

Interstellar Probes and Habitable Worlds

A probability model for impacts on other planets and Earth

Dr. Robert Westerman

Purpose. This report estimates how often an uncrewed interstellar probe might reach a habitable planet, and distinguishes that broad possibility from the much more specific question of whether one has impacted Earth. It uses published exoplanet-occurrence estimates, exact probability formulas under stated assumptions, and scenario calculations. It does not treat any unidentified observation as evidence of an alien probe.

Main finding. The enormous number of potential worlds means that a very small per-world success rate could still make at least one event likely somewhere. Current astronomy does not measure the key rate: how often a habitable world produces a civilization that launches probes which successfully reach another habitable world. The equations therefore yield conditional scenarios and thresholds, not a measured probability that Earth was visited.

1. What the planet estimates tell us

Kepler and Gaia data have been used to estimate the occurrence of rocky planets in the habitable zones of Sun-like stars. A 2021 Bayesian analysis reported central estimates of roughly 0.37 to 0.60 rocky habitable-zone planets per star, depending on how the analysis extrapolates beyond the best-observed orbital periods. Its credible intervals are broad, reflecting the small number of detected small planets. “Habitable zone” means conditions may allow liquid water; it does not establish that a planet is actually habitable or inhabited. [1]

Population benchmark	Candidate worlds used here	How to interpret it
Milky Way	300 million	NASA estimate for a defined class of potentially habitable rocky worlds around Sun-like stars. [2]
Observable universe	4×10^{21}	Order-of-magnitude scenario: about 2×10^{22} stars multiplied by 0.2 habitable-zone planets per star in the Frank–Sullivan framework. [3]

These are benchmarks, not precise counts of all habitable planets over the full history of the cosmos. The universe-wide value is especially useful for illustrating how large numbers change the mathematics; it should not be read as a verified census.

2. Probability model

Let N be the number of candidate source worlds, f the probability that one source world produces a civilization that launches probes early enough, n the number of probes it launches, and q the probability that one probe achieves the specified outcome by the present. For the “somewhere” question, q includes reaching and impacting a habitable destination. For the Earth question, q must include targeting Earth specifically.

$$P(\text{at least one event}) = 1 - \{1 - f[1 - (1 - q)^n]\}^N$$

The model assumes independent source worlds and independent probe outcomes after a civilization launches. Inside the braces, $1 - (1 - q)^n$ is the probability that at least one of a civilization’s n probes succeeds. Multiplying by f gives the success chance per candidate source world; raising that world’s failure chance to N and subtracting from one gives the chance of one or more successes overall.

For rare per-world events, define $g = f[1 - (1 - q)^n]$. Then:

$$P(\text{anywhere}) = 1 - (1 - g)^N \approx 1 - e^{-Ng}$$

3. “Has it happened somewhere?”

Using $N = 4 \times 10^{21}$ candidate worlds as the observable-universe benchmark, the following table shows how the result changes with the assumed combined success probability g per candidate world.

Assumed g per candidate world	Probability of ≥ 1 event somewhere
10^{-24}	0.40%
10^{-23}	3.92%
10^{-22}	32.97%
10^{-21}	98.17%

The threshold can also be solved in reverse. For probability P , $g = 1 - (1 - P)^{(1/N)}$, which for small g is approximately $-\ln(1 - P) \div N$. With $N = 4 \times 10^{21}$, a 95% chance requires $g \approx 7.49 \times 10^{-22}$ —about one successful source world per 1.34×10^{21} candidate worlds.

For the Milky Way benchmark $N = 300$ million, the corresponding 95% threshold is about 1.0×10^{-8} , or one successful source world per 100 million candidate worlds. That illustrates the “many opportunities” effect: a tiny per-world probability can yield a high probability of at least one event. It does not tell us whether the real g is above or below the threshold.

4. “Has a probe hit Earth?”

An Earth impact is a narrower event than an impact on any habitable planet. For a simple illustration, suppose there are N candidate sources and destinations, each civilization chooses destinations uniformly, and a probe has a 10% chance of successfully reaching and impacting its selected destination. Then q for Earth is s/N , where $s = 0.10$. For large N and small per-probe Earth-hit probability, the model simplifies to $P(\text{Earth impact}) \approx 1 - e^{-fns}$.

