STATEMENT OF RESEARCH INTERESTS

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I had my training in complex chaotic systems, with a focus on non-linear classical and quantum dynamics and statistical physics. My research employs a combination of analytical calculations and large-scale numerical simulations (Monte Carlo simulations, integration of ordinary and stochastic differential equations for molecular dynamics, matrix diagonalization).

I am the group leader, together with Prof. F. Borgonovi, of the Quantum Biology group within the *Interdisciplinary Laboratories for Advanced Materials Physics* (iLAMP): http://centridiricerca.unicatt.it/ilamp-quantum-biology-research-2107

The general themes of my current research interests are emergent effects in open quantum systems, focusing on the interplay of different environments. Together with an applicative interest, the purpose of my investigation is also to address basic theoretical questions such as the quantum/classical transition. The understanding of emergent properties and the discovery of new ones, are among the grand challenges in Condensed Matter Physics and in Basic Energy Science [1].

In particular I am currently working on the following research topics: energy transport in light harvesting systems, within the Quantum Biology group in Italy and other international collaborations; photon localization in cold atomic clouds, in collaboration with the experimental group of R. Kaiser at INLN (CNRS) in Nice, France; cooperative effects in spin systems with long range interaction in collaboration with L. F. Santos at Yeshiva University, USA.

My past research focused on transport properties of open quantum systems and on magnetic properties of nanoscopic systems. In particular I have worked on topics related to transport in mesoscopic systems (i.e. Universal Conductance Fluctuations, Anderson Localization), dynamics and statistical mechanics of small magnetic systems and quantum computation and information.

Below I give a brief presentation of my recent and past research interests (below each Section I have listed my papers on the subject).

RECENT RESEARCH INTERESTS

FROM NATURAL PHOTOSYNTHETIC COMPLEXES TO ARTIFICIAL QUANTUM DEVICES.

To build quantum devices able to work robustly at room temperature is a formidable task, since perturbations induced by external environments tend to destroy quantum behaviour. Recent experimental results suggest that understanding how natural photosynthesis works might help in this task. The primary step of photosynthesis, photon capture from the Sun

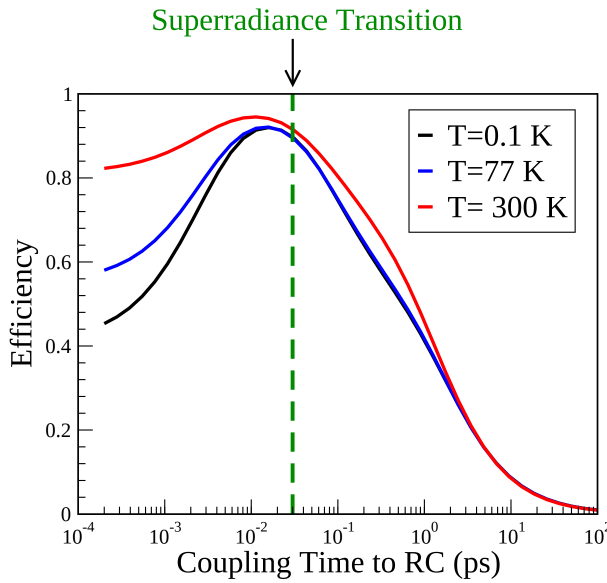

FIGURE 1. Efficiency of energy transport for different Temperature (T) of the FMO photosynthetic complex as a function of the coupling strength to the Reaction Center, is maximized around the Superradiance Transition (ST). Figure taken from Ref. [1] of this Section.

and transport of the resulting photo-excitation to a reaction center (RC), is performed by antenna complexes in most photosynthetic organisms (e.g. plants, algae, bacteria). This photon capture and energy transfer occur with an efficiency exceeding 95%, which is hard to explain by classical models of transport. Surprisingly, evidence of quantum coherent effects, which may explain such high efficiencies, has been found in photosynthetic systems [2]. These findings raise many questions, including: how can quantum coherence be preserved in macromolecules in a wet and hot environment? How can quantum coherence help the functionality of photosynthetic systems?

All these questions are also of paramount importance for building quantum devices. Understanding how coherences can be preserved at room temperature will impact quantum information technologies that aim to do precisely this. Moreover, light harvesting is a key issue in basic energy science for gathering solar energy, and understanding how natural photosynthesis performs so efficiently will inspire artificial (even biomimetic) light harvesting technologies. Finally, since photosynthetic systems are able to work in low intensity light (some bacteria operate in extremely low photon flux conditions), they can inspire the design of precise photon sensors.

