Framework for analyzing the Fermi Paradox

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Abstract

The Fermi paradox asks why evidence of extraterrestrial Intelligent Civilizations (IC) with the ability to communicate has not been observed if the galaxy is abundant with habitable planets. A four-step quantitative framework was developed that incorporates pre-biological (galactic/star/planetary), biological, temporal, and detection bottlenecks. The first step estimates conditional probabilities for: the Galactic Habitable Zone (GHZ), pre-planet stellar environment, long-term planetary HZ, planet habitability, and long-term climate/chemistry. The result was ~58,000 habitable planets in the Milky Way galaxy over cosmic history. Step two applies Carter's hard-steps model to estimate the probability (P) of intelligent life emerging within a ~5 Gyr habitable window. By adopting seven evolutionary steps with characteristic timescale of 1 Gyr, the model yields P ~ 0.095. Thus, ~5,500 IC existed in the Milky Way over cosmic time. Step three incorporates temporal overlap using a civilization lifetime of 10,000 years and an effective galactic lifetime of 5 billion years, reducing the expected number of contemporary IC to ~0.011 or effectively zero. Step four calculates radio detection limits based on a 12,000 Lyr radius, restricting detection to 6% of the galaxy.

Thus, the absence of confirmed radio contact is consistent with the combined effects of habitability constraints, IC evolutionary timescales, temporal non-overlap, and detection limits. This is true even when significantly more optimistic assumptions prevail. Under this framework, the lack of observed signals does not constitute a paradox but rather an expected outcome.

Keywords: Intelligent Civilization (IC), Biological bottlenecks, Non-biological bottlenecks, Exoplanets, Fermi Paradox, Drake equation, Carter equation, Milky Way, Radio detection constraints, SETI, Temporal overlap, Technosignatures, Habitable Zone (HZ)

1. Introduction

The Fermi paradox asks: if the galaxy contains vast numbers of habitable planets, why has no evidence of extraterrestrial intelligent civilizations been observed? In other words, if the galaxy is teeming with life, where is everybody?

Based on the immense number of planets (billions) and the opportunity for evolution like ours on earth, Intelligent Civilizations (IC), with the ability to communicate, should be common, but no contact or proof exists via direct communication, planet/galaxy technosignatures or confirmed probes/UFOs. This is the Fermi Paradox. Is there a way to analyze this paradox?

This article, relying on concepts from the Drake Equation (reference description in Note insert), the Brandon Carter hard steps formula, temporal overlap, and detection limitations, proposes a “comprehensive” framework for analyzing the Fermi Paradox.

2. Method - Framework Overview

The apparent absence of contact can be explained in two ways: IC are extremely *rare*, or IC exist but have not been *detected*. The framework has four steps briefly described below.

The first step defines pre-biological filters in five sequential phases graphically shown in Figure 1: A. Milky Way Habitable Zone (HZ); B. Pre-planet stellar environment; C. Long-term stable HZ planets; D. Planet Habitability; and E. Climate/chemistry.

Second step, calculates, using the Carter equation of “hard” biological emergent steps, the biological probability of IC existing over a star’s habitable lifetime and then estimates the number of IC in the Milky Way by multiplying the number of habitable planets from step one by the probability that IC evolves.

Third, calculate the number of present-day IC considering temporal overlap. The equation uses lifetime of civilization (L) and lifetime of the galaxy (T). A discussion of the potential impact of non-biological technology (AI machine-based technologies) is also included.

Fourth, examine the primary detection constraint for receiving radio messages, vast inter-stellar and intergalactic distances, from a few light years to millions of light years for remote galaxies.

This framework, a conceptual methodology, is modular with basically independent steps. Note that the framework has three underlying assumptions: water is a basic requirement, life is biological and carbon based, and detection is based on radio communication.

3. First Step. Pre-Biological five phases and calculations

This first step uses five pre-biological bottlenecks (filters) to calculate the number of habitable planets in the Milky Way. Reference Table 1, for detailed calculations of this first framework component. The Appendix contains references, additional justification logic, and plausible ranges for all the bottleneck parameters.

Each of the bottleneck's survival conditional probabilities is expressed as fraction for all calculations. These fractions can be independently challenged, revised, or replaced based on new research. The conclusions do not depend on any single parameter choice, but on the cumulative effect of sequential constraints. While dependencies between some bottlenecks likely exist - for example between rocky planet occurrence and magnetic field generation, planet mass and atmospheric retention, or land fraction and climate regulation – the impact of such correlations is unknown. Future exoplanet observations will refine individual terms or collapse correlated factors, although the cumulative suppression from sequential constraints is not expected to vary more than an order of magnitude.

Note. The Drake Equation's intent is to calculate the number of coexisting communicating civilizations in our MW. The equation includes rate of star formation, fraction stars with planets, fraction that are earths, fraction of planets that form life, fraction of life that develop intelligence, fraction intelligent life that communicate, and lifetime of civilization.

