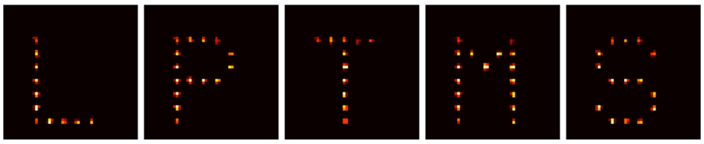
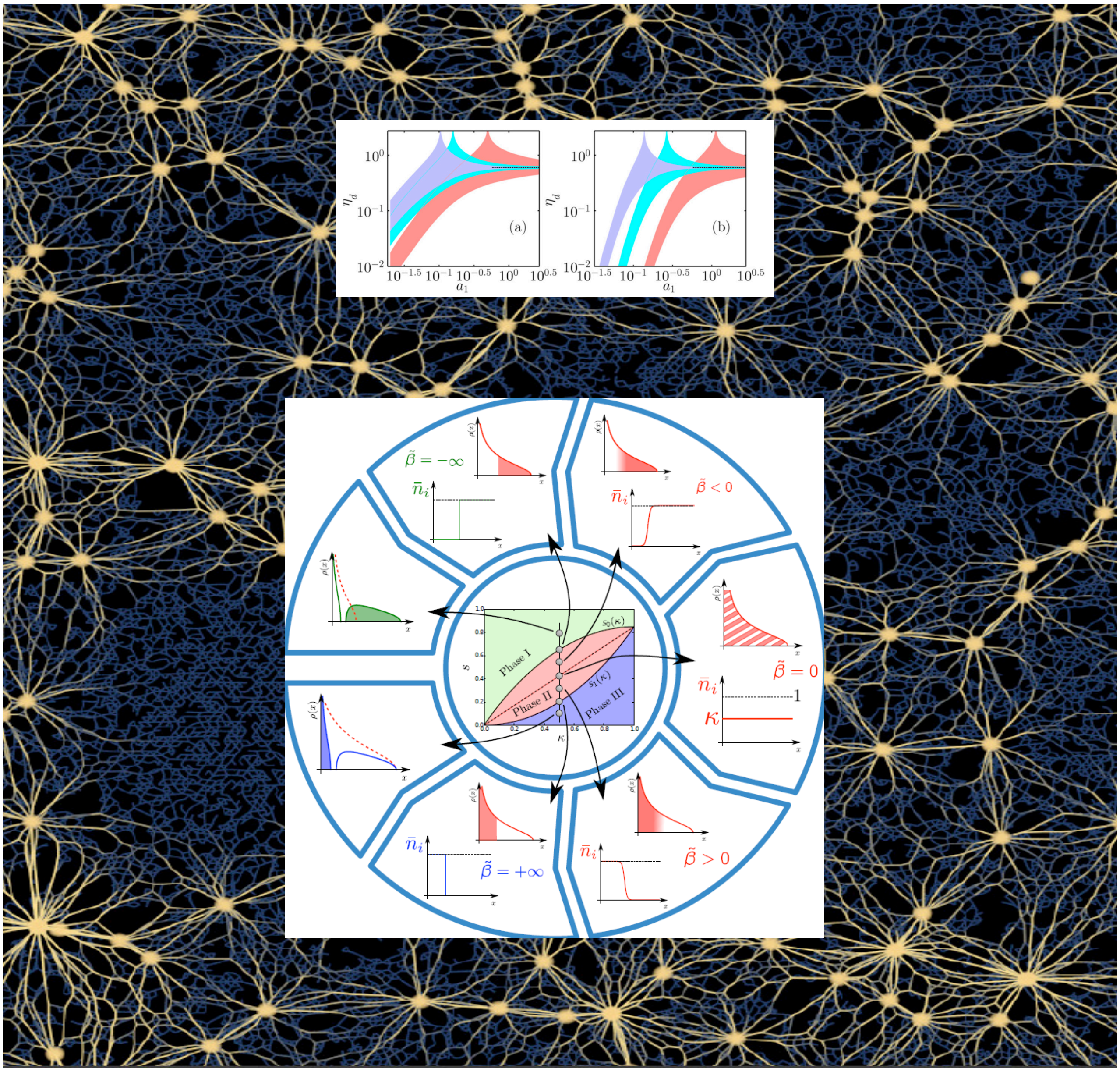
HCERES 2013-2018



Fluorescence images of individual atoms trapped in arrays of optical tweezers separated by a few micrometers (courtesy of A. Browaeys, IOGS, 2017)



<u>A glimpse of research at LPTMS</u>: controlling three-body observables by a Floquet drive (Sykes, Landa & Petrov, upper picture), random matrix theory wheel of fortune (Grabsch, Majumdar & Texier), stress generation in a biopolymer network (Ronceray & Lenz, background).

1. Presentation of the laboratory and its environment

Introduction
The LPTMS (Laboratoire de Physique Théorique et Modèles Statistiques) is a joint Paris-Sud University and CNRS unit (Unité Mixte de Recherche 8626). We are currently located in the valley of Orsay campus. End of 2018, we will change premises to occupy a brand new building, on the plateau.

The laboratory turns 20 years old in 2018. Initially an offspring of the "Division de Physique Théorique" within the Orsay Nuclear Physics Institute, its activities gradually expanded to cover a large gamut of subjects in the realm of statistical physics. Research at LPTMS aims at modeling, qualitatively understand, and quantitatively describe complex phenomena arising in diverse areas of ("low-energy") physics and related disciplines. Our activities thereby highlight the common grounds between condensed matter and quantum fluids, span a spectrum of themes pertaining to equilibrium and non-equilibrium statistical systems, and explore a growing number of interfaces, with mathematics, computer science, biology, or social sciences in particular. In essence, our effort is in understanding emergent and collective phenomena.

2 – Visibility, accolades and overview of achievements

The lab visibility starts with the quality of the staff, collaborators and corresponding scientific production. Among the **500 peer-reviewed articles** we published between January 2013 and May 2018 (excluding proceedings), there are more than **70 papers in the Physical Review Letters or Physical Review X**, and about **90 including journals such as PNAS, Nature, Nature Physics, Nature Communications, Science and Cell**. Yet, visibility can also be assessed from other perspectives. During the 2013-2018 time-span, several lab members

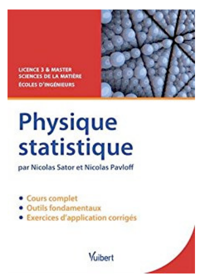
- received distinctions: ERC grants for G. Shlyapnikov and M. Lenz, several adjunct professorships for S. Majumdar (Raman Research Institute, VARJA, Tata Institute of Fundamental Research), IUPAP

Young Scientist prize and EMBO Young Investigator award for M. Lenz, Institut Universitaire de France for S. Franz and E. Trizac, Paris-Sud seed funds for C. Texier, Outstanding APS Referee award for D. Petrov, E. Bogomolny and G. Shlyapnikov), trophée Tangente award for H. Krivine; besides, several of our students received awards (prizes from the Bettencourt-Schueller foundation, French-Italian PhD prize, IOP best paper in J. Phys. A); we also note that among former LPTMS graduates, there are 3 CNRS bronze medal, 2 ERC recipients, one SFP Langevin prize, and some already are full professors,

- were invited as plenary speakers in main conferences, named lectures, summer schools (StatPhys 2013, StatPhys 2016, Liquid Matter, Berkeley Statistical Mechanics Meeting, Rutgers Statistical Mechanics Conference, Les Houches, Gordon Conference, APS March Meeting, KITP, Cargèse, IHP, ESI, Newton Institute, Simons Center, etc), and have been active in the African Institute for Mathematical Sciences.
- have participated in various European networks (including ETN, ITN), editorial boards (JSTAT, Phys. Rev. Lett. where S. Majumdar has been a divisional associate editor, J. Stat. Phys., J. Phys. A, EPL...),
- acted in governing bodies at the national or international scale (CNRS where P. Leboeuf was a deputy director for physics during 5 years, Institut Henri Poincaré where G. Schehr is a member of the board of directors, Les Houches where T. Jolicoeur was the head of the predoctoral program, Comité National de la Recherche Scientifique where S. Franz and V. Terras were or are active, Conseil National des Universités for C. Texier, ANR panel for N. Pavloff and S. Ouvry, European Physical Society...),
- occupied high profile positions (M. Mézard at ENS Paris, P. Leboeuf at CNRS/INP then IDEX Paris-Saclay).

