A Neutron Star Hidden Inside a Black Hole

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The Shadow of M87*



Image credit: EHT Collaboration / ESO (2019).

Event Horizon Telescope Collaboration, *First M87 Event Horizon Telescope Results. I. The Shadow of the Supermassive Black Hole*, Astrophys. J. Lett. 875, L1 (2019), doi:10.3847/2041-8213/ab0ec7.

The Universe as a Black Hole (1972)

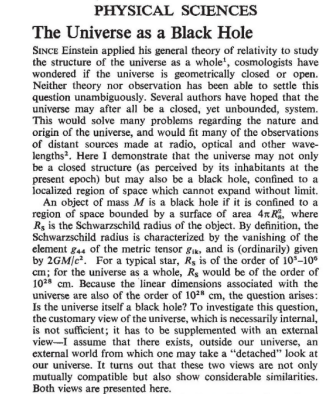
R. K. Pathria

Closed, dust-filled universe; $\Lambda = 0$.

Maximum expansion = horizon scale

$$R_{\text{max}} = \frac{2GM}{c^2} = r_s$$

A universe could lie inside a black hole in a larger universe.



PHYSICAL SCIENCES

The Universe as a Black Hole

SINCE Einstein applied his general theory of relativity to study the structure of the universe as a whole[1], cosmologists have wondered if the universe is geometrically closed or open. Neither theory nor observation has been able to settle this question unambiguously. Several authors have hoped that the universe may after all be a closed, yet unbounded, system. This would solve many problems regarding the nature and origin of the universe, and would fit many of the observations of distant sources made at radio, optical and other wavelengths[2]. Here I demonstrate that the universe may not only be a closed structure (as perceived by its inhabitants at the present epoch) but may also be a black hole, confined to a localized region of space which cannot expand without limit.

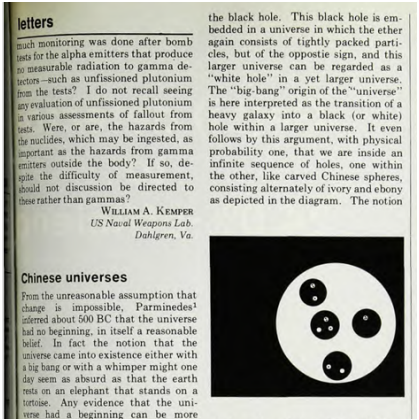
An object of mass M is a black hole if it is confined to a region of space bounded by a surface of area $4\pi R_s^2$, where R_s is the Schwarzschild radius of the object. By definition, the Schwarzschild radius is characterized by the vanishing of the element g_{44} of the metric tensor g_{ik}, and is (ordinarily) given by $2GM/c^2$. For a typical star, R_s is of the order of 10^5–10^6 cm; for the universe as a whole, R_s would be of the order of 10^{28} cm. Because the linear dimensions associated with the universe are also of the order of 10^{28} cm, the question arises: Is the universe itself a black hole? To investigate this question, the customary view of the universe, which is necessarily internal, is not sufficient; it has to be supplemented with an external view—I assume that there exists, outside our universe, an external world from which one may take a "detached" look at our universe. It turns out that these two views are not only mutually compatible but also show considerable similarities. Both views are presented here.

R. K. Pathria, *The Universe as a Black Hole*, Nature 240, 298–299 (1972), doi:10.1038/240298a0.
S. Khakshournia, *A note on Pathria's model of the universe as a black hole*, arXiv:1412.0105.

Chinese Universes (1972)

Physics Today
Chinese universes
I. J. Good 1972





letters

much monitoring was done after bomb tests for the alpha emitters that produce no measurable radiation to gamma detectors—such as unfissioned plutonium from the tests? I do not recall seeing any evaluation of unfissioned plutonium in various assessments of fallout from tests. Were, or are, the hazards from the nuclides, which may be ingested, as important as the hazards from gamma emitters outside the body? If so, despite the difficulty of measurement, should not discussion be directed to these rather than gammas?

