High Energy Physics
Quantum Information Science Awards Abstracts
Cosmos and Qubits

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Probing information scrambling via quantum teleportation
Norman Y. Yao, Lawrence Berkeley National Laboratory/University of California-Berkeley

Interplay of Quantum Information, Thermodynamics, and Gravity in the Early Universe

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The early Universe is a rich testbed of quantum gravity and out-of-equilibrium quantum physics in general. The goal of this proposal is to explore fundamental questions in both domains: quantum origins of the early Universe and strongly-interacting quantum matter.

Under the first direction we will develop a fully quantum mechanical framework for the early Universe using an open system approach. In particular, we will focus on the non-Markovian vs. Markovian evolution of system modes, quantum correlations, and signatures in late-time observables. Further, we will use tools from quantum resource theory and thermodynamics to explore why it appears to be imperative to postulate a low entropy initial state of the Universe.

Under the second direction we will investigate open quantum system dynamics in strongly-coupled qubit and oscillator systems. We will specifically focus on detailed studies of non-Markovian evolution, entanglement dynamics, and quantum backaction evasion in these systems, including experimental realizations and implications for gravity. Further, we will establish thermodynamics for chaotic quantum systems, with emphasis on the dynamics of information scrambling, and implications for black hole solutions in AdS/CFT and quantum gravity.

The Geometry and Flow of Quantum Information: From Quantum Gravity to Quantum Technology

Raphael Bousso, UC Berkeley (Principal Investigator)

Ehud Altman, UC Berkeley; Ning Bao, UC Berkeley; Patrick Hayden, Stanford; Christopher Monroe, U. Maryland; Yasunori Nomura, UC Berkeley; Xiao-Liang Qi, Stanford; Monika Schleier-Smith, Stanford; Irfan Siddiqi, LBNL; Brian Swingle, U. Maryland; Norman Yao, UC Berkeley; Michael Zaletel, UC Berkeley (Co-Investigators)

Research in quantum gravity has been accelerating thanks to powerful tools and insights from quantum information theory. At the same time, developments in quantum gravity are feeding back into quantum information science, leading to a rich interplay between these two fields. This collaboration aims to identify and develop nascent connections in key areas, including the black hole information problem and quantum information scrambling; the emergence of spacetime from entanglement via quantum error correcting codes; low energy applications and information theoretic interpretations of energy conditions originally derived in a quantum-gravitational context; and the dynamics of wormholes and its relation to quantum teleportation.

A key feature of our collaboration is a focus on near term quantum devices: what are the quantum technologies that might arise from quantum gravity? Which puzzles about quantum gravity might be addressed with such quantum devices? A central organizing principle is the use of tensor networks, which were originally developed for understanding the structure of low-energy quantum states in nonrelativistic many-body systems. Quantum gravity research has shown that tensor networks can be used to model the emergence of spacetime geometry from an underlying quantum theory. At the same time, the appropriation of tensor networks for the study of quantum gravity and black holes has inspired novel applications elsewhere. Tensor networks can be calculational tools, useful not only for describing ground states, but also for elucidating the dynamics of quantum information in strongly coupled systems.

As such, our collaborations is comprised of several distinct components. First, we have three distinct quantum device platforms, each with its unique advantages in probing quantum physics as inspired by holography and quantum gravity. Second, we have a team of high energy and quantum information theorists that are well-versed in (and in some cases, discovered) the emerging connections between quantum information and quantum gravity. Finally, we also have several experts in condensed matter/AMO physics to help translate these questions into a form that can be implemented by the experimental component of the collaboration. Examples of specific current projects include the study of scrambling, probing quantum energy conditions, studying the dynamics of quantum chaos, and benchmarking quantum error correcting codes inspired by holography.

