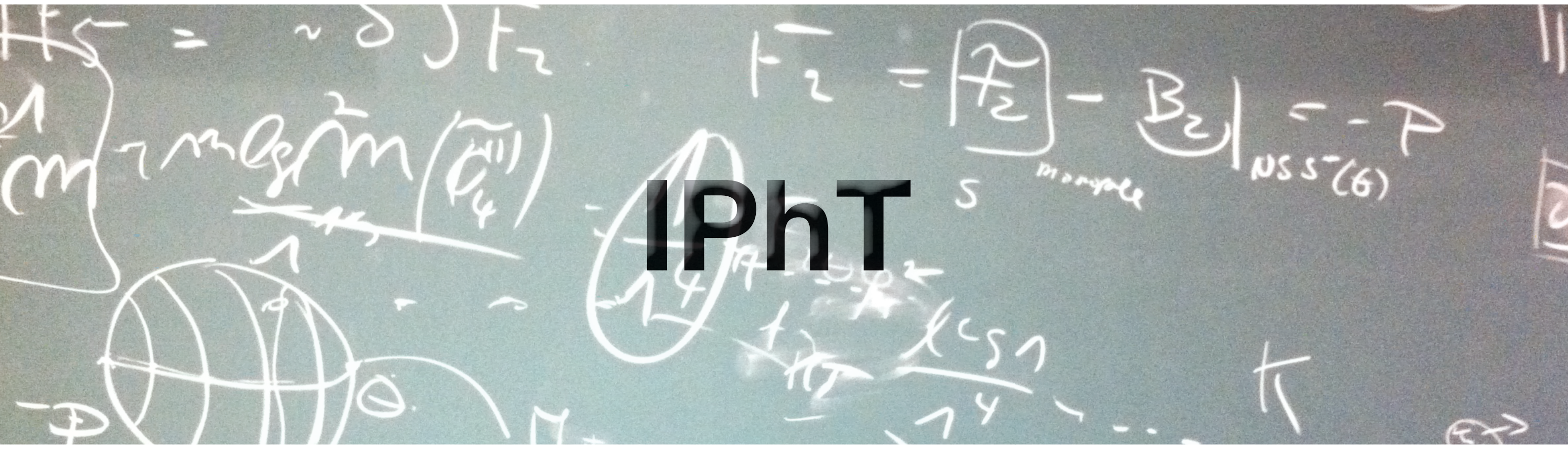
Institut de Physique Théorique



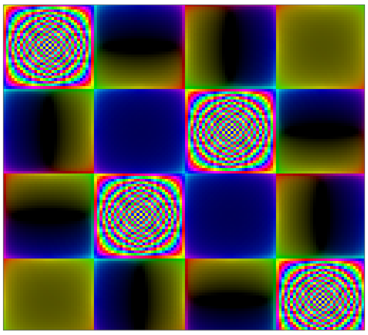
A wide range of research projects are pursued in the Service de physique théorique. They extend from the study of fundamental interactions, with the aim of understanding the primordial universe, to the modeling of biological structures. They also include the mathematical analysis of complex systems in statistical mechanics and in field theory. Underlying the diversity of the systems under study is a profound unity of the mathematical forms used to describe them.

Commissariat à l’énergie atomique
et aux énergies alternatives
Direction des Sciences de la matière
Saclay

Mathematical Physics

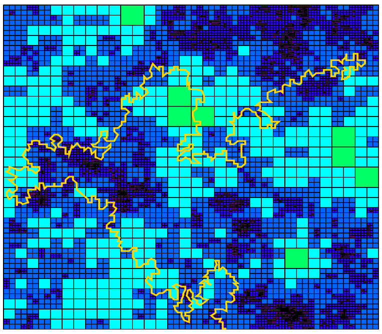
Quantum chaos, dynamical systems & field theory

The dynamics of very simple systems can lead to complex movements at long times. For example, the trajectories of a particle in a stadium shaped billiard are unstable and they eventually fill all the billiard. This system has a quantum analogue: a wave propagating insed a cavity of the same shape. The semi-classical approach allows the analysis of the stationary modes and their localization properties by taking into account the long-time properties of the classical system. This kind of simple mathematical models allow to apprehend various physical systems, such as electrons in mesoscopic bi-dimensional systems, propagation of light in optical fibers, accoustical cavities, or propagation of seismic waves. From a theoretical point of view, systems with infinite number of degrees of freedom, the renormalization group turns out to be an invaluable tool for proving straightforwardly and rigorously various properties of perturbative quantum field theories. Ths vast field of research is thus on the border between mathematics and physics, with many and varied applications, ranging from turbulence to quantum decoherence.



