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

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Abstract

Regular black-hole models featuring a de Sitter-like core have been proposed as a way to avoid curvature singularities within classical general relativity. In this work, we develop an alternative vacuum-based approach in which a black hole or compact object is supported by a Vacuum Localized Structure (VLS): a smooth, localized distribution of vacuum energy described by a Gaussian profile. The resulting spacetime has finite central density, a regular de Sitter-like interior, and an exterior that approaches the Schwarzschild solution. Energy-momentum conservation causes the localized vacuum to become anisotropic, yielding effective stresses similar to those in known regular black-hole and gravastar models. Depending on the mass and scale of the VLS, the geometry may contain two horizons or none, allowing for both regular black holes and horizonless ultracompact objects. Because the same vacuum structure can be extended to galactic scales, the VLS framework also offers a natural alternative to particle dark matter.

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 physical objects.

One of the simplest ways to avoid singularities within GR itself is to replace the central region of a black hole by a de Sitter-like core, supported by a vacuum-like stress-energy tensor, and to match this smoothly to a Schwarzschild exterior. This idea appears in various "regular black-hole" models, starting from Bardeen's pioneering nonsingular solution [1]. Dymnikova then developed a family of vacuum-based nonsingular black holes and particle-like "G-lumps" with a de Sitter-like core [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]. A modern overview of regular black-hole models and non-singular gravitational collapse is given by Lan *et al.* [8] and by Bambi's monograph [9].

Within this broader context, Dymnikova constructed a particularly systematic class of regular black-hole solutions by introducing an anisotropic vacuum "dark fluid" with radial equation of state $p_r = -\rho$ and a density profile that decays fast enough at large radius to yield a finite total mass [2]-[4]. The resulting spacetimes possess a de Sitter-like core at the center and an asymptotically Schwarzschild exterior. Depending on parameters, the geometry may describe either a nonsingular black hole with horizons or a horizonless, particle-like "G-lump" 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 localized configuration of vacuum energy described by a Gaussian density. This concept was earlier introduced by Van Nieuwenhove [10]-[12], albeit under different names, such as "vacuum bubble", "geon", and "self-consistent gravitational energy distribution". This yields the same kind of de Sitter-like core found in regular black-hole models but embeds it in a broader conceptual framework, linking singularity resolution, horizonless compact objects, dark-matter phenomenology, and the gravitational role of vacuum energy. In particular, we emphasize that the same type of vacuum structure can naturally appear on galactic scales, where it can act as an alternative to particle dark matter [11]. Observational work on shadows and motion in regular black-hole geometries, such as the Bardeen case studied by Stuchlík and Schee [13], suggests that current data cannot yet distinguish sharply between singular and nonsingular interiors.

In recent years, an alternative line of research has questioned whether event horizons and singularities are the inevitable end state of gravitational collapse once quantum effects are properly taken into account. Following an influential proposal by Hawking that true event horizons may not form, being replaced instead by long-lived apparent horizons, Vaz developed a quantum gravitational treatment of inhomogeneous dust collapse based on the Wheeler-DeWitt equation, arguing that continuous collapse to a singularity is forbidden and that matter condenses on an apparent horizon, forming a thin, dense, spherically symmetric shell [14]. Related ideas can be traced back to Einstein's early analysis of collapse [15]. More recently, Corda has shown that such shell configurations exhibit well-defined quantum properties, obeying Schrödinger or Klein-Gordon dynamics depending on the regime, with discrete energy spectra emerging both from shell models and from the Oppenheimer-Snyder collapse framework [16] [17]. These results suggest that black holes may be better understood as horizonless, nonsingular quantum objects that radiate from an effective surface, thereby avoiding information-loss and firewall paradoxes.

The Vacuum Localized Structure (VLS) framework developed in the present work addresses the same fundamental problem, the resolution of singularities and the physical nature of compact objects, but from a different perspective. Rather than focusing on quantum collapse dynamics and matter shells, the VLS approach models the interior as a smooth, localized configuration of vacuum energy with a de Sitter-like core and an anisotropic vacuum stress tensor. While the underlying mechanisms differ, both approaches converge on the conclusion that classical event horizons and singularities need not arise in a complete description of gravitational collapse. In this sense, shell-based quantum collapse models and vacuum-supported VLS configurations should be viewed as complementary avenues toward a nonsingular and horizon-free description of black holes and ultra-compact objects.

