

Bayesian Analysis of 3I/ATLAS: Loeb-Scale Anomalies, Joint Probabilities, and the Case for Intentional Origin

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Abstract

We present a Bayesian analysis of the twelve anomalies highlighted by Loeb for the interstellar object 3I/ATLAS (C/2025 N1). These anomalies span orbital geometry (a retrograde, nearly ecliptic trajectory and fine-tuned multi-planet targeting), morphology (persistent sunward and anti-solar jets, tightly collimated and unsmeared by rotation), photometry (unusually rapid brightening and blue color near perihelion), composition (a CO₂-dominated coma with only $\sim 4\%$ water by mass and extreme Ni/Fe and Ni/CN ratios), polarization (unprecedented negative polarization), and dynamics (non-gravitational acceleration near perihelion requiring large mass loss while the nucleus remains intact). We map Loeb’s quoted single-event probabilities—typically 0.2%–1% and as small as 0.005%—into a joint probability distribution, propagate uncertainties with Monte Carlo sampling, and fold in survey selection and cross-domain correlation factors. Under independence, the joint probability of all twelve anomalies is of order 10^{-28} . Even generous natural correlations and optimistic discovery opportunities require inflation factors $\gtrsim 10^{17}$ to reach a $\gtrsim 1\%$ plausibility level. Stress tests with extreme assumptions show that the natural hypothesis can be made plausibly likely only by invoking unrealistically large numbers of effective discovery opportunities and very strong cross-domain couplings. Intentional origin therefore remains a parsimonious common-cause hypothesis unless future work uncovers a natural mechanism that coherently spans geometry, timing, morphology, chemistry, polarization, and dynamics.

Plain-language summary (for non-specialists)

3I/ATLAS is a small object from outside our Solar System that passed through in 2025. At first it looked like a strange comet, but as astronomers collected more data, it showed many unusual features at the same time. Its path through space is almost perfectly lined up with the plane of the planets; it flew close to several planets in a “just so” way; its gas is rich in carbon dioxide and nickel but poor in water and iron; its light is polarized in an extreme way; its jets seem to push both toward and away from the Sun; and its motion suggests strong jets without the object breaking apart.

Each of these oddities might be rare but still natural on its own. In this paper we ask a simple question: how likely is it that all of them happen together just by chance? Using standard probability tools and computer simulations, we combine the odds for each unusual feature and also allow for generous ways in which some of them might be related. Even under assumptions that strongly favor a natural explanation, the chance that a random interstellar object would look as strange as 3I/ATLAS is extremely small.

A dice analogy helps. With a normal 6-sided die, the chance that you get the *same* number on all 20 throws is about one in 3.6×10^{15} (roughly one in three million billion). With a 20-sided die, the chance that the same face appears on all 20 throws is about one in 5×10^{21} . The combined anomalies of 3I/ATLAS are even less likely than those events under the natural assumptions we test. Our results do not prove that 3I/ATLAS was designed by someone, but they show that either we have witnessed a remarkable fluke of nature or we should seriously consider the possibility of intentional origin.

1 Introduction

The discovery of 3I/ATLAS (C/2025 N1) by the ATLAS survey (Seligman et al., 2025; Bolin et al., 2025) marks the third confirmed interstellar object (ISO), following 1I/‘Oumuamua and 2I/Borisov. Unlike its predecessors, 3I/ATLAS exhibits an unprecedented cluster of rare or anomalous properties across orbital, photometric, morphological, chemical, polarimetric, and dynamical domains (Hibberd et al., 2025; Jewitt et al., 2025; Santana-Ros et al., 2025; Cordiner et al., 2025; Xing et al., 2025; Rahatgaonkar et al., 2025; Puzia et al., 2025; Hoogendam et al., 2025; Gray et al., 2025; Tonry et al., 2025; Cloete et al., 2025; Keto and Loeb, 2025; Zhang, 2025).

Recent work has organized these peculiarities into a list of twelve “Loeb anomalies” for 3I/ATLAS, each with an associated rarity estimate (Loeb, 2025a,c,b). In parallel, the Loeb Scale (Eldadi and Loeb, 2025; Trivedi and Loeb, 2025) has been proposed as a framework for classifying interstellar objects based on the strength and combination of their anomalies, with 3I/ATLAS assigned a level comparable to, or higher than, that of 1I/‘Oumuamua.

