Semester 3: Choose three 6 ECTS courses (core courses), see the general FunPhys curriculum

---

Teaching location for the following 6-credit courses: North pole of the Sciences Faculty: St-Jerome or Chateau-Gombert.

Plasma-Wall Interaction, Discharge Plasmas-S3

Plasma-Wall Interaction, Discharge Plasmas

Contact: G. Cartry

- Introduction à la physique et à la technologie des plasmas froids et des plasmas radio-fréquences
- Modèle fluide et cinétique 0D et 1D d'une décharge dans un gaz noble
- Introductions à la physique et technologie des plasmas radio-fréquences
- Comportement d'un plasma a proximité d'une paroi, flux de chaleur et de particules
- Diagnostics des plasmas froids: par sondes, mesures de ne, Te & par spectroscopie optique

Magnetic Confinement Fusion-S3

Magnetic Confinement Fusion

Contact: P. Beyer

I) Choix de la configuration magnétique :
• trajectoires, compensation des dérives de courbure.

II) Equilibre et stabilité MHD dans un tore :
• équilibre magnétique, principales instabilités
• domaine opérationnel : disruptions, limites en bêta, "Edge Localized Modes", dents de scie
• perte de stabilité due aux particules rapides

III) Confinement dans un tore :
• transport collisionne, transport turbulent
• pertes radiatives
• lois d'échelle adimensionnelles

IV) Chauffage et génération de courant (physique) :
• propagation d'ondes, interaction résonnante onde / particule
• faisceau de particules neutres.

V) Éléments de contrôle des particules et de la chaleur :
• principe d'un divertor, rayonnement, transport radiatif, recyclage, puissance dépose sur les éléments de première paroi.
• transport des impuretés, des cendres, de l'hydrogène / deutérium.

VI) Éléments d'extraction de la puissance et des particules :
• conception des éléments de première paroi, pompage.

Stars and Galaxies-S3

Stars and Galaxies

Contact: Olivier Ilbert and Patrice Theulé

I. Galaxies in the universe: a general introduction

1. The Milky Way: recongnizing it as galaxy
2. Elliptical and spiral galaxies,rotation acurves and darm matter halo
3. The general framework of galaxy formation and evolution

II. Radiation from galaxies: from the observations to the physical contentof galaxies

1. Galaxies at all wavelengths: brief presentation of the whole spectrum
2. Star formation rates and stellar mass measurements
3. Gaseous and dust components
4. The process of star formation

III. Detailed view of spiral galaxies and their secular evolution

1. Galaxy formation :the primordial disk
2. Formation and stability of the disk,orbits in the disk
3. Formation of the arms,the bar and the bulge
4. Importance of instabilities at nigh redshift

IV. Galaxy evolution within the dark matter structures

1. The star formation history and the dark matter structure growth
2. the dark matter halos and stellar mass functions:AGN and SN feddback
3. Impact ogf the environment,mergers and formation of the elliptical galaxies

V. Galaxy evolution from the local to the distant universe

1. The local inverse and the distant universe
2. The stellar mass assembly
3. Statistics:spacial distribution, counts,luminosity functions and biases

VI. Active Galaxy Nucleii

1. What is an active galaxy? a central black hole as engine, the accretion disk
2. The unification model
3. AGN-galaxy co-evolution: quenching of the star formation

VII. The first galaxies and reionisation

1. Cosmological reionization, Gunn-Peterson effect
2. Clumpy IGM:absorbing systems
3. The cosmic web: IGM-galaxy connection

VIII. Phases and processes in the interstellar medium

IX. The neutral medium

X. The ionized medium

XI. Interstellar dust and PAHs

XII. Chemical processes in the interstellar medium

XIII. Chemistry of various objects

Galaxies and Cosmology-S3

Galaxies and Cosmology

Contact: Christophe Adami

I. Basic description of the cosmological model

1. General framework
2. Privileged models and main cosmological parameters

II. Constraining the characteristics of the Universe: key methods

1) The growth of structure

- Initial matter density perturbations
- Dynamical evolution of the large-scale structure and redshift-space distortions
- Weak lensing tomography
- Massive structures, cluster physics and redshift evolution

