QUantum
Systems,
Elementary Fields,
Radiation, **C**osmos
and **Y**nteractions

QUERCY 2022

Le Bastit, Rocamadour (France)

VOL.III. . . No.14

FROM MAY 28, 2022 TO JUNE 4, 2022

By ANDRÉS F. SANTANDER-SYRO

& OLIVIA CHITARRA

Major advances in modern research often come from interactions among scientists working in different areas of the same discipline. This workshop will bring together high-level 3rd year PhD students from several areas of Physics. The goals are promoting the pedagogical diffusion of their work, and the exchange of ideas and experimental/theoretical techniques, to an audience broader than just the community of specialists of their own field.

Scope

The last year of doctoral studies is an important turnover in the career of a young researcher: the successful PhD candidate has not only mastered the essential theoretical and technical know-how of a given area of research, but also produced original results that mark her/his assimilation into a community of specialists. But while advanced PhD candidates are already well prepared to brainstorm with colleagues of their own domain, they often lack exposure to, and training in, an exchange of ideas or a pedagogical popularization of their work among a broader community of researchers in other areas of their discipline. Yet, in todays complex landscape of ultra-specialized research, important advancements and major breakthroughs often come from such exchanges. Thus, it appears essential to prepare the young generation to the challenge of such multifaceted work from their initial steps as independent researchers.

This workshop will bring together high-level 3rd year PhD students of Physics in a relaxed, friendly atmosphere, with the aim of encouraging the pedagogical diffusion of their work to an audience broader than just the community of specialists of their own field, and thus promoting, from the early stages of their career, a strong exchange of ideas and experimental/theoretical techniques with other areas of Physics. A few senior scientists working in several areas of current research in Physics will also participate, with the aim of stimulating the discussions and helping to create thought provoking interchanges.

Each participant will give two talks: a pedagogical introduction to her/his general field of research (30 min), followed by an equally instructive part exposing her/his work (30 min)

Overview

JUNIOR TALKS

SENIOR TALKS

SCHEDULE

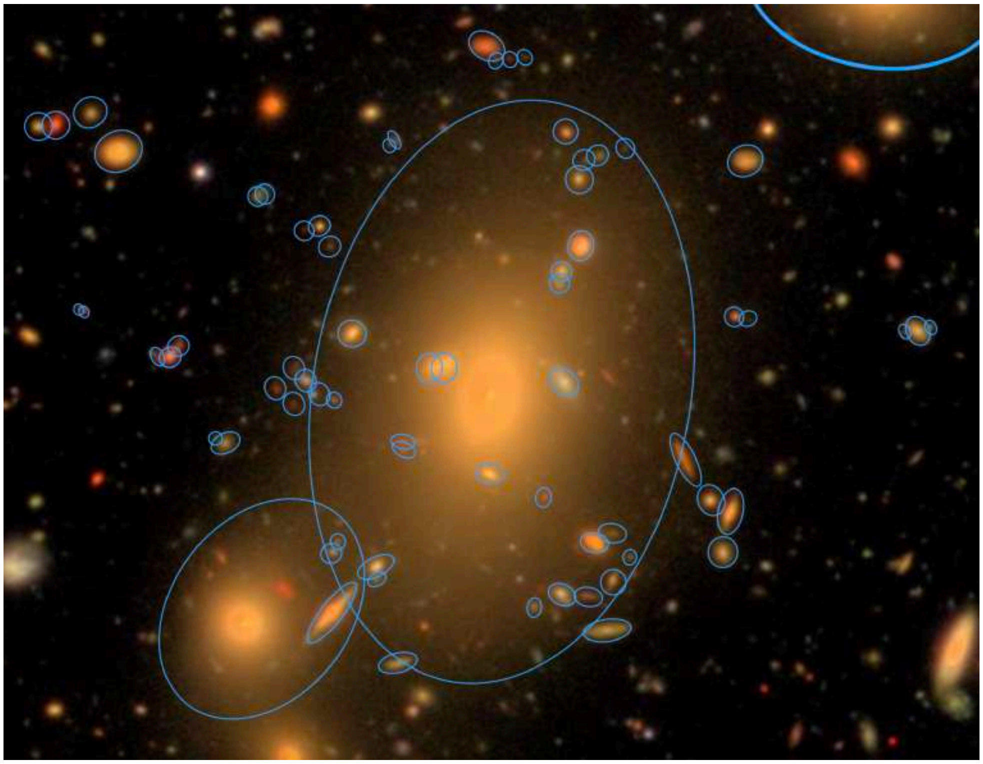
	Saturday 28/05	Sunday 29/05	Monday 30/05	Tuesday 31/05
8:30-9:30		Breakfast	Breakfast	Breakfast
9:30-10:00		Olivia I	Thomas I	Abigail I
10:00-10:15		Q&A	Q&A	Q&A
10:15-10:45		Olivia II	Thomas II	Abigail II
10:45-11:00		Q&A&C	Q&A&C	Q&A&C
11:00-11:30		Raphaël I	Andrés I	Valentin I
11:30-11:45		Q&A	Q&A	Q&A
11:45-12:15		Raphaël II	Andrés II	Valentin II
12:15-12:30		Q&A	Q&A	Q&A
12:30-14:30		Lunch	Lunch	Lunch
14:30-15:00	Arrival	Etienne I	Discussions	Discussions
15:00-15:15		Q&A		
15:15-15:45		Etienne II		
15:45-16:00		Q&A&C		
16:00-18:30		Discussion		
18:30-19:30	Welcome			
19:30-00:00	Dinner	Dinner	Dinner	Dinner

	Wednesday 01/06	Thursday 02/06	Friday 03/06	Saturday 04/06
8:30-9:30	Breakfast	Breakfast	Breakfast	Breakfast
9:30-10:00	Hubert I	Marina I	Jean-Baptiste I	Departure
10:00-10:15	Q&A	Q&A	Q&A	
10:15-10:45	hubert II	Marina II	Jean-Baptiste II	
10:45-11:00	Q&A&C	Q&A&C	Q&A&C	
11:00-11:30	Alice I	Mathieu I	Yanis I	
11:30-11:45	Q&A	Q&A	Q&A	
11:45-12:15	Alice II	Mathieu II	Yanis II	
12:15-12:30	Q&A	Q&A	Q&A	
12:30-14:30	Lunch	Lunch	Lunch	
14:30-15:00	Discussions	Discussions	Discussions	
15:00-15:15				
15:15-15:45				
15:45-16:00				
16:00-18:30				
18:30-19:30				
19:30-00:00	Dinner	Dinner	Dinner	

Hubert BRETONNIERE

Institut d'Astrophysique Spatiale, Université Paris-Saclay, 91400, Orsay, France

Detecting overlapping galaxies with Machine Learning



Example of a crowded galaxy field with a lot of blended galaxies (image from the Hyper Suprime-Cam at the Subaru Telescope).