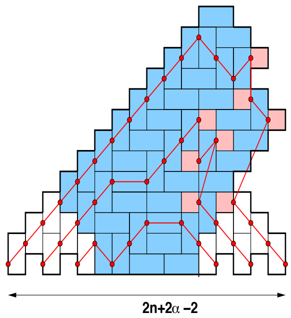
Combinatorial statistical physics

The statistical physics involves a precise counting of the states and configurations of a system, and thus is intimately related to combinatorics. The link between critical phenomena on the 2d regular lattices and their “gravitational” version on fluctuating lattices is the key of the solution for a number of problems in statistical mechanics (polymers, hard-core particles) and in mathematics (three-color problem, meanders). The study of the laws obeyed by the random matrices allowed to discover new invariants of the enumerative algebraic geometry which include and generalize some invariants Gromov-Witten, knot, etc.), and more generally to explore the asymptotic expansion of integrable systems. The combinatorial approach is an alternative to the traditional approaches like field theory and matrix models. For example, cutting the graphs to trees allowed to determine the statistics of the internal distances on the random lattices.



Conformal theories & integrable systems

The integrable systems possess an important number of conserved quantities. They are useful for studying non-perturbative phenomena in systems which are subject to strong statistical or quantum fluctuations. Their analysis uncovers remarkable algebraic and geometric structures, with applications ranging from physics to pure mathematics. This is equally the case for conformal fields theories, which are central to the construction of string theory and which are also the perfect tools for studying critical 2d statistical systems or 1d quantum systems. They are also used to characterize certain stochastic and fractal universal growth processes. Integrable models also occur in the study of supersymmetric gauge theories, where they allow to explore the strong coupling regime and to prove that these theories are dual to string theories in curved space-time.



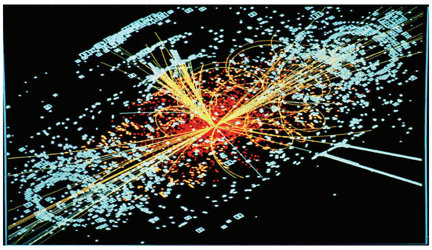
String theory & quantum gravity

The de Broglie wavelength of a particle moving in region of high energy density or near black hole is very large, and can become of the same order as the curvature radius of the spacetime. In such circumstances the classical laws of gravity are altered by quantum effects. The best candidate for a quantum theory of gravity is string theory, in which the particles are replaced by extended objects. Our researchers study string theory in various geometric configurations, both by using algebraic and differential geometry techniques to study its compactifications and by using supergravity techniques to attack long-standing problems like Hawking’s information paradox or the microscopic origin of the black hole entropy. They also use the gauge/gravity duality to study strongly-coupled systems similar to the quark-gluon plasma produced at the LHC or to those appearing in condensedmatter physics.

Particle physics - Astrophysics

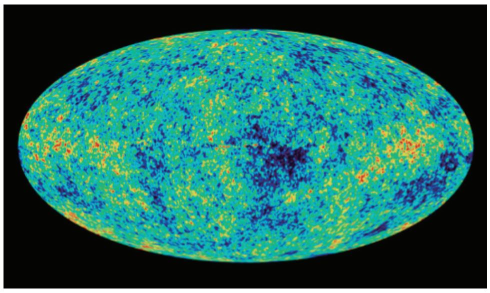
The Standard Model & beyond

The Standard Model describes the fundamental building blocks of matter (quarks and leptons) and their interactions. Particle accelerator experiments have been testing it faultlessly for the last thirty years with unprecedented accuracy. One of the key elements of this theory, the Higgs boson, whose role is to provide a mass to the elementary particles, is under high scrutiny at the Large Hadron Collider (LHC) at CERN. Despite its success in describing a host of experimental results, the Standard Model fails to explain observations such as the existence of dark matter, the matter-antimatter asymmetry, the acceleration of the expansion of the Universe, and the smallness of neutrino masses. Moreover, certain theoretical conundrums find no explanation within the Standard Model, e.g. the quantum instability between the electroweak scale and the Planck scale, at which gravitational interactions become strong. Beyond the standard model physics strives to give answers to these puzzles by envisaging more fundamental theories involving new particles and their interactions, or employing model-independent techniques with which one can extract information relevant to those theories directly from experimental data (high-energy collisions, cosmic rays, cosmological observations, neutrino oscillations, rare decays...). Several key phenomena such as the dynamics of the electroweak symmetry breaking, the nature and properties of dark matter, the origin of the mass of neutrinos, and also the nature of dark energy are under study using these complementary approaches.



