Vacuum Localized Structures: Nonsingular Black Holes and Dark-Matter Candidates

Rudi Van Nieuwenhove
Independent Researcher

Dessel, Belgium
rvnieuwe@gmail.com

Abstract

We present a vacuum-based model of nonsingular compact objects supported by a Vacuum Localized Structure (VLS): a smooth, spatially localized configuration of vacuum energy described by a Gaussian density profile. The VLS is modeled as an anisotropic vacuum stress configuration obeying the radial equation of state $p_r = -\frac{1}{3}\rho$, with tangential stresses fixed by energy–momentum conservation. In this framework the effective gravitational source is the Tolman combination of density and pressures.

Although the energy density is highest at the center, the effective gravitational source vanishes there. The dominant contribution to curvature arises from a finite-radius region where the vacuum energy density changes most rapidly. In this sense the gravitational field is generated mainly by a surrounding "vacuum shell" rather than by a central mass.

Depending on the compactness, the resulting spacetimes may possess horizons or be entirely horizonless, allowing for both nonsingular black holes and ultracompact vacuum objects. Possible observational implications, including gravitational-wave echoes from horizonless configurations, are briefly discussed. Because the same type of vacuum structure can naturally extend to galactic scales, the VLS framework also provides a unified setting for compact objects and extended vacuum halos, with potential relevance for dark-matter phenomenology.

Keywords

Vacuum Localized Structure (VLS), Horizonless ultracompact object, Nonsingular black hole, Quantum gravity, Gravitational-wave echoes, Dark matter alternatives

1. Introduction

Classical general relativity (GR) predicts that sufficiently strong gravitational collapse leads to spacetime singularities. The singularity theorems of Penrose and Hawking show that, under broad conditions, curvature invariants inevitably diverge inside black holes. These singularities are widely regarded as signaling the breakdown of the classical theory rather than the existence of physical objects.

A long-standing approach to avoiding singularities within GR is to modify the stress–energy content of the interior of compact objects. Many so-called "regular black-hole" models replace the classical singularity by a nonsingular vacuum-supported region and match this smoothly to an exterior Schwarzschild geometry. This idea appears in various constructions, starting from

Bardeen's pioneering nonsingular solution [1]. Dymnikova subsequently developed a systematic class of vacuum-based regular black holes and particle-like "G-lumps" supported by anisotropic vacuum stresses [2–4]. Related models include the Hayward metric [5] and the gravastar scenario of Mazur and Mottola [6], with stability further analyzed by Visser and Wiltshire [7]. Modern overviews of regular black-hole models and nonsingular gravitational collapse are given by Lan et al. [8] and by Bambi [9].

Within this broader context, Dymnikova introduced the notion of an anisotropic "vacuum dark fluid," characterized by a vacuum-like radial equation of state and a density profile that decays sufficiently rapidly at large radius to yield finite total mass [2–4]. The resulting geometries are everywhere regular and asymptotically Schwarzschild, and may describe either nonsingular black holes with horizons or horizonless, particle-like configurations of vacuum energy.

Although mathematically related to these models, the present work develops a different physical interpretation. The source is understood as a Vacuum Localized Structure (VLS): a smooth, spatially localized configuration of vacuum energy described by a Gaussian density profile. This concept was introduced earlier by Van Nieuwenhove [13–15], under different names such as "vacuum bubble," "geon," and "self-consistent gravitational energy distribution." In the VLS framework, gravity is attributed directly to a structured vacuum stress configuration rather than to an effective fluid or an enclosed mass distribution.

A central feature of the present formulation is that the effective gravitational source is the Tolman combination of energy density and pressures, rather than the energy density alone. With the revised vacuum equation of state adopted here, the central region of a VLS is regular, isotropic, and gravitationally neutral. The gravitational field is generated predominantly by a surrounding region where the vacuum stresses vary with radius. Compact objects in this framework are therefore best interpreted as *vacuum-shell–generated geometries*, not as mass distributions with vacuum cores.

This shift in interpretation embeds nonsingular black holes in a broader conceptual framework that links singularity resolution, horizonless ultracompact objects, galactic dark-matter phenomenology, and the gravitational role of vacuum energy. In particular, the same type of vacuum structure can naturally arise on galactic scales, where it may act as an alternative to particle dark matter [14]. In this view, galactic halos and compact objects represent different curvature regimes of the same underlying vacuum phenomenon.