3.1 Galactic Habitable Zone, GHZ (A)

The starting point for the calculation is the total number of stars in the Milky Way, estimated at 200 billion. The spectral-type fractions follow standard stellar population statistics for the Milky Way disk; M type stars dominate the Milky Way accounting for approximately 75% of all stars, with 10% G type and 12% K type; remaining stellar types are excluded due to short lifetimes.

A fraction of Milky Way stars exist in habitable zones with moderate supernova rates and long-term orbital stability which primarily reflects stellar density within the galactic disk. This equates to the Galactic Habitable Zone (GHZ) fraction, 0.2. Thus, after applying GHZ constraints, the effective number of candidate stars is reduced for all spectral classes and yields approximately 4.0×10^9 G stars, 4.8×10^9 K stars, and 3.0×10^{10} M stars. These are metal-rich (C, O, N, Mg, Si, and Fe) second and third generation stars necessary for rocky planet formation.

All bottleneck references in the appendix provide ranges for the probabilities (converted to fractions), selected values are range averages and do not represent direct measurements.

3.2 Pre-planet main sequence stellar environment, bottlenecks for potential planets (B)

Pre-main sequence radiation (B1, B2)

This calculation accounts for early stellar conditions before stars reach their Main Sequence (MS). Pre-MS high-energy radiation suppresses habitability for close-in planets, particularly for M stars, where prolonged pre-MS luminosity and XUV output are over an order of magnitude more damaging to close-in HZ planets than for G or K stars, 1 versus 0.1. Thus, M star's numerical dominance, about ten times more than G stars, is negated by an equal magnitude damaging high pre-MS stellar radiation which may eliminate/reduce water and atmosphere from a potential planet. After calculations, ~11.8 billion planets are candidates.

Multiple star systems (B3)

Multiple star systems are less stable than single stars, thus, systems permitting ≥1 Gyr stable HZ orbits are retained, about 45% of net G/K/M stars. After these computations, ~5.3 billion Milky Way stars are possible homes for planets.

As Table 1 shows, except for spectral-type fractions and pre-main-sequence radiation, all other bottleneck values are assumed constant across stellar types. This is arbitrary but acknowledges the difficulty in discerning among stellar types.

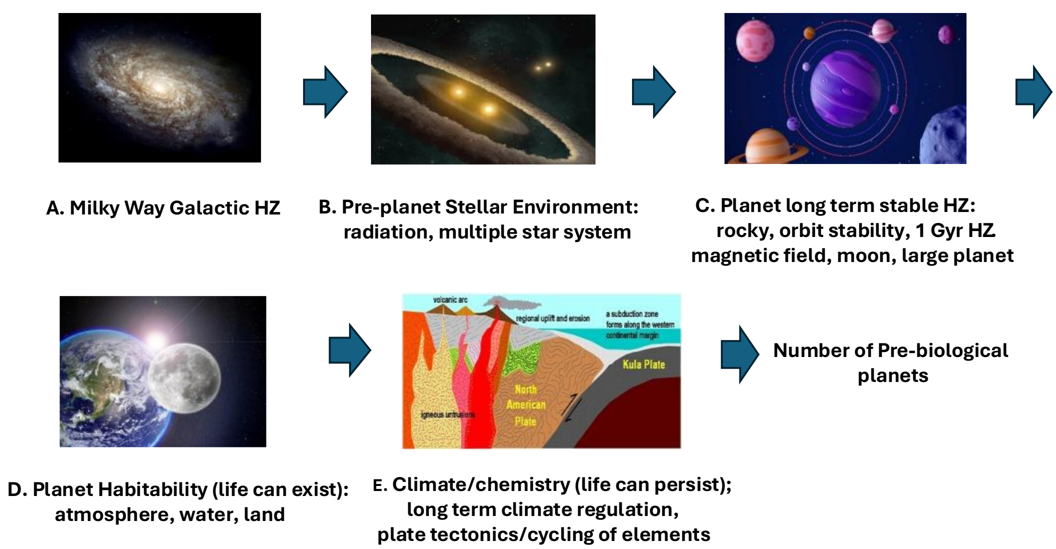

Figure 1. Step One. Pre-biological five phases, bottlenecks for habitable planets

3.3 Planet physical characteristics (C)

Rocky planets in HZ (C1)

Adopting a representative habitable-zone rocky planet occurrence rate of ~0.2 per Sun-like star is consistent with Kepler-based observational estimates. While occurrence rates vary by spectral type, for simplicity, a uniform value of 0.2 is adopted for all three star types.

HZ stability ≥ 1Gyr (C2)

Long-term orbital stability depends on system architecture and spacing between planets and the adopted habitable-zone definition. Assuming continuous residence in the HZ is necessary for at least one billion years, a 10% probability is assigned. This means a planet remains in a stable orbit within the habitable zone, avoiding strong perturbations from giant planets or stellar companions.

Magnetic field (C3)

Magnetic field generation and persistence, providing planet protection/shielding, depend on core size, heat flow, rotation, and the coupled thermal evolution of mantle and core. As with Earth, a magnetic field provides necessary atmospheric protection from cosmic rays and excessive radiation, a 30% probability.

