Frozen Stars as a Unified Source of Cosmic Structure and Acceleration

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Abstract. A unified explanation for dark matter and dark energy may emerge from *frozen stars*, ultracompact, horizonless objects. If two distinct populations exist—one primordial (Population A) acting as cold dark matter and another forming post-recombination (Population B) driving late-time acceleration—this framework naturally accounts for structure formation and an evolving equation of state without a cosmological constant. Within Buchert's formalism, the growth of Population B alters the expansion rate via gravitational backreaction, inducing a Hubble dipole and contributing to the CMB hemispherical asymmetry. Population A deepens gravitational wells, accelerating early structure formation. The model aligns with cosmic equation of state constraints, suggesting acceleration as an emergent gravitational effect rather than vacuum energy.

1 Introduction

The fundamental nature of dark matter and dark energy remains an open question in cosmology. We propose a unified framework in which *frozen stars* [1], ultracompact horizonless objects motivated by string-theoretic ideas such as fuzzballs and gravastars [6, 7], form in two distinct populations: Population A behaves as cold dark matter, while Population B emerges later and drives cosmic acceleration via gravitational backreaction. This mechanism naturally explains large-scale structure formation, late-time acceleration, and observed anisotropies in the Hubble parameter and CMB. Unlike exotic new fields or modifications to general relativity, this approach relies solely on nonlinear gravitational effects, making it a minimal yet powerful alternative. By modifying the effective cosmic expansion rate within Buchert's formalism, frozen stars provide an alternative to ΛCDM that aligns with key observational constraints while predicting new testable signatures in structure formation and cosmic anisotropies.

2 Two-Population Frozen Star Model

In this model, frozen stars are divided into two distinct populations with complementary roles in cosmic evolution.

Population A frozen stars form primordially, before recombination, from small-scale overdensities seeded during inflation. Their abundance follows the standard cold dark matter scaling, meaning they remain gravitationally influential throughout structure formation. Their comoving density evolves as:

$$\rho_A(z) = \rho_{A0}(1+z)^3, \tag{1}$$

where ρ_{A0} is the present-day density. These horizonless, compact objects cluster into halos, seeding galaxy formation, contributing to gravitational lensing, and affecting galactic rotation curves. Microlensing surveys constrain their possible masses, making them viable in the asteroid-mass regime ($\lesssim 10^{-8} M_\odot$) or at supermassive scales ($\gtrsim 100 M_\odot$).

Population B frozen stars emerge much later, after recombination, coinciding with star and galaxy formation. Unlike Population A, which behaves as conserved dark matter, Population B dilutes more slowly over cosmic time, meaning its gravitational influence increases relative to other components. Their comoving density follows a modified power law:

$$\rho_B(z) = \rho_{B0}(1+z)^m, \quad m < 3. \tag{2}$$

As these objects accumulate, they introduce inhomogeneities that modify the cosmic expansion rate. Their growing presence enhances gravitational backreaction effects, which in turn influence the large-scale structure and can lead to an emergent acceleration of the universe's expansion—mimicking dark energy without requiring a cosmological constant.

Table 1 below summarizes the distinct roles of the two populations:

Epoch	**Population A**	**Population B**
Primordial (high z)	Forms from inflationary fluctuations	Not present
Dark Ages ($z \sim 30$–1100)	Seeds halos, deepens gravitational wells	Not present
Structure Formation ($z < 10$)	Clusters into halos, enhances baryonic collapse	Emerges via stellar/compact collapses, alters local expansion
Late Universe ($z \lesssim 0.7$)	Remains bound in halos, preserves large-scale structure	Drives gravitational backreaction and acceleration

Table 1: Roles of frozen star populations: Population A provides early gravitational seeds, while Population B grows later to modify the expansion dynamics.

This two-population framework provides a unified model in which Population A serves as a cold dark matter analog, influencing structure formation at early times, while Population B modifies cosmic expansion at later times. The resulting dynamics naturally explain key cosmological phenomena, including dark matter-like effects and late-time acceleration, without requiring exotic new fields.

3 Backreaction as a Foundation for Cosmic Expansion

Buchert's averaging formalism provides a framework to account for the influence of inhomogeneities on cosmic expansion [2, 3]. Unlike the standard ΛCDM model, which assumes a homogeneous universe on large scales, real cosmic structures exhibit local variations in expansion, shear, and curvature. These deviations contribute to an additional term in the effective expansion equations, known as the kinematical backreaction $\mathcal{Q}_{\mathcal{D}}$, which modifies cosmic acceleration.

