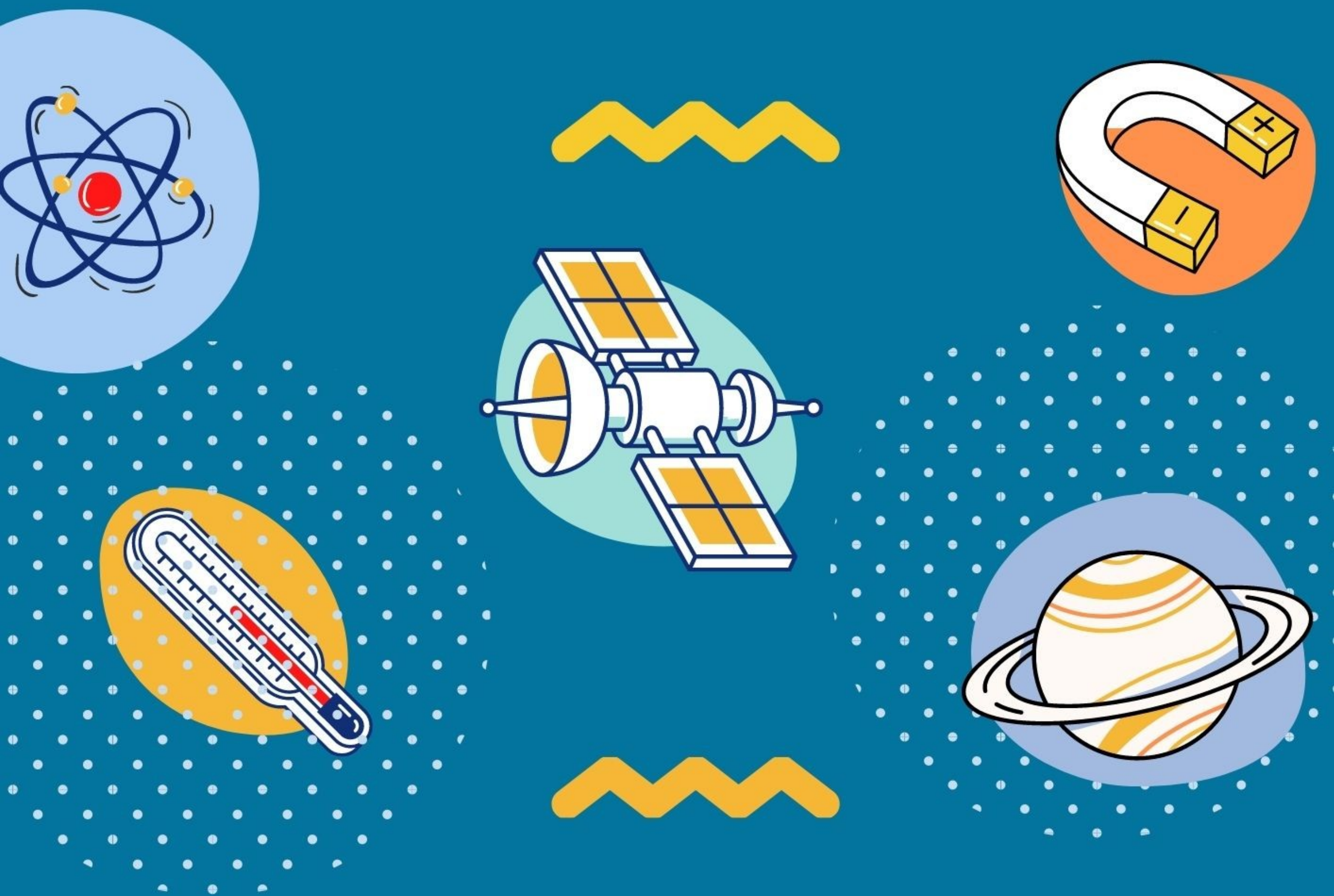
# Quercy-2021

Physics Junior Workshop on
QUantum systems, Elementary Fields, Radiation, Cosmos & (Y)nteractions

## BOOKLET OF ABSTRACTS



05 - 12 June 2021
Le Bastit / Rocamadour
France

# PARTICIPANTS



**Organizers:**

- Silke Biermann
- Andrés F. Santander-Syro
- Daniela Galárraga

# Junior Speakers

# Magnetic textures : From their microscopic origin and their Observation to their Manipulation by Magnetic Fields and Spin-Polarized Currents

**Léo Bergès**, Raphael Weil, João Sampaio, Alexandra Mougin
*Laboratoire de Physique des Solides, Université Paris Saclay, 510 Rue André Rivière, 91400 Orsay*

Magnetism is a fascinating property of matter that originates from the angular momentum of electrically charged particles like electrons or protons. The electronic spin and orbital momentum origins of magnetic moments are nicely displayed on the Periodic Table, where the magnetic response simply follows orbital filling of shells. When the different interactions are favourable, the magnetic moments carried by electrons become ordered and produce a Ferromagnet, with a macroscopic moment. Ferromagnets are usually known for bulk materials as magnets that we find on fridges and in dynamos, but their applications are actually much broader, from sensors, cooling apparatus, to medical applications.