We note that the large majority of lab members – more than twice the mean national figure – has been awarded a “*Prime d'Excellence Scientifique*” (PES/PEDR), either by CNRS or by the University. Our important implication in local committees, and in the “*Investissements d'Avenir*” program was summarized in section 1. We turn to conferences, several large scale of which, plus winter or summer schools, were organized under the auspices of the lab (total of 38 events, see Appendix 3). A large number of those has been supported by our administrative staff. The lab is also involved in the organization of the recurrent “*Journées de Physique Statistique*”, a well known two-day meeting point taking place in Paris end of January.

The lab visibility also goes through the publication of monographs. C. Texier addressed an undergraduate audience with his books “*Mécanique quantique, cours et exercices corrigés*” (L and M levels, Dunod, second edition in 2015) and 'Physique statistique, des processus élémentaires aux phénomènes collectifs” (same level and editor, in collaboration with G. Roux, 2017). LPTMS capitalizes on competition since another pair (N. Pavloff from the lab and N. Sator, a former PhD student of ours, now at Sorbonne-Université) published “*Physique Statistique*” (Vuibert), a year before. We have already presented publications for the public at large in section 2.



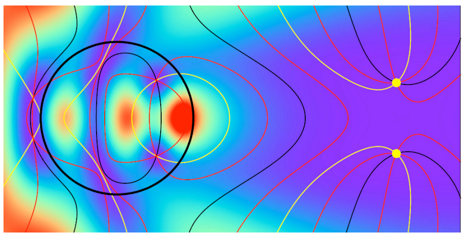
Finally, we enjoy an active visitor program (40 to 50 people per year for stays that exceed the week), and we can further gauge the lab attractiveness by the quality of the students (17 PhDs currently under way), and the post-docs (currently 11). For instance, we had about 40 applications for the lab post-doc in 2016, in spite of a suboptimal timing. In 2018, our assistant professor position attracted 45 applicants, out of which 10 were shortlisted, and were truly high level. This represents about the same pressure as for the notoriously difficult CNRS junior competition (around 200 applications for 4 positions), with strong overlap for the best files.

3 – Scientific report

The present scientific report is for the period between January 2013 and June 2018. It is not meant to be exhaustive, but aims at providing an overview of the research performed, and focuses on a number of highlights. It goes with the complete list of publications provided in Appendix 4, where the references mentioned below can be found. They are ordered by team for convenience, and cited such that [T1-n] is for the regular peer reviewed article number *n* of team 1 etc. [CSP-n] stands for the production involving members of different teams (Common Scientific Production). Proceedings and book chapters are gathered separately, under [T1-Mn], where the M stands for “Miscellaneous”. Most of our papers can be found on the ArXiv, and are systematically uploaded on HAL repository.

3.1 Condensed matter and quantum fluids

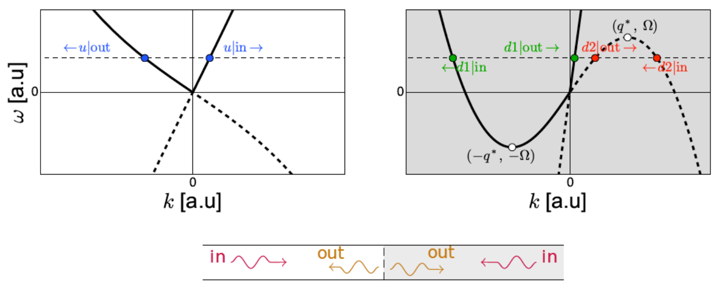
There are currently 8 permanent members, 6 PhD students and 2 post-docs in the team, The main topics in recent years have been at the crossroads between atomic or molecular physics on the one hand, and condensed matter on the other. This includes a number of strongly correlated systems. Topological features appear in different clothing across a large fraction of our completed, ongoing, or future projects.



Analog Hawking radiation

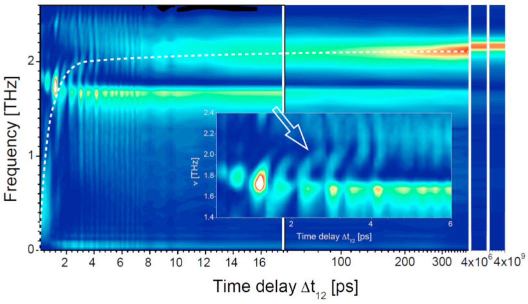
We have proposed to study momentum correlation for detecting acoustic Hawking radiation in Bose-Einstein condensates. Indeed, one of the most celebrated predictions of the late Stephen Hawking is the fact that black holes are not completely black, but emit a small radiation triggered by vacuum fluctuations. For practical reasons, it cannot be detected. Yet, it has been proposed that hydrodynamical systems exhibiting a kinetic structure similar to that realized at the horizon of a gravitational black hole would emit an analogous acoustic radiation. One of the major goals of scientists working in the domain of analogous gravity is to detect and study the quantum properties of this acoustic Hawking radiation. We have analyzed the flow of a quasi-1D Bose-Einstein condensate past an obstacle realizing an acoustic horizon (the upstream flow is subsonic, while downstream is supersonic). The theoretically evaluated momentum correlation pattern across this horizon displays clear signatures of analogous Hawking radiation, with a structure induced by the correlations between the Hawking phonon (emitted upstream) and its partner which is dragged by the downstream supersonic flow. Moreover, the intensity of these correlations gives a direct measure of the entanglement of the two quasi-particles. We proposed several realistic scenarios for measuring this entanglement and showed that the signal is quite resilient to thermal decoherence: the signature of the quantum non separability persists even at temperatures larger than the chemical potential, which is quite remarkable [T1-36].

[Permanent member involved: N. Pavloff]

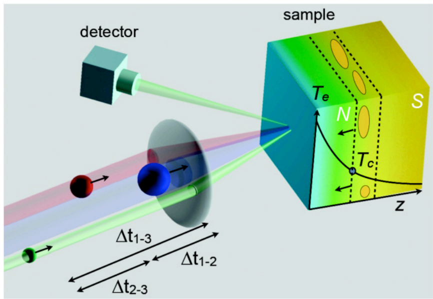


Collective phenomena in layered materials

We modeled spatio-temporal evolution after optical pumping of excitons which are coupled to a symmetry-breaking order parameter. A quasi-condensate of excitons appears as a macroscopic quantum state which then evolves by interacting with other degrees of freedom prone to instability. This coupling leads to self-trapping of excitons; this locally enhances their density which then can exceed a critical value and trigger a dynamical phase transition. The system consequently becomes stratified into domains which are persistent, evolving through a sequence of merging events, after the initiating excitons have recombined. The theoretical work was inspired by experiments performed in Japan as well as in France (Rennes Univ.) [T1-56, T1-57].



