UNIVERSITÀ DEGLI STUDI
DI TORINO

Department of Physics
"Department of Excellence" Project

1. Introduction

In 2017, the Italian Ministry for University and Research (MIUR) compiled a list of the Departments of Italian public Universities eligible for funding within the "Departments of Excellence" program. The ranking list was provided by the national evaluation agency ANVUR. Among the 350 top departments, 180 were selected for funding in excess of 7 million euros each, for five years (https://en.unito.it/news/university-turin-awarded-among-best-italian-universities).

The Department of Physics of the University of Torino was ranked third best in Italy in its field and first among those whose project was submitted to peer review evaluation of the proposal.

The Department and its project were evaluated positively in terms of quality of research, scientific outlook and didactic organization, and for compliance with the research objectives of "Industry 4.0". In the scientific project, the Department presented a development strategy in three main lines of research:

- Innovative sensors and detectors
- Dark universe and cosmic messengers
- Physics of Complex Systems

The objectives of these research lines are rooted in the advancement of our understanding of the physical world at the fundamental level but are designed to allow and promote the development of technological transfer and applications of the conceptual and theoretical methods to external fields.

Alongside the theoretical, numerical and experimental activities that characterize each line of research and which are outlined in detail in this report, these lines share three methodological approaches which are transversal to the project and which can therefore profit of a synergic approach: the development and application of cutting-edge technologies, the analysis of large amounts of data based on innovative approaches such as data mining and machine learning, and the exploitation of high-performance computing facilities.

The research activities are closely linked to the two educational programs of our Department at the master's degrees level: Master's Degree in Physics and Master's Degree in Physics of Complex Systems. Furthermore, they are the basis of the activities of our two PhD programs: Doctoral School in Physics and Doctoral School in Physics of Complex Systems for Life Sciences. Part of the project's resources will therefore be used to reinforce this educational offer, thus fostering the formation of a new generation of young researchers able to combine and make synthesis of more classical physical skills (modelling of complex systems, numerical simulations, use of advanced instrumentation) with skills in artificial intelligence and advanced statistical analysis.

https://en.unito.it/news/university-turin-awarded-among-best-italian-universities

2. Presentation of the Department

The Department of Physics (DP) holds a long, high-level academic tradition, and is characterized today by numerous areas of excellence at an international level. Research activities are focused in the following sectors:

- *Physics of fundamental interactions*. The DP has a consolidated tradition of excellence in high energy physics, both at the theoretical and experimental level. It is engaged in large experimental efforts at the main international laboratories, like CMS (CERN), with an essential contribution to the discovery of the Higgs Boson, and ALICE (CERN); in synergy with these experiments, it develops cutting-edge theoretical studies concerning precision phenomenology of the Standard Model of elementary particles, hadronic physics and nuclear theory; the DP has a long tradition on frontier topics in quantum field theory and string theory.

- *Astro-particle physics, cosmology and astrophysics*. In continuity with research on fundamental interactions, the DP pursues studies on the large-scale structure of the Universe, on the nature of dark matter and dark energy, as well as on high energies astrophysics; this is accompanied by activities on the physics of cosmic rays, with participation in large international collaborations, among which AUGER and Fermi.

- *Physics of complex systems*. Using advanced and innovative methods of statistical mechanics and data analysis, biological systems and gene regulation networks are studied, with important medical applications for oncological therapies; the physics of meteorology and climate is pursued with studies on greenhouse gas transport processes and with paleoclimatology analyses; nonlinear physics methods are applied to turbulence and the interactions between biological and fluid systems.

- *Applied physics*. The DP has a long-standing and central role in the development of instrumentation for medical applications, in the simulation and data management of diagnostic imaging and in therapy of tumors with radiation - activity developed in collaboration with the National Center for Oncological Hadrotheray (CNAO) of Pavia - and has produced academic spin-offs for medical imaging (Detector, Dixit, I-SEE) that obtained a relevant commercial and adoption impact. The DP is at the forefront in the study and functionalization of advanced materials (diamond, graphene, superconductors at high critical temperature) for the development of new devices, sensors and applications, in collaboration with the Interdepartmental Center "Nanostructured Surfaces and Interfaces" (NIS). In the Cultural Heritage sector, it carries out important diagnostic and dating activities on objects of historical and artistic interest, together with the spin-off TecnArt and the center of Conservation and Restoration La Venaria Reale.

The DP collaborates closely with several national Institutes and Research Centers, including the National Institute of Nuclear Physics (INFN), the National Research Council (CNR), the National Institute of Astrophysics (INAF), the National Institute of Metrological Research (INRiM) and the Interuniversity Consortium for Space Physics (CIFS). It is home to the recently established Arnold-Regge International Center for Theoretical Physics (ARCenter). It collaborates with a large number of international and trans-national institutions, including CERN, NASA, the Max Planck Instituts and numerous universities and research institutions of recognized excellence all over the world.

SCIENTIFIC PRODUCTION

As evidenced by the results of the national evaluation of scientific research (VQR – Valutazione della Qualità della Ricerca), the scientific output of the DP is characterized by a high quality and a high percentage of publications at the level of excellence. By way of example, in the period 2012-2016: 36% of publications is in the 'top 10% most-cited worldwide', 53% in the top 10% journals, 84% of publications made with international collaborators; one third of staff members have an h-index over 30 (Scopus data). In the period 2006-2016, 3 patent proposals and 3 patents were filed. In confirmation of the attractiveness of the DP, 5 awadress of the higly-competitive Montalcini Young Researchers Program have chosen the DP as their workplace since 2012 to today.

INSTRUMENTATION AVAILABLE

The research activities can count on numerous instrumental equipments present within the DP, including:

- ***High-Performance Computing Cluster OCCAM*** (Open Computing Cluster for Advanced data Manipulation, since 2016), connected to the national research computing network GARR, installed at the DP and managed by the University's Competence Center on Scientific Computing (C3S), of which the DP is promoter.

- ***Innovative Sensors Laboratory***, equipped with a clean room for the development of new ionizing radiation detectors, biosensors and quantum sensors, and equipment for the manufacture and characterization of advanced materials.

- ***Linear Accelerator Laboratory*** (since 2017), committed to testing and development of detectors for medical applications, cultural heritage, characterization of materials and neutron metrology.

- ***TurLab fluid dynamic laboratory***, equipped with a rotating tank for 3D studies of turbulent motions and simulation of atmospheric flows (part of the European EUHIT network).

- ***X-ray imaging and thermoluminescence Laboratory***, dating for Cultural Heritage.

Most of these installations operate in Open Access for academic or industrial partners.

Numerous collaborations are active with private local companies, including Fiat Chrysler Automobiles (automotive), ITT Friction Techologies (aerospace, transportation, manufacture), Fiat Research Center (automotive), Thales Alenia Space (aerospace), Selex Galileo (electronics and space technologies), Vishay (semiconductors, electronics), Prima Electro (embedded electronics), IREN (energy), Federottica (optics), Agilent (vacuum).

TEACHING

The DP is the Department of reference for two Master's Degrees (Physics and Physics of Complex Systems) and for their corresponding Doctoral courses. It contributes to the teaching of the master's degree courses in the scientific and medical areas, holding a role of particular relevance in the master's degree in Materials Science and in the doctoral course in Chemical and Materials Technologies. The DP coordinates the School of Specialization in Medical Physics (collaborating with local health companies) and is member of the Doctorates in "Technology Driven Sciences: Technologies for Cultural Heritage" and "Modeling and Data Science". 97% of our research doctors in the three-year period 2014-2016 are employed, 74% in academic research, 59% abroad, confirming the high level of preparation provided.

3. Project "Department of Excellence" - Three Challenges in The Physics of The Future: Innovative Sensors, Cosmic Messengers, Complex Systems

The "Department of Excellence" (DoE) project has been designed to promote scientific excellence, in order to allow the DP to consolidate and extend a leadership position on the national and international scene and to profit of the funding to set a long-term process of qualitative growth, sustainable also beyond the 5 years term of the current project.

