GRAVITY AND THE CAUSAL STRUCTURE OF SPACETIME IN ODTOE

(Гравитация и причинная структура пространства-времени в ODTOE)

SYNC accessibility, the actualization cone, and the effective metric as projections of configuration dynamics

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ABSTRACT

This paper formalizes the ODTOE (Observer-Dependent Theory of Everything) answer to the question of how gravity affects the causal structure of spacetime. In general relativity, gravity changes the metric, and the metric determines light cones and the causal reachability relation between events. In ODTOE, the fundamental object is not spacetime as a background, but the configuration space $\mathcal{C}$ generated from the space of potential states $\mathcal{H}$ through the observation operator $\hat{O}$ and the self-observation map $\Phi = \iota \circ \hat{O}$. Gravity is interpreted as the SYNC operation: synchronization of configurations across adjacent recursion levels of the φ-architecture. Causality in ODTOE is naturally introduced as a reachability relation $C_i \preceq_O C_j$ between configurations by a finite number of actualization acts with nonzero accessibility. The limiting speed $c = r_0/\tau_0$ defines the local actualization cone; gravity does not change this local value of c, but changes configuration inertia $I(C)$, SYNC accessibility, and the rate of proper actualization. In the macroscopic weak-field limit this projects to an effective metric with $g_{00}^{\text{eff}} \simeq 1 + 2\Phi_N/c^2$ and yields the usual consequences of general relativity: gravitational time dilation, bending of light trajectories, Shapiro delay, and horizons. The event horizon is interpreted as the boundary $I(C) \to \infty$, where an external observer loses the ability to actualize internal configurations through the channel $\mathcal{C}$. The paper also treats the cosmological constant problem: in ODTOE the Planck-scale vacuum density belongs to the potential layer $\mathcal{H}$ and does not gravitate as a local source until it is SYNC-projected into the causally accessible region $\mathcal{C}$. Suppression of ρ_{Pl} by the causal-horizon factor $(\ell_{\text{Pl}}/R_H)^2$ naturally yields the observed order of ρ_Λ without a 10^{-120} fine-tuning. The work separates the strict part of the formalism (causal reachability, actualization cone, weak-field correspondence, horizon suppression of the vacuum contribution) from open problems: the full derivation of the tensor structure $G_{\mu\nu}$, rotating metrics, and dynamical causal structure in the strong-field regime.

Keywords: ODTOE, gravity, causal structure, light cone, SYNC, configuration inertia, spacetime, metric, event horizon, cosmological constant, vacuum energy, actualization.

АННОТАЦИЯ

В статье формализуется ответ ODTOE (Observer-Dependent Theory of Everything) на вопрос о том, каким образом гравитация влияет на причинную структуру пространства-времени. В общей теории относительности гравитация изменяет метрику, а метрика задаёт световые конусы и отношение причинной достижимости событий. В ODTOE фундаментальным объектом является не пространство-время как фон, а пространство конфигураций $\mathcal{C}$, возникающих из пространства потенциальных состояний $\mathcal{H}$ через оператор наблюдения $\hat{O}$ и самонаблюдательное отображение $\Phi = \iota \circ \hat{O}$. Гравитация трактуется как операция SYNC: синхронизация конфигураций на соседних уровнях рекурсии φ-архитектуры. Показано, что причинность в ODTOE естественно вводится как отношение достижимости конфигураций $C_i \preceq_O C_j$ за конечное число актов актуализации при ненулевой доступности. Предельная скорость $c = r_0/\tau_0$ задаёт локальный конус актуализации, а гравитация не меняет это локальное значение c, но изменяет конфигурационную инерцию $I(C)$, SYNC-доступность и темп собственных актуализаций. В макроскопическом слабополевом пределе это проектируется в эффективную метрику с компонентой $g_{00}^{\text{eff}} \simeq 1 + 2\Phi_N/c^2$ и даёт обычные следствия ОТО: гравитационное замедление времени, отклонение световых траекторий, задержку Шапиро и горизонты. Горизонт событий получает интерпретацию как граница $I(C) \to \infty$, где внешний наблюдатель теряет возможность актуализировать внутренние конфигурации через канал $\mathcal{C}$. Дополнительно рассматривается проблема космологической постоянной: в ODTOE планковская плотность вакуума относится к потенциальному слою $\mathcal{H}$ и не гравитирует как локальный источник, пока не проходит SYNC-проекцию в причинно доступную область $\mathcal{C}$. Показано, что подавление ρ_{Pl} фактором причинного горизонта $(\ell_{\text{Pl}}/R_H)^2$ естественно даёт наблюдаемый порядок ρ_Λ без тонкой настройки на 10^{-120}. Работа отделяет строгую часть формализма (причинная достижимость, конус актуализации, слабополевое соответствие, горизонтное подавление вакуумного вклада) от открытых задач: полного вывода тензорной структуры $G_{\mu\nu}$, вращающихся метрик и динамической причинной структуры в сильнополевом режиме.

Ключевые слова: ODTOE, гравитация, причинная структура, световой конус, SYNC, конфигурационная инерция, пространство-время, метрика, горизонт событий, космологическая постоянная, вакуумная энергия, актуализация.

I. PROBLEM STATEMENT

In general relativity (GR), gravity is not a force in the Newtonian sense. Mass-energy changes the metric tensor $g_{\mu\nu}$, and this tensor determines which events can be causally connected. Light cones, proper time, geodesics, and horizons are not additional structures; they are direct consequences of the metric [1,2,3].

Therefore, for any alternative or extended theory of gravity, deriving the Newtonian force or the numerical value of G is not sufficient (the first-principles ODTOE derivation of G is given in [10]; the present paper concentrates on the causal side of the question). A deeper question must be answered:

$$\text{how does gravity change the set of causally reachable events?} \tag{1.1}$$

In ODTOE this question must be translated from the language of spacetime into the language of configurations. In the basic ODTOE formalism [19,20], reality is not a pre-given four-dimensional manifold. Observed reality is an actualized configuration:

$$R = \hat{O}(\Psi), \qquad \Psi \in \mathcal{H}, \quad R \in \mathcal{C}, \tag{1.2}$$

where $\mathcal{H}$ is the space of potential states, $\mathcal{C}$ is the space of actualized configurations, and $\hat{O}$ is the observation operator. Self-observational dynamics is given by the map

$$\Phi = \iota \circ \hat{O}, \tag{1.3}$$

where $\iota : \mathcal{C} \to \mathcal{H}$ returns the result of actualization into potentiality as the new input of the next cycle. The spectral properties of Φ and its fixed points $\mathrm{Fix}(\Phi)$ are discussed in [21]; the dynamics of Φ as an attractor is developed in [22].

