

Workshop on Theory and Practice of Adiabatic Quantum Computers and Quantum Simulation

*The Abdus Salam International Centre for Theoretical
Physics, Trieste (Italy)*

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Organizers:

Eliot Kapit (Tulane University)

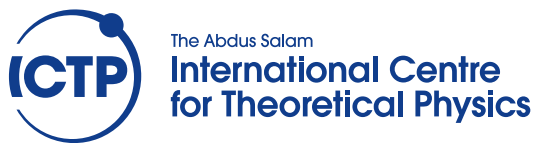
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Sebastiano Pilati (International Centre for Theoretical Physics)

Giuseppe Santoro (International School for Advanced Studies)

Antonello Scardicchio (International Centre for Theoretical Physics)



Invited Speakers

- 1) **Steven ADACHI** (Lockheed-Martin)
Application of Quantum Annealing to Training of Deep Neural Networks
- 2) **Mohammad AMIN** (D-Wave Systems Inc.)
Quantum Boltzmann Machine using a Quantum Annealer
- 3) **Sergio BOIXO** (Google Inc.)
Characterizing Quantum Supremacy in Near-Term Devices
- 4) **Bikas K. CHAKRABARTI** (Saha Institute)
Quantum Tunnelling & Ergodicity in Quantum Spin Glasses
- 5) **Elisabeth CROSSON** (Caltech)
Ground state expansion and the spectral gap of stoquastic Hamiltonians
- 6) **Amit DUTTA** (IIT Kanpur)
Dynamics of Decoherence: Universal scaling of decoherence factors
- 7) **Rosario FAZIO** (ICTP)
Quantum/Simulated Annealing and open adiabatic dynamics in Ising ferromagnets
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- 11) **Sergey I. KNYSH** (Nasa)
Spin-glass bottlenecks in quantum annealing
- 12) **Chris LAUMANN** (University of Washington)
(De)-localization in mean-field quantum glasses
- 13) **Peter LOVE** (Tufts University)
Testing Adiabatic Quantum Computers Using Simple Quantum Simulation
- 14) **Shunji MATSUURA** (Niels Bohr Institute)
Phase transitions in quantum error correction
- 15) **Roderich MOESSNER** (MPI-PKS, Dresden)
Simulating quantum spin systems

- 16) **Alejandro PERDOMO-ORTIZ** (NASA)
A quantum-assisted algorithm for sampling applications in machine learning
- 17) **Anatoli POLKOVNIKOV** (Boston University)
Geometric and counter-diabatic optimization of quantum annealing protocols
- 18) **Marek RAMS** (Jagiellonian University)
Inhomogeneous quasi-adiabatic driving of quantum critical dynamics in disordered spin chains
- 19) **Vadim N. SMELYANSKIY** (Google Inc.)
Scaling analysis and instantons for quantum spin tunneling and Quantum Monte Carlo simulations
- 20) **Shivaji SONDHI** (Princeton University)
DMRG and Many Body Localized Systems
- 21) **Sei SUZUKI** (Saitama Medical College)
Universal scaling for a quantum discontinuity critical point and an adiabatic time evolution
- 22) **Peter YOUNG** (University of California at Santa Cruz)
Spin glasses and Adiabatic Quantum Computing
- 23) **Marko ŽNIDARIČ** (University of Ljubljana)
Classical simulation of open quantum systems

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1. **Boris CHESCA** (Loughborough University)
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2. **Uwe Robert FISCHER** (Seoul National University)
"Photonic" Cat States from Strongly Interacting Matter Waves
3. **Kentaro IMAFUKU** (AIST)
Fictitious but Efficient Annealing Dynamics, and Role of Quantum Entanglement Therein
4. **Peter MASON** (Loughborough University)
Adiabatic Evolution of the Random transverse-field Ising Spin Chain
5. **Chihiro NAKAJIMA** (Tohoku University)
Computational property of quantum annealing of integer factorization problem
6. **Patrick Henri Jean NAVEZ** (University of Crete)
Expansion in large coordination number for the quantum Ising model
7. **Valter POGOSOV** (VNIIA)
Parametric excitation of a superconducting qubit due to a nonadiabatic modulation of Lamb shift
8. **Sergey REMIZOV** (VNIIA)
Suppression of inhomogeneous broadening of qubit ensemble under optimized driving
9. **Kazutaka TAKAHASHI** (Tokyo Institute of Technology)
Hamiltonian engineering for many-body quantum systems by shortcuts to adiabaticity

Flash talks & Posters

- 1) **Philip CROWLEY** (London Centre for Nanotechnology)
Quantum and Classical in Adiabatic Quantum Computation
- 2) **Yuki SUSA** (Tokyo Institute of Technology)
Semi-classical potential for quantum annealing with antiferromagnetic fluctuation
- 3) **Marcos DE OLIVEIRA** (UNICAMP)
Quantum simulation of the Anderson Hamiltonian with an array of coupled nanoresonators: delocalization and thermalization effects
- 4) **Estelle Maeva INACK** (SISSA-ICTP)
Simulated quantum annealing of double-well and multiwell potentials
- 5) **Gianni MOSSI** (SISSA-ICTP)
On the quantum spin glass transition on the Bethe lattice
- 6) **Tommaso ZANCA** (SISSA)
Quantum annealing speedup over simulated annealing on random Ising chains
- 7) **Hazmatally GOOLAM HOSSEN** (University of KwaZulu-Natal)
Non-reversal Open Quantum Walks
- 8) **Fateme HEYDARI-NASAB** (IASBS)
Checker-board supersolid phase in the multi-component Bose-Hubbard model on the square lattice

Application of Quantum Annealing to Training of Deep Neural Networks

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In Deep Learning, a well-known approach for training a Deep Neural Network starts by training a generative Deep Belief Network model, typically using Contrastive Divergence (CD), then fine-tuning the weights using backpropagation or other discriminative techniques. However, the generative training can be time-consuming due to the slow mixing of Gibbs sampling. We investigated an alternative approach that estimates model expectations of Restricted Boltzmann Machines using samples from a D-Wave quantum annealing machine. We tested this method on a coarse-grained version of the MNIST data set. In our tests we found that the quantum sampling-based training approach achieves comparable or better accuracy with significantly fewer iterations of generative training than conventional CD-based training. Further investigation is needed to determine whether similar improvements can be achieved for other data sets, and to what extent these improvements can be attributed to quantum effects.

