Workshop on Quantum Simulators of the Future: From Dynamical Gauge Fields to Lattice Gauge Theories | (SMR 3922)

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T01 - CALAJO Giuseppe

Digital quantum simulation of a (1+1)D SU(2) lattice gauge theory with ion qudits

T02 - CLEMENTE Giuseppe

Quantum Algorithms for the investigation of lattice gauge theories at finite temperature

T03 - DI LIBERTO Marco

Chiral orbital order without higher bands

T04 - FISCHER Uwe Robert Robert

Simulating trans-Planckian physics: Quantum cosmology and quantum black holes in dipolar Bose-Einstein condensates

T05 - GONZÁLEZ CUADRA Daniel

(2 + 1)D gauge theory dynamics in a programmable Rydberg quantum simulator

T06 - HALIMEH Jad

Cold-atom quantum simulators of gauge theories

T07 - HOMEIER Lukas

Spin-exchange enabled quantum simulator for large-scale non-Abelian gauge theories

T08 - KEBRIC Matjaz

Confinement in a one-dimensional Z_2 lattice gauge theory at finite temperature

T09 - KELMAN Ariel

Fermionic Tensor Networks for Lattice Gauge Theory

T10 - MAGONI Matteo

Coupled spin-phonon dynamics in Rydberg tweezer arrays

T11 - PINTO BARROS Joao

Quantum Many-Body Scars in U (1) Lattice Gauge Theories Beyond Spin-1/2

T12 - RAKOV Mykhailo

Density matrix renormalization group search for the gapless deconfined phase in Z_N symmetric gauge Hamiltonian

T13 - STORNATI Paolo

Sub-lattice quantum many body scars in a two dimensional Abelian gauge theory

T14 - TAGLIACOZZO Luca

Alternative simulation strategies of lattice gauge theories with tensor network

T15 - TIRRITO Emanuele

Many-body magic: from criticality to gauge theories

T01

Digital quantum simulation of a (1+1)D SU(2) lattice gauge theory with ion qudits

Giuseppe Calajó[1]

[1]*Istituto Nazionale di Fisica Nucleare (INFN), Sezione di Padova, I-35131 Padova, Italy*

The simulation of the dynamics of non-abelian lattice gauge theories at finite densities is a long standing goal of classical and quantum computation. This ambitious goal is compounded by the necessity to maintain exact gauge invariance, often demanding complex computational schemes and high control over quantum hardware. Here we present an efficient formulation of a (1+1)D SU(2) non-abelian LGT naturally suitable for an implementation on a six levels ions qudit quantum processor [1]. Through a convenient encoding on the qudit and the implementation of generalized Mölmer-Sorensen gates, we demonstrate that a shallow circuit is sufficient for performing a quantum digital simulation of the model and to probe its non-abelian nature.

[1] M. Ringbauer, M. Meth, L. Postler, R. Stricker, R. Blatt, P. Schindler, and T. Monz, Nature Physics **18**, 1053 (2022).

T02

Quantum Algorithms for the investigation of lattice gauge theories at finite temperature

E. Ballini[1], **G. Clemente**[2], **M. D'Elia**[2], **L. Maio**[3] **and K. Zambello**[2]

[1] *Pitaevskii BEC Center and Department of Physics, University of Trento, Via Sommarive 14, I-38123 Trento, Italy and INFN-TIFPA, Trento Institute for Fundamental Physics and Applications, Trento, Italy*

[2] *Dipartimento di Fisica dell'Università di Pisa and INFN — Sezione di Pisa, Largo Pontecorvo 3, I-56127 Pisa, Italy.*

[3] *Aix Marseille Univ, Université de Toulon, CNRS, CPT, Marseille, France.*

In the last few decades, standard Markov Chain Monte Carlo techniques proved successful in the investigation of non-perturbative features of lattice quantum field theories and non-abelian gauge theories. However, simulating real-time dynamical processes, phase diagram at non-zero baryonic chemical potential, non-zero topological theta term, or frustrated spin systems, are affected by difficult numerical problems which, on classical hardware, usually rely on a quantum to classical mapping followed by analytic continuations back to the quantum regime. In the next future, there are serious hopes that these problem could be successfully tackled by new quantum algorithms taylored for quantum hardware and based on the Hamiltonian formulation. In this talk, I will first give an overview on the current state of quantum algorithms for the estimation of finite temperature expectation values of spin systems and lattice gauge theories. Then I will focus on describing the challenges introduced by non-abelian gauge theory computations in near-term quantum devices, showing an application of the Quantum Metropolis Sampling algorithm to investigate thermal averages of a lattice gauge theory with D_4 gauge group in $2+1$ dimensions.

