Gravitational Potential as Cumulative Relativistic Interaction Delay: Evidence from Planets, Galaxies, and Galaxy Clusters

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Abstract

Gravity is traditionally described through the curvature of spacetime or, in the Newtonian limit, through the gravitational potential generated by mass. In this work, we explore the possibility that gravitational phenomena may be interpreted as manifestations of cumulative relativistic interaction delays associated with finite-speed propagation within self-gravitating systems. Rather than modifying established gravitational laws, the approach seeks to provide a causal interpretation of gravitational potential and spacetime curvature in terms of accumulated propagation delays between source and observer.

The proposed interpretation is examined across three distinct astrophysical regimes. First, self-gravitating planetary and stellar bodies are considered. The framework implies a connection between characteristic internal propagation speeds and escape velocities through the equivalence of the associated relativistic time-dilation factors. Comparison with observational data reveals a close correspondence between these quantities in gravity-shaped bodies possessing coherent internal propagation paths.

Second, the framework is extended to galaxies, where gravitational and kinematic time-dilation effects coexist. In this mixed regime, orbital motion contributes significantly to the cumulative delay, providing a natural interpretation of the observed connection between characteristic velocities and gravitational dynamics.

Third, galaxy clusters are examined as systems in which collective kinematic effects become increasingly important relative to gravitational time-dilation contributions. Observed relations among velocity dispersion, gravitational redshift, and lensing mass are shown to be consistent with the hypothesis that these observables probe a common underlying delay structure. In this interpretation, planetary interiors, galaxies, and galaxy clusters probe cumulative interaction delays through internal material propagation, mixed material–gravitational interactions, and large-scale gravitational dynamics, respectively.

The results suggest that cumulative relativistic interaction delay provides a unified phenomenological interpretation of gravitational behavior across multiple astrophysical scales. The proposed framework preserves the observed gravitational phenomenology described by General Relativity while offering a possible physical explanation for the origin of the associated spacetime curvature. This interpretation motivates further investigation of finite-speed interaction effects in self-gravitating systems.

1. Introduction

Gravity is conventionally described as the curvature of spacetime produced by mass-energy [1]. In the weak-field limit, this curvature is represented by the gravitational potential, which successfully describes a wide range of phenomena from planetary motion to the dynamics of galaxies and galaxy clusters. General Relativity provides an exceptionally accurate mathematical description of these effects, yet the physical origin of spacetime curvature remains an open conceptual question.

Historically, several approaches have sought a deeper interpretation of gravity. Mach's principle suggested that local inertial properties may be influenced by the global distribution of matter, emphasizing the relational character of gravitational phenomena [2]. More recently, thermodynamic approaches have demonstrated that the Einstein field equations can be derived from underlying statistical or information-theoretic principles [3], implying that gravity may emerge from a more fundamental physical process rather than representing a fundamental interaction in its own right. Alternative emergent interpretations of gravity have also been proposed [4].

The present work explores a related possibility. We investigate whether gravitational phenomena may be interpreted as manifestations of cumulative relativistic interaction delays associated with finite-speed propagation within self-gravitating systems. In this view, gravitational potential is not replaced, nor are the equations of General Relativity modified. Instead, the gravitational potential is interpreted as an effective measure of the accumulated propagation delay between source and observer. Spacetime curvature is interpreted as the observable geometric manifestation of an underlying cumulative delay structure.

A central motivation for this interpretation is the observation that finite propagation speeds are a universal feature of physical interactions. Whenever information, momentum, or stress is transmitted through matter, a finite propagation time is required. The cumulative effect of such delays is generally negligible in weakly coupled systems, but may become significant in large self-gravitating structures where propagation occurs through extended matter distributions and over long interaction paths. If so, gravitational phenomena may admit a description in terms of cumulative propagation delays while remaining observationally consistent with established gravitational theory.

The present paper examines this possibility across three distinct astrophysical regimes. First, self-gravitating planetary and stellar bodies are considered. A relation is identified between characteristic internal propagation speeds and escape velocities through the equivalence of the associated relativistic time-dilation factors. Second, the framework is extended to galaxies, where both gravitational and kinematic time-dilation effects contribute to the observed dynamics. Third, galaxy clusters are examined as systems in which collective kinematic effects become increasingly important relative to gravitational time-dilation contributions. Together, these systems provide three complementary observational windows into the role of cumulative interaction delays across gravitational scales.

The purpose of this work is therefore not to propose a modification of General Relativity, but to explore whether a common delay-based interpretation can provide a causal description of gravitational phenomena across planetary, galactic, and cluster scales. The resulting framework remains phenomenological and is evaluated primarily through its consistency with observed gravitational behavior.

To this end, Section 2 introduces the concept of gravitational potential as cumulative interaction delay. Section 3 examines empirical indications from planetary and stellar bodies. Section 4 extends the interpretation to galaxies, while Section 5 considers galaxy clusters. The implications, limitations, and possible physical significance of the proposed interpretation are discussed in Section 6, followed by concluding remarks.

