PhD Open Days

Collapse or Collide: Improved Analysis of Black Hole Formation

PhD in Physics

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Motivation & Goal

Gravitational collapse allows us to probe general relativity (GR) in extreme conditions. The goal of this project is to apply a more complex, elastic, matter model to collapsing objects and thus gain a better understanding of their dynamics and specific signatures.

Gravitational Collapse

The simplest matter model used in GR is that of non-interacting particles, dust. It ignores any pressure, allowing absolute contraction. It shows the general properties of complete collapse [1]:

- Continuous contraction;
- Formation of an Event Horizon (EH);
- For an external observer the surface of the star converges with the event horizon and fades away.

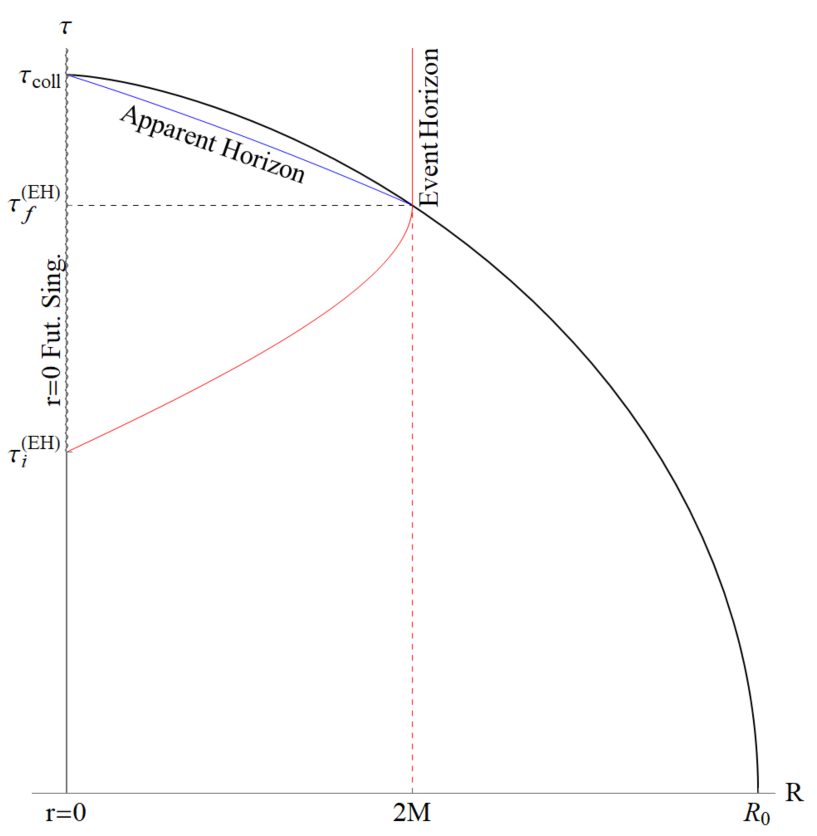

Figure 1: The observer falling with the star sees every process.

