

Article

Not peer-reviewed version

Projectional Dissipation and Phase Perturbations in Black Hole Mergers – A TAP Perspective

[Qun Chen](#) *

Posted Date: 3 November 2025

doi: 10.20944/preprints202511.0044.v1

Keywords: irreversibility; TAP theory; cosmological anisotropy; quantum thermodynamics



Preprints.org is a free multidisciplinary platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This open access article is published under a Creative Commons CC BY 4.0 license, which permit the free download, distribution, and reuse, provided that the author and preprint are cited in any reuse.

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Projectional Dissipation and Phase Perturbations in Black Hole Mergers — A TAP Perspective

Qun Chen

Independent Researcher; chenqun@gmail.com

Abstract

We propose a new interpretation of black hole merger dynamics based on the TAP (Thermodynamic Asymmetry from Projection) framework. In this view, the irreversible growth of the event horizon area is not merely a gravitational consequence but a geometric manifestation of higher-dimensional informational dissipation. We further predict that phase micro-perturbations (*tail-wave echoes*) may arise as transient signatures of projectional asymmetry, potentially detectable in gravitational-wave residuals such as GW150914 and GW250114. The model offers a unified understanding linking temporal irreversibility, black hole thermodynamics, and cosmic-scale projection structures.

Keywords: irreversibility; TAP theory; cosmological anisotropy; quantum thermodynamics

1. Introduction

The arrow of time remains one of the deepest unresolved questions in modern physics [1,2]. While the fundamental equations of both classical and quantum mechanics are symmetric under time reversal, our macroscopic experience and thermodynamic laws exhibit an unambiguous directionality. General Relativity (GR) elegantly describes how mass and energy curve spacetime [5], but it offers no explanation for why physical processes unfold irreversibly from past to future. Similarly, quantum mechanics permits time-reversed evolution at the microscopic level, yet observation and decoherence consistently select a preferred direction of causality [6,7].

Black hole thermodynamics provides an especially sharp manifestation of this paradox. The Bekenstein–Hawking entropy relation establishes a deep correspondence between horizon area and information content [8,9], suggesting that irreversibility is somehow embedded in spacetime geometry itself. However, these results are descriptive rather than explanatory: they quantify entropy growth but do not reveal its physical origin. As Penrose emphasized [3], the second law of thermodynamics assumes an initial low-entropy state of the universe, but why such a state existed—or why the universe evolves irreversibly from it—remains unsolved. Even within statistical mechanics, the reduction from microscopic reversibility to macroscopic asymmetry is still conceptually incomplete [4,10].

The **Thermodynamic Asymmetry from Projection (TAP)** framework [13] proposes that temporal asymmetry arises from *projectional dissipation*: a process in which higher-dimensional informational structures are geometrically projected into lower-dimensional spacetimes. During this projection, not all correlations among the higher-dimensional degrees of freedom can be preserved; the resulting information loss manifests as entropy growth, and the asymmetry of that loss defines the arrow of time. Unlike the holographic principle [11,12], which assumes unitary boundary encoding, TAP explicitly allows non-unitary, dissipative mappings—thereby providing a geometric origin for thermodynamic irreversibility.

In this interpretation, every irreversible process corresponds to an incomplete projection of higher-dimensional coherence. Black hole mergers, with their extreme curvature and boundary dynamics, represent natural laboratories for testing this concept: they act as localized “projection events” in which information loss, horizon-area growth, and gravitational-wave emission are tightly coupled [14]. If TAP is correct, these events should leave measurable traces in the form of faint post-merger

oscillations or phase micro-perturbations that encode the dissipation rate of the projection process itself.

This paper develops that idea in a quantitative form. Section 2 establishes the geometric foundation of projectional dissipation; Section 3 draws analogies from known dissipative systems; Section 4 derives testable predictions for gravitational-wave observations; and Section 5–6 extend the discussion to cosmological scales and philosophical implications. In doing so, we aim not only to propose a falsifiable model of time's arrow, but also to unify thermodynamics, information theory, and spacetime geometry within a single projectional framework.

2. Theoretical Framework: TAP and Projectional Dissipation

At the heart of the **TAP framework (Thermodynamic Asymmetry from Projection)** lies a simple but radical proposition:

The arrow of time and the growth of entropy are both consequences of how a higher-dimensional informational structure projects into a lower-dimensional spacetime.

This projection is not merely a mathematical mapping — it represents a *physical reduction of dimensional information capacity*. When a complete higher-dimensional manifold is observed through a lower-dimensional interface, part of its informational coherence becomes inaccessible. That loss manifests within the lower-dimensional frame as an increase of entropy, and its direction defines temporal irreversibility.

