

Exploring The Feasibility of Interstellar Propulsion: Assessing Sub-Century Travel to Alpha Centauri Under Modern Constraints

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ABSTRACT: The pursuit of interstellar travel has long pushed the boundaries of physics and engineering and has tested the limits of what humanity can utilize our resources to engineer a vision to escape the bounds of our solar system to reach nearby stars. The target is Alpha Centauri, which is 4.37 light-years away from Earth. Recent research in interstellar rocket designs, both theoretical and experimental, includes nuclear pulse rockets, nuclear thermal rockets, light sail propulsion, antimatter propulsion, and more designs. This review investigates the feasibility of such interstellar propulsion systems and designs, with practical constraints placed upon them, with an emphasis on the availability of resources and the constraints of physics. Through the amalgam of existing rocket propulsion studies and direct calculations using mathematical equations, this paper evaluates several leading propulsion models against the known limits of material endurance, physics, and energy scalability. Preliminary studies suggest that interstellar travel itself is practical based on physics, but achieving it within a century of travel is a vast aspiration beyond our Earthbound limitations, present-day energy production, and our technological limitations. This paper aims to contribute to interstellar exploration research by identifying pathways for feasible sub-century star transit among existing models and designs.

KEYWORDS: Propulsion Systems, Star Transit, Laser Lightsails, Alpha Centauri, Light Years.

■ Introduction

Ever since the dawn of our journey to conquer space, humanity has pursued one question above all others: Are we alone? This was a daring question that we ourselves knew when we started our quest, an epiphany predating all our space efforts. In fact, it was in the 1830s that astronomer Thomas Henderson revealed the vast distance between us and the nearest possible source for life, another star,¹ Alpha Centauri, then approximated at 3.57 light-years (ly), though later approximated at 4.37ly, a large distance we might never reach even with the technology of 2026 and beyond. Figure 1 shows how vast these distances really are, using a scaled measure to compare the distance between Earth and Alpha Centauri.

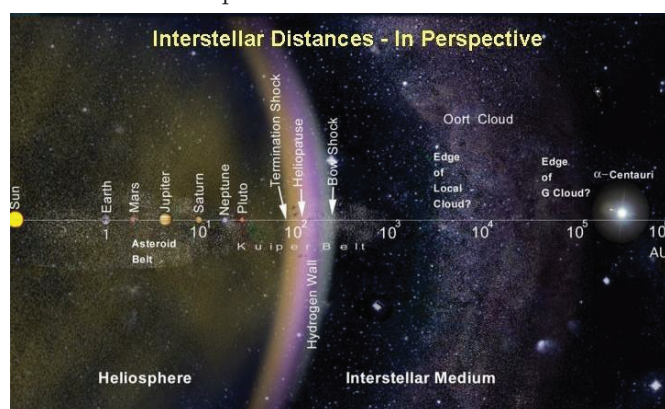


Figure 1: A visualization of the distance from the Sun to A.Centauri. Taken from R.Meraldt & P.Liever, JPL.

But years passed, new ideas came out; some were thought to be absurdities, yet some remain to this day a possibility for interstellar travel, not ruled out by science, formulated by the brilliance humanity has had to offer. These ideas include: nuclear pulse rockets; nuclear thermal rockets; laser lightsails, specifically Breakthrough Starshot;² and other concepts³ which include theoretical/hypothetical models for interstellar exploration, which include antimatter propulsion, warp drives, and many more, which will be explored thoroughly in this paper. Nonetheless, achieving a star transit, especially within our lifetimes, has some requirements. These *requirements* all center on one particular necessity: a speed of around 10% of the speed of light (0.1c), the benchmark for interstellar travel.⁴ This would take us to Alpha Centauri in about 42 years or so with minimal time dilation and relativistic effects, a limitation of technology preventing us from traveling at further percentages of the speed of light (>0.3c). As per the principles of relativistic energy proposed by Albert Einstein,⁵ it requires immense energy—beyond anything practical, considering the resources required for a small probe to reach even a fraction of the speed of light. Calculated by Einstein's formula for relativistic kinetic energy, determined by *Kinetic Energy* ($K.E$)= $mc^2(\gamma-1)$, where the Lorentz factor (γ) is given by $\gamma = 1/\sqrt{1-(v^2/c^2)}$. To put this into scale, using this formula, for a probe of around 1000 kg or 1 tonne to reach even 10% of the speed of light (threshold for relativistic speeds), it would take the object approximately 4.53×10^{17} joules of energy, implausible at our current state. This paper aims to assess both realistic models and hypothetical models of interstellar vessels, with the final goal of determining

the feasibility of all these concepts/models, as well as of what resources we have right now and what resources we may have in the future. This will result in the conclusion of whether or not the form of transport assessed can reach Alpha Centauri within a century. Feasibility in this scenario is defined as whether or not a journey between two stars, specifically our Sun and Alpha Centauri, is possible with a balance of theoretical and practical understandings of physics and engineering at play.

This paper demonstrates that laser lightsails are the most feasible interstellar transit method relative to the other models. This is because it has a comparatively lower resource requirement as well as more practical technology involved; both of these reasons will be explained during the course of the paper, specifically in the conclusion.

This paper is going to analyze the methods of “interstellar travel” proposed by previous scientists, aiming to provide a framework for establishing which interstellar travel method or “vessel” would be the best chance humanity has as of right now to venture into interstellar territory. This paper analyzes multiple interstellar transport vessels, including recently developed models such as the Breakthrough Starshot lightsail and Antimatter Propulsion Rockets. It has a detailed and definite analysis of all such models identified, which separates it from most “older” papers and reviews that are not updated with analyses of modern scientific concepts.

■ Comprehensive Secondary Review

The paper utilizes a systematic literature review methodology to critically analyze and assess the feasibility of interstellar travel vessels, both realistic and highly theoretical vessel designs. The paper analyses prior studies that explore the same topic or a topic within the lines of what has been identified. Key papers are sourced (1970s–2026) from databases such as Google Scholar, BIS, AIAA, PDG, and NASA databases. These papers are filtered by their citation metrics, as well as their relevance to the analysis, ensuring that the papers are not only highly relevant but are taken from reputed journals with high credibility, indicated by a high citation count.

The paper also aims to provide analytical improvements to existing studies exploring the feasibility of interstellar travel with modern data calculations taken from other papers. The paper addresses the gaps identified in previous papers by acclaimed researchers such as I. A Crawford,⁴ Robert L Forward,⁷ and other researchers identified in the paper who are consistently referenced. The paper analyzes a few widespread gaps in identifying the feasibility of interstellar travel, which include:

1) Material Advancements: Considering the improvements in previous analyses with current materials that have increased performance,

2) Modern Developments: The paper keeps in mind modern concepts and ideas newly proposed, such as Breakthrough Starshot (proposed in 2016).

