Star collapse in loop quantum gravity: beyond the marginally trapped case

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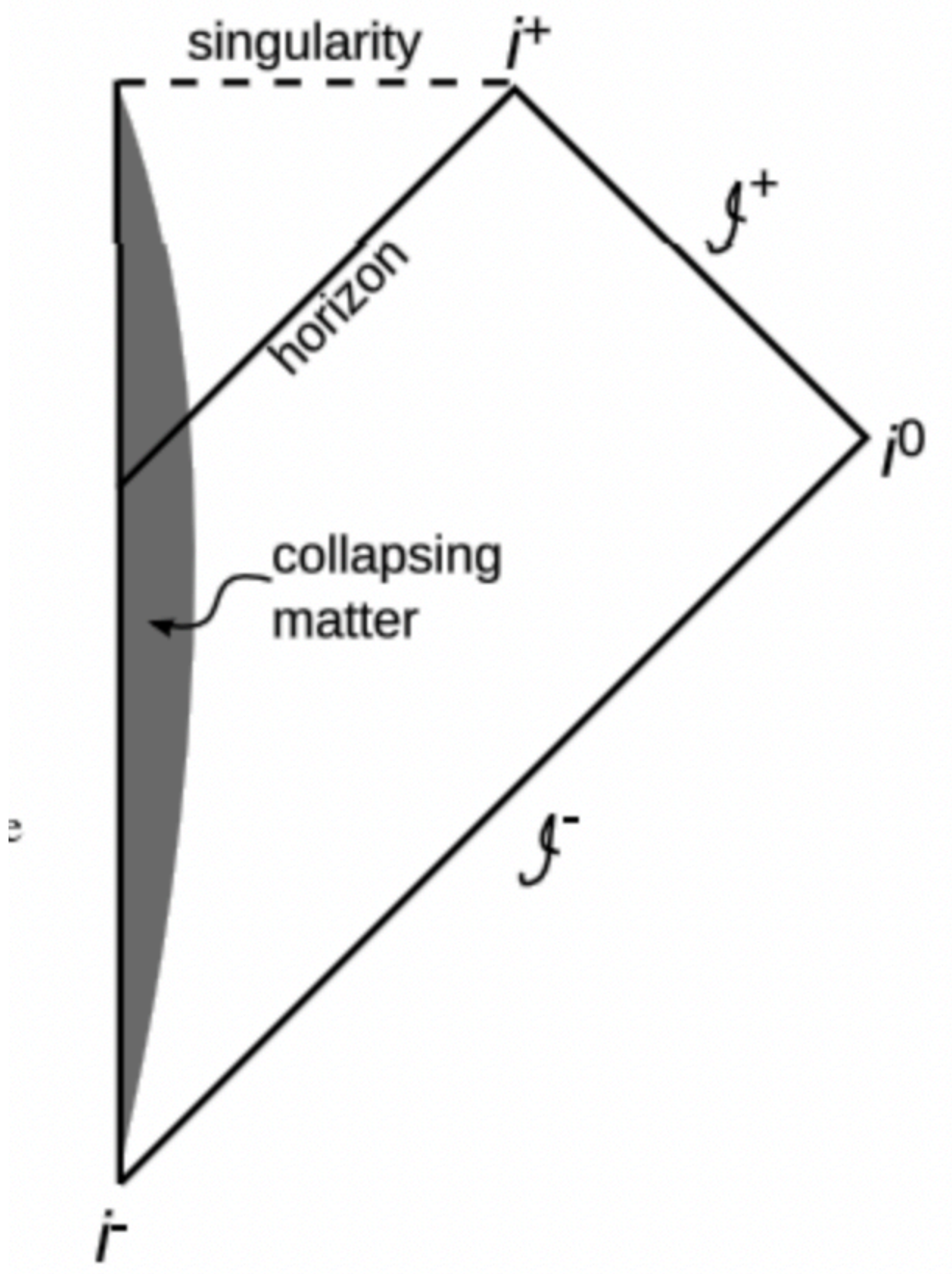
Cipriani, FF, Wilson Ewing, arXiv:2404.04192

Introduction

Since the seminal work by Oppenheimer and Snyder, black hole formation from star collapse in general relativity has been an intense research topic.



The assumptions behind the model are:

- Spherical symmetry.
- Pressure-less scalar field (dust) as source.
- An initial energy density profile given by an Heaviside function.

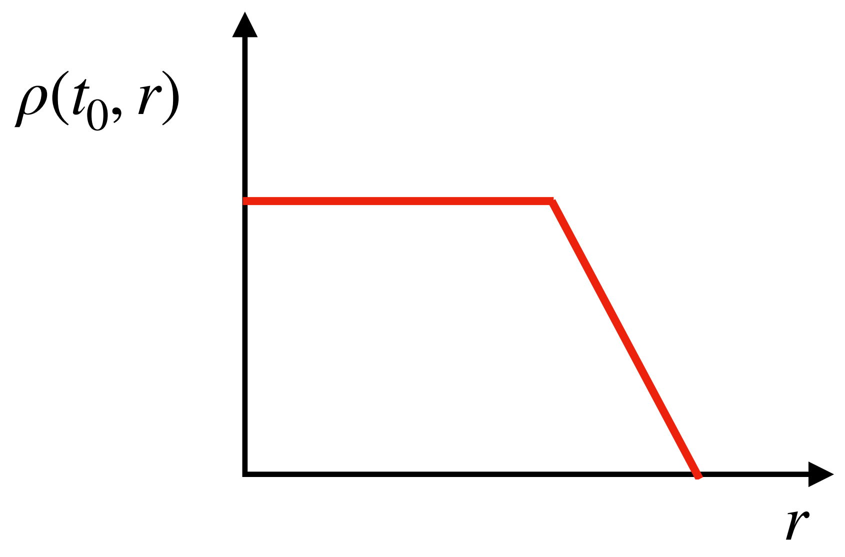
How does this picture change if we modify Einstein equations by taking in account **quantum gravity effects**?

