University of British Columbia, Kelowna, British Columbia.
e-mails: mtodesco@msl.ubc.ca;
loren.rieseberg@botany.ubc.ca

1. Lv, J. *et al. Nature* **641**, 732–739 (2025).
2. Vijverberg, K., Ozias-Akins, P. & Schranz, M. E. *Front. Plant Sci.* **10**, 128 (2019).
3. Chaikam, V., Molenaar, W., Melchinger, A. E. & Boddupalli, P. M. *Theor. Appl. Genet.* **132**, 3227–3243 (2019).
4. Yang, S. *et al. Development* **135**, 3501–3509 (2008).
5. Del Bel, Z. *et al. Plant Growth Regul.* **102**, 51–64 (2024).
6. Noyes, R. D. & Rieseberg, L. H. *Genetics* **155**, 379–390 (2000).

The authors declare no competing interests.
This article was published online on 2 April 2025.

Astrophysics

Black hole fly-by modelled with landmark precision

Zhengwen Liu

A prediction of the gravitational waves produced by interacting black holes achieves high precision and demonstrates the link between general relativity and geometry. **See p.603**

In 2015, the first direct detection of gravitational waves opened an exciting window for exploring the Universe[1]. Gravitational waves are ripples in space-time produced by the acceleration of massive objects, and were first predicted by Einstein's general theory of relativity[2] in 1916. The equations that describe these waves are notoriously difficult to solve, but on page 603, Driesse *et al.*[3] report a landmark-precision prediction of the gravitational waves produced by two black holes flying past each other. Using methods developed in particle physics, the researchers formulate an approximation to Einstein's equations of gravity. Their results will guide future gravitational-wave observations and demonstrate a link between the mathematics of general relativity and geometry.

A decade ago, the cosmos could be observed only with light, or occasionally with subatomic particles called neutrinos. Now, however, astronomers can observe cosmic phenomena such as black-hole collisions by measuring the gravitational waves that these events produce. Gravitational waves are detected using ultra-sensitive instruments called interferometers, which measure how ripples in space-time affect the interference of light. Each gravitational signal is a 'fingerprint' of a cosmic event, but to interpret an interferometer measurement, physicists must use Einstein's equations to make highly precise theoretical predictions of the gravitational waves produced by that event.

Driesse and colleagues tackle the two-body problem — the conundrum of how to predict the relative motion of two massive objects interacting through gravity. More specifically, the researchers considered what happens when two black holes fly past each other. Their goal was to predict the trajectory of the black holes during the interaction, as well as how much energy is radiated away as gravitational waves. In most cases, physicists tackle this problem using numerical simulations, in which an initial guess of the object's trajectories is refined over many steps. Although such simulations are powerful, they are computationally expensive and slow.

An alternative approach is to find an approximate solution to Einstein's equations using a method called perturbation. In this approach, the quantity of interest is expressed as a power series — a mathematical formula consisting of an infinite series of terms, in which successive terms involve a relevant physical parameter raised to an increasingly higher power. This parameter must be sufficiently small for the terms in the series to become progressively smaller, enabling the calculation to be stopped when the desired precision is reached. In Driesse and colleagues' work, the quantity of interest is the change in momentum of one of the two interacting black holes, which can be expressed in powers of Newton's gravitational constant, G.

To formulate this power series, Driesse and colleagues use techniques originally developed in the field of particle physics. The mathematical framework that describes the interaction between fundamental particles is called quantum field theory (QFT). Driesse and colleagues use a formalism of QFT that integrates over all possible paths that the system can take through space-time. Classical predictions can be extracted from this quantum-mechanical description by discarding the quantum contributions to the gravitational field between the black holes. This enables theoretical physicists to use the well-developed and systematic tools of particle physics to describe the interactions between astronomical objects, and makes calculations much simpler than in full quantum theory.