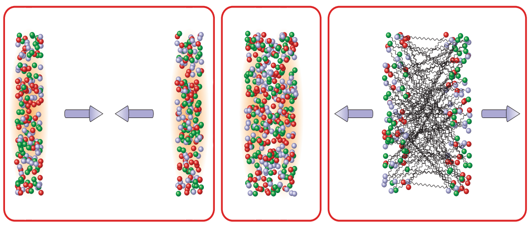
Astroparticle physics & Cosmology

Cosmology aims at retracing the history of our Universe since the Big Bang, in order to understand its content as well as its large scale structure. The astrophysical objects that we observe today (galaxies, clusters of galaxies...) are due to the gravitational collapse of small density irregularities that appeared in the primordial universe. Our research topics range from studies of the primordial universe (statistical properties of the initial fluctuations, generation of gravitational waves or magnetic fields...) to studies of the gravitational dynamics of large-scale structures in the recent universe (spatial distribution of galaxies...). These theoretical predictions are confronted with observations to constrain cosmological scenarios (measures of the temperature fluctuations of the cosmic microwave background, of the distribution of clusters of galaxies, of the distortion of the images of background galaxies by the gravitational potential along the line of sight...). Observational cosmology also confronts particle physics with numerous problems. The nature of dark matter, of dark energy, the origin of the matter-antimatter asymmetry, the nature of the inflaton and the space-time cosmological structure, are all questions which physicists are attempting to answer.



Quantum chromodynamics & Hadronic physics

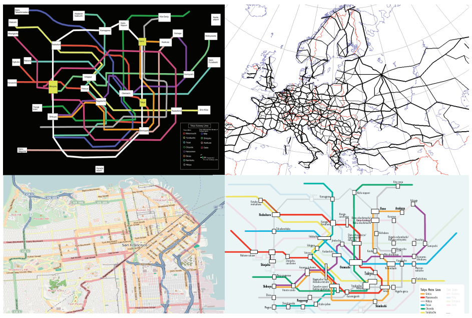
Quantum chromodynamics (QCD) is the fundamental theory that underlies the strong nuclear interactions. It governs the short-distance interactions of quarks and gluons, which are the constituents of protons and neutrons. QCD explains the confinement of quarks and gluons inside these particles. Understanding the strong interactions is crucial to the analysis of data collected by experiments running at the Large Hadron Collider (LHC) at CERN. QCD interactions have the remarkable property of becoming weaker at shorter distances, which allows use of a perturbative approach to study high-energy processes. Conversely, it becomes stronger at long distances. This strong-coupling regime motivates the study of effective theories, or of related theories with additional symmetry, such as maximal supersymmetry, and of dual string pictures. QCD may also require non-perturbative techniques in situations involving a large number of particles, even at weak coupling. This happens in the wavefunction of a proton or nucleus: the gluon density increases rapidly with energy until it saturates, a situation that can be handled by the so-called 'color glass condensate'. At high temperatures, nuclear matter undergoes a deconfinement transition to form a quark-gluon plasma. Its properties can be studied in ultra-relativistic heavy-ion collisions at the LHC and at the Relativistic Heavy Ion Collider (RHIC) at Brookhaven.



