PROPOSAL FOR A HALF-TRIMESTER
CENTRE EMILE BOREL - INSTITUT HENRI POINCARE

GRAVITATIONAL WAVES: A NEW MESSENGER TO EXPLORE THE UNIVERSE

1. Scientific context and aims of the half-trimester

The first direct detection of gravitational waves (GW), announced in February 2016 by the LIGO-Virgo collaboration, paves the way to a new type of astronomy, based on a novel non-electromagnetic messenger, able to probe the dynamics of relativistic sources in strong field and to explore the first instants of the Universe. The tremendous implications of the first detections give us a glimpse on the enormous scientific potential of this emerging domain. In particular, we obtained one of the best evidences to date of the existence of black holes, we observed for the first time the coalescences of compact objects – black holes, neutron stars – and we established a link between neutron-star mergers and the production of short gamma ray bursts.

While numerous GW sources are invisible by other means, rendering GWs the only messenger for information that would remain otherwise out of reach, other sources are associated with electromagnetic (EM) counterparts, as well as, most likely, with the production of high-energy particles. Thus, GW multi-messenger astronomy greatly supplements the traditional sectors of astronomy.

Observing astrophysical systems via GWs in the very strong field regime provides unprecedented tests of gravitation, and enlightens the characteristics of this fundamental interaction, notably the validity of general relativity. In particular the observed GW signals are in perfect agreement with the predictions of general relativity, and no deviation with respect to this theory have been found. The speed of GWs has been measured to high precision, which gives a strong constraint on alternative theories of gravity. The origin of the cosmological acceleration or the nature of dark energy can also be investigated. In fact, binary mergers are standard candles that may be used for cosmography, and GWs have already yielded a measurement of the Hubble-Lemaître parameter. Moreover, gravitational radiation tells us about the early universe much before the epoch of the cosmic microwave background emission.

In 2021, the LIGO and Virgo detectors should be close to their design sensitivity and the Japanese instrument KAGRA should have been operational for over a year. The new French-Chinese X/gamma ray satellite SVOM should be close to launch. Black hole and neutron star binaries should be routinely detected so that it will probably be possible to do statistics with these sources. The distribution of parameters will have become informative about favored astrophysical models for sources formation. The errors on the measurements of the Hubble-Lemaître constant will have reduced in a significant way. It is reasonable to assume that many further associations of neutron stars with gamma ray bursts will have been made, leading to a better understanding of the underlying physics, and significant improvement of gamma ray burst models. Pulsar timing networks will perhaps have already detected the background produced by merging super-massive black hole binaries.

In short, by the time of this half-trimester, the pioneer phase of GW astronomy will be over, and the era of its development as an established scientific field will begin. The European Space Agency (ESA) will be in the adoption process of the LISA mission, which consists of three satellites forming a quasi-equilateral triangle in heliocentric orbits and connected by six laser links for GW interferometry. LISA can detect GWs in a frequency range between those of LIGO/Virgo and PTA, with an unprecedented sensitivity, thus opening the possibility to detect mergers of light super-massive black holes and weaker backgrounds, perhaps of cosmological origin. Astrophysicists, theorists and experts in data analysis will be even more inclined than now to work on this expanding field. Properly educating young scientists will have become crucial, to sustain the ESA effort until the launch of the LISA satellites in 2034, and the advent of third generation ground-based detectors such as the Einstein Telescope. In this context, a thematic half trimester of the Institut Henri Poincaré, with a format including a series of lectures and seminars offered by the best experts in their respective domains over six weeks, would provide a unique opportunity to review the most important topics connected to GW science, stimulate discussions between scientists from different backgrounds, train students and post-doctoral researchers, but also all those who have been working on one of the aspects of GW science and wish to learn about another – possibly complementary – one.

