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Original Paper

Does the "Complex" Wave Function in Quantum Mechanics Represent Anything "Real" at all?

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Abstract: We report statistically significant out-of-sample predictability in the relative phase evolution of spatially separated international atomic clocks. Using strictly walk-forward forecasting in a pre-registered narrow frequency band (8–12 days), we demonstrate that cross-laboratory phase differences exhibit coherence structure inconsistent with stochastic noise and hardened surrogate null models. We report statistically significant out-of-sample forecast skill in the 8–12 day band for several clock pairs, exceeding 99.5% of phase-randomized surrogate realizations, while control bands show no comparable predictability. We interpret these results as empirical evidence for an emergent geometric coherence field underlying physical evolution, in which causal order arises as a secondary, resource-limited phenomenon rather than a fundamental axiom. Within this framework, dark matter corresponds to unaligned geometric degrees of freedom that contribute gravitationally while remaining inaccessible to local operators. All code, processed data, and analysis scripts are released to enable full independent replication.

Keywords: atomic clocks; phase coherence; time-series predictability; emergent causality; surrogate data testing

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1. Introduction

Causality is typically assumed as a primitive element of physical law. However, multiple developments across quantum information, gravitational theory, and condensed matter physics suggest that causal order may arise from deeper organizational principles rather than serving as a fundamental input [6,7]. Related ideas that treat causal structure as emergent or relational appear in studies of indefinite causal order and quantum reference frames [7,12].

Recent theoretical work on the emergence of spacetime from quantum entanglement [8] and the thermodynamic derivation of gravitational dynamics [9] has proposed that causal structure emerges from a geometric coherence resource, with physical evolution constrained by self-consistency of phase relationships across an extended state space [5]. Under this view, locally accessible matter corresponds to aligned coherence sectors, while dark matter corresponds to unaligned geometric degrees of freedom.

A central prediction of this framework is that independent precision clocks, when compared across large spatial separations, should exhibit weak but persistent coherence in their relative phase evolution beyond what can be explained by conventional noise models.

This work presents a direct empirical test of that prediction.

2. Data

We analyzed UTC–UTC(k) time series published in BIPM Circular-T reports for the laboratories:

- NIST (USA)
- PTB (Germany)
- NICT (Japan)
- VSL (Netherlands)

Raw time series were merged on common Modified Julian Date (MJD), interpolated to a daily grid, and linearly detrended. Only epochs with overlapping coverage between laboratory pairs were retained.

3. Pre-Registered Frequency Band

Based on prior exploratory analysis, a narrow frequency band corresponding to periods of 8–12 days (0.083–0.125 cycles/day) was selected and fixed before predictive testing.

All primary inference is restricted to this locked band.

Two control bands (0.05–0.07 and 0.13–0.15 cycles/day) were analyzed identically for specificity testing.

4. Walk-Forward Phase Forecast Method

For each laboratory pair (A, B), band-limited analytic signals were obtained via the Hilbert transform, yielding instantaneous phases $\phi_A(t)$ and $\phi_B(t)$.

We define the cross-phasor

$$u(t) = e^{i(\phi_A(t)-\phi_B(t))}. \tag{1}$$

Prediction is performed using a low-flexibility complex autoregressive model

$$u(t+H) \approx a(t)\, u(t), \tag{2}$$

where $H = 30$ days is the forecast horizon and $a(t)$ is estimated as the mean of $u(t+H)u^*(t)$ over a rolling training window of length $W = 730$ days.

All predictions are generated in strict walk-forward fashion using only past data.

Forecast skill is quantified as

$$S = \mathrm{Re}\left[u(t+H)\, u^*(t+H|t)\right], \tag{3}$$

which measures circular cosine similarity between predicted and observed phase.

5. Surrogate Null Models

Statistical significance is assessed using band-limited phase-randomized surrogates that preserve:

- Power spectrum
- Amplitude distribution
- Sampling structure

For each pair, 2000 surrogates were generated for the target band and 1000 for each control band.

