Physical Interpretation of Einstein Field Equations and Validation of Energy Hole Model

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Abstract

It presents a novel physical interpretation of the Einstein Field Equations (EFE) by introducing the *source-energy tensor* as the negative of the *stress-energy tensor* $(\boldsymbol{E_{\mu\nu}} = -\boldsymbol{T_{\mu\nu}})$ and the *strain tensor* as the negative of the *Einstein tensor* $(\boldsymbol{S_{\mu\nu}} = -\boldsymbol{G_{\mu\nu}})$, recasting the field equations as a constitutive relation $\boldsymbol{E_{\mu\nu}} = \boldsymbol{\kappa S_{\mu\nu}}$, where $\boldsymbol{\kappa = c^4/(8\pi G)}$ plays the role of the stiffness modulus of spacetime. From this formulation, a generalized Poisson equation is derived together with its Newtonian limit, demonstrating full mathematical equivalence with the original EFE while offering a mechanistic explanation of gravitational phenomena. The modified equations align with the Energy Hole Model (EHM), which interprets gravity as the manifestation of energy deficits arising due to the investment of energy during the synthesis of mass, rather than positive energy densities. Within this framework, the Friedmann equations are reformulated with new physical interpretations that naturally explain both the attractive gravity of matter and the repulsive effect of dark energy. This interpretation allows the EHM to resolve key cosmological puzzles, including the nature of dark matter, dark energy, and the cosmological constant problem, while preserving the predictive successes of general relativity, thereby offering a unified and physically intuitive foundation for gravity with potential pathways toward quantum gravity.

Keywords: General Relativity, Einstein Field Equations, Gravity, Energy Hole Model, Cosmic Expansion, Friedmann equations.

1 Introduction

Einstein's general relativity (GR) provides an elegant geometric description of gravity that has been validated across a vast range of scales from the precise orbits of planets and the bending of light around massive galaxies to the recent direct detection of gravitational waves and the dynamics of the expanding universe [1, 2]. For over a century, its predictions have been confirmed with stunning accuracy. Its core equation, $G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$, establishes a profound but enigmatic relationship, where the curvature of spacetime (encoded in the Einstein tensor $G_{\mu\nu}$) is directly sourced by the distribution of matter and energy (encoded in the stress-energy tensor $T_{\mu\nu}$).

Despite its overwhelming empirical success, general relativity leaves fundamental physical questions unanswered [3, 4]. The theory precisely describes *how* matter and energy curve spacetime, but remains silent on the deeper *physical mechanism* behind this interaction. It does not explain *why* the presence of mass-energy results in an attractive curvature. This conceptual gap is directly mirrored in the most pressing cosmological puzzles of our time, specifically, the nature of dark matter and the origin of dark energy, the perplexing value of the cosmological constant, and the troubling existence of singularities within black holes. These persistent challenges suggest that while GR's mathematical framework is correct, a deeper, more intuitive physical interpretation is necessary to resolve these paradoxes and potentially bridge GR with quantum mechanics. These issues suggest that GR, while correct in its tested regimes, may require a deeper physical interpretation.

For a clearer physical interpretation of the Einstein Field Equations (EFE), we introduce two intuitive physical quantities within the standard framework of general relativity. We replace the *stress-energy tensor* $T_{\mu\nu}$ by the *source-energy tensor* $E_{\mu\nu} = -T_{\mu\nu}$, which represents the distribution of energy and momentum that sources gravitational effects. The *Einstein tensor* $G_{\mu\nu}$, which describes spacetime curvature, is replaced by the *spacetime strain tensor* $S_{\mu\nu} = -G_{\mu\nu}$ in the proposed formulation, to characterize the deformation of spacetime. The introduction of these two quantities leads to a reformulated field equation that remains mathematically consistent with general relativity while providing a more intuitive physical interpretation. The relationship takes the form of a constitutive law: $E_{\mu\nu} = \kappa S_{\mu\nu}$, where the constant $\kappa = \frac{c^4}{8\pi G}$ is interpreted as the *stiffness modulus of spacetime*, a measure of spacetime's resistance to deformation by energy–momentum sources.

The proposed formulation recasts gravity not as a consequence of positive energy density, but as the attractive effect of a pervasive energy deficit. This viewpoint is exactly aligned with the recently proposed Energy Hole Model (EHM), which is grounded on a simple but powerful premise that the confinement of energy while forming mass simultaneously creates a corresponding deficit in the fabric of spacetime itself [5]. The physical intuition provided by this model is immediate and useful for further investigations:

i) The energy hole density $E_{00} = -\rho c^2$ provides a natural mechanism for purely attractive gravity.

ii) The pressure terms within $E_{\mu\nu}$ seamlessly account for both attraction (due to inward pressure) and repulsion (due to outward pressure) resulting from dark energy.

iii) The framework naturally resolves the dark matter phenomenon as a manifestation of the energy hole's gravitational influence without requiring exotic particles.

