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Posted Date: 18 May 2026

doi: 10.20944/preprints202605.1089.v1

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Where is Everybody? The Causal Disconnect and the Limits of Interstellar Detectability

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Abstract

The Fermi Paradox ("Where is everybody?") refers to the apparent contradiction between the visualisable abundance of extraterrestrial civilizations and the continued absence of confirmed detections. This work explores whether finite communicative lifetimes, combined with Galactic distance scales and the finite speed of light, can substantially suppress the probability of causal overlap between technological civilizations. Using a simplified stationary Galactic model $(v \approx 0)$ within a Minkowski spacetime framework, technological civilizations are represented as finite world-line segments generating expanding "Information Shells" through electromagnetic signal propagation. Within this interpretation, successful detectability requires overlap between the communicative intervals of different civilizations in both space and time. For representative communicative lifetimes of order $L \sim 10^3$ years, the effective causal reach of detectable signals remains small compared with typical interstellar separations expected in sparse-civilization scenarios. Using a heuristic overlap model, we estimate that for $N = 100$ contemporaneous civilizations distributed throughout the Milky Way, the effective causal-overlap probability remains below 1%. The analysis further considers long-term engineering limitations on autonomous probes and persistent signalling systems, including radiation damage, impact erosion, and power degradation, collectively described here as a "Hardware Filter." In addition, the work distinguishes between the total biological lifetime of a civilization and its externally detectable communicative phase, suggesting that advanced civilizations may evolve toward increasingly low-leakage or radio-quiet technological states. Within this framework, the apparent "Great Silence" may emerge naturally from finite communicative windows, spacetime separation, and engineering constraints even if intelligent life itself is not intrinsically rare.

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1. Introduction

For over half a century, the Search for Extraterrestrial Intelligence (SETI) has largely operated under the assumption that technologically detectable civilizations, if sufficiently numerous, may eventually establish indirect causal contact through electromagnetic signals. However, the continued absence of confirmed detections, commonly referred to as the 'Great Silence,' suggests that additional physical constraints can strongly limit mutual detectability. The Milky Way, a disk approximately 100,000 light-years in diameter and roughly 1,000 light-years thick near the Galactic center, must therefore be considered not only as a vast spatial structure, but also as a four-dimensional spacetime system governed by the finite propagation speed of information [1–3].

Traditional formulations such as the Drake Equation [4] primarily treat the communicative lifetime of a civilization (L) as a temporal parameter contributing to the number of contemporaneous technological civilizations in the galaxy. While this framework is highly valuable for estimating the possible abundance of intelligent life, it does not by itself address the causal requirements for successful signal exchange across galactic distances. Electromagnetic signals propagate at the finite speed of light and therefore occupy only a finite expanding region of spacetime during a civilization's communicative phase. Consequently, the existence of multiple civilizations does not necessarily imply mutual detectability. Successful contact additionally requires sufficient overlap in both spatial separation and temporal activity windows.

Several prior studies have explored related constraints on interstellar contact. Balbi [2] demonstrated that the temporal distribution of civilisations across cosmic history strongly suppresses mutual detectability, even when their total number is large. Grimaldi [3] modelled signal coverage geometrically across the galactic disk, deriving detection probabilities as a function of emitter density. Lares et al. [5] used Monte Carlo simulations to estimate causal contact probabilities, independently arriving at similarly low intersection rates. Most recently, Rahvar & Rouhani [1] derived constraints on civilisational lifespan directly from galactic geometry, finding results broadly consistent with a regime of widespread isolation. The present work builds upon and extends these findings in four distinct ways. First, we recast L not as a statistical variable but as a geometric spacetime structure represented by the thickness of an 'Information Shell' in Minkowski spacetime thereby making the causal constraint explicit and directly visualisable through world-line analysis. Second, we introduce a heuristic parametric estimate for the Causal Intersection Probability ($P_{total} = P_{space} \times P_{time}$) where P_{space} and P_{time} are the spatial and temporal overlap probability and present it as a parametric function of both L and N simultaneously (where N is the density of technological civilizations in the milky way galaxy and all these will be discussed elaborately in this article), suggesting that the observed SETI null result may place qualitative constraints on the combined parameter space of communicative lifetime and civilization density. Third, we introduce the Hardware Filter i.e., engineering degradation of autonomous probes as an independent, quantifiable secondary constraint that prior models have not addressed. Fourth, we propose the 'Inward Transition' as a physically motivated mechanism terminating the communicative window L, motivating the model's central assumptions using considerations of energetic cost, systemic complexity, and technological sustainability.

In this work, we interpret the communicative lifetime L not only as a temporal duration, but also as a geometric scale that determines the radial extent of a civilization's expanding information shell in spacetime. Expressed in light-years through the finite propagation speed of electromagnetic signals, L defines the maximum causal reach of a civilization during its detectable phase. Within this framework, the number of civilizations N is not by itself sufficient to determine the likelihood of contact; rather, detectability additionally depends on the spatio-temporal density and overlap of these finite information shells. If the characteristic separation between civilizations substantially exceeds the causal reach associated with their communicative lifetimes, mutual detection may become strongly suppressed even when multiple civilizations exist simultaneously within the galaxy.

