HIGHLIGHTS 2018

Laboratoire de physique

ÉCOLE NORMALE SUPÉRIEURE DE LYON

Benjamin Huard team's experimental room at Laboratoire de physique.

On the lab's request, illustrator Hélène Bléhaut spent two weeks in the lab to meet and document the work atmosphere. She interviewed PhD students, researchers, engineers and managers, attended seminars, lectures, runs of experiments and was treated numerous coffees to have a global look on what it's like to work and live here. She made sketches mostly in real time from various atmospheres and people.

Foreword

Thierry Dauxois
Director of the lab

The 2018 issue of the «Highlights» publication of the Laboratoire de Physique gathers facts, events or research achievements of 2016 & 2017. This gives a flavor of the different aspects of our engaging research environment, and in particular the diversity and the novelty of some research projects, signatures of the dynamism of the research atmosphere. This is only a partial selection of the research topics addressed in the Lab, which are detailed in our website.

Several members of the Lab have been awarded distinctions and prizes: D. Bartolo received the De Gennes prize, D. Le Tourneau the Palmes Académiques, L. Savary the F. Nevill Mott prize, while A. Bérut, R. Hamon, G. Michau were rewarded for their PhD. We present here their brief portraits.

The involvement of the Laboratory in teaching has been especially emphasized by the success of the ENS student team in the International Physicists' Tournament: the team, coached by N. Taberlet and N. Plihon and colleagues has won two successive French Championships and one World Title.

Another richness of the Laboratoire can be found in its numerous international links exemplified by the creation during these two years of two Laboratoire International Associé, with Chile and Norway. Finally, the present issue also features STAPHYS26, the largest and most wide ranging conference in statistical mechanics which took place in Lyon in July 2016: almost all scientific fields of the lab have been represented during this week. It was a wonderful success thanks to the involvement of the whole Lab at all levels.

The purpose of this document is also to present some examples of recent scientific achievements within the laboratory to a wide audience. We believe that the origin of these results lies in the excellent quality of our PhD students and post-docs, and the high level of expertise of our technical staff members. These are a foundation of the stimulating atmosphere within the Laboratoire de Physique that drives research of the highest standard.

Lyon, January 2018

Contents

Lab Presentation

The Laboratoire de Physique is affiliated to three institutions: ENS de Lyon, CNRS and Université Lyon 1, all members of Université de Lyon. Its scientific activities cover various fields, from statistical physics to hydrodynamic turbulence, including also mathematical physics and signal processing together with soft and condensed matter. The creation of this multidisciplinary approach is particularly fostered by the strong association with the physics teaching activities at ENS de Lyon, called *Master Sciences de la Matière*.

The diversity of topics studied allows our laboratory to tackle both established and emerging problems, using the highest quality modeling and experimental techniques. Our diverse expertise allows us to advance exact theoretical results, to use the most advanced numerical approaches, or to perform groundbreaking experiments, for which we often create innovative instrumentation.

Research topics can be gathered into eight themes: Hydrodynamics and Geophysics, Soft Matter, Physics of Biological Systems, Mathematical Physics and Fundamental Interactions, Condensed Matter, Infophysics, Signal and Systems, Statistical Physics, Instrumentation and Imaging. From an administrative point of view, the laboratory is organized into four research teams, which only partially overlap with the above themes splitting. Research topics are transverse to the teams, and researchers are used to contribute to different themes through very dynamics and efficient collaborations.

The scientific activities of the laboratory are the culmination of the effort of 70 CNRS researchers or faculty, who benefit from the expertise of the 15 members of the technical staff in the mechanical and electronic workshop, the system manager team and the invaluable administrative assistants. Last, but not least, a large part of the dynamism of the laboratory can be attributed to our 50 PhD students and 25 postdoctoral fellows, whose enthusiasm, talent and dedication help drive us forward into new areas of research.

Antoine Bérut

Ronan Hamon

Gabriel Michau

A. Bérut, R. Hamon, G. Michau

Saint-Gobain prize 2015

Abertis Chair prizes 2016 and 2017

PhD students excellence

A large proportion of lab members are PhD students and they all contribute to the science issued from the Physics Lab. Over the period 2016-2017, three students have been rewarded with specific PhD prizes, reflecting the high-level science of this place.

Antoine Bérut obtained the 2015 Saint-Gobain prize (delivered in 2017) for his experimental work on the interactions of brownian particles. Using optical tweezer networks, he was able to investigate the hopping statistics of these thermally sensible particles between distinct energetic wells.

Ronan Hamon was rewarded in 2016 by the Abertis Chair prize, which is attributed every year for outstanding works in the field of transport infrastructure management. During his PhD thesis, Ronan developped original methods in order to analyze the datas of Lyon's public bike rental (« Vélo'V »). These methods, lying at the boundary between signal processing and networks dyamics, are well suited in order to facilitate decision making in the infrastructure management.

Finally, Gabriel Michau was rewarded in 2017 by both the national and international Abertis Chair prize for his works on data management from Bluetooth detectors. He worked on the potentialities of these detectors for transport applications by characterising the data, their noises and biases. This led in particular to new methodology of vehicle trajectory reconstruction.

