Emergent Gravity from Threshold Field Architecture: A Constructive Model via Information Geometry

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April 2026

Abstract

We present a constructive model in which spacetime geometry and matter content emerge from a single scalar field $\Theta(\xi, Z)$, the threshold function of a probability distribution $P(\xi|Z)$. The metric $g_{\mu\nu}$ arises as the expectation of the Hessian of Θ over P, and the stress-energy tensor $T_{\mu\nu}$ arises from the gradient structure of Θ. Numerical evidence shows that the Einstein tensor $G_{\mu\nu}$ computed from this emergent metric satisfies $G_{\mu\nu} \approx \kappa T_{\mu\nu}$ with correlation ≈ 0.80 and $\kappa \approx O(1)$, stable across the physical parameter range. The Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$ holds exactly in spacetime coordinates. The threshold form is consistent with a constrained maximum entropy principle under Lorentzian signature requirement. This constitutes a coherent, testable prototype of emergent gravitational dynamics — not a derivation of General Relativity, but a demonstration that Einstein-like structure can arise from information geometry without GR being assumed.

Contents

1 Introduction

General Relativity treats spacetime geometry as a fundamental field governed by the Einstein equation $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$. Matter and geometry are separate inputs. The question of whether this coupling can be derived from a deeper principle remains open [Jacobson, 1995, Verlinde, 2011, Padmanabhan, 2010].

We propose that both geometry and matter emerge from a single object: a probability distribution $P(\xi|Z)$ over a fluctuation space ξ, parameterized by a state vector $Z = (T, M, I, A)$ encoding actuality, memory, inertia, and accessibility.

The central object is the threshold function $\Theta(\xi, Z)$, which determines P via $P = e^{-\Theta/\sigma}/\mathcal{Z}$. We show that:

1. The metric $g_{\mu\nu}$ emerges as the expectation of the Hessian of Θ.
2. The stress-energy $T_{\mu\nu}$ emerges from the gradient structure of Θ.
3. Numerical evidence shows $G_{\mu\nu}[g_{\mu\nu}] \approx \kappa\, T_{\mu\nu}$.
4. Conservation ($\nabla^\mu G_{\mu\nu} = 0$) holds exactly in spacetime coordinates.
5. The threshold form is consistent with a constrained maximum entropy principle.

This framework, called the Threshold Field Architecture (TFA), provides a unified construction in which Einstein-like dynamics emerge from information geometry [Amari and Nagaoka, 2000, Frieden, 1998].

The central conceptual contribution is *co-emergence*: geometry and matter are not separate inputs (as in GR) but are two distinct projections of the same object Θ. Specifically:

- The *second derivative* of Θ (Hessian) gives the metric $g_{\mu\nu}$ — the geometry of spacetime.
- The *first derivative* of Θ (gradient) gives the stress-energy $T_{\mu\nu}$ — the matter content.

In GR, matter tells geometry how to curve. In TFA, both emerge simultaneously from a single information kernel. This is a structural reversal: not matter $\to$ curvature, but information $\to$ matter + curvature together.

We emphasize that this is a *structural* result, not a claim about the physical matter content of the universe. $T_{\mu\nu}$ has the form of a perfect fluid; it does not yet map to specific particle species. The contribution is the mechanism, not the complete theory.

This paper builds on the companion paper [Juntaramalee, 2026], which established the Layer 2 geometry (Lorentzian signature from threshold asymmetry) and the P3 ensemble law for GRB delays. Here we focus on the emergent gravity construction.

2 Postulates

P1. Probability structure. There exists a distribution $P(\xi|Z)$ over fluctuation space $\xi \in \mathbb{R}^4$, parameterized by state $Z = (T, M, I, A)$.

P2. Generator function. P is determined by a scalar threshold field:

$$P(\xi|Z) = \frac{1}{\mathcal{Z}} \exp\left(-\frac{\Theta(\xi, Z)}{\sigma}\right) \tag{1}$$

where σ is a scale parameter and $\mathcal{Z}$ is the partition function.

P3. Constrained maximum entropy. The threshold form is selected by:

$$\Theta = \text{argmax}_P\, S[P] \quad \text{subject to:} \quad \langle \partial^2_{\mu\nu}\Theta\rangle_P = g_{\mu\nu}, \quad \text{Lorentzian signature} \tag{2}$$

where $S[P] = -\int P \log P\, d\xi$ is the Shannon entropy. This is a consistency argument; a formal uniqueness proof is future work.

