Found Phys (2011) 41:1532–1541
DOI 10.1007/s10701-011-9577-9

Quantum Non-Gravity and Stellar Collapse

C. Barceló · L.J. Garay · G. Jannes

Received: 5 August 2010 / Accepted: 14 June 2011 / Published online: 6 July 2011

Abstract Observational indications combined with analyses of analogue and emergent gravity in condensed matter systems support the possibility that there might be two distinct energy scales related to quantum gravity: the scale that sets the onset of quantum gravitational effects E_B (related to the Planck scale) and the much higher scale E_L signalling the breaking of Lorentz symmetry. We suggest a natural interpretation for these two scales: E_L is the energy scale below which a special relativistic spacetime emerges, E_B is the scale below which this spacetime geometry becomes curved. This implies that the first 'quantum' gravitational effect around E_B could simply be that gravity is progressively switched off, leaving an effective Minkowski quantum field theory up to much higher energies of the order of E_L. This scenario may have important consequences for gravitational collapse, inasmuch as it opens up new possibilities for the final state of stellar collapse other than an evaporating black hole.

C. Barceló · G. Jannes
Instituto de Astrofísica de Andalucía (IAA-CSIC), Glorieta de la Astronomía, 18008 Granada, Spain

L.J. Garay
Departamento de Física Teórica II, Universidad Complutense de Madrid, 28040 Madrid, Spain

L.J. Garay
Department of Physics, King's College London, Strand, London WC2R 2LS, UK

L.J. Garay · G. Jannes
Instituto de Estructura de la Materia (IEM-CSIC), Serrano 121, 28006 Madrid, Spain

G. Jannes (✉)
Low Temperature Laboratory, Aalto University School of Science, PO Box 15100, 00076 Aalto, Finland
e-mail: jannes@ltl.tkk.fi

Keywords Quantum gravity · Black hole singularity · Emergent gravity · Fermi liquids

1 Introduction

Indications from recent cosmic ray and other high-energy observations show that there exist stringent bounds on the most commonly expected types of Lorentz violation at the Planck level [1, 2]. Two possible interpretations stand out. Either Lorentz invariance is a truly fundamental symmetry of our universe, valid at all energies. Or Lorentz invariance is nevertheless violated, but at an energy E_L much higher than the Planck scale E_B.

It is thought-provoking to realise that this second option is precisely a crucial condition for an emergent theory of gravity based on a fermionic system (similar in some aspects to certain condensed matter systems) to work [3]. We will briefly describe how the Einstein equations can be recovered within such an emergent gravity framework, and specifically for Fermi-liquid-like systems. Then we will explore a rather surprising consequence of this proposal: The physics at energies above the Planck scale (but still below the much higher Lorentz violation energy scale E_L) could be described essentially as standard quantum field theory in a Minkowski spacetime. This opens up the possibility of new final stages for the gravitational collapse of ultra-heavy objects which avoid the formation of a general relativistic singularity. In particular, we suggest that an object similar to an isothermal sphere could after all be recovered as a natural outcome of such a collapse.

2 Emergent Gravity, a Tale of Two Scales

In a Fermi liquid like the A-phase of helium three (^{3}He-A), there exist two important energy scales relevant for our discussion [3–5]. One is the energy scale E_B below which bosonisation in the system starts to develop. This scale marks the onset of the superfluid behaviour of ^{3}He-A. At energies below E_B, the different bosons effectively appearing in the system (e.g. through Cooper-pairing) condense and start to exhibit collective behaviours. The other energy scale E_L is the Lorentz scale below which the quasiparticles of the system start to behave relativistically (as Weyl spinors). This occurs in ^{3}He-A because then the momentum space topology of the vacuum has Fermi points. It is in the immediate surroundings of these Fermi points that such a relativistic behaviour appears.[1]

At energies below both characteristic scales, one can describe the system as a set of Weyl spinors coupled to emergent background electromagnetic and gravitational fields. For a particular Fermi point, these effective electromagnetic and

[1] Fermions obey a relativistic Dirac equation near all types of Fermi surfaces, but only in the directions perpendicular to the Fermi surface, as a consequence of the Atiyah-Bott-Shapiro construction [6, 7]. In order to reproduce true Lorentz invariance in an emergent gravity setting, the relevant topological object must therefore be zero-dimensional, i.e.: a Fermi point.

gravitational fields encode, respectively, the position of the point and its effective "light-cone" structure. Both electromagnetic and gravitational fields are built from condensed bosonic degrees of freedom. Apart from any predetermined dynamics, these bosonic fields will acquire additional dynamical properties through Sakharov's induction mechanism [8, 9]. Integrating out the effect of quantum fluctuations in the fermionic fields *à la* Sakharov, one obtains a one-loop effective action for the geometric field, to be added to any pre-existing tree level contribution. Since $E_{\rm B}$ marks the energy scale above which the geometrical picture based on the bosonic condensate disappears, the integration cut-off is precisely this $E_{\rm B}$.

