# Contents

# 1

# Physique Statistique des Systèmes Complexes (PhyStat)

**The PhyStat group addresses a large variety of problems using the analytical and numerical tools of statistical physics, and in particular, out of equilibrium statistical physics. It has developed a strong activity in the field of soft condensed matter physics (ionic fluids, polymers, lipidic films...), biophysics of the cell membrane and DNA/proteins, and behavioral biology/physics of society, collaborating and sharing contracts with several experimental groups of biologists and physicists. The PhyStat group also has a strong expertise in fundamental statistical physics, in particular regarding the applications of stochastic processes in various contexts, exactly solvable models, and the physics of long-range interacting systems (with applications to astrophysics, fluid turbulence, chemotaxis...).**

## 1.1 Statistical mechanics for biophysics and soft condensed matter

*N. Destainville, M. Manghi*

In the group, applications of statistical mechanics to biophysics, biology and soft matter range from fundamental research to more applied works, notably in collaboration with experimental groups (in Toulouse, Montpellier, Germany and Italy), where questions raised by experimental facts are explored.

### DNA and tethered particle motion

*DNA denaturation bubble dynamics*

Using metadynamics simulations, F. Sicard (postdoc, LPT, 2013-15), N. Destainville and M. Manghi have studied how a metastable DNA denaturation bubble of a dozen of base-pairs closes and possibly re-opens. By constructing the free-energy landscape (Figure 1.1), it has been shown that the closure/nucleation of such a metastable bubble is controlled by the cooperative twist of all the bubble base-pairs. Closure times of 50 $\mu$s, as measured by Altan-Bonnet *et al.*, have been obtained and nucleation times on the order of 1 ms have been predicted [13, 37].

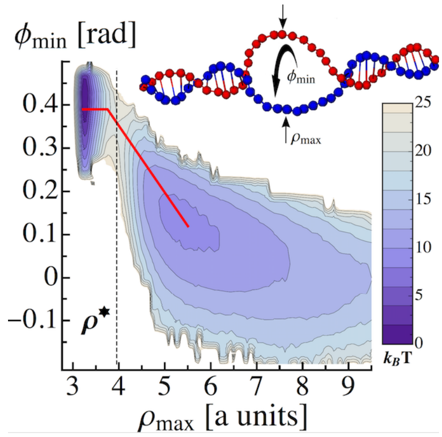


***Figure 1.1 :*** *Free energy lanscape associated with the bubble nucleation/closure mechanism. The maximum distance between bases is $\rho_{\max}$ and the minimum twist angle between successive base pairs, $\phi_{\min}$. In red the minimum free energy path [13].*

*DNA studied by Tethered Particle Motion*

The collaboration between biophysicists of the IPBS, L. Salomé, C. Tardin, and N. Destainville and M. Manghi on the Tethered Particle Motion (TPM) experiments – the 2D amplitude of motion $R_{||}$ of a particle tethered to a substrate by a DNA provides informations on its conformation in quasi force-free conditions – started 10 years ago, and continued with the Ph.D. of A. Brunet (2012-15), who combined experimental and numerical works. Thanks to the development of the massive parallelization of the TPM setup, fine experiments on the DNA structure have been realized. The decrease of $R_{||}$ when the temperature is increased from 15 to 60°C has been shown to be due only to the increase of the bending entropy, in accordance with the Worm-Like-Chain (WLC) model [48]. Using simulations to solve the inverse problem together with an adapted WLC model, a spontaneous curvature angle of $\simeq 19°$ has also been shown to be induced by $CA_6CGG$ A-tracts [15]. This new type of biophysical measurement paves the way to the characterization of the geometry of biologically relevant DNA sequences and can also be applied to the measurement of protein-induced bending angles.

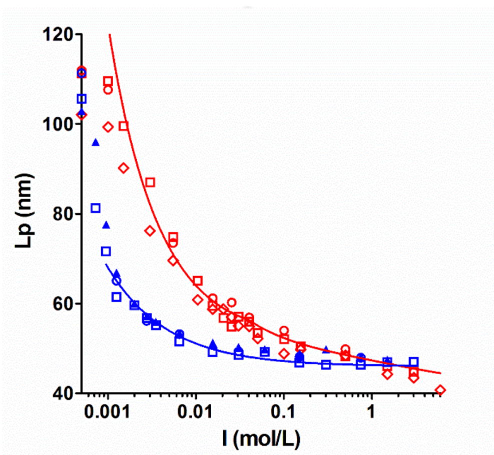


***Figure 1.2 :*** *Influence of the ionic strength on the persistence length of the double-stranded DNA for monovalent metallic ($Li^+$, $Na^+$, $K^+$, red symbols) and divalent ($Mg^{2+}$, $Ca^{2+}$, $Pu^{2+}$, blue symbols) ions, adjusted by curves from recent theories [79].*

Finally, the role of the ionic strength $I$ (related to the salt concentration in the solution) on the DNA – which is negatively charged – persistence length $L_p$ is a long standing issue in biophysics. The amplitude of motion $R_{||}$ has been measured over a wide range of ions and salt concentrations. Using exact Monte Carlo sampling, the persistence length $L_p(I)$ has been properly extracted (Figure 1.2). A unique decay for monovalent or divalent metal ions has been measured, perfectly described by recent theories which take into account the non-linear electrostatic effects as well as the finite diameter of the DNA [17, 79]. This study will thus make it possible to predict conformational changes of complex structures formed by DNA both *in vitro* and *in vivo*.

*DNA dynamics in confined viscoelastic electro-hydrodynamics flows*

In collaboration with A. Bancaud (LAAS, Toulouse), M. Manghi studied the dynamics of DNA molecules, visualized by fluorescence microscopy (Figure 1.3), conveyed in a fluid flow in micrometric channels with an opposing electrophoretic force. This (so-called $\mu$LAS) technology allows the separation, concentration and analysis of nucleic acids with a very high definition. Using statistical physics and hydrodynamics, it has been showed that the viscoelastic transverse force induced by the polymeric solvent is at the origin of the success of the technology and a model has been developed, allowing quantitative predictions in accordance with the DNA size separation experiments [51].

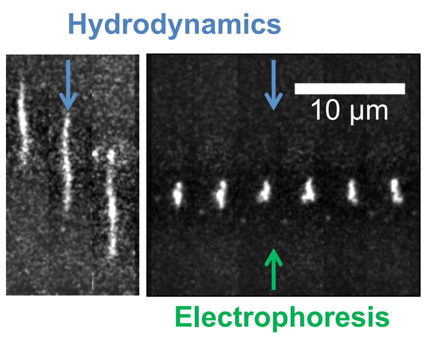


***Figure 1.3 :*** *DNA response to hydrodynamic flow (left) and then combined with the opposite electrophoretic force (right) at different successive times.*

For equal and opposite hydrodynamic and electrophoretic forces, the DNA is maintained at rest, but stretched and confined near the walls. Surprisingly, its stretching is lower than for shear flows in solution. By developing a suitable Rouse model, it has been shown that this is due to the coupling of the transverse and longitudinal movements of the monomers, induced by the viscoelastic transverse force. Using Brownian dynamics simulations, it has been proposed that the intermittent DNA fluctuations that are observed are associated with a "tumbling" dynamics characterized by the cyclic winding of terminal monomers around the center of mass [80].

### *Biomembrane organization*

With the ultimate motivation of giving a comprehensive picture of biomembrane organization embracing both their protein and lipid complexity, membrane nanodomains have been studied by the PhyStat group for about 20 years now. A cell membrane contains several thousand of different protein and lipid species that ensure a large variety of biological functions. They must self-organize to accomplish their task, the basic bricks being nanodomains of size $\sim 100$ nm.