Statistical physics- Condensed matter

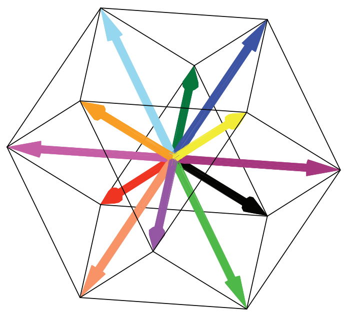
Non-equilibrium & disordered systems

The new frontier in statistical physics is to build a general theory for systems out of equilibrium, continuously evolving with time. No theoretical framework is available that would encompass the physics of systems interacting with their environment through continuous exchanges of charge, spin, energy, momentum. Yet, in Nature, heat and matter fluxes are ubiquitous and systems far from equilibrium are the majority rather than the exception. Artificial devices (complex networks, urban patterns) as well as living matter provide us with prominent examples. The IPhT is a major actor in the study of these crucial issues. A global perspective on time-dependent processes involving a large number of interacting elementary constituents requires elaborate theoretical tools that can developed using techniques of quantum field theory, conformal symmetries, SLE and integrable systems. Exact solutions of models far from equilibrium have allowed us to determine rare events statistics and large deviations functions that play the role nonequilibrium thermodynamic potentials. Sophisticated renormalization procedures, at the level of the configuration space and of its dynamics, have been developed to characterize the evolution and phase transitions in random systems (spin glasses, polymers, colloids). All these methods are now applied very successfully to interdisciplinary subjects such as computer science (constraint satisfaction, error correcting codes, analysis of search algorithms) and biology (genetic and evolutionary models). The study of various networks, smart-grids, and their evolution in space and time have fundamental applications in epidemiology and in controlling the spread of infectious diseases. Finally, the quantitative study of geographic and urban networks using the mathematical apparatus of statistical mechanics is a rapidly developing theme that offers a very promising cross-disciplinary perspective.



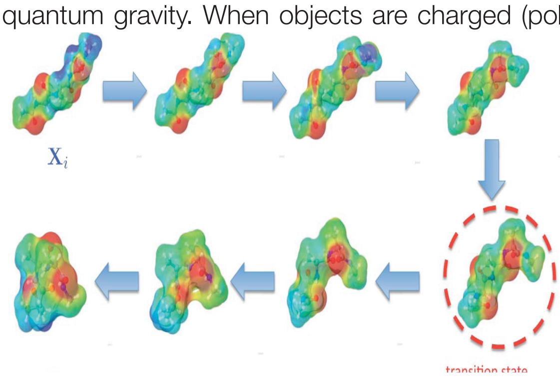
Quantum systems & condenser matter

La physique de la matière condensée traite de phénomènes quantiques spectaculaires qui se passent à l'échelle macroscopique, lorsque la température est suffisamment basse. La supraconductivité, ou conduction de courant électrique sans résistance, la superfluidité, ou écoulement sans frottement, l'effet Kondo, l'effet Hall quantique fractionnaires, dans lequel les porteurs de charge se fractionnent sous l'effet des interactions et des fortes fluctuations quantiques sont autant d'exemples de ces phénomènes remarquables et mystérieux. Suite à leur observation expérimentale, ces phénomènes quantiques sont étudiés théoriquement par des méthodes de théorie des champs, associées à des techniques numériques avancées. Les modèles, bien définis à l'échelle microscopique, sont encore mal compris à l'échelle macroscopique lorsque les interactions entre les électrons deviennent trop fortes. Des composés complexes de spins frustrés, ainsi que des systèmes hors d'équilibre sont aussi étudiés en profondeur à l'Institut.



Soft matter & biological systems

Polymers provide physical realizations of stochastic processes such as Brownian motion or self-avoiding random walks. Other types of stochastic processes control the functioning of molecular motors and the folding of proteins. Some universal aspects of membranes (flexible films, biological membranes) are closely related to the random geometries studied in string theories and quantum gravity. When objects are charged (polyelectrolytes, charged membranes) or possess internal degrees of freedom, their physical and geometrical properties may be deeply modified: new phases may appear. Random polymer physics governs the complex interactions between chemically different monomers in biopolymers. One can study the denaturation of DNA or protein folding and RNA within this framework. For the latter, the classification of folded forms can be done using tools of topology (genus, Euler characteristic) and this leads to the development of powerful algorithms for structure prediction. In addition, most biopolymers carry charges, and the Coulomb interaction determines their universal properties of aggregation and solvation in the cell.



Institut de Physique Théorique

From past to future ...

Research in theoretical physics at the CEA goes back to its origins. In 1947, within the Service of Physics and Chemistry at the Fort de Chatillon, two years after the creation of the CEA, a group of researchers sought by colleagues from all backgrounds develop their taste for abstraction and modeling. Jacques Yvon didn't hesitate to consider a pile as an infinite plane without reflector! Already one afternoon a week is devoted to theoretical physics, joined in 1950 by Claude Bloch and Philippe Meyer. Theoretical nuclear physics, and through neutronics, statistical physics emerge as major themes.

