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JBIS CONTENTS

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OUR MISSION STATEMENT

The British Interplanetary Society promotes the exploration and use of space for the benefit of humanity, connecting people to create, educate and inspire, and advance knowledge in all aspects of astronautics.

How long does the human civilization need to last in order to observe another advanced intelligence in the Universe?

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Why do we appear to be alone in the Universe? We argue that even if an advanced civilization in another galaxy evolved to be remarkably similar to us (using radio waves for communication) it would still be highly unlikely for us to detect them. For instance, if such a civilization were located 10^6 light-years away, by the time our radio signals reached them, their civilization (and possibly ours) may no longer exist. The central idea is that the spatio-temporal separation between intelligent civilizations may be so vast that, even if a radio-transmitting civilization does emerge, it is unlikely to be noticed by others. This is because, at any given moment, there may be no other civilizations both advanced enough and close enough to detect each other's presence. We present a mathematical model for estimating the probability of detecting radio-transmitting advanced civilizations. This model highlights the profound difficulty involved in such detection. A further important consideration is that other civilizations may not communicate using the electromagnetic spectrum or think in symbolic terms as we do. For example, birds display high levels of intelligence but likely do not use symbolic representations of the world. While symbols shape how we think and communicate, other life forms (on Earth or elsewhere in the Universe) may rely on entirely different mechanisms for cognition and communication. We may need to open our minds to alternate forms of life which may be more abundant in the Universe but may not look like life as we know it, and may not communicate (or think) like us. Our work suggests that, in order to detect or be detected, advanced civilizations must endure for very long periods. This mathematical perspective not only underscores the challenges of discovering extraterrestrial intelligence, but also invites us to reflect on the uniqueness of our planet and the conditions necessary for mutual detection in the cosmos.

Keywords: Detecting Extraterrestrial Intelligence, Radio Transmissions, Communication Protocol

1 INTRODUCTION

Why does humanity appear to be alone in the Universe? One possibility is that intelligent, life-bearing civilizations are so widely separated across space and time that even if one develops the capability to transmit signals, there may be no other civilizations advanced enough to detect them at that moment. The immense distances and the fleeting overlap of technological windows could make interstellar communication exceedingly rare.

Another key idea is that other civilizations are unlikely to communicate in the same ways that we do (radio and electromagnetic spectrum) or think in the ways we do (symbols and mathematics, e.g. birds are extremely intelligent but likely do not have symbolic representations of the world). Symbols are how we think and communicate [1]. However other life forms (even on Earth and potential life forms elsewhere in the Universe) may use different mechanisms to think and communicate.

In this work, we present a simple model of the difficulty of observing advanced civilizations. Our model suggests that the probability of detecting advanced civilizations may be limited by the lifetime of civilizations. The vast distances that may separate stars and the amount of time spent in traversing those distances, dictates that civilizations need to be long-lived in order to detect intelligent signals from far away stars.

2 ANALYSIS

We assume we are talking about radio transmitting civilizations. We assume a civilization has a mean lifespan of L years. In what follows, we assume that L refers to the average duration that an advanced civilization transmits (and receives) radio signals after reaching the necessary technological level.

The probability, per unit volume of space, of bearing a living civilization that is advanced enough to detect radio transmission, is denoted by ρ.

The volume of space covered by the radio transmission of an advanced civilization during its lifespan (L) is given by the volume of a sphere of radius L: $\frac{4}{3}\pi L^3$.

The probability that another advanced civilization co-occurs in this volume is given by the product of this volume and the probability (per unit volume) that a living civilization advanced enough to detect radio transmissions (ρ) is also in this volume.

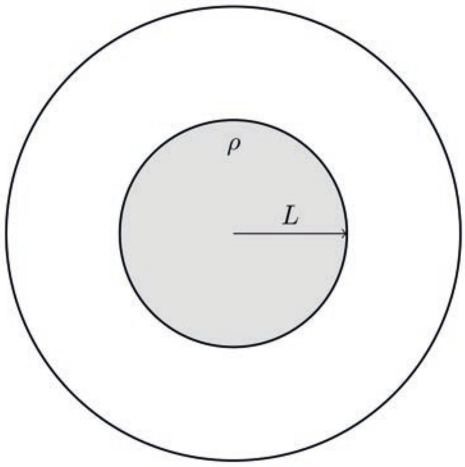

Fig.1 In this figure, light or information has spread for a distance of L light years in the L years that an advanced civilization has existed. The civilization is assumed to exist at the center of the sphere. The lifetime of the radio-transmitting phase of this civilization is L years. In these years, the information transmitted by the civilization has covered a sphere or radius L. ρ denotes the probability, per unit volume of space, of bearing a civilization that is advanced enough to detect radio transmission. The volume of the spherical annular region is given by $\frac{4}{3}\pi L^3$. The probability that another advanced civilization co-occurs in this volume is given by the product of this volume and the probability (per unit volume) that a living civilization that is also advanced enough to detect radio transmissions (ρ). This leads to the following condition that should be approximately equal to 1 if we are to observe radio transmissions from other intelligent civilizations: $\frac{4}{3}\pi L^3 \rho \approx 1$.

This is explained in Fig. 1. This leads to the following condition that should be approximately equal to 1 if we are to observe radio transmissions from other intelligent civilizations:

$$\frac{4}{3}\pi L^3 \rho \approx 1 \tag{1}$$

There are numerous bottlenecks to achieving a life bearing planet that also evolves a radio-transmitting intelligent civilization. We assume that radio transmissions are a universal mode of communication.

3 GENERAL FORM OF THE COSMIC LONELINESS EQUATION

We can simplify our original equation to get the following:

$$\frac{4}{3}\pi L^3 pd \approx 1 \tag{2}$$

where d is the density of stars and the probability of life/civilization on planets or other celestial objects around each star is p. L is the average lifetime of an advanced radio-emitting civilization, where it can also depend on d and p.

We can write L as a function of p and d and rewrite the equation more generally as (for an advanced civilization to be detected):

$$\frac{4}{3}\pi L(p,d)^3 pd \approx 1 \tag{3}$$

Hence we require, for an advanced civilization to be detected, the quantity $\frac{4}{3}\pi L(p,d)^3 pd$ should be as high as possible.

We propose calling Eq. 3 the *Cosmic loneliness equation*.

Code for experimenting with these analyses is available from the following repository [2]. A free instance of this application can also be accessed on the following website (the website has all functionality without requiring any software installation) [3].

4 RESULTS

4.1 Empirical analysis of the Cosmic loneliness equation

We can rewrite Eq. 3 as the following condition in order that we (the human civilization) can detect another advanced civilization:

$$L^3 \approx \frac{3}{4\pi pd} \tag{4}$$

Rearranging and restating as an inequality we have the following condition

$$L \geq \sqrt[3]{\frac{3}{4\pi pd}} \tag{5}$$

The density of stars (d) is approximately 1 in 320 cubic light years in our stellar neighbourhood [4, 5]. Substituting this value yields:

$$L \geq \frac{4.2}{\sqrt[3]{p}} \tag{6}$$

The lifetime of the human civilization needs to scale as:

$$L \geq \mathcal{O}(\frac{1}{\sqrt[3]{p}}) \tag{7}$$

If p is really small due to complexities of developing and sustaining an advanced lifeform and other evolutionary bottlenecks (see Section Effect of probability of developing life p), then the lifetime of the human civilization needs to be longer in order to detect another rare event.

For example, if p is 10^{-12} then L needs to be at least 42,400 years for us to be able to detect another advanced civilization. If p is 10^{-15} then L needs to be 424,000 years.

We note that these estimates refer to the means; the standard deviations may be large. So it may indeed be possible for the human civilization to be short-lived and yet detect a signal.

We sampled L from a large range of 10^{-3} to 10^{-30} uniformly on a logarithmic scale. We kept d fixed at the value of 1 in 320 cubic light years in our stellar neighbourhood [4, 5]). We then calculated the minimum value of L required to detect another advanced civilization. We use the equation $L \geq \sqrt[3]{\frac{3}{4\pi pd}}$ to calculate these values.

The resulting distribution of L, on a logarithmic scale, is shown in Fig. 2. We note that L denotes the lifetime of the advanced radio-transmitting phase of human civilization. For example, we have been transmitting and receiving radio signals for only approximately 100 years (even though modern human civilizations have been around for much longer).

We note that these distributions are for descriptive purposes only. The aim here is only to understand the nature of the problem. Our purpose is not to derive precise estimates of L: this will have huge uncertainties.

The plot in Fig. 3 shows the non-linear dependence of L on

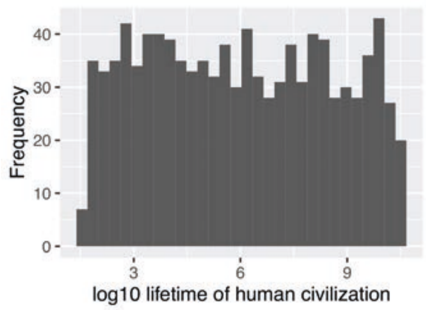

Fig.2 The distribution of the lifetime of the advanced radio-transmitting phase of the human civilization that allows it to detect another radio-transmitting advanced civilization (*L*) on a logarithmic scale. *d* (density of stars) was fixed to 1 star in 320 cubic light years and *p* (probability of another star developing an advanced radio-transmitting civilization) was varied from 10^{-3} to 10^{-30}. We use the equation $L \geq \sqrt[3]{\frac{3}{4\pi pd}}$ to calculate the minimum value of *L*.

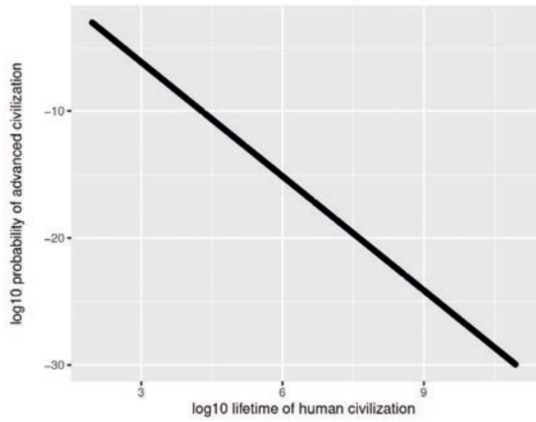

Fig.4 A plot of the logarithm of *ρ* (probability of another star developing an advanced radio-transmitting civilization) vs. the logarithm of *L* (lifetime of the advanced phase of human civilization).

p. As p gets lower, L needs to be progressively higher to detect this rare event. Crucially there is a non-linear dependence between p and L.

We can also plot the logarithm of p vs. the logarithm of L. This is shown in Fig. 4. This will be a straight line since we have the following equation:

$$\log L_{min} = -\frac{1}{3}p + c \tag{8}$$

where L_{min} is the minimum value of L required to detect the presence of another advanced radio-transmitting civilization and c is a constant.

4.2 Analysis of the putative effect of density of stars

Our simple model can be used to investigate the effects of varying different components. At the center of a galaxy, stars are much closer to each other but probability of life is probably much less. We can expand ρ to have two components: density of stars (d) and a probability of life (and an advanced civilization) on each star (p).

$$\rho = d \cdot p \tag{9}$$

d maybe higher towards the center of galaxy but p maybe lower: this is due to likely collisions with other stars in a crowded neighbourhood, chaotic orbits and proximity to a massive black hole close to the Galactic center.

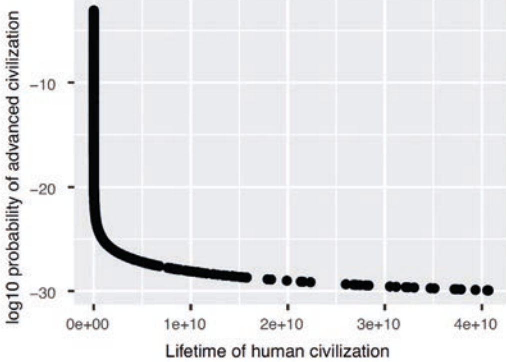

Fig.3 A plot of log10 *p* (probability of another star developing an advanced radio-transmitting civilization) vs. *L* (lifetime of the advanced phase of human civilization). This shows the non-linear dependence of *L* on *p*.

Hence we can rewrite our principal equation as:

$$\frac{4}{3}\pi L^3 \cdot d \cdot p \approx 1 \tag{10}$$

We can envision how L and p might depend on the density of stars in the neighbourhood d. For example, just as a thought exercise, we can imagine that the lifetime of a radio transmitting civilization is inversely proportional to the local density of stars. This maybe because a greater density of stars can increase the likelihood of stable planetary orbits being perturbed by the gravitational pull of stars that are close by. For example, assume a planet is in the habitable zone of its star. A perturbation from a nearby star can make it orbit further away from its parent star (in our case the Sun). This may in turn lead to extinction of life on the planet.

Let us assume a hypothetical scenario where the lifetime of a radio transmitting civilization (L) is inversely proportional to the local density of stars (d).

$$L \propto \frac{1}{d} \tag{11}$$

Similarly we can imagine that the probability that a star has a planet that has an advanced civilization also depends on the local density of stars. For the same reason as above, we can imagine an inverse relationship:

$$p \propto \frac{1}{d} \tag{12}$$

We now use these relationships in Eq. 4 and get the following relationship:

$$\frac{4\pi}{3d^3} \approx 1 \tag{13}$$

This hypothetical relationship, which can be validated or invalidated with experimental data as it becomes available, suggests that as a neighbourhood gets denser, the probability of observing advanced biological life decreases. According to this hypothetical scenario, the probability of detecting life may increase as we move away from dense regions, e.g. the Galactic center. The Galactic center, in the Milky Way for example, has a supermassive black hole and a highly dense region of stars. There may be some experimental evidence of the absence of radio-emitting civilizations emanating from the center of the Galaxy [6]. However we note that the absence of evidence is not evidence of absence.

All of these hypotheses can be validated or invalidated as additional data becomes available. Our equation is general enough to accommodate data as it becomes available. It can also suggest data collection strategies. For example, we can preferentially sample for radio signals in less dense stellar neighbourhoods (away from the Galactic center).

We can also experiment with alternative formulations of how L varies with d. A hypothetical relationship is shown below in the form of a simple inverse quadratic relationship:

$$L \propto \frac{1}{(d-a)^2+b}$$

This would lead to a parabolic curve: a function where the lifetime of the radio-transmitting phase of an advanced civilization (L) is maximized for a certain value of d (local density of stars).

We can use a similar parabolic relationship for how p (the probability that an advanced civilization develops) varies with d:

$$p \propto \frac{1}{(d-a)^2+b}$$

We can now plug these relationships into the equation below:

$$\frac{4}{3}\pi L^3 \cdot d \cdot p \approx 1 \tag{14}$$

and get the following relationship:

$$\frac{4}{3}\pi \frac{d}{((d-a)^2+b)^4} \approx 1 \tag{15}$$

The behaviour of a simplified version of Eq. 5 for a = 10 and b = 5 (arbitrarily chosen values) is shown in Fig. 5.

This hypothetical relationship, which can be validated or invalidated with experimental data as it becomes available, suggests the following: there may be an optimal density of stars at which the probability of detecting an advanced civilization may become maximal.

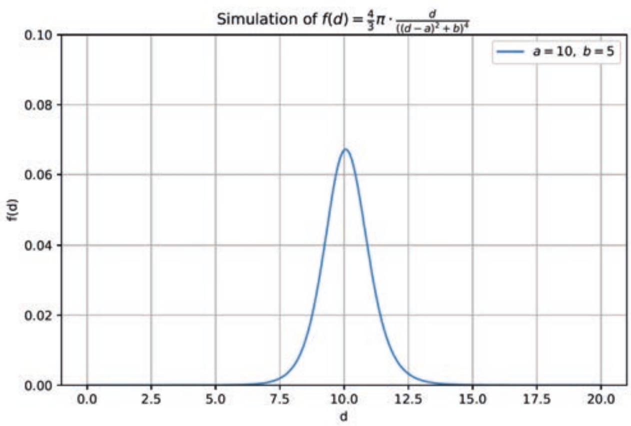

Fig.5 The behaviour of a simplified version of the expression $\frac{4}{3}\pi \frac{d}{((d-a)^2+b)^4}$ for the arbitrarily chosen values of a = 10 and b = 5.

