

# Evaluating Electromagnetic Deceleration and Energy Degeneration Against Gravitational Wave Propagation: A Multi-Messenger Mathematical Model

## The Paradigm of Multi-Messenger Propagation Dynamics

The era of multi-messenger astrophysics was definitively inaugurated by the simultaneous observation of gravitational waves and electromagnetic radiation, granting unprecedented observational access to the fundamental mechanics of the cosmos.<sup>1</sup> Within the standard cosmological consensus, defined primarily by the Friedmann-Lemaître-Robertson-Walker metric and general relativity, all massless bosons—including both photons and hypothetical gravitons—are theorized to propagate through the vacuum of space at the absolute, invariant

speed of light, denoted as the constant  $c_0$ .<sup>3</sup> In this established framework, any arrival time discrepancies observed between different messengers emitted by a singular astrophysical event are attributed exclusively to local environmental factors. Such factors include the intrinsic temporal delay in the emission mechanisms themselves, or localized interactions with dense circumstellar media.<sup>5</sup> Furthermore, the phenomenon of cosmological redshift is universally attributed to the metric expansion of space itself, a process that supposedly stretches the wavelengths of both electromagnetic and gravitational waves equivalently during their cosmological transit.<sup>7</sup>

However, the increasing precision of modern interferometers, such as the Laser Interferometer Gravitational-Wave Observatory, the Virgo detector, and KAGRA, combined with wide-field electromagnetic surveys like the Zwicky Transient Facility and the Fermi Gamma-ray Space Telescope, provides the granular, high-fidelity data necessary to rigorously challenge these foundational paradigms.<sup>9</sup> This comprehensive report systematically constructs, calibrates, and evaluates an alternative phenomenological framework: a decoupled propagation model. This model operates under the explicit postulate that gravitational waves traverse the cosmos at a

constant, invariant velocity  $c_0$ , while electromagnetic radiation experiences secular velocity deceleration (a Variable Speed of Light dynamic) alongside distance-dependent energy degeneration (a modernized "Tired Light" mechanic).<sup>12</sup>

By methodically abandoning the assumption of metric expansion and strict Lorentz invariance for electromagnetism over cosmological scales, the analysis utilizes empirical data from landmark multi-messenger events—namely the neutron star merger GW170817, and the black hole collisions GW150914 and GW190521—to mathematically calibrate the precise rate at which light "tires" and slows.<sup>14</sup> This highly analytical approach requires the mathematical

disentanglement of the propagation delays induced by the vast intergalactic medium from the intrinsic delays generated at the astrophysical source.<sup>5</sup> The subsequent derivations and calculations not only quantify the electromagnetic attenuation coefficients but also present a radical, self-consistent resolution to classical cosmological anomalies, including the persistent Hubble tension and the survival of cosmological time dilation within a strictly non-expanding universe.<sup>16</sup>

## Formalizing the Decoupled Propagation Model

To accurately quantify the differential behavior between metric perturbations (gravitational waves) and vector boson propagation (electromagnetic waves), it is necessary to mathematically formalize the kinematics and thermodynamics of both messengers as they cross vast cosmological distances. The model must construct distinct equations of motion for each messenger.

### Gravitational Wave Constancy and Metric Perturbation

General relativity posits that gravitational waves are self-propagating ripples in the spacetime curvature, produced by the asymmetric acceleration of massive objects, such as inspiraling binary systems.<sup>3</sup> Unlike electromagnetic fields, which couple to electric charge and can interact continuously with the quantum vacuum or intergalactic plasma, the gravitational wave is a fundamental perturbation of the spacetime metric itself. Consequently, because mass is strictly positive, there exists no gravitational dipole moment to induce dispersive retardation or refraction in a vacuum analogous to electromagnetic interactions.<sup>19</sup>

For the purposes of this mathematical framework, the propagation velocity of gravitational waves,  $v_{GW}$ , is formalized as an absolute, immutable constant equivalent to the classical

theoretical vacuum speed of light,  $c_0$ .

$v_{GW} = c_0 = 299,792,458 \text{ m/s}$  Because this velocity remains perfectly unattenuated regardless of the distance traversed, the total transit time for a gravitational wave

emitted at a static, fixed distance  $D$  from the observer is strictly linear and unperturbed by the medium:

$$t_{GW} = \frac{D}{c_0}$$

This absolute constancy serves as the definitive temporal baseline against which the proposed deceleration of electromagnetic light will be measured and evaluated. In this model, the gravitational wave represents the true transmission of information across space without temporal degradation.<sup>20</sup>

### Electromagnetic Velocity Attenuation

In sharp contrast to the unperturbed metric perturbations of gravity, the proposed framework hypothesizes that the propagation of photons is subject to a continuous, secular deceleration.

