Annual Report 2022
Illuminating the dark universe with gravitational waves

Details

Villum Programme: Villum Investigator Programme
VILLUM project number: 37766
Project title: Illuminating the dark universe with gravitational waves
Name of PI: Vitor Cardoso

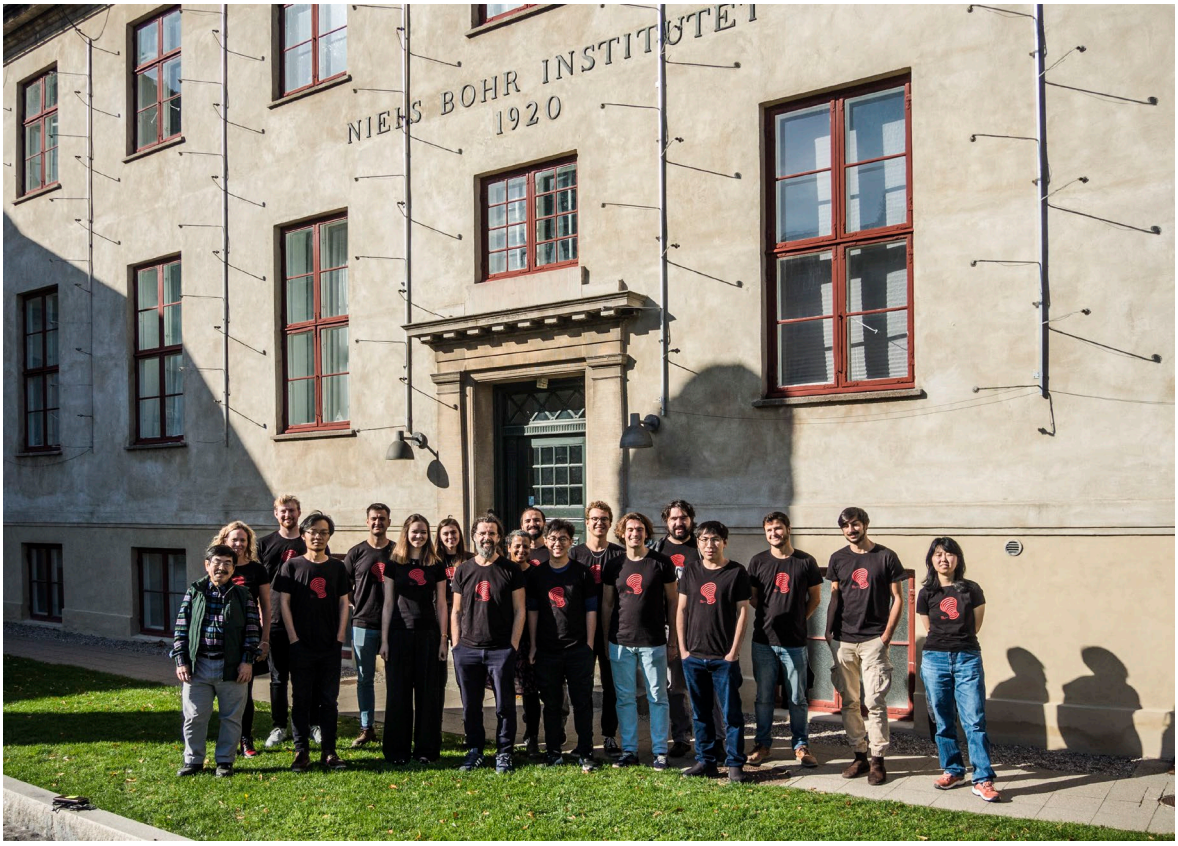
PROJECT - Illuminating the dark universe with gravitational waves 2022

Abstract. Gravitational-wave astronomy opened a new window to a previously invisible universe. Driven by this momentous event, gravitational physics is experiencing a revolution, and is an exciting line of research with an immense discovery potential. The project proposes to provide new and clear tests of gravity in the strong field regime, of black hole physics and on the existence of new fundamental fields in our universe, and help to constrain dark matter structures with gravitational-wave astronomy. We will lay down a precise roadmap for black hole spectroscopy, including a characterization of nonlinear ringdown. We will quantify the evidence for horizons in the cosmos, using electromagnetic and gravitational-wave observations. The project will establish a team, leading efforts to understand lensed gravitational-wave events and its cosmological implications. This coordinated program will study and test the strong-field regime of gravity and the matter content of our universe. The proposed program will significantly advance our knowledge of Einstein's field equations and their role in foundational questions, including the fate and resolution of spacetime singularities. The coming years will be crucial to determine new directions. The proposed research will secure Danish leadership in the knowledge of gravity as a fundamental interaction.

