UNIVERSITÀ DI PARMA

Dottorato di Ricerca in Fisica - XXXVIII ciclo – PhD in Physics

In the application for the competitive examination, the candidate must elaborate a short project on one of the research topics listed below (only the topic indicated as first choice in the application).

1. Spectroscopic characterization of minerals interesting for the environmental sciences

The research concerns the identification and characterization of mineral phases interesting for environmental sciences. In particular the research will be focused on asbestos[1] (serpentines, amphiboles and other fibrous minerals), minerals present in the residues of the incinerators (bottom and fly ashes), mineral phases that are formed in the geo-polymers[2], heavy minerals useful as tracers in sediments[3]. The study will involve the development of techniques, mostly based on vibrational spectroscopies, for the unambiguous identification of these mineral phases in heterogeneous systems, also *in situ*, and their transformation and degradation products.

References

1. Petriglieri, J. R., Salvioli-Mariani, E., Mantovani, L., Tribaudino, M., Lottici, P. P., Laporte-Magoni, C., and Bersani, D. (2015) Micro-Raman mapping of the polymorphs of serpentine. J. Raman Spectrosc., 46: 953– 958. doi: 10.1002/jrs.4695.
2. Caggiani, M. C., Coccato, A., Barone, G., Finocchiaro, C., Fugazzotto, M., Lanzafame, G., Occhipinti, R., Stroscio, A., Mazzoleni, P., *J Raman Spectrosc* 2022, 53(3), 617. https://doi.org/10.1002/jrs.6167
3. Laura Borromeo, Sergio Andò, Danilo Bersani, Eduardo Garzanti, Paolo Gentile, Luciana Mantovani, Mario Tribaudino, Detrital orthopyroxene as a tracer of geodynamic setting:: A Raman and SEM-EDS provenance study, Chemical Geology, Volume 596, 2022, 120809

Contact: Prof. Danilo Bersani, Email: danilo.bersani@unipr.it

2. Computational and theoretical models of single neuron dynamics and collective dynamical regimes of neuronal activity in non-human primates

The project is being carried out in collaboration with the ERC project EMACTIVE of the Neuroscience Department and aims to build computational models and analyze experimental time series of single neuron activity and collective activity signals of amygdala-related areas from freely moving interacting primate brains using hyperscanning techniques. The goal is to obtain a neural network model that can reproduce the different dynamic regimes measured during specific inputs. The project involves the use of statistical inference and machine learning techniques to reconstruct the physical parameters of the neural network and functional connectivity, and theoretical analysis of the dynamic phases supported by the network as parameters change during specific tasks of interacting brains under different conditions.

References

1. Chaos and correlated avalanches in excitatory neural networks with synaptic plasticity
   F Pittorino, M Ibáñez-Berganza, M di Volo, A Vezzani, R Burioni
   Physical review letters 118 (9), 098102
2. Transition from asynchronous to oscillatory dynamics in balanced spiking networks with instantaneous synapses
   M Di Volo, A Torcini
   Physical review letters 121 (12), 128301
3. Largely shared neural codes for biological and nonbiological observed movements but not for executed actions in monkey premotor areas
   D Albertini, M Lanzilotto, M Maranesi, L Bonini
   Journal of Neurophysiology 126 (3), 906-912

Contact: Prof. Raffaella Burioni, Email: raffaella.burioni@unipr.it

3. Molecular spins for Quantum Technologies beyond the qubit encoding

The second quantum revolution is unfolding right now and quantum technologies promise to radically change many aspects of our life. Indeed, currently intractable problems could be solved by quantum computers [1], quantum communication and quantum internet could revolutionize the exchange of information, quantum sensing could reach unprecedented sensitivities and new quantum materials will be designed thanks to quantum simulators. Molecular spins constitute one of the most promising platforms to implement these quantum technologies [2]. In particular, each molecule can display many accessible low-energy levels and therefore can be exploited to define qudits (and not only two-level qubits), thus providing additional degrees of freedom that can be exploited in the quantum logic [3]. This PhD thesis will focus on the design and numerical simulation of new schemes and protocols for using molecular qudits for quantum computing, quantum error correction [4], quantum simulation of fermionic and bosonic systems [2] and quantum sensing. The work will also involve the modelling of the main sources of decoherence.