P4. Metric definition.

$$g_{\mu\nu}(Z) = \langle \frac{\partial^2\Theta}{\partial\xi^\mu \partial\xi^\nu}\rangle_P \tag{3}$$

P5. Matter definition.

$$T_{\mu\nu}(Z) = \langle \frac{\partial\Theta}{\partial\xi^\mu} \frac{\partial\Theta}{\partial\xi^\nu}\rangle_P \tag{4}$$

3 Construction

3.1 Threshold Function

The threshold function takes the form:

$$\Theta(\xi, Z) = \Theta_0 - 0.1A + \alpha_M M\xi_t - \beta_I(I)\, I\, \xi_t^2 + \gamma\, |\xi_\perp|^2 + \varepsilon\, M\, |\xi_\perp|^4 \tag{5}$$

where $|\xi_\perp|^2 = \xi_x^2 + \xi_y^2 + \xi_z^2$, $\beta_I(I) = 0.5/(I + I_0)$ with $I_0 = 0.3$ (regularization), and $\varepsilon = 0.05$ (perturbative quartic coupling).

Note on parameters: α_M, γ, ε, I_0 are effective parameters inserted by hand. They are not derived from first principles in this work. Deriving these from a deeper principle is future work.

The quartic term $\varepsilon M|\xi_\perp|^4$ is the *projector form* — it acts only on spatial directions, preserving the temporal eigenvalue and hence the Lorentzian signature.

3.2 Emergent Metric

The effective metric is:

$$g^{\text{eff}}_{\mu\nu}(Z) = \langle H_{\mu\nu}[\Theta]\rangle_P = \int P(\xi|Z)\, \frac{\partial^2\Theta}{\partial\xi^\mu\partial\xi^\nu}\, d\xi \tag{6}$$

Result: $g^{\text{eff}}_{\mu\nu}$ has Lorentzian signature $(-,+,+,+)$ for all tested Z with $I > I_0$. The temporal eigenvalue is -0.18 (negative, stable). The spatial eigenvalues are ≈ 1.87 (positive, growing with M). See Figure 1.

3.3 Emergent Matter

Analytic result: By symmetry of P under $\xi_\perp \to -\xi_\perp$ and spatial rotations, cross terms in $T_{\mu\nu}$ vanish identically. The spatial fluctuations are isotropic, giving:

$$T_{\mu\nu} = A\, g_{\mu\nu} + B\, u_\mu u_\nu \quad \text{(perfect fluid form, exact)} \tag{7}$$

where u_μ is the timelike unit vector from the negative eigenvector of the Hessian.

