CEMPI : a presentation

Acronym of the project	**CEMPI**
Titre du projet en français	Centre Européen pour les Mathématiques, la Physique, et leurs Interactions
Project title in English	European Centre for Mathematics, Physics, and their Interactions
Project manager	Nom/Name: De Bièvre Prénom/First name: Stephan Etablissement / Institution : Université Lille 1 Laboratoire / Laboratory : Paul Painlevé Numéro d'unité/Unit number : UMR8524

Institution leading the project

Nom de l'établissement / Institution name	Statut / Status
PRES Lille Nord de France	Établissement public de coopération scientifique

Partners

Laboratory	Unit number	Research organization reference
Paul Painlevé	UMR 8524	Université Lille 1, CNRS
PHLAM	UMR 8523	Université Lille 1, CNRS

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Summary

The book of nature is written in the language of mathematics, Galileo Galilei

The general setting. At the core of the CEMPI LABEX lies the partnership of the mathematicians of the Laboratoire P. Painlevé with the physicists of the "Physique des Lasers, Atomes et Molecules" laboratory (PhLAM). This partnership will create in Lille a unique research unit with a spectrum extending all the way from pure mathematics to experimental and applied physics. A structured and close collaboration with top level institutes abroad (Aberdeen, Bristol, Fields, Leuven, Louvain, Max Planck Bonn, Photonics@be IAP, SISSA), many of them geographically close to Lille, will thus establish a European centre of the highest quality for fundamental and applied interdisciplinary research, training and technological development. The focus will be on selected research topics at the rich interface of mathematics and physics. First, the CEMPI researchers will address a number of key mathematical, physical and technological problems arising from complex behaviour in non-linear optical systems, a field in which PhLAM excels. In addition, they will make major advances in further areas of strength of CEMPI, which have promising interactions with other fields in physics, but also with other sciences, like biology and computer science.

Clearly then, the core asset of CEMPI is, *first,* that it brings together the complementary competence of the pure and applied mathematicians of the Laboratoire Paul Painlevé, whose internationally recognized expertise covers many fields of mathematics, with that of the physicists of PhLAM, whose characteristic strongpoint is their tightly integrated theoretical and experimental approach to the understanding of complex behaviour in optical and biological systems. *Second*, the unique situation of Lille as a European crossroads at the centre of the Paris-London-Brussels triangle will enable intense collaboration of researchers in Lille with relevant research teams of the highest quality from the selected foreign institutes listed.

Research projects. The first and main focus area of CEMPI research, engaging about 65% of its forces, is

FOCUS AREA 1: THE INTERFACE OF MATHEMATICS AND PHYSICS, with three themes: (1) NONLINEAR COLLECTIVE DYNAMICS IN COMPLEX ATOMIC AND OPTICAL MANY-BODY SYSTEMS: DETERMINISTIC AND STOCHASTIC ASPECTS; (2) ALGEBRAIC GEOMETRY, MODULAR FORMS WITH APPLICATIONS TO PHYSICS; (3) OPERATOR ALGEBRAS, HARMONIC ANALYSIS, QUANTUM GROUPS WITH APPLICATIONS TO PHYSICS.

In addition, there are two emerging interdisciplinary Focus Areas, that currently engage about 35% of CEMPI researchers and that will be further developed in the course of the project, depending on the opportunities that present themselves. They are

FOCUS AREA 2: THE INTERFACE OF PHYSICS AND BIOLOGY and

FOCUS AREA 3: THE INTERFACE OF MATHEMATICS AND THEORETICAL COMPUTER SCIENCE. The latter develops two themes: (1) ALGEBRAIC TOPOLOGY, HIGHER CATEGORIES, OPERADS, WITH APPLICATIONS TO THEORETICAL COMPUTER SCIENCE; (2) GRAPHS AND GROUPS, WITH APPLICATIONS TO THEORETICAL COMPUTER SCIENCE.

Undergraduate, graduate and post-graduate training. CEMPI's core strengths, as outlined above, will prove crucial in the graduate and post-graduate level training of young top-level scientists and engineers, with strong interdisciplinary competence and international experience. An English language Master's Degree in "Mathematical Engineering – Advanced Scientific Computing," recently created under the impulse of, among others, the two partner laboratories, will play a piv-

otal role in this part of the project. In addition, undergraduate summer research fellowships will attract bright young students, and expose them to cutting-edge research.

Thematic semester. As an important tool for the achievement of both its research and training goals, CEMPI will organize each year a thematic semester on one of the themes of the project. This initiative will give the CEMPI scientists the opportunity to collaborate over an extended period of time with some of the world's leading researchers in their subject. The scheme thus follows the highly successful model of mathematics research institutes such as the Fields Institute. We note that, starting in January 2012, the Université Lille 1 will be the first university in Europe to be affiliated to Fields. CEMPI will therefore benefit from the many advantages offered by Fields to its affiliated universities.

Socio-economic impact. The understanding and control of complex phenomena occurring in optical fibres, and in atomic physics experiments, will provide new effects leading to exciting opportunities for the development of ultrafast communication technology. The remarkable experimental platforms operated by PhLAM are ideally suited to obtain breakthrough results in this quest. Technology transfer will be enhanced through the creation of a joint laboratory with Draka, the largest worldwide optical fibre producer. In addition, the Centre will publish the courses of its winter schools and support the ongoing efforts of the Departments of Mathematics and Physics in their goal of science popularization.

Governance. Governance of CEMPI is carried out by a scientific coordinator and executive board, together with a steering committee and a scientific advisory board that accompany CEMPI's development strategy. This structure has been designed to ensure a smooth interaction between the two partner laboratories. Technical and secretarial staff handle CEMPI'S daily operation.

Institutional Strategy. The CEMPI project heralds a new era for its two partner laboratories, in the natural continuation of their recent history. The Université Lille 1 supports CEMPI through the opening of junior and senior faculty positions, as well as (post)doctoral fellowships. In the IDEX project "Lille Évolutions", it is projected to be the main building block of an emerging research cluster; in this role, it will have considerable impact on the development of the mathematics and physics communities in Lille, and more generally in northern France.

Conclusion. Through its unique integrated approach to the development of mathematics and physics, simultaneously covering cutting edge fundamental theoretical and experimental research, top quality training, and technological applications, the CEMPI will play a major role in the French and European scientific landscape.

1. Technical and scientific description of the project

1.1. Program description, vision, ambition and scientific strategy

CEMPI: erasing borders

Scientific vision. As the acronym CEMPI suggests, two simple but crucial ideas are central to this LabEx. The first refers to the term "Interactions.'' It stems from the observation that the recent history of the two partner laboratories of the project (Painlevé and PhLAM) has prepared them ideally to make significant innovative research advances at the confluence of mathematics and physics on the one hand, and at the confluence of those disciplines with the other sciences, notably biology and computer science, on the other. The second idea underlying the CEMPI proposal is the conviction that the particular situation of Lille as a European crossroads at the centre of the Paris-London-Brussels triangle constitutes a major asset in the scientific sphere, in very much the same way it does in the economic, political and cultural spheres.

Concerning the first point, a brief account of the recent history of the two laboratories is in order. The Laboratoire Paul Painlevé was created in 2004 in order to bring together the pure and the applied mathematicians of the Université Lille 1 in one structure. In the following years, the decision was made by both the University and the CNRS to strengthen the applied mathematics teams of the new laboratory. A considerable number of junior and senior professors as well as CNRS researchers were hired, particularly in the area of partial differential equations, numerical simulation, scientific computing, probability and statistics. The opening on the Villeneuve d'Ascq campus of a new INRIA research centre in 2007 brought with it the creation of the INRIA team-project SIMPAF, specializing in the numerical study and theoretical analysis of particle and fluid systems. A second such INRIA team in statistics is currently being launched. Over the same period, the mathematicians at Paul Painlevé have developed research contacts with other scientists and laboratories on campus and have instituted new interdisciplinary Master's programs. One such program is of particular relevance to the current project. The "Master's in Mathematical Engineering – Advanced Scientific Computing," an English language program, was created in September 2010 as the result of a joint effort of, among others, mathematicians of Painlevé and physicists of PhLAM.

The "Physique des Lasers Atomes et Molécules" (PhLAM) laboratory was created in 1998, when two laboratories supported by the University and the CNRS decided to join their forces under the direction of Pierre Glorieux. Since then, research at PhLAM has been characterized by close cooperation between experimentalists and theoreticians, and by a constant dialog with scientists belonging to other fields: mathematicians, biologists, chemists, and astrophysicists. This tradition is exemplified by PhLAM's organization of interdisciplinary workshops and seminars supported by the University Lille 1 (through the Fédération de Physique) and the CNRS (PEPS Physique Théorique), and has resulted in close cooperation with several mathematicians from the Painlevé Laboratory. Another consequence of this collaboration has been the participation of both laboratories in the creation of the above mentioned Master's in Mathematical Engineering – Advanced Scientific Computing, which, as will be discussed in Section 1.3, is a central element of the CEMPI training program.

