

What Constrains Life in the Milky Way?

Earth’s Chronology, Radio Silence, and the Empty Sky

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Abstract

No observation yet calibrates the biological factors of the Drake equation, so the useful question is which observations constrain them at all, and how much. We build two models of life in the Milky Way and use them to compare three observations. The first model follows a synthetic census of planets through stellar evolution, water loss, and phenomenological biological transition rates. The second propagates uncertainty in shared population parameters and can update the origin-of-life hazard on Earth’s chronology. At default rates the planet-history model gives 5.15×10^9 worlds where life emerged, 3.09×10^6 that reached technology, and 164 radio-capable systems now; a tenfold slower innovation rate leaves 0.23. Across these scenarios the three observations differ sharply in leverage. A radio null in an illustrative narrow search is nearly uninformative (expected detections $\sim 10^{-15}$). Earth’s early life moves conclusions by an amount that depends strongly on the prior. The absence of conspicuous expansion is decisive: with the default abundance of technological origins, a common-expansion scenario predicts an empty sky with likelihood $\approx e^{-1685}$. Most of the probability that we are alone therefore comes from uncertainty in shared rates, not Poisson chance, and the empty sky forces a choice between rare technological origins and rare or inconspicuous expansion.

1 Introduction

The Drake equation organizes a population estimate into factors; the difficult question is what observations justify for each factor. [Sandberg et al. \(2018\)](#) showed that broad uncertainty distributions can assign appreciable probability to very sparse populations even when mean counts are large. Their numbers depend on those distributions, especially the low-rate tails; the durable lesson is to propagate shared uncertainty rather than multiply point estimates.

Earth’s early life supplies evidence, but it is a selected history. [Spiegel and Turner \(2012\)](#) showed that conditioning on enough time for observers can leave slow abiogenesis compatible with the data. This does not make the chronology uninformative: [Kipping \(2020\)](#) obtained limiting Bayes factors of 2.8 or 8.7 favoring rapid origins, depending on which early-life evidence is accepted. With a proposed 4.2 Ga last universal common ancestor (LUCA), [Kipping \(2025\)](#) reports nominal odds of 13:1 within that analysis. Evidence for rapid origins under suitable conditions does not measure how common those conditions are across planets.

If the biological rates cannot be measured, the productive question is which observations constrain them, and how strongly. We address it with two models, accessible interactively at

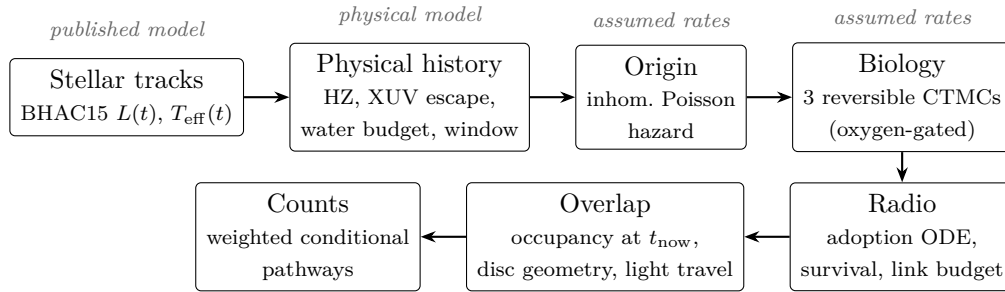


Figure 1: The process-model pipeline. Stellar tracks are published theoretical models. The physical layer uses simplified escape and climate prescriptions. Biological rate scales and response curves are scenario assumptions; the full pipeline is not fitted to astrobiological observations.

roonscape.ai/life. A planet-history model connects stellar and planetary histories to assumed transition rates (Section 2); a probability explorer asks how distributions over population parameters affect outcomes (Section 3). Both are phenomenological: laboratory mechanisms and Earth’s history shape their equations, but nothing calibrates their biological defaults, and the two models answer differently posed questions, so their headline counts need not agree. Section 4 reports conditional results. Sections 5 and 6 then compare three observations—Earth’s chronology, radio silence, and the absence of visible expansion—and find that only the last has decisive leverage.

2 The planet-history process model

The process model computes expected counts over a synthetic census of planets in a present-day habitable-zone sample, following one assumed Earth-like route: lasting surface habitability → abiogenesis → complex cells → complex multicellularity → technological capacity → radio emission → temporal and spatial overlap with a terrestrial observer. The route itself is an assumption; transitions are planet-level first establishments, and completed capacities persist until the habitat closes. Figure 1 summarizes the pipeline.

2.1 Population and physical histories

The census holds $S - 1$ stellar hosts with $S = 10^{11}$, removing one Solar-System host in the population normalization. Four representative masses (0.3, 0.7, 1.0, $1.2 M_{\odot}$) have number shares 0.75/0.15/0.07/0.03. Rocky habitable-zone occurrence anchors are 0.0858 planets per M dwarf from Bergsten et al. (2023) and 0.37 per FGK host from Bryson et al. (2021). Both concern $0.5\text{--}1.5 R_{\oplus}$ planets and conservative habitable-zone definitions, but their stellar samples and extrapolations differ. Applying these values to four Galactic classes, including transporting the latter estimate to the representative K dwarf, is an additional assumption. Host shares and uniform ages on $[0.1, \min(10, t_{\text{track}})]$ Gyr are also scenario choices.

Each planet follows one fixed orbit through the bundled Baraffe et al. (2015) luminosity tracks, with instellation drawn log-uniformly between the Kopparapu et al. (2014) habitable-zone limits evaluated at the planet’s current age, an initial water inventory log-uniform within ± 0.5 dex of one Earth ocean, and a nutrient factor $n \in [0.3, 0.9]$. Sampling uses a shifted Halton sequence; the standard calculation uses 64 cohorts per class (256 planets), 16 conditional

pathways per planet, and 220 base time intervals on a quadratically refined grid with event boundaries (delivery epochs, XUV saturation times) inserted exactly.

