Physics of Complexity @ ISC

2025

CNR-ISC

Consiglio Nazionale delle Ricerche
Istituto dei Sistemi Complessi

Physics of Complexity @ ISC

The **Institute of Complex System** (*ISC*) of the National Research Council (*CNR*) was created in 2004.

The science of complexity studies the emergence of collective properties in systems with a large number of interacting elements. These elements might be atoms in a physical context or say macromolecules in a biological one, but also individuals or companies in a socio-economic context.

Focusing on the structure of the interconnections and the general architecture of systems, the science of complexity departs from the traditional approach based on individual components.

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ISC Units

Sesto Fiorentino
Via Madonna del Piano 10, 50019 Sesto Fiorentino, Firenze

Sapienza
Piazzale Aldo Moro, 5, 00185 Roma

Taurini

Via dei Taurini 19, 00185 Roma

Torino

Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino

Directorate and central administration

Via dei Taurini 19, 00185, Roma

Stefano Boccaletti

Sesto Fiorentino unit

CNR-ISC

contacts

stefano.boccaletti@gmail.com
Via Madonna del Piano 10. 50019 Sesto Fiorentino, Italy
https://en.wikipedia.org/wiki/Stefano_Boccaletti

keywords

- *Complex systems and networks*
- *Synchronization and control of chaotic dynamics*
- *Pattern formation and competition in extended systems*

Research topics

Stefano Boccaletti's major research lines regarded the theoretical modelling of pattern formation and competition in nonlinear active and passive optics, in excitable media, the study of adaptive strategies for chaos recognition, control and synchronization, the study of synchronization in spatially extended systems and in complex networks.
He has co-authored the first experimental evidence of bulk-boundary transition in pattern formation in nonlinear active optics, and the first experimental evidence of domain coexistence in two-dimensional pattern formation in passive optics.
He has also introduced a new adaptive technique for chaos recognition and control, which has been successfully applied for chaos targeting, filtering noise from chaotic data sets, and chaos synchronization, both theoretically and experimentally. The control algorithm has been extended to infinite dimensional systems (delayed dynamical systems) for the control of defects and space-like structures in amplitude turbulent regimes, and also to space extended systems for the control of turbulent states.
Boccaletti co-authored the first direct experimental evidence of control of complex two-dimensional patterns in nonlinear passive optics.
From 1998, Boccaletti has also studied experimental control and synchronization of chaos in fluid dynamics, with reference to a Bénard-Marangoni convective flow, as well as application of control of chaos for communication.
Recently, Boccaletti co-authored several influential research papers discussing synchronization phenomena in complex networks and introducing selection criteria for the wiring topology that enhance the emergence of synchronized dynamics in weighted scale-free networks, as well as in random graphs. Furthermore, Boccaletti studied regulation phenomena of complex networks, and how these latter ones can be used as a proper tool in computational system biology. He introduced the classification method of complex networks networks in terms of their propensity to synchronization, which is the common standard today.
The monograph ¨Complex Networks: Structure and Dynamics¨, published in Physics Reports on 2006, received more than 13,600 citations (Google-Scholar), and converted into the most quoted paper ever appeared in the Annals of that Journal.

Pierfrancesco Di Cintio

Sesto Fiorentino unit

contacts

Pierfrancesco.dicintio@cnr.it
Office: CNR-ISC Via Madonna del Piano 10, 50019 Sesto Fiorentino (Firenze) Room B135
https://www.isc.cnr.it/staff-members/pierfrancesco-di-cintio/

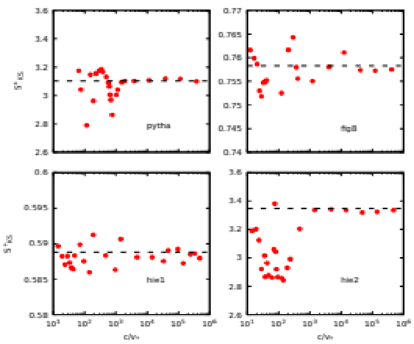
keywords

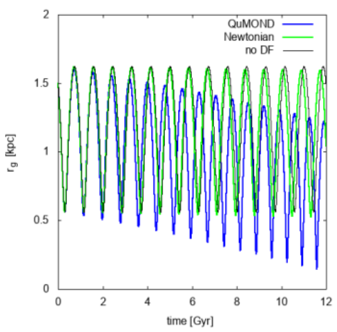
- *Stellar dynamics*
- *N-Body simulations*
- *Chaos in dynamical astronomy*

Research topics

The research interests of Pierfrancesco Di Cintio range from the study of chaos in few-body problems to the collective effects and relaxation in the gravitational N-body problem in both Cold dark matter and Modified gravity scenarios. With the aid of computational and semi-analytical techniques, most of his recent results concerned the scaling of the chaoticity with N, and the interplay between collective and local instabilities.

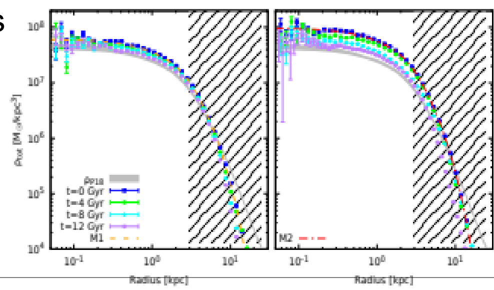
One of the most relevant recent results is that for some special configurations of the gravitational 3-body problem, the dynamical entropy (and hence the degree of chaos) is not a monotonic function of the strength of general-relativistic (i.e. post-Newtonian) corrections. Relativistic precession could have a “stabilizing effect” on some families of chaotic orbits.





Modified Newtonian Dynamics (MOND) is an alternative theory of gravity that does not need to introduce the evanescent Dark Matter, and amounts to a modification of the classical Lagrangian of gravitational forces. Some recent work on the dynamical friction in MOND evidenced that under certain conditions this process is more efficient than in Newtonian gravity, explaining the missing satellite problem in dwarf galaxies.

In the context of Lambda-CDM scenario, the dynamics of satellites of the Milky Way was studied by means of high resolution N-body simulations. Accurate models of the mass loss history for the Fornax Dwarf spheroidal galaxy evidenced that the system held almost all its stellar mass component, undermining the hypothesis that its high stellar fraction in globular clusters is a result of a massive barionic mass loss upon entering the Milky way.



Lucia Gardini

Sesto Fiorentino unit

CNR-ISC

contacts

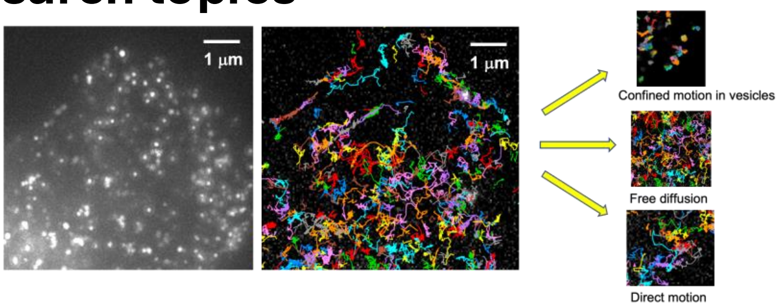
lucia.gardini@cnr.it
Office: 134, Ed. B; Lab: 40 Ed. B
https://www.isc.cnr.it/staff-members/lucia-gardini/

keywords

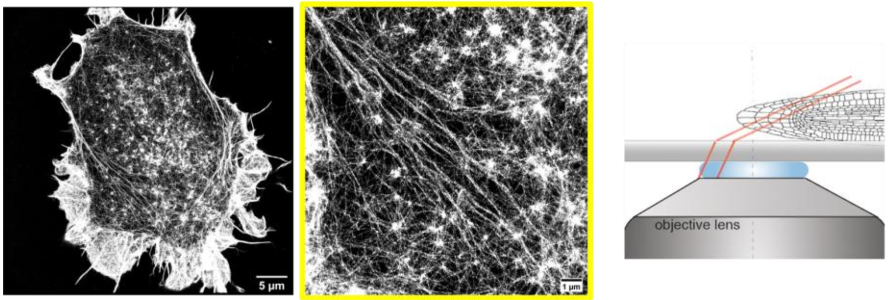
- *Biophotonics*
- *Single molecule localization microscopy*
- *Optical manipulation*

Research topics

Single molecule tracking. Through advanced optical techniques it is possible to localize single fluorescent molecules below the diffraction limit, with 10 nm accuracy in the three dimensions .

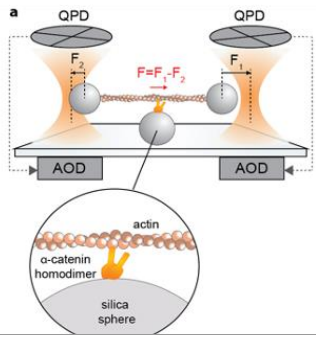


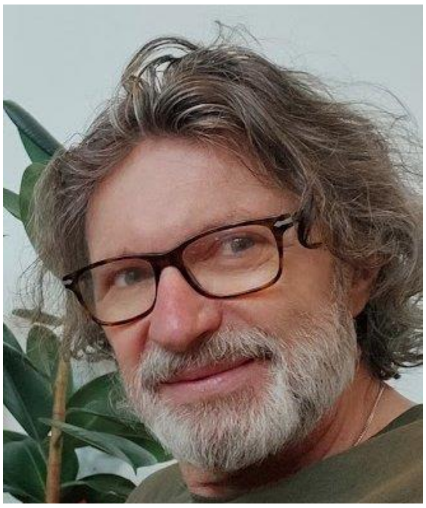
By tacking single molecules in living cells it is possible to visualize directly the behavior of the proteins of interest under controlled conditions. By fine analysis and modeling of the obtained trajectories it is possible to directly study the molecular mechanisms of protein-protein interaction in the living cell.



Localization based super-resolution microscopy. By localizing single photo-switchable fluorescent molecules with nanometer precision it is possible to reconstruct the morphology of proteins distribution far below the optical diffraction limit. Moreover, thanks to custom developed inclined illumination super-resolution imaging can be achieved also in thick samples up to 100 microns in depth.

Optical manipulation of molecules is achieved through double optical tweezers. This system allows to both measure and apply forces (pN-nN) to proteins interacting in an *in vitro* microfluidic system. This is the only way to measure how external forces regulate enzymes kinetics. Optical manipulation in the "three-beads" configuration can be applied to actin/actin-binding enzymes or DNA/DNA-binding proteins interactions.





Giovanni Giacomelli

Sesto Fiorentino unit

contacts

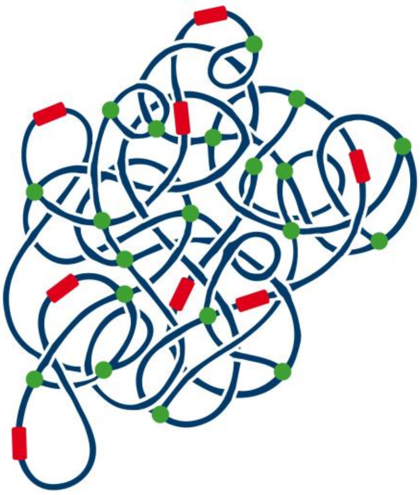
giovanni.giacomelli@cnr.it
Office: Room B055
https://sites.google.com/view/giovannigiacomelli

keywords

- *Complex active optical networks*
- *Long delay dynamical systems*

Research topics

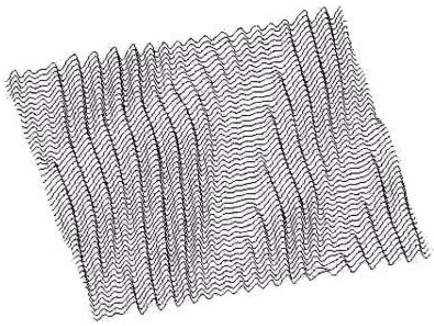
Complex active optical networks



A complex optical network can be realized with single-mode optical fibers (physical links) connected via optical couplers. One or more link can be active, i.e. able to provide coherent optical gain. The resulting system, for a suitable amount of gain can exhibit laser emission: we named it LANER (lasing network). The laner represents the generalization of the laser (which can be seen as the simplest laner) in the case of multiple gain sections and a cavity with a complex topology induced by the connections.

Long delay dynamical systems

Real-world systems can be strongly influenced by time delays occurring in self-coupling interactions, due to the unavoidable finite signal propagation velocities. When the delays become significantly long, complicated high-dimensional phenomena appear and a simple extension of the methods employed in low-dimensional dynamical systems is not feasible.



Stefano Iubini

Sesto Fiorentino unit

CNR-ISC

contacts

stefano.iubini@cnr.it
Office: Via Madonna del Piano 10, Room B131
https://scholar.google.it/citations?user=6b3BtLgAAAAJ

keywords

- *Nonequilibrium statistical physics*
- *Nonlinear dynamics and chaos*
- *Localization processes and slow relaxation*

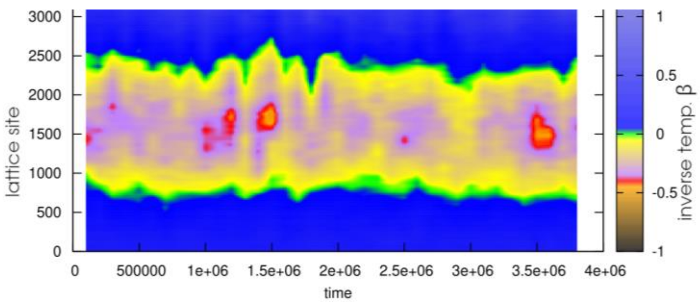
Research topics

Coupled-transport phenomena

Within the vast class of nonequilibrium phenomena, the physics of coupled transport is a growing field with potentially revolutionary technological innovations. The knowledge of systems where two or more species of irreversible flows may occur and influence one another dates back to the discoveries by Seebeck and Peltier of thermoelectricity in the XIX century. The basic principle of such materials is the capacity of converting a temperature difference into another kind of imbalance (e.g. a voltage) *and vice-versa*. My research is focused on the study of fundamental statistical-mechanical aspects of coupled transport in simple microscopic models.

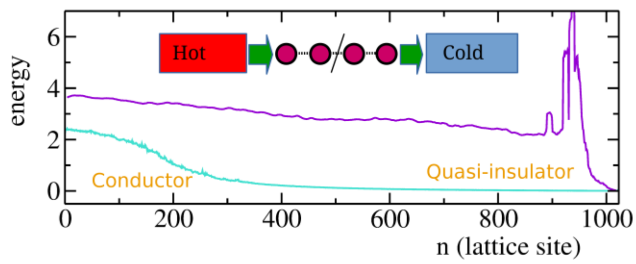
Absolute negative temperatures

Negative-temperature states are unusual regimes in which higher-energy states are more populated than lower ones. Current research lines address the problem of the onset of negative temperatures in nonequilibrium setups, including transport and localization processes in nonlinear lattices.



Localization phenomena

I am interested in problems involving extremely slow relaxation processes in clean (i.e. not disordered) nonlinear lattices. They may be originated by spontaneous localization of energy and imply the breakdown of ergodicity. The related phenomenology is very rich and strongly affects the thermodynamics of the system.



Thomas Kreuz

Sesto Fiorentino unit

CNR-ISC

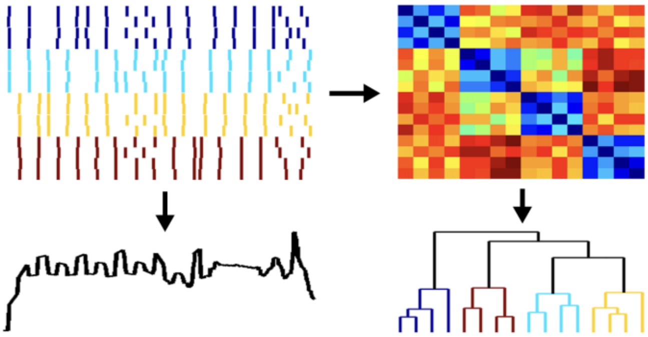
contacts

thomas.kreuz@cnr.it
Office: B130
Via Madonna del Piano 10; 50019 Sesto Fiorentino
https://www.thomaskreuz.org (personal)
https://www.firenze-neuro.org (lab)

keywords

- *Computational Neuroscience*
- *Analysis of electrophysiological data*
- *Measures of Synchronization and Directionality*

Research topics



As a computational neuroscientist with a physics background (Google Scholar profile), my main interest is the analysis of electrophysiological data such as the EEG and spike trains (sequences of action potentials emitted by neurons). Within this context my group has developed three software packages designed to monitor spike train synchrony: SPIKY (Matlab graphical user interface), PySpike (Python library) and cSPIKE (Matlab library):

SPIKY PySpike cSPIKE

Two recent articles:

In our most important work of the last few years we perform a spatiotemporal analysis of cortical activity obtained by wide-field calcium images in mice before and after stroke. Our new spatiotemporal propagation indicators can uncover neural correlates of motor deficits caused by stroke and of functional recovery during rehabilitation. Such insights pave the way towards more targeted post-stroke therapies.
Cecchini G, ..., Kreuz T. PLOS Comp Biol 17: e1008963 (2021)

Our latest study deals with latency, global temporal shifts between spike trains. We propose a new algorithm of multivariate latency correction which optimises the spike time alignment of sparse neuronal spike trains with well-defined global spiking events and for the first time ever it is able to do so even when these events overlap.
Mariani A, ..., Kreuz T. J Neurosci Methods 416, 110378 (2025)

Stefano Lepri

Sesto Fiorentino unit

CNR-ISC

contacts

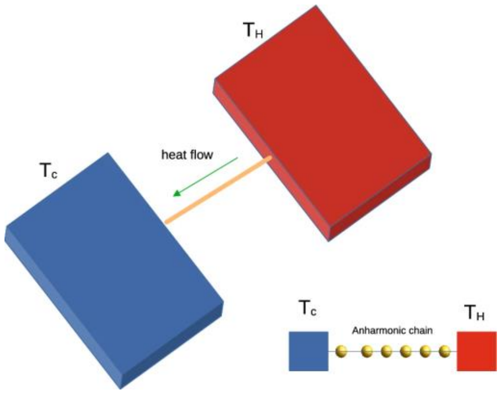
stefano.lepri@cnr.it
Office: room 161 B
http://sites.google.com/view/stefanolepri

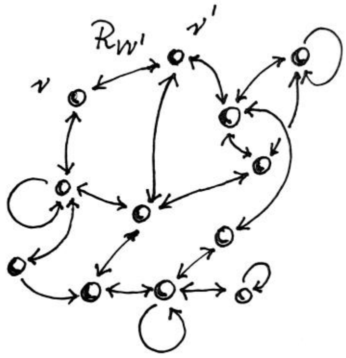
keywords

- *Nonequilibrium statistical physics*
- *Nonlinear dynamics and chaos*

Research topics

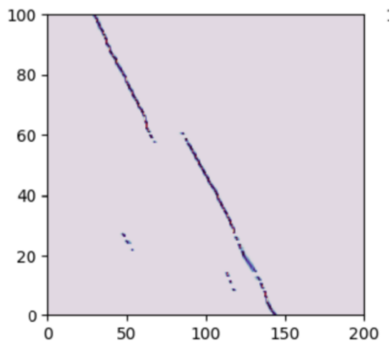
Anomalous transport in low-dimensions Energy transfer in small nano-sized systems can be very different from that in their macroscopic counterparts due to reduced dimensionality, interaction with surfaces, disorder, and large fluctuations. Those ingredients may induce non-diffusive heat transfer to be taken into account on small scales. [Riv. Nuovo C. 2023, 46, 105–161].





Large deviations and thermalization: relaxation to equilibrium is a fundamental process where nonlinearity is crucial. It can be regarded as a diffusion on a network in normal-modes space. Large-deviation methods can thus be applied to quantify possibly slow, different from average, relaxation pathways [JSTAT,2024 073208]

Quasi-integrable systems out of equilibrium: Perturbed nonlinear integrable many-body problems occur in many physical contexts. The set in of thermalization, chaos, and hydrodynamics is yet to be understood. For the perturbed Toda chain, a novel approach is proposed based the evolution of the Lax eigenvalues as a proxy for soliton scattering at finite temperature [arXiv:2504.15919].



