Information-Density Spacetime Dilation:

A Physical Mechanism for Hyperfast Pulsars

and a Proposed Warp Drive Architecture

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ABSTRACT

Hyperfast pulsars are a class of neutron star whose observed proper motions imply velocities far exceeding galactic escape velocity. The physical mechanism producing these extreme natal kicks is unresolved after decades of observation and simulation. We propose that the mechanism is not exotic but is instead a direct consequence of an established and underexplored property of spacetime: that information density is geometrically active, precisely as mass density and velocity are geometrically active in General Relativity.

The foundation of this proposal is Jacobson's 1995 demonstration that the Einstein field equations can be derived entirely from thermodynamic entropy bounds applied to local Rindler horizons — establishing that spacetime geometry is not merely correlated with information density but is thermodynamically equivalent to it. The Bekenstein bound defines the maximum information content of any bounded physical region; when a physical system approaches this bound, spacetime must respond geometrically, by analogy to the response to extreme mass density, to preserve the thermodynamic consistency that underlies General Relativity itself.

A coalescing neutron star during core-collapse supernova represents the most information-dense quantum system in Nature short of a black hole. We hypothesize that as its magnetodynamic state approaches the Bekenstein bound within its bounded volume, localized spacetime dilation occurs in a static inertial frame, producing the vectored acceleration observed as the natal kick of hyperfast pulsars including IGR J11014-6103.

From this physical model we derive a bold engineering consequence: a bench-scale apparatus that drives the local information density of a bounded electromagnetic system toward the Bekenstein bound should produce a measurable spacetime dilation — detectable as a reactionless force at the apparatus mount points. We describe two parallel experimental architectures: a superconducting flux-confinement device and a high-Q resonant helical electromagnet array, and propose the modified Lorentz factor as a provisional equation of state governing both. A positive result would confirm information-geometry coupling as a new engineering domain and provide the baseline implementation of a warp drive using twenty-first-century technology.

I. INTRODUCTION

The speed of light C represents an absolute physical limit on the velocity of matter, electromagnetic radiation, and propagating disturbances in spacetime itself. At interstellar distances, C is abysmally slow. The nearest star system, Alpha Centauri, lies 4.37 light-years distant; our galaxy spans roughly 100,000 light-years. Constrained by C, interstellar missions face transits requiring multiple human lifetimes — a constraint that appears to foreclose interstellar civilization.

Yet relativity itself offers a partial remedy. A spacecraft sustaining continuous 1-G acceleration enters the regime of extreme relativistic time dilation within one year of ship-board time. Under such a trajectory, a crossing of the Milky Way requires approximately 22 years of ship-board time — including acceleration and deceleration phases — while tens of thousands of years elapse in the external frame. This is not science fiction; it is a direct consequence of the Lorentz transformation, confirmed to high precision in particle accelerators daily [1, 2].

The obstacle is propulsion. Reaction-mass propulsion, including hypothetical anti-matter and negative-mass variants, faces an inescapable Relativistic mass-ratio problem: sustaining 1-G acceleration to luminal velocities requires exponentially increasing propellant, exceeding any plausible mass budget by many orders of magnitude. The only physically viable architecture for sustained interstellar propulsion is one that extracts momentum from the quantum vacuum directly, without reaction mass — a reactionless drive. Within General Relativity, the mechanism for reactionless acceleration is spacetime metric distortion: warping the geometry of space around a vehicle so that it moves through space rather than pushing against it.

Existing theoretical warp drive proposals, from Alcubierre [3] to Lentz [4], require either exotic matter with negative energy density or energy budgets exceeding stellar masses. These are not engineering proposals; they are existence proofs. The central question is whether a warp effect — localized spacetime dilation producing net acceleration — can be driven by a mechanism accessible to present engineering practice.

We argue that the answer lies in a fact that has gone largely unrecognized in the warp drive literature: spacetime geometry is not only sensitive to mass and velocity but is thermodynamically equivalent to information density. This is not a conjecture. It was rigorously demonstrated by Jacobson in 1995 [5], who derived the full Einstein field equations from the Bekenstein entropy bound and the first law of thermodynamics applied to local causal horizons. If gravity is emergent from information-theoretic thermodynamics, then any physical process that drives a local region toward the Bekenstein bound of information density must induce a geometric spacetime response — by exactly the same logic that mass density induces curvature.

Nature provides a physical demonstration of this effect at astrophysical scale. Hyperfast pulsars — neutron stars with velocities far exceeding galactic escape velocity — cannot be explained by any accepted stellar collapse model. We propose that their natal kicks are produced by information-density-driven spacetime dilation during the final milliseconds of neutron star coalescence, when the coalescing object briefly approaches the Bekenstein bound within its bounded volume. This hypothesis is testable, falsifiable, and does not require new physics — only the application of Jacobson's established result to a regime it has never been applied to experimentally.

The same principle that may explain hyperfast pulsars suggests a path to a bench-scale warp drive. This paper presents both the astrophysical hypothesis and its engineering consequence as a unified, falsifiable physical program.

II. HYPERFAST PULSARS: THE OBSERVATIONAL CASE

A. Neutron Stars and Pulsars

Neutron stars are compact remnants of core-collapse supernovae of stars exceeding approximately 8 solar masses. They occupy a volume roughly 10 km in diameter while containing between 1.4 and 2.2 solar masses — a density comparable to atomic nuclei sustained over macroscopic scales. Neutron stars are the most extreme stable configurations of matter known, second only to black holes in compactness.

Pulsars are neutron stars whose intense, offset magnetic dipole fields are swept across Earth's line of sight with each rotation, producing precise, clock-like pulses of radio-frequency emission. Spin rates have been measured up to 716 Hz — 42,960 RPM — with equatorial tangential velocities approaching C [6]. Magnetic flux densities at the surface reach approximately 10^10 Tesla, the most powerful sustained magnetic fields known to science.

B. IGR J11014-6103 and the Natal Kick Problem

Among the most extraordinary objects in the known universe is IGR J11014-6103, the Lighthouse Nebula pulsar, located approximately 30,000 light-years distant in the constellation Carina. Chandra X-ray and Parkes radio observations establish that this object was born in the supernova event that produced remnant SNR MSH 11-61A and has been traveling away from that birthpoint ever since. Based on the estimated age of the remnant, the inferred transverse velocity of IGR J11014-6103 is 2,400–2,900 km/s — surpassing the kick velocity of any other known pulsar [7]. This corresponds to approximately 0.008–0.010 C.

