Gravity in ECSM: An Ordinary-Three-Dimensional Coherent Recovery of General Relativity

Effective gravitational sector and conditional finite-response strong-field extension

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Abstract

We formulate the effective gravitational sector of the Emergent Condensate–Superfluid Medium (ECSM) programme in ordinary three-dimensional physical space. An evolution parameter orders change but is not a fourth physical direction. The formulation takes as inputs a coherent finite-response medium, stable localized excitations, a response-speed bound c_R, and universal coherent matter coupling; these inputs have not all been derived from a single microscopic parent. In the proposed interpretation, matter changes local medium burden, stress, and transport, affecting the dressing and acceleration of other excitations. A weak longitudinal response is accompanied by clock, electromagnetic, and rotational sectors. For the nonlinear *ideal coherent branch*, we adopt an effective constitutive action with process-rate, symmetric collective-response, and transport variables. Its constrained equations are constructed to coincide mathematically with the ADM form of general relativity. This is exact recovery *within the adopted effective action*, not a derivation of that action from ECSM microphysics. Nonzero finite-length and memory corrections instead give approximate GR recovery only where the corresponding dimensionless terms are negligible. A bounded material-capacity functional and finite-response constitutive laws specify a *candidate* strong-field extension, but neither a common nonlinear action covering all sectors nor a physical material-state prescription and constraint-preservation analysis has yet been completed. The compactness curves shown here are conditional stationary diagnostics, not universal saturation predictions; no parameter-fixed family of stable compact-object interiors has been solved. We state the recovery limits, open derivations, and quantitative tests required to falsify the proposal.

Keywords: emergent gravity; general relativity; finite-response medium; ordinary three-dimensional space; coherent recovery; material response; strong-field gravity; ECSM

1 Introduction

General relativity (GR) provides the most successful classical description of gravitation. Its predictions have survived precision tests ranging from gravitational redshift and solar-system dynamics to binary pulsars, gravitational waves and horizon-scale imaging. The modern experimental situation therefore places a severe requirement on any alternative framework: it

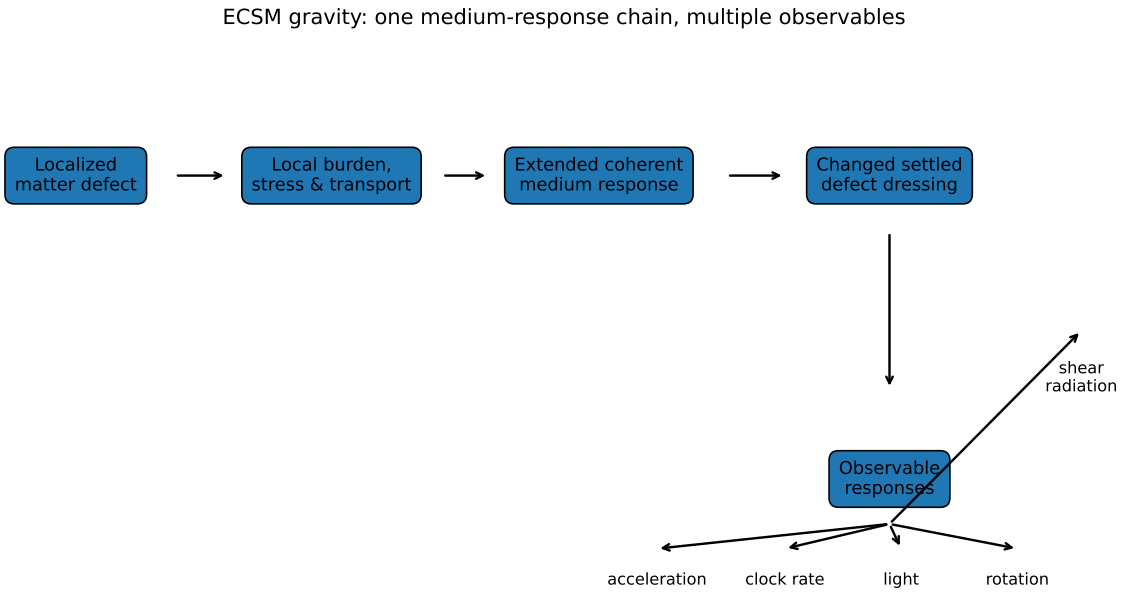

Figure 1: Canonical ECSM gravity mechanism. A localized matter excitation changes the common medium's burden, stress and transport state; coherent coupling produces an extended response; the changed settled dressing of other excitations yields acceleration and the same response projects into clock, optical, rotational and transverse-shear observables.

must recover GR extremely accurately wherever GR is already well tested, while identifying a physically motivated regime in which a departure could occur.

ECSM approaches this problem from a different ontological starting point. Physical space is taken to be ordinary three-dimensional extension. An evolution parameter λ orders successive physical states but is not treated as an additional physical dimension. Matter is not a second substance inserted into an otherwise empty arena; it is represented as a persistent localized excitation of a common coherent medium. The medium possesses finite stiffness, finite response speed, finite response time and finite constitutive capacity. Time measured by clocks is consequently treated as a rate of physical change rather than as a fundamental coordinate substance.

The gravitational question is then not posed as "how does matter curve spacetime?" but as a response problem:

localized matter excitation → local burden, stress and transport change → extended coherent response → changed equilibrium dressing of other matter → acceleration.

The central requirement of this paper is that each arrow in this chain be represented by an explicit functional or variational relation.

The aim is not to replace one unexplained primitive gravitational force with another. The medium itself and a small number of its constitutive properties are allowed to be primitive, just as every physical theory must stop at some foundational layer. Gravity, however, is required to be downstream of those medium properties.

Earlier ECSM work developed several components of this programme separately: a finite longitudinal response and inertial dressing; an ordinary-three-dimensional non-geometric treatment of clock rates and optical propagation; rotational response; weak tensor/shear transport; local Lorentz recovery; and an earlier strong-field extension written in a metric-first language. These sector developments are documented in the coherence, core-architecture, local-Lorentz,

electromagnetic-response and beyond-coherent-limit papers [18–22]. The hostile-audit revision of the ECSM core subsequently sharpened the claim boundary: universal coherent-response relations are foundational/calibrated closures of the effective coherent branch rather than microscopic theorems; the common-speed statement applies to physical characteristics rather than to a universal coefficient ratio; and local constitutive strain must be distinguished from the gapless radiative shear-transport modes [1–6].

The present paper consolidates these developments into a focused ECSM gravitational sector. It is not intended to be a theorem paper for the whole ECSM programme. The construction has four main goals.

First, gravity must have an ECSM-native causal mechanism in ordinary three-dimensional variables. Second, the coherent branch must reproduce the tested observables of GR without treating spacetime geometry as the physical cause. Third, the gravitational sector must contain the correct constrained degrees of freedom and two propagating transverse modes. Fourth, the theory must specify how the coherent continuation fails when the medium reaches finite capacity or cannot reconfigure quickly enough.

The result is an effective gravitational theory conditional on clearly stated upstream ECSM inputs, not a claimed microscopic derivation of the entire programme. The coherent branch is intentionally GR-equivalent in its observables. Consequently its agreement with Mercury, Shapiro delay, binary pulsars or gravitational-wave phasing is a recovery requirement rather than independent evidence for ECSM. The discriminating content lies instead in finite-response effects that cannot be freely retuned for individual datasets.

2 Scope, ontology and epistemic classification

2.1 Physical ontology

The physical ontology used in this paper is deliberately narrow:

1. physical extension is ordinary three-dimensional space;
2. λ orders the succession of medium states;
3. an unloaded coherent reference laboratory fixes the operational normalization $d\tau_{\mathrm{ref}} = d\lambda$ and the spatial unit;
4. the coherent response-speed bound is denoted c_R;
5. matter is represented as a stable localized excitation of the same medium;
6. relativistic geometric objects may be introduced only after ECSM observables have been derived, and then only as comparison variables.

No fundamental spacetime metric, spacetime curvature, geodesic law, graviton ontology or spacetime gravitational wave is assumed.

2.2 Boundary of the gravity paper

This paper deliberately separates the gravitational problem from the wider ECSM theorem programme. The division of labour is:

Status in this paper	Content
Upstream ECSM inputs	common-medium ontology; matter as stable localized excitations; coherent response-speed bound c_R; universal normalized coherent coupling/UCRP; existence of a long-wavelength collective response sector.
Gravity-sector construction	weak longitudinal response; matter acceleration as dressing-energy response; clock, optical and rotational response; nonlinear coherent gravity closure; constraint and radiation structure; downstream GR comparison; finite-capacity strong-field extension.
Outside present scope	microscopic derivation of the complete stable-particle spectrum; proof of universal coupling from that spectrum; reduction of every collective coefficient from the microscopic parent; Standard-Model completion; homogeneous cosmology; full merger numerics.

The upstream items are not presented as results of this paper. Conversely, the fact that they remain subjects of the broader ECSM programme does not prevent the gravitational sector from being formulated and tested as an effective theory, just as a sector paper may legitimately work from a previously defined matter model or constitutive principle without rederiving the whole parent theory.

2.3 Statement classes

To prevent recovery results from being mistaken for novel predictions, every central statement falls into one of five classes.

Foundational closure. A constitutive property adopted at the effective ECSM level. Examples include universal normalized coherent source coupling and finite constitutive capacity.

Definition. An operational or mathematical definition of an ECSM variable, such as the burden B or collective response tensor C_{ij}.