2.1. Informational Projection and Dissipation

Let \mathcal{I}_n denote an information-complete structure embedded in n -dimensional space. When projected into a lower-dimensional observational domain \mathcal{M}_3 , a fraction of its internal correlations becomes inaccessible:

$$\mathcal{I}_n \longrightarrow \mathcal{M}_3 : \quad dS = -dI_{\text{accessible}} > 0 \quad (1)$$

The inequality expresses the fundamental TAP statement:

$$\frac{dS}{dt} > 0 \quad \iff \quad \frac{dI_{\text{accessible}}}{dt} < 0 \quad (2)$$

Entropy, therefore, is not an abstract measure of disorder but a *projectional metric of lost correlations*. Every irreversible process — whether the cooling of a star, the merging of two black holes, or the evolution of consciousness — can be traced to the same geometric cause: the dissipation of information during dimensional reduction.

2.2. Geometric Expression in Black Hole Mergers

In General Relativity, when two black holes merge, the total event horizon area A after merger satisfies the area theorem:

$$A_{\text{final}} \geq A_1 + A_2 \quad (3)$$

TAP interprets this inequality not as a thermodynamic coincidence but as a *manifestation of information dissipation across the projection boundary*. The excess area can be expressed as:

$$\Delta A = A_{\text{final}} - (A_1 + A_2) \quad (4)$$

This ΔA corresponds to the *geometric residue* of irretrievable information — the spatial imprint of time's directionality. Hence, a geometric-informational equivalence emerges:

$$\Delta A \propto \Delta S \propto -\Delta I \quad (5)$$

The irreversible increase of horizon area thus encodes the same principle that governs the thermodynamic arrow of time, but now generalized to spacetime geometry itself.

2.3. Physical Meaning of Projectional Dissipation

Projectional dissipation is not a metaphor; it is a structural phenomenon. Whenever a system's boundary conditions constrain the full dimensional description, information must be compressed or discarded. The observer within the reduced dimensionality perceives this as "time passing" — the continuous conversion of potential configurations into realized states.

This perspective redefines causality: cause and effect are not discrete events linked by an external time, but rather the sequential disclosure of higher-dimensional geometry through an irreversible projection process.

2.4. The TAP Principle Restated

In compact symbolic form, the TAP principle can be written as:

Higher-Dimensional Information: \mathcal{I}_n	(6)
Projection Operator: $\mathcal{P}_{n \rightarrow 3}$	
Observed Entropy Growth: $dS = -dI_{\text{accessible}}$	
Arrow of Time: Orientation of $(\mathcal{P}_{n \rightarrow 3})$ under information loss.	

This represents the **central symmetry-breaking mechanism** of TAP: time's direction does not arise from stochastic fluctuations but from a geometric bias in the projection operator itself.

The next section compares this projectional asymmetry with analogous dissipative structures observed in other physical systems.

3. Analogy Across Dissipative Systems

The projectional asymmetry proposed by TAP finds structural analogues in multiple dissipative systems across physics. While these systems differ vastly in scale—from optical cavities to macroscopic spacetime—they all exhibit a unifying pattern: *irreversibility emerges when a system loses information through constrained boundary coupling.*

3.1. Driven–Dissipative Quantum Systems

In driven open quantum systems, steady-state fluctuations and decoherence arise as the environment continuously absorbs information from the system. Recent analyses [18] show that such systems reach non-equilibrium stationary states characterized by persistent microscopic dissipation. The TAP correspondence here is clear: the system's Hilbert space acts as a high-dimensional information reservoir, while the environment functions as a lower-dimensional projection channel. The irreversible loss of coherence in quantum correlations parallels the projectional dissipation responsible for time's arrow.

3.2. Optical Microresonators and Dissipative Solitons

Optical microresonators exhibit self-organized pulse structures known as *dissipative Kerr solitons* [16,24]. These localized waveforms balance nonlinearity, dispersion, and loss to maintain a stable oscillatory form. Each soliton represents a dynamic equilibrium between continuous driving (energy inflow) and dissipation (energy outflow). In the TAP interpretation, this behavior is analogous to *tail-wave perturbations* following a projection event: the system stabilizes by releasing surplus informational curvature into its dissipative boundary. Just as solitons mark the interface between order and loss, the TAP tail-wave signature traces the re-stabilization of spacetime geometry.

3.3. Nonlinear Duffing Chains and Perturbation Propagation

Classical many-body models such as driven dissipative Duffing chains [17] demonstrate that localized perturbations do not vanish instantly but propagate as exponentially decaying *tails*. These tails encode the residual energy of coupling between oscillators, forming a memory of the system's

previous configuration. This mirrors TAP's prediction that post-merger gravitational systems retain faint phase micro-oscillations—a geometric afterimage of the projectional mismatch between pre- and post-merger states.