The backreaction term depends on the variance of the local expansion rate θ and the shear tensor $\sigma_{\mu\nu}$, quantifying how inhomogeneities affect the global evolution of space-time. It is defined as:

$$\mathcal{Q}_{\mathcal{D}} = \frac{2}{3}\left(\langle\theta^2\rangle_{\mathcal{D}} - \langle\theta\rangle_{\mathcal{D}}^2\right) - 2\langle\sigma^2\rangle_{\mathcal{D}}, \tag{3}$$

where angle brackets denote volume averages over a domain $\mathcal{D}$. This term directly enters the domain-averaged acceleration equation,

$$3\frac{\ddot{a}_{\mathcal{D}}}{a_{\mathcal{D}}} + 4\pi G\langle\rho\rangle_{\mathcal{D}} = \mathcal{Q}_{\mathcal{D}}, \tag{4}$$

which governs the effective cosmic expansion in the presence of structure.

In the frozen star model, Population B frozen stars introduce significant inhomogeneities at late times. Their increasing abundance leads to local variations in expansion, amplifying the backreaction term $\mathcal{Q}_{\mathcal{D}}$ over time. If the fraction of space influenced by these objects grows as $f(t) = f_0(t/t_0)^{\beta}$, this effect strengthens, altering the expansion rate. Since cosmic time and redshift are related by $t \propto (1+z)^{-3/2}$ in a matter-dominated era, the evolution of $f(z)$ can be directly linked to observable redshift-dependent quantities.

As $\mathcal{Q}_{\mathcal{D}}$ grows, its contribution to the effective Friedmann equation,

$$H_{\mathcal{D}}^2 = \frac{8\pi G}{3}\langle\rho\rangle_{\mathcal{D}} - \frac{1}{6}\langle\mathcal{R}\rangle_{\mathcal{D}} + \frac{1}{6}\mathcal{Q}_{\mathcal{D}}, \tag{5}$$

becomes comparable to the energy density contribution, leading to an emergent acceleration of the cosmic scale factor. This mechanism offers an alternative explanation for late-time cosmic acceleration, eliminating the need for a cosmological constant while naturally incorporating observed anisotropies in the Hubble expansion.

4 Effective Equation of State and DESI Constraints

Recent analyses by the DESI collaboration [4], combining DESI, Planck, and supernova data, suggest that a two-parameter $w(z)$ extension to ΛCDM effectively captures observed trends, including a possible phantom crossing at low redshift ($z \lesssim 0.3$). The frozen star model provides an alternative interpretation of these findings, as shown in Figure 1.

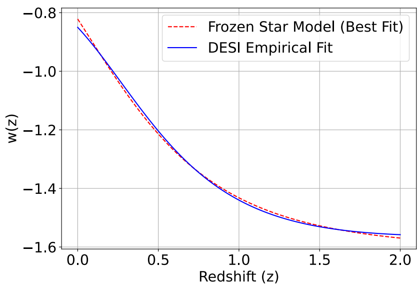

Fig. 1: Comparison of the Frozen Star Model with DESI Data [4]. Optimal parameters: $p_{\text{frozen}_0} = -0.58$, $p_{\text{matter}} = -0.57$, $\rho_{\mathcal{D}0} = 1.00$, $\rho_{\text{frozen}_0} = 0.39$, $n = 4.22$, $m = 4.30$.

In this framework, the total effective energy density consists of standard matter and frozen star contributions, with Population B evolving more slowly than standard components. The effective equation of state is given by

$$w_{\text{eff}}(z) = \frac{p_{\text{matter}}(z) + p_{\text{frozen}_0}(1+z)^m}{\rho_{\mathcal{D}}(z) + \rho_{\text{frozen}_0}(1+z)^n}. \tag{6}$$

The key feature of this model is the dynamically significant negative pressure from Population B frozen stars, which alters cosmic expansion.

DESI approximates the dark energy equation of state as

$$w_{\text{DESI}}(z) = w_0 + w_a \cdot \frac{1-a}{a^2 + (1-a)^2}, \tag{7}$$

where $a = (1+z)^{-1}$, with w_0 and w_a controlling its present value and evolution. By optimizing the frozen star model against $w_{\text{DESI}}(z)$, best-fit parameters are obtained. The results ($n > 3$, $m > 3$) indicate that Population B frozen stars cluster differently from standard cold dark matter and contribute to an evolving negative pressure component.