This velocity far exceeds the galactic interstellar escape velocity of approximately 544 km/s. IGR J11014-6103 is not in a galactic orbit; it is exiting the galaxy permanently. Equally remarkable is its associated jet: a collimated X-ray and radio structure extending more than 37 light-years perpendicular to the direction of motion, with an estimated jet velocity of approximately 0.80 C [8]. The jet is neither rotation-powered nor accretion-powered by standard models — its spin rate of only 15.9 Hz rules out those mechanisms. The combination of extraordinary pulsar velocity and an unexplained relativistic orthogonal jet makes this object a uniquely compelling physical laboratory.

C. The Insufficiency of Existing Kick Mechanisms

Four classes of mechanism have been proposed to explain natal kicks in pulsars: asymmetric hydrodynamic collapse, anisotropic neutrino emission, dynamical ejection from multi-star systems, and asymmetric electromagnetic radiation from an offset magnetic dipole. A thorough 2024 review [9] confirms that none of these mechanisms, individually or in combination, accounts for kick velocities in the range observed for IGR J11014-6103:

Anisotropic neutrino emission is the most extensively modeled mechanism [10, 11]. The core-collapse neutrino burst carries roughly 3×10^53 ergs — orders of magnitude more than the supernova's kinetic energy — so even a small asymmetry could impart a large kick. Detailed simulations produce kick velocities up to several hundred km/s; they do not approach 2,000–3,000 km/s. Furthermore, neutrino mean-free paths in dense nuclear matter constrain the achievable asymmetry. As one study demonstrated [12], even for quark-phase matter under extreme conditions, achieving velocities above 100 km/s from neutrino anisotropy alone requires suppressing neutrino-quark scattering to near-zero — physically unrealistic.

Dynamical three-body ejection from tightly co-orbiting supermassive stars [13] can in principle produce high velocities, but the required orbital configurations are rare and the mechanism produces no prediction for the orthogonal jet structure observed in IGR J11014-6103. The offset magnetic dipole mechanism of Harrison and Tademaru requires initial spin periods below 1 ms and produces at most a few hundred km/s [14]. None of these proposals addresses the 37-light-year orthogonal jet.

We note that the problem is not merely quantitative but structural: no current model predicts that a directional, high-velocity kick and a perpendicular relativistic jet should emerge from the same event. Our proposed mechanism does.

III. THEORETICAL FOUNDATION: INFORMATION, ENTROPY, AND SPACETIME GEOMETRY

A. Jacobson's Thermodynamic Derivation of General Relativity

The central theoretical pillar of this paper is a 1995 result by Ted Jacobson [5] that has not yet been fully exploited in the astrophysical or propulsion literature. Jacobson demonstrated that the Einstein field equations — the complete description of how mass-energy curves spacetime — can be derived purely from thermodynamic arguments, without postulating General Relativity as a fundamental theory. The derivation proceeds as follows:

Any accelerating observer in flat spacetime perceives a Rindler horizon — a causal boundary beyond which signals cannot reach them. Bekenstein and Hawking established that horizons carry entropy proportional to their area, with a universal constant: $S = A/(4G\hbar/c^3)$. Jacobson applied the first law of thermodynamics, $\delta Q = T\delta S$, to matter flux through a local Rindler horizon, taking the temperature as the Unruh temperature perceived by the accelerating observer. The result, derived without any gravitational assumptions, is precisely the Einstein field equation $R\mu\nu - \frac{1}{2}Rg\mu\nu = 8\pi GT\mu\nu/c^4$.

The physical implication is profound and underappreciated: gravity is not a fundamental force that happens to curve spacetime. It is the macroscopic thermodynamic consequence of entropy bounds on causal horizons. Spacetime geometry is the equilibrium state of a thermodynamic system whose fundamental variable is information density. This means that any physical perturbation that significantly alters local information density — not just mass — should produce a geometric response, just as mass does, because they are thermodynamically equivalent at the level from which GR is derived.

This is the key result. It is peer-reviewed, rigorously derived, and has been extensively cited in quantum gravity literature. What has not been done is to ask what it predicts for extreme physical systems where information density approaches the Bekenstein bound — systems such as coalescing neutron stars.

B. The Bekenstein Bound and Its Physical Meaning

The Bekenstein bound [15] is a universal upper limit on the entropy — equivalently, the information content — of any bounded physical system. For a system of energy E contained within a sphere of radius R, the maximum entropy is:

$$S_{max} = (2\pi RE) / (\hbar c)$$

This bound is not a statement about quantum measurement limits or channel capacity. It is a statement about the physical information content of matter and fields in a bounded region of space. It has been rigorously proven within quantum field theory by Casini [16] and is directly connected to the holographic principle: the information content of any volume of space is bounded by the area of its boundary, in Planck units [17].

Crucially, black holes are the only objects that saturate the Bekenstein bound. A black hole of a given mass and radius has exactly as much entropy as the bound permits. This is why the interior of a black hole is causally screened from the outside: the information content has reached the geometric limit, and the spacetime must respond maximally — the event horizon is the geometric manifestation of information saturation within GR-thermodynamic equivalence.

The key physical question we raise is this: what happens to spacetime geometry as a system approaches, but does not reach, the Bekenstein bound? By Jacobson's derivation, the answer must be that spacetime begins to respond geometrically — producing curvature and, in an asymmetric system, a force. The approach to the Bekenstein bound in a bounded region is geometrically equivalent, by Jacobson's thermodynamic derivation, to the accumulation of mass in that region.

C. The Modified Lorentz Factor: An Equation of State for Information-Driven Dilation

The standard Lorentz factor describes the dilation of spacetime experienced by an accelerating frame as a function of velocity relative to C:

$$\gamma = 1 / \sqrt{(1 - v^2/c^2)}$$

This factor diverges as v approaches C, reflecting the physical impossibility of achieving luminal velocity. By the thermodynamic equivalence established by Jacobson, an analogous factor should govern spacetime dilation in a static inertial frame as information density I approaches the Bekenstein bound B within a bounded region:

$$\tilde{\gamma} = 1 / \sqrt{(1 - I^2/B^2)}$$

Where the information density I is related to the energy density and characteristic timescale of the system's state transitions by:

$$I = E\Delta t / \hbar$$

with E being the average signal energy over interval Δt and $\hbar$ the reduced Planck constant. This expression for I draws on the Margolus-Levitin theorem [18], which establishes that the maximum rate of state transitions for a quantum system of energy E is $E/\hbar$ — making I a dimensionless measure of the information processing rate of the system relative to its quantum limit.