Now, in order for the geometrical degrees of freedom to follow an Einsteinian dynamics, two conditions are required:

1. *Special relativity dominance or* $E_{\rm L} \gg E_{\rm B}$: For the induction mechanism to lead to an Einstein-Hilbert term $\sqrt{-g}R$ in the effective Lagrangian, the fluctuating fermionic field must "feel" the geometry (i.e., it must fulfil a locally Lorentz-invariant equation) at all scales up to the cut-off. The term $\sqrt{-g}R$ appears multiplied by a constant proportional to $E_{\rm B}^2$, which originates from an integral of the type $\int k\mathrm{d}k$ [8]. The correct value for Newton's constant G in the Einstein-Hilbert action is then recovered precisely if one identifies the cut-off energy $E_{\rm B}$ with the Planck energy. Now, this ($\int k\mathrm{d}k$)-dependence of the gravitational coupling constant tells us that the quantum fluctuations which are most relevant in producing the Einstein-Hilbert term are those with energies close to the cut-off, that is, around the Planck scale. Therefore, to ensure the induction of an Einstein-Hilbert term, these fermionic fluctuations with energies close to the Planck scale must be perfectly Lorentzian to a high degree. This can only be ensured if $E_{\rm L} \gg E_{\rm B}$.
2. *Sakharov one loop dominance*: One also needs that the induced dynamical term dominates over any pre-existing tree level contribution.

Unfortunately, such special relativity dominance is not realised in ^{3}He-A, where the opposite happens: $E_{\rm B} \gg E_{\rm L}$, nor in any other known condensed matter system [10]. Therefore the effective dynamics of the gravitational degrees of freedom emerging in real laboratory condensed matter systems are not relativistic but of fluid-mechanical type. This crucial observation could well be related to the following. Perhaps the fact that $E_{\rm L} \ll E_{\rm B}$ in condensed matter models is related to the *background dependence* of these models, contrarily to what happens in certain theories of quantum gravity such as Loop Quantum Gravity.

But what about the gravitational degrees of freedom of our universe? What if gravity were really emergent along the described scenario and the previous two conditions were fulfilled? In particular, what if $E_{\rm L} \gg E_{\rm B}$, unlike what happens in any known condensed matter system? Indeed, if gravity is to be an emergent phenomenon, its underlying structure will not have the exact same properties as ordinary matter. The microscopic system underlying general relativity cannot simply be a condensed matter system, but a condensed-matter-*like* system, whose specific characteristics we do not really know.

3 The Realm of Quantum Non-gravity

The following conceptual image could then follow from these considerations. Whatever the microscopic details of the ultra-high-energy fermionic theory of our universe (and whatever symmetry, Galilean or otherwise, this theory may possess), as the energy decreases below E_L, the degrees of freedom start to behave as fermionic spinwaves in a Lorentz-invariant background geometry: A special relativistic spacetime emerges. Then, as the energy further decreases below E_B, some of the fermions couple into effective bosons which condense to provide the dynamical degrees of freedom of the geometry: Spacetime becomes curved. Note that since the dynamics of the spacetime is induced, the Weinberg-Witten theorem [11] does not apply. As far as the collapse scenario that we will describe in the next section is concerned, the energy scale E_L could even be infinite, so that no Lorentz invariance violations would take place. In general terms, E_L plays little role in this scenario. To emphasise the crucial point, let us invert the reasoning and increase the energy, starting from our low-energy world. Then the first 'quantum' gravitational effect taking place at the Planck scale E_B would simply be that gravity is progressively switched off and the curved geometry becomes flat. One would be left with the effective paradigm of standard Effective Quantum Field Theory in Minkowski Spacetime with an energy cutoff at E_L (for related ideas, see [12]). Of course, beyond E_L there would still remain some yet-to-be-discovered full-fledged theory of 'quantum gravity'.

Even the energy density in a neutron star (where the distance between the neutrons is of the order of their Compton wavelength 10^{-15} m) is roughly eighty orders of magnitude below the Planck energy density. General relativity is therefore recovered even in the extremely dense scenarios occurring in neutron stars. Next, we will take a speculative look at what could happen in even denser situations.