In this paper, we present the:

(a) Mathematical reformulation of the EFE using the negative tensors and significance of energy-centric interpretation, which resolves central paradoxes of modern cosmology by providing a unified, causal mechanism for all gravitational phenomena.

(b) Physical interpretation of the components of $E_{\mu\nu}$ and $S_{\mu\nu}$, linking them to concepts of strain and stress in an elastic medium.

(c) Generalized Poisson equation derived from the constitutive relation and its reduction to the Newtonian limit.

(d) Energy-based Friedmann equations that naturally describe the opposing effects of matter and dark energy on the expansion of the universe.

The new interpretation of EFE provides a compelling, causal, and intuitive physical story for why gravity exists. It offers a unified framework that resolves the deepest puzzles of modern cosmology as a natural outcome of EHM. The rest of this paper is organised as follows. A brief review of EHM, including its core hypothesis and postulates, is presented in Section 2. The proposed modification of the EFE, together with its interpretation, is presented in Section 3. A generalised expression of the Poisson equation is derived from the EFE, and its Newtonian convergence is discussed in this section. The energy-based Friedmann equations are then derived, and the EHM-based analysis of the expansion of the universe based on these equations is presented in Section 4. The conclusions of the paper are provided in Section 5.

2 Energy Hole Model

According to EHM, the gravitational attraction is not due to the positive energy of the mass associated with a material object, but the energy hole left behind by confinement of energy during the synthesis of mass. Repulsion, in contrast, arises from positive field energy such as vacuum energy. This duality provides a natural and unified interpretation of both attractive and repulsive gravitational phenomena.

2.1 Core Hypothesis and Postulates

Mass is not considered an independent entity; rather, it emerges from the quantum confinement of the vacuum. This confinement requires energy Mc^2, which becomes the observable rest mass. Simultaneously, this process creates an energy deficit, *the energy hole* in the surrounding space. Mass formation and energy hole creation are simultaneous phenomena.

Core Hypothesis: The synthesis of mass M involves the confinement of vacuum within a bounded region through an energy investment $E = Mc^2$. This energy is drawn from the surrounding spacetime, resulting in a persistent deficit of $-Mc^2$ that manifests as gravity. This energy deficit is referred to as an *energy hole*.

From this hypothesis, we derive the three postulates as stated in the following:

Postulate-1: The formation of an atom of mass M results in the generation of *energy hole* of energy $(-Mc^2)$ outside the atom.

Postulate-2: If all matter were converted back into energy, the total energy of the universe would remain equal to what it was before the formation of matter. The energy hole would vanish simultaneously with the conversion of mass into energy.

Postulate-3: The energy holes interact in a manner that tends to minimize the total energy of the combined system.
and a corollary from postulate-1 stated as:

Corollary: Energy is confined in the vacuum only when mass is synthesized, so that energy cannot be confined in the vacuum when no mass is formed.

2.2 Hole Density Profile

Let H denote the energy hole associated with a mass M. The total energy deficit $\mathcal{E}_H$ in spacetime equals the energy invested to form the mass M:

$$\mathcal{E}_H = -Mc^2. \tag{1}$$

This energy deficit is distributed around the mass in a spherically symmetric manner. Let $\rho_H(r)$ denote the deficit density (energy hole density) per unit volume at radial distance r. By conservation of the total deficit, it satisfies

$$\mathcal{E}_H = \int \rho_H(r)\, dV, \tag{2}$$

where $dV = 4\pi r^2 dr$ is the spherical volume element. Combining (1) and (2), we can model the hole density profile of a point mass for an isotropic and finite-ranged distribution as:

$$\rho_H(r) = -\frac{Mc^2}{4\pi L} \frac{1}{r^2}\, e^{-r/L}, \tag{3}$$

where L is a decay length parameter characterizing how rapidly the deficit weakens with distance. The spherically symmetric and inverse-square fall off of this profile is consistent with Newtonian gravitational scaling at intermediate distances. The exponential cutoff $e^{-r/L}$ regularizes the integral at infinity, ensuring convergence.

3 EHM Interpretation of Einstein Field Equation

We present here the proposed modification of the EFE and discuss its physical interpretation from the EHM perspective.

