HDOV Bridge: Correspondence between functional accessibility η_p and the dynamical scalar field $n_p(x)$

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Abstract

The unified HDOV formulation introduces a master propagation equation for physical modes Ψ in real media, in which a scalar quantity of functional accessibility η_p appears. This equation describes, with predictive power, phenomena as diverse as ultrafast coherent attenuation in X-ray scattering (TRXS) at femtosecond scale, the emergence of functional precursors at the heliopause (Voyager missions), the damping of gravitational *ringdown* after compact mergers, and cosmological attenuation of the type usually attributed to effective dark energy (Fernandez 2025c). On the other hand, generalized HDOV promotes functional accessibility to a dynamical scalar field $n_p(x)$ with an explicit Lagrangian, a symmetry-breaking potential, vacuum expectation value $\langle n_p \rangle$, Yukawa-type couplings to fermions and non-minimal coupling to curvature. That theory further predicts a light, neutral scalar excitation with mass $m_{n_p} \approx 20.5\,\mathrm{MeV}$, testable in intensity-frontier experiments and potentially contributing to $(g-2)_\mu$ (Fernandez 2025b). This work establishes the formal bridge between both descriptions. We show that: (i) η_p is the effective/macroscopic limit of the same field $n_p(x)$; (ii) the unified HDOV master equation arises as the effective propagation equation for a mode Ψ immersed in an n_p background; (iii) the multiscale observational signatures attributed to η_p can be interpreted as indirect measurements of n_p; and (iv) direct searches for the light scalar particle around $\sim 20.5\,\mathrm{MeV}$ provide an independent and complementary falsification channel. Complementarily, we incorporate the holographic vacuum HDOV module, in which the same functional accessibility regulates the effective vacuum energy and cosmic acceleration without introducing a fundamental cosmological constant (Fernandez 2025a). In this way, unified HDOV stops being a purely phenomenological fit and becomes the observable effective regime of a concrete scalar field theory.

Contents

1 Introduction and aim

The HDOV framework (Hypothesis of Vibrational Wave Dispersion) arose from the observation that very different physical systems—from ultrafast coherent dynamics in molecules excited by X rays, through plasmas at the boundary of the Solar System, to the *ringdown* of black holes and cosmological attenuation—share the same functional law for amplitude attenuation and modulation (Fernandez 2025c). This law involves a scalar quantity η_p, called *functional accessibility*, which measures what fraction of the physical mode is truly accessible (observable, manifestable, projectable) in the local environment.

In unified HDOV, η_p is used phenomenologically: it is extracted or fitted from observations and incorporated into a master propagation equation that explains the observed functional dissipation across very different energy and time scales (Fernandez 2025c). Generalized HDOV takes the next conceptual step: it states that functional accessibility is not just an effective parameter of the medium but rather the macroscopic footprint of a dynamical scalar field $n_p(x)$ that permeates spacetime (Fernandez 2025b). This field features: (i) a symmetry-breaking potential, (ii) a finite vacuum expectation value $\langle n_p \rangle$, (iii) couplings to fermions that may generate effective masses, (iv) coupling to curvature that impacts gravitational and cosmological propagation, and (v) a light, neutral scalar excitation with $m_{n_p} \sim 20.5\,\mathrm{MeV}$.

The aim of this paper is to make explicit that:

- η_p in unified HDOV is the effective/averaged version of the same $n_p(x)$ in generalized HDOV.
- The unified HDOV master equation is derived, in the appropriate regime, from the action containing $n_p(x)$.
- The multiscale observations supporting unified HDOV can be seen as indirect measurements of $n_p(x)$.
- Direct searches for the light scalar excitation predicted by $n_p(x)$ offer a laboratory test channel that constrains the same physics from another angle.