*Curvature-composition coupling*

In a field-theoretic approach, the local composition $\phi$ is coupled to the membrane shape, more precisely to the local curvature $\Delta h$ because some membrane constituents locally impose a spontaneous curvature. In addition the membrane bending modulus can depend on $\phi$ because some phases have an increased rigidity. G. Guéguen, whose Ph.D.was supervised by M. Manghi and N. Destainville (2013-16), studied such a model by also taking into account the differential composition of both membrane leaflets, and got original results about the system phase diagram. Notably, mesophases emerge, some of which are specific to the spherical geometry because the symmetry between both leaflets is explicitly broken [2, 50]. In order to challenge these analytical results, an original numerical model of tessellated vesicle was later developed. Before coupling concentration and curvature, the renormalization of the surface tension with the UV cutoff was studied, together with the non-equivalence between the various definitions of surface tension [45]. A shape transition was predicted analytically and observed numerically when the renormalized surface tension becomes negative: the vesicle becomes flaccid. The curvature-concentration coupling is the object of J. Cornet's Ph.D (2017-20) (Figure 1.4).

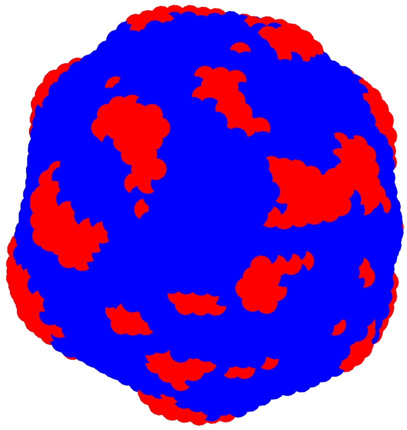

***Figure 1.4 :*** *Numerical model of diphasic vesicle where concentration and curvature are coupled. The red phase imposes a stronger curvature. Mesophases emerge in equilibrium, which is quantitatively compared to the theory.*

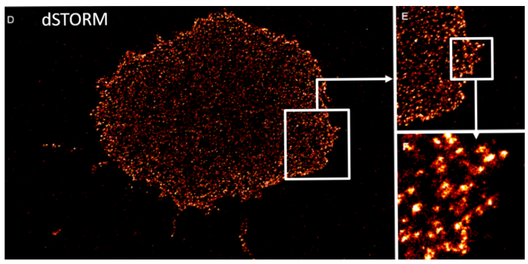


***Figure 1.5 :*** *Experimental dSTORM image of LFA-1 domains [47].*

*Experimental study of tetraspanin nanodomains*

By using the super-resolution fluorescence microscopy technique STED, T. Lang (Bonn, Germany) and L. Florin (Mainz, Germany) study the membrane organization of a class of scaffolding proteins called tetraspanins, in collaboration with N. Destainville [1]. The observations are compatible with N. Destainville's former theoretical predictions, as reviewed in Ref. [36]. In particular, the typical nanodomain size depends weakly on protein concentration when they are over-expressed by cells.

*Experimental study of LFA-1 nanodomains in T-cells*

By using another super-resolution microscopy technique (d-STORM), L. Dupré and S. Allart (CPTP, Toulouse) study LFA-1 nanodomains in T-cell immunological synapses (Figure 1.5). The long-term goal of this collaboration with N. Destainville and M. Manghi, which already led to a common publication [47], is to decipher the mechanical mechanisms implicated in the adhesion process between the T-cell and its target cell, and in particular the role of the T-cell cytoskeleton. So far, the implication of LPT's researchers has led to the improvement of the statistical tools, such as correlation functions, used to characterize the membrane organizations.

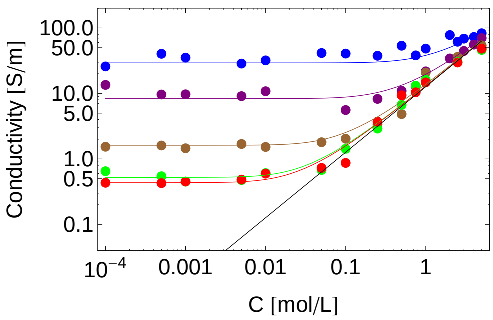


**Figure 1.6 :** *Experimental conductivity of track-etched nanopores and theoretical fit for various nanometric radii [16].*

### Charged complex liquids in nanopores

In collaboration with J. Palmeri (L2C, Montpellier) and B. Loubet (postdoc, LPT, 2014-16), M. Manghi has developed a variational field-theoretic approach for electrolytes by including the excluded volume interactions between ions [38]. Using the Carnahan-Starling formula and the introduction of an UV cutoff, they were able to fit the available Monte Carlo results for the excess chemical potential against the salt concentration (up to 5 mol/L); obtain the Bjerrum first-order phase transition at low $T$ (the ordered phase corresponds to the formation of dipoles); and extend this approach to the case of an electrolyte in a cylindrical nanopore, in which the dielectric exclusion induces an ionic capillary evaporation phase transition.

In collaboration with experimentalists in Montpellier and numericians in Besançon, gathered in the ANR projects TRANSION and IONESCO, M. Manghi and J. Palmeri developed analytical models to study the ionic transport in synthetic nanopores. These models were compared to experiments on unique track-etched nanopores and single-walled carbon nanotubes [16, 46]. Using the mean-field Poisson-Nernst-Planck equations, they included new physical mechanisms to understand the variations of the nanopore conductance against the reservoir salt concentration and $p$H such as : fluid slippage at the nanopore (hydrophobic) surface, the electro-osmotic contribution (advection of ions by the fluid flow), and surface charge regulation [52]. The obtained analytical formula allows them to fit conductance measurements in these nanopores and to characterize them by their radius, saturation charge density, $pK$ and slipping length (Figure 1.6). The relatively high conductance is attributed to the residual charge densities, between 0.01 and 0.1 C/m$^2$ (unexpected in the case of track-etched nanopores) and large electro-osmotic contribution, essentially due to high fluid slippage. The nature of the negative surfacic groups remains to be elucidated. In some cases, non-linear voltage-current curves have been measured which have been modeled by local electrostatic barriers, possibly associated to the formation of charged chemical groups at the nanopore extremities.

## 1.2 Collective phenomena in living groups

*C. Sire*

Since 2013, C. Sire has been collaborating with the leading behavioral biology group of G. Theraulaz (CRCA, Toulouse) on the understanding of collective phenomena in living groups: fish, sheep, cells... and humans. This fruitful collaboration also involves several other experimental (LAAS Toulouse, CPTP Toulouse, Hokkaido University, University of Tokyo, EPFL) and theoretical (IRPHE Marseille, University of South California, Loughborough University, Beijing Normal University, Groningen University, CEA Saclay, Toulouse School of Economics) groups. This activity led to 3 CNRS press releases and to a certain media coverage (see PhyStat publication list for details).

### Fish schools

*Phase diagram of a realistic fish model*

In [4], we have studied the phase diagram of a realistic fish model by varying the intensity of the attraction and alignment interactions between fish. The model recovers the usual swarming, schooling, and milling phases, as well as a more exotic elongated phase (Fig. 1.7). We also showed that near the transition line between two phases, the fluctuations in the schooling or milling order parameters sharply increase and that the sensibility/susceptibility of a fish to a perturbation increase proportionally [18]. In a sense, we recovered in a non-Hamiltonian realistic dynamical model of living active matter an equivalent of the fluctuation-dissipation theorem.

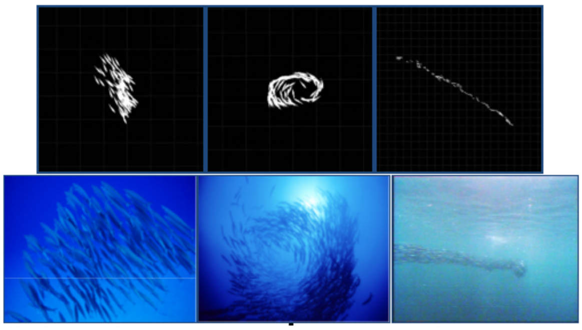

*Figure 1.7 : From left to right: the schooling, milling, and elongated phase as reproduced by the model (top)... and in real life [4, 18].*

We extended the model to take into account the fluid, by describing fish as effective interacting dipoles, perturbing the fluid motion and hence the motion of other fish [71] (PRL Editors' Suggestion and media coverage). We found that the phase diagram of this model is similar to the one without the fluid, but with an additional phase where the school collectively performs large-scale quasi-circular trajectories. In addition, in the ordered phases, we showed that the fish swim faster than without taking the role of the fluid into account and that the fish now avoid staying at the side of each other (internal structuration of the school).

