PEOPLE
MARIE CURIE ACTIONS

INTERNATIONAL RESEARCH STAFF EXCHANGE SCHEME

CALL: FP7-PEOPLE-2011-IRSES

PART B

QICFT

QUANTUM INTEGRABILITY, CONFORMAL FIELD THEORY AND TOPOLOGICAL QUANTUM COMPUTATION

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B1 Quality of the Exchange Programme

B1.1 Main objectives and relevance of the joint exchange programme

The purpose of this proposal is to acquire new knowledge in the theoretical area of quantum integrability/conformal field theory and, in particular, to make applications toward novel exciting fields, such as the recently born subject of topological quantum computation. Our aim is to blend our new theoretical understanding --which has a valuable interest on its own -- with the ever increasing results directly coming from the experimental set-ups. The proposal aims at bringing in close contact leading groups in Europe, in the US, in South America, Russia and China, and to disclose original research opportunities in a broad range of scientific themes, including: (a) fundamental problems of quantum statistical physics, in particular topics like thermalization in out-of-equilibrium extended quantum systems; (b) theoretical studies on infinite dimensional quantum systems, non-abelian symmetries and duality properties of quantum field theories; (c) quantum spin chains and low-dimensional materials, with the full control of their physical properties; (d) emerging broad interdisciplinary areas, as non-abelian anyons and topological quantum computation.

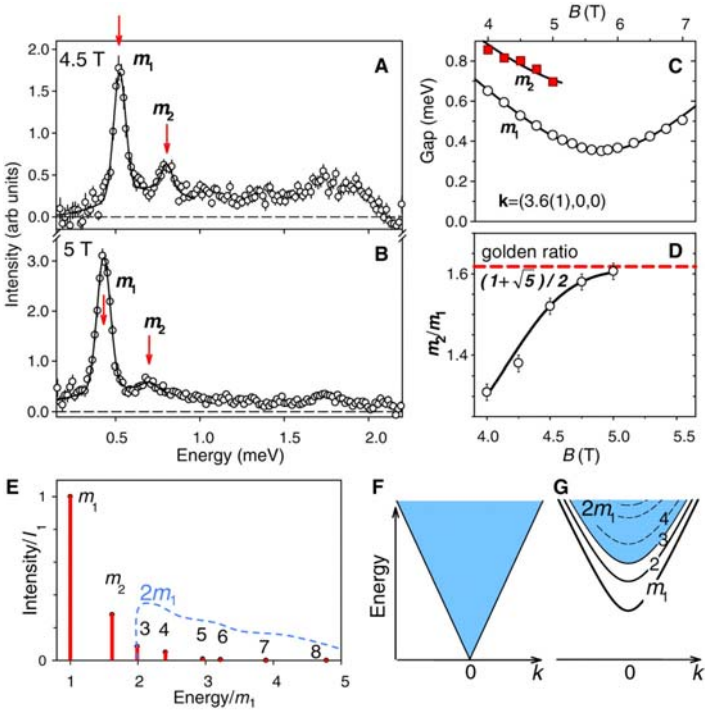
As discussed below, there are several interesting open problems which deserve full scrutiny. For this reason, the research activity gathers together leading expertise in quantum field theory, condensed matter and statistical physics. Partners of the proposal are international leading groups in this scientific area:

Europe
- R. Peierls Centre for Theoretical Physics, Univ. Oxford UK **(UOXF)**: J.L. Cardy, F. Essler and S. H. Simon;
- Scuola Internazionale Superiore di Studi Avanzati, Trieste IT **(SISSA)**: G. Mussardo and G. Delfino;
- Istituto Nazionale di Fisica Nucleare IT **(INFN)**: A. Cappelli and F. Colomo (Florence), P. Calabrese (Pisa);
- Consejo Superior de Investigaciones Cientificas, Madrid ES **(CSIC)**: G. Sierra and M. A. Martin-Delgado;
- Institute of Theoretical Physics, Univ. Amsterdam NL **(UVA)**: J.S. Caux and K. Schoutens;

Foreign countries
- Brookhaven National Laboratories, USA **(BNL)**: A. Tsvelik and R. Konik;
- Landau Institute for Theoretical Physics**,** Moscow RU **(Landau)**: A. Belavin;
- V.A. Steklov Mathematical Institute of the Russian Academy of Sciences, St. Petersburg RU **(PDMI-RAS)**: A. G. Pronko;
- Depart. de Fisica, Univ. Nacional de La Plata, La Plata AR **(La Plata)**: Daniel Cabra;
- Instituto de Fisica de Sao Carlos, Univ. Sao Paulo BR **(Sao Paulo)**: F. Alcaraz and M. Martins;
- Zhejiang Institute of Modern Physics, Univ. Zhejiang, Hangzhou China **(Zhejiang)**: Xin Wan;

All the scientists involved in this proposal are Principal Investigators (PI) in their Institution, and they are responsible of groups of young researchers (both junior faculty members or post-doc fellows) who will greatly benefit of the exchange research programme between the partners.

In order to put in perspective the scientific area which concerns this proposal, it is worth to mention that recent years have seen fascinating convergences between many themes of physics and mathematics never experienced before. Topics as quantum field theory, conformal invariance, integrable models, statistical physics, quantum spin chains, anyons, cold atoms -- from one side -- and infinite-dimensional algebras, combinatorics, topology and geometry -- from another side -- have witnessed an impressive development thanks to their mutual cross-fertilization. The exact methods of low dimensional quantum systems have been crucial for promoting new research activities in emerging fields such as quantum phase transitions, cold atoms, entanglement, quantum computation and off-equilibrium quantum statistical systems. The increasing number of experimental data coming either from neutron scattering, interferometry and transport studies and clever optical lattice devices, have led to the exciting possibility of comparing abstract and beautiful theoretical ideas on new phases of matter with precise experimental results. The unifying concepts that have come increasingly to the fore by these new developments are both conformal invariance and quantum integrability[1]. The implications and scope of these concepts have grown dramatically since their first appearance in physics in the late Sixties and have been now extended to many fields, in particular in the context of many-body quantum systems. More significantly, conformal field theory (CFT) and integrable models (IM) have recently shown their high potentiality in describing very precisely several physical set-ups. For instance, sophisticate integrable field theory predictions about the exceptional E_8 Lie algebra present in the mass spectrum and the peaks of the spin correlator of the quantum Ising model[2] have been confirmed by impressive neutron scattering experiments[3] (see Figure).



Neutron scattering data, Coldea at al. Science 2010

Integrability and conformal field theory have recently allowed to obtain, among other things: effects of thermal phase fluctuations in new materials[4], universal ratios of critical point[5], the determination of the so-called Artic curve in the six-vertex model[6], new topological realization of quantum gates[7], exact correlation functions after a quantum quench and several measures of entanglement[8] -- all quantities which are extremely useful from the experimental point of view. In condensed-matter physics, integrable Sine-Gordon model proves to be not only a bold theoretical *model* but also a well-established

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[1] A..B. Belavin, A.B. Polyakov and A.B. Zamolodchikov, *Infinite conformal symmetry in 2D quantum field theory,* Nucl. Phys.B241, 333 (1984); J.L. Cardy, *Operator content of 2D conformally invariant theories,* Nucl.Phys.B 270,186 (1986); C. Gomez, M. Altaba, G. Sierra, *Quantum Groups in Two-dimensional Physics*, Cambridge University Press (1996); G. Mussardo, *Statistical Field Theory. An Introduction to Exactly Solved Models of Statistical Physics*, Oxford University Press (2009).

[2] A.B. Zamolodchikov, *Integrable field theory from conformal field theory,* Adv. Stud. Pure Math. 19, 641 (1989); G. Delfino, G. Mussardo, *The Spin spin correlation function of Ising model in a magnetic field at T = T(c),* Nucl.Phys.B 455:724-758,1995.

[3] R. Coldea et al, *Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E(8) Symmetry,* Science 327:177-180,2010.

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[7] M. Burrello, H. Xu, G. Mussardo, X. Wan, *Quantum hashing with the icosahedral group,* Phys.Rev.Lett.104:160502, 2010; H. Xu, X. Wan, *Constructing Braids for Low-Leakage Topological Quantum Computing,* Phys.Rev.A78, 042325 (2008).

[8] P. Calabrese, J.L. Cardy, *Entanglement entropy and conformal field theory,* JPA 42, 504005 (2009); *Time dependence of correlation functions after a quantum quench*, Phys.Rev.Lett. 96, 136801 (2006); I. Kuzmenko, F. Essler, *Dynamical correlations in the spin 1/2 Heisenberg XXZ Chain*, Phys. Rev. B, 79, 024402 (2009); F.Alcaraz, V. Rittenberg, G. Sierra, *Entanglement in Far From Equilibrium Stationary States,* Phys. Rev. E Vol. 80, pg. 030102(R) (2009)

theory of quantum Luttinger liquid behavior, nicely matching with experiment[9]. In one-dimensional cold atoms, the integrability of a quantum field theory recently allowed the solution of a long-standing problem, i.e. the computation of all the one-point correlation functions of the Bose interacting gas[10], and to determine its finite temperature recombination rate.

It is also relevant to mention recent exciting theoretical developments in pure CFT, where the so-called AGT conjecture[11] reveals a deep connection between two-dimensional CFT and N=2 supersymmetric four-dimensional gauge field theories. This correspondence provides a remarkable explicit representation for the so-called conformal block coefficients in terms of the Nekrasov partition function that was not known in the framework of two-dimensional CFT[12]. Equally important is to exploit all physical consequences of the duality related to the so-called AdS/CFT correspondence[13], which can disclose new perspectives on strongly correlated systems.

Based on all these recent advances, it is now clear that conformal field theory and quantum integrable models are extremely useful tools for describing and revealing fascinating new phenomena of low-dimensional physics: understanding, for instance, the key concepts of quantum entanglement (a measure of information density) needs a thorough knowledge of topological field theory, while progress in future technology, like quantum computation, necessitates the mastering of conformal field theory, infinite dimensional algebras and their representation theory. Equally important is the integrability of the XY model for the scope of studying the vortex dynamics in cold atoms system[14] while Bethe Ansatz techniques may help in pinning down a demanding topic as quantum transport on a very tiny scales or growth models[15]. Moreover, all new knowledge acquired on quantum integrable models can be extremely significant to understand phenomena which are deeply related to breaking of integrability, in particular to address a central idea in modern physics such as that of confinement: this effect -- predicted to occur in low-dimensional quantum systems with topological excitations[16] -- has been recently observed in condensed matter experiments[17].

Through this international collaborations, which involves several international leading experts on the different facets of the topic and a large transfer of knowledge from Europe to non-EU countries and viceversa, our aim is to achieve new control on novel aspects of matter which have been recently discovered and deepening, at the same time, our theoretical toolbox. In particular we will direct our efforts at: (a) working out the physical consequences of quantum integrability and conformal invariance; (b) studying the new perspective in quantum field theory disclosed by recent correspondence between gauge theories and CFT; (c) pairing up theory with experiments performed both in cold-atom physics and condensed matter systems.

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[10] M. Kormos, G. Mussardo, A. Trombettoni, *Expectation Values in the Lieb-Liniger Bose Gas,* Phys. Rev. Lett. 103, 210404 (2009), selected for Virtual Journal of Atomic Quantum Fluids, Vol.1, Issue 6.

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[12] A. Belavin and V. Belavin, *AGT conjecture and Integrable structure of Conformal field theory for c=1.* e-Print: arXiv:1102.0343 [hep-th]

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[15] F. Alcaraz, V. Rittenberg, *A conformal invariant growth model,* J. Stat. Mech. (2010) P12032

[16] D. Controzzi, G. Mussardo *Mass Spectrum of the Two-Dimensional O(3) Sigma Model with a θ Term,* Phys. Rev. Lett. 92, 021601 (2004); G. Delfino, G. Mussardo, *Nonintegrable aspects of the multifrequency Sine-Gordon model,* Nucl. Phys. B516 :675-703,1998; G. Delfino, P. Grinza, G. Mussardo, *Decay of particles above threshold in the Ising field theory with magnetic field,* Nucl. Phys. B 737:291-303,2006.