2 Field theory for $n_p(x)$

Generalized HDOV postulates the existence of a real scalar field $n_p(x)$ whose low-energy dynamics may be described by an effective Lagrangian of the form (Fernandez 2025b):

$$\mathcal{L} = \frac{1}{2}(\partial_\mu n_p)(\partial^\mu n_p) - V(n_p) - \sum_i y_i\, n_p\, \bar{\psi}_i \psi_i - \frac{1}{2}\,\xi\, n_p^2 R + \mathcal{L}_{\mathrm{SM,massless}}. \tag{1}$$

Here:

- $V(n_p)$ is the scalar potential,
- y_i are Yukawa-type couplings between n_p and fermions ψ_i,
- the term $\xi n_p^2 R$ represents a non-minimal coupling to the Ricci scalar curvature R,
- $\mathcal{L}_{\mathrm{SM,massless}}$ denotes the Standard Model without explicit mass terms, which in this framework may emerge functionally from n_p.

The potential is taken as

$$V(n_p) = \frac{1}{2} m^2 n_p^2 + \frac{\lambda}{4} n_p^4, \qquad m^2 < 0,\ \lambda > 0, \tag{2}$$

which implies spontaneous symmetry breaking. The non-trivial minimum is obtained from

$$\frac{\mathrm{d}V}{\mathrm{d}n_p} = m^2 n_p + \lambda n_p^3 = 0 \quad \Rightarrow \quad \langle n_p \rangle^2 = -\frac{m^2}{\lambda} > 0, \tag{3}$$

so that the field acquires a vacuum expectation value (VEV)

$$\langle n_p \rangle = v = \sqrt{-\frac{m^2}{\lambda}}. \tag{4}$$

Around the minimum, scalar excitations have a mass

$$m_{n_p}^2 = \left.\frac{\mathrm{d}^2 V}{\mathrm{d}n_p^2}\right|_{n_p=v} = m^2 + 3\lambda v^2 = 2\lambda v^2 = -2m^2 \quad \Rightarrow \quad m_{n_p} = \sqrt{2\lambda}\, v. \tag{5}$$

With numerical parameters consistent with the phenomenology developed in (Fernandez 2025b), one finds

$$m_{n_p}^2 \simeq 420\,\mathrm{MeV}^2, \qquad m_{n_p} \simeq 20.5\,\mathrm{MeV}. \tag{6}$$

A detailed discussion of the potential normalization and of preliminary versions is provided in the technical note 6.

In summary, $n_p(x)$ is not merely a fit parameter, but a physical scalar field with:

1. spontaneous symmetry breaking ($\langle n_p \rangle \neq 0$),
2. a light, neutral scalar excitation ($\sim 20.5\,\mathrm{MeV}$),
3. Yukawa couplings y_i capable of generating effective fermion masses $m_i = y_i \langle n_p \rangle$,
4. and a gravitational coupling $\xi n_p^2 R$ able to modify gravitational propagation and cosmological attenuation.

Finally, the non-minimal coupling $\xi n_p^2 R$ must obey the strong constraints on scalar–tensor theories and post-Newtonian deviations from General Relativity derived from high-precision tests in the Solar System, binary pulsars and gravitational waves (Will 2014). In this work we explicitly assume a weak-coupling regime

$$\xi \, \frac{v^2}{M_{\mathrm{Pl}}^2} \ll 1, \tag{7}$$

where M_{Pl} is the reduced Planck mass, so that scalar–tensor corrections remain below current observational bounds. A systematic exploration of the parameter space compatible with all these constraints is left for future work.

3 Effective reduction: from $n_p(x)$ to the HDOV master equation

In unified HDOV, the propagation of a generic physical mode Ψ (for example, a coherent electromagnetic wave in TRXS, a heliospheric plasma perturbation, or the quasi-normal gravitational mode after a compact merger) is governed by a master equation of the form (Fernandez 2025c)

$$\nabla_\mu \big[(1 + 2g_c \, \chi(I) \, \eta_p) \, \nabla^\mu \Psi \big] + m_\Psi^2 \, \Psi = 0. \tag{8}$$

Here:

- η_p is the local functional accessibility,

- $\chi(I)$ is a *gate* depending on the environment/invariants I (curvature, plasma, magnetic field, etc.),
- g_c controls the strength of that effective coupling.