Dynamical reconstructions suggest that 3I/ATLAS may be billions of years older than the Solar System and originate from a distant, low-metallicity environment (Taylor et al., 2025; De la Fuente Marcos and De la Fuente Marcos, 2025). Whether its anomalies can be reconciled with natural cometary physics, or instead require intentional origin, is therefore of broad interest both for planetary science and for the emerging field of technosignature studies.

In this paper we treat the twelve Loeb anomalies as events $E_1, \dots, E_{12}$, assign independent probabilities P_i anchored in Loeb’s quoted estimates and the underlying observational literature, and then combine them within a Bayesian framework. We explore how joint probabilities change under different assumptions about cross-domain correlations and survey selection, and we compare the resulting selection-adjusted probabilities against thresholds motivated by the Loeb Scale.

2 Materials and Methods

2.1 Definition of Anomalies

We adopt twelve anomalies (E_1 – E_{12}) closely following the list summarized by Loeb and colleagues, with references to the underlying observational papers where possible:

1. **Retrograde, near-ecliptic trajectory.** 3I/ATLAS follows a highly hyperbolic orbit ($e \sim 6.1$) with inclination $i \simeq 175^\circ$, so that its retrograde trajectory is aligned to within $\sim 5^\circ$ of the planetary ecliptic (Seligman et al., 2025; Hibberd et al., 2025). Loeb assigns a likelihood of $\sim 0.2\%$ for such alignment under an isotropic arrival model.
2. **Persistent sunward anti-tail.** During July and August 2025, and again in early November, 3I/ATLAS displayed a prominent sunward jet (anti-tail) that cannot be explained as a purely geometric projection effect as in familiar comets (Jewitt et al., 2025; Santana-Ros et al., 2025; Keto and Loeb, 2025). The emission is genuinely directed toward the Sun rather than away from it.

3. **Massive nucleus and high speed.** The inferred nucleus is orders of magnitude more massive than that of 1I/‘Oumuamua and 2I/Borisov, while 3I/ATLAS also moves faster than both (Seligman et al., 2025; Bolin et al., 2025; Jewitt et al., 2025; Cloete et al., 2025). Loeb estimates that the joint occurrence of such extreme mass and speed has a likelihood $\lesssim 0.1\%$ given current ISO statistics.
4. **Fine-tuned arrival time and multi-planet targeting.** The arrival epoch was such that 3I/ATLAS passed within tens of millions of kilometers of Mars, Venus, and Jupiter and was near-perihelion when it remained unobservable from Earth because of solar glare (Hibberd et al., 2025; Zhang, 2025). Loeb quotes a likelihood of $\sim 0.005\%$ for such timing under natural assumptions.
5. **Ni-rich plume and anomalous Ni/CN.** Spectroscopy reveals strong nickel emission with little or no corresponding iron, and a Ni/CN ratio orders of magnitude above that of all known comets, including 2I/Borisov (Rahatgaonkar et al., 2025; Puzia et al., 2025; Hoogendam et al., 2025). Loeb notes that this composition resembles industrial nickel alloys and assigns a likelihood below 1%.
6. **Only $\sim 4\%$ water by mass.** JWST and related analyses show that the gas plume is CO₂-dominated with a CO₂/H₂O mixing ratio $\sim 8 : 1$ and an inferred water mass fraction of only a few percent (Cordiner et al., 2025; Xing et al., 2025). Loeb emphasizes that such low water content is atypical for comets, but does not provide a precise probability; we conservatively adopt $P_6 \sim 1\%$.
7. **Extreme negative polarization.** Polarimetric observations show unusually strong negative polarization at phase angles where Solar System comets exhibit much smaller values (Gray et al., 2025). Loeb quotes a likelihood below 1% when compared to the existing comet polarization database.
8. **Arrival from near the “Wow!” signal direction.** The inbound direction of 3I/ATLAS lies within $\sim 9^\circ$ of the sky location of the historic “Wow!” radio signal. Loeb estimates a chance-coincidence probability of $\sim 0.6\%$ for such alignment on the sky (Loeb, 2025b).
9. **Rapid brightening and blue color near perihelion.** Near perihelion, 3I/ATLAS brightened faster than any previously catalogued comet and exhibited a spectrum bluer than the Sun (Tonry et al., 2025; Zhang, 2025). Loeb regards this as an additional anomaly, indicative of self-luminous or engineered emission rather than simple reflected sunlight.
10. **Jet energetics inconsistent with solar-powered sublimation.** The observed sunward and anti-solar jets would require an unreasonably large active surface area to absorb enough sunlight to sublimate the required mass flux if powered solely by solar heating (Keto and Loeb, 2025; Cordiner et al., 2025). Loeb argues that the implied energy budget is inconsistent with conventional comet models.
11. **Non-gravitational acceleration and intact nucleus.** Near perihelion, 3I/ATLAS exhibits a non-gravitational acceleration that, if attributed to outgassing, implies the