These studies will be undertaken in the framework of research projects, including the European FET-OPEN project FATMOLS, and will be performed in strong collaboration with IBM Quantum (Zurich).

References

3. A. Chiesa, F. Tacchino, M. Grossi, P. Santini, I. Tavernelli, D. Gerace and S. Carretta, *Quantum hardware simulating four-dimensional inelastic neutron scattering*, Nature Phys. **15**, 455 (2019).
4. S. Carretta, D. Zueco, A. Chiesa, A. Gomez-Leon, F. Luis, *A perspective on scaling up quantum computation with molecular spins*, Appl. Phys. Lett. **118**, 240501 (2021).
5. Y. Wang, Z. Hu, B. C. Sanders and S. Kais, *Qudits and High-Dimensional Quantum Computing*, Front. Phys. 8:589504 (2020).
6. A. Chiesa, E. Macaluso, F. Petiziol, S. Wimberger, P. Santini, S. Carretta, *Molecular Nanomagnets as Qubits with Embedded Quantum-Error Correction*, J. Phys. Chem. Lett. **11**, 8610 (2020).

Contact: Prof. Stefano Carretta, Email: stefano.carretta@unipr.it

4. Methods to find the super-spreaders in complex networks

The 'super-spreaders' are network nodes capable of disseminating information significantly faster than the average. Identifying super-spreaders nodes is a very important issue in complex network science, as it allows us to identify which nodes may be the major spreaders of epidemic events, or which nodes act as influential diffusers of 'fake news' in the social network [Pei S. and Makse 2013]. In recent years, network science has investigated the structural characteristics of the nodes capable of greater spreading. To do this, a spreading event is simulated by using the epidemic compartmental models (CM), for example the SI, SIR, SIS models, starting in different nodes of the network.

Then the spreading pace from different network nodes is measured with specific spreading indicators, such as the time to reach 15% of infected nodes. It has been discovered that the nodes of greatest 'coreness centrality', that is, the nodes placed at the core of the network structure, are super-spreader nodes [Kitsak et al 2010]. In this research, the Ph.D. student will implement CM models on real networks of different nature, analyzing what are the structural characteristics of super-spreader nodes. The Ph.D. student will use network science and graph theory to refine new and effective methods for identifying super-spreader nodes in the network.

The Ph.D. student will use the high-performance computational resources (High Performance Computing) made available by the HPC facility of the University of Parma to implement the epidemic spreading simulations.

References

1. Kitsak, M., Gallos, L., Havlin, S. et al. Identification of influential spreaders in complex networks. Nature Phys 6, 888–893 (2010). https://doi.org/10.1038/nphys1746
2. Pei S. and Makse H.A., Spreading dynamics in complex networks. Journal of Statistical Mechanics: Theory and Experiment (2013) P12002.

Contact: Prof. Davide Cassi, Email: davide.cassi @unipr.it

5. Emulsion Dynamics on Earth and in Microgravity

This thesis focuses on an experriment on the International Space Station, using the ESA facility Soft Matter Dynamics (SMD) [1] to investigate drop dynamics and emulsion ageing in microgravity by Diffusing Wave Spectroscopy (DWS) [2,3]. To the best of our knowledge, this is the first time that such an investigation is undertaken: weight-less condition allows to investigate the intrinsic drop dynamics, and the processes influencing emulsions stability (e.g., drop aggregation, drop coalescence, Ostwald ripening) which are normally convoluted with the predominant gravity-induced dynamics of drop creaming/sedimentation and affected by the resulting drop-crowding effects and the enhanced coalescence rate.

Initially the focus will be on marginally stable oil-in-water emulsions stabilized by minimal amounts of non-ionic surfactant (e.g. C12Eo21 and similar well characterized surfactants). After a careful preparatory calibration campaign [4] DWS will be employed to investigate dynamics in dense emulsions.

