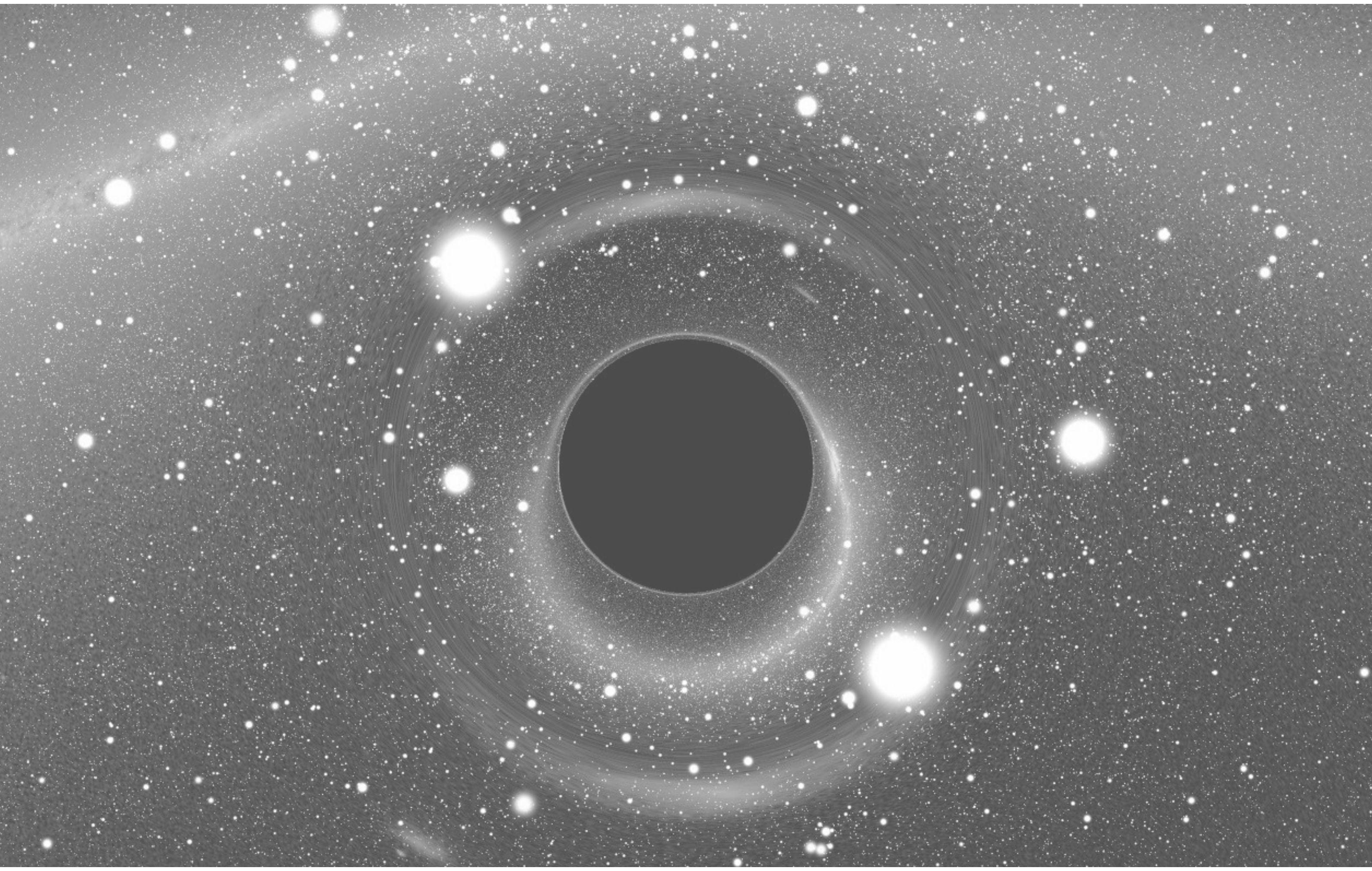
ACTIVITY REPORT 2017-2021



ASTROPARTICULE ET COSMOLOGIE

Gravitation

Resp: E. Chassande-Mottin (-2018) and S. Babak (2018-)

The Gravitation team was created in January 2016 to gather in a single team all researchers involved in gravitational wave science, formerly distributed in various groups. The team is composed of 6 permanent researchers (2 University/MCF, 3 CNRS and 1 emeritus), 5 PhD students and two postdoctoral fellows. Four other PhD students are co-advised in the context of a collaboration with colleagues from other groups at APC or with other institutes (in particular, IPGP).

The team core scientific interest is gravitational-wave astronomy. The team is involved in the development and exploitation of both ground-based observatories with advanced Virgo, and the space-based observatory LISA. All team members are involved in the international collaborations that develop and exploit those instruments.

The team develops a wide range of activities going from instrument science (R&D, instrument design and simulation, commissioning), data analysis (methods, software implementation) and astrophysics (source physics, models, multi-messenger astronomy in connection to high-energy or neutrino astronomy).

The team is also involved in activities connected to the above core priorities that are possible seeds for future main projects. The team participates to the development of future detector generation (Einstein Telescope), and contributes to the gravitational-wave science using other windows, specifically pulsar timing array with the EPTA and IPTA.

In parallel to the research on gravitational waves, the team pursues activities in connection to ("Newtonian") gravity measurements and their application to geosciences in collaboration with Institut de Physique du Globe de Paris (IPGP), with the support of the LabEx UnivEarthS.

Ground-based detectors

Advanced Virgo

Advanced Virgo[16] is a second generation gravitational-wave detector aiming at a ten-fold improvement in sensitivity over the first generation that was operated during the period 2007-2010. Advanced Virgo started operation on August 1st 2017 when it joined Advanced LIGO during the science run O2 thus forming a global, world-wide detector network. About two years after O2, this network resumed operation during the 1-year long science run O3 with an enhanced sensitivity (by about a factor of 2).

[16] Acernese, F. *et al.* (Virgo Collaboration). "Advanced Virgo: a second-generation interferometric gravitational wave detector". In: *Class. Quantum Grav.* 32.2 (2015), p. 024001.

During the two science runs, LIGO and Virgo have observed 50 GW signals in total gathered in the GWTC catalog(s).[17] The catalog is largely dominated by signals from binary black hole mergers with total mass ranging from 15 to 150 solar masses, thus evidencing the existence of a population of heavy stellar-mass black holes, that had eluded conventional astronomical observations. The GWTC catalog also comprises two signals associated with the merger of binary systems of neutron stars,

[17] R. Abbott et al. "GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run". In: *Phys. Rev. X* 11 (2021), p. 021053. arXiv: 2010.14527 [gr-qc].

including GW170817, and two other signals possibly associated to mixed systems formed by a neutron star and a black hole.

