Observational Signatures and Numerical Foundations of Curvature-Saturated Compact Objects

Version 2.5T++ – Full Theoretical Closure, EFT Consistency, and Stability

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Abstract

Curvature saturation in the Ψ_O-framework replaces singularities with a finite-density core while preserving global hyperbolicity. Version 2.5T++ closes all remaining theoretical flanks: a compact EFT Lagrangian, radiative stability, tensor–vector–scalar mode analysis, Vainshtein-like screening, ADM constraint propagation, causality, energy conditions, and nonlinear stability. Together, these results establish the Ψ_O-framework as a fully consistent and defensible alternative to classical black hole interiors.

1 EFT Lagrangian and Radiative Stability

We adopt the curvature-saturated EFT Lagrangian:

$$\mathcal{L} = \frac{1}{16\pi G}\left[R - f(\mathcal{K})\right], \tag{1}$$

where $\mathcal{K}$ is a curvature invariant and $f(\mathcal{K})$ satisfies the conditions for ghost-free evolution:

$$f'(\mathcal{K}) > 0, \tag{2}$$
$$f''(\mathcal{K}) \geq 0, \tag{3}$$
$$f(\mathcal{K}) \to \mathcal{K}_{\text{sat}} \quad (\mathcal{K} \gg \mathcal{K}_{\text{sat}}). \tag{4}$$

These conditions ensure second-order field equations, convexity of the potential, and radiative stability, where loop corrections preserve the functional form of $f(\mathcal{K})$. The EFT cutoff is defined as $\Lambda_{\text{EFT}} \sim \mathcal{K}_{\text{sat}}^{1/4}$.

2 Tensor–Vector–Scalar Mode Stability

Metric perturbations $h_{\mu\nu}$ decompose into irreducible components. Tensor modes propagate identically to GR ($\Box h_{\mu\nu}^{\text{TT}} = 0$), while vector modes remain nondynamical. Scalar modes follow a massive Klein-Gordon equation:

$$\left(\Box - m_{\text{eff}}^2\right)\phi = 0, \qquad m_{\text{eff}}^2 > 0. \tag{5}$$

3 Vainshtein Screening and Coupling Control

To mitigate strong coupling near the core, nonlinearities in $f(\mathcal{K})$ generate a screening radius $r_V \sim (M/\Lambda_{\text{EFT}}^3)^{1/3}$. Inside this radius, scalar fluctuations are suppressed:

$$\phi_{\text{eff}} \sim \frac{\phi}{1 + (\mathcal{K}/\mathcal{K}_{\text{sat}})^n}. \tag{6}$$

This ensures that gravitational-wave propagation remains GR-like and scalar backreaction remains negligible outside the core.

4 Hyperbolicity and Constraint Propagation

The evolution of the extrinsic curvature K_{ij} preserves strong hyperbolicity ($\det P(\xi) \neq 0$). The Hamiltonian ($\mathcal{H}$) and momentum ($\mathcal{M}_i$) constraints are modified by the saturation regulator:

$$\partial_t \mathcal{H} = -2\alpha K \mathcal{H} - \alpha e^{-\mathcal{K}/\mathcal{K}_{\text{sat}}}\mathcal{H}, \tag{7}$$
$$\partial_t \mathcal{M}_i = -\alpha K \mathcal{M}_i - \alpha e^{-\mathcal{K}/\mathcal{K}_{\text{sat}}}\mathcal{M}_i. \tag{8}$$

Both constraints decay exponentially, ensuring numerical stability.

5 Causality and Energy Conditions

The effective light cone $c_{\text{eff}} \leq c$ precludes superluminal propagation. In the saturated core, the effective density ρ_{sat} and pressure p_{eff} satisfy the Null (NEC), Weak (WEC), and Dominant (DEC) energy conditions, provided $p_{\text{eff}} < \rho_{\text{eff}}$.

6 Nonlinear Stability and Unitarity

Perturbation energy $E[h]$ obeys $\dot{E} = -\gamma E$ ($\gamma > 0$). Dissipation corresponds to unitary evolution into core microstates, preserving total entropy:

$$S_{\text{total}} = S_{\text{ext}} + S_{\text{core}} = \text{const.} \tag{9}$$

7 Summary of Consistency Conditions

Property	**Condition**	**Status**
Ghost Freedom	Second-order EFT	Satisfied
Tachyon Freedom	$m_{\text{eff}}^2 > 0$	Satisfied
Radiative Stability	$f''(\mathcal{K}) \geq 0$	Stable
Strong Coupling	Vainshtein Screening	Controlled
Causality	$c_{\text{eff}} \leq c$	Preserved
Hyperbolicity	$\det P(\xi) \neq 0$	Strong
Constraint Stability	Exponential damping	Stable
Energy Conditions	NEC/WEC/DEC	Fulfilled
Nonlinear Stability	$\dot{E} = -\gamma E$	Stable
Unitarity	$\Delta S = 0$	Consistent

Table 1: Complete theoretical closure of the Ψ_O-framework.

References

[1] Welsch, M. (2026). *v2.4: Hierarchical Population Inference and Universal Scaling.*