A Formal Correspondence between the UAT Causal Membrane

and the Penrose Superradiance Process:
Towards a Geometric Foundation for the Effective Matter Density

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Abstract

We present a formal correspondence between the causal membrane of the Unified Applicable Time (UAT) framework and the Penrose superradiance process in rotating black hole geometries. Within the UAT framework, the effective matter density is given by the phenomenological relation $\Omega_m^{(\text{eff})} = \Omega_b \times \kappa_{\text{crit}} \times \varphi \times (1 - \phi_*/\eta)$. We show that this relation admits a natural interpretation as a superradiant amplification process, where the causal membrane plays the role of an effective ergosphere. The thermal calibration margin ($\phi_*/\eta = 0.07$) is identified with the geometric deficit $1 - k_{\text{early}}^2 \approx 0.065$ arising from the lapse function $N = k_{\text{early}} = 0.967$ in an Arnowitt-Deser-Misner (ADM) decomposition. The amplification factor $\kappa_{\text{crit}} \times \varphi$ is interpreted as the shift vector coupling that governs frame-dragging in the causal geometry. We emphasise that this is a formal correspondence, not a rigorous derivation. The UAT metric tensor remains to be constructed from the UAT Lagrangian, and the identification of the causal membrane with an ergosphere is an analogy that awaits rigorous geometric proof. Nevertheless, the numerical concordance between the independently calibrated parameters and the Penrose efficiency formula suggests that superradiance may be the underlying physical mechanism responsible for the observed dark matter density.

1 Introduction

In a previous publication [4], a phenomenological relation was presented linking the bare baryon density Ω_b to the observed effective matter density Ω_m:

$$\Omega_m^{(\text{eff})} = \Omega_b \times \kappa_{\text{crit}} \times \varphi \times (1 - \phi_*/\eta) \tag{1}$$

where $\kappa_{\text{crit}} = 4.978$ is the Ivancho limit, $\varphi \approx 1.618$ is the golden ratio, and $\phi_*/\eta = 0.07$ is the thermal calibration margin. The relation reproduces the Planck 2018 value of Ω_m with a deviation of 0.55%. However, it was explicitly acknowledged that Eq. (1) is a phenomenological ansatz, not a derivation from first principles.

The purpose of the present document is to explore a possible geometric foundation for this relation. We show that the structure of Eq. (1) —a bare quantity amplified by geometric factors and reduced by a dissipative term— is formally identical to the efficiency formula for the Penrose superradiance process [1] in rotating black hole geometries. Furthermore, we show that the numerical value of the thermal margin (0.07) emerges naturally as the geometric deficit $1 - k_{\text{early}}^2$ when the quantum braking factor is interpreted as the lapse function in an ADM decomposition of the causal metric.

We emphasise at the outset that this is a **formal correspondence**, not a rigorous derivation. The UAT metric tensor has not been constructed from the UAT Lagrangian, and the identification of the causal membrane with an ergosphere is an analogy. Its value lies in providing a plausible physical mechanism —superradiant amplification— for the phenomenological success of Eq. (1).

2 The Penrose Superradiance Process

2.1 Original Formulation

In 1969, Roger Penrose demonstrated that energy can be extracted from a rotating black hole [1]. A particle falling into the ergosphere —the region outside the event horizon where frame-dragging forces all observers to rotate with the black hole— can split into two fragments. One fragment falls into the event horizon with negative energy (relative to an observer at infinity), while the other escapes with more energy than the original particle possessed. The escaping fragment has effectively "stolen" rotational energy from the black hole.

The efficiency of this process is governed by the geometry of the ergosphere and the angular momentum of the black hole. For extremal Kerr black holes, the maximum efficiency approaches 29%.

2.2 Experimental Realisation in Metamaterials

In 2020, a team at the CUNY Advanced Science Research Center led by Andrea Alù demonstrated a laboratory analogue of the Penrose process using temporally modulated metamaterials [2]. By varying the electromagnetic properties of a stationary medium in time and space, they created an effective rotational drag without any mechanical motion. Waves interacting with this modulated medium emerged amplified, extracting energy from the modulation source. This experiment demonstrated that superradiance is not exclusive to astrophysical black holes but can manifest in any system with appropriate temporal and spatial modulation.

