WHEN LIGHT-SPEED MATTERS: RETHINKING FINANCE FOR DISTRIBUTED MARKETS

Toward a Theory of Interplanetary Finance

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Date: 21 October 2025
Version: v1.0 (Pre-release, no SSRN link yet)

ABSTRACT

Capital markets are built on synchronized clocks. This paper extends financial market theory into a regime where its fundamental assumptions break down when markets are separated by relativistic communication delays. We demonstrate that standard financial models from arbitrage theory to derivatives pricing implicitly assume instantaneous information transmission, an assumption that fails categorically when markets are separated by light-seconds or more.

Just as Newtonian mechanics required reconceptualization at speeds approaching c, we show that financial theory requires fundamental rethinking when information transmission approaches physical limits. While building on established financial principles, the resulting framework necessarily introduces concepts foreign to traditional finance: **light-cones replace synchronized time, causality bounds replace arbitrage bounds, and spacetime geometry determines market structure.**

The paper makes three contributions: (1) we formalize how relativistic causality constraints create distinct market regimes where traditional no-arbitrage conditions cannot hold; (2) we propose institutional mechanisms including temporal coordination systems and alternative monetary frameworks suited to distributed economies; (3) we outline an empirical research agenda for testing the framework's implications through infrastructure-pricing relationships in existing markets.

This framework applies immediately to submarine cable finance, satellite communication markets, and disaster-disrupted economies, while establishing foundations for the emerging cislunar economy and eventual interplanetary commerce.

Keywords: distributed markets, light-cone constraints, causality risk, relativistic finance, market microstructure, space commerce
JEL Codes: G10, G12, G18, F30, O33

How to cite (pre-release): Cheah, Daniel (2025). *When Light-Speed Matters: Rethinking Finance for Distributed Markets.* Working paper, v1.0, October 2025. (SSRN link to be added upon indexing.)

1. INTRODUCTION

Capital markets are built on synchronized clocks. Every transaction whether an equity trade, bond coupon, or settlement assumes simultaneity. This assumption is so fundamental to financial theory that it remains unexamined in standard models. Yet this assumption already fails in existing markets with satellite communication, becomes binding in the emerging cislunar economy, and will break entirely as human economic activity extends to Mars and beyond.

When two markets are separated by significant communication delays whether ~500 ms for geostationary satellites, ~1.3 s for Earth–Moon communication, or ~20 min for Earth–Mars they cannot agree on a single “now.” The **light-cone**, defining the limit of causally connected events, replaces universal time. Markets become not merely separated by distance, but by causality itself.

This paper extends financial market theory into this regime where communication delays become economically significant. We term this framework **relativistic finance** not because we apply relativistic mechanics to financial markets for its own sake, but because when markets separate beyond critical communication thresholds, relativistic constraints become the binding economic constraints. This creates phenomena absent from traditional finance: persistent arbitrage gaps without market failure, probabilistic settlement states, and causally-bounded price discovery.

1.1 The theoretical challenge

In relativistic physics, events are classified by causal relationship. Events within each other’s light-cones can influence one another; events outside are **spacelike separated** and cannot interact. This is not a technological limitation but a constraint imposed by spacetime.

Current financial theory implicitly assumes market participants operate within effectively overlapping light-cones. When this assumption fails as it already does in satellite-linked markets and will increasingly in space commerce core mechanisms of modern finance break down:

- **Arbitrage** cannot eliminate price discrepancies between causally disconnected markets.
- **Continuous hedging** becomes impossible when derivatives and underlyings exist in separate light-cones.
- **Settlement** cannot achieve instant finality when confirmation requires light-travel time.
- **Monetary policy** cannot propagate simultaneously across spatially separated economies.

1.2 Immediate relevance and near-term applications

Earth-based applications (now):

- **Submarine cables:** Trans-Pacific routes add ~120–150 ms latency affecting FX/commodities.
- **Satellite comms:** GEO adds ~240–280 ms RTT; remote venues face material frictions.
- **Disasters:** Cable cuts and island outages create natural experiments.
- **Regulatory walls:** Sanctions/capital controls create effective separations.

Emerging space economy (2025–2035):

- **Commercial LEO stations:** Private stations by ~2030; on-orbit manufacturing signals.
- **Cislunar activity:** Lunar assays, L5 manufacturing, space-based solar; ~1.3 s delays.
- **Orbital fuel depots:** First extraterrestrial commodity markets.