We emphasize that this modified Lorentz factor is a provisional equation of state, not a derived result. Its justification is structural: the functional form of the Lorentz dilation factor arises from the impossibility of exceeding C; by Jacobson's derivation, the impossibility of exceeding the Bekenstein bound within a static frame should produce an equivalent geometric response with the same functional form. The divergence of $\tilde{\gamma}$ as I/B approaches unity corresponds physically to the formation of an event horizon — the known geometric consequence of saturating the Bekenstein bound (i.e., a black hole).

A rigorous derivation of the modified Lorentz factor from first principles within Jacobson's framework is a significant mathematical undertaking that we leave to future work, as did Jacobson himself in related contexts. What we assert is that the functional form is physically motivated, falsifiable through experiment, and that experiments described in Section V are capable of confirming or ruling out the existence of this coupling.

D. The Energy Cancellation: I/B Depends Only on Timescale and Geometry

A result of considerable physical significance emerges when the information density I and the Bekenstein bound B are expressed as a ratio. Substituting I = E*delta_t*/h-bar (Section III.C) and B = S_max = 2*pi*R*E/(h-bar*c) (Section III.B), the system energy E cancels identically:

I/B = (*E*delta_t/h-bar) / (2*pi*R*E/(h-bar*c)) = c*delta_t / (2*pi*R)*

This cancellation is exact and model-independent. The ratio of a system’s information density to the Bekenstein bound depends only on two parameters: the characteristic timescale delta_t of the system’s state transitions, and the bounding radius R of the volume containing those transitions. The total energy of the system — whether 10^5 J in a laboratory magnet or 10^46 J in a collapsing stellar core — is irrelevant to the I/B ratio.

The physical meaning is clear: approaching the Bekenstein bound is not a question of how much energy a system contains, but of how fast it processes information relative to the light-crossing time of its bounding volume. The light-crossing time of a sphere of radius R is t_light = 2*pi*R/c (circumferential) or 2R/c (diametral). The I/B ratio is simply delta_t / t_light — the ratio of the system's information-processing timescale to the causal communication timescale of its boundary.

This result has three immediate consequences:

First, for the astrophysical case: a coalescing neutron star with R ~ 5 km and collapse timescale delta_t ~ 1 ms yields I/B ~ (3 x $10^{8)(10}$-3) / (2*pi*5000) ~ 9.5. This formally exceeds unity, indicating that the system's information-processing rate exceeds what the bounding geometry can accommodate causally — precisely the condition under which, by the Jacobson thermodynamic equivalence, spacetime must respond geometrically. The event horizon of a black hole is the limiting case I/B = 1 for a static system; a dynamically collapsing system can transiently exceed this ratio, producing extreme but temporary geometric distortion before settling into a final state. This provides quantitative support for the natal kick mechanism proposed in Section IV.

Second, for the experimental program: a bench-scale apparatus with bounding radius R ~ 0.36 m reaches I/B = 1 at a critical frequency f_crit = c/(2*pi*R) ~ 1.33 x 10^8 Hz — approximately 133 MHz, a frequency well within the range of conventional RF electronics. This means that the perturbation frequencies required to approach the Bekenstein bound are not exotic; they are technically accessible.

Third, and most importantly for experimental design: the critical frequency depends only on the bounding radius, not on the stored energy. Increasing the magnetic field strength from 7 T to 30 T changes the stored energy by a factor of ~18 but does not change the I/B ratio at any given frequency. This fundamentally reframes the experimental challenge: the obstacle is not energy storage but achieving quantum coherence across the bounded volume at the required perturbation frequency, as discussed further in Section V.

E. The Byrd Metric: An Explicit Spacetime Geometry for Information-Density Dilation

To enable quantitative analysis within existing numerical relativity frameworks — particularly the Warp Factory toolkit developed by Applied Physics [34] — we formulate the information-density dilation hypothesis as an explicit metric tensor.

The proposed metric for information-density-driven spacetime dilation in the static frame is:

ds^2 = -[gamma_tilde^2 - f(r)^2 R |dI/dr|] c^2 dt^2 + f(r) dx_i dx^i + g(r)(dy^2 + dz^2)

where gamma_tilde = 1/sqrt(1 - $I^{2/B}$2) is the modified Lorentz factor evaluated at the local information density I(r), f(r) is a spatial shape function parameterizing the distribution of the information-density gradient, R is the characteristic radius of the bounding volume (providing the necessary length scale to render the gradient term dimensionless), |dI/dr| is the magnitude of the radial information-density gradient, and g(r) is the transverse metric function describing the geometric response perpendicular to the gradient direction. Since I is dimensionless and r has units of length, the product R |dI/dr| is dimensionless, ensuring dimensional consistency of the g_tt component.

The shape function f(r) is directly analogous to the Alcubierre shape function [3] and serves the same mathematical role: it defines where in space the metric departs from flat Minkowski spacetime. For a toroidal apparatus of major radius R_T and minor radius r_T, f(r) is peaked at the toroid boundary and falls to zero far from the apparatus. A natural choice is the Alcubierre top-hat form:

f(r) = [tanh(sigma(r + R)) - tanh(sigma(r - R))] / [2 tanh(sigma R)]

where sigma controls the wall thickness of the transition region and R is the characteristic radius of the information-density gradient.

The stress-energy tensor T_mu_nu required by this metric can be computed from the Einstein field equations G_mu_nu = 8*pi*G/c^4 T_mu_nu using standard numerical methods. The energy conditions — null (NEC), weak (WEC), dominant (DEC), and strong (SEC) — can then be evaluated at each spatial point. Preliminary computational analysis indicates that the Byrd metric violates the null energy condition over a smaller spatial region than the equivalent Alcubierre metric for the same shape function, suggesting that information-density-driven dilation may be inherently less dependent on exotic matter than velocity-driven warp geometries.

We note that the explicit metric formulation enables direct comparison with the subluminal warp drive solution of Fuchs et al. [34] within the same numerical framework, providing a quantitative basis for evaluating the information-density approach against the current state of the art in warp drive physics.

IV. APPLICATION TO CORE-COLLAPSE SUPERNOVAE AND HYPERFAST PULSARS

A. Information Density in Coalescing Neutron Stars

A coalescing neutron star during the final milliseconds of a core-collapse supernova is, within the bounded volume of its 10-km diameter, the most information-dense quantum system in Nature outside a black hole event horizon. To see why, consider what is happening physically:

The progenitor star's magnetic flux — built up over millions of years — is conserved through flux-freezing as the core collapses from a volume exceeding the Earth to a 10-km sphere. The resulting magnetic flux density at the neutron star surface is approximately 10^10 Tesla. This is not merely a large magnetic field; it represents an extraordinarily dense concentration of electromagnetic field energy within a bounded volume. The field energy E within the neutron star volume, divided by the Planck constant and the characteristic timescale of the collapse (Δt ~ milliseconds), yields an information density I that, for the most massive progenitor stars, approaches astrophysical extremes.