2. Gravitational Potential as Cumulative Interaction Delay

2.1 Motivation

General Relativity describes gravity through spacetime curvature, while Newtonian gravity describes it through a gravitational potential. Both formulations successfully predict gravitational phenomena across a wide range of scales. However, neither formulation directly identifies a physical mechanism responsible for the emergence of the associated potential or curvature.

The present work explores the possibility that gravitational potential may be interpreted as a manifestation of cumulative relativistic interaction delay. The central idea is that all physical interactions propagate at finite speed and therefore require finite transmission time. In an extended self-gravitating system, the total propagation delay between a source and an observer is determined not only by the direct separation between them, but also by the cumulative influence of the intervening matter distribution.

Within this interpretation, gravity is not treated as a separate interaction superimposed on matter. Rather, the observed gravitational potential reflects the integrated delay structure associated with finite-speed interaction propagation throughout the system.

2.2 Delay Potential

Consider an observer located at position $\boldsymbol{r}$ relative to a self-gravitating mass distribution. Let $\Psi(\boldsymbol{r})$

denote the cumulative interaction delay between the observer and the source distribution.

The physical motivation for identifying gravitational potential with cumulative interaction delay is provided by gravitational time dilation. Since the gravitational potential appears directly in the weak-field time-dilation factor, any quantity reproducing the observed delay of clocks must necessarily reproduce the observed gravitational potential.

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{\Phi}{c^2} \qquad (1)$$

The proposed interpretation identifies the gravitational potential as a measure of this cumulative delay:

$$\Phi(\boldsymbol{r}) \propto -\Psi(\boldsymbol{r}). \tag{2}$$

The negative sign reflects the observational fact that stronger gravitational potentials correspond to larger accumulated delays and therefore slower clock rates.

This identification does not modify the functional form of the gravitational potential. Instead, it assigns a physical interpretation to the quantity already appearing in Newtonian gravity and in the weak-field limit of General Relativity. The proposal therefore differs from a simple change of notation. The delay potential is interpreted as a physically measurable quantity through gravitational time dilation, gravitational redshift, and the characteristic velocity scales examined in the following sections.

2.3 Connection with Gravitational Time Dilation

A natural link between delay and gravity is provided by gravitational time dilation.

In the weak-field limit of General Relativity,

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{GM}{Rc^2} = 1 - \frac{v_e^2}{2c^2}, \tag{3}$$

where

$$v_e = \sqrt{\frac{2GM}{R}} \tag{4}$$

is the escape velocity.

This expression shows that gravitational potential can be expressed directly in terms of a relativistic delay factor. The quantity GM/R determines the reduction of clock rate relative to a distant observer.

Within the present interpretation, gravitational time dilation is viewed as the observable manifestation of accumulated interaction delay. The gravitational potential therefore measures not only the strength of the gravitational field but also the cumulative delay associated with interaction propagation between source and observer.

2.4 Source–Observer Interpretation

The cumulative delay need not be associated with a unique radial propagation path. In general, the effective delay depends on the matter distribution linking source and observer.

For highly symmetric systems, such as approximately spherical planets and stars, the dominant contribution may be represented by a single characteristic propagation path. For more complex systems, including galaxies and galaxy clusters, the cumulative delay reflects the integrated influence of distributed interaction pathways and may incorporate both gravitational and kinematic contributions.

The delay potential is therefore inherently relational: it characterizes the interaction history connecting source and observer rather than representing an intrinsic property of either location individually.

2.5 Scope of the Interpretation

The present interpretation does not propose a modification of General Relativity. The Einstein field equations, the Newtonian limit, and the observed phenomenology of gravitational systems are retained.

Instead, the proposal concerns the physical meaning of the gravitational potential and the associated spacetime curvature. In this view, curvature is interpreted as the observable geometric manifestation of an underlying cumulative delay structure generated by finite-speed interactions within self-gravitating systems.

The following sections examine whether such an interpretation is supported by observational evidence across planetary, galactic, and cluster scales.

3. Empirical Indications of Delay-Based Gravity

3.1 Propagation Speeds and Gravitational Potentials

If gravitational phenomena are related to cumulative interaction delays arising from finite-speed propagation, one expects a connection between characteristic propagation speeds within self-gravitating bodies and their gravitational potentials.

In the weak-field limit of General Relativity,

$$\Delta t'/\Delta t \approx 1 - \frac{GM}{Rc^2} = 1 - \frac{v_e^2}{2c^2}, \tag{5}$$

where

$$v_e = \sqrt{\frac{2GM}{R}} \tag{6}$$

is the escape velocity.

A propagation process characterized by velocity v_{prop} is associated with the leading-order kinematic time-dilation factor

$$\Delta t'/\Delta t \approx 1 - \frac{v_{\text{prop}}^2}{2c^2}. \tag{7}$$

3.2 Time-Dilation Equivalence

Equating the leading-order delay terms gives

$$\frac{v_{\text{prop}}^2}{2c^2} \approx \frac{v_e^2}{2c^2}, \tag{8}$$

and therefore

$$v_{\text{prop}} \approx v_e. \tag{9}$$

This relation does not arise from matching velocities directly. It follows from equating the corresponding relativistic time-dilation factors.

