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## Optimal Measurements for Scalable Quantum Technologies

Dirk Englund  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

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09/03/2020  
Final Report

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# **Optimal Measurements for Scalable Quantum Technologies**

## **Final Report**

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**AFOSR Grant No:** FA9550-14-1-0052

**Title:** Optimal Measurements for Scalable Quantum Technologies

**Principal Investigator:** Dirk Englund

**Lead Institution:** Massachusetts Institute of Technology (MIT)

**AFOSR Program Manager:**

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The rules of quantum mechanics enable technologies that are inherently more powerful than their classical counterparts, including unconditionally secure communication, quantum computing, and quantum-enhanced precision sensing. A central challenge standing in the way of scalable quantum technologies is the need for fundamentally improved quantum measurement and state verification (QMSV) techniques. The objective of this program of experimental and theoretical research was to establish unified optimal QMSV protocols for leading quantum information processing (QIP) architectures, and to use them to overcome roadblocks standing in the way of scaling to higher performance systems. Our team succeeded on these goals across the various qubit platforms, making major strides towards creating, controlling, and measuring many-body quantum systems.

The experimental component of this program focused on leading room-temperature semiconductor and photonic quantum technologies, which already supersede classical technologies in certain applications such as nanoscale sensing and secure optical communications. Recent advances in QMSV, such as compressive sensing or ancilla-assisted tomography, have been shown to offer dramatic improvements in QIP applications, but studies can be complicated by the complex mesoscopic environment in semiconductors (especially in ambient conditions) or the short coherence time and weak interaction of photons. This MURI program therefore also investigated some of the most mature QIP architectures: trapped ions and superconducting circuits. These provide excellent test-beds to investigate QMSV protocols in large multi-qubit atomic systems and to many-photon systems with high nonlinearities. The study of multiple modalities furthermore motivates the development of unified QMSV protocols to connect diverse physical systems, e.g., in quantum networks. The quantum estimation protocols aimed to enable scalable characterization of quantum devices using experimentally available physical resources and novel computational algorithms, such as randomized local quantum sampling, compressive sensing, and adaptive Bayesian inference.

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MIT, Cambridge, MA, March 20, 2015

Dr. James Lawton (AFOSR), Dr. Tristan Nguyen (AFOSR), Dr. Tatjana Curcic (AFOSR)

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<sup>1</sup>Massachusetts Institute of Technology; <sup>2</sup>Yale University; <sup>3</sup>Harvard University; <sup>4</sup>Joint Quantum Institute, University of Maryland

### **Financial Execution:**

*3-Year Based Period:* FY2012, \$831,880 (3 months); FY2013, \$2,439,507 (12 months); FY2014, \$2,441,586 (12 months); FY2015, \$1,614,908 (9 months). Base total: \$7,327,880.

*2-Year Option Period:* FY2016, \$820,099 (4 months); FY2017, \$2,451,246 (12 months); FY2018, \$1,631,205 (8 months). Option total: \$4,902,550.

As of the end of the award, the full obligated amount of both the base and option periods (\$12,230,430) have been expended.

## **MURI Team Achievements To-Date**

|                                                            |   |
|------------------------------------------------------------|---|
| Most Recent Government Review and Government Participants: | 1 |
| MURI Consortium Research Team Members                      | 2 |
| Financial Execution:                                       | 2 |

## **MURI Team Achievements To-Date**

### **I. Progress on Compressive Quantum Measurements, Optimal Tomography of Continuous-Variable Bosonic States, and Error-Corrected Quantum States**

#### **II.A Update on Development of Scalable Cluster State Generation and Quantum Computational Primitives**

#### **II.B Quantum Machine Learning (theory)**

|                                         |   |
|-----------------------------------------|---|
| Quantum generative adversarial learning | 7 |
|-----------------------------------------|---|

### **III. Theory of Quantum Tomography of Many-Qubit Systems**

#### **IV.A. Universal Programmable Linear Optics**

#### **IV.B. Chip Integration of Nonclassical Light Sources**

#### **IV.C. Logic Gates between photonic qubits**

#### **IV.D. Superconducting Nanowire Single-Photon Detectors (SNSPD) & Logic**

#### **IV.E Machine Learning On Photonic Circuits**

|                                      |    |
|--------------------------------------|----|
| Very Large-Scale Neural Networks     | 16 |
| Quantum Neural Networks              | 16 |
| Variational Quantum Unsampling (VQU) | 16 |

### **V. Classical-Quantum Optical Networks & Quantum Illumination**

|                                         |    |
|-----------------------------------------|----|
| V.A Floodlight Quantum Key Distribution | 17 |
|-----------------------------------------|----|

|                                        |    |
|----------------------------------------|----|
| Plans for the Remainder of the Program | 18 |
|----------------------------------------|----|

#### **V.B Gaussian phase-matching in PPKTP**

|                                 |    |
|---------------------------------|----|
| Plans for Remainder of Program: | 20 |
|---------------------------------|----|

#### **V.C Floodlight QKD**

|                                 |    |
|---------------------------------|----|
| Plans for Remainder of Program: | 21 |
|---------------------------------|----|

### **VI. Photons with Controlled Interactions: Chi-2 Nonlinear Optical Interactions**

|                                                                                          |    |
|------------------------------------------------------------------------------------------|----|
| Photon-mediated interactions between long-lived quantum memories in a diamond nanocavity | 28 |
|------------------------------------------------------------------------------------------|----|

|                                                                               |    |
|-------------------------------------------------------------------------------|----|
| Spectral alignment of single-photon emitters in diamond using strain gradient | 29 |
|-------------------------------------------------------------------------------|----|

|                                                                              |           |
|------------------------------------------------------------------------------|-----------|
| Phonon networks with SiV centers in diamond waveguides                       | 29        |
| Statistical Analysis of Nitrogen Vacancy Production                          | 30        |
| Strain engineering of the silicon-vacancy center in diamond                  | 32        |
| Controlling the coherence of a diamond spin qubit through strain engineering | 33        |
| Fiber-Coupled Diamond Quantum Nanophotonic Interface                         | 34        |
| <b>Related Theory, Materials, and Methods</b>                                | <b>36</b> |
| <b>Transitional Planning:</b>                                                | <b>36</b> |
| Educational Impact and Outreach                                              | 37        |
| Team Activities                                                              | 38        |
| <b>Individual Awards</b>                                                     | <b>38</b> |
| <b>Publications and Pre-Prints</b>                                           | <b>39</b> |

**Program Objective:** The rules of quantum mechanics enable technologies that are inherently more powerful than their classical counterparts, including unconditionally secure communication, quantum computing, and quantum-enhanced precision sensing. A central challenge standing in the way of scalable quantum technologies is the need for fundamentally improved quantum measurement and state verification (QMSV) techniques. The objective of this program of experimental and theoretical research is to establish unified optimal QMSV protocols for leading quantum information processing (QIP) architectures, and to use them to overcome roadblocks standing in the way of scaling to higher performance systems.

**Scientific Approach:** The experimental component of this program focuses on leading room-temperature semiconductor and photonic quantum technologies, which already supersede classical technologies in certain applications such as nanoscale sensing and secure optical communications. Recent advances in QMSV, such as compressive sensing or ancilla-assisted tomography, have been shown to offer dramatic improvements in QIP applications, but studies can be complicated by the complex mesoscopic environment in semiconductors (especially in ambient conditions) or the short coherence time and weak interaction of photons. This MURI program therefore also investigates some of the most mature QIP architectures: trapped ions and superconducting circuits. These provide excellent test-beds to investigate QMSV protocols in large multi-qubit atomic systems and to many-photon systems with high nonlinearities. The study of multiple modalities furthermore motivates the development of unified QMSV protocols to connect diverse physical systems, e.g., in quantum networks. The quantum estimation protocols are targeted to enable scalable characterization of quantum devices using experimentally available physical resources and novel computational algorithms, such as randomized local quantum sampling, compressive sensing, and adaptive Bayesian inference.

### **Achievements:**

This MURI program has led to numerous major advances, including over 200 publications (including >50 in high-profile journals such as Nature, Science, and Physical Review Letters) and several patent applications. The following sections summarize major advances, as organized by research themes.

## **I. Progress on Compressive Quantum Measurements, Optimal Tomography of Continuous-Variable Bosonic States, and Error-Corrected Quantum States**

One motivation for compressive measurements is in the area of quantum simulation, to explore physical and chemical systems in condensed phases where effective many-body interactions are known to be almost sparse; in particular, for Hamiltonian fine estimation and characterization of system-bath interactions for open quantum systems. The verification of the internal and external Hamiltonians are a necessary step towards efficient simulations of many-body physics on a quantum computer or on other controllable quantum systems. Hamiltonian estimation is of particular significance for estimating selective properties of biological or chemical interest in molecular systems and nanostructures with typically sparse Hamiltonians by incorporating knowledge of model structure properties. A major focus of this MURI is to apply compressive sensing to efficient quantum state/process verification estimation of photonics integrated circuits,

semiconductor NV centers, superconducting circuits, and trapped ions. This section reviews recent theoretical progress on compressive sensing techniques.

*Lead: Liang Jiang, Yale University.*

### Performance and structure of single-mode bosonic codes

The Yale team (in collaboration with Barbara Terhal) systematically compared the performance of various single-mode continuous variable quantum error correcting codes. We provided such a comparison by determining the entanglement fidelity of all codes with respect to the bosonic pure-loss channel (i.e., photon loss) after the optimal recovery operation. We then compared achievable communication rates of the combined encoding-error-recovery channel by calculating the channel's hashing bound for each code. Cat and binomial codes perform similarly, with binomial codes outperforming cat codes at small loss rates. Despite not being designed to protect against the pure-loss channel, GKP codes significantly outperform all other codes for most values of the loss rate. We show that the performance of GKP and some binomial codes increases monotonically with increasing average photon number of the codes. In order to corroborate our numerical evidence of the cat-binomial-GKP order of performance occurring at small loss rates, we analytically evaluated the quantum error-correction conditions of those codes. For GKP codes, we found an essential singularity in the entanglement fidelity in the limit of vanishing loss rate[1].

### Achieving the Heisenberg limit in quantum metrology using quantum error correction

The Yale team (in collaboration with John Preskill) investigated quantum metrology assisted by quantum error correction. Quantum metrology has many important applications in science and technology, ranging from frequency spectroscopy to gravitational wave detection. Quantum mechanics imposes a fundamental limit on measurement precision, called the Heisenberg limit, which can be achieved for noiseless quantum systems, but is not achievable in general for systems subject to noise. As illustrated in Fig. 1, we studied how measurement precision can be enhanced through quantum error correction, a general method for protecting a quantum system from the damaging effects of noise. We found a necessary and sufficient condition for achieving the Heisenberg limit using quantum probes subject to Markovian noise, assuming that noiseless ancilla systems are available, and that fast, accurate quantum processing can be performed. When the sufficient condition is satisfied, a quantum error-correcting code can be constructed that suppresses the noise without obscuring the signal; the optimal code, achieving the best possible precision, can be found by solving a semidefinite program[2].

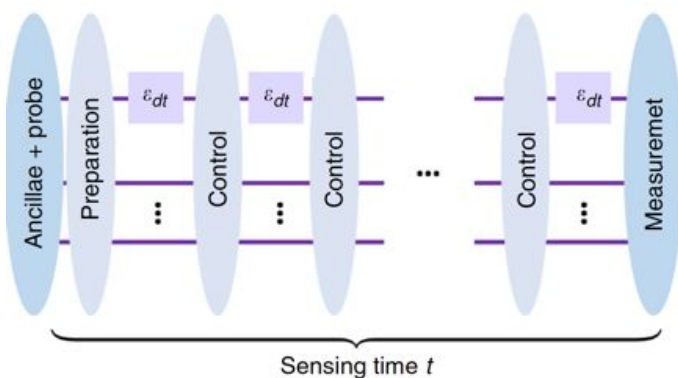


**Figure 1. The sequential metrology scheme: One probe sequentially senses the parameter for time  $t$ , with quantum controls applied every  $dt$ .**

## **Deep Neural Network Probabilistic Decoder for Stabilizer Codes**

Yale team investigated using deep neural network decoder for quantum stabilizer codes. Neural networks can efficiently encode the probability distribution of errors in an error correcting code. Moreover, these distributions can be conditioned on the syndromes of the corresponding errors. This paves a path forward for a decoder that employs a neural network to calculate the conditional distribution, then sample from the distribution - the sample will be the predicted error for the given syndrome. We present an implementation of such an algorithm that can be applied to any stabilizer code. Testing it on the toric code, it has a higher threshold than a number of known decoders thanks to naturally finding the most probable error and accounting for correlations between errors[3].

## **II.A Update on Development of Scalable Cluster State Generation and Quantum Computational Primitives**

The groups of PIs Lloyd and Englund developed protocols for demonstrating Anderson localization and the interplay between coherence, decoherence, and static noise on a programmable optical quantum information processor[4].

The Englund and Yale groups are developing a new loss-tolerant linear optic approach for creating error-corrected qubits encoded in the quantum parity code. This code is shown to be useful for a new resource-efficient one-way all-optical quantum repeater protocol. Most conventional quantum repeaters are based on probabilistic Bell measurement and entanglement swapping at the repeater nodes. This process requires two-way communication between repeater stations. The quantum parity code can provide protection against loss with only one-way communication and greatly increase the success probability of Bell measurements using linear optics components. Using these properties, the improved repeater scheme can surpass the limit of repeaterless communication[5] using relatively small (few photonic qubits) codes. We found that these improvements reduce the resources required to beat the repeaterless bound by a factor of 10 to around  $10^5$  photon sources/repeater station, depending on the device performance assumptions. A manuscript has been in progress, somewhat delayed by the graduation of two of our students, but should be done soon.

## **II.B Quantum Machine Learning (theory)**

The Lloyd group at MIT has introduced several new Quantum Machine Learning algorithms, and is currently working on the experimental demonstration of some of these algorithms. They recently published a review paper which presents an overview of the progress in this field [*Nature* 549, no. 7671, (2017)].

## Quantum generative adversarial learning

Generative adversarial networks (GANs) represent a powerful tool for classical machine learning: a generator tries to create statistics for data that mimics those of a true data set, while a discriminator tries to discriminate between the true and fake data. The learning process for generator and discriminator can be thought of as an adversarial game, and under reasonable assumptions, the game converges to the point where the generator generates the same statistics as the true data and the discriminator is unable to discriminate between the true and the generated data. Prof Lloyd and Dr. Christian Weedbrook introduced the notion of quantum generative adversarial networks (QuGANs), where the data consists either of quantum states, or of classical data, and the generator and discriminator are equipped with quantum information processors. They showed that the unique fixed point of the quantum adversarial game also occurs when the generator produces the same statistics as the data. Since quantum systems are intrinsically probabilistic the proof of the quantum case is different from – and simpler than – the classical case. They also show that when the data consists of samples of measurements made on high-dimensional spaces, quantum adversarial networks may exhibit an exponential advantage over classical adversarial networks. See publication for detail[6].

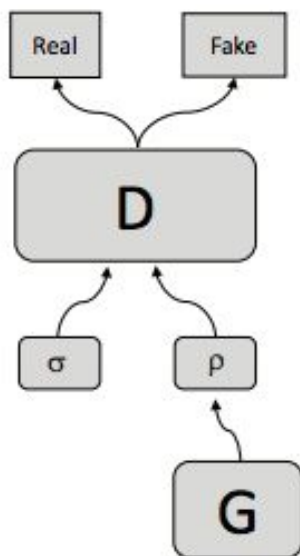


Figure 2: Schematic of a general quantum generative adversarial network (QuGAN) protocol. The ultimate goal of this adversarial game is for the discriminator (D) to determine whether the input data is real ( $\sigma$ ) or fake ( $\rho$ ). Here G is the generator which generates fake data hoping to fool the discriminator. We consider a variety of QuGAN situations. Firstly, where the real data is quantum, the generator is quantum (and hence generates fake quantum data), and the discriminator is quantum. Secondly, the real data is quantum, the generator is classical and the discriminator is either classical or quantum. Finally, we consider the case where the real data is purely classical and the generator and discriminator are both quantum.

