1 CONTEXT AND PREVIOUS ACHIEVEMENTS

1.1 CONTEXT AND SCOPE OF THE PROJECT

The Labex CEMPI (Centre Européen pour les Mathématiques, la Physique et leurs Interactions) is a project of the Laboratoire de Mathématiques Paul Painlevé (LPP) and the Laboratoire de Physique des Lasers, Atomes et Molécules (PhLAM), both Unité Mixte de Recherche of ULille and CNRS. Thanks to the diverse expertise of its 173 permanent faculty members affiliated with ULille, CNRS and Inria, CEMPI conducts a continuum of fundamental and applied research that is remarkably broad in the French mathematical and physical communities, stretching from pure and applied mathematics to experimental and applied physics. Two notable successes of CEMPI are the training of highly skilled mathematicians and physicists ready for interdisciplinary research in academia and industry, and technological innovation in fibre optics, in close collaboration with Equipex FLUX. As a distinctive principle, CEMPI emphasizes interactions between mathematics and physics as well as with other sciences: at these interfaces, original ideas are inspired, new science flourishes and disruptive technologies emerge. A telling example is provided by topographic optical fibres, a new type of fibre with periodically varying diameter developed at PhLAM. The new nonlinear effects induced by this geometry not only allow CEMPI researchers to build innovative light sources but also lead to highly complex behavior and open mathematical questions. Their analysis has required the joint expertise of LPP and PhLAM, in collaboration with CEMPI invited professor S. Trillo (Ferrara) and had led to key advances, published in the best physics journals (Nature Photonics, Phys. Rev. X, Phys. Rev. Lett.), and recognized by the award of the most prestigious French prize in optics to CEMPI researcher A. Kudlinski[1]. In this continuing interaction, mathematics provides physicists with conceptual tools and methods to tame difficult problems, and physics, coming from PhLAM or elsewhere, provides mathematicians with interesting problems from which they can generalize and design new concepts.

The overall ambition of CEMPI is to create innovative concepts, theories and devices to tackle and disentangle the complexity of the world around us. Specifically, but not exhaustively, we aim to: work on the structure of wave turbulence in optical fibres; focus on problems in biology and ecology using probabilistic or statistical approaches; model how the liver synchronizes to meal timing; build quantum and photonic simulations of outstanding condensed matter problems with unparalleled flexibility; harness the complex dynamics of electron bunches in synchrotrons to boost the major light source facilities around the world; design innovative optical fibres for high-speed internet communications; exploit linear dynamical systems to solve problems in ergodic theory; investigate quantum topology and its connections with representation theory; study the local structure of Coulomb gases; improve machine learning's mathematical foundation using random matrix theory; work on important conjectures concerning laminations and foliations; focus on arithmetic study of curves, of coverings and of their moduli spaces; design efficient numerical methods, robust with respect to model parameters. Those challenges lie indeed within the domains in which CEMPI researchers have established international leadership and are currently pushing the state of the art. In these problems, fundamental questions interact with high-priority societal challenges of the French and European research strategies, such as multiplying the bandwidth of internet links to match ever increasing communication needs, developing smart algorithms to analyse massive datasets or deciphering the role of the biological clock in obesity and type 2 diabetes. Our project is perfectly aligned with the last prospective report of the Institut National des Sciences Mathématiques et de leurs Interactions (INSMI) of the CNRS, which in particular puts forward the study of complex dynamical systems with the use of probabilistic and statistical methods, the interaction between arithmetic and topology, representation theory, machine learning, etc. as well as with the conjuncture report of the section 04 (atomic physics and optics) of the French National Committee for Scientific Research which highlights nonlinear optical systems as perfect tools to investigate complex dynamics and ultracold atom gases as quantum simulators of condensed matter systems.

[1] *Here, and hereafter, names of CEMPI researchers are underlined.*

1.2 MAIN PREVIOUS ACHIEVEMENTS [2]

Research achievements.

A sample of outstanding scientific results:

- Stability results in motivic and p-adic integration have important applications in the Langlands program. In [Duke Math. J. 167 (2018)], R. Cluckers & al proved stability under integration and Fourier transform of a concrete class of functions containing all globally subanalytic functions and their complex exponentials.
- In the Thurstonian approach to 3-dimensional topology, it is crucial to understand the structure of locally homogeneous 3-manifolds. In [Invent. Math. 204 (2016)], F. Guéritaud, F. Kassel and J. Danciger described combinatorially a parametrization of the set of all Margulis spacetimes.
- Understanding Coulomb gases is a key problem in statistical mechanics. In [J. Funct. Anal. 275 (2018)], D. Chafaï, A. Hardy and M. Maïda, whose CEMPI authors have been recently recruited, obtained concentration of measure inequalities for such gases.
- A fundamental question in complex geometry is the existence of the Lyapunov exponent for holomorphic foliations on complex surfaces. Analysing the singularities of a foliation, V.-A. Nguyên [Invent. Math. 212 (2018)] proved that most holomorphic foliations admit a unique Lyapunov exponent, which is intrinsic and canonical.
- The behaviour of high energy eigenstates is a central problem in quantum chaos. G. Rivière and H. Hzari [Adv. Math. 290 (2016)] improved Sogge's estimates on the growth of eigenfunctions of the Laplacian on negatively curved surfaces.
- By building a "time microscope" tracking the time variation of optical fields with a resolution of 80 fs, Tikan et al. [Nature Photonics 12, 228 (2018)] could record a real-time movie of how the optical analogue of a "rogue wave" develops. This casts light on the mechanisms leading to such extreme phenomena but also suggests fascinating links between optical turbulence and coherent solutions of the nonlinear Schrödinger equation.
- In the Fermi-Pasta-Ulam recurrence, a nonlinear many-body system returns to its initial state, contradicting the laws of statistical mechanics. Mussot et al. [Nature Photonics 12, 303 (2018)] showed experimentally that an optical version of this paradoxical phenomenon is actually periodical and induces a phase shift in the field. Remarkably, this provides new insights into the physics of frequency combs (2005 Physics Nobel prize).
- Utilizing a quasi-periodically kicked cold atomic gas, and its mathematical equivalence with a two-dimensional crystal, Manai et al. [Phys. Rev. Lett. 115 (2015)] provided the first experimental evidence of two-dimensional Anderson localization, a type of metal-insulator transition whose theoretical prediction led to the 1977 Nobel prize, and verified that the localization length depends exponentially on disorder strength.

Besides topographical fibres (Section 1.1), two notable examples of interdisciplinary publications at CEMPI among one hundred are: 1) the study of shape deformation by B. Tumpach (LPP) in collaboration with M. Daoudy (CRISTAL, ULille computer science lab), that was featured in [Notices of the Americal Mathematical Society 63 (2016)] 2) the modelling of how the liver clock synchronizes with meal timing across the day/night cycle by the team of M. Lefranc (PhLAM) in collaboration with B. Staels of the Labex "European Genomics Institute for Diabetes" (EGID), and suggesting chronotherapeutical protocols for restoring normal clock function under nutritional stress and in obesity and diabetes [Woller et al., Cell Rep. 17 (2016)].

Awards and distinctions

- J.C. Garreau was awarded the **Prix Leconte of the Académie des Sciences** (2015), for his work on the quantum simulation of disordered systems with cold atoms;
- F. Kassel was awarded the **Médaille de Bronze of the CNRS** (2015), for her work on Lie groups, hyperbolic geometry and spectral theory;

[2] *For more details on CEMPI activities, we refer to its website*

- A. Virelizier received the **Ferran Sunyer i Balaguer Prize** (2016), for the monograph "Monoidal categories and topological field theory" in the Birkhäuser series "Progress in mathematics";
- C. Evain received the **J.-L. Laclare prize of the French Physical Society** (2017) for his work on accelerator physics, introducing original approaches combining accelerator and laser physics, photonics and nonlinear dynamics;
- A. Jollivet received the **EAIP Young Scientist Award of the Eurasian Association** for Inverse Problems (2014);
- A. Kudlinski was awarded the prestigious **Fabry de Gramont prize from the French Optical Society** (2018) for his contributions to nonlinear photonics and his work on the dynamics of the modulation instability and the propagation of solitons in topographic optical fibres;
- A. Furlan was awarded the 2018 **1-Primer prize from the Région Hauts-de-France** for his biological studies on the dynamics of assembly of supramolecular complexes in the context of transcriptional regulation, using fluorescence microscopy;
- R. Cluckers obtained in 2014 **the ERC Consolidator Grant MOTMELSUM** (1M euros) to work on motivic Mellin transforms and exponential sums through arithmetic geometry; F. Kassel obtained in 2016 **the ERC Starting Grant DiGGeS** (1M euros) to work towards a classification of discrete subgroups of semisimple Lie groups in higher real rank; A. Amo, was awarded in 2013 the **ERC Starting Grant HONEYPOL** (1.5M euros) to study polaritons confined to lattices. He joined PhLAM in 2017; the CEMPI biophysical team, expert in manipulating living cells with light, is a partner of the **ERC Consolidator Grant NANOBUBBLE**, obtained by K. Braeckmans (UGent & ULille) in 2014, which utilizes light to deliver of drugs and nanomaterials in cells.
- V. Gritsenko became Senior Member of the IUF (2013); A. Mussot became Junior Member of the IUF (2015).