3) Energy Factor: The paper identifies the energy required to produce such vessels and successfully operate them.

4) Hypothetical Models: The paper explores hypothetical vessels, which are rooted in theory rather than practice, such as warp drives, antimatter propulsion systems, and wormhole transit.

The paper aims to use these gaps, paired with identified information in previous papers, to create a new analysis, explaining the feasibility of each possible vessel in relation to one another, and to create a complete analysis.

■ Discussion

This section of the paper analyzes the various propulsion systems and interstellar transit concepts identified as potential prospects for real-life implementation. Each section will use a comprehensive secondary analysis, as well as a detailed overview of whether or not a transit method is practically feasible and mathematically viable.

Laser Lightsails:

This section goes over the concept of laser lightsails, specifically the ones modeled in the project Breakthrough Starshot. The section aims to identify whether this concept is practically feasible, with respect to the availability of resources as of right now and in the future. The mathematical feasibility of laser lightsails will be evaluated in this paper, as well as the resource requirements and theoretical performance for this vessel. A laser lightsail, also known as a laser-pushed lightsail, is an interstellar travel concept that relies on a regular solar sail being accelerated by a gigawatt-scale beam of light, pushing it to nearly 20% of the speed of light ($0.2c$). A lightsail is composed of 2 major parts: a highly reflective sail about a few nanometers thick, similar in purpose to a sailing ship, and a small probe at the center of the sail where crucial parts like communication gear, navigation, and a miniature camera are placed. The most important part of this design is the sail itself, one that is designed to reflect nearly all the rays of light that fall upon it. It works on the principle of light having momentum (p), as discovered by physicist James Clerk Maxwell and later formulated into an equation by Albert Einstein,⁸ given by the formula $E=pc$. The lightsail uses this framework to gain momentum when photons bombard the sail and get reflected, transferring their momentum to the lightsail. However, this process is “too slow” for the lightsail to reach relativistic speeds, with a model lightsail sent into space by the Planetary Society only reaching a maximum of 8.89 km/s or 32000 km/h. This brings in the necessity to increase the number of photons that get reflected by the lightsail, which a laser can do. The light-based laser, composed of a massive amount of photons and hence a massive amount of energy, can accelerate the lightsail to significant speeds using the energy-momentum relation, reaching up to $0.2c$, and able to reach Alpha Centauri within 20 years, as shown in Figure 2.

The following sections will identify the various hindrances that prevent the laser lightsail from being feasible as of right now. These hindrances include:

- i) Mass scaling;
- ii) Laser dynamics and sail material challenges;
- iii) Communications, navigation, and camera systems;

- iv) Collisions with space dust;
- v) Lack of a braking system.

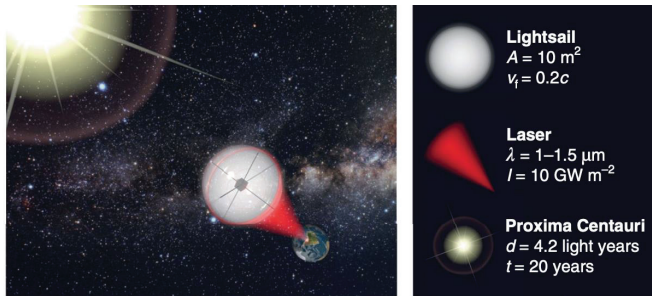


Figure 2: Vision for the Starshot nanocraft. A phased array of lasers, or a light beamer, will propel the nanocraft towards Proxima Centauri. The nanocraft consists of the lightsail, discussed in this Perspective, and a nanochip that will collect data to transmit back to Earth. Taken from Harry. A Atwater's paper "Material challenges for the Starshot Lightsail."

Hindrance: Mass Scaling:

Breakthrough Starshot is a gram-scaled model of a laser-lightsail designed for interstellar travel. The reason for this mass scaling is that it requires significantly less energy to accelerate a probe of a lower mass to relativistic speeds when compared to a probe of a higher mass, as dictated by Einstein's general relativity. This mass is the *first* practical hindrance identifiable when looking at Breakthrough Starshot, with the idea of fitting in all navigation, communication, and camera technologies within a gram scale, unrealistic when thinking of current technology available as of 2026. It is extremely difficult for us to design a probe with a total mass of less than 1 kg, let alone a gram-scale probe, with significant technological advancement required to reduce this mass to the required amount of less than 1 gram.⁹

Hindrance: Laser Dynamics and Sail Materials:

The *second* practical hindrance of the Starshot laser lightsail is the phased array laser itself. Requiring a scale of energy too high, the laser array is something not achievable as of today. In this case, the laser would have to deliver an array with a net intensity of about 10 GW m^{-2} across the sail of an area of 16 m^2 for a 100 - second duration, a currently unachievable feat.⁹

The laser system is likely to be an optically dense phase array of many individual laser elements, such as kW-scale solid-state diode laser-amplifiers.^{10,11} The laser system would have to sustain a consistent array without overheating, without consideration of the atmosphere absorbing energy from the laser. The laser system has to be precisely controlled, and nanoscale engineering has to be conducted to precisely control the trajectory of the probe in the exact direction at which the probe could escape the solar system and go towards Alpha Centauri. Atmospheric refraction should be taken into account when the transition of the medium from the atmosphere (1.0003) to the vacuum of space (1.0000) takes place. This is to precisely control the direction at which the probe is pointed, ensuring that Starshot can travel precisely towards Alpha Centauri with a very low margin of error (<1%) for the directional travel.

The fact that the laser array is ground-based vastly amplifies scintillation. Scintillation is where a material emits light after absorbing high-ionizing radiation, which, in the case of

Starshot, can be a heavy downside. While space-based arrays counter this issue, they increase the price by countless magnitudes. This scintillation causes random intensity fluctuations and beam wander in the laser, distorting the array's focused spot on the probe's sail, which induces lateral accelerations and could potentially curve its trajectory off course. Thermal and material limits also hinder the effectiveness of the array,¹⁰ while the sail is theorized to be a perfect reflector of light; that is not practically possible.¹⁰ This comes into play when considering the large scale of the laser, approximately 10^{16} J or more, with the sail needing to reflect 99.999% of light to prevent the material from heating or being damaged by the concentrated array.¹⁰

The leading prospect material for the sail is a dielectric mirror, one of the few man-made materials capable of reaching and even exceeding the required reflectivity of 99.999%. The mirror works by layering thin, transparent materials with alternating high and low refractive indexes, causing light waves to interfere with it *constructively*, resulting in extremely high reflectivity (>99.9%) for specific wavelengths.

