Proposal for an INFN Research Network (Iniziativa Specifica)

Section I:

Title:

Statistical Field Theory, Low-Dimensional Systems, Integrable Models and Applications

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Acronym:

SFT

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Keywords

- Quantum field theories out of equilibrium
- Entanglement
- Topological quantum field theories
- Conformal invariance, phase transitions and universality classes
- Low-dimensional quantum field theory: integrability and its breaking

Abstract

This project aims at making progress on a series of outstanding questions coming from statistical field theory and the area of quantum extended systems. Guiding lines for the project are the exact and non-perturbative methods of quantum field theory, considerably refined in recent years thanks to developments in conformal field theories, exactly solvable lattice models and quantum integrable systems. A key feature of all these approaches is their ability to enlighten and account for strong coupling phenomena in quantum systems with infinite degrees of freedom. Applications of quantum field theory beyond the realm of high-energy physics nowadays form an extremely rich research area, dealing with quantum devices, cold atom gases, quantum spin chains, topological phases of matter and quantum systems out of equilibrium.

We plan: (1) to tackle important aspects of quantum field theory out of equilibrium and work out applications thereof (thermalization and its violation, the role of non-local conserved charges, the emergence of the Generalized Gibbs Ensemble, the exact computation of multi-point correlators, the manifestation of supersymmetry out of equilibrium, exact solutions of quantum spin chains); (2) to enlighten significantly the universal properties of quantum entanglement (its proper measure for multiple partitions of the system, the spread of entanglement after a quantum quench, the topological information encoded in the entanglement spectrum); (3) to reveal the properties of the new discovered topological phases of matter (identification of the relevant topological field theories in three dimensions, the role of boundary excitations and boundary states, transport properties, the use of the gauge/gravity correspondence); (4) to explore new universality classes of critical phenomena by using conformal invariance combined with very efficient numerical methods, the Truncated Conformal Space Approach and the conformal bootstrap, as well as the finite-size techniques (applications to wetting phenomena, percolation, cold atoms in a trap, KPZ model, Potts model and Ising-like models above two dimensions); (5) to study the emergence of new physical phenomena related to quantum integrability and its breaking (confinement of topological excitations, spectrum of neutral excitations, Majorana zero modes, massless Renormalization Group flows, many-body localization).

Composition of the participant Research Units:

- INFN Section: Trieste
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    - Gesualdo Delfino
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- INFN Section: Firenze
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- INFN Section: Pisa
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- INFN Section: Genova
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    - Post-docs, Ph.D students, Fellows
        - *none at the moment*

- INFN Section: Cosenza
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- INFN Section: Milano
  - Staff members
    - Sergio Caracciolo
  - Post-docs, Ph.D students, Fellows
    - Enrico Malatesta

Section II

Status of the relevant research field; scientific context, objectives and envisaged achievements of the proposed network program:

The present project covers five domains of research that are deeply interconnected: (1) statistical properties of quantum field theories out of equilibrium, (2) entanglement in quantum extended systems, (3) topological field theories in two and three space dimensions, (4) conformal invariance and universality classes, (5) integrable models and breaking of integrability. Let's present the status of each topic and the milestones we would like to reach for any of them.

(1) Statistical properties of quantum field theories out of equilibrium. A key question of statistical physics is under which conditions an extended quantum system subjected to a quantum quench (an abrupt change of parameters in its Hamiltonian) reaches a stationary state, characterized by an effective ``thermal'', i.e. equilibrium, distribution. Exact methods of conformal field theory and integrable massive systems can effectively answer this question, as well as thoroughly unfold the rich aspects of the out-of-equilibrium dynamics. In conformal or integrable field theories, a very useful notion is related to the so-called Boundary States, which simultaneously encode properties of initial states and describe its subsequent out-of-equilibrium dynamics. In integrable quantum field theories out of equilibrium, the infinite number of conservation laws lead to Generalized Gibbs Ensembles that better describe the long-time behavior of the system.