- A. Bérut, PhD, 2015 : http://tel.archives-ouvertes.fr/tel-01417805v1
- R. Hamon, PhD, 2015 : http://tel.archives-ouvertes.fr/tel-01216173v1
- G. Michau, PhD, 2016 : http://tel.archives-ouvertes.fr/tel-01192759v1

Lucile Savary
2017 F. Nevill Mott Prize

Correlated quantum materials

Lucile in 5 dates

2014 PhD Univ. California, Santa-Barbara

2014 Post-Doc MIT

2016 Michelson Postdoctoral Prize

2016 CNRS Researcher, ENS de Lyon

2017 F. Nevill Mott Prize

Lucile's research focuses on the theory of strongly correlated quantum materials. This involves understanding how a large number of spins and electrons interact in solids, and what novel phenomena, such as the emergence of new particles in matter, can result. Down the road, new kinds of electronics and sensors might make use of these unusual properties. What Lucile enjoys best is proposing and analyzing microscopic models tailored to produce specific phenomenology, as well as collaborating with experimentalists to explain puzzling observations in the lab. Lucile is best known for the development of the theory of quantum spin ice in rare-earth pyrochlore materials - electrical insulators where rare-earth atoms sit at the vertices of a lattice of corner-sharing tetrahedra. There, strong, anisotropic, interactions between localized magnetic moments allow a "quantum spin liquid" to emerge, a truly quantum phase of matter which reproduces emergent quantum electrodynamics with a photon and electric and magnetic monopoles, that may in principle be seen with the right experimental probes.

Lucile received her PhD in 2014 from UCSB, where she worked in the group of L. Balents. She then moved to the Department of Physics at MIT as a Gordon and Betty Moore Postdoctoral Fellow, and joined CNRS in 2016.

In 2017, Lucile received the F. Nevill Mott Prize, awarded to a person who has made significant contributions to the theory of strongly correlated electrons, with the citation "For realistic theories of exotic phases and criticality in several quantum materials." She was also awarded the 2016 Michelson Postdoctoral Prize in recognition of excellence in science and science communication.

More and references

• Savary & Balents, Reports on Progress in Physics 80, 016502 (2016)

• Savary, Nature Comm. to appear, arxiv 1511.01505

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Denis Bartolo

Pierre-Gilles de Gennes prize 2016

Soft and Active matter

Denis in 5 dates

2003 PhD U. Paris 6

2006 Lecturer U. Paris 7

2009 Paris emergence award

2012 Prof. ENS de Lyon

2016 de Gennes prize

Denis Bartolo combines experiments and theory to elucidate collective phenomena in soft and active materials. He and his group have recently been fascinated by active liquids: liquids capable of spontaneous flows. On the experiment front, they managed to motorize millions of colloidal particles as small as one tenth of a hair diameter. They showed that these micro robots can self-assemble into fluids that endlessly flow even in the absence of external drive thereby resulting in mesmerizing dynamical patterns in closed geometries. More recently, taking advantage of microfludic techniques, they have elucidated the robustness to disorder of these emergent flows. On the theory front, in collaboration with the Vitelli group, they have established an unanticipated analogy between sound propagation in active fluids and electronic transport in quantum topological insulators, hence opening the way to design strategies for functional active metamaterials. These examples only highlight a prototypical facet of Bartolo's work which is inspired both by fundamental and applied challenges.

Denis Bartolo is a physics engineer from ESPCI Paris. He obtained a PhD in theoretical physics from Pierre et Maris Curie University in 2003. He was appointed Maitre de Conférence at Paris Diderot University in 2006, was awarded the Paris Emergence prize in 2009, and joined the Institut Universitaire de France and ENS de Lyon in 2012 as a professor of physics. In 2016, his contributions to active-matter physics were distinguished by the biannual Pierre-Gilles de Gennes prize which recognizes outstanding contributions to condensed matter physics at the Conference From Solid State to Biophysics.

• Morin *et al.*, Nature Physics, 13, 63 (2017)

• Souslov *et al.*, Nature Physics, 13, 1091 (2017)

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Denis Le Tourneau

Palmes académiques

Mechanical Engineering

Denis in 5 dates

1995 Industrial Design graduation

2002 Joins ENS de Lyon

2005 Assistant Ingérieur

2017 Ingénieur d'Etudes

2017 Palmes académiques

Denis Le Tourneau joined ENS de Lyon in 2002 with a firm expertise in mechanical engineering gained when working at INSA de Lyon and IUT Nancy. Over the last 15 years, Denis developed skills in Computer Numerical Control (CNC) machining and designed, realized and assembled a number of unique experimental setups in close collaboration with researchers - he realized more than 1400 parts ! Denis's realizations span a broad range of physical situations from basic fluid dynamics, turbulence, high pressure material studies or biophysics. Denis has designed experiments weighting a few grams (a micro tweezer) to more than one ton (a fully equipped tank on a large turntable), dedicated to high pressure experiments (1000 bars) or space environment - he was instrumental in the recent MATISS project on biocontamination, lead by CNES and operated by T. Pesquet during the Proxima mission on the International Space Station in 2016.

