
Pasquale Calabrese

Date of Birth: June 16th, 1976
Place of Birth: Isernia, Italy
Citizenship: Italian

CURRICULUM VITAE ET STUDIORUM

Present position Ricercatore in formazione
Dip. di Fisica, Università di Pisa
Largo Pontecorvo 3, 56127 Pisa, Italy
phone: +39-050-2214959
e-mails: calabres(at)df.unipi.it, pcalabre(at)scienze.uva.nl
webpage: <http://staff.science.uva.nl/~pcalabre/>

Education:

1990 – 1995 Scientific High School in Isernia, Italy
July 1995 High School Leaving Exam: *60/60*

10/1995 – 03/2000 Undergraduate studies in Physics, Pisa University
Laurea in Physics: *110/110 cum laude*
Title of Laurea Thesis: “Analytical Properties of Callan-Symanzik β Function
in Two-dimensional ϕ^4 Theories”, in Italian
Advisor: E. Vicari (Pisa University, Italy)

01/2001 – 09/2003 PhD Student, Scuola Normale Superiore, Pisa, Italy
PhD Thesis’ Title: “Critical Behavior of Systems with Complex Symmetries”
Supervisor: E. Vicari (Pisa University, Italy)

Research:

10/2003 – 09/2005 PostDoc at Oxford University
10/2005 – 10/2006 PostDoc at Institute for Theoretical Physics, Amsterdam U.
06/2006 – present Ricercatore in Formazione at Pisa University (tenure track)
Collaborators: J Cardy (Oxford), J-S Caux (Amsterdam), L Cugliandolo (Paris)
M Campostrini (Pisa), F Essler (Oxford), R Fazio (Pisa)
A Faribault (Munich), A Gambassi (SISSA, Trieste),
P Le Doussal (Paris), M Mintchev (Pisa)
B Nienhuis (Amsterdam), A Pelissetto (Rome)
R Santachiara (Paris), A Sokolov (St. Petersburg),
L Tagliacozzo (Brisbane), E. Tonni (MIT), E Vicari (Pisa)

List of publications

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- [2] P. Calabrese, J. Cardy, and B. Doyon, *Entanglement entropy in extended quantum systems*, J. Phys. A **42** (2009) 500301.
- [3] P. Calabrese, M. Campostrini, F. Essler, and B. Nienhuis, *Parity effects in the scaling of block entanglement in gapless spin chains*, [0911.4660].
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- [16] R. Santachiara and P. Calabrese, *One-particle density matrix and momentum distribution function of one-dimensional anyon gases*, JSTAT P06005 (2008) [0802.1913].

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- [17] P. Calabrese, A. Pelissetto, and E. Vicari, *Static and dynamic structure factors in three-dimensional randomly diluted Ising models*, Phys. Rev. E **77** 021126 (2008) [0711.3673].
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Brief Research Description:

Quantum quenches

Understanding the non-equilibrium dynamics of extended quantum systems after the trigger of a sudden, global perturbation (quench) represents a daunting challenge, especially in the presence of interactions. The main difficulties stem from both the vanishing time scale of the quench event, which can thus create arbitrarily high energy modes, and its non-local nature, which curtails the utility of local excitation bases.

Until recently it was, however, largely an academic question, because the time scales over which most condensed matter systems can evolve coherently without coupling to the local environment are far too short, and the effects of dissipation and noise are inescapable. The experimental realization of cold atomic systems with a high degree of tunability of Hamiltonian parameters, and the ability to evolve in time with negligible dissipation, has reignited the study of many-body quantum systems away from equilibrium. How Gibbs or any other relaxed states can ultimately result from unitary dynamics is a question that has received a lot of attention, but which still lacks a general understanding.

In Ref. [28, 21] we showed that the time-dependence of correlation functions following a quantum quench may be extracted using methods of boundary critical phenomena. For $d = 1$ this allowed to use the powerful tools of CFT in the case of critical evolution. All our findings may be explained in terms of a picture generally valid, whereby quasiparticles, entangled over regions of the order of the correlation length in the initial state, then propagate with a finite speed through the system.