The physical layer evolves a water reservoir under XUV-driven, energy-limited hydrogen escape,

$$\dot{M}_H = \frac{\epsilon \pi R_p^3 F_{\text{XUV}}}{GM_p}, \quad F_{\text{XUV}}(t) = 10^{-3} F_{\text{bol}} \times \begin{cases} 1 & t \leq t_{\text{sat}}, \\ (t/t_{\text{sat}})^{-1.23} & t > t_{\text{sat}}, \end{cases} \quad (1)$$

with $\epsilon = 0.15$ and $t_{\text{sat}} = 1$ Gyr (M) or 0.1 Gyr (FGK). While an ocean is condensed, loss is capped by diffusion-limited hydrogen escape through a cold trap ($f_H = 10^{-5}$ in an assumed oxygen background); in a steam state the energy limit applies directly. Earth mass and radius are used by default for every candidate planet. A suitable retained atmosphere and removal of residual oxygen are assumed; bulk atmospheric escape is not calculated. Water mass loss is $9\times$ the hydrogen loss (stoichiometry of H_2O). A time interval is *usable* when the planet sits inside the habitable zone with a condensed ocean holding at least 1% of an Earth ocean; a planet *qualifies* when its longest usable run spans at least 0.2 Gyr. All biology is confined to that window—no future stellar lifetime is credited, and (by explicit modeling choice) radio systems do not outlive habitat closure.

2.2 Origin of life as an inhomogeneous Poisson process

Abiogenesis is a first event of an inhomogeneous Poisson process with hazard

$$\lambda(t) = \Lambda \left[f_L n \min(1, w(t)) + (1 - f_L) n e^{-t/\theta_h} \min(1, w(t)) \right], \quad (2)$$

combining a wet-dry surface route and a hydrothermal route whose opportunity decays with interior heat ($\theta_h = 3$ Gyr); $f_L = 0.3$ is land fraction, $w(t)$ the water reservoir in oceans, and $\Lambda = 10^{\sigma_{\text{site}} + \sigma_{\text{rate}}}$ an *effective establishment scale*, 1 Gyr^{-1} by default. Only the product Λ affects results; its factorization into a site count (10^{12}) and a per-site rate ($10^{-12} \text{ Gyr}^{-1}$) is presentational, and the interface exposes the product as the primary control. Nothing in current origins-of-life chemistry measures Λ ; its consequences are compared with those of later-stage rates in Section 4.2.

2.3 Biological transitions as continuous-time Markov chains

Later transitions are modeled as small continuous-time Markov chains with explicitly reversible intermediates, evaluated by uniformization after holding rates constant on each grid interval: for column generator Q (entry Q_{ji} is the rate from state i to j) with maximal exit rate ν ,

$$p(t + \Delta) = e^{-\nu\Delta} \sum_{k \geq 0} \frac{(\nu\Delta)^k}{k!} \left(I + \frac{1}{\nu} Q \right)^k p(t), \quad (3)$$

truncated at $K = \lceil m + 14\sqrt{m+1} + 32 \rceil$ terms with $m = \nu\Delta \leq 12$ per piece, with numerical accuracy checked against closed-form fixtures. Complex cells use a three-state chain (free-living $\rightleftharpoons$ association $\rightarrow$ integrated cell) at reference rates of one event per Gyr; complex multicellularity uses an analogous chain (ungrouped $\rightleftharpoons$ grouped $\rightarrow$ differentiated); technological capacity uses an n -rung birth-death ladder ($n = 3$ abstract requirements) with cultural transfer efficiency 0.7 and regression rate $k 10^{-0.5} \text{ Gyr}^{-1}$ from intermediate rung k .

Transitions are gated by a planetary oxygen proxy $O(t)$ obeying the toy budget

$$\dot{O} = \max(0, s - \sigma_0 e^{-t/\tau_\sigma}) - \gamma O, \quad t \geq t_{\text{origin}} + \Delta_p, \quad (4)$$

with $O = 0$ before source onset, applied only within the habitat window. The source $s = 1.2n$ switches on a fixed $\Delta_p = 0.3$ Gyr after abiogenesis. The other terms are a geological reducing sink $\sigma_0 e^{-t/\tau_\sigma}$ indexed to *absolute* planetary age ($\sigma_0 = 1.4$, $\tau_\sigma = 1$ Gyr), and first-order loss $\gamma = 0.5 \text{ Gyr}^{-1}$. Gates take the saturating form $g(O) = O/(O + K)$ with stage-specific half-saturation constants ($K = 0.01, 0.1, 0.2$ for cells, multicellularity, and technology), motivated qualitatively by oxygen-requirement and oxygen-suppression results (Mills et al., 2014; Bozdog et al., 2021) but not fitted to them; the default cell gate retains an anoxic floor of 0.2, and a zero-source anoxic scenario is available. The model does not assign a probability to the evolution of oxygenic photosynthesis: under nonzero source settings an oxygen-producing ecology follows abiogenesis after a fixed lag by construction.

For each planet, the origin probability is computed from its integrated hazard. An origin time is then sampled conditional on success, with the success probability retained as a weight. Subsequent stages propagate a CTMC, retain absorption mass by time segment, and draw conditional completion times by bisection of the segment flow. Products of these probabilities weight downstream histories. Sixteen such paths per planetary cohort give 4,096 weighted paths at standard settings. Rare successes can therefore contribute even when ordinary event sampling would produce no successes at all. These are weighted integration paths, not 4,096 equally likely inhabited planets. A larger sample resolves the specified model more accurately; it does not learn the unknown rates.