When a telescope observes the Universe, it takes photographs of a part of the sky. Those photographs are 2D plans, where all the objects that are in the line of sight are projected into the focal plane of the instrument. Losing the information about the distance of the object, its depth in the sky, is one of the major problems in astrophysics and cosmology.

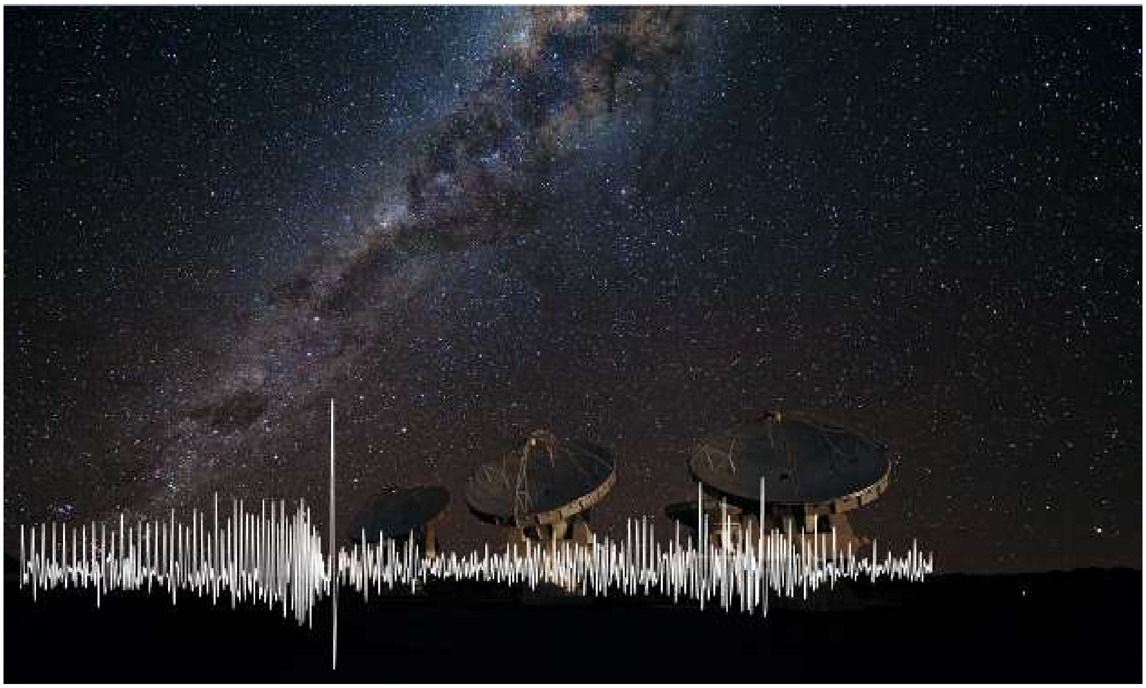
One consequence of this 3D to 2D projection is that objects of the sky that are in the same line of sight but physically separated because having a different depth will overlap in the final observation. We call this phenomenon *blending*, and the task to identify and separate those sources *deblending*. Measuring the shapes of galaxies is one of the main measurements for cosmological survey, which can "easily link the ellipticity of galaxies to the main parameters of our Universes mathematical model. But remember: blending leads to separated galaxies merging in the Telescope photograph ! Thus, measuring the shape of those galaxies becomes very challenging, or even impossible if we don't identify that a galaxy is blended. Studies show that for next generation of galaxy surveys, this effect can be one of the main systematics, i.e. error in the measurements, which will lead to very biased predictions !

During my presentation, I will first present a global overview of Machine Learning, its basics, its strengths and caveats. Then, I will present our method to detect those specific blended galaxies, thanks to a Deep Learning algorithm. I will then explain the different solutions we have used to have a probabilistic detection of galaxies, which give a pixel-wise uncertainty for our large sky detection images. Finally, I will show you that we obtain state-of-the-art results, both in purity and completeness, with an unprecedented depth of detection, for isolated, blended or even truncated galaxies !

Olivia CHITARRA

Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, 91400, Orsay, France

High resolution spectroscopy for the detection of new species in the interstellar medium



High resolution spectroscopy consists in the observation of the rotational structure of molecular species. Contrary to other spectroscopic techniques, the rotational structure is unique for each molecule and the determination of the rotational spectrum allows for the distinction of members of a molecular family. Rotational transitions can be measured in several spectral domains from energetic domains (such as the UV or VUV spectral domains allowing for the measurement of rovibronic transitions) to low frequency ones (such as the microwave domains enabling the measurement of pure rotational transitions). My PhD subject is based on the measurement of pure rotational transitions, in other words transitions within the electronic and vibrational ground state. In this presentation, I will introduce the concept of high resolution spectroscopy, why it is important to measure pure rotational spectrum and applications of that technique.