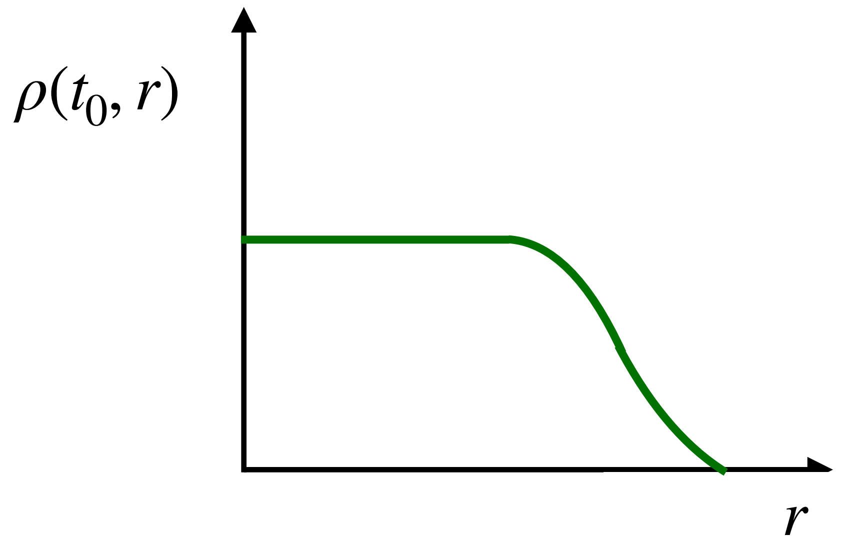
Introduction

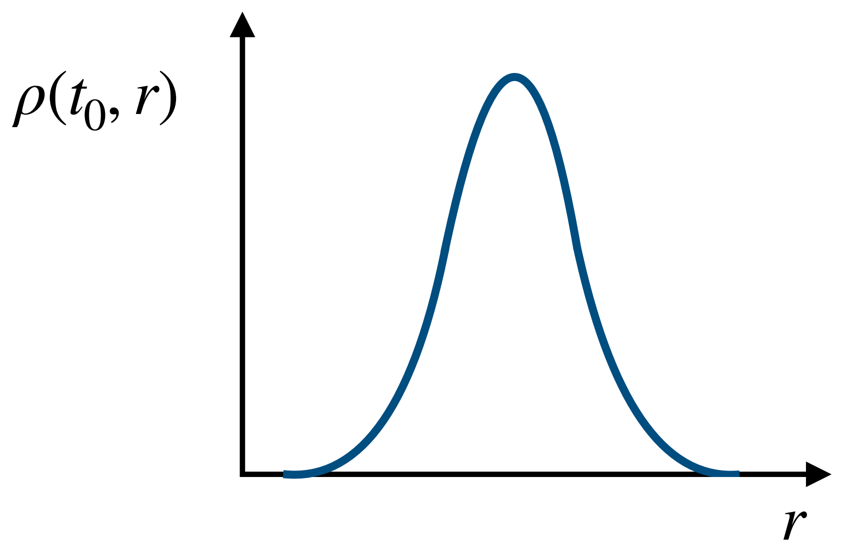
The quantum LQG-inspired OS model predicts a symmetric dynamics around the bounce point $\left(\rho_{bounce} = \frac{3}{8\pi G\gamma^2\Delta} \equiv \rho_c\right)$.