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Chinese universes

From the unreasonable assumption that change is impossible, Parminedes[1] inferred about 500 BC that the universe had no beginning, in itself a reasonable belief. In fact the notion that the universe came into existence either with a big bang or with a whimper might one day seem as absurd as that the earth rests on an elephant that stands on a tortoise. Any evidence that the universe had a beginning can be more

the black hole. This black hole is embedded in a universe in which the ether again consists of tightly packed particles, but of the oppostie sign, and this larger universe can be regarded as a "white hole" in a yet larger universe. The "big-bang" origin of the "universe" is here interpreted as the transition of a heavy galaxy into a black (or white) hole within a larger universe. It even follows by this argument, with physical probability one, that we are inside an infinite sequence of holes, one within the other, like carved Chinese spheres, consisting alternately of ivory and ebony as depicted in the diagram. The notion

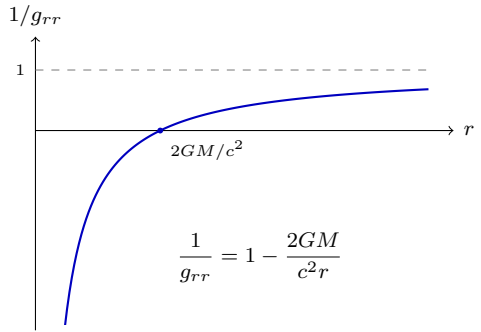
Nested universes: a historical conjecture inspired by Chinese concentric spheres.

[1] I. J. Good, *Chinese universes*, Physics Today 25(7), 15 (1972). doi:10.1063/1.3070923.

Inside a Black Hole

The familiar picture

- Gravitational collapse produces an event horizon.
- Classical Schwarzschild geometry has a central curvature singularity.
- A static material interior is not available in its trapped region.



$r \to 0^+ : \ 1/g_{rr} \to -\infty$; zero at $r = 2GM/c^2$.

Regular Spacetime and Matter

Replace the singular center; introduce matter.

Regular spacetime + **Matter**

Special matter sources

e.g., nonlinear electrodynamics

Bardeen / Hayward

Modified gravity

e.g., infinite-order gravity

Field matter

Field equations

Baryonic matter

Equations of state (EoS)

[5] X. E. Wang, *From Bardeen-boson stars to black holes without event horizon*, arXiv preprint, arXiv:2305.19057.
[6] Y. Yue and Y.-Q. Wang, *Frozen Hayward-boson stars*, JCAP 05 (2025) 066, arXiv:2312.07224.

Regular Spacetime + Field Matter

Within the Bardeen / Hayward framework

Boson stars (scalar field)	2305.19057 2312.07224 2502.14153 2512.10197
Proca stars (vector field)	2503.16265
Dirac stars	2312.07400 2409.14402
Charged	2407.11355
Axion field	2407.17278

Quasi-topological gravity

Infinite order

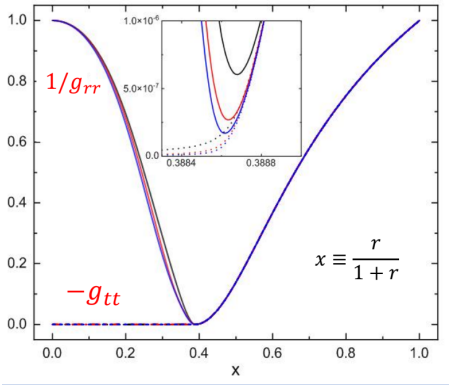
Boson stars: 2406.08813

Scalarization

Bardeen / Hayward

2509.08549

What Does “Frozen” Mean?



