# Time-Crystalline Emergence of Relational Time at a CPT-Symmetric Boundary

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**Abstract**

Recent experimental realizations of time crystals have demonstrated that robust temporal order can emerge through spontaneous breaking of time-translation symmetry in non-equilibrium systems. Motivated by these developments, we propose a minimal theoretical framework in which physical time itself emerges as an ordered phase of a relational variable. Within a CPT-symmetric scenario featuring two conjugate sectors sharing a common quantum vacuum, we identify the relative phase $\Delta\phi$ as a natural temporal order parameter. We show that near a CPT-invariant, atemporal boundary, the autonomous dynamics of $\Delta\phi$ generically admits stable limit-cycle solutions analogous to time-crystalline order. This transition corresponds to spontaneous time-translation symmetry breaking (STTSB) and selects a preferred relational clock without assuming any external time parameter.

## 1 Introduction

The nature of time remains one of the central open problems in fundamental physics. Timeless formulations of quantum gravity, such as the Wheeler–DeWitt equation $\hat{H}\Psi = 0$, eliminate any preferred notion of temporal evolution [7].

Following the CPT-symmetric cosmological framework introduced by Boyle et al. [4] and early considerations of time-reversal symmetry by Sakharov [5], we model the vacuum as a CPT-invariant state. We interpret this static configuration in the spirit of Barbour's Platonia [6], where no fundamental temporal ordering exists. The emergence of dynamics is then understood as spontaneous time-translation symmetry breaking [1, 2], a phenomenon experimentally demonstrated in non-equilibrium systems [3].

## 2 Relational Phase and Atemporal Boundary

We define the relative phase

$$\Delta\phi = \phi_+ - \phi_- \tag{1}$$

as the fundamental dynamical degree of freedom. Evolution is parametrized by a monotonic relational ordering parameter $\tau$, which does not correspond to any physical clock or proper time, but merely labels configurations in phase space, consistent with relational approaches to quantum mechanics [8].

## 3 Dynamical Model

We consider the minimal autonomous nonlinear equation admitting limit cycles:

$$\Delta\phi'' + \epsilon(\Delta\phi^2 - 1)\Delta\phi' + \omega_0^2 \sin(\Delta\phi) = 0, \tag{2}$$

where primes denote derivatives with respect to $\tau$. From an effective field theory perspective, such anti-damping terms arise generically when strongly coupled or non-equilibrium degrees of freedom are integrated out [9, 10].

### 3.1 Physical Motivation: Vacuum Instability

Near $\Delta\phi = 0$, corresponding to the CPT-invariant timeless vacuum, inter-sector coupling acts as a non-equilibrium vacuum pump, producing effective negative damping and rendering the synchronized state unstable. As $\Delta\phi$ grows, positive damping is restored, stabilizing the dynamics into a limit cycle.

## 4 Emergence of a Time-Crystalline Phase

The system evolves toward a stable periodic orbit,

$$\Delta\phi(\tau) \to \Delta\phi_0 + A\sin(\omega_\phi \tau + \varphi_0), \tag{3}$$

constituting spontaneous time-translation symmetry breaking.

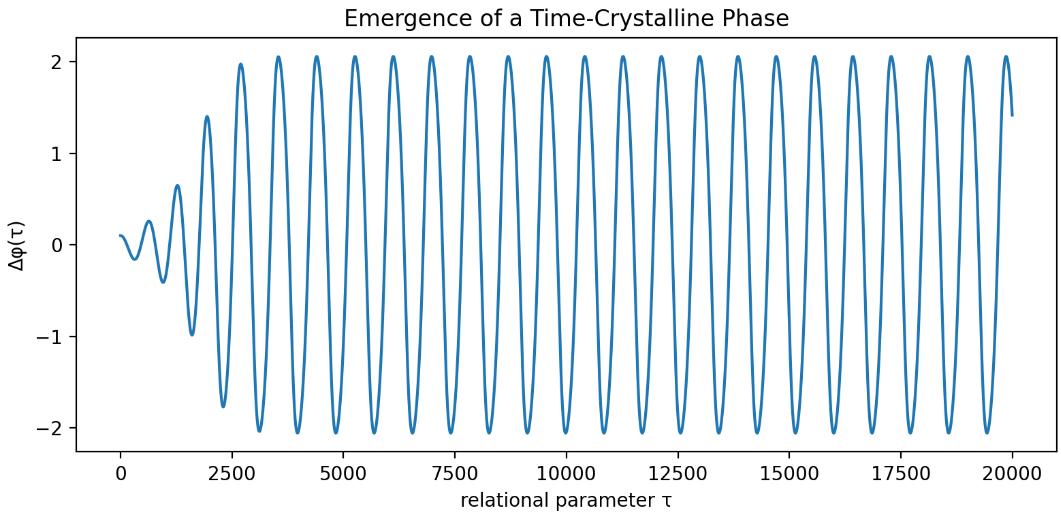


Figure 1: Emergence of a time-crystalline phase: $\Delta\phi(\tau)$ evolves from a small perturbation into a stable periodic oscillation, defining an emergent relational clock.