From the setup specifications, its design involving innovative technical solutions, and its realization within the workshop (with modern CNC machine tools) or its subcontracting, Denis manages all aspects needed to complete unique solutions not available from the shelves. He also constantly interacts with the team of four in the mechanical workshop to promote innovative technical solutions.

The Palmes académiques awarded to Denis are a clear recognition of his technical expertise. This award emphasizes also the excellence of all members of the technical team, since thanks to their valuable skills, the lab has achieved numerous experimental breakthroughs in physics. The workshop recently invested in four 3D printers and the team of four has been on the first line bringing this new technology to the lab...

awards

More and references

• Tapia, Le Tourneau & Géminard, EPJ Techn. Instrum. 3, 1 (2016)

• Dauxois *et al.*, Procedia IUTAM 20, 120-127 (2017)

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http://www.ens-lyon.fr/PHYSIQUE/presentation/news/palmes-denis

International Physicists' Tournament

2016 French selection: 1st / 6
2016 Int'l selection: 1st / 16

2017 French selection: 1st / 9
2017 Int'l selection: 4th / 18

The team of University de Lyon represented France at the international level and won the 2016 edition

The International Physicists Tournament is a world-wide competition for undergraduate students where teams gather to compare their solutions to open problems in physics, during *Physics Fights*. Unlike the typical physics exam, the problems must not only be presented, but also challenged and reviewed by the other participants allowing students to respectively assume the roles of researchers, referees and editors.

In addition to the challenge that the tournament represents, it provides students with an exciting and eye-opening experience in which they learn how to design experiments with the aim of solving physics problems, and to constructively criticise scientific solutions. Each year a selection of seventeen problems is proposed to the teams, such as: «Devise a method to estimate the jump height of pop-corns based on measurements of the sound of the pop», «What is the maximum height of a tower made of gelatin-based LEGO bricks?», «What is the time required to synchronise one hundred metronomes?»...

In 2016, the team of University de Lyon, trained at ENS de Lyon, participated for the first time in the french national selection and won the international tournament.

The Laboratoire de Physique has been deeply involved in the training of the team, from the implication of permanent staff (N. Taberlet and N. Plihon), of postdoc or postgrad students (A. Caussarieu and J. Ferrand), useful advices from the various experts, to the use of research instruments. Moreover, some of the work initiated by the student team was deepened by researchers and led to publications or inspiration for new research projects.

- Chemin *et al.*, Am. J. Phys. 85, 485 (2017)
- Taberlet *et al.*, Am. J. Phys. 85, 905 (2017)
- Plihon *et al.*, Eur. J. Phys. 38, 065204 (2017)

http://www.iptnet.info http://france.iptnet.info/

Laboratoire International Associé

Material sciences and condensed matter physics

A Laboratoire International Associé (LIA) is a research laboratory « without walls» supported by the CNRS, and aimed at structuring existing collaborations between researchers from different institutions and different countries. Two such laboratories have been recently launched led by teams from the lab thanks to their own input.

The LIA « Material : structure and dynamics » was created in 2016 between french and chile research teams in condensed matter physics. It involves the Physics Lab in Lyon and two more labs from Paris (Langevin Institute, and Physics /mechanics of heterogeneous media), together with three chilean institutions : Universidad de Chile, Universidad de Santiago de Chile, and Pontificia Universidad Católica de Valparaíso. The scientific project is well balanced between experiments and theory. It deals with complex matter physics with applications in biophysics and geophysics.

The second LIA entitled « Deformation, flow and fracture of disordered materials » gathers researchers from two labs in Lyon (Physics lab and Light / Matter Institute) with researchers from two norwegian institutions (University of Oslo and University of Trondheim). The scientific project of the LIA is a natural follow-up of current experimental, numerical and theoretical research activities between collaborating teams in both countries. It aims at studying mechanical instabilities characterizing the physical properties of heterogeneous materials, and their consequences in terms of geophysical hazards.

consortium

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STATPHYS 2016

An international conference on statistical physics

1250 attendees
400 presentations
720 posters
8 parallel sessions

The 26th edition of the IUPAP International Conference series STATPHYS was held in Lyon from 18th to 22nd July 2016. STATPHYS is the largest and most wide ranging conference in statistical physics, covering all aspects of the field with applications in physics, chemistry, mathematics, the biological sciences and to complex systems in the macroscopic world.
The conference took place at the Palais des Congrès de Lyon, a superb facility. In addition to many French delegates, the largest delegations were from Japan (119), Germany (94), United States (85), Italy (73) and South Korea (70). More than 50 nationalities were represented including participants from Georgia, Kuwait, New Zealand, Philippines or Uzbekistan.
In the unanimous opinion of the participants, the level of plenary talks and different contributions was outstanding, as well as the posters Sessions. New scientific collaborations have emerged from these numerous presentations, or thanks to discussions during walks in the beautiful close by Parc de la Tête d'Or, or even thanks to an intercontinental football tournament, the first Statphys World Cup!
Statphys26 has once again been a wonderful illustration of the international adventure that is Science. It has shown us that the mixing of backgrounds, approaches and origins is surely the way to go, taking us together towards uncharted territories and new discoveries. We are delighted that Statphys26 has ended in such a great success.
The Laboratoire de Physique was extensively involved in the conference at all levels, making many scientific contributions, as well as providing organization and planning from the local organizing committee and support during the conference from students and staff.