Moon and large planet (C4, C5)

Two stabilizers, considered optional (probability = 1) based on uncertain impact on a planet's long-term HZ position, are a large orbiting moon and giant planet in the solar system. A planet having a large moon like earth's is not very probable (< 0.1), although if present, it supports planet obliquity/rotation stability. However, alternative processes**,** such as favorable multi-planet configurations, low-eccentricity orbits, or rapid planetary rotation might perform the same function.

A giant planet in the solar system, like Jupiter, provides impact regime shielding and comet/asteroid clearing that protects the planet, but the requirement is debatable. Not counting either potential bottleneck is an arbitrary decision.

3.4 Planet Habitability, life can exist (D)

Atmospheric retention (D1)

Atmospheric retention depends on gravity, stellar XUV history, escape efficiency, and subsequent replenishment via volcanic outgassing or secondary atmosphere formation. Outcomes vary widely with planet mass, composition, and irradiation histories. The probability a planet can retain an atmosphere, is 20%.

Sustained liquid surface water (D2)

Habitable zone placement is necessary but not sufficient for long-term surface water. Climate feedback (including clouds and greenhouse balance) can produce divergent outcomes such as waterworlds or ice worlds. Thus, there is a 30% probability for sustaining liquid surface water.

Exposed land mass (D3)

The prevalence of waterworlds versus mixed land–ocean planets is unknown and not currently observable with available instruments. Land fraction matters for weathering, nutrient cycling, and long-term climate stability. Land requirement probability is estimated at 30%.

3.5 Climate/chemistry, life can persist (E)

Long term climate regulation (E1)

Long-term climate regulation depends on carbon–silicate cycling efficiency, tectonic regime, volatile cycling, and surface–interior connection. The probability of a long-term carbon–silicate cycle, 20%.

Plate tectonics and cycling elements (E2)

The prevalence of Earth-like plate tectonics is unknown; outcomes depend on planet mass, heat flux, and water content. Regarding oxygen, if there is too little oxygen present when the core forms, phosphorus will fuse with heavy metals such as iron and become locked up in the core. Phosphorus is then no longer available to form DNA or RNA. But if too much oxygen is present when the core forms, that leads to phosphorus remaining in the mantle. Element recycling caused by plate tectonics is a 50% probability.

3.6 Results of pre-biological bottlenecks

The combined pre-biological probability for habitable pre-biological planets is P = C x D x E, ~1.1×10^{-5}. Thus, assuming all bottlenecks, except one, have the same values, there are a total of ~58,000 ($5.3 \times 10^{9} \times 1.1 \times 10^{-5}$) pre-biological habitable planets that have ever existed in the Milky Way. Prior to considering biological constraints and temporal overlap, the number of long-lived habitable planets per Milky Way–like galaxy is significant (but not millions). This relatively small number supports the Rare Earth Hypothesis.

The estimate is comparable to other calculated values that range from ~0.6×10^{5} to 2.5×10^{5} Earth-like habitats in the Galactic disk [Lammer et al. 2024; Scherf et al. 2024].

4. Second Step. Biological Evolutionary Constraints

This section explains how biological bottlenecks inhibit the evolution of an IC. The step replaces three terms in the Drake equation (fraction of planets that form life, fraction of life that develop intelligence, and fraction of intelligent life that communicate) with the Carter equation of "hard" biological evolutionary steps [Carter, 1983]. The framework's steps two through four are listed in Table 2.

Step one Pre-biological bottlenecks/filters	Fraction and stars/planets	Stellar type and Comments G	 K	 M
A. Galactic (Milky Way) Habitable Zone	Stars			
1. Potential Milky Way stars	2.0×10^{11}			
2. Stars in Galactic HZ (GHZ)	0.2	Spiral arm density, less supernova		
3. Stars after galactic filtering	4.0×10^{10}			
4. Spectral-type fraction G/K/M stars		0.1	0.12	0.75
5. Stars total and G/K/M net, 97% of stars	3.9×10^{10}	4.0×10^{9}	4.8×10^{9}	3.0×10^{10}
B. Pre-planet stellar environment				
1. Pre-MS radiation eliminate/reduce H_2O/atmos. (M stars)		1	1	0.1
2. Number of G/K/M stars after M reduction	11.8×10^{9}	4.0×10^{9}	4.8×10^{9}	3.0×10^{9}
3. Multiple/single star system with stable ≥1 Gyr orbit	0.45	Unstable orbits, more variables		
4.. Total net available G/K/M stars in Milky Way = B	**5.3×10^{9}**	Stars available for hosting planets		
C. Long-term stable HZ planets	Planets			
1. Rocky HZ occurrence	0.2	Planet in HZ and adequate size		
2. Continuous HZ residence and orbit stability ≥ 1Gyr	0.1	Suitable spacing, size of planets		
3. Magnetic field (for protection/shield)	0.3	Provides cosmic ray protection		
4. Large Moon for obliquity/rotation stability	1*	Optional, promotes orbit stability		
5. Jupiter - giant-planet (impact regime modifier)	1*	Optional, possible shielding		
Fraction net	6×10^{-3}			
D. Planet habitability (life can exist)				
1. Atmosphere retained (pressure and persistence)	0.2	Based on gravity, radiat., volc. act.		
2. Sustained liquid surface water	0.3	Avoid waterworld and ice world		
3. Exposed land	0.3	Required for land animals		
Fraction net	1.8×10^{-2}			
E. Climate/chemistry (life can persist)				
1. Long-term climate regulation	0.2	Provide carbon-silicon cycling		
2. Plate tectonics/geochemical cycling elements	0.5	Assures O, N, P		
Fraction net	0.1			
Summary Pre-biological probabilities				
1. Pre-biological planets probability, P = C x D x E	**1.1×10^{-5}**			
2. Pre-biological planets, Planets = B x P	**58,000**			
* Optional stabilizers. Not included in baseline.				