We also considered the time evolution of the entropy of entanglement [30]. Using field-theoretical path integral methods as well as explicit computations for the transverse Ising spin chain, we showed that the entanglement entropy increases linearly with time t up to $t = \ell/2v$ (v being the maximum speed of propagation of signals), after which it saturates at a value proportional to ℓ . We interpreted this behavior as a consequence of causality in a quasi-classical approach. Several of these findings has been later confirmed in Heisenberg chains with time dependent density matrix RG [29]. For the XY chain, using Toeplitz matrix representation and multidimensional phase methods, we provided analytic results for large blocks and for all times, showing explicitly the linear growth in time followed by saturation [14]. In Ref. [15] we generalized this approach to the presence of a domain wall in the initial state discussing possible connections with the stochastic Loewner evolution.

In Ref. [9] we showed that nonperturbative methods based on integrability can prove sufficiently powerful to completely characterize quantum quenches. We illustrated this using a model of fermions with pairing interactions (Richardson's model). The effects of simple (and multiple) quenches on the dynamics of various important observables have been discussed. Many of the features we found are expected to be universal to all kinds of quench situations in atomic physics and condensed matter.

In Ref. [19] we considered the dynamics resulting from preparing a 1D quantum system in the ground state of two decoupled parts, then joined together and left to evolve unitarily with a translational invariant Hamiltonian (a local quench). In the case when the corresponding theory is conformal, we studied the evolution of the entanglement entropy for different bi-partitions of the line. We also considered the behavior of one- and two-point correlation functions. All our findings may be explained in terms of a picture, that we believe to be

valid more generally, whereby quasiparticles emitted from the joining point at the initial time propagate semiclassically through the system.

Quantum Entanglement

Quantum entanglement is considered a basic tool to develop quantum information and communication protocols. However there is now also a growing interest in using entanglement measures to characterize extended quantum systems, in particular to understand the interplay between quantum entanglement and quantum criticality.

In this field, my main interest is the study of the so called *Entanglement Entropy*. Suppose a whole system is in a pure quantum state $|\Psi\rangle$, and an observer A measures only a subset A of a complete commuting observables, while another observer B measures the remainder. A's reduced density matrix is $\rho_A = \text{Tr}_B |\Psi\rangle\langle\Psi|$. The Entanglement entropy S_A is just the von Neumann entropy $S_A = -\text{Tr} \rho_A \log \rho_A$ associated to this reduced density matrix.

In [37], we carried out a systematic study of the entanglement entropy in relativistic quantum field theory describing the scaling limit of extended quantum systems close to a quantum critical point. For the case of a 1+1-dimensional critical system, whose continuum limit is a conformal field theory with central charge c , we re-derived the result $S_A \sim (c/3) \log \ell$ when A is a finite interval of length ℓ in an infinite system, and extended it to many other cases: finite systems, finite temperatures, systems with boundaries, and when A consists of an arbitrary number of disjoint intervals. For such a system away from its critical point, when the correlation length ξ is large but finite, we showed that $S_A \sim \mathcal{A}(c/6) \log \xi$, where \mathcal{A} is the number of boundary points of A . To check these prediction we developed a Corner-Transfer-Matrix approach for the calculation of S_A in simple integrable models.

In Ref. [7] we generalized the CFT prediction to the case two disjoint intervals for a Luttinger liquid (free compactified boson). $\text{Tr} \rho_A^n$ for any integer n is calculated as the four-point function of a particular type of twist fields and the final result is expressed in a compact form in terms of the Riemann-Siegel theta functions. Our predictions have been checked against existing numerical data. In Ref. [4] we generalized this study to critical Ising models. We provided analytic results based on CFT that have been quantitatively checked in numerical simulations of the one-dimensional quantum system and the two-dimensional classical one. Only by taking properly into account finite-block corrections to the scaling, theory and numerics agree.