The main objectives of this research are to understand the emergence of cooperative effects in natural light harvesting complexes, and to design biomimetic technologies for light harvesting and precision sensing that exploit these effects. Recently, see Fig. (1), we have investigated the robustness of cooperative effects in photosynthetic complexes, such as superabsorbtion and supertransfer. These phenomena are induced by the creation of delocalized states that are able to absorb light or to transfer energy with rates that scale up with the system's size.

To analyze photosynthetic systems, and understand the emergent cooperative phenomena detailed above, it is necessary to understand the behavior of open quantum systems subjected to strong interaction with different environments. Indeed, antenna complexes interact with the electromagnetic field (EMF), to which photo-excitations can be lost by photon emission, with molecular vibrations (e.g. phonon bath), which induces thermalization and loss of quantum coherences (dephasing), and with the RC, at which photo-excitations can be trapped. We model the interaction with the EMF and with the RC by means of a non-Hermitian Hamiltonian approach to open quantum systems, which allows to go beyond the weak coupling regime. It is in this regime that the novel cooperative effects described above, superabsorbtion and supertransfer, emerge.

6) *Optimal efficiency of quantum transport in structured disordered systems with applications to light-harvesting complexes*
*G. G. Giusteri, **G.L.Celardo** and F. Borgonovi*
arXiv:1508.01613

5) *A superradiance-based biological switch*
*Fausto Borgonovi and **G.L.Celardo***
AIP Conf. Proc. **54**, *1619 (2014).*

4) *Cooperative robustness to dephasing: Single-exciton superradiance in a nanoscale ring to model natural light-harvesting systems*
***G. L. Celardo**, Paolo Poli, Luca Lussardi, and Fausto Borgonovi*
Phys. Rev. B **90**, *085142 (2014).*

3) *Cooperative robustness to static disorder: Superradiance and localization in a nanoscale ring to model light-harvesting systems found in nature*
***G. L. Celardo**, Giulio G. Giusteri, and Fausto Borgonovi*
Phys. Rev. B **90**, *075113 (2014).*

2) *A Quantum Biological Switch Based on Superradiance Transitions*
*D. Ferrari, **G. L. Celardo** , G.P. Berman, R.T.Sayre, F. Borgonovi*
The Journal of Physical Chemistry C **118**, *20 (2014).*

1) *Superradiance Transition in Photosynthetic Light-Harvesting Complexes*
***G.L.Celardo** , F. Borgonovi, V.I. Tsifrinovich, M. Merkli and G.P. Berman,*
The Journal of Physical Chemistry C, **116**, *22105 (2012).*

INTERPLAY OF SUPERRADIANCE AND DISORDER WITH APPLICATIONS TO COLD ATOMS.

Realistic systems are usually subject to the effects of different environments. Understanding their interplay is essential for technological and theoretical advancements.

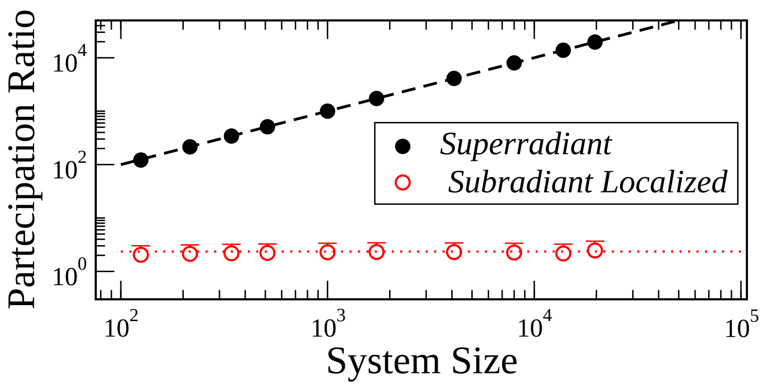

FIGURE 2. Open $3D$ Anderson model: coexistence of extended superradiant states and localized subradiant states due to the interplay of opening and disorder. Figure taken from Ref. [2] of this Section.