4 Nonsingular Gravitational Collapse

4.1 Single-Bounce Model

Consider the simple case of a spherical shell of matter collapsing from an infinite radius under its own gravitational pull. We take it to be sufficiently massive to overcome the pressure of the Pauli exclusion principle as it collapses. As the collapse advances towards the formation of a general-relativistic singularity, the energy and momentum of the constituent particles are constantly increasing, taking advantage of the gravitational potential well. Eventually, the shell radius approaches a critical value where the energy of the infalling particles becomes of the order of the Planck scale E_B. Then, within the scenario described above, gravity would be progressively switched off and the particles just perceive the Minkowski structure which persists up to much higher energies. This means that the total energy of the infalling particles becomes a conserved quantity and does not further increase once beyond E_B.

The fate of the shell is from now on governed by standard relativistic quantum field theory. All the particles in the shell can be seen as the past external fermionic lines of a quantum scattering process. The final result of the collision will be another

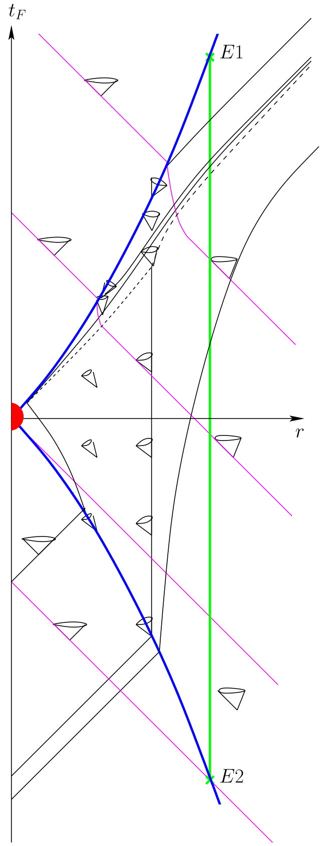

Fig. 1 (Color online) Generalised Finkelstein diagram for a single collapse-and-bounce of a shell of matter (*thick blue line*) coming from spatial infinity. The light-cone causal structure is displayed, together with some relevant ingoing (*purple*) and outgoing (*black*) null rays. In the central *red* patch, general relativistic notions of curvature do not apply. The *vertical green line* depicts the world-line of an observer at a fixed radius

collection of particles with the same total energy and momentum. For simplicity, let us assume that the final collection of particles maintains the spherical shell shape and that dissipation is negligible. Then, after the collision, an equivalent shell could be recovered with the same critical radius but now expanding in time. Once the shell has expanded beyond the critical radius (or critical density), the general relativistic notions of spacetime curvature again apply.

The resulting geometry is shown schematically in Fig. 1 in an extrapolation of the standard ingoing Finkelstein coordinates. The thick blue line represents the shell as it collapses and then bounces back. For simplicity we draw a configuration with one single bounce, corresponding to a shell collapsing from spatial infinity. (For stellar configurations starting the collapse from a finite radius, there would be an infinite set of collapse-bounce-expansion cycles in the idealised case of absence of any dissipative and relaxation mechanism). The small central red patch represents the region in which gravity is not operating and dynamics is governed exclusively by quantum field theory in a flat spacetime. The thin black lines represent different outgoing null rays. The dashed line represents the first outgoing causal signal connecting the shell, just after its bounce, with the external world. The region below the dashed diagonal line is geometrically identical to the standard general relativistic formation of a black hole from a collapsing shell. However, the existence of a bounce makes the extension of this geometry above the dashed line completely different from the standard case: it acquires features from a white-hole spacetime.

A crucial aspect of this geometry is the following. Consider the two events $E1$ and $E2$ marked by green crosses in Fig. 1 and two particular timelike curves connecting them, corresponding to:

- an observer $O1$ associated with a free-falling observer attached to the shell (the thick blue line),
- a second observer $O2$ at rest at a fixed radius r (the vertical green line) well outside the shell's Schwarzschild radius R_S: $r \gg R_S$.

The time intervals between both events as measured by these two observers are of the same order of magnitude. Indeed, the delay in the collapsing phase observed by the outer observer at a fixed radius is roughly compensated for by the rapid accumulation of all the light rays emitted after the shell has crossed its Schwarzschild radius again on the way out. The main essential difference between both time measurements is a factor due to the gravitational field suffered by the outside observer $O2$, which is very close to one for sufficiently distant positions.