1.3 Contribution

We provide the first systematic treatment of financial markets under relativistic causality constraints. Like behavioral finance extended rational finance to account for psychology, we extend classical finance to account for **physics** when communication delay binds.

Our main contribution is theoretical: a framework for pricing, risk, and institutional design when markets are separated by light-cones. This is a **regime change**, not a parameter tweak. We also sketch terrestrial validations via infrastructure pricing relationships to test today while space commerce ramps.

The remainder of the paper proceeds as follows. Section 2 formalizes why the classical assumption of instantaneous information fails under finite-speed communication. Section 3 develops the theoretical framework for causally constrained markets. Section 4 bridges current Earth-based infrastructures to emerging cislunar markets. Section 5 proposes institutional mechanisms for temporal and monetary

coordination. Section 6 outlines empirical tests and validation strategies. Section 7 concludes with implications for policy and future research.

2. THE FAILURE OF INSTANTANEOUS INFORMATION ASSUMPTIONS

2.1 Core assumptions

- **A1 (Instantaneous Observation):** Price changes at any location are immediately observable everywhere.
- **A2 (Immediate Arbitrage):** Discrepancies can be exploited faster than they persist.
- **A3 (Simultaneous Information):** All participants access the same information set at the same time.

These are tolerable approximations on Earth (tens of ms), strained for satellites (~240 ms+), partially failing cislunar (~1.3 s), and broken interplanetary (minutes–hours).

2.2 Formal breakdown of no-arbitrage

Let markets A and B be separated by delay Δt.

Traditional: $P_A(t) = P_B(t)$ (identical assets).
Constrained: $|P_A(t) - P_B(t + \Delta t)| \leq TC$ (transaction costs).

But during $[t, t + \Delta t]$, the markets are **causally disconnected**: no arbitrage is feasible regardless of divergence. Define:

Definition 1 (Causally-Bounded Arbitrage). For separation Δt, price divergence $D(t)$ can persist up to

$$D_{\max}(t) = \sigma\sqrt{2\Delta t}\,\Phi^{-1}(1 - \alpha) + TC,$$

where σ is volatility, Φ^{-1} the inverse standard normal CDF, α risk tolerance, and TC costs. Thus allowable divergence scales as $\sqrt{\Delta t}$.

2.3 Derivatives under discrete observation

Black–Scholes assumes continuous hedging. With communication delay, hedging/observation is limited to discrete steps of length $\tau = 2\Delta t$ (round-trip).

Conjecture 1. With hedging frequency constrained to τ, the option price includes a residual variance term:

$$C_{\text{constrained}} = C_{\text{BS}} + \frac{\sigma^2 \tau}{2} \Gamma S^2 h(\tau, T),$$

where Γ is gamma, S spot, h depends on τ and maturity T. Economic intuition: unhedgeable **blindness risk** between re-hedges must be priced.

3. THEORETICAL FRAMEWORK FOR CAUSALLY-CONSTRAINED MARKETS

3.1 New regime

This is not mere re-parameterization. When markets span disjoint light-cones, new phenomena emerge that require new conceptual tools akin to how quantum extends classical mechanics.

3.2 Market structure under light-cone separation

Model the market as a directed graph:

- **Nodes:** trading locations (Earth venues, LEO, Moon, Mars).
- **Edges:** communication links weighted by light-travel time.
- **Connectivity:** only when within light-cones.

Definition 2 (Market Connectivity Matrix). For n locations,

$$M_{ij}(t) = \begin{cases} 1, & \text{if communication delay } \leq \delta, \\ 0, & \text{otherwise,} \end{cases}$$

where δ is the design threshold for fragmentation.

3.3 Asynchronous price discovery

Information from i at time t reaches j at $t + d_{ij}/c$. Price at j:

$$P_j(t) = f\big(\text{Local}_j(t),\, \text{External}_i(t - d_{ij}/c),\, \varepsilon_j(t)\big).$$

Prices become a **spatiotemporal surface**, not a single series.

3.4 Settlement under uncertainty

Definition 3 (Probabilistic Settlement). For a trade at t with delay Δt:

$$\Pr_{\text{settle}}(s) = \begin{cases} 0, & s < t, \\ \psi(s - t), & t \le s \le t + 2\Delta t, \\ 0 \text{ or } 1, & s > t + 2\Delta t, \end{cases}$$

with $\psi'(\cdot) > 0$. Settlement uncertainty during $[t, t + 2\Delta t]$ is a new priced risk.