The central hypothesis explored here is that communicative phases may often be relatively short compared with galactic distance scales. Under such conditions, the finite speed of light acts as a strong causal constraint, potentially producing effective isolation between civilizations whose active epochs do not sufficiently overlap in spacetime. We refer to this condition as a "causal disconnect," in which technologically active civilizations may remain mutually undetectable despite coexisting within the same galaxy.

2. Physical Motivation and Causal Detectability

The motivation for exploring this framework is primarily physical, arising from the interplay between finite communicative lifetimes, Galactic distance scales, and the finite propagation speed of information.

2.1. Temporal Desynchronization of Civilizations

A central consideration in SETI studies is not only the existence of technological civilizations, but also the degree to which their communicative phases overlap in time. In a universe approximately

13 billion years old, even communicative lifetimes lasting several thousand years represent only a very small fraction of cosmic history. Consequently, civilizations may emerge and disappear at widely separated epochs despite coexisting within the same galaxy over astronomical timescales.

The primary motivation of the present work is to examine how finite communicative lifetimes and light-speed propagation jointly influence the probability of causal overlap (reach) between civilizations. Within this framework, detectability depends not solely on the total number of civilizations that may exist throughout galactic history, but also on the temporal overlap of their technologically active phases. The analysis therefore shifts emphasis from the mere existence of extraterrestrial civilizations toward the spacetime conditions required for mutual detectability.

2.2. Possible Sociological Implications of Causal Isolation

Beyond the physical constraints discussed above, the possibility of causal isolation may also have broader sociological implications. Contact between civilizations separated by large differences in technological development could produce complex cultural and political responses rather than necessarily generating immediate global unification. Historical interactions between human societies with strongly asymmetric technological capabilities have often produced significant social disruption, although direct analogies to extraterrestrial contact remain highly speculative.

Within the framework proposed here, long-term causal isolation may represent a natural consequence of finite communicative lifetimes and galactic distance scales rather than a paradox requiring biological explanations alone. One possible implication is that technologically developing civilizations may evolve largely independently over astronomical timescales, with limited external interference or information exchange. Whether such isolation is ultimately beneficial, detrimental, or neutral for societal development remains uncertain and lies outside the scope of the present physical analysis. Nevertheless, the possibility of prolonged civilizational isolation provides an additional perspective from which to interpret the continued absence of confirmed extraterrestrial contact.

2.3. Engineering Constraints on Long-Duration Interstellar Systems

A further secondary motivation for the present study arises from the engineering challenges associated with long-duration interstellar communication and exploration. Although autonomous probes and long-lived transmitters are often proposed as mechanisms for extending the detectable presence of a civilization beyond its biological or technological lifetime, such systems would likely operate under significant physical and engineering constraints. Over sufficiently long timescales, exposure to radiation, micrometeoroid impacts, material degradation, and power-source limitations may progressively reduce the reliability and operational lifetime of interstellar systems.

These considerations do not imply that long-range probes or persistent signalling infrastructures are impossible. However, they suggest that maintaining detectable interstellar activity over timescales comparable to galactic transit distances may require substantial technological robustness and long-term energy investment. Such engineering limitations may therefore act as an additional factor reducing the effective duration of detectable interstellar communication.

2.4. Reference Timescales for Communicative Lifetimes

(1) *Empirical technological trajectory*: Human civilization has possessed radio communication technology for approximately 120 years. Over this relatively short period, communication systems have already evolved toward increasingly efficient, low-leakage, and highly directional architectures, including fibre-optic transmission, compressed digital encoding, and narrow-beam signalling. If similar trends occur elsewhere, the phase during which a civilization emits strong omnidirectional radio leakage into interstellar space may represent only a limited fraction of its technological history.

(2) *SETI reference estimates*: Early SETI analyses by Frank Drake and Carl Sagan frequently considered communicative lifetimes ranging from 10^3 to 10^4 years as plausible order-of-magnitude estimates for technological civilizations. The present work adopts $L \approx 1000$ years as a

representative lower-end reference case for exploring the consequences of short communicative windows. Importantly, the analysis is not restricted to this single value; Table 1 examines the behavior of the model across several orders of magnitude in L.

(3) *Complexity and energetic constraints*: Technological civilizations may be viewed as highly organized dissipative systems requiring sustained energy throughput and increasingly complex infrastructural coordination [6]. Historical human societies have often experienced periods of instability or transformation following rapid increases in systemic complexity, although extrapolation to extraterrestrial civilizations remains highly uncertain. Within this context, communicative lifetimes of order 10^3 years may plausibly represent one possible regime in which civilizations either undergo major structural transitions, reduce large-scale electromagnetic leakage, or shift toward more localized and energy-efficient communication technologies.