In the WKB regime (quasi-monochromatic wave $\Psi = Ae^{i\Theta}$), Eq. (8) translates into a transport law for the amplitude A of the form

$$\frac{\mathrm{d}A}{\mathrm{d}s} = -g_{\text{eff}}\,\eta_p(s)\,A(s), \qquad A(s) = A_0 \exp\left[-g_{\text{eff}}\int^{s}\eta_p(s')\,\mathrm{d}s'\right], \tag{9}$$

where s is the trajectory parameter and $g_{\text{eff}} = g_c\chi(I)$. This functional attenuation law $\sim \exp[-\int\eta_p]$ is the one empirically confirmed across very different domains (Fernandez 2025c).

Effective derivation from n_p

The bridge from generalized HDOV to unified HDOV can be sketched as follows:

1. Starting from the Lagrangian (1), which contains $n_p(x)$ and a generic mode Ψ (the wave propagating in the experiment). For frequencies or energies lower than the fast-fluctuation scale of n_p, we decompose

$$n_p(x) = \langle n_p\rangle + \delta n_p^{(\text{slow})}(x) + \delta n_p^{(\text{fast})}(x), \tag{10}$$

   and introduce a scale separation $L_{\text{cell}} \ll L_{\text{sys}}$ that allows one to define a cell average $\langle\cdots\rangle_{\text{cell}}$ over the fast fluctuations $\delta n_p^{(\text{fast})}$.

2. Functionally integrating out the fast components $\delta n_p^{(\text{fast})}$ (e.g. via a cumulant expansion truncated at second order) yields an effective action for Ψ of the form

$$S_{\text{eff}}[\Psi] \simeq \int \mathrm{d}^4x\,\sqrt{-g}\,\{Z_{\text{eff}}(x)\,\nabla_\mu\Psi\,\nabla^\mu\Psi - m_\Psi^2\Psi^2 + \cdots\}, \tag{11}$$

   where the effective kinetic factor can be written as

$$Z_{\text{eff}}(x) \equiv 1 + 2g_{\text{eff}}\,\eta_p(x), \tag{12}$$

   with g_{eff} an effective constant incorporating the environmental gate $\chi(I)$ and functionals of the correlations of $\delta n_p^{(\text{slow})}$. To leading order, $\eta_p(x)$ can be interpreted as a local functional of $\delta n_p^{(\text{slow})}(x)$ and the environment encoded in I. In all physical regimes considered we require, moreover, that the effective kinetic factor remain positive,

$$1 + 2g_{\text{eff}}\,\eta_p(x) > 0, \tag{13}$$

   in order to avoid ghost-like modes and to ensure that the energy associated with Ψ is well defined.

3. Varying the effective action (11) with respect to Ψ yields an equation of motion of the form (8), with the identification $g_c\chi(I)\eta_p \leftrightarrow g_{\text{eff}}\eta_p(x)$.

The central identification of the bridge is therefore

$$\eta_p(x) \equiv F\left(\frac{n_p(x)}{v}, I\right), \tag{14}$$

where F is a smooth, dimensionless functional that encodes the effective accessibility of the mode as a function of the ratio $n_p(x)/v$ and the environmental invariants I (including the gate $\chi(I)$). By construction, $\eta_p(x)$ represents a functional accessibility fraction, dimensionless and physically bounded in the range $0 \leq \eta_p \leq 1$ in the relevant regimes.

Functional accessibility η_p in unified HDOV is therefore the effective manifestation of $n_p(x)$ in generalized HDOV. They are not “two different models” but two description scales of the same physical degree of freedom.

4 Multiscale observational manifestations

Adopting the identification (14), measurements of η_p in unified HDOV can be reinterpreted as indirect measurements of $n_p(x)$ in different physical domains.