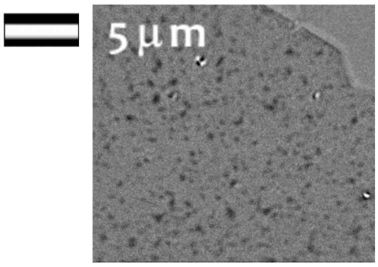
When studied in thin films, interface interactions become much stronger than in bulk materials which will reveal a rich diversity of properties, such as complex magnetic textures, ranging from cms to nms, with complex dynamics dependent on their structure and topology. Material engineering allows us to tune the competition between interactions like the Exchange interaction, Dzyaloshinskii-Moriya interaction (DMI), and Anisotropic interaction (from bulk, surface or demagnetizing effect). Electric transport measurements, like the Anomalous Hall Effect, or magnetometry measurements by SQUID allow to probe the magnetic response to temperature or magnetic field. However, the more complex study of the dynamics of spin waves – the wave excitations of the magnetic order – allows a much more precise and rich characterization of the magnetic properties of the material.

The surface magnetization of materials can be observed by magneto-optical effect like the Kerr effect (MOKE) that simply rotates the polarization plane of light when reflected by a magnetic material. Microscopes using this effect allow for a direct observation of the magnetization direction and strength that will modulate the contrast of an image.

After this discussion on general aspects of magnetism we will continue our way by exploring the zoology of magnetic textures [1], and its diversity of shapes, from uniform magnetic domains, to stripes textures up to nanometric bubble magnetic textures. These magnetic bubbles, referred as Skyrmions, are specifically interesting objects because of their chiral origin (DMI) and topological properties. As other magnetic textures, they can be manipulated by magnetic fields or spin polarized currents, but their robustness and small size [2] make them the perfect candidates for next generation magnetic storage [3] or magnetic based computing devices [4].

In my thesis, I study magnetic skyrmions in a particular material: Rare-Earth/Transition-Metal Ferrimagnets. Like antiferromagnets, these are double magnetic lattices materials [5], which exhibit quite unique properties such as a strong dependence of their magnetization or angular momentum with temperature (fig1b), with drastic consequences for the stability and dynamics of skyrmions (fig1a).2

a)




b)

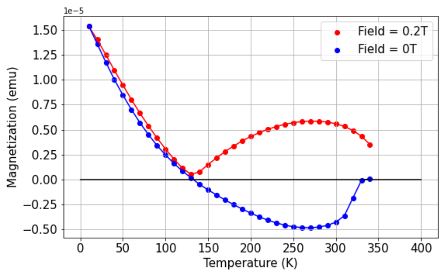



Figure 1 : a) MOKE image of Ferrimagnetic Skyrmions in a thin film of Ta(1)/Pt(5)/CoGd (5)/Ta(5) (in nm). b) SQUID measurement of magnetization versus temperature for a ferrimagnetic thin-film, showing at 130K the magnetic compensation (no net magnetisation).

[1] J. McCord : J.Phys D : Appl. Phys. 48 333001 (2015)
[2] L. Caretta et al Nat. Com 13, 1154–1160(2018)
[3] J. Sampaio, S. Rohart, A. Thiaville et al , Nat Nano. 8, 839 (2013)
[4] X. Zhang et Al. Sci. Rep 5, 9400 (2015)
**[5] E. Haltz , L. Berges, A. Mougin, J. Sampaio et al Phys. Rev. B 103, 014444 (2021)**

# On the quest for nanoscale light emitters with the electron microscope

**Noémie Bonnet**
Laboratoire de Physique des Solides, Université Paris-Saclay , *510 Rue André Rivière, 91400 Orsay*

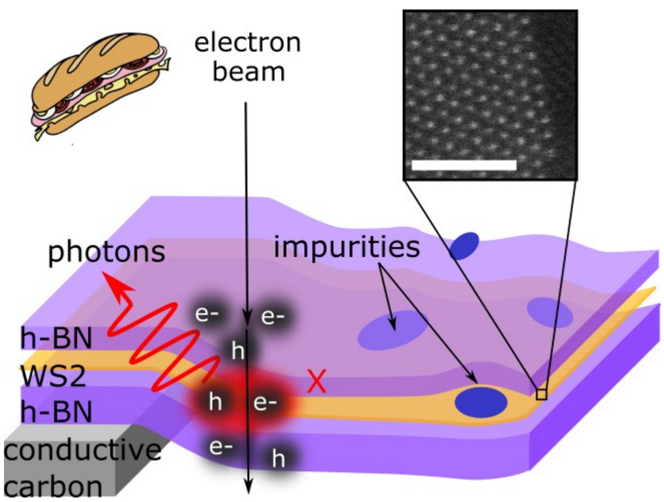
Nanoscale light emitters enable the study of novel properties of light sources where the emitter is smaller than the wavelength of the photons produced. They have attracted considerable attention in the past few years since they have the potential for applications such as nanoscale diodes or optically-based quantum devices, such as qubits (quantum bits). The latter are based on single atomic defects in diamond -as such defects can indeed act as individual light emitters.