2.4 Radio emission, survival, and overlap

Technological first passage feeds a commissioning model. Emergent technology enters an engineering queue with lag $t_e = E_b/(P_i \iota) \approx 3.2 \times 10^3$ yr (build energy 10^{20} J, industrial power 10^{13} W, investment fraction 10^{-4}), then acquires radio capability at rate $\alpha = (10^6 \text{ yr})^{-1}$ against pre-adoption death at $\mu = (10^7 \text{ yr})^{-1}$:

$$\dot{w} = j(t) - (\alpha + \mu) w, \quad b(t) = \alpha w(t), \quad (5)$$

where j is the (lagged, death-decayed) influx density and b the commissioning rate. Technology first-passage mass is spread uniformly within each numerical segment before this calculation; segment integrals are evaluated in closed form with series-protected small-argument branches. Commissioned systems survive with exponential lifetime of mean 10^5 yr by default (fixed-length and Weibull wear-out variants are provided), giving a present-epoch occupancy $A(t_{\text{now}}) = \int b(u) S(t_{\text{now}} - u) du$ in closed form for the exponential case. “Radio-capable now” counts systems retaining the capability, including those switched off or pointed elsewhere.

The illustrative detection layer uses an Arecibo-like link budget: a 305 m dish at 2.38 GHz with aperture efficiency 0.7 gives gain 4.05×10^7 and, at 550 kW, an EIRP of 2.2×10^{13} W; a receiving survey with SEFD 10 Jy, 3 Hz channels, 150 s integrations, and SNR threshold 10 yields a sensitivity horizon of 128.2 pc. Sources are distributed in an exponential disc ($R_d = 2.6$ kpc, $h_z = 0.3$ kpc, $R_\odot = 8.2$ kpc); the fraction of the disc within the horizon is 1.27×10^{-5} , and signals are lagged by light travel per distance shell. Fixed-beam pointing ($1/G$ of the sky), duty cycle 0.1 over 3 visits, and fractional band/sky coverage of 10^{-2} each with recovery 0.95 combine to an effective coverage of 6.4×10^{-13} . This is *one narrow hypothetical search*, not a reconstruction of real SETI coverage (Wright et al., 2018; Sheikh et al., 2025).

3 The probability explorer

The second model keeps the classical ladder,

$$N_{\text{active}} = (S - 1) \eta f_h f_\ell f_e f_m f_i f_s \min(L/T, 1), \quad T = 10^{10} \text{ yr}, \quad (6)$$

but treats each factor as an uncertain shared population parameter rather than a known constant: 12,000 seeded draws each select one parameter vector (log-uniform within displayed bounds for the non-origin factors), and expected counts are computed per draw. Uncertainty here is uncertainty about *one* galaxy’s shared parameters, not planet-to-planet randomness; an optional Gaussian copula links habitability, complex cells, and multicellularity without changing their marginals.

3.1 A hierarchical origin prior

The origin factor is decomposed as

$$f_\ell = g \sum_k w_k \left(1 - e^{-X r_k W/5}\right), \quad (7)$$

separating (i) a *required-chemistry fraction* g of otherwise-qualified habitats, (ii) a shared *reference integrated hazard* X over 5 Gyr, and (iii) between-world environmental variation via three classes with weights $(\frac{1}{4}, \frac{1}{2}, \frac{1}{4})$ and hazard multipliers $(10^{-d}, 1, 10^d)$ normalized to unit mean; W is the lifeless opportunity window. Five prior families describe the same reference-environment success probability $p_5 = 1 - e^{-X}$: a Jeffreys Beta($\frac{1}{2}, \frac{1}{2}$) reference benchmark, a bounded log-uniform scenario on $[10^{-6}, 1]$, a uniform benchmark, a log-normal hazard scenario $\log_{10} X \sim \mathcal{N}(0, 2^2)$ with quantile and tail-belief elicitation, and an extreme-width scenario $\log_{10} X \sim \mathcal{N}(0, 50^2)$ inspired by the rate-uncertainty treatment of Sandberg et al. (2018). No family is preferred and none are averaged. Their commitments differ sharply: under the Jeffreys benchmark, 12.8% of prior mass lies outside $p_5 \in [0.01, 0.99]$ and $P(p_5 \leq 10^{-10}) = 6.4 \times 10^{-6}$; under the extreme-width scenario the corresponding outside-mass is 97.9%—a strong commitment about extremes, not a neutral expression of ignorance.

3.2 What would justify a prior?

No prior is neutral. A prior uniform in success probability is not uniform in rate, and the Jeffreys prior for unselected Bernoulli trials is not the Jeffreys prior for our observer-selected timing likelihood. A bounded log-uniform prior on $p_5 \in [\epsilon, 1]$ gives equal mass to each decade, but its lower bound is a substantive claim: it rules out rarer rates rather than admitting ignorance about them, and $\epsilon = 10^{-6}$ is an exploratory cutoff, not a limit from prebiotic chemistry. A log-normal hazard can be motivated by many multiplicative contributions, but neither a two-decade nor a fifty-decade width follows from the name of the distribution. Where data cannot distinguish priors, the honest report is the spread across them; averaging families would need model weights we do not have.

The default explorer fixes $g = 1$, environmental spread $d = 0$, $W = 5$ Gyr, $S = 10^{11}$, and copula correlation zero. Independent log-uniform ranges are $\eta \in [0.1, 0.6]$, $f_h \in [0.1, 1]$, $f_e \in [0.01, 1]$, $f_m \in [0.1, 1]$, $f_i \in [10^{-3}, 1]$, $f_s \in [0.1, 1]$, and $L \in [10^3, 10^7]$ yr. These bounds, as well as the origin prior, determine Table 3.

3.3 Integrating rare-event probabilities

The reported zero-count probability uses a conditional-Poisson approximation, $P(\text{none}) = \mathbb{E}[e^{-N}]$. Rare low-rate scenarios can dominate this integral while being absent from 12,000 ordinary draws. An earlier release suffered this failure (Section 8). The current estimator integrates the origin dimension using adaptive Gauss–Legendre panels, including refinement for an Earth-updated likelihood. It evaluates $\varphi(s) = \mathbb{E}_X[\exp(-10^s \pi(X))]$, where $\pi(X) = \sum_k w_k [1 - e^{-X r_k W/5}]$ excludes the chemistry fraction g . It then integrates independent log-uniform factors (including g) by convolution on a grid in the log multiplier s . The grid integrals use piecewise-linear interpolation and cumulative trapezoidal sums, and intermediate copula correlations retain outer Monte Carlo sampling. Paired grids at $h = 0.01$ and 0.005 diagnose resolution, and unresolved results are flagged.