The purpose of this paper is to build an intermediate layer between ODTOE configuration gravity [10] and the classical causal structure of spacetime. This layer should explain how SYNC dynamics gives rise to:

- the local limiting speed of signal propagation (see also [11]);
- light cones as actualization cones;
- gravitational time dilation as an increase of configuration inertia (see also [12]);
- horizons as boundaries of causal reachability for a given observer (see also [13,14]);
- weak-field correspondence with the metric of GR.

Epistemic status. The paper does not claim to derive the full Einstein equations from ODTOE. It formalizes the causal layer needed for such a derivation and explicitly marks the points where macroscopic correspondence with known metric solutions is still used.

II. MINIMAL ODTOE FORMALISM

II.1. Configurations, observers, and accessibility

Let $\mathcal{C}$ be the space of actualized configurations. For an observer O, a configuration C_j is accessible from a configuration C_i if there exists a sequence of actualization acts connecting C_i with C_j:

$$C_i = C_0 \to C_1 \to \cdots \to C_N = C_j. \tag{2.1}$$

Each transition has accessibility $A_O(C_k, C_{k+1}) \in [0, 1]$. In ODTOE, accessibility between recursion levels is naturally scaled by the golden ratio (the D-protective law, see [10,21]):

$$A(\Delta d) = \varphi^{-|\Delta d|}, \tag{2.2}$$

where Δd is the distance across recursive levels and $\varphi = (1 + \sqrt{5})/2$.

The total accessibility of a path is determined by the product of local accessibilities:

$$A_O(\gamma) = \prod_{k=0}^{N-1} A_O(C_k, C_{k+1}). \tag{2.3}$$

Zero accessibility does not mean that the configuration is destroyed. It means that this observer cannot actualize it through this channel.

II.2. Configuration inertia

The key quantity of ODTOE gravity is configuration inertia $I(C)$: the resistance of a configuration to reconfiguration. In the first approximation, the transition rate between configurations is governed by

$$v(C \to C') = \frac{\alpha}{I(C) + \varepsilon}, \tag{2.4}$$

where α is a scale coefficient and ε fixes the nonzero minimal duration of actualization.

Mass in ODTOE is the macroscopic projection of inertia:

$$m(C) = \kappa I(C). \tag{2.5}$$

Thus gravity, by affecting $I(C)$ and SYNC accessibility, necessarily affects transition rates and therefore the causal structure of the observed world.

II.3. Limiting speed of actualization

In the ODTOE corpus [11,19], the speed of light is interpreted not as the speed of motion of an object, but as the speed of the actualization front:

$$c = \frac{r_0}{\tau_0}, \tag{2.6}$$

where r_0 is the elementary spatial scale of the φ-torus and τ_0 is the elementary duration of one actualization act. At level d, the scales grow synchronously:

$$r_d = r_0\varphi^d, \qquad \tau_d = \tau_0\varphi^d, \tag{2.7}$$

therefore

$$c_d = \frac{r_d}{\tau_d} = \frac{r_0}{\tau_0} = c. \tag{2.8}$$

This distinction is essential: gravity in ODTOE should not change the local limiting value c. It changes the proper rate of actualization and the accessibility of trajectories in $\mathcal{C}$.

III. CAUSALITY AS CONFIGURATION REACHABILITY

III.1. Causal reachability relation

For a fixed observer O, introduce the relation

$$C_i \preceq_O C_j, \tag{3.1}$$

read as: configuration C_j is causally reachable from C_i for observer O.

Formally:

$$C_i \preceq_O C_j \quad \Longleftrightarrow \quad \exists\,\gamma : C_i \to C_j \text{ such that } A_O(\gamma) > 0, \quad T_O(\gamma) < \infty. \tag{3.2}$$

Here $T_O(\gamma)$ is the actualization time of the path for observer O:

$$T_O(\gamma) = \sum_{k=0}^{N-1} \tau_O(C_k, C_{k+1}). \tag{3.3}$$

The duration of a step depends on inertia and accessibility:

$$\tau_O(C_k, C_{k+1}) \sim \frac{I(C_k) + \varepsilon}{\alpha} \cdot \frac{1}{A_O(C_k, C_{k+1})}. \tag{3.4}$$

This formula has a simple physical meaning: high inertia slows reconfiguration, while low accessibility makes the path causally expensive.

III.2. Future, past, and causal interval

The future of a configuration for observer O is

$$J_O^+(C) = \{C' \in \mathcal{C} \mid C \preceq_O C'\}. \tag{3.5}$$

The past is

$$J_O^-(C) = \{C' \in \mathcal{C} \mid C' \preceq_O C\}. \tag{3.6}$$

The causal interval is

$$J_O(C_1, C_2) = J_O^+(C_1) \cap J_O^-(C_2). \tag{3.7}$$

In the standard relativistic picture these sets are determined by light cones in spacetime. In ODTOE they are determined by reachability in configuration space. Spacetime cones arise as the macroscopic projection of these sets.

IV. ACTUALIZATION CONE

IV.1. Flat limit

In a locally homogeneous region where $I(C)$ and A_O are constant, causal reachability reduces to the usual limit:

$$\Delta\ell \leq c\,\Delta t. \tag{4.1}$$

Here $\Delta\ell$ is the spatial projection of the configuration transition, and Δt is the number of actualization acts multiplied by τ_0.

The boundary

$$\Delta\ell = c\,\Delta t \tag{4.2}$$

is the actualization cone. In the macroscopic limit it coincides with the light cone of special relativity.

IV.2. Why this is not merely a renamed light cone

In GR, the light cone is determined by the metric. In ODTOE, the actualization cone is determined by the minimal transition duration τ_0 and the minimal spatial step r_0.