2) The geometry of the Universe
- Supernovae type 1A as standard candles
- Cosmic Microwave Background: physical sources and anisotropy
- Baryon Acoustic Oscillations
- Weak gravitational lensing

3) Large-scale structure and galaxy distribution: numerical stimulations and analytical prescriptions
- High-performance computing and numerical modelling
- From intergalactic to circumgalactic medium
- Modelling physical processes in the ISM: star formation and feedback
- Matching models and observations

III. The planned milestone and key projects

1. The milestones
2. Related key projects: present and future

Atomic and Molecular Physics, Spectroscopy-S3

Atomic and Molecular Physics, Spectroscopy

Contacts: P. Theulé, M. Koubiti, O. Peyrusse and J. Rosato

The students will follow core lectures on atomic spectroscopy. They will then choose between a fundamental track and an instrumental track.

Core curriculum :
Atomic physics (M. Koubiti, O. Peyrusse)
- reminder of quantum mechanics
- theory of multielectronic atomic structure

- atomic and ionic spectroscopy
- heavy atoms spectroscopy

Fundamental track :
Molecular physics (P. Theulé)
- basis of molecular spectroscopy
- rotational spectroscopy
- vibrational spectroscopy
- electronic spectroscopy

Line broadening theory (J. Rosato)
- formalism introduction
- collisions induced line broadening
- statistical theory
- quantum theory of line broadening
- selected applications

Instrumental track : (R. Guirlet, N. Fedorczac)
- Infrared thermography
- ECE
- Thomson diffusion
- far IR Interferometry / polarimetry
- Reflectometry
- Michelson, Fabry-Pérot
- visible, UV, X spectrscopy
- Bolometry
- soft X-rays
- hard X-rays

Prerequesite : quantum mechanics, statistical physics

Teaching location for the following 6-credit courses : South pole of the Sciences Faculty: Luminy.

Relat_Universe_S3

The Relativistic Universe

Contact: Pr. Christian Marinoni

What's up there in the sky that may shed light on fundamental physics? This is the question around which this course is organized. After reviewing some fundamental aspects of general relativity, we will present the physical principles of the standard model of cosmology. The goal is to understand the key features of the large-scale structure of space-time : its geometry, energy content and dynamics. To this purpose we will study cosmic symmetries and conservation principles, we will solve Einstein field equations in the presence of fluids of different nature, and we will determine the relativistic kinematics of particles in a moving background. Once the formalism is set up, we will explore the physics at work during the various stages of cosmic evolution, paying special attention to describe the primordial inflationary phase and the dark energy phase. Notably, we will exploit these two puzzling phenomena as a pretext to explore eventual departures from the general relativistic theory of gravity, such as the existence of extra-dimensions or of additional scalar degrees of freedom. The most conspicuous portion of the course will be devoted to present relativistic perturbation theory, the gravitational paradigm that allows to understand how large-scale structures of the universe, such as galaxies, grew out of small initial energy fluctuations of quantum nature. We will show what theory tells us about the spatial arrangement of matter and energy in the cosmos and we will contrast predictions against available empirical evidences. The goal is to present evidences supporting the standard model, point to critical aspects that are still at stake and lively debated in the field, as well as discuss crucial predictions that still need to be confirmed. On the methodological side, we will provide the students with the basic conceptual and mathematical tools for eventually contributing to this discovery process.

Lecture material is displayed on the chalkboard and discussed in dynamical interaction with the students. This will allow interspersing conceptual presentations with practical exercitations, ideally facilitating the assimilation process. Handouts containing exercises and problems will be distributed on a weekly basis so that students can continuously monitor their level of comprehension. Lecture notes, deepening and completing the subjects covered in class, will also be available. Cosmology uses methods from nearly all fields of physics, among which are general relativity, statistical physics, nuclear and atomic physics, particle physics and field theory. We will not assume preliminary knowledge in any specialized field. Indeed, with very few exceptions, the derivation of every formula begins with basic physical principles. Of course some knowledge of general relativity, differential geometry and particle physics would be helpful, but this is not a necessary condition for understanding the lectures.