Derived consequence. A result obtained from the frozen effective equations, such as the inverse-radius exterior of the longitudinal response or the two-mode tensor sector.

Downstream comparison. A mapping to familiar GR/SR quantities after ECSM observables have been derived. PPN parameters and the effective comparison line element belong here.

Open downstream calculation. A numerical or microscopic problem that does not require a new gravitational law, such as a full rapidly rotating saturated interior or a binary merger evolution.

This classification follows the hostile-audit standard already adopted in the ECSM Core V1.0 revision [1].

2.4 Foundational gravity assumptions

The gravitational sector used here takes four principal gravity-level inputs/closures. Their deeper derivation, where applicable, belongs to the wider ECSM parent programme.

A1. Common-medium matter. Stable matter is a localized excitation of the same coherent finite-response medium that carries long-range response.

A2. Universal coherent response. Stable matter excitations possess a universal normalized long-range coupling in the coherent branch, and coherent clocks, electromagnetic propagation,

rotational response and long-range stress transport share the appropriate common response structure. This is the UCRP-level closure, not a microscopic theorem [2].

A3. Single relational update closure. Different local decompositions of the same physical update must compose consistently, with differences represented only by ordinary three-dimensional relabelling. Under the locality and two-derivative assumptions used below, this selects the coherent kinetic and spatial response structure. This is mathematically analogous to the closure logic underlying canonical reconstructions of GR, including the Hojman-Kuchar-Teitelboim result, but is interpreted here as a rule for three-dimensional medium-state updates rather than as a statement that spacetime is fundamental [7, 8].

A4. Finite constitutive capacity and response. The medium has a finite allowed response load and a finite dynamical response kernel. The unlimited coherent continuation is therefore not physically admissible once the capacity surface is reached.

The paper does not claim that A1–A4 have all been derived from deeper constituents. They define the present effective stopping level.

3 Weak non-geometric gravity from finite longitudinal response

3.1 Longitudinal response action

A representative weak longitudinal sector is

$$S_\phi = \int d\lambda\, d^3x \left\{ \frac{A}{2}\left[\dot{\phi}^2 + \ell_\phi^2 |\nabla\dot{\phi}|^2\right] - \frac{\kappa}{2}\left[|\nabla\phi|^2 + \ell_\phi^2 (\nabla^2\phi)^2\right] + g\, n_m \phi \right\}. \tag{1}$$

Variation yields

$$(1 - \ell_\phi^2 \nabla^2)\left(A\ddot{\phi} - \kappa\nabla^2\phi\right) = g\, n_m. \tag{2}$$

The equation is a finite-response medium equation. A localized matter source changes the medium state; gravity has not yet been introduced as a force.

For a point source in the static limit,

$$\phi(r) = \frac{g}{4\pi\kappa r}\left(1 - e^{-r/\ell_\phi}\right). \tag{3}$$

At distances much greater than the smoothing length, this illustrative static response approaches 1/r, with an inverse-square gradient. At finite smoothing length it differs from the exact ADM/GR branch; their nonlinear matching is not derived here (Appendix C).

For identical response cells the observable gravitational combination is

$$G_{\text{eff}} = \frac{g^2}{4\pi\kappa m_I^2}, \tag{4}$$

or, more generally, in invariant source notation,

$$G_{\text{eff}} = \frac{G_0^2}{4\pi K_\phi}, \tag{5}$$

where $G_0 = Q_\phi/m_I$ is the universal coherent source-charge to inertial-mass ratio [1, 2]. Only such invariant combinations are observable; field normalization alone is not.

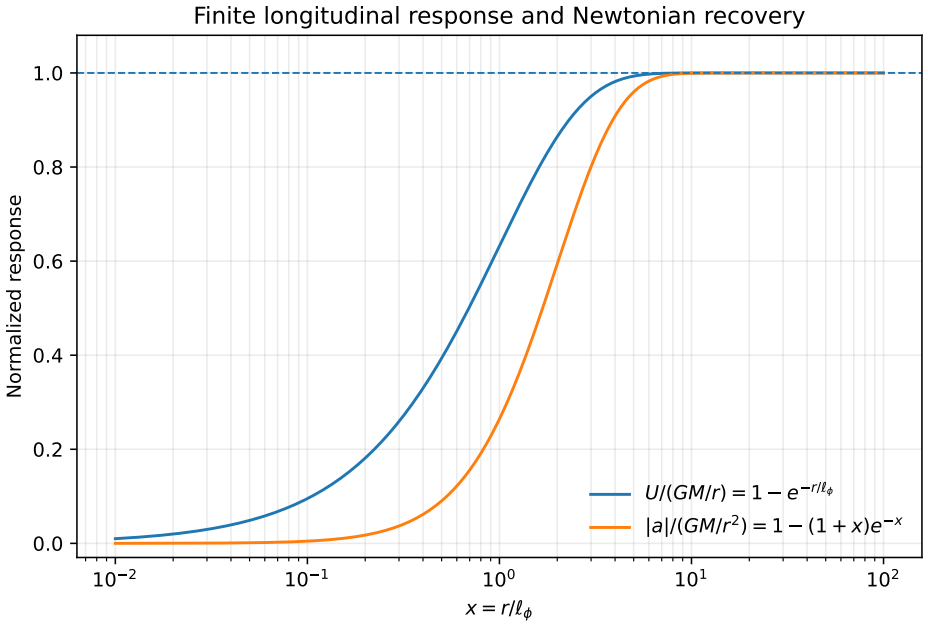

Figure 2: Finite longitudinal response. The normalized static potential and acceleration approach the Newtonian forms exponentially for $r \gg \ell_\phi$ while remaining smoothed at short distance. No observational data are fitted in this figure; both curves are direct consequences of Eq. (3).

Define the positive ECSM potential

$$U \equiv \frac{g}{m_I}\phi, \tag{6}$$

so that at long range

$$U(r) = \frac{GM}{r}. \tag{7}$$

The conventional Newtonian potential is $\Phi = -U$.

3.2 Weak acceleration as dressing-energy response

A stable matter excitation has a settled kinetic and internal dressing state. In a slowly varying weak background, the collective-coordinate Lagrangian takes the form

$$L_A = -m_A c_R^2 + \frac{1}{2} m_A v^2 + m_A U + \cdots . \tag{8}$$

Therefore

$$\mathbf{a} = \nabla U + O\left(B^2, \frac{Bv^2}{c_R^2}, \text{finite-response terms}\right), \tag{9}$$

where

$$B \equiv \frac{U}{c_R^2}. \tag{10}$$

For $U = GM/r$,

$$\mathbf{a} = -\frac{GM}{r^2}\hat{\mathbf{r}}. \tag{11}$$

The physical interpretation is direct. The source excitation changes the equilibrium state of the surrounding medium. A second excitation has a different settled energy at different positions in that response. Motion toward lower settled energy appears macroscopically as gravitational attraction.

The same m_A multiplies the kinetic and static response terms in Eq. (8), so the test-body mass cancels from Eq. (9). Universal free fall at this effective level is therefore a consequence of a shared dressed matter response once the universal source normalization of A2 is imposed. The universality itself remains a constitutive closure that must ultimately be explained by deeper matter microphysics.

4 Universal coherent response: clocks, optics and rotation

4.1 Process-rate response

The coherent burden B is operationally normalized through a stable matter clock:

$$R_\tau(B) = e^{-B}. \tag{12}$$

For identical stationary clocks,

$$1 + z = e^{B_e - B_o}. \tag{13}$$

In the weak field, $B = -\Phi/c_R^2$, giving

$$\frac{\Delta\nu}{\nu} = \frac{\Delta\Phi}{c_R^2} + O(B^2). \tag{14}$$

Thus acceleration and clock slowing are not assigned separate gravitational causes. Both depend on the same local burden variable.

4.2 Electromagnetic constitutive response

The corrected split electromagnetic action is

$$\mathcal{L}_{\mathrm{EM}} = \frac{\epsilon_* Z_E}{2}E^2 - \frac{Z_B}{2\mu_*}B_{\mathrm{em}}^2, \qquad \epsilon_*\mu_* = c_R^{-2}. \tag{15}$$

UCRP-1 assigns reciprocal amplitudes to the electric and magnetic constitutive sectors. In the coherent weak branch,

$$Z_E = Z_c e^{2B}, \qquad Z_B = Z_c e^{-2B}. \tag{16}$$

The coordinate propagation index is therefore

$$n_{\mathrm{opt}}^2 = \frac{Z_E}{Z_B}, \qquad n_{\mathrm{opt}} = e^{2B}. \tag{17}$$

Equation (17) is an exact identity of the reduced weak UCRP model. It is not assumed to remain an exact all-orders strong-field identity once the full nonlinear collective response becomes important.

To leading order,

$$n_{\rm opt} = 1 + \frac{2GM}{c_R^2 r} + O(B^2), \tag{18}$$

which yields the standard leading light-deflection coefficient,

$$|\alpha| = \frac{4GM}{bc_R^2}, \tag{19}$$

and the corresponding leading Shapiro delay. The local observer still measures the common coherent speed after clock and ruler co-response; $n_{\rm opt}$ is a propagation quantity relative to the asymptotically normalized coordinates, not a claim that local vacuum optics behaves like an ordinary dielectric laboratory medium [1, 2].