Accordingly, $L \approx 1000$ years should be interpreted in this work as an illustrative reference timescale rather than a universal physical limit or a law. The broader parametric analysis presented in Table 1 is intended to explore how varying communicative lifetimes influence the probability of causal overlap across galactic distances.

3. The Geometry of Contact

In this section, we move from the conceptual motivation of the paper to its spacetime framework to understand why contact is so rare. Because interstellar communication depends on both spatial separation and signal propagation time, the interaction is naturally described within a Minkowski spacetime representation.

3.1. World Lines

In relativistic spacetime, every physical object follows a world line, i.e., a trajectory through space and time. Technological civilizations can similarly be represented by finite world-line segments corresponding to the duration of their communicative or detectable phases. Figure 1 schematically illustrates this framework, with Earth represented at the spatial origin $(x = 0)$ and a distant technological civilization represented at a finite spatial separation.

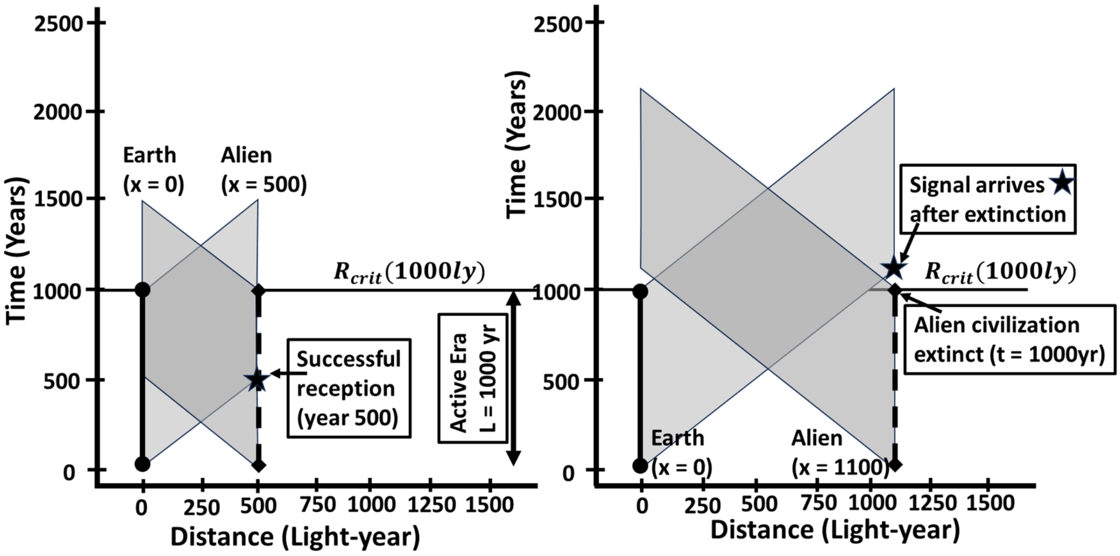

Figure 1. Schematic representation: *Earth and Alien civilization have a 1,000-year technological lifespan* (L) *and are 500* ly *and 1100* ly *away from each other, the alien civilization's world line is approximately vertical under the stationary approximation* $v \approx 0$. *In spacetime coordinate, light propagates along 45° null trajectories. The electromagnetic signals emitted by civilizations are bounded by two parallel lines corresponding to beginning and end of Active Era.*

doi:10.20944/preprints202605.1089.v1

In general, relative stellar motion within the Galactic disk would produce slightly inclined world lines in spacetime coordinates. However, throughout the present analysis we adopt the simplifying approximation $v \approx 0$, corresponding to negligible relative motion compared with the speed of light. Under this stationary approximation, the world lines may be treated as approximately vertical in the spacetime diagram, allowing the causal geometry of signal propagation to be visualized more clearly.

3.2. Expanding Information Shells and Causal Propagation

Electromagnetic communication is not emitted from a single spacetime point, but continuously throughout the detectable lifetime L of a technological civilization. A civilization that broadcasts detectable signals over a finite interval therefore generates an expanding region of causal influence (reach) in spacetime. In the present framework, this region may be represented as an outward-propagating "information shell" bounded by the leading and trailing edges of the transmitted signal.

In spacetime diagrams using units where the speed of light defines the causal slope, the propagation boundaries of the signal follow null trajectories corresponding to light-speed propagation (Figure 1). Mutual detectability between two civilizations requires sufficient overlap between a civilization's world line and the incoming information shell generated by another civilization. If the signal passes a planetary system before or after its technologically active interval, then causal overlap does not occur despite the physical propagation of the signal through that region of space. In this sense, detectable electromagnetic signals may continue propagating through spacetime long after the originating civilization has ceased detectable activity.