Hence this approach can suggest new hypotheses, e.g. there maybe a Galactic “Goldilocks Zone” where advanced civilizations may thrive. This maybe far away from the Galactic center where density of stars is very high but also not too distant from the center. Quantitative simulations have suggested that life was probable around an annular region 13,000 light years from the galactic center and is/was most probable 8 billion years from the start of the Big Bang [7].

4.3 Effect of lifetime of civilization *L*

In this section, we will examine the effect of L (lifetime of the radio-transmitting phase of an advanced civilization). Let us then revisit the Cosmic loneliness equation:

$$\frac{4}{3}\pi L(p,d)^3 pd \approx 1 \tag{16}$$

Currently we do not have data about the behaviour of L (p, d) and how it depends on p and d. Hopefully in the coming centuries more data will be collected that will allow us to estimate this function. Our work advances the theory before data is collected and may even guide data collection strategies.

The model suggests that if civilizations are short-lived then there is a low probability of observing life.

Maybe all civilizations ultimately collapse and do not develop further. Advanced civilizations may also collapse after they reach a certain size. This could be due to ecosystem collapse or conflicts (nuclear conflict in the case of humanity).

It is also possible that most life forms do not develop civilizations and do not develop beyond microbes/simple life forms. This could be due to extinction events due to random asteroid hits (as has happened in the history of our planet) or some genetic/biological bottleneck.

Predicting extinction and evolutionary events is extremely difficult. For example, two identical planets may have very different evolutionary and extinction events over their geological lifespans [8]. Extinction events like the K-T event (asteroid hit), which wiped out the dinosaurs, are random stochastic events; it eventually led to the rise of mammals and intelligent primates like us. These kinds of events are very difficult to predict and yet radically change the evolutionary trajectory of the biosphere of a planet.

Likewise, evolutionary events like the Cambrian explosion (which led to a sudden increase in the diversity of species on Earth) are hard to predict, as are events like the Snowball Earth event. The Snowball Earth event is hypothesized to have occurred around 2 billion years ago and covered much of Earth in snow and ice.

Ice has high reflectivity and reflects a lot of solar radiation. If ice sheets extend beyond the arctic regions, the increased reflectivity (of solar radiation incident on Earth) can decrease global temperatures. This ensures that more ice is created which in turn further decreases global temperatures. This feedback loop may have caused a Snowball Earth event in the past [9]. This covered the entire surface of our planet in ice.

One way the Earth may have recovered from this is volcanic emissions leading to an accumulation of carbon dioxide in the atmosphere [10]. This may have led to another feedback loop: the accumulation of carbon dioxide in the atmosphere would have led to a greenhouse effect, which may have warmed Earth enough to melt the ice. This may have reduced the amount of solar radiation reflected back and started increasing the temperatures, and hence melting more of the ice.

Hence we see the possible critical role of feedback loops in ensuring that the Earth remained habitable for a considerable period of time.

It is unclear which planets can have these kinds of self-regulatory correcting mechanisms (which may have helped Earth recover from the snowball event) as proposed by James Lovelock [11] (Gaia hypothesis) [12]. The Gaia hypothesis [12] postulates that the ecosystem is a self-regulating complex system, that under certain circumstances, can preserve itself. If the operating parameters for this complex system go out of certain bounds, the system may never recover. These concepts were captured in a hypothetical simplified model called "Daisyworld" [12].

These simple models suggest that even if life evolves, and life is self-sustaining, in certain circumstances extinction can occur. Hence even if civilizations advanced enough to communicate with radio signals did evolve, they may not last long (on cosmic scales).

There are many questions to ponder when considering the lifespan of an advanced civilization:

1. Why and how do civilizations collapse? Do the number of people increase and diseases spread more rapidly?
2. Why do ecosystems and civilizations collapse?
3. Is recovery guaranteed? Are there certain conditions where recovery may not happen?

Tectonic plates and tectonic activity are also probably required for sustaining internal heat of planets. This is apart from other habitability and "Goldilocks zone" conditions thought to be required for sustaining life as we know it (carbon based life forms). Other conditions are no large disturbances in the Solar system or stellar neighbourhood (such as large stars passing by and perturbing the orbits of planets), the presence of a satellite (in order to have tidal effects on water bodies), the presence of a stable atmosphere, etc.

We also need to open our minds to alternate forms of life which may be more abundant in the Universe but may not look like life as we know it (carbon based life-forms we see on Earth) [13].

One example of using our imagination to visualize an alternative form of life is in the science-fiction writer Sir Arthur C. Clarke's story *Crusade* [14]. The writer imagines a life-form made of liquid helium that lives on a cold dark planet far away from any star and heat source. The life form lives in extremely cold temperatures, is made of liquid helium and uses superconducting currents to communicate and perform computation. The writer flips the anthropocentric paradigm on its head when he says this novel life-form finds it hard to imagine that life could exist on a planet where water exists in a liquid state.

This goes to show how anthropocentric our view of life has become. How would we even communicate with such a life-form, even if it did exist somewhere?

Others [8] have advocated similar viewpoints:

"To find ET [extra-terrestrial intelligence], we must expand our minds beyond a deeply rooted Earth-centric perspective and reevaluate concepts that are taken for granted …." " If we unbind our minds, it should not matter whether ET [extra-terrestrial intelligence] looks or thinks like us, has a logic that makes any sense to us, or uses familiar technology for interstellar communication" [8].

Carl Sagan in his novel *Contact* [15] had echoed similar sentiments when he wrote:

"… we are trapped by our time and our culture and our biology. How limited we are, by definition, in imagining fundamentally different creatures or civilizations. And separately evolved on very different worlds, they [alien intelligence] would have to be very different from us."

We hope these perspectives will challenge us to come up with alternatives to our current anthropocentric viewpoints of life. This may motivate novel ways to search for intelligence elsewhere in the Universe.

4.4 Effect of probability of developing life p

In this section, we explore the probability of developing life, p. The Great Filter Hypothesis [16] suggests that there are a number of hurdles that need to be overcome:

1. in order to have life,
2. have intelligent life that can survive the vagaries of Nature like asteroid hits and climate change, and
3. the emergence of complex life-forms that ultimately may lead to emergence of advanced spacefaring civilizations.

Life itself may evolve very differently on other planetary or stellar systems, and may not be recognizable to life as we know it [13].

Advanced life (life as we know it) may be very rare as the number of evolutionary transitions (multi-cellularity, sexual reproduction, etc.) and their likelihood is likely very low [17, 18].

At present, we are unable to get accurate estimates of p. It maybe that p is very small.

In our own analysis (see Section 4.1 *Empirical analysis of the Cosmic loneliness equation)*, we vary ρ over a large range.

4.5 Connections to the Drake equation

Our approach has some connections to the Drake equation. The Drake equation is shown below:

$$N = R_{*} \times f_p \times n_e \times f_l \times f_i \times f_c \times L \tag{18}$$

where the variables are:

N = the number of civilizations in the Milky Way galaxy with which communication might be possible (i.e. which are on the current past light cone).

R_* = The average rate at which stars are formed.

f_p = Proportion of stars with planets.

n_e = Mean number of planets per star on which life is possible.

f_l = Proportion of planets that could support life and on which life actually develops.

f_i = Proportion of planets with life on which intelligent life develops.

f_c = Proportion of civilizations that develop technology that sends detectable signals into space.
L = The total time over which the civilizations are detectable.

Let the radius of the Milky Way galaxy be R_M. Then the density of civilizations in the Milky Way is given by:

$$\frac{N}{\frac{4}{3}\pi R_M^3} \tag{19}$$

In order for these civilizations to detect each other, there needs to be at least one civilization within L light years of each other, i.e. at least one in a sphere of radius L. This has a density of:

$$\frac{1}{\frac{4}{3}\pi L^3} \tag{20}$$

Hence the density of civilizations in the Milky Way needs to be greater than this critical density, giving us the following relationship:

$$\frac{N}{\frac{4}{3}\pi R_M^3} \geq \frac{1}{\frac{4}{3}\pi L^3} \tag{21}$$

This leads to the following constraint on the lifetime of a civilization:

$$L \geq \frac{R_M}{\sqrt[3]{N}} \tag{22}$$

Substituting the variables in the Drake equation, we get:

$$L \geq \frac{R_M^{\frac{3}{4}}}{\sqrt[4]{f_p n_e f_l f_i f_c}} \tag{23}$$

We discuss the results of some basic simulations using this equation. The radius of our galaxy is approximately 46,250 light-years.

Even in a highly optimistic scenario (parameters: f_p = 1, n_e = 0.4 , f_l = 1, f_i = 0.5, f_c = 0.5), it will take us approximately 5,600 years to detect intelligent life. The advanced stage of our civilization has not existed for that long.

In a pessimistic scenario (parameters: f_p = 0.1, n_e = 0.001, f_l = 0.1, f_i = 0.0000000001, f_c = 0.0000000001), it will take us approximately 5 billion years. Hence our civilization needs to be very long-lived in order to detect signs of intelligent life in the Galaxy.

We note that at this stage, we are in no position to estimate these parameters with any certainty. These are parameters which are likely to have a lot of uncertainty. We hope that with more observations and scientific advances, we can get more certainty around estimates of these parameters.

5 LIMITATIONS AND FUTURE WORK

Our work has a number of limitations. We outline some of these in this section.

All our estimates refer to the means. However the standard deviations may be large. For example, if p is 10^{-12} then L needs to be at least 42,400 years for us to be able to detect another advanced civilization. These estimates are the means and the standard deviations can be quite large. So it may indeed be possible for the human civilization to be short-lived and yet detect a signal.

There are additional ways to extend this work. One extension is if a civilization emits radio waves for some time and then perishes. We can attempt to quantify how much time should elapse before this signal is detected even after the civilization has perished.

The duration of a techno-signature can also be decoupled from the lifetime of the civilization L producing it [19]. There are different regimes of communication that also matter, e.g. in some regimes the duration of the signature is important and also the rate at which the signature is emitted [20].

As a corollary, if an advanced civilization wants to communicate with other life forms and wants to maximize its probability of detection, it needs to be: 1) long-lived and/or 2) have long-lived emitters that send out signals long after the civilization has perished. These can be stationary or moving probes that emit signals. These can also be passive relics (machines with a power supply and some rudimentary computing power) that can be discovered by other civilizations upon close physical inspection (astro-archaeology).

The temporal distribution of communicating lifeforms and the effect on detectability has also been investigated before [21]. This can be incorporated in our model.

The number of detectable signatures within a certain radius is also an indication of the probable number of civilizations in the Galaxy or the observable Universe [22].

Artificial Intelligence (AI) and mathematical models can also help inform search for extra-terrestrial intelligence. These can include computational simulations of possible life-like systems [13] and methods to help detect signals from sensor measurements [23].

6 DISCUSSION

The lifespan of Earth's biosphere has been estimated to be approximately 1 billion years [24]. Within this time, Earth may lose all its water into space. The lifespan of the biosphere could be taken as an upper limit for the lifespan of an advanced civilization [24] (assuming it is not post-biological: please see points above). For Earth, this has been estimated to be between 0.9 to 1.5 billion years [24].

The average lifetime of empires has been estimated to be approximately 220 years [25]. Sebastian von Hoerner estimated the average duration of civilization as 6,500 years and the average distance between civilizations as 1,000 light years [26]. The average lifespan of mammals has been estimated to be 1 million years (11 million years for invertebrates) [27].

The time to contact alien civilizations has been estimated to be between 25 to 2,000 years [28]. Others have estimated that humanity can expect to contact an alien civilization approximately 1,500 years from now [29]. [30] investigated a probabilistic version of the Drake equation and estimated that even if optimistically there were 100,000 civilizations in our Galaxy, they would be separated by distances of hundreds of light-years (suggesting that the time to contact another civilization may be of the order of a few hundred years even in a very optimistic scenario). The spatio-temporal nature of this search process has also been investigated in [31]. The opportunities for interacting with alien intelligences may be few and far between given the huge separations in space and time between two civilizations. This has been called the Spatio-Temporal-Variance explanation for the Fermi paradox [31].

A far more liberal upper bound on the lifetime of an advanced civilization can be obtained in the following way: an upper bound on the lifetime of an advanced civilization like ours may be set by the amount of time spent by our star (Sun) in the main sequence (the Sun will leave the main sequence in approximately another 5 billion years) [32]. In other words, the environment may place a hard limit on the emergence and extinction (if it is a likely outcome) of an advanced civilization like ours [32]. For example, atmospheric oxygen likely constrained the emergence of multicellular organisms [32]. We note that we cannot rule out the possibility that highly advanced civilizations may be able to extend the lifespan of their host stars [33].

Our work complements previous work showing time to probable contact (with an extraterrestrial civilization) and couples it to potential estimates of lifetimes of the advanced phase of our civilization (L).

Our work suggests that advanced civilizations must be long-lived in order to maximize the chance of being detected as well as detecting the presence of other advanced civilizations.

Even if life arose again on Earth (if we were to reset the initial conditions and replay evolution), there is no guarantee that an advanced, technologically capable civilization would emerge. For example, had the K–T extinction event not occurred and the asteroid impact not wiped out the dinosaurs, it is plausible that large reptilian lineages might have continued to dominate the planet. Mammals may never have risen to ecological prominence. Would such dominant reptiles have been capable of evolving toward spaceflight? Could some reptilian lineage have eventually developed the cognitive and physiological traits necessary for advanced technology? We do not know. Life evolves in variegated, contingent ways, deeply influenced by historical chance and stochastic events. Evolutionary paths are contingent and unpredictable.

The number of active civilizations in the Galaxy is given by the Drake equation. Being able to communicate with them is another matter. Our equation puts that into quantitative footing.

We flip the paradigm on its head and we instead estimate how long does human civilization need to live in order to have a good chance of detecting or being detected by another advanced civilization.

If two civilizations are separated by several thousand light-years, it is possible that one or both cultures may become extinct before meaningful dialogue can be established. Human searches may be able to detect their existence, but communication will remain impossible because of distance. It has been suggested that this problem might be ameliorated somewhat if contact and communication is made through a Bracewell probe. A Bracewell probe is a hypothetical concept proposed as a means for extraterrestrial civilizations to communicate across vast distances in space [34]. Instead of using radio waves or other forms of electromagnetic communication, a Bracewell probe would be a self-contained robotic spacecraft sent to other star systems. The key idea behind a Bracewell probe is that it would serve as a sentinel, capable of waiting for long periods until it encounters a technological civilization.

It is possible that a probe (or system of probes) equipped with advanced intelligence may outlive the civilization which created and launched it. This would be one way to artificially extend the effective "lifetime" of a civilization. It would ensure that human civilization is remembered (and potentially detected) long after extinction.

Quantitative simulations suggest that intelligent life may have existed in the Milky Way billions of years ago (and also perished) [35]. This maybe another explanation of why we have not observed any signs of extra-terrestrial intelligence yet. Taken together these simulations may suggest that life is spatio-temporally separated from us; either separated from us by large distances and/or time. This maybe yet another explanation for why we have not observed signs of intelligent life yet.

Typical estimates of the lifetime of civilizations (L) maybe in the order of 10^4 years [19, 21]. p is likely extremely small due to the all the complex reasons outlined in Section 4.4 *Effect of probability of developing life p*.