3.4 An observer-conditioned Earth update

The optional Earth-timing update uses a stylized two-exponential model motivated by observer-conditioned analyses (Spiegel and Turner, 2012; Kipping, 2020), rather than reproducing either published posterior: an origin waits at rate $\lambda = X/5$, a single exponential delay at rate ν then leads to observers, and the data are “life by a , first observers at b ,” conditioned on observers arriving before a habitable deadline $T_\oplus$:

$$\mathcal{L}(\lambda, \nu) = \frac{\lambda \nu e^{-\nu b} c h((\lambda - \nu)c)}{P(t_{\text{origin}} + t_{\text{delay}} \leq T_\oplus)}, \quad c = \min(a, b), \quad h(x) = \frac{1 - e^{-x}}{x}, \quad (8)$$

with $h(0) = 1$ and defaults $a = 0.704$, $b = 4.404$, $T_\oplus = 5.304$ Gyr (habitability from 4.404 Ga, microbial life by 3.7 Ga, observers now) and editable chronology presets down to a 4.2 Ga LUCA scenario (Kipping, 2025). The denominator is evaluated by a positive-term log-space expression stable at equal and extreme rates; as both rates vanish the conditional likelihood approaches $2a/T_\oplus^2$ rather than zero, so extreme slow-origin tails survive conditioning. The update reweights the reference hazard X only— g , environmental spread, and every later-stage fraction remain untouched, and our own existence is not counted a second time as an ordinary planetary success. Unequal delay-mean bounds average conditional likelihoods uniformly in log τ .

4 Results (conditional on stated scenarios)

4.1 Default scenario

Table 1 and Figure 2 give the default-scenario ladder for both models. The process model’s present-day habitable-zone census holds 1.57×10^{10} candidate worlds, of which 8.88×10^9 sustain a qualifying habitability window; 5.15×10^9 ever develop life, 3.09×10^6 ever reach technological capacity, and 163.7 retain radio capability at the present epoch. The illustrative narrow search expects 1.3×10^{-15} detections: with 164 radio-capable systems galaxy-wide, only 2.1×10^{-3} lie within the 128 pc horizon, and pointing, duty cycle, and coverage remove the rest. A null in this search barely changes the likelihood of even this populated scenario.

In the probability explorer under the default Jeffreys benchmark, the median draw holds 7.0 signaling worlds active now, with a central 90% interval of $[6.1 \times 10^{-3}, 5.0 \times 10^3]$ —six orders of magnitude, from “effectively alone” to “thousands”—and $P(\text{no others active now}) = 29.2\%$.

Table 1: Default-scenario ladders. Process-model entries are expected counts over the synthetic census; explorer entries are per-stage medians over 12,000 draws under the Jeffreys origin benchmark (prior, no Earth update). The columns answer differently posed questions and need not agree.

#	Stage	Process model	Explorer (median)
1	Candidate worlds	1.57×10^{10}	2.46×10^{10}
2	Lasting habitat	8.88×10^9	7.74×10^9
3	Life ever emerged	5.15×10^9	3.00×10^9
4	Complex cells	2.34×10^9	2.45×10^8
5	Complex multicellularity	8.43×10^8	7.60×10^7
6	Technological capacity	3.09×10^6	2.22×10^6
7	Radio commissioned / signaling ever	2.80×10^6	7.23×10^5
8	Active / radio-capable now	163.7	7.0

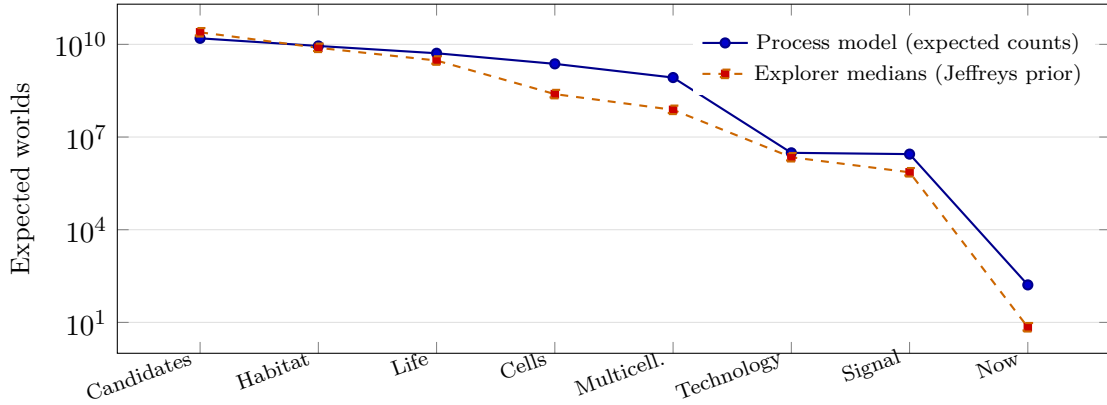


Figure 2: The eight-stage ladder under default assumptions in both models (logarithmic scale). The process-model count falls by about eight orders of magnitude from candidates to radio-capable systems now; the explorer medians fall by about ten. Most of the fall comes from uncalibrated biological and temporal assumptions.

The variance decomposition attributes the spread in $\log N_{\text{active}}$ mostly to temporal overlap (life-time, 39.7%), technological intelligence (22.4%), and abiogenesis (18.7%), with complex cells at 10.1% and all astrophysical factors under 3% each. These shares follow from the assumed ranges, but the qualitative point is robust: the uncertainty that matters is biological and temporal, not astronomical.

4.2 Sensitivity to rate assumptions

Table 2 changes one process-model rate at a time. Origin establishment Λ at 10^{-2} Gyr^{-1} reduces life counts by a factor of 51 and radio-capable systems by 60; lowering cell integration a hundredfold leaves microbial counts unchanged but reduces technology by a factor of 54. Lowering the pre-technological innovation rate tenfold reduces radio-capable systems by a factor of 720, close to the 10^3 expected in the slow-rate limit, where three sequential advances must all occur within a finite window. Neither Earth’s chronology nor radio silence distinguishes the rows of Table 2; Section 6 shows that the absence of visible expansion can.

