

A Cyclic 4D-Time Universe Model: Bounce, Expansion, and Turnaround Controlled by Closed Time Geometry

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Abstract

We propose a conceptual cosmological framework in which the fourth dimension—time—is not infinite, but cyclic and bounded. This closed time geometry provides a natural mechanism for both the initiation of cosmic expansion (the bounce) and its termination (the turnaround), removing the need for external triggers. We derive an effective Friedmann equation, inspired by Loop Quantum Cosmology (LQC), that incorporates quantum corrections to avoid singularities, and show how a large- a turnaround can arise through curvature or an effective negative cosmological term. The bounce is interpreted as a single-frame quantum state, linking emergent time concepts with cyclic and conformal cosmological models. We highlight how this approach differs from both LQC and Conformal Cyclic Cosmology (CCC), and sketch potential observational signatures in the CMB and primordial gravitational waves. While speculative, the closed-time ansatz yields falsifiable predictions in principle and motivates further work on entropy bounds and observational signatures.

1 Introduction

The classical theory of general relativity predicts singularities at the Big Bang and inside black holes, where the equations cease to be valid. Loop Quantum Cosmology (LQC) provides a resolution through quantum corrections that replace singularities with bounces [1, 2]. Other cyclic approaches, such as the ekpyrotic/cyclic scenario [3], posit a sequence of universes but often leave the termination of expansion unspecified. Penrose’s Conformal Cyclic Cosmology (CCC) [4] offers an alternative by identifying the remote future of one aeon with the Big Bang of the next through conformal rescaling.

The proposal developed here differs in a key way: time itself is treated as a closed arc, with expansion and contraction bounded by its periodicity. This *cyclic 4D-time* ansatz eliminates the need for ad hoc triggers and provides a unified geometric controller for both the bounce and the turnaround.

2 Framework

2.1 Cyclic Time Ansatz

We posit periodic cosmic time $\tau \in [0, T)$ such that $a(\tau + T) = a(\tau)$. Turning points occur at a_{\min} (bounce) and a_{\max} (turnaround), where $\dot{a} = 0$. It is convenient to define an effective potential

$$\dot{a}^2 + U(a) = 0, \quad U(a) \equiv -a^2 \left[\frac{8\pi G}{3} \rho(a) \left(1 - \frac{\rho(a)}{\rho_c} \right) - \frac{k}{a^2} \right]. \quad (1)$$

The cycle period is

$$T = 2 \int_{a_{\min}}^{a_{\max}} \frac{da}{\sqrt{-U(a)}}, \quad (2)$$

which is finite if both turning points exist.

2.2 Effective Friedmann Equation from a Hamiltonian

Following LQC, the effective Hamiltonian constraint is

$$\mathcal{C}_{\text{eff}} = -\frac{3}{8\pi G \gamma^2 \lambda^2} a^3 \sin^2(\lambda b) + \rho(a) a^3 = 0, \quad (3)$$

with Barbero–Immirzi parameter γ and area gap $\lambda = \sqrt{\Delta}$. This yields

$$H^2 = \frac{8\pi G}{3} \rho(a) \left(1 - \frac{\rho(a)}{\rho_c} \right) - \frac{k}{a^2}, \quad \rho_c = \frac{3}{8\pi G \gamma^2 \lambda^2}. \quad (4)$$

Convention. We set $\Lambda = 0$ to avoid double counting; all vacuum-like terms, including closed-time effects, are absorbed into $\rho(a)$.

Bounce. At $a = a_{\min}$, $H = 0$ implies $\rho = \rho_c$. Using the effective Raychaudhuri equation,

$$\dot{H} = -4\pi G(\rho + P) \left(1 - 2\frac{\rho}{\rho_c} \right) + \frac{k}{a^2},$$

one finds $\dot{H} > 0$ for $k = 0$ and $\rho + P > 0$, confirming stability.

Turnaround. At $a = a_{\max}$, $H = 0$ implies

$$\frac{8\pi G}{3} \rho(a_{\max}) \left(1 - \frac{\rho(a_{\max})}{\rho_c} \right) - \frac{k}{a_{\max}^2} = 0.$$

A turnaround may therefore be achieved either by (i) a negative effective vacuum term (as introduced below), (ii) positive curvature $k = +1$, or (iii) a bare negative Λ . In this model, we interpret the effective negative term as a consequence of compact time.

2.3 Closed Time as Effective Dynamics

Compactifying cosmic time as $\tau \in S^1$ motivates an additional contribution. We adopt a phenomenological ansatz

$$\rho_{\text{CT}}(R_\tau) = -\frac{\sigma}{R_\tau^4}, \quad R_\tau = T/2\pi. \quad (5)$$

This negative scaling ensures a turnaround at large a , with effective $\Lambda_{\text{eff}} = 8\pi G \rho_{\text{CT}} < 0$. *Remark.* In QFT, compact Euclidean time yields a positive $\propto T^4$ energy density; hence the negative sign here is an assumption requiring future derivation.