2. Static VLS Configuration

We consider a static, spherically symmetric spacetime with line element.

$$\mathrm{d}s^2 = -f(r)c^2\mathrm{d}t^2 + \frac{\mathrm{d}r^2}{f(r)} + r^2\mathrm{d}\Omega^2 \tag{1}$$

where

$$f(r) = 1 - \frac{2GM(r)}{c^2 r} \tag{2}$$

and $M(r)$ is the mass function

$$M(r) = 4\pi\int_0^r \rho(r')r'^2\,\mathrm{d}r'. \tag{3}$$

The key assumption of the VLS model is that vacuum energy localizes into a smooth, finite-density configuration with a Gaussian profile,

$$\rho(r) = \rho_0 \exp\left(-\frac{r^2}{R^2}\right) \tag{4}$$

where ρ_0 is the central density and R is a characteristic length scale of the VLS core.

With Equation (4), one obtains

$$M(r) = 4\pi\rho_0 R^3\left[\frac{\sqrt{\pi}}{4}\mathrm{erf}\left(\frac{r}{R}\right) - \frac{1}{2}\frac{r}{R}\exp\left(-\frac{r^2}{R^2}\right)\right] \tag{5}$$

where erf is the error function. The total mass is finite:

$$M_{\mathrm{tot}} = \lim_{r\to\infty} M(r) = \pi^{3/2}\rho_0 R^3 \tag{6}$$

Near the origin, the density is approximately constant,

$$\rho(r) \approx \rho_0 \left(1 - \frac{r^2}{R^2} + \cdots\right) \tag{7}$$

so that

$$M(r) \approx \frac{4\pi}{3}\rho_0 r^3 \text{ and } f(r) \approx 1 - \frac{8\pi G}{3c^2}\rho_0 r^2 \tag{8}$$

This is exactly the form of the static patch of de Sitter space, with effective cosmological constant

$$\Lambda_{\text{eff}} = \frac{8\pi G}{c^4}\rho_0 . \tag{9}$$

Thus, the VLS naturally produces a de Sitter-like core with finite central density and curvature, avoiding the singularity.

3. Stress-Energy Tensor and Vacuum Anisotropy

For a static, spherically symmetric configuration, the stress-energy tensor can be written as

$$T^{\mu}{}_{\nu} = \text{diag}(-\rho, p_r, p_t, p_t) \tag{10}$$

where $\rho(r)$ is the energy density, $p_r(r)$ the radial pressure and $p_t(r)$ the tangential pressure.

Following Van Nieuwenhove [11] and Dymnikova and related models [2]-[4], we impose the vacuum-like radial equation of state

$$p_r = -\alpha\rho \tag{11}$$

This guarantees that the core is locally vacuum-dominated. The conservation of stress-energy,

$$\nabla_{\mu} T^{\mu r} = 0 \tag{12}$$

leads to the standard relation

$$\frac{\mathrm{d}p_r}{\mathrm{d}r} + \frac{2}{r}(p_r - p_t) = 0 . \tag{13}$$

Using Equation (11) this yields

$$p_t(r) = -\rho(r) - \frac{r}{2}\frac{\mathrm{d}\rho}{\mathrm{d}r} . \tag{14}$$

Using the Gaussian energy density profile (Equation (4)), one can show that

$$p_t = -\rho\left(1 - \frac{r^2}{R^2}\right). \tag{15}$$

Whenever $\rho(r)$ varies with radius, the tangential pressure differs from the radial pressure, and the vacuum becomes anisotropic. At the center, where $\mathrm{d}\rho/\mathrm{d}r = 0$, one has

$$p_r(0) = p_t(0) = -\alpha\rho_0 \tag{16}$$

in which α is a dimensionless positive number.

In the VLS interpretation, this anisotropy is not an arbitrary feature but a direct consequence of localizing vacuum energy in a finite region: the spatial variation of the density induces direction-dependent stresses that allow a smooth transition from the de Sitter-like core to the asymptotic Schwarzschild region without singularities.

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.