## A Quantum Hopfield Neural Network

Quantum computing allows for the potential of significant advancements in both the speed and the capacity of widely-used machine learning techniques. The Lloyd group employed quantum algorithms for the Hopfield network, which can be used for pattern recognition, reconstruction, and optimization as a realization of a content addressable memory system. They showed that an exponentially large network can be stored in a polynomial number of quantum bits by encoding the network into the amplitudes of quantum states. By introducing a new classical technique for operating the Hopfield network, they leveraged quantum algorithms to obtain a quantum

computational complexity that is logarithmic in the dimension of the data. This potentially yields an exponential speed-up in comparison to classical approaches. They also present an application of our method as a genetic sequence recognizer. For details, see the publication[7].

### **A Quantum Recurrent Neural Network**

Lloyd group has developed new quantum algorithms for a recurrent neural network, namely the Hopfield network, which can be used for pattern recognition, reconstruction, and optimization as a realization of a content addressable memory system[7]. It turns out that an exponentially large network can be stored in a polynomial number of quantum bits by encoding the network into the amplitudes of quantum states. By introducing a new classical technique for operating such a network, they can leverage quantum techniques to obtain a quantum computational complexity that is logarithmic in the dimension of the data. This potentially yields an exponential speed-up in comparison to classical approaches. They present an application of the method as a genetic sequence recognizer.

### **An efficient quantum algorithm for spectral estimation**

Beside these algorithms on Quantum Machine Learning, Lloyd group also developed an efficient quantum implementation of an important signal processing algorithm for line spectral estimation: the matrix pencil method, which determines the frequencies and damping factors of signals consisting of finite sums of exponentially damped sinusoids [NJP 19, 033005 (2017)]. The algorithm provides a quantum speedup in a natural regime where the sampling rate is much higher than the number of sinusoid components. Some of the techniques developed in this project are expected to be useful for other quantum algorithms as well - consecutive phase estimations to efficiently make products of asymmetric low rank matrices classically accessible and an alternative method to efficiently exponentiate non-Hermitian matrices. Interestingly, the algorithm features an efficient quantum-classical division of labor: The time-critical steps are implemented in quantum superposition, while an interjacent step, requiring only exponentially few parameters, can operate classically. It turns out that frequencies and damping factors can be obtained in time logarithmic in the number of sampling points, exponentially faster than known classical algorithms.

## **III. Theory of Quantum Tomography of Many-Qubit Systems**

*Advances by Luming Duan, U. Michigan, and collaborators:*

Over the past year, the U. Michigan group and collaborators proposed an efficient method to perform Hamiltonian tomography for general quantum many-body systems with arbitrary couplings. Characterization of qubit couplings in many-body quantum systems is essential for benchmarking quantum computation and simulation. They proposed a tomographic measurement scheme to determine all the coupling terms in a general many-body Hamiltonian with arbitrary long-range interactions, provided the energy density of the Hamiltonian remains finite. Different from quantum process tomography, this scheme is fully scalable with the number of qubits as the required rounds of measurements increase only linearly with the number of coupling terms in the Hamiltonian. The scheme makes use of synchronized dynamical decoupling pulses to simplify the many-body dynamics so that the unknown parameters in the Hamiltonian can be retrieved one by one. This scheme was used to simulate the performance of the scheme under the

influence of various pulse errors and show that it is robust to typical noise and experimental imperfections. [8]

The Michigan group also proposed an efficient certification method for Boson samplers. A boson sampling device could efficiently sample from the output probability distribution of noninteracting bosons undergoing many-body interference. This problem is not only classically intractable, but its solution is also believed to be classically unverifiable. Hence, a major difficulty in experiment is to ensure a boson sampling device performs correctly. We present an experimental friendly scheme to extract useful and robust information from the quantum boson samplers based on coarse-grained measurements. The procedure can be applied to certify the equivalence of boson sampling devices while ruling out alternative fraudulent devices. We perform numerical simulations to demonstrate the feasibility of the method and consider the effects of realistic noise. Our approach is expected to be generally applicable to other many-body certification tasks beyond the boson sampling problem[9] (Wang, Duan, arxiv/160102627).

The Michigan group proposed another experimental model to demonstrate quantum supremacy. We introduce an intermediate quantum computing model built from translation-invariant Ising-interacting spins. Despite being non-universal, the model cannot be classically efficiently simulated unless the polynomial hierarchy collapses. Equipped with the intrinsic single-instance-hardness property, a single fixed unitary evolution in our model is sufficient to produce classically intractable results, compared to several other models that rely on implementation of an ensemble of different unitaries (instances). We propose a feasible experimental scheme to implement our Hamiltonian model using cold atoms trapped in a square optical lattice. We formulate a procedure to certify the correct functioning of this quantum machine. The certification requires only a polynomial number of local measurements assuming measurement imperfections are sufficiently small[10]. (Gao, Wang, Duan, Phys. Rev. Lett. 118, 040502 (2017)).

The Michigan group proposed a method to detect out-of-time-order correlators and information scrambling in an atomic many-body system. Out-of-time-order correlators (OTOC), recently being the center of discussion on quantum chaos, are a tool to understand the information scrambling in isolated many-body quantum systems. Quantum chaotic models are expected to scramble the information fastest and hence show exponential decay of OTOC. We proposed a disordered ladder spin model which can be designed in a scalable cold atom setup to detect OTOC with a protocol utilizing the sign reversal for the evolution backward in time. Our model shows exponential decay in early-time with power-law tails before its scrambling time and a range of lightcones from sublinear to superlinear as the system becomes more correlated and nonlocal. Based on our results, one can observe how the information scrambling changes in the transition from well-studied 1D models to unexplored 2D models in a setting where the interactions are local[11]. (Ceren B. Dag and L.-M. Duan, <https://arxiv.org/abs/1807.11085>).

## **IV. Quantum Technologies in Photonic Integrated Circuits (PICs)**

### **IV.A. Universal Programmable Linear Optics**

*Advances by Englund group and collaborators:*

A primary challenge to quantum optics experiments on PICs has been the need to fabricate custom chips for each experiment, which is an expensive and time-consuming process. In addition, useful algorithms typically require PICs to be tuned between consecutive processing steps or experiments. There is now a strong interest to develop reconfigurable circuits that not only allow rapid prototyping of experiments but also high-fidelity optical gates that appear to be achievable only with some degree of post-production tunability[12,13].

To answer this need, the Englund group at MIT proposed and experimentally developed a programmable photonic integrated circuit for high-fidelity quantum computation and simulation[12]. They showed that this programmability overcomes two major impediments to quantum optics on a chip: it removes the need for a full fabrication cycle for each experiment and allows for compensation of fabrication errors. This programmability can dramatically improve gate photonic gate fidelities to >99.99% using fabrication processes available at modern foundries. In a collaboration with the Lloyd group, they have shown that this type of programmable ‘quantum photonic processor’ (QPP) also enables entirely new areas of investigation in quantum random walks, including a statistically robust study of the evolution of entangled photons in disordered quantum walks [14].

There are two common circuit architectures used for performing arbitrary unitary operations on a set of optical modes; the first, proposed by Reck et al. (Reck et al., 1994), consists of a triangular circuit of Mach-Zehnder interferometers (MZIs), while the second, proposed by Clements et al. (Clements et al., 2016), is a rectangular configuration of MZIs. For an  $N \times N$  circuit, both architectures are capable of performing an arbitrary operation in the  $SU(N)$  Lie group.

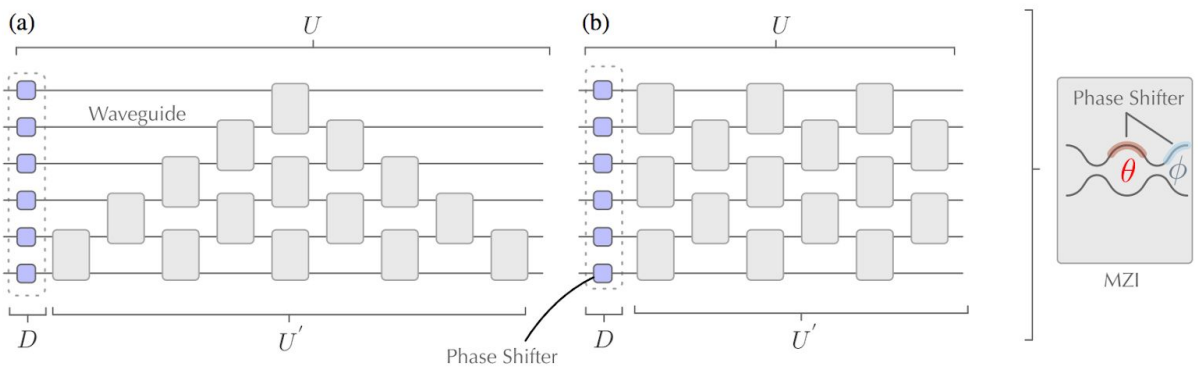


**Figure 1** Two circuit configurations of Mach-Zehnder interferometers (MZIs) can be used to compute unitary operations on optical modes. The left image (a) depicts the triangular (Reck) configuration (Reck et al., 1994), while the right image (b) depicts the rectangular (Clements) configuration (Clements et al., 2016). Each block in the diagram is a Mach-Zehnder interferometer capable of computing an arbitrary  $2 \times 2$  unitary operation and composed of two 50-50 splitters, with an internal phase shifter for setting the relative power splitting of the device and an external phase shifter for setting the relative phase of the outputs.

However, the number of MZIs required for an  $N \times N$  universal circuit scales as  $O(N^2)$ , which for large  $N$  requires significant area on a photonic die and makes it challenging to build large circuits

given current fabrication costs. In addition, each MZI requires at least four electrical pins, which entails tremendous difficulty in packaging and control of these PICs: a 20 x 20 programmable nanophotonic processor (PNP), for instance, will require the ability to interface with more than 800 electrical pins. The packaging process is particularly demanding and requires developing strategies for fiber attach for optical I/O, die attach to mechanical packaging, thermal control, electrical interposer design, wirebonding and/or flip-chip die bonding to the interposer, and software development for automated calibration and control. These difficulties make application-specific PICs, where the design is optimized for one specific function, an extremely challenging approach as systems on chip become more complex.

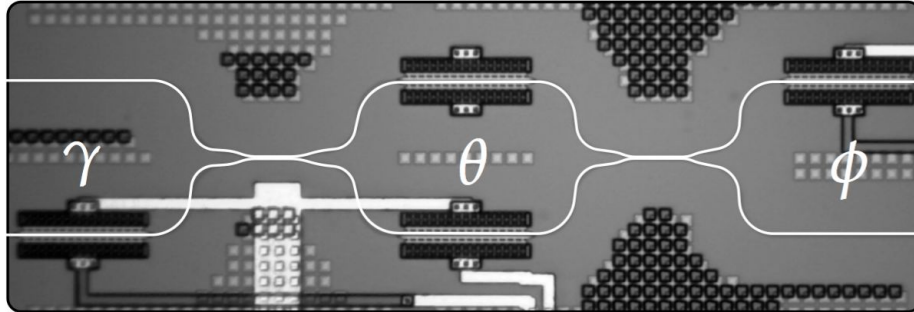


**Figure 2** A Mach-Zehnder interferometer implemented on a silicon photonic platform from the system shown in Harris et al. (2017). The phase shifters  $\theta$ ,  $\phi$  are implemented with thermo-optic phase shifters which modulate the refractive index of silicon by applying heat. An MZI with an internal and external phase shifter can compute an arbitrary operation in SU(2).

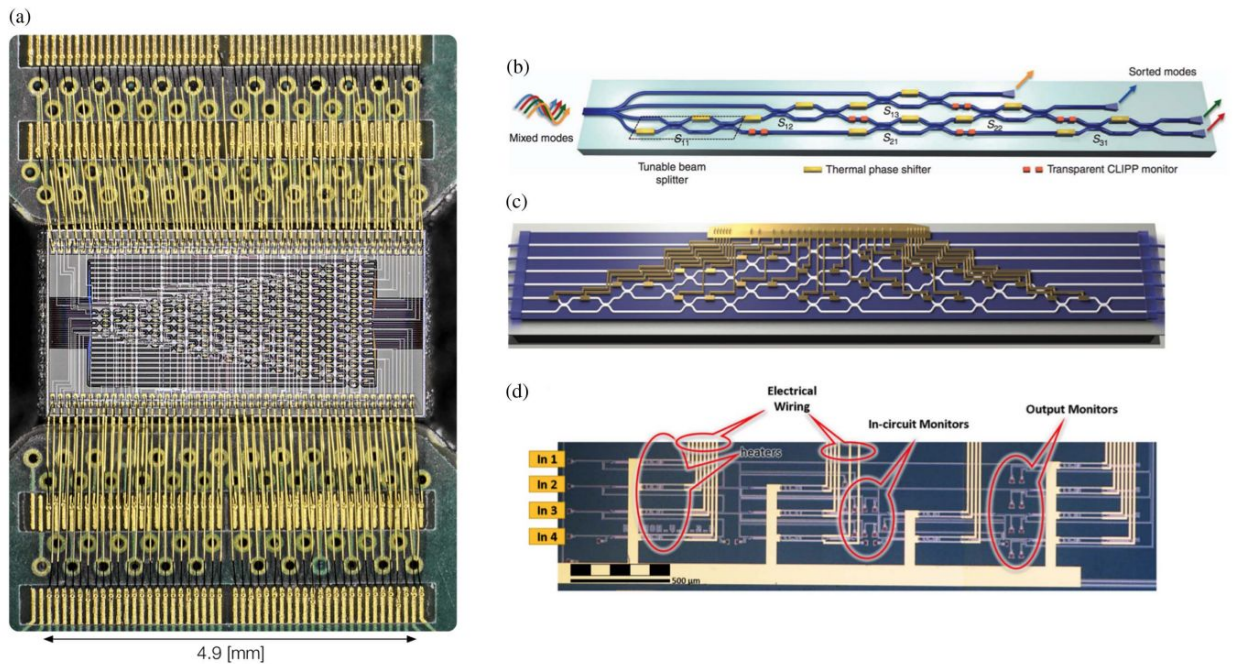


**Figure 3** Earlier demonstrations of programmable nanophotonic processors. a) 26-mode, 88-MZI partially-connected nanophotonic processor used for demonstrations in quantum simulation and artificial intelligence (Harris et al., 2017; Shen et al., 2017). b) 4-mode fully-connected

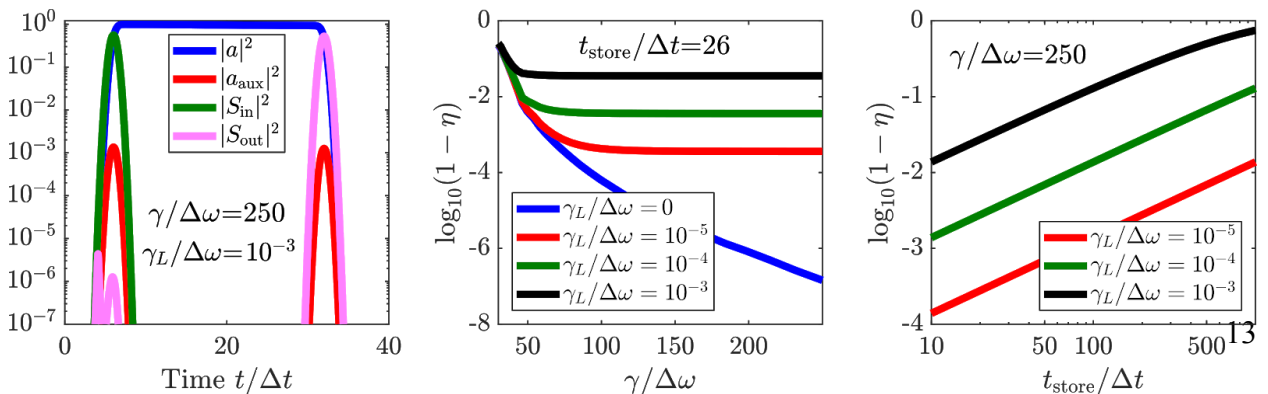
self-configuring nanophotonic processor used for automatic unscrambling of mixed modes (Annoni et al., 2017). c) Germanium-doped glass 6-mode fully-connected PNP designed for photonic quantum information processing (Carolan et al., 2015). d) 4-mode universal linear optical circuit demonstrated as a switch matrix and adaptive beam coupler (Ribeiro et al., 2016).

