

The X17 Anomaly as a Constraint-Satisfaction Problem: A Holographic SYK/JT/Z Solver with Falsification Protocol

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Received: August 31, 2026; Manuscript No: JMPM-26-8102; Editor Assigned: September 02, 2026; PreQc No: JMPM-26-8102 (PQ); Reviewed: October 02, 2026; Revised: October 21, 2026; Accepted: October 24, 2026; Published: November 13, 2026

Citation: Kain AD (2026). The X17 Anomaly as a Constraint-Satisfaction Problem: A Holographic SYK/JT/Z Solver with Falsification Protocol. J. Math. Phys. Mech. Vol.1 Iss.1, November (2026), pp:377-384.

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ABSTRACT

We reformulate a contested nuclear anomaly as a multi-constraint inverse problem and construct a layered holographic solver. As a test case, we apply the solver to the X17 anomaly – an e^+e^- pair creation excess in 8Be, 4He, and 12C transitions consistent with a new light boson ($m \sim 17$ MeV) with protophobic couplings. Despite extensive searches, no Standard Model extension simultaneously explains the mass, narrow width, angular distribution, and coupling suppression. We formalise the anomaly as a constraint vector $CX17 = \{C1, \dots, C7\}$ and propose a layered solver: an SYK sector for the composite resonance mass and narrow width (C1, C3); a JT gravity sector for Schwarzschild-induced Fano interference (C2); and a Z2 geometric sector for exponential protophobic suppression via bulk flavor-brane separation (C4). Remaining constraints (nuclear universality, production stability, branching suppression) emerge as consistency conditions (C5–C7). The framework yields a testable prediction within the explored parameter range: a skewed Fano lineshape with $0.4 \lesssim q \lesssim 1.8$, distinct from a symmetric Breit-Wigner. A complete falsification protocol (Section 5) defines seven monitors with violation thresholds; any single monitor failure invalidates the entire mapping. This constraint-satisfaction approach is of general interest to mathematical physics and effective modelling, as it provides a structured, falsifiable pipeline for mapping empirical anomalies to universal solver classes. Disconfirmation is treated as a positive scientific outcome under this protocol, not merely a null result.

Keywords: X17 Boson; SYK Model; JT Gravity; Holographic Duality; Protophobic Coupling; Fano Resonance; Constraint Satisfaction; Falsification Protocol

INTRODUCTION

The X17 Anomaly

Since 2016, the ATOMKI collaboration has reported an excess of e^+e^- pairs in internal pair conversion following nuclear transitions in 8Be, 4He, and 12C [1,2,3]. The invariant mass peaks at $m_{ee} \sim 17$ MeV with an unresolved width (~ 1 MeV). The angular distribution deviates from QED expectations, and the inferred couplings are protophobic: $|g_p/g_n| \sim 0.1$. Recent independent evidence from the PADME experiment strengthens the case for a common origin [4].

The signal remains contested; independent confirmation is pending. This paper adopts the working hypothesis that the anomaly is real and of particle origin. All conclusions are conditional.

Why a Holographic Constraint-Satisfaction Approach?

Standard mediator classes (dark photon, axion-like, Z') struggle to simultaneously satisfy all seven constraints without fine-tuning [5]. We therefore take a different route: treat the anomaly as an inverse problem and propose a layered solver inspired by holographic duality.

The SYK model provides a solvable chaotic system with a composite operator spectrum and a Schwarzschild soft mode [6, 7, 8]. JT gravity captures the universal low-energy dynamics of the Schwarzschild [9]. A Z2 geometric sector generates protophobic suppression via bulk flavor-brane separation. The combination suggests a structural correspondence between the empirical constraint space and the solver's output space, within the present parameterisation. This constraint-satisfaction approach is of general interest to mathematical physics and effective modelling, as it provides a structured, falsifiable pipeline for mapping empirical anomalies to universal solver classes.

What This Paper Does Not Claim

The scope of this paper is deliberately narrow. It does not claim the following.

Physical and ontological claims.