Local organizing commitee:
Angel Alastuey, Fatiha Bouchneb, Thierry Dauxois, Peter Holdsworth, Michel Peyrard, Nicolas Taberlet.
http://statphys26.sciencesconf.org

Focus

Quantum integrable models

Balancing model integrability and effective solvability

On the use of integrable models

Integrable systems appear everywhere in modern theoretical physics both in statistical mechanics and quantum field theory with applications ranging from condensed matter to gauge and string theories. In mathematics, they are at the origin of the theory of quantum groups, with applications in knot theory, topology of 3-dimensional manifolds and combinatorics to cite a few. In physics, they have provided an exclusive framework where to develop techniques leading to exact results for strongly coupled interacting systems out of the reach of perturbative analysis, hence giving crucial benchmarks for the numerical analysis of more general (non-integrable) interacting systems. In the last fifty years, substantial progresses have been made for example in the exact solution of the spectrum and dynamics (see figure) of some classes of integrable systems in low dimension, i.e. for two-dimensional statistical mechanics systems and 1+1-dimensional lattice quantum systems and quantum field theories.

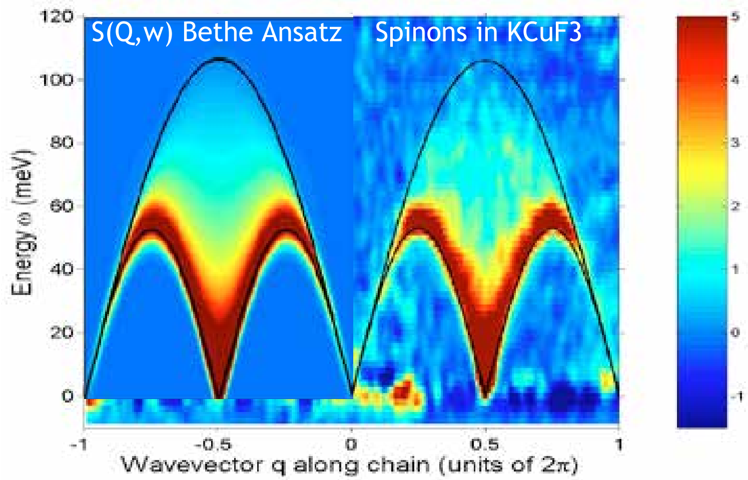
Quantum inverse scattering

Despite the successes of these methods, the integrability property (existence of a large/infinite number of commuting conserved charges) does not provide by itself the solution of a given model, stressing the need for developing effective resolution methods. In the framework of the quantum inverse scattering (the method allowing for a systematic description of quantum integrability) several different techniques have been developed in order to characterize the spectrum, e.g. the famous Bethe Ansatz and its Algebraic version (ABA) and the Baxter's Q-operator. However, large classes of important integrable models have been so far left unsolved, generating the paradox to have the integrability property without explicit solvability of the corresponding systems. Remarkable examples, related to out of equilibrium dynamics, are the open spin 1/2 quantum XXZ and XYZ chains with general integrable boundary conditions. The complete characterization of their spectrum has been a longstanding problem that we have achieved only recently using quantum Separation of Variables (SoV)

Separation of variables

Seeking for a method allowing to put on the same footing the integrability of a model and its effective solvability, the quantum version of the SoV, first introduced by Sklyanin for some specific integrable models, seems to be the natural starting point. It can be seen as the natural quantum analogue of the classical separation of variables in the Hamilton-Jacobi's theory. Our recent results prove that SoV method can be adapted and implemented for a wide class of integrable quantum models out of the reach of pre-existing methods.

Effective resolution of an integrable model



Legend: *Dynamical structure factors for the XXX spin 1/2 Heisenberg chain, Bethe ansatz based (left, Caux and Maillet, Phys. Rev. Lett. 95, 077201 (2005)) and experimental results (right, courtesy A. Tennant - Hahn-Meitner Institute, Berlin).*

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References:

- Niccoli, J. Stat. Mech. P10025 (2012)
- Kitanine, Maillet & Niccoli, J. Stat. Mech. P05015 (2014)
- Kitanine, Maillet, Niccoli & Terras, J. Phys. A: Math. Theor. 50, 224001 (2017)

Mechanical metamaterials

Obtaining new mechanical material properties using designed structures

Metamaterials

The field of mechanical metamaterials is a broad and interdisciplinary subject ranging from large structures to compliant and biological matter. It focuses on the interplay between geometry and mechanics and its applications to the areas of morphing and deployable structures, energy harvesting, censor and actuators, among others. A new paradigm is emerging where elastic instabilities (e.g. buckling and snapping) are seen as routes to novel mechanical properties as opposed to modes of failure. Hence, many new research trends, such as adaptive and morphing structures, require a better grasp of how slender structures undergo large deformations.