Publication record. CEMPI has published 1040 articles in international refereed journals over the 2013-2018 period, with statistics showing the quality of the research:

- 10% of CEMPI physics publications (30 in 2013-2018, compared to 16 over 2008-2013) have appeared in the top 10% of physics journals (according to Web of Science, corresponding to an impact factor of 5.5 and above). An impressive 25% (75) of them are in the top 10% of physics articles in terms of citations (4 articles in the top 1%). Most notably, CEMPI now publishes in journals where it never did: 2 Nature Photonics, 2 Nature Communications, 1 Science and 1 Advances in Optics and Photonics papers were published in 2018, with two other Nature communications papers in 2016 and two Optica papers. All this shows a clear Labex effect.
- 6% of CEMPI mathematics publications (41 in 2013-2018, compared to 34 over 2008-2013) have appeared in the top 5% of mathematics journals (according to MathSciNet, corresponding to a MCQ of 2 and above), 12% have appeared in the top 10% and 25% in the top 15%.
- 12% of the CEMPI publications are interdisciplinary. This means they are co-signed by scientists of two different disciplines.
- 80% of the CEMPI scientific production is the result of an international collaboration between one or more CEMPI researchers and a colleague from a foreign university.

The 25% top publications of CEMPI over the period 2013-2018 are listed in the Appendix to this document.

Training. CEMPI has been very successful in training at the Master, doctoral and post-doctoral level. Indeed, 80% of CEMPI-funded postdocs left the project for tenured or tenure-track positions in France and abroad, at École Polytechnique, Paris 6, Lyon, Dijon, FNRS (Belgium), Marburg, Beirut. Moreover, CEMPI witnessed a 20% increase of Ph.D. students in 2013-2018 compared to 2008-2013. Currently, there are 57 doctoral students within CEMPI, up from 48 in 2012. This demonstrates the leverage effect of CEMPI funding, which represented only 10% of the total and was completed by external sources, accounting for the remaining 90%: ULille, Inria, industry, foreign stipends, Ecole Normale Supérieure, École Polytechnique, ... During the last 5 academic years (2013-2017), 70 Masters were delivered to foreign students. They accounted for 33% of the students (48% from the Lille region and 19% from other French regions), clear evidence of CEMPI's attractiveness. One third of the Masters students continued in a PhD program. Furthermore, professional insertion is excellent (98% of students, 60% in private sector) and 45% of graduate students find an engineering position.

The Mathematics Department of ULille has set up a convention with the on-site engineering school École Centrale de Lille (ECL), an ISITE ULNE partner, which allows the engineering students to perfect their initial mathematics training and to complement their engineering degree with a mathematics degree. The number of ECL students registered in the Bachelor in Mathematics (3 year degree program) has been multiplied by 5 (from 6 students in 2012 to 30 in 2018) and represents now one-third of the students. In addition, thanks to the above partnership, the ECL students of the « Engineering program in Data Analysis & Decision Making » (DAD), which is oriented principally to data science for engineers, have the possibility to obtain the Master of Pure and Applied Mathematics. In this manner, through the contact this offers them with the CEMPI research teams, they obtain a valuable research experience; 7 students every year choose to seize this opportunity.

CEMPI International attractiveness and visibility has been developed through concerted actions:
- The **annual thematic semester** organized by CEMPI on the Villeneuve d'Ascq campus of ULille and/or with foreign partners attracts each year over 500 visitors from France and abroad. Nearly 60 visiting professors spent at least one month at CEMPI for collaborations and research courses.
- The **46th congress of the European Group of Atomic Systems, EGAS 2014** (250 participants, Lille, June 1-4 2014) featured S. Haroche and D. Wineland, who shared the Physics Nobel Prize 2012.
- The congress **Banach Algebras and Applications 2015** (100 participants), held at the Fields Institute in Toronto, was co-organized by CEMPI.
- The **satellite Summer School** (55 participants) **to the 8th International Conference on Lévy Processes** took place in Lille, from July 18 to 22, 2016.
- The semester **on "Non-positive curvature actions and geometry[3]"** (2017) at the Isaac Newton Institute (Cambridge) was co-organized by CEMPI.
- The **second congress of the Société Mathématique de France** (200 participants, June 2018) chose Lille as its venue. Several of the French invited speakers at ICM Rio 2018 gave a talk.
- Three LPP members (F. Guéritaud, S. Grivaux, G. Rivière) have given invited talks at the **Séminaire Bourbaki**.
- V. Gritsenko is one of the coordinators of the project *Mirror Symetry and Automorphic Functions* (2017-2022) funded by the Russian Government (2,5M. Euros).
- F. Kassel has presented her joint work with F. Guéritaud and J. Danciger at the International Congress of Mathematics 2018.
- The LPP **colloquium**, the CEMPI inaugural conference, distinguished lecture series and thematic semesters welcomed a number of prestigious speakers: Fields Medalists Alain Connes, M. Hairer, T. Gowers and C. Villani; L. Saint-Raymond, member of the French Académie des Sciences.

International collaboration. In 2012, CEMPI established a network of partnerships with reputed universities and institutes: KU Leuven, Université Catholique de Louvain (UCL) and IAP Photonics @ BE (Belgium), the universities of Bristol and Aberdeen (United Kingdom), Max Planck Institute (Germany), the Fields Institute (Toronto) and SISSA (Italy). CEMPI has also historical and close collaborations with Ghent University, which together with KU Leuven and UCL is a privileged partner of ULille and of ISITE ULNE. In 2018, CEMPI has signed new partnerships with Berlin Mathematical School, Scuola Normale Superiore (Pisa), Imperial College of London, University of Tübingen.

Socio economic impact and technology transfer. One core asset of CEMPI is the Fibertech optical fibre manufacturing facility, also supported by Equipex FLUX, which is the most versatile equipment of its kind in a European academic environment. The combination of this unique platform and of the optical expertise of CEMPI

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3 *https://www.newton.ac.uk/event/npc*

teams had led to the creation of two joint laboratories. The first one is with Prysmian/Draka, the world leader in optical fibres and telecommunication cables (total annual sales: 8 billion euros), and concerns the design of innovative high-capacity fibres for Internet. The second one is with CEA/CESTA, which operates the Laser MegaJoule in Bordeaux, the most powerful inertial confinement fusion facilities in the world (building cost: 6 billion euros) and concerns the development of ultra-high-power fibre lasers.

These joint laboratories add to industrial contracts of the two CEMPI laboratories with more than 30 regional and national companies (PhLAM: Draka/Prysmian, LSO Médical, Mader, Indelec, Genes Diffusion, Horiba Jobin Yvon, MC2, CEA/CESTA, Eolite, Amplitude Systèmes, CEA List/CEA Tech, Thalès, Alcatel-Lucent, Leukos, Novae, Cai Labs, Beam; LPP: Banque Accord, Arcelor-Mittal, Alstom, Décathlon, Running care, Auchan, C4X, Cylande, Florimont Desprez, Leroux, NFID), totalling over 1.5 M€ in 2017. Four patents were published and two were submitted, concerning fiber optics or biotechnology (see Annexe). The CARSIMAGE project of the PhLAM biophotonics group was supported by SATT Nord (300 K€) to develop new biological imaging methods based on stimulated Raman scattering. With the help of the CPER project Photonics4Society, PhLAM teams contribute to the development of two startup companies (Section 2.3). They have also developed a platform for teaching Fibre to the Home (FTTH) technology to technicians of internet operators in the context of massive fibre network deployment in the Hauts de France region. LPP valorisation activity is mainly in software development, and benefits from a partnership with Inria Lille Nord-Europe research center, which provides excellent engineering support both for software (see, e.g., the statistical online platform MASSICCC), contract management and collaboration opportunities. An Inria spin-off specialized in predictive maintenance for industry, PAM, is currently been created on the basis of software developed and successfully used in previous contracts.

Both at LPP and PhLAM, events are regularly organized to bring together the expertise of CEMPI researchers and the needs of the companies. In particular, LPP is involved with other regional laboratories in the Centre d'Interaction Mathématiques Entreprises (CIME), designed to be a central meeting point for public and private researchers. In January 2018, 32 PhD students and six local companies worked together for one week.

Knowledge dissemination and scientific popularization. Besides publications in refereed journals, it is important that knowledge is synthetized in reference monographs and diffused to the general public. In collaboration with Springer, CEMPI launched the CEMPI subseries of Lecture Notes In Mathematics/Physics. Two volumes were published in 2015, 2017, with a third one following at the end of 2018. CEMPI researchers are also very active in science popularization, organizing exhibits for the general public, offering internships for high school students and elaborating interactive scientific content. In particular, D. Hennequin was awarded in 2013 the Jean Perrin prize of the French Physical Society for his contributions to popularization. For Unisciel, the online scientific university, he and coworkers developed 75 5-minute movies addressing each a specific question, some of them with more than 500 000 views on YouTube, as well as a massive open online course (MOOC) based on these movies, which in two sessions attracted 15000 people from 80 countries.

CEMPI budget 2012-2019. Leverage effect. CEMPI has been awarded an average annual budget of 625 000 euros, distributed as follows: 65 %: salaries (invited professors, postdocs, doctoral students, master fellowships); 20%: equipment and consumables; 15 %: organization of and participation in conferences and other operating costs.