The main context of my project is the interstellar medium (ISM). The only information astrophysicists can exploit from the ISM is the light after it has reacted with various objects. Therefore, by absorption or emission of light, astrophysicists are able to know the molecular composition of this medium along with the physical conditions of this medium (like the temperature). The knowledge of the molecular composition of the ISM is essential to understand physical and chemical processes. To do so, astronomical surveys are permanently measured by observatories. More and more facilities are dedicated to the microwave and millimeter-wave spectral domain[1]. The rotational fingerprint of all species present in the ISM are available in surveys recorded in this spectral region. Therefore, unambiguous assignments can be proposed leading

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[1] https://www.eso.org/public/france/teles-instr/alma/

to the detection of species in the different sources of the ISM. To date, about 280 molecules[1] (neutral and reactive species) have been detected and 90% have been detected thanks to high resolution spectroscopy. However, to be able to assign new transitions and therefore detect new species, laboratory studies are warranted beforehand.

My PhD subject is to perform high resolution studies on new species in the laboratory in order to enable their search and detection in the ISM. More specifically, I will first present my work on benzonitrile[2] and adamantane derivatives. Then, I focused on the synthesis and detection of radicals (reactive species), species under-detected in the ISM compared to stable ones. It could be explained by a lack of work in the laboratory. I will present my results on three radicals formed from methanol[3],[4] (CH3OH) and acetonitrile[5],[6] (CH3CN). Finally, I developed a pulsed jet discharge experiment. The supersonic expansion created allows us to study species (synthesized by an electric discharge) in the same conditions of temperature than the ones of the ISM. I will present the preliminary results I obtained with this new set-up.

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[1] http://www.astrochymist.org/astrochymist_ism.html

[2] B. McGuire et al., Science (2018) 359

[3] C. Bermudez et al., Astronomy and Astrophysics (2017) A9

[4] Y. Endo et al., The Journal of Chemical Physics, (1984) 81

[5] S. Saito et al., The Journal of Chemical Physics (1997) 107

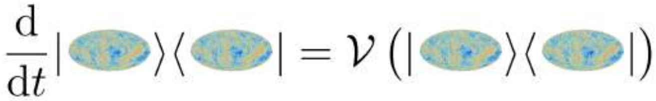
[6] H. Ozeki et al., American Astronomical Society (2004) 617

Thomas COLAS

Institut d'Astrophysique Spatiale, Université Paris-Saclay, 91400, Orsay, France

An Open Universe: open quantum systems, dissipation and decoherence in the early universe

One of the most striking predictions of the standard model of cosmology is to trace back the origin of stars, galaxies and all the structures of our universe to quantum fluctuations of the primordial vacuum. This feature makes cosmology an interesting playground to test quantum mechanics in its most extreme regimes. Yet, such an ambitious program requires an accurate description of the quantum history of the universe.



Cosmological observations of the Cosmic Microwave Background and of the Large Scale Structures of the universe are fully consistent with primordial perturbations from quantum mechanical origin. Current constraints favor models where a single scalar degree of freedom leads the dynamics of the early universe[1]. Yet, these models suffer theoretical drawbacks and are difficult to embed in realistic settings. On the other hand, extensions to single-field models are difficult to describe at the quantum level and often fail to explain why a simple single field setting works so well at describing the data.

Effective Field Theories aim at providing a systematic way to consider extensions to the single-field setting, incorporating the knowledge of unknown physics in a parametrically controlled manner. This research program has been successful at describing corrections to the single-field statistics by computing N-point functions to an unprecedented precision and now turns to investigate genuinely quantum effects[2]. In order to grasp the implications of multifield extensions at the quantum level, the formalism needs to incorporate non-unitary effects such as dissipation and decoherence. To achieve this goal, cosmologists and high energy physicists may rely on tools developed in quantum information theory, quantum optics and condensed matter. In particular, the Theory of Open Quantum Systems[3] is well suited to tackle these questions. One of its central ingredients are master equations. Ubiquitous in quantum optics where they describe the effects of an almost unspecified environment on the evolution of measurable degrees of freedom, they rely on assumptions that do not straightforwardly extend to cosmology where the background is dynamical, the Hamiltonian time-dependent and the environment out-of-equilibrium. Hence, our work aims at implementing master equations in the cosmology and benchmark their efficiency. At the crossroads of various fields, this research program may allow us to know if we can observationally prove the quantum origin of cosmic structures.

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[1] Planck Collaboration, *Planck 2018 results, VI. Cosmological parameters*, A&A, Volume 641, September 2020

[2] Burgess, C. P., Holman, R., Tasinato, G., Open EFTs, *IR effects & late-time resummations: systematic corrections in stochastic inflation*, JHEP, Volume 2016, 153, January 2016

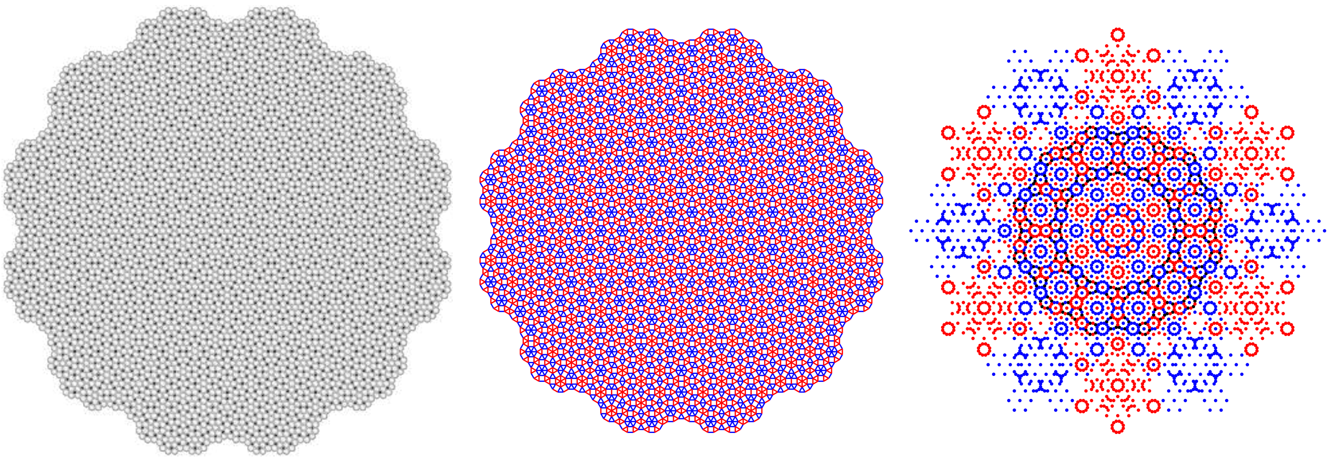
[3] Breuer, H.-P., Petruccione F., *The Theory of Open Quantum Systems*, Oxford University Press, 2007

In the first part of my talk, I will introduce the theory of Open Quantum Systems with a particular emphasis on non-unitary processes. In the second part, I will show why the early universe can be considered as an one of them. We will discuss how dissipation and decoherence happen in the early universe and what are their consequences on the generation of cosmic structures. Finally, I will present my work on the implementation of master equations in cosmological settings.