One of the issues in studying these systems comes from the optical diffraction, which limits measurements to few hundreds of nanometers. For this reason, instead of using all-optical excitations, the nanoscale emitters were studied with a fast electron beam (about 100 keV) which, thanks to its small associated wavelength, can be focused on an Ångström-sized spot. This enables the individual excitation of emitters that are separated even by just by a few nanometers from each other.

The fast electron beam is produced in a scanning transmission electron microscope (STEM). Its scattering on a thin sample allows for the detection of multiple signals, from which optical, chemical and structural information can be extracted. All these combined pieces of information enable the full-characterization at the nanometer scale of photon emitters. The understanding of such systems is crucial for their controlled production in devices.

In the first part of my talk, I will present how the fast electron beam interacts with matter to produce a variety of measurable signals, including cathodoluminescence (CL) which is the luminescence triggered by exciting with electrons, and electron energy-loss spectroscopy, which measures the energy of the transmitted beam across the thin sample. Next, I will introduce the light-interferometry used to distinguish single photon sources from other types of light-emitters.

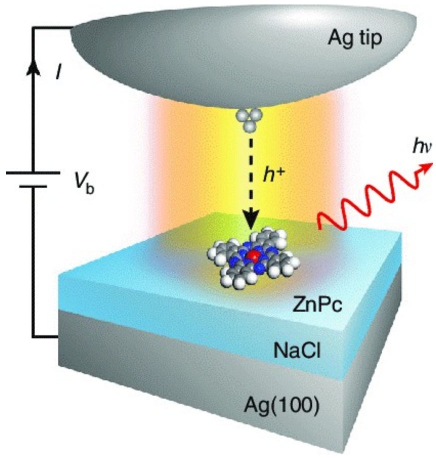
In the second part of my talk, I will show actual measurements of the signals presented in the first part of my talk, measured on a Van der Waals heterostructure, which is a micrometer-sized sandwich between two types of thin films: an insulating material, hexagonal boron nitride (h-BN), is placed like the bread of the sandwich, and a semiconducting 2D material, tungsten disulfide ($WS_2$), is the filling of the sandwich. These 2D materials have attracted interest due to their unusual properties, such as the light emission occurring only when the material is in monolayer. The use of the heterostructure for cathodoluminescence is crucial and will be explained in the presentation.




Scheme of the sample used for the second part of my talk. The inset shows an atomically-resolved image of the monolayer inside the h-BN, where the bright atoms are tungsten.
A scheme of the light-emission (CL) process shows the electron beam crossing the sample, exciting electrons (e-) and holes (h) in the sample, which are attracted by coulomb interaction to form excitons (X). The excitons then recombine in the semiconductor, which is energetically favorable, to emit light.

# Investigations on the growth and luminescence of organic molecules using a scanning tunneling microscope

**Rémi Bretel**
*Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, CNRS, 598 Rue André Rivière, 91405, Orsay, France*
*Institut für Physikalische und Theoretische Chemie der Universität Bonn, 53115 Bonn, Germany*




Schematic diagram of light emission of a molecule excited by inelastic electron tunneling from an STM.
*Zhang, L. et al. (2017). Electrically driven single-photon emission from an isolated single molecule. Nature communications, 8(1), 1-7.*

Light matter interaction is a very dynamic field of research, and so is surface science. Combining the two is at the heart of solving today's problems in optoelectronics. More precisely, finding miniaturized and efficient ways to absorb and emit light at the nanoscale is a hot topic. The main limitations of current optoelectronic circuits is the size of the light sources. In general, the limit is diffraction, which gives a minimum resolution upwards of 200nm for visible light. Several solutions exist, but each has its own advantages and constraints. In our work, single molecules and molecular aggregates are considered as the light emitting devices. However, to be able to excite single molecules and small aggregates, a spatial resolution of the order of the nanometer is required. Scanning tunneling microscopy (STM) is a spectroscopic and imaging technique that is widespread in surface sciences. It consists in scanning a sharp metallic tip on the surface of a sample, while keeping the tip-sample gap small enough (1 nm or less) to allow electrons to cross this gap by quantum tunneling. This way, the tip "probes" the electronic wavefunctions of the atoms underneath; thus, an image of the sample surface with spatial resolution on the atomic scale may be measured. In addition, the tunneling current from the STM tip can be used to excite molecules adsorbed on the sample surface, e.g., to put molecules in an excited electronic state. Subsequently, the excited molecules may return to their ground state by emitting a photon, which may be measured by using a detector in the far field. Combining the atomic resolution of STM with the possibility to excite molecules yields a unique tool, thanks to which luminescence and vibrational spectroscopy with submolecular resolution become possible. This technique is particularly interesting to investigate the optical properties of molecular aggregates.

In the first part of my talk, I will introduce the working principles of an STM, light absorption and emission in a molecule, and touch on a few achievements on this field of research. In the second part, I will show some of my results on the growth of chains and aggregates of quinacridone, a molecule with promising applications in optoelectronics, and on the STM-induced luminescence of quinacridone molecules, using a low-temperature STM (at 78 K) under ultrahigh vacuum.