In Ref. [13] We derived the distribution of eigenvalues of the reduced density matrix of a block of length ℓ in a one-dimensional system in the scaling regime. The resulting "entanglement spectrum" is described by a universal scaling function depending only on the central charge of the underlying CFT. This prediction has been checked against exact results for the XX chain. We also showed how the entanglement gap closes when ℓ is large.

In Ref. [11] we performed an exact study of the block entanglement in XXZ spin-chain at $\Delta = 1/2$, providing an analytic expression for the reduced density matrix of n spins in a chain of length L for $n \leq 6$ and arbitrary but odd L . From this, the entanglement entropy, the moments of the reduced density matrix, and its spectrum are obtained. We explicitly constructed the "entanglement Hamiltonian" as the logarithm of this matrix.

In Ref. [5] we studied the entanglement entropy in excited states of spin chains. We considered the XY model in a transverse field and the XXZ Heisenberg spin-chain. For the latter, we developed a numerical application of algebraic Bethe Ansatz. We found two main

classes of states with logarithmic and extensive behavior, that can be related to the locality properties of the Hamiltonian having a given state as ground state.

In Ref. [3] We considered the Rényi α -entropies for Luttinger liquids. We showed that there are subleading terms that oscillate with frequency $2k_F$ (the Fermi wave number of the LL) and exhibit a universal power-law decay with ℓ . The new critical exponent is equal to $K/(2\alpha)$, where K is the LL parameter. We presented numerical results for the anisotropic XXZ model and the full analytic solution for the free fermion (XX) point.

We reviewed in Ref. [6] most of the result in the field.

Correlation functions in 1D Quantum gases

The recent observations of 1D trapped atomic gases provide a unique opportunity for extending our understanding of the physics of these many-body systems. The 1D regime can be investigated theoretically by making use of the integrability of the model. However, although the Bethe Ansatz solution of the delta-interacting 1D Bose gas is known since 40 years, dynamical correlation functions resisted until recently all efforts toward an exact calculation.

The most promising approach for an analytic calculation of correlation functions makes use of the so-called Algebraic Bethe Ansatz. In this framework the correlation functions are written as sums of matrix elements (called also form-factors) over the full set of excited states. Matrix elements of the most relevant observables are known since the early ninety, but their expression is a determinant of matrix whose entries are rational functions of the analytical unknown Bethe rapidities. These so cumbersome expressions blocked any further development toward a full analytical calculation.

For this reason we developed a new method that mixes integrability and numerics to calculate very precisely correlation functions for finite length/particles Bose gases [27, 24]. The overall strategy is very simple: the form-factors are calculated for each excited state inserting the numerical solutions to the Bethe equations in the determinant representation. However for number of particles that compares well with experimental data (i.e. of the order of hundreds) the number of excited states we have to consider is approximately 10^8 . This large number of states requires a very smart scanning of the Fock space of the model, in order to not loose days of computation only for tiny contributions. The method we developed is applicable to any integrable model as long as the determinant representation of the matrix elements is known, and we have coined it the ABACUS method.

We applied successfully the ABACUS method for the calculation of the zero-temperature dynamical density-density [27] and one-particle correlation functions [24] in the 1D repulsive Bose gas. Their static limits (that are obtained as a subset of our results) corresponds to the experimental measured structure factor and the one-body density matrix.

Another major application of the Algebraic Bethe Ansatz approach has been the understanding of the 1D attractive Bose gas. In fact, this model was usually considered as pathological because a proper thermodynamic limit is not readily defined. However we showed [23, 20] that, in spite of the bad thermodynamic limit, zero-temperature static and dynamical correlation functions can be exactly calculated directly from the integrability of the model and very simple closed analytical expressions have been obtained [23, 20].

We are currently extending these methods to understand other physical situations of 1D gases, as for example finite temperature, out-of-equilibrium correlations, different statistics

(Bose-Fermi mixtures, anyons) etc...