Etienne FAYEN

Laboratoire de Physique des Solides, Université Paris-Saclay, 91400, Orsay, France

Quasicrystals in simple numerical models



The first figure shows a mixture of particles of two sizes arranged in a perfect dodecagonal quasicrystal. While our eyes can spot a high degree of order, it is impossible to rationalise the structure as the repetition of a unit cell. The second figure displays the underlying tiling of squares and triangles obtained by joining neighbouring large particles. The last figure is the somewhat more abstract perpendicular *representation of the structure, which is linked to its diffraction pattern. For larger and larger patches, this representation would converge to a dense fractal of 12-fold non-crystallographic symmetry.*

We usually classify solids at the microscopic level by their structures. Glass and plastics usually exhibit a disordered structure, while metals or salts typically form crystals, in which the building blocks are extremely well-ordered on a periodic lattice. Aside from those two usual categories, a new class of solids was discovered in the 80's. These solids, later to be called quasicrystals, possess long range order but lack the translation symmetry of ordinary crystals. They obey tight construction rules, but cannot be described as the mere repetition of a unit cell. First considered as rare oddities, they are nowadays regularly observed in very different systems, ranging from metallic alloys to soft matter systems such as nanoparticles and macro-molecules. This suggests that general principles stabilise those complex structures. The goal of my PhD is to look for minimal ingredients for quasicrystals self-assembly, using simple numerical models.

In the first presentation, I propose to introduce the fascinating structure of quasicrystals, and walk you through the rich phenomenology of "quasicrystallography". In addition, I will quickly review Monte Carlo and molecular dynamics numerical simulation methods, upon which my work heavily relies.

In the second presentation, I wish to tell the sprawling and serendipitous exploration of the field carried out together with my advisors, as a –hopefully– clear and linear *a-posteriori* story.

Alice FAZZINI

Laboratoire pour l'Utilisation des Lasers Intenses, École Polytechnique, 91128, Palaiseau, France

Laser-driven shocks of astrophysical interest

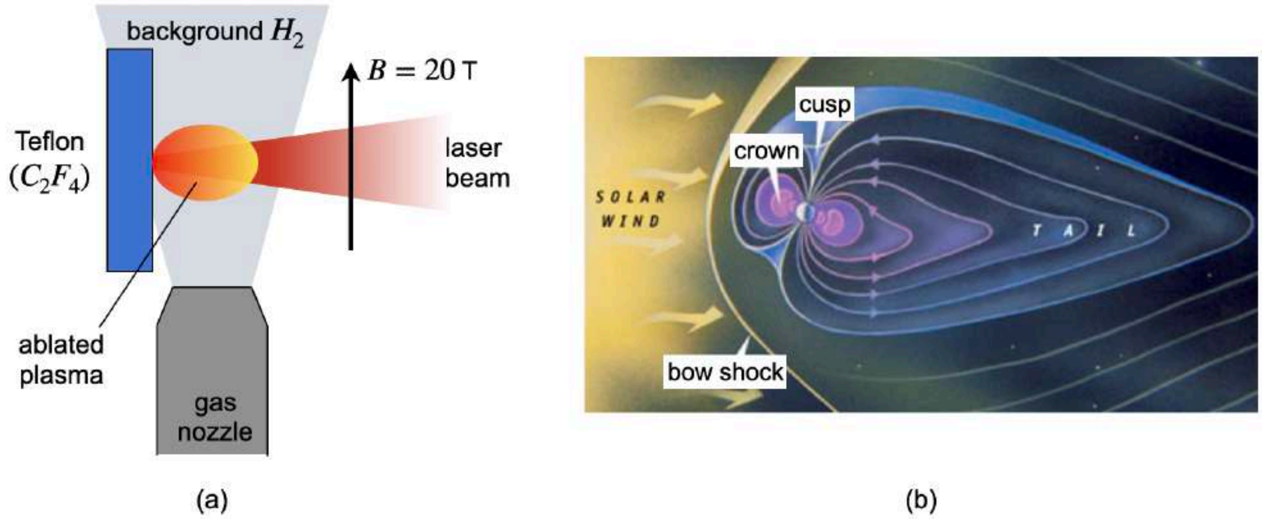
The huge progress made over the last decades in the development of high-energy lasers has allowed the access, in the laboratory, to extreme physical conditions of astrophysical relevance. The so-called laboratory astrophysics is the field of study that focuses on the experimental investigation of astrophysical phenomena which, through the use of similarity criteria, can be emulated in the laboratory.

Here, we will concentrate on the study of collisionless shock waves, which are phenomena taking place in many astrophysical contexts, such as supernova explosions and bow shocks. They are held responsible for the production of supra-thermal particles (the so-called cosmic rays), whose energization mechanisms are nowadays not fully understood.

A shock is a thin discontinuity layer that separates two media characterized by different values of their physical quantities. In neutral fluids, a shock is mediated by short-range binary collisions, which dissipate into heat the kinetic energy of the fluid crossing the shock. In plasmas, the interaction between particles takes place through the long-range Coulomb force. In the Universe, where most of the matter is in the state of plasma, we witness the formation of shock structures much thinner than the typical particle mean free path. In this case, we talk about collisionless shocks.