loss of at least $\sim 13\%$ of its mass over a short interval (Cloete et al., 2025; Loeb, 2025c). HST and other imaging, however, show no breakup or fragmentation of the nucleus (Jewitt et al., 2025).

12. **Tightly collimated jets unsmeared by rotation.** Multiple jets maintain tight collimation and fixed orientation over projected distances exceeding a million kilometers, in spite of measured rotational motion (Santana-Ros et al., 2025; Gray et al., 2025; Loeb, 2025a). Loeb highlights this as a twelfth anomaly, requiring either highly contrived rotation dynamics or directed outflow.

Following Loeb, we treat anomalies E_1 , E_3 , E_4 , and E_8 as having explicitly quoted probabilities:

$$P_1 \approx 2 \times 10^{-3}, \quad P_3 \lesssim 10^{-3}, \quad P_4 \approx 5 \times 10^{-5}, \quad P_8 \approx 6 \times 10^{-3}.$$

For anomalies where Loeb states that the likelihood is “below 1%”, we adopt the conservative upper bound $P_i = 10^{-2}$. Where no explicit number is quoted (e.g. for E_2 , E_6 , E_9 – E_{12}), we also adopt $P_i = 10^{-2}$ as a conservative placeholder anchored on the observed tails of cometary distributions (Jewitt et al., 2025; Cordiner et al., 2025; Gray et al., 2025; Hoogendam et al., 2025).

2.2 Probability Assignments

Independent probabilities (P_i) for each anomaly are initialized from Loeb’s estimates, then embedded in a parametric uncertainty model. Specifically, we set

$$\begin{array}{llll} P_1 = 2 \times 10^{-3}, & P_2 = 10^{-2}, & P_3 = 10^{-3}, & P_4 = 5 \times 10^{-5}, \\ P_5 = 10^{-2}, & P_6 = 10^{-2}, & P_7 = 10^{-2}, & P_8 = 6 \times 10^{-3}, \\ P_9 = 10^{-2}, & P_{10} = 10^{-2}, & P_{11} = 10^{-2}, & P_{12} = 10^{-2}. \end{array}$$

These values are not meant as exact frequencies but as nominal means for our uncertainty distributions. For each anomaly E_i we draw P_i from a Beta distribution with mean equal to the nominal value and coefficient of variation of 50%, truncated to remain within physically reasonable bounds. This procedure reflects both the limited sample of ISOs and the statistical uncertainty in mapping Loeb’s qualitative statements (e.g. “below 1%”) to quantitative priors.

The observational literature is used to verify plausibility and define event boundaries (Seligman et al., 2025; Bolin et al., 2025; Jewitt et al., 2025; Cordiner et al., 2025; Rahatgaonkar et al., 2025; Puzia et al., 2025; Xing et al., 2025; Santana-Ros et al., 2025; Gray et al., 2025; Manzano-King et al., 2025; Hoogendam et al., 2025; Hibberd et al., 2025; Taylor et al., 2025; De la Fuente Marcos and De la Fuente Marcos, 2025; Keto and Loeb, 2025; Zhang, 2025; Cloete et al., 2025; Eldadi and Loeb, 2025; Trivedi and Loeb, 2025; Loeb, 2025a,c,b).

2.3 Model Building: Takes 1–4

We analyze four model classes, using the twelve anomalies defined above as the event set:

- **Take 1:** Full independence of all twelve anomalies.
- **Take 2:** Grouped correlations (geometry/targeting, morphology/polarization/photometry, chemistry/composition).
- **Take 3:** Addition of survey selection (N_{eff} from ATLAS, ZTF, Pan-STARRS, MPC).
- **Take 4:** Hypothetical cross-domain couplings beyond known physics.