Quantum Boltzmann Machine using a Quantum Annealer

Mohammad Amin

D-Wave Systems

Machine learning is a rapidly growing field in computer science with applications in computer vision, voice recognition, medical diagnosis, spam filtering, search engines, etc. In this presentation, I will introduce a new machine learning approach based on quantum Boltzmann distribution of a transverse-field Ising Model. Due to the non-commutative nature of quantum mechanics, the training process of the Quantum Boltzmann Machine (QBM) can become nontrivial. I will show how to circumvent this problem by introducing bounds on the quantum probabilities. This allows training the QBM efficiently by sampling. I will then show examples of QBM training with and without the bound, using exact diagonalization, and compare the results with classical Boltzmann training. Finally, after a brief introduction to the D-Wave quantum annealing processor, I will discuss the possibility of using such processors for QBM training and application.

Characterizing Quantum Supremacy in Near-Term Devices

Sergio Boixo

Google, Venice, CA 90291, USA

A critical question for the field of quantum computing in the near future is whether quantum devices without error correction can perform a well-defined computational task beyond the capabilities of state-of-the-art classical computers, achieving so-called quantum supremacy. We study the task of sampling from the output distributions of (pseudo-)random quantum circuits, a natural task for benchmarking quantum computers. Crucially this requires a direct numerical simulation to solve classically, with computational cost exponential in the number of qubits. This requirement is typical of chaotic systems. We extend previous results in computational complexity to argue more formally that this sampling task must take exponential time in a classical computer. We study the convergence to the chaotic regime using extensive supercomputer simulations, modeling circuits with up to 42 qubits - the largest quantum circuits simulated to date for a computational task that approaches quantum supremacy. We argue that while chaotic states are extremely sensitive to errors, quantum supremacy can be achieved in the near-term with approximately fifty superconducting qubits. We introduce cross entropy as a useful benchmark of quantum circuits which approximates the circuit fidelity. We show that the cross entropy can be efficiently measured when circuit simulations are available. Beyond the classically tractable regime, the cross entropy can be extrapolated and compared with theoretical estimates of circuit fidelity to define a practical quantum supremacy test.

Quantum Tunnelling & Ergodicity in Quantum Spin Glasses

Bikas K. Chakrabarti

Saha Institute

We will discuss the effect of quantum tunnelling on the static behaviour of the infinite-range (SK) spin glass phases & transitions. Detailed numerical results, both from exact diagonalization and Monte Carlo for the effective Suzuki-Trotter Hamiltonian will be presented.

Ground state expansion and the spectral gap of stoquastic Hamiltonians

Elisabeth Crosson

Caltech

Using a mapping from stoquastic Hamiltonians to Markov chains that generalizes previously known constructions I'll describe a new characterization of the spectral gap in terms of the conductance or vertex expansion of the ground state probability distribution. By quantitatively relating the spectral gap to the presence of bottlenecks in multi-modal ground state distributions we will further our understanding of the kinds of probability distributions that stoquastic adiabatic optimization can sample from efficiently. I'll also discuss the implications of these bounds for stoquastic Hamiltonians with k -local off-diagonal terms, as well as a partial extension of the bounds to the non-stoquastic case.

Dynamics of Decoherence: Universal scaling of decoherence factors

Amit Dutta
IIT Kanpur

We study the time dependence of the decoherence factor (DF) of a qubit globally coupled to an environmental spin system (ESS) which is driven across the quantum critical point (QCP). In the limit of weak coupling we analyze the time evolution of the DF in the vicinity of the QCP (chosen to be at $t=0$) and define three quantities, namely, the generalized fidelity susceptibility $\chi_F(\tau)$ (defined right at the QCP), and the decay constants $\alpha_1(\tau)$ and $\alpha_2(\tau)$ which dictate the decay of the DF at a small but finite $t(>0)$. Using a dimensional analysis argument based on the Kibble-Zurek healing length, we show that $\chi_F(\tau)$ as well as $\alpha_1(\tau)$ and $\alpha_2(\tau)$ indeed satisfy universal power-law scaling relations with τ and the exponents are solely determined by the spatial dimensionality of the ESS and the exponents associated with its QCP. Remarkably, using the numerical t-DMRG method, these scaling relations are shown to be valid in both the situations when the ESS is integrable and nonintegrable and also for both linear and nonlinear variation of the parameter.

Quantum/Simulated Annealing and open adiabatic dynamics in Ising ferromagnets

Rosario Fazio

The Abdus Salam International Centre for Theoretical Physics

In my talk I will discuss several different issues related to the adiabatic driving of a quantum system through a quantum critical point. I will first consider the effect of an external bath on the defect formation by studying the Lindblad dynamics in a one-dimensional Ising model and in the case of some exactly solvable free fermion models. I will then move considering an infinite range spin-1/2 model exhibiting both first and second order phase transitions depending on some external parameter. Here I will compare adiabatic quantum dynamics with simulated annealing.

Entanglement in Adiabatic Quantum Computation

Andrew G. Green

London Centre for Nanotechnology

Entanglement is an important resource for adiabatic quantum computation. By considering the quantum adiabatic algorithm performed upon a sub-manifold of Hilbert space with a bounded degree of entanglement, one may determine the resources required to solve a given problem [Crowley et al PRA90, 042317 (2014), Bauer et al ArXiv:1501.06914]. I shall discuss this and the role of the environment in restricting the available entanglement resources. Understanding the dynamics of this process may inspire new methods of error correction for adiabatic computation.