2.3 Key Features of the Penrose Process

Three features of the Penrose process are relevant to the present discussion:

1. **An ergosphere:** A region where frame-dragging is so intense that no observer can remain stationary. The boundary of the ergosphere is defined by the condition $g_{tt} = 0$, where g_{tt} is the time-time component of the metric.

2. **Negative energy states:** Within the ergosphere, certain trajectories possess negative energy relative to infinity. The absorption of these negative-energy states by the black hole is what powers the amplification.

3. **Amplification of the escaping component:** The fragment that escapes carries more energy than the original incident particle. The amplification factor depends on the geometry of the ergosphere and the black hole's angular momentum.

3 The UAT Causal Membrane as an Effective Ergosphere

3.1 The ADM Decomposition of the Causal Metric

The Arnowitt-Deser-Misner (ADM) formalism [3] decomposes a generic space-time metric into spatial slices evolving in time:

$$ds^2 = -N^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt) \tag{2}$$

where N is the **lapse function** (governing the rate of proper time relative to coordinate time), β^i is the **shift vector** (governing the spatial dragging of coordinates), and γ_{ij} is the spatial metric on the constant-time hypersurfaces.

The time-time component of the metric is:

$$g_{tt} = -N^2 + \gamma_{ij}\beta^i\beta^j \tag{3}$$

In flat Minkowski space-time, $g_{tt} = -1$ (the Killing vector is purely temporal). In a rotating Kerr geometry, the shift vector β^i grows near the black hole, and the condition $g_{tt} = 0$ defines the boundary of the ergosphere.

3.2 Hypothesis: The Causal Membrane as an Ergosphere

We hypothesise that the UAT causal membrane can be described by an effective ADM metric in which:

- The **lapse function** is identified with the quantum braking factor: $N = k_{\text{early}} = 0.967$. This encodes the slowing of proper time relative to coordinate time due to the quantum brake.
- The **shift vector** β^i encodes the spatial dragging induced by the causal overflow ($\varepsilon = 1 - k_{\text{early}} = 3.3\%$) and the geometric structure of the 8-phase coherence array.

Under this hypothesis, the condition for the existence of an ergosphere ($g_{tt} \geq 0$) becomes:

$$\gamma_{ij}\beta^i\beta^j \geq N^2 = k_{\text{early}}^2 \tag{4}$$

3.3 The Geometric Origin of the 7% Margin

Computing the square of the lapse function:

$$N^2 = k_{\text{early}}^2 = (0.967)^2 \approx 0.935 \tag{5}$$

If the unperturbed metric (in the absence of causal drag) would satisfy $g_{tt} = -1$, the presence of the quantum brake introduces a geometric deficit:

$$\boxed{\Delta_{\text{geom}} = 1 - N^2 = 1 - k_{\text{early}}^2 \approx 0.065 \approx 6.5\%} \tag{6}$$

This value is strikingly close to the thermal calibration margin $\phi_*/\eta = 0.07$ (7%) and to the doubled causal overflow $2\varepsilon = 0.066$ (6.6%). We propose that the 7% margin is not an ad hoc calibration but the **minimum geometric deficit** required to satisfy the ergosphere condition (4). In other words, the causal membrane cannot function as an amplifying surface unless the lapse function is sufficiently reduced from unity, and the required reduction is precisely the observed 7%.

3.4 The Amplification Factor as Superradiant Gain

In the Penrose process, the energy extracted by the escaping particle is proportional to the angular momentum of the black hole and the geometry of the ergosphere. In the UAT framework, the amplification of the baryonic density is governed by the product $\kappa_{\text{crit}} \times \varphi$, which we interpret as the effective shift vector coupling:

$$\boxed{\eta_{\text{UAT}} = \kappa_{\text{crit}} \times \varphi \times (1 - \Delta_{\text{geom}})} \tag{7}$$

where $\kappa_{\text{crit}} = 4.978$ encodes the maximum frame-dragging strength (the Ivancho limit), $\varphi \approx 1.618$ encodes the geometric resonance of the 8-phase array (analogous to the quadrupole moment of the Kerr geometry), and $(1 - \Delta_{\text{geom}})$ is the fraction of energy that survives absorption by the membrane.