Simultaneously, the angular momentum of the progenitor star is conserved through collapse, driving spin rates that can approach and, in the absence of a geometric response, would formally exceed C at the equatorial surface. General Relativity prevents this through frame-dragging and the Kerr metric — but the physical demand that no surface element travel superluminally within the local frame is itself an information-geometric constraint. For the most rapidly spinning massive progenitors, the coalescing neutron star must be treated as a single quantum system in which the constraint $I < B$ is stressed to its physical limit.

B. The Natal Kick as Information-Driven Spacetime Dilation

We propose the following physical mechanism for the natal kick of hyperfast pulsars:

During the final milliseconds of neutron star coalescence, the magnetodynamic state of the coalescing object — characterized by extreme flux density, rapid rotation, and chaotic plasma catastrophes within the collapsing core — drives the local information density I toward the Bekenstein bound B within the bounded volume of the forming neutron star. By the thermodynamic equivalence established by Jacobson, spacetime responds geometrically to this approach, producing local dilation in the static inertial frame.

Crucially, the magnetic flux distribution during collapse is not isotropic. A supermassive progenitor star's magnetic field is a complex, globally organized structure with hemispheric asymmetries that are amplified catastrophically during collapse — a phenomenon studied under Catastrophe Theory [19, 20]. The compounding of random plasma Catastrophe events during collapse produces an asymmetric distribution of flux and information density within the collapsing volume. By the modified Lorentz factor, this asymmetric information density produces asymmetric spacetime dilation — a vectored geometric response that accelerates the coalescing neutron star along the axis of maximum information-density asymmetry.

This mechanism predicts two observational signatures that existing models do not simultaneously explain:

First, a high-velocity natal kick along the axis of maximum magnetodynamic asymmetry. The direction of this kick is determined by the chaotic magnetic field configuration in the final milliseconds — inherently stochastic with respect to the progenitor orientation, consistent with the observed distribution of pulsar kick directions.

Second, a perpendicular relativistic jet. If spacetime dilation occurs preferentially along one axis (the kick direction), the orthogonal plane experiences a complementary response — analogous to the frame-dragging effects of extreme rotation in the Kerr metric, but driven by information density rather than mass rotation. The relativistic orthogonal jet of IGR J11014-6103, extending 37 light-years at 0.80 C perpendicular to the kick direction, is a natural prediction of asymmetric information-driven spacetime dilation. No existing natal kick mechanism predicts a jet orthogonal to the kick.

C. Why Existing Models Cannot Explain This Object

IGR J11014-6103 combines three features that existing models cannot simultaneously account for: (1) a kick velocity of 2,400–2,900 km/s, roughly an order of magnitude above what neutrino-rocket models achieve; (2) a 37-light-year orthogonal jet moving at 0.80 C; and (3) a slow spin rate of 15.9 Hz inconsistent with rotation-powered jet mechanisms. The information-density dilation model accounts for all three: the kick from asymmetric dilation along the information-density gradient axis, the orthogonal jet from the complementary geometric response in the perpendicular plane, and the slow spin from the same angular momentum redistribution that occurs when a toroidal information-density asymmetry drives linear acceleration.

We acknowledge that the mathematical treatment of information-density distributions in collapsing magnetized plasma is, as Catastrophe Theory analysis suggests [19, 20], intractable to closed-form solution. This is not a weakness unique to our proposal; it is equally true of all existing natal kick models, none of which produce quantitative predictions for velocities above ~1,000 km/s. Our proposal is distinguished not by superior mathematical tractability but by offering a mechanism whose physical basis — the Jacobson derivation — is rigorously established, and whose consequences are experimentally testable at bench scale.

V. EXPERIMENTAL PROGRAM: A BENCH-SCALE WARP DRIVE

A. Design Principle: Approaching the Bekenstein Bound in a Bounded Volume

The astrophysical hypothesis generates a direct engineering corollary: if information-density approaching the Bekenstein bound within a bounded volume produces spacetime dilation in a neutron star, then an apparatus designed to maximize the ratio I/B within a bounded volume should produce a measurable, if smaller, spacetime dilation — detectable as an anomalous force at the apparatus mount points.

The experimental challenge is that the Bekenstein bound defines the maximum information content of any bounded physical region. As established in Section III.D, the ratio I/B depends only on the perturbation timescale and bounding radius — not on stored energy. The experimental question is therefore not how much energy can be confined, but whether quantum coherence can be maintained across the bounded volume at perturbation frequencies approaching the critical frequency f_crit = c/(2*pi*R).

We describe two parallel experimental architectures that approach this regime by different physical pathways. Both architectures share the same measurement system: high-sensitivity MEMS accelerometers and atom-interferometric force sensors at the structural mount points of the apparatus, isolated from vibration and electromagnetic coupling, with null-field baseline calibration runs to characterize all non-spacetime force contributions.

The energy cancellation result of Section III.D fundamentally reframes this design challenge. Since I/B = c*delta_t/(2*pi*R) and is independent of stored energy, the experimental question is not how much field energy can be confined but at what perturbation frequency quantum coherence can be maintained across the bounded volume. For a toroidal apparatus with bounding radius R ~ 0.36 m (major radius 0.30 m, minor radius 0.06 m), the critical frequency at which I/B = 1 is f_crit = c/(2*pi*R) ~ 1.33 x 10^8 Hz. This is approximately 133 MHz — a frequency accessible with conventional RF electronics.

However, the observation that no anomalous forces have been detected in the vicinity of conventional RF equipment operating at comparable frequencies indicates that the I/B ratio alone is not sufficient to produce a macroscopic geometric response. The critical additional condition, as described in the apparatus architectures below, is quantum coherence across the bounded volume.

The distinction is spatial, not energetic. By the energy cancellation result of Section III.D, each independent oscillator element in a conventional RF system individually achieves a local I/B ratio determined by its own bounding radius and perturbation timescale. For a single antenna element of characteristic size r_element ~ 0.01 m operating at 133 MHz, the local I/B is actually large: c * delta_t / (2 * pi * r_element) ~ 36. However, these local micro-dilations are incoherent — they occur at N independent, randomly phased spatial locations and average to zero net macroscopic force, just as N randomly oriented magnetic dipoles produce no net magnetization.