Quantum-Classical Monte Carlo Algorithm for Simulating AQC

Itay Hen

University of Southern California

I will present a hybrid Monte Carlo algorithm designed to simulate quantum and classical systems at equilibrium. The method is based on a novel decomposition of the quantum partition function devised to bridge the algorithmic gap between quantum and classical thermal simulation algorithms. I will argue that the algorithm is suited to tackle quantum many-body systems that exhibit a range of dominant fluctuations from ‘fully-quantum’ to ‘fully-classical and as such is especially applicable to simulations of adiabatic quantum computing processes.

This is a joint work with Tameem Albash and Gene Wagenbreth.

Quantum vs classical optimization: A status update on the arms race

Helmut G. Katzgraber

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To date, a conclusive detection of quantum speedup remains elusive. However, recent results from quantum Monte Carlo simulations, as well as the D-Wave 2X quantum annealer show a scaling that clearly outperforms state-of-the-art classical simulated annealing. In this talk an overview of recent benchmarks, as well as attempts to "tickle" any quantumness out of quantum annealing machines is given. Furthermore, we present a generic framework to validate benchmarks and to detect parameter regimes where quantum annealing might excel over classical heuristics. As such, we provide capabilities to aide in the search for the "killer" application for quantum optimization technologies. Finally, an overview of different sequential, non-tailored, as well as specialized tailored classical state-of-the-art algorithms is given. Current quantum annealing technologies must outperform these to claim the crown in the race for quantum speedup.

Work done in collaboration with F. Hamze (D-Wave Systems Inc), Sergei Isakov (Google Inc.), S. Mandra (Harvard), H. Munoz-Bauza (Texas A&M University), H. Neven (Google), A. Ochoa (Texas A&M University), A. Perdomo-Ortiz (NASA), S. Schnabel (Leipzig University), W. Wang (Texas A&M University) Z. Zhu (Texas A&M University)

Spin-glass bottlenecks in quantum annealing

Sergey Knysh

NASA Ames Research Center

Frustrated spin systems exhibit bottlenecks (where the gap separating the ground state from excited states is small) inside the spin glass phase. These are in addition to the phase-transition bottleneck, which for many interesting problems is easier to navigate. Using a toy model as an illustration, I will argue that the number of spin-glass bottlenecks is logarithmic in system size. In practical terms it implies a crossover from polynomial to exponential scaling of complexity for larger sizes, when spin-glass bottlenecks become dominant. Implication of this result for more realistic spin glasses (e.g. Sherrington-Kirkpatrick model) will also be addressed.

Testing Adiabatic Quantum Computers Using Simple Quantum Simulation

Peter Love

Tufts University

Validation of Adiabatic Quantum computers is a significant problem. One of the advantages of the Adiabatic model is that it does not require the rapid pulsed controls necessary in the gate model of quantum computation. However, eschewing this level of control also makes state and process tomography impossible in purely adiabatic hardware, and hence the quantum nature (if any) of such devices has to be established by indirect evidence. In this talk I will describe how to use Adiabatic quantum computers based on the transverse-field Ising model to simulate elementary one-dimensional quantum systems, and discuss the quantum properties of the machines that can be exhibited by such simulations. I will also discuss how to detect the presence of one type of beyond-transverse-Ising coupling, namely the XX couplings of interest for non-stoquastic Adiabatic machines.

A quantum-assisted algorithm for sampling applications in machine learning

Alejandro Perdomo-Ortiz

NASA Ames Research Center

An increase in the efficiency of sampling from Boltzmann distributions would have a significant impact in deep learning and other machine learning applications. Recently, quantum annealers have been proposed as a potential candidate to speed up this task, but several limitations still bar these state-of-the-art technologies from being used effectively. One of the main limitations is that, while the device may indeed sample from a Boltzmann-like distribution, quantum dynamical arguments suggests it will do so with an instance-dependent effective temperature, different from the physical temperature of the device. Unless this unknown temperature can be unveiled, it might not be possible to effectively use a quantum annealer for Boltzmann sampling. In this talk, we present a strategy to overcome this challenge with a simple effective-temperature estimation algorithm. We provide a systematic study assessing the impact of the effective temperatures in the learning of a kind of restricted Boltzmann machine embedded on quantum hardware, which can serve as a building block for deep learning architectures. We also provide a comparison to k -step contrastive divergence (CD- k) with k up to 100. Although assuming a suitable fixed effective temperature also allows to outperform one step contrastive divergence (CD-1), only when using an instance-dependent effective temperature we find a performance close to that of CD-100 for the case studied here. We discuss generalizations of the algorithm to other more expressive generative models, beyond restricted Boltzmann machines.

Geometric and counter-diabatic optimization of quantum annealing protocols

Anatoli Polkovnikov

Boston University

In this talk I will discuss two complimentary approaches for optimization of quantum annealing protocols (i) based on minimizing the quantum length as defined through the geometric tensor and (ii) on adding counter-diabatic terms to the driving Hamiltonians. In particular, I will discuss how non-adiabatic corrections leading to transitions appear in the moving frame and how one can minimize them. I will present a new variational approach for finding counter-adiabatic terms and will show that in some generic problems it can increase final fidelity of the annealing protocol by many orders of magnitude. I will also mention possible extensions of these approach to imaginary time, amenable to quantum Monte-Carlo simulations.

Inhomogeneous quasi-adiabatic driving of quantum critical dynamics in disordered spin chains

Marek M. Rams¹, Masoud Mosheni², and Adolfo del Campo³

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We introduce an inhomogeneous protocol to drive a disordered quantum spin chain quasi-adiabatically across a quantum phase transition and minimize the residual energy of the final state. The number of spins that simultaneously reach the critical point is controlled by the length scale of the inhomogeneity in which the magnetic field is modulated, introducing an effective size that favors adiabatic dynamics. The dependence of the residual energy on this length scale and the velocity at which the magnetic field sweeps out the chain is shown to be nonmonotonic. We determine the conditions for an optimal suppression of the residual energy of the final state and show that inhomogeneous driving can outperform conventional adiabatic schemes based on homogeneous control fields by several orders of magnitude.