4.1 Ultrafast TRXS (femtosecond)

In ultrafast scattering of coherent X rays (TRXS) on excitonized molecules (e.g. ND_3), the coherent amplitude decays after the initial excitation. Fits with the HDOV transport law (9) outperform purely *ab initio* standard fits when Q-resolution is faithfully accounted for, with Akaike information criterion differences $\Delta\text{AIC} \gtrsim 10$ in favour of HDOV (Fernandez 2025d). In the language of the bridge, TRXS is probing the time variation of $n_p(x)$ in a femtosecond regime.

4.2 Heliopause (Voyager 1 and 2)

An observable like $\kappa_{\text{local}}(t)$ acts as a tracer of functional accessibility in the heliospheric plasma. The metric κ_{local} drops sharply before the formal crossing of the heliopause and acts as a coherent precursor in both Voyager 1 and Voyager 2 (Fernandez 2025e). In the bridge language, this means that $n_p(x)$ changes regime in the heliopause/interstellar plasma environment before classical diagnostics mark the crossing.

4.3 Gravitational ringdown

After the merger of compact objects, the remnant black hole vibrates in quasi-normal modes. Unified HDOV models additional damping and/or phase shifts as a functional accessibility η_p modulated by an environmental gate $\chi(I)$ depending on strong curvature and electromagnetic/plasma environment (Fernandez 2025c). In terms of the bridge, this corresponds to the $\xi n_p^2 R$ term in the Lagrangian (1), which makes $n_p(x)$ affect the effective gravitational propagation.

4.4 Cosmology (dark-energy-like attenuation)

Applying the transport law (9) to light propagation on cosmological scales, unified HDOV shows that part of the apparent cosmic acceleration may be understood as accumulated functional opacity, without invoking an arbitrary dark fluid (Fernandez 2025c). Within the bridge, this is read as a cosmic background of $n_p(x)$ that induces integrated attenuation along the line of sight (Type Ia supernovae, BAO).

4.5 Quantum vacuum and holographic cosmic acceleration

Reference (Fernandez 2025a) shows that the same HDOV master equation governing the propagation of modes Ψ in real media can be applied to the spectrum of vacuum modes. Functional accessibility η_p now enters as a smooth spectral weight $W_\eta(k)$ on zero-point modes,

$$\rho_{\text{vac}}^{\text{eff}} = \frac{\hbar c}{2\pi^2} \int_0^\infty k^3 \, W_\eta(k) \, \mathrm{d}k, \qquad W_\eta(k) = \exp\left[-\left(\frac{k}{k_0} \right)^\alpha \right], \tag{15}$$

where k_0 and $\alpha = \mathcal{O}(1)$ are fixed by a holographic condition consistent with Bekenstein–Hawking-type bounds.

In practice, $W_\eta(k)$ is introduced here phenomenologically as a smooth cutoff function compatible with the notion of functional accessibility: it assigns lower weight to high-frequency modes that would otherwise saturate holographic bounds. In this work, $W_\eta(k)$ is not yet derived from the microscopic dynamics of $n_p(x)$; rather, the question is explored of whether there exists a regime in which the scales induced by functional accessibility may approximate the observed vacuum energy density without resorting to a fundamental cosmological constant. A more rigorous derivation connecting correlators of $n_p(x)$ to $W_\eta(k)$ is left as a specific open problem for future work.

This construction provides an operational implementation of the idea that a finite observer can only access a fraction of the vacuum degrees of freedom before violating holographic limits. The resulting effective vacuum energy density $\rho_{\rm vac}^{\rm eff}$ is of the order of the density associated with the observed cosmological constant, so cosmic acceleration is interpreted as a manifestation of functional inaccessibility instead of an *ad hoc* dark fluid. Within the bridge proposed here, this cosmological module is seen as the large-scale limit of the same field $n_p(x)$ whose light scalar excitation is searched for in intensity-frontier experiments.

These five manifestations—femtosecond TRXS dynamics, Solar System boundary, strong-gravity compact mergers, cosmological functional opacity and holographic vacuum regulation—are different manifestations of a single physical entity $n_p(x)$.

