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New black hole simulator may shed more light on contradiction in fundamental physics

A newly proposed experiment promises to create a "tabletop" black hole that could prove whether information is truly lost when black holes evaporate. The idea that information could be lost this way has created a paradox in our current understanding of basic physics.

43 years ago, Stephen Hawking combined quantum field theory with Einstein's theory of general relativity and discovered black hole evaporation. The debate over whether information is really lost during Hawking evaporation has persisted ever since. Almost all the contemporary leading theoretical physicists have participated in this "black hole war". In quantum mechanics, the probability, or information, must be preserved before and after a physical process. The seeming loss of information as a result of the black hole evaporation therefore implies that general relativity and quantum mechanics, the two pillars of modern physics, may be in conflict.

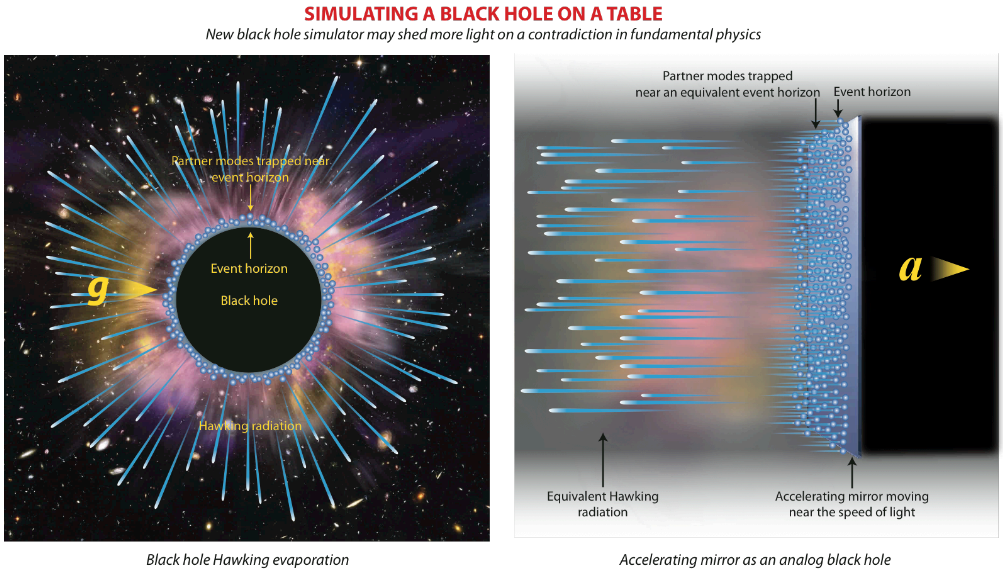

Fig.1: Accelerating mirror mimics evaporating black hole. Left: Black hole Hawking evaporation and the trapping of the partner modes near the horizon. Right: An accelerating mirror also has a horizon and can also emit Hawking particles and trap their partner modes. The analogy between these two systems may be appreciated via Einstein's equivalence principle.

So far investigations of this paradox have been mostly theoretical because of the difficulty of observing black holes in their later stages, when this potential contradiction is most acute. According to theory, a solar-size black hole would take 10^{67} years to evaporate entirely, yet our universe is only about 10^{10} years old. Therefore essentially all astrophysical black holes are too young to provide useful clues on the information loss paradox even if they are observed, such as that responsible for the gravitational waves observed by LIGO in 2016.

Now, in a paper that was published in Physical Review Letters on January 23 (Phys. Rev. Lett. **118**, 045001 (2017); http://journals.aps.org/prl/issues/118/4), Pisin Chen, Professor of Physics and Director of the Leung Center for Cosmology ad Particle Astrophysics (LeCosPA), National Taiwan University, and Gerard Mourou, Professor and Director of International Center for Zeta-Exa-Watt Science and Technology (IZEST), École Polytechnique, conceived a laboratory black hole to simulate this evaporation. Using state-of-the-art laser and nanofabrication technologies, they plan to mimic black hole evolutions at their later stage, to reveal crucial details on how information may be preserved during black hole evaporation.

