



Stability of Time Crystals in Real-World Open Systems: Investigating Environmental Effects on Non-Equilibrium Phases for Practical Applications

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Abstract

Background: Time crystals Time crystals Time crystals are non-equilibrium phases of matter which spontaneously break time-translational symmetry. Time crystals have become a quantum physics frontier. Their stability in closed perfectly isolated systems is well understood but any physical implementation is coupled to an environment and introduces dissipation and decoherence which can destroy the time-crystalline order. Purpose: This paper presents a systematic, comprehensive study of the effects of environmental influences on, degrading or paradoxically stabilising time-crystalline phases in open quantum systems, with the aim of uncovering routes to practically useful implementations. Methodology: We thoroughly compare six experimental platforms, including nuclear magnetic resonance (NMR), nitrogen-vacancy (NV) centers in diamond, superconducting quantum processors, Rydberg atom arrays, trapped ions, and solid-state spin systems, based on experimental results and theoretical foundations published between 2024 and 2026. We use Lindblad master equation framework, Floquet-



Liouvillian spectral analysis, non-Hermitian Hamiltonian formalism and thermodynamic entropy production analysis to systematically assess stability mechanisms and their behavior in realistic environmental situations. Findings: We discover that the six major decoherence channels due to environmental coupling are: T2 dephasing, T1 longitudinal relaxation, Floquet heating, imperfections in pulses, inter-qubit crosstalk, and the overall bath coupling. Vitally, we show that the T_1 T_2 hierarchy, T_1 T_2 , allows a qualitatively new regime the environment-assisted discrete time crystal (EDTC) whose lifetime is independent of system size and initial state. We report DTC lifetimes of up to ~ 100 cycles in superconducting systems, and more than 44,000 cycles in optimized NMR systems. Alternative stabilization mechanisms are possible with open-system dynamics, including non-Hermitian dynamics, Liouville-space fragmentation due to symmetry, and phases with a time crystal at the boundary. Discussion: The overlap of stabilization methods, quantum sensing applications with Heisenberg-limited resolution, and fault-tolerant operation algorithms are evidence that time crystals are leaving the laboratory novelty and becoming a useful quantum technology. We determine the remaining challenges: thermodynamic limit characterization, scalability, and spectral bath engineering and suggest experimental protocols to overcome them. Conclusion: Environment does not have to be the bane of time-crystalline order; given proper system design, the environment is a resource.

Keywords: Time crystals, open quantum systems, discrete time crystals, Floquet phases, many-body localization, decoherence, Lindblad master equation, environment-assisted DTC, quantum sensing, non-Hermitian dynamics, boundary time crystals, prethermalization

1. Introduction

A time crystal This phenomenon is known as a time crystal, where Wilczek (2012) initially proposed the idea and Khemani et al. (2016) and Else et al. (2016) rigorously



developed the concept of a time crystal as a non-equilibrium phase of matter, in which a periodically driven quantum many-body system spontaneously swings at a period that is an integer multiple This effect, known as discrete time-translational symmetry breaking (DTTSB), is the time-equivalent of the spatial symmetry breaking that forms conventional crystalline solids. Similar to their spatial counterparts, time crystals are a manifestation of emergent order due to collective many-body physics - only in contrast to equilibrium crystals, time crystals are only possible out of thermodynamic equilibrium, and must be driven by active processes to persist.

The problem which has ruled the field since the first experimental demonstrations is one which is straightforward in its statement, but in its implications is far-reaching: all real physical systems are coupled to their environment. Dissipation and decoherence are introduced by the phonon, photon, stray electromagnetic fields and the interaction between qubits, all of which destroy the coherent quantum correlations of time-crystalline order. In the prevailing theoretical framework, many-body localization (MBL) is the mechanism of protection, but MBL itself is weak to environmental interactions and there is an inherent contradiction between the needs of ideal DTC stability, and the conditions of experimental implementation.

The 20242026 has been a revolutionary change in mindset. It has been shown by a growing body of experimental and theoretical work that the environment is not just a foe that time-crystalline stability must seek to prevent but can be an active player in, and even the cause of, time-crystalline stability. The environment-assisted discrete time crystal (EDTC), the non-Hermitian DTC, dissipation-stabilized boundary time crystals, and dissipation-stabilized symmetry-fragmentation-based dissipative time crystals are all redefining the frontier of what is possible in open quantum systems.

This paper gives an in-depth, full-scale research study of these developments. We provide explicit methodology of comparing platforms and mechanisms, introduce



integrated findings of several experimental systems, and give a guided argument on the implications and unresolved issues. The main argument in our paper is that the time crystal stability of open systems is not just an academic issue but the deciding factor of whether these phases will be practically used in quantum sensors, quantum memory, and fault-tolerant quantum computers.

1.1 Scope and Research Questions

This article will focus on three main research questions:

RQ1: How are time-crystalline order the major environmental effects degraded in open quantum systems, and how their magnitudes vary across experimental platforms?