[1] M.M. Rams, M. Mosheni, and A. del Campo, arXiv:1606.07740

[2] M. Mosheni, A. del Campo, and M.M. Rams, *in preperation*

Scaling analysis and instantons for quantum spin tunneling and Quantum Monte Carlo simulations

Vadim Smelyanskiy

Google, Venice, CA 90291

We develop an instantonic calculus for the thermally-assisted tunneling decay rate in a fully connected quantum spin model. We show that the tunneling decay problem can be mapped onto the Kramers escape problem of a classical random dynamical field. This dynamical field is simulated efficiently by Path Integral Quantum Monte Carlo (QMC). We show that the exponential scaling with the number of spins of the quantum tunneling rate and the escape rate of the QMC process are identical. We provide further examples where QMC has quadratic speed up in scaling over quantum tunneling.

DMRG and Many Body Localized Systems

Shivaji Sondhi

Princeton University

Many body localized systems are characterized by eigenstates with low entanglement. I will report on a set of studies that take advantage of this to construct eigenstates of MBL Hamiltonians and Floquet drives via generalizations of the celebrated density matrix renormalization group method. I will give evidence that it is possible to go beyond the sizes accessible by exact diagonalization despite the extremely small gaps that characterize the bulk of the spectrum.

Universal scaling for a quantum discontinuity critical point and an adiabatic time evolution

Sei Suzuki

Saitama Medical University

Quantum discontinuous transitions attract much attention as difficulties of quantum annealing. Here we study a quantum version of a discontinuity critical point (QDCP). We evaluate the critical exponents associated with a QDCP using the appropriate scaling relations. We then study a nearly adiabatic time evolution in the vicinity of a QDCP and propose the scaling relation for the defect density and the residual energy characterized by associated critical exponents. These predictions are numerically verified for the XXZ chain, establishing the existence of a Kibble-Zurek scaling for a dynamics across a QDCP.

Spin glasses and Adiabatic Quantum Computing

A. P. Young

University of California Santa Cruz

In this talk I will discuss various aspects of spin glass physics which are relevant for Adiabatic Quantum Computing. These include the phase transition which occurs on lowering the temperature in classical spin glasses, and on lowering the transverse field at zero temperature in quantum spin glasses. An unusual feature of classical spin glasses is that a line of transitions, the de Almeida-Thouless (AT) line, occurs in a magnetic field at least in mean field theory. The question of whether a quantum AT line can occur at zero temperature will be raised. A particular emphasis on the talk will be on chaos in spin glasses, which can be due to a change in temperature (T-chaos), or a change in interactions (J-chaos), or, in the quantum case, a change in the transverse-field (TF-chaos). The difficulties caused by chaos in spin glasses when solving problems by Adiabatic Quantum Computing will be discussed. It will also be pointed out that more work needs to be done to see to what extent there is a correlation between these different types of chaos among different problem instances.

Classical simulation of open quantum systems

Marko Znidaric

University of Ljubljana

One of the central questions of (adiabatic) quantum computation is, when do quantum computations outperform classical ones? In order to answer it we have to understand computation power of both quantum and classical systems. This talk will deal with computational power of classical simulations. For a physicist an especially important class of problems is understanding physics of a particular system. I will briefly mention systems that we do know how to efficiently solve, and those that seem hard. Then I will focus on systems that are coupled to the environment, in particular a situation described by the Lindblad master equation. It turns out that classical simulations of such systems can be efficient even though the Hamiltonian version is difficult. Therefore, opening a system to the outside world – a situation that is arguably a relevant one – can sometimes render the problem easier.

High- T_c Josephson junctions for quantum computation

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Abstract

So far, almost exclusively, Josephson junctions made of low transition temperature (low- T_c) superconductors like Al have been used for the implementation of superconducting qubits for quantum computation. This is because low- T_c junctions have superior performances and their fabrication technology is far more advanced relative to the case of junctions made of high transition temperature (high- T_c) superconductors such as YBCO. However, unlike low- T_c superconductors, high- T_c superconductors are d-wave superconductors and this feature offer the possibility to naturally build π -loops-based qubits. Indeed, high- T_c junctions have been proposed as excellent candidates for device implementation of circuits based on π -loops in quantum computing with [1] or without [2] the topological restriction imposed by the bicrystal technique. Several recent very significant developments in the area of high- T_c junctions fabrication [3, 4] and their improved sensitivity [5] opens the possibility to reconsider their use for quantum computation. Indeed very significant progress has been reported in the area of step-edge junction technology [4, 5] that offers the advantage of using low cost MgO substrates and the flexibility of implementing complex 2D large array configurations involving many tens of thousands of SQUIDs. Also in [5] the white flux-noise performances of high- T_c SQUID-arrays operating above 77K and fabricated using the bicrystal technology outperformed even single low- T_c -SQUIDs operating at 4.2 K.

References

- [1] R. R. Schulz, B. Chesca, B. Goetz, C.W. Schneider, A. Schmehl, H. Bielefeldt, H. Hilgenkamp, J. Mannhart, and C.C.Tsuei, *App. Phys. Lett.* **76**, 912 (2000).
- [2] L. B. Ioffe, V. B. Geshkenbein, M. V. Feigel'man, A. L. Fauchère and G. Blatter, *Nature*, **398**, 679 (1999).
- [3] J. Du, J.Y. Lazar, S. K. H. Lam, E. E. Mitchell, and C. P. Foley, *Supercond. Sci. Technol.* **27**, 095005 (2014).
- [4] E. E. Mitchell, K.E. Hannam, J.Y. Lazar, K.E. Leslie, A. Grancea, S.T. Keenan, S. K. H. Lam, and C. P. Foley, *Supercond. Sci. Technol.* **29**, 06LT01 (2016).
- [5] B. Chesca, D. John and C.J. Mellor, *Appl. Phys. Lett.* **107**, 162602 (2015).