3.3 Observational Correspondence

For Earth, the average compressional-wave velocity in the inner core is approximately $v_{\text{prop}} \approx 11.2\ \text{km s}^{-1}$ [5], [21], while the escape velocity is $v_e \approx 11.2\ \text{km s}^{-1}$.

For Mars, seismic observations from the InSight mission indicate characteristic core propagation velocities near $v_{\text{prop}} \approx 5\ \text{km s}^{-1}$ [6], while the escape velocity is $v_e \approx 5.0\ \text{km s}^{-1}$.

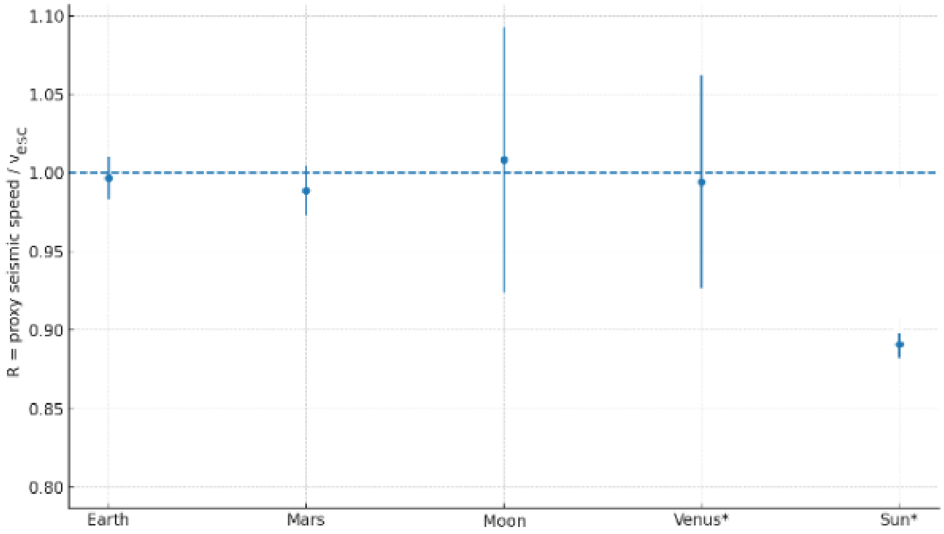

Figure 1. Seismic–escape velocity ratio $R = v_{\text{prop}}^{\text{rad}}/v_e$ for representative gravity-shaped bodies. Earth and Mars use direct seismic constraints; Moon, Venus, and Sun are based on lunar seismology, interior modeling, and helioseismic inversions, respectively. The Moon is corrected for the proposed non-radial propagation geometry associated with tidal locking. Asterisks indicate model- or inversion-based estimates. Error bars represent source-based uncertainty ranges.

The comparison may be expressed through the dimensionless ratio

$$R = \frac{v_{\text{prop}}}{v_e}. \tag{10}$$

Values near

$$R \approx 1 \tag{11}$$

indicate that the propagation and gravitational delay scales are comparable. The observed clustering near $R \approx 1$ was not used to construct the delay framework but emerged as an empirical test of the proposed interpretation.

The correspondence extends beyond the two directly seismically constrained cases. Figure 1 shows representative values of the R -ratio for gravity-shaped planetary and stellar bodies. Earth and Mars provide the strongest direct seismic constraints, while the Moon, Venus, and Sun are included as model- or inversion-based tests of the same scaling. The plotted uncertainties are source-based estimates and are intended to indicate the present observational and modeling spread rather than formal universal errors. The figure suggests that gravity-shaped bodies cluster near $R \approx 1$, whereas objects lacking coherent gravity-dominated interiors are not expected to obey this relation.

For Earth, Mars, Venus [13] and Sun [12] the characteristic propagation velocity is taken from the gravity-dominated core region rather than from crustal or mantle averages. This choice is motivated by the fact that the gravitational acceleration reaches its maximum within the deep interior and remains approximately constant throughout much of the core. Consequently, the core provides the most representative propagation environment for comparison with the global gravitational potential.

For tidally locked bodies, the dominant propagation path differs from the radial case. Circumferential propagation is estimated for Moon, where the P-wave velocity through the mantle [7] is equal to ~π times the escape velocity. Thus, the generalized correlation is between the escape velocity and the average radial propagation component of the pressure wave:

$$\bar{v}_{prop}^{rad} \approx v_e \tag{12}$$

The larger uncertainty associated with the solar value likely reflects the greater complexity of stellar propagation processes compared with planetary interiors.

3.4 Gravity-Shaped Bodies

The correspondence is not expected to hold universally. The derivation assumes a body whose structure is primarily determined by self-gravity and which possesses coherent internal propagation paths connecting the source region and the observer.

Planets and stars satisfy these conditions to a good approximation. Their interiors are organized by gravitational equilibrium and support large-scale propagation pathways through continuous material media.

