Journal of High Energy Physics, Gravitation and Cosmology, 2025, 11(2), 224-229
https://www.scirp.org/journal/jhepgc
ISSN Online: 2380-4335
ISSN Print: 2380-4327

Quantum Origin of the Event Horizon

Miguel Socolovsky

Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Cd. Universitaria, Ciudad de México, México
Email: socolovs@nucleares.unam.mx

How to cite this paper: Socolovsky, M. (2025) Quantum Origin of the Event Horizon. *Journal of High Energy Physics, Gravitation and Cosmology*, **11**, 224-229.
https://doi.org/10.4236/jhepgc.2025.112018

Received: January 18, 2025
Accepted: March 28, 2025
Published: March 31, 2025

Abstract

An analysis of the Penrose-Carter diagram of the gravitational collapse of a thin shell of radiation in Minkowski spacetime supports the idea of a quantum origin of the event horizon, and therefore of the concomitant collapse process. The analysis is based on the unavoidable presence of a length scale in the conformal compactification of both Minkowski and Schwarzschild spacetimes, which in a natural way can be identified with the Planck length. One should arrive at the same conclusion, however, with a more involved mathematical description, for any other collapse process with a not naked singularity *i.e.* protected by an event horizon.

Keywords

Event Horizon, Minkowski-Schwarzschild Spacetimes, Thin Shell Collapse

1. Introduction

As is well known the Penrose-Carter (P-C) [1] [2] diagram representing the gravitational collapse of a thin shell of radiation in Minkowski spacetime, can be constructed starting from the diagrams in **Figure 1** and **Figure 2** [3]-[5]:

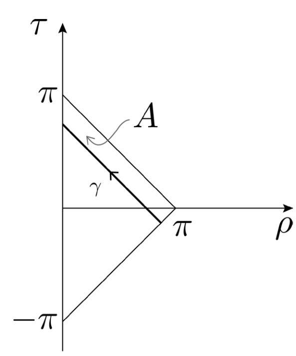

Figure 1. P-C M.

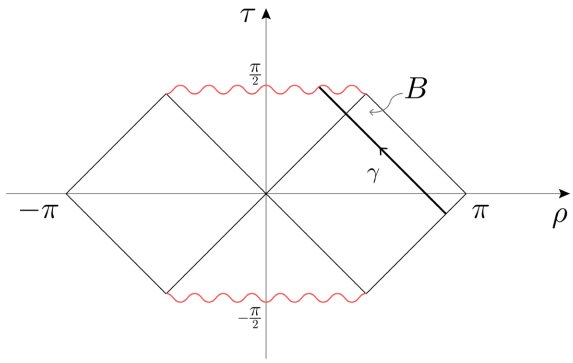

Figure 2. P-C S.

In **Figure 1** and **Figure 2**, respectively representing Minkowski (M) and Schwarzschild (S) spacetimes, the dark black line represents the falling shell (spherical symmetry allows to restrict the analysis to one ray, γ). Below γ spacetime is M, and above it is S. So, region A in **Figure 1** must be replaced by region B in **Figure 2**, leading to the spacetime diagram for the whole collapsing process of **Figure 3**:

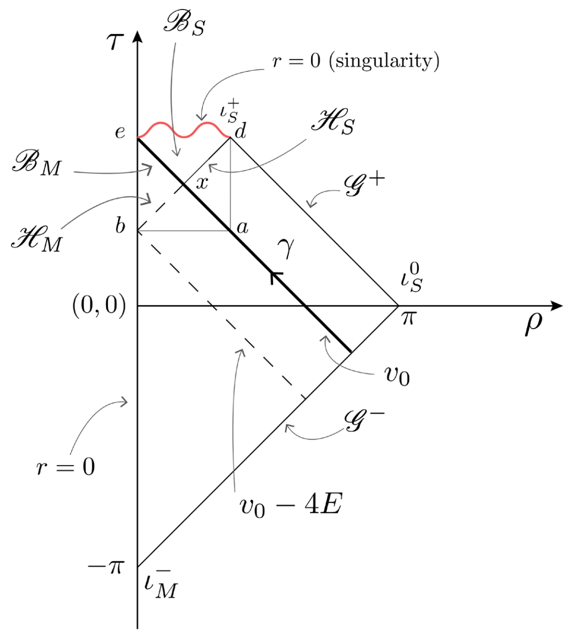

Figure 3. P-C MS.

