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Causal-Symmetric Informational Gravitation as an Effective Stress-Energy Extension of General Relativity

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Abstract

A covariant effective model is formulated in which general relativity is extended through an informational contribution to the source sector while the geometric side of the Einstein equation remains unchanged. The additional source is described by an informational stress-energy tensor obtained from metric variation of an effective action. The construction is motivated by causal boundary alignment, defined as the effective degree of statistical constraint between preparation-side and outcome-side boundary structure. At the microscopic level, such alignment may be represented by a bounded operational quantum-information parameter. At the spacetime level, it is represented by an effective macroscopic closure variable rather than by direct identification with the microscopic parameter.

The informational sector is constructed from coarse-grained fields I^{A}, a positive-definite internal metric A_{AB}, a context-dependent reference state σ_Z, and a coarse-grained relative-entropy-type scalar $D_{cg}(\rho \parallel \sigma_Z)$. Since relative entropy is dimensionless, its contribution to gravitation requires an energy-density scale α and a dimensionless coupling χ. A minimal effective action is introduced with canonical kinetic terms and an informational potential $V_{info} = \alpha\chi D_{cg} + V_0(I)$. Variation with respect to the metric yields an informational stress-energy tensor that supplements the ordinary matter tensor in the Einstein equation.

The total stress-energy tensor is covariantly conserved whenever the total action is diffeomorphism invariant. The standard general-relativistic limit is recovered when informational coupling or informational deviation is negligible, or when the informational sector becomes a constant vacuum-like contribution. In homogeneous cosmology, the informational sector has the formal structure of a canonical scalar-type component. In the potential-dominated regime, it behaves as an effective vacuum-like source. The canonical kinetic sector satisfies the null energy condition for positive-definite A_{AB}. The resulting equations define an effective source-sector model in which coarse-grained informational deviation contributes to gravitational curvature through a variational stress-energy tensor.

Keywords: informational gravitation, causal symmetry, effective stress-energy, relative entropy, general relativity, cosmology, spacetime, boundary alignment, quantum information

1. Introduction

General relativity relates spacetime curvature to stress-energy through the Einstein field equation. In the standard formulation, the geometric side is determined by the metric, the Ricci tensor, the scalar curvature, and the cosmological term, while the source side contains ordinary matter and radiation [1,2]. Quantum-field-theoretic treatments on curved backgrounds show that the relation between local fields, states, and spacetime geometry is technically subtle, especially when quantum states and effective local quantities are discussed [3]. These considerations motivate source-sector extensions that are formulated cautiously at the effective level.

The present article formulates such an extension. The additional contribution is an informational stress-energy tensor associated with causal boundary alignment. In this article, causal boundary alignment denotes the effective degree of statistical constraint between preparation-side and outcome-side boundary structure. At the microscopic level, such alignment can be represented by operational quantum-information maps. At the spacetime level, the corresponding structure is represented by macroscopic closure variables that enter the source sector through an effective action.

In the minimal formulation, the geometric side of the Einstein equation is not modified. This distinguishes the present construction from modified-gravity models that alter the curvature sector [4]. The field equation is written as

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G\left(T_{\mu\nu}^{m} + \Theta_{\mu\nu}^{info}\right), \qquad (1)$$

where $T_{\mu\nu}^{m}$ denotes ordinary matter and radiation, and $\Theta_{\mu\nu}^{info}$ is an informational stress-energy tensor derived from an effective informational action.

The informational sector is based on a coarse-grained relative-entropy-type scalar $D_{cg}(\rho \parallel \sigma_Z)$. Here ρ denotes the effective state under consideration and σ_Z denotes a context-dependent reference state. The notation ρ (x), when used below, denotes a coarse-grained local or quasi-local state assignment in the macroscopic effective description. It is not assumed to be a fundamental pointwise density operator of a complete quantum field theory. The reference state σ_Z is not treated as a universal final state of nature. It is fixed by the adopted boundary structure, coarse-graining prescription, and observational context.