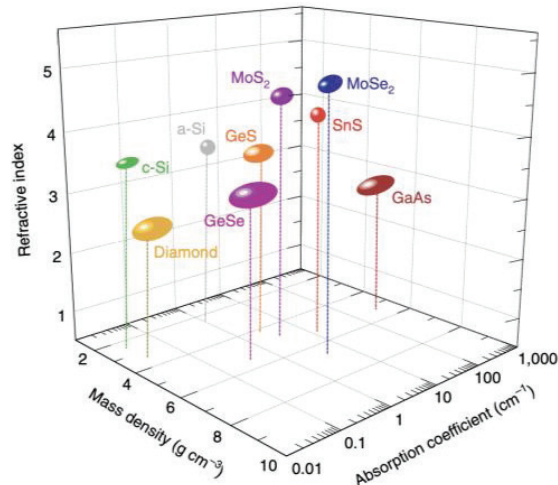


Figure 3: Graph of Refractive Index, Mass-density, and the absorption coefficient of potential materials that can be used for lightsails. Taken from Harry. A Atwater's paper "Material challenges for the Starshot Lightsail."

The drawback with this material is that each layer of the mirror must be a quarter of a wavelength thick, and the mirror itself must have an area of 1 m^2 , something that hasn't been achievable to date. Materials research explores new materials like graphene, a material actively being researched by the Breakthrough Starshot team to this day due to its extremely low thickness (0.34-0.35 nm), low mass (0.77 milligram (mg) per m^2), and its high tensile strength, which could potentially withstand the laser array. The problem is that it isn't very reflective at all (0.1-0.3%), meaning that an additional layer of reflective coatings or reflective material would be required for it to be used on a lightsail. Other materials, despite having low absorption coefficients, low mass densities, and high refractive indexes, have tradeoffs, as illustrated by Figure 3 shown above.⁹

Hindrance: Communication, Navigation, and Camera Systems:

The *third* major problem with the concept of a laser lightsail is the communication and navigation system, which, within

the weight of 1 g, can only communicate weak signals that will be impacted by a Doppler effect due to the high velocity of the spacecraft, causing a shift in the wavelength of the signal emitted.¹¹ This problem can be solved in 1 major way: making the communication system more powerful (stronger signals), which would normally require a bigger antenna to be used. But this isn't possible due to the strict constraints placed on the mass of the probe, with innovations required in the precision of the signal, a sub-arcsecond precision. Potential solutions include gravitational lensing, which is the use of a star's gravity to focus the signal back towards Earth, laser communication, and a relay concept where a line of probes passes the data between each other, a complex and unlikely alternative. The expected data would consist of images of exoplanets, stars, and scientific measurements (such as radiation, magnetic fields, and gases in space). However, fitting all the required sensors into the camera combined with the navigation and communication systems within a single gram is virtually impossible with present technology. When bringing in the idea of a navigation system, a gyro and a star tracker can likely be placed within a gram's weight, but the idea that they can sustain the high acceleration undergone by the probe, which requires radiation-hardened MEMS that can survive 15000 g, is unlikely.¹² When talking about the camera, while medical equipment for surgical purposes can go beneath the gram-mark, none of them meet the image quality requirements for the Breakthrough Starshot mission, which requires a minimum of 2 megapixels (MP).¹³

Hindrance: Collisions with space dust:

The fourth problem that arises is the likelihood of collision with space dust, most likely to occur with interplanetary dust, a factor only limited by the low exposure time of the probe to this form of dust within the solar system. The problem of collisions lessens significantly when entering the Oort cloud and the interstellar space between our solar system and the Centauri system, with an approximate particle density of 1 atom per cubic centimeter, making collisions unlikely. When setting aside the probability of collisions, an actual collision with interstellar and interplanetary dust could cause surface erosion over the sail itself; the erosion largely varies depending on the dust that it collided against, a factor purely determined by probability we ourselves don't know yet, but one that is for sure not likely. The greatest risk comes with passing through interstellar clouds like the Oort cloud, with an approximate density of 10^9 atoms per km^3 , where an impact is not likely but cannot be ruled out.¹⁴

Hindrance: Lack of a braking system:

The *fifth* and last problem identified in this paper is the lack of braking in the probe,¹⁵ meaning the sail would drift past the Centauri system, leaving only a short window for capturing photos. Despite this issue, the braking system is seemingly impossible to place onto the lightsail, considering the mass requirements, with the use of stars' own radiation/gravity to slow down the probe, or otherwise known as photo-gravitational assist, theorized to be one of the solutions to this braking problem. The main challenge arising with this is the

precision required, especially important here considering the unpredictable forces and radiation at play when encountering the star system, requiring precise calculations, measurements, and orientation to achieve this, something practically improbable considering our lack of knowledge of the Alpha Centauri star system.

Despite these problems, the lightsail has emerged as the premier option for humans to send a fully operating probe to another star system, with most of the problems either already solved or close to being solved, far less "hypothetical" and "impractical" as compared to the other transit options, which will be discussed in this paper.

Nuclear Pulse Rockets:

This section reviews nuclear pulse rockets, determining the current feasibility of the design mathematically and practically based on resource availability. The section will utilize a comparative analysis in comparing the resources required for this project to go interstellar with the resources we currently have right now.

Nuclear Pulse Rockets, as envisioned in Project Orion,¹⁶ propel spacecraft by detonating small nuclear fission/fusion bombs behind a pusher plate to generate thrust from expanding plasma. The rocket works by detonating the bomb, which releases massive amounts of neutrons and X-rays that heat the propellant to millions of degrees in Kelvin.¹⁷ This propellant is instantly vaporized and ionized, releasing plasma that expands at 19–31 km/s in the form of a "fireball," which creates impulse when striking the pusher plate and accelerates the rocket. The "fireball" accelerates at 10000 g peaks, which is theoretically too great for a pusher plate to handle. Due to this, a shock absorption mechanism is implemented in the rocket, which utilizes hundreds of hydraulic absorbers to convert these 10000 g peaks into a constant 1–4 g acceleration, distributing force evenly across the vehicle mass. Figure 4 shows the implementation of these systems into the rocket, with a detailed structure of where these mechanisms are implemented into the rocket, helping understand the thrust process through visual demonstration.