Interacting anyonic systems

One of the most striking results of modern physics is that in three spatial dimensions particles are either bosons or fermions, i.e. the wave-function of identical objects is either symmetrical or antisymmetrical under the permutations of space coordinates. Conversely, in lower dimensions generalized anyonic statistics, with intermediate properties between bosons and fermions are possible. 2D free excitations with fractional braiding statistics are considered a key ingredient to describe fractional quantum Hall effect, but still very little is known about truly interacting anyonic model.

In Ref. [22] we gave a universal description of correlation functions of one-dimensional anyonic gapless systems in the low-momentum regime. We pointed out a number of interesting features, including universal oscillating terms with frequency proportional to the statistical parameter and beating effects close to the fermion points. The results have been applied to the one-dimensional anyonic Lieb-Liniger model and checked against the exact results in the impenetrable limit.

In Ref. [16] we presented a systematic study of the Green functions of a one-dimensional gas of impenetrable anyons. We showed that the one-particle density matrix is the determinant of a Toeplitz matrix whose large N asymptotic is given by the Fisher-Hartwig conjecture. We provided a careful numerical analysis of this determinant for general values of the anyonic parameter, showing in full details the crossover between bosons and fermions and the reorganization of the singularities of the momentum distribution function. We showed that the one-particle density matrix satisfies a Painleve VI differential equation, that is then used to derive the small distance and large momentum expansions. We found that the first non-vanishing term in this expansion is always k^{-4} , that is proved to be true for all couplings in the Lieb-Liniger anyonic gas and that can be traced back to the presence of a delta function interaction in the Hamiltonian.

In Ref. [10] we proposed a generalization of the replica trick that allows to calculate the large distance asymptotic of off-diagonal correlation functions in anyonic models with a proper factorizable ground-state wave-function. We applied this new method to the exact determination of all the harmonic terms of the correlations of a gas of impenetrable anyons and to the Calogero Sutherland model. Our findings have been checked against available analytic and numerical results.

In Ref. [12] we studied anyonic Luttinger liquids wires jointing at a single point. The model on the full line was solved with bosonization and the junction of an arbitrary number of wires was treated imposing boundary conditions that preserve exact solvability in the bosonic language.

Critical Aging

Systems with slow dynamics are currently under intensive experimental and theoretical investigation. In some circumstances their dynamics becomes so slow that they can not equilibrate in finite time, evolving always in non-equilibrium conditions and displaying novel dynamic phenomena as aging. Quite recently it has been realized that this may also be the case in non-complex systems. Therefore, simple models such as classical non-disordered ferromagnets

quenched at or below their critical point have become very useful toy models to test some of the key ideas put forward in the context of complex systems. The fluctuation-dissipation ratio (FDR) has been introduced as a sort of measure of the "distance" from an equilibrium evolution. It has also been shown that, at least for some mean-field glass models, the FDR can be used to define a non-equilibrium temperature. The interesting question is whether this allows one to devise a non-equilibrium thermodynamics, and whether this is true for non mean-field models as well. In view of these open questions, there has been recently a lot of activity around the aging dynamics of ferromagnetic systems, with particular efforts to determine the FDR at criticality, by means of MCs and exact solutions of specific models. Universality of critical phenomena, on the other hand, can be exploited to provide field-theoretical predictions for the quantities (such as two-time response and correlation functions of the order parameter) which characterize the non-equilibrium dynamics following a quench to the critical point.

We used the field-theoretical RG approach [55] to investigate the relevant aging properties of the non-equilibrium dynamics following a quench from the high-temperature phase to the critical point. We considered (among the others) the non-equilibrium relaxational dynamics (Model A) of the d -dimensional $O(N)$ vector model in ϵ -expansion [55, 51, 34] and the weakly dilute Ising model [50]. We studied also the conserved dynamics (Model B) for the $O(N)$ [32] model and the dynamics of a non-conserved order parameter coupled to a conserved density (Model C) [48].