The weak expansions

$$R_\tau = 1 - \zeta_\tau B + q_\tau B^2 + \cdots, \qquad \Psi_{\rm opt} = \eta_B B + \cdots \tag{20}$$

give

$$\zeta_\tau = 1, \qquad q_\tau = \frac{1}{2}, \qquad \eta_B = 2. \tag{21}$$

The downstream PPN dictionary then yields

$$\gamma_{\rm eq} = 1, \qquad \beta_{\rm eq} = 1. \tag{22}$$

These are coherent recovery consequences, not independent empirical predictions of ECSM.

4.3 Rotational response

Let

$$\Omega_W \equiv -\frac{1}{2}\nabla \times \mathbf{W}. \tag{23}$$

The weak UCRP rotational response can be written as a three-dimensional response-cost functional in which longitudinal acceleration burden and rotational burden share the appropriate coherent normalization. Variation gives the transverse equation

$$\nabla^2 \mathbf{W} = \frac{16\pi G}{c_R^2}\,\mathbf{j}_T. \tag{24}$$

For localized angular momentum $\mathbf{J}$,

$$\mathbf{W}_{\rm far} = -\frac{2G}{c_R^2}\frac{\mathbf{J}\times\mathbf{r}}{r^3} + \cdots. \tag{25}$$

Frame-dragging-like precession is therefore interpreted as medium rotational/transport response rather than literal dragging of physical spacetime [2].

5 Nonlinear coherent gravity in ordinary three-dimensional variables

The weak scalar and rotational sectors are not by themselves sufficient to reproduce the complete relativistic gravitational phenomenology. A nonlinear collective response tensor is required.

5.1 Collective response variables

The coherent gravitational state is represented by

$$\mathcal{X}_G = \{N, C_{ij}, W^i\}. \tag{26}$$

Here

- N = exp(-B) is an effective process-rate variable, not by itself a material load (Appendix C.4);
- C_{ij} is a positive symmetric collective constitutive-response tensor on ordinary three-space;
- W^i is the local transport/circulation response.

C_{ij} is not identified with the local microscopic strain variable q_{ij} of the broader ECSM parent. The local constitutive strain may possess restoring terms and gapped dynamics. The gapless gravitational shear modes are long-wavelength normal modes of the collective stress-response kernel [1].

Define

$$K_{ij} \equiv \frac{1}{2Nc_R}\left(\dot{C}_{ij} - \mathcal{L}_W C_{ij}\right), \qquad K = C^{ij}K_{ij}. \tag{27}$$

K_{ij} measures the objective rate of collective constitutive deformation after transport by W^i has been removed.

Let $\mathcal{R}_C$ denote the intrinsic three-dimensional second-derivative incompatibility scalar constructed from C_{ij}. Mathematically it is the Ricci scalar of the positive three-dimensional tensor C_{ij}; physically it is interpreted only as a measure of mismatch among neighbouring collective response states. No physical spacetime curvature is asserted.

5.2 Coherent action and relational-update closure

The coherent action is

$$\boxed{S_G^{\mathrm{coh}} = \frac{c_R^4}{16\pi G}\int d\lambda\, d^3x\, N\sqrt{C}\left[\mathcal{R}_C + K_{ij}K^{ij} - K^2\right].} \tag{28}$$

Equation (28) is the central ECSM-G coherent equation.

The relative kinetic coefficient is significant. A more general quadratic rate term $K_{ij}K^{ij} - \lambda_K K^2$ generically propagates an additional scalar or requires an extra preferred update structure. The present closure adopts the single-relational-update condition A3: different local decompositions of a physical update must close into ordinary three-dimensional relabelling rather than create an independent scalar gravitational update. Under the locality and two-derivative assumptions used here, this selects the DeWitt kinetic combination with $\lambda_K = 1$ and the minimal spatial incompatibility scalar $\mathcal{R}_C$. This is closely related mathematically to the canonical closure results

of ADM and Hojman, Kuchar and Teitelboim [7, 8]. In ECSM the result is interpreted as a closure of medium-state updates, not as evidence that spacetime itself is fundamental.

Equation (28) is therefore best regarded as the principal *gravity-level constitutive closure* of this paper. It is not claimed here to have been obtained by integrating the microscopic strain variable q_{ij} and all other parent modes out of a solved ECSM microphysical model. The single-relational-update condition A3 motivates the choice and fixes the desired constrained coherent structure within the stated locality and derivative assumptions, while empirical recovery fixes its normalization. The fact that Eq. (28) is ADM-equivalent is intentional: this paper asks for an ECSM gravitational sector whose coherent branch reproduces the observed GR dynamics. A companion parent-reduction theorem would be required to show that this particular collective action is forced by deeper ECSM microphysics rather than adopted as the effective gravitational constitutive law.

5.3 Matter source projections

For arbitrary coherent matter variables Ψ, take

$$S_m = \int d\lambda\, d^3x\, N\sqrt{C}\,\mathcal{L}_m\Big(\Psi, N^{-1}D_\lambda\Psi, C^{ij}\partial_i\Psi\partial_j\Psi, \ldots\Big), \tag{29}$$

with

$$D_\lambda \equiv \partial_\lambda - \mathcal{L}_W. \tag{30}$$

Define the native source projections variationally:

$$\varepsilon \equiv -\frac{1}{\sqrt{C}}\frac{\delta S_m}{\delta N}, \tag{31}$$

$$j_i \equiv \frac{1}{\sqrt{C}}\frac{\delta S_m}{\delta W^i}, \tag{32}$$

and

$$\Sigma^{ij} \equiv \frac{2}{N\sqrt{C}}\frac{\delta S_m}{\delta C_{ij}}. \tag{33}$$

The normalization of j_i may equivalently be absorbed into its definition; the convention above is chosen to give the constraint form below. These objects are three-dimensional energy/burden density, momentum-current density and stress. A four-dimensional stress-energy tensor is not a primitive ECSM object. The quantities in Eqs. (31)–(33) are effective gravitational source projections; calculating them for a specific microscopic ECSM defect or Standard-Model field is an upstream matter-sector task rather than a derivation attempted in this paper.

5.4 Constraint equations

Variation with respect to N gives

$$\boxed{\mathcal{R}_C + K^2 - K_{ij}K^{ij} = \frac{16\pi G}{c_R^4}\varepsilon.} \tag{34}$$

Variation with respect to W^i gives

$$\nabla_j \left(K^{ij} - C^{ij} K \right) = -\frac{8\pi G}{c_R^3} \, j^i. \tag{35}$$

N and W^i do not possess independent kinetic terms. They enforce one scalar and three momentum constraints.

Variation with respect to C_{ij} supplies the nonlinear evolution equation. A convenient form is

$$\frac{1}{c_R}(\partial_\lambda - \mathcal{L}_W) K_{ij} = \nabla_i \nabla_j N - N \left[\mathcal{R}_{ij} + K K_{ij} - 2 K_{ik} K^k_j \right] + \mathcal{S}_{ij}, \tag{36}$$

where the matter-source contribution is

$$\mathcal{S}_{ij} \equiv \frac{8\pi G N}{c_R^4} \left[\Sigma_{ij} - \frac{1}{2} C_{ij} (\Sigma - \varepsilon) \right].$$

up to equivalent rearrangements obtained by using the scalar constraint. Here $\Sigma = C^{ij} \Sigma_{ij}$.

Equations (34)–(36) are the complete coherent ECSM-G gravitational system at effective level.

6 Degrees of freedom, pressure sourcing and gravitational radiation

6.1 Degree-of-freedom count

The symmetric tensor C_{ij} contains six configuration variables and six conjugate momenta. One scalar and three vector first-class constraints remove eight phase-space dimensions. The physical phase space therefore has

$$12 - 2 \times 4 = 4 \tag{37}$$

dimensions, corresponding to

$$\boxed{\text{2 propagating gravitational configuration modes.}} \tag{38}$$

The burden and transport responses remain physically observable through constrained fields but do not introduce additional freely propagating weak gravitational polarizations.

6.2 Pressure and stress as sources

For a static weak configuration $K_{ij} = 0$. Combining the scalar constraint with the trace of Eq. (36) gives

$$\nabla^2 B = -\frac{4\pi G}{c_R^4} (\varepsilon + \Sigma). \tag{39}$$

For isotropic pressure, $\Sigma = 3p$, so

$$\boxed{\nabla^2 B = -\frac{4\pi G}{c_R^4}(\varepsilon + 3p).} \tag{40}$$

For nonrelativistic matter $\varepsilon \simeq \rho c_R^2$ and $p \ll \rho c_R^2$, giving the ordinary Poisson equation. Pressure therefore contributes because it is physical stress stored in the same response system; it is not added as a separate relativistic correction by hand.

6.3 Linearized shear sector

Set

$$C_{ij} = \delta_{ij} + h_{ij} \tag{41}$$

and impose the scalar and vector constraints. The propagating transverse-traceless part satisfies

$$\partial_i h_{ij}^{TT} = 0, \qquad h_{ii}^{TT} = 0. \tag{42}$$

The quadratic action becomes

$$\boxed{S_{TT}^{(2)} = \frac{c_R^4}{64\pi G}\int d\lambda\, d^3x \left[\frac{\dot{h}_{ij}^{TT}\dot{h}_{ij}^{TT}}{c_R^2} - \partial_k h_{ij}^{TT}\partial_k h_{ij}^{TT}\right].} \tag{43}$$

Hence

$$\boxed{\left(\frac{1}{c_R^2}\partial_\lambda^2 - \nabla^2\right) h_{ij}^{TT} = +\frac{16\pi G}{c_R^4}\Sigma_{ij}^{TT}.} \tag{44}$$

The coherent branch therefore contains two gapless transverse shear/stress-transport modes propagating at

$$c_T = c_R. \tag{45}$$

In ECSM ontology these are disturbances of the common medium, not waves of physical spacetime.

