Pis'ma v ZhETF, vol. 124, iss. 11, pp. 913 – 915 © 2026 December 10

From gravastar to central singularity

G. E. Volovik[1)]

Landau Institute for Theoretical Physics, 142432 Chernogolovka, Russia

Submitted 9 August 2026
Resubmitted 4 October 2026
Accepted 20 October 2026

We consider the model of the regular black hole, which demonstrates that the gravastar is thermodynamically unstable towards the Schwarzschild black hole with singularity.

DOI: 10.7868/S3034576626120011

Gravastar [1–4] is a compact, non-singular solution of Einstein equations – the alternative to the Schwarzschild black hole with central singularity. It has an interior de Sitter region and an exterior Schwarzschild geometry, which are separated by a phase boundary. This horizonless object has no central singularity. Its entropy is determined by the thermodynamics of the thin shell and it is much smaller than the entropy of the Schwarzschild black hole. There is however a view [5–10], that the interior of the black hole can undergo a transition from being regular to containing a central singularity, see also [11].

To resolve this controversy we consider a simplified model of gravastar, in which the surface energy and its entropy are neglected. This model demonstrates that the gravastar is thermodynamically unstable towards the Schwarzschild black hole with singularity, i.e. the process of the transition is accompanied by increasing entropy. The particular scenarios of the decay is via the de Sitter bubble inside the black hole. The bubble contracts and its entropy increases. Finally it forms the small size core with Planck energy density – the Planck star [12]. This is a kind of the singular core, which in the further step transforms to the central singularity.

We use Painleve–Gullstrand (PG) metric [13, 14] $ds^2 = -dt^2 + (dr - v(r)dt)^2 + r^2 d\Omega^2$, where the shift velocity $v(r) = -\sqrt{R/r}$ for black holes, and $v(r) = \sqrt{R/r}$ for white holes; here $R = 2M$ is the radius of a hole and M is its mass. The black hole entropy $S_{\rm BH}(M) = 4\pi M^2$ can be obtained using the processes of quantum tunnelling in which the rate of the process is determined by the difference in the entropy between initial and final states [15–17]. For the horizonless gravastar [18] $v(r) = -\sqrt{R/r}$ for $r > R$ and $v(r) = -r/R$ for $r < R$. The core of this black hole corresponds to the contracting de Sitter state $v(r) = Hr$ with negative Hubble parameter, $H = -1/R$. The local temperature of the homogeneous de Sitter state and its entropy density and energy density are [18]:

$$T_{\rm dS} = \frac{H}{\pi}, \quad s_{\rm dS} = \frac{3}{4}H, \quad \epsilon_{\rm dS} = \frac{3}{8\pi}H^2. \tag{1}$$

For the expanding de Sitter spacetime, the local temperature is twice the Gibbons–Hawking temperature $T_{\rm GH} = H/2\pi$, which is related to the cosmological horizon. For contracting de Sitter, where $H < 0$, the temperature $T_{\rm dS}$ and entropy density $s_{\rm dS}$ are both negative. The horizonless gravastar has zero entropy, since the positive entropy $A/4G$ of black hole horizon and the negative entropy $-A/4G$ of cosmological horizon of the contracting de Sitter cancel each other.

The intermediate state between the gravastar and the Schwarzschild black hole is the de Sitter bubble, which occupies the part of the interior. If

$$\frac{E_{\rm P}^2}{M} \ll |H| \ll E_{\rm P}, \tag{2}$$

where $E_{\rm P}$ is the Planck energy, the radius of de Sitter bubble is much smaller than the radius of the black hole horizon, $r_0 \ll R$, but the bubble is still classical. Here instead of the central singularity one has the small de Sitter bubble with radius r_0 such that

$$r_0^3(H) = \frac{2M}{H^2} \ll R^3. \tag{3}$$

The de Sitter bubble contains the cosmological horizon with radius $r_H = 1/|H|$, which is much smaller than the radius of the bubble,

$$r_H^3 = 1/|H|^3 = \frac{1}{2M|H|}\,\frac{2M}{H^2} = \frac{r_0^3(H)}{2M|H|} \ll r_0^3(H) \ll R^3. \tag{4}$$

In this limit the bubble mimics the de Sitter Universe, which size is much larger than the cosmological horizon, but the Universe is well inside the black hole.