# Stochastic thermodynamics: when statistical physics applies to small systems

**Lydia Chabane**
*Laboratoire de Physique des 2 Infinis Irène Joliot Curie (IJCLab), Université Paris-Saclay, UMR9012 - CNRS,* 15 Rue Georges Clemenceau, 91405 Orsay, *France*

When I have to explain my thesis subject to 10 years-old children, I ask them the following question : « why does an ice cube melt ? » And they give the following answer : « because of heat ». The temperature difference between the ambient air and the ice cube induces heat - which is a transfer of energy - between our system (the ice cube) and its environment (the surrounding air), which will impose its temperature on the system. These energy exchanges are studied within the framework of a rather empirical field called *thermodynamics*.

Later, a more mathematical theory appears and formalizes the results of thermodynamics: it's *equilibrium statistical mechanics*. It makes use of probability theory to deduce the behavior and the physical properties of **equilibrium** systems with a **very large number of particles** (like a gas, or the ice cube) from the laws governing its microscopic constituents. As emphasized, statistical mechanics deals with macroscopic systems. In these systems, the number of particles is so large that physical observables *s*uch as heat and work have negligible fluctuations and can be approximated by their mean values. However, if we consider systems with few degrees of freedom, these fluctuations become considerable and the physical quantities are not fixed by their mean values anymore and become random (or *stochastic*) variables. These considerations gave raise to the emergent field of *stochastic thermodynamics.* It relies on the theory of stochastic processes to describe the nonequilibrium dynamics of small systems such as colloidal particles, biopolymers, enzymes, etc.

In my first talk, I will describe the mathematical framework of stochastic thermodynamic and we will see how thermodynamic quantities (with their fluctuations) are defined within this theory.
Maybe your remember obscure terms from you statistical mechanics lectures such as microcanonical, canonical and ensemble equivalence? In my second talk, we will see how these equilibrium concepts are generalized, and I will address the problem of conditioning thermodynamic quantities on a rare fluctuation in periodically driven systems…

***...Despite all this, the kids still think that I do experiments on ice cubes.***

# Physical properties of cosmic filaments

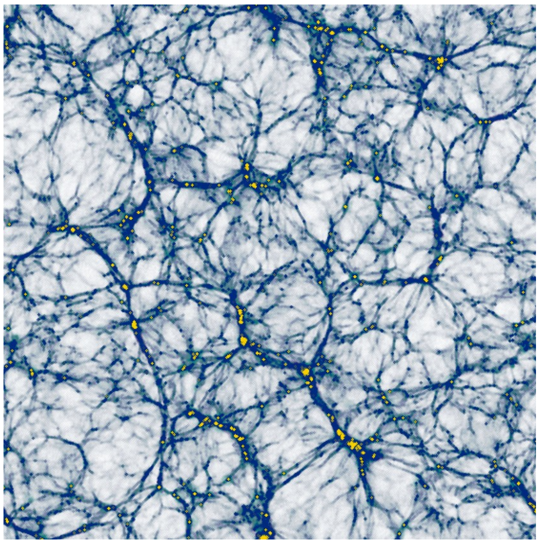
**Daniela Galárraga**
*Institut d'Astrophysique Spatiale, Université Paris-Saclay, Rue Jean-Dominique Cassini, 91440 Bures-sur-Yvette, France*

Under the action of gravity, matter in the largest scales of the Universe ($10^{22}-10^{24}$ m) is assembled to form a gigantic network, called the Cosmic Web.

This network is composed of four different types of structures, which are the nodes, filaments, walls and voids (see figure). Traced by galaxies, the cosmic web forms a web-like pattern, similar to that of neurons in our brain.

According to recent numerical simulations, around 50% of the total mass of the Universe might reside in the filaments of the Cosmic Web, thus tying our understanding of matter in the largest scales to that of filaments.

Nevertheless, these cosmic structures are very challenging to observe and not well understood, and as a consequence, a large fraction of matter is 'missing' in our observations today.



2d slice of the IllustrisTNG simulation. Blue, green and yellow colours show respectively dark matter, gas and stars.

By analysing large scale, hydro-dynamical simulations, I will present a study of the physical properties of cosmic filaments. I aim at answering the following questions: How are galaxies distributed around filaments, what are the properties of gas in these structures, and how can we detect it?

I will show that filaments can be separated into two different populations: the short and puffy ones, which might act as bridges of matter in the denser regions of the Cosmic Web, and the long filaments, that are thinner and live in less-dense environments.

I will show that these structures are essentially made by gas in a warm and a diffuse state, that is called the warm-hot intergalactic medium (WHIM), and that might be detected using the Sunyaev–Zel'dovich effect. Apart from WHIM gas, cores of filaments also host large contributions of other hotter and denser phases, but the exact composition depends on the type of filament. By building temperature and pressure radial profiles, I will show that gas in filaments is isothermal up to distances of 1.5 Mpc from the cores, with an average temperature of T = $4-13\times10^{5}$ K. Pressure at cores of filaments is on average P = $4-12\times10^{-7}\,keV\,.cm^{-3}$, which is $\sim$1000 times lower than pressure measured in observed clusters of galaxies. Finally, I will present an estimation of the observed Sunyaev-Zel'dovich signal from cores of filaments, and these results will be compared with recent observations.