For all the models just mentioned we computed and analyzed the scaling behaviors of the two-time response and correlation functions of the order parameter, the associated universal scaling functions, and the long-time limit of the FDR. This analysis allowed us to provide the first numerical predictions for the FDR of non-exactly solvable models (the only ones considered in the preceding literature). Some of our results have been nicely confirmed by MCs. Furthermore we provided also new estimates for quantities which have not yet been measured, but that can be determined by experiments or MCs. All these findings are summarized in our recent review article on the aging properties of critical systems [32].

We addressed also the problem of the definition of a non-equilibrium effective temperature T_{eff} at the critical point, on the basis of the FDR. Some numerical findings seem to indicate that this quantity is indeed independent of the observable used to define it. Motivated by these results we have studied the general properties of response and correlation functions for a generic observable of the $O(N)$ vector-model. It turned out that within the MF approximation the FDR is actually independent of the specific observable, whereas this is no longer the case beyond MF, as we explicitly checked in a one-loop computation [34].

We also investigated within the RG approach and by means of MCs the general scaling properties of the two-time response and correlation functions for the Model A dynamics of the Ising universality class when considering a sudden heating from the low-temperature phase to the critical point [26].

In collaboration with A. Gambassi and L. Cugliandolo are currently trying to extend these concepts to Quantum Phase Transitions.

Critical phenomena

Finally, I have been interested in an accurate determination of critical quantities (exponents, amplitude ratios, equation of state . . .) of systems described by Landau-Ginzburg Hamiltonians with complex symmetries, such as models with randomness, disorder, anisotropies, frustration

and/or competing order parameters. In collaborations with P. Parruccini, A. Pelissetto, A. Sokolov, and E. Vicari, I was able to give precise theoretical estimates of universal quantities calculating and analyzing, by means of powerful resummation techniques, higher-order perturbative RG series both in fixed dimension $d = 3$ (up to *six loop*), $d = 2$ (up to *five loop*), and $\epsilon = 4 - d$ expansion (up to *five loop*). We found that, beside improving the accuracy, in some cases higher-order calculations turned out to be necessary to determine the correct physical picture in physical dimensions $d = 2, 3$. A short account of these works can be found in the two brief reviews [43, 66].

International and teaching activity

- Three-month European ESF grant to visit the Instituut voor Theoretische Fysica of the Universiteit van Amsterdam (April-June/2007).
- Visiting Professor at Ecolé Normale Supérieure in Paris (February 2009).
- Scientific editor (with J. Cardy and B. Doyon) of a special issue of J. Phys. A entitled “*Entanglement entropy in extended quantum systems*”, J. Phys. A **42** 500301 (2009).

Teaching

- June 2009, Course on “Entanglement entropy and quantum field theory” for the PhD school of Pisa University (12 hours).
- Teaching at several international schools (full list below).

Supervising

List of PhD students:

- Vincenzo Alba, started in January 2008, co-supervised with Prof. Ettore Vicari
- Maurizio Fagotti, started in January 2009.

List of Master students:

- Maurizio Fagotti, September 2008, “Dinamica di non equilibrio di correlazioni ed entanglement in una catena di spin” (partially published as [14]).
- Helene Grandclaude [visiting student], September 2008, “Quench dynamics of 1D Bose gas”
- Michele Pepe, October 2008, “Effetti di confinamento in gas quantistici unidimensionali” (article in preparation).

Conferences and Schools:

- “Quantum Matter in Low Dimensions: Opportunities and Challenges”, 30 August-24 September, 2010, Nordita, Stockholm [**Invited speaker**]
- STATPHYS24, 19-23 July, 2010, Cairns, Australia [**Invited speaker**]
- INSTANS Summer School, June 20-July 3, 2010 Centro de Ciencias de Benasque Pedro Pascual, [**Invited Lecturer**]
- “Quantum Information Concepts for Condensed Matter Problems”, 14-25 June, 2010, Max-Planck Institute for Physics of Complex Systems, Dresden [**Invited speaker**]
- “MECO conference” 15-19th March 2010, Nancy [**Invited speaker**].