The connection with causal-symmetric quantum descriptions is operational rather than ontological. Time-symmetric and post-selection-based approaches show that preparation-side and outcome-side conditions can both enter the formal description of quantum processes [5,6]. In the present model, this idea is not used to introduce controllable retrocausal signaling. It is used only to motivate an effective alignment structure whose macroscopic imprint may enter the gravitational source sector. The bounded operational boundary-alignment parameter used in quantum-information settings is therefore distinguished from the spacetime-level closure variable used below [7].

Since relative entropy is dimensionless, an energy-density scale is required before such a quantity can contribute to a gravitational source term. The effective density scale is denoted by α, while a dimensionless coupling is denoted by χ. The leading informational contribution to the potential is then proportional to $\alpha\chi D_{cg}$. This construction is consistent with the use of information-theoretic quantities in thermodynamic and quantum-information settings [8,9], while the treatment of relative entropy at the effective gravitational level remains explicitly coarse-grained [10]. A related effective treatment of informational energy in a causal-symmetric spacetime setting has formulated an information-density contribution at the cosmological level [11].

Thermodynamic and informational approaches to gravitational dynamics provide a broader context for considering whether spacetime source structures may admit information-theoretic contributions [12-15]. The present construction is narrower: it does not derive the Einstein equation thermodynamically and does not modify the curvature side of the field equation. It defines an additional effective source sector by a variational principle.

The paper is organized as follows. Section 2 summarizes the notation. Section 3 defines causal boundary alignment and distinguishes the bounded operational parameter from spacetime-level closure variables. Section 4 introduces the informational variables and the relative-entropy contribution. Section 5 defines the minimal effective action. Section 6 derives the informational stress-energy tensor. Section 7 gives the field equations and conservation law. Section 8 states the general-relativistic limit. Section 9 gives the homogeneous cosmological reduction. Section 10 discusses scaling behavior. Section 11 states the null-energy-condition baseline. Section 12 summarizes consistency conditions and scope.

2. Notation

Table 1. Notation and Definitions

Symbol	**Meaning**
ρ	effective state of the system
$\rho(x)$	shorthand for a coarse-grained local or quasi-local state assignment
σ_Z	context-dependent reference state
κ	bounded operational boundary-alignment parameter
$\gamma(t)$	continuous-time relaxation rate
$\mathcal{K}(x)$	spacetime-level alignment closure variable
$\mathcal{K}(a)$	homogeneous cosmological alignment closure variable
$D_{cg}(\rho \parallel \sigma_Z)$	coarse-grained relative-entropy-type scalar
α	energy-density scale
χ	dimensionless informational coupling
I^A	coarse-grained informational fields
A_{AB}	positive-definite internal field-space metric
V_{info}	informational potential
$V_0(I)$	stabilizing or self-interaction potential
$\Theta_{\mu\nu}^{info}$	informational stress-energy tensor
$T_{\mu\nu}^{m}$	ordinary matter and radiation stress-energy tensor

Q	effective exchange term between matter and informational sectors

Throughout the paper, the metric signature (-+++) is used, and units are chosen such that c = $\hbar$ = 1, unless stated otherwise. Greek indices denote spacetime indices, while capital Latin indices label the internal informational field space.

3. Boundary Alignment and Spacetime-Level Closure

Let ρ be a density operator and let σ_Z be a valid reference density operator satisfying $\sigma_Z \geq 0$ and Tr(σ_Z) = 1. A minimal operational boundary-alignment map can be written as

$$\Lambda_\kappa(\rho) = (1-\kappa)\rho + \kappa\sigma_Z, \qquad 0 \leq \kappa \leq 1 \tag{2}$$

This map is completely positive and trace preserving, since it is a convex combination of the identity channel and a replacement channel. The parameter κ is dimensionless and bounded. It measures boundary alignment at the operational quantum-information level [7].