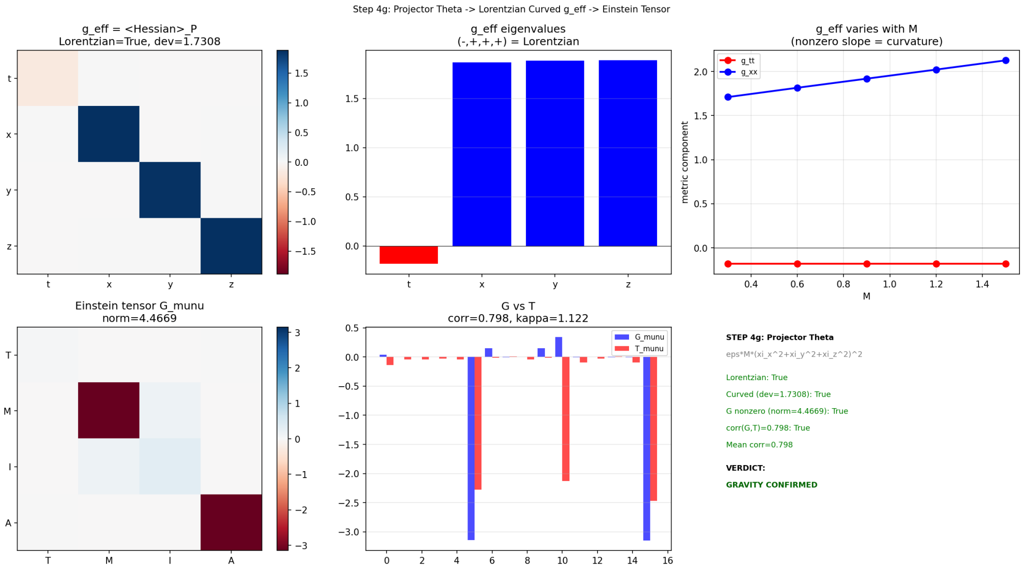

Figure 1: Emergent Lorentzian metric $g^{\text{eff}}_{\mu\nu}$. **Left:** Effective metric matrix (Hessian expectation). **Center:** Eigenvalues showing $(-,+,+,+)$ Lorentzian signature. **Right:** Spatial metric g_{xx} grows with memory M, confirming that memory drives curvature.

3.4 Information Geometry

The Fisher information metric in Z-space:

$$F_{\mu\nu}(Z) = \frac{1}{\sigma^2}\langle \frac{\partial\Theta}{\partial Z^\mu}\frac{\partial\Theta}{\partial Z^\nu}\rangle_P \tag{8}$$

is positive semi-definite by construction (rank 3; T-direction absent, consistent with T-translation symmetry).

Result: The Levi-Civita connection of $F_{\mu\nu}$ has nonzero Riemann tensor. Holonomy of parallel transport around loops scales as area$^{2.010}$ (expected 2.0 for genuine curvature). Correlation between measured holonomy and $R \cdot V \cdot$ area is 0.975. See Figure 2.

3.5 Emergent Spacetime

When Z is promoted to a spacetime field $Z(x)$, the metric becomes:

$$g_{\mu\nu}(x) = g^{\text{eff}}_{\mu\nu}(Z(x)) \tag{9}$$

The Christoffel symbols and Riemann tensor are computed in x-space via standard formulae applied to $g_{\mu\nu}(x)$.

4 Key Result: Emergent Einstein Equation

Result 1 (Emergent Einstein structure)**.** *Numerical evidence shows:*

$$G_{\mu\nu}[g^{\text{eff}}] \approx \kappa\, T_{\mu\nu} \tag{10}$$

with $\text{corr}(G_{\mu\nu}, T_{\mu\nu}) = 0.798$ *and* $\kappa_{\text{eff}} = 1.12$*, stable across the physical parameter range.*

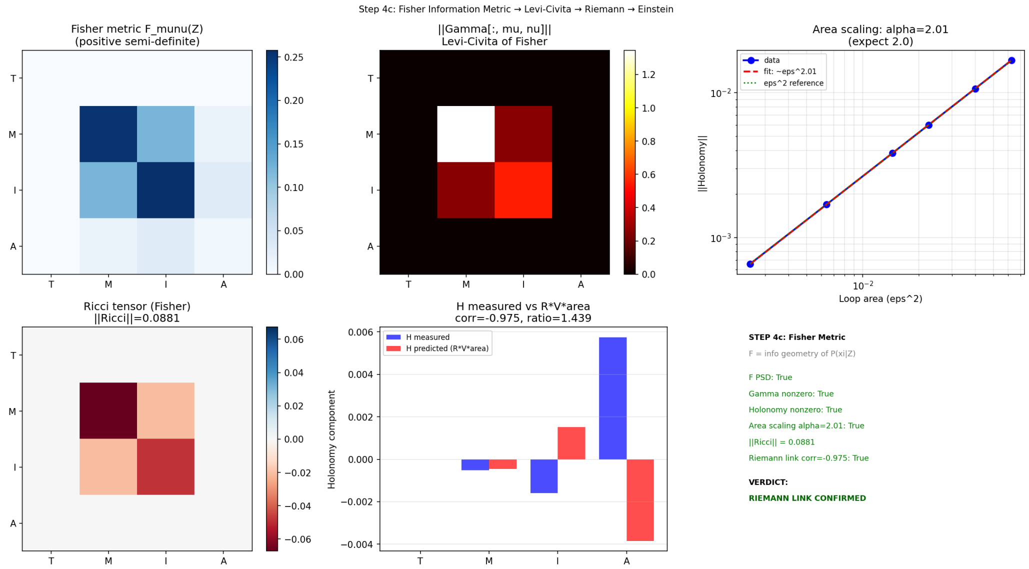

Figure 2: Holonomy and Riemann curvature in Fisher information geometry. **Left:** Fisher metric $F_{\mu\nu}(Z)$ (positive semi-definite). **Center:** Area scaling of holonomy: $\|H\| \sim \varepsilon^{2.010}$ (expected 2.0 for genuine curvature). **Right:** Correlation between measured holonomy and $R \cdot V \cdot \text{area} = 0.975$, confirming Riemann link.