3.4. Universality of Projection–Dissipation Duality

Across these examples, a universal structure emerges:

$$\text{Projection} \longleftrightarrow \text{Loss of Correlations} \longleftrightarrow \text{Emergent Directionality.} \quad (7)$$

Whether in optical, quantum, or classical systems, directionality (time, phase, or information flow) is always born from the same condition: an open boundary that limits information return. TAP extends this universality to spacetime itself, proposing that the fabric of reality obeys the same principle that governs dissipative systems—yet on a geometric scale.

Thus, before searching for TAP's signatures in black hole mergers, we recognize that nature already exhibits analogous projection–dissipation dynamics at every accessible level of complexity.

4. Predicted Observable Signatures

If projectional dissipation is a genuine geometric mechanism, its effects should leave faint but measurable traces in astrophysical observations. Black hole mergers, being among the most extreme dissipative events in the universe, provide an ideal testing ground for TAP predictions.

4.1. Tail-Wave Echoes and Phase Micro-Perturbations

In TAP, when two event horizons merge, the alignment of their respective projection surfaces induces transient mismatches in curvature and informational coherence. This produces short-lived, low-amplitude oscillations following the primary ringdown phase. We denote these as *tail-wave echoes* or *phase micro-perturbations*.

The expected form of the signal may be represented as

$$\delta\phi(t) \approx f(M, a) e^{-\lambda t} \sin(\omega_{\text{tail}}t + \psi_0), \quad (8)$$

where

- M is the final black hole mass,
- a is the spin parameter,
- λ is the geometric dissipation rate (linked to ΔA),
- ω_{tail} is the effective tail frequency,
- and ψ_0 is the phase offset from the main ringdown mode.

Unlike standard quasi-normal mode (QNM) oscillations, these micro-perturbations are not inherent eigenmodes of the black hole spacetime, but geometric afterimages of the projection process itself.

4.2. Relation to Horizon Area Surplus

The TAP framework links these perturbations to the non-linear surplus in horizon area,

$$\Delta A = A_{\text{final}} - (A_1 + A_2), \quad (9)$$

interpreted as the irreversible informational residue of the merger. The dissipation rate λ is expected to scale with this surplus:

$$\lambda \propto \frac{\Delta A}{A_{\text{final}}}. \quad (10)$$

Hence, the strength and duration of the tail-wave echoes encode the degree of projectional irreversibility. The measurable parameters $(\lambda, \omega_{\text{tail}})$ therefore serve as observable fingerprints of dimensional information loss.

4.3. Potential Observational Targets

Gravitational-wave events such as **GW150914** and **GW250114** offer ideal datasets for investigating TAP effects. Preliminary analyses [14,15] have already reported possible residual signals consistent with faint, exponentially damped echoes at post-merger timescales of $t \sim 0.1\text{--}0.3$ s.

TAP refines this interpretation by proposing that:

1. The echo structure arises from curvature-phase realignment between two merging projection surfaces.
2. The decay constant λ corresponds to the geometric dissipation rate, linked to horizon-area growth.
3. Multiple mergers can be statistically stacked to reveal consistent phase-tail patterns buried below the current noise floor.

4.4. Detectability and Falsifiability

From an experimental standpoint, TAP introduces a rare feature: it is directly falsifiable. If repeated cross-event analyses and weighted residual stacking fail to reveal any correlated post-ringdown perturbations, then the projectional dissipation model can be ruled out at astrophysical scales.

Conversely, the detection of even weak but phase-consistent echoes would represent the first empirical signature of *geometric dissipation in spacetime itself*.

Either outcome advances the field:

- **No signal detected:** spacetime projection is purely geometric and lossless.
- **Signal detected:** temporal directionality emerges as a measurable physical phenomenon.

In both cases, black hole mergers serve as natural laboratories for exploring the foundational question of why time possesses an arrow.

5. Discussion and Cosmological Implications

The TAP framework, while motivated by local phenomena such as black hole mergers, has implications that extend to the largest observable structures in the universe. If time's direction and entropy growth arise from projectional dissipation, then the same mechanism must also leave signatures on cosmological scales, where the universe itself behaves as a global projection system.

5.1. From Local to Cosmic Projection

In TAP, the universe can be regarded as a three-dimensional projection of a higher-dimensional information manifold \mathcal{I}_n . The boundary of this projection corresponds to the observable cosmic horizon. At such a scale, small irregularities in the projection geometry would appear as anisotropies in both energy distribution and phase coherence.

This leads to a unified interpretation: black hole mergers represent *localized projection realignments*, while cosmological anisotropies reveal *slow, large-scale projection curvature*. Both arise from the same underlying informational geometry.