On August 17 2017, LIGO and Virgo detected GW170817[18] associated to the merger of two neutron stars, located in NGC4993, at a distance of 40 Mpc. This detection was accompanied, in the seconds, hours and months that followed, by the cascade observation of electromagnetic waves emitted by this same source in a wide range of wavelengths, from radio waves to gamma rays.[19] This makes it the first astrophysical phenomenon observed by both its gravitational and electromagnetic radiation. This event is rich in implications, first of all for the phenomenology of gamma-ray bursts, but also for cosmology and fundamental physics.

[18] B. P. Abbott et al. "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral". In: *Phys. Rev. Lett.* 119.16 (2017), p. 161101. arXiv: 1710.05832 [gr-qc].

[19] B. P. Abbott et al. "Multi-messenger Observations of a Binary Neutron Star Merger". In: *Astrophys. J. Lett.* 848.2 (2017), p. L12. arXiv: 1710.05833 [astro-ph.HE].

Currently, the detector undergoes the first phase of the so-called Advanced Virgo + upgrade which is expected to lead to a factor of 2 improvement in sensitivity during the up-coming science run O4 (2022-2023) jointly with Advanced LIGO. The second phase of the upgrade aims at another factor of 2 sensitivity enhancement leading to a binary neutron star range of 200-250 Mpc for the future science run O5 (2025). Looking further ahead, the observational strategy after O5 is being debated and defined in the framework of an on-going study of the possible scenarios of upgrades for the Virgo and LIGO detectors. This will constitute a major step towards the advent of the third generation detectors (Einstein Telescope and Cosmic Explorer).

The Virgo team includes 20 members (10 permanent staff, 10 doctoral and postdoctoral fellows). The team's activities range from the design and development of the Advanced Virgo detector to its scientific exploitation.

Data analysis and scientific exploitation The team is involved in the analysis of LIGO and Virgo data through many projects. Over the period from Jul 2017 to Oct 2021, the team made direct contributions to *23 articles* of the LIGO and Virgo Collaborations (4 as chair of the paper writing team, 13 as members of the paper writing team, 10 as members of the internal review committee). Those articles include major discovery papers and catalog papers such as,[20] interpretation papers (constraints on the astrophysical distribution of compact binaries, test of general relativity), various searches (signals from cosmic strings, persistent gravitation waves from isolated compact stars, stochastic backgrounds) and the main reference paper for the open data release.

[20] B. P. Abbott et al. "GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence". In: *Phys. Rev. Lett.* 119.14 (2017), p. 141101. arXiv: 1709.09660 [gr-qc]; Abbott et al., "GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral".

A member of the group had leading role in the data analysis organization, with the co-responsibility of compact binary search group (Edward Porter, 2016-2020).

The team develops a range of R&D data analysis projects that are inline with the core activities of the LIGO-Virgo Collaboration. Those include work and developments for: fast Bayesian methods for binary parameter estimation, advanced search methods for transient sources (ANR Wavegraph), contribution to waveform models (EOBNR), new tests of General Relativity (e.g., spacetime symmetry breaking), new ways to constrain the so-called "galactic field" binary formation scenario based on numerical simulations with the MESA software, algorithms for the reconstruction and characterization of the gravitational wave polarizations (ANR Ricochet) and machine-learning based methods for the detection of compact binaries from single-detector data and for the rapid computation of waveform approximants.

The group is particularly active in areas connected to cosmology and tests of general relativity. The group developments in this sector include alternative measurements of the Hubble constant or other cosmological parameters from gravitational wave observables, with or without electromagnetic counterparts. See, e.g., Fig. 14 from[21] which provides prospects for the latter possibility, often referred to as dark sirens.

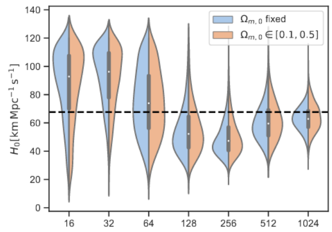


Figure 14: Posterior distributions on H_0 vs the number of detected gravitational wave events obtained by fixing Ω_m or not. The horizontal black dashed line indicates the true value.

[21] S. Mastrogiovanni et al. “Cosmology in the dark: On the importance of source population models for gravitational-wave cosmology”. In: *Phys. Rev. D* 104.6 (2021), p. 062009. arXiv: 2103.14663 [gr-qc].

Operations The team made significant contributions to the detector operations. Member of the group had leading role in the release of LIGO/Virgo data through the GWOSC [22] (Eric Chassande-Mottin, since 2017, and Agata Trovato, 2017-2021) – see Fig. 15 – and in the preparation of the alert production from the data (Sarah Antier, liaison for Virgo during the preparation of O3). Nine members of the group have performed shifts for detector characterization, electromagnetic follow-up, or parameter estimation during the science run O3.

[22] http://gw-openscience.org

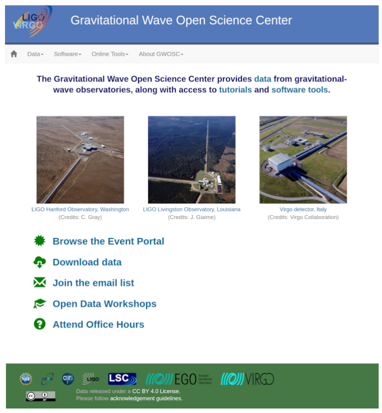


Figure 15: Home page of the Gravitational-Wave Open Science Center

R&D on quantum noise reduction through squeezing techniques The team is involved in two R&D techniques to improve the sensitivity of gravitational-wave detectors through squeeezing techniques.

R&D on frequency-dependent squeezing with filter cavity — One of the main upgrades of Advanced Virgo + is the integration of a 285m filter cavity for the realization of frequency dependent squeezing: a technology which allows to reduce quantum noise over the whole detector bandwidth. Since 2015, the team has participated to the construction of a full-scale filter cavity prototype at the National Astronomical Observatory of Japan (NAOJ). The team realized the analog electronics for several control loops of the experiment and contributed to the installation and commissioning of the experiment during multiple visiting periods in Japan. The demonstration of frequency dependent squeezing with this filter cavity has been achieved in 2020.[23] The experience acquired with this project will be crucial for the implementation of the AdVirgo + filter cavity, currently under commissioning.

[23] Yuhang Zhao et al. “Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors”. In: *Phys. Rev. Lett.* 124 (17 2020), p. 171101.