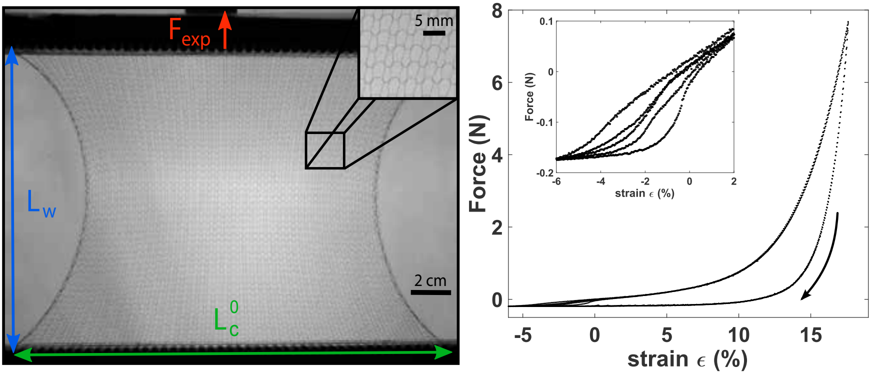
Origami based metamaterials

Literally "folding paper," the art of origami is fundamentally the study of the generation of dramatic changes of a material's appearance and bulk mechanical properties via the application of a sequence of highly localized deformations. Origami lattices are a prototypical metamaterial, readily converting an unwieldy film into a robust device capable of reliable and simple actuation. Origami geometry, in which energy considerations are discarded, is a useful technique for generating framing problems of interest, but its is insufficient to yield mechanical insight. Indeed, the competition between creases and faces elastic energies leads to dramatically different behavior than what geometric models might predict. For example, face bending increases the space of possible configurations and can generate a pathway for an origami mechanism to follow while transitioning through a geometrically forbidden configuration to a lower energy state.

Knitted fabrics

Knitting is not only a mere art and craft hobby but also a thousand year old technology. Unlike weaving, it can produce loose yet extremely stretchable fabrics with almost vanishing rigidity, a desirable property exhibited by hardly any bulk material. In contrast with the extensive body of related empirical knowledge and despite a growing industrial interest, the physical ingredients underlying these intriguing mechanical properties remain poorly understood. To make some progress in this direction, we are presently studying a model tricot made of a single elastic thread knitted into the common pattern called stockinette. On the one hand, we experimentally investigate its tensile response and measure local displacements of the stitches during deformation. On the other hand, we derive a first-principle mechanical model for the displacement field based on the yarn bending energy, the conservation of its total length and the topological constraints on the constitutive stitches. A second study concerns the local fluctuations of the deformation field around the homogeneous state. Indeed the inter-yarn friction induces local stick-slip events that propagate through the stitch network following an avalanche-like behavior.

Mechanical response of knitted fabric



Legend: *Picture of the deformed stockinette-knit fabric (left). Mechanical response of the fabric over 5 loading–unloading cycles (right).*

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References:

- Brunck *et al.*, Phys. Rev. E. 93, 033005 (2016).
- Reid *et al.*, Phys. Rev. E. 95, 013002 (2017).
- Poincloux *et al.*, preprint 2018.

Topological origin of equatorial waves

A surprising connection between geophysics and condensed matter

The mystery of equatorially trapped waves

Atmospheric and oceanic equatorial waves are temperature anomalies that propagate along the equator on a planetary scale. Some of these waves can only head east. This is the case of equatorial Kelvin waves, observed for instance in the Pacific as a precursor of the El Nino phenomenon. These unidirectional waves were discovered in the 1960s, but their physical origin remained hitherto mysterious. Borrowing tools from topology used in recent years in condensed matter physics, we have brought to light an unexpected analogy between these geophysical waves and electronic waves.

From condensed matter to classical mechanics

Topology allows one to classify objects according to the possibility that one has to pass from one to another in a continuous way. Thus, a coffee cup and a donut belong to the same topological class because one can deform continuously the coffee cup until forming a donut. The topology also makes it possible to classify more abstract objects such as families of waves propagating in a given material. In this case, the topological properties no longer describe the existence of holes in the material, but of singularities in this set of waves. Condensed matter physicists established a correspondence between the number of these singularities and the number of unidirectional edge states propagating without dissipation along the edges of these materials. These one-way propagating states are thus said to be topologically protected as they cannot be removed by continuous variation of the parameters describing the physical system. It was then realized that topological protection occurs in a variety of physical systems beyond condensed matter: cold atoms, optics, microfluidic devices...