Considering the variety and richness of the research lines already active in the Physics Department, the achievement of the objectives requires to concentrate the resources made available by the DoE program on specific lines which are already consolidated in the Physics Department and which offer large margins of growth in relation to the human and infrasctructural resources currently available. The lines have been identified with reference to best international practices, based on the following quality objectives:

O1) Excellence in research on topics with great development prospects in the international context for the coming decades.
O2) Excellence in the ability to promote further attraction of external funds and talented researchers and students.
O3) Excellence in synergy with the local economic and industrial context, also in relation to the priorities of the National Industry 4.0 Plan.
O4) Sustainability over time of the progress made during this program.

Based on these objectives, three lines of research have been identified, presented here in the form of Work Packages (WP):

WP1) Innovative sensors and detectors
WP2) Dark universe and cosmic messengers
WP3) Physics of complex systems

In addition to the theoretical, modeling and experimental activities characterizing each research line, they have in common three important methodological strands, transversal to the project: the development and application of frontier technologies, the analysis of large amounts of data, and advanced numerical methods. The allocation of resources, infrastructure and personnel will take into account these common elements: specifically, the development of the identified scientific lines requires an investment and update in those large research infrastructures already present in the DP and relevant for the project.

Let us now describe in detail the development of the three WPs.

WP1 - SCIENTIFIC OBJECTIVES

The development of innovative sensors and detectors is strategic for the experimental research lines in which the Department is involved: from medical physics, advanced materials and cultural heritage, to experimentation with particle accelerators and in the astro-particle field. The topic is therefore interdisciplinary, with a high technological content, and with industrial repercussions. The development action will be focused on strengthening the Innovative Sensors Laboratory and on the development of electronics for signal control and processing.

WP1 activities are subdivided into two main areas:

a) Synthesis, characterization and functionalization of advanced materials (diamond, SiC, BN, graphene, high critical temperature superconductors), and development of new sensors and devices for applications in metrology, biophysics, electronics and optoelectronics. The aim is to strengthen the activities focused on materials of interest for new quantum technologies: specifically, the acquisition of a new ion implantator is envisaged.

b) Development of silicon detectors with performances beyond the state of the art for spatial and temporal resolution, capable of operating in hostile environments. These detectors are essential both for fundamental physics experiments in particle and astroparticle physics and for applied physics activities already rooted at the Physics Department, in particular medical physics (qualification of therapeutic beams and dosimetry), physics of cultural heritage and study of materials for industrial applications. For this activity, the acquisition of highly specialized instrumentation for the characterization and assembly of silicon detectors is foreseen.

The activities of WP1 also require a common infrastructure in the electronic and microelectronic field to create integrated readout systems with low noise.

WP1 - MILESTONES AND TEMPORAL DEVELOPMENT

Startup (2018-19)

M1.1) Optimization of protocols and instrumentation for the characterization of single photon diamond emitters, realized by implantation; design of the new ion implantator.
M1.2) Completion of the R&D phase for new silicon detectors, in view of: LHC experiments in high luminosity conditions; future telescopes for the search for very-high-energy photon sources; applications in ion-beam tumor therapy.

Consolidation (2020-2022)

M1.3) Implementation of the new implanter and definition of the parameters and protocols for implantation in diamond, SiC and Si.
M1.4) Construction and development of detectors for the LHC; design of a silicon photomultiplier chamber for the Large Size Telescopes of the Cherenkov Telescope Array.
M1.5) Construction of an apparatus for real-time qualification of radiation therapy with ion beams.

The experimental activity is organized as follows.

New ion implantation facility:
- 2018: Identification, regulation and preparation of suitable premises.
- 2019-2020: Design, installation and commissioning of the ion implantator.
- 2021: Start of N, Sn, Si diamond implantations.

New internal silicon pixel trackers and timing detectors:
- 2018: R&D and test on prototypes.
- 2019: Finalization of the R&D phase and choice of technology.
- 2020: Start of production of sensors and electronics.
- 2021-2022: Assembly and installation in experiments.

WP1 - INNOVATIVE VALUE, ORIGINALITY AND BENCHMARK

The activity of the ion implantator will be focused on the low fluence implantation, both of N and of elements of group IV (C, Si, Ge, Sn), which are showing great potential in the creation of diamond and SiC color centers, in the field of quantum technologies. The infrastructure will have unique characteristics on the national scene and prominent on the European scene. Benchmark: Henry Royce Institute, UK; University of Leipzig.

The developed detectors will combine high performance in spatial resolution (less than 10 microns), temporal (about 30 ps), and reading speed (greater than 1 Mframe/s), allowing the creation of devices for new-physics studies. This will make the DP a national and international reference center in the development of silicon detectors. These results require the development of an innovative readout architecture in 65nm CMOS technology, which will allow the DP to position itself at the level of international excellence in the sector. Benchmark: Bonn Universitaet and CNRS Strasbourg.

WP1 - COHERENCE WITH THE QUALITY AND IMPACT OBJECTIVES

Investments in advanced infrastructures will allow a rapid growth of the experimental potential of the DP, allowing to activate new collaborations with the main international players in the sector (O1). The acquired infrastructures will also continue to be developed and operated beyond the end of the program (O4).

The development of new detectors and new electronics will allow DP researchers to contribute significantly to major international experiments, facilitating the obtaining of key positions, making a significant contribution to the number of publications, and increasing the leadership role in future competitive bids (O1, O2, O4).

Light sensors based on silicon technology will be applied in the aerospace field and in initiatives falling within the Industry 4.0 Program (Technology Driver (TD): Advanced Manufacturing Solutions) (O3).

The activity on quantum devices and sensors will allow the DP to attract funds from international research programs (EU Quantum Technology Flagship, Advanced Materials in H2020 and FP9), and will open the possibility of contracts with companies interested in new semiconductor doping techniques or surface treatment, within the Mechatronics hub of the Piedmont region (O2, O3).

WP1 will contribute to the development of 3 out of 6 of the Key Enabling Technologies indicated by the European Commission (Microelectronics, Advanced Materials, Photonics), allowing to contribute to innovation in various industrial sectors (O3).

The ion implantator will be included in UniTo's Open Access Lab project and made available to public and private local research institutions and companies, to allow them to experiment with doping techniques in semiconductors and for the functionalization of surfaces of materials for biomedical use (O3).

The activities of the Innovative Sensors Laboratory will be part of the DP plan aimed at strengthening the teaching laboratories for the master’s degrees, both in curricular courses and for thesis and doctoral thesis activities.

WP2 - SCIENTIFIC OBJECTIVES

The nature and evolution of the structure of the Universe and its components, ordinary and obscure, will be focal themes in physics and astrophysics for the coming decades. Observing the Universe will provide unprecedented quantities of data, both for the distribution of matter in the cosmos and for the components of the astro-particle cosmic radiation: radio, X, gamma, cosmic rays and gravitational waves. The skills of the DP in the theoretical study and in the development of detectors provide us with a strong starting point, on which to insert now the priority of enhancing our ability to process and interpret incoming data.

The chosen strategy passes through a methodological innovation: the combined and synergistic analysis of the data of the large astro-particle, cosmological and astrophysical surveys, and the consequent theoretical interpretation, with the aim of identifying a solution to the problems of dark matter and dark energy. The methodology consists in creating innovative statistical tools, starting from those we have designed in recent years. We will develop and use knowledge discovery algorithms, advanced data mining techniques and machine learning methods with and without supervision. The application of these techniques with the synergistic method proposed by us represents an important novelty on the international scene.

The scientific objective will be, in parallel, accompanied by a growth in the didactic offer and an update of our Physics Department facilities and instrumentation.

WP2 - MILESTONES AND TEMPORAL DEVELOPMENT

The long-term goal is the complete characterization of the cosmic messengers and of the information they can lead to the solution of the dark matter and dark energy problems. The path carried out within the project is structured as follows.

Startup (2018-19)

M2.1) Theoretical development of data cross-correlation techniques and their application to the cross-correlation of gamma rays (Fermi-LAT) and weak lensing (Dark Energy Survey, with which we have an exclusive collaboration agreement on this topics).
M2.2) Development of new data-analysis methods based on data mining and machine learning techniques applied to astro-particle physics.
M2.3) Entry into the LOFAR Consortium and first phase of data collection and analysis.

Consolidation (2020-2022)

M2.4) Extension, improvement and consolidation of the techniques developed in the Startup phase and their application to the new major international missions: radio (Square Kilometer Array), gamma radiation (Cerenkov Telescope Array), cosmological surveys (Euclid, LSST).
M2.5) Preparation study for galactic survey missions (e.g. Theia).
M2.6) Analysis and interpretation of LOFAR data; feasibility study for the installation of a second-generation radio astronomy station in Piedmont; second phase of data collection.