References:

1. S. Weinberg, Gravitation and Cosmology, John Wiley & Sons (1972),
2. V. Muckhanov, Physical fundations of Cosmology, Cambridge University. Press (2005),
3. D.S. Gorbunov & V. A. Rubakov, Introduction to the theory of the universe, World scientific (2011)
4. D.S. Gorbunov & V. A. Rubakov, Cosmological perturbations and inflationary Theory , World scientific (2011)
5. P. Peter & J.-P. Uzan, Primordial Cosmology, Oxford University Press (2005),
6. S. M. Carrol, Spacetime and Geometry, Addison Wesley (2004)

QFT_S3

Quantum Field Theory

Contact: Federico Piazza & Laurent Lellouch

Quantum Field Theory (QFT) provides a theoretical framework for the description of systems with an infinite number of degrees of freedom, as opposed to Quantum Mechanics (relativistic or not) which deals with systems possessing only a finite number of degrees of freedom. Accordingly, the framework of QFT is relevant to many areas of theoretical physics, e.g. statistical physics or condensed matter physics. When QFT is elaborated in the context of systems invariant under special relativity transformations, it provides an appropriate framework for the description of the fundamental interactions occurring in particle physics. Lectures will provide a broad introduction to the inner workings of relativistic QFTs, but also a concrete working tool to derive predictions from these theories.

Outline of the course

Chap. 1: The problems of relativistic, single-particle quantum mechanics

- a. Construction of a relativistic single-particle quantum mechanics
- b. Violations of causality
- c. The need for a multiparticle theory

Chap. 2: From Fock space to quantum field theory and back

- a. Construction of Fock space and occupation number representation
- b. Harmonic oscillator formalism
- c. Observables and the need for a quantum theory of fields
- d. From quantum field theory to Fock space

Chap. 3: Ingredients for constructing a relativistic quantum field theory

- a. Review of lagrangian and hamiltonian mechanics
- b. Canonical quantization
- c. The Lorentz group and its representations
- d. The Poincaré group, its representations and the notion of a particle

Chap. 4: Action functionals for relativistic quantum field theory

- a. Behavior of local fields under the Poincaré group: from scalar to spin-2 fields
- b. General properties of the action for relativistic fields
- c. Continuous symmetries, Noether’s theorem and conserved charges
- d. The action for scalar fields

Chap. 5: The quantum field theory of spinors

- a. The action for spinor fields
- b. Generators of Poincaré transformations
- c. Solutions of the free Dirac equation
- d. Canonical quantization of the Dirac field
- e. Fock space for fermions
- f. The fermionic propagator

Chap. 6: Building spinor QED

- a. Electromagnetic interactions of the Dirac field
- b. Covariant theory of the photon
- c. Canonical quantization of the gauge field
- d. The photon propagator

Chap. 7: S-matrix expansion, Wick’s theorem and QED at tree level

- a. The S-matrix expansion
- b. Wick’s theorem
- c. Derivation of QED’s Feynman rules
- d. The cross section and Compton scattering
- e. Bremsstrahlung, infrared divergences and Bloch-Nordsieck theorem

Chap. 8: Radiative corrections and renormalization

- a. $O(\alpha)$ corrections to tree-level processes
- b. Vacuum polarization and renormalization of the charge
- c. Electron self energy and charge and mass renormalization
- d. Renormalization of external lines

- e. Vertex correction and Ward identity
- f. Counter terms and bare lagrangian g. Applications: anomalous magnetic moments and Lamb shift

Chap. 9: Higher order radiative corrections and renormalizability (heuristic)

- a. One-particle irreducible diagrams at higher orders
- b. Skeleton diagrams and systematic calculations at higher orders
- c. Primitive divergences and renormalizability

Chap. 10: Dimensional regularization

- a. Different kinds of regularization
- b. Mathematical preliminaries: analytic continuations, integrals in d-dimensions and Feynman parametrization
- c. Vacuum polarization revisited

Chap. 11: Functional methods and path integrals

- a. From quantum mechanics to the Feynman path integral
- b. Path integrals and scattering
- c. Gaussian integrals in many bosonic and fermionic dimensions

Chap. 12: Non-abelian gauge theories

- a. Invariance under an SU(N) gauge symmetry
- b. Yang-Mills theory
- c. Path integral quantization of Yang-Mills theory: Faddeev-Popov approach
- d. SU(N) quantum chromodynamics and its Feynman rules

Prerequisites (though some reminders will be given):

- Special relativity: Lorentz transformations, covariant notation, scalars, four-vectors, higher rank tensors,...