To illustrate this assertion, let us make an order-of-magnitude estimate of the time needed for a typical neutron star of two solar masses to collapse almost in free-fall from an initial radius twice its Schwarzschild radius, and bounce back. Take such a neutron star with $R_{\rm ns} = 12$ km and surface gravity $a_{\rm ns} = g \times (R_{\rm earth}/R_{\rm ns})^2 \sim 2.5 \times 10^6$ m/s^2. A Newtonian estimate for the proper time of the free-fall collapse measured by observer $O1$ gives

$$\tau_{\rm FF} = \sqrt{\frac{2R_{\rm ns}}{a_{\rm ns}}} \sim 0.1 \text{ s}. \tag{1}$$

The symmetry of the process indicates that the total time for the collapse and bounce (the time between the events $E1$ and $E2$ in Fig. 1) measured by the first observer is $\tau_{O1} = 2\tau_{\rm FF}$. In terms of the Finkelstein time

$$t_{\rm F} = t + 2M \ln(r - 2M)/2M \tag{2}$$

(with t the Schwarzschild time), if the 'apparent singularity' is located at $t_{\rm F} = 0$, then the first event $E1$ (the onset of the collapse) is located at $t_{\rm F} = -t_{{\rm F}E1} \sim -\tau_{\rm FF}$. Again, for symmetry reasons, the total proper time between the two events as measured by the second observer is $\tau_{O2} \sim (1 - 2M/r)^{1/2} \times (2t_{{\rm F}E1})$. So, for sufficiently large r, indeed, $\tau_{O1} \sim \tau_{O2}$.

In Fig. 2 we have drawn the conformal diagram associated with the previous single-bounce geometry. Note that although this conformal diagram is similar to the one proposed by Ashtekar and Bojowald in [15] (their Fig. 2), in the sense that they both contain a region where the classical notions of general relativity break down, they represent entirely different scenarios. One difference can readily be seen in the causal structure depicted by the conformal diagrams. The Ashtekar-Bojowald diagram contains a region of *future-trapped closed surfaces*. In our simple one-bounce model there is in addition a region of *past-trapped closed surfaces*, which is absent

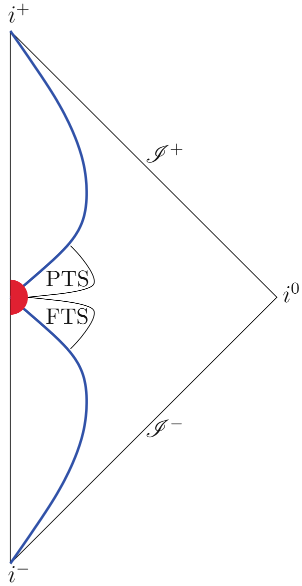

Fig. 2 (Color online) Conformal diagram for our scenario (simple case of a single bounce). Causally, this spacetime is equivalent to Minkowski spacetime. General relativity breaks down in the central *red* region. The regions containing closed Future Trapped Surfaces (FTR) and closed Past Trapped Surfaces (PTR) are also displayed

in the Ashtekar-Bojowald diagram. Considering now the entire geometry, not just the causal structure, it is not difficult to see that the 'space-like' shaped strong-gravity region in [15] is intersected by a large set of rays incoming from $\mathscr{I}^-$. This is not the case for the nearly 'point-like' region in our geometry (see Fig. 1). Remember that a single collapse-and-bounce process in our scenario lasts less than a second, as estimated above. In the Ashtekar-Bojowald proposal, on the other hand, the trapped regions disappear through an extremely slow (quasi-eternal) evaporation process. If one uses similar conformal compactification factors to draw both conformal diagrams, the relative size and shape of both strong gravity regions can also be seen by comparing both conformal diagrams.

To summarise, contrarily to the diagram of Ref. [15], our diagram does not represent a slowly evaporating black hole with a regular final phase. Rather, it represents a perfect bounce, and so just a simplified description of a very brief transient stage in the evolution of the collapsing matter towards a final non-black-hole equilibrium state. In particular, the formation of trapped surfaces displayed in Fig. 2 will be part of the transient collapse-bounce epoch but will not take part in the description of the final equilibrium state.

4.2 Multiple Bounces and Relaxation

In this scenario, the whole stellar collapse process does not lead to a final stage consisting of a slowly evaporating black hole. Instead, after several of the rapid bounces discussed above in a simple model, the collapsing matter could reach an equilibrium, provided that some dissipation and relaxation mechanisms are present (as will always happen in any realistic model) such as emission of gravitational radiation due to departures from sphericity and dynamical friction.