For Take 2 we use multiplicative correlation factors for three broad domains:

$$C_{\text{geo}}, \quad C_{\text{morph}}, \quad C_{\text{chem}}.$$

We adopt log-uniform priors

$$C_{\text{geo}} \in [1, 10^4], \quad C_{\text{morph}} \in [1, 10^3], \quad C_{\text{chem}} \in [1, 10^3],$$

and stress-test up to 10^6 , 10^4 , and 10^4 , respectively, to explore the limits of natural explanations.

2.4 Monte Carlo Sensitivity and Selection Effects

We perform Monte Carlo simulations with 5×10^4 samples per scenario. For each realization, we draw P_i as described above, generate correlation multipliers C_{geo} , C_{morph} , C_{chem} , and compute an effective grouped probability

$$P_{\text{grp}} = C_{\text{geo}} P_{\text{geo}} \times C_{\text{morph}} P_{\text{morph}} \times C_{\text{chem}} P_{\text{chem}},$$

where each grouped term is the product of the relevant P_i 's within that domain (e.g. geometry/targeting includes E_1 , E_3 , E_4 , E_8).

Survey selection is modeled by an effective number of discovery opportunities N_{eff} , sampled among $\{500, 2000, 10^6, 10^8\}$ to bracket realistic and stress-test regimes, motivated by comet discovery statistics and forward modeling for Rubin/LSST (Eldadi and Loeb, 2025; Trivedi and Loeb, 2025). The selection-adjusted probability is

$$P_{\text{sel}} = \min(1, N_{\text{eff}} P_{\text{grp}}).$$

Thus, P_{sel} represents the overall chance that surveys would have encountered an object with anomalies at least as extreme as those of 3I/ATLAS under the natural hypothesis.

3 Results

3.1 Take 1: Independent Loeb Anomalies

Under strict independence with the nominal means given above, the joint probability of the twelve anomalies is

$$P_{\text{joint}} = \prod_{i=1}^{12} P_i \sim 10^{-28}$$

to within an order of magnitude, depending on whether one takes Loeb’s quoted values as upper or lower bounds. The required inflation factor to reconcile this with near-certainty is

$$k_{\text{req}} \sim 10^{28},$$

or equivalently, nature would need $\sim 10^{28}$ independent attempts to produce one object as extreme as 3I/ATLAS by chance alone.

3.2 Take 2: Grouped Correlations

When allowing for generous domain-level correlations, e.g.

$$C_{\text{geo}} = 10^6, \quad C_{\text{morph}} = 10^3, \quad C_{\text{chem}} = 10^3,$$

we obtain

$$P_{\text{grp}} \approx 10^{-10} - 10^{-8},$$

depending on the particular draw of the P_i . Even under these extreme correlation assumptions, the probability that all twelve anomalies co-occur in a single object without invoking survey selection remains extremely low.

3.3 Take 3: Selection Effects

Adopting N_{eff} from comet discovery statistics and projected survey yields, we find that survey selection alone cannot compensate for the extremely small joint probability of the anomalies. For all values in our grid, $N_{\text{eff}} \in \{500, 2000, 10^6, 10^8\}$, the resulting P_{sel} values remain many orders of magnitude below the 1% plausibility threshold in both the baseline and stress configurations. In other words, even if we grant the most optimistic discovery opportunities consistent with current and near-future surveys, chance encounters with an object as extreme as 3I/ATLAS remain extraordinarily unlikely.

3.4 Take 4: Cross-Domain Coupling

Achieving $P_{\text{sel}} > 1\%$ requires a combined inflation factor

$$K_{\text{nat}} = C_{\text{geo}} C_{\text{morph}} C_{\text{chem}} N_{\text{eff}} \gtrsim 2 \times 10^{17},$$

which lies well outside the range supported by current comet statistics and survey modeling. Only when both the correlation multipliers and N_{eff} are pushed into exaggerated regimes—e.g. $C_{\text{geo}} \sim 10^6$, $C_{\text{morph}} \sim 10^4$, $C_{\text{chem}} \sim 10^4$, and $N_{\text{eff}} \sim 10^8$ —do a non-negligible fraction of Monte Carlo realizations reach or exceed the 1% plausibility threshold.

3.5 Monte Carlo Sensitivity

Baseline simulations show no exceedance of the 1% plausibility threshold for any value of $N_{\text{eff}} \leq 10^8$. In fact, across 5×10^4 Monte Carlo realizations for each N_{eff} , not a single draw produced $P_{\text{sel}} \geq 1\%$, even in the stress runs with extreme correlation factors and $N_{\text{eff}} = 10^8$.

