlier than the BBN epoch, $a \sim 10^{-10}$.

Future turnaround

$$a_1' = 2.9532$$

Expansion halts when the scale factor is about three times its present value.

The remaining sampled nuisance parameters are $\Delta M = -0.0670^{+0.0133}_{-0.0154}$ and $\omega_b = 0.0222 \pm 0.0001$ for the cyclic fit.

Model Comparison: the joint fit favours the cyclic scenario

Model	$N_{\rm par}$	$\chi^2_{\rm min}$	AIC	BIC	$\ln \mathcal{Z}$
Cyclic	7	1828.29	1842.29	1880.65	-938.34
ΛCDM	5	1859.58	1869.58	1896.98	-951.65

Δ**AIC**	Δ**BIC**	$\Delta \ln \mathcal{Z}$
-27.29	-16.33	$+13.30$

Interpretation

The improvement remains substantial despite two additional parameters. The Bayesian evidence corresponds to strong/decisive support for the cyclic model on the Jeffreys scale, within the likelihood and prior choices adopted in the analysis.

Differences are defined as cyclic minus ΛCDM; hence lower AIC/BIC and higher $\ln \mathcal{Z}$ favour the cyclic scenario.

A broader class of bouncing and cyclic cosmologies

The construction is naturally generalized to

$$H^2(a) = \frac{8\pi G}{3c^2}\,\rho(a)\,g(a),$$

with

$$g(a) = \prod_{i=1}^{n}\left(1-\frac{a_i}{a}\right)^{\nu_i}\prod_{j=1}^{n'}\left(1-\frac{a}{a'_j}\right)^{\nu'_j}.$$

Examples

- Loop quantum cosmology: high-density corrections can generate a bounce.
- $f(R)$ gravity: ultraviolet and infrared terms can supply roots at both scales.
- Quintom / ekpyrotic models: effective components can generate zeroes.

Unifying viewpoint

The background dynamics is organized by the location, number, and multiplicity of the zeroes of $g(a)$. Finite-time cyclic evolution requires simple zeroes at both ends of the allowed interval.

These examples share related effective zero structures; they are not dynamically identical.

What is established and what remains to be done?

What this analysis establishes

- A minimal modified-potential ansatz yields a nonsingular background with a bounce and a turnaround.
- The two turning scales can be constrained with current background data.
- The joint fit and information criteria favour the cyclic parametrization over the ΛCDM reference model.
- Fixed zeroes bound the cycle amplitude.

Open theoretical questions

- Construct a complete covariant action reproducing the desired potential.
- Analyse perturbations and stability through the bounce.
- Establish consistent pre-bounce initial conditions and mode propagation.
- Complete the thermodynamic analysis: entropy production may change the cycle duration even if the amplitude stays fixed.

Important scope statement: the present likelihood analysis constrains the homogeneous background; a full covariant perturbation-level validation is future work.

Take-home message

1. A phenomenological modification of the Newtonian potential, preserving standard gravity in the tested range, can introduce two cosmological zeroes.
2. A simple zero at small a produces a finite-time bounce; a simple zero at large a produces a finite-time turnaround.
3. The resulting background can closely track ΛCDM over the observed era while admitting a cyclic extension.
4. Joint CC, Pantheon$^+$, BAO, CMB and BBN constraints favour the cyclic model over the ΛCDM reference within the analysis assumptions.

Thank you!

Questions and Discussion