	2013 – CEMPI		2017 – CEMPI	
Sources	Quantity	Total budget	Quantity	Total budget
ANR	12	886 400 €	17	937 300 €
IUF	/	/	1	15 000 €
Other PIA	2	708 000 €	2	347 900 €
REGION	1	29 300 €	8	309 600 €
CPER	2	651 400 €	1	3 157 000 €
EU	5	44 700 €	12	389 000 €
INDUSTRY	9	600 700 €	27	1 517 900 €
Total	**32**	**2 920 500€**	**69**	**6 673 678 €**

The leverage effect of CEMPI funding manifests itself principally in two ways. First, CEMPI supports preliminary work on promising subjects, allowing our researchers to apply successfully for more significant grants from ANR, the European H2020 programme, or now the ISITE ULNE project, thus pushing the CEMPI project further. Second, CEMPI is also a quality label that creates trust in our research and excellence, allows us to obtain more PhD grants and facilitates structural investment from institutions such as through the CPER project Photonics4Society, funded by Région Hauts-de-France, French government and EU (12 M€ over 2015-2020). Additionally, the increased reactivity makes it easier to engage in industrial contracts. The leverage effect is clearly demonstrated by the table, which compares the external funding received by CEMPI in 2013 and in 2017 and shows that it more than doubled over this four-year period.

Evaluation of CEMPI. The 2015 midterm evaluation of CEMPI identified a single weakness, advising that an increased effort to attract foreign guest research could be beneficial for the international outreach of CEMPI. To that end, we increased by 50% the funding for travel to important conferences, notably for younger researchers, and boosted the flow of foreign visitors to about 14 one-month visitors/year. We have also worked on attracting top-level long-time guest professors. In 2018-2019, Prof. R. Hertz (Penn State) will spend his sabbatical year at CEMPI; Prof. Hertz, invited speaker at ICM 2010 and recipient of the Brin Prize (2015) is a world-renowned expert on dynamical systems. His visit will allow him to continue his work with L. Flaminio on the Greenfield-Wallach conjecture and will provide exciting opportunities for the dynamical systems group, in particular D. Karaliolios, CEMPI postdoc in 2018-2019. In the framework of the 2019 CEMPI Thematic Semester, we will also host Prof. T. Arakawa for a three-month research stay. Prof. T. Arakawa is an invited speaker at ICM 2018, where he will present work partially elaborated in collaboration with Prof. A. Moreau. Overall, our visiting scholar program has been very successful in terms of publications: the 57 guest professors that visited us for one month or more in the period 2013-2018 have published over 100 papers with CEMPI researchers.

In 2017, CEMPI organized a scientific day to present its activities to its scientific advisory board, comprising such prominent scientists as J. Dalibard, professor at Collège de France, J. Dudley, former president of the European Physical Society, or G. van der Geer (Amsterdam), among others. The written official report of the advisory board was very positive, "congratulating CEMPI for its impressive achievements and success during the last two years", noting that "solid collaborations have arisen on genuinely interdisciplinary topics", that "CEMPI has demonstrated that it successfully fosters interdisciplinary research, leading to high-impact publications (…), that "CEMPI is uniquely positioned to play a central role in stimulating this type of research further (given that interdisciplinary research will become more important in research)", and that "the graduate school is functioning very well, and indeed well beyond expectations". They also commended "the leadership of CEMPI to work proactively to explore ways of ensuring the long-term continuation of CEMPI".

2 PROJECT DESCRIPTION AND EXPECTED IMPACT

2.1 SCIENTIFIC SCOPE AND CONTENTS OF THE PROJECT FOR THE NEXT FINANCING PERIOD, EXPECTED IMPACT

We propose here a completely redesigned research project for CEMPI, based on our six-year experience with interdisciplinary research and training. The project is organized in three new focus areas combining expertise from all disciplines involved, replacing the previous structure in terms of disciplines and their interactions. Its research objectives and implementation take into account two key points. First, our increased attractiveness has allowed us to hire, in the last five years, over 30 talented researchers who dynamize new topics of great interest, which are at the core of our new project. Second, the new CEMPI project will be carried out in the context of the ISITE ULNE project, and it is important that CEMPI actions contribute to the structuration of ULNE and to its success. This will in particular be achieved by stimulating interactions with laboratories and institutes beyond the core research units LPP and PhLAM, at ULille, Pasteur Institute of Lille and Inria in the context of the third Focus Area below.

FOCUS AREA I: DYNAMICS

The study of dynamical systems in their broad sense has been considerably reinforced at CEMPI with the recent hiring of 16 high-level researchers with expertise in this field. They bring new points of view and opportunely strengthen current research groups in analysis, geometry, probability, partial differential equations, cold atom physics and nonlinear optics. Solitary waves or optical turbulence in light propagating along an optical fibre, quantum chaos in ultracold atomic gases, the dynamics of electron bunches in particle accelerators lead to fundamental open questions at the interface of mathematical and physics. In mathematics, the study of dynamical systems is a major research subject which has intrinsic interactions with Geometry, Topology and Analysis. We identified the following themes:

I.A Nonlinear dynamics of complex systems

Context/scientific challenges and goals. Nonlinear partial differential equations (PDE) modelling physical systems can display a very complex dynamics due to energy exchange between frequency eigenmodes. Additional challenges arise when such equations have a *geometrical structure*, which can be Hamiltonian (e.g., the non-linear Schrödinger equation (NLSE), the KdV equation or the Ginzburg-Landau equation) or of gradient-flow type (which account for a loss of energy or information along time: the Boltzmann equation, ...).

The NLSE has a special standing because of its ubiquity in physics: it describes equally well waves traveling across the ocean, light pulses propagating along optical fibres or, under the name of Gross-Pitaevskii, the dynamics of Bose-Einstein condensates, a new state of matter where atoms share the same quantum state. Because of the unifying role of mathematics, this theme is highly interdisciplinary, with strong connections to other fields besides pure and applied mathematics and optics, notably hydrodynamics. Indeed, CEMPI researchers study optical analogues of dispersive shock waves arising when a dam breaks, or of the generation of giant waves localised in space and time (“rogue waves”). Understanding the turbulent regimes generated by the NLSE and their relation to coherent NLSE solutions which appear transiently in turbulence, such as solitons, breathers or localised waves, is a formidable problem both from a physical and a mathematical perspective.

Furthermore, the energy flow from large to small scales in turbulent cascades, leading to a stationary frequency spectrum, is a universal phenomenon; the dynamical mechanisms involved remain largely unknown. Even the interaction of a few modes can lead to non-trivial effects, as is illustrated by the Fermi-Pasta-Ulam recurrences observed in topographic fibres during the modulational instability (Section 1.1). Lattices of polariton microcavities (Theme II.A) form another ideal experimental system for studying wave turbulence and are now present at PhLAM, following the recent arrival of A. Amo, an ERC laureate. In dissipative laser systems also, the high-dimensional dynamics of multimode regimes and the structure of their state space are poorly understood.

Further understanding of optical turbulence will be one major objective of this theme. This will require combining mathematical approaches such as the inverse scattering transform, or the analysis of NLSE solutions with the state-of-the-art experimental techniques that have been developed at PhLAM for ultra-high-speed imaging of optical fields. As with any high-dimensional dynamical system, the objective is to decompose the complexity of the behavior in simpler terms, for example by identifying the regular solutions, solitons or localized waves that the system approaches transiently as it evolves erratically and to understand the mechanisms of this phenomenon. CEMPI researchers will also attack the fast-rising topic of quantum turbulence, which covers not only turbulence in the Gross-Pitaevski equation but also the dynamics of vortices in a Bose-Einstein condensate.

In the presence of such complexity, carrying out *in silico* experiments is essential to identify the interesting new phenomena, but requires the development of reliable numerical methods to approximate the solutions of the systems under study, a challenge CEMPI researchers will take on. The main challenges for numerical analysts concern the preservation of the geometric structure of the system when discretizing and the robustness of the numerical schemes with respect to the parameters (highly contrasted physical parameters, long time asymptotics).

Relevance of CEMPI teams. CEMPI researchers have recorded the first real-time movie of the formation of a rogue wave on a turbulent background [Nature Photonics 12 (2018)], shown the genericity of the Peregrine soliton in NLSE dynamics [PRL 119 (2017)], characterized the statistics of optical intensity and shown the formation of heavy tails associated with extreme events [PRL 114 (2015)]. They have studied the stability of solitons and soliton chains [J. Diff. Eq. 258 (2015); Arch. Rat. Mech. Ana. (2018), in press], detailed the blow-up properties of solutions to the KdV equation [Bull. Sci. Math. 141 (2017)] and developed accurate numerical schemes that are structure preserving [Found. of Comp. Math. 17 (2017)].

I.B Dynamics in (Non-)Equilibrium Statistical Mechanics

Context/scientific challenges and goals. Statistical mechanics aims at deriving the laws of macroscopic systems (thermodynamics, fluid mechanics,...) from the quantum mechanical or classical laws ruling the behaviour of its microscopic constituents. Despite a long history, it still presents formidable challenges.

Equilibrium statistical mechanics strives to explain and describe the states of matter and their phase transitions. Long-range interactions, a source of particularly arduous difficulties, have attracted much recent attention. A long-standing physical and mathematical problem is crystallization: when and why is it favorable for atoms to periodically arrange themselves? This question is part of the more general problem of self-organization. Coulomb gases are of particular interest. Such systems occur in quantum mechanics, in modelling the Ginzburg-Landau vortices and are related to random matrix theory. The understanding of their local behavior, in relation with the Abrikosov conjecture, is a major challenge. In a long-term project with T. Leblé, probabilists from LPP will explore an original approach towards a rigorous derivation of the rigidity and self-organization properties that have been predicted to occur at the local scale. In addition, the design and study of Markovian dynamics having the equilibrium states of the Coulomb gases as unique stationary states is of considerable numerical and theoretical interest.