5.2. CMB Anomalies as Phase Anisotropies

The Cosmic Microwave Background (CMB) provides the oldest snapshot of the projection boundary observable to us. Although remarkably uniform, it exhibits several well-known anomalies, including the so-called *Cold Spot* and the *Axis of Evil* alignment [19,20]. These large-angle deviations from isotropy have resisted complete explanation within the standard Λ CDM cosmology.

TAP interprets these anomalies as manifestations of weak *phase anisotropies* in the global projection field. Let $\Phi(x)$ denote the projected potential field on the three-dimensional observational manifold. A small phase deviation $\epsilon(x)$ from the higher-dimensional structure leads to:

$$\delta\Phi(x) = \Phi_0 \sin(\omega t + \epsilon(x)), \quad (11)$$

where $\epsilon(x)$ encodes spatial variations in projection phase. Regions where $\epsilon(x)$ deviates coherently from zero appear as statistically significant temperature anisotropies in the CMB.

Thus, what we interpret as primordial fluctuations may instead represent geometric ripples in the projection interface. The persistence and alignment of such anomalies suggest that the universe's large-scale homogeneity is not fundamental but *emergent through projectional averaging*.

5.3. Informational Irreversibility on the Cosmological Scale

If the arrow of time originates in projectional dissipation, then the universe's evolution from low to high entropy is not a random thermodynamic process, but a directional unfolding of geometry. Cosmic expansion and entropy increase reflect the same underlying principle observed in black hole mergers: an irreversible information flow from higher- to lower-dimensional states.

In this view, cosmological time t_{cos} is not a parameter within the projection, but a cumulative measure of information lost from the higher-dimensional domain:

$$t_{\text{cos}} \propto \int dI_{\text{lost}}. \quad (12)$$

The progression of time therefore corresponds to the accumulation of dissipation across the entire cosmic projection.

5.4. Toward an Observational TAP Cosmology

Several observational strategies could help probe this framework:

- **Cross-correlation analysis** between CMB phase anomalies and large-scale structure (LSS) distributions to test for coherent projectional signatures.
- **Spectral distortion searches** in the CMB to detect non-thermal relics of projectional dissipation at early epochs.
- **Polarization alignment studies** to evaluate whether the Axis of Evil corresponds to a preferred projection direction rather than a statistical fluctuation.

If confirmed, such findings would imply that both the cosmic arrow of time and the microscopic arrow observed in black hole systems originate from the same geometric principle: **the asymmetry of information projection**.

5.5. Broader Theoretical Context

TAP naturally complements existing frameworks:

- It extends the *holographic principle* by introducing dissipation and directionality absent in standard holography.
- It aligns with *thermodynamic cosmology*, yet replaces the notion of random entropy increase with structured, geometry-driven information loss.
- It provides a physical underpinning for Prigogine's *dissipative structures*, situating them within the geometry of spacetime rather than within chemical or biological systems.

In this synthesis, the universe emerges not as a static hologram but as a continuously evolving projection—a living interface between higher-dimensional coherence and lower-dimensional observation.

5.6. Summary of Cosmological Implications

1. The arrow of time arises universally from projectional dissipation.
2. Black hole mergers represent localized, high-intensity projection events.
3. CMB anomalies encode large-scale geometric irregularities of the same origin.
4. Temporal evolution corresponds to the integral of informational loss across the cosmic boundary.

Thus, TAP offers a unifying lens through which local and global irreversibility can be understood within a single geometric–informational framework.

6. Conclusion

The **Thermodynamic Asymmetry from Projection (TAP)** framework reinterprets the arrow of time, entropy increase, and cosmological structure as emergent consequences of *geometric information projection*. From the merging of black holes to the background radiation of the cosmos, every irreversible process is unified under one principle: *when higher-dimensional information is projected into a lower-dimensional domain, correlations are lost, and that loss defines the direction of time.*

6.1. From Geometry to Temporality

Classical physics treats time as a coordinate and entropy as a statistical quantity. TAP reframes both as outcomes of dimensional geometry. The increase of black hole horizon area,

$$\Delta A = A_{\text{final}} - (A_1 + A_2) > 0,$$

is not simply a manifestation of energy redistribution, but the spatial record of informational dissipation. In the same way, the cosmic expansion and entropy growth express the large-scale unfolding of projectional asymmetry.

Thus, temporality itself becomes a geometric phenomenon— a signature of the universe’s mode of self-disclosure. Time does not *flow*; it is *revealed*, slice by slice, through projectional loss.

6.2. Scientific Implications

The TAP perspective offers three experimentally relevant consequences:

1. **Astrophysical Verification:** Detectable *tail-wave echoes* and phase micro-perturbations in post-merger gravitational-wave data could reveal dissipation at spacetime boundaries.
2. **Cosmological Corroboration:** Persistent anomalies in the CMB, such as the Cold Spot or Axis of Evil, may represent projectional phase anisotropies on cosmic scales.
3. **Theoretical Integration:** TAP provides a geometric–informational basis for the second law of thermodynamics and for the universality of temporal asymmetry.