4. Spacetime Conditions for Detectability

To illustrate the concept of 'causal disconnect,' we consider two schematic spacetime scenarios shown in Figure 1. In both cases, the communicative lifetime of each civilization is assumed to be $L = 1000$ years. One extraterrestrial civilization is located at a distance of 500 light-years from Earth, while a second case considers a civilization located at 1100 light-years. These examples demonstrate how finite communicative lifetimes combined with light-travel delays can produce qualitatively different detectability outcomes even for otherwise similar civilizations.

4.1. Causal Successful and Unsuccessful Detectability

In the first scenario, the extraterrestrial civilization is located at a distance of 500 light-years from Earth. Since the signal propagation time is shorter than the assumed communicative lifetime ($500 < 1000$ years), the expanding information shell intersects the technologically active interval of the receiving civilization. Under these conditions, causal overlap (reach) becomes possible, and mutual detectability will in principle occur within the shared active period.

In the second scenario, the extraterrestrial civilization is located at a distance of 1100 light-years from Earth while retaining the same communicative lifetime of $L = 1000$ years. In this case, the light-travel time exceeds the duration of the detectable phase. As a result, the expanding information shell reaches the target system only after the receiving civilization has ceased detectable activity, preventing causal overlap despite the continued physical propagation of the signal through space.

This comparison illustrates that the existence of multiple technological civilizations within the galaxy does not by itself guarantee detectability. Instead, successful signal detection depends critically on the relationship between communicative lifetime and interstellar separation once finite propagation speed is taken into account.

4.2. The Role of Relative Stellar Motion:

In the simplified stationary approximation discussed above $(v \approx 0)$, the characteristic distance over which causal overlap occurs is approximately equal to the communicative lifetime L expressed in light-years. In practice, however, stars within the Galactic disk possess relative velocities

doi:10.20944/preprints202605.1089.v1

with respect to one another. Consequently, the spatial separation between two civilizations may evolve during the signal propagation interval.

For the illustrative case in which one civilization recedes approximately along the line of sight with relative velocity v, the effective signal-closing speed can be approximated as $(c-v)$. Under this simplified kinematic picture, the permitted causal-overlap distance is correspondingly reduced relative to the stationary case. In the limiting and highly unrealistic case $v \to c$, the effective overlap distance would become extremely small, substantially suppressing the possibility of successful detectability. For typical stellar velocities within the Milky Way $(v \sim 10^{-4}c$ to $10^{-3}c)$, this correction remains small compared with the dominant effect arising from finite communicative lifetimes themselves. Nevertheless, relative stellar motion slightly narrows the available overlap window relative to an idealized static geometry and therefore acts as a secondary contribution to causal separation.

To establish a baseline-estimate for intra-galactic detectability, we therefore adopt the limiting approximation $v \approx 0$, corresponding to negligible relative motion compared with the speed of light. Under this stationary approximation, the characteristic (effective) causal-overlap (reach) distance becomes approximately $R_{crit} \approx cL$ where R_{crit} is expressed in light-years when L is measured in years and $c = 1$ light-year per year. For a communicative lifetime of $L = 1000$ years, civilizations separated by distances substantially greater than approximately 1000 light-years would experience strongly reduced probabilities of causal overlap (reach) within their active intervals.

The illustrative example discussed in Figure 1 demonstrates this threshold behaviour. At a separation of 500 light-years, the signal arrival time remains shorter than the assumed communicative lifetime, allowing causal overlap to occur. At a separation of 1100 light-years, however, the signal arrives approximately 100 years after the detectable phase has ended, preventing successful detectability despite the continued propagation of the signal through space.

These examples illustrate that finite communicative lifetimes combined with galactic distance scales will naturally generate extended regimes of effective causal isolation between civilizations even in the idealized stationary limit [2,5].

5. Statistical Constraints on Causal Detectability

In this section, we extend the idealized two-civilization geometry developed above to a simplified statistical model of a galaxy containing many technological civilizations distributed throughout the Galactic disk. The analysis estimates the civilization density required for significant causal overlap and examines how finite communicative lifetimes influence the probability of successful detectability across galactic distances. We additionally consider whether long-lived technological remnants or autonomous systems could substantially extend the effective duration of detectable activity in the next section.

5.1. Galactic Volumetrics and the Density of Technological Civilizations

To estimate the conditions under which causal overlap becomes likely, we compare the characteristic overlap (effective) region associated with a communicative lifetime L to the total effective volume of the Milky Way. As a simplified approximation, the Galaxy is modeled as a cylindrical disk with radius $R_{gal} = 50{,}000$ light-years and thickness $H = 1000$ light-years, giving a total Galactic volume $V_{gal} = \pi R_{gal}^2 H \approx 7.85 \times 10^{12} \mathrm{ly}^3$.