A holographic description of nuclei: The paper does not claim that nuclear physics is governed by SYK fermions or JT gravity, or that nuclei have a holographic dual. SYK and JT gravity are used as solvable representatives of a universality class (a composite operator spectrum with a Schwarzian soft mode); the gravitational language is interpretive, not ontological.

A literal gravitational or string state: The X17 boson is not claimed to be a gravitational or string excitation, and the Z2 flavor-brane picture is not claimed to describe physical branes.

The existence of the X17: The ATOMKI signal remains contested. All conclusions are conditional on the anomaly being real and of particle origin. That the solver can accommodate the constraints is not evidence that the anomaly is real, and the mapping does not prove that the X17 exists.

Derivational Claims

A first-principles derivation: The solver parameters (κ , J , N , δ , d/l , η) are not derived from an underlying theory. The values quoted in Section 3 are order-of-magnitude choices intended to show that the solver's parameter space can intersect the empirical region. The brane separation d is an inferred lower bound ($d/l \gtrsim \ln 10$), not a prediction.

A parameter-free construction: Each of the four parameters sampled in Appendix B is constrained mainly by one observable (κ by C1, δ by C7, d/l by C4, η by C2). The claim is limited to the existence of a connected viable region of parameter space, not to the absence of tuning.

A calculated Fano interval: The range $0.4 \lesssim q \lesssim 1.8$ is not obtained here from an explicit evaluation of the Schwarzian self-energy. It is a template range used to place the falsification boundary of Section 5, and it is not mathematically unique.

Uniqueness. Other mechanisms, or other members of the same universality class, may satisfy the same constraints. Agreement with the constraint vector does not single out this construction.

Statistical Claims

A probability or rigorous naturalness measure: The survival fraction ($\sim 0.4\%$) is not a probability that the model is correct. It depends on the chosen priors and constraint windows. It is evaluated on the five constraints that the Appendix B code applies directly (C1–C4 and C7); C5 and C6 are argued structurally in Section 4 and are not tested in the sampling.

A preference for the framework over alternatives: The Bayesian comparison uses qualitative surrogate likelihoods, not experimental covariance matrices, and compares against a single dark-photon surrogate with hand-set penalties. The resulting evidence ratio demonstrates the pipeline and is not a measurement. No comparison with axion-like or Z' models is computed.

Falsification Claims

Confirmation by survival: If all seven monitors pass, the mapping is consistent with the data available. It is not thereby confirmed.

Refutation of holography in general. A violated monitor falsifies this mapping, with these parameter ranges and thresholds. It does not refute the SYK model, JT gravity, or holographic methods generally.

Thresholds derived from full experimental error models: The monitor thresholds of Table 3 are motivated by current experimental resolutions and are not derived from detector covariance matrices.

Within these limits, the mapping is heuristic, analogical, and falsifiable a tool for organising constraints and generating testable predictions.

Constraint System: CX17

We formalise the empirical situation as a set of seven constraints (Table 1). A viable theory must satisfy all simultaneously.

We write the constraint vector $C_{X17} = (C_1, \dots, C_7)^T \sim 0$ (within experimental uncertainty). The goal: find a mapping M from a set of solver parameters to C_{X17} such that all constraints are satisfied across a connected region of the solver's parameter space rather than at a single tuned point.

ID	Observable
C1	Invariant mass peak $m_{X} \approx 17 \text{ MeV}$
C2	Angular correlation anomaly: Fano asymmetry, $q \sim O(1)$, positive
C3	Narrow width $\Gamma_X \lesssim 1 \text{ MeV}$ (unresolved)
C4	Protophobic coupling $ g_p/g_n \lesssim 0.1$

C5	Nuclear universality $\sigma(^8\text{Be}) \sim \sigma(^4\text{He}) \sim \sigma(^{12}\text{C})$
C6	Production stability $d\Sigma/dE \sim 0$ near resonance
C7	Branching suppression $\text{BR}(X \rightarrow e^+e^-) \ll 1$

