# Do stars die too long?

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Current proposals for regularizing the classical singularity of black holes present long-lived trapping horizons, with enormous inaccessible evaporation lifetimes. We propose an alternative regularization model, inspired in condensed matter gravitational analogues, in which the collapse of a stellar object would result in a genuine time-symmetric bounce. In geometrical terms this amounts to the connection of a black-hole geometry with a white-hole geometry in a regular manner. The complete bouncing geometry is a solution of standard classical general relativity everywhere except in a transient region that necessarily extends beyond the gravitational radius. The duration of the bounce as seen by external observers is very brief. This motivates the search for new forms of stellar equilibrium.

We would dare say that nowadays most specialists think that an event horizon is a too-idealized notion and that it will have no place in a next-level theory replacing General Relativity, e.g. when quantum effects are taken into account. It is largely believed that these strict black holes will be substituted by regularly evaporating black holes and, correspondingly, event horizons substituted by long-lived trapping horizons. The very notion of event horizon makes it impossible that any astrophysical observation could verify their existence in any of the candidate dark and compact regions. For this reason, it appears more reasonable to propose alternative and verifiable (at some level) hypotheses regarding the nature of the objects hidden in this dark and compact regions.

As already mentioned, the most common hypothesis is that these objects are regularly evaporating black holes. However, although this hypothesis is in principle verifiable, in practice it seems out of reach for the human kind in any foreseeable future. This constitutes the lifetime problem of evaporating black holes[1]. Hawking's original calculation[2] concluded that black holes should evaporate quantum mechanically, but at an extremely slow rate if only they contain any realistic initial mass. Hawking initially believed that the final evaporation would be accompanied by a loss of information[3]. At present there are several scenarios showing that the evaporation can proceed in a perfectly regular way with no final loss of information (see e.g. Refs. 4–6). However, these scenarios maintain the slowly-evaporating-horizon characteristic. The gigantic lifetime of the trapping horizon makes it difficult to believe on the verifiability of the actual presence of a trapping horizon in any reasonable time expand. This is seldom presented in the literature as a problem, more as a "such is life" fact. However, in our view it constitutes a strong motivation to seek for the viability of an alternative scenario devoid of the lifetime problem.

In Newtonian gravity one can imagine arbitrarily small balls with arbitrarily large masses and design non-collision scattering processes with arbitrarily small impact parameter, characterized by an acceleration phase (falling into the gravitational potential) followed by a deceleration phase (climbing the gravitational potential). The entire scattering is perfectly time symmetric. By considering the balls as hard spheres subject to elastic collisions or non-interacting with each other when coming into superposition (i.e., transparent to each other), one could even make a precise head-on collision. This process will also consist of the previous two phases.

Now, general-relativistic situations in which a lump of matter is climbing a gravitational potential can easily be found. One can also think of the following idealized thought experiment. Two equal balls with sufficiently small mass-to-radius ratio are thrown directly towards each other. Imagine that they are transparent to each other. In the case in which no horizon forms (i.e., sufficiently low kinetic energy in the collision), if one neglects the gravitational wave emission due to the encounter, the resulting trajectories will be perfectly time symmetric, again with acceleration and deceleration phases. Within standard classical general relativity the situation radically changes if a horizon forms. In a collision with sufficiently high kinetic energy the two balls in the previous example will form a horizon. The time-symmetric deceleration phase will disappear and be substituted by a black hole remnant. Somewhat surprisingly, although white-hole solutions exist mathematically, in supposedly realistic situations one never encounters potential-climbing cases beyond the Schwarzschild radius.

The fading into oblivion of the white-hole district is arguably the strongest departure of general relativity from Newtonian gravity. There seems to be a prejudice against exploring the possibility and implications of really having genuine bouncing solutions. As we will see, there are indeed good reasons for this prejudice to exist, but also for taking the bold leap of exploring beyond it[1]. Our analysis shows that this can be done consistently only under the following assumption: There should exist an underlying causality that is explored only when Planck energies are at stake. This background causality should be non-dynamical and trivial in the sense of containing no horizons whatsoever, the simplest example one can think of being a Minkowskian structure. Otherwise general-relativistic light cones could not suffer such a dramatic turn. The only possibility apparently left would be that the light cones did not quickly reverse its tilting but only slowly recover their unbent positions before collapse. The geometry would be the one described, for instance, in Ref. 7, or more recently in Ref. 8.

Our assumption can be motivated both from particle physics and condensed matter physics. On the one hand, our proposal connects naturally with Rosen's reformulation of general relativity as a nonlinear theory on a flat Minkowski background[9]. This reformulation indeed goes further than the standard formulation of general relativity in the sense that it is a convenient effective framework to describe the switching-off of gravity at high energies. Rosen's reformulation can be understood as the long-wavelength limit of a nonlinear theory of gravitons (see Ref. 10 and references therein). It is still an open possibility that an ultraviolet completion of such a theory would exhibit asymptotic freedom (as its QCD cousin). On the other hand, similar ideas also appear when thinking of gravity as an emergent notion in a condensed matter framework[11] (see also Ref. 12). The nonlinear theory of gravity describes in that case the behaviour of collective degrees of freedom. There, it is reasonable to think that the first quantum gravitational effect is that, above some Planckian energy scale, the collective degrees of freedom corresponding to gravity are diluted, leaving a Minkowskian background for the matter excitations.