For a representative communicative lifetime of $L = 1000$ years, the corresponding characteristic causal-overlap (reach) scale is approximately $R_{crit} \approx 1000$ light-years in the stationary limit $(v \approx 0)$. Approximating the accessible reach region as a cylindrical volume with radius 1000 light-years and thickness $H = 1000$ light-years that gives $V_{crit} = \pi(1000\mathrm{ly})^2(1000\mathrm{ly}) \approx 3.14 \times 10^9 \mathrm{ly}^3$.

The approximate number of civilizations required for substantial overlap between neighbouring causal regions can then be estimated as $N \approx V_{gal}/V_{crit} \approx (7.85 \times 10^{12})/(3.14 \times 10^9) \approx$

doi:10.20944/preprints202605.1089.v1

2500. This estimate suggests that if the total number of simultaneously active civilizations is substantially smaller than this value, the typical separation between neighbouring civilizations exceeds the effective causal-overlap (reach) distance associated with $L = 1000$ years.

For two-way communication, the effective separation scale must be smaller because a return signal must also arrive within the communicative interval. In the simplified symmetric case, this corresponds to a characteristic separation of approximately $R_{crit} \approx 500$ light-years for $L = 1000$ years. Using the same volumetric approximation, one obtains $N_{2-way} \approx V_{gal}/[\pi(500\text{ly})^2 H] \approx 10{,}000$ civilizations. Thus, sustained bidirectional communication requires substantially higher civilization densities than for one-way detectability alone.

The underlying statistical argument can be understood qualitatively through a simple density analogy: if detectable regions occupy only a small fraction of the total Galactic volume, then civilizations are unlikely to lie within one another's causal-overlap regions unless the total civilization density becomes sufficiently large. The threshold estimates $N \approx 2500$ therefore represents the approximate density scale at which neighbouring overlap volumes begin to populate the Galactic disk significantly under the assumptions of the present model.

In practice, this estimate likely represents an upper bound because technological civilizations preferentially occupy the Galactic Habitable Zone rather than the full Galactic disk volume.

To illustrate the sparse-civilization regime, consider the representative case $N = 100$ distributed throughout the Galactic volume. Using the characteristic (effective) area-per-civilization approximation $D^2 = V_{gal}/(N\pi H)$, the mean separation becomes approximately $D \approx 5000$ light-years.

The spatial overlap probability can then be estimated as the ratio between the accessible causal-overlap (reach) volume and the effective territorial volume ($V_{ter} = \pi D^2 H = V_{gal}/N$) associated with a single civilization, giving $P_{space} \approx V_{crit}/V_{ter} \approx (L/D)^2 \approx 0.04$(4%). A temporal overlap factor can similarly be estimated using units in which $c = 1$ light-year per year, spatial separations and light-travel times become numerically equivalent and hence $P_{time} \approx L/D \approx 1000/5000 = 0.2$(20%), representing the fraction of the active information shell by inter-civilization separation scale occupied at a given epoch. Here P_{time} is introduced as a simplified order-of-magnitude estimate for the probability that two civilizations remain simultaneously active during the signal propagation interval associated with their mean separation D. The expression is not intended as a rigorous stochastic derivation, but rather as a heuristic scaling relation within the simplified framework adopted in the present model.

Assuming spatial position and technological activation time are statistically uncorrelated under the $v \approx 0$ approximation, a simplified combined estimate for the causal-overlap probability becomes $P_{total} = P_{space} \times P_{time} \approx (L/D)^3 \approx 0.008$(0.8%). This result illustrates that even in a galaxy containing many technological civilizations, finite communicative lifetimes combined with large mean separations will strongly suppress the probability of mutual detectability. Under such sparse conditions, most information shells would propagate through regions of space without intersecting the active technological interval of another civilization. This cubic scaling is only intended as an order-of-magnitude estimate. The numerical pre-factor depends on the geometric idealization, but the cubic dependence on (*L*/*D*) is robust within the stationary sparse-regime approximation

Table 1 illustrates how the combined overlap probability P_{total} varies as a function of both communicative lifetime L and civilization number N. Within the simplified assumptions of the present model, the results suggest communicative lifetimes substantially below 10^4 years are expected to reduce detectability substantially within the simplified framework adopted here.

Table 1. Causal intersection probability P_{total} as a function of communicative lifetime L and number of concurrent technological civilizations N in the static-galaxy approximation $(v \approx 0)$. The mean inter-

civilization separation D is computed using $D^2 = V_{gal}/(N\pi H)$. Probabilities are estimated using the heuristic relation $P_{total} \approx (L/\mathrm{D})^3$, capped at 100% when $R_{crit} \geq \mathrm{D}$.