*Measuring and modeling social interactions*

In [72], we have introduced a systematic methodology to reconstruct the social interactions between an individual and a physical object (or the wall of the confining setup; see Fig. 1.8) and between two individuals, hence allowing to build faithful and realistic "equations of motion" for fish (and lymphocytes [68], and more recently, humans). The resulting explicit model reproduces faithfully the experimental distributions characterizing the relative position and heading angle of a fish with respect to the wall or another fish, as well as dynamical observables (like the angle change distribution between kicks).

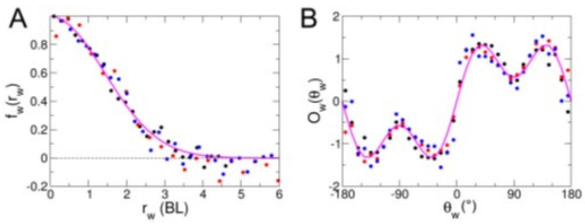


*Figure 1.8 : Intensity of the angle change of a fish [72] as a function of the distance $r_{\mathrm{W}}$ to the wall (A; $r_{\mathrm{W}}$ measured in body length – BL) and the angle $\theta_{\mathrm{W}}$ between the fish heading and the normal to the wall (B). The 3 colors correspond to tanks of radius 176, 250, 356 mm.*

The measured interaction functions depict how an individual effectively perceives its environment. Contrary to physical forces, social interactions do not satisfy the law of action-reaction and are not conservative, depending explicitly on the "angle of view" and relative orientation of two individuals. In the context of fish schools, our results give for the first time an explicit, precise, and realistic form for the repulsion (short range), attraction (long range), and alignment (short and medium range) interactions between fish appearing in previous purely phenomenological models (see also [8] in *Other realizations*).

*Influential neighbors and information cascade*

Having measured the social interactions between two individuals, a central question is to understand how these interactions are combined in larger groups. Are pair interactions simply added like in physics, or are there effectively more influential neighbors? We have addressed this question in experiments where a group of fish swimming in an annulus-shaped tank is performing collective U-turns [53, 70]. We also studied the cascade of information leading to the collective U-turn of groups of size $N = 2, 4, 5, 8, 10, 20$ fish and showed that an Ising-like model was able to grasp the most important features of the experiments [70]. More recently (article submitted), we compared the collective behavior of small robots to that of real fish (and to our model) to test various hypotheses for the combination of social interactions.

### *Human groups*

*Collective motion and separation tasks*

Following the same procedure as for fish (see above), we performed a series of experiments where 1 or 2 human subjects were walking "randomly" in circular arenas of different radius, in order to measure there social interaction with the external boundary and with another individual. The resulting model is in very good agreement with experiments involving $N = 1, 2, 5, 10, 22$ pedestrians, reproducing position/heading/velocity distributions, nearest neighbors correlations, and velocity time correlation functions (article under completion).

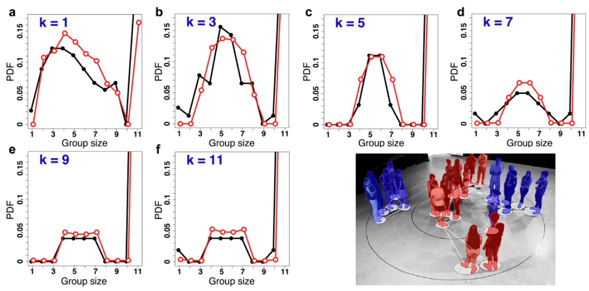


*Figure 1.9 : Distribution of group sizes in the final state (no beep) as a function of $k$ (experimental/model results in black/red).*

We exploited this model to understand experiments where 22 subjects were allocated a random color (blue or red) unknown to them. The subjects were told that their location tag on their left shoulder would beep if their "environment" is not of the same color as them. The goal for the subjects is to ultimately find a spatial configuration where nobody beeps anymore. Unbeknown to the subjects, an individual would actually beep if the majority of their $k$ nearest neighbors was not of the same color as them ($k = 1, 3, 5, 7, 9, 11, 13$ depending on the experiment). This experiment associates to each subject an artificial sensory device (the "beep") characterizing their environment that we can fully control (the value of $k$). We have characterized the group performance in separating in unicolor groups and showed that $k = 7$ was enough to obtain the best performance (Fig. 1.9; article submitted).

*Collective estimation tasks*

A group of subjects are asked 30 "difficult" questions (like "How many stars are there in the Milky Way?)" in order to minimize the effect of prior knowledge. Subjects first give their personal estimate. Then, the mean of the 3 final estimates of previous participants is provided to them and they exploit this social information to give their own final estimate which will be used to recompute the mean for the next participants (Fig. 1.10).

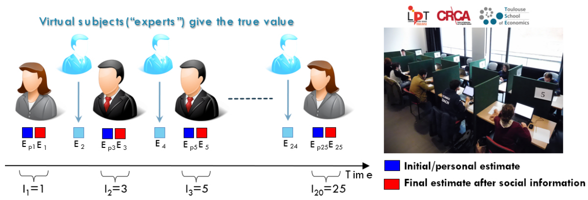


*Figure 1.10 : Summary of the experiment conducted in [54].*

Moreover, unbeknown to the subjects, a variable fraction (0 %, 20 %, 40 %, 80 % depending on experiments) of virtual subjects giving the true answer (or an incorrect answer in more recent experiments) are inserted between the human subjects [54], hence influencing the social information provided to the next participants. In these experiments conducted in France and Japan (a total of 15000 estimates recorded), we showed that 5 robust social traits emerge, including: keeping one's initial estimate, following the social information, or compromising. Moreover, we showed that the farther the personal estimate is from the social information, the more subjects are following the latter. These observation allowed us to build a model faithfully reproducing the performance of the 5 identified categories in ultimately guessing the right answer, depending on the fraction of virtual agents.

These experiments allowed us to measure and model quantitatively how subjects exploit social information to make their final estimate, and how external information (provided by the virtual agents; true or incorrect) influence the group.

*Collective search and evaluation tasks*

We have conducted a series of experiments mimicking the search and rating ("stars") of the best "products" that users commonly perform on web services like *TripAdvisor*, *Airbnb*, or sellers like *Amazon*. The products were distributed in a $15 \times 15$ grid and each cell would contain an hidden number representing the value/quality of the corresponding product. The subjects open cells in parallel and rate them by leaving from 0 to 5 stars in the cell. After each turn, the grid would show colored cells, the darker cells corresponding to those in which the most stars have been deposited. We gave different different monetary incentives to the subjects (no incentive or incentive depending on whether they found the best "products" and/or on the ratings they gave) and studied the individual and collective performance to discover the best products and to give a mean rating fairly representing the value of the products. Moreover, we identified and characterized the main strategies adopted by the participants: revisiting their best cell so far, visiting dark cells collectively marked by the group, or exploring yet unvisited/unmarked cell, rating cells honestly or not. Finally, we built artificial agents applying these strategies, and optimizing them. This work is still under completion, and we plan in the future to have virtual agents interacting with human subjects.

## 1.3 Theoretical astrophysics

The nature of dark matter and dark energy is still unknown and remains one of the greatest mysteries of modern cosmology. We have carried out a series of works in order to shade light on these dark components.

### *Equation of state of the Universe*

*P.-H. Chavanis*

We have first developed a cosmological model [5, 11, 21, 73] which describes the complete evolution of the Universe, from the early inflation to the late accelerated expansion, by a single quadratic ($ax^2 + bx + c$) equation of state whose coefficients are related to the Planck constant $\hbar$ and to the cosmological constant $\Lambda$. From that equation of state, we have constructed a scalar field theory with a single potential $V(\varphi)$ that unifies the inflation in the early Universe and the cosmon in the late Universe. This scalar field has been called the vacuumon. Its mass is imaginary in the early universe, its modulus being of the order of the Planck mass $M_P = (\hbar c/G)^{1/2} = 2.18 \times 10^{-5}\,\mathrm{g}$, and is equal to the mass $m_\Lambda \sim \hbar\sqrt{\Lambda}/c^2 = 2.08 \times 10^{-33}\,\mathrm{eV}/c^2$ predicted by string theory in the late universe.

