# SYLLABUS Academic year 2019/2020

## (ANNEX TO THE TRAINING PROGRAMME)

Each PhD student must attend courses corresponding to 12 credits by choosing advanced courses organized:

- by the Doctoral Programme in Physics
- by the Master degree in Physics, or by other similar Master degree courses
- by other similar Doctoral programmes

Other mandatory activities include:

- Research activity followed by a tutor assigned by the Doctoral Programme Committee.
- Attendance of seminars organised by his/her own Research group
- Attendance of Dialogues, Colloquia and Joint Colloquia organized by the Department of Physics also on topics different from the research activity carried out by the PhD students.

Each student must submit his/her study plan to the Doctoral Programme Committee for the approval. The study plan must be previously agreed with the tutor.
The credits should be achieved within the end of the first year with the extension to the first semester of the second year only for Master degree courses activated in that time (for up to 6 credits).
PhD students can obtain up to 6 credits for the attendance of International Schools (Summer/ Winter school, etc.) upon the authorization by the tutor and the Doctoral Programme Committee and after passing an exam.

### Courses organized by the Doctoral School in Physics – a.y. 2019/2020

| Professor | Course | Credits | Hours |
|---|---|---|---|
| R.S. BRUSA ** (COORDINATORE) | **ADVANCED TECHNIQUES IN EXPERIMENTAL PHYSICS** | 3 | 21 |
| M. FERRARI, A. CHIASERA, A. CHIAPPINI | **OPTICAL AND SPECTROSCOPIC DIAGNOSTIC OF MATERIALS FOR PHOTONICS** | 3 | 21 |
| L. PAVESI | **INTEGRATED CLASSICAL AND QUANTUM PHOTONICS** | 3 | 21 |
| R. IUPPA, G. A. PRODI | **FUNDAMENTAL INTERACTIONS (PART OF THE LM COURSE)** | 3 | 21 |
| A. PERRECA | **ADVANCED INTERFEROMETRY** | 3 | 21 |
| A. QUARANTA | **QUANTUM SENSING** | 3 | 21 |
| R. BATTISTON, L. BRUZZONE, S. VITALE | **SPACE-BASED OBSERVATION TECHNIQUES AND METHODS** | 6 | 42 |
| M. RIZZI | **ENTANGLEMENT IN MANY-BODY SYSTEMS: FROM CONCEPTS TO ALGORITHMS** | 3 | 21 |
| TALENT (Training in Advanced Low-Energy Nuclear Physics) | **TO BE DEFINED** | 6 | 45 |
| ECT* (European Centre for theoretical Studies in Nuclear Physics and related Areas) | **ECT* DOCTORAL TRAINING PROGRAMME 2019** | * | |
| SISSA (Scuola Internazionale Superiore di Studi Avanzati) | **TO BE DEFINED** | * | |

*Up to 6 credits.
**Prof. Brusa will coordinate the course with the support of the professors of the experimental research Laboratories.

# ADVANCED TECHNIQUES IN EXPERIMENTAL PHYSICS, PROF. R.S. BRUSA

## Prerequisites

The knowledge of a physics graduate is requested.

## Contents

This course is organized as a collection of 4 lecture cycles on different topics in advanced experimental physics. Each cycle is given by an invited scientist or a member of the department, and consists in about 4-5 hours of lectures. The topics are selected every year in experimental research areas of interest of the physics department, giving priority to topics not already discussed in other dedicated PhD courses, as for instance:

1) Antimatter experiments, anti-hydrogen, positron beams, atomic physics experiments with positronium, positron and positronium for matter studies;
2) Applications of particle beams in medicine;
3) Biophysics, in particular methods for the conditioning/investigation of single biological molecules and for the imaging;
4) Cold gases condensates, atomic interferometry;
5) Instrumentation and methods for observational astrophysics and cosmology;
6) Instrumentation and methods in condensed matter and glasses and in surface science;
7) Instrumentation for synchrotron radiation and free electron laser based experiments;
8) Particle and radiation detectors;
9) Photonic devices;

The selection of topics of the course depends also on the availability of lecturers coming from other research institutes. The schedule of the course has to match the agenda of the lecturers and it is provisionally planned.

## Schedule

Period: between December 2019 and June 2020
*Further information*: robertosennen.brusa@unitn.it;

## Exam

PhD students will give a seminar of 20 minutes on an experimental topic related to the four lectures or to an experimental research presented in the Dialogues, Colloquia and Joint Colloquia. The topic is freely chosen by the PhD student but must be previously agreed with the coordinators of the course and must be different from the field of research of the PhD student.