6.4 Quadrupole radiation

For a slow isolated source,

$$h_{ij}^{TT}(r,\lambda) = \frac{2G}{c_R^4 r}\ddot{Q}_{ij}^{TT}\left(\lambda - \frac{r}{c_R}\right). \tag{46}$$

The energy flux of Eq. (43) gives

$$\boxed{P_{\mathrm{GW}} = \frac{G}{5c_R^5}\left\langle \dddot{Q}_{ij}\,\dddot{Q}_{ij}\right\rangle.} \tag{47}$$

Thus the same G controls weak attraction and coherent gravitational radiation. The 1/5 quadrupole coefficient is a consequence of the two-mode coherent action once universal source normalization is imposed, not an independently fitted radiation constant.

7 General relativity as a downstream coherent comparison

7.1 Comparison dictionary

Only after N, C_{ij} and W^i have been assigned their ECSM physical meanings do we define the comparison line element

$$ds^2_{\rm eq} = -N^2 c_R^2 d\lambda^2 + C_{ij}(dx^i + W^i d\lambda)(dx^j + W^j d\lambda). \tag{48}$$

Equation (48) is a mathematical packaging of already-defined ECSM observables. It is not asserted to be a fundamental physical spacetime.

The key mathematical result is that Eq. (28) is exactly the ADM form of the Einstein gravitational action for the comparison variables in Eq. (48), up to the standard spatial boundary contribution [7, 8]. Consequently the coherent ECSM equations are mathematically equivalent to the Einstein equations written for the comparison object:

$$\boxed{\text{ECSM coherent response equations} \Longleftrightarrow G_{\mu\nu}[g_{\rm eq}] = \frac{8\pi G}{c_R^4} T^{\rm eq}_{\mu\nu}.} \tag{49}$$

Equation (49) is a recovery theorem, not an ontological identification.

With the explicitly adopted A3 closure, the pure two-derivative coherent action (28) is GR-equivalent. This exact statement applies to that ideal action, not automatically to the finite-length kernel (1)-(3), the retarded response or capacity terms. At nonzero smoothing length and response time, recovery is approximate when the corresponding dimensionless corrections are negligible; see Appendix C.

7.2 Post-Newtonian recovery

For a static weak spherical source define

$$u(r) = \frac{GM}{c_R^2 r}. \tag{50}$$

The coherent exterior gives, in isotropic form,

$$N = 1 - u + \frac{1}{2}u^2 + O(u^3), \tag{51}$$

and

$$C_{ij} = \left(1 + 2u + \frac{3}{2}u^2 + \cdots\right)\delta_{ij}. \tag{52}$$

The matter packet reduction yields

$$L = -mc_R^2 + \frac{1}{2}mv^2 + mU + \frac{m}{c_R^2}\left[\frac{1}{8}v^4 + \frac{3}{2}Uv^2 - \frac{1}{2}U^2\right] + \cdots, \tag{53}$$

which gives the standard coherent 1PN periapsis advance

$$\Delta\varpi = \frac{6\pi GM}{a(1-e^2)c_R^2}. \tag{54}$$

The PPN comparison coefficients are

$$\gamma = 1, \qquad \beta = 1, \tag{55}$$

with the coherent preferred-frame and nonconservative PPN parameters vanishing in the ideal A3 branch. ECSM does not claim that a microscopic background rest state is observationally absent to all orders; preferred-frame residuals away from coherence remain a falsification channel.

7.3 Exact coherent spherical exterior

In isotropic radius ρ, define

$$x = \frac{GM}{2c_R^2\rho}. \tag{56}$$

The coherent vacuum solution is

$$N = \frac{1-x}{1+x}, \tag{57}$$

$$C_{ij} = (1+x)^4\delta_{ij}, \tag{58}$$

$$W^i = 0. \tag{59}$$

The process burden is therefore

$$B = \ln\frac{1+x}{1-x}. \tag{60}$$

The weak equality between the scalar burden and the isotropic spatial response is not an exact strong-field identity; the nonlinear response contains distinct temporal and spatial collective components.

7.4 Coherent rotating exterior

The same equations admit the rotating vacuum branch whose comparison representation is Kerr. In a Boyer-Lindquist-type comparison chart, let

$$\mu = \frac{GM}{c_R^2}, \qquad a = \frac{J}{Mc_R}, \tag{61}$$

$$\Sigma = r^2 + a^2\cos^2\theta, \qquad \Delta = r^2 - 2\mu r + a^2, \tag{62}$$

$$A = (r^2+a^2)^2 - a^2\Delta\sin^2\theta. \tag{63}$$

The corresponding comparison variables may be written

$$N = \sqrt{\frac{\Sigma\Delta}{A}}, \tag{64}$$

$$C_{rr} = \frac{\Sigma}{\Delta}, \quad C_{\theta\theta} = \Sigma, \quad C_{\phi\phi} = \frac{A \sin^2\theta}{\Sigma}, \tag{65}$$

with azimuthal transport proportional to

$$W^{\phi} = -\frac{2\mu a r c_R}{A}, \tag{66}$$

up to the orientation sign convention of Eq. (48). In ECSM this describes coupled rotational transport and anisotropic constitutive response, not rotating physical space.

8 Finite constitutive capacity: candidate strong-field extension

GR-equivalent coherence cannot by itself distinguish ECSM experimentally. The extension below is a conditional material-response ansatz, not yet one nonlinear completion of the full coherent gravity and matter system.

8.1 Physical load coordinates

Let Z^A denote canonically normalized local departures from an unloaded *physical medium state*, including appropriate combinations of

$$B_{\mathrm{mat}}, \quad Q^i{}_j, \quad \delta n, \quad \delta\chi, \ldots, \tag{67}$$

where

$$Q^i{}_j = \frac{1}{2}\left[\ln\left(\bar{C}^{-1}C\right)\right]^i{}_j \tag{68}$$

is a candidate logarithmic collective strain relative to a specified reference state $\bar{C}_{ij}$. Identifying that collective variable with a microscopic material deformation remains a parent-reduction task.

Let G_{AB} be a positive physical response matrix to be derived from the stable parent Hessian. Define the local load

$$\mathcal{Y}^2 = Z^A G_{AB} Z^B. \tag{69}$$

The following expression is *schematic*; every term must have a physical medium definition and compatible units, with positive channel weights incorporated in G_{AB}:

$$\begin{aligned} \mathcal{Y}^2 \supset\; & B_{\mathrm{mat}}^2 + \mathrm{tr}(Q_{\mathrm{mat}}^2) + \ell_{\mathrm{sat}}^2 |\nabla_{\mathrm{mat}} B_{\mathrm{mat}}|^2 \\ & + (c_R \tau_{\mathrm{resp}})^2 \|K_{\mathrm{mat}}\|^2 + \frac{|\mathbf{v}_{\mathrm{rel}}|^2}{c_R^2} + \cdots . \end{aligned} \tag{70}$$

The proposed finite-capacity admissibility condition is

$$\mathcal{Y} \le \mathcal{Y}_{\mathrm{cap}} < \infty. \tag{71}$$

Neither $\mathcal{Y}_{\mathrm{cap}}$ nor the material-state map is fixed by the ADM lapse or by existing observations.

8.2 Capacity as a variational inequality

Conditional on a well-defined material-state functional, extremize the medium response subject to Eq. (71), with normal reaction multiplier Λ. The associated complementarity conditions are

$$\Lambda \geq 0, \tag{72}$$

$$\mathcal{Y}^2 - \mathcal{Y}_{\mathrm{cap}}^2 \leq 0, \tag{73}$$

$$\Lambda(\mathcal{Y}^2 - \mathcal{Y}_{\mathrm{cap}}^2) = 0. \tag{74}$$

A representative constitutive evolution equation takes the schematic form

$$\begin{aligned} I_{AB} D_\lambda^2 Z^B - K_{AB} \nabla_C^2 Z^B + \partial_A U_0 + \Lambda G_{AB} Z^B \\ + \int^\lambda \Gamma_{AB}(\lambda - \lambda') D_{\lambda'} Z^B \, d\lambda' = J_A. \end{aligned} \tag{75}$$

The capacity multiplier vanishes away from the active boundary; this does *not* eliminate independent finite-length or retarded-response corrections. Exact GR equivalence applies to the adopted ideal coherent ADM-equivalent action. The distinct weak-response sector agrees approximately for $k\ell_\phi \ll 1$ and negligible relevant memory corrections. The common nonlinear action, material-state prescription, and preservation of all coupled constraints are not yet established (Appendix C).

8.3 Conditional stationary burden and finite capacity

For a static, zero-transport *comparison* description, the stationary clock-rate diagnostic is

$$B_{\mathrm{stat}} = -\ln N. \tag{76}$$

This is not a local material scalar under arbitrary re-slicing. Only if a separately specified medium-rest state yields a physical burden B_{mat} with a strictly positive load coefficient g_B may one assert

$$\mathcal{Y}^2 \geq g_B B_{\mathrm{mat}}^2, \qquad g_B > 0. \tag{77}$$

The resulting conclusion is conditional:

$$\begin{array}{c} \text{An unbounded physical material burden is inadmissible} \\ \text{under the specified finite-capacity functional.} \end{array} \tag{78}$$

A vanishing static lapse by itself neither proves saturation nor rules out a causal horizon. An operational material reference and transformation rule are required (Appendix C).