In the first part of my talk, I will introduce the domain of laboratory astrophysics performed with high-energy lasers. This will be accompanied by basics of laser-plasma interaction and the similarity criteria used to link astrophysical and laboratory processes.

In the second part of my talk, I will present the results that we have obtained in our recent experimental campaigns. In detail, we will focus on the characterization of a single fast shock structure and on the interaction between two of such structures. For both, we will highlight their interest with respect to the particle energization and to astrophysical phenomena.



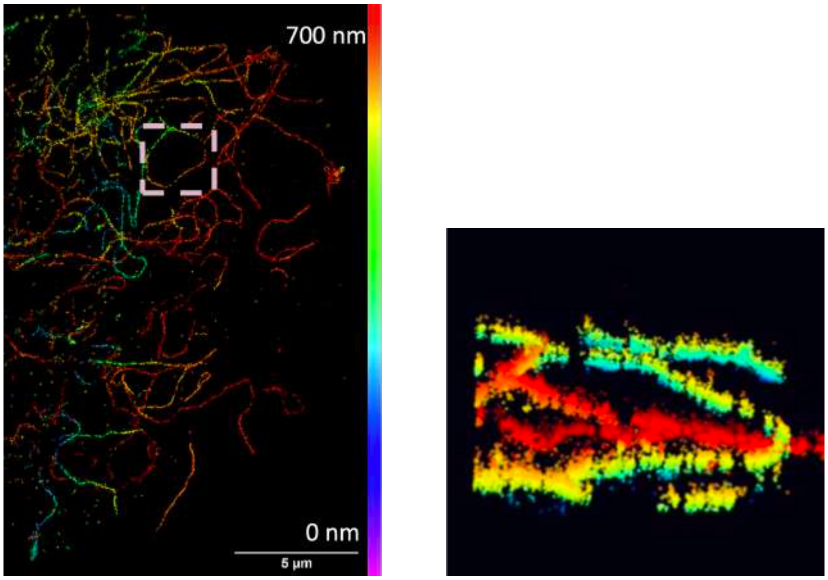
(a) Typical experimental setup for the generation of laser-driven magnetized shocks.
(b) Bow shock formation due to the interaction between the solar wind and the Earth magnetosphere.

Abigail ILLAND

Institut des Sciences Moléculaires d'Orsay, Université Paris-Saclay, 91400, Orsay, France

Time modulated excitation for enhanced 3D fluorescence nanoscopy

Diffraction has long been considered as a fundamental limitation to the spatial resolution of optical imaging systems. In fluorescence microscopy, it is normally not possible to image structures smaller than 200 nm. In particular, the nanometric organization of the cellular cytoskeleton, which plays a key role in biology, cannot be imaged using classical fluorescence microscopy. But in the recent years, many super-resolution microscopy approaches have been developed which led to the Nobel Prize in chemistry in 2014[1][2][3]. One technique in particular, Single molecule localization microscopy (SMLM), makes it possible to achieve a lateral positioning accuracy of around 10 nm for the emitters. This approach uses chemical and/or physical properties of the fluorophores to acquire them at different times. In a first part of my talk, fluorescence microscopy and its limitations will be presented. Once these limitations will be introduced, different super-resolution techniques will be described.



(a) (b)

(a) U2OS cell with vimentin labeled with AF 647, imaged at the coverslip. (b) Close-up transverse cut corresponding to the white- boxed region in (a)

In Single molecule localization microscopy, the position of the fluorophores is usually found using the spatial parameters of a fitted PSF (Point Spread Function). The localization precision of the emitters will

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[1] Stefan W. Hell and Jan Wichmann, "Breaking the diffraction resolution limit by stimulated emission: stimulated-emission-depletion fluorescence microscopy," Opt. Lett. 19, 780-782 (1994)

[2] Moerner, W. E. and Kador, L., Optical detection and spectroscopy of single molecules in a solid, Phys. Rev. Lett., 10.1103/PhysRevLett.62.2535 (1989)

[3] Betzig E. et al., Breaking the Diffraction Barrier: Optical Microscopy on a Nanometric Scale, Science, 10.1126/science.251.5000.1468 (1991)

then strongly depend on the shape of the PSF, which will be degraded due to the aberrations depending on the deepness in the sample. A new method based on time modulated structured illumination was recently proposed. This method is called ModLoc and a factor 2 of improvement has been achieved compared to more classical methods laterally [1]. ModLoc can also be applied for an improvement of the axial resolution. And therefore, be a 3D imaging method. This technique where the excitation differs from other widefield microscopy methods will also lead to new implementations in the detection part of the microscope.

The setup and the comparison with more classical SMLM setups will be presented in a second part of my talk. Various implementations of ModLoc will be discussed and different strategies to improve furthermore its performances will be described. Preliminary results on a new implementation of ModLoc using 2 microscope objectives instead of 1 will also be discussed.

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[1] Jouchet, P. et al.. Nanometric axial localization of single fluorescent molecules with modulated excitation. Nat. Photonics 15, 297304 (2021). https://doi.org/10.1038/s41566-020-00749-9

Raphaël SALAZAR

Synchrotron SOLEIL, L'Orme des Merisiers, 91190, Saint-Aubin, France

Photoemission, 2D materials and ferroelectricity

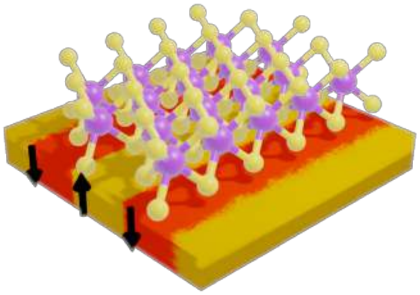


Diagram an heterostructure of the 2D material WSe_2 *and a ferroelectric substrate with domains of opposite polarization*