## Optical and Spectroscopic Diagnostic of Materials for Photonics, dr. M. Ferrari, A. Chiasera, A. Chiappini

### Prerequisites
The typical skills of a Physics, Engineering graduate are requested.

### Contents
Phenomenological course

**Programme**
- Introduction to Glass Photonics
- From bulk to nano- and microscale photonics systems
- Rare earth –activated glasses
- Photonics devices fabrication and assessment
- Radiative and non-radiative transitions
- Transition probability
- Energy transfer
- Optical parameters, dispersion curve
- Absorption and emission cross sections; Quantum efficiency
- Light scattering for characterization of material properties
- Confined structures: Planar waveguides
- Confined structures: Nanospheres
- Confined structures: Direct and inverse opals
- Confined structures: Spherical Microresonators
- Confined structures: 1D - Microcavities
- Nanocomposites systems and transparent glass ceramics
- Integrated optics
- Resonant florescence line narrowing and spectral hole burning
- Single ion emission
- Homogeneous and inhomogeneous emission and absorption band
- Energy conversion
- Energy trapping
- Plasmonic structures
- Fluorescence enhancement using different sensitizers – metallic and semiconductor nanoparticles, lanthanides ions, nanocrystals.
- Fibers and fiber lasers
- Nano -micro thermometers
- Solar energy conversion by quantum cutting.
- Lightning
- Persistent luminescence
- Scintillators

### Schedule
From January to March 2020

### Exam
Seminar and discussion

### Bibliography
Specific papers and books will be suggested during the lectures

## INTEGRATED CLASSICAL AND QUANTUM PHOTONICS, PROF. L. PAVESI

### Prerequisites

The knowledge of the Maxwell equations, of Quantum Mechanics, of the physics of semiconductors and of the basics of optical devices.

### Contents

This course is organized as a journal club, where a seminal paper on the course argument is introduced and discussed during each class. The basic concepts behind the papers will be presented and the individual integrated circuits will be carefully analyzed. Students have to read the papers before the class and it is expected that during each class the students will contribute to the discussion via their own understanding of the paper. A selection of papers will be proposed at the course start and those which will be used will be determined on the basis of the student interests. A possible list of topics is

1) Integrated optical network
2) Optical biosensors
3) Photonic neural network
4) General purpose microwave photonics processors
5) On-chip quantum interference between silicon photon-pair sources
6) Quantum simulation with interacting photons
7) Quantum teleportation on a photonic chip

### Schedule

Period: January – February 2020

### Exam

PhD students will report on a paper, different from those discussed in the classes, about the course topic and which has been agreed with the lecturer. The student presentation will last 20 minutes.

### Bibliography

To be suggested.

## Fundamental Interactions, dr R. Iuppa and prof. G.A. Prodi

### Contents

**Description**

This course aims at describing frontier experiments on fundamental interactions, pointing out common and distinctive features of different fields of Physics. We will discuss the most important observational results of the last two decades in High Energy Physics, Flavor Physics, Astroparticle Physics and Search for Dark Matter, Neutrino Physics and Astrophysics, Gravitational Wave Astronomy and Cosmology. Lectures will be focused on experimental techniques, showing strength points and explaining intrinsic limits of sensitivity.

**Organization**

This is a lecture course in which topics are presented by the teacher.

**Course objectives**

- To provide PhD students with basic knowledge of modern experimental techniques applied in research fields different from theirs.
- To introduce PhD students to scientific methods and techniques widespread in particle and astroparticle Physics.
- To give PhD students a taste of what the hunt for Dark Matter currently.

**Course topics**

- Gravitational Wave Astronomy, compact binary stars populations, tests of General Relativity and consequences in cosmology.
- Standard Model and Beyond. The ΛCDM model.
- Detecting particles, how to.
- The problem of MASS. The electroweak sector. LEP, Tevatron and the LHC. The Higgs sector. Searches for New Physics.
- The problem of BARYOGENESIS. CP violation. CPT violation measurements. Cosmic antimatter asymmetry.
- The problem of DARK MATTER. Hypotheses. Spin-dependent/spin-independent. The WIMP miracle. Direct and indirect searches.
- The problem of NEUTRINOS. Neutrino mass. Neutrino oscillation. Neutrinoless double-beta decay. Astrophysical neutrinos.

### Schedule

Part of the LM Course, see LM program

### Exam

Grading plan
Written exam (quizzes): 25%
Short report on a topic agreed with the teacher: 25%
Oral exam: 40%
Attendance: 10%

### Bibliography

Teacher notes will be made available on time.

## ADVANCED INTERFEROMETRY, DR A. PERRECA

### Prerequisites

The knowledge of physics at graduate level is requested.

### Contents

The course will present advanced interferometric techniques for current and future experiments. Interferometry is an important investigative technique in the fields of astronomy, photonics, engineering metrology, optical metrology, plasma physics, biomolecular interactions, optometry and quantum mechanics. Several interferometers topology are widely used in science for the measurement of small displacements, refractive index changes and surface irregularities down to quantum limited sensitivity. This course will describe principles and effects of various interferometry topologies and example of applications.