R&D on frequency-dependent squeezing generation with EPR entanglement An R&D is on-going about a new technique to achieve a broadband reduction of quantum noise by using a pair of Einstein-Podolsky-Rosen (EPR) entangled photons to produce frequency-dependent squeezed light.

The development at APC has concerned the design and test of a solid Fabry-Perot etalon, shown in Fig. 16 behaving as an optical resonator whose length is tuned via thermal expansion driven by a fine and stable temperature control (0.01°C). The purpose of this optical component is to separate the two entangled fields, by transmitting the "signal" field and reflecting the "idler" beam. The finesse was chosen in order to achieve the best beam separation and to get the simplest possible control of the cavity.

The system's optical properties and thermal stabilization was tested in an ad-hoc characterization setup. The system meets the requirements for the signal/idler transmission and reflection and for the short-term and long-term thermal stability.

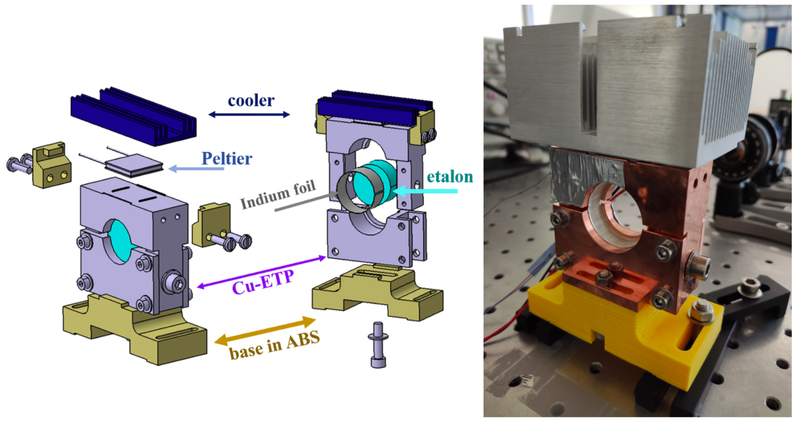


Figure 16: Solid Fabry-Perot etalon realized to separate the two entangled beams used in new technique to achieve a broadband reduction of quantum noise in GW detector by using a pair of Einstein-Podolsky-Rosen (EPR) entangled photons to produce frequency-dependent squeezed vacuum.

Contributions to Advanced Virgo+ (design, construction and commissioning)

Optimisation of the optical design of Advanced Virgo + The 2nd phase of the Advanced Virgo + focuses on the thermal noise reduction. This is achieved by enlarging by 60 % the laser beam dimension and the mirrors themselves at the extremities of the arm cavities. The team has estimated the optimal transmissivity of the main optics in this new configuration. This optimisation of sensitivity allows to an improvement of the range to binary neutron stars.[24]

[24] Jonathon Baird and Matteo Barsuglia. "Fine-Tuning the Optical Design of the Advanced Virgo+ Gravitational-Wave Detector Using Binary-Neutron Star Signals". In: *Galaxies* 8.4 (2020).

Mode-matching telescopes The team is responsible for the realization of the "mode-matching" telescopes for Advanced Virgo, which are used to magnify and adapt the main laser source to the interferometer and to collect the out-coming beam (which contains the GW information) as well as the beam transmitted by the arm cavities and a pick off of the power recycling cavity, used for the interferometer control. These five telescopes were designed, constructed, tested and integrated in the detector by the group. For the 1st phase of Advanced Virgo+ (2022), two baffles have been developed and integrated to the optical set-up of the telescope at the output port of the interferometer (detection bench), as shown in Fig. 17. The goal of these baffles is to mitigate stray light impinging on the optical components of this telescope, as it can degrade the interferometer sensitivity. The baffle design has been optimised to fulfill constraints on their mass and resonance frequency.

For the second phase of Advanced Virgo+ leading to the science run O5 (2025) the team is in charge of the re-design and realisation of the new mode-matching telescopes that are compliant with the larger beam size. The re-design activity mainly concerns the telescopes for the beams transmitted by the arm cavities end mirrors.

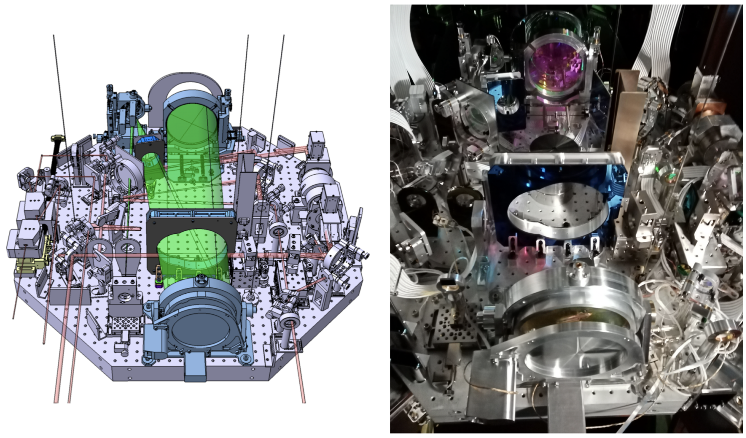


Figure 17: Global view of the optical bench at the detection port of Advanced Virgo (CAD design on the left and a picture on the right). The absorbing baffles designed by the team to mitigate stray light impinging on the optical components of the beam-reducing telescope are evidenced.

Wide-band photodiods for the new locking scheme The first phase of the AdVirgo + upgrades includes the installation of an additional mirror (known as signal recycling mirror) at the output port of the interferometer. This modification allows to shape the sensitivity of the detector and improve its astrophysical reach. This change requires a new scheme based on an auxiliary green laser for the control of the interferometer. The team is responsible of the development of fibered high-frequency photodiodes needed for this new scheme. These photodiodes and the associated electronics shown in Fig. 18 were succesfully produced within the specifications and were integrated in the detector, thus contributing to the global control of the interferometer.

Figure 18: Fibered high frequency photodiodes needed for the new Advanced Virgo control scheme, which uses auxiliary green laser beams

Frequency dependent squeezing The team contributes to the commissioning of the 285-meter filter cavity used to generate frequency-dependent squeezed light used to reduce quantum noise at all frequencies. Thanks to the experience acquired during the R&D project at NAOJ (see above) the team made important contributions to the commissioning of the cavity mirror suspensions, to the control and optical characterization of the cavity. The team will participate to the measurement of the frequency dependent squeezing.

Contribution to the "post-O5" study and Einstein Telescope technical design The O5 science run is expected to finish around 2027-2028. The strategy for the transition between the end of O5 and the advent of the third generation detectors (~ 2035-2040) is still to be defined. The team is involved in the definition of this strategy and the possible scenario of instrument upgrades through participation to the Virgo post-O5 committee. Moreover, the team is involved in the ET instrument science board (ISB), in charge of the ET technical design report, in particular in the squeezing working group.