A closely related subject is the dynamics of electron bunches which travel at relativistic speeds along storage rings in synchrotrons. Here also, the long-range electromagnetic interaction leads to a complex dynamics responsible for instabilities studied directly via the Newton equations or using kinetic theory with the Vlasov-Fokker Planck equation. Based on recent successes, the main objectives are to harness the spatial structures appearing in the microbunching instability to generate coherent THz radiation and to control the instabilities that distort synchrotron signal at high power, thus achieving stable operation over a wide range of parameters.

A central topic in non-equilibrium statistical mechanics is the description of the behaviour of energy, charge and matter currents in non-equilibrium steady states. A question of much recent interest is the understanding of anomalous behavior, such as anomalous diffusion of heat or matter. CEMPI researchers will continue recent collaborations on the identification and rigorous justification of the universality classes that are expected to describe the types of anomalous behavior as well as the challenging study of boundary effects in such systems.

The dynamical mechanisms responsible for approach or return to equilibrium are another central issue in non-equilibrium statistical mechanics. CEMPI researchers have made progress in their understanding in the weak-coupling regime, but the exploration of strong coupling regimes in both classical and quantum systems is an important further challenge, closely linked to the thermalization issues described under theme I.A.

Relevance of CEMPI teams. Experts in statistical physics at both PhLAM and LPP together with specialists of random matrices at LPP – many of them recently hired - constitute an ideal team to make progress on the above topics, building on their recent successes [Prob. Th. Rel. Fields (2014), J. Diff. Eq. (2018), J. Funct. Ana. (2018), Comm. Math. Phys. (2018), Arch. Rat. Mech. Ana. (2018), in press]. The PhLAM accelerator group pioneered the nonlinear dynamics of electron bunches, a theme in which it was first to show emission of coherent THz radiation [Nature Physics 4, 390 (2008)], and to image the microbunching instability in real time [Phys. Rev. Lett. 113 (2017)].

I.C Geometry and group actions

Context/scientific challenges and goals. Following the proof of several key conjectures of Thurston, there has been much progress in the interaction between geometry and low-dimensional topology. Perelman's geometrization theorem assigns a canonical geometry to essentially any 3-manifold; the Ending lamination theorem by Brock-Canary-Minsky gives a nearly full picture of the deformation space of hyperbolic 3-manifolds (the richest class); Agol's virtual fibration theorem captures strong features of 3-manifold fundamental groups among all discrete groups... The variety of techniques used in these results is astonishing: geometric group theory, differential geometry, partial differential equations, geometric limits, quasiconformal geometry, representation theory, dynamics, "cut-and-paste" topology, ... All these fields interact in deep ways, which can only be understood through a massive expansion of our perspective and classes of examples. For affine manifolds, one important challenge is to construct examples with interesting fundamental groups. Recent progress on that front raises the question: if two discrete groups can be realized as fundamental groups of affine manifolds, does the same hold of their free product? What about amalgamated products, or other constructions such as wreath products, graph products? We also plan to study the deformation space of an affine manifold and describe its boundary in terms of laminations, partly mimicking the theory of Kleinian groups; and to describe affine manifolds as renormalized limits of homogeneous manifolds (which holds true in dimension 3).

A field with a stronger dynamical systems flavour is the study of Anosov and pseudo-Anosov flows on 3-manifolds. Whereas the situation for surface bundles is well-understood, many interesting problems persist in the general case, starting from definitional ones (e.g., the degree of smoothness required). We plan to extend to general flows, under suitable conditions, the relationships known to exist for surface bundles between "veering" triangulations, sphere-filling curves defined by Cannon and Thurston, and the flow dynamics.

Relevance of CEMPI teams. Key developments in affine geometry took place in Lille [Invent. Math. 204 (2016)] and continue to unfold there. Also, LPP provides valuable local expertise on the dynamics of flows [Geom. Funct. Anal. 26 (2016)], on the transition from Gromov-hyperbolic groups to relatively hyperbolic ones [J. Reine Angew. Math. 710 (2016)], on the dynamics of buildings. The strong diversity of interests within the geometry team in Lille is a great match for the complex interplay of problems and techniques in this field.

I.D Holomorphic and Linear Dynamics

Context/scientific challenges and goals. Holomorphic dynamical systems is a first major subject, with intrinsic interactions with Geometry, Topology and Analysis. We will work on several important conjectures in the theory of laminations and foliations. A new method in holomorphic dynamics of one variable, based on Nevanlinna theory and on integral means, has been introduced by a CEMPI researcher, developing the thermodynamic formalism and its applications for a large class of entire and meromorphic functions and transcendental functions (e.g. Bowens formula, the variation of the hyperbolic dimension, multifractal formalism of the equilibrium states, beyond hyperbolicity,...). We will study the continuity and stability of these wandering Fatou domains. Finally, we will search for fine properties of the bifurcation current of a family of holomorphic maps on projective spaces and study the bifurcation current in the context of meromorphic maps on compact Kähler manifolds.

Second, we will attack various problems involving linear dynamical systems. Glasner-Weiss recently proved that any ergodic probability-preserving system is isomorphic to a linear dynamical system. This spectacular advance testifies of the richness of linear dynamical systems, opening opportunities to use them for solving problems in ergodic theory (e.g. study of sets of non-recurrence, existence of certain pathological systems, Anosov flows on compact manifolds, ergodic-theoretic aspects of Kazhdan's Property (T) for groups...). Another goal is the famous Invariant Subspace/Subset Problem (e.g. links with the recent Argyros-Haydon construction of spaces with very few operators, further investigation of operators of Read's type, invariant subspace theorems for analytically-defined classes of operators, study of model operators on the de Branges-Rovnyak spaces) using approaches and methods ranging from functional analysis to complex analysis and random matrix theory.

Relevance of CEMPI teams. Several new concepts to measure the dynamics of an operator have been introduced in Lille and the CEMPI analysis group is a world leader in linear dynamics [Trans. Amer. Math. Soc. 369 (2017), Adv. In Math. 265 (2014), J. Funct. Anal. 273 (2017)]. Some of the scientific challenges we plan to study are connected to the geometry of groups, thus we will benefit of the expertise of the geometry team of CEMPI (Theme I.C). Moreover, the group of complex geometry has been recently reinforced by the hiring of two high-level researchers who have a great expertise in holomorphic dynamics and bring new point of views [Invent. Math. 212 (2018), Ann. Sci. Éc. Norm. Supér. 51 (2018), Adv. Math. 331 (2018)].

I.E Innovative optical fibres

Context/scientific challenges and goals. Besides investigating fundamental questions in dynamics, CEMPI teams utilize their expertise in optics and the Fibertech fibre-drawing platform to design innovative optical fibres for telecommunication links and high-power lasers. To match an ever-increasing demand in Internet bandwidth, there is a need for new multiplexing methods besides conventional frequency multiplexing, such as spatially multimode multiplexing. PhLAM has demonstrated its expertise in multimode optical amplification and propagation in fibres and will continue to design systems more and more suitable for the needs of industry, in collaboration with Prysmian (world leader in internet fibres), Nokia and CAI Labs. Another area of application is the design of all-fibre high-power laser systems that are more compact and stable than the solid-state devices currently used and are thus suitable for operation in Laser MegaJoule, the French laser ignition facility for testing thermonuclear weapons, operated by CEA/CESTA. Finally, CEMPI teams have demonstrated the first multimodal nonlinear lens-less endoscope, which allows innovative imaging in a clinical setting.

Relevance of CEMPI teams. PhLAM has joint laboratories with Prysmian/Draka and CEA/CESTA. It is also a partner of a FUI project on multimode links with Alcatel Lucent, Prysmian/Draka and CAI Labs, and of the PIA project 4F to set up the future French fibre industry, gathering French major industrial and academic actors.

FOCUS AREA II: TOPOLOGY AND APPLICATIONS

The ground-breaking works of Riemann and Poincaré, and later of Grothendieck, revealed that topology and derived methods are a fundamental tool to study many problems in physics, geometry, algebra or arithmetic. CEMPI has experts of these methods and of their application fields, and have been reinforced by 9 recent hirings. Bringing them together will give to the partners an opportunity to valorise these recruitments, to develop synergies and to be at the forefront of subjects located at thematic interfaces. In particular, we will focus on three main projects:

II.A Quantum and photonic simulations, topological matter.

Context/scientific challenges and goals. Recent advances in solid-state physics, such as the fractional quantum Hall effect, topological insulators, or Anderson localisation are revolutionizing our understanding of magnetic, electric, and transport properties of matter. The difficulty of manipulation at nanoscopic scale has led to the design of “quantum simulators”, physical systems in which the dynamics of a complex Hamiltonian can be implemented and studied with exquisite control. PhLAM masters the two most interesting simulators: ultracold atoms in optical lattices and photons in coupled resonators and waveguides. As illustrated by the 2016 Physics Nobel prize, topological effects in condensed matter and simulators are a hot topic, creating a promising opportunity of interaction between LPP and PhLAM. Effects that depend on topological invariants are robust to small deformations and can be utilized to overcome losses, disorder or distortions of a system. A hallmark topological effect is the appearance of edge states localized at the boundaries between regions associated with different invariants. The invariants used today by physicists are basic analogues of the Gauss linking number and are not always defined. Thus, more general mathematical invariants and concepts such as homotopy groups will provide new insights into the physics of these systems. Conversely, physical systems will offer interesting examples from which mathematicians can elaborate new concepts. Using atomic and photonic simulators, CEMPI researchers will study graphene physics, the influence of spin-orbit coupling, the role of symmetry in Anderson transition, nonlinear many-body dynamics of strongly interacting particles.