Project status. 2022 was the first year of the project, and it has been an exciting beginning of activities for the Villum-funded Strong group led by Prof. Vitor Cardoso, the only team in Denmark focusing on Einstein's theory, black holes and gravitational waves. The Strong group studies fundamental questions, which relate to gravity in mostly unexplored regimes: is gravity described by Einstein's theory? Do black holes exist? What happened at the beginning of the Universe? Can we use black holes as probes of other interactions? To realize the tremendous underlying discovery potential, we combine unique know-how in theory together with observations.

Recruitment and setting the team. During the course of 2022, we established an outstanding group of people, the Strong group. Apart from the PI, one PhD student and the Coordinator, most of the group was recruited and onboarded from September and onwards, and the team currently consists of two Assistant Professors (*Maarten van de Meent* and *Jose Maria Ezquiaga*), four Postdocs (*Gregorio Carullo*, *Yifan Chen*, *Shilpa Kastha*, *David Perenniguez*), six PhD students (*Marina de Amicis, Conor Dyson, Evelyn-Andreea Ester, Thomas Spieksma, Jaime Redondo Yuste and Chun Lung Chan),* a Research Coordinator (*Julie de Molade*) and a web/IT consultant (*João Vasconcelos*). The scientific staff was selected among hundreds of candidates, which signals a strong wish in the research community to work at the Niels Bohr Institute and with the PI, and underlines the quality of the team we have in place now. Consequently, there is also a high degree of internationalization in the Strong team, which includes members from over 12 countries worldwide. Two postdocs and two PhD students are funded by the DNRF Chair grant, and one long-term visitor, who joined in December, is

funded by a Chinese fellowship, but the bulk of the group's activities are funded by Villum. There is also a great interest from visitors to join the group for shorter or longer periods of time, resulting already in six visitors in the last 5 months of 2022 as well as one speaker as part of the five Gravity Seminars initiated and hosted in the Fall.



The Strong team in front of the Niels Bohr Institute, October 2022

A vibrant research environment. The Strong Group meets weekly to discuss new publications and ideas and to listen to specialized talks by group members or visitors. In the Fall of 2022, we hosted the event: *Inauguration of the Villum Investigator project: Illuminating the Dark Universe with Gravitational Waves*, in which the foundation also participated. This was a great way to kick-start the group, as most of the team were in Copenhagen by the end of September. We also started the Gravity Seminar series this Fall, which is co-organized with 3 other members of the Niels Bohr International Academy. The Gravity Seminar series brings in reputed speakers from outside the institute, and we expect to have 4-6 speakers funded by the Villum grant each year as part of the series. To build cohesion and well-being within the group, we also organize regular social events, which have been a success and where visitors also join. These include introductions to NBI by the NBI Archive, sights in Copenhagen and experiencing Danish traditions like 'hygge'.

Even though the group is only 5 months old, it has gained a reputation already, which explains how we attracted 3 MSc students and a one-year, self-funded scholar from China, as well as several short- - and long-term visitors from abroad (Italy, Portugal, Japan, Brazil, Germany). We have an informal partnership with Instituto Superior Técnico, University of Lisbon, where the PI also holds an ERC grant. This grant will be used to bring many of the ERC members over to NBI to foster an even more dynamic research environment. We have also established a partnership with Cambridge, which will materialize itself in 2023 through the 'Kavli-Villum School for PhD students', which is scheduled to

