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Hidden Quantum Effect in General Relativity

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Abstract

If the Planck length is chosen as the natural length scale of the Universe, the Penrose-Carter diagram associated with the classical gravitational collapse of a thin spherical shell of massless matter reveals, beyond and in agreement with the claimed non locality of the horizon, a quantum nature of the whole process.

Keywords

Spherical Collapse, Penrose-Carter Diagram, Quantum Effect

Perhaps the simplest classical gravitational collapse process is that of a thin spherical shell of massless particles (light rays in the geometrical optics approximation) in Minkowski space with the observer at its origin. Because of the spherical symmetry, to describe the main qualitative features of the *result of the collapse* it is enough to study the Penrose-Carter (P-C) diagram ([1] [2]) associated with one of the light rays which form the shell. This is represented in **Figure 1** ([3] [4]). The coordinates τ (time) and ρ (space) are dimensionless *i.e.* $[\tau]=[\rho]=[length]^0$. This is a consequence of the construction of the P-C diagrams (in this case for Minkowski and Schwarzschild spacetimes) where an arbitrary length scale Λ must be necessarily introduced to pass from quantities with dimensions of length to dimensionless quantities in the compactification procedure, which needs the use of the arctan or arctanh functions.

The upper part of the dotted green line representing the path followed by the collapsing shell is Schwarzschild, while the lower part is Minkowski. Point C at the left vertex of the Schwarzschild singularity (red dashed line) represents the final state of the collapsed shell. In fact, neither C nor the rest of the singularity are part of the resulting spacetime. Lines of constant r in both regions, from $r=0$ to $r=+\infty$ are represented by the continuous lines from ι^- (past timelike infinity) to ι^+ (future timelike infinity); at their intersections with the

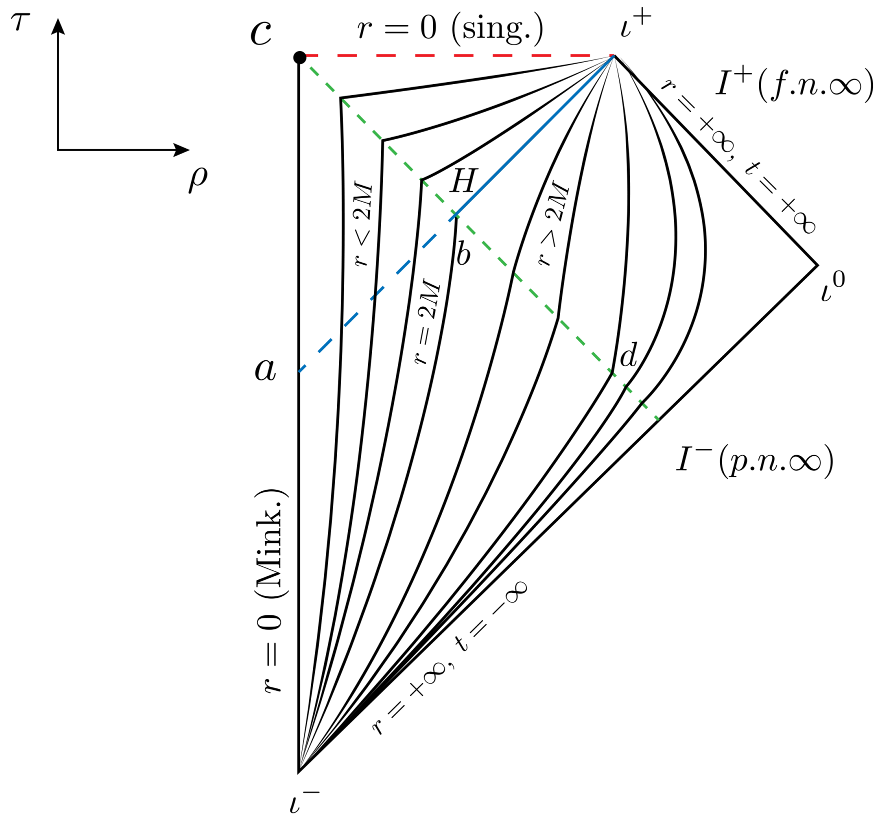

Figure 1. Thin spherical shell collapse of massless particles.