- Quantum Mechanics at M1 level: Hilbert space, Dirac notation, angular momentum...

- Elements of group theory: continuous groups, (projective) representations,...

- Classical field theories: Euler-Lagrange equations, symmetries, Noether’s theorem(s)...

References:

- Peskin and Schroeder: An Introduction to Quantum Field Theory

- Schwartz: Quantum Field Theory and the Standard Model - Weinberg: The Quantum Theory of Fields, vols. 1 & 2

- Ryder: Quantum Field Theory - Ramond: Field Theory - A Modern Primer

- Itzykson and Zuber: Quantum Field Theory

Advanced Particle Physics-S3

Advanced Particle Physics

Contact: Pr. Mossadek Talby

The course is organized as follows: It begins with a short introduction and overview of elementary particles and fondamental interactions followed by the description of the unit system used in particle physics. After this short introduction, the first chapters deal with (continue and discrete) symmetries and conservation laws and reviews relativistic kinematics of particle interactions and decays. The following chapters represent the main components of this course. We start with the Dirac equation its solutions as free particle Spinors and study their properties and different bilinear froms. It is followed by three important chapters describing electromagnetic, strong and weak interaction and decay processes. In these three chapters the technique used to compute from Feynman diagrams and rules the differential cross sections and decay rates of several scattering and decay processes of elementary particles will be presented and studied in detail. Several concepts and properties will be introduced, studied and used in these three chapters such as "crossing symmetry", "running coupling constant", "Quark mixing" .... In the last two chapters of the course we will first introduce and study the Standard model of particle physics and the Brout-Engler-Higgs mechanism and second we will in one hand review and study the Parton model and on the other hand discuss and study elements of perturbative QCD.

References:

1. D. Griffiths, Introduction to Elementary Particles, John Wiley & Sons (1987),
2. D.H. Perkins, Introduction to High Energy Physics, 4th Edition, Cambridge University. Press (2000),
3. F. Halzen & A.D Martin, Quarks & Leptons, John Wiley & Sons (1984),
4. C.P. Burgess & G.D Moore, The Standard Model: A Primer, Cambridge University Press (2011),
5. M.E. Peskin & D.V. Schroeder, An introduction to Quantum Field Theory, Addison-Wesley Advanced Book Program (1995),
6. J-P. Derendinger, Th´eorie quantique des champs, Presses polytechniques et universitaires romandes (2008)

General Relativity_S3

An introduction to General Relativity

Contacts: A. Perez

1. Introduction:
   1. Spacetime in pre-relativistic and relativistic physics.
   2. Spacetime metric.
   3. General relativity.
2. Mathematical tools:
   1. Manifolds.
   2. Vectors and forms.
   3. Tensors, the metric tensor.
   4. Abstract index notation.
   5. Derivative operators.
   6. Curvature.
   7. Geodesics.
   8. Cartan calculus.

3. The Einsteins equations:
    1. Space time in pre and relativistic physics (revisit).
    2. Special relativity.
    3. Matter: the energy momentum tensor.
    4. Derivation of Einsteins equations.
4. Homogenous and Isotropic Cosmology:
    1. Homogeneity and isotropy.
    2. Dynamics.
    3. The cosmological redshift, Horizons.
    4. Brief account of the evolution of our universe.
5. The Schwarzshild solution:
    1. Derivation of the vacuum Schwarzshild solution.
    2. The interior solution.
    3. Testing the Schwarzshild geometry with test particles (timelike and null geodesics).
    4. Singularities and the Kruskal extension.
6. Black Holes:
    1. Black Holes and the cosmic censor.
    2. Stationary Black Holes (the Kerr-Newman solution).
    3. The Penrose mechanism.
    4. Superradiance.
    5. Black Hole Thermodynamics (first encounter).
7. Quantum effects in stationary black holes:
    1. Quantum fields theory on curved space-times (basic structure).
    2. Particle creation by the gravitational field.
    3. Particle creation by black holes (the Hawking temperature).
    4. The Hartle-Hawking vacuum.
    5. Black hole thermodynamics (complete discussion).
    6. Implications for quantum gravity.