At this point in time, the two laboratories are thus in an excellent position to take their collaborative initiatives to a higher level through the creation of CEMPI. This collaboration will be centred on the theme *NONLINEAR COLLECTIVE DYNAMICS IN COMPLEX ATOMIC AND OPTICAL MANY-BODY SYSTEMS: DETERMINISTIC AND STOCHASTIC ASPECTS*, of Focus Area "The interface of mathematics and physics'' (described in detail in Section 1.2). This interface is not in any way limited to the fields covered by the above theme. In fact, the mathematicians of CEMPI will explore further domains, such as the study of modular forms, as well as of operator algebras, which have applications in other parts of physics, such as string theory. These additional domains form the subject of the two themes of the Focus Area "The interface between mathematics and physics." The international affiliates, that are an essential part of the project, will be of the highest importance here, as is discussed in Section 1.2.

Finally, the reference to "Interactions" in the acronym CEMPI expresses that the CEMPI project has the long-term goal of substantially advancing interactions of other sciences with mathematics, with physics, or both. Members of the CEMPI project already actively pursue two such fields: one at the confluence of physics and biology and one at the juncture of mathematics and theoretical computer science, constituting two further Focus Areas of CEMPI of smaller size. CEMPI will seek opportunities to strengthen them, or to create other such interdisciplinary Focus Areas, depending on where CEMPI will be better placed to produce high impact results for science and society.

Let us now turn to the second core idea of CEMPI, mentioned at the beginning of this section, regarding Lille's central position in Europe. Lille enjoys exceptionally good connections by plane, fast rail and road with all major cities in France, as well as in Belgium, the Netherlands, England and large parts of Germany (by train: Brussels – 35 minutes, Paris – 1h, London - 1h30, Bonn - 3h45). Lille has a local airport with convenient connections to the major French cities. In addition, two international airports are easily reached from Lille: Charles de Gaulle-Roissy (Paris) is a 50 minute train ride away from the centre of Lille, and the Brussels International Airport can be reached by car or train in little over an hour. Lille is an open, pleasant and vibrant city, with a rich cultural and culinary life, a variety of convenient accommodations at reasonable prices, and it is always much appreciated by foreign visitors to the University campus, which lies a ten minute subway ride from the heart of the city.

The CEMPI Labex has taken up the opportunity offered by this exceptional situation by closely associating itself with research teams of the highest quality from selected foreign institutes in neighbouring countries, such as the Universities of Aberdeen and Bristol, Leuven and Louvain-la-Neuve, as well as the Max Planck Institute of Mathematics (Bonn), the Belgian Photonics@be Interuniversity Attraction Pole as well as SISSA (Trieste – Italy). Here, we wish to simply point out that the proximity of many of these institutions will be a major asset to the yearly thematic semesters organized by CEMPI, and will allow for intense collaboration between scientists, e.g. through short thematic working sessions, and create rich opportunities for the centre's Master's and Ph.D. students. The goal is to transform the Villeneuve d'Ascq campus into a meeting ground and focal point for the research subjects central to CEMPI.

Thematic semesters. As an important tool towards achieving its scientific and training goals, CEMPI will organize yearly thematic semesters (February-July) centred on one of the themes of its scientific program. Each semester will comprise

- a two-week Winter School, targeted at doctoral students and junior researchers, presenting at the start of the Semester an overview of its principal topics by leading experts in the field;
- a second year Master course, offered for credit to students at Lille 1 (and to the Universities affiliated with CEMPI);
- two international conferences or workshops;
- a weekly seminar and a CEMPI Distinguished Lecture Series.

The Centre will nominate a Research Chair, chosen for his outstanding scientific reputation in the field, who will be actively involved in the scientific orientation of the semester, and will be invited for its full duration. Top-level researchers in the area will be offered visiting scholarships for long-term participation in the program, and postdoctoral fellows will be hired in the field. The CEMPI Distinguished

Lecture Series will consist of three lectures of which the first will be public and widely advertised. CEMPI, together with its affiliated foreign institutions, already comprises a large base of excellent scientists. This will be key to the organization of major scientific programs. In addition, affiliation with the Fields Institute provides a source of funding through the Institute's General Scientific Activity program, and creates the opportunity to publish Winter School and Workshop lectures in the Fields Institute Communications Series, as well as the material of the special Master course in the Fields Institute Monograph Series. The organization of thematic semesters is thus a crucial vehicle to achieve the scientific aims of the CEMPI project, by bringing the world's top researchers in a given field to the Université Lille 1 campus for an extended period of time, thus fostering intense collaboration and joint publication with the CEMPI scientists.

Infrastructure. The Villeneuve d'Ascq campus of the Université Lille 1 has the full infrastructure needed for the organization of workshops, conferences, and summer schools. The Department of Mathematics possesses a pleasant, well-equipped lecture hall that seats fifty, and is reserved for this purpose. Similarly, PhLAM has a larger lecture hall seating about 100. In addition, within the context of the Campus Grand Lille project, a learning centre with a large amphitheatre will be built in the coming years on the Villeneuve d'Ascq campus, as well as housing for guest scientists and students. Both laboratories, and in particular their technical and administrative staff, bring to the project a well-established tradition of welcoming long and short term foreign visitors[1], and of organizing thematic semesters as well as major scientific events. As an example, in June 2010 and June 2011, the Painlevé laboratory organized two major international conferences in Le Touquet with the help of funding from the region "Nord-Pas de Calais"; each had a budget of about 50Keuros. Similarly, PhLAM organized the "Eleventh Experimental Chaos and Complexity Conference[2]," in June 2010 on the Villeneuve d'Ascq campus. Also, the "Twenty Second Banach Algebra Conference" is scheduled to be hosted by the Painlevé laboratory in 2015.

Pull effects and strategic vision. A distinctive feature of CEMPI is the existence in Theme 1 of two continuous chains of interconnects ranging all the way from pure mathematics to experimental physics or industrial applications[3]. The strategy of CEMPI will be to develop other such interdisciplinary chains, thereby creating a research and training unit that will be quite unique on the national and international level. The advisory board will be consulted regularly on this aspect of CEMPI strategy. The creation of CEMPI will reshape the mathematics and physics communities in Lille and northern France in major ways. First, the activities of the centre will greatly increase the national and international attractiveness of the mathematics and physics Master's and Ph.D. programs by offering graduate students immediate access to a range of top level scientists from neighbouring countries, regarding both their course selection and internships. This will result in an increased student population of high quality. The ensuing benefits for both the quality and quantity of the scientific production of the mathematics and physics communities in Lille are self-evident. Moreover, the professional opportunities offered by the presence of CEMPI will provide the mathematics and physics departments of northern France in general and of Lille in particular with an addi-

[1] Which every year include about 20 invited scientists, who visit for one or several months, financed by the Université Lille 1 or the CNRS.

[2] http://nonlineaire.univ-lille1.fr/ECC11/

[3] See Section 1.2 for details.

tional tool to attract top level faculty, the quality of which will in turn be crucial in maintaining the high standards ensuring the long term success of the Centre.

On-site strategy. The CEMPI project is, within the IDEX "Lille Évolutions", the main building block of an emerging cluster. The university will accompany the Labex through the hiring of eight permanent junior and senior faculty and 16 (post)doctoral fellows. In the first four years of operation of CEMPI, one senior and one junior position will be opened in the fields that lie at the intersection of Painlevé and PhLAM. The successful candidates will be expected to have a double competence, enabling them to interact both with the mathematicians and physicists of CEMPI, enhancing the interaction between its two partner laboratories. Such interdisciplinary positions have recently been successfully created at the CNRS[4]. The other positions will be used in accordance with CEMPI's development strategy.

1.2. SCIENTIFIC DESCRIPTION OF THE RESEARCH PROJECT

The unreasonable effectiveness of mathematics, Eugene Wigner

In this section, we give a detailed description of the CEMPI research project. We structure the presentation along the lines outlined in the summary with which this document starts: a major Focus Area centred on the interface of mathematics and physics, with three themes, and two additional Focus Areas for interdisciplinary research on the borderline between biology and physics on the one hand, and on mathematics and theoretical computer science on the other.

FOCUS AREA 1: THE INTERFACE OF MATHEMATICS AND PHYSICS

THEME 1: NONLINEAR COLLECTIVE DYNAMICS IN COMPLEX ATOMIC AND OPTICAL MANY-BODY SYSTEMS: DETERMINISTIC AND STOCHASTIC ASPECTS

If you attack a mathematical problem directly, very often you come to a dead end [...] and you feel that if only you could peer round the corner,

there might be an easy solution.

There is nothing like having somebody else beside you, because he can usually

peer round the corner. [M. Atiyah, Collected works, vol. 1, paper 12, p. 233]

The general setting. Describing, understanding, predicting and controlling the complex physical phenomena occurring in nonlinear classical or quantum dynamical systems with a large or infinite number of degrees of freedom provides many outstanding challenges in mathematics and in many fields of physics. How does a collective dynamics emerge from the interactions of individual entities? What are the system's ergodic properties and how are asymptotic states, if they exist, approached? What are their properties? What instabilities occur and how can one control them? Although general principles and techniques to handle such questions have been developed over the last decades, they are not universally applicable, and a great variety of the observed complex phenomena remain badly understood. When nonlinearities are combined with fluctuations coming from either quantum mechanics or from stochastic forcing, many additional fascinating physical phenomena appear that are hard to explain and control.