In contrast, small asteroids, rubble-pile objects, or strongly heterogeneous structures lack coherent gravity-dominated interiors. In such systems, propagation paths become fragmented by discontinuities and local material variations. Consequently, no simple relation between characteristic propagation speed and escape velocity is expected.

3.5 Interpretation

The correspondence between propagation speeds and escape velocities does not by itself establish a causal relation. However, it provides empirical evidence that quantities traditionally treated as independent may be linked through a common relativistic delay scale.

Within the present framework, the relation is interpreted as an indication that gravitational potential and internal propagation dynamics are both manifestations of cumulative interaction delay.

The following section examines whether a similar interpretation can be extended beyond planetary interiors to galactic systems, where collective motion contributes significantly to the observed dynamics.

4. Extension to Galaxies

4.1 Gravitational and Kinematic Time Dilation

Unlike planetary interiors, galaxies are not dominated by a single continuous material medium through which interactions propagate. Instead, their dynamics are dominated by the collective motion of stars, gas, and dark components distributed throughout the system.

In addition to gravitational time dilation, moving bodies experience kinematic time dilation. For a characteristic orbital velocity v_{rot}, the leading-order relativistic contribution is

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{v_{\mathrm{rot}}^2}{2c^2}. \tag{13}$$

The total delay associated with a galactic system therefore contains both gravitational and kinematic contributions,

$$\Psi_{\mathrm{tot}} = \Psi_g + \Psi_k. \tag{14}$$

In the weak-field limit, the corresponding time-dilation factor may be written approximately as

$$\frac{\Delta t'}{\Delta t} \approx 1 - \frac{GM(r)}{rc^2} - \frac{v_{\mathrm{rot}}^2}{2c^2}. \tag{15}$$

Unlike planetary interiors, where internal propagation dominates, galactic systems occupy a mixed regime in which both gravitational and kinematic delay contributions are significant.

4.2 Delay Interpretation of Galactic Rotation

Observed galactic rotation curves remain approximately flat at large radii, implying that orbital velocities remain nearly constant even where visible matter density decreases substantially.

Within the present framework, the observed dynamics are interpreted as a manifestation of cumulative delay arising from both the gravitational potential and the collective kinematic structure of the system.

The kinematic contribution increases with the velocity of the orbiting population and therefore becomes increasingly important in extended galactic disks. As a result, the cumulative delay experienced by an observer is determined not only by the enclosed mass but also by the collective motion of the system.

From this perspective, flat rotation curves indicate the persistence of a nearly constant delay contribution associated with large-scale orbital motion.

4.3 Gravitational-to-Kinematic Delay Transition

The delay interpretation predicts that the relative importance of gravitational and kinematic contributions should vary with galactic radius. In the inner region of a galaxy, the enclosed mass and gravitational potential dominate the local delay structure. At larger radii, where observed rotation curves remain approximately flat, the kinematic contribution associated with orbital motion becomes increasingly important.

This transition can be expressed schematically as

$$\Psi_{\mathrm{tot}}(r) = \Psi_g(r) + \Psi_k(r), \tag{16}$$

with

$$\Psi_g(r) \sim \frac{GM(r)}{rc^2} \tag{17}$$

and

$$\Psi_k(r) \sim \frac{v_{\mathrm{rot}}^2(r)}{2c^2}. \tag{18}$$

Thus, the dominant delay tracer changes from gravitational potential in the inner region to orbital motion in the outer disk. This provides a natural interpretation of flat rotation curves as a regime in which the kinematic delay contribution remains approximately constant with radius.

Figure 2 uses eq.15 and illustrates the predicted transition between gravitational and kinematic delay contributions based on observations of luminosity and orbital velocities for U111 [15-18]. In the inner galaxy, gravitational time dilation dominates the cumulative delay structure. At larger radii, the kinematic contribution associated with orbital motion becomes increasingly important and eventually exceeds the gravitational component. The observed flat rotation curve emerges in the region where the total delay becomes approximately constant. The transition radius corresponds approximately to the region where the kinematic and gravitational delay contributions become comparable.

An iterative evaluation is required for predictive purposes because the orbital velocity depends on the gravitational delay structure, while the kinematic delay associated with that velocity contributes back to the total effective delay. In practice, the rotation curve can therefore be estimated by successively updating the total delay field until the predicted velocity profile converges.