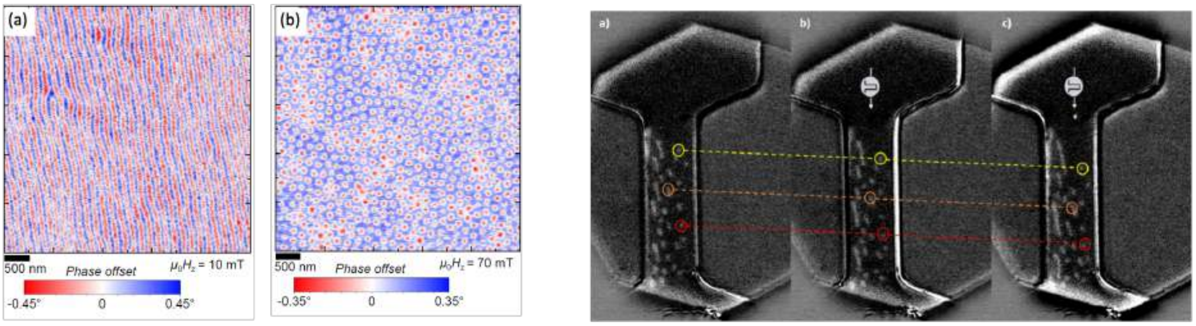
The electronic band structure is the single most important property of a material that determines its behavior in a wide range of conditions. It affects in particular the optical (absorption/emission spectra) and transport properties making its understanding essential to device engineering. Here we will show how the electronic band structure is formed from the discrete symmetries and periodic potentials inside matter. We will first approach this object from the theoretical point of view, building a solid step by step from the bounded electron in an atom. We will also take the opposite route from the free electron to the electron in a solid. We will then introduce angular resolved photoelectron emission spectroscopy (ARPES) as a direct experimental measurement of electronic band structures and from it refine our understanding of the photelectron spectroscopy beyond one-electron pictures.

In a second part we will dive in the control of 2D materials with ferroelectricity. Such multilayers based on quantum materials (complex oxides, topological insulators, transition-metal dichalcogenides, etc) have enabled the design of devices that could revolutionize the microelectronics and optoelectronics sectors. Here we demonstrate the large-scale integration of compounds from two different highly-multifonctional families: perovskite oxides and transition-metal dichalcogenides (TMDs). We couple $BiFeO_3$, a room-temperature multiferroic oxide, and WSe_2, a semi-conducting two-dimensional material with potential for photovoltaics and photonics. After quickly presenting these two family of materials we will explain how the induced dipole at the interface from the ferroelectric substrate can lift the degeneracy of electronic states in the valence band of WSe_2. We will then discuss the results of our angle resolved photoemission spectroscopy measurements and in the way highlight some fine photoemission effects.

Yanis SASSI

Unité Mixte de Physique, CNRS, Thales, Université Paris-Saclay, 91767, Palaiseau, France

Skyrmion, a magnetic topological object, and its future applications



(a) (b)

Left: (a) MFM observation of a) a stripe phase b) and a skyrmion lattice phase. Right: Coherent skyrmion motion observed by MOKE. a) Observation after nucleation and after b) 10 c) and 20 pulses.

During the past decades the field of magnetism has shown a lot of interest because of its multiple applications. Among them we can list a large range of sensors, data storage and data computing devices and even some biomedical applications. Behind all of this relies a particularity of some elements from the periodic table to exhibit a net and ordered magnetic moment. We call them ferromagnets.

And with the trend to downscale every component, in order to increase their amount in a limited space, those ferromagnets have been used in thin films with thicknesses down to a few nanometers. But when reducing the size of an object, one increases the role of interfaces compared to bulk systems. This leads to new properties that we can be tuned by changing the materials at the interface with the ferromagnetic layer (oxyde, heavy metals or even 2D materials) in order to create new types of magnetic textures.

In the first part of this talk we will see different magnetic textures such as the uniform state, wormy state and stripe phases (Fig1.a) and understand how we are able to continuously go from one to the other, for example using magnetic external field. Then we will go in the details of all the energies involved in their stabilization and resulting from the Heisenberg interaction, the Dzyaloshinskii-Moriya interaction, different anisotropies and dipolar interactions. Finally, we will describe the skyrmion case (Fig1.b), which can be assimilated to a magnetic soliton with topological properties, and how to image them with magnetic force microscopy (MFM) or Kerr effect microscopy (MOKE).

In the second part we will go further concerning the study of the skyrmions and discuss how they could be used for future applications. For example, we will describe their motion under train of nanoseconds electrical pulses (Fig2) and underline their behaviour in various geometries. We will finish by describing antiferromagnetic skyrmions which are a slightly different object with even better properties.

Valentin SAUVAGE

Institut d'Astrophysique Spatiale, Université Paris-Saclay, 91400, Orsay, France

Development of a sub-Kelvin refrigerator for space missions: How to use Helium to observe the early universe?

The Cosmic Microwave Background was emitted 380 000 years after the Big Bang. This relic radiation from the early universe remains observable by specific sensors. From its prediction (Gamov, 1940) to the first detection (Penzias&Wilson, 1965), many observations of the CMB were performed (ground, balloon, parabolic rocket, satellite,), improving the precision of the measurements. In 2009 was launched the Planck Space Telescope, to map the CMB with an unrivaled sensitivity of the main instrument: HFI (High-Frequency Instrument). This sensitivity was obtained mainly by cooling down the detectors at 100 mK. This temperature was generated by an Open-Cycle Dilution Refrigerator (OCDR).

OCDR works with two isotopes of Helium (3 & 4). 3He and 4He are mixed to produce a cooling power, then the mixture is released in space. The refrigerator has worked in space for more than 2 years, lifetime limited by the quantities of Helium that were onboard. For future longer missions in need of these very low temperatures (and high thermal stability), the development of a Closed-Cycle Dilution Refrigerator (CCDR) for which the mixture will be recycled is required. A Demonstrator Model (DM) working in a laboratory environment has already been developed. However, for operation in space, this system will need to work without gravity and be able to sustain the high level of vibrations during launch without any damages.