“Photonic” cat states from strongly interacting matter waves

Uwe R. Fischer and Myung-Kyun Kang

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We consider ultracold quantum gases of scalar bosons, residing in a coupling strength–density regime in which they constitute a twofold fragmented condensate trapped in a single well [1]. It is shown that the corresponding quantum states are, in an appropriate Fock space basis representing (modified) Schwinger bosons, identical to the photon cat states familiar in quantum optics, which correspond to superpositions of coherent states of the light field with a phase difference of π . In marked distinction to photon cat states, the very existence of matter wave cat states however crucially depends on the many-body correlations of the constituent particles. We consequently establish that the quadratures of the effective “photons,” expressing the highly nonclassical nature of the macroscopic matter wave superposition state, can be experimentally accessed by measuring the density–density correlations of the interacting quantum gas [2, 3].

- [1] Philipp Bader and Uwe R. Fischer, *Fragmented many-body ground states for scalar bosons in a single trap*, Phys. Rev. Lett. **103**, 060402 (2009).
- [2] Myung-Kyun Kang and Uwe R. Fischer, *Revealing single-trap condensate fragmentation by measuring density-density correlations after time of flight*, Phys. Rev. Lett. **113**, 140404 (2014).
- [3] Uwe R. Fischer and Myung-Kyun Kang, *“Photonic” cat states from strongly interacting matter waves*, Phys. Rev. Lett. **115**, 260404 (2015).

Fictitious but Efficient Annealing Dynamics, and Role of Quantum Entanglement Therein

Kentaro IMAFUKU, and Shiro Kawabata

National Institute of Advanced Industrial Science and Technology (AIST)

Motivated by the idea of the annealing computations, we investigate a mechanism which drives an initial state into a ground state of a given Hamiltonian. Instead of natural dynamics in physics, however, we dare to introduce/consider a fictitious dynamics[1]

$$\frac{d}{ds} \hat{U}_s = -i\hat{\eta}_s \hat{U}_s, \quad \hat{U}_0 = \text{Identity Operator} \quad (1)$$

with

$$\hat{\eta}_s := -i[\hat{H}, |\varphi_s\rangle\langle\varphi_s|], \quad \text{and} \quad |\varphi_s\rangle := \hat{U}_s|\varphi_0\rangle. \quad (2)$$

On the fictitious dynamics, efficiency and mechanism of the convergence are demonstrated with examples. In particular, by applying the approach to Hamiltonian of Ising model, we show that the classical gradient descent mechanism interestingly appears as a classical approximation of the proposed dynamics, and that quantum entanglement plays an essential role to make the dynamics superior to the classical one.

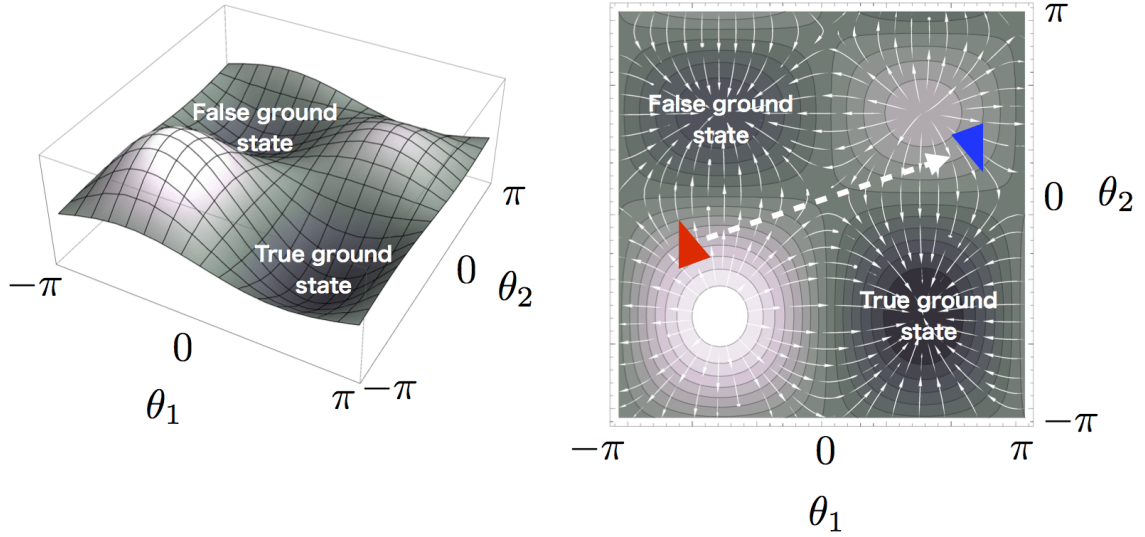


Figure 1: The left figure shows the potential (or energy landscape) defined as $H(\theta_1, \theta_2) := \sum_{i=1}^2 h_i \sin \theta_i + \sum_{i<j} J_{ij} \sin \theta_j \sin \theta_i$. In the right figure, the white solid arrows represent the gradient descent forces by the potential. Besides the forces, the dynamics generates an “entangled component (represented by the downward blue triangle)” in a symmetrical position with respect to the origin. The force at the position drives the component to the true ground state whereas the force at the position of original state does not.

[1] K. Imafuku and S. Kawabata, manuscript in preparation.

Adiabatic Evolution of the Random Transverse-field Ising Spin Chain

Peter Mason, Alexandre Zagoskin, and Joseph Betouras

Department of Physics, Loughborough University

A quantum adiabatic computation is one in which the governing Hamiltonian is slowly varied in time, starting from an initial Hamiltonian for which the ground state is known, and ending with a final Hamiltonian, the ground state of which encodes our desired solution. Throughout the evolution we always remain in the ground state. Such a technique to establish the solution of a computational task in a quantum simulation, together with quantum annealing, can be extremely effective, and is employed for instance in the D-wave devices.