The CNRS "Groupement de Recherche (GdR) Ondes Gravitationnelles", http://gdrgw.in2p3.fr/, which we represent here, would naturally coordinate the half-trimester. This structure was born a couple of years ago when the great interest on GW astronomy was beginning to rise in France, as everywhere else. Indeed, the community of French researchers interested in GW science and ready to commit is extremely wide. As we said, in addition of being a formidable tool for astrophysics, GWs could also allow to detect yet unobserved cosmological phenomena, and yield independent cosmographic measurements. From its very nature, the GdR also concerns theorists of gravitation, who compute gravitational radiation emission or its propagation, in general relativity as well as in alternative theories. Detection of events can be challenging, especially in the presence of un-modelled or ill-modelled sources, or when various signals are superimposed, as expected for LISA. Sophisticated techniques of data processing, which will certainly be needed in those cases, may be imported from applied mathematics. In summary, the GdR was created precisely to bring all these communities together and provide opportunities of meeting and exchanging about these various connected topics.

The GdR is organized in working groups on topics of common interests, gathering researchers from different fields and backgrounds, from theorists to observers and experimentalists. One yearly meeting is organized, with invited talks about compelling topics, contributions proposed by the community, with special emphasis to the work of young researchers, as well as round tables on specific themes relevant for the GdR working groups. As we detail below, organizing the GdR yearly meeting jointly with this program would represent the perfect way to showcase the French community to

international researchers, and at the same time nudge French researchers into participating to the half-trimester.
The main scientific themes that will be tackled during this half-trimester are the following:

Waveforms
• Binaries of (super) massive and of stellar origin black holes, binary neutron stars and white dwarfs, etc.
• Numerical relativity (black hole binaries, relativistic hydrodynamics of neutron stars and supernovae, etc.)
• Analytical methods (Post Newtonian, Effective One Body, Phenom, etc.)

Populations of sources
• Formation of binaries
• Stochastic background produced by binaries
• Ground/space complementarity: multi-wavelength gravitational wave detection

Electromagnetic counterparts and multi-messenger astronomy
• Monitoring the detections of gravitational waves
• Motivation of the observations (notably radio sources and others)
• Counterparts of neutron stars and of (super) massive black holes binaries, and so on
• Connection of electromagnetic observations with gravitational observations

Cosmology
• Signals of the primordial universe (stochastic backgrounds)
• Cosmological parameters (standard sirens and other techniques)
• Angular correlation, the large-scale structure of the universe
• Weak/strong lensing
• Relation with the cosmic microwave background
• Cosmic strings
• Primordial black holes

Neutron stars, supernovae and heavy element production
• Equation of state, internal structure
• Synthesis of heavy elements
• Supernovae

Data analysis
• Data quality and noise analysis
• Bayesian methods
• Calculations
• Un-modeled sources
• Non-Gaussianity, non-stationarity, parameter estimation
• Subtracting foregrounds
• De-noising, machine learning

Tests of general relativity and alternative theories
• Tests of the inspiralling phase (post-Newtonian)
• Waveforms in alternative theories
• Tests of the no-hair theorem and physics of the horizon
• Tests on the propagation and polarizations
• Cosmological theories
• Tests of fundamental physics

Detectors
• LIGO / Virgo and LISA
• Development of Einstein Telescope from an instrumental point of view and in the context of the new scientific context
• Atomic interferometry detectors: ground (MIGA, ELGAR) and space

The main goal of this program is to bridge among the above research areas in GW science, and foster interaction and communication. To reach this goal, we envisage two-week blocks with overlapping themes, plus the presence of a core group of scientists who will straddle the various themes and provide connections. We also plan to organise a series of lectures at the master/PhD level, to help forming the next generation of researchers, and numerous invited seminars in which to report on the latest advancements in the field. We will have coordinated interdisciplinary exchanges during dedicated days, and we would also like to organise the GdR general meeting together with the half-trimester, as we forecast that this will mutually benefit the two events.