A continuous-time effective representation may be written as

$$\dot{\rho}(t) = -\gamma(t)(\rho(t) - \sigma_Z), \qquad \gamma(t) \geq 0 \tag{3}$$

where $\gamma(t)$ is a relaxation rate. The solution is

$$\rho(t) = e^{-\Gamma(t)}\rho(t_0) + (1 - e^{-\Gamma(t)})\,\sigma_Z, \qquad \Gamma(t) = \int_{t_0}^{t} \gamma(s)ds \tag{4}$$

For $\gamma(t) \geq 0$, the coefficient 1-$e^{-\Gamma(t)}$ lies in the interval [0,1]. Thus the continuous-time solution has the same convex interpolation structure as the operational alignment map.

The bounded operational parameter κ and the relaxation rate $\gamma(t)$ have different mathematical roles. In the spacetime-level effective model, the corresponding macroscopic alignment structure is denoted by $\mathcal{K}$(x), or, in a homogeneous cosmological setting, by $\mathcal{K}$(a).

The quantity $\mathcal{K}$ is not identified with the bounded microscopic parameter κ. It is a spacetime-level closure variable that parameterizes the macroscopic imprint of boundary alignment. The minimal model does not assign an independent equation of motion to $\mathcal{K}$(x). It enters only through closure relations such as

$$\chi(x) = \chi_0 F\big(\mathcal{K}(x)\big), \qquad D_{cg}(x) = D_0 G(\mathcal{K}(x)) \tag{5}$$

where F and G are model-dependent functions. If $\mathcal{K}(x)$ is promoted to a dynamical field, additional kinetic and potential terms must be added to S_{info}. That extension is not part of the minimal source-sector model.

No-signaling is imposed as a consistency condition. Boundary alignment may affect the effective statistical description or the source-sector structure, but it does not provide a controllable channel for signaling outside the causal structure of the effective metric.

4. Informational Variables and Relative-Entropy Contribution

The effective informational sector is described by the set

$$\Xi = \{I^A, \mathcal{K}, \alpha, \chi, D_{cg}, \sigma_Z\} \tag{6}$$

The fields I^A are coarse-grained informational fields, with A labeling an internal field space. The quantity $\mathcal{K}$ denotes the spacetime-level boundary-alignment closure variable. The function α carries dimensions of energy density, χ is dimensionless, and D_{cg} is a coarse-grained relative-entropy-type scalar.

The informational deviation from the reference state is represented by $D_{cg}(\rho \parallel \sigma_Z)$. The subscript indicates that the quantity is coarse-grained and effective. The present model does not require a unique microscopic definition of a local quantum relative-entropy density. The notation $D_{cg}(\rho(x) \parallel \sigma_Z(x))$ denotes a macroscopic scalar obtained after coarse-graining over a local or quasi-local region. It should not be read as a pointwise von Neumann relative-entropy density of a fundamental quantum field-theoretic state. This distinction is essential because relative entropy is naturally defined for states on algebras or finite regions, whereas the present gravitational source sector requires an effective scalar variable [3,10].

For the conservative baseline sector, the following conditions are assumed:

$$D_{cg}(\rho \parallel \sigma_Z) \geq 0, \qquad \alpha(x) \geq 0, \qquad \chi(x) \geq 0. \tag{7}$$

A leading informational energy-density contribution is then

$$\rho_{info}^{(0)}(x) = \alpha(x)\chi(x)D_{cg}(\rho(x) \parallel \sigma_Z(x)). \tag{8}$$

The superscript indicates that this is the leading potential contribution. In a field-theoretic model with kinetic terms, the full energy density also contains kinetic and gradient contributions from the informational fields I^A.

The role of α is dimensional. Since relative entropy is dimensionless, α converts the informational deviation into an energy-density contribution. The function χ controls the strength with which the informational deviation participates in the effective gravitational source sector.

5. Minimal Effective Informational Action

The total action is

$$S_{tot} = S_{grav}[g] + S_m[g, \Psi] + S_{info}[g, \Xi]. \tag{9}$$

where S_{grav} is the gravitational action, S_m is the action for ordinary matter and radiation fields Ψ, and S_{info} is the effective informational action.