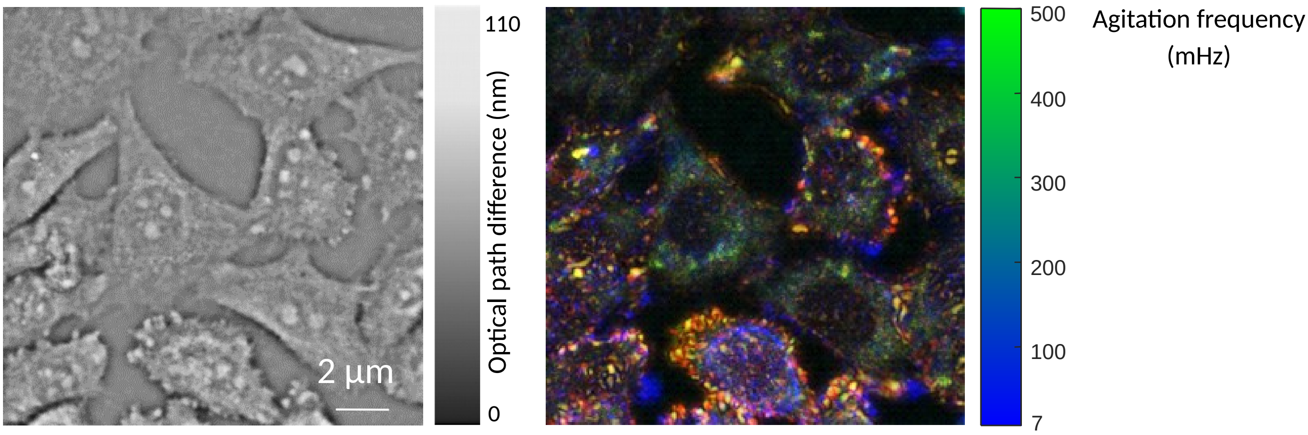
# 3D microscopy of intracellular dynamics and viscosity

**Clémence Gentner**
*Institut de la Vision, Photonics department, Sorbonne Université, 17 rue Moreau, 75012 Paris, France*

Health research is in constant need of new imaging techniques to push even further the limits of the invisible. In three-dimensional microscopy, not only the amplitude of the illumination is recorded, but also its phase. Thus, more than a convenient 3D reconstruction, phase imaging offers new contrast possibilities, for example when imaging transparent objects: depth and refractive index changes do not affect light intensity, but are directly proportional to the phase.

Wavefront or phase measurements rely on interferometry. Indeed, the interference between the light coming from an object and a reference beam that did not meet the object create a pattern encoding information on both the amplitude and the phase (the whole complex field). Several techniques exist, such as optical coherence tomography (OCT), holography, and wavefront sensing. My introduction talk will be an overview of the physical principles behind these methods.

The interferential nature of 3D microscopy allows associating a heterodyne detection: a temporal beating between the two interferometric paths produces a stroboscopic effect on the image. Therefore, very high frequencies can be measured (up to tens of MHz) with any type of camera. By imaging the dynamics of biological components in cells or tissues, I can provide a way to study their metabolism (see figure). Furthermore, I transposed this principle on injected nanoparticles probing the viscosity of the medium through their rotational dynamics (either Brownian or magnetically induced). These two imaging applications will be developed in my second talk, along with the development of heterodyne holography and dynamic wavefront sensing.




CHO cells imaged by wavefront sensing.
Left : Quantitative phase image (QPI), showing high details precision in transparent cells.
Right : Dynamic QPI: a color contrast corresponding to the metabolism variations is revealed.

# Chasing the triplet states of isolated peptides in gas phase

**Floriane Grollau,** V. Dmello, M.A. Gaveau, E. Gloaguen, V. Brenner, M. Briant et M. Mons
*Laboratoire Interactions, Dynamiques et Lasers, CEA, CNRS, Université Paris-Saclay, Bâtiment 701 - Orme des Merisiers, 91191 Gif-sur-Yvette, France*

Gas-phase physical chemistry is a huge field with many applications in astrophysics, atmospheric chemistry, biology, etc. A wide variety of molecules or molecular complexes (association of several molecules) can be studied. Moreover, many physical and chemical processes can occur that are of interest: collisions between molecules, chemical reactions, photon-molecule interaction, etc. After giving an overview of the different types of research in this field, I will focus my talk on the studies performed in my group.

The gas phase, unlike the condensed or liquid phase, allows molecules to be isolated from each other and from their environment. The individual behavior of the molecules can then be studied and directly compared with theoretical predictions. It is also possible to simulate the effect of the environment by generating molecular complexes. My research group focuses on molecules or complexes of biological interest. Most biological molecules are very floppy and adapt to their environment to act on a specific site. Thus, one of our research axes is to determine all the conformations of a molecule studied as a model of a biological molecule. Optical spectroscopy is a very relevant technique to obtain this molecular structural information. Of course, once the molecule absorbs a photon, one can also be interested in how the absorbed energy is distributed over the many degrees of freedom of the molecule and the electronic states. This is another research axe in my group in which I have been involved.

In the second part of my talk, I will present the different spectroscopy techniques used during my PhD (IR and UV/Vis spectroscopy, pump-probe) and other experimental techniques such as supersonic jet and mass spectrometry. The third part of my talk will be devoted to one of the results of my PhD: the detection of triplet states in peptide models. This study is part of the general issue of understanding the processes existing in proteins, which allow them to relax excess energy after UV excitation. This excess energy could cause serious damages to the structure of proteins and thus on their functions in the biological environment.

