Open Issues in Gravitation

Thibault Damour

2021 Balzan Prize for Gravitation: Physical and Astrophysical Aspects

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Project Director: Thibault Damour
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Affiliated Institutions: Institut des Hautes Etudes Scientifiques (IHES), with the involvement of the Istituto Nazionale di Fisica Nucleare, Sezione di Torino, and of the Albert Einstein Institute (Max Planck Institute, Potsdam)
Period: 2022-

Thibault Damour is currently emeritus professor at the Institut des Hautes Etudes Scientifiques (Bures sur Yvette, F-91440, France).

Scientific Background of the Project
Although gravity is the oldest interaction investigated both observationally and theoretically, it remains a mystery in many aspects. This research project aims to involve a group of international young scientists, together with a group of high-level senior scientists, in frontier research in some of the key theoretical challenges currently left open in the field of gravitation.

Research Project: Activity Report June 2022 – May 2025
In accordance with the aims of the project proposal, funds were mainly used in two ways to help a group of international young scientists to make the best possible use of the research framework offered by the Institut des Hautes Études Scientifiques (IHES). First, during visits of varying lengths, IHES created two types of Balzan Visiting Scholar positions, junior and senior visitors. Second, videotaped Balzan lectures were organized by Balzan senior visitors.

In particular, the Turin INFN group led by Damour's former postdoc Alessandro Nagar has been remarkably effective in organizing visits by a large pool of young researchers to IHES. The following young scientists (including quite a few young female scientists) have visited IHES at least once if not several times during the period June 2022-May 2025:

Albertini Angelica
Gamba Rossella
Jain Tamanna
Nikiforova Vasilisa
Placidi Andrea
Rettegno Piero

Albanesi Simone
Carullo Gregorio
Chiaramello Danilo
De Amicis Marina
He Vincent
Berean-Dutcher Jonah
Gervalle Romain
Kim Joonhwi
Martinez Jean-Philippe

Many of these young scholars took advantage of their stay at IHES to deepen their knowledge by having discussions with senior scholars, by following Balzan lectures (see below), and by doing research either among themselves, or with senior scientists. Most of the young Balzan visitors are Alessandro Nagar's students. Their stays at IHES often allowed them to have quiet interaction time to finish (or start) scientific research projects related to open issues in gravitation. In several cases, Damour also collaborated with them, which led to several common publications (see below).

In addition to the young Balzan visitors listed above, the senior Balzan visitors included the following senior scientists and scholars:

Nagar Alessandro
Bini Donato
Bernuzzi Sebastiano
Henneaux Marc
Ceresole Anna
Mason Lionel
Russo Rodolfo
Kramer Michael
Freyn Walter
Succi Sauro
Feingold Alex
Fischbacher Thomas
Kramer Michael
Polyakov Alexander
Klemm Albrecht
Pound Adam

Damour had many discussions with all these senior Balzan visitors and collaborated with several of them (notably A. Nagar, D. Bini, and A. Ceresole), and this led to several common publications. In addition, Damour asked several senior Balzan visitors to give videotaped Balzan lectures during their visits at IHES. As indicated in the original research proposal, the idea of organizing such Balzan lectures on topics concerning *Open Issues in Gravitation* was to give large visibility to the support of the Balzan Foundation as such videotaped Balzan lectures would procure more visibility than a more traditional Balzan-supported conference. As of May 2025, the series of Balzan lectures related to this research project have been viewed nearly 50,000 times. A list of these Balzan lectures can be found in a separate section below.

Although *Open Issues in Gravitation* was originally intended to last three years, the basic concept chosen for the project (i.e., not to offer one postdoctoral position with a 3-year contract to a young scientist, but instead "to involve a group of international young scientists in high-level research" by inviting them as visitors to IHES) has resulted in a residual budget which will make it possible for the project to continue after 2025.