Relevance of the CEMPI teams. Using cold atoms, the PhLAM quantum chaos group achieved in 2008 the first experimental observation of the 3D Anderson transition, 50 years after the prediction by Nobel laureate P.W. Anderson that disorder turns a metal into an insulator. Major results have followed, like the observation of coherent forward scattering [Nature Commun. 9, 1382 (2018)] or of 2D Anderson localization [Phys. Rev. Lett. 115, 240603 (2015)]. A. Amo, who joined PhLAM in 2017, is leading an ERC project based on coupled microcavity lattices, where photons coupled to electronic excitations (polaritons) provide a unique platform to investigate turbulence and topological properties of matter. He recently demonstrated the first laser functioning in a topologically –protected mode [St-Jean et al., Nature Photonics 11, 651 (2017)]. LPP provides expertise on the mathematical background of topology and homotopy theory with a renowned research group in this domain. Recent striking publications include the monograph (Progress in Mathematics, 32 Birkh auser/Springer, Cham, 2017) and [Adv. Math. 326 (2018), JEMS (to appear)].

II.B Homotopical methods in arithmetic.

Context/scientific challenges and goals. The arithmetic study of Riemann surfaces, their coverings and moduli spaces, through representations of their fundamental groups, would be one of the leading themes of this project. A prominent subtopic is the Inverse Galois Problem, in which new techniques including twisting families of coverings have been recently introduced, allowing one to tackle some related famous problems, including the Beckmann-Black arithmetic lifting problem, the classification of finite groups with a generic extension and the local-global Grunwald problem. In terms of moduli spaces those techniques amount to investigate the existence of rational points vs. rational lines on certain varieties, thus directly related to some diophantine conjectures of Lang, which currently have only been established in the case of curves due to the celebrated works of Faltings. The project will seek to generalize Mazur's approach for modular curves, to the case of modular surfaces (of Picard type) using advanced tools from geometry and Langlands theory of automorphic forms. The profinite nature of the Galois situation leads to organizing moduli spaces in infinite towers. The Grothendieck-Teichmüller group is a structure, shaped on this tower, which encodes the information that one can get on Galois groups through their action on Riemann surfaces. Research of the CEMPI project has made explicit a connection between this group and the operad of little 2-discs, a classical object of topology. We intend to explore generalizations of this correspondence, motivated by newly discovered applications of the little discs operads in knot theory. Homotopical methods are also used to construct p-adic L-functions for motives. Those are the main objects in Iwasawa theory, an area of forefront research (Fields Medals). We propose to construct new p-adic L-functions for automorphic forms over general linear groups and families thereof, study their zeroes and orders of vanishing, which is expected to shed light on some long standing problems in analytic number theory.

Relevance of CEMPI team. The CEMPI topology group, reinforced by recent recruitments, has a great expertise in applications of operads to Grothendieck-Teichmüller theory [Mathematical Surveys and Monographs 217, American Mathematical Society, 2017] and in applications of triangulated categories [Compos. Math. 152 (2016)]. The CEMPI team in Arithmetic has several experts with significant contributions to: non-archimedian motivic aspects [Annals of Mathematics, 171 (2010)], arithmetic geometry [Duke Math. J. 165 (2016)], Inverse Galois Problem and Modular Towers [Annales Sci. E.N.S. 51 (2018)], Anabelian geometry [J. Algebraic Geom., 24 (2015),Mordellicity of modular surfaces [Documenta Math. 20 (2015)].

II.C Representation theory

Context/scientific challenges and goals. From its origins in the topological works of Lie and Cartan, representation theory has developed in a constant dialogue with geometry, topology and arithmetic. Understanding these interactions raises exciting mathematical challenges, potentially leading to major mathematical advances. When the cohomology algebras of a group are finitely generated, its modular representations can be reinterpreted in terms of the geometry and topology of a variety. The most prominent example of such a dictionnary is the theory of support varieties, which has recently led to important advances in the modular representation theory of finite groups schemes. We plan to first develop tools for cohomological computations (in the finite group and in more general contexts where theory of support varieties still applies), whose ultimate goal is to understand how representation-theoretic properties are related to cohomological varieties when the theory of support varieties does not apply, for example with classical matrix groups. Another goal is to investigate the connections between representation theory and quantum topology, where physics could provide an interesting insight, for example the Higgs branch conjecture of Beem and Rastelli saying that this topological invariant associated to superconformal field theories in four dimension coincides with the associated variety of certain vertex algebras. The first known examples came from Deligne's exceptional series and special cases of the conjecture have been recently proved.

A new light on Khovanov's celebrated categorification of the Jones polynomial would be shed by the universal surgical approach yielding an algebraic description of quantum invariants of 3-manifold (in terms of certain braided Hopf algebras and diagrams) and is expected to give a starting point for their categorification. Finally representation theory of p-adic groups also bear great arithemetic significance as envisionned by Langlands in his programm. While such complex representations connect directly to the themes of automorphic forms and to global Galois representations presented in 2.B, the study of the much richer theory of p-adic and mod p representations connect to p-adic Hodge and p-adic Langlands theories - a highly competitive area of research recently distinguished by a Fields medal.

Relevance of CEMPI teams. Recently, LPP has recruited five specialists with significant contributions related to representation theory, such as quantum and super groups [*Int. Math. Res. Notices* (2016)], group homology [Comment. Math. Helv. 90 (2015), Duke Math. J. 151 (2010)] or vertex algebras [*J. Inst. Math. Jussieu*, 17 (2018)]. The project provides an opportunity for them to work together and to develop representation theory as one of the domains of excellence of CEMPI.

FOCUS AREA III: BIOLOGY / STOCHASTIC MODELLING / DATA SCIENCE

This Focus Area is an evolution of the second and third Focus Areas of the original CEMPI project, which aimed to develop interactions of mathematics and physics with biology and computer science. This evolution was motivated by the integration into CEMPI in 2015 of the LPP probability and statistics team (30 permanent staff), and its recent reinforcement through the hiring of 5 new faculty members, notably in data science and statistics. Here, we will focus on scientific problems where probabilistic or statistical approaches play an important role. An interesting domain of application is biology, because fluctuations due to heterogeneities in populations or to small numbers of molecules in cellular biology must be taken into account. However, biological phenomena also follow deterministic laws and how the two descriptions integrate with each other is of fundamental importance. More generally, we will distinguish problems whose analysis requires models and those which can be studied via data science and statistical approaches. We will focus on and sustain on three projects for which promising and exciting developments are expected:

III.A Probabilistic models in ecology and population dynamics

Context/scientific challenges and goals. Mathematics for ecological and public health questions receives increasing interest, as illustrated by the 'year of Mathematical Biology' 2018 organized by EMS. Deterministic and probabilistic methods have been recently developed, including spatial, temporal and genetic dimensions.

Models with network structures are increasingly important: gene regulation models, graphs describing dominance relations, networks spreading infectious disease with geographical and temporal dimensions, stability of trophic or pollinating networks structuring population dynamic models are examples. Not only should graph theory be married to probability theory and dynamical systems, but also these applications trigger new fundamental questions. For instance, several applications are related to the old problem of random walks on a graph: extensions to new random walks on the underlying simplicial complexes connect to cohomological theory. Describing the graph topology also leads to statistical questions associated with sampling effects, modelling of multiple and multitype interactions and predictions.

A second hot topic deals with multi-level models. For example, nested coalescents used for the modelling of phylogenies in dynamical stochastic trait-structured populations have applications to pathogen evolution. Coupling these processes with geographical data, we would like to model and predict the dynamics of seasonal diseases such as the flu. Another example are mathematical models for multi-level individual-centered systems which naturally appear for modelling antibiotic resistance in bacteria. The study of their behaviour in time involves fine limit theorems and careful handling of scales.

Relevance of CEMPI teams. Our expertise in mathematics for evolution and phylogenetics modelling, for spatial statistics and functional data analysis, and for their applications to public health and epidemiology is recognized world-wide [Hepatology 63, 1090 (2016), Ann. Stat., to appear, Bull. Math. Biol. 6 (2014), J. of Clinical Epidemiology 82 (2017)]. New collaborations between CEMPI mathematicians and biologists from ULille have lead to joint publications [J. Math. Bio. 71 (2015), J. Theoret. Biol. 411 (2016)] and a co-supervised Phd.

III.B Data science and machine learning via determinental processes.

Context/scientific challenges and goals. One of the trendiest fields of modern data analysis is « machine learning », at the border of mathematics and computer science, which is about self-improving stochastic algorithms to answer questions by prediction or classification, provided enough data are available. However, solid guaranties on the efficiency of such algorithms based on rigorous mathematics are only partial and still under intense investigation. On the other hand, several random objects from mathematical physics such as random matrices and determinantal point processes (DPPs) have recently been extensively studied and have promising applications to this area of data analysis. For instance, random matrices are already a useful tool in machine learning via concentration inequalities. We will improve the mathematical basis of machine learning by building further on random matrix theory as well as developing new techniques involving DPPs or Gaussian analytic functions (GAFs). More specific topics include: speeding up numerical integration methods with DPPs (e.g. for Bayesian statistics); leverage the repulsion feature of DPPs for efficient variable selection; noise reduction using new explicit formulas for time-frequency transforms of the noise in terms of GAFs; subgaussian concentration inequalities for DPPs and random matrices for non-asymptotic prediction intervals and classification.

