International
Journal of Nano Research

ISSN: 2581-6608
Volume 9: 1
Int J Nano Rech 2026

Informational Energy in a Causal–Symmetric Framework for Spacetime

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Abstract

In causal–symmetric approaches to quantum theory and space-time, the dynamical content of the universe may be modeled in terms of boundary conditions at both temporal ends together with an informational medium that couples these boundary constraints to interior degrees of freedom. In this article, the notion of energy is analyzed within such a causal–symmetric informational setting. A geometric definition of total energy is combined with an informational contribution built from a coarse-grained relative-entropy functional between the actual state ρ and an effective reference state σ_Z associated with the adopted boundary structure. At the level of homogeneous cosmology, we adopt the leading-order effective ansatz.

$$\rho_{\text{info}}(a) \approx \alpha(a)\chi(a)D_{\text{cg}}\big(\rho(a)\ \backslash\sigma_Z\big),$$

Where, $\chi(a)$ is a dimensionless effective coupling function, $\alpha(a)$ is a scale-setting factor with the dimensions of energy density, and D_{cg} denotes a coarse-grained effective relative-entropy functional. This density enters the Friedmann equation alongside matter and radiation and provides a concrete information-theoretic candidate for a dark-energy-like sector. The local geometric definition of energy remains unchanged, and the informational sector contributes an additional, well-defined component to the total energy budget. If one further admits an effective invariant speed c_{eff} at the level of the model, the standard mass–energy relation retains its algebraic form, with the informational sector contributing an effective mass density $\rho_{\text{info}} / c_{eff}^2$. The construction is formulated so as to remain compatible with local energy conservation and with thermodynamic interpretations of gravity, while avoiding the

introduction of an ad hoc dark-energy term.

Keywords: Causal symmetry, Informational energy, Space-time, Relative entropy, Dark energy, Cosmology, Quantum information, Thermodynamic gravity.

Abbreviations: GR: General Relativity; QFT: Quantum Field Theory; GKSL: Gorini–Kossakowski–Sudarshan–Lindblad; CPTP: Completely Positive Trace-Preserving; FRW: Friedmann–Robertson–Walker.

Introduction

Standard general relativity (GR) treats energy–momentum as the source of spacetime curvature via the Einstein equation

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}, \tag{1}$$

where $T_{\mu\nu}$ is the stress–energy tensor of matter and radiation, and Λ is a cosmological constant. In this setting, the notion of energy is defined geometrically, and local energy–momentum conservation is encoded in $\nabla_\mu T^{\mu\nu} = 0$. Yet the physical status of dark energy remains unclear: the cosmological constant is usually inserted as an additional parameter,

Article Information

Article Type: Research article
Article Number: IJNR131
Received Date: 09 April, 2026
Accepted Date: 14 May, 2026
Published Date: 21 May, 2026

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Citation: Rubenstein E (2026) Informational Energy in a Causal–Symmetric Framework for Spacetime. Int J Nano Rech Vol: 9, Issu: 1 (01-05).

whereas its microscopic or informational interpretation remains open.

A broad literature has explored time symmetry in quantum theory, informational and thermodynamic treatments of physical systems, relative entropy as a structural measure, and equation-of-state perspectives on gravity [1-8]. Motivated by these lines of thought, the present article studies an effective causal–symmetric model in which the energy budget of spacetime includes not only matter and radiation, but also an informational contribution associated with the deviation of an actual state ρ from an effective reference state σ_Z.

The aim is intentionally limited. This article does not claim that the relative-entropy contribution derived below is already established as a fundamental sector of nature. Rather, it asks whether a causal–symmetric effective description can be formulated in a mathematically transparent way such that:

- the geometric definition of energy as a projection of the total stress–energy tensor remains unchanged;
- an additional informational energy density can be written in terms of a relative-entropy contribution;
- in homogeneous cosmology, this informational term can behave as a dark-energy-like component;
- the construction remains compatible with local conservation of total energy–momentum;

and, if an effective invariant speed c_{eff} is admitted within the model, the usual algebraic form of the mass–energy relation is preserved.

The article is organized as follows. Section 5 introduces the causal–symmetric informational framework at the effective level. Section 6 recalls the geometric definition of total energy and the decomposition into matter and informational sectors. Section 7 constructs an informational energy density using relative entropy and an effective coupling structure. Section 8 discusses the relation to standard energy notions and the optional introduction of an effective invariant speed. Section 9comments on locality and validity conditions. Section 10 summarizes the conceptual picture.

Throughout, units with $c=\hbar=1$ are adopted unless otherwise noted, and the metric signature is $(-,+,+,+)$. Greek indices $\mu,\nu,\ldots$ denote spacetime indices, and repeated indices are summed over.