In **Figure 3**: a, b, x, e and d are distinguished points to be explained below; the wavy red line is the singularity; ι_S^+ and ι_S^0 respectively are the future timelike and spacelike infinities in S; $\mathscr{G}^+$ and $\mathscr{G}^-$ are future and past null infinities, $\mathscr{G}^+$ in S and $\mathscr{G}^-$ part in S and part in M; the segment bd represents the event horizon $\mathscr{H} = \mathscr{H}_S \cup \mathscr{H}_M$, with the solid part $\mathscr{H}_S$ within S, and the dashed part $\mathscr{H}_M$ in M; the triangle above bd is the black hole region $\mathscr{B} = \mathscr{B}_M \cup \mathscr{B}_S$, with $\mathscr{B}_M \subset M$ and $\mathscr{B}_S \subset S$ ($\mathscr{B}_S$ contains trapped surfaces but $\mathscr{B}_M$ does not); E is the energy (mass) of the shell.

If by MS we denote the whole resulting spacetime, it is clear that the black hole region is the complement with respect to MS of the causal past of $\mathscr{I}^+$, *i.e.*

$$\mathscr{B} = MS \setminus J^-\left(\mathscr{I}^+\right) \tag{1}$$

with the horizon being its boundary:

$$\mathscr{H} = \partial\mathscr{B}. \tag{2}$$

It is in this sense that $\mathscr{H}$ is considered a global non-local object; its existence (or definition) requires knowledge (or information) of the future null infinity, hence the words "teleological" or "clairvoyant" [6].

The dimensionless P-C coordinates (ρ,τ), inherited from the conformally compactified spacetime M (up to a trivial translation along the ρ-axis) can be written in terms of the Eddington-Finkelstein (E-F) "ingoing" coordinates (v,r) where, in M, the advanced time v is given by $v=t+r$, where t and r are the usual time and radial coordinates in both M and S. On xd, $r=2E$, while on bx, r grows from 0 at b to $2E$ at x. From the S metric

$$\mathrm{d}s^2 = \left(1-\frac{2E}{r}\right)\mathrm{d}v^2 - 2\mathrm{d}v\mathrm{d}r - r^2\mathrm{d}\Omega^2 \tag{3}$$

(for completeness we included the spherical part $\mathrm{d}\Omega^2 = \mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\varphi^2$) radial light rays are solutions of

$$\left(\left(1-\frac{2E}{r}\right)\mathrm{d}v - 2\mathrm{d}r\right)\mathrm{d}v = 0, \tag{4}$$

from which the incoming ray γ is described by

$$v = v_0 = const., \tag{5}$$

while $\mathrm{d}v - 2\mathrm{d}r = 0$ describes $\mathscr{H}_M$ with solution [5]

$$r(v) = \frac{v-v_0}{2} + 2E. \tag{6}$$

So, $r(v_0) = 2E$, and the value of v corresponding to the "birth" of the horizon at $r=0$ (point b) is

$$v = v_0 - 4E, \tag{7}$$

represented by a dashed line in **Figure 3**.

From **Figure 3**, it is clear that any flash of light emitted by an observer at $\tau_b - \epsilon$ ($\tau_b + \epsilon$) for arbitrary small ϵ reaches (does not reach) $\mathscr{I}^+$, or equivalently, does not reach (reaches) the singularity. So, b is a distinguished or privileged point. But when this occurs, the shell (ray γ) passes through the spacetime point a, much before its arrival to $\mathscr{H}$ at x. How does b "knows" that γ passes through a? It is clear that there is no entanglement mechanism between a and b, at the same time, there is no classical explanation for this phenomenon. The question then is if quantum physics can in any way give some argument to sustain that fact.

We use the geometrical system of units (GSU) in which $c = G = 1$.

2. Collapse and Planck Constant

Since the referred conundrum lies in the M part of the P-C diagram of **Figure 3**, it is enough to restrict the discussion to this region. The conformal compactification of the M space (and also of S) requires a length scale to bring infinity to finite distance. It is natural to adopt the Planck length $L_{Pl}=\sqrt{\frac{G\hbar}{c^3}}$ as such a scale [7]; in the GSU it reduces to $\sqrt{\hbar}$.

