QLCI – CI: Institute for Quantum Computing and Control (IQC^2) at MSU

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Project Summary: This is a proposal to form a Quantum Leap Challenges Institute (QLCI) at Michigan State University (MSU). This institute, the "Institute for Quantum Computing and Control (IQC^2)", will address the research themes of **Quantum Computation** and **Quantum sensing** with specific focus on Noisy Intermediate Scale Quantum (NISQ) systems. The IQC^2 at MSU is made up of a broad spectrum of researchers spanning multiple areas of expertise focused on the development of quantum hardware, theory and algorithms. IQC^2 partners include diverse organizations across academia, government and industry.

Intellectual Merit: The IQC^2 at MSU will address present-day and future grand challenges of quantum information science (QIS) through key experimental, theoretical and algorithmic advances in **quantum computation** and **quantum sensing** needed to harness the full power of the noisy quantum hardware of today and pave a path to the scalable fault tolerant technologies of tomorrow. Key to achieving these goals is breaking down and understanding the role of noise in quantum information systems, not only to exploit NISQ machines, but to push beyond the NISQ-era. In particular, the IQC^2 team will: **(1)** Construct a hybrid low-temperature nitrogen-vacancy (NV) center scanning microscope to quantify noise in NISQ-era superconducting qubits and hybrid quantum systems; **(2)** Model and validate noise measurements on NISQ-era superconducting qubits and NV centers to develop novel quantum sensors; **(3)** Develop precise noise models for hardware-agnostic multi-qubit systems to dramatically improve NISQ-era machines; **(4)** Design novel quantum algorithms that take into account specific noise models for optimization, chemistry, nuclear physics and data science; **(5)** Develop experimental infrastructure for controllably placing and coupling adjacent color centers in diamond, a step which is required to realize their potential as a scalable qubit system; **(6)** Develop a world leading quantum work force recruiting and training program; **(7)** Facilitate new partnerships in QIS and serve as a national hub for discussion, research, design, development and training.

This multidisciplinary effort between physicists, chemists, engineers, mathematicians, computer and data scientists, and algorithm developers will enable the identification and quantification of the noise-limiting obstacles in NISQ-era qubits based on superconducting circuits, color centers in diamond, trapped electrons and hybrid quantum systems. Ultimately, these advances will be critical to building the scalable quantum processors of the future. These efforts will deliver new quantum sensors to investigate the coherence of established quantum technologies and provide deep insight into the structure of noise in these quantum systems. Direct models and simulations will be built to understand these noise sources and new methods will be developed to operate qubits in the presence of noise and to engineering entanglement using noise as a tool. New quantum algorithms will be developed for optimization, quantum machine learning, hardware-aware quantum compiling, quantum annealing as well as "quantum inspired" algorithms run on specialized hardware that directly incorporate these noise structure models. The work will also push the boundaries of NISQ by investigating the utility of variational methods for simulating chemical structure, quantum field theories and nuclear matter on NISQ-era cloud hardware as these applications are emerging as "killer apps".

Broader Impacts: The long-term sustainability of the QIS effort includes buy-in from academia, national labs, industry and startup companies, all working together, to build a diverse national pipeline of workforce-ready quantum researchers who will turn the scientific discoveries of today into the private sector quantum technologies of tomorrow. Close collaborations with IBM, Google, Ford Motor Company, Fraunhofer USA, Lawrence Berkeley National Laboratory (LBNL), the Facility for Rare Isotope Beams (FRIB), D-Wave Systems, EeroQ Inc., The Unitary Fund and Northrop Grumman are central to the vision of the IQC^2 and a sustainable quantum future. Through joint internships, boot-camps, hackathons, workshops, course-development, technology transfer and IP sharing, the IQC^2 at MSU will serve as a hub through which these partners will interface, connect and collaborate, to accelerate the advance of next-generation quantum computing systems and ensuring that the future STEM workforce is well-prepared for a new quantum-based world, and to engage the public in the seemingly sci-fi-like quantum universe.

Key Words: quantum information science, quantum computing, quantum sensing, quantum algorithms, NISQ, superconducting qubits, NV centers, diamond, electrons on helium, QAOA, quantum machine learning, quantum annealing, VQE, quantum inspired algorithms, quantum workforce development

(1) Cross-Disciplinary Research Team: The Institute for Quantum Computing and Control (IQC^2) at MSU is made up of a broad spectrum of researchers spanning multiple areas of expertise focused on the development of quantum hardware, theory and algorithms. IQC^2 partners include a diverse array of institutions and organizations ranging across academia, government and industry.

Michigan State University Senior Personnel

Name	Department	Name	Department
(A) Angela K. Wilson (PI)	CHEM	(A) Andrew J. Christlieb (co-PI)	CMSE,MTH
(T) Mark I. Dykman (co-PI)	PHY	(E) Marcos Dantus (co-PI)	CHEM
(E) Johannes Pollanen (co-PI)	PHY	(T) John D. Albrecht	ECE,CheMS.
(A) Alexei Bazavov	PHY,CMSE	(E) Norman O. Birge	PHY
(E) Timothy Grotjohn	ECE	(A) Matthew J. Hirn	CMSE,MTH
(A) Morten Hjorth-Jensen	NSCL,PHY	(T) Ilya Kachkovskiy	MTH
(A) Dean Lee	NSCL,PHY	(A) Huey-Wen Lin	PHY,CMSE
(T) Mohammad Maghrebi	PHY	(A) Elizabeth Munch	CMSE,MTH
(E) John Papapolymerou	ECE	(T) Michael Shapiro	MTH
(T) Jeffrey H. Schenker	MTH	(A) Andrea Shindler	NSCL

Key: (A) Algorithm, (E) Experiment, (T) Theory

Expertise and Roles: **PI Angela Wilson** will direct the institute and coordinate interactions with external partners. Her group will also develop variational methods for quantum simulation of molecules. **Wilson** along with **co-PI's Andrew Christlieb** and **Johannes Pollanen** will form the the executive committee that will lead the institute. **Timothy Grotjohn** will grow ultra-high purity quantum-grade diamond incorporating precision nitrogen doping layers. **co-PI Marcos Dantus** will focus on generating and imaging color centers in diamond using ultrafast optical techniques. **co-PI Pollanen** will develop quantum acoustic sensors and new qubits based on hybrid quantum systems and electrons on helium, he will also coordinate collaboration with the institute's private sector partners. **co-PI Johannes Pollanen, Norman Birge** and **John Papapolymerou** will study noise in superconducting qubits and resonators. **John Albrecht** will produce device simulations using quantum Monte Carlo methods, tying theory to experiment. **co-PI Mark Dykman** has recently been honored with a Faculty Research Award on Quantum Computing by Google and he will lead and the institute's theory team and study noise in multi-qubit systems. IQC^2 theory efforts will be supported by **Michael Shapiro, Ilya Kachkovskiy, Mohammad Maghrebi** and **Jeffrey Schenker**. The IQC^2 algorithm team will develop novel noise resistant algorithms for a wide variety of applications including nuclear physics (**Morten Hjorth-Jensen, Dean Lee, Andrea Shindler**), quantum field theories (**Alexei Bazavov, Huey-Wen Lin)**, quantum machine learning and compiling (**Matthew Hirn**) and optimization (**Elizabeth Munch, Matthew Hirn, Dean Lee**). **co-PI Andrew Christlieb** will develop "quantum inspired" algorithms on specialized classical hardware. He will also supervise outreach and education efforts.

