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A. Barrau, T. Cailleteau, X. Cao, J. Diaz-Polo, and J. Grain

Phys. Rev. Lett. **107**, 251301 — Published 16 December 2011

DOI: [10.1103/PhysRevLett.107.251301](https://doi.org/10.1103/PhysRevLett.107.251301)

# Probing Loop Quantum Gravity with Evaporating Black Holes

A. Barrau\* and T. Cailleteau†

*Laboratoire de Physique Subatomique et de Cosmologie, UJF, INPG, CNRS, IN2P3  
53, avenue des Martyrs, 38026 Grenoble cedex, France*

X. Cao‡

*Ecole Polytechnique  
Route de Saclay, 91128 Palaiseau, France*

J. Diaz-Polo§

*Institute for Gravitation and the Cosmos & Physics Department  
Penn State, University Park, PA 16802-6300, USA*

*and  
Department of Physics and Astronomy  
Louisiana State University,  
Baton Rouge, LA 70803-4001, USA*

J. Grain¶

*Institut d'Astrophysique Spatiale, Universit Paris-Sud, CNRS  
Btiments 120-121, 91405 Orsay cedex, France*

This letter aims at showing that the observation of evaporating black holes should allow the usual Hawking behavior to be distinguished from Loop Quantum Gravity (LQG) expectations. We present a full Monte-Carlo simulation of the evaporation in LQG and statistical tests that discriminate between competing models. We conclude that contrarily to what was commonly thought, the discreteness of the area in LQG leads to characteristic features that qualify evaporating black holes as objects that could reveal quantum gravity footprints.

PACS numbers: 04.70.Dy, 04.60.-m

*Introduction*– Loop Quantum Gravity (LQG) is a promising framework to non-perturbatively quantize General Relativity (GR) in a background invariant way (see [1] for introductory reviews). Interestingly, it has now been demonstrated that different approaches, based either on quantizations (covariant or canonical) of GR, or on a formal quantization of geometry lead to the very same LQG theory. As for any tentative theory of quantum gravity, experimental tests are however still missing. Trying to find possible observational signatures is obviously a key challenge. In this article we address the following question : could there be objects in the contemporary universe whose observation would lead to a clear signature of LQG ? Fortunately, the answer turns out to be positive. Although small black holes have not yet been directly observed, they could have been formed by different mechanisms in the early universe (see, *e.g.*, [2] for a recent review) or even by particle collisions. We don't review here the well known possible production mechanisms, but instead we focus on how to use the evaporation of microscopic black holes to investigate the discriminating power of the emitted spectrum. Three different possible signatures will be suggested. Although one should be careful when pushing the limits of the LQG approach to black holes to the microscopic limit, our results rely on features of the area spectrum and are rather insensitive to small modifications in the theoretical framework.

*Theoretical framework*– The state counting for black holes in LQG relies on the isolated horizon framework (see, *e.g.*, [3] for an up-to-date detailed review). The isolated horizon is introduced as a boundary of the underlying manifold before quantization. For a given area  $A$  of a Schwarzschild black hole horizon, the physical states arise from a punctured sphere whose punctures carry quantum labels (see, *e.g.*, [4] for a detailed analysis). Two labels  $(j, m)$  are assigned to each puncture,  $j$  being a spin half-integer carrying information about the area and  $m$  being its corresponding projection carrying information about the curvature. They satisfy the conditions :

$$A - \Delta \leq 8\pi\gamma\ell_P^2 \sum_{p=1}^N \sqrt{j_p(j_p + 1)} \leq A + \Delta, \quad (1)$$

where  $\gamma$  is the fundamental Barbero-Immirzi parameter of LQG,  $\Delta$  is a “smearing” area and  $p$  labels the different punctures, and

$$\sum_{p=1}^N m_p = 0, \quad (2)$$

which corresponds to the requirement of a horizon with spherical topology. Many specific features of the entropy were derived in this framework [5]. Although the proportionality between the entropy and the area is indeed

recovered (when choosing correctly the  $\gamma$  parameter) in the classical limit, the quantum structure still leaves a clear footprint at microscopic scales.

Long ago, Bekenstein and Mukhanov postulated that due to quantum gravitational effects the area of a black hole should be proportional to a fundamental area of the order of the Planck area [6] (the argument has recently been updated in [7]). This led to the idea of possible exciting probes of quantum gravity through associated lines in the evaporation spectrum. However, following the pioneering work of Rovelli [8], it was soon realized that the situation is drastically different in LQG where the spacing of the energy levels decreases exponentially with the energy, therefore closing any hope for detection [9]. In (the first paper of) [5] a possible observational effect was suggested based on an exact computation of entropy and the observation of an effective discretization of it. In this letter we re-address this issue and show that at least three different signatures can in fact be expected. Two of them are, as it could be expected, related with “Planck scale” black holes whereas the last one works also for larger black holes.