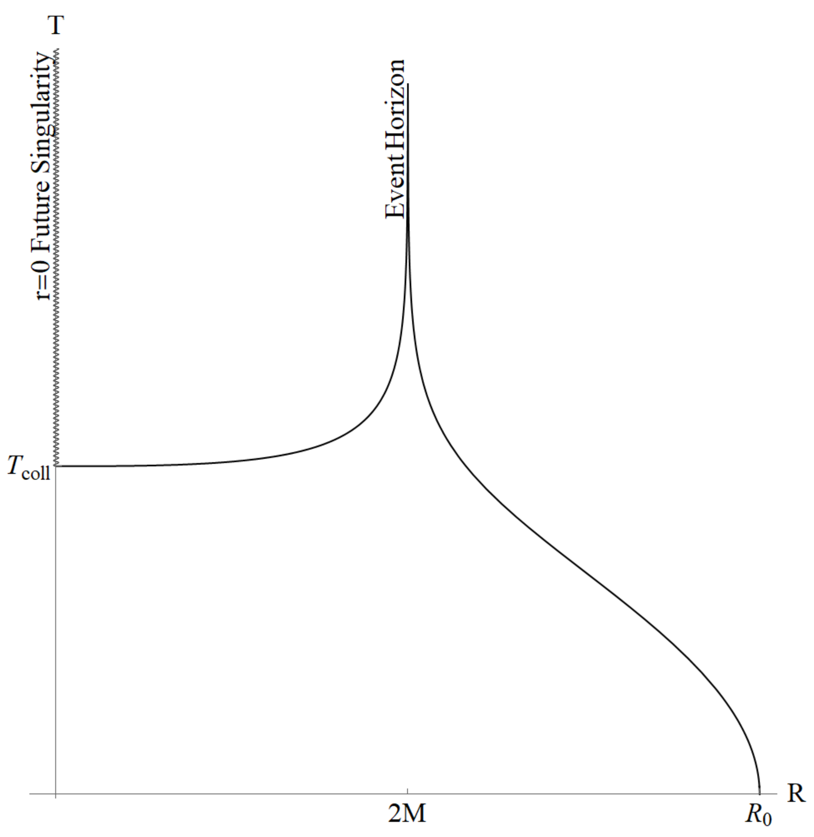

Figure 2: The exterior observer sees the surface go to the EH.

Black Hole Formation

- The mechanisms of Black Hole (BH) formation depend on the matter model used;
- Perfect fluids are currently the most used models in simulations;
- These only consider radial (isotropic) pressures, and may be too simple to describe collapse realistically;
- More complex models may show additional effects detectable through gravitational wave astronomy.

Relativistic Elasticity

We consider an equation of state whereby density is a function of the invariants of a reference spacetime state, $h^a{}_b$, [2]

$$\rho \equiv \rho(h^a{}_b)$$

The difference between the present and reference states relates to the pressures.

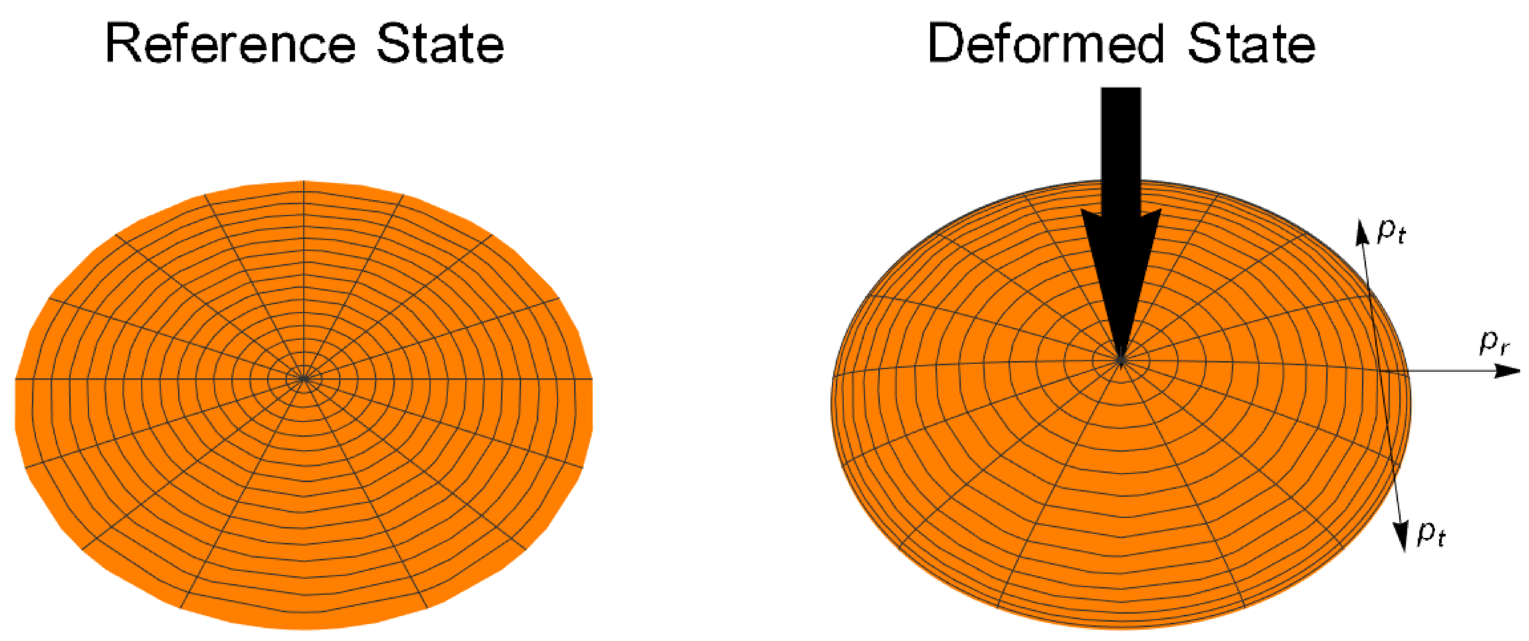

Figure 3: Vertically "squished" spherical geometry. Spacetime deforms non-homogeneously and isotropic and anisotropic pressures appear as the volume elements are compressed one against the other.