The CEMPI distinction. To make progress on questions of such generality, it is often fruitful to analyse specific systems. The CEMPI Labex will concentrate on the experimental, theoretical and mathematical study of the interplay between

[4] A "Chargé de Recherche" in biophysics was appointed in PhLAM in September 2011.

dynamical determinism and fluctuations in three selected nonlinear systems: cold-atom experiments, light pulses in optical fibers and relativistic electron bunches. Those systems, for which PhLAM disposes of outstanding experimental facilities, offer key advantages. First, from the experimental perspective, since time scales are very short, many data can be collected in a limited time. Secondly, many quantities are easily measured and control parameters can be flexibly adjusted. Finally, from the theoretical perspective, accurate models for these experimental systems can be derived from first principles and one then observes that they have closely related mathematical descriptions, based on nonlinear PDE such as the nonlinear Schrödinger equation and its perturbations, or on various kinetic equations. The Painlevé experts in dynamical systems theory and the analysis of partial differential equations, in scientific computing, in stochastic processes, and in mathematical physics, will contribute their mathematical know-how to make progress on elucidating the observed phenomena. CEMPI will thus build on its unique spectrum of expertise, spanning the full range from pure mathematics to experimental physics. In fact, tight integration between theory and experiments and a strong background in dynamical systems theory, hallmarks of the Laboratoire PhLAM, will facilitate the interaction with the mathematicians of Painlevé.

Scientific goals. The first part of this theme revolves around two sets of problems in *quantum chaos*. The first one concerns the effect of interactions, modeled by a nonlinearity in their evolution equation, on the localization properties of quantum kicked rotors, experimentally realized in cold-atom experiments. The Quantum Chaos Group at PhLAM has gained international reputation for their experimental work on non-interacting kicked rotors, which are equivalent to the Anderson model and in which they made the groundbreaking observation of the famous Anderson transition. The group will develop a new experimental setup to test the effects of interaction on these questions in a Bose Einstein condensate of ^{39}K atoms. Recently, with D. Delande (Ecole Normale Supérieure), it initiated an ANR-funded theoretical and numerical study of the effects of interactions between the atoms on their localization properties. This work will require the accurate very long time numerical simulation of the nonlinear system. The derivation of long time integrators for ordinary or partial differential equation, a specialty of the applied mathematics team in CEMPI, will prove invaluable. In addition, conceptual problems arise as well. For example, controversy in the literature suggesting the very definition of "localization" should be re-investigated in this new context will be explored using the expertise the mathematical physicists of CEMPI in such issues. In fact, on the mathematical level, the long time behavior of kicked systems, even linear ones, is not well understood when the kicks are strong, and difficult even when the kicks are weak. It is then of interest to see if the few results valid for arbitrary kick strengths extend to the nonlinear situation.

The second set of quantum chaos problems in this project concerns the semi-classical analysis of quantum systems with a chaotic classical limit. For *confined systems*, such as particles in a potential trap, or geodesic flows on compact manifolds, a central question is the semi-classical limit of the quantum eigenfunctions. There is great interest in this subject, as witnessed by the recent Fields Medal (2010) awarded to E. Lindenstrauss, in part for his work on such issues. Many questions remain open, in particular on the characterization of the possible semi-classical eigenfunction limits in terms of the ergodic properties of the underlying classical Hamiltonian dynamics. The Université Lille 1 supported recently hired faculty of Painlevé with a "Bonus Qualité Recherche" grant (2011-

2013) to work on these topics at the intersection of spectral analysis, geometry and Hamiltonian dynamics, and number theory. On a related issue, the characterization of chaotic dynamical systems of low or intermediate dimension using mathematical tools such as knot and braid theory, singularity theory and simplicial homology, for which there is a tradition at PhLAM, will be further explored; the algebraic topologists of Painlevé will bring welcome new expertise to this project.

Unconfined systems, i.e. systems with an unbounded phase space, are another playing field for quantum chaos. The non-interacting kicked rotor, already mentioned, is a first example. A second one are cold atoms in optical lattices, an analogue of the Lorentz gas. On the classical side, one question is the role of the local dynamics on global transport properties. Another concerns the dynamical mechanisms for approach to equilibrium in such systems, when coupled to an infinite dimensional reservoir or their behavior under stochastic forcing. The works by the physicists and mathematicians of CEMPI on these subjects concern similar systems in different regimes. Their complementary viewpoints, and the possibility of realizing them experimentally, will lead to fruitful interactions on the many open questions in this field. On the mathematical side, this research involves aspects of Hamiltonian perturbation theory, as well as stochastic processes and stochastic differential equations, for which Painlevé offers valuable expertise. The quantum dynamical behavior of those systems and its comparison with the underlying classical dynamics, constitutes a further long term CEMPI research project.

It is clear from what precedes that quantum chaos provides a first example of a chain of interconnects within CEMPI, reaching all the way from pure mathematics to experimental physics.

Let us finally point out that the Department of Mathematics of the University of Bristol – a CEMPI partner - has very strong groups working on quantum chaos and on ergodic theory, which will bring their expertise to CEMPI.

The second part of this theme concerns the study of *optical fibers*, in particular photonic crystal fibers (PCF), which are key to information and communication technology, and form an unmatchable platform to explore complex nonlinear phenomena. Variants of the NonLinear Schrödinger Equation (NLSE), which govern their evolution are indeed relevant to many fields of physics. The versatility of the PhLAM fiber fabrication facility, together with CEMPI expertise in the theory and mathematics of nonlinear propagation, will lead to original research approaches. It will be clear from what follows that this theme provides a second example of an long chain of interconnects within CEMPI, linking technological applications to pure mathematics via experimental and theoretical physics.

A first topic are optical “rogue waves” (RW), a term originally designating abnormally high ocean surface waves, sometimes associated with mysterious shipwrecks. Although such waves do indeed exist, and are much more common than was thought, their nature and origin are still much debated. Experimental evidence of optical rogue waves in a fiber system has been established recently, notably at PhLAM in the continuous (CW) regime, and has received considerable attention since. Indeed, the self-focusing NLSE equation describes the dynamics of both optical RW and ocean RW so that the study of the one could provide insight into the other. Moreover, controlling the generation of high-energy pulses in optical systems would be extremely useful. Recent PhLAM publications have identified a possible mechanism for the formation of optical RW. CEMPI physicists and mathematicians propose to further study them in a two-pronged strategy. First, in a dynamical approach, they will explore the effect of various perturbations of the NLSE on RW formation. The perturbed NLSE contains a nontraditional mix of second and third order derivatives with nonlinearities, each term inducing different effects in various asymptotic regimes. As a first step, the mathematicians will therefore focus on linking the behavior of the solutions to the different physical parameters. Questions of regularity, long time properties of solutions and existence of solitons will be assessed, as well as the possible role of soliton collisions in rogue wave formation. For the numerics, asymptotic preserving schemes will have to be derived to take into account small parameter regimes and the understanding of the behavior of the solutions with respect to boundary conditions or initial data will require specific numerical integrators. This part of the program was initiated about six months ago and is currently under way. Second, we will try to explain the slowly decaying L-shaped probability distribution of rogue wave intensity. We will investigate how the properties of this distribution depend on the various terms in the underlying equations and on the random initial data. This research will be the object of a collaboration between the physicists of PhLAM and the probabilists of Painlevé working on statistical mechanics problems.

Optical fibers are also ideal laboratories for exploring open questions in statistical mechanics. In a second topic, we will study experimentally and theoretically nonlinear propagation of localized waves in spatially modulated fibers fabricated at PhLAM. A periodic variation of dispersive and nonlinear properties induces nontrivial behavior in ultrashort solitonic waves or modulationally unstable optical waves. In the latter situation, the generation of multiple spectral resonances due to spatial periodicity has recently been evidenced at PhLAM. We will investigate how this affects a quasi-periodic behavior observed, which is equivalent to a Fermi-Pasta-Ulam recurrence. A third topic is wave turbulence. When incoherent light propagates in a nonlinear optical fiber, interactions between spectral components drive its optical spectrum towards an equilibrium state. If nonlinearities are small, the equilibrium state can be obtained from weak-turbulence theory, which applies to a variety of physical problems but still lacks quantitative comparisons with experiments. A first test of theory will be to observe and characterize the predicted but not yet observed thermalization and wave condensation. On the theoretical side, it is important to understand when other descriptions such as interacting soliton gases become necessary to describe fully nonlinear regimes. These two physical problems are connected with mathematical studies of the approach to equilibrium.

The third part of this theme concerns the dynamics of *electron bunches*. The emission of radiation by accelerated charged particles is exploited in large light source facilities such as storage rings and Free-Electron Lasers (FELs). However, relativistic electron bunches traveling around storage rings or in linear accelerators are hard to control as they display a very complex collective nonlinear dynamics. PhLAM is a leading actor in this field, and has privileged access to the SOLEIL (France) and UVSOR (Japan) synchrotron facilities. Understanding the complex spatio-temporal dynamics observed at high gain in these devices is key to extending their operational domain but can also suggest breakthrough mechanisms, such as for generating high-power coherent radiation in the teraHertz range by microstructuring electron bunches.