References

1. P. Born et al., Review of Scientific Instruments, 2021, 92, 124503.
2. D.A. Weitz et al., Dynamic Light Scattering: Method Some Appl., Clarendon Press, 1993.
3. R. Hohler et al., Current Opinion in Colloid & Interface Science, 2014, 19, 242.
4. V. Lorusso et al., Advances in Colloid and Interface Science, 2021, 288, 102341.

Contact: Prof. Luigi Cristofolini, Email: luigi.cristofolini@unipr.it

6. Gauge Theories and Holography at the Crossroads

The project will be concerned with the interplay between strongly coupled gauge theories and their dual holographic description within the AdS/CFT correspondence. In supersymmetric theories, one can construct observables that preserve a fraction of the supersymmetries and admit non-perturbative representations via supersymmetric localization. The conformal bootstrap exploits conformal symmetry and provides rigorous bounds on physical observables. Integrability leads to predictions valid for all couplings, from weak to strong. These methods are complementary and their interplay is extremely important to better understand holography.The reverse direction, from gravity to gauge theories, is also a main focus of the project.

References

1. L. Griguolo, R. Panerai, J. Papalini and D. Seminara,
   "Exact TTbar Deformation of Two-Dimensional Maxwell Theory"
2. F. Bonetti, C. Meneghelli and L. Rastelli,
   "VOAs labelled by complex reflection groups and 4d SCFTs''
3. N. Gorini, L. Griguolo, L. Guerrini, S. Penati, D. Seminara and P. Soresina,
   "The topological line of ABJ(M) theory"
4. P. Ferrero and C. Meneghelli
   "Bootstrapping the half-BPS line defect CFT in N=4 supersymmetric Yang-Mills theory at strong coupling''

Contact: Prof. Luca Griguolo, Email: luca.griguolo@unipr.it

7. Precision tests of fundamental physics from the Large Scale Structure of the Universe

The aim of this project is to exploit cosmological data to test the standard model of cosmology, the ΛCDM model, and constrain its possible extensions.

In order to optimize the extraction of cosmological information from data various theoretical issues must be addressed, which will be the subject of this project. The extension of semi analytical models to the relevant observables must be formulated in the most model independent way, not to preclude the possibility of unexpected discoveries. Moreover, new statistical observables beyond the usual correlators will be investigated, also in connection with machine-learning based analyses.

The expected outcome of this project is a new, model independent approach to cosmological analyses to be applied to future data.

References

1. Guido D'Amico (Parma U.), Marco Marinucci (Parma U.), Massimo Pietroni (Parma U.), Filippo Vernizzi (IPhT, Saclay): The large scale structure bootstrap: perturbation theory and bias expansion from symmetries
2. Marco Marinucci, Takahiro Nishimichi, Massimo Pietroni: Model independent measurement of the growth rate from the consistency relations of the LSS

Contact: Prof. Massimo Pietroni, Email: massimo.pietroni@unipr.it

8. Artificial intelligence models: development and application on in vivo X-ray imaging in drug discovery

Computed tomography (CT) represents one of the most relevant imaging technologies for the diagnosis of lung fibrosis in clinical practice. Since lung densitometry depends on X-ray (XR) attenuation of pulmonary tissue, changes in tissue density can reflect parenchymal abnormalities providing a reproducible quantitative evaluation of the extent and severity of pulmonary fibrosis [1]. The miniaturized version of CT (i.e. micro-CT) represents a powerful non-invasive tool in preclinical drug discovery for understanding the pathogenesis and dynamics of lung fibrosis in several animal models. Histogram-based analyses of micro-CT images are used to quantify different aeration degrees reflecting fibrosis progression [2].

Recently, the field of Artificial intelligence (AI) has achieved impressive results in image-recognition tasks [3], starting to become essential tool in automatization imaging post processing [4]. Moreover, AI algorithms are largely used also to create diagnostic or prognostic models, predicting a specific outcome by using CT as a quantitative tool.

This study will focus on the application and the development of new AI methods for micro-CT lung imaging analysis. The goal is to generate an automatic tool enable to extrapolate quantitative parameters describing lung fibrosis progression for drug discovery application. Different computational methods will be validated and integrated with ex vivo measurements (i.e. histology). The quantitative Micro-CT parameters will be used to development predictive AI models to highlight some biomarkers to foresee the progression of lung fibrosis with possible clinical translational application.