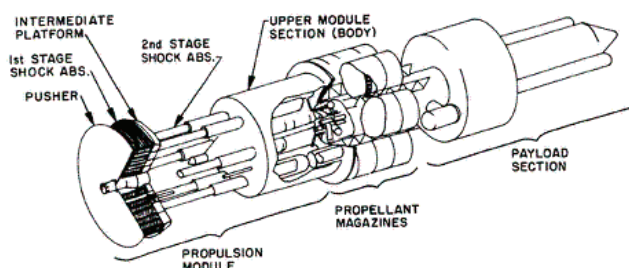


Figure 4: The image above is a detailed structure of a nuclear-pulse rocket with numerous individual components identified, such as the propellant magazines and the payload section, among others. Taken from an article from the "Department of Electrical and Electronic Engineering" titled "nuclear pulse propulsion."

Concepts of nuclear pulse rockets enable interstellar travel by consistent thrust and impulse through controlled nuclear explosions, helping the rocket reach fractions of the speed of light, theoretically up to 10%, but practically up to 5% in ideal conditions.¹⁸ Fission rockets are capped at about 20–100 km/h,

whereas fusion-based rockets range from 0.01-0.1c. This is primarily due to the much higher plasma exhaust velocities, occurring due to fusion's higher energy density and lighter reaction products. Plasma velocity scales as $v_{ex} \propto \sqrt{2E/m}$ where v_e is the exhaust velocity of plasma.¹⁹ The exhaust velocity is much higher for fusion reactions because the mass of the ions ejected/yielded is much lower compared to fission products from U-235 or Pu-239. This can be shown by the reactions themselves, with the example of deuterium and tritium fusion with Lithium-6 Deuteride (LiD) as a fuel being compared to U-235 fission as shown below:

Fusion: ${}^6\text{Li} + {}^1\text{n} \rightarrow {}^4\text{He} + {}^3\text{H} + \text{energy}$ (fission reaction to produce tritium)

${}^2\text{H} + {}^3\text{H} \rightarrow {}^4\text{He} + {}^1\text{n} + \text{energy}$ (Deuterium-Tritium Fusion)

Fission: ${}^{235}\text{U} + {}^1\text{n} \rightarrow {}^{141}\text{Ba} + {}^{92}\text{Kr} + 3{}^1\text{n} + \text{Energy}$ (splitting of uranium nucleus)

These reactions show that fission reactions have ions of much higher masses (Ba-141, Kr-92) when compared to Alpha particles released by fusion reactions, allowing for the exhaust velocity of fusion reactions to be much higher than that of fission reactions.

This can be further shown by the Tsiolkovsky rocket equation,¹⁹ which calculates the maximum velocity achievable by a propellant-based rocket, given by $\Delta v = v_e \ln(m_0/m_f)$, utilizing mass ratios to show why fusion reactions are preferred, where m_0 is the total mass of the rocket and m_f is the final total mass. When comparing fusion-based and fission-based rockets, fusion has a much higher exhaust velocity (v_e) as previously assessed. Now, comparing the two of them, with the final velocity of fission being 25 km/s and for fusion being 3200 km/s, the mass ratio (m_0/m_f) in the Tsiolkovsky rocket equation required for fission rockets is 10^{120} , and the mass ratio required for fusion rockets is 6.52, the latter of which is the only feasible possibility. Assuming that we would want the rocket to travel at 0.01c, which would take approximately ~440 years for the fusion rocket to reach Alpha Centauri, whereas it is impossible for the fission rocket. The energy required for the rocket to travel at such speeds can be calculated using the formula for Kinetic energy, $E_k = (1/2)mv^2$, where v is the exhaust velocity of plasma. A total propellant mass of 5.2×10^9 kg and a velocity of 0.01c is needed for an interstellar-scale version of the nuclear pulse, with 2.3×10^{21} J of energy required for this. A vessel like this would be "city-sized", as described by Project Orion itself.¹⁶ The amount of energy itself is practically implausible, with a scaled estimate of around ~1 million nuclear fusion bombs required to power this gargantuan vessel, each weighing approximately 5 tons. For instance, we only have around 10,000 nuclear fusion missiles on Earth today. Not to mention that the scale of a vessel like this requires immense structural engineering, with the engineering required far beyond our capabilities today. The pusher plate would also have to be able to sustain the plasma "fireballs" expanding at considerably high speeds for nuclear pulse rockets to be a viable form of interstellar travel. The pusher plate aspect is considered impractical as of today due to the lack of any such materials on Earth which can sustain extreme temperature plasma (1,000,000 K+) expanding at rapid velocities.¹⁷ However, if ever this design came

to fruition, ignoring all of the impractical aspects of the design, it could be viable with the use of cryogenic sleeper ships to sustain life for the extremely long travel time of 440 years. It is also possible to send unmanned missions using this form of transit. The travel time could also be improved if we could increase the velocity of the ship from 0.01c to 0.1c, reducing it to almost 44 years with the help of relativistic speeds and massive energy scaling. However, another reason this mission isn't likely to happen is the 1963 nuclear test ban,²⁰ which disallows the use of nuclear bombs in active testing, a major necessity for this program to become experimental, showcasing that political reasons could be at the forefront of why nuclear pulses

This leads to the conclusion that nuclear pulse rockets are currently unviable for *sub-century* transit times to Alpha Centauri, as well as transit to Alpha Centauri on a general basis within the next millennia, when considering the practicalities of the large-scale energy requirements to power the vessel.

Nuclear Thermal Rockets and Nuclear Fusion Rockets:

This section analyses the feasibility of nuclear thermal rockets and nuclear fusion rockets, aiming to identify their practical and mathematical feasibility. It aims to identify the amount of fuel required for these rockets to successfully go interstellar, using that constant to identify whether or not the concept is feasible as of right now.

Nuclear Thermal Rockets:

A Nuclear Thermal Rocket²¹ (NTR) is a rocket ship that uses a nuclear reactor to heat a liquid propellant, typically liquid hydrogen, which gets heated up to extreme temperatures and rapidly expands through a nozzle to create highly efficient thrust by expelling the gas at high exhaust velocities (v_e). This is shown in Figure 5, as shown below, showing how plasma is expelled through the nozzle and how the process is undergone. The primary use of the NTR is to provide a more efficient alternative to chemical rockets via the use of nuclear fission for heat instead of chemical combustion. Liquid Hydrogen is among the most efficient fuels available, consistently performing better in terms of specific impulse compared to other rocket fuels such as liquid oxygen and liquid methane.