Supporting grants

2015-2019	ANR Wavegraph - PI: E. Chassande-Mottin
2016-2021	H2020 Asterics
2016-2021	CEPIFRA project with IIT Mumbai Co-PI: Eric Chassande-Mottin
2017-2022	H2020 NEWS
2019-2024	H2020 AHEAD2020

Team

M. Arène, P. Auclair, S. Babak, P. Bacon, J. Baird, M. Barsuglia, W. Bertoli, E. Bréelle, C. Buy, E. Capocasa, F. Cortavarria, E. Chassande-Mottin, S. Chaty, F. Feng, L. Haegel, K. Leyde, S. Marsat, S. Mastrogiovanni, C. Nguyen, E. Porter, P. Prat, D. Steer, P. Stevens, A. Trovato, G. Vannoni. Are also part of the team: Cyril Cano (PhD, GipsaLab), Irina Dvorkin (MCF SU, IAP), Federico Garcia (postdoc, now at IAR, Argentina), Nicolas Lebihan (DR CNRS, GipsaLab), Benoît Revenu (CR CNRS, Subatech)

Permanent scientist | Fix-term scientist | Permanent technical staff | Fix-term technical staff | Associate

Scientific leader and/or Technical project manager

Einstein Telescope

The goal of Einstein Telescope is to gain an order of magnitude in sensitivity with respect to Advanced Virgo and Advanced LIGO and to enlarge the bandwidth of the detector down to 1-2 Hz (compared to 10 Hz for Virgo). The current design is to have 10 km arms placed in an underground site. Moreover, the detector is conceived as a xylophone, composed by two different sub-detectors working at different frequency bands, and merged together (similar to two electromagnetic telescopes sensitive to slightly different wavelengths). To fully resolve the two GW polarisations predicted by GR with a single detector, ET has a triangular shape leading to 3 independent Michelson interferometers. An alternative design (currently under discussion) could be to have 2 L-shaped detectors. The ET infrastructure is conceived to be able to accommodate future detector upgrades for the next few decades. The project has been recently inserted in the ESFRI roadmap for research infrastructures. If funded, the plan is to start the construction in 2027 and data taking in 2036. The APC is currently strongly involved in the project through two leading positions: the coordination of the french ET community (Matteo Barsuglia) and the co-chair of the Observational science board (Ed Porter). Moreover, the APC team is contributing to the instrument technical design, on the squeezing group.

The data analysis for ET will be extremely challenging. Unlike the current analysis for 2G ground-based detectors, it is expected that when operational, each year ET will observe 10^6 BBH mergers out to a redshift of $z \sim 50$ and 10^5 BNS mergers with almost 100 EM counterparts. Furthermore, given the planned low frequency cutoff for ET, not only will these signals be observable for hours to days in the detector, but many of them will be overlapping not only with each other, but also with multiple instrumental glitches and artefacts.

To tackle these issues and guarantee the maximum science extraction, the ET has formed the ET Observational Science Board (OSB). The current mandate of the OSB is to complete the ET Blue Book on a 4 year timescale. During this period, one member of the group (Ed Porter) is co-chair of the OSB. As ET is still in its formulation phase, the main activities of the OSB have been the creation of different scientific divisions, the assignment of division chairs, and the creation of a practical infrastructure for the board (i.e. wikis, mailing lists, communication channels etc.). At the end of September 2021, the OSB chairs organised an online kick-off workshop to announce the existence of the OSB to the wider scientific community. This was an extremely successful event with over 400 participants.

Team

M. Barsuglia, E. Capocasa, E. Porter, J.-P. Thermeau

Permanent scientist | Fix-term scientist | Permanent technical staff | Fix-term technical staff | Associate

Scientific leader and/or Technical project manager

Space-based detector

LISA

In 2016, the spectacular success of the European Space Agency (ESA)'s LISA Pathfinder mission has paved the way for the Laser Interferometer Space Antenna (LISA), the much anticipated flagship mission of low-frequency Gravitational Waves astronomy. LISA will target mHz frequencies and thus, in particular, systems involving BHs in the $10^4 - 10^7\,M_\odot$ mass range. The LISA mission has completed Phase A (industrial study) and is currently going through the mission formulation review at ESA with no technical or operational problems identified so far. LISA will enter Phase B (industrial production) in 2022 and proceed to launch around 2034 (nominally), or even earlier if technical readiness is deemed satisfactory. LISA consists of 3 satellites, forming a giant interferometer - with 2.5 million km arm length - orbiting the Sun about 20° behind the Earth (see Fig. 20 and 19).

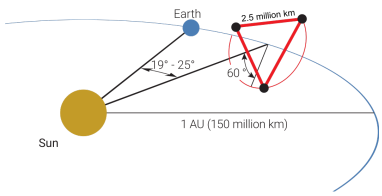


Figure 19: Schematic view of the LISA constellation

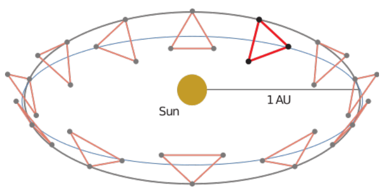


Figure 20: Schematic view of the LISA orbits around the Sun

APC is involved in the exploration of scientific abilities of LISA to contribute to the fundamental physics (testing General Relativity theory, inferring cosmological parameters, probing the early universe) and to identification of formation and evolution channels of GW sources. Our research is summarized in the growing number of LISA publications (20 papers published over the last year). On the project side we have two major responsibilities: on data processing and instrumentation which we now describe in details.

Contributions to the data processing One major contribution of the team to the LISA mission is prototyping of the LISA's Distributed Data Processing Center (DDPC). DDPC is the platform from which the daily LISA data analysis will be performed during (and after) the mission operation. The team brings its expertise on both the infrastructure design and development of the data analysis.

Ground segment infrastructure The team is one of the main contributors to the design of the Science Ground Segment and of the infrastructure of the DDPC led by CNES. Research and development activities have been on-going over the past 8 years. The common development environment and the prototype of the DDPC built at APC are currently used by LISA consortium for data/instrument simulation and data analysis. The team is also responsible for setting a number of collaborative services (based on CCIN2P3 infrastructure) for the LISA Consortium: Git repositories with continuous integration hosting all softwares, document management system, wiki, database with web interface and websites.

Data analysis The LISA data analysis is a challenging task that requires the integration of different methods for the signal extraction and noise reduction (e.g., laser frequency noise suppression). LISA data are expected to be dominated by the gravitational-wave signals. Thousands sources simultaneously present in the data have to be disentangled.