L(years) $= R_{crit}(ly)$	**$N = 50$**	**$N = 100$**	**$N = 500$**	**$N = 2500$**	**$N = 10,000$**
$L = 100$**yr**	*0.0003%*	*0.0008%*	*0.009%*	*0.1%*	*0.8%*
$L = 1{,}000$**yr** ★	*0.28%*	*0.8%†*	*8.9%*	*100%**	*100%**
$L = 10{,}000$**yr**	*100%**	*100%**	*100%**	*100%**	*100%**

values used in the calculations:

- $N = 50 \rightarrow D \approx 7070\mathrm{ly}$
- $N = 100 \rightarrow D \approx 5000\mathrm{ly}$
- $N = 500 \rightarrow D \approx 2236\mathrm{ly}$
- $N = 2500 \rightarrow D \approx 1000\mathrm{ly}$
- $N = 10{,}000 \rightarrow D \approx 500\mathrm{ly}$

★ Primary reference case used throughout the paper.

† $P_{total} = (1000/5000)^3 = 0.008 \approx 0.8\%$.

* P capped at 100% when $\mathrm{R_{crit}} \geq \mathrm{D}$ (signal shell already encloses nearest neighbour).

Key insight: Table 1 illustrates a transition between regimes of low and high causal-overlap probability as both communicative lifetime L and civilization number N increase. Within the simplified assumptions of the present model, communicative lifetimes below $L \sim 10^4$ years are expected to reduce detectability substantially within the simplified framework adopted here even for moderately populated galaxies, whereas larger L values rapidly increase overlap probabilities across a broad range of civilization densities.

Accordingly, the null result of SETI searches reflects finite spacetime overlap constraints even if technological civilizations are not intrinsically rare within the Galaxy.

6. The Hardware Filter: Mechanical Limits to the World Line

A common counter-argument to finite communicative lifetimes is that autonomous probes, archival transmitters, or long-duration robotic systems could substantially outlive their biological creators and thereby maintain detectability over extended timescales. However, interstellar space constitutes a highly destructive operational environment. Even long-lived autonomous systems remain subject to cumulative hardware degradation, radiation damage, power decay, and impact erosion over multi-century or millennial timescales. These engineering limitations collectively define a practical "Hardware Filter" on the persistence of technological detectability. These engineering constraints apply specifically to externally detectable technological systems rather than necessarily to the survival of the originating civilization itself.

6.1. Interstellar Erosion and Impact Damage

The nearest stellar system, the Alpha Centauri system, lies approximately 4.37 light-years from Earth. By comparison, the fastest human-made spacecraft to date, the Parker Solar Probe, reaches peak velocities of approximately $190\ \mathrm{km\,s^{-1}}$, corresponding to only $\sim 6 \times 10^{-4}c$. At such velocities, even an idealized direct trajectory to Alpha Centauri would require several thousand years.

Over these timescales, collisions with interstellar dust grains and micrometeoroids become a significant engineering concern. At relativistic or near-relativistic velocities, even micron-scale particles possess substantial kinetic energy and will progressively erode exposed surfaces, optical systems, communication arrays, and shielding layers. Without active maintenance or self-repair capability, cumulative impact damage could eventually compromise the long-term functionality of autonomous probes.

6.2. Radiation Damage and Long-Term Information Degradation

High-energy cosmic rays and charged particles can progressively damage long-duration electronic systems through cumulative radiation exposure. Radiation-induced single-event upsets ("bit flips") can corrupt stored information or alter computational states in digital electronics. Over sufficiently long operational timescales, accumulated memory corruption, software instability, and semiconductor degradation will significantly reduce system reliability unless extensive redundancy and radiation-hardening strategies are employed.

In addition to transient computational errors, prolonged exposure to ionizing radiation can physically alter semiconductor lattice structures and degrade sensor performance. Even if partial functionality survives, failures in communication control, antenna orientation, or navigation systems can render a probe effectively undetectable or unable to maintain meaningful signal transmission.

6.3. Power Source Half-Lives

Long-duration interstellar communication also requires persistent energy generation. Contemporary deep-space missions commonly employ Radioisotope Thermoelectric Generators (RTGs), many of which rely on the decay of Plutonium-238 with a half-life of approximately 88 years. Over millennial timescales, the available power output decreases substantially due to radioactive decay. After roughly 1000 years, the remaining power would fall to a small fraction of its initial value, significantly limiting the ability of the system to sustain high-power communication, active navigation, or onboard computation.

Because electromagnetic signals weaken with distance according to inverse-square geometric spreading, extremely long-range communication across several thousand light-years would require either substantial transmission power, highly directional beam stability, or persistent infrastructure support over comparable timescales.

Various advanced propulsion concepts have been proposed to mitigate the limitations of conventional fuel-based spacecraft, including laser-driven light sails, passive retroreflectors, fusion propulsion, and nuclear pulse propulsion architectures. Some of these concepts avoid the need for large onboard propellant reserves or long-duration RTG dependence. Nevertheless, they introduce different long-term engineering challenges associated with structural degradation, radiation exposure, micrometeoroid bombardment, and system reliability over extremely long transit durations.