The injection or pumping of charge into some layered materials leads to the formation of globules or to a network of charged domain walls created by the intrinsic Coulomb instability of the super-lattice of self-trapped electrons [T1-31, T1-50, T1-84, T1-102]. Monte Carlo simulations [T1-109] of this 2D classical charged lattice gas show an ordering phase transition followed by a gradual coalescence of point defects into interconnected segments of domain walls, which subsequently branch at vertices where vorticity is concentrated. The surprising effective attraction coming from the purely repulsive Coulomb interactions follows from the charge fractionalization across the domain wall.



Broken symmetry states in quasi-1D electronic systems respond to charge injection or spin polarization by forming a concentration of microscopic topological defects - the solitons [T1-M6]. Under cooling, the ensemble of solitons in a coupled array of chains undergoes two phase transitions: confinement of individual solitons into bound pairs; then aggregation of microscopic solitons into macroscopic domain walls. This was confirmed by Monte Carlo studies including the destructive role of long range Coulomb interactions [T1-71].

[Permanent member involved: S. Brazovski]

Cold atom physics

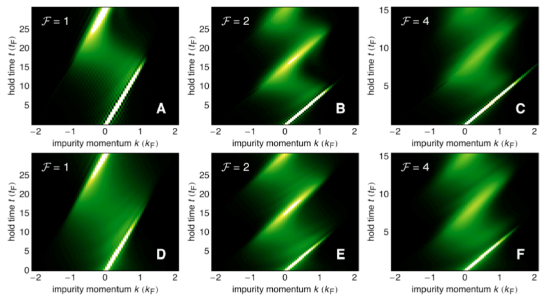
We developed a theory describing a stable topological px+ipy superfluid of (identical) microwave-dressed polar molecules in 2D optical lattices, which is promising for topologically protected quantum information processing. A sizable critical temperature of tens of nanokelvins is achievable here due to the long-range character of the intermolecular dipole-dipole interaction. We then showed that moderate 2D lattices strongly reduce the rates of inelastic decay processes for short-range interacting identical fermionic atoms compared to free space, still retaining a sizable critical temperature for p-wave superfluidity. This result is now in the agenda of experimental groups as it provides the most spectacular way of creating topological p-wave superfluids [T1-62,T1-89].

Together with D. Papoular (Cergy) and the experimental group of M. Zhan (Wuhan, China), we considered collisional stability of a two-atom system in a small trap, which indicated the possibility of creating two-qubit quantum gates using atoms in different states. The next work was on the creation of the CNOT gate and entangled state of two atoms of different isotopes (rubidium) via Rydberg blockade, with almost no crosstalk at short interatomic distances. These investigations open new horizons for quantum computing with cold atoms [T1-104].

In the domain of exotic quantum fluids, the work concerned finding generic and stable supersolid states in free space. These exotic states should demonstrate both crystalline order and superfluidity (fluid with a crystal structure of the density). We found and described dilute supersolid states of dipolar bosons (polar molecules or magnetic atoms) in a bilayer geometry, where unlike in a single layer the emerging 3-body repulsion prevents the collapse of the supersolid. Ultracold polar molecules are now actively studied and experiments on superfluid properties of supersolids may become a new domain in nanophysics [T1-44].

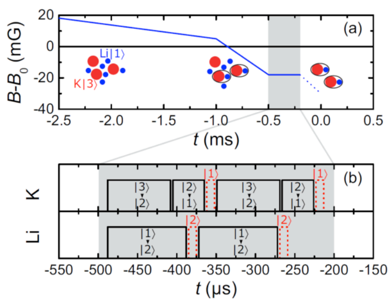
In the domain of non-conventional disordered quantum systems, we first considered weakly interacting bosons in the quasiperiodic potential representing a superposition of a deep lattice and a shallow incommensurate lattice. We then described the interaction-induced localization-delocalization transition at finite temperatures. This revealed an anomalous "freezing with heating" phenomenon in which an increase in temperature leads to fluid-insulator transition, thus favoring the insulator state. The work with X. Deng, L.

Santos, and B.L. Altshuler considered dipolar excitations propagating via dipole-induced exchange among immobile molecules randomly spaced in a 3D lattice. It was shown that all eigenstates are extended, but can be non-ergodic. This is the first work that found bands of extended non-ergodic states in a physical system and it indicates a possibility of a novel ergodic-nonergodic phase transition [T1-26, T1-61].



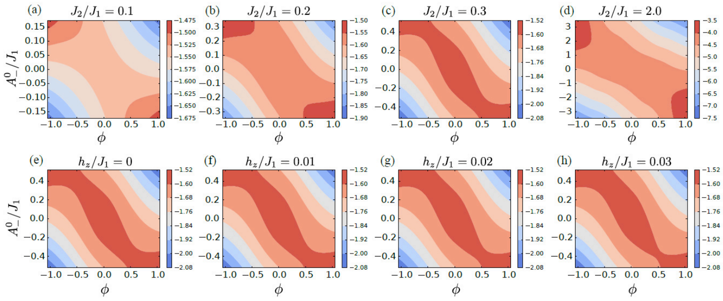
We have experimentally investigated the quantum motion of an impurity atom that is immersed in a strongly interacting one-dimensional Bose liquid and subject to an external force. We find that the momentum distribution of the impurity exhibits characteristic Bragg reflections at the edge of an emergent Brillouin zone. While Bragg reflections are typically associated with lattice structures, in a strongly correlated quantum liquid they result from the interplay of short-range crystalline order and kinematic constraints on the many-body scattering processes in the one-dimensional system. As a consequence, the impurity exhibits periodic dynamics that we interpret as Bloch oscillations, which arise even though the quantum liquid is translationally invariant. Our observations are supported by large-scale numerical simulations [T1-96].

According to the mean-field theory, a condensed Bose-Bose mixture collapses when the interspecies attraction becomes stronger than the geometrical average of the intraspecies repulsions. We have shown that instead of collapsing, such a mixture gets into a dilute liquid-like droplet state stabilized by quantum fluctuations, thereby providing a direct manifestation of beyond mean-field effects. We have studied various properties of the droplet and found, in particular, that in a wide range of parameters, its excitation spectrum lies entirely above the particle emission threshold. The droplet thus automatically evaporates itself to zero temperature, a property that is potentially interesting from the viewpoint of sympathetic cooling of other systems. This theory turned out to be relevant also for dipolar gases tuned close to the collapse instability. Droplets stabilized by such beyond-mean-field effects have recently been observed experimentally in dipolar Dy and Er atoms, as well as in Potassium mixtures. The physics beyond-mean-field in the weakly-interacting regime is currently of broad interest in the domain of ultracold gases [T1-48].
[Permanent members involved : G. Shlyapnikov, D. Petrov, M. Zvonarev]

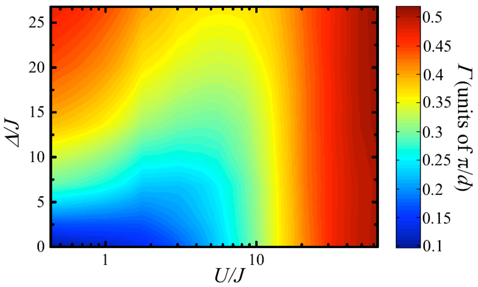


Strongly interacting Quantum systems

Topology is a mathematical concept that aims at classifying shapes by some features that are robust against deformation. Tools from differential geometry provide an analytic description of surface and volume that help to compute some of these invariants, such as Chern numbers. In quantum mechanics, differential geometry appears for instance when varying the Hamiltonian parameters or in the Brillouin zone of some non-interacting particles Hamiltonian. Since the 80s, it has been demonstrated that some observables, for instance conductivity of a quantum Hall material, are connected to the topological structure of the wavefunctions. A current trend in condensed matter physics is to further explore these aspects and to extend them in the case of interacting particles. In this context, we discussed the simplest geometry that allows for a quantum flux to pierce through, the two-leg ladder. In the case of interacting bosons, as realized in experiments, we found a physics reminiscent of the fractional quantum Hall effect [T1-99]. In two-dimensions, we proposed a way to create a topological Hamiltonian for bosons using Floquet engineering [T1-100]. Last, by studying the bosonic version of the Kane-Mele model, we found that such systems host an exotic chiral phase in the Mott regime [T1-113].