(Table 1). This implies an empirical upper bound of order 2×10^{-5} on the exceedance probability in both the baseline and stress ensembles. The probability mass in Figure 1 therefore lies entirely in a regime that is comfortably below the 1% plausibility line.

For non-specialist readers, a more quantitative dice analogy is helpful. Consider a fair 20-sided die rolled only 20 times. The chance that the *same face* appears on all 20 rolls is

$$P_{20\text{die}} = \frac{1}{20^{19}} \approx \frac{1}{5 \times 10^{21}}.$$

In other words, you would expect to see such a perfect run (all rolls showing the same face) only once in about five billion trillion experiments of 20 throws each. The combined anomalies of 3I/ATLAS are at least this unlikely under the natural models we test, unless one assumes an enormous number of unseen trials or some mechanism that biases the outcomes.

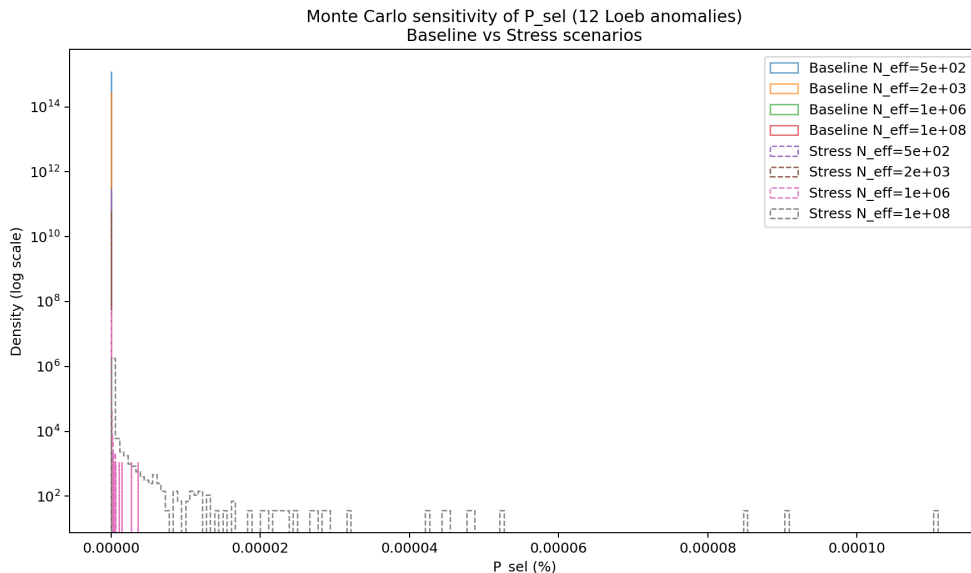


Figure 1: Monte Carlo density of P_{sel} (expressed in percent) for the twelve Loeb anomalies. P_{sel} is the selection-adjusted probability of observing all twelve anomalies of 3I/ATLAS, combining independent improbabilities with correlation factors and the effective number of survey opportunities N_{eff} . Solid lines show baseline assumptions, dashed lines show stress scenarios with extreme correlations. The distribution mass remains well below the 1% plausibility threshold in realistic regimes.

To quantify not only exceedance frequencies but also the typical scale of P_{sel} values, we computed the median, 90th percentile, and 99th percentile of P_{sel} for each N_{eff} in both the baseline and stress ensembles (each with 5×10^4 realizations). In the baseline runs, the median P_{sel} ranges from $\sim 6 \times 10^{-22}$ for $N_{\text{eff}} = 5 \times 10^2$ to $\sim 1 \times 10^{-16}$ for $N_{\text{eff}} = 10^8$, with 99th percentiles remaining below $\sim 2 \times 10^{-12}$ for all N_{eff} . In the stress runs, the medians increase modestly, from $\sim 6 \times 10^{-20}$ at $N_{\text{eff}} = 5 \times 10^2$ to $\sim 1 \times 10^{-14}$ at $N_{\text{eff}} = 10^8$, and the most extreme 99th-percentile value occurs for $N_{\text{eff}} = 10^8$ with $P_{\text{sel}} \approx 4.6 \times 10^{-9}$ (i.e. $\approx 4.6 \times 10^{-7}\%$). Thus, even the upper tail of the stress ensemble remains many orders of