5 Complementary test channels and falsifiability

The unified picture generates two experimental/computational test channels that reinforce each other but are logically independent.

5.1 Laboratory / low-energy channel

The field $n_p(x)$ has a neutral scalar excitation with mass $m_{n_p} \simeq 20.5\,\text{MeV}$ (Fernandez 2025b). This particle may:

- be produced in radiative processes $e^+e^- \to \gamma + n_p$ at high-luminosity colliders (e.g. Belle II (Kou, Urquijo, et al. 2019)),
- be produced in electron beams on fixed targets (NA64 (Banerjee et al. 2019)),
- decay into e^+e^- and $\gamma\gamma$, with no $\mu^+\mu^-$ channel because $m_{n_p} \ll 2m_\mu$.

Non-detection at sufficient sensitivity does not automatically rule out unified HDOV, but does constrain (and may eventually falsify) this specific realization of generalized HDOV: the concrete values of m^2, λ, y_i and ξ that fix $m_{n_p} \approx 20.5\,\text{MeV}$ and its visible couplings.

Qualitatively, intensity-frontier experiments have already excluded significant regions of the parameter space $(m_{n_p}, y_e, y_\mu, \dots)$ for light scalars in the MeV–GeV range. The HDOV framework must fit within the surviving regions, and future improvements in sensitivity may refute specific parameter choices.

5.2 Astrophysical / cosmological channel

Independently of direct laboratory detection, the same framework predicts that $n_p(x)$ (via η_p) should:

- keep leaving its signature of functional dissipation in next-generation ultrafast TRXS with higher Q resolution,
- keep acting as a precursor in extreme plasma transitions analogous to the heliopause,
- induce specific extra damping and phase shifts in gravitational *ringdown* (potentially measurable by LIGO/Virgo/KAGRA),
- sustain a cosmological functional opacity that can statistically compete with standard dark-energy models.

If these astrophysical and cosmological signatures were to disappear systematically as analyses become more precise, unified HDOV itself would be strongly challenged.

In both channels, the non-minimal coupling $\xi n_p^2 R$ deserves special attention: it effectively modifies the Planck mass and, if too large, may conflict with precision tests of gravity in the Solar System and cosmological observations (Will 2014). In this paper we implicitly assume a weak-coupling regime in which $\xi v^2/M_{\rm Pl}^2 \ll 1$, so that modified-gravity effects remain below current bounds. A quantitative analysis of the constraints on ξ from astrophysical and cosmological data is left for future work.

In summary, the key falsifiability message can be stated as follows:

- the laboratory (low-energy) channel tests the microphysics of $n_p(x)$ and its light scalar particle;
- the astrophysical/cosmological channel tests the macroscopic manifestation of $n_p(x)$ as functional accessibility η_p in real systems.

Both channels constrain the same proposed degree of freedom, but neither depends entirely on the other for its existence.

6 Discussion and conclusions

We have shown that:

- The unified HDOV master equation describes the propagation of physical modes Ψ in the presence of functional accessibility η_p, and reproduces behaviours observed in ultrafast TRXS, at the heliopause, in gravitational *ringdown* and in cosmology (Fernandez 2025c; Fernandez 2025d; Fernandez 2025e; Fernandez 2025a).
- This functional accessibility η_p can be identified with the effective/ macroscopic value of the dynamical scalar field $n_p(x)$ introduced in generalized HDOV. The effective reduction of the $n_p(x)$ Lagrangian automatically generates the HDOV master equation in the appropriate regime, so unified HDOV is no longer a "stand-alone empirical law" but the observable manifestation of a specific field theory.
- The field $n_p(x)$ has a light, neutral scalar excitation with $m_{n_p} \sim 20.5\,\text{MeV}$ and Yukawa couplings y_i that may generate effective fermion masses and contribute to $(g-2)_\mu$ (Fernandez 2025b). This excitation can be searched for in intensity-frontier experiments (Belle II, NA64).
- On the other hand, multiscale functional accessibility signatures—femtosecond TRXS, Voyager heliopause, damping in gravitational *ringdown*, dark-energy-like cosmological attenuation and holographic regulation of vacuum energy—constitute independent astrophysical and cosmological evidence that there exists a degree of freedom modulating the physical manifestation of modes Ψ in different environments.