THEME 2: ALGEBRAIC GEOMETRY, MODULAR FORMS, WITH APPLICATIONS TO PHYSICS

State of the art and relevance of CEMPI. We first describe the rich variety of work in this field done by the mathematicians of CEMPI, with several applications in physics. The automorphic product discovered by R. Borcherds (Fields Medal 1998) relates different mathematical subjects such as vertex algebras, Kac–Moody algebras, modular forms and algebraic geometry. In physics it was used by ICM speaker Dijkgraaf. Gritsenko–Hulek–Sankaran (GHS) applied it to the last open problem in Weil's program on moduli of K3 surfaces, a result reported by C. Voisin at the Bourbaki seminar. Between 1997 and 2000, Gritsenko and Nikulin classified reflective modular forms that are denominators of Lorentzian Kac-Moody algebras, and this work today counts more than 120 citations from the physics literature. An efficient basis for the work on this theme is the permanent French–German seminar on modular forms between the universities of Lille, Aachen, Köln, Siegen and the Max Planck Institute in Bonn[5].

The higher-dimensional analogs of K3 surfaces, discovered by A. Beauville, are irreducible symplectic varieties (ISV). They have been intensively studied by both mathematicians and physicists: Aspinwall–Morrison, Debarre–Voisin, Gukov–Vafa–Witten, Huybrechts, Markushevich, Mukai, O'Grady and others. The ISVs are the main object of study of the ANR project VHSMOD (2009–2012), coordinated in Lille, with the Collège de France, ENS d'Ulm, the Universities of Grenoble and Nantes as further nodes.

The ISVs have two aspects, a geometric one and an arithmetic one, related by the fact that geometric properties of ISVs are reflected by their lattice polarization. The GHS method extends to moduli of ISVs. In the Number Theory and Algebraic Geometry Group of the Lab. Painlevé, related objects are intensely studied: moduli spaces over number fields, Shimura varieties, analyzed in terms of representations of the absolute Galois group and automorphic forms and profinite towers of moduli spaces, which are a topic of two Marie Curie European networks GTEM, coordinated in Lille.

The ISV's have many links to other domains well represented at CEMPI. CEMPI researchers are currently developing the analytical counterpart of the theory of symplectic varieties, studying the topological and analytical aspects of singularities as well as quantization in the presence of phase space singularities. Other areas of interest include the study of algorithmic and complexity problems for desingularizations and stratifications of algebraic varieties whose Hodge-theoretic aspects lead to the theory of motives.

Concerning this last point, we recall that the theory of motives was boosted by M. Kontsevich, who applied motivic integration to a proof of physicists' conjectures on mirror symmetry for Calabi-Yau manifolds. It is an extremely active field today, due to powerful applications in geometry, representation theory and to the Langlands Program. The foundational paper by Denef–Loeser, reported by Denef at ICM, counts more than 120 citations. Recent developments are due to collaborations between Leuven, Paris, and Lille, which has in particular lead to a proof of the Fundamental Lemma of the Langlands Program by CEMPI researcher R. Cluckers and co-workers T. Hales and F. Loeser, based on the work of B. Ngô (Fields Medal 2011).

Scientific goals. Problems on ISVs: (1) New constructions of ISVs, smooth or singular, via symplectic groups actions, Lagrangian fibrations, or as moduli spaces of objects on varieties with symplectic-like pieces in derived categories. (2) Extending the Gritsenko-Hulek-Sankaran (GHS) method to new lattices,

[5] MPIM is affiliated to CEMPI.

including those of singular ISVs, and to lattice polarizations of rank >1. *Problems beyond ISVs:* (3) Application of the GHS method to other arithmetic quotients which are moduli of conformal field theories. (4) Constructions of new reflective modular forms with applications to Kac-Moody algebras, string theory and partition functions of quantum microstates of supersymmetric black holes. (5) Understand the significance of classical phase space singularities in quantum problems and in particular the arisal of an unexpected tunnelling effect between singular strata, opening the door to a huge unexplored territory. (6) Applications to coding theory, related to Focus Area 3 of the present project. *Further ramifications:* (7) Study of Uhlenbeck-Donaldson and Feehan–Taubes type compactifications for moduli of (framed) sheaves (a joint project with SISSA[6] in Trieste). (8) Constructions of J-holomorphic curves and exploring the associated topological field theories. (9) Producing algorithms of moderate complexity for resolutions and stratifications of singularities. (10) Study of the space of arcs of 3-dimensional singularities via deformations of surface singularities. *Motives:* (11) Further development of motivic Fourier analysis on vector spaces over local fields. A far-reaching goal is to build a full motivic version of Fourier analysis for all locally compact groups, starting by algebraic groups over local fields.

THEME 3: OPERATOR ALGEBRAS AND SPACES, QUANTUM GROUPS WITH APPLICATIONS TO PHYSICS.

State of the art and timeliness. This part of the project explores the fruitful interplay between functional and harmonic analysis via operator algebra and operator space theory. Originating from the mathematical formulation of quantum mechanics, the former has direct applications to physics, especially quantum statistical mechanics and quantum field theory, and to numerous mathematical disciplines, such as representation theory, ergodic theory and differential geometry, in particular through the seminal work of Fields Medalist A. Connes. The recent theory of operator spaces, or "quantized functional analysis", has had a transformative impact on abstract harmonic analysis. There is currently great worldwide interest in these fields, as witnessed by major, innovative monographs by E.G. Effros and Z.-J. Ruan, and G. Pisier. We also note thematic programs in these subjects – of six months at the Fields Institute (in 2007 and planned for 2014, with lead organizers G. Elliott, respectively, A.T.-M. Lau and M. Neufang), and of three months at the Institut Henri Poincaré (in 2011, organized by D. Gaboriau, S. Popa and S. Vaes) – and the series of large international conferences on Banach Algebras, planned for 2015 in Lille with CEMPI researchers as lead organizers.

Scientific goals and relevance of CEMPI.

Towards Harmonic Analysis on Quantum Groups. A fascinating framework for the fruitful interaction of the above-mentioned fields is the theory of locally compact quantum groups, as presented in 2000 by J. Kustermans and S. Vaes. Topological quantum groups have attracted the attention of mathematicians and theoretical physicists since Fields Medalist V.G. Drinfeld's 1986 ICM talk. Kustermans–Vaes's theory provides the perfect setting for Pontryagin duality beyond locally compact abelian groups, as well as for non group-like deformation algebras arising in mathematical physics, such as S.L. Woronowicz's famous twisted SU(2) group. CEMPI forms a unique cluster of expertise to significantly advance the present rapid development of harmonic analysis on locally compact quantum

[6] SISSA is affiliated to Painlevé.

groups. In particular, S. Vaes (invited speaker at ICM 2010) and A. van Daele, both at the CEMPI affiliated institution K.U. Leuven, have played a pivotal role in the creation of modern quantum group theory. As a sample research direction at CEMPI, we mention the representation theoretical model for completely bounded multiplier algebras over quantum groups, developed by M. Junge, M. Neufang, Z.-J. Ruan, and N. Spronk. This representation allows the expression of quantum group Pontryagin duality as a commutation relation. Subsequently, various specific classes of multipliers are being studied by the CEMPI operator algebra specialists and collaborators. M. Kalantar and M. Neufang have shown that certain invertible multipliers can be identified with elements of the intrinsic group of the dual quantum group. This leads to quantum group invariants – in particular generalizing Heisenberg's bicharacters – whose determination is an important task. The new representation is also naturally linked with the quantum analogues of the convolution and pointwise product, defined on the space of trace class operators *T(H)* over the Hilbert space *H* of a quantum group, as first investigated by M. Neufang in the commutative case. Kalantar-Neufang have recently derived a formula that links both products via a certain anti-commutation relation on the tensor product level. This may be the starting point for an abstract duality theory beyond quantum groups. Numerous intriguing problems arise from this circle of ideas, some of which have been studied by Z. Hu, M. Neufang and Z.-J. Ruan. CEMPI is ideally suited to make most important progress on this program including the systematic study of convolution algebras over locally compact quantum groups, and thus the development of quantum harmonic analysis.

Dynamical Systems and Ergodic Theory. In this extremely active area, probability, functional analysis, harmonic analysis and group theory meet in a mutually stimulating fashion. Given an operator *T* on a Banach space *X*, one considers the iterates of *T* as a discrete dynamical system. While properties such as chaos, mixing, and topological transitivity are usually associated with non-linear phenomena, for infinite-dimensional *X* all these are possible in the linear setting. A recent significant treatise on these topics is due to F. Bayart and CEMPI researcher E. Matheron. Several important results on linear dynamical systems, e.g. concerning the construction of natural invariant measures for *T* and the study of their ergodic properties, were obtained by CEMPI mathematicians C. Badea, S. Grivaux, and collaborators E. Abakumov, A. Atzmon, T. Eisner, V. Müller, and M. Roginskaya. Of fundamental importance are operators of convolution with probability measures on a locally compact group, leading to the study of harmonic functions. These form an algebra of functions on the Poisson boundary, an object studied extensively since H. Furstenberg's seminal work. M. Izumi initiated the investigation of Poisson boundaries associated with quantum groups. W. Jaworski and M. Neufang have given a description of the Poisson boundary for a natural non-commutative dynamical system via a crossed product formula, answering a problem raised by Izumi. This result has recently been extended to random walks on locally compact quantum groups by Kalantar-Neufang-Ruan. Clearly, amenability is a central notion in quantum group theory, and concepts such as Kazhdan's property (T) and the Haagerup property – also known as Gromov's a-T-menability – are being studied in the quantum group setting. These play a significant role in geometric group theory, an intriguing connection with Theme 6 of CEMPI. With Lille and Bristol, CEMPI creates a unique combination of research strengths in the latter field with operator algebras, quantum groups and dynamical systems; we note in particular the strong functional and harmonic analysis group at CEMPI. At the same time, our representation theoretical approach allows for a similar study of large algebras, such as biduals, creating fascinating links to the Kadison–Singer Conjecture which is closely related to the operator convolution product mentioned above.