According to Einstein's equivalence principle, an accelerating mirror moving near the speed of light shares some common features with a true black hole. In both cases, there exist an event horizon. Interacting with quantum fluctuations in vacuum near the horizon, both will emit Hawking particles and trap their partner modes (Fig.1) until the black hole evaporates entirely or the accelerating mirror suddenly stops. By then the partner modes will be released. The purpose of this proposed experiment is to see whether and how the Hawking particles and their partners are entangled and therefore how the information would be preserved.

It is known that an intense laser traversing a plasma would push the intercepting plasma electrons to its back, which is called by experts the "plasma wakefields". Triggered by extremely intense lasers, such plasma density perturbations can be so concentrated that it can serve as a flying reflecting mirror. The authors pointed out in the paper that by properly tailoring the increase of the density of a thin-film target using nanofabrication technology, a relativistic plasma mirror would accelerate as the driving laser continues to enter higher density regions. At the time when the laser leaves the thin-film target, the plasma mirror would abruptly stop its motion, which mimics the ending of the Hawking evaporation (see Fig.2).

In addition to being published by Physical Review Letters, one of the most prestigious physics journals in the world, this paper, entitled "Accelerating Plasma Mirrors to Investigate Black Hole Information Loss Paradox", was highlighted by PRL as "Editors' Suggestion". In addition, it was featured as a "Synopsis" in American Physical Society's online magazine *Physics* (http://physics.aps.org) on January 23, 2017. On the average only a small percentage of PRL papers received such an honor.

An international collaboration has been formed, which consists of National Taiwan University, École Polytechnique, Kansai Photon Research Institute in Kyoto, and Shanghai Jiao Tong University, to carry out this experiment.

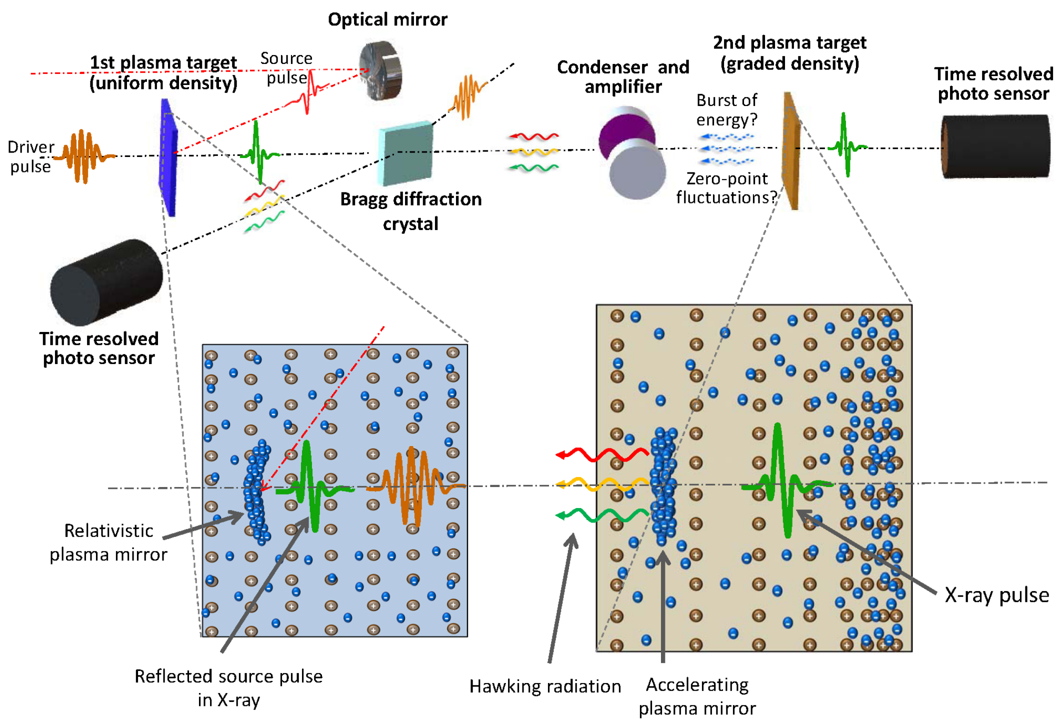

Fig.2: A schematic diagram of the proposed analog black hole experiment. The first, gaseous and uniform plasma target is used to prepare a high intensity x-ray pulse. The x-ray pulse will then induce an accelerating plasma mirror due to the increasing plasma density in the second target. As the mirror stops abruptly, it will release either a burst of energy or zero-point fluctuations. The entanglement between either of these signals and the Hawking photons emitted earlier is measured upstream.