Giancarlo Margheri

Sesto Fiorentino unit

CNR-ISC

contacts

giancarlo.margheri@cnr.it
Office: Via Madonna del Piano 10, 50019, Sesto Fiorentino, Firenze
Tel : 055 522 6654

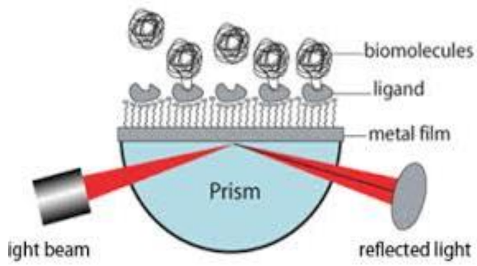
keywords

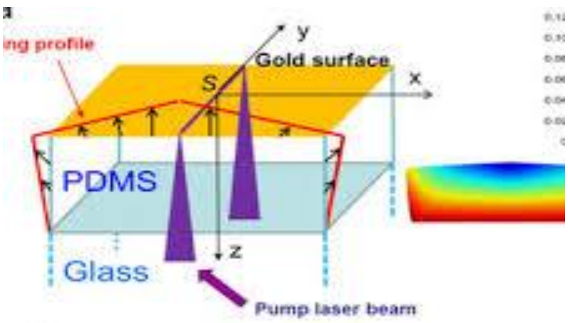
- *Plasmonics*
- *Long focus beams generation*
- *Optical design for laser ablation*

Research topics

1) Plasmonic sensors and active all-optical devices. **2)** Generation of Bessel beams in the UV-Vis spectrum and in the THz band via thermooptomechanical changes of bilayers **3)** Design of optical layouts to implement laser ablation aimed at the preparation of functionalized gold nanoparticles

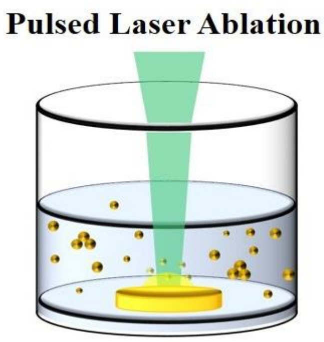
Plasmonic sensors are unique, exceptionally sensitive tools to check the affinity between an immobilized receptor and a ligand. This allows to insight the complex nature of the ligand-receptor binding of outmost importance in the farmacological studies. The sensitivity of plasmonic tecnique is used to sense other kinds of physical quanities, or even to fabricate active all-optical tools.

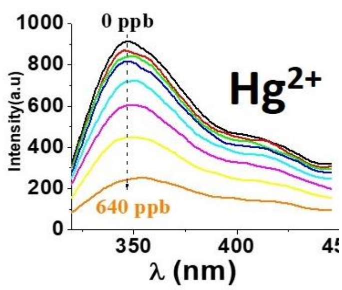




Systems to provide longitudinally extended focal regions are very important in many application fields, from medical (ex: OCT) to space communications. By exploiting mechanical and/or thermooptical changes, we fabricate devices that produce cosine or Bessel shaped beams, aimed to work in the UV-VIS up to THz spectral regions.

We study the formation of gold nanoparticles by laser ablation. The ablation rate is a usual issue when using this technique. The proper design of the optical power delivery is conducted in ISC-CNR, while the experimental part is carried out at the University of Rio de Janeiro.





Massimo Materassi

Sesto Fiorentino unit

contacts

massimo.materassi@cnr.it
Office: via Madonna del Piano 10, 50019 Sesto Fiorentino (FI), Italy
http://www.materassiphysics.com

keywords

- *Dissipation and metriplectic formalism*
- *Space Weather, ionospheric and plasma physics*
- *Mathematical Ecology*

Research topics

Dissipation. In the field of analytical mechanics, non-dissipative systems are represented through the Hamiltonian formalism, which makes all the dynamical aspects of the system as a by-product of algebraic operations (Poisson brackets or quantum commutators), in addition to symmetries. The challenge is to do the same thing for dissipative systems, putting together “mechanical” and “thermodynamical” elements in the same formalism. The metriplectic formalism makes precisely this for classical systems: my study aims at widening the application of this formalism, on the one hand, and at learning something more on the “fundamental” nature of dissipation, on the other.

Space Weather. The study of Sun’s forcing on Earth, and of the planet’s response, is a laboratory for a huge variety of theoretical studies and data analysis applications. Subjects studied: ionospheric turbulence and scintillation, magnetic reconnection, metriplectic theories of plasma, stochastic equations of plasma, space plasma statistics.

http://geomag.org/info/magnetosphere.html0

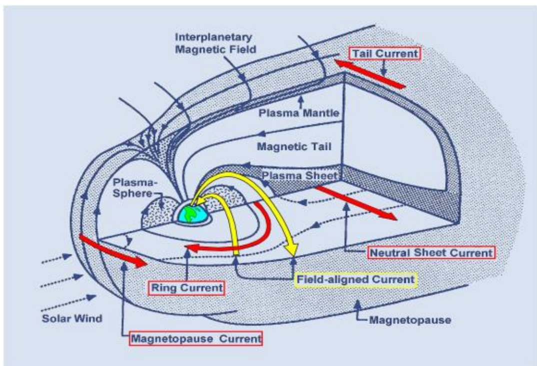
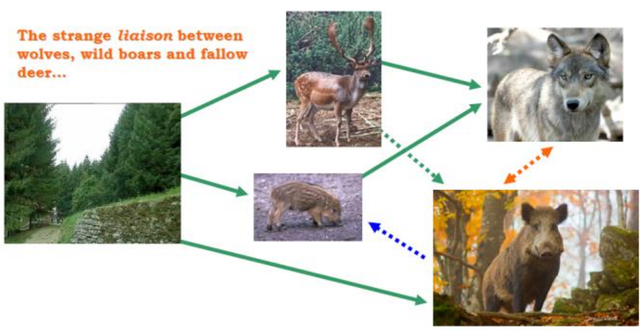


Fig. 1: A sketch of the magnetosphere (modified from Kivelson and Russel (1995))



Mathematical ecology. The science of dynamical systems may be very useful to represent the interactions among animal and vegetal populations in trophic webs. Formulating dynamical models of ecosystems allows for: predicting the environment evolution; tracing causal relationships between processes and, possibly, taking measures to favor wildlife’s conservation.

Simona Olmi

Sesto Fiorentino unit

CNR-ISC

contacts

Simona.olmi@cnr.it
Office: via Madonna del Piano 10,
Office 131 Edificio B
https://www.isc.cnr.it/staff-members/simona-olmi/

keywords

Nonlinear Dynamics
Computational Neuroscience
Synchronization

Research topics

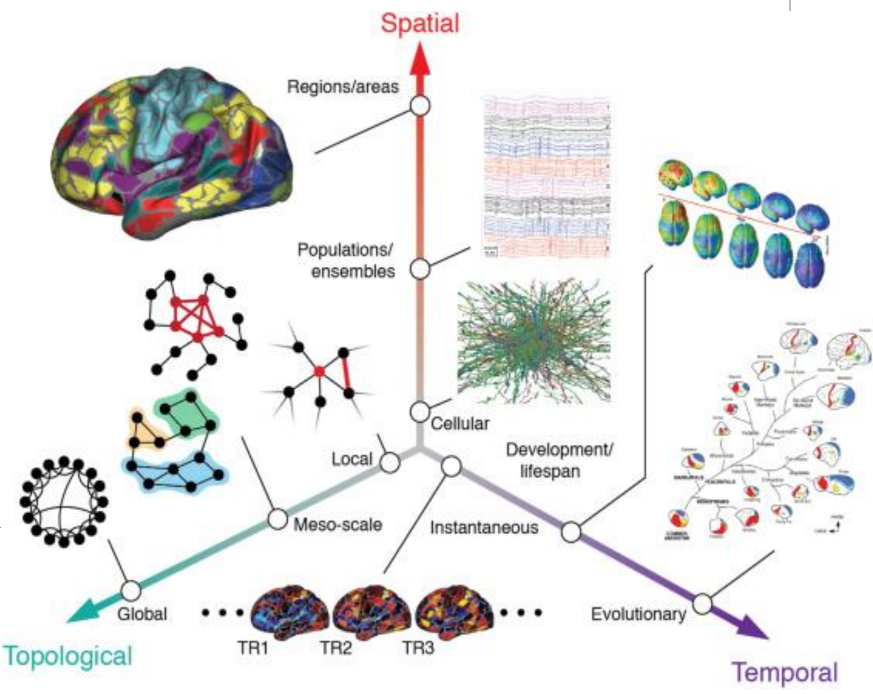
The science of complexity is a new and extremely trans-disciplinary field of research. Complex systems are those composed of a large number of interacting elements, so that the collective behaviour of those elements goes far beyond the simple sum of the individual behaviours. Initially the concept of complex systems was mainly associated with the temporal evolution of systems made up of many interacting units each characterized by highly nonlinear dynamics. In the last decade the interest has moved towards an even more intriguing subject: the emergence of nontrivial collective dynamics in networks composed of elements whose evolution is extremely simple, like oscillators with periodic dynamics.

My research investigation is focused on interacting sub-populations of oscillators, with the goal of characterizing the dynamics both at the macroscopic (collective) level, as well as at the level of each sub-population (mesoscopic level). Two apparently quite distant research fields where the mesoscopic evolution of sub-networks is extremely relevant are neural circuits and electrical power-grids. Theoretical methods and techniques developed for coupled oscillators (exact reduction methodologies) can be profitably applied in the context of neural networks and power-grids, since these systems can be mathematically modelized as networks of coupled phase oscillators.

Olmi, Petkoski, Guye, Bartolomei, Jirsa, *PLoS Comp Bio* (2019)
Van Schependom, Baetens, Nagels, Olmi, Beste, *Communications Biology* (2024)
Olmi, Politi, *Phys Rev Lett* (2025)

Computational Neuroscience Lab

The lab is active in Florence since 2006 and it is presently composed of 4 permanent researchers and 1 post-doc.
https://www.firenze-neuro.org/



Paolo Politi

Sesto Fiorentino unit

CNR-ISC

contacts

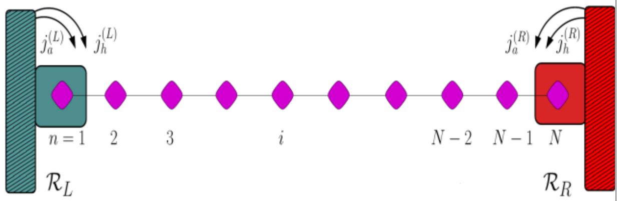
Paolo.Politi@cnr.it
Office: Via Madonna del Piano 10, 50019 Sesto F.no
https://sites.google.com/site/ppoliti/

keywords

- *Nonequilibrium Statistical Physics*
- *Relaxation dynamics*
- *Condensation/Localization*

Research topics

This is the typical setup for studying a one-dimensional lattice of length N, whose ends are attached to two thermal reservoirs: if they are equal, the system can attain an equilibrium state; if they are different, the system is kept out-of-equilibrium and currents may flow across it.



In the former case we might be interested in the equilibrium properties as well as in the relaxation dynamics towards equilibrium. A classical problem of relaxation occurs after a quenching process when, e.g., temperature is suddenly decreased through a critical point: the system relaxes towards an ordered state, starting from a disordered one, through a coarsening process. A recent question related to such process is if relaxation becomes faster as you move away from the final state (Mpemba effect).

If reservoirs are different, the system is in out-of-equilibrium conditions and in the simplest case the system attains a Nonequilibrium Steady State. An interesting scenario may appear if several quantities are conserved by bulk dynamics: such constraints may lead the system towards a phase where, e.g., energy is spatially localized. If so, suitable out-of-equilibrium setups may induce localization even if each reservoir, separately, would drive the system towards a non-localized state.

Localization may also be accompanied by the rising of negative absolute temperatures, since entropy decreases with increasing the energy.

Bruno Tiribilli

Sesto Fiorentino unit

CNR-ISC

contacts

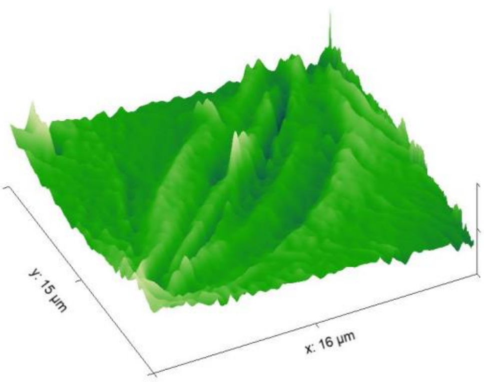
bruno.tiribilli@cnr.it
Office: B134
Address Via Madonna del Piano 10, 50019 Sesto Fiorentino, Firenze
http://bt.nanobioscience.eu

keywords

- *Atomic Force Micrcoscopy*
- *Microcantilever sensors*
- *Educational robotics*

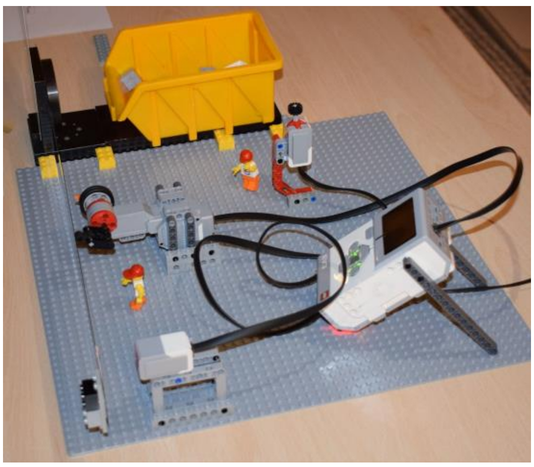
Research topics

AFM. Atomic force microscopy is my main interest, with a focus on imaging (scanning) biological samples in close collaboration with biomedical scientists. I am also interested in the study of new AFM techniques closely related to AFM cantilever dynamics and feedback control.



MIcrocantilever Based sensors. By observing the frequency and amplitude response of a microcantilever, it is possible to perform accurate measurements of the viscosity or viscoelasticity of liquids. In particular, for a self-oscillating cantilever, we have shown that by introducing a controlled delay in the feedback loop that generates the self-oscillations, it is possible to identify nonlinear operating conditions that increase or cancel the sensitivity to density, viscosity, or added mass. The development of these techniques could be the basis for compact and reliable devices for the real-time detection of small variations in the rheological parameters of Newtonian and non-Newtonian fluids, with interesting applications in the industrial and biomedical fields.

With the aim of providing new tools to schools, we have created a game-based learning path, focused on building and programming robots capable of tackling a specific technical/scientific problem. Educational robotics offers new opportunities for students and teachers. I am attracted to this methodological approach because it is known that learning through play is an important strategy to promote student engagement, teamwork, inclusion and the development of holistic skills. Educational LEGO kits are my favorite platform.



Alessandro Torcini

Sesto Fiorentino unit

CNR-ISC

contacts

alessandro.torcini@fi.isc.cnr.it
Office: via Madonna del Piano 10, Sesto Fiorentino
https://www.firenze_neuro.org

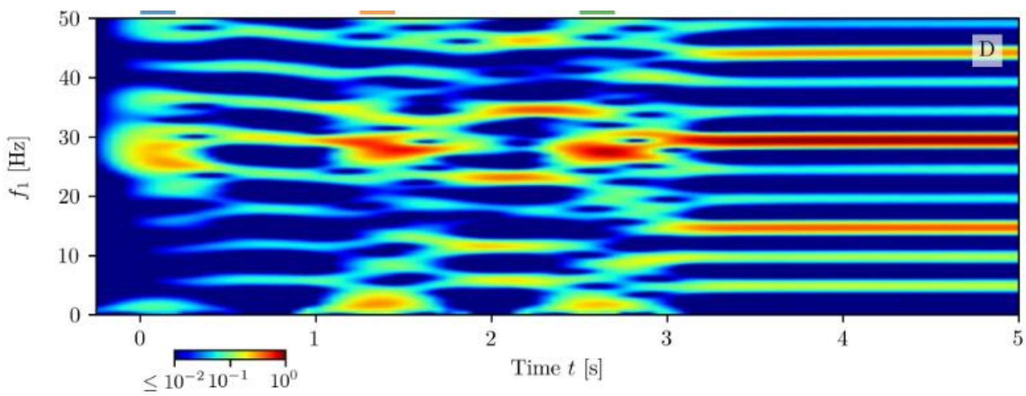
keywords

- *Complex Systems*
- *Neural Dynamics*
- *Neural Mass Models*

Plastic neural networks

Computational neuroscience is an interdisciplinary discipline in which modeling and analysis tools derived from mathematics, physics and computer science are used to investigate how the nervous system processes information. It mostly relies on the development, simulation, and analysis of multi-scale models of brain function, from the level of molecules through single neurons and neuronal networks up to cognition and behaviour. The activity of the last years done in collaboration with Dr. Simona Olmi (ISC,CNR) and her PhD and master students concerns the development of exact mean-field (neural mass) models encompassing realistic biological features, as short-term synaptic plasticity or spike frequency adaptation. These models have applications in describing short-term memory as well as effects of cholinergic modulation in the hippocampus.

H. Taher, A. Torcini, S. Olmi, "Exact neural mass model for synaptic-based working memory", PLOS Computational Biology , 16(12): e1008533 (2020)
A. Ferrara, D. Angulo-Garcia, A. Torcini and S. Olmi, "Population spiking and bursting in next generation neural masses with spike-frequency adaptation", Physical Review E 107, 024311 (2023)



Paola Verrucchi

Sesto Fiorentino unit

CNR-ISC

contacts

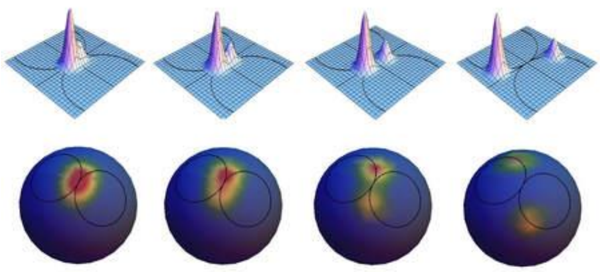
Paola.verrucchi@cnr.it
Office: Dipartimento di Fisica ed Astronomia, Universita' di Firenze, via G. Sansone 1, 50019 Sesto F.no (FI)
http://paolaverrucchi.weebly.com

keywords

- **Quantum foundations**
- **Quantum information**
- **Quantum many-body systems**

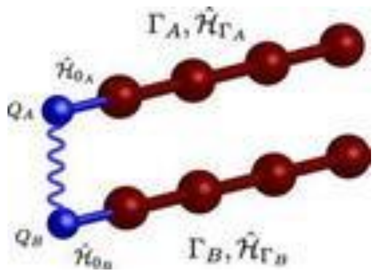
Research topics

Many of the fundamental question in recent years-physics are related with the way "time" enters our description of the real world: we tackle the problem referring to a new formalism based on generalized coherent states and the quantum-to-classical crossover.The formalism is also applied to the way black-holes can be described as quantum objects playing the role of perfect clocks for evolving systems.



Quantum information is the theory that describes the measurement process in its most profound aspects, suggesting quantum sensing protocols (such as those aimed at measuring time), as well as connections between thermodynamics, information paradoxes and gravity, topics that we study based on quantum foundations analysis.

Most of the basic ideas and protocols of quantum information theory find their ideal setting in the realm of quantum many body systems, as they most often provide the real objects described by prototypical models. Quantum spin chains as communication channels, networks of solid-state quantum devices distributed on hybrid networks, or fotonic devices for secure distribution, are just some of the possible applications we are considering.



Luca Angelani

Sapienza unit

contacts

luca.angelani@cnr.it
Office: Fermi Building, 111
https://www.roma1.infn.it/~angelans/

keywords

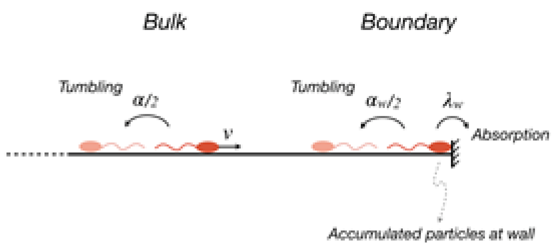
- *Active Matter*
- *Run-and-tumble motions*
- *Modeling and simulations*

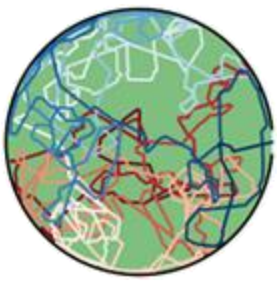
Active Matter

Active matter refers to systems composed of self-propelled units, from animals, cells and bacteria to motile artificial particles and microrobots. The rich phenomenology manifested at the single particle and population level poses a challenge both theoretically and experimentally, having a multidisciplinary character, involving many disciplines, from physics and biology to mathematics and microengineering.