The Aubry-Andre model can be realized experimentally using two incommensurate lattices filled with cold atoms. This highly controllable setup has been recently used in two emblematic topics of disordered quantum systems: Bose glass physics and many-body localization. In this context, we have been involved in the recent experimental investigation of the interaction versus disorder phase diagram [T1-16,T1-66], testing some of our previous predictions. Inhomogeneity and finite temperature effects play a key role in the interpretation, while non-thermalization issues observed at strong interaction could be a fingerprint of many-body localization. We also proposed Bragg spectroscopy as a probe of the localization mechanism [T1-12], which is different from the usual Anderson mechanism.
An ongoing direction for quantum simulators is to gain precision and reach longer lifetime. In the context of Rydberg based quantum simulators, we have contributed to numerical simulations of a proposal made by colleagues at College de France [T1-111]. It shows promising results that call for a deeper understanding of the proposed setup.
[Permanent member involved: G. Roux]

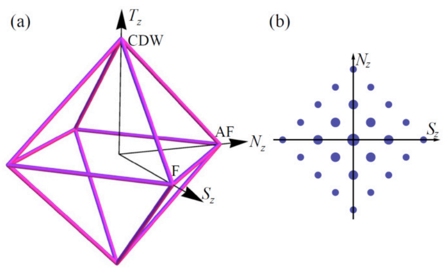


Geometry dependent decoherence in metallic devices

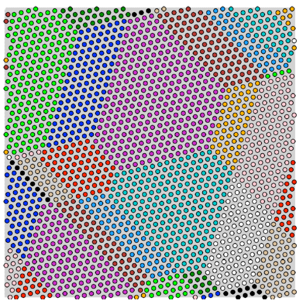
Phase coherence has been a major question in condensed matter as it concerns the frontier between the classical and the quantum worlds. A relevant playground to investigate this problem is the study of electronic transport in metallic devices. Several probes of phase coherence have been used in the mesoscopic physics community: persistent currents in metallic rings, weak localisation, or mesoscopic conductance fluctuations. In particular, this raised the question whether these various tools provide the same definition for the phase coherence length, which is the fundamental scale above which quantum interferences are destroyed. In a series of earlier theoretical works with several collaborators, we investigated the role of geometry of the device on decoherence, which is important in order to interpret the experimental data in metallic rings or grids, the most convenient devices for studying interference effects. This is crucial as it permits to interpret correctly the temperature dependences observed and identify the microscopic mechanisms governing decoherence, dominated by electronic interaction at low temperature. A first experimental validation was provided within a collaboration with the team of H. Bouchiat at LPS (Orsay), by investigation of the weak localisation of large grids. We also collaborated with an experimental team of Institut Néel which has compared the phase coherence obtained from weak localisation in long metallic wires (i.e. averaged properties) and the one extracted from the Aharonov-Bohm oscillations of a single ring (i.e. from mesoscopic fluctuations). This work is reported in Ref. [T1-2] where two lengths have been demonstrated to coincide.
[Permanent member involved: C. Texier]

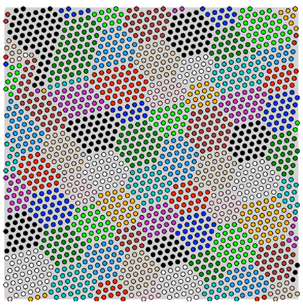
Quantum Hall physics

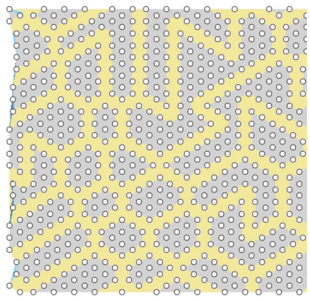
Two-dimensional electron gases under a strong perpendicular field exhibit incompressible liquid states that are the realm of the fractional quantum Hall effect. A successful theoretical paradigm is the "composite fermion", an entity made of one electron bound to two flux quanta, whose main virtue is to map the fractional quantum Hall onto the integer quantum Hall effect. This is a powerful idea since this latter effect can be understood without interactions. For half-filling of the lowest Landau level, the theory predicts the formation of a gapless Fermi sea of these quasiparticles which do not feel the external applied magnetic field. It is known that the situation is more complex in the second Landau level where instead of this Fermi sea, experiments show again an incompressible i.e. gapped state. It was proposed some time ago that the effective composite fermions may have a pairing instability which leads to the gapped state at filling nu=5/2. This state, called the "Pfaffian" state, remains mysterious nowadays notably if one realizes that its particle-hole conjugate is also a good candidate to describe the 5/2 state. In the real world, virtual transitions of electrons towards both higher and lower Landau levels break the particle-hole of an isolated Landau level and hence decide which is chosen between the Pfaffian and its partner dubbed the "AntiPfaffian". Detailed studies by numerical techniques on massively parallel computers have given evidence for the Pfaffian state, leading to definite falsifiable predictions for various transport properties. It remains to be seen if real samples have anything to do with the Pfaffian predictions [T1-46,T1-50].



[Permanent member involved: Th. Jolicoeur]

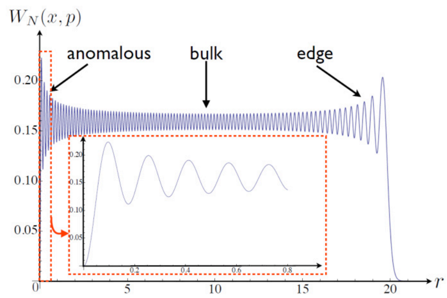






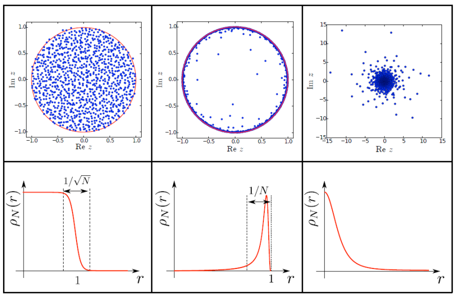
3.2 Statistical physics, field theory and integrable systems

This group (currently 10 permanent members, 5 PhD students and 2 post-docs) is a front runner in a broad range of topics in diverse areas of statistical physics (extreme value and record statistics, localisation problems in disordered systems, stochastic processes), with a strong proficiency in random matrix theory, and quantum statistical mechanics in low dimensions. The study of non-equilibrium dynamics in quantum many-body systems, together with quantum information theory and entanglement has also been the thrust of research in the last five years.