#### IV.B. Chip Integration of Nonclassical Light Sources

An important challenge for this MURI lies in the development of high-efficiency, scalable sources of single and entangled photons. To this end, we have developed classical control techniques for silicon photonic quantum computing[15]. Quantum computing architectures necessitate exquisite control over a large number of individual quantum systems which are highly sensitive to environmental fluctuations, and diagnosing errors via measurements typically causes unavoidable perturbations. Leveraging the very same classical laser fields required for photon generation as a probe to diagnose and correct errors, we have developed an in situ optimal control protocol which monitors and corrects errors in parallel to the optical quantum computation without disturbing the physical qubit. We implemented our technique on a silicon quantum photonic chip containing micro-ring resonators and thermo-optic phase shifters for photon generation and quantum state engineering. Our protocol reduces static and dynamic errors in the resonance positions of the rings by up to two orders of magnitude and enables us to demonstrate error-corrected quantum state engineering.

#### IV.C. Logic Gates between photonic qubits

The Englund group has analyzed how single-photon-level nonlinearities can be used for two-photon gates[16–18]. In that work we identified key limitations to the gate fidelity when using a passive device without any external controls to assist the photon-photon interaction. To further improve the fidelity, we are now analyzing dynamic capture and release of target and control photons. We have identified an all-optical control scheme for the capture and release process. It relies on the coupling between two modes of a resonator induced by two strong control fields. The third order nonlinear process known as Bragg-scattering four wave mixing allows exchange of a photon between the two modes if it is accompanied by a photon exchange between the pumps and the energy separation between the two modes of each set are identical. We derived the temporal behavior of the amplitude and phase of the pump fields leading to complete absorption of an incoming photon wave packet. The fidelity of a controlled phase gate based on cross-phase modulation will then approach unity as the duration of the gate operation approaches infinity (in the absence of loss). In the presence of loss, there are three contributions to fidelity degradation. i) The impossibility of perfectly capturing a pulse of finite duration. ii) Optical loss from the stored cavity mode. iii) The optimal temporal shape of the control pulses depends on whether the input state contains one or two photons.



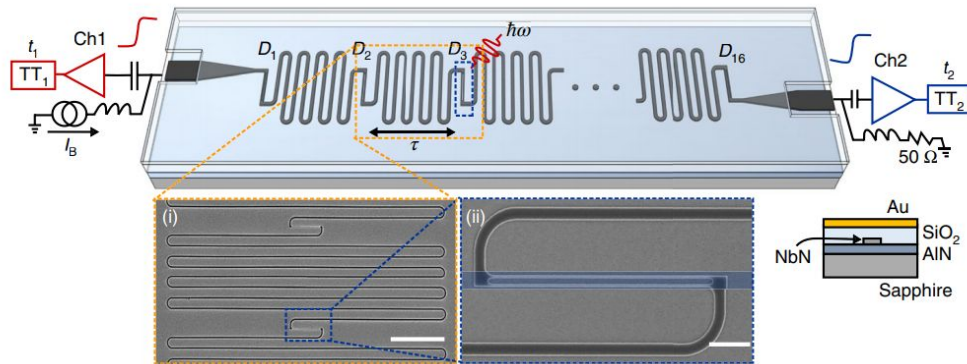
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**Figure 4** Capture and release efficiency of single photon in lossy resonator. The photon wave packet,  $S_{in}$ , is a Gaussian with a temporal FWHM  $\Delta t$  and spectral width  $\Delta\omega$ . The storage mode,  $a$ , of the cavity has intrinsic decay rate  $\gamma_L$  and the auxiliary mode,  $a_{aux}$ , is coupled to the waveguide with the rate  $\gamma$ . The efficiency  $\eta$  is defined as the overlap integral between the input and output wave packet,  $S_{out}$ , and includes both effects of loss and distortions of the wave packet.

pulses must be used in either case. In Fig. 4, we numerically explore i) and ii). The left panel shows an example of the temporal evolution of the input and output wave packets as well as the storage and auxiliary cavity modes. The center panel shows that fidelity degradation from i) can be arbitrarily small by increasing  $\gamma/\Delta\omega$  (blue curve). The right panel shows the effect of ii) as a function of the storage time. Our initial investigation indicates that a storage time of  $\sim 100\Delta t$  is sufficient to achieve a  $\pi$  phase shift while keeping the fidelity degradation from iii) below 1%. In Ref. [18] we found that  $\chi^{(2)}$  nonlinearities are significantly more promising than  $\chi^{(3)}$ , especially considering recent advances in fabrication of high quality factor resonators in  $\text{LiNbO}_3$ .

#### IV.D. Superconducting Nanowire Single-Photon Detectors (SNSPD) & Logic

Photonic quantum computing and quantum simulation rely on efficient classical single-photon detection over many spatial modes. SNSPD is currently the best-performing single-photon detector, but reading out large number of SNSPDs is an outstanding challenge due to the stringent requirement on the thermal load at cryogenic temperatures. The Berggren and Englund groups have demonstrated a scalable SNSPD array that requires minimum number of readout lines through delay-line multiplexing [19] (Zhu et al., 2018). The ultra-compact delay line utilizes the anomalously slow phase velocity of the plasmonic-like superconducting nanowire transmission. By exploring the timing logic and output pulse shapes in the array, they have demonstrated both coincidence counting and photon number resolution (Figure 5). To understand the device operation, the Berggren group has conducted detailed studies on the microwave dynamics in the nanowire, and build comprehensive models and simulation tools that incorporate both the hotspot dynamics and microwave properties [20] (Zhao et al. 2018).



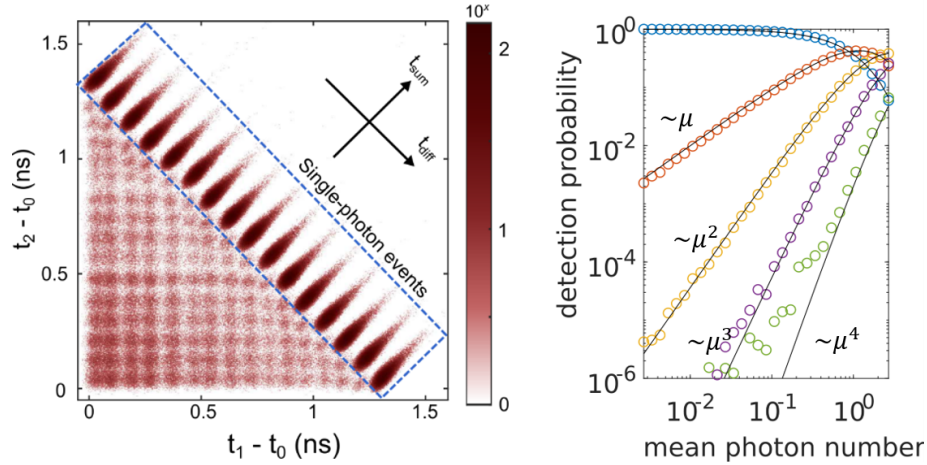
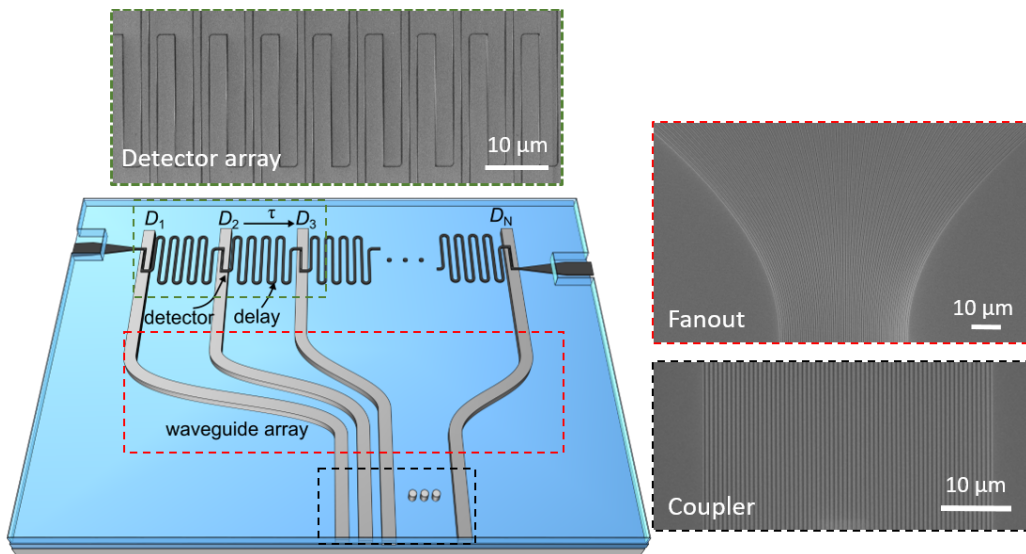


Figure 5: (Top) Device layout for a sixteen-element detector. The detector is a two-terminal array that connects a chain of single-photon detector segments using slow-wave nanowire delay lines. The nanowire was designed to be a microstrip waveguide with a dielectric spacer and a top ground plane. (i) SEM of the delay line, which consisted of a 300-nm-wide meandered nanowire. Scale bar, 10  $\mu\text{m}$ . (ii) SEM of a detector segment, which consisted of two 80-nm-wide parallel nanowires. Scale bar, 1  $\mu\text{m}$ . The blue band marks the site for future waveguide integration. (Bottom) Coincidence counting (left) and photon number resolution (right) using the delay-line-multiplexed SNSPD array.

The two groups are currently working on integrating a 65-element detector array on silicon photonic waveguides and have shown preliminary fabrication results of the full integrated device (see Fig. 6). This device will enable on-chip detection of quantum walking photons over 65 spatial modes---the largest quantum circuit with integrated detectors. The photonic circuits is fabricated on a silicon-on-insulator substrate, and the SNSPD array is directly fabricated on top of the optical waveguides.



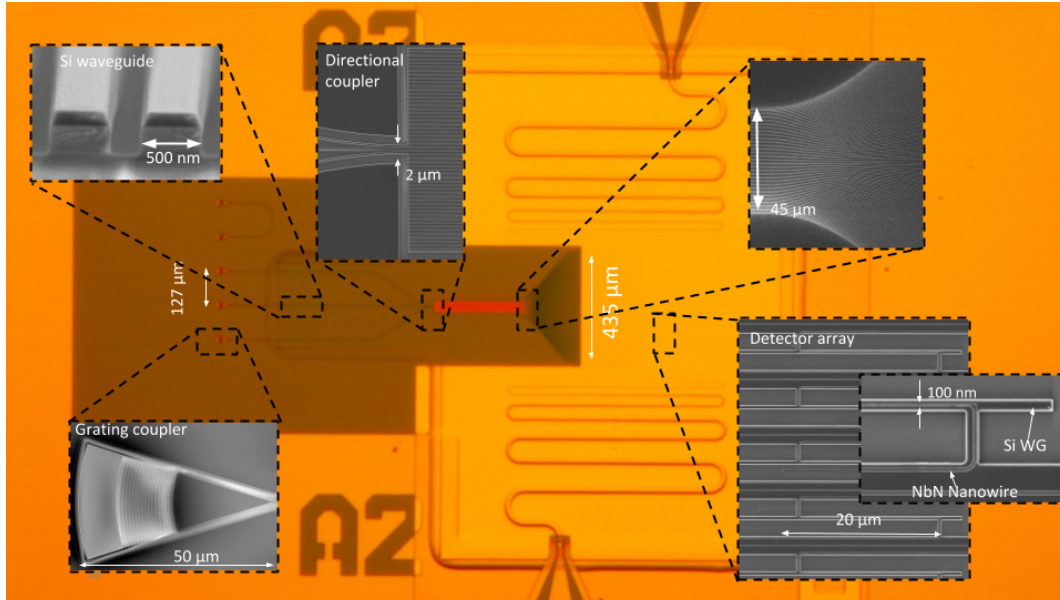


Figure 6: On-chip detection of quantum-walking photons (on-going work). (Top) Correlated photon pairs will be injected to 2 of the 65 coupled Si waveguides, undergo a continuous quantum walk, then fanout to 65 separate spatial modes and be detected using the delay-line-multiplex SNSPD arrays. (Bottom) Prototype fabricated device: insets show the main elements.

#### IV.E Machine Learning On Photonic Circuits

Artificial Neural Networks, an area of research that has recently received an explosion of interest, are algorithms that mimic the signal processing architecture of the brain. These methods have dramatically improved the state-of-the-art in speech recognition, visual object recognition, object detection, and many other scientific domains such as drug discovery and genomics. However, today's computing hardware is very inefficient (slow and power-hungry) at implementing neural networks (maybe not surprising since the hardware was designed for von Neumann computing). Speech recognition software (e.g., Apple's Siri) must be done on the cloud because it is too taxing on a mobile phone, and vision is even more challenging. Real-time image processing is much more power hungry. This power inefficiency is a big problem for many applications, especially in mobile platforms. Certain other applications also demand faster, more power-efficient approaches, such as high-speed signal processing, e.g., in RF photonics. Many efforts have been made to increase the computing speed of artificial neural networks. Among these methods, neuromorphic computing, where electronic devices are tuned to have an optimized architecture for computing on neural networks, is one of the most advanced techniques.

Recently, the groups of Prof. Marin Soljacic (Physics, MIT) and Prof. Englund developed a new architecture for a fully-optical neural network that promises a computational speed enhancement of at least two orders of magnitude and an energy consumption reduction of three or more orders of magnitude over state-of-the-art electronics. In addition, the performance gap between this optical architecture and electronics broadens with neural network size. We experimentally

demonstrated [21] the core components of the architecture using a new class of fully programmable nanophotonic processor[14] to implement—for the first time—a coherent, fully-connected neural network, see the figure below.

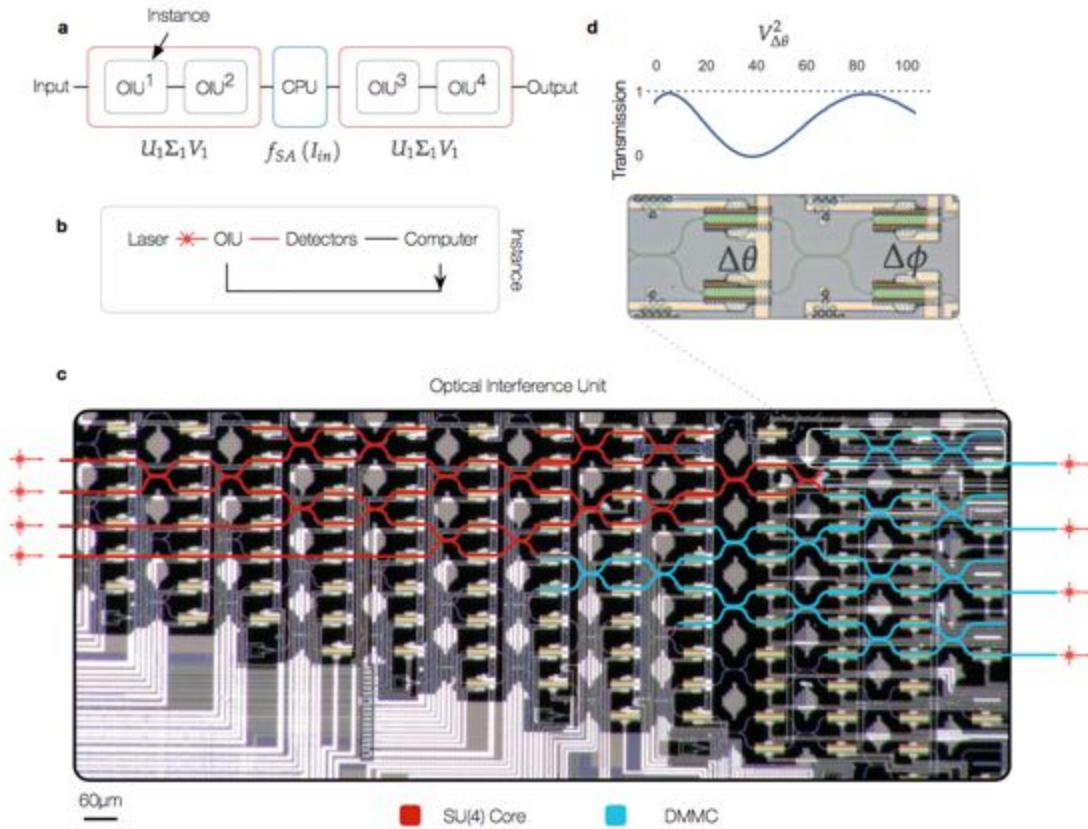


Figure 7: Illustration of Optical Interference Unit a. Schematic representation of our 2-layer ONN experiment. The programmable nanophotonic processor is used 4 times to implement the deep neural network protocol. After the first matrix is implemented, a nonlinearity associated with a saturable absorber is simulated in response to the output of layer 1. b. The experimental feedback and control loop used in the experiment. Laser light is coupled to the OIU, transformed, measured on a photodiode array, and then read on a computer. c. Optical micrograph illustration of the experimentally demonstrated optical interference unit which realizes both matrix multiplication (highlighted in red) and attenuation (highlighted in blue) fully optically. The spatial layout of MZIs follows the Reck proposal[22]— enabling arbitrary SU(4) rotations by programming the internal and external phase shifters of each MZI ( $\theta_i$ ,  $\phi_i$ ). d. Schematic illustration of a single phase shifter in the Mach-Zehnder Interferometer and the transmission curve for tuning the internal phase shifter.