WP2 - INNOVATIVE VALUE, ORIGINALITY, BENCHMARKS AND COHERENCE WITH THE QUALITY AND IMPACT OBJECTIVES

Our benchmarks are the Physics Departments of the large international universities operating in the sector (GRAPPA Amsterdam, Heidelberg, JBCA Manchester), and the good practices of the large research bodies that today invest in the production, study and interpretation of large amounts of data (NASA, ESA, CERN). The level of our presence in large partnerships and our impact in their analyses define our international competitiveness.

The development of the project is highly innovative in terms of the methodologies chosen (O1). It is of high impact, for the focus on issues with great development prospects in the context of physics in the coming decades (study of the ordinary and dark components of the Universe) (O2). The project is multidisciplinary, combining the aspect of data mining (O3) with the study and theoretical interpretation of data with very different origins and characteristics (the whole "multi-messenger" spectrum on the one hand; the distribution of the galaxies and their gravitational distortions on the other). The expected results will allow us to undertake a path of rapid growth, to make the DP a center of reference at the European level in the study of the dark components of the Universe (O1), able to play a guiding and coordinating role on these issues also within the main international collaborations (Euclid, SKA and LOFAR) (O4). This will be a basis on which to leverage for a highly qualified participation in competitive individual and collective Europeans calla such as ERC and ITN (O2, O4).

The extensive development of data mining methods will be part of the activities supporting Industry 4.0 strategies linked to TD "Big Data Analytics" (O3).

One strength of the project is the fact that the DP, unique case in Italy, has signed an agreement with INAF to participate into the international consortium "ILT - International LOFAR Telescope". This will allow exclusive access to new low-frequency radio data (O4), in an almost unexplored region of the spectrum, with coverage equal to 70% of the sky, and will be a distinctive element for achieving the project objectives.

WP3 - SCIENTIFIC OBJECTIVES

The objective of WP3 is the development of innovative methods for the study of complex systems, combining the most advanced techniques of statistical mechanics with large-scale numerical simulations, and with the treatment of the consequent large amounts of data through innovative analysis approaches, such as data mining and machine learning. The activities of WP3 are closely linked to the master's degree in Physics of Complex Systems and to the Doctorate in Complex Systems for Life Sciences, which offers highly innovative didactic initiatives (first examples of this type in Italy) and attracts students from all over Italy and from abroad. Part of the resources of the project will be used to strengthen this didactic offer: notable scientific and educational effects are therefore expected, with the training of a new generation of young researchers able to combine classical physical skills (modeling complex systems, numerical simulations) with artificial intelligence skills and advanced statistical analysis.

WP3 is divided into two research themes:

a) ***Computational Biophysics***. The primary objective is the development of innovative analysis tools for the integration, study and modeling of large amounts of biomedical data. This will be followed by the application of the tools developed to gene regulation and cell signal transduction networks, to identify potential pathological changes and guide therapies in the so-called "precision medicine". The results already achieved by the DP team in these research directions form the basis for future developments.

b) ***Turbulence and nonlinear waves***. In the fluid dynamics field, the primary objective is a better understanding of small-scale turbulence, responsible for the physical processes underlying the dynamics of the atmosphere and the ocean, in particular turbulent convection and extreme events associated with the formation of "microbursts". Furthermore, using numerical simulations and laboratory experiments, the production of vorticity by surface waves, a fundamental and poorly understood ingredient of ocean dynamics, and the control of waves by means of metamaterials will be investigated.

WP3 - MILESTONES AND TEMPORAL DEVELOPMENT

Startup (2018-19)

M3.1) Development of new data mining tools, machine learning and Montecarlo simulations for the analysis and integration of genomic data; tests of algorithms with public databases (TCGA, Allen Brain Atlas).
M3.2) Construction of a new experimental infrastructure with wave generation, control and attenuation systems based on the innovative concept of metamaterial; new numerical tools for the study of turbulent convection and the characterization of extreme events.

Consolidation (2020-2022)

M3.3) Preparation of the protocol for Open Source supply of the codes developed in the startup phase; use of the results for applications in oncology (taking advantage of the consolidated experience in the DP), and in the emerging sector of quantitative neuroscience.

M3.4) Update of the public database (TurBase, available at CINECA) of the data produced by the numerical simulations.

The experimental activity will be organized as follows.

- 2018: Preparation of premises for experimental infrastructure.
- 2019: Installation of a new infrastructure for generation and control of waves with metamaterials; TurLab hardware and software upgrade.
- 2020: Production and data analysis.

WP3 - INNOVATIVE VALUE, ORIGINALITY AND BENCHMARKS

The DP aims to become one of the first centers in Italy to create an integrated IT platform to tackle serious pathologies both of oncological and neurological type (Benchmark: CSB, ETH Zurich; IBENS, ENS Paris). The strong interdisciplinary dimension of this WP is based on the constructive collaboration already existing between the University of Torino medical doctors and physicists.

The turbulence and non-linear physics group of the DP is one of the leading groups in Italy and in Europe in the numerical study of non-linear and turbulent systems (Benchmark: Ecole Normale Superieure de Lyon). The new infrastructure for wave control and TurLab upgrade will allow to extend excellence to the experimental approach.

WP3 - COHERENCE WITH THE QUALITY AND IMPACT OBJECTIVES

The results of the biomedical line will have a significant socio-economic impact, following the ever-closer collaboration with the laboratories operating in the biomedical field in the Torino area, given the growing need to process and model large amounts of data for the so-called "precision medicine". The integration of our methodologies with modern biomedical investigation techniques will allow a significant progress in the identification of effective therapies and identification of drugs for the treatment of cancer and serious neurodegenerative diseases (O1, O3). Research in the field of data mining and machine learning methods will contribute to the development of the "Big Data Analytics" TD of the Industry 4.0 Program. (O2, O3).

For the fluid dynamics line, the upgrade of the TurLab laboratory will allow the DP to maintain and develop an experimental structure of excellence and play a growing role in European research projects in the sector, such as the EuHIT network (O2, O4).

Fluid dynamics research also fosters collaboration with regional bodies such as the Regional Agency for Environmental Protection (ARPA) and the Environmental Monitoring and Modeling Laboratory (LAMMA), which will have direct access to the achieved results and the developed techniques (O3).

In the teaching area, the joint doctorate between DP and the Department of Oncology is a point of reference at both national and international levels. The resources of the project will allow to enrich the curriculum with themes related to Big Data and Machine Learning, allowing to attract talented students and researchers from abroad (O1, O2, O3).

4. Scientific Results and Achievements 2018-2019

This Section summarises the scientific activities pursued in the first two years of the project, highligthing the main results and achievements obtained. The corresponding publications are listed in the Annexes Section.

WP1 - SENSORS AND INNOVATIVE DETECTORS

The WP1 can be internally divided in two main research lines: a) development and application of silicon-based particle detectors; b) advanced materials and new devices.

a) Development and application of silicon-based particle detectors

a-1) Detectors for the LHC High-Lumi phase

The DP is involved in the CMS experiment for the High-Lumi upgrade phase. The activities in our Department are focused on the construction of a CMS Inner Tracker with a performance better than the present one and of a new Endcap Mip Timing Detector.

The Inner Tracker is the main detector in CMS for the pattern recognition. The DP is giving contributions on many aspects of the project but one of the most relevant is the development of the readout chip in 65nm CMOS technology. The main features of this extremely sophisticated chip are: radiation tolerant, low power dissipation (1 W/cm2), low noise (10^{-6} at 1200e threshold), high hit rate (3 GHz/cm2) and trigger rate (1 MHz with 12.5 µs buffer) capabilities. Different architectures were developed inside the international collaboration RD53 and in May 2019 the final front-end architecture was chosen by the CMS collaboration, thus opening up the phase of the design of the final chip. During summer 2019 fifteen 12" wafer of RD53A chips were successfully tested in Torino using the new CM300 semi-automatic probe station that has been acquired using the infrastructure budget of this project. This has allowed to start the calibration of the automated wafer testing procedure with the CM300 probe station that will be finalized using wafers from the next engineering run.