Causal–Symmetric Informational Framework

The effective description considered here assumes that the physically relevant macroscopic history may be constrained by boundary conditions at both temporal ends. Between these boundaries, the dynamical degrees of freedom are described by a state ρ on an appropriate Hilbert space or algebra of observables, together with classical fields including the spacetime metric $g_{\mu\nu}$ and informational variables.

In this picture, the informational sector is characterized by:

a coarse-grained informational current or configuration $I^a(x)$, representing how boundary constraints are communicated into the interior;

a dimensionless effective coupling function $\chi(x)$, which measures the strength with which the informational structure contributes at the macroscopic level;

a scale-setting factor $\alpha(x)$, with dimensions of energy density, which converts the relative-entropy contribution into an effective energetic quantity;

an effective reference state σ_Z, understood here as a context-dependent reference density operator associated with the adopted two-boundary description;

an underlying relative-entropy structure based on $D(\rho \setminus \sigma_Z)$, whose coarse-grained cosmological counterpart is denoted by $D_{\text{cg}}(\rho(a) \setminus \sigma_Z)$.

It is important to keep the role of σ_Z modest. In the present manuscript, σ_Z is not introduced as a universal microscopic final state of nature. Rather, it is an effective reference state used to parameterize the informational sector within the specific model under consideration. Its precise form may depend on the adopted boundary structure, coarse-graining procedure, and measurement context.

At the formal level, the present effective framework is intended to remain compatible with standard completely positive trace-preserving (CPTP) evolution at the microscopic level, and with Gorini–Kossakowski–Sudarshan–Lindblad (GKSL) type descriptions whenever a local open-system reduction is considered.

The dynamics of the informational sector and its coupling to geometry are encoded at the effective level in a total action of the form

$$S_{\text{tot}} = S_{\text{grav}}[g] + S_{\text{matter}}[g,\Psi] + S_{\text{info}}[g, I, \chi, \alpha, \rho, \sigma_Z], \qquad (2)$$

where S_{grav} is the gravitational action, $_{\text{matter}}$ is the action for standard matter and radiation fields Ψ, and S_{info} is an effective informational action.

Variation of S_{tot} with respect to the metric yields an effective Einstein equation of the form

$$G_{\mu\nu} = 8\pi G\left(T_{\mu\nu}^{\text{matter}} + \Theta_{\mu\nu}^{\text{info}}[\Xi]\right), \qquad (3)$$

where, Ξ collectively denotes the informational variables, and $\Theta_{\mu\nu}^{\text{info}}$ is the informational contribution to the stress–energy tensor. The matter stress–energy tensor is obtained from S_{matter} in the usual way, while the informational contribution is defined by

$$\Theta_{\mu\nu}^{\text{info}} = -\frac{2}{\sqrt{-g}}\frac{\delta S_{\text{info}}}{\delta g^{\mu\nu}}. \qquad (4)$$

The total stress–energy tensor is therefore

$$T_{\mu\nu}^{\text{tot}} = T_{\mu\nu}^{\text{matter}} + \Theta_{\mu\nu}^{\text{info}}. \qquad (5)$$

Provided that the effective total action is diffeomorphism invariant, the contracted Bianchi identity implies

$$\nabla_\mu T^{\mu\nu}_{\text{tot}} = 0. \quad (6)$$

This expresses local conservation of total energy–momentum, while still allowing exchange between matter and informational sectors:

$$\nabla_\mu T^{\mu\nu}_{\text{matter}} = -\nabla_\mu \Theta^{\mu\nu}_{\text{info}}. \quad (7)$$

In ordinary local regimes, the informational variables are assumed to vary slowly enough that the exchange term is negligible and standard matter conservation is recovered to high accuracy.

Geometric Definition of Total and Informational Energy

In any spacetime with metric $g_{\mu\nu}$ and stress–energy tensor $T^{\text{tot}}_{\mu\nu}$, the energy density measured by an observer with four-velocity u^μ is given by

$$E_{\text{tot}}(x,u) = u^\mu u^\nu T^{\text{tot}}_{\mu\nu}(x). \quad (8)$$

This definition is geometric and does not depend on a specific microphysical interpretation of the underlying sectors.

Using the decomposition

$$T^{\text{tot}}_{\mu\nu} = T^{\text{matter}}_{\mu\nu} + \Theta^{\text{info}}_{\mu\nu},$$

one may define

$$E_{\text{matter}}(x,u) = u^\mu u^\nu T^{\text{matter}}_{\mu\nu}(x), \quad (9)$$

$$E_{\text{info}}(x,u) = u^\mu u^\nu \Theta^{\text{info}}_{\mu\nu}(x), \quad (10)$$

so that

$$E_{\text{tot}}(x,u) = E_{\text{matter}}(x,u) + E_{\text{info}}(x,u). \quad (11)$$

In a homogeneous and isotropic cosmology, evaluated in the rest frame of a comoving observer, E_{tot} reduces to the total energy density entering the Friedmann equations. The central question is therefore how to model E_{info} in terms of the informational variables and the underlying relative-entropy structure associated with $D(\rho \ \backslash \sigma_Z)$, together with its coarse-grained cosmological counterpart $D_{\text{cg}}(\rho(a) \ \backslash \sigma_Z)$.