[17] B. Lake et al. *Confinement of fractional quantum number particles in a condensed-matter system,* Nature Physics 6, 50 - 55 (2009)

B1.2 Work Packages and milestones

WP	Title	Beneficiary/Partners	Start month	End Month
1	Thermalization and Off-Equilibrium Properties of Extended Quantum Systems	UOXF, SISSA, INFN, UVA, BNL, Sao Paulo	01/2012	12/2014
2	Entanglement in Quantum Extended Systems	UOXF, INFN, CSIC, La Plata, Sao Paulo	01/2012	12/2013
3	Quantum Spin Chains and Physical Properties of New Materials	UOXF, INFN, UVA BNL, Landau, PDMI-RAS, La Plata	01/2012	12/2013
4	Topological Phase of Matter and Quantum Computation	UOXF, SISSA, INFN, CSIC, UVA, Zhejiang	01/2013	12/2015
5	Conformal Field Theory, Integrability and Duality Relations	SISSA, INFN, Landau, PDMI-RAS, Sao Paulo	01/2014	12/2015
6	Pairing up Theory with Experiments	UOXF, SISSA, INFN, CSIC, UVA, BNL, La Plata, Zhejiang	01/2013	12/2015

Work Package (WP)1. Thermalization and Off-Equilibrium Properties of Extended Quantum Systems. Starting date: 01/2012. Duration: 36 months. Partners: UOXF, SISSA, INFN, UVA, BNL, Sao Paulo. Leading researchers involved: J.L. Cardy and F. Essler (UOXF); G. Mussardo (SISSA); P. Calabrese (INFN); J.S. Caux (UVA); R. Konik (BNL), F. Alcaraz (Sao Paulo).

Objectives: The full control of time-evolution of extended quantum systems.

Milestones: Thermalization properties in integrable and non-integrable quantum systems.

Description

Control of extended quantum systems may have a relevant part for a clever design of future technological devices, in particular in the direction of quantum computation. A relevant question concerns the possibility to have macroscopic quantum systems with a purely integrable dynamics: such a possibility could disclose a new way of storing, without dissipating, quantum information as the time goes by. But how can we detect if a quantum system is integrable or not? What signatures can we have for it? If a quantum system is subjected to an abrupt change of its Hamiltonian and then is let to evolve by the unitary dynamics of the new Hamiltonian, the questions are: does it thermalize or not? Will it have memory of its initial state? Is there a difference between integrable and non-integrable dynamics, as recent experimental results[18] seem to suggest? Basic properties of Boundary Field Theory[19], Integrable Field Theory[20] and breaking thereof[14] can help in clarifying

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[18] T. Kinoshita, T. Wenger, and D. S. Weiss, *A quantum Newton's cradle*, 2006 Nature 440, 900.

[19] P. Calabrese and J.L. Cardy, *Quantum Quenches in Extended Systems*, JSTAT P06008 (2007)

[20] D. Rossini, A. Silva, G. Mussardo, G. Santoro, *Effective thermal dynamics following a quantum quench in a spin chain*, Phys. Rev. Lett. 102, 127204 (2009); D. Fioretto, G. Mussardo, *Quantum Quenches in Integrable Field Theories*, invited paper in New Journal of Physics 12, (2010).

many of these intriguing aspects.

Finding answer to the questions above and understanding the connection between ergodicity, non-integrability and thermalization in extended quantum systems remains one of the main goals of this proposal. We plan to considerably expand the present theoretical toolbox relative to off-equilibrium quantum systems with the efficient and elegant methods provided by Form Factor, Boundary Field Theory and Bethe Ansatz approaches. Quantum relaxation is surprisingly similar to the physics of non-trivial condensate (like BCS state) and we believe that methods based on quantum integrability can provide a natural mechanism for their full control and understanding.

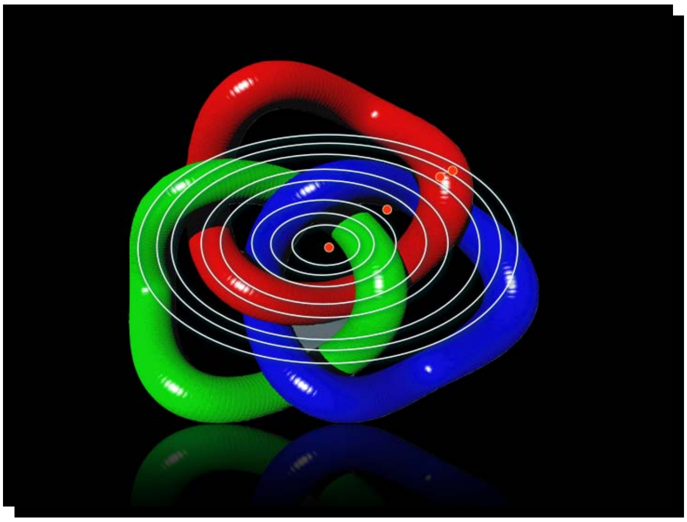
WP2. <u>Entanglement in Quantum Extended Systems</u>. Starting date: 01/2012. Duration: 24 months. Partners: UOXF, INFN, CSIC, La Plata, Sao Paulo. Leading researchers involved: J.L.Cardy (UOXF); P. Calabrese and A. Cappelli (INFN); G. Sierra (CSIC); D. Cabra (La Plata); F. Alcaraz (Sao Paulo).

Objectives: CFT predictions on entanglement in quantum extended systems.

Milestones: 1. Applications to quantum transport; 2. Interplay between thermal and entanglement entropy.

Description

Entanglement is one of the most fundamental and fascinating features of quantum mechanics, yet in some ways the most mysterious: performing a local measure may instantaneously affect the outcome of local measurements far away. This phenomenon has been the basis for the development of new topics of research as quantum information and communication. A very recent and rich field of research concerns the understanding of the role of entanglement in many-body systems. Beside its own fundamental theoretical interest, a principal reason for the success of the entanglement entropy as an entanglement measure in extended quantum systems is surely its universal scaling at one-dimensional (1D) conformal critical points. The equation $S = c/3 \ln (\ell a) + c'$ has become one of the most ubiquitous formulas in the last five years' literature, appearing in fields as apparently unrelated as quantum information, condensed matter, and high energy physics. The reasons for this prominence are clear: it is a single quantity, easily measurable in numerical simulations, that at the same time gives the location of the critical point and one of its most important characterization, the central charge c of the underlying conformal field theory (CFT).



We plan to clarify the use of entanglement in quantum information and, at the same time, to measure the entanglement entropy out of equilibrium, in the setup of a local quench. The main idea is to relate the entanglement between two half-chains to the distribution of the electrons passing towards the contact between them. In two semi-infinite chains (which are leads in actual experiments) initially disconnected and then joined together at some time t_0, there is the passage of electrons (if the leads are two Fermi seas, the quasi-particles of above are real electrons). The transport at this quantum point contact is described by the theory of quantum noise: we shall try to properly modify it for taking into account interactions and describing other universality classes than free electrons.

Another interesting topic to understand is the empirically observed correspondence between entanglement entropy and entanglement spectrum obtained from the reduced density matrix and those relative to the thermal density. For a so-called topological fluid, namely a gapped many-body electron state with topological features, such as that of the quantum Hall effect at zero temperature, the reduced density matrix is obtained by tracing out a part of the system. The thermal density is instead obtained by the Gibbs measure for the system in the same reduced geometry. The correspondence and interplay between the two quantities is rather remarkable and its comprehension can shed light on the properties of topological fluids.

WP3. **Quantum spin chains and physical properties of new materials.** Starting date: 01/2012. Duration: 24 months. Partners: UOXF, INFN, UVA, BNL, Landau, PMDI-RAS, La Plata. Leading researchers involved: A. Tsvelik and R. Konik (BNL); F. Essler (UOXF); J.S. Caux and K. Schoutens (UVA); F. Colomo and P. Calabrese (INFN); A.G. Pronko (PDMI-RAS); D. Cabra (La Plata).

Objectives: Getting analytical control of physical properties of new low-dimensional quantum systems.

Milestones: 1. Spectral and optical properties; 2. Dimensional crossover in coupled chains

Description

Among the various systems, one dimensional (1D) and quasi-one dimensional (quasi-1D) systems are a fantastic playground for quantum phase transitions (QPTs), with rather unique properties. There are various reasons for that special behavior. First, purely 1D systems are rather unique. Contrary to their higher dimensional counterparts, interactions play a major role since in 1D particles cannot avoid the effects of interactions. This transforms any individual motion of the particles into a collective one. In addition to these very strong interaction effects, in 1D the quantum and thermal fluctuations are pushed to a maximum, and prevent the breaking of continuous symmetries, making simple mean-field physics inapplicable. The combination of these two effects leads to a special universality class for interacting quantum systems, known as Luttinger liquids (LLs). The important point is that we take the LL to be in a critical phase, in which correlations decrease, at zero temperature, as power laws of space and time. This makes the system extremely fragile to external perturbations and leads to many QPTs. Examples of such perturbations are the effects of a lattice, which lead to a Mott transition, and disorder that leads to localized phases such as Anderson localization or the Bose glass. Each of these transitions is characterized by a quantum critical point (QCP) that can be computed from LL theory. The 1D nature of LLs has other consequences: the excitations can fractionalize. In particular, an excitation such as adding an electron can split into several collective excitations, such as one carrying spin but no charge, called a spinon and one carrying charge but no spin, called a holon.

There is a category of perturbations that is at the frontier of our theoretical knowledge. These are the perturbations that are produced by the coupling of several 1D systems. Then, when one parameter, for example the temperature or the inter-chain coupling, is varied, the system crosses over from a 1D situation with exotic LL physics, to the more conventional high dimensional one. How one can reconcile such different physical limits, for example recombining the spinons and holons to re-form an electron, to perform such a dimensional crossover is a very challenging and still open question. Such questions are not only important on the theoretical side but have direct applications to experimental systems such as organic or inorganic superconductors[21], spin chains and ladders[22] and cold atomic systems[23]which provide realizations of such coupled 1D systems.

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[21] Chem. Rev. 104, (2004), special issue on Molecular Conductors; F. Wang et al., Phys. Rev. Lett. 103, 136401 (2009); J. Hager et al., Phys. Rev. Lett. 95, 186402 (2005); X. Xu and et al., Phys. Rev. Lett. 102, 206602 (2009), and refs. therein.

[22] D. A. Tennant, R. A. Cowley, S. E. Nagler, and A. M. Tsvelik, *Measurement of the spin-excitation continuum in one-dimensional $KCuF_3$ using neutron scattering,* Phys. Rev. B 52, 13368 (1995); E. Dagotto and T. M. Rice, *Surprises on the Way from One- to Two-Dimensional Quantum Magnets: The Ladder Materials,* Science 271, 5249 (1996); E. Dagotto, *Experiments on ladders reveal a complex interplay between a spin-gapped normal state and superconductivity,* Rep. Prog. Phys. 62, 1525 (1999).