We have also proposed a unification of dark matter and dark energy in terms of a single dark fluid described by a logotropic equation of state ($\sim \ln x$). In this model [23, 39, 57, 81], dark matter corresponds to the rest mass of the dark fluid ($mc^2$) and dark energy corresponds to its internal energy ($u$). The logotropic dark fluid depends on a new fundamental constant of physics $\Lambda$. Postulating that $\Lambda$ has the same value as Einstein's cosmological constant implies that the present proportion of the dark energy in the Universe is $\Omega_{\mathrm{de},0} = e/(1+e) \simeq 0.731$ in good agreement with the observations.

At the cosmological scales, the logotropic model is indistinguishable from the $\Lambda$CDM model up to the present [57]. It will start deviating from the $\Lambda$CDM model in about 38.3 Gyrs, when it becomes phantom. At that moment, the energy density will increase with time as the Universe expands instead of tending towards a constant. This implies a super-accelerating expansion (super de Sitter). Interestingly, the $\Lambda$CDM model is recovered in the limit $\hbar \to 0$ of the logotropic model suggesting a connection with quantum gravity.

At the galactic scale, the logotropic model is able to solve some of the problems of the $\Lambda$CDM model [23, 39]. It leads to dark matter halos presenting density cores, instead of cusps, that are privileged by observations. More interestingly, it is able to account *without free parameter* to the universal surface density of dark matter halos.

Indeed, it yields the formula

$$\Sigma_0^{\rm th} = 0.01955 \frac{c\sqrt{\Lambda}}{G} \simeq 133\, M_\odot/{\rm pc}^2, \qquad (1.1)$$

which is in excellent agreement with the measured value of the surface density of the dark matter halos $\Sigma_0^{\rm obs} = 141^{+83}_{-52}\, M_\odot/{\rm pc}^2$. As a result, the logotropic model can account for the mass-radius relation of dark matter halos, for the Tully-Fisher relation, and for the universal mass of dwarf spheroidals (dSphs).

On the other hand, we have noted [81] that the surface density of dark matter halos turns out to be of the same order of magnitude as the surface density of the electron $\Sigma_e = m_e/r_e^2 = m_e^3 c^4/e^4 = 54.9\, M_\odot/{\rm pc}^2$. Using our formula (1.1), we can thus express the mass of the electron in terms of the cosmological constant as

$$m_e = \alpha \left( \frac{\Lambda \hbar^4}{G^2 c^2} \right)^{1/6}, \qquad (1.2)$$

where $\alpha = e^2/\hbar c \simeq 1/137$ is the fine-structure constant. This suggests an intriguing connection between atomic and cosmic scales.

### *BEC dark matter halos*

*P. H. Chavanis, A. Suarez*

We have developed a model of dark matter halos made of self-gravitating bosons in the form of Bose-Einstein condensates (BEC).

We have considered the case of bosons with an attractive $\lambda\varphi^4$ self-interaction (axions) and we have showed that axion stars can exist only below a maximum mass [41]

$$M_{\rm max} = 5.073 \frac{M_P}{\sqrt{|\lambda|}}. \qquad (1.3)$$

In the case of the QCD axion with $m = 10^{-4}\,{\rm eV/c^2}$ and $\lambda = -7.39 \times 10^{-49}$ the maximum mass is very small, of the order of $M_{\rm max} = 2.16 \times 10^{-8}\, M_\oplus$. This leads to mini axion stars called "axteroids". In the case of ultralight axions (ULA) with $m = 2.19 \times 10^{-22}\,{\rm eV}/c^2$ and $\lambda = -3.10 \times 10^{-91}$, it is of the order of the size of dark matter halos ($M_{\rm max} = 10^8\, M_\odot$).

We have studied the collapse of axion stars above the maximum mass [41]. In particular, we have shown that the collapse time scales as $(M/M_{\rm max} - 1)^{-1/4}$ close to $M_{\rm max}$. Then, we have taken into account a repulsive $\varphi^6$ self-interaction in the expansion of the potential $V(\varphi)$ and we have studied phase transitions between dilute and dense axion stars [74]. We have obtained a phase diagram presenting a triple point separating dilute axion stars, dense axion stars, and black holes.

In parallel, we have developed a hydrodynamic representation of the Klein-Gordon-Einstein (KGE) equations based on the Madelung-de Broglie transformation [25, 27, 55, 56, 67, 76]. We have used this hydrodynamic approach to study the development of inhomogeneities in a BEC dark matter universe. This leads to a generalization of the famous Jeans instability criterion involving quantum and general relativistic effects [76].

Inspired by the BEC model we have developed a cosmological model incorporating a stiff matter era in the very early universe in which the velocity of sound is equal to the velocity of light [24, 28]. We have obtained a new analytical solution for the evolution of the scale factor of the Universe that includes stiff matter in addition to dark matter and dark energy. This provides a generalization of the Einstein-de Sitter (EdS) and ΛCDM models.

### *General relativistic Fermi gas and fermionic King model*

*P.-H. Chavanis, G. Alberti*

We have studied the nature of phase transitions in a self-gravitating gas of fermions at finite temperature in general relativity [83] (see also *arXiv:1902.04854*). When the particle number $N \ll N_{\rm OV}$, where $N_{\rm OV} = 0.398\, M_P^3/m^3$ is the Oppenheimer-Volkoff limit, we recover the Newtonian results. When $N > N_{\rm OV}$ we evidenced an interesting situation in which the Fermi gas first undergoes a phase transition from a gaseous phase to a condensed phase (e.g. a neutron star) at a critical temperature $T_c$, then collapses towards a black hole at a smaller temperature $T'_c$. In that case, quantum mechanics cannot prevent gravitational collapse. This is the finite temperature generalization of the Oppenheimer-Volkoff seminal result. We also made the connection with the supernova phenomenon [8].

A limitation of the previous model is that we have to confine the fermions within a box in order to prevent their evaporation when $T > 0$. However, in another study (restricted to Newtonian gravity) [20, 30], we have discussed the nature of phase transitions of self-gravitating systems in the context of the fermionic King model which takes into account the escape of particles above a tidal energy. We showed that the phenomenology of these phase transitions is the same when the tidal radius in the King model is replaced by a "box".

### *Generalized Schrödinger equation*

*P.-H. Chavanis*

Using Nottale's theory of scale relativity, and including dissipative effects, we have derived a nonlinear generalization of the Schrödinger equation [59, 61, 75]. It is equivalent to an equation of the form $D\mathbf{U}/Dt = -\nabla\Phi - \gamma\mathbf{U}$ where $D$ is a scale covariant derivative operator, $\mathbf{U}(\mathbf{r}, t)$ is a complex velocity field and $\gamma$ is a complex friction coefficient. Interestingly, the real part of $\gamma$ produces an ordinary friction term $\xi$ and its imaginary part produces a temperature term $T$. They are related by a form of quantum fluctuation-dissipation theorem. This equation unifies the equations of quantum mechanics (Schrödinger) for $\xi = 0$ and Brownian theory (Smoluchowski) for $\xi \to +\infty$. We have used this equation to describe dark matter halos with a quantum core and an isothermal halo [59, 75].

### *Inhomogeneous Lenard-Balescu equation*

*P.-H. Chavanis, J. B. Fouvry, C. Pichon*

We now have at our disposal the exact kinetic equation of self-gravitating systems at the order $1/N$, where $N$ is the number of stars in the system. This inhomogeneous Lenard-Balescu equation (Heyvaerts 2010, Chavanis 2012) takes into account spatial inhomogeneity and collective effects. It allows us to describe rigorously situations which were inaccessible until now: stellar discs, globular clusters, galactic centers around a supermassive black hole... Recently, it has been possible to solve this equation in order to study the secular evolution of stellar systems [26, 29, 62, 66, 82]. We demonstrated the importance of collective effects to "boost" the relaxation of stellar discs and showed the formation of a "ridge" in action space. We also evidenced an out-of-equilibrium phase transition from an axisymmetric disk to a bar.