This proof-of-principle demonstration of the optical neural network (ONN) focused on performing the matrix transformations in the optical domain, using signals encoded into the intensities of four waveguides. Optics allows very large matrix transformations to be performed at the speed of light and with very little power. The students of Prof. Englund and Prof. Marin Soljacic's groups presented the concept of ONNs at two top business competitions -- Harvard's

Presidential challenge and MIT's \$100K challenge -- and won first place in both. They started two VC-backed companies, LightMatter and Lightelligence, that are now seeking to scale up the technology to solve difficult machine learning challenges. LightMatter recently introduced their first chip, Mars, which is slated to start competing against leading machine learning-focused tensor processors by the likes of Intel next year.

## **Very Large-Scale Neural Networks**

Englund and Dr. Ryan Hamerly developed several new types of deep neural network architectures based on serialized encoding of binary data. In addition, we developed a scheme to perform products between signal data and weight data using the process of homodyne detection. These advances indicate that it may be possible to cut energy consumption due to data movement by more than an order of magnitude[23]. Since data movement consumes the great majority of deep neural networks as they are implemented today on tensor processing or graphical processing units, our work indicates that the overall power consumption of deep neural networks could be reduced by more than an order of magnitude using photonic fan out, weight distribution, and opto-electronic multiplier devices. We stress that this new approach can readily be scaled to hundreds of thousands, and conceivably tens of millions, of optoelectronic neurons. We have demonstrated a proof-of-concept of this work and are working on several publications on fully connected and convolutional deep neural network processors.

## **Quantum Neural Networks**

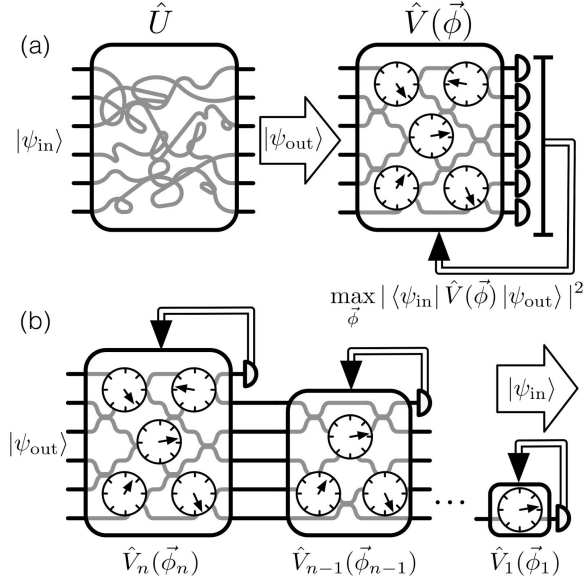
*Teaching a quantum system to train itself.* Given an experimental quantum computing device, is it necessary to painstakingly analyze all gate fidelities, error models, etc? We are analyzing how a programmable quantum system such as the QPP can train itself. The QPP is a promising system to address this problem because the photonic qubits are very well behaved -- their decoherence and bit flip errors are inherently extremely small.

Physically motivated quantum algorithms for specific near-term quantum hardware will likely be the next frontier in quantum information science. Here we show how many of the features of neural networks for machine learning can naturally be mapped into the quantum optical domain by introducing the quantum optical neural network (QONN). Through numerical simulation and analysis we train the QONN to perform a range of quantum information processing tasks: including newly developed protocols for quantum optical state compression, reinforcement learning, and black-box quantum simulation. We consistently demonstrate our system can generalize from only a small set of training data onto states for which it has not been trained. Together, our results point toward both a powerful design tool for quantum optical systems, and, by leveraging advances in integrated quantum photonics, a promising architecture for next generation quantum processors. See our publication here[24].

## **Variational Quantum Unsampling (VQU)**

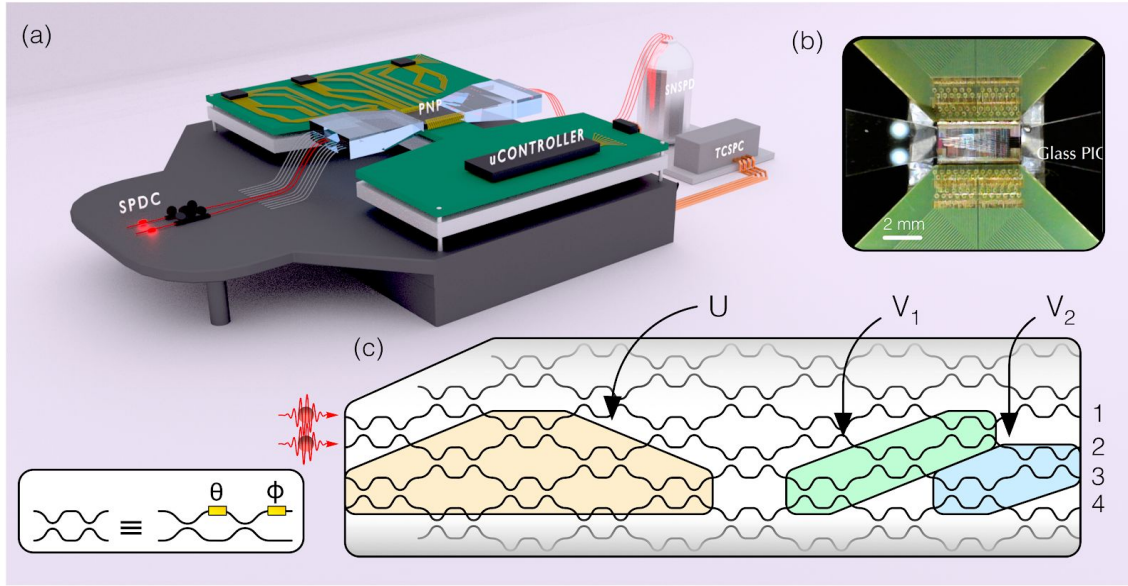
Quantum algorithms for non-universal quantum machines have emerged as a promising route towards demonstrating near-term quantum advantage over classical systems [25]. In these systems samples are typically drawn from probability distributions which — under plausible

complexity theoretic conjectures — cannot be efficiently generated classically. Rather than first define a physical system and then determine the plausibility of efficient sampling, we ask the converse question: given a small number of samples, what features of the physical system can we efficiently learn? In a collaboration between MIT (Carolan, Englund, Lloyd, Wong), Google (Mohseni), Zapata Computing (Olson) and Elenion Technologies (Hochberg), we introduced the Variational Quantum Unsampling (VQU) protocol: a nonlinear quantum neural network approach for verification and inference of near-term quantum circuits outputs[26].



**Variational Quantum Unsampling.** (a) Given a state  $|\psi_{out}\rangle = U|\psi_{in}\rangle$ , the task is to find the circuit that returns  $|\psi_{in}\rangle$ , thus determining some features of  $U$ . The variational quantum unsampling protocol feeds this state into a controllable quantum circuit and optimizes the parameters  $\phi$  to find the time reversed condition that  $V(\phi)|\psi_{out}\rangle = U^\dagger|\psi_{out}\rangle$  over the known input state. (b) Directly optimizing for this condition is inefficient in the qubit number, therefore the layer-wise approach breaks the problem up such that at each stage only a polynomially sized subset of the entire Hilbert space is optimized for.

While the principle of our approach is platform independent, each quantum processor will leverage unique structure in their particular architecture to efficiently implement our protocol. We implement a proof-of-concept demonstration of the optical VQU procedure on a state-of-the-art quantum photonic processor comprising three stages: (1) photon generation via spontaneous parametric down-conversion (SPDC), (2) reconfigurable quantum circuitry on a programmable nanophotonic processor (PNP) (3) single photon detection, all within an actively configured feedback loop for optimization [see Fig 2(a)]. See Methods for a description of the full experimental setup. The PNP comprises 88 reconfigurable Mach-Zehnder interferometers arranged in a mesh, that enables different regions of the device to be used for separate quantum operations. In Fig. 2(c) the sampling circuit is shown in orange, and the unsampling layers are shown in green and blue. Alongside quantum verification, our protocol has broad applications; including optimal quantum measurement and tomography, quantum sensing and imaging, and ansatz validation.



**Experimental VQU.** Pairs of photons are first generated via spontaneous parametric down-conversion (SPDC) and delivered to a programmable nanophotonic processor (PNP) which is mounted on top of a Peltier cooling system to maintain thermal stability. After propagating through the circuit photons are out-coupled and delivered to an array of superconducting nanowire single photon detectors (SNSPDs). Coincidence events are recorded by a time correlated single photon counting system (TCSPC), which are output to a classical computer which controls a micro-controller unit that drives all 176 on-chip thermo-optic phase shifters.

### Recurrent Ising Machines in Integrated Photonics

Conventional computing architectures have no known efficient algorithms for combinatorial optimization tasks, which are encountered in fundamental areas and real-world practical problems including logistics, social networks, and cryptography. Physical machines have recently been proposed and implemented as an alternative to conventional exact and heuristic solvers for the Ising problem, one such optimization task that requires finding the ground state spin configuration of an arbitrary Ising graph. However, these physical approaches usually suffer from decreased ground state convergence probability or universality for high edge-density graphs or arbitrary graph weights, respectively.

The groups of Prof. Marin Soljacic (Physics, MIT) and Prof. Englund have developed the Photonic Recurrent Ising Sampler (PRIS), a novel heuristic algorithm for quickly sampling from distributions of difficult combinatorial optimization problems [27]. Leveraging the fast matrix-vector product and arbitrary unitary capability of the programmable nanophotonic processor, we demonstrated a proof-of-principle integrated nanophotonic recurrent Ising sampler (INPRIS) capable of converging to the ground state of various 4-spin graphs with high probability [28]. The INPRIS exploits experimental physical noise as a resource to speed up the ground state search. By injecting additional extrinsic noise during the algorithm iterations, the INPRIS explores larger regions of the phase space, thus allowing one to probe noise-dependent physical observables. Since the recurrent photonic transformation that our machine imparts is a

fixed function of the graph problem, and could thus be implemented with optoelectronic architectures that enable GHz clock rates (such as passive or non-volatile photonic circuits that do not require reprogramming at each iteration), our work paves a way for orders-of-magnitude speedups in exploring the solution space of combinatorially hard problems.

## **V. Classical-Quantum Optical Networks & Quantum Illumination**

How can one use an optical link between two parties to (1) maximize data transmission between them and (2) bound or minimize the information leaked to a possible adversary? The answers to these questions depend on the quantum states of light injected into the channel and the types of measurements performed on it. Not surprisingly, the theory of optimal quantum measurements has a long history in optical communications, where it was initiated to determine and, if possible, build systems that approach the ultimate communication-performance limits set by the quantum nature of light. Despite forty years of research, these remain topics of considerable current interest, with much of it driven by the need to find explicit experimental configurations that approximate the quantum measurements that emerge from theory. Furthermore, optimal receivers are needed to push toward ultimate quantum limits on communication. The dynamic nature of some optical channels—e.g., unguided propagation through the earth’s turbulent atmosphere—as well as the intrinsic requirement for quantifying channel impairments in QKD, propelled an additional need for the program’s theory efforts on optimal quantum measurements and state verification. That need was to find optimal realizable means to measure and verify the characteristics of optical communication channels -- which could answer, for example, how secure the channel is. In this area, the MURI saw rapid progress in theory and experiment of quantum illumination, pioneered by MURI PIs Shapiro and Lloyd [29,30]. In particular, a focus of this MURI was to apply optimal quantum measurement and state verification techniques to quantum illumination (QI) targeted at secure communications. As summarized below, the work by Shapiro and Wong has led to new QI-based communication schemes that promise physically secure communication at unprecedented rates.

### **V.A Floodlight Quantum Key Distribution**

The Shapiro-Wong group has developed a new quantum key distribution (QKD) protocol called Floodlight QKD (FL-QKD) [31], [US Patent 109,389,526] *that is capable of gigabits per second (Gbps) secret-key rates over a 50-km fiber link without multiplexing. FL-QKD has proven security against the optimum frequency-domain collective attack, and it is completely immune to passive eavesdropping.* In what follows we provide an explanation of how FL-QKD achieves its remarkable performance.

Loss is the bane of all QKD systems, and is the essential reason that protocols prior to FL-QKD are limited to secret-key rates at metropolitan-area distances that are far below the Gbps range needed for Gbps transmission of one-time-pad-encrypted large data files. Whereas classical communications can deal with loss by transmitting many photons per bit, QKD systems must protect themselves against the undetectable passive eavesdropper, viz., one that captures all the light that has leaked out of the quantum channel. Consequently, QKD protocols like BB84 transmit at most  $\sim 1$  photon per bit to defeat such an attacker. This low-flux transmission makes

systems using these protocols have secret-key rates well below Gbps unless they use a massive amount of multiplexing, with its attendant cost and complexity. FL-QKD is different. It uses low-brightness transmission ( $< 1$  photon/mode) to thwart the passive eavesdropper, but many modes/bit to ensure that the transmitted photons per bit suffices for a high secret-key rate despite channel loss. FL-QKD is a two-way protocol. Alice sends a low-brightness portion of broadband amplified spontaneous emission (ASE) light to Bob. Bob then encodes the light using binary phase-shift keying (BPSK), amplifies it to overcome the return-path loss, and sends it back to Alice. Alice employs her remaining high-brightness ASE light for broadband homodyne detection of the encoded key bits for key generation. Alice and Bob perform photon-coincidence measurements — using broadband photon pairs from a parametric downconverter — to monitor the integrity of the Alice-to-Bob quantum channel, thus defeating an eavesdropper who attempts to inject her own light into Bob’s terminal. The combination of channel monitoring and low-brightness Alice-to-Bob transmission makes FL-QKD secure against the frequency-domain collective attack, which encompasses both passive eavesdropping and active light injection by Eve. FL-QKD requires no new technology for implementation, and is capable of a 2 Gbps secret-key rate over a 50-km-long fiber link, a rate that is orders of magnitude higher than those of existing protocols.