Informational Energy and Relative Entropy

In statistical mechanics and information theory, relative entropy provides a natural measure of informational distinguishability between two states. For density operators ρ and σ_Z on a common Hilbert space, the quantum relative entropy is

$$D(\rho \ \backslash \sigma_Z) = \mathrm{Tr}(\rho \log \rho) - \mathrm{Tr}(\rho \log \sigma_Z), \quad (12)$$

provided the support of ρ is contained in the support of σ_Z [4,8]. It is non-negative and vanishes if and only if $\rho = \sigma_Z$.

In the present effective framework, σ_Z is not interpreted as a unique microscopic final condition of the universe. It is instead a model-dependent reference state associated with the adopted boundary structure. The quantity $D(\rho \ \backslash \sigma_Z)$ therefore measures the informational deviation of the actual state from that effective reference configuration.

In the cosmological discussion, the quantity entering the effective energy density is not the exact microscopic von Neumann relative entropy of a local quantum-field state, but a coarse-grained functional

$$D_{\text{cg}}\left(\rho(a) \ \backslash \sigma_Z\right), \quad (13)$$

associated with the homogeneous state at scale factor a. Formally, one may regard D_{cg} as the output of a coarse-graining map from microscopic states to homogeneous effective states, followed by evaluation against the corresponding effective reference state. The detailed construction of this map is left open in the present paper; only its effective output is used at the macroscopic level.

Motivated by standard informational free-energy ideas [3,7], we represent the informational contribution by a lowest-order effective expansion in a coarse-grained informational scalar. At leading order, we retain only the term linear in the effective relative-entropy functional and write

$$\rho_{\text{info}}(a) \approx \alpha(a)\chi(a) D_{\text{cg}}\left(\rho(a) \ \backslash \sigma_Z\right), \quad (14)$$

where $\chi(a)$ is dimensionless, $\alpha(a)$ supplies the required energy-density scale, and $D_{\text{cg}}(\rho(a) \ \backslash \sigma_Z)$ is the coarse-grained relative-entropy functional introduced above. Higher-order contributions, including nonlinear functions of D_{cg}, gradient corrections, and direct invariants built from I^a, are neglected in the present leading-order truncation.

In the homogeneous FRW sector, we assume that the informational contribution can be represented effectively as a perfect-fluid component with energy density $\rho_{\text{info}}(a)$ and pressure $p_{\text{info}}(a)$.

The total energy density then takes the form

$$\rho_{\text{tot}}(a) = \rho_{\text{matter}}(a) + \rho_{\text{info}}(a), \quad (15)$$

and the Friedmann equation becomes

$$H^2(a) = \frac{8\pi G}{3}\left(\rho_{\text{matter}}(a) + \rho_{\text{info}}(a)\right) - \frac{k}{a^2}, \quad (16)$$

where $H(a)$ is the Hubble parameter and k is the spatial curvature parameter.

At this level of description, the informational equation-of-state parameter is defined by

$$w_{\text{info}}(a) = \frac{p_{\text{info}}(a)}{\rho_{\text{info}}(a)},$$

where $p_{\text{info}}(a)$ is the effective pressure associated with the informational sector in the homogeneous FRW reduction. In the present paper, no microscopic derivation of p_{info} is attempted. Instead, we restrict attention to the vacuum-dominated effective regime in which gradient terms, explicit time-derivative corrections, and anisotropic stresses are subleading. Under that additional assumption, the informational sector is modeled as approximately vacuum-like, so that

$$w_{\text{info}} \approx -1.$$

Away from that regime, $w_{\text{info}}(a)$ should be treated as model-dependent.

This does not establish a fundamental dark-energy theory, but it provides a conceptually explicit effective parameterization of a dark-energy-like component.

Relation to Standard Energy Notions and an Effective Invariant Speed

Mass–energy relation in the informational framework

The present framework does not alter the local algebraic form of the mass–energy relation. It instead enriches the composition of the total energy density by including an informational sector.

When discussing the effective mass–energy relation, we temporarily restore a model-dependent local invariant speed c_{eff} for dimensional clarity. No derivation of c_{eff} is given in the present paper. Rather, the following discussion is conditional: if the effective background informational structure is such that local observers may consistently parameterize their kinematics in terms of a local invariant speed c_{eff}, then one may write

$$E = mc_{\text{eff}}^2, \quad E = \hbar\omega. \tag{17}$$

This use of c_{eff} is therefore purely model-internal in the present article and should not be read as an independent empirical claim.