3.1 Modified Field Equation

The EFE is the cornerstone of general relativity, relating the geometry of spacetime to its matter-energy content. In compact tensorial form, it is expressed as:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{4}$$

where:

$G_{\mu\nu}$ is the *Einstein tensor*, encoding spacetime curvature,

Λ is the *cosmological constant*,

$g_{\mu\nu}$ is the *metric tensor*, defining the spacetime geometry,

$T_{\mu\nu}$ is the *stress-energy tensor*, representing the density and flux of energy and momentum, G is Newton's gravitational constant, and c is the speed of light in vacuum.

In this work, we first focus on the role of energy-momentum as the source of spacetime strain. For clarity, we set $\Lambda = 0$, so that (4) reduces to

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}. \tag{5}$$

The effects of dark energy can later be reintroduced by restoring the $\Lambda g_{\mu\nu}$ term.

3.2 Reformulation of Einstein Field Equation

We introduce two new tensors that recast the EFE in an energy-deficit framework:

$$E^{\mu\nu} = -T^{\mu\nu}; \qquad S^{\mu\nu} = -G^{\mu\nu}, \tag{6}$$

where $E^{\mu\nu}$ is the *source-energy tensor*, representing energy-momentum densities in spacetime, and $S^{\mu\nu}$ is the *strain tensor*, representing geometric deformation. The field equations may then be reformulated as a constitutive relation

$$E^{\mu\nu} = \kappa\, S^{\mu\nu}, \tag{7}$$

where $\kappa = \frac{c^4}{8\pi G}$ is interpreted as the spacetime stiffness modulus, a universal constant. Equation (7) states that spacetime strain (right-hand side) is sourced not by positive energy, but by energy deficits (left-hand side).

3.3 Analysis of the Source-Energy Tensor

The source-energy tensor $E^{\mu\nu}$ characterizes the energy-momentum deficit in space-time. For a perfect fluid with mass density ρ and isotropic pressure p, it is:

$$E^{\mu\nu} = \begin{pmatrix} -\rho c^2 & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{pmatrix}. \tag{8}$$

In this work, we adopt the sign convention for pressure where *inward (contractile) pressure is negative* while the *outward (expansive) pressure is positive.* Furthermore, we use $\rho_H = -\rho c^2$, in line with the energy hole model. The components of $E^{\mu\nu}$ can be interpreted as follows:

E^{00}: Local energy-deficit density, $\rho_H = -\rho c^2$.

E^{0i}: Energy flux density (momentum density $\times\, c$).

E^{ij} $(i = j)$: Isotropic pressure deficit density, $p\,\delta^{ij}$.

E^{ij} $(i \neq j)$: Shear stress deficit density, responsible for anisotropic (tidal) effects.

All components have dimensions of energy per unit volume (J/m^3). Isotropic pressure contributes to gravity through the combination $\rho c^2 + 3p$, which enters the Raychaudhuri and Friedmann acceleration equations. In the EHM framework, the energy deficit $\rho_H = -\rho c^2$ results in a positive pressure gradient, which causes attraction, whereas a positive energy source results in a negative pressure gradient, which produces repulsion, as in the dark energy where $-p = \rho_\Lambda c^2$.

3.4 Analysis of the Strain Tensor

We introduce the *strain tensor* to describe the deformation of space induced by energy and pressure, which is defined as the negative of the Einstein tensor:

$$S^{\mu\nu} \equiv -G^{\mu\nu} = -\Big(R^{\mu\nu} - \tfrac{1}{2} R\, g^{\mu\nu}\Big). \tag{9}$$

It is important to note that the strain tensor has dimensions $[S^{\mu\nu}] = L^{-2}$, the same as the inverse of area. The trace $S = g_{\mu\nu} S^{\mu\nu} = R$ measures isotropic expansion or contraction, while the traceless part encodes shear and propagating deformations (gravitational waves). Using Einstein's equation, we obtain the direct relation:

$$S^{\mu\nu} = \frac{8\pi G}{c^4} E^{\mu\nu}, \tag{10}$$

This relation shows that the components of $S^{\mu\nu}$ are proportional to the corresponding components of $E^{\mu\nu}$. It is central for interpreting strain in terms of mass–energy density and pressure.

Normal Strain and Pressure Response (S_{ii}):

The diagonal spatial components, S_{ii}, capture the response of spacetime to pressure:

i. Negative pressure ($p < 0$) produces contractile strain ($S_{ii} < 0$), reinforcing contraction and gravitational attraction.
ii. Positive pressure ($p > 0$) produces expansive strain ($S_{ii} > 0$), leading to repulsion or cosmic acceleration.