## 5 Discussion and Outlook

The model provides a minimal and physically motivated mechanism for the emergence of time from an atemporal vacuum. Temporal order appears as a phase of non-equilibrium dynamics rather than as a fundamental background parameter.

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## References


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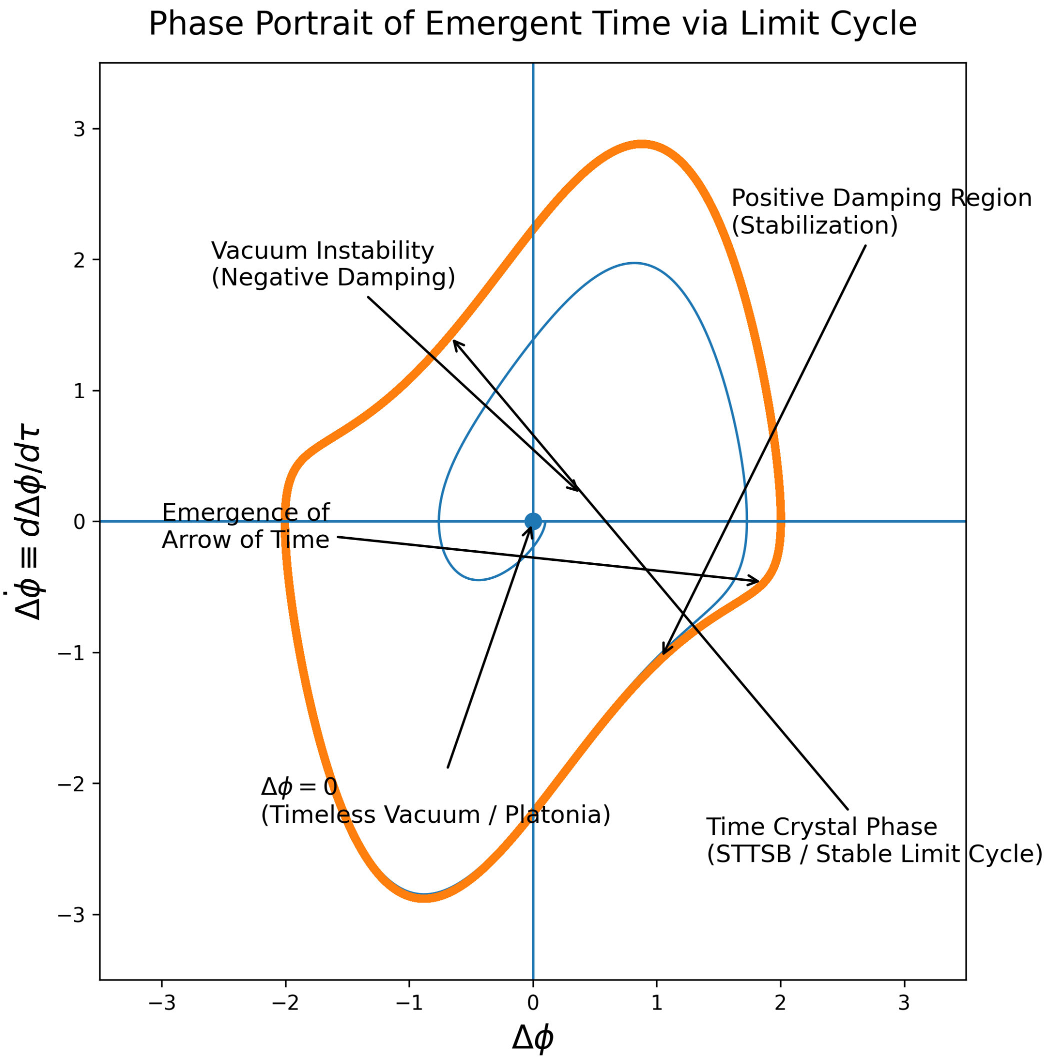


Figure 2: Phase portrait of emergent time. The origin $\Delta\phi = 0$ represents a timeless CPT-invariant vacuum rendered unstable by negative damping. The system spirals outward toward a stable limit cycle corresponding to a time-crystalline phase (STTSB).


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