(2) Overview of the IQC^2 at MSU: Noise is a key limiting factor in the progress of modern quantum information science (QIS), a fact that was emphasized by John Preskill of Caltech when he coined the current era of quantum computing as the "*Noisy Intermediate-Scale Quantum (NISQ) Era*" [1]. This era is defined by access to noisy quantum computers having $\sim$ 10's of qubits that can be used as test-beds for relatively small-scale prototype quantum algorithms, but are unable to perform broadly useful or transformative computation. The grand challenge in QIS is to ultimately overcome the NISQ-era and develop large-scale quantum processors capable of running complex quantum algorithms or realizing scalable quantum error correction [2]. Simultaneously, it is vital to identify disruptive benefits that can be achieved using the NISQ systems that are in existence today.

MSU has a long-standing legacy in QIS, having established the MSU *Institute for Quantum Science* in 2002, which has recently evolved into the MSU *Center for Quantum Computing, Science, and Engineering*. Pioneering work in the field, such as that done by **Mark Dykman** on the operation of quantum gates when the coupling between qubits can not be turned off, laid the foundation for current QIS research at MSU. This work is now recognized as instrumental to the operation of the majority of quantum computing systems. In 2018 **Dykman** was recognized by Google for his past, and on-going, contributions to QIS. From these beginnings, MSU's strengths in QIS have grown to now span more than 20 faculty from multiple disciplines, who have come together for this effort. These include long-time experts like **Mark Dykman** to junior faculty like **Johannes Pollanen**, who is already prominent in the field and has co-founded a quantum computing start-up company. Independent of this proposed institute, MSU continues to pursue QIS with commitment to hire six additional faculty in quantum information science and engineering, who will be embraced by the IQC^2 as they are hired. With so many experts in one location that cross multiple disciplines, this unique group provides a strong gravity for why MSU is the ideal location for tackling the issue of noise in QIS.

Intellecutal Merit: The Institute for Quantum Computing and Control (IQC^2) at Michigan State University will address present-day and future grand challenges of QIS by producing key experimental, theoretical and algorithmic advances in **quantum computation** and **quantum sensing** needed to harness the full power of the noisy quantum hardware of today and pave a path to the scalable fault tolerant [2] technologies of tomorrow. Key to achieving these goals requires breaking down and understanding the role of noise in quantum information systems, not only to exploit NISQ machines, but to push beyond the NISQ-era. In particular, the IQC^2 team will:

- Construct a hybrid low-temperature NV center scanning microscope to quantify noise in NISQ-era superconducting qubits and hybrid quantum systems (see section 4 and 7).
- Model and validate noise measurements on NISQ-era superconducting qubits and nitrogen-vacancy (NV) centers to develop novel quantum sensors (see section 4).
- Develop precise noise models for hardware-agnostic multi-qubit systems to dramatically improve NISQ-era multi-qubit machines (see section 4).
- Design novel quantum algorithms that take into account specific noise models for optimization, chemistry, and data science to demonstrate quantum advantage on NISQ-era machines (see section 4).
- Develop experimental infrastructure for controllably placing and coupling adjacent color centers in diamond, required to realize their potential as a scalable qubit systems (see section 4).
- Develop a world leading quantum work force recruiting and training program (see section 5 and 6).
- Facilitate new partnerships in QIS and serve as a national hub (see Fig. 1) for discussion, research, design, development and training (see section 7).

This is an effort that reaches across disciplines and requires tight collaboration between physicists, chemists, engineers, mathematicians, and data scientists. Experimentalists at the IQC^2 will identify, and quantify, the noise sources and structures in NISQ-era qubits based on superconducting circuits, color centers in diamond, trapped electrons and hybrid quantum systems. In the long term, these advances will be critical to building the scalable quantum processors of the future. In the short term, these efforts will deliver new quantum sensors to investigate, and vastly improve, the level of noise in these established quantum technologies. Experimental inputs on the noise structure in these systems will allow IQC^2 mathematicians and theoretical quantum information scientists to build direct models and simulations to validate our understanding of the noise sources and to develop novel methods for qubit operation in the presence of noise and for engineering entanglement and coherence using noise as a tool. With these noise models in-hand, institute experts in computational data science and machine learning (ML) will deliver "noise-aware" next-generation NISQ algorithms for optimization, quantum ML, hardware-aware quantum compiling, quantum annealing as well as "quantum inspired" algorithms run on specialized hardware. The IQC^2 algorithm team will also push the boundaries of NISQ by investigating the utility of variational methods for simulating chemical structure, quantum field theories and nuclear matter on NISQ-era cloud-connected hardware as these applications are emerging as killer-apps [3] for modern-day hybrid quantum-classical methods.

Broader Impacts: The research agenda proposed below will produce breakthroughs on a number of clearly defined challenges within a 5-year period, however the vision of the IQC^2 is much bolder and broader. The long term sustainability of the QIS effort requires buy-in from academia, national labs, industry and startup companies, all working together, to build a diverse national pipeline of workforce-ready quantum researchers who will turn the scientific discoveries of today into the private sector quantum technologies of tomorrow. We view our close collaborations with IBM, Google, Ford Motor Company, Fraunhofer USA, Lawrence Berkeley National Laboratory (LBNL), the Facility for Rare Isotope Beams (FRIB), D-Wave Systems, EeroQ Inc., The Unitary Fund and Northrop Grumman as central to the vision of the IQC^2 and a sustainable quantum future. Through joint internships, boot-camps, hackathons, workshops, course-development, technology transfer and IP sharing, the IQC^2 at MSU will serve as a hub (see Fig.1) through which these partnerships will interface, connect and collaborate.

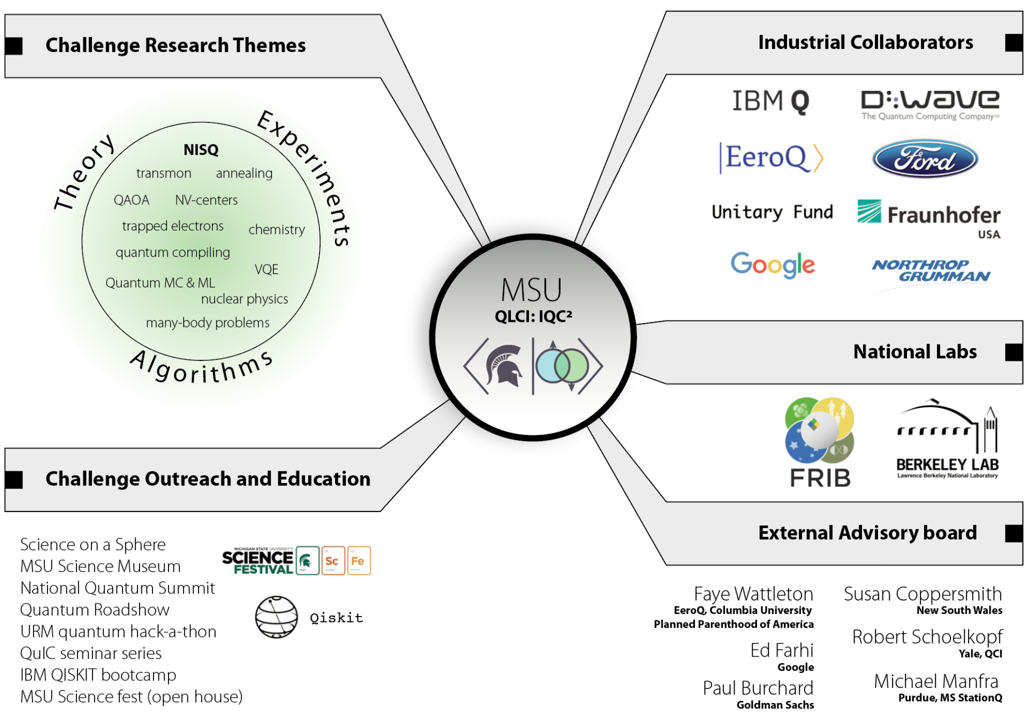

Figure 1: Overview of the IQC^2 at MSU. The Institute serves as a central hub, bringing together our research activities, education and outreach efforts, industrial partners and national labs and guided by an expert external advisory board.