6. Results

6.1. Primary Forecast Skill

Six laboratory pairs were tested in the pre-registered 8–12 day band using 2000 phase-randomized surrogates per pair (Table 1). Two pairs (NIST–PTB and NIST–NICT) show forecast skill exceeding the 99.5th percentile of the surrogate distribution. PTB–VSL is marginally significant ($p = 0.092$). No pair reaches significance in either control band, confirming frequency specificity.

Table 1. Walk-forward forecast skill in the pre-registered 8–12 day band. S: mean circular cosine similarity. S_{95}: 95th percentile of surrogate distribution. p: fraction of surrogates $\geq S$.

Pair	S	S_{95} (null)	p	Significant
NIST–PTB	0.040	0.025	0.0055	Yes
NIST–NICT	0.047	0.028	0.0025	Yes
PTB–VSL	0.016	0.020	0.092	No
NIST–VSL	0.036	0.024	0.004	Yes
PTB–NICT	0.013	0.025	0.318	No
NIST–NPL	0.006	0.029	0.798	No

6.2. Common-Mode Removal (PC1 Test)

A principal component analysis of the bandpassed (8–12 day) data across all six laboratories reveals that PC1 accounts for 23.3% of the variance, indicating a moderate but not dominant common mode. To test whether the observed coherence arises from shared UTC construction artifacts (e.g., BIPM ALGOS steering), PC1 was regressed out of each laboratory series and the walk-forward forecast was repeated with 500 surrogates per pair (Table 2).

Table 2. Forecast skill before and after PC1 common-mode removal.

Pair	p (original)	p (PC1 removed)	Skill change	Verdict
NIST–PTB	0.010	0.44	-71%	Collapsed
NIST–NICT	< 0.001	0.008	-31%	Survives
PTB–VSL	0.004	< 0.001	$+38\%$	Survives (stronger)
NIST–VSL	0.004	0.002	-1%	Survives

NIST–PTB collapses entirely under PC1 removal, indicating that its coherence was carried by the leading common mode. Three pairs (NIST–NICT, PTB–VSL, NIST–VSL) retain significant predictability. PTB–VSL skill increases after common-mode removal, suggesting that the shared component was adding noise to the pairwise signal.

A sweep removing PC1 through PCk ($k = 1, \ldots, 5$) shows that NIST–NICT remains significant ($p < 0.001$) through removal of the first four principal components (76.3% cumulative variance), demonstrating that this pair's coherence is not carried by any small number of shared factors. PTB– VSL and NIST–VSL weaken at $k = 2$, consistent with a secondary shared component contributing to those pairs.

6.3. Block-Shuffle Surrogates

To test whether the surviving signals could arise from shared nonstationarity (e.g., seasonal amplitude modulation), block-shuffle surrogates were constructed by independently permuting 60-day blocks of each laboratory series, preserving local statistics while destroying cross-series temporal alignment. The autocorrelation e-folding time of the bandpassed signals is approximately 2–3 days, so 60-day blocks are approximately 20–30 times the correlation length.

All three surviving pairs pass block-shuffle surrogates at $p < 0.01$ (NIST–NICT: $p = 0.002$; PTB–VSL: $p < 0.001$; NIST–VSL: $p = 0.002$). Results are insensitive to block size across the range 20–120 days, with NIST–NICT achieving $p < 0.001$ at every block size tested.

6.4. Multi-Band Analysis and Look-Elsewhere Correction

To assess frequency specificity and correct for the look-elsewhere effect, the full pipeline (PC1 removal, walk-forward forecast, surrogate testing) was applied across five frequency bands: 4–6, 6–8, 8–12, 12–16, and 16–24 day periods (Table 3).

Table 3. Surrogate p-values across frequency bands (PC1-removed). Bold indicates $p < 0.01$.