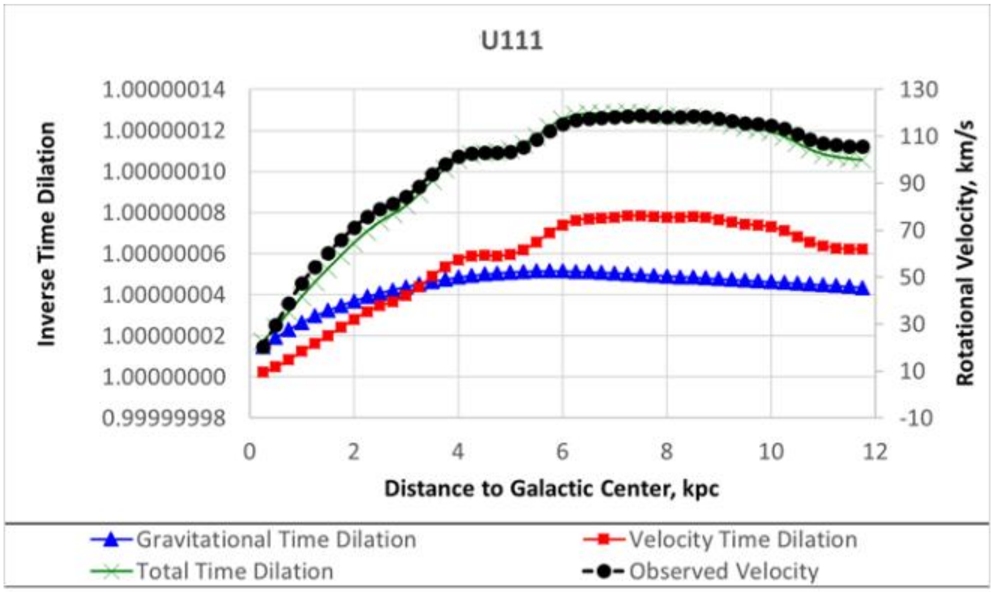

Figure 2: Indicative relation based on eq. 15 illustrating the conceptual galactic transition

More explicitly, one may begin with the baryonic mass distribution and compute the corresponding gravitational delay contribution

$$\Psi_g^{(0)}(r). \tag{19}$$

The resulting delay field yields a first estimate of the orbital velocity profile

$$v_{\mathrm{rot}}^{(0)}(r), \tag{20}$$

from which the associated kinematic delay contribution

$$\Psi_k^{(0)}(r) \tag{21}$$

can be evaluated. The total delay field is then updated according to

$$\Psi_{\mathrm{tot}}^{(1)}(r) = \Psi_g^{(0)}(r) + \Psi_k^{(0)}(r). \tag{22}$$

The updated delay field produces a revised velocity profile, which in turn generates a revised kinematic contribution. Repeating this procedure yields a sequence

$$\Psi_{\mathrm{tot}}^{(n)}(r), \tag{23}$$

that converges toward a self-consistent solution. Within the present interpretation, the observed galactic rotation curve corresponds to this converged delay structure. The procedure is analogous to iterative methods commonly employed in gravitational, radiative-transfer, and self-consistent field calculations.

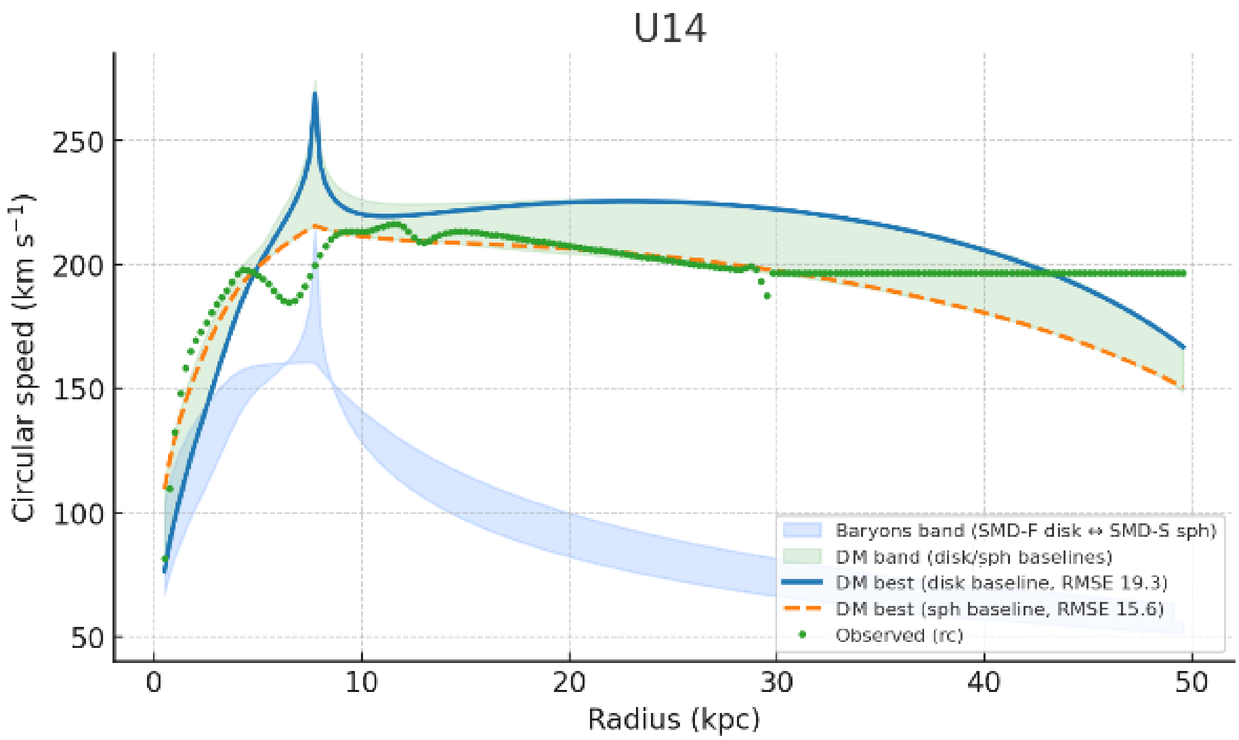

Figure 3: Iterative galactic reconstruction based on the delay model (DM)