Random matrix theory (RMT) and its various applications

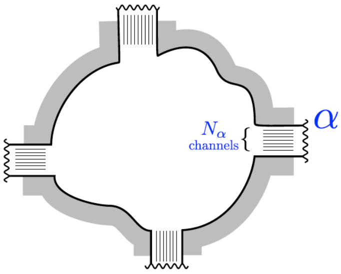
A novel subject related to the distribution of eigenvectors of non-standard random matrices was attacked. Inspiration comes from the recent observation that careful measurements of neutron resonance widths contradict the Porter-Thomas law, considered as one of the most universal benchmarks of random matrix theory. Different scenarios have been proposed to explain this disagreement. In [T2-124], we found an exact solution of a model put forward earlier for this purpose. The results demonstrate that certain modifications of random matrices are indeed capable to explain the experimental observations. The methods used in [T2-124] allow to find an exact solution of the Rosenzweig-Porter model [T2-161], which recently caught the attention of physicists and mathematicians. It is characterized by the existence of unconventional non-ergodic phase. The obtained solution is in excellent agreement with numerical simulations and constitutes the first instance of an exact solution for a model with non-trivial fractal dimensions. Very recently, the investigations of power-law banded random matrices was initiated in the intermediate regime where no analytical methods can be applied. The results demonstrate the existence of a new eigenvector distribution. The latter is quite different from the Porter-Thomas law but shares a number of universal properties with it.



An important universal observable in many-body disordered systems is the ratio of two consecutive level spacings, as it is often insensitive to the details of the global density of states. We studied the statistical properties of this ratio, in a variety of random matrix models and explored its universality [CSP-1, T2-2].

An interesting exact connection was uncovered, between the positions of 1d non-interacting fermions in a harmonic trap at zero temperature and the eigenvalues of random matrices belonging to the Gaussian Unitary Ensemble (GUE). Exploiting this connection, new results were found for the edge properties of fermions. Generalization to higher dimensions, finite temperature and arbitrary potentials was achieved. At finite temperature and in one dimension, the edge properties of fermions were shown to be related to the height distribution in the 1+1 dimensional Kardar-Parisi-Zhang equation. Another application of this mapping to GUE has been to compute the full counting statistics and the entanglement entropy of the fermions in a trap [T2-46,T2-65,T2-71,T2-109,T2-142, CSP-21,CSP-28].

A related effort addressed the statistics of the largest eigenvalue in a class of random matrix models, in particular its large deviation properties. The large deviation function was shown to have a non-analytic behavior at a critical value of its argument, the fingerprint of a universal third-order phase transition from a strong coupling to a weak coupling phase. This third-order phase transition was shown to be generic and appeared in a number of *a priori* unrelated models in statistical physics [T2-43,T2-114,T2-133,T2-153,CSP-9,CSP-11]. *This body of work was highlighted in Nature Physics (by M. Buchanan), Quanta Magazine (by N. Wolchover) and also as a CNRS news item ("alerte scientifique").*

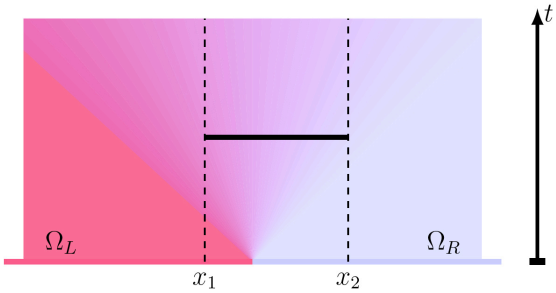


Another important observable in RMT is the linear statistics of eigenvalues, e.g. the Wigner time delay associated with mesoscopic transport in quantum cavities. Several results were derived for the statistics of Wigner time delay, using Coulomb gas method [T1-39, T1-67, T1-82, CSP-11]. By adapting this technique, a new class of truncated linear statistics (involving only a restricted number of large eigenvalues) was introduced and studied in [CSP-25, CSP-26].

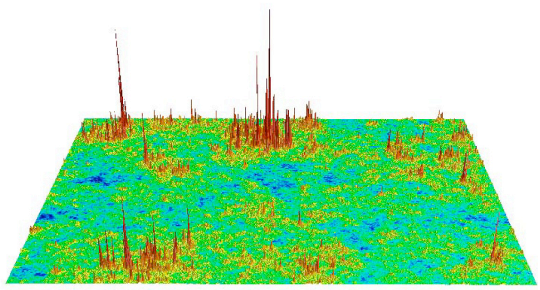
During the last few years, **localization theory** has remained a question of central interest. Our studies have clarified the links between the Dyson-Schmidt route to 1D localization and the approach using the product of random matrices. In particular, the role of the Weyl function has been discussed in detail in [T2-M9]. Another intriguing issue is to understand why the Lyapunov exponent is often expressed in terms of special functions, in particular hypergeometric [CSP-2]. It was shown that these special functions are eigenstates of some operators, which occur in the representation theory of semi-simple Lie groups.
Motivated by the physics of the Anderson localization, another line of research focused on the statistical properties of the products of random matrices in various models and obtained several exact results for the associated Lyapunov exponent [T1-17,CSP-2,CSP-3]. Its fluctuations were worked out in [CSP-16]. A more general multichannel model (Dirac equation with random mass) was considered in [T1-68], presenting topological phase transitions driven by the disorder.
[Permanent members involved: Bogomolny, Comtet, Giraud, Majumdar, Schehr, Texier+ Roux from team 1]

Quantum statistical physics in low dimensions

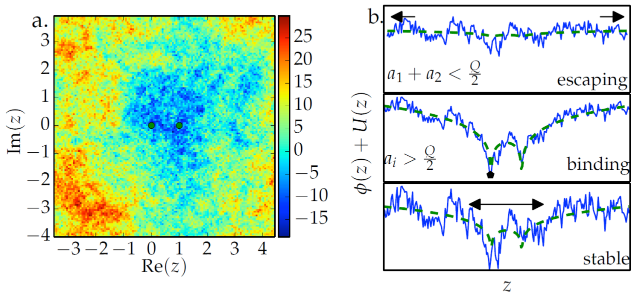
We studied the **nonequilibrium dynamics of low-dimensional many-body quantum systems** [P-5, P-6, P-7, P-8, P-9, P-10,P-11]. In particular, the late-time behaviour of local observables in the XXZ chain (a paradigm of interacting integrable model) has been analyzed [P-14,P-16]. We found new conservation laws in the quantum XY model [P-12], and identified two mechanisms of pre-relaxation: one of them is based on the breaking of non-abelian integrability, while the other is related to spontaneous symmetry breaking at exactly zero temperature. Quench dynamics in the presence of inhomogeneities in the initial state was addressed [P-15], also when the Hamiltonian has localized defects. These investigations resulted in the development of what is now known as ``generalized hydrodynamics'', which has the remarkable by-product of giving an exact analytic expression for the expectation value of the currents of conserved operators in interacting models solvable by Bethe ansatz [P-17].