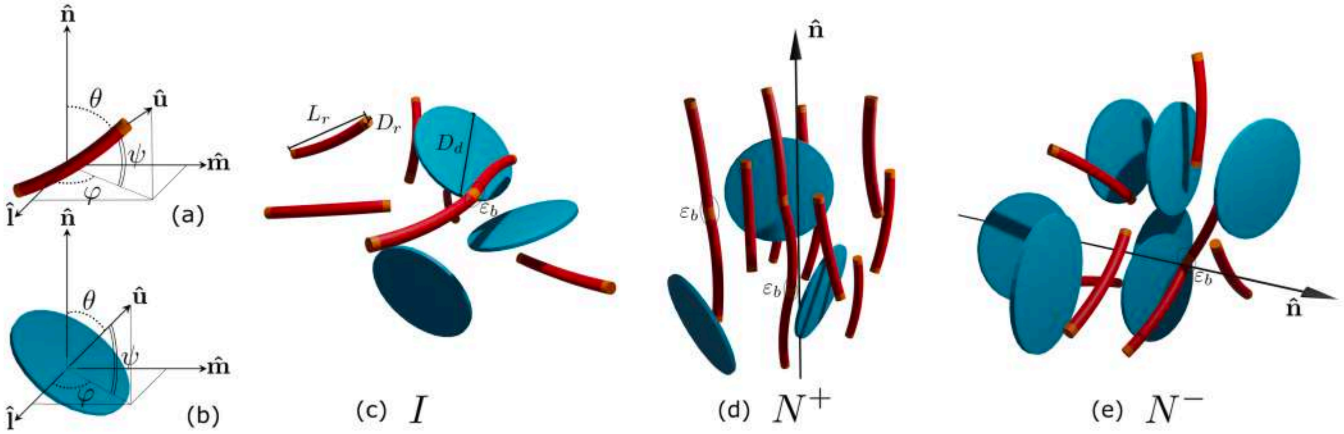
Current CAD model of the CCDR Structural and Thermal Model, able to match both thermal and structural requirements.

During the first time slot, I will present the scientific context of the CMB observations, from the historical aspects to the instrumental outcome. This will end with an introduction to the physical and instrumental aspects of the OCDR. Then, I will present the limits of the OCDR, and the need for a CCDR for future missions. A description of all the challenges (and planned solutions) will be done to reach a fully functional Engineering Model.

Marina TORRES-LAZARO

Laboratoire de Physique des Solides, Université Paris-Saclay, 91400, Orsay, France

Phase behavior of hybrid liquid crystals



Schematic representation of the various liquid crystal phases emerging for discs mixed with polymerizing rods: (a) - and (b) - Principal angles describing the orientation $\widehat{\boldsymbol{u}}$ *of a single rod monomer - and disc - with respect to the molecular director* $\widehat{\boldsymbol{n}}$*. (c) Isotropic phase* I*. (d) rod uniaxial nematic phase* N^+*. (e) discotic uniaxial nematic phase* N^- *in which the reversibly polymerizing rods are dispersed* anti-nematically*.*

Liquid crystals (LCs) represent a state of matter intermediate between crystalline solids, which are characterized by a regular periodic arrangement of atoms or molecules, and isotropic liquids, which lack any type of order. Classification of various phases is usually based on the concepts of symmetry relevant to liquid crystals such as orientational order, translational order, or chirality.

During the first part of my double talk, I will very briefly introduce some key concepts to understand LC phases formed by anisotropic colloidal particles. An overview of some relevant LC phases will be exposed and we will explore the Onsager theory, which explains why orientational order arises when increasing concentration.

For my second talk, I will explain some consequences observed in mixtures of two different components, their resulting phase diagrams at the isotropic-nematic regime (low particle concentrations), and briefly introduce the depletion interaction. I will finish by presenting a few results obtained during the completion of my thesis, through both analytical and simulational approaches.

Jean-Baptiste TOUCHAIS

Laboratoire de Physique des Solides, Université Paris-Saclay, 91400, Orsay, France

Graphene with inhomogeneous order parameter: a first approach to deal with substrate incommensuration.

The study of matter in our everyday surroundings is attributed to the notoriously broad field of condensed matter. In particular, crystals stood out for a long time due to their regular shape and transparence. We now understand that these properties stem from the ordered nature of the material. The study of crystalline materials is the purview of solid state physics, an entire subfield of condensed matter physics. One of the first achievements of solid state physics was the first quantum mechanical understanding of metals which carry electrical current and insulators which do not through the hybridization of atomic levels into bands of energy. Although the formalism has its limits, it allowed tremendous progress e.g. in semi-conductor physics which is the basis for the electronics revolution. Still, conventional band theory does not distinguish insulators, however, it is now established that some insulators have conducting edges while others do not. This is a consequence of the structure of the bands themselves and is the seed of topological band theory. It is characterized by features which are robust against some types of perturbations, including disorder. This robustness makes it interesting to the electronics sector as current electronics reaches limits due to the nanoscopic scale. Even more ambitious people hope to be able to use topological matter to create many robust qubits for the quantum computer.

In this particular context, a material garnered a lot of attention : graphene. Graphene is a 2D honeycomb lattice of carbon atoms. This specific structure makes electrons at low energies behave as if they were massless. Although this property is highly interesting, graphene by itself is topologically trivial because it lacks a key ingredient for topological bands : spin-orbit coupling. Spin-orbit coupling, as the name implies, is a coupling between the momentum of the particle and its spin. This effect is more pronounced with heavy atoms which are absent in graphene. A solution is then to add a substrate with heavy atoms to the sample so that electrons can feel the spin-orbit of the substrate. However, because the susbstrate is by definition composed of different atoms than graphene, we expect that the two lattices are incommensurate - that is the ratio between the lattice parameters are irrational making the overall structure non periodic. Consequently, we also expect that the induced spin-orbit will be inhomogeneous over the whole sample. Hence our work to build an understanding of disordered spin-orbit through simpler fundamental types of inhomogeneities.