Critical horizon: $r_0 > 0$

$$g_{rr}^{-1}(r_0) = \min_r g_{rr}^{-1} \to 0^+.$$

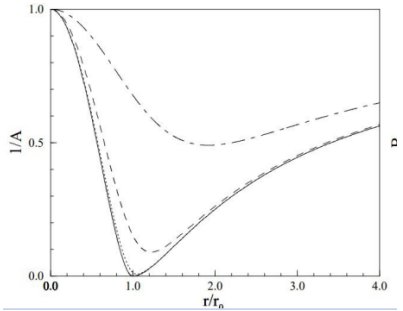
- **Near-zero minimum:** $\sim 10^{-7}$ in the figure; closer approach is limited by numerical accuracy.
- **Frozen interior:** $-g_{tt} \ll 1$; very large redshift for a distant observer.
- **Black-hole-like exterior:** approaches an extremal geometry.
- **No actual horizon:** redshift is expected to diverge only in the limiting configuration.

A highly redshifted, horizonless “frozen star”.

Metric illustration reproduced from Y.-Q. Wang, *Recent Progress on Frozen Stars*, conference presentation (2026), supplied by the presenter.

Magnetic monopoles

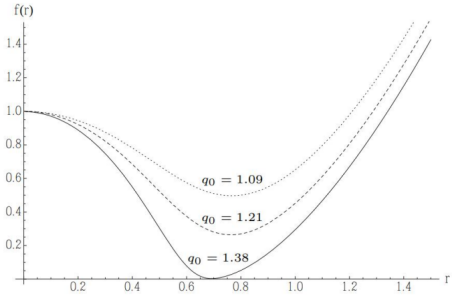
Lue–Weinberg



Einstein–Yang–Mills–Higgs matter near the black-hole threshold. The minimum of $1/A$ approaches zero.

$2+1$ boson stars (2014)

Stotyn–Chanona–Mann



A complex scalar in AdS_3 approaches an extremal BTZ limit, interpreted as a regular star inside a degenerate horizon.

[8] A. Lue and E. J. Weinberg, *Magnetic monopoles near the black hole threshold*, Phys. Rev. D 60, 084025 (1999).
[10] S. Stotyn, M. Chanona and R. B. Mann, *Numerical Boson Stars with a Single Killing Vector II: the D=3 Case*, Phys. Rev. D 89, 044018 (2014), arXiv:1309.2911.

Bardeen Neutron Stars

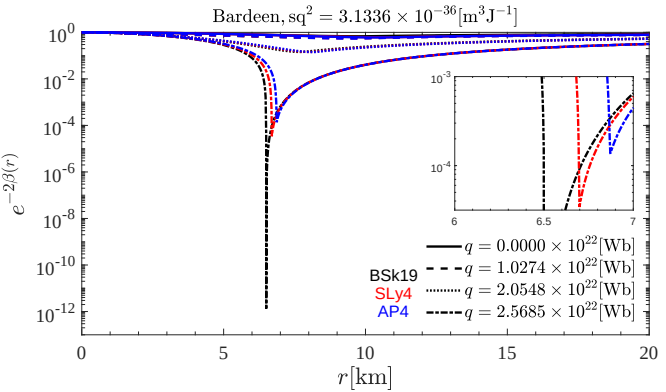
Einstein–Bardeen model

$$\mathcal{L} = \frac{c^3 R}{16\pi G} + \frac{\mathcal{L}_m + \mathcal{L}_{\mathrm{NED}}}{c}.$$

$$\mathcal{L}_{\mathrm{NED}} = -\frac{3}{2sq^2}\left[\frac{\sqrt{2q^2FC_d}}{1+\sqrt{2q^2FC_d}}\right]^{5/2}.$$

Baryonic fluid: nuclear equations of state.

Result: a near-frozen metric minimum.



[11] C. Tan and Y.-Q. Wang, *Frozen Neutron Stars*, arXiv preprint, arXiv:2509.09338.