The dimensionless P-C coordinates (ρ,τ) in terms of the E-F coordinates (v,r) are then given by [8]

$$\tau\left(v,r;\sqrt{\hbar}\right)=\operatorname{arctg}\left(\frac{v}{\sqrt{\hbar}}\right)+\operatorname{arctg}\left(\frac{v-2r}{\sqrt{\hbar}}\right)=\operatorname{arctg}\left(\frac{2\sqrt{\hbar}(v-r)}{\hbar-v(v-2r)}\right), \tag{8}$$

and

$$\rho\left(v,r;\sqrt{\hbar}\right)=\operatorname{arctg}\left(\frac{v}{\sqrt{\hbar}}\right)-\operatorname{arctg}\left(\frac{v-2r}{\sqrt{\hbar}}\right)=\operatorname{arctg}\left(\frac{2\sqrt{\hbar}r}{\hbar+v(v-2r)}\right). \tag{9}$$

At x, $r=2E$ and $v=v_0$; then

$$\tau_x\left(v_0,2E;\sqrt{\hbar}\right)=\operatorname{arctg}\left(\frac{2\sqrt{\hbar}(v_0-2E)}{\hbar-v_0(v_0-4E)}\right), \tag{10}$$

and

$$\rho_x\left(v_0,2E;\sqrt{\hbar}\right)=\operatorname{arctg}\left(\frac{4\sqrt{\hbar}E}{\hbar+v_0(v_0-4E)}\right), \tag{11}$$

and so

$$\begin{aligned}\rho_a&=2\rho_x\left(v_0,2E;\sqrt{\hbar}\right)\equiv\rho_a\left(v_0,2E;\sqrt{\hbar}\right)=2\operatorname{arctg}\left(\frac{4\sqrt{\hbar}E}{\hbar+v_0(v_0-4E)}\right)\\&=\operatorname{arctg}\left(\frac{8\sqrt{\hbar}E\left(\hbar+v_0(v_0-4E)\right)}{\left(\hbar+v_0(v_0-4E)\right)^2-16\hbar E^2}\right).\end{aligned} \tag{12}$$

Since $\rho_b=0$, the P-C spacelike distance between a and b is given by

$$l_{ba}\left(v_0,2E;\sqrt{\hbar}\right)=\rho_a-\rho_b=\rho_a\left(v_0,2E;\sqrt{\hbar}\right). \tag{13}$$

Since at b, $r=0$ and $v=v_0-4E$,

$$\tau_b\left(v_0,2E;\sqrt{\hbar}\right)=\tau_a\left(v_0,2E;\sqrt{\hbar}\right)=\operatorname{arctg}\left(\frac{2\sqrt{\hbar}(v_0-4E)}{\hbar-(v_0-4E)^2}\right). \tag{14}$$

Finally, the equation for the falling shell is

$$\tau=-\rho+const. \tag{15}$$

with $const.=\rho_a+\tau_a$ given by (12) and (14). Also, $\tau_e=\tau_d=\tau_b+l_{ba}$.

3. Discussion

The appearance of the Planck constant $\hbar$ or, equivalently, of the Planck length

L_{Pl}, in the expression of the length of the segment ba in the P-C diagram for the gravitational collapse of a thin null shell in M spacetime, can be understood as an indication that *the formation of the event horizon has a quantum origin*. In the limit $\hbar \to 0$, $l_{ba} \to 0$, which suggests the disappearance of the horizon. However, there are several objections that can be done to this conclusion: 1) The P-C diagram is not a physical spacetime, but only an artifact to "bring" infinity to finite distance and so obtain a global picture of the corresponding spacetime. True, but: why not suppose that it is also useful to reveal properties which remain hidden otherwise e.g. without a conformal transformation (even if the latter does not belong to the diffeomorphism group of General Relativity)? 2) The choice of a particular length scale Λ needed to perform the conformal transformation is not mandatory [9] since the qualitative information of the P-C diagram would not be modified. However, the natural choice $\Lambda = L_{Pl}$ eliminates a dose of arbitrariness of the diagram and gives it more physical content. 3) It is clear that there is no quantum entanglement between the spacetime points b and a, responsible for the birth of H at b when γ passes through a. However, without the introduction of a length scale Λ, in particular L_{Pl}, there would be no evidence of an otherwise hidden quantum imprint, and the phenomenon would remain in the land of the "teleological" or "clairvoyance", which clearly are not physical concepts. As is reviewed in [10], the teleological aspect also disappears for dynamical horizons.