Run-and-tumble motions

The analytical study of run-and-tumble equations in a wide variety of situations allows us to give insights into many issues, such as first-passage problems, transport properties, entropy production, trapping, boundary condition problems.



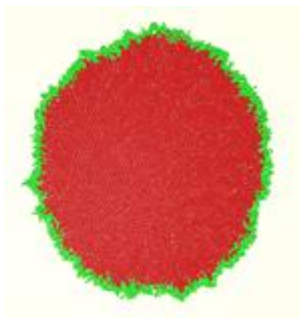


Confined active matter

The out-of-equilibrium character of active systems results in non-trivial effects when considering confining environments, such as accumulation at walls, clusters formation, optimal escapes, rectification of motion.

Proliferating active matter

Living organisms not only self-propel but also self-reproduce. The study of proliferating cellular aggregates in different contexts (confinement, external fields, complex environments) is a fascinating emergent field of research in active matter.



Roberta Angelini

Sapienza unit

CNR-ISC

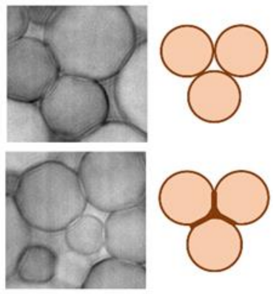
contacts

Roberta.angelini@cnr.it
Office: Room 110, Building CU033, Physics Department, Sapienza University, piazzale Aldo Moro 5, 00185 Rome
https://www.roma1.infn.it/~angerob/

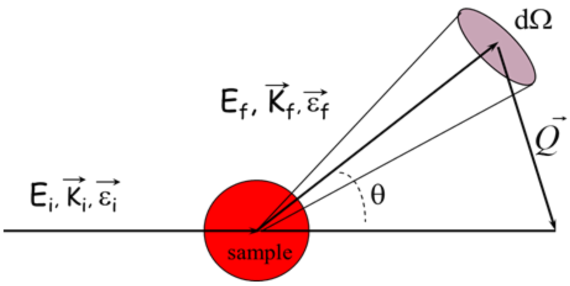
keywords

- *Soft Matter physics*
- *Rheology*
- *X-ray scattering*

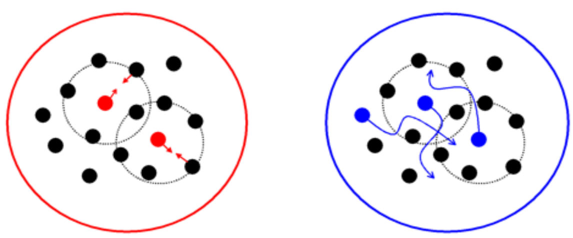
Research topics



- **Soft Matter Physics and Complex Fluids**: Investigation of the structural, dynamic, viscoelastic and thermal properties of soft materials, including soft colloids, as microgels and emulsions, polymers, gels, and complex fluids aiming in understanding their microscopic interactions and phase transitions.

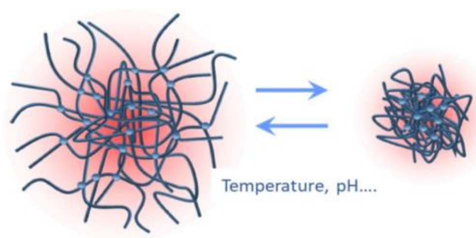


- **X-ray and Neutron Scattering**: Use of advanced scattering techniques, such as small angle x-ray and neutron scattering (SAXS, SANS) and x-ray photon correlation spectroscopy (XPCS) to study the microscopic and mesoscopic structure and dynamics of materials.



- **Glass Transition and Dynamical Arrest**: Study of glassy dynamics, including the transition from fluid to arrested states in colloidal suspensions and polymeric systems.

- **Smart Nano- and Micro-structured Materials**: Design and characterization of stimuli-responsive materials for applications in nanotechnology and biophysics. Particularly those based on poly(N-isopropylacrylamide(PNIPAM), focusing on their synthesis, structural properties, and responsiveness to external stimuli. These materials have potential applications in various fields, including biomedical engineering and smart materials.



Andrea Baldassarri

Sapienza unit

CNR-ISC

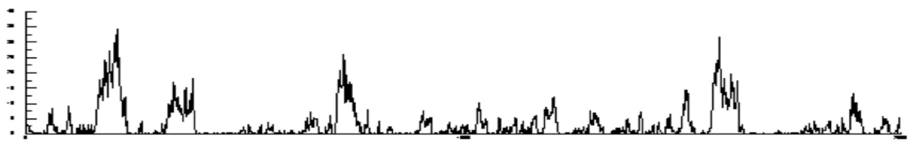
contacts

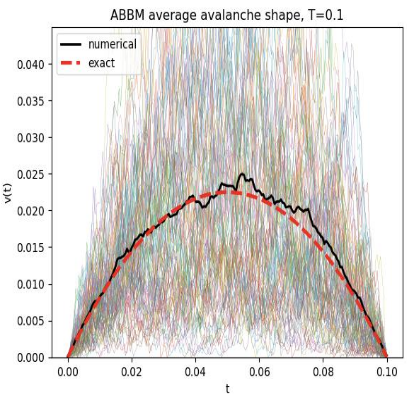
Andrea.baldassarri@cnr.it
Office: Address
https://www.isc.cnr.it/staff-members/andrea-baldassarri/

keywords

- *Non-equilibrium statistical physics*
- *Stochastic processes*
- *Stochastic thermodynamics*

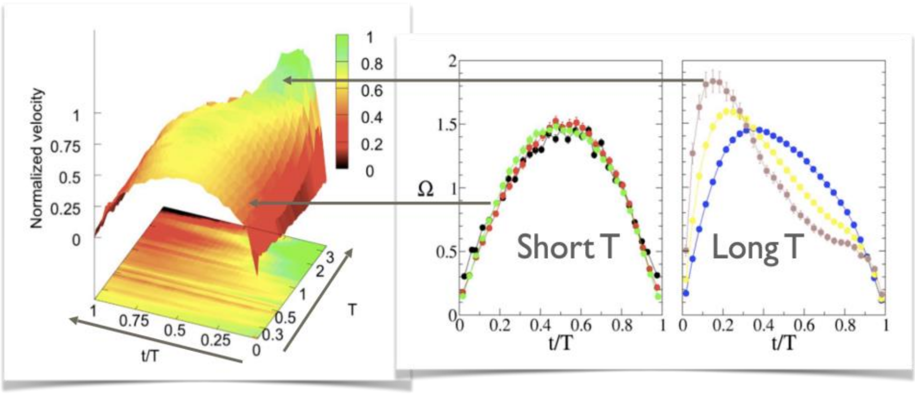
I'm interested in non-equilibrium physics, in particular the possibility to understand and characterize dissipative dynamics from statistical analysis of noisy and fluctuating measures. I considered the case of "crackling-noise", i.e. bursty signals that can be described as a sequence of avalanches, typical in many physical phenomena (earthquakes, friction, etc.). A measure of interest has been introduced to this aim: the average shape of the avalanche (or average fluctuation shape).





From the theoretical point of view, I'm trying to leverage on the theory of stochastic processes, to compute analytically the shape for simple models (e.g. ABBM/CIR/Bessel process) in order to connect measurable features (as the asymmetry) with quantity of interest in stochastic thermodynamics (e.g. entropy production, dissipation, work and heat exchanges)

Data analysis from experimental measures, for instance irregular stick-slip dynamics in granular friction, can be compared with paradigmatic models for non equilibrium dynamics, as the Brownian Gyrator, recently introduced as an example of "heat engine at the nanoscale".



The Brownian Gyrator, and its possible non-linear extensions, provide an ideal framework to develop and check ideas and techniques, at the crossing between non equilibrium dynamics, stochastic thermodynamics and control theory.

Valentina Brosco

Sapienza unit

CNR-ISC

contacts

valentina.brosco@cnr.it
Office: Physics Department, Fermi Building, Room 109
https://www.isc.cnr.it/staff-members/valentina-brosco/

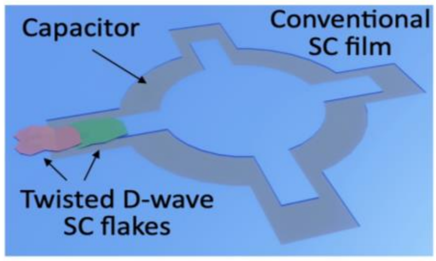
keywords

- *Quantum hardware*
- *Quantum optics and dissipation*
- *Many-body quantum systems*

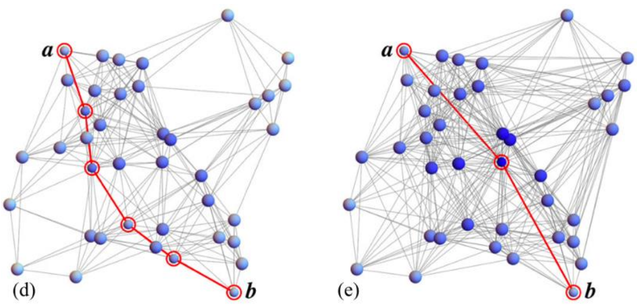
Research topics

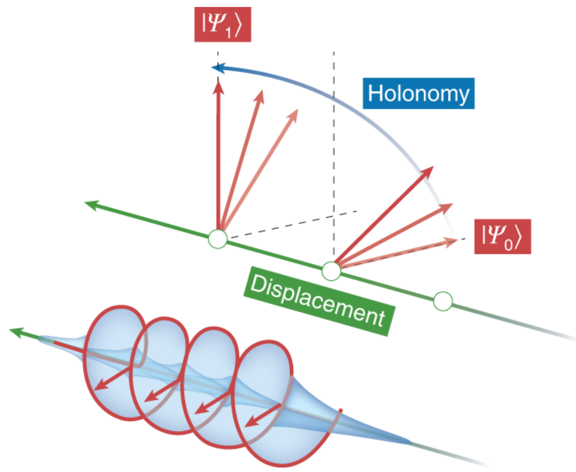
My research lies at the intersection of condensed matter physics and quantum information science, focusing on understanding quantum devices from their microscopic Hamiltonians to engineer novel functionalities and identify universal behaviors using methods from many-body physics and quantum statistical mechanics.

Currently, a central focus is on **superconducting quantum circuits** where we investigate the opportunities arising from the integration of novel materials, different encoding strategies as well as various applications to quantum sensing and simulation.

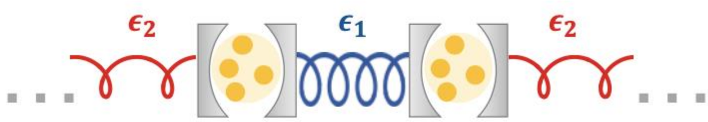


Another line of research aims at describing and optimizing **quantum communication networks**. Ongoing work include trusted-node-based communication strategies and entanglement networks





Further activity studies the interplay of **topology and non-linearity** in parametrically driven lattices as well as the possibility to employ **non-Abelian holonomies** to control on light propagation in topological photonic lattices.



Silvia Capuani

Sapienza unit

CNR-ISC

contacts

silvia.capuani@cnr.it
Office: NMR and Medical Physics Laboratory, Physics Dpt.
Fermi Building, Room 319, Sapienza University of Rome
https://www.isc.cnr.it/staff-members/silvia-capuani/

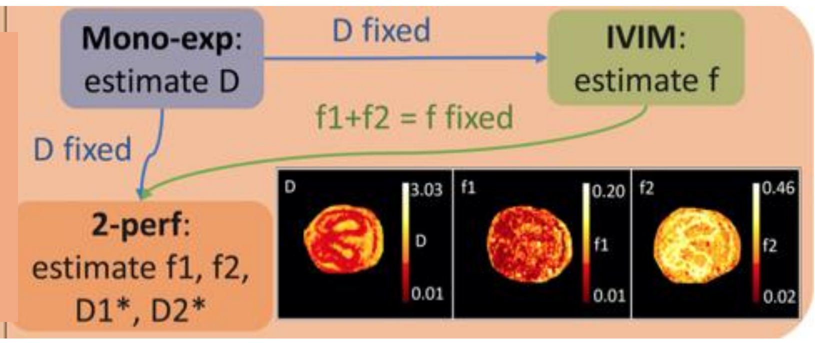
keywords

- *MRI for Medical Diagnosis*
- *Molecular diffusion by NMR*
- *Cultural Heritage diagnostics*

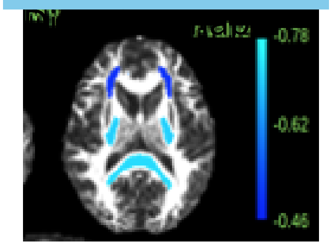
Research topics

My research focuses on both theoretical and experimental aspects of Nuclear Magnetic Resonance (NMR). The highly interdisciplinary and cross-cutting research includes the design and development of new MRI contrast mechanisms, mainly based on molecular diffusion, for improved diagnostics in both medicine and the field of cultural heritage.
I develop advanced NMR protocols for the early diagnosis of neurodegenerative, musculoskeletal, oncological, and fetal disorders. I lead an NMR laboratory equipped with both high- and low-field portable instrumentation. Through agreements, I carry out translational research on clinical MRI scanners at IRCCS institutions such as Santa Lucia Foundation and hospitals including Umberto I and Tor Vergata in Rome.

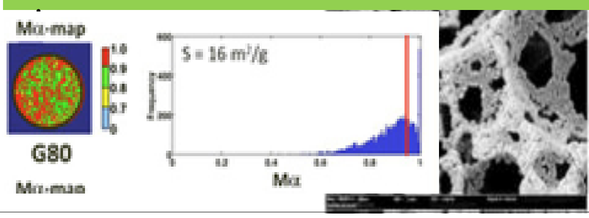
Model fitting for Diffusion and Perfusion MRI maps in fetal brain

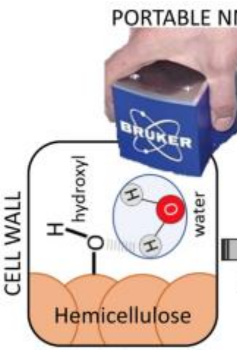


Aging: Anomalous

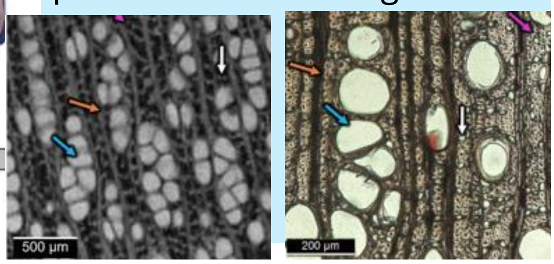


Normal, Anomalous and non-Gaussian diffusion in liquids, gels, porous systems and excised





Wood investigation by portable NMR and high-field



Francesca Colaiori

Sapienza unit

CNR-ISC

contacts

francesca.colaiori@cnr.it
Office: 510 Fermi Building, Sapienza
https://www.linkedin.com/in/francescacolaiori

keywords

- *Complex Networks*
- *Network Epidemiology*
- *Social Dynamics*

Research topics

Optimizing epidemidemic outcomes with limited resources

How can we use scarce resources to best reduce disease burden and mortality? My work focuses on evaluating the impact of vaccination strategies to support evidence-based policies. A key question arises when vaccines require multiple doses: is it more effective to prioritize broad first-dose coverage or to complete the full schedule promptly?

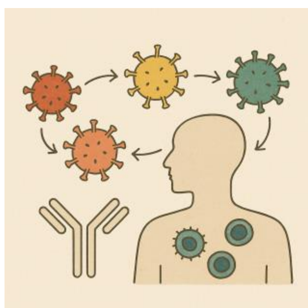
Coupling opinion dynamics with epidemics

BeSAFE
Behavioral and Social Aspects in Fighting Epidemics

Epidemic trajectories are shaped not only by biology, but also by how people perceive and respond to risk. I study how information spread, behavioral feedback, and social influence interact with disease dynamics—asking, for example, how fear, trust, and misinformation can alter the course of an outbreak.

Immune-Evolutionary epidemic Models

Pathogens evolve as they spread, interacting with host immunity in complex ways. I develop models that couple viral evolution with immune dynamics to understand how new variants emerge and persist. These tools help anticipate long-term risks, especially from strains with increased transmissibility or immune escape.



Giulio Costantini

Sapienza unit

CNR-ISC

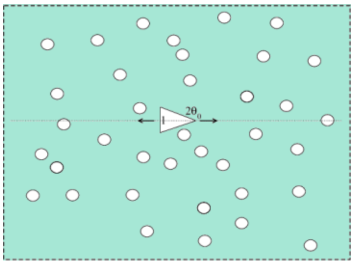
contacts

giulio.costantini@cnr.it
Office: p.le A. Moro 2, c/o Dip. Fisica Sapienza, Ed. Fermi, stanza 319

keywords

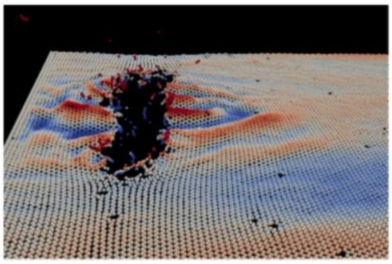
- *Out-of-equilibrium statistical mechanics*
- *Stochastic processes in complex systems*
- *Scaling and size-dependent phenomena*

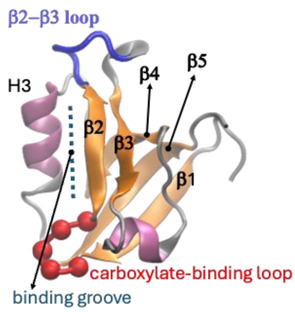
Research topics



Nonlinear dynamics and noise-driven transport
Noise and discreteness can serve functional roles in driven systems far from equilibrium. In granular ratchets and kink-bearing lattices, entropic forces enable controlled transport and signal transmission, redefining fluctuations and nonlinearity in synthetic and biological systems.

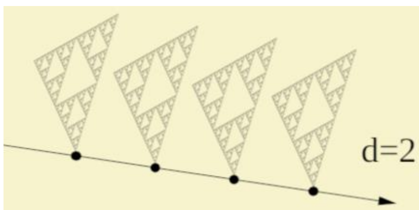
Plasticity and mechanical failure in microscale materials
Mechanical response in small-scale crystalline systems is dominated by intermittent deformation and fracture. The scaling of stress avalanches and the critical role of sample size in plastic flow and crack propagation reveal universal features relevant for designing reliable advanced materials.





Protein aggregation and cellular biomechanics
Membrane composition, oxidative stress, and protein homeostasis reveal how misfolded aggregates form out of equilibrium. Allosteric signaling in proteins like ubiquitin links dynamics to function, showing how mechanical and biochemical coupling shape cellular regulation.

Diffusion and anomalous transport in complex systems
Diffusion in biological and porous media often deviates from Brownian norms, as sub- and superdiffusion in structured environments challenge transport universality; new NMR tools reveal how complexity shapes diffusion.