How can we increase L? An advanced civilization can leave long-lived artificial beacons that transmit signals and/or detect signals of life. L can be artificially increased, if there are long-lived sentinel probes equipped with artificial intelligence (AI), which are capable of detecting radio signals from advanced civilizations [34].

AI has the potential to accelerate the search for intelligence elsewhere in the Universe. Some have surmised that AI also has the potential to cause human extinction and hence act as a Great Filter for intelligence in the Universe [36]. It seems likely that a prudent use of AI along with international regulations may benefit humanity and its quest for intelligence in the Universe.

We note that there are many plausible explanations for the apparent lack of extra-terrestrial intelligence (informally called the Fermi Paradox). Some of these are reviewed in [37]. In this work, we examine only a few of the many possible solutions to the Fermi Paradox.

Some have suggested that alien life may be too incomprehensible. Sir Arthur C. Clarke hypothesized that "our technology must still be laughably primitive; we may well be like jungle savages listening for the throbbing of tom-toms, while the ether around them carries more words per second than they could utter in a lifetime" [38].

An advanced civilization can maximize its chances of being detected by being long-lived. This has implications for how we view our own fragile planet. If we do not value our ecosystem, our civilization may collapse and the Universe may never know of our existence.

Our work suggests that advanced civilizations may need to be long-lived in order to maximize the chance of being detected as well as detecting the presence of other advanced civilizations. This mathematical perspective can allow us to appreciate our planet and our place in the Universe, and may allow us to understand why detecting extraterrestrial intelligence may be very difficult.

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Estimating the Prevalence of Malicious Extraterrestrial Civilizations

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This paper attempts to provide an estimation of the prevalence of hostile extraterrestrial civilizations through an extrapolation of the probability that we, as the human civilization, would attack or invade an inhabited exoplanet once we become a Type-1 civilization – in the Kardashev Scale – capable of nearby interstellar travel. The estimation is based on the world's history of invasions in the last century, the military capabilities of the countries involved, and the global growth rate of energy consumption. Upper limits of standard deviations are used in order to obtain the estimated probability of extraterrestrial invasion by a civilization whose planet we send a message to. Results show that such probability is two orders of magnitude lower than the impact probability of a planet-killer asteroid. Similarly, when we compare the estimated intelligence quotient (IQ) of an advanced civilization with the correlation between intelligence and aggression in humans, a negligible probability of extraterrestrial agression is found. These findings could serve as a starting point for an international debate about sending the first serious interstellar radio messages to nearby habitable planets.

Keywords: Search for Extraterrestrial Intelligence, Alien Life, Habitable Exoplanets, Kardashev Scale, Drake Equation, Fermi Paradox

1 INTRODUCTION

Active SETI (Active Search for Extra-Terrestrial Intelligence), sometimes referred as METI (Messaging to Extra-Terrestrial Intelligence), is a form of SETI that has been barely practised since the first interstellar radio message, the Arecibo Message, was sent in 1974 to the globular star cluster M13. Since then, there have been some attempts to contact potentially habitable exoplanets, such as Gliese 581 c, Tau Ceti f, and GJ 273 b. As of today, only GJ 273 b, located 19 light years away, remains considered to be potentially habitable, with an estimated Earth similarity of 85% [1]. The message, which was sent under a project called 'Sónar Calling GJ 273 b' [2], will arrive in 2029, and any response to Earth would be received as of 2041. The problem is that the message only contained music and a scientific tutorial to decode it. That is, it was a symbolic piece that did not contain any message, and therefore unlikely to be decrypted by any civilization provided that it exists.

The cause why there has been no serious attempts to send a radio message to a potentially habitable exoplanet is because there has been no international debate to discuss the possibility of doing it, and there has been no discussion because there is a prevailing fear in the scientific community that the message could be picked up by a malicious extraterrestrial civilization. Such civilization could be more advanced than ours, and perhaps interested in exploiting the resources of our planet by force.

For this reason, it becomes urgent to find an approximation to determine how likely it would be that an intelligent civilization living in the exoplanet we message has malicious intentions and poses a threat to humanity. Zero risk is unlikely to exist. However, if such risk is similar than that of other natural catastrophic events that could affect the entire Earth, then the advantages that would derive from finding and communicating with an intelligent civilization could greatly exceed its drawbacks. Ironically, this would be the case if the extraterrestrial civilization is far more advanced than ours, which may allow us to improve our technology -including in the field of medicine- and provide humanity with significant benefits.

Moreover, it is important to point out that human exploration -through projects such as Starshot- could reveal our location to a hypothetical extraterrestrial civilization. Starshot is considered the most serious concept so far for unmanned interstellar travel, with an initial budget of 100 million dollars. The idea is sending thousands of nanocrafts to potentially habitable exoplanets, the first one being Proxima Centauri b. Any civilization in those planets might be able to spot the nanocrafts and even perhaps calculate the trajectory from where they came from. Sending a radio message to those exoplanets beforehand would be a safer procedure to determine whether or not they are inhabited, since discovering the origin of radio signals would be much harder than that of nanocrafts – e.g. we have still not found the source of the Wow! Signal. Once humanity sends a radio signal to an exoplanet and receives no response, sending nanocrafts there would become safer.

2 METHODOLOGY

Humanity is used in this paper as a reference point to argue how a similar civilization could behave in the future. This methodology has been previously used by other authors. For example, in 2015, Adam Stevens, Duncan Forgan and Jack O'Malley James, considered a range of scenarios in which humans could extinguish their own civilization [3]. From that, the authors addressed the possibility that intelligent civilizations that destroy themselves could produce signatures observable by humanity.

2.1 Global invasion and energy consumption

The estimation of the probability of an intelligent civilization being malicious is based on the probability of humanity posing that same threat to them once it becomes a Type-1 civilization capable of nearby interstellar travel. To do so, a frequency distribution of the countries that have invaded others between 1914 and 2022 is conducted. This period of time was chosen for emcopassing the highest number of invasions in the last century, starting with World War 1. A total of 51 countries are found to have invaded another country at some point during the referred time frame. Data was extracted from the 'Correlates of War' database [4]. The invaders in World War I and II are limited to those that initially started the invasions and triggered the rest of them. Those invasions that formed part of a large occupation plan including several countries are counted as a single invasion. Moreover, civil wars and asymmetric warfare in general are not taken into account since they do not involve the invasion of any foreign territory.

The probability of invasion of a country is defined here as its probability to invade another country. For an invasion to take place there must exist both the intention to commit the aggression as well as the capability to do so. Thus, the probability of invasion of each country is weighted with its percentage of global military expenditure, which can be considered as a variable of capability. For example, the US has 14 invasions in the period studied -representing 8.86% of the world's total-, and the country also has 38% -i.e. 0.38- of the global military expenditure [5]. After multiplying both parameters, we obtain an estimated 3.36% probability that the US invades another country.

With a weighted average mean, the individual probabilities of invasion are then added and divided by the total number of countries in order to estimate the current human probability of invasion of an extraterrestrial civilization. With the upper limit obtained from the standard deviation of the human probability of invasion and the average rates of global invasion as well as energy consumption, an exponential growth calculation allows us to estimate the probability of invasion of a Type-1 civilization. The minimum estimated number of potentially habitable planets in our galaxy and the upper limit of the standard deviation of the estimated number of intelligent civilizations in our galaxy allow us to obtain the probability that the exoplanet we message has complex life. This probability is then multiplied by the probability that any civilization has malicious intentions, which yields the total probability that the exoplanet we specifically send an interstellar message to is inhabited by a malicious civilization. Based on that same upper limit, we can obtain the population of those that would be malicious and, therefore, likely to invade or attack the Earth.

2.2 Aggression and intelligence

In this case, the estimation of the probability of an intelligent civilization being malicious is based on the correlation between human aggression and intelligence. A 2018 study by Louis Jacob, Josep Maria Haro, and Ai Koyanagi [6] examined data from the 2007 Adult Psychiatric Morbidity Survey to explore the relationship between intelligence and violent behavior. IQ levels were estimated using the National Adult Reading Test (NART), while violent behavior was defined as involvement in a physical altercation or intentionally harming someone within the past five years. Logistic regression analysis was used to assess this association.

The study included 6,872 participants aged 16 and older. Findings showed that as IQ increased, the prevalence of violent behavior decreased, with 16.3% of individuals in the IQ range of 70-79 reporting violent acts, compared to only 2.9% in the 120-129 IQ range. Even after accounting for factors such as demographics, childhood adversity, and mental health conditions, individuals with lower IQ scores had higher odds of engaging in violence. Their research concluded that lower IQ is linked to a greater likelihood of violent behavior in the UK population.

This correlation between aggression and intelligence will be extrapolated to the case of a more intelligent civilization uisng the Flynn Effect. This effect describes the steady rise in IQ scores over time, first identified by James Flynn in 1984. His research showed an increase of 13.8 IQ points from 1932 to 1978, averaging about 3 points per decade. Later studies, including one in 2009, confirmed this trend by analyzing IQ gains across various versions of the Stanford-Binet and Wechsler intelligence tests between 1972 and 2006 [7]. The average yearly increase remained consistent at approximately 0.31 IQ points, reinforcing Flynn's original findings.

3 RESULTS

3.1 Global invasion and energy consumption

After calculating the weighted probabilities of invasion of each country (see Fig. 1), and considering that Earth has a total of 195 official countries, the estimated probability of invasion by a Type-0 civilization as humanity not capable of interstellar travel is 0.026%. However, given the threat that a malicious civilization would indeed pose, it is better to work with the upper-limit of the estimated probability of invasion as well as number of intelligent civilizations in our galaxy. The upper limit of the standard deviation gives a probability of invasion of 0.028%.

Now we have to search for a correlation between the global probability of invasion and the global energy consumption, which reflects technological advancement in the Kardashev Scale. In the last 50 years [see Fig. 2], the frequency of invasions has been decreasing at an average rate of 1.15% per year [4]. Meanwhile, world energy consumption has been increasing at a steady pace of 2.24% [8]. We can extrapolate the data to determine whether a more advanced civilization could be more or less prone to invade our planet than humanity invading theirs. With an average global consumption of 3.14E13 watts and the yearly increase of 2.24% mentioned before, humanity is expected to become a Type-1 civilization (1E16 watts) in 259.5 years. Such civilization has an estimated probability of 0.0014% of invading another one.

In 2010, Claudio Macconne wrote a threat assessment -now unclassified- for the US Defense Intelligence Agency, titled 'An Introduction to the Statistical Drake Equation'. Maccone calculated there could be anything between zero and 15,785 (upper

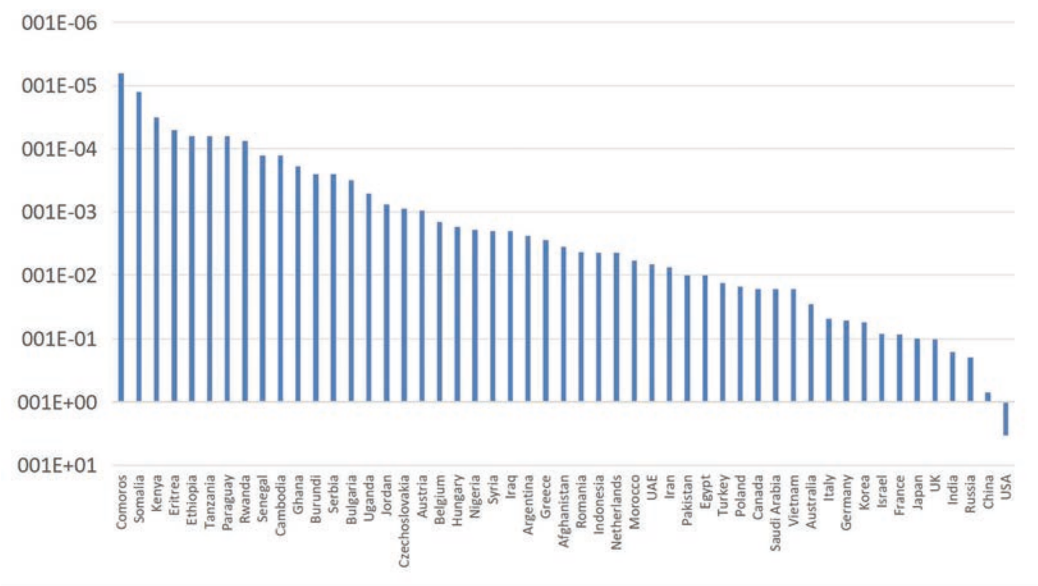

Fig.1 **Logarithmic-scale distribution of weighted probabilities of invasion by country; this scale was used to avoid visual distortion from US data.**

limit) possible civilizations of extraterrestrial origin [9]. Given that we want to consider the worst possible scenario, that is, the one with the highest number of malicious civilizations, its estimation would be based on the upper limited calculated by Maccone, therefore yielding a total of 0.22 civilizations.

However, we want to calculate the probability that the exoplanet we specifically send a message to is inhabited by a malicious civilization. Not every habitable exoplanet is expected to have complex life. Based on the estimated number of potentially habitable planets in our galaxy, which is a minimum of 40 billion planets [1], and the upper limit of the estimated number of civilizations (15,785), the probability that the planet we message has a civilization with malicious intentions goes down to 5.52E-8 %.

We can now compare the probability of invasion of a civilization more advanced than humanity with the probability of a planet-killer asteroid collision. The impact probability of a Chicxulub-like asteroid (which led to the extinction of 75% of life) is only one every one hundred million years, or 1E-6 % [10]. The probability of extraterrestrial invasion by a civilization whose planet we message is, therefore, around two orders of magnitude lower than the probability of a planet-killer e asteroid collision. Some attempts are currently being made through NASA's DART mission to deflect potentially hazardous asteroids such as Didymos B, a 160 m asteroid, much smaller than the Chicxulub asteroid of 10 kilometers in diameter. Asteroids recently discovered such as the 70 m 2024 YR4, have an impact probability of 1E-3% [10]. The possibility of an asteroid colliding with Earth will always exist, including those of interstellar origin that we are not aware of.