Applications to Quantum Information Theory. Our representation gives rise to intriguing new classes of quantum channels, stemming from quantum group actions. These are of great interest in quantum information theory, in particular since channels from dual quantum groups commute, and are noiseless with respect to the dual quantum group. In the finite-dimensional situation, the completely bounded minimal entropy has been calculated explicitly by Junge-Neufang-Ruan, and the structure of their fixed points is known, thanks to the description of the Poisson boundary, due to Kalantar-Neufang-Ruan. Using methods developed by U. Haagerup and M. Musat in 2011, J. Crann and M. Neufang have shown that a certain class of these channels disprove the famous Asymptotic Quantum Birkhoff Conjecture; the first counter-examples to the latter, which is also related to one of the most fundamental open problems in operator algebra theory, Connes's Embedding Conjecture, were found by Haagerup-Musat (2011) and, independently, by D. Ostrev, A. Oza and P. Shor. Much more is to be expected from these quantum channels! A related fascinating question is to find a quantum mechanical interpretation, or even experimental implementation, of the quantum convolution and pointwise product of density operators in *T(H)* over a quantum group. CEMPI is ideally placed to make advances of great impact on these problems, through the expertise in quantum optics and cold atoms at PhLAM, and in mathematical physics at Painlevé and at its affiliated foreign institutes Bristol and Leuven.

In addition to the main Focus Area just described, there are two emerging interdisciplinary Focus Areas, that will be further developed in the course of the project, and that currently engage about 35% of CEMPI researchers.

FOCUS AREA 2: THE INTERFACE OF PHYSICS AND BIOLOGY

Genome sequencing efforts have greatly improved our vision of how inheritable biological information is structured. However, more is needed to understand how life can make complex decisions in complex environments. Genomes are in fact highly dynamic, with gene activities varying in time and across cell types. Real-time monitoring of the molecular state of living cells, thanks to sophisticated microscopy techniques and fluorescent reporters, has revealed how the complexity of life unfolds both in time and space. Genomic and imaging approaches have confirmed that most biological functions do not depend on isolated genes or molecules but on complex webs of interactions, which are dynamic, spatially organized and strongly nonlinear. This must be taken into account when designing therapeutic strategies or diagnoses, since the level of one molecular actor or its response to a perturbation is affected by the whole network.

We will use the expertise of PhLAM in nonlinear dynamics, systems and computational biology, nonlinear optics and molecular physics to bring new insights into the dynamics of living systems, theoretically and experimentally. Our project will leverage existing and emerging collaborations with the biophotonics and biological nano-systems groups at the Interdisciplinary Research Institute (IRI) in Lille, who have complementary competences in biology, biophotonics, statistical physics and molecular dynamics. A distinctive asset is the strong link established between PhLAM and the Institute for Complex

Systems and Mathematical Biology of the University of Aberdeen[7] directed by Celso Grebogi, a leading expert in complex systems and nonlinear dynamics. This collaboration connects CEMPI with the well-developed UK network of systems biology centres. Painlevé laboratory expertise in probability theory and stochastic processes as well as in partial differential equations will be useful in the development of the project.

Mathematical models provide a coherent view of a biological interaction network. Working with biologists, we will construct such models from quantitative analyses of experiments and explore them to unveil the design principles which underlie information processing and robust decision making in living cells. A PhLAM publication, highlighted by CNRS in its 2010 scientific report, has thus shown how oscillator physics is exploited by a microscopic alga to build a biological clock insensitive to external fluctuations. Similarly, concepts from nonlinear dynamics coupled to advanced imaging methods will be harnessed to understand how biological networks organize themselves to ensure robust orchestration of cell decisions, appropriate responses to oxidative or thermal stress, or self-organization in slime molds. Understanding how robustness to fluctuations emerges from network-level properties and how biological functions utilize noise is also a goal.

The synergy between theory, mathematics and experiments in the CEMPI project will be highly beneficial to PhLAM and Painlevé members as well as to their partners at IRI. Physicists, with their combined competences in theory and experiments, will be key to connect mathematicians to biologists. Mathematicians in collaboration with physicists will be essential to develop new concepts and to adapt dynamical system theory, which was shaped by celestial mechanics, to the unique properties of living systems.

FOCUS AREA 3: THE INTERFACE OF MATHEMATICS AND THEORETICAL COMPUTER SCIENCE

THEME 1: ALGEBRAIC TOPOLOGY, HIGHER CATEGORIES, OPERADS WITH APPLICATIONS TO THEORETICAL COMPUTER SCIENCE.

State of the art. In this part of the CEMPI project, we explain recent research in algebraic topology, as well as new promising interplays, which we will develop between this branch of mathematics and various topics of mathematics and theoretical computer science. The theory of higher categories, together with the language of operads and homotopical algebra, provide the common mathematical background which deeply links this research. First, in the domain of mathematics, higher categories and operads have recently been used in significant advances on the definition of the chiral homology theory which models fine topological invariants associated to manifolds. In this approach, the connection between the topological objects and their chiral invariants is encoded by higher categorical structures derived from E_n-operads, a significant class of operads initially introduced in topology. Recent work by CEMPI researcher B. Fresse providing a precise relationship between homotopy automorphisms of E_2-operads and Grothendieck-Teichmüller groups, hints at new connections between this subject, and a striking theme of Kontsevich: the applications of Grothendieck-Teichmüller theory to the deformation-quantization process in mathematical physics. Closely related applications of E_n-operads in topology concern the branch of rational homotopy theory, of which applications have

[7] A CEMPI affiliated institute.

greatly been developed by fruitful exchanges between the universities of Lille and Louvain-la-Neuve, a CEMPI affiliate institute. In computer science, our proposal is motivated by recent work of colleagues of the laboratory PPS (Paris) showing that higher categories and homotopical algebra methods provide a suitable framework for the study of rewriting problems and foundational issues in programming language semantics.

Scientific goals. In topology, our main objective is to define a Sullivan type model for chiral homology, and for similarly defined homology theories (arising from applications of quantum field theory ideas), in order to work out an effective version of the corresponding topological invariants. To realize this program, we will rely on the expertise of the Lille centre in rational homotopy, operad theory, and string topology. The main milestone of this research, which is the core objective of a new ANR grant "HOGT" (based in Lille, 2011), is the definition of higher dimensional versions of the Grothendieck-Teichmüller groups (as groups of homotopy automorphisms of operads) in order to model internal symmetries of chiral homology. This research, at the junction of topology, higher category theory, mathematical physics, and arithmetic, will involve the expertise of the corresponding research groups of the CEMPI project. The computer science part of our program will be addressed in close cooperation with colleagues of the computer science laboratory PPS), building further on recent fruitful interactions, as witnessed by the participation of a PPS team to the CNRS research network GDR2875 "Topologie Algébrique et Applications", and by the joint supervision of students for research training. In this collaboration, we mostly intend to investigate an emerging connection between homotopy theory and type theory, which provides a new insight on foundational issues in programming language semantics. The basic idea is that the traditional notion of equality between programs should be replaced by a notion of homotopy deformation describing how two programs are equal. In a related domain, recent work by Lafont-Métayer-Worytkiewicz provides a solid basis for the applications of homotopical algebra methods to the definition of new computational invariants, and we also aim to develop this subject.

THEME 2: GRAPHS AND GROUPS WITH APPLICATIONS TO THEORETICAL COMPUTER SCIENCE

State of the art. Graphs appear in virtually every science, from Biology to Physics. Recently, many programmes (counting among their participants several CEMPI researchers) have focused on knowledge exchange on graphs: "Limits of graphs in group theory and computer science", (Bernoulli Center, Lausanne, 2007); "Metric geometry, algorithms and groups", (Institut Henri Poincare, Paris, 2011); "Discrete Analysis" (Isaac Newton Institute, Cambridge, UK, 2011); `Quantitative Geometry' at MSRI, Berkeley, August 15 - December 16, 2011. In computer science, many problems are solved by embedding a combinatorial structure into a well-understood metric space. Two classes of graphs are important here: expander graphs, much used in computational complexity theory, coding theory, cryptography and median graphs, relevant in algorithm design, optimization theory, phylogenetics etc. Many constructions of expanders come from Cayley graphs (e.g. quotients of groups with property (T), such as arithmetic lattices). This meets an older theme in mathematics, connecting combinatorial structures of groups/graphs with the structure of spaces the groups acts on. Instances of this theme are the theory of hyperbolic groups, of properties (T) and Haagerup/a-T-menability, the use of triangulations of manifolds to solve topological problems. Uniform embeddings into Banach spaces became main stream when their relevance to the conjectures of Novikov and Baum-Connes was displayed through work of G. Yu, M. Gromov and V. Lafforgue. Gromov devised a notion of random group to prove the existence of groups containing expanders in their Cayley graphs, thus not uniformly embeddable. Random groups are hyperbolic (result of Gromov) and have property (T) (result of Zuk). A parameter called compression measures how well a certain group can embed into a Banach space. A. Naor and Y. Peres (both at Microsoft Research) related the compression to the speed of divergence of random walks. Their arguments use Markov processes and Functional Analysis techniques (due to the late Nigel Kalton).