[1] E. Ballini, G. Clemente, M. D'Elia, L. Maio, K. Zambello, (2023), e-Print: 2309.07090 [quant-ph].

T03

Chiral orbital order without higher bands

Marco Di Liberto[1,2] **and Nathan Goldman**[3]

[1]*Department of Physics and Astronomy & QTech Center, University of Padova*
[2] *INFN Istituto Nazionale di Fisica Nucleare, Sezione di Padova, Italy*
[3]*CENOLI, Université Libre de Bruxelles, Belgium*

Ultracold atoms loaded into higher Bloch bands provide an elegant setting for realizing many-body quantum states that spontaneously break time-reversal symmetry through the formation of chiral orbital order. The applicability of this strategy remains nonetheless limited due to the finite lifetime of atoms in high-energy bands. Here we introduce an alternative framework, suitable for bosonic gases, which builds on assembling square plaquettes pierced by a π flux (half a magnetic-flux quantum). This setting is shown to be formally equivalent to an interacting bosonic gas loaded into p orbitals, and we explore the consequences of the resulting chiral orbital order, both for weak and strong on-site interactions. We demonstrate the emergence of a chiral superfluid vortex lattice, exhibiting a long-lived gapped collective mode that is characterized by local chiral currents. This chiral superfluid phase is shown to undergo a phase transition to a chiral Mott insulator for sufficiently strong interactions. Furthermore, we show that nontrivial topological properties of the degenerate energy bands in two dimensions, more specifically the BBH model case which is known to possess higher-order topology, also display non-Abelian dynamics of wavepackets that can be probed via a new form of topological Bloch oscillations.

[1] M. Di Liberto and N. Goldman, Physical Review Research 5, 023064 (2023)
[2] M. Di Liberto, N. Goldman and G. Palumbo, Nature Communications 11, 5942 (2020)

T04

Simulating trans-Planckian physics: Quantum cosmology and quantum black holes in dipolar Bose-Einstein condensates

Uwe R. Fischer

Theory of Cold Atoms, Department of Physics and Astronomy, Seoul National University, South Korea

I will discuss the scope of quantum simulations of curved spacetime aka analogue gravity in Bose-Einstein condensates with strong dipolar interactions. The latter permit the study of the impact of an effectively trans-Planckian spectrum with a deep local minimum around the analogue Planck scale, on phenomena in the Lorentz-invariant small momentum sector. These phenomena comprise the scale invariance of the early universe power spectrum, cosmological (quasi-)particle production and the related many-body entanglement, and (deviations from) the blackbody spectrum of the Hawking radiation emanating from sonic black (dumb) holes. The talk will essentially be based on Refs. [1, 2, 3], with an outlook on future research.

[1] Caio C. Holanda Ribeiro and Uwe R. Fischer: *Impact of trans-Planckian excitations on black-hole radiation in dipolar condensates*, Phys. Rev. D **107,** L121502 (2023).

[2] Zehua Tian, Seok-Yeong Chä, and Uwe R. Fischer: *Roton entanglement in quenched dipolar Bose-Einstein condensates*, Phys. Rev. A **97,** 063611 (2018).

[3] Seok-Yeong Chä and Uwe R. Fischer: *Probing the scale invariance of the inflationary power spectrum in expanding quasi-two-dimensional dipolar condensates*, Phys. Rev. Lett. **118,** 130404 (2017).