The effective matter density is then:

$$\Omega_m^{(\text{eff})} = \Omega_b \times \eta_{\text{UAT}} \tag{8}$$

which is precisely Eq. (1) with the thermal margin replaced by its geometric interpretation $\Delta_{\text{geom}} \approx 0.07$.

4 Discussion

4.1 Status of the Correspondence

The correspondence presented in this document is **formal**, not **rigorous**. The following elements are missing for a complete geometric derivation:

1. **The UAT metric tensor $g_{\mu\nu}$ has not been constructed.** The ADM decomposition requires an explicit metric derived from the UAT Lagrangian or from the UAT field equations. Until such a metric is available, the identification of $N = k_{\text{early}}$ and the interpretation of $\kappa_{\text{crit}} \times \varphi$ as the shift vector norm remain hypotheses.

2. **The ergosphere condition has not been proven.** We have shown that the numerical values are consistent with the ergosphere interpretation, but we have not demonstrated that the UAT field equations admit a solution with $g_{tt} > 0$ in the vicinity of the causal membrane.

3. **The Penrose process requires a splitting of the incident wave.** In the cosmological context, the "incident wave" is the baryonic flux, but the mechanism by which it splits into an absorbed component (the 7%) and an amplified component (the 93%) has not been derived from the UAT dynamics.

4.2 What the Correspondence Achieves

Despite these limitations, the formal correspondence provides three valuable contributions:

1. **A physical interpretation for the phenomenological relation.** Eq. (1) is no longer an isolated numerical curiosity; it is a candidate efficiency formula for a superradiant process in the causal membrane.

2. **A geometric origin for the 7% margin.** The value $\phi_*/\eta = 0.07$, previously calibrated empirically, emerges as the natural geometric deficit $1 - k_{\text{early}}^2$ required for ergosphere formation.

3. **A connection to established physics.** Superradiance is a well-understood phenomenon in black hole thermodynamics and has been experimentally demonstrated in metamaterials. The UAT framework, through this correspondence, becomes connected to a broader class of physical systems.

4.3 Falsifiable Predictions

If the causal membrane indeed operates as a superradiant amplifier, the following predictions follow:

1. **The "negative energy" absorbed by the membrane should be detectable.** In the Penrose process, the absorbed component carries negative energy. In the UAT framework, this absorbed energy is dissipated as the causal overflow, which we have previously predicted to manifest as a low-frequency spectral line at $f_\varepsilon = 6.18$ Hz [5].

2. **The amplification should exhibit saturation.** Just as the Penrose process has a maximum efficiency, the UAT amplification should saturate at the Ivancho limit ($\kappa_{\text{crit}} = 4.978$). Attempts to extract more energy should result in membrane rupture (the Thermodynamic Overdrive regime).

3. **The process should be independent of the baryonic substrate.** Any form of energy incident on the causal membrane should undergo the same amplification, suggesting that the 8-coil interferometer should detect the same $R_{\text{geom}} = 0.2791$ residual regardless of the physical medium (copper, optical fibres, acoustic resonators).

5 Conclusion

We have presented a formal correspondence between the UAT causal membrane and the Penrose superradiance process. The phenomenological relation $\Omega_m^{(\text{eff})} = \Omega_b \times \kappa_{\text{crit}} \times \varphi \times (1 - \phi_*/\eta)$ admits a natural interpretation as the efficiency formula for superradiant amplification in an effective ergosphere, where the lapse function $N = k_{\text{early}} = 0.967$ and the thermal margin $\phi_*/\eta = 0.07$ is identified with the geometric deficit $1 - N^2 \approx 0.065$.

We emphasise that this is a formal correspondence, not a rigorous derivation. The construction of the full UAT metric tensor and the proof of the ergosphere condition from the UAT field equations remain tasks for future work. The value of the present document lies in providing a plausible physical mechanism —cosmological superradiance— for the numerical success of the effective matter density relation.

$$\boxed{\text{The structure is Penrose. The constants are Percudani.}}$$

$$\boxed{\text{The correspondence is formal. The proof is pending.}}$$

References

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Formal Correspondence Note — July 13, 2026
This document presents a formal analogy, not a rigorous geometric derivation.
The UAT metric tensor remains to be constructed.

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