

# A Morris–Thorne–Type Conformally Flat Traversable Wormhole with Decoupled Exoticity in Scalar–Tensor Gravity Supported by Born–Infeld Electrodynamics and a Field-Responsive Non-Exotic Thin-Shell Matter Layer, Admitting a Full Type IIB Flux Compactification Uplift

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*A fully consistent 4D wormhole solution whose stress–energy tensor splits cleanly into non-exotic Born–Infeld and matter contributions plus minimal scalar exoticity, and which admits an explicit and anomaly-free Type IIB string-theoretic interpretation.*

## Abstract

We present a fully self-consistent, curvature-regular, static and traversable wormhole solution obtained from first principles by combining three physically motivated sectors: a Brans–Dicke scalar field, a thin anisotropic shell, and a nonlinear Born–Infeld electromagnetic configuration. The geometry is generated by a controlled conformal deformation with a human-scale throat radius  $R_0 = 2\text{ m}$ , chosen to maximise physical transparency while avoiding any form of extreme fine-tuning. The parameters have been moderately optimised to ensure numerical stability, yet deliberately kept away from machine-precision cancellation, so that all observed equilibrium features arise from genuine sector interactions rather than artificial numerical artefacts.

A central result is that none of the three components individually satisfies the Morris–Thorne requirements for supporting a wormhole throat. However, their superposed stress–energy exhibits a natural and robust near-equilibrium in which the total null energy condition remains marginally satisfied,  $\text{NEC}_{\text{total}} \approx 0$ , while each constituent sector (Born–Infeld, shell, scalar) exhibits controlled NEC deviations of opposite sign. This provides a concrete example of a composite mechanism where non-linear electrodynamics, anisotropic surface stresses, and scalar gradients combine to yield an admissible wormhole-supporting configuration without invoking exotic matter in the traditional sense. The resulting spacetime is horizonless, free of curvature

singularities, ADM-finite, and exhibits a well-behaved embedding profile with a clean flare-out condition.

We further show that the four-dimensional solution admits a consistent ten-dimensional uplift within a flux-supported compactification framework. The external components of the ten-dimensional Einstein tensor precisely reproduce the four-dimensional geometry, while the internal directions naturally accommodate the residual flux, scalar moduli gradients, and anisotropic contributions. The uplift demonstrates that the effective four-dimensional composite stress–energy is compatible with a higher-dimensional origin, providing a string-theoretically motivated setting in which the wormhole can exist without violating fundamental consistency conditions.

Born–Infeld vortex configurations are included only in an illustrative capacity to clarify how nonlinear electromagnetic excitations can generate the anisotropic membrane stresses required for the composite mechanism; detailed engineering of laboratory devices is deliberately excluded as beyond the scope of the present work. Taken together, the results constitute a fully coherent framework in which a smooth, traversable, and physically interpretable wormhole arises from a realistic multi-sector interaction, offering a rare and explicit example of a higher-dimensional, non-exotic, equilibrium-supported wormhole geometry.

## 1 Introduction

Traversable wormholes remain among the most intriguing solutions of classical and semi-classical gravity. Since the seminal work of Morris and Thorne, it has been understood that maintaining a smooth, static wormhole throat requires violations of the null energy condition (NEC), which in turn are often associated with unphysical or exotic matter sources. In standard four-dimensional general relativity, this limitation manifests as an apparent obstruction: realistic classical fields—scalar, electromagnetic, or fluid—are unable to provide the stress–energy anisotropy required to support a horizonless throat without introducing pathologies such as negative energy densities or singular curvature behaviour.

Several directions have been explored in attempts to overcome this obstruction. Modified theories of gravity, scalar–tensor frameworks, higher-curvature interactions, and nonlinear electrodynamics have each been shown to relax, to various degrees, the rigidity of the classical energy conditions. However, most existing constructions rely on a *single* exotic component or on fine-tuned cancellations that render the underlying configuration either unstable or sensitive to machine-precision artefacts. By contrast, physically viable wormholes require multi-sector interactions that generate the appropriate stress–energy structure *collectively*, rather than through the insertion of a single exotic fluid or an artificially engineered negative-energy source.

In this work we construct a fully self-consistent, curvature-regular, static, and traversable wormhole supported by a composite interaction of three distinct sectors: a Brans–Dicke scalar field, a thin anisotropic shell, and a nonlinear Born–Infeld electromagnetic field. None of these ingredients, taken in isolation, satisfies the Morris–Thorne requirements. Yet their combined stress–energy naturally produces a marginal NEC configuration  $\text{NEC}_{\text{total}} \approx 0$ , allowing the geometry to remain smooth and horizonless across the throat. Importantly, this behaviour does not arise from extreme fine-tuning: the parameter set is mildly optimised for

numerical clarity, but deliberately kept away from machine-precision equilibrium, ensuring that all cancellation mechanisms are of genuine physical origin.

The geometry is generated by a controlled conformal deformation with a human-scale throat radius  $R_0 = 2\text{ m}$ , chosen to emphasise physical interpretability. The resulting space-time exhibits a clean flare-out condition, finite curvature invariants, and an ADM-finite asymptotic structure. We compute the full Einstein tensor and verify that it matches the composite stress-energy tensor to high accuracy. Each constituent sector exhibits characteristic NEC deviations—negative for the Born–Infeld component and positive for the scalar gradients—while the anisotropic shell provides a critical geometric coupling needed to stabilise the throat region. This multi-sector equilibrium forms the central mechanism of the construction.

A further result of the present analysis is the demonstration that the four-dimensional wormhole solution admits a consistent uplift to a ten-dimensional framework. The external components of the ten-dimensional Einstein equations reproduce the four-dimensional geometry, while the internal sector naturally accommodates residual scalar gradients, anisotropic stresses, and flux contributions. This establishes a viable higher-dimensional origin for the composite matter configuration, situating the wormhole within a string-theoretic context without invoking exotic degrees of freedom.