The main platform for developing and testing data analysis methods is the LISA Data Challenge (LDC) [25]. This project was initially built from scratch at APC (2017-2020) and is now developed by a working group with more than 100 members. The LDC working group is in charge of producing the simulated LISA data and developing a set of state-of-the-art data analysis methods, addressing detection and characterization of all known sources (Galactic binaries, massive or stellar-mass black-hole binaries, extreme mass ratio inspirals, stochastic GW signals, etc.). Tests include robustness against the presence of gaps in the data (due to antenna repointing) and noise artifacts (glitches, long-term non-stationary noise components).

[25] `https://lisa-ldc.lal.in2p3.fr/`

In the past four years three challenges have been released and one more is under way. The team played a major role in the coordination, the development of the software platform for simulating and publishing data sets, and in the development of the data analysis algorithms for detecting binary sources and stochastic GW signal. The software LISANode used for simulating the instrument was originally developed at APC.

This project benefited from the wide range of expertise present in the group, in particular GW signal modelling from merging black holes (see below) and from astrophysical knowledge of population of GW sources. This helped with the production of accurate but also fast GW signal generation algorithms, whose implementation and optimization is in progress. Finally, the team maintains a series of data analysis tutorials in order to ease and speed-up the development of new techniques especially for the groups new to the LISA project.

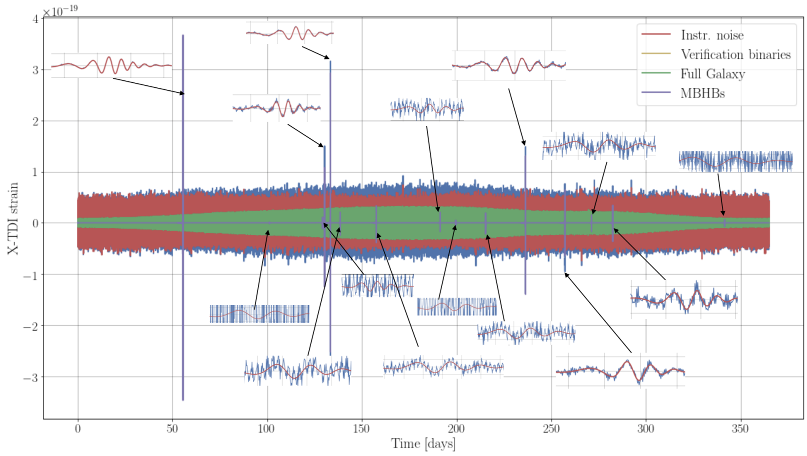


Figure 21: Simulated LISA data (training data set for the challenge "Sangria"). Data contains 30 mln Galactic white dwarf binaries and 15 merging massive black hole binaries

Instrument performance and noise budget The team is in charge of the LISA Performance working group. The main task of this group is to develop a bottom-up physical model of the instrument performance from low level instrument technical specifications up to the science requirements.

The modelling encompasses the optical metrology noises, like shot noise and stray light noises as well as the test mass acceleration noise models directly inherited from LISA Pathfinder. The team is in charge of developing the analytical modelling of the ground segment noise contributions through the Time-Delay Interferometry algorithm. These models are part of the baseline performance model.

The performance activity is at the cross-road of a wide range of expertise as the requirements specifications developed and delivered by the consortium for the phase A review are compliant with the performance model. The group supports ESA in its requirements engineering process and trade off studies. Moreover the models has also been shared with both industrial primes acting as a reference budget with supporting parametric model. Our key role in the performance Working Group directly benefit from the APC leading role in the DDPC and the French instrument activities.

Figures of merit The team has developed a set of figures of merit to quantify the scientific performance of a specific mission design. The objective is to propagate the noise budget all the way to the science investigations and assess abilities of the current mission configuration to fulfill the science objectives outlined in the science requirement document. Figures of merit are formulated as a set of numbers computed for each scientific investigation with associated metrics that allow to judge "goodness" of a given mission design. This collaboration-wide project implies a significant coordination effort between the LISA science group and the APC team. Documents presenting the rational and justification for the selected figures-of-merit, as well as the results of the phase A noise budget have been delivered for the Mission Formulation Review.

Contributions to the experiment The APC is involved in the LISA project since its creation in 2005 and participation to LISA Pathfinder. The experimental contribution to the LISA Pathfinder mission was centered on the optical tests of the Laser Modulation Unit. The first R&D activity directly related to the LISA mission was then dedicated to the application of molecular laser frequency stabilization to space-based experiment.

Over the last few years, the LISA team at the APC worked on different topics linked to the preparation and the French contribution to the mission.

LISA on Table LISA performance relies on high-precision metrological measurements, and on complex digital noise reduction techniques, such as TDI (Time Delay Interferometry). It is necessary to validate both the 'basic' technological bricks, but also the ability to correctly extract information from the entire measurement chain (involving optical benches, electronic measurements and processing of the collected data).

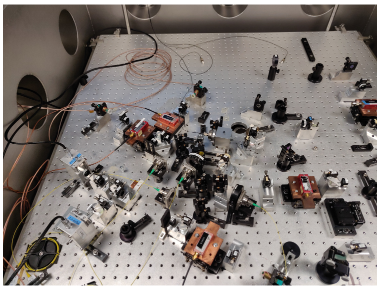


Figure 22: The interferometric bench of the LISA on Table experiment

With an optical frequency stabilised to a few tens of $Hz/\sqrt{Hz}$, the laser frequency noise is 7 to 8 orders of magnitude larger than the sensitivity targeted for LISA. This reduction can be achieved with the TDI techniques as demonstrated by simulations with current noise models. However, instrumental effects are only partially included in those simulations because of numerical limitations and lack of satisfactory physical models.

It is therefore important to experimentally simulate signals representative of LISA, that are as realistic as possible and acquired by devices similar to those envisaged. Once acquired, these signals are processed - digitally - by the same algorithms as those planned for LISA, in particular TDI, and their performance with 'real' signals is tested.

The LISA on Table (LOT) experiment was developed with this goal in mind, with the main objective of testing TDI with interferometric, heterodyne signals acquired by a prototype phasemeter and representative of the LISA signals, in particular, representative of the propagation delays and Doppler fluctuations between the satellites in the constellation (see 23).[26]

[26] M Laporte et al. "Status of the LISA On Table experiment: a electro-optical simulator for LISA". in: *Journal of Physics: Conference Series* 840.2017JPhCS.840a2014L (2017), p. 012014. URL: http://adsabs.harvard.edu/cgi-bin/nph-data_query?bibcode=2017JPhCS.840a2014L&link_type=ABSTRACT.