Milestones: Full control of the time evolution of extended quantum systems. Thermalization properties in integrable and non-integrable quantum field theories and their differences. Identification of fast and long time scales. Pre-thermalization aspects. Linear and non-linear response functions. Detailed characterization of the Initial States in quench processes by means of Boundary Field Theory, Integrable Field Theory and Bethe Ansatz. Form Factor Approach for computing correlators. Developing the Generalized Gibbs Ensemble formalism, also including the non-local charges. Supersymmetric models out of equilibrium. AdS/CFT correspondence for out of equilibrium systems. Restoration of symmetry under time evolution.

(2) Entanglement in quantum extended systems. Entanglement measures have become extremely useful tools for characterizing states of matter, in particularly at zero temperature and when the traditional symmetry breaking pattern of Landau-Ginzburg type does not apply. In order to deepen these studies, exact results for entanglement observables in interacting systems are needed, for instance for the so-called *negativity.* The study of these quantities will be addressed by the methods of conformal field theory (also making use of the AdS/CFT correspondence) and integrable quantum field theories. Another important work-plan regards the so-called Entanglement Spectrum that can be regarded as an important fingerprint for different topological phases of matter, complementing the more traditional approaches based on energy spectrum analyses.

Milestones: Entanglement measures using conformal theory (entanglement negativity, mutual information and entropy for various geometries). Entanglement spectrum in topological states. Entanglement in open quantum systems and entanglement transfer for realizing high quality information flow through homogeneous quantum systems.

(3) Topological field theories in two and three space dimensions. Topological phases have no local order parameter but nevertheless present some kind of nonlocal order manifesting itself in long-range topological correlations (as e.g. Aharonov-Bohm phases) and massless excitations at the boundary. These phases can be described by low-energy effective theories that are topological gauge theories and conformal field theories. Originated with the fractional Hall effect, this research area recently boosted due to the experimental observation of topological phases in insulators and semiconductors in absence of external magnetic field and, moreover, in three dimensions.

Milestones: Study non-Abelian statistics in the quantum Hall effect and its experimental signatures, such as interferometry and heat transport in various geometries. Develop effective field theories of topological insulators and superconductors in three dimensions with interacting fermions; their classification and stability analysis using quantum anomalies of continuous and discrete symmetries. Describe topological phases in lattice spin systems of the Kitaev and Wen type, and apply these results to realizing Topological Quantum Computation, together with the implementation of explicit protocols for the key quantum gates.

(4) Conformal invariance and universality classes. Conformal invariance is an ever green source of inspiration for understanding the emergence of new universality classes and their properties, in particular the spectrum of excitations, the finite-size scaling properties and other quantities.

Milestones: Devise numerical and analytic implementations of the conformal bootstrap in higher dimensions. Study of the universality classes of the 3d Ising model and related models, the universal properties of the wetting transitions, of interfaces in Potts models and related models. Develop the finite-size theory for controlling systems such as cold atoms in a trap.

(5) Integrable models and breaking of integrability. Quantum integrability has proved to be a key tool in understanding the critical properties of numerous quantum systems at equilibrium, such as spin chains or the delta-function Bose gas. Long-standing problems, as e.g. the Ising model in a magnetic field, have been solved thanks to integrable techniques while the *Bethe Ansatz* and the associated non-linear integral equations have given access to the analytic structure of the free energy of quantum models. Breaking integrability also proves to be a rich subject, thanks to the emergence of new physical phenomena, such as the confinement of topological excitations.

Milestones: Compute the spectrum of excitations in weakly non-integrable field theories. Develop semi-classical methods for N=2 supersymmetric theories. Study confinement of topological excitations and the non-locality of perturbing operators. Characterize the many-body localization using integrable models. Investigate the duality relations, such as that connecting the Nekrasov partition function of N = 2 supersymmetric gauge theory in 3d with the conformal blocks of the Liouville field theory in 1d.