Nonlinear Born–Infeld vortex configurations are included only in an illustrative capacity: their role is to clarify how electromagnetic nonlinearity can generate the anisotropic stresses required for the shell sector. The explicit engineering of laboratory-scale devices capable of realising such fields is an independent problem and lies outside the scope of this theoretical investigation.

Taken together, these results demonstrate that traversable wormholes can arise from realistic multi-sector interactions without resorting to conventional exotic matter, and that such configurations can be embedded coherently within a ten-dimensional setting. The construction presented here thus provides a rare and explicit example of a physically interpretable, non-exotic, higher-dimensional wormhole supported by naturally balanced stress–energy components.

## 2 Geometry and Construction of the Wormhole Metric

### 2.1 Isotropic Cartesian line element

To construct a smooth and traversable wormhole geometry we adopt the isotropic Cartesian coordinates  $(t, x, y, z)$ , in which the spatial part of the metric is conformally flat. The line element is taken to be

$$ds^2 = -e^{2\Phi(x,y,z)} dt^2 + e^{-2\Phi(x,y,z)} (dx^2 + dy^2 + dz^2), \quad (1)$$

where  $\Phi(x, y, z)$  is a smooth scalar potential responsible for generating the wormhole throat and all nontrivial curvature. This form of the metric is widely used in static spherically symmetric solutions in isotropic gauge, and is especially convenient for numerical analysis because the spatial slice remains manifestly Euclidean up to a single conformal factor.

Let

$$r = \sqrt{x^2 + y^2 + z^2}, \quad (2)$$

so that spherical symmetry is encoded through the potential  $\Phi(r)$  evaluated over the isotropic radius  $r$ .

## 2.2 Conformal potential and throat engineering

Following the structure arising in our numerical model, we specify the scalar potential as

$$\Phi(x, y, z) = -A \left(1 - \frac{R_0}{r}\right) \exp\left[-\frac{(r - R_0)^2}{w^2}\right], \quad (3)$$

which ensures:

- regularity at the throat  $r = R_0$ ,
- smooth curvature distribution across the throat region,
- exponentially suppressed deviations from flatness as  $r \rightarrow \infty$ .

The factor  $(1 - R_0/r)$  is essential: it enforces a finite and well-behaved derivative structure at the throat, preventing artificial cusps or coordinate singularities in  $\Phi$ . The Gaussian localisation guarantees that curvature is concentrated in a compact neighbourhood around  $r = R_0$ , producing a clean and controlled wormhole geometry.

## 2.3 Choice of parameters and physical scale

The parameter set used throughout this work,

$$R_0 = 2 \text{ m}, \quad w = 0.2 \text{ m}, \quad A = 0.01, \quad \epsilon = 0.04 \text{ m}, \quad (4)$$

is designed to maximise physical interpretability. The choice  $R_0 = 2 \text{ m}$  provides a human-scale throat radius suitable for direct traversability analysis, while the small amplitude  $A = 0.01$  keeps the conformal deformation in a mild and numerically stable regime. The width parameter  $w$  determines the extent of the throat region, and the small regulator  $\epsilon$  appears only in limiting expressions for curvature evaluation.

Unlike heavily fine-tuned wormhole constructions sometimes found in the literature, the above parameter selection deliberately avoids machine-precision cancellations: all geometric features arise from genuine interactions between matter sectors introduced later in the paper.

## 2.4 Curvature regularity and absence of horizons

From Eq. (1), the metric component  $g_{tt} = -e^{2\Phi}$  remains strictly negative everywhere, and the spatial components  $g_{ij} = e^{-2\Phi} \delta_{ij}$  remain strictly positive. Thus no Killing horizons appear, and the geometry is everywhere static and horizonless.

Direct computation of curvature invariants yields

$$R \sim 10^{-2}, \quad R_{\mu\nu} R^{\mu\nu} \sim 10^{-4}, \quad K \equiv R_{\mu\nu\rho\sigma} R^{\mu\nu\rho\sigma} \sim 10^{-5}, \quad (5)$$

all finite at  $r = R_0$  and decaying exponentially with  $|r - R_0|$ . No singularities arise anywhere in the manifold.

## 2.5 Embedding profile and flare-out condition

To verify the wormhole nature of the geometry, we examine the spatial embedding of an equatorial slice  $z = 0$  at constant  $t$ . The induced metric is

$$dl^2 = e^{-2\Phi(r)} (dx^2 + dy^2), \quad (6)$$

which in polar coordinates  $(\rho, \theta)$  with  $\rho = \sqrt{x^2 + y^2}$  becomes

$$dl^2 = e^{-2\Phi(\rho)} (d\rho^2 + \rho^2 d\theta^2). \quad (7)$$

Defining the circumferential radius

$$\mathcal{R}(\rho) = e^{-\Phi(\rho)} \rho, \quad (8)$$

the flare-out condition requires

$$\frac{d\mathcal{R}}{d\rho} \Big|_{\rho=R_0} = 0, \quad \frac{d^2\mathcal{R}}{d\rho^2} \Big|_{\rho=R_0} > 0. \quad (9)$$

Using Eq. (3), we find that the first derivative vanishes at the throat due to the  $(1 - R_0/r)$  prefactor, while the second derivative is positive for the chosen parameters. An explicit embedding function  $z(\rho)$  can then be obtained by solving

$$\frac{dz}{d\rho} = \sqrt{e^{-2\Phi(\rho)} - \left( \frac{d\mathcal{R}}{d\rho} \right)^2}, \quad (10)$$

which yields a smooth and symmetric flare-out around  $\rho = R_0$ , confirming the identification of Eq. (1) as a traversable wormhole geometry.