We also allow a mild R_τ -dependence of the polymer scale,

$$\rho_c(R_\tau) = \frac{3}{8\pi G \gamma^2 \tilde{\lambda}^2(R_\tau)}, \quad \tilde{\lambda}^2(R_\tau) = \lambda^2 \left[1 + \chi \left(\frac{\ell_{\text{P}}}{R_\tau} \right)^2 + \dots \right].$$

Cycle quantization (heuristic). A Bohr–Sommerfeld-type condition,

$$\oint p_a da = 2\pi N \hbar, \quad N \in \mathbb{Z}_{\geq 0},$$

may discretize allowed (a_{\min}, a_{\max}, T) , though a full Dirac quantization is required for rigor.

3 Results

3.1 Cyclic Scale Factor

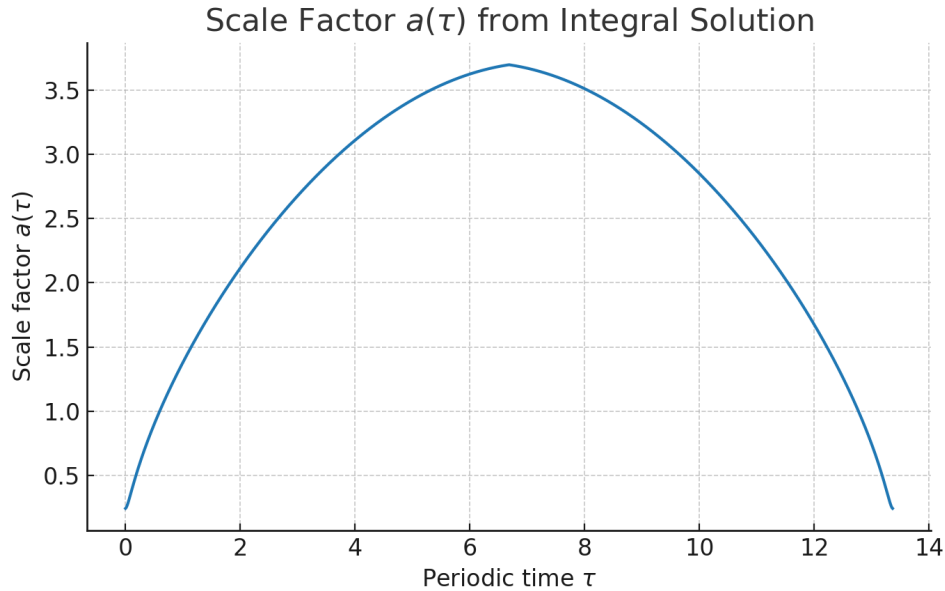


Figure 1: Scale factor from the integral solution. $a(\tau)$ reconstructed with $\rho_c(R_\tau)$ and $\rho_{\text{CT}}(R_\tau)$ included. Bounce (a_{\min}) and turnaround (a_{\max}) are marked.

3.2 Effective $H^2(a)$

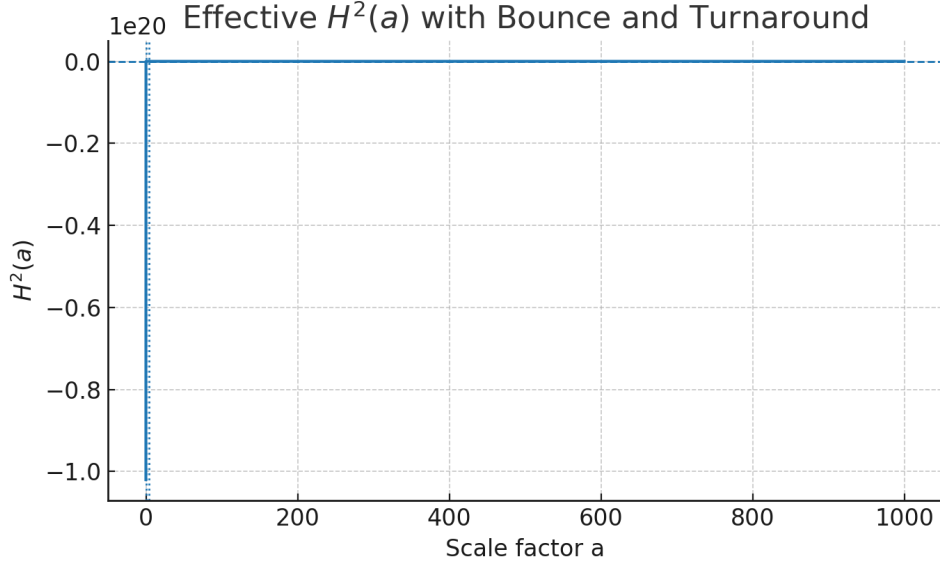


Figure 2: Effective $H^2(a)$. Numerically computed $H^2(a)$ for the toy parameters, with zeros marking the bounce and turnaround.