Simone Felicetti

Sapienza unit

CNR-ISC

contacts

simone.felicetti@cnr.it
Office: Fermi Building 206
https://www.isc.cnr.it/staff-members/simone-felicetti/

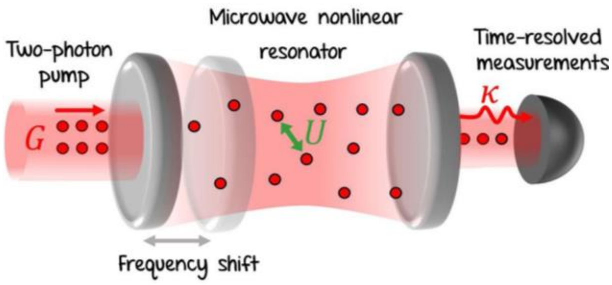
keywords

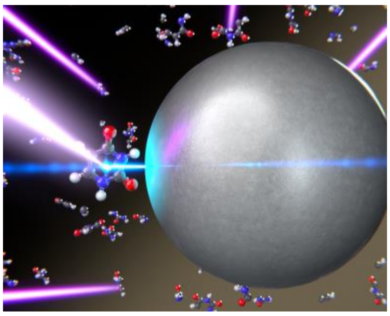
- *Quantum Optics Theory*
- *Quantum Information Theory*
- *Quantum Devices*

Research topics

Theoretical physicist in the field of Quantum Science and Technology, I primarily focus on fundamental aspects, but I also enjoy working on the design of technological applications. My current research activity follows three main axes:

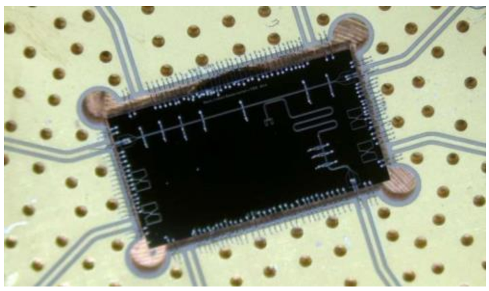
(1) Quantum Sensing, intended as a **conceptual framework** to investigate fundamental properties of the quantum world and as a **practical method** to design quantum technologies.
- Communications Physics 8 (1), 74 (2025)
- Physical Review Letters 133 (4), 040801 (2024)





(2) Quantum light-matter interactions, especially in extreme or unconventional regimes, achievable with parametric, ultrastrong or nonlinear couplings. I derive and analyze quantum models for a variety of solid-state, molecular and atomic devices.
- PRX Quantum 4, 030326 (2023)
- JPCL 11 (20), 8810 (2020), on the cover

(3) Experimental collaborations, I frequently collaborate with experimental groups working with various quantum technologies, contributing to experimental design as well as data analysis and interpretation.
- Nature Communications 16 (1), 1954 (2025)
- PRX Quantum 6 (2), 020301 (2025)



Yuri Gerelli

Sapienza unit

CNR-ISC

contacts

yuri.gerelli@cnr.it
Office: Fermi Building, 421
https://www.isc.cnr.it/staff-members/yuri-gerelli/

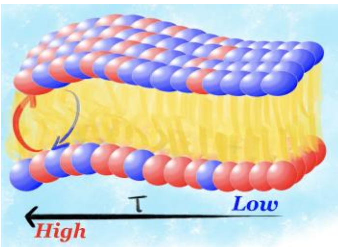
keywords

- *Structural Dynamics in Soft Condensed Matter*
- *Membrane Biophysics & Self-Organizing Systems*
- *Scattering Techniques in Experimental Biophysics & Soft Interfaces*

Research topics

Physics of lipid membranes

Lipid membranes are widely used as model systems to study the fundamental properties of biological cell membranes. Their ability to self-organize into complex, yet highly functional structures makes them ideal platforms for exploring how structure relates to function at the molecular level.



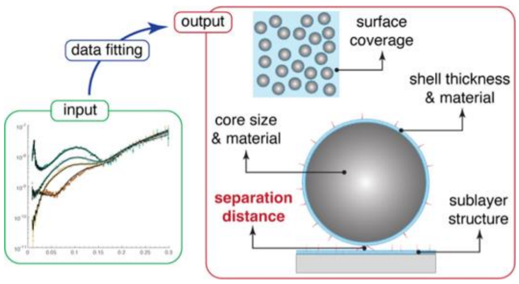
These studies provide insights into essential cellular processes and help guide the design of lipid-inspired materials and devices in biotechnology and medicine.

Y. Gerelli, *Phys. Rev. Letters* 122, 148101 (2019)
L. Porcar and Y. Gerelli, *Soft Matter* 16, 7696 (2020)

Nanoscale characterization of soft and biological interfaces

Soft and biological interfaces exhibit hierarchical structures, with key features ranging from the nanometre to the micron scale. In biological environments, many critical interactions occur at nanometric distances, making high-resolution structural characterization essential. Techniques like neutron and X-ray reflectometry enable precise, non-invasive probing of thin films with sub-nanometre accuracy.

When combined with advanced modelling, these methods can reveal the composition and organization of complex interfacial systems. Notable applications include the absolute measurement of the separation distance between nanoparticles and lipid membranes, and the characterization of a key process in the early stages of amyloid fiber formation.



A. Armanious, Y. Gerelli, *et al. JACS* 144, 20726 (2022)
A. Martel *et al. JACS* 139, 137-148 (2017)

Silvia Gentilini

Sapienza unit

CNR-ISC

contacts

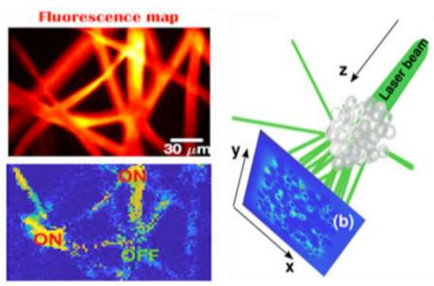
silvia.gentilini@cnr.it
Office: Room 410 – Fermi Building- Physics Department
http://website.address

keywords

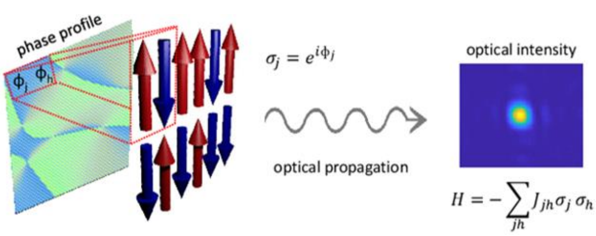
- *Photonics*
- *Nonlinear optics*
- *Disordered systems*

Research topics

My background is in optics and photonics, with a focus on light propagation in complex and disordered media. My current interest stands at the intersection of nonlinear optics, complex systems, and biomedical applications, and is driven by a strong interest in both fundamental understanding and interdisciplinary applications.

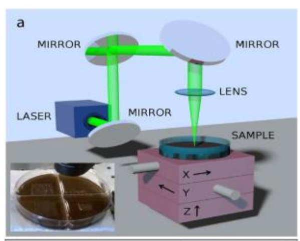


When electromagnetic radiation travels through a scattering medium, a plethora of phenomena can emerge. The study of such phenomenology is important from a fundamental point of view and for the realisation of innovative technology. A paradigmatic example is represented by the random laser, which has allowed the experimental demonstration of the replica symmetry breaking in the glass transition.



In the framework of optical computing I work on the realization of platforms that mimic spin systems to address complex combinatorial optimization problems. By exploiting the free propagation of tailored beam, we develop photonic Ising machines capable of emulating spin interactions.

In the context of biophotonics, I develop collaborations with the aim of implementing optical tools for biomedical applications. This includes biosensing based on microlasers, utilised to achieve single-molecule detection. I also work on laser printing techniques for the fabrication of personalised scaffolds for maxillofacial prosthesis.



Neda Ghofraniha

Sapienza unit

contacts

neda.ghofraniha@cnr.it
Office: Physics Department, La Sapienza University
Room 410, Fermi Building
https://sites.google.com/view/neda-ghofraniha/home

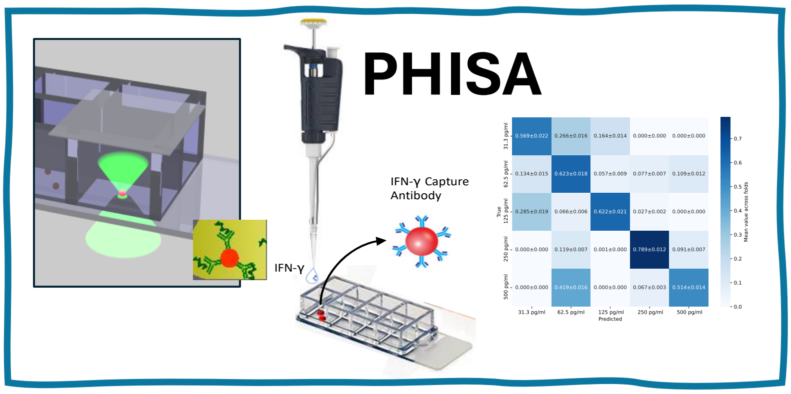
keywords

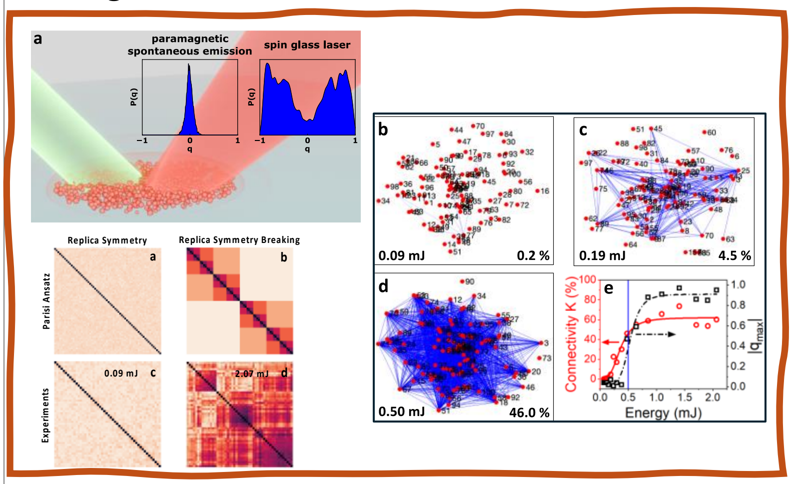
- *Microlaser*
- *Random Photonics*
- *Biosensing*

Research topics

We successfully use polymeric **whispering gallery microlasers as biosensors** for detecting small amounts of proteins. They have the advantage of working in free space without any need for waveguiding for input excitation or output signal detection.

Highly accurate, label-free and specific detection is realized by using a photonic immunosorbent assay based on microlasers. Limit of detection for interferon gamma is 10 pg mL^{-1}. Spectra are classified with machine learning and AI assisted biosensor is developed for antigen testing.





Random lasers have been proposed as excellent photonic counterparts of spin glasses with robust **replica symmetry breaking** features.

We experimentally investigate the ultrametric structure of the replica space with clustered domains, as predicted in the Parisi Ansatz. We are working on graph representation and network analysis.

Nicoletta Gnan

Sapienza unit

contacts

Nicoletta.gnan@cnr.it
Office: Dept. of Physics, Fermi Building , room 111
https://sites.google.com/view/nicolettagnan/home?authuser=0

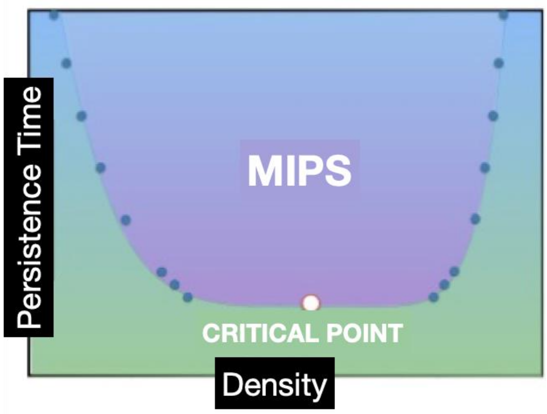
keywords

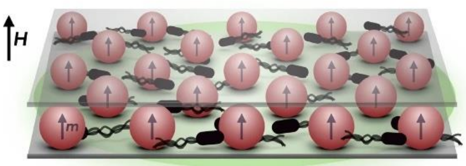
- *Modelling and Simulations of Soft Matter*
- *Statistical Mechanics*
- *Active Matter*

Research topics

Active matter at the micron scale includes systems, from bacteria to self-propelled colloids, that consume energy to move and self-organize into complex structures. Through large-scale simulations and theory, I aim to understand and control their collective behavior and phase transitions.

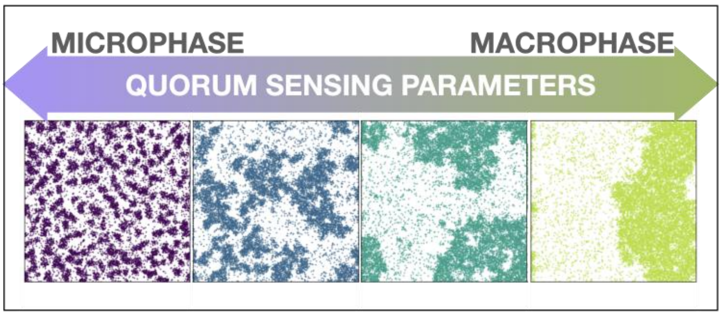
Phase transitions and criticality are central to equilibrium statistical mechanics, but extending these concepts to active matter can challenge our understanding of universality and scaling. My research has focused on whether critical behavior emerges at the endpoint of motility-induced phase separation (MIPS) and on understanding how non-equilibrium dynamics modify critical signatures.





Melting in active solids ranges from KTHNY-like transitions to entirely non-equilibrium pathways when non-reciprocal interactions take place. My research focuses on the melting dynamics of colloidal crystals driven by bacteria, aiming to characterize and understand how activity alters the melting scenario.

Active field theories predict phenomena like microphase separation but it remains unclear how to realize these in particle-based models. I've chosen to study quorum sensing particles, since for this special case it is possible to establish a one-to-one mapping between theory and the model parameters.



Andrea Gnoli

Sapienza unit

CNR-ISC

contacts

andrea.gnoli@cnr.it
Laboratory: Fermi Building, room 012
https://www.isc.cnr.it/staff-members/andrea-gnoli

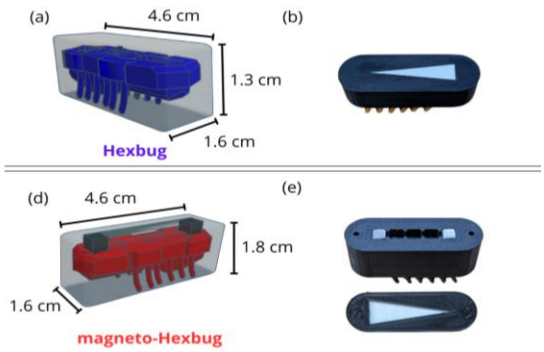
keywords

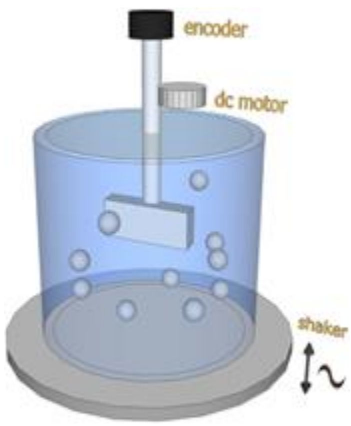
- *Granular materials*
- *Active matter*
- *Brownian motors*

Research topics

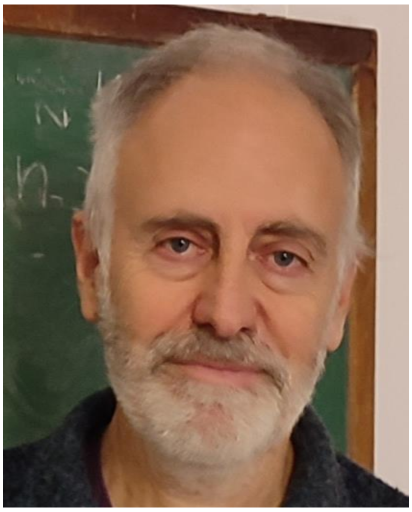
Granular materials are made of macroscopic grains like sand, salt, powders. Experiments on granular materials are able to prove interesting theories in the field of nonequilibrium statistical physics. In the Granular Chaos Laboratory, we realize many different experiments in various configuration, such as 1d, 2d and 3d, using beads of many sizes and various materials. With the aid of high-speed video cameras we can even reconstruct the trajectories of single grains gaining information on the behavior of the material as a whole.

With the aid of various 3d printers, that are at the core of the 3d printing service, we realize self-propelled particles. Self-propulsion is obtained by using geometric asymmetries while tailored shells, used for tracking and for housing small magnets (for the study of magnetic interactions) are made for existing mini bots (also known as hexbugs).





Brownian motors are a class of devices that extract useful work from noise. Such an extraction, which is impossible in the classical equilibrium thermodynamic framework, is made possible through the use of granulars that are, by definition, in non equilibrium conditions. The rectification of fluctuations is challenging from the experimental point of view and the final direction of motion is not easily predicted without a suitable theoretical model.



José Lorenzana

Sapienza unit

CNR-ISC

contacts

jose.lorenzana@cnr.it
Office: c/o Dip. di Fisica, Sapienza,
Piazzale Aldo Moro 2, I-00185 Rome
https://sites.google.com/view/jose-lorenzana/home

keywords

- *Quantum materials*
- *Superconductors*
- *Non-equilibrium physics*

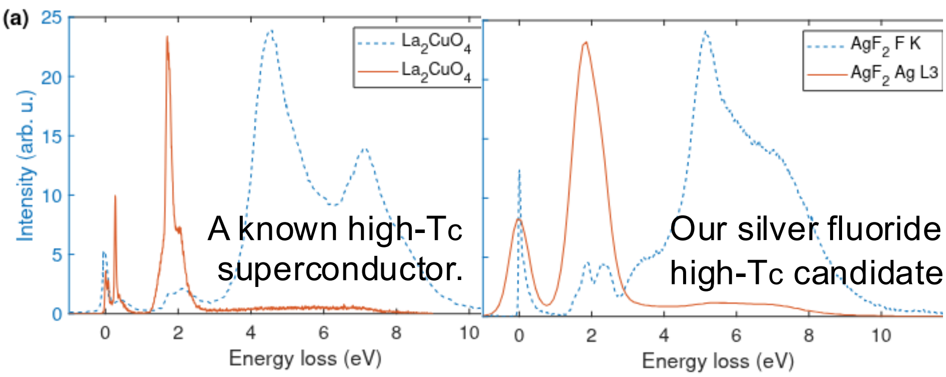
Quantum Materials

My main interest are quantum materials intended as systems in which different quantum phases compete producing unusual collective behavior. While my carrier has been in theoretical physics in the last years, I have shifted also to experimental studies building interdisciplinary groups in collaboration with experienced physicists and chemists.

The quest for new Superconductors

Superconductivity can foster quantum technologies so to develop and understand new and unconventional materials can expand our quantum materials toolbox. We are exploring nickel hydrides and silver fluorides as possible new high Tc superconductors. In addition, we have investigated the superconductivity mechanism in very low-density materials.

Find the differences: The electronic structure of a silver fluoride and a cuprate look identical according to advanced spectroscopy techniques (RIXS). Could silver fluorides be the next generation of high-Tc materials?

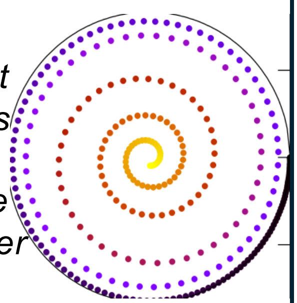


Non equilibrium for quantum technologies

"Forget about the transient and concentrate on the equilibrium state" is not anymore true. For quantum technologies the transient is the device!. We study superconductors very far from equilibrium and how to keep them there.

Snapshot of the of an out-of-equilibrium superconducting wave function.

Each point represents amplitude and phase of a Cooper pair.



Stefania Melillo

Sapienza unit

CNR-ISC

contacts

stefania.melillo@cnr.it
Office: Physics Department – Sapienza University
CU 033 – Room 412
http://cobbs.it

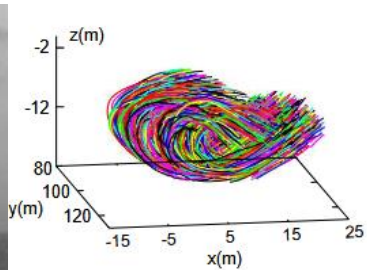
keywords

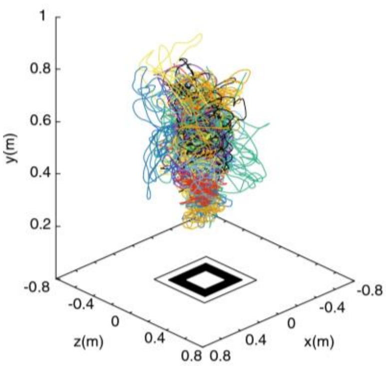
- *Collective Behavior*
- *Physical Biology*
- *3D Experiments*

Research topics

Collective behavior is a widespread phenomenon in nature. Flocks of birds, swarms of insects, colonies of cells, they all share a common trait: the presence of long range correlation, which allows individuals to influence each other on large scales even in the absence of a leader. How individuals interact with each other and following which mechanisms it gives rise to such correlation? To answer these questions, we need data.