For the probability of invasion by a messaged extraterrestrial civilization to reach the impact probability of a Chicxulub-like asteroid, we could send a maximum of 18 interstellar messages to different potentially habitable exoplanets. That limit increases when comparing it with the impact probability of smaller yet global-scale asteroids. For example, the impact probability of a 1 km asteroid that would produce a global catastrophe is 0.001% – one every 100,000 years. Such asteroid would produce an estimated number of near 2 billion deaths [10]. For the probability of invasion by a messaged extraterrestrial civilization to reach such probability, we could send a maximum of 18,000 messages

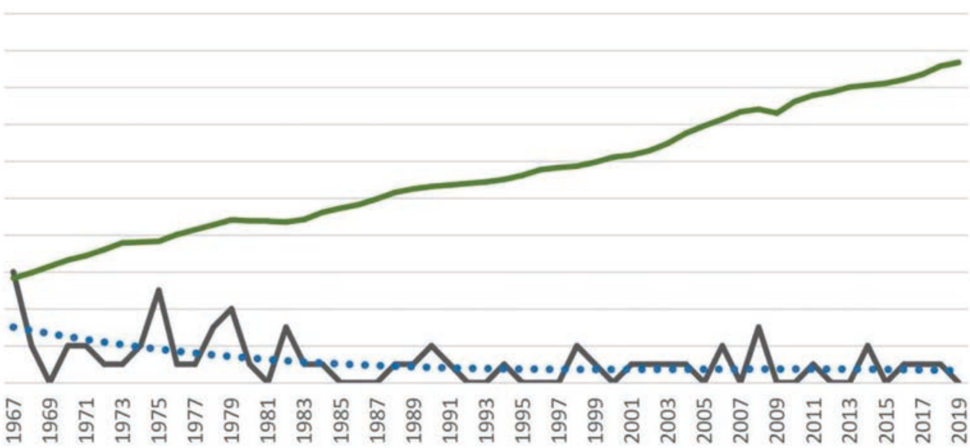

Fig.2 **Comparison between global invasion frequency (gray) and energy consumption (green) from 1967 to 2019**

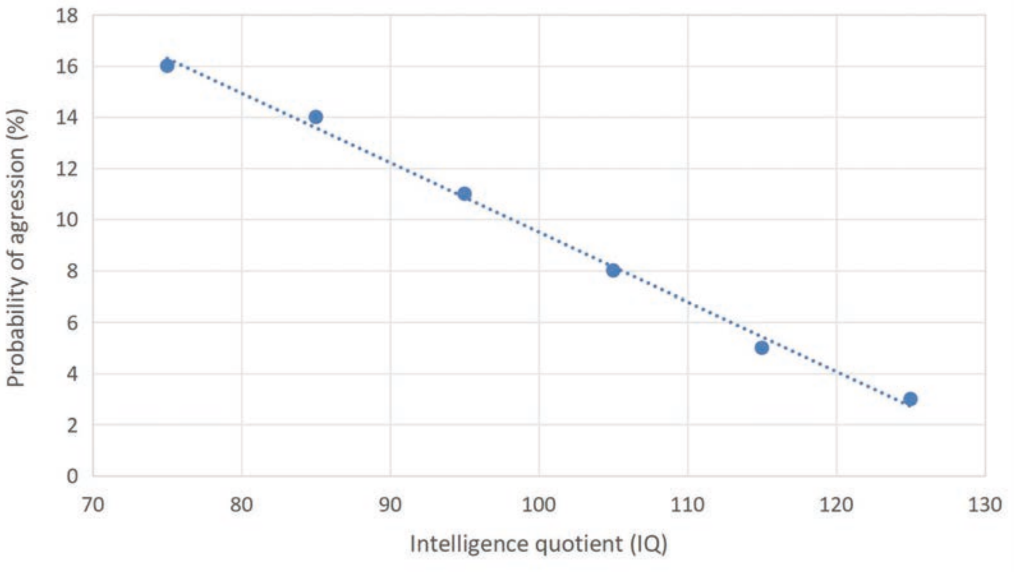

Fig.3 **Regression line of IQ (x-axis) and aggression (y-axis), using data from Jacob et al., 2018.**

to different habitable planets, which would increase our chances of extraterrestrial contact while minimizing the risks.

3.2 Aggression and intelligence

Considering a mean IQ of 102 [6], a 0.3-point increase per year in intelligence based on the Flynn Effect [7], and that humanity is expected to become a Type-1 civilization in approximately 260 years, such advanced civilization would have an average IQ of 180 points. Fig. 3 shows the correlation between IQ means and probability of aggression.

For every point increased in intelligence quotient, there is an approximate 0.26% decrease in probability of aggression. We can therefore say that for an IQ of 180 points, which would correspond to the estimated IQ average of an intelligent civilization capable of interstellar travel, the probability of aggression is close to zero.

4 CONCLUSIONS

An extrapolation from all the invasions that occurred on Earth in the last century shows an estimated probability of 5.52E-8 % that a messaged extraterrestrial civilization – or a faction of it – would have hostile intentions towards humanity, as well as a total of 0.22 malicious civilizations. Such a low probability is due to the fact that the estimated number of potentially habitable planets [1] is much higher than the number of Type-1 civilizations capable of nearby interstellar travel [9].

Moreover, there seems to be an indirect correlation between the human probability of invasion and the world's development based on energy consumption. The more developed humanity is, the less likely invasions are. Similarly, there appears to exist a more direct correlation between the human intelligence and its probability of aggression. In other words, the more intelligent a human is, the less likely to become agressive. When extrapolated to an estimated extraterrestrial IQ of 180 points, a negligible probability of aggression is obtained.

The neglectability of this result together with an estimated probability of extraterrestrial invasion -calculated from global invasion and energy consumption- two orders of magnitude lower than that of a planet-killer asteroid collision, should open the door to the next step. This step could consist in having an international debate to determine the conditions under which the first serious interstellar radio or laser message would be sent to a nearby potentially habitable exoplanet.

The main limitation of this study lies in the possibility of extraterrestrials having a brain with a chemical composition different than humans. Moreover, the probabilities of invasion are cumulative, which means that sending radio messages to several potentially habitable planets raises the total to the sum of all of them. Nonetheless, this still yields an extremely low probability. We could send up to 18,000 interstellar messages to different exoplanets and the probability of invasion by a malicious civilization would be the same as that of an Earth collision with a global-catastrophe asteroid.

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APPENDIX 1

Country	Invasions	%	Expenditure	Weight	Probability
Russia	10	6.329113924	3.1	0.031	0.196202532
UAE	1	0.632911392	1.07	0.0107	0.006772152
Senegal	2	1.265822785	0.01	0.0001	0.000126582
Ghana	1	0.632911392	0.03	0.0003	0.000189873
Turkey	3	1.898734177	0.7	0.007	0.013291139
Israel	11	6.962025316	1.2	0.012	0.083544304
Kenya	1	0.632911392	0.005	0.00005	3.16456E-05
Comoros	1	0.632911392	0.001	0.00001	6.32911E-06
Ethiopia	1	0.632911392	0.01	0.0001	6.32911E-05
USA	14	8.860759494	38	0.38	3.367088608
UK	5	3.164556962	3.2	0.032	0.101265823
Canada	2	1.265822785	1.3	0.013	0.016455696
Australia	3	1.898734177	1.5	0.015	0.028481013
Poland	4	2.53164557	0.6	0.006	0.015189873
Pakistan	3	1.898734177	0.53	0.0053	0.010063291
Uganda	2	1.265822785	0.04	0.0004	0.000506329
Rwanda	2	1.265822785	0.006	0.00006	7.59494E-05
Burundi	1	0.632911392	0.04	0.0004	0.000253165
Eritrea	1	0.632911392	0.008	0.00008	5.06329E-05
Saudi Arabia	1	0.632911392	2.6	0.026	0.016455696
Egypt	3	1.898734177	0.53	0.0053	0.010063291
Syria	4	2.53164557	0.08	0.0008	0.002025316
Iraq	4	2.53164557	0.08	0.0008	0.002025316
China	8	5.063291139	14	0.14	0.708860759
India	7	4.430379747	3.6	0.036	0.159493671
Iran	1	0.632911392	1.2	0.012	0.007594937
Argentina	2	1.265822785	0.19	0.0019	0.002405063
Vietnam	10	6.329113924	0.26	0.0026	0.016455696
Tanzania	1	0.632911392	0.01	0.0001	6.32911E-05
Somalia	1	0.632911392	0.002	0.00002	1.26582E-05
Indonesia	2	1.265822785	0.35	0.0035	0.00443038
Morocco	2	1.265822785	0.47	0.0047	0.005949367
Cambodia	1	0.632911392	0.02	0.0002	0.000126582
Bulgaria	1	0.632911392	0.05	0.0005	0.000316456
Hungary	3	1.898734177	0.09	0.0009	0.001708861
Afghanistan	1	0.632911392	0.56	0.0056	0.003544304
Nigeria	3	1.898734177	0.1	0.001	0.001898734
France	5	3.164556962	2.7	0.027	0.085443038
Korea	4	2.53164557	2.15	0.0215	0.05443038
Jordan	1	0.632911392	0.12	0.0012	0.000759494
Netherlands	1	0.632911392	0.7	0.007	0.00443038
Japan	6	3.797468354	2.6	0.026	0.098734177
Italy	5	3.164556962	1.5	0.015	0.047468354
Germany	3	1.898734177	2.7	0.027	0.051265823
Paraguay	1	0.632911392	0.01	0.0001	6.32911E-05
Belgium	1	0.632911392	0.23	0.0023	0.001455696
Greece	2	1.265822785	0.22	0.0022	0.00278481
Romania	3	1.898734177	0.23	0.0023	0.004367089
Czechoslovakia	1	0.632911392	0.14	0.0014	0.000886076
Serbia	1	0.632911392	0.04	0.0004	0.000253165
Austria	1	0.632911392	0.15	0.0015	0.000949367

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Filtered Feynman Path Integrals and Emergent Gravity: A Toy Model for Warp Metrics and Wormhole Formation

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We propose a novel framework in which filtered Feynman path integrals give rise to emergent gravitational curvature, enabling toy models of warp bubbles and wormhole geometries. Using a Levenberg-Marquardt-inspired filtering process, quantum histories are selectively rendered per spacetime voxel based on coherence, suppressing nonclassical trajectories and allowing negative energy densities to emerge as coherence gradients across adjacent regions. This voxel-based structure permits the generation of effective stress-energy conditions compatible with Alcubierre type metrics and ER=EPR-connected topologies. As a secondary implication, this framework offers a natural suppression mechanism for quantum vacuum energy, potentially resolving the 120 orders of magnitude discrepancy between quantum field theory and the observed cosmological constant. The model connects filtered quantum information, path integral optimization, and exotic spacetime engineering under a unified computational interpretation.

Keywords: Fermi Paradox, Artificial Radiation, Detection Limits, Extraterrestrial Aliens, Warp Drive, Wormholes

1 INTRODUCTION

The generation of exotic spacetime geometries – such as warp bubbles and traversable wormholes – traditionally requires energy conditions that are difficult to satisfy with known matter fields. In particular, the stress-energy configurations required for solutions like the Alcubierre metric [1] or traversable wormholes [2] demand localized regions of negative energy density, often violating classical energy conditions. Quantum field theory allows such configurations in principle (e.g. via Casimir effects or squeezed states), but no consensus mechanism has been demonstrated that robustly generates and sustains the required curvature.

In this work, we propose that such exotic metrics may arise naturally from a filtered version of the Feynman path integral. Inspired by optimization theory – specifically the Levenberg-Marquardt (LM) algorithm – we model quantum histories as being selectively rendered through a coherence weighted filtering process. In this formulation, only the most classically consistent paths survive per spacetime voxel, while non-classical or incoherent trajectories are exponentially suppressed. This selective rendering framework induces energy gradients across adjacent voxels, which we propose act as effective curvature sources. In regions of sharp coherence differentials, this can produce negative energy densities, potentially realizing the geometric conditions needed for warp or wormhole-like solutions.

The filtered-path voxel model also provides a compelling side benefit: it offers a natural explanation for the long-standing cosmological constant problem. In standard QFT, vacuum fluctuations contribute an energy density on the order of $\rho_{\text{vac}}^{\text{QFT}} \sim 10^{113}$ J/m^3, yet observations suggest $\rho_{\Lambda}^{\text{obs}} \sim 10^{-9}$ J/m^3 [3,4]. Our model suppresses unphysical vacuum contributions through quantum coherence filtering, allowing only rendered paths to contribute to observable energy. This results in a dramatic reduction of vacuum energy density – on the order of 120 magnitudes – without fine-tuning or symmetry-based cancellation.

We build on Wheeler's quantum foam paradigm [5] by introducing a voxelized spacetime structure, where each voxel stores a filtered zero-point energy $\langle E_{\text{voxel}} \rangle = \langle \Psi | \hat{H}_{\text{ZPE}} | \Psi \rangle$. We find that matching the observed dark energy density implies a voxel size on the order of tens of astronomical units, a scale consistent with causal coherence breakdown in semi-classical cosmology. This scale also aligns with the decoherence horizon beyond which path histories lose quantum coherence and collapse to classical outcomes.

Conceptually, this model integrates perspectives from quantum computation, holography, and information-based spacetime emergence [6-8]. It shares conceptual ground with recent work by Duarte [9], who analyzed multi-path quantum interference using hypergraph structures. Where Duarte explores interference topology, we treat filtered coherence as the mechanism for gravitational field generation. The result is a unified model connecting filtered path summation with metric engineering.

This paper proceeds as follows: Section 3 introduces the standard Feynman path integral and identifies the overcounting problem. Section 4 presents our filtering mechanism based on Levenberg-Marquardt optimization. Section 5 defines the voxel-based structure of spacetime and its relation to rendered quantum histories. Section 6 develops the gravitational interpretation, showing how voxel coherence gradients induce curvature, and demonstrating toy models of warp and wormhole-like metrics. We conclude in Section 9 with implications for quantum gravity and suggestions for experimental verification.

2 THE COSMOLOGICAL CONSTANT PROBLEM

The cosmological constant Λ was originally introduced by Einstein as a modification to his field equations to allow for a static universe [10]. While the discovery of the universe's expansion made this unnecessary, the concept returned with the realization that the expansion is accelerating [11, 12]. In the context of general relativity, this acceleration can be explained by a small, positive value of Λ, interpreted as a vacuum energy density associated with empty space.

Quantum field theory (QFT), on the other hand, predicts that even the vacuum is teeming with energy due to quantum fluctuations. Each field mode contributes a zero-point energy of $\frac{1}{2}\hbar\omega$, and integrating over all modes up to a high-energy cutoff Λ_c yields a vacuum energy density:

$$\rho_{\text{vac}}^{\text{QFT}} \sim \frac{\hbar}{c^3}\int_0^{\Lambda_c} \omega^3 d\omega \sim \frac{\hbar\Lambda_c^4}{c^3} \tag{1}$$

If Λ_c is taken to be the Planck scale ~ 10^{19} GeV, the result is $\rho Q^{FT}_{vac} \sim 10^{113}$ J/m3. Observations of Type Ia supernovae, cosmic microwave background anisotropies, and large-scale structure constrain the actual vacuum energy density to be [13]:

$$\rho_\Lambda^{\text{obs}} \sim 10^{-9}\,\text{J/m}^3 \tag{2}$$

which is smaller by roughly 10^{122} in absolute value, or 10^{120} if one assumes a natural cutoff below the Planck scale.

This mismatch – sometimes called the worst theoretical prediction in the history of physics – has prompted a wide range of attempted solutions: supersymmetry cancellations, anthropic arguments in the landscape of string theory, vacuum sequestering, and nonlocal gravity models [3, 7, 14-18]. However, no proposal to date has convincingly reconciled the predictions of QFT with cosmological observations in a falsifiable and widely accepted way.

In this work, we explore an alternative resolution. Rather than assuming that every quantum fluctuation contributes to the vacuum energy, we propose that only those consistent with a rendered, classical path through spacetime contribute measurably. We treat the path integral as a filtered sum over histories, where off-path contributions are suppressed in a manner inspired by optimization theory, leading to a voxel-scale cutoff in the effective zero-point energy.

3 FEYNMAN PATH INTEGRALS AND OVERCOUNTING

In the path integral formulation of quantum mechanics, a quantum amplitude is computed by summing over all possible trajectories (paths) that a system can take between initial and final states. For a scalar field , the generating functional is given by [19-22]:

$$Z = \int \mathcal{D}\phi\, e^{iS[\phi]/\hbar} \tag{3}$$

where $S[\phi]$ is the classical action of the field configuration. In Euclidean signature, the integral becomes:

$$Z = \int \mathcal{D}\phi\, e^{-S_E[\phi]/\hbar} \tag{4}$$

with $S_E[\phi]$ the Euclidean action. This formalism elegantly captures interference, tunneling, and non-classical effects.

However, when applied to the vacuum state, this summation includes an enormous number of virtual processes and field fluctuations, each of which contributes to the vacuum energy density. Unlike classical paths which dominate the classical limit via the stationary action principle, the offshell paths – those that deviate significantly from the classical trajectory – still contribute, albeit with rapidly oscillating phases. In flat spacetime QFT, these contributions are typically renormalized away or absorbed into counterterms, but gravity couples to the absolute energy density, making the problem intractable [3,14].