In particular, externally driven concepts such as laser sail systems transfer much of the energy burden from the spacecraft to the originating civilization. However, this merely relocates the persistence problem rather than eliminating it; the source civilization must maintain large-scale transmission infrastructure, beam stability, and precise targeting capability throughout the acceleration and communication interval, potentially over many centuries or millennia. Proposed alternatives such as laser sail probes or passive relay systems therefore do not fully remove the finite-duration constraint emphasized throughout this paper. Instead, they shift the requirement toward the long-term persistence of either the transmitting infrastructure, the probe architecture itself, or both. Within the framework developed here, the effective communicative lifetime L must therefore include not only biological civilization longevity but also the operational survival time of any associated technological systems.

Consequently, although advanced autonomous probes can extend detectability timescales beyond those of their originating civilizations, presently understood engineering limitations suggest that maintaining reliable interstellar communication capability over multi-millennial durations remains a substantial challenge. The proposed "Hardware Filter" should therefore be interpreted as a potential contributing factor that further suppresses long-range causal overlap rather than as an absolute technological impossibility.

7. Discussion of the Causal Disconnect Framework

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It is instructive to compare the present framework with recent independent work addressing the detectability problem in SETI. Rahvar and Rouhani [1] derive constraints on communicative lifetime from Galactic geometry using a complementary statistical approach and similarly conclude that relatively short detectable lifetimes can strongly suppress interstellar detectability. The present analysis extends this line of reasoning in several ways: (i) by introducing the explicit Information Shell geometry within a Minkowski spacetime framework, (ii) by constructing the heuristic overlap relation $P_{total} = P_{space} \times P_{time}$, and (iii) by identifying long-term technological degradation ("Hardware Filter") as an additional engineering constraint on persistent detectability.

Although the present framework remains highly simplified, the convergence between independent statistical and spacetime-geometric approaches suggests that finite communicative lifetimes combined with Galactic distance scales will substantially limit the probability of causal overlap between civilizations. Within this interpretation, the apparent "Great Silence" may emerge naturally from spacetime and engineering constraints without requiring that intelligent life itself be intrinsically rare.

Within the framework developed here, two distinct mechanisms act together to suppress long-range detectability. The first is temporal mismatch arising from finite communicative lifetimes relative to Galactic light-travel times. The second is the cumulative degradation of long-duration technological systems operating in interstellar environments. Together, these effects suggest that the absence of confirmed extraterrestrial detections will not necessarily imply the absence of intelligent life, but rather the rarity of sustained causal overlap between civilizations separated by large spacetime intervals.

In this sense, the present framework can be interpreted as a physical constraint on detectability that complements the population-based reasoning embodied in the Drake Equation.

7.1. Difference from the Drake Equation

The Drake Equation, ($N = R^* f_p n_e f_l f_i f_c L$) introduced by Frank Drake in 1961, provides a probabilistic estimate for the number of communicative technological civilizations currently existing within the Milky Way [4]. Its parameters describe successive astrophysical, biological, and technological factors contributing to the emergence of detectable civilizations, while L represents the duration over which detectable signals are emitted.

The present framework differs conceptually from the Drake Equation in that it focuses not on the existence of civilizations alone, but on the spacetime conditions required for causal overlap between them. In this interpretation, the number of civilizations N is only one component of detectability; the spatial separation between civilizations and the finite duration of detectable activity become equally important constraints. Comparison of Drake Equation with our 'Causal Disconnect Framework' is shown in Table 2.

Table 2. Comparison between the Drake Equation and the Causal Disconnect Framework:.

Feature	Drake Equation	Causal Disconnect Framework
Primary Goal	Estimates the number of communicative civilizations currently existing in the Galaxy	Examines the probability of causal overlap and detectability between civilizations
Role of (L)	(L) increases the expected number of detectable civilizations (N)	(L) determines the spacetime extent of the communicative interval and causal-overlap scale
Spatial Consideration	Typically, does not explicitly include spatial separation between civilizations	Explicitly incorporates interstellar distance (D) and finite signal propagation time

Feature	Drake Equation	Causal Disconnect Framework
Temporal Consideration	Civilizations are counted as simultaneous populations	Detectability depends on overlap between finite communicative intervals
Detectability Assumption	Existence of communicative civilizations is often implicitly associated with detectability	Existence alone does not guarantee detectability if causal overlap is absent
Main Interpretation	Population-based estimate of extraterrestrial civilizations	Spacetime-based framework for detectability suppression

Note: A large value of N does not necessarily imply high detectability if civilizations remain widely separated in spacetime relative to their communicative lifetimes. Within the present framework, successful detection depends not only on the total civilization population, but also on the effective spacetime density of active communicative regions. Consequently, even galaxies containing many civilizations can remain observationally quiet if their Information Shells rarely overlap within finite technological lifetimes.