Table 1. Pre-biological bottleneck calculations

Step	Framework steps two-four	
Two	Biological Filters, hard evolutionary steps (*n*)	7
	Timescale per step (*s* in Gyr)	1
	Effective habitability window (*t* in Gyr)	5
	Carter probability IC formed over star's life	0.0949
	Total MW estimated IC = Planets x IC formed	
	Number of planets	5.5×10^4
	Times Carter probability	~0.1
	IC total	5.5×10^3
Three	Expected present-day civilizations	
	Civilization longevity (*L* years)	10,000
	Galactic timescale (*T* years)	10×10^9
	Galactic time available (T_A years)	5×10^9
	Temporal overlap fraction, $F_A = (L/T_A)$	2.0×10^{-6}
	Present-day IC (F_A x IC total)	1.1×10^{-2}
Four	IC detected in 12,000 Lyr radius	
	Percent of galaxy, 0.06 x Pres. Day IC	6.6×10^{-4}

Table 2. Calculations for steps two-four

In the Carter model, the probability, *P*, of completing all sequential steps, biological evolutionary bottlenecks, within a given time (*t*) is based on the star type and three parameters: *n* = number of hard evolutionary hard steps, *s* = characteristic timescale per step, and *t* = the habitability (biological evolutionary) window. Following Carter's hard-steps method, the emergence of IC is treated as the last step in a sequence of rare evolutionary transitions occurring within the available habitable window. The equation is: $P = (t/(ns))^n$ for $t < ns$ and $P = 1$ for $t \geq ns$.

Although Carter did not identify the nature of each hard step, other scientists have recommended *n* in the range of 4-7 steps [Mills et al., 2025]. Reference Table 3 for a proposed seven step model that includes: Abiogenesis, Eukaryotic Life, Planetary Oxidation, Multicellular Life, Complex Multicellular Life (includes intelligence displayed in whales and dolphins), Advanced Intelligence (humans), and Technological Intelligent Civilizations (referred to as ICs, advanced societies capable of electromagnetic communication, nuclear weapons, internet, AI, etc.).

	Event	Gyr*	Comment	Examples
0	Earth habitable	0	Relative Initial start, 4.5B years ago	Earth
1	Abiogenesis, Prokaryotic life	0.5	One time event, self-replicating, one cell, no nucleus	Bacteria, methanogens, thermophiles
2	Eukaryotic life	1.5	One time event, self-replicating, one cell, nucleus, organelles, DNA	Amoeba, algae, yeast
3	Planetary oxidation	0.75	Global transition enabling high energy metabolism, requirement for large complex organisms	Atmospheric oxygen
4	Multicellular life	1.5	Evolved multiple times (25-30), larger and need more energy, require oxygen, less adaptive than microbes	Animals, plants, fungi, algae
5	Complex multicellular life	0.5	Evolved very few times, organs, nervous systems, basic intelligence	Primarily animals
6	Advanced intelligence	**	Large brains, abstraction, cumulative culture	Humans
7	Technology civilization	**	Nuclear capability, electromagnetic communications	Industrial society, atomic weapons, TV, internet
	Total	4.75		

* Observed elapsed time, in Gyr, between successive transitions on Earth; these values represent one realized history.

** Lapsed times for final steps are not shown because short, realized intervals do not imply low intrinsic difficulty.

Table 3. Hard Evolutionary Steps

As shown in Table 2, the number of steps, *n*, equals seven; the time per step, *s*, is assumed to be 1 Gyr; and the biological evolutionary window, t = 5 Gyr. This results in approximately a ten percent probability of an IC evolving.

A comparison of Carter probabilities shows that reducing the number of hard steps from seven to five or reducing the characteristic step timescale from 1 Gyr to 0.5 Gyr, increases the probability of success within a 5 Gyr window from ~10% to near unity.

After non-biological filters reduce a planet's habitability by four orders of magnitude, the minimal effect of biological filtering, in the range of 0.1 to 1.0, is surprising.