The gravitational part is taken in the Einstein-Hilbert form,

$$S_{grav} = \frac{1}{16\pi G}\int d^4x\sqrt{-g}(R - 2\Lambda). \tag{10}$$

A minimal baseline informational action is chosen as

$$S_{info} = -\int d^4x\sqrt{-g}\left[\frac{1}{2}A_{AB}g^{\mu\nu}\nabla_\mu I^A\nabla_\nu I^B + V_{info}\right]. \tag{11}$$

Here $\mathrm{A_{AB}}$ is a positive-definite internal field-space metric, meaning $\mathrm{A_{AB}}\nu^A\nu^B > 0$ for any nonzero internal vector ν^A. The informational potential is written as

$$V_{info} = \alpha(x)\chi(x)D_{cg}\big(\rho(x) \parallel \sigma_Z(x)\big) + V_0(I). \tag{12}$$

All quantities entering V_{info} are treated as scalar effective variables under diffeomorphisms. In particular, α and χ are scalar closure functions of the effective variables, not fixed coordinate-dependent background functions. This assumption is required for the minimal action to remain compatible with covariant conservation of the total stress-energy tensor.

The term $V_0(I)$ collects stabilizing or self-interaction contributions for the informational fields. The term $\alpha\chi D_{cg}$ is the leading relative-entropy contribution to the effective potential.

In the minimal metric variation, D_{cg} is treated as an effective scalar variable after coarse-graining. Its microscopic dependence on ρ, σ_Z, and the adopted coarse-graining prescription is not varied independently unless a more detailed model specifies that dependence. If D_{cg}, ρ, σ_Z, α, or χ contain additional explicit metric dependence, their variations produce additional model-dependent terms in the informational stress-energy tensor.

The action above is a minimal conservative baseline. More general effective models may include non-minimal curvature couplings, higher-derivative operators, non-canonical internal metrics, dynamical equations for $\mathcal{K}(x)$, or additional informational degrees of freedom. Those extensions are not required for the source-sector construction developed here.

6. Informational Stress-Energy Tensor

The matter stress-energy tensor is defined by

$$T^m_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S_m}{\delta g^{\mu\nu}}. \tag{13}$$

The informational stress-energy tensor is defined analogously by

$$\Theta^{info}_{\mu\nu} = -\frac{2}{\sqrt{-g}}\frac{\delta S_{info}}{\delta g^{\mu\nu}}. \tag{14}$$

For the minimal action of Section 5, and neglecting additional explicit metric dependence of D_{cg}, ρ, σ_Z, α, and χ, the leading-order informational stress-energy tensor is

$$\Theta_{\mu\nu}^{info} = A_{AB}\nabla_\mu I^A\nabla_\nu I^B - g_{\mu\nu}\left[\frac{1}{2}A_{AB}g^{\alpha\beta}\nabla_\alpha I^A\nabla_\beta I^B + V_{info}\right]. \tag{15}$$

If the omitted metric dependence is specified, the full stress-energy tensor becomes

$$\Theta_{\mu\nu}^{info,full} = \Theta_{\mu\nu}^{info} + \Delta_{\mu\nu}^{cg}\,, \tag{16}$$

where $\Delta_{\mu\nu}^{cg}$ denotes the additional metric-variation contribution from the coarse-graining structure and state dependence. The minimal model sets $\Delta_{\mu\nu}^{cg} = 0$.
The total stress-energy tensor is

$$\mathrm{T}_{\mu\nu}^{tot} = \mathrm{T}_{\mu\nu}^{m} + \Theta_{\mu\nu}^{info}. \tag{17}$$

Thus the informational sector enters the gravitational field equations as an ordinary variational source term.

7. Field Equations and Conservation Law

Variation of the total action with respect to the metric yields the field equation already stated in Eq. (1). The geometric side has the standard Einstein form. The extension is entirely in the effective source sector. If the total action is diffeomorphism invariant, the contracted Bianchi identity implies

$$\nabla^\mu(\mathrm{T}_{\mu\nu}^{m} + \Theta_{\mu\nu}^{info}) = 0. \tag{18}$$

Equivalently,

$$\nabla^\mu\mathrm{T}_{\mu\nu}^{m} = -\nabla^\mu\Theta_{\mu\nu}^{info}. \tag{19}$$

This equation allows exchange between ordinary matter and the informational sector while preserving the local conservation of total stress-energy. In regimes where the informational sector varies slowly or couples weakly to ordinary matter, the exchange term may be negligible and the ordinary matter sector is separately conserved to leading order.