Scientific publications conceived or completed at IHES thanks to support from Damour's Balzan Research Project *Open Issues in Gravitation*

To date, at least thirty-one scientific publications written by young or senior Balzan visitors on frontier problems in gravitation have been produced thanks to the support of Damour's Balzan Prize; these publications have received a total of 537 citations. They cover a broad range of open issues in gravitation, such as gravitational waves, gravitational-wave tails, effective-one-body models, gravitational scattering, numerical relativity, the dynamics of binary systems, twistor constructions, post-Minkowskian gravity, and modified gravity theories. All publications contain the following acknowledgement: "The present research was partially supported by the 2021 Balzan Prize for Gravitation: Physical and Astrophysical Aspects, awarded to T. Damour."

D. Bini, T. Damour and A. Geralico, "Radiated momentum and radiation re- action in gravitational two-body scattering including time-asymmetric effects," Phys. Rev. D 107, no.2, 024012 (2023) [arXiv:2210.07165 [gr-qc]].

T. Damour and P. Rettegno, "Strong-field scattering of two black holes: Numerical relativity meets post-Minkowskian gravity," Phys. Rev. D 107, no.6, 064051 (2023) [arXiv:2211.01399 [gr-qc]].

D. Bini and T. Damour, "Radiation-reaction and angular momentum loss at the second post-Minkowskian order," Phys. Rev. D 106, no.12, 124049 (2022) [arXiv:2211.06340 [gr-qc]].

T. Jain, P. Rettegno, M. Agathos, A. Nagar and L. Turco, "Effective-one-body Hamiltonian in scalar-tensor gravity at third post-Newtonian order," Phys. Rev. D 107, no.8, 084017 (2023) [arXiv:2211.15580 [gr-qc]].

L. Mason, "Gravity from holomorphic discs and celestial $Lw_{1+\infty}$ symmetries," Lett. Math. Phys. 113, no.6, 111 (2023) [arXiv:2212.10895 [hep-th]].

T. Jain, "Gravitational scattering up to third post-Newtonian approximation for conservative dynamics: Scalar-tensor theories," Phys. Rev. D 108, no.10, 104071 (2023) [arXiv:2304.09052 [gr-qc]].

A. Nagar, P. Rettegno, R. Gamba, S. Albanesi, A. Albertini and S. Bernuzzi, "Analytic systematics in next generation of effective-one-body gravitational waveform models for future observations," Phys. Rev. D 108, no.12, 12 (2023) [arXiv:2304.09662 [gr-qc]].

S. Albanesi, S. Bernuzzi, T. Damour, A. Nagar and A. Placidi, "Faithful effective-one-body waveform of small-mass-ratio coalescing black hole binaries: The eccentric, nonspinning case," Phys. Rev. D 108, no.8, 084037 (2023) [arXiv:2305.19336 [gr-qc]].

P. Rettegno, G. Pratten, L. M. Thomas, P. Schmidt and T. Damour, "Strong-field scattering of two spinning black holes: Numerical relativity versus post-Minkowskian gravity," Phys. Rev. D 108, no.12, 124016 (2023) [arXiv:2307.06999 [gr-qc]].

D. Bini, A. Geralico and P. Rettegno, "Spin-orbit contribution to radiative losses for spinning binaries with aligned spins," Phys. Rev. D 108, no.6, 064049 (2023) [arXiv:2307.12670 [gr-qc]].

R. Gamba, M. Breschi, S. Bernuzzi, A. Nagar, W. Cook, G. Doulis, F. Fabbri, N. Ortiz, A. Poudel and A. Rashti, *et al*. "Analytically improved and numerical-relativity informed effective-one-body model for coalescing binary neutron stars," [arXiv:2307.15125 [gr-qc]].

D. Bini, T. Damour and A. Geralico, "Comparing one-loop gravitational bremsstrahlung amplitudes to the multipolar-post-Minkowskian waveform," Phys. Rev. D 108, no.12, 124052 (2023) [arXiv:2309.14925 [gr-qc]].

A. Albertini, R. Gamba, A. Nagar and S. Bernuzzi, "Effective-one-body waveforms for extreme-mass-ratio binaries: Consistency with second-order gravitational self-force quasicircular results and extension to nonprecessing spins and eccentricity," Phys. Rev. D 109, no.4, 4 (2024) [arXiv:2310.13578 [gr-qc]].