Table 2: One-at-a-time rate sensitivity in the process model (standard numerical settings, seed 0). Each row lowers a single starting rate; every other input is fixed. $P(\text{none}) = e^{-N_s}$ at the stated rates.

Scenario	Life ever	Technology ever	Radio-capable now	$P(\text{none now})$
Default	5.15×10^9	3.09×10^6	163.7	8×10^{-72}
Origin rate $\times 10^{-2}$	1.02×10^8	4.98×10^4	2.73	6.5%
Cell integration $\times 10^{-2}$	5.15×10^9	5.74×10^4	3.33	3.6%
Innovation rate $\times 10^{-1}$	5.15×10^9	4.13×10^3	0.227	79.7%

Table 3: Signaling worlds active now across five reference origin priors, before and after the observer-conditioned Earth-timing update (12,000 shared draws; medians of expected counts; $P_0 = \mathbb{E}[e^{-N}]$ by the quadrature of Section 3.3). ESS is the Kish effective sample size under the update.

Origin prior	Before Earth timing		Reference origin updated		ESS
	Median	P_0	Median	P_0	
Jeffreys Beta($\frac{1}{2}, \frac{1}{2}$)	7.0	29.2%	11.1	25.7%	10,017
Bounded log-uniform $[10^{-6}, 1]$	0.023	70.0%	0.032	67.9%	11,713
Uniform in p_5	9.7	25.8%	12.1	24.3%	11,030
Log-normal hazard $\mathcal{N}(0, 2^2)$	4.9	33.6%	14.4	24.7%	8,427
Extreme width $\mathcal{N}(0, 50^2)$	0.039	57.7%	8.4	33.3%	8,657

4.3 Prior robustness and the Earth update

Table 3 spans the five origin priors for the “active now” outcome. Before any Earth evidence, the alternative prior families move the median from 0.023 (bounded log-uniform) to 9.7 (uniform) active worlds and the probability of galactic solitude from 25.8% to 70.0%. For the probability that no other world ever developed life, the same five priors give 1.8×10^{-10} (uniform), 7.0×10^{-6} (Jeffreys), 5.8×10^{-7} (log-normal), an underflow ($< 10^{-300}$; the bounded scenario’s 10^{-6} floor forces roughly 10^3 or more expected living worlds under the other default bounds), and 42.0% under the extreme-width scenario—the last recovering the qualitative conclusion of Sandberg et al. (2018) that wide rate uncertainty places substantial mass on an empty galaxy, though our decomposition borrows only their rate distribution and cannot reproduce their published figures.

Earth’s chronology is informative, but how informative depends on the prior. It matters most where the prior puts mass on very slow origins: the extreme-width prior’s solitude probability falls from 57.7% to 33.3% and its median rises about 200-fold, while the log-normal case falls from 33.6% to 24.7% and the Jeffreys case only from 29.2% to 25.7%. After the update, the five priors still span 24%–68% solitude. Some prior dependence must remain, because the conditional likelihood stays finite as origins become arbitrarily slow. These updates assume a 1 Gyr observer-delay mean; other delay assumptions and chronologies change them.

4.4 Numerical resolution is not scientific uncertainty

Table 4 compares the standard process calculation with a doubled time grid, a tripled planetary sample on that grid, and a shifted quasi-Monte Carlo sample. The listed outcomes move by up to about 11%, and most by a few percent. That is numerical error at fixed assumptions, orders of magnitude smaller than the scientific sensitivity in Table 2.

Table 4: Numerical-resolution runs of the process model at default assumptions. Differences measure approximation sensitivity only; the scientific assumptions are identical across rows.

Run	Life ever	Technology ever	Radio-capable now	Settings
Standard	5.152×10^9	3.085×10^6	163.7	256×16 , 220 steps
Finer time grid	5.196×10^9	3.135×10^6	168.1	256×16 , 440 steps
Larger sample	5.330×10^9	2.923×10^6	158.2	768×16 , 440 steps
Shifted sample	5.207×10^9	3.425×10^6	171.7	256×16 , 220 steps, seed 1

5 Solitude is a statement about shared rates

5.1 A large expected count does not imply near-certainty of company

Let θ denote shared uncertain parameters, and D the data used to update them. With conditional Poisson counts,

$$P_0 = \int e^{-N(\theta)} p(\theta | D) d\theta \geq e^{-\mathbb{E}[N|D]}. \quad (9)$$

The inequality follows from convexity and needs no hundred-decade prior. For illustration, assign 99% weight to the default process scenario ($N_1 = 163.661$) and 1% to the slower-innovation scenario ($N_2 = 0.227281$). The mixture has $\mathbb{E}[N] = 162.027$, yet

$$P_0 = 0.99e^{-163.661} + 0.01e^{-0.227281} \simeq 0.00797, \quad (10)$$

about 0.80%, against 4.3×10^{-71} from exponentiating the mean (the weights are a thought experiment, not a posterior). At any single rate vector with a large count, solitude is essentially impossible: the default alone gives 8.4×10^{-72} . The explorer’s 29% therefore comes almost entirely from uncertainty in shared rates, not from Poisson chance. Billions of planets reduce sampling noise at a given rate but leave uncertainty in that rate untouched, which is why the question “are we alone?” reduces to a question about priors on a few rates. Figure 3 (left) shows how little weight on a sparse scenario it takes.

5.2 Heterogeneity can reduce prevalence at fixed mean opportunity

For a planet with integrated origin hazard X , success has probability $p(X) = 1 - e^{-X}$. Concavity implies

$$\mathbb{E}[1 - e^{-X}] \leq 1 - e^{-\mathbb{E}[X]}. \quad (11)$$

If every planet receives $X = 1$, 63.2% develop life. If only a fraction f receive all the opportunity, with $X = 1/f$ there and zero elsewhere, the mean hazard remains one but prevalence becomes $f(1 - e^{-1/f})$. At $f = 0.1$, only 10.0% develop life. Extra opportunity on already fertile worlds cannot compensate for barren worlds once success saturates. This illustrative two-environment example is separate from the explorer’s three-class parameterization. An observer-selected planet will preferentially occupy a successful environment; its history does not directly reveal the frequency of such environments.