Prototyping optical benches for testing the LISA instruments In the organisation of the LISA space mission, the development of the main elements of the instrument is the responsibility of a consortium of European countries, including France, with a strong contribution from NASA. The French contribution to the LISA instrument covers 3 main activities: the establishment of a scientific data processing centre, the establish-

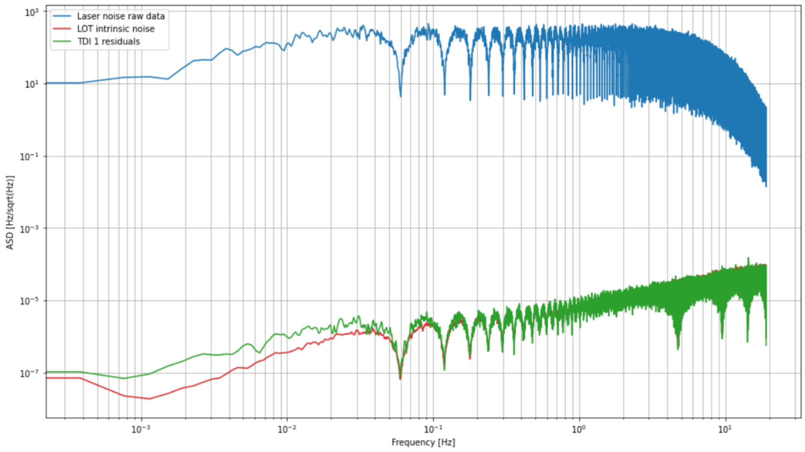


Figure 23: Performance of the LISA On Table experiment. The reduction factor of the injected noise (top curve) is 7 to 8 orders of magnitude

ment and monitoring of a scientific performance model and a strong participation in the testing and validation of partially or fully integrated instruments.

The contribution proposed by France in the framework of the LISA AIVT (Assembly, Integration, Validation and Testing) focuses on two crucial steps:

- The full responsibility for the functional and performance tests of the metrological core of the instrument, named IDS (Interferometric Detection System) and including the optical bench (with its different mounted elements), the signal acquisition system (phasemeter) and the laser source. The IDS is an early development stage to validate the Engineering (EM) and then the Qualification (QM) models of the instrument components. This step is crucial to globally validate the instrument concept and to reach a level of validation that cannot be achieved with a fully integrated instrument.

- The provision of benches and support for metrological (optical) performance tests of the fully integrated instrument (called MOSA: Movable Sub-Assembly). These tests, extensive on the qualification model and more limited on the 6 flight models (and 2 'spares'), aim to reproduce some of the IDS level measurements (in order to validate the 'correct' integration of the instrument) as well as to carry out a set of calibrations and alignment corrections.

This positioning puts French laboratories at the core of the realisation and fine understanding of the instrument, which is essential for the scientific exploitation of the data.

The role of the French laboratories, under the technical and financial guidance of CNES, is to set up the techniques and procedures that will enable the metrological performance of the LISA instrument to be validated on the ground at the IDS and MOSA levels.

This work has taken on much greater importance since the mission entered phase A (mid 2018). It is indeed necessary to define and demonstrate precisely (through the realisation of prototypes) the different integration

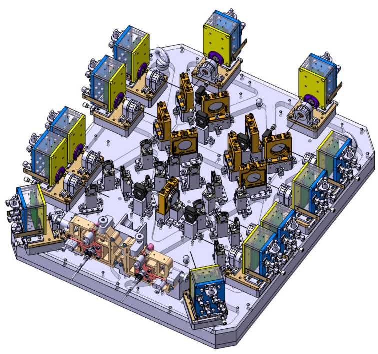


Figure 24: 3D view of the demonstration interferometric optical benches for LISA integration

and test benches before 2024 and the adoption of the mission (which signs the firm commitment of the different national agencies).

This process involves the development of two interferometric bench demonstrators, aiming at demonstrating the feasibility of testing the LISA instrument at the required performance level.

The work on these benches started at the end of 2019 at the APC and with partner laboratories. The first bench is based on traditional manufacturing (Invar metal plate and commercial optics). This 'engineering model' is entirely developed by laboratories. The second bench uses the expertise of an external company to design a Zerodur bench with optically contacted components (offering greater dimensional stability). Figure 24 shows the two versions of these benches. Their development has been delayed due to the health situation, but all procurement and technical implementation has now been completed.

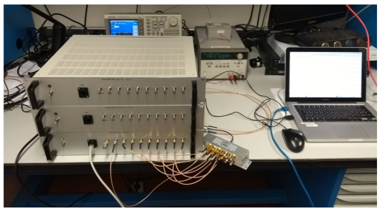


Figure 25: Digital phasemeter for MIFO and ZIFO optical benches

The assembly of the metallic bench has been fully completed in the laboratory workshops and the optical fine tuning has begun. In partnership with CEA/Irfu the team has also developed high stability phasemeters based on an original design from the Albert Einstein Institute (Hannover), see Fig. 25. Current activities now focus on the integration of the various peripheral subsystems to the bench itself including the laser source developed at SYRTE, the control/command software from CPPM, the thermal shielding from LAM, harnesses, etc. The installation in the vacuum tank (environment necessary to obtain the desired thermal stability) and then the tests will take place until Feb 2022. Some elements of the bench (injectors and photoreceptors) will then be unmounted and sent to the Winlight company for installation on the Zerodur bench.

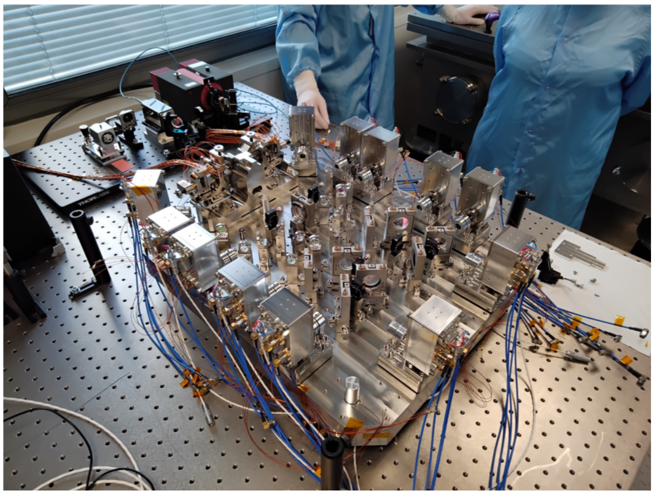


Figure 26: Integrated MIFO optical bench

Figure 26 shows the MIFO bench in the final stages of optical integration (using an optical centering bench and a three-dimensional measuring machine).