Relevance of CEMPI teams. The weekly discussion group at LPP on random matrices, organised by the local experts on the topic [Ann. Proba. 2016, Elec. J. Proba. 2016, Const. Approx. 2017], recently focused on concentration theory [Prob. Th. Rel. Fields 2014, J. Funct. Ana. 2018] with a particular outlook towards machine learning problems. In addition to probabilists, analysts and statisticians from LPP, it attracts researchers from the computer science laboratory CRIStAL (SEQUEL (Sequential Learning)), which are external to CEMPI, but within the research Hub 3 of the ISITE ULNE. This fruitful interaction has led to two PhD students working on these interdisciplinary topics.

III.C Deterministic and stochastic processes in cellular biology.

Context/scientific challenges and goals. To maintain life and respond to stimuli, living cells rely on networks of genes interacting through feedback loops, which encode, transmit and process biological information. Deciphering the complex dynamics of these networks requires to combine mathematical modelling with real-time imaging of the molecular dynamics in living cells. Designing modelling paradigms that integrate the deterministic behaviour of biological systems with fluctuations due to small molecule numbers is an open but stimulating problem. Combining mathematical and experimental approaches in close collaboration with biologists, CEMPI researchers will study how cell proliferation is coordinated with differentiation during embryonic development, how the dynamics of stress response can be utilised to design anti-cancerous strategies, and how the synchronisation of the liver biological clock with meal rhythms is compromised in obesity and diabetes. They will also study the mechanisms regulating gene activity in response to molecular signals.insit

Relevance of CEMPI teams. CEMPI researchers modelled how neural progenitors decide between proliferating and differentiating to neurons during development [Development 142, 477 (2015)], used their expertise in biophotonics in a collaborative work showing the anti-cancerous activity of compounds in melanoma cells [Cancer Cell 6, 805 (2016)], and designed the first mathematical model of how the liver clock is entrained by metabolic day/night cycles [Cell Reports 17, 1087 (2016)]. This is an example of an interhub collaboration between CEMPI (`Digital World' Hub) and Labex EGID (`Health' Hub) of the ISITE ULNE of the type we will further develop. CEMPI technical expertise in observing and manipulating living cells with light and microfluidics is also mobilized in ERC project Nanobubbles (led by Ghent University).

2.2 Research-Learning interface and expected impact

Ambition/contours. CEMPI's ambition is to further develop its leading international program for training highly skilled mathematicians and physicists prepared for interdisciplinary research in academia and industry. They will be reputed for their ability to forge conceptual tools and mathematical models in complex problems mobilizing several disciplines. For that purpose, it will develop a two-pronged strategy. First, a series of new ambitious actions described below will be put in place from the Bachelor to the postdoctoral level. Second, CEMPI's experience of interdisciplinarity and its links with the ECL are essential building blocks of the training program of the research Hub `Digital World' of the ISITE ULNE and of its `Deep Tech' Graduate School.

Actions

- **Mentor**: each student integrating the CEMPI program will be assigned a member of the faculty as a mentor for the duration of his studies. The mentor is one of the researchers of our laboratories and will advise the student on the different training programs and help him to understand the local and global research and business environment and national and international job opportunities.
- **Complementary courses at the Masters and Doctoral:** each year, we will propose complementary courses of 24 hours each on specific topics related to CEMPI scientific program, to improve the excellence and the interdisciplinarity of the training program. These courses will be directed at master and PhD students, but also at postdocs and staff wishing to engage in interdisciplinary research. They will be taught either by our own professors or research staff (CNRS-Inria), or by the CEMPI invited professors. Courses will be suggested by the training coordinator, the fellowship PhD coordinator and the directors of the master programs and approved by the executive committee of the CEMPI.
- **Student/postdoc taught tutorial courses**: all students and post-doctoral researchers benefiting from a CEMPI fellowship will provide each year 24 hours of tutorials to lower-level CEMPI students.
- **CEMPI Friday Afternoon Meetings**: to increase the scientific and social connections between the students and the researchers, regular Friday Afternoon Meetings for all students of the CEMPI training program will host seminars given by the students, research mini-courses or colloquia by our researchers or invited professors, discussions/conferences on various issues of general interest...
- **Outward mobility**: all CEMPI doctoral students will be encouraged to have an international mobility of few months in a world class institution, taking advantage of our network of international CEMPI partners (KU Leuven, Max Planck Institute, Fields Institute, SISSA, Imperial College, Scuola Normale Superiore Pisa,…) and of distinguished researchers (e.g. ERC grant holders who have accepted to support us: M. Burger, J.-F. de Bobadilla, T. Claeys, P. Gonçaleves, T. Hausel, C. Liverani, C. Mouhot, P. Nowak, Z. Rudnick, U. Zannier, S. Vaes, T. Willwacher).
- **Delocalized summer school**: CEMPI will propose regular delocalized summer schools on subjects of interest to CEMPI, which will increase the global presence and visibility of CEMPI in strategic places in the world. An international university, with a pool of high-level students and researchers will be the ideal partner. Our international CEMPI partners will be first (but not only) considered.
- **Actions for parity**: We intend to address the lack of gender parity in mathematics and physics. (1) Each year, a short course centred around gender issues and equal opportunity will be attended by female and male CEMPI fellows, and ideally also by their mentors (2) If scientifically possible, young female CEMPI fellows will be mentored by senior female researchers, with long-term benefits according to several international studies. (3) We will invite a significant number of women professors. (4) We will help CEMPI doctoral/postdoctoral female fellows who have a baby, e.g. by extending their contract.
- **English teaching**: The international context of CEMPI motivates the use of English in training programs. 50% of the CEMPI master program is currently in English (75% for the 2nd year). The goal is to reach 100% in 2022.
- **Fellowships**: to increase the excellence of our entrance flux, we will continue to attract high-level students from other universities in France and abroad via our successful master, doctoral and postdoctoral fellowship program. We will also continue our program of post-doctoral fellowships. We plan to fund over the duration of the project

23 two-year Master fellowships, 6 three-year doctoral fellowships and 9 one-year postdoctoral fellowships. This represents a minor part of the complete fellowship pool available to CEMPI students, due to support from our partners obtained thanks to the CEMPI visibility and leverage effect.

On-site development strategy - `Deep Tech' Graduate School of the ISITE ULNE.

The `Deep Tech' Graduate School (GS) of the ISITE ULNE is in its development phase and will be fully operational in September 2020, when the new accreditation of the ULille curricula with the ministry will come into effect (Section 2.4). Its main ambition is to train Master and Phd students with backgrounds in the natural or human sciences and to provide them with hybrid skills in modelling, interdisciplinary thinking and technological development, for a better entrepreneurial and societal integration. The `Deep Tech' GS will build on a number of master degrees of the ISITE ULNE consortium among which feature the three CEMPI affiliated masters of ULille:

- *Master of "Engineering Mathematics"* (Department of Mathematics): the first year provides a general background in scientific computing, statistics and data analysis, in preparation for the second year which proposes a choice between two specializations. The first one is centered on modelling, numerical simulation, supercomputing and their bridging and the second one is centered on statistics, data sciences and machine learning. See here for details.
- *Master "Pure and applied mathematics"* (Department of Mathematics): during the first year, the students receive a broad training in fundamental and applied mathematics covering all standard domains: algebra, geometry, analysis, numerical analysis and probability. After one year, the students choose a specialization in fundamental or applied mathematics. See here for details.
- *Master "Physics" (Department of Physics)*: the first year of the fundamental physics program provides core physics background, in particular in atomic physics, statistical physics, optics, as well as specialist courses preparing for the five available second-year curricula. Two of them contribute to CEMPI: "light-matter interaction" (LMI), with emphasis on lasers, photonics, cold atom physics, and "medical and biological physics" (MBP), which emphasizes biophotonics and modelling of dynamical phenomena in cellular regulation networks. See here for details.

CEMPI faculty, post-doctoral and Phd students will participate in the supervision of the internships of the `Deep Tech' Master students within the GS Deep Tech Lab. This laboratory has the ambition to bring together researchers, faculty, companies and start-ups in two-years projects related to deep tech innovation, harnessing the latest scientific advances.

The successful partnership with ECL (Section 1.2) will be strengthened to include a machine-learning component in the context of the `Deep Tech' GS and in line with the research theme III.B.

The CEMPI research-training programs will work with the Centre for Pedagogical and Digital Innovation of the ISITE ULNE, providing infrastructure for and guidance on interactive teaching practices and active pedagogy.

2.3 Valorization strategy of the project and socio-economic impact

The numerous industrial partnerships currently active with regional, national, and global companies have been mentioned before, as well as the two joint laboratories with Prysmian/Draka, the largest producer of optical telecommunication cables in the world and with CEA/CESTA, operating the Laser MégaJoule. These fruitful partnerships will continue in the near future. Here, we mention recent evolutions which shape the near future.

PhLAM is a key partner of the PIA project 4F, funded with 7 million euros for 2017-2021. The 4F project aims at developing and structuring the french optical fibre industry of the future, to design innovative fibres for light amplification and transport and invent a new generation of industrial lasers. It gathers four public laboratories (Ecole polytechnique, XLIM/Limoges, FOTON/Lannion and PhLAM) and seven major industrial actors (Amplitude Systemes, Eolite Systems, Quantel, Keopsys, Thales, Azur Light Systems et GLO Photonics).