The field equations for the informational fields follow from variation with respect to I^A. In the minimal model with constant A_{AB}, one obtains

$$\mathrm{A}_{\mathrm{AB}}\nabla_\mu\nabla^\mu I^B - \frac{\partial V_{info}}{\partial I^A} = 0. \tag{20}$$

If A_{AB} depends on the fields, the corresponding field-space connection terms must be added. If D_{cg}, α, or χ depend on I^A, their derivatives contribute to $\partial V_{info}/\partial I^A$.

8. General-Relativistic Limit

The standard general-relativistic limit is recovered under several conditions. If the informational coupling vanishes, $\chi(x) \to 0$, then the leading relative-entropy contribution decouples from the source sector. If the actual state is effectively aligned with the reference state, $D_{cg}(\rho \parallel \sigma_Z) \to 0$, then the leading informational density contribution vanishes.

If the kinetic and gradient terms of the informational fields are negligible and the informational stress-energy tensor becomes vacuum-like,

$$\Theta_{\mu\nu}^{info} = -\rho_{\Lambda,info} g_{\mu\nu}, \tag{21}$$

with approximately constant $\rho_{\Lambda,info}$, then the field equation reduces to

$$G_{\mu\nu} + \mathit{\Lambda}_{eff} g_{\mu\nu} = 8\pi G T_{\mu\nu}^{m}, \qquad \mathit{\Lambda}_{eff} = \mathit{\Lambda} + 8\pi G \rho_{\mathit{\Lambda},info}. \tag{22}$$

Thus the model reduces to ordinary general relativity with an effective cosmological term. Deviations from GR require non-negligible informational coupling, nonzero informational deviation, gradients or dynamics of I^A, or nontrivial cosmological scaling.

9. Homogeneous Cosmology

For a Friedmann-Robertson-Walker background,

$$ds^2 = -dt^2 + a(t)^2 \left[\frac{dr^2}{1-kr^2} + r^2 d\Omega^2\right], \tag{23}$$

and homogeneous informational fields $\mathrm{I}^{\mathrm{A}} = \mathrm{I}^{\mathrm{A}}(t)$, the informational energy density and pressure are

$$\rho_{info} = \frac{1}{2} A_{AB} \dot{I}^A \dot{I}^B + V_{info}, \tag{24}$$

$$p_{info} = \frac{1}{2} A_{AB} \dot{I}^A \dot{I}^B - V_{info}. \tag{25}$$

The equation-of-state parameter is therefore

$$w_{info} = \frac{\frac{1}{2} A_{AB} \dot{I}^A \dot{I}^B - V_{info}}{\frac{1}{2} A_{AB} \dot{I}^A \dot{I}^B + V_{info}}. \tag{26}$$

The cosmological reduction has the same formal structure as a canonical scalar-field dark-energy sector, but with an informationally specified potential. Consequently, the potential-dominated regime,

$$\frac{1}{2} A_{AB} \dot{I}^A \dot{I}^B \ll V_{info}, \tag{27}$$

gives

$$\rho_{info} \simeq V_{info}, \qquad p_{info} \simeq -V_{info}, \qquad w_{info} \simeq -1. \tag{28}$$

If $V_0(I)$ is negligible or approximately constant relative to the leading informational contribution, then

$$\rho_{info} \simeq \alpha(a)\chi(a)D_{cg}\big(\rho(a) \parallel \sigma_Z(a)\big). \tag{29}$$

This analogy is formal and does not by itself solve the cosmological constant problem [16-20]. Kinetic contributions shift the equation of state away from the vacuum-like regime.
The total energy density is

$$\rho_{tot} = \rho_m + \rho_r + \rho_{info}, \tag{30}$$

where ρ_m is matter density and ρ_r is radiation density. The first Friedmann equation becomes

$$H^2 = \frac{8\pi G}{3}(\rho_m + \rho_r + \rho_{info}) - \frac{k}{a^2} + \frac{\Lambda}{3}. \tag{31}$$

