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Black hole remnants and the information loss paradox☆

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ABSTRACT

Forty years after the discovery of Hawking radiation, its exact nature remains elusive. If Hawking radiation does not carry any information out from the ever shrinking black hole, it seems that unitarity is violated once the black hole completely evaporates. On the other hand, attempts to recover information via quantum entanglement lead to the firewall controversy. Amid the confusions, the possibility that black hole evaporation stops with a "remnant" has remained unpopular and is often dismissed due to some "undesired properties" of such an object. Nevertheless, as in any scientific debate, the pros and cons of any proposal must be carefully scrutinized. We fill in the void of the literature by providing a timely review of various types of black hole remnants, and provide some new thoughts regarding the challenges that black hole remnants face in the context of the information loss paradox and its latest incarnation, namely the firewall controversy. The importance of understanding the role of curvature singularity is also emphasized, after all there remains a possibility that the singularity cannot be cured even by quantum gravity. In this context a black hole remnant conveniently serves as a cosmic censor. We conclude that a remnant remains a possible end state of Hawking evaporation, and *if it contains large interior geometry*, may help to ameliorate the information loss paradox and the firewall controversy. We hope that this will raise some interests in the community to investigate remnants more critically but also more thoroughly.

A review paper written by LeCosPA's director Prof. Pisin Chen, LeCosPA's junior fellow Dr. Dong-han Yeom, and LeCosPA's former PhD student Dr. Yen Chin Ong (who currently holds a fellow position at the Nordic Institute for Theoretical Physics), has been published by *Physics Reports*.

The article, designated *Physics Reports* (2015) 1-45, is freely available online for a limited period, until January 16, 2016. The arXiv version is available at http://arxiv.org/abs/1412.8366.

Left to right: Prof. Pisin Chen, Dr. Yen Chin Ong, Dr. Dong-han Yeom

Physics Reports is a highly prestigious journal that aims to keep the physics community up-to-date on developments in a wide range of topics by publishing timely reviews which are more extensive than just literature surveys but normally less than a full monograph. It has a high impact factor of 20.033 as of 2014, and a 5-year impact factor of 24.573. In comparison, Nature Physics 2014 impact factor is 20.147, and its 5-year impact factor is 19.78.

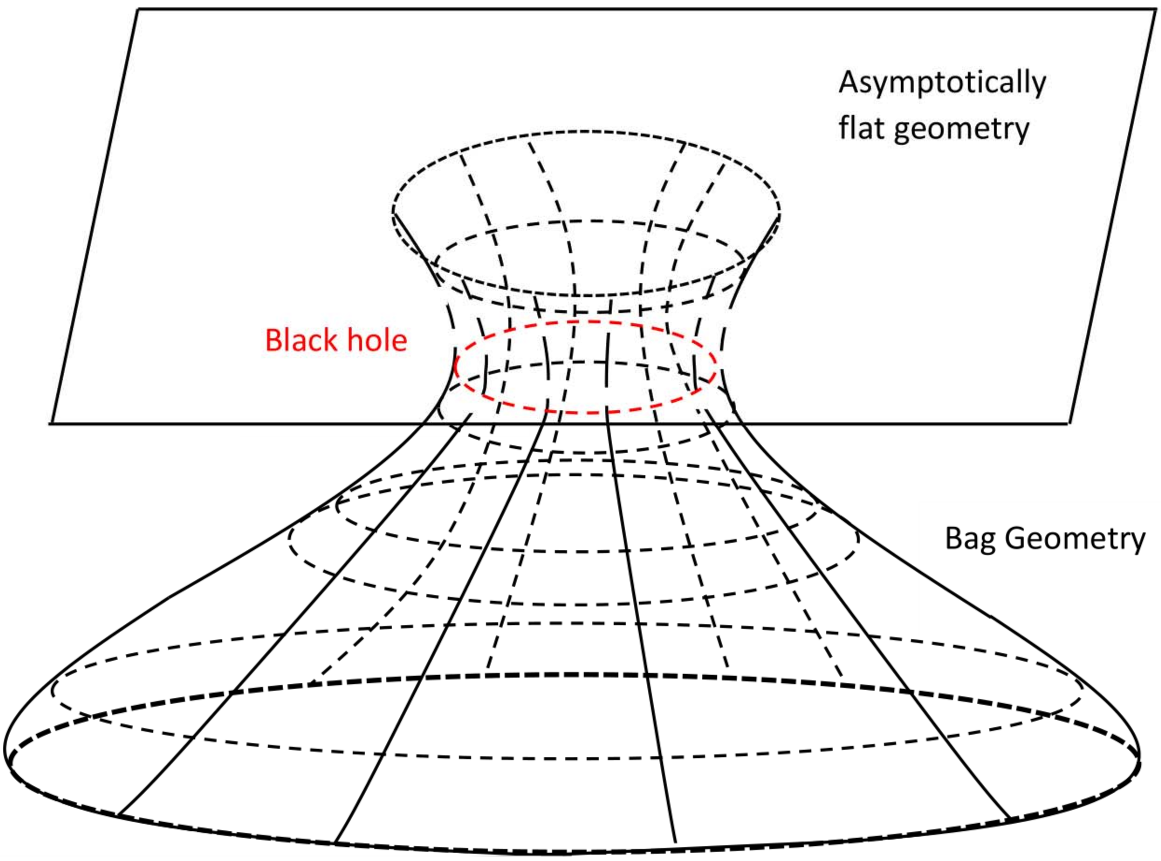
The idea to perform a literature survey and write a review on black hole remnant was conceived in early 2014 by Prof. Chen and Dr. Ong, and was mainly motivated by the information loss paradox in black hole physics, as well as its latest incarnation in the form of the firewall [1]. These paradoxes involve the end state of a black hole under Hawking evaporation, and the information storage capacity of a black hole. In the literature, however, not much attention is given to the possibility that black hole evaporation could stop when some new physics comes in at high enough temperature. If this is indeed what happens, then the black hole will remain there, perhaps indefinitely, as a "remnant". Usually in remnant scenarios, this happens when the black hole already reaches a very small size, typically the order of a Planck length.