The resulting IC fraction is 0.0949. Multiplying this fraction and the pre-biological number of eligible planets, 58,000, yields an estimated 5,500 IC ever arising over the Galaxy's lifetime. Thus, the galaxy is not teeming with IC, but thousands certainly may have existed.

5. Step Three. Present-Day Civilizations and Temporal Overlap - How long they last.

5.1 Direct overlap calculations

To estimate the number of IC coexisting at the present cosmic period, a temporal overlap factor is applied to the total number of IC that have existed over cosmic history.

The overlap fraction, F, is defined as the ratio of civilization longevity, L, to the relevant cosmic timescale T. For $L << T$, this suggests $F = L/T$. The assumption for IC longevity is $L = 10{,}000$ years. The cosmic timescale for a spiral galaxy is $\sim T = 10^{10}$ years. However, T must be modified for galactic time available (T_A years) since only the last ~4-6 Gyr of galactic history is available for producing contemporary IC (based on Earth evolutionary duration). Thus, there exist an evolutionary delay of, on average, ~5 Gyr and $T_A = T$ minus evolution delay or 5 Gyr (10 Gyr – 5 Gyr). This results in an overlap fraction of $F_A \sim 2 \times 10^{-6}$. Applying this factor to the ~5,500 IC that have arisen over the history of the Milky Way yields virtually no IC existing at the present period $\sim 1.1 \times 10^{-2}$.

If the typical longevity of civilizations exceeds 10,000 years, the expected number of contemporaneous civilizations increases proportionally and conversely decreases proportionally; one factor that may decrease longevity is the Great Filter (ahead of us) which contemplates a civilization self-destructing via nuclear war or ecological death. Conversely, extended lifetimes might result from an IC transitioning to non-biological forms. The AI impact is discussed next.

5.2 Non-biological future of IC

How will AI or advanced technology change IC's lifetime, L, in the temporal overlap equation? There are two opposing views on this issue. The first more obvious view is that L would increase dramatically since non-biological systems may exist indefinitely, well beyond IC based on biology. In a second view, lifetimes decrease by destabilizing IC. Thus, there is potential to fundamentally alter the lifetime of IC.

In the first view, AI enables civilizations to transcend biological constraints. Machine-based AI systems are not limited by metabolism, reproduction, or harsh environments and could, in principle, persist for millions or billions of years. In this scenario, intelligent civilizations transition into long-lived, post-biological forms, greatly increasing their longevity, L. Martin Rees supports this concept: "Few doubt that machines [AI] will gradually surpass … our distinctively human capabilities. Will this take decades or centuries? Either way the timescales for technological advance are but an instant compared to the three or four billion years of Darwinian selection that led to humanity's emergence … Humans could be a transitional species, marking the end of Darwinian evolution, but jump-starting evolution of machines that themselves over the next few billion years design a succession of ever more capable ones.” [Rees, 2024].

In the second view, advanced AI reduces the longevity of IC by raising the probability of self-destruction. For example, AI societies may experience accelerated technological change that outpaces social, political, or ethical adjustment, increasing the probability of collapse. Also, AI may create destructive technologies, for example, chemical/biological weapons, which destroy humanity. An extreme position of this second view, described as the Great Filter ahead of us, assumes AI always destroys its creators.

Although a significant factor, longevity is dictated by assumptions about the future, not empirical evidence, thus a compromise quantitative assumption, AI does not change the previously calculated number of present-day IC in the Milky Way ≥ ~1.1×10^{-2}.

6. Step Four. Detection - Why do we not see them?

6.1 Detection overview

Detection of an IC is either circumstantial via technosignatures or definitive. Technosignatures provide circumstantial evidence, possibly strong evidence, of IC life. They may represent artificial processes or structures. Examples are a) byproducts of energy consumption - chemical pollutants or industrial gases; b) artificial lighting; c) waste heat from excessive energy consumption; and d) orbital megastructures, for example, hypothetical Dyson spheres (large energy collectors used by advanced IC society to harness more energy from their sun). However, distinguishing between natural and artificial technosignatures remains a major challenge. Although some technosignatures may be detectable at distances far beyond radio technology they provide circumstantial evidence and thus are not included in the analysis.

Definitive detection can be physical, for example, discovering interstellar objects (spaceship/probes) or an IC’s message, as in the movie Contact. Commonly cited reasons for not receiving messages are: vast interstellar and intergalactic distances – millions and billions of light years for remote galaxies – a major factor for receiving messages; communication technology not based on electromagnetic radiation (photons), but possibly based on more speculative technology, for example, gravitational waves, neutrinos, dark matter or other means; lack of an ICs motivation to pursue contact or reveal existence; and energy requirements for communication/travel – conserving energy might be a priority.

6.2 Detection using radio communication.

The analysis in this step focuses specifically on definitive detection of a message using radio communication technology. It calculates detection limitations arising from vast distances in space. A recent study concluded that 12,000 light years was the maximum distance a strong directional radio transmission could be detected based on realistic assumptions about transmitter power and receiver sensitivity [Sheikh, 2025].