Separately, an inward medium flow could define a *characteristic trapping condition* when its inward speed meets the local outward disturbance speed:

$$|u_n| = c_{\mathrm{eff}}. \tag{79}$$

This is a candidate response-boundary diagnostic, not a consequence of Eqs. (71)–(78) alone; it permits finite constitutive variables and requires an independent causal propagation analysis.

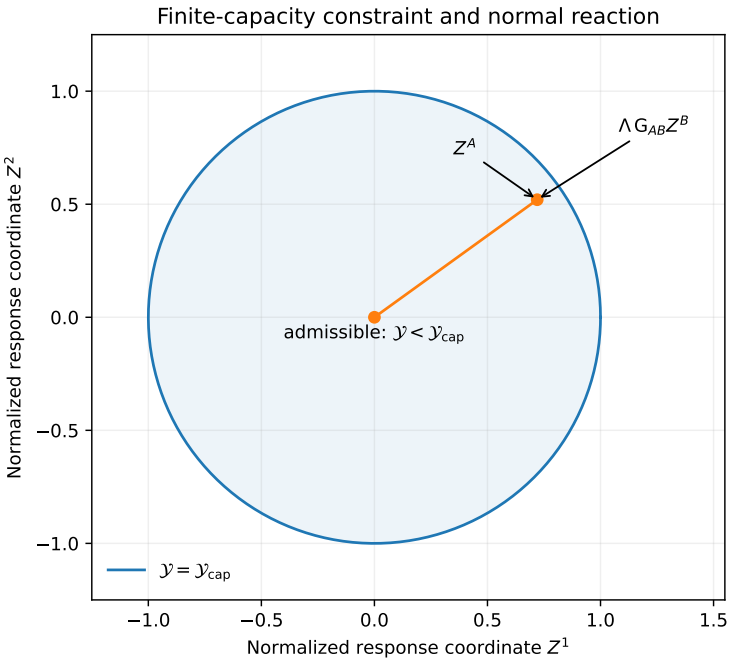

Figure 3: Finite-capacity closure as a variational inequality. The physical response state is restricted to $\mathcal{Y} \leq \mathcal{Y}_{\mathrm{cap}}$. In the interior of the admissible set the multiplier is zero; on the boundary the reaction $\Lambda\, \mathsf{G}_{AB} Z^B$ acts normal to the capacity surface and is solved by the constrained dynamics rather than prescribed as an independent pressure profile.

8.4 Finite response time

The retarded kernel Γ_{AB} in Eq. (75) describes transfer of energy from resolved collective response into unresolved medium modes. The full parent can remain conservative even when the reduced subsystem exhibits damping.

In a one-pole overdamped reduction,

$$K_t \ddot{y} + \Gamma_y \dot{y} + \mu_y^2 y = J_y, \tag{80}$$

with

$$\tau_{\mathrm{resp}} = \frac{\Gamma_y}{\mu_y^2}. \tag{81}$$

The principal mode speeds satisfy

$$c_a^2 = \mathrm{eig}(\mathsf{I}^{-1}\mathsf{K}), \tag{82}$$

and the causal gate is

$$0 < c_a^2 \leq c_R^2. \tag{83}$$

The coherent shear modes saturate the common characteristic c_R; internal amplitude or coherence modes may be slower or gapped.

9 Static spherical response and conditional compact objects

9.1 Spherical response equations

For a static nonrotating state write

$$N(r) = e^{\nu(r)}, \qquad W^i = 0, \tag{84}$$

and use areal gauge for the collective spatial response,

$$C_{ij}dx^i dx^j = \frac{dr^2}{F(r)} + r^2 d\Omega^2, \qquad F(r) = 1 - \frac{2Gm(r)}{c_R^2 r}. \tag{85}$$

For total ECSM energy density ε, radial stress p_r and tangential stress p_t, the coherent gravitational equations reduce to

$$\boxed{\frac{dm}{dr} = \frac{4\pi r^2}{c_R^2}\varepsilon,} \tag{86}$$

$$\boxed{\frac{d\nu}{dr} = \frac{G\left[m + 4\pi r^3 p_r/c_R^2\right]}{c_R^2 r^2\left(1 - 2Gm/c_R^2 r\right)},} \tag{87}$$

and stress balance

$$\boxed{\frac{dp_r}{dr} = -(\varepsilon + p_r)\frac{d\nu}{dr} + \frac{2}{r}(p_t - p_r).} \tag{88}$$

In ECSM these equations describe balance among ordinary-three-dimensional collective response variables. Their mathematical identity with the corresponding GR spherical equations is a consequence of the coherent recovery theorem, not a return to spacetime ontology.

At a regular centre,

$$m(r) = \frac{4\pi\varepsilon_c}{3c_R^2}r^3 + O(r^5), \tag{89}$$

and spherical symmetry requires

$$p_r(0) = p_t(0). \tag{90}$$

If the saturated medium contributions remain finite, the centre is locally regular.

Outside the loaded region,

$$\varepsilon = p_r = p_t = 0, \tag{91}$$

so $m = M$ and

$$F = 1 - \frac{2GM}{c_R^2 r}, \qquad N = \sqrt{1 - \frac{2GM}{c_R^2 r}}, \tag{92}$$

recovering the exact coherent Schwarzschild exterior in areal coordinates.

9.2 Capacity transition compactness: stationary illustration

For illustration only, identify the medium-clock diagnostic with the static-rest response of Eq. (60), normalized at infinity, and suppose it reaches a chosen $B_{\rm cap}$. This identification is *not* a universal, re-slicing-independent material-capacity criterion. Write

$$q = \tanh\left(\frac{B_{\rm cap}}{2}\right). \tag{93}$$

The nominal isotropic transition radius is

$$\rho_* = \frac{GM}{2c_R^2 q}. \tag{94}$$

The corresponding areal compactness of this coherent exterior comparison is

$$\mathcal{C}_* = \frac{GM}{R_* c_R^2} = \frac{2q}{(1+q)^2} < \frac{1}{2}. \tag{95}$$

Within this particular static-rest diagnostic, $\mathcal{C}_*$ is independent of mass if $B_{\rm cap}$ is universal. Requiring the nominal onset to lie within the coherent Schwarzschild photon region yields the illustrative inequality

$$B_{\rm cap} > \ln\sqrt{3} \simeq 0.5493. \tag{96}$$

This is an *exterior comparison*, not a universal physical saturation theorem or a parameter-fixed compact-object prediction. For large $B_{\rm cap}$,

$$\mathcal{C}_* = \frac{1}{2} - \frac{1}{2}e^{-2B_{\rm cap}} + \cdots. \tag{97}$$

Increasing $B_{\rm cap}$ drives this diagnostic toward $\mathcal{C}_* = 1/2$; it does not establish a stable post-transition interior.

9.3 Prior compact-object benchmark

Earlier ECSM strong-field work constructed illustrative shell/core solutions and computed a static tidal benchmark. For a compact-support branch with core fraction $x_c = 0.90$ and compactness

$$\mathcal{C} = \frac{GM}{Rc_R^2} = 0.475, \tag{98}$$

the reduced calculation reported approximately

$$k_2 \simeq 3.74 \times 10^{-5}, \qquad \Lambda_{\rm tidal} \simeq 1.03 \times 10^{-3}. \tag{99}$$

A coupled parent-field perturbation calculation recovered the reduced result in a frozen-field limit, while active parent fields could shift its value. These numbers are *legacy illustrative benchmarks*, not universal predictions of the present capacity ansatz. Because the prior profiles used prescribed stress structures, a parameter-fixed prediction requires solving a common nonlinear finite-response action, material-state constraint, and stability conditions.

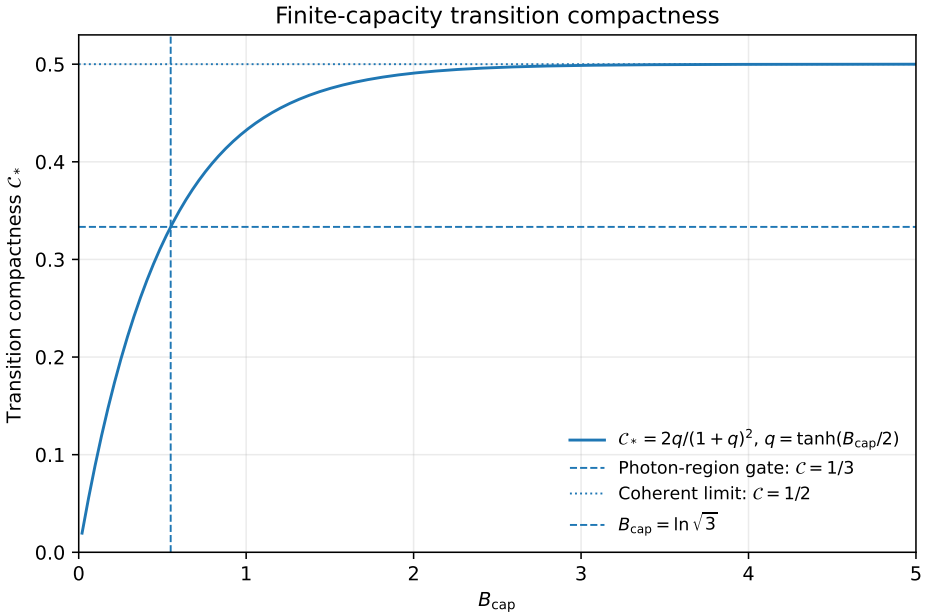

Figure 4: Conditional stationary-exterior capacity diagnostic from Eq. (95). Dotted reference lines show the coherent photon-region and compactness comparison values. The displayed transition radius is illustrative, not a derived material saturation prediction; a physical reference state and a joint nonlinear completion remain outstanding.