[1)]e-mail: volovik@itp.ac.ru

The total energy of the de Sitter bubble of volume $V = (4\pi/3)r_0^3$ is equal the black hole mass, $M = \epsilon_{\rm dS}V$, and thus the entropy of the bubble is:

$$S_{\rm dS}(H) = s_{\rm dS}V = s_{\rm dS}\frac{M}{\epsilon_{\rm dS}} = -\frac{2\pi M}{|H|}. \qquad (5)$$

The total entropy of the black hole with de Sitter bubble is the sum of the entropy of de Sitter bubble and the entropy of the black hole horizon $S_{\rm BH} = 4\pi M^2$:

$$S_{\rm BH}(M,H) = S_{\rm dS}(H) + S_{\rm BH}(M) = \qquad (6)$$

$$= S_{\rm BH}(M)\left(1 - \frac{1}{2M|H|}\right) = S_{\rm BH}(M)\left(1 - \frac{1}{R|H|}\right). \qquad (7)$$

At $|H| \to 1/R$, the entropy tends to zero. Since Eq. (7) is valid in both limits, $|H| \gg 1/R$ and $|H| \to 1/R$, this demonstrates that the suggested model is relevant for description of thermodynamics of the black hole with de Sitter bubble, and Eq. (7) can be used for the qualitative consideration in the whole range of $|H| \geq \frac{1}{2M}$.

The sum of entropies in Eq. (6) can be interpreted in the following way. It is the sum of entropies of the regions $r < r_0$ and $r_0 < r < \infty$. The entropy of the first region comes from the dark energy of the de Sitter bubble, $S(r < r_0) = S_{\rm dS}(H)$. The region $r_0 < r < \infty$ does not contain matter fields, but it contains the event horizon at $r = R$. The horizon, being the source of irreversibility, contributes the entropy $S(r > r_0) = S_{\rm hor} = \pi R^2 = S_{\rm BH}(M)$.

For $|H| = 1/2M$ the de Sitter bubble occupies the whole volume, and its negative entropy cancels the entropy of the black hole horizon. However, this state with zero entropy is thermodynamically unstable with respect to the contraction of the de Sitter bubble, which leads to an increase in entropy. The thermodynamic arrow of time indicates that the Schwarzschild black hole with central singularity is the equilibrium state.

The process of decay of gravastar towards the singularity leads to formation of the peculiar object – the bubble with energy density of Planck scale, $\epsilon \sim E_{\rm P}^4$. This object, which is the precursor of the singularity, is formed when $|H|$ reaches the Planck energy scale, $|H| \sim \sim E_{\rm P}$, and curvature reaches Planck level, $\mathcal{R} \sim 1/l_{\rm P}^2$. Then from Eq. (3) one obtains the size of the formed core:

$$r_0(E_{\rm P}) \sim l_{\rm P}\left(\frac{M}{E_{\rm P}}\right)^{1/3} \gg l_{\rm P}\,. \qquad (8)$$

The same result is obtained considering the Kretschmann scalar [19], which for Schwarzschild black hole of mass M is $K = 48M^2/r^6$. It becomes on the order of Planck scale for $r \sim r_0(E_{\rm P})$ in Eq. (8).

The size of the Planck-density core depends on the black hole mass M and thus it can be macroscopically large, although it is much smaller the black hole radius. This macroscopic core with Planck energy density is a kind of the regular singularity (or integrable singularity [6]). The entropy $S_{\rm core}$ of the Planck-density core is large, but still is much smaller than the black hole entropy.

Note that we do not consider the real dynamical route from the regular gravastar to the black hole with central singularity. The consideration is pure thermodynamical, and the thermodynamic route does not coincide with the dynamic path, which is determined by equations of motion. In the thermodynamic route, entropy increases from almost zero gravastar entropy to the entropy of the Schwarzschild black hole. We do not take into account the gravastar boundary. The boundary is important for the existence of the gravastar, but its entropy is negligibly small compared to the entropy of a Schwarzschild black hole, and thus it can be neglected in thermodynamics. Of course, in a dynamic context, the boundary may create an energy barrier along this path; however, this does not alter the fundamental tendency toward increasing entropy. The barrier will finally be overcome, say, via quantum tunneling.