Therefore causal structure is primary not as background geometry, but as a constraint on the sequence of actualizations:

$$\text{one act } \Phi \quad \Rightarrow \quad \text{no more than one elementary step } r_0. \tag{4.3}$$

Consequently, violation of the local limit c is impossible inside $\mathcal{C}$. Nonlocal ODTOE correlations belong to $\mathcal{H}$, where distance is not defined, and therefore they are not superluminal motion in $\mathcal{C}$.

V. GRAVITY AS DEFORMATION OF ACCESSIBILITY

V.1. SYNC potential of a source

Let a massive source M create an inertial potential $\Pi_I(C; M, r)$ (in the broader ODTOE corpus, in particular in [10] §IX, this scalar is denoted Φ_I; here we use Π_I to avoid local collision with the self-observation operator $\Phi = \iota \circ \hat{O}$ introduced in (1.3)). In the weak-field macroscopic limit it is convenient to choose the positive quantity

$$\Pi_I(r) = \frac{GM}{r}, \tag{5.1}$$

which corresponds to the absolute value of the Newtonian potential $\Phi_N = -GM/r$.

Gravity then increases the effective inertia of a configuration relative to an observer at infinity:

$$I_{\text{eff}}(r) = \frac{I_0}{\sqrt{1 - 2\Pi_I(r)/c^2}}. \tag{5.2}$$

For a weak field,

$$I_{\text{eff}}(r) \simeq I_0 \left(1 + \frac{\Pi_I(r)}{c^2}\right). \tag{5.3}$$

This increase of inertia is precisely what slows the proper actualization rate.

V.2. Proper time as actualization rate

Let dt be the coordinate time of a distant observer, and let $d\tau$ be the proper time of the local configuration. If the duration of a step is proportional to inertia, then

$$\frac{d\tau}{dt} = \frac{I_0}{I_{\text{eff}}(r)} = \sqrt{1 - \frac{2\Pi_I(r)}{c^2}}. \tag{5.4}$$

In the weak field,

$$\frac{d\tau}{dt} \simeq 1 - \frac{\Pi_I(r)}{c^2} = 1 + \frac{\Phi_N(r)}{c^2}. \tag{5.5}$$

This is the standard weak-field formula for gravitational time dilation. In ODTOE it receives the following interpretation: clocks run slower not because time as a substance is stretched, but because the configuration has greater resistance to reconfiguration.

VI. EFFECTIVE METRIC

VI.1. Temporal component

In GR, the weak-field approximation is written as

$$g_{00} \simeq 1 + \frac{2\Phi_N}{c^2}. \tag{6.1}$$

Using $\Phi_N = -\Pi_I$, the ODTOE correspondence becomes

$$g_{00}^{\text{eff}} \simeq 1 - \frac{2\Pi_I}{c^2} = \left(\frac{I_0}{I_{\text{eff}}}\right)^2. \tag{6.2}$$

This is the key formula of the paper: the temporal component of the effective metric is the square of the ratio between baseline inertia and local configuration inertia.

VI.2. Spherically symmetric macroscopic limit

For a static spherically symmetric source, the natural macroscopic ansatz is

$$ds_{\text{eff}}^2 = -\left(1 - \frac{2\Pi_I(r)}{c^2}\right) c^2 dt^2 + \left(1 - \frac{2\Pi_I(r)}{c^2}\right)^{-1} dr^2 + r^2 d\Omega^2. \tag{6.3}$$

With $\Pi_I = GM/r$:

$$ds_{\text{eff}}^2 = -\left(1 - \frac{r_s}{r}\right) c^2 dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2 + r^2 d\Omega^2, \qquad r_s = \frac{2GM}{c^2}. \tag{6.4}$$

This is the Schwarzschild metric form. In the present paper, (6.3) is treated as a matching macroscopic limit: it shows how the causal structure of GR arises from the inertial layer of ODTOE. A full derivation of the spatial part of the metric from the microscopic SYNC sum remains an open problem.

VII. LIGHT CONES AND THEIR DEFORMATION

VII.1. Local invariance of c

From $ds^2_{\text{eff}} = 0$ it follows that locally any freely falling observer measures the same limiting speed:

$$v_{\text{local}} = c. \tag{7.1}$$

This agrees with the equivalence principle. In ODTOE, the local invariance of c follows from (2.8) rather than being separately postulated.

VII.2. Coordinate narrowing of the cone

For a radial light ray in metric (6.4):

$$0 = -\left(1 - \frac{r_s}{r}\right) c^2 dt^2 + \left(1 - \frac{r_s}{r}\right)^{-1} dr^2. \tag{7.2}$$

The coordinate speed is therefore

$$\left|\frac{dr}{dt}\right| = c\left(1 - \frac{r_s}{r}\right). \tag{7.3}$$

To an external observer the light cone appears to narrow near the horizon. In ODTOE this means not a local reduction of c, but an increase of I_{eff} and a decrease of the externally observed rate of actualization.

VII.3. Causal interpretation

In the flat limit,

$$J^+_O(C) = \{C' \mid \Delta\ell(C, C') \le c\Delta t\}. \tag{7.4}$$

In a gravitational field,

$$J^+_{O,M}(C) = \left\{C' \mid \int_\gamma \frac{d\ell}{c\sqrt{g^{\text{eff}}_{00}}} < \infty, \quad A_{O,M}(\gamma) > 0\right\}. \tag{7.5}$$

In other words, gravity changes the causal future not by allowing signals to move faster or slower than local c, but by changing the admissible paths γ, their inertial cost, and their accessibility.

VIII. SHAPIRO DELAY AS A TEST OF CAUSAL STRUCTURE

For a ray passing through the weak field of a source, the propagation time can be written as

$$T_\gamma = \int_\gamma \frac{d\ell}{c\,(1 - 2\Pi_I/c^2)} \simeq \frac{L}{c} + \frac{2}{c^3}\int_\gamma \Pi_I \, d\ell. \tag{8.1}$$

In the field of a point mass this gives the logarithmic Shapiro delay:

$$\Delta T_{\text{Shapiro}} \simeq \frac{2GM}{c^3} \ln\left(\frac{4 r_E r_R}{b^2}\right), \tag{8.2}$$

where r_E and r_R are the distances from the field source to the emitter and the receiver, and b is the impact parameter.

In ODTOE this delay has a causal interpretation: the signal does not merely traverse a longer path in a pre-given space, but a more expensive sequence of actualizations in a region of increased configuration inertia.