The cumulative effect of summing over all possible histories leads to a vacuum energy that scales quartically with the ultraviolet cutoff [3,14]:

$$\rho_{\text{vac}} \sim \int^{\Lambda_c} \frac{d^3k}{(2\pi)^3}\frac{1}{2}\hbar\omega_k \propto \Lambda_c^4 \tag{5}$$

As discussed earlier, with a cutoff at the Planck scale, this results in an energy density of ~ 10^{113} J/m^3, which is many orders of magnitude above what is observed.

This overcounting problem can be seen as arising from the treatment of the path integral as a uniformly weighted sum over all configurations, without any mechanism to suppress those paths that are physically irrelevant, redundant, or inconsistent with macroscopic classicality. In analogy to overfitting in machine learning or overparameterization in optimization, the path integral may include "noise" that does not correspond to observable phenomena, yet contributes energetically to the vacuum.

In the next section, we explore how this summation can be reinterpreted as an optimization process, filtered to retain only those histories that contribute constructively to the rendered, classical structure of spacetime.

4 LEVENBERG–MARQUARDT FILTERING OF HISTORIES

In classical optimization theory, the Levenberg-Marquardt (LM) algorithm provides a robust method for solving nonlinear least-squares problems by interpolating between the Gauss–Newton algorithm and gradient descent [23, 24]. It accomplishes this by introducing a damping term that suppresses updates along directions of high curvature or poor convergence, effectively filtering out contributions that do not improve the solution.

We draw a conceptual analogy between this filtering mechanism and the behavior we propose for the Feynman path integral in the context of quantum gravity. Rather than interpreting the path integral as a literal sum over an unbounded number of quantum histories with equal significance, we hypothesize that nature performs an internal optimization, rendering only those paths that contribute to the emergent classical reality. This is consistent with ideas in quantum decoherence and consistent histories, but here we formalize the filtering through a mathematical parallel to LM damping.

In the LM algorithm, an iterative update rule modifies the step direction via:

$$\boldsymbol{x}_{n+1} = \boldsymbol{x}_n - (J^\top J + \lambda I)^{-1} J^\top \boldsymbol{r} \tag{6}$$

where J is the Jacobian matrix, r is the residual vector, and λ is the damping parameter. The addition of λI regularizes the inversion, suppressing directions with low information gain. In our analogy, the amplitude assigned to each path in the Feynman sum is similarly damped by an information-based penalty function, favoring trajectories that contribute constructively to a stable emergent history.

Let the modified path integral include a filtering term $F[\varphi(x)]$ such that:

$$Z[J] = \int \mathcal{D}\phi \, \exp\left(iS[\phi] - \gamma \mathcal{F}[\phi(x)]\right) \tag{7}$$

where γ is a damping parameter analogous to λ, and $F[\varphi(x)]$ penalizes field histories that deviate significantly from the dominant or classical path. In this way, the path integral becomes an optimization over configuration space, with quantum coherence preserved only for high-weight paths.

To provide a concrete form for the filtering operator $F[\varphi(x)]$, we conjecture that it penalizes deviations from classical coherence via a local field-functional norm. A natural choice is:

$$\mathcal{F}[\phi(x)] = \int d^4x \left| \frac{\delta S[\phi]}{\delta \phi(x)} \right|^2 \tag{8}$$

which assigns greater suppression to configurations where the action is not stationary. This parallels the Levenberg-Marquardt method in which steep residual gradients are damped. Here, the filter penalizes quantum histories with large deviations from the classical equations of motion.

Alternatively, in analogy with higher-derivative smoothness constraints, one could adopt a curvature-based penalty:

$$\mathcal{F}[\phi(x)] = \int d^4x \left[\alpha \left(\partial_\mu \phi \partial^\mu \phi\right)^2 + \beta(\phi)^2\right] \tag{9}$$

where α and β are weighting parameters. This form suppresses rapid field oscillations and high momentum configurations, functioning as a soft UV cutoff without imposing a hard energy limit.

These candidate filter forms are not unique, but serve to demonstrate that the filtering process can be mathematically realized as a damping term in the path integral – regularizing the quantum sum and guiding it toward classical coherence. We emphasize that the precise form of $F[\varphi(x)]$ remains an open question. The expressions above are presented as motivated prototypes, not final derivations.

This approach allows us to reinterpret the suppression of vacuum energy not as a renormalization artifact, but as a consequence of nature's tendency to regularize overcounted histories. Only paths that pass a certain filter – representing physical realizability or constructive coherence – contribute to observable quantities like the cosmological constant. The rest are exponentially damped, much like suboptimal solutions in optimization.

The filtering term $F[\varphi(x)]$ can be interpreted as modifying the weight assigned to each path $[\varphi(x)\rangle$ in the total amplitude. In Dirac notation, the filtered generating functional becomes:

$$Z[J] = \int \phi \, \langle 0| e^{i\hat{S}[\phi]} e^{-\gamma \hat{\mathcal{F}}[\phi]} |0\rangle \tag{10}$$

where $S\hat{}[\varphi]$ is the action operator acting on field configurations $|\varphi(x)^{\text{i}}$, and $\hat{\mathcal{F}}[\varphi]$ is the filter operator that penalizes incoherent or nonclassical histories. The vacuum projection |0ih0| ensures that only paths contributing to the rendered reality from the vacuum dominate. This formalism reframes the path integral as a coherence-weighted expectation value over histories:

$$Z[J] = 0 e^{i\hat{S}[\phi] - \gamma \hat{\mathcal{F}}[\phi]} 0 \tag{11}$$

This construction naturally suppresses high-frequency or high-deviation modes in analogy with Levenberg–Marquardt damping, enforcing a projection onto quasi-classical, high-weight paths.

4.1 Motivation from the Two-Slit Experiment

Feynman's two-slit experiment provides a pedagogical foundation for the path integral approach to quantum mechanics. In this formulation, the amplitude for a particle to arrive at a position x on a detection screen is given by the coherent sum over all possible paths connecting the source and the screen, including paths that go through slit A, slit B, or even take wildly nonclassical trajectories [25]. In Dirac notation, this is typically written as:

$$\langle x \rangle \, \psi = \langle x \rangle \, A \, \langle A \rangle \, \psi + \langle x \rangle \, B \, \langle B \rangle \, \psi + \cdots \tag{12}$$

where $|\psi\rangle$ is the initial state at the source, and $|A\rangle$, $|B\rangle$ are intermediate positions at the slits. The ellipsis represents additional trajectories which, though formally included in the sum, interfere destructively due to rapid phase oscillations or geometric cancellation.

Although the number of possible paths between the source, the slits, and the detection screen is formally infinite, the total measurable energy or detection probability remains finite and is governed by the modulus squared of the total wavefunction, $|\Psi(x)|^2$. This implies that while quantum mechanics sums over all histories, nature ultimately renders only the statistically weighted result at the point of detection. Only a narrow class of coherent, quasi-classical paths survive to contribute constructively to the observed interference pattern. In this way, the two-slit experiment reveals a physical filtering mechanism embedded in the quantum formalism.

This principle is captured succinctly by the Dirac-Feynman summation rule, as formulated by Duarte and Taylor [25, 26]:

$$\langle d \,|\, s = \sum_{j=1}^{N} \langle d |\, j \, \langle j \,|\, s \rangle \tag{13}$$

where the quantum amplitude from initial state $|s\rangle$ to final state $|d\rangle$ is given by the coherent sum over a basis of intermediate states $|j\rangle$. This formalism underscores that all meaningful transitions occur through coherent summation of virtual intermediary events.

In terms of spatial propagation, this can be expressed via complex wavefunctions associated with intermediate positions:

$$\langle j \rangle \, s = \Psi(r_{js}) e^{-i\varphi} \tag{14}$$

$$\langle d \rangle \, j = \Psi(r_{dj}) e^{-i\phi} \tag{15}$$

where the wave function Ψ and its phase encode spatial separation and interference between source and detector via intermediate state *j*. The full state is thus an entangled composition of all these histories.

Following this logic, we propose that the vacuum energy observed in any region of spacetime must likewise reflect only the rendered contributions of a filtered set of histories. That is, while quantum field theory allows for an infinite vacuum energy density via the unfiltered path integral, the actual energy present in rendered spacetime is finite, bounded, and voxel-specific. We define this rendered zero-point energy per voxel as:

$$\langle E_{\text{rendered}} \rangle = \langle \Psi | \hat{H}_{\text{ZPE}} | \Psi \rangle \tag{16}$$

where $\hat{H}_{\text{ZPE}}$ is the zero-point Hamiltonian and $|\Psi\rangle$ is the dominant field configuration selected by coherence filtering. This average energy is no longer Planck-scale but rather consistent with cosmological observations when integrated over a suitably large voxel size.

We generalize this insight to quantum field theory in curved spacetime. At each voxel of spacetime, the path integral is filtered such that paths far from classical coherence are exponentially suppressed. In our formulation, this is implemented via a damping term in the exponential, inspired by Levenberg-Marquardt optimization. The result is a coherence-weighted sum over field configurations $|\Psi\rangle$, where only histories close to the classical trajectory survive the filter.

We begin by writing the filtered generating functional in Dirac notation:

$$Z[J] = \int \phi \, \langle 0 | e^{i\hat{S}[\phi]} e^{-\gamma \hat{\mathcal{F}}[\phi]} | 0 \rangle \tag{17}$$

where $\hat{S}[\phi]$ is the action operator acting on field configurations $|\,\phi(x)$ and $\hat{\mathcal{F}}[\phi]$ is the filter operator that penalizes incoherent or nonclassical histories. The vacuum projection $|0\rangle\langle 0|$ ensures that only paths contributing to rendered reality from the vacuum dominate. This formalism reframes the path integral as a coherence-weighted expectation value over histories:

$$Z[J] = 0 e^{i\hat{S}[\phi] - \gamma \hat{\mathcal{F}}[\phi]} 0 \tag{18}$$

This construction naturally suppresses high-frequency or high-deviation modes in analogy with Levenberg-Marquardt damping, enforcing a projection onto quasi-classical, high-weight paths. It also allows us to reinterpret the rendered universe as a classical projection of filtered quantum amplitudes – just as the interference pattern in the two-slit experiment emerges from a highly selective set of coherent histories.

4.2 Curvature Smoothness and Gravitational Wave Sensitivity

The Einstein field equations,

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{19}$$

describe the smooth curvature of spacetime generated by an averaged, classical stress-energy distribution. However, our voxelized model of spacetime implies that the rendered vacuum energy may vary slightly from voxel to voxel due to local fluctuations in filtered path amplitudes. Each voxel possesses a rendered energy:

$$E_{\text{voxel}} \rangle = \langle \Psi | \hat{H}_{\text{ZPE}} | \Psi \rangle \tag{20}$$

which can differ slightly from adjacent voxels. These variations are sub-Planckian and bounded by the filtering mechanism, implying that the resulting curvature differences are too small to manifest as observable kinks in the classical Einstein tensor.

To estimate this, consider the curvature shift between two neighboring voxels of size $L \sim 10^{13}$ m (approximately 80 AU), where the energy difference is δE. The associated curvature perturbation is:

$$\Delta R \sim \frac{8\pi G}{c^4} \frac{\delta E}{L^3} \tag{21}$$

For $\delta E \ll E_{\text{Plank}}$, this perturbation is orders of magnitude below current observational limits, and would be averaged out in any coarse-grained treatment of spacetime curvature. Thus, such voxellevel energy variations are effectively invisible to Einstein's equations, similar to how microscopic roughness on a dish antenna does not affect radio focusing unless it exceeds a wavelength-scale threshold.

However, this residual ”roughness” of the vacuum energy distribution may induce small-angle scattering, phase decoherence, or diffraction-like effects in gravitational waves propagating across many voxels. This is conceptually analogous to Ruze's equation in radio astronomy, which quantifies gain loss due to surface roughness [27]:

$$\frac{G}{G_0} = e^{-(4\pi\sigma/\lambda)^2} \tag{22}$$

where σ is the RMS surface roughness and λ is the wavelength. In our case, voxel energy fluctuations could introduce effective ”spacetime roughness” that modifies gravitational wave coherence across cosmological baselines.

We propose an analogous concept for spacetime: *a Ruze-like suppression factor* that limits the classicality of spacetime curvature due to voxel-scale discontinuities in the zero-point energy field. Let δE represent the energy difference between neighboring voxels due to imperfect cancellation of off-path contributions, and λ_c represent the characteristic wavelength of gravitational curvature in that region (e.g., from nearby mass-energy). Then the effective contribution of vacuum energy to curvature can be modeled as:

$$\mathcal{R}_{\text{eff}} = \mathcal{R}_0 \cdot \exp\left[-\left(4\pi \frac{\delta E}{\lambda_c E_{\text{voxel}}} \right)^2 \right] \tag{23}$$

where R_0 is the expected Ricci curvature from an idealized smooth energy distribution, and E_{voxel} is the average rendered energy per voxel.

This form implies that fine-grained, high-frequency vacuum energy fluctuations contribute negligibly to large-scale curvature, as their effects cancel out via destructive interference or incoherence. Only coherent voxel-scale structures with slowly varying E values across adjacent voxels produce persistent curvature. This directly motivates the use of filtering in the path integral—without it, the roughness-induced decoherence would destroy the smooth classical geometry of general relativity.

Moreover, if there exists a minimum coherence length below which voxel-to-voxel energy fluctuations no longer average out, the residual effect may manifest as scattering, diffraction, or noise in gravitational wave propagation—an exciting avenue for future phenomenology.

5 VOXELIZED SPACETIME AND THE RENDERING OF QUANTUM HISTORIES

We define a voxel as a finite coherence zone within which a filtered quantum history is rendered. In this framework, spacetime is not a continuous manifold but an emergent structure formed by the projection of dominant Feynman paths selected through a Levenberg-Marquardt-style optimization filter. Each voxel represents a localized region where quantum fluctuations collapse to a quasiclassical trajectory, and off-path contributions are exponentially suppressed.

Within each voxel, we assign a rendered energy density given by the coherence-weighted expectation value:

$$\langle E_{\text{voxel}} \rangle = \langle \Psi | \hat{H}_{\text{ZPE}} | \Psi \rangle \tag{24}$$

where $\hat{H}_{\text{ZPE}}$ is the zero-point Hamiltonian, and |Ψi is the dominant field configuration surviving the path integral filter. This energy is not uniformly distributed but arises from a coherence-weighted selection over virtual paths. As a result, adjacent voxels may have slightly different rendered energies, giving rise to gradients across the spacetime lattice.

The effective voxel scale can be estimated by requiring that the total vacuum energy integrated across all voxels yields the observed dark energy density:

$$\rho_\Lambda \sim \frac{\langle E_{\text{voxel}} \rangle}{L^3} \tag{25}$$

where L is the linear size of a voxel. Solving for L, given $\rho\Lambda \sim 10^{-9}$ J/m^3 and assuming each voxel contains energy on the order of a massive astrophysical body ($\sim 10^{30}$ J), yields $L \sim 10^{13}$ m, or roughly 80 astronomical units.

This distance scale aligns closely with estimates of causal coherence length in semiclassical cosmology and suggests a natural cutoff for interference effects in quantum field theory. Beyond this scale, off-path histories become incoherent, and the universe renders only the dominant configuration. In this way, voxelized spacetime acts as a quantum information lattice, and the geometry of classical reality emerges from the filtering structure imposed on the path integral.

This framework sets the stage for interpreting gradients in voxel energy as effective curvature sources, as developed in Section 6.

6 FILTERED PATH INTEGRALS AND EMERGENT GEOMETRY: TOWARD WARP METRICS AND WORMHOLES

Building on the filtered path integral framework described in prior sections, we now propose that spatial gradients in coherence-weighted energy across rendered spacetime voxels may generate effective curvature analogous to general relativity. Specifically, we suggest that such voxel-scale energy differentials can reproduce exotic spacetime geometries, including negative energy densities required for traversable wormholes and warp bubbles.