We first investigate possible topological electron modes bound to domain-walls between several types of domains in graphene with spin-orbit coupling. Our domain walls are not covered by the standard theorem which already links band topology to edge behaviour. However we can still use what is called a spectral flow theorem when we neglect some scattering process caused by inhomogeneities. We check the validity of this assumption through exact numerical diagonalisation of lattice models. We find that the bound states that do exist do not have the same robustness properties as their topological edge mode counterpart and we also evidence a new type of protected boundary modes which can be mapped onto well known boundary modes in bilayer graphene. We then consider a system which is disordered everywhere down to the atomic scale. We characterise the disorder with two parameters : a correlation length and a standard deviation. In the large correlation length limit we identify a one parameter scaling which corresponds with previous

approaches which neglected some scattering process. When the correlation length becomes comparable with the lattice scale, the one parameter scaling can break down depending on the nature of the disordered term. We propose analytical justifications for such behaviours.

My first talk will be a pedagogical introduction to band theory and its extension topological band theory. I will then show their application to graphene. With my first talk as a basis, I will then introduce my own work in the second talk. The first part on domain walls will be a mix of standard results presented in the first part but looked at through another point of view and new results. In the second part I will present some results on fully disordered systems.

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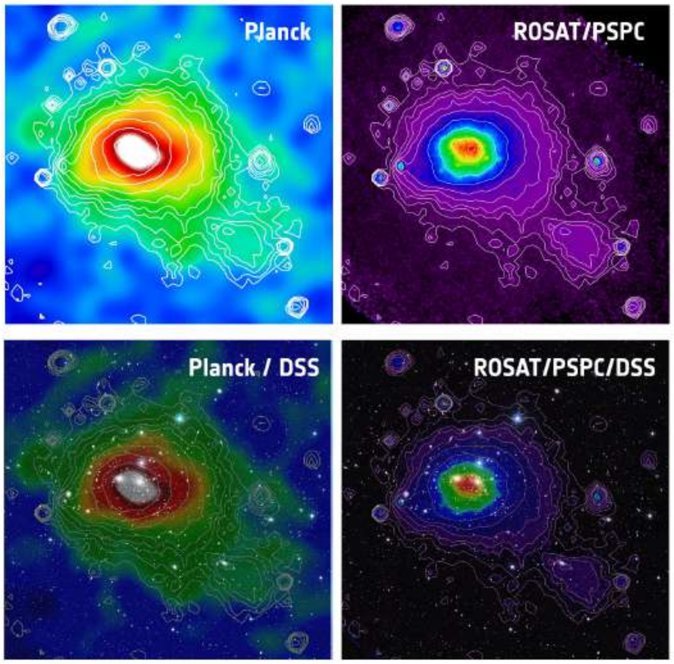
Galaxy clusters: physical laboratories and cosmological probes

Galaxy clusters are among the largest bound cosmological structures in the present day Universe. With typical masses in the range $10^{14}-10^{15}$ solar masses, they harbour from hundreds to thousands of galaxies, bound together by gravity. They are genuine nodes that reside at the intersection of the cosmological filaments that constitute the cosmic web. In addition to galaxies, which actually represent only $\sim 5\%$ of their content, they contain about 80% Dark Matter and 15% hot and dilute gas. Both numerical simulations of structure formation and multi-wavelength observations of galaxy clusters have allowed us to get a solid understanding of these cosmological objects, but many more questions have arisen too.



Images of the Coma cluster, a very hot and nearby cluster of galaxies, as it appears through the Sunyaev-Zel'dovich effect (top left, seen by the Planck satellite) and in X-ray emission (top right, measured by the ROSAT satellite). For comparison, the images are shown superimposed on a wide-field optical image of the Coma cluster from the Digitised Sky Survey in the two lower panels.

I will first give an overview of what we know about galaxy clusters, observationally and theoretically. I will also show how the census of the entire population of galaxy clusters is used to obtain cosmological information about the entire Universe. Recently revealed tensions between results deduced from different cosmological probes lead us to reconsider some of the assumptions made so far when interpreting observations. In my second talk, we will see how mapping and understanding the the rich and complex physics occurring in the gas contained in galaxy clusters may hold the key to relieving these tensions.

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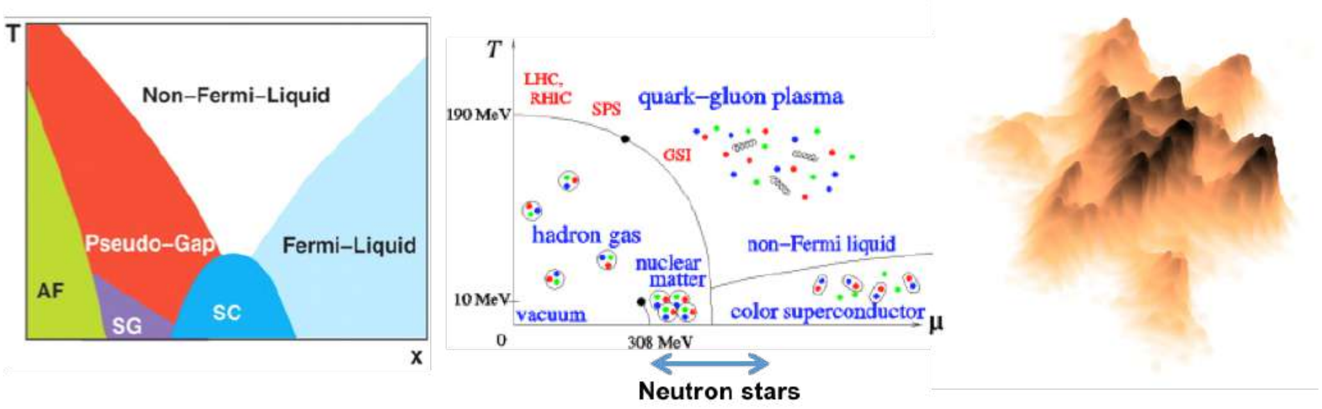
Strongly Correlated Electron Systems and Novel States of Quantum Matter

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.



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.*

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 above, 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 URu2Si2. 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.