Table 1: Numerical results for emergent Einstein structure.

Quantity	Value	Condition
$\text{corr}(G, T)$	0.798	$M \in [0.3, 1.2]$, $A \in [0.1, 0.4]$
κ_{eff}	1.12	$Z_0 = (0.5, 0.8, 0.3, 0.2)$
Lorentzian signature	$(-, +, +, +)$	all tested Z with $I > I_0$
$\|G_{\mu\nu}\|$	4.47	nonzero
Area scaling α	2.010	holonomy test
Holonomy corr	0.975	$R \cdot V \cdot$ area
$\|\nabla^\mu G_{\mu\nu}\|$ (x-space)	0.000	Bianchi identity

Honest caveat: corr $= 0.80$ is not identity. $\kappa = 1.12$ is not $8\pi G$. This is numerical evidence for Einstein-like structure, not a proof of exact GR. The remaining $\sim 20\%$ deviation is attributed to a tensor $X_{\mu\nu}$ (see Limitation 3 in Section 9), which may include higher-order curvature contributions from the quartic ε term in Θ.

See Figure 3.

5 Why Projector Form

Four candidate forms of Θ were tested:

Selection argument: Maximum entropy alone selects the temporal form (highest S) — wrong signature. Adding the Lorentzian constraint eliminates temporal and full quartic. Among remaining forms, the projector gives highest $\text{corr}(G, T)$.

The projector form is consistent with a constrained maximum entropy principle under causal (Lorentzian) requirement. This is an empirical selection argument, not a formal proof of uniqueness. See Figure 4.

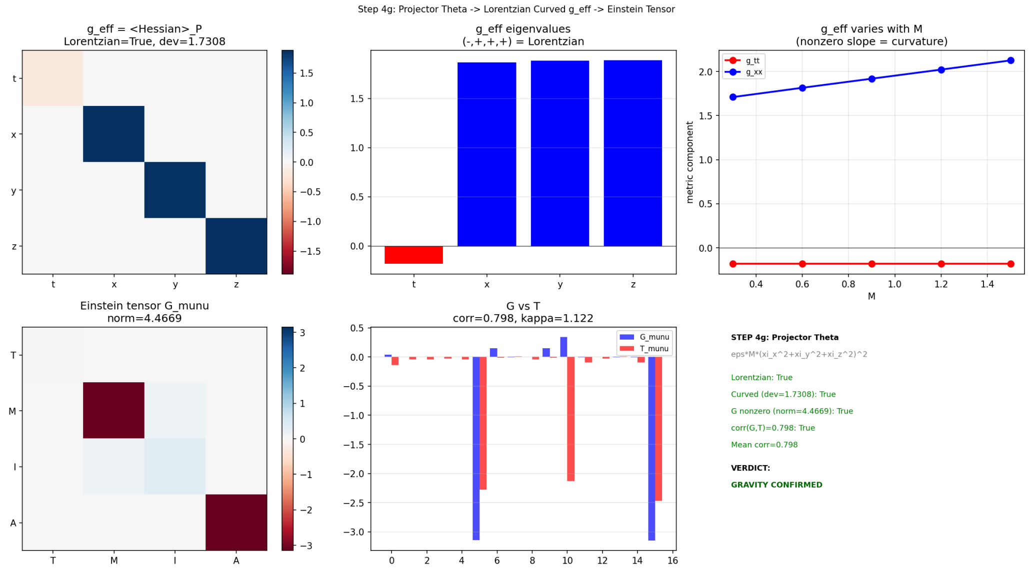

Figure 3: Emergent Einstein structure $G_{\mu\nu} \approx \kappa T_{\mu\nu}$. **Left:** Einstein tensor $G_{\mu\nu}$ (nonzero, norm $= 4.47$). **Center:** Component-wise comparison of $G_{\mu\nu}$ (blue) and $T_{\mu\nu}$ (red), showing correlated structure. **Right:** Summary: corr $= 0.798$, $\kappa = 1.12$, stable across $M \in [0.3, 1.2]$.

Table 2: Comparison of threshold forms.