Team

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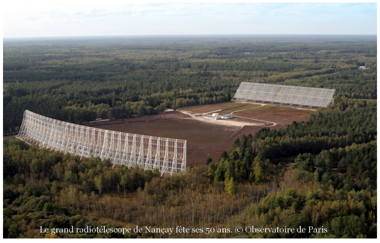

Figure 27: Nançay radio telescope

Pulsar timing array

Pulsar timing array (PTA) experiments, which monitor and measure arrival times pulses from millisecond pulsars, have been established to search for GW signals in the nanohertz band. There are several physical processes which cause deviations from the expected arrival times of radio pulses among which (the most relevant to us) are GWs. The most promising sources in the nHz part of the GWs spectrum are super-massive black hole binaries (SMBHBs) that form via the mergers of massive galaxies. Orbiting SMBHBs produce a stochastic GW background (GWB), individual periodic continuous signals and transient GW bursts. The GWB manifests as a temporally and spatially correlated noise process in the arrival times of pulses. The strain spectrum of such a background is predicted to have the power-law form $h(f) = A(f/1\mathrm{yr}^{-1})^{-2/3}$ where A is the strain amplitude. There are other potential sources of GWB in the PTA band those are: network of cosmic strings, quantum fluctuations of the gravitational field amplified by inflation and various other energetic process in the early Universe such as phase transition, turbulence. Three major world-wide PTA collaborations, NanoGrav (North America), European Pulsar Timing Array (EPTA) and PPTA (Australia) form an International PTA that is consortium of consortia. Recently Indian collaboration InPTA has joined IPTA and the Chinese PTA in the process of its formation.

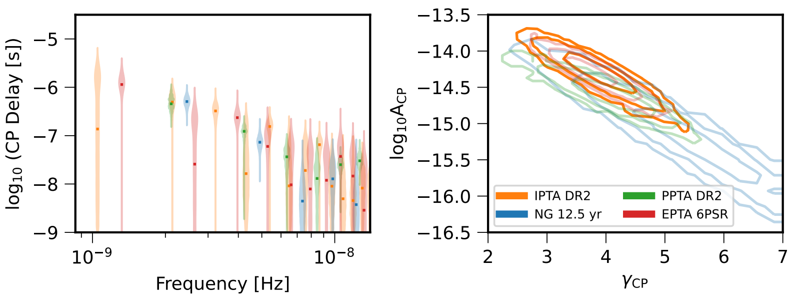

Figure 28: Common red noise observed by all three PTA collaborations. Left: estimated spectrum in each dataset. Right: Estimation of the amplitude and the spectral index of common red noise signal reported by each PTA. The slope is consistent with what we expect from the population of SMBHBs.

A small subgroup (2 part-time permanent members and 2 PhD students) are members of European Pulsar Timing Array collaboration and are involved in the data analysis searching for GW signals. This work takes place in the context of a close collaboration with the CNRS group at Orleans (LPC2E) and scientists working on Nancay radio telescope supported by an ANR grant.

The most important recent result is the independent discovery of the common red noise process. First it was reported by NANOGrav collaboration using Green Bank and Arecibo telescopes (2020) then this result was confirmed by PPTA using data from the Parkes radio telescope, and recently similar confirmation came from EPTA (using 5 largest European telescopes).[27] This is a red-noise like signal which has common spectral properties (PSD is $S(f) = A^2(f/1\mathrm{yr}^{-1})^{-\gamma}$) for all pulsars in the array, moreover the spectral index γ is consistent with what is expected from the GWB produced by a population of SMBHBs. Having a common red-noise signal is *necessary* but not sufficient for claiming GWB detection. An isotropic stochastic GW signal (within GR) induced very special correlations across pulsar data described by Hellings-Downs curve. This curve predicts correlation coefficient for each pair of pulsars which is the function of only angular separation of pulsars in the sky. The data analysised by each PTA is not sensitive enough to claim detection of those spatial correlations, in fact the data provides no significant evidence for, or against, Hellings-Downs correlations.

[27] S. Chen et al. “Common-red-signal analysis with 24-yr high-precision timing of the European Pulsar Timing Array: Inferences in the stochastic gravitational-wave background search”. In: *Mon. Not. Roy. Astron. Soc.* 508.4 (2021), pp. 4970–4993. arXiv: 2110.13184 [astro-ph.HE].

The group has analyzed 6 most sensitive EPTA pulsars spanning almost 24 years of radio observations. Our particular contribution was in modelling noise in each pulsar’s data.[28] Given complexity of radio emission by pulsars, its interaction with interstellar medium and with solar system environment, we might have quite a few different noise sources contributing to a total budget. We have performed Bayesian analysis customising the noise model for each pulsar and confirmed presence of the common red noise signal. We have also analysed IPTA data for presence of continuous GW signals from individual SMBHBs, we have found no strong evidence for presence of such GWs.

[28] A. Chalumeau et al. “Noise analysis in the European Pulsar Timing Array data release 2 and its implications on the gravitational-wave background search”. In: (2021). arXiv: 2111.05186 [astro-ph.HE].

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Gravitational-wave modelling

The gravitational-wave science based on compact binary signals is the theater of a unique interplay between theory and data analysis. Detecting and extracting signals from compact binaries, such as binary black holes or binary neutron star systems, requires to compare the data to a model of the waveforms. The two-body problem in general relativity and the problem of gravitational-wave generation is a difficult nonlinear problem with no known general solution that is the object of a very active field of theoretical physics. To tackle this challenge, different approaches are combined: analytical methods provide perturbative in the inspiral phase, far from coalescence, while the very non-linear merger of the two bodies is covered by heavy numerical simulations of the full spacetime.

After many years of continuous progress, we now have at our disposal waveform templates combining analytical and numerical information, that played an instrumental role in enabling the scientific results of LIGO and Virgo. Among these families of models, we could cite phenomenological models (Phenom), effective-one-body models (EOB), and numerical relativity surrogates.

It is important to note that we have an uneven coverage of the parameter space, and that the requirements on the accuracy of waveform models are more stringent for loud signals. Thus, the progress in waveform modelling needs to accompany the improvement in the detector sensitivity. Already, we arrive at a point where differences between waveform models are noticeable for sources at the margins of the parameter space covered by our models. This will be an outstanding challenge for future detectors including third generation detectors on the ground and LISA in space, where high signal-to-noise ratios are expected.

Team members have been actively involved in both the Waveform group of the LIGO/Virgo collaboration, which includes implementing waveform-generating codes, as well as particpating in code reviews for the crucial codes that are at the basis of LIGO/Virgo analysis in production. Group members have also been involved in the Waveform working group of the LISA consortium, coordinating a work package for the waveforms of stellar mass black holes. Additionally, group members have contributed to advances in a number of directions.