I coordinate 3D experimental activities at CoBBS group. We collect 3D data on starling flocks and midge swarms in their natural environment, and develop computer vision and tracking software, to reconstruct the 3D trajectory of each individual in the group.





We recently opened a new line of research. We defined an experimental protocol to collect 3D data on lab-adapted Malaria mosquitoes (*Anopheles Gambiae*) swarming in a large cage. With this setup, we were able to benchmark wild-type swarms and observe mating events and male-male competition, never documented before at the 3D level within a swarm. We also discovered that, unexpectedly, malaria swarms exhibit features different from midge swarms.

Mosquito-borne diseases pose a severe threat to global health, against which gene drive is offering new hope. We are now developing a new technology, which will allow performing reliable tests on the efficacy of modified genes.

Mauro Missori

Sapienza unit

CNR-ISC

contacts

mauro.missori@cnr.it
Office: Physics Dept, Fermi Building CU033, room 409
https://www.isc.cnr.it/staff-members/mauro-missori/

keywords

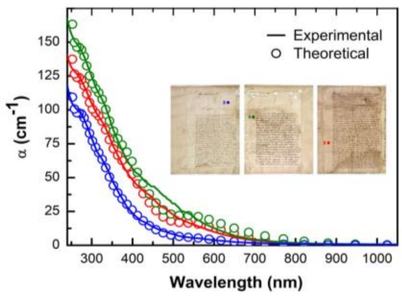
- *Physics applied to cultural heritage*
- *Optics of inhomogeneous media*
- *THz spectroscopy and imaging*

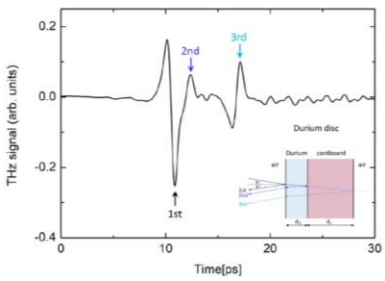
Research topics

My interdisciplinary research focuses on investigating materials using electromagnetic radiation (UV, Vis, IR, THz). I develop methods to study inhomogeneous materials made of fibers, nano/microparticles, and metamaterials. Applications include non-invasive diagnostics of cultural heritage and extend to spectroscopy, photonics, and soft matter.

Advancing Spectroscopic Methods for Heritage Science

I use non-invasive optical spectroscopy (UV, Vis, NIR) to study artworks. My research advances fiber optic reflectance spectroscopy (FORS) for quantitative analysis, focusing on colorant concentration and material degradation through Kubelka–Munk theory and DFT simulations.



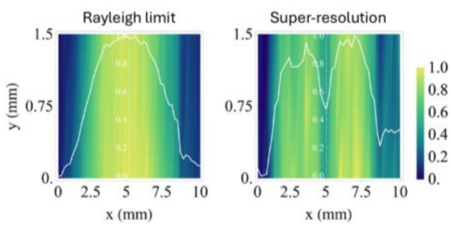


THz Spectroscopy and Imaging for Nondestructive Testing

Terahertz (THz) spectroscopy and imaging enable nondestructive testing of layered and composite materials. THz radiation penetrates dielectrics, allowing internal inspection without contact or damage. It reveals hidden structures and layer thickness in artifacts and materials.

THz Photonics

Pulsed THz emission enables the study of diffusive propagation in disordered photonic structures through phase and velocity measurements. It also allows investigation of Fano resonances and bound states in the continuum (BIC) in dielectric metamaterials. Structured illumination techniques achieve super-resolution beyond the Rayleigh limit in THz imaging.



Marco Montuori

Sapienza unit

CNR-ISC

contacts

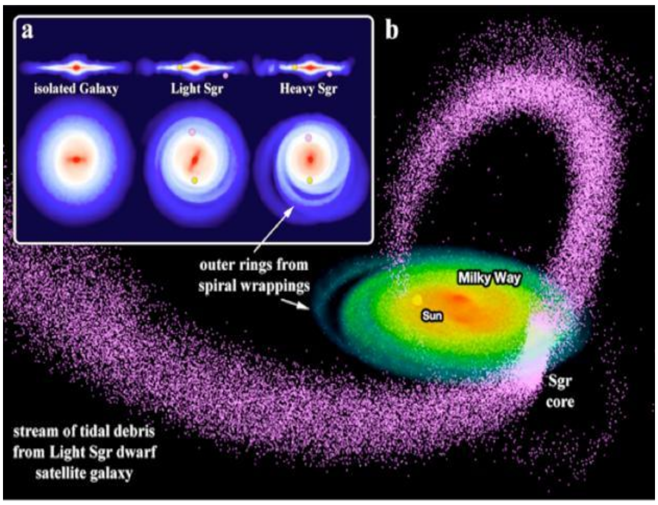
Marco.montuori@cnr.it
Office: room n. 510, Fermi Building, Physics Dept
http://website.address

keywords

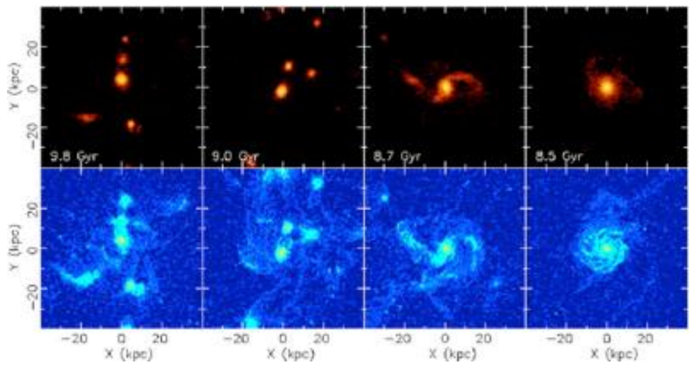
- *Milky Way structure and dynamics*
- *Galaxy formation and evolution*
- *N-body simulations and data analysis*

Galaxy formation and evolution

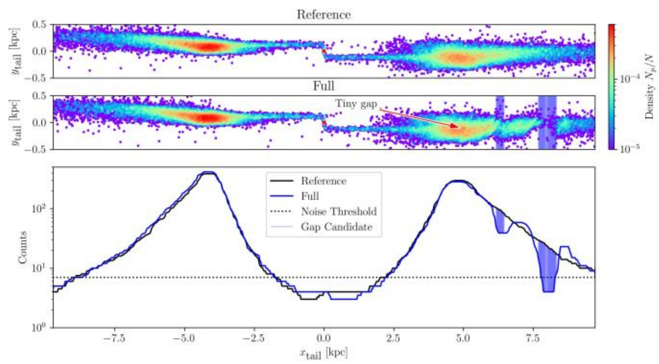
The Milky Way as other galaxies, is an evolving system, due to internal and environmental processes as well. There is not a unique process for the formation of different galactic components, but very likely several process at (maybe ?) different times. Through numerical simulation and observational comparison we are exploring the formation and evolution of Milky Way



Milky Way structure and substructure



Dark matter constitutes a fundamental component of galaxies. The tidal tails of the Milky Way's globular clusters serve as powerful probes for investigating its properties. Comparative analysis of observations, theoretical models, and numerical simulations can provide critical insights into the nature of dark matter on galactic scales.



Andrea Ninarello

Sapienza unit

CNR-ISC

contacts

andrea.ninarello@cnr.it
Office: Fermi building - 206
https://scholar.google.com/citations?user=eT2C-boAAAAJ

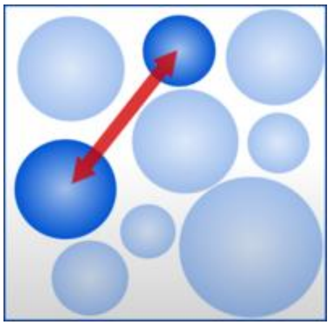
keywords

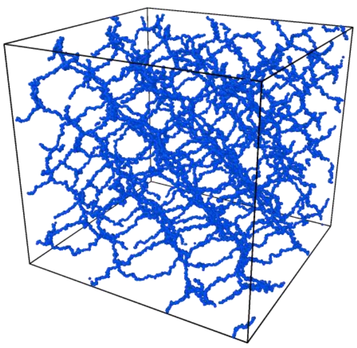
- *Supercooled Liquids and the Glass transition*
- *Polymer Networks and Microgels*
- *Computational Methods for Soft Matter Physics*

Research topics

My research focuses on the theoretical and computational study of soft matter, particularly glasses and polymers. I'm interested in how microscopic interactions lead to complex collective behavior, such as the glass transition, slow dynamics, and mechanical response. I use molecular dynamics and Monte Carlo simulations as well as machine learning tools to explore these phenomena across multiple scales.

I use advanced Monte Carlo methods to equilibrate supercooled liquids at exceptionally low temperatures, enabling in-depth analysis of their thermodynamic and structural properties. This allows me to study key quantities like configurational entropy, vibrational density of states, and energy landscape topology near the glass transition.





I develop and employ computational models to investigate how hydrogels and microgels respond to environmental stimuli. By tuning their structure and crosslinking, I uncover how these factors affect swelling and mechanical behavior. I focus on how topology influences thermoresponsiveness and how thermodynamics drives unique mechanical responses, helping to design smart, responsive polymer materials.

I exploit generative artificial intelligence to efficiently sample equilibrium states in soft matter, fostering access to challenging regimes like criticality and glassiness that are difficult to reach with traditional simulations.

Valentina Palmieri

Sapienza unit

CNR-ISC

contacts

valentina.palmieri@cnr.it
Office: Physics Institute, Catholic University of Sacred Heart
https://www.isc.cnr.it/staff-members/valentina-palmieri/

keywords

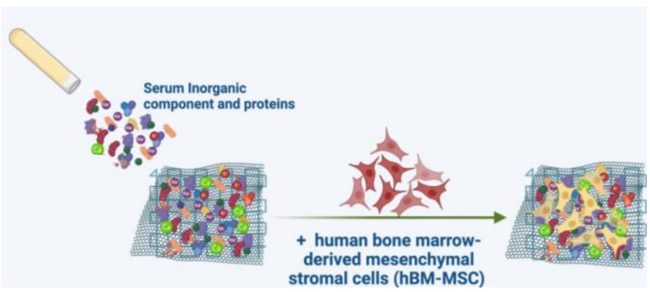
- *Nanomedicine for cancer therapy*
- *3D printing and laser printing of graphene*
- *Bacterial interactions with nanomaterials*

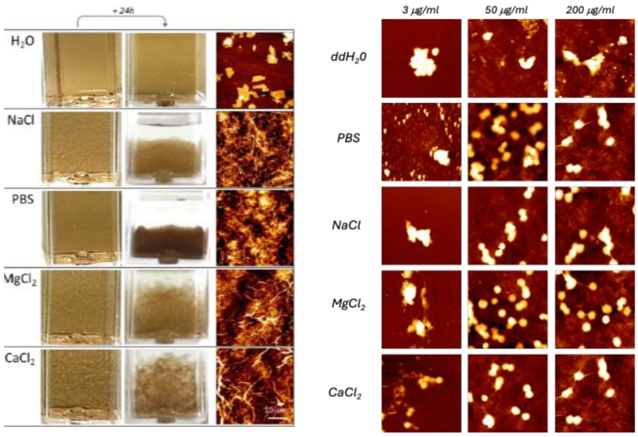
Graphene Oxide Protein Corona

Graphene oxide (GO) is a two-dimensional nanomaterial characterized by a sheet-like carbon structure functionalized with oxygen-containing groups, which confer high hydrophilicity, a large specific surface area, and pronounced chemical reactivity. These properties make GO a highly promising candidate for biomedical applications.

In the presence of bodily fluids, GO can selectively adsorb proteins, leading to the formation of the so-called protein corona, which significantly influences its biocompatibility and the immune response of the host. In the context of personalized medicine, the use of GO as a tunable surface has opened new perspectives for controlling protein adsorption and cellular response according to individual patient characteristics. These studies have led to the development of a project focused on 3D-printable bone implant biomaterials, with optimized properties obtained through laser printing techniques. Such techniques enable the microstructuring of the GO surface, locally modifying its chemistry and the selective adsorption of osteoconductive salts and proteins.

2D Materials, 2017 5(1) 015027
Materials Today Bio 25 (2024) 100986
Mater. Adv., 2024, 5, 4772-4785

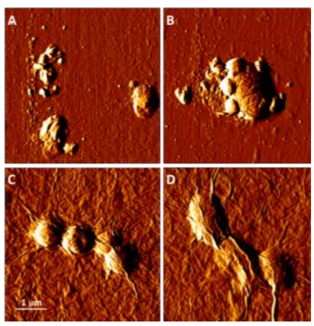




Graphene oxide and bacteria

GO has also specific interactions with microorganisms, closely linked to its colloidal stability, surface charge, and sheet size. At low concentrations, GO can compromise the integrity of microbial cell membranes through cutting (A-B), while at higher concentrations it tends to form stable complexes with bacteria through a mechanism known as trapping (C-D), which can selectively inhibit or, in some cases, promote bacterial proliferation. This biphasic behavior has been confirmed in clinically relevant pathogens such as Staphylococcus aureus, Mycobacterium tuberculosis, and SARS-CoV-2.

ACS Biomaterials Science & Engineering 2017 3(4), 619-627
iScience 24, 102788 July 23,
Nano Today, 100883, 2020
Carbon 194, 34-41, 2022



Oriele Palumbo

Sapienza unit

CNR-ISC

contacts

oriele.palumbo@cnr.it
Office: Physics Dpt, Marconi Building, room 311 or 359
http://www.sapienza.isc.cnr.it/your-details/userprofile/oriel.html

keywords

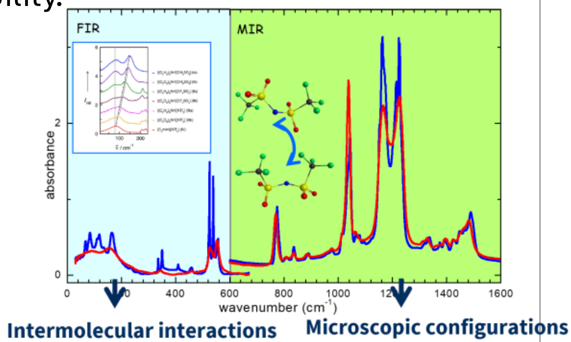
- *Spectroscopies*
- *Innovative materials for energy storage*
- *Inter- and intra-molecular interactions*

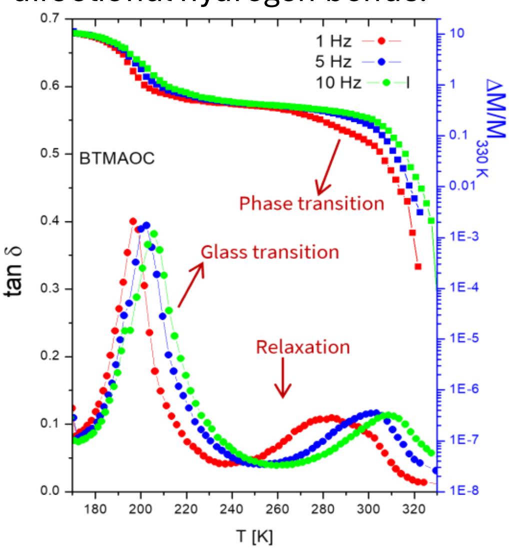
Green and sustainable solvents

Ionic liquids (ILs) and deep eutectic solvents (DES) are largely studied for their properties, such us low vapor pressure, high ionic conductivity, high stability and good solvent capacity, which make them particularly relevant in energy storage and electrochemistry applications as well as in biomedical applications. These properties can be tailored by means of a proper choice of the composing units in pure ILs or of the components in mixtures.

A deep understanding of their microscopic properties and of the interactions within their components is fundamental in order to master such possibility.

Our research uses vibrational (IR) and mechanical spectroscopies combined with ab initio simulations to provide information about the microscopic configurations, the phase transitions, the dynamics and the kind of interactions occurring in the system, particularly focusing on the presence of strong and directional hydrogen bonds.





IR results showed the evidence of the CH···O hydrogen bonding in imidazolium ILs, while, in DES, IR combined with ab-initio calculations highlighted the role that hydrogen bonding plays in the lowering of their melting temperature which is the typical DES signature.

The development of an innovative technique to study the mechanical spectrum of ionic liquids by means of a DMA provided results which shed light on the effect of conformational flexibility on the properties of ionic liquids.

Annalisa Paolone

Sapienza unit

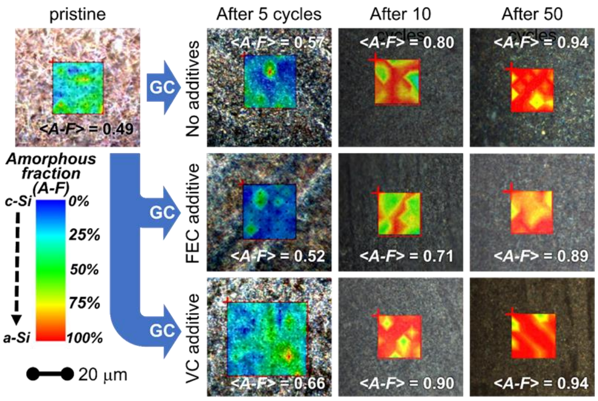
contacts

annalisa.paolone@cnr.it
Office: Physics Department, Sapienza University, Building Marconi, room 311 or 359
https://www.researchgate.net/profile/Annalisa-Paolone

keywords

- *Spectroscopies*
- *Innovative materials for energy storage*
- *Innovative materials for gravitational wave detectors*

Innovative materials for energy storage

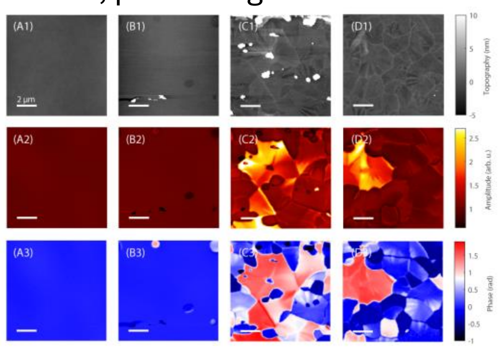


Energy storage is extremely important as renewable energies are intermittent and non predictable. Surplus energy obtained by renewable means must be stored to be available when needed. The investigation of materials for energy storage is valuable both for the basic understanding of the mechanisms behind their applications and for the optimization of performance. In my research group, one of the research lines is dedicated to the storage of energy in lithium and post-lithium batteries.

One intriguing field of investigation is the development of a thin layer, called Solid-Electrolyte Interphase (SEI), which develops during battery use due to the decomposition of the electrolyte and preserves the electrode material. Its composition and mechanical properties must be finely tuned, and indeed, in our group, we investigated by means of spectroscopic techniques the composition of the SEI and the amorphization of the electrode material.

Another active field is the investigation of the hydrogen absorption properties of innovative materials. In this context, we studied some high-entropy alloys formed by five equimolar metals and found promising hydrogen content and, in some cases, promising kinetics of absorption.

I am involved in the search for innovative materials that could improve the sensitivity of gravitational wave detectors; the presence of argon left by the synthesis in the amorphous structure and the occurrence of local defects or crystallization have a negative impact. I actively contribute to this field by mass spectrometry and near-field infrared spectroscopy investigations.