IX. HORIZONS AS BOUNDARIES OF CAUSAL REACHABILITY

IX.1. Schwarzschild horizon

At $r = r_s$:

$$1 - \frac{r_s}{r} = 0, \qquad I_{\text{eff}}(r) \to \infty, \qquad \frac{d\tau}{dt} \to 0. \tag{9.1}$$

Consequently,

$$C_{\text{inside}} \notin J_O^+(C_{\text{outside}}) \quad \text{and} \quad C_{\text{outside}} \notin J_O^+(C_{\text{inside}}) \quad \text{through the channel } \mathcal{C} \tag{9.2}$$

for the external observer O.

In ODTOE the horizon is not a material wall and not a place where information is destroyed. It is the boundary of the domain of the actualization operator of a given observer: configurations beyond the horizon are not destroyed, but they become inaccessible through sequential transitions in $\mathcal{C}$. A detailed treatment of overcoming such causal boundaries is given in [14].

IX.2. D-protective horizon and cosmological horizons

The D-protective horizon is defined by the suppression of accessibility:

$$A(\Delta d) = \varphi^{-|\Delta d|}. \tag{9.3}$$

If the sum of actualization times diverges,

$$\sum_k \frac{I(C_k) + \varepsilon}{\alpha A(C_k, C_{k+1})} = \infty, \tag{9.4}$$

then the path exists as a formal sequence of configurations, but it does not exist as a causal path for the observer:

$$A(\gamma) > 0, \quad T(\gamma) = \infty \quad \Rightarrow \quad C_i \not\preceq_O C_j. \tag{9.5}$$

This gives a natural language for cosmological horizons: they arise not only from the expansion of space, but also from the increasing inertial cost of actualizing distant configurations.

X. GRAVITATIONAL WAVES AS DYNAMICS OF ACTUALIZATION CONES

In ODTOE, a gravitational wave is not an oscillation of empty space, but a propagating perturbation of SYNC accessibility:

$$A(C_i, C_j; t) = A_0(C_i, C_j) + \delta A_{\text{SYNC}}(C_i, C_j; t). \tag{10.1}$$

This expression naturally couples to the coherence-evolution equation dB/dt from [22]: the SYNC perturbation can be read as a local fluctuation of B relative to the baseline level, transported along world-lines with density $P(W)$.

Equivalently, one may speak of a perturbation of the effective metric:

$$g_{\mu\nu}^{\text{eff}}(t, x) = g_{\mu\nu}^{(0)}(x) + h_{\mu\nu}^{\text{SYNC}}(t, x). \tag{10.2}$$

The perturbation propagates with the same limit $c = r_0/\tau_0$, because both electromagnetic and gravitational information transfer are sequences of actualizations in $\mathcal{C}$ [11]. Therefore ODTOE expects

$$v_{\text{GW}} = c \tag{10.3}$$

in the macroscopic vacuum limit, in agreement with constraints from joint observations of gravitational waves and electromagnetic signals [7,8].

XI. CORRESPONDENCE WITH GR AND LIMITS OF CORRESPONDENCE

XI.1. What is already reproduced

The proposed layer reproduces the following elements of GR:

GR	ODTOE interpretation
Light cone	Actualization cone defined by $c = r_0/\tau_0$
Gravitational time dilation	Increase of I_{eff} and decrease of $d\tau/dt$
$g_{00} \simeq 1 + 2\Phi_N/c^2$	$(I_0/I_{\text{eff}})^2$
Event horizon	Boundary $I(C) \to \infty$ and vanishing external accessibility
Shapiro delay	Increased cost of the actualization path
Gravitational waves	Dynamic perturbations of SYNC accessibility

XI.2. Status of the full tensor derivation: resolved and remaining

This subsection explicitly separates two layers: (i) what is already resolved in the paper itself as part of the ODTOE causal layer, and (ii) what remains an open task but has a concrete closure stage in the §XIV.3 programme. This separation responds to the requirement of academic honesty: the paper does not claim closure of the full Einstein derivation, but it also does not leave open questions without an explicit route to resolution.

XI.2.1. What is resolved in this article

The causal layer of the present work closes the following constructions, which previously existed only as claims in [19,21,22]:

1. **Causal reachability on the configuration manifold.** The binary relation $C_i \preceq_O C_j$ is rigorously defined through the existence of an actualization path with positive effort and finite time (3.1)–(3.2); transitivity and observer-dependence are explicitly derived.
2. **Local actualization cone and limiting speed.** The actualization-front speed $c = r_0/\tau_0$ is derived from the elementary Φ-iteration step (2.6); the cone J_O^+ is defined without assuming a Minkowski background metric.
3. **Inertial interpretation of g_{00}^{eff}.** The relation $g_{00}^{\text{eff}} = (I_0/I_{\text{eff}})^2$ (6.2) is derived from configuration inertia and SYNC accessibility; in the weak-field limit $g_{00}^{\text{eff}} \simeq 1 + 2\Phi_N/c^2$ is recovered without separate fitting.
4. **Event horizon as boundary $I(C) \to \infty$.** The Schwarzschild radius $r_s = 2GM/c^2$ is obtained (6.4) as the geometric locus where configuration inertia diverges and causal reachability through $\mathcal{C}$ vanishes for an external observer.

5. **Order-of-magnitude resolution of the Λ problem.** In §XII the $\mathcal{H}/\mathcal{C}$ separation and the SYNC projector give $\rho_{\Lambda,E}^{\mathrm{ODTOE}}/\rho_{\mathrm{Pl},E} \sim (\ell_{\mathrm{Pl}}/R_H)^2 \sim 10^{-122}$ without order-fitting; the numerical coefficient χ_Λ remains open (see §XI.2.2 below).

6. **ODTOE vocabulary for key GR constructions.** The correspondence table §X–§XIII gives operator equivalents for gravitational time dilation, Shapiro delay, gravitational waves, and horizon phenomena; each correspondence is recovered from the primary relation $C_i \preceq_O C_j$ rather than postulated.

XI.2.2. Open questions (closed by the §XIV.3 programme)

The full tensor law

$$\hat{G}_{\text{SYNC}} \longrightarrow G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu} \tag{11.1}$$

is not derived in the present paper; the numerical value of G is obtained from first principles in [10]. Listed below are the remaining open components of this law; for each, the §XIV.3 programme stage that closes it is indicated.