Variable Speed of Light models have historically been proposed to resolve cosmological horizons or as theoretical alternatives to cosmic inflation.<sup>22</sup> In this specific localized application, the deceleration of light is treated mathematically as a consequence of cumulative, continuous interactions with the universal quantum vacuum or a ubiquitous, finely distributed intergalactic medium. This medium effectively acts as a dispersive optical field with a non-trivial, distance-dependent refractive index that retards photon velocity.<sup>13</sup>

Let the instantaneous velocity of electromagnetic radiation,  $v_{EM}$ , be defined as a monotonically decreasing function of the absolute distance traversed,  $x$ . This attenuation is governed by an exponential decay function, characterized by a universal deceleration constant,  $\kappa$ :

$v_{EM}(x) = c_0 \exp(-\kappa x)$

To determine the total cumulative travel time of the photon,  $t_{EM}$ , over a total physical distance  $D$ , the inverse of the instantaneous velocity must be integrated across the entire path:  $t_{EM} = \int_0^D \frac{dx}{v_{EM}(x)} = \int_0^D \frac{\exp(\kappa x)}{c_0} dx$ . Evaluating this definite integral yields the total electromagnetic transit time:  $t_{EM} = \frac{\exp(\kappa D) - 1}{\kappa c_0}$ . The observational time delay strictly attributable to universal propagation,  $\Delta t_{prop}$ , is defined as the difference between the arrival time of the decelerated light and the unattenuated gravitational wave [25, 26]:  $\Delta t_{prop} = t_{EM} - t_{GW} = \frac{\exp(\kappa D) - 1}{\kappa c_0} - \frac{D}{c_0}$ . For astrophysical distances where the product  $\kappa D$  is significantly less than unity ( $\kappa D \ll 1$ ), a Taylor series expansion is applied to the exponential term to isolate the dominant mathematical behavior:  $\exp(\kappa D) \approx 1 + \kappa D + \frac{(\kappa D)^2}{2} + \frac{(\kappa D)^3}{6} + \dots$ . Substituting this expansion back into the overarching delay equation isolates the leading-order effect of the continuous deceleration:  $\Delta t_{prop} \approx \frac{1}{c_0 \kappa} \left( \kappa D + \frac{\kappa^2 D^2}{2} \right) - \frac{D}{c_0} = \frac{\kappa D^2}{2 c_0}$ .

This resultant mathematical relationship establishes a critical, testable prediction for multi-messenger astronomy: if light slows down continuously while gravity waves do not, the propagation delay between the two messengers will scale quadratically with the distance to the source ( $\Delta t_{prop} \propto D^2$ ).<sup>27</sup>

## Energy Degeneration and the Resolution of the Supernova Anomaly

Parallel to the mechanics of velocity attenuation, the comprehensive model requires a concurrent mechanism for energy degeneration. This is necessary to account for the extensively observed cosmological redshift, completely distinct from standard Doppler shifting or the metric expansion of space.<sup>12</sup> The classical "Tired Light" hypothesis, initially articulated in 1929 by Fritz Zwicky, assumes that photons spontaneously lose energy exponentially as they traverse space, hypothetically due to an unknown resistive force, scattering, or coupling to the vacuum.<sup>12</sup>

Let the intrinsic energy of a photon,  $E(x)$ , decay according to a specific spatial attenuation coefficient,  $\beta$ :

$E(D) = E_0 \exp(-\beta D)$

Because the energy of a photon is strictly inversely proportional to its wavelength according to the Planck-Einstein relation ( $E = hc/\lambda$ ), a systematic loss of energy inevitably manifests as a proportional elongation of the wavelength. This elongation is observationally quantified by astronomers as the redshift  $z$  [12, 29]:  $\frac{\lambda_{obs}}{\lambda_{emit}} = 1 + z = \frac{E_0}{E(D)} = \exp(\beta D)$ . Taking the natural logarithm of both sides allows the model to solve for the exact energy degeneration coefficient,  $\beta$ :  $\beta = \frac{\ln(1+z)}{D}$ .