Given the flattened geometry of the Milky Way's disk, an area-based comparison is appropriate. A detection radius of 12,000 light-years corresponds to approximately 6% of the Milky Way's disk area (relative to a galactic radius of ~50,000 light-years). Applying this geometric constraint to the estimated ~1.1 x 10^{-2} IC that survive temporal overlap, yields an expected detectable number of IC on the order of 6.6×10^{-4} i.e., effectively zero.

This assumed detection estimate excludes additional implicit communication and observing filters, for example, IC motivation to transmit, radio beam alignment with Earth, transmission interval over IC's lifetime (maintain the temporal overlap assumption), and the frequency/timing/sensitivity coverage of our surveys. These factors, if included, would further reduce detection expectation.

This detection analysis demands two conclusions: first, the probability of receiving a radio message from within the Milky Way is realistically negligible; and second, direct radio communication from beyond our galaxy is virtually impossible.

7. Sensitivity

7.1 Optimistic assumptions

A high-level sensitivity analysis is now appropriate with the objective of choosing optimistic assumptions. The four steps that potentially could increase the number of IC with different assumptions are: pre-biological bottlenecks; biological evolutionary constraints; temporal adjustments; and detection constraints. How does the result change when using very optimistic assumptions?

Future exoplanet research will clarify pre-biological bottlenecks, possibly adding or correlating factors. If the overall impact were changed by two orders of magnitude, a combination of fewer bottlenecks and higher probabilities, then the Milky Way would contain ~5.8 million habitable zone planets (58,000 x 100).

If the biological evolutionary calculation had fewer hard steps, say four, or shorter duration hard steps, say 0.5 Gyr, an IC evolving would be assured, resulting in 5.8 million IC. This is because for optimistic scenarios the Carter expression exceeds unity and is therefore capped at $P = 1$.

Considering temporal adjustments, if IC lifetime extended one hundred times longer (10^4 to 10^6 years), the temporal overlap factor F_A (L/ T_A) increases from 10^{-6} to 10^{-4}. Thus, there would be 1,160 contemporaneous IC ($5.8 \times 10^6 \times 2 \times 10^{-4}$).

The number of detectable civilizations via radio communications scales approximately with the square of the radius because the Milky Way is a thin disk. Increasing the detection radius from 12,000 lyr to 50,000 lyr increases the searchable area by a factor of about 17 (0.06 x 17 = ~1), so almost all the IC might be detectable, ~1,000.

How are the results impacted if the most optimistic scenario for these four steps – hundred times improvement in pre-biological survival, an accelerated biological evolution, two orders of magnitude longer civilization lifetime, and maximum galactic detection coverage **-** is used in the calculations? When this optimistic analysis reduces the filtering by a factor of ~1.7 million (100 x 10 x 100 x 17), the model yields approximately 1000 radio messages detectable from Earth under idealized assumptions (reference Table 4). Thus, the framework, under optimistic assumptions, remains consistent with a SETI scenario in which intentional radio transmissions are present, and detection may be probable by sensitive surveys.

However, if several previously mentioned implicit communication and detection assumptions are treated as additional filters, the optimistic estimate of ~1,000 detectable radio messages could be close to zero. Thus, the implicit detection assumptions may play a significant role, and detection would be far less probable.

7.2 Fortuitous circumstances

Another sensitivity approach, without modifying the assumptions, is to imagine that SETI monitoring encounters fortuitous circumstances relating to temporal overlap and detection.

	Assumed		**Very optimistic**	
Start with 2 x10^{11} stars in Milky Way	**Fraction**	**Planets**	**Fraction**	**Planets**
Pre-biological Bottlenecks (Step One)	2.9 x 10^{-7}	58,000	2.9 x 10^{-5}	5.8 x 10^{6}
Biological filter probability (Step Two)	0.095	5,500	1	5.8 x 10^{6}
Present day IC, temporal overlap (Step Three)	2 x 10^{-6}	1.1 x 10^{-2}	2 x 10^{-4}	1,160
IC radio detection (Step Four)	0.06	6.6 x 10^{-4}	≤ 1 (17xs)	~1,000

Table 4. Sensitivity analysis

The quantitative analysis was based on randomly distributed IC in the Milky Way; thus, deliberate radio-message detection is overwhelmingly unlikely.   However, if a contemporary IC existed within 100 light-years and intentionally targeted Earth with a sufficiently powerful signal, detection is possible. It would require just one contemporary IC committed to extraterrestrial communication. These circumstances provide rational and incentive for SETI searching.

7.3 Extrapolating scenario to the entire universe.

Since previous calculations were based on our own Milky Way galaxy, as was the Drake equation, it is now appropriate to extrapolate planet totals to the entire universe. For simplification, the assumption is 100 billion large spirals in the observable universe. It is true that counting elliptical, irregular, and many dwarf galaxies the total number of galaxies might be 10 times more. However, since spirals are two thirds of major galaxies, they contain most of the stars/planets and provide a reasonable count for extrapolation.