6.1 Voxel Energy Gradients as Metric Sources

Let each voxel of spacetime contribute a rendered energy $\langle E_{\text{voxel}} \rangle = \langle \Psi | \hat{H}_{\text{ZPE}} | \Psi \rangle$ filtered from the full path ensemble. Then, as proposed earlier, local curvature can be approximated by gradients in this coherence-weighted energy field:

$$R_{\mu\nu} \propto \nabla_\mu \nabla_\nu \langle E_{\text{voxel}} \rangle \tag{26}$$

Regions where the voxel energy exhibits sharp gradients – especially negative differentials – may correspond to effective stress-energy configurations $T^{00} < 0$, violating the classical energy conditions. These may mimic the conditions necessary for spacetime shortcuts such as wormholes or warp geometries. This interpretation echoes the broader body of work on exotic geometries supported by negative energy densities, such as those explored in Lorentzian wormhole theory [28].

6.1 Toy Model for Warp Bubble Curvature

In the Alcubierre warp metric [1], the stress-energy tensor requires a shell of negative energy density to generate superluminal contraction/expansion in front of and behind the bubble. In our framework, such a configuration could arise when adjacent voxels render paths of differing coherence weight, such that:

$$\delta \langle E_{\text{voxel}} \rangle < 0 \quad \Rightarrow \quad T^{00} < 0 \tag{27}$$

The metric deformation could then be interpreted not as requiring exotic matter directly, but as the emergent effect of filtered coherence fields across the voxel lattice. This coherence-gradient-based approach parallels earlier efforts to minimize the energy requirements for warp metrics through geometric compression techniques [29]. In prior work, this idea was extended by embedding the warp geometry within anisotropic media and layered metamaterials, demonstrating that metric deformation could arise from engineered stress-energy tensors rather than exotic matter [30]. The coherence-gradient toy model presented here offers a complementary mechanism rooted in filtered quantum histories rather than material properties.

6.3 Wormholes and ER=EPR Threads from Filtered Coherence

Filtered voxel connectivity may allow for quantum-coherent paths linking classically disconnected regions of spacetime. If such filtered histories persist across distant voxels, they may define effective nontrivial topologies akin to Einstein-Rosen bridges (wormholes).

This picture aligns with the ER = EPR conjecture [31], where entangled systems correspond to geometrically connected spacetimes. In our model, voxel-level filtering may select entangled paths that bridge large separations, forming the informational backbone of traversable wormholes in a rendered spacetime fabric.

6.4 Experimental Implications and Future Directions

If warp-like or wormhole-like geometries can emerge from coherence-weighted voxel filters, then future tests might include:

- Searching for effective negative energy densities in Casimir-like systems with engineered coherence,
- Simulating filtered Feynman paths in discrete quantum computing environments (e.g., Qiskit),
- Examining lensing anomalies or time delays near astrophysical compact objects that may reflect filtered

wormhole paths.

Further theoretical work is needed to define a metric from coherence gradients and to map the full set of conditions under which filtered voxel configurations generate physically admissible warp geometries.

7 FILTERED PATHS AS THE ORIGIN OF DARK ENERGY

In our model, the enormous vacuum energy predicted by quantum field theory is not rendered in full, but instead suppressed through a coherence-weighted filtering process embedded in the structure of spacetime itself. The dominant histories selected by Levenberg-Marquardt-style optimization represent the paths that survive this suppression and become realized as classical trajectories. All other histories – the vast landscape of off-shell, incoherent, or destructive interference paths – are mathematically present but physically unrealized.

We now propose that the observed cosmological constant is not a prediction error, but the measurable residual of this universal filtering process. That is, dark energy arises from the faint statistical trace of suppressed quantum possibilities that are not fully rendered but still exert a nonzero influence on the geometry of spacetime.

$$\rho_\Lambda = \langle E_{\text{filtered}} \rangle_{\text{voxel}} \ll \rho_{\text{vac}}^{\text{QFT}} \tag{28}$$

In this interpretation, the cosmological constant $\rho\Lambda$ is not a bare parameter to be calculated from a cutoff-dependent sum over modes, but rather the filtered energy per voxel that remains after a quantum optimization selects the most probable history. The unfiltered energy density QFT ~ 10^{113} J/m^3 is exponentially suppressed across each rendered region, leaving behind only ρ_{vac} the faint glow of quantum activity: *the heat from the GPU*, so to speak.

This reinterpretation elegantly sidesteps the traditional fine-tuning problem. Instead of asking why the vacuum energy is so small, we ask: *How efficient is nature's rendering engine?* The answer lies in the structure of the filtering operator $F|\varphi|$ and its suppression scale, which we link to the voxel size. The larger the voxel, the more aggressively off-path contributions are pruned, and the lower the residual energy.

The cosmological constant thus becomes a measure of the inefficiency of the universe's path integral filter – a byproduct of quantum decoherence, not a fundamental constant to be inserted by hand. It reflects the degree to which unrendered paths still back-react on spacetime via quantum fluctuations that are not entirely erased.

This view also offers a testable prediction: if the cosmological constant truly originates from a voxelized filtering process, then the vacuum energy should exhibit subtle anisotropies or scale dependent effects at the voxel scale. While these may be currently below detection thresholds, they open the door to new approaches in quantum gravity phenomenology.

Ultimately, this model invites us to consider dark energy not as a mysterious substance or exotic field, but as the natural thermodynamic residue of the universe's own optimization procedure—a faint but persistent echo of the infinite quantum possibilities that never came to be.

8 IMPLICATIONS AND PREDICTIONS FOR QUANTUM GRAVITY AND OBSERVABLES

The filtered path integral model we propose has several profound implications for quantum gravity, cosmology, and the interpretation of quantum mechanics. It suggests that spacetime itself is not a smooth manifold in the traditional sense, but an emergent structure rendered from filtered quantum histories within finite information volumes—voxels—whose energy content arises from a weighted projection of the Feynman sum.

8.1 Testable Anisotropies at the Voxel Scale

If the cosmological constant originates from rendered voxel-scale contributions, then subtle anisotropies or statistical variations in the vacuum energy density should be present at the scale of the voxel. Although suppressed below Planck sensitivity, these features could imprint themselves on cosmological observables such as:

- Small-scale anisotropies in the cosmic microwave background (CMB),
- Slight directional variations in Type Ia supernova Hubble diagrams,
- Low-frequency noise or phase decoherence in gravitational wave signals,
- Angular-dependent weak lensing effects that deviate from standard ΛCDM expectations.

These predictions are consistent with the notion of a residual energy field derived from suppressed, but not entirely nullified, path contributions.

Assuming the observed vacuum energy density is $\rho\Lambda \sim 10^{-9}$ J/m^3, and voxel size L ~ 10^{13} m, the rendered zero-point energy per voxel is:

$$E_{\text{voxel}} = \rho_\Lambda \cdot L^3 \approx 10^{-9} \cdot (10^{13})^3 \text{ J} \approx 10^{30} \text{ J} \tag{29}$$

This is roughly the rest mass energy of Jupiter (E ~ 10^{30} J), indicating that each voxel represents an extremely large but diffuse energy density consistent with cosmic acceleration.

8.2. Scale-Dependent Decoherence and the Quantum-Classical Boundary

The LM-style filtering mechanism implies a decoherence threshold, wherein path histories below a certain coherence level are filtered out. This introduces a natural, scale-dependent mechanism for the emergence of classicality. The voxel size provides an effective cutoff below which quantum fluctuations no longer contribute to large-scale curvature or observable dynamics. This concept could offer a dynamical explanation for:

- The emergence of classical trajectories in macroscopic systems,
- The quantum-to-classical transition in cosmological inflation,
- The absence of high-frequency vacuum modes in low-energy gravitational observations.

8.3. Constraints on Voxel Size from Observations

Our earlier derivation suggests that the voxel scale required to suppress QFT-predicted ZPE to observed levels lies in the range L ~ 10^{13} m, or approximately 80 AU. Future missions capable of mapping quantum noise, phase stability, or vacuum fluctuations at large interplanetary scales – such as LISA [32], pulsar timing arrays [33], or deep space interferometers [32] – may be able to place bounds on such a voxelization scale by probing for coherent structure or unexpected noise features.

For gravitational waves of wavelength $\lambda \sim 10^{10}$ m, and RMS voxel energy fluctuations $\delta E/E \sim 10^{-5}$, the Ruze-like suppression is:

$$\frac{G}{G_0} = \exp\left[-(4\pi \cdot 10^{-5})^2\right] \approx 1 - 6 \times 10^{-8} \tag{30}$$

suggesting that decoherence would be extremely subtle but possibly detectable with ultrasensitive instruments like LISA or PTAs after cross-correlation over long baselines. If voxel structure induces local anisotropies at the 80 AU scale, then the angular scale on the last scattering surface is:

$$\theta \sim \frac{L}{D_{\mathrm{CMB}}} \sim \frac{10^{13}\,\mathrm{m}}{10^{26}\,\mathrm{m}} \sim 10^{-13}\,\mathrm{rad} \sim 10^{-8}\,\mathrm{arcsec} \tag{31}$$

These are well below current angular resolution, but could modulate polarization or B-mode spectra in subtle ways in future ultra-high-resolution CMB missions.

While these estimates suggest that voxel-induced effects are small, they provide a target for future observations. Gravitational wave background anisotropies, low-frequency phase decoherence, or unexpected statistical correlations in CMB polarization could serve as indirect probes of voxel scale filtering. Further work is needed to model these predictions numerically.

8.4 Interpretation of the Cosmological Constant as a Quantum Information Residue

Perhaps most profoundly, this framework reinterprets the cosmological constant as a thermodynamic and informational residue of a computational process. Rather than invoking a new field or exotic component of the universe, dark energy becomes the byproduct of rendering decisions within a universal quantum simulation framework. This is consistent with:

- Wheeler's "it from bit" philosophy [34],
- Emergent spacetime scenarios in AdS/CFT [8],
- Tensor-network and circuit complexity proposals for holographic duality [35,36].

This shifts the cosmological constant problem from an issue of ultraviolet divergence to one of emergent architecture: how nature selects, weights, and renders paths to form the geometry we experience.

8.5 Prediction: Residual Gravitational Scattering from Spacetime Roughness

If voxel-scale energy roughness produces Ruze-like suppression of curvature transmission, then gravitational waves traversing cosmological distances should exhibit scattering, angular blurring, or stochastic noise beyond that predicted by classical GR. This opens an avenue for detecting quantum structure in spacetime via high-precision gravitational wave astronomy. Cross-correlation noise residuals in LISA [32] or the Einstein Telescope [37] could potentially reveal this voxel-induced decoherence.

8.6 Potential Link to Black Hole Information and Decoherence

Finally, this filtered path framework may offer insight into black hole evaporation and the information paradox. If rendering is tied to coherence thresholds, then the transition from a unitary superposition of paths to a projected classical outcome could mimic the behavior of information loss in black hole horizons. The voxelized path filter may serve as a model for firewall phenomena, scrambling, and quantum hair effects.

8.7 Gravity as a Gradient of Rendered Path Weights

In our voxelized spacetime model, each voxel represents a region where only a coherence-weighted dominant path survives the Feynman sum. The local energy content of this voxel is defined by:

$$\langle E_{\mathrm{voxel}} \rangle = \langle \Psi | \, \hat{H}_{\mathrm{ZPE}} \, | \Psi \rangle \tag{32}$$

where the dominant field configuration $|\Psi\rangle$ arises from LM-style filtering of all possible quantum histories.

If adjacent voxels possess slightly different values of E_{voxel}, then a gradient emerges in the density of rendered path amplitudes. We propose that this gradient acts as a proxy for curvature, effectively generating a gravitational field without requiring fundamental gravitational degrees of freedom.

Let the difference in filtered path density between neighboring voxels be defined as:

$$\nabla E_{\mathrm{rendered}} \sim \frac{\delta \langle E_{\mathrm{voxel}} \rangle}{\delta x} \tag{33}$$

Then the local curvature tensor could be emergently defined as a function of this filtered energy gradient:

$$R_{\mu\nu} \propto \nabla_\mu \nabla_\nu \langle E_{\mathrm{voxel}} \rangle \tag{34}$$

This reframes gravity not as a separate field, but as the information-theoretic second derivative of coherence-weighted path integrals over spacetime. The Ricci tensor, and hence Einstein's equations, become an emergent macroscopic approximation to gradients in the rendered information landscape.

Gravity, in this view, is the result of imperfect coherence – an informational surface tension between what is rendered and what is filtered out.

8.8 Connections to AdS Bulk Reconstruction and Causal Set Theory

The voxel-based filtering mechanism proposed here resonates with several paradigms of emergent spacetime in quantum gravity. In the AdS/CFT correspondence, bulk geometry is conjectured to emerge from entanglement structure in a lower-dimensional boundary theory. Our framework suggests that bulk curvature gradients – interpreted as gravity – may likewise emerge from gradients in coherence-weighted path densities across adjacent voxels. This parallels proposals in tensor network models of AdS/CFT, where entanglement entropy governs the emergence of spatial connectivity and bulk depth [8, 35, 36]. The voxel filter, by projecting dominant histories, effectively performs a bulk reconstruction from boundary-like coherence criteria, echoing the spirit of holographic duality.

Additionally, the discrete, causally connected voxel structure we invoke invites comparison with causal set theory [38,39], in which spacetime is a fundamentally discrete partial order of events. In our model, rendered voxels encode both energy and causal continuity, forming a lattice-like structure of classicality within which geodesics and curvature gradients emerge statistically. This coherence-weighted rendering process may serve as an effective low-energy realization of a causal set, where links correspond to filtered transitions between voxels of persistent coherence.

8.9 Physical Motivation for the Voxel Scale

While the voxel scale $L \sim 80\text{AU}$ was initially introduced to match the observed value of the cosmological constant, this distance is not arbitrary. We argue that it corresponds to a fundamental physical threshold – the causal decoherence length over which quantum histories cease to interfere coherently and collapse to classical trajectories.

In a relativistic quantum field theory, long-range coherence requires causal connectivity within the past light cone. At large scales, environmental decoherence and entanglement with the cosmic background (e.g., CMB, galaxy formation) lead to effective classicalization. The distance scale beyond which a single quantum field mode cannot remain phase-coherent with its entangled history is bounded by the horizon scale or interaction-induced decoherence length.

Assuming decoherence is driven by gravitational interactions at finite temperature, we estimate the causal coherence length L_c by balancing decoherence time τ_D with signal travel time:

$$L_c \sim c\,\tau_D \sim \frac{\hbar c^5}{G k_B T_{\text{vac}}^2} \tag{35}$$

where $T_{\text{vac}} \sim 10^{-29}$ K is the effective Gibbons-Hawking temperature associated with de Sitter space. This yields a scale on the order of 10-100 AU, depending on the coupling model and horizon curvature.

Alternatively, one can interpret the voxel as the largest scale at which off-path quantum histories can interfere meaningfully. Beyond this, the universe renders only the dominant (classical) path within that region. This aligns with causal set theory [38] and bulk-boundary holography [8], where spatial regions encode finite information and cannot resolve arbitrarily fine-grained path histories.

Thus, the voxel scale is not ad hoc, but corresponds to a physically motivated coherence cutoff beyond which decoherence, thermalization, and emergent classicality dominate.

8.10 Comparison to Existing Approaches to the Cosmological Constant Problem

A wide array of proposals have been advanced to explain the discrepancy between quantum vacuum energy and the observed value of the cosmological constant. These include symmetry-based cancellations such as supersymmetry [3], anthropic selection within a string theory landscape [17], vacuum sequestering mechanisms [15], and nonlocal modifications to gravity [7, 18].

Supersymmetry offers a partial cancellation of bosonic and fermionic vacuum modes, but this cancellation is broken at low energies, and LHC results have failed to confirm minimal SUSY extensions of the Standard Model. Anthropic arguments, while statistically appealing in a multiverse context, offer little predictive power and remain experimentally inaccessible.