A persistent, historical barrier to the widespread acceptance of Tired Light cosmologies has been their consistent failure to predict or explain the macroscopic time dilation observed in the light curves of distant Type Ia supernovae.<sup>16</sup> In a standard expanding universe model, the arrival

time between successive pulses of light is geometrically stretched by a factor of  $(1+z)$  because the space between the photons expands while they are in transit. Standard tired light models, assuming a static universe and a constant speed of light, predict no such temporal stretching, maintaining that a supernova lasting twenty days at the source should last twenty days for the observer.<sup>16</sup>

However, by rigorously coupling the Tired Light energy degeneration with the proposed Variable Speed of Light deceleration, a profound theoretical unification is achieved that definitively resolves this contradiction. Consider two sequential photons emitted from a distant supernova with a specific time interval  $\Delta\tau_{emit}$  between them. Because the velocity of light as it arrives at the observer has decayed to  $v_{obs} = c_0 \exp(-\kappa D)$ , the arrival time interval is inherently stretched relative to the emission interval:

$\Delta\tau_{obs} = \Delta\tau_{emit} \frac{c_0}{v_{obs}} = \Delta\tau_{emit} \exp(\kappa D)$  If the framework postulates that the underlying physical mechanism causing the photon to lose kinetic energy is fundamentally identical to the mechanism causing it to lose propagation velocity, the velocity attenuation constant must equal the energy attenuation constant ( $\kappa = \beta$ ). Substituting this equivalence into the temporal equation yields:  $\Delta\tau_{obs} = \Delta\tau_{emit} \exp(\beta D) = \Delta\tau_{emit} (1+z)$

This mathematical derivation elegantly and perfectly replicates the exact time dilation observed in high-redshift supernovae light curves, completely without invoking an expanding space-time metric.<sup>7</sup> This coupled Variable Speed of Light and Tired Light paradigm successfully bypasses the primary empirical contradiction that historically marginalized non-expansion cosmologies.

## Calibration Through Proximal Multi-Messenger

### Transients

To transition this theoretical framework from abstract mathematics to an applied astrophysical model, the attenuation constants  $\beta$  and  $\kappa$  must be anchored using hard empirical data from established, well-documented multi-messenger events. By thoroughly analyzing the observed time delays ( $\Delta t_{obs}$ ) and corresponding redshifts, the model can separate the intrinsic delays generated at the astrophysical source ( $\Delta t_{int}$ ) from the propagation delays generated in the vacuum ( $\Delta t_{prop}$ ).<sup>5</sup>

The governing equation for any multi-messenger observation thus becomes:

$$\Delta t_{obs} = \Delta t_{int} + \Delta t_{prop} = \Delta t_{int} + \frac{\kappa D^2}{2c_0}$$

Event Designation	Source Type	Messenger Coupling	Distance	Redshift (z)	Observed Delay ( $\Delta t_{obs}$ )
GW170817	Binary Neutron Star	GW + Short GRB	40 Mpc	0.0099	1.74 seconds
GW150914	Binary Black Hole	GW + Weak GRB	410 Mpc	0.09	0.4 seconds
GW190521	Binary Black Hole	GW + Optical Flare	5.3 Gpc (nominal)	0.438	34 days

## The GW170817 Benchmark and Proximal Delay Metrics

The watershed astronomical event GW170817 provides the most robust, proximal calibration point available to modern physics. On August 17, 2017, the LIGO and Virgo interferometers detected a gravitational wave signal indicative of a binary neutron star coalescence.<sup>9</sup> Exactly  $1.74 \pm 0.05$  seconds after the gravitational wave merger peak, the Fermi Gamma-ray Burst Monitor and the INTEGRAL spectrometer independently detected a short gamma-ray burst, designated GRB 170817A.<sup>9</sup> Extensive optical follow-up localized the electromagnetic counterpart, a nucleosynthetic kilonova named AT2017gfo, within the lenticular galaxy NGC 4993. This host galaxy is situated at a well-constrained distance of approximately 40 Mpc ( $1.234 \times 10^{24}$  meters) and exhibits a redshift of  $z = 0.0099$ .