Phenylalanine is one of the three amino acids (a protein is an assembly of amino acids) that present an absorbing chromophore in the UV region with the phenyl ring (Phe). Depending on the molecule, the lifetime of the first excited singlet state (after absorption of a UV photon) could be long enough to allow conversion to a triplet state. This process is a radiationless transition between two electronic states with different spin multiplicity (forbidden transition). Triplet states are known to be long-lived states storing the energy for a long period of time. Therefore, the conversion to a triplet state could be a problem if there is no efficient relaxation process, as fragmentation of the molecule could occur due to the too large stored energy. However, the dynamics (time evolution) of triplet states is not well known. My PhD study aims to unravel these dynamics for peptide models containing a Phe ring. In particular, we want to understand the role of molecule size on the formation of triplet states and the role of chemical groups on their dynamics.

After presenting the structural studies of the different peptides, I will present the kinetic model we have developed to explain how the first singlet state located on the Phe ring of the peptide relaxes to the ground state.

# Using impurities to create states that are protected against… impurities!

**Sarah Pinon**
*Institut de Physique Théorique, Université Paris Saclay, CEA CNRS, Orme des Merisiers, 91190 Gif-sur-Yvette Cedex, France*

One of the most trendy topics in condensed matter physics is the study of so-called topological systems. These systems present, in particular, peculiar states on their edges. For example a topological insulator is an insulating material where conducting states exist at its edges, which means that the electrons can only move at the edges of the material. In topological superconductors, one can (theoretically) find edge states known as Majorana quasiparticles: they possess properties similar to the Majorana particles studied in high energy physics. What makes these states even more interesting, is their robustness to perturbations : as long as the perturbation doesn't break some specific symmetry, the states will not disappear and their properties will remain unchanged. This can include for instance changing the shape of the material's edge, applying a stronger electric field, or even adding impurities to the material. Proof of this robustness came with great excitement as it means topology could have applications in quantum computation : the protected states observed in topological materials could be used as fault-tolerant qubits, immune to quantum decoherence, thus greatly reducing the number of errors that can occur during a computation.

The first part of my talk will be such a general introduction to topological systems. In the second part, I will present a theoretical technique which allows to study topological edge states. This technique, which involves impurities (thus the title of my talk), can actually be used to study edge-related phenomena in general, but for a more pedagogical approach the talk will focus on applying the technique to one (or two, if time allows) topological system : a topological insulator described by the Kane-Mele model.

A mysterious picture, which represents a few of the fascinating facets of condensed matter topology. (Taken from the cover of *Topological Insulators* by P. Kotetes)

# Exotic phase transitions in systems of correlated electrons

**Maximilian Thees**
*Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, CNRS, 598 Rue André Rivière, 91405, Orsay, France*

The field of strongly correlated electrons directly attacks one of the strongest limitations of the standard quantum theory of solids: while we can solve Schrödinger's equation exactly for systems of a single particle, the introduction of a second particle already requires approximations. In order to deal with the $10^{23}$ electrons per $cm^3$ present in regular solids, their interactions are completely neglected.

However, physics cannot only be altered by these interactions, but some phenomena are completely *defined* by them: magnetism can be enabled, electron repulsion or scattering can limit their mobility sufficiently to render classical metals insulating.
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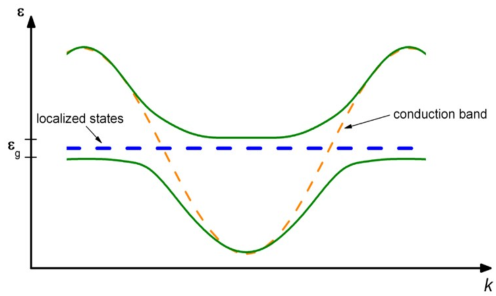
In order to understand these phenomena, we take a look at their *onset*. External parameters such as temperature, pressure or carrier density can drive a phase transition into a regime where these phenomena occur, which we can in turn directly compare to regimes we somewhat understand.




*Hybridisation between localised and conduction electrons creates a gap - and becomes directly visible in reciprocal space! Taken from wikimedia*

In the first part, an overview of the physics of strongly correlated electrons will be given, and briefly discussed how this can cause a system to transition to a new phase via the Mott metal-to-insulator transition or the Kondo effect.

In the second part, angle-resolved photoelectron spectroscopy (ARPES) will be introduced as a means to journey into reciprocal space, where the effects of hybridization in $URu_2Si_2$ and the elusive Mott-transition in $V_2O_3$ can be directly observed.