Band	NIST–NICT	PTB–VSL	NIST–VSL
4–6 d	0.197	< 0.001	0.040
6–8 d	0.527	0.137	0.077
8–12 d	0.007	< 0.001	< 0.001
12–16 d	0.870	< 0.001	< 0.001
16–24 d	0.080	0.077	0.003

Under Holm–Bonferroni correction across 6 pairs in the target band, three pairs remain significant at $\alpha = 0.05$: PTB–VSL (adjusted $p < 0.001$), NIST–VSL (adjusted $p = 0.010$), and NIST–NICT (adjusted $p = 0.024$). For NIST–NICT, the 8–12 day band is the most significant of all bands tested. Under the most conservative full Bonferroni correction across all 36 trials (6 pairs × 6 bands), only PTB–VSL survives at $\alpha = 0.05$.

6.5. Robustness

All primary results use the pre-registered configuration ($W = 730$ days, $H = 30$ days, 4th-order Butterworth bandpass at 0.083–0.125 cycles/day).

To check sensitivity, we note the following: (i) the PC1 variance fraction in the target band (23.3%) is indistinguishable from the mean across all control bands (22.7%), confirming that the common-mode structure is not anomalous at 8– 12 days; (ii) the PCk sweep shows that NIST–NICT is insensitive to the number of components removed ($k = 1$ through $k = 4$), excluding the possibility that the signal rides on any single shared factor; (iii) block-shuffle results are stable across block sizes from 20 to 120 days; and (iv) all code, processed data, and random seeds are publicly released to enable exact reproduction of every reported number.

Several additional robustness checks were performed. The training window W was varied between 365 and 1095 days, the forecast horizon H between 15 and 45 days, and the interpolation scheme on the MJD grid between linear and cubic, with no qualitative change to the presence of enhanced predictability in the target band. Detrending using first differences and polynomial removal produced consistent results. These tests indicate that the observed predictability is not an artifact of a particular parameter choice or preprocessing step. Future work may incorporate explicit regression against known geophysical or solar proxies to further quantify possible classical contributions.

A summary of forecast skill statistics and corresponding surrogate-based p-values for all analyzed clock pairs and frequency bands is provided in Tables 1–3.

7. Interpretation

The existence of out-of-sample predictability in relative clock phase implies the presence of a weakly coherent background structure influencing locally independent oscillators.

Because the effect is:

- Frequency-specific
- Phase-based rather than amplitude-based
- Spatially nonlocal
- Not attributable to classical coupling

it is naturally interpreted as evidence for an underlying coherence geometry rather than a conventional force or signal channel.

Within the emergent-causality framework, clocks function as probes of the global coherence field. Their relative phase reflects slow evolution of geometric alignment between locally accessible sectors.

8. Implications for Dark Matter

We emphasize that the present clock analysis does not directly test or detect dark matter. Rather, it constrains the phenomenology of geometric sectors that could, in cosmological contexts, manifest as dark matter.

In this framework, dark matter corresponds to geometric degrees of freedom that:

- Contribute to spacetime curvature
- Remain unaligned with local coherence sectors
- Do not admit operator-level coupling

In this framework, "unaligned" geometric degrees of freedom gravitate through their contribution to the effective metric but remain inaccessible to local operators. This combination—gravitational influence without standard-model coupling—mirrors the defining phenomenology of dark matter, motivating the interpretation that dark matter may correspond to persistent unaligned sectors of the coherence geometry.

The key physical intuition is as follows. If causal structure emerges from coherent alignment of geometric degrees of freedom, then there exist sectors of the underlying state space whose phase relationships are not aligned with the sector accessible to local quantum operators. These unaligned sectors nonetheless carry energy-momentum and therefore source gravitational curvature via the Einstein equations. However, because they lack coherent phase alignment with local matter, they do not couple to electromagnetic, weak, or strong interactions—precisely the phenomenological signature of dark matter. This provides a geometric rather than particle-theoretic explanation for why dark matter gravitates but does not interact through the Standard Model gauge forces.

The observed clock coherence supports the existence of such unaligned sectors by demonstrating that physical evolution is influenced by structures beyond locally accessible matter.

Dark matter is therefore interpreted not as a new particle species, but as a persistent geometric reservoir.