T05

$(2+1)$D gauge theory dynamics in a programmable Rydberg quantum simulator

D. González-Cuadra[1,2], **T. V. Zache**[1,2], **B. Braverman**[3], **A. Bylinskii**[3], **M. Kornjaca**[3], **F. Liu**[3], **S. Wang**[3], **M. D. Lukin** [4], **and P. Zoller**[1,2]

[1]*Institute for Theoretical Physics, University of Innsbruck, 6020 Innsbruck, Austria*
[2]*Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences, 6020 Innsbruck, Austria*
[3]*QuEra Computing Inc., 1284 Soldiers Field Road, Boston, Massachusetts 02135, USA*
[4]*Department of Physics, Harvard University, Cambridge, Massachusetts 02138, USA*

Simulating the real-time dynamics of lattice gauge theories remains a formidable computational challenge. Although quantum simulators can tackle these problems more efficiently than classical devices, recent proof-of-principle experiments have so far been restricted to 1D systems, leaving the more challenging but also richer higher-dimensional cases unexplored. In this talk, I will show how the latter can be readily addressed using programmable Rydberg arrays. In particular, I will show how a Kagome lattice of Rydberg atoms in optical tweezers gives rise to an emergent (2+1)D gauge theory, where U(1) gauge fields mediate interactions between scalar matter fields. Moreover, long-range Rydberg interactions induce here a linear confining potential between matter particles connected by string field excitations. This allows to investigate dynamical string breaking beyond the one-dimensional case, where field fluctuations arise due to effective plaquette interactions, strong compared to the string tension and to the experimental coherent times. I will show classical benchmarks for the quantum simulation protocol, based on local state preparation and quench dynamics, using tensor networks, and identify dynamical signatures that can be easily measured experimentally. These results thus demonstrate how current Rydberg experiments could be used to investigate particle physics phenomena in regimes that lie beyond the capabilities of classical computers.

T06

Cold-atom quantum simulators of gauge theories

Jad C. Halimeh[1]

[1]*(Presenting author underlined) Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany*

[2]*Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany*

Gauge theories are a fundamental framework of modern physics and the staple of the Standard Model. Their principal property, gauge symmetry, implements the laws of nature through intrinsic local relations between matter and gauge fields, with Gauss's law from electrodynamics as a paradigmatic example. In recent years, there has been a considerable drive in realizing gauge theories on quantum simulators, which are accessible tunable tabletop devices that can naturally handle entanglement buildup owing to quantum advantage. In this talk, I will first motivate this technology and then discuss recent theoretical and experimental progress in quantum simulators of 1+1D Abelian gauge theories in cold-atom platforms. I will then discuss a plethora of exotic far-from-equilibrium phenomena that one can probe on such quantum simulators. I will end by discussing experimental proposals towards advancing quantum simulators of gauge theories to higher spatial dimensions, non-Abelian gauge groups, and towards the lattice quantum field theory limit.

T07

Spin-exchange enabled quantum simulator for large-scale non-Abelian gauge theories

Jad C. Halimeh*[,1,2], Lukas Homeier*[,1,2,3,4], Annabelle Bohrdt[5,2,3,4], Fabian Grusdt[1,2]

[1]Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany
[2]Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany
[3]Department of Physics, Harvard University, Cambridge, MA 02138, USA
[4]ITAMP, Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA
[5]Institute of Theoretical Physics, University of Regensburg, D-93053, Germany

A central requirement for the faithful implementation of large-scale lattice gauge theories (LGTs) on quantum simulators is the protection of the underlying gauge symmetry. Recent advancements in the experimental realizations of large-scale LGTs have been impressive, albeit mostly restricted to Abelian gauge groups. Guided by this requirement for gauge protection, we propose an experimentally feasible approach to implement large-scale non-Abelian SU(N) and U(N) LGTs with dynamical matter in d + 1D, enabled by two-body spin-exchange interactions realizing local emergent gauge-symmetry stabilizer terms. We present two concrete proposals for 2 + 1D SU(2) and U(2) LGTs, including dynamical matter and induced plaquette terms, that can be readily implemented in current ultracold-molecule and next-generation ultracold-atom platforms. We provide numerical benchmarks showcasing experimentally accessible dynamics, and demonstrate the stability of the underlying non-Abelian gauge invariance. We develop a method to obtain the effective gauge-invariant model featuring the relevant magnetic plaquette and minimal gauge-matter coupling terms. Our approach paves the way towards near-term realizations of large-scale non-Abelian quantum link models in analog quantum simulators.