Extrapolating based on assumed assumptions (0.011 present day IC in the Milky Way times ~100 billion comparable Milky Way galaxies) equals ~1.1 billion IC, a number suggesting a universe rich in intelligence.

In this scenario, if unknown speculative forms of communication (faster than light speed) were available for detection, contact might be possible or probable depending on IC's intent and our ability to receive the message.

8. Conclusion

The article started with a question: If the galaxy is teeming with life, where is everybody? The four-step framework addressed the two implied issues: are ICs intrinsically rare, and what factors impede their detection. This framework provides a quantitative resolution of the Fermi paradox by challenging its core assumptions: IC should be common and detectable.

The first two steps estimate the number of IC that arise, concluding that 5,500 IC evolved over the Milky Way's lifetime. This number reflects the large cumulative effect of sequential bottlenecks for non-biological planet habitability, comparable to Earth's environment, and the modest effect of biological hard steps for the evolution of an IC.

Although thousands of intelligent civilizations may have arisen over the Milky Way's lifetime, when temporal overlap is considered, the number of IC in the present time declines to 1.1×10^{-2}, virtually zero. After distance radio detection constraints are considered, the expected IC will drop more than an order of magnitude to 6.6×10^{-4}. Thus, the absence of contact, via radio communication, is predictable, and the silence of the Milky Way galaxy is an expected outcome rather than a paradox.

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Appendix. Logic for selecting probabilities/fractions for Step One bottlenecks.

This appendix summarizes the logic and references for the probabilities used in Step One as listed in Table 1. Ranges reflect plausible variation across modeling assumptions and observational uncertainty. Values are estimates rather than direct measurements. Justification on two controversial bottlenecks is more extensive (C3, C4). AI was used to find references and predict fraction ranges.

A2. Galactic Habitable Zone (GHZ) fraction (0.10–0.30, selected 0.20)

The GHZ fraction is not directly observable and depends on supernova rates, metallicity gradients, radial migration, and how galactic habitability is defined (narrow ring versus broader disk). Published GHZ models span a wide range because they weigh these factors differently [Lineweaver et al., 2004; Prantzos, 2008; Gowanlock et al., 2011].

Metallicity varies with galactic radius and stellar age. Terrestrial planet formation appears viable across a broader metallicity range, thus stars in the GHZ are assumed to be metal-rich [Fischer and Valenti, 2005; Kunimoto and Matthews, 2020].

B1. Pre-MS high-energy radiation (G: 0.10–0.25; K: 0.10–0.30; M: 0.002–0.03, selected G = 1; K = 1; M = 0.1)

The high-energy (XUV) radiation environment during the pre-main-sequence phase varies strongly with stellar mass and rotational evolution. Young stars show wide spreads in spin-down timescales and the duration of magnetic activity, producing large variation in cumulative XUV exposure [Tu et al., 2015]. This variability is especially pronounced for M dwarfs (0.1), which experience prolonged pre-MS contraction and elevated XUV emission [Luger and Barnes, 2015]. The adopted ranges reflect uncertainty in the long-term negative impact of stellar high-energy on each stellar type. But, since evolution on earth survived pre-MS radiation, G and K stars are not impacted.

B3. Stable HZ orbits in multiple-star systems (0.30–0.60, selected 0.45)

The fraction of multiple-star systems that permit stable habitable zone orbits depends on binary separation, eccentricity, and whether planets occupy S-type (circumstellar) or P-type (circumbinary) configurations. Stability criteria differ among dynamical studies, and observational surveys indicate a substantial population of wide binaries that remain dynamically favorable [Holman and Wiegert, 1999; Raghavan et al., 2010; Eggl and Georgakarakos, 2015; Marzari, F. et al., 2016].

C1. Rocky planet present (0.1–0.3, selected 0.20)

Occurrence rates for small rocky planets are limited by Kepler/TESS-era analyses but remain sensitive to stellar type, period distributions, and radius cutoffs. Adequate planet size assures sufficient gravity for long-term atmospheric retention [Rogers, L.A., 2015] and is assumed. The commonly cited Kepler-based estimates for rocky planets in the habitable zone around Sun-like stars cluster around ~0.1–0.3 per star, depending on definition of "rocky" and HZ width. For M dwarfs, a higher occurrence is often estimated (~0.3–0.5) [Kopparapu et al., 2013].

The adopted range reflects conservative versus more optimistic interpretations of the occurrence statistics [Petigura et al., 2013; Kunimoto and Matthews, 2020; Bryson et al., 2021].

C2. Continuous HZ residence ≥ 1 Gyr (0.05–0.20, selected 0.10)

A planet is required to remain in a stable orbit within the habitable zone, avoiding strong perturbations from giant planets [Raymond, S. N. et al., 2011] or stellar companions [Holman, M.J., and Wiegert, P.A., 1999] for ≤ 1 Gyr. Thus, long-term orbital stability depends on system architecture and spacing between planets [Pu and Wu, 2015; Obertas et al., 2017]. Also, sustained habitable zone residence depends on the adopted habitable zone definition. More restrictive classical HZ limits motivate lower fractions, whereas expanded boundaries suggest higher fractions [Kasting et al., 1993; Kopparapu et al., 2013].