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- “Physics in the plane: From condensed matter to string theory”, March 1-5, 2010 Center of Physics in Les Houches [**Invited speaker**]
 - “Journées de Physique Statistique 2010”, January 28-29, 2010, Paris [**Invited speaker**]
 - Summer College on “Nonequilibrium Physics from Classical to Quantum Low Dimensional Systems”, July 6-24, 2009, ICTP Trieste (Italy) [**Invited Lecturer**]
 - Amsterdam Summer Workshop 2009, July 6-11, 2009, Amsterdam (The Netherlands) [**Invited**]
 - Beg Rohu Summer School on “Quantum systems out of equilibrium, June 15-29, 2009, Bretagne (France) [**Invited speaker**]
 - QUROPE school on “Quantum Information and Many-Body Systems”, May 3-17, 2009, Cortona (Italy) [**Invited Lecturer**]
 - Arnold Sommerfeld Summer School on “(Boundary) Conformal Field Theory: Introduction and Applications”, October 6- 10, 2008, Munich, (Germany) [**Invited Lecturer**]
 - “Low-dimensional Quantum Field Theories and Applications”, September 7-12, 2008, Florence (Italy).
 - “Statistical Physics and Low Dimensional Systems” May 21-23, 2008, Nancy (France) [**Invited Speaker**]
 - “Integrability in the AdS/CFT correspondence”, January 29-31, 2008, Utrecht, (The Netherlands).
 - “Fields, Lattices and Condensed Matter, A symposium in honour of John Cardy’s 60th birthday”, December 14-15, 2007, Oxford (UK).
 - “Statistical Field Theory of Quantum Devices”, July 16-19, 2007, Perugia (Italy) [**Invited Speaker**].
 - “Statphys 23”, July 9-13, 2007, Genova (Italy).
 - “Low-D Quantum Condensed Matter 2007”, July 2-7, 2007, Amsterdam (The Netherlands) [**Invited**].
 - “Landelijk Seminarium”, April 13, 2007 (The Netherlands) [**Invited Speaker**].
 - “Quantum Information and Many-Body Quantum Systems”, March 26-30, 2007, Centro Ennio de Giorgi, Pisa (Italy).
 - “Physics at Veldhoven”, January 23-24, 2007, Veldhoven (The Netherlands).
 - “Informal Meeting on Statistical Physics”, December 14-15, 2006, SISSA, Trieste (Italy).
 - “Quantum Criticality”, August 7-18, 2006, Lorentz Center, Leiden (The Netherlands).
 - “INSTANS Summer School Conference”, June 12-16, 2006, Villa Olmo, Como (Italy) [**Invited Speaker**].

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- “Statistical Physics and Low Dimensional Systems” May 17-19, 2006, Nancy (France) [**Invited Speaker**]
 - “FOM-Decemberdagen”, December 13-14, 2005, Veldhoven (The Netherlands)
 - “Third Annual Meeting of the EU Network”, September 12-16, 2005, Santiago de Compostela (Spain) [**Invited Speaker**].
 - “Low-D Quantum Condensed Matter 2005, Amsterdam Summer Workshop”, July 25-30, 2005, Amsterdam (Netherlands).
 - “CORTONA 2005, XXVII Convegno Informale di Fisica Teorica”, May 25-28, 2005, Cortona (Italy) [**Invited Speaker**].
 - “9-th UK meeting on Integrable Models”, April 22-23, 2005, London (UK).
 - “Quantum Entanglement in Physical and Information Sciences”, December 14-18, 2004, Centro Ennio De Giorgi, Pisa (Italy).
 - “XII Workshop on Statistical Mechanics and non Perturbative Field Theory”, September 29 - October 1, 2004, Bari (Italy).
 - “Lengthscales and Heterogeneous Dynamics in Glassy Materials”, September 22-25, 2004, New College, Oxford (UK).
 - “IX Convegno Nazionale di Fisica Statistica e dei Sistemi Complessi”, June 22-24, 2004, Parma University, Parma (Italy).
 - “Integrable Models and Applications”, September 15-20, 2003, Florence (Italy).
 - International School of Physics Enrico Fermi “The Physics of Complex Systems (New Advances and Perspectives)” July 1-11, 2003, Varenna, Como Lake (Italy).
 - “XI Workshop on Statistical Mechanics and non Perturbative Field Theory”, September 26-28, 2002, Bari (Italy).
 - “International Conference on Theoretical Physics TH-2002”, July 22-27, 2002, UNESCO, Paris.
 - “V International Conference Renormalization Group 2002”, March 10-16, 2002, Strba (Slovakia).
 - “Summer School on Low-Dimensional Quantum Systems: Theory and Experiments”, July 16-27, 2001, ICTP, Trieste (Italy).
 - “Quantum Monte Carlo: Recent Advances and Common Problems in Condensed Matter and Field Theory”, July 3-6, 2001, Trent (Italy).