In conclusion, we considered the oversimplified model of regular black hole. We did not take into account the surface tension of the boundaries between different regions of the black hole. Nevertheless the model demonstrates that the gravastar with the de Sitter core is thermodynamically unstable towards the Schwarzschild black hole with central singularity. It provides the route from the gravastar to Schwarzschild black hole, where the entropy increases from the almost zero value to the black hole value $S_{\rm BH} = A/4G$.

I thank Francisco Lobo for discussion, and Hideki Maeda and Jorge Ovalle for correspondence.

Funding. This work was supported by ongoing institutional funding. No additional grants to carry out or direct this particular research were obtained.

Conflict of interest. The author of this work declares that he has no conflicts of interest.

1. E. Mottola, *Gravitational Vacuum Condensate Stars, Regular Black Holes, Towards a New Paradigm of Gravitational Collapse*, ed. by C. Bambi (Springer Singapore, 2023), p. 283; arXiv:2302.09690 [gr-qc].

2. R. Carballo-Rubio, F. Di Filippo, S. Liberati, and M. Visser, *Singularity-free gravitational collapse: From regular black holes to horizonless objects*, in *Regular Black Holes, Towards a New Paradigm of Gravitational*

Collapse, ed. by C. Bambi (Springer, Singapore, 2023), p. 353; arXiv:2302.00028 [gr-qc].

3. P. O. Mazur and E. Mottola, "Gravitational vacuum condensate stars", PNAS **101**, 9545 (2004).
4. I. Dymnikova, "Vacuum nonsingular black hole", Gen. Rel. Grav. **24**, 235 (1992).
5. J. Ovalle, "Interior evolution of Regular Schwarzschild Black Holes", Phys. Lett. B **881**, 140912 (2026); arXiv:2509.00816.
6. R. Casadio, A. Giusti, A. Kamenshchik, and J. Ovalle, "On gravitational collapse and integrable singularities", Eur. Phys. J. C **86**, 1018 (2026); arXiv:2605.01808.
7. J. Ovalle, R. Casadio, and A. Kamenshchik, "Schwarzschild black hole singularity formation", Phys. Rev. D **113**, 064042 (2026); arXiv:2603.06451 [gr-qc].
8. S. Aoki and J. Ovalle, "An analytic model for a total process of gravitational collapse: from star to Schwarzschild black hole", Eur. Phys. J. C **86**, 741 (2026).
9. F. S. N. Lobo and M. E. Rodrigues, "Entropy release from Minkowski breaking in regular Schwarzschild black holes", arXiv:2607.14079.
10. F. S. N. Lobo and M. E. Rodrigues, "Entropy dynamics in gravitational collapse: From Minkowski breaking to de Sitter thermodynamics", arXiv:2607.24349.
11. H. Maeda, "Fake Schwarzschild and Kerr black holes", Class. Quant. Grav. **42**(23), 235005 (2025); arXiv:2410.11937 [gr-qc].
12. C. Rovelli and F. Vidotto, "Planck stars", Physics **23**, 12 (2014); arXiv:1401.6562
13. P. Painlevé, "La mécanique classique et la théorie de la relativité", C. R. Acad. Sci. (Paris) **173**, 677 (1921).
14. A. Gullstrand, "Allgemeine Lösung des statischen Einkörper-problems in der Einsteinschen Gravitationstheorie", Arkiv. Mat. Astron. Fys. **16**, 1 (1922).
15. G. E. Volovik, "From black hole to white hole via the intermediate static state", Mod. Phys. Lett. A **36**, 2150117 (2021); arXiv:2103.10954.
16. G. E. Volovik, "Macroscopic quantum tunneling: from quantum vortices to black holes and Universe", ZhETF **162**, 449 (2022) [G. E. Volovik, "Macroscopic quantum tunneling: from quantum vortices to black holes and Universe", JETP **135**, 388 (2022)]; arXiv:2108.00419.
17. M. K. Parikh and F. Wilczek, "Hawking radiation as tunneling", Phys. Rev. Lett. **85**, 5042 (2000).
18. G. E. Volovik, "Thermodynamics and decay of de Sitter vacuum", Symmetry **16**, 763 (2024); https://doi.org/10.3390/sym16060763.
19. E. J. Shaya, "The Quantum Boundary of Black Hole Interiors: Signature Failure and the Termination of Mass Inflation", arXiv:2606.15423.