Having worked on black hole remnant in the context of the generalized uncertainty principle about a decade ago [2], and subsequently explored the possible role of black hole remnant as dark matter [3], Prof. Pisin Chen has always wanted to find out possible connections between the black hole remnant notion and the information loss paradox. Since no comprehensive review on black hole remnant exists, it was decided then that the time was ripe to write one. Dr. Yeom joined the project when he started his LeCosPA fellowship in the fall of 2014.

The vision of the authors was to not only provide the physics community with a useful literature survey, and a pedagogical introduction into this fascinating subject, but also to include new analysis and novel thoughts. Since there is a large amount of works involving black hole remnants, the authors decided to focus on two issues:

(1) Existence of remnants: A literature survey was conducted on the various theories and models that allow for the existence of black hole remnants. The objections that are usually put forward to argue against the existence of remnants are discussed in details.
(2) The role of remnants in resolving black hole paradoxes: Even if a black hole remnant can exist, it does not mean that a remnant can resolve either the information loss paradox or the firewall controversy. This is a separate issue that needs to be analyzed carefully.

Indeed, it is argued in the review paper that black hole remnants can only help to ameliorate these problems if it contains a nontrivial, large, interior. An example of this is the "bag of gold" of John Wheeler, as illustrated below. In other words, although the black hole appears rather small from the outside, the strong curvature of spacetime allows it to contain more space inside than one could infer from its area alone. A black hole remnant should therefore not be viewed as a point particle in standard quantum field theory.



This is in tension with holography, which is widely believed to be a robust feature of any consistent theory of quantum gravity. The spirit of holography would dictate that all the information of a black hole is encoded on its horizon only. However, the authors believe that it is important to further examine the difference between statistical entropy, and that of the Bekenstein-Hawking entropy of the black hole.

In the review paper, the authors have also emphasized that it is important *not to* ignore the singularity of the black hole. While it is widely believed that a full theory of quantum gravity would resolve the singularity, *it might not*. Since information can fall into the singularity (or something else that replaces the singularity, if it is indeed resolved), it is possible that the information loss paradox will not be entirely resolved until we truly understand singularities.

This year the physics community celebrates the centenary of Einstein's general relativity. *Geometry is the central pillar of the edifice of general relativity*. It is only apt that one pays more attention to what geometry has to say in issues regarding gravity. One should try to understand black hole interior spacetime as well as its singularity with a similar spirit. One should not sweep singularities under the carpet with the hope that quantum gravity will eventually take care of that.

This Physics Reports review article ends with the following question:

"Is there really such a thing as *the* solution to the information loss paradox? After all, one sometimes speculates that the dark sector may actually be quite rich and there could be more than one type of dark matter. Similarly, there are various types of black holes with different dimensions, of varying topologies and distinct asymptotic geometries. It also seems that some black holes can be destroyed by quantum gravitational effect or tunneling, instead of ending as remnants. So should there indeed be a universal solution to the information loss paradox, or perhaps different black holes preserve unitarity in different ways?"

This sentiment is echoed by Prof. Stephen Fulling, who remarked in his talk during the Hawking Radiation Conference held in Stockholm in August 2015 (which is co-organized by Dr. Ong), that perhaps black holes with different initial conditions have different end states.

References:

[1] Ahmed Almheiri, Donald Marolf, Joseph Polchinski, James Sully, "Black Holes: Complementarity or Firewalls?", JHEP 02 (2013) 062, [arXiv:1207.3123 [hep-th]].

[2] Ronald J. Adler, Pisin Chen, David I. Santiago, "The Generalized Uncertainty Principle and Black Hole Remnant", *Gen. Rel. Grav.* 33 (2001) 2101-2108, [arXiv:gr-qc/0106080].

[3] Pisin Chen, Ronald J. Adler, "Black Hole Remnants and Dark Matter", *Nucl. Phys. Proc. Suppl.* 124 (2003) 103-106, [arXiv:gr-qc/0205106].