Vacuum sequestering models attempt to decouple the vacuum energy from spacetime curvature by introducing global constraints on the action. While elegant in principle, these often rely on ad hoc Lagrange multipliers or non-dynamical fields, raising questions of consistency and naturalness.

Nonlocal gravity theories suppress vacuum energy contributions through infrared modifications to the Einstein-Hilbert action. However, these typically involve nontrivial changes to causality and the structure of the field equations, which are challenging to reconcile with standard quantum field theory.

In contrast, the approach proposed here does not alter the structure of gravity or introduce exotic global constraints. Instead, it reframes the path integral itself as a coherence-filtered rendering process, suppressing contributions from high-frequency and incoherent field configurations. This mechanism preserves the local structure of quantum field theory while offering a new explanation for why the cosmological constant appears small: it reflects only the filtered, rendered vacuum energy after nature's internal optimization.

This model is also distinct from emergent gravity proposals like those of Padmanabhan [6] and Verlinde [40], which posit gravity as an entropic or thermodynamic force. While conceptually aligned in treating gravity as emergent, our model grounds this emergence in filtered quantum coherence across a voxelized spacetime lattice, offering a more explicit connection to Feynman's path integral and computational optimization.

Ultimately, our proposal aims not to replace the formal structure of QFT or GR, but to reinterpret the cosmological constant as the thermodynamic residue of a filtered quantum simulation process. It provides a falsifiable and conceptually grounded alternative to the prevailing paradigms, with testable consequences at the gravitational and cosmological scale.

9 CONCLUSION

We have proposed a novel framework in which filtered Feynman path integrals give rise to emergent gravitational curvature, enabling toy models of warp bubbles and traversable wormholes. By applying a Levenberg-Marquardt-inspired filtering process to the quantum sum over histories, we showed how coherence gradients across voxelized spacetime regions can induce effective stress-energy differentials, including localized violations of classical energy conditions.

This coherence-weighted rendering mechanism offers a natural explanation for how exotic geometries – such as those envisioned in the Alcubierre and Morris-Thorne metrics – may arise from filtered quantum information, without requiring exotic matter fields. The model is consistent with and extends prior work on warp field engineering in anisotropic media, presenting a complementary interpretation rooted in emergent quantum coherence rather than material design.

As a secondary implication, this framework provides a physically grounded explanation for the cosmological constant discrepancy. By filtering out incoherent quantum paths, the path integral naturally suppresses zero-point energy contributions, reducing the effective vacuum energy density by many orders of magnitude without invoking symmetry-based cancellations. The voxel scale required to match observations falls near the estimated coherence horizon for semiclassical decoherence –

suggesting a deep link between gravitational geometry, emergent classicality, and the limits of quantum information propagation.

We have outlined several testable consequences, including gravitational wave decoherence, anisotropies in the cosmic microwave background, and simulation pathways via discrete quantum systems. While speculative in scope, this model offers a falsifiable and computationally interpretable bridge between quantum mechanics and emergent gravity. It invites us to view the universe not as a pre-existing manifold, but as a filtered projection of quantum histories – where geometry itself is the residue of rendered coherence.

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Estimating the Maximum Lifetime of Alien Civilizations Consistent With the Fermi Paradox; and Ours As Well

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The Fermi Paradox states that technologically-advanced extraterrestrial aliens should be widespread given the universe's age, yet none have been observed. There are three possible explanations: 1) technologically advanced aliens don't exist (besides us) 2) they exist but collapse before they can be detected, or 3) they reach an advanced technological level beyond our detection capabilities. This paper deals with the second and third possibilities and places an upper limit on their technological lifetimes consistent with the Fermi Paradox. The absence of artificial extraterrestrial radiation is the starting point. Using SETI's radiation detection limit, radiation's distance attenuation, and the maximum power heat dissipation the aliens would tolerate; allows a distance to be determined beyond which it would be impossible to detect aliens' radiation. Since time and distance are equivalent for radiation, this also places an upper limit on their technological lifetimes within the assumptions made. Under ideal conditions, aliens would last from 500 years to 1,300 years before either collapsing or advancing to a higher and undetectable technological level. Further, a fundamental law of nature must exist to explain the complete absence of alien signals. Most importantly, using a more reasonable non-ideal energy conversion efficiency shows we may only have 50 to 300 years left before we reach a tipping point and either collapse or ascend.

Keywords: Fermi Paradox, Artificial Radiation, Detection Limits, Extraterrestrial Aliens

1 ANALYTICAL APPROACH

It is assumed that technologically-advanced, extraterrestrial civilizations exist, and at least for a time, they unintentionally emit passive electromagnetic radiation, just as we do. Further, we have yet to detect such signals. Combining this with radiation's properties yield an upper limit on alien civilizations' technological lifetime

First consider the inverse square law. As we look deeper into space, the alien transmitter power would need to increase to be detected since radiation diminishes as one over the distance squared. Because of the exceedingly large distances involved, there comes a point in which it is not plausible an alien race would build such large transmitters. This is further constrained by the transmitters' less than perfect power conversion efficiency which would lead to unreasonably high atmospheric temperature increases that the aliens would surely avoid.

The approach taken is to calculate lifetime upper limits since these can be quantified.

For convenience, civilizations are classified as[1]:

[1]These stages are not consistent with the Kardashev scale, which classifies civilizations according to their ability to harness energy. The stages used here are for the paper's convenience only.

NOMENCLATURE

Symbol	Description	Units
ΔT	Atmospheric temperature rise	K
η	Energy conversion efficiency	
C_p	Specific heat	W hr K^{-1} kg^{-1}
d	Distance from Earth to alien planet	ly
f_c	Fraction of intelligent civilizations that emit passive radiation	
f_i	Fraction of life capable planets that develop intelligent life	
f_l	Fraction of life capable planets where life develops	
f_p	Fraction of stars with planets	
m	Alien planet's atmospheric mass	kg
N	Number of Stage II civilizations that we can detect	
n_e	Mean number of planets that could support life for each star with planets	
P	Power	W
P_{LOD}	Minimum signal that SETI can detect	W m^{-2}
P_{New}	Power needed to achieve P_{req} after the conversion efficiency (η) is applied	W
P_{req}	Minimum power required for alien emissions to be detected by SETI	W
P_{waste}	Power dissipated into alien's atmosphere	W
R^*	Rate of star formation	yrs^{-1}
t	Stage II's lifetime	yrs
t_h	Time to heat up alien's atmosphere	yrs
T_{sink}	Temperature of sink for rejected heat	K
T_{source}	Temperature of source that drives solar cells	K

- Stage I - civilizations that have not yet advanced enough to emit electromagnetic radiation.
- Stage II - civilizations that are emitting passive radiation. We entered Stage II in 1920 with the first commercial radio transmission from KDKA in Pittsburgh.
- Stage III - civilizations that have advanced to such a degree that whatever their radiation emissions are, we are either incapable of detecting them or we are not attempting to do so.

A lack of detection means that either the Stage II civilization advanced to Stage III or collapsed; satisfying the Fermi Paradox.

Given that science is universal, it is assumed that whatever happens to alien Stage II civilizations will also happen to us and in a similar timeframe.

The following sections expand on these concepts.

2 TWO CRITICAL ASSUMPTIONS

First, the Fermi Paradox can only include alien civilizations that are possible to observe, and in the case of this analysis, only those with passive radiation emissions strong enough and long enough for us to detect. All analyses addressing the Fermi Paradox are so restricted and include only a subset of all possible alien civilizations meeting this criterion. For instance, if Mars had a thriving civilization that ended millions of years ago, their emissions would have passed us before the present and we would not have had the opportunity to detect it and they would therefore be excluded from this, or any other, analysis.

Second, an important assumption is that a lack of detection must mean the Stage IIs either collapsed or ascended. Following Hart's logic [1], given the almost limitless available time (billions of years), one would expect at least one, if not more, Stage IIs to have been observed if this was not true. The likelihood of all of them, without exception, being undetectable for other reasons, without a single outlier, is unreasonable and should be dismissed. Hence, the maximum distance, d, must equal the alien's maximum lifetime, t.

Hart's intention was to prove aliens do not exist. The focus of this analysis is on the two remaining possibilities.

3 TWO ADDITIONAL POINTS

Most Fermi hunters focus on the absence of physical artifacts, which is an unnecessary constraint. Before we spot, or are visited by, alien spacecraft, the civilization would have to first project their radiation signature. So it is possible they exist but never achieve interstellar travel. By ignoring the necessity for interstellar capability, this paper lowers the bar which captures a greater number of possibilities.

Also, this paper provides a credible alternative to the "*we are the only ones in the universe*" school of thought.

4 LIGHT CONE

Fig.1 is a one-spatial dimension light cone which shows the path of passive emitted radiation from any Stage II alien planet, relative to Earth. The horizontal axis shows the time before the present and the vertical axis the distance from Earth. Earth is at the origin at the present time.

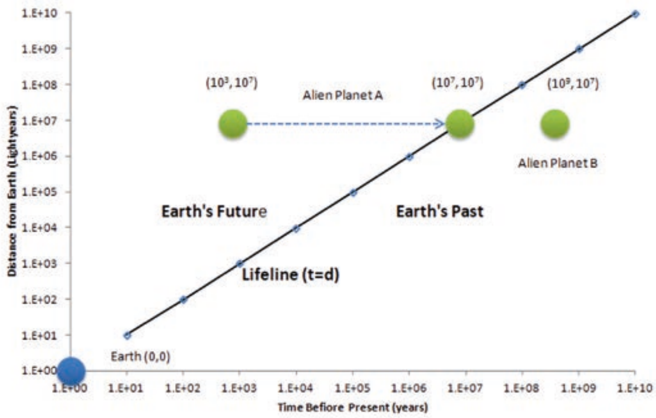

Fig.1 **Light Cone Showing Emissions from a Stage II Civilization.**

Since the emitted radiation travels at light speed, distance and time are equivalent. For instance, radiation emitted at 1,000 light years (ly) away will take 1,000 years to reach Earth.

A 45° Lifeline separates events in the past (below the line), in the future (above the line), and observable by us (on the line). Anything below the Lifeline would have passed Earth before the present so we would not have had the opportunity to detect it. Anything above the Lifeline would not have yet reached Earth. It is only that which falls on the Lifeline that can be detected. Here a planet would radiate for a time exactly equal to its distance from us and these are the only signals we can possibly observe.

As an example, alien planet A is at 10 million *ly* from us and entered Stage II 1,000 years ago. Its emitted radiation would not have yet reached us. On the other hand, if planet A started emitting radiation 10 million years ago (equivalent to its distance from us) it would just be arriving at Earth and presumably we would detect it. Finally, planet B is shown at the same distance, 10^7 ly, but with its emissions ending 10^9 years ago. Its radiation would have passed us long before the present.

5 MAXIMUM LIFETIME AND DISTANCE EQUIVALENCE

A Stage II'S maximum lifetime must equal its distance from earth. Consider the following four points. First, all Stage IIs must be on the Lifeline to be detected. Second, they are emitting continuously, just as we do. Third, SETI has not detected any. And finally, anything below the Lifeline would be in Earth's past and no longer observable.

An example best illustrates this equivalence. See the three light cones in Fig. 2. Consider a Stage II, 1,000 *ly* away that has been transmitting for 500 years. It might be on the Lifeline (A), but it might not (B). Its location on Fig. 2 is therefore indeterminate. But it if was at least 1,000 years old, some part of its existence must intersect the Lifeline (C). No other outcome is possible. Since it has not been detected, it is concluded it can be no older than 1,000 years and its maximum lifespan is equal to its distance from us.

6 INVERSE SQUARE LAW

The SETI Institute has been listening for alien transmissions since 1984 and SETI like experiments have been carried out since 1960 with the Ozma project. The minimum signal they

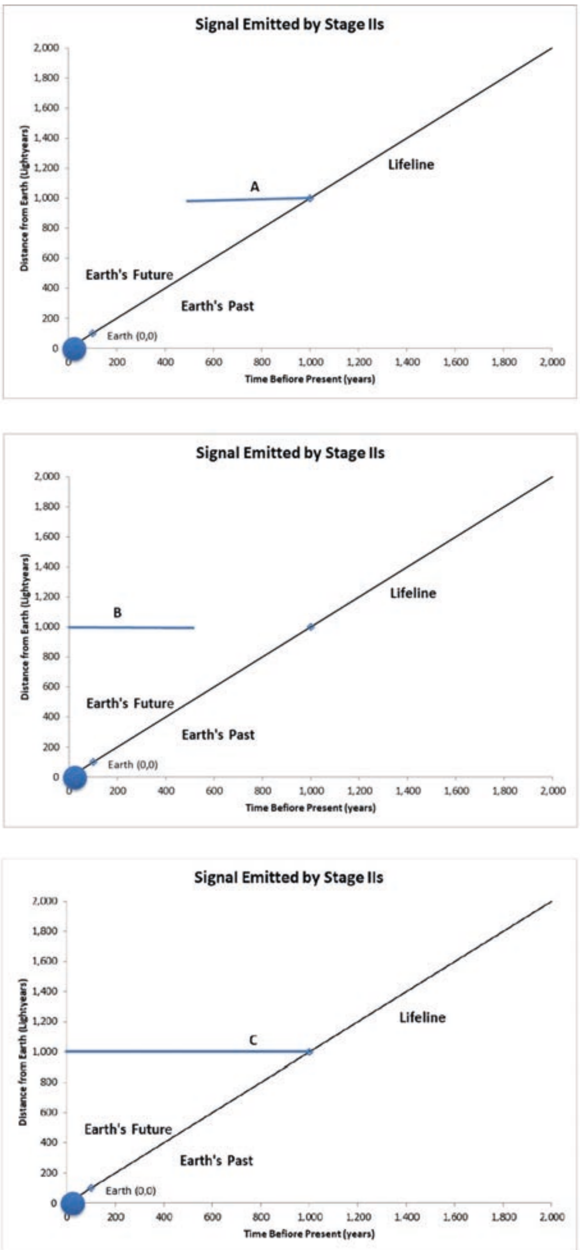

Fig.2 **Light Cones. A (top); B (middle); C (bottom).**

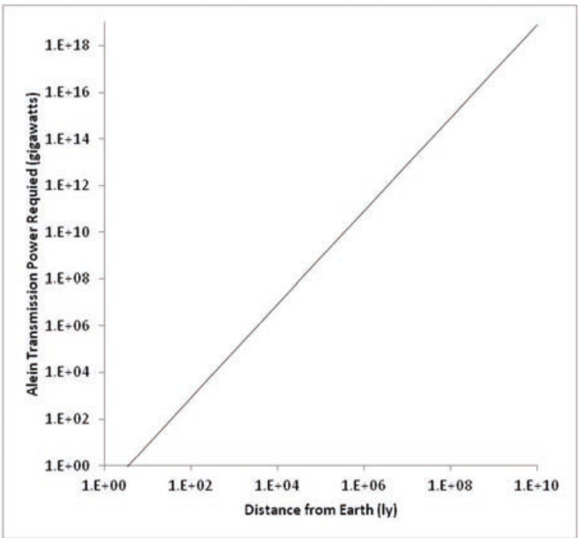

Fig.3 **Required Emitted Power to be Detected on Earth.**

can detect, assuming a one Hz bandwidth and presumed long integration time, is [2]:

$$P_{LOD} = 7.14 * 10^{-26} \left[\frac{W}{m^2}\right] \tag{1}$$

From the inverse square law, the emitted power will drop off as:

$$\frac{P}{4\pi d^2} \tag{2}$$

So, the necessary alien emitted power to be detected is:

$$P_{req} = P_{LOD} 4\pi d^2 \ [W] \tag{3}$$

A log-plot of this is shown in Fig. 3[2]. At 10 *ly* away, the required power is 8.03 gigawatts; at 1,000 *ly* the power increases to 8.03 × 10^4 gigawatts; at 100,000 *ly* (the edge of our galaxy) it is 8.03 × 10^8 gigawatts. The further away, the less likely aliens would build transmitters large enough for us to detect.