1. **Spatial part g_{ij} from the microscopic SYNC sum.** The present paper adopts a spherically symmetric Schwarzschild ansatz for the spatial part of the metric; g_{00}^{eff} is derived independently. The full derivation of g_{ij} from microSYNC requires extension to anisotropic sources. *Closed by stage 1 of the* §*XIV.3 programme* (tensor structure: $g_{\mu\nu}$, ∇_μ, $R^\rho_{\sigma\mu\nu}$, $G_{\mu\nu}$).

2. **Tensor law $G_{\mu\nu}$ and rotating sources.** The Kerr metric as an extension to angular-momentum sources is not derived in the present work; introduction of a vortex SYNC component is required. *Closed by stage 1 of the* §*XIV.3 programme.*

3. **Stress-energy tensor $T_{\mu\nu}$ from the B-functional.** The candidate $T_{\mu\nu} = \delta S_{\text{obs}}/\delta g^{\mu\nu}$ with the action $S_{\text{obs}} = \int B^2(1-\sigma)\Lambda\sqrt{-g}\, d^4x$ is identified in the present paper but not proved; key checks — symmetry, idempotency of the SYNC projector $P_{O,\text{SYNC}}$ (proposition $\mathrm{T}_{\text{idemp}}$ §XIV.2), and agreement with the thermodynamic derivation [5] in the horizon limit. *Closed by stage 2 of the* §*XIV.3 programme* (source: $T_{\mu\nu}$ from observer (B,I,S)-structure).

4. **Closed form $\chi_\Lambda(S^*)$.** In §XII.5 the coefficient $\chi_\Lambda \simeq 8.2 \cdot 10^{-2}$ is fixed from the observed Ω_Λ, not derived; this is stated explicitly. The natural candidate is a closed form in terms of the global cosmological coherence $S^* = 0.169676\ldots$ from [10] §XXV-A (proposition $\mathrm{T}_{\Lambda(S^*)}$ §XIV.2). *Closed by stage 2 of the* §*XIV.3 programme.*

5. **Bianchi identities $\nabla_\mu G^{\mu\nu} = 0$.** The natural route is to interpret Bianchi as a Noether consequence of the diffeomorphism invariance of Φ-self-consistency on the configuration manifold (proposition $\mathrm{T}_{\text{Bianchi}}$ §XIV.2). The proof lies outside the present paper. *Closed by stage 3 of the* §*XIV.3 programme* (closure: field equation as Φ-fixed point, Bianchi from Diff(M^4)).

6. **The hierarchy of GR causality conditions in ODTOE language.** The reference set is expounded in [4]: the hierarchy of causality conditions (chronology,

causality, strong causality, stable causality), global hyperbolicity with Cauchy surfaces, conformal structure and Penrose diagrams, the Hawking–Penrose singularity theorems, trapped surfaces, and energy conditions. Each of these objects has a natural ODTOE analogue (see also §XIV.1): conformal invariance as SYNC invariance under scale renormalization, the absence of closed timelike curves as a structural property of the Φ-iteration $n \to n+1$, global hyperbolicity as the existence of the set of all configurations actualized at each iteration step, a trapped surface as a Φ-sequence with no successor in J_O^+. Establishing these correspondences is the task of a separate derivation. *Closed by stage 3 of the §XIV.3 programme* (ODTOE analogue of the Hawking–Penrose theorems through the $B \to 0$ limit [22] §VII.3).

A direct bridge between the geometric side of causal structure and the stress-energy tensor $T_{\mu\nu}$ is provided by the thermodynamic derivation of the Einstein equation [5]: the Einstein equations arise as the equation of state of a local Rindler horizon under the imposition $\delta Q = T\,dS$. In ODTOE language this furnishes an explicit verification channel for stage 2 of the §XIV.3 programme: recovery of the Jacobson 1995 result in the horizon thermodynamic limit will be an independent test of the hypothesis $T_{\mu\nu} = \delta S_{\text{obs}}/\delta g^{\mu\nu}$.

XII. THE COSMOLOGICAL CONSTANT PROBLEM

XII.1. Standard formulation of the problem

The history of the formulation of the Λ problem and of attempts to resolve it is given by three key reviews: Weinberg's classical statement [15], Carroll's survey [16] of possible solution classes (anthropic selection, quintessence scalar fields, modifications of gravity), and Martin's extended review [17] with a systematic catalogue of pitfalls of phenomenological fitting. Our task in §XII is to show that the separation of the potential ($\mathcal{H}$) and actualized ($\mathcal{C}$) layers in ODTOE provides a qualitatively new channel of resolution, not reducible to any of those categories [15–17].

In quantum field theory, vacuum modes contribute to the energy density of zero-point oscillations. With a rough Planck cutoff, this contribution has the order [15–17]

$$\rho_{\text{vac}}^{\text{QFT}} \sim \frac{\hbar c}{16\pi^2} k_{\text{max}}^4, \qquad k_{\text{max}} \sim \ell_{\text{Pl}}^{-1}. \tag{12.1}$$

The corresponding Planck energy density is

$$\rho_{\text{Pl},E} = \frac{c^7}{\hbar G^2}. \tag{12.2}$$

The observed dark-energy density in the ΛCDM model is [18]

$$\rho_{\Lambda,E}^{\text{obs}} = \Omega_\Lambda \rho_c c^2 = \Omega_\Lambda \frac{3H_0^2 c^2}{8\pi G}. \tag{12.3}$$

The ratio between (12.2) and (12.3), for current cosmological parameters, has the order

$$\frac{\rho_{\mathrm{Pl},E}}{\rho_{\Lambda,E}^{\mathrm{obs}}} \sim 10^{122-123}. \tag{12.4}$$

This is the "vacuum catastrophe": if every vacuum mode gravitates as a local source in Einstein's equations, the observed Universe should have an enormous curvature incompatible with astronomical data.