Four-Dimensional Non-Polynomial Gravity: Frozen Stars

Four-dimensional gravity

$$S_g = \frac{c^3}{16\pi G}\int d^4x\sqrt{-g}\,\mathcal{L}_g,$$

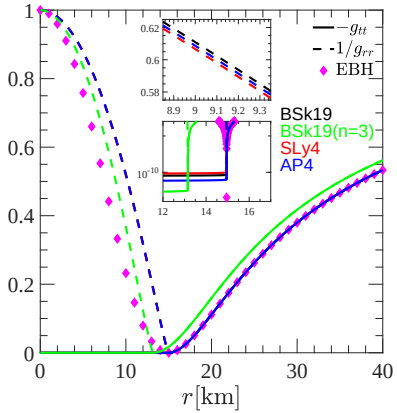
$$\mathcal{L}_g = R + \sum_{n=2}^{\infty}\alpha_n \mathcal{Z}_{(n)}.$$

Selected characteristic function

$$h(\psi) = \frac{\psi}{1-\alpha^2\psi^2}, \quad \psi = \frac{1-f}{r^2}.$$

$$r^3 h(\psi) = \frac{2Gm_b(r)}{c^2}.$$

Frozen signature: suppressed lapse and near-zero radial minimum.



[12] C. Tan and Y.-Q. Wang, *Frozen Neutron Stars in Four-Dimensional Non-polynomial Gravities*, arXiv preprint, arXiv:2512.23525.

Four-Dimensional Non-Polynomial Gravity: Mass and Radius

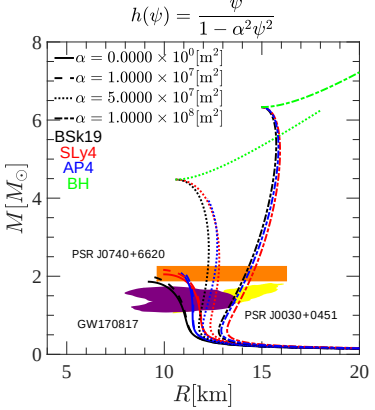
Coupling ranges

α in units of 10^7 m^2

EOS	Lower	Upper
BSk19	0.9	9.0
SLy4	0.0	8.0
AP4	0.0	9.0

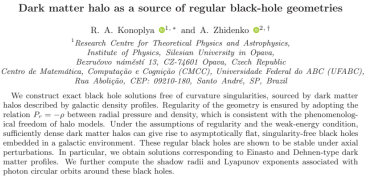
Allowed ranges overlap the freezing threshold.

Model- and EOS-dependent; not stability bounds.



[12] C. Tan and Y.-Q. Wang, *Frozen Neutron Stars in Four-Dimensional Non-polynomial Gravities*, arXiv preprint, arXiv:2512.23525.

Anisotropic Halo: Matter Source



Dark matter halo as a source of regular black-hole geometries

R. A. Konoplya [1,*] and A. Zhidenko [2,†]

[1] *Research Centre for Theoretical Physics and Astrophysics, Institute of Physics, Silesian University in Opava, Bezručovo námˇestí 13, CZ-74601 Opava, Czech Republic*

[2] *Centro de Matemática, Computação e Cognição (CMCC), Universidade Federal do ABC (UFABC), Rua Abolição, CEP: 09210-180, Santo André, SP, Brazil*

We construct exact black hole solutions free of curvature singularities, sourced by dark matter halos described by galactic density profiles. Regularity of the geometry is ensured by adopting the relation $P_r = -\rho$ between radial pressure and density, which is consistent with the phenomenological freedom of halo models. Under the assumptions of regularity and the weak-energy condition, sufficiently dense dark matter halos can give rise to asymptotically flat, singularity-free black holes embedded in a galactic environment. These regular black holes are shown to be stable under axial perturbations. In particular, we obtain solutions corresponding to Einasto and Dehnen-type dark matter profiles. We further compute the shadow radii and Lyapunov exponents associated with photon circular orbits around these black holes.