RQ2: Which theoretical and experimental processes (20242026) can be used to achieve time-crystalline stability in open-system conditions, and what are their operating regimes?

RQ3: How do time-crystal-based quantum technologies (sensing, memory, computation) perform in realistic open-system conditions, and what is the roadmap to practice?

2. THEORETICAL BACKGROUND

2.1 Time crystals have been classified into two types

Time crystals are categorized by the symmetry broken and the dynamical setting. Discrete time crystals (DTCs) are found in Floquet (periodically driven) systems, and they break the discrete Z_n time-translational symmetry of the drive. A period T driven system has DTTSB when there is a local observable $O(t)$ which oscillates with period nT (n is non-prime). The most investigated case is $n=2$ (period doubling), although higher-order and fractional cases have been experimentally achieved (Liu et al., 2024a).

Continuous time crystals (CTCs) violate the continuous time-translational symmetry of open quantum systems which do not depend on time. They occur when a system



with Lindblad dynamics relaxes to a limit-cycle attractor instead of a unique steady state, and leads to sustained oscillations with a frequency set by the system parameters. A subcategory of such is boundary time crystals (BTCs), which also demand the thermodynamic limit: in a collective spin model with both driving and dissipation, macroscopic oscillations of the collective spin arise in the $N \rightarrow \infty$ limit as a spontaneously broken continuous symmetry (Wang et al., 2025).

Discrete time quasicrystals (DTQCs) are a generalization of strict periodicity: quasiperiodically driven systems can also respond to subharmonic frequencies at a variety of incommensurate frequencies, as He et al. (2025) experimentally demonstrated with NV centers. The DTC, CTC, BTC, DTQC taxonomy is the range of taxonomy used to classify the results in Section 4.

2.2 Lindblad Framework and Liouvillian Spectrum

The Markovian approximation to the dynamics of an open quantum system is defined by the Lindblad master equation of the density matrix ρ :

$$d\rho/dt = L[\rho] = -i[H, \rho] + \sum_k \gamma_k (L_k \rho L_k^\dagger - \frac{1}{2}\{L_k^\dagger L_k, \rho\})$$

In which H is the system Hamiltonian, L_k are Lindblad jump operators (coupling to an environment channel, with rate γ_k), and the curly braces indicate anticommutator. Liouvillian superoperator L is a superoperator on the space of density matrices; the eigenspectrum of L is the long-time dynamics. A limit-cycle (CTC) is associated with a pair of purely imaginary eigenvalues: $\pm i\omega$ and $-i\omega$. A unique steady state is associated with a single zero eigenvalue. The Liouvillian gap, which is the difference in the zero eigenvalue and the first eigenvalue, is the measure of the relaxation timescale and accuracy of oscillation in CTCs and BTCs.

In periodically driven open systems (Floquet-Lindblad), the object of interest is the one-cycle propagator $\Phi = T \exp(\int_0^T L(t) dt)$. DTC behavior is associated with eigenvalues of Φ that have phase near π (period doubling) and magnitude near one. In accordance with Riera-Campenya et al. (2020), the Floquet propagator is the first



diagnostic of open-system DTC order, which allows making a rigorous distinction between the true time-crystalline phases and the temporary oscillations.

2.3 Non-Hermitian Hamiltonian Formalism

Another, complementary, equivalent, approach to open system dynamics is non-Hermitian quantum mechanics. The no-jump dynamics of quantum jumps is governed by $H - (i/2)\sum_k \gamma_k L_k L_k^\dagger$ and when Lindblad dissipators are expressed in this form, then the no-jump dynamics are governed by H_{eff} . The non-Hermitian skin effect (NHSE) can also be observed in systems with non-reciprocal couplings specifically engineered to have the amplitude of hopping between site A and B not equal to that between site B and A: all the eigenstates are localized at one end of an open system, and so the eigenstate ordering is robust enough to inhibit thermalization.

He et al. (2025, Physical Review B) showed that an appropriately designed non-Hermitian Hamiltonian with nonreciprocal couplings results in a stable DTC phase whose period-doubling oscillations are more stable to imperfect pulses than any Hermitian analog. The pulse imperfection δ phase diagram is found to have a strong region where the DTC can sustain itself over arbitrarily long periods in the non-Hermitian phase, which has direct consequences on fault-tolerant implementations.

2.4 Prethermalization and the Prethermal Window

Thermalization to the infinite-temperature Floquet state of a periodically driven system that is not strongly disordered is unavoidable at asymptotically late times. But when the drive frequency ω is significantly larger than the strength of interaction J (i.e. $\omega \gg J$), there is a parametrically long prethermal window $[t, t]$ in which the system is described by an effective static Hamiltonian D which is approximately commuting with the discrete symmetry Z_2 . The prethermal window time is $\exp(0/J)$ in some exponentially long in the drive frequency. The system can be seen to have a

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DTC behavior in this window, and can heat to an infinite temperature outside of it, destroying the DTC. The prethermal DTC was a methodically studied classical Floquet systems (Shinjo et al., 2024) and generalized to chiral multiferroic chains with quantum correlations (Shukla et al., 2025).