This suggests that cosmic acceleration may arise from gravitational back-reaction rather than a cosmological constant. Future observations, including BAO and redshift-space distortion measurements, will further test this model's implications for large-scale structure.

5 CMB and Hubble Dipole Anisotropies

The frozen star framework naturally predicts anisotropies in both the CMB and the Hubble expansion due to a primordial dipole in the spatial distribution of Population A frozen stars. This initial asymmetry, modeled as a small dipolar variation in their density, seeds a hemispherical power asymmetry (HPA) in the CMB. The observed temperature fluctuations exhibit a dipolar modulation [8],

$$\Delta T(\hat{n}) = \Delta T_0(\hat{n}) \left[1 + A_{\text{dip}}\, \hat{n} \cdot \hat{p}\right], \tag{8}$$

with an amplitude $A_{\text{dip}} \approx 0.07$.

As Population B frozen stars form and accumulate, they enhance this initial dipole through gravitational backreaction, leading to an anisotropic integrated Sachs-Wolfe (ISW) effect,

$$\Delta T_{\rm ISW}(\hat{n}) \propto \int \frac{d\Phi}{dt}\, ds\, [1 + A_{\rm ISW}\, \hat{n} \cdot \hat{p}]\,. \tag{9}$$

This process reinforces the observed CMB asymmetry, linking the structure of frozen stars to large-scale anisotropies.

The same mechanism influences the Hubble expansion. As Population B accumulates preferentially along the dipole axis, it amplifies the backreaction term $\mathcal{Q}_{\mathcal{D}}(\hat{n})$, modifying the expansion rate in different directions. This leads to a measurable dipolar modulation of the Hubble constant,

$$H_{\rm eff}(\hat{n}) = H_0\, [1 + \epsilon\, (\hat{n} \cdot \hat{p})]\,, \tag{10}$$

where $\epsilon \sim 0.03$–0.1 quantifies the anisotropy. This aligns with the observed "Hubble dipole" in Type Ia supernova studies, suggesting that the clustering of frozen stars could be responsible for directional variations in the cosmic expansion rate.

6 Early Galaxies at High Redshift

Recent JWST observations have revealed massive, evolved galaxies at $z > 10$ that challenge standard ΛCDM predictions [5]. In the two-population frozen-star framework, Population A frozen stars provide a natural explanation for this early structure formation. As compact, horizonless relics of primordial overdensities, Population A objects generate deep gravitational potential wells at early times [1, 6]. Denoting their local spatial density by $\rho_A(\mathbf{x}, t)$, the associated Newtonian potential is approximated by

$$\Phi_A(\mathbf{x}, t) \approx -4\pi G \int \frac{\rho_A(\mathbf{x}', t)}{|\mathbf{x} - \mathbf{x}'|}\, d^3\mathbf{x}'. \tag{11}$$

The enhanced potential accelerates baryonic collapse, as described by

$$\ddot{\mathbf{r}}_{\rm gas} \approx -\nabla \Phi_A(\mathbf{x}, t), \tag{12}$$

which effectively shortens the collapse timescale $t_{\rm collapse}$ and allows gas to condense and fragment into stars at earlier epochs than in conventional scenarios.

Moreover, because Population A frozen stars lack event horizons, their gravitational influence does not trigger strong accretion-driven radiation. This permits gas to remain bound within halos, promoting sustained star formation. The rate of gas infall can be approximated by

$$\dot{M}_{\rm gas} \approx \frac{\rho_{\rm gas}}{t_{\rm collapse}}, \tag{13}$$

leading to a self-reinforcing cycle that accelerates stellar mass growth and ultimately produces the massive high-redshift galaxies observed by JWST.

7 Conclusions

The unified frozen-star framework incorporates nonsingular, quantum-gravity-motivated compact objects into a cosmological setting, offering a gravitational alternative to black holes. Future observations can test the existence and impact of frozen stars through various astrophysical and cosmological probes. JWST deep fields can assess whether early structure formation aligns with Population A clustering, while weak lensing and baryon acoustic oscillation measurements may reveal primordial potential wells. Large-scale structure and ISW analyses can probe Population B's gravitational backreaction, with Hubble dipole measurements offering a key test. Microlensing surveys (MACHO, EROS, OGLE, Subaru) can constrain Population A's mass range and abundance. Gravitational-wave detectors such as LIGO, Virgo, and LISA may identify frozen star mergers via distinctive inspiral dynamics, quasinormal modes, and late-time ringdown echoes.

The unified frozen-star framework might be a promising direction, but as with any alternative theory, rigorous tests against the full suite of cosmological observations will be essential.

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