Scientific goals: We propose a set of problems, several of which have been formulated by Computer Science specialists.

Property (T), a-T-menability. Several strong versions of property (T) satisfied only by higher rank lattices were recently discovered and studied by V. Lafforgue and by several CEMPI researchers.

Our goals are to understand the relationship between these properties; to study the randomness of these strengthened versions of (T); to find the minimal density ensuring that random groups have property (T) (below one third, according to Zuk), and the maximal density granting random a-T-menability.

Expanders and coding. We will investigate if finite quotients of groups with strong versions of property (T) are expanders satisfying stronger properties; if generic expanders may embed uniformly into uniformly convex Banach spaces; if other explicit examples of non-embeddable expanders exist, besides the arithmetic constructions of V. Lafforgue. Various algebraic geometry constructions yield error-correcting codes, and there are many interesting problems to investigate in this setting: the properties of the limit curve, the relations between the normalized coding distance and the capacity of codes etc.

Compression, median graphs. Many classes of groups are relevant for the problems presented: lattices in Lie groups, Coxeter groups, braid groups, mapping class groups, Thompson's group, etc. Our goals are to find for which classes or sub-classes the Naor-Peres inequality becomes an equality; to find the possible values of compression in each (sub)class (it is known that any number between 0 and 1 is the compression of some group); to combine these with recent results by CEMPI researchers to provide a better understanding of the compression and new examples of median spaces.

The CEMPI contribution. The CEMPI researchers possess a wide spectrum of expertise that covers nearly every mathematical tool required for the success of the project. A very strong group works on the geometry of hyperbolic and relatively hyperbolic groups, property (T) and Haagerup, and combinatorics of hyperbolic reflective groups. There is also a lot of activity on harmonic analysis on graphs, combinatorics of finite graphs and cellular automata. The importance of randomness in the study of discrete structures and high-dimensional phenomena is one of the key mathematical discoveries of the last thirty years and in this respect CEMPI is fortunate to have experts in the theory of Markov processes, Brownian motion, geometry of Banach spaces, spectral theory and harmonic analysis.

The expertise of the algebraic geometry group of CEMPI will allow to study error-correcting codes arising from constructions of algebraic geometry. CEMPI researcher D. Grigoryev's research branches also toward Kolmogorov complexity with applications to issues around the 13-th Hilbert problem. The coding theory (in particular the binary Golay code and the Mathieu groups) is a main tool of a new research project in this direction.

The work on this part of the CEMPI project will also greatly benefit from the expertise in the affiliated research groups from the University of Bristol, Leuven and Louvain. The ANR Blanc 10-BLAN 0116 (2010-2014, based in Lille) and ANR Blanc "Facettes des groupes discrets" (2011-2015, pole at Lille) also closely connect to this project.

1.3. Impact on training

The training of interdisciplinary scientists from the Masters to the postdoctoral level will be an essential part of CEMPI's activities. Strong emphasis will be placed on early contact with cutting edge research, on international experience, and on job placement. Below, we first describe the current organization of the mathematics and physics education in Lille, to then explain in which ways it will be boosted and transformed through the activities of CEMPI.

Master's and Ph.D. degrees: the current situation. In France, the two year Master's program follows a three year Bachelor's degree, which starts after high school. The Mathematics Department of the Université Lille 1 offers a large variety of Master's degrees (evaluated A by the AERES) of which the Painlevé mathematicians are the principal organizers. In addition to two research oriented Master's programs in pure and applied mathematics[8] a training program for high school mathematics teachers, and a program in statistics, it has recently (2010) created two new diplomas, one in mathematical finance, and one in scientific computing[9]. The goal pursued with these programs is to improve the attractiveness of mathematics studies by offering an increased variety of career options. Similarly, the Physics Department of the Université Lille 1 offers a Master's degree[10] (evaluated A by the AERES) in which PhLAM is strongly involved, with several options leading either to an academic or an industrial career. Ph.D. students are recruited from the research oriented Master's degrees, from the Ecoles Normales, and from abroad. The mathematics graduate program belongs to the "Ecole doctorale" SPI, the physics one to "SMRE."

Master's and Ph.D. degrees: the CEMPI distinction. The Master's degrees particularly relevant to the CEMPI project are the three research Master's degrees and especially the recently created English language interdisciplinary "Master's in Mathematical Engineering: Scientific Computing" (evaluated A by the AERES) a joint venture of, among others, Painlevé and PhLAM faculty. The latter attracts mathematics and physics bachelors, but also other science students. Rather than adding a different Master's degree to this already rich offer, we have found it more pertinent to further strengthen these degrees, through the following three-pronged strategy, that we will also apply to the Ph.D. programs:

- Boost the recruiting of top quality students;
- Internationalize the Master's and Ph.D. training;
- Boost the job placement.

Recruiting and internationalization. There are two additional student populations

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8 In collaboration with the Universities of Artois, Calais and Valenciennes and the Universities of francophone Belgium.

9 http://mathematiques.univ-lille1.fr/Formation/Masters-de-l-UFR-de-Mathematiques/

10 http://master-physique.univ-lille1.fr/

from which we wish to draw for our Master's programs, beyond the traditional ones issued from the Lille mathematics and physics Bachelor's degrees. First, increasing numbers of French engineering students wish to complete their training with a Master's or Ph.D. in science. In France engineering schools are mostly separated from the university campuses and it is currently a recognized challenge to attract engineering students to the higher university degrees. CEMPI wishes to be a central actor in this endeavour. As an example, every year a few students from the Ecole Centrale de Lille – located next to the Lille 1 campus - follow a mathematics Master's program, in parallel with their engineering studies; efforts are made by both parties to improve program coordination to make this easier for the students and thereby increase the flux. The international character of the Lille faculty provides a second opportunity for attracting excellent Master's and Ph.D. students. Indeed, many faculty members, originally from Eastern Europe, North Africa or Asia, have kept close contacts with their home institutions, providing them with access to top-level students.

To tap into these populations, four specific actions are planned. *First*, we will respond to the growing student demand for international experience through the privileged contacts of CEMPI with high profile foreign institutes, which will offer them opportunities for Master's internships abroad. In addition, graduate courses will be made available by some of the affiliated foreign institutes through video-conferencing. The experience of the CEMPI affiliates Bristol and the Fields Institute with such long-distance learning will be of great value here. Finally, every year a specialized second year Master's course, on a topic related to the thematic semester, will be taught by one of the visiting international experts. *Second*, the absence of adequate student funding puts the French Master's programs at a decisive disadvantage to its foreign competitors: the Master's fellowships that are part of CEMPI will allow us to counter this. The Master's fellows that do particularly well will then be offered Ph.D. funding. *Third*, we will increase joint Ph.D. degrees between Lille and foreign institutes ("co-tutelles"), and notably with our foreign affiliates, who have expressed great interest in this. *Finally*, we will organize an efficient advertising of our degrees, focusing precisely on the target populations described above. We expect to use CEMPI as a basis for the creation of an Erasmus Mundus program within a few years.

Annual CEMPI winter school This annual event, part of CEMPI's Thematic Semester described in Section 1.1, is an essential ingredient of CEMPI's doctoral and postdoctoral training program.

Job placement The number of academic positions is limited and contrary to what happens in other countries, it is not yet common to see Ph.D. graduates in mathematics, and in particular in pure mathematics, obtain jobs in industry. The general orientation of CEMPI, joining as it does conceptual but interdisciplinary research, experimentation and technological innovation, is particularly well adapted to change this state of affairs for our students. As a concrete measure, we will give mathematics graduate students the opportunity to enrich their curriculum with physics courses and vice-versa and to take advantage of the great variety of courses offered within the two departments in order to diversify their skills and knowledge base and make them adapted to today's job market competence. The next AERES evaluation of our University's teaching programs in 2013 will provide us with the opportunity to work out the details of this initiative and to consolidate the changes.

Undergraduate Research Fellowships To give young students an early research experience, the CEMPI proposal includes a request for undergraduate summer fellowships. These will allow excellent mathematics, physics and engineering students to come to work on a research project in the partner laboratories, typically after their third year of university study. Such programs exist in particular in the Fields Institute (Toronto), one of CEMPI's international affiliates, and we will benefit from their experience in setting up a Lille version. We expect this program to provide a basis for graduate student recruiting.

The deployment of an FTTH (Fibre To The Home) telecommunications network in Northern France has considerable job-creation potential, provided specialized technicians can be trained locally. The photonics team of PhLAM is setting up such training starting in November 2011, aimed at the employees of local cable companies. This will clearly increase the notoriety of the PhLAM fiber facility and know-how with the local and national businesses in the telecommunications sector, and hence to additional funding for its research and development activities.

1.4. Socio-economic impact

CEMPI: Cutting-edge research at the confluence of mathematics and physics: transforming today's theory into tomorrow's technology.