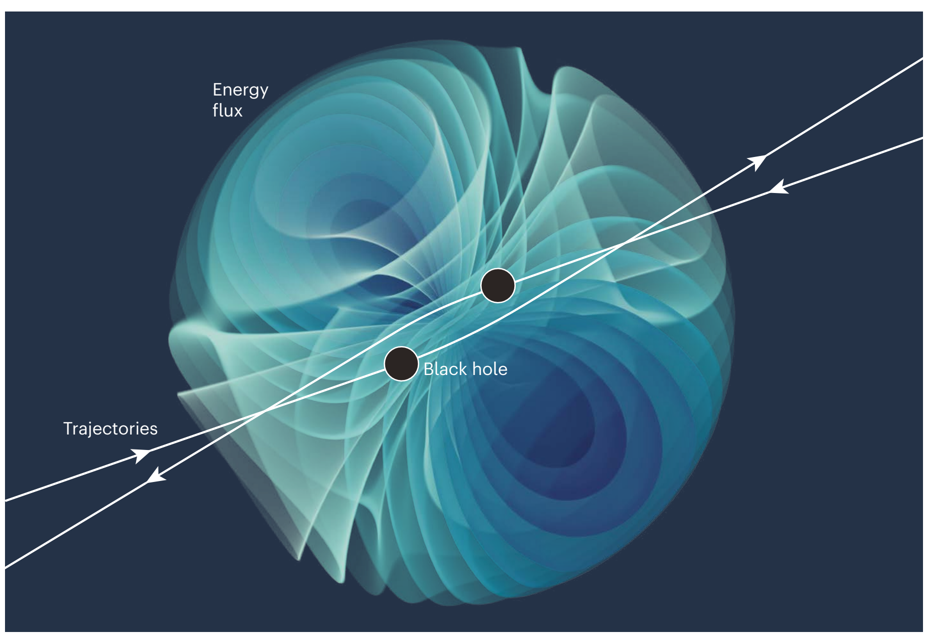

Figure 1 | Gravitational-wave energy radiated during black-hole fly-by. When two black holes pass close to each other, they interact through the gravitational force. Driesse and colleagues[3] formulate an approximation of the gravitational-wave equation for interacting black holes. As the black holes fly past each other, their trajectories deflect because of the gravitational interaction. Contours indicate the rate at which energy is radiated away as gravitational waves (energy flux). Darker colours indicate higher energy flux. Previous work has modelled interacting black holes by solving an approximation of the gravitational-wave equations, but Driesse and colleagues' result surpasses previous predictions in its precision.

Perturbation is used to estimate physical quantities in QFT, and the same mathematical approach can be adapted to describe the classical gravitational interaction of massive objects such as black holes[4,5]. The systematic method used for the perturbation approximation of QFT was developed by the physicist Richard Feynman[6]. Contributions to each term in the perturbation expansion can be represented by diagrams known as Feynman diagrams, in which propagating particles are denoted by lines that interact at connecting nodes. Feynman diagrams with closed loops, which are needed to calculate corrections to the perturbation series, can be represented by mathematical objects called Feynman loop integrals. The solution to Einstein's gravitational equations can therefore be estimated by evaluating the loop integrals associated with many Feynman diagrams.

Driesse and colleagues calculated an exact solution by evaluating hundreds of Feynman diagrams. This is known as an analytical approach. In previous works, the perturbation series for the two-body problem has been computed up to the fourth term[7–11], and some fifth-term contributions have been calculated for the case in which no energy is dissipated during the interaction[12]. Driesse and colleagues have extended the analytical calculation of two-body gravitational interaction observables at the fifth term. They calculate how each black hole's momentum changes, the angle by which each is deflected, and the amount of energy that is radiated away as gravitational waves (Fig. 1). Their results represent the highest precision in analytical relativity so far.

Feynman integrals can be associated with geometric objects, and Driesse and colleagues' work uncovers links between general relativity and geometry. Many Feynman-loop integrals are functions called generalizations of logarithms, which can be defined on surfaces known as Riemann spheres. For these cases, well-developed analytical techniques from particle physics can be applied to calculate the integrals. Driesse and colleagues' approximation to the Einstein equations includes Feynman-loop integrals that are related to more complex geometric objects called Calabi–Yau manifolds. These are a class of geometric objects that extend the doughnut-shaped torus into higher, even-numbered dimensions. The discovery of these functions in Driesse and colleagues' analysis echoes Galileo's insight, expressed in his book *The Assayer* (1623), that the Universe "is written in the language of mathematics".

Driesse and colleagues' work is a breakthrough in analytical relativity. Their high-precision results will drive the development of even more accurate models of gravitational waves. These will be crucial to interpreting observations from future gravitational-wave experiments, such as the Einstein Telescope in Europe and the space-based Laser Interferometer Space Antenna (LISA). However, the authors' model does not calculate all the fifth-order terms, and computing these extra contributions to the perturbation series remains a challenge. Extending their work to fully characterize gravitational two-body dynamics at the fifth order is essential, both to advance our understanding of gravitational dynamics and to detect other types of cosmic events that produce gravitational waves.