The Mip Timing Detector is a new detector of the CMS experiment that will be endowed with a high-resolution timing information for charge particles over a wide pseudorapidity range. It is divided in a Barrel part and in two Endcap's. The technology chosen in September 2019 by CMS for the Endcap (almost 15 m^2) is based on Ultra Fast Silicon Detectors (UFSD) whose R&D is under Torino responsibility. The UFSDs project, i.e LGAD detectors optimized for timing in HEP, started in Torino already in 2016. Different productions have been studied within this project. The main feature is to have better than 40 ps resolution up to 1.5 1015 n cm^{-2} s^{-1}. Few vendors are on the market: Hamamatsu (Japan), Fondazione Bruno Kessler (Italy), NDL(China), CNM(Spain). Torino has connections with all of them: in particular with FBK a strong collaboration is ongoing. In 2018 the main FBK production has been focused on the use of Carbon in the gain layer implantation to mitigate radiation effects and to preserve the timing resolution at high dose, and on the lithography technique to get sensors of large dimensions, typically 4 x 24 pads 3 mm2 each. In 2019 a couple of new productions addressed systematically how to minimize the interpad regions in order to limit the sensor dead area and to optimize the p-stop doping to get better performances. Moreover, the sensor geometries have been designed to properly match the front-end electronics in order to perform an appropriate system test.

a-2) Development of monolithic active pixel sensors

ALICE ITS2: During the years 2018 and the first months of 2019 the main activity has been the construction of the constituent elements of the outermost layers of the new Inner Tracking System (ITS) of the ALICE experiment at LHC. The building blocks of this detector are the ALPIDE chips. The Torino group has contributed initially to the design of part of the chip, and of the Flex Printed Circuit (FPC) used to distribute power and signal to the sensors and to the development of the assembly procedure for the outer barrel staves. The construction of the staves, coordinated by the Torino group, finished in December 2019. The staves are now assembled in half layers/half barrels and are being commissioned for the installation in the ALICE experiment, foreseen for summer 2020.

LIMADOU Tracker: In year 2019 the HEPD-02 project, part of the CSES 2 space mission, was officially approved. The project intends to build a detector to measure charged particle flux fluctuations in the ionosphere. The Torino group is involved in the design and construction of the particle tracker, made of ALPIDE chips as the ALICE ITS. In particular we have the responsibility of the design of the Flex Printed Circuit (FPC) which was finalised in 2019 and the production of at least 50 modules, each made of 10 chips. The first modules will be built in January 2020. A contribution of ~100k€ from ASI will co-fund the activities of the "Department of Excellence" project, starting from January 2020.

ARCADIA: The collaboration ARCADIA explores the possibility of building fully depleted monolithic pixel sensors. We aim at proposing a design which could be adapted to different applications, the most relevant being high energy physics at future accelerators, particle tracking in space and medical physics. The activities started recently with the preparation of a narrow beam laser set-up to investigate the performance of the prototypes, pixel by pixel. The set-up was completed in 2019 and used for the characterization of few prototypes.

All the activities see the contribution of a PhD student who has started his course of study in December 2019.

a-3) Medical applications

The innovative silicon sensors developed within WP1 are an appealing alternative to gas ionization chambers commonly used for beam monitoring in particle therapy. Sensitivity to single particles, limited thickness, fast response time and outstanding time resolution can be exploited for developing a new generation of faster monitoring devices to implement advanced delivery modalities. Two systems are being developed to directly count the number of beam particles delivered with a sensitive area from 3x3 cm2 and to measure the beam energy with time-of-flight techniques.

Dedicated UFSD strip sensors, designed and produced at the Fondazione Bruno Kessler (FBK, Trento, Italy), were fully characterized in laboratory and tested on the clinical proton beams of the Centro Nazionale di Adroterapia Oncologica (CNAO, Pavia, Italy) and the Centro di Protonterapia di Trento (Trento, Italy). It was proven that, in the energy range used in clinics, a counting efficiency above 98% can be achieved up to an average rate of 2 MHz per channel (up to 10 MHz using an online pileup correction method) and that an energy sensitivity corresponding to 1 mm range in tissues can be easily achieved with the coincidence of two sensors 70 cm apart.

For the counting operation a 24 channels custom front-end ASIC prototype (ABACUS) has been designed and produced in a CMOS 110 nm technology, based on a fast amplifier with self-reset capabilities, aiming at discriminating signals up to a maximum instantaneous rate of 100 MHz per channel. Using custom readout boards, the integration with the FPGA based readout was developed tested and successfully.

a-4) Application of Silicon Photomultipliers in Astroparticle experiments

Silicon Photomultipliers (SiPMs) are emerging as a valid alternative to Vacuum Photomultiplier Tubes (PMTs) in several astroparticle experiments. Their high intrinsic gain, the single photon sensitivity, the large dynamic range, the mechanical robustness, the low bias voltage and the possibility to operate also with high level of background light are some of the reasons that made SiPM largely used in the field. For instance, in the Cherenkov Telescope Array (CTA), the next generation international ground-based gamma-ray observatory, several telescope types will have SiPMs as photosensors. Torino is involved in the experiment and is proposing a camera with solid state sensors instead of PMTs for the future upgrades of the Large Size Telescopes. The challenging aspect of the project is to produce a large sensitive area (~5 cm^2) read as a single channel. During the first two years (2018-2019), a laboratory for the SiPM characterization has been set up and first ideas to produce a large area detector able to work with high noise rate (~500 MHz) have been developed and tested. The resulting baseline idea is to perform an analog summation of the signals of several (12-16) small SiPM pixels and to shorten the signal (~5 ns FWHM) by means of a pole-zero cancellation circuit. SiPMs of different producers (e.g.: Hamamatsu, FBK, SensL) have been considered as possible options for the prototypes.

A Ph.D. student is working at these activities since October 2018.

b) Advanced materials and new devices.

The main activities carried out in 2018-2019 are focused on the synthesis, characterization and functionalization of advanced materials and the development of new devices and sensors for applications in metrology, biophysics, (opto)electronics, and can be summarized as follows:

- Development of a new lithographic methodology based on an ultra-thin suspended mask of graphene grown by CVD on Cobalt;
- Development of an innovative photoresist-free nano-patterning technique based on focused intense X-ray beams, for the functionalization high-critical-temperature superconducting oxides;
- Application of the Ion Beam Induced Charge (IBIC) technique for the measurement of the radiation hardness of semiconductor devices and detectors;
- Development of innovative diamond-based biosensors for the detection of both electrical and chemical signals of living cells;
- Development of a new metrological protocol based on tip-enhanced Raman Spectroscopy (TERS) for applications in agricultural and food analysis.

With regards to the specific focus on Quantum Technologies:

- Defect-engineering and quantum-optical characterization of novel single-photon emitters in solid state: discovery and characterization of a new class of single-photon emitters based on group IV impurities in artificial diamond;
- Quantum-enhanced electrometry based on optically active spin defects in solid state: development of innovative techniques for the local mapping of electromagnetic fields within solid-state devices at high spatial resolution and based on the spin properties of nitrogen-vacancy complexes in diamond;
- Innovative ion- and laser-based strategies for the fabrication of quantum devices: development of novel techniques based on focused ion and laser beams for the engineering of quantum sensors and quantum light emitters;

- Metrologic standardization of solid-state-based single-photon emitters: a systematic pilot study on the qualification of the quantum-optical properties of solid-state single-photon emitters produced within the project. A dedicated report on this subject was published in the “Research Highlights” section of Nature Physics 15, 110 (2019).

All of the above-listed activities have been carried out in close collaboration with national (among which: INRiM and INFN) and international (Leipzig University, Ruđer Bošković Institute, European Network of Metrological Institutes) partners.

WP2 - THE DARK UNIVERSE AND COSMIC MESSENGERS

The activities of WP2 have covered a wide range of topics aimed at the understanding of the visible and invisible components of the Universe.

Astroparticles

A major line of research has been the statistical study of cosmic radiation fields, mostly gamma rays, to underpin their composition at the unresolved level.

We have performed the deepest investigation of the angular power spectrum of the gamma-ray sky by employing 8 years of Fermi-LAT data with the highest purity, obtaining that its energy dependence is suggestive of the presence of two unresolved populations.