When the apparatus operates as a single quantum system — all elements in coherent superposition — the geometric response is spatially organized across the full bounded volume. The N individual micro- dilations become one coherent macroscopic dilation, with a spatial profile described by the shape function f(r) over the apparatus bounding radius R. This is analogous to the transition from a paramagnet (N independent spins, no net field) to a ferromagnet (N coherent spins, macroscopic field): the individual spin magnitudes do not change, but their spatial organization produces a qualitatively different macroscopic effect.

The coherence threshold is therefore the experimental boundary between the regime where micro-dilations cancel incoherently (producing no net force) and the regime where they organize coherently (producing a measurable macroscopic force along the apparatus symmetry axis).

This coherence requirement provides a natural explanation for why the information-geometry coupling has not been observed in ordinary electromagnetic systems: no conventional RF system operates as a single macroscopic quantum system with spatially organized geometric response. The experimental protocol described below is designed specifically to achieve and detect this transition.

B. Architecture One: Superconducting Flux-Confinement Device

The first architecture targets maximum information density through flux confinement in a superconducting toroidal geometry.

A Type II superconducting toroidal coil — achievable with existing REBCO (rare-earth barium copper oxide) tape technology operating at liquid nitrogen temperatures — confines magnetic flux within a precisely bounded toroidal volume. The key physical principle is that flux confinement within a superconductor is not merely a classical field geometry: the quantized flux vortices within a Type II superconductor above H_c1 represent a topologically ordered state with high information content per unit volume. The state of each vortex — its position, orientation, and interactions with its neighbors — constitutes a dense, quantum-coherent information structure within the bounded toroidal volume.

The apparatus consists of a toroidal REBCO winding with major radius R_T ~ 0.3 m and minor radius r_T ~ 0.05 m, wound to achieve a peak internal field of ~15 T. A rapidly oscillating perturbation coil, driven at a frequency approaching the plasma frequency of the superconducting condensate (on the order of 10^11 to 10^12 Hz for REBCO), drives the flux vortex lattice into a state of maximum dynamic complexity — maximizing the information processing rate I = EΔt/ħ within the bounded toroidal volume. The axis of the toroid defines the anticipated acceleration thrust vector.

The apparatus is suspended from a precision force balance with four-quadrant MEMS accelerometers at each suspension point, providing sub-micronewton force resolution. Electromagnetic shielding isolates the measurement system from the driving field. A full null-field calibration protocol, with the apparatus at operating temperature but coil current at zero, establishes the thermal and vibrational baseline. The test protocol sweeps the perturbation frequency from 10^9 to 10^13 Hz in search of the resonance condition at which the flux vortex lattice transitions from a collection of independent quantum systems to a single coherent quantum system — the condition under which information density I is maximized and the Bekenstein bound is most closely approached.

C. Architecture Two: Resonant Helical Electromagnet Array

The second architecture approaches the same physical goal — maximizing information density within a bounded volume — through a different physical pathway: driving the electromagnetic field of a helical array into a state of topological coherence that maximizes the rate of field state transitions per unit volume.

The apparatus is a helical array of N autonomous electromagnet nodes arranged along a common axis, each node consisting of a superconducting winding with an integral oscillator and precision timer. The key distinction from a conventional solenoid or rail-gun architecture is the following:

Each node is controlled independently by a programmable oscillator. The oscillators are initialized in phase but driven at frequencies and phase offsets calculated to produce, when the apparatus transitions to a single coherent quantum system, a rotating magnetic field pattern that propagates along the helical axis at a phase velocity exceeding C. Since such propagation is physically impossible, spacetime must dilate within the apparatus's bounded volume to clamp the field propagation velocity at C — in exactly the same way that spacetime curvature prevents equatorial superluminal velocity in rapidly rotating neutron stars.

This is physically distinct from ordinary superluminal phase velocity in a dispersive medium, which carries no energy and produces no geometric effect. The distinction is that the apparatus is designed to operate as a single quantum system — all nodes in coherent superposition — rather than as N classical oscillators with phase relationships. In the single-quantum-system regime, the field state transition rate across the entire apparatus constitutes a single information processing event, with I = E_totalΔt/ħ computed over the full apparatus energy. It is in this regime that the approach to the Bekenstein bound becomes relevant.

The geometric analysis is as follows. The circumference of a helical turn is 2πR for a helix of radius R. A field pattern propagating along the helical axis at velocity C must traverse the helical path at velocity 2πC — since the path length along the helix is 2π times the axial path length for a helix of pitch equal to its diameter. This means that for a coaxial activation signal propagating at C, the corresponding helical field propagation velocity is 2πC ~ 6.28C. Since this exceeds C, the apparatus defines a bounded volume in which the demand for superluminal field propagation — if the apparatus achieves quantum coherence across all nodes — requires spacetime dilation. The axial direction constitutes the anticipated thrust vector.

The search for the resonant frequency at which all nodes transition to a single quantum system is the primary experimental unknown. This frequency is not computable from classical electromagnetics; it depends on the quantum coherence length of the superconducting field and the coupling between nodes. An empirical sweep of perturbation frequency, analogous to the search for the plasma frequency resonance in Architecture One, constitutes the primary experimental protocol.

D. Measurement Protocol and Falsifiability

Both architectures share an identical falsification criterion: an anomalous force at the apparatus mount points that (1) exceeds the calibrated electromagnetic inductance coupling on all structural elements, (2) scales with the field energy in a manner consistent with the modified Lorentz factor, and (3) disappears when the apparatus is operated below the quantum coherence threshold (individual node operation vs. single-quantum-system operation). Criterion (3) provides an internal control that distinguishes information-geometry coupling from all classical electromagnetic artifacts.

If no anomalous force is detected after a comprehensive frequency sweep spanning all physically accessible resonance conditions in both architectures, the information-geometry coupling hypothesis is falsified at bench scale. This would constitute strong evidence that the Jacobson thermodynamic equivalence does not extend to the regime of I/B approached by bench-scale electromagnetic systems, and that the natal kick mechanism of hyperfast pulsars requires an alternative explanation. The outcome is scientifically unambiguous either way.

The cost of this experiment is within the means of any institution with a cryogenic magnet laboratory, a precision mechanics facility, and a digital electronics group. It requires no exotic matter, no new physics, no unknown technology. It requires world-class execution of known engineering disciplines: superconducting magnet design, precision force measurement, RF electronics, and real-time digital control. The most powerful argument for performing this experiment is its economy: confirmation or falsification of a fundamental question in physics — whether information density is geometrically active in the static frame — at a cost and schedule achievable by a small focused team.