*Emission lines in the Planck regime*– We first consider the evaporation of a black hole in the deep quantum regime. To this aim, we have developed a dedicated and optimized algorithm. It is based on the ideas given in [3] and it was enhanced with an efficient numeration scheme using a breadth-first search. As the projection constraints is very time consuming, this improvement is mandatory to perform the computation up to high enough Planck areas. The evaporation is considered both according to the pure Hawking law and according to the LQG theory. In each case, we model the evaporation by expressing the probability of transition as the exponential of the entropy difference multiplied by the greybody factor. Arguments for the reliability and generality of this approach are given in [10]. As it can be seen from Fig. 1, some specific lines associated with the transitions occurring in the very last stages of the evaporation can be identified in the LQG spectrum whereas the pure Hawking spectrum is naturally smooth. Two subtle points have to be taken into account. First, the usually assumed “optical limit” of the greybody factors induces a heavy distortion of the spectrum. The use of exact greybody factors, obtained by solving the quantum wave equations in the curved background of the black hole, is in this case mandatory. To be maximally conservative, we have used the very same greybody factors in the Hawking case and in the LQG case. Any difference, as could be possibly expected due to an LQG-inspired metric modification (see, *e.g.* [11]), would only make the discrimination between models easier. We have also assumed that the Hawking evaporation stops at the same mass as expected in LQG (namely  $0.4 M_{Pl}$ ), once again to be as conservative

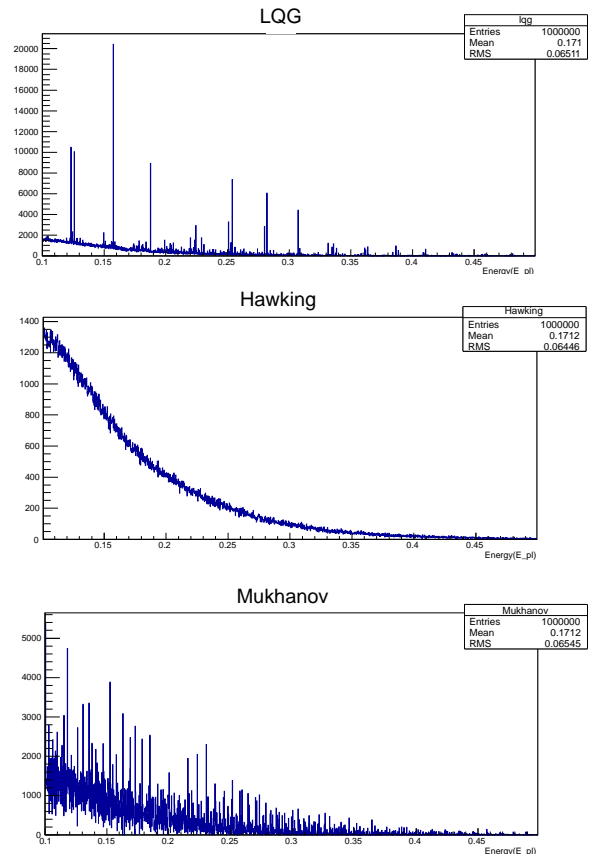


FIG. 1: Spectrum of emitted particles in LQG, in the pure Hawking case, and in the Mukhanov-Bekenstein approach, from top to bottom.

as possible. Second, even if one focuses on the “high energy” emission, say above  $0.15 M_{Pl}$ , the contribution from states with a lower temperature is far from being negligible. We have therefore pushed the computation of the area states, together with their multiplicity, up to  $200 A_{Pl}$  to ensure that the number of missed quanta remain smaller than a few percent.

Several Monte-Carlo simulations were carried out to estimate the circumstances under which the discrimination between LQG and the standard behavior is possible. At each step, the energy of the emitted particle is randomly obtained according to the relevant statistics and to the (spin-dependent) greybody factor. Most simple statistical tests fail to capture the intricate nature of the specific LQG features. We have therefore chosen to use a (slightly improved) Kolmogorov-Smirnov (K-S) test. The K-S statistics quantifies the distance between the cumulative distribution functions of the distributions and can be used for a systematic study of possible discrimination (see, *e.g.* [12]). By investigating the K-S excess as a function of the energy, we have optimized the relevant interval

for each relative error. As this latter is assumed to be known, it is meaningful to use it as an input for the statistical procedure. Figure 2 shows the number of black holes that should be observed, for different confidence levels and as a function of the relative error on the energy reconstruction, to discriminate the models. Clearly with either enough black holes or a relatively small error, a discrimination is possible, therefore leading to a clear LQG signature. To still remain maximally conservative, we have only considered emitted leptons. For a detector located nearby the black hole, and due to the huge Lorentz factors, the electrons, muons and taus can be considered as stable whereas quarks do not have enough time to fragment into hadrons.