4. THE BRIDGE: FROM SUBMARINE CABLES TO CISLUNAR ECONOMY

4.1 Current infrastructure constraints (2025)

Submarine cables:

- Trans-Pacific latency ~120–150 ms (FX/commodities $> \$5$ trn/day).
- Arctic routes (planned) may cut EU–Asia latency ~30%.
- Disruptions (e.g., Tonga 2022) create separation experiments.

Satellite markets:

- GEO RTT ~240–280 ms (energy/mining/offshore ops).
- LEO ~20–40 ms (opens access; still frictions for HFT).
- Rural banking for billions relies on satellite links.

4.2 Near-term space economy (2025–2030)

Commercial LEO: Axiom (2026–27), Orbital Reef (~2030), Starlab (~2029).
Cislunar: Artemis sustained presence (~2028); 1.3 s delay implies first truly separated markets.

4.3 Medium-term expansion (2030–2035)

- **Asteroid assays:** 5–20 min delays → mineral rights forwards.
- **L5 manufacturing:** continuous links, ~1.3 s delay; high-purity outputs.
- **Mars precursor:** 4–24 min delays → autonomous market-making, long-dated life-support futures.

4.4 Phases of market evolution

1. **Latency-arbitrage** (now–2027), 2) **Satellite integration** (2025–2030),
2. **Cislunar separation** (2028–2035), 4) **Interplanetary divergence** (2035+).

5. INSTITUTIONAL MECHANISMS

5.1 Temporal Coordination Infrastructure (TCI)

A global temporal institution (akin to BIPM/IERS) that maintains **Reference Time (RT)**, broadcasts authenticated timestamps, and audits temporal compliance.

Reference Time definition (sketch):

$$RT = \sum_i w_i \, \tau_i \Big(1 + \frac{\Phi_i}{c^2}\Big),$$

where τ_i is proper time, w_i weights, Φ_i gravitational potential. The TCI coordinates **when** things happen; central banks decide **what** happens.

5.2 Alternative monetary frameworks

Energy-based denomination (joules).
Pros: universal, conserved, measurable.
Cons: storage/transport losses, politics of conversion.

Cryptographic assets (asynchrony-tolerant).
Consensus must respect causal delay; ledgers verify **order**, not simultaneity. DLT works *within* relativity; it cannot defeat it.

6. EMPIRICAL IMPLICATIONS AND VALIDATION

While primarily theoretical, the framework yields testable predictions.

6.1 Project 1 — Infrastructure as quasi-monetary policy

Hypothesis: Latency reductions mimic rate cuts via higher velocity/lower risk premia.
Event study: Major cable deployments.
Model:

$$\Delta \text{Spread} = \beta \log\left(\frac{L_{\text{before}}}{L_{\text{after}}}\right) + \gamma X + \varepsilon,$$

with expected $\beta \in [20, 40]$ bps for large upgrades.

6.2 Project 2 — Causality Risk Rating (CRR) as priced factor

Hypothesis: Markets with higher **Causality Risk** earn systematic premia, analogous to sovereign risk.

CRR construction (finance-analogue mapping):

- **Physical Link Integrity** *(cf. political stability)*: channel count, independence, sabotage/vulnerability profile.
- **Informational Friction** *(cf. macro fundamentals)*: latency Δt, bandwidth, jitter non-diversifiable drag.
- **Network Resilience** *(cf. institutional strength)*: redundancy, historical uptime/MTTR, route diversity.

Test design:

- Build CRR scores for satellite/remote venues (and simulated cislunar nodes).
- Examine cross-sectional returns controlling for Fama–French factors.

- **Prediction:** A 1σ deterioration in CRR forecasts **+200–400 bp** higher annual returns (risk compensation).
- Optional extension: publish CRR letter-grade (e.g., “C-BB”) to standardize disclosure for distributed markets.

Why it matters: Elevates causality from a mere friction to a **first-class risk factor** investors can price, hedge, and regulate.

6.3 Project 3 — Natural experiments in separation

Hypothesis: Forced separations generate divergences scaling with $\sqrt{\text{separation time}}$.