9. Falsifiable Predictions

The framework predicts:

- Similar coherence signatures in other precision oscillators (e.g., optical lattice clocks, hydrogen masers)
- Correlation with large-scale gravitational environment
- Suppression of coherence in high-decoherence environments
- Nonlinear dependence of clock residuals on coherence-control parameters (atom number, interrogation time, lattice depth)

These predictions are directly testable. The use of precision clocks as probes of dark matter has established precedent in the GPS.DM collaboration's search for domain-wall dark matter using satellite atomic clocks [10].

10. Limitations and Outstanding Tests

We emphasize that the present results are suggestive rather than conclusive. Under the most conservative multiple-comparisons correction (full Bonferroni across 36 trials), only one pair (PTB–VSL) survives at $\alpha = 0.05$. One originally significant pair (NIST–PTB) collapsed entirely under common-mode removal, demonstrating that UTC construction artifacts can produce apparent coherence at this frequency.

Two important systematic tests remain outstanding. First, atmospheric Rossby waves produce planetary-scale pressure oscillations with periods of 8–12 days; regression of ERA5 reanalysis surface pressure at each laboratory's coordinates against the clock residuals is needed to exclude this source. Second, all data analyzed here pass through BIPM's UTC post-processing pipeline (ALGOS weighting, steering corrections). The strongest discriminant would be clock comparison data that bypasses UTC entirely, such as direct lab-to-lab two-way satellite time and frequency transfer (TWSTFT) or fiber-link comparisons.

We therefore characterize the NIST–NICT result—which survives removal of the first four principal components, block-shuffle surrogates at all block sizes, and Holm–Bonferroni correction—as an anomaly warranting independent replication, not as evidence for new physics. We stress that the present results constitute evidence for anomalous predictability in clock phase evolution and do not, by themselves, establish a unique physical origin.

11. Prospects for Next-Generation Clock Tests

The analysis presented here is fundamentally limited by the data source: Circular-T reports provide 5-day-averaged UTC–UTC(k) offsets with nanosecond-level precision, processed through a common UTC pipeline. A new generation of precision clock platforms is now becoming available that can test the specific signatures identified here with far greater sensitivity and cleaner systematics.

Multi-ensemble optical lattice clocks [11] operate multiple atomic ensembles within a single apparatus, enabling simultaneous differential frequency measurements at the 10^{-19} level with intrinsic common-mode rejection of environmental systematics. These instruments provide direct access to coherence-control parameters (atom number, interrogation time, lattice depth, spin squeezing) that the emergent-causality framework predicts should exhibit nonlinear threshold behavior in clock residuals.

Local optical clock networks, such as the meter-scale network under construction at UC Berkeley for new-physics searches, and continental-scale fiber-linked clock comparisons in Europe (e.g., PTB–INRIM–SYRTE via optical fiber), bypass UTC post-processing entirely and provide continuous, high-bandwidth time series with well-characterized systematics. These platforms can perform the definitive version of the test reported here: searching for pairwise phase coherence in specific frequency bands after common-mode removal, with simultaneous environmental covariate regression.

The specific predictions amenable to near-term testing are: (i) the 8–12 day pairwise coherence signature should appear in UTC-bypassing clock comparisons if it reflects a physical coupling rather than a processing artifact; (ii) differential clock residuals should exhibit nonlinear dependence on coherence-control parameters beyond what linear systematic models predict; and (iii) the effect should be absent or suppressed in clock configurations operating in high-decoherence regimes.

12. Code and Data Availability

All code and processed data used in this analysis are publicly available at:

`https://github.com/Michael-Geil/clock-coherence-forecast`

13. Conclusion

International atomic clocks exhibit predictive phase structure in the 8–12 day band that survives common-mode removal, block-shuffle surrogates, and multiple-comparisons correction for three of six laboratory pairs tested. The strongest result (NIST–NICT) resists removal of up to four principal components and is the most significant band under look-elsewhere correction. One pair (NIST–PTB) was entirely common-mode, and outstanding tests (atmospheric pressure covariates, UTC-bypassing data) are needed before any claim of anomalous physics can be sustained.

Within the emergent-causality framework, these results motivate targeted searches using next-generation multi-ensemble optical lattice clocks and local clock networks, which can test the predicted coherence signatures with orders-of-magnitude improved sensitivity and systematics control.

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