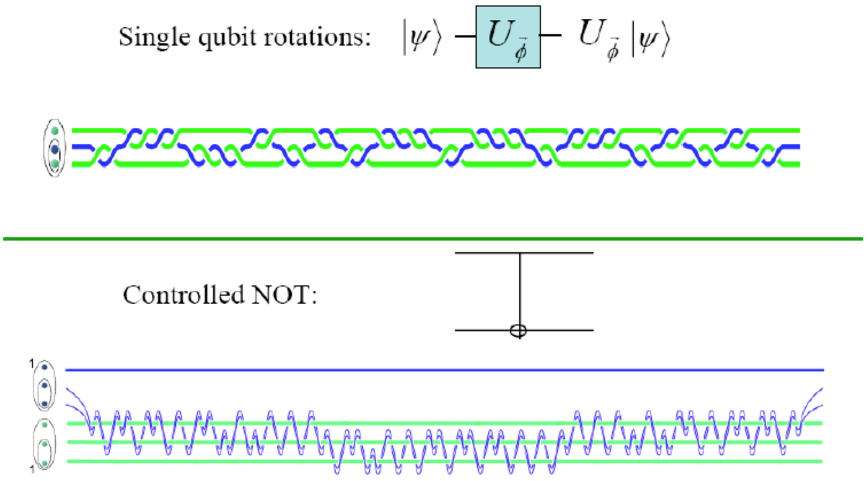
WP4. Topological Phase of Matter and Quantum Computation. Starting date: 01/2013. Duration: 36 months. Partners: UOXF, SISSA, INFN, CSIC, UVA, Zhejiang. Leading researchers involved: K. Schoutens (UVA); A. Cappelli (INFN); G. Mussardo (SISSA); S. Simon (UOXF); G. Sierra and M. A. Martin-Delgado (CSIC); X. Wan (Zhejiang).

Objectives: Theoretical understanding of materials with topological properties and topological excitations.

Milestones: 1. Description of interacting-anyon systems; 2. Realization of quantum gates by braiding.

Description

Topological phases of matter[24,25]challenge our understanding of order/disorder and fall outside of the well-established Landau paradigm of spontaneously symmetry breaking. At the same time, these phases have many peculiar properties, including exotic non-Abelian statistics of their excitations. Such fundamentally new physics, deeply rooted in quantum statistical properties of matter and low-dimensional quantum field theory, requires advanced theoretical methods for its description and may lead to interesting technological applications. The main dynamical features are encoded into the braiding of the quasi-particle excitation world-lines, i.e. if they form or not a knot in 2+1 space-time. Such excitations are called anyons and they occur, for instance, in the Quantum Hall Effect. Physical systems with these properties open the possibility of topologically protected error-free and decoherence-free quantum information processing based on braids. Spurred to a large extent by the potential promise of this application (and the concomitant funding supplied by both industry and government agencies), the field of topological quantum computation has exploded in the last few years. If such braiding operations could be physically realized, knots would form the basis for an entirely new kind of computer, whose power would vastly outstrip that of current, classical computers.



Universal set of fault-tolerant quantum gates in terms of braidings of anyons

For this reason, the search for topological phases has been particularly intense and our aim is to make a solid research plan for identifying such phases. Perhaps the simplest one is the chiral p-wave superfluid where vortices are Majorana fermions which inherit nontrivial braiding statistics[26]. Exciting progress toward the realization of similar phases in cold atom systems has also recently been made[27] and it would be extremely interesting if, one day, the elusive Majorana particles will

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[23] I. Bloch, J. Dalibard, and W. Zwerger, *Many-body physics with ultracold gases,* Rev. Mod. Phys. 80, 885 (2008).

[24] A. Kitaev, *Anyons in an exactly solved model and beyond*Annals of Phys. **303** 2 (2003); ibid **321** 2 (2006).

[25] For a recent review of this field, see C. Nayak, S. H. Simon, A. Stern. M. Freedman, and S. Das Sarma, *Non-abelian anyons and Topological Quantum Computation*, Rev. Mod. Phys. **80**, 1083 (2008).

[26] N. Read and D. Green, *Paired states of fermions in two-dimensions with breaking of parity and time reversal symmetries, and the fractional quantum Hall effect,* Phys. Rev. B 61, 10267 (2000); G. E. Volovik, *The Universe in a Helium Droplet* (Clarendon, Oxford, 2003).

[27] N. R. Cooper and G. V. Shlyapnikov, *Stable Topological Superfluid Phase of Ultracold Polar Fermionic Molecules*

be discovered in this way. A great theoretical effort is also needed to identifying microscopic models that would lead to topological phases of matter in their low energy limit. Although the effective hydrodynamical description of anyons is given in terms of Chern-Simons gauge theories, a natural formulation of their configuration space can be set up by a two-dimensional integrable loop gas, thus realizing a natural correspondence between the braid matrix of the particles and the scattering matrix of the associate (1+1) dimensional quantum field theory. It is interesting to note that the resulting picture can be also put in strict correspondence with the Temperley-Lieb algebra that stays behind many exactly solvable models[28]. Our aim is to thoroughly investigate the dynamics of these quantum loop gases and of interactive anyon systems. It is also important to analyze string-net models[29], especially because they are closely related to lattice gauge theories. These systems, and possibly new ones, may provide keen and novel tools for engineering topological phases of matter.

Once one realizes a potentially useful topological phase of matter, it remains a nontrivial issue how one can use it to perform quantum computation: it remains, indeed, a challenging problem figuring out how such a computer should be constructed and how algorithms should be implemented. In the last few years, however, several schemes[30] have been developed for implementing the details of such a device: the one that, by far, provides the fastest implementation of a search of braiding operations has been recently proposed in the paper[31].

WP5. Conformal Field Theory, Integrability and Duality Relations. Starting date: 01/2014. Duration: 24 months. Partners: SISSA, INFN, Landau, PMDI-RAS, Sao Paulo. Leading researchers involved: A. Belavin (Landau); A. Pronko (PDMI-RAS); G. Mussardo and G. Delfino (SISSA); F. Colomo (INFN); F. Alcaraz and M. Martins (Sao Paulo).

Objectives: Understanding the phases of statistical models, the role of boundary conditions and the web of dualities which link quantum field theories.

Milestones: 1. Understanding the AGT conjecture in CFT; 2. Spatial phase separations induced by boundary conditions.

Description

Recently a very interesting relation between the Nekrasov partition function of N = 2 conformal invariant SU(2) gauge theory and the conformal block of the Liouville field theory was proposed[32]. It seems that this is the first example of a precise mathematical relationship between quantum field theories defined at different space-time dimensions. There have been various attempts at checking this AGT relation at lower instanton numbers by direct evaluation of Liouville correlation functions[33]. There have also been attempts at proving the relation by comparing the recursion

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Phys. Rev. Lett. 103, 155302 (2009).

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[32] L. F. Alday, D. Gaiotto, and Y. Tachikawa, *Liouville Correlation Functions from Four-dimensional Gauge Theories*, Lett. Math. Phys. 91 (2010) 167–197.

[33] A. Mironov, A. Morozov and S. Shakirov, *Matrix Model Conjecture for Exact BS Periods and Nekrasov Functions*, JHEP 1002, 030 (2010); A. Morozov and S. Shakirov, *The matrix model version of AGT conjecture and CIV-DV*

relation satisfied by the descendants of the conformal blocks and Nekrasov's partition function[34]. This topic may be seen as one of the boldest conjectures put forward in recent years to disentangle the dynamics of quantum field theories and statistical models. Another bold conjecture is the one which relates classical gravity in anti-deSitter space to conformal field theory on the boundary: the so called AdS/CFT (anti-de Sitter/ Conformal field theory) correspondence[35] have become very important in higher energy theoretical physics over the last ten years, and many papers have being published about the subject. One reason is that this correspondence can be used to understand strongly interacting field theories by mapping them to classical gravity. The main idea is as follows: Large N gauge theories (which are strongly coupled conformal field theories) in d space-time dimensions are mapped to a classical gravitational theory in d + 1 space-time dimensions which are asymptotically AdS. In fact, it is a strong-weak coupling duality: when one theory is coupled weakly, the dual description involves strong coupling, and vice versa. Arguments showing that some quantum field theories (QPT) are secretly quantum theories of gravity and therefore we can use them to compute observables of the QFT, when the gravity theory is classical, can be found in the recent paper[36]. The number of theories that can be studied using the correspondence is still small: it is hoped that these theories can be used to capture essential features of theories realized in nature, and it is what we plan to study.

Integrability plays a crucial role in the investigation of another interesting phenomenon, namely spatial phase separation induced by boundary conditions. Consider, for example, a two-dimensional system whose parameters are tuned in such a way to be in a disordered phase, while its boundary conditions are chosen so that only ordered configurations are admissible in the proximity of the boundary. In the presence of strong correlations, it may happen that such boundary conditions induce ordered regions extending macroscopically from the boundaries deeply inside the bulk of the system. In such situation, spatial phase separation emerges, with ordered regions contiguous to the boundary, sharply separated from a central disordered region by a smooth curve, called arctic curve in the case of dimer models. Essentially the same phenomena appear in other contexts, with different names, such as limit shape (in the statistics of Young diagrams[37] and rhombi tilings[38]), or interface (in random growth models for two-dimensional crystals[39]). More generally, the problem consists in finding the limit shapes and fluctuations of random two-dimensional surfaces arising, for instance, in plane partitions (or in three-dimensional Young diagrams, or in the melting of a faceted crystal), and also in dimer models on planar bipartite graphs with fixed boundary conditions, when described in terms of the height function. In these contexts, the arctic curve is usually referred to as the frozen boundary of the limit shape. The standard example of an arctic curve is the famous arctic circle which appeared in the study of domino tilings of large Aztec diamonds. The name originates from the fact that in most configurations the dominoes are 'frozen' outside the circle inscribed into the diamond, while the interior of the circle is a disordered, or 'temperate', zone. The study of all these aspects involves a fascinating interplay between integrability, discrete mathematics, combinatorics and statistical physics.

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[34] V. A. Fateev and A. V. Litvinov, *On AGT conjecture,* JHEP 1002, 014 (2010)

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[38] H. Cohn, M. Larsen, and J. Propp, *The shape of a typical boxed plane partition*, New York J. Math. 4 (1998), 137.

[39] M. E. Fisher, *Walks, walls, wetting and melting*, J. Stat. Phys. 34 (1984), 667–729.

WP6. Pairing up Theory with Experiments. Starting date: 01/2013. Duration: 36 months. Partners: UOXF, SISSA, INFN, CSIC, UVA, BNL, La Plata, Zhejiang. Leading researchers involved: K. Schoutens and S.Caux (UVA); A. Cappelli (INFN); G. Mussardo (SISSA); S. Simon (UOXF); G. Sierra and M. A. Martin-Delgado (CSIC); D. Cabra (La Plata); X. Wan (Zhejiang).

Objectives: Comparison of theoretical predictions with experiments.

Milestones: 1. Experimental signatures of quantum quench; 2. Signatures of non-Abelian fractional statistics; 3. Study of topological phases of matter.

Description

1. Historically experimental studies of out of equilibrium evolution have been hampered by the effects of dissipation and decoherence, which put very restrictive limits on the time scales available for observing truly unitary time evolution. In recent years such limitations have been overcome in cold atomic experiments. The first experiment of quantum quench[40] involved a two-dimensional Bose gas loaded in an optical lattice: here, it was possible to follow the non-equilibrium quantum dynamics of the systems after quenching from the superfluid to Mott insulting phase. This experiment revealed the purely quantum nature of the evolution through the amazing effect of ``Collapse and revival of Bose-Einstein condensate''.

In another experiment[41] the quantum analogous of the ``Newton craddle'' has been realized with Bose gases. It consists of two different Bose-Einstein condensates prepared in different position and loaded at equal distance from the center of an harmonic potential. During the evolution, the two condensates move toward to each other, interact in the center of the potential and then separate again. It has been possible to observe thousand oscillations that are characteristic of the one-dimensional system, thermalization being achieved after few oscillations in three-dimensional condensates.

In the recent paper by S. Trotzky et al. not yet published, the more complicated situation of a one-dimensional Bose gas in an optical superlattice has been considered. For short enough time the experimental results are fully consistent with numerical simulations, showing the clear quantum nature of the evolution and the ability to measure it. The experiment can probe longer times than those reachable by numerical methods, showing that optical lattices are nowadays effective quantum simulators. Finally, the measured asymptotic times are fully compatible with a thermal ensemble, posing several puzzles on thermalization.