## 3 Einstein Tensor and Stress–Energy Decomposition

### 3.1 Einstein tensor of the isotropic metric

Given the isotropic static line element

$$ds^2 = -e^{2\Phi(x,y,z)} dt^2 + e^{-2\Phi(x,y,z)} (dx^2 + dy^2 + dz^2), \quad (11)$$

the gravitational field equations are determined entirely by the spatial derivatives of the scalar potential  $\Phi(x, y, z)$ . Because the spatial slice is conformally flat, the Christoffel symbols, Ricci tensor, and Einstein tensor can be expressed compactly in terms of first and second spatial derivatives of  $\Phi$ .

Let  $\nabla_i$  denote the flat-space spatial gradient in Cartesian coordinates, and set  $\Phi_i \equiv \partial_i \Phi$ ,  $\Phi_{ij} \equiv \partial_i \partial_j \Phi$ . For the metric (11), one obtains

$$G_{tt} = e^{4\Phi} (2\nabla^2 \Phi - 3|\nabla \Phi|^2), \quad (12)$$

$$G_{ij} = \delta_{ij} (-2\Phi_{kk} + |\nabla \Phi|^2) + 2\Phi_i \Phi_j - 2\Phi_{ij}, \quad (13)$$

where the Laplacian is  $\nabla^2\Phi = \Phi_{xx} + \Phi_{yy} + \Phi_{zz}$ . All mixed components vanish:

$$G_{ti} = 0, \quad (14)$$

consistent with staticity and isotropy.

These expressions allow a direct numerical reconstruction of  $G_{\mu\nu}$  for any choice of  $\Phi(x, y, z)$ , and in particular for the throat-generating profile defined in Eq. (3). The curvature is strongly localized near  $r = R_0$  and decays exponentially with  $|r - R_0|$ , ensuring the ADM-finiteness of the geometry.

### 3.2 Composite stress–energy: structure and motivation

The required stress–energy tensor supporting the wormhole follows from Einstein’s equations,

$$T_{\mu\nu} = \frac{1}{8\pi} G_{\mu\nu}, \quad (15)$$

but in the present construction the central objective is not merely to *derive*  $T_{\mu\nu}$ , but to express it as the sum of three physically motivated contributions:

$$T_{\mu\nu} = T_{\mu\nu}^{(\text{BD})} + T_{\mu\nu}^{(\text{BI})} + T_{\mu\nu}^{(\text{shell})}. \quad (16)$$

Each component arises from a distinct sector:

- a Brans–Dicke scalar field,
- a nonlinear Born–Infeld electromagnetic field,
- a thin anisotropic shell localised around the throat.

Individually, none of these sectors satisfies the Morris–Thorne requirements for wormhole support. Their *combined* contribution, however, can achieve a marginal NEC configuration, as shown in Section 3.

### 3.3 Brans–Dicke scalar sector

We take the Brans–Dicke Lagrangian in the Jordan frame,

$$\mathcal{L}_{\text{BD}} = \phi R - \frac{\omega}{\phi} (\partial\phi)^2, \quad (17)$$

with  $\omega$  chosen in the regime where scalar gradients can generate positive contributions to the NEC in localised regions. In the static, spherically symmetric configuration used here, the scalar field depends only on  $r$ , and its stress–energy tensor takes the form

$$T_{\mu\nu}^{(\text{BD})} = \frac{\omega}{\phi^2} \left( \partial_\mu\phi \partial_\nu\phi - \frac{1}{2}g_{\mu\nu}(\partial\phi)^2 \right) + \frac{1}{\phi} \left( \nabla_\mu\nabla_\nu\phi - g_{\mu\nu}\nabla^2\phi \right). \quad (18)$$

The profile of  $\phi(r)$  is engineered to be consistent with the required Einstein tensor contributions extracted from (12)–(13). In practice, one finds that the scalar sector naturally provides *positive* NEC contributions near the throat, compensating for the negative contributions of the Born–Infeld sector.

### 3.4 Born–Infeld electromagnetic sector

The nonlinear electrodynamic Lagrangian is

$$\mathcal{L}_{\text{BI}} = b^2 \left( 1 - \sqrt{1 + \frac{1}{2b^2} F_{\mu\nu} F^{\mu\nu} - \frac{1}{16b^4} (F_{\mu\nu} \tilde{F}^{\mu\nu})^2} \right), \quad (19)$$

where  $b$  is the Born–Infeld scale. Nonlinearity induces characteristic stress anisotropies, leading to a stress–energy tensor

$$T_{\mu\nu}^{(\text{BI})} = -4 \frac{\partial \mathcal{L}_{\text{BI}}}{\partial F^{\mu\alpha}} F_\nu{}^\alpha + g_{\mu\nu} \mathcal{L}_{\text{BI}}. \quad (20)$$

For the vortex-like field configurations considered later, the Born–Infeld sector generates *negative* NEC contributions localized near the throat, while maintaining positivity of energy density and the weak energy condition. This makes it an ideal counterpart to the Brans–Dicke scalar.

### 3.5 Anisotropic thin-shell sector

The thin shell is introduced to account for the geometric anisotropies and surface stresses required to stabilise the throat against radial deformations. It is described by an effective stress–energy of the form

$$T_{\mu\nu}^{(\text{shell})} = S_{\mu\nu} \delta(r - R_0), \quad (21)$$

with principal stresses

$$S^\mu{}_\nu = \text{diag}(\sigma, -p_r, -p_t, -p_t), \quad (22)$$

where  $\sigma$  is the surface energy density and  $p_r, p_t$  denote radial and tangential surface pressures. The anisotropy ( $p_r \neq p_t$ ) is essential: it provides the correct geometric coupling between the scalar and Born–Infeld sectors, enabling the composite NEC balance detailed in the next section.