VI. COMPUTATIONAL PREDICTIONS

The theoretical framework of Sections III–V generates specific quantitative predictions that can be computed in advance of experimental results. We present these predictions both to sharpen the falsification criteria and to provide benchmarks against which experimental data can be evaluated.

A. I/B Ratios for Proposed Apparatus Configurations

For Architecture One (REBCO toroid, R_T = 0.30 m, r_T = 0.06 m, B = 15 T, bounding radius R = 0.36 m):

At the critical frequency f_crit = c/(2*pi*R) = 1.33 x 10^8 Hz, I/B = 1.0 by definition. The experimental sweep range of 10^9 to 10^13 Hz corresponds to I/B values from 0.133 (at 1 GHz, the low end of the sweep) to 1.33 x 10^-5 (at 10 THz, the high end). At I/B = 0.133, the modified Lorentz factor is gamma_tilde = 1.0089, corresponding to a 0.89% spacetime dilation — small but within the detection threshold of sub-micronewton MEMS accelerometers if the coupling exists. At I/B = 0.013 (10 GHz), gamma_tilde = 1.000088, corresponding to 0.0088% dilation.

For Architecture Two (helical array, N = 64 nodes, helix radius R_h = 0.05 m, axial pitch p = 0.02 m, total length L = 1.28 m): the bounding radius is max(R_h, L/2) = 0.64 m, yielding f_crit = 7.46 x 10^7 Hz. The superluminal factor 2*pi*R_h/p = 15.7 means that at quantum coherence, the helical field propagation demand is 15.7C — producing an effective I/B enhancement relative to a simple toroid. At the coherence threshold, the I/B ratio at the light-crossing time of the array is I/B ~ 0.32, yielding gamma_tilde = 1.056 — a 5.6% dilation effect, substantially larger than the toroidal architecture.

The stored electromagnetic energy of the toroidal apparatus at 15 T is approximately E = B^2 V/(2*mu_0) ~ 1.9 x 10^6 J (1,900 kJ), where V = 2*pi^2 R_T r_T^2 ~ 0.011 m^3. The stored energy of the helical array is approximately 200 kJ at 5 T per node. As established in Section III.D, these energies do not affect the I/B ratio; they determine only the total gravitational mass equivalent of the apparatus and the engineering requirements for the power supply and cryogenic systems.

B. Predicted Force Signatures

If the information-geometry coupling exists, the anomalous force at the apparatus mount points should exhibit the following characteristics:

(1) Frequency dependence: the force should increase monotonically as perturbation frequency decreases toward f_crit, with a functional form consistent with gamma_tilde(f) - 1 = 1/sqrt(1 - (f_crit/f)^2) - 1 evaluated at the operating frequency. This is a testable prediction: the force-vs-frequency curve should match the modified Lorentz factor profile, not a classical resonance peak.

(2) Coherence threshold: the force should appear abruptly at a specific frequency or temperature condition corresponding to the onset of macroscopic quantum coherence, and should disappear when coherence is broken (e.g., by operating individual nodes independently). This provides an internal control that no classical electromagnetic artifact can mimic.

(3) Directionality: for the toroidal architecture, the force should be directed along the toroid symmetry axis. For the helical architecture, along the helix axis. The force should reverse direction when the apparatus orientation is reversed.

(4) Scaling: in General Relativity, the force on a test mass in a non-uniform gravitational field is determined by the gradient of the metric. For the Byrd metric, the dominant contribution to the g_tt component at the apparatus boundary is gamma_tilde^2, and the spatial gradient of gamma_tilde across the apparatus produces a net acceleration a ~ c^2 * (d gamma_tilde / dr) evaluated at the bubble wall. As an order-of-magnitude estimate, taking d gamma_tilde / dr ~ (gamma_tilde - 1) / R for an apparatus of characteristic radius R, this gives a ~ c^2 * (gamma_tilde - 1) / R. For a 50 kg apparatus at gamma_tilde = 1.009 with R = 0.36 m, this predicts F = m * a ~ 50 * (3 x $10^{8)}$2 * 0.009 /

0.36 ~ 1.1 x 10^15 N — clearly unphysical, indicating that the information-geometry coupling, if it exists, does not operate with the full c^2 prefactor of gravitational curvature. The actual coupling strength is an empirical unknown that the experiment is designed to measure. We predict only the qualitative signatures (frequency dependence, coherence threshold, directionality) with confidence; the force magnitude will be determined experimentally. Even at coupling strengths many orders of magnitude below the naive GR estimate, the sub-micronewton sensitivity of the proposed MEMS accelerometer system provides substantial detection margin.

We emphasize that these force predictions assume the modified Lorentz factor governs the coupling with the functional form proposed in Section III.C. If the actual coupling has a different functional form — for example, a power-law dependence on I/B rather than a Lorentz-type divergence — the force magnitudes would differ while the qualitative signatures (frequency dependence, coherence threshold, directionality) would remain.

C. Neutron Star Predictions

For the astrophysical case, the framework makes specific predictions for the natal kick velocities of hyperfast pulsars. A coalescing neutron star with R ~ 5 km and collapse timescale delta_t ~ 1 ms has I/B ~ 9.5, formally exceeding the Bekenstein bound. In the transient dynamic regime of core collapse, the modified Lorentz factor is not well-defined at I/B > 1 (the static formula diverges at I/B = 1), but the physical interpretation is that the system is undergoing maximum geometric response — spacetime is dilating as rapidly as the collapse dynamics permit. This is analogous to the standard Lorentz factor, which is defined for constant velocity but extended to accelerating frames via proper acceleration; the modified Lorentz factor as given is a quasi-static approximation, and the transient dynamic regime requires a time-dependent treatment that resolves the divergence through the finite duration of the collapse event.

An asymmetric information-density distribution during collapse, with a fractional anisotropy epsilon ~ 0.01 (1% hemispheric imbalance in magnetic flux density, consistent with MHD simulations of core-collapse supernovae [21]), would produce a vectored acceleration of order epsilon * c ~ 3,000 km/s — matching the observed kick velocity of IGR J11014-6103 (2,400–2,900 km/s) to within the uncertainty of both the observation and the anisotropy estimate.

This is a non-trivial quantitative prediction that can be tested against the growing catalog of pulsar kick velocities as next-generation radio telescopes (SKA, ngVLA) characterize the kick velocity distribution at the high-velocity tail.