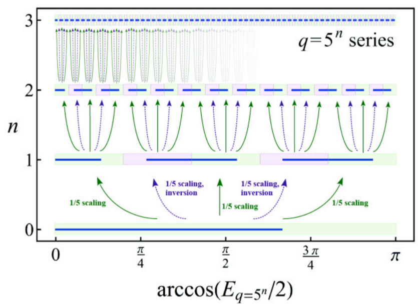
A significant effort was invested in characterizing the **multi-fractality of quantum wavefunctions**. Quantum particles in a disordered potential can be localized by quantum interferences, a phenomenon first described by Anderson. At the localization-delocalization transition, wavefunctions have multifractal amplitude distributions. Various models with such a critical behaviour were proposed and studied [T2-34, T2-74], allowing the exploration of basic mechanisms and properties associated with quantum multifractality: symmetry of critical exponents, link with spectral compressibility, connection with logarithmically correlated processes and extreme value statistics. *This work led to a CNRS "alerte scientifique" in 2014.*



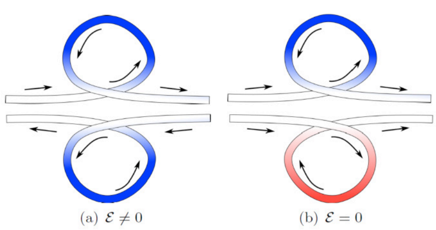
Conformal Field Theory provides a method of choice for unraveling the intricacies of two-dimensional statistical models. These include geometrical properties of clusters in critical percolation addressed using the numerical 2D conformal bootstrap technique [T2-10, T2-22, T2-55, T2-95, T2-122], the calculation of the symmetry function in Toda theories [T2-61, T2-101, CSP-22], the Casimir effect with inhomogenous boundaries [CSP-19, CSP-24] and the connection between Liouville field theory and log-correlated random variables [CSP-17, CSP-20, CSP-23, CSP-29]. In the latter case, an exact mapping was established between specific Liouville field theory and the Gibbs measure statistics of a thermal particle in a 2D Gaussian Free Field plus a logarithmic confining potential. The probability distribution of the position of the minimum of the energy landscape was obtained exactly by combining the conformal bootstrap and one-step replica symmetry breaking methods. Operator product expansions in Liouville Field Theory allowed to unveil novel universal behaviours of the log-correlated Random Energy models.



For **quantum integrable systems** in one-dimension, Bethe Ansatz is perhaps the most famous method of resolution, but there exist numerous integrable situations in which it cannot be directly applied. During the last five years, we studied several such examples: the antiperiodic XXZ chain [T2-88], the antiperiodic elliptic solid-on-solid model [T2-115], and the celebrated eight-vertex model with all types of quasi-periodic boundary conditions, including notably the long-standing problem of the periodic case with an odd number of sites [T2-119]. For all these models, the quantum Separation of Variables method has been used to diagonalize the Hamiltonian, and the usual separation characterization of the spectrum has been reformulated into a more manageable description in terms of a functional T-Q equation of Baxter's type, i.e. a set of Bethe-type equations. In simple cases (antiperiodic [T2-113] and open [T2-140] XXX chains), the scalar products of separate states have moreover been computed in a simple and manageable form, in terms of the roots of these Bethe equations.



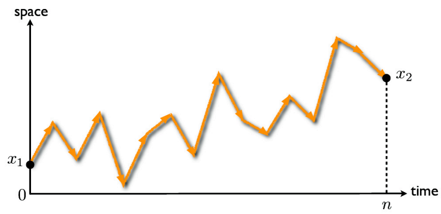
The moments of the modified Bessel functions, that appear in the perturbative Feynman expansion in a model of a random magnetic impurity, were investigated [T2-20]. In [T2-19] and [T2-49] we focused on the properties of the winding angle (in velocity space rather than in the position space), in analogy with the Thomas precession (spin-orbit). Two models in 2d were studied, where the currents associated with these winding angles were shown to be concentrated at the edges of the sample. In [T2-47, T2-66, T2-86, T2-120, T2-146, T2-156] spectral properties of the quantum Hofstadter Hamiltonian were analyzed using various techniques. These include the "sieving phenomenon", calculation of the moments of the Hamiltonian as well as the Thouless bandwidth formula and its generalization.
[Permanent members involved: Fagotti, Giraud, Ouvry, Santachiara, Terras+ Rosso and Emig from team 3]



Diverse areas of statistical physics

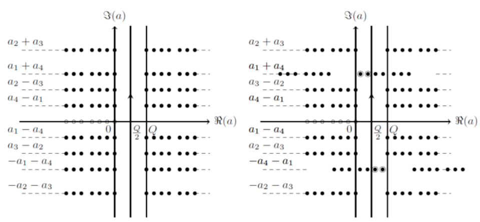
Quantum information. Characterization and detection of multipartite entanglement is largely an open question. We developed a theory of multipartite entanglement of spin states [T2-131], and in particular established a tensor representation allowing to make connections with a well-studied problem in mathematics, the truncated moment problem [T2-147]. Various analytical results we obtained, and an algorithm based on semi-definite programming was developed. In collaboration with mathematicians, the connections between entanglement and tensor eigenvalues [T2-126] were also investigated.

Stochastic resetting. The phenomenon of stochastic resetting was addressed in various clothings. Any stochastic process evolving under its own natural dynamics, when subjected to a resetting to the initial condition at random times, approaches at long times a nontrivial non-equilibrium stationary state. The corresponding dynamics was shown to be rather unusual, and to involve a dynamical phase transition [T2-84]. An optimizable and efficient search algorithm ensued. This was demonstrated exactly for various random-walk models [T2-12,T2-25,T2-35,T2-85,T2-127], including Lévy flights [T2-42]. Furthermore, the resetting dynamics was also studied for extended systems such as fluctuating interfaces, leading to non-trivial height-distribution in the reset induced stationary state [CSP-14].



Extreme value statistics and related topics. Computing the statistics of extremes, or of records, in a correlated time series is a hard problem with a wealth of applications, ranging from climate studies to finance. An example of such a correlated series is a random walk sequence (including Lévy flights), for which several exact results for extreme and record statistics were obtained over the last few years [T2-11,T2-14,T2-16,T2-21,T2-52,T2-112]. For instance, for a discrete time random walk sequence of n steps, when does the maximum occur and what is its value? What about the next maximum? These questions naturally emerge when studying the statistics of aftershocks in earthquake models. Similar problems pertaining to the gap (between the two first maxima) and order statistics are also relevant for branching random walks in one dimension. Exact solutions were achieved in a series of works [T2-16, T2-44, T2-52, T2-92, T2-93, T2-118, T2-144, T2-145]. Another application is in two dimensions where the properties of convex hulls of a correlated stochastic processes (such as Brownian motion and branching Brownian motions) were computed exactly using a connection to extreme value statistics of the associated 1d-component process [T2-67, T2-68, T2-69, CSP-5]. These results were applied to understand the geometrical properties of the home range of animals in ecological models, as well as to describe the outbreak of epidemics of animal populations [CSP-5]. Related questions arise for systems with many particles, interacting or not. For instance, the distribution of the span (i.e., the distance between the rightmost and leftmost sites visited by the walker) of a system of N noninteracting Brownian motions on a line is rather non-trivial, with interesting scaling behavior for large N, that was computed exactly in [T2-14]. For interacting walkers, these questions are even more challenching. In the specific case when the walkers are non-intersecting, explicit results were obtained for their extreme statistics in [T2-41]. A topical review on the subject of records and extremes was written [T2-136].

[Permanent members involved: Giraud, Majumdar, Schehr + Rosso from team 3]

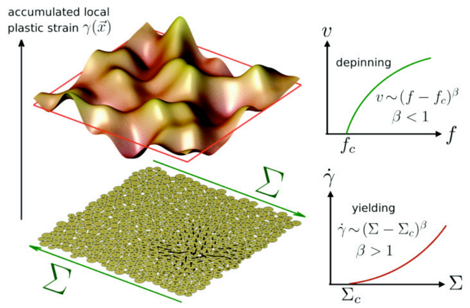


3.3 Disordered systems, soft matter and interdisciplinary applications

The group (currently 6 permanent members, 6 PhD students and 7 post-docs) is active in a variety of problems, from amorphous, glassy and disordered media to soft condensed matter. A particular thrust deals with interdisciplinary applications, with works in biology, urban science, nuclear hyperpolarization, and sociophysics to understand how collective decisions emerge.