Topological invariants in shallow water

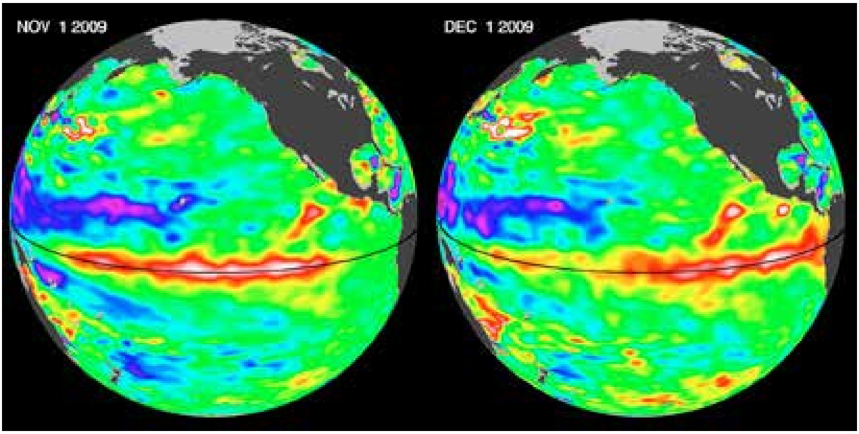
We have shown that topology can also be used to understand the existence of unidirectional geophysical fluid waves, like the Kelvin waves trapped at the equator. We have considered for that purpose a thin layer of fluid surrounding a rotating sphere, described by the celebrated shallow water equations, used for instance by Laplace to describe tides in the oceans. This system has the essential ingredients for the appearance of topological waves thanks to the dual role played by the Coriolis force: on the one hand, it breaks the time-reversal symmetry, similarly to the magnetic field in the quantum Hall regime (the archetypal topological insulator); on the other hand, it changes sign along the equator, making it play a role similar to that of a boundary, say between two electronic gases subjected to opposite magnetic fields.

We calculated a topological invariant for families of waves, that corresponds to the number of singularities in this set of waves, and related it to the number of unidirectional states observed at the equator, thus unveiling their topological origin. We are now looking for what could be the other physical manifestations of topology in fluid waves.

Topological waves

focus

An equatorial Kelvin wave heading east before an El Nino event



Legend: *Propagation of a temperature anomaly in the Pacific Ocean. A blob of positive temperature anomaly (in red) has travelled across the ocean along the equator over one month. Image: Courtesy NASA/JPL-Caltech. Source: Jet Propulsion Laboratory.*

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References:

• Delplace, Marston & Venaille, Science 358(6366), 1075-1077 (2017)
• Nature Physics Editorial, Topology on top, Nature Physics. 12, 615 (2016)

Gone with the wind

Particles in flows : so common and still so mysterious

Particles in fluids

Understanding the dynamics of flows carrying inclusions is a crucial problem for many disciplines : astrophysics, chemical engineering, environmental sciences. The problem is by no means easy and reveals a web of intricate levels of complexity, making the simple question 'what is the settling velocity of a dense sphere in a turbulent environment?' still unsolved. Small density matched particles follow the flow and are used as fluid tracers in experiments. Big and/or density mismatched particles deviate from fluid tracers and are generically called 'inertial'. They can exhibit quite peculiar phenomena, such as turbulent unmixing. The situation becomes even more complicated if the particles are 'active' (self-propelled) or if they exchange mass, momentum or energy with the carryier flow. For both passive and active particles, if the amount of inclusion is high, the system becomes fully coupled as the particles modify the flow itself, which in turn feed back on the dynamics of particles. In this context, the investigations we carry aim at elucidating the fundamental mechanisms of particle-flow interactions at all these levels of complexity.

A unique arsenal of experimental tools

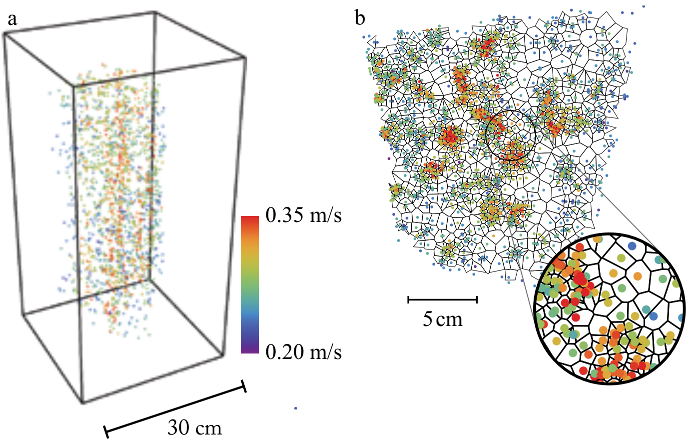
In facing such challenging problems, our available weapons used to be rather limited as accurate Lagrangian Particle Tracking (LPT) measurements have long been difficult. Our laboratory has pioneered the development of high resolution Lagrangian techniques and counts today a unique arsenal of tools, including scattering particle tracking (using acoustic or optical Doppler), direct optical tracking and instrumented particles. We are now able to track in 3D the dynamics of multiple particles with a high degree of accuracy. To complete our toolbox, we have also developed efficient particle tracking algorithms (including novel camera calibrations, new stereo-matching approaches, rotational tracking, etc.) as well as dedicated post-processing data analysis tools optimizing the robustness of statistical estimators regarding experimental noise and allowing to access ever subtler diagnosis, such as conditional Lagrangian statistics of velocity and local particle concentration (e.g. combining Voronoï tesselation and LPT).

A variety of physical processes to be unveiled

These tools have led to major results regarding the multi-scale dynamics of particles both in homogeneous/isotropic and non-homogeneous/anistropic turbulence (including Rayleigh-Bénard convection), but also striking phenomena in non-turbulent flows. These include the detailed characterization of Lagrangian turbulence, the interplay between clustering and settling, the coupling between translational and rotational dynamics, the role of finite size and collective effects, etc...