Let us detail how the switching-off of gravity can be described. The action of a theory of this sort should be expressible in terms of a composite field $g_{ab} = \eta_{ab} + \lambda h_{ab}$, where $\eta_{ab}$ is the flat background metric, $h_{ab}$ the graviton field and $\lambda$ the coupling constant which controls the nonlinearities of the gravitational sector as well as the coupling to matter (take Rosen's formulation as an example, see Ref. 10). The field equations of this theory are equivalent to the Einstein field equations for a metric $g_{ab}$. Thus in this regime one recovers general relativity, with a (generally curved) metric $g_{ab}$ controlling the effective causality of the spacetime. However, the structure of the theory permits us to consider the limit $\lambda \to 0$, in which the nonlinearities disappear and matter is effectively decoupled from the graviton field, which evolves separately as a free field. In this limit the causality of spacetime, given by $\eta_{ab}$, is no longer dynamical. The two conceptual frameworks above suggest that when high-energy phenomena are involved, this limit is indeed reached so that the underlying causality in the system, which is Minkowskian with no horizons whatsoever, is unveiled.

This view prioritizes the role of matter with respect to the dynamical causal structure contained in $g_{ab}$, and brings the general-relativistic and Newtonian descriptions of matter scattering in the presence of gravity a step closer to each other. Let us discuss the qualitative picture of our proposal, thinking about what happens in a local region around the distribution of matter undergoing gravitational collapse and making use of the figure 1. The mathematical details of the solution can be found in Refs. 1,13 (a geometry causally equivalent to this one has also been presented in Ref. 14; however, as opposed to our proposal, the geometry in that paper is such that the total duration of the bounce as seen by external observers is extremely long, so it does not solve the lifetime problem). When a lump of matter undergoes the gravitational collapse process (Oppenheimer-Snyner collapse[15]), at some point it will enter the regime in which the local causal structure is Minkowskian and there is no trace of gravity. After a scattering process which takes place in the absence of gravity and which can be idealized as a first approximation as dissipationless, the lump of matter will effectively bounce back, now expanding in time. Notice that it is not needed to consider that some kind of repulsive force acts in this regime, and that its existence would only lead to quantitative changes in this picture. If we keep following the expanding distribution of matter we will

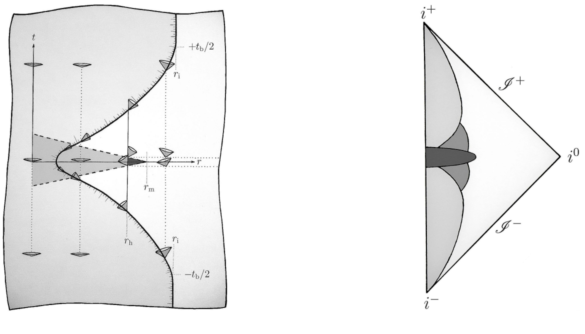

Fig. 1. *Left:* Collapse and time-symmetric bounce of a stellar object in our proposal (thick line). The past thick dashed line from $r = 0$ to $r_{\mathrm{m}}$ marks the boundary where the non-standard gravitational effects start to occur. In all the external white region the metric is Schwarzschild. Between the two thick dashed lines the metric is not Schwarzschild, including the small dark grey triangle outside the Schwarzschild radius $r_{\mathrm{h}}$. *Right:* Penrose diagram. Globally it has the same causality as Minkowski spacetime. Locally it has some peculiarities. The dark grey region represents a non-standard gravitational field. The down and up grey regions are respectively regions with outer and inner trapped surfaces. The light grey regions on the left-hand side are those filled by matter. There are no long-lived trapping horizons of any sort.

exit the high-energy regime in which the causal structure is not dynamical and the usual general-relativistic picture with a gravitational field $g_{ab}$ will be restored. However, this dynamical causal structure is a secondary character in this story, so that it will naturally adapt itself to the distribution of matter in spacetime, with the corresponding light cones pointing outwards.

The gravitational switching-off and -on process we have described would have an interpretation in general relativity in terms of an effective energy content that violates certain energy conditions in some regions. We advance here the following interpretation of the ideal dissipationless bouncing process. When the collapsing structure reaches Planckian densities it acquires a "quantum modification" leading to an effective density which, at some point becomes negative and thus repulsive. This negative density is compensated by a burst of positive energy that is expelled out of the structure through the underlying causality (this is what the bottom thick dashed line in Fig. 1 intends to represent). This positive energy burst reaches some point $r_{\mathrm{m}}$ outside the gravitational radius. The time-reversed process should not be understood as a sort of collapse of this energy burst, but rather as describing the attenuation of the effect of its propagation through the dynamical geometry.