The IQC^2 will benefit from the guidance of a expert external advisory board made up of world leaders in quantum computing experiment (**Robert J. Schoelkopf, Michael J. Manfra**), theory (**Susan N. Coppersmith**) and algorithms (**Edward H. Farhi**) as well as leaders in QIS private sector (**Faye Wattleton, Paul Burchard**). Close, regular interaction with these advisors will help to guide the trajectory of the IQC^2 and ensure that the institute stays true to its vision and is meeting its technological, educational and workforce development milestones (see Section 9).

QIS is poised to be the next revolution in computing. To address issues of equality, inclusion and diversity, core to the vision of the center is a strong outreach program that seeks to engage underrepresented populations in the field of quantum computing (see section 10). We seek to develop novel methods of engagement, through the development of Science on a Sphere, workshops and hackathons that target members of underrepresented populations at a range of ages. These will be done in consultation with the MSU Diversity Programs Office, with the intent of utilizing best practices from the beginning. For example, the retention rate for Women In Engineering, as supported by the program, fluctuates between 82% to 92%, as opposed to men where the retention rate is $\sim 65\%$ in engineering. The IQC^2 full-time outreach coordinator will implement best practices to create community to support under-represented populations in QIS.

(3) Overview of the state-of-the-art in the NISQ-era: Quantum computing relies on the coherent dynamics of quantum bits (qubits) and their coherent manipulation. Therefore, noise is a major, or even the major, impediment to the advancement of quantum computing, both in the NISQ-era and beyond. To advance QIS the capability to understand, predict, minimize and manipulate the behavior of noise in quantum systems is vitally needed for both designing and using these systems. A complete understanding of noise will impact nearly every aspect of quantum information processing, from the development of improved hardware and quantum sensors to the design of next-generation "noise-resistant" quantum algorithms. Understanding noise in quantum systems, in all its complexity, must be achieved to progress beyond the NISQ-era.

Large industrial teams are racing toward "quantum sumpremacy" [4, 5], when engineered quantum systems without error correction can no longer be simulated on classical supercomputers. Despite claims in the popular media, this achievement will not, by itself, produce large-scale broadly useful quantum computers [1]. These more powerful machines are likely still relatively far in the future (~ 20 years or more). "Quantum supremacy" is a beginning, not the end. Beyond it are "quantum advantage" (when quantum computers actually perform useful tasks, *e.g.* in chemistry, optimization, or finance) and fault tolerance (when large-scale error correction can be implemented to unlock the ultimate power of quantum computers). Significant work remains to be done to overcome the limitations of the NISQ-era in which we find ourselves today. Below we describe the state-of-the-art as it pertains to the noisy quantum systems and algorithms that form the research backbone of the IQC^2 at MSU.

(3.1) Superconducting qubits, diamond NV centers, and hybrid quantum systems – Theory and Experiment: A defining, and confining, characteristic of the NISQ-era is the assumption that coherence of qubits can be destroyed by Gaussian or Poissonian noise processes. Recent experiments have shown that this is not the case [6] but rather that quantum coherence is a dynamical property with non-trivial time evolution of its own [7]. To move beyond incremental advances will require theoretical breakthroughs in the modeling and simulation of noise, and its effect, in multi-qubit systems. Of vital important is the understanding of the coupling between qubits and their noisy environment to enhance coherence, and to develop quantitative models of the sources of error, the ways they couple to qubits, and the resulting noise and error statistics. As NISQ systems continue to grow in size, theoretical advances are needed to design improved multi-qubit measurement and control protocols in the presence of noise. Without significant breakthroughs in our understanding of noise sources and their structure, QIS systems are doomed to be nothing more than an novelty. Once we truly understand these noise in these quantum systems, we will be poised to make real progress, with the promise of leveraging existing NISQ-era platforms to demonstrate quantum advantage.

On the experimental side, extensive progress in superconducting (SC) qubits has made them a viable platform for building scalable quantum simulators and universal processors [8–10]. In particular, the circuit quantum electrodynamic (cQED) architecture [11, 12], wherein SC qubits are controlled and read out with a superconducting microwave resonator, has been successful for implementing complex qubit control protocols and extending the coherence of quantum information stored in superconducting circuits. Coherence times $\gtrsim 10\ \mu s$ are now routinely achieved in SC qubit systems containing $\sim$ 10's of qubits. However, building and operating larger than proof-of-concept NISQ systems will require individual qubits with an even higher level of coherence and resistance to noise. Estimates for combined threshold error rates indicate the need for coherence times at least $1000\times$ longer than gate and measurement times [2, 13, 14]. In the most optimistic case, this corresponds to at least and order of magnitude needed improvement in coherence for

SC qubits. For qubits based on SC circuits, the major sources of noise and decoherence can be traced back to microscopic materials defects in, or on, the device. These defects are typically close to the substrate surface or within the qubit itself. They include dielectric two-level states (TLS), which lead to qubit energy relaxation [15] as well as fluctuating magnetic defects, which lead to qubit dephasing [16–19]. Noise also comes in through the interaction of the qubit with its electromagnetic environment. Non-equilibrium quasiparticles in the superconducting material are known [20–24] to lead to qubit decoherence and microwave loss as are trapped magnetic flux in the device [25, 26].

On the other hand, relative to SC qubits nitrogen-vacancy (NV) centers in diamond represent a relatively low-noise QIS material system. NV centers can be produced to have electronic spin coherence lifetimes of milliseconds [27] at room temperature and on the order of seconds at cryogenic temperatures [28]. Moreover, the quantum state of an NV center can be controlled with RF, microwave and optical techniques for initialization, coherent manipulation and readout. These properties make NV centers potentially ideal tools for probing noise in other quantum systems (*e.g.* SC qubits) and for incorporation into hybrid quantum devices and sensors [29–33]. However important challenges must be solved to reliably and scalably build NV center coupled sensors with precisely controlled spatial placement and number of defect centers. The direct coupling of two NV centers has been demonstrated [34], but they must be quite close to each other ($\sim$ 10's nm). Additional challenges remain for coupling NV centers to SC qubits and understanding and mitigating the degradation of their coherence by bulk and surface impurities. Solving these challenges is vital to the continued advancement of color centers in diamond as a precision quantum noise sensor.

(3.2) NISQ-era quantum algorithms: While quantum algorithms with vastly improved performance relative to the best classical algorithms are theoretically known [35], the nascent and noisy state of present-day quantum computing hardware precludes their large-scale execution [36]. Put simply, noise and decoherence are confining quantum computing to the NISQ-era. However, there are ways to move forward, both with NISQ-era systems and beyond. For example, a class of algorithms based on variational methods has recently been proposed [37, 38], which are well-suited for operation on industrial NISQ-era cloud-connected machines (*e.g.* the "IBM-Q Experience"). In essence, these algorithms use a parameterized quantum circuit to evaluate an objective function *e.g.*, the energy of a molecule such as molecular hydrogen [39] or water H_2O [40] and a classical optimizer to minimize the cost function. By relying on beneficially short-depth quantum circuits, this class of algorithms show potential for being robust to certain errors [41] and correspondingly have been successfully implemented on photonic [37], superconducting [42], and trapped-ion [43] architectures for the ground state energies of small molecules [44]. These methods are general purpose and numerous of applications are possible from combinatorial optimization [45] to quantum chemistry [46], as well as for computing excited state energies [47], *e.g.* in mass-renormalization calculations of scalar quantum field theories. Additionally, variational algorithms have recently been proposed for matrix diagonalization [48] with applications ranging from ML to condensed matter physics, and hardware-aware quantum compiling [49], which is critical for successful implementation of any quantum algorithm.