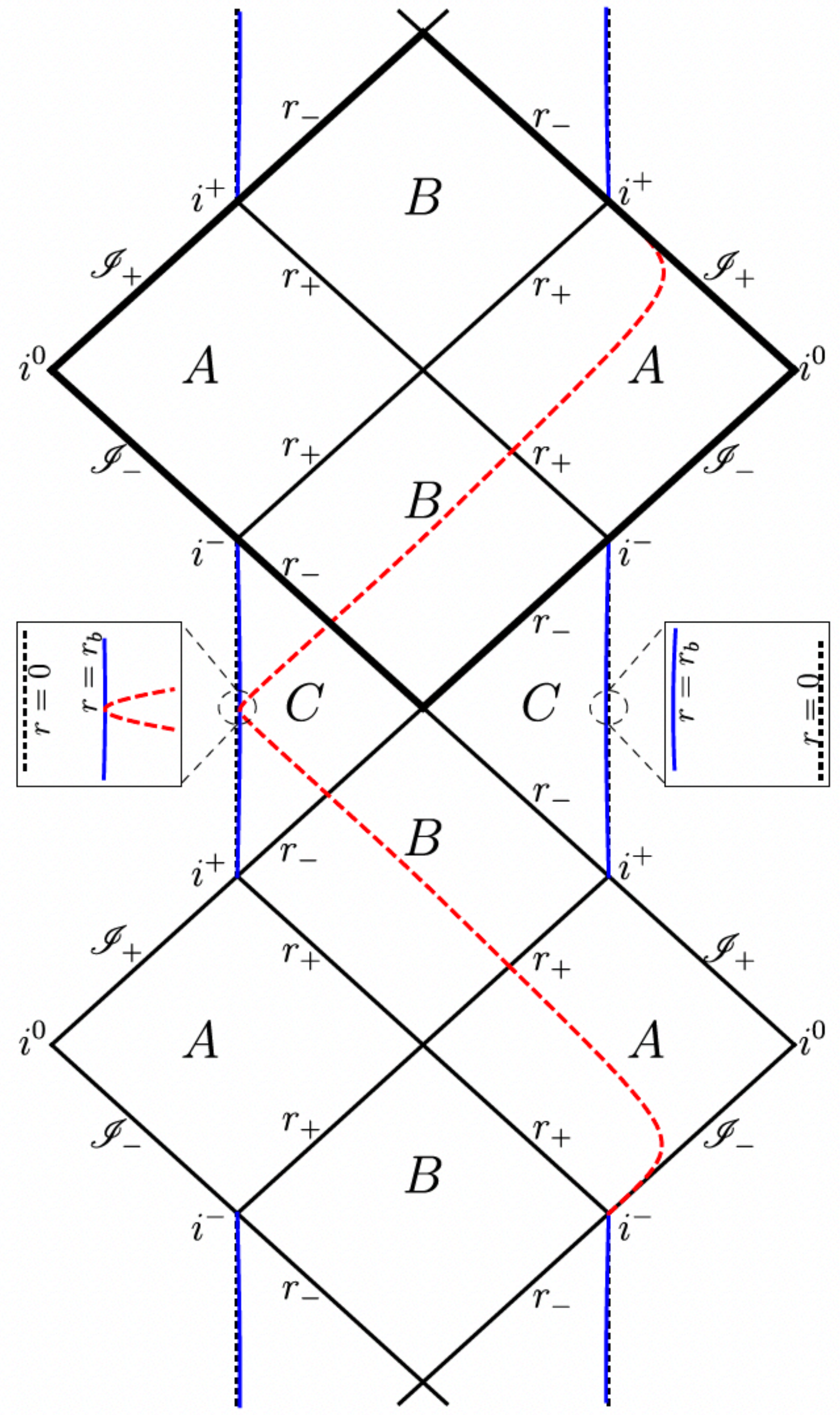
[Lewandowski, Ma, Yang, Zhang, 2023; Giesel, Liu, Singh, Weigl, 2023; FF, Rovelli, Soltani, 2023]

- How does the picture change if we consider continuous initial energy density profiles?









- What happens if we consider profiles beyond marginally trapped configurations?

[Lewandowski, Ma, Yang, Zhang, 2023]

Qualitative picture

1. Collapse phase: the energy density of the star progressively increases and its volume decreases; when the horizon forms the star becomes as a black hole.

2. Bouncing phase: when the energy density of the core becomes planckian, the shells of the core bounce and crush the collapsing shells of the tail.

→ A *shell-crossing singularity* forms, together with a *discontinuity* in the gravitational field.

Qualitative picture

3. Shockwave phase: rapidly all the outgoing shells in the core merge in the singularity, that slowly moves outward together with the shock in the gravitational field.

4. Explosion: when the shock reaches the horizon the black hole disappears and an external observer will eventually see a violent explosion which carries the whole energy of the collapsed star.

Effective equations in the areal and dust-time gauges

The metric describing this dynamics is studied in generalized Painlevé-Gullstrand coordinates:

$$ds^2 = -dt^2 + \frac{x^2}{1+\varepsilon(x,t)}(dx + N^x dt)^2 + x^2 d\Omega^2 \qquad N^x = -\frac{x}{\gamma\sqrt{\Delta}} sin\left(\frac{2\sqrt{\Delta}B}{x^2}\right)$$

And the quantum corrected field equations in Ashtekar-Barbero variables in these coordinates:

$$\dot{B}(x,t) = -\partial_x\left(\frac{x^3}{2\gamma\Delta} sin^2\frac{\sqrt{\Delta}B}{x^2}\right) + \frac{\gamma}{2}\varepsilon(x,t)$$

$$\dot{\varepsilon}(x,t) = -\partial_x\left[\frac{x\varepsilon}{2\gamma\sqrt{\Delta}} sin\left(\frac{2\sqrt{\Delta}B}{x^2}\right)\right] + \frac{\varepsilon}{2\gamma}\partial_x\left[\frac{x}{\sqrt{\Delta}} sin\left(\frac{2\sqrt{\Delta}B}{x^2}\right)\right]$$

Numerical methods

Equations of this kind (balance laws) usually develop discontinuities (shocks) in the field variables, and when this happens the equations break down.

But: they can be studied in their integral form (weak solutions). This is commonly done in fluid dynamics, but also to dynamically extend shell-crossing singularities in general relativity *[Nolan, 2003]*.