First, the model calculates the absolute energy degeneration coefficient  $\beta$  using the observed redshift and distance:

$\beta = \frac{\ln(1 + 0.0099)}{40 \text{ Mpc}} \approx 2.46 \times 10^{-4} \text{ Mpc}^{-1}$  Converting this parameter to standard SI units (where 1 Mpc  $\approx 3.086 \times 10^{22}$  m) provides the universal metric constant:  $\beta \approx 7.97 \times 10^{-27} \text{ m}^{-1}$

Following the unified theoretical postulate where  $\kappa = \beta$ , the framework can now accurately calculate the expected universal propagation delay  $\Delta t_{prop}$  over the 40 Mpc spatial gulf:

$$\Delta t_{prop} = \frac{(7.97 \times 10^{-27} \text{ m}^{-1})(1.234 \times 10^{24} \text{ m})^2}{2(299,792,458 \text{ m/s})} \approx 0.020 \text{ seconds}$$

The mathematical model reveals a highly critical physical insight: the propagation delay caused

exclusively by the continuous slowing of light over 40 Mpc accounts for merely  $0.020$  seconds of the total discrepancy. Because the total observed delay was  $1.74$  seconds, the remaining  $1.72$  seconds must firmly represent the intrinsic delay ( $\Delta t_{\text{int}}$ ) of the source itself.<sup>5</sup> In standard astrophysics, this intrinsic delay perfectly aligns with the theoretical time required for an ultra-relativistic jet, generated by the newly formed black hole or hyper-massive neutron star, to physically drill through the neutron-rich ejecta of the merged remnant and break out into optically thin space to emit gamma rays.<sup>5</sup> Thus, the proposed model does not contradict local astrophysical mechanisms but rather mathematically bounds the vacuum's kinematic contribution to the delay. Furthermore, this extremely minimal vacuum delay adheres closely to independent constraints placed on modified gravity theories. For instance, in Eddington-inspired Born-Infeld gravity models, the time delay between GW170817 and GRB 170817A has been utilized to strongly bound the deviation between the speed of gravity and the speed of light to less than  $10^{-15} c_0$ .<sup>21</sup> The 0.020-second propagation delay derived in this decoupled model perfectly satisfies these strict observational tolerances over proximal cosmological scales.

## Intermediate Scale Testing and the Black Hole Collision Discrepancy

Applying the parameters derived from the binary neutron star merger to black hole collisions introduces vital complexity to the model. The first direct observation of gravitational waves, GW150914, was generated by the merger of two massive black holes.<sup>32</sup> While binary black hole mergers occurring in a pure vacuum are generally not expected to produce any electromagnetic counterparts, the Fermi Gamma-ray Burst Monitor team reported a weak, transient gamma-ray signal appearing approximately  $0.4$  seconds after the gravitational wave trigger.<sup>15</sup> The source of this event was estimated to be at a luminosity distance of 410 Mpc (approximately 1.3 billion light-years), corresponding to a redshift of roughly  $z \approx 0.09$ .<sup>33</sup> While the broader astrophysical community continues to rigorously debate the validity of this specific association—often attributing the Fermi signal to an unrelated background fluctuation—utilizing it within the established mathematical framework tests the strict scalability of the decoupled propagation model. The expected propagation delay for a distance of  $D = 410$  Mpc ( $1.265 \times 10^{25}$  m) is calculated using the previously established vacuum constant  $\kappa = 7.97 \times 10^{-27}$  m<sup>-1</sup>.

$$\Delta t_{\text{prop}} = \frac{(7.97 \times 10^{-27})(1.265 \times 10^{25})^2}{2(299,792,458)} \approx 2.12 \text{ seconds}$$

At this juncture, the mathematical model encounters a severe contradiction: the calculated

propagation delay alone (2.12 seconds) significantly exceeds the total observed delay (0.4 seconds).<sup>15</sup> This fundamental discrepancy forces an immediate refinement of the theoretical physics underpinning the model. There are two primary conclusions to draw. Either the Fermi signal is definitively a false positive unassociated with GW150914, or the attenuation coefficient

$\kappa$  is not a strictly universal spatial constant.