In 1959, the theoretical physics team is still comprised in the Service de Physique Mathématique whose main mission within the Département d'Etude des Piles is the theoretical study of reactors. This team publishes articles on nuclear physics, the many-body problem and superconductivity. Very quickly, particle physics became an important theme.

The Service de Physique Théorique (SPhT), created the 21st of February 1963, has a staff of twenty CEA agents. At the same time doctorates appear at the lab and in 1964 began the hiring of CNRS physicists. Shortly after moving to l'Orme des Merisiers in 1968, quantum field theory is emerging as a major topic of research in the laboratory. Followed in the next couple of decades by conformal field theories and matrix models, particle physics, astrophysics and string theory, and the physics of condensed matter and biological systems.

January 1st, 2008, the Service de Physique Théorique enters a new status and became the Institut de Physique Théorique (IPhT). In total, more than 500 people have so far shared the life of the Institute, not to mention the many visitors from all countries: leading researchers whose contributions are very challenging and brilliant postdocs, who contribute significantly to the scientific life and to the establishment of lasting relationships with laboratories around the world. Building on the success of the Institute, many of its researchers have reach out to prestigious universities and research organizations in France and abroad.

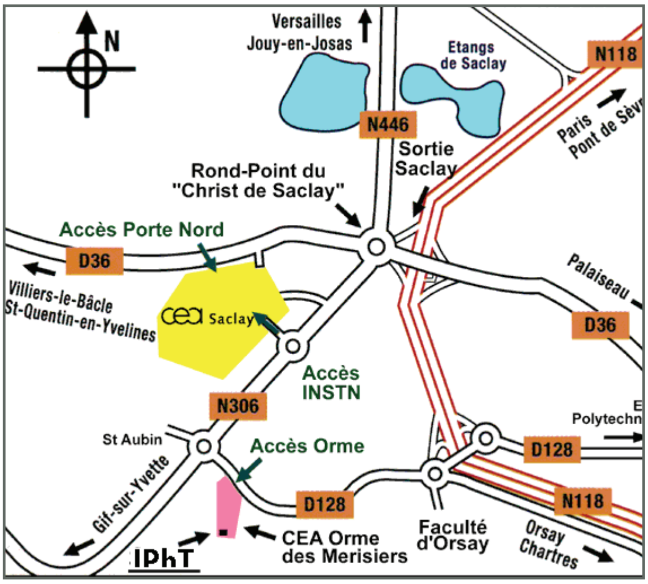
More than 6000 publications, around 40 books and over 200 thesis were produced at the Institute. In addition to this production, numerous scientiific conferences, international seminars and summer schools were organized (the IPhT has contributed greatly to the growth of the Ecole des Houches). Continuing a tradition that dates back to A. Abragam, C. Bloch, A. Herpin, A. Messiah and Mr. Trocheris, researches of the IPhT teach in the laboratory and also in the Grandes Ecoles and French and foreign Universities. Many of these courses have been published and have became classics of literature (Messiah, Mehta, Itzykson-Zuber, des Cloizeaux-Jannink, Gaudin, Blaizot-Ripka, Negele-Orland, Zinn-Justin, Balian, Itzykson-Drouffe, etc).

Scientific prize and distinctions punctuate the history of IPhT, with over one hundred, including a dozen foreign awards, a dozen medals CNRS and numerous awards from the Academy of Sciences and the French Physical Society. Members of the IPhT have served or serve in the academies of sciences in France and abroad. Finally, eight members so far are winners of the European Research Council grant (ERC).

At the CEA, the IPhT depends on the Direction des Sciences de la Matiere (DSM), and in 2001, with one third of its workforce belonging to it, became a associated research unit of the CNRS, sealing officially its link with the national research center. The Institute also hosts academics and researchers from other laboratories and participate to numerous European research networks and international exchange programs. At first at the service of other activities, theoretical physics is gradually recognized as independent research topic. After an unscheduled emergence within the CEA, what now became the Institut de Physique Theorique has developped from the need first felt by its member and then by the CEA directorate. Its success is born from the conjunction of unpredictable new ideas and multidisciplinary skills that the Institute has cultivated for nearly 50 years.

IPhT

By RER



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