These three experiments clearly indicate that the theoretical methods and results described in the WP1, and also WP3, can have immediate physical application. As already stressed before, the one-dimensional dynamics is the most interesting, and at the same time it requires specific theoretical tools, developed in this project.

2. Several earlier topics have been centered on anyons, low-energy excitations with fractional charge and fractional statistics. The main physical system for observing anyons is the fractional quantum Hall effect, whose experimental aspects have been investigated for over twenty years. While fractional charge has been observed more than ten years ago, fractional statistics has not yet been definitely confirmed. The non-Abelian statistics, the exchange statistics of a multiplet of degenerate anyon excitations, corresponding to a multidimensional unitary transformation of the corresponding vector wave function, is intensively studied experimentally. The recent surge of activity has been triggered by the proposal of Topological Quantum Computation discussed earlier. The direct observation of fractional and non-Abelian statistics by the interference phase acquired by excitations encircling one another is very difficult to obtain, due to the instability of the Hall system of electrons placed at very low temperature and high magnetic field. Recent experiments and theoretical/phenomenological approaches have thus look for indirect signatures that might be easier to observe.

The current peaks though an isolated Hall droplet have been seen and their patter has been shown to be characteristic of the low-lying spectrum of edge excitations, that correspond with the anyon

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[40] M. Greiner et al., Nature 419 51 (2002).

[41] T. Kinoshita, T. Wenger, and D. S. Weiss, Nature 440, 900 (2006).

excitations in the bulk of the droplet. These patterns have been extensively studied both theoretically and experimentally.

Another experimental signature that is specific of non-Abelian statistics is the zero-temperature entropy due to the quantum degeneracy of these anyon multiplets. This entropy could be experimentally determined by the thermopower, the ratio of transport coefficients due to the applied electric and thermal gradients. A recent experiment has indicated that the thermopower measurement is feasible in the near future at the required precision. In summary, an intense experimental and theoretical activity is observed in this domain.

3. Topological phases of matter challenge our understanding of the very meaning of order and disorder — they fall outside of the well-established Landau paradigm whereby states of matter are classified according to their broken symmetries: they cannot be described by any local order parameter. At the same time, these phases of matter have many peculiar properties, including exotic braiding statistics of their excitations (that are the one discussed above for quantum Hall effect), that clearly distinguish them from conventional quantum matter. However, there are important topological phases that are not connected to anyonic statistics. Among them, the most studied in recent years are the so-called "Topological insulators". In these insulators, spin-orbit effects take the role of an external magnetic field in the quantum Hall, with spins of opposite sign propagating in opposite directions along the edge[42]. Photoemission measurements[43] of the surface of Bi_(1-x) Sb_x provide robust evidences that this material is a realization of a topological insulator in three dimensions, showing that topological phases are not peculiarity of the two-dimensional world. After this first material a number of other tridimensional topological insulators has been experimentally probed[44]. The theory also predicts the existence of topological superconductors, but they have not yet been identified in nature.

Furthermore, there exists many theoretical predictions (the topological magneto-electric effect, image magnetic monopoles, axion electrodynamics, spin-charge separation and fractionalization, exciton condensations) in topological insulators and superconductors that may be soon probed in experiments.

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[42] B. A. Bernevig et al, Science 314, 1757 (2006).

[43] D. Hsieh et al, Nature 452, 970 (2008).

[44] See e.g. Xia et al, Nature Physics 5, 398 (2009), Chen et al Science 325, 178 (2009).

List of milestones

In summary, the activity described in the Work Packages has led to the identification of some milestones that are summarized in the following table, including the date of their expected accomplishment.

List and schedule of milestones			
WPs n°.	**Milestone name**	**Lead Partner Organization short name**	**Delivery date**
1	Thermalization properties in integrable and non-integrable quantum systems	SISSA	12/2014
2	Applications to quantum transport	Sao Paulo	12/2013
2	Interplay between thermal and entanglement entropies	CSIC	12/2012
3	Spectral and optical properties	BNL	12/2013
3	Dimensional crossover in coupled chains	La Plata	12/2013
4	Description of interacting anyon systems	UOXF	12/2015
4	Realization of quantum gates by braiding	SISSA	12/2014
5	Understanding the AGT conjecture in CFT	Landau	12/2014
5	Spatial phase separations induced by boundary conditions	PDMI-RAS	12/2014
6	Experimental signatures of quantum quench	INFN	12/2013
6	Signatures of non-Abelian fractional statistics	INFN	12/2014
6	Study of topological phases of matter	UVA	12/2015

The pattern of secondements, the Gantt chart and the overall plan of research exchanges is presented in the Implementation section B 3.

B1.3 Scientific quality of the partners

J.L. Cardy (Oxford) and **A.B. Belavin** (Landau Institute) are among the founders of CFT. Their deep contributions to the development of the subject are very well known (the paper[45] of A. Belavin, together with A.Polyakov and A.B. Zamolodchikov, which opened the field of conformal invariance has collected up to now 2500 citations, while one of the most known papers[46] by J.L.

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[45] A.B. Belavin, A.B. Polyakov and A.B. Zamolodchikov, *Infinite conformal symmetry in 2D quantum field theory,* Nucl. Phys.B241, 333 (1984)

[46] J.L. Cardy, *Operator content of 2D conformally invariant theories,* Nucl.Phys.B270,186 (1986);

Cardy on modular invariance has 767 citations. Both authors have an impressive record of publications (A. Belavin, 67 papers with 6200 citations while J.L. Cardy 136 paper with 7600 citations). Their works have promoted many different new lines of research, among which: integrable structure in gauge theories, solitons, modular invariance, entanglement entropy, phase transitions, universal ratios of the Renormalization Group, percolation, self-avoiding walks, quantum quenches, etc.

For his outstanding contributions, **J.L. Cardy** has received the Boltzmann medal, the Onsager Prize and the Heinmann Prize. He is also the author of the book[47] *"Scaling and Renormalization in Statistical Physics"* (Cambridge Univ. Press).

Fabian Essler (Oxford) is an international renown expert of quantum spin chain, quantum magnetism, and exact methods of Bethe Ansatz. He is the author of the book[48] *"The one-dimensional Hubbard model"* (Cambridge Univ. Press). This model, which described interacting electrons in narrow energy bands, has been applied to problems as diverse as high-T_c superconductivity, band magnetism and the metal-insulator transition. Fabian Essler is also known for his review article on finite temperature effects in quantum systems[49].

Steve Simon (Oxford), former Department Director at Bell Labs Alcatel-Lucent Technologies in New York and now Professor of Theoretical Physics at Oxford University, has been one of the pioneer of the studies in topological properties of matter and topological quantum computation, where he has made several seminal papers[50]. He has made the proposal of observing Majorana fermions in special superconductor and he has promoted the construction of fault-tolerant quantum gates in terms of braiding of anyons.

Giuseppe Mussardo (Coordinator) (SISSA) is credited for the development of low-dimensional quantum systems, on which he wrote the book[51] *"Statistical Field Theory. An Introduction to Exactly Solved Models"* (Oxford Univ. Press). He has published 81 articles which have collected 2000 citations. His recent interests involve cold-atoms, quantum quenches and topological quantum computation. Together with Gesualdo Delfino (Trieste), he has achieved the exact computation of the quantum correlators of the Ising model in a magnetic field and he has computed the decay of its quasi-particle excitations[52], results that have recently received a striking confirmation by recent neutron scattering experiments[53]. G. Mussardo and G. Delfino have also opened the research in the largely unexplored area of quantum non-integrable models, where they have pointed out the striking phenomenon of confinement of topological excitations. Using field theory methods and non-relativistic limit thereof, G. Mussardo has also proposed a new method to tackle the exact computation of the quantum correlators of the Lieb-Liniger model. These quantities have direct applications in experiments on cold atom in a guideline[54].

Gesualdo Delfino (SISSA) is an expert of integrable quantum field theory. He has carried on an intense investigation of universal ratios of Renormalization Group in several classes of universality,

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[47] J.L. Cardy, *Scaling and Renormalization in Statistical Physics*, Cambridge University Press (1996)

[48] F.Essler, H. Frahm, F. Gohmann, A. Klumper, V. Korepin, *The One-Dimensional Hubbard Model,* Cambridge Univ. Press

[49] F.H.L. Essler and R.M. Konik, *Finite Temperature Dynamical Correlations in Massive Integrable Quantum Field Theories*, J. Stat. Mech. Theor. Exp., P09018 (2009).

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[51] G. Mussardo, *Statistical Field Theory. An Introduction to Exactly Solved Models in Statistical Physics*, Oxford Univer. Press (2009).

[52] P. Grinza, G. Delfino, G. Mussardo, *Decay of particles above threshold in the Ising model in a magnetic field,* Nucl. Phys. B737, 291-303, 2006; G. Delfino and G. Mussardo, *The spin-spin correlation function in two-dimensional Ising Model*, Nucl. Phys. B 455, 724-758, 1995.

[53] R. Coldea et al, *Quantum Criticality in an Ising Chain: Experimental Evidence for Emergent E(8) Symmetry,* Science 327:177-180,2010.

[54] M. Kormos, G. Mussardo, A. Trombettoni, *Expectation Values in the Lieb-Liniger Bose Gas,* Phys. Rev. Lett. 103, 210404 (2009), selected for Virtual Journal of Atomic Quantum Fluids, Vol.1, Issue 6 (eds. W. Ketterle, P. Greiner, P. Zoller).

for example those of the Ising model and percolation[55].

Andrea Cappelli (INFN) is a renowned expert in conformal field theory and its application to condensed matter systems. His work on the fractional Hall effect has been dealing with the description of anyon excitations with the W-infinity symmetry of incompressible quantum fluids, the interplay between Abelian and non-Abelian anyons and other aspects. In some recent papers[56], he has determined experimental signatures of non-Abelian anyons in the Coulomb blockade conductance peaks and the thermopower.

Filippo Colomo (INFN) has strong expertise in lattice exactly-solvable models. His recent interests lies in mathematical problems of statistical physics, with main focus on calculation of correlation functions in lattice statistical models and quantum spin chains, with applications to entanglement, enumerative combinatorics, and phase separation phenomena[57].

Pasquale Calabrese (INFN) is a relatively young researcher with an impressive list of relevant results in conformal field theory, statistical mechanics and integrable systems, both analytic and numerical. In collaboration with J.L. Cardy, he obtained the general expression of the entanglement entropy of CFT mentioned several times in this document. Together they also wrote pioneering papers on quantum quenches. Together with J.S. Caux, he developed precise numerical methods to compute the correlation functions of integrable spin chains for comparison with neutron scattering experimental data.

German Sierra (CSIC) is well known for his profound contributions in quantum groups and CFT. His expertise ranges from quantum spin chain to superconductivity, from integrable models to superconductivity. He is recently involved in the development of the approach of infinite matrix product states in low-dimensional systems, and in the computation of entenglement entropy in Quantum Hall Effect. He is the author of the book[58] “Quantum Groups in Two-Dimensional Physics” , which a reference text in the study of two-dimensional systems. He is also well known for his original papers on Riemann conjecture, directly inspired by quantum systems[59].

Miguel Angel Martin-Delgado (CSIC) is a well-known expert in the areas of Quantum Information and Condensed Matter Physics. He has worked on a wide range of topics, from strongly correlated systems, such as spin chains and ladders, to Topological Quantum Computation, where he has proposed the novel topological color codes. More recently he has been very active in the field of quantum simulation, that use cold atoms in optical lattices to simulate non-Abelian gauge fields and the Quantum Hall effect. He is the coauthor of a widely used Review of Modern Physics on quantum computation published in 2002.

Kareljan Schoutens (Amsterdam), currently Director of the Institute of Theoretical Physics in Amsterdam, is well-known for his advances in the physics of Quantum Hall effect and anyon system, where he combined sophisticate techniques of CFT with physical insights coming from experiments[60]. He has also played a very important role in the promotion of topological quantum computartion[61]. He has published 73 papers with 2700 citations altogether.