While NISQ-era quantum algorithms have seen initial success, many exciting challenges remain for dramatically improving these algorithms and scaling them to larger systems. A recent result shows that random circuit structures have vanishing gradients as the size of the circuit increases [50] highlighting the importance of choosing an appropriate circuit, and noise, structure, for the problem at hand. Additionally, the best method for initializing parameters in variational quantum algorithms is unknown, though some strategies have been proposed [51]. Parameter optimization has been studied numerically [52] and theoretically [53], and while gradient-based [54] and gradient-free [48] optimization methods have been recently studied, research is needed to demonstrate scalability. Additionally, applications must be developed for new use cases, *e.g.* in nuclear physics [55] and lattice gauge theories, both with and without noise. Finally, an equivalent definition of variational quantum algorithms as quantum neural networks has opened the door to classification and other machine learning problems on near-term noisy quantum computers [56–60].

(4) Major research activities:

(4.1) Experimental Research at the IQC^2: The overarching goal of the IQC^2 is to investigate, mitigate and utilize noise in QIS systems to demonstrate "quantum advantage" in the NISQ-era and ultimately to advance quantum computing beyond NISQ. This begins with experimental work needed to reveal the structure and sources of noise in NISQ systems based on SC qubits and diamond NV centers. These systems are of particular interest because of their already established success in the NISQ-era as well as their future potential. We will leverage our extensive experimental expertise in working with these systems to reveal their underlying noise structure. These efforts will open the door to developing altogether new hybrid quantum devices and noise sensors and provide key insights into the structure of quantum noise that will enable new algorithms to take advantage of NISQ-era machines. To accelerate technological innovations, the resulting deliverables described below will be made available to our broad national quantum network of external partners.

The field of quantum acoustics [61] provides unique and powerful tools for investigating surface noise sources in SC circuit based qubits. In particular, the acoustic transport of piezoelectric surface acoustic waves (SAWs) [62] is an ideal, highly-sensitive, surface-selective probe to quantitatively understand two-level states (TLSs) on the surfaces of thin films and substrates used for fabrication of SC qubits. The group of **Pollanen**, with support from **K.W. Murch** (Washington University in St. Louis), will utilize piezoelectric SAW measurements to probe dielectric TLSs on different qubit substrates and thin superconducting films to investigate the concentration of surface defects as well as their spatial and spectral distribution. TLSs in silicon substrates can be investigated in a flip-chip devices where the electric field co-propagating with the SAW on a piezoelectric chip such as lithium niobate, evanescently couples through an indium bump-bond-defined air-gap to a silicon chip under test. **Pollanen's** group have already demonstrated the effectiveness of this flip-chip coupling using SAWs to probe charge carriers in two-dimensional materials [63].

Quantum electrical transport is also a sensitive probe of TLS induced noise. In fact in mesoscopic conducting systems transport is a well-established probe of TLS fluctuators in those systems. The **Birge** group has demonstrated that dissipative quantum tunneling in submicrometer scale wires are sensitive to the dynamics of single TLS defects [64] and that similar techniques can be leveraged to reveal the energy distribution of quasiparticles within the wire. **Birge** will extend these transport techniques to probe TLS defects on the surface of high purity substrates used for fabrication of SC qubits. To enable electrical measurements, hybrid devices incorporating a sensing layer of exfoliated graphene on top of a otherwise highly insulating qubit substrate will be used. This work is a collaboration with **E.A. Henriksen** at Washington University in St. Louis who has recently demonstrated the use of graphene as a proximity probe of otherwise insulating materials [65]. Magneto-transport measurements will reveal the phase coherence time τ_ϕ of charges carriers in the graphene to provide a complementary view of the TLS disorder in the qubit substrate [66].

IQC^2 researchers will also develop the tools needed to produce novel NV center/SC qubit hybrid systems for quantum noise sensing. High-purity diamond material will be grown (**Grotjohn**) containing nitrogen δ-doping layers, which will be used for both in-house IQC^2 research and shared with the broad community of scientists working on color centers in diamond. At the IQC^2 **Dantus** will use ultrafast pulsed laser techniques [67,68] and super-resolution microscopy [69] to introduce NV-centers and image their location. With these techniques it should be possible to precisely and controllably position individual NV centers having a separation of ~ 10 nm needed to produce entanglement between adjacent NV center electronic states. Quantum state bench-marking of this diamond material will be accomplished using multi-photon excitation microscopy at room temperature (**Dantus**), and by coupling to high-coherence transmon qubits in flip-chip devices at low temperatures [30, 63, 70] (**Pollanen**). Qubit relaxation (T_1, T_2, T_ϕ) times and "spin-locking" methods [71] will test the quantum-grade of this ultra-pure diamond material in precisely the environment where NV center/SC qubit hybrid systems show promise for quantum memory applications [31, 72]. **Papapolymerou** [73,74] and his group will design novel microwave resonators to enhance the coupling dynamics of tailored microwave fields to SC qubits and NV centers and methods to mitigate frequency cross-talk issues in multi-qubit systems. These joint efforts will culminate in the development of a custom low temperature ($\sim$ 10 mK) NV center/SC qubit hybrid microscope for performing scanned confocal microscopy of NV centers and simultaneous measurement of coupled microwave resonators and SC qubits (see **Section 7: Major partnerships and infrastructure development activities**). This hybrid microscope will be a novel sensor platform for detailed understanding of noise in a variety of quantum devices based on superconducting circuits, diamond color centers, two-dimensional materials, and more.

The experimental projects described up to this point involve quantifying noise in, and improving the state-of-the-art of, established NISQ-era quantum information science systems and devices. However, continued progress requires constant innovation and the development of new materials, devices and systems. In this spirit, **Birge** and **Pollanen** are designing transmon qubits with a variety of magnetic [75,76] and insulating junctions, which offer potential improvements in scaling for quantum simulation and qubit control [77]. Additionally, **Pollanen's** group has recently [78] demonstrated the viability of hybrid quantum systems incorporating quantum fluids with 3D transmon qubits, which they will extend to add flexibility to resonator frequency tuning [78–82] to combat qubit frequency-crowding issues in noisy multi-qubit systems [83–85].

(4.2) Theoretical Research at the IQC^2: The results from IQC^2 experimental advances will serve as a foundation for the development of new theoretical models for the structure, energy spectrum and statistics of the noise in single and multi-qubit systems. These detailed models are vital to nearly every aspect of QIS, ranging from understanding of decoherence in multi-qubit systems to developing new protocols for quantum measurement and control. Where qubit-qubit interactions are not turned off, as is the case in the overwhelming majority of the current NISQ hardware implementations, it is necessary to understand how long a multi-qubit system can stay in a prepared state in the presence of noise with a known structure. This is the many-body localization problem [86–90]. The state can decay because excitations can propagate from qubit to qubit, leading to deleterious error synchronization [91], a problem that can be expressed in terms of a localization lifetime [92–94]. For single-particle states there are rigorous results for different kinds of noise [95,96], but the many-qubit problem has not been addressed in depth, but must be to apply the concept to realistic quantum computers. The localization lifetime will be studied (**Dykman, Shapiro, Schenker**) for realistic mechanisms of qubit-qubit coupling and various experimentally-informed noise spectra and statistics. The solutions should demonstrate how to avoid quantum error synchronization, as it will give the time interval where such synchronization does not occur. A potentially powerful tool for exploiting this localization is the application of a quasiperiodic potential to the qubit system. In fact **Kachkovskiy** has shown [97, 98] that a large class of qasiperiodic potentials can be used to assist in localizing excitations.