Advanced Quantum Statistical Physics-S3

Advanced Quantum Statistical Physics

subtitle: "statistical quantum field theory and nanophysics"

Contact: Thierry Martin

This research-oriented course in a field theory course applied to statistical mechanics (albeit non-relativistic). It starts with applications of the second quantized formalism. The Kubo- Greenwood linear response formula is studied in terms of Green's functions (time ordered Green's functions, retarded Green's functions, imaginary time Green's functions and the correspondence between them). Applications to quantum transport are derived showing Gauge invariance. An alternative for transport is the scattering approach due to Landauer. We present here its second quantized version, where Wick's theorem and the grand canonical formalism are employed to compute thermo averages.

Next, after recalling coherent states and the single particle path integral, the field theoretical path integral formalism is derived for bosons and fermions (the latter using Grasmmann variables). It allows the formulation of thermodynamical quantities in terms of Feynman diagrams. The microscopic theory of superconductivity is derived in the Bogoliubov framework for inhomogeneous system and the Bardeen Cooper Schrieffer (BCS) framework. The DC Josephson effect through a quantum dot is studied via functional integral methods. Transport process between superconductors are described. The course continues with the study of correlated fermions in one-dimension, using the bosonization technique (fermions expressed as complex exponentials of bosonic fields), which are also called « Luttinger liquids ». Application to quantum transport in nano-wires are described. This allows to take the opportunity to introduce the momentum shell renormalization group technique, in order to predict the transport properties of a one-dimensional wire in the presence of a weak or strong potential barrier.

References:

•Huang, Statistical Mechanics
•Doniach & Sondheimer, Green’s functions for the solid state physicist
•Negele & Orland, Quantum many particle systems Chaikin and Lubensky, Principles of condensed matter physics.
•T. Martin, in «Nanophysics: Coherence and Transport » École d'été de Physique des Houches Session LXXXI H. Bouchiat, S. Gueron, G. Montambaux, J. Dalibard eds
•De Gennes, Superconductivity fo Metals and Alloys
•Abrikosov, Fundamental of the theory of metals

•Abrikosov, Gorkov and Dyaloshinsky, Quantum Field Theory Methods in Statistical Physics

•Altland and Simons, Condensed Matter Field Theory

Statistical Physics-II-S3

Statistical Physics II

Contact: Elena Floriani or Marco Pettini

Statistical Physics II (Master de Physique) - presentation

This course is composed of two parts: the first one concerns the dynamical foundations of equilibrium statistical mechanics, the Riemannian geometric theory of Hamiltonian chaos and its application to the topological theory of Phase Transitions. The second part of the course concerns stochastic processes, the description of non-equilibrium properties and the fluctuation-dissipation theorem.

The Stat Phys II course is appropriate for a course of study in condensed and soft matter physics, in complex systems, and in biophysics. Even though, for example, phase transitions are ubiquitous in nature from cosmology and astrophysics down to elementary particles and quantum field theory, and a modern theory of phase transitions phenomena is the main focus of the first part of the course.

Basic elements of tensor calculus, differential geometry and differential topology are given during the course which is thus self-contained from the point of view of the mathematical concepts and methods used.

The first part covers the following topics:

Dynamical Foundations of Statistical Mechanics

- Invariant Measure for the Hamiltonian Dynamics on the energy level sets.
- The Irreversible Approach to Equilibrium. The Zeroth Law of Thermodynamics.
- Loschmidt’s paradox, the Poincaré recurrence theorem, the Kac recurrence theorem, connection with microscopic chaos.
- Ergodicity and Mixing: Khinchin ergodic theorem, Birkhoff ergodic theorem, metric transitivity and Hamiltonian chaos.