Figure 3 illustrates an example of the iterative procedure applied to a representative galactic rotation curve for U14 [15-18]. Starting from the observed baryonic mass distribution, an initial gravitational delay field is computed and used to estimate the orbital velocity profile. The resulting kinematic contribution is then incorporated into the total delay field, producing an updated velocity estimate. Repeating this procedure yields convergence toward a self-consistent solution.

The example demonstrates that the delay framework is not limited to qualitative interpretation. Given a baryonic mass distribution, the cumulative delay field can be evaluated iteratively to generate a predicted rotation curve. The observed velocity profile corresponds to the converged solution of this procedure.

4.4 Relation to the Radial Acceleration Relation

An important empirical result is the radial acceleration relation (RAR), which links the observed acceleration in rotationally supported galaxies to that expected from the visible matter distribution [8],[19].

$$g_{obs} = f(g_{bar}). \tag{24}$$

The existence of a tight relation between baryonic matter and observed dynamics suggests that galactic motion is governed by a common underlying quantity.

Within the delay interpretation, this quantity is identified with the cumulative delay structure of the system. Both the gravitational and kinematic contributions arise from the same underlying propagation constraints and therefore remain closely correlated.

The observed regularity of the RAR is consistent with the hypothesis that galactic dynamics are controlled by a common delay scale rather than by independent gravitational and kinematic processes.

4.5 Interpretation

Galaxies occupy an intermediate regime between planetary interiors and galaxy clusters.

In planetary systems, the dominant observable is the characteristic internal propagation speed. In galaxies, collective orbital motion becomes an equally important tracer of the delay structure.

The transition from propagation-dominated systems to motion-dominated systems therefore occurs naturally as the characteristic scale of the gravitational system increases.

4.6 Implications

The delay interpretation provides both a unified physical interpretation and a self-consistent computational framework in which internal propagation speeds, orbital velocities, and gravitational potentials are understood as different manifestations of cumulative relativistic interaction delay.

This interpretation does not modify the observed phenomenology of galactic dynamics. Rather, it offers an alternative physical explanation for the empirical relations observed in rotationally supported galaxies.

The cumulative delay framework naturally generates velocity scales of several hundred kilometers per second within the Milky Way. Interestingly, these scales are comparable to the peculiar velocity inferred from the CMB dipole. A detailed analysis of such large-scale implications lies beyond the scope of the present work.

The following section examines whether the same framework can be extended to galaxy clusters, where collective velocity dispersion becomes the dominant observable.

5. Extension to Galaxy Clusters

5.1 Velocity Dispersion and Gravitational Potential

Galaxy clusters represent the largest gravitationally bound structures in the Universe. Unlike planetary interiors or galactic disks, they are not characterized by coherent material propagation pathways or ordered rotational motion. Instead, their dynamics are dominated by the collective velocity dispersion of their member galaxies.

For a virialized cluster, the virial theorem [14] gives

$$\sigma^2 \sim \frac{GM}{R}, \tag{25}$$

where σ is the velocity dispersion, M is the cluster mass, and R is a characteristic cluster radius.

The corresponding gravitational time-dilation term is

$$\frac{GM}{Rc^2} \sim \frac{\sigma^2}{c^2}. \tag{26}$$

This relation indicates that the characteristic kinematic time-dilation scale of the cluster is directly linked to its gravitational potential.

Within the delay interpretation, both quantities represent different manifestations of the same cumulative delay structure.

5.2 Gravitational Redshift in Galaxy Clusters

A direct observational probe of gravitational potential in galaxy clusters is provided by gravitational redshift measurements [10].

In the weak-field limit,

$$z_g \approx \frac{\Delta\Phi}{c^2}, \tag{27}$$

where $\Delta\Phi$ is the difference in gravitational potential between source and observer.

Observations have detected systematic gravitational redshift signals in galaxy clusters consistent with the predictions of General Relativity [10].

Within the present framework, these measurements may be interpreted as direct observations of variations in the cumulative delay field. The observed redshift therefore provides an independent probe of the same delay structure that governs cluster dynamics.

5.3 Velocity Dispersion, Lensing, and Delay Structure

Galaxy clusters exhibit a remarkable correlation between velocity dispersion and gravitational lensing mass [11].

Conventionally, both observables are interpreted as tracers of the total gravitational mass of the system.

Within the delay interpretation, the correlation may alternatively be viewed as evidence that both observables probe a common underlying delay structure. Velocity dispersion reflects the kinematic contribution to the cumulative delay, while lensing [20] measures the integrated gravitational manifestation of that delay. The fact that lensing mass, velocity dispersion, and gravitational redshift scale consistently with one another suggests that they probe the same underlying delay structure through independent observational channels.