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[55] G. Delfino, J. Viti, *On three-point connectivity in two-dimensional percolation*, J.Phys.A44:032001,2011; G. Delfino, J. Viti, *Universal properties of Ising clusters and droplets near criticality*, Nucl.Phys.B840:513-533,2010; G. Delfino, J. Viti, J. Cardy, *Universal amplitude ratios of two-dimensional percolation from field theory*, J.Phys. A43:152001, 2010.

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[61] E. Ardonne, K, Schoutens, *Wavefunctions for topological quantum registers* , Ann. Phys. 322 (2007) 201-235,

Jean Sebastian Caux (Amsterdam) is credited for his remarkable contributions in computing dynamical correlation functions of quantum spin systems and cold-atoms, where he combined analytic techniques of Bethe Ansatz with optimized numerical codes[62]. He has a very solid experience and a robust list of publications in several topics of condensed matter, made with his former supervisor A. Tsvelik.

Alexei Tsvelik (BNL) is originally from Landau Institute and now PI in Brookhaven National Laboratories, is a renown scientist in the field of condensed matter, where he introduced techniques coming from conformal field theory and integrability to understand the behavior of new material. His scientitic interests range from quasi-one dimensional material to strongly correlated systems, from low dimensional magnetism to transport in quantum wires, and they also include graphene, bosonization and form factors in integrable field theory. He is the authors of two acclaimed books on those subjects[63]. He has published 150 articles which have collected 3700 citations (from Web of Science).

Robert Konik (BNL) is known for his studies of conformal and integrable field theories in the fields of low-dimensional strongly correlated materials, quantum magnetism, quantum dots. Particularly important, in the context of this application, is his expertise on finite temperature effects[64] and Bethe ansatz computation[65].

Andrei G. Pronko (PDMI-RAS) is interested in mathematical problems of statistical physics, with main focus on calculation of correlation functions in integrable models of statistical mechanics and quantum spin chains, with applications to enumerative combinatorics and phase separation phenomena. His most recent notable results concern the arctic curve of six-vertex model and the limit shape of alternating-sign matrices (in collaboration with F. Colomo).

Daniel Cabra (La Plata) as recently come back to Argentina (La Plata), to start a new group of young researchers at University of La Plata. In the past he held a professorship position at the Physics Department of the University of Strasbourg (France). He has promoted an intense research on application of modern techniques of theoretical physics in condensed matter physics, establishing a strong collaboration with European groups[66]

Francisco Alcaraz (Sao Paulo) is among the first theoretical physicists who seek conformal invariance into lattice statistical models[67] and his studies have been very instrumental in clarifying CFT into statistical physics. More recently, he has promoted an intense research on entanglement properties of extended quantum system, establishing in particular a collaboration with the group of German Sierra in Madrid[68]. He is one of the leading scientific figure in Brazil, where he has

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[62] J.-S. Caux and J. M. Maillet, *Computation of Dynamical Correlation Functions of Heisenberg Chains in a Magnetic Field*, Phys. Rev. Lett. 95, 077201 (2005); J.-S. Caux, R. Hagemans and J. M. Maillet, *Computation of dynamical correlation functions of Heisenberg chains: the gapless anisotropic regime,* J. Stat. Mech. (2005) P09003; J.-S. Caux and P. Calabrese, *Dynamical density-density correlations in the one-dimensional Bose gas*, Phys. Rev. A 74, 031605(R) (2006).

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[65] A. Gogolin, R. Konik, A. Ludwig, H. Saleur, *Counting statistics for the Anderson impurity model: Bethe ansatz and Fermi liquid study*, Ann. Phys. (Leipzig) 16, 678 (2007)

[66] H. Feldner, Z.Y. Meng, A. Honecker, D. Cabra, S. Wessel, F. Assad, *Magnetism of Finite Graphene Samples: Mean-Field Theory compared with Exact Diagonalization and Quantum Monte Carlo Simulation,* Phys. Rev. B 81, 115416 (2010); M. Moliner, D. Cabra, A. Honecker, P. Pujol, F. Stauffer, *Magnetization Process of the Classical Heisenberg Model on the Shastry-Sutherland Lattice,* Phys. Rev. B 79, 144401 (2009)

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promoted a school of young researchers and the opening of the International Institute of Physics in Natal (University of Rio Grande, Brazil).

Xin Wan (Zhejiang) is an emerging young theoretical physicist in China. After he took his PhD from Princeton University, he held the position of Leader Investigator at the Aisa Pacific Center for Theoretical Physics in South Korea, and he recently went back to China to joint the Faculty of Zhejian Institute of Modern Physics at Hangzhou (China). He received the Faculty Award for Excellence, Zhejiang University, 2007, the Ray Grimm Memorial Prize in Computational Physics, Princeton University, 1999 and the T. D. Lee Fellowship in Physics, Fudan University, 1990. He made several important contributions in Quantum Hall Effect[69] and topological quantum computation[70].

B1.4 Complementarities/synergies between the partners

One of the main qualities of this proposal is the well-balanced set of complementary expertise that the different groups in Europe and outside Europe bring together. On one side, in fact, there are very strong expertise on formal aspects of CFT and integrable models, in terms of the leading scientists of the nodes of Oxford, SISSA, INFN, Landau Institute, Steklov Institute and San Carlos. On the other side, there is a very solid knowledge on modern aspects of condensed matter theory, in terms of the scientists of the nodes of Amsterdam, Brookhaven, La Plata. Moreover, these expertise are further complemented by a very robust knowledge of topological phases of matter and quantum computation, in terms of the scientists of the node of Hangzhou, Amsterdam, INFN and SISSA. Studying exactly solvable models is an intellectual and rewarding task but more importantly is the spectrum of applications that exactly quantum solvable models can find in physics world. They can open, in fact, a thorough control on a vast range of physical phenomena. This is a task where all groups of this proposal can contribute with their own expertise and skill. Therefore, setting up such an international team of can result in an enormous boost to knowledge in quantum systems with many degrees of freedom and their applications. In particular:

(a) on the topic of thermalization in extended quantum systems, new synergies are expected to come from the blending of theoretical ideas of boundary conformal field theory (promoted by J.L. Cardy and P. Calabrese), integrable models (promoted by J.S. Caux, F. Essler, G. Mussardo and their collaborators) and control of experimental set-ups provided by scientists of Brookhaven National Laboratories.

(b) new perspectives on the formal aspects of integrable models can be disclosed by the collaboration of the scientists of Landau Institute (A. Belavin and his group) - who can provide all powerful knowledge of conformal field theory -, G. Sierra in Madrid, who is a world-leader of quantum group and Yang-Baxter equations, A. Pronko in San Petersburg, who has an excellent expertise on lattice statistical model, G. Mussardo and G. Delfino at SISSA, and A. Cappelli and F. Colomo at INFN, who have performed in the past thorough studies of different classes of universality of integrable models. Further synergy will come from a new numerical code - based directly on conformal field theory states - developed by R. Konik at Brookhaven Nat. Lab. In order to establish on a sound ground the validity of duality between different theories it is required the coherent effort of the groups of Landau Institute and SISSA, who can bring together

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[69] Zi-Xiang Hu, E. H. Rezayi, Xin Wan, and Kun Yang, *Edge-mode velocities and thermal coherence of quantum Hall interferometer,* Phys. Rev. B 80, 235330 (2009); Hua Chen, Zi-Xiang Hu, Kun Yang, E. H. Rezayi, and Xin Wan, *Quasiparticle tunneling in the Moore-Read fractional quantum Hall state*, Phys. Rev. B 80, 235305 (2009); Zi-Xiang Hu, Hua Chen, Kun Yang, E. H. Rezayi, Xin Wan, *Ground state and edge excitations of quantum Hall liquid at filling factor 2/3,* Phys. Rev. B 78, 235315 (2008).

[70] Michele Burrello, Giuseppe Mussardo, and Xin Wan, *Topological Quantum Gate Construction by Iterative Pseudogroup Hashing,* New J. Phys. 13, 025023 (2011), Focus on Topological Quantum Computation; Michele Burrello, Haitan Xu, Giuseppe Mussardo, and Xin Wan, *Topological quantum hashing with the icosahedral group,* Phys. Rev. Lett. 104, 160502 (2010); .Haitan Xu and Xin Wan, *Constructing functional braids for topological quantum computing,* Phys. Rev. A 78, 042325 (2008), selected for the Virtual Journal of Quantum Information and the Virtual Journal of Nanoscale Science & Technology.

complementary knowledge and techniques on conformal blocks, correlation functions etc. Analysis of boundary conditions in statistical models will see the close collaboration between scientists of the INFN node and those of the Steklov Institute in St. Petersburg.

(c) new advances on entanglement can be made thanks to the close interaction of the leading scientists in this topic (J.L. Cardy-Oxford, P. Calabrese-INFN) with scientists like G. Sierra (Madrid) and F. Alcaraz (San Carlos), who are pursuing a similar research but focused on statistical models. Additional advantages on this topic are also expected from the complementary approach of D. Cabra (La Plata), who is working on the same topic from a purely condensed matter point of view.

(d) topological phases of matter can be efficiently investigated thanks to the complementary skills of K. Schoutens (Amsterdam), A. Cappelli (INFN), S. Simon (Oxford) and X. Wan (Hangzhou). While the former two scientists tend to follow an analytic approach, the latter scientists are also versatile in numerical approaches, which may be quite useful for detailed checks of wave functions, energies, etc. Further investigation on topological quantum computation can be triggered by a close collaboration of the European groups of Amsterdam, Oxford and SISSA, together with the Chinese group in Hangzhou.

(e) important synergies between partners can be set to place on the study of new low-dimensional material and cold atoms, where there is an excellent European expertise in the group of Oxford, especially in F. Essler, in La Plata with D. Cabra, and in the US scientists of Brookhaven Nat. Labs, especially A. Tsvelik. Such studies prove to be quite effective if they are accompanied by strong analytic techniques which come from integrable field theory and integrable models. Such expertise is available in the groups of SISSA (G. Mussardo and collaborators) and Amsterdam (J.S. Caux and collaborators).

B2 Transfer of Knowledge.

B2.1 Quality and mutual benefit of the transfer of knowledge

In choosing this set of participants, we mean to assemble a broadly based (interdisciplinary) group of theorists all over the world in quantum field theory and statistical/condensed matter physics, each of them with a distinctive expertise. Doing so, one of our purposes is to expose the young scientists to a wide-ranging scientific environment, much beyond than what could be available at any individual node. The various partners are linked by their common interest in the frontiers of low-dimensional quantum systems and applications, and by a well-established scientific collaboration. Furthermore, many scientists involved in this proposal have been working together in the organization of conferences, summer schools, workshops and lecture series. Over the years, productive and fruitful scientific exchanges have been established between different groups with a lively interaction among all scientists. All these activities reflect the high level of coherence and cohesion of the proposed network, as well as the efficient organization skills of its partners in carrying out a research and training activity. With this proposal we would like to further strengthen the quality of our scientific/networking activities and to promote beyond its present size.

Thanks to the visit exchanges and the organization of workshops, in the four year of the grant there will be a significant transfer of knowledge to and from Europe on topics which are at the current frontline of theoretical physics. This will be realized through several different levels.

For instance, from the interaction with scientists of Brookhaven National Laboratories and La Plata, the European groups can acquire new fundamental knowledge on highly sophisticate techniques to understand experimental data about new materials: this involves frustrated quantum spin liquids, fractionalization of excitations, thermal fluctuations, magnetic structures in stripe ordered state, spin density waves in graphene, etc.