## 1.4 KPZ universality in finite volume

*S. Prolhac*

KPZ universality in $1+1$ dimension, from Kardar, Parisi and Zhang, describes large scale fluctuations of a field $h(x, t)$ appearing in a variety of systems such as growing interfaces, disordered conductors or one-dimensional classical and quantum fluids. During the past twenty years, KPZ universality has been an increasingly active topic in mathematical physics, at the interface between non-equilibrium statistical physics and probability theory, with a growing number of exact results and rigorous theorems.

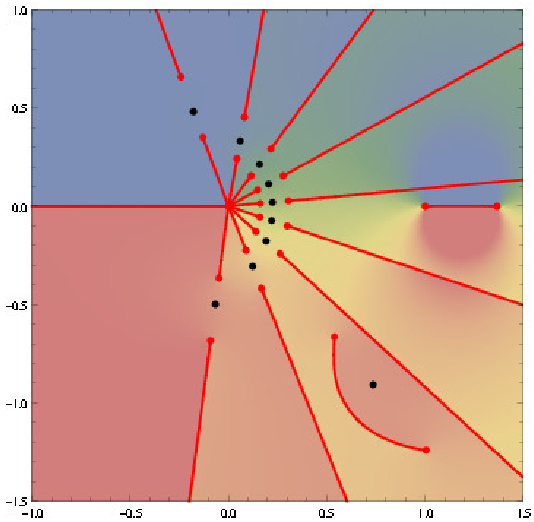


**Figure 1.11 :** *Bethe roots* $\mathrm{e}^{\mathrm{i}k_j}$ *related to the momenta* $k_j$ *of quasi-particles in ASEP, a microscopic model from KPZ universality.*

Most exact results so far have been concerned with the fluctuations of an infinitely long interface, for which the width of the interface grows forever in time as $t^{1/3}$, with a spatial correlation length of $t^{2/3}$. Beyond these exponents characteristic of KPZ universality, detailed statistics of the height are known, with interesting connections to random matrix theory (Tracy-Widom distributions, Airy processes). Some exact results are also known for the universal renormalization group flow between the equilibrium and KPZ fixed points, with in particular simple expressions for large deviations around the equilibrium fixed point [64, 78].

Recently, KPZ universality has been studied in finite volume, in particular for an interface with periodic boundary conditions [12, 31, 32, 33, 43, 44, 65, 77]. There, the width of the interface eventually saturates, and the random process $x \mapsto h(x,t)$ converges to a stationary state where the interface is described by a Brownian bridge. The convergence to the stationary state involves exponential decay of relaxation modes, and has been computed exactly recently [43] using Bethe ansatz integrability of a specific microscopic model in KPZ universality, the asymmetric simple exclusion process (ASEP), see figure 1.11. The relaxation modes can be understood as particle-hole excitations [12] with dispersion $k^{3/2}$ at both edges of the Fermi sea representing the stationary state.

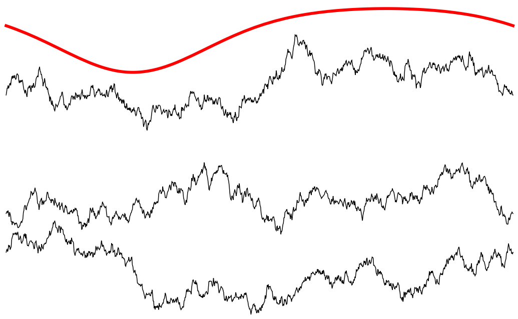

*Figure 1.12 : Non-intersecting Brownian bridges conditioned to stay under a curve.*

Fluctuations of the KPZ interface in the stationary state are typically Gaussian. Large deviations around the typical fluctuations however exhibit a non-Gaussian behavior. It was shown recently [77] that these large deviations, as well as late time corrections to them, can be expressed for general initial condition in terms of extreme value statistics of Brownian bridges, or equivalently, non-intersecting Brownian bridges conditioned to stay under a curve representing the height of the interface in the initial condition, see figure 1.12. Comparison with exact Bethe ansatz results for KPZ lead in particular [77] to new conjectures for the probability that a gas of non-intersecting Brownian bridges crosses specific moving boundaries. For instance, preparing initial positions of infinitely many Brownian bridges with consecutive distances independent exponential random variables of parameter $s$, the conditional probability that the second topmost bridge stays under the topmost one knowing that all the other bridges never intersect is conjectured to be equal to $\sqrt{2\pi}\, s \exp(-\varphi^{-1}(s))$, with $\varphi^{-1}$ the inverse function of $\varphi(v) = -\mathrm{Li}_{3/2}(-\mathrm{e}^{v})/\sqrt{2\pi}$, where $\mathrm{Li}_{3/2}$ is the polylogarithm of index $3/2$.

# 2 Project: Physique Statistique des Systèmes Complexes (PhyStat)

## 2.1 Statistical mechanics for biophysics and soft condensed matter

Three ongoing collaborations will be carried on during the next 5 years. (1) The collaboration between Montpellier (experiments), Toulouse (theory) and Besançon (simulations) will continue on the study of the transport of ions through metallic and semiconductor carbon nanotubes, eventually controlled by a gate electrode that modifies surface properties. A Ph.D. thesis on this subject will start in September 2019. Both fundamental and more applied issues will be studied, such as the modeling of the electrolyte-nanopore interface, the coupling between electronic and ionic transport or the Coulomb blockades. (2) Concerning the biomembranes organization topic, a multi-scale interdisciplinary project involving experimental, numerical (IPBS, Toulouse) and theoretical groups (LPT) has started in 2018 on the organization of membranes containing mycobacterial (PGLs and DIMs lipids) virulence factors produced by tuberculosis or leprae mycobacterium. The goal is to understand how these specific lipids strongly interact with the plasma membrane and generate large modifications of the biophysical properties of the membrane. (3) The recent work on the experimental study of LFA-1 nanodomains in T cells has led to the more ambitious NanoTCell project, recently funded by the Federal University of Toulouse, in collaboration between LPT (modeling) CPTP-Toulouse (superresolution microscopy experiments) and Morgan Huse's group in New-York, USA (micropillar experiments). A Ph.D. thesis will start in October 2019 on the biophysical exploration of nanoscale dynamics at the immunological synapse of T cells, co-supervised by LPT and CPTP. The project relies on the study of unique experimental models consisting in T cells from immunodeficient patients.

## 2.2 Collective phenomena in living groups interacting with virtual agents

Concerning fish schools, the LPT and CRCA have just started a collaboration with a robotics team at EPFL (Switzerland). The goal is to program a robot fish with the social interactions quantitatively measured in Hemigrammus (and more recently, in zebra-fish) and study the closed-loop interaction of this robot with actual fish. Our modeling methods will be complemented by machine learning methods to control the robot. Apart from measuring the fish-robot interaction, an interesting issue is to "open the (black) box" of the machine learning algorithm by also obtaining an explicit model describing its behavior (and to compare it with the model directly inferred from the fish behavior). The control of a fish school by a (few) robot fish will also be addressed. A collaboration with the University of Beijing (first article just submitted) studies the implementation of interaction rules obtained in fish to control a swarm of small robots ($4 \times 4$ cm) moving on a table. Finally a project with IRT (an ANR project reached the last evaluation stage; results pending) aims at studying the interaction of real fish with realistic looking virtual fish projected on the walls of the tank. Again, the aim is to produce virtual fish able to control a real fish school, the latter interacting with the virtual fish with social interactions as close to the actual fish-fish interactions as possible.

As for human groups, the measure of social interactions following the same methodology as for fish is almost completed. This should lead to much more realistic models for human crowds than the current phenomenological models – used in particular to model dense crowds in the movie industry or to model pedestrian flows in large public buildings – especially at medium density (at high pedestrian density, current physical models are good enough, the "free will" of humans being strongly constrained). In addition, we have built a VR setup which will allow us to measure interactions between human subjects immersed in a virtual environment. The same setup will permit to study decision processes (like taking the left or right corridor) in the context of minority games, and also study the interactions of human subjects with virtual subjects programmed with the proper measured interaction rules. Finally, the experiment mimicking evaluation processes at play on websites like *TripAdvisor* or *Amazon* will be extended to include the interaction of human subjects with a (potentially large) number of virtual agents applying the strategies identified in the study presented in the scientific report.