10 Dynamic response, tides, ringdown and absorption

The same finite-response operator must control all strong-field deviations. This prevents independent tuning of tidal response, ringdown and reflection.

10.1 Global perturbation operator

After constraints are eliminated, collect the observable coherent shear mode and internal finite-response coordinates into

$$\mathbf{u}_{\ell m} = \begin{pmatrix} \Psi_{\ell m} \\ \boldsymbol{\xi}_{\ell m} \end{pmatrix}. \tag{100}$$

The quadratic perturbation action can be written

$$S_\ell^{(2)} = \frac{1}{2}\int d\lambda\, dr \left[(D_\lambda \mathbf{u})^T \mathbf{M} (D_\lambda \mathbf{u}) - (\partial_r \mathbf{u})^T \mathbf{P} (\partial_r \mathbf{u}) - \mathbf{u}^T \mathbf{H}_\ell \mathbf{u} \right]. \tag{101}$$

In frequency space,

$$\boxed{\mathbf{D}_\ell(\omega) = \mathbf{A}_\ell - \omega^2 \mathbf{M} - i\omega \boldsymbol{\Gamma}(\omega),} \tag{102}$$

where

$$\mathbf{A}_\ell = -\partial_r(\mathbf{P}\partial_r) + \mathbf{H}_\ell. \tag{103}$$

A sufficient nonrotating linear-stability gate is

$$\mathbf{M} > 0, \qquad \mathbf{P} > 0, \qquad \mathbf{H}_\ell \geq 0, \qquad \mathrm{Re}\,\mathbf{\Gamma}(\omega) \geq 0. \tag{104}$$

Under regular and outgoing/dissipative boundary conditions these inequalities exclude exponentially growing linear modes.

10.2 Integrating out internal response

Write the operator in block form,

$$\begin{pmatrix} D_T & \mathbf{C}^\dagger \\ \mathbf{C} & \mathbf{D}_I \end{pmatrix} \begin{pmatrix} \Psi \\ \boldsymbol{\xi} \end{pmatrix} = 0. \tag{105}$$

Eliminating the internal coordinates gives

$$\boxed{[D_T - \Sigma_{\rm ECSM}(\omega)]\,\Psi = 0,} \tag{106}$$

with

$$\boxed{\Sigma_{\rm ECSM}(\omega) = \mathbf{C}^\dagger \mathbf{D}_I^{-1}(\omega)\mathbf{C}.} \tag{107}$$

The same self-energy modifies tidal response, ringdown frequencies, damping, absorption and reflection.

10.3 Dynamic Love response

For an external quadrupolar tidal field,

$$Q_{2m}(\omega) = -\lambda_2(\omega)\mathcal{E}_{2m}(\omega). \tag{108}$$

The susceptibility takes the generic form

$$\lambda_2(\omega) = \lambda_{\rm contact} + \mathbf{b}^\dagger \mathbf{D}_I^{-1}(\omega)\mathbf{b}. \tag{109}$$

If the internal operator is diagonalized into stable modes,

$$\boxed{\lambda_2(\omega) = \lambda_\infty + \sum_a \frac{g_a^2}{\omega_a^2 - \omega^2 - i\gamma_a\omega}.} \tag{110}$$

The static Love number is the $\omega \to 0$ limit. A small static deformability does not preclude resonant finite-frequency effects when ω approaches an internal mode.

For a causal passive response,

$$\boxed{\mathrm{Re}\,\lambda_2(0) - \lambda_2(\infty) = \frac{2}{\pi}\int_0^\infty \frac{\mathrm{Im}\,\lambda_2(\omega)}{\omega}\,d\omega.} \tag{111}$$

Equation (111) is a useful internal consistency relation connecting static deformability and dissipation.

10.4 Core impedance and reflection

Integrating the saturated interior to its matching region defines an effective boundary impedance

$$\mathcal{Z}_\ell(\omega) = \left.\frac{\partial_{r_*}\Psi}{\Psi}\right|_{r_*}. \tag{112}$$

For a local exterior wave

$$\Psi = e^{-ikr_*} + \mathcal{R}_\ell e^{ikr_*}, \qquad k = \omega/c_R, \tag{113}$$

the reflection coefficient is

$$\boxed{\mathcal{R}_\ell(\omega) = \frac{ik + \mathcal{Z}_\ell}{ik - \mathcal{Z}_\ell}.} \tag{114}$$

A regular finite core can therefore be nearly perfectly absorbing if $\mathcal{Z}_\ell \simeq -ik$. The absence of late-time echoes does not by itself exclude a finite interior; it constrains the impedance.

11 Empirical constraints and falsification programme

The coherent branch is intentionally required to reproduce established relativistic phenomenology. Current measurements leave little room for weak coherent deviations.

11.1 Weak equivalence principle

The MICROSCOPE mission found no violation of the weak equivalence principle between titanium and platinum test masses, constraining the Eotvos parameter to

$$\eta_{\mathrm{Ti,Pt}} = (-1.5 \pm 2.3_{\mathrm{stat}} \pm 1.5_{\mathrm{syst}}) \times 10^{-15} \tag{115}$$

at the quoted one-sigma uncertainties [9]. ECSM therefore requires the coherent normalized source coupling $Q_{\phi,A}/m_{I,A}$ to be composition independent at least to this level in the tested regime.

11.2 Short-range longitudinal smoothing

The weak point-source response of Eq. (3) is equivalent to a Newton-plus-Yukawa form with strength $\alpha = -1$ and range ℓ_ϕ. Torsion-balance measurements find Newtonian gravity consistent down to tens of micrometres and limit gravitational-strength Yukawa interactions to ranges below approximately $38.6\,\mu$m at 95% confidence [10]. If the ECSM point-response kernel applies universally to the macroscopic source geometry of those experiments, this implies

$$\ell_\phi \lesssim 38.6\,\mu\mathrm{m}. \tag{116}$$

Consequently the weak longitudinal smoothing scale cannot simultaneously be an astrophysical compact-object regularization scale; strong-field saturation must be a distinct constitutive effect.

11.3 Solar-system and pulsar recovery

PPN tests, gravitational time delay, light deflection, lunar ranging and planetary dynamics constrain deviations from the GR weak-field branch tightly; see Will for a comprehensive review [11]. In ECSM these are recovery tests of the frozen coherent closure. They are not treated as independent evidence favouring ECSM because the coherent coefficients are part of the branch definition.

Strong-field binary-pulsar timing provides an especially severe consistency test. The double pulsar PSR J0737-3039A/B measures several post-Keplerian effects and confirms the quadrupolar radiation description of GR to high precision [12]. ECSM-G therefore requires any finite-response correction to be negligible in the double-pulsar regime unless it is already included consistently across all measured effects.

11.4 Gravitational-wave propagation and polarization

The joint observation of GW170817 and GRB 170817A constrains the propagation speed of gravitational waves to be extremely close to the speed of light over astrophysical distance [13]. ECSM satisfies this on the coherent branch through $c_T = c_R = c_\gamma$ operationally. Any finite-response dispersion must become negligible in the observed frequency and loading regime.

The latest cumulative LIGO-Virgo-KAGRA strong-field tests available at the time of writing use 168 confident events in GWTC-5.0 and find no significant evidence for non-GR residuals, anomalous propagation, additional polarizations or inconsistent remnant behaviour [14]. This strongly restricts the allowed size of $\Sigma_{\mathrm{ECSM}}(\omega)$ across the observed compact-binary population.

11.5 Horizon-scale compact-object observations

Event Horizon Telescope observations of Sagittarius A* find the observed ring scale compatible with Kerr expectations at the present precision and constrain ordinary reflective or thermally radiating surface alternatives [15]. ECSM does not generically predict a bright material surface. A finite-capacity core with an absorptive transport boundary can remain externally Kerr-like. Nevertheless EHT data constrain any capacity onset or reflective response that would significantly shift the photon region or produce incompatible surface emission.

11.6 Parameter discipline

The discriminating finite-response quantities must descend from one fixed medium parameter set. At minimum the model contains the weak longitudinal scale ℓ_ϕ, a capacity scale represented by $\mathcal{Y}_{\mathrm{cap}}$ or an equivalent B_{cap} in the spherical branch, and one or more independent dynamical response times or internal stiffness ratios that survive reduction from the parent.

These parameters may not be refitted independently for Mercury, pulsars, stellar-mass compact objects and supermassive compact objects. The central empirical programme is therefore a global likelihood problem:

$$\mathcal{L}_{\mathrm{total}}(\Theta_{\mathrm{ECSM}}) = \mathcal{L}_{\mathrm{lab}}\mathcal{L}_{\mathrm{SS}}\mathcal{L}_{\mathrm{pulsar}}\mathcal{L}_{\mathrm{GW}}\mathcal{L}_{\mathrm{EHT}}\cdots , \tag{117}$$

with one common parameter vector Θ_{ECSM}.