The Russian schools of Landau Institute and Steklov Institute are renown for their deep expertise in mathematical physics and techniques related to integrability, such as Bethe Ansatz, Inverse

Scattering Methods, Quantum Separation of Variables, etc. Therefore, from these two groups and also from the group in San Carlos -- who also has strong expertise on these topics -- the European groups can learn both the refined mathematical methods to handle conformal/ integrable systems and the new challenge problems that such systems: the existence of duality relations between quantum field theories of different dimension is one of them, but there are also interesting open aspects related to spectra of excitations in quantum spin chains or exactly solvable models.

For what concerns topological quantum computation, European groups can largely benefit from the interaction with the group of Xin Wan in Hangzhou: not only for the latest developments in this fast-developing field but also in the architecture of new software needed to implement the quantum gates and the possible physical realizations thereof.

On the other hand, European groups present a large set of scientific interests and strong academic skill and, for these reasons, they can be extremely effective in promoting new research directions in groups outside Europe which, presently, do not have the proper academic strength, either for historical reasons or for historical circumstances. It is fair to say, for instance, that in the recent past years many outstanding senior scientists left Russia to go abroad: such huge brain-draining has caused a great damage to the youngest generations of Russian scientists, which can be partially cured by a very close interaction with European groups. The groups in South America and China, on the other hand, are led by outstanding scientists but they are generally quite small: be part of an international collaboration of large scale can be enormously helpful in developing a new generation of scientists in these countries.

European groups, for instance, has largely promoted and expanded the area of quench dynamics in extended quantum systems, thanks to the relevant contributions of the groups in Oxford, Amsterdam, SISSA and INFN. Control of extended quantum systems may have a relevant part for a clever design of future technological devices, in particular in the direction of quantum computation. A relevant questions concerns the possibility to have macroscopic quantum systems subjected to a purely integrable dynamics: such a possibility could disclose a new way of storing, without dissipating, quantum information as the time goes by. But how can we detect if a quantum system is integrable or not? What signatures can we have for it? If a quantum system is subjected to an abrupt change of the parameters of its Hamiltonian, does it thermalize or not? Will it have memory of its initial state? Is there a difference between integrable and non-integrable dynamics, as recent experimental results[71] seem to suggest? Answer to these questions may come from subjects as Boundary Field Theory[72], Integrable Field Theory[73] and breaking thereof[14] -- largely developed by European groups -- but it will require the help of the capabilities of the various groups outside Europe. For instance, it will require the powerful numerical techniques developed by R. Konik at Brookhaven National Labs, or the analytic tools of Form Factors and Bethe Ansatz promoted by Landau Institute and San Carlos. The overall effort will definitely increase the quality of the research made in the individual groups all over the world and will lead to a new robust set of knowledge on these topics. It is worth to mention that quantum relaxation is surprisingly similar to the physics of non-trivial condensate (like BCS state) and therefore the genuine competence in condensed matter present in the groups of BNL, Madrid and La Plata can be largely useful.

In the area of topological quantum computation, there will be a large mutual benefit for the European groups of Amsterdam, SISSA, INFN and Madrid, and for the group in Hangzhou in China. The Amsterdam and INFN nodes have well established record of contributions in Quantum Hall Effect, which is the paradigmatic physical systems with anyon excitations.

Another topic, closely related to quantum quenches, in which there will be large benefit of the participants is the comprehension of entanglement. Recent studies, mainly carried by the node of Oxford (J. Cardy) and INFN (P.Calabrese) have made clear that the control of conformal invariance is crucial for the understanding of the non-local properties of quantum mechanics of

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[71] T. Kinoshita, T. Wenger, and D. S. Weiss, *A quantum Newton's cradle*, 2006 Nature 440, 900.

[72] P. Calabrese and J.L. Cardy, *Quantum Quenches in Extended Systems*, JSTAT P06008 (2007).

[73] D. Rossini, A. Silva, G. Mussardo, G. Santoro, *Effective thermal dynamics following a quantum quench in a spin chain*, Phys. Rev. Lett. 102, 127204 (2009); D. Fioretto, G. Mussardo, *Quantum Quenches in Integrable Field Theories,* invited paper in New Journal of Physics 12, (2010).

extended systems. Pushing the present computations (relative to bipartite systems) to systems with multi-components is a challenge which needs not only sophisticate expertise of conformal field theory but also powerful numerical codes such as the density matrix renormalization group or tensor product network. The advance in this field can greatly benefit from the numerical skill of the groups in Madrid and La Plata.

B2.2 Adequacy and role of staff exchanged with respect to the transfer of knowledge

The scientists involved in this proposal are among those who have paved the way to significant developments in the area of integrable models, conformal invariance and applications thereof. They have also acquired a significant experience in training the young generations, creating well-recognized schools in their own countries. Oxford, with J. Cardy, F. Essler and S. Simon, is currently a leading center of studies in conformal field theory, integrable systems and topological quantum computation; SISSA, in addition to an intense research on quantum integrability and the realms of its application carried on by G. Mussardo and G. Delfino, has also promoted in 2006 a specific PhD program in Statistical Physics, that attracts each year many students and post-docs: moreover, G. Mussardo and A. Cappelli (INFN) have gained an important skill in organizing research activities on a large scale and they have been directly involved in the organization of many international events all over the world (conferences, extended programmes, focused workshops). K. Schoutens is currently the Director of the Physics Department in Amsterdam and in the last ten years he has been the promoted of a very successful summer conference, where scientists from Europe, the US and other countries gather together for discussing the latest developments in the field of low-dimensional systems, topological computation and integrable model. J.S. Caux, in Amsterdam, has been recently the winner of an important national grant, that will enable him to set up a young group of collaborators around him, to tackle questions concerning quantum quenches, off-equilibrium dynamics and correlation functions in integrable systems. G. Sierra, in Madrid, has served for many year in the National Committee of hiring young scientists and has played a very important role in the promotion of science in his own countries. For instance he has developed the range of activities of the center in Benasque, where many conferences and schools have been organized in recent years.

A. Belavin is one of the founders of conformal field theory and in Russia he has strongly taking care of the training of young generation at the Landau Institute, where many other leading scientists have left the country. He ha been very active in organizing activities which bring European scientists in Russia and in establishing close contacts among groups in Europe. He has played a major role in keeping alive the strong tradition of mathematical physics in integrable models in Russia. A.G. Pronko is a recognised scientist from Steklov Math Institute at St.Petersburg, a famous research institute with great traditions. Holding a permanent research position, he often travels abroad and keeps active contacts with researchers from other countries; among others, he has a strong link with the INFN node in Italy. Xin Wan has previously held a professorship position at the Asian Pacific Center of Theoretical Physics (APCTP) at Pohang (South Korea) and got PhD degree and post-doctoral fellowship in the US: he decided to go back to China and set a new group in Hangzhou. At APCTP he coordinated the group of Condensed Matter and he played an important role to bring visibility to APCTP in terms of organization of conferences and workshop. He has promoted the field of topological computation, establishing a solid collaboration with the analogous group in SISSA, Italy. F. Alcaraz is a leading brazilian physicist, who is also the promotor of the recent established center of theoretical physics in Natal, with the aim of promoting theoretical physics in Brazil. He has long term collaboration with groups in Europe. D. Cabra has recently come back to La Plata (Argentina) after a professorship position in Strasbourg. When he was in Europe, he was the promoter of the 5-year grant INSTANS of the European Science Foundations and has significantly contribute to build up a coherent group of young scientists in France and Germany in the field of strongly correlated systems. He has also been the organizer of a Summer School in Les Houches in 2008. A. Tsvelik is the coordinator of the Condensed Matter group at the Brookhaven National Laboratories and very influential physicists in the area of low-dimensional systems. Originally from Landau Institute, in the past he has held a professorship position at the Physics Department of Oxford: he has always kept a keen link with his original country and he has promoted a strong collaboration with European groups, in particular the one in Oxford.

Altogether, the above scientists prove to have the right capability of carrying on an intense programme of research at the international scale.

B3 Implementation

B3.1 Pattern of secondments, capacities and plan for the overall management of the exchange programme

The collaboration between the partners of this project will involve a series of scientific visits, i.e. secondments, of experienced (ER) and early stage (ESR) researchers to each other research group that are described in the following table.

Gantt chart of secondments

WP n°	EU Partners	TC/ICPC Partners	TC/non ICPC Partners	Sec. Type	n° months Incoming EU and Outgoing EU Secondements			
					Year 1	Year 2	Year 3	Year 4
1	UOXF, SISSA, INFN, UVA	Sao Paulo	BNL	ER	4	4	4	
				ESR	4	4	4	
2	UOXF, INFN, CSIC	La Plata, Sao Paulo		ER	3	3		
				ESR	4	4		
3	UOXF, INFN, UVA	Landau, La Plata, PDMI-RAS	BNL	ER	5	5		
				ESR	6	6		
4	UOXF, SISSA, INFN, CSIC,UVA	Zhejiang		ER		2	2	2
				ESR		3	3	3
5	SISSA, INFN	Landau, PDMI-RAS, Sao Paulo		ER			3	3
				ESR			4	4
6	UOXF, SISSA, INFN,CSIC, UVA	La Plata, Zhejiang	BNL	ER		6	6	6
				ESR		6	6	6
tot				ER	12	20	15	11
tot				ESR	14	23	17	13

The secondments are divided according to the Work Packages: for each year of the project, the total number of man/months of visit among the partners are indicated, summed over those incoming and outgoing the EU. The overall figure is the following: the requested funding is sufficient for at least one-month visit per subject, per year and per pair of laboratories, one being inside EU and the other outside EU (these are the supported secondments in this scheme). Clearly, other secondments among pairs of European partners (or non-EU pairs) will also occur within the same WP, but they are not detailed here being not eligible for funding. More specific description of secondments for each partner is given in the financial request, the form A4.

Research in theoretical physics is carried individually or in small groups and does not require very precise time and task planning. Moreover, the developments of the research themes and the timetable for achieving specific results are very difficult to predict. Therefore, it is important to maintain a large flexibility of planning after fixing definite long-term goals.

Typically, a one-month visit per year, complemented by short visits on other funds and meetings at conferences, is enough to carry on a long-distance collaboration between experienced researchers. The daily discussion and interaction can be realized by using modern electronic means (e-mail, internet telephony etc.). Therefore, we believe that the proposed amount of research exchanges is appropriated for achieving the Milestones indicated in the Work Packages.

The secondment of early stage researchers instead requires multiple-month stays, because the daily contact with the senior scientist is very important for them; moreover, longer stays let them to be exposed to the flux of information inside active laboratories. Therefore, in this project, multiple-month secondments of ESR will be considered, especially for researcher coming from TC/ICPC partners. These are very formative for the Ph-D students and effective for reaching the goal of transfer of knowledge.

Regarding ESR coming from EU partners, we remark that European Ph-D school usually have their own sources of funds that support periods of visit abroad for some months within the 3-4 years of Ph-D training. These funds can be used to complement the IRSES support towards ESR secondments. Summarizing, the support requested in this project for ESR secondments will not exceed too much the ER amount; the IRSES funds will be mostly used for visits of ESR coming from ICTP partners that have less opportunities of travelling.

Focus Months

Regarding both ER and ESR, another kind of scientific exchanges is proposed, that will be called "Focus Months". These are the so-called scientific programmes, of extended workshops, where a relatively limited number of researchers (from 10 to 30) get together and work on specific topics in a rather informal Department-like way. This type of scientific meeting is presently very popular in theoretical physics and each major EU country has one Institute or scientific facility that run this type of activities on a monthly basis (up to six months in some cases). On the other hand, this kind of activity is missing in most of non-EU ICPC's.

Therefore, we propose to use the secondment support provided by IRSES to organize one-month extended workshop either in Europe, by allowing to invite a larger number of non-EU participants, or in one ICPC Institute, thus providing support for moving more European research to the non-EU location. Clearly, the organization of the Focus Month requires at least comparable additional funds to invite enough other participants whose secondment is not supported within IRSES. The availability of the extra funds will be detailed in the following discussion.