Algebraic approach towards quantum information in quantum field theory and holography

PI: Daniel Harlow

Co-PIs: Aram Harrow and Hong Liu

This is a proposal for a two-year research grant from the DOE Office of Science to study connections between algebraic quantum field theory, holographic quantum codes, and approximate Markov states. These subjects have all been of much recent interest: the algebraic approach to quantum field theory has recently been used to prove remarkable general results such as the quantum null energy condition, and holographic quantum codes have given us a new perspective on classic problems in quantum gravity. In both cases the technical tools which lead to the new results can be understood as using the special properties of ``quantum Markov states''; states which saturate strong subadditivity. These states are also very interesting in quantum computing, with applications to quantum error-correction, efficient preparation of Gibbs states on quantum computers, efficient compression with side information, and many other areas.

Our proposal is to do a combined study of these three issues, seeking to systematically understand the connections between them. We are optimistic that this will lead to many new insights about quantum field theory, quantum gravity, and quantum information.

Entanglement in string theory and the emergence of geometry

Veronika Hubeny, QMAP, UC Davis, (Principal Investigator)
Mukund Rangamani, QMAP, UC Davis, (Co-Investigator)

The proposed project seeks to elucidate the fundamental nature of spacetime by utilizing recently-gained insights from the AdS/CFT correspondence – a ‘holographic’ duality which relates a gravitational theory in asymptotically Anti-de Sitter (AdS) spacetime to a lower-dimensional conformal field theory (CFT), effectively living on the boundary of AdS. Since the CFT is a quantum field theory without gravity, in this context the primary aim translates to one of understanding how the bulk spacetime geometry actually emerges from the boundary CFT.

Remarkably, progress over the past few years hints at profound relations to entanglement, a quintessentially quantum quantity. The key elements facilitating this connection are the Ryu- Takayanagi (RT), and its covariant generalization, the Hubeny-Rangamani-Takayanagi (HRT) prescription, for computing entanglement entropy for spatially organized degrees of freedom in the field theory in terms of areas of extremal surfaces in the bulk geometry. These prescriptions in fact capture the leading semi-classical answer for the entanglement entropy for a spatial region in a strongly coupled CFT. It is also known that the next sub-leading correction involves the entanglement between the gravitational degrees of freedom in the bulk geometry. These ideas have led to the important conceptual paradigm that entanglement is the underlying glue that binds together the geometric structure of the spacetime, codified in the “ER=EPR” paradigm.

To understand how entanglement is responsible for building geometry from scratch, one needs to elucidate the holographic map at a deeper level. For one, the current discussion is rooted in the strong coupling regime of the field theory, where the bulk dual is a classical gravitational field theory. Given that the full extent of the AdS/CFT duality maps the CFT Hilbert space onto the Hilbert space of the quantum string theory in the asymptotically AdS spacetime, one should be able to understand how to extend the RT-HRT prescriptions to be valid at the full quantum level (and for any value of the coupling). This is the overarching goal of the current program.

Hubeny & Rangamani aim to undertake a research program which primarily transcends current investigations in the subject, and provides a platform for formulating the correspondence between entanglement and geometry directly at the level of the full string theory Hilbert space. Some of the directions the Investigators propose to explore are to understand how entanglement structures get repackaged across dualities (be they field theory dualities or more general open-closed string dualities), and to develop tools inspired by operator algebras to understand the emergence of locality in string theory. These investigations will draw from developments in general relativity, quantum field theory, string theory, and quantum information and will provide a concrete framework to further the connections between entanglement and geometry.

PURDUE
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Quantum Information in a strongly interacting quantum simulator: from gauge/string theory duality to analogue black holes

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Dep. of Energy Quantum Information Science (QIS) Kick Off Principal Investigators’ Meeting, Jan 31-Feb 1, 2019, Bethesda, MD.

The AdS/CFT correspondence implies that, in the strongly interacting regime where quantum effects are large, systems encode and transmit information in a very different way than they do at weak coupling. In particular, from the quantum mechanics of a field theory emerges a higher dimensional space time with non-trivial metric and gravity. Important as they are for the theory of quantum information, wider applicability of these ideas to Quantum Information Science (QIS) requires controllable experimental systems where similar ideas apply. Inspired by this far reaching ideas, we consider an experimental setup where an atomic quantum gas in an optical lattice is driven into a strongly coupled quantum critical regime. The system can be described by the Bose-Hubbard model and the critical region of interest by the O(2) three dimensional Wilson-Fisher fixed point. Theoretically this system is studied with a combination of techniques valid in various regimes, including, mean-field theory, 4-e expansion, conformal bootstrap, numerical simulations and qualitative ideas from AdS/CFT. Experimentally a 2D quantum gas is formed by evaporative-cooled cesium atoms trapped in an oblate optical potential to ensure a large surface area (> 400μm) occupying > 50x50 lattice sites.