We also made substantial progress on the major remaining theory issue with regards to FL-QKD: extending its security proof to include protection against coherent attacks. Toward that end we have built upon the classical-capacity additivity of noisy entanglement-assisted quantum channels that one of our team developed in [Phys. Rev. Lett. **118**, 200503 (2017)]. Using that result, we have Gaussian QKD protocols — which includes FL-QKD — by: (1) demonstrating that coherent-attack security can be reduced to collective-attack security for *all* two-way QKD protocols; (2) identifying two different constraints that each provide intrusion parameters which bound an eavesdropper’s coherent-attack information for any two-way Gaussian protocol; and (3) applying our results to FL-QKD. In progress, when the MURI program concluded, was a proof — built on the preceding framework — that FL-QKD can be made secure against a coherent Gaussian attack, using channel measurements similar to those already employed for ensuring collective-attack security.

Although FL-QKD, with BPSK modulation, is capable of unprecedented secret-key rates (SKRs) over metropolitan-area fiber connections, we studied whether the use of high-order signal constellations, such as employed in conventional coherent-detection fiber-optic communication, could provide increased performance. It turned out [Phys. Rev. A **98**, 012323 (2018)], i.e., use of quadrature phase-shift keying (QPSK) can nearly double FL-QKD’s SKR. Going beyond QPSK, i.e., to high-order quadrature-amplitude modulation (QAM), does *not* offer FL-QKD the benefit that this signal constellation affords in conventional communication, because Eve derives too much information from the amplitude modulation inherent in QAM.

## V.B Gaussian phase-matching in PPKTP

Generation of pure-state single-mode photons is an essential quantum photonic resource for many applications such as bosonic sampling, photonic quantum computing, and heralded generation of entangled photon pairs. The method used by the Shapiro-Wong group for

generating single-mode photons at the telecom band is based on ultrafast SPDC in PPKTP with a Gaussian phase-matching profile under extended phase-matching conditions and with a transform-limited Gaussian pump.

Measurements reported in Opt. Express **25**, 7300 (2017) [32] show the results of our initial efforts in generating and characterizing spectrally factorable biphotons, yielding an inferred heralded-state spectral purity of 99%, the highest to date without any spectral filtering, based on a second-generation PPKTP crystal with an improved Gaussian phase-matching profile. The nearly perfect inferred heralded-state spectral purity was achieved at a pump bandwidth of 0.95 nm and with a Gaussian phase-matching function that suppresses the side lobes effectively to generate a nearly circularly symmetric biphoton state (see Fig. 8).

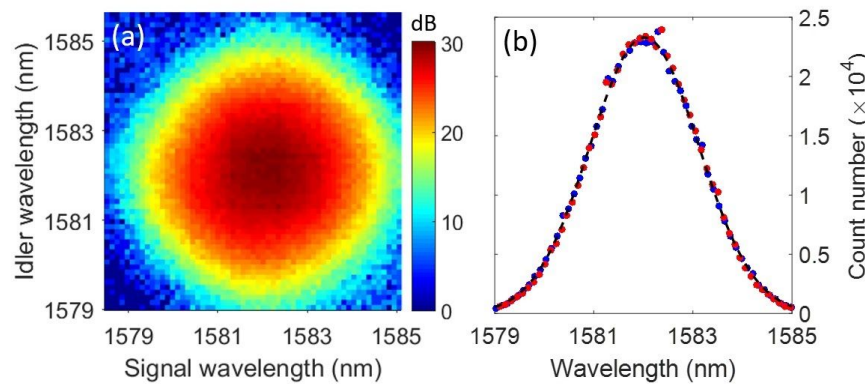


Figure 8. (Left) Joint spectral intensity plot with 0.11 nm resolution in log scale, and (Right) signal (red) and idler (blue) marginal distributions in linear scale per 0.11-nm bandwidth, of biphoton state for 0.95 nm pump bandwidth.

The definitive measurement for verifying the purity of the heralded single-photon state is a Hong-Ou-Mandel (HOM) interference measurement between two independently heralded single photons. This is accomplished by first generating two separate pairs of single-mode entangled photons at two different times, then separating and detecting the two idler photons as triggers, and interfering the two signal photons. We set up the four-fold HOM coincidence measurement by measuring the HOM interference between two heralded signal photons separated by 8 pump repetition periods ( $\sim 100$  ns). Initial results show purity of only 87% because the pulsed pump laser did not have the required characteristics for generating high purity heralded states of single photons. In particular, the pump laser was not transform limited with a Gaussian spectral shape. In collaboration with NIST we installed a lithographically generated Gaussian-shaped transmission mask, together with a pair of diffraction gratings, to control the spectral shape and bandwidth of the pump. Figure 9 shows our most recent four-fold HOM interference measurements with a visibility of 98.4% in which a mild 10-nm bandpass spectral filter is used for the SPDC output, which corresponds to a heralded-state purity of 99.2%, as reported in Optics Express **27**, 11626 (2019). The high purity implies that the heralded single photons are truly indistinguishable, and the generation technique provides an essential resource for measurement-based quantum information processing and quantum network applications.

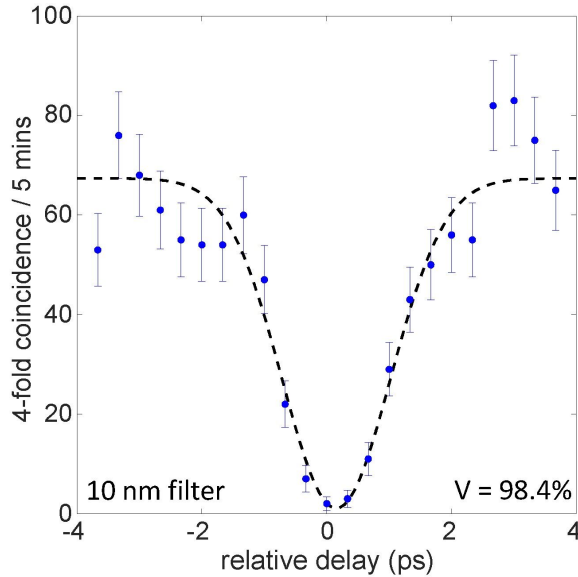


Figure 9. Hong-Ou-Mandel interference measurement between two heralded signal photons produced by spectrally engineered SPDC in PPKTP and separated by 8 pump repetition periods. Four-fold coincidence counts are based on measuring the two trigger idler photons and the accompanying heralded signal photons. Measurement results without subtraction of accidental coincidence counts yields raw visibility of 98.4%.

### V.C Floodlight QKD

The Shapiro-Wong group previously implemented a table-top proof-of-concept experiment for demonstrating the basic principles of Floodlight QKD (FL-QKD) using a 16-nm classical broadband light source and running at a BPSK modulation rate of 100 Mbps. For a one-way channel loss of 10 dB (equivalent to that of a 50 km fiber length), the system achieved a secret-key rate of 55 Mbps against the optimum collective Gaussian attack, as reported in Phys. Rev. A **95**, 012332 (2017) [33]. The reported FL-QKD secret-key rate is over 50x higher than that of the state-of-the-art BB84 system for the same channel loss, but is far lower than the predicted Gbps performance that is limited by the low bandwidth of the available equipment in this preliminary experiment.

More recently we have upgraded the experimental setup to substantially boost the FL-QKD throughput to Gbps rates, by replacing the phase modulator and homodyne receiver with higher speed versions (20 GHz for the former and 14 GHz for the latter). The BPSK modulation rate is increased to 7 Gbps, and the phase-locked loop has been modified to handle the higher modulation rate. Measurements with the upgraded setup show a secret-key rate of 1.3 Gbps against the optimal collective Gaussian attack, as displayed in Fig. 10 below and reported in Quantum Sci. Technol. **3**, 025005 (2018) [34]. The performance is currently hampered by the long coincidence-counting acquisition time for channel monitoring due to single-photon detector saturation. We have also upgraded the phase-locked loop control system by using three types of control actuators: Bob's electro-optic modulator to handle fast-changing phase variations, a piezoelectrically-controlled free-space length for the slowly varying length changes, and a temperature control loop to take care of the long-term thermal drift of the setup, resulting in

phase-locked durations of ten of minutes limited only by the range of the thermal loop [Zhang, CLEO 2018] [35]. Future improvements include implementing quadrature-phase shift keying encoding [Zhuang et al, 2018] [35] to double the secret-key rates.

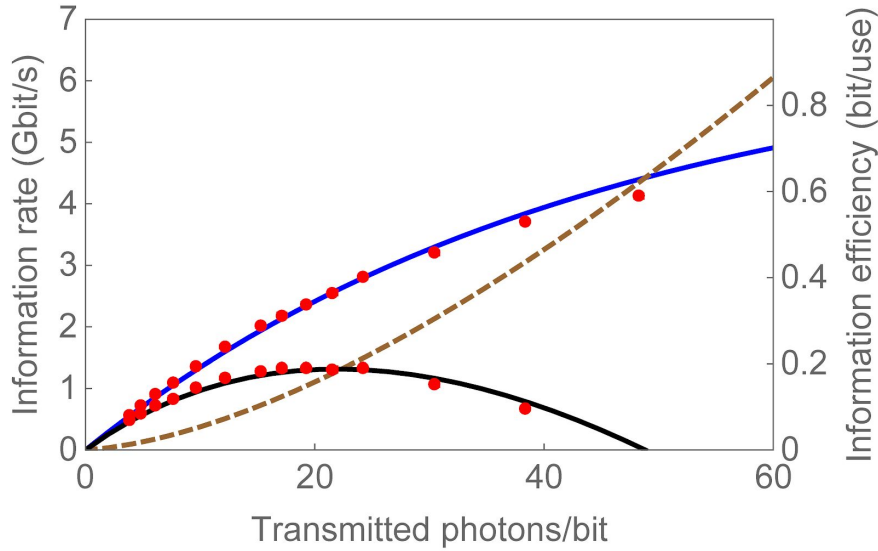


Figure 10. Floodlight QKD experimental results. Demonstrated secret-key rates versus Alice's transmitted photons per bit. Red points: experimental measurements. Blue curve: Alice and Bob's Shannon information; Dashed brown curve: upper bound on Eve's Holevo information for her optimum collective Gaussian attack; Black curve: secret-key rate for Eve's optimum collective Gaussian attack (with no injection by Eve).

## VI. Photons with Controlled Interactions: Chi-2 Nonlinear Optical Interactions

### VI. Single-Photon $\chi^{(2)}$ Interactions and Their Applications

In keeping with our program's focus on optimal measurements and scalable quantum technologies the MIT team took on new efforts — based on the presumption that single-photon  $\chi^{(2)}$  interactions will become available (see, Sec. IV.C for our program's effort in realizing single-photon nonlinearities) — that offer enhanced performance in nonclassical state generation and quantum sensing, and new paradigms for optics-based quantum computation with hardware-efficient quantum error-correcting codes. This section summarizes the results that have been obtained, preceded by a brief discussion of the resources assumed in all of those applications.

#### VI.A. Full-Quantum versus Pumped $\chi^{(2)}$ Interactions

Three-wave mixing interactions in  $\chi^{(2)}$  media are mainstays of quantum optics: spontaneous parametric downconversion (SPDC) is the premier source of entangled and hyperentangled photon pairs; optical parametric amplifiers generate squeezed-vacuum states; sum-frequency generators serve as quantum-state frequency converters that transform the 1550-nm-wavelength photons suitable for long-distance fiber propagation to the wavelengths

needed by trapped ion or neutral atom memories while difference-frequency generators serve as quantum-state frequency converters for the reverse interface. As routinely employed, all of these functionalities rely on what we call *pumped*  $\chi^{(2)}$  interactions in that they are three-wave mixers involving pump, signal, and idler beams with one of them being in such a strong coherent state that it acts as a nondepleting classical field. The new state generation, sensing, and computation paradigms we have introduced need *full-quantum*  $\chi^{(2)}$  interactions, in which all three beams are quantum, indeed typically at the single-photon or few-photon level. As will be seen below, our applications will also employ linear optics and may also incorporate some pumped  $\chi^{(2)}$  interactions.

## VI.B. Unity-Efficiency Parametric Downconversion via Amplitude Amplification

As currently implemented, SPDC sources of nonclassical light rely on strong coherent-state pump beams. These pumps do not suffer appreciable depletion in the downconversion process, meaning that their conversion efficiencies are exceedingly low. Moreover, the number of signal-idler pairs that are emitted in response to a pump pulse is random. To circumvent these drawbacks, we focused our attention on SPDC using  $n$ -photon Fock-state pumps. We proposed and analyzed a scheme using such pumps that interlaces SPDC processes with nonlinear sign gates (NSGs) in a series of iterations — which mimic the well-known Grover algorithm for database sorting — to generate  $n$  signal-idler pairs with unity efficiency when the downconverters' crystal lengths are chosen appropriately [36]. Our proof of unity-efficiency conversion presumed  $n \gg 1$  and allows each Grover iteration to employ a different crystal length. Because the precision with which those crystal lengths must be realized becomes increasingly demanding as  $n$  increases, we evaluated the conversion efficiencies at a fixed crystal-length precision. Furthermore, to reduce our scheme's resource burden, we performed our efficiency evaluations assuming that all Grover iterations use the same crystal. We found that complete conversion is maintained for  $1 \leq n \leq 5$ , and that our approach's conversion efficiencies — although less than 100% — still exceed those of a conventional (no NSGs) downconverter for  $n$  values up to 50. Thus, even using the same crystal for all Grover iterations with finite crystal-length precision, our approach can efficiently prepare heralded single-photon states as well as dual-Fock ( $|n\rangle|n\rangle$ ) states and multi-photon path-entangled states for  $n \leq 5$ .

## VI.C. Optimum Quantum Receiver for Quantum Illumination

Quantum illumination (QI) is an entanglement-enhanced paradigm for target detection that thrives on entanglement-breaking loss and noise [29]. Its minimum error-probability quantum receiver enjoys a 6 dB advantage in error-probability exponent over optimum classical illumination (CI) using the same transmitted photon number. Remarkably, QI's advantage occurs despite the initial entanglement being completely destroyed. Prior to our work, the only in-principle realization of QI's optimum quantum receiver requires a Schur transform on a quantum computer, so that its physical implementation is unlikely to occur in the near future. Previously, the best known sub-optimum QI receivers [37] — one of which, the optical parametric amplifier (OPA) receiver, has been demonstrated experimentally[38] — can only realize a 3 dB error-probability exponent advantage. By bridging the 3 dB performance gap between the sub-optimum and optimum receivers with an implementation more feasible than a

quantum computer [39], we provided a result of particular significance for its application potential and for its deepening our understanding of entanglement-enhanced metrology.

Our optimum QI-receiver architecture based on sum-frequency generation (SFG). In the weak-signal limit, the SFG unitary maps QI target detection to the well-studied problem of single-mode coherent state discrimination. Analytical calculation and Monte Carlo simulations confirmed that this SFG receiver's performance approaches QI's quantum Chernoff bound (QCB) [2] asymptotically. Adding a feed-forward (FF) mechanism yields the FF-SFG receiver, whose error probability achieves the Helstrom bound. The FF-SFG receiver is potentially promising for other quantum-enhanced sensing scenarios, such as phase estimation, and it enlarges the toolbox for quantum-state discrimination. In particular, it is the first architecture — short of a quantum computer — for optimum discrimination of multi-mode Gaussian mixed states, a major step beyond the optimum discrimination of single-mode pure states.

#### VI.D. Advancing the Applicability of Quantum Illumination for Target Detection

Up to and including our introduction of the FF-SFG receiver, analyses of QI target detection had all presumed equally-likely target absence or presence and Bayesian — specifically, minimum error-probability — performance criterion. But Bayesian analysis is *not* the preferred approach for target detection, owing to the difficulty of accurately assigning prior probabilities to target absence and presence and appropriate costs to false-alarm (Type-I) and miss (Type-II) errors. Instead, radar theory opts for the Neyman-Pearson performance criterion, in which optimum target detection maximizes the detection probability,  $P_D = \Pr(\text{decide present} \mid \text{present})$ , subject to a constraint on the false-alarm probability,  $P_F = \Pr(\text{decide present} \mid \text{absent})$ . (The detection probability satisfies  $P_D = 1 - P_M$ , where  $P_M = \Pr(\text{decide absent} \mid \text{present})$  is the miss probability.) In Ref.[40] we showed that our FF-SFG receiver [39] is optimum for the Neyman-Pearson criterion, and we used the analysis from to obtain the receiver operating characteristic (ROC) — i.e., the trade-off between  $P_D$  and  $P_F$  — for optimum QI target detection, and compared it to the ROCs of QI target detection with OPA reception and optimum CI target detection.