Observational studies of shadows and particle motion in regular black-hole geometries, such as the Bardeen case investigated by Stuchlík and Schee [16], indicate that current data cannot yet clearly distinguish between singular and nonsingular interiors. This motivates continued exploration of physically well-founded nonsingular models and of their potential observational signatures.

2. Static VLS Configuration

We consider a static, spherically symmetric spacetime

$$ds^2 = -e^{2\Phi(r)}c^2dt^2 + e^{2\Lambda(r)}dr^2 + r^2(d\theta^2 + \sin^2\theta\, d\phi^2). \tag{1}$$

The source is taken to be an anisotropic vacuum stress configuration,

$$T^{\mu}{}_{\nu} = \mathrm{diag}\big(-\rho(r),\, p_r(r),\, p_t(r),\, p_t(r)\big). \tag{2}$$

The independent Einstein equations are

$$\begin{aligned}
G^{t}{}_{t} &= -\tfrac{1}{r^2} + e^{-2\Lambda}\left(\tfrac{1}{r^2} - \tfrac{2\Lambda'}{r}\right) = -\tfrac{8\pi G}{c^2}\rho, \\
G^{r}{}_{r} &= -\tfrac{1}{r^2} + e^{-2\Lambda}\left(\tfrac{1}{r^2} + \tfrac{2\Phi'}{r}\right) = \tfrac{8\pi G}{c^4}p_r, \\
G^{\theta}{}_{\theta} &= e^{-2\Lambda}\left(\Phi'' + \Phi'^2 - \Phi'\Lambda' + \tfrac{\Phi' - \Lambda'}{r}\right) = \tfrac{8\pi G}{c^4}p_t.
\end{aligned} \tag{3}$$

Stress–energy conservation yields

$$\frac{dp_r}{dr} = -(\rho c^2 + p_r)\Phi' + \frac{2}{r}(p_t - p_r). \tag{4}$$

VLS equation of state and anisotropy

$$p_r = -\tfrac{1}{3}\rho c^2, \tag{5}$$

$$\rho(r) = \rho_0 e^{-r^2/R^2}, \tag{6}$$

$$p_t = -\tfrac{1}{3}\rho c^2 + \tfrac{r^2}{3R^2}\rho c^2. \tag{7}$$

The Tolman source is

$$\rho_{\mathrm{act}} = \rho + \frac{p_r}{c^2} + 2\frac{p_t}{c^2} = \frac{2r^2}{3R^2}\rho(r). \tag{8}$$

Regularity of the core

$$\rho \simeq \rho_0, \quad p_r \simeq p_t \simeq -\tfrac{1}{3}\rho_0 c^2, \quad e^{2\Lambda} \simeq 1 + \tfrac{8\pi G\rho_0}{3c^2}r^2. \tag{9}$$

Depending on the compactness parameter, the geometry admits two horizons, one degenerate horizon, or none.

Regular black-hole models in the literature typically follow one of two approaches: either the metric is chosen first and the corresponding stress–energy tensor is deduced (“geometry-first”), or a physically motivated stress–energy tensor is specified and the metric is derived from the Einstein equations (“matter-first”). The VLS framework belongs to the second class, in which the vacuum’s anisotropic stress provides the source of a smooth, nonsingular interior geometry.

3. Relation to Dymnikova’s Vacuum Dark Fluid

Dymnikova introduced the concept of a “vacuum dark fluid” as a phenomenological description of the stress–energy required to support nonsingular compact objects within classical general relativity [2–4]. In her framework, the source is modeled as an anisotropic vacuum-like medium, with a radial equation of state of vacuum type and tangential stresses fixed by energy–momentum conservation. With suitable density profiles, this construction leads to geometries that are regular at the origin and asymptotically Schwarzschild at large radius.

Mathematically, the present VLS solutions belong to the same broad class of anisotropic vacuum configurations. In both approaches, anisotropy arises inevitably once vacuum energy is spatially localized, and the tangential pressure is not chosen arbitrarily but follows from the conservation laws. Both frameworks admit finite central densities, finite curvature invariants, asymptotically Schwarzschild behavior, and the possibility of both horizon and no-horizon solutions.

The physical interpretation, however, is fundamentally different.

In Dymnikova's models, the anisotropic vacuum is introduced as an effective "dark fluid" whose role is to support a de Sitter–like core and thereby regularize the black-hole interior. The central region acts as a vacuum core, and the nonsingular behavior is directly associated with this de Sitter–type structure.