Each of these consequences is *falsifiable*. The framework does not rely on metaphysical assumptions but on geometric observables, linking thermodynamics, general relativity, and information theory within one coherent structure.

6.3. Philosophical Reflection: Time, Letting Go, and Awareness

The implications of TAP extend beyond physics. If time’s arrow is the product of informational dissipation, then every irreversible process—including the unfolding of life and consciousness—is part of the same projectional dynamics.

In this context, the act of *letting go* (*Fangxia*) takes on a precise scientific meaning: to align with the natural direction of projection, to cease resisting the geometry of irreversibility. What philosophy calls *acceptance*, TAP defines as *minimizing informational turbulence*. Awareness becomes the self-reflective moment when the projection recognizes its own unfolding.

Thus, the border between physics and philosophy dissolves. Entropy, causality, and consciousness all arise as different expressions of the same deeper asymmetry— the one that allows the universe to manifest.

6.4. Outlook

Future research may extend TAP in several directions:

- Developing a formal mathematical model of the projection operator $\mathcal{P}_{n \rightarrow 3}$ and its curvature–dissipation tensor.
- Performing statistical echo searches across multiple gravitational-wave events to constrain the dissipation rate λ .
- Mapping TAP’s predictions onto early-universe dynamics to test whether projectional anisotropy could serve as an alternative explanation for inflationary or dark-energy phenomena.

Each step moves the theory closer to a unified framework where time’s arrow, information loss, and geometric structure become different facets of a single physical law.

6.5. Final Synthesis

The TAP theory does not seek to replace existing physics, but to illuminate what they all presuppose: the origin of direction, the reason asymmetry exists at all.

If verified, TAP would reveal that the universe’s most fundamental law is not equilibrium, but **dissipation**; not symmetry, but **the geometry of loss**.

In that realization, physics meets philosophy: what we experience as the passing of time is the universe continuing to project itself, moment by moment, through every act of transformation, awareness, and release.

“If the world is a projection, then we are its light.”

Appendix A: Mathematical Modeling of Dissipative Projection

The following section outlines a preliminary mathematical structure for the TAP framework, linking geometric dissipation, horizon area surplus, and information loss. While the formalism is simplified, it provides a starting point for quantifying projectional asymmetry.

A.1 Projection Operator and Information Mapping

Let \mathcal{I}_n denote the n -dimensional informational manifold and \mathcal{M}_3 the observable spacetime submanifold. The projection is represented by a non-isometric operator:

$$\mathcal{P}_{n \rightarrow 3} : \mathcal{I}_n \rightarrow \mathcal{M}_3, \quad (\text{A13})$$

such that for any informational state vector $|\psi\rangle \in \mathcal{I}_n$,

$$|\phi\rangle = \mathcal{P}_{n \rightarrow 3}|\psi\rangle. \quad (\text{A14})$$

Because $\mathcal{P}_{n \rightarrow 3}$ is not unitary, it does not preserve inner products:

$$\langle\phi|\phi\rangle = \langle\psi|\mathcal{P}^\dagger\mathcal{P}|\psi\rangle < \langle\psi|\psi\rangle. \quad (\text{A15})$$

This inequality encodes *information loss during projection*, corresponding to the dissipative arrow of time.

A.2 Dissipation Tensor and Geometric Asymmetry

We define a local *projection-dissipation tensor* $\Pi_{\mu\nu}$ as:

$$\Pi_{\mu\nu} = g_{\mu\nu}^{(3)} - \mathcal{P}_\mu^\alpha \mathcal{P}_\nu^\beta g_{\alpha\beta}^{(n)}, \quad (\text{A16})$$

where $g_{\mu\nu}^{(3)}$ is the induced 3D metric and $g_{\alpha\beta}^{(n)}$ is the parent manifold metric. The trace of this tensor defines a scalar measure of projectional dissipation:

$$\Lambda_{\text{proj}} = \text{Tr}(\Pi_{\mu\nu}) = g_{(3)}^{\mu\nu} \Pi_{\mu\nu}. \quad (\text{A17})$$

For weak projections ($\|\Pi_{\mu\nu}\| \ll 1$), Λ_{proj} approximates the fractional loss of geometric consistency and is directly related to the effective dissipation rate λ in the macroscopic regime.

A.3 Information Entropy and Dissipation Rate

Let S_{info} denote the informational entropy on \mathcal{M}_3 . Its rate of increase under projection follows:

$$\frac{dS_{\text{info}}}{dt} = k_B \lambda, \quad (\text{A18})$$

where k_B is Boltzmann's constant. This defines λ as the proportionality constant between information loss and entropy growth.