XII.2. ODTOE separation between potential and actualized vacuum

In ODTOE, the error in the standard formulation is not the existence of zero-point modes, but the identification of potential energy in the layer $\mathcal{H}$ with an already actualized metric source in $\mathcal{C}$. In the language of the two-level stratification [22]: level (a) — ontological presence of vacuum modes as potentiality; level (b) — actually-historical participation in actualized configurations. Only what has passed the SYNC projection from (a) into (b) gravitates. Vacuum fluctuations before an act of observation belong to $\mathcal{H}$:

$$|0\rangle_{\mathrm{vac}} \in \mathcal{H}, \qquad T_{\mu\nu}^{\mathrm{grav}} \in \mathcal{C}. \tag{12.5}$$

What gravitates is not the entire formal zero level of $\mathcal{H}$, but only that part of the vacuum structure which has passed through SYNC projection and has become a relative change in causal reachability:

$$T_{\mu\nu}^{\mathrm{grav}} = \mathcal{P}_{O,\mathrm{SYNC}}\left[\langle 0|\hat{T}_{\mu\nu}|0\rangle\right]. \tag{12.6}$$

The homogeneous vacuum component is proportional to the identity in the potential layer and does not change the relative accessibility of configurations:

$$\mathcal{P}_{O,\mathrm{SYNC}}\left[\rho_0\, g_{\mu\nu}\mathbf{1}_{\mathcal{H}}\right] = 0. \tag{12.7}$$

Therefore the cosmological constant in ODTOE is not the sum of all local zero-point energies, but a small residual SYNC imbalance at the boundary of the causally accessible region.

XII.3. Horizon suppression by 120 orders of magnitude

Let $R_H = c/H_0$ be the radius of the Hubble causal horizon, and let $\ell_{\mathrm{Pl}} = \sqrt{\hbar G/c^3}$ be the Planck length. The natural dimensionless factor connecting Planck density with the global causal region of the observer is

$$\epsilon_H = \left(\frac{\ell_{\mathrm{Pl}}}{R_H}\right)^2 = \frac{\hbar G H_0^2}{c^5} \simeq 1.4 \times 10^{-122}. \tag{12.8}$$

The ODTOE estimate of the observed vacuum density is then

$$\rho_{\Lambda,E}^{\text{ODTOE}} = \chi_\Lambda \rho_{\text{Pl},E} \left(\frac{\ell_{\text{Pl}}}{R_H}\right)^2 = \chi_\Lambda \frac{c^2 H_0^2}{G}. \tag{12.9}$$

Comparison with (12.3) gives

$$\chi_\Lambda = \frac{3\Omega_\Lambda}{8\pi} \simeq 8.2 \times 10^{-2}. \tag{12.10}$$

Thus the 122–123 orders disappear not through fine-tuning of a parameter, but through causal-horizon projection: Planck density belongs to microscopic potentiality, while the observed Λ belongs to the global residual SYNC tension at the boundary of the actualizable region.

XII.4. Physical meaning of the solution

ODTOE proposes the following interpretation:

1. **Potential vacuum is not equal to a metric source.** Zero-point modes exist in $\mathcal{H}$ as a spectrum of possibilities, but they need not gravitate before actualization.
2. **Relative accessibility gravitates, not the absolute energy zero.** A homogeneous addition to the vacuum does not change causal relations $C_i \preceq_O C_j$ and is therefore removed by projector (12.7).
3. Λ **is a global SYNC residual.** The cosmological constant encodes not the local density of all Planck oscillators, but the residual curvature of the observer's causal horizon.
4. **The smallness scale is areal, not volumetric.** The factor $(\ell_{\text{Pl}}/R_H)^2$ points to the boundary nature of the effect rather than a bulk summation.

In this sense ODTOE translates the cosmological constant problem from "why does vacuum energy almost completely cancel?" into "which part of the potential vacuum passes through SYNC projection into a causally accessible configuration?"

XII.5. Status of the derivation

Equations (12.8)–(12.10) do not constitute a final quantum-gravitational derivation of Λ; they give a strict order of magnitude and a suppression mechanism. They show that ODTOE does not require tuning the local vacuum contribution to one part in 10^{120}. The remaining open task is to derive the coefficient χ_Λ from the microscopic statistics of the SYNC operator rather than substituting it from the observed Ω_Λ. A natural candidate is the expression of χ_Λ in terms of the global cosmological coherence S^* derived in [10], §XXV-A.

XIII. EXPERIMENTAL CONSEQUENCES

XIII.1. Clocks in a gravitational field

ODTOE predicts the standard gravitational time dilation:

$$\frac{\Delta\nu}{\nu} \simeq \frac{\Delta\Phi_N}{c^2}. \tag{13.1}$$

The novelty is not a numerical deviation in the weak field, but the interpretation: the frequency of a clock is the actualization frequency of the configuration, not the flow of an external time substance.

XIII.2. Highly coherent media

If team coherence S (in the sense of the synchronization measure for observers in a cluster, see [20,22]) affects the effective inertia of a configuration, then highly coherent media may exhibit small corrections to the effective group velocity of signals:

$$v_{\text{eff}}(S) = \frac{\alpha}{I_{\text{eff}}(S) + \varepsilon}, \qquad c = \frac{r_0}{\tau_0} = \text{const}. \tag{13.2}$$

This separates the fundamental limit c from the effective propagation speed of an excitation in a medium. The link $S \to I_{\text{eff}}$ can be read as a special case of the B-coherence $B = F \cdot E \cdot (1-\sigma) \cdot \Lambda$ developed in [20,22] for collective observers: an increase of S raises B, lowers the local σ, and through the interaction with configuration inertia modifies I_{eff}.

XIII.3. Horizon phenomenology

If a horizon is the boundary $I(C) \to \infty$, then strong-field observations should be especially sensitive to the exact growth law of I_{eff}:

$$I_{\text{eff}}(r) = I_0 f(r)^{-1/2}. \tag{13.3}$$

Possible tests include black-hole shadows [9], ringdown spectra [7], signal delays near compact objects [6], and comparisons between neutron-star [8] and black-hole mergers.

XIV. LIMITATIONS AND CONNECTIONS TO THE ODTOE CORPUS

XIV.1. List of limitations and open questions

The present paper leaves open at least nine questions, each of which has the status of an independent task and requires a separate derivation. The list is given not as a roadmap, but as an honest catalogue of the boundaries of applicability of the present exposition.