We plan to have one such Focus Month every year of the project, according to the following table.

Secondments for Focus Months

FM n°	WP n°	EU Partners	TC/ICPC Partners	TC/non ICPC Partners	Sec. Type	n° months Incoming EU and Outgoing EU Secondements			
						Year 1	Year 2	Year 3	Year 4
1	1,2,3	INFN			ER	7			
					ESR	9			
2	4		Zhejiang		ER		7		
					ESR		6		
3	5		Sao Paulo		ER			7	
					ESR			6	
4	6	UVA			ER				7
					ESR				7
tot						7	7	7	7
tot						9	6	6	7

For each year, the table reports the requested support for ER and ESR to participate to the Focus Month located in the indicated EU partner's Institute (first and forth year) and ICPC partner's Institute (second and third year).

Specifically:

- The Focus Month in the first year of the project can be run in conjunction with the two-month workshop "New states of matter in and out of equilibrium", at the G. Galilei Institute of Theoretical Physics (GGI), Arcetri, Florence, that is scheduled for next Spring. The GGI is the facility for extended workshops run by INFN, one of the EU partners of this project. This Focus Month will give the opportunity for establishing interactions and start collaborations on the topics of the WP n.1,2,3, that begin in the first year of the project. These topics correspond to those of the GGI workshop.
- The Focus Months of the second and third years will be organized in ICTP countries, China and Brazil. The corresponding partner Institutes have good experience in organizing conference and workshops at their places. These activities are very important for the Transfer of Knowledge, because local scientists and students will have the opportunity to interact on a long-term basis with several expert scientists from the EU partner Institutes.
- The Focus Month of the second year will be centered on the topics of the WP n.4 that begins the same year, and its location at the Zhejiang University has been chosen for the particular involvement of the partner in this WP.
- The Focus Month of the third year will similarly be addressing the subject of the WP n.5 beginning that year and will take place at the Sao Carlos Institute of Physics, one partner of the project with strong expertise and role in this WP.
- The Focus Month of the last year will take place at the Institute of Theoretical Physics, Univ. of Amsterdam (UVA) and will have a rather different function. This Institute has been organizing a one-week conference on low-dimensional quantum condensed matter and anyon physics every two/three years for more than a decade and is a traditional meeting occasion for the international scientific community to which the partners of this project belong. It is likely that one edition of such conference will be organized within the fourth Focus Month. By taking place in the last year of the project, this monthly activity will give the opportunity to summarize the achieved results and present them to a large audience.

In conclusion, the Focus Month activities will take advantage of the capacities (facilites, infrastructures) provided by some partners of the project and will dwell on the expertise of several participating scientists in organizing common research activities that has been describe before.

B4 Impact

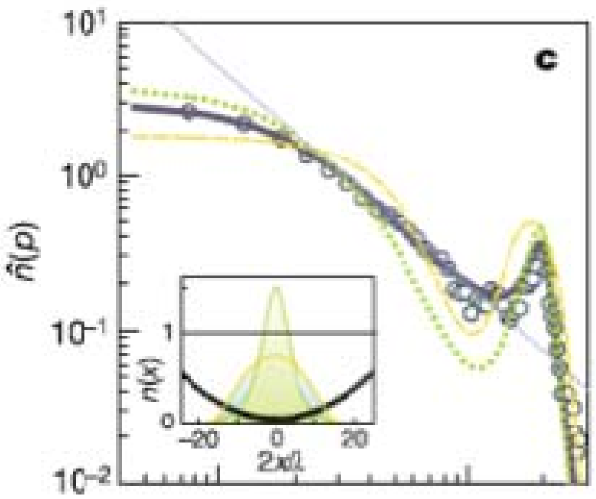
B4.1 Scientific impact

The domain of low-dimensional quantum systems has recently witnessed a rapid outpouring of experimental results never seen before, which have set an ideal physicist's playground. At the end of this project we expect to reach a sound knowledge on a series of new topics of large scientific impact.

For instance, one of the fundamental problems of extended quantum systems is the computation of correlation functions of various order parameters. Beside the theoretical intrinsic interest of this problem, it is worth stressing that correlation functions are the key quantities that let us leave the frame of pure theoretical formalism and get in touch with the real world of experiments: their Fourier transform is nothing else but the structure factors measured in scattering experiments. Theoretical computation of correlation functions is, in general, a rather difficult task, usually achieved with partial success through perturbative methods, which can be either of weak or strong coupling type. These methods, however, prove to be largely inadequate in dealing with accurate recent experiments. In the picture on the left, for instance, we report the momentum distribution of an array of one-dimensional cold atoms: the experimental data (i.e. the dots) show a distinct discrepancy from the theoretical predictions of perturbation theories which were successfully applied in the past (yellow and dotted lines). These and similar sets of data definitely call for new exact theoretical formalisms, which we plan indeed to achieve. Similarly, we expect to make progress on issues like finite-temperature and finite-size effects, which directly control several experiments.

To enlarge our knowledge on all these aspects, quantum integrability is the method which may have the larger impact. For instance, using the so-called Form Factor approach and acquiring experience by the explicit solution of several models, we expect to make progress on the ambitious goal to find the differential equations satisfied by the quantum correlators. Such a progress will lead to a significant step forward in the general understanding of quantum systems.

Another issue on which we expect our research to have a large impact is the simplification of the Bethe Ansatz techniques. To appreciate the nature of this question, it is worth reminding that Bethe Ansatz is well suited for finding the exact expression of the ground state energy (or other thermodynamical quantities) but much less suited for the computation of correlation functions -- a well known drawback of this technique. Famous examples are given by the integrable Lieb-Liniger (which describes with great accuracy equilibrium and dynamical properties of interacting bosons in quasi 1D geometry, cigar-like geometry) whose thermodynamics was already solved in 1963[74], or by the Heisenberg quantum spin chain, whose thermodynamics properties were addressed by Bethe in his renowned paper of 1931[75]. On the contrary, computation of correlation functions of these and related models, addressed by pure Bethe Ansatz techniques, proves to be an incredibly hard problem, not yet solved, and the partial results made so far have required a true tour de force[76] for their application. The present status of art can be overturned by taking advantage of a recent proposal on non-relativistic limit of quantum field theories[77] that has opened a completely new perspective on the problem. If such a proposal can be generalized to other systems we will able then to successfully tackle the computation of correlation functions of models of physical interest which have resisted to any attempts made so far: they include, for instance, quantum spin chains and multi-component fermionic systems, where the results are limited due to the nested nature of Bethe Ansatz equations. Such computations have a direct experimental counterpart in experiments in quasi one-dimensional geometries, where the parameters of the effective 1D Hamiltonian can be easily tuned modifying the trapping potential felt by the atoms.



Momentum distribution of one dimensional cold atoms in a trap (Parades et al. Nature 2004)

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[74] E.H.Lieb, W. Liniger, *Exact analysis of an interacting Bose gas, I. The general solution and the ground state,* Phys. Rev. 130, 1605 (1963); E.H. Lieb, *Exact analyis of an interacting Bose gas, II. The excitation spectrum,* Phys. Rev. 130, 1616 (1963).

[75] H. Bethe, *On the theory of metals. Eigenvalues and eigenfunctions of a linear chain of atoms*, Zeit.f. Physik 71, 205 (1931).

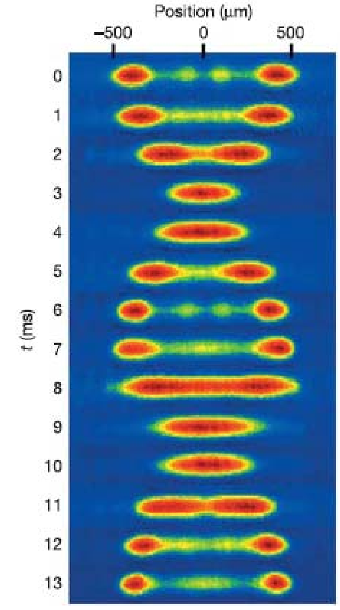
[76] See, for instance, V.E. Korepin, N.M. Bogoliubov, and A.G. Izergin, *Quantum inverse scattering method and correlation functions*, (Cambridge University Press, 1993).

[77] M. Kormos, G. Mussardo, A. Trombettoni, *Expectation Values in the Lieb-Liniger Bose Gas,* Phys. Rev. Lett. 103, 210404 (2009), http://lanl.arxiv.org/abs/0909.1336.

Our research may also have an impact on another important open problem, i.e. how to deal with finite temperature effects. Finite temperature has many physical consequences -- it alters the life-time of particle excitations and influences the energy level distribution -- giving rise to a series of effects that strongly affect the experimental outputs. The customary approach of a theoretical physicist is to work at T=0 in order to simplify things. This, however, may be very far from reality. One may conceive to take into account finite temperature effects by using the Keldysh formalism but, whoever has worked with it, knows perfectly the technical skills needed for its application. Equally unappealing is its level of abstraction. Fortunately, at least for quantum integrable models, some researchers in this proposal have introduced an alternative and very promising approach that deals directly with the occupation numbers. We expect therefore to have an impact on many related topics, such as the correct interpretation of data relative to quantum transport processes, for instance, or the identification of quantum phase transitions and so on. Equally important is to firmly establish -- as all previous studies seem to suggest -- whether the same formalism applies for describing systems at a finite density, after all the most common situation in experimental setups.

We also expect to have an impact on the understanding of finite-size effects: computations in finite size can be enormously important for experiments of ultracold atoms in ring geometries, on which a huge amount of experimental effort is focusing.

There will be also an impact in a new understanding of breaking integrability. In pairing up theory with experiments, one should obviously keep in mind the presence of microscopic effects that may significantly spoil the integrability encoded in the large scale properties of quantum systems: it is therefore natural to further develop the theory on various integrability breaking mechanisms, extending the previous analysis of Form Factor Pertubation Theory[16] or semi-classical methods[78]. The analytic control of the phenomena coming from the breaking of integrability -- such as confinement, decays of the heavier particles, occurrence of resonances, false vacuum decay, etc. -- is one of the most interesting issues of QFT and may have also intriguing consequences in understanding off-equilibrium dynamics, as discussed below.



Endless oscillations of cold atom after a quantum quench (from T. Kinoshita, Nature 2006).

Part of our researches will approach the dynamics of quantum systems brought away from equilibrium. Thanks to highly anisotropic optical lattices, it has been recently possible to build essentially one-dimensional systems[79] and study the coherent non-equilibrium dynamics of these integrable models[80]. Recent and fascinating experiments [81][82] have stimulated large theoretical interest on the subject and called for a better understanding of the connection between ergodicity, integrability and thermalization in the dynamics of strongly interacting quantum system. We plan to develop a profound understanding of interacting extended quantum systems, in particular on the mechanisms which allow thermalization in extended quantum systems rule by a unitary dynamics. Such studies can lead to the proper comprehension of gas of hard-core bosons [32] (the so-called Tonks-Girardeau model), or the experimental

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[78] See, for instance, G. Mussardo, *Neutral Bound States in Kink-like Theories,* Nucl.Phys.B 779:101-154,2007. e-Print: hep-th/0607025.

[79] B. Paredes et al. *Tonks-Girardeau gas of ultracold atoms in an optical lattice*, 2004 Nature 429, 277; T. Kinoshita, T. Wenger, and D. S. Weiss, *Observation of a One-Dimensional Tonks-Girardeau Gas,* 2004 Science 305, *1125.*

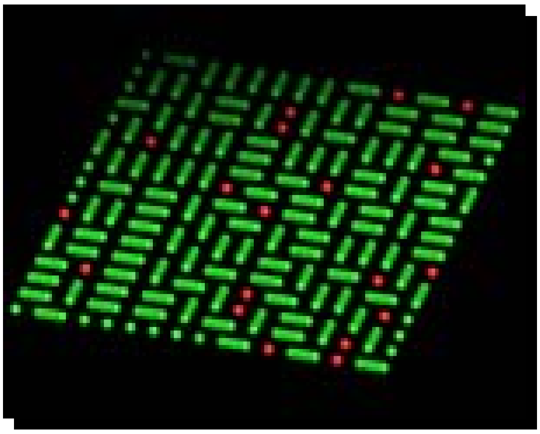
[80] T. Kinoshita, T. Wenger, and D. S. Weiss, *A quantum Newton's cradle*, 2006 Nature 440, 900.