In collaboration with the experimental group led by Robin Kaiser, at INLN (CNRS) in Nice, France [3], we are investigating the interplay of disorder and Superradiance in cold atomic clouds. The main experimental goal is to achieve photon trapping by different means, such as Anderson localization [4] and Dicke subradiance [5]. It is known that Super and Subradiance can occur in these systems, but the possibility to observe Anderson localization in $3D$ atomic clouds was questioned due to the presence of long range interaction among the atoms.

In order to address this problem, we analyzed the effect of the opening in a simple but paradigmatic disordered model: the Anderson model. In particular we analyzed a $3D$ open Anderson model in which a particle, in addition to hop to nearest-neighbour sites, can also escape from any site to a common decay channel in the continuum. This kind of opening induces a strong long range hopping between the sites of the Anderson model, similarly to what happens in cold atomic clouds. Contrary to expectations, we show that the opening does not destroy all features of Anderson localization. Specifically we found that for large disorder and large opening, the response of the system to disorder strongly depends on the initial state: while superradiant states remain extended, showing cooperative robustness to disorder, subradiant states have an hybrid nature, preserving strong signatures of Anderson localization, for instance they have a size independent participation ratio, see Fig.(2).

4) *Non-Hermitian Hamiltonian approach to quantum transport in disordered networks with sinks: validity and effectiveness*
G.G. Giusteri, F. Mattiotti and ***G. L. Celardo***
Phys. Rev. B **91**, *094301 (2015).*

3) *Superradiance, disorder, and the non-Hermitian Hamiltonian in open quantum systems*
G.L.Celardo *, A. Biella, G. G. Giusteri, F. Mattiotti, Y. Zhang and L. Kaplan AIP Conf. Proc.* **64**, *1619 (2014).*

2) *Subradiant hybrid states in the open 3D Anderson-Dicke model*
A. Biella, F. Borgonovi, R. Kaiser, ***G.L. Celardo***
EuroPhys. Lett. **103***, 57009 (2013).*

1) *Interplay of superradiance and disorder in the Anderson Model*
G.L. Celardo*, A. Biella, L. Kaplan and F. Borgonovi,*
Fortschritte der Physik **61***, 250 (2013),*
Special Issue on "Quantum Physics with Non-Hermitian Operators: Theory and Experiment".

FROM SUPERRADIANCE TO ZENO DYNAMICS IN LONG RANGE INTERACTING SYSTEMS. The Superradiant and Subradiant effects can be connected with the Quantum Zeno effect [6]: the opening can be seen as a continuous measurement performed on the system by the environment. In open quantum systems the Superradiant effect originates from long range interaction between the different components of the system induced by the coupling to a common environment. It is thus a natural question to investigate whether effects similar to Superradiance and Zeno are a general feature of long range interacting systems. For this purpose we are studying disordered tight binding models with long range hopping between the sites, which are relevant in many realistic systems, such as photon transport in cold atomic clouds and exciton transport in molecular systems. We are also investigating many body long range interacting spin systems which can be experimentally implemented in ion traps. In this case we have shown that, as the system size increases, the dynamics becomes more confined into invariant subspaces. In such subspaces, the dynamics is effectively shielded from long-range interaction, that is it occurs as if long-range interaction was absent. Shielding is a cooperative effect, since the time over which it is effective diverges with system size. Contrary to the common expectation that long-range interaction should always induce an instantaneous spread of information in the thermodynamic limit, the shielding effect may lead to a finite velocity of the propagation of information or even the entire freezing of the dynamics, even in absence of disorder. This shielding phenomenon can be related to the quantum Zeno effect, which refers to the freezing of the dynamics into invariant subspaces in a system under continuous measurement. Thus long-range interaction plays a role similar to a measuring apparatus.

1) *Cooperative Zeno shielding in many-body spin systems with long-range interaction: localization and light cone*
Lea F. Santos, Fausto Borgonovi and ***G. L. Celardo***
arXiv:1507.06649.

PAST RESEARCH INTERESTS

STATISTICAL THEORY OF TRANSPORT AND NUCLEAR REACTIONS. In the past years I studied open quantum systems under the assumptions of Random Matrix Theory (RMT). We analyzed the interplay of intrinsic dynamics (chaotic or regular) and degree of opening of the system in determining statistical properties of transport in mesoscopic systems and statistical properties of nuclear reactions. The effect of Superradiance transition was also pointed out. Recently we suggested an explanation for the deviations from Porter-Thomas distribution of neutron resonance width distribution, observed in recent experiments [7].