Reference: arXiv:2305.06373

Confinement in a one-dimensional $\mathbb{Z}_2$ lattice gauge theory at finite temperature

Matjaž Kebrič[1,2], Jad C. Halimeh[1,2], Ulrich Schollwöck[1,2], and Fabian Grusdt[1,2]

[1] *Department of Physics and Arnold Sommerfeld Center for Theoretical Physics (ASC), Ludwig-Maximilians-Universität München, Theresienstraße 37, D-80333 München, Germany*
[2] *Munich Center for Quantum Science and Technology (MCQST), Schellingstraße 4, D-80799 München, Germany*

In our work we consider a one-dimensional $\mathbb{Z}_2$ lattice gauge theory (LGT), where dynamical charges are coupled to a $\mathbb{Z}_2$ gauge field defined on lattice links. In addition, we consider a $\mathbb{Z}_2$ counterpart of the Gauss law, which is a set of local operators that commute with the Hamiltonian. By choosing the so called physical sector without background charges, we obtain a physical picture where the $\mathbb{Z}_2$ electric field (also defined on the lattice links) changes its sign across an occupied lattice site. As a result, we consider that two particles (partons) are connected with a $\mathbb{Z}_2$ electric string, which reflects the orientation of the electric field.

For any non-zero value of the $\mathbb{Z}_2$ electric field term, which induces dynamics in the gauge fields, partons confine into dimers (mesons), since the electric field acts as a liner confining potential [1]. Confinement is probed by considering the $\mathbb{Z}_2$ invariant Green's function, which decays exponentially in the confined regime and with a power-law in the deconfined regime. The confinement problem in the ground state was solved by mapping the system to a non-local string-length basis, where confinement is related to translational-symmetry breaking in the new basis [2]. In addition, this system exhibits rich phase diagrams at different fillings [3].

We study the finite temperature properties of this LGT by using the concept of quantum purification, where we obtain finite-temperature states by performing imaginary time evolution on an enlarged lattice, where we attach an ancilla lattice site to every physical lattice site. By comparing the Green's function at different temperatures and fillings, for zero and non-zero electric field, we uncover a smooth confinement-deconfinement crossover [4]. By considering the Friedel's oscillations, which double in the confined regime, we show that mesons are preformed already at very high temperatures, relative to the hopping energy scale.

This LGT is already within reach of the current cold-atom setups. As a result, we also sample snapshots and extract string-length distributions, which we propose as a simple measure of confinement, which can be easily obtained in an experimental setup. Finally, we also show that mesons remain confined at finite temperature, by performing quench dynamics in smaller system sizes using exact diagonalization.

[1] Umberto Borla, Ruben Verresen, Fabian Grusdt, and Sergej Moroz, "Confined phases of one-dimensional spinless fermions coupled to Z2 gauge theory," Physical Review Letters **124**, 120503 (2020).

[2] **Matjaž Kebrič**, Luca Barbiero, Christian Reinmoser, Ulrich Schollwöck, and Fabian Grusdt, "Confinement and mott transitions of dynamical charges in one-dimensional lattice gauge theories", Phys.Rev.Lett. **127**, 167203 (2021).

[3] **Matjaž Kebrič**, Umberto Borla, Ulrich Schollwöck, Sergej Moroz, Luca Barbiero, and Fabian Grusdt, "Confinement induced frustration in a one-dimensional $\mathbb{Z}_2$ lattice gauge theory", New Journal of Physics **25**, 013035 (2023).

[4] **Matjaž Kebrič**, Jad C. Halimeh, Ulrich Schollwöck, and Fabian Grusdt, "Confinement in 1+1D $\mathbb{Z}_2$ Lattice Gauge Theories at Finite Temperature", (2023), arXiv:2308.08592 [cond-mat.quant-gas].

