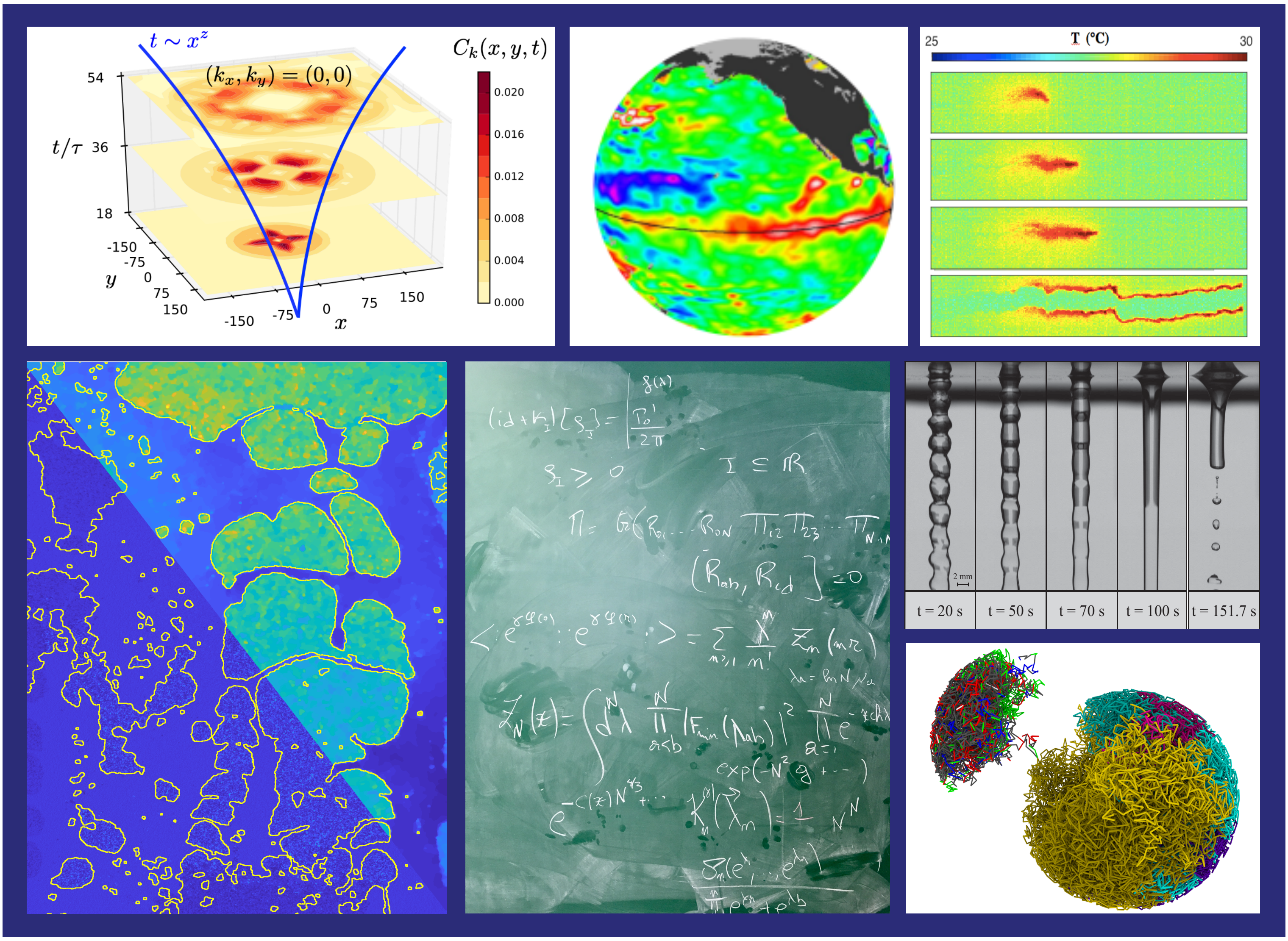
Lab PHYS
ENS de LYON

Activity Report 2014-2019

Laboratoire de Physique
CNRS UMR 5672
École Normale Supérieure de Lyon
Université Claude Bernard Lyon 1



cnrs

ENS DE LYON

UCB Lyon 1

Département d'évaluation
de la recherche

Research Unit
Self-assessment document

—
EVALUATION CAMPAIGN 2019-2020
GROUP A

GENERAL INFORMATION

Name of the unit concerned by the current contract: **Laboratoire de Physique**

Acronym of the current contract: **LPENSL**

Scientific field : **ST2 Physique**

Scientific sub-domains in descending order of importance:

ST2-3 Matériaux, structure et physique solide
ST5-3 Mécanique des fluides
ST6-3 Automatique, signal, image
ST2-2 Physique moléculaire, plasma, optique

Director for the current contract: **Thierry DAUXOIS**

Director for the next contract: **Jean-Christophe GÉMINARD**

Type of application:

Identical renewal ■ Fusion, scission, restructuring ☐ *Ex nihilo* creation ☐

Academic institutions and affiliated organisms:

List of Institutions and Organisms supervising the Research Unit for the current and next contract:

- Ecole normale supérieure de Lyon (ENS de Lyon)
- Centre National de la Recherche Scientifique (CNRS)
- Université Claude Bernard Lyon 1 (UCBL)

Choice of the research unit's interdisciplinary evaluation:

Yes ☐ No ■

Clinical research activities:

Yes ☐ No ■

Contents

I. OPERATIONAL ORGANISATION CHART

LABORATOIRE DE PHYSIQUE

Organigramme au 30 Juin 2019

DIRECTION
Thierry DAUXOIS

*Effectif : **161***

SERVICES COMMUNS

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MAUDUIT Laurence (CNRS, TCE)

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DOLIQUE Vincent (CNRS, IR)

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II. SCIENTIFIC REPORT

T1R. Hydrodynamics and Geophysics: *Report*

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Post-docs: T. Barois, G. Bousselin, T. Busser, Y. Dossmann, A. Dubois, J. Friedrich, L. Grigorio, C. Herbert, T. Homan, S. Huisman, T. Jamin, F. Jucha, D. Kuzzay, M. Lopez-Caballero, C. Mauger, S. Paillat, R. Pereira, A. Ponomarenko, A. Poyé, F. Ragone, J. Rolland, V. Shukla, C. Toupoint

PhD students: B. Bourget, S. Boury, C. Brouzet, F. Cabrera, G. Davis, V. Désangles, D. Dumont, G. Guichardaz, E. Horne, P. Huck, P. Husseini, C.-E. Lecomte, T. Lestang, O. Liot, N. Machicoane, P. Maurer, C. Picard, G. Pillet, R. Poryles, A. Renaud, J. Reneuve, E. Rusaouën, C. Sánchez, J. Sautel, M. Serres, T. Tangarife, S. Vincent

The laboratory has a long tradition and strong competences in experimental and theoretical fluid mechanics, from standard hydrodynamics to multiphase flows, often motivated by geophysical applications. Building on its expertise in the generation of internal waves through an undulating boundary, a group has explored various aspect of weakly nonlinear dynamics in rotating stratified laboratory experiments, from the emergence of wave attractors to the fate of triadic resonant instabilities, with application to the understanding of mixing in the ocean and the generation of large scale flows in the atmosphere. A new perspective on geophysical waves has been brought through the application of ideas from topology originally developed in condensed matter. Rare events algorithms have been developed to predict extreme climatic events such as heat waves and abrupt transitions between different circulation regimes at planetary scale. Plasma physics and magnetohydrodynamics have also been investigated, mostly experimentally and numerically, in order to understand the parameters leading to dynamo onset, and plasma turbulence. The laboratory has developed over the years original experimental characterisations of thermal convection, from the idealised geometry of Rayleigh and Bénard, to thermal optimisation of building heating by studying the effect of roughness at the boundaries, together with new theoretical formulations of the problem. The laboratory is well recognised internationally for its contributions on fundamental aspects of two and three dimensional fluid turbulence. Theoretical tools rely on modern formalisms such as large deviation technics and probabilistic approaches to model the fluctuating nature of incompressible and homogeneous flows, and related extreme events. These investigations have been usually carried out in parallel to state-of-the-art experimental developments, mainly Lagrangian tracking of idealised flows. These studies have been generalised to more complex, non homogeneous configurations, with additional applications to mixing, transport of inertial particles, and fluid-structure interactions. More recently, activities have been developed to understand basic hydrodynamics of superfluids, and experimentally through its active participation to a collaborative project on quantum turbulence. Another set of activities deal with the characterisation of multiphase flows, from fundamental studies on the interplay between grains, gas and liquids, to the segregation dynamics in asteroids to volcanic bursting and earthquake dynamics.

A. *Internal Waves*

Geophysical motivation. Owing to a stable stratification and to Earth rotation, atmospheres and oceans support the propagation of internal inertia-gravity waves (IGW). These waves are an essential component of our climate system, as they redistribute energy and momentum at planetary scales. For instance, small scale mixing in the ocean is thought to be primarily driven by the release of energy due to IGW breaking, with a direct impact on the large scale overturning circulation. In the upper atmosphere, the generation of strong winds is primarily induced by momentum transfers from IGW, with a spectacular manifestation given by quasi-biennnial reversals of equatorial stratospheric winds (QBO). In both cases, the effect of IGW must be parametrised for accurate predictions at larger time scales. Reliable parametrisations require a thorough understanding of the physics underlying IGW generation, propagation and breaking in idealised configurations. Since IGW have unique exotic properties, such as non-specular reflection along a solid wall, their study continues to provide challenging problems with an interest on their own for physicists.

Internal wave generation. (T. Peacock, Boston). Thanks to the versatility of the wave-maker developed and improved in the past years, we have experimentally investigated several questions, described below, using wave profiles that are ubiquitous in the geophysical context. The energy flux injected into the internal wave field was either at global scale using the first vertical mode of internal waves or unidirectional internal gravity wave beams with a con-

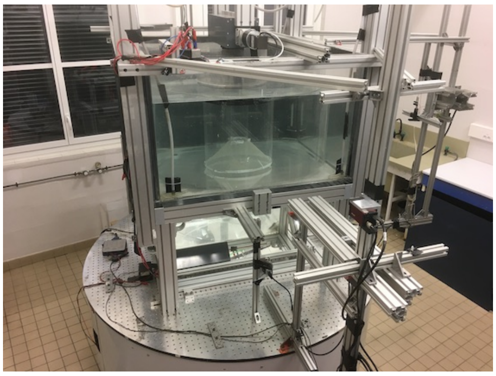

Figure 1: The rotating platform PERPET with an axisymmetrical experimental set-up.

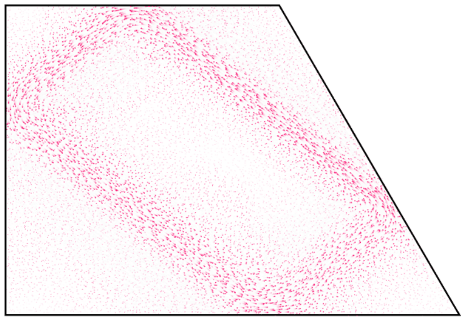

Figure 2: Internal wave attractor using experimental/numerical data.

fined profile. To better mimic wave generation in 3D natural environments, we have also adapted a multi-plate wave-maker to produce robust axisymmetric wave fields of arbitrary radial structure. By virtue of the underlying symmetry, this advance is also naturally conducive to incorporating background rotation into the experimental investigations. This device allowed us to study the geometric focusing of an internal wave beam [129], as well as resonant axisymmetric modes [87], which, in both cases, lead to enhanced wave amplitude and nonlinear instabilities (see Fig. 1).

Internal wave attractor. (E. Ermanyuk, Novosibirsk, L. Maas, Utrecht, I. Sibgatullin, Moscow). The study which has attracted a lot of attention was related to a trapezoidal geometry of the confined fluid domain. In such a configuration, the focusing of internal waves prevails, leading to convergence of internal wave rays toward closed loops, the internal wave attractors. Using experiments and numerical simulations, we have investigated the dissipation mechanisms taking place in the attractor (see Fig. 2). We have predicted that in 3D geometries, the wave energy ends up forming 2D internal wave attractors because of the refractive focusing mechanism. In particular, using dynamical system theory, we emphasised that a wave emitted in a simple canal leads to trapezium-shaped attractors in the transverse direction and we observed them experimentally [141].

Triadic Resonant Instability. An efficient pathway to transfer energy from the large scales of the injected energy to small scales where dissipation occurs is the triadic resonant instability (TRI). This process corresponds to the destabilisation of a primary wave with the spontaneous emission of two secondary waves of lower frequencies and different wave lengths. First, we have theoretically, numerically and experimentally shown the key role played by the finite width of the internal wave beam on the threshold of the instability or on the selection criteria of the secondary wave frequencies and wave vectors [81]. We predicted that the combination of this finite width effect and global rotation leads to an enhanced TRI, which we confirmed experimentally using the rotating platform [53] (see Fig. 1).

We also evidenced that the high concentration of energy in attractors makes them prone to TRI. Indeed, depending on geometrical parameters, different scenarios of instability have been highlighted. At high amplitude, the attractor models a cascade of triadic interactions transferring energy from large-scale monochromatic input to multi-scale internal-wave motion, providing the first signatures of a discrete internal wave turbulence [42].

Mean flow. (T. Akylas, Boston, L. Maas, Utrecht, L.-P. Nadeau, Québec). The attenuation of an IGW wave beam generates strong horizontal vertical flows through a mechanism analogous to acoustic streaming [43]. We have investigated the possibility for boundary internal wave streaming, showing it to be an efficient way to transport sediments [60]. We have revisited a classical model for wave-mean flow interactions known to capture the salient features of the quasi-biennial oscillation (QBO), with the spontaneous emergence of low frequency flow reversals driven by fast internal gravity waves. We described the first route to chaos in this model and used it to propose a dynamical system point of view of an unexpected and intriguing disruption of periodicity in the QBO reported in 2016, with possible applications to other planetary atmospheres [61].

Mixing. (B. Ecke, Los Alamos, L. Gostiaux, LMFA, J. Sommeria, LEGI). Mixing processes in the ocean are still scarcely understood, in spite of their important role to convert kinetic energy into potential energy, to maintain the ocean stratification. To tackle this issue experimentally, we have adapted to a continuously stratified fluid an experimental technique, PIV/PLIF, that allows for simultaneous measurements of velocity and density fields. We have observed isopycnal overturns, correlated with the appearance of TRI, and obtained an estimate of the turbulent diffusivity, with values of about 10 times the molecular diffusivity [102]. Using similar vizualization tools, we have investigated mixing induced by gravity currents interacting with their surrounding fluid. Using in particular statistical data analysis, we studied the intermittency of the turbulent interface and the probability distribution of the density overturns, relating it to kinetic energy probability distribution. Regarding the theoretical aspect, we have proposed a novel approach to predict the irreversibility of mixing and its efficiency as the most probable outcome of turbulent stirring, depending on the stratification profile and the amount of energy injected into the system [183]. This approach is a phenomenological generalisation of equilibrium statistical mechanics previously used to describe mixing of vorticity and self-organization in 2D flows.

B. Wave Topology in Fluids

Topological protection. The concept of topologically-protected transport along the edge of physical systems was born three decades ago in the context of quantum Hall electronics. Thirty years later, in the early 2010's, a second topological revolution occurred when physicists realized that topological protection is not specific to quantum electronic systems, and applied this concept to virtually all areas of physics. Simply put, waves turn out to be protected from disorder and backscattering when emerging at the boundary separating bulk materials characterized by different topological invariants called Chern numbers, that describe topological properties of the bulk eigenmodes.

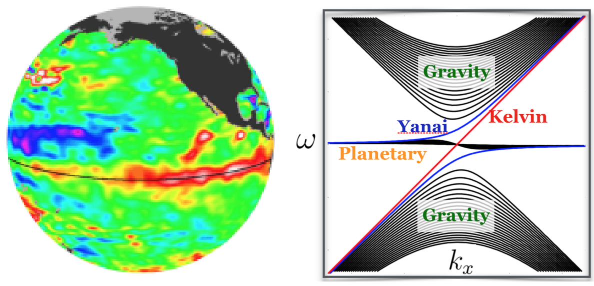

Figure 3: Left: temperature anomaly propagating eastward along the equator before an El Nino Event (credit NASA SVS). Right: dispersion relation for equatorial waves. Two modes transit from one band to another. This property has a topological origin, encoded into a Chern number of value 2.

Applications to geophysics and active matter (V. Vitelli, Chicago; B. Marston, Brown; C. Tauber, Zurich) Over the last few years, we have pioneered the application of these ideas to gas and liquids, from microfluidics to planetary flows. We demonstrated the propagation of two sound modes in active fluids assembled from self-propelled colloids, and established the propagation of topologically protected sound waves in active-microfluidic networks. The topological sound waves are the active-fluid analogs to the edge channels of quantum hall effect [64]. We computed the Chern number of shallow water flows in a rotating planet to unveil the topological origin of heat waves involved in El Nino phenomenon [44]. We related these topological properties to the dual role of Coriolis force, that breaks time-reversal symmetry, and changes sign at the equator thereby trapping waves at the boundary between the two hemispheres (see Fig. 3). We found a different class of topological properties in compressible stratified flows with broken mirror symmetry and predicted the emergence of new topological waves in stellar interiors.We established a new bulk-boundary correspondence for continuous media, with application to unidirectional waves trapped along a coast in oceanic basins [178].

C. Statistical mechanics approach to climate

Rare events in turbulence and climate. Transitions between attractors in turbulent flows are ubiquitous. However nearly no numerical study exist for genuine turbulent flows, because of the prohibitive cost of numerical computations that last hundreds or millions of turnover times. For the first time in turbulent flows, a rare event algorithm from statistical mechanics has been used. Thousands of transitions have been computed in the barotropic quasi-geostrophic model, a simple model of Jupiter's troposphere [792]. This first study led to the striking result that transitions occur through a predictable path (instanton phenomenology) although the transition times are random. Unexpectedly in this truly non equilibrium system, the transition rates are given by an Arrhenius law, reminiscent of equilibrium thermodynamics. Those analogies with thermally activated nucleations open a new understanding of what settles the very long term behavior of turbulent flows.

The study of extremes events in climate dynamics is of a primary societal importance. For this problem too, rare event algorithms led to drastic progress with a gain of a factor 100 to 1000 in the required computational effort to study extreme heat waves [874]. This led to the unexpected observation of extreme teleconnection patterns. They feature a planetary scale correlation of the flow that produces local extreme heat waves. These results had a large media coverage and should change the paradigm for studying extremes in the climate community. Rare event algorithms are also useful to study the tail of the probability distribution of extreme drags on objects embedded in turbulent flows [860]. Large deviation theory has been used to study intermittency in a simple models of turbulent cascades [109].

Statistical mechanics of geostrophic turbulence. Over the past years, we have developed theoretical tools to study the self-organization of geophysical flows into jets and vortices. First, while the Robert-Sommeria-Miller equilibrium statistical mechanics has proved relevant to describe large-scale structures in two-dimensional and geostrophic flows [79], its generalization to more complex models was hampered by very difficult theoretical challenges. The equilibrium statistical mechanics of the Shallow Water model and of the axisymmetric Euler flow has been solved [158, 179], and we have used this approach to discuss sudden stratospheric warming [194].

Kinetic theory. We have also developed a the-

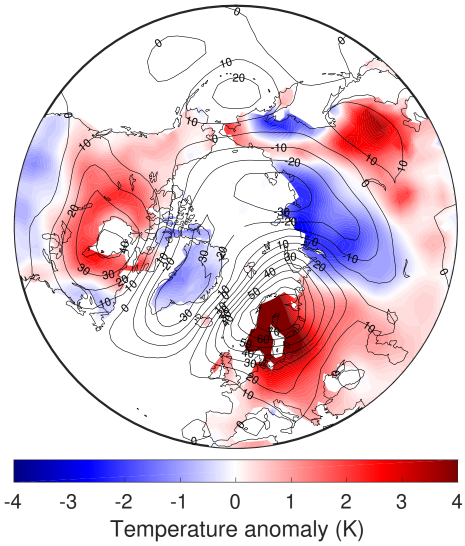

Figure 4: Teleconnection pattern for extreme European heat waves (colour: temperature anomalies, lines: 500hPa geopotential anomalies)

oretical approach to study geophysical flows in a weakly out-of-equilibrium regime, when large-scale structures evolve much slower than turbulent fluctuations. While such approaches were hitherto introduced on a heuristic basis, we have provided a theoretical justification, based on stochastic averaging [78]. Kinetic theory has allowed us to compute the mean velocity profile and Reynolds stress tensor in two cases: the 2D vortex condensate [46] and barotropic jets such as the jets of Jupiter [191].

D. *MHD and plasma turbulence*

MHD turbulence: dynamos and instrumentation. (ENS Paris, CEA Saclay, Obs. Nice) Following our previous contributions on turbulent dynamos, and in particular within the VKS collaboration, we have (i) shown how a flow bistability affects the dynamics of the magnetic field [134], (ii) applied extreme value statistical tools to predict the dynamo onset [104], (iii) proposed a new mechanism for the dynamo generation from numerical simulations [48]

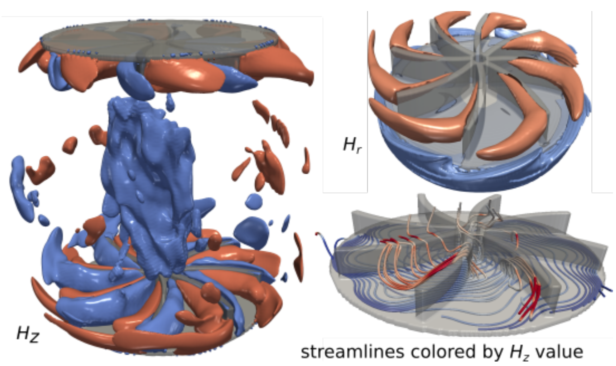

Figure 5: Simulations of the VKS dynamo using penalization methods reproducing all experimental results [48].

Tech transfer of a patented velocity measurement technique has been supported by SATT Pulsalys and led to collaborations with major industrial players to develop advanced industrial prototypes for the measurement of high temperature liquid metals flowrates [89] in various configurations.

Plasma turbulence. (U.Wisconsin, IJL Nancy). The velocity field / magnetic field coupling strongly depends on the physical parameters and in particular on the magnetic Prandtl number (P_m, the ratio of the kinematic viscosity over the magnetic diffusivity). While Pm is always very low in liquid metals, it may vary over several orders of magnitude in plasmas thanks to modifications of collisional processes between ions and electrons. We have developed a dedicated experimental setup [57] to address (i) how large scale and controlled plasma flows may be imposed, (ii) transport phenomena for the velocity and the magnetic fields. A large effort has been dedicated to the development of plasma instrumentation [98, 101] and flow drive techniques relying on the interaction of currents with magnetic fields [190], leading to a fully operational experimental device for the investigation of controlled plasma flow interactions and plasma wave-turbulence.

E. *Convection*

Turbulent thermal convection is involved in atmospherical and oceanic flows and influence transport of particles in many kind of flows. It is a very complex situation with very reach physics. The fundamental brick is the thermal plume that develops when a part of the flow is locally heated. On the other side when a plate is heated numerous plums develop and merge, giving rise to a large scale circulation. The interaction between those structures is highly non-linear and largely not understood. In laboratory experiments the Rayleigh-Bénard cell with smooth plate is commonly used because of its ease of operation and because it contains most of the relevant physical ingredients : large scale flow, thermal plumes, interactions with walls, boundary layers, all of which interact together. We have tried to model separately the behaviour of bulk, boundary layers and small scales transport, at Rayleigh number between 10^9 and 10^{12}.

Bulk Behavior. We have used a cell with a constraint center to isolate the bulk from the boundary layers. The flow has been shown to exhibit purely inertial behaviour ; moreover several regimes have been put in evidence when tilting the cell [97].

Boundary perturbation. Surfaces in nature are always rough resulting in a perturbed boundary layer, so we performed measurement in a cell with rough boundaries.The Nusselt number (that is governed by the thermal boundary layer) is increased in a clearly non trivial way (the augmentation is larger than the increased surface of heat exchange). Thanks to the Euhit European Project we have performed very well resolved measurements in a rough boundary at the barrel of Ilmenau (Germany) showing that the increasing is compatible with a boundary layer transition to turbulence [50]. Complementary measurements in a water cell were performed in Lyon, showing that velocity fluctuations increase all over the cell [120] and that the increasing in the Nusselt number saturates when the roughness height increases [63].

Very High Rayleigh Plumes. Using the shadowgraph technics we start investigating very high Rayleigh number convective flows operated in low temperature liquid He. A glass Cryogenic apparatus have been realised thank to the JC ANR projet Cryograd and measurements are beginning.

Lagrangian Tracking. Lagrangian analysis of temperature and velocity are one of the big challenges in environnemental fluid mechanics. We have performed this analysis in our well controlled experimental conditions using a large scale (a tenth of the cell size) instrumented particle that allows for lagrangian 2D heat flux measurements. We have compared it to numerical simulations (NS) realized by S. Chibbaro (Paris). Heat flux shows non gaussian statistics in good agreement with NS (at least at the scales of interest) [51]. Lagrangian 3D tracking with micrometric particles have been realized to look at small scales properties of turbulence in a specially dedicated octagonal cell (Fig. 6). We could follow simultaneously several hundreds of particles and have shown that the large scale dynamics influences the motion till to the smallest scales of the flow [121]. Work is being pushed further to investigate pair dispersion.

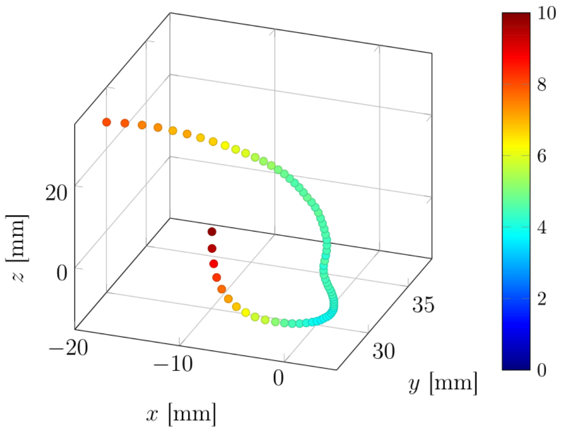

Figure 6: Trajectory of one particle in the cell center. The color bar indicates the magnitude of velocity.

F. *Fundamentals of Turbulence*

Irreversibility in turbulent flows. The energy transfer between scales in a turbulent flows is fundamentally irreversible i.e. it is not invariant under the transformation $t \to -t$. How to quantify this irreversibility was not known. With the helpf of experiments and numerical simulations, we have observed several manifestations of irreversibility. The first one concerns "flight-and-crash" events, which consists in slow increase of kinetic energy of particles, followed by an abrupt loss of energy. The asymmetry between gains and losses of kinetic energy along a particle trajectory suggest to look at the asymmetry factor (the skewness): $I \equiv -(\langle(\partial_t E)^3\rangle / \langle(\partial_t E)^2\rangle^{3/2}$. This quantity was found to be proportional to the Taylor scale Reynolds number, R_λ^2 [67]. Later contributions led to the remark that I_r is in fact related to the vortex stretching, a fundamental process leading to the formation of small scales in turbulence [156]. The irreversibility of turbulence also manifests itself in the separation between two particles, or in the way a set of particles deforms [82, 118].

Local structure of Eulerian turbulence. (C. Garban, ICJ) The local structure of three-dimensional turbulence, and its statistical behaviours, is an emblematic problem of non-linear physics. While the phenomenological framework mostly developed by Kolmogorov gives a consistent picture of what is observed in experimental measurements and numerical simulations, it is almost unrelated to the dynamics given by the Navier-Stokes equations. As a consequence, key parameters of this phenomenological theory, such as the averaged Holder exponent $H = 1/3$ and the intermittency intensity, remain empirical and estimated on data.

A first step toward linking these free parameters to the equations of fluid mechanics is the modelling of the random velocity fields at play (such as velocity), as they are observed and depicted in the phenomenology of Kolmogorov. This what we propose to do.

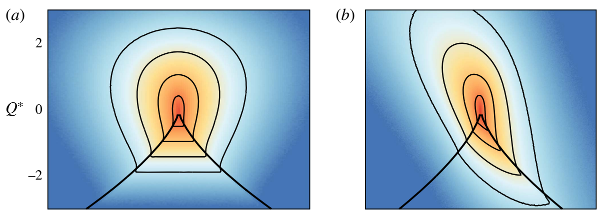

Figure 7: Joint probability density of the two principal invariants of the velocity gradient tensor R and Q in a (a) Gaussian case, and in (b) an intermittent version of the fields that reproduces the characteristic teardrop shape.

We have studied in details, from both a numerical and mathematical perspectives, a three-dimensional incompressible (i.e. divergence free) velocity field that appears to be an excellent candidate for being an appropriate representation of stationary 3d-turbulence. This field is made up, as a first layer, of a fractional random field able to reproduce the singular nature of velocity in a Gaussian approximation. As a second layer, the underlying white vectorial noise is transformed in a nonlinear fashion using a matrix generalisation of a stochastic multifractal measure. It gives a long range correlated structure to the formerly depicted Gaussian field, able to reproduce the non-Gaussian nature of the fluctuations, including the physics of energy transfers and intermittency. Numerical and mathematical developments are provided in Ref. [55].

Multifractal modeling of velocity gradient dynamics (R.M. Pereira, L. Moriconi (UFRJ)). Another aspect of fluid turbulence and its universal manifestations may be seen along Lagrangian trajectories while following the full velocity gradient tensor, which encodes both deformation and rotation. Once again, this dynamics has been precisely observed in both experimental and numerical flows, and we propose in this work the stochastic modelling of its fluctuations. To do so, we take from the Navier-Stokes the main ingredients that govern the stretching of vorticity, and rely on further probabilistic modelling of unclosed terms (such as pressure Hessian). We are then led to propose a nonlinear and non-Markovian stochastic ordinary tensorial differential equation that is shown, numerically, to reproduce with great accuracy the observed geometry of the fluctuations. Numerical and mathematical investigations are provided in [56].

Extreme gradients in turbulent flows. A natural starting point to study the formation of extreme velocity gradients, one of the hallmark of fluid turbulence, consists in asking how much can gradients be amplified by the nonlinearies in the flow – the celebrated singularity problem. In this spirit, the problem of interaction between two vortex tubes has been reconsidered. A mechanism for iterative amplification of vorticity has been proposed [90]. Experimental tests based on the head-on collision between two vortex rings indeed suggests an iterative process, leading to vorticity at increasingly small scales [131]. In a related spirit, simulations at extremely high resolutions, over a large range of turbulence intensity have led to the observation of a power law dependence of the most intense velocity gradients as a function of the Reynolds number [96].

Mixing in chemically induced compressible flows. (ILM, LMFA) Mixing of colloids in the presence of salt gradients is affected by diffusiophoresis, which cause a drift between the velocity of the particles and the fluid. This was addressed in the context of chaotic advection (Fig. 8) and turbulence which showed that observations can be understood and predicted in the framework of compressible flows [59, 128, 172].

Large scale experiment and modelling of dispersion (LEGI, LMFA, ESWIRP, ONERA). We performed the largest grid turbulence experiment ever attempted, in the S1MA wind-tunnel of ONERA at Modane (Fig. 9). The unique size of the experiment allowed to achieve measurements with unequaled resolution and to constitute a reference data-base of fundamental properties of turbulence, now open to the scientific community. We have proposed a new theoretical approach of relative turbulent dispersion based on an iterative ballistic cascade phenomenology, which we have recently extended to the case of inhomogeneous and anisotropic turbulence (thermal convection and channel flow) [41, 82, 115].

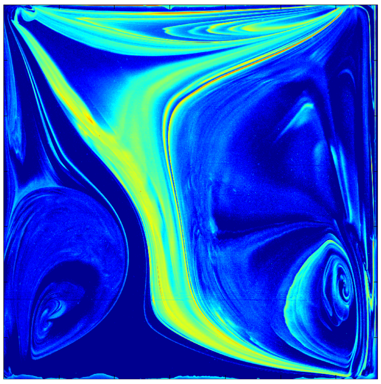

Figure 8: Colloids concentration field measured in a Hele-Shaw cell by Laser Induced Fluorescence.

Figure 9: The large scale (10 meters in diameter) turbulence generating grid in its final position in the convergent of the S1MA wind tunnel of ONERA in Modane.

G. Particles and turbulence

Particles transported in turbulent flows (LEGI, LMFA, OCA Nice, EuHIT). The dynamics of material particles and tracers in turbulent flows was addressed experimentally by particle tracking velocimetry. We focused on the influence of finite size and density effects on the temporal dynamics of the particles, and on the unmixing properties of inertial particles (preferential concentration) which tend to segregate in clusters under the action of turbulence. More recently we started to investigate the modulation of turbulence in highly seeded flows [52, 114, 125, 127, 174].

Fluid structure interactions (LEGI, KIT (Karlsruhe)). The coupling of objects with a surrounding flow is often responsible for non-trivial wake and path instabilities. Among such peculiar phenomena, we have investigated path instabilities of towed spheres as well as the trapping of spheres in inhomogeneous flows. We have also showed that within a certain range of Galileo number, the emergence of individual wake instabilities triggers collective effects where the settling of an ensemble of spheres tend to self-organise in rapidly falling columns (Fig. 10) [47, 74, 139].

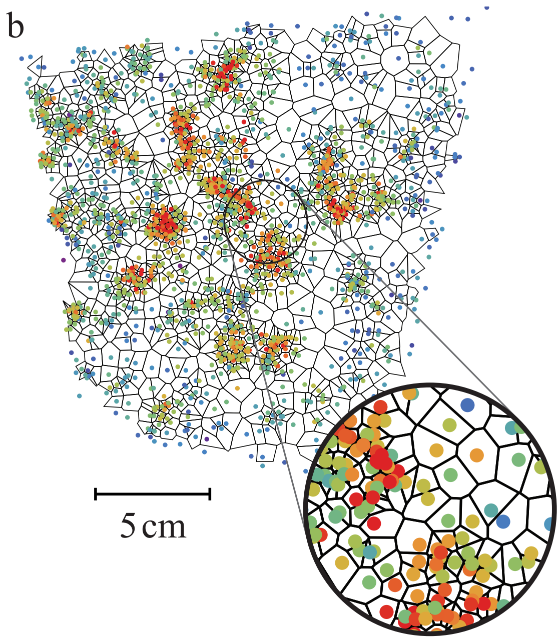

Figure 10: Settling columns of particles seen from above emphasised with Voronoï tesselations.

Turbulence in clouds: Collision rate between droplets and ice crystals The role of turbulence has been recently put forward to explain the fast formation of precipitation drops, starting from very small droplets or ice-crystals. The sling effect, due to the possibility of drops to be centrifuged out of vortices in the flow has been quantified, and its importance has been clearly characterised [58, 188].

Ice crystals in clouds, approximately shaped as spheroids, settle in the flow and collide to form larger particles. With simplifying assumptions about the dynamics, we obtained a systematic description of the orientation of settling crystals [110], and determined the collision rate between crystals [117], and between crystals and droplets [137].

H. *Dynamics of superfluids*

Local structure of superfluids. Quantum turbulence consists in the entanglement of very large number of quantum vortices, which reconnect and produce a complex velocity field. To model and simulate this large number of vortices, simplified models have to be used, such as the local induction approximation (LIA). However, these models need to be made consistent with the actual small scale properties of superfluids.

That is why we perform smaller scale, but realistic numerical simulations of the Gross-Pitaevskii equations. They allow us to probe the local structure of superfluids. In particular, we take into account the nonlocal interaction potential, which is introduced to mimic the roton minimum, an essential feature for superfluidity. This investigation of the local structure of superfluids allows to test models such as LIA, and eventually suggests how to improve them.

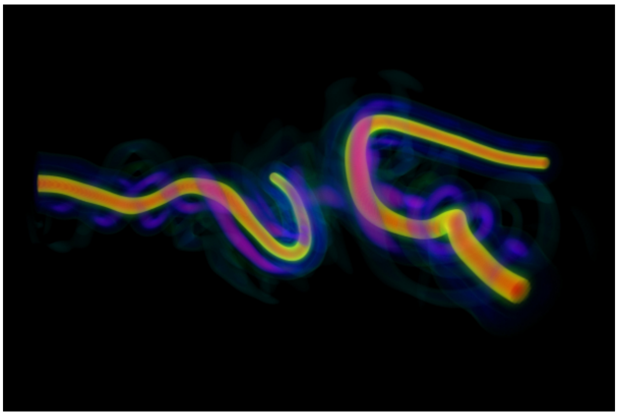

Figure 11: 3D visualization of the superfluid density during the reconnection a two quantum vortices.

Quantum turbulence. (ANR Écouturb, SHREK consortium). High Reynolds number turbulence of quantum fluids is produced by forcing a co-flow with mechanical stirring, such as counter-rotating propellers. These kinds of experiments are collaborative national efforts, and benefit from the large-scale cryogenic infrastructures of our partners of the SHREK consortium in Grenoble. We participate in the design of those projects [160], and contribute dedicated local velocity sensors [165]. The analysis of the local turbulent fluctuations provides insight on the physics of superfluid hydrodynamics, such as intermittency of quantum turbulence [161]. In particular, superfluid von Kármán flows with smooth or rough disks are operated: the torque on the disk is a global quantity which is sensitive to very small scales (the viscous sublayer in the classical case). New dedicated local velocity sensors are being developed, for the lower entraiment cases, and tested in our laboratory inside a glass cryostat.

I. *Multiphase flows and geological applications*

Vorticity-aligned structures in sheared suspensions. Dilute suspensions of repulsive particles exhibit a Newtonian response to flow that can be accurately predicted by the particle volume fraction and the viscosity of the suspending fluid. However, such a description fails when the particles are weakly attractive. In a simple shear flow, suspensions of attractive particles exhibit complex, anisotropic microstructures and flow instabilities that are poorly understood and plague industrial processes. One such phenomena, the formation of log-rolling flocs, which is ubiquitously observed in suspensions of attractive particles that are sheared while confined between parallel plates, is an exemplar of this phenomenology. Combining experiments and discrete element simulations, we have demonstrated that this shear-induced structuring is driven by hydrodynamic coupling between the flocs and the confining boundaries [68].

Washboard road instability. The washboard road instability consists in the growth of a ripple pattern which appears on a sand or gravel track subjected to repeated passages of vehicles. This intriguing phenomenon is studied through laboratory-scale experiments, as well as using Discrete Elements Method numerical simulations that we have developed. Recently we have quantitatively studied the impact of the cohesion within the granular media (due to capillary bridges) on the main features of the instability : critical velocity, wavelength and growth rates.

Segregation in rubble-pile asteroids. Rubble-pile asteroids are small celestial bodies made of individual blocks solely held together by their weak self-gravity. They have attracted much interest in recent years due to success of several space missions. One of the most striking features of theses bodies is the heterogeneity of their surface. While some regions consist in fine sand or powder, large boulders seem to accumulate in other parts. We have studied segregation processes through numerical simulations in order to investigate if the known mechanisms on Earth for sand piles still apply to asteroids. By submitting a self-gravitating assembly of grains to repeated quakes, we managed to reproduce the radial segregation observed on actual asteroids.

Gas release through liquid-saturated grains. (G. Varas, Valparaíso, A. Gay, Montpellier) Fluid migration and expulsion at the ocean floor is a widespread phenomenon which has drastic consequences on the environment or the industry. Striking examples include natural seep areas, possible links between giant methane release and climate change, gas blowout and subsequent bubble plumes during offshore drilling. This process has been studied experimentally by injecting gas through a single point in liquid-saturated sands. Although the initial gas invasion may lead to very different structures (percolation vs. fracture), the system exhibits a long-term dynamics which does not depend on the initial pattern [66]. Injecting gas at the bottom of the cell induces a fluidization of the granular bed, in which convection rolls develop and entrain bubbles and particles *downward*, that are further captured and advected upwards by the central gas channel [148, 157]. The presence of obstacles in the bed affects the stability of the gas channel, which exhibits, under given conditions, an intermittent behavior [147]. In addition, we considered the liquid layer above the initially sedimented granular bed. Grains are entrained in the bubbles wake and the resulting suspension exhibits heterogeneities in space and time which are related to the injected gas flow-rate, the particle characteristics (size, density, polydispersity) and the effective gravity in the system. We focused on the emergence of extreme events such as large and violent gas releases, strong inhomogeneities, sudden fluidization or collapse. Experimental results have been used to interpret field measurements on natural seep areas (*pockmarks*) in collaboration with Géosciences Montpellier [107].

Solid foams: innovative materials for catalysis applications. (R. Philippe, CPE Lyon) In chemical engineering, catalysts, often solid particles, play a major role in enhancing multiphase reactions. In the classical configuration of dense micro-packed beds, the high pressure loss requires important energy costs to force the gas-liquid flow. We test in the laboratory innovative materials: open cell solid foams (Fig. 12). Hydrodynamic regimes of joint gas-liquid flows through these highly porous media (up to 96% porosity) were quantified in confined reactors [169, 171]. Applications to surface contact optimization was performed in collaboration with the Signal Processing Team [745].

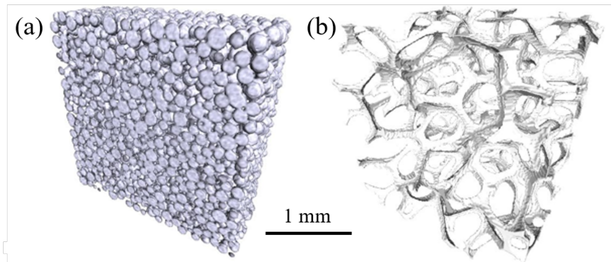

Figure 12: (a) Classical packed beads (spherical glass particles) vs. (b) open cell solid foam (glassy carbon, 96% porosity).

Film bursting and volcanic activity. (F. Melo, Santiago de Chile) Understanding the acoustic signal produced by giant bubbles bursting on volcanoes is a key point for accessing the bubbles overpressure inside the magmatic conduit, and further predict volcanic hazards. We quantified the transition between the linear and nonlinear acoustic regimes by modeling the bubble explosion with the rupture of elastic membranes over overpressurized cavities [166]. The membrane rupture dynamics has a direct influence on the acoustic signal characteristics [167].

Earthquakes length selection. The onset of sliding motion is conditional on the propagation of rupture fronts that detach the contacting asperities forming a frictional interface. These ruptures are the most common mechanism for an earthquake. We have unraveled the different mechanisms responsible for rupture arrest along model laboratory-faults. Propagating ruptures have been shown to be true shear cracks, driven by singular fields at their tip and fracture mechanics have been successfully used to describe rupture arrest along homogeneous frictional interfaces. Performing high-temporal-resolution measurements of the real contact area and strain fields, we have demonstrated that the same framework provides an excellent quantitative description of rupture arrest along interfaces with heterogeneous fracture properties and complex stress distributions.

Hydrodynamics and Geophysics: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
B. Bourget	Ondes internes, de l'instabilité au mélange. Approche expérimentale.	1 july 2014	P. Odier, T. Dauxois
C. Brouzet	Internal wave attractors: from geometrical focusing to non-linear energy cascade and mixing	1 july 2016	T. Dauxois, S. Joubaud
V. Désangles	Forçage à grande échelle d'une colonne de plasma faiblement magnétisée: influence d'une cathode emissive de grande taille	30 november 2018	N. Plihon
R. Guichardaz	Shape dynamics and clustering processes of particles transported by turbulent flows: a stochastic approach	13 october 2016	A. Pumir
E. Horne	Transport properties of internal gravity waves.	29 october 2015	P. Odier, S. Joubaud
P. Huck	Particle dynamics in turbulence : from the role of inhomogeneity and anisotropy to collective effects	6 december 2017	R. Volk
C.-E. Lecomte	Instabilités dans un milieu granulaire : tôle ondulée sur un lit de sable, et ségrégation au sein des astéroïdes lâches	13 july 2018	N. Taberlet
T. Lestang	Numerical simulation and rare events algorithms for the study of extreme fluctuations of the drag force acting on an obstacle immersed in a turbulent flow	25 september 2018	F. Bouchet
O. Liot	Approches innovantes en convection thermique turbulente. Influence des rugosités et étude Lagrangienne	10 december 2015	F. Chilla, J. Salort
N. Machicoane	Particules matérieles en écoulement turbulent. Transport, dynamique aux temps longs et transfert thermique	18 july 2014	R. Volk
P. Maurer	Approche expérimentale de la dynamique non-linéaire d'ondes internes en rotation.	22 june 2017	P. Odier, S. Joubaud
C. Picard	Mise en suspension de particules immergées par injection de gaz	5 july 2018	V. Vidal, S. Joubaud
G. Pillet	Attracteurs d'ondes internes à trois dimensions : Analyse par tracés de rayons et étude expérimentale	6 july 2018	T. Dauxois
R. Poryles	Instabilités et piégeage de bulles dans des fluides complexes	18 july 2017	V. Vidal
A. Renaud	On wave mean flow interactions in stratified fluids	8 october 2018	A. Venaille, F. Bouchet
E. Rusaouën	Échanges turbulents en convection thermique	8 october 2014	F. Chilla, J. Salort
C. Sánchez	Modelo experimental de la dinámica de estallido y emisión acústica en volcanes	2 march 2015	V. Vidal
M. Serres	Etude hydrodynamique d'un écoulement gaz-liquide dans un milieu poreux confiné	22 june 2017	V. Vidal

Main contracts

4 European: ERC TRANSITION (50%), Marie Curie TRANSTURB (50%), Marie Curie WAVE ATTRACTOR, EuHIT, ESWIRP
11 ANR: CRYOGRAD, DISET, DYNAMO, ECOUTURB, LIOUVILLE, LTIF, ONLITUR, STRATIMIX, TEC2, TUNAMIX, WTF
4 LABEX IMUST: DENViB, GLIFSO, WDT, PlumeX
3 IDEX Lyon: Breakthrough "Particles", "Academics", Impulsion "Friction"
1 IUF: Joubaud
Companies: IFPEN, Maturation SATT PULSALYS

Editorial responsibilities

Bourgoin Mickaël:
New Journal of Physics, Invited Editor for the focus on Particles in Turbulence.
Chevillard Laurent:
Europhysics Letters, Member of the editorial committee.
Bouchet Freddy:
JSTAT, Member of the editorial committee.

Organized conferences

Bouchet Freddy:
Theoretical Advances in Planetary Flows and Climate Dynamics, Les Houches (France), March 2015
Statistical mechanics and computation of large deviation rate functions, ENS de Lyon (France), June 2015
Adaptive Multilevel Splitting et événements rares, Ecole des Ponts, Champs sur Marne (France), June 2016
Extreme events in the Earth and planetary sciences, Warwick university (UK), July 2016

ENS de Lyon meets SISSA, ENS de Lyon (France), December 2017
Nonequilibrium Systems in Physics, Geosciences, and Life Sciences, ICTP Trieste (Italy), May 2018
Bouchet Freddy, Venaille Antoine:
Les Houches summer school, turbulence and climate, Les Houches (France), August 2017
Bourgoin Mickaël:
New Challenges in Turbulence Research III, Les Houches (France), March 2014,
New Challenges in Turbulence Research IV, Les Houches (France), March 2016,
Turbulent Cascades II, Lyon (France), December 2017,
Systèmes Hors Equilibre, Lyon (France), November 2018,
New Challenges in Turbulence Research V, Les Houches (France), April 2019
Chillà Francesca, Bernard Castaing:
High Rayleigh Number Convection, Les Houches (France), January 2010
Dauxois Thierry:
Nonlinear Effects In Internal Waves Conference, Cornell University (USA), June 2014
Environmental Fluid Dynamics: Confronting Grand Challenges, Les Houches (France), January 2019
Plihon Nicolas:
The Dimensionality of Turbulence (Euromech 561 Colloquium), Coventry (UK), May 2014
Turbulence, magnetic fields and self-organization in lab. & astro plasmas, Les Houches (France), March 2015
Vidal Valérie:
CMG 2016, Geophysics, from Mathematics to Experiments, Paris (France), June 2016
Mini-colloque RNL 2018 Non Linéarité et Tremblements de Terre, Paris (France), March 2018
Venaille Antoine:
New challenges in internal waves, CBP/ENS de Lyon (France), October 2015

155 publications in peer reviewed journals: see T1B.

T2R. Soft Matter: *Report*

Permanent Members: M. Adda-Bedia, D. Bartolo, L. Bellon, S. Ciliberto, C. Crauste-Thibierge, V. Dolique, R. Everaers, E. Freyssingeas, J.-C. Géminard, T. Gibaud, S. Joubaud, S. Manneville, P. Oswald, S. Santucci, A. Steinberger, N. Taberlet, V. Vidal

Post-docs: N. Ali, S. Ceccia, V. Chikadi, D. Cottinet, M.-A. Fardin, P. Grasland-Mongrain, J. Hem, S. Kosgodagan Acharige, H. Lastakowski, M. Leocmach, M. Levant, R. Perez-Aparicio, B. Saint-Michel, R. Sahli, F. Tapia, J. Weijs

PhD students: I. Andrade, N. Bain, A. Bricard, J.-B. Caussin, A. Chardac, N. Dagès, M.J. Dalbe, N. Desreumaux, V. De Zotti, L. Favreau, J. Ferrand, D. Geyer, R. Jeanneret, T. Jules, M. Le Blay, B. Levaché, P. Lidon, A. Morin, C. Odier, C. Perge, R. Poryles, G. Poy, L. Thorens

Over the last five years, we have continued developing a wide range of studies in the field of Soft Condensed Matter Physics, combining experimental work with theory and numerical simulations. The leitmotif of our research are instabilities in complex materials. Materials range from liquid crystals, melted polymers, elastomers, emulsions, gels, foams, mechanical metamaterials, active colloids to granular and biological materials. In order to understand and establish links between the building blocks of such materials and their macroscopic physical properties (as for instance aging, flow, resistance to rupture), we have combined experimental and theoretical tools used in many different fields of physics and engineering (optics, acoustics, non-linear and statistical physics). Thanks to the development of model systems and state-of-the-art instrumentation, we have applied those tools on a wide range of scales - from the nano/microscopic constituents, through the coarse grained mesoscopic level, and up to the macroscopic scale of the systems considered. This multi-scale approach constitutes the cornerstone of our work, highlighted in the following detailed description of our studies: from the nano-mechanics of carbon nanotubes, to the design of self-assembled structures, and the deformation, fluidization up to the failure of both brittle and ductile heterogeneous materials. Finally, we underline that a strong effort has been placed on bridging the gap between fundamental studies and real-world applications, as witnessed by active industrial collaborations. We are therefore conducting a multi-disciplinary approach, which as a result stimulates many collaborative efforts within the various teams of our laboratory, transverse to the various themes presented in this report, and also active exchanges with numerous world renowned institutes, national and international.

A. *Instabilities in complex materials: flow, yielding and fracture*

Triggering and characterizing instabilities in complex materials are at the heart of this section. A wide range of instabilities are studied such as surface undulations in flowing foams [202] (Fig. 13), shear thickening in corn starch [220], strain hardening in natural latex gels [314], wrinkling in casein gels [209], mechanical instabilities in flowing gels [254] and granular materials [226, 333] with special emphasis on the decrease of the effective frictional coefficients of a granular layer due to controlled mechanical vibrations [208]. In the next, we develop a few examples.

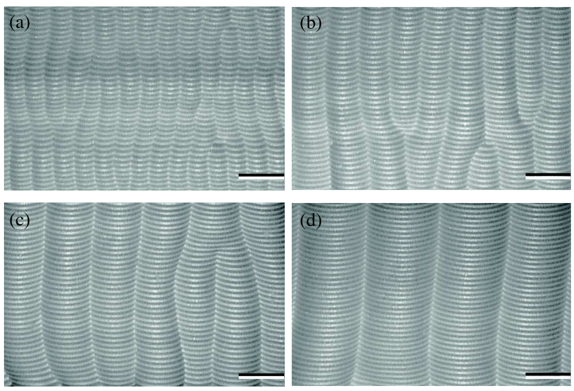

Figure 13: Surface undulation at the free surface of a foam layer subjected to an in-plane elongation. Scale bar 1 cm. The layer thickness ranges from (a) 2.5 to (d) 8.2 mm.

Solid–liquid transition in colloidal gels – Colloidal gels are composed of colloidal particles embedded in a solvent at low volume fractions that form an elastic three-dimensional space-spanning network. Using different types of colloids ranging from proteins to industrially-relevant particles such as silica or calcite, we have shown that the yielding transition, i.e. the shear-induced transition from a solid state to a fluid state, is most often heterogeneous both in space and time [258, 259, 280, 305]. Access to local flow features of optically opaque complex materials under shear, including shear bands, fractures or wall slip is given by a previously-developed ultrasonic scanner coupled to rheometry a technique. This technique was extended to oscillatory shear and to the simultaneous measurement of the local concentration in particle suspensions [320, 321]. Such spatio-temporal dynamics explains the strong hysteresis and avalanche-like behaviours that are widely observed in the rheology of yield stress materials [197, 271, 311]. In the case of irreversible yielding, the transition displays strong analogies with the rupture of brittle solids [273]. In certain cases, the rupture point can even be predicted [268, 322].

Grains under high-intensity ultrasound – We have shown that high-frequency ultrasonic waves may unjam and fluidize granular sediments thanks to the acoustic radiation pressure [211]. This effect can also be used to push on individual grains embedded in a gel matrix and deduce interesting local rheological features of the surrounding gel [278, 279].

Mecanical behaviour of strained polymer films – We initiated in 2013 a long term collaboration with LPMA (Solvay, Saint-Fons) based on mechanical studies of polymer films. The highly sensitive dielectric techniques developed at the LPENSL [217] is used to perform *in situ* measurements under imposed strain rate on polycarbonate (PC) films (see Fig. 14). This has never been done before, especially in the frequency range of mechanical relaxation, the α-range. We find that the dielectric response of stretched PC below the yield stress behaves as if it was heated up at a temperature just below its glass transition temperature, $T_g \approx 423$ K for PC. The mechanical rejuvenation modifies the dielectric response at frequencies smaller than 10 Hz, whereas for higher frequencies the spectrum is only slightly modified [302]. After the yield stress, we find an acceleration of the dynamics at softening, followed by a strong decrease of mobility during hardening.

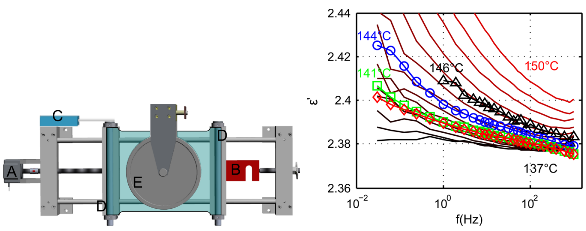

Figure 14: On the left : Experimental setup of dielectric microscopy during stretching: motor (A), load cell (B), linear transducer (C), sample fastening cylinders (D) and electrods for dielectric measurements (E). On the left, Real part of the dielectric permittivity ε, measured under deformation (line with symbols) at the maximum of the force, as a function of frequency at strain rates. Real parts of the permittivity for sample at rest at temperatures from 137 to 150 Celsius degrees (simple lines) were represented as a function of frequency.

Stick-Slip Peeling – Everyone has experienced the unpleasant screechy sound when peeling-off packing-tape, direct consequence of the jerky motion of the peel front, moving at a speed that alternates between slow (stick) and fast (slip) phases [199]. This dynamical rupture instability results from the coupling between the elastic tape and the nonlinear rheology of the adhesive [339]. Our experiments show that the peeling angle is a control parameter of the instability [240], and unveil the crucial role played by inertial effects [239, 241]. Moreover, thanks to ultra-fast direct imaging of the detachment front dynamics at high peel velocities, we have revealed a complex and puzzling multi-scale process [198]: the peel front locally advances by microscopic steps in the main peel direction, due to the periodic propagation of rapid fracture kinks in the transverse direction, e.g. sideways, across the tape width, at ultrasonic frequencies. This micro-instability constitutes an elementary brick of the classical macroscopic stick-slip oscillations of the peel front. Our study highlights the essential role of the inertia and flexural rigidity of the ribbon, showing that the elastic energy needed to bend locally the ribbon is converted into an increase of kinetic energy acquired by the peeled tape during a micro-slip.

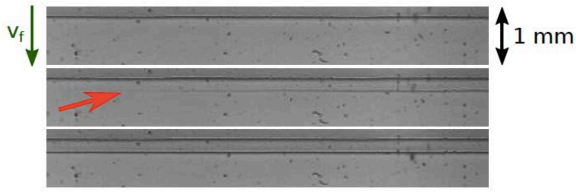

Figure 15: Chronophotography of the peel front (time interval between each image is 20 μs) during a typical experiment. The red arrow indicates the tip of the fracture kink, which propagates in the transverse direction.

"En passant" cracks – Our experimental observation of a repulsive behavior between two initially collinear cracks growing towards each other and leading to a hook-shaped path questioned the validity of the principle of local symmetry within linear elastic fracture mechanics theory [238]. We could finally solve this apparent dilemma [223], thanks to a detailed numerical study, providing the precise geometric conditions for the existence of this repulsive phase. We could reveal a multi-scale behavior of the repulsive-attractive transition, explaining its ubiquitous occurrence, but also the difficulty to predict the final cracks' paths [269].

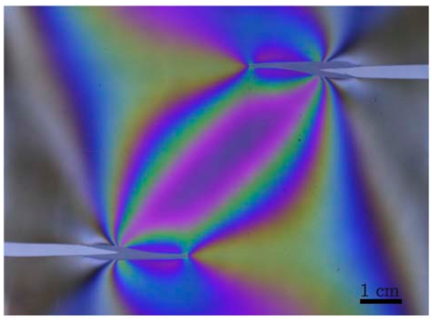

Figure 16: Photo-elasticity of two interacting cracks in a stressed (mode I loading) polycarbonate film.

B. *When hydrodynamics and soft matter concepts mingle*

Hydrodynamics may mingle with soft matter in many ways. For instance, how does a background fluids with viscoelastic properties changes the hydrodynamics. How does the wettability of a surface influence the flow rate?

Bubbles instabilities and fragmentation – Bubbles rising in confined polymer solutions exhibit spontaneous oscillations or fragmention above a critical volume. Based on experimental studies, we quantified the different regimes from a round, small bubble to cusped bubbles with vertical trajectories, and finally cusped oscillating or fragmenting bubbles. The fragmentation process was interpreted in terms of a viscous fingering recalling the Saffman–Taylor instability. Interestingly, the finger growth is directly controlled by the bubble size [219].

Flows in heterogeneous media – Building on model micro-fludic experiments we demonstrated and explained a series of wetting transition controlling the dynamics of liquid imbibing confined environments. These wetting transitions occur at macroscopic scales and control large-scale imbibition patterns out of reach of the conventional viscous fingering picture [214, 274].

Draining of complex material through an orifice – Flow of a fluid through an orifice as well as wetting of a fluid onto a solid surface are two different aspects of fluid mechanics. The first ones date back to Torricelli (1643) and Young (1805). Since these seminal works, many studies have been carried out on this topic because of its importance in many natural and industrial processes. However, no investigations have considered the effect of fluid wetting conditions onto the outer surface at the outlet orifice on tank draining [201]. We have investigated this issue for flows through holes of millimeter size; *i.e.* whose diameter is of the order of the capillary length. Although the flow still follows a "Torricelli's law", wetting strongly affects the speed of drainage that goes through a minimum as the outside surface of the tank bottom plate changes from hydrophilic to hydrophobic. This effect lies in the meniscus that forms at the hole outlet. A simple model calculating the kinetic energy variation within the meniscus captures the key points of this phenomenon. Another striking effect of wetting is the existence of a periodic jet shape disturbance from the onset of the flow, occurring at the hole outlet. To our knowledge such a phenomenon, has never been described so far. This disturbance is the macroscopic signature of a periodic instability of the shape of the meniscus (Fig. 17).

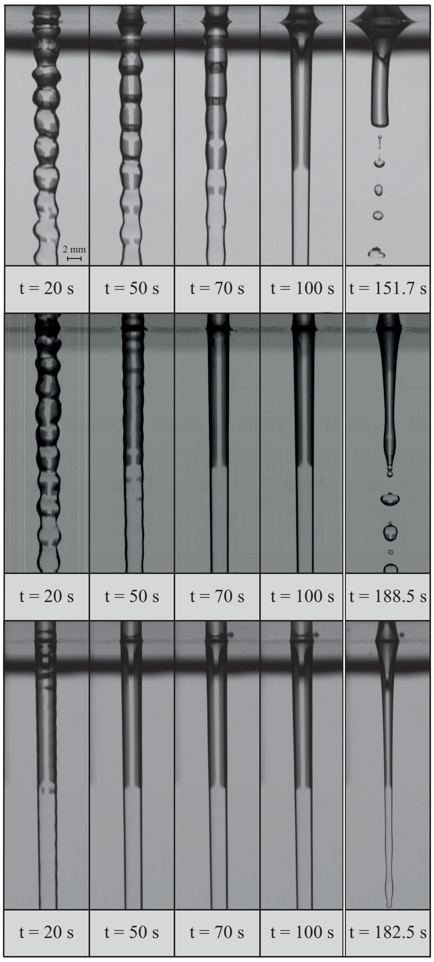

Figure 17: Snapshots of the jet at different times during tank draining through an orifice for three different wetting conditions. Top: flow through a very hydrophilic material. Middle: flow through a slightly hydrophilic material. Bottom: flow through a slightly hydrophobic material. Both the disturbance duration and amplitude depend on the bottom plate wettability.

C. *Self-assembly: turning on the synergy between building blocks*

Self-assembly is the phenomenon in which a collection of objects spontaneously arranges into mesoscopic structures. The complexity of the mesoscopic structure is encoded is the building blocks and the physics that drive its condensation. Although the fundamental and driving questions in self-assembly have persisted from the birth of the field up to the present – Can the global behavior of a system be engineered using local rules set by the building blocks properties? How do local rules interlace with physics principles and determine global behavior? – the complexity has drastically increased over the years. In the next, we develop a few examples such as the never ending mystery of the Lehman effect, the role chirality and attraction in self-assembly of colloidal rods, loop opening in predominately double-folded polymer structures, or the emergence of collective motion of synthetic flock and human crowd.

Thermomechanical effects in nematic and cholesteric liquid crystals – The Lehmann effect is the rotation of cholesteric droplets subjected to a temperature gradient. We have shown that this effect also exists in nematic liquid crystals providing that the director field is twisted inside the droplets [205] (Fig. 18). In usual experiments, the droplets coexist with their isotropic liquid but they can also be suspended in a partially miscible liquid [290]. Several mechanisms have been proposed to explain the rotation. The first one is based on the existence of thermomechanical or chemomechanical couplings [296, 310]. This explanation proposed by Leslie in 1968 became a paradigm but must be abandoned because it predicts far too small rotation velocities and even sometimes the bad sense of rotation [287]. By contrast, a melting-recrystallization process seems promising to explain the Lehmann effect when the droplets coexist with their isotropic liquid [295], whereas Marangoni flows are clearly responsible for the rotation in emulsions [290].

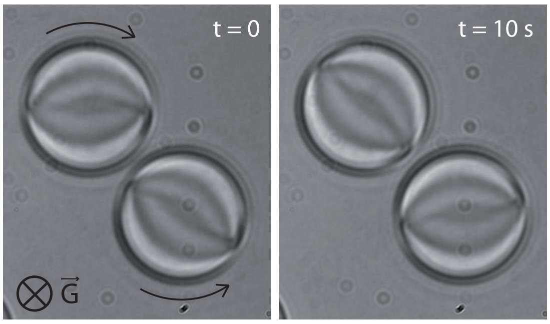

Figure 18: Lehmann effect in a nematic liquid crystal. Note that, contrary to cholesterics, the droplets can rotate in both directions because they can be twisted to the right or to the left equivalently.

Rheology of liquid crystals – A homeotropic nematic slab has been studied when it is subjected to a dilation-compression sinusoidal deformation of small amplitude. Contrary to previous theoretical predictions, it has been shown that the nematic phase behaves in the linear regime as a viscoelastic fluid whose elastic and loss moduli have been calculated and measured [289]. Similar experiments with a homeotropic sample of smectic-A LC has shown that its response is nonlinear even at very small amplitude of deformation. This plastic behavior has been explained by taking into account the crossing between the edge dislocations that climb parallel to the layers and the screw dislocations joining the surfaces limiting the sample [294]. The role of the Cottrell clouds that form around the edge dislocations when the smectic phase is doped with nanoparticles has also been studied [216].

Anchoring of liquid crystals – Controlling the anchoring of liquid crystals (LC) on surfaces is important both for fundamental purposes and for the development of LC-based devices. We studied the dynamics of memorization of an easy axis when a nematic sample treated for planar sliding anchoring with a liquid polymer is maintained during a long time in a fixed orientation [286]. We also studied the kinetics of photosensitive nematic cells that incorporate an azobenzene-based self-assembled monolayer [215]. In particular, we characterized the photoinduced homeotropic-to-planar transition and the subsequent reverse relaxation in terms of the underlying isomerization of the photosensitive layer. Finally, we studied the role of anchoring energy on the texture of cholesteric droplets by Finite-element simulations and experiments [308].

Filamentous phages as building block for reconfigurable and hierarchical self-assembly – Filamentous phages such as fd-like viruses are rod-like colloids that have well defined properties such as their diameter, length, rigidity, charge and chirality. Engineering those virus leads to a library of rods with slightly different properties which are used as building blocks for self-assembly. Their condensation in aqueous solution with additive depletants produces a myriad of structures ranging from isotropic/nematic droplets [281], achiral membrane seeds [267], twisted ribbons π-wall [343], pores, colloidal skyrmions, Möbius anchors, scallop membranes [256, 343] to membrane rafts [324] and 2D crystals [257]. First, those structures reinforce the general notion that through a careful choice of particle shapes, sizes, and concentrations it is possible to ?engineer entropy?. Second those structures are very sensitive to external stimuli so that it is possible to manipulate the structures and trigger shape shifting transitions. Third, those structures represent a showcase of analogies between objects which belong to different fields of science such lipid bilayers, pores in cells, membrane rafts, solid state skyrmions, superconductors, and Möbius strips.

Figure 19: Filamentous phages as building block for reconfigurable and hierarchical self-assembly – colloid membrane to twisted ribbon transition induced through temperature sensitive chiral interactions, 3D-LC Polscope image, image height 31 μm.

Multiscale modeling of linear, ring and branched polymers – Randomly branched polymer chains (or trees) are a classical subject of polymer physics with connections to the theory of magnetic systems, percolation and critical phenomena. More recently, the model has been reconsidered for RNA, supercoiled DNA and the crumpling of topologically-constrained polymers. While solvable in the ideal case, little is known exactly about randomly branched polymers with volume interactions. Flory theory [200] provides a simple, unifying description for a wide range of branched systems, including isolated trees in good and theta-solvent, and tree melts. Beyond the Gaussian approximation, computer simulations [316, 317] and scaling arguments reveal a rich scenario including generalized Fisher-Pincus and Kramers relations for key distribution functions [317]. We are particularly intrigued by the relation to crumpling untangled (ring) polymers [315], where local loop opening in predominately double-folded structures [222] might have profound implications for the dynamics. This line of work forms the basis of our attempts to develop quantitative models of chromosome folding discussed in the section on Biological Physics.

Colloidal flocks – Combining theory and model experiments based on colloidal robots capable of self-propulsion and of sensing the orientation. of their neighbors, we laid out a research program on the collective motion of synthetic flocks. In particular, we established the fist-order nature of the flocking transition and investigated the robustness of flocks to challenging environments including structural disorder and external field opposing collective motion [212, 284]. We also showed how proximity interactions results in the collective arrest of polar flocks in the form of a Motility Induced Phase separation: high density flocks freeze into lively active solids that continuously re-arrange their amorphous structure [203].

Figure 20: Left: Active colloids self-assembled into a spontaneously flowing liquid. Right: Start corral of the 2018 Chicago marathon [196].

Crowds as soft materials – Studying the dynamic response of pedestrian crowds to boundary perturbations, we inferred an active-liquid description of crowd motion. We conducted our experiments observing the start corrals of massive marathon races around the world. Calibrating our model on measurements performed on runners gathered in Chicago in 2016 allowed us to predict the crowd motion in the start corrals of five different marathon races separated by thousands of kilometers in space and years in time [196].

Mechanical 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 disgarded, 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.

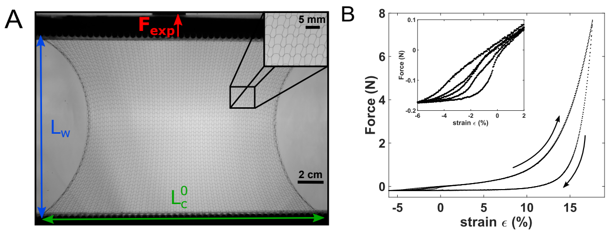

Figure 21: The mechanical response of a knitted fabric. (A) Picture of the deformed stockinette-knit fabric showing the topology of the stitches and their layout in the typical catenary shape. (B) Mechanical response of the fabric over 5 loading–unloading cycles. The strain is defined by $\varepsilon = (L_w - L_w^0)/L_w^0$ such that the origin $\varepsilon = 0$ corresponds to the extension above which the force signal is persistent over the cycles. The inset zooms in the force curves close to $\varepsilon = 0$ and for different cycles during the loading phase.

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 study a model tricot made of a single elastic thread knitted into the common pattern called stockinette, Fig. 21. 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 [218, 307].

D. Nanomechanics with soft objects

Handling and imaging single building blocks of soft materials remains a challenge. To this purpose, we have set up several tools for experimental investigations of soft matter physics in the nanometer range:

Optolyse and Nano'sup platforms – The Optolyse platform is a cross site project (ILM, LHC) aiming at providing tools to investigate light-matter interaction. The LPENSL is hosting a low noise chamber, consisting of a large anechoic Faraday cage to insulate the experiments from acoustic and electromagnetic external perturbations. A home made high resolution AFM (Atomic Force Microscope) dedicated to thermal noise and dielectric measurements will soon populate the vibration isolated optical table inside the chamber. The laboratory Nano'sup platform gathers:

- a commercial AFM (JPK NW 4) mounted on an inverted microscope with fluorescence imaging capacities. This shared tool is well suited for soft matter and biophysics experiments.
- a SEM (Scanning Electron Microscope, ZEISS Supra 55 VP) with EDX sensing and e-beam lithography options. This shared tool addresses sample preparation and characterization across many experimental topics, from soft matter to quantum physics.
- our home made AFMs using quadrature-phase differential interferometers to reach ultra high resolution in deflection measurement (down to $10^{-15}\mathrm{m}/\sqrt{\mathrm{Hz}}$), aiming at thermal noise and nanomechanical investigations.

Functionalized force microscopy: micro-rheology and contact dynamics – To investigate the interactions between a fiber partially dipped into a liquid and its surrounding fluid, we have built a dedicated hanging-fiber AFM setup, based on our Nano'sup platform AFMs. A cylindrical fiber with a radius between 50 nm and 5 μm is glued on an AFM cantilever. By measuring the thermal noise spectrum of the cantilever as a function of the dipping depth of the fiber (see Fig. 22), we probe the dissipation and added mass due to the viscous layer around the fiber. A mechanical coupling between the fiber and the cantilever complicates these measurements, so we have developed a data analysis procedure that overcomes this difficulty [244]. We then show that the dissipation and the added mass depend on a unique parameter, namely the ratio of the probe radius R to the thickness of the viscous boundary layer δ. The resulting master-curve display two simple limit regimes at high and low R/δ ratios [247]. Thank to this work, the hanging-fiber AFM technique can now be used to perform quantitative micro-rheology measurements in fluids that can be opaque, for viscosities between 1 and 1000 mPa.s and frequencies between 5 and 500 kHz. This approach is complementary to direct immersion of the cantilever in a transparent liquid, for which thermal noise analysis also lead to quantitative microrheology measurements [195], with application to biological sensing (protein unfolding) [213].

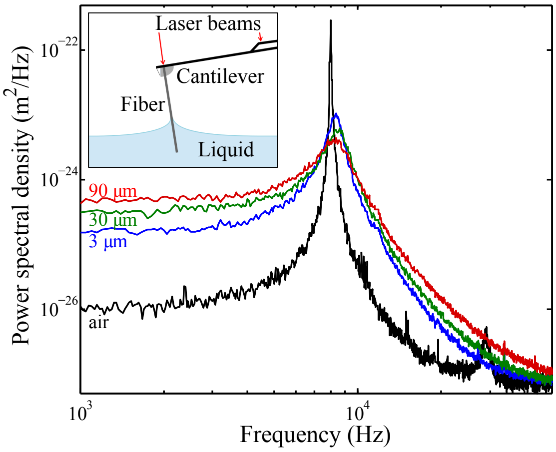

Figure 22: Thermal deflection spectrum of a hanging-fiber AFM probe in air and at several dipping depths in hexadecane. Inset: sketch of the setup.

We also use the hanging-fiber AFM setup to measure the capillary force as a function of the dipping angle i of the cylinder, to investigate experimentally for the first time this common situation where the liquid meniscus is asymmetric. The results are compatible with a vertical capillary force varying as $1/\cos i$, in agreement with a recent theoretical prediction [207].

We are currently investigating the coupling between the fiber and the capillary waves on the liquid surface, depending on the meniscus shape and the oscillation amplitude of the fiber. To do so, we have heavily modified the setup in order to use the interferometer to map the height of the capillary waves around the fiber. We have also replaced the AFM cantilever by a self-sensing quartz tuning fork.

In the same spirit, we functionalize AFM tips with a carbon nanotube (CNT) or a CNT loop, and bring it in contact with a solid surface. The high resolution force versus distance curves demonstrate a peeling geometry for the contact, and directly lead to the energy of adhesion of the CNT with the substrate. Our measurements are useful to evaluate quantitatively the Van der Waals interaction between CNTs and several materials [210], but also to picture the dynamics of the nano-mechanical contact. A power law frequency dependence of the stiffness indicates viscoelastic dissipation processes of this contact [276].

Indicators Soft Matter

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
N. Bain	Hydrodynamics of polarized human crowds: experiments and theory	16/11/2018	D. Bartolo
A. Bricard	Dynamique collective de colloïdes autopropulsés	24/02/2014	D. Bartolo
J.-B. Caussin	Collective dynamics of self-propelled particles: waves, vortex, swarm, braiding	25/06/2015	D. Bartolo
M.J. Dalbe	Instabilité de Stick-Slip lors du pelage d'un adhésif	06/11/2014	S. Santucci
N. Desreumaux	Emulsions microfluidiques et rouleurs colloïdaux : effets collectifs en matière molle forcée loin de l'équilibre	08/04/2015	D. Bartolo
J. Ferrand	Ecoulements et écrasements de fluides: effet du mouillage et de la rhéologie	15/09/2017	E. Freyssingeas, S. Joubaud
V. De Zotti	Instabilité de pelage d'un ruban adhésif: effet de l'inertie sur la dynamique multi-échelle du front de détachement	29/06/2018	S. Santucci
R. Jeanneret	Auto-organisation, echo et traffic microfluidique	24/02/2014	D. Bartolo
B. Levaché	Dynamique d'imbibition en milieux confinés	03/03/2014	D. Bartolo
P. Lidon	Effet d'ultrasons de puissance sur les matériaux mous	08/07/2016	S. Manneville, N. Taberlet
C. Odier	Imbibition forcée en milieu poreux	09/10/2017	D. Bartolo
A. Morin	Colloidal flocks in challenging environments	18/09/2018	D. Bartolo
C. Perge	Imagerie ultrasonore dans les matériaux mous	03/07/2013	S. Manneville, N. Taberlet
R. Poryles	Instabilités et piégeage de bulles dans des fluides complexes	18/07/2017	V. Vidal
G. Poy	Sur la pertinence du modèle thermomécanique dans la rotation Lehmann des gouttes cholestériques et nématiques	06/12/2017	P. Oswald

Main contracts

2 European: ERC USoft, OutEFluCOP (10%)
12 ANR: HiResAFM, NanoFluiDyn, Liqui2D, Stick-Slip, AdhesiP, T-ERC Pho-Fo, Harb, JCJC StruBaDy, FluidiDense, MiTra, VISIONs, WTF
1 LABEX IMUST: GLIFSO
1 IDEX Lyon: NoGelPo
3 Region : Acrheo, Optolyse, DyLoFiPo
Companies: Solvay, Total SA

Organized conferences

D. Bartolo.
Out of Equilibrium and Active Soft Matter, Roscoff (France), June 2016
Flowing soft matter: Bridging the gap between statistical physics and fluid mechanics, Udine (It.), June 2014
R. Everaers.
Computational Physics: Multiscale modeling of materials, 5th Les Houches School (France), May 2015
Computational Astrophysics, 6th Les Houches School (France), May 2016
J.-C. Géminard.
Matière, Structure et Dynamique, Lyon (France), July 2017
T. Gibaud.
Colloque sur les systèmes anisotropes auto-organisés, Lyon (France), September 2017
S. Manneville.
Session "Rhéologie", Congrès Français de Mécanique, Lille (France), August 2017
Workshop CECAM "Gels 2017", Lyon (Fr), June 2017
Session "Rencontre Mécanique-Physique", Congrès Français de Mécanique, Lyon (France), August 2015
Session "Advanced Techniques", Annual European Rheology Conference, Nantes (France), April 2015
S. Santucci.
From Stone Age to Modern Physics: a story of crack patterns, Lyon (France), April 2014
Mini-symposium at the 21st European Conference on Fracture, Catania (Italy), June 2016
LIA-D-FFRACT meeting, Kick-off & Goals, Oslo (Norway), November 2017
LIA-D-FFRACT meeting, 2nd Edition, Courmayeur (Italy), March 2018
V. Vidal.
RNL 2018: Non Linéarité et tremblements de terre, Paris (France), March 2018
CMG 2016: Geophysics, from Mathematics to Experiments, Paris (France), June 2016
Rheovolc 2015, Hakodate (Japon), June 2015
Rheovolc 2014, Chamonix (France), December 2014

Editorial responsibilities

J.-C. Géminard.
Papers in Physics, Editor.
T. Gibaud.
Scientific Reports, Member of the Editorial Board.
D. Bartolo.
SciPost, Editorial Board Fellow.

149 publications in peer reviewed journals: see T2B.

T3R. Physics of Biological Systems: *Report*

Permanent Members: B. Audit, V. Bergeron, P. Borgnat, M. Castelnovo, R. Everaers, E. Freyssingeas, F. Montel, C. Faivre-Moskalenko, J.F. Palierne, M. Peyrard, C. Place, A. Pumir, C. Vaillant

Post-docs: J.-M. Arbona, P. Carrivain, R. Schram, J. Rodriguez Ramos

PhD students: Z. Mokhtari, J. Bernaud, Y. Carrasco-Salas, N. Haddad, L. Menou, B. Molcrette, T. Verdier

Since the early 90s and the pionneering works of M. Peyrard on theoretical modeling of biomolecules such as DNA, research on the "Physics of Biological Systems" has become an active and consolidated transversal theme of the laboratory. We concentrate our research effort in deciphering the physical principles and mechanisms by which living systems, such as cells of unicellular and multicellular organisms as well as viruses, properly adapt in response to external cues like changing environments (chemical, mechanical, thermal or nutrient availability stresses) and/or developmental signals. Our interests span a broad range of length and time scales: from single molecules to cell nuclei, and from single cells to organisms; from DNA transcription and replication processes to cellular internal reorganisation and cell motility, from developmental epigenetic gene regulation to evolutionary genome adaptation. The projects often combine experimental work, the analysis of massive amounts of experimental data, and physical modeling using both analytical and numerical techniques. An increasing number of projects is carried out in collaboration with (mostly experimental) colleagues from biology laboratories at ENS de Lyon and elsewhere.

A. *From molecular assemblies to viruses*

DNA-RNA interactions (R-loops). (V. Vanoosthuyse, LBMC) 5% of chromosomes are formed by "R-Loops", a DNA/RNA hybrid resulting from transcription, some of which are toxic. Using AFM, we visualize R-Loops objects produced by in vitro transcription (Fig. 23). Our results suggest that R-Loops adopt a particular conformation that introduces architectural stress into the DNA. Combining quantitative single molecule AFM imaging and biochemical experiments on different genes, we have that R-loops differ by their architectures and that the organization of the non-template strand is a fundamental characteristic of R-loops, which could explain that only a subset of R-loops is associated with replication-dependent DNA breaks.

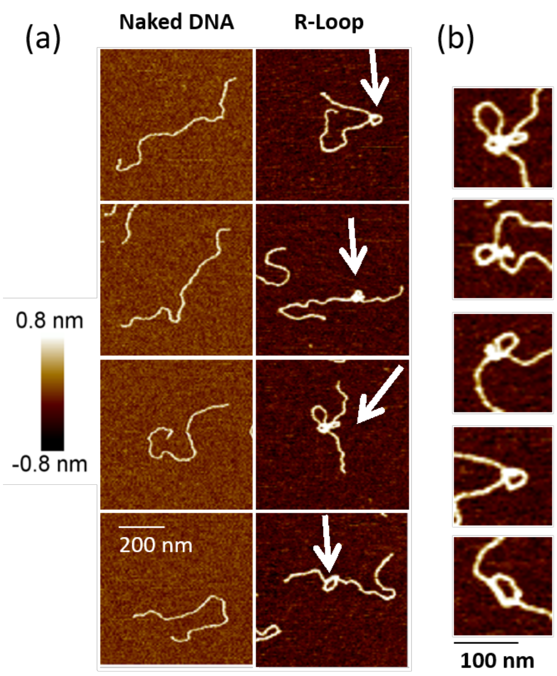

Figure 23: R-loops formed in the AIRN gene after in vitro transcription and visualized by AFM microscopy. (a) The left column represents the naked DNA before transcription. The DNA of the right column has been transcribed and accumulates complex structures indicated by arrows. (b) magnification of observed R-Loops structures.

Viral self-assembly. (S. Manley, Lausanne D. Muriaux, Montpellier) We studied experimentally and theoretically the self-assembly of virus-like particles of HIV-1. We showed that the presence of viral nucleic acid allows to regulate the size distribution of these particles, unlike foreign nucleic acids, and we explained these observations using an entropic mechanism [370]. We further developed statistical methods to extract particle shapes from raw datas obtained by super-resolution microscopes, which permits localization of individual proteins with roughly 25 nm accuracy. In this case, the need for statistical methods was imposed by strongly overlapping uncertainties for localization within the viral particle [391]. Modeling self-assembly scenario of HIV-1 with a continuous flux of monomers, we predicted that viral particle production should occur as burst waves, in qualitative agreement with the observations of almost synchronized budding sites within individual cells [354]. Furthermore, focusing on the shape of individual viral particles, it is observed that most viruses are either regular and icosahedral, or irregular and elongated. Based on a thin shell elasticity model of viral self-assembly, we identified the physical parameter at the single protein level responsible for this observation, the spontaneous curvature of the protein. Indeed, for small values of this parameter, regular structures have lower mechanical energies and are therefore observed, while irregular structures are favored for large values [347].

Virus disassembly and thermal stability. (A. Salvetti, CRCL) During viral replication, genome uncoating from viruses is different for each viral families, but in many cases, the physical mechanisms are unclear. This is the case for AAV viruses, which nevertheless are largely used as promising gene therapy vectors. We investigated the stability of AAV with respect to temperature increase. By combining AFM imaging and theoretical modeling, we identified at least two disassembly pathways at the single viral particle level: either the genome is ejected from an almost intact capsid, or the genome is released from completely ruptured capsids. We observed modulations of this pathway for different subtypes of AAV, and quantification of the pathway permits to evaluate protein-protein binding energies, in agreement with literature [361].

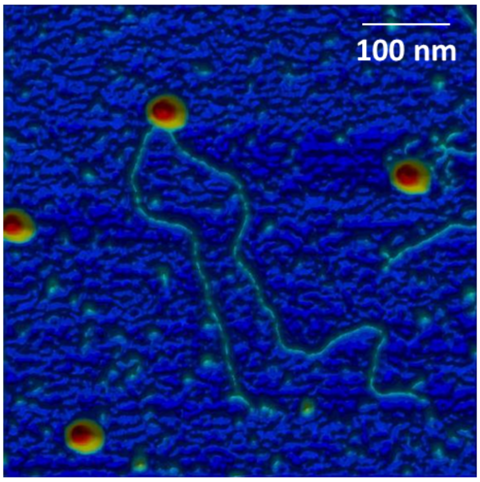

Figure 24: AFM image of AAV8 capsids incubated for 15minutes at $T = 60°C$, with partially ejected single-stranded DNA genomes. Using such high resolution images, the length of ejected DNA can be measured over viral capsid population as a function of temperature or micro-environment conditions.

Neutron scattering studies of oriented DNA (ANSTO) The original experiments of Rosalind Franklin on the structure of DNA were performed on fibers containing oriented molecules. We have kept the spirit of theses studies but extended them using modern methods to investigate the thermal denaturation of the double helix. We used DNA films made of parallel fibers. The "dry" fibers used in our original experiments contained crystalline domains where the DNA helices are very close to each other, which might alter the denaturation curve. In new experiments we immerse the fibers in a solution so that they swell, to increase the intermolecular distance. The process is controlled by osmotic pressure to prevent a full dissolution of the fibers. A pilot study was made in ANSTO (Sydney, Australia) and a more systematic investigation in ILL (Grenoble) refined the results [374, 393]. The data were quantitatively analyzed using the Peyrard− Bishop−Dauxois model. The experiments and analysis showed that long segments of double-stranded DNA persist until the last stages of melting and that there appears to be a substantial increase of the DNA dynamics as the melting temperature of the DNA is approached.

Flexibility and conformation of DNA is solution (ANSTO, ILL, Universität Erlangen) To probe our theoretical results on the role of fluctuational openings on the flexibility of DNA we carried a series of small-angle-scattering experiments using X-rays and neutrons in ANSTO, Universität Erlangen (Germany) and ILL. The SAXS experiments in ANSTO gave an interesting and unexpected "by-product". We showed that the intensity of the signal, in the limit of zero scattering angle, can be used to monitor the fraction of fully denatured DNA molecules. In DNA the fraction of denatured base-pairs can easily be monitored by measuring UV absorption, but this does not tell us whether the open pairs belong to partly open molecules or if the two DNA strands are fully separated. Our method answers this question [394]. Besides studying DNA flexibility, the SAXS and SANS experiments allowed us to answer an old question about DNA structure [352]. In 1953, J.D. Watson and F.H.C. Crick built a three-dimensional model of the famous double helix of DNA, which earned them the Nobel Prize. But this discovery did not end the story of DNA structure. In 1975, F.H.C. Crick and A. Klug proposed a second model, suggesting kinks in DNA. In our study, combining small-angle X-Ray and neutron scattering with a statistical physics analysis of the data we showed that kinks can indeed exist in some DNA sequences in solution. This confirms the intuition of Crick and Klug and opens a new view point on DNA structure. The well known image of the rigid double helix has to be completed, and for instance viruses might take advantage of such kinks to pack DNA in their capsides.

B. *From chromatin to cell nucleus*

Nucleosome and genomics (J.-N. Volff, F. Brunet, IGFL; H. Schiessel, Leiden) The chromatin fiber constitutes the first step in the hierarchical folding of DNA in the nucleus of eukaryotic cells. Typically 80% of genomic DNA is bound inside nucleosome core particles, where 147 bp of DNA tightly wrap around an octamer of histone proteins. The sequence dependent histone-DNA interaction in the nucleosome is thus a fundamental mechanism of genomic compaction and regulation, which remains largely unknown despite increasing structural knowledge of the complex. We have proposed a framework for the extraction of a nanoscale histone-DNA force-field from a collection of high-resolution structures, which may be adapted to a larger class of protein-DNA complexes [380]. In particular, we have provided a statistical mechanical analysis of the physics behind the "nucleosome positioning code" [355, 389].

We have previously developed a physical model of nucleosome formation based on sequence-dependent bending properties of the DNA double-helix based on experimental data obtained in yeast. This model enlighten the predominance of "statistical" positioning scenario where nucleosome order around Nucleosome Inhibitory Energy Barriers (NIEBs) encoded via unfavorable sequences that potentially resist the structural distortions required by nucleosome formation. We used this model to predict the existence of about 1.6 millions NIEBs over the 22 human autosomes and to question nucleosomal positioning rules in human. NIEBs of meansize 153 bp correspond to nucleosome-depleted regions (NDRs) and are bordered by compacted nucleosome ordering both in vitro, as expected, but also in vivo suggesting an absence of chromatin remodeling. NIEBs and neighboring nucleosomes homogeneously cover 37.5% of the human genome. We showed that ubiquitous "Master" replication Origins (MaOris) in contrast to cell-type-specific MaOris are highly enriched in NIEBs, suggesting the former are defined by the DNA sequence while the latter are epigenetically regulated. Nucleosomal ordering at NIEBs' borders strongly correlates with oscillations in sequence composition as well as in interspecies and intraspecies mutation rates along these regions, revealing the existence of selections linked to nucleosome positioning at these loci. Supporting this hypothesis, we observed that NIEBs with compacted neighboring nucleosomes are indeed ubiquitous to all vertebrates tested. We finally reported a strong association between NIEB borders and the poly(A) tails of Alu sequences in human. These results suggest that NIEBs provide adequate chromatin patterns favorable to the integration of Alu retrotransposons and, possibly to various transposable elements in the genomes of primates and other vertebrates. NIEB-encoded nucleosome positioning thus appear as a major driving force of vertebrate genome evolution.

Genome folding and replication (O. Hyrien, IBENS; G. Cavalli, Montpellier; A. Rosa, Trieste)

Genomes of eukaryotes are partitioned into domains of functionally distinct chromatin states that are either permissive (active states) or repressive (inactive states) to transcription. These domains are stably inherited across many cell generations and can be remodeled in response to developmental and external cues, hence contributing to the robustness and plasticity of expression patterns and cell phenotypes. Remarkably, recent studies indicate that these 1D chromatin domains tend to fold into 3D interactions domains forming specialized nuclear chromatin compartments. In collaboration with biologists, we have addressed the question of the coupling between genome folding and chromatin states. We have developped block co-polymer models with effective specific interactions between monomers that depend on their local chromatin states (e.g. active vs inactive). Using various numerical approaches, (Self-Consistent Gaussian Field Approximation, kinetic Monte-Carlo on lattice, Molecular Dynamics (Fig. 25)) we showed

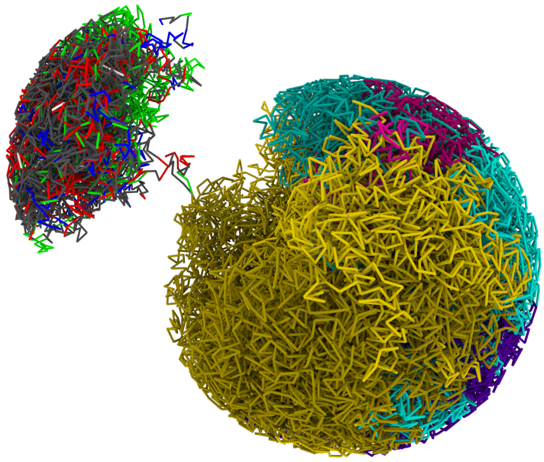

Figure 25: Spatial conformation of chromosomes inside cell nucleus: Snapshot of a Molecular Dynamics simulation (P. Carrivain). To illustrate the weak intermingling between chromosomes (forming the so-called "chromosome territories") we artificially extracted one chromosome; for that chromosome, colors correspond to local chromatin states (red: active; black, green, blue: inactive)

that the folding properties of chromosomes as observed by Hi-C and microscopy experiments in fly cells during embryogenesis, is consistent with a - weak - microphase separation of the different chromatin domains [350, 375, 377]. Consistently with earlier theoretical works, we confirm that large-scales generic conformation are dominated by memory of initial post-mitotic organisation of chromosomes due to the very slow "crumpling" dynamical regime. To address the role of 3D organisation on gene regulation, we developped a theoretical framework, the "Living chromatin" model [351] that explicitly couples the local dynamics of chromatin states with the global 3D folding dynamics of the chain; we show that enhancing chain condensation drives the system through a phase transition, with the emergence of stable 1D chromatin domains. This result enlightens the crucial role of spatial colocalisation (via chain condensation) in maintaining a robust genes co-expression/repression pattern.

We initiated a research program to model the emergence of the spatio-temporal DNA replication program from the nuclear structural organisation. Our first results [344, 372] showed that the "universal" time dependence of DNA replication kinetics experimentally observed in eukaryotes can be accurately recovered (i) in a non-local model of DNA replication by picturing replication initiation as a two-state system considering all possible transition configurations and taking into account the chromatin's fractal dimension, and (ii) in a molecular description taking into consideration the recycling of diffusing replication factors and replication origins localization. These studies show that, to a large extent, the dynamics of eukaryotic DNA replication is a collective phenomenon that emerges from the stochastic nature of replication origins initiation.

Dynamics of a cell nucleus and dynamic light scattering experiments. The knowledge of the internal dynamics of a living cell nucleus appears essential for the comprehension of the functioning of eukaryotic cells. To investigate this dynamics, we have developed a specific Dynamic Light Scattering experimental set-up as well as new ways of analysing the temporal variations of the scattered light intensity in order to extract the internal dynamics of the nucleus. Thanks to that combination we are able to probe the nucleus dynamics over 7 order in magnitude in time, from 10^{-5} to 10^{2} s. The very short time dynamics ($\sim 10^{-5} - 10^{-4}$ s) the dynamics very likely correspond to Brownian diffusion of small objects within the nuclear environment; such as proteins, nucleotides, the long time regime ($\sim 0.1 - 10^{2}$ s), very likely correspond to Brownian diffusion of protein clusters, nuclear bodies and chromatin fibres, while the time range extending from about a few 10^{-4} s to 0.5 s seems to depend on the enzymatic activity of the nucleus.

Plasticity of the Nuclear pore (O. Faklaris, CRBM; M. Penrad-Mobayed, IJM) Biological nanopores are involved in many essential functions of the cell ranging from protein expression (translocons) to environmental sensing (ion channels). A prominent example of this important role is the nuclear pore complex. This large macromolecular complex is involved in the regulation of all the molecular exchanges between cell nucleus and the cytoplasm. It shows an exceptional chemical selectivity and an ability to transport species directionally, which are not explained until now. We have used nuclear envelopes extracted from Xenopus to analyse its plasticity. First using super-resolution microscopy we have shown that during the oocyte development the nuclear pores self-organize on a square lattice to 2D nanocrystals and change their internal diameter to adapt to the transcriptional state of the cell [353]. We have also demonstrate that the presence of proteins involved in the nuclear cytoplasmic transport as importin may impact the internal diameter of the pores.

An artificial mimic of the a nuclear pore (P. Guegan, IPCM, J.C. Lacroix, ITODYS) Filtration is a key process in the chemical, food, water treatment and biotechnology industries. It is crucial in emerging environmentally friendly technologies, which require the efficient and rapid sorting and recycling of materials and molecules used. In this work, we designed intelligent, selective and efficient filters that have recognition properties and are able to adapt their permeability to passing molecules, as biological tissues and organisms naturally do. Our approach is biomimetic and inspired by the functioning of the nuclear pore. Its exceptional selectivity makes it a candidate of choice for improving the functioning of filtration processes. We develloped near field optical technique to measure the transport of single molecules through modified nanoporous arrays [358]. We showed that the grafting of hydrophobic polymers forming a dynamic gel inside artificial pores made it possible to increase the selectivity of nanoporous membranes and to sort molecules according to their charge and hydrophobic character. In addition, by using the coil-globule transition of these polymers we have shown that it is possible to open or close these functionalized pores at will with a temperature change of less than 1°C.

C. From cells to tissue

Advanced microscopy for cell biology (P. Bouvet, CRCL) To demonstrate the effect of nucleolin on the growth dynamics of microtubules, we have developed an experiment to observe the growth of microtubules in vivo by TIRF microscopy. TIRF microscopy makes it possible to obtain a very good image quality by freeing oneself from the background noise of volume. We have thus been able to show that nucleolin participates to the dynamics of microtubules by allowing slower but more stable growth of microtubules [348]. Probes adapted to far red for Stochastic Optical Reconstruction Microscopy (STORM) super-resolution fluorescence microscopy were made and imaged on lipoparticles (latex beads covered with a lipid bilayer) [356, 379]. The dSTORM microscopy makes it possible to overcome the diffraction limit in optical microscopy. Fluorophores are activated stochastically and the center of the diffraction spot is determined with a precision of the order of ten nanometers.

Actin Microrheology The cytoskeleton of eukaryotic cells is a network of semi-flexible actin filaments. Using high-bandwidth microrheology [345] we study the scale-dependent mobility of micron-sized probe particles, revealing two opposing noncontinuum elastic effects: entropic depletion reduces the effective network rigidity, while local nonaffine deformations of the network substantially enhance the rigidity at low frequencies, eventually leading to a size-independent response and strong violation of the generalized Stokes formula. We show that a simple model of lateral bending of filaments embedded in a viscoelastic background leads to an intermediate scaling regime for the apparent elastic modulus $G' \sim \omega^{9/16}$, closely matching the experiments. These results demonstrate that non-affine bending deformations can be dominant for the mobility of objects of the size of vesicles and organelles in the cell.

Biomechanics of Soft Tissues, Soft organs (liver, rate, pancreas, brain, skin) exhibit power-law temporal response to deformation, with a non-linear strain-hardening regime that kicks in at low to moderate deformation. This regime is ascribed to the presence of inextensible fibers, in contrast with the strain-softening non-linearity most commonly associated to coiled macromolecules. Such a regime has indeed been found in skin at low deformation, just before a strain-hardening regime [384]; this may be understood in terms of competing effects of collagen and elastin fibers.

Waves in biological systems Waves play an important role in a wealth of biological processes. Particular emphasis has been put on the synchronization of waves in the uterus before delivery [395], or in chemotactic cells, before and after stimulation by a chemoattractant pulse [349, 383].

Bacterial Motility (L. Lemelle, LGL; P. Hubert, CEA Grenoble, FINOVI) Pathogenic bacteria remain a major public health concern. In particular, the first contact between the motile bacterium and the surface of a cell has been little studied in mechanistic terms. Thus we have characterized the behavior of motile bacteria during their interaction with human cells [373]. We were able to show alterations of the swimming due to the cellular presence. We are also currently working with CNES on microgravity experiments in the international space station to study surface contamination under microgravity.

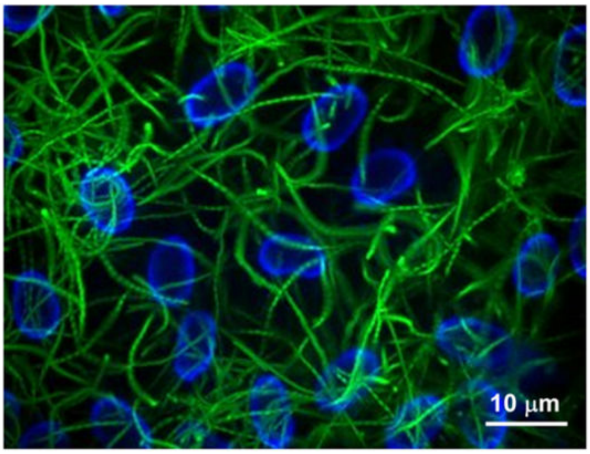

Figure 26: Image of fluorescence microscopy showing traces of the trajectories of the bacteria (green) above the human cells (nuclei in blue).

D. *Advanced Neuro-rehabilitation Therapies*

Transversal research in Advanced Neuro-rehabilitation Therapies is a collaborative effort between the CNRS and be Hospice Civil de Lyon, HCL. The primary objective is to transfer cutting-edge technologies to help people overcome their paralysis. The scientific approach we use is experimental and relies on evidence-based clinical outcomes. We identify new and promising technologies and align their use directly with patient needs. Owing to the fact that the principle investigator of this project became tetraplegic after a bicycle accident in 2013, there exists a seamless connection between the fundamental scientific research carried out and its ultimate utilization for paralyzed end-users.

One of the primary tools we use in this work is electrical stimulation. In particular, non-invasive transcutaneous electrical stimulation, such as transcranial direct-current stimulation, tDCS, and functional electrical stimulation, FES. tDCS over the motor cortex can generate so-called efferent signals that reach out from the spinal cord to the paralyzed muscle groups, while FES uses weak electrical fields to trigger action potentials that provoke muscle contractions and afferent signals back to the spinal cord. Coupling these involuntary procedures with voluntary motor imagery to reinforce these signals and their pathways is at the core of our scientific approach. This work can have both curative and preventative medical outcomes. Curative outcomes can result from the plasticity of the CNS (particularly the brain in the case of stoke victims) while preventative measures arise from exercising the paralyzed limbs, which promotes cardiovascular health and blood flow, thereby reducing the risk of pressure sores and increasing the strength of the bones.

These treatments are essentially "exercising" the CNS, and like any exercise needs to be done repetitively and systematic. Therefore ease-of-use, user-friendliness, cost and the enjoyment of the treatment must be considered at every stage of development. For these reasons we are incorporating our stimulation tools into E-textiles and smart clothing.

To ensure that our therapies are lucid and enjoyable, we develop and install new functional electrical stimulation equipment for cycling, rowing and walking. In addition, virtual and augmented reality tools are used to help facilitate and motivate individuals to reach their peak abilities and remain motivated to do so. This activity is in partnership with the non-profit association ANTS who have a 120 m^2 handicap sports training facility on the ENS de Lyon campus. With this facility we work closely with disabled individuals to best understand their sensation of both physical and psychological fatigue during different physical tasks. Theses sensations are compared with quantitative measurements of ElectroEncephaloGraph (EEG) recordings that monitor the motor cortex. The fatigue measures are correlated with our physiological muscle fatigue studies to obtain a global understanding of how to best optimize rehabilitation therapies. Our research also addresses the ethical challenges we are faced with concerning the integration of humans and machines. The notion of an augmented human via technological tools, such as FES, and how these tools are both individually and socially excepted are addressed from both a psychoanalytical and sociological point-of-view. Data is collected through individual interviews with both disabled and able-bodied individuals. Moreover, therapies are developed that promote social interaction together with physical activity.

In addition to our local collaborations with the labex CORTEX, this research activity has also fostered scientific neuro-rehabilitation collaborations between ENSL and the Swiss laboratories ETH and Ecole polytechnique fédérale de Lausanne, (EFPL) in Lausanne, Switzerland. International joint projects for the development of new electrostimulation equipment and protocols are also underway with the University of Belgrade and the University of Glasgow.

Physics of Biological Systems: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
N. Haddad	Analyse et modélisation du repliement spatial de l'épigénome	17 November 2016	C. Vaillant, D. Jost
T. Verdier	Self-assembly of enveloped virus : theoretical dynamics and method for fluorescence measurements analysis	13 November 2015	M. Castelnovo
J. Bernaud	Propriétés physiques de capsides virales étudiées à l'échelle du virus unique par microscopie à force atomique : exemples du rétrovirus VIH-1 et du parvovirus AAV	25 October 2015	M. Castelnovo, C. Faivre-Moskalenko
J.D. Julien	Physical basis of morphogenesis: coupling between mechanics and growth of plants and yeasts	18 Décember 2015	A. Boudaoud, A. Pumir
Z. Mokhtari	Étude de la dynamique interne du noyau d'une cellule vivante, par des expériences de diffusion dynamique de la lumière	21 May 2015	E. Freyssingeas

Main contracts

3 ANR
2 FRM, 1 AFM Telethon, 2 INCa, 1 FINOVI, 1 INSERM
1 CNES

Editorial responsibilities

Peyrard Michel:
Journal of Biological Physics, Member of the editorial board.

Organized conferences

Audit Benjamin:
International Conference on Systems Biology (ICSB 2018), Lyon (France), Octobre 2018
Lyon SysBio, Lyon (France), Novembre 2014, Novembre 2015, Novembre 2016, Novembre 2017
Everaers Ralf:
Multiscale Modeling and Experimental Approaches to Genome Organization, Les Houches, April 2017
Gibaud Thomas, Montel Fabien:
CFCL 2017, Lyon (France), Septembre 2017
Montel Fabien:
Congrès C'Nano, Lyon (France), Décembre 2017 2016
Nanofluidics in Physics and Biology, Lyon (France), Juillet 2018
Moskalenko Cendrine:
Workshop MechanoBiology and Physics of Life 1th, 4th edition, Lyon (France), Janvier 2016, 2019
Vaillant Cédric, Everaers Ralf:
Integrating genomics with hierarchical physical models of DNA and chromosomes Lyon (France), Juin 2015

53 publications in peer reviewed journals: see T3B.

T4R. Mathematical Physics and Fundamental Interactions: *Report*

Permanent Members: J. Bouttier, F. Delduc, K. Gawedzki, M. Geiller, K. Kozlowski, E. Livine, M. Magro, J.M. Maillet, G. Niccoli, H. Samtleben

Post-docs: T. Kameyama, N. Merino

PhD students: A. Baguet, C. Charles, Q. Chen, C. Eloy, A. Feller, C. Goeller, S. Goomanee, Y. Herfray, S. Lacroix, T. Ortiz, Q. Pan, B. Pezelier, C. Tauber, L. Vignoli

Directions of research in the mathematical physics theme include classical and quantum integrable models, conformal field theories and their applications, supergravity and superstring, and quantum gravity. The field of Integrable models has been and remains one of the important subjects of research in the theme. It has been reinforced during the last period by the arrival of one CNRS researcher (transfer from IMB-Dijon) and one CEA researcher (from IPhT-Saclay through a 5 years temporary availability agreement). During these last years, emphasis has been put on the use and generalization of the method of Separation of Variables for the characterization of the spectrum and computation of correlation functions of quantum integrable lattice models. Deep studies of dynamical and thermal correlation functions have also been performed together with rigorous analysis of Bethe ansatz solutions for the Heisenberg XXZ chain. New results have been obtained in the framework of classical integrable sigma models, concerning in particular an integrable coupling of two such models. Finally, application of techniques used in integrable models to stochastic processes is a new field of research in our theme, which allows for a fruitful interaction with mathematicians. In another direction, out of equilibrium phenomena and topological phases in condensed matter have been studied using field theory techniques. The field of extended supergravity also has given rise to many new important results stemming from collaborations with researchers all around the world. As an example, the construction of the exceptional supergravity theory based on the infinite dimensional algebra E_9 involves researchers from five different institutes. The scope of the studies in Quantum Gravity has been considerably widened and strengthened by the recruitment of a new young CNRS researcher (this was one of the five priorities of the Laboratory for the present contract). In particular, among many other results, it has been shown how such important aspects of high energy physics as renormalization and holography may show up in this framework. The research activity in the mathematical physics theme has led to more than 100 publications, given in the main bibliography, while we have cited, as required, 20% of them only (namely the ones we consider to be the most representative) in the present report.

A. *Integrable Models.*

Integrable models are studied in the theme from many different viewpoints, ranging from computation of quantum correlation functions to properties of classical integrable field theories and applications to stochastic processes. These models 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.

Classical integrable σ-models

Integrable non-linear σ-models play a fundamental role in physics. We have maintained the originality of our approach which consists in focusing on the algebraic structure sustaining integrability at the classical hamiltonian level.

The program initiated in [404] has been extended. Several steps led us to build a three-parameter integrable deformation of so-called $\mathbb{Z}_4$ permutation supercosets. These include supercosets which are relevant for string theory and the AdS/CFT correspondence, namely $AdS_3 \times S^3$ and $AdS_3 \times S^3 \times S^3$.

One way to characterize an integrable field theory is the existence of an infinite dimensional algebra of hidden symmetries. This algebra has been determined in the case of the classical Yang-Baxter σ-model. More precisely, we have proved that this infinite-dimensional algebra is the classical analogue of a quantum loop algebra.

We have also developed a novel procedure which enables to construct new classical integrable field theories with arbitrarily many free parameters. It is based on the recent interpretation of integrable σ-models as realizations of affine Gaudin models. The method consists in assembling two affine Gaudin models into a single one. The resulting affine Gaudin model depends on a parameter γ in such a way that the limit $\gamma \to 0$ corresponds to the decoupling limit. This also shows that one can associate integrable field theories with affine Gaudin models having arbitrarily many sites. This is a completely unforeseen possibility which is expected to have a very high impact by widely broadening the landscape of known integrable

σ-models. Furthermore, this framework sheds new light on the nature of integrability in σ-models at the level of the action. A first application of this method to integrable σ-models leads to the action announced in [403] and which couples an arbitrary number of principal chiral model fields on the same Lie group, each with a Wess-Zumino term.

Quantum Separation of Variables

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 of quantum integrable models, e.g. the famous Bethe Ansatz and Algebraic Bethe Ansatz (ABA), the Baxter's Q-operator approach and the quantum separation of variables (SoV) which generalizes to quantum models with many degrees of freedom the paradigmatic Hamilton-Jacobi method of classical mechanics. Initiated by Sklyanin in the 80's, the main advantage of this method is that it is not an ansatz. As such, it leads to the complete characterization of the spectrum of the integrable models that can be considered within this framework.

However, large classes of important integrable models were left unsolved until quite recently, 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 open problem that we have solved by extending the Sklyanin's quantum separation of variables (SoV), see e.g. [405], to these cases and proving its equivalent characterization by solutions of finite difference functional (quantum spectral curve) equations of the famous Baxter's T-Q equations type [412]. Our recent results prove that the Sklyanin's SoV method can be adapted and implemented for a wide class of integrable quantum models out of the reach of pre-existing methods, e.g. the sine-Gordon and chiral-Potts models with general integrable boundary conditions. Beyond the complete spectrum characterization, the results on scalar products and form factors pioneered in [413] have settled the basis to compute correlation functions in the SoV framework with techniques that we first developed in the ABA framework about 20 years ago. We have moreover set up [400] the first steps of a method that would allow to access to the leading large-N behavior of the class of N-fold multiple integrals whose specific instances yield the form factors of local operators computed in the SoV framework.

Despite these successes, 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 particular the resolution of integrable models based on higher rank algebras has been a longstanding open question within the Sklyanin's SoV method or its extensions. In a series of papers starting with [417] we have addressed this problem by providing a new SoV scheme based on the sole knowledge of a complete set of conserved charges and the structure constants of their commutative algebra. In particular, the SoV basis for the transfer matrices of the considered models is generated by the repeated action of the transfer matrix itself on a generic state of the Hilbert space. Therefore, some new fundamental understanding of quantum integrability has been achieved, establishing a new method based only on the use of the integrable quantum structure, i.e., the complete set of symmetries of the models, to get their resolution (spectrum and dynamics). This new SoV approach has the potential to be universal, putting on the same footing the integrability and the effective solvability of quantum models. It has been used already to solve the spectral problem of higher rank integrable quantum spin chains with general integrable boundaries, overcoming longstanding open problems of the original Sklyanin's SoV approach. Many important questions, regarding in particular the dynamics of the models solved with this new SoV approach are now under study.

Correlation functions: static and dynamical

The long-distance asymptotic behavior of zero temperature static correlation functions in the massless regime XXZ spin-1/2 chain is expected to exhibit various universal features which have been argued to be grasped by free boson field theory. By building on form factor expansions, we have continued the development of an approach based on first principles that allows us to extract the long-distance behavior of static multi-point correlation functions of the XXZ chain. These results also allowed us to establish [415] a rigorous connection between the operator content of a sub-sector of the XXZ chain and the one of the free boson field theory. This work clearly identifies the microscopic mechanisms at the root of the appearance of a universal behavior in the model. We have also adapted the form factor approach to the exact computation of dynamical correlation functions in the XXZ chain. Namely, we provided an exact and explicit computation of the thermodynamic limit of the form factor expansion of dynamical correlation functions in the massless regime of the zero temperature XXZ spin-1/2 chain. This is the first kind of such results for an interacting massless model with bound states. Finally, we also managed to obtain an explicit description of the dynamical correlation functions of the XXZ spin-1/2 chain at finite temperature [409], which was based on the concept of thermal form factor expansions.

Thermodynamic limit of the XXZ chain

The characterization of the thermodynamic limit of observables in the XXZ spin 1/2 chain relies on the so-called condensation property of Bethe roots, which was conjectured by Húlten in 1938. So far, the conjecture could only be proven in certain regimes of the anisotropy where the analysis simplifies drastically in that one can build then on tools issuing from convex analysis or perturbation techniques. We rigorously proved this conjecture for any values of the anisotropy [414], hence solving a long standing problem. Our proof is quite general, in particular independent on the sign of the couplings, and appears to be applicable to a large class of quantum integrable models.

Schur processes and integrable probability

A very active field at the interface between theoretical physics and mathematics is *integrable probability*: in a nutshell, it consists in applying techniques originating from the study of quantum integrable systems to stochastic processes, typically describing problems of out-of-equilibrium statistical physics.

A central model in this topic is the *Schur process*, whose specific instances have applications to the study of domino and lozenge tilings, last-passage percolation, the totally asymmetric exclusion process, and generally speaking problems in the so-called Kardar-Parisi-Zhang universality class. An interesting feature of the Schur process is that it is actually a free fermionic model in disguise: this allows to obtain exact expressions for its correlation functions, in a form useful for asymptotics. We however emphasize that this does not make it at all trivial, for instance it has only been recently understood how the periodic version of the process corresponds to a finite-temperature ensemble of fermions [398]. Another recent advance deals with free boundaries, which map to certain "superconducting" fermionic states that appear not to have been considered before. Our motivation for studying these different types of boundary conditions is that they lead to new asymptotic behaviors: for instance, the distributions governing extreme value (or edge) statistics are nontrivial deformations of the Tracy-Widom distributions of random matrix theory. Also, there is an intriguing connection with solutions of the Kardar-Parisi-Zhang equation at finite time, on which our approach should give new insight.

B. *Conformal field theories and applications*

Techniques of mathematical physics are applied to study properties of condensed matter systems and characterize topological phases.

Nonequilibrium CFT

The energy transfer through a junction of quantum wires with Luttinger liquids at different temperatures and chemical potentials was described in [407]. The junctions were modeled by conformal defects in the tensor-product of CFT's describing the wires. The case of a wire described by CFT smoothly interpolating between different equilibria was exactly solved exhibiting universal balistic heat and charge waves with non-trivial profiles.

Geometry of Topological Phases

The geometry of bundle gerbes was used to construct topological indices of static and periodically driven time-reversal invariant crystals. This allowed to express the $\mathbb{Z}_2$ valued Kane-Mele-type indices of noninteracting systems by the topological Wess-Zumino and Chern-Simons action functionals [408].

C. *String theory and supergravity.*

String theory is a theory to describe nature at the smallest length scales, which replaces the concept of point-like elementary particles by extended strings. Its consistency requires the embedding into a ten-dimensional geometry which poses the immediate challenge as to how to consistently compactify the extra dimensions. Over recent years, generalized and exceptional geometry have emerged as underlying structures and powerful tools. The extended nature of the fundamental objects — strings and membranes — gives rise to a natural "stringy" generalization of Riemannian geometry which is based on the exceptional duality groups appearing in string/M-theory. This has led to remarkable progress in the study of string and gravity compactifications. In particular, exceptional geometry unifies the local symmetries of supergravity theories by combining geometric diffeomorphisms with matter gauge transformations into single so-called generalised Lie derivatives on an extended space-time. The resulting manifestly duality covariant theories — so-called exceptional field theories — combine IIA and IIB supergravity, depending on how the physical space is embedded into the exceptional space-time.

Exceptional geometry

In [411] and a series of subsequent papers, we have completed the construction of the exceptional field theories based on all finite-dimensional duality groups, including the largest exceptional duality group E_8 whose construction necessitates the proper inclusion of dual gravitational degrees of freedom. The full construction includes the fermionic degrees of freedom with an embedding in superspace which naturally merges with the extended space-time.

More recently, the construction of exceptional field theories has been pushed to the first infinite-dimensional duality group, the affine Kac-Moody algebra E_9 based on the loop algebra of E_8 [401]. With coordinates transforming in the unique level-1 highest-weight representation, we have constructed generalized diffeomorphisms and an invariant action functional that reproduces all known super-gravities.

Related work has been devoted to analyzing the underlying mathematical structures within the framework of higher gauge and L_∞ structures.

Consistent truncations

With the highly non-linear nature of gravity and super-gravity theories, it is a notoriously difficult problem as to whether the truncation to a finite subset of fields is a consistent one. Such truncations are at the heart of many holographic applications. In particular, they allow to uplift solutions of a lower-dimensional theory to solutions of 10-/11-dimensional supergravity. Exceptional field theories have proven to be a very powerful tool for the study of consistent truncations. Developing and using these techniques, in [397], we have established the final proof that IIB supergravity allows for a consistent truncation around the background $AdS_5 \times S^5$. Conjectured since 1985, when the lower-dimensional theory was constructed by Gunaydin, Romans and Warner, this truncation plays a central role in the AdS/CFT correspondence. Our explicit embedding formulae have further allowed to compute the uplift of holographic RG flows, relevant for the holographic description of non-conformal deformations of SYM theory.

Classification of supergravity solutions

Supersymmetric AdS vacua of 10-/11-dimensional supergravity play an important role in the AdS/CFT correspondence. Developing the necessary algebraic tools [406] gives an exhaustive scan of extended supersymmetric AdS vacua in maximal $D = 4$ supergravity. Subsequent work has revealed the higher-dimensional origin of these solutions. Techniques from exceptional field theory have been put to use more recently in order to construct and classify supersymmetric warped AdS_7 vacua of massive IIA and AdS_6 vacua of IIB supergravity.

D. *Quantum Gravity*

Another axis of development of the research activities of the theme is quantum gravity. This is a big challenge for theoretical physics since the wake of both quantum mechanics and general relativity a century ago. This challenge has now been renewed by the rise of quantum technologies and the recent direct observation of gravitational waves. The goal is to define a theory describing gravity at all scales of distance and energy, from sub-particle scales to astrophysical and cosmological scales. It should provide a unified framework for quantum field theory and general relativity, capable of describing the quantum fluctuations of the space-time itself. There are a few thriving approaches to this longstanding issue, among which string theory, loop quantum gravity, exact renormalization group and non-commutative geometry.

The team has historically focused on loop quantum gravity (LQG) and studied during this past few years the renormalization and coarse-graining of the theory. It has also widen its scope of research, studying holography in quantum gravity, seeking for new formulations of general relativity, working on cosmology and on massive gravity in an effort towards phenomenology and generally pursuing the consequences of our work in pure mathematics.

LQG Renormalization and coarse-graining

Since LQG describes the quantum space-time geometry at the Planck scale at $10^{-35}m$, the theory needs to be renormalized over tremendous scales to apply it to astrophysics or cosmology. Beside developing models for phase transitions in LQG, our main goal has been to define a consistent framework to coarse-grain the spin network states of quantum geometry in LQG. We have showed that their structure needs to be generalized during the coarse-graining process. This leads to consider loopy spin networks, which define a Fock space of Wilson loops with local excitations of curvature. Such techniques are also applicable to lattice gauge theory [402].

Surface state and holography in LQG

In quantum gravity, dynamics and renormalization are interlaced with the notion of holography: dynamics of the quantum geometry of a region of space-time can be entirely encoded in a theory living on its boundary. This led us to reformulate spin network states in terms of quantum surface states, investigate their dynamics and decoherence and show how surface states could encode all the physical data of the theory, thereby realizing holography in LQG [416].

Holographic dualities

Quantum gravity in 3D formulated as a topological field theory is the perfect arena to investigate boundary theories and holography. Working with the discrete Ponzano-Regge path integral for 3d gravity, we obtained the key result that 3d quantum gravity is dual to the 2d Ising model on the boundary [399]. This led to a new geometrical formula for the zeroes of the Ising partition function. We further recovered the asymptotic BMS formula for 3d quantum gravity obtained from the AdS/CFT correspondence and hints of the integrability of Ponzano-Regge boundary theories [416].

Reformulations of General Relativity

Since general relativity as a field theory of the metric leads to a non-renormalisable quantum theory, it is natural to seek reformulations of general relativity as better starting points for its quantization. This has led to new formulations and beautiful results related to twistors and Hitchin theory of 3-forms [410].

Quantum Cosmology

The natural arena to test gravity theories is cosmology. In this context, we have uncovered a conformal symmetry for homogeneous isotropic cosmology (FRW) in general relativity and in LQG, allowing to write the dynamics as a $SL(2,\mathbb{R})$ flow and mapping it onto conformal quantum mechanics involved in the AdS_2/CFT_1 correspondence.

Massive Gravity

We have written down for the first time a first-order connection and triad action for 3d gravity which propagates a massive graviton. The mass generation mechanism is based on a breaking of the internal Lorentz symmetry, and we thus hope to extend this construction to 4d, which would have important conceptual and phenomenological implications.

Mathematical Physics and Fundamental Interactions: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
T. Ortiz	Two dimensional maximal supergravity, consistent truncations and holography	07/07/2014	H. Samtleben, D. Tsimpis
C. Tauber	Trois applications d'une approche géométrique à la théorie conforme des champs	01/12/2015	K. Gawedzki
C. Charles	Renormalization and Coarse-graining of Loop Quantum Gravity	25/11/2016	E. Livine
A. Baguet	Exceptional Field Theory and Supergravity	30/06/2017	H. Samtleben
A. Feller	Entanglement and Decoherence in Loop Quantum Gravity	23/10/2017	E. Livine
Y. Herfray	New Avenues for Einstein's Gravity : from Penrose's Twistors to Hitchin's Three-Form	27/10/2017	K. Krasnov, E. Livine
B. Pezelier	Separation of variables and new quantum integrable systems with boundaries	01/06/2018	J.M. Maillet, G. Niccoli
S. Lacroix	Modèles intégrables avec fonction twist et modèles de Gaudin affinee	04/07/2018	M. Magro, B. Vicedo

Main contracts

3 ANR: DefIS, DIMERS, STOSYMAP
2 PICS
1 PEPS INSMI

Editorial responsibilities

Bouttier Jérémie
Mathematical Physics, Analysis and Geometry, Editor.
Krzysztof Gawedzki:
Annales Henri Poincaré, Editor in chief.
Livine Etera:
Europhysics Letters, Associate Editor.
Classical & Quantum Gravity, Member of the Advisory Panel.
Maillet Jean Michel
Annales Henri Poincaré, Editor of the "integrable models" section.
SciPost Physics, Member of the Advisory board.
SciPost Physics, Member of the Editorial College.

Organized conferences

Bouttier Jérémie.
Journée cartes, Lyon (France), November 2015
Quantum integrable systems, conformal field theories and stochastic processes, Cargèse September 2016
Winter school on Combinatorics and Interactions, Marseille (France), January 2017
Mini-school on Random maps and the Gaussian free field, Lyon (France), May 2017
Kozlowski Karol.
Correlation functions in quantum integrable models ... and beyond, Lyon (France), October 2017
Maillet Jean Michel.
Integrability vs. Non-Integrability in Statistical Mechanics, Simons Center, Stony Brook (USA), March 2015
Session "Integrable models", ICMP 2018, Montréal (Canada), July 2018
Samtleben Henning.
Recent Developments in Supergravity Theories, Istanbul (Turquie), June 2014
Journées de Physique Mathématique, BPS States, Hitchin Systems and Quivers, Lyon, September 2014
Journées de Physique Mathématique, Quantum Computing, Lyon (France), September 2015
Supergravity, What Next, Florence (Italie), September/October 2016
Journées de Physique Mathématique, QFT on Curved Space-Time, Lyon (France), June 2017
Journées de Physique Mathématique, Quantum Chaos, Lyon (France), June 2018

105 publications in peer reviewed journals: see T4B.

T5R. Condensed Matter and Quantum Information: *Report*

Permanent Members: D. Carpentier, P. Degiovanni, P. Delplace, A. Fedorenko, K. Gawedzki, M. Geiller, P. Holdsworth, B. Huard, F. Mezzacapo, E. Orignac, T. Roscilde, L. Savary

Post-docs: N. Cottet, R. Dassonneville, M. Droth, C. Dutreix, L. de Forges de Parny, M. Marciani, A. Rançon

PhD students: E. Brillaux, C. Cabart, N. Cottet, A. Essig, M. Faulkner, Q. Ficheux, I. Frérot, M. Fruchart, C. Gray, T. Louvet, D. Malpetti, D. Markovic, R. Menu, T. Peronnin, V. Raban, B. Roussel, J. Stevens, J. Thibaut, E. Thibierge, L. Kumar Uperti

In the laboratory, research in Condensed Matter and Quantum Information covers a broad spectrum of topics including strongly correlated systems, mesoscopic physics, topological matter and physical systems for quantum information. In topological matter, we have expanded our research activities from topological insulators and spin ice to semi-metals and artificial matter using periodically driven physical systems. Specifically, we have focused on electrical transport properties and identified new topological states. In strongly correlated matter, we have explored new mechanisms for superconductivity in exotic matter, the dynamics of phase transitions in spin chains, magnetic monopoles and artificial gauge fields. In quantum information, the newly arrived experimental group on superconducting circuits has demonstrated quantum simulations and investigated measurement backaction in quantum mechanics by continuous measurement of incompatible observables. On the theory side, the electron quantum optics formalism has been reinterpreted as quantum signal processing, thereby providing a general method to analyze a quantum electrical current down to single electron wave-function. Finally, new quantum bounds on fluctuations in generic many body systems have also been identified based on measurable quantities which directly quantify the metrological potential of many-body states.

A. *Topological matter*

The historically strong activity of the group on topological matter evolved during the last five years beyond traditional topoligical insulators, focusing on subjects ranging from relativistic electronic phases to topological states realized in optical metamaterials and magnetic phases.

Topological hetero-junction. (LPS, Orsay; LPA, ENS Paris; Univ. Wurzburg, Allemagne) The typical signature of a topological insulator is the existence of robust states at its surface. In [553, 581] we have revisited this old characterization, and demonstrated that other higher energy states exist at such a surface beyond those traditionally considered. This leads to a clear signature in the high frequency response in agreement with the experiments performed by the ENS-Wurzburg members of the collaboration.

Relativistic (semi-)metals. (Institute of Physics, Zagreb, Croatia; UGA) Topology allows to identify materials in which electrons behave as massless relativistic particles. These are called Weyl and Dirac semimetals. In such materials, the relativistic dynamics of electrons leads to peculiar properties, which attracted considerable attention recently. In particular, their unusual electromagnetic response can be interpreted as a manifestation of a high energy phenomenon, the chiral anomaly. In [564] we studied the signature of the chiral anomaly in the magnetoconductance of a short conductor made out of a Weyl semimetal. We showed that the linear behavior at high magnetic field of its conductance constitues an unambiguous signature of this chiral anomaly.

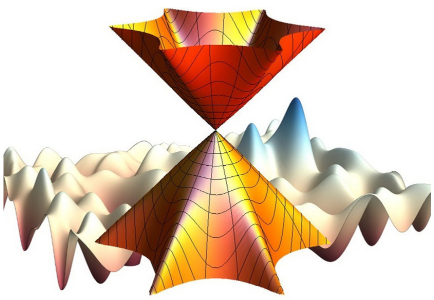

Figure 27: Dispersion around a Weyl node in the presence of a random potential (schematic picture).

While topology describes the robustness of these relativistic semimetals to various perturbations, the case of disorder has to be treated separately. Indeed, while weak disorder is irrelevant, a strong enough disorder modifies the properties of the semimetal: a finite density of states is created by disorder at the band crossing. In spite of numerous efforts, the understanding of this quantum phase transition remained elusive. In [502] we have shown that the fluctuations of the randomness beyond the standard Gaussian approximation invalidate previous field-theoretic descriptions of this transition. We have demonstrated how to overcome this obstacle by deriving and solving a functional renormalization group for the whole disorder distribution, and related its solutions to those of the celebrated Porous Medium Equation bringing a beautiful connection between the physics of quantum disordered systems and in fluids mechanics.

We have also studied the signature on transport properties of a topological transition occuring in two dimensional relativistic semi-metals. The critical point of the Dirac semimetal to insulator transition is a remarkable semi-Dirac state with linear dispersion in one direction and quadratic dispersion in the perpendicular direction. With impurities [519], a strong anisotropy with vanishing conductivity along the quadratically dispersing direction is obtained at the transition when the Dirac points sit at the Fermi level.

Floquet dynamics (InPhyNi) Periodically driven systems beyond adiabaticity – called Floquet systems – may develop topological properties beyond those of static topological insulators at equilibrium. We defined a new $\mathbb{Z}_2$-valued invariant for 2d periodically driven crystals with time-reversal symmetry and related it to the Kane-Mele index of the quantum spin Hall effect [506, 525]. We also introduced $\mathbb{Z}$-valued invariants for 1d periodically driven crystals with chiral symmetry [520, 547] and proposed an optical coupled-waveguides setup to excite and observe the topological boundary modes [521].

A Floquet-Green function formalism was developed to investigate the electronic transport properties of Floquet insulators in 2d [549]. We shown that the differential conductance can probe the quasi-energy Floquet spectrum when tuning the chemical potential of the input lead. In particular, it provides a physical signature of the topological chiral edge modes of the driven system in multi-terminal geometry, and reaveals a quantization under certain conditions.

We introduced a phase rotation symmetry to explain the existence of the anomalous Floquet topological states where the existence of chiral topological boundary states is not related to the Chern number anymore, and applied this theory to various discrete-time quantum walks in 2d [529].

Topology and electrostatics There is a striking similarity between the monopole picture of spin ice and the generalised electrostatics of Maggs and Rossetto (MR 2002) that is the basis of an intelligent algorithm for simulating Coulomb systems [505]. We have exploited this synergy in the context of a celebrated emergent electrostatic system, the Kosterlitz-Thouless (KT) phase transition. We showed [540] that this emergence in a short range Hamiltonian is intimately related to MR electrostatics and that the Villain approximation for two-dimensional continuous spin systems (Villain 1975) is an exact mapping to it. We show that the KT transition corresponds to an ergodicity breaking between topological sectors which are quantised fluctuations of the harmonic mode of the emergent field.

B. *Strongly Correlated Matter*

Low-dimensional quantum magnetism, quantum phase transitions and unconventional superconductivity. (Jozef Stefan Institute, Slovenia; LNCMI, CEA Grenoble, NEEL; LPT Toulouse; MIT) Our theoretical investigations on low-dimensional quantum magnetism have focused

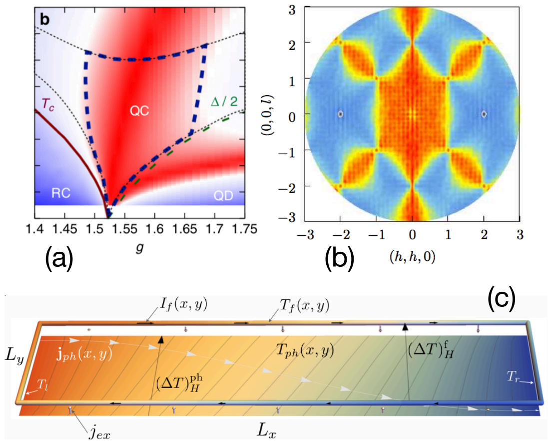

Figure 28: (a) Quantum critical fan in the 2d quantum Ising model, as reconstructed from the scaling of the order-parameter quantum variance [512]; (b) Simulated neutron scattering off a spin ice monopole crystal. Long rang order (grey scale 220 Bragg peaks) coexist with a spin liquid with Couloomb phase correlations [505]. ; (c) Temperature profile in a thermal Hall bar of the Ising anyon phase and its majorana edge mode [585].

on coupled XXZ chains. We have focused on an experimental realization of such a model Hamiltonian provided by the spin chain material $Ba_2Co_2V_2O_8$, and on the transition to a gapless phase upon applying a field, which displays a crossover from a Luttinger liquid at high T and long-range ordering at low T, studied via the NMR relaxation rate [557]. The same relaxation rate has been investigated at the ordering transition of coupled easy-plane XXZ chains via combination of numerical (QMC) and analytic methods (RPA, SCHA) [534]. Another line of investigations has concentrated on paradigmatic quantum phase transitions of magnetic models (quantum Ising model, Heisenberg bilayer), and it has led to the quantitative reconstruction of the finite-temperature quantum critical regime (quantum critical fan) making use of quantum correlations, accessible via e.g. neutron spectroscopy [512] (see also the section “Quantum correlations in many-body systems”). Following up on a series of experiments on the superconducting half-Heusler materials, we investigated a possible superconducting mechanism (polar phonons) and superconducting gap functions in these three-dimensional spin-orbit coupled materials [517].

Frustrated magnetism. (University College, London, Max Planck Dresden, U. Waterloo, LOMA, KITP, U. Minnesota) Our theoretical efforts on frustrated magnetism have concentrated on the static and dynamic properties of spin liquids - classical and quantum. The monopole picture of spin ice was reformulated from a field theoretic point of view in which the apparent fragmentation of the magnetic moments into two distinct parts is a natural consequence. The monopole fluid can be driven through a crystallisation transition in which the two parts coexist - one showing long range antiferromagnetic order and the other, a spin liquid with ferromagnetic correlations [505]. In dynamic studies in the presence of a low frequency AC magnetic field, model spin ice was shown to have the non-Ohmic corrections to monopole conductivity predicted by Onsager's Wien effect in complete analogy with a weak electrolyte [513]. On the quantum side, motivated by recent thermal conductivity experiment in a magnetic field in the Kitaev quantum spin liquid candidate $RuCl_3$, we showed in great generality that a system formed of a fermionic edge mode coupled to phonons in its bulk displayed a *quantized* Hall conductivity if the coupling between the edge and the bulk phonons was *strong* enough [585]. In a parallel line of research, we have developed an effective variational Ansatz (long-range entangled plaquette state) which allows for a flexible variational optimization of the sign structure of the coefficients in the ground-state wave function of frustrated quantum magnets.

Quantum quenches and periodic driving in ultracold atoms. (U. Bonn; U. Salerno; U. Bologna) A general theme of our theoretical investigations on cold-atom physics has been the study of quantum quenches in atomic-physics quantum simulators. The post-quench spreading of correlations within a causal lightcone - defined by the propagation of entangled quasi-particle excitations - has been investigated for a one-dimensional Bose gas after an interaction ramp [503]; in long-range XXZ spin models realized by trapped-ion and Rydberg atom arrays, where the long range nature of interactions leads to a divergence of the group velocity of quasiparticles [544] and to a superballistic spreading of correlations [509]; and in quantum Ising models, relevant to the physics of Rydberg atoms, possessing (quasi-)flat bands of excitations which can lead to spin localization after local quenches [569]. Moreover we have investigated the absence of post-quench thermalization due to many-body localization in a model of interacting spinless fermions in a quasi-periodic potential (mimicking incommensurate optical superlattices), showing how the quench dynamics can show signatures of a many-body mobility edge [570]. Finally we have investigated the response of cold-atom models to periodic modulation of the Hamiltonian, by monitoring the energy absorption. In the one-dimensional case, the response to super-lattice modulation has been analyzed for the Bose-Hubbard [560] and the Fermi-Hubbard model [559] using both time-dependent DMRG and bosonization. It was shown that the different phases of these models could be distinguished by superlattice modulation techniques.

Artificial gauge fields and topological properties in ultracold atoms. (Univ. College London) A further unifying theme of our theoretical studies on ultracold atoms has been the study of artificial gauge fields and related topological properties, connected with impressive recent experimental advances. A substantial part of our attention has been dedicated to quantum phase transitions in bosonic two-leg ladders under flux, studied with a combination of Luttinger liquid theory and DMRG. In particular we investigated the transition between a Meissner-like phase

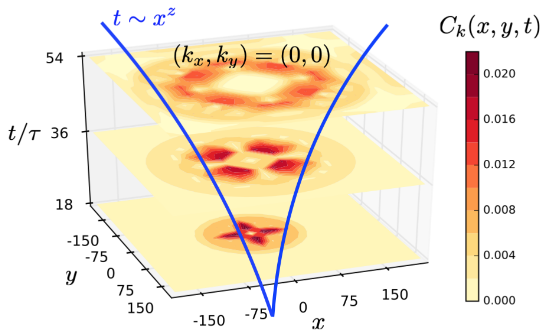

Figure 29: Post-quench dynamics in a quantum dipolar 2d XY model: shown here is the evolution of the correlations the uniform magnetization of 10x10 subsystems (shifted by the vector (x, y)) starting from the mean-field ground state; the blue line indicates a non-linear time-space relationship with a z=1/2 dynamical exponent.

and a vortex-like phase induced by a growing magnetic flux threading the ladder, where we unveiled that a hopping amplitude driven incommensuration is formed when the applied flux is π times the number of particles per rung [530, 531, 572]. In the presence of interchain repulsion, a new charge-density-wave phase was found to appear in between the Meissner and the vortex phase, separated from the former by an Ising transition and a Kosterlitz-Thouless transition respectively [526, 571]. A further line of research has involved the development of a novel semiclassical approach (bosonic auxiliary-field Monte Carlo) [565] relying fundamentally on the fast spatial decay of quantum correlations (see section "Quantum correlations in many-body systems") at finite temperature – much faster than that of ordinary correlations [566]; this approach does not suffer from the sign-problem pathology of quantum Monte Carlo, and it allowed us to study the transitions of hardcore bosons on a frustrated triangular lattice with π-flux. Finally we devoted our attention to the topological properties of the phase of the bosonic field associated with ultracold bosons on a ring lattice: we have numerically investigated the quantum vs. thermal fluctuations of the winding number of the phase, and their very distinct signatures in current experiments on matter-wave interference [576].

Extended-range repulsive interactions (KTH Stockholm, Sweden) We have studied monodisperse classical systems interacting via a large class of extended-range purely repulsive interactions (ERI) relevant to ongoing experiments with polymers, vortex matter, and cold Rydberg-dressed atoms. Using molecular dynamics simulations, we have shown that these systems in 2D can realize a new type of phase-change behavior, where crystalline and amorphous structures can be easily tuned by heat pulses [532]. In the quantum regime, work in progress based on quantum Monte Carlo demonstrates that ERI may lead, on a lattice, to intriguing scenarios such as first-order supersolid-supersolid phase transitions and out-of-equilibrium states with possible coexistence of glassiness and superfluidity.

C. Quantum information

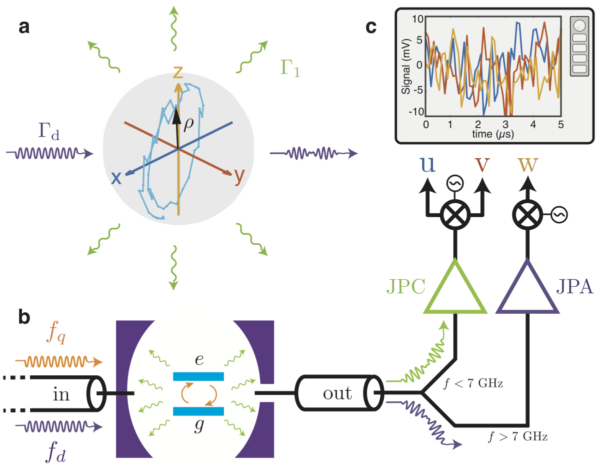

Figure 30: a. One observed quantum trajectories followed by a superconducting qubit [508]. b. Scheme of the setup that intercepts both spontaneous emission and dephasing signals. c. A single measurement record leads to the trajectory in a.

Quantum information with superconducting circuits. (Quantic team-Paris, Yale, Néel) We have proposed [543] and realized [515] a quantum simulator based on superconducting circuits to effectively reach the ultrastrong coupling regime between two oscillators. We could observe the signature of the predicted ground state entanglement in the microwave radiation of a circuit.

Several quantum information applications require to reach input microwave powers that are so high that the superconducting circuits stop operating as expected. This fact hinders the development of quantum error correction with Schrödinger cat states of light and only inconsistent theories were proposed to explain the high power behavior. We have participated in an experiment aimed at probing the circuit dynamics at large power [558]. Owing to our measurements, we know understand how the artificial atom that superconducting qubits realize ionize in presence of a strong drive, even far off-resonance. Our work enables us to envision a way to protect superconducting non-linearities from sensitivity to large powers.

We have also realized an experiment that tracks all three Pauli operators of a qubit simultaneously for the first time [508] (Fig. 30). It offers a new way for qubit tomography by simple raw averaging. We offer a textbook illustration of the impact of the choice of a particular measurement setup on the evolution of a quantum system, especially when competing incompatible detectors are used. 30 different representative regimes of decoherence and drive including Zeno blockade and undisturbed unitary evolution were used to record the quantum trajectories of the qubit.

Electron quantum optics. (LPA ENS Paris & CPT Marseille) We have developped the theoretical formalism of electron quantum optics in close collaboration with the group of Gwendal Fève at the Laboratoire Pierre Aigrain (LPA) [504]. Our theoretical predictions for single electron decoherence [507] have been successfully used to interpret the experimental data from an Hong Ou Mandel experiment [568]. Since, in our framework, effective screened Coulomb interactions are described through edge-magnetoplasmon scattering, we have thus been able to address the issue of decoherence control which is crucial for potential applications such as information processing using single electron excitations. We have shown that electronic decoherence can be strongly mitigated by using a lower coupling material such as graphene and that, even in a strong coupling material such as AlGaAs/GaAs, an appropriate sample design could efficiently limit decoherence below a certain energy scale [523]. In parallel, we have deepened the development of the core formalism of electron quantum optics by properly defining the intrinsic 2nd electronic coherence and proposed a generalized Franson interferometry to measure it [582]. Motivated by its potential applications to high precision sensing of the electromagnetic field at the submicronic and sub-nanosecond scales, we have reinterpreted electron quantum optics in terms of *quantum signal processing* (see Signal Processing section of this Report). We have finally developped a generalization of the Kahrunen-Loève analysis to electron quantum optics to extract single electron and hole wavefunctions within a given electron beam, as well as their emission probabilities and coherences. This method has been successfully applied in the experiment demonstrating for the first time our ability to analyze a quantum electrical current down to single particle states.

Quantum correlations and entanglement in many-body systems. Our theoretical investigations have focused on the quantification of quantum correlations (not possessing any quantum analog) in quantum many-body systems, and on their potential use as resources for quantum technology tasks. Making use of elementary quantities in statistical physics (fluctuation and response functions) we have introduced two new concepts, the one of *quantum variance* [545] and the one of *quantum correlation function* [514], capturing the pure quantum contribution of the fluctuations of a given observable, and the correlations among such fluctuations for observables referred to two arbitrary subsystems, respectively. The quantum variance offers two efficiently calculable and potentially measurable bounds to the quantum Fisher information [552]; and it inherits from the latter the property of being a witness of multipartite entanglement, as well as that of assessing the fundamental metrological potential of a many-body state for phase estimation, that we have investigated in [511] for quantum critical states in fundamental models of quantum phase transitions.

Condensed matter and Quantum information: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
C. Cabart	Measurement and control of electronic coherences	18/09/18	P. Degiovanni
N. Cottet	Energy and information in fluorescence with superconducting circuits	20/11/18	B. Huard
Q. Ficheux	Quantum trajectories with incompatible decoherence channels	07/12/18	B. Huard, Z. Leghtas
I. Frerot	Quantum statistical approach to quantum correlations	09/10/17	T. Roscilde
M. Fruchart	Topological phases of periodically driven crystals	05/10/16	D. Carpentier, K. Gawedzki
T. Louvet	Relativistic phases in condensed matter	12/07/18	D. Carpentier, A. Fedorenko
D. Malpetti	Thermodynamics of strongly correlated bosons on a lattice: new insights and numerical approaches	16/12/16	T. Roscilde
D. Marković	Applications of the Josephson mixer: ultrastrong coupling, quantum node and injection locking in conversion	14/12/17	B. Huard
B. Roussel	Autopsy of a quantum electrical current	15/12/17	P. Degiovanni
E. Thibierge	Cohérence à 1 et 2 électrons en optique quantique électronique	15/06/15	P. Degiovanni

Main contracts

2 European: QMICS, SEQUOIA
10 ANRs: IGNITION, 1SHOTRELOADED, DIMERS, ANR-ERC, QUANTEM, DIRAC3D, SEMITOPO, TOPODYN, ARTIQ, EELS
1 IUF: Roscilde
1 US Army: HiPS
IdexLyon: 1 breakthrough compensation

Editorial responsibilities

Gawedzki Krzysztof:
Annales Henri Poincaré, Editor in chief.
Savary Lucile:
Physica B: Condensed matter, Member of the editorial board.

Organized conferences

Carpentier David, Delplace Pierre:
Mini-colloque des 15ème Journées de la Matière Condensée, Bordeaux (France), August 2016
TopoLyon 2016, Lyon (France), October 2016
Bartolo Denis, Carpentier David, Delplace Pierre, Huard Benjamin, Savary Lucile, Venaille Antoine:
TopoLyon workshop series, Lyon (France), December 2018, April 2019 and May 2019
Degiovanni Pascal:
Réunion plénière du GDR Information Quantique, Lyon (France), December 2014
Delplace Pierre, Venaille Antoine:
Interdisciplinary workshop on topological phenomena Lyon (France), November 2017
Fedorenko Andrei, Holdsworth Peter, Orignac Edmond and Roscilde Tommaso:
MECO42, Lyon (France), February 2017
Huard Benjamin:
Quantum Information and Measurement, Paris (France), April 2017
Les Rencontres de Moriond, La Thuile (Italy), March 2019
Quantum Thermodynamics Conference 2019, Espoo (Finland), June 2019
Mezzacapo Fabio and Roscilde Tommaso:
ENIQMA 2018: Entangled Interacting Quantum Matter, Lyon (France), November 2018
Roscilde Tommaso:
Quantum Gases and Quantum Coherence, Bad Honnef (Germany), April 2018
ENIQMA 2017: Entangled Interacting Quantum Matter, Lille (France), November 2017
Quantum Gases and Quantum Coherence, Salerno (Italy), August 2016
Classical and Quantum Fluids out of Equilibrium, Villard de Lans (France), July 2016
4th Les Houches School for Computational Physics, Les Houches (France), June-July 2014
Savary Lucile:
French Pyrochlore Magnets Meeting, Orsay (France), April 2018

85 publications in peer reviewed journals: see T5B.

T6R. Infophysics, Signal and Systems: *Report*

Permanent Members: P. Abry, B. Audit, P. Borgnat, L. Chevillard, P. Degiovanni, P. Flandrin, N. Garnier, P. Jensen, N. Pustelnik, S. Roux, C. Vaillant

Post-docs: J.-M. Arbona, R. Cazabet, S. De Nigris, M. Foare, J. Harmouche, M. Jiu, R. Leonarduzzi, G. Lozenguez, J. Schmitt, J. Spilka

PhD students: J. Barbier, E. Bautista-Ruiz, R. Boulos, J. Cambe, A. Costard, D. Barbe, J. Frecon, C. Granero Belinchon, R. Hamon, H. Kabalane, G. Michau, M. Morini, B. Pascal, M. Roux, F. Sémércurbe, H. Sevi, N. Tremblay, Y. Kaloga

A foremost research theme at the Physics Lab. is to develop Information sciences by considering that Physics is deeply connected to signal and data processing. More broadly this work in information sciences has led, since the early years of the Lab., to large and diverse projects in "info-physics", contributing at the highest international research level both for the methodologies in physics and signal processing, and for selected and relevant applications. The spirit of the theme is to promote back and forth interplays between information processing and physics or applications, calling for and nurturing new advanced methods in signal and image processing. The achieved results cover many topics, in optimization methods, especially for inverse problems, in processing methods for data on graphs, and works on theory and models for nonstationary data, scale invariance or non Gaussian data. Also, an originality is to base this research on wide range of applications: in physics, multiscale studies of genomic data, biomedical studies (e.g., heart rate variability analysis or neuroscience), and social or transportation sciences. The successes of these research lines are supported by various international and national collaborations, as well as publications in top-ranked journals and many funded projects.

A. *Nonstationarity*

Disentangling multicomponent signals. Different decomposition approaches have been improved and compared for disentangling multicomponent nonstationary signals into meaningful AM-FM components [613]. Emphasis has been put on data-driven methods such as reassignment/synchrosqueezing techniques that have been made more versatile [687], Empirical Mode Decomposition for which an on-line algorithm has been proposed [686], and that has been improved thanks to optimisation-based algorithms which we developed both in 1D and 2D [616, 619], Singular Spectrum Analysis that has been given a sliding version [605], and a sparsity-based approach for cross-terms removal in Wigner distributions [683]. New theoretical advances have been accompanied by the development of algorithms gathered in a comprehensive and freely accessible Matlab toolbox [688].
Time-frequency zeros and filtering. In contrast with traditional approaches that focus on locally large values of a time-frequency distribution for identifying signal components embedded in broadband noise, it has been shown that "signal domains" can be delineated by suitably selecting time-frequency zeros, grouped by a Delaunay triangulation [596]. The rationale has been discussed in connection with the theory of Gaussian Analytic Functions, and the effectiveness of the method has been evidenced by the filtering and denoising of gravitational wave chirps [681].

B. *Scale invariance: Theory, models and applications*

Advanced multifractal theory. Significant advances in univariate multifractal theory have been achieved. First, it was shown that new local regularity exponents, p-exponents, and their corresponding multiscale quantities, p-leaders, grounding multifractal analysis on L^p norms, $p > 0$, permit richer data analysis (negative regularity, oscillating or lacunary singularities,...) [611, 628, 629, 713] and improved estimation performance [727]. Second, a Bayesian framework has been devised to achieve improved estimation performance for the multifractality parameter for small sample size data, which notably permits to analyze spatial variations of multifractal properties in textures [666, 778]. Third, borrowing concepts from out-of-equilibrium statistical physics, the first procedure that permits to obtain non necessarily concave multifractal spectra has been devised [723, 726].
Multivariate scale-free dynamics. While scale-free dynamics remained so far confined to univariate modeling, we developed multivariate scale-free analysis. First, it was shown that multivariate self-similarity can be theoretically studied efficiently and robustly implemented using a multiscale eigen-value representation of the multivariate multiscale wavelet spectrum [587, 626, 627]. Second, multivariate multifractal analysis, that codes for statistical dependencies that are not accounted for by correlations, was shown to be far more complicated to formalize [722, 784] and is currently been further investigated.
Scale-free modeling. In [592], theoretical developments on fractional Brownian motion (fBm) are proposed, consisting of an explicit definition of the fractional Gaussian noise (fGn), that allows to define in an unambiguous way fBm (or any linear transform), not only as a process, but as a solution of a stochastic differential equation (SDE). The proposed procedure consists in regularizing the underlying dynamics over a small time scale ϵ. The particular case of a linear damping is investigated, explaining the chosen terminology of fractional Ornstein-Uhlenbeck.

Multifractal in Applications. *Internet Traffic:* (K. Fukuda, R. Fontugne, University of Tokyo, Japan). Elaborating on a 20-year old founding contribution, showing that long range dependence was a major property in computer network trafic, a longitudinal study of 14 years of Internet traffic, from MAWI repository, enabled us to show that the scale-free dynamics of Internet traffic remained incredibly stable across years, despite Internet being an ever changing "beast" [597]. We also provided significant understanding of the mechanisms producing such scale-free dynamics. *Art Investigations:* (MoMA, New York city, Yale University). We have shown, using multiscale anistropic representations, that large databases of art photographic paper textures can be efficiently characterized at fine scales (at mm^2) and thus clustered, hence offering museum conservators and art scholars fast and reproducible groupings of art works, further permitting authentication, attributions,. . . [588, 632, 633, 718].

C. *Optimization and inverse problems*

Nonsmooth optimization. Since 2010, significative advances in nonsmooth optimization allows the signal and image processing research to access new information. This class of optimization can be referred to as *proximal algorithms* and exploit the concept of *sparsity*. We contributed to the development and knowledge of these algorithms by first deeply studying the computation of the proximity operator of a sum of two functions and its impact on computational load [617]; second, by deriving a large panel of closed form expression of epigraphic projections [593] allowing us to deal with nonlinear constraints that can be encountered in inverse problems [618] or supervised learning [655, 716, 717]; and finally, by contributing to the extension of proximal algorithms for the nonconvex setting with convergence guarantees to a critical point [684] allowing us to revisit the Mumford-Shah problem, a pioneer work of image reconstruction.

Change-point detection/segmentation. The identification of sharp changes in signal or interface detection in images stay a challenging question that we revisited by making use of *total variation* (TV), which exploits the sparsity of the data after a finite difference transform. We derived fast processing with a limited number of parameters in order to exploit data extracted from physics experiments. In [599, 693–696], we proposed an operational strategy that combines hierarchical Bayesian and Potts model formulations, with the double aim of automatically tuning the regularization parameter and of maintaining computational efficiency. Another direction was explored in [691] providing an efficient on-the-fly algorithm to detect change-point in multivariate data, whose quality is controlled by a practitioner-tunable parameter, acting as a trade-off between quality and computational cost. We propose a new segmentation approach enroling scale-free descriptors estimation into a TV denoising procedure [616, 618, 618, 744, 745], which can appear has one of the first procedure performing simultaneously estimation and segmentation with a small computational load due to the strong convexity of the data term. We refer to II T1R I for application to multiphasic flows in porous medium.

Image reconstruction. The concept of TV has been extended to *non-local TV* (NLTV), which has emerged as a useful tool in variational methods for image recovery problems due to its simplicity and efficiency. First, we extended the NLTV-based regularization to multicomponent images by taking advantage of the Structure Tensor (ST) resulting from the gradient of a multicomponent image [594] and formulating it as a constrained convex optimization approach in order to facilitate the choice of the hyper-parameters. Second, we analysed the impact of NLTV and of an original approach based on sparse local patch dictionaries for the regularization of the estimate in structured illumination microscopy image reconstruction [590, 672].

D. *Graph signal processing and complex networks*

Graph Signal Processing. The analysis of data indexed on nodes of graphs can be done by importing concepts of signal processing, and this coined as Graph Signal Processing (GSP). We continued our efforts to develop the general framework in GSP, and contributed also to explain the approach with a review chapter [622] and several talks or workshops. We designed novel methods in GSP on filterbanks based on connected subgraphs [621], on Empirical Mode Decomposition on graphs [769], about Least Min Square filters [743], and on analytical signals on graphs [772, 773]. Another set of works was about Graph Fourier Transform on directed graphs [759, 760], that was tackled by proposing to use the random walk operator as reference operator on a graph, showing that it leads to a conveniently defined Fourier analysis on directed graphs. We revisited parametric modeling of graph signals and semi-supervised clustering, as well as the of continuous and discrete wavelets for directed graphs [761].

Dynamical graphs. In many situations, the data to study consist of a dynamic graph, that evolves with time and whose structure has to be extracted. We have developed an exploratory method to study the dynamics of graphs, inspired from time-frequency ideas (II T6R A). The principle is to first map graphs as a collection of components [709] embedded in a space, thanks to multidimensional scaling. Leveraging a relabeling of the nodes to better follow the structure [708] at a given instant, we have shown how to explore the time-evolution of components of a graph and of its structure [604].

Clustering of complex data. In various applications, the previous methods were leveraged for clustering using GSP [767], e.g. for genomics [591, 652] (see II T6R F), or for art photography studies [588] (see II T6R B). New methods were developed also in the case of semi-supervised learning [674], when one disposes of some known labels. Finally, the dynamical case was also tackled, by studying how nonnegative matrix factorization can help to exhibit groups and their time evolution in graphs [707, 710].

E. Information processing for physics

Methodology and applications in fluid turbulence. In contrast to traditional methods, which are either linear or assuming linear interactions, information theory offers a complete set of tools to explore not only the — possibly non-Gaussian — statistics of a process (with Shannon entropy), but also its non-linear dynamics (with entropy rate) [703] as well as its complete temporal dependencies (with auto-mutual information). Using high resolution experimental signals, the relevance of such tools to describe fluid turbulence has been explored [601, 705]. A new insight into the intermittency phenomena and a quantitative exploration of the modified Kolmogorov-Obukhov theory and its propagator formulation — which was previously very difficult to assess — was made possible [602, 706].

Methods for electron quantum optics. Recent progresses in electron quantum optics (see II T5R C) have suggested interesting connexions with signal processing. In particular, we have shown how ideal quantum interferometers perform basic signal processing operations such as linear filtrering (ideal electronic Mach-Zehnder and Franson interferometers) or analog overlaping of electronic coherences that should be seen as the quantum signals carried by the many body electronic fluid propagating along a quantum Hall edge channel [577]. A generalization of the Kahrunen-Loève analysis for electron quantum optics has also been developped with the aim of decomposing the single-electron coherence of an arbitrary quantum electrical current into elementary electron and hole excitations.

F. Chromatin and genomic data analysis

Genome-wide chromosome conformation capture technologies (HiC) provides the matrix of 3D colocalization frequencies between all pairs of chromosme loci. We contributed two open-source methods to respond to the new computational challenge to objectively extract from these data structural motifs characteristic of genome organization. Based on a hierarchical clustering approach accounting for the polymeric nature of chromatin, *IC-Finder* is a robust computationally-efficient algorithm to segment the genome into interaction compartments (IC) like TADs and to infer higher-order levels of chromatin organization [603]. Using a graph representation of HiC data and the fast multi-scale community mining algorithm based on spectral graph wavelets developed by SiSyPhe team (see II T6R D), we observed that there exist structural domains of all sizes up to chromosome length and demonstrated that the set of structural communities forms a hierarchy of chromosome segments [591]. These structural decompositions of chromosomes allowed us to quantify the conservation across scales of the structural organization between human cell lines [591], and the correlation between the partition of genome into chromatin states and 3D structural domains in *Drosophila* and human [603].

The spatiotemporal program of metazoan DNA replication is highly regulated during development and altered in cancers. However, the molecular mechanisms coordinating the activation of the $\sim 10^5$ replication origins required at each cell cycle remains poorly understood. To address this question, we performed integrative analyses of genome-wide (i) DNA replication profiles, (ii) chromosome epigenetic mark profiles, and (iii) gene expression profiles obtained in diverse human cell lines. It revealed (i) specifics of the chromatin organization of an embryonic stem cell line compared to 5 somatic cell lines, in particular a gene-poor but highly dynamic chromatin state instead of the "usual" close heterochromatin state [608], and (ii) the coupling of 2 repressing chromosome marks (H4K20me1 and H3K27me3) as a key regulator of replication origins activation [747]. We questioned replication plasticity using the latest high resolution replication data (Replication Fork Directionality profiles at 10kb, Coll. IBENS) [624]. We observed that (i) changes in the replication program are widespread but largely disconnected from transcription changes, (ii) cancer cell replication profiles are more similar to non-cancer cells of similar developmental origin than to different cancer types, and (iii) their exists recurrent RFD changes in specific tumor progression pathways. This work clarifies replication program modification during cell differentiation and tumorigenesis.

G. Biomedical signal Processing

Intrapartum fetal heart rate variability. (M. Doret, HFME, Hospices Civils de Lyon) We have shown that characterizations of temporal dynamics in intrapartum fetal heart rate, based on several different signal processing tools (scattering transform [657], multifractal attributes [679], auto-mutual information [702]) permit to monitor intrapartum fetal acidosis. Then, to comply to the request of a clinically usable decision rule, based on a few understandable features, we made a new and original proposition to the field for low pH (hence fetal acidosis) prediction: Starting from a large number of very different features, a multivariate sparse support vector machine (machine learning) procedure has been assessed, showing that the two phases of the delivery process need to be analyzed independently, and that the procedure picks a very small number of features, essentially based on clinical practice, rather than on advanced signal processing tools [589, 765]. Then, observing that entropy rates constitue valuable features for intrapartum fetal acidosis detection, higher order entropy rate and auto mutual information were further proposed to tackle dependencies in highly non-Gaussian medical signals [702, 704].

Adult heart rate variability. (Y. Yamamoto, University of Tokyo) We have shown that multiscale and multifractal analyses permit to characterize efficiently heart rate variability in adults and the efficient discrimination between healthy subjects and Congestive Heart Failure (CHF) patients [615, 724]. We also recently showed that an original non Gaussian multiscale analysis permits to predict Survivors versus non survivors in CHF patients [776, 779].

Macroscopic brain activity. (Neurospin & B. He, NYC, USA) Analyzing fMRI data, we have shown that scale-free dynamics of human brain activity manifest in cross-regional interactions, thus bringing together two related fields that had remained so far studied separately: resting-state networks and scale-free dynamics [659]. Further, in a study conducted at the NIH (bethesda, USA), we have shown the humans' ability to make valid predictions based on temporal regularities inherent in natural stimuli and further revealed the neural mechanisms underlying such predictive computation [735]. Finally, comparing MEG data at rest and during a learning task, we have shown that infraslow (below the Hz) brain activity is well characterized by scale-free dynamics, with weaker self-similarity (correlations) and higher multifractality (higher order dependencies) during task, thus indicating a faster and burstier brain activity compared to rest [609]. We also developed a wavelet-based algorithm using spectral phase to detect spike-wave discharge (SWD) in neuroelectrical recordings allowing us to robustly detect and classify SWD in mouse models of absence epilepsy [749].

Combining multifractal analyses of digital mammograms and infrared thermograms to assist in early breast cancer diagnosis. [600] We used a 1D wavelet transform modulus maxima (WTMM) method to analyze the temporal fluctuations of breast skin temperature recorded with an infrared (IR) camera from a panel of patients with breast cancer. This study showed that the multifractal complexity of temperature fluctuations observed in healthy breasts, is lost in the region of the malignant tumor in cancerous breasts. We applied the 2D WTMM method to analyze the spatial fluctuations of breast density in the X-ray mammograms of the same patients. Compared to the correlated roughness fluctuations observed in the healthy areas, some clear loss of correlations is detected in malignant tumor foci. These physiological and architectural changes in the environment of malignant tumors detected in both thermograms and mammograms open new perspectives in computer-aided multifractal methods to assist in early breast cancer diagnosis.

H. Analyses of Social and Human Activities

Transportation. In the study of transportation, we first continued works on Bike-Sharing Systems, from their data of usage, and proposed a sociological study of who are the users of such BSS (at least in Lyon) [623]. Then, we have shown how to better model graphs representing such transportation data, by modifying the so-called gravity model in transportation [653, 654].

A second set of works was to solve an inference problem in transportation: the estimation of origin destination matrix for traffic, formulated by us as a variational problems on a graph. The need is to estimate car flows while disposing of measurements on nodes and only a sub-sampling of trajectories along the edges thanks to Bluetooth records [740]. This was solved with non-smooth convex optimization (II T6R C) and one result is that the physics-inspired term (e.g., the Kirchhoff law at nodes) were relevant in this framework to correctly compare the estimation to real-world data [614, 737].

Multifractal analysis of cities. Studies in geography are strongly dependent on the size of the spatial units used for the analysis. This has been expressed as the Modifiable Areal Unit Problem (MAUP): it is impossible to identify a single spatial partition that would be most appropriate to analyze it. In this respect, multifractal analysis is an interesting tool for geographers, and we quantify the MAUP by multifractal dimensions and characterize the spatial distribution of population density in France [620]. The main result is a typology map of population density that uses the MAUP as a descriptive tool. A second study is to characterize mainland France, known to be divided in two agrarian systems: enclosed field systems with scattered settlements and openfield systems with grouped settlements. To determine whether the shape of urban areas varies with the type of built patterns in their periphery, we propose a new method – the Geographically Weighted Fractal Analysis – that allows us to characterize built patterns without making prior distinction between urban patterns and suburban or rural patterns [757].

Analysis of social systems. We have analyzed many real social systems with different tools, revealing some of previously unknown features. Scientometric approaches allowed us to understand scientific fields and their evolutions [715, 732, 734]. For example, using a bottom-up approach of the subfield structure of nanoscience research, we have shown that there is not a single way of dealing with the nanoworld, but four distinct strategies that are adopted by countries depending on their history. In [648], we have analyzed election results and showed that if an opinion convergence mechanism is strong enough, one should expect the emergence of a cultural field, a slowly evolving, local quantity around which individual attributes fluctuate in a finite range. Beyond the development of formal methods, it is important to deal with the political consequences of analyzing social data. In collaboration with sociologists and philosophers, we have shown that there is an implicit politics of social models [856, 877].

Infophysics, Signal and Systems: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
Rasha Boulos	Human genome segmentation into structural domains: from chromatin conformation data to nuclear functions	10/12-10/15	B. Audit
Aude Costard	Estimation de la structure d'indépendance conditionnelle d'un réseau de capteurs : application à l'imagerie médicale	10/11-11/14	P. Abry, P. Borgnat; S. Achard, O. Michel (GIPSA-lab, Grenoble)
Jordan Frecon	Méthodes d'optimisation pour l'analyse de processus invariants d'échelle	09/13-10/16	P. Abry, N. Pustelnik
Carlos Granero-Belinchon	Multiscale Information Transfer in Turbulence	09/15-09/18	S. Roux, N. Garnier
Ronan Hamon	Analyse de réseaux temporels par des méthodes de traitement du signal. Application au système de vélos en libre-service à Lyon	09/12-09/15	P. Flandrin, P. Borgnat; C. Robardet (LIRIS, Lyon)
Roberto Leonarduzzi	Wavelet-leader-based multifractal analysis: automatic scaling range selection, p-leader-based multifractal formalism and application to biomedical signals	09/10-09/14	P. Abry ; M.-E. Torres (UNL, Argentina)
Gabriel Michau	Estimation de matrices origine-destination lien: optimisation convexe et non lisse avec inférence de trajectoires Bluetooth	05/13-07/16	P. Abry, P. Borgnat, E. Chung, A. Nantes (QUT, Brisbane)
Matteo Morini	Tools for Understanding the Dynamics of Social Networks	10/13-09/17	E. Fleury (LIP), P. Jensen
Marine Roux	Inférence de graphes par une procédure de test multiple avec application en Neuroimagerie	01/15-09/18	P. Borgnat, S. Achard (GIPSA-lab), I. Gannaz (ICJ), E. Roquain (UParis Sud)
Harry Sevi	Analyse harmonique sur graphes dirigés et applications : de l'analyse de Fourier aux ondelettes	11/15-11/18	P. Borgnat ; G. Rilling (CEA)
Nicolas Tremblay	Réseaux et signal : des outils de traitement du signal pour l'analyse des réseaux	09/11-10/14	P. Borgnat

Main contracts

8 ANR: ASTRES, AMATIS, MultiFracs, GRAPHSIP, LightComb, NanoPoRep, FETUSES, VEL'INNOV.
1 LABEX IMUST: MITT
1 IDEX Lyon: Breakthrough "Academics"
2 Companies: TOTAL, AZOTH SYSTEMS.

Editorial responsibilities

Abry Patrice:
IEEE SPTM, Member of the Technical Committee.
EURASIP, Member of the Technical Committee.
ICASSP, Member of Program Committee.
GRETSI, Member of Program Committee.
Audit Benjamin:
BMC Bioinformatics, Associate Editor
Borgnat Pierre:
IEEE Transactions on Signal Processing, Associate Editor.
Jensen Pablo:
Big Data & society, Membre du Comité Éditorial.
Pustelnik Nelly:
IEEE Signal Processing Letters, Associate Editor.
IEEE MLSP, Member of the Technical Committee
EURASIP, Member of the Technical Committee.

Organized conferences

Patrice Abry:
ICASSP, 2017.
SPaM 2017, Oxford (UK), 2017.
GRETSI 2015, Lyon (France), 2015.
SPaM, Lyon (France), 2015.
Benjamin Audit:
International Conference on Systems Biology (ICSB 2018), Lyon (France), octobre 2018.
Lyon SysBio, Lyon (France), novembre 2014, novembre 2015, novembre 2016, novembre 2017.

Pierre Borgnat:
Summer School "Graph Signal Processing", Aussois (France), September 2018.
Graph Signal Processing Workshop, Lausanne (Suisse) June 2018
2nd Colloque international "Complexity & Cliometrics", Lyon (France), June 2018
Journée "Trajectoires dynamiques et réseaux : approches quantitatives", Lyon (France) May 2017
Semester "Network science", Lyon (France), March-June 2016
Complexity & Cliometrics, Lyon (France), June 2016
GRETSI 2015, Lyon (France), September 2015
Pablo Jensen:
Complexity & Cliometrics', Lyon (France), June 2016
Trajectoires dynamiques et réseaux : approches quantitatives, Lyon (France) May 2017
Complexity & Cliometrics, Lyon (France), June 2018
Nelly Pustelnik:
IEEE MLSP Aalborg (Denmark) 2018.
SMAI Mode, 2017.
Statos 2016.

200 publications in peer reviewed journals and conference proceedings : see T6B.

T7R. Statistical Physics: *Report*

Permanent Members: A. Alastuey, S. Aumaître, L. Bellon, F. Bouchet, S. Ciliberto, C. Crauste-Thibierge, T. Dauxois, V. Demery, V. Dolique, A.Fedorenko, K. Gawedzki, J.-C. Géminard, C. Herbert, P. Holdsworth, B. Huard, P. Jensen, A. Naert, A. Petrosyan, M. Peyrard, A. Pumir, T. Roscilde, S. Santucci, N. Taberlet, A. Venaille

Post-docs: B. Besga, I. Martinez, F. Mogavero, C. Nardini, T. Nemoto, R. Planet, J. Pereda, B. Pottier, F. Puosi, A. Rancon, J. Reygner, V. Sechenyh, I. Theurkauff, J. Wouters

PhD students: A. Bérut, M. Champion, X. Clotet, N. Cottet, J.-Y. Chastaing, C. Devailly, A. Fontana, M. Geitner, A. Le Cunuder, D. Lopes Cardozo, R. Pedurand, D. Wendland

Statistical physics is one of the historical themes present in the laboratory since its creation in 1987. Its original contour, which was restricted to equilibrium and transport properties of simple fluids, was soon enlarged towards signal processing and non-linear phenomena. In fact, this evolution reflects what happened at the larger scale in the physics community, where the tools of statistical physics proved their efficiency in a wide range of topics, including hydrodynamics, soft and condensed matter, biophysics, active matter, social systems, etc. Such spreading is well illustrated in our laboratory through transverse collaborations between various teams, whose works are described in other sections. Here, we focus on recent topics which are nowadays at the heart of the field, namely long-range interacting systems, rare events and out-of-equilibrium aspects. The laboratory has acquired a strong expertise in these domains, as attested by textbooks and review or vulgarization papers published in prestigious journals.

A. *Long range interactions and critical phenomena*

Long-range interactions emerge in a wide variety of many-body systems. Since the end of the 90's, an increasing number of works in the literature has been devoted to the cases where the interaction potential is not screened by collective mechanisms. We wrote a comprehensive book on the corresponding recent advances. The research in this field has been also pursued, in particular for equilibrium properties of self-gravitating systems and for out-of equilibrium features. The long-standing study of quantum Coulomb systems at equilibrium has been also continued. Besides the previous cases where the interactions between the particles or objects are primarily long-ranged, effective long-range interactions can be generated by collective phenomena, for instance at critical points where the divergent correlation length induces Casimir-like forces. Various novel approaches to such phenomena have been established, with important theoretical and experimental consequences for a wide class of physical systems. Eventually, the interplay between primary and effective long-range interactions may also intervene in various phase transitions, as analyzed for the Bose-Einstein condensation and for the liquid-gas transition of classical electrolytes.

Physics of Long-range Interacting Systems This book describes the statistical mechanics and out-of-equilibrium dynamics of solvable systems with long-range interactions. The seed of all particular features of these systems, both at equilibrium and out-of-equilibrium, is the lack of additivity. A satisfactory understanding of properties generally considered as oddities only a couple of decades ago has now been reached: ensemble non-equivalence, negative specific heat, negative susceptibility, ergodicity breaking, out-of-equilibrium quasi-stationary-states, anomalous diffusion, etc. The first two parts describe the theoretical and computational instruments needed for addressing the study of both equilibrium and dynamical properties of systems subject to long-range forces. The third part of the book is devoted to discuss the applications of such techniques to the most relevant examples of long-range systems.

Relaxation processes We considered generalized ϕ^4 models with power-law decaying interactions to investigate the effects of Hamiltonian and Langevin microscopic dynamics on the growth laws of domains in coarsening: the two dynamics exhibit scaling regimes characterized by different scaling laws for the coarsening dynamics. We also studied the out-of-equilibrium fluctuations of the work done on the system by a time-dependent external force [850]. To go beyond the studies on toy models, we have also considered these questions to analyze on the one hand relaxation process on two-dimensional flows with varying interaction range [182] and, on the other hand, dipolar systems within the microcanonical and canonical ensembles. We have shown that the system displays all the properties characterizing long-range interacting systems, especially ergodicity breaking, presence of negative specific heat and emergence of partially antiferromagnetic quasi-stationary states.

Self-gravitating systems In general, real self-gravitating systems, like globular clusters, are in out-of-equilibrium quasi-stationary states. Nevertheless, it is instructive to study the corresponding equilibrium states within the micro-canonical ensemble, which is *a priori* the most appropriate statistical ensemble since the total energy is fixed a priori. The attractive gravitational interaction has to be regularized at short distances for preventing the collapse between point objects. Within the introduced microscopic description, we analyze the validity of the celebrated mean-field hydrostatic approach for computing the mass density profile [794]: the number of objects has to be sufficiently large, so local equilibrium states emerge, and they entirely depend on the short-range part of the pair interactions. These validity conditions are tested in a one-dimensional model of self-gravitating hard rods which is solvable [831].

Quantum plasmas at equilibrium The first principles description of a quantum plasma in terms of a mixture of electrons and nuclei interacting *via* the Coulomb potential, is crucial for dealing simultaneously with recombination and screening processes. The Feynman-Kac representation of the equilibrium density matrix leads to the introduction of an equivalent classical gas of loops, for which powerful diagrammatic techniques, taking into account Coulomb interactions in a non-perturbative way, are developed. This formalism is well suited for low-density and finite-temperature regimes, and it has been applied to the hydrogen-helium mixture which is of crucial importance in astrophysical systems, in particular in the Sun [813, 878]. The corresponding equation of state is derived by using analytic properties of the screened interaction [814], as well as quantum Monte Carlo computations of partition functions for He atoms, H^- and H_2^+ ions [878].

New approaches for critical Casimir forces Truncation of the diverging correlation length near a second order phase transition gives a singular contribution to the confining forces – the critical Casimir force. We have made three novel theoretical approaches to this phenomenon, all with manifest experimental consequences. The search for experimental realizations has so far ignored magnetic systems - a surprising fact given that they have long been considered as the paradigm for studies of criticality. In [829], we have created and tested a new protocol based on generalized thermodynamic forces. It could be adapted to experiments on magnetic thin films, or to systems as diverse as ferroelectrics, liquid crystals or polymers and could give access to all universality classes including quantum criticality. In [805] we have directly simulated the force in a binary mixture near the demixing transition, opening the door to Casimir force fluctuations and to non-equilibrium protocols. Finally, in [806] we have exploited the equivalence between quantum and classical systems in d and $d+1$ dimensions respectively, as well as the relationship between length and inverse temperature to extract Casimir forces in three dimensions from finite temperature non-perturbative renormalization group analysis of 2D quantum systems. This work gives convincing estimates of universal Casimir scaling functions in three dimensions for all O(N) models using theoretical methods other than simulation, while it also opens the door to experiments in cold atom systems.

We want to check several of these theoretical results by measuring with high accuracy the properties of the critical Casimir forces with an AFM technique. Due to the high accuracy of our apparatus we measured

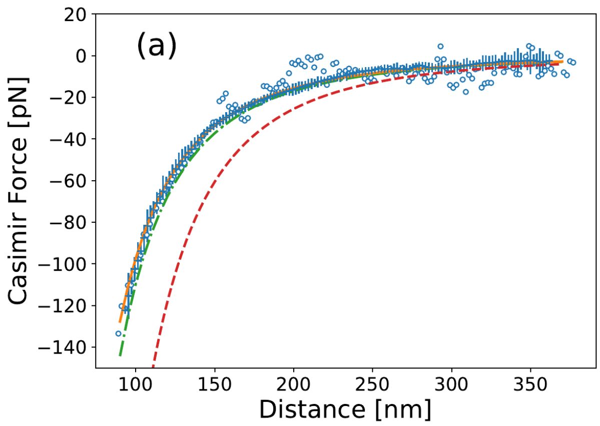

Figure 31: **Measure of the Casimir force between two golden surfaces in a nitrogen atmosphere**.Blue points correspond to the mean measured force.The continuous lines correspond to realistic models whereas dashed red line to the the ideal case (from [858]).

the role of the surfaces roughness in the standard electromagnetic Casimir forces in liquid and gases. In collaboration with a Dutch team, we demonstrated that roughness corrections to the forces are not negligible [858]. The measure of the critical Casimir is still running.

Bose-Einstein (BE) condensation It was first discovered for an ideal gas as an effect of quantum statistics. For the homogeneous infinite system, namely in the absence of any trapping potential like in cold atoms experiments, the effects of particle interactions on such transition has been a long-standing issue, which answer is not yet well established. In particular the role of the potential range was almost never analyzed in the literature. Within the familiar Hartree-Fock approximation, we showed that, at finite temperatures, for sufficiently long-range repulsive interactions, the BE condensation breaks down [787], contrarily to the short-range case where the BE condensation should persist. Such breakdown is due to the destructive interplay at large distances between the ideal critical correlations on the one hand and the particle interactions on the other hand.

Ionic criticality Classical ionic systems are expected to undergo a liquid-vapor transition, as observed in various experiments, and also predicted by theoretical approaches. The universality class of the corresponding critical point has been widely studied, with controversial results. At the moment, the most common belief is in favor of the Ising class. A satisfactory answer to this fundamental question requires to analyze the large-distance behavior of particle and charge correlations at the critical point. In fact, various works suggest that the long-range tails in particle critical correlations ultimately pollute the charge correlations with algebraic tails. This in turn implies the violation of the perfect screening of external charges, while the fourth moment of the charge correlations should diverge, in agreement with finite-size scaling Monte Carlo simulations. We derived a new sum rule which expresses this fourth moment in terms of thermodynamic quantities [810]. Such sum rule should be an useful guide for phenomenological approaches which account for the expected vanishing of the density of free charges at the critical point.

B. *Rare events and large deviation theory*

The determination of the small probability of rare events is often of great practical importance because they might have dramatic consequences. Large deviation theory is the main tool for the analysis, both at the theoretical and at the algorithmic levels. It allows to describe the statistics of macroscopic variables, currents, transition trajectories, transitions rates, starting from known statistics in path spaces for both equilibrium and non equilibrium dynamics. Various problems are considered ranging from transport properties of chains to the instabilities of the Solar system, and including climate dynamics or strong concentration inhomogeneities.

Interacting particle systems out-of-equilibrium Large deviation theory can be used to define a non-equilibrium free energy (or quasi-potential) that describes the probability of macro-states. In order to obtain explicit results, a perturbative approach to all orders for the calculation of the quasi-potential was developed [791]. It was applied at the lowest orders to the analysis of the dynamics of a system of 1d particles with mean-field interactions driven out of equilibrium.

Systems at equilibrium driven by small noises The transition rates between attractors are given by the classical Eyring–Kramers formula, established in its more general version by theoretical physicist in the 70' (Langer). A rigorous mathematical proof has been given by the group of Bovier during the last decade. The generalization of this classical formula to non-equilibrium dynamics has been derived recently, under generic although not fully general assumptions [825]. The derivation combines large deviation theory and path integrals.

Non-equilibrium dynamics In systems with time scale separation, when the average of the force is non zero, rare events are not given by diffusive approximation of the slow variable. A Fokker-Planck approximation is then not sufficient to study the rare events and one has to develop a large deviation theory of the fluctuations beyond the Gaussian approximation [822].

Rare event algorithms Because they are so rare, extreme events and transition paths are very difficult to observe. One can sample them very efficiently using rare event algorithms developed in statistical physics. However in order to deal with complex dynamics, these algorithms had to be adapted to partial differential equations [875], deterministic dynamics [884], and to the computation of return times [860]. The theoretical study of these algorithms also suggested to propose canonical feedback control [866], in order to improve their efficiency. These improvements have been crucial for applications in turbulent flows and climate dynamics [792, 823, 874].

Non-equilibrium statistical physics approach to rare events in astronomy For more than ten years, it is known that the chaotic solar system might be destabilized by a possible resonance between Mercury and Jupiter orbits. Establishing the probability of the first occurrence time for this event is a theoretical and numerical challenge. A natural hypothesis was that the noise created by the asteroid belt on the main planets, together with the Freidlin-Wentzell large deviation theory, could explain this rare event. Through a careful theoretical computation, the amplitude of this noise was estimated [882], ruling out this hypothesis. One has then to study the intrinsic chaotic dynamics of the eight planet to understand the destabilization. In a reduced model, on time scales of billions of years, we have demonstrated that Mercury resonance occurs through an instanton phenomenology: transition paths follow a predictable path called precursor.

Extreme concentration of matter Very uneven distributions of matter or energy occur in a wide range of situations. We have focused here on elementary problems, to describe the formation of regions with extreme concentration [881]. In simple dynamical systems with chaotic properties (positive Lyapunov exponents), we showed the existence of regions of phase space with strong *convergence*, which leads to the formation of extremely large concentrations, as well as empty ("void") regions [871]. We have introduced and solved a model of aggregation-fragmentation-diffusion of trails, which leads to an characterization of the size of the trails, as well as of the "void" regions [802].

C. *Out of equilibrium and stochastic processes*

In out of equilibrium situations, specific fluctuations associated with random processes play a crucial role in the dynamics, as well as in the generation of steady states. Such situations are often encountered in confined and small devices, but they also occur at the macroscopic level, like in earthquakes or frictional systems for instance. Interestingly, the fluctuation-dissipation theorem at equilibrium no longer holds, and transient versions based on stochastic thermodynamics can be derived in some cases. New dynamical phase transitions are observed, while fast relaxation processes towards equilibrium can be efficiently triggered. Eventually, chaotic dynamics may take place, displaying extreme and rare events which turn to be correlated in time, like avalanches in disordered elastic media. The laboratory produced both theoretical and experimental results on very different out of equilibrium and stochastic systems ranging from micro systems to social models passing through disordered and dissipative systems. Within the context of stochastic thermodynamics we wrote the introduction for the special issue of JSTAT on "Unsolved Problem on Noise" [867] and for an article in Nature Nanotechnology [840]. Finally a review on the experimental aspects of stochastic thermodynamics was demanded by the PRX editors [796].

Thermal noise of micro-cantilevers in and out of equilibrium. (LiPHY (Grenoble), LMA) We develop continuously a set of extremely high precision interferometers and other optical setups to measure the Brownian motion of micro-cantilevers, typically those used in atomic force microscopy. Thanks to the latest developments, fluctuations of deflection are resolved with a resolution better than the fm [870]. This world leading sensitivity is used to study the thermal noise on a wide frequency range (DC to 100 kHz). At equilibrium, the FDT (Fluctuation Dissipation Theorem) is used to assess the mechanical response of the sample. This strategy helps for instance in characterising the mechanical losses of the optical coatings of gravitational wave detectors, with the LMA [803, 807]. A cryogenic bench has been set up in the LMA as part of this collaboration, for further characterisation at low temperature.

Out of equilibrium, the FDT cannot be applied any more and many questions are still open with respect to the behavior of thermal noise in such a case. Our experiments demonstrate for example that in some cases, driven systems actually fluctuate *less* than what one would expect from the naive extension of equilibrium properties. Specifically, we create a NESS (Non Equilibrium Steady State) by shining a few mW of laser light on the tip of a micro-lever in vacuum: the absorbed power heats the lever and finds its way out through the clamped end at room temperature. The resulting temperature gradient is huge, as we can reach a temperature difference over 1000 K on a 500 μm length [808]. However, for a raw silicon cantilever, thermal fluctuations remain in the vicinity of those measured in equilibrium at room temperature ! This observation is interpreted using an extension of the FTD, computed in collaboration with E. Bertin (LiPHY,Grenoble), taking into account the spatial fields of temperature and mechanical dissipation: when clamping losses are dominant (the case of a raw silicon lever), fluctuations are insensitive to the actual temperature of the rest of the cantilever. To strengthen our conclusions, we perform a similar experiment on a cantilever coated with an amorphous material, which distribute the damping on the whole length [803]: in this case the fluctuation amplitude follows the mean temperature (defined by an average weighted by the local dissipation) [800].

Brownian particles and electric circuits Within the framework of the ERC contract Outeflucop several experiments have been developed. We worked on the stochastic heat transfer between two heat sources at different temperatures coupled only by the thermal fluctuations. In the past we have studied the problem in electric circuits with a potential coupling. We extended the study to Brownian particles for which the coupling is viscous [818]. A Fluctuation Theorem has been derived for the heat flux induced by the viscous coupling [815, 817]. A direct comparison between the results in electric circuits and Brownian particles has been also published in [816], where we discuss the analogies and differences of the viscous and potential coupling. In collaboration with a team of the Max Planck in Dresden, we study the stochastic properties of work in a periodically driven electric circuit [848] In collaboration with Baiesi's team in Padova, we used the results of these experiments for testing an out of equilibrium Fluctuation Dissipation Theorem, useful to compute the response of a system submitted to a temperature difference, when this difference is suddenly changed [812, 885].

Phase transitions A new Transient FDT has been studied using the quench at the critical point of the Fredericks transition in liquid crystals, where equilibrium FDT cannot be applied [876]. We have also revisited old measurements in an aging gel showing that the previously observed violation of FDT was a problem of interpretation related the data analysis [820]. We have observed and characterized a critical Casimir induced synchro- nization of the motion of Brownian particles driven by an external force [862]. Making measurements close to the critical point of a second order phase transition allows us to observe and to explain theoretically an oscillating phase transition induced by a localized constant perturbation [798].

Fluctuations at macroscopic scale. Stochastic thermodynamics applies when fluctuations are dominant. This is often implicitly assumed to occur in micron-scale systems as the one described in the previous section. However fluctuations may play an important role also in macroscopic systems driven out of equilibrium.

Within this context, we developed several experiments at macroscopic scales between a few millimeters and a dozen of centimeters. Our systems, such as granular gases [834], turbulent free jet at large Reynolds number, elastic plate in wave turbulent regime and nonlinear sliding blocks [789], must be driven to compensate the intrinsic dissipation. We validated, for all available criteria, the analogy between such macroscopic Non-Equilibrium Steady States (NESS) systems and micro-scale systems. This analogy holds as far as stochastic thermodynamics concepts are concerned: a heuristic use of the Gallavotti-Cohen Fluctuation Theorem and of the Fluctuation-Dissipation Theorem give effective temperatures $kT_{\text{eff.}}$ that agree to within 10%; The mean heat flux between two NESS systems is proportional to the effective temperature difference [795, 859], and the fluctuations of heat flux follows the extended fluctuation theorem (XFT) proposed by Jarzynski et al. in 2004. The important outcome is that, for all criteria investigated, no departure could be evidenced by changing the scale or the dissipation. We therefore consider for now the analogy as validated.

The significant advantage of working at human-scale is that any physical observable is easier to measure than at micron-size systems. As a consequence, many measurements are possible at cm-scale that are not at micron-scale. Besides, thanks to our newly

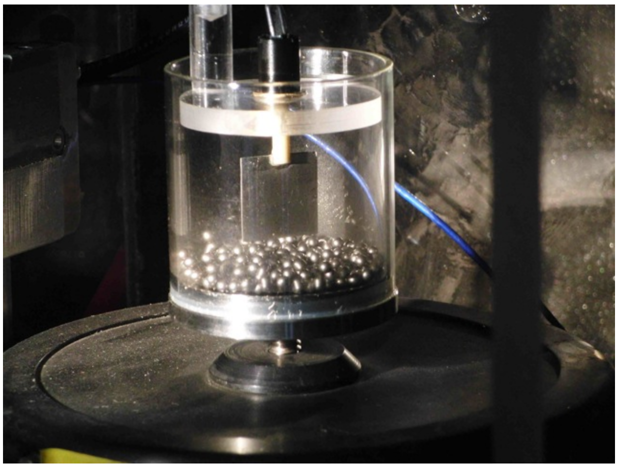

Figure 32: Granular-gas experimental system. A 2 cm diameter blade, fixed on the shaft of a dc micro-motor, on the axis of rotation of a 5 cm cell, is used as a 'thermometer' plunged in a gas consisting of a few hundreds of 3 mm stainless steel beads.

defined effective temperature, we are presently characterizing the transition from soft to hard turbulence, as defined in the 90^{s}.

Engineered Swift Equilibration (ESE) Motivated by our measurements on stochastic thermodynamics we look for optimization processes which allow a system to relax to a new equilibrium position much faster than its relaxation time. To do that we designed a protocol, named Engineered Swift Equilibration (ESE), that shortcuts time-consuming relaxations. We implement the process experimentally (on Brownian particles and AFM cantilevers) showing that it allows the system to reach equilibrium 100 times faster than the natural equilibration rate [838, 846, 857, 863]. The method paves the way for applications in micro- and nano-devices, where the reduction of operation time represents as substantial a challenge as miniaturization. Many questions remain open on this subject [839] that we will developed in the next years. An ANR started in January 2019 for a 4 years period has been obtained on this subject. Furthermore a patent has been submitted for the application of ESE to fast AFM measurements of surface potentials.

Information and Thermodynamics In 2012 we got a very interesting result by measuring for the first time the amount of energy necessary to erase a bit of information. We have shown experimentally that in the limit of long erasure processes the bound $k_B T \log 2$ can be approached in the quasi-static regime but not exceeded. This article is a major result because it strengths the connection between information and thermodynamics. This research on information and thermodynamics connections is in full development for the important consequences that it might have both for computation and for feedback controls based on Maxwell demon. Indeed a perspective article has been written for Physics Today in 2015 [861]. Other experimental results have been summarized in [819].

Another interesting theme that has been developed in the laboratory is the link between information and energy in quantum mechanics. We have build and characterized the first quantum version of a Maxwell demon [797] using superconducting circuits. Our experiment enables to directly measure the work extracted from the working agent by the demon and also to perform a state tomography of the memory of the demon. We have later proposed an engine that uses quantum measurement as a fuel [845].

Dynamics of forced probe particles in single file systems. The probes dynamics is another aspect of out of equilibrium. Using a hydrodynamic approach, we have shown that several driven probes in a single-file system can remain bound and move together, or unbind and move apart, depending on the external forces applied on them (Fig. 33). This transition is universal for diffusive single-file systems with short-range interactions [790]. When no external forces are exerted, the correlations between the positions of the probes have been completely characterized for the symmetric exclusion process at large density, using first passage time properties of the vacancies [869].

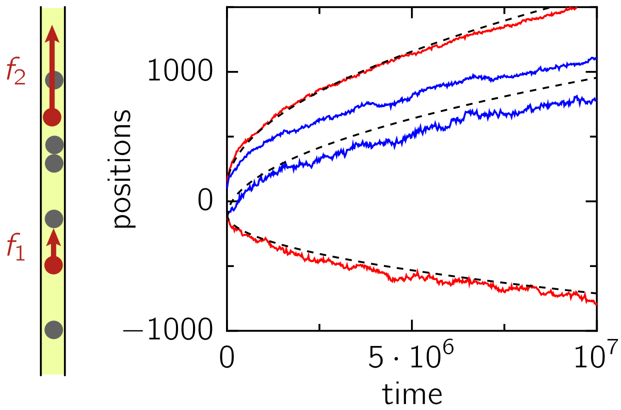

Figure 33: Two probe particles are submitted to external forces in a single-file system, their positions are shown as a function of time in two situations: blue, the probes remain bound and move as a whole, red, the probes unbind and move apart. The dashed lines show the theoretical prediction of our hydrodynamic model.

Stochastic dynamics of frictional systems Another subject, which concerns the statistical physics of driven sliding systems, has been developed both experimentally and theoretically. Specifically we studied experimentally the dynamics of a chain of sliders connected through elastic springs in frictional contact with an inclined plane. The dynamics is induced either by cyclic expansions and contractions of the rest length of the springs [821] or by the increase of the tilt [788]. In both cases, we focus on the creep, permanent or preceding the avalanche, paying special attention to the internal dynamics of the sliders.

From the theoretical side, we developed a method to describe the multiple scales which contribute to friction phenomena. The idea is to use a master equation to describe contact breaking and reforming, and to combine an ensemble of individual contacts into a "macro-contact" which can evolve with time. This approach was used to study seismic quiescence in earthquakes, this unexpected calm period which precedes some large events. We investigated the origin of seismic quiescence with a generalized version of the Burridge–Knopoff model for earthquakes and showed that it can be generated by a multi-peaked probability distribution of the thresholds at which contacts break. Such a distribution is not assumed *a priori* but naturally results from the aging of the contacts. This provides a generic understanding for seismic quiescence, which encompasses earlier specific explanations and could provide a pathway for a classification of faults [793].

Effect of quenched disorder on large-scale properties and phase diagrams of many-body systems This is a challenging problem in out of equilibrium statistical physics. Functional Renormalization group (FRG) is a powerful method which allows one to study a large class of phenomena dominated by disorder. The examples include elastic systems such as imbibition fronts in porous media and crack propagation in disordered materials as well as classical and quantum disordered spin systems. In [811], we studied the dynamics of a d-dimensional system of $O(N)$ quantum rotors in the presence of random fields. While single particle localization is rather well understood within the standard theory of Anderson localization, localization of interacting particles is a much more complicated problem where many questions remain open. We showed that localization of interacting spin waves is described by a zero temperature quasi-classical fixed point similar to one dimensional many body localization described by an infinite randomness fixed point. Both thermal and quantum fluctuations turn out to be dangerously irrelevant like the temperature in the random field Ising model. This drastically changes the dynamic scaling picture that one could expect from a naive RG treatment. Appearance of non-analyticity in the FRG prevents the system from equilibration by inducing an activated dynamics with diverging barriers at finite temperature and localization of spin waves at zero temperature.
Self-avoiding walks (SAWs) and loop-erased random walks (LERWs) are two ensembles of random paths with numerous applications in mathematics, statistical physics and quantum field theory. While SAWs are described by the $N \to 0$ limit of ϕ^4-theory with $O(N)$-symmetry, LERWs have no obvious field-theoretic description. In [880], we analysed two candidates for a field theory of LERWs, and discovered a connection between two a priori unrelated theories. The first theory is the $O(N)$ symmetric ϕ^4 model at $N = -2$ whose link to LERWs was known in two-dimensions due to conformal field theory. The second theory is a model of charge-density waves (CDWs) pinned by quenched disorder, whose relation to LERWs had been conjectured earlier using analogies with Abelian sandpiles. In [880], we showed that both theories yield identical results to 4-loop order and gave a non-perturbative proof of their equivalence. This fact, overlooked for decades, drastically simplifies the study of the depinning transition for periodic elastic systems. We also prove that both models can be used to describe LERWs in arbitrary dimension d. This connection allowed us to compute the dynamic critical exponent for CDWs at the depinning transition and the fractal dimension of LERWs in $d = 3$ with unprecedented accuracy in excellent agreement with numerical simulations.
Avalanches & Depinning We studied the avalanche dynamics of interfaces, slowly driven through random media, focusing on the imbibition dynamics of a viscous wetting fluid invading a model fracture [236, 237, 804, 841], and the slow crack propagation along a weak heterogeneous interface [323, 853]. A scale-dependent statistical analysis of the temporal behavior of the spatially averaged velocity of those fronts reveals a strongly intermittent dynamics with global avalanches, resulting from localized bursts, that fulfill scaling relations expected close to a critical depinning transition.
For the fracture study, a striking result has been to reveal the artificial appearance of temporal correlations between avalanches ("aftershocks"), resulting from their measuring procedure (thresholding) [261, 853]. Furthermore, we have shown that the collective motion of cell migration occurs by bursts of activity described by scaling laws, similar to the ones observed for material failure or fluid imbibition [837].

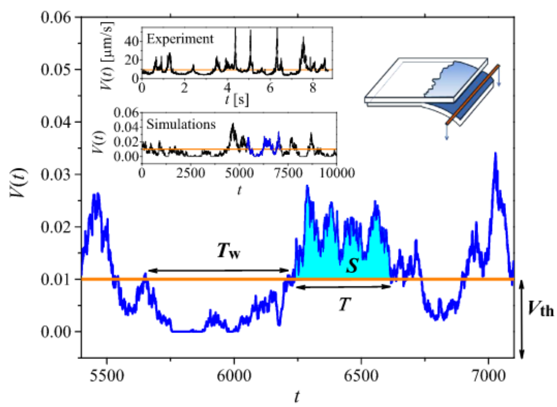

Figure 34: Planar crack-front velocity time series $V(t)$, with avalanches of size S, duration T, and waiting time T_W, resulting from applying a finite threshold level V_{th}.

Models of social systems These systems are intrinsically out of equilibrium and simple models may be conceptually useful to correct our intuitive interpretation of social mechanisms. For example, the segregation model proposed by Schelling [801] helps understanding why the collective state reached by agents may be different from what each of them seeks individually. However, their relevance for real social systems is moot. What is more, since physicists have always needed to 'tame' the world inside laboratories to make their models relevant, we suggest that social modeling might be linked to human taming, a smashing political project [877].

Statistical Physics: *Indicators*

Defended PhD Thesis

Name	Title	Date	Supervisor(s)
X. Clotet	Imbibition in a model open fracture	11/07/2014	S. Santucci, J. Ortin (UiB)
M. Geitner	Température effective d'un système hors équilibre : fluctuations thermiques d'un microlevier soumis à un flux de chaleur	23/10/2015	L. Bellon
A. Bérut	Interactions et fluctuations de particules browniennes piégées par des pinces optiques	07/07/2015	S. Ciliberto A. Petrosyan
C. Devailly	Fluctuations thermiques : un outil pour étudier les fluides simples et binaires à l'échelle du micron.	16/12/2014	S. Ciliberto, A. Steinberger
A. Le Cunuder	Étude expérimentale des forces de Casimir	07/03/2017	S. Ciliberto, A. Petrosyan
D. Lopez Cardozo	Finite size scaling and the critical Casimir force: Ising magnets and binary fluids	22/10/2015	P. Holdsworth
M. Champion	Mécanique statistique des systèmes auto-gravitants	29/06/2015	A. Alastuey
D. Wendland	The equation of state of the Hydrogen-Helium mixture with application to the Sun	30/10/ 2015	A. Alastuey, V. Ballenegger
N. Cottet	Energy and information in fluorescence with superconducting circuits	20/11/2018	B. Huard
J.Y. Chastaing	Mécanique statistique de systèmes macroscopiques hors-équilibre	13/07/2016	J.C.Geminard, A. Naert
E Woillez	Stochastic description of rare events for complex dynamics in the Solar System	21/09/2018	F. Bouchet
T. Tangarife	Kinetic theory and large deviations for stochastic jets	16/11/2015	F. Bouchet

Main contracts

3 European: ERC OUTEFLUCOP(90%), ERC TRANSITION(50%), Marie Curie TRANSTURB (50%)
1 MegaGrant (Russia)
1 ANR: STATE

Editorial responsibilities

Angel Alastuey, Freddy Bouchet, Sergio Ciliberto
Journal of Statistical Mechanics, Associate Editors
Sergio Ciliberto, Alain Pumir
Physical Review E, Members of the editorial committee
Thierry Dauxois, Alain Pumir
Journal of Physics A, Members of the editorial committee

Organized conferences

Angel Alastuey
Strongly Coupled Coulomb Systems, Santa Fe (USA), juillet 2014
Strongly Coupled Coulomb Systems, Kiel (USA), juillet-août 2017
Angel Alastuey, Thierry Dauxois, Peter Holdsworth, Michel Peyrard, Nicolas Taberlet
STATPHYS26, Lyon (France), July 2016
Freddy Bouchet
Theoretical Advances in Planetary Flows and Climate Dynamics, Les Houches (France), March, 2015.
Statistical mechanics and computation of large deviation rate functions,Lyon (France), June 2015
Adaptive Multilevel Splitting et événements rares, Paris (France), June 2016.
Extreme events in the Earth and planetary sciences , Warwick(Great Britain), July 2016.
Fundamental aspects of turbulent flows in climate dynamics , Les Houches (France), July-August 2017
ENS de Lyon meets SISSA, Lyon (France), December 2017.
Nonequilibrium Systems in Physics, Geosciences, and Life Sciences, Trieste (Italy), May 2018.
Andrei Fedorenko, Peter Holdsworth, Tommaso Roscilde
Middle European Cooperation in Statistical Physics (MECO42), Lyon (France), February 2017.
Stephane Santucci:
Avalanche Dynamics and Precursors of Catastrophic Events, Les Houches (France), Février 2019
Crackling Materials, Nordita Program, Stockholm (Sweden), Juin 2018
Statistical Physics of Materials, Satellite Meeting of Stat. Phys.16, Aussois (France), Juin 2016
Avalanches and Intermittency, Courmayeur (Italy), Mars 2015
Avalanches Shapes, Courmayeur (Italy), Janvier 2014
Alain Pumir
From Pattern Formation to Turbulence, Bad Staffelstein (Germany), Juin 2019.

99 publications in peer reviewed journals: see T7B.

III. PUBLICATIONS

A. Monographies

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[2] *Explorations in Time-Frequency Analysis*, P. Flandrin, Cambridge University Press (2018).

[3] *Physics of Long-Range Interactions*, A. Campa, T. Dauxois, D. Fanelli and S. Ruffo, Oxford Univ. Press (2014).

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[5] *Physics and Mathematical Tools: methods and examples*, A. Alastuey, M. Clusel, M. Magro and P. Pujol, World Scientific (2015).

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B. Chapters of Books

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[8] *New exponents for pointwise singularities classification*, P. Abry, S. Jaffard, R. Leonarduzzi, C. Melot and H. Wendt, in "Recent Developments in Fractals and Related Fields", J. Barral and S. Seuret (Eds), Birkhäuser (2017).

[9] *Mechanical Sensing of Living Systems — From Statics to Dynamics*, F. Argoul, B. Audit and A. Arneodo, in "Biosensors — Micro and Nanoscale Applications", T. Rinken (Ed), InTech (2015).

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[11] *Confiner les liquides pour les comprendre*, D. Bartolo and C. Cottin Bizonne, in "L'eau à découvert", A. Euzen, C. Jeandel and R. Mosseri (Eds), CNRS Editions (2015).

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[15] *Kinetic theory and quasilinear theories of jet dynamics*, F. Bouchet, C. Nardini and T. Tangarife, in "Zonal Jets: Phenomenology, Genesis, and Physics", B. Galperin and P. L. Read (Eds), Cambridge University Press (2019).

[16] *Some Aspects of Lagrangian Dynamics of Turbulence*, M. Bourgoin, in "Mixing and Dispersion in Flows Dominated by Rotation and Buoyancy", H. Clercx and G. J. Van Heijst (Eds), Springer (2017).

[17] *Some Aspects of the Collective Dynamics of Particles in Turbulent Flows*, M. Bourgoin, in "Collective Dynamics of Particles: From Viscous to Turbulent Flows", C. Marchioli (Ed), Springer (2017).

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[22] *Maxwell's demon in superconducting circuits* N. Cottet and B. Huard, in "Thermodynamics in the quantum regime — Recent Progress and Outlook", F. Binder, L. Correa, C. Gogolin, J. Anders and G. Adesso (Eds), Springer (2019).

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[34] *Avalanches, non-Gaussian fluctuations and intermittency in fluid imbibition*, J. Ortin and S. Santucci, in "Avalanches in Functional Materials and Geophysics. Understanding Complex Systems", E. Salje, A. Saxena and A. Planes (Eds), Springer (2017).

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