Proposed activities and role of the various Research Units

The project is carried out by seven teams -- tied by well-established scientific collaborations -- that actually involve a large part of the Italian researchers working in Statistical Field Theory. Let us first mention the top expertises in each group. The Trieste team (TS) is the largest one and its activities cover all the five research lines of the project: his members have given many contributions to the study of out of equilibrium systems (Calabrese, Mussardo, Gambassi), to the exact computation of correlation functions in integrable systems (Mussardo, Delfino), to entanglement (Calabrese, Tonni), to cold atoms systems (Trombettoni, Calabrese, Mussardo), and to describe the breaking of integrability (Mussardo, Delfino). The Florence (FI) team has a leading expertise in conformal field theory (Cappelli). Research topics involve the quantum Hall effect and topological states of matter (Cappelli), integrable spin systems (Colomo), entanglement measures in spin systems and, more recently, in open systems (Cuccoli, Vaia, Verrucchi). The Torino (TO) group has a strong expertise in lattice field theories (Caselle, Panero) and integrable models (Tateo). The Genova (GE) team has a good record in the application of effective field theories to low-dimensional systems such as the quantum Hall effect, quantum wires and arrays of Josephson junctions (Maggiore, Magnoli). The unit of Pisa (PI) has remarkable expertises on phase transitions (Vicari), topological theories (Guadagnini) and low-dimensional systems (Mintchev). Researches of the Cosenza (CS) team are experts in correlated electron systems on the lattice and their continuum quantum field theory version (Giuliano) and quantum-time evolution (Plastina). The unit of Milan (MI) includes a leading expertise in statistical field theory (Caracciolo).

The specific research projects are listed hereafter together with the team collaborations that will develop them, divided in the five domains mentioned before.

(1) Statistical properties of quantum field theories out of equilibrium.

(TS, PI, FI): Detailed studies of quantum integrable dynamics after the quench, with the determination of Generalized Gibbs Ensembles and correlation functions. We will also use techniques borrowed by random matrix theory and non-perturbative methods of exactly solvable models. We plan to complete the analysis of models like the Sine and Sinh-Gordon models, and the non-relativistic Lieb-Liniger model in its attractive or repulsive regime. We shall also compare quantum field theories at large occupation numbers with the corresponding classical field theories, and study quantum quenches in higher dimensional field theory.

(TS, CS, FI): Out-of-equilibrium dynamics in one-dimensional fermionic systems. We plan to analyze transport properties at a junction between a topological superconductor and more than one interacting spinless quantum wires (Luttinger liquids). We shall study the stable phases in which Majorana fermions emerge at the contact. We also plan to analyze impurity problems for trapped fermion gases and their out-of-equilibrium quantum thermodynamics, due to the switching of the impurity at a finite temperature.

(TS, CS, FI): Use of quantum spin chains and their soliton excitations for faithful transmission of quantum information. We shall compute the concurrence and one-tangle via quantum Monte Carlo simulations and exact analytical results. We shall analyze the dynamics for entanglement transfer through quantum systems.

(CS, FI) The study of out of equilibrium properties of spin systems, in particular in connection with the decoherence dynamics of simple quantum objects coupled to spin environment.

(MI, PI, TS) Analysis of the Abelian Sandpile Model, whose dynamics shows sudden bursts of activity, the avalanches in the sandpile, which eventually drive the system into an out-of-equilibrium steady state. Many exact results and connections with statistical mechanics models and conformal field theories have been already revealed and we expect to identify others.

(GE, CS) The study of thermoelectric transport properties of strongly correlated systems using holographic methods. The momentum dissipation in the conformal theory can be implemented by breaking diffeomorphism invariance in the dual gravitational theory. The main goal is to find a model with the expected thermodynamics and transport properties for the strange metal phase of High T_c superconductors.

(2) Entanglement in quantum extended systems.

(TS, PI): Entanglement entropies in exactly solvable models. Study of entanglement entropies and entanglement spectrum, via Corner Transfer Matrix analytic techniques in integrable models and by numerical methods.