Finally, we want to mention that the claim of the present work has an indubitable relation with the results of Dai *et al.* [11], Vaz [12], and Corda [13], which treat black holes as macroscopic quantum objects. In particular in [12] and [13], though by different approaches, the gravitational collapse of a dust star treated quantum mechanically, leads to the formation of a thin spherical shell which plays the role of an apparent horizon (rather than an event horizon) and obeys the Klein-Gordon equation in the relativistic regime and the Schroedinger equation in the non-relativistic approximation. Also, no singularity is formed. The conclusion of the present analysis should also be valid for the case of apparent horizons (e.g. Vaidya spacetime as another example [5] [14]) since the appearance of a quantum signal like $\sqrt{\hbar}$ in Penrose diagrams is a necessary consequence of the involved *conformal* compactification (unless one allows the presence of an arbitrary length scale Λ).

Acknowledgements

The author thanks for hospitality to the Instituto de Astronomía y Física del Espacio (IAFE-UBA-CONICET), Argentina, where part of this work was done, to Ernesto F. Eiroa at IAFE and the students Josué G. Mateos, Osmar E. López and Axel E. Rangel at ICN-UNAM for useful discussions, and to Oscar Brauer at the University of Leeds, UK, for the drawing of the Figures.

Conflicts of Interest

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

References

[1] Penrose, R. (1962) The Light Cone at Infinity. *International Conference on Relativistic Theories of Gravitation*, Warsaw and Jablonna, 25-31 July 1962, 369-373.

[2] Carter, B. (1966) Complete Analytic Extension of the Symmetry Axis of Kerr's Solution of Einstein's Equations. *Physical Review*, **141**, 1242-1247. https://doi.org/10.1103/physrev.141.1242

[3] Susskind, L. and Lindesay, J. (2004). An Introduction to Black Holes, Information and the String Theory Revolution. World Scientific Publication. https://doi.org/10.1142/5689

[4] Zee, A. (2013) Einstein Gravity in a Nutshell. Princeton University Press.

[5] Blau, M. (2022) Lecture Notes on General Relativity. Bern University.

[6] Senovilla, J.M.M., Macias, A. and Maceda, M. (2010) Black Holes and Trapped Surfaces. *AIP Conference Proceedings*, Mexico, 19-23 July 2010, 123-135. https://doi.org/10.1063/1.3531621

[7] Wilczek, F. (2005) On Absolute Units, I: Choices. *Physics Today*, **58**, 12-13. https://doi.org/10.1063/1.2138392

[8] Socolovsky, M. (2023) Conformally Compactified Minkowski Spacetime and Planck Constant. *Journal of High Energy Physics*, *Gravitation and Cosmology*, **9**, 1062-1066. https://doi.org/10.4236/jhepgc.2023.94077

[9] Gourgoulhon, E. (2023) Geometry and Physics of Black Holes. Laboratoire Univers et Théories, Paris, France.

[10] Ashtekar, A. (2025) Black Hole Horizons and Their Mechanics. In: *Encyclopedia of Mathematical Physics*, Elsevier, 343-351. https://doi.org/10.1016/b978-0-323-95703-8.00020-3

[11] Dai, D., Minic, D. and Stojkovic, D. (2022) On Black Holes as Macroscopic Quantum Objects. *Frontiers in Physics*, **10**, Article 891977. https://doi.org/10.3389/fphy.2022.891977

[12] Vaz, C. (2014) Black Holes as Gravitational Atoms. *International Journal of Modern Physics D*, **23**, Article 1441002. https://doi.org/10.1142/s0218271814410028

[13] Corda, C. (2023) Schrödinger and Klein-Gordon Theories of Black Holes from the Quantization of the Oppenheimer and Snyder Gravitational Collapse. *Communications in Theoretical Physics*, **75**, Article 095405. https://doi.org/10.1088/1572-9494/ace4b2

[14] Poisson, E. (2004) A Relativist's Toolkit: The Mathematics of Black-Hole Mechanics. Cambridge University Press.