Table 1: Empirical Constraint System For The X17 Anomaly

Solver Architecture: SYK $\rightarrow$ JT $\rightarrow$ Z2

The complex SYK model with N fermions, a q -body interaction, and a spontaneously broken $U(1)$ yields a pseudo-Goldstone boson with mass:

$$m_X^2 = \frac{\kappa}{N} J^2$$

where J is the SYK coupling and κ the explicit symmetry breaking parameter. We do not derive these numbers from first principles; rather, we note that there exists a choice of parameters within the natural range of the SYK model that yields $m_X \sim 17$ MeV. This parameter choice is illustrative of the SYK sector's capacity to generate the required scale, not a unique prediction. The constraint-satisfaction logic only requires that the solver's parameter space intersects the empirical region, which it does for the broad ranges explored in Appendix B. Concretely, for $J \sim 1$ MeV (nuclear scale), $N \sim 10^2$ (typical in SYK numerics), and $\kappa \sim 30$, we obtain m_X

~ 17 MeV. The mapping only requires that the SYK sector can produce a resonance at the observed scale, which it generically can for $\kappa \sim O(10)$.

The total width receives contributions from mixing with SM currents:

$$\Gamma_X \sim \frac{\delta^2}{\kappa} J.$$

This estimate uses illustrative values $\delta \sim 10^{-2}$, $\kappa \sim 30$, $J \sim 1$ MeV; the exact width is parameter-dependent within the natural ranges of the SYK construction. With $\delta \sim 10^{-2}$ this yields $\Gamma_X \sim 100$ keV, well below detector resolution – satisfying C3.

JT Gravity Sector: Fano Interference (C2)

In the JT gravity dual, the scalar field ϕ (dual to the composite operator O) propagates in a background with a Schwarzian soft mode. The retarded Green's function near resonance takes the form:

$$G_O^R(\omega) = \frac{Z}{\omega - m_X + i\Gamma_X/2 - \Sigma(\omega)},$$

where the self-energy $\Sigma(\omega) \sim \lambda\omega^{1-\eta}$ arises from coupling to the Schwarzian bath [8]. (This soft mode is the universal infrared dynamics of the many-body system, analogous to hydrodynamic modes in statistical mechanics.) Expanding to leading order, the interference between the resonant amplitude and the non-resonant QED background produces a Fano lineshape:

$$\frac{d\sigma}{dm_{ee}} \propto \frac{(q + \epsilon)^2}{1 + \epsilon^2}, \quad \epsilon = \frac{m_{ee} - m_X}{\Gamma_X/2},$$

where the Fano parameter q is predicted to be positive and of order unity, as required by C2.

Quantitative Fano prediction: Within the phenomenologically relevant η range explored here ($0.2 \lesssim \eta \lesssim 0.5$), the mapping $q = \text{Re}[\Sigma']/\text{Im}[\Sigma']$ yields the approximate interval $q \in [0.4, 1.8]$. This interval reflects the parameter choices in the Schwarzian self-energy and is not mathematically unique; it serves to define the falsification boundary rather than a precise prediction of the true value.

Primary falsification criterion: Within the phenomenologically relevant parameter range explored here, the holographic template yields a Fano asymmetry parameter approximately in $0.4 \lesssim q \lesssim 1.8$. A future measurement yielding a symmetric or near-symmetric lineshape ($|q| < 0.2$) would directly falsify the framework.

Z2 Geometric Sector: Protophobic Coupling (C4)

We introduce a bulk Z_2 flavor symmetry that separates proton and neutron flavor branes by a geodesic distance d in the emergent AdS_2 direction. The bulk-to-boundary propagator for a light scalar at low energy scales as $e^{-\gamma/l}$, where γ is the brane position. Thus

$$g_p = g_0, \quad g_n = g_0 e^{-d/l},$$

or equivalently,

$$\left| \frac{g_p}{g_n} \right| = e^{-d/l}.$$

We do not derive d from independent physics; rather, we show that if a geometric separation exists, then the protophobic ratio is exponential. Constraint C4 ($|g_p/g_n| \lesssim 0.1$) then implies $d/l \gtrsim \ln 10$. This is an inferred lower bound, not a prediction. A dynamical origin for d (e.g., from a bulk scalar potential) is possible but not required for the structural mapping.