The combined continuity equation is

$$\dot{\rho}_{tot} + 3H(\rho_{tot} + p_{tot}) = 0. \tag{32}$$

If the matter and informational sectors exchange energy, this may be decomposed as

$$\dot{\rho}_m + 3H(\rho_m + p_m) = Q, \tag{33}$$

$$\dot{\rho}_{info} + 3H\big(\rho_{info} + p_{info}\big) = -Q, \tag{34}$$

where Q is the effective exchange term. For $Q = 0$, the two sectors are separately conserved.
The spacetime-level alignment structure may be represented by a scale-dependent closure variable $\mathcal{K}(a)$.
Closure relations such as

$$\chi(a) = \chi_0 F(\mathcal{K}(a)), D_{cg}(a) = D_o G(\mathcal{K}(a)) \tag{35}$$

specify how boundary alignment enters the effective cosmological source sector. The functions F and G must be specified before observational constraints can be computed.

10. Scaling Law and Effective Equation of State

For phenomenological cosmology, the informational density may be parametrized by

$$\rho_{info}(a) = \rho_{info,o} a^{-n}. \tag{36}$$

This is not a fundamental requirement of the model. It is a useful phenomenological scaling form for connecting the effective source sector to cosmological observables.
If the informational sector is separately conserved, $Q = 0$, then

$$\dot{\rho}_{info} + 3H\left(\rho_{info} + p_{info}\right) = 0. \tag{37}$$

Using $p_{info} = w_{info}\rho_{info}$, one obtains

$$\dot{\rho}_{info} + 3H\left(1 + w_{info}\right)\rho_{info} = 0. \tag{38}$$

For Eq. (36), the time derivative is

$$\dot{\rho}_{info} = -nH\rho_{info}. \tag{39}$$

Substitution into Eq. (38) gives, for $H\rho_{info} \neq 0$,

$$w_{info} = -1 + \frac{n}{3}. \tag{40}$$

Thus *n* = *0* gives vacuum-like behavior, *n* = *3* gives dust-like scaling, and *n* = *4* gives radiation-like scaling. If $Q \neq 0$, the relation is modified by the exchange term and cannot be inferred from the scaling law alone without specifying Q.

Without specifying α(a), χ(a), D_{cg}(a), and Q, the cosmological sector defines a class of effective models rather than a unique predictive cosmology. The scaling law is therefore a phenomenological reduction, not a final cosmological fit. This restriction is deliberate: the aim of the present article is to establish the covariant stress-energy structure of the informational sector before imposing model-specific closure functions. Standard scalar-field and dark-energy analyses provide the broader context for this type of effective cosmological reduction [16-20].

11. Null Energy Condition in the Minimal Sector

Proposition. For the minimal canonical informational sector with positive-definite A_{AB}, the null energy condition is satisfied.

The null energy condition requires $\Theta^{info}_{\mu\nu} n^\mu n^\nu \geq 0$ for every null vector n^μ satisfying $g_{\mu\nu}n^\mu n^\nu = 0$. For the minimal informational stress-energy tensor in Eq. (15), contraction with $n^\mu n^\nu$ yields

$$\Theta^{info}_{\mu\nu} n^\mu n^\nu = A_{AB}(n^\mu \nabla_\mu I^A)(n^\nu \nabla_\nu I^B), \tag{41}$$

because the potential term is proportional to $g_{\mu\nu}n^\mu n^\nu$, which vanishes for a null vector. Since A_{AB} is positive definite,

$$A_{AB}(n^\mu \nabla_\mu I^A)(n^\nu \nabla_\nu I^B) \geq 0. \tag{42}$$

Thus the canonical kinetic sector satisfies the null energy condition in the minimal model. This statement applies only to the canonical kinetic part of the minimal sector. The effective vacuum-like pressure in the potential-dominated regime arises from the potential contribution and does not imply null-energy-condition violation. Any violation of the null energy condition would require additional non-minimal couplings, non-canonical kinetic structure, higher-derivative terms, or other extensions beyond the conservative baseline considered here.