## 2.3 Statistical mechanics of self-gravitating fermions and bosons: application to the problem of dark matter

Future projects will aim at contributing to the elucidation of the nature of dark matter which is one of the biggest challenge of modern cosmology. P.-H. Chavanis has been working on different dark matter models in which the dark matter particle is a fermion or a boson with an attractive or a repulsive self-interaction (or simply no self-interaction at all) in addition to the gravitational interaction. He has also considered the case of more exotic particles or scalar fields described by a logotropic equation of state. These various models combine elements of astrophysics and statistical physics. Indeed, one has to couple quantum statistics (Fermi-Dirac or Bose-Einstein) to an attractive long-range interaction (Newtonian gravity or general relativity). This leads to a rich variety of phase transitions, instabilities and critical phenomena. So far, these different models (fermions, bosons, logotropes) are compatible with the astrophysical and cosmological observations but a priori only one of them should be ultimately selected (except, of course, if dark matter is made of different types of particles). At present, these models are studied by different communities and one specificity of this work is to have contributed to all of these approaches. P.-H. Chavanis has therefore a privileged position to compare them, determine their respective strengths and weaknesses, and contribute to ultimately select the most relevant model. This is the plan for the years to come. In parallel, this topic is a good opportunity to develop more fundamental physics. In particular, several developments are in progress: a notion of generalized thermodynamics and generalized quantum mechanics leading to unusual entropies (generalizing the Boltzmann entropy), unusual equations of state (generalizing the isothermal equation of state), and unusual wave equations (generalizing the Schrödinger equation). These generalizations may be relevant to the still poorly understood problem of dark matter.

## 2.4 Boundary effects for KPZ fluctuations

Much progress happened in the last few years about KPZ fluctuations in finite volume with periodic boundary conditions, as reviewed in the PhyStat scientific report. Future work will consider the more experimentally relevant setting of a system coupled at both ends to an external environment. Of particular interest will be the relaxation modes of KPZ fluctuations to their stationary state, the topology of their underlying phase space, and the expected relation to extreme value statistics of Brownian processes. A PhD student will start working on this project in October 2019, after doing a M2 internship on the same topic between April and July 2019.

# 3

# Articles published in peer-reviewed journals

**The diversity of subjects treated at LPT translates into an equally large variety of scientific journals and conferences where LPT scientists publish and present their work.**

**The LPT scientists have published around 420 articles in peer-reviewed journals during the past five years. Number of publication per LPT thematic group (including a few preprints):**

- **Fermions Fortement Corrélés (FFC):xxx**
- **Cohérence Quantique (Quantware): xxx**
- **Physique Statistique des Systèmes Complexes (PhyStat): 83**
- **Systèmes de Fermions Finis – Agrégats (Agrégats): xxx**

❍ The **average number of authors** on a LPT article is close to 3: 1.4 permanent researcher at LPT, 0.4 LPT postdoc or PhD student, 1.4 non LPT researcher (including LPT visitors). The names of LPT permanent researchers are underlined and those of LPT postdocs/PhD students are dash-underlined in the publication list below and elsewhere in this document.

❍ Since 2009, more than **300 different authors** are involved in the LPT publications (excluding LPT permanent staff, postdocs, and PhD students). They work in **nearly 200 different institutions**[1] including **9 laboratories on the Toulouse campus**.

❍ Percentage of LPT publications since 2009 having **at least one author from a foreign institution**[2] **(32 countries involved)**: Germany ∼ 20 %, USA ∼ 10 %, Russia ∼ 6 %, Italy, Slovenia, UK (∼ 5 % each), Argentina, Belgium, Switzerland (∼ 4 % each)... The home institution of the main French collaborators outside Toulouse of the LPT scientists are the Université Paris-Sud, CEA Saclay, Université Pierre et Marie Curie, Université and ENS Lyon, Université de Montpellier, and ENS Paris.

❍ The following publication list includes, among others, 34 articles published in *Physical Review Letters* (and around 140 *Physical Review A-E*), and 1 in *Nature Communications*[2]. The LPT publications listed below have already attracted ∼ 3000 citations (900 in 2013), in ∼ 1800 citing articles without self-citations.

❍ 11 LPT articles solely published in APS journals were highlighted as *APS Editors' suggestion* and 6 were featured in *Physics*.

❍ Most LPT publications since 2006 are referenced on ArXiv and on the CNRS HAL repository.

1. Analyzing search results for LPT publications on ISI Web of Sciences.
2. In addition to APS journals (accounting for almost half of LPT publications), the main journals where LPT scientists publish their work are (cited according to the number of published articles): *European Physical Journal B, D, E, +, Journal of Physics A-C, New Journal of Physics, Europhysics Letters, Journal of Chemical Physics, Journal of Statistical Mechanics...*

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# 4

# International and national conferences

**The LPT scientists have intervened in more than 350 international and national conferences during the past five years. Number of presentations per LPT thematic group:**

**— Physique Statistique des Systèmes Complexes (PhyStat): 58**

**The diversity of subjects treated at LPT translates into an equally large variety of conferences where LPT scientists present their work.**

## 4.1 Physique Statistique des Systèmes Complexes (PhyStat)

[1] M. Manghi, *Ionic transport in nanopores*, invited talk at the *Workshop Water depollution: from applications to fundamental, from physical-chemistry to processes* (Montpellier, France, March 2014).

[2] N. Destainville, *Role of long-range protein-protein in the formation, stability and specialization of bio-membrane nano-domains*, invited talk at the *CECAM Workshop on "Simulation of bimolecular interactions with inorganic and organs surfaces as a challenge for future nanotechnologies"* (Toulouse, France, 24-26 March 2014).

[3] N. Destainville, *Organization of proteins breaking the up-down symmetry in membranes under tension*, invited talk at the *Interdisciplinary Workshop on "Membrane Dynamics"* (Paris, France, 24-26 March 2014).

[4] M. Manghi, *Closure dynamics of DNA denaturation bubble*, poster at the *Liquids 2014: 9th Liquid Matter Conference* (Lisbon, Portugal, July 2014).

[5] C. Sire, *Analytical results for a realistic model for fish schools*, invited talk at the *Workshop on Advances in Non Equilibrium Statistical Mechanics* (Galileo Galilei Institute for Theoretical Physics, Florence, Italy, 16-30 May 2014); Chairman of a session.

[6] C. Sire, *Models of fish school based on experiments*, invited talk at the *Workshop on collective swimming* (22-26 September 2014, ETH - Villa Garbald, Switzerland).

[7] P.-H. Chavanis, Program *Wave-Flow Interaction in Geophysics, Climate, Astrophysics, and Plasmas* (Santa Barbara, USA, 23 May - 18 June 2014).

[8] P.-H. Chavanis, Conference *SigmaPhi* (Rhodes, Greece, 7-11 July 2014).

[9] P.-H. Chavanis, Conference *Magnetic fields from the sun to black holes: In memory of Jean Heyvaerts* (Paris, France, 17-19 November 2014).

[10] P.-H. Chavanis, Conference *X Mexican School on Gravitation and Mathematical Physics "Reaching a Century: Classical and Modified General Relativity's Attempts to explain de evolution of the Universe"* (Playa del Carmen, Mexico, 1-5 Decembre 2014).

[11] N. Destainville, *Role of torsion in DNA denaturation bubble closure and nucleation*, invited talk at the *13th workshop "Statistical Physics and Low Dimensional Systems"* (Pont-à-Mousson, France, 2015).

[12] N. Destainville, *When biology meets physics – a converging view on membrane microdomains?*, invited talk at the *2nd Toulouse Conference in Integrated Structural Biology* (Toulouse, France, 2015).

[13] N. Destainville, *Dynamical plasma membrane organization in nano-domains: role of inter-protein forces and of exchanges with the cytosol*, invited talk at the *Workshop "Molecule Trajectories in Cellular Spaces: promoting interactions between theoreticians and experimentalists"* (Lyon, France, 2015).

[14] C. Sire, *Non-equilibrium Statistical Mechanics*, invited lecture at the *Les Houches Doctoral Training in Statistical Physics* (Les Houches, France, 22 June-3 July 2015).

[15] C. Sire, *Models of fish school based on experiments*, invited review talk at the *Conférence CCT 15, Chaos, Complexity and Transport* (Marseille, France, 1-5 June 2015).