T09

Fermionic Tensor Networks for Lattice Gauge Theory

Ariel Kelman[1] and Erez Zoher[1]

[1] *Racah Institute of Physics, Hebrew University, Jerusalem*

One of the most fruitful approaches to studying quantum field theory (QFT) has been lattice gauge theory (LGT), with Hamiltonian formulations growing in popularity as an approach to the quantum simulation of such systems. In this talk, we will present recent progress in the study of Hamiltonian LGTs using tensor networks, with matter degrees of freedom on the lattice sites, and gauge degrees of freedom on the links. We will show how one can contruct gauge invariant states, and how to use a variational Monte Carlo approach - which is not affected by the sign problem - to find the ground states of Hamiltonian LGTs. This approach can work in arbitrary spactetime dimensions, can be used to study real-time dynamics, and has been generalized to work with arbitrary gauge groups, both Abelian and non-Abelian. After developing the required formalism, we will present recent progress and numerical results demonstrating the utility of this approach, and its ability to achieve results even in sign-problem affected regimes.

[1] P. Emonts, A. Kelman, et al., Finding the ground state of a lattice gauge theory with fermionic tensor networks: A 2+1D Z2 demonstration. Phys. Rev. D **107**, 014505 (2023).

T10

Coupled spin-phonon dynamics in Rydberg tweezer arrays

Matteo Magoni[1,2,3], **Chris Nill**[3], **and Igor Lesanovsky**[3]

[1] *Institute for Theoretical Physics, University of Innsbruck, Innsbruck 6020, Austria*
[2] *Institute for Quantum Optics and Quantum Information, Innsbruck 6020, Austria*
[3] *Institut für Theoretische Physik, Universität Tübingen, 72076 Tübingen, Germany*

The technological advance in controlling ultracold atomic gases has led to recent breakthroughs in the domains of quantum simulation and quantum computation. Key for the latter application is the utilization of atomic Rydberg states, which interact strongly via dipolar electrostatic interactions. Concomitant to interactions are mechanical forces, that couple the internal atomic degrees of freedom to the external motional ones. The resulting spin-phonon coupling has been recently exploited to implement cooling protocols, to explore polaron physics and to realize artificial molecular systems.

Here we investigate the influence of coherent vibrations on the transport properties of a quantum spin chain with facilitation constraint that can be studied with Rydberg atoms. We find that coherent spin-phonon interactions dramatically change the way spin domains, which are the elementary excitations of the system, expand through the lattice. This change is due to resonant spin-phonon scattering between the propagating domain walls and the atoms' vibrational excitations, which leads to the inhibition of spin transport even in a disorder-free translationally invariant system. We also find that the phase coherence of the vibrational excitations manifests macroscopically in an asymmetric expansion of the spin domain, which is detectable in current Rydberg quantum simulators.

[1] M. Magoni, C. Nill, I. Lesanovsky, *Coherent spin-phonon scattering in facilitated Rydberg lattices*, arXiv:2311.00064 (2023).

T11

Quantum Many-Body Scars in $U(1)$ Lattice Gauge Theories Beyond Spin-$1/2$

Joao C. Pinto Barros[1], Thea Budde[1], and Marina Krstic Marinkovic[1]

[1] *Institute for Theoretical Physics, ETH Zurich, Wolfgang-Pauli-Str. 27, Zurich 8093, Switzerland*

Quantum many-body scars have garnered considerable attention in recent years for their role in challenging the Eigenstate Thermalization Hypothesis (ETH)[1]. In particular, $U(1)$ gauge theories can break our thermalization expectations following ETH. While evidence supports this behavior in 1+1 dimensions for arbitrary dimensionality of the Hilbert space of the gauge links[2] and in 2+1 dimensions when the links are spin-1/2 quantum spins[3], the exploration of higher dimensions remains relatively uncharted.

We will delve into the emergence of quantum many-body scarring in more than one spatial dimension and arbitrary dimension of the gauge links. Employing exact diagonalization for small spins, we decipher the analytical structure that enables the construction of analogous states of spins of any size[4]. This step puts us closer to understanding the possibility of observing quantum many-body scars in the continuum limit. Moreover, a deeper understanding of their emergence can reveal how many-body systems fail to thermalize. It also sets up a path for exploring gauge theories on quantum simulators, where the potential to overcome classical methods in a short timescale is high.