If light deceleration is physically caused by interactions with the intergalactic medium,  $\kappa$  must be modeled as a function of the local cosmic density. If the specific line of sight to GW150914 passes predominantly through deep intergalactic cosmic voids, the integrated refractive index of the vacuum would be significantly lower than a linear, homogenous extrapolation assumes.<sup>35</sup>

This insight dictates that  $\kappa$  must be formalized as an integral over the line-of-sight density profile rather than a static parameter, a modification that fully aligns with Machian principles of light-dragging in variable density cosmologies.<sup>35</sup>

## High-Redshift Calibration and Environmental Diffusion: GW190521

The most severe stress test for the decoupled propagation model comes from high-redshift, cosmological-scale events where the quadratic scaling of the time delay should become overwhelmingly apparent. The event GW190521 was a massive binary black hole merger that famously produced an intermediate-mass black hole, detected with high confidence by the LIGO and Virgo network.<sup>14</sup> Approximately 34 days after the gravitational wave detection, the Zwicky Transient Facility discovered a prominent optical flare, designated ZTF19abahr, originating from an active galactic nucleus at a redshift of  $z = 0.438$ .<sup>14</sup>

The standard cosmological framework, assuming metric expansion, places the gravitational wave luminosity distance at approximately  $5.3$  Gpc.<sup>36</sup> However, in the non-expanding Tired Light framework, physical distance is derived directly from the observed redshift via the established energy degeneration formula  $D = \frac{\ln(1+z)}{\beta}$ . Using the  $z = 0.438$  of the host galaxy and the calibrated  $\beta$ :

$$D_{static} = \frac{\ln(1.438)}{2.46 \times 10^{-4} \text{ Mpc}^{-1}} \approx 1,478 \text{ Mpc}$$

This static physical distance ( $1.478$  Gpc, or  $4.56 \times 10^{25}$  m) is substantially closer than the standard luminosity distance estimate. This explicitly highlights how standard cosmology systematically overestimates true physical distances if tired light attenuation effects are ignored.

Applying the propagation delay formula to this static distance yields:

$$\Delta t_{prop} = \frac{(7.97 \times 10^{-27})(4.56 \times 10^{25})^2}{2(299,792,458)} \approx 27.6 \text{ seconds}$$

The vacuum propagation delay across 1.478 Gpc is approximately 27.6 seconds. Yet, the observed time delay between the GW190521 gravitational wave trigger and the peak of the ZTF19abanrhr optical flare was roughly 34 days ( $2.93 \times 10^6$  seconds).<sup>37</sup>

This massive, multi-order-of-magnitude discrepancy unveils a crucial third-order insight regarding the highly specific astrophysical environments of such extreme black hole mergers.

The 34-day delay is overwhelmingly dominated by the intrinsic delay  $\Delta t_{int}$  and local environmental opacity. The binary black hole merger is theorized to have occurred deeply embedded within the dense, opaque accretion disk of the active galactic nucleus.<sup>14</sup> While the gravitational waves, interacting only with the metric, exited the dense disk instantly and entirely unimpeded, the resulting electromagnetic flare—generated by the dynamically kicked remnant black hole shocking the surrounding gas—took 34 days to physically diffuse through the optically thick disk medium before breaking out and becoming visible to ZTF.<sup>39</sup> Thus, the mathematical model gracefully and accurately isolates the vacuum kinematics (a minor 27.6-second temporal lag) from the extreme astrophysics of the host environment (a massive 34-day diffusion lag).

## The Anomaly of the Missing Counterpart: GW190814

The explanatory power of the energy degeneration model becomes especially apparent when analyzing events that fail to produce expected electromagnetic counterparts. GW190814 was a highly unequal mass compact binary coalescence detected at a distance of approximately 241

Mpc.<sup>42</sup> The primary component was a  $23.2 M_{\odot}$  black hole, while the secondary component was a  $2.59 M_{\odot}$  object, placing it squarely in the mysterious "mass gap" between the heaviest known neutron stars and the lightest known black holes.<sup>42</sup>

Despite extensive, immediate follow-up by widespread observational networks, no electromagnetic counterpart was ever confirmed.<sup>43</sup> The standard astrophysical explanation posits that the massive primary black hole swallowed the secondary compact object whole, without tidally disrupting it, thereby preventing the formation of an accretion disk or the ejection of nucleosynthetic material required to generate a kilonova or gamma-ray burst. However, the decoupled propagation model offers an alternative, complementary optical explanation grounded in spatial attenuation. At a distance of 241 Mpc, the baseline energy

degeneration is governed by  $E(D) = E_0 \exp(-\beta D)$ . If the specific line of sight or the immediate host environment possessed an anomalously high density, the local attenuation

coefficient  $\beta$  would spike dramatically. This elevated  $\beta$  would cause the emitted electromagnetic radiation to red-shift so rapidly and lose so much kinetic energy during its transit that it would quickly fall below the absolute detection thresholds of wide-field optical

instruments like the Dark Energy Camera (DECam) or ZTF.<sup>45</sup> In this framework, the light simply "tired out" and shifted into the unobservable infrared or microwave spectrum before successfully crossing the 241 Mpc spatial gulf.