For the sake of completeness, we have finally implemented a K-S test between the LQG spectrum and the Bekenstein-Mukhanov one. Once again, the discrimination is possible with an even smaller number of black holes as the lines are sitting at clearly different places.

Even if the Hawking and Mukhanov hypotheses are not expected to be reliable in the Planck era, this analysis shows that a discrimination between LQG and other tentative approaches is possible.

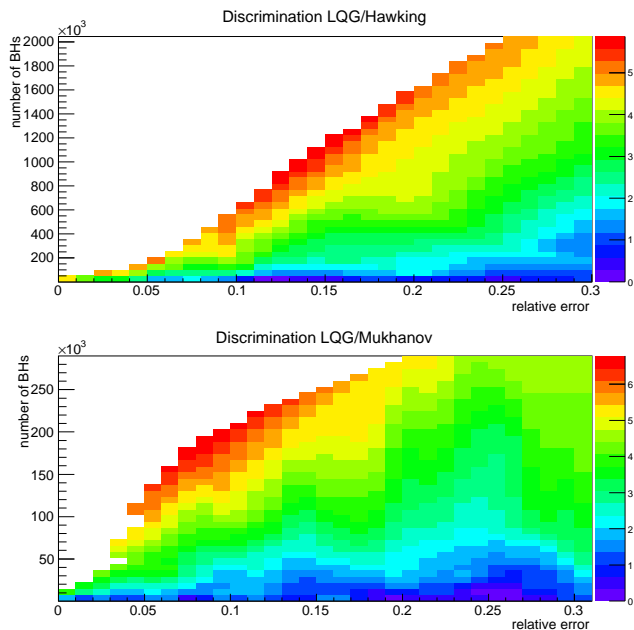


FIG. 2: Number of evaporating black holes that have to be observed as a function of the relative error on the energy reconstruction of the emitted leptons for different confidence levels (the grey scale corresponds to the number of standard deviations). The first row corresponds to the discrimination between LQG and the Hawking hypothesis and the second row between LQG and the Mukhanov-Bekenstein hypothesis.

*Low energy emission in the Planck regime*— There is a second specific feature associated with the endpoint of

the evaporation process. In LQG, the last transitions take place at definite energies, of the order of the Planck scale, associated with the final lines of the mass spectrum. On the other hand, in the usual Hawking picture, the most natural way to implement a minimal mass is to assume a truncation of the standard spectrum ensuring energy conservation. Even if no minimal mass is assumed, the spectrum has to be truncated to ensure that the black hole does not emit more energy than it has. This is also the case in some string gravity models [13]. This leads to the important consequence that the energy of the emitted quanta will progressively decrease and asymptotically tend to zero. It is possible to distinguish this “low-energy” emission associated with the endpoint from the (much more numerous) “low-energy” particles emitted before (when the black hole temperature was lower) thanks to the dynamics of the process. For example, as soon as one considers gamma-rays with energies lower than  $8 \times 10^5$  GeV, the “endpoint” emission will take place at least  $100 \mu\text{s}$  after the initial emission, making both signals easily distinguishable. Those “relic” quanta will be emitted with mean energies decreased by a factor  $1/4$  at each step (for scalars and fermions). The time interval between consecutive emissions will typically increase with decreasing energies as  $E^{-3}$ . At 100 TeV, the mean interval is around 1 s. This feature of the “standard” spectrum is therefore very different from the absence of low energy particles expected in the LQG case.

This probe should however be considered with care as it is less reliable than the two other ones suggested in this work, being dependent on the specific assumption made for the evaporation endpoint in the Hawking case.