Additionally, measurement of one qubit naturally affects the state of the others when qubit couplings are "always-on". Minimize this effect in the presence of noise is critical for operating present-day medium-size quantum computers, where "reshuffling" errors between the qubits is a problem [99] and noise can strongly enhance the reshuffling probability. This will be investigated (**Dykman, Shapiro**) for condensed-matter based implementations of quantum computers being studied by the experimental group at the IQC^2. Noise can further complicate quantum non-demolition (QND) measurements, and **Dykman, Shapiro, Schenker** and **Kachkovskiy** will design methods to minimize the effect of noise on QND measurements using distorted quantum operators for which the commutators are small. A key part of the theory effort is the ability to effectively tie general theoretical ideas to concrete experimental results. **John Albrecht** will produce device simulations of single and multi-qubit SC circuits and resonator structures using a combination of finite element techniques, coupled cluster theory and quantum Monte Carlo methods. These simulations will also include modeling of the tools used to take key measurements.

Noise also plays an important role in quantum simulation. Building upon the quantum simulation expertise of **Maghrebi** [100–104] and his group, the IQC^2 theory team will explore quantum simulation of non-equilibrium states subjected to a time-dependent drive in the presence of realistic noise sources, which have the potential to be mapped onto NISQ-era multi-qubit systems connected to the cloud.

(4.3) Quantum Algorithm Development at the IQC^2: Understanding noise will enables the design of quantum algorithms. For example, optimizers routinely rely on adding random fluctuations to avoid getting stuck in a shallow potential minimum. If the noise is clearly quantified, quantum optimizers could be designed to use the native noise within the system for this purpose. Design of quantum kernel learning algorithms for ML could again leverage naturally occurring noise within the systems. The theoretical noise models and qubit control protocols developed by the IQC^2 theory team will provide a sophisticated understanding of realistic noise structures in multi-qubit systems, which can then be leveraged by the institutes algorithm team to build next-generation noise-resilient quantum algorithms. Our explicit objectives are to build algorithms leveraging this understanding of noise in all applications to enable "quantum advantage".

This naturally applies to variational quantum eigensolvers (VQE) [105] and the quantum approximate optimization algorithm (QAOA) [38] and is particularly appealing as these are mappable on to present-day NISQ hardware and have the potential to demonstrate "quantum advantage". By leveraging the high performance computing (HPC) expertise in the Department of Computational Mathematics Science and Engineering (CMSE) at MSU the group of **Hirn** and **Christlieb** will develop classical numerical techniques to handle variational quantum algorithms with large numbers of parameters in the presence of noise with a well-defined fingerprint. They will also investigate using native, and engineered noise, as a tool for accelerating QAOA and variational quantum state diagonalization [48]. Hardware-aware quantum compiling algorithms [49] will also be developed as hardware specific noise sources constrain the type and number of gates allowed for a given algorithm. Additionally, in collaboration with Ford Motor Company the IQC^2 and CMSE will investigate "quantum" inspired algorithms based on simulated annealing (**Albrecht**) developed on specialized hardware, *e.g.* field programmable gate arrays (FPGAs) (**Christlieb**).

To ultimately achieve "quantum advantage" on noisy quantum machines requires the development of quantum algorithms for new and more complex test cases, which is already an active area of research at MSU. In particular **Lee** and his group are developing new algorithms based on variational adiabatic evolution and error stabilization to tackle quantum annealing problems, while **Munch** and collaborators at D-Wave systems are utilizing annealing to optimize aspects of topological data analysis [106]. Building upon her expertise **Wilson** and her group will develop HPC accelerated variational methods for chemical simulation and IQC^2 experts in nuclear and high-energy physics are developing new variational and quantum simulation methods for lattice gauge field theories [107] (**Bazavov**, **Lin**, **Shindler**) and the quantum many-body problem (**Hjorth-Jensen**). These applications often rely on using Monte Carlo methods (**Albrecht**), which can be designed to work in the presence of biased noise.

(5) Training and workforce development: MSU is committed to leading in the area quantum computing as part of its core identity. MSU has already demonstrated its commitment to leading science in the 21st century, and to train the next generation of scientists, through the creation of the Department of Computational Mathematics, Science and Engineering (CMSE). The department focuses on the science of algorithms and their application in STEM. CMSE has hired 25 faculty over the past 4 years and has grown to a total of 35 faculty, with 20 of the faculty focusing on data science and 15 of the faculty focusing on scientific computing. Faculty have joint appointments in 12 different departments and the curriculum taught out of CMSE provide students exposure to cutting edge topics in data science and scientific computing. Because of the broad background in computing in STEM, CMSE is an ideal environment to train students in quantum algorithms and their application to key areas of STEM. Further, junior IQC^2 scientists will participate in a dynamic cross-disciplinary team. The institute will emphasize training outside the student's or postdoc's immediate areas of expertise and travel funds will be available to IQC^2 junior scientists to encourage cross-training at external workshops. Junior scientists will also participate in yearly self-evaluation and goal-setting exercises to set and evaluate career progress metrics.

Formal QIS training at MSU: MSU clearly defines quantum computing as a vital part of computing in the 21st century, and is committed to being a leader in this field as well as training the next generation of scientists in QIS. MSU has a vibrant community of over 20 faculty working on a range of aspects related to **Quantum Computing** and **Quantum Sensors**. This group has been actively engaged in smaller teams for more than a decade but has been working as a cohesive larger group focused on noisy QIS over the past 6 months. This effort has produced plans for a series of three new courses on QIS at the graduate level and one at the undergraduate level, which the IQC^2 faculty view as vital for training. The three courses can be defined as 1) computing on an ideal quantum computer, 2) quantum algorithms in a noisy environment (NISQ-era systems), 3) theoretical and experimental underpinnings of quantum computing systems. The first course is about what could be achieved using and ideal noise-less quantum computer, and is meant to be pen and paper. The second course builds on the type of work our collaborator **Will Zeng** has developed for compiling and running algorithms on NISQ-era systems. The third course focuses on the cutting edge of quantum hardware with the course notes quickly evolving over time as the field advances. Students would take the first course, followed by either of the two additional courses, depending on interest in NISQ algorithms or hardware. Further, we will develop an undergraduate course which is a scaled back version of course 2, with the goal of getting advanced undergraduates excited about quantum computing and encouraging them to consider advanced studies in the area. As MSU Physics and CMSE already heavily use Jupyter notebooks in teaching, these new QIS courses will be taught in a flipped classroom using Jupyter notebook with material shared widely with existing and future partners via GitHub.

IQC^2 Internship Program: In addition to these courses, MSU believes in practical hands-on training experiences for students at all levels. CMSE sends over 60% of its graduate students on summer internships to our partners at national labs (LLNL, LANL, LBNL, Sandia etc.) and industry (IBM, Amazon, Google, Ford, etc.). Using this expertise, the IQC^2 will cultivate an active internship program at the graduate level in quantum computing as part of the training students undergo. Because we have many faculty working in the areas of quantum sensors and quantum computing, we have strong exisiting connections to build from. In fact a number of former MSU students and postdocs now work for the quantum computing teams at IBM, Google, Northrop Grumman and EeroQ and have already students working as interns at IBM-Q this summer. Additionally, Ford Motor Company as well as IQC^2 national lab partner LBNL have both expressed interest in building and strengthening graduate QIS internship programs. **co-PI Christlieb** will work with these partners to facilitate these opportunities and seek to cultivate future partnerships.

QIS training of Undergraduates and Underrepresented Groups: As part of its land-grant tradition, MSU prides itself on engaging undergraduates in a research experience during their time at the institution. This is done through the honors college and the Professorial Assistant program, which target students within their first two years as well as the Diversity Programs Office out of the College of Engineering and Capstone Courses which encourage students to do a mini-thesis research project. To engage undergraduates, especially those from populations underrepresented in QIS, we will actively work with these MSU programs as well as offer a capstone course in quantum computing, to introduce undergraduates to QIS.