7 ALIEN TRANSMITTER'S POWER CONVERSION USING THE IDEAL CARNOT EFFICIENCY

Converting energy from one form to another always results in some dissipation, which will heat the Stage II's atmosphere[3], putting a limit on how much power they can practically emit.

The amount of dissipated energy can be calculated as a function of the overall transmitter energy chain's efficiency. This can next be related to an atmospheric temperature rise.

$$P_{new} = \frac{P_{req}}{\eta} \tag{4}$$

$$P_{waste} = P_{new} - P_{req} \tag{5}$$

$$P_{waste} = P_{req}\left(\frac{1}{\eta} - 1\right) \tag{6}$$

The alien planet's air temperature rise:

$$(P_{waste})t_h = mC_p(\Delta T) \tag{7}$$

Combining equations 3, 6, and 7:

$$t = d = \left(\frac{mC_p\left(\frac{\eta}{1-\eta}\right)}{4\pi P_{LOD}}\left(\frac{\Delta T}{t_h}\right)\right)^{\frac{1}{2}} \tag{8}$$

where $\Delta t/t_h$ is the atmospheric heat-up rate.

The Carnot efficiency is the maximum efficiency possible, and for that reason is used here. Taking solar energy as an example, since it uses the star's surface temperature resulting in the highest possible thermal efficiency; and assuming their star is similar to our sun; their source temperature is

---

[2]SETI's observations are intermittent and cover only portions of the sky. However, since it is assumed Stage IIs broadcast continuously, after a time, SETI will have observed all quadrants.

[3]It is unlikely Stage IIs would use space based transmitters for their intraplanetary communications since it would be much simpler and cheaper to keep the transmitters on the ground.

their star (5,778 K) and their sink is their atmosphere (294 K), yielding an upper limit:

$$\eta = 1 - \frac{T_{sink}}{T_{source}} = 1 - \frac{294}{5778} = 94.9\% \quad (9)$$

Further, Type O through M stars have different temperatures [3] resulting in η ranging from 98.5% to 90.3%. See Table 1.

Fig. 4 shows Stage II's lifetimes as a function of atmospheric temperature rise (ΔT), heat-up time (t_h), and energy conversion efficiency (η). The following Earth-like values were used.

$$m = 5.15 \times 10^{18}\ \text{kg}$$

$$C_p = 0.28\ \text{Whr kg}^{-1}\ {}^{\circ}\text{K}^{-1}$$

A limit can be placed on ΔT by considering the Intergovernmental Panel on Climate Change's (IPCC) view that we need to prevent our atmospheric temperature rise going above 1.5 °C to avoid significant planet-wide damage. While this relates to greenhouse gases, it can be broadly applied to any phenomenon that heats up an atmosphere. After all, what sensible civilization would want to exceed this limit and willingly cause irreversible damage to their planet? Unfortunately, we are now at 1.6 °C [4]. So perhaps 2 °C is a more realistic choice. The increase in radiative cooling to space from this small temperature increase is less than 3% and is ignored.

Next, some restrictions can be placed on t_h. We are tolerating 130 years starting from our 1920 Stage II ascendance to the 2050 IPCC-imposed deadline for net zero greenhouse gas emissions. However, given our poor track record, perhaps 150 years is a more realistic choice.

Using these numbers, $t_h/\Delta T = 75$. In any event, reasonable changes to $t_h/\Delta T$ will not change the analysis' conclusions.

Putting all this together, Table 1 shows the Stage II lifetimes for each star type, along with their proportional distribution. Hence, the lifetimes range from 501 years to 1,331 years with a number weighted average of 537 years.

8 A FUNDAMENTAL LAW OF NATURE MUST EXIST THAT ACCOUNTS FOR STAGE IIS' FATE

The analysis implies that a yet to be discovered fundamental law of nature must exist to explain the absence of Stage IIs. If random events caused Stage IIs absence there would necessarily be outliers. Since none have been found, random events are ruled out which means there must be systemic causes that force all Stage IIs to ascend or collapse. Therefore, an unwavering fundamental law of nature must be at work to affect their total absence.

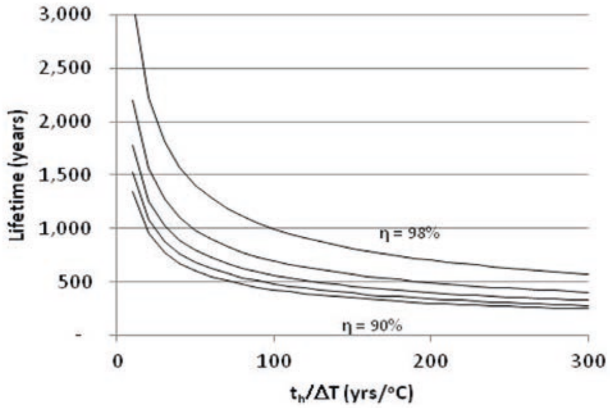

Fig.4 Aliens' Lifetime with Carnot Efficiency In Steps of 2%.

9 WHAT CONCLUSIONS ABOUT US?

Since all Stage IIs must follow this fundamental law, then so must we. Assuming similar timeframes and within the numerous assumptions of this analysis, from Table 1 we have no more than 1,226 years (1,331–105) to 396 years, with a number weighted average of 432 years left, before we either collapse or ascend to Stage III.

But these are upper limits. Using more realistic conversion efficiencies; that of the theoretical limit for multi-junction solar cells at 86.8% (not achievable in practice) and the current maximum laboratory efficiency at 46% (likely to be improved over time)[5]; we may have only 47 to 316 years left (Fig. 5). We are perilously close to the edge.

The analysis suggests our status quo is unsustainable. We will either collapse or ascend in a rather short time.

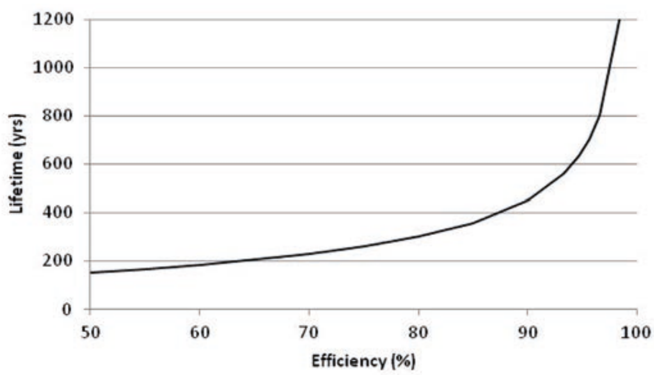

Fig.5 Lifetimes Using Non-Ideal, Realistic Conversion Efficiencies ($t_h/\Delta T = 75$).

TABLE 1: Stage II Lifetimes ($t_h/\Delta T = 75$)

Star Type	B	A	F	G	K	M	Average Lifetime (yrs)
Average temp (K)	20,000	8,750	6,750	5,600	4,450	3,050	
Carnot efficiency	98.5%	96.6%	95.6%	94.7%	93.3%	90.3%	
Lifetime (yrs) and distance (ly)	1331	875	765	694	613	501	
% Stars	0.12%	0.61%	3.00%	7.60%	12.00%	76.00%	
Weighted average lifetime (yrs)	1.60	5.34	22.95	52.74	73.56	380.76	537

10 STAGE II POPULATION DENSITY USING A MODIFIED DRAKE EQUATION

The Drake Equation qualitatively approximates the number of intelligent civilizations in our galaxy and is:

$$N = R_* f_p n_e f_l f_i f_c L \tag{10}$$

It can be made quantitative by redefining it as follows:

- Only detectable Stage II civilizations are included
- Only upper limits are considered in the same fashion as the above Stage II lifetimes are upper limits. Therefore:
  - $f_l = 1$ – all planets that can develop life do so.
  - $f_i = 1$ – all planets that develop life will also develop intelligent life.
  - $f_p = 1$ – all stars will have planets.
  - $f_c = 1$ – all life that develops intelligence will also achieve Stage II at some point and will emit passive radiation.
  - L = Stage II lifetimes, as developed above, are 501 to 1,331 years with a weighted average of 537 years.
- R_* is known at about 6 to 7 per year in our galaxy [6]
- n_e has been estimated to be about 0.4 [7]. This seems optimistic as it requires almost every other star to have had a Stage II civilization. However, it will be used as an upper limit.

Hence, there are at most 1,400 Stage II civilizations in our galaxy with a range of 1,200 to 3,700.

Modeling the galaxy as a disk 100,000 *ly* in diameter and 1,000 *ly* thick, the Stage II's average population density is 1.8×10^{-10} #/ly^3.

11 ALIENS WILL NEVER FIND US[4]

It is unlikely Stage II aliens will detect us since we have been emitting radiation for too short of a time and its leading edge has been highly attenuated. We emerged as a Stage II civilization around 1920, 105 years ago, emitting 100 W [8]. Our emissions will have traveled 105 *ly*, which is only 0.1 % the length of our galaxy and 0.000,000,001% of the universe.

Further, because of the inverse square law, our emissions are only 8.0×10^{-36} Wm^{-2} at 105 *ly* away. So an alien detector would need to be that sensitive, which is nine orders of magnitude better than ours.

It gets worse. Assume the Stage IIs are evenly distributed throughout the galaxy. Multiplying the above Stage II's population density by our volume of influence extending 105 *ly*, yields at most 1.4×10^{-3} Stage II civilizations; quite small and nearly zero.

So for us to be detected, the aliens would need to build a sensitive detector, have some reason to do so, be within 105 light years of Earth, not be detected in spite of their own passive emissions, and with a low probability of even existing that close to us. A highly dubious confluence of events that likely never happened or will happen.

12 HOW WOULD ALIENS INTENTIONALLY EMIT A SIGNAL?

What if aliens wanted to broadcast an asynchronous message to be heard by the greatest possible number of civilizations? How might they? Clearly, the inverse square law limits their abilities since getting their messages deep into space would require building impracticably large transmitters. But why build such a large power source when their star would serve the same purpose? For instance, our sun provides 3.9×10^{17} GW of power, not easily duplicated. So using their star, the problem becomes modulating its output.

One way they might consider is to put a plate in front of the star (semaphoric signaling) that would block some of its light and that could be turned on and off (rotate it along its axis for instance). How big of a plate could we detect? Looking at NASA's transit method to spot exoplanets provides an answer and is currently about 0.27 times the Earth's radius [9]. That would require a plate over 1,000 miles across.

Of course, the number of alien civilizations capable of modifying their star's signal and then of those who would want to, would be much less than the total number of Stage II civilizations. So, while possible, it is unlikely.

13 WHERE SHOULD SETI LOOK?

Section 5 puts a limit on the distance SETI can detect alien emissions to about 1,331 ly for passive emissions. Beyond that it is unlikely aliens would build transmitters powerful enough for SETI to observe.

Detecting intentional semaphoric signals is different since the radiation constraints detailed above don't apply. Perhaps the transit method can be used by looking for artificial fluctuations in a star's output. Our current technology may not be sufficiently sensitive.

Also, aliens could use targeted directional beams such as lasers, to lessen the inverse square law's effect. But that would require the aliens' intent at interstellar communications, which is not the subject of this paper.

It is possible alien civilizations have found ways around the limitations presented here, which is a reason to look further out. This paper is simply commenting on what our current scientific knowledge predicts.

14 SUMMARY

In spite of the optimistic assumptions made, Stage II civilizations will last between 500 years to 1,300 years before either collapsing or ascending to Stage III. This addresses the Fermi Paradox in that it calculates the alien lifetimes necessary for consistency. Using these lifetimes results in at most 1,200 to 3,700 Stage IIs in our galaxy. Given that there are possibly millions of habitable planets in the Milky Way, speaks to either their dismal survival rate or quick ascension.

A bit troubling is the lack of outliers. It is not so much that we haven't detected any Stage IIs, but rather that we haven't detected even one. If Stage II lifetimes followed a Normal Distribution, which is not far-fetched, there should be outliers we

[4]Aliens might find us through our biosphere signature which has been advertising the possibility of a life-bearing planet for millions of years. But this is not a technological signature which this paper focuses on and there would be nothing to distinguish us from all the other possible planets in the galaxy with similar signatures.

would see, which we haven't. Is it possible that collapse or ascension is so complete that no one ever escapes it? In which case, there must be a yet to be discovered fundamental law of nature acting on all Stage IIs to cause their absence.

Building on the previous results, it is improbable Stage II aliens will find us.

Another result shows that aliens, wishing to broadcast an asynchronous signal could easily do so by putting a modulating plate in front of their star.

Also, SETI, in looking for artificial emissions, may be limited to only 1,330 *ly* out.

Most importantly, assuming all Stage IIs follow the same scientific laws and in similar timeframes, we have between 50 to 300 years left before we either collapse or ascend. This analysis suggests our status quo is unsustainable and our civilization will reach a tipping point in a rather short time.

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To: the Editor, *JBIS*
4 August 2025

Re: Why does the Wow! Signal have narrow bandwidth?

In 2021, I published a suggestion that the enigmatic Wow Signal, detected in 1977, might credibly have been leakage from an interstellar power beam, perhaps from launch of an interstellar probe [1]. I used this leakage to explain the observed features of the Wow Signal: the power density received, the Signal's duration and frequency. The power beaming explanation for the Wow accounted for all four of the Wow parameters, including the fact that the Wow observation has not recurred.

At the 2023 annual Breakthrough Discuss meeting, Mike Garrett of Jodrell Bank inquired "I was thinking about the Wow signal and your suggestion that it might be power beam leakage. But it's not obvious to me why any technical civilization would limit their power beam to a narrow band of < = 10 kHz. Is there some kind of technical advantage to doing that or some kind of technical limitation that would produce such a narrow-band response?"

After thinking about it, I have concluded that there is 'some kind of technical advantage' to narrow bandwidth. In fact, it is required for high-power beaming systems.

A Beamer Made of Amplifiers

High power systems involving multiple sources are usually built using amplifiers, not oscillators, for several technical reasons. For example, the Breakthrough Starshot system concept has multiple laser amplifiers driven by a master oscillator, a so-called master oscillator-power amplifier (MOPA) configuration. Amplifiers are themselves characterized by the product of amplifier gain (power out divided by power in) and bandwidth, which is fixed for a given type of device, their 'gain-bandwidth product'. This product is due to phase and frequency desynchronization between the beam and electromagnetic field outside the frequency bandwidth [2].

For power beaming applications, to get high power on a distant target is essential. Therefore, for high power, each amplifier will have a small bandwidth. Then the number of amplifiers is determined by the power required.

So you get narrow bandwidth by using very high-gain amplifiers to essentially "eat up" the gain- bandwidth product. For example, in a klystron, there are multiple high-Q cavities that result in high gain. The high-gain SLAC-type klystrons had gains of about 100,000. Bandwidths for high power amplifiers on Earth are about one percent of one percent, 0.0001, 10^{-4}. The Wow! bandwidth is 10 kHz/1.41 GHz, about 10^{-5}.

So yes, the physics of amplifiers limits bandwidth in beacons and power beams because both would be built to provide very high power. So, with very high gain in the amplifiers, small bandwidth is the result.

This fact about amplifiers is another reason to think that power beaming leakage is the explanation for the Wow. Earth could have accidentally received the beam leakage. Since stars constantly move relative to each other, later launches using the Wow! beam will not be seen from Earth. Therefore, I predicted that each failed additional search for the Wow! to repeat is more evidence for this explanation.

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