Assumed f	Probes n per civilization	Assumed success s	Calculated Earth-impact probability
10^{-6}	1,000	10%	0.010%
10^{-4}	1,000	10%	1.00%
10^{-2}	1,000	10%	63.21%
10^{-2}	3,000	10%	95.02%

Every entry in the table is a scenario, not an empirical estimate. Neither f , n , nor s is known for extraterrestrial civilizations. The model also assumes uniform target choice; deliberate prioritization of worlds with biosignatures or other detectable features would change the Earth result.

5. Physical constraints on travel and impact

Travel time

A constant-speed estimate is $t \approx d/v$. Using Voyager 1’s reported speed of about 17 km/s relative to the Sun as a reference gives approximately 1.76 million years for 100 light-years and 17.6 million years for 1,000 light-years. These are illustrative straight-line travel times; actual journeys must account for stellar motion, gravity, propulsion, and the fact that the target planet moves during transit. [4]

Targeting Earth

At a distance d , Earth's angular radius is approximately $\theta \approx R_{\oplus}/d$. At 100 light-years, this is about 6.7×10^{-12} radians, or 1.4 microarcseconds. A mission designed for an impact would need a trajectory that intersects Earth's future position. Navigation precision, course corrections, and survival over the journey determine the relevant q ; none has a measured extraterrestrial value.

Impact versus intact arrival

A high-speed impact does not imply an intact or recognizable spacecraft. If the hypothesis requires an artifact to remain identifiable today, the model needs additional terms for surviving impact, geological preservation, and detection. A 2026 review of Solar System technosignature searches notes that impacts can be destructive and that existing surveys have incomplete coverage; identifying a candidate object as artificial is a separate challenge from detecting it. [5]

6. What Bayesian analysis can and cannot add

A Bayesian calculation can average the event probability over distributions for uncertain parameters:

$$P(E | D) = \int P(E | \theta) p(\theta | D) d\theta$$

Here D is the evidence and θ collects unknown rates for life, intelligence, probe launches, targeting, travel, survival, and impact. When those rates are not measured, the posterior depends strongly on the priors assigned to them. Greater computational precision cannot replace missing evidence.

A 2025 Bayesian analysis of Earth's early life history reported odds favoring rapid abiogenesis under its Earth-analog assumptions, but it does not estimate the fraction of habitable planets that develop technology or launch probes. [6] More broadly, an earlier "archaeological" Drake-equation analysis showed how abundant habitable planets could make past technological civilizations plausible while leaving civilization frequency highly uncertain. [3]

Conclusion

The mathematics supports the central intuition: if there are enough candidate worlds, even an exceedingly rare successful interstellar mission can make at least one impact likely somewhere in cosmic history. Under the universe-scale benchmark used here, a combined per-world success rate around 10^{-21} gives a calculated probability above 98% that the event occurred somewhere.

The same calculation cannot establish that Earth was hit. That probability depends on unknown rates of technological life, probe launches, target selection, travel success, and impact. The defensible conclusion is therefore: a probe reaching a habitable planet is physically plausible; its probability somewhere is highly sensitive to unknown rates; and no reliable statistical percentage for an impact on Earth can currently be extracted from exoplanet counts alone.

Sources

- [1] Bryson et al. (2021). "The Occurrence of Rocky Habitable-zone Planets around Solar-like Stars from Kepler Data." *The Astronomical Journal*, 161, 36. Bayesian occurrence estimates and credible intervals. [Open source](#)
- [2] NASA Science (2020). "About Half of Sun-Like Stars Could Host Rocky, Potentially Habitable Planets." NASA's summary of the Kepler–Gaia result and 300-million-world estimate. [Open source](#)
- [3] Frank & Sullivan (2016). "A New Empirical Constraint on the Prevalence of Technological Species in the Universe." *Astrobiology*, 16(5), 359–362. [Open source](#)
- [4] NASA Science. "Voyager 1." Mission overview and spacecraft speed. [Open source](#)

- [5] Lazio (2026). “Technosignatures in the Solar System.” arXiv preprint for IAU Symposium 404; discussion of probe detectability, impacts, and survey limits. [Open source](#)
- [6] Kipping (2025). “Strong Evidence That Abiogenesis Is a Rapid Process on Earth Analogs.” *Astrobiology*, 25(5). [Open source](#)