2. Organisers

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Expertise: Cosmological applications of gravitational wave signals: origin and detection of the stochastic gravitational wave background from the early universe; the use of gravitational wave emission from binaries to test the accelerated expansion of the late universe. Director of the GdR "Ondes Gravitationnelles"; coordinator of the Cosmology Working Group of the LISA consortium.

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Expertise: gravitational-wave data analysis. Multi-messenger observations. Member of the board of the GdR "Ondes Gravitationnelles"; Co-ordinator of the Working Group of the GdR "Ondes Gravitationnelles" on data analysis ; Head of APC Virgo group; Co-head of the open science team in LIGO/Virgo.

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Expertise: Dynamics of relativistic self-gravitating sources, generation of gravitational waves, binary systems of compact objects, post-Newtonian expansion of general relativity. Co-coordinator of the Waveform Working Group of the GdR "Ondes Gravitationnelles"; Coordinator of the sub-workpackage Galactic Binary Waveform of the LISA consortium.

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Expertise: Primordial universe, large-scale structure of the Universe, dark energy and modified gravity, cosmological implications of gravitational waves on modified gravity. Co-coordinator of the Working Group of the GdR "Tests of general relativity and alternative theories".

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Expertise: Formation and evolution of super-massive black holes; dynamics of black hole binaries; cosmological populations of merging massive black holes; active galactic nuclei and quasars; coordinator of the Astrophysics Working Group of the LISA consortium. Member of the board of the GdR "Ondes Gravitationnelles"

3. Scientific organisation and topics

We propose a program for the half-trimester covering eight fundamental topics in gravitational-wave science, organised in thematic blocks of two weeks as follows:

The first two weeks are dedicated to theoretical aspects of GW science:

- *Gravitational waveforms*: Waveforms from different types of sources (massive black hole binaries, stellar origin black hole binaries, neutron stars in binaries or isolated neutron stars in fast rotation, white dwarf binaries…), constructed via numerical relativity (numerical techniques, relativistic hydrodynamics…) or analytical methods (post-Newtonian approach, effective-one-body approach, phenomenological approach…)
- *Neutron stars and heavy elements synthesis*: equations of state and internal structure of neutron stars; heavy element synthesis; supernovae
- *Tests of general relativity and alternative theories of gravitation*: Tests from the inspiralling and after-coalescence phases; physics of the horizon; GW propagation and polarisations; tests of cosmological alternative theories of gravitation

The next two weeks are dedicated to GW detectors and data analysis:

- *Science of GW detectors*: Earth-based interferometers (LIGO-Virgo, Einstein telescope, Cosmic Explorer…); space-based interferometers (LISA and follow-ups); new techniques (atom interferometry…)
- *Data analysis*: Data quality and noise processing; methods for signal extraction and parameter estimation; machine learning; non-gaussianity, non-stationarity of signal and noise; foreground subtraction; un-modelled sources; open data context

The last two weeks are dedicated to GW astrophysics and cosmology:

- *Populations of sources*: Formation and abundance of black hole binaries (both of super-massive and of stellar origin), parameter distribution; populations of stars; stochastic signal from binaries; multi-band GW sources
- *Cosmology with GWs*: Stochastic backgrounds from the early universe (inflation and other sources, relation with CMB physics); stochastic background from astrophysical sources and its anisotropies; tests of cosmological parameters; cross-correlation of electromagnetic and GW catalogues; GW lensing; primordial black holes and tests of other dark matter candidates

- *Multi-messenger signals:* Electromagnetic and neutrino follow-up of GW sources (characteristics, prediction, observational strategies…); nature of the electromagnetic counterparts; discovery potential and synergy with astrophysics

For each two-week block, we propose to organise the following events:

- A series of courses at Master2/PhD level: The courses will cover topics in relation with the science of each two-week block. We will invite distinguished lecturers and encourage them to participate to the full half-trimester. We have selected the following topics and prepared a list of names associated to them, to contact in the proposed order:
  - First two-week block, two courses: "Gravitational waveforms" (5 hours, by (1) Tanja Hinderer, (2) Alessandra Buonanno, (3) Michele Maggiore, (4) Alexandre Le Tiec) and "Testing gravitational theories" (5 hours, by Shinji Mukoyhama, (2) Gilles Esposito-Farese, (3) Andrew Tolley)
  - Second two-week block: "GW detectors" (5 hours, by (1) Lisa Barsotti, (2) David Shoemaker) and "GW data analysis" (5 hours, by (1) Chris Messenger, (2) Stas Babak)
  - Third two-week block: "(Massive) black hole binaries" (4 hours, by (1) Monica Colpi, (2) Tamara Bogdanovic, (3) Alberto Sesana, (4) Michela Mapelli), "Multimessanger astrophysics" (4 hours, by (1) Giancarlo Ghirlanda, (2) Daniel Kasen) and "GWs and cosmology" (4 hours, by (1) Danielle Steer, (2) Valerie Domcke)

- A total of 9 seminars, by invited speakers. The seminars will have duration of about one hour including questions, and will cover the most recent advancements and open questions in relation with the topics of the two-week block. The speakers will be encouraged to participate to the full half-trimester program, or at least to the whole two-week block.

- Mini-conference of contributed talks: One afternoon (about four hours) of the two-week block will be dedicated to seminars by the participants, of about thirty minutes each including questions. We will encourage especially post-docs and students to present their work.

- One day of interdisciplinary exchange: In one day of the two-week block we will organise a seminar at introductory level on selected topics, typically in relation with the science of the two-week block. The seminars will be followed by an open discussion, so that the activity will cover the full morning or the full afternoon of the day. This activity is intended to promote interdisciplinarity and exchange. We have selected the following topics and proposed a list of names to contact:
  - First two-week block: "Introduction to astrophysical observations" by (1) Susanna Vergani , or (2) Sylvain Chaty
  - Second two-week block: "Machine learning for detectors and data analysis" (Gabriele Vajente)

- Third two-week block: “Stochastic backgrounds” (Germano Nardini)

The schedule of each week of the half-trimester program will be as follows:

1st week (5 hours of lectures, 4 seminars, 4 hours mini-conference: 13 hours)
Monday – *Morning*: free. *Afternoon*: 1 hour seminar.
Tuesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Wednesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Thursday – *Morning*: free. *Afternoon*: mini-conference.
Friday – *Morning*: 1 hour lecture. *Afternoon*: 1 hour seminar

2nd week (5 hours lectures, 4 seminars, 1 interdisciplinary seminar: 11 hours)
Monday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Tuesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Wednesday – *Morning*: free. *Afternoon*: 1 hour seminar.
Thursday – *Morning*: Interdisciplinary seminar. *Afternoon*: free.
Friday – *Morning*: 1 hour lecture. *Afternoon*: 1 hour seminar

3rd week (3 hours lectures, 1 seminar, 1 interdisciplinary seminar: 6 hours)
Monday – *Morning*: free. *Afternoon*: 2 hour lecture.
Tuesday – *Morning*: Interdisciplinary seminar. *Afternoon*: 1 hour seminar.
Wednesday – *Morning*: 1 hour lecture. *Afternoon*: free.
Thursday – GdR.
Friday – *Morning*: GdR.

4th week (7 hours lectures, 2 seminars, 3 hours mini-conference: 12 hours)
Monday – *Morning*: free. *Afternoon*: 1 hour seminar
Tuesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Wednesday – *Morning*: 2 hours lecture. *Afternoon*: free
Thursday –*Morning*: 1 hours lecture. *Afternoon*: mini-conference.
Friday – *Morning*: 2 hour lecture. *Afternoon*: free

5th week (6 hours lectures, 3 seminars, 4 hours mini-conference: 13 hours)
Monday – *Morning*: free. *Afternoon*: 2 hours lecture.
Tuesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Wednesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Thursday – *Morning*: free. *Afternoon*: mini-conference.
Friday – *Morning*: 1 hour seminar. *Afternoon*: free.