5) ***G.L.Celardo*** *, N. Auerbach, F.M. Izrailev, V.G. Zelevinsky, Phys. Rev. Lett.* **106***, 042501 (2011).*
4) *S. Sorathia, F. M. Izrailev,* ***G. L. Celardo****, V. G. Zelevinsky and G. P. Berman, EuroPhys. Lett.* **88** *27003, (2009).*
3) ***G. L. Celardo****, F. M. Izrailev, V. G. Zelevinsky and G. P. Berman, Phys. Lett. B* **659***, 170 (2008).*
2) ***G. L. Celardo****, V. Zelevinsky, F. Izrailev, and G. P. Berman, Phys. Rev. E* **76***, 031119 (2007).*
1) ***G. L. Celardo****, S. Sorathia, F. M. Izrailev, V. G. Zelevinsky, and G. P. Berman, CP995, Nuclei and Mesoscopic Physics - WNMP 2007, ed. P. Danielewicz, P. Piecuch, and V. Zelevinsky.*

SUPERRADIANCE AND TRANSPORT IN NANOSYSTEMS. We have investigated electron transport through a finite one dimensional sequence of square potential barriers, which is a paradigmatic model in solid state physics. The main question that we intended to address was whether in a realistic situation the coupling to the external environment can be increased up to the point where a Superradiance transition occurs. We have shown that the Superradiance transition occurs already in this simple model as the coupling to the external world is increased by adjusting the widths or heights of the external potential barriers. We showed that maximal transmission is obtained at the Superradiance transition. The analysis has been extended to multidimensional systems and to branched-circuit systems, which are very relevant to information technology.

4) *S.Sorathia, F.M.Izrailev, V.G.Zelevinsky,* ***G.L.Celardo*** *, Phys. Rev. E* **86***, 011142 (2012).*
3) *A. Ziletti, F. Borgonovi,* ***G.L. Celardo*** *, F.M. Izrailev, L. Kaplan and V.G. Zelevinsky, Phys. Rev. B* **85***, 052201 (2012).*
2) ***G. L. Celardo****, A. M. Smith, S. Sorathia, V. G. Zelevinsky, R. A. SenâĂŹkov, and L. Kaplan, Phys. Rev. B 82, 165437 (2010).*
1) ***G.L.Celardo*** *and L. Kaplan, Phys. Rev. B 79, 155108 (2009).*

ERGODICITY BREAKING AND MAGNETIC DECAY IN NANOSYSTEMS. Magnetism at the nanoscale has important consequences in the technology of memory and information processing devices. The quest for improving magneto-storage density calls for the realization of smaller and smaller magnetic units. Understanding the time scale of magnetic relaxation is essential to use nanoscopic devices in information technology, i.e. nanoscopic memory units.

Our starting point in this research was the discovery of an ergodicity breaking energy threshold in isolated anisotropic spin systems. We called this threshold Topological Non-connectivity Threshold (TNT), see also Ref.s [8]. Below this threshold the system, when isolated, is non ergodic, namely it cannot explore the available constant energy surface, since the available phase space is separated in at least two disconnected regions, characterized by a different sign of the magnetization. We have also demonstrated that in case of long range interaction among the spins, the disconnected energy portion determined by the TNT remains finite, even in the thermodynamic limit. This fact shows that we can have a many body system which is not ergodic in a relevant part of its spectrum, even in presence of non linear dynamics and for large number of particles.

On the other hand for nanoscale structures, the TNT has important consequences both for short and long range interacting spins. When the system is in contact with an heat bath, this threshold represents an effective energy barrier for magnetic reversal, so that for average thermal energy below the TNT, the relaxation times depends exponentially on this energy barrier. Our analysis showed that for long range interaction this energy barrier grows as some power of the volume of the particle. This remarkably contrast with the behaviour of short range interacting systems, where the energy barrier is proportional to the cross-sectional particle area, rather than to its volume. Long range interaction among the spins could thus induce stable ferromagnetic behaviour in nanoscopic systems at room temperature.

Note that in many realistic situations one needs to go beyond nearest neighbour coupling, taking into account the long range nature of the interaction [9] . It is the case, for instance, of the dipolar interaction in 3–d systems, or of the so–called RKKY (Ruderman-Kittel-Kasuya-Yosida) interaction.