In [40] we made another advance that brings QI target detection closer to real applications. Until that work, QI analyses had all assumed that the target return has known amplitude and phase, something that seldom occurs in lidar applications. At lidar wavelengths, most target surfaces are sufficiently rough that their returns are speckled, i.e., they have Rayleigh-distributed amplitudes and uniformly-distributed phases. It is crucial, therefore, to show that QI maintains a target-detection performance advantage over CI for a target return with random amplitude and phase. In Ref. [41], we compared QI and CI target detection for Rayleigh-fading targets in the flat-fading limit, when the complex-field envelope of the target return from a single transmitted pulse suffers multiplication by a time-independent Rayleigh-distributed random amplitude and a time-independent uniformly-distributed random phase shift. We showed that QI with OPA reception fails to offer any performance advantage over CI in this case. QI with SFG reception does provide an advantage over CI: when  $M \langle \kappa \rangle N_S / N_B \gg 1$ , its error probability is a factor of  $1/\ln(M \langle \kappa \rangle N_S / N_B)$  lower than that of optimum CI, which transmits a coherent state and uses heterodyne reception. Here,  $M \gg 1$  is the QI transmitter's time-bandwidth product,  $N_S$  is its

brightness,  $\langle \kappa \rangle$  is the target return's average intensity, and  $N_B \gg 1$  is the background light's brightness.

## **VI.E. Microwave Quantum Illumination and Its Realistic Assessment**

Although initial work — and a great deal of follow-on research — has assumed that QI target detection is done at optical frequencies, the advantageous operating regime for QI target detection is one in which there is bright (many photons per mode) background light to contend with. Such, however, is *not* the case at optical frequencies unless there is active jamming, whereas high-brightness background is the norm at microwave frequencies where most target-detection radars operate. Thus enormous interest followed publication of [Phys. Rev. A **114**, 080503 (2015)], in which Shapiro and collaborators reported a theoretical system for performing microwave QI. Unfortunately, this paper's publication engendered a considerable amount of unwanted hype, in addition to its salutary beginning of microwave QI experiments. Prof. Shapiro, however, has set the record straight on QI target detection — at both optical and microwave frequencies — in “The Quantum Illumination Story” [arXiv:1910.12277v4 [quant-ph], to appear in IEEE Aerospace and Electronic Systems Magazine].

## **VI.F. Entanglement-Enhanced Lidars for Simultaneous Range and Velocity Measurements**

Lidars measure distance from the time delay incurred in roundtrip propagation to and from a reflecting object, and they measure velocity from the frequency shift imparted by reflection from an object that is in motion relative to the lidar. At the single-photon level, the Arthurs-Kelly uncertainty relation seemingly limits the time-delay measurement's root-mean-square error to be at least the reciprocal of the frequency-shift measurement's root-mean-square error. In [Phys. Rev. A **96**, 040304 (2017)], we showed how to circumvent the preceding limit by exploiting entanglement between a signal photon the lidar transmits to interrogate the object of interest and an idler photon that it stores for a joint quantum measurement with the light reflected back to the lidar. In particular, preparing an initial two-photon entangled state whose time-bandwidth product is much greater than unity, and using a special disentangling operation on the returned signal and retained idler photons before measuring them individually, yields a single-photon-transmitting lidar whose uncertainty product for its time-delay and frequency-shift measurements equals the reciprocal of the initial state's time-bandwidth product, thus circumventing the Arthurs-Kelly limit. This entanglement-enhanced lidar could find application whenever minimizing the transmitted photon flux is of paramount importance.

## **VI.G. Distributed Quantum Sensing Using Continuous-Variable Multipartite Entanglement**

Distributed quantum sensing uses quantum correlations between multiple sensors to enhance the measurement of unknown parameters beyond the limits of unentangled systems. In [Phys. Rev. A **97**, 032329 (2018)] we described a sensing scheme that uses continuous-variable multipartite entanglement to enhance distributed sensing of field-quadrature displacement. By dividing a squeezed-vacuum state between multiple homodyne-sensor nodes using a lossless beam-splitter

array, we obtain a root-mean-square (rms) estimation error that scales inversely with the number of nodes (Heisenberg scaling), whereas the rms error of a distributed sensor that does not exploit entanglement is inversely proportional to the square root of number of nodes (standard quantum limit scaling). Our sensor's scaling advantage is destroyed by loss, but it nevertheless retains an rms-error advantage in settings in which there is moderate loss. Our distributed sensing scheme can be used to calibrate continuous-variable quantum key distribution networks, to perform multiple-sensor cold-atom temperature measurements, and to do distributed interferometric phase sensing.

## VI.H. Qudit-Basis Universal Quantum Computation using $\chi^{(2)}$ Interactions

The efficiencies of  $\chi^{(2)}$  interactions have been steadily improving over the past decade, making the prospect of full-quantum  $\chi^{(2)}$  interactions worth considering in the context of quantum computation. Toward that end we have shown that such interactions offer a powerful approach to photonic quantum computation. Specifically, in (Niu, Chuang, and Shapiro 2018a) we have proved that full-quantum  $\chi^{(2)}$  interactions — together with linear-optics transformations and quantum-state frequency conversion (a pumped  $\chi^{(2)}$  interaction that has already been demonstrated with high efficiency) — enable universal quantum computation in  $(n+1)$ -dimensional qudit basis of the  $n$ -pump-photon subspace. Because any  $d$ -qudit unitary gate can be described by a Lie group element of  $SU[(n+1)^d]$ , the universality of a given class of Hamiltonians is directly related to that class's Lie algebra and the Lie group it generates via the exponential map. Thus, we used Lie-algebra analysis to identify code subspaces that are closed under  $\chi^{(2)}$  Hamiltonian evolutions. Our Lie-algebra analysis underlies the symmetry-operator formulation of qudit-basis error-correcting codes for photon-loss errors and the universal gate-set constructions in the encoded basis (see Sec. VI.I). Hence, our proposal provides a  $\chi^{(2)}$  approach to photonic quantum computation that is robust to photon loss.

## VI.I Hardware-Efficient Bosonic Quantum Error-Correcting Codes

In (Niu, Chuang, and Shapiro, 2018b), we established a symmetry-operator framework for designing quantum error-correcting (QEC) codes based on fundamental properties of the underlying system dynamics. Based on this framework, we proposed three hardware-efficient bosonic QEC codes that are suitable for  $\chi^{(2)}$ -interaction based quantum computation in multimode Fock bases: the  $\chi^{(2)}$  parity-check code, the  $\chi^{(2)}$  embedded error-correcting code, and the  $\chi^{(2)}$  binomial code. All of these QEC codes detect photon-loss or photon-gain errors by means of photon-number parity measurements, and then correct them via  $\chi^{(2)}$  Hamiltonian evolutions and linear-optics transformations. Our symmetry-operator framework provides a systematic procedure for finding QEC codes that are not stabilizer codes, and it enables convenient extension of a given encoding to higher-dimensional qudit bases. The  $\chi^{(2)}$  binomial code is of special interest because, with  $m \leq N$  identified from channel monitoring, it can correct  $m$ -photon-loss errors, or  $m$ -photon-gain errors, or  $(m - 1)$ th-order dephasing errors using logical qudits that are encoded in  $O(N)$  photons. In comparison, other bosonic QEC codes require  $O(N^2)$  photons to correct the same degree of bosonic errors. Such improved photon efficiency underscores the additional error-correction power that can be provided by channel monitoring. We also developed quantum Hamming bounds for photon-loss errors in the code subspaces

associated with the  $\chi^{(2)}$  parity-check code and the  $\chi^{(2)}$  embedded error-correcting code, and we proved that these codes saturate their respective bounds. Our  $\chi^{(2)}$  QEC codes exhibit hardware efficiency in that they address the principal error mechanisms and exploit the available physical interactions of the underlying hardware, thus reducing the physical resources required for implementing their encoding, decoding, and error-correction operations, and their universal encoded-basis gate sets.

## VI.J Resource Theory of Non-Gaussian Operations

Non-Gaussian states and operations are crucial for various continuous-variable quantum information processing tasks. To quantitatively understand non-Gaussianity beyond states, we established a resource theory for non-Gaussian operations in (Zhuang, Shor, and Shapiro 2018). In our framework, we considered Gaussian operations as free operations, and non-Gaussian operations as resources. We defined entanglement-assisted non-Gaussianity generating power and showed that it is a monotone that is nonincreasing under the set of free superoperations, i.e., concatenation and tensoring with Gaussian channels. For conditional unitary maps, this monotone can be analytically calculated. As examples, we showed that the non-Gaussianity of ideal photon-number subtraction and photon-number addition equal the non-Gaussianity of the single-photon Fock state. Based on our non-Gaussianity monotone, we divided non-Gaussian operations into two classes: (i) the finite non-Gaussianity class, e.g., photon-number subtraction, photon-number addition, and all Gaussian-dilatable non-Gaussian channels; and (ii) the diverging non-Gaussianity class, e.g., the binary phase-shift channel and the Kerr nonlinearity. This classification also implies that not all non-Gaussian channels are exactly Gaussian dilatable. Our resource theory enables a quantitative characterization and a first classification of non-Gaussian operations, paving the way towards the full understanding of non-Gaussianity.

## VII. Photons with Controlled Interactions: Superconducting Circuit Systems

The preceding section described the team's progress in photonic quantum systems in semiconductor PICs and fiber networks. Much of the difficulty of those systems stems from the fact that controlling and interacting optical photons is still extremely difficult. What is possible if photons can be stored for many oscillations in cavities and efficiently interacted via nonlinearities? Such experiments are now possible using microwave photons in superconducting circuits and show what will be possible when better fabrication and stronger nonlinear are developed in the optical domain. This section summarizes progress by the Yale group and collaborators on a leading superconducting circuit QED system.

### Deterministic teleportation of a quantum gate between two logical qubits

Yale team demonstrated deterministic teleportation of a quantum gate between two logical qubits. For modular quantum computer, an essential tool for universal quantum computation is the teleportation of an entangling quantum gate. As illustrated in Figure 11, we experimentally demonstrated a teleported controlled-NOT (CNOT) operation made deterministic by utilizing real-time adaptive control. Additionally, we take a crucial step towards implementing robust, error-correctable modules by enacting the gate between logical qubits, encoding quantum information redundantly in the states of superconducting cavities. Such teleported operations have significant implications for fault-tolerant quantum computation, and when realized within a

network can have broad applications in quantum communication, metrology, and simulations. Our results illustrate a compelling approach for implementing multi-qubit operations on logical qubits within an error-protected quantum modular architecture. [42]

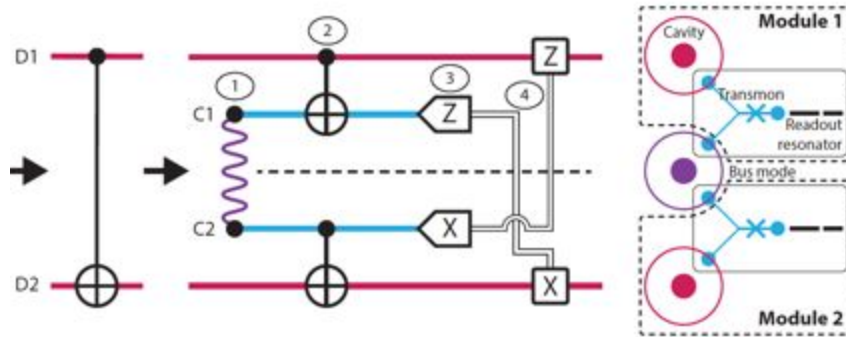


Figure 11 (Left panel) Teleported CNOT circuit between D1 and D2. The teleported CNOT circuit requires (1) entanglement between C1 and C2 (purple meander), (2) local operations, (3) measurement of C1 and C2, and (4) classical communication (double lines) and feedforward operations. (Right panel) Experimental realization (schematic top view) in a 3D cQED implementation. Each module consists of a data qubit defined as a coaxial 3D cavity (magenta), a communication qubit defined as a Y-shaped transmon qubit (cyan), and a Purcell-filtered, quasi-planar, stripline readout resonator (black). In this experiment, the two modules are linked by an additional mode that serves as a bus mode.

## VIII. Experimental Platforms for Optimal Quantum Measurements and State Verification in Many-Body Quantum Systems

A major goal of this program is developing methods to verify different kinds of many-body entanglement scalably, meaning that the required resources in the detection should scale at most polynomially with the number of qubits. To summarize, the approaches can be classified as using error correction in state verification and compressive measurements already mentioned in Section I.

### VIII.A Semiconductor Spins in Diamond

*Progress by Lukin group and collaborators:*

The Lukin group realized a new solid-state qubit with a long coherence time based on the negatively-charged silicon-vacancy (SiV<sup>-</sup>) color center in diamond which has recently emerged as a promising system for quantum photonics. Its symmetry-protected optical transitions enabled creation of indistinguishable emitter arrays and deterministic coupling to nanophotonic devices. The Lukin group demonstrated coherent control and suppression of phonon-induced dephasing of the SiV<sup>-</sup> electronic spin coherence by five orders of magnitude by operating at temperatures below 500 mK. By aligning the magnetic field along the SiV<sup>-</sup> symmetry axis, spin-conserving optical transitions and single-shot readout of the SiV<sup>-</sup> spin with 89% fidelity were achieved. Coherent control of the SiV<sup>-</sup> spin with microwave fields is used to demonstrate a spin coherence time  $T_2$  of 13 ms and a spin relaxation time  $T_1$  exceeding 1 s at

100 mK. These results establish the SiV– as a promising solid-state candidate for the realization of scalable quantum networks [43].

The Lukin group used a novel color center in diamond, Germanium-Vacancy (GeV), to realize a fiber-coupled quantum nanophotonics platform. GeV optical transitions were shown to have a high quantum efficiency and to be nearly lifetime broadened in nanophotonic diamond waveguides. These properties yield an efficient interface between waveguide photons and a single GeV center without the use of a cavity or slow-light waveguide. As a result, a single GeV center reduces waveguide transmission by  $18\pm 1\%$  on resonance in a single pass. We used a nanophotonic interferometer to perform homodyne detection of GeV resonance fluorescence. By probing the photon statistics of the output field, the Lukin group demonstrated that the GeV–waveguide system was nonlinear at the single-photon level [43]. [*Bhaskar et al, PRL (2017)*]

### **Photon-mediated interactions between long-lived quantum memories in a diamond nanocavity**

Photon-mediated interactions between quantum systems are essential for realizing quantum networks and scalable quantum information processing. The Lukin and Loncar teams demonstrated such interactions between pairs of silicon-vacancy (SiV) color centers strongly coupled to a diamond nanophotonic cavity. When the optical transitions of the two color centers were tuned into resonance, the coupling to the common cavity mode results in a coherent interaction between them, leading to spectrally-resolved superradiant and subradiant states. The team used the electronic spin degrees of freedom of the SiV centers to control these optically-mediated interactions. These experiments pave the way for implementation of cavity-mediated quantum gates between spin qubits and for realization of scalable quantum network nodes. See publication here[44]

Ruffin Evans, Mihir K. Bhaskar, Denis D. Sukachev, Christian T. Nguyen, Alp Sipahigil, Michael J. Burek, Bartholomeus Machielse, Grace H. Zhang, Alexander S. Zibrov, Edward Bielejec, Hongkun Park, Marko Loncar, Mikhail D. Lukin, “Photon-mediated interactions between quantum emitters in a diamond cavity,” *Science*, in press arXiv:1807.04265 (Jul 11 2018).