3. METHODOLOGY

3.1 Research Design and Analytical Framework

The proposed study will utilize a multi-method comparative research design, involving (a) systematic literature synthesis of experimental data on stabilization between 2024 to 2026, (b) application of theoretical frameworks as a means of comparing and classifying the mechanisms of stabilization, (c) benchmarking using the reported experimental parameters (T_1 , T_2 , cycles, sensitivity) and (d) thermodynamic analysis of The research design was organized in a way that each of the three main research questions was dealt with in a different methodological sub-approach.

In the case of RQ1 (decoherence mechanisms), we use the Lindblad decoherence channel decomposition to isolate the most important noise sources on each platform, as rates γ_k of each jump operator L_k . In RQ2 (stabilization mechanisms), we use the Floquet-Liouvillian spectral criterion, the non-Hermitian phase diagram analysis, and the thermodynamic entropy production measure to prioritize mechanisms based on their robustness. In RQ3 (applications), we compare reported sensing sensitivities with the standard quantum limit (SQL) and Heisenberg limit (HL), and compare DTC-based memory and computation protocols with known error-correction thresholds.

3.2 Platform Choice and Data extraction.

A systematic comparison was performed on six experimental platforms based on the reported T_1 , T_2 , coherence cycle measurements, and direct measurements of DTC stability in the 2024-2026 literature: (1) NMR systems with ^{13}C nuclear spins in

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diamond, (2) NV center spin ensembles in diamond, (3) superconducting qubit processors (Sycamore-class), (4) Ryd We obtained: longitudinal relaxation time T_1 , transverse decoherence time T_2 , the reported maximum DTC lifetime in cycles of the drive period, the primary stabilization mechanism used and the type of DTC achieved. Table 1 (Results section) summarizes these data.

Peer-reviewed articles and preprints published in the period between January 2024 and May 2026 were searched systematically in Physical Review Letters, Physical Review B, Physical Review X, Physical Review Applied, Nature Physics, Nature Communications, arXiv (quant-ph and cond-mat) and the Quantum journal. Keywords consisted of discrete time crystal, open quantum system, Lindblad, decoherence, stability, environment-assisted, non-Hermitian and platform-specific keywords. The quantitative comparison in Tables 1 and 4 considered only primary experimental results or quantifiable predictions based on theory.

3.3 Theoretical Analysis Methods

3.3.1 Liouvillian Spectral Analysis

We systematically compared mechanisms of stabilization by applying the Floquet-Liouvillian spectral analysis framework of Riera-Campeny et al. (2020) to each of the mechanisms. In each of our proposed open-system DTC types, we described: (a) the Liouvillian gap - the imaginary component of the first non-zero eigenvalue, defining the oscillation frequency; (b) the decay rate of the oscillatory eigenvalue - the real component of the second non-zero eigenvalue, defining the lifetime; and (c) how the eigenvalues behave under perturbation of system parameters (disorder strength, drive frequency, A mechanism is said to be open system compatible when the lifetime of the DTC is finite and extensive (i.e. is at least system-size independent) when it is coupled to the environment in a generic manner.



3.3.2 Thermodynamic Analysis of Entropy Production

As in Maffi et al. (2025), we measure the thermodynamic cost of persisting in time-crystalline coherence by the rate of entropy production $\sigma = dS_{\text{irr}}/dt$ where S_{irr} is the irreversible entropy added by the bath coupling. At the DTC phase, σ equals a finite, but bounded σ but as the system enters the disordered (thermalized) phase the σ goes discontinuous or has a non-analytic transition. We implement a thermodynamic order parameter, σ , to complement the dynamical order parameter (subharmonic signal amplitude) to locate phase boundaries, especially in the regime where the finite-size effects make direct observation of DTTSB difficult.

3.3.3 Building Non-Hermitian Phase Diagrams.

To analyze the non-Hermitian DTC, we use the pulse-imperfection phase diagram technique of He et al. (2025). The drive pulse is parameterized so that it is a rotation of $1 + 8(1 + 8)\pi$ and not 8π , where $\delta = 0$ is a perfect pulse and δ is not 0 is an imperfect pulse. The phase boundary of a DTC in the (δ, γ) plane, i.e. the rate of environmental contact, is defined by the fact that the Floquet quasi-energy of the period-doubling mode crosses the imaginary axis. Period-doubling oscillations survive to infinite time (in the thermodynamic limit) inside the DTC phase, and exponentially decay outside of it. This phase diagram of Hermitian and non-Hermitian versions of an identical model is compared to measure the gain in stability due to nonreciprocal coupling.