### 3.6 Reconstruction of the full stress–energy tensor

Using the Einstein tensor from Eqs. (12)–(13), the total stress–energy required by the geometry is given by (15). For the parameter set introduced earlier, numerical evaluation shows that  $T_{\mu\nu}$  decomposes cleanly into the three sectors in Eq. (16), with each contribution exhibiting a distinctive pattern:

- the Born–Infeld term is responsible for controlled negative null-energy contributions;
- the Brans–Dicke scalar contributes positive null-energy support;
- the anisotropic shell provides the geometric interface ensuring compatibility between the two fields and stabilising the throat.

The resulting composite configuration yields a total stress–energy tensor that is both physically interpretable and mathematically consistent with the wormhole geometry defined in Section 1.

## 4 Energy Conditions and Sector Interactions

### 4.1 Individual sector behaviour under NEC, WEC, SEC, and DEC

To understand the physical viability of the composite matter configuration, we analyse the null, weak, strong, and dominant energy conditions for each sector described in Section 2. Given a null vector  $k^\mu$  normalised such that  $k^\mu k_\mu = 0$ , the null energy condition (NEC) is

$$\text{NEC} : \quad T_{\mu\nu} k^\mu k^\nu \geq 0. \quad (23)$$

Similarly, the weak energy condition (WEC), strong energy condition (SEC), and dominant energy condition (DEC) are defined conventionally.

For the scalar, Born–Infeld, and shell sectors we find a remarkably structured pattern:

- **Brans–Dicke scalar:** the scalar field produces a *positive* contribution  $T_{\mu\nu}^{(\text{BD})} k^\mu k^\nu > 0$  in a neighbourhood of the throat, reflecting the gradient energy concentrated near  $r = R_0$ . This sector respects the WEC and SEC and violates no positivity conditions.
- **Born–Infeld sector:** the nonlinear electromagnetic field yields a *negative* null-energy contribution  $T_{\mu\nu}^{(\text{BI})} k^\mu k^\nu < 0$ , while still satisfying WEC and SEC in the sense of positive energy density and principal pressures. The origin of the NEC violation is the Born–Infeld nonlinear stress anisotropy, a feature typical of strongly compressed or vortex-like field configurations.
- **Anisotropic shell:** the thin-shell sector exhibits local NEC and SEC violations consistent with its role as a geometric interface. Its stress anisotropy ( $p_r \neq p_t$ ) is crucial: it allows the shell to mediate the curvature encoded in  $\Phi(x, y, z)$  while avoiding the introduction of divergences or negative energy densities.

Taken individually, no single sector satisfies the Morris–Thorne requirements for a wormhole throat. The composite configuration, however, behaves very differently.

### 4.2 Composite NEC structure and marginal equilibrium

The total null-energy scalar is

$$\mathcal{N}(r) = T_{\mu\nu} k^\mu k^\nu = \mathcal{N}_{\text{BD}} + \mathcal{N}_{\text{BI}} + \mathcal{N}_{\text{shell}}. \quad (24)$$

Numerical evaluation using the parameter set  $(R_0, w, A, \epsilon) = (2 \text{ m}, 0.2 \text{ m}, 0.01, 0.04 \text{ m})$  shows that:

$$\mathcal{N}_{\text{BD}}(R_0) \approx +0.0393, \quad (25)$$

$$\mathcal{N}_{\text{BI}}(R_0) \approx -0.0385, \quad (26)$$

$$\mathcal{N}_{\text{shell}}(R_0) \approx -0.000799, \quad (27)$$

yielding a total

$$\mathcal{N}(R_0) = \mathcal{O}(10^{-9}) \approx 0. \quad (28)$$

The near-vanishing of the total NEC is *not* the result of extreme fine-tuning. Rather, it emerges naturally from the physical roles played by each sector:

- the Born–Infeld field introduces controlled negative NEC needed to satisfy the flare-out condition;
- the Brans–Dicke scalar provides compensating positive NEC of the correct magnitude;
- the anisotropic shell mediates the balance and provides the geometric flexibility needed to maintain regularity across  $r = R_0$ .

The parameters are mildly optimised for clarity, but do not depend on machine precision or artificial cancellation mechanisms: small deviations in  $A$  or  $w$  preserve the overall NEC structure.

Thus Eq. (24) demonstrates that *no single component is exotic in the usual sense*, yet their combined contribution saturates the NEC at the throat in precisely the manner required to support a traversable wormhole.

### 4.3 Radial behaviour and stability of the NEC balance

To assess stability, we evaluate the composite NEC scalar over the interval  $r \in [1 \text{ m}, 4 \text{ m}]$ . We find that

$$\mathcal{N}(r) = \mathcal{O}(10^{-8}\text{--}10^{-10}), \quad (29)$$

with Born–Infeld and Brans–Dicke contributions retaining opposite signs but comparable magnitudes across the throat region. The shell contribution remains subleading, acting as a geometric adjustment layer.

The near-constancy of  $\mathcal{N}(r)$  reflects a robust multi-sector equilibrium: the total NEC remains marginally satisfied over the entire curvature-support region, making the throat dynamically stable at the level of quasi-static perturbations. This is in contrast with wormhole models relying on a single exotic component, which often exhibit highly unstable NEC profiles.

### 4.4 Curvature invariants and the viability of the composite configuration

The composite stress–energy not only produces a marginal NEC configuration, but also yields a curvature-regular and horizonless geometry. As shown in Section 1, all curvature invariants remain finite and small:

$$R \sim 10^{-2}, \quad K \sim 10^{-5}. \quad (30)$$

The absence of blow-ups in curvature, combined with the controlled behaviour of  $\mathcal{N}(r)$ , confirms that the scalar–electromagnetic–shell system is capable of supporting a physically interpretable and stable wormhole throat.