Local and Virtual Community of Learning: Our work in developing flipped classroom materials for QIS translates into creating on-line learning experiences that will have broad impact. The material and modules from these courses will be distributed freely to those looking for a place to start learning about QIS and the institute will offer in-person sessions for people to visit the institute and have questions answered by IQC^2 quantum experts. Further, we will create short courses based around developing hot topics in QIS. CMSE has developed one month one credit courses in bio-informatics for post graduate training and we will utilize this format at IQC^2 also. We will invite our one month visitors to teach these classes based on their work. Subsequently the IQC^2 will edit and create the flipped material to place these short courses online for others to use and enjoy, creating a "Local and Virtual Community of Learning".

(6) Major activities in research coordination and community engagement: Research coordination for the Institute will be done in many ways, as described, in part, in the **Management Plan** supporting documentation. In terms of research coordination, there will be institute meetings at multiple levels. At one level,

coordination will entail regular meetings to keep abreast of progress on the major scientific projects, and modify directions as needed. These meetings will include: **(1) Investigators and partners:** These weekly meetings began approximately half a year ago, and will continue, with a focus on developments by the team, in the field, and on new directions. Scientific and technological challenges will be discussed, and guest experts will be invited to participate in person or remotely, as appropriate. Once a month, the entire team, including students and postdoctoral fellows will meet for discussions and presentations.
(2) Thrust (algorithm, theory, experiment) groups: Each of these groups will meet separately to focus upon challenges and progress in each of their areas. The meetings will rotate between all investigators (including students) as well as senior investigators only. **(3) Executive committee (EC) meetings with thrust leaders:** To coordinate the research being done, there will be monthly meetings with the EC and the thrust leaders. **(4) Team and board members:** Annually, there will be a meeting for all who participate in the Institute to discuss research accomplishments and directions. **(5) Graduate students and postdoctoral fellows** will also have their own weekly meetings. Already, MSU has a vibrant Quantum Information and Computational Seminar (QuIC) series. This was a grassroots efforts started by graduate student Ryan LaRose. He began this seminar on his own, and then approached departments at MSU and companies to help see the seminar series to support external speakers. We will continue this series, expanding to include postdoctoral fellows, providing a student- and postdoctoral-fellow driven route for presentations, and interactions with speakers that they select. Institute postdoctoral fellows and graduate students will have the role of coordinating engagement activities for other junior scientists at the National Quantum Summit.

To aid in facilitating direction and coordination between the various areas, postdoctoral fellows will be available to investigators on collaborative projects, where a postdoctoral fellow is shared by two or three investigators. The **Institute's Internal Board**, which will be comprised of one member of the EC, who will serve as an *ex official* member, a representative from each thrust area, the outreach coordinator, and managing director of the Institute, will review brief ($\sim$ 2-page) proposals for project support, and postdoctoral fellows will be supported for two years. (Longer opportunities may be possible, but would need to be leveraged with support from participating MSU departments or other sources.)

National Quantum Summit: The research-focused events described above will enable coordination of the efforts across the IQC^2. However, a significant part of the institute involves engagement at the national level. To facilitate this level of engagement, annually, the IQC^2 will hold a national research summit, inviting all PI's of the funded NSF QLCI Conceptualization Grants (CG), as well as other critical stakeholders, to participate. The summits will provide opportunities to present recent research, forums to discuss evolving quantum leap grand challenges, and opportunities to form new partnerships. Several QLCI CG awardees will be invited to serve on the organizing committee for these quantum summits.

To enhance the team effort, we are engaging experts in team science who will provide training at the start of the program to all investigators on maximizing effectiveness when being a part of such a team. Throughout the effort, these experts will be included in multiple meetings of their choosing, as well as the annual meetings, to provide advice to the EC to help foster the strength and success of the team.

Community Engagement: The IQC^2 will reach out not only to the scientific community, but the broader community as well. For the research community, as noted, the Institute will host an annual National Quantum Summit. There will also be multiple opportunities for engagement including seminar visits, visiting scientist opportunities, and workshops. As described in Section 5, modules will be developed for the scientific and engineering communities to learn more about quantum computing. Seminars and workshops will be recorded and made available for viewing on You-Tube or other similar online media. An annual quantum algorithm hack-a-thon will be held to bring together scientists from across the country to participate in algorithm challenges. After the first offering, and online option will also be available so sites across the country can hold their own quantum algorithm hack-a-thons, in conjunction with IQC^2 hack-a-thons.

In terms of reaching a broad audience in the sciences and engineering for future workforce development, it is noted that there are a very limited number of women and underrepresented minorities (URMs) in quantum computing. To address this challenge, each year, a workshop will be held to bring undergraduate and graduate student women and URMs from across the country to the Institute for training and mentorship in quantum computing. Based on MSU undergraduate and graduate student experiences, workshop participants will spend a day writing their first code to perform quantum teleporation of a qubit on the IBM-Q Experience, or on other emerging cloud-based systems. This experience will provide participants with hands-on experience to learn how these systems work in practice. Communication will continue with these individuals when they return to their home institutions, and opportunities will be provided to continue remotely on a project. This network of participants will help to serve as a recruiting pool for graduate student and postdoctoral opportunities in the institute to aid in diversifying the future workforce.

To reach out to the general public, several routes will be pursued. The first is the development of a quantum computing Science on a Sphere module for museums across the globe. The IQC^2 will provide the MSU Museum with two graduate students to develop software for a quantum computing module that can then be offered internationally via the Science on a Sphere network. There are over 150 facilities across the globe offering Science on a Sphere all around the world, reaching millions of visitors per year. This is a room-sized, high resolution, global display system introduced by the National Oceanic and Atmospheric Association (NOAA) to better represent global phenomena.

The IQC^2 website will be a public gateway providing connections to social media (Twitter, Instagram, Facebook etc.). The IQC^2 website will chronicle our latest scientific breakthroughs via internet and social media outlets, with stories that are geared to the general public. Additionally the institute will produce 30-second video clips on science for non-technical audiences to be shown on YouTube. In addition to these virtual outreach efforts, the IQC^2 will also developed a Quantum Computing Roadshow to explain quantum computing for K-12, with emphasis on K-8, providing hands-on activities for students. The activities will be available for a classroom or larger groups of students, or more informal settings, such as a sports game tailgate events, which will be called “Quantum ‘Gating”.

(7) Major partnerships and infrastructure development activities:

External Advisory Board: The progress of the IQC^2 toward its scientific, training and workforce development goals will guided by a strong collaboration with a 6 member External Advisory Board consisting of leaders in the public and private sectors of quantum information experiment, theory and algorithms. The memberships of the inaugural External Advisory Board is listed below (Note that these prominent researchers and professionals have already agreed to serve on the Board should the IQC^2 receive funding:

- *Robert J. Schoelkopf* (Yale University and Quantum Circuits Inc.)
- *Susan N. Coppersmith* (University of New South Wales)
- *Michael J. Manfra* (Microsoft Station Q Purdue)
- *Edward H. Farhi* (Google and MIT)
- *Faye Wattleton* (EeroQ Inc., former President of Planned Parenthood Federation of America)
- *Paul Burchard* (Head of Research in R&D and Managing Director at Goldman Sachs)

Major External Partnerships: As shown in Fig.1 the IQC^2 will benefit from a wide range of partnerships with industrial collaborators working on quantum computing. These, already existing, partnerships not only involve QIS research but also the fostering of outreach and workforce development activities. On the research side, MSU has a long-standing diamond research partnership with Fraunhofer USA Inc., a 501(c)(3) non-profit organization incorporated in the USA. The Fraunhofer USA Center for Coatings and Diamond Technology (CCD), which offers applied research and development services to external customers from industry to government, has been located on the MSU campus since 2003. **Timothy Grotjohn** currently serves as the R&D Director of the CCD. Additionally, **co-PI Johannes Pollanen** is a co-founder and CTO of EeroQ Inc., a quantum hardware startup company based jointly in Lansing MI and Brooklyn NY. EeroQ Inc. is partnered with MSU to perform sponsored research to explore the possibility of developing ultra-sensitive charge sensors and novel qubits based on the quantum motion of trapped electrons. In collaboration with Northrop Grumman Corporation, **Birge's** is working to develop controllable-phase Josephson junctions as memories for superconducting classical supercomputers [108]. In quantum information theory, **Mark Dykman** and **Mohammad Maghrebi** have active collaborations with the Google AI Quantum Theory Team and **Elizabeth Munch** works with colleagues at D-Wave to use quantum annealing for topological data analysis [106]. Collaborative quantum algorithm development is also underway with governmental collaborators at the Facility for Rare Isotope Beams (FRIB) (**Lee, Hjorth-Jensen**) and Berkeley Lab (**Wilson**).