collapse path these lines are continuous but not differentiable. Each point in both regions represents a 2-sphere of the corresponding radius. It is clear that these spheres at the black hole (the upper triangle) are trapped surfaces. The horizon H is represented by the diagonal blue line at $r = 2M$, extending from the point b with coordinates $(\tau_b, \rho_b) = (\tau_b, \sqrt{2}M/\Lambda)$ where H is intersected by the collapsing shell, to ι^+. Its prolongation into the Minkowski sector is represented by the blue dashed line, extending from point b to point a with coordinates $(\tau_a, \rho_a) = (\tau_a, 0)$. τ_a, τ_b, τ_d with $\tau_a = \tau_d$ are arbitrary, since the point at I^- (past null infinity) where the incoming ray representing the collapsing shell births, is arbitrary.

Point a with $\tau = \tau_a$ is very particular: 1st.: it is determined by the point d in the path of the collapsing light ray, *even before the instant* τ_b *where the ray crosses the Schwarzschild event horizon H*; 2nd.: if at $\tau = \tau_a - \varepsilon$, $0 < \varepsilon \ll 1$, the observer at rest at $r = 0$ of the Minkowski space emits a light ray, this ray reaches I^+ (future null infinity) at $r = +\infty$ and $t = +\infty$; instead, if the ray is emitted at $\tau = \tau_a + \varepsilon$, the ray dies at the singularity ($r = 0$ in Schwarzschild). However, between d and a with spatial separation

$$\Delta\rho = \rho_d - \rho_a = \frac{2\sqrt{2}M}{\Lambda} \tag{1}$$

there is no signal at all, which is a clear indication of a *non local* effect of the classical collapse process or, at least, of the birth of the future horizon. This fact is commonly called the *teleological* aspect [5] of the formation of the horizon. Without a further discussion, this fact is a sort of "mistery", which can not have room in a physical theory.

There is no known non-locality in classical physics. Yes in quantum mechanics: entanglement is the most clear example ([6] [7] [8] [9]). The previous description of the shell collapse process (as well as other more realistic collapses) uses the geometric system of units (*gsu*) $G = c = 1$ and, as we mentioned before, an arbitrary length scale Λ. In our Universe, the unique available natural length scale is the Planck length $l_{Pl} = \sqrt{G\hbar/c^3}$ which, in the *gsu* system reduces to $\sqrt{\hbar}$. So,

$$\Delta\rho = \frac{2\sqrt{2}M}{\sqrt{\hbar}}. \tag{2}$$

The apparently strange "classical" non-locality of the horizon formation begins to be clarified by the appearance of the Planck constant, essence of quantum mechanics. The non-locality is quantum, not classical, though of a distinct nature of an entanglement effect. It is as if general relativity, from which the above collapse processes follow, hides, in its formulation, a quantum world.

As a final remark, it is clear that the quantum nature of the non-locality of the horizon formation can not be detected if one remains in a description based in Eddington-Finkelstein or Kruskal-Szekeres coordinates [10]. Only the description based on the P-C diagrams *i.e.* after the compactification process, reveals it. It is interesting to observe however, that through the use of dimensionless Schwarzschild and Kruskal Szekeres coordinates (which necessarility involves the introduction of a lenght scale), Dai *et al.* [11] arrive at the conclusion on black holes as macroscopic quantum objects. To the same conclusion arrive separately Vaz [12] and Corda [13] [14]. Both authors consider the condensation of quantum dust shells (massive matter). In ref. [12] the collapse to a singularity is avoided by quantum gravity effects (discretization on a lattice of the Wheeler-DeWitt equation), analogously as ordinary atoms do not collapse due to quantum mechanics; the final product being a compact dark star, but not a singularity covered by an event horizon. In refs. [13] [14] the set of Vaz's quantum shells is retrieved as a sort of "gravitational atom" described in a non-relativistic approximation by a gravitational Schrödinger equation, and by the Klein-Gordon equation in a full relativistic description.

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Conflicts of Interest

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

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