*Peaks in the higher-mass regime*— Up to now, the analysis was mostly focused on lines associated with the discreteness of the area, as could be seen on Fig 1. However, LQG specific features also lead to broader peaks in the spectrum, with a clear pseudo-periodicity, as shown in Fig 3. Those peaks are associated with the “large scale” structure of the area spectrum. This periodicity has been discussed in much detail (see [3] and references therein). We have observed this behavior up to  $200 A_{Pl}$  with an exact computation of the area eigenvalues and we have checked it up to  $400 A_{Pl}$  with a dedicated Monte-Carlo Markov Chain (MCMC) algorithm. Although some recent arguments suggest that this periodicity is damped for higher masses [14], they cannot rule out the possibility of a “revival” of the periodicity at larger areas (or even in the asymptotic limit), so it is relevant to study the possible observational effects that this periodicity would have in the macroscopic regime, in agreement with the assumption made in most of the literature on the subject. We here assume that it remains valid up to arbitrary large masses. This is not an unavoidable prediction of LQG but this is clearly a possibility that arises, to the best of our knowledge, only in this framework. This makes it a potentially interesting probe.

The mean area gap  $dA$  between peaks can be shown to be independent of the scale. As, for a Schwarzschild black hole,  $dA = 32\pi M dM$  and  $T = 1/(8\pi M)$ , this straightforwardly means that  $dM/T = cte$  where  $dM$  refers to the mass gap between peaks. This is the key-point for detection : in units of temperature, which is the natural energy scale for the emitted quanta, the mass gap does *not* decrease for increasing masses. Any observable feature associated with this pseudo-periodicity can therefore be searched for through larger black holes.

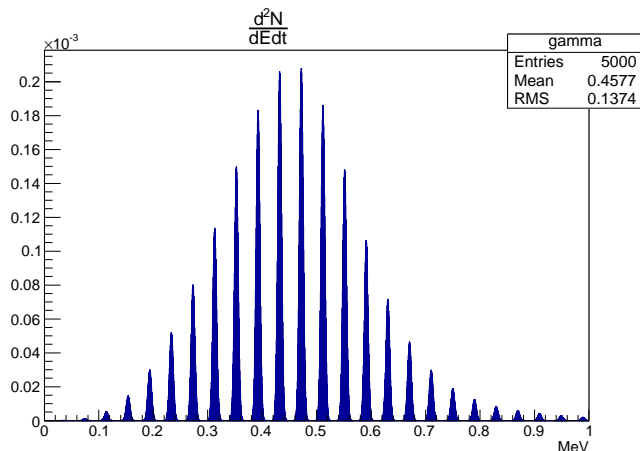


FIG. 3: Instantaneous spectrum of a  $\sim 100$  keV black hole taking into account the LQG modulation of the entropy.

This opens up the question of a possible detection of LQG effects with evaporating primordial black holes (PBHs) in astrophysical circumstances. If PBHs were formed with a continuous mass spectrum  $n_i(M_i)$ , where the subscript  $i$  stands for initial values, it is now deformed according to  $n(M) \propto M^2$  for  $M < M_*$  and  $n(M) \approx n_i(M)$  for  $M > M_*$  where  $M_* \approx 10^{15}g$  is the initial mass of a black hole whose lifetime is of the order of the age of the Universe. This is just due to the Hawking evaporation leading to  $dM/dt \propto M^{-2}$ . In such a case, it is easy to show that the peak structure of the instantaneous spectrum will be immediately washed out. The convolution of the individual spectra with the mass distribution will lead to a Hawking-like  $E^{-3}$  integrated spectrum. We have checked this expected behavior with a Monte-Carlo simulation. It should also be pointed out that the peak structure of the “end-of-the-life” spectrum, which is superimposed with the lines, is *not* due to the pseudo-periodic structure of the entropy but to transitions to the last states, *i.e.* with the discreteness of the area eigenvalues.

However, this does not at all close the issue of observing LQG features with astrophysical PBHs. The continuous mass spectrum (typically scaling as  $M^{-5/2}$ ) was an hypothesis historically associated with a possible high normalization of the primordial power spectrum (or a

very blue tilt) which is ruled out by CMB observations. Realistic models for PBH formation are now associated with phase transitions (see, *e.g.*, [16]) or other phenomena leading to black holes formed at a given mass  $M_c$ . If this mass is smaller than  $M_*$ , those black holes have already disappeared. If  $M_c > M_*$ , that is if the horizon mass at the formation time was larger than  $10^{15}g$ , those black holes are evaporating so slowly that their mass has nearly not changed. As not only the mass loss rate but also the area loss rate does decrease with the mass ( $dA/dt \propto 1/M$ ), the peak structure exhibited in Fig. 3 should be observed from such black holes. In this case, the instantaneous spectrum, together with its peak structure, can directly be probed. If the mass is higher than typically  $10^{17}g$  the black hole will emit only massless particles, that is photons ( $\sim 12\%$ ) and neutrinos ( $\sim 88\%$ ). The electromagnetic signal is not anymore contaminated by gamma-rays due to the decay of neutral pions as quarks cannot be emitted. Although the redshift integration will slightly smear out the structures, a very clean signature can therefore be expected as no mass integration is anymore involved in the possibly observed signal. In addition, one can show that the total number of photons received per second by a detector of area  $S$  can be written as:  $\Phi \sim 10^4 \times \frac{\rho_{PBH}}{\rho_c} \times \left(\frac{10^{17}g}{M}\right)^2 \times S$  where  $\rho_c = 3H^2/8\pi G$  is the “cosmological” critical density and  $\rho_{PBH}$  is the density of primordial black holes. This leads to a macroscopic signal for quite a large range of masses and densities.