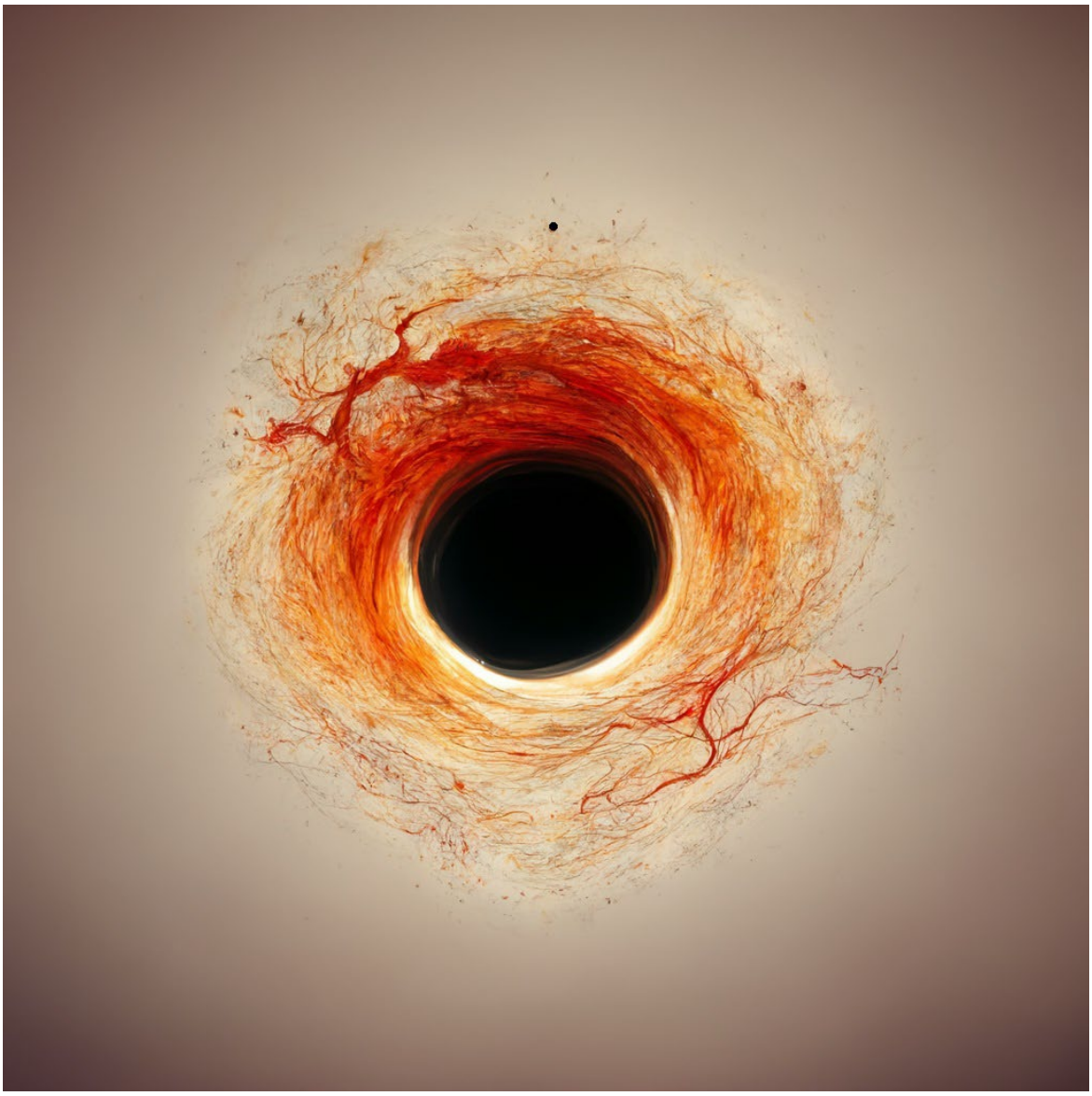
take place in Greece.

Important research results. The team has bid for membership of LISA (the largest European Space Agency mission, composed of thousands of members, and of which Prof. Cardoso is a Board member). This will enable the team to lead NBI efforts in this direction, and we are happy to announce that the group was formally accepted on January 9, 2023.

We published over 30 papers in leading international journals, including a number of articles in high-profile journals, such as *Nature Astronomy*, *Physical Review Letters* and *Physical Review D Letters*. Two of the Strong publications were selected by the Editors of *Physical Review Letters* as scientific interdisciplinary achievements.

Highlights include a *Nature Astronomy* work on the capabilities of the Event Horizon Telescope to also do particle physics, a *Nature Physics* article on the possible origin of the progenitors of one of the latest gravitational-wave events, or a *Physical Review Letters* (Editor's Suggestion) article on the lensing of gravitational waves. We highlight also a *Physical Review Letters* work on gravitational-wave science: next generation of gravitational-wave detectors will observe signals from small compact objects orbiting supermassive black holes inside galactic cores. Modeling such extreme-mass ratio systems is a daunting task on its own, made even more challenging by the recent black hole images of M87 and Sagittarius A* which indicate highly complex descriptions of galactic centers. Accretion disks, dark matter halos, and tertiary companions are all expected to affect the binary evolution. But to understand the importance of astrophysical environments, or whether they can undermine tests of General Relativity, one needs accurate gravitational-waveform models for the radiation emitted by these binaries. In a *Physical Review Letters* article, Prof. Cardoso and collaborators employed relativistic perturbation techniques to study black holes surrounded by generic matter distributions. The outcome of this study is the first fully relativistic formalism handling gravitational-wave emission in spherically symmetric, but otherwise generic, spacetimes, without weak-field and slow-motion approximations.