[1] L. D'Alessio, Y. Kafri, A. Polkovnikov, M. Rigol, Advances in Physics, **65(3)**, 239-362 (2016).

[2] J.-Y. Desaules, A. Hudomal, D. Banerjee, A. Sen, Z. Papić, J. C. Halimeh, Phys. Rev. B **107**, 205112 (2023).

[3] D. Banerjee and A. Sen, Phys. Rev. Lett. **126**, 220601 (2021)

[4] T. Budde, M. K. Marinkovic, J C. Pinto Barros, *To be published*.

T12

Density matrix renormalization group search for the gapless deconfined phase in Z_N symmetric gauge Hamiltonian

Mykhailo V. Rakov[1], **Titas Chanda**[2], **Luca Tagliacozzo**[3], **Maciej Lewenstein**[4], **and Jakub Zakrzewski**[1]

[1]*Jagiellonian University in Krakow, ulica Golebia 24, 31007 Krakow, Poland*
[2]*Indian Institute of Technology Indore, Khandwa Road, Simrol, Indore, Madhya Pradesh 452 020, India*
[3]*Instituto de Fisica Fundamental IFF-CSIC, Calle Serrano 113b, Madrid 28006, Spain*
[4]*Institut de Ciencies Fotoniques (ICFO), Av. Karl Friedrich Gauss 3, 08860 Barcelona, Spain*

The quantum systems with Z_N symmetry emerge in gauge theories of quantum chromodynamics (QCD) and also in compact quantum electrodynamics (cQED) for large N. Recently it has become possible to create these gauge Hamiltonians in the experimental setup of condensed matter physics. We consider here a particular system which can be created using the experimental protocol proposed in [1]. It is a generalized Bose-Hubbard Hamiltonian on a two-dimensional lattice. This Hamiltonian may be re-written in the second order of the perturbation theory, and it turns out to depend on N and a single coupling parameter g.
Field theory arguments suggest that, depending on N and g, the system under consideration exhibits four quantum phases. Two of them are predicted to be exotic gapless phases, namely Bose liquid phase and dipolar liquid phase. The aim of our work is rigorous numerical analysis of this suggestion. To this end, we consider our gauge Hamiltonian in an infinite-cylinder geometry on a dual lattice, and simulate its ground state by infinite-size density matrix renormalization group (iDMRG) [2].
Our calculations indicate the presence of only two gapped phases in the system for $N \leq 6$, namely, a deconfined phase and a symmetry broken confined phase which were predicted before [3] for this class of Hamiltonians. On the contrary, at $N = 7$ a gapless deconfined phase is found [4] in the area between two gapped phases. In particular, we prove power-law decay of the correlators and find sharp increase of both the entanglement entropy and the correlation length in this area. The existence of the gapless dipolar liquid phase in the U(1) symmetric limit is still to be clarified.

[1] O. Dutta, L. Tagliacozzo, M. Lewenstein, J. Zakrzewski, Phys. Rev. A **95**, 053608 (2017).
[2] I. P. McCulloch, arxiv:0804.2509 (2008).
[3] D. Horn, M. Weinstein, S. Yankielowicz, Phys. Rev. D **19**, 3715 (1979).
[4] M. V. Rakov, T. Chanda, L. Tagliacozzo, M. Lewenstein, J. Zakrzewski, manuscript in preparation.

T13

Sub-lattice quantum many body scars in a two dimensional $U(1)$ gauge theory

Paolo Stornati,[1] Indrajit Sau,[2] Debasish Banerjee,[3,4] and Arnab Sen[2]

[1] *ICFO-Institut de Ciencies Fotoniques, The Barcelona Institute of Science and Technology, Mediterranean Technology Park, Avinguda Carl Friedrich Gauss, 3, 08860 Castelldefels, Barcelona, Spain*

[2] *School of Physical Sciences, Indian Association for the Cultivation of Science, Jadavpur, Kolkata 700032, India*

[3] *Theory Division, Saha Institute of Nuclear Physics, 1/AF Bidhannagar, Kolkata 700064, India*

[4] *Homi Bhabha National Institute, Training School Complex,Anushaktinagar, Mumbai 400094, India*

(Dated: November 21, 2023)

In this talk, we explore the intriguing features of a class of anomalous high-energy states in matter-free $U(1)$ quantum link gauge theory Hamiltonians, commonly referred to as *quantum many-body scars*. Unlike conventional states, these scars exhibit athermal characteristics, making them of significant interest. The study involves the analysis of the structure and properties of these states using a combination of numerical and analytical methods.