From Micro to Macro: Statistical Ensembles

- The Link with Thermodynamics
- Szilard’s derivation of Gibbs’ canonical measure from the second principle of thermodynamics
- Legendre transform and the microcanonical measure
- The gran-canonical ensemble

Geometric theory of Hamiltonian chaos

- Geometrization of Hamiltonian dynamics in the framework of Riemannian differential geometry
- Geometric explanation of the origin of chaos in Hamiltonian flows

Phase Transitions

- Phenomenology, Clausius-Clapeyron equations for first and second order phase transitions. Ehrenfest classification of phase transitions
- The mean-field approximation; the Bethe-Peierls approximation
- The Yang-Lee Theorem and the Circle-Theorem
- Landau theory of symmetry-breaking phase transitions
- Hamiltonian Dynamics and Statistical Mechanics: Numerical Investigation of Phase Transitions
- Geometry and chaos for Hamiltonian flows associated with systems undergoing phase transitions
- The Topological Theory of phase transitions and its applications

The second part covers the following topics:

- Stochastic Processes
- Stochastic differential equations
- The Wiener process
- The Ornstein-Uhlenbeck process
- Correlations, white noise
- The Wiener-Khinchine theorem
- Brownian motion as a stochastic process

Markov Processes

- The Chapman-Kolmogorov equation

- Diffusion processes: the Fokker-Planck equation
- Detailed balance
- Onsager relations in linear systems
- Nyquist theorem

Jump Processes and the Master Equation

- The Poisson process
- The generating function
- The predator-prey model

Markov Chains

- Stationarity
- Recurrent and transient states
- Ergodicity
- Convergence to steady state

Fluctuation – Dissipation

- Linear response theory
- Kramers-Kronig relations
- The Fluctuation-Dissipation theorem

A presentation of the course can be found at the following link

https://drive.google.com/drive/folders/14bPWDYwieQn-euos3Rdg9lU8odPSCzym?usp=sharing

For any further information write to : elena.floriani@univ-amu.fr and/or marco.pettini@univ-amu.fr

Reference material:

- M. Pettini, Geometry and Topology in Hamiltonian Dynamics and Statistical Mechanics, (Springer, NY, 2007).

- M. Nakahara, Geometry, Topology and Physics, (IOP Publishing, 2003).

- C. W. Gardiner, Handbook of Stochastic Methods for Physics, Chemistry and the Natural Sciences (Springer, New York, 1990)

- K. Jacobs, Stochastic Processes for Physicists: Understanding Noisy Systems (Cambridge University Press, Cambridge, 2010).

- S. R. De Groot, P. Mazur, Non-Equilibrium Thermodynamics (Dover, New York, 1984).

- L. Reichl, A Modern Course in Statistical Physics (Wiley - VCH).

Dynamical Systems and Non-Linear Physics-S3

Dynamical Systems and Non-Linear Physics

Contact: Alain Pocheau or Xavier Leoncini

Dynamical Systems and Chaos

- Basics : Introduction to the notion of dynamical systems, examples of non-linear systems, Discrete and Continuous time, from one to the other, Poincaré section. Reminders on differential equations and vector fields, and on linear systems and phase portraits.
- Local properties: Stability of fixed points, equilibrium for maps and flows, linearisation, Lyapunov function, attractors and basin of attraction. Stable and unstable manifolds, Bifurcations
- Global properties: Cantor sets, and fractals, notion of invariant measure, ergodicity and mixing. Birkhoff Theorem, Lyapunov exponent. Entropy, transport properties.
- Hamiltonian systems and chaos: Liouville equation, Integrability, actions-angles, variables, perturbation theory, Chririkov criterion, KAM theorem, Arnold diffusion.

Spatio-temporal systems : instabilities and self-organization

- Instabilities : Nature and method (base system, linearization, eigenmodes, spectrum)
- Examples (thermoconvection, Turing, …)
- Non-linearities and central manifold reduction, mode interaction and amplitude saturation
- From motifs to patterns (multi-scale expansions, Fredholm alternative, envelope equation, Ginzburg-Landau equation, phase diffusion equation, …) Selection mechanisms (structures, wave number, front speeds,…)
- Roads to chaos in dissipative systems: : Hopf Bifurcations, the Landau approach, Poincaré system, and first return maps, Bernoulli system, logistic map, subharmonic cascade (period doubling)/Feigenbaum, sensitivity to initial conditions, the Lorentz model (mode truncation and closure, bifurcations, strange attractors). Intermittency and roads to chaos.