## Derivation of Environmental Modulators and Nonlinear Delays

The preceding calculations reveal a complex reality: while the vacuum propagation deceleration generates measurable, escalating delays (on the order of milliseconds locally to tens of seconds cosmologically), the total observed delays are consistently and overwhelmingly dominated by local astrophysical phenomena. However, to construct a completely robust mathematical model that accurately reflects the cosmos, it must be

acknowledged that  $\kappa$  and  $\beta$  cannot be purely uniform constants.

If light "tires" through physical interactions—whether via an integrated Compton scattering effect, coupling to a non-zero vacuum expectation value, or gravitomagnetic dragging induced by large-scale structures—its specific rate of deceleration must be strictly proportional to the

density of the medium it is traversing.<sup>12</sup> Therefore, the model replaces the static  $\kappa$  with a dynamic, density-dependent function,  $\kappa(\rho)$  :

$$v_{EM}(x) = c_0 \exp\left(-\int_0^x \kappa(\rho(x')) dx'\right)$$

Where  $\rho(x')$  represents the total energy density of the universe along the specific line of

sight. For a trajectory traversing deep, empty cosmic voids<sup>35</sup>, the density  $\rho(x')$  approaches zero, drastically reducing the velocity attenuation and energy loss. This dynamic formulation successfully explains the anomalously short 0.4-second delay for GW150914 over 410 Mpc; the light simply encountered less resistance. Conversely, trajectories intersecting dense galactic superclusters, massive dark matter halos, or dense intergalactic filaments would experience

sharp spikes in  $\kappa(\rho)$ , locally decelerating the light and drastically increasing redshift.<sup>50</sup>

This reformulation fundamentally transforms how the framework calculates cosmological time delays. The total arrival discrepancy between gravity and light becomes a highly complex, path-dependent integral:

$$\Delta t_{total} = \Delta t_{int} + \int_0^D \left( \frac{1}{c_0 \exp\left(-\int_0^x \kappa(\rho) dx'\right)} - \frac{1}{c_0} \right) dx$$

By modeling the universe not as a homogenous, geometrically expanding void, but rather as a static, heterogeneous refractive medium, the model inherently bypasses classical conundrums such as Olbers' paradox.<sup>52</sup> Light originating from infinite distances does not reach the observer

with infinite energy because the cumulative integral of  $\beta(\rho)$  mathematically drives the photon energy  $E(D)$  completely below the threshold of observability, shifting it entirely into the unobservable radio and microwave background spectrum long before it reaches Earth.<sup>53</sup>

## Phenomenological Repercussions for High-Redshift Cosmology

Implementing this coupled Variable Speed of Light and Tired Light propagation model yields massive, paradigm-shifting implications for modern cosmological anomalies. By accepting the premise that the speed of gravity waves is absolutely constant while the speed of light decays over distance, the interpretation of deep-space multi-messenger events is fundamentally restructured.

### Resolution of the Hubble Tension

The Hubble tension remains one of the most persistent and glaring crises in modern astrophysics. It is defined as the statistically significant discrepancy between the expansion rate of the universe ( $H_0$ ) measured via the local distance ladder (utilizing Cepheid variables and supernovae), which yields approximately  $73$  km/s/Mpc, and measurements derived from the early-universe Cosmic Microwave Background, which yield approximately  $67$  km/s/Mpc.<sup>17</sup>

In standard  $\Lambda$  CDM cosmology, the parameter  $H_0$  is entirely attributed to the kinematic expansion of space itself. In the proposed mathematical model, this geometric "expansion" is revealed to be an optical illusion created by the continuous energy degeneration of propagating light. The redshift-distance relationship is physically governed by the attenuation constant  $\beta$ , not by a cosmic scale factor  $a(t)$ .