We have then observed the first evidence of the presence of a cross-correlation between the gamma-ray sky and the matter distribution in the Universe traced through weak lensing, for which we employed the Dark Energy Survey Y1 catalog. We found that the signal is mostly localised at small angular scales and high gamma-ray energies, with a hint of correlation at extended separation: blazar emission is likely the origin of the small-scale effect, while at large separation an additional component, compatible with dark matter emission, appears to be present.

We have further studied the impact of cross-correlations by measuring this signal in correlation of Fermi-LAt data with a series of galaxy catalogs and cluster catalogs. The observed signal has then been used to constrain the models of astrophysical gamma-ray sources and of particle dark matter. This has also been complemented by adding the photon one-point statistics to the autocorrelation signal for gamma-rays, which allowed us to derive novel constraints on the unresolved source populations.

We proposed to study dark matter by adopting, as a novel technique, neutral hydrogen (HI) intensity mapping as a tracer of the dark matter distribution and cross correlating HI with gamma ray emission produced by dark matter, deriving the forecasts on the impact of this signal in the investigation of the dark matter parameter space by cross-correlating Fermi-LAT data and MeerKAT and SKA future capabilities.

Finally, we proposed to investigate the cosmological X–ray emission associated to the possible radiative decay of sterile neutrinos by cross correlating the intensity mapping of this line emission with catalogs of galaxies tracing the dark matter distribution at different redshifts.

We also studied the radio signal of axion-like particles in different astrophysical targets, showing that the effect of stimulated emission may amplify the photon flux by several orders of magnitude. For axion-photon couplings allowed by astrophysical and laboratory constraints (and possibly favored by stellar cooling), we find the signal to be within the reach of next-generation radio telescopes such as the Square Kilometer Array.

Cosmic Rays and Gamma Rays

We deeply investigated the physics of leptons around galactic sources and their connected emission in the gamma-ray band. We have discovered a halo of gamma rays in the Fermi-LAT data in the direction fo the Geminga pulsar. Furthermore, we have found a zone of suppressed diffusion around

Geminga, and around several other sources detected emitting gamma rays at energies greater than the TeV. We also studied the prospects to verify a possible hint of a dark matter signal in cosmic antiprotons by forecasting the ensuing signal in the antideuteron and antihelium channels with GAPS and AMS.

Cosmology

We defined a new pipeline to analyse large-scale structure survey data with harmonic-space power spectra, useful for both fundamental cosmology and cross-correlation of cosmological and astrophysical observables. The work has been carried on within the Euclid Consortium and the SKA Cosmology SWG to coordinate shared efforts to the optimization of survey strategies and mock-data analyses.

We have derived methods, based on mock catalogs, to determine the covariance matrix for correlation functions, power spectrum and bispectrum of galaxy catalogs.

Clusters of Galaxies

We set up the tool to measure the mass accretion rate of galaxy clusters and we measured the mass accretion rate of 132 clusters in the redshift range (0.0 – 0.3) and mass range (10^{14} – 10^{15}) Msun/h. We then set up the Blooming Tree Algorithm, a tool to identify the substructures of galaxy clusters in their inner and outer regions, in order to provide a complementary method for the measure of the mass accretion rate of galaxy clusters. Finally, we created the Omnibus catalogue that contains 227 clusters, the largest catalogue of clusters with a dense survey of spectroscopic redshifts of galaxies out to ~3 times the virial radius.

We carried out a deep statistical analysis of the large-scale environment of radio galaxies in the local Universe. This was based on the application of clustering algorithms in comparison with a new method developed to discover new galaxy clusters surrounding radio galaxies. Then, on individual galaxies, we performed the multifrequency analysis of two radio sources belonging to the Third Cambridge catalog (3C), namely 3C17 and 3C196.1. For the former, a nearby quasar, the comparison between radio, X-ray and new optical spectroscopic observations allowed us to discover a rare galaxy cluster surrounding it. On the other hand, for the latter, one of the most peculiar sources observed during our X-ray snapshot survey for which we obtained two Chandra proposals, we discovered the largest known X-ray cavity in the sky filled by radio plumes of this nearby, hybrid, radio galaxy. We also investigated the hot atmosphere and the environments on kpc scale of IC 4296.

Dynamics of Dwarf Galaxies

We set up the algorithms for the Bayesian analysis of the catalogues of radial velocities and proper motions of stars within nearby dwarf galaxies expected to be measured with future astrometric missions, similar to the proposed Theia mission. We also set up the mock catalogues of stars for the validation of the algorithms.

Modified Gravity

We derived the covariant formulation of Refracted Gravity, a phenomenological theory of gravity that mimics the dark matter and the dark energy with a single scalar field. We validated Refracted Gravity on small scales with the kinematics of the disk galaxies from the DiskMass Survey. We revisited the phenomenology of gravitational lensing in Conformal Gravity and its tensions with observations.

Hypervelocity stars

We set up a 3-body and a 4-body numerical simulation to model the ejection of hypervelocity stars (HVS) from a massive black hole (MBH) and from a binary system of massive black holes (BMBH) located at the center of the Milky Way and generate the HVS ejection velocity distribution. We also set up a numerical code to study the HVS trajectories across the Galaxy, for any given HVS ejection velocity distribution. We are now studying the phase space distribution of simulated HVSs to either constrain the shape of the dark matter halo of the Milky Way or quantify the predictions of theories of modified gravity as, e.g., MOND and Refracted Gravity.

Active galaxies*: *Blazars

We completed a long-term project on blazar variability to search for possible periodic signals in the optical light curves that we acquired from 2002 to 2012 for a sample of 31 blazars, either established or potential emitters in the very-high-energy gamma-ray domain. The analysis of the optical light curves by means of a forward-casting approach demonstrated that a significant, periodic signal is present in only one target (Mkn 421), a rate consistent with a false-alarm rate.

We continued our optical spectroscopic campaign of gamma-ray blazar candidates that could be potential counterparts of the unidentified gamma-ray sources and we reported the discovery of about 50 additional blazars, mostly belonging to the BL Lacs class. Additional ~20 observing nights have been also awarded to our group to continue this successful campaign. Then we compiled and published two new catalogs of gamma-ray blazars. For candidates selected on the basis of the infrared colors and for all these sources lying in the footprint of the Sloan Digital Sky Survey we also carried out the optical characterization. Finally, we presented the first systematic, statistical analysis of the X-ray-to-gamma-ray connection for the blazars observed by Fermi.

Active galaxies*: *Compact radio galaxies

In the field of compact radio galaxies, we performed X-ray observations, by means of the Chandra X-ray Observatory, of a sample of ``compact symmetric objects'', i.e. extragalactic radio sources that are entirely contained within the inner ~1 kpc of the host galaxy. Our observations show that the population of compact symmetric objects is bimodal: sources that are heavily absorbed in the X-ray domain (i.e., with $N_H>10^{23}$ cm^{-2}) are characterized by systematically smaller radio sizes than less absorbed ($N_H<10^{23}$ $cm^{-}2$) sources with the same radio luminosity. Our work suggests that part of the compact radio galaxies may indeed be compact because their expansion is suppressed by a dense interstellar medium, whereas the remaining part may be compact because of youth. We also performed the first hard X-ray observations of the extremely compact radio galaxy OQ+208, with the NuStar X-ray telescope: the results of our spectral modeling and broad-line optical classification of the source suggest a porous structure of the obscuring torus for this source. Finally, we studied the jet production efficiency in a sample of compact radio galaxies and found that these sources do not reach the highest possible level of jet production efficiency, as expected in the case of magnetically arrested disks around maximally spinning black holes.

We also built a new catalog of extragalactic, compact radio sources, whose size does not exceed 60 kpc, i.e., the size of their host galaxy (COMP2CAT). This catalog can be used to investigate the evolutionary scheme of radio galaxies.

Active galaxies: ***Extended radio galaxies and LOFAR***

As members of the LOFAR consortium, in the framework of the Nearby AGN Working Group, we carried out a detailed study of a very extended (~450 kpc), nearby, FR-I radio galaxy 3C 449. By combining low-frequency LOFAR data at 150 MHz with archival VLA data at higher frequencies, we derived spectral frequency maps with unprecedently high resolution, that will enable us to constrain the spectral and dynamical age of the source and test particle acceleration models. In this context, we were granted 1,000,000 CPU hours on the Italian HPC Center Cineca, to perform the first 3D magneto-hydrodynamical simulations of the jets of 3C 449 with so tight observational constraints. In this first period, we joined the LOFAR collaboration: Torino University, through the Physics Department, is now part of the Italian LOFAR Consortium together with INAF.