12 Relation to analogue and emergent gravity

The broad idea that effective relativistic propagation can emerge in condensed-matter or fluid-like systems is well established in analogue-gravity research [16, 17]. Analogue models demonstrate that horizon structures, effective metrics and relativistic wave equations can arise from nonrelativistic or non-geometric microscopic systems. They do not, by themselves, provide a fundamental theory of astrophysical gravity.

ECSM differs in ambition and in claim structure. It is not presented merely as an analogue of a pre-existing gravitational geometry. The medium response is proposed as the physical origin of the gravitational observables themselves. At the same time, the present paper deliberately stops at effective-theory level. The universal coherent-response closure and the single-relational-update condition are adopted structural principles. Their deeper microscopic derivation remains an open programme.

The exact GR recovery of the coherent action should therefore be regarded as both a strength and a limitation. It ensures compatibility with the large body of successful relativistic tests, but it means that ordinary coherent observations do not distinguish ECSM from GR. The experimental content lies in the finite-response extension and in cross-sector null relations that are fixed by the common medium architecture.

13 Discussion

13.1 What is explained and what is merely re-described?

A frequent objection to emergent-gravity models is that replacing the word "spacetime" by "medium" can leave the explanatory structure unchanged. ECSM-G avoids that only if the medium coupling is functionally explicit.

At weak field, the source action produces Eq. (2), the Green response produces Eq. (3), and the defect energy produces Eq. (9). The attraction therefore has a mechanism: a localized excitation changes the common medium; neighbouring medium states are coupled; a long-range response forms; and another localized excitation re-equilibrates in that response.

At nonlinear level, the same logic is encoded in Eqs. (28)–(36). Matter energy, current and stress source one constrained collective response. The packet, clock, optical and rotational observables are different projections of that response rather than separate phenomenological force rules.

The theory does not explain why the medium exists, just as an effective condensed-matter theory does not necessarily explain why its ultimate microscopic constituents exist. Nor does it yet derive the universal coherent source normalization from the full stable particle spectrum. Those are upstream parent-theory questions rather than claims made by this gravity-sector paper.

13.2 Is the coherent theory simply GR in different variables?

Mathematically, the nonlinear coherent gravitational dynamics are GR-equivalent after the comparison dictionary of Eq. (48) is introduced. That fact should not be obscured. The coherent action has the ADM structure and therefore inherits the Einstein dynamics.

The physical claim is narrower: the variables are assigned a medium-response ontology before the comparison dictionary is introduced. The GR-equivalent mathematics is an adopted ADM-equivalent effective closure consistent with A3, not a uniqueness result derived from the microscopic parent. Without finite-response departures or a deeper microphysical derivation, this distinction could remain empirically underdetermined. ECSM becomes physically discriminating through finite-response effects or independently derived cross-sector constraints.

13.3 Singularities and black objects

If a microscopic, physically specified medium obeys the postulated finite-capacity inequality, a diverging *material* load is inadmissible within that description. This is a conditional statement about a proposed constitutive law, not a demonstration that all solutions remain regular or that spacetime geodesic completeness follows. No universal regular interior has been derived here.

Nor does a material capacity imply visible compact-object surfaces or exclude one-way causal behaviour. Such behaviour requires analysis of the physical propagation characteristics and flow. The observational issue is whether one parameter-fixed finite-response law generates measurable departures in tidal susceptibility, absorption, ringdown, photon-region response or mergers.

13.4 Parameter economy and falsifiability

The ideal coherent ADM-equivalent branch inherits G and c_R as observed recovery constants once its closure coefficients are fixed. Any genuine predictive power of the proposed extension requires finite-response constants that are jointly fixed, not re-tuned independently for each dataset.

The variational capacity ansatz replaces arbitrary pressure profiles with an admissible set, but its material-state map, capacity $\mathcal{Y}_{\mathrm{cap}}$, response matrix G_{AB}, and memory kernel remain to be derived or constrained. Their common nonlinear action and preservation of the coupled constraints are not yet established. Consequently the extension is *not* a fully specified, parameter-free compact-object solver.

14 Scope boundary, dependencies and downstream work

The remaining tasks fall into distinct levels and should not be conflated.

14.1 Upstream ECSM dependencies

Universal coherent matter-source normalization enters as an effective/UCRP assumption; it has not been derived for the complete spectrum of stable excitations. The collective response C_{ij} is not yet fully reduced from microscopic parent strain q_{ij}. The material response matrix, a defined medium-rest reference and the physical capacity threshold likewise remain parent-level derivations.

14.2 Downstream gravitational calculations

The proposed finite-response extension does not yet furnish a common constraint-preserving nonlinear action or a solved, parameter-fixed set of static and rotating interiors. Its earlier tidal benchmarks establish feasibility in restricted example models only; they are not predictions of the present ansatz. Existence, stability, regularity, ergoregions, binary dynamics and merger waveforms require further calculation after the medium-state prescription and all couplings are fixed.

14.3 Empirical discrimination

No observation currently distinguishes ECSM from GR on the coherent branch: the effective action is selected to recover the established GR dynamics. Independent tests must therefore concern either finite-response departures predicted from a single frozen constitutive model, or cross-sector identities derived without assuming the target coefficients. Preferred-frame effects, extra polarizations, dispersion, tidal response, absorption, short-range forces and compact-object spectroscopy remain future tests, not verified anomalies.

15 Conclusion

This work formulates an *effective* gravitational sector for ECSM in ordinary three-dimensional space. The common coherent medium, persistent localized matter and universal coupling are adopted from upstream ECSM proposals. Within those conditions, gravitational phenomena are interpreted as physical medium-state reconfiguration and corresponding changes in dressed excitation energy.

The weak sector combines an illustrative finite longitudinal response with clock, optical and rotational response. The nonlinear ideal coherent closure is deliberately chosen so that its constrained equations coincide mathematically with the standard ADM gravitational equations. The resulting Newtonian, post-Newtonian, radiative and compact-exterior correspondences are therefore *effective recovery results*, not proofs that the ECSM microscopic parent uniquely generates this action.

The coherent gravitational action is

$$S_G^{\mathrm{coh}} = \frac{c_R^4}{16\pi G} \int N\sqrt{C}\left(R_C + K_{ij}K^{ij} - K^2\right) d\lambda\, d^3x.$$

The separate finite-length kernel introduces departures from exact coherent equivalence whenever $k\ell_\phi$ or memory terms are non-negligible. The candidate capacity law

$$\mathcal{Y} \le \mathcal{Y}_{\mathrm{cap}}$$

requires physical medium-state variables, not merely a chosen lapse or coordinate description. Its stationary compactness curve is an illustrative external diagnostic. A common nonlinear action coupling the coherent and finite-response sectors, a well-defined material reference, and constraint-preserving evolution have *not* been established. Consequently no universal saturation radius, singularity-free solution or parameter-fixed compact-object spectrum is claimed.

The contribution is a clearly bounded effective construction and a set of conditional strong-field hypotheses open to quantitative falsification. The next steps are to derive the material response and source normalization from one parent, construct a consistent nonlinear finite-response evolution system, establish its stability, and test the resulting fixed predictions against independent observations.

A Compact equation ledger

The core causal chain is

$$\text{matter} \to \text{medium source} \to \text{collective response} \to \text{changed defect dressing} \to \text{acceleration}. \tag{A1}$$

The weak longitudinal response is

$$(1-\ell_\phi^2\nabla^2)(A\ddot{\phi}-\kappa\nabla^2\phi)=gn_m. \tag{A2}$$

The static point response is

$$\phi(r)=\frac{g}{4\pi\kappa r}(1-e^{-r/\ell_\phi}). \tag{A3}$$

The coherent burden and clock response are

$$B=U/c_R^2, \qquad R_\tau=e^{-B}. \tag{A4}$$

The weak electromagnetic closure is

$$Z_E=Z_c e^{2B}, \qquad Z_B=Z_c e^{-2B}. \tag{A5}$$

The nonlinear coherent action is

$$S_G^{\mathrm{coh}}=\frac{c_R^4}{16\pi G}\int N\sqrt{C}(\mathcal{R}_C+K_{ij}K^{ij}-K^2)d\lambda d^3x. \tag{A6}$$

The scalar and momentum constraints are

$$\mathcal{R}_C+K^2-K_{ij}K^{ij}=\frac{16\pi G}{c_R^4}\varepsilon, \tag{A7}$$

$$\nabla_j(K^{ij}-C^{ij}K)=-\frac{8\pi G}{c_R^3}j^i \tag{A8}$$

The transverse wave equation is

$$(c_R^{-2}\partial_\lambda^2-\nabla^2)h_{ij}^{TT}=+\frac{16\pi G}{c_R^4}\Sigma_{ij}^{TT}. \tag{A9}$$

The quadrupole power is

$$P_{\mathrm{GW}}=\frac{G}{5c_R^5}\left\langle \dddot{Q}_{ij}\dddot{Q}_{ij}\right\rangle. \tag{A10}$$

The finite-capacity conditions are

$$\Lambda\geq 0, \qquad \mathcal{Y}^2\leq\mathcal{Y}_{\mathrm{cap}}^2, \qquad \Lambda(\mathcal{Y}^2-\mathcal{Y}_{\mathrm{cap}}^2)=0. \tag{A11}$$

B Falsification residuals

The weak coherent branch supplies several null relations that cannot be independently retuned:

$$R_{\mathrm{WEP}}^{AB} = \frac{(Q_{\phi,A}/m_{I,A})}{(Q_{\phi,B}/m_{I,B})} - 1 = 0, \tag{B1}$$

$$R_{\mathrm{sh}} = \frac{G_T}{G_{\mathrm{eff}}} - 1 = 0, \tag{B2}$$

and, within the reduced weak UCRP regime,

$$R_{\mathrm{CO}} = \ln n_{\mathrm{opt}} + 2 \ln R_\tau = 0. \tag{B3}$$

Finite-response residuals must be generated by the frozen response operator. Schematically,

$$R_a = F_a(\omega\tau_{\mathrm{resp}}, k\ell_\phi, \mathcal{Y}/\mathcal{Y}_{\mathrm{cap}}, \text{boundary state}, \ldots), \tag{B4}$$

with the same microscopic/effective coefficients appearing across all datasets.