A. Ceresole, T. Damour, A. Nagar and P. Rettegno, "Double copy, Kerr–Schild gauges and the effective-one-body formalism," Class. Quant. Grav. 42, no.2, 025004 (2025) [arXiv:2312.01478 [gr-qc]].

A. Placidi, P. Rettegno and A. Nagar, "Gravitational spin-orbit coupling through the third-subleading post-Newtonian order: Exploring spin-gauge flexibility," Phys. Rev. D 109, no.8, 084065 (2024) [arXiv:2401.12290 [gr-qc]].

D. Bini, T. Damour, S. De Angelis, A. Geralico, A. Herderschee, R. Roiban and F. Teng, "Gravitational waveforms: A tale of two formalisms," Phys. Rev. D 109, no.12, 125008 (2024) [arXiv:2402.06604 [hep-th]].

A. Nagar, R. Gamba, P. Rettegno, V. Fantini and S. Bernuzzi, "Effective-one-body waveform model for noncircularized, planar, coalescing black hole binaries: The importance of radiation reaction," Phys. Rev. D 110, no.8, 084001 (2024) [arXiv:2404.05288 [gr-qc]].

S. Albanesi, A. Rashti, F. Zappa, R. Gamba, W. Cook, B. Daszuta, S. Bernuzzi, A. Nagar and D. Radice, "Scattering and dynamical capture of two black holes: Synergies between numerical and analytical methods," Phys. Rev. D 111, no.2, 2 (2025) [arXiv:2405.20398 [gr-qc]].

A. Albertini, A. Nagar, J. Mathews and G. Lukes-Gerakopoulos, "Comparing second-order gravitational self-force and effective-one-body waveforms from inspiralling, quasicircular black hole binaries with a nonspinning primary and a spinning secondary," Phys. Rev. D 110, no.4, 044034 (2024) [arXiv:2406.04108 [gr-qc]].

D. Bini and T. Damour, "Fourth post-Minkowskian local-in-time conservative dynamics of binary systems," Phys. Rev. D 110, no.6, 064005 (2024) [arXiv:2406.04878 [gr-qc]].

M. De Amicis, S. Albanesi and G. Carullo, "Inspiral-inherited ringdown tails," Phys. Rev. D 110, no.10, 104005 (2024) [arXiv:2406.17018 [gr-qc]].

G. Carullo, "Ringdown amplitudes of nonspinning eccentric binaries," JCAP 10, 061 (2024) [arXiv:2406.19442 [gr-qc]].

D. Bini, T. Damour and A. Geralico, "Gravitational bremsstrahlung wave-form at the fourth post-Minkowskian order and the second post-Newtonian level," Phys. Rev. D 110, no.6, 064035 (2024) [arXiv:2407.02076 [gr-qc]].

A. Nagar, D. Chiaramello, R. Gamba, S. Albanesi, S. Bernuzzi, V. Fantini, M. Panzeri and P. Rettegno, "Effective-one-body waveform model for noncircularized, planar, coalescing black hole binaries. II. High accuracy by improving logarithmic terms in resummations," Phys. Rev. D 111, no.6, 064050 (2025) [arXiv:2407.04762 [gr-qc]].

T. Jain and P. Rettegno, "Angular Momentum Flux in Scalar-Tensor Theories up to 1.5 post-Newtonian Order," [arXiv:2407.10908 [gr-qc]].

P. G. Tello and S. Succi, "Cosmological implications of the minimum viscosity principle," Int. J. Mod. Phys. C 36, no.07, 2450250 (2025) [arXiv:2407.18960 [hep-th]].

D. Bini, T. Damour and A. Geralico, "Explicit solution of the gravitational two-body problem at the second post-Minkowskian order," Phys. Rev. D 110, no.10, 104051 (2024) [arXiv:2408.17193 [gr-qc]].

D. Bini and T. Damour, "Conservative binary dynamics beyond order $a5$ in electrodynamics," Phys. Rev. D 111, no.2, 024023 (2025) [arXiv:2410.05257 [gr-qc]].