We published the LOFAR observations of 4C+19.44, one of the first observations carried out at low radio frequency by the LOFAR facility using all international stations and we reported, for the first time, the discovery of a low-frequency spectral curvature in the relativistic jet knots of this quasar. Then we created and published the first catalog of Wide Angle Tailed radio galaxies base on radio, infrared and optical observations that will be now investigated at low radio frequencies with the LOFAR telescope. Finally, we published the analysis of the extended X-ray emission in the nearby low radio frequency target: 3C459. This was entirely based on a follow up Chandra observation awarded to our group.

The activities of WP2 have been pursued whithin a large network of international collaborations: Harvard-Smithsonian Center for Astrophysics, USA; Beijing Normal University, China; Netherlands Institute for Radio Astronomy (ASTRON), The Netherlands; Astronomical Observatory of the Jagiellonian University, Poland; University of Turku, Finland; NASA Goddard Flight Space Center; International LOFAR Telescope; Fermi-LAT Collaboration; Dark Energy Survey Collaboration; GRAPPA Amsterdam University, The Netherland; Institute of High Energy Physics, Chinese Academy of Sciences, China; University of the Western Cape, South Africa; Queen Mary University of London, UK; The University of Manchester, UK; University of Geneva, Switzerland.

Members of the WP2 have responsibility roles in international Collaborations: M. Regis is a team member of the “Evolutionary Map of the Universe” (EMU) project and PI of the cross team-science project “Particle DM searches” (EMU will use ASKAP to map the entire Southern Sky in the radio continuum and detect about 70 million radio sources); S. Camera coordinates for the Euclid Consortium the Work Package "Dark Matter and Particle Cosmology" inside the Theory Science Working Group (SWG) and co-coordinates the Work Package "Photo-z Clustering" inside the Galaxy Clustering SWG, while for SKA co-coordinates the Focus Group "Synergies" inside the Cosmology Science Working Group and is co-chair of the Science Working Group "Cosmology".

Members of the WP2 coordinate additional national and international grants, whose funding and activities contribute to the activities of this project: N. Fornengo is PI of the project "The Dark Universe: A Synergic Multimessenger Approach" funded by MIUR and of the project "The Anisotropic Dark Universe" funded by Compagnia di San Paolo and University of Torino; F. Massaro is PI of the Fermi proposal The optical spectroscopic campaign of gamma-ray blazar candidates: 10 yrs after the fermi launch" in Cycle 11 (2018), of the Chandra proposal "Completing the Chandra extragalactic 3CR survey" in Cycle 20 (2018), of the Fermi proposal "Hunting gamma-ray blazars with optical spectroscopic observations" in Cycle 12 (2019), of the Chandra proposal: "X–raying the unknown 3CR extragalactic sky" in Cycle 21 (2019), of the Chandra white paper/proposal for CCT projects "X-ray surveying radio-loud active galaxies and their large-scale environments", of the ASI-

AAE 2018 project "Radio-loud active galaxies in the Chandra era: from the 3CR towards the B2 catalog"; M. Regis is PI of the research grant “From Darklight to Dark Matter: understanding the galaxy/matter connection to measure the Universe” by MIUR and of the research grant “Deciphering the high-energy sky via cross correlation” funded by the agreement ASI-INAF n. 2017-14-H.0; F. Donato is PI of the research grant "Inverse Compton Haloes around Pulsar Wind Nebulae" funded by the agreement ASI-INAF n. 2017-14-H.0. S. Camera is grantholder of the "Rita Levi Montalcini" Program for Young Talented Researchers "PROMETHEUS – Probing and Relating Observables with Multi-wavelength Experiments to Help Enlightening the Universe’s Structure".

WP3 - PHYSICS OF COMPLEX SYSTEMS

WP3 is divided into two research branches themes: a) biophysics and b) waves and turbulence.

a) Biophysics

The common ground of the research activity is the applications of statistical physics techniques to different biological problems, often in close contact with experimentalists. We applied this methodology in three main directions:

1) One of our main goals was to develop tools for the identification of the so called “driver genes” of various pathologies and in particular of cancer, and at the same time to model the occurrence and development of these pathologies. We pursued our analyses in the framework of the so called “Personalized Medicine”, i.e. following the idea that each patient is different from any other patient and that the impressive progress in Molecular Biology techniques and the large amount of new high-throughput data may allow to disentangle the peculiar “personal” features of the pathology in each single patient. Along this line we studied in particular a class of genes known as “MicroRNAs” and discussed their interplay with the epigenetic layer of regulation and their role in breast cancer development. We also studied how to extract information from gene expression data using Matrix Factorization, Hopfield like methods, sophisticated discretization profiles or keeping into account the methylation profiles of mRNAs.

2) In parallel, we developed a more theoretically driven approach to study the large-scale datasets often found in biology, starting from the observation that many of the systems they describe have an inherent modular structure and share common statistical laws. The goal is to build a mathematical framework and a set of testable models to describe the properties of these systems in the spirit of statistical mechanics. Examples of interest are genomes of different species in terms of their gene composition, cells of different types in terms of the genes they transcribe. But the examples are not limited to biology and include texts of natural language in terms of word composition or technological systems, such as computers in terms of installed software packages. In this “Big Data” era, the amount of available large-scale data sets that can be described as component or modular systems will definitely grow very fast. It is the right time to develop mathematical tools to address this large class of systems.

A general goal is to discern properties that are related to function from “null” statistical effects. In natural language, this can be key for instance to develop search engines based on semantics or for topic modeling. In genomics, the identification of methods to define what can be explained as the result of neutral evolution from what is functional and under selection is still a general open problem.

3) A different basic biological question we have worked on is the control of cell cycle and cell size. In particular, we developed data-driven quantitative models of cell-cycle control based on experimental data in bacteria that challenged classic theories in microbiology, and that can be in the next future extended to other cell types and, more importantly, to cells with disregulated cell-cycle control such as cancer cells.

b) 1) Waves and 2) Turbulence

1) One of the milestones of WP3 packages is the realization of a new experimental device for the attenuation of surface gravity waves based on the concept of metamaterial. Coastal systems are among the most vulnerable areas in our planet and, due to climate change processes such as sea level rise or an increasing occurrence of extreme events, the beaches will increasingly face the phenomenon of erosion. Within this aim, a new device based on the concept of metamaterial has indeed been developed; an Italian and European patent has been submitted with first-round positive referee reports. A proof of concept experiment has been performed in a wave tank of 2 m x 0.5 m x 0.25 m equipped with a mechanical wave maker. The physics behind the device is based on the classical concept of resonance: a number of inverted pendula, anchored at the bottom of the sea through a rope, are distributed in a lattice, under the surface level. The pendula have a proper frequency of oscillation that is a function of the length of the rope and of their mass. If the frequency of the propagating surface gravity waves is close to the frequency of the pendula, experimental results show clearly the attenuation of the wave energy through the tank. Also, in view of this experiment we developed a novel optical technique for the measurement of the surface waves.

With the intent of having a full comprehension of the mechanism of wave damping, a numerical method for solving the full Navier-Stokes equations has been developed from scratch. The governing equations coupled with the volume of fluid interface tracking technique for the modelling of the liquid phases are solved; a direct-forcing immersed-boundary method is adopted for the fluid-structure interaction. A manuscript to be submitted to the Journal of Computational Physics containing the description of the numerical method and the first test cases is under preparation. Besides the DE funding, the present research project is funded by the FET project (Bio-Inspired Hierarchical MetaMaterials) recently approved by the EU.