Given that λ is observable through post-merger gravitational-wave tails, this provides a bridge between information geometry and measurable astrophysical data.

A.4 Horizon Area Surplus and Dissipative Work

In black hole mergers, the TAP relation connects the dissipation rate λ to the horizon area surplus:

$$\lambda = \eta \frac{\Delta A}{A_{\text{final}}}, \quad (\text{A19})$$

where η is a dimensionless geometric coupling constant. Substituting this into the entropy relation yields:

$$\frac{dS_{\text{info}}}{dt} = k_B \eta \frac{\Delta A}{A_{\text{final}}}. \quad (\text{A20})$$

Integrating over the ringdown phase gives the total informational work done by projection:

$$W_{\text{proj}} = \int_0^{t_f} \lambda(t) dt = \eta \ln \left(\frac{A_{\text{final}}}{A_1 + A_2} \right). \quad (\text{A21})$$

Thus, the logarithmic area relation encodes the irreversible “work” associated with aligning two projection surfaces—a geometric analog of dissipative thermodynamic work.

A.5 Phase Perturbation Spectrum

The residual phase perturbations following a merger can be modeled as a damped spectral response to the dissipation tensor:

$$\delta\phi(\omega) = \int \Pi_{\mu\nu}(t) e^{-i\omega t} dt. \quad (\text{A22})$$

The observable power spectrum $P(\omega)$ is then:

$$P(\omega) = |\delta\phi(\omega)|^2 \propto \frac{\lambda^2}{(\omega^2 - \omega_0^2)^2 + \lambda^2}. \quad (\text{A23})$$

This Lorentzian form predicts that as $\lambda \rightarrow 0$, the spectrum becomes sharply resonant—corresponding to idealized, lossless geometry. As λ increases, the resonance broadens, reflecting increasing dissipation and directional entropy.

A.6 Unified Projection–Dissipation Identity

We may summarize the core TAP mathematical identity as:

$$\boxed{\frac{dS_{\text{info}}}{dt} \propto \Lambda_{\text{proj}} \propto \frac{\Delta A}{A_{\text{final}}} \propto \lambda.} \quad (\text{A24})$$

In words: the rate of entropy increase equals the degree of geometric inconsistency equals the relative area surplus equals the macroscopic dissipation rate.

This identity formalizes the arrow of time as an emergent property of the universe’s projection geometry.

A.7 Discussion

Although this mathematical framework remains preliminary, it offers a self-consistent pathway for linking geometry, information, and dissipation. Future extensions may include:

- a full tensorial expansion of $\Pi_{\mu\nu}$ including back-reaction terms,
- numerical simulations of projection-induced ringdown signatures,
- and quantum-information analogues connecting TAP to holographic entanglement entropy.

Ultimately, these equations suggest that every irreversible event— from a black hole merger to the unfolding of consciousness— shares a single mathematical essence: the geometry of informational loss across dimensional boundaries.

Appendix B: Statistical Detection Framework for TAP Tail-Wave Signals

This appendix outlines a statistical methodology for identifying weak, phase-coherent *tail-wave perturbations* predicted by the TAP model in post-merger gravitational-wave data. The approach integrates residual analysis, stacking, and phase-alignment techniques to enhance signal-to-noise ratio (SNR) for sub-threshold dissipative features.

B.1 Data Selection and Preprocessing

We utilize publicly available strain data from the LIGO–Virgo Collaboration (LVC) for confirmed binary black hole (BBH) merger events, including GW150914, GW170104, GW170814, and GW250114. Each dataset is preprocessed through the following stages:

1. Bandpass filtering in the range 20–1024 Hz to remove seismic and high-frequency noise components.
2. Time-domain whitening to flatten the detector noise spectrum.
3. Windowing of the post-merger segment ($t_0 < t < t_0 + 0.5$ s), where t_0 is the end of the inspiral–merger phase.
4. Normalization of amplitude to unit variance across the selected segment.

After preprocessing, each strain time series $h_i(t)$ is decomposed into a theoretical ringdown model $h_i^{\text{QNM}}(t)$ and a residual term:

$$r_i(t) = h_i(t) - h_i^{\text{QNM}}(t), \quad (\text{A25})$$

where $h_i^{\text{QNM}}(t)$ is computed using the best-fit quasi-normal mode (QNM) parameters provided by the LVC catalog.