[16] P.-H. Chavanis, Workshop *Spine* (Cambridge, England, 22-26 June 2015).

[17] P.-H. Chavanis, Conference *Fourteenth Marcel Grossmann Meeting* (Roma, Italy, 12-18 July 2015).

[18] S. Prolhac, *Current fluctuations for totally asymmetric exclusion on the relaxation scale*, invited talk at the *Workshop Progress in Nonequilibrium Statistical Mechanics* (Nice, France, June 2015).

[19] S. Prolhac, *Current fluctuations for totally asymmetric exclusion on the relaxation scale*, invited talk at the *Integrable Systems and Quantum Symmetries XXIII* (Prague, Czech Republic, June 2015).

[20] S. Prolhac, *Time evolution of fluctuations for TASEP on the relaxation scale*, invited talk at the *Workshop, Laboratoire J.-A. Dieudonné, Université Nice Sophia Antipolis* (Nice, France, October 2015).

[21] M. Manghi, *Ionic transport through hydrophobic nanopores theory and experiments*, talk at the *STATPHYS26 Conference* (Lyon, France, 18-22 July 2016).

[22] M. Manghi, *Interplay between base-pairing and chain degrees of freedom in DNA*, talk at the *Workshop CECAM: Mesoscopic Modeling in Physics of Molecular and Cell Biology* (Toulouse, France, 10-13 October 2016).

[23] N. Destainville, *Closure/opening of denaturation bubbles of DNA in solution*, talk at the *GDR Architecture et Dynamique Nucléaire (ADN)* (Paris, France, 2016).

[24] C. Sire, *Physics of Society*, invited talk at the *Colloque Représentation du Vivant* (Université Jean Jaurès, Toulouse, France, 14–15 June 2016).

[25] C. Sire, *Phase diagram of a realistic model of fish schools*, invited talk at the *Workshop on Fluid Mechanics and Collective Behavior: From Cells to Organisms* (Conference Centre Monte Verità in Ascona, Switzerland, 3-7 April 2016).

[26] C. Sire, Co-organization of the *Workshop* Collective behaviour in the Big Data era: Can we enhance collective intelligence in human groups ?, with A. Blanchet (Toulouse School of Economics), M. Roy (Laboratory for Analysis and Architecture of Systems, Toulouse), and G. Theraulaz (CRCA, Toulouse) (Manufacture des Tabacs, Toulouse, France, 14–15 April 2016).

[27] C. Sire, Co-organization of the *Workshop on Urban Physics* with the COPIL of the CNRS (CNRS headquarter, Paris, France, 21 October 2016).

[28] P.-H. Chavanis, Conference *Essential Cosmology for the Next Generation* (Playa del Carmen, Mexico, 10-16 January 2016).

[29] P.-H. Chavanis, Conference *Cosmology after Planck: what is next?* (Les Houches, France, 24-29 April 2016).

[30] P.-H. Chavanis, Conference *The secular evolution of self-gravitating systems over cosmic ages* (Paris, France, 24-27 May 2016).

[31] P.-H. Chavanis, Conference *Statphys26* (Lyon, France, 18-22 July 2016).

[32] P.-H. Chavanis, Conference *XI Mexican School on Gravitation and Mathematical Physics "Quantum Gravity: schemes, models and phenomenology"* (Playa del Carmen, Mexico, 5-9 December 2016).

[33] S. Prolhac, *Finite-time fluctuations for TASEP on the relaxation scale*, invited talk at the *Workshop Mathematical and Theoretical Physics approaches to the KPZ equation* (Grenoble, France, February 2016).

[34] S. Prolhac, *KPZ universality in 1+1 dimension*, invited talk at the *Journée IRSAMC* (Toulouse, France, December 2016).

[35] S. Prolhac, *Finite-time fluctuations for the asymmetric exclusion process on the relaxation scale*, invited talk at the *StatPhys 26* (Lyon, France, July 2016).

[36] S. Prolhac, *Finite-time fluctuations for the asymmetric exclusion process on the relaxation scale*, invited talk at the *Journée LPT-IMT* (Toulouse, France, June 2016).

[37] M. Manghi, *Modeling dielectric exclusion effects in ionic transport through hydrophobic nanopores*, invited talk at the *International Conference: Membranes in Drinking and Industrial Water*, (Leeuwarden, Netherlands, February 2017).

[38] M. Manghi, *Theory and experiments on ionic transport through hydrophobic nanopores*, invited talk at the *Strongly Coupled Coulomb Systems* (Kiel, Germany, July-August 2017).

[39] N. Destainville, *How pinching a DNA plectoneme facilitates the interaction between distant genes*, talk at the *GDR Architecture et Dynamique Nucléaire (ADN)* (Paris, France, 2017).

[40] C. Sire, *Social interactions and collective states in fish schools*, invited talk at the *Workshop on Multiscale Analysis and Modeling of Collective Migration in Biological Systems* (9–13 October 2017, Bielefeld, Germany).

[41] C. Sire, *Social interactions and collective states in fish schools*, invited talk at the *Workshop on Cross-disciplinary approaches for building intelligent swarms of drones* (13–14 November 2017, TSE, Toulouse, France).

[42] P.-H. Chavanis, Conference *Collisionless Boltzmann (Vlasov) Equation and Modeling of Self-Gravitating Systems and Plasmas* (Marseille, France, 30 October - 3 November 2017).

[43] P.-H. Chavanis, Conference *Stellar Dynamics in Galactic Nuclei* (Princeton, USA, 29 November - 1 December 2017).

[44] P.-H. Chavanis, Conference *VII Essential Cosmology for the Next Generation* (Playa del Carmen, Mexico, 10-16 December 2017).

[45] S. Prolhac, *Exact results for KPZ universality in 1+1 dimension*, invited lectures at the *Cargèse summer school: Exact methods in low dimensional statistical physics* (Cargèse, France, July - August 2017).

[46] M. Manghi, *Role of the surface tension in the shape transition of vesicles*, invited talk at the *Workshop Biophysics : today and beyond. The physics of unconventional systems* (Montpellier, France, 3–5 April 2018).

[47] M. Manghi, *Theoretical insights in electrolyte transport through nanopores* invited talk at the *Journées de la Matière Condensée* (Grenoble, France, 27–31 August 2018).

[48] M. Manghi, *Influence of surface characteristics on nanopore conductivity*, invited talk at the *International workshop on physics of membrane processes* (Bologna, Italy, 2 September 2018).

[49] N. Destainville, *What is the energy required to pinch a DNA plectoneme?*, invited talk at the *CECAM-Lorentz joint workshop "Multiscale-modelling of nucleosomes and their positioning on DNA"* (EPFL Lausanne, Suisse, 2018).

[50] N. Destainville, *Statistical physics of protein organization in cell membranes*, invited talk at the *Symposium "Multidisciplinarity for the benefit of nano-oncology"* (Toulouse, France, 2018).

[51] N. Destainville, *What is the energy required to pinch a DNA plectoneme?*, talk at the *Conference "Chromatin Meets South 2018"* (Montpellier, France, 2018).

[52] N. Destainville, *Curvature-induced domain formation in biomembranes*, poster at the *4th International Conference on Physics and Biological Systems* (Gif-sur-Yvette, France, 2018).

[53] C. Sire, *Social interactions and collective states in fish schools*, invited talk at the *Workshop on Swarm robotics* (25–26 October 2018, Rome, Italy).

[54] P.-H. Chavanis, Conference *MX Dark Matter* (Playa del Carmen, Mexico, 3-5 November 2018).

[55] P.-H. Chavanis, Conference *XII Mexican School on Gravitation and Mathematical Physics "Black holes and gravitational waves"* (Playa del Carmen, Mexico, 5-10 November 2018).

[56] S. Prolhac, *Brownian bridges for late time KPZ fluctuations in finite volume*, invited talk at the *Conference Integrable Probability Boston 2018* (Boston, USA, May 2018).

[57] S. Prolhac, *KPZ fluctuations in finite volume*, invited talk at the *Young Researchers Meeting on Integrable Systems* (Cergy, France, June 2018).