Inside the CPER project Photonics4Society, PhLAM coordinates the development of two startup companies. 1) Linoptics designs several types of fibre lasers designed for laser engraving, lidars (light radars) in cars, wind speed measurement, … 2) Gecko Light designs fibre components to be integrated in laser systems, such as a pulse stretcher for high-power amplification, fibres with tailored dispersion curves, Bragg grating mirrors, fibres with flat profile modes… Sophisticated techniques originating in CEMPI research, such as multimode operation, nonlinear mode condensation, topographic profiling, are harnessed in these designs. LPP is also active in this domain: PAM, an Inria spin-off, will soon be created as a software publisher dedicated to predictive maintenance for industry (using machine learning and statistical learning), capitalizing on software successfully used in several past contracts.

Three universities of Région Hauts-de-France (ULille, Université d'Artois, Université de Picardie), CNRS and Inria are combining their efforts to develop a common regional pole on artificial intelligence aiming to stimulate research, applications and valorisation for the creation of start-ups on this topic. The CEMPI brings its strong skill on the stochastic sides of this project.

CEMPI will continue its efforts in science popularization and the publication of the CEMPI Subseries of Lecture Notes in Mathematics/Physics (Springer).

2.4 Scientific and pedagogical integration into the strategy of the ISITE ULNE and of the CEMPI partners

CEMPI has had from the start a strong impact on its academic environment in Lille and its region and this will perdure. LPP and PhLAM have created an effective scientific collaboration at the interface of mathematics and physics, with increasingly visible and continuously progressing results (Section 1.2).

CEMPI has been a driving force in the construction of the ISITE ULNE: the CEMPI scientific coordinator (S. De Bièvre) was involved in the writing of the IDEX/ISITE project and was twice a member of the delegation that defended it before the PIA international jury (2015, 2016). The existence of the four Labex coordinated by the ISITE ULNE, including CEMPI, was a key point of the success of ULNE and an essential ingredient of its conception. As a result, the new CEMPI project is perfectly aligned with the ambition and strategy of ISITE ULNE and its institutional partners (ULille, CNRS, Inria, École Centrale, Institut Pasteur,...) to "transform research and higher education in the Hauts-de-France Region," to create a "world-class University ranked in Europe's top 50 in ten year's time" and to "reinforce international visibility, attractiveness and competitiveness.''. To realize that ambition, ULNE has designed a research strategy based on three research "hubs": "Precision Human Health", "Science for a Changing Planet" and "Human-friendly Digital World". CEMPI operates at the core of the third hub, where it is essential for taking on the challenge ``Taming complexity with innovative conceptual tools'', central to this hub. Steps have been taken to coordinate the governance of the four Labex programs with that of the ISITE ULNE (Section 3.1).

Taking note of the many synergies between CEMPI and the ISITE ULNE briefly outlined below and of their essential contribution to the success of both, the ULNE Steering Committee has decided to allocate annually 215 667 euros (overhead excluded) to the renewed CEMPI project in order to help implement planned ISITE ULNE actions in line with the coordinated ISITE ULNE and CEMPI development strategy. This measure ensures that CEMPI will continue to dispose, in 2020-2024, of the same annual budget from the PIA as in 2012-2019. We refer to Section 4 for the detailed CEMPI budget.

The ISITE ULNE thus develops within the research Hub `Digital World' a "Deep Tech" Graduate School, which will train future scientists and engineers to utilize the latest advances in science to design breakthrough innovations and to work in interdisiciplinary teams. To set it up, ULNE has appointed M. Douay (Director of PhLAM, member of CEMPI Executive Committee and coordinator of its socio-economic impact actions). CEMPI, whose training program was a graduate school "avant la lettre" (Section 1.2), will thus be an essential building block here as well and its expertise and experience will be essential to the success of the "Deep Tech" GS.

Further ISITE ULNE actions to which CEMPI will contribute are "Sustain excellence in research and innovation" and "Expand excellence in research and innovation," which aim to strengthen and to expand the perimeter of excellence within the ULNE consortium. Indeed, the interdisciplinarity of its research themes allows CEMPI to promote interactions within its own research hub, with computer science and nano-technology in particular, but also with the two other hubs, especially Hub 1 (Health), where a collaboration with the Labex EGID is already active (Section 1.2) and has been funded in the first ULNE call for projects (february 2018). The skills and experience of

CEMPI with interdisciplinary science thus allow it to be a driving force for both the "sustain'' and "expand" strategies of the ISITE ULNE. CEMPI will also contribute to the action "Reinforce research international visibility, attractiveness and competitiveness" of ISITE ULNE through its international network of collaborators and partners (Section 1.2) and through its training program (Section 2.2) to which it attributes 30% of its budget.

Moreover, to strengthen the LPP-PhLAM collaboration, and to consolidate joint themes, the two laboratories have agreed to hire one junior and/or one senior professor with outstanding expertise both in applied mathematics (PDE, scientific computing, probability theory) and in one of the core CEMPI physics themes (cold atom physics, quantum optics, nonlinear optics,...). For this purpose, CEMPI will rely on the talent attraction programs of partner institutions (MEL, ULNE, Region), as well as on the support of ULille, CNRS and Inria to make a permanent position available, in accordance with their human resource strategy.

CEMPI is also active in establishing links between ULille and the engineering schools in the ISITE ULNE (Section 2.2).

Inria is another important member of the ISITE ULNE consortium that plays an increasing role for CEMPI programs. LPP has currently 20 faculty members involved in 3 Inria Joint Project Teams ("Equipe Projet"), Mephysto-post, Modal and Rapsodi. Their lines of research on interactions between Mathematics, Physics and Machine Learning are integrated in the new CEMPI project. Seven Inria researchers are currently members of LPP, up from only 1 in 2012. Multidisciplinary cooperations have led to the creation and development of the platform BILILLE, devoted to projects in genomic with statistical and data science developments, and which relies on the expertise of statisticians of the Inria Modal team.

Last but not least, CEMPI will contribute actively to the socio-economic impact of ULille and ISITE ULNE with its strong dynamics in this area, in collaboration with the Equipex FLUX and its participation to the Photonics4Society CPER project (as described in Section 2.3).

Through CEMPI, LPP and PhLAM share, defend and propagate jointly a common view on the development of fundamental scientific research, training and economic transfer. CEMPI has become, and will continue to be, a major driving force for innovative action in research, training and economic impact within ULille and ULNE.

3 Partnership organisation

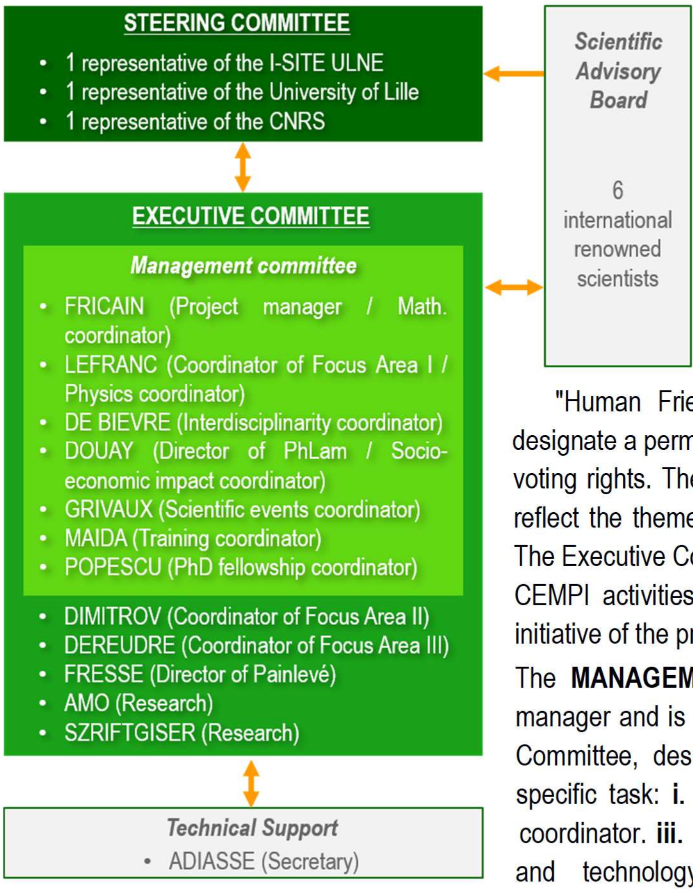
3.1 Governance

In the mid-term evaluation of 2015, the governance was very positively evaluated. Thus, we decided for effectiveness to maintain its overall structure while taking into account the creation in 2017 of the ISITE ULNE. The CEMPI governance is characterized by its "Flexibility, Efficiency, Reactivity, Simplicity!" motto**.** It is articulated around the Steering Committee, the Executive Committee presided by the project manager, the Management Committee and the Scientific Advisory Board. While retaining the existing governance, we decided to renew the team to take into account emerging themes and the renewal in the faculty. The project manager will thus change in January 2020 and a new steering committee is proposed.