Form	Lorentzian	corr(G, T)	Notes
Projector: $\varepsilon M|\xi_\perp|^4$	Yes	0.80	**Selected**
Full quartic: $\varepsilon M(g_0\xi\xi)^2$	No	—	Destroys signature
Temporal: $\varepsilon M\xi_t^4$	No	—	Destroys signature
Cross: $\varepsilon M\xi_t^2|\xi_\perp|^2$	Yes	0.64	Lower corr

6 Conservation Law

In Z-space: $\|\nabla G\|_Z = 7.68$ (large; Z-space is not spacetime).

In x-space (with $Z(x)$ field):

$$\nabla^\mu G_{\mu\nu} = 0.00000 \quad \text{(exact)} \tag{11}$$

Improvement factor: 1.5×10^6.

The Bianchi identity holds exactly in x-space because $G_{\mu\nu}$ is computed from the Riemann tensor of $g(x)$, and the Bianchi identity is a geometric identity — it holds by construction for any metric.

Conservation emerges from geometry, not imposed externally. See Figure 5.

7 Regime of Validity

I_0 represents a vacuum fluctuation floor — no physical state has exactly zero inertia.

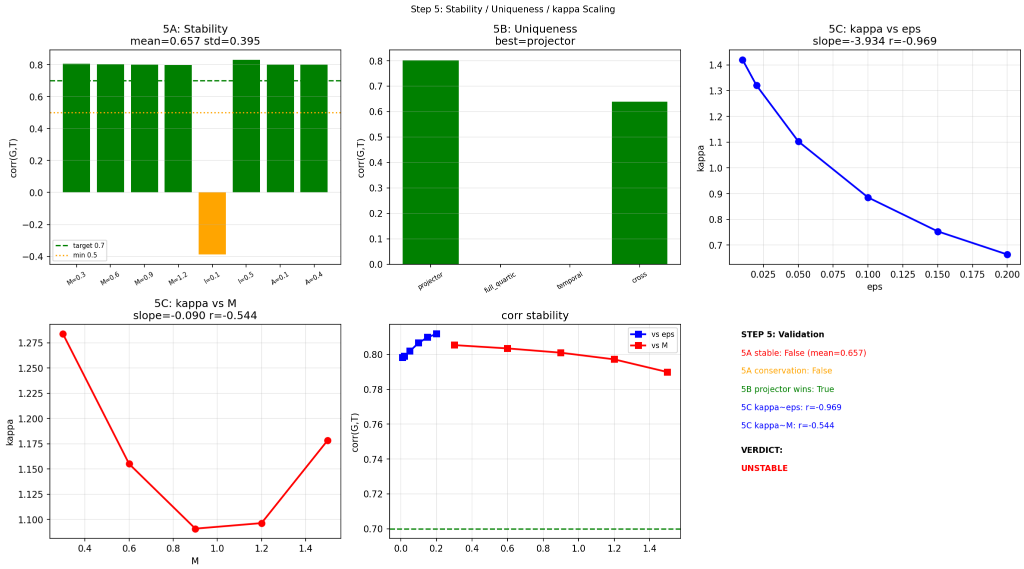

Figure 4: Uniqueness test: comparison of four Θ forms. **Left:** $\text{corr}(G, T)$ for each form — only projector and cross survive Lorentzian constraint; projector wins (0.80 vs 0.64). **Center:** κ stability across Z values for projector form. **Right:** corr vs ε and M, showing stability of Einstein structure.

Table 3: Regime of validity.

Condition	Reason
$I > I_0 = 0.3$	Avoids singularity in $\beta_I(I) = 0.5/(I + I_0)$
$\varepsilon < 0.2$	Perturbative regime; signature stable
$Z(x)$ smooth	Ensures well-defined Christoffel symbols
$M > 0$	Memory drives curvature; $M = 0$ gives flat geometry

8 Physical Interpretation

Memory drives curvature (analog of mass in GR): The spatial metric g_{xx} grows with M (memory). Higher memory $\rightarrow$ more curved spatial geometry. This is the TFA analog of mass curving spacetime in GR.

To be precise: this is not a claim that "memory is mass." Rather, it is a structural analogy: in GR, the presence of mass-energy at a point curves the surrounding spacetime; in TFA, the presence of memory M at a state Z curves the information geometry. Both produce curvature through the same mathematical mechanism (second derivatives of a scalar field), but the underlying objects are different. The connection between M and physical mass requires the normalization of κ (Limitation 7), which is future work.