We employed the **WENO-Godunov method** for the reconstruction of the solution at the boundaries, and a **TVD Runge-Kutta 3** for the time evolution *[Liu, Osher, Chan, 1994]*.

Together with $B(x,t)$ and $\varepsilon(x,t)$ at each time step we constructed two quantities useful to understand the dynamics:

$$\rho(x,t) = -\frac{1}{4\pi x^2}\left(\dot{B} + \frac{x}{2}\partial_x \varepsilon\right)$$ Dust energy density

$$\Theta(x,t) = \frac{4(1+\varepsilon)}{x^2}\theta_+\theta_-$$ Product of null expansions, whose zeroes give the locations of the horizon(s)

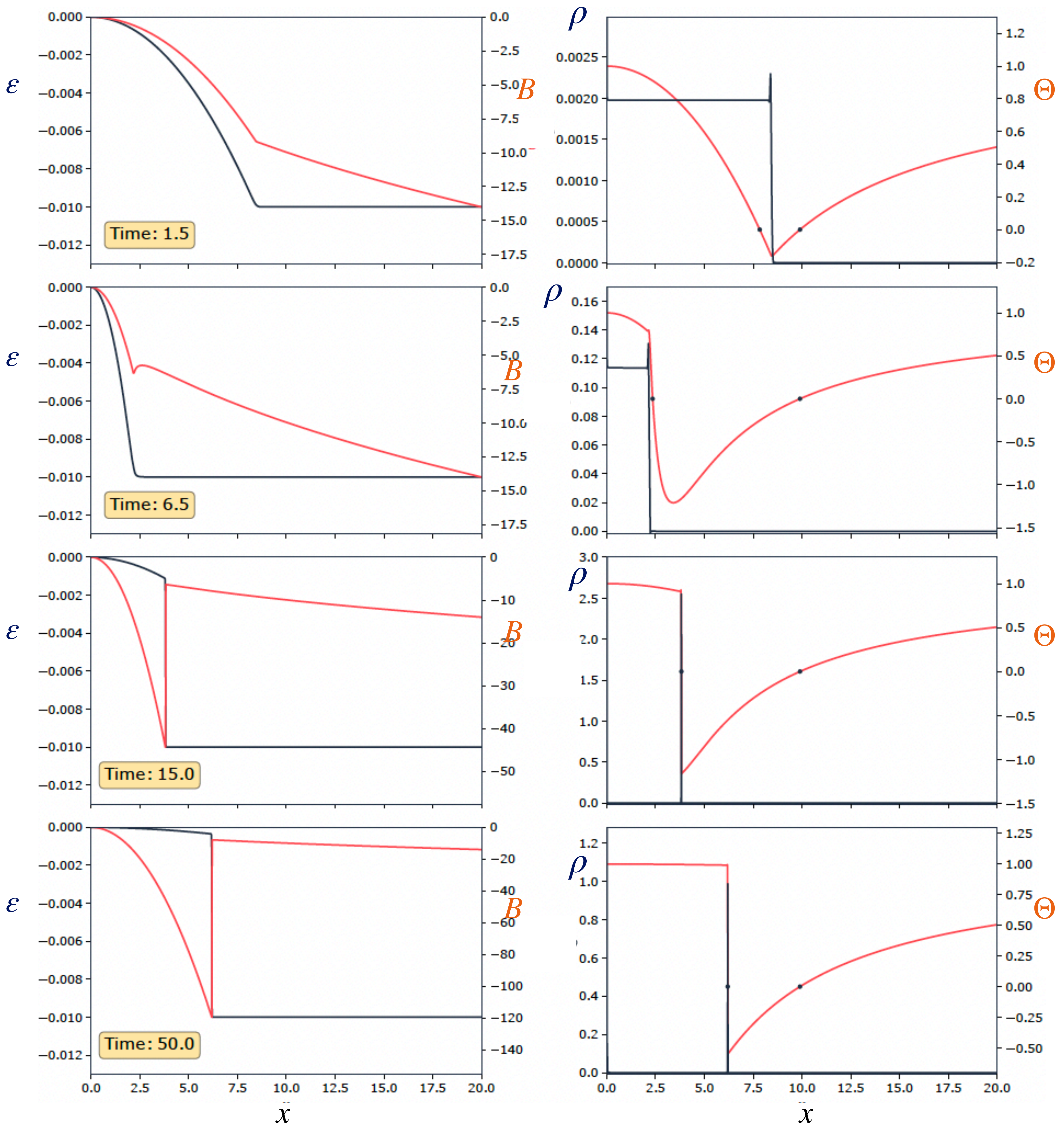
Numerical simulations

Initial profile with a sharp boundary

$$\varepsilon(x,t_0) = \begin{cases} -\alpha \dfrac{x^2}{x_0^2}, & \text{for } x < x_0 \\ -\alpha, & \text{for } x \geq x_0 \end{cases} \qquad (\alpha > 0)$$

$$\rho(x,t_0) = \begin{cases} \rho_0, & \text{for } x \leq x_0 \\ \rho_0 \dfrac{x_1 - x}{x_1 - x_0}, & \text{for } x_0 < x \leq x_1 \\ 0, & \text{for } x > x_1 \end{cases}$$