In this labex at the frontiers of mathematics and physics, which merges complex systems theory with atomic and optical physics, an exceptional synergy of skills and expertise will uncover new phenomena leading to innovative devices and applications. Indeed, the outstanding experimental platforms operated by PhLAM (optical fibre fabrication facilities, cold-atom experiments) or to which PhLAM has privileged access (SOLEIL and UVSOR synchrotrons) are not only ideal laboratories for assessing mathematical hypotheses and developing new concepts, but will also provide industrial applications. Additionally, a better understanding of biological functions using quantitative approaches will be relevant to health. More precisely, beyond its obvious resonance in fundamental science, CEMPI research will impact the following areas:

- **Devices and Applications:** In close collaboration with the EQUIPEX project FLUX, alternatives and disruptive technologies will be developed in optical telecommunications, laser marking (bottleneck for photovoltaic developments), biomedical engineering, as well as in the generation of teraHertz and synchrotron radiation.
- **Health:** Insights into the workings of circadian clocks, the cell cycle, or other core biological regulation networks, will suggest new therapeutic strategies.
- **Technological transfer:** An important target of CEMPI is to significantly improve transfer to industry as evidenced by the creation of a joint laboratory of PhLAM/IRCIA and Draka, the largest worldwide optical fiber producer, which is located in the region "Nord–Pas de Calais".
- **Societal impact:** the applications were chosen with partners having access to a growing market and who will therefore be potentially hiring. In the telecommunication field, for instance, 160 million kilometres of fibres were deployed in the world in 2011, with even more expected in 2012. The scientific knowledge and know-how developed in this labex will lead to the elaboration of new fibres for optical sources (and therefore for fibre laser manufacturers), that Draka expects to produce.

It is then clear that this project brings together academic and industrial companies (from fiber manufacturer (Draka) to fiber end users (Eolite, Amplitude

Systems, Osyris, Thales, Quantel...)) who strongly support this project. We note that CEMPI will rely on the skills of the recently created SATT "Nord de France Valo" for all technology transfer activities issued from its research results.

In addition, to make the courses of the CEMPI Winter Schools (see Section 1.1) available to a wide audience, they will be published. The affiliation of CEMPI with the Fields Institute provides the opportunity to include them in the Fields Institute Communication Series. CEMPI will also participate in science popularization, notably through its Distinguished Lecture Series.

2. ORGANIZATION AND GOVERNANCE

2.1. SCIENTIFIC COORDINATOR

Pr. S. De Bièvre, born in 1959, earned a Ph.D. in Physics (Rochester NY) and an HDR in Mathematics (Paris). He held positions at the University of Toronto and at the physics and mathematics departments of the Université Paris 7, before being appointed Professor of Mathematics at the Université Lille 1 in 1996. He is the author of 57 publications in mathematical physics through which he has made contributions on diverse subjects, such as Anderson localization and quantum chaos. He has supervised 8 Ph.D. theses.

He is currently the director of the "Groupement de Recherche Dynamique Quantique'' (2009-2012) which brings together about one hundred researchers from 8 physics and 18 mathematics laboratories around France, working on a variety of topics: wave dynamics around black holes, open systems and non-equilibrium statistical mechanics, quantum information theory, decoherence, semi-classical analysis etc.

Prof. De Bièvre has (co)organized a number of scientific meetings or conferences and has extensive experience with the hiring of temporary and permanent faculty, through his service as member or president of numerous hiring committees, both in his home institution and at other French universities. He has also served in the Scientific Board (Conseil Scientific) and the Board of Directors (Conseil d'Administration) of the Université Lille 1. He heads the "Analyse Numérique et EDP'' team of Painlevé (14 permanent faculty).

2.2. PARTNERSHIP

2.2.1 PARTNERS' DESCRIPTION, RELEVANCE AND COMPLEMENTARITY

The CEMPI project is an initiative of two of the largest science laboratories of the Université Lille 1: the Laboratoire Paul Painlevé, which is a mathematics laboratory covering a wide spectrum of mathematical fields, and the PhLAM, a physics laboratory centred on the experimental and theoretical study of the interaction of matter with light. Their complementarity is obvious. Together, they form the core of the CEMPI project. In what follows we first give a short description of those two structures, as requested.

LABORATOIRE PAINLEVE http://math.univ-lille1.fr/

Research and innovation. The Laboratory Paul Painlevé – a research unit associated to the CNRS (UMR 8524) and to the Université Lille 1 - boasts a permanent faculty of about 110 mathematicians covering a wide spectrum of pure and applied mathematics. The laboratory also benefits from an 11 member administrative and technical staff and hosts about 45 PhD students and PostDocs. In the latest AERES evaluation, the laboratory received an overall A rating, with A+ in scientific quality, world wide reputation and attractiveness.

CEMPI : a presentation

The laboratory is composed of 5 research teams: Analysis, Arithmetic and Algebraic Geometry, Geometry and Topology, Numerical Analysis and Partial Differential Equations, Probability and Statistics, which are all involved in the CEMPI project. More than 550 papers have been published in international journals by the teams participating in CEMPI over the last four years.

As leading member of the «Fédération de Recherches en Mathématiques du Nord-Pas de Calais », it enjoys a close partnership with the other laboratories of mathematics of the region. The laboratory welcomes many foreign researchers on a regular basis and its members closely collaborate with mathematicians from all over the world. An important asset of the laboratory is the "Bibliothèque Régionale de Recherche en Mathématiques", which houses 16000 books and 360 international journals with more than 200 active subscriptions. This library is open to all mathematicians of the region. The laboratory is strongly involved in scientific computing and has a cluster equipped with last generation processors.

Research contracts. The laboratory manages seven ANR contracts in the fields concerned by the CEMPI project. In addition the CEMPI researchers of Painlevé participate in several other ANR programs. The laboratory is strengthened by many international contracts such as GDRE, European networks, INTAS networks, Tournesol, Gilibert, Procope, EGIDE programs and PICS.

Higher education. The Laboratoire Paul Painlevé is strongly involved in the organization and training at the Master's level (See Section 1.3). Every year, about 20 Master's students spend a research semester in the laboratory and 8-10 PhD students begin their thesis.

Organization. The lab is organized into 5 research groups. The head of each group belong to the first circle around the director, and is consulted regularly. The laboratory council reflects the diversity of the members of the lab and meets regularly. A secretarial staff including three administrative officers assists the director.

Participation in other 'Investissement d'avenir' programs. The laboratory participates in the Equipex project "iDive", a project for an innovative technology platform in support of the research program "Interdisciplinary Cluster for the Advancement of Visual Studies" (iCAVS).

PHLAM: PHYSIQUE DES LASERS, ATOMES ET MOLECULES

http://www-phlam.univ-lille1.fr/

Research and innovation. The "Laboratoire de Physique des Lasers, Atomes et Molécules" (PhLAM) is a joint structure of the Université Lille 1 and the CNRS (UMR 8523), ranked A+ by the AERES in 2009. The personnel count of the lab is around 120: 80 permanent staff, 40 PhD students and post-docs. The lab's scientific activity concerns the interaction between light and matter, explored both theoretically and experimentally. PhLAM contains 5 research groups: Photonics, Non-linear optics and dynamics, Atomic physics, Molecular spectroscopy and applications and Theoretical molecular physics. The first three participate in the Labex CEMPI project, representing about 50% of the laboratory personnel.

The equipment available at PhLAM includes a technical platform for the production of photonic crystal fibres. Many continuous and pulsed light sources are available as well, including high power lasers for the optical characterization of the fibres and "preforms". A femtosecond laser with tunable pulse width and various characterization devices is a common facility for all the teams of PhLAM. State-of-the-art experiments in atomic physics are also developed.

More than 140 papers have been published in international journals by the PhLAM teams participating in CEMPI over the last four years.

Research contracts. At the European level, PhLAM currently participates in the HiDEaS network (High Dimensional Entangled Systems), the ACTINET network and the Interreg IV: Plasmobio program. At the national level, 10 projects implying the different teams participating in this LABEX are currently funded by the national agency for research (ANR). The lab is present in more than 10 GDR (research networks funded by CNRS), and pilots one of those. PhLAM is also member of the GRIFON network (Groupement de recherche et d'innovation pour les fibres optiques de nouvelle génération), which has a close collaboration with industrial partners, notably Draka-Comteq, the number one in the world for optical fibre production. During the last years, several patents have been deposited, mainly by the photonics group.

Higher education. PhLAM is strongly involved in the organization and training at the Master's level (See Section 1.3). Every year, about 10 Master's students spend a research semester in PhLAM and 8-10 PhD students begin their thesis. We are also active in the doctoral school Metamorphose from the ULB (Brussels).

Organisation. The head of each of the 5 groups belong to the first circle around the director, and is consulted regularly. The laboratory council reflects the diversity of the members of the lab and meets every 2-3 weeks. An administrative officer assists the director, as well as secretarial staff of two full time and one half time collaborators.

Participation in other "Investissement d'avenir" programs. EQUIPEX: PhLAM is participating in 4 "EQUIPEX" projects: FLUX (coordinated by PhLAM), Refimeve+ (Metrological Fibre Network with European Vocation), SPIDERMASS and META.