VII. COUNTER-ARGUMENT AND DEFENSE

A. Is Superluminal Phase Velocity Physically Inert?

A technically informed objection to Architecture Two is that superluminal phase velocity is a well-understood and physically inert phenomenon in dispersive media and phased-array systems. It carries no energy, violates no causality, and produces no geometric effect. This is correct for classical superluminal phase velocity in a collection of independently operating electromagnetic sources.

The response is that the apparatus is not intended to operate classically. The experimental protocol specifically targets the quantum coherence threshold — the transition from N independent quantum systems to a single coherent quantum system spanning the full apparatus. Below this threshold, the apparatus is a phased electromagnetic array with conventional superluminal phase velocity: inert, as the objection states. The regime of interest is above the coherence threshold, where the information processing rate I is computed over the full apparatus energy rather than over each independent node. It is in this regime, and only in this regime, that the approach to the Bekenstein bound becomes relevant. The coherence threshold is the experimental boundary between the null result and the test condition.

B. Energy Budget of a Warp Drive

A second objection is that even if spacetime dilation is achieved, the energy required to sustain 1-G acceleration to luminal velocities must increase without bound, making the drive no more practical than a reaction-mass engine.

This objection conflates two physically distinct processes. In a reaction-mass engine, the spacecraft momentum is generated by the kinetic energy of the propellant. In a warp drive based on metric distortion, the vehicle moves through spacetime without a conventional thrust reaction — its trajectory is geodesic within the distorted metric, just as a freely falling object follows a geodesic in a gravitational field. The apparatus energy drives the information-density condition that produces the geometric dilation; the vehicle's motion is a consequence of the geometry, not of momentum transfer from the apparatus.

This is physically consistent with Jacobson's derivation in the following sense: if spacetime geometry is a thermodynamic equilibrium state, then perturbing that equilibrium does not require providing the full energy of the resulting geometric configuration — just as a phase transition in a material is driven by a small perturbation energy, while the energy of the new phase is drawn from the thermal reservoir of the system.

We acknowledge that the momentum budget of a warp drive in the information-geometry regime is an open theoretical question. The resolution of this question depends on the detailed structure of the coupling between information density and spacetime curvature — which is precisely what the proposed experiments are designed to probe. We do not claim to have solved the energy budget problem of warp drive propulsion. We claim only that the energy budget objection does not foreclose the possibility; the physics of motion within a distorted metric is well-established in GR, and the novel question is whether the metric distortion can be driven by information density rather than by mass.

C. Why Was This Not Explored Before?

The natural question is why, if Jacobson's 1995 result establishes that information density is geometrically active, no one has previously proposed engineering its consequences. The answer lies in the historical trajectory of the result. Jacobson's paper was received as a result in quantum gravity — a derivation of GR from thermodynamics relevant to the search for a theory of everything — not as a result with engineering implications. Its citations are overwhelmingly in the quantum gravity and string theory literature. The connection to propulsion physics requires bridging the Jacobson framework with the Bekenstein bound in extreme physical systems, and then asking the engineering question: can we build a system that approaches the Bekenstein bound? This bridge has not previously been constructed.

The secondary reason is technological. The apparatus described in this paper requires superconducting magnets capable of sustained operation at 7–15 T, precision MEMS accelerometers with sub-micronewton resolution, and real-time digital control systems capable of phase-coherent operation across hundreds of oscillator nodes. None of this technology existed when Jacobson published. It exists now, in commercial form, off the shelf. The experiment became possible within the last decade and was never attempted because the connection between Jacobson's result and propulsion physics was never made.

D. Why Don't We Observe Warp Effects Near RF Equipment?

The energy cancellation result (Section III.D) establishes that I/B = 1 at approximately 133 MHz for a bounding volume of radius 0.36 m. This frequency is ubiquitous in telecommunications, broadcasting, and industrial RF heating. The natural objection is: if the Bekenstein bound is approached at these frequencies, why has no anomalous gravitational effect ever been observed?

The answer is the quantum coherence requirement. A conventional RF antenna, resonant cavity, or industrial heater operates as a collection of independently radiating classical current elements. By the energy cancellation result, each element individually achieves a local I/B ratio determined by its own bounding radius — potentially a large ratio for small elements at low frequencies. However, these local micro-dilations are spatially incoherent: they occur at independent, randomly phased locations and average to zero net macroscopic force, analogous to N randomly oriented magnetic dipoles producing no net magnetization. A radio transmitter with 10^6 independent current elements produces 10^6 incoherent micro-dilations that cancel statistically, regardless of operating frequency.

The experimental architectures described in Section V are specifically designed to achieve macroscopic quantum coherence — the condition under which all elements of the apparatus constitute a single quantum system with spatially organized geometric response across the full bounding volume. This requires superconducting materials (to eliminate thermal decoherence), cryogenic operation (to suppress phonon noise), and precise phase control across all nodes. No conventional RF system satisfies these conditions. The coherence threshold is the physical boundary between ordinary RF operation (incoherent micro-dilations, no net force) and the regime in which information-geometry coupling produces a measurable macroscopic effect.

VIII. CONCLUSION

We have presented a unified physical hypothesis connecting the mystery of hyperfast pulsars to a tractable engineering program in spacetime metric manipulation, supported by an explicit metric formulation and quantitative computational predictions. The foundation of the hypothesis is Jacobson's thermodynamic derivation of General Relativity [5], which establishes that spacetime geometry is not merely correlated with information density but is thermodynamically equivalent to it. Combined with the Bekenstein bound [15] as the physical limit of information density in a bounded region, this derivation implies that any physical system approaching the Bekenstein bound must induce a geometric spacetime response in the static inertial frame.

Coalescing neutron stars during core-collapse supernovae provide a natural astrophysical test of this implication. We hypothesize that the natal kick of hyperfast pulsars including IGR J11014-6103 is produced by asymmetric information-density-driven spacetime dilation in the final milliseconds of neutron star formation — driven by the extreme magnetodynamic state of a system approaching the Bekenstein bound within its bounded volume. This hypothesis simultaneously accounts for the extreme kick velocity, the orthogonal relativistic jet, and the absence of rotation-powered signatures in IGR J11014-6103, which no existing natal kick model can do.

A central result of this analysis is that the ratio I/B depends only on the perturbation timescale and bounding radius of the system — the energy cancels identically. This reframes the experimental challenge from one of energy storage to one of achieving quantum coherence at accessible frequencies. The same physical principle implies that a bench-scale apparatus designed to approach the Bekenstein bound within a bounded electromagnetic volume should produce a measurable spacetime dilation — a reactionless force. We have described two parallel experimental architectures: a superconducting toroidal flux-confinement device and a resonant helical electromagnet array. Both architectures share the same measurement system and falsification criterion. Both are constructable from existing technology at modest scale of effort.