We have to clearly distinguish between the collapse process and subsequent relaxation phase on the one hand, and the final resulting (quasi-)stationary body on the other. Even if several of the previously described rapid collapse-bounce phases were necessary to reach a (quasi-)stationary configuration, the collapse-relaxation phase will last only a few seconds as seen by distant observers. After that phase, the most reasonable result is to end up with a quasi-stationary astronomical body much like a compact and dark star, with its surface very close but outside of the gravitational radius associated with its entire mass and therefore, with no horizons of any kind. One could consider the conformal diagram associated with an "eternal idealization" of such an object in which it has always been there in the past and will be there forever in the future. This conformal diagram, equal to the trivial conformal diagram associated with Minkowski spacetime, is completely unrelated to the conformal diagram in Fig. 2 which represents an idealised model of a single collapse-bounce process in which the shell starts and ends at spatial infinity.

4.3 The Resulting Body

One possibility for such an equilibrium configuration that has been examined in detail recently [13], and which fits nicely with the scenario that we are speculating on here, is a 'black star': A material body with a real and in principle astrophysically explorable surface, and a non-empty interior, filled with matter at least one order of magnitude denser than neutron stars. As a consequence of its large gravitational red-shift, such an object would be extremely dim and nearly indistinguishable from a black hole in the strict sense of general relativity. It would be supported by the most basic form of quantum pressure: the one provided by the quantum vacuum polarisation, which can be huge for configurations maintaining themselves close to the formation of a horizon [13]. An interesting aspect of this proposal is that it permits to 'cure' general relativistic singularities in a way that takes the important notion of isothermal spheres to its limit. Indeed, the black stars just discussed can be interpreted as limiting cases of isothermal spheres in the sense that the entire structure maintains itself with a density profile

$$\rho \lesssim \frac{1}{8\pi} \frac{c^2}{Gr^2}, \tag{3}$$

from its centre up to its surface which is located at a finite radius R_{bs}. This density profile represents a body in which the mass within any radius $r < R_{\text{bs}}$ is forever on the verge of forming a horizon. Note that the central $1/r^2$ divergence is not there in the real density profile but only in the limiting situation, which will never be reached. Let us also mention that in [14] it was shown that black stars could emit Hawking-like radiation mimicking in this respect evaporating black holes. Hawking radiative effects would make each inner sphere to emit with a temperature approximately proportional to the inverse of the mass enclosed in its radius r,

$$T(r) \sim \frac{\hbar c^3}{8\pi G M(r)} \sim \frac{\hbar c}{4\pi r}, \tag{4}$$

and so increasing towards the centre. This would cause the inner volumes to evaporate rapidly, further regularising the real central density.

Although evaporating black holes with a regular final phase might not have a strict event horizon, in astrophysical terms they can be described as hollows in spacetime which last almost eternally. As we have discussed, the astrophysical description of black stars is completely different. In the literature there are other proposals of black hole mimickers similar in spirit to our proposal. Due to its closeness let us mention here Mottola-Mazur's gravastars [16]. These objects don't have horizons either and they differ from our proposal in that their interior is a vacuum solution of the Einstein equations.

4.4 A Potentially Observable Consequence

We end this section by presenting a potentially testable experiment that would clearly distinguish black holes from black stars (or gravastars). The main feature that this experiment uses is that black stars have a real physical surface while the boundary of a black hole is an event horizon. If we sent a radar signal straight towards a black hole it would be completely absorbed (in the geometric approximation, at least) and hence no echo would return. In contrast, if the same experiment were performed towards a black star whose surface were located at a radius $r_s \gtrsim 2M$, then the time needed for the signal to go from an observation point at r_0 to the black star surface and back would be given by

$$T = 2\int_{r_s}^{r_0} \frac{\mathrm{d}r}{1-2M/r} = 2\left(r_0 - r_s + 2M \ln \frac{r_0 - 2M}{r_s - 2M}\right). \tag{5}$$

The relevant remark is that the general relativistic delay is logarithmic so that, even though it diverges for a proper black hole, it decreases to small values very rapidly as the bouncing point departs from $2M$. For instance, for a solar mass black star with a radius larger than its Schwarzschild radius (3×10^3 m) by the tiny amount of 10^{-75} m (which is about 10^{-40} times the Planck length), a radar signal sent from a distance of 8 light-minutes ($= r_0/c$) would acquire a gravitational delay of only 4 milliseconds and would echo back after about 16 minutes (plus 4 milliseconds), in sharp contrast with the infinite amount of time necessary in the case of a proper black hole.