### **Photonic tensor networks produced by a single quantum emitter**

The Lukin team developed and analyzed a protocol to generate two dimensional tensor network states using a single quantum system that sequentially interacts with a 1D string of qubits. This is accomplished by using parts of the string itself as a quantum queue memory. This could be physically implemented with a single atom or atom-like system coupled to a 1D waveguide with a distant mirror, where guided photons act as the qubits while the mirror allows the implementation of the queue memory. We identified the class of many-body quantum states that can be produced using this approach. These include universal resources for measurement based quantum computation and states associated with topologically ordered phases. One example protocol explicitly developed is to deterministically create a 2D cluster state in a quantum nanophotonic experiment, that allows for a realization of a quantum computer using a single atom coupled to light.

### **Optical Control of a Single Nuclear Spin in the Solid State**

The Lukin team demonstrated a novel method for coherent optical manipulation of individual nuclear spins in the solid state, mediated by the electronic states of a proximal quantum emitter. Specifically, using the nitrogen-vacancy (NV) color center in diamond, they demonstrated control of a proximal  $^{14}\text{N}$  nuclear spin via an all-optical Raman technique. A thorough evaluation was done of the extent to which the intrinsic physical properties of the NV center limit the performance of coherent control, finding that it is ultimately constrained by the relative rates of transverse hyperfine coupling and radiative decay in the NV center's excited state, see Ref. [45].

We investigated thermalization dynamics of a driven dipolar many-body quantum system through the stability of discrete time crystalline order. Using periodic driving of electronic spin impurities in diamond, we realize different types of interactions between spins and demonstrate experimentally that the interplay of disorder, driving and interactions leads to several qualitatively distinct regimes of thermalization. For short driving periods, the observed dynamics are well described by an effective Hamiltonian which sensitively depends on interaction details. For long driving periods, the system becomes susceptible to energy exchange with the driving field and eventually enters a universal thermalizing regime, where the dynamics can be described by interaction-induced dephasing of individual spins. Our analysis revealed important differences between thermalization of long-range Ising and other dipolar spin models. See reference here[46].

### **Spectral alignment of single-photon emitters in diamond using strain gradient**

A major challenge for solid-state quantum networks is that emitters have different environments, which causes photons from different emitters to be spectrally distinguishable. To solve this problem, the Loncar group demonstrated spectral alignment of two solid-state single-photon emitters by utilizing the strain gradient. Multiple germanium vacancy (GeV) color centers in diamond were created in diamond microcantilevers using focused ion beam implantation. The strain response of the electronic energy levels of the GeV was measured by inducing an electrically controlled strain in the device. Leveraging the large strain gradient, the team tuned two GeVs in the spot to emit at the same optical wavelength. This strain gradient tuning can be used to realize spectrally identical quantum emitters for on-chip integrated quantum systems[47].

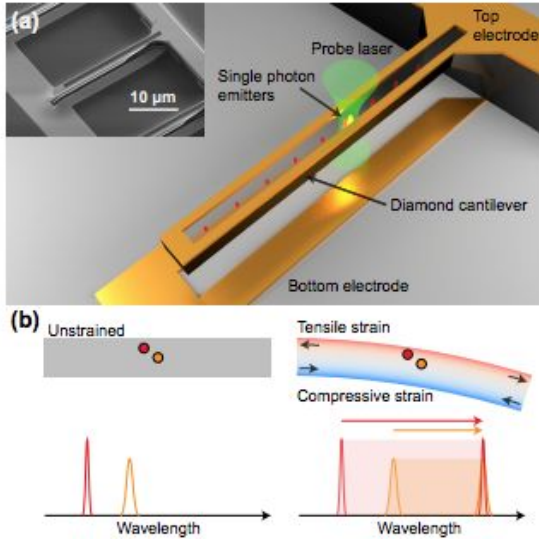


Figure 12: Multiple solid-state emitters spectrally tuned by strain gradient. (a) Schematic of a diamond microcantilever. Voltage applied between the top and bottom electrodes produces an electrostatic force on the cantilever, generating strain. Multiple GeVs at a single site can be simultaneously accessed optically by a probe laser. Inset: scanning electron microscope image of a diamond microcantilever. (b) Illustration of spectral alignment of two emitters with the strain gradient. Emission spectra of the two emitters are initially different (left), and are brought in resonance by strain gradient in the deflected cantilever (right).

### Phonon networks with SiV centers in diamond waveguides

With support of the NSF EFRI, the Loncar and Lukin teams made major advances in strain control of quantum emitters. As mentioned above, the corresponding phonon-emitter coupling also opens up an entirely new possibility for entanglement distribution through *phonon networks*. Working with theorist Peter Rabl, the team proposed and analyzed a novel realization of a solid-state quantum network, where separated silicon-vacancy centers are coupled via the phonon modes of a quasi-1D diamond waveguide[48]. In this approach, quantum states encoded in long-lived electronic spin states can be converted into propagating phonon wavepackets and be re-absorbed efficiently by a distant defect center. The analysis shows that under realistic conditions, this approach enables the implementation of high fidelity, scalable quantum communication protocols within chip-scale spin-qubit networks. Apart from quantum information processing, this setup constitutes a novel waveguide QED platform, where strong-coupling effects between solid-state defects and individual propagating phonons can be explored at the quantum level.

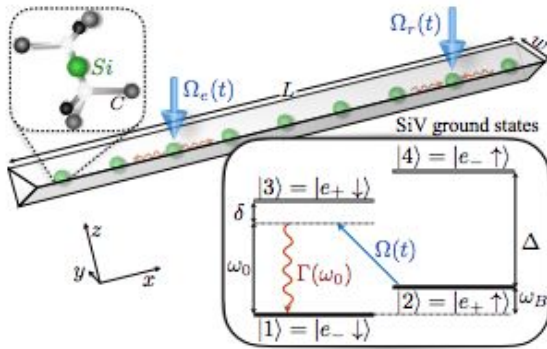


Figure 13: Setup. An array of SiV defects is embedded in a 1D phonon waveguide. The inset shows the level structure of the electronic ground state of the SiV center. A tunable Raman process involving the excited state  $|3\rangle$  is used to coherently convert the population of the stable state  $|2\rangle$  into a propagating phonon, which can be reabsorbed by any other selected center along the waveguide. See text for more details.

## Statistical Analysis of Nitrogen Vacancy Production

The Englund group performed a careful analysis of nitrogen vacancy (NV) centers produced by the implantation of monatomic  $^{15}\text{N}$  atoms into diamond followed by high-temperature annealing. This study investigated the spin and optical properties of large numbers of such NV centers. The data were acquired using our ‘robotic microscopes’ for automated characterization of color centers. This robotic data acquisition allowed us to systematically characterize large numbers of NV centers in an identical fashion. These studies revealed that the NVs with good optical properties are entirely created from the naturally occurring  $^{14}\text{N}$  isotope.

During implantation ions are accelerated towards the diamond, such that the N is implanted at a depth that depends on the implantation energy. Before coming to a halt in the diamond, the nitrogen atoms create damage within the crystal, displacing carbon atoms from their lattice site and leaving behind a vacancy. This study leads us to believe that this damage hinders the optical properties of the implanted nitrogen, while simultaneously providing vacancies that diffuse to naturally abundant  $^{14}\text{N}$ .

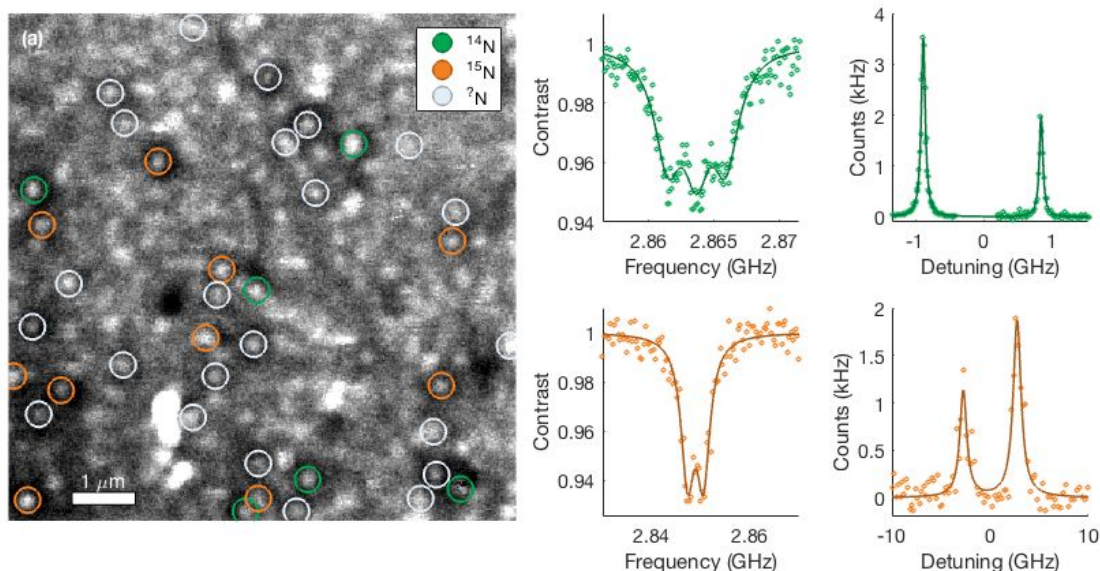


Figure 14: (left) Fluorescent Scan showing a representative density of NVs. The sample was implanted with  $^{15}\text{N}$  at a depth of 100 nm (85 keV) with a dose of  $10^9 \text{ N/cm}^2$  and subsequently annealed at 1200 C. (middle column) The top (green) data set shows a representative electron-spin resonance (ESR) for an NV formed with a  $^{14}\text{N}$ . Below (orange) shows an ESR spectrum of an NV formed with a  $^{15}\text{N}$ . (right column) The corresponding optical PLE spectrum taken for the same NV as the ESR showing the Ex and Ey transitions.

To coarsely determine the NVs' ZPL frequency, we illuminate with 532 nm light and record a spectrum. From the spectrum, we can position a resonant laser and perform a PLE scan. Finally, we split out the ground state spin transitions using a permanent magnet outside the cryostat. By sampling the 4 possible orientation frequencies, we can quickly determine which in orientation to perform a fine ODMR scan.

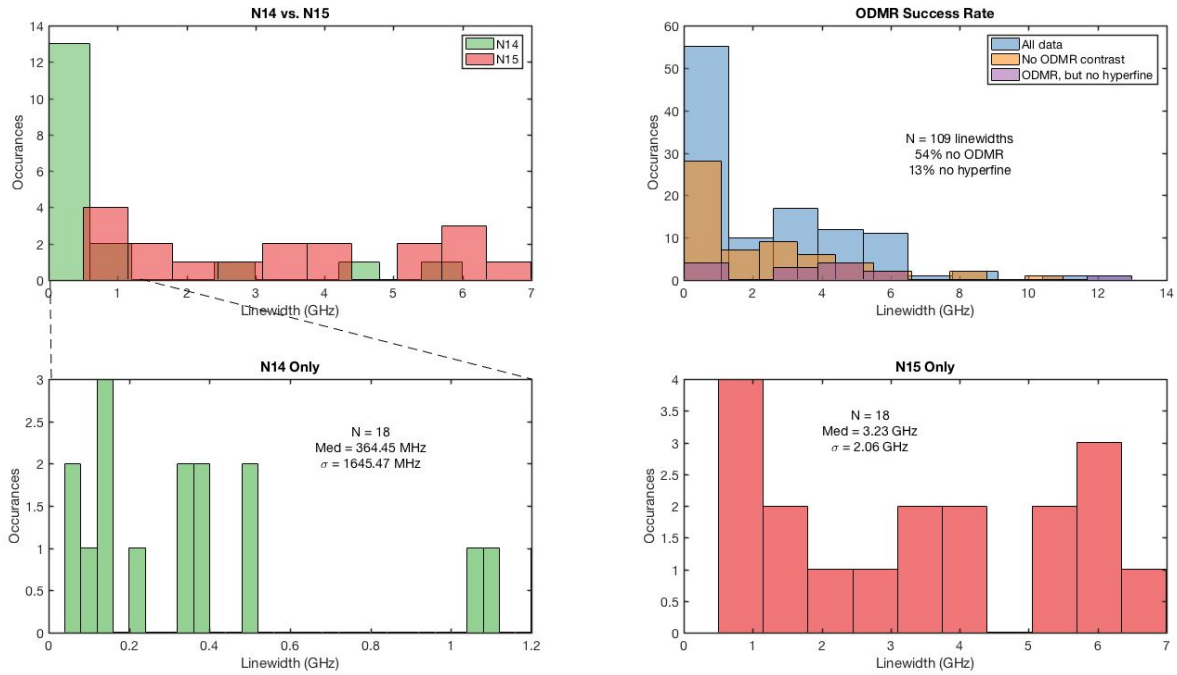


Figure 15: The result of performing the PLE measurement across 50 NVs, showing the difference between the two nitrogen isotopes.

Only 46% (50 total) of all NVs that showed a nice PLE spectrum also showed contrast in their ODMR signal. Of that set, 72% (36 total) had resolvable hyperfine transitions, 50/50 between  $^{14}\text{N}/^{15}\text{N}$ . The median ZPL linewidth for N14 was 364 MHz, while N15 was 3.23 GHz.

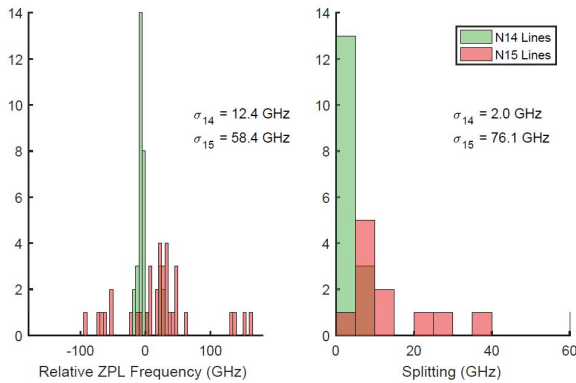


Figure 16: The additional damage due to implantation should manifest itself more on the NVs created via the implanted  $^{15}\text{N}$ . Axial strain results in an overall ZPL shift, while transverse strain will split the ZPL  $E_x$  and  $E_y$  transitions. The distribution of these shifts for both NV isotopes are shown in the figure above. The  $^{15}\text{N}$  indeed exhibits higher axial and transverse strain.

## Strain engineering of the silicon-vacancy center in diamond

The Loncar and Lukin groups demonstrated the control of the electronic structure of the silicon-vacancy (SiV) color-center in diamond by changing its static strain environment with a nano-electro-mechanical system. This allows deterministic and local tuning of SiV optical and spin transition frequencies over a wide range, an essential step towards multiqubit networks. They inferred the strain Hamiltonian of the SiV revealing large strain susceptibilities of order 1 PHz/strain for the electronic orbital states. They identified regimes where the spin-orbit interaction results in a large strain susceptibility of order 100 THz/strain for spin transitions, and propose an experiment where the SiV spin is strongly coupled to a nanomechanical resonator.

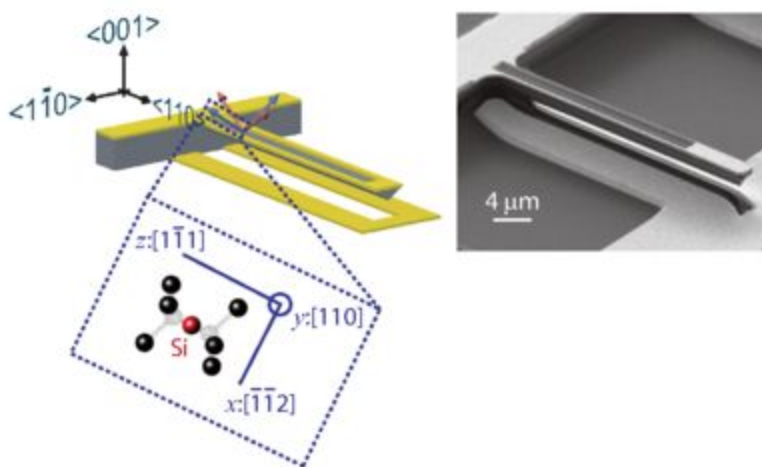


Figure 17: Left: Schematic of the diamond cantilever device and surrounding electrodes. Diamond crystal axes relative to the cantilever orientation are shown. Four possible orientations of the highest symmetry axis of an SiV are indicated by the four arrows above the cantilever. Under application of strain, these can be grouped into axial (red) and transverse (blue) orientations. The molecular structure of a transverse-orientation SiV as viewed in the plane normal to the cantilever axis is shown below, and crystal axes that define the internal coordinate frame of the color center are indicated. The  $z$  axis is the highest symmetry axis, which defines the orientation of the SiV. Right: SEM image of diamond cantilever NEMS device.