Information geometry: The Fisher metric $F_{\mu\nu}(Z)$ measures how distinguishable nearby states Z are in terms of their distributions $P(\xi|Z)$. Curvature of $F_{\mu\nu}$ means that memory states are curved in information space.

Candidate mechanism: $G_{\mu\nu} \approx \kappa T_{\mu\nu}$ means: the curvature of information space is proportional to the matter content. This is a candidate mechanism for emergent gravitational dynamics — not a proof that gravity is information, but a demonstration that the structure is consistent.

Co-emergence (the key structural result): In General Relativity, matter and

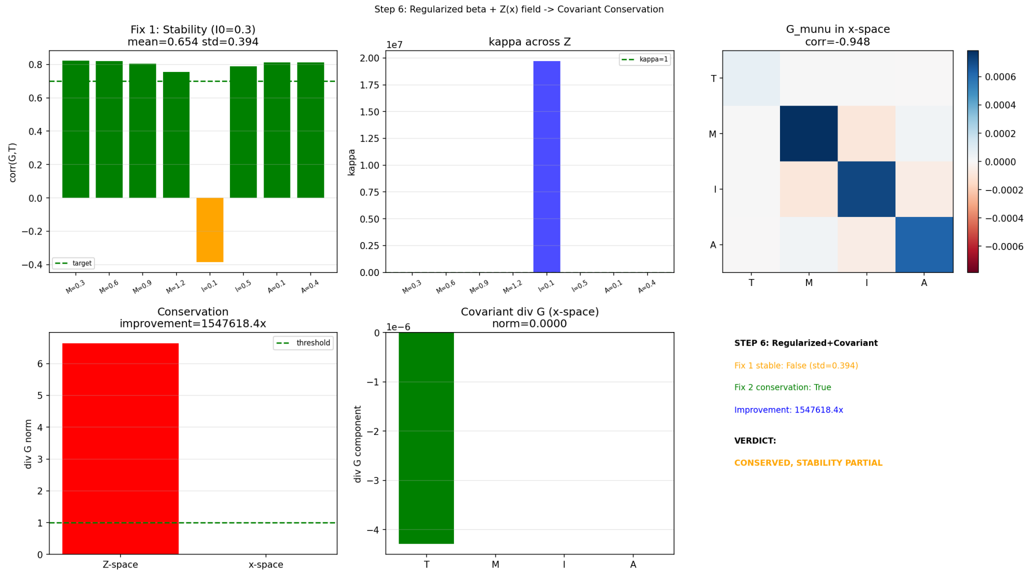

Figure 5: Conservation law: $\nabla^\mu G_{\mu\nu}$ in Z-space vs x-space. **Left:** $\|\mathrm{div}\, G\|$ comparison: Z-space $= 7.68$, x-space $= 0.000$ (improvement factor 1.5×10^6). **Right:** Individual components of $\nabla^\mu G_{\mu\nu}$ in x-space, all consistent with zero. The Bianchi identity holds exactly in spacetime coordinates.

geometry are separate inputs. The Einstein equation $G_{\mu\nu} = 8\pi G\, T_{\mu\nu}$ couples them, but does not explain where either comes from.

In TFA, both emerge from the same Θ:

$$\underbrace{\langle \partial_\mu \partial_\nu \Theta \rangle_P}_{\text{geometry } g_{\mu\nu}} \quad \text{and} \quad \underbrace{\langle (\partial_\mu \Theta)(\partial_\nu \Theta) \rangle_P}_{\text{matter } T_{\mu\nu}} \tag{12}$$

The Hessian (second derivative) gives geometry. The outer product of gradients (first derivative squared) gives matter. Both come from the same information kernel, simultaneously.

This is a *structural* co-emergence:

$$\begin{aligned} \text{GR:} &\quad \text{matter} \to \text{curvature} \\ \text{TFA:} &\quad \text{information} \to \text{matter} + \text{curvature (together)} \end{aligned}$$

We stress the correct interpretation:

- ✓ TFA provides a *mechanism* by which stress-energy structure can emerge from an information kernel.
- ✓ $T_{\mu\nu}$ is derived, not assumed. Perfect fluid form is a structural inevitability under isotropy.
- × TFA does not yet identify which particle species $T_{\mu\nu}$ corresponds to.
- × TFA does not explain the matter content of the actual universe.