Here we consider a renormalisation group treatment [1, 2] on the strongly disordered random one-dimensional transverse-field Ising spin chain where the bonds J_{ij} and horizontal fields h_i are time-dependent and chosen to reflect an adiabatic evolution of the governing Hamiltonian. Under the condition that the renormalisation process occurs at fixed time, a set of coupled second order, nonlinear PDE's can be written down in terms of the random distributions of the bonds and fields. Solution of these flow equations at the relevant critical fixed points leads us to the establish the critical behaviour of the flow as the Hamiltonian is adiabatically evolved. We will present these critical flows as well as discussing the issue of duality, before making connections to quantum adiabatic computations.

[1] D.S. Fisher, Phys. Rev B **51**, 6411 (1995).

[2] C. Dasgupta, S. Ma, Phys. Rev. B **22**, 1305 (1980).

Computational property of quantum annealing of integer factorization problem

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The computational property of the prime factorization in quantum annealing is investigated with focuses on quantum phase transition. A Hamiltonian constructed in the sense of a combinatorial-optimization problem is considered. On the Hamiltonian, the quantum phase transition and minimal energy gap is discussed via the numerical diagonalization and the quantum Monte Carlo simulation. The classical version of this study is uploaded to arXiv as [1].

[1] C. Nakajima, M. Ohzrki, arXiv:1605.01310.

Expansion in large coordination number for the quantum Ising model

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Abstract— Quantum lattice systems are encountered in many field of physics: solid states, ultracold gases, quantum optics, and metamaterials. For this class of systems, we establish a set of hierarchy equations describing the non equilibrium time evolution of the n -site spatial correlation reduced density matrices and solve it iteratively through a $1/Z$ expansion where Z is the coordination number. We focus on the particular study of quench dynamics of the quantum Ising model.

1. INTRODUCTION

The quantum lattice systems are encountered in many field of physics: solid states, ultracold gas and quantum metamaterials such as photonic band gap materials. The typical examples are the Bose or Fermi Hubbard models, the array of quantum dots or Josephson junctions, or the Heisenberg spin model. More recently, the Jaynes-Cumming-Hubbard model describing the interaction of light with two-level atoms (Rydberg atoms) in a lattice has attracted considerable interests since it displays interesting phenomena such as coulomb blockade or polaritons-like excitations. An accurate modelling of these many body systems may help to understand many open problems encountered for example in high temperature superconductivity, oxytronic, topological insulator or graphene. With these lattice models, we wish to describe the non equilibrium phenomena resulting from a sudden external perturbation, for example, those in the cold gas resulting from a quench from an insulating state to a superfluid state or those in a oxyde material resulting from a brutal change in the electronic density of state caused by the radiation of a laser or electronic scattering.

In this paper, we investigate these lattice systems from a general point of view using the $1/Z$ expansion method where Z is the coordination number. This method developed by us [1, 5] assumes that the coordination number Z is large and that the next order corrective terms $1/Z^i$ give decreasingly smaller contributions to the lattice system dynamics. This formalism provides a general framework of hierachical equations for n -sites reduced density matrices allowing to systematically determine the equilibrium properties such as the ground states [7, 8] but also to describe the non equilibrium dynamics [1, 5]. Below are the aspects under active and/or future considerations.

2. THE $1/Z$ EXPANSION IN LATTICE GASES IN THERMODYNAMIC EQUILIBRIUM: BOSONS, FERMIONS AND SPIN

We are currently working on the Bose-Hubbard model that describes cold atoms trapped in lattice sites in order to test the accuracy of $1/Z$ expansion techniques [1, 6, 5, 4]. Comparisons with other methods (exact diagonalisation, perturbation techniques, Monte-Carlo, ...) allow to assess the convergence of the expansion. Recently, we achieved this expansion at finite temperature [7] and showed that this method describes the entire crossover region from weak coupling (superfluid regime) to strong coupling (Mott insulating regime).

The Heisenberg model for the spin magnet has been described with this formalism [3]. Recently, we show the convergence of the expansion for the determination of the quantum transition point in the quantum Ising model [8].

3. NON EQUILIBRIUM ASPECTS OF A LATTICE BOSON GAS

The $1/Z$ expansion method can be applied to study non equilibrium physical phenomena. We are currently studying the behavior of quantum fluctuations in cold gases by changing suddenly the parameters of the hamiltonian (sweeping). One of the typical example is the Kibble-Zurek mechanism where a sudden quench towards a phase transition to superfluid phase results in the domain

formation. In one of our work, these domain formations originates from quantum fluctuations of an initial the Mott phase suddenly swept in the superfluid regime [1]. A similar study has been done for a quench within a Mott phase with a an explicit description of the relaxation towards a prethermalized state [5]. Another example is the Sauter-Schwinger mechanism that predicts the production of electron-positron pairs that appear when a strong electric field is applied to the quantum vacuum. By analogy, such a tilt (bias force) has been introduced in the Bose lattice in the Mott-insulating phase and creates instead doublon-holon pairs [2].

4. QUANTUM ISING MODEL

In our last work [8], we use the $1/Z$ expansion to describe the ground state and the quench dynamics of the quantum Ising model in one, two and three dimensions. Our method reproduces quite well the physics of this model such as the quantum phase transition between the paramagnetic and ferromagnetic phases or also the excitation spectrum. Such a model happens to describe the dynamics of array of Josephson junctions such as squids perturbed by an external magnetic field under the conditions of long decoherence time. Such structures are designed nowadays by the D-Wave company and are potentially promising for adiabatic quantum computations such as annealing. Numerous studies have currently been achieved in order to check the adiabaticity during the annealing and to assess whether the D-wave devices preserve its quantum characteristics. Our recent developments [8] may provide more insights on the understanding of the quantum fluctuations generated by these devices.

5. CONCLUSIONS

From the examples above, we illustrate how the large coordination number expansion method reveals to be useful for an understanding of the quantum phenomena involved in quantum lattice devices such as matematerials. The last recent developments have brought new insights on the efficiency and the powerfulness of the method.