2) Another milestone of the WP3 is the development of numerical tools for the study of turbulent convection and extreme events in turbulent flows. The first part of the project has been focused on numerical studies of the Rayleigh-Taylor (RT) turbulent convection, which occurs when a cold layer of fluid is placed on top of a hot one. The gravitational instability at the interface between the fluids causes the development of a turbulent mixing layer with a quadratic growth in time. By means of high-resolution numerical simulations, we have analysed several factors which influence the convective process. First, we have shown that an initial nonuniform temperature background changes the temporal scaling of the mixing layer growth, and we have proposed a closure model which reproduces analytically the mean temperature profile observed in the simulations. As a second case, we have considered a RT flow which evolves in a porous medium, which has been modeled by a bed of rigid spheres. We have shown that reducing the porosity of the medium causes an increase of the friction experienced by the flow and a linear growth of the mixing layer. In the third study we have investigated the effects of a periodic modulation of the gravity, discovering a novel mechanism of relaminarization of turbulence: the alternating acceleration, which initially produces a turbulent mixing layer, at longer times suppresses the turbulent fluctuations and stops the growth of the mixing layer. In the last case we have studied the effects of rotation on the bulk turbulent convection forced by an imposed linear temperature gradient. Our results show that the Coriolis force induces a bidimensionalization of the flow and causes an increase of the heat flux with a maximum at intermediate Rossby numbers.

In the second part of the project we have investigated the extreme events which occur within a turbulent flow. The dynamics of the large-scale structures of a turbulent flow is characterized by phases of slow accumulation of kinetic energy interrupted by intermittent events of rapid energy discharge, during which the kinetic energy is transferred toward the small dissipative scales. These events are responsible for the breaking of the time reversal symmetry in turbulence, which can be observed in the dynamics of Lagrangian tracers. We have shown that the symmetry breaking persists also in a reversible shell model of turbulence, in which the viscous term is modified in such a way to guarantee formally the time-reversibility. Moreover, we have discovered that intermittent extreme events of energy exchange occur also in the interactions between small-scale turbulent flow and large-scale coherent vortices (the so-called "turbulent condensate”) which spontaneously develop in turbulent thin layers. These events result in bursts of energy dissipation which reduce the energy of the condensate.

5. Strategy and Perspectives for the next term (2020-2022)

WP1 - SENSORS AND INNOVATIVE DETECTORS

a) Development and application of silicon-based particle detectors

a-1) Detectors for the LHC High-Lumi phase.

Concerning the design and testing of the Inner Tracker readout chip, we will proceed toward the submission of the prototype of the CMS readout chip (engineering run), the calibration of the automated wafer testing procedure with the CM300 probe station on 50 wafers from the engineering run and the submission of the final CMS readout chip (production run). The construction of the Inner Tracker requires about 14k readout chips which have to be tested before the assembly with the Si-sensor. Torino is responsible of testing 50% of the readout chips (roughly 100 chip/wafer with an expected yield of 70% and a testing operation of about 1 day/wafer).

Activities in Torino beyond the design & test of the readout chip are foreseen, specifically the characterization of roughly 1k Inner Tracker modules (high rate test under X-ray machine + stress test during thermal cycles) prior to installation on the mechanical structures and the integration (assembly + system test) of the TBPX.

As for the design and testing of the Ultra Fast Silicon Detector of the Mip Timing Detector, the activities will concern the assembly and test of the first UFSD proto-modules on a 5 x 5 pads geometry, the submissions of a large prototype (16 x 16 pads) (engineering runs using different vendors) and finally the setting up of the module test facility in Torino. These activities will be followed by a phase of measurements and comparison of the different vendors' performances after the engineering runs, followed by the selection of the vendors, the set up of the procedure for a full size production and finally the set up of the CM300 semiautomatic probe station for UFSD sensor qualification. The construction of the CMS MTD Endcap will require to assembly and test 9000 modules obtained by coupling the UFSD sensors with the front-end chip: Torino is responsible of the assembly and test of about 2250 modules (25% of the full production). The ETL module assembly schedule will take place in 2022-2024/ ETL installation in 2025 at CERN.

a-2) Development of monolithic active pixel sensors

The activities related to ALICE will embrace the ITS2 phase with commissioning of the tracker in the laboratory, the installation in the ALICE experiment and the commissioning of the tracker in the experiment, followed by the start of data taking with proton and Lead beam at the LHC expected in 2020. Phase ITS3 will then start with the design of a new chip, which will be a thin (~30um) sensor of wide area, used for building the 3 layers of the Inner Barrel. It will be curved around the beam pipe and directly connected with the services outside the acceptance region. Torino will focus on the studies of the collection electrode and of the front-end electronics and pursue the study of the interconnection of curved silicon detectors, for which we will consider both Tab Bonding and Laser Soldering techniques.

Concerning the LIMADOU Tracker, the activities will move to the production of the prototypes and the evaluation of the production process, the validation of the prototypes for space application, the production of the constituent elements (staves) and the assembly and validation of the Qualification

Model of the tracker. These activities will be followed by the assembly and validation of the Flight Model and by the space qualification and launch of the satellite.

The activities related to ARCADIA will be focussed on the design of new prototype sensors, the submission of a new chip and test structures and the start of tests on prototypes, followed by a new submission of the large area sensor and a beam test of the produced prototypes.

We are also exploring interconnection techniques alternative to wire wedge bonding, in particular, TAB (Tape Automated Bonding) and Laser Soldering. TAB was already used for ITS1 in the ALICE experiment. It has many advantages, the first being the mechanical robustness of the connection and the low material budget of the circuit. Since it is based on circuits with Al lines on polyamide, the procurement of adhesiveless aluminum-polyamide foils is required. Moreover, the company producing the FPC has to provide very precise and stable etching processes, both of the Al and of the plastic substrate. A collaboration with colleagues already active in the field has started, and contacts with companies (FBK Trento) interested in joining the effort were recently established. The new wire bonding machine purchased in the framework of WP1 activities can be used also for TAB bonding. To this aim, we will design and produce FPC for TAB bonding and test the interconnection on different sensors, specifically with ITS2 ALPIDE. Furthermore, we will develop the laser soldering technique with a machine purchased in 2019 and that will be delivered soon. The laser soldering technique could be useful both in the interconnection of chips to FPCs but also for any precision welding of micrometric dimensions: we will therefore proceed with the installation of the machine and start of the training phase, design and production of FPC to test laser soldering on different devices, feasibility studies of laser soldering for different applications: flex printed circuits to silicon devices; SMD components on micro boards; micro pads through diamond structures.

a-3) Medical applications

In 2020-2021 the two prototype systems for counting the number of delivered beam particles and for measuring the beam energy will be fully equipped and tested at the three Italian clinical facilities as well as clinical centers abroad. This requires submitting a second version of the ABACUS ASIC, producing larger size sensors for the counter, finalizing the front-end board the FPGA firmware and designing the motorized mechanical system for the time-of-flight device. Apart from providing the proof of principle (applications during patient treatments would require increasing the sensitive area to 20x20 cm^2 which is out of the scope of this project), the two devices will be used for beam monitoring in radiobiological experiments and their use quality assurance procedures will also be tested.

a-4) Application of Silicon Photomultipliers in Astroparticle experiments

In the next term of the project, different prototypes will be built with SiPMs of different vendors and will be compared. The best performing ones will be integrated in a SiPM-based camera module of the Large Size Telescope of CTA, for a direct comparison in the field with the current PMT modules. The development of the individual pixels (the equivalent of the 2.5'' PMTs) will require the design of a PCB hosting the DC-DC converter to provide the bias voltage to the SiPMs and the ASIC performing the summation of the signals of the different SiPMs into a single output and its shaping. The SiPM-based modules will use the same readout electronics currently in use for the PMTs. As a second stage, the possibility of a completely new, fully digital, camera will be also explored.

All tests involving artificial light sources and controlled environment will be held in the Torino Laboratories.

b) Advanced materials and new devices

The X-ray nanopatterning technique will be applied for the functionalization of semiconducting and superconducting oxides both at Synchrotron Radiation facilities (e.g. ESRF) and within the new "SAX" laboratory, equipped with a novel high-brilliance X-ray source, which makes X-ray nanopatterning possible on a University laboratory scale.

In the field of bio-sensing, different classes of devices will be fabricated, allowing the investigation of a wide range of topics: from the study of the cell-to-cell communication in order to identify the causes of neurodegenerative diseases (Parkinson disease, Alzheimer disease), to the radiobiology experiments in which the irradiation dose and the cellular activity are monitored simultaneously and in real-time.

Regarding Quantum Technologies, all of the present activities are based on the functionalization of diamond induced by ion irradiation of the samples.