Konoplya–Zhidenko
Phys. Rev. D 113, 043011 (2026)

Anisotropic stress–energy tensor

$$T^{\mu}{}_{\nu} = \mathrm{diag}(-\rho, p_r, p_\perp, p_\perp)$$

Vacuum equation of state

$$p_r = -\rho.$$

Tangential pressure from conservation

$$p_\perp = -\rho - \frac{r}{2}\rho'.$$

From $\nabla_\mu T^{\mu\nu} = 0$.

Interpretation: Although dark-energy-like, $p_r = -\rho$ is motivated by unified dark-sector and vacuum-like or self-interacting dark-matter models. This relation is assumed to hold only in the central region of a galaxy.

[14] R. A. Konoplya and A. Zhidenko, *Dark matter halo as a source of regular black-hole geometries*, Phys. Rev. D 113, 043011 (2026), arXiv:2511.03066.

Einasto Density and Horizon Formation

Einasto density $G = c = 1$

$$\rho(r) = \rho_0 e^{-(r/h)^{1/n}}.$$

ρ_0: central density; h: scale; n: shape.

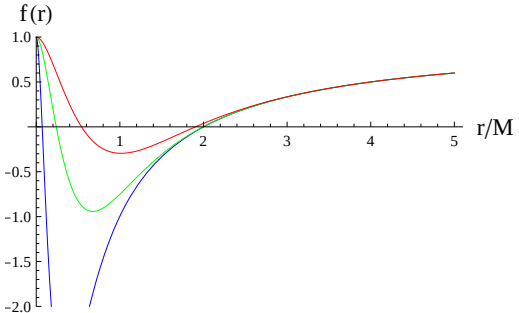
Exponential example: $n = 1$

$$\boxed{\rho = \rho_0 e^{-r/h}}, \quad M = 8\pi\rho_0 h^3.$$

$$m(r) = M\left[1 - e^{-r/h}Q(r)\right],$$

$$Q(r) = 1 + \frac{r}{h} + \frac{r^2}{2h^2},$$

$$f(r) = 1 - \frac{2m(r)}{r}.$$



$h/M = 0.1$ (blue), 0.2 (green), 0.3 (red).

$h = 0.2M$: $r_- \simeq 0.2391M$, $r_+ \simeq 1.9943M$.

[14] R. A. Konoplya and A. Zhidenko, *Dark matter halo as a source of regular black-hole geometries*, Phys. Rev. D 113, 043011 (2026), arXiv:2511.03066.

Energy Conditions of the Halo

$$\rho = \rho_0 e^{-r/h}, \qquad p_r = -\rho, \qquad p_\perp = -\rho - \frac{r}{2}\rho', \qquad G = c = 1.$$

Condition	Relevant inequalities	Result
NEC / WEC	$\rho \geq 0,\ \rho + p_r = 0,\ \rho + p_\perp = r\rho/(2h) \geq 0$	All radii
SEC	$\rho + p_r + 2p_\perp = \rho(r/h - 2) \geq 0$	$r \geq 2h$
DEC	$\rho \geq \lvert p_r \rvert,\ \rho \geq \lvert p_\perp \rvert$	$r \leq 4h$

For $h = 0.2M$: SEC is violated at $r < 0.4M$; DEC is violated at $r > 0.8M$.

[14] R. A. Konoplya and A. Zhidenko, *Dark matter halo as a source of regular black-hole geometries*, Phys. Rev. D 113, 043011 (2026), arXiv:2511.03066.

Two-Component Model

$$S = \int d^4x\sqrt{-g}\left[\frac{c^3 R}{16\pi G} + \frac{\mathcal{L}_b + \mathcal{L}_d}{c}\right].$$

$$G_{\mu\nu} = \frac{8\pi G}{c^4}\left(T^{(b)}_{\mu\nu} + T^{(d)}_{\mu\nu}\right).$$

Baryonic matter

Perfect-fluid neutron star.