The existence of a tight empirical relation between these quantities suggests that they are not independent observables, but rather different projections of the same underlying physical quantity.

5.4 Collective Kinematics as a Delay Tracer

Galaxy clusters differ fundamentally from planetary interiors and galaxies in the manner through which the delay structure is probed.

For planetary systems, the relevant observable is the characteristic propagation speed within a continuous material medium.

For galaxies, the dominant observable becomes the orbital velocity of the stellar population.

For galaxy clusters, the principal observable is the collective velocity dispersion of the constituent galaxies.

The progression from internal propagation speed to orbital velocity and finally to velocity dispersion reflects a transition in the dominant observational tracer of cumulative interaction delay as the scale of the gravitational system increases.

5.5 Interpretation

The cluster observations considered above suggest that velocity dispersion, gravitational redshift, and lensing mass are linked through a common relativistic delay scale.

Within the present framework, galaxy clusters provide a particularly important test because they probe the delay structure through multiple independent observables. The observed consistency among these measurements supports the hypothesis that cumulative interaction delay may provide a unified interpretation of gravitational phenomena across astrophysical scales.

The following section discusses the implications and limitations of this interpretation and its relation to existing approaches to gravity.

6. Interpretation and Theoretical Implications

6.1 A Common Delay Scale Across Gravitational Systems

The preceding sections identified empirical relations connecting characteristic propagation speeds, orbital velocities, velocity dispersions, gravitational redshifts, and gravitational potentials across a wide range of astrophysical systems.

Although these observables arise in very different physical environments, they exhibit a common feature: each is associated with a relativistic time-dilation scale proportional to a characteristic velocity squared divided by c^2.

For planetary interiors, this scale is traced by internal propagation velocities. For galaxies, it is traced by orbital motion. For galaxy clusters, it is traced by collective velocity dispersion. The appearance of a common delay scale across these systems suggests that quantities traditionally treated as independent may be manifestations of a single underlying propagation constraint.

Within the present interpretation, this common quantity is identified with cumulative relativistic interaction delay.

6.2 Relation to General Relativity

The proposed framework does not modify the mathematical structure of General Relativity.

The Einstein field equations, gravitational time dilation, gravitational redshift, and the weak-field Newtonian limit are retained unchanged. Consequently, all observational tests successfully described by General Relativity remain valid within the present interpretation.

The distinction lies in the physical interpretation assigned to the gravitational potential and the associated spacetime curvature.

In General Relativity, curvature provides a geometric description of gravitational phenomena. In the present framework, the same curvature is interpreted as the observable manifestation of an underlying cumulative delay structure generated by finite-speed interactions within self-gravitating systems.

The proposal therefore concerns the origin of curvature rather than its mathematical description.

6.3 Relation to Mach’s Principle

Mach’s principle suggested that local physical properties may depend upon the global distribution of matter in the Universe.

The delay interpretation naturally exhibits a similar relational character. Because the cumulative delay depends upon the matter distribution connecting source and observer, gravitational behavior is not determined solely by local conditions but also by the larger structure through which interactions propagate.

In this sense, the delay framework may be viewed as a finite-propagation realization of Machian ideas [22]. The influence of matter is transmitted through interaction pathways requiring finite propagation time, and the resulting cumulative delay manifests observationally as gravitational potential and spacetime curvature.

6.4 Relation to Emergent and Thermodynamic Approaches

Several modern approaches have proposed that gravity may emerge from deeper physical processes rather than representing a fundamental interaction [3,4].

Among the most influential examples is Jacobson’s derivation of the Einstein field equations from thermodynamic considerations [3], demonstrating that spacetime dynamics may arise from underlying microscopic degrees of freedom.

The present interpretation shares a similar philosophical motivation. However, rather than invoking thermodynamic variables, it focuses on finite propagation times and the cumulative delays associated with interaction transmission.

The framework therefore does not attempt to replace General Relativity, but instead seeks a causal interpretation for the quantities already appearing in the theory.

6.5 Implications for Gravitational Phenomenology

The observations considered in this work suggest a hierarchical progression across gravitational scales.

Planetary interiors probe cumulative delay through internal propagation processes. Galaxies probe the same delay structure through large-scale orbital motion. Galaxy clusters probe it through collective velocity dispersion and gravitational redshift.

Despite the differences among these systems, the same relativistic delay scale appears repeatedly in the associated observables.

If this interpretation is correct, gravitational potential may represent a measurable manifestation of cumulative interaction delay rather than an independent physical entity. The observed spacetime curvature would then correspond to the geometric expression of this delay structure.

6.6 Limitations and Future Work

The present work is phenomenological in nature and does not address the microscopic origin of the proposed delay structure.

Instead, it focuses on observational relations linking propagation speeds, orbital velocities, velocity dispersions, and gravitational potentials across multiple astrophysical scales.

Further work is required to determine whether the delay interpretation can be formulated within a complete theoretical framework and whether additional observational tests can distinguish it from alternative descriptions of gravity.