Pisin Chen

Gerard Mourou

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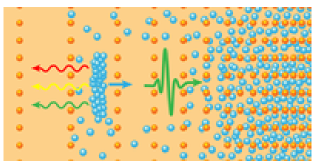
Dear Sir or Madam,

We are pleased to inform you that the Letter



Accelerating plasma mirrors to investigate the black hole information loss paradox

Pisin Chen and Gerard Mourou

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has been highlighted by the editors as an Editors' Suggestion. Publication of a Letter is already a considerable achievement, as *Physical Review Letters* accepts fewer than 1/4 of submissions, and is ranked first among physics and mathematics journals by the Google Scholar five-year h-index. A highlighted Letter has additional significance, because only about one Letter in six is highlighted as a Suggestion due to its particular importance, innovation, and broad appeal. Suggestions are downloaded twice as often as the average Letter, and are covered in the press substantially more often. If Suggestions were a separate publication, they would have an Impact Factor of 13. More information about our journal and its history can be found on our webpage prl.aps.org.

Yours sincerely,

Hugues Chaté
Editor
Physical Review Letters

Pierre Meystre
Editor in Chief
Physical Review

「類比黑洞」可能解答四十年未決的重要物理悖論

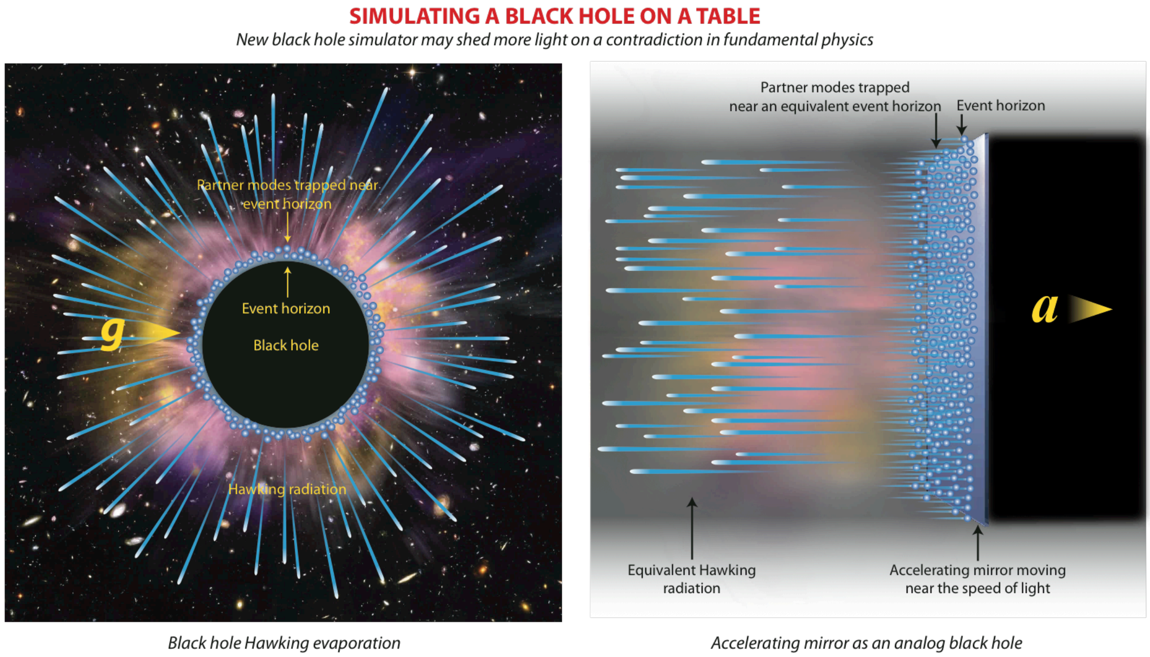
國立臺灣大學與法國綜合理工大學

聯合發布新聞稿

105 年 1 月 24 日

台法兩位科學家提出一個新穎的實驗構想，建議在實驗桌上打造出黑洞，來檢驗黑洞霍京蒸發是否真的會導致信息遺失。這個黑洞信息遺失悖論已經困擾了物理學界四十幾年，因為它撼動了物理學的根基。