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Parametric excitation of a superconducting qubit due to a nonadiabatic modulation of Lamb shift

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The investigation of responses of quantum systems on nonadiabatic modulation of their parameters is of interest both from the viewpoint of realization of various fundamental QED effects and for purposes of quantum computation. Indeed, high-speed gates can induce various nonstationary QED effects related to vacuum amplification and parametric generation of excitations from vacuum via counter-rotating wave processes which are usually neglected. Both the understanding and the control of such effects is of great importance. One of such phenomena is the dynamical Lamb effect, induced by a nonadiabatic modulation of atomic level Lamb shift [1], which was initially predicted for a natural atom placed into a cavity with time-dependent parameters. We here study the dynamical Lamb effect and accompanying quantum phenomena for the case of a coupled superconducting qubit-resonator system under variation of either the coupling energy [2, 3] or resonator frequency. Energy dissipation is taken into account. We reveal various dynamical regimes in which dynamical Lamb effect can be effectively suppressed or enhanced in comparison with other channels of a parametric qubit excitation. We also find that the effect of energy dissipation on the dynamics of such systems can be highly nontrivial. One of the most striking results is that photon generation from vacuum can be strongly enhanced due to the qubit relaxation, which opens a new channel for such a process.

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Suppression of inhomogeneous broadening effects of qubit ensemble under optimized driving

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One of the crucial distinctions of artificial qubits from natural atoms is that their excitation energies are in many cases tunable *in situ* by external magnetic fields. The flip side of this tunability is unavoidable disorder in excitation frequencies and, as a consequence, inhomogeneous broadening of the density of states in qubit ensembles. This effect is related to fundamental mechanisms such as an exponential dependence of excitation energy on Josephson and charging energies in superconducting qubits or spatial fluctuations of background magnetic moments in systems based on NV-centers in diamonds.

It is known a number of methods to suppress the effect of disorder, such as an atomic frequency comb (AFC) which is based on a frequency-selective optical pumping and subsequent transitions to metastable auxiliary hyperfine states or cavity protection' effect related to a decreasing of relaxation rate of collective qubit modes proportional to the spectral broadening.

We propose another universal technique of effective suppression of inhomogeneous broadening in spectral density of realistic qubit ensemble coupled to transmission line[1]. Our technique is based on applying of optimally chosen electromagnetic pulse with smooth envelope. We study excitation dynamics of an off-resonant qubit subjected to a strong classical electromagnetic driving field with a large reference frequency and slow envelope. Within this solution we optimize the envelope to achieve a preassigned accuracy in qubit synchronization.

This technique can be applied to excite qubits as well as to prepare entangled states of the inhomogeneously broadened qubits.

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Hamiltonian engineering for many-body quantum systems by shortcuts to adiabaticity

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We study the engineering of the optimal time-dependent Hamiltonian by using the method of shortcuts to adiabaticity. This method allows us to control the adiabatic quantum states with a finite speed. There exist several formulations of the method and we focus on the inverse engineering of the Hamiltonian. The existence of the Lewis–Riesenfeld dynamical invariant is the essential ingredient of the method and we can actually show the optimality of the driving by using the minimum action principle [1].

We apply the inverse engineering to quantum spin systems. By using the equation for the dynamical invariant, we design the optimal annealing schedule. The schedule is determined for a given adiabatic passage. It can be obtained without solving the differential equations. By using this method, we can discuss the efficiency of the annealing schedule.

We consider several possible applications.

- Transverse Ising model

$$\hat{H}(t) = f(t) \left(- \sum_{i,j=1}^N J_{ij} \hat{S}_i^z \hat{S}_j^z - \sum_{i=1}^N h_i \hat{S}_i^z \right) - \Gamma(t) \sum_{i=1}^N \hat{S}_i^x.$$

For mean-field systems, the equation for the dynamical invariant takes a simple form and we easily find the time dependence of the coupling functions $f(t)$ and $\Gamma(t)$. We discuss general properties of the annealing schedule which are applicable to non-mean-field systems.

- One-dimensional quantum XX model

$$\hat{H}(t) = - \sum_{i=1}^N J_i(t) \left(\hat{S}_i^x \hat{S}_{i+1}^x + \hat{S}_i^y \hat{S}_{i+1}^y \right) - \sum_{i=1}^N h_i(t) \hat{S}_i^z.$$

The isotropic XX model is solved by using the Jordan-Wigner transformation. We discuss how the inverse engineering is applied when we have the phase transitions [2]. We also solve the anisotropic XX model by using the solutions of the Toda equations [3]. We show that the results from the classical nonlinear integrable systems, such as the KdV equations and Toda equations, are directly applied to quantum adiabatic dynamics. For example, we can realize the adiabatic control of spin-state transfer by using the soliton solutions of the Toda equations.

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Quantum and Classical in Adiabatic Quantum Computation

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Adiabatic transport provides a powerful way to manipulate quantum states. By preparing a system in a readily initialized state and then slowly changing its Hamiltonian, one may achieve quantum states that would otherwise be inaccessible. Moreover, a judicious choice of final Hamiltonian whose ground state encodes the solution to a problem allows adiabatic transport to be used for universal quantum computation. However, the dephasing effects of the environment limit the quantum correlations that an open system can support and degrade the power of such adiabatic computation. We quantify this effect by allowing the system to evolve over a restricted set of quantum states, providing a link between physically inspired classical optimization algorithms and quantum adiabatic optimization. This perspective allows us to develop benchmarks to bound the quantum correlations harnessed by an adiabatic computation. We apply these to the D-Wave Vesuvius machine with revealing though inconclusive results.