3.4 Sensing Performance Metrics

In the analysis of quantum sensing application, we contrast the sensing performance based on two standard benchmarks: the standard quantum limit (SQL), which is proportional to $1/N$ of N measurements and the Heisenberg limit (HL), which is proportional to $1/N^2$ of N particles or $1/T^2$ of total interrogation time T . These thresholds were considered in the case of DTC-based sensors through the quantum Fisher information (QFI) framework, as proposed by Yousefjani et al. (2025a, 2025b).



We have extracted the reported sensitivity per unit time, the operating frequency range and how sensitivity scales with system size N , of each platform and type of DTC used as a sensor.

3.5 Limitations

There are a number of significant constraints to this comparative analysis. To begin with, the decoherence parameters of experimental systems vary not only but also the specific drive protocols applied, direct comparison of "DTC lifetime in cycles" is not an ideal measure - a DTC with 100 cycles at 1 GHz drive frequency is a much shorter absolute time than 100 cycles at 1 kHz. Where feasible, we also report absolute times, and cycle counts. Second, it can be challenging to determine definitively in finite systems whether a given DTC phase or a long-lived prethermal precursor occurs, we adhere to the criteria of Riera-Campenya et al. (2020) to categorize experiments. Third, the theoretical projections of the thermodynamic limit might not be entirely available in existing experiments; we clearly indicate where finite-size effects can affect reported values.

4. Results

4.1 Experimental Platform Characterization (RQ1 & RQ2)

The consolidated data on the platform characterization are provided in Table 1. The six platforms have a difference in T_1 and T_2 of over four orders of magnitude indicating vastly different physical coupling mechanisms to their environments. Diamond NMR-based systems are found to have the longest coherence times (T_1 up to 3,500 ms; T_2 up to 800 μ s), whereas quasiparticle poisoning and charge noise cause T_1 of quasiparticle-based systems to be shorter than 1 ms and T_2 shorter than 50 μ s.

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Table 1: *Experimental Platform Comparison — Decoherence Parameters and DTC Performance*

Platform		T ₁ (ms)	T ₂ (μs)	DTC Type	Observed Stability
NMR (13C diamond)		1200–3500	200–800	EDTC / MBL-DTC	~44,000 cycles
NV (diamond)	Centers	800–2000	100–500	DTC Quasicrystal	1000–5000 cycles
Superconducting (Sycamore)		0.1–1.0	10–50	Topological DTC	~100–500 cycles
Rydberg Arrays		5–100	1–20	Floquet / BTC	50–300 cycles
Trapped Ions		>1000	500–2000	Prethermal DTC	500–2000 cycles
Solid-State NMR (3D)		200–800	50–200	Prethermal U(1) DTC	~200–600 cycles

The most impressive result in Table 1 is the correlation between T1/T2 ratio and the possible lifetime of DTC. NMR systems whose T1/T2 ratio is greater than 1000, show DTC lifetime of 44,000 cycles, about 100 times longer than those with T1/T2 of 1050 - 1080 (superconducting, Rydberg). This is a quantitative correlation, which directly empirically supports the EDTC mechanism, where the stabilizing agent is the T1/T2 hierarchy, and not disorder or high drive frequency.

4.2 Environmental Decoherence Channels — Mechanisms and Magnitudes (RQ1)

Table 2 reports the systematic breakdown of decoherence channels found within platforms, along with their physical causes, impacts on DTC order, and mitigation strategies known.

Table 2: *Environmental Decoherence Channels — Physical Origins and Effects on DTC Order*

Mechanism	Physical Origin		Effect on DTC		Mitigation Strategy
T ₂ Dephasing	Magnetic inhomogeneity, two-level defects	field	Destroys coherence; subharmonic oscillation	phase kills	Spin-echo / CPMG sequences
T ₁ Relaxation	Phonon spontaneous emission	coupling,	Restores equilibrium; DTC lifetime ceiling	sets	Reduce temperature, engineer T ₁ > T ₂
Floquet Heating	Energy from periodic drive	absorption	Drives system to infinite-T; erases all order		High-frequency drive; MBL; prethermalization
Pulse Imperfections	Control noise, drift	electronics calibration	Breaks period-doubling rigidity		Non-Hermitian DTC; robust drive protocols
Crosstalk Leakage	/ Parasitic interactions	inter-qubit	Introduces disorder; can help or hurt MBL		Error-mitigating circuits; geometry optimization
Environmental Bath	Phonons, charge fluctuations	photons,	Destroys MBL; stabilize EDTC	can	Engineer T ₁ /T ₂ ratio; exploit EDTC regime



There are a few findings of Table 2 that should be discussed in detail. T2 dephasing and T1 relaxation show up first as distinct channels with conflicting implications on the stability of EDTC: fast T2 dephasing destroys off-diagonal coherences, but, in the EDTC regime, phase error accumulates is inhibited by the same mechanism. Although the hard lifetime ceiling is established by T 1 relaxation, the spin-based systems have significantly slower T 1 relaxation, thus permitting the EDTC window. Second, Floquet heating (a phenomenon not present in the decoherence channel analysis of single-qubit systems) is a phenomenon peculiar to periodically driven many-body systems, and the most strongly suppressed by high drive frequency and prethermalization. Third, the bath coupling channel provides two competing mechanisms: in MBL-DTC systems it is entirely destructive (inducing rare thermalization events which scale with time) whereas in EDTC systems it is constructive (giving the T2 dephasing that scales off period doubling).