# Unveiling matter in our Galaxy using the Planck satellite: from interstellar physics to the origins of our Universe

**Clément Walter**
*Laboratoire de Physique de l'Ecole Normale Supérieure, 24 rue Lhomond, 75005 Paris, France*

The Planck mission is our current greatest endeavour to probe the Cosmic Microwave Background (CMB), the first light able to travel our Universe, and emitted when it was only ~380000 years old. During almost 5 years, the Planck satellite mapped our entire sky along 9 frequency bands to gather as much data as possible on the CMB, providing us with a rich knowledge of the early times of the Universe, as well as its evolution. However, the unprecedented accuracy and wealth of information came hand in hand with an unprecedented complexity in the data, and therefore in its treatment and analysis. This complexity is due to the vast amount and diversity of systematic noise sources, as well as the presence of what is called the foreground emissions: a sum of various signals from our galaxy and masking the CMB (e.g. thermal dust emission, synchrotron, and free-free continua, plus CO rotational lines).

In a first part, I will introduce the main specificities of the Planck mission and its data. I will present a few of the main discoveries that it already provided, such as the accurate characterisation of the very small temperature anisotropies of the CMB, expected to be the seeds from which the large-scale structures of the Universe have evolved. But there is still much that we haven't uncovered! I will introduce some of what still lies ahead, both in terms of fundamental science and data analysis methodology, paving the way for the ambitious upcoming CMB observation projects. I will present the algorithm used to produce maps ("map-making") from the data of Planck's High Frequency Instrument (HFI), by projecting the temporal data stream onto the sky, while cleaning some systematics which can only be accounted for at the end of the data treatment procedure. This map-making algorithm, called SRoll, uses templates of the foreground emissions to guide its determination of the different components. The algorithm and the input templates it depends on are still actively being studied and improved.

Secondly, I will present how I have been using the SRoll algorithm to improve the $^{12}CO$ and $^{13}CO$ rotational lines emission templates. The goal of this improvement is twofold: an enhanced accuracy in the component separation procedure, and an increase in our knowledge of the galactic CO emission. The former is essential to achieve the goals of the future CMB survey missions, where the expected observations will require a decrease in error level and residual level of a few orders of magnitude. We will need better templates and more knowledge of the foreground emissions to improve their separation from the CMB signal if we hope to achieve the aforementioned decrease. The latter has great scientific interest since the CO rotational signal is the main tracer of matter in the Interstellar Medium (ISM), and given the fact that the Planck data is currently the only survey able to produce full-sky maps of this emission. During this work, we identified the naively unexpected presence of a molecular emission in the 143GHz band, spatially correlated to the CO emission, which cannot be neglected during the CO identification and the component separation, and we started investigating the presence of CO emission at high latitudes, which cannot be explained by the standard mechanisms typically at play in the dense molecular clouds.

# 2D Semiconductors to Tune Spin Transport

**Victor Zatko**
*Unité Mixte de Physique CNRS/Thales, Université Paris-Saclay, 1 Avenue Augustin Fresnel, 91767 Palaiseau, France*

Magnetism played a key role in the revolution of data storage that we are going through. The amount of stored information has been multiplied by 10000 over the last 20 years. Behind the massive data center and new ultra fast and low power magnetic memories (MRAMS), one can find the same physical concept: spintronics. In spintronics, the information is no longer carried by the charge of the electron as silicon based technologies but by its spin.

In parallel, the field of 2D materials as exploded, with experimental results highlighting unique properties foreseen to be suitable for applications. While very recent, the introduction of atomically thin 2D materials in spintronics devices has already shown some promising properties spintronics [1]. It was shown that a single atomic layer of these 2D materials associated to some ferromagnets (FM) can lead to radical change in spin transport[2].

The recent advent on the wide family of 2D semiconductors Transition Metal Dechalcogenides (TMDCs) opened new opportunities for further tailoring of spintronics properties.

The first talk will be a general overview of spintronics and the benefits of combining spintronics and 2D materials while in the second part I will be presenting results on $WS_2$ based Magnetic Tunnel Junctions (Figure 1). We will detail a protocol to fabricate these devices with step by step characterizations in support (Raman spectroscopy, photoluminescence, AFM measurements…) which aims at preserving interfaces spin properties by avoiding oxidations and degradations. The fabrication process is further validated by the measurements of magnetoresistance signals above state of the art for 2D semiconductors based spin valve. We then present experimental results on $WS_2$ spin-filtering tunability with thickness that we discuss in light of its peculiar thickness band-structure evolution, with Density Functional Theory calculations in support. Our work opens the way to the integration of different members of the very large TMDCs family, in order to reveal their spin transport properties in MTJs [3].

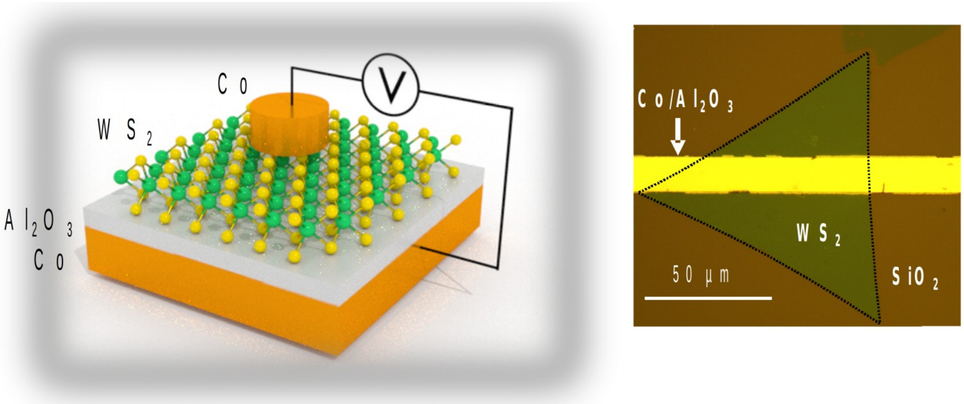



Figure 1: Scheme and optical image of the WS2 based Spin Valve.