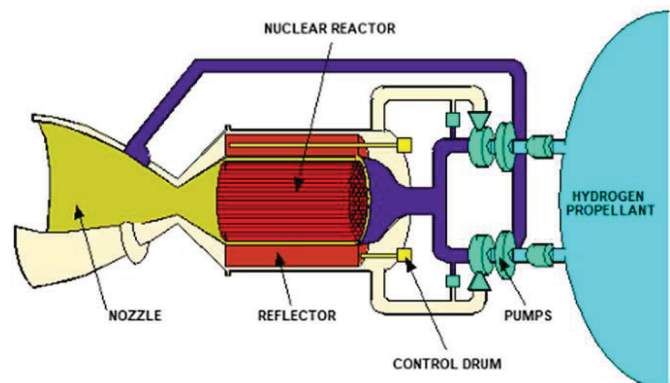


Figure 5: A detailed model of an NTR rocket and its parts aimed at depicting how the rocket generates thrust. Taken from an article by "The Conversation" titled "Nuclear rockets could travel to Mars in half the time – but designing the reactors that would power them isn't easy."

However, an NTR cannot scale up to being an interstellar vessel because liquid propellant cannot achieve high enough exhaust velocities to have interstellar capabilities. As per the Tsiolkovsky rocket equation, it cannot reach the desired velocities to make interstellar travel possible. This is shown by the calculations below:

$$\Delta v = v_e \ln(m_0/m_f)$$

Taking the velocity as 9 km/s with a velocity of 0.1c.

$$(m_0/m_f) = 10^{120}$$

This mass ratio is impossible with current technology and likely even with future technologies. This makes the NTR an unrealistic and implausible vessel for interstellar transit, rather emphasizing its use for interplanetary travel, which is a realistic possibility. Though the energy density of fuels drastically limits the possible expansion of propellant-based rockets to interstellar levels, propellants in the future with GigaJoule/Kg energy densities have the potential to be used for interstellar transit, though none have been discovered as of yet and most likely will not be discovered in the near future. This is also its intended usage, with NASA having plans for using the vessel for Mars transit, among other possibilities.

Nuclear Fusion Rockets (Daedalus Project):

While a traditional propellant-based NTR cannot go interstellar, another nuclear-rocketship was proposed to. That is Project Daedalus,²² a nuclear fusion rocket using deuterium fusion as the core propellant and using nuclear reactors to fuse them at high temperatures to expel helium gas at high exhaust velocities along with plasma. The rocket contains massive spherical tanks containing highly pressurized helium-3 gas and deuterium gas, as shown in Figure 6.

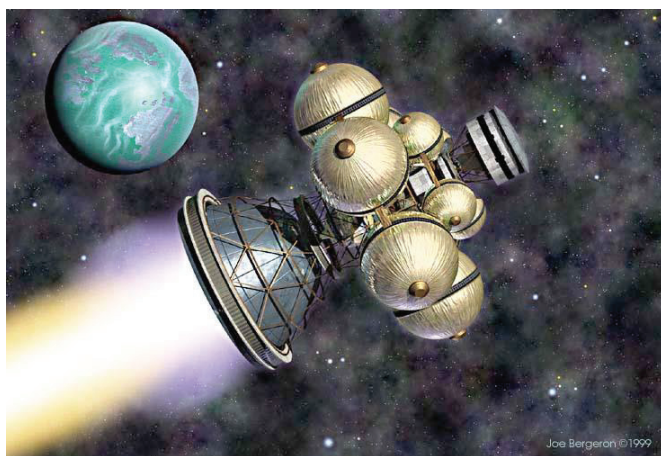


Figure 6: A hypothetical visualization of the Daedalus vessel traveling in space. Taken from an article by “The Velvet Rocket” titled “Project Daedalus.”

While a Daedalus rocket is scientifically feasible with viable mass ratios as per the Tsiolkovsky rocket equation, it requires an extremely large amount of deuterium and helium-3 fuel, approximately 50000 tons.²⁴

This is practically impossible to gather on Earth due to the scarcity of helium-3, so scientists proposed mining this fuel on Jupiter, a gas giant with abundant sources of helium-3. This is the first feasibility challenge of Project Daedalus, as space mining is a concept of the far future, one that we have not

implemented successfully. The scale of space mining is also a massive limitation when considering the requirement of over 50000 tons of fuel. The mining would also take a large amount of time, almost 20 years.

The second challenge is the necessity for pellet microfusion or inertial confinement fusion (ICF),²³ where pellets containing deuterium and helium-3 are compressed and heated to extremely high temperatures using precision lasers to drive fusion.

The lasers would have to be extremely precise for this task, with perfect timing required and high energy recovery, the latter of which has a 17.5% burn-up, or in other words, meaning that only 17.5% of the deuterium and helium-3 undergo fusion.²³ While the remaining 82.5% is unburnt propellant, which still provides momentum to the rocket but doesn't add to the fusion energy of the rocket. In lab conditions, ICF can achieve a maximum of 2-4% burn-up, vastly different from the conditions of a space vacuum. This results in even lower practical burn-up rates, less than 1% when considering the massive scale-up from nanoscale experiments to space vessels operating on kg-scales.²⁴

The vessel could reach approximately 12% of the speed of light and was targeting Barnard's star,²² a target it could reach in 50 years, whereas it could reach Alpha Centauri in about 40 years. All said, the immense scale of this vessel combined with the impracticalities of its fuel usage renders the concept currently impractical; however, with future advancements in helium-3 production, laser internal confinement fusion (ICF), and rocket scaling, we may be able to go interstellar with the Daedalus fusion rocket.

Antimatter Propulsion Systems:

This section aims to analyze the feasibility of antimatter propulsion, identifying the concept's feasibility through the calculation of the mass of antimatter required for rocketships to go interstellar at particular velocities. The review will use this calculation of the antimatter mass required to assess the feasibility of the concept; this is because antimatter can only be obtained in limited quantities, with the quantity being the primary requirement for propulsion systems.

“Antimatter” is defined as the mirror image of normal matter,²⁵ the matter that surrounds us everywhere today. Normal matter consists of protons, electrons, neutrons, quarks, neutrinos, and more.²⁵ Antimatter particles have the same mass as normal matter particles but have opposite charges and different quantum numbers (baryon and lepton numbers). Our solar system and the entire observable universe seem to be composed overwhelmingly of normal matter, rather than antimatter, a problem or “paradox” that has puzzled physicists for almost a century.²⁶ This was due to the fact that most physicists believed that when the Big Bang occurred, antimatter and normal matter should've been equally distributed, which isn't the case as per our current identifications. When Antimatter and Normal Matter meet or “collide”, they “annihilate” and undergo conversion into pure energy in the form of high-energy photons, neutrinos, or other particles.²⁷ This can be modeled by Einstein's energy-mass equivalence, $E=mc^2$, where the energy

released by annihilation can be measured by multiplying the combined mass (m) of the colliding particles by the speed of light squared (c^2). This comes into play for propulsion systems when considering the immense energy produced by annihilation compared to its mass. For a gram total of antimatter and matter, 9×10^{13} joules of energy are produced in annihilation. Comparatively, one gram of enriched nuclear fuel composed of U-235 releases 8.22×10^{10} joules of energy, and one gram of hydrogen fuel releases 1.2×10^5 joules of energy. Due to this significant energy density, matter annihilation is a huge prospect for space propulsion systems, offering more advantages than any other propulsion system available to us.