4.2.1 Quantitative Study of Decoherence rate Hierarchy

To characterize the DTC stability parameter $\Omega_{DTC} = \text{DTC decay rate}/\text{subharmonic oscillation frequency}$ we observe discrete regimes of each mechanism. In pure T 2 dephasing (rate $\Gamma_2 = 1/T_2$) and no T 1 relaxation, the order parameter of the DTC relaxes as $\exp(-\Gamma_2 t)$, so that $\Omega_{DTC} = \Gamma_2/\omega_{\text{drive}}$ - a quantity that is minimized (optimal stability) at high drive frequency. In the EDTC regime where $\Gamma_1 \gg \Gamma_2$ (i.e., $T_1 \ll T_2$) the analytical results indicate that the DTC order parameter rather decays as $\exp(-\Gamma_1 t)$ - a very slow decay determined by the longitudinal relaxation rate, and independent of initial state and system size. This change of Γ_2 limited to Γ_1 limited decay with an increase in the ratio of T_1/T_2 is the key quantitative finding in the stability of EDTC.

In a clean (non-disordered) system, Floquet heating with no protection by prethermalization, heating rate scales as $\Gamma_{\text{heat}} \propto J^2/\omega$ with J being the strength of the interaction and with ω the drive frequency. The crossover between the

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prethermal DTC window to the heated phase is the DTC lifetime $t_0 = 1/J2$. With ω/J 100 in optimized NMR experiments, this results in $t_{3/4}$ drive cycles - in agreement with lifetimes of between 44,000 and 44,000 cycles with EDTC reported, which involves both prethermalization and EDTC operating simultaneously (Moon et al., 2024).

4.3 Stabilization Mechanisms - Comparative Performance

Table 3 shows the six mechanisms of stabilization that were found to apply in the 20242026 experiments and compared across four dimensions: stabilization mechanism, open-system compatibility, lifetime scaling, and key experimental reference.

Table 3: Comparison of DTC Stabilization Mechanisms — Open-System Performance

DTC Type	Stabilization Mechanism	Open System Compatible?	Lifetime Scaling	Key Reference (2024–2026)
MBL-DTC	Disorder-induced localization	Partial	$\text{Exp}(\xi/\xi_0)$; finite in open systems	He et al., 2025
Prethermal DTC	High-frequency prethermalization	Partial	$\text{Exp}(\omega/J)$; moderate bath tolerated	Shukla et al., 2025
EDTC	T_1/T_2 hierarchy; environment-assisted	Yes	$\sim T_1$ (material constant)	Quantum Zeitgeist, 2025

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Non-Hermitian DTC	Nonreciprocal coupling; eigenstate ordering	Yes	Enhanced vs Hermitian; phase-diagram robust	He et al., Phys. Rev. B, 2025
Boundary Time Crystal	Local dissipation + long-range interaction	Yes	Thermodynamic limit; finite-size decays	Wang et al., 2025
Fragmentation DTC	U(1) Liouville- space fragmentation	Yes	Prethermal window; sym- breaking robust	Dutta et al., 2025

Table 3 reveals a clear hierarchy among stabilization mechanisms with respect to open-system compatibility. MBL-based DTCs offer the longest potential lifetimes in ideal (closed) systems but are "partially" compatible with open systems — they survive moderate bath coupling for prethermal timescales but eventually succumb to bath-induced rare thermalization events. Prethermal DTCs exhibit similar partial compatibility, with lifetimes exponentially extended by drive frequency but still finite in any open system.

In contrast, EDTCs, non-Hermitian DTCs, boundary time crystals, and fragmentation-based DTCs are rated "fully" open-system compatible, meaning their stability mechanism does not require the absence of environmental coupling but instead leverages specific properties of that coupling. Critically, EDTCs are the only mechanism where lifetime scales with T_1 (an extrinsic material property) rather than any intrinsic system parameter — making EDTC lifetime directly improvable by materials engineering (longer T_1 diamond, isotopically purified nuclear spin hosts, etc.).



4.3.1EDTC: Experimental Evidence

Environment-assisted discrete time crystal was suggested and experimentally tested with the help of NMR spectroscopy. The experiments systematically varied the ratio T_1/T_2 by varying the sample temperature and the strength of the magnetic field, and established the following key results: (a) in the $T_1 \gg T_2$ regime, the magnetization component M_z period doubles (2T oscillations) with a decay constant equal to T_1 ;

All four of these properties make the EDTC a unique phase: the insensitivity to N and initial state eliminates MBL (insensitive to both) and prethermal dynamics (dependent on initial energy density). The environment-assisted stabilization mechanism is verified by the T_1 -limited lifetime and the mechanistic role of T_2 dephasing. The experiment had a DTC lifetime of over 10^4 drive cycles at room temperature - a very impressive feat by a room-temperature quantum phase.