The **new project manager** is Emmanuel Fricain, 47 years old, Professor at Lille University since 2012. He obtained his PhD in 1999 at Bordeaux University and was appointed « Maître de Conférence » at Lyon University in 2000. He is the author of 40 publications in the domain of analysis and of a two-volume monograph on de Branges—Rovnyak spaces published at Cambridge University Press. He supervised 3 PhD theses, with a fourth in progress, and 1 postdoctoral student. He is the deputy director of LPP since 2015. E. Fricain has joined the CEMPI executive committee in 2015 and has since participated yearly in the scientific committees for the Master/postdoc fellowships and invited professor positions.

The **PROJECT MANAGER,** together with the Executive Committee, defines the scientific and pedagogical strategy of CEMPI on the basis of the present programme. He appoints a Management Committee within the Executive Committee to run the daily operations of CEMPI. Together with the Management Committee, he organises calls for all scientific, pedagogical and socio-economic impact projects within CEMPI as well as the hiring procedure for the

CEMPI fellowships and visiting positions. The project manager and the relevant committee produce a ranking of the proposals or fellowship applications, which is submitted to and possibly amended by the Executive Committee, iterating the process until an agreement is reached. Together with the Executive Committee, the project manager proposes each year a budget for endorsement by the Steering Committee and organises the writing of an annual report; it describes the progress made and is submitted to the Steering Committee and the Scientific Advisory Board for evaluation.



The **EXECUTIVE COMMITTEE** is composed of 12 representatives from the two partner laboratories: 8 from LPP and 4 from PhLAM. The project manager presides over the Executive Committee, whose members are appointed by the Steering Committee based on a list proposed by the project manager. The directors of the two partner laboratories are members of the Executive Committee or may designate a representative. The research Hub "Human Friendly Digital World" of the ISITE ULNE may designate a permanent guest to the Executive Committee, without voting rights. The composition of the Executive Committee must reflect the themes covered by the CEMPI scientific programme. The Executive Committee is responsible for the smooth running of CEMPI activities. It meets at least every three months, at the initiative of the project manager.

The **MANAGEMENT COMMITTEE** is presided by the project manager and is composed of up to 7 members of the Executive Committee, designated by the project manager, each with a specific task: **i.** PhD fellowship coordinator. **ii.**Scientific events coordinator. **iii.** Training coordinator. **iv.** Socio-economic impact and technology transfer coordinator. **v.** Interdisciplinarity coordinator. **vi.** Mathematics coordinator. **vii.** Physics coordinator.

The **STEERING COMMITTEE** is composed of one representative of the ISITE ULNE, who presides it, and two representatives of ULille and CNRS. The Région Hauts de France may designate a permanent guest to the Steering Committee, without voting rights. The Steering Committee meets once a year. It reviews CEMPI activity, based on the annual report, assesses the strategy and make suggestions for adjustments based on recommendations by the Scientific Advisory Board. It approves the budget; it appoints the Executive Committee based on a list proposed by the project manager. If the latter was to step down, the steering committee selects a new project manager based on proposals made by its members and the Executive Committee.

The **SCIENTIFIC ADVISORY BOARD** is composed of 5 to 6 internationally renowned scientists, including one biologist and one computer scientist. Members are proposed by the project manager and endorsed by the Executive and Steering Committees. The Scientific Advisory Board meets once a year at the initiative of the Executive Committee. It reviews the quality of CEMPI work based on the annual reports and the long-term scientific strategy. It makes recommendations for scientific and training strategy.

TECHNICAL SUPPORT CEMPI can count on the considerable experience of the secretarial staff and technicians of the partner labs. In addition, a full-time secretary dedicated to CEMPI is provided by ULille.

EVALUATION. The progress of CEMPI project will be measured with standard performance indicators of academic excellence in research and teaching, which include record of publications, 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. In addition, particular attention will be paid to the capacity of CEMPI for: (i) creating inter-partner collaborations; (ii) setting up new interdisciplinary chains of interconnects; (iii) working effectively with its affiliated foreign institutes for research and training; (iv) attracting top-level scientists to its thematic semesters; (v) filing patents.

SITE COORDINATION. The coordination of CEMPI governance with ULNE governance will be ensured by the participation of CEMPI project manager in the coordination committee of the research "Human-Friendly Digital World" hub, as well as by the participation of a ISITE ULNE representative to the steering committee. The governance will also ensure a good coordination between CEMPI partner labs and master programs.

3.2 Consortium modifications

The official composition of the consortium in terms of teams is the same as in 2012 except that the Probability and Statistics team of LPP (30 members) is now also part of it, after joining CEMPI in 2015.

3.3 Partners' description, relevance and complementarity

CEMPI partners are **1) the Laboratoire de Mathématiques Paul Painlevé** (130 professors and researchers+56 PhD and postdoctoral students). The topics cover the whole spectrum of mathematics with a structure in 5 research teams; **2) three teams of the Laboratoire de Physiques des Lasers, Atomes et Molécules Phlam**. (43 professors or researchers + 28 PhD and postdoctoral students).

Scientifics themes	PhLAM	LPP
Nonlinear dynamics of complex systems.	DYSCO, Phot, PCA	PDE
Systems with long-range interactions: equilibrium states and dynamics.	DYSCO	Proba
Geometry and group actions.		Geo
Holomorphic and linear dynamics.		Anal, Geo
Innovative optical fibres.	Phot	
Quantum and photonics simulations, topological matter.	DYSCO, PCA	Topo
Homotopical methods in arithmetic.		Arith, Topo
Representation theory.		Alg, Arith, Topo,Geo
Probabilistic models in ecology and population dynamics.		Proba, Stat, PDE
Data science and machine Learning via determinental processes.		Proba, Stat
Deterministic and stochastic processes in cellular biology.	DYSCO	Proba, Stat

Research team (number of members): PDE: Partial Differential Equations (22), Proba: Probability (16), Geo: Geometry (14), Anal : Analysis (24), Alg: Algebraic geometry (10), Arith: Arithmetic (14), Topo: Topology (13), Stat: Statistic (17) (LPP teams). DYSCO: Dynamics of Complex Systems (20), Phot: Photonics (15), PCA: physics of cold atoms (8) (PhLAM teams).

4 Funding Justification

4.1 Expenses justification

The Labex budget over 5 years amounts to € 48 888 337. The total funding request (overhead costs included) amounts to € 1 960 396 over the duration of the project.

Personnel costs. 35% of the total CEMPI funding request (€ 694 682) is for salaries of non-permanent personnel and complementary courses. Visiting faculty positions correspond to invitations of period from one to six months and allow to develop international research collaborations with CEMPI faculty and courses for Graduate School students. PostDoc fellowships, PhD fellowships and research internship remuneration will contribute to the excellence of our entrance flux by attracting high-level students from other universities in France and abroad.

Operating costs. 41% of the total CEMPI funding request (€ 798 000) is for external service provisions and consumables. Those funds will also serve to finance i. Master's fellowships ii. travel and accommodation of CEMPI faculty to conferences and workshops as well as of invited visitors to CEMPI. Further external services provisions concern the Fibertech optical fibre manufacturing (maintenance or clean-up contracts).

Equipment costs. 16% of total CEMPI's request to ANR (€ 322 500) is for new equipment and optical sources (continuous or pulsed lasers, Optical parametric oscillators), which are necessary to extend the existing experiments or build new experimental set-ups.

4.2 Funding plan

CEMPI total funding over 5 years is € 48 888 337, of which € 1 960 396 is requested in this funding application, € 39 662 535 is provided by ULille *personnel valorisation*, € 6 182 069 by CNRS *personnel valorisation.* The remaining € 1 078 337 come from ISITE ULNE who, by its considerable financial contribution to the project, clearly manifests its commitment to the CEMPI application for extension (See Section 2.4 and below). In return, the new CEMPI project is perfectly aligned with the ambition and strategy of ISITE ULNE and its institutional partners.

Institutional partners funding	2020	2021	2022	2023	2024	Total
PIA / ANR	**€ 392 079**	**€ 392 079**	**€ 392 079**	**€ 392 079**	**€ 392 079**	**€ 1 960 396**
ISITE ULNE*	€ 215 667	€ 215 667	€ 215 667	€ 215 667	€ 215 667	€ 1 078 337
ULille	*€ 7 932 507*	*€ 7 932 507*	*€ 7 932 507*	*€ 7 932 507*	*€ 7 932 507*	*€ 39 662 535*
CNRS	*€ 1 236 413*	*€ 1 236 413*	*€ 1 236 413*	*€ 1 236 413*	*€ 1 236 413*	*€ 6 182 069*
Total budget	**€ 9 776 667**	**€ 9 776 667**	**€ 9 776 667**	**€ 9 776 667**	**€ 9 776 667**	**€ 48 888 337**

**without gestion and environments costs.*

CEMPI will contribute to collective actions for the benefit of structuring the site (Section 2.4 and table below).

ISITE ULNE funding	Contribution to the strategic axes of ISTE ULNE
Visiting senior and junior professors	F1: Setting up of the Thematic Graduate Schools; R3: Reinforce research international visibility, attractiveness and competitiveness
Postdoc fellowships	R3: Reinforce research international visibility, attractiveness and competitiveness
PhD fellowships	F1: Setting up of the Thematic Graduate Schools; R2: Expand excellence in research and innovation
Master's fellowships	R4: Setting up a doctoral incubator; F1: Setting up of the Thematic Graduate Schools
Internship remuneration	R3: Reinforce research international visibility, attractiveness and competitiveness
Complementary courses	F1: Setting up of the Thematic Graduate Schools
Delocalized summer school	R3: Reinforce research international visibility, attractiveness and competitiveness
Deep Tech Lab project	F1: Setting up of the Thematic Graduate Schools