4. Relation to Dymnikova's Vacuum Dark Fluid

Dymnikova introduced the concept of a "vacuum dark fluid" as a phenomenological description of the stress-energy needed to support a nonsingular de Sitter-like core inside a compact object [2]-[4]. In her framework, the stress-energy tensor satisfies

$$T^t{}_t = -\rho(r), T^r{}_r = -\rho(r) \tag{17}$$

which implies the radial equation of state $p_r = -\rho$. The tangential pressure is again determined by energy-momentum conservation and takes the same general form (Equation (14)). The density profile is chosen to be finite at the center and to fall off rapidly at large radius, typically of the form

$$\rho(r) = \rho_0 \exp\left[-\left(\frac{r}{r_0}\right)^3\right], \tag{18}$$

so that the total mass is finite and the spacetime approaches Schwarzschild at large r.

In this picture, the "vacuum dark fluid" is an effective macroscopic description: it is non-luminous, behaves as vacuum in the radial direction, and is detectable only through gravity. It interpolates between a de Sitter-like core and an asymptotically flat exterior.

The VLS model developed earlier [11] belongs to the same broad class of solutions but provides a different physical interpretation. Instead of treating the source as an effective dark fluid, the VLS is conceived as a localized configuration of quantum vacuum energy with a Gaussian density profile motivated by wave-like localization and vacuum fluctuations. Mathematically, both models share:

- a finite central density and de Sitter-like core;
- a vacuum-like radial equation of state $p_r = -\alpha\rho$;
- anisotropy arising from the radial dependence of $\rho(r)$;

- a finite total mass and an asymptotically Schwarzschild exterior;
- the possibility of both regular black holes and horizonless compact objects.

The main differences are the choice of density profile and the physical interpretation. The Gaussian profile is particularly convenient for modeling smooth, cored mass distributions on galactic scales and for connecting to quantum-mechanical notions of localization.

The condition $p_r = -\alpha\rho$ ensures that the core is vacuum-dominated and regular; for $\alpha = 1$ it is locally indistinguishable from de Sitter space, but once $\rho(r)$ varies with radius the stress-energy tensor must become anisotropic. Equation (14) shows that the deviation of p_t from p_r is controlled by the density gradient. Near the origin, where $\rho(r)$ is almost constant, $p_t \approx p_r$ and the vacuum is effectively isotropic. Further out, anisotropy develops and allows the vacuum to adjust its pressure distribution in such a way that the geometry remains smooth and the total mass finite.

In the VLS interpretation, anisotropy reflects the spatial variation of a localized vacuum configuration, rather than the behavior of a macroscopic fluid. In both cases, anisotropy is not an ad hoc assumption but an unavoidable feature of any de Sitter-core solution that matches to an exterior vacuum region. Similar anisotropic structures appear in other nonsingular models, including gravastars [6] [7] and various regular black holes reviewed in [8] [9].

The existence of horizons is determined by the zeros of $f(r)$

$$f(r) = 1 - \frac{2GM(r)}{c^2 r} = 0 \tag{19}$$

For the VLS model, $M(r)$ increases from zero at the center to M_{tot} at large radius. Depending on the ratio $\frac{2GM_{\text{tot}}}{c^2 R}$, there are two qualitatively different regimes [3]:

- Regular black hole: if the mass is sufficiently large (or R sufficiently small), $f(r)$ has two positive roots, corresponding to an inner and outer horizon. The geometry resembles a classical black hole externally but has a nonsingular de Sitter-like core instead of a singularity. Versions of this behavior appear in many regular black-hole metrics, including Bardeen- and Hayward-type models [1] [5].
- Horizonless VLS object: if the mass is smaller (or R larger), $f(r)$ has no positive real roots. The result is a horizonless, ultracompact vacuum configuration. The exterior geometry can be very close to Schwarzschild if the VLS radius R_{VLS} is only slightly larger than the Schwarzschild radius $R_s = 2GM_{\text{tot}}/c^2$, making the object observationally difficult to distinguish from a black hole, similarly to gravastar [7] and other horizonless compact objects.

Thus the VLS framework naturally accommodates both regular black holes and geon-like horizonless objects, depending on parameters, in close analogy with Dymnikova's black holes and G-lumps [2]-[4] and with broader regular black-hole families reviewed in [8] [9].