Zhengwen Liu is at the Shing-Tung Yau Center and School of Physics, Southeast University, Nanjing, 210096, China.
e-mail: zhengwen.liu@seu.edu.cn

1. Abbott, B. P. *et al. Phys. Rev. Lett.* **116**, 061102 (2016).
2. Einstein, A. *Sitzungsber. K. Preuss. Akad. Wiss.* **1**, 688–696 (1916); available at https://go.nature.com/44djq7e.
3. Driesse, M. *et al. Nature* **641**, 603–607 (2025).
4. Goldberger, W. D. & Rothstein, I. Z. *Phys. Rev. D.* **73**, 104029 (2006).
5. Damour, T. *Phys. Rev. D* **97**, 044038 (2018).
6. Feynman, R. P. *Phys. Rev.* **76**, 769–789 (1949).
7. Dlapa, C., Kälin, G., Liu, Z. & Porto, R. A. *Phys. Rev. Lett.* **128**, 161104 (2022).
8. Bern, Z. *et al. Phys. Rev. Lett.* **128,** 161103 (2022).
9. Dlapa, C., Kälin, G., Liu, Z., Neef, J. & Porto, R. A. *Phys. Rev. Lett.* **130**, 101401 (2023).
10. Damgaard, P. H., Hansen, E. R., Planté, L. & Vanhove, P. *J. High Energy Phys.* **2023**, 183 (2023).
11. Jakobsen, G. U., Mogull, G., Plefka, J. & Sauer, B. *Phys. Rev. Lett.* **131**, 241402 (2023).
12. Driesse, M. *et al. Phys. Rev. Lett.* **132**, 241402 (2024).

The author declares no competing interests.

Medical research

Highly sensitive method finds rare RNAs in blood

Trine B. Rounge & Jonas Paulsen

A method for examining RNAs in blood samples offers a clinical tool to detect and monitor cancer and to assess immune responses to vaccination. **See p.759**

DNA and RNA are normally inside intact cells, but in the case of some diseases, such as cancer, cells release small amounts of these molecules, which circulate in the bloodstream. Detecting these 'cell-free' nucleic acids using a blood test called a liquid biopsy is a powerful non-invasive tool for diagnosis and for monitoring disease status. Identifying cell-free DNA and RNA from diseased cells is challenging because these molecules are rare among the many others found in blood. Therefore, detection methods must be extremely sensitive to specifically identify disease-associated molecules. Established methods can detect such DNAs of interest in blood samples[1], and the spotlight is now turning to RNA. On page 759, Nesselbush *et al.*[2] present a highly sensitive method, called RARE-seq, that detects clinically relevant rare RNAs, using refined laboratory approaches and bioinformatics.

The discovery[3] of nucleic acids circulating in blood was made in 1948. Cell death, inflammation, communication between cells or the development of cancer can cause cells to release their contents, enabling trace amounts of DNA and RNA to enter the bloodstream. By the 1970s, it was known[4] that cell-free circulating tumour DNA (ctDNA) in the blood of people with cancer can be used to monitor disease and treatment outcomes. In 2016, the US Food and Drug Administration (FDA) approved the use of ctDNA to diagnose lung cancer[5].

A landmark study[6] in 2021 offered an early comprehensive examination of the use of cell-free RNA to detect cancer. This revealed that identifying RNAs from highly expressed tumour genes improves cancer-detection sensitivity, particularly when cancer detection by ctDNA is difficult. Nesselbush and colleagues now refine key steps of that pipeline for cancer detection by RNA. The authors' technique provides a substantial boost to detection sensitivity, showing a more than 50-fold increase in sensitivity compared with the previous conventional method for the analysis of RNA in blood.

Detecting rare, disease-derived cell-free RNAs in blood is a challenge similar to trying to hear whispers in a noisy, crowded room — a signal easily drowned out by the many other RNAs found in blood. To meet this challenge, the authors present a finely tuned method that improves every step of the conventional process, to enhance detection of these elusive RNAs (Fig. 1). Nesselbush and colleagues optimized blood collection, RNA extraction, the speed used to process blood in a centrifuge device, the sequencing method and the bioinformatic analyses.

The authors' research showcases the power of jointly improving advanced laboratory and bioinformatics protocols to accelerate