For a finite comoving volume V, the total energy is

$$E_{\text{tot}}(a) = \left(\rho_{\text{matter}}(a) + \rho_{\text{info}}(a)\right)V. \tag{18}$$

One may then define effective masses associated with matter and informational components:

$$m_{\text{matter}}(a) = \frac{\rho_{\text{matter}}(a)V}{c_{\text{eff}}^2}, \quad m_{\text{info}}(a) = \frac{\rho_{\text{info}}(a)V}{c_{\text{eff}}^2}. \tag{19}$$

Thus

$$E_{\text{tot}}(a) = m_{\text{matter}}(a)c_{\text{eff}}^2 + m_{\text{info}}(a)c_{\text{eff}}^2 = m_{\text{tot}}(a)c_{\text{eff}}^2, \tag{20}$$

with

$$m_{\text{tot}}(a) = m_{\text{matter}}(a) + m_{\text{info}}(a). \tag{21}$$

Therefore,

$$E_{\text{tot}} = m_{\text{tot}}c_{\text{eff}}^2. \tag{22}$$

The informational sector then contributes an effective mass density $\rho_{\text{info}} / c_{\text{eff}}^2$. In the limit $\rho_{\text{info}} \ll \rho_{\text{matter}}$, the standard relation is recovered to high accuracy. If ρ_{info} becomes cosmologically relevant, it modifies the total energy budget without changing the formal structure of the mass–energy relation.

Connection to classical GR and field theory

From the viewpoint of classical GR and QFT, the present construction can be read as an effective extension of the total stress–energy tensor. Standard matter fields are treated conventionally, while the informational sector contributes an additional source term.

In weak-field and small-scale regimes, where the informational variables vary slowly, the informational sector contributes only a nearly homogeneous background and ordinary GR is recovered to excellent approximation. In stronger-field or cosmological regimes, the informational contribution may become non-negligible and can modify the effective energy budget. The geometric definition of energy, however, remains unchanged.

Local Construction and Conditions of Validity

The expression for ρ_{info} has been written in a homogeneous and isotropic setting, using a hydrodynamic coarse-graining in which informational variables are defined over macroscopic regions. A more microscopic description would require local operator algebras, a refined treatment of the reference state σ_Z, and a local version of the informational action.

The hydrodynamic approximation is assumed valid when there is a separation of scales between a microscopic correlation length ξ, a coarse-graining scale ℓ_c, and a macroscopic curvature scale $L_{\text{curv}}(x)$ such that

$$\xi \ll \ell_c \ll L_{\text{curv}}(x). \tag{23}$$

In that regime, each coarse-graining cell may be treated as approximately homogeneous, and the informational energy density may be represented by a scalar field $\rho_{\text{info}}(x)$ built from the coarse-grained functional $D_{\text{cg}}(\rho \; \backslash\sigma_Z)$ together with the effective functions χ and α.

This construction is intended only as a leading-order effective description. It does not yet specify a unique microscopic completion of the informational sector. Its role is to provide a mathematically explicit pathway for discussing how relative entropy could enter the macroscopic energy budget and curvature in a causal–symmetric setting.

Conceptual Picture and Conclusion

Within the causal–symmetric effective framework developed here, the universe is described not only by matter fields and spacetime geometry, but also by an informational sector associated with the deviation of an actual state from a context-dependent reference state. The key point is not to redefine energy geometrically, but to allow the total stress–energy tensor to contain an additional informational contribution.

At the level of homogeneous cosmology, this leads to the effective informational energy density

$$\rho_{\text{info}}(a) \approx \alpha(a)\chi(a)D_{\text{cg}}\left(\rho(a) \; \backslash\sigma_Z\right), \tag{24}$$

which enters the Friedmann equation alongside matter and radiation. In the simplest approximation, this term can behave like a dark-energy-like sector.

The framework remains compatible with local conservation of total energy–momentum, subject to the diffeomorphism-invariance assumption stated above. If one additionally admits an effective invariant speed c_{eff} within the model, the mass–energy relation retains its usual algebraic form, with the informational sector contributing an effective mass density $\rho_{\mathrm{info}} / c_{\mathrm{eff}}^2$.

Taken together, these results suggest that a causal–symmetric informational description of spacetime can be formulated in a way that is mathematically transparent and conceptually compatible with standard energy notions, while opening a route toward an informationally structured dark-energy-like contribution. The framework should be read as an effective proposal, not as a completed microscopic theory.

Funding

No funds, grants, or other financial support were received for conducting this study.

Competing Interests

The author declares no conflict of interest.

Author Contributions

The author conceived the study, developed the causal-symmetry operational framework, carried out the analytical derivations, and wrote and revised the manuscript.

Data Availability

Data sharing does not apply to this article as no datasets were generated or analyzed during the current study. All derivations and results are contained in this manuscript.

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