Equation of state: BSk19 or SLy4.

$$p = p(\rho).$$

Negligible direct interactions

Direct detection and Bullet Cluster observations (Clowe et al., 2006; Randall et al., 2008) motivate

$$\boxed{\sigma_\chi \ll \sigma_N}.$$

Consequently, the two components are independently conserved:

$$\boxed{\nabla_\mu T^{\mu\nu}_{(b)} = 0} \qquad \boxed{\nabla_\mu T^{\mu\nu}_{(d)} = 0}.$$

Modified TOV Equations

Halo density and radial pressure

$$\boxed{\rho_d(r) = \rho_0 \exp\left[-\left(\frac{r}{h}\right)^{1/n}\right]} \qquad \boxed{p_{r,d}(r) = -\rho_d(r)c^2}$$

$$f(r) \equiv g_{rr}^{-1} = 1 - \frac{2Gm_{\text{all}}(r)}{c^2 r}, \qquad m_{\text{all}} = m_b + m_d.$$

$$\frac{dm_b}{dr} = 4\pi r^2 \rho, \qquad \frac{dm_d}{dr} = 4\pi r^2 \rho_d.$$

Modified Tolman–Oppenheimer–Volkoff equation

$$\frac{dp}{dr} = -\frac{G\left[c^2 m_{\text{all}}(r) + 4\pi r^3 p_{\text{all}}(r)\right]\left[p(r) + c^2\rho(r)\right]}{c^2 r\left[c^2 r - 2Gm_{\text{all}}(r)\right]}.$$

$$p_{\text{all}}(r) = p(r) + p_{r,d}(r).$$

Halo contributions: enclosed mass m_d and radial pressure $p_{r,d}$.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Numerical Setup

Initial-value problem: adaptive fourth-order Runge–Kutta

Central boundary conditions — Eq. (19)

$$r_\delta = 10^{-10}\,\mathrm{m} \ll R, \qquad m_b(r_\delta) = \frac{4\pi}{3} r_\delta^3 \rho_c.$$

$$\rho(r_\delta) = \rho_c, \qquad p(r_\delta) = p_c.$$

- Integrate the modified TOV equations to the stellar surface $r = R$, where $p = \rho = 0$.
- Results are independent of r_δ when it is sufficiently small compared with R.
- Use BSk19 and SLy4; restrict baryonic densities to their causal limits, where $c_s^2 = dp/d\rho \leq c^2$ (see below).

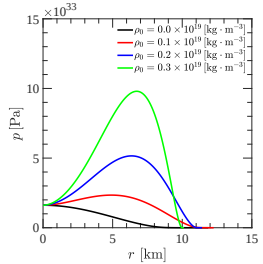
EOS	BSk19	SLy4
ρ_{max} [kg m^{-3}]	3.3814×10^{18}	3.0075×10^{18}

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Pressure Profiles

STRUCTURAL RESPONSE Pressure profiles and stellar radius

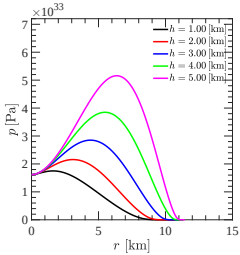
A Central density ρ_0



Fixed: $h = 5$ km, $n = 1$.

Response: $R \uparrow \rightarrow R \downarrow$

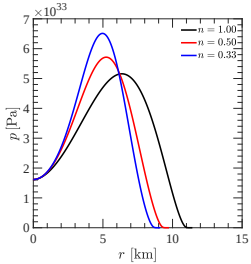
B Radial scale h



Fixed: $\rho_0 = 0.2 \times 10^{19}$, $n = 1$.

Response: $R \downarrow \rightarrow R \uparrow$

C Profile shape n



Fixed: $\rho_0 = 0.2 \times 10^{19}$, $h = 5$ km.

Response: $R \uparrow$

Within the displayed range.

Common setup: BSk19; **neutron-star central density** $\rho_c = 0.5 \times 10^{18}$ kg m^{-3}.