With regard to training and workforce development, MSU has a well-established pipeline of quantum computing internships and job-placement at IBM, Google, Northrop Grumman and EeroQ with multiple current and former graduate students and postdocs now positioned at these companies. Additionally, we are currently working closely with the quantum algorithm team at Ford Motor Company to establish a quantum internship program at the Ford Research and Innovation Center in Dearborn. The Unitary Fund is a grant program run by IQC^2 collaborator **Will Zeng** that funds explorers across the world to work on open source quantum computing. The Unitary Fund will work with IQC^2 members to both develop quantum algorithms and algorithm training modules. Additionally we are organizing a 2-3 day QisKit Bootcamp in collaboration with IBM-Q, which will be held at MSU in the Fall semester 2019.

Major Infrastructure Development: Leveraging our partnership with the Fraunhofer USA CCD, the IQC^2 will develop major experimental infrastructure in **Year 1-2** to produce NV centers in ^{12}C ultra-pure quantum-grade diamond substrates and epitaxial layers as a platform for building quantum devices coupled to SC qubits. A centerpiece of this effort will be a custom low temperature NV center/qubit hybrid microscope for performing scanned confocal microscopy of NV centers and simultaneous measurement of coupled microwave resonators and SC qubits. **This hybrid microscope be a precision tool for accurately sensing and quantifying noise of SC qubit systems and materials, with nano-scale spatial resolution.** Photon-echo coherence measurements on NV centers in this hybrid microscope will allow us to interrogate coherences in both the diamond material and the coupled SC qubit system over an extremely large bandwidth from picoseconds to seconds. The hybrid microscope will be housed in a cryogen-free dilution refrigerator with optical access via multi-mode and single-mode optical fibers and low temperature and ultra-high vacuum compatible attocube nano-positioners at 10 mK. The development of this quantum benchmarking tool is a collaboration between the IQC^2 researchers **Grotjohn**, **Dantus**, **Pollanen** and **J.P. Davis** at the University of Alberta who's group has built a scanning system with similar specification for quantum optomechanical experiments in a dilution refrigerator [109]. We have budgeted $\sim$ \$1.75 M in Year 1 of this project to purchase the relevant equipment needed to build the ultra-high purity diamond deposition reactor and hybrid low-temperature confocal microscope. The system will serve as a platform for internal institute members, as well as external collaborators, to perform measurements on hybrid SC qubit/NV center devices and investigate their noise structure at the relevant temperatures for quantum information processing.

(8) Evidence of cross-disciplinary team engagement and synergy:

Synergy between the three pillars of the IQC^2 (Experiment, Theory, and Algorithms) will turn *experimental results* on noise in real quantum systems and devices into *theory* inputs for noise modeling, device simulation, and the creation of new *quantum algorithms*. This tight feedback loop between the pillars is essential to propel the QIS field beyond the NISQ-era. This begins with the leadership of the IQC^2, which began at MSU when **Mark Dykman** established the original "Institute for Quantum Sciences" at MSU back in 2002, based on collaborative work between himself and IQC^2 member **Michael Shapiro**, leading to a number of impactful joint papers, particularly Ref. [92, 93, 110]. This institute also created fertile ground at MSU for future efforts in QIS. To build upon this early thought leadership, we will leverage our team's solid track record of leading large and diverse scientific efforts like the one we propose here. Before coming to MSU **Angela Wilson** established and directed the highly successful Center for Advanced Scientific Computing and Modeling from 2005-2016 at the University of North Texas, involving 20 faculty and over 100 investigator and bringing in $\sim 1/3$ of the university externally funded research dollars. **Timothy Grotjohn** is the RD Director of the Fraunhofer Center for Coatings and Diamond Technologies (CCD) located on the MSU campus and coordinates the research efforts of the center as well as interactions between the center and external researchers. **John Albrecht** recently worked as a DARPA Program Manager with a broad portfolio of microelectronics and devices. Over a 5 year period, **co-PI Andrew Christlieb** built a team of 17 faculty from 11 different departments in Natural Science and Engineering to carry out the difficult work of building a department to provide training on the multidisciplinary topic of computing in STEM. The efforts of the team launched a new department providing a Ph.D. program in Computational Mathematics, Science and Engineering (CMSE), a minor in CMSE and a new minor and BS in Data Science. This department also serves as the head of the new Bio-Informatics training program at MSU, as well as a new NRT in computational biology. CMSE was designed to have a collaborative interdisciplinary culture to foster collaboration across disciplines. As evidence, 22 of the CMSE faculty have a total of 33 interdisciplinary collaborative grants that cross traditional boundaries. The core mission of CMSE is closely aligned with quantum computing developments and the department will hire two new faculty in this direction.

In addition to this expertise in leading large scientific teams, the members of the IQC^2 already have numerous existing collaborations. In physics, **Pollanen** and **Dykman** work together to investigate the dynamics of the strongly correlated systems of electrons on helium. This is joint experimental and theory work supported by the NSF via Grant no. DMR-1708331. In this direction **Hjorth-Jensen** is collaborating with **Pollanen** and **Dykman** to employ tools from many-body simulation to model multi-qubit gates with electrons on helium. Additionally **Pollanen** and **Birge** have already started developing superconducting qubit devices containing magnetic junctions this summer. On the engineering side, **Timothy Grotjohn** and **John Albrecht** have long-standing collaborations working on diamond, its defect structure and use in electrical devices (see Section 10). The members of the IQC^2 involved with nuclear physics and lattice gauge theories (**Lee, Hjorth-Jensen, Bazavov, Lin, Shindler**) have been working together for years on a wide range of questions in nuclear theory, which are vital to mapping these problems onto quantum circuit Hamiltonians. These connections provide a jumping-off-point for the collaborations that form the core of the IQC^2.

The leadership team has been has been working closely for more than a year to build a tight-knit quantum ecosystem at MSU. This work began with a Interdisciplinary Mixer on QIS at MSU in March 2018 facilitated by the Office of the VP for Research at MSU and the MSU Center For Interdisciplinary. This mixer was followed by the **MSU Workshop on Quantum Information Science: Are we at the crossroads?** (Sept. 30 - Oct. 3, 2018), which was supported by the NSF via Grant no. DMR-1843472. This workshop brought together world leaders in QIS to discuss the near future of the field, including the physical implementations of quantum computers, the most interesting open questions in the field, and the challenging fundamental and applied problems of quantum science. These grass-roots efforts have now culminated in MSU launching the new "Center for Quantum Computing Science and Engineering" locally to support the sustainability of QIS efforts at MSU and provide a hub for QIS connectivity to the mid-West and beyond. This new Center will be directed by **Angela Wilson** with **Andrew Christlieb** and **Johannes Pollanen** serving as associate directors.