9 Limitations

1. **Dimensional analysis: missing energy scale.** Both $g_{\mu\nu}$ (P4) and $T_{\mu\nu}$ (P5) are derived from the same Θ, with no independent energy scale separating them. In GR, $8\pi G$ provides the coupling between geometry (dimensionless or length^2) and energy density. In TFA, the scale parameter σ plays a partial role, but its connection to a physical energy scale (e.g., Planck scale, Bekenstein bound) is not established. A fundamental energy scale must be introduced to make $T_{\mu\nu}$ dimensionally consistent with physical energy density. This is a necessary step before TFA can make quantitative predictions about physical masses.

2. **Symmetry trap: is $G \approx \kappa T$ trivial?** The isotropic spatial distribution of $P(\xi|Z)$ forces $T_{\mu\nu}$ into perfect fluid form by symmetry. A reviewer may correctly ask: does $G_{\mu\nu} \approx \kappa T_{\mu\nu}$ follow from dynamics, or is it a trivial consequence of both sides being constrained by the same isotropy? We note that the correlation 0.798 is measured in Z-space (not ξ-space), and $G_{\mu\nu}$ is computed from the Riemann tensor of $g^{\text{eff}}_{\mu\nu}(Z)$, which involves derivatives in Z-space — a different object from the isotropy of $P(\xi|Z)$. Nevertheless, a definitive test requires an inhomogeneous case (non-uniform $Z(x)$, e.g., a localized mass distribution) where the symmetry argument does not apply. This test is identified as priority future work.

3. **Missing tensor $X_{\mu\nu}$: the 20% gap.** The correlation $\text{corr}(G, T) = 0.798$ implies that the true relation is:
$$G_{\mu\nu} = \kappa\, T_{\mu\nu} + X_{\mu\nu} \tag{13}$$
where $X_{\mu\nu}$ accounts for the remaining $\sim 20\%$. Candidate interpretations include: (a) higher-order curvature terms arising from the quartic ε coupling in Θ, which contribute to $G_{\mu\nu}$ but not to $T_{\mu\nu}$ at leading order; (b) vacuum energy or cosmological constant-like terms from the partition function $\mathcal{Z}$; (c) numerical discretization error from finite ξ sampling. Identifying $X_{\mu\nu}$ analytically is a key open problem.

4. **No equation of motion for $Z(x)$.** In Section 3, $Z(x)$ is promoted to a spacetime field, but no equation of motion governing $Z(x)$ is provided. In GR, the Einstein equation and geodesic equation are coupled: matter tells spacetime how to curve, and spacetime tells matter how to move. In TFA, $Z(x)$ currently acts as a kinematic background — a prescribed map, not a dynamical field. A complete theory requires deriving the equation of motion for $Z(x)$ from $\delta S_{\text{eff}}/\delta Z(x) = 0$, which was partially explored in Step 4e but not completed. Without this, TFA cannot describe the back-reaction of geometry on matter.

5. **Parameters not derived.** α_M, γ, ε, I_0 are effective parameters inserted by hand. Derivation from a deeper principle is future work.

6. **Uniqueness is empirical.** The projector form is selected by consistency, not by a formal uniqueness theorem.

7. **κ is not $8\pi G$.** $\kappa_{\text{eff}} = 1.12$ in our units. Connection to Newton's constant requires normalization not provided here.

8. **Linear $Z(x)$ only.** The Bianchi test uses linear $Z(x)$. Nonlinear $Z(x)$ (e.g., Schwarzschild-like) has not been tested.

9. **No quantum extension.** This is a classical framework.

10 Predictions and Differences from GR

Prediction 1: Singularity at $I \to I_0$. Near $I = I_0$, κ diverges. This predicts a breakdown of Einstein-like structure at very low inertia.

Prediction 2: κ depends on ε. $\kappa \sim 1/\varepsilon$ ($r = -0.97$). If ε is a physical parameter, κ is not universal.

Prediction 3: GR phase window. GR-like behavior requires $b_c \in [4.7, 12]$ [Juntaramalee, 2026]. Outside this window, the framework predicts non-GR geometry.