7.2. Detectability Constraints in Sparse-Civilization Regimes

The Drake Equation can yield large values of N if sufficiently long communicative lifetimes are assumed. However, the present framework suggests that short communicative lifetimes will produce extremely low causal-overlap probabilities even when multiple civilizations coexist within the Galaxy. For example, in the representative case $N = 100$ and $L = 1000$ years, the mean separation between civilizations remains several thousand light-years, substantially larger than the characteristic (effective) causal-overlap scale.

An intuitive analogy is that of fireflies distributed throughout a vast forest. The Drake Equation estimates how many fireflies can exist, whereas the present framework asks whether their flashes overlap sufficiently in space and time to become mutually visible. If the flashes are too brief relative to the size of the forest, most fireflies may never observe one another despite simultaneously inhabiting the same environment. Within this interpretation, the absence of confirmed extraterrestrial detections may reflect limited spacetime overlap rather than necessarily implying the rarity of intelligent life itself.

8. The “Inward Transition”: Communicative Compression and Radio Quietness

The adoption of a characteristic communicative lifetime of order $L \sim 10^3$ years can also admit an alternative interpretation beyond simple civilizational collapse. Within the present framework, L should be understood primarily as the duration of effective interstellar detectability rather than the total biological or cultural lifetime of a civilization. An advanced civilization may continue to exist for much longer timescales while progressively reducing its externally detectable electromagnetic footprint.

One possible scenario is that increasing technological sophistication drives communication systems toward higher informational efficiency, lower energy dissipation, and increasingly localized communication architectures. In such a transition, highly directional transmission, compressed signalling, fiber-based infrastructure, quantum communication schemes, or other low-leakage technologies could substantially reduce unintentional radio emission into interstellar space. The civilization would therefore become progressively more difficult to detect despite continued technological advancement.

In this interpretation, the “Great Silence” may not necessarily indicate extinction, but rather a transition from a comparatively noisy technological phase toward a more energy-efficient and observationally quiet state. The parameter L would then represent the finite duration of the civilization’s high-leakage phase rather than the end of its existence.

From this perspective, one possible speculative scenario is that long-term technological evolution may favour localized optimization over persistent large-scale broadcasting or interstellar expansion. As communication systems become more efficient, civilizations may increasingly rely on tightly directed or internally networked communication methods rather than isotropic radio leakage. Such a transition would naturally suppress the probability of accidental detectability by distant observers.

This possibility is particularly relevant because the causal-overlap limitations discussed in previous sections already impose severe constraints on interstellar communication over Galactic distance scales. Under such conditions, sustained high-power omnidirectional broadcasting may become energetically inefficient relative to localized information-processing strategies. Within this framework, the communicative lifetime L represents a technological transition scale rather than a strict survival limit. A civilization could persist biologically or culturally while simultaneously undergoing a contraction of its externally detectable communication footprint. In this sense, the communicative world line relevant to SETI observations may terminate long before the civilization itself disappears.

One speculative interpretation is that civilizations encounter increasing systemic complexity as technological interdependence grows. Such complexity may either destabilize long-term large-scale broadcasting systems or incentivize transitions toward more stable, lower-leakage communication regimes. In either case, the duration of detectable electromagnetic emission may remain relatively short compared with Galactic timescales. The continued absence of confirmed extraterrestrial detections is at least qualitatively consistent with scenarios involving finite communicative windows, whether these arise from civilizational collapse, technological transition, or long-term radio quietness. Within the present framework, the SETI null result may therefore place indirect constraints on the combined relationship between communicative lifetime, technological detectability, and civilization density.

9. Conclusion: Finite Communicative Windows and Galactic Silence

The framework developed in this paper suggests that finite communicative lifetimes, combined with large interstellar separations and the finite speed of light, are expected to substantially suppress the probability of causal overlap between technological civilizations. Even if intelligent life is relatively widespread throughout the Galaxy, civilizations may remain effectively undetectable to one another when their communicative windows are short compared with Galactic distance scales. Within this interpretation, the apparent “Great Silence” may emerge naturally from spacetime geometry, temporal desynchronization, and long-term engineering limitations rather than necessarily requiring that intelligent life itself be exceedingly rare. The analysis presented here therefore reframes the SETI null result as a problem of finite overlap in spacetime rather than solely one of biological scarcity.

In this framework, technological civilizations resemble transient signals propagating through a vast Galactic environment, with most communicative phases failing to intersect within the limited temporal windows available for mutual detection. The principal challenge for long-term civilizations may therefore not be merely achieving technological emergence, but sustaining detectable communicative persistence over timescales comparable to Galactic light-travel distances. The present framework also raises broader questions regarding the long-term evolutionary trajectory of technological civilizations. If interstellar communication remains fundamentally constrained by finite communicative lifetimes and large spacetime separations, advanced societies may preferentially invest in localized optimization, planetary-scale sustainability, virtual environments, or highly efficient low-leakage information systems rather than persistent interstellar broadcasting. Although such possibilities remain speculative, they are qualitatively consistent with the broader interpretation developed throughout this work.

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