In the updated VLS framework, by contrast, the source is interpreted as a genuine localized vacuum structure rather than as an effective macroscopic fluid. Moreover, with the revised equation of state $p_r = -\frac{1}{3}\rho$, the interior is no longer de Sitter. The Tolman combination that governs the active gravitational density, $\rho_{\text{act}} = \rho + \frac{p_r}{c^2} + 2\frac{p_t}{c^2}$, vanishes at the center of the configuration. The core is therefore gravitationally neutral: energy density and pressures remain finite, but they do not act as a local gravitational source. Curvature is generated predominantly by a surrounding region where the vacuum density varies with radius. The VLS object is thus best interpreted not as a mass distribution with a vacuum core, but as a self-gravitating vacuum shell geometry.

From this perspective, the essential role of anisotropy also changes. In Dymnikova's picture, anisotropy is primarily a mechanism that allows the vacuum dark fluid to interpolate between a de Sitter core and an exterior vacuum region. In the VLS interpretation, anisotropy reflects the intrinsic spatial structuring of the vacuum itself. It is a direct consequence of localizing vacuum energy in a finite region of space, and it controls how the gravitational field is distributed between a neutral interior and an active surrounding shell.

Despite these physical differences, both approaches share several important mathematical features:

finite central density and finite curvature invariants, anisotropy induced by the radial variation of vacuum energy, asymptotically Schwarzschild exterior geometry, the possibility of regular black holes and horizonless ultracompact objects.

4. Potential Barrier, VLS Surface, and Gravitational-Wave Echoes

A key physical difference between a true black hole and a horizonless ultracompact object concerns the behavior of perturbations in the near-horizon region. This difference can be understood in terms of two generic features of the spacetime: the curvature-induced effective potential (the "potential barrier") and the physical or effective boundary of the VLS (the "VLS surface").

The propagation of scalar, electromagnetic, and gravitational perturbations in a static, spherically symmetric spacetime is described by the Regge–Wheeler formalism [10]. After separation of variables using spherical harmonics, labeled by the multipole index l, one obtains a radial wave equation with an effective potential. The index $l = 0,1,2,$ ...arises from the angular dependence of the perturbation, and for gravitational waves only $l \geq 2$contributes. The resulting effective potential contains an angular-momentum term proportional to $l(l+1)/r^2$and a curvature term determined by the background geometry.

For objects whose exterior geometry is Schwarzschild-like, this potential possesses a pronounced peak near the photon sphere. This peak acts as a partially reflective curvature barrier: perturbations approaching it from either side are partly transmitted and partly reflected. Importantly, this potential barrier is a generic feature of compact relativistic geometries and is present irrespective of whether the object possesses an event horizon.

If the compact object is a horizonless VLS, then its interior vacuum structure has a physical or effective inner region at a radius slightly larger than the would-be Schwarzschild radius. At this location the classical exterior geometry transitions to the structured vacuum interior. Perturbations reaching this region are not absorbed, as they would be by an event horizon, but are instead at least partially reflected. The precise reflectivity depends on the detailed microphysics of the VLS, but reflection is expected on general grounds whenever a horizon is absent and the interior is regular.

The potential barrier near the photon sphere and the structured vacuum interior together form a resonant cavity. A burst of gravitational radiation produced during a compact-object merger is therefore expected to behave as follows. A portion of the radiation tunnels through the potential barrier and escapes to infinity, producing the familiar black-hole-like ringdown signal. Another portion propagates inward and is reflected by the inner vacuum structure. The reflected wave then travels outward, encounters the curvature barrier again, and is partially transmitted to infinity while the remainder is reflected back inward.

This process can repeat many times, giving rise to a sequence of late-time, exponentially damped gravitational-wave echoes. The time delay between successive echoes is approximately the light-travel time across the cavity, that is, twice the tortoise-coordinate distance between the photon-sphere barrier and the effective VLS surface. When the VLS structure is extremely compact and its inner region lies very close to the would-be Schwarzschild radius, this time delay becomes large. In that regime, echoes are weak and widely separated in time, making them difficult to detect.

A true black hole, by contrast, possesses an event horizon that effectively absorbs incoming radiation. No reflection occurs from the interior, and therefore no echoes are produced. The existence or absence of late-time echoes thus provides a potential observational discriminator between horizon-bearing black holes and horizonless ultracompact VLS objects.

