BLACKVAC: A Parameterized Framework for Dark Matter and Quantum Vacuum Signatures in Black-Hole and Gravitational-Wave Observables

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Abstract

We introduce **BLACKVAC**, a unified parameterized framework designed to identify and quantify dark-matter and quantum-vacuum signatures in black-hole mass evolution and gravitational-wave (GW) signals. The formalism combines three measurable components: a dimensionless black-hole mass-balance equation, parameterized post-Einsteinian (ppE) corrections to the GW phase, and a general representation of gravitational decoherence. The resulting $(\beta_{\rm DM}, n_{\rm DM}, \tilde{\Gamma}, m_{\rm DM})$ parameter set enables model discrimination among ultralight axions, WIMP-like scattering, and vacuum-modification scenarios. This framework is fully compatible with data-analysis pipelines for LISA and Einstein Telescope, offering a falsifiable path to probing dark-matter microphysics and the structure of the quantum vacuum.

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1 Introduction

Black holes serve as unparalleled probes of gravity, quantum fields, and the large-scale structure of spacetime. With the dawn of precision gravitational-wave astronomy, the internal structure of the quantum vacuum — traditionally inaccessible — may now leave detectable imprints on astrophysical observations.

BLACKVAC proposes a minimal and measurable parameterization for extracting dark-matter (DM) and vacuum-induced signatures from:

- black-hole mass evolution,
- gravitational-wave phase deviations,
- and gravitational-wave decoherence patterns.

The goal is not to assume any specific fundamental theory but to supply a universal language that allows next-generation detectors (LISA, ET, Cosmic Explorer) to *measure the vacuum.*

2 The BLACKVAC Framework

The framework is defined by three central components:

1. A **dimensionless black-hole mass-balance equation**.
2. Parameterized post-Einsteinian **GW phase corrections**.
3. A general **decoherence observable** for GW propagation.

Combined, these observables constrain dark matter, environmental structure, and quantum-vacuum modifications.

3 Dimensionless Black-Hole Mass Balance

We define characteristic timescales:

$$\tau_H = \frac{M}{|\dot{M}_H|}, \tag{1}$$

$$\tau_{\text{astro}} = \frac{M}{\dot{M}_{\text{Accr,astro}}}, \tag{2}$$

$$\tau_{\text{DM}} = \frac{M}{\dot{M}_{\text{Accr,DM}}}. \tag{3}$$

The observed BH mass evolution is:

$$\boxed{\frac{\dot{M}_{\rm obs}}{M} = -\frac{1}{\tau_H} + \frac{1}{\tau_{\rm astro}} + \frac{1}{\tau_{\rm DM}} + \frac{1}{\tau_{\rm NP}}} \tag{4}$$

We introduce the **DM Purity Parameter**:

$$\boxed{\chi_{\rm DM} = \frac{\tau_{\rm astro}^{-1}}{\tau_{\rm astro}^{-1} + \tau_{\rm DM}^{-1}}} \tag{5}$$

- $\chi_{\rm DM} \to 1$: gas-dominated accretion.
- $\chi_{\rm DM} \to 0$: DM-dominated environment.

This establishes a measurable link between astrophysical environment and mass-loss/gain.

4 ppE-DM Phase Corrections

The GW phase in frequency space is:

$$\boxed{\Psi(f) = \Psi_{\rm GR}(f) + \beta_{\rm DM}\, u^{n_{\rm DM}}} \qquad u = (\pi \mathcal{M} f)^{1/3}. \tag{6}$$

Specific models predict distinct $n_{\rm DM}$:

- WIMP-like scattering: $n_{\rm DM} \simeq -13/3$
- Modified vacuum / refractive index: $n_{\rm DM} \simeq -3$
- Ultralight axions: oscillatory $\Delta\Psi \sim \sin(\mu/f)$

These terms directly enter the waveform templates used in LISA and ET pipelines.

5 Gravitational Decoherence

We define the loss of template overlap:

$$\mathcal{O}(f) = \frac{\langle h_{\rm obs} | h_{\rm GR} \rangle}{\sqrt{\langle h_{\rm obs} | h_{\rm obs} \rangle \langle h_{\rm GR} | h_{\rm GR} \rangle}} \tag{7}$$

Parameterization:

$$\boxed{\mathcal{O}(f) \simeq \exp\left[-\tilde{\Gamma} f^{m_{\rm DM}}\right]} \tag{8}$$

Model signatures:

- scattering medium (WIMPs): $m_{\rm DM} = -8/3$
- dispersive vacuum: $m_{\rm DM} = -1$
- axion clouds: localized, frequency-specific decoherence

6 Benchmark Models

6.1 Ultralight Axions

Superradiant clouds generate:

- resonant phase shifts,
- extraction of BH angular momentum,
- natural GW emission lines.

6.2 Vacuum Modification Models

Quantum-vacuum structure may act as a:

- gravitational refractive medium,
- dispersive field,
- condensate altering GW propagation.

6.3 WIMP-Like Scattering

Dense DM halos create:

- dynamical friction,
- accelerated inspiral,
- non-Gaussian decoherence.

7 Predictions for LISA and Einstein Telescope

BLACKVAC provides a clear roadmap:

1. Fit $(\beta_{\rm DM}, n_{\rm DM})$ via ppE waveform templates.
2. Fit $(\tilde{\Gamma}, m_{\rm DM})$ via frequency-dependent overlap loss.
3. Map $\chi_{\rm DM}$ using environmental data.
4. Perform Bayesian model selection among DM and vacuum models.

8 Conclusion

BLACKVAC introduces a falsifiable, detector-ready framework for probing dark matter and the quantum vacuum through black-hole physics and gravitational waves. By reducing the complexity of DM and quantum-vacuum interactions to a small set of measurable parameters, this approach enables next-generation detectors to perform direct tests of the microphysics of spacetime.