C3. Magnetic field (0.10–0.50, selected 0.30)

The generation and long-term survival of a planetary magnetic dynamo depend on core thermal evolution, heat flux at the core–mantle boundary, and internal composition. Dynamo scaling laws show that convective intensity and planetary rotation influence dipole strength and persistence [Olson and Christensen, 2006; Zuluaga and Cuartas, 2012]. Because exoplanet dynamos are not directly observable, estimates rely on theoretical and comparative planetology models [Foley and Driscoll, 2016].

Mantle convection regime can further shorten or extend dynamo lifetimes [van Summeren et al., 2013]. The lower bound corresponds to conservative assumptions where only a minority of rocky planets sustain long-lived protective dynamos; the upper bound reflects optimistic assumptions where dynamo-sustaining thermal and rotational conditions are common among terrestrial planets. The adopted range reflects uncertainty in dynamo longevity across plausible terrestrial planet conditions.

C4. Large Moon / obliquity stability (0.01–0.20, optional selection 0.08/1)

Large moons formed via giant impacts may be rare, and Earth's Moon may represent a contingent outcome. Obliquity can be stabilized by alternative architectures (favorable multi-planet configurations, low-eccentricity orbits, or rapid planetary rotation might perform the same function) but their prevalence and effectiveness are uncertain [Laskar et al., 1993].

The adopted interval is a plausibility range rather than a directly measured frequency. N-body impact simulations suggest that "massive moon" outcomes may occur at the few-percent to a few-tens-percent level, with estimates spanning ~1/45 to ~1/4 in a published survey of Earth–Moon analog formation [Elser et al., 2011]. The Moon's dynamical role in preventing large chaotic obliquity excursions motivates treating "stabilizing Moon-like configurations" as a subset of massive-moon outcomes [Laskar et al., 1993].

If the giant-impact hypothesis for lunar formation is correct, multiple conditions must be satisfied, encouraging a low probability. The lower bound corresponds to a conservative subset of the low-end formation frequency, while the upper bound reflects a discounted fraction of the optimistic formation estimate [Waltham, 2004]. Not counting this potential bottleneck is an arbitrary decision.

C5. Giant-planet (Jupiter-like) architecture (0.10–0.50, optional selection 0.30/1)

Giant planets can either increase or decrease impact flux depending on their masses and orbital configurations. Numerical results are mixed on whether giant planets are net protective or net hazardous over long timescales, so the adopted range reflects this unresolved ambiguity [Horner and Jones, 2008, 2009; Raymond et al., 2011]. Not counting this potential bottleneck is an arbitrary decision.

D1. Atmosphere retained (0.10–0.30, selected 0.20)

Atmosphere retention varies widely with planet mass, composition, and irradiation histories [Wordsworth and Pierrehumbert, 2013].

D2. Sustained surface liquid water (0.10–0.50, selected 0.30)

Climate feedback (including clouds and greenhouse balance) can produce divergent outcomes such as runaway greenhouse or snowball states. The adopted range reflects model sensitivity and uncertainty in stabilizing feedback strength [Kasting et al., 1993].

D3. Exposed land fraction (0.10–0.50, selected 0.30)

Modeling indicates that for partially ocean-covered planets, silicate weathering behavior and habitable-zone theory can be relatively insensitive to land fraction provided some exposed land exists [Abbot et al., 2012]. However, formation scenarios allow many rocky habitable-zone planets to acquire water inventories substantially exceeding Earth's, potentially producing waterworlds [Kite and Ford, 2018]. Deep-water cycling and seafloor-pressure feedback can, under some conditions, partition water into the mantle and permit exposed continents [Cowan and Abbot, 2014], but population-level prevalence remains uncertain and model-dependent [Simpson, 2017; Höning et al., 2023]. The lower bound corresponds to conservative assumptions where most planets are waterworlds; the upper bound reflects optimistic assumptions where exposed land is common due to cycling feedback.

E1. Long-term climate regulation (0.10–0.50, selected 0.20)

Models show both robust thermostatic behavior and regimes where regulation fails [Walker et al., 1981; Foley, 2015]. Because the prevalence of effective long-term climate regulation on rocky planets remains controversial, a broad range of 0.10–0.50 is adopted, with a representative value of 0.20 used in the baseline model.

E2. Plate tectonics / geochemical cycling (0.20–0.70, selected 0.50)

Numerical models support both stagnant-lid and mobile-lid regimes under plausible conditions, motivating the adopted wide range [Lenardic et al., 2016].

One recent study analyzed oxygen content [Walton, 2026]. Walton and his co-authors demonstrated through computer modeling that only in a narrow range of medium-level oxygen conditions — known as a chemical Goldilocks zone — will both phosphorus and nitrogen remain in the mantle in sufficient quantities.