Toy Parameters

Parameter	Value	Description
ρ_{m0}	1.0	Matter-like density ($\propto a^{-3}$)
ρ_{r0}	0.1	Radiation-like density ($\propto a^{-4}$)
ρ_{vac}	-0.02	Effective negative term (proxy for ρ_{CT})
ρ_c	100.0	Critical density (bounce)
k	0	Spatial curvature

Table 1: Toy parameters used to generate the illustrative figures.

4 Discussion

Compared to LQC [1], this retains the quantum bounce but introduces a built-in turnaround. Unlike CCC [4], contraction is preserved. The model resonates with emergent-time perspectives such as Hartle–Hawking [5] and Rovelli [6].

Comparison with Other Cyclic Proposals

	LQC	CCC (Penrose)	Cyclic 4D-Time (this work)
Bounce mechanism	Quantum-geometry bounce at $\rho = \rho_c$	None (aeon-to-aeon conformal identification)	Bounce at $\rho = \rho_c(R_\tau)$
Turnaround mechanism	None (expansion continues)	Not applicable	Negative $\rho_{CT}(R_\tau)$, or equivalently $k > 0$ or $\Lambda < 0$
Time structure	Linear, unbounded	Infinite succession of aeons	Compact time $\tau \in S^1$
Contraction phase	Optional/absent	Removed by conformal rescaling	Present; closes the cycle
Novel element	Polymer corrections ρ_c	Conformal identification	Unified bounce+turnaround via closed time

Table 2: Comparison of cyclic universe proposals.

Entropy and the Arrow of Time

Cyclic models face the entropy problem: why entropy does not accumulate monotonically across cycles. CCC invokes conformal thinning of massive degrees of freedom. In the closed-time framework, one may speculate that the compact geometry enforces entropy reset mechanisms via holographic bounds or quantum information limits. Another possibility, inspired by CCC, is that massive particles decay away between cycles, thinning entropy carriers before the next bounce. Alternatively, holographic entropy bounds might cap entropy per cycle, forcing a reset. These ideas remain speculative, but they provide concrete targets for future theoretical and observational work.

$$S \leq \frac{A}{4G\hbar}, \quad (6)$$

which represents the Bekenstein–Hawking entropy bound. Future work should test whether compact time naturally enforces such a cap, preventing monotonic buildup.

Observational Outlook

- **CMB anomalies:** oscillatory modulation of the primordial power spectrum, with scale set by R_τ . For R_τ of order 10^2 – 10^3 in Planck units, features would appear in the CMB at multipoles $\ell \sim 20$ – 30 . Roughly, features scale as $\ell \sim \pi/\theta \sim \pi D_A/R_\tau$, where D_A is the angular diameter distance to last scattering. A precise mapping requires perturbation analysis in compact time, which is left for future work. Current Planck observations show mild low- ℓ anomalies that might be consistent with such periodic modulation, although their statistical significance remains debated.
- **Gravitational waves:** cyclic bounce signatures in the tensor spectrum, potentially observable with next-generation detectors such as LISA or Cosmic Explorer.

- **Entropy cycling:** relic non-Gaussian features or suppressed entropy growth as traces of entropy reset between cycles.

Bounce as a wavefunction. In a Wheeler–DeWitt minisuperspace approximation, $\Psi(a)$ near a_{\min} can be modeled as Gaussian-peaked. Since $H = 0$ at the bounce, extrinsic curvature vanishes and comoving observers share a common frame.

5 Conclusions

We have presented a toy model where compact time controls both bounce and turnaround. This differs from LQC (bounce only) and CCC (no contraction). While speculative in its closed-time interpretation, the framework is internally consistent and suggests falsifiable signatures.

In particular, both the CMB and the primordial gravitational wave background can serve as observational probes of the compact-time radius R_τ , allowing the model to be directly constrained by upcoming data.

Perturbations evolve as

$$v_k'' + (k^2 - \frac{z''}{z})v_k = 0, \quad \mu_k'' + (k^2 - \frac{a''}{a})\mu_k = 0,$$

where primes denote derivatives with respect to conformal time η (distinct from the periodic cosmic time τ).

References

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