Leonardo Parisi

Sapienza unit

contacts

leonardo.parisi@cnr.it
Office: Physics Department, Sapienza University
CU033 Building, Room 412
http://www.cobbs.it

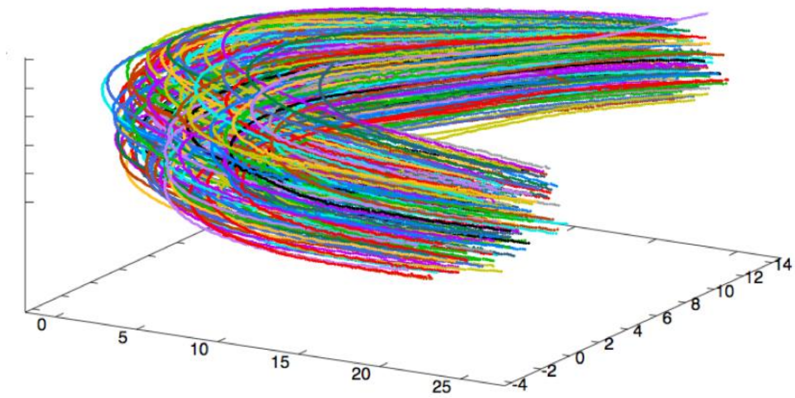
keywords

- *Collective Behavior*
- *Physical Biology*
- *Computer Vision*

Research topics

I was born as a computer scientist and over the years have specialized in the study of **collective behavior**. I have always believed that a solid foundation in computer science could open doors in any field, and so far I haven't been wrong. I have specialized in **computer vision** and particularly in **3D tracking**. Over the years I have applied these skills in various fields: from studying insect swarms to bird flocks to tracking space debris.

In recent years I have been a member of the CoBBS group, which studies collective animal behavior through stereometric experiments conducted both in the field and in the laboratory. These studies require advanced computer vision software for both detection and 3D tracking. Historically, the group has been involved in studying s**warms of midges** and **flocks of starlings**.



More recently we have established two new research lines. One on **malarial mosquito** swarm behavior and the other on **cell colony** dynamics. Within the CoBBS Lab, I am among those responsible for designing and organizing experimental activities, with a focus on developing the software and electronics needed for laboratory operations and data analysis.

Andrea Puglisi

Sapienza unit

CNR-ISC

contacts

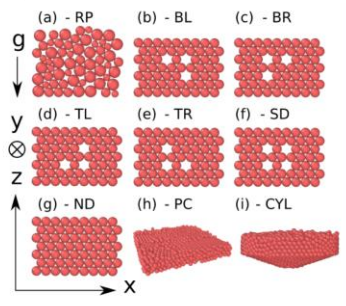
andrea.puglisi@cnr.it
Office: p.le A. Moro 2, c/o Dip. Fisica Sapienza, Ed. Fermi, stanza F406
https://sites.google.com/view/andrea-puglisi-physics

keywords

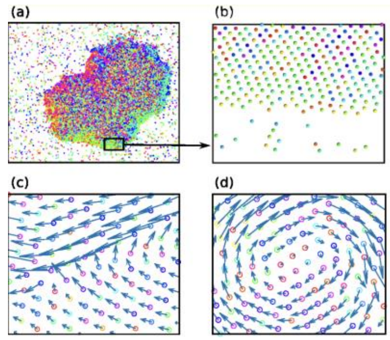
- *Out-of-equilibrium statistical mechanics*
- *Stochastic Processes*
- *Complex matter (granular , sperms, etc.)*

Research topics

I have studied for many years the statistical mechanics of fluidized granular materials (kinetics, hydrodynamics, structure, non-equilibrium properties). Building upon my experience with granular models, I have investigated some problems in the more general field of non-equilibrium statistical mechanics for steady states (fluctuation-response relations, large deviation theory for stochastic processes, fluctuations of currents and entropy production).

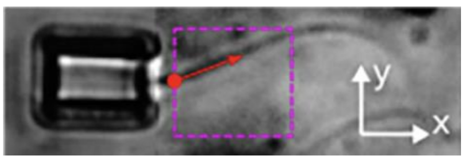


From 2010, I have set up a laboratory where I led sever experiment with vibro-fluidized granular materials. A second line of research developed between 2005-2015 has been the study, through information theory and agent-based models, of the dynamics of language.



Since 2016 I started a new line of research in active matter, that is matter made of simple self-propelling units (bacteria, birds, cars) which display fascinating collective motion. Starting in 2019 I led several experiments and theoretical investigations on the physics of sperms. These “particles” are fascinating micro-motors converting ATP fuel into beating of the tail with a periodic travelling wave pattern decorated by complex out-of-equilibrium fluctuations.

Since 2024 I am the Principal Investigator of the PRIN Project SNO-MINK dedicated to non-equilibrium inference, that is understanding if systems are dissipative or not by only looking to few observables. The team of the project includes other colleagues of ISC and colleagues from Sapienza and Vanvitelli Universities.



Tommaso Rizzo

Sapienza unit

CNR-ISC

contacts

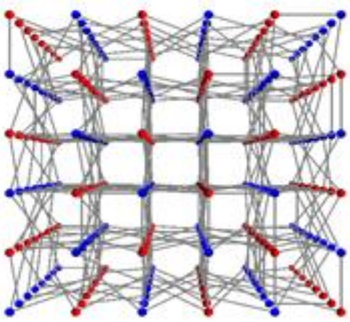
tommaso.rizzo@cnr.it
Office: Room 309, Fermi Building, Sapienza University

keywords

- *Disordered Systems*
- *Supercooled liquids and Glasses*
- *Spin-Glass*

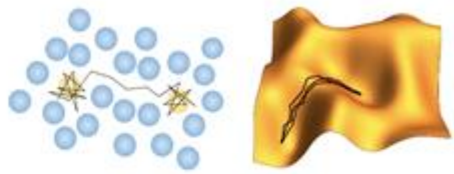
Research topics

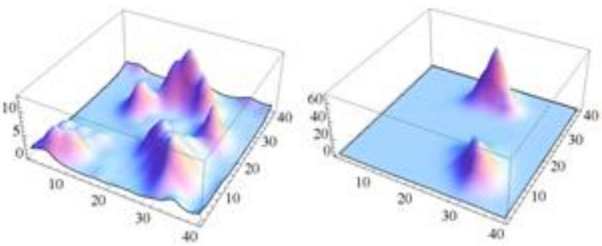
Disordered systems and glasses are pivotal in statistical physics for exploring non-equilibrium dynamics, metastability, and complex energy landscapes. They challenge traditional ordered-phase theories, revealing universal behaviors like aging and avalanches. Studies of spin glasses, structural glasses, and amorphous materials deepen our understanding of emergent disorder-driven phenomena, with applications in artificial intelligence, biophysics, and material science.



Key models in disordered statistical physics include the Sherrington-Kirkpatrick spin glass for frustration, Edwards-Anderson for local disorder, and Random Energy Model for extreme landscapes. Mean-field glasses (Mode-Coupling Theory) and RFIM (random-field Ising) capture metastability, avalanches, and non-equilibrium dynamics, bridging theory and amorphous materials.

I investigate these systems—along with kinetically constrained models—using a range of analytical and numerical approaches, such as the replica and cavity methods, dynamical field theory, Monte Carlo simulations, and path integral techniques.





Fundamental questions driving my research include: What governs the glass transition? How does the spin-glass transition manifest in finite dimensions?

Barbara Ruzicka

Sapienza unit

CNR-ISC

contacts

barbara.ruzicka@cnr.it
Office: Physics Department, Sapienza University
CU033 Building, Room 110
https://www.roma1.infn.it/~ruzickb/

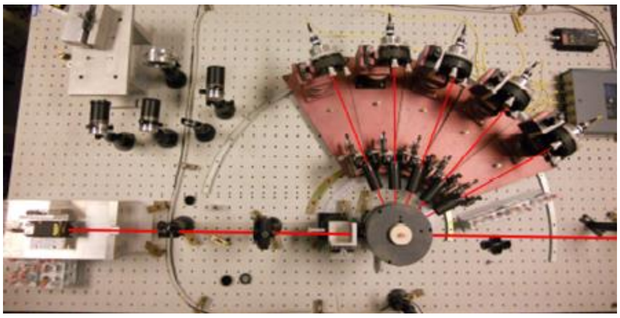
keywords

- *Soft Matter*
- *Dynamic Light Scattering*
- *Neutron & X-ray Scattering*

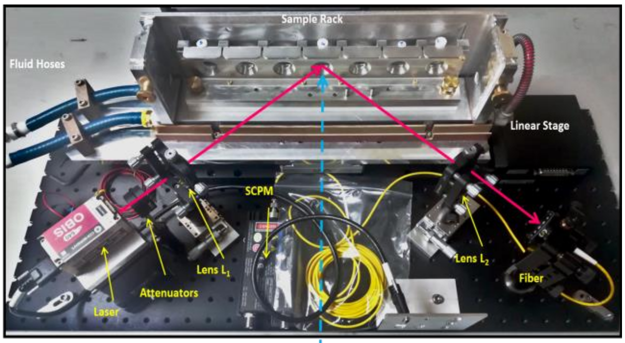
Research topics

Structure and dynamics, phase diagram and gel/glass transitions of soft matter systems.

Structure and dynamics are investigated through conventional, synchrotron and neutron techniques. Measurements are performed in the Soft Matter Laboratory: Light Scattering, where Dynamic Light Scattering (DLS), Multiangle DLS and Multispeckle DLS techniques are available (see Figure). These are complemented by Large Scale Facilities techniques such as Small Angle X-ray (SAXS) and X-ray Photon Correlation Spectroscopy (XPCS) and Small Angle Neutron Scattering (SANS).
A new DLS-SANS setup, that permits simultaneous measurements of the dynamics and structure of the samples, has been designed and implemented and is now available at ISIS neutron source (see Figure).



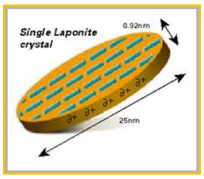
Multiangle DLS



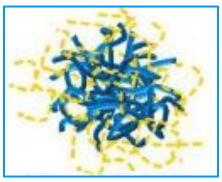
DLS – SANS Setup

In particular, the investigated systems range from hard to soft colloidal particles, to biomolecules and proteins, to complex fluids, for the understanding of their physical properties and for their application in health & biopharma, in bioengineering and in nanodevices.

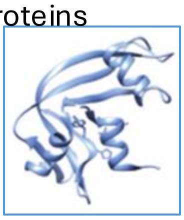
Laponite



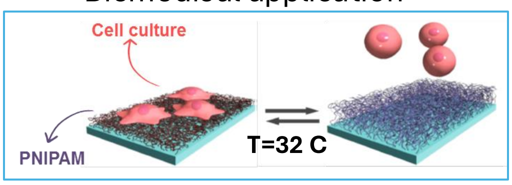
Microgels



Proteins



Biomedical application



Antonio Scala

Sapienza unit

CNR-ISC

contacts

antonio.scala@cnr.it
Office: Fermi Building, 510
https://iris.cnr.it/cris/rp/rp24367

keywords

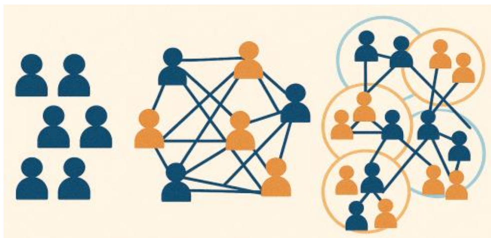
- *FIsica Statistica e Computazionale*
- *Social Media e Network Economy*
- *Modelli a supporto delle Decisioni e del Policy Making*

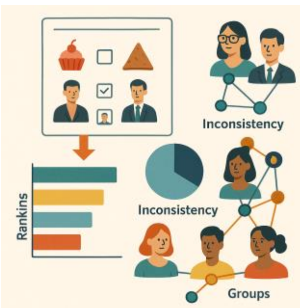
Research topics

Antonio Scala ha conseguito la Laurea in Fisica presso l'Università di Napoli "Federico II" e un PhD in Fisica della Materia Condensata alla Boston University. Ricercatore senior presso l'Istituto per i Sistemi Complessi del CNR, lavora nei campi della fisica statistica, delle reti complesse, della fisica computazione e dei sistemi socio-tecnici.

Le sue ricerche recenti si articolano lungo tre linee principali:

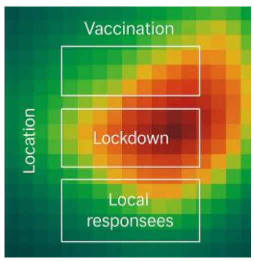
Reti sociali e valore delle piattaforme
Studia come le piattaforme digitali crescono in valore attraverso la formazione di gruppi e comunità, superando i modelli tradizionali di network effect.





Decisioni distribuite con informazione incompleta
Sviluppa metodi matematici (es. AHP sparso) per supportare decisioni collettive anche in contesti con dati parziali, come logistica, emergenze e pianificazione.

Modelli adattivi per epidemie
Propone strategie data-driven per la gestione dinamica di epidemie, combinando modelli epidemiologici con ottimizzazione di vaccini, lockdown e risposte locali.



Simona Sennato

Sapienza unit

contacts

Simona.sennato@cnr.it
Office: Physics Dept, Fermi Builing CU033, room 421
https://www.isc.cnr.it/staff-members/simona-sennato/

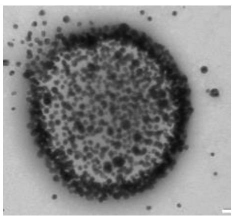
keywords

- *soft colloids*
- *colloidal aggregation*
- *biomimetic membrane systems*

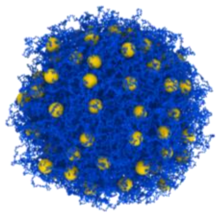
Research topics

My activity is devoted to the experimental investigation of physico-chemical mechanisms driving the self-assembly of supramolecular structures in aqueous dispersions, with special attention to soft colloids which can be tailored for developing nano-biotechnological applications.

Soft plasmonic microgels-nanoparticles complexes: from fundamentals to applications



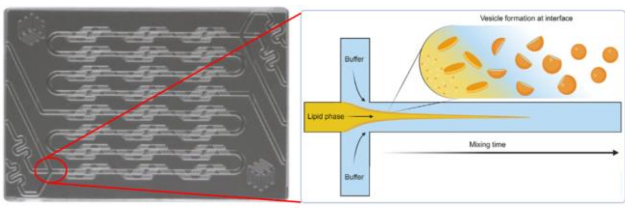
The complexation of plasmonic nanoparticles and thermoresponsive microgels is investigated to understand their micro and macroscopic features and provide the elements for the rational design of hybrid systems with tunable optical properties for sensing applications. Experiments are complemented by numerical simulations, in collaboration with E. Zaccarelli (CNR-ISC).



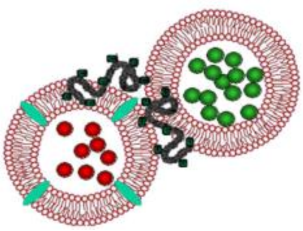
Brasili, F et al.
ACS AMI , (2023)

Protocols for the controlled synthesis of colloidal particles by microfluidics.

On-chip approaches are used for the fabrication of liposomes, polymeric nano- and micro- particles and metallic nanoparticles and for investigating their interaction with other macromolecules in controlled and confined environments.



Liposomes & lipid assemblies for drug delivery application.



By light scattering, microscopy and spectroscopy, supramolecular structures based on lipid vesicles (liposomes) able to deliver biologically active substances, also from natural source, and drugs, are studied, with particular focus on therapy of infectious diseases. Thermodynamic and structural investigation of model lipid membranes by Langmuir trough is used to clarify specific aspects related to drug-membrane interaction.

Alessandro Taloni

Taurini unit

CNR-ISC

contacts

Nome.alessandro.taloni@cnr.it
Office: via dei taurini 19, 00185 Roma
https://www.isc.cnr.it/staff-members/alessandro-taloni/

keywords

- Anomalous diffusion
- Fractional Langevin dynamics
- Complex systems

Research topics

My research explores the physics of complex systems through the lens of stochastic processes, statistical mechanics, and interdisciplinary modeling. My work bridges theoretical physics with applications in biology, soft matter, and materials science. I have made significant contributions to the understanding of anomalous transport, elasticity, and the integration of AI in biomedical research. My approach combines analytical theory with computational tools to uncover universal principles in diverse systems.

I have developed theoretical frameworks based on the fractional Langevin equation to describe anomalous diffusion in confined and heterogeneous environments. These models are crucial for understanding transport in biological systems—such as intracellular dynamics and DNA motion—as well as in soft matter. My recent work extends these concepts to interpret Nuclear Magnetic Resonance (NMR) signals, offering new insights into molecular diffusion in complex media.

In the field of materials science, I have contributed to the understanding of frictional precursors, thermally activated fracture, and the mechanical behavior of micro- and nanoscale systems. I have also advanced theoretical models that extend classical elasticity, including a generalization of the Euler-Bernoulli theory for extensible elastica. My work provides a deeper understanding of how materials deform and fail under stress, with implications for both engineering and biological tissues.

I apply AI and machine learning to biomedical data, particularly in the context of neurodegenerative diseases. I am a key contributor to the European BEHIND-MS project, which investigates the role of Epstein-Barr virus in multiple sclerosis. My work focuses on developing predictive models using MRI and clinical data to assess disease progression, aiming to improve early diagnosis and personalized treatment strategies.

Massimiliano Viale

Sapienza unit

CNR-ISC

contacts

massimiliano.viale@cnr.it
P.le Aldo Moro, 2 c/o Sapienza Physics Department,
"E. Fermi" Building, Room 414
https://www.isc.cnr.it/groups/cobbs/

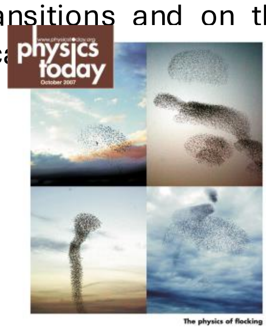
keywords

- *Collective Behavior*
- *Stochastic Processes*
- *Out-of-Equilibrium Statistical Mechanics*

Research topics

I earned my PhD in physics on disordered systems and optimization algorithms inspired by the analogy between spin glasses and NP-problems. During my postdoctoral research and the subsequent ten years, I studied biological collective behavior, focusing on flocks of birds and swarms of midges.

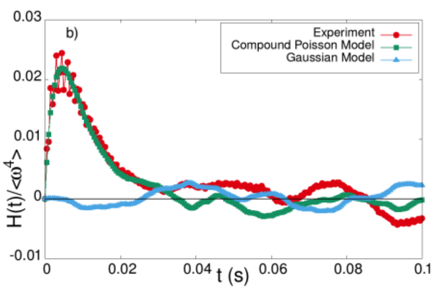
To analyze experimental data, infer the properties of these systems, and develop new theoretical models of collective behavior, I devised innovative multi-body tracking algorithms and statistical inference methods and I worked on the statistical mechanics of phase transitions and on the hydrodynamic approach to active matter, checking all through extensive numerica



Interaction ruling animal collective behavior depends on topological rather than metric distance
Proceedings of the national academy of sciences 105 (4), 1232-1237
Scale-free correlations in starling flocks
Proceedings of the National Academy of Sciences 107 (26), 11865-11870
Information transfer and behavioural inertia in starling flocks
Nature physics 10 (9), 691-696
Dynamic scaling in natural swarms
Nature Physics 13, 914–918

Currently I work on general issues concerning stochastic processes forced by not only Gaussian noise and on the possibility to infer effective models of real complex systems from incomplete information. In particular, I wonder what conditions allow me to determine whether a system is out of equilibrium or not if I can only observe a small portion of the phase space and have no information about the system's response to perturbations. By the way, I handle stochastic thermodynamics but I still have a complicated relationship with the concept of entropy production in non-physical models.

I also research on cilia and flagella in biology and on the mechanisms that allow them to swim.



Conceptual and practical approaches for investigating irreversible processes
New Journal of Physics 27 (4), 041201
Statistical features of systems driven by nonGaussian processes: theory & practice
Journal of Statistical Mechanics: Theory and Experiment 2023 (113202), 34
Revealing the nonequilibrium nature of a granular intruder
Physical Review Letters 131 (7), 078201
Inference of time irreversibility from incomplete information
Physical Review Research 4 (4), 043103

Emanuela Zaccarelli

Sapienza unit

CNR-ISC

contacts

emanuela.zaccarelli@cnr.it
Office: Physics Dept, Fermi building, room 106
https://www.roma1.infn.it/~zaccarel/

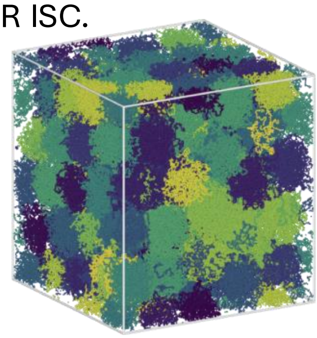
keywords

- *Multi-scale simulations of soft matter systems*
- *Microgels and polymer networks, proteins, biopolymers, colloids*
- *Effective interactions, structure and dynamics, elasticity and rheology*

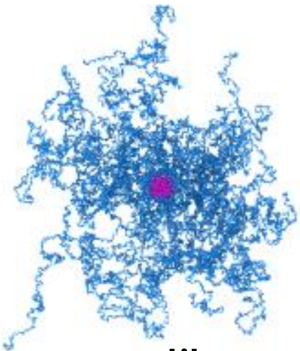
Research topics

My research activity is focused on **developing coarse-grained models for soft matter systems** able to describe experimental systems at quantitative level with the minimum number of ingredients. For this, I usually bridge the scale from atomistic to monomer or particle-resolved treatments, employing a variety of numerical simulation techniques, from Molecular and Langevin Dynamics to Dissipative Particle Dynamics. My simulations are often complemented by experiments also carried out at CNR ISC.