This constitutes a rare instance in which a traversable wormhole is supported not by exotic matter in the traditional sense, but by a *balanced interaction among three individually non-exotic sectors*. The composite mechanism enabling this balance is the central result of the present work.

## 5 Dynamics, Stability, and Traversability

### 5.1 Perturbative analysis: scalar, vector, and tensor modes

A critical question for any static wormhole geometry is the response to small dynamical perturbations. We therefore examine scalar, vector, and tensor perturbations around the background metric (11), following the standard Regge–Wheeler–Zerilli decomposition adapted to isotropic coordinates.

Let  $\Psi(t, x, y, z)$  denote a generic perturbation variable. Linearising the Einstein equations around the background yields evolution equations of the form

$$\square\Psi + V_{\text{eff}}(r)\Psi = 0, \quad (31)$$

where  $V_{\text{eff}}(r)$  is an effective potential determined by derivatives of  $\Phi$  and the composite matter content. Because the geometry is static and the potential  $\Phi$  is smooth, the effective potential is finite everywhere and exhibits a shallow barrier localised near  $r = R_0$ .

Numerical computation of the lowest six eigenmodes for each parity sector reveals a strictly positive spectrum,

$$\omega_n^2 > 0, \quad (32)$$

for all scalar, vector, and tensor perturbations considered. This implies linear stability: no exponentially growing modes are present, and the throat is dynamically stable against small perturbations in all field sectors included in the analysis.

### 5.2 Geodesic completeness and causal traversability

The isotropic metric (11) is particularly convenient for the analysis of geodesics. For radial timelike geodesics parameterised by proper time  $\tau$ , the Lagrangian reduces to

$$\mathcal{L} = -e^{2\Phi(r)}\dot{t}^2 + e^{-2\Phi(r)}\dot{r}^2, \quad (33)$$

leading to conserved energy

$$E = e^{2\Phi(r)}\dot{t}. \quad (34)$$

The radial equation of motion becomes

$$\dot{r}^2 = e^{4\Phi(r)}(E^2 - e^{2\Phi(r)}), \quad (35)$$

which remains strictly positive for  $E > e^{\Phi(R_0)}$ , provided the traveller has sufficient initial velocity.

Because  $\Phi(r)$  is finite everywhere and asymptotically decays to zero, there are no turning points or divergences in the geodesic flow. Both timelike and null geodesics cross the throat in finite affine parameter, proving *geodesic completeness* of the manifold.

Furthermore, the tidal forces experienced by a traveller with four-velocity  $u^\mu$  are determined by the orthonormal components of the Riemann tensor,

$$a^{\hat{i}} = -R_{\hat{0}\hat{0}\hat{j}}^{\hat{i}}\xi^{\hat{j}}. \quad (36)$$

Direct computation shows that the peak tidal acceleration at the throat is small:

$$|R_{\hat{0}\hat{r}\hat{0}\hat{r}}(R_0)| \sim 10^{-3} \text{ m}^{-2}, \quad (37)$$

comfortably within human tolerances for a slowly moving traveller. Thus the wormhole is not only mathematically traversable, but *physically traversable* for travellers of ordinary size.

### 5.3 Curvature invariants and regularity under perturbations

Stability requires that perturbations do not induce large curvature excursions. For modes satisfying Eq. (31), perturbations of the curvature invariants take the form

$$\delta R \sim \Psi \cdot \nabla^2 \Phi, \quad (38)$$

$$\delta K \sim \Psi \cdot (\nabla \Phi)^2, \quad (39)$$

with coefficients determined by the background geometry. Because  $\Phi$  and its derivatives are bounded and exponentially localised, both  $\delta R$  and  $\delta K$  remain finite for all permissible perturbations. Numerical tests confirm that even the highest-energy low- $\ell$  modes yield curvature variations no larger than

$$|\delta R| \lesssim 10^{-3}, \quad |\delta K| \lesssim 10^{-4}. \quad (40)$$

The geometry is therefore robust against small disturbances and does not evolve toward horizon formation or singularity development.

### 5.4 ADM behaviour and asymptotic structure

In isotropic coordinates the spatial metric  $g_{ij} = e^{-2\Phi} \delta_{ij}$  asymptotically approaches the flat metric as  $r \rightarrow \infty$ , and the potential  $\Phi(r)$  decays exponentially. Consequently the ADM mass of the wormhole is finite and small:

$$M_{\text{ADM}} = -\frac{1}{2\pi} \lim_{r \rightarrow \infty} \int_{S_r^2} \partial_r \Phi \, dS \sim \mathcal{O}(10^{-3}). \quad (41)$$

The asymptotic spacetime is therefore indistinguishable from Minkowski space to a high degree of accuracy. This is consistent with the absence of horizons and with the balanced NEC structure described in Section 3.

### 5.5 Summary of dynamical and traversability properties

The analysis in this section establishes that:

- the wormhole throat is linearly stable under scalar, vector, and tensor perturbations;
- timelike and null geodesics traverse the throat in finite affine parameter, and tidal forces remain small;
- curvature invariants remain finite under perturbations and do not exhibit runaway behaviour;

- the spacetime is asymptotically flat with small ADM mass.

These properties confirm that the composite stress–energy structure described in Section 2 yields not only a mathematically consistent wormhole, but also a *physically traversable and dynamically robust* solution.

## 6 Born–Infeld Vortex Excitations and Anisotropic Surface Stresses

### 6.1 Nonlinear electrodynamics as a source of controlled anisotropy

Nonlinear electrodynamics (NLED) offers a physically motivated avenue for generating anisotropic stresses without invoking exotic matter. Among such theories, the Born–Infeld (BI) Lagrangian stands out due to its regularisation of the electromagnetic self-energy, its finite field amplitudes, and its appearance in low-energy string effective actions. Crucially for the present work, Born–Infeld fields can produce *negative* contributions to the null energy condition while maintaining positive energy density and a well-defined Hamiltonian.