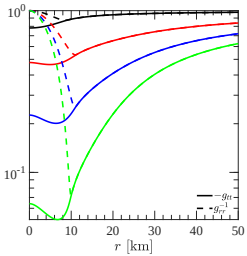
Vary one halo parameter at a time; halo densities are in kg m^{-3}.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Metric Profiles

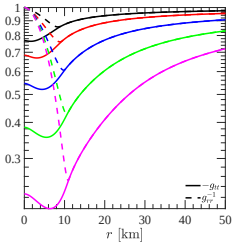
GEOMETRIC RESPONSE Solid: $-g_{tt}$ Dashed: g_{rr}^{-1}

A Central density ρ_0



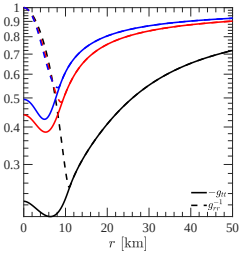
Fixed: $h = 5$ km, $n = 1$.

B Radial scale h



Fixed: $\rho_0 = 0.2 \times 10^{19}$, $n = 1$.

C Profile shape n



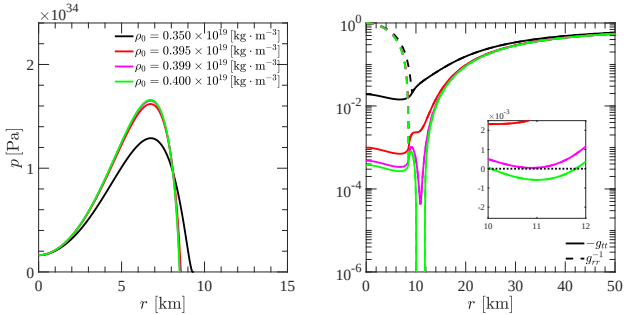
Fixed: $\rho_0 = 0.2 \times 10^{19}$, $h = 5$ km.

Common setup: BSk19; **neutron-star central density** $\rho_c = 0.5 \times 10^{18}$ kg m^{-3}.
Vary one halo parameter at a time; halo densities are in kg m^{-3}.

Physical interpretation: changing the halo alters the depth and position of the metric minima.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Horizon Formation

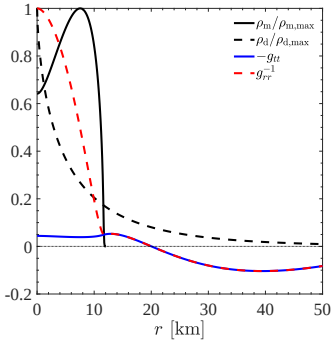


Fixed halo parameters: $n = 1$, $h = 5\,\text{km}$. At $\rho_0 = 0.40 \times 10^{19}\ \text{kg}\,\text{m}^{-3}$:

$$f_{\min} = -5.8152 \times 10^{-4}, \qquad R = 8.51\ \text{km} < r_- \simeq 10.06\ \text{km} < r_+ \simeq 11.79\ \text{km}.$$

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Extended Horizon Shell

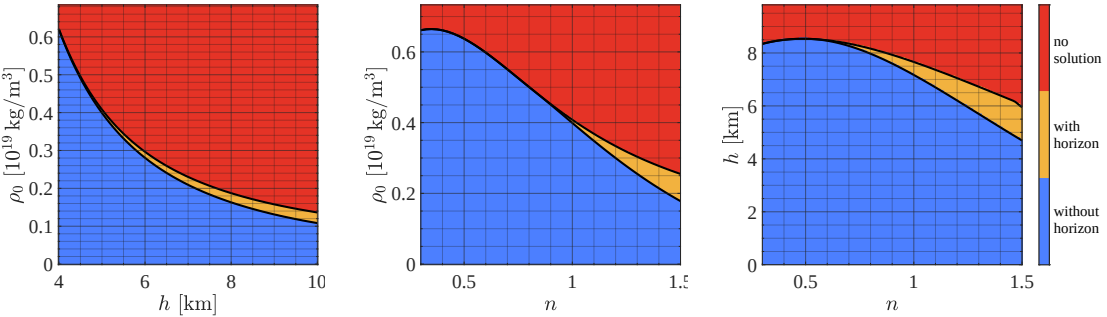


$$n = 1.5, \quad h = 5 \text{ km},$$
$$\rho_0 = 0.20 \times 10^{19} \text{ kg m}^{-3}.$$