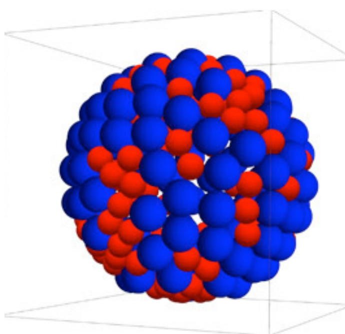
Disordered, amorphous and glassy systems

We attacked the **physics of avalanches** from various angles, from glassy systems or close to jamming [T3-154] to non-conventional statistics displayed by realistic models. In particular we studied the shear of amorphous solids and showed the presence of a pseudo-gap of the excitation that is at the origin of an extended criticality [T3-93] and new scaling relation between critical exponents. Our study pointed to a connection between the yielding transition of sheared amorphous materials and the depinning transition of an elastic interface [T3-61]. More recently, we studied the long-standing problem of ultra-slow motion of a magnetic domain wall in presence of a small magnetic field (creep regime). This reveals the existence of large spatio-temporal patterns composed by main shocks and aftershocks [T3-153] similar to the ones of earthquakes models [T3-56].



[Permanent member involved: Rosso]

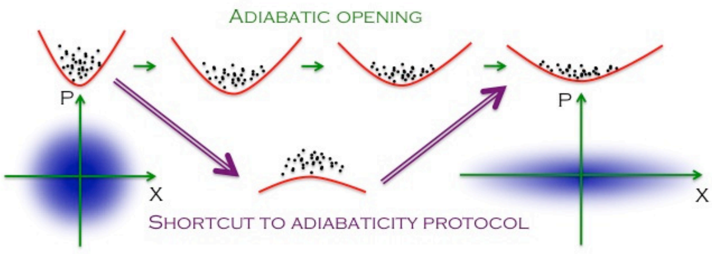
When jamming meets constraint satisfaction problem. Glassy phenomena in condensed matter can be viewed as a manifestation of generic features emerging in complex energy landscapes. Our interest has been in the applications of the mean field theory of glasses in Computer Science and Information Theory, with an effort to progress in the theory of structural glasses, the description of the route to the glass transition on the one hand and the properties of glasses at low temperature on the other. During the reporting period, in addition to network dynamics related studies [T3-44,T3-71,CSP-27], we formulated a quasi-equilibrium description of glassy relaxation and aging that allows to exploit static approximations to describe slow dynamics [T3-8]. We here highlight one line of research that has proven successful, dealing with universality at the jamming transitions [T3-84 ,T3-127,T3-155], as can be found in amorphous packings of spheres.



Jamming points are reached through athermal compression, when the space where particles can move decreases to zero. The system is then mechanically marginally stable and critical. At variance with usual phase transitions, the critical exponents –which are nontrivial– do not appear to depend on space dimension, and have been computed within mean field theory. We have connected jamming to the Constraint Satisfaction Problem of optimization theory, in the case of continuous variables, studying a neural network, the perceptron, close to the capacity limit for storing random patterns: the jamming transition of the model. The perceptron is a machine-learning algorithm with a long history of applications. Parameters dependent, one has a convex or a nonconvex optimization problem: jamming is non critical in the former but critical in the latter. In the convex case, jamming is approached from a liquid phase while in the nonconvex case, it occurs from a marginal glass phase. Surprisingly, we find the same exponents as when packing spheres. We conjecture a unique superuniversality class for continuous nonconvex Constraint Satisfaction Problems, depending on the glassy nature of the configurations in the vicinity of jamming.
[Permanent member involved: Franz]

Soft-Matter and physics-biology interface

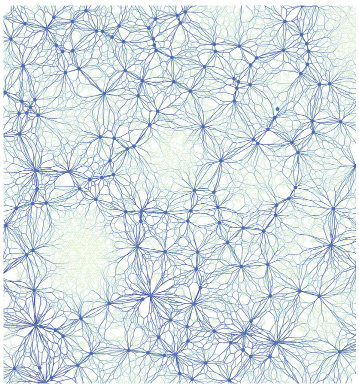
We have achieved a better description of strongly-coupled charged colloids, a difficult problem due to the failure of traditional mean-field approaches [T3-24,T3-139,T3-181]. This required the shaping of analytical tools that allowed to solve pending questions in the field of Wigner Crystals [T3-110]. We also emphasize here our progress in computing analytically the electrostatic bending rigidity of rigid charged charged polymers, a long-standing problem, with the conclusion that the bare persistence length of double-stranded DNA has hitherto been overestimated by some 20% [T3-142].



From an impossible equilibration to better AFM imaging protocols. In 1872, Boltzmann wrote a most influential paper establishing a key bridge between microscopic dynamics and macroscopic irreversibility, through the so-called H-theorem: a dilute gas thereby evolves towards equilibrium, where it is ruled by Maxwell-Boltzmann statistics. He soon after realized that when the gas is confined by a harmonic trap, more general time-dependent solutions could exist, where the mean size and temperature of the gas oscillate with time without dissipation, giving rise to 'breathing modes'. These results were hitherto considered as mathematical curiosities, but in 2015 though, the first three dimensional realization of these breathers was

achieved at JILA with Rubidium atoms, see our News&Views [T3-89]. In collaboration with D. Guéry-Odelin (Toulouse), we have recently shown that this class of solutions could be extended, in particular to time-dependent trapping of classical or quantum gases [T3-50]. The trap frequency then becomes a function of time. The new exact solutions for the Boltzmann equation hold for arbitrary short-range interaction potentials, and can be used to propose an original molecular manipulation technique. The idea, in a reverse engineering perspective, is to work out what time-dependent confining potential is required to achieve a fast prescribed time evolution of the state of the system, thereby short-cutting slow transformations. Since magnetic confinement techniques for cold atoms do not offer the same degree of control as their optical counterpart and in an effort to test our predictions in the lab, we initiated a collaboration with the group of S. Ciliberto in Lyon. Our idea was then exported and worked out in two different contexts, 1/ for a Brownian confined colloid [T3-134], a typical soft matter system, where the dynamics is ruled by a Fokker-Planck equation, and 2/ to shorten the equilibration time of an AFM cantilever [T3-133]. The latter study unexpectedly led to a patent for improved AFM protocols. Other H-theorem related works were led in the field of granular gases, where we have conjectured a Lyapunov functional for the dynamics of free and forced system, a so far elusive question (collaboration with mathematicians, and former LPTMS post-docs).
[Permanent member involved: Trizac]. These works led to two CNRS news items ("alertes scientifiques").