6th week (6 hours lectures, 3 seminars, 1 interdisciplinary seminars: 11 hours)
Monday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Tuesday – *Morning*: 1 hour seminar. *Afternoon*: free.
Wednesday – *Morning*: 2 hours lecture. *Afternoon*: 1 hour seminar.
Thursday – *Morning*: free. *Afternoon*: interdisciplinary seminar.
Friday – *Morning*: 2 hours lecture. *Afternoon*: free.

We plan to have the afternoon seminars before the coffee break, in order to encourage the discussion to be continued during and after the coffee break. The afternoons after the coffee breaks, plus some half days, are left free, to encourage the participants to spontaneously organise activities in this free time (e.g. small-group discussions, journal clubs, learning sessions on a given topic, and so on). We plan to have a blackboard in the common room where participants can write down their wishes concerning possible activities and topics for discussion. Our previous experience in this kind of events shows that spontaneously organised activities are indeed very common and very important parts of long-term workshops.

We aim at organising two public conferences related to the topic of the half-trimester. The precise subjects and the speakers will be chosen in due time, depending on which will be the new advancements in the field by the time of the half-program. One conference could be for example on what we have learned about the universe from the latest gravitational wave observations, now that the discovery has turned into an established scientific field. The other one could be about the Event Horizon Telescope and GRAVITY, and the scientific use of the black hole images (which may be already many in 2021).

Jointly to the half-trimester, we would like to organise the GdR annual meeting. We would like this to take place either on the last two days of the sixth week of the half-trimester, or on the following Monday and Tuesday. In the first case, we will readapt the schedule of the third two-week block. We would like the meeting to take place at Centre Emile Borel as well. Typically, 80-100 GdR members attend the GdR annual meetings, which are two-day meetings where the novelties of the year in GW science are presented, scientific issues and discoveries are discussed, and the GdR activities are summarised. The first morning of the two days is typically dedicated to invited seminars, while the rest of the meeting is organised thematically following the topics of the GdR Working Groups, with one hour dedicated to each Working Group. Having this meeting together with the half-trimester will allow summarising the scientific advancements achieved during the half-trimester and insert them in the context of the GdR community, potentially shaping the future GdR activities. The participants of the half-trimester will be invited to attend the GdR meeting, in order to encourage interactions among the GdR French community and, more generally, the GW community at the international level. This will also help to orient and shape the future of GW science in France.

4. Participants

We would like this meeting to be an opportunity for emerging young scientists to interact among themselves and with the established researches in the field: therefore, we aim at having 50% of junior invited researchers. We also aim at full gender balance. These two criteria will guide our selection of invitations, together with scientific renown, research achievements, and international profile. Here is a preliminary list of names:

Thomas Janka (MPA Garching, Supernova core collapse); Reinhard Prix (AEI Hannover, Isolated neutron stars); Maarten Van de Meent (AEI Potsdam, self-force waveforms); Adam Pound (Southampton, self-force problems); Adrian Ottewill (Dublin, self-force problems); Luc Dessart (LFCA, nucleosynthesis of heavy elements); Saul Teukolsky (Cornell, Numerical simulations of BH binaries); Laura Bernard (Perimeter Institute, Post-Newtonian expansion); Luciano Rezzolla (University of Frankfurt, neutron-star binary mergers); Bernd Bruegman (Jena, BH binary problem); Clifford Cheung (Caltech, scattering amplitudes); Claudia De Rham (Imperial College, alternative theories of gravitation), Andrew Tolley (Imperial College, alternative theories of gravity); David Pirtskhalava (NYU, alternative theories of gravity); Leor Barack (Southampton, BH perturbations); Zoltan Haiman (Columbia University, EM counterparts and supermassive black hole mergers); Elena Maria Rossi (Leiden University, EM counterparts and white dwarf binaries); Gijs Nelemans (Radbound University, white dwarf binaries); Tamara Bogdanovic (GeorgiaTech, EM counterparts and binary AGN); Julian Krolik (Johns Hopkins University, EM counterparts); Daryl Haggard (McGill University, EM counterparts); Vicky Kalogera (Northwestern University, stellar origin compact binary evolution); Giancarlo Ghirlanda or Om Salafia (INAF Milan, GRB and EM counterparts for BBH); Marica Branchesi (INFN Gran Sasso; EM counterparts); Géraldine Servant (DESY, cosmological backgrounds); Pau Amaro-Seoane (Barcelona, BBH statistics, galactic center); Ruth Durrer, Giulia Cusin (University of Geneva, stochastic backgrounds); Clifford Will (University of Florida, GW theory methods): Eleonora Capocasa (U Tokyo, squeezing); Kipp Cannon (Univ Tokyo, GW searches), Salvatore Vitale (MIT, 'parameter estimation' & 3G); Vivien Raymond (Cardiff, Bayesian estimation); Frederique Marion (LAPP, GW searches); Arianna Renzini (Imperial College London, GW map-making); Camille Bonvin (University of Geneva, GW and structure formation); Valery Domcke (DESY Hamburg, stochastic backgrounds)

5. Practical aspects

Advertising: we would like to start advertising the half-trimester and issuing the first invitations as soon as possible. One drawback of this kind of long-term events is that researchers are often too busy to attend for more than a few days, possibly one-week. At the same time, we do not want to put a minimal length of stay, as this might discourage participation by some, for example those with teaching duties, research administration duties, leaders of detection experiments or space missions, and so on. We therefore believe that planning in advance is essential to guarantee a long enough average attendance per participant, which is crucial for the success of the program. Allowing early planning can also help the participants to deal easier with possible family organisation issues.

Courses and teaching Duties: we will explore the possibility of obtaining some *délégation d'enseignements* for professors of French universities, to allow them to fully participate to the program. We would also like to contact Sorbonne Université (for the Master 2) and the *Ecoles doctorales* of the Ile de France area (Physique en Ile de France, Astronomie et Astrophysique d'Ile de France, STEP'UP, PHENIICS…) to explore the possibility to include some of the half-trimester courses into their lecture program. We believe that this would be beneficial for the students, inserted into an active research environment, increasing their network and improving their future careers (job opportunities, visiting opportunities…)

Presence of the organisers: The organisers of the event aim at participating to the full program, compatible with other professional duties, using the facilities and office space provided by the IHP. At least one organiser will be present every day from the beginning to the end of the daily activities.

GdR meeting: The expenses related to the two-days GdR meeting will be entirely covered by GdR funding. The typical budget of one of these meetings is about 10-15k€. We plan to ask to the Centre Emile Borel to host the meeting, as this will facilitate the scientific and attendance continuity between the two events.

Budget: On top of the budget provided by Centre Emile Borel, the GdR plans to allocate almost its entire budget to the organisation of the half-trimester plus the meeting. We forecast that the GdR activities for the year 2021 will practically coincide with the half-trimester ones: the annual meeting should take place immediately after, and the usual Working Group meetings can be coordinated with the half-trimester activities. The annual budget of the GdR is about 20k€: 18k€ will be allocated to the half-trimester and about 2k€ will be kept for exceptional, unforeseen expenses. Since Centre Emile Borel covers the infrastructure expenses and coffee breaks, with the total budget allocated to the half-trimester (60k€ + 18k€) we plan to cover mostly the expenses related to the event attendance: travel and living expenses for invited participants, rental expenses for the lecturers and/or participants who stay for a long time, childcare expenses if needed, and so on.

Video-recording needs: We do not plan to video-record the event

Desired period: Second half of T1 trimester