B.2 Residual Stacking and Phase Alignment

The TAP-predicted tail-wave signal $\delta\phi(t)$ is expected to exhibit a consistent relative phase across multiple merger events, modulated primarily by the mass-scaled frequency ratio:

$$\omega_{\text{tail}} \propto \frac{1}{M_{\text{final}}}. \quad (\text{A26})$$

To exploit this universality, we define a normalized residual template:

$$r'_i(t) = r_i\left(\frac{t}{M_{\text{final},i}/M_0}\right), \quad (\text{A27})$$

where M_0 is a reference mass (e.g., $60M_\odot$). Residuals are then aligned in phase via cross-correlation maximization:

$$\Delta t_i = \arg \max_{\tau} \int r'_i(t)r'_{\text{ref}}(t + \tau) dt, \quad (\text{A28})$$

where $r'_{\text{ref}}(t)$ is an arbitrary reference residual (e.g., from GW150914). Phase-aligned residuals are then averaged to form a stacked signal:

$$R(t) = \frac{1}{N} \sum_{i=1}^N r'_i(t + \Delta t_i). \quad (\text{A29})$$

This procedure suppresses uncorrelated detector noise while preserving any physically coherent post-merger oscillation shared across events.

B.3 Spectral and Phase-Coherence Analysis

The Fourier transform of the stacked residual,

$$\tilde{R}(\omega) = \int R(t)e^{-i\omega t} dt, \quad (\text{A30})$$

is used to compute the power spectral density (PSD):

$$P(\omega) = |\tilde{R}(\omega)|^2. \quad (\text{A31})$$

The TAP hypothesis predicts an exponentially damped oscillatory component:

$$R(t) \sim e^{-\lambda t} \sin(\omega_{\text{tail}}t + \psi_0), \quad (\text{A32})$$

which produces a Lorentzian peak in the PSD centered at ω_{tail} with width λ .

To confirm physical coherence, we calculate the normalized phase-coherence index:

$$C(\omega) = \frac{|\sum_i e^{i\phi_i(\omega)}|}{N}, \quad (\text{A33})$$

where $\phi_i(\omega)$ is the phase of $\tilde{r}'_i(\omega)$. Values $C(\omega) \rightarrow 1$ indicate high coherence across events, consistent with a universal physical origin.

B.4 Statistical Significance and Control Tests

To estimate significance, we perform Monte Carlo resampling:

1. Shuffle the phase alignment order across residuals and recompute $R(t)$.
2. Generate 10,000 synthetic realizations to establish a null distribution of $P(\omega)$.
3. Compute the empirical p-value for observed peaks at ω_{tail} .

A detection is considered significant if:

$$p < 10^{-3} \quad \text{and} \quad C(\omega_{\text{tail}}) > 0.6. \quad (\text{A34})$$

Additional control tests include:

- **Time-reversal check:** reversing $r_i(t)$ should destroy the coherent peak.
- **Cross-detector consistency:** the signal should appear in both Hanford and Livingston data.
- **Null injections:** simulated ringdown-only waveforms must not reproduce the same feature.

B.5 Expected Parameter Constraints

If a statistically significant Lorentzian excess is observed, the parameters $(\omega_{\text{tail}}, \lambda)$ can be fit using non-linear least squares:

$$P(\omega) = A \frac{\lambda^2}{(\omega^2 - \omega_{\text{tail}}^2)^2 + \lambda^2}. \quad (\text{A35})$$

From the TAP relation $\lambda \propto \Delta A / A_{\text{final}}$, one can then estimate the geometric dissipation ratio:

$$\Gamma_{\text{geo}} = \frac{\lambda}{\omega_{\text{tail}}}. \quad (\text{A36})$$

A non-zero, consistent Γ_{geo} across multiple events would constitute strong evidence for projectional dissipation.

B.6 Summary of Detection Pipeline

1. Acquire and preprocess LVC strain data for selected BBH mergers.
2. Subtract best-fit QNM models to isolate residuals.
3. Normalize and mass-scale the residuals.
4. Phase-align and stack across multiple events.
5. Compute $P(\omega)$ and $C(\omega)$ spectra.
6. Assess significance via Monte Carlo shuffling and cross-detector validation.

Outcome:

- A null result ($p > 0.05$) constrains TAP by setting an upper bound on λ .
- A positive detection ($p < 10^{-3}$, coherent phase) reveals the first empirical trace of geometric dissipation in spacetime.

B.7 Broader Relevance

Beyond gravitational-wave astronomy, this methodology demonstrates how *multi-event coherence stacking* can probe extremely subtle physical effects that lie below single-event detectability. If successful, it establishes a template for analyzing dissipative projections in other domains—ranging from condensed-matter oscillations to cosmological phase anisotropies.

The TAP framework thus transforms gravitational-wave data analysis from mere source characterization into a fundamental test of the arrow of time.

Acknowledgments: The author thanks collaborators and discussion partners for insights linking high-dimensional information geometry, gravitational wave analysis, and cosmological structure.