5 Conclusion

To summarise, we suggest that the first 'quantum' correction to gravity could be that gravity just switches off at high energies, leaving essentially a Minkowskian quantum field theory. Of course, many questions with respect to such a scenario remain to be explored. More detailed calculations will be presented in future work. Here, however, we have already wished to emphasize two points. First, such a suggestion is not as exotic as may seem at first sight. Indeed, the underlying arguments are based on a combination of observational indications and analyses from gravitational analogies in condensed matter systems, more specifically from the well-established physics of Fermi liquids. Second, these general considerations are sufficient to hint at the possibility that evaporating black holes might not be the end-point of stellar collapse. In the concrete example that we have discussed here, an equilibrium situation could be reached in which the final object is a limiting case of an isothermal sphere. We have shown that, although these object can mimic black holes in many respects, they have specific characteristics which would completely distinguish them from black holes.

Acknowledgements Financial support was provided by the Spanish MICINN through the projects FIS2008-06078-C03-01 and FIS2008-06078-C03-03 and by Junta de Andalucía through the projects FQM2288 and FQM219. The authors want to thank J.L. Jaramillo, S. Liberati, S. Sonego and M. Visser for some illuminating discussions.

References

1. Jacobson, T., Liberati, S., Mattingly, D.: Lorentz violation at high energy: concepts, phenomena and astrophysical constraints. Ann. Phys. **321**, 150 (2006). arXiv:astro-ph/0505267
2. Maccione, L., Taylor, A.M., Mattingly, D.M., Liberati, S.: Planck-scale Lorentz violation constrained by ultra-high-energy cosmic rays. J. Cosmol. Astropart. Phys. **0904**, 022 (2009). arXiv:0902.1756 [astro-ph.HE]
3. Volovik, G.: From quantum hydrodynamics to quantum gravity. In: Kleinert, H., Jantzen, R.T., Ruffini, R. (eds.) Proceedings of the 11th Marcel Grossmann Meeting on General Relativity. World Scientific, Singapore (2008). arXiv:gr-qc/0612134
4. Volovik, G.E.: The Universe in a Helium Droplet. Clarendon, Oxford (2003)
5. Volovik, G.E.: Fermi-point scenario for emergent gravity, PoS QG-Ph:043 (2007). arXiv:0709.1258 [gr-qc]
6. Atiyah, M.F., Bott, R., Shapiro, A.: Clifford modules. Topol. 3 Suppl **1**, 3 (1964)
7. Hořava, P.: Stability of Fermi surfaces and K-theory. Phys. Rev. Lett. **95**, 016405 (2005). hep-th/0503006
8. Sakharov, A.D.: Vacuum quantum fluctuations in curved space and the theory of gravitation. Sov. Phys. Dokl. **12**, 1040 (1968). Dokl. Akad. Nauk Ser. Fiz. **177**, 70 (1967)
9. Visser, M.: Sakharov's induced gravity: a modern perspective. Mod. Phys. Lett. A **17**, 977 (2002). arXiv:gr-qc/0204062
10. Barceló, C., Liberati, S., Visser, M.: Analogue gravity. Living Rev. Relativ. **8**, 12 (2005). arXiv:gr-qc/0505065. http://www.livingreviews.org/lrr-2005-12
11. Weinberg, S., Witten, E.: Limits on massless particles. Phys. Lett. B **96**, 59 (1980)
12. Boughn, S.: Nonquantum gravity. Found. Phys. **39**, 331 (2009). arXiv:0809.4218 [gr-qc]
13. Barceló, C., Liberati, S., Sonego, S., Visser, M.: Fate of gravitational collapse in semiclassical gravity. Phys. Rev. D **77**, 044032 (2008). arXiv:0712.1130 [gr-qc]
14. Barcelo, C., Liberati, S., Sonego, S., Visser, M.: Hawking-like radiation does not require a trapped region. Phys. Rev. Lett. **97**, 171301 (2006). arXiv:gr-qc/0607008
15. Ashtekar, A., Bojowald, M.: Black hole evaporation: a paradigm. Class. Quantum Gravity **22**, 3349 (2005). arXiv:gr-qc/0504029
16. Mazur, P.O., Mottola, E.: Gravitational vacuum condensate stars. Proc. Natl. Acad. Sci. **101**, 9545–9550 (2004). gr-qc/0407075