[1] Review: Piquemal-Banci et al. J. Phys. D: Appl. Phys. 50, 203002 (2017).
[2] Piquemal-Banci et al. ACS Nano 12, 4712 (2018).
[3] Zatko et al. ACS Nano 12, 14468 (2019)

# Senior Speakers

# Forthcoming...

**Silke Biermann**
*CPHT, Ecole Polytechnique, 91128 Palaiseau cedex, France*

# Forthcoming...

**Mathieu Langer**
*Institut d'Astrophysique Spatiale, Université Paris-Saclay, Rue Jean-Dominique Cassini, 91440 Bures-sur-Yvette, France*

# Strongly Correlated Electron Systems and Novel States of Quantum Matter

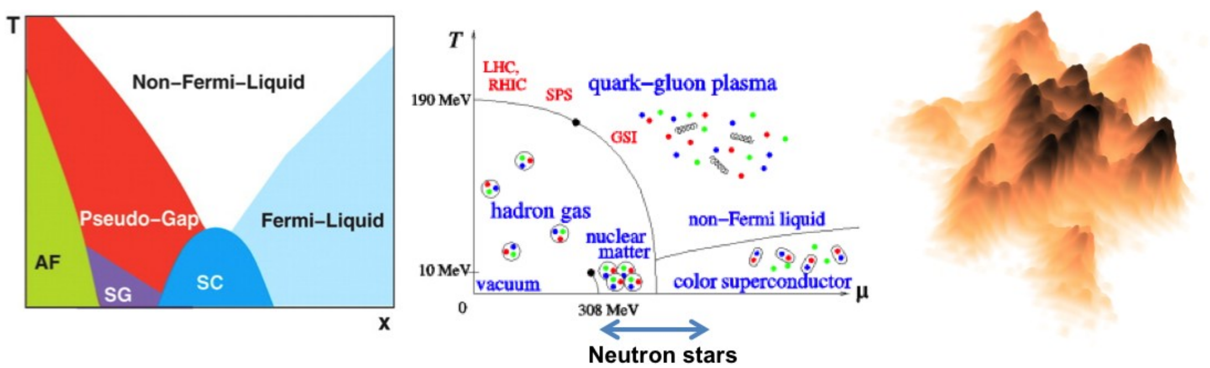
**Andrés F. Santander-Syro**
*Institut des Sciences Moléculaires d'Orsay – Université Paris-Saclay & CNRS,* 598 Rue André Rivière, 91400, *Orsay, France*

The physics of strongly interacting fermions is the common thread in several open problems at all scales of the Universe. Think about the quarks confined inside a nucleon, or the nucleons in compact heavy nuclei, or the quark matter in super-dense neutron stars. As it turns out, several classes of materials, some of them present in our daily life, display strongly interacting electrons – sometimes in conjunction with boundary conditions confining the electrons in two or one dimensions. Such strong electron correlations give rise to a broad realm of phase transitions and exotic, often poorly understood, states of matter showing remarkable macroscopic properties, such as high-temperature superconductivity, large magneto-resistance, or metal-to-insulator transitions – as illustrated in the figure below, left panel, for a copper-oxide superconductor.

In my first talk, I will introduce the general problem of strongly interacting fermions, and show how strong electron interactions arise in some types of materials. I will discuss the observed consequences of such behaviour, their possible relation to other problems in physics (e.g., the phase diagram of quark matter, central panel in the figure), and their potential applications.

In my second talk, I will show how we can experimentally study the quantum-mechanical electronic states in such materials –i.e., how we can directly *measure* the eigen-energies of their Schrödinger equation, even if nobody knows yet how to calculate them analytically! I will then discuss the application of such a technique to the case of two emblematic problems of modern Condensed Matter Physics:

- The two-dimensional electron systems confined at the surface of insulating transparent oxides (figure below, right panel), which are a playground for the study of many fundamental issues in correlated-electron systems, and are promising for a future "oxide-based" electronics.
- The study of how the electronic states change across the so-called "hidden-order" transition in $URu_2Si_2$. Such a second-order phase transition is clearly observed in many experiments, but the associated broken symmetries remain so-far unknown, earning it the soubriquet of the "Higgs problem" of Condensed Matter Physics.




**Strongly correlated fermion systems.** Left, generic phase diagram (temperature vs chemical potential of electrons) of a high-temperature copper-oxide superconductor, showing the *observed* antiferromagnetic (AF), pseudo-gap, spin-glass (SG), superconducting (SC), non-Fermi-liquid, and Fermi-liquid phases. Middle, *hypothetical* phase diagram (temperature vs chemical potential of quarks) of QCD quark matter (courtesy Andreas Ipp, TU-Wien). Right, experimental Fermi surface of a 2D electron system tailored at the surface of an insulating transparent oxide.

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