(TS, PI) Entanglement measures in two dimensional conformal field theories. We shall compute the entanglement entropies for subsystems made of several disjoint parts, the entanglement negativity and its behavior at finite temperature and volume, and other quantities such as the entanglement of formation and the squashed entanglement.

(TS, FI, CS) Study of the entanglement spectrum. We shall investigate and characterize topological states, such as quantum Hall states, Chern insulators and topological insulators, by means of their entanglement spectra, that are obtained via optimized numerical methods for large systems.

(3) Topological phases of matter in two and three dimensions

(TS, FI, GE, PI): Effective theories of topological states of matter. We shall study the edge excitations of topological BF theories in 2 and 3 space dimensions: their stability, the nature of helical fermionic excitations and the classification of universality classes provided by anomalies. We shall also study other topological gauge theories that can describe interacting systems in 3 space dimensions.

(TS, FI): Quantum Hall states in ultracold atomic systems. We will explore the dynamical deformation of the rotating gas from a ring-shaped to a harmonic trapping potential, thus allowing the study of the transition between the Tonks-Girardeau regime in rotating rings and the fractional quantum-Hall regime. We shall also analyze fermionic gases under non-Abelian gauge potentials and realizable scenarios for the simulation of the Spin Hall effect.

(TS, PI): Non-relativistic field theory applications to cold-atoms. This is a promising route to solve cold atom systems with dipolar and long range interactions. Moreover we are working on the theoretical proposal to implement gauge field dynamics and (3+1) Dirac fermions by using appropriate settings of cold atom systems.

(GE, FI) We shall study possible phase transitions in topological superconductors and the related discontinuities in the Josephson current-phase relation. Such discontinuities can be experimentally revealed by a characteristic temperature dependence of the current.

(4) Conformal invariance and universality classes

(FI, TO, GE, TS) Study of 3d universality classes through conformal bootstrap and duality properties of quantum field theories in different dimensions. The recently revived conformal bootstrap for 4-point functions will be implemented numerically and analytically. In particular, we plan to develop an approximate expansion in d=2+epsilon.

(GE, PI, TO) Study of correlation functions near a critical point. The knowledge of the dimensions and OPE coefficients of the most relevant operators of O(N) models in 3d gives the opportunity to study the two point correlation functions of the magnetization and energy operators off-criticality. Part of this program has already been realized for the Ising model.

(MI, PI) Study of the Euclidean Matching Problem, a particular combinatorial optimization problem traditionally considered in computer science and mathematics. Ideas and methods that have been developed in the context of statistical mechanics of systems with frustration and disorder can be effectively applied to this problem.

(PI, TS) Finite size study of trapped cold atoms and determination of the equation of state.

(5) Integrable models and breaking of integrability

(TO, FI, TS) Exploiting the newly-discovered mathematical structure called the Quantum Spectral Curve, we shall study the thermal properties of the 1D fermionic Hubbard model, such as its finite temperature correlation lengths and correlation functions at high temperature.

(TO, FI) Study of supersymmetric gauge theories in 3D and 4D, the N=4 super-Yang Mills and the N=6 super Chern-Simons, by using integrable model tools.

(TS, FI, CS, GE) Analysis of the spectrum of Majorana fermions; the effects of Majorana fermions at the endpoints of topological superconductors wires on the transport properties of mesoscopic hybrid rings.