[81] M. Greiner, O. Mandel, T. W. Hansch, and I. Bloch, *Collapse and Revival of the Matter Wave Field of a Bose-Einstein Condensate,* 2002 Nature (London) 419, 51

[82] A. Lamacraft, *Quantum quenches in a spinor condensate*, Phys. Rev. Lett. 98, 160404 (2007); L. E. Sadler et al., *Spontaneous symmetry breaking in a quenched ferromagnetic spinor Bose-Einstein condensate*, Nature 443, 312 (2006).

realization[83] of spin 1/2 fermion Yang-Gaudin model[84]. We expect to have also an impact in further refining the notion of Boundary States[85]: for integrable field theory and for integrable boundary conditions as well, the structure of the Boundary State is particularly appealing: it is a coherent state made of infinite number of particles, organized in pair of equal and opposite momentum, i.e. it has the same structure of a BCS state[86] [87].

We expect new developments on completely new phases of matter, which occur in (2+1) dimensional systems and which can be fully analyzed thanks to conformal field theories. We believe that our studies can shed new light on the important open problem of topological order of low dimensional quantum systems. These models not only support universal quantum computation but they presently pose an intriguing theoretical problem: topological ordered states are not characterized in terms of the usual Landau-Ginzburg breaking of symmetry, but rather peculiarly, they usually have more symmetries than the original Hamiltonian. Our studies can also contribute to clarify quantum dimer models[88], Josephson junction arrays[89] or cold atom[90].



Our studies can have also a strong impact in the analysis of anyonic systems, and they can also help to establish a bridge with the study of integrable models such as the O(n) and Q-state Potts models[91], closely related to the Temperely Lieb Algebra behind integrable models. In the lattice models, the topological phases are typically associated to a spin-charge separation phenomenon. This phenomenon, in turn, can be regarded as due to strongly-coupled lattice gauge theories. In (2+1) dimensional systems, spin-charge separation can only occur if these gauge theories are in a deconfined phase, and this is possible only for discrete gauge groups. Hence, another possible outcome could be the realization of topological phases through lattice models built on discrete gauge groups[92]. This may also shed light on still the unsolved three-dimensional Ising model, i.e. the simplest example of lattice gauge theory.

In the past, the close relation between Chern-Simons theories and Rational Conformal Field Theory has proved to be extremely beneficial, in particular for the purpose of proposing trial ground state wave-functions for various values of the fillings fractions of the Fractional Quantum Hall Effect. It should be stressed that, beyond Fractional Quantum Hall Effect and p-wave superconductivity, topological phases have not been directly observed in experiment. We expect to make progress in understanding the reasons why topological phases are so elusive: are they

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[83] H. Moritz *et al.*, *Confinement Induced Molecules in a 1D Fermi Gas,* Phys. Rev. Lett. 94, 210401 (2005).

[84] M. Gaudin, *Un systems a une dimension de fermions en interaction,* Phys. Lett. A 24, 55 (1967); C. N. Yang, *Some Exact Results for the Many-Body Problem in one Dimension with Repulsive Delta-Function Interaction,* Phys. Rev. Lett. 19, 1312 (1967).

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unstable? Do they exist only in small regions of parameter space of the Hamiltonians? Are we missing the appropriate tools? This search for diagnostics of topological order will naturally lead to a further question: to which extent do topological phases at zero temperature survive at finite temperature? This point is of particular importance because thermal fluctuations are inevitably present in real systems. Recently the robustness of the Kitaev's model at finite temperature has been seriously questioned and we intend to investigate this issue in great detail: is it just a specific feature of the Kitaev's model or is it a general aspect of topological phases? A subject closely related to the previous one and which has recently witnessed a dramatic convergence of mathematical and physical insights is the field of topological quantum computation. Although still in its early stage, this new emerging area promises to be the catalyst for a very productive collaboration among several fields of physics, mathematics and computer science.

Our studies can also have an impact in clarifying subtle issues of anyonic physics. If non-abelian anyons of quantum Hall effect have the advantage of their (fractional) electric charge -- which can be used, in principle, to manipulate them -- much more elusive is the experimental control of non-abelian anyons arising, for instance, in chiral p-wave superfluid with vortices. The presence of these vortices alters the Dirac equation for the electrons, in particular they may trap the zero-modes of the fermionic fields. The zero modes are discrete and they are in a finite number for each vortex - a profound result due to Atiyah-Singer index theorem, which relates the occurrence of special symmetric solutions of differential equations to the topology of their parameters. The zero energy of the Majorana fermion in a single vortex is believed to be topologically protected against weak disorder. However, with more than one vortex, a physical relevant question is whether the exponential localization and hybridization of the Majorana state is a property only of a clean system, or is it robust against the inclusion of disorder, and if this is the case up to which degree. Another unique property of the p-wave order parameter that needs to be fully explored is the existence of low energy chiral states, localized along the edge of the sample. If a single vortex is present, the Majorana state is split between the vortex core and the edge and a measurement of density of state could provide final evidence of the elusive Majorana fermions. However, in practice, such a measurement may be prohibitively difficult and should be explored alternative ways: it would be indeed rather disappointing to miss the opportunity of observing Majorana fermion, an excitation so long sought in nature.

Another impact could be on the studies of chains of interacting anyons of Fibonacci type[93], which can support a wide variery of collective ground states ranging from extended critical to gapless phases and gapped phases with ground-state degeneracy. Even more surprising is the emergence of the minimal unitary models of conformal field theories, since the critical phases and the topological symmetry of these anionic quantum chains result to be precisely described by the classes of universality of multicritical Ising and Potts models. Our research can help in identifying which is the hidden non-local symmetry that is the classical analog of the topological symmetry of the one-dimensional quantum chain of anyons.

On the subject of topological computation, there could be an impact in making progress on fault tolerant realization of quantum gates. The structure of topological phases is extremely complex and imposing the traditional qubit architecture may not be the most efficient scheme for implementing quantum computation. One must make a realistic estimate of the error processes in these systems and develop the theory of quantum information over noisy quantum channels based on non-local degrees of freedom.

B4.2 Relevance of the proposed partnership to the area of collaboration and the ERA

Europe is the center of excellence in the study of CFT and integrable systems and has been the world leader of several recent major developments in this area. Further enlarging the collaboration on these topics to leading groups abroad (in particular the Landau Institute and Brookhaven National Laboratories) could be beneficial for a larger community of young scientists also in less

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developed countries, such as Brazil, Argentina and Chile, who would like to start a career in such rapidly developing field. Moreover, we would like to turn such excellence towards real world applications and new exciting developments, like topological quantum computation, where there could be an exellent collaboration and interaction between the groups involving in quantum computation in Europe (Madrid and INFN) and the group in China. One of our scopes will be to bridge theoretical findings with new experimental data: on this aspect there exist collaborations and relationships between the researchers of this proposal but mostly on a sporadic basis, and we have no doubt that their integration in a single network will be of great benefit to the collective effort. In particular, it will foster interactions between the most formal and the most applied researchers, and, hopefully, draw on considerable but slightly estranged resources to develop a unique program of research, bridging advanced theory to advanced experimental applications. It is reasonable to expect that this interdisciplinary project will lead to european leadership and large international collaboration in a very exciting area of physics. Low-dimensional and nano-systems have opened new fields in physics and mathematics, showing us how to conceive Nature in ways formerly beyond our imagination. At this level, matter shows different and amazing properties and the borders between different scientific and technical disciplines fade. It is now clearly identified as a strategic priority for many groups in the US and it is likely to remain the same in the future decade. Many of the discoveries and of the theories mentioned so far in this survey have been developed by European scientists and have had an impact on the development of numerous technical devices, either by disclosing completely new domains of physics or by providing ideas upon which such devices can be built. However, no matter how successful or important a discovery made by a single group in Europe may be, its impact will be significantly weakened without an appropriate level of general comprehension or sharing of knowledge at a European and international scale. The scientific international cooperation provided by this project is an appropriate tool to reach such a cultural synthesis, to widen the cooperation between different domains of knowledge and to promote the communication on this achievement to other academic communities. In our opinion, the accomplishment of this process goes through the awareness of the substantial unity of scientific knowledge and of the profound relationships which link physical phenomena apparently different and distant. Therefore, the added value brought to the European community by the IQCFT project should be measured not only according to its achievement on concrete leading-edge scientific themes with potential technological applications, but also and especially considering the effort to overpass the narrow limits of the specialization in different disciplines. We believe that the proposal meets the objectives of the European Research Area and the Community policy to improve the entrepreneurial character of researchers as well as the positive attitude to change the education and training perspectives. Moreover, the idea of blending – in the same Team – both theoretical and applied expertises is meant to promote collaboration and a rewarding exchange of ideas between the two scientific communities, often secluded. The major developments in science and technology generally derive from curiosity driven research but there are often handicaps, due to scientific jargons, cultural barriers or different levels of education in different countries, which prevent a better sharing of their benefits. This is indeed one of the main motivations and an added value to the community of the present proposal, i.e. the possibility to set up a stimulating international scientific atmosphere where talented young researchers can share good practices by working in close collaboration with more experienced researchers. Such cultural atmosphere will stimulate the achievement of world-wide excellence on leading topics of basic research of high interest, which will have in the near future a great impact on European science, by enriching its intellectual inheritance and its degree of attractiveness.

B4.3 Potential to develop lasting collaboration with the eligible Third Country partners

The opportunities provided by this grant can open the way to several long-lasting collaboration between the European partners and the oversea countries. The comprehension of the physical and mathematical aspects of many topics listed in this proposal requires a time that is longer than the duration of this programme.

All European scientists are therefore strongly interested to keep an alive collaboration with their colleagues oversea and there are indeed very good reasons for such an expectation: thanks to the visit exchanges and the meetings organized in the four years, we believe we could be created the conditions for setting up a future exchange plan of junior scientists, at the level of post-doc or PhD students. First of all, all European groups run a PhD program focused on the themes of this proposal and all of them are eager to attract students from outside Europe in order to increase the level of internationalization. Moreover, economic and social conditions are rapidly changing in countries like Russia, Brazil, Argentina and China, and for European young scientists it could be a very attractive possibility to spend a year ot two abroad in physics departments of those countries in order to acquire professional experience. Similarly, the Brookhaven National Laboratories is eager to attract researchers from Europe for their broad background and their ability to work in several areas of physics.

Partners of this proposal have been previously in contact and have also taken part in the organization of several international events (for instance, the extended programme “Quantum Field Theory in Low-dimension” at the Galileo Galilei Institute in Florence 2008; the Landau meeting 2008 “Integrable Models”; the workshop “Statistical Integrable Models”, in Brisbane, satellite conference at StatPhys24 in 2010; the coming conference “ The beauty of integrability: low-dimensional physics, statistical models and solitons” in the new born International Centre of Theoretical Physics in Natal, Brazil; etc). Given the opportunity to set up a IRSES European grant the collaboration can be further strengthen and enlarged to a wider community which includes also Argentina and China.

The topics concerning this proposal have a long tradition and, we believe, a long life-time since they concern with the fundamental quest of better understanding quantum systems with infinite degrees of freedom, a topic with intriguing theoretical questions and with potential experimental fall-outs.

B5 Ethical Issues

There are no ethical issues associated with this proposal: there is nothing concerning with Human Embryo/Foetus, nothing concerning with humans, there are no genetic information processing or privacy issue, nor research on animals. Similarly, there is nothing concerning with military use.