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Appendix C. Revision 2: coherent limit and physical capacity

This appendix forms part of the revised ECSM gravity manuscript. It states the regime and observable definitions that delimit the effective conclusions of Sections 3, 7–9.

C.1 Sourced shear response and radiation convention

Using $C_{ij} = \delta_{ij} + h_{ij}$ and the positive stress convention of Eq. (33), $\delta S_m = \frac{1}{2}\int d\lambda\, d^3x\, \Sigma_{ij}^{TT}\, \delta h_{ij}^{TT}$ in the unloaded weak background. With the quadratic action in Eq. (43), integration by parts gives

$$\delta(S_{TT}^{(2)} + S_m) = \int d\lambda\, d^3x \left[-\frac{c_R^4}{32\pi G} \left(c_R^{-2}\partial_\lambda^2 - \nabla^2 \right) h_{ij}^{TT} + \frac{1}{2}\Sigma_{ij}^{TT} \right] \delta h_{ij}^{TT}. \tag{C1}$$

Thus the sourced field equation in Eqs. (44) and (A9) is

$$\boxed{\left(c_R^{-2}\partial_\lambda^2 - \nabla^2 \right) h_{ij}^{TT} = +\frac{16\pi G}{c_R^4}\, \Sigma_{ij}^{TT}.} \tag{C2}$$

This positive source sign is consistent with the retarded waveform and radiated-power normalization in Eqs. (46)–(47) for the same h_{ij}^{TT} convention. The GR-equivalent nature of this relation still depends on the explicitly adopted coherent action.

C.2 Exact and approximate recovery are different limits

The pure two-derivative, A3-constrained gravitational action (28) is ADM-equivalent. That equivalence is an *exact effective-action statement* only for the ideal coherent subsector as defined. The separate longitudinal model (1)–(3), at nonzero ℓ_ϕ, is not the same exact theory. Its static linear kernel in a homogeneous medium is

$$\widehat{\mathcal{G}}_\ell(k) = \frac{1}{\kappa k^2(1 + \ell_\phi^2 k^2)} = \frac{1}{\kappa}\left[\frac{1}{k^2} - \frac{1}{k^2 + \ell_\phi^{-2}} \right]. \tag{C3}$$

It tends to $1/(\kappa k^2)$ for $k\ell_\phi \to 0$ and yields relative corrections of order $(k\ell_\phi)^2$ in that static perturbative regime. The limit $\ell_\phi \to 0$ gives the unmodified long-range scalar response; it does not itself constitute a derivation of the full ADM action from the scalar field. For time-dependent states, the memory operator must likewise be negligible under the relevant frequency and material-load conditions, not merely because $Y < Y_{\rm cap}$.

Accordingly, $\Lambda = 0$ below the capacity surface removes *only* the capacity reaction. It cannot eliminate finite-wavelength or finite-rate terms. No nonlinear combined action producing both the exact ADM sector and the proposed finite-length and memory corrections has been derived here. The paper treats the latter as conditional effective corrections awaiting that matching calculation. The numerical bounds in Section 11.2 apply only when the point-source kernel is physically present in the tested macroscopic regime.

C.3 Dimensional and physical normalization of load

Since K_{ij} as written in Eq. (27) has dimensions L^{-1} (when λ is a time parameter), the dimensionless rate coordinate is $(c_R\tau_{\rm resp})K_{ij}^{\rm mat}$, not $\tau_{\rm resp}K_{ij}$. In Eq. (70), $B_{\rm mat}$, $Q_{\rm mat}$, $\ell_{\rm sat}\nabla_{\rm mat}B_{\rm mat}$, $(c_R\tau_{\rm resp})K^{\rm mat}$ and $v_{\rm rel}/c_R$ denote schematic *physical material-state coordinates*, with the positive dimensionless coefficients included in G_{AB}. Their microscopic normalizations have not been computed. $K^{\rm mat}$ is an objective rate of the selected medium state in a physically specified material update; it must not silently be identified with K_{ij} calculated on an arbitrarily chosen ADM slice. The shift W^i by itself is not an invariant material drift velocity.

C.4 Selecting the material state: what is, and is not, established

A physical capacity rule requires a reference medium configuration and a material update/flow prescription that determine measurable load coordinates before a constraint is imposed. A candidate clock coordinate is

$$B_{\mathrm{mat}}(\mathcal{Q}, u; \text{protocol}) := -\ln\left(\frac{\nu_{\mathrm{std}}(\mathcal{Q}, u)}{\nu_{\mathrm{std}}(\mathcal{Q}_0, u_0)}\right), \tag{C4}$$

where $\mathcal{Q}$ denotes physical medium state, u its specified material update/flow, and ν_{std} the rate of a reference standard excitation under a matched operational comparison. Universality across actual excitation species and a global comparison protocol remain open derivation requirements. Equation (C4) is thus a *proposed physical definition*, not an already computed function of the microscopic parent.

The lapse N of the exact ADM-equivalent comparison is not itself a scalar material load under a change of slicing. In a stationary exterior with asymptotically normalized stationary time, the norm of the stationary clock flow can instead be represented by

$$R_{\mathrm{stat}} = \sqrt{N^2 - \frac{C_{ij}W^iW^j}{c_R^2}}, \qquad B_{\mathrm{stat}} = -\ln R_{\mathrm{stat}}, \tag{C5}$$

only where those stationary worldlines are timelike. For the static Schwarzschild exterior $W^i = 0$, this equals N; in a Painlevé–Gullstrand slicing, the same stationary Killing flow has $N = 1$ but $C_{ij}W^iW^j/c_R^2 = 2GM/(c_R^2 r)$, giving the same $R_{\mathrm{stat}} = \sqrt{1 - 2GM/(c_R^2 r)}$ in the exterior. Hence the vanishing of a particular static lapse cannot, by itself, establish physical saturation. Furthermore the stationary norm ceases to define a clock rate wherever that Killing flow is not timelike (e.g. at a Kerr ergoregion boundary), so (C5) is not a general-purpose capacity variable.

If a distinct physical medium congruence u is introduced to define B_{mat}, its equations and transformation properties must be specified. The resulting finite-response theory may not retain the full refoliation freedom or the two-mode constraint count of the exact ideal ADM branch; constraint preservation and dynamical well-posedness would require a separate check. This paper does not claim to have supplied that full parent reduction.

C.5 Status of the compactness diagnostic

Equations (93)–(97) are correct algebraically *within the specified static-rest identification* $B_{\mathrm{mat}} = B_{\mathrm{stat}} = B_{\mathrm{cap}}$. In that branch, putting $q = \tanh(B_{\mathrm{cap}}/2)$ gives

$$C_* = \frac{2q}{(1+q)^2}, \qquad B_{\mathrm{cap}} > \ln\sqrt{3} \quad \Longrightarrow \quad C_* > \tfrac{1}{3}. \tag{C6}$$

This is an illustrative exterior photon-region criterion, *not* a slicing-independent prediction of a physical onset radius. Neither a regular compact-object interior nor its stability, absorption properties, Love numbers or ringdown frequencies follow from this algebra alone. Those results require solving a fully specified physical load functional with the associated constrained dynamical equations and boundary conditions.

Scope: This revision preserves ECSM's ordinary-three-dimensional medium ontology; the comparison variables and stationary clock norm are used only as mathematical/operational tests of the coherent effective equations.

Author declarations and version information

Submission version

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Disclosure of substantive AI assistance

OpenAI ChatGPT was used substantively during ECSM research and manuscript preparation, including theory discussions, drafting, equation checking, numerical exploration and editorial revision. AI-assisted checks are not independent scientific validation. The author retains full responsibility for every claim, equation, citation, interpretation and outstanding error.

Related research and prior dissemination

The manuscript builds upon and overlaps with earlier ECSM work publicly disseminated on Zenodo, including *ECSM Gravity Without Curvature* (DOI 10.5281/zenodo.21294135) and *General Relativity as the Coherent Limit of a Finite-Response Medium* (DOI 10.5281/zenodo.20968071). These antecedents and others are cited, not presented as unpublished novel work.

Reproducibility and limitations

This work is an effective theoretical proposal. It introduces no new experimental data. Exact coherent GR recovery follows from an adopted ADM-equivalent effective action, not from a completed microscopic medium derivation. The physical material state, a joint nonlinear finite-response action and preservation of coupled constraints remain to be established. Earlier compact-object calculations are illustrative benchmarks, not parameter-fixed predictions of the current extension.