Constraint Closure: C5–C7 as Consistency Conditions

C5 – Nuclear Universality

This separation dis is a property of the bulk embedding, independent of the specific nuclear state. Hence dis is nucleus-independent – explaining why ^8Be , ^4He , and ^{12}C give consistent signals.

C6 – Production Stability

The SYK spectral density $\rho(\omega)$ has no kinematic threshold; the resonance arises from an internal pole. Variations in beam energy rescale the amplitude but do not shift the peak position. Thus $dm_X/dE \sim 0$, satisfying C6.

C7 – Branching Suppression

The visible decay width into e^+e^- is suppressed by two factors: the weak mixing δ and the $1/N$ compositeness. The dominant decays are into the hidden SYK sector. The observed branching ratio from ATOMKI is $\text{BR}(X \rightarrow e^+e^-) \sim 6 \times 10^{-6}$ [1,2,3]. [Author check: confirm this is the intended reference for the branching-ratio figure before submission – the original manuscript left this citation unresolved and it has been provisionally matched to the core ATOMKI series rather than guessed at random.] Our estimate

$$\text{BR} \sim \frac{\delta^2}{N}$$

with $\delta \sim 10^{-2}$, $N \sim 10^2$ gives $\sim 10^{-6}$, consistent with observation. The broader ranges $\delta \in [10^{-3}, 10^{-1}]$, $N \in [50, 200]$ produce BR spanning 10^{-8} to 10^{-4} , comfortably encompassing the observed value without fine-tuning – satisfying C7.

Experimental Falsification Protocol

We specify seven monitors (M1–M7) corresponding to constraints C1–C7, each with a violation threshold and decision rule (Table 3). A single violation invalidates the entire mapping.

The falsification thresholds are motivated by current experimental resolutions. For M1, the 0.5 MeV window is set at roughly twice the ATOMKI energy resolution (~ 0.3 MeV). For M2, $|q| < 0.2$ is set just below the predicted minimum of 0.4, ensuring that a symmetric lineshape would eliminate the framework. For M7, the threshold of 10^{-5} is one order of magnitude above the measured cluster of $3^{-6} \times 10^{-6}$, allowing for future upward revisions while preserving the falsification logic.

Constraint	Solver Component	Status
C1	SYK spectral pole	Satisfied within current uncertainties
C2	JT Schwarzian interference	Satisfied within current uncertainties
C3	SYK width suppression	Satisfied within current uncertainties
C4	Z2 geometric separation	Satisfied within current uncertainties
C5	Embedding invariance	Satisfied within current uncertainties
C6	Spectral rigidity	Satisfied within current uncertainties
C7	Mixing + $1/N$	Satisfied within current uncertainties

Table 2: Constraint satisfaction summary. All entries are conditional on the anomaly being of particle origin and on the validity of the heuristic mapping. See Section 5 for falsification criteria

Monitor	Constraint	Violation Threshold
M1	C1	$ m_X - 17 > 0.5$ MeV

M2	C2	$ q < 0.2$ or negative
M3	C3	$\Gamma_X > 1$ MeV (resolved)
M4	C4	$ g_p/g_n > 0.2$
M5	C5	$\sigma(8\text{Be})/\sigma(4\text{He})$ outside $[0.5, 2.0]$
M6	C6	$d\Sigma/dE > 3\sigma$ variation
M7	C7	$\text{BR}(X \rightarrow e^+e^-) > 10^{-5}$

Table 3: Falsification Monitors

The falsification flow is sequential: if any monitor fails $\Rightarrow$ STOP, mapping falsified. If all pass $\Rightarrow$ the mapping is consistent with current data (not “confirmed”).

Relationship to Existing BSM Proposals

The SYK/JT/Z framework addresses constraints that conventional mediators struggle with:

Dark photon (A): Couples to electric charge; cannot be protophobic without extreme fine-tuning of kinetic mixing.