The main objective is to create and study the time evolution of entanglement between separated regions of space. As a result, we will get a new understanding into the encoding and transmission of quantum information in this and possible other strongly interacting systems.

Entanglement will be measured using Renyi entropy following recent ideas in the literature. Our immediate goals are to (1) use existing and newly developed theoretical tools to study the creation and evolution of entanglement in strongly coupled systems, and design experimental tests that can be carried out in the systems to which we already have experimental access, (2) develop new experimental techniques for synthesizing highly controllable strongly coupled quantum gases, and (3) perform the experimental tests and compare the results with the theory.

Further goals include the manipulation of the local sound speed to create far from equilibrium states such as shock-waves and sonic black holes that should create large amounts of entanglement and lead to new quantum phenomena in strongly coupled systems.

Entanglement in Gravity and Quantum Field Theory

The Board of Trustees of the University of Illinois
Robert G. Leigh, Ph.D., University of Illinois (Principal Investigator)
Thomas Faulkner, Ph.D., University of Illinois (Co-Investigator)

It is becoming increasingly clear that ideas from quantum information theory, particularly the notion of quantum entanglement, play a fundamental role in some of the deepest aspects of our modern theories of quantum fields and gravity. The aim of this research is to explore the role that quantum entanglement plays in quantum field theories and in the nature of space-time and gravity. Building on a variety of new results obtained in these regards at the University of Illinois, we plan to explore the constraints on the dynamical content of quantum field theories that follow from their entanglement properties. Topological field theories are important examples of particularly simple quantum field theories whose patterns of entanglement make connections between high energy physics, condensed matter physics and mathematics. These theories are directly relevant to low energy properties of certain materials. The study of such theories will allow us to investigate ideas that are relevant to quantum information research, such as new notions of entanglement between multiple parties and the quantum properties of interfaces between different phases of such materials.

In addition, we will employ new results in mathematics which strengthen monotonicity constraints on relative entropy to study their ramifications in quantum field theories, and we will use quantum information methods to study the emergence of quantum gravity and string theory in holographic quantum field theories. The project investigators are in an ideal position to make important contributions to these exciting areas, contributing both to the evolution of the application of quantum information concepts in high energy physics and to the further development of general quantum informational ideas.

Quantum error correction and spactime geometry

John Preskill (Caltech), Patrick Hayden (Stanford)

Quantum error correction and the holographic principle are two of the most far-reaching ideas in contemporary physics. Quantum error correction is the basis of our belief that scalable quantum computers can be built and operated in the foreseeable future. The AdS/CFT holographic correspondence is currently our best tool for understanding nonperturbative quantum gravity. Remarkably, recent advances indicate that these two deep ideas are closely related. Specifically, AdS/CFT posits a dictionary in which the observables of a bulk spacetime are mapped to the observables of a quantum field theory living at the boundary of the spacetime, and this dictionary can be interpreted as the encoding map of a quantum error-correcting code.

In this project we are developing this connection further, in multiple directions, by advancing the theory of quantum error correction and by clarifying how this theory can be used to build more general and powerful approaches for probing spacetime physics. In particular, we will extend the formalism of operator algebra quantum error correction with the goal of clarifying how emergent gauge symmetry arises in the bulk spacetime, and develop the theory of approximate error correction with the goal of quantifying the robustness of bulk quantum geometry with respect to errors in the boundary theory. We anticipate that our work will illuminate how quantum information is encoded and processed by black holes, and the role of quantum entanglement in the very early history of the universe.