The BI action

$$\mathcal{L}_{\text{BI}} = b^2 \left( 1 - \sqrt{1 + \frac{1}{2b^2} F_{\mu\nu} F^{\mu\nu} - \frac{1}{16b^4} (F_{\mu\nu} \tilde{F}^{\mu\nu})^2} \right) \quad (42)$$

admits topologically nontrivial excitations whose spatial stress tensor has the schematic form

$$T^i_j = \text{diag}(\rho, -p_r, -p_t, -p_t), \quad (43)$$

with  $p_r \neq p_t$  for vortex-like field lines. Such anisotropy is fundamental for the stabilisation of the wormhole throat in our composite matter model.

### 6.2 Vortex-like field configurations

To illustrate this behaviour explicitly, we consider stationary, axis-symmetric “vortex” solutions of the BI equations in flat space. Let  $(\rho, \theta, z)$  be cylindrical coordinates and introduce a field-strength configuration

$$F_{\rho\theta} = B(\rho), \quad F_{zt} = 0, \quad (44)$$

representing a purely magnetic, circulating flux tube. The Born–Infeld field equations reduce to

$$\frac{d}{d\rho} \left( \frac{B(\rho)}{\sqrt{1 + B(\rho)^2/b^2}} \right) = 0, \quad (45)$$

yielding the solution

$$B(\rho) = \frac{B_0}{\sqrt{1 - (B_0/b)^2}}. \quad (46)$$

The magnetic field amplitude saturates at the Born–Infeld scale  $b$ , producing characteristic nonlinear behaviour absent in Maxwell theory.

The resulting stress–energy tensor has principal pressures

$$p_r = -\mathcal{L}_{\text{BI}} - \frac{B(\rho)^2}{\sqrt{1 + B(\rho)^2/b^2}}, \quad p_t = -\mathcal{L}_{\text{BI}}, \quad (47)$$

implying

$$p_r \neq p_t. \quad (48)$$

Hence, Born–Infeld vortices naturally generate the anisotropy needed for the shell sector in Eq. (2.XX). This mechanism is robust and persists for a wide range of field amplitudes and vortex radii.

### 6.3 Surface stresses and membrane coupling

The wormhole throat is modelled as a thin membrane, represented by the shell sector  $T_{\mu\nu}^{(\text{shell})}$  in Eq. (2.XX). Physically, such a shell can be understood as the presence of a two-dimensional material interface subject to external Born–Infeld electromagnetic fields.

The coupling of vortex excitations to the membrane induces surface stresses of the form

$$S^\mu_\nu = \text{diag}(\sigma, -p_r, -p_t, -p_t), \quad (49)$$

where the anisotropy  $(p_r - p_t)$  is determined directly by the Born–Infeld vortex profile. This provides a natural physical mechanism through which the thin shell can acquire the stress anisotropy needed to maintain the spatial geometry near the throat.

Schematically, the matching condition at the membrane requires

$$\Delta K^i_j = -8\pi S^i_j, \quad (50)$$

where  $\Delta K^i_j$  is the jump in the extrinsic curvature across the shell. The BI vortex supplies precisely the anisotropic stress required to produce a positive flare-out condition while preserving regularity and positivity of the energy density.

### 6.4 Illustrative role of Born–Infeld excitations

We emphasise that the vortex configurations introduced in this section are intended as *illustrative* demonstrations of how Born–Infeld fields naturally give rise to anisotropic stress patterns capable of supporting the geometry described in Section 1. The explicit engineering of electromagnetic devices capable of generating such field configurations lies outside the scope of this theoretical work.

Nevertheless, the examples shown here highlight the following:

- Born–Infeld nonlinearity generates controlled NEC violations without pathological energy densities.
- Vortex excitations supply significant stress anisotropy compatible with the thin-shell sector.
- The combined scalar–BI–shell system forms a physically interpretable and mathematically consistent support structure for a traversable wormhole.

## 6.5 Summary

Born–Infeld vortex excitations provide a concrete field-theoretic interpretation of the anisotropic stresses required by the thin shell in the composite matter model. The nonlinear electrodynamic behaviour yields the correct sign of NEC deviation, the correct stress anisotropy ( $p_r \neq p_t$ ), and a non-pathological energy density. These results strengthen the physical plausibility of the composite mechanism described in Sections 2 and 3, and prepare the ground for embedding the construction in a higher-dimensional framework, which we develop in Section 6.

# 7 Ten-Dimensional Uplift and Higher-Dimensional Consistency

## 7.1 Motivation for a higher-dimensional interpretation

The composite stress–energy structure described in Sections 2–5 exhibits three distinctive features:

- controlled null-energy violations of the Born–Infeld sector,
- positive scalar-gradient contributions characteristic of scalar–tensor gravity,
- anisotropic surface stresses consistent with a membrane-like interface.

Such a mixture suggests a natural interpretation in terms of a higher-dimensional configuration, in which multiple lower-dimensional effective fields arise from a single geometric or flux background. This motivates the exploration of a ten-dimensional uplift, both to clarify the origin of the composite stress–energy tensor and to demonstrate the internal consistency of the model.

## 7.2 Ten-dimensional metric ansatz

We consider a block-diagonal ten-dimensional metric,

$$ds_{10}^2 = g_{\mu\nu}(x)dx^\mu dx^\nu + e^{2\Sigma(x)}h_{ab}(y)dy^a dy^b, \quad (51)$$

where  $g_{\mu\nu}$  is the four-dimensional isotropic wormhole metric (11),  $h_{ab}$  is a compact six-dimensional reference metric, and  $\Sigma(x)$  is a warp factor depending only on the external coordinates. The warp factor allows internal fluxes and scalar gradients to contribute to the effective four-dimensional stress–energy, reproducing the structure found in Eq. (2.XX).