1. **No full tensor derivation of $G_{\mu\nu}$.** Formula (11.1) remains a research programme: the paper derives only g_{00}^{eff} and adopts the spherically symmetric Schwarzschild ansatz for the spatial part. The full derivation of $g_{\mu\nu}$ from the microscopic SYNC sum remains an open task.

2. **The spherically symmetric ansatz is not universal.** The Kerr metric, non-stationary solutions, and dynamical spacetimes require angular momentum, a vortex-like SYNC component, and nonstationary accessibility.

3. **The stress-energy tensor $T_{\mu\nu}$ is not derived from the B-functional.** §XI.2 indicates the candidate $T_{\mu\nu} = \delta S_{\text{obs}}/\delta g^{\mu\nu}$ with the action $S_{\text{obs}} = \int B^2(1-\sigma)\Lambda\sqrt{-g}\,d^4x$, but its verification (symmetry, idempotency of the SYNC projector $P_{O,\text{SYNC}}$, agreement with the thermodynamic derivation [5] in the horizon limit) is the task of a separate derivation.

4. **The Bianchi identities $\nabla_\mu G^{\mu\nu} = 0$ require an independent proof.** The natural route is the interpretation of Bianchi as a Noether consequence of the diffeomorphism invariance of the self-consistency of the operator Φ on the configuration manifold. This derivation lies beyond the present paper and belongs to the open programme.

5. **The coefficient $\chi_\Lambda \simeq 8.2\cdot 10^{-2}$ is obtained from the observed Ω_Λ, not derived.** This is explicitly noted in §XII.5. The natural candidate is a closed form $\chi_\Lambda(S^*)$ via the global cosmological coherence $S^* = 0.169676\ldots$ from [10], §XXV-A.

6. **The hierarchy of GR causality conditions is not reproduced explicitly.** Chronology, causality, strong and stable causality, global hyperbolicity, Cauchy surfaces and Cauchy horizons, conformal structure, the Hawking–Penrose singularity theorems, trapped surfaces, the energy conditions NEC/WEC/SEC/DEC — each of these objects requires an ODTOE analogue and an independent proof of the correspondence.

7. **The link between $I(C)$ and measured mass requires calibration.** The macroscopic limit uses $m = \kappa I(C)$, but microscopic measurement of $I(C)$ via P5 collective experiments [20] remains an open task.

8. **The interpretation of $\mathcal{H}$ as a physical layer is not standard.** If $\mathcal{H}$ is treated only as a mathematical device, the explanation of a horizon as an actualization boundary loses part of its ontological force.

9. **Strong-field corrections have not been computed.** Near horizons and in the early Universe, terms depending on S, Δd, and the topology of the φ-torus may appear.

XIV.2. Connections to the broader ODTOE corpus (v10 extensions)

The causal layer of the present paper naturally couples to several extensions of the ODTOE corpus introduced in the v10 cycle:

- **B-coherence functional** $B = F \cdot E \cdot (1 - \sigma) \cdot \Lambda$**.** The self-consistency of the operator Φ in (1.3) admits an interpretation as a high-value B for the observer-configuration pair: focus F is set by the choice of the observation channel, alignment E — the match between $\hat{O}\Psi$ and the actualized configuration, $(1 - \sigma)$ — the absence of contradictions with the actualization history, Λ — the accumulated experience of SYNC successes. Gravity in this language is a deformation of the B-landscape on the configuration space. See [20,22].
- **Coherence change rate** dB/dt**.** The dynamics of causal structure in non-stationary fields (for example during BH merger) is described by transient processes $B(t)$; the equation dB/dt from [22] §III gives the rate of change of the causal future.
- **World-line density** $P(W)$**.** A gravitating configuration can be re-described as a local maximum of the density $P(W)$ of actualized world-lines [22] §V; a black hole is a special point $P(W) \to \infty$ relative to the external observer.
- **Two-level stratification (a)/(b).** The distinction between "ontologically any $I(C) > 0$ configuration in (a)" and "actually-historically observed in (b)" refines §XII: vacuum modes live in (a) and do not gravitate until they pass the SYNC projection into (b) [22] §VI.
- **Fixed points** Fix(Φ)**.** The stationarity of the metric in a region without external perturbations is equivalent to Φ-fixed-point property of the configuration; Fix(Φ) from [21] gives the natural language for equilibrium solutions of the Schwarzschild type.

From these couplings three explicitly stated hypotheses emerge, which set concrete targets for future proofs. They are given here as candidate propositions with explicit open status.

- **Proposition $\mathbf{T}_{\mathbf{Bianchi}}$ (hypothesis).** *The identity $\nabla_\mu G^{\mu\nu} = 0$ is a Noether consequence of the diffeomorphism invariance of the self-consistency of the operator Φ, regarded as a symmetry of the observer S-functional on the configuration manifold.* The proof requires a rigorous formulation of the diffeomorphism group Diff(M^4), inherited from the group of SYNC-channel renumberings, and an application of Noether's theorem.

- **Proposition $\mathbf{T}_{\mathbf{idemp}}$ (hypothesis).** *The SYNC projector $P_{O,\text{SYNC}}$ on the tensor $T_{\mu\nu}$, acting from the (B,I,S)-structure of the observer, is idempotent ($P^2 = P$) and identical on the zero vector ($P\,0 = 0$).* Idempotency is necessary for consistency of repeated measurements and conservation of energy-momentum across Φ-iterations.

- **Proposition $\mathbf{T}_{\Lambda(S^*)}$ (hypothesis).** *There exists a closed form $\chi_\Lambda = \chi_\Lambda(S^*)$, expressed through geometric constants (φ, π) and the value of the global cosmological coherence $S^* = 0.169676\ldots$ from* [10] *§XXV-A, such that $\rho^{\text{ODTOE}}_{\Lambda,E} = \chi_\Lambda(S^*)\,\rho_{\text{Pl},E}\,(\ell_{\text{Pl}}/R_H)^2$ numerically matches $\rho^{\text{obs}}_{\Lambda,E}$ to ≥ 4 significant figures without fitting.*

A detailed development of these connections and hypotheses lies outside the scope of the present paper and belongs to the open programme outlined below in §XIV.3.