2.2.2 Qualification, role and involvement of the partner units

As explained above, all research teams of the Painlevé Laboratory, and three out of five from PhLAM, will participate in the CEMPI project. In addition, a number of well-established mathematicians of the laboratories participating in the Fédération du Nord des Mathématiques will contribute to the CEMPI research, as well as several physicists from neighbouring universities. And finally, CEMPI will benefit from its privileged relationship with a number of top-level foreign institutions, as explained before.

The following table lists the principal researchers involved in the organization and governance of the CEMPI project.

Surname	First name	Position	Domain	Partner	Organization	Contribution in the project
Besse	Christophe	Professor	Mathematics	Painlevé	Université Lille 1	Research Representative Painlevé
Dèbes	Pierre	Professor	Mathematics	Painlevé	Université Lille 1	Training coordinator
De Bièvre	Stephan	Professor	Mathematics Physics	Painlevé	Université Lille 1	Principal investigator
Douay	Marc	Professor	Physics	PhLAM	Université Lille 1	Coordinator Socio-Economic Impact
Drutu	Cornelia	Professor	Mathematics	Painlevé	Université Lille 1	Theme coordinator

Fresse	Benoit	Professor	Mathematics	Painlevé	Université Lille 1	Theme coordinator
Garreau	Jean-Claude	Research Dir.	Physics	PhLAM	Université Lille 1	Research
Gritsenko	Valery	Professor	Mathematics	Painlevé	Université Lille 1	Theme coordinator
Lefranc	Marc	Professor	Physics	PhLAM	Université Lille 1	Theme coordinator Representative PhLAM
Markouchevitch	Dimitri	Professor	Mathematics	Painlevé	Université Lille 1	Research
Neufang	Matthias	Professor	Mathematics	Painlevé	Université Lille 1	Theme coordinator
Taki	Majid	Professor	Physics	PhLAM	Université Lille 1	Theme coordinator

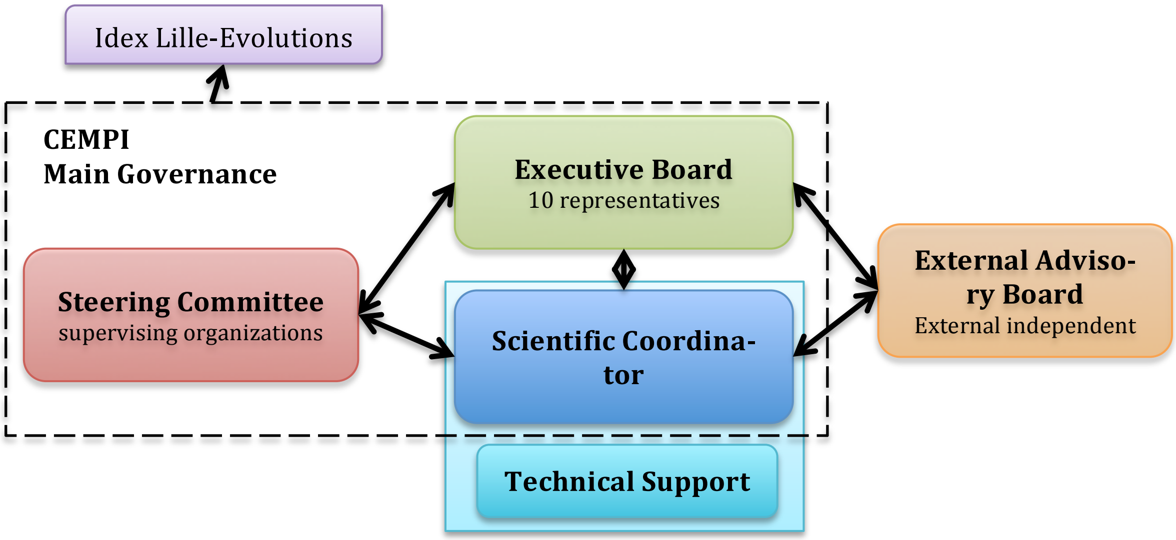
2.3. GOVERNANCE

The CEMPI governance is articulated around four main governing bodies: the scientific steering committee, the scientific coordinator and the executive board, and the advisory board.

SCIENTIFIC COORDINATOR The scientific coordinator, Prof. S. De Bièvre, together with the executive board, defines the scientific strategy on the basis of the scientific programme described in the present document. He organises the call for thematic semesters and other scientific projects as well as the advertising of the fellowships and visiting positions. He produces a ranking of the proposals and applications after consulting with the executive board. The criteria for selection will be the scientific quality, the relevance to the scientific programme, and the contribution to the training of young scientists. The scientific advisory board and other international experts will be solicited to evaluate the projects and applications; the experts will be appointed by the scientific coordinator and the executive board. For matters pertaining to graduate studies the graduate student advisors of the mathematics and physics departments will be consulted. The scientific coordinator submits the ranked list of projects or candidates to the steering committee, who endorses it. In case of disagreement, the process is renewed until convergence. Together with the executive board, the scientific coordinator proposes a budget that needs to be endorsed by the steering committee. The scientific coordinator organizes the writing of the annual report in collaboration with the executive board; the report will describe the progress made, and is submitted to the steering committee and the scientific advisory board for evaluation.

EXECUTIVE BOARD The executive board is composed of 11 representatives from the two Labex partners: 7 from Painlevé and 4 from PhLAM. The scientific coordinator presides over the executive board. The directors of the two partner laboratories are members of the executive board, or may designate a representative. Its members are otherwise appointed by the steering committee on the basis of a list proposed by the scientific coordinator. One member will coordinate the training program, one will be in charge of the socio-economic impact. The overall composition of the executive board must reflect the themes covered by the Labex scientific programme. The executive board is responsible for the smooth running of all aspects of the CEMPI activities, as described above. It meets at least every 6 months, at the initiative of the scientific coordinator.

STEERING COMMITTEE The steering committee is composed of three representatives from each of the two partner institutions (Université Lille 1, CNRS). It meets at least once a year.



It is in charge of reviewing the Labex scientific production, on the basis of the annual report, presented to the committee by the scientific coordinator. The steering committee will also assess the strategy and endorse the list of selected projects and applicants, following the procedure described above. It approves the budget; it appoints the executive board on the basis of a list proposed by the scientific coordinator. If the coordinator was to step down, the steering committee selects a new coordinator on the basis of proposals made by its members and the executive board.

ADVISORY BOARD The advisory board is composed of 5 to 6 internationally renowned scientists, including one biologist and one computer scientist, and a representative of the Regional Council. The scientists are proposed by the scientific coordinator and endorsed by the executive board and the steering committee. The advisory board meets at the initiative of the executive board. It reviews the quality of the scientific production on the basis of the annual reports and the long-term scientific strategy. It makes recommendations for scientific strategy.

TECHNICAL SUPPORT CEMPI can count on the considerable experience of the secretarial staff and computer technicians of the two partner labs. To deal with the extra workload associated with the Centre, a half time secretarial assistant and a half time computer engineer will be hired to join the existing teams.

EVALUATION The progress of CEMPI will be measured with all the usual performance indicators of academic excellence in research and teaching, which include publication record, invited conferences, number and quality of Ph.D. theses, job placement of master's and Ph.D. students, etc. Another important indicator will be the level of transfer of CEMPI research to innovative technologies by industrial partners such as Draka. In addition, for CEMPI, particular attention will be paid to its capacity for: (i) creating inter-partner collaborations; (ii) setting up new interdisciplinary chains of interconnects of the type described previously in this project; (iii) working effectively with its affiliated foreign institutes for research and training; (iv) attracting top-level scientists to its thematic semesters; (v) filing patents.

2.4. Institutional strategy

The CEMPI project is, within the IDEX "Lille Évolutions", the main building block of an emerging cluster. The Université Lille 1 will accompany the Labex through the hiring of eight permanent junior and senior faculty over the course of the project. It is in particular expected that, in the first four years of operation of CEMPI, one senior and one junior position will be opened in the fields that lie at the intersection of Painlevé and PhLAM. The successful candidates will be expected to have a double competence, enabling them to interact both with the mathematicians and physicists of CEMPI, enhancing the interaction between its two partner laboratories and strengthening the interconnections joining mathematics to experimental physics and industrial applications. We note that such interdisciplinary positions have recently been successfully created at the CNRS[11]. The other positions will be filled in accordance with the CEMPI strategy outlined above. In addition, the University will endow CEMPI with 16 doctoral or postdoctoral positions over the course of its existence. This support comes in addition to the current support of the University to the partner labs of CEMPI.

3. Funding

CEMPI has been awarded 5.000.000 euros, for an eight-year period starting in 2012. About 70% will be devoted to personnel costs that will be used to fund invitations of junior and senior faculty, postdocs, doctoral fellowships, master's fellowships etc., as well as for administrative and technical staff. The remaining 30% of the funds will be used for equipment and operating costs of the experimental platforms, for the acquiring of new computer clusters, as well as for travel costs of CEMPI researchers and of participants in the CEMPI thematic semesters.

This funding will be combined with the habitual support of the University, the CNRS and the partner laboratories for research, training and industrial development. To this has to be added the specific support pledged by the university to the CEMPI project. In addition, the affiliation of the Université Lille1 to the Fields Institute, brings a source of funding for the organisation of workshops and conferences to the CEMPI project.

[11] A Chargé de Recherche" in biophysics (CID CNRS 43) was appointed in PhLAM in September 2011.