In more formal terms, we have shown that there exists an entire family of geometries, with functional and parametric degrees of freedom which at the moment cannot be fixed without knowing additional features of the underlying theory. However, the most relevant details are robust with respect to these variations, and can be summarized as follows. The time lapse associated with the collapse is very short (of the order of milliseconds for neutron-star-like initial configurations) for geometries which simply regularize the behaviour of the collapse near the singularity. This is equally true both for observers attached to the structure as well as for distant stationary observers. It is mandatory that a certain open region outside the Schwarzschild radius deviates from the usual static and spherically symmetric solution. This deviation as well as the matter bounces will lead to characteristic imprints in the transient phase. While a detailed study must be done in order to find experimental signatures of these phenomena, the short timescales associated with all these processes are encouraging.

The plausibility of the time-symmetric bounce process rests on the assumption that the general-relativistic description of gravity is not fundamental, so that modifications to the dynamical behaviour of the spatiotemporal causal structure at high energies are conceivable. The standard view is that "quantum corrections" to a general-relativistic geometry could only occur in high curvature regions. Our discussion points out that this assertion contains at least one assumption that is typically unstated: The non-existence of a deeper causality of Minkowskian character (that is, with no horizons). If this causality exists, it is not difficult to imagine that the echo of the high-energy collision produced in the location where the classical singularity was supposed to appear would be transmitted outside through the deeper (high-energy) causality, and modify the effective light-cone structure (i.e., the light-cone structure of general relativity) even in places with very small effective curvature. One also has to take into account that the non-general-relativistic modification of the effective light-cone structure we speak about occurs just in a brief transient region, being the manifestation of the rapid process of switching off and on of gravity. The existence of this deeper causality is indeed a necessary and sufficient assumption, thus making a tight connection between certain properties of the high-energy behaviour of the gravitational interaction and low-energy solutions which do not present the lifetime problem.

This rapid bounce alternative radically changes the discussion of the possible endpoints of gravitational collapse. In particular, it makes plausible that the final object is a compact object with no horizons whatsoever. As with other compact objects in nature, the structure of the transient would be given by "dirty" (non-geometrical) physics whose details still need to be filled out. If this view is indeed realized in nature, black holes could just be an idealized approximation to the ultimate stationary objects.

The transient phase should leave some traces, for instance, in the physics of gamma ray bursts (GRBs) and its coincident gravitational-wave emission. One would expect some signatures associated with a reverberant collapse. In the collapsar model of GRBs however (see ,e.g., Ref. 16) the emission zone is supposed to be very far from the collapsed core. This means that the connection between the processes at the core and those at the external wind shells could be very far from direct. The signatures should be clearer however in the spectrum of gravitational waves. The last part of the gravitational-wave signal should clearly distinguish between the standard relaxation towards a black hole and the presence of bouncing processes.

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## References

1. C. Barceló, R. Carballo-Rubio, L. J. Garay and G. Jannes, The lifetime problem of evaporating black holes: mutiny or resignation, *Classical and Quantum Gravity* **32**, p. 035012 (February 2015).
2. S. W. Hawking, Particle Creation by Black Holes, *Commun. Math. Phys.* **43**, 199 (1975).
3. S. W. Hawking, Breakdown of Predictability in Gravitational Collapse, *Phys. Rev.* **D14**, 2460 (1976).
4. L. Susskind, *The Black Hole War: My Battle with Stephen Hawking to Make the World Safe for Quantum Mechanics* (Little, Brown, 2008).
5. A. Ashtekar and M. Bojowald, Black hole evaporation: A Paradigm, *Class. Quant. Grav.* **22**, 3349 (2005).
6. S. W. Hawking, Information Preservation and Weather Forecasting for Black Holes, *ArXiv e-prints* (January 2014).
7. T. A. Roman and P. G. Bergmann, Stellar collapse without singularities?, *Phys. Rev.* **D28**, 1265 (1983).
8. C. Rovelli and F. Vidotto, Planck stars, *International Journal of Modern Physics D* **23**, p. 42026 (December 2014).
9. N. Rosen, General relativity and flat space. i, *Phys. Rev.* **57**, 147 (1940).
10. C. Barceló, R. Carballo-Rubio and L. J. Garay, Unimodular gravity and general relativity from graviton self-interactions, *Phys. Rev.* **D89**, p. 124019 (June 2014).
11. C. Barceló, L. J. Garay and G. Jannes, Quantum Non-Gravity and Stellar Collapse, *Found. Phys.* **41**, 1532 (2011).
12. G. Jannes, *Emergent gravity: the BEC paradigm.* July 2009.
13. C. Barceló, R. Carballo-Rubio and L. J. Garay, Mutiny at the white-hole district, *International Journal of Modern Physics D* **23**, p. 42022 (October 2014).
14. H. M. Haggard and C. Rovelli, Black hole fireworks: quantum-gravity effects outside the horizon spark black to white hole tunneling, *ArXiv e-prints* (July 2014).
15. J. R. Oppenheimer and H. Snyder, On continued gravitational contraction, *Phys. Rev.* **56**, 455 (1939).
16. A. MacFadyen and S. E. Woosley, Collapsars: Gamma-ray bursts and explosions in 'failed supernovae', *Astrophys. J.* **524**, p. 262 (1999).