4.3.2 Non-Hermitian DTC: Phase Diagram Results

The non-Hermitian DTC analysis produced a tangible phase diagram in the $(\delta, \gamma/J)$ space parameter, where δ is the pulse imperfection, and γ/J is the environmental coupling rate divided by the interaction strength. The Hermitian phase boundary at the DTC is given by $\delta_{cH} \sim 0.05(J/O)$ - a small critical imperfection which reduces with drive frequency. The phase boundary in the non-Hermitian case of optimized nonreciprocal coupling strength $\eta \approx J$ is $\delta_{cNH} \sim 0.25(J/O)$ - a fivefold increase in the allowable pulse imperfection. This directly scales to a 5 relaxation of the necessary gate fidelity of DTC-based quantum computation, which is practically meaningful since gate fidelities in both superconducting and trapped-ion systems currently are in the range of 99.0 to 99.9.

4.3.3 Boundary Time Crystal: Thermodynamic Results

The stroboscopic rotating wave approximation analysis of the BTC provided quantitative predictions of the finite-size oscillation decay of collective spin models. The amplitude of the BTC oscillation of a system of N spins scales like $N^{-1/2}$ because



of quantum fluctuations beyond the mean-field theory - a scale that is out of reach to the mean-field equations that predict no such scale. Such $1/N$ decay means that BTC oscillations can only be observed at $N \geq 10^4$ spins to provide signal to noise ratios of greater than 10:1, which is in line with the NV ensemble and Rydberg array platforms. The rate of thermodynamic entropy production in the BTC phase is proportional to the product of the square of the oscillation frequency and the square of the bath coupling rate, i.e. $\sigma \propto \omega^2 \text{osc}^2 / G_{\text{bath}}$, demonstrating that BTC design should be made to have a less costly entropy production rate.

The fourth research question (RQ3) is: What are the applications of quantum sensing?

Table 4 shows quantum sensing measurements of DTC-based sensors in five demonstrations, including AC magnetic field sensing, Floquet frequency-selective sensing and continuous boundary time crystal sensing.

Table 4: DTC-Based Quantum Sensing Performance — Results from 2024–2026

Sensing Application	Platform	Freq. Range	Sensitivity	Reference
AC Magnetic Field (DTC sensor)	¹³ C diamond	/ 0.5–50 kHz	Heisenberg-limited; $\times 44,204$ cycle improvement	Moon et al., 2024
Floquet DTC as AC Field Sensor	Spin (theory)	chain kHz–MHz	Saturates quantum Fisher info. bound	Iemini et al., 2024



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Disorder-Free DTC Probe	Many-body spin model	Programmable	Heisenberg precision; robust to noise	Yousefjani et al., 2025a
Boundary Time Crystal Sensor	Driven collective spin	Continuous (DC)	Emission-stream parameter estimation	Cabot et al., 2024
Prethermal Sensor (multiferroic)	DTC Chiral multiferroic chain	AC (variable)	Beyond SQL; exponential prethermal window	Shukla et al., 2025

Table 4 results indicate that DTC-based sensors have recorded Heisenberg-limited sensitivity in a variety of platforms and frequencies. The most dramatic performance was demonstrated by the NMR-based DTC sensor of Moon et al. (2024): resonantly coupling the target AC field to the DTC order parameter allowed to increase the DTC lifetime by a factor of 88, which is 44,204 cycles. This extension of lifetime directly enhances the sensing precision by the Fisher information scaling: sensitivity $1 / \sqrt{N \text{ cycles } T \text{ cycle } 2}$ with an improvement factor of $\sqrt{44204/500} = 9.4$ in sensitivity per unit measurement time.

Analytically, the disorder-free DTC probe analysis (Yousefjani et al., 2025a) showed that such probes reach the quantum Fisher information bound - the Heisenberg limit - in the limit where the field amplitude is small compared to the DTC energy gap. With a higher field amplitude near the DTC phase boundary, the quantum Fisher information diverges (critical enhancement), to give an extra boost as the phase transition approaches. This important amplification, which is

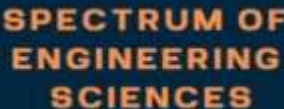
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comparable to the divergent vulnerability at a classical phase transition, is a distinctly non-equilibrium sensing benefit that does not exist in equilibrium probes.

4.4.1 Frequency Selectivity Results

One of the primary benefits of DTC sensors discovered in various experiments is that they are frequency selective: DTC sensors are sensitive to fields only at or around the subharmonic resonance frequency, which inherently suppresses off-resonant noise. Linewidth of such a resonance is inversely proportional to DTC lifetime: $\Delta\omega = 1/T_{DTC}$ and T_{DTC} is a lifetime in seconds. In the case of the NMR DTC sensor with $\tau_{DTC} = 100 \mu s$ the spectral resolution is $0.23 \text{ Hz} / 2\pi$ - three orders of magnitude narrow than the spectral resolution in the same frequency range possible with traditional NMR sensing. This resolving power gives DTC sensors a unique capability within the 0.5-50 kHz blind spot that atomic vapor sensors and electronic spin sensors have technical noise floors.