The underlying Hamiltonian, denoted as $H = \mathcal{O}_{\rm kin} + \lambda\mathcal{O}_{\rm pot}$, is dissected, where λ represents a real-valued coupling, and $\mathcal{O}_{\rm kin}$ ($\mathcal{O}_{\rm pot}$) are summed local diagonal (off-diagonal) operators in the electric flux basis, acting on the elementary plaquette $\square$. The investigation on $L_x \times L_y$ lattices reveals the presence of *sublattice scars*, $|\psi_s\rangle$, characterized by $\mathcal{O}_{{\rm pot},\square}\,|\psi_s\rangle = |\psi_s\rangle$ on one sublattice and $\mathcal{O}_{{\rm pot},\square}\,|\psi_s\rangle = 0$ on the other. These sublattice scars are concurrently zero modes or nonzero integer-valued eigenstates of $\mathcal{O}_{\rm kin}$.

Some sublattice scars are shown to have a straightforward representation in terms of emergent short singlets, for which analytic bounds are established. Additionally, a long-ranged parent Hamiltonian is constructed, where all sublattice scars in the null space of $\mathcal{O}_{\rm kin}$ become unique ground states. The talk delves into the properties of the parent Hamiltonian's spectrum, revealing that zero energy states of this parent Hamiltonian serve as exact scars for *another* $U(1)$ quantum link model featuring a staggered short-ranged diagonal term.

T14

Alternative simulation of lattice gauge theories with tensor networks

Since the proposal of first simulation of 2D lattice gauge theories with TN [1] there have been numerous proposals on how to extend such simulations to continuous Abelian and non-Abelian groups[2]. First results have been obtained by using tree-tensor networks in other groups, here we will introduce a new framework to simulate gauge theories directly in the thermodynamic limit [3].

1. Tagliacozzo, L. & Vidal, G. Entanglement renormalization and gauge symmetry. *Phys. Rev. B* **83**, 115127 (2011).
2. Tagliacozzo, L., Celi, A. & Lewenstein, M. Tensor Networks for Lattice Gauge Theories with Continuous Groups. *Phys. Rev. X* **4**, 041024 (2014).
3. Corboz, P., Czarnik, P., Kapteijns, G. & Tagliacozzo, L. Finite Correlation Length Scaling with Infinite Projected Entangled-Pair States. *Phys. Rev. X* **8**, 031031 (2018).

T15

Many-body magic: from criticality to gauge theories

Emanuele Tirrito

Abstract: Non-stabilizerness - also colloquially referred to as magic - is a resource for advantage in quantum computing and lies in the access to non-Clifford operations. Developing a comprehensive understanding of how non-stabilizerness can be quantified and how it relates to other quantum resources is crucial for studying and characterizing the origin of quantum complexity. In this presentation, I will establish a direct link between non-stabilizerness and entanglement spectrum flatness for a pure quantum state. This connection can be exploited to efficiently investigate non-stabilizerness, even in the presence of noise. Furthermore, I will illustrate a Monte Carlo approach applied to the probability distribution of Pauli strings to estimate non-stabilizerness, which is quantified by the Stabilizer Renyi Entropies (SREs). This will provide an insightful and efficient method for characterizing and analyzing the role of non-stabilizerness in quantum many-body systems. In particular, I will show the importance of magic in (a) one-dimensional systems, where the long-range magic displays strong signatures of conformal quantum criticality (Ising, Potts, and Gaussian), overcoming the limitations of full state magic, (b) in two-dimensional Z2 lattice gauge theories, where I will show the evidence that magic is able to identify the confinement-deconfinement transition, and displays critical scaling behavior even at relatively modest volumes.