Section III:

List of the most significant publications of the last five years of each Research Unit related to the proposal:

1. INFN Section: Trieste
    1. G. Mussardo, Infinite-time average of local fields in an integrable quantum field theory after a quantum quench, Phys. Rev. Lett. 111, 100401, (2013)
    2. A. C. Cubero, G. Mussardo, M. Panfil, Quench Dynamics in Two-Dimensional Integrable SUSY Models, J. Stat. Mech. 1603 (2016) 033115
    3. F. Essler, G. Mussardo, M. Panfil, Generalized Gibbs ensembles for quantum field theories, Phys. Rev. A 91 051602, (2015)
    4. P. Calabrese, F. Essler, M. Fagotti, Quantum quench in the transverse-field Ising chain, Phys. Rev. Lett. 106, 227203 (2011)
    5. P. Calabrese, P. Le Doussal, Exact solution for the Kardar-Parisi-Zhang equation with flat initial conditions, Phys. Rev. Lett. 106, 250603 (2011)
    6. G. Gori, A. Trombettoni, Conformal invariance in three dimensional percolation, J. Stat. Mech. P07014 (2015)
    7. S. Paladugu, A. Callegari, Y. Tuna, L. Barth, S. Dietrich, A. Gambassi, G. Volpe, Nonadditivity of Critical Casimir Forces, Nature Comm. 7, 11403 (2016)
    8. M. Marcuzzi, J. Marino, A. Gambassi, A. Silva, Prethermalization in a nonintegrable quantum spin chain after a quench, Phys. Rev. Lett. 111, 197203 (2013)
    9. V. Ros, M. Müller, A. Scardicchio, Integrals of motion in the many-body localized phase, Nucl. Phys. B 891, 420 (2015)
    10. M. Picco, R. Santachiara, J. Viti, G. Delfino, Connectivities of Potts Fortuin-Kasteleyn clusters and time-like Liouville correlator, Nucl. Phys. B 875 (2013) 719

2. INFN Section: Firenze
    1. A. Cappelli, E. Randellini, Multipole expansion in the quantum Hall effect, JHEP 03 (2016) 105
    2. A. Cappelli, E. Randellini, Partition functions and stability criteria of topological insulators, JHEP 12 (2013) 101
    3. F. Colomo, A.G. Pronko, Thermodynamics of the Six-Vertex Model in an L-Shaped Domain, Commun. Math. Phys. 339 (2015)
    4. D. Calvani, A. Cuccoli, N. Gidopoulos, P. Verrucchi, Parametric representation of open quantum systems and crossover from quantum to classical environment, PNAS 110, 6748 (2013)
    5. L. Banchi, A. Bayat, P. Verrucchi, S. Bose, Non-Perturbative Entangling Gates between Distant Qubits using Uniform Cold Atom Chains. Phys. Rev. Lett.106, 140501 (2011)

3. INFN Section: Pisa
    1. C. Bonati, M. D'Elia, H. Panagopoulos, E. Vicari, Change of the theta dependence of 4D SU(N) gauge theories across the deconfinement transition, Phys. Rev. Lett. 110 (2013) 252003
    2. M. Campostrini, J. Nespolo, A. Pelissetto, E. Vicari, Finite-size scaling at first-order quantum transitions, Phys. Rev. Lett. 113 (2014) 070402
    3. E. Guadagnini, F. Thriller, Path-integral invariants in abelian Chern-Simons theory, Nucl. Phys. B 882 (2014) 450
    4. V. Caudrelier, M. Mintchev, E. Ragoucy, Quantum wire network with magnetic flux, Phys. Lett. A 377 (2013) 1788
    5. M. Mintchev, L. Santoni, P. Sorba, Energy transmutation in nonequilibrium quantum systems, J. Phys. A 48 (2015) 055003

4. INFN Section: Genova
    1. M. Caselle, G. Costagliola, N. Magnoli, Numerical determination of OPE coefficients in the 3D Ising model from off-critical correlators, Phys. Rev. D 91, 061901 (2015)
    2. A. Amoretti, A. Braggio, N. Magnoli, D. Musso, Bounds on charge and heat diffusivities in momentum dissipating holography, JHEP 1507 (2015) 102
    3. A. Amoretti, A. Braggio, G. Caruso, N. Maggiore, N. Magnoli, On the introduction of a boundary in topological field theories, Phys. Rev. D 90, 125006 (2014)
    4. A. Amoretti, A. Blasi, N. Maggiore, N. Magnoli, 3D Dynamics of 4D Topological BF Theory With Boundary, New J.Phys. 14 (2012) 113014
    5. M. Carrega, D. Ferraro, A. Braggio, N. Magnoli, M. Sassetti, Anomalous charge tunneling in the fractional quantum Hall edge states at filling factor v=5/2. Phys. Rev. Lett. 107, 146404 (2011)