5.3 A radio null carries almost no information

For search expectation $\mu(\theta)$, a zero-detection likelihood is $e^{-\mu(\theta)}$ under a Poisson search model. A null shifts odds only when competing scenarios predict materially different μ . The default

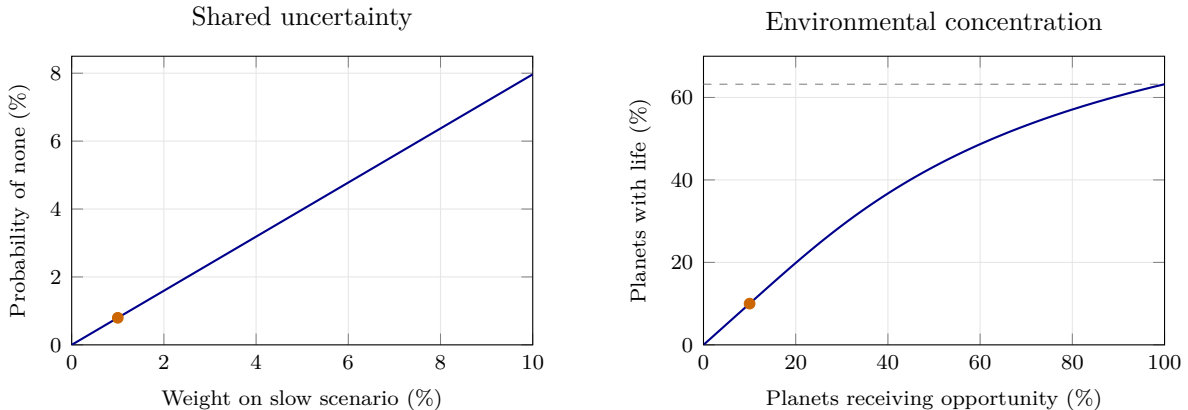


Figure 3: Two worked examples, not fitted distributions. Left: mixing the two process scenarios raises P_0 to 0.80% at just 1% weight on the low-count scenario. Right: concentrating a fixed total hazard lowers population success; the dashed line is success with equal opportunity on every planet. Orange points mark the examples in the text.

hypothetical radio search has $\mu \simeq 1.3 \times 10^{-15}$, so a null is almost certain even in the populated default scenario; geometry alone leaves only 0.00207 radio-capable systems within the instrument horizon, before pointing, duty cycle, and coverage. Real SETI surveys differ in detail (Wright et al., 2018), but narrow searches for short-lived, local emission share this weakness. Expansion is different, as Section 6 shows.

5.4 A second origin is different from another descendant

Earth’s many species do not constitute independent trials of abiogenesis. A confirmed independent origin could constrain rare-origin hypotheses much more strongly than an additional descendant of the same origin (Spiegel and Turner, 2012). Such an update would require evidence against contamination or shared ancestry, plus a likelihood for how the target was selected and how life was detected. It would update origins under those conditions; it would not by itself establish that complex cells, intelligence, or persistent technology are common.

6 The empty sky and persistent expansion

6.1 Why radio lifetime is the wrong bottleneck for probes

The step from radio technology to autonomous industry may be far easier than the evolutionary transitions before it. The model’s three innovation rungs all occur *before* technological capacity, and short radio lifetimes do not imply short lifetimes for descendants that have left the home world.

Self-replication requires a reproducible industrial system that extracts resources, makes components, supplies energy, repairs machinery, and launches descendants; Borgue and Hein (2021) present a partially self-replicating concept that still imports components. The probability and delay are therefore uncertain. That uncertainty does not justify a sequence of tiny independent penalties, because engineering capabilities and decisions to expand are correlated. Reluctance by most civilizations also does not help if a persistent minority can spread.

An idealized relay with hop distance d , cruise speed v , and replication/launch delay τ advances at

$$v_f = \frac{d}{d/v + \tau}. \quad (12)$$

For $d = 5$ light-years and $\tau = 1,000$ yr, crossing 100,000 light-years takes 120, 30, or 21 Myr at cruise speeds $0.001c$, $0.01c$, or $0.1c$, respectively. This kinematic illustration assumes reliable hops and an unbroken chain of usable targets; settlement simulations show both rapid expansion and partially occupied regimes (Carroll-Nellenback et al., 2019). Either way, a front need not approach light speed to cross the Galaxy many times over in billions of years.

6.2 Why historical origins matter

The relevant population is the expected number M_{old} of technological origins old enough to launch persistent descendants, not the 164 systems radio-capable now. Even the default 3.09 million ever-technological worlds are not yet this population: some are too young, and the present-day habitable-zone selection excludes other possible historical origins.

As a diagnostic only, suppose their count is Poisson with mean M_{old} and origins are independently marked, conditional on the chosen parameters. Each has a joint probability q_{eff} of producing expansion that would reach us or create a signature recognized by now. Under these assumptions,

$$P(D_{\text{exp}} \mid M_{\text{old}}, q_{\text{eff}}) = e^{-M_{\text{old}} q_{\text{eff}}}, \quad (13)$$

where D_{exp} denotes no recognized expansion. If, illustratively, all 3.085×10^6 default technological origins qualified as old, $q_{\text{eff}} = 10^{-4}$ would give $P(D_{\text{exp}}) \simeq 10^{-134}$. Maintaining a likelihood of at least 0.05 would require $q_{\text{eff}} \lesssim 9.7 \times 10^{-7}$. More generally, the empty sky requires $M_{\text{old}} q_{\text{eff}} \lesssim 3$: it constrains the *product* of technological abundance and expansion propensity, and cannot say which factor is small.