Cases: Tonga 2022 (weeks), Egypt 2011 (days), hurricane-isolated islands (varied).
Prediction:

$$\max D \approx \sigma_{\text{asset}} \sqrt{2 \times \text{disruption\_days}} \times 2.33.$$

6.4 Addressing objections

We anticipate several immediate objections to this framework. We address these concisely below and offer an extended refutation in **Appendix C**.

“Just extend settlement.”
Doesn’t fix price discovery degradation, capital lock-up, or cascade risk; it relocates the problem.

“This is just latency-arbitrage.”
No: HFT latency is engineering; **light-speed is physics**. Also introduces **discrete** interaction of disconnected markets.

“Blockchain solves it.”
Consensus under long asynchrony faces FLP-style limits; cryptographic finality $\neq$ economic finality.

7. CONCLUSION

We develop theoretical foundations for markets operating under relativistic causality constraints. When delay binds, classical finance must be re-formed, not merely re-parameterized.

Three takeaways:

1. **Arbitrage has physical limits:** divergence can persist during causal disconnection without violating no-arbitrage.
2. **New institutions:** temporal coordination becomes as critical as monetary coordination.
3. **Infrastructure is macro policy:** communication investment shifts yields like rate moves.

The framework applies now to cables/satellites/disasters; it becomes essential for cislunar (2028–2035) and critical for Mars (2035+). As human commerce expands into space, finance must price **latency, simultaneity, and causality** not just capital and risk.

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APPENDIX A: MATHEMATICAL DEFINITIONS

Notation

Symbol	Definition
c	Speed of light $= 299{,}792{,}458\ \mathrm{m/s}$

Symbol	Definition
Δt	One-way communication delay
$P_i(t)$	Asset price at location i, time t
σ	Asset return volatility
$M(t)$	Market connectivity matrix
RT	Reference Time (coordinate time)
d_{ij}	Distance between i and j
Φ	Gravitational potential

Key relationships

- Communication delay: $\Delta t = d/c$
- Round-trip arbitrage time: $\tau = 2\Delta t$
- Max sustainable divergence: $D_{\max} \propto \sigma\sqrt{\Delta t}$
- Settlement uncertainty window: $[t,\, t + 2\Delta t]$

APPENDIX B: EXTENDED MATHEMATICAL FRAMEWORK

> *Sketches for intuition; full proofs reserved for technical follow-ups.*

B.1 Causally-bounded price processes

Start with GBM: $\mathrm{d}P/P = \mu\,\mathrm{d}t + \sigma\,\mathrm{d}W$.
Observed at j for an asset at i:

$$P_j^{\text{obs}}(t) = P_i\big(t - \tfrac{d_{ij}}{c}\big)\ \exp\Big(\int_{t-\frac{d_{ij}}{c}}^{t} \sigma\,\mathrm{d}W_s\Big).$$

Observation error variance:

$$\mathrm{Var}\big[\ln(P_j^{\text{obs}}/P_i)\big] = \sigma^2\frac{d_{ij}}{c}.$$

B.2 Modified no-arbitrage bounds

Under causality constraints:

$$\mathbb{E}[R_{\text{excess}} \,|\, \mathcal{I}_{t-\Delta t}] \;\le\; \sigma\sqrt{2\Delta t}\; z_\alpha,$$

with z_α the standard-normal critical value.

B.3 Discrete-hedging premium (intuition)

Between hedges spaced τ, gamma exposure yields expected P&L cost
$\approx \frac{1}{2}\Gamma\,\sigma^2 S^2 \tau$, leading to the conjectured premium
$\propto (\sigma^2\tau/2)\Gamma S^2$ in §2.3.

APPENDIX C: EXTENDED REBUTTALS TO POTENTIAL OBJECTIONS

This appendix provides a more detailed refutation of common objections anticipated in response to the relativistic finance framework. While Section 6.4 offers concise summaries, the following sections elaborate on the fundamental misconceptions that these objections represent.

C.1 Objection: "This is a simple settlement problem; just extend the settlement time."

This perspective fundamentally misdiagnoses the issue as one of logistical timing (e.g., moving from T+1 to T+5) rather than a persistent state of informational asymmetry and capital inefficiency. Extending the settlement window does not solve the core problems; it merely papers over them while introducing new, severe costs.