5. INFN Section: Torino
    1. A. Cavaglià, M. Cornagliotto, M. Mattelliano, R. Tateo, A Riemann-Hilbert formulation for the finite temperature Hubbard model, JHEP 1506 (2015) 015
    2. A. Cavaglià, D. Fioravanti, N. Gromov, R. Tateo, Quantum Spectral Curve of the N=6 Supersymmetric Chern-Simons Theory, Phys.Rev.Lett. 113 (2014) 021601
    3. M. Caselle, M. Panero, D. Vadacchino, Width of the flux tube in compact U(1) gauge theory in three dimensions, JHEP 02 (2016) 180
    4. M. Caselle, D. Fioravanti, F. Gliozzi, R. Tateo, Quantisation of the effective string with TBA, JHEP 1307 (2013) 071

6. INFN Section: Cosenza
    1. I. Affleck, D. Giuliano, Topological superconductor-Luttinger liquid junctions, J. Stat. Mech. P06011 (2013)
    2. G. Campagnano, P. Lucignano, D. Giuliano, A. Tagliacozzo, Spin-orbit coupling and Josephson effect in nanowires, J Phys C 27, 205301 (2015)
    3. E. Eriksson, A. Nava, C. Mora, R. Egger, Tunneling spectroscopy of Majorana-Kondo devices, Phys. Rev. B 90, 245417 (2014)
    4. P. Haikka, J. Goold, S. McEndoo, F. Plastina, S. Maniscalco, Non-markovianity, Loschmidt echo, and criticality: A unified picture, Phys. Rev. A 85, 060101(R) (2012)
    5. T.J.G. Apollaro, C. Di Franco, F. Plastina, M. Paternostro, Memory-keeping effects and forgetfulness in the dynamics of a qubit coupled to a spin chain, Phys. Rev. A 83, 032103 (2011)

7. INFN Section: Milano
    1. S. Caracciolo, M. Gherardi, M. Papinutto, A. Pelissetto, Geometrical Properties of Two-Dimensional Interacting Self-Avoiding Walks at the Theta-Point, J Phys A 44 (2011), 115004
    2. S. Caracciolo, A. Sportiello, Exact integration for height probabilities in the abelian sandpile model, J Stat Mech (2012), P09013
    3. S. Caracciolo, C. Lucibello, G. Parisi, G. Sicuro, Scaling Hypothesis for the Euclidean Bipartite Matching Problem, Phys Rev E 90 (2014), 012118
    4. S. Caracciolo, G. Sicuro, Quadratic stochastic Euclidean bipartite matching problem, Phys Rev Lett 115 (2015), 230601

List of the main international collaborations related to the proposal:

LAPTH Annecy; Durham Univ.; Univ. de Santiago de Compostela; IPhT, Saclay; PDMI-Steklov, St. Petersbourg; Theoretical Physics, Oxford Univ.; LPTHE, Univ. Paris VI; LPTHE, ENS, Paris; LIPN Univ. Paris 13; Dept. of Physics, Melbourne; S; J.Franck Inst., Univ. of Chicago; King's College, London; Dept. of Physics and Astronomy, Univ. College London; Rutherford Appleton Laboratory, Oxford; Dept. of Physics, Univ. British Columbia, Vancouver; Int. Inst. of Physics, Natal; CSIC, Madrid; Dept. of Physics, Univ. of California at Berkeley; Physics and Astronomy Dept., Durham Univ.; IFT, Univ. of Amsterdam; Brookhaven Nat. Lab.; Queen's University, Belfast; H. Heine Universitaet, Duessledorf.