Axion-like particle (ALP): Pseudoscalar coupling predicts a different angular distribution ($JP = 0^-$) not matching the IPC excess.

Z with family-dependent charges: Requires ad-hoc charge assignments to suppress pro-ton coupling while enhancing neutron coupling. The charge ratio e_p/e_n must be set to < 0.1 by hand, with no symmetry protection.

The holographic approach offers two novel features: (i) the protophobic suppression is geometric, not a tuned charge assignment; (ii) the Fano interference arises from a universal Schwarzian soft mode, not from a dedicated resonance-continuum coupling. Neither feature is present in standard EFT treatments.

Illustrative Bayesian Comparison and Naturalness Metrics

To move beyond qualitative accommodation, we perform an illustrative model comparison and a naturalness analysis. Details of the surrogate likelihood construction and prior choices are provided in Appendix B; here we summarise the findings.

Survival-volume analysis: Defining the survival fraction as

$$f_{\text{surv}} = \frac{\int \mathbf{1}_{C(\theta) \text{ satisfied}} \pi(\theta) d\theta}{\int \pi(\theta) d\theta},$$

we evaluate it via Monte Carlo sampling over the four-dimensional holographic prior space specified in Appendix B. The printed prior ranges yield a surviving fraction of approximately 0.4% after applying the five constraints that the sampling code tests directly (C1–C4 and C7); C5 and C6 are argued structurally in Section 4 and are not part of this sampling. The dominant restriction is C1 (mass), which imposes a narrow window on κ – the SYK scale parameter – reducing the prior volume to about 2.2%. The remaining tested constraints (C2–C4, C7) are broad or non-binding in combination, leaving a connected surviving region rather than isolated islands. This indicates that, while the mass scale must be set correctly to match the observed 17 MeV peak, the tested constraints are satisfied across a well-defined volume of parameter space rather than at a single tuned point. This metric is scan-dependent and does not represent a fundamental probability; its value lies in demonstrating that the constraint set is not trivially satisfied by a tiny, isolated corner of parameter space.

Bayesian comparison (illustrative): Using surrogate Gaussian likelihoods for the seven constraints (Appendix B), we obtain a log-evidence difference of about 18 (seed 42) against a single dark-photon surrogate model. This corresponds to a Bayes factor of order 108 under these specific surrogate likelihoods, and is driven largely by the hand-set penalties in the dark-photon surrogate; comparisons with axion-like and Z' models are not computed. Important interpretational caveat: this value is an illustrative demonstration of how the framework can be embedded into a Bayesian model-comparison pipeline, not definitive phenomenological measurements. The likelihood functions are qualitative surrogates, not derived from experimental covariance matrices.

Constraint Set Applied	Representative Surviving Fraction
Prior (no constraints)	100%
After C1 (mass: $16.5 \text{ MeV} < m_{\text{sub}X\text{sub}} < 17.5 \text{ MeV}$)	$\sim 2.2\%$
After C1 + C3 (width: $\Gamma_{\text{sub}X\text{sub}} < 1 \text{ MeV}$)	$\sim 2.2\%$ (C3 non-binding)
After C1 + C3 + C7 (BR: $10^{-6} < \text{BR} < 10^{-5}$)	$\sim 0.55\%$
After C1 + C3 + C7 + C4 (protophobia: $ g_{\text{sub}p\text{sub}}/g_{\text{sub}n\text{sub}} < 0.1$)	$\sim 0.5\%$

After all tested constraints (C1–C4 and C7)	~0.4%
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Table 4: Sequential constraint survival in the holographic parameter space. Values are from the Monte Carlo implementation in Appendix B with seed 42 (independently reproduced; see verification notes).

CONCLUSION

We have reformulated the X17 anomaly as a constraint-satisfaction problem and presented a layered SYK/JT/Z holographic solver whose parameter space contains a connected, non-isolated region satisfying the five constraints tested numerically (C1–C4, C7; ~0.4% prior survival), with the mass scale providing the dominant restriction. The remaining two constraints (C5, C6) are argued structurally rather than tested numerically. All of this holds within the present heuristic parameterisation and the limits stated in Section 1.3. The framework predicts a Fano-asymmetric lineshape with $0.4 \lesssim q \lesssim 1.8$ and a geometric origin for protophobia.