12. Consistency Conditions and Scope

The model is subject to several consistency conditions. The microscopic boundary-alignment map must remain completely positive and trace preserving. The reference state σ_Z must be a valid density operator in the operational setting and must remain context-dependent.

The spacetime-level alignment variable $\mathcal{K}$(x) is an effective closure variable. It is not directly identified with the bounded operational parameter κ. The minimal model does not assign an independent equation of motion to $\mathcal{K}$(x).

The total action must be diffeomorphism invariant in order for the total stress-energy tensor to be covariantly conserved. Therefore, all effective quantities entering V_{info}, including D_{cg}, α, χ, and σ_Z, are treated as scalar objects or scalar closure functions in the minimal covariant description. The relative-entropy-type scalar D_{cg} is dimensionless, and its contribution to the source sector requires an energy-density scale α.

No-signaling is imposed. Boundary alignment does not provide a controllable communication channel outside the causal structure of the effective metric.

The standard general-relativistic limit must be recovered when informational coupling or informational deviation is negligible, or when the informational stress-energy tensor reduces to a constant vacuum-like term.

The minimal model does not require exotic matter. The canonical kinetic sector satisfies the null energy condition for positive-definite A_{AB}.

The effective action does not specify a complete microscopic origin of σ_Z, D_{cg}, α, χ, or $\mathcal{K}$. These quantities must be specified by a more detailed microscopic model or by phenomenological closure relations before unique empirical predictions can be derived.

13. Discussion

The model defines a source-sector extension of general relativity in which the additional contribution is obtained from a variational informational action. The geometric side of the Einstein equation is unchanged, and the informational sector enters only through $\Theta_{\mu\nu}^{info}$. This distinguishes the construction from modified-gravity models that alter the curvature side of the field equations.

The minimal sector has the structure of a canonical multi-scalar effective field model with an informational potential. Its distinguishing feature is the composition of the potential, where the leading term is proportional to a coarse-grained relative-entropy-type scalar. The use of D_{cg} is deliberately macroscopic: no unique microscopic local entropy density is assumed.

In cosmology, the model defines a class of effective source sectors rather than a unique predictive cosmology. A specific phenomenological or microscopic closure must determine α(a), χ(a), D_{cg} (a), $\mathcal{K}$ (a), and any exchange term Q. Once these functions are specified, the model can be confronted with standard cosmological constraints. The present formulation therefore provides the covariant source-sector structure; it does not by itself claim a completed cosmological parameter fit.

14. Conclusion

A covariant effective model of causal-symmetric informational gravitation has been formulated as a source-sector extension of general relativity. The additional contribution is an informational stress-energy tensor derived from an effective action containing canonical informational fields and a relative-entropy-type potential.

The leading informational potential is $V_{info} = \alpha\chi D_{cg}(\rho \parallel \sigma_Z) + V_o(I)$ where D_{cg} is dimensionless, α supplies the energy-density scale, and χ controls the coupling strength. Metric variation yields the effective field equation (1). Diffeomorphism invariance implies local conservation of total stress-energy. The standard general-relativistic limit is recovered when the informational sector decouples, when informational deviation vanishes, or when the informational stress-energy tensor becomes a constant vacuum-like contribution.

In homogeneous cosmology, the informational density enters the Friedmann equation as an additional effective component. In the potential-dominated limit, it behaves as a vacuum-like sector. For a separately conserved power-law scaling, $\rho_{info} \propto a^{-n}$, the effective equation-of-state parameter is $w_{info} = -1 + n/3$. The canonical kinetic sector satisfies the null energy condition for positive-definite internal metric A_{AB}.

The resulting equations define a covariant effective source-sector model in which coarse-grained informational deviation contributes to gravitational curvature through a variational stress-energy tensor, while the geometric structure and low-energy limit of general relativity are preserved.

Conflict of Interest

The author declares no conflict of interest.

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