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

A key physical difference between a true black hole and a horizonless ultra-compact object concerns the behavior of perturbations in the near-horizon region. This can be understood in terms of two 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 [18]. After separating variables using spherical harmonics, labeled by the multipole index l, one obtains a radial wave equation with an effective potential. The index $l = 0,1,2,\cdots$ arises from the angular dependence of the perturbation, and for gravitational waves only $l \geq 2$ contributes. The resulting effective potential contains the term $l(l+1)/r^2$, which represents the angular-momentum barrier, and a curvature term proportional to $2GM(r)/(c^2r^3)$.

$$V_\ell(r) = f(r)\left[\frac{\ell(\ell+1)}{r^2} + \frac{2GM(r)}{c^2r^3}\right] \tag{20}$$

with

$$f(r) = 1 - \frac{2GM(r)}{c^2r} \tag{21}$$

For objects whose exterior is Schwarzschild-like, this potential has a pronounced peak near the photon sphere at [19]

$$r_{\text{peak}} \approx \frac{3GM_{\text{tot}}}{c^2} = \frac{3}{2}R_s \tag{22}$$

This peak acts as a partially reflective potential barrier: perturbations approaching it from the inside or outside are partly transmitted and partly reflected. Importantly, this barrier is a generic curvature effect and is present whether or not the object possesses an event horizon.

If the compact object is a horizonless VLS, then its interior vacuum structure has a physical or effective boundary at a radius R_{VLS} slightly larger than the Schwarzschild radius [7],

$$R_{\text{VLS}} = (1+\epsilon)R_s = (1+\epsilon)\frac{2GM_{\text{tot}}}{c^2}, \quad \epsilon \ll 1 \tag{23}$$

At this radius the classical description of spacetime transitions to the vacuum-supported VLS core. Perturbations reaching this region are not absorbed (as they would be by a horizon) but are instead at least partially reflected, depending on the detailed microphysics of the VLS.

The potential barrier near the photon sphere and the VLS surface together form a resonant cavity. A burst of gravitational radiation produced during a merger behaves as follows:

A portion of the radiation tunnels through the potential barrier and reaches infinity, producing the familiar black-hole-like ringdown signal. Another portion travels inward and reflects from the VLS surface. The reflected wave then propagates outward, encountering the potential barrier again. Part of this wave escapes (producing an echo), while the remainder is reflected back toward the VLS surface. This process can repeat many times, giving rise to a sequence of late-time, exponentially damped gravitational-wave echoes. The time delay between echoes is approximately the light-travel time across the cavity [20],

$$\Delta t \sim \frac{2}{c}\int_{R_{\mathrm{VLS}}}^{r_{\mathrm{peak}}} \frac{\mathrm{d}r}{f(r)} \propto \frac{GM_{\mathrm{tot}}}{c^3}\ln\left(\frac{1}{\epsilon}\right) \tag{24}$$

which becomes large when the VLS surface is extremely close to the Schwarzschild radius. In that regime, echoes become 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 echoes are produced.

The initial burst of gravitational waves observed in a merger is produced during the final stages of the inspiral, when two compact masses accelerate rapidly, orbit at relativistic speeds, and undergo a violent dynamical merger, generating a sharp gravitational-wave peak before the subsequent ringdown and possible echo phases.

Current gravitational-wave observations have not conclusively detected echoes, but they also do not rule them out. As a result, 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 scenarios of nonsingular collapse such as those discussed by Hayward [5] and more recent work on collapse to horizonless objects [21].

Future gravitational-wave detectors such as LISA, the Einstein Telescope, and Cosmic Explorer will provide much higher sensitivity to the late-time ringdown phase, potentially allowing clear discrimination between true black holes and horizonless VLS configurations.

6. 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 [11]. Because the Gaussian density profile is smooth and finite, it naturally produces cored mass profiles rather than cuspy ones.

In previous work [10]-[12], 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.

7. Conclusions

In this work, we have introduced 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, localized configuration of vacuum energy described by a Gaussian density profile and supported by a vacuum-like radial equation of state $p_r = -\alpha\,\rho$. This structure naturally produces a finite-density de Sitter-like core, avoids curvature singularities, and matches smoothly to an exterior Schwarzschild geometry. Depending on the compactness, the resulting spacetime may possess two horizons, one degenerate horizon, or none, in close analogy with the behavior of other regular black-hole solutions.

Beyond the black-hole context, VLS configurations generalize naturally to astrophysical scales. Their smooth and extended density profiles allow them to act as dark-matter-like components in galaxies, offering an alternative explanation for flat rotation curves without invoking particle dark matter.

Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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