The initial burst of gravitational waves observed in a merger is produced during the final stages of the inspiral and coalescence, when two compact objects accelerate rapidly, orbit at relativistic speeds, and undergo a violent dynamical interaction. This generates a sharp gravitational-wave peak followed by the prompt ringdown and, in the case of horizonless objects, by possible late-time echoes.

Current gravitational-wave observations have not conclusively detected echoes, but they also do not rule them out. Consequently, both regular black holes with horizons and horizonless ultracompact VLS objects remain astrophysically viable, in line with the broader regular black-hole literature reviewed in [8,9] and with recent work on nonsingular collapse to compact, horizonless configurations [17].

Future gravitational-wave detectors such as LISA, the Einstein Telescope, and Cosmic Explorer will provide much higher sensitivity to the late-time ringdown phase. These instruments may therefore be capable of probing the near-horizon structure of compact objects and of testing whether the endpoints of gravitational collapse are true black holes or vacuum-supported VLS configurations.

5. VLS Structures as Dark-Matter Candidates

One of the distinctive features of the VLS framework is that it extends naturally to astrophysical scales. The same mechanism that produces a localized vacuum structure on black-hole scales could, in principle, operate with much larger characteristic radius R and lower central density ρ_0, yielding vacuum-supported mass distributions on galactic scales [14]. Because the Gaussian density profile is smooth and finite, it naturally produces cored mass profiles rather than cuspy ones.

In previous work [13-16], we explored the possibility that such VLS configurations could model galactic rotation curves without invoking particle dark matter. The Gaussian profile leads to rotation curves that are approximately flat over a wide radial range and that can be adjusted by changing R and ρ_0 (see equation (4)). Moreover, VLS structures are non-luminous and interact only gravitationally, making them phenomenologically similar to dark matter. This is conceptually comparable to proposals in which regular black holes or gravastar-like objects act as dark-matter constituents, but here the emphasis is on smooth, extended vacuum halos rather than compact massive remnants.

From this perspective, VLS objects inhabit a spectrum of scales:

- on small scales, they can appear as nonsingular black holes or horizonless ultracompact objects;
- on intermediate scales, they may resemble massive compact halo objects;
- on large scales, extended VLS configurations may act as dark-matter halos in galaxies.

This unifies singularity resolution and dark-matter phenomenology within a single vacuum-based framework.

6. Conclusions

In this work we have developed the concept of a Vacuum Localized Structure (VLS) as a physically motivated, nonsingular alternative to the classical black-hole interior. A VLS is defined as a smooth, spatially localized configuration of vacuum energy described by a Gaussian density profile and supported by an anisotropic vacuum equation of state $p_r = -\frac{1}{3}\rho$. The tangential stresses arise self-consistently from energy–momentum conservation.

A central result of this framework is that the effective gravitational source is not the energy density alone but the Tolman combination of density and pressures. For the VLS configuration considered here, this active gravitational density vanishes at the center. The interior is therefore regular, isotropic, and gravitationally neutral. Curvature remains finite everywhere, and the gravitational field is generated predominantly by a surrounding region where the vacuum stresses vary with radius. The compact object is thus best interpreted as a self-gravitating vacuum-shell geometry rather than as a mass distribution with a repulsive core.

Depending on the compactness of the vacuum structure, the resulting spacetimes may possess two horizons, a single degenerate horizon, or none. The VLS framework therefore naturally accommodates both nonsingular black holes and horizonless ultracompact objects. In the absence of a horizon, the structured vacuum interior together with the photon-sphere potential barrier forms a resonant cavity that may give rise to late-time gravitational-wave echoes. Future gravitational-wave detectors could therefore provide observational tests of the near-horizon structure predicted by this model.

Beyond the black-hole context, VLS configurations extend naturally to astrophysical scales. Their smooth density profiles and vacuum origin allow them to act as extended, non-luminous gravitational structures, providing a unified framework in which nonsingular compact objects, horizonless ultracompact configurations, and galactic-scale vacuum halos may be viewed as different curvature regimes of the same underlying phenomenon.

Taken together, these results support the view that localized vacuum structures may play a much broader role in gravitational physics than traditionally assumed. By allowing the vacuum itself to organize into self-gravitating configurations, the VLS framework offers a simple and geometrically transparent route to singularity resolution, new classes of compact objects, and potentially new perspectives on the gravitational role of vacuum energy.

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