(9) Milestones and evaluation mechanisms:

(9.1) Milestones and metrics of scientific success: fThe critical scientific milestones of the IQC^2 are: the construction of the hybrid low-temperature NV center scanning microscope for noise measurement (**Year 1-2**); reliable production of coupled color centers in diamond (**Year 2-3**); theoretical validation of noise measurements on single SC qubits and NV centers (**Year 2**); development of noise models for generic multi-qubit systems (**Year 1-3**); development of quantum algorithms that take into account generic noise models (**Year 1-3**); measurement of multi-qubit/NV center hybrid quantum systems and the theoretical validation of these measurements taking into account the major noise sources (**Year 4-5**); incorporation of the explicit noise models coming out of the experiment and theory groups into next generation quantum algorithms (**Year 4-5**). An important measure of the IQC^2 success of these efforts are papers that cross boundaries between theory, experiment and algorithms. By the middle of year 3 the collaborations fostered by the IQC^2 should lead to at least a third of the joint papers accomplishing this goal. Institute publications will be co-authored by at least 2 IQC^2 faculty. Prior to publication, joint manuscripts will be submitted to the EC at least three weeks prior to the intended submission date to solicit feedback, though intent to publish should be shared with the EC at least a few months in advance, when possible, to provide the chance to engage the media in institute press releases. Faculty will follow their own institutional review as appropriate.

In addition to these 5 year scientific goals, the IQC^2 we will track the following metrics: number papers and joint papers; new scientific iniatives; new collaborations involving two or more institute personnel; the number of new collaborations with external partners; and the number of internship opportunities produced for both junior members as well as students trained in our curriculum. We will also track the effectiveness of our efforts to support the scientific efforts of the quantum computing community outside of MSU by fostering new collaborations between academic institutions and industry that otherwise would not exist with targeted workshops. The IQC^2 will track the effectiveness of these workshops using feedback from participant surveys to adjust the strategy of the workshops to enhance public and private partnerships.

(9.2) Training and outreach milestones and metrics: In addition to our scientific goals, the number of students trained, the ease with which institutions are able to use IQC^2 QIS curricula, and the number of underrepresented individuals that the institute draws into the quantum computing community are fundamental metrics of success. The institute will develop surveys to track student success and outcomes with the MSU Center for Statistical Training and Consulting (CSTAT). We will work with the Diversity Program's Office out of the College of Engineering to ensure that we are actively implementing best practices for recruiting and retaining members from under-represented groups in QIS. In years 1 and 2 we will develop and disseminate new curricula that will cover quantum algorithms, hardware and theory. In addition to the 20 graduate researchers and 10 postdocs associated with the IQC^2, we anticipate training an additional 15-30 students per year in quantum computing, which will be carried out in collaboration with **Will Zeng (Unitary Fund)**, **IBM**, and **Google**. These curricula will be taught in flipped-class room formats using Jupyter notebooks. Additionally, by the end of year 2 we will have run the first in a series of QIS workshops developed specifically to engage under-represented populations in quantum computing. In year 3 we will develop a undergraduate course in quantum algorithms, with will generate enthusiasm about quantum computing. A metric of success for this effort is the number of undergrads seeking post-grad quantum training beyond this course. This Jupyter notebook based undergraduate course will also be made freely available to the broader QIS community via GitHub. In years 4 and 5 we will continue our efforts in the educational arena.

(10) Pertinent achievements under prior NSF support: In 2002 MSU established the "Institute for Quantum Sciences", as one of the first QIS institutes anywhere in the world. Building on this, in Fall 2018, **Dykman**, **Birge** and **Pollanen**, with College of Natural Science Dean Phillip Duxbury organized the "MSU Workshop on Quantum Information Science: Are we at the crossroads?", supported by NSF via Grant no. DMR-1843472, \$10,000. **Intellectual merit** was associated with bringing together world leaders in QIS to discuss the near future of the field, the physical implementations of quantum computers, the most interesting open questions, and the grand challenges in QIS. **Broader impacts** involved the inclusion of participants from outside of academia and providing opportunities to student and postdoctoral attendees to learn about quantum research and technology development at companies and industry labs (Google, IBM, and MITRE). **Angela Wilson**: CHE-1213874/DMR-1636555 ("Composite Methodologies Towards Quantitative Predictions across the Periodic Table", \$113,224, 9/15/12-9/14/13) and CHE-1362479/DMR-1636557 ("Computational Methodologies and Strategies for the Heavy Elements", \$454,212, 7/1/14-12/31/18) which resulted in 35 publications to date (and two manuscripts submitted) and over 150 presentations (70 invited talks). **Intellectual merit** has been the development of quantum mechanical strategies for better and/or more efficient descriptions of energetic properties of transition metal species and heavy element species. **Broader impacts** were in workforce development for underrepresented groups in computational chemistry.

Andrew Christlieb: NSF DMS-1418804 “A Practical Approach to Rothe’s Method”, $205,000, 7/16/2014-7/15/2018, **Intellectual merit**: Development of implicit methods for solving partial differential equations based on fast convolutions ideal for inverting stiff linear operators ideally suited for multi-core computing. **Broader impacts**: Trained two graduate students and introduced a new class of solvers to the community.

Pollanen and Dykman: NSF DMR 1708331, “Many-body dynamics of electrons on helium” $430,983.00, 4/1/2017-5/31/2020, **Intellectual merit** is focused on studying the dynamics of the system of electrons trapped on the surface of superfluid helium and interaction with the quantum field of the vibrations of the helium surface. **Broader impacts** development of a quantum physics blog titled “ThinkQuantum”, which highlights QIS research being performed at MSU featuring guest bloggers from academia and industry.

John Albrecht and Timothy Grotjohn: NSF 1628958, “DMREF: Doping and Defects in Diamond for Electronics”, $1,000,000, 9/1/16-8/31/20, **Intellectual merit**: Investigation of ion implantation for forming doping profiles in diamond and improving diamond quality for electronic applications. **Broader impacts** include the graduation of one PhD student, the development of an online graduate level course on “Diamond Technology”, and diamond substrates and epi-layers being made widely available.

Marcos Dantus: NSF CHE 1836498, “QLC: EAGER: Quantum control of energy transfer pathways and chemical reactions”, $294,286, 9/30/2018 - 9/29/2020. The **intellectual merit** this project is to take advantage of excited quantum state molecular reactivity. The **broader Impacts** will produce a series of educational videos on the topic of quantum control of chemistry.

John Papapolymerou, ECCS – 1600417, Amount: $475,000, Period: 9/14/2015-8/31/2019 “EARS: Development of tunable frequency selective limiters based on novel magnetic nanomaterials for RFI mitigation in a crowded spectrum environment”, **Intellectual Merit**: Development of cost effective thick (>2 microns) magnetic films compatible with integrated circuits and characterization of RF lines up to 10 GHz [73, 74, 111]. **Broader Impacts**: The realization of cost effective, compact, highly integrated RF hardware with inherent RFI mitigation capability for the first time ever.

Matthew Hirn: NSF DMS-1620216 “Three dimensional deep wavelet scattering for quantum energy interpolation.” $191,775, 9/1/2016-8/31/2019: **Intellectual Merit**: Development of a novel approach for the regression of quantum chemical energies based on a 3D scattering transform. **Broader Impacts**: Enable cutting edge research in lithium ion batteries through a collaboration with Prof. Yue Qi at MSU.

Elizabeth Munch: DMS-1800446: CDS&E: “Collaborative Research: Machine Learning on Dynamical Systems via Topological Features”, $101,672, 9/2016-8/2019. **Intellectual Merit:** Development of new methods for combining machine learning with topological data analysis (TDA).**Broader Impacts:** Created a publicly available open source python code which lowers the barrier for entry into utilizing TDA.

Huey-Wen Lin: NSF 1653405 “CAREER: Constraining Parton Distribution Functions for New-Physics Searches” $435,000.00, 8/1/17-7/31/22 **Intellectual Merit**: Use high-performance computing to study the probability distribution of fundamental particles within a nucleon on classical computers using the theoretical tool “lattice gauge theory”. **broader impact** Developed a game to teach the general public about “quantum chromodynamics”. The game is available to download for Android and Apple