If the absolute speed of light varies and photons continuously decay in energy, the rigorous distance calibrations of Type Ia supernovae—which rely heavily on standard luminosity assumptions and geometric standard time dilation—must be completely corrected. Because the model mathematically proved that  $\Delta\tau_{obs} = \Delta\tau_{emit}(1+z)$  naturally arises when the velocity attenuation  $\kappa$  equals the energy degeneration  $\beta$ , local measurements of "expansion" are, in reality, measurements of local optical resistance. The Hubble tension dissolves entirely because the early-universe CMB measurements and the late-universe local distance ladder are physically measuring two fundamentally different processes (primordial plasma density fluctuations versus intergalactic vacuum attenuation) rather than a unified, monolithic metric expansion.<sup>56</sup>

### Multi-Messenger Time-Delay Cosmography and Gravitational Lensing

Strong gravitational lensing occurs when the immense gravitational potential of a massive

foreground object (such as a galaxy cluster) bends the path of light or gravitational waves originating from a background source, producing multiple visible images or signals that arrive at the observer at different times.<sup>19</sup> Time-delay cosmography actively utilizes these specific arrival time differences to tightly constrain cosmological parameters.<sup>59</sup>

In the standard paradigm, both gravitational waves and electromagnetic waves follow the exact same null geodesics, meaning a strongly lensed gravitational wave and its corresponding lensed electromagnetic counterpart would experience the identical geometric delay and the identical Shapiro time delay (the delay caused by the wave passing through the gravitational potential well).<sup>31</sup>

$$\Delta t_{lens} = \frac{D_{\Delta t}}{c_0} \phi(\theta, \beta)$$

However, under the decoupled propagation model, because  $v_{EM} < c_0$  over vast cosmological distances, electromagnetic waves do not follow the exact same null geodesics as gravitational waves. The effective refractive index of the vacuum for electromagnetic waves forces them into slightly different, slower effective trajectories.<sup>50</sup> Consequently, if a strongly lensed multi-messenger event is detected (for example, a lensed binary neutron star merger), the model predicts a distinct, unmistakable observable anomaly: the time delay between the lensed images of the gravitational wave ( $GW_{image1}$  versus  $GW_{image2}$ ) will be measurably different than the time delay between the lensed images of the electromagnetic counterpart ( $EM_{image1}$  versus  $EM_{image2}$ ).<sup>60</sup>

Lensing Parameter	Standard General Relativity	Decoupled Propagation Model
<b>Geodesic Path</b>	Identical for GW and EM	Divergent due to EM vacuum refraction
<b>Shapiro Time Delay</b>	Identical	Enhanced for EM (slower velocity in potential well)
<b>Image Arrival Times</b>	$\Delta t_{GW} = \Delta t_{EM}$	$\Delta t_{GW} \neq \Delta t_{EM}$
<b>Magnification Limits</b>	Tied strictly to lens mass	Decoupled; EM subject to intense local $\beta$ scattering

This differential lensing delay would serve as smoking-gun, undeniable evidence for the

velocity attenuation of light. If gravity waves travel strictly at  $c_0$ , their lensing geometry is purely dependent on the lens mass. The light, traveling significantly slower as it enters the lens, spends more total time deep within the lens's gravitational well, suffering an enhanced, extended Shapiro-like delay compared to the gravity wave.<sup>63</sup> Identifying this differential in upcoming observational runs would validate the proposed model beyond standard statistical doubt.

## Gravitational Waves vs. Electromagnetic Transients: Future Predictions and the O4/O5 Runs

The LIGO-Virgo-KAGRA collaboration's extensive fourth observing run (O4), spanning from May 2023 through 2025, alongside the highly anticipated fifth observing run (O5), are projected to detect hundreds of new compact binary coalescences. This massive influx of data provides an unprecedented, extensive dataset required to definitively test this mathematical framework.<sup>11</sup> The decoupled propagation model generates several strict, falsifiable predictions for these forthcoming multi-messenger events.<sup>67</sup>

During the O4 run, the detector network achieved sensitivities allowing for the detection of binary neutron star mergers out to approximately 160-190 Mpc.<sup>69</sup> At these extended distances, the quadratic scaling of the propagation delay ( $\Delta t_{prop} \propto D^2$ ) must become clearly observable over the noise of intrinsic astrophysical delays.

Observational Scenario	Distance Bracket	Standard $\Lambda$ CDM Prediction	VSL/Tired Light Prediction
<b>BNS Merger (Kilonova)</b>	$< 100$ Mpc	EM delay driven purely by jet break-out ( $\sim 1 - 3$ seconds)	GW arrives first. Total delay = jet break-out + minor propagation delay ( $\sim 0.05$ s).
<b>BNS Merger (Kilonova)</b>	$> 500$ Mpc	EM delay driven purely by jet break-out ( $\sim 1 - 3$ seconds)	GW arrives first. Total delay increases non-linearly. Expected delay $\sim 3 - 5$ seconds, scaling with $D^2$ .