I recently established an ***in silico* model of polymer networks**, which quantitatively reproduces experimental thermoresponsive microgels in bulk and at interfaces. I am further exploiting this unique expertise to investigate:



many microgels

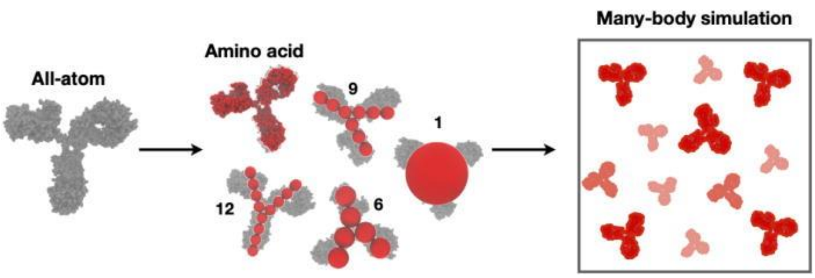


star-like

hollow

- the influence of **internal architecture** (from star-like to hollow and ultra-low-crosslinked) on the **collective behavior**
- how microgels interact with metallic nanoparticles to develop new **nanosensors**
- **hydrogels** and their interesting elastic properties at low crosslinker concentration

In collaboration with Lund University, I aim to be able to predict the **viscosity of monoclonal antibodies solutions** for improving drug administration. Our modeling includes key ingredients: anisotropic Y-shape and charge heterogeneity of the protein.



Andrea Zaccaria

Sapienza unit

CNR-ISC

contacts

andrea.zaccaria@cnr.it
Office: Stanza109, Edificio Fermi, Dipartimento di Fisica, Università Sapienza, p.le A. Moro 2, Roma
www.isc.cnr.it/staff-members/andrea-zaccaria

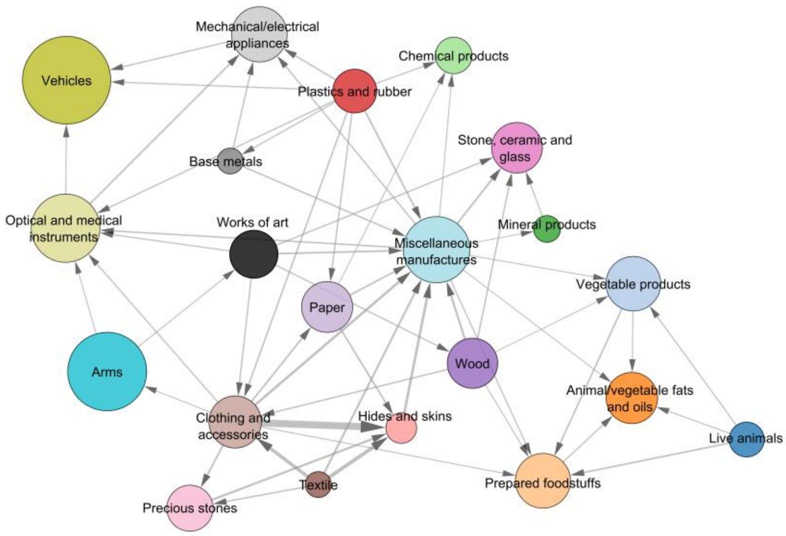
keywords

- *Economic Complexity*
- *Artificial Intelligence*
- *Complex Networks*

Research topics

Economic Complexity applies network theory and machine learning to economics, particularly to the study of the industrial and technological activities of countries and companies. These methodologies have been adopted by the European Commission and the World Bank Group for their policy analyses. My present research activity focuses on:

1. The introduction of a directed **network of products** and **machine learning** approaches to study and predict the development of countries and companies. This allows the assessment of products' feasibility and provides practical guidance for industrial policies.
2. Reconstruction of a **product-level input-output network** (see figure beside) based on a unique database reporting the imports and exports of companies. This permits a detailed analysis of the resilience of national and international **supply chains**.



3. A multipartite approach for the analysis of **the interplay among Science, Technology, and Production** to connect, for instance, the patenting activity of a given country with its industrial production with a time delay of up to 30 years.
4. Investigation of the relationship between the **diversification strategies of companies** and their **economic performance**. We have shown that companies that patent in a coherent way have higher productivity and that high-growth firms export products a) typically exported by wealthier countries or b) *outside* the respective core production area.

Guido Caldarelli

Taurini unit

contacts

Guido.Caldarelli@cnr.it / Guido.Caldarelli@unive.it
Office: Director office, Via dei Taurini 19, 00185 Rome
http://www.guidocaldarelli.com

keywords

- *Complex Networks*
- *Social Systems (Financial, Information, Historical)*
- *Materials*

Research topics

My main interest is in **complex networks**: theory and applications. I introduced a new model of growth based on quenched disorder, a new centrality called DebtRank for financial systems (used now by Central Banks in their stress tests) and a RG scheme based on Laplacian. I applied these theorretical frameworks to a variety of physical and social situations.

We have introduced a Laplacian **renormalization group** approach based on diffusion for analyzing complex networks. This method identifies meaningful spatiotemporal scales in heterogeneous networks. As in the original case we are able to decimate the original structure, defining supernodes at every passage of rescaling.

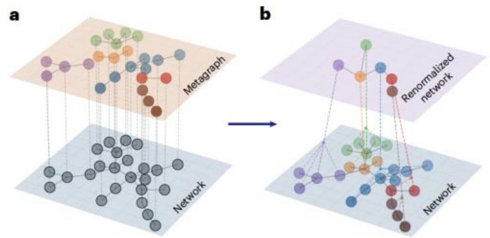
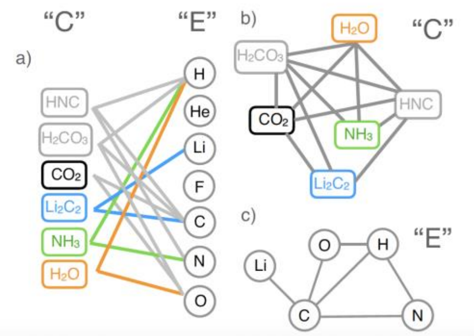
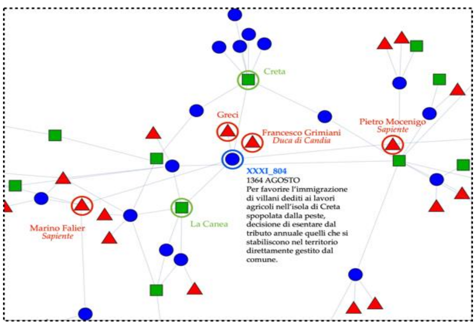


Fig. 2 | Sketch of the Kadanoff supernodes procedure. a, The lower layer shows the case of a BA network ($N = 24$, $m = 1$) and the upper layer shows ζ for $\tau = 1.96$. Different colours identify the Kadanoff supernodes. **b,** Each block becomes a single node incident to any edge of the original ones.



The use of Complex Networks can help also the quest for **new materials**, as the chemical space needs to be explored with innovative tecqniques that allow us to group together families of materials with the same properties. On this application, I am the founder of the spin-off company RARA Factory (http://rarafactory.tech)

My most recent project is based on the mapping of **Venetian society** across the years based on the documents of the State Archive of Venice. Thanks to these methodologies we have been able to discover the societal development of the Serenessima Republic of Venice, mapping in a quantitative way the importance of places, families, commerce in crucial times for the life of the Republic.



Andrea Cavagna

Taurini unit

CNR-ISC

contacts

Andrea.cavagna@cnr.it
Office: Via dei Taurini 19, room 411
https://www.isc.cnr.it/staff-members/andrea-cavagna/

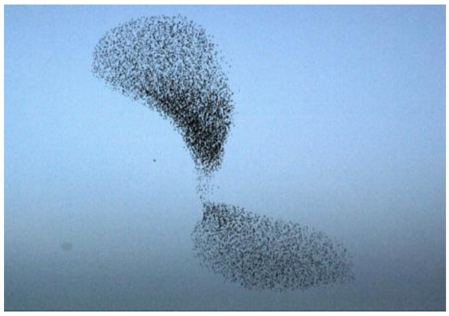
keywords

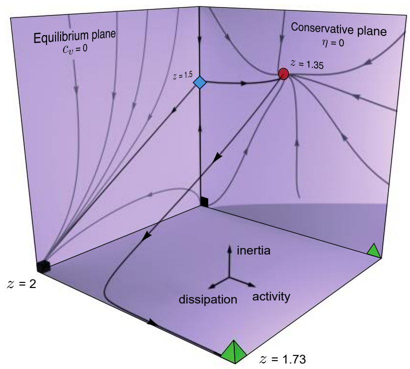
- *Statistical Physics*
- *Physical Biology*
- *Collective Behaviour*

Research topics

Collective behaviour in biological systems cuts across spatial and temporal scales: ranging from colonies of cells, up to insect swarms, and bird flocks, collective behaviour entails concepts as diverse as coordination, interaction, information transfer, and group decision-making. By conducting innovative experimental observations on bird flocks, insect swarms and cell colonies, my objective is to develop novel field-theoretical approaches.

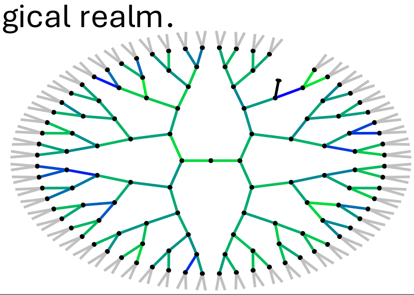
Flocks - I am developing a novel marginal field theory for the description of the dynamics of collective systems. The new non-linearities of the theory are akin to a Fermi-Pasta-Ulam-Tsingou dynamics, suggesting that directional information within natural flocks of starlings is transported by nonlinear solitary waves.





Swarms - My theoretical objective is to extend the Renormalization Group to off-equilibrium biological systems and prove that in presence of strong correlations, short-scale biological details can be disregarded and simpler, more general models can capture the essence of the phenomena. This is the gist of universality, a deep and very incisive concept in statistical physics, which I believe we may be ushering in to the biological realm.

Stem Cells - Surgical use of cell-material has attracted attention for more than 20 years, reflecting large and mostly unmet patient demand. We tackle this problem by assessing the in vitro clonal growth of bone marrow stromal cells and by studying the hereditary patterns they produce.



Claudio Castellano

Taurini unit

contacts

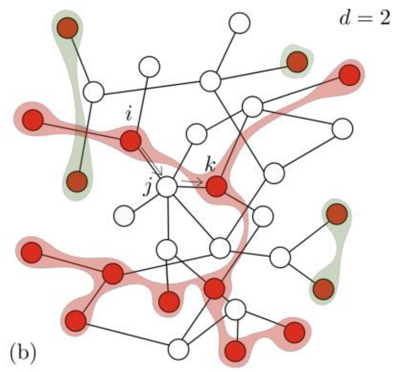
claudio.castellano@cnr.it
Office: Via dei Taurini 19, 00185 Roma, Room 409
http://sites.google.com/site/claudiocastellanohome/home

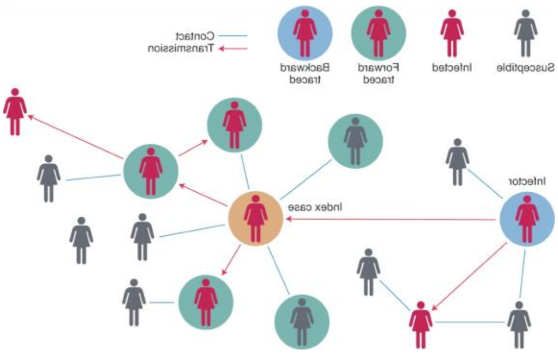
keywords

- *Complex networks*
- *Epidemic spreading*
- *Social dynamics*

Research topics

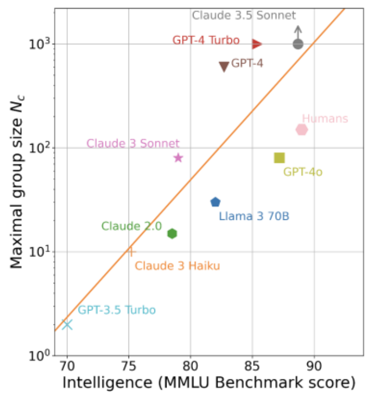
Percolation beyond nearest neighbors: Standard percolation theory assumes that two active nodes belong to the same cluster if there is a path of adjacent active nodes between them. Nontrivial processes, defined in a more general way, consider percolation clusters not necessarily coinciding with topologically connected components.





Spreading phenomena on networks: Pathogens, behaviors, innovations, news, rumors are transmitted via contacts between individuals and thus propagate in populations. How does the topology of interaction patterns affect spreading phenomena? What interventions can favor or hinder them?

LLM's opinion dynamics: Large language models (LLMs) are increasingly deployed in collaborative tasks involving multiple agents, forming an "AI agent society" where agents interact and influence one another. Whether such groups can spontaneously coordinate on arbitrary decisions without external influence—a hallmark of self-organized regulation in human societies—remains an open question.



Massimo Cencini

Taurini unit

CNR-ISC

contacts

massimo.cencini@cnr.it
Office: via dei Taurini 19, 00185 Roma
http://denali.phys.uniroma1.it/~cencini

keywords

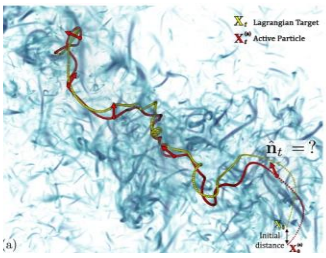
- *Turbulence and turbulent transport with data and equation informed approaches*
- *Chaos and dynamical systems*
- *Biological applications*

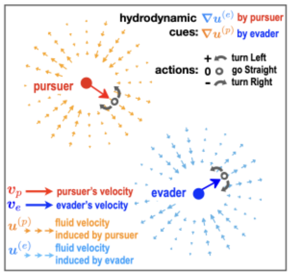
Control of swimming agents in fluid flows

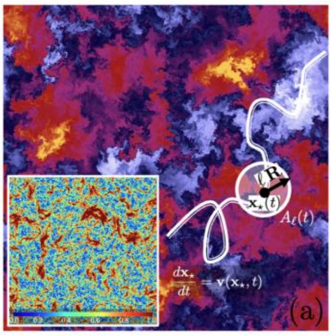
In the last five years I have been working on problems involving the control of agents in turbulent and laminar flows. These theoretical studies are relevant to applications e.g. to nano/micro medicine and to biological modeling, such as prey-predator interactions or animals searching for mating/food. The idea is that such agents have limited maneuverability and need to learn how to exploit cues (which could be hydrodynamical [1,2,3] or olfactory [4]) some tasks. I have used both reinforcement learning [1,2] and optimal control techniques [3,5]

We considered both single and multi-agent problems.

[1] F. Borra et al. Phys. Rev. Fluids 023103 (2022)
[2] C. Calascibetta et al. EPJE 46, 9 (2023)
[3] Comm. Phys. 6, 256 (2023)
[4] L. Piro et al. arxiv: 2025.11291 (2025)
[5] F. Borra et al. JSTAT 083401 (2021)





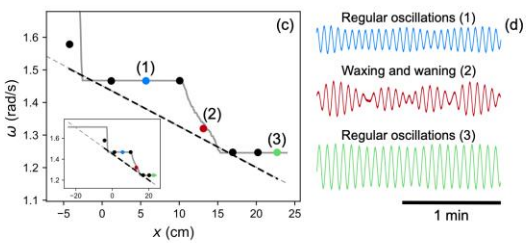


Hidden symmetries in hydrodynamics

In the last few years, a few studies have suggested that hydrodynamic field theories possess a hidden symmetry that can be used to rationalize anomalous scaling laws. Recently we have investigated the presence and consequences of such hidden symmetries in the case of passive scalar turbulence.

C. Calascibetta et al. arxiv 2504.11616 (2025)

Synchronization in biology Many biological tissues, such as e.g. mammals' intestine or pial arteriole, can be modeled as oscillatory media. In the presence heterogeneities these media can parcellate, i.e. form cluster synchronization. *M. Sellier-Prono, M. Cencini, D. Kleinfeld & M. Vergassola arxiv: 2502.09264 (2025).*



Roberto Coccurello

Taurini unit

CNR-ISC

contacts

roberto.coccurello@cnr.it
Laboratory of Neurometabolism and Neurodegeneration LNN) Santa Lucia Foundation (FSL) IRCCS - Via del Fosso di Fiorano 64 - 00143 Roma, Italia

keywords

- Neuroinflammation
- Obesity, metabolic dysfunction and CNS Interaction
- Neurodegeneration

Research topics

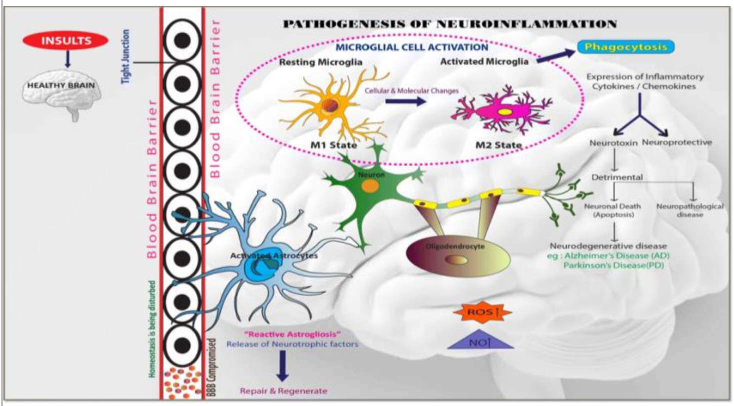
My research lies at the interface of **neuroscience, metabolism, and exploration of defective cognition**, with a strong translational focus on understanding the biological basis of complex disorders such as **neurodegeneration, obesity**, and **metabolic dysfunction**.

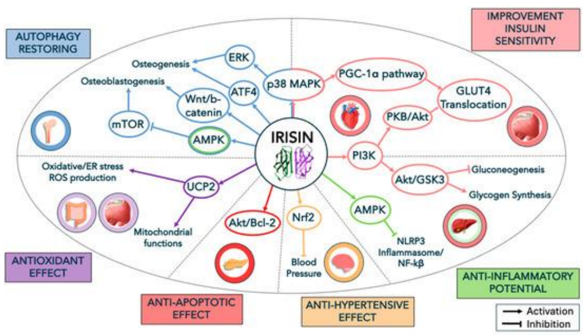
Neurodegenerative Diseases: Investigating the pathophysiology of Alzheimer's disease, with particular attention to tau protein alterations and potential therapeutic interventions, such as monoclonal antibodies targeting toxic tau fragments.

Metabolic Dysregulation: Exploring the mechanisms underlying weight gain and metabolic disturbances induced by atypical antipsychotics, utilizing murine models to elucidate these effects.

Energy Metabolism and Inflammation: Studying the role of purinergic receptors, particularly P2X7, in regulating energy expenditure and fatty acid oxidation, and their implications in metabolic disorders.

Exercise Physiology and Hormonal Regulation: Examining the multifaceted hormone irisin, produced during physical activity, and its potential therapeutic effects across various conditions, including metabolic disorders and neurodegenerative diseases. My research combines **in vivo behavioral neuroscience**, **molecular biology**, and **metabolic profiling.** I actively collaborate across institutional boundaries and disciplines, contributing to joint efforts that link **central nervous system disorders** with **peripheral metabolic signaling**. My commitment is to advancing basic research with **clinical and therapeutic relevance**, especially in the context of brain aging, cognitive decline, and systemic inflammation.