The mapping is structural, not ontological. Its value lies in testability: Section 5 provides a complete falsification protocol. The framework may ultimately prove incorrect; its value lies in providing concrete failure conditions that future experiments can test. If future experiments uphold all monitors, the SYK/JT/Z2 template remains a coherent effective description within the assumptions of this paper; it should be compared against alternative models as data improve. Disconfirmation – a violated monitor – would eliminate this mapping at the stated parameter ranges and thresholds, which is a contribution to science; it would not by itself refute SYK, JT gravity, or holographic methods in general.

Interpretational Boundaries

Purpose

This appendix clarifies the interpretational scope of the SYK/JT/Z framework and prevents common misreadings.

Objection 1: “Why SYK? Isn’t that arbitrary?”

Response: SYK is not a physical assumption; it is an existence proof of a solvable system with the required properties (large- N solvability, conformal regime, Schwarzian mode, composite resonances). Any alternative with the same universal features would be interchangeable. The choice of SYK is therefore representative of a universality class, not an ad-hoc model selection.

Objection 2: “Is JT gravity an overreach for nuclear physics?”

Response: JT gravity is used only as an effective description of the Schwarzian soft mode – a universal low-energy sector. No claim of literal spacetime gravity in nuclei is made. The gravitational language is interpretive, not ontological.

Objection 3: “Is this just curve fitting?”

Response: The solver has four sampled parameters (κ , δ , d/l , η), each constrained chiefly by one observable, so it is not a parameter-free derivation (Section 1.3). What it adds beyond a fit is the joint analysis of the viable region and a pre-specified falsification protocol (Section 5) with binary evaluation. A single monitor violation falsifies the mapping as specified here; retuning the parameter ranges afterwards would constitute a new mapping, not a rescue of this one.

Objection 4: “What would actually falsify it?”

Response: Any single monitor violation (Table 3) – particularly a symmetric lineshape (M2) or kinematic instability (M6) – falsifies the entire mapping. The model is fragile by design.

Interpretational Boundary

The framework is not a claim about fundamental nuclear dynamics, not a holographic dual of QCD, and not a fitted EFT. It is a structured constraint-to-solver mapping that organises a multi-observable anomaly into a testable system. Under this protocol, disconfirmation is treated as a contribution, not a failure.

Toy Monte Carlo Implementation

This appendix provides a minimal, self-contained Python implementation of the evidence estimation and survival-fraction computation described in Section 6.1. The code below is reproduced exactly as used to generate the results in this paper; the output block has been verified to match its actual execution (seed 42). Note that the survival check applies the windows for C1–C4 and C7 only; in the likelihood functions, C5 and C6 enter as fixed constant terms that do not depend on the sampled parameters, so they do not discriminate between parameter values or models.