When talking about propulsion, annihilation becomes a prospect when considering interstellar transit because it is one of the few propulsion systems—if not the only one—that can significantly scale up spacecraft velocities to relativistic scales purely based on meeting energy requirements. The annihilation reaction most viable for space travel is proton-antiproton annihilation, where protons of positive charge collide with antiprotons of negative charge. The reaction is shown below:

$p + \bar{p} \rightarrow 2\pi^- + 2\pi^+ + \pi^0$, where π represents a pion, a primarily unstable particle which then further decays into electrons and positrons, gamma rays (photons), and neutrinos. The primary energy produced by these comes from gamma rays, which are high-energy electromagnetic waves. When used in propulsion, the electrons and positrons produced move at relativistic speeds of about $0.2c$ to $0.3c$; this provides magnetic nozzle thrust in propulsion when these particles are fired out through the nozzle, accelerating the rocket. This can be put into perspective using the relativistic rocket equation,²⁸ as shown below:

$$\Delta v = c \tanh^{-1}(v/c) (\ln(m_0/m_f))$$

where Δv is the final velocity, and v is the exhaust velocity. Using this formula, the required mass ratios can be identified to produce speeds of $0.1c$, $0.25c$, and $0.50c$. For $0.1c$, the mass ratio of m_0/m_f is 1.49, which, in scale, is approximately 24.5 kg of antimatter and 24.5 kg of matter. At this speed, it would approximately take 86 years to travel to Alpha Centauri. For $0.25c$, the mass ratio is 2.78, which, in scale, is approximately 89 kg of antimatter and 89 kg of matter. At this speed, it would take approximately 34.4 years to travel to Alpha Centauri. For $0.5c$, the mass ratio is 9.0, which, in scale, is approximately 400 kg of antimatter and 400 kg of matter. At this speed, it would approximately take 17.2 years to travel to Alpha Centauri.

While Antimatter Propulsion would allow us to reach Alpha Centauri within a century of travel time, it is a technology beyond what we could achieve right now. This is primarily due to the 3 reasons. The first is the lack of production capabilities,²⁹ with CERN, one of the only facilities in the world capable of producing antimatter, and the largest one, only producing 1-2 nanograms of antiprotons annually, at an efficiency of 10^{-9} . This means that 10^{27} joules of energy would be required to produce just a gram of antimatter, let alone the 24.5 kg required for the bare minimum required for sub-century interstellar transit. The second issue is the lack of storage technology, with penning traps only being able to hold micrograms for minutes at a time via magnetic fields.³⁰ The environment in space, due to

charge effects, can cause these antiprotons to leak at larger densities and scales; with kilogram requirements posing significant storage risks due to annihilation from antimatter leakage. The third and last issue is the lack of thrust efficiency, with 40% of energy escaping as unstable gamma rays,³¹ combined with pion beams, as well as muons escaping the nozzle before decay, reducing practical efficiency to about 50%. This results in an increase in mass ratios to accommodate this inefficiency, leading to almost double the amount of antimatter required to produce theoretical thrust, alongside the increased scaling requirements and containment requirements, making it highly unlikely that annihilation thrust can be efficient. This is further reinforced by Figure 7, as shown below, which shows how likely protons and antiprotons are to annihilate at different collision energies. It matches the data shown above by showing that low energies or slow particles give high annihilation rates with pion beams for thrust, as shown by the 0.2 - $0.3c$ speed of relativistic electrons and positrons. High energies make annihilation rates low, explaining why CERN needed vast power to produce a tiny yield of antiparticles. This can be explained by quantum field theory (QFT), which states that protons and antiprotons are bundles of quark fields.³² When quarks and antiquarks touch, they cancel out via the strong force of gluons, releasing energy that forms pions. This explains why cancellation is easier at low speeds and harder at higher speeds, explaining efficient thrust from low annihilation or low speeds, and also why accelerators struggle to make antiprotons.

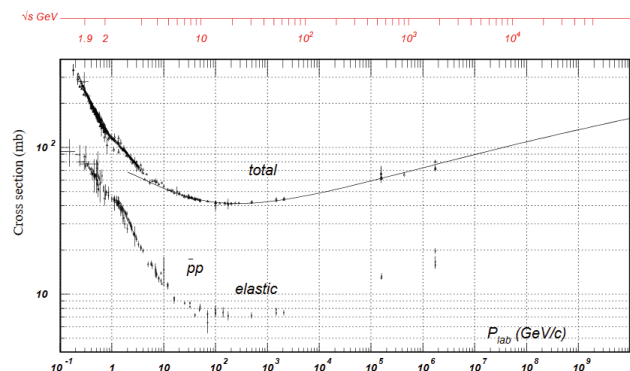


Figure 7: log-log plot of proton-antiproton total/elastic cross-sections (mb) vs energy squared (GeV^2). Taken from an article by “The Physics Stack Exchange” about quantum field theory in antiproton-proton collisions.

Solutions for the problem of producing antimatter are often difficult to find, but one proposed solution is to harvest antimatter from space,³³ which is seemingly abundant in antiprotons formed from cosmic rays and solar flares, found in trace amounts and low densities. Scientists have theorized finding large amounts of antiprotons in Jupiter, while unlikely due to the fact that antimatter annihilates very quickly when in contact with normal matter. This solution would require us to find antimatter hotspots in deep space, with abundant spots in the center of our galaxy, as well as spots near supernovas. This, alongside development in our particle accelerators, especially in improving the efficiency in producing antiprotons and antiparticles, is key to increasing our antimatter production to reach a threshold where we can produce enough for interstellar transit, among other potential uses.

Faster Than Light (FTL) Travel:

This section of the paper assesses the feasibility of hypothetical frameworks for interstellar travel, including wormhole transit and Alcubierre warp drives. The review will analyze how “theoretical” these concepts are, with a practical assessment of whether or not these concepts can become viable in practice, rather than just being rooted in scientific theory.