The course is organized as follows:

Topology

- Plane waves and Gaussian beams. Michelson Interferometer: contrast, displacement sensitivity, shot noise. Fabry-Perot cavities: stability, resonance condition, finesse. The Pound-Drever-Hall technique for the locking of cavities. Other interferometer topologies: Sagnac interferometer, Mac-Zehnder interferometer: scheme and characteristics. More interferometric techniques: time delay interferometry, laser-ranging interferometry.

Advanced Interferometry for Gravitational Waves detectors

- Brief introduction to gravitational waves. Detection of gravitational waves. LIGO-Virgo interferometers at the time of their detections: Detection principle, Main noise contributions, Sensitivity curve. Future earth based GW detectors. Project for space based interferometers

More application of advanced interferometry

- Interferometry for the Gravity Recovery and Climate Experiment GRACE: introduction and working principle, current results. The next future: Grace follow-on.
- Interferometry for rotation measurements: the Sagnac effect. Application: ring-laser and gyro-lasers. Ring lasers for geodesy measurements. Ring lasers for general relativity measurements. The Lens-Thirring effect.

Improving the interferometer sensitivity

- Quantum nature of light. Coherent and squeezed states. Application of squeezed light in advanced interferometry: the case of GW interferometers.

### Schedule

From January 2020

### Exam

Seminar and discussion

### Bibliography

Specific papers and books will be suggested during the lectures

# QUANTUM SENSING, PROF. A. QUARANTA

## Prerequisites

. Properties of electrical and magnetic fields.
. Optics.
. Electromagnetic waves.
. Principles of quantum mechanics.

## Contents

. Measurements and noise.
. Principles of photon detection.
. Single photon sources.
. Detection of entangled photons.
. Principles of quantum sensing.
. Advantages of quantum sensing.
. Examples and proof of principles of quantum sensing.

## Schedule

. The course will be held during the second half of April 2020.

## Exam

. The exam will be a seminar about a topic selected by the student

## Bibliography

. The bibliography is a collection of papers on the arguments discussed during the course. All the papers will be available during the course.

# SPACE-BASED OBSERVATION TECHNIQUES AND METHODS, PROFF. R. BATTISTON, L. BRUZZONE, S. VITALE

## Contents

1. Gravitational wave detectors in space (S. Vitale)
    - Gravitational waves basics
    - Sources
    - Gravitational wave detectors
        - Geodesic motion and LISA Pathfinder
        - Time delay interferometry and the LISA detector
        - Other space borne detectors
    - Other applications of curvature detectors
2. Particle detectors in space (R. Battiston)
    - Sources of Cosmic Radiation
    - Cosmic ray detectors
    - X- and gamma-ray detectors
    - Optical detectors
    - Millimeter and infrared detectors
3. Radar and multispectral sensors in Earth observation and planetary exploration (L. Bruzzone)
    - Basics on remote sensing instruments
    - Multispectral and hyperspectral scanners
    - Radar for imaging (side-looking radar and synthetic aperture radar)
    - Radar for subsurface investigations (ground penetrating radar, radar sounder)
    - Examples of use of the instruments in missions for Earth observation (e.g. Worldview, Sentinel, Cosmo-Skymed, Prisma) and planetary exploration (e.g., JUICE, Cassini, Mars Express, MRO)

## Schedule

To be defined.

## Exam

To be defined.

## Bibliography

To be defined.

# ENTANGLEMENT IN MANY-BODY SYSTEMS: FROM CONCEPTS TO ALGORITHMS, DR. M. RIZZI

## Prerequisites

Prerequisite for this course is a fair knowledge of the following topics:
- quantum mechanics (Hilbert spaces, probabilities, unitary evolutions, spin and Pauli matrices, composite systems, possibly density matrices)
- basic quantum many-body theory and statistical mechanics concepts (Fermionic/Bosonic statistics, 2nd quantization formalism, possibly some concept of renormalization and/or critical exponents)
- basic computer programming (language is not too important: e.g. Fortran, C++, Matlab, Mathematica)

The class will include a practical part consisting in writing up a simple Density Matrix Renormalization Group (DMRG) code based on Matrix Product States (MPS) formalism in order to solve some simple problems and to provide you a potential instrument for further studies in many fields.

## Contents

After a brief introduction of entanglement and other quantum information concepts (overlapping to other classes), leading to the Tensor Network Ansatz family, we will focus on their use as tools to investigate many-body systems and their quantum phases, both from the conceptual and from the computational point of view. The concepts and tools are so general that they can find application in different current research fields like, e.g., cold atoms in optical lattices, spins in magnetic materials, electrons in solids, quantum chemistry, topological materials, and so on.