## Controlling the coherence of a diamond spin qubit through strain engineering

One of the major challenges in this program is to limit the uncontrolled interaction of the color center system with its environment. Whereas techniques to mitigate the impact of fluctuating electric and magnetic fields from the environment are well-developed (many developed in with NSF EFRI support), suppression of decoherence from thermal lattice vibrations is typically achieved only by lowering the temperature of operation. The Loncar and Lukin groups developed an nano-electro-mechanical system (NEMS) to mitigate the effect of thermal phonons on a solid-state quantum emitter without changing the system temperature. They showed that strain control allows for both an impressive range of optical tunability and significantly improved spin coherence. Their results also indicate that it may be possible to achieve strong coupling between the SiV spin and single phonons, which can lead to the realisation of phonon-mediated quantum gates and nonlinear quantum phononics.

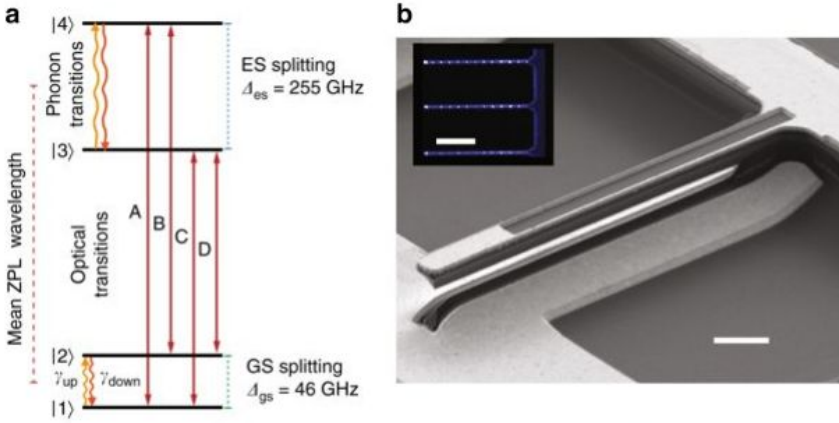


Figure 18: *Description of the SiV- and NEMS system.* a Electronic level structure of the SiV- showing the mean zero phonon line (ZPL) wavelength, frequency splittings between orbital branches in the ground state (GS) and excited state (ES) ( $\Delta_{gs}$  and  $\Delta_{es}$ , respectively) at zero strain, and the four optical transitions A, B, C, and D. Also shown are single-phonon transitions in the GS and ES manifolds. b Scanning electron microscope (SEM) image of a representative diamond NEMS cantilever. Dark regions correspond to diamond, and light regions correspond to metal electrodes. Scale bar corresponds to 2  $\mu\text{m}$ . (Inset) Confocal photoluminescence image of three adjacent cantilevers. The array of bright spots in each cantilever is fluorescence from SiV-centres. Inset scale bar corresponds to 10  $\mu\text{m}$

### Fiber-Coupled Diamond Quantum Nanophotonic Interface

Building upon recent demonstrations of nanophotonic waveguides and optical cavities in single-crystal diamond, our team demonstrated on-chip diamond nanophotonics with a high-efficiency fiber-optical interface achieving >90% power coupling at visible wavelengths. This approach was used to demonstrate a bright source of narrow-band single photons based on a silicon-vacancy color center embedded within a waveguide-coupled diamond photonic crystal cavity. The fiber-coupled diamond quantum nanophotonic interface results in a high flux (approximately 38 kHz) of coherent single photons (near Fourier limited at <1-GHz bandwidth) into a single-mode fiber, enabling possibilities for realizing quantum networks that interface multiple emitters, both on chip and separated by long distances.

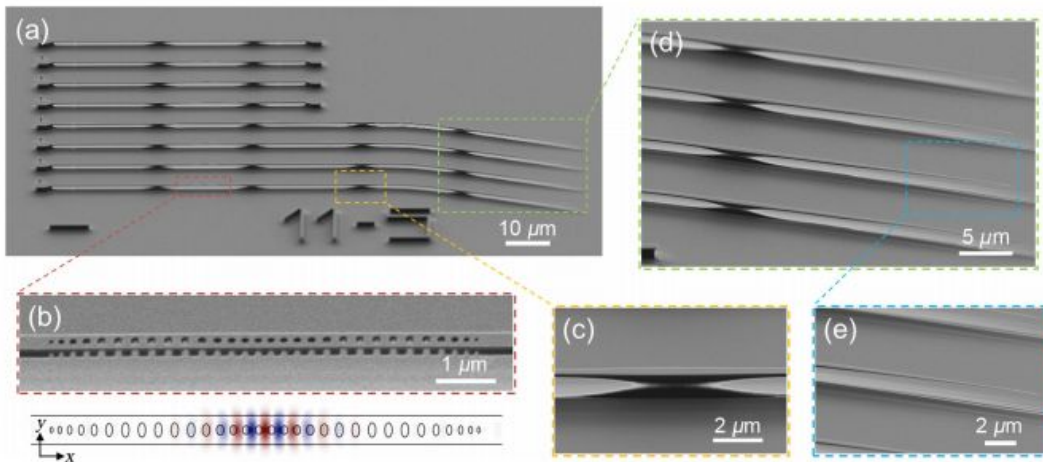


Figure 19: *On-chip diamond nanophotonic structures*. SEM images of (a) an array of diamond nanophotonic structures fabricated using angled etching. The four key components in each device are (1) freestanding diamond waveguides, (2) integrated diamond nanobeam photonic crystal cavities [panels (b) with the top-down electric field profile of the fundamental optical-cavity-mode inset], (3) vertical waveguide support structures [panel (c)], and (4) freestanding diamond waveguide tapers [panels (d) and (e)].

Photon-mediated interactions between quantum systems are essential for realizing quantum networks and scalable quantum information processing. We demonstrated such interactions between pairs of silicon-vacancy (SiV) color centers strongly coupled to a diamond nanophotonic cavity. When the optical transitions of the two color centers are tuned into resonance, the coupling to the common cavity mode results in a coherent interaction between them, leading to spectrally-resolved superradiant and subradiant states. We used the electronic spin degrees of freedom of the SiV centers to control these optically-mediated interactions. Our experiments pave the way for implementation of cavity-mediated quantum gates between spin qubits and for realization of scalable quantum network nodes.

The negatively-charged silicon-vacancy (SiV<sup>-</sup>) color center in diamond has recently emerged as a promising system for quantum photonics. Its symmetry-protected optical transitions enable creation of indistinguishable emitter arrays and deterministic coupling to nanophotonic devices. Despite this, the longest coherence time associated with its electronic spin achieved to date (~250 ns) has been limited by coupling to acoustic phonons. We demonstrated coherent control and suppression of phonon-induced dephasing of the SiV<sup>-</sup> electronic spin coherence by five orders of magnitude by operating at temperatures below 500 mK. By aligning the magnetic field along the SiV<sup>-</sup> symmetry axis, we demonstrated spin-conserving optical transitions and single-shot readout of the SiV<sup>-</sup> spin with 89% fidelity. Coherent control of the SiV<sup>-</sup> spin with microwave fields is used to demonstrate a spin coherence time  $T_2$  of 13 ms and a spin relaxation time  $T_1$  exceeding 1 s at 100 mK. These results establish the SiV<sup>-</sup> as a promising solid-state candidate for the realization of scalable quantum networks.

We demonstrated a quantum nanophotonics platform based on germanium-vacancy (GeV) color centers in fiber-coupled diamond nanophotonic waveguides. We showed that GeV optical transitions have a high quantum efficiency and are nearly lifetime-broadened in such nanophotonic structures. These properties yield an efficient interface between waveguide photons and a single GeV without the use of a cavity or slow-light waveguide. As a result, a single GeV center reduces waveguide transmission by  $18 \pm 1\%$  on resonance in a single pass. We used a nanophotonic interferometer to perform homodyne detection of GeV resonance fluorescence. By probing the photon statistics of the output field, we demonstrated that the GeV-waveguide system is nonlinear at the single-photon level.

### **VIII.B Many-Body Quantum Systems Based on Trapped Ions**

The University of Maryland Ion Trap group has proceeded along two fronts in the demonstration of entanglement validation in larger collections of qubits. Using the programmable ion quantum computer, they demonstrated full universal control over up to 7 qubits. They also observed

developed a system of 50+ trapped ion qubits with tunable long-range interactions and individual single-shot measurements with 99% efficiency, allowing the extraction of all possible correlation functions. These results are described below:

### **1. Quantum applications with up to N=7 trapped ion qubits.**

Using individual addressing of up to 7-ion chain of qubits, the UMD team demonstrate modular and reconfigurable quantum circuits to realize simple algorithms that can easily be verified without resorting to multi-qubit entanglement measures. Demonstrations include:

- (a) A comparison of simple quantum algorithms (Bernstein-Vazirani, Hidden Shift) between the 5-qubit ion trap system and the 5-qubit IBM Quantum Experience, showing the effect of qubit connectivity on algorithm success [Proc. Natl. Acad. Sci. 114, 13 (2017)].
- (b) Grover's quantum search algorithm on 3 qubits, with all possible single and dual marked element oracles[49].
- (c) Encoding of a  $[[4,2,2]]$  fault-tolerant error-detection circuit, showing protection from the encoding step in addition to itinerant errors, and showing consistency with a lack of any correlated errors [50].
- (d) Implementing a quantum circuit that provides a positive test for the scrambling features of a given unitary process [16].

### **2. Entanglement Dynamics with up to 53 Trapped Ion Qubits**

Using global optical control of the motional modes of a static linear crystal of many ions in a linear trap, the UMD team has demonstrated various aspects of nonequilibrium qubit dynamics:

- (a) Prethermal behavior of up to 10 qubits with long-range Ising interactions, showing a saturation of dynamics that do not represent the ultimate expected thermal equilibrium states [Science Advances 3, e1700672 (2017)].
- (b) By driving the many body system with a Floquet Hamiltonian of Ising couplings alternating with a transverse effective field and disordered local qubit fields, a stable "Time Crystal" that is resistant to perturbations in the drive characteristics [Nature 543, 217 (2017)].
- (c) A quench of the Ising model in a variable transverse field with up to 53 qubits has shown signatures of a dynamical phase transition, where the mean domain size in the string displays a cusp at a particular value of the transverse field. This is the largest quantum simulation ever performed with individually measureable qubits [Nature 551, 601 (2017)].
- (d) A cryogenic ion trapping system with more than 100 ions, designed for large scale quantum simulation of spin models [19].

### **Related Theory, Materials, and Methods**

None to add to theory, materials, and methods described in MURI Team Achievements Section above.

### **Transitional Planning:**

The Englund group has worked with Rome Laboratory to transition programmable photonic integrated circuits and electronics drivers. We have one new publication[51] and another under review.

## **Educational Impact and Outreach**

MIT:

- Cambridge Science Festival, 2014, 2015, 2016, Nano-observatory Days. This event invites the public in to view the nanofabrication facilities at MIT. Participatory demos of photolithographic processes and electron and ion microscopes are shown. More than 100 members of the general public attend this event.
- Boston Museum of Science NanoDays, 2014, 2015, 2016, 2017, 2018. This annual, day-long event brings in nanoscience researchers from the Boston area to run interactive, hands-on demonstrations for hundreds of museum guests of all ages, from toddlers to adults.
- DayCon, Harvard University “Science In The News”, 2018. This event is a free, one-day conference with interactive science demonstrations across various research areas, from microbiology to climate science to quantum information. Approximately 100 community members of all ages attended and engaged in activities.
- East Boston High School Science Fair, 2016, 2017. Members of our team volunteered as judges for the annual science fair at East Boston High School, collectively evaluating around 50 student projects and discussing their own research at MIT.
- Science on Saturday Outreach program. Planning and participation in Science on Saturday, 2016, EECS day. This event engaged approximately 1000 K-12 students and their parents in demonstrations and hands-on activities around electronics, computer science, and optics.
- MIT iQuISE Program: The MURI supported research by a number of graduate students and post-doctoral students currently being trained. Many of these students participated in and helped to organize MIT's interdisciplinary quantum information for science and engineering (iQuISE) program. The mission of iQuISE is to provide the first comprehensive education-to-employment pathway for students in quantum information science and engineering. The entirely student-run organization hosts a weekly lunch seminar series with speakers from university, government, and industry labs. The wide variety of speakers who are interested in recruiting talent from the iQuISE community reflects the rapidly growing employment opportunities for students with expertise in quantum information science. Rather than creating just another seminar series, the student leaders of iQuISE also focus heavily on community-building activities by hosting ice-cream socials, organizing weekend hikes, and embarking on visits to local industry labs (such as IBM, and BBN). As a reflection of the interdisciplinary aspect of quantum information science, the funding for iQuISE comes from the generous financial support of the Research Lab for Electronics (RLE), Laboratory for Nuclear Sciences (LNS), and the physics departments. Since its creation in 2008, the iQuISE program has supported to completion nearly 30 PhD students, and, by the end of this decade, expects to have an alumni network comprised of more than 60 trained scientists within the field of quantum information science.

University of Maryland:

The Monroe Group at the University of Maryland actively contributes interactive laboratory tours and demonstration booths at the annual “Maryland Day” exposition on the campus of the University of Maryland. In 2014 and 2016, the group also staffed a Joint Quantum Institute and University of Maryland booth at the USA Annual Science Exposition in Washington, DC. C. Monroe has given several public lectures at high schools and Maryland and MIT alumni events in the Washington/Baltimore region, promoting STEM fields and quantum physics to young students and the interested public.

### **Team Activities**

The team has had regular video conference and in-person meetings to coordinate on research tasks.

### **List of Awards & Publications:**

#### **Individual Awards**

#### **Faculty Awards:**

##### **Dirk Englund:**

2020 Alexander Humboldt Fellowship  
Bose Research Fellow (2018)  
OSA Lomb Medal (2017)  
2016 R&D100 Award  
2017 ACS Photonics Young Investigator Award.

##### **Mikhail Lukin:**

Elected to National Academy of Science (2018)  
National Security Science and Engineering Fellowship (2015)  
Julius Springer Prize for Applied Physics (2015)  
Distinguished Lecturer, Lewiner Institute for Theoretical Physics (Technion, Israel) (2015)  
Alexander M. Cruickshank Lecturer Award, Gordon Research Conferences (2016)

##### **Karl Berggren:**

Frank Quick Innovation Fellowship (2016)  
Elected to Fellow of AAAS (2015)  
Elected to Fellow of IEEE (2015)  
Paul F. Forman OSA Team Engineering Award (2015)

##### **Christopher Monroe:**

Elected to National Academy of Science (2016)  
APS Arthur Schawlow Prize for Laser Science (2015)

**Robert Schoelkopf:**

Elected to National Academy of Science (2015)

**Jeffrey Shapiro:**

Elected to Fellow of SPIE (2014)

**Franco Wong:**

Elected to Fellow of Optical Society of America (2014)

**Student Awards:**

Shantanu Debnath (Maryland), finalist APS DAMOP Thesis Prize (2017)

Emily Toomey (MIT), National Science Fellowship

Andrew Dane (MIT), NASA Graduate Research Fellowship

Nicholas Harris (MIT): Intelligence Community Postdoctoral Fellowship

Mihika Prabhu (MIT), National Science Fellowship

Greg Steinbrecher (MIT), Facebook Fellowship

Darius Bunandar and Nicholas Harris (MIT): MIT \$100K business challenge; Harvard \$75k President's Innovation Challenge; MIT Sandbox Innovation Challenge

Quntao Zhuang (MIT), 2016-2017 Claude E. Shannon Research Assistant

Murphy Yuezhen Niu (MIT), 2017-2018 Claude E. Shannon Research Assistant

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