$$\alpha = 0.01,\ x_0 = 10,\ M = 5$$



Black hole life-time

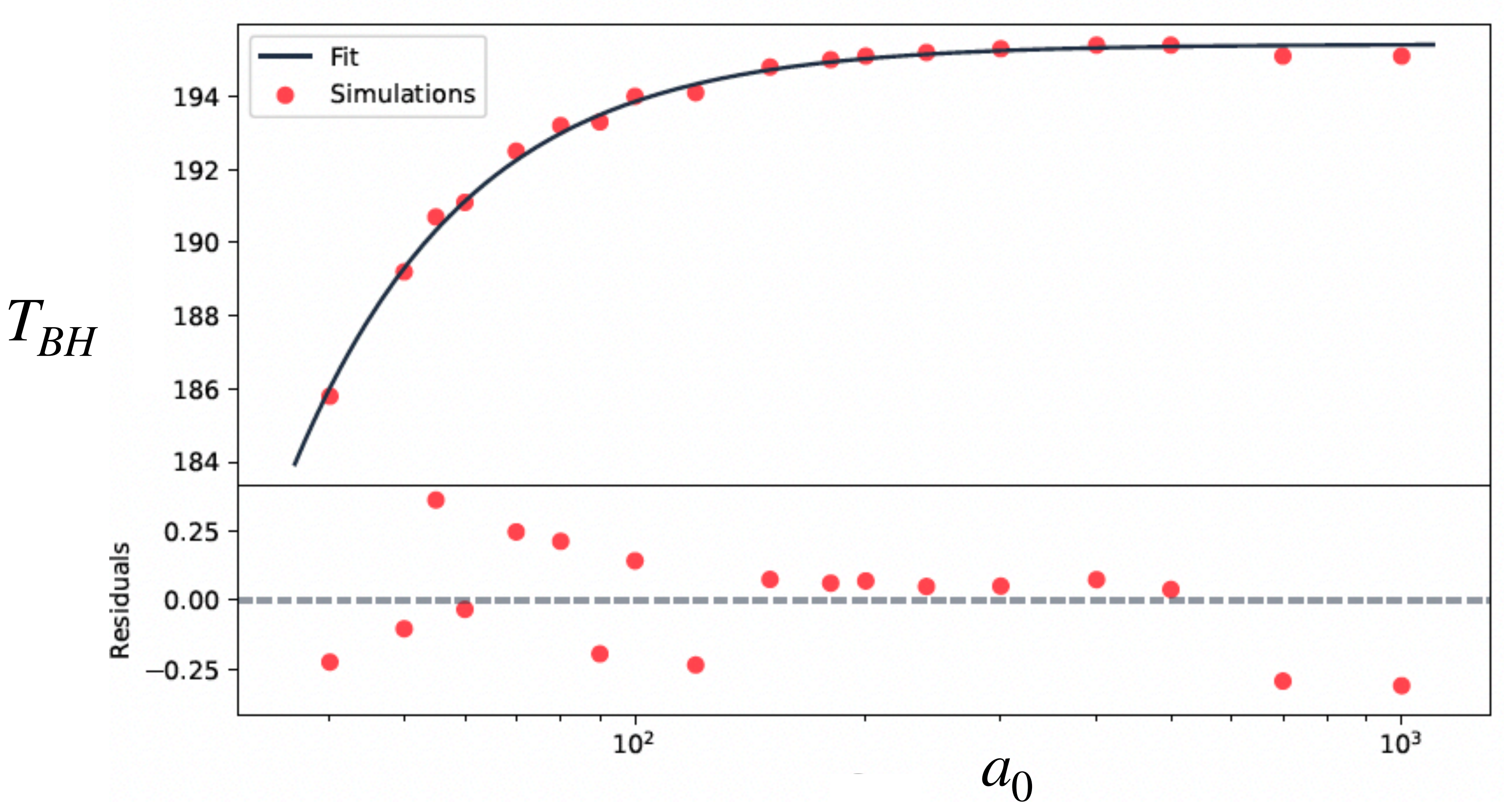
The black hole life-time can be estimated analytically by studying the shock-wave velocity through the Rankine-Hugoniot condition:

Post-bounce phase — Pre-bounce phase

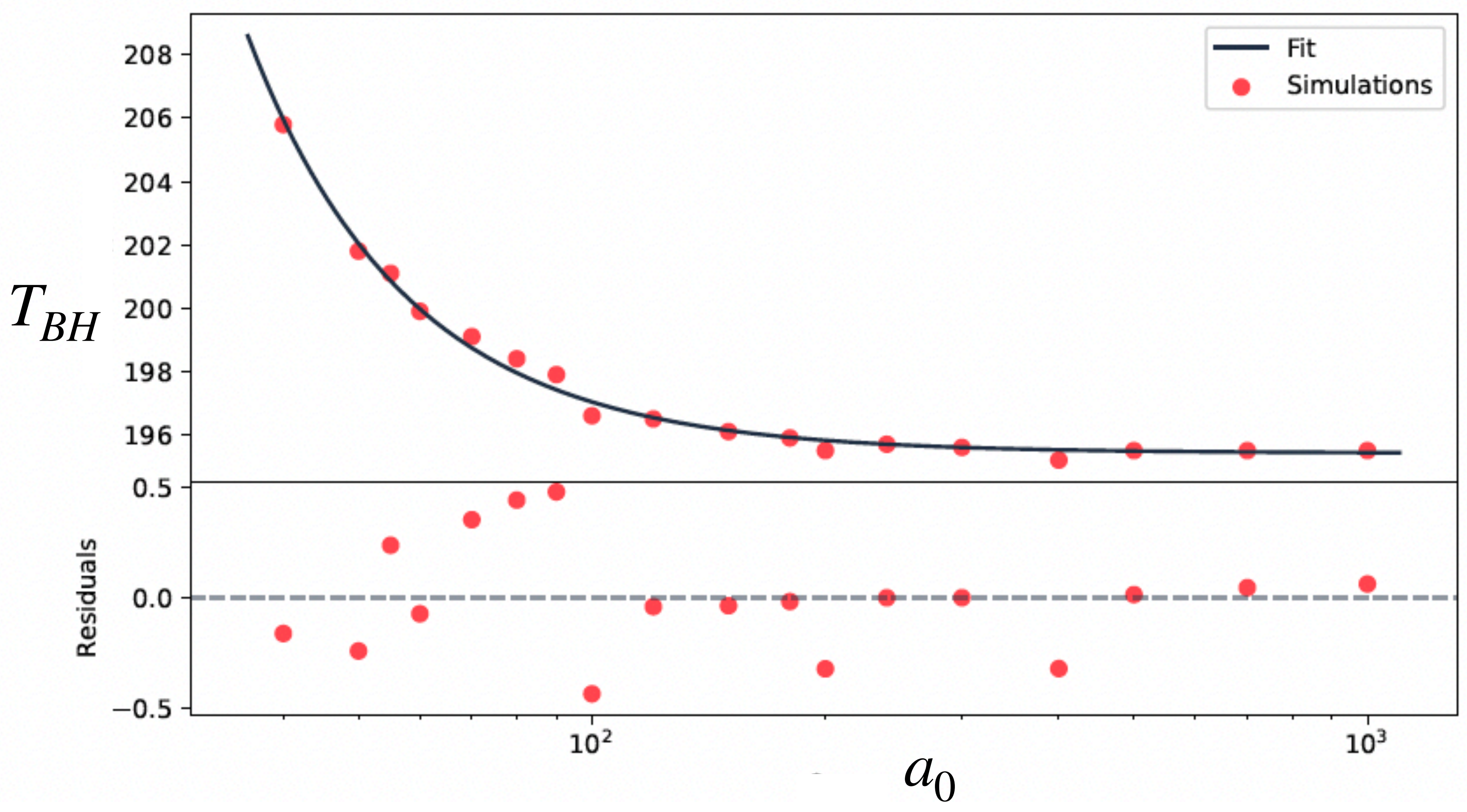
$$T_{BH} \sim \boxed{\frac{\pi R_s^2}{\gamma\sqrt{\Delta}(-\alpha^3)}[2ln(1-\alpha)+\alpha(\alpha+2)]} + \boxed{\beta R_s}$$