The theoretical aspect will be complemented by a practical part, via the development of your own simple Density Matrix Renormalization Group (DMRG) code based on Matrix Product States (MPS) formalism in order to solve some simple problems (e.g. compute low energy spectra and/or structure factors of toy systems).

A tentative outline of the lectures is:

1. Intro: General motivation on Entanglement in Many-Body Systems
2. Intro: General idea behind Tensor Networks (TN), a menu thereof & three viewpoints on them
3. Rudiments of TN: graphical notation, area-law of entanglement, information-based renormalization, gauge freedom & canonical forms
4. Rudiments of TN: contractions & costs, extraction of observables & correlations, some exact examples
5. TN as numerical tool: description of usual goals (ground states / dynamics / thermal ensembles) & typical systems treated, Algorithm 1 – Time-Evolving Block Decimation (TEBD) for Matrix Product States (MPS)
6. TN as numerical tool: Algorithm 2 – Ground-State Variational Search, concept of Matrix Product Operator
7. TN as numerical tool: Algorithm 3 – Time-Dependent Variational Principle (TDVP) for longer-range models, Algorithm 4 – some rudiments of Thermal Ensembles
8. Advanced topic: Symmetry groups (quantum numbers) in TN algorithms, why and how (details on Abelian, hints to non-Abelian cases)
9. Advanced topic: Projected Entangled Pair States (PEPS) for 2D systems, generalities, algorithms & exact cases
10. Advanced topic / Outlook: a bird-eye view on all what we did not touch in detail (parent Hamiltonians, topological order, classification of phases, continuous MPS, holography, quantum chemistry, etc.)

This is not a too rigid scheme, and may be adapted on-the-fly to the skills and interests of the participants.

## Schedule

November 2019 to January 2020

## Exam

Free choice between the following options:

i) Little seminar on a selected topic of interest
ii) Short essay on a self-made numerical simulation
iii) Traditional oral exam

## Bibliography

1) do not feel scared by the articles, they are just as good as (or even more than) book chapters (and anyway we can help you through)
2) in case you are not able to download them (it should be possible from the Uni-Account), let us know and we will provide PDF's to you.

General literature on Quantum Information
- Quantum Computation and Quantum Information - Nielsen and Chuang - Cambridge Univ. Press
- Lecture Notes on Quantum Information - Preskill - www.theory.caltech.edu/people/preskill/ph229
- Computational Many-Particle Physics - edited by H Fehske, R Schneider, and A Weiße - Springer 2008 - http://link.springer.com/book/10.1007/978-3-540-74686-7/page/1
- special issue of Journal of Physics A, Vol 42, Num 50 - edited by Calabrese, Cardy, Doyon
- Amico, Fazio, Osterloh, Vedral - Rev. Mod. Phys. 80, 517 (2008) - arXiv:quant-ph/0703044
- Horodecki^4 - Rev. Mod. Phys. 81, 865 (2009) - arXiv:quant-ph/0702225
- Eisert, Cramer, Plenio - Rev. Mod. Phys. 82, 277 (2010) - arXiv:0808.3773

Specific literature on Tensor Networks
- Orus, Annals of Physics 349, 117-158 (2014) — arXiv:1306.2164v3
- Schollwöck - Ann. Phys. 326, 96 (2011) - arXiv:1008.3477

Deeper literature on Tensor Networks
- Schollwöck - Rev. Mod. Phys. 77, 259 (2005) - arXiv:cond-mat/0409292
- Cirac - lecture notes from Les Houches - arXiv:1205.3742
- Verstraete, Cirac, Murg - Adv. Phys. 57, 143 (2008) - arXiv:0907.2796
- Cirac, Verstraete - Jour. Phys. A 42, 504004 (2009) - arXiv:0910.1130
- Orus, Eur. Phys. J. B 87: 280 (2014) — arXiv:1407.6552v2

Own literature on Tensor Networks
- De Chiara, **MR**, Rossini, Montangero, J. Comput. Theor. Nanosci. 5, 1277_1288 (2008) (codesource www.dmrg.it),
- Silvi, Tschirsich, Gerster, Jünemann, Jaschke, **MR**, and Montangero, SciPost Phys. Lecture Notes 8 (2019)
- P. Schmoll, S. Singh, **MR**, R. Orús, arXiv:1809.08180

## TALENT 2019

Programme not yet available: http://www.ectstar.eu/talent

## ECT* DOCTORAL TRAINING PROGRAMME 2020

Programme not yet available: http://www.ectstar.eu/node/4497

## SISSA COURSES

Courses of the Master degree in Physics (http://offertaformativa.unitn.it/it/lm/fisica/studiare-e-frequentare)
Starting in the second semester of the a.y. 2019/2020.