Whether cumulative interaction delays also contribute to large-scale cosmological observables remains an open question and lies beyond the scope of the present work.

Nevertheless, the empirical relations discussed in this study suggest that cumulative relativistic interaction delay may provide a useful and physically intuitive interpretation of gravitational phenomena across planetary, galactic, and cluster systems.

7. Conclusions

This work explored the possibility that gravitational phenomena may be interpreted as manifestations of cumulative relativistic interaction delays associated with finite-speed propagation within self-gravitating systems.

Rather than modifying the mathematical framework of General Relativity, the proposed approach seeks to provide a causal interpretation of gravitational potential and spacetime curvature in terms of accumulated propagation delays between source and observer. Within this interpretation, gravitational time dilation represents the observable manifestation of an underlying delay structure generated by finite-speed interactions.

The framework was examined across three distinct astrophysical regimes. For planetary and stellar bodies, a connection was established between characteristic internal propagation speeds and escape velocities through the equivalence of the associated relativistic time-dilation factors. Observational data indicate a close correspondence between these quantities in gravity-shaped bodies possessing coherent internal propagation paths.

The interpretation was then extended to galaxies, where gravitational and kinematic time-dilation effects coexist. In this regime, orbital motion provides an additional contribution to the cumulative delay structure, offering a natural interpretation of the observed connection between characteristic velocities and galactic dynamics.

Finally, galaxy clusters were considered as systems in which collective velocity dispersion becomes a dominant observational tracer of the delay structure. The observed relations among velocity dispersion, gravitational redshift, and lensing mass were shown to be consistent with the hypothesis that these observables probe a common relativistic delay scale.

Whether cumulative interaction delays also contribute to cosmological observables remains an open question beyond the scope of the present study.

Taken together, planetary interiors, galaxies, and galaxy clusters provide three complementary observational windows into the role of cumulative interaction delays across gravitational scales. The recurrence of a common delay scale among these systems suggests that quantities traditionally treated as independent may be manifestations of a shared underlying propagation constraint.

The proposed framework preserves the observed phenomenology of General Relativity while offering a possible physical interpretation for the origin of the associated spacetime curvature. Although the microscopic origin of the delay structure remains an open question, the empirical relations discussed in this work motivate further investigation of finite-speed interaction effects in self-gravitating systems.

Data Availability

The study uses publicly available observational data obtained from previously published sources cited in the reference list. No new observational datasets were generated. Derived quantities and illustrative calculations presented in this work were obtained from these publicly available data.

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Appendix A. Choice of Characteristic Propagation Velocity

A key aspect of the core regime is the observed correspondence between internal propagation speeds and escape velocity. This relation can be understood from the fact that, in a self-gravitating body, the elastic properties of the material are not independent of gravity. The bulk modulus K governing P-wave propagation is set by the internal pressure, which in turn is determined by gravitational confinement.

$$\overline{v}_{prop}^{\,rad} \sim \sqrt{\frac{K}{\rho}} \sim \sqrt{\frac{GM}{R}} \sim v_{esc} \tag{28}$$

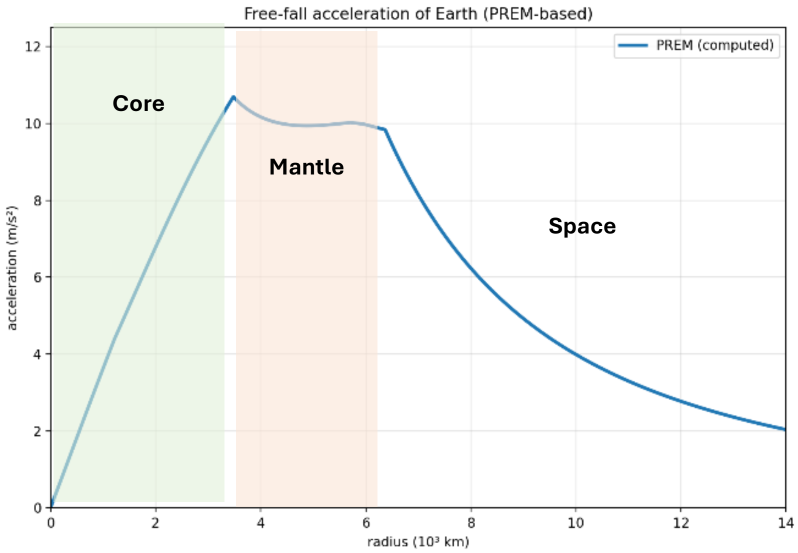

Figure 4: Earth's gravity according to the Preliminary Reference Earth Model (PREM)

The free-fall acceleration profile inside a self-gravitating body reveals how gravitational delay may accumulate with radius. The nearly linear increase of g(r) through the core indicates that the gravitational influence accumulates coherently with radius within the gravity-dominated interior Beyond the core, in the mantle and crust, density and rigidity variations introduce discontinuities, and $g(r)$ becomes irregular—signifying interference between partially decoupled delay pathways.

This scaling is consistent with the time-dilation equivalence derived in Section 3.2, providing both relativistic and material interpretations of the same correspondence.

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