import numpy as np

```

from scipy.stats import norm, uniform, loguniform from scipy.special import logsumexp
np.random.seed(42) # for reproducibility
def log_likelihood_holo(theta):
    """Holographic model log-likelihood (mock mapping from Section 3)."""
    kappa, delta, d_over_l, eta = theta
    m_pred = 17.0 * np.sqrt(kappa / 30.0) # C1
    gamma_pred = (delta**2 / kappa) * 1.0 # C3
    q_pred = 0.5 + 2.0 * eta # C2
    g_ratio_pred = np.exp(-d_over_l) # C4
    br_pred = (delta**2 / 100.0) # C7
    ll = 0.0
    ll += norm.logpdf(m_pred, loc=17.0, scale=0.3) # C1
    ll += norm.logpdf(q_pred, loc=1.0, scale=0.5) # C2 (softer)
    if gamma_pred > 1.0: # C3 soft
        ll += -20.0 * (gamma_pred - 1.0)
    ll += norm.logpdf(g_ratio_pred, loc=0.05, scale=0.15) # C4 softer
    ll += norm.logpdf(1.0, loc=1.0, scale=0.4) # C5
    ll += norm.logpdf(0.0, loc=0.0, scale=0.08) # C6
    ll += norm.logpdf(np.log10(br_pred), loc=np.log10(6e-6), scale=0.6) # C7
    return ll
def log_likelihood_dp(theta):
    """Dark photon model with ad-hoc protophobia tuning."""
    m_x, eps, eps_ratio = theta
    g_ratio_pred = eps_ratio
    q_pred = 0.0
    br_pred = eps**2 * 1e-4
    ll = 0.0
    ll += norm.logpdf(m_x, 17.0, 0.3)
    ll += norm.logpdf(q_pred, 1.0, 0.5) - 2.5 # C2 penalty
    ll += norm.logpdf(g_ratio_pred, loc=0.05, scale=0.15) # C4
    ll += norm.logpdf(1.0, loc=1.0, scale=0.6) # C5
    ll += norm.logpdf(0.0, loc=0.0, scale=0.15) # C6
    ll += norm.logpdf(np.log10(br_pred), loc=np.log10(6e-6), scale=0.6)
    return ll
# Priors (widened for conservatism)
def prior_holo():
    kappa = loguniform.rvs(1, 200)
    delta = loguniform.rvs(1e-3, 1e-1)
    d_l = uniform.rvs(0, 20)
    eta = uniform.rvs(0.1, 0.8)
    return np.array([kappa, delta, d_l, eta])
def prior_dp():
    m_x = uniform.rvs(10, 15)
    eps = loguniform.rvs(1e-4, 1e-2)
    eps_ratio = uniform.rvs(0.01, 0.99)
    return np.array([m_x, eps, eps_ratio])
def monte_carlo_evidence(log_lik_func, prior_func, n_samples=50000):
    lls = np.zeros(n_samples)
    for i in range(n_samples):
        theta = prior_func()
        lls[i] = log_lik_func(theta)
    log_evid = logsumexp(lls) - np.log(n_samples)

```

```

return log_evid, np.mean(lis)
# Survival fraction check
def check_constraints_holo(theta):
    """Return True if all seven constraints are satisfied.""" kappa, delta, d_over_l, eta = theta
    m_pred = 17.0 * np.sqrt(kappa / 30.0) gamma_pred = (delta**2 / kappa) * 1.0 q_pred = 0.5 + 2.0 * eta
    g_ratio_pred = np.exp(-d_over_l) br_pred = (delta**2 / 100.0)
    if not (16.5 <= m_pred <= 17.5): return False if not (0.2 <= q_pred <= 2.0): return False if gamma_pred > 1.0: return False
    if g_ratio_pred > 0.2: return False
    if not (1e-6 <= br_pred <= 1e-5): return False return True
Run evidence comparison n_samples = 50000
log_z_holo, _ = monte_carlo_evidence(log_likelihood_holo, prior_holo, n_samples) log_z_dp, _ =
monte_carlo_evidence(log_likelihood_dp, prior_dp, n_samples)
print(f"log Z_Holo : {log_z_holo:.2f}") print(f"log Z_DP : {log_z_dp:.2f}")
print(f"log(Z_Holo / Z_DP) : {log_z_holo - log_z_dp:.2f}")
# Survival fraction computation (illustrative) n_prior = 50000
survived = []
for _ in range(n_prior): th = prior_holo()
if check_constraints_holo(th): survived.append(th)
print(f"Survival fraction: {len(survived)/n_prior*100:.1f}%")
Typical output (with seed 42):
log Z_Holo : -3.66 log Z_DP : -21.98
log(Z_Holo / Z_DP) : 18.32 Survival fraction: 0.4%

```

The survival fraction may vary with random seed; the broad range reported in Table 4 re-reflects this scan-dependence. Full code, including corner plots, is available from the author upon request. [Author check: insert a public repository link here if one exists under a non-CELL-Series name/URL, e.g. a plain GitHub or Zenodo link, rather than leaving this as "upon request" if a public archive is preferred.]

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