自從霍京（Stephen Hawking）教授在 1974 年結合廣義相對論與量子場論，發現黑洞蒸發效應（圖一左）以來，物理學界對於黑洞蒸發是否會導致信息遺失，持續進行了正反兩面的爭論，幾乎所有當代最有影響力的理論物理學家都加入了這場「黑洞戰爭」。信息遺失問題之所以重要，是因為它觸及了量子力學的一個基本出發點，那就是在任何一個物理的過程中，它的機率必須守恆。而黑洞霍京蒸發卻似乎破壞了這條基本戒律。它暗示相對論與量子力學，這廿世紀的兩大物理革命以及所有近代物理的基礎，或許不能相容。



圖一：加速反射鏡可以模擬黑洞霍京蒸發。左：黑洞霍京輻射及其被困在黑洞事件視平線的對偶型。右：一個加速的反射鏡也有視平線，也會輻射霍京粒子及困住對偶型。兩者的相似性可以從愛因思坦的「等價原理」來理解。

雖然這個議題如此重要，可是四十年來它的研究僅止於理論的爭辯而極少實驗進展。這主要是因為黑洞信息遺失問題的關鍵點是在黑洞蒸發的晚期、當它快要燒完的時候，而宇宙中絕大多數的黑洞都比太陽的質量還大。根據理論，這種黑洞要完全蒸發，需要 10^{67} 年之久，而宇宙從大霹靂到現在，才不過 138 億(1.38×10^{10})年。相對於黑洞的壽命，它們都還在嬰兒期。所以即使能觀測到（例如 2016 年 LIGO 發現釋放重力波的黑洞），也無法對信息遺失問題置一詞。

今年 1 月 23 日，國際重量級物理學術期刊《物理論壇通訊》（Physical Review Letters) 發表了臺大物理系及天文物理所教授兼「梁次震宇宙學與粒子天文物理學中心」主任陳丕燊與法國綜合理工大學（Ecole Polytechnique）教授兼「國際超強雷射科技中心」（IZEST）主任 Gerard Mourou 共同撰寫的論文。兩位作者在文章中提出一個新穎的實驗構想，利用日新月異的超強雷射及奈米技術打造「類比黑洞」（圖一右），來模擬黑洞蒸發的晚期。

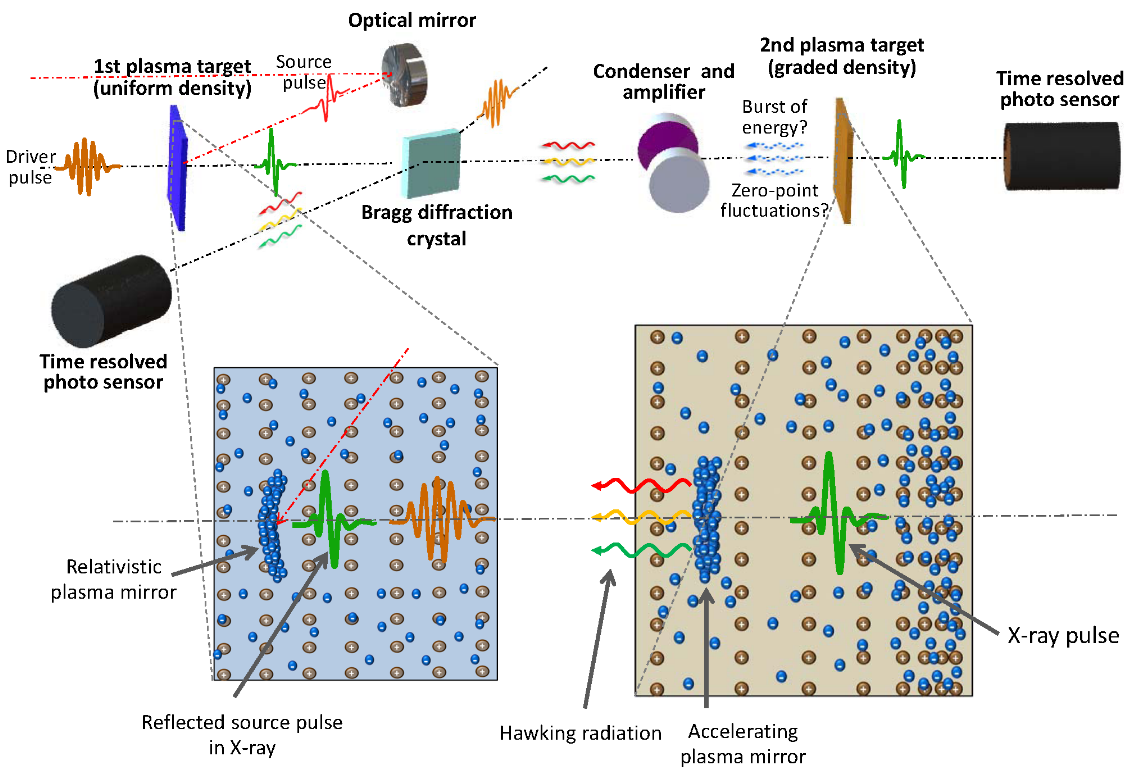
跟據愛因思坦的「等價原理」，加速的反射鏡和黑洞在某些物理機制上很相似。譬如說，兩者都有「事件視平線」（event horizon）。當真空量子波動撞上黑洞或鏡面時，兩者都會射出霍京粒子、並且把真空波動裡霍京粒子的對偶模式（partner mode）困在視平線上（圖一），直到黑洞完全蒸發或加速鏡面突然停止、因此視平線突然消失時，這些真空對偶模式才能終於被大量釋放出來。這個實驗的目的，就是要了解信息如何透過真空波動中霍京粒子和他們的對偶模式之間的「量子糾纏」而保存下來。