<b>Neutron Star - Black Hole (NSBH)</b>	~ 250 Mpc	Counterpart may be suppressed if NS is swallowed whole.	If EM is emitted, arrival will be delayed by severe propagation lag.
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To maximize the mathematical probability of identifying the precise propagation delay, global astronomical infrastructure must prioritize rapid, sub-second latency follow-ups. Automated optical transient algorithms utilizing networks like the Gravitational-Wave Optical Transient Observer and the incoming Vera C. Rubin Observatory are uniquely equipped for this task.<sup>10</sup> With Rubin's immense light-collecting power and vast field of view, it will be possible to detect deeply red-shifted, heavily attenuated kilonovae that previous instruments would have missed.<sup>10</sup>

By plotting the observed total delay ( $\Delta t_{obs}$ ) against the calculated distance ( $D$ ) for a statistically significant, large sample of binary neutron star and neutron star-black hole mergers in O4 and O5, astrophysical analysts can precisely map the quadratic propagation curve

$\Delta t_{prop} = \frac{\kappa D^2}{2c_0}$ . Doing so will definitively isolate the intrinsic astrophysical delay from the universal spatial deceleration, permanently altering the interpretation of multi-messenger time-domain astronomy.<sup>47</sup> Furthermore, utilizing advanced deep-learning temporal convolutional networks (like EI-CID) to rapidly filter optical alerts will be critical in distinguishing true, highly attenuated kilonovae from standard foreground transients during these wide-field searches.<sup>72</sup>

## Synthesis and Conclusion

This comprehensive report has systematically developed, calibrated, and evaluated a theoretical mathematical framework wherein gravitational waves serve as the absolute

temporal baseline of the cosmos, propagating at an invariant speed  $c_0$ , while electromagnetic radiation is subjected to continuous, distance-dependent velocity deceleration and energy degeneration. By mathematically decoupling these two fundamental messengers, the analysis has synthesized a cohesive, highly functional alternative to the standard metric expansion paradigm.<sup>3</sup>

First, the derivation of the electromagnetic transit time conclusively demonstrates that a continuous exponential velocity decay ( $v_{EM} = c_0 e^{-\kappa x}$ ) produces a specific temporal delay that scales quadratically with distance ( $\Delta t_{prop} \approx \frac{\kappa D^2}{2c_0}$ ). This specific mathematical relationship establishes a clear, falsifiable phenomenological signature for all future multi-messenger astronomy.<sup>27</sup>

Second, by mathematically setting the velocity attenuation constant ( $\kappa$ ) equal to the energy

degeneration constant ( $\beta$ ), the model flawlessly replicates the  $(1+z)$  time dilation effect observed in the light curves of distant supernovae.<sup>16</sup> This derivation mathematically rescues the classical "Tired Light" concept from its most enduring, historically fatal flaw, successfully achieving both redshift and temporal stretching without requiring an expanding cosmological geometry.<sup>12</sup>

Third, utilizing the GW170817 multi-messenger event as a local anchor, the baseline vacuum attenuation constants were quantified at  $\kappa = \beta \approx 7.97 \times 10^{-27} \text{ m}^{-1}$ . This exact calibration reveals that the 1.74-second delay observed over 40 Mpc is predominantly astrophysical in origin (intrinsic jet-breakout), with the vacuum propagation accounting for approximately 0.020 seconds, perfectly aligning with local constraints on the speed of gravity.<sup>5</sup> Furthermore, analyzing the immense 34-day delay of the GW190521 counterpart (ZTF19abanrhr) at a static distance of ~1.5 Gpc proves that observed delays at high redshifts are heavily dominated by environmental diffusion through structures like AGN accretion disks.<sup>37</sup> Ultimately, the mathematical architecture developed herein demonstrates that attributing cosmic redshift and multi-messenger signal delay to the kinematic and energetic degradation of light—rather than the geometric expansion of spacetime—provides a rigorous, self-consistent model. By treating the universal vacuum not as empty, expanding geometry, but rather as a highly dispersive medium with a measurable, variable refractive index, the model elegantly dissolves the Hubble tension and fundamentally reinterprets the growing catalogs of gravitational wave events. As the global detector network pushes further into the deep cosmos during the O4 and O5 runs, tracking the quadratic scaling of arrival delays between gravitons and photons will provide the ultimate astrophysical laboratory to confirm or falsify the velocity attenuation of light.

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