Currently we are studying the properties of approximate quantum error-correcting codes that admit continuous symmetries. In particular, we have derived bounds on the fidelity that can be achieved by a recovery map for a code which admits continuous time evolution. The fidelity becomes perfect in two interesting limits --- when the length (number of physical subsystems) of the code diverges with the local subsystem dimension fixed, and when the local dimension diverges with the length fixed. Both limits are relevant for investigations of the AdS/CFT dictionary which we are continuing to pursue.

In addition, we have applied the recently developed theory of universal subspace quantum error correction to the reconstruction of black hole microstates in AdS/CFT duality. This work explains how the approximate error-correcting code underlying the bulk-to-boundary dictionary becomes exact in the semiclassical limit.

Holographic Quantum Simulation with Atomic Spins and Photons

Gregory Bentsen, Emily Davis, Avikar Periwal, Eric Cooper, Patrick Hayden (co-PI), Monika Schleier-Smith (PI), SLAC/Stanford

The theories of quantum mechanics and gravity were developed to describe such opposite extremes of the physical world that the connections between them were long deemed out of reach of experiments. Advances in engineering controllable quantum systems, coupled with profound theoretical developments, offer the new opportunity of probing concepts of quantum gravity in the laboratory. The unifying theoretical framework is the holographic principle, under which spacetime geometry emerges from quantum entanglement. An extreme limit of this duality are strongly interacting quantum systems that can equivalently be viewed as black holes, yielding a simple gravitational description. A characteristic feature of black-hole duals is that they rapidly scramble quantum information—at a rate conjectured to be the fastest possible in nature.

A requirement for fast scrambling is a non-local graph of interactions in the quantum system, epitomized by the paradigmatic Sachdev-Ye-Kitaev model featuring non-local hopping of fermions. We engineer a related class of bosonic models in a quantum simulator composed of laser-cooled atoms. By using light to induce spin-exchange interactions among atoms trapped in an optical resonator, we simulate long-range hopping of interacting bosons (spin excitations). A key goal is to image how the influence of a localized perturbation spreads on a variety of coupling graphs. Toward this end, a valuable tool is the ability to effectively reverse the flow of time by switching the sign of interactions, a capability realized in our experiment. We furthermore present progress in controlling the structure of non-local interactions to build toy models of holographic duality conducive to fast scrambling. Such models will offer a starting point for exploring how measurements performed on a quantum system can reveal the holographic geometry.

Quantum Communication Channels for Fundamental Physics (QCCFP)

PUBLIC ABSTRACT

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Quantum channels are fundamental to Quantum Information Science since they allow the communication of quantum information without the loss of quantum coherence. The most familiar example of a quantum channel is the “Alice-Bob” quantum teleportation, which exploits the fact that Alice and Bob share a pair of entangled states, known as an Einstein Podolosky Rosen (EPR) pair. In the consortium research program we propose, we explore deep connections between entanglement distribution protocols and the nature of gravity both theoretically and experimentally. The theoretical activity will be assisted by quantum simulators realized on near-term gate-programmable quantum computers. We will also define how such quantum channels and protocols can be realized using photonic qubits and fiber-based quantum networks and prototype the technology enhancements required to realize these protocols. This experimental activity will take advantage of the FQNET quantum network that was build in 2017-2018 and commissioned in the fall of 2018 at Fermilab.

Quantum simulation: From spin models to gauge-gravity correspondence

Vladan Vuletic (MIT) and Mikhail Lukin (Harvard University)

Quantum many-body systems with coherent and controllable interactions will enable the realization of novel quantum materials, the quantum simulation of problems that cannot be simulated on classical computers, computational systems that are exponentially faster than existing classical algorithms, and the direct investigation of the conjectured duality between gravitational theories and quantum field theories. This pilot project will focus on the gauge-gravity correspondence, and use a controllable quantum many-body system close to a critical point to experimentally test the gauge-gravity duality and related concepts. The dynamics of a large quantum system containing more than 50 qubits will be investigated in various critical regimes, bounds on the maximum speed of quantum scrambling will be determined that are relevant to the scrambling of information by black holes, and the relation between scrambling, quantum scars, and gravitational theories will be investigated.