References

1. Carroll, S. M. (2010). *From Eternity to Here: The Quest for the Ultimate Theory of Time*. Dutton, New York.
2. Price, H. (1996). *Time's Arrow and Archimedes' Point: New Directions for the Physics of Time*. Oxford University Press, Oxford.
3. Penrose, R. (1989). *The Emperor's New Mind: Concerning Computers, Minds, and the Laws of Physics*. Oxford University Press, Oxford.
4. Lebowitz, J. L. (1993). Macroscopic laws, microscopic dynamics, time's arrow and Boltzmann's entropy. *Physica A: Statistical Mechanics and its Applications*, 194(1–4), 1–27. [https://doi.org/10.1016/0378-4371\(93\)90068-M](https://doi.org/10.1016/0378-4371(93)90068-M).
5. Misner, C. W., Thorne, K. S., & Wheeler, J. A. (1973). *Gravitation*. W. H. Freeman and Company, San Francisco.
6. Zeh, H. D. (2007). *The Physical Basis of the Direction of Time* (5th ed.). Springer, Berlin.
7. Zurek, W. H. (2003). Decoherence and the transition from quantum to classical. *Reviews of Modern Physics*, 75(3), 715–775. <https://doi.org/10.1103/RevModPhys.75.715>.
8. Bekenstein, J. D. (1973). Black holes and entropy. *Physical Review D*, 7(8), 2333–2346. <https://doi.org/10.1103/PhysRevD.7.2333>.
9. Hawking, S. W. (1975). Particle creation by black holes. *Communications in Mathematical Physics*, 43(3), 199–220. <https://doi.org/10.1007/BF02345020>.

10. Davies, P. C. W. (1974). *The Physics of Time Asymmetry*. University of California Press, Berkeley.
11. 't Hooft, G. (1993). Dimensional reduction in quantum gravity. *arXiv preprint gr-qc/9310026*. <https://arxiv.org/abs/gr-qc/9310026>.
12. Susskind, L. (1995). The world as a hologram. *Journal of Mathematical Physics*, 36(11), 6377–6396. <https://doi.org/10.1063/1.531249>.
13. Chen, Q. (2025). *Thermodynamic Asymmetry from Projection (TAP): A Geometric Framework for Time's Arrow and Entropy Emergence*. Preprint, OSF. <https://osf.io/project/tap-theory/>.
14. Cardoso, V., Franzin, E., & Pani, P. (2016). Is the gravitational-wave ringdown a probe of the event horizon? *Physical Review Letters*, 116(17), 171101. <https://doi.org/10.1103/PhysRevLett.116.171101>.
15. Conklin, R. S., Holdom, B., & Ren, J. (2018). Gravitational wave echoes through new windows. *Physical Review D*, 98(4), 044021. <https://doi.org/10.1103/PhysRevD.98.044021>.
16. Herr, T., et al. (2012). Temporal solitons in optical microresonators. *Nature Photonics*, 6(7), 480–487. <https://doi.org/10.1038/nphoton.2012.127>.
17. Dey, S., & Livi, R. (2020). Spatio-temporal spread of perturbations in a driven dissipative Duffing chain. *Physical Review E*, 101(4), 042217. <https://doi.org/10.1103/PhysRevE.101.042217>.
18. Hodaie, H., et al. (2025). Many-body perturbation theory for driven dissipative quasiparticle flows and fluctuations. *arXiv preprint*, arXiv:2510.19124 (in press).
19. Planck Collaboration. (2018). Planck 2018 results. I. Overview and the cosmological legacy of Planck. *Astronomy & Astrophysics*, 641, A1. <https://doi.org/10.1051/0004-6361/201833880>.
20. Akrami, Y., et al. (Planck Collaboration). (2019). Planck 2018 results. VII. Isotropy and statistics of the CMB. *Astronomy & Astrophysics*, 641, A7. <https://doi.org/10.1051/0004-6361/201833882>.
21. Feynman, R. P. (1965). *The Character of Physical Law*. MIT Press, Cambridge, MA.
22. Joos, E., Zeh, H. D., Kiefer, C., Giulini, D. J. W., Kupsch, J., & Stamatescu, I. O. (2003). *Decoherence and the Appearance of a Classical World in Quantum Theory*. Springer, Berlin.
23. Schlosshauer, M. (2019). Quantum decoherence. *Physics Reports*, 831, 1–57. <https://doi.org/10.1016/j.physrep.2019.10.001>.
24. Kippenberg, T. J., Gaeta, A. L., Lipson, M., & Gorodetsky, M. L. (2018). Dissipative Kerr solitons in optical microresonators. *Science*, 361(6402), eaan8083. <https://doi.org/10.1126/science.aan8083>
25. Zurek, W. H. (2022). Emergence of the classical from within the quantum universe. *Physical Review A*, 105(5), 052206. <https://doi.org/10.1103/PhysRevA.105.052206>.

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.