A full calculation needs origin times and positions, launch delays, expansion behavior, interactions, an observation model, and selection of our observer location. If O denotes our existence and the chosen sampling rule for observers, the update takes the form $p(\theta \mid D_{\text{exp}}, O) \propto p(D_{\text{exp}} \mid \theta, O)p(\theta \mid O)$; the unconditioned expression in Eq. (13) cannot simply substitute for this likelihood. The implemented branch below separates the coverage calculation from additional sky evidence. It does not supply the observer-conditioned prior $p(\theta \mid O)$.

6.3 Galactic occupation and visibility

Every weighted technology-transition segment contributes to a histogram of lookback times. A transition at planetary age a on a planet of present age A_p occurred $A_p - a$ ago; the earlier planet-age formation plot is not a Galactic birth history. Let $B(t)$ be the potential technological-origin rate at lookback time t , before external occupation, and let $B_{>}(t) = \int_t^\infty B(u) du$. Positions follow the existing normalized Galactic density $\rho(\mathbf{x})$. Conditional on these intensities, potential origins form a space-time Poisson process.

A single joint probability q marks an origin as producing a persistent expanding lineage after delay δ . All fronts expand permanently at the same speed v_f . Descendants survive home-world habitat closure and radio shutdown. Occupation prevents later independent origins and launches. Under these assumptions, potential launches suppressed inside an earlier front are geometrically redundant: they cannot outrun it. Integrating the union of fronts therefore handles overlap without counting hypothetical suppressed launches as actual civilizations.

The expected number of potential fronts that can reach position $\mathbf{x}$ by lookback time t is

$$A(\mathbf{x}, t) = q \int \rho(\mathbf{y}) B_{>} \left(t + \delta + \frac{|\mathbf{x} - \mathbf{y}|}{v_f} \right) d^3 y. \quad (14)$$

The probability that this location remains free is $e^{-A(\mathbf{x}, t)}$. Writing its population average as $F(t) = \int \rho(\mathbf{x}) e^{-A(\mathbf{x}, t)} d^3 x$, the expected independent technological origins and established expanding lineages are

$$N_{\text{independent}} = \int_0^\infty B(t) F(t) dt, \quad N_{\text{launch}} = q \int_0^\infty B(t + \delta) F(t) dt. \quad (15)$$

These are unconditional population expectations. Actual accepted origins and launches are correlated by occupation; we do not apply a Poisson zero-count formula to their expected counts.

For the conspicuous benchmark, all occupied domains emit immediately recognizable persistent light, with complete sky recognition. Let $r = |\mathbf{x}_\odot - \mathbf{y}|$. The potential launches visible now but outside the Solar arrival cone have exposure

$$V_{\text{out}} = q \int \rho(\mathbf{y}) [B_{>}(\delta + r/c) - B_{>}(\delta + r/v_f)] d^3 y. \quad (16)$$

Conditioning on the Solar location remaining unreached leaves these disjoint Poisson regions independent, giving

$$P(\text{empty sky} \mid \text{Sun unreached}, \theta) = e^{-V_{\text{out}}}. \quad (17)$$

The separate quantity $e^{-A(\mathbf{x}_\odot, 0)}$ is a counterfactual location-coverage diagnostic. Multiplying it into an already observer-conditioned likelihood would reuse that selection; including it in a joint experiment at a fixed, unconditioned location is a different calculation. Neither expression alone specifies a posterior over the scenario parameters. In inconspicuous mode, the branch supplies no sky evidence while retaining physical occupation.

The starting scenario sets $q = 0.1$, $\delta = 10,000$ yr, cruise speed $0.01c$, hop spacing 5 light-years, and replication time 1,000 yr. The resulting $v_f = 0.00333c$ gives a 30 Myr ideal Galactic crossing. Applied to the default 3.085×10^6 potential technological origins, occupation leaves an expectation of 10.55 independent origins and 1.055 established expanding lineages. Solar arrival exposure is 3.068×10^5 and visible-only exposure is 1.685×10^3 : given an unreached Sun, the conspicuous benchmark predicts an empty sky with likelihood approximately e^{-1685} . This is the strongest evidential statement in the paper. The default biological scenario, combined with a 10% chance of conspicuous expansion, is ruled out by the empty sky. Escaping the refutation requires far fewer old technological origins than the default, or expansion that is much rarer, later, slower, or less visible. The 10% launch chance is an illustration, not a preferred prior. What is robust is that the absence of visible expansion constrains these parameters far more tightly than Earth's chronology or radio silence.

Continuous source-density quadrature avoids artificial empty neighborhoods from a finite source sample, and adaptive time integration resolves the short interval before early expansion suppresses further origins. Finer spatial integration changes the four principal count and exposure quantities by at most 0.17% in this scenario.

6.4 What Hanson and colleagues infer

[Hanson et al. \(2021\)](#) model civilizations that expand persistently, visibly transform occupied regions, and exclude later independent origins there. A power law describes candidate appearances, and treating our cosmic date as representative of potential expanding origins calibrates

its timescale. Expansion cuts off future origins, offering an explanation for apparent human earliness. With conspicuous territories, the absence of visible domains favors fast fronts: their light arrives only shortly before occupation, limiting visibility to an unoccupied observer. Their scenarios yield roughly 40–50% occupied cosmic volume now and encounters in about 0.2–2 Gyr if our descendants expand. In their reference calculation, expecting even one other historical Milky Way civilization requires a non-grabby-to-grabby ratio of order 10^4 or larger. These are conditional results, not measured frequencies. “Quiet” here does not mean radio-silent: it means failing at least one defining property of persistent, conspicuous expansion. Hanson explicitly clarifies that the associated $\sim 10^{-4}$ transition chance is not his estimate of humanity’s chance of becoming grabby (Hanson, 2024).

Our model has not reproduced or quantitatively tested these conclusions. Its uniform host ages capped at 10 Gyr cannot assess the future distribution of cosmic origins. Its arbitrary three pre-technology rungs do not estimate the hard-step exponent in Hanson’s appearance law. Its M-dwarf water-loss histories also do not establish whether very long-lived future planetary environments can support independent observers. Our large default population and Hanson’s sparse one therefore reflect different models and conditioning, not an empirical disagreement—though the calculation above shows our default is hard to reconcile with an empty sky if expansion is common and conspicuous, which is the tension Hanson’s model is built to address.