Faster Than Light (FTL) travel³⁴ is a theoretical and hypothetical framework in which spacecraft can travel at speeds greater than the speed of light (c) of 3×10^8 m/s in a vacuum. FTL is currently considered impossible via relativity, where objects would need to have imaginary mass and infinite energy. This violates causality, which states that an effect cannot happen before its cause, with the violation occurring because FTL travel can allow time travel into the past, causing paradoxes such as the grandfather paradox.³⁵ The grandfather paradox is a thought experiment in which a local contradiction is highlighted: if you travel back in time to before your father was conceived by your grandfather and kill your grandfather, you would never have been born, meaning you couldn’t have traveled back in time to kill your grandfather in the first place, creating an impossible-to-imagine loop or “paradox”. FTL travel would allow us to reach Alpha Centauri and beyond, in near-instantaneous times, due to the nature of FTL travel exceeding the speed of light, allowing for infinite speeds.

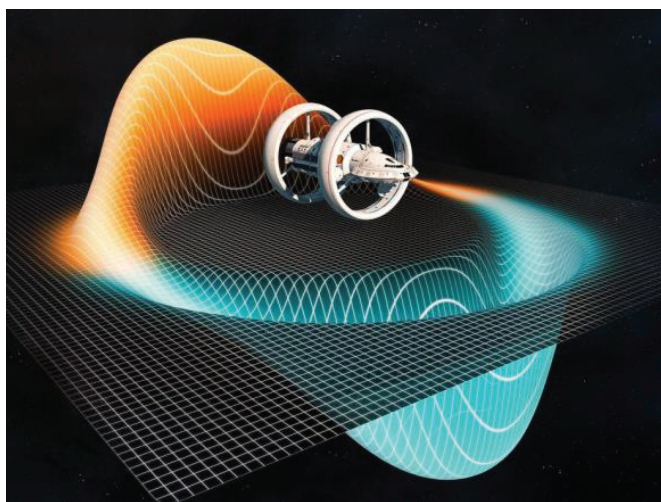


Figure 8: A visualization of the Alcubierre warp drive, contracting Space at its front and expanding it at the back, “warping space-time”. Taken from an article about the warp drive by the Space Newsletter.

The main forms of FTL travel proposed by researchers include the Alcubierre Warp Drive³⁶ and Wormhole Travel.³⁷ The Alcubierre drive proposes that space-time can be warped, contracting space in front of the ship and expanding it at the back of the ship, creating a “warp bubble” that carries the ship along FTL speeds as shown by Figure 8. While mathematically consistent with Einstein’s general relativity, it requires exotic matter³⁷ with negative energy density and immense energy, negative in nature.

The warp drive is often conceived in science fiction, without much practical experimentability, due to its nature of violating the fundamental laws of relativity and causality.

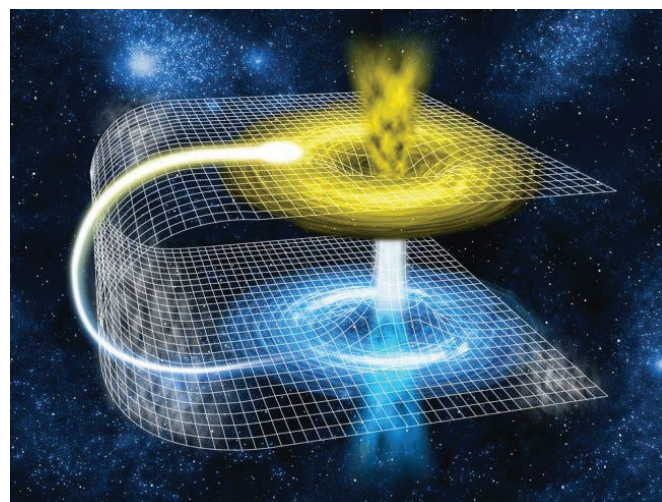


Figure 9: A visualization of a wormhole creating a hole in space-time, allowing for a means to travel between two points in 3D space directly. Taken from an article by “Medium” about the latter.

²²The other solution is wormholes, which act as shortcuts through space-time, essentially creating a direct path between two discrete points in space-time without traveling to them in a direct path, as shown by Figure 9. General Relativity suggests that they would collapse instantly and that they would need exotic matter with infinite energy to be stabilized.³⁶ Wormholes are also not proven to exist, with no observational proof, further adding to their “hypothetical” state of conceivability. Wormholes are often present in science fiction rather than real-life experiments and studies, due to their requirement of exotic matter, another term unproven.

Summary of discussion and comparison between interstellar vessels:

This section of the paper is the summary of all the analyses of the “feasibility of different interstellar space travel vessels and the methods they utilize”. This paper hypothesizes that laser lightsails are the most feasible interstellar transit method relative to both realistic and theoretical models due to the resource scaling and technological requirements being much lower relative to these systems.

Table 1: A comparison of the energy requirements of different interstellar vessels and their respective transit times. Made with the help of the findings in this paper.

Vessel	Energy Requirement/J	Transit Time
Laser Lightsail (starshot)	10^{11}	20-50 years
Nuclear Pulse Rocket	10^{16}	40-80 years
Nuclear Fusion Rocket (daedalus)	10^{20}	50-100 years
Antimatter	10^{17}	100-150 years
Warp Drives	-10^{44} (negative energy)	Instant-Weeks
Wormholes	Infinite	

The hypothesis restated above holds after the analysis conducted. This is because the laser lightsail is not only the vessel that needs the least energy to operate when compared to other models, as shown above by Figure 10; it is also the most practically applicable model among the lot. This is because much of the laser lightsail’s design is grounded in realistic modeling, without any design being explicitly implausible, with the aspect

of the laser array being a bit unrealistic due to the significant energy requirements, but something that can be achieved in the future with significant advancements in energy production. With the development of the laser, the development of reflective sail technologies is advancing, already being developed in the form of a dielectric mirror; this will likely be achieved in the near future with significant scientific advances in the study of reflective materials. The other unrealistic aspect is the controlled mass of only 1 g, with the lack of sufficient parts to build a navigation system, communication system, and a camera being evident. With these implementations in order, the lightsail is proven to be capable of achieving interstellar travel to Alpha Centauri within 20 years at a velocity of $0.2c$, grounded in physics and accurately modeled far less than the sub-century transit requirement posited as a metric of "feasibility" in the introduction. Even though it isn't likely that we achieve a fully operating model of Starshot within our lifetimes, it isn't something too unrealistic. Especially when compared to the other interstellar vessel designs, which is the next part of the discussion. While significant advances are required in the field of science to create a fully functional and operating laser lightsail as described in Breakthrough Starshot, these advances are significantly more rooted in realism when compared to nuclear pulse rockets, nuclear fusion rockets, nuclear thermal rockets, and antimatter propulsion systems.