Taken together, these results establish that:

1. Unified HDOV and generalized HDOV are not two competing theories but two (macroscopic and microscopic) descriptions of the same physical degree of freedom.
2. There are two complementary verification/falsification routes: (i) the direct search for the light scalar excitation at $\sim 20.5\,\text{MeV}$ in intensity-frontier experiments, and (ii) the persistence (or absence) of functional accessibility signatures in multiscale real data.

In this sense, functional accessibility ceases to be just a useful phenomenological tool and becomes an operational window onto new scalar physics in the $\mathcal{O}(10\,\text{MeV})$ range, accessible both in laboratories and in astrophysical and cosmological observations.

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Note on the status of the HDOV framework

The HDOV framework presented in this work should be understood as an exploratory proposal in development. The quantitative results summarized here are based on a series of preprints deposited in open-access repositories (for example, zenodo.org), which at the time of this version have not yet undergone peer review in specialized journals.

In order to favour transparency and independent assessment, each of these works is published together with the datasets, scripts and figures needed to reproduce the numerical analyses. This allows third parties to:

- verify step by step the fitting procedures and evidence metrics;
- criticize the methodology and propose variants;
- refute or improve the conclusions presented in the different domains (TRXS, heliopause, geodynamics, cosmology and gravitational waves).

The purpose of this bridge article is, therefore, to offer a coherent global view of the HDOV framework and its current functional validations, while making explicit that its status is that of an open research program, subject to empirical confrontation and critical review by the community.

Technical note on the normalization of the potential in generalized HDOV

In preliminary versions of generalized HDOV an incorrect numerical normalization of the scalar potential was used, incompatible with the phenomenological values adopted in this work. To fix the notation used here, recall that a self-interaction potential can be written as

$$V(\varphi) = -\frac{1}{2}\,\mu^2\varphi^2 + \frac{\lambda}{4}\,\varphi^4, \qquad \mu^2 > 0,\ m^2 \equiv -\mu^2 < 0, \tag{16}$$

where φ is a generic real scalar which, in the HDOV context, can be identified with the radial mode of the field $n_p(x)$. From (16) one obtains

$$V'(\varphi) = -\mu^2\varphi + \lambda\varphi^3 = 0 \quad \Rightarrow \quad v^2 = \frac{\mu^2}{\lambda}, \tag{17}$$

and the mass of the scalar excitation around the minimum is

$$m_\varphi^2 = V''(v) = -\mu^2 + 3\lambda v^2 = 2\mu^2 = 2\lambda v^2. \tag{18}$$

With numerical values consistent with the phenomenology developed in (Fernandez 2025b), one has

$$v \approx 32.4\,\mathrm{MeV}, \qquad \lambda \approx 0.20 \quad \Rightarrow \quad m_\varphi \approx \sqrt{2\lambda}\,v \approx 20.5\,\mathrm{MeV}, \tag{19}$$

and

$$m^2 = -210\,\mathrm{MeV}^2 \quad (\text{not } -105\,\mathrm{MeV}^2), \qquad m_\varphi^2 = 2\lambda v^2. \tag{20}$$

Yukawa couplings can be parametrized compactly as

$$y_f = \kappa_f\,\frac{m_f}{v}, \qquad 0 < \kappa_f \le 1, \tag{21}$$

and, in particular,

$$y_e = \kappa_e \frac{m_e}{v}, \qquad \kappa_e \ll 1 \quad \text{(adjusted to experimental bounds).} \tag{22}$$

This parametrization summarizes the correction and fixes the numerical dictionary assumed both in (Fernandez 2025b) and in the present manuscript.

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