Equations of the Dynamics

For a spacetime metric of the form

$$\mathrm{d}s^2 = -\mathrm{e}^{2\chi}\mathrm{d}t^2 + \mathrm{e}^{2\omega}\mathrm{d}r^2 + r^2\mathrm{d}\Omega^2$$

And relations

$$p_r = n^2\frac{\partial\epsilon}{\partial n} + nz\frac{\partial\epsilon}{\partial z} \quad , \quad p_t = n^2\frac{\partial\epsilon}{\partial n} - \frac{1}{2}nz\frac{\partial\epsilon}{\partial z}$$

With n the density, z the anisotropy and $\rho=n\varepsilon$ the equation of state. The system is then described as a function of state variables (χ,ω,ρ).

Critical Phenomena

Of particular interest is criticality, i.e. invariance with scale of the profile of physical quantities.

- Occurs at the threshold of BH formation [3];
- Shows up in the form of echoes, either continuous or discrete;
- May show specific signatures of extreme curvature.

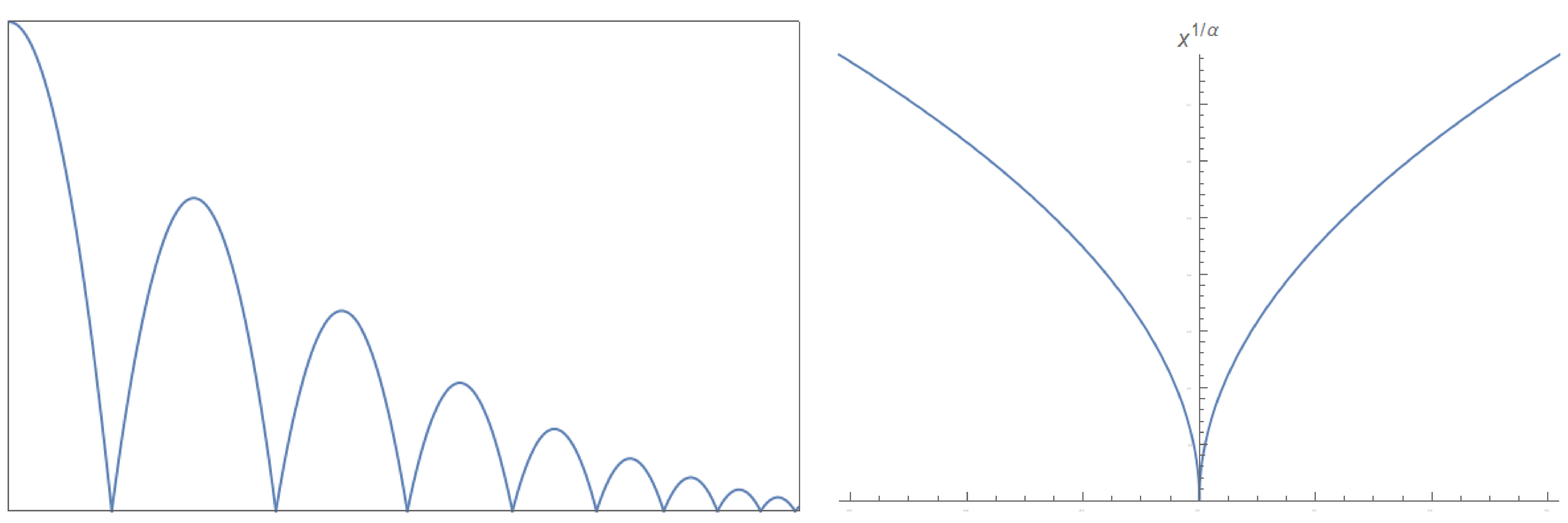

Figure 4: Examples of discrete and continuous self-similar profiles.

References

[1] D. L. F. G. Silva, "Gravitational Collapse and Black Holes", MSc. Thesis, Instituto Superior Técnico, Lisbon (2020)

[2] M. Karlovini and L. Samuelsson, "Elastic Stars in General Relativity I Foundations and Equilibrium Models", Class. Quant. Grav. 20 (2003) 3613-3648

[3] C. Gundlach and J. M. Martín-García, "Critical phenomena in gravitational collapse", Living Rev. Relativ. 10 (2007) 5

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