In consideration of this strong strategic relevance, as planned in the project proposal, the Solid State Physics group employed the allocated resources within the project for the installation of a multi-elemental 100 kV ion implanter at the departmental class-10'000 cleanroom. The implanter design (commissioned to Prof. J. Meijer's group - University of Leipzig) was completed in December 2019 and the installation/commissioning is expected for the end of 2020.

The new facility will allow the implantation of all the chemical species that form stable negative ions, with energies up to 100 keV for the creation and engineering of new quantum-optically-active defects in solid state. The location of the irradiation facility at the presently available cleanroom will allow both pre-irradiation (e.g. cleaning, masking) and post-irradiation (e.g. annealing) processes under highly controlled conditions. Besides well-established structural, optical and electronic characterization techniques, performed in collaboration with the National Metrological Institute (INRiM), the recent acquisition of a state-of-the-art optical cryostat is expected to provide a deeper insight into the performances of quantum emitters at low temperatures.

Although the ion implanter setup was primarily motivated by Quantum Technology purposes, it will be installed in an "Open Access" laboratory of the University of Torino, and hence will be made accessible to external institutions and companies for different purposes. In this regard, the proximity, in the same cleanroom, of the ion implanter and of a high-power focused and pulsed laser, has already triggered the interest of a local semiconductor industry to perform systematic investigations of the laser induced thermal annealing technique for the activation of dopants in Silicon. This applied research will be carried out within a three-year collaboration agreement.

WP2 - THE DARK UNIVERSE AND COSMIC MESSENGERS

Astroparticles

We will perfect our measurement and interpretation of the cross-correlation between Fermi-LAT gamma rays and the DES weak lensing catalog, by extending the analysis to the now-available 11 years of gamma-ray data and Y3 DES catalog. This should allow us to understand the origin of the large-separation signal observed with the current analysis. We also plan to perform a global analysis of all cross-correlation observables currently available.

We plan to extend to investigation of the cross-correlation signals to other frequencies, notably to the radio emission, in order to leverage on spectral differences between dark matter and astrophysical sources production of the electromagnetic signal.

We started to investigate how machine learning methods could help in searching for a dark matter signal in the multiwavelength spectrum produced by dark matter annihilation or decay.

We aim at performing the cross-correlation of DES maps (both galaxies and cosmic weak-lensing shear) with the EMU data. First EMU observations of DES fields are ongoing. We will also measure the two-point correlation between EMU and Fermi-LAT data and the three-point correlation among these and DES. EMU observations will also look at diffuse emissions induced by particle DM in the halo of single nearby objects, such as local group dwarf galaxies, clusters of galaxies and massive nearby galaxies.

We will explore alternative strategies to detecting individual missing baryon emission and sterile neutrino lines in X-ray spectra. The problem can be tackled by cross correlating of the emission line signal collected by Athena XIFU with the spatial position of galaxies in redshift surveys. Emission lines will not be detected individually. Instead, we aim at indirect detection of characteristic features in the 2-point cross-correlation function through which it will be possible to constrain the spatial distribution of the warm-hot gas or particle dark matter.

Cosmic Rays and Gamma Rays

We plan to apply the results achieved so far to predict the flux of position from pulsar wind nebulae reaching the Earth, and demonstrate which room is eventually left to a possible contribution from galactic dark matter annihilation into positrons. We also aim at looking for the presence of other gamma-ray haloes in the Fermi-LAT data for other pulsar wind nebulae. In parallel, we will work on the gamma-ray statistics in order to establish the emission of extragalactic sources in the non resolved Fermi-LAT flux region, and to test the nature of the so-called galactic center excess in the Fermi-LAT data. Finally, we will study the cross sections relevant for the production for secondary antiparticles in the Galaxy, in particular antiprotons and positrons.

Cosmology

Completion of the work in progress on the definition of methods and processes to analyse large-scale structure survey data, in preparation of the Euclid and SKA data releases.

Clusters of galaxies

We will apply the Blooming Tree Algorithm to the Omnibus catalogue to measure the accretion rate of clusters as function of mass and redshift. We will explore the dependence of the mass accretion rate on the theory of gravity.

Dynamics of Dwarf Galaxies
We will quantify the accuracy of the proper motion measures required to constrain the distribution of the dark matter in the dwarves and to distinguish between Newtonian and modified gravity theories.

Modified Gravity
We will validate the covariant formulation of Refracted Gravity with the Hubble diagram of SNIa. We will also validate Refracted Gravity on small scales with the kinematics of elliptical galaxies and dwarf galaxies.

Hypervelocity stars
We plan to explore the accuracy of the proper motion measures that future astrometric missions must have to significantly constrain the shape of the Milky Way dark matter halo and to distinguish between Newtonian and modified gravity theories.

Active galaxies - Compact and extended radio galaxies, LOFAR
We plan to continue our X-ray observational project to investigate the absorption properties of compact radio galaxies by means of Chandra and NuStar data. We also plan to investigate the correlation between the X-ray emission and the mid-infrared properties of compact radio galaxies by means of IRAS and WISE archival data. We plan to study radio galaxies of sample 3C seen by LOFAR and study 3C sources not identified with Chandra, LOFAR, WISE and optical observations. We plan to perform a spectroscopic follow up of blazars candidates with flat radio spectrum at frequencies below GHz and study the extended emission in BL Lac type objects. Large scale environmental analysis of radio galaxy samples selected between GHz and MHz are programmed.

WP3 - Physics of Complex Systems

a) Biophysics

We plan to strengthen our current research lines along the following directions. First, we wish to continue the development of methods to integrate large biological datasets of different molecular nature and to extract synthetic relevant information, in particular in the perspective of personalized precision medicine. In this context, we will move on two parallel directions: (i) we plan to enlarge our network of collaborations with biologists and medical researchers in the area to widen the relevant applications of our consolidated computational techniques; (ii) we will continue our theoretical work on the statistical physics of "component systems" to build new tools and null models for the data analysis.

We are also increasing our research efforts in the growing field of Machine Learning. Machine Learning (and specifically Deep Learning) techniques are becoming essential tools both in industry and in academic research, and this is especially true in computational biology. However, the widespread use of these tools is not always matched with a theoretical understanding of their properties and limitations. Large neural networks are indeed a complex system and as such can be studied with statistical physics methods. We therefore plan to expand our research in the field of machine learning along two main directions, again trying to strike a balance between basic theory and applied research.

The main theoretical research direction we are pursuing aims to address properties of deep neural networks that still lack a clear theoretical explanation, such as their extremely good generalization performances, using methods of complex systems theory.

The second more applied line of research leverages on the common data structure of several available large-scale datasets to import and modify machine learning techniques developed in different fields to biological problems. For example, we are currently adapting topic modelling techniques developed in natural language processing to analyse and classify gene expression patterns of cancer cells.

We believe that enhancing and extending our research efforts in this field will have an important impact on the quality of our teaching and on the attractiveness of our master program in Physics of Complex Systems. In fact, there is an increasing demand for scientists that are well versed in machine learning techniques. A lively research activity is the ideal way to train such scientists while increasing the visibility of our department, boost internal collaborations as well as liaisons with local industries.

b) Waves and Turbulence

For what concerns the problem of attenuation of waves, the Department has started a process of acquiring a new large wave flume. In December 2019 a public tender for inviting companies to provide their offer for building the new experimental facility has been opened. The required dimensions for the flume are 0.6 m x 0.6 m x 20 m length. The new programmable wave maker will allow to generate waves with many different frequencies and sea states that reproduce the statistical properties of real ocean waves. An important task will be to understand which is the optimal spacing and geometry (with respect to the wavelength to be attenuated) of the pendula required to maximize the attenuation. We will be able to test different configurations with the aim of damping the largest frequency range. The numerical simulations of the Navier-Stokes equation will provide also new insights on the mechanism of attenuation and complement the experimental results. A request of external financial support for increasing the Technology Readiness Levels of the device is under way.

We also plan to push forward our research line concerning the numerical study of the turbulent convection and extreme events, following two main directions. The first objective is to pursue the investigation of the physical properties of convection in different physical setups. In particular we will continue the study of convection in porous media by means of numerical simulations of the Darcy model. The second objective is to develop new numerical and theoretical tools to study the statistics of extreme events in turbulence. Within this part of the project we will explore the possibility to use machine learning techniques for the purpose of identifying the physical mechanisms which cause the extreme events.