Two assumptions deserve separate scrutiny. First, the inference from our data depends on the observer reference class, prior, and assumptions about future habitability. Second, successful expansion need not visibly transform most matter or starlight. Friederich and Wenmackers (2023) develop these objections; they limit the cosmic inference without showing that interstellar probes are impossible. A sparse network of probes and a conspicuous galaxy-transforming civilization require different detection likelihoods.

Our Galactic branch lets technological abundance, expansion propensity, delay, speed, and conspicuousness vary, but a cosmological extension would also need an appearance history, a future-habitability model, and an explicit observer reference class. If expansion is nearly inevitable and conspicuous, the empty sky implies that old technological origins are rare. Adding unsupported independent failure factors would hide that conclusion rather than escape it.

7 What is identified, and what is not

The distinction is between the evidence for a mechanism, the calibration of its parameters, and the numerical accuracy of a calculation made with them.

Literature inputs and physical models. Occurrence anchors are survey-derived extrapolations with specific domains (Bryson et al., 2021; Bergsten et al., 2023). Stellar tracks are theoretical evolution calculations (Baraffe et al., 2015); habitable-zone boundaries are climate-model results (Kopparapu et al., 2013, 2014). Escape, link-budget, and disc-geometry prescriptions add further approximations.

Biological calibration. The origin establishment scale, transition and reversal rates, oxygen-production onset, and gate constants have no fitted population-level likelihood here. Nor are the explorer’s later-stage fractions inferred from observations. Earth chronology and laboratory experiments constrain some mechanisms and conditional timing, but do not determine this full parameter vector. The interpretation of long evolutionary delays is also contested: Snyder-Beattie et al. (2021) infer rarity under hard-step assumptions, while Mills et al. (2025) propose environmental gating as an alternative; neither settles whether the steps are hard.

Future biosignature surveys or an independently established second origin could supply likelihoods for parts of the model, but only with explicit target selection, detection efficiency, false-positive rates, and dependencies between environments.

8 Validation

Four LLM critics reviewed statistical inference, biological evidence, presentation, and comprehension on 12 September 2026; this was an internal audit, not peer review. Two findings changed the models.

Rare-tail estimation. An earlier release estimated $P(\text{no other life})$ under the log-normal prior as 4.34×10^{-63} by Monte Carlo; independent Simpson integration gives 5.785×10^{-7} . The draws had missed the low-rate tail that controls the expectation, a 56-order-of-magnitude error that ordinary sampling diagnostics would not reveal. The current estimator (Section 3.3) gives 5.78559×10^{-7} , a relative difference of 2.4×10^{-5} .

Oxygen-proxy causality. The reducing sink was originally indexed to time since abiogenesis, so delaying the origin of life shifted the planet’s geology. It now uses absolute planetary age, checked against closed-form solutions (maximum relative error 9.9×10^{-9}).

Seven validation scripts cover ladder arithmetic, physical and radio calculations, biological first passage, the oxygen clock, origin priors and Earth likelihoods, zero-count integration, and presentation. An expansion suite adds 771 assertions, including conserved birth mass, analytic cone fixtures, disabled and inconspicuous expansion, and spatial and temporal refinement. These check the implementation, not the scientific defaults.

9 Limitations

The population is a present-day habitable-zone sample, excluding formerly habitable worlds outside that selection. The assumed Earth-like route omits alternative biochemistries and technologies; aquatic-only technology is not a separately implemented pathway. Completed native biological capacities persist until habitat closure, and native radio systems do not survive that closure. Neither workspace includes a Galactic star-formation history. The expansion branch assumes permanent, equal-speed fronts; finite-lived lineages, settlement gaps, moving stars, and heterogeneous speeds require other models. Its visibility likelihood is an ideal benchmark, not a likelihood for actual SETI or artifact searches. The explorer assumes approximately uniform origin times over 10^{10} yr for temporal overlap, and its Earth update uses a simplified constant-hazard chronology. The process model has no posterior over its biological rates or expansion parameters. The original ladder remains a counterfactual native census without occupation; it does not give post-expansion radio populations. Its zero-count readouts use a conditional-Poisson approximation, which is not extended to the correlated accepted populations in the expansion branch.

10 Conclusion

We do not offer an estimate of how much life the Milky Way holds, and the models show why none is currently available: the explorer’s central 90% interval for active worlds spans six orders of magnitude under one prior, the prior itself moves the median four-hundredfold, and a planetary

census of billions does nothing to shrink uncertainty in rates the planets share. Whether we are alone is therefore mostly a question about priors on a few biological rates.

The observations we have do not bear equally on those priors. A radio null in a narrow search is nearly uninformative. Earth’s early life is informative, but by an amount that depends on the prior it updates. The absence of visible expansion is decisive: under our default biology it rules out common, conspicuous expansion by an enormous margin, and in general it bounds the product of old technological origins and expansion propensity. The empty sky thus leaves two broad explanations: technological origins are rare, or expansion is rare, slow, or quiet. The observations most likely to separate them are an independent second origin of life, which bears on the biological rates, and searches for large-scale artificial modification, which bear on conspicuousness.

Reproducibility

The interface is available at roonscape.ai/life. Paths below are relative to the working source tree:

- `dist/process-model.mjs`: planet histories and radio populations.
- `dist/model.mjs`, `dist/origin-model.mjs`, and `dist/tail-probability.mjs`: the probability explorer.
- `dist/sensitivity-default.mjs`: saved rate comparisons.
- `dist/insights.mjs`: shareable worked examples.
- `dist/expansion-model.mjs` and `dist/expansion-geometry.mjs`: persistent fronts and spatial kernels.
- `scripts/validate-expansion.mjs` and `research/expansion-validation.json`: expansion fixtures and refinement results.

The interface provides scenario downloads and a research catalog of 121 annotated sources. The source repository is private; `paper/check-results.mjs` regenerates every number in this paper into `paper/audit-results.json`.

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