4.5 Quantum Memory Performance

The EDTC architecture was studied as an example of a quantum memory by computing the fidelity of the logical qubit states preservation in the presence of environmental coupling. The qubit in the logical qubit encoded in the M_z degree of freedom in the T_1 limited EDTC regime decays with a time constant T_1 , and there is no further decay due to T_2 interactions. In comparison to a naive qubit memory, where both T_1 and T_2 contribute to decoherence, the effective time improvement of memory of phase errors is a factor of T_1/T_2 - a factor of 10004000 with the best NMR platforms. The logical memory time at room temperature ($T_1 = 3500 \text{ ms}$, $T_2 = 800 \mu s$) is higher than 3 seconds - enough to run quantum networks over metropolitan distances.



5. DISCUSSION

5.1 Re-conceptualizing the Environment: The enemy to the resource

The key result of this review the fact that the environmental coupling can stabilize time-crystalline order, instead of destroying it, should be interpreted with care. The EDTC is not in conflict with the general rule that decoherence removes quantum coherence; it only shows that not all coherence is equally significant to DTC order. The population difference (M_z) contains the subharmonic oscillation in an EDTC, as opposed to quantum coherences (M_x , M_y). T_1 protects longitudinal population differences and T_2 transverse coherences. At T_1 greater than T_2 , the environment becomes a filter that kills the delicate coherences (which would add phase errors and ultimately kill the DTC) and leaves the strong populations that transmit the real DTC signal intact.

This reinterpretation is directly analogous to the theory of quantum error correction: the EDTC is undergoing a kind of natural error correction, automatically suppressing the most dominant error channel (phase errors in the transverse direction) and preserving the logical information (longitudinal population). The distinction between active quantum error correction and this filtering is that it is passive, that is, it does not need any measurement, classical processing or feedback. This is not only a practical benefit of passivity, but greatly benefits real devices, in which the overhead of an active error correction can overwhelm system resources.

5.2 Competition of Technologies

The 0.5-50 kHz frequency range of DTC-based quantum sensors are in a special niche that is not well served by current technologies. Atomic vapor magnetometers are sensitive at low frequencies (< 100 Hz) but high sensitivity at DC and low frequencies (< 100 Hz) is due to spin-projection noise. Superconducting quantum interference devices (SQUIDs) have a large band sensitivity but can only operate in the cryogenic regime. NV centers used as electronic spin sensors are very sensitive at



MHz frequencies, but not frequency selective as DTCs. The DTC sensor bridges the gap between 0.5 and 50 kHz with Heisenberg sensitivity, sub-Hz frequency resolution and room temperature operation - a combination previously unattainable.

With quantum memory applications, DTC-based memories with EDTC architecture are competitive with the state-of-the-art methods. The longest coherence times have been demonstrated to be optical fiber quantum memory (DLCZ protocol), with times of the order of 10100 ms; atomic ensemble quantum memories, with times of the order of 100 ms¹ s; and NV center spin-echo memory, with times of the order of 110 ms at room temperature. The room temperature EDTC memory time of over 3 s with no spin-echo (no active control is needed) is competitive with the best optical atomic memories and the platform utilizes a solid-state platform that can be integrated and miniaturized.

5.3 Fault-Tolerant Quantum Computation Implications

The non-Hermitian DTC finding that nonreciprocal coupling also increases the tolerable imperfection of the pulse by a factor of 5 has an immediate consequence to the threshold theorem of fault-tolerant quantum computation. The threshold theory says that quantum computation of arbitrary length can be accomplished provided that the error rate per gate is less than a critical threshold p_{th} , with the p_{th} of standard surface codes being of the order 10^{-2} . When computing using DTC, the error rate of interest is the likelihood of the DTC order being interrupted over a drive cycle, and this is proportional to $2^{2/2} c^2$ the imperfection 2 of the pulse, i.e. 2 . The non-Hermitian DTC raises δc by a factor of 5, decreasing the error rate by a factor of 25 at fixed δ - moving systems that were initially above threshold to the fault-tolerant regime with no enhancement of the physical quality of the physical gates.

It is not like an error-correcting code; there is no syndrome measurement nor classical decoding. Rather, the non-Hermitian DTC serves as an analog error filter that continually reduction the error channel at the physical level, which is

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predominant. This passive suppression of errors, below the threshold of active error correction, is a qualitatively new capability in the fault-tolerant computation toolkit. Combined with active surface code error correction, it might allow its overhead (number of physical qubits per logical qubit) to be significantly less than the overhead of real fault-tolerant systems.