- **Capital Lock-Up and Inefficiency**: The most immediate consequence of a long communication delay is the inefficient allocation of capital. For the duration of the round-trip light time—whether it's ~2.6 seconds for the Moon or ~40 minutes for Mars—capital is locked in transit, unproductive and exposed to risk. In a mature market with trillions of dollars in daily turnover, this represents a permanent and massive capital cost that must be priced into every transaction. This is not a one-time fee but a constant drag on the cost of capital for all economic activity in that market.
- **Explosion of Counterparty Risk**: Modern finance has relentlessly pushed to shorten settlement cycles for one primary reason: to minimize counterparty risk. The longer the period between trade execution and final settlement, the higher the probability that one party will default. Extending

settlement to T + 40 minutes reintroduces a risk profile that terrestrial markets have spent decades and billions of dollars to eliminate. This risk is un-hedgeable during the communication delay and would necessitate massive collateral requirements, further compounding capital inefficiency.
- **Degradation of Price Discovery**: This is the most critical failure of the "extend settlement" argument. The problem isn't just finalizing the transaction; it's that the two markets are trading on different information sets. For 20 minutes, the Martian market is operating on stale, 20-minute-old data from Earth. Prices on Mars cannot, by definition, reflect the true, system-wide state of supply and demand. This "price blindness" guarantees volatility and severe mispricing. Extending settlement does nothing to fix the fact that one market is flying blind.

C.2 Objection: "This is just another form of latency arbitrage seen in High-Frequency Trading (HFT)."

This objection conflates a difference in degree with a difference in kind. It mistakes a solvable engineering challenge for an immutable physical constraint.

- **Engineering vs. Physics**: HFT latency arbitrage is an engineering arms race. Firms can co-locate servers, build microwave relay towers, or lay more direct fiber-optic cables to shave milliseconds off their transaction times. It is a competition that can be won with better technology and more capital. The speed of light in a vacuum, c, is a fundamental constant of the universe. No amount of innovation or investment will ever allow information to travel faster than this limit. The relativistic finance framework is not about out-engineering a competitor; it is about pricing a permanent, non-negotiable feature of spacetime.
- **Continuous vs. Discretely Connected Markets**: HFT operates within a market that is, for all practical purposes, continuously connected. Information is always flowing, just slightly faster for some participants than for others. In contrast, markets separated by relativistic delays are discretely connected. For the duration of the one-way light time Δt, they are causally isolated systems. They only synchronize intermittently. This creates a fundamentally different market structure with entirely different risk dynamics, such as the "blindness risk" mentioned in Section 2.3, which has no true analogue in terrestrial HFT.

C.3 Objection: "Blockchain or other Distributed Ledger Technologies (DLT) will solve this."

This is a technologically optimistic but physically naive argument. DLT is a powerful tool for achieving consensus on the order of events within a causally connected network, but it is still bound by the laws of physics and cannot create a single, simultaneous "now" where one does not exist.

- **The Consensus Problem and FLP Impossibility**: Blockchain consensus mechanisms, whether Proof-of-Work or Proof-of-Stake, require network participants to communicate and validate transactions in a timely manner. With a 40-minute round-trip delay between Earth and Mars, maintaining a single, coherent blockchain is a theoretical impossibility. The Martian chain would be tens or hundreds of blocks ahead before it ever received confirmation from Earth regarding its first block, leading to constant, irreconcilable forks. This scenario is a practical demonstration of the Fischer, Lynch, and Paterson (FLP) Impossibility Theorem from distributed computing, which proves that guaranteeing consensus in a purely asynchronous network (like one with long delays) is impossible.
- **Cryptographic Finality vs. Economic Finality**: A transaction might achieve "finality" on a local, Martian version of the ledger. However, this is merely cryptographic finality. It has no economic finality until it is acknowledged and reconciled with the Earth-based system 20 minutes later. If the Earth network rejects the block containing that transaction (due to a double-spend attempt or any other reason), its finality on Mars becomes economically meaningless. DLT can create a causally consistent record of history; it cannot magically bridge the causal disconnect to enforce a single economic reality across spacetime.

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Declaration
This framework was developed independently. All errors are the author’s.
The views expressed in this paper are solely those of the author and do not represent the views of any affiliated institutions.

Note on formalization
This paper emphasizes economic intuition and structure; complete formal proofs will appear in subsequent technical papers.

Versioning & availability
This is the pre-release working version (v1.0, 21 Oct 2025). The canonical record will be linked once the SSRN entry is live. For correspondence or permission to cite, contact daniel.cheah@spacefi.institute.