To start, nuclear pulse rockets are completely unrealistic due to their substantial size and scale, paired with the requirement of up to a million nuclear fusion bombs. This count is not only hyper-unrealistic in terms of our current production capabilities, but also unrealistic in terms of the amount of uranium and plutonium deposits present on Earth, not enough to build a million nuclear fusion bombs. This also pairs with our lack of infrastructure capabilities to build a "city-scaled" vessel, which is required to pursue interstellar destinations such as Alpha Centauri. Alongside this, we would have to discover new materials capable of withstanding high-temperature plasma constantly barraging against them to ensure a working pusher plate is designed to allow the rocket to work. All these factors combine and make a concise point against the possibility of nuclear pulse rockets being used for interstellar travel, due to the implausibility in its design, even though they can theoretically reach Alpha Centauri within a century.

Secondly, Nuclear Thermal Rockets (NTR) are chemical rockets using a fusion or fission reactor to generate thrust by rapidly heating liquid hydrogen. The fact that it is a chemical rocket itself proves that the design isn't feasible for interstellar travel, especially interstellar travel within a century's duration. This is because the liquid propellant cannot produce enough exhaust velocity to accelerate the rocket to the required relativistic speeds. While not shown in the figure above, no NTR rocket will ever be capable of achieving interstellar travel due to the combustion-oriented process of flight.

The other nuclear rocket considered is the nuclear fusion rocket, as imagined in Project Daedalus. The reason this design is also impractical and not feasible is that it relies on laser inertial confinement fusion (ICF), a process that has less than 1% efficiency in terms of fusing deuterium and helium-3 mol-

ecules into sufficient gas to create enough thrust, rendering the exhaust velocities too low to even consider going interstellar. The other reason being that there is no possible way to generate enough helium-3 on Earth to power this rocket, with the idea of space-mining/harvesting being considered but implausible due to insignificant advancements in the field of space harvesting in the current day.

When talking about antimatter propulsion, it has significant groundwork and theory laid upon it to prove that it is possible, with antiproton annihilation creating more than enough energy to take us to Alpha Centauri if enough antimatter is accumulated. Only 89 kg of antimatter is required to take a spaceship to $0.25c$. However, when you look at the key term only, it reveals a lot, because we are only able to produce a few nanograms of antimatter on an annual basis. While antimatter propulsion is the most energy-dense form of propulsion available to us, we simply can't get our hands on enough antimatter to make this system possible. Even if we can scale up antimatter production with the increase in the number of particle accelerators, we wouldn't be able to contain or store the antimatter without risking leakage, which can lead to annihilation and hence major safety concerns. This, paired with the inefficiency of antimatter production, currently at 10^{-9} , makes antimatter propulsion improbable to be implemented in the near future, rendering it unfeasible even though it theoretically can achieve sub-century star transit.

The last option explored, FTL travel — that of the Alcubierre warp drive and Wormhole travel — is heavily rooted in theory but completely neglected in practice. While wormholes and the Alcubierre warp drive do offer us a direct path to a potential interstellar system, they aren't proven, and they might not be proven in the near future, rendering them unfeasible as of right now without any significant scientific advancements in the field. These transit methods require the discovery of exotic matter, matter with negative energies and immense energy, often infinite. FTL travel itself is highly paradoxical in nature, with the specifications of going faster than light with an object of mass impossible as per general relativity, allowing an object to go back in time, creating paradoxes like the grandfather paradox, violating causality, and hence unfeasible as of right now.

This analysis shows that while all of these designs may be unfeasible as of right now, the laser lightsail is the most practical because it is the least impractical, which proves the hypothesis stated in this paper's introduction to be correct, based on the extensive analysis conducted on each interstellar transit vessel.

■ Conclusion

Continuing directly from the discussion, the laser-lightsail has been identified as the most effective and "practically feasible" interstellar travel vessel. Restated from the discussion, the laser-lightsail is the most "feasible" because it has the least energy requirements relative to the other vessels (referenced in Table 1), alongside having the most realistic material requirements, while also having the quickest travel times when compared to the other vessels.

However, other key findings include: Antimatter Propulsion could be the future of interstellar travel if we can find a way to produce enough antimatter and store it. The mass requirements are around 24.5 kg to reach Alpha Centauri in a sub-century time of 89 years. Nuclear Pulse Rockets remain largely impractical due to the large quantity of nuclear-fusion bombs required, on the scale of millions. This is further perpetuated by the fact that no pusher plate can withstand the extreme temperatures of the plasma produced (upwards of a million K) from the fusion process undergone in the rocket; While contained fusion rockets expelling fusion byproducts as propellant, such as Project Daedalus, are mathematically consistent, they require tons of helium-3 fuel. This is not achievable, as we cannot produce large amounts of helium-3 fuel, meaning that we would have to invent new methods of production. Furthermore, laser internal confined fusion (ICF) is a new-modern nuclear fusion method using highly precise methods that is used in this rocket, however it only has an efficiency of around 2-4%, meaning that we would have to improve the efficiency of laser ICF for this to be applicable; Nuclear thermal rockets (NTR) using liquid hydrogen propellant and nuclear fusion to expel this propellant are impossible for interstellar travel. This is because unobtainable amounts of propellant would be required, exceeding 10^{100} kg, for this rocket to be viable. However, NTR can be feasible for interplanetary travel to nearby planets like Mars, Jupiter, and further beyond, as nuclear fusion is extremely efficient with liquid-hydrogen combustion when covering smaller distances within our solar system. Moreover, wormholes and Alcubierre warp drives are purely theoretical prospects for interstellar travel. While they do not exist and cannot exist according to the laws of physics, as they require exotic matter, if they did, they would certainly be the most efficient process for interstellar travel due to near-instantaneous transit times.

All in all, using this explanation, it is understood that laser lightsails (Starshot) are the most feasible as of today, with Nuclear Pulse Rockets following (fusion-based), then the Antimatter Propulsion System, followed by the Daedalus Project model, after which the theoretical models of wormholes and warp drives enter the frame. This clear order showcases that Laser lightsails, while still not being practical as of today, have the most potential to become a realistic solution in the future, with the rest being less practical comparatively.

To conclude, while interstellar travel remains largely impractical as of 2026, it could be feasible with future advancements in physics and propulsion, which scientists predict could happen by the year 2113, keeping our hopes of going interstellar alive, helping us possibly answer the famed question proposed eons ago: are we alone? All in all, from the extensive analysis conducted, it is highly recommended that researchers look into advancing our research on laser lightsails and the Starshot model, working on improving current material and technology constraints, followed by energy practicalities.

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During the preparation of this work, I used ChatGPT and Claude to find sources for my research and to double-check my

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