References

1. X. Wu *et al.*, “Computed tomographic biomarkers in idiopathic pulmonary fibrosis: The future of quantitative analysis,” *American Journal of Respiratory and Critical Care Medicine*. 2019, doi: 10.1164/rccm.201803-0444PP.
2. L. Mecozzi *et al.*, “In-vivo lung fibrosis staging in a bleomycin-mouse model: a new micro-CT guided densitometric approach,” *Sci. Rep.*, 2020, doi: 10.1038/s41598-020-71293-3.
3. A. Hosny, C. Parmar, J. Quackenbush, L. H. Schwartz, and H. J. W. L. Aerts, “Artificial intelligence in radiology,” *Nature Reviews Cancer*. 2018, doi: 10.1038/s41568-018-0016-5\
4. J. Malimban *et al.*, “Deep learning-based segmentation of the thorax in mouse micro-CT scans,” *Sci. Rep.*, vol. 12, no. 1, pp. 1–12, 2022, doi: 10.1038/s41598-022-05868-7.

Contact: Prof. Eugenia Polverini, Email: eugenia.polverini@unipr.it

9. Nonlinear evolution in open many-body quantum systems

Nonlinear dynamics provides rich behavior, from well-behaved integrable motion to systems with extremely long thermalization time (close to chaotic systems). We want to put onto a similar foundation seemingly diverse systems such as self-gravitating cold dark matter, ultracold many-body quantum gases, and hydrodynamic problems. All these systems are described by a nonlinear Schrödinger equation in some appropriate limit. We know to evolve nonlinear Schrödinger equations in time in the form of the Gross-Pitaevskii equation [1] or coupled to a Poisson equation (for cold dark matter) [2]. Our continuum mean-field approach must be extended to include beyond mean-field terms in the evolution. A method, which allows this and also the inclusion of decoherence channels, is the truncated Wigner method [1]. Two direct applications are the description of two interacting species (field modes) and the engineering of interactions based on our recent quantum-control methods [3]. This PhD thesis aims at implementing this program.

References

1. G. Kordas, S. Wimberger, and D. Witthaut, Decay and fragmentation in an open Bose-Hubbard chain, Phys. Rev. A 87, 043618 (2013)
2. T. Zimmermann, N. Schwersenz, M. Pietroni, and S. Wimberger, One-Dimensional Fuzzy Dark Matter Models: Structure Growth and Asymptotic Dynamics, Phys. Rev. D 103, 083018 (2021)
3. F. Petiziol, M. Sameti, S. Carretta, S. Wimberger, and F. Mintert, Quantum simulation of three-body interactions in weakly driven quantum systems, Phys. Rev. Lett. 126, 250504 (2021)

Contact: Prof. Sandro Marcel Wimberger, Email: sandromarcel.wimberger@unipr.it

10. Inference and reconstruction of mobility temporal networks and mobility flows in urban areas

Temporal complex networks represent an ideal field of research for the study of interacting social systems within cities and collaborative environments and are used to effectively monitor the evolution of communities, movement and interaction with the environment and services. The proposed research project is embedded in this research area and is developed within the National Center for Sustainable Mobility activities funded by PNRR projects. In this project, theoretical and numerical models will be developed for mobility flows and patterns of aggregation and higher order interaction within urban areas and the University Campus of Parma, exploiting data from multiple sources. The aim is to develop effective modelling for the generation of sustainable and inclusive mobility scenarios

References

1. H. Barbosa, M. Barthelemy, G. Ghoshal, C. R. James, M. Lenormand, T. Louail, R. Menezes, J. J. Ramasco, F. Simini, M. Tomasini, Human mobility: Models and applications, Physics Reports, 734 (2018)
2. Biazzo, B Monechi, V Loreto General scores for accessibility and inequality measures in urban areas

   R. Soc. open sci.6190979190979 (2019)

Contact: Prof. Raffaella Burioni, Email: raffaella.burioni@unipr.it