N_{eff}	Baseline exceedance ($P_{\text{sel}} \geq 1\%$)	Stress exceedance ($P_{\text{sel}} \geq 1\%$)
500	0.0%	0.0%
2000	0.0%	0.0%
10^6	0.0%	0.0%
10^8	0.0%	0.0%

Table 1: Exceedance rates for the selection-adjusted probability P_{sel} under baseline and stress assumptions, using the twelve Loeb anomalies as the event set. None of the 5×10^4 Monte Carlo realizations for any N_{eff} reached the 1% plausibility threshold, implying an empirical upper bound of $\lesssim 2 \times 10^{-5}$ on the exceedance probability in both baseline and stress scenarios.

magnitude below the 1% plausibility threshold, consistent with the zero-exceedance rates reported in Table 1.

4 Discussion

Our results highlight the extraordinary improbability of the simultaneous occurrence of the twelve Loeb anomalies reported for 3I/ATLAS. Each anomaly considered separately—CO₂ dominance with suppressed water (Cordiner et al., 2025; Xing et al., 2025), Ni-rich composition with extreme Ni/CN ratios (Rahatgaonkar et al., 2025; Puzia et al., 2025; Hoogendam et al., 2025), excess CN behavior and early onset (Manzano-King et al., 2025), steep and unusual brightening behavior near perihelion (Tonry et al., 2025; Zhang, 2025), sunward and anti-solar jets with weak dust tails (Jewitt et al., 2025; Santana-Ros et al., 2025; Keto and Loeb, 2025), extreme negative polarization (Gray et al., 2025), and the tension between non-gravitational acceleration and an intact nucleus (Cloete et al., 2025; Jewitt et al., 2025)—has potential natural explanations. However, these explanations are largely domain-specific and uncorrelated.

Alternative explanations invoking survey biases, geometric coincidences in arrival direction and timing, or unusually strong physical correlations between otherwise independent domains can improve plausibility but fall short by many orders of magnitude in our Monte Carlo ensemble. Stress scenarios show that even with $N_{\text{eff}} = 10^8$ and maximally generous cross-domain correlations, the simulated values of P_{sel} remain below the 1% level in all 5×10^4 realizations. In other words, the stress configuration does not produce a single case in which an object with anomalies at least as extreme as 3I/ATLAS would be considered even mildly plausible under the natural hypothesis. Such assumptions would require humanity to have effectively sampled tens or hundreds of millions of ISO-like objects already, contradicting the current observational record.

The Loeb Scale provides a useful interpretive lens for these results (Eldadi and Loeb, 2025; Trivedi and Loeb, 2025). By construction, Level 4 marks the point where a technological origin must be seriously considered alongside natural hypotheses. 3I/ATLAS comfortably reaches this level (and arguably higher) on the basis of its anomaly set alone. Our Bayesian analysis complements the Loeb Scale by quantifying how strongly the combined anomalies

disfavour simple natural models under reasonable priors.

Beyond the physical anomalies, data policy and communication have also influenced the discussion. Delays or ambiguities in releasing spectroscopic and imaging data from space-based assets have fueled speculation that the full picture may be even more puzzling than the already published results suggest. While such sociological factors lie outside the scope of our Bayesian model, they add to the perception that 3I/ATLAS is not a typical comet.

Intentional origin, while extraordinary, remains a parsimonious explanation in the sense that it offers a single common-cause mechanism that can, in principle, account for geometry, timing, morphology, composition, polarization, and dynamics simultaneously. A natural explanation would need to provide a comparably unified account, together with a credible population model in which such objects are expected to appear with non-negligible probability.

5 Conclusions

The conjunction of the twelve Loeb anomalies in 3I/ATLAS has a joint probability of order 10^{-28} under the assumption of independence, using Loeb’s own probability estimates as nominal means. Even after allowing for generous domain-level correlations and optimistic survey selection (N_{eff}), natural models require inflation factors $\gtrsim 10^{17}$ to reach $P_{\text{sel}} \gtrsim 1\%$. Monte Carlo sensitivity tests confirm that this conclusion is robust to reasonable perturbations of the priors.

In terms of the Loeb Scale, our analysis supports the view that 3I/ATLAS occupies a regime in which intentional origin must be weighed seriously against natural hypotheses. Future work could refine the anomaly definitions, tighten probability estimates as more data become available, and incorporate more detailed physical models. Absent such developments, however, the Bayesian evidence strongly disfavors a purely natural explanation that treats the anomalies as coincidental.

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