Towards post-Newtonian waveforms at the 4th PN order Post-Newtonian results form the bedrock of all waveform models, as they give perturbative analytical predictions for the inspiral. The current frontier lies at the already high 4PN order (the 4th order in the $(v/c)^2$ series), where the dynamics is known but the waveform remains to be computed. Team members have taken part in an effort to compute the main piece of this waveform computation, the mass quadrupole moment of the system.[29]

[29] Tanguy Marchand et al. "The mass quadrupole moment of compact binary systems at the fourth post-Newtonian order". In: *Class. Quant. Grav.* 37.21 (2020), p. 215006. arXiv: 2003.13672 [gr-qc].

Machine learning approach to the properties of merger remnants The waveforms can only be computed with expensive numerical relativity simulations. It is crucial to interpolate in-between those scarce data; this knowledge then re-enters waveform models, as well as tests of general relativity. Members of the group have developed a novel approach based on machine learning techniques to train a network on the available numerical results, improving on previously existing fits.[30]

[30] Leïla Haegel and Sascha Husa. "Predicting the properties of black-hole merger remnants with deep neural networks". In: *Class. Quant. Grav.* 37.13 (2020), p. 135005. arXiv: 1911.01496 [gr-qc].

A Phenomenological waveform model in the time-domain Phenomenological waveforms are the baseline model used by data analysis. They are easy to use, being built as an analytical ansatz with parameters fitted to numerical relativity results. Team members have contributed to a new high-accuracy model that has been built in the time domain, including precession effects, giving waveform modellers a new handle to work with.[31]

[31] Héctor Estellés et al. "Phenomenological time domain model for dominant quadrupole gravitational wave signal of coalescing binary black holes". In: *Phys. Rev. D* 103.12 (2021), p. 124060. arXiv: 2004.08302 [gr-qc].

A new generation of EOB model with higher harmonics Effective-one-body waveforms are one of the three main families of models used in data analysis. They are built as a refactoring of post-Newtonian analytical results, with a merger phase informed by numerical relativity data. Members of the group took part in building the new generation of this model, including precession as well as higher harmonics in the signal for the first time. This model is one of the three main models that has been used in the analysis of the O3 run of LIGO/Virgo, providing an important comparison point to other results.[32]

[32] Serguei Ossokine et al. "Multipolar Effective-One-Body Waveforms for Precessing Binary Black Holes: Construction and Validation". In: *Phys. Rev. D* 102.4 (2020), p. 044055. arXiv: 2004.09442 [gr-qc].

Accelerating the evaluation of EOB waveforms with higher harmonics Effective-one-body are slow to evaluate in general, since they integrate numerically a trajectory, but waveform computational performance is a bottleneck for data analysis, and in particular parameter estimation codes. This has sparked efforts to algorithmically accelerate them, with Reduced Order Models (ROMs) trained on a set of precomputed waveforms. Team members have contributed to the construction of such a ROM for an effective-one-body model with aligned spins and higher harmonics.[33]

[33] Roberto Cotesta, Sylvain Marsat, and Michael Pürrer. "Frequency domain reduced order model of aligned-spin effective-one-body waveforms with higher-order modes". In: *Phys. Rev. D* 101.12 (2020), p. 124040. arXiv: 2003.12079 [gr-qc].

Modelling environmental effects for stellar-mass black holes in orbit around AGNs In the LISA context, stellar-mass black holes such as observed by ground-based observatories might be detectable at low frequencies, when the system is still far away from coalescence. Such systems could be affected by their environment due to accretion or dynamical friction. In particular, the possible association of GW190521 with a ZTF counterpart has raised a lot of interest by the possibility of having such a system emitting from an orbit within the accretion disk of an AGN. On top of matter effects, gravitational lensing could also play a role. Team members have been part of an ongoing effort to model these effects, implement them in data analysis tools and explore what such systems could tell us.[34]

[34] Alexandre Toubiana et al. "Detectable environmental effects in GW190521-like black-hole binaries with LISA". in: *Phys. Rev. Lett.* 126.10 (2021), p. 101105. arXiv: 2010.06056 [astro-ph.HE].

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Connection to geophysics

The team contributed to an interdisciplinary activity in collaboration with IPGP to detect prompt gravity signals from earthquakes. The goal would be to produce faster early-warning alerts for earthquakes and also a new way to study seismic phenomena, alternative to the seismic waves. The team developed a conceptual design of a earthquake gravity signal detector (PEGASEWS), based on a double torsion bar and with an interferometric readout.

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Selected publications

Abbott, B. P. et al. “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral”. In: *Phys. Rev. Lett.* 119.16 (2017), p. 161101. arXiv: 1710.05832 [gr-qc].

– “Multi-messenger Observations of a Binary Neutron Star Merger”. In: *Astrophys. J. Lett.* 848.2 (2017), p. L12. arXiv: 1710.05833 [astro-ph.HE].

Abbott, R. et al. “GWTC-2: Compact Binary Coalescences Observed by LIGO and Virgo During the First Half of the Third Observing Run”. In: *Phys. Rev. X* 11 (2021), p. 021053. arXiv: 2010.14527 [gr-qc].

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García, Federico et al. “Progenitors of low-mass binary black-hole mergers in the isolated binary evolution scenario”. In: *Astron. Astrophys.* 649 (2021), A114. arXiv: 2103.03161 [astro-ph.HE].

Mastrogiovanni, S., D. Steer, and M. Barsuglia. “Probing modified gravity theories and cosmology using gravitational-waves and associated electromagnetic counterparts”. In: *Phys. Rev. D* 102.4 (2020), p. 044009. arXiv: 2004.01632 [gr-qc].

Mastrogiovanni, S. et al. “Cosmology in the dark: On the importance of source population models for gravitational-wave cosmology”. In: *Phys. Rev. D* 104.6 (2021), p. 062009. arXiv: 2103.14663 [gr-qc].

Toubiana, Alexandre et al. “Detectable environmental effects in GW190521-like black-hole binaries with LISA”. In: *Phys. Rev. Lett.* 126.10 (2021), p. 101105. arXiv: 2010.06056 [astro-ph.HE].

Vallisneri, Michele et al. “Time-delay interferometry without delays”. In: *Phys. Rev. D* 103.8 (2021), p. 082001. arXiv: 2008.12343 [gr-qc].

Zhao, Yuhang et al. “Frequency-Dependent Squeezed Vacuum Source for Broadband Quantum Noise Reduction in Advanced Gravitational-Wave Detectors”. In: *Phys. Rev. Lett.* 124 (17 2020), p. 171101.