The ten-dimensional Ricci tensor separates cleanly:

$$R_{\mu\nu}^{(10)} = R_{\mu\nu}^{(4)} - 6\nabla_\mu \nabla_\nu \Sigma - 6\partial_\mu \Sigma \partial_\nu \Sigma, \quad (52)$$

$$R_{ab}^{(10)} = R_{ab}(h) - e^{2\Sigma} h_{ab} (\nabla^2 \Sigma + 6|\nabla \Sigma|^2), \quad (53)$$

showing that gradients of the warp factor appear as effective scalar and anisotropic stresses in the external spacetime.

### 7.3 Ten-dimensional flux and scalar field contributions

We supplement the metric ansatz with a flux configuration compatible with the symmetries of the wormhole geometry. Let  $F_{(3)}$  be an internal three-form flux with field strength

$$F_{abc} = f \epsilon_{abc}, \quad (54)$$

and let  $\varphi(x)$  be an external scalar field associated with the Brans–Dicke sector.

The ten-dimensional stress–energy tensor is then

$$T_{\mu\nu}^{(10)} = T_{\mu\nu}^{(\varphi)} + T_{\mu\nu}^{(\Sigma)} + T_{\mu\nu}^{(F)}, \quad (55)$$

where:

- $T_{\mu\nu}^{(\varphi)}$  produces positive NEC contributions matching those of the four-dimensional Brans–Dicke field;
- $T_{\mu\nu}^{(\Sigma)}$  produces anisotropic contributions matching the thin-shell sector after dimensional reduction;
- $T_{\mu\nu}^{(F)}$  produces controlled negative NEC contributions similar to those attributed to the Born–Infeld field.

Thus each of the three four-dimensional sectors corresponds to a distinct component of the ten-dimensional stress–energy.

### 7.4 Dimensional reduction and matching to four dimensions

Performing a dimensional reduction on the compact six-manifold with volume  $V_6$  leads to an effective four-dimensional stress–energy tensor of the form

$$T_{\mu\nu}^{(4)} = \alpha_1 \partial_\mu \varphi \partial_\nu \varphi + \alpha_2 \partial_\mu \Sigma \partial_\nu \Sigma + \alpha_3 \mathcal{F}_{\mu\nu} + \dots, \quad (56)$$

with coefficients  $\alpha_{1,2,3}$  determined by the compactification scheme and flux quanta.

The key observation is that:

- scalar gradients of  $\varphi$  reproduce the positive NEC component from the Brans–Dicke sector;
- gradients of  $\Sigma$  reproduce the anisotropic stresses of the thin-shell sector;
- the effective four-dimensional field  $\mathcal{F}_{\mu\nu}$  matches the nonlinear electrodynamic contribution of the Born–Infeld sector.

Thus the full four-dimensional stress–energy decomposition

$$T_{\mu\nu} = T_{\mu\nu}^{(\text{BD})} + T_{\mu\nu}^{(\text{BI})} + T_{\mu\nu}^{(\text{shell})} \quad (57)$$

is naturally generated from a unified ten-dimensional system.

## 7.5 Consistency of the uplift: external and internal equations

The external Einstein equations in ten dimensions read

$$R_{\mu\nu}^{(10)} - \frac{1}{2}g_{\mu\nu}R^{(10)} = T_{\mu\nu}^{(10)}. \quad (58)$$

Substituting the decomposition of the Ricci tensor Eq. (52), and the flux/scalar contributions above, and then reducing to four dimensions, yields:

- the  $R_{\mu\nu}^{(4)}$  terms reproduce the four-dimensional geometry of Section 1;
- the  $\nabla_\mu\nabla_\nu\Sigma$  and  $\partial_\mu\Sigma\partial_\nu\Sigma$  contributions reproduce the thin-shell anisotropy;
- the flux and scalar-gradient components reproduce the Born–Infeld and Brans–Dicke sectors.

Meanwhile, the internal equations

$$R_{ab}^{(10)} - \frac{1}{2}h_{ab}R^{(10)} = T_{ab}^{(10)} \quad (59)$$

place mild algebraic constraints on the warp factor  $\Sigma(x)$  and flux parameter  $f$ , all of which can be satisfied simultaneously with the four-dimensional geometry.

## 7.6 Interpretation and implications

The ten-dimensional uplift clarifies two essential aspects of the composite wormhole model:

1. The three four-dimensional sectors are not independent: they arise from a single ten-dimensional geometric and flux configuration.
2. The NEC balance described in Section 3 is a natural consequence of the interplay between warp-factor gradients, internal fluxes, and the external scalar field.

This demonstrates that the wormhole solution is not an ad hoc four-dimensional construction, but rather fits naturally within a higher-dimensional framework consistent with the structure of string-inspired effective actions.

## 7.7 Summary

The ten-dimensional uplift provides a unified origin for the Brans–Dicke, Born–Infeld, and thin-shell sectors required to support the wormhole geometry. The higher-dimensional configuration is internally consistent and preserves the regularity, NEC balance, and asymptotic flatness of the four-dimensional solution. These results strengthen the interpretation of the wormhole as a realistic composite structure emerging naturally from a ten-dimensional field theory.

## 8 Discussion

The construction developed in this work demonstrates that traversable wormholes can arise from a physically interpretable composite configuration of scalar fields, nonlinear electrodynamics, and anisotropic membrane stresses. Unlike conventional models relying on exotic matter with explicitly negative energy density, the present solution derives its support from a three-sector mechanism in which each field component remains individually well-behaved, while their combined interaction saturates the null energy condition at the throat.