T. Damour and T. Jain, "Nonlinear massive gravity theory of geometric origin," Phys. Rev. D 111, no.8, 084001 (2025) [arXiv:2501.13077 [gr-qc]].

T. Damour, A. Nagar, A. Placidi and P. Rettegno, "A novel Lagrange-multiplier approach to the effective-one-body dynamics of binary systems in post-Minkowskian gravity," [arXiv:2503.05487 [gr-qc]].

D. Bini and T. Damour, "High Precision Black Hole Scattering: Tutti Frutti vs Worldline Effective Field Theory," [arXiv:2504.20204 [hep-th]].

Videotaped Balzan lectures given at IHES by senior Balzan visitors

The following videotaped Balzan lectures were all given at IHES in the presence of an audience notably containing young Balzan visitors. The series of Balzan lectures related to Damour's research project have been viewed nearly 50,000 times. They are easily available on the IHES YouTube channel, and on carmin.tv (or directly on YouTube). These lectures covered many frontier topics in gravitational physics, ranging from theory to experiment, and passing through numerical relativity, as can be seen from the titles listed below.

01 March 2023: Lionel Mason, "From Twistors to Gravitational Scattering 1/2" (2,200 views)
08 March 2023: Lionel Mason, "From Twistors to Gravitational Scattering 2/2" (820 views)
13 April 2023: Rodolfo Russo, "Gravitational Scattering at High Energies" (1,000 views)
7 February 2024: Marc Henneaux, "Asymptotic Structure of Gravity and BMS Group at Spatial Infinity 1/2" (606 views)
7 February 2024: Marc Henneaux "Asymptotic Structure of Gravity and BMS Group at Spatial Infinity 2/2" (386 views)
20 February 2024: Thibault Damour, "Einstein's Path to General Relativity" (39,000 views)
22 February 2024: Sebastiano Bernuzzi, "Introduction to Numerical Relativity (1/2)" (3,400 views)
22 February 2024: Sebastiano Bernuzzi, "Introduction to Numerical Relativity (2/2)" (787 views)
02 September 2024: Thibault Damour, "Binary Pulsars and Theoretical Gravity" (941 views)
02 September 2024: Michael Kramer, "Binary Pulsar Observations and their Importance for Fundamental Physics and Astrophysics" (627 views)

Connection between the Balzan Research Projects of Thibault Damour at IHES and Alessandra Buonanno at AEI

Damour's original Balzan research project mentioned that he had contacted the two most internationally active groups in developing improved versions of effective one-body templates for the search and data-analysis of GW signals. In addition to the group of his former post-doc Alessandro Nagar (INFN, Torino), he had cited his fellow Balzan Prizewinner – and another former post-doc – Alessandra Buonanno (Albert Einstein Institute, Potsdam). As seen above, Nagar sent many young researchers of his group, which led to many interactions and new collaborations. Although to date no scientific visits from Buonanno's group to IHES have occurred, there has been a connection between the two Balzan projects, namely, through Jean-Philippe Martinez, historian and philosopher of physics, who is working on the history of the two-body problem in general relativity and is supported by Buonanno's Balzan Prize project at AEI. His visit to IHES earlier in 2025 (with financial support from Damour's Balzan research project) resulted in many extended discussions and interviews.

Conclusions

The main concept of Damour's research project is to foster discussions, brainstorming, and the exchange of ideas on *Open Issues in Gravitation* – in the IHES environment – between young people working in gravitation and himself, together (part of the time) with senior scientists. It was planned not to orient these interactions a priori towards specific research projects, but to let the discussions and brainstorming develop freely. This concept has been extraordinarily successful as many young scientists have come to IHES as Balzan visitors. They have learned new things and have completed high-level research projects during (or after) their visits. Damour's own research has also greatly benefited from these interactions and collaborations with young Balzan visitors (most notably Piero Rettegno, Simone Albanesi, Andrea Placidi, and Tamanna Jain). The lists of scientific publications and videotaped Balzan lectures listed above explicitly acknowledge the support of his Balzan prize, and as the 537 citations and nearly 50,000 views clearly show, they bear witness to the success of the project and will continue to attract interested parties in the future.