Fabio Cecconi

Taurini unit

CNR-ISC

contacts

fabio.cognome@cnr.it
Office: Via dei Taurini 19 (4th floor room 410)
http://denali.phys.uniroma1.it/~cecconif/

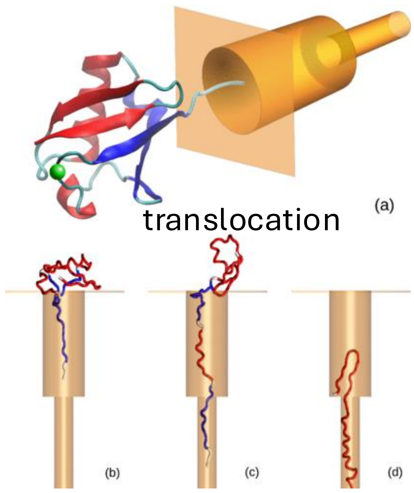
keywords

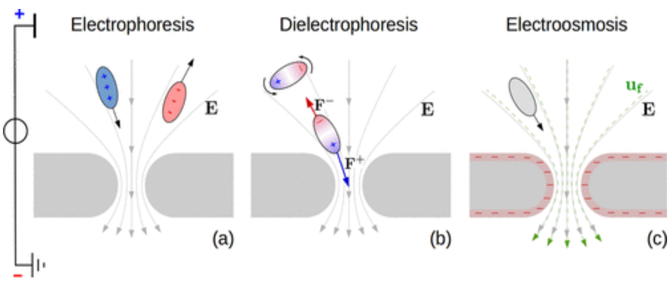
- *Nanotechnology*
- *Nanoscale pores*
- *Molecular transport*

Theory and simulation of Nanopore Technology

Nanopore transport is transforming science and technology with its ability to control the motion of molecules across nanoscale pores. Nanopores (NP) serve as powerful tools for sensing, sequencing, and filtering at molecular level. Applications include: biopolymer sequencing, drug delivery and advanced filtration. They enable real-time, label-free analysis of single molecules with exceptional sensitivity and speed.

We investigate NP transport to acquire fundamental knowledge and optimize the sensing process and pore architectures. Our approach integrates statistical mechanics, stochastic processes and bio-computation to describe the translocation dynamics of the molecules to be analyzed.

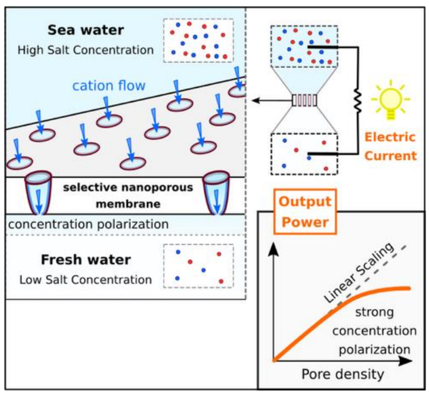




Capture process

We also study capture processes of analytes in NP by using basic principles of nanofluidics and electrochemistry.

Power extraction form salinity gradient due to the mixing of electrolyte solutions at different concentrations through selective NP-membranes is a promising application of NPs to renewable energy (Blue Energy). We studied how charge interference among NPs strongly limits their integration on membranes and the power extracted from devices.



Laura Fanfarillo

Taurini unit

CNR-ISC

contacts

laura.fanfarillo@cnr.it
Office: Via dei Taurini 19, room 408
https://laurafanfarillo.wordpress.com

keywords

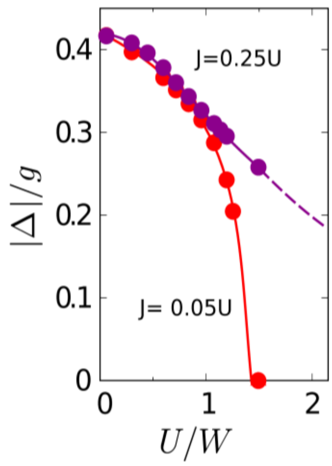
- *Superconductivity*
- *Strongly correlated electron systems*
- *Critical phenomena*

Research topics

We explore how complex interactions between electrons give rise to emergent quantum phenomena, using field-theoretical and analytical tools to uncover the organizing principles behind correlated materials.

Uncovering Collective Phenomena in Quantum Materials
We use advanced field-theoretical and analytical methods to explore the rich landscape of quantum materials. Our approach has provided new insights into a wide range of phenomena—from unconventional superconductivity and nematicity to transport anomalies and pair-density waves. By capturing the essential collective dynamics emerging from complex electronic interactions, our work deepens the understanding of quantum phases and supports the design of novel materials with tailored functionalities.

Exploring Complexity in Correlated Quantum Materials How strong electronic interactions shape the behavior of quantum materials? We develop theoretical tools to characterize strongly correlated electron systems, revealing how electronic correlations give rise to exotic metallic behavior, characterized by orbital selectivity and high-spin correlations. We analyze the interplay of electrornic correlations and superconductivity and demonstrated that the dynamical properties of Hund's correlated metal can enhance boson-mediated superconductivity, offering a new perspective on pairing mechanisms in multiorbital systems. Building on these results, we are now investigating the broader interplay between electronic correlations and a variety of quantum phases, with the long-term goal of advancing predictive frameworks for quantum material design.



Rosanna Larciprete

Taurini unit

CNR-ISC

contacts

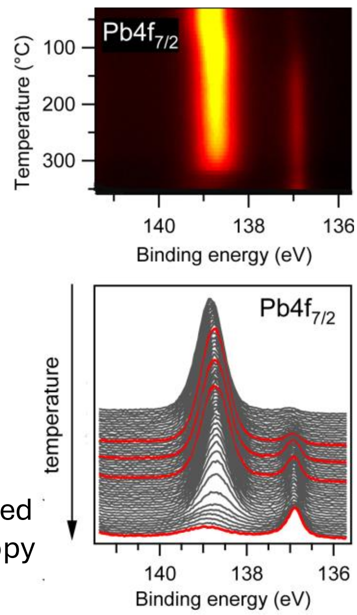
rosanna.larciprete@cnr.it
Office: via dei Taurini 19
http://www.isc.cnr.it

keywords

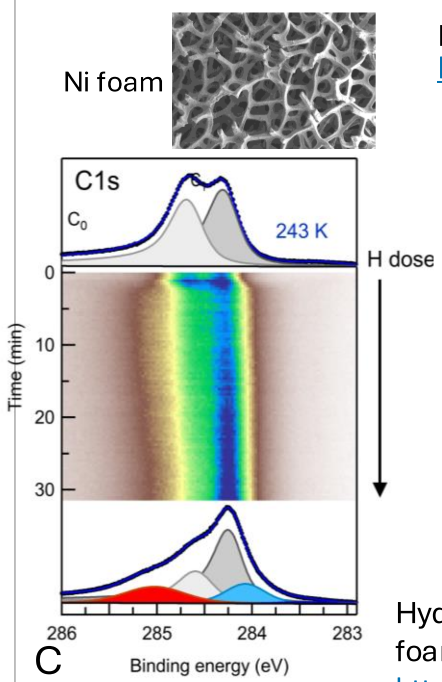
2D materials
surface reactions
electronic spectroscopies

Physico-chemical reactions at surface and interfaces.

The breaking of crystalline symmetry at the material surface leads to atomic relaxations and reconstructions, which can modify the interlayer distance and create new local geometries, influencing the structural, electronic and chemical properties. We combine electronic and microscopic diagnostics to investigate the surface reactions triggered by external agents in nanostructured materials, organic/inorganic interfaces, ultrathin films and heterostructures and to understand how the local atomic structure and the presence of defects modifies the reactivity of surface sites.



Thermal evolution of the Pb component in mixed perovskite monitored by core level spectroscopy
https://doi.org/10.3390/ma14143954



Functionalization of 2D materials.

Functionalization is a key strategy to adapt 2D materials to the stringent requirements of different technological fields, ranging from nanoelectronics to energy storage. Our research relies on the use of electron spectroscopies coupled with structural techniques, scanning probe microscopy and theoretical calculations to optimize synthesis methods and to understand how the addition of defects, heteroatoms and functional groups influence the structural and functional properties of several classed of 2D materials (graphene, transition metal dichalcogenides, MXenes).

Hydrogenation of the graphene layer deposited on Ni foam followed by C1s spectroscopy.
https://doi.org/10.1016/j.carbon.2022.07.050i

Laura Pilozzi

Taurini unit

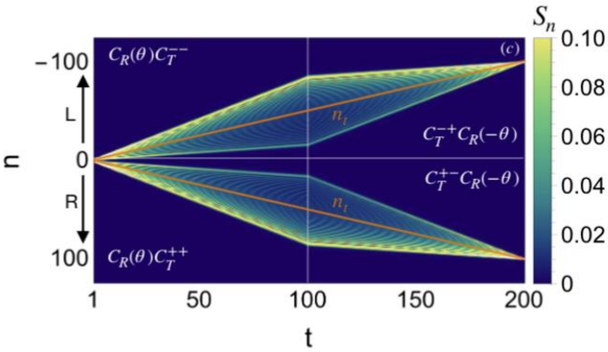
contacts

laura.pilozzi@cnr.it
Office: Via dei Taurini 19, 00185 Roma, Room 409
https://www.isc.cnr.it/staff-members/laura-pilozzi/

keywords

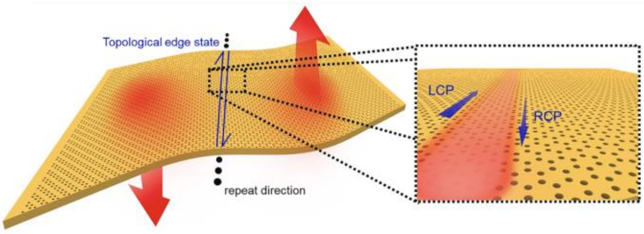
- *Topological photonics*
- *Synthetic gauge fields*
- *BIC states*

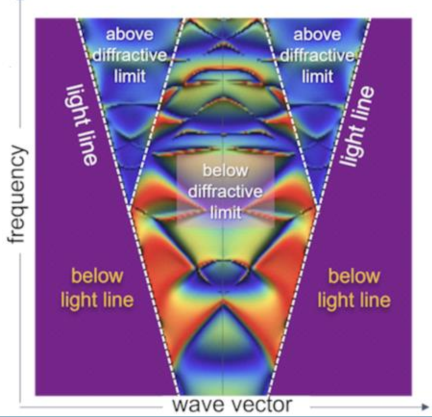
Research topics



Thouless pumping, a **topological phenomenon** yielding quantized transport in slowly and cyclically modulated lattices, allows to engineer quantum walks with tunable features. Holonomic transformations enable full control of the state of quantum systems for the realization of fault-tolerant conditional quantum gates.

Synthetic gauge fields in topologic photonic graphene can be generated by strain-engineering. Chiral strain creates opposite fields in two domains resulting in Landau levels with the same energy spacing but different topological numbers, with the strain strongly affecting the degree of localization of edge states.





Bound states in the continuum (BIC) have recently attracted attention for their promising applications in photonics. Surface shaping in 3D printed structures allows to modify dispersion relations and provide a pathway to generate BIC states and high Q resonances in the THz range.

Marco Pretti

Torino unit

CNR-ISC

contacts

marco.pretti@cnr.it
Office: Corso Duca degli Abruzzi 24 – 10129 Torino
https://orcid.org/0000-0001-7603-4627

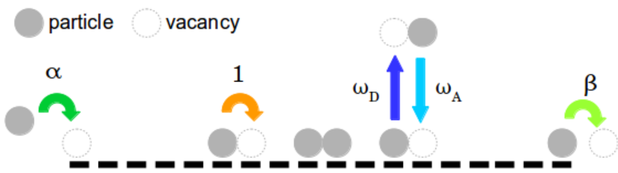
keywords

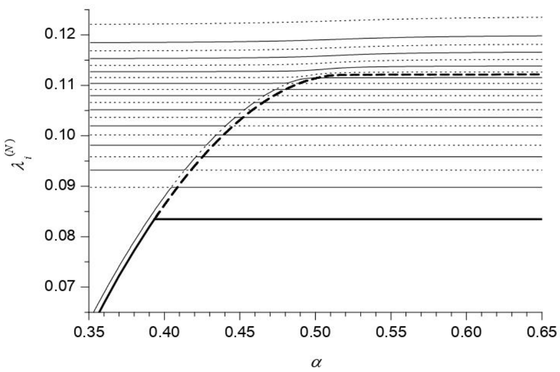
- *Out-of-equilibrium model systems, asymmetric exclusion processes*
- *Nonequilibrium steady states, dynamical phase transitions*
- *Statistical inference algorithms: belief propagation*

Research topics

My research activity is focused on the statistical mechanics of phase transitions, in the last few years mainly regarding **out-of-equilibrium model systems**, such as asymmetric exclusion processes (ASEPs), in the framework of approximate mean-field-like theories.

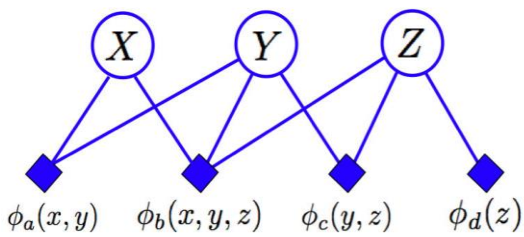
There are many variants of ASEPs, mostly inspired by either vehicular or biological traffic problems. For instance, the ASEP with Langmuir kinetics is meant to mimic either a highway with on-off ramps or the motion of molecular motors on so-called microtubules (see figure).





ASEPs are characterized, in certain conditions, by peculiar **nonequilibrium phase transitions**, usually denoted as **dynamical**. Such phenomena appear as singularities in the relaxation rates of the system toward its **nonequilibrium steady state**, without any effect on the steady state itself. Mean-field methods can point out the related structural changes in the relaxation spectrum (see figure).

A lot of **statistical-inference problems** of high technical importance (e.g., error correction for digital transmission over a noisy channel) can be formalized in terms of calculation of a Boltzmann distribution for Ising- or Potts-like models defined on heterogeneous graphs (see figure). **Belief propagation** is a very efficient family of algorithms to perform such calculations, based on statistical-mechanical methods of the mean-field type.



Daniela Grasso

Torino unit

CNR-ISC

contacts

daniela.grasso@cnr.it
Office: Corso Duca degli Abruzzi 24, 10129 Torino
http://website.address

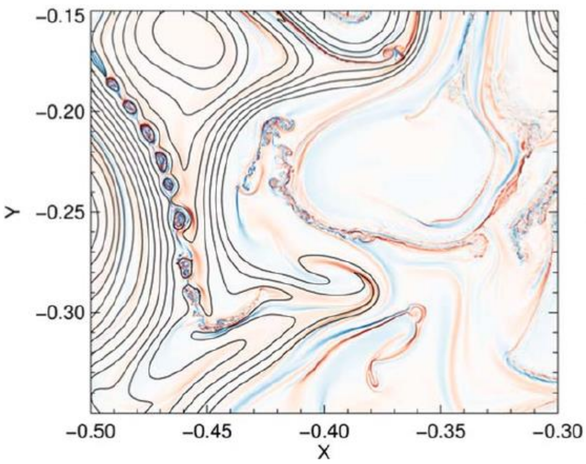
keywords

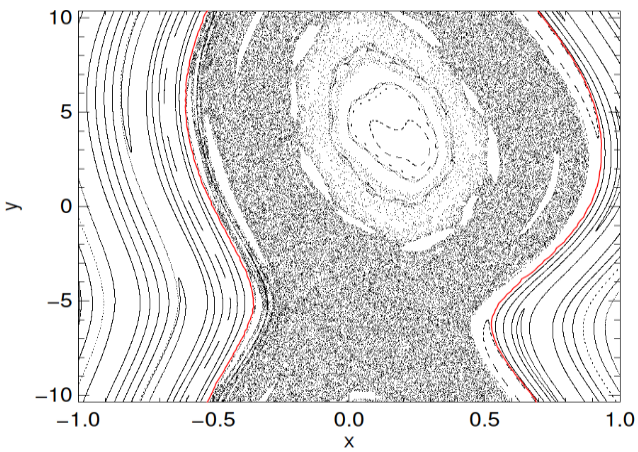
- *Plasma and fluids instabilities,*
- *Nonlinear dynamics and Hamiltonian systems*
- *Numerical techniques*

Magnetic reconnection in fusion and astrophysical plasmas

My research activity is focused on Magnetic reconnection (MR), a fundamental plasma process occurring in conducting fluids and plasmas. Phenomena related a MR event are: solar flares, aurora, instabilities in thermonuclera fusion devices...

One of the main problem in astrophysical context is the influence that multiple reconnection events have on the turbulent cascade in collisionless plasmas. Here fluid and magnetic instabilities coexist and compete





Runway electrons, high energetic particles that accelerate near the speed of light, are generated during extreme reconnection events leading to a plasma disruption in fusion devices.
REs are a serious threat for large tokamak machines. Studying how they spread in chaotic magnetic fields is of paramount importance

Antonio Maria Scarfone

Torino unit

contacts

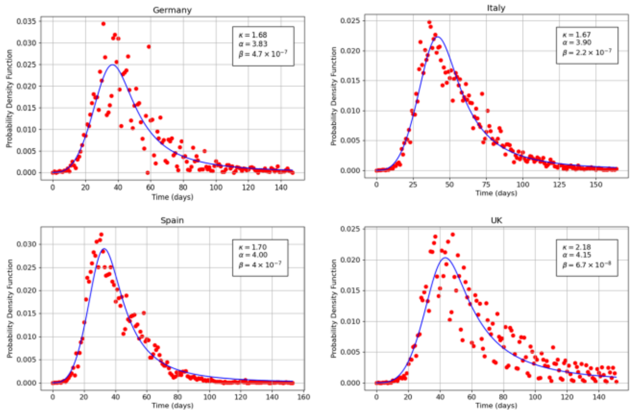
Antoniomaria.scarfone@cnr.it
Office: DISAT – Politecnico di Torino
https://www.isc.cnr.it/staff-members/antonio-maria-scarfone/

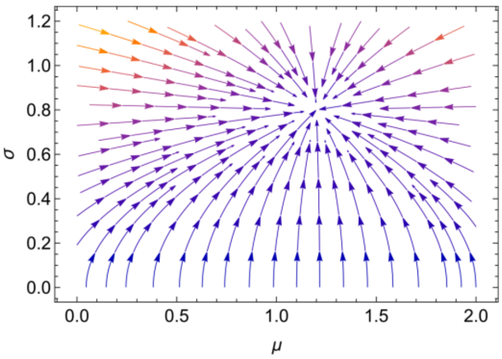
keywords

- *Non-extensive statistical mechanics*
- *Information geometry*
- *Kinetic equations*

Research topics

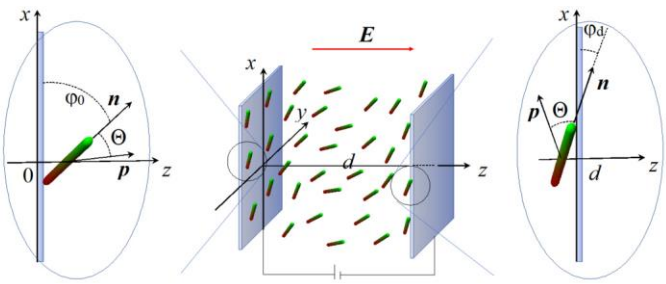
Within the **non-extensive statistical mechanics**, we investigate the epistemological structure of the statistical mechanics based on a wide variety of generalized entropies, from which probability distributions with power-law tails can be derived. Potential applications on physical and physical-like systems are considered like, i.e., the distribution of contagions and deaths in the Covid19 pandemic event.





Information geometry is a powerful framework for studying families of probability distributions from a geometric perspective. The geometric tools characterizing affine differential geometry are used to investigate the mathematical structure underlying non-extensive statistical mechanics and out-of-equilibrium thermostatistics using gradient flow equations obtained from generalized entropic forms.

Kinetich equations are used to study irreversible processes described by Fokker-Planck equations characterized by non-increasing Lyapunov functionals. Poisson-Nernst-Planck equations with suitable boundary conditions are used to investigate chemical-physics processes in electrolytic cells and nematic/colesteric liquid crystals.



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