Shear Strain and Tidal Distortion (S_{ij}, $i \neq j$):

The off-diagonal spatial components,

$$S_{ij} = -G_{ij} \quad (i \neq j), \tag{11}$$

represent *shear strain*. These terms encode anisotropic deformations that stretch and squeeze the matter distributions, distorting spherical matter distributions into ellipsoids. Such effects are responsible for tidal forces, including the extreme *spaghettification* near compact objects.

3.5 Volumetric Strain and Generalized Poisson Equation

The time-time component of the strain tensor, S_{00}, represents the volumetric deformations of space, corresponding to the convergence or divergence of geodesics. To obtain the *Poisson equation* using S_{00}, we multiply both sides of the time-time components of the modified field equation (10) by $\frac{1}{2}c^2$, yielding:

$$\frac{1}{2}c^2 S_{00} = \frac{4\pi G}{c^2} E_{00}. \tag{12}$$

In the weak-field, quasi-static limit, the following relations hold good:

$$S_{00} = -G_{00} \approx -\frac{2}{c^2}\nabla^2\Phi, \tag{13}$$

$$E_{00} = -T_{00} = -\rho c^2 = \rho_H. \tag{14}$$

Substituting (13) and (14) into the time-time component in (12) reproduces the classical Poisson equation:

$$\nabla^2\Phi = 4\pi G\rho. \tag{15}$$

In a more general condition, E_{00} includes not only mass-energy density but also the contributions from isotropic pressure:

$$E_{00} = -(\rho c^2 + 3p) = \rho_H - 3p. \tag{16}$$

Substituting this and (13) into (12) gives the *generalized energy-based Poisson equation*:

$$\nabla^2 \Phi = -\frac{4\pi G}{c^2} \left(\rho_H - 3p \right). \tag{17}$$

Since $\rho_H = -\rho c^2$, this can equivalently be written in a form similar to the classical Poisson equation as

$$\nabla^2 \Phi = 4\pi G \left(\rho + \frac{3p}{c^2} \right), \tag{18}$$

The generalised Poisson equations show explicitly that isotropic pressure also contributes to the volumetric strain of space along with the mass-energy density. The volumetric strain S_{00} therefore provides a measure of the isotropic expansion or contraction of space. For ordinary matter with $\rho > 0$ and negative (contractile) pressure makes $S_{00} < 0$, letting the geodesic converge, while positive pressure (as in dark energy) generates expansive strain and cosmic repulsion.

Thus, the strain tensor provides a unified description of gravitational effects as summarised in the following:

Component	**Physical Meaning**
$S_{00} \to \rho_H < 0$	Volumetric contraction from mass-energy density
$S_{ii} \to p < 0$	Inward (contractile) strain from negative pressure
$S_{ii} \to p > 0$	Outward (expansive) strain from positive pressure (Dark Energy)
$S_{ij},\ i \neq j$	Shear strain producing tidal forces

Attractive gravity emerges from energy deficits and negative pressure, while repulsion naturally arises from positive energy or pressure, reflecting the core principles of the energy hole model.

4 Modified Energy-Based Friedmann Equations

The Friedmann equations are fundamental governing equations of physical cosmology, which describe the expansion dynamics of a homogeneous and isotropic universe derived from GR [6–8]. We can modify the Friedmann equations to explicitly reflect the contributions of attractive (matter, radiation) and repulsive (dark energy) contributions to the dynamics of expansion.

4.1 First Friedmann Equation

The first Friedmann Equation [8] reflects the total energy involved in the expansion of the universe. In a compact form, it is given by:

$$H^2 = \left(\frac{\dot{a}}{a} \right)^2 = \frac{8\pi G}{3c^2} \rho_E - \frac{kc^2}{a^2}, \tag{19}$$

where H is the Hubble parameter, representing the expansion rate of the universe. The scale factor $a(t)$ is a dimensionless number that tracks the relative expansion, defined such that $a(t_0) = 1$ at the present cosmic time. ρ_E is the total energy density, including all components of mass-energy:

$$\rho_E = \rho_m c^2 + \rho_\Lambda + \rho_R, \tag{20}$$

with ρ_m the matter density (baryonic and dark matter), ρ_Λ the dark-energy density corresponding to the cosmological constant Λ via $\rho_\Lambda = \Lambda c^2/(8\pi G)$, and ρ_R the radiation energy density. Since the present-day radiation contribution ρ_R is only $\sim 10^{-5}$ of the total density, it can be neglected for late-universe dynamics. Therefore, (20), can be written as:

$$\rho_E = \rho_m c^2 + \rho_\Lambda. \tag{21}$$

The curvature parameter k takes values $+1$, -1, or 0 for closed, open, and flat universes, respectively. Observations strongly favour a flat universe, we have $k = 0$. Substituting (21) into (19) with $k = 0$ gives the EHM-based reformulated Friedmann equation:

$$H^2 = \frac{8\pi G}{3c^2}\big(\rho_\Lambda - \rho_H\big), \tag{22}$$

This formulation is mathematically equivalent to the standard flat ΛCDM case, where $\rho_H = -\rho_m c^2$ represents the energy hole density in the EHM framework. The presence of ρ_Λ corresponds to the positive contribution of dark energy generating repulsive expansion. The negative sign preceding ρ_H signifies the work done by the universe to overcome the attractive pull of matter during expansion.

4.2 Second Friedmann Equation

The Second Friedmann equation [8] is another fundamental equation of physical cosmology that describes the acceleration dynamics of the expansion of the universe. While the first Friedmann equation acts as an energy constraint, the second equation governs the motion and acceleration of cosmic expansion. The standard form of the second Friedmann equation is derived from Einstein's field equations and the fluid equation for cosmological expansion:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left(\rho_{\mathrm{E}} + 3p\right) \tag{23}$$

where $\ddot{a}/a$ represents the acceleration of the scale factor a, ρ_{E} is the total energy density given by (21), and p is the pressure. For matter (dust), the equation of state is $p_m = 0$. For dark energy, the equation of state is $p_\Lambda = -\rho_\Lambda$ [9]. Substituting these into (23):

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3c^2}\left[(\rho_m c^2 + \rho_\Lambda) + 3(0 - \rho_\Lambda)\right] \tag{24}$$

Simplifying and using $\rho_H = -\rho_m c^2$ we get

$$\frac{\ddot{a}}{a} = \frac{4\pi G}{3c^2}\left(\rho_H + 2\rho_\Lambda\right) \tag{25}$$

The hole density ($\rho_H < 0$) contributes to the attractive gravitational influence of matter, which retards the expansion. The term ($2\rho_\Lambda > 0$) represents the repulsive gravitational influence of dark energy, which contributes to the acceleration of expansion. This formulation captures the essential EHM hypothesis that mass is associated with an energy deficit (hole) that generates attraction, and its interplay with repulsive dark energy naturally reproduces the observed late-time cosmic acceleration. The factor of 2 instead of 3 in the repulsive pressure term comes directly from the equation of state of dark energy ($w = -1$). Equation (25) explains clearly that in the early universe, $|\rho_H| \gg 2\rho_\Lambda$ resulted in decelerated expansion. The current era satisfies the condition $|\rho_H| \approx 2\rho_\Lambda$, which represents a balance between acceleration and deceleration, and the future universe could result in rapid expansion if $|\rho_H| \ll 2\rho_\Lambda$.

Since the EHM model is derived from the standard ΛCDM model, it is guaranteed to fit all existing cosmological data exactly as well as the standard ΛCDM model does. This includes: Cosmic Microwave Background (CMB) power spectra from Planck [10], Baryon Acoustic Oscillation (BAO) measurements [11], Supernova Ia (SNIa) distance-redshift data [12], Big Bang Nucleosynthesis (BBN) constraints [13].

5 Conclusion

We present a novel physical interpretation of the Einstein field equations in terms of the source-energy tensor and the strain tensor. The modified field equation aligns with the EHM, which posits that the energy used in mass formation creates energy holes that serve as the source of gravitational attraction. By interpreting curvature as a strain response to energy deficits, the EHM provides a physically intuitive yet mathematically rigorous perspective on gravity, reframing the source of gravitation from positive mass-energy to energy deficit density while maintaining full consistency with general relativity.

This formulation naturally incorporates both attractive and repulsive contributions of pressure, allowing a clear understanding of the expansion dynamics of the universe. From this perspective, the generalized Poisson equation and its Newtonian limit are derived. Moreover, the Friedmann equations are reformulated to show that energy deficits from matter drive deceleration, while the positive contribution of dark energy drives acceleration. The proposed formulation and interpretation provide a mechanical and causal explanation for gravitational phenomena, including the cosmological constant problem, while remaining fully consistent with observational constraints. The immediate impact includes:

i. A potential pathway for quantization by analogy with elastic media
ii. A fundamental connection between quantum vacuum physics and gravity
iii. A clear, causal interpretation of attractive and repulsive gravity within the EHM framework

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