Work in Strong was recognized with a number of awards and honors. Prof. Cardoso was elected to the Lisbon Academy of Sciences (an honor conferred upon one member of the scientific community per year, on average), and was awarded an ERC Advanced Grant. Assistant Prof. Jose Ezquiaga was awarded an INTERACTIONS fellowship as well as a Young Villum Investigator Grant and he was elected co-chair of the new LIGO-Virgo-KAGRA lensing group. Postdoc Gregorio Carullo was equally awarded an INTERACTIONS fellowship and was shortlisted for several permanent positions, despite just finishing his PhD. Prof. Cardoso was invited to lead the fundamental science working group of ngEHT (the follow-up to the instrument which took the first-ever image of a black hole) and to lead the fundamental science studies for an international team studying future gravitational-wave detectors. Research from the Strong Group is already receiving international attention: highlights include a number of invitations to deliver colloquia, plenary talks and seminars worldwide (in the past few months, in Germany, Italy, Korea, Spain, The Netherlands, Portugal, UK, US, etc.). Prof. Cardoso was interviewed several times (including by the Science Magazine, broad-audience journals, radio and television shows in Portugal) to comment on the latest scientific results in the field. Prof. Cardoso hosted a popular science podcast ((IN)PERTINENT, 12 episodes) which was co-hosted by Portugal's the most popular comedian in the country (Joana Marques).



Artistic view of an extreme mass ratio-system (a large black hole and small, orbiting star or black hole) in the presence of an environment. Image by Kyriakos Destounis.

Challenges. We were faced with some initial challenges in the hiring of our PhD students, especially due to Danish legislation and foreign Master's degrees. This took a considerable amount of time and effort, and we were forced to employ one of the candidates, who came with a Msc from Cambridge, on a 4+4 year scheme. At the scientific level, all the activity is going according to plan. The team is superb. As a consequence, we have had too many requests for short- and long-term, some self-funded, visitors. Requests from prospective PhD students and Postdocs are surpassing the team's capability, as well as collaboration requests. Due to an internal restructuration at NBI and since the team is growing fast with so many requests for visitors, office space in the institute has recently become an issue, and funding to keep growing and maintaining stability on a longer term is an important issue, which we will follow closely in the coming period.

Planned project activities for 2023. For the coming year, we have a number of planned initiatives

already in place. These include the hiring of two Postdocs (*Rodrigo Panosso Macedo* and *Takuya Katagiri*, already interviewed and selected), and the hosting of several long-term visitors, consequence of a very competitive call for scientific proposals (made by a consortium of institutes – NBI, Cambridge, Nottingham, Rome, SISSA – led by our team).

We will organize three international meetings during the summer of 2023 (Infinity on a Gridshell, the 26th Capra meeting and a LISA meeting). We are now also finalizing the details of the Kavli-Villum Summer School for PhD students, organized jointly with Cambridge University and scheduled for September. We are teaming up with the Albert Einstein Institute also for a very special event to take place a couple of years from now.

We strongly believe that science is a quest to understand our universe, and that such a quest can only be made complete, if we understand all the different perspectives of such a search. Because of this, we are organizing a call for residencies by artists/writers/musicians to see the daily life of a scientists, to communicate with us and to express their experience through an artistic deliverable. This collaboration will broaden the horizons of the artistic community, as well as that of the Strong group.

We are currently working on three lines of research, which will continue through 2023-2025: we are re-designing black hole spectroscopy (a field that Prof. Cardoso pioneered in 2005) to include nonlinearities, mode couplings, etc. We are studying the feasibility to detect the bending of gravitational waves (so-called gravitational-wave lensing), and the fundamental science that can be extracted from such events. Finally, we are extending self-force calculations in black hole spacetimes to second order and comparing against Numerical Relativity efforts. Finally, as we are a large team, there are equally a number of smaller exploratory projects planned for the years' coming.