Semi-classical potential for quantum annealing with antiferromagnetic fluctuation

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We see the quantum annealing (QA) process by evaluating the semi-classical potential on the basis of the spin-coherent state. QA is developed for efficiency solving a problem such as a combinatorial optimization by finding a ground state of a final target Hamiltonian. QA is accomplished by varying Hamiltonian from a trivial one \hat{H}_i to a target one \hat{H}_f such as

$$\hat{H}(s) = (1 - s)\hat{H}_i + s\hat{H}_f \quad (0 \leq s \leq 1), \quad (1)$$

where s is a time evolution parameter. In Ref. [1], Farhi and his colleagues proposed the detour paths instead of the straight path from initial to final Hamiltonian such as

$$\hat{H}(s) = (1 - s)\hat{H}_i + s\hat{H}_f + s(1 - s)\hat{H}_e, \quad (2)$$

where \hat{H}_e is a extra Hamiltonian to trace the detour paths. They showed that the detour paths contribute to find the ground state correctly under the certain Hamiltonian such that we can not reach the ground state without the detour paths. Noting that they evaluate the semi-classical potential for the Hamiltonian to see the capability of the detour paths, and the potential clearly supports their conclusion. Also in other studies [2–5], the spin-classical potential is used validly.

In present study, we focus on the ferromagnetic p -spin model which can be reduced to Glover problem for $p \rightarrow \infty$. In Ref. [6], the antiferromagnetic fluctuation (AFF) is additionally introduced to the Hamiltonian (1) as follows

$$\hat{H}(s, \lambda) = s\{\lambda\hat{H}_f + (1 - \lambda)\hat{V}_{\text{AFF}}\} + (1 - s)\hat{H}_i. \quad (3)$$

Here, \hat{V}_{AFF} denotes AFF and λ is another time evaluation parameter. This Hamiltonian is proposed for avoiding the first-order transition which causes an inefficiency of QA for the p -spin model claimed in Ref. [7]. Actually, they have proven that AFF works well. Although the concepts of the Hamiltonian (2) and (3) are similar, their background are not same. We see such physics of the Hamiltonian (3) by considering the semi-classical potential. Consequently, the semi-classical potential allows us to intuitively confirm that AFF contributes to avoid the first-order transition and generates the second-order transition.

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Quantum simulation of the Anderson Hamiltonian with an array of coupled nanoresonators: delocalization and thermalization effects

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The possibility of using nanoelectromechanical systems as a simulation tool for quantum many-body effects is explored. It is demonstrated that an array of electrostatically coupled nanoresonators can effectively simulate the Bose-Hubbard model without interactions, corresponding in the single-phonon regime to the Anderson tight-binding model. Employing a density matrix formalism for the system coupled to a bosonic thermal bath, we study the interplay between disorder and thermalization, focusing on the delocalization process. It is found that the phonon population remains localized for a long time at low enough temperatures; with increasing temperatures the localization is rapidly lost due to thermal pumping of excitations into the array, producing in the equilibrium a fully thermalized system. Finally, we consider a possible experimental design to measure the phonon population in the array by means of a superconducting transmon qubit coupled to individual nanoresonators. We also consider the possibility of using the proposed quantum simulator for realizing continuous-time quantum walks.

Simulated quantum annealing of double-well and multiwell potentials

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We analyze the performance of quantum annealing as a heuristic optimization method to find the absolute minimum of various continuous models, including landscapes with only two wells and also models with many competing minima and with disorder. The simulations performed using a projective quantum Monte Carlo (QMC) algorithm are compared with those based on the finite-temperature path-integral QMC technique and with classical annealing. We show that the projective QMC algorithm is more efficient than the finite-temperature QMC technique, and that both are inferior to classical annealing if this is performed with appropriate long-range moves. However, as the difficulty of the optimization problem increases, classical annealing loses efficiency, while the projective QMC algorithm keeps stable performance and is finally the most effective optimization tool. We discuss the implications of our results for the outstanding problem of testing the efficiency of adiabatic quantum computers using stochastic simulations performed on classical computers.

Quantum annealing speedup over simulated annealing on random Ising chains

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We show clear evidence of a quadratic speedup of a quantum annealing (QA) Schrödinger dynamics over a Glauber master equation simulated annealing (SA) for a random Ising model in one dimension, via an equal-footing exact deterministic dynamics of the Jordan-Wigner fermionized problems. This is remarkable, in view of the arguments of H. G. Katzgraber et al. [1], since SA does not encounter any phase transition, while QA does. We also find a second remarkable result: that a “quantum-inspired” imaginary-time Schrödinger QA provides a further exponential speedup, i.e., an asymptotic residual error decreasing as a power law $\tau^{-\mu}$ of the annealing time τ .

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Non-reversal Open Quantum Walks

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A new model of non-reversal quantum walk is proposed. In such a walk, the walker cannot go back to previously visited sites but it can stay static or move to a new site. The process is set up on a line using the formalism of Open Quantum Walks (OQWs). Afterwards, non-reversal quantum trajectories are launched on a 2-D lattice to which a memory is associated to record visited sites. The “quantum coins” are procured from a randomly generated unitary matrix. The radius of spread of the non-reversal OQW varies with different unitary matrices. The statistical results have meaningful interpretations in polymer physics. The number of steps of the trajectories is equivalent to the degree of polymerization, N . The root-mean-square of the radii determines the end-to-end distance, R of a polymer. These two values being typically related by $R \sim N^\nu$, the critical exponent, ν , is obtained for $N \leq 400$. It is found to be closely equal to the classical Flory exponent. However, for larger N , the relationship does not hold anymore. Hence, a different relationship between R and N is suggested.

Checker-board supersolid phase in the multi-component Bose-Hubbard model on the square lattice

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Supersolid phase is a phase that has diagonal and off-diagonal long-range order simultaneously [1, 2]. It was shown that checker-board supersolid (CSS) phase with non-zero component of static structure factor $q = (\pi, \pi)$ and non-zero superfluid order is unstable on the square lattice with short-range of interactions[1, 2].

In this work we introduce a generalized Bose-Hubbard model with two component bosons and stable CSS phase in the short-range of interactions. We calculated ground state phase diagram numerically by using cluster mean-field approach that is the case of mixing mean-field and exact solution. Finally we found effects of temperature on the phase diagram.

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