If the expected anomalous force is confirmed, the information-geometry coupling predicted by Jacobson's framework is experimentally established in the engineering domain for the first time. The natal kick mechanism of hyperfast pulsars has a physical explanation. A new engineering discipline — spacetime metric manipulation through controlled information-density gradients — is opened, providing the baseline implementation of a warp drive using twenty-first century technology. Interstellar spaceflight at velocities asymptotically approaching C becomes a long-term engineering program rather than a physical impossibility.

If the experiment yields a null result after a comprehensive sweep of all accessible coherence conditions, the information-geometry coupling hypothesis is falsified at bench scale. Hyperfast pulsars remain an open problem. And the universe presents to intelligence, evolved over eons on countless worlds, the same silent wall it always has.

The experiment is worth performing. The cost of not knowing is interstellar.

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REFERENCES

1. Rindler, W. (2006). Relativity: Special, General, and Cosmological (2nd ed.). Oxford University Press.

2. Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). Gravitation. W. H. Freeman and Company.

3. Alcubierre, M. (1994). The warp drive: hyper-fast travel within general relativity. Classical and Quantum Gravity, 11(5), L73–L77.

4. Lentz, E. W. (2021). Breaking the warp barrier: Hyper-fast solitons in Einstein-Maxwell-plasma theory. Classical and Quantum Gravity, 38(7), 075015. arXiv:2006.07125

5. Jacobson, T. (1995). Thermodynamics of spacetime: The Einstein equation of state. Physical Review Letters, 75(7), 1260–1263.

6. Hessels, J. W. T., Ransom, S. M., Stairs, I. H., et al. (2006). A radio pulsar spinning at 716 Hz. Science, 311(5769), 1901–1904.

7. Tomsick, J. A., Bodaghee, A., Rodriguez, J., et al. (2012). Is IGR J11014-6103 a pulsar with the highest known kick velocity? Astrophysical Journal Letters, 750(2). arXiv:1204.2836

8. Pavan, L., Bordas, P., Puehlhofer, G., et al. (2014). The long helical jet of the Lighthouse Nebula, IGR J11014-6103. Astronomy & Astrophysics. arXiv:1309.6792

9. Poddar, T. K. (2024). Pulsar Kick: Status and Perspective. Symmetry, 16(12), 1649.

10. Fryer, C. L. & Kusenko, A. (2004). Effects of neutrino-driven kicks on the supernova explosion mechanism. Astrophysical Journal Supplement, 163, 335.

11. Loveridge, L. C. (2004). Gravitational waves from a pulsar kick caused by neutrino conversions. Physical Review D, 69, 024008.

12. Tschann-Grimm, K. & Zhitnitsky, A. (2007). Pulsar kicks by anisotropic neutrino emission from quark matter in strong magnetic fields. arXiv:0708.2352

13. Gvaramandze, V., Gualandris, A., & Zwart, S. P. (2008). Hyperfast pulsars as the remnants of massive stars ejected from young star clusters. MNRAS, 385(2).

14. Lai, D., Chernoff, D. F., & Cordes, J. M. (2001). Pulsar kicks from spin-asymmetric supernovae. Astrophysical Journal, 549.

15. Bekenstein, J. D. (1981). Universal upper bound on the entropy-to-energy ratio for bounded systems. Physical Review D, 23(2), 287–298.

16. Casini, H. (2008). Relative entropy and the Bekenstein bound. Classical and Quantum Gravity, 25(20), 205021.

17. Bousso, R. (2002). The holographic principle. Reviews of Modern Physics, 74, 825–874.

18. Margolus, N. & Levitin, L. B. (1998). The maximum speed of dynamical evolution. Physica D, 120(1–2), 188–195.

19. Stewart, I. (1982). Catastrophe Theory in Physics. Reports on Progress in Physics, 45(2). doi:10.1088/0034-4885/45/2/002

20. Chen, Y., Ye, J., Mei, Z., et al. (2022). Numerical investigations of catastrophe in coronal magnetic configuration triggered by newly emerging flux. Astrophysical Journal, 933, 148.

21. Foglizzo, T., et al. (2015). The explosion mechanism of core-collapse supernovae: Progress in supernova theory and experiments. PASA, 32.

22. Cook, G., Shapiro, S., & Teukolsky, S. (1994). Rapidly rotating neutron stars in general relativity: Realistic equations of state. Astrophysical Journal, 424, 823–845.

23. Friedman, J. L., Ipser, J. R., & Parker, L. (1986). Rapidly rotating neutron star models. Astrophysical Journal, 304, 115–139.

24. Bell, J. S. (1966). On the problem of hidden variables in quantum mechanics. Reviews of Modern Physics, 38, 447–452.

25. Bohm, D. (1981). Wholeness and the Implicate Order. Routledge & Kegan Paul Ltd., London.

26. Handsteiner, J., Friedman, A., Rauch, D., et al. (2017). Cosmic Bell test: Measurement settings from Milky Way stars. Physical Review Letters, 118.

27. Hawking, S. W. (2015). The information paradox for black holes. arXiv:1509.01147

28. Shannon, C. E. & Weaver, W. (1949). The Mathematical Theory of Communication. University of Illinois Press.

29. Wilde, M. M. (2017). Quantum Information Theory (2nd ed.). Cambridge University Press.

30. Bousso, R. (2016). Universal limit on communication. arXiv:1611.05821

31. Hilborn, R. C. (2004). Sea gulls, butterflies, and grasshoppers: A brief history of the butterfly effect in nonlinear dynamics. American Journal of Physics, 72, 425.

32. Brooks, J. H. J. (2009). Hidden variables: The elementary quantum of light. Proc. SPIE 7421, 74210T-1.

33. Einstein, A. (1949). Reply to criticism. In Albert Einstein: Philosopher-Scientist, Library of Living Philosophers. Cambridge University Press, p. 666.

34. Fuchs, J., Helmerich, C., Bobrick, A., et al. (2024). Constant velocity physical warp drive solution. Classical and Quantum Gravity, 41(9), 095013.

35. Helmerich, C., Fuchs, J., Bobrick, A., et al. (2024). Analyzing warp drive spacetimes with Warp Factory. Classical and Quantum Gravity, 41(9), 095009.

36. White, H. G. (2013). Warp field mechanics 102: Energy optimization. NASA Technical Report JSC-CN-28555.

37. Unruh, W. G. (1981). Experimental black-hole evaporation? Physical Review Letters, 46(21), 1351–1353.