$$\alpha = \pm \frac{x_0^2}{a_0^2}$$

$\alpha > 0$

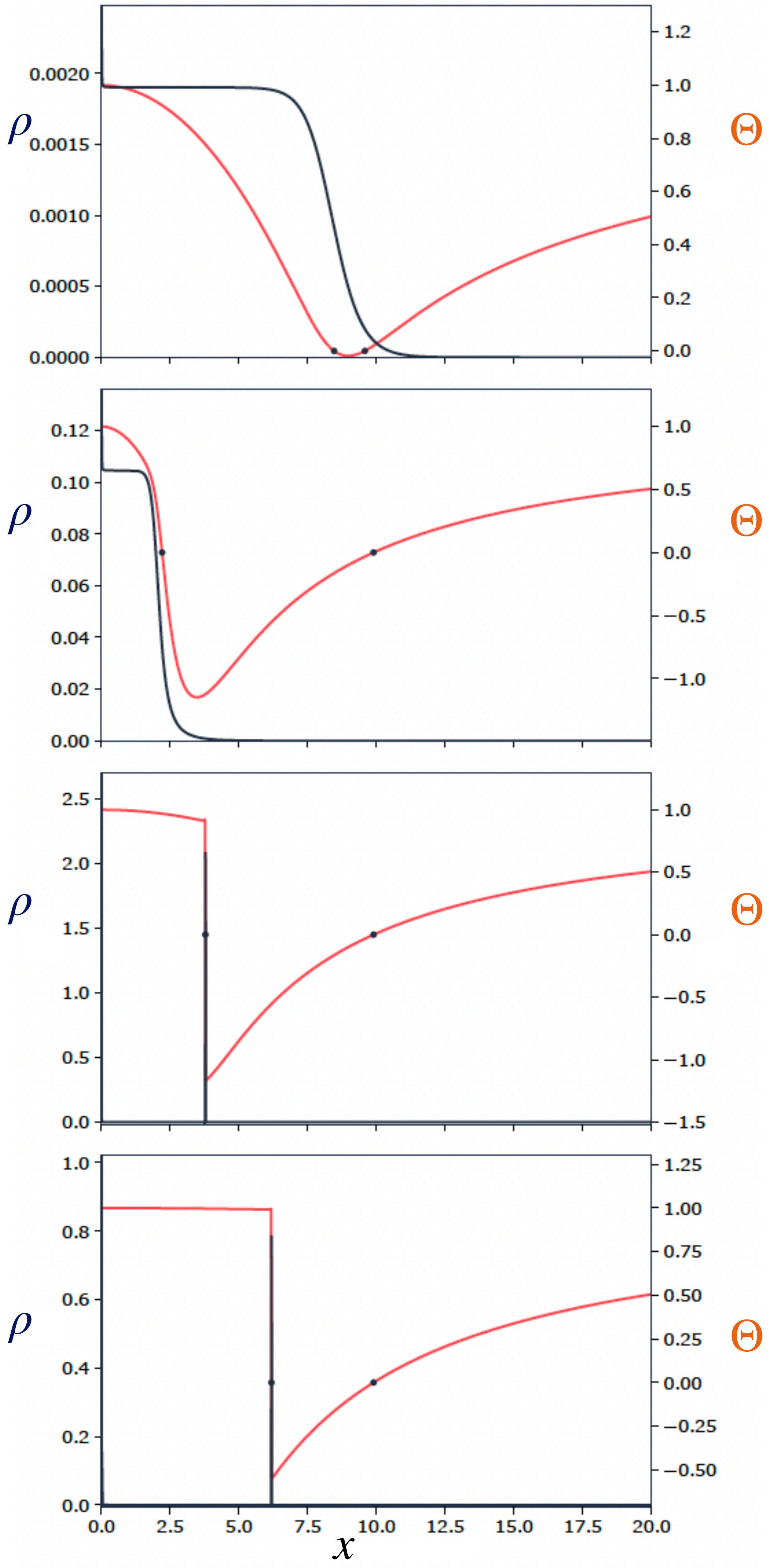


$\alpha < 0$

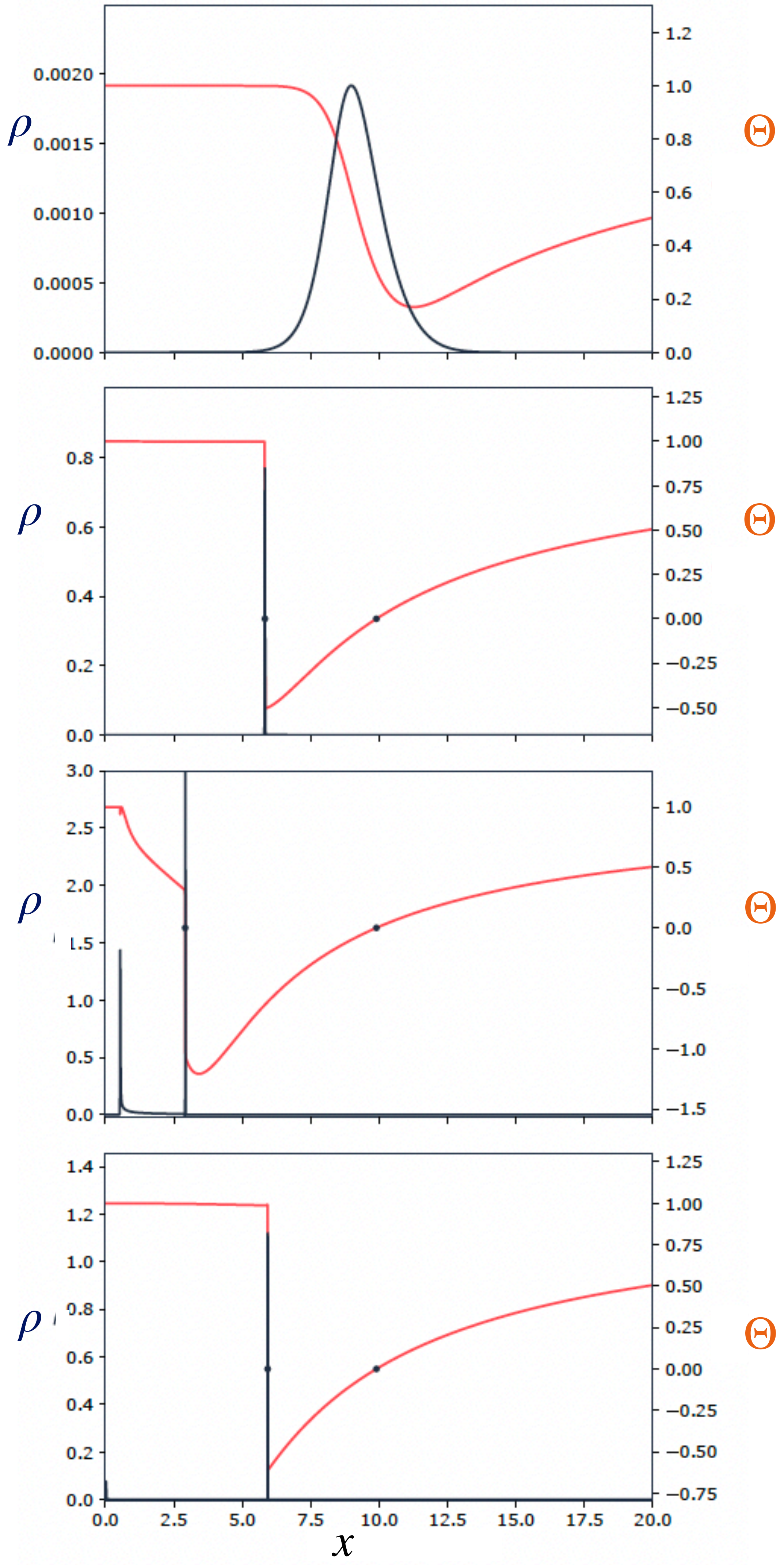


Other initial profiles

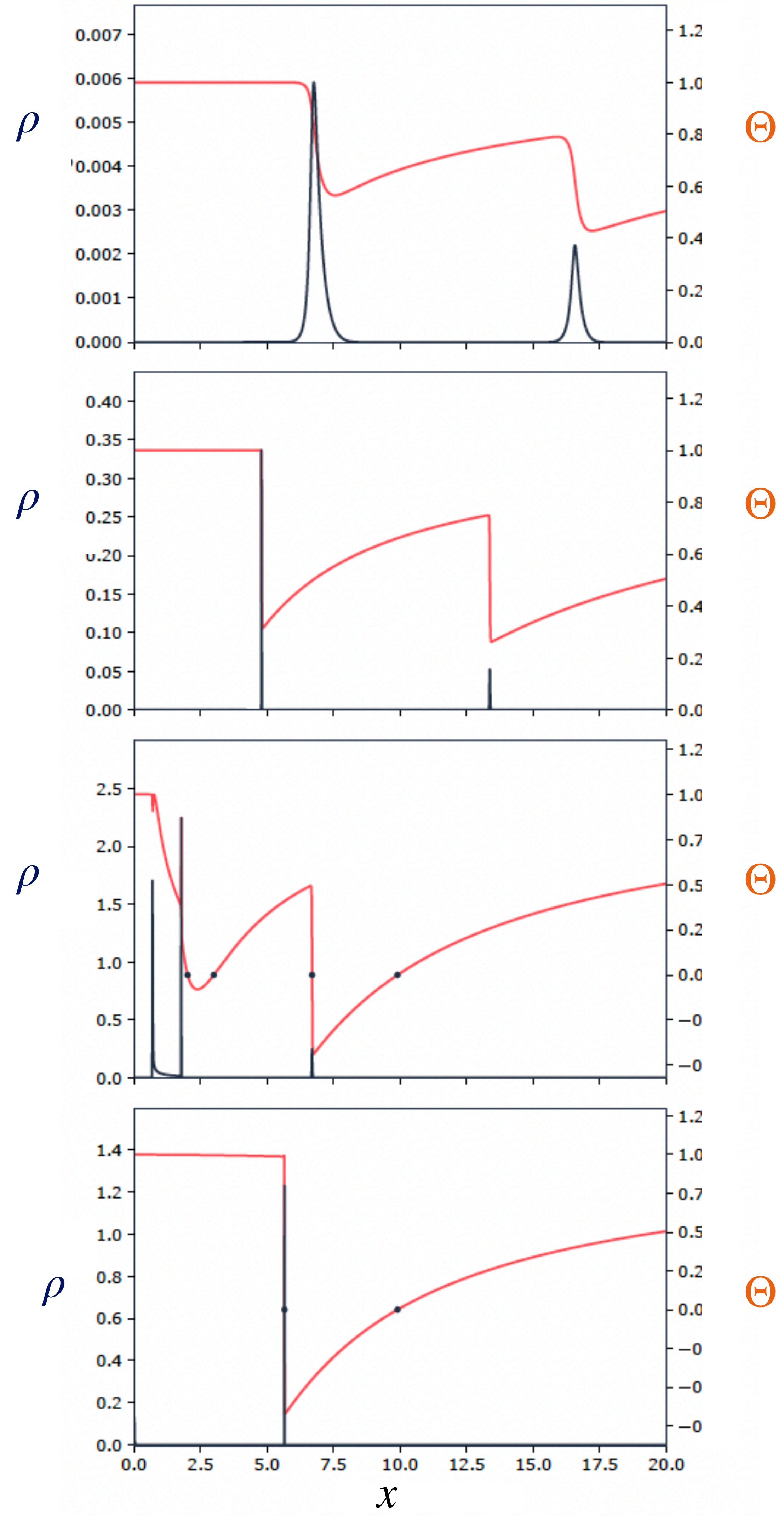
Hyperbolic tangent



Single gaussian profile



Double gaussian profile



Conclusions

- This effective LQG-based star collapse model predicts a bounce and the formation of an outgoing propagating **shockwave of matter**, also for profiles **beyond the marginally bound one** ($\alpha \neq 0$).

  $\longrightarrow$ It provides a **distinct signature** of quantum gravity, since an observer outside the horizon will see a **black hole exploding**, a phenomenon completely excluded by the classical theory.

- The black-hole lifetime depends both on the **gravitational mass** of the original star and the **spatial curvature**. For macroscopic black holes it is much smaller that the Page time, therefore the information loss paradox could be completely avoided.

Thank you for your attention!