**Conclusion**– In this letter, we have shown that the specific features of the area of black holes in loop quantum gravity can lead to observational signatures. Although detecting evaporating black holes is in itself a challenge, we have established that footprints of the underlying quantum gravity theory might indeed be observed in this way. This opens a possible new window to probe LQG.

**Acknowledgements**– We would like to thank Adeline Choyer with whom this study was initiated. This work was partially funded by the NSF grant PHY0854743 & PHY0968871, the Eberly research funds of Penn State and Spanish MICINN grant ESP2007-66542-C04-01.

\* Electronic address: aurelien.barrau@cern.ch

† Electronic address: thomas.cailleteau@lpsc.in2p3.fr

‡ Electronic address: xiangyu.cao@polytechnique.edu

§ Electronic address: jacob@phys.lsu.edu

¶ Electronic address: grain@apc.univ-paris7.fr

- [1] C. Rovelli, arXiv:1102.3660v5; C. Rovelli, *Quantum Gravity*, Cambridge, Cambridge University Press, 2004; C. Rovelli, Living Rev. Relativity, 1, 1 (1998); L. Smolin, arXiv:hep-th/0408048v3; T. Thiemann, Lect. Notes Phys., 631, 41 (2003); T. Thiemann, *Modern Canonical Quantum General Relativity*, Cambridge, Cambridge

- University Press, 2007; A. Perez, arXiv:gr-qc/0409061v3; P. Dona & S. Speziale, arXiv:1007.0402V1
- [2] B.J. Carr *et al.*, Phys. Rev. D, 81, 104019 (2010)
  - [3] I. Agullo *et al.*, Phys. Rev. D, 82, 084029 (2010)
  - [4] A. Ashtekar, J.C. Baez, A. Corichi, and K. Krasnov, Phys. Rev. Lett, 80, 904 (1998); A. Ashtekar, J.C. Baez, K. Krasnov, Adv. Theor. Math. Phys. 4, 1 (2000); A. Corichi, J. Diaz-Polo, and E. Fernandez-Borja, Class. Quantum Grav. 24, 243 (2007); A. Corichi, J. Diaz-Polo and E. Fernandez-Borja, Phys. Rev. Lett. 98, 181301 (2007)
  - [5] J. Diaz-Polo and E. Fernandez-Borja, Class. Quantum Grav., 25, 105007 (2008); I. Agullo, J. Diaz-Polo, and E. Fernandez-Borja, Phys. Rev. D, 77, 105024 (2008); I. Agullo *et al.*, Phys. Rev. D, 80, 084006 (2009)
  - [6] J. Bekenstein and V. Mukhanov, Phys. Lett. B, 360, 7 (1995)
  - [7] G. Dvali, C. Gomez & S. Mukhanov, arXiv:1107.0870v1
  - [8] C. Rovelli, Phys. Rev. Lett., 77, 3288 (1996)
  - [9] C. Rovelli, Helv. Phys. Acta., 69, 582 (1996)
  - [10] S. Massar and R. Parentani, Nucl. Phys. B, 575, 333 (2000)
  - [11] E. Alesci and L. Modesto, arXiv:1101.5792v1 [gr-qc]
  - [12] G.R. Shorack & J.A. Wellner, *Empirical Processes With Application to Statistics*, Philadelphia, Society for Industrial & Applied Mathematics, 2009.
  - [13] S. Alexeyev *et al.*, Class. Quantum Grav., 19, 4431 (2002)
  - [14] J.F. Barbero, G. Eduardo, E.J. Villasenor, Phys. Rev. D, 83, 104013 (2011) ; X. Cao *et al.*, in preparation
  - [15] J.F. Barbero, E.J. Villasenor, Phys. Rev. D, 77, 121502 (2008)
  - [16] K. Jedamzik & J.C. Niemeyer, Phys. Rev. D, 59, 124014 (1999)