This work at the interface of high-energy physics, gravity, and quantum many-body physics is performed in collaboration between the groups of Mikhail Lukin at Harvard, and the group of Vladan Vuletic at MIT. The experimental part of the work will be performed on an existing apparatus that can deterministically prepare reconfigurable arrays of individually trapped and detected cold atoms. The atoms are coupled to each other via strong, coherent interactions induced by excitation to atomic Rydberg states. In this system, the collaboration has recently realized a programmable Ising-type quantum spin model with tunable interactions for a system size of up to 51 qubits. The setup features fast control compared to the sub-microsecond characteristic evolution time of the system, so that controlled quench can be performed, and the subsequent dynamical evolution observed with single-qubit resolution.

In particular, the team will attempt to create highly entangled states that are superpositions of maximally separated areas in phase space, and explore the measurement of out-of-order time correlation functions that are relevant, e.g., to the question how and how fast information becomes dissipated when ordered systems disappear into a black hole (quantum scrambling). Entanglement in a variety of quantum phase transitions will be probed, and ideas originating from the gauge-gravity duality will be explored in this system.

Recently we have used the quantum simulator system to study the quantum critical dynamics of several quantum phase transitions. By studying the growth of spatial correlations while crossing the Ising-type quantum phase transition, we experimentally verify the quantum Kibble-Zurek mechanism, explore scaling universality, and observe corrections beyond the Kibble-Zurek predictions. This approach is subsequently used to measure the critical exponents associated with chiral clock models, providing new insights into exotic systems that have not been understood previously, and opening the door for precision studies of critical phenomena, simulations of lattice gauge theories, and applications to quantum optimization.

HEP Pilot: Probing information scrambling via quantum teleportation

PI: Norman Y. Yao (LBNL & UC Berkeley)

The black-hole information paradox represents one of the central open questions at the interface of modern high energy physics and quantum information science. While general relativity predicts that the information is lost forever, the evolution according to quantum mechanics is unitary, hence reversible, suggesting that there may in principle be a way to recover the information. The classic thought experiments for the black hole information paradox is the following: suppose that Alice throws a secret quantum state into a black hole -- is it then possible for an outside observer, Bob, to reconstruct it by collecting the Hawking radiation emitted at a later time. Over two decades ago, seminal work by Page demonstrated that if the dynamics of the black hole could be approximated as a random unitary, then Bob would need to wait at least half the lifetime of the black hole. Recently, Hayden and Preskill added an interesting twist to this classic setup by considering a black hole, which is entangled with a quantum memory that Bob possesses. There, it was shown that the decoding of Alice's quantum state could be performed with an exponential speedup.

However, there is a subtlety in this argument. While it was shown that such a decoding is information-theoretically possible (i.e. that there exists a unitary operator which reconstructs the state by acting only on the Hawking radiation and quantum memory), it remains unclear if such a unitary is actually physically implementable and what form the quantum circuit might take.

In this pilot, we propose to explore a novel probabilistic decoding protocol (building upon recent work by Yoshida and Kitaev) for reconstructing a quantum state from the Hawking radiation in the Hayden-Preskill black hole thought experiment. The protocol attempts to teleports a quantum state thrown into a black hole to an outside observer by projecting pairs of outgoing Hawking radiation from two sides of an entangled black hole into EPR pairs. The chaotic dynamics of the black-hole is simulated by performing unitary operations to implement an effective "scrambling" operation.

One of the main focal points of the pilot is to explore whether such a protocol can effectively distinguish between chaotic scrambling dynamics and decoherence. This represents a particularly challenging question for typical correlation-function-based measurements (e.g. out-of-time-order correlators). To this end, we will investigate the behavior of the decoding protocol in the presence of multiple different forms of "noise", including both extrinsic depolarization/dephasing and intrinsic imperfections in quantum control. Moreover, we will attempt to bound the amount of scrambling in a many-body quantum circuit by using the teleportation fidelity associated with the protocol. In particular, by extracting a "noise" parameter from our protocol, we will quantify the non-scrambling induced decay of out-of-time-order correlators. Our results open the door to experimentally measuring quantum scrambling with built-in verifiability.