[58] N. Destainville, *Protein nanodomains and spontaneous curvature*, talk at the *conference "Membrane Biophysics of Exo-Endocytosis: From Model Systems to Cells"* (Mandelieu, France, April 2019).

# 5

# Defended and ongoing PhD theses

## 5.1 Physique Statistique des Systèmes Complexes (PhyStat)

[1] A. Brunet, *Étude à l'échelle de la molécule unique des changements conformationnels de la molécule d'ADN*, thèse de doctorat de l'Université de Toulouse (oct. 2012-nov. 2015) ; encadrants : N. Destainville & C. Tardin (IPBS).

[2] G. Guéguen, *Vésicules lipidiques sous tension : des mésophases aux transitions de formes*, thèse de doctorat de l'Université de Toulouse (oct. 2013-nov. 2016) ; encadrants : M. Manghi & N. Destainville.

[3] J. Cornet, *Étude numérique de la déformation de vésicules composites* (titre provisoire), thèse de doctorat de l'Université de Toulouse en cours (depuis 01/10/2017) ; encadrants : M. Manghi & N. Destainville.

[4] B. Jayles, *Effects of information quantity and quality on collective decisions in human groups*, thèse de doctorat de l'Université de Toulouse (oct. 2014-déc. 2017) ; encadrants : C. Sire & G. Theraulaz (CRCA).

[5] G. Alberti, *Statistical Mechanics of Self-Gravitating Systems in General Relativity*, thèse de doctorat de l'Université Toulouse III - Paul Sabatier (Date de soutenance : 17/11/2017) ; encadrant: P.-H. Chavanis.

# 6

# Habilitations à Diriger des Recherches (HDR)

## 6.1 Physique Statistique des Systèmes Complexes (PhyStat)

# 7

# Other realizations and achievements

**This annex lists major contributions or achievements of the LPT scientists in various domains, including [a]:**

- **Organization of conferences and schools**
- **Books as writers or editors**
- **Main achievements in education (responsible of a Master...)**
- **Popularization of science and diffusion of knowledge**
- **Prizes and honors**
- **Major administrative responsibilities**
- **Coordinator (or important partner) of major contracts (EU, ANR...)**
- **Author of commercial or major open source softwares**
- **...**

*a.* **Except for the two first items, most achievements are described in French**

## 7.1 Physique Statistique des Systèmes Complexes (PhyStat)

**• Organization of conferences and schools**

[1] M. Manghi et N. Destainville ont organisé le Workshop CECAM "Mesoscopic Modeling in Physics of Molecular and Cell Biology", à Toulouse du 10 au 13 octobre 2016 (environ 40 participants).

[2] C. Sire, Co-organization of the *Workshop "Collective behaviour in the Big Data era: Can we enhance collective intelligence in human groups ?"*, with A. Blanchet (Toulouse School of Economics), M. Roy (Laboratory for Analysis and Architecture of Systems, Toulouse), and G. Theraulaz (CRCA, Toulouse) (Manufacture des Tabacs, Toulouse, France, 14–15 April 2016).

[3] C. Sire, Co-organization of the *Workshop on Urban Physics* with the COPIL of the CNRS (CNRS headquarter, Paris, France, 21 October 2016).

**• Main achievements in education (responsible of a Master or Bachelor program...)**

[4] M. Manghi est responsable du parcours Master 1 Physique du Vivant (M1 PFA-PV) de la mention Physique et Applications de l'Université Toulouse III – Paul Sabatier (anciennement M1 PCVS jusqu'en 2016). Ce Master a pour objectif de former des étudiants en physico-chimie, matière molle et biophysique. Il est également responsable des modules d'enseignement *Biophysique* et *Stages* de ce master.

[5] N. Destainville est responsable du Master 2 Physique du vivant, qui suit le M1 PFA-PV précédent. Il est responsable de plusieurs modules d'enseignement du M2.

[6] M. Manghi est responsable du programme de Physique dans le parcours spécial BioMIP (Bio-Math-Info-Physique) adossé à la licence Sciences de la Vie de l'UPS qui a ouvert en sept. 2016 et de divers autres modules d'enseignement, *Phénomènes hors-équilibre et processus irréversibles* (M2 PFA PV et PF), *Matière Molle* (M1 PFA PF) et *Thermodynamique* (L2 Phys, PC, SP et SC).

- **Popularization of science and diffusion of knowledge**

[7] C. Sire réalise de 15 à 30 interventions par an dans le domaine de la vulgarisation scientifique (collèges/lycées, festivals, associations, milieu médical, médias...). Les présentations (parfois en vidéo) et résumés sont disponibles sur cette page consacrée entièrement à la vulgarisation.

[8] V. Lecheval, C. Sire, G. Theraulaz, *La danse organisée des bancs de poissons*, *La Recherche* n°537, p. 40-45 (juillet-août 2018) ; article en PDF.

- **Major administrative responsibilities and contract coordination**

[9] N. Destainville a été membre élu du Conseil d'Administration de *l'Université Toulouse III-Paul Sabatier* (2012-2015).

[10] N. Destainville a été Vice-président délégué aux personnels et au dialogue social (VP-RH) de *l'Université Toulouse III-Paul Sabatier* (2012-2015).

[11] N. Destainville est actuellement Chargé de mission Pilotage et subsidiarité auprès du Président de *l'Université Toulouse III-Paul Sabatier* (2016-présent).

[12] N. Destainville est actuellement Directeur de l'IRSAMC (FR 2568 UPS/CNRS/INSA-T) qui fédère 4 laboratoires de physique et chimie fondamentales toulousains (LCAR, LCPQ, LPCNO, LPT) (2016-présent).

[13] C. Sire est membre du conseil scientifique et de gouvernance du LABEX CIMI (maths-informatique, Toulouse).

[14] M. Manghi a été membre élu du Collège Scientifique (Rang B, Section 29) *Physique et Sciences de l'Univers* et du *Groupe d'Avancement* (Rang B, Maîtres de Conférences) de l'Université Toulouse III – Paul Sabatier (2013-2017).

[15] M. Manghi est membre élu du Comité Sciences de la Matière de l'Université Toulouse III – Paul Sabatier (2015- 2020).

[16] M. Manghi est membre nommé du conseil de département de Physique de l'Université Toulouse III – Paul Sabatier (2016-2021).

[17] N. Destainville a été responsable scientifique (partenaire LPT) d'un projet ANR en collaboration avec l'équipes de L. Salomé à l'IPBS et F. Cornet au LMGM (Toulouse) : projet TPM-on-a-chip (2011-2015).

[18] M. Manghi est responsable scientifique (partenaire toulousain) de 2 projets ANR en collaboration avec des équipes de Montpellier (Institut Européen des Membranes et Laboratoire Charles Coulomb) et Besançon (Laboratoire Nanomédecine, Imageire et Thérapeutiques): TRANSION, *TRANSport IONique au sein de canaux-ioniques biologiques confinés dans des nanopores : approche expérimentale et théorique* (2013-2017) et IONESCO, *Couplage entre transports ionique et électronique dans les nanotubes de carbone mono-feuillets* (2019-2022). M. Manghi a été également Coordinateur du projet Défi CNRS interdisciplinaire INFINITI, *Membranes lipidiques : Connexion entre les simulations numériques à l'échelle du lipide et les modèles théoriques continus des vésicules fluctuantes* en collaboration avec l'équipe Integrative Biological NMR de l'Institut de Pharmacologie et Biologie Structurale (2018).

[19] C. Sire, G. Theraulaz (CRCA), et A. Blanchet (TSE) ont été partenaires du projet MUSE – *Multi-displinary study of emergence phenomena* (2015-2017, IDEX Toulouse, ANR Grant ANR-11-IDEX-0002-02 ; 110 k€). C. Sire et G. Theraulaz sont partenaires de SMARTCROWD, *Étude*

*expérimentale et modélisation des processus impliqués dans les décisions collectives de groupes humains*, projet financé et renouvelé par le CNRS, AMI Sciences Sociales et Cognitives des Comportements Collectifs (S2C3) (2015-2019 ; 60 k€ au total). C. Sire et G. Theraulaz sont partenaires d'un projet *PHC Germaine de Staël* avec l'EPFL (collaborations scientifiques/missions – 2019-2020).