當超強雷射穿越電漿時，在相互作用下，會使得電漿中的自由電子被推到雷射的後方，堆積成一面極高密度的電漿反射鏡，並且尾隨雷射同步前進（圖二）。作者們指出，運用奈

米技術，可以製造出密度逐漸加大的薄膜靶。超強雷射打進薄膜後，會瞬間把薄膜融成電漿並產生反射鏡。而當雷射及電漿反射鏡逐漸進入薄膜中密度較大的「深水區」時，它們將會逐漸加速。當雷射結束薄膜穿越時，電漿反射鏡也隨之而突然停止，這正像黑洞蒸發到最後完全消失一樣。因此原則上這個系統可以模擬黑洞蒸發的末期，提供關於信息遺失悖論極珍貴的實證基礎。

難得的是，這篇論文：”Accelerating Plasma Mirrors to Investigate Black Hole Information Loss Paradox” (《以加速電漿反射鏡研究黑洞信息遺失悖論》Phys. Rev. Lett. **118**, 045001 (2017); http://journals.aps.org/prl/issues/118/4) 還被 PRL 編輯群特別選出，做為”Editors’ Suggestion”（類似「店長推薦」），而且美國物理學會的機關網路雜誌 *Physics* (http://physics.aps.org) 也於同一天（1 月 23 日）特別撰文推薦介紹。只有極少數的 PRL 文章能獲得這個殊榮。

陳丕燊教授等不及文章的正式發表，已經組織了一個國際團隊，要把這個實驗儘快做出來。它的成員除了臺大梁次震中心，還有法國綜合理工大學的「國際超強雷射科技中心」(IZEST)、日本國立量子科技中心(QST)之「關西光子研究所」(KPRI)、及上海交通大學。



圖二：結合雷射及奈米科技的「類比黑洞」實驗構想。首先，用一束可見光雷射打進一個氣態且均勻的電漿（圖左的藍色靶），經由電漿反射鏡的反射，這個可見光束反射後轉化成了 X 光。接著把這個高強度的 X 光射進一個由奈米技術製造的薄膜靶。這個靶的密度逐漸增大，導致 X 光及尾隨在後的電漿反射鏡不斷加速，並因此而射出霍京粒子（圖右的棕色靶）。當雷射結束穿越時，大量的被困住的真空波動對偶粒子將被瞬間釋放。量測兩者間的量子糾纏，可以提供關於黑洞信息如何保存的珍貴實証資訊。

圖三：兩位作者：臺大物理系及天文物理所教授兼「梁次震宇宙學與粒子天文物理學中心」主任陳丕燊及法國綜合理工大學（Ecole Polytechnique）Gerard Mourou 教授 。