Main Talks:

Quantum quenches:

- 07/2009 ICTP Summer college (set of lectures)
- 06/2009 Beg Rohu Summer school
- 12/2007 Sissa/ICTP, joined cond-mat seminar, Trieste
- 09/2007 ENS Paris
- 09/2007 Nancy U.
- 09/2007 Max Planck Inst., Stuttgart
- 03/2006 Florence U.
- 03/2006 Amsterdam (Conformal lunch)

Entanglement Entropy and Quantum Field Theory:

- 11/2009 ITF Amsterdam University Colloquium
- 05/2009 Cortona School (set of lectures)
- 10/2008 Sommerfeld School, Munich (set of lectures)
- 09/2008 Florence-GGI workshop
- 06/2008 Barcelona U.
- 04/2008 Paris-Sud monthly seminar
- 07/2007 Perugia (SFIDE conf.)
- 04/2007 Landelijk Seminarium, Amsterdam
- 02/2007 Genova U.
- 10/2006 Neaples U.
- 05/2006 Nancy (StatPhys Conf.)
- 05/2006 Utrecht U.
- 11/2005 Spth-CEA, Saclay, Paris
- 11/2005 Conformal Lunch (Amsterdam university)
- 11/2005 Durham
- 10/2005 Pisa U.
- 09/2005 Santiago De Compostela, EUCLID meeting
- 07/2005 Imperial College, London
- 06/2005 Rome La Sapienza U.
- 05/2005 Cortona (Convegno Fisica Teorica)
- 04/2005 London (ICFT 2005)
- 03/2005 Paris Orsay
- 12/2004 Pisa (Quantum Entanglement conference)
- 09/2004 Bari (SMFT 2004)
- 06/2004 Parma (Convegno StatPhys)
- 06/2004 Pisa U.

Main Talks(continue):

Correlation functions in 1D Bose Gases:

05/2008 Nancy (StatPhys Conf)
02/2008 Hannover U.
12/2007 Oxford U.
10/2007 Spth-CEA, Saclay, Paris
09/2007 ENS Paris
12/2006 Trieste (StatPhys Meeting)
06/2006 Como (Instans Meeting)

Aging in Critical Systems:

10/2006 Amsterdam U.
10/2004 Salerno U.
08/2003 ICTP Trieste
01/2003 Pisa U.

Finite Temperature Phase Transition in QCD:

06/2005 Oxford/RAL Seminar Series

Divergent Series in Field Theory and Borel Resummation:

05/2004 Oxford U. Forum

Critical Behavior of Systems with Complex Symmetries (several topics):

11/2003 Oxford U.
06/2003 Max Planck Inst., Stuttgart
12/2002 SNS Pisa
09/2002 Bari (SMFT 2002)
03/2002 Strba (RG 2002)
02/2002 Pisa U.

Referees:

John L. Cardy Oxford University, Oxford, UK
e-mail: cardy@thphys.ox.ac.uk

Jean-Sébastien Caux Amsterdam University, Amsterdam, Netherland
e-mail: jcaux@science.uva.nl

Ettore Vicari Pisa University, Pisa, Italy
e-mail: vicari@df.unipi.it