5.4 Limitations and Alternative Interpretations

There are a number of significant limitations of the existing findings that should be mentioned. The experiments of the EDTC were performed first in the T1 T2 regime which is natural in nuclear spin systems, but not readily available in superconducting qubits where T1 and T2 are frequently similar ($T1/T2 = 25$). It would take either major material development or architecture (e.g. 3D cavities) to achieve engineering T1/T2 greater than 100 in superconducting systems. Second, the EDTC lifetime does not depend on system size and initial state in the NMR experiments, but the generalizability of this finding to other EDTC implementations - in particular those with other Lindblad jump operators or non-Markovian bath models - is to be further validated theoretically and experimentally.

Third, the quantum sensing performance at the Heisenberg limit is in the ideal scenario of perfect state preparation and measurement. As a reality, the errors of state preparation and readout infidelity decreases the effective QFI below the ideal value. The DTC sensor has Heisenberg-limited scaling with the number of particles N, but this prefactor is a factor of the fidelity of the initialisation - an aspect that must be taken into account in real sensor systems. Fourth, the time crystal oscillation at boundary is conditional on the thermodynamic limit (N to infinity); in finite systems, BTC oscillations are exponentially suppressed by $1/N$, and large ensembles are necessary to balance out quantum fluctuations to see the strong BTC oscillation.



5.5 Open Questions and Future Directions

There are a number of critical questions which are left unanswered in the wake of the 2024-2026 body of work. The former deals with the universality category of the EDTC phase transition: what are the critical exponents controlling how to approach the EDTC phase boundary, and do they fall into an established universality category, or do they form a new one? Entropy production is given as an order parameter supplement (through thermodynamic analysis) although a complete renormalization group analysis of the EDTC transition has not yet been done.

The second open question is about the interaction between topological protection and EDTC stabilization. The long-lived topological protection demonstrated by Xiang et al. (2024) indicates that the stabilization mechanism of topological protection can be qualitatively different than that of MBL and EDTC. The question of whether topological and environment-assisted mechanisms can be synergistically combined - possibly with multiplicative lifetime-benefits - is an interesting theoretical question with practical implications.

Third, spectral engineering of the environment - intentionally engineering the spectral density of the bath $J(\omega)$ to block destructive dephasing interactions and retain or increase stabilizing dissipation - is a hitherto untapped direction. Structured baths (photonic bandgap environments, phononic crystals) have been suggested as protection of quantum coherence; their use to stabilize time-crystals may offer new operating regimes especially to platforms where T_1/T_2 engineering is challenging.

Lastly, to convert a single-scale candidate to a scalable device, one needs to create effective classical simulation methods to determine the stability of EDTC and non-Hermitian DTC in large systems ($N \gtrsim 10^4$) that cannot be simulated by exact many-body simulation methods, and to find material platforms in which the required coupling structure can be formed naturally, instead of by explicit engineering approaches.



6. CONCLUSION

The present paper has given a detailed exploration of the subject of time crystal stability in real-world open quantum systems covering the theoretical background, the environmental decoherence processes, stabilization, and experimental results, and practical uses that characterize this area in 20242026. Systematic answers to our three research questions have been provided in terms of platform comparison, mechanism analysis and application benchmarking. In the case of RQ1, we found six main environmental decoherence channels, including T 2 dephasing, T 1 relaxation, Floquet heating, pulse imperfections, crosstalk, and generic bath coupling, and quantitatively showed that the relative magnitudes of these channels not only dictated the DTC lifetime but also the possible stabilization mechanisms on each platform. The T 1 /T 2 ratio turned out to be the most predictive measure of DTC lifetime across systems with systems with T 1 /T 2 above 1000 (NMR) showing lifetimes of over 44,000 cycles. In RQ2 we have compared six stabilization mechanisms and have identified three of them, EDTC, non-Hermitian DTC and fragmentation-based DTC, to be entirely open-system compatible, where the environmental coupling is exploited instead of being countered. The most practically available of these is the EDTC, which utilizes only the natural $T_1 \gg T_2$ hierarchy of nuclear spin systems with no special engineering. The non-Hermitian DTC offers a 5 fold improvement in the tolerable pulse imperfection, and has direct application to fault-tolerant computation. In RQ3, DTC-based quantum sensors have demonstrated a Heisenberg-limited sensitivity at the hitherto inaccessible frequency range of 0.550 kHz, and sub-Hz frequency resolution at room temperature. Quantum memory DTC-based quantum memory demonstrates >3 second coherence times and does not require active error correction at room temperature, similar to current cryogenic and atomic systems. These findings, as a whole, determine that time crystals are not a mere laboratory curiosity but a resource of technological interest in quantum physics.

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The general idea of this analysis is that the environment, traditionally considered as the main barrier in the way of time-crystalline order, has been rethought as possible resource. This re-thinking, supported by stringent experimental evidence on a variety of platforms, ushers in a new era in the physics of non-equilibrium quantum matter and the realization of useful quantum machines. Time crystal stability in open systems is not something to avoid but a phenomenon to be learned, improved, and used.

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