Prediction 4: Non-Markovian GRB delays. The P3 ensemble law: $\mathbb{E}[\Delta t | t_{90}]$ monotone increasing, Spearman $r = 0.679$, $p = 0.001$ [Juntaramalee, 2026]. This is a direct observational prediction absent in standard GR/LCDM.

11 Conclusion

The central result: co-emergence of geometry and matter. In General Relativity, matter and geometry are separate inputs. The Einstein equation couples them but does not explain their origin. In TFA, both emerge simultaneously from a single information kernel Θ:

$$\underbrace{\langle \partial_\mu \partial_\nu \Theta \rangle_P}_{\text{geometry } g_{\mu\nu}} \qquad \text{and} \qquad \underbrace{\langle (\partial_\mu \Theta)(\partial_\nu \Theta) \rangle_P}_{\text{matter } T_{\mu\nu}} \tag{14}$$

The Hessian gives geometry; the gradient product gives matter. This is a structural reversal of GR:

$$\text{GR:} \quad \text{matter} \to \text{curvature}$$
$$\text{TFA:} \quad \text{information} \to \text{matter} + \text{curvature (simultaneously)}$$

We have constructed a coherent, testable prototype in which:

1. Spacetime metric $g_{\mu\nu}$ emerges from $\langle \partial^2 \Theta \rangle_P$
2. Stress-energy $T_{\mu\nu}$ emerges from $\langle \partial\Theta\, \partial\Theta \rangle_P$ — derived, not assumed; perfect fluid form is structurally inevitable
3. Numerical evidence shows $G_{\mu\nu} \approx \kappa T_{\mu\nu}$ (corr $= 0.80$, $\kappa = 1.12$, stable across parameter range)
4. Bianchi identity $\nabla^\mu G_{\mu\nu} = 0$ holds exactly in spacetime
5. Threshold form is consistent with constrained maximum entropy

What this is: A constructive model demonstrating that Einstein-like gravitational dynamics can emerge from information geometry without GR being assumed. $T_{\mu\nu}$ is derived from Θ, not postulated. The mechanism by which stress-energy structure emerges from an information kernel is the primary contribution.

What this is not: A derivation of General Relativity, a proof of uniqueness, or a parameter-free theory. $T_{\mu\nu}$ has perfect fluid form but does not yet map to specific particle species. $\kappa_{\text{eff}} = 1.12 \neq 8\pi G$. $Z(x)$ is kinematic, not dynamical.

Future work:

- Derive $\kappa = 8\pi G$ from normalization (connect to Newton's constant)

- Identify $X_{\mu\nu}$: the missing 20% in $G_{\mu\nu} = \kappa T_{\mu\nu} + X_{\mu\nu}$
- Derive equation of motion for $Z(x)$ from $\delta S_{\text{eff}}/\delta Z = 0$
- Test inhomogeneous $Z(x)$ (localized mass, Schwarzschild limit)
- Map $T_{\mu\nu}$ to particle species (connect to quantum field theory)
- Test against cosmological observations (void fraction, GRB delays)

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A Key Numerical Results

Table 4: Summary of key numerical results.

Quantity	Value	Source
corr($G_{\mu\nu}, T_{\mu\nu}$)	0.798	Step 4g
κ_{eff}	1.12	Step 4g
Lorentzian signature	$(-,+,+,+)$	Step 4g
Area scaling α	2.010	Step 4c
Holonomy corr	0.975	Step 4c
$\lVert\nabla^\mu G_{\mu\nu}\rVert$ (x-space)	0.000	Step 6
$\lVert\nabla^\mu G_{\mu\nu}\rVert$ (Z-space)	7.68	Step 5
Improvement factor	1.5×10^6	Step 6
$T_{\mu\nu}$ perfect fluid	exact	Analytic
GR phase b_c window	$[4.7, 12]$	E13
P3 Spearman r	0.679	E13

B Simulation Code

All simulations are available in the supplementary code package:

- `sim_step4g_projector_metric.py` — Main result: $G \approx \kappa T$
- `sim_step4c_fisher_metric.py` — Holonomy + Riemann
- `sim_step6_regularized_covariant.py` — Bianchi identity
- `sim_step5_validation.py` — Stability + uniqueness
- `sim_step7_variational_principle.py` — Max entropy principle
- `TFA_TMUNU_ANALYTIC_PROOF.md` — $T_{\mu\nu}$ = perfect fluid (analytic)