- The halo is more extended.
- A lower ρ_0 suffices in this example.
- The negative-f region is wider and deeper than in the $n = 1$ example.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Parameter Space

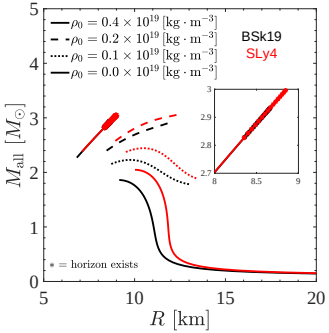


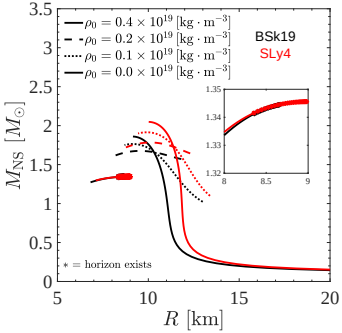
Blue: no horizon **Orange:** neutron star inside a black hole **Red:** no admissible equilibrium

Parameter slices: (a) $n = 1$ (b) $h = 5$ km (c) $\rho_0 = 0.2 \times 10^{19}$ kg m^{-3}.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Mass–Radius Relations





$$M_{\rm NS} = m_b(R), \quad M_{\rm DM} = m_d(R), \quad M_{\rm all} = M_{\rm NS} + M_{\rm DM}.$$

Asterisks identify horizon-containing configurations.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Numerical Robustness

Check	Variation	Change in $f_{\min}$
ODE tolerance	`RelTol` : $10^{-4} \to 10^{-12}$	$\lesssim 10^{-11}$
Maximum step	$0.1 \to 100$ m	$\sim 10^{-14}$
Solver family	Explicit Runge–Kutta vs. implicit stiff solver	$\sim 10^{-11}$

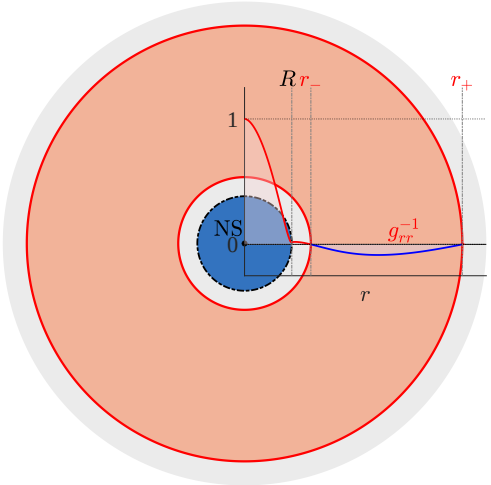
$$|f_{\min}| = 5.8152 \times 10^{-4} \quad \gg \quad \text{reported numerical variations.}$$

Take-home message

These checks support numerical robustness.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

A New Possibility



Limitations and Outlook

Established in this model

- Regular stellar equilibrium inside the inner horizon.
- A finite horizon-containing parameter window.
- Examples for BSk19 and SLy4.
- Numerical robustness checks.

Still open

- Radial and nonlinear stability.
- Inner-horizon instability and global evolution.
- A formation channel.
- Distinguishable external observables.

Astrophysical caveat: the required halo densities greatly exceed conventional DM-halo expectations.

[13] C. Tan and Y.-Q. Wang, *A Neutron Star Hidden Inside a Black Hole*, arXiv preprint, arXiv:2608.06224.

Thanks for your attention!