9) *F Borgonovi,* ***G.L. Celardo****, Journal of Physics: Condensed Matter 25* **10***, 106006 (2013).*
8) *F.Borgonovi,* ***G.L.Celardo****, Journal of Statistical Mechanics-Theory and Experiment, P05013, (2010).*
7) *F. Borgonovi,* ***G. L. Celardo****, B. Goncalves, and L. Spadafora, Phys. Rev. E* **77***, 061119 (2008).*
6) *R. Trasarti-Battistoni, F. Borgonovi, and* ***G. L. Celardo****, EPJ B* **50***, 69 (2006).*
5) *F. Borgonovi,* ***G. L. Celardo****, and R. Trasarti-Battistoni, EPJ B* **50***, 27 (2006).*
4) *F. Borgonovi,* ***G. L. Celardo****, A. Musesti, R. Trasarti-Battistoni, and P. Vachal, Phys. Rev. E* **73***, 026116 (2006).*
3) ***G. L. Celardo****, J. Barre, F. Borgonovi, and S. Ruffo, Phys. Rev. E* **73***, 011108 (2006).*
2) *F. Borgonovi,* ***G. L. Celardo****, and G. P. Berman, Phys. Rev. B* **72***, 224416 (2005).*
1) *F. Borgonovi,* ***G. L. Celardo****, M. Maianti, and E. Pedersoli, Journal of Statistical Physics* **116***, 1435 (2004).*

QUANTUM INFORMATION. Building a "useful" quantum computer is still a great theoretical and experimental challenge. The problems involved are numerous and pertain to all aspects of quantum computation: initial state preparation, evolution, and the final state read–out, which produces the output of the computation. We have analyzed a solid state model of quantum computation, and we showed how it is possible to reduce the errors that appear during the dynamical evolution of the system. Furthermore, we also considered the effect of external errors, modeled as random unitary perturbations on the evolution of the system. We showed that a modified quantum algorithm is more stable with respect to external unitary perturbations.

2) *__G. L. Celardo__, C. Pineda, and M. Znidaric, IJQI,* **3***, 3 (2005).*
1) *G. P. Berman, F. Borgonovi, __G. L. Celardo__, F. M. Izrailev, and D. I. Kamenev, Phys. Rev. E* **66***, 056206 (2002).*

CHAOS AND THERMALIZATION. It is well known that in spite of dynamical disorder (high sensitivity of individual trajectories to initial conditions), chaotic systems display good statistical order (weak dependence of statistical properties on initial conditions). On this basis, it is possible to give a statistical description even of small systems, which lie outside the realm of statistical mechanics. It is also natural to ask whether well known methods of statistical mechanics apply in the case of small chaotic systems. We demonstrated that single particle level occupation numbers can be described using standard statistical mechanical distributions (Bose-Einstein or Fermi-Dirac), even for small isolated systems. This means that a chaotic interaction can play the role of an internal heat bath.

1) *F. Borgonovi, __G. L. Celardo__, F. M. Izrailev, and G. Casati, Phys. Rev. Lett.* **88***, 054101 (2002).*

CONTROLLING ION CHANNEL DYNAMICS (BIOPHYSICS). Ion channels are macromolecular "pores" in cell membranes, through which various ionic substances are allowed to pass. To a large degree, ion channels determine the properties of excitable cells in nerve and muscle tissue, and are at the center of intense studies in biophysics. Ion channels possess several metastable states, which can be modeled as local minima of a certain potential profile. Transitions between metastable states are thermally activated, and are also influenced by the electrical potential difference between the internal and external parts of the cell. It has been pointed out in [10] that applying a time dependent external potential can induce a focusing of the ion channel on a single metastable state. Preliminary experimental verification of this has been presented in [11]. We investigated out of equilibrium stationary distributions induced by a stochastic dichotomous noise on double and multi-well models for ion channels. Ion-channel dynamics is analyzed both through over-damped Langevin equations and master equations. As a consequence of the external stochastic noise, we proved a non trivial focusing effect, namely the probability distribution is concentrated only on one state of the multi-well model. We also showed that this focusing effect , which occurs at physiological conditions, cannot be predicted by a simple master equation approach.

1) *L. Ponzoni, __G. L. Celardo__, F. Borgonovi, L. Kaplan, A. Kargol, Phys. Rev. E* **87***, 052137 (2013).*

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