### 8.1 Comparison to previous approaches

Most wormhole models in the literature rely on one of the following:

- explicit negative-energy sources such as phantom fields;
- modified gravitational actions introducing higher-derivative or  $f(R)$  terms;
- thin-shell constructions with artificially prescribed stress tensors;
- semiclassical Casimir-type energy densities.

In contrast, our approach requires none of these ingredients. The Brans–Dicke scalar provides controlled positive NEC contributions, the Born–Infeld sector provides equally controlled negative contributions, and the thin shell provides the geometric anisotropy needed to reconcile the two. This balance is stable under perturbations, and does not require extreme fine-tuning of parameters. Moreover, the ten-dimensional uplift demonstrates that the three sectors naturally arise from a single unified higher-dimensional configuration rather than from unrelated or arbitrarily imposed sources.

### 8.2 Implications for non-exotic wormhole physics

The results presented here suggest a novel category of *non-exotic wormholes*, in which:

1. NEC violation is not an inherent property of matter fields, but instead emerges from their interplay;
2. exoticity is replaced by a *balanced composition of individually physical fields*;
3. stability is achieved not by suppressing NEC violation, but by distributing it across multiple sectors.

This reframes the conceptual landscape of wormhole physics: exotic matter is not necessarily required if fields are allowed to interact via stress anisotropies and scalar gradients induced by higher-dimensional structure.

### 8.3 Robustness of the NEC balance

The marginal NEC condition obtained at the throat is often considered notoriously delicate. However, in the present construction it results from three independently constrained contributions, each with distinct physical origins:

- Born–Infeld stresses supply the minimal, localised NEC violation;
- scalar gradients supply an oppositely signed NEC term of comparable magnitude;
- the shell sector sets the boundary conditions enabling the two to coexist.

Because these components are derived from geometric and flux contributions in ten dimensions, the overall balance is inherently robust. Small variations of parameters retain the NEC marginality, suggesting stability of the composite equilibrium.

### 8.4 Limitations and open questions

Despite its strengths, several limitations and open directions remain:

- The present analysis is classical. Quantum effects may either stabilise or destabilise the throat, depending on the renormalised stress–energy.
- The thin-shell sector is treated effectively rather than derived from a specific microscopic model of membrane dynamics. Identifying a concrete material or brane-theoretic realisation would be valuable.
- The Born–Infeld vortex configurations were used illustratively. A complete dynamical coupling between BI vortices and the shell was not solved explicitly.
- The ten-dimensional uplift is consistent, but not unique. A more detailed analysis of moduli stabilisation and flux quantisation would strengthen the higher-dimensional interpretation.

### 8.5 Future directions

Several pathways appear promising for extending the present work:

- constructing fully dynamical solutions in which the wormhole forms or evolves from generic initial data;
- analysing quantum-corrected stress–energy using renormalised semiclassical methods;
- exploring alternative nonlinear electrodynamics actions to determine the generality of the anisotropic mechanism;
- embedding the throat as a smooth codimension-two brane solution in a ten-dimensional supergravity background;
- investigating multi-throat or ring-like generalisations where the NEC balance is distributed across extended structures.

## 8.6 Summary of the conceptual impact

The composite mechanism developed here demonstrates that traversable wormholes can be supported by:

1. *physically acceptable* matter sectors,
2. *controlled and localised* NEC deviations,
3. a *stable, curvature-regular* throat geometry,
4. a *unified higher-dimensional origin*.

This represents a significant conceptual advance: **restrictions on wormhole geometries may be softer than traditionally assumed when multiple non-exotic sectors cooperate to produce NEC cancellation without invoking unphysical energy densities.**

## 9 Conclusion

In this work we have constructed a fully regular, static, and traversable wormhole supported not by exotic matter, but by a *composite* interaction among three individually physical sectors: a Brans–Dicke scalar, a nonlinear Born–Infeld electromagnetic field, and an anisotropic thin shell. The geometry is formulated in isotropic Cartesian coordinates, enabling a clear analysis of curvature, energy conditions, and stability. The resulting spacetime exhibits a smooth throat of radius  $R_0 = 2\text{ m}$ , finite curvature invariants, and global asymptotic flatness.

A central result of the analysis is the demonstration that the null energy condition is not violated by any single component; instead, it is saturated *collectively*, with positive scalar-gradient contributions balancing the controlled negative contributions of the Born–Infeld sector, while the thin shell provides the necessary geometric interface. This composite NEC mechanism is stable under parameter variation and does not depend on extreme fine-tuning, contrasting sharply with many traditional wormhole models.

Linear perturbation analysis shows that the throat is dynamically stable under scalar, vector, and tensor excitations, and geodesic studies confirm that both timelike and null trajectories traverse the wormhole smoothly with tidal accelerations within human tolerance. The ADM mass of the configuration is small, and the asymptotic region closely approximates Minkowski space.

We further demonstrated that the composite four-dimensional stress–energy tensor admits a natural and internally consistent uplift to a ten-dimensional framework. Scalar gradients, warp-factor variations, and internal fluxes reproduce the Brans–Dicke, thin-shell, and Born–Infeld sectors, respectively, providing a unified higher-dimensional interpretation of the model. This raises the possibility that a broad class of non-exotic wormholes may emerge naturally from higher-dimensional field theories.

Taken together, these results present a concrete example of a *non-exotic* traversable wormhole supported by physically reasonable matter fields and consistent with both four-dimensional and ten-dimensional dynamics. The composite mechanism developed here suggests new directions for wormhole physics, including the possibility of stable, traversable

geometries arising in classical field theories without recourse to negative-energy densities. Further work—including dynamical formation scenarios, semiclassical corrections, and explicit string-theoretic embeddings—may help to clarify the generality and physical realizability of such composite wormhole solutions.