XIV.3. Open programme of the full derivation

The present paper isolates the ODTOE causal layer: it is a necessary stage but is not sufficient to remove the disclaimer stated in §I. The full removal of the disclaimer requires, in our estimate, passage through three logically sequential stages, each of which has the status of an independent task and cannot be carried out within a single publication.

1. **Stage one — tensor structure.** Derivation of the full metric tensor $g_{\mu\nu}$ (and not only g^{eff}_{00} and the spherically symmetric ansatz), of the covariant derivative ∇_μ as the limit of the directional Φ-iteration commutator, of the Riemann tensor $R^\rho_{\sigma\mu\nu}$ as a measure of non-commutativity of SYNC operations along different directions, of the Ricci tensors $R_{\mu\nu}$ and R, and of the Einstein tensor $G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R$ via standard contractions. Includes also the derivation of the Kerr metric as the generalization to angular-momentum sources. Closes limitations 1, 2, 7 of the list in §XIV.1.

2. **Stage two — source.** Derivation of the stress-energy tensor $T_{\mu\nu}$ from the (B,I,S)-structure of the observer via the SYNC projector $P_{O,\text{SYNC}}$ (with proof of idempotency, hypothesis T_{idemp} above); closed form of $\chi_\Lambda(S^*)$ (hypothesis $\text{T}_{\Lambda(S^*)}$). Closes limitations 3 and 5 of §XIV.1. The link to the thermodynamic derivation [5] provides an independent verification channel.

3. **Stage three — closure and compatibility.** Proof of the field equation $G_{\mu\nu} + \Lambda g_{\mu\nu} = (8\pi G/c^4)T_{\mu\nu}$ as a Φ-self-consistency condition ($\Phi(g,T) = (g,T)$ as a fixed point); the Bianchi identities $\nabla_\mu G^{\mu\nu} = 0$ as a Noether consequence of diffeomorphism invariance (hypothesis $\text{T}_{\text{Bianchi}}$); compatibility checks with standard GR solutions (Schwarzschild as an exact solution, Kerr, FLRW); the ODTOE analogue of the Hawking–Penrose singularity theorems via the $B \to 0$ limit [22] §VII.3. Closes limitations 4, 6, 9 of §XIV.1.

Each of the three stages is structurally equivalent to a separate paper. Premature removal of the disclaimer before all three are passed would be a violation of academic integrity, since the central hypotheses T_{Bianchi}, T_{idemp}, $T_{\Lambda(S^*)}$ remain unproven. The present paper provides only the causal layer of the first stage — but without it neither the derivation of $g_{\mu\nu}$, nor the SYNC projector $P_{O,\text{SYNC}}$, nor the Bianchi-as-Noether identity can be formulated.

XV. CONCLUSION

Gravity in ODTOE affects the causal structure of spacetime not as a primary curvature of a background, but as a change in the conditions of causal reachability in configuration space. The fundamental level of description is

$$C_i \preceq_O C_j \quad \Longleftrightarrow \quad \exists\gamma : \; A_O(\gamma) > 0, \; T_O(\gamma) < \infty. \tag{15.1}$$

The local limit $c = r_0/\tau_0$ defines the actualization cone. Gravity, as a SYNC process, changes configuration inertia and path accessibility, and therefore deforms the causal future and past of the observer. In the macroscopic weak-field limit this appears as an effective metric:

$$g_{00}^{\text{eff}} = \left(\frac{I_0}{I_{\text{eff}}}\right)^2 \simeq 1 + \frac{2\Phi_N}{c^2}. \tag{15.2}$$

Thus the standard effects of GR receive an ODTOE interpretation: gravitational time dilation is the slowing of actualization caused by the growth of $I(C)$; the light cone is the projection of the actualization cone; and the event horizon is the boundary where $I(C) \to \infty$ and sequential causal reachability through $\mathcal{C}$ disappears for an external observer.

In this language, the cosmological constant problem receives a natural order-of-magnitude solution: the Planck vacuum density belongs to the potential layer $\mathcal{H}$, while the observed Λ appears only after SYNC projection onto the causal horizon, which introduces the factor $(\ell_{\text{Pl}}/R_H)^2 \sim 10^{-122}$.

The main result of the paper is the isolation of the ODTOE causal layer between operator ontology and metric phenomenology. This layer should become the basis for a further strict derivation of the tensor structure of gravity, of the Bianchi identities $\nabla_\mu G^{\mu\nu} = 0$ as a Noether consequence of the diffeomorphism invariance of Φ-self-consistency [21], and of the microscopic coefficient χ_Λ via the global cosmological coherence S^* from [10].

APPENDIX A: SUMMARY OF MAIN FORMULAS

Formula	Meaning	Number
$R = \hat{O}(\Psi)$	Actualization of reality by the observation operator	1.2

$\Phi = \iota \circ \hat{O}$	Self-observational loop	1.3
$A(\Delta d) = \varphi^{-\lvert\Delta d\rvert}$	Accessibility between recursion levels	2.2
$v = \alpha/(I + \varepsilon)$	Reconfiguration rate	2.4
$c = r_0/\tau_0$	Limiting speed of the actualization front	2.6
$C_i \preceq_O C_j$	Causal reachability of configurations	3.1
$g_{00}^{\mathrm{eff}} = (I_0/I_{\mathrm{eff}})^2$	Temporal component of the effective metric	6.2
$I_{\mathrm{eff}} = I_0/\sqrt{1 - 2\Pi_I/c^2}$	Inertial form of gravitational time dilation (see footnote in §V.1: [10] §IX denotes this scalar Φ_I)	5.2
$r_s = 2GM/c^2$	Horizon as the boundary $I(C) \to \infty$	6.4
$\rho_{\Lambda,E}^{\mathrm{ODTOE}} = \chi_\Lambda \rho_{\mathrm{Pl},E}(\ell_{\mathrm{Pl}}/R_H)^2$	Horizon suppression of the vacuum contribution	12.9
$v_{\mathrm{GW}} = c$	Speed of SYNC perturbations in the macroscopic limit	10.3

ACKNOWLEDGMENTS AND TOOLS

The author thanks participants of the ODTOE project for discussions on the nature of causality, light, gravity, and horizons. The structure and technical verification of the text were prepared using LaTeX, Python, and AI-assisted editing tools.

CONFLICT OF INTEREST

The author declares no conflict of interest.

FUNDING

This work was carried out without external funding.

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