We now focus on investigating subtler features, including the dynamics of active particles, of interacting (magnetic) particles and the back-reaction of the particles on turbulence in massively seeded flows.

Columnar settling of particles in a quiescent fluid



Legend: *(a) 3D reconstruction of 2mm glass spheres settling in water, colored by their velocities. (b) Top view of fig.(a) showing Voronoï tessellation, which emphasizes the column formation.*

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focus

Signal processing and modeling for the genome

Investigating the structure-function relationship in cell nuclei

Toward a 4D view of nuclear regulation

Eukaryotic cells enclose their genome in the limited volume of their nucleus. In human, 2 meters of DNA are packaged within a radius of 10 micro-meters, which is equivalent to fitting 10 km of a (very thin) string within a tennis ball! Despite this formidable folding, operating nuclear functions like gene transcription and DNA replication demand that genome accessibility be maintained. This is achieved thanks to a highly dynamic folding of DNA into an ordered 3D protein-DNA structure called chromatin. Since the initial sequencing of complete genomes including the human genome, the development of new experimental techniques exploiting the power of massive parallel DNA sequencing, has enabled to construct 1D maps of genome activity along chromosomes at diverse stage of cell differentiation or in pathological situations, and also, more recently, to assemble co-localisation frequency matrices between all DNA loci capturing 3D chromatin conformations. It ensues new data analysis and modeling challenges in order to fully capture nuclear functions dynamics in both space and time.

Multiscale structural organisation of the human genome

We used graph theory to identify structural motifs from chromatin 3D conformation data in human cell lines. Conformation data were represented as networks of physical interactions. Structural motifs were then delineated as communities of these networks using a fast multi-scale community mining algorithm based on spectral graph wavelets that has no a priori on the size and on the nature of the structural motifs. This approach resulted in multi-scale structural decompositions of the human genome into hierarchies of chromosome intervals of length ranging from the resolution (100 kb) to the chromosome lengths (10 Mb). These novel decompositions provide an original framework to question structural organisation and its relationship to functional regulation.

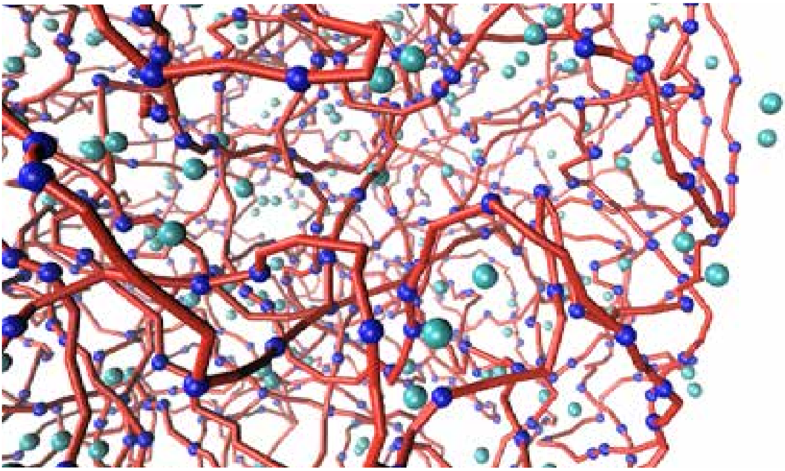
Universal DNA replication kinetics

It was reported ten years ago that the spatially averaged, time-dependent rate of DNA replication origin activation has a universal shape among eukaryotes. This shape would be the non-trivial result of a selective process for a robust S-phase. However, the mechanistic explanation of this universal behaviour has remained unclear. We introduced a simple model where the recycling of diffusing replication factors and the localisation of potential origins are sufficient ingredients to explain the universality of DNA replication kinetics. This work underlines that structural organisation within eukaryote nuclei is a major driving force of biochemical kinetics, contributing to the regulation of all nuclear processes involving the search of a DNA target by a diffusing factor. We now develop molecular dynamics simulations to study how spatio-temporal correlations of the replication program can be explained by the diffusion of replication factors in the 3D chromatin structure specific to each eukaryotic organism.

Computational biology

focus

Molecular Dynamics simulations of DNA replication



Legend: *DNA replication origins (blue beads) are specific loci of the chromatin fibre (red tube). Origin activation depends on the encounter with diffusing initiation factors (green beads).*

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Observing and controlling quantum trajectories

How does a quantum bit evolve when it is measured gently?

Reordering questions changes the outcomes

A bit of information takes the values 0 and 1. Information being physical, they correspond to two states of a physical system. When the system is isolated enough it enters the quantum world and becomes a quantum bit (or qubit). Its state now spans a ball instead of being binary valued and is defined by three coordinates x, y and z (see Fig.a). Owing to quantum rules, acquiring information about any of these coordinates disturbs the qubit state. Consequently, measuring x before z leads to different outcomes than measuring z before x. This fact is known as the incompatibility between measurements. Recently, it became possible to perform these measurements in a gentle manner that disturbs the qubit only slightly hence allowing to simultaneously perform incompatible measurements.

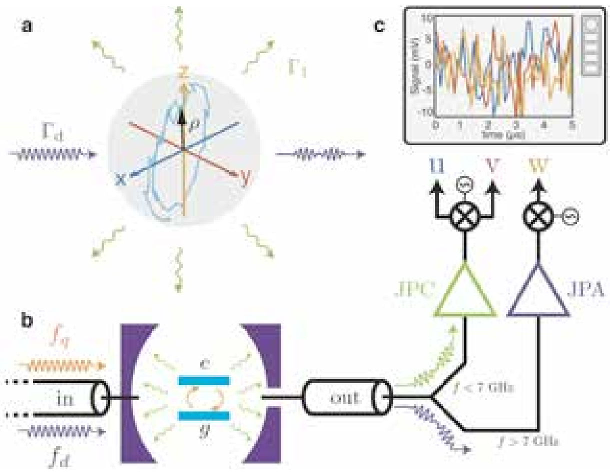
Getting simultaneous partial information on non-commuting questions

Using two energy levels of a superconducting circuit cooled down at 20 mK as a qubit, the Quantum Circuit group managed to simultaneously extract a small fraction of a bit of information about the x, y and z coordinates. The trick consists in intercepting the information that leaks out of the qubit, which is at the origin of decoherence. In order to get a meaningful measurement record, we developed a superconducting microwave amplifier setup that degrades the signal by so small an input noise that it is comparable to vacuum fluctuations. The decoherence comes in two flavors depending on how the qubit's information is leaking out of it. First, the qubit can spontaneously emit photons into its environment leading to qubit relaxation (green waves in Fig.a,b). We enclosed the qubit inside of a microwave cavity so that the spontaneous emission is channeled into our detector that measures the complex amplitude of the emitted field. The real and imaginary parts of the amplitude (u and v in Fig.b,c) contain a fraction of bit of information about x and y. Second, the qubit can couple to objects whose state depends on the qubit energy leading to dephasing (purple waves in Fig.a,b). In our experiment, the driven cavity is such an object and its transmitted field amplitude (w in Fig.b,c) gives a quantity of information about z that is proportional to the drive power.

Tracking and controlling the qubit state depending on measurement records

A direct averaging of these signals thus leads to a new way to perform a full tomography of a qubit along all its coordinates. Beyond this average signal, considering a single measurement record (Fig.c) allows us to track the trajectory of the qubit state in the ball (Fig.a)! We have observed the impact of measurement backaction on the qubit trajectories in various regimes from Rabi oscillations to Zeno effect, when the cavity measurement freezes the evolution of the qubit. Going beyond this observation, we have used the measurement records in real time to stabilize any state of the qubit by feedback.

Quantum trajectories of a qubit



Legend: *a. One observed quantum trajectory followed by a superconducting qubit. b. Scheme of the setup that intercepts both spontaneous emission and dephasing signals. c. A single measurement record leads to the trajectory in a.*

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PhD

- C. Brouzet - Internal wave attractors : from geometrical focusing to non-linear energy cascade and mixing (T. Dauxois, S. Joubaud)
- C. Charles - Renormalization and Coarse-graining of Loop Quantum Gravity (E. Livine)
- J.-Y. Chastaing - Mécanique statistique de systèmes macroscopiques hors-équilibre (J.C. Géminard, A. Naert)
- J. Frecon - Méthodes d'optimisation pour l'analyse de processus invariant d'échelle (P. Abry, N. Pustelnik)
- M. Fruchart - Topological phases of periodically driven crystals (D. Carpentier, K. Gawedzki)
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- D. Malpetti - Thermodynamics of strongly correlated bosons on a lattice: new insights and numerical approaches (T. Roscilde)
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- A. Feller - Entanglement and Decoherence in Loop Quantum Gravity (E. Livine)
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- P. Huck - Particle dynamics in turbulence : from the role of inhomogeneity and anisotropy to collective effects (R. Volk)

PhD

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- C. Odier - Imbibition forcée en milieu poreux (D. Bartolo)
- R. Poryles - Instabilités et piégeage de bulles dans des fluides complexes. (V. Vidal)
- G. Poy - Sur la pertinence du modèle thermomécanique dans la rotation Lehmann des gouttes cholestériques et nématiques (P. Oswald, A. Dequidt)
- B. Roussel - Autopsie d'un courant électrique quantique (P. Degiovanni)
- M. Serres - Étude hydrodynamique d'un écoulement gaz-liquide dans un milieu poreux confiné (V. Vidal, R. Philippe - LGPC)
- L. Streppa - Characterizing mechanical properties of living C2C12 myoblasts with single cell indentation experiments: application to Duchenne muscular dystrophy (F. Argoul, L. Schaeffer - LBMC)

defenses

Habilitations à diriger des recherches (HDR)

- A. Venaille - Ondes, turbulence et invariants dans les fluides géophysiques
- M. Magro - Intégrabilité hamiltonienne et eta-deformation de la supercorde $AdS_5 \times S^5$

HIGHLIGHTS 2018

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