Statistical physics in the cell. In **biophysics,** our work consists in theoretical and physical approaches in close collaboration with experimentalists and biologists (at MIT, the University of Chicago, the University of Geneva as well as several French laboratories). We highlight two main contributions concerning the **cytoskeleton** and the **cell membrane**. [T3-136] is a milestone in a long-term endeavor to elucidate the geometrical origins of actomyosin activity through both theory and experimental collaborations. The essence of the project is to question a fundamental biological function that the community has too long held for granted, namely that mixtures of cytoskeletal filaments and motors generate contraction. While the geometrical foundation of this contractility is straightforward in the well-organized striated muscle, its origin in the much more versatile disordered actomyosin assemblies found throughout non-muscle cells is confounded by a fundamental symmetry between contraction

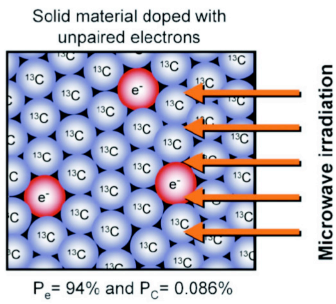


and extension (Lenz *et al.*, *Phys. Rev. Lett.* 2012). We have offered a simple solution to this puzzle, namely that the elastic properties of actin gels themselves rectify *any* motor-induced forces towards contraction while also amplifying them considerably. By questioning muscle-like mechanisms as the only valid paradigm for actomyosin contraction, this body of work could redefine a cornerstone of our understanding of cell motility, and demonstrates that crucial biomechanical processes can be elucidated through concepts of emergent collective behaviors originating in simple mechanical nonlinearities.

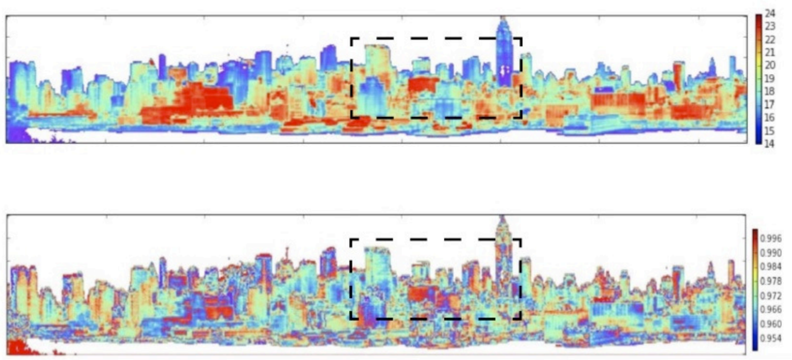
The second contribution highlighted here, [T3-78], illustrates our activity in the field of membrane-protein interactions and our close work with experimentalists – here A. Roux along with the Scheuring group – to elucidate questions of direct interest to biologists. We investigate the protein complex ESCRT-III, which remodels lipid membranes in many cellular processes. Our collaborators use electron microscopy, micromanipulation experiments and high-speed imaging to characterize the function of this complex on multiple length and time scales. We use theory to unify and bridge the gap between experimental techniques and infer the missing biophysical information. We thus reconstruct a coherent picture of the biologically crucial – but not directly observable – mechanical stresses that underly the function of ESCRT-III. Theory is thus involved at all levels in this study, from data analysis to the understanding of the main mechanism (largely based on an original proposal in Lenz et al., *Phys. Rev. Lett.* 2009), to the formulation of critical predictions that we successfully validate.
[Permanent member involved: Lenz]. These works led to two CNRS news items ("alertes scientifiques").

Statistical physics in the hospital

Nuclear Magnetic Resonance is one of the most powerful tools to obtain *in vivo* images with peerless resolution and pronounced contrast between different tissues. Groundbreaking perspectives for NMR rely on the possibility of designing novel contrast agents with huge levels of nuclear spin polarization. **Dynamic Nuclear Polarization** (DNP) is to date the most flexible and effective technique to increase the nuclear polarization by 4 to 5 orders of magnitude. Its traditional explanation goes back to Abragham and is based on the idea that the spin system, when irradiated, cools down to an effective thermodynamic state characterised by a low spin temperature. Yet, what is the microscopic origin of this temperature? In these last five years, we strived to answer this question, first with phenomenological approaches [T3-3], and then with models of disorder interacting quantum spins [T3-79, T3-193]. Our conclusions are that the DNP performances are related to the ergodicity properties of the spin system. In particular, when the latter is many-body localised, a weak hyperpolarization is reached, while in the so-called Eigenstate-Thermalization Hypothesis phase, hyperpolarization is efficient. We predict an optimal DNP performance at the transition between both regimes. Recently, we established a collaboration with a leading NMR group who confirmed our main picture [G. Bodenhausen, PSL & Sorbonne Université]. At the moment, our theory is the only one that predicts correctly the performance of DNP as a function of the radical concentration.



[Permanent member involved: Rosso]. This work was chosen as a highlight by PALM Labex.



Statistical physics in the city: urban science.

While one research direction over the last 5 years has applied methods of statistical physics to a plethora of systems, such as the field of fluctuation induced effects, multidisciplinary activities emerged in urban science (traffic and climate models). As an example, we describe our work on **Urban Thermodynamics.** Cities are home to the majority of the world's population and thus significantly determine global energy consumption, waste, and pollution. The dynamics of the urban energy budget, especially the thermal exchange between the

densely built infrastructure and the surrounding environment, are not well understood. We have studied the dependence of Urban Heat Island (UHI) on urban geometry [T3-172]. Multi-year urban-rural temperature differences (the intensity of UHI) and building footprints data combined with a heat radiation scaling model, are used to demonstrate for more than 50 cities world-wide that city texture – measured by a building distribution function and the sky view factor – explains city-to-city variations in nocturnal UHI. In a second line of research, we map surface radiations from nearly 100 blocks of Manhattans West Side in New York City [T3-168]. This includes measurements using a hyperspectral imaging instrument, and a theoretical radiosity model for calculating the measured radiation [T3-152]. The model results are subsequently compared with the measured values.
Our results show a strong correlation between nocturnal UHI and the city texture. This points to urban design parameters that can be modulated to mitigate UHI in planning and retrofitting of cities. In a broader context, our work suggests that tools and methods from statistical physics, at the right scale, can provide means to quantitatively address the response of cities to climate. These results complement previous studies on factors influencing day-time UHI. For our study of surface temperatures in New York City, the close comparison of temperature values derived from measurements and the computed surface temperatures implies that our geospatial, thermodynamic model applied to urban structures, is promising for accurate and high resolution analysis of urban surface temperatures. The next step is to implement a time dependent analysis.
[Permanent member involved: Emig]. This work attracted national coverage, with an article entitled "C'est chaud une ville la nuit", in "CNRS le Journal" (2018).

Statistical physics in the City: sociophysics and mean-field games

Mean field games were introduced independently by Lasry/Lions, and by Huang/Malhamé/Caines, in order to bring a new approach to optimization problems with a large number of interacting agents. The description of such models splits in two parts: one describing the evolution of the density of players in some parameter space, the other the value of a cost functional each player tries to minimize for himself, anticipating on the rational behavior of the others. This rapidly growing field has until now been developed essentially by applied mathematicians and engineering science researchers with the collaboration of economists and other social sciences. With T. Gobron (Cergy), we have demonstrated that physicists can bring a specific and relevant contribution to the field, by providing a deeper understanding of the solution of the Mean-Field Games models. This is particularly true in the case of Quadratic Mean Field Games, in which the dynamics of each player is governed by a controlled Langevin equation with an associated cost functional that is quadratic in the control parameter. In such cases, we have shown that there exists a deep relationship with the non-linear Schrödinger Equation in imaginary time. This makes it possible to transfer to the analysis of Mean-Field Games a wealth of techniques and approximation tools developed by physicists in the latter context. The case of positive strong coordination in particular can be essentially understood in terms of the motion of a soliton. Its formation and evolution can be obtained from the analog of the Ehrenfest relations as well as from the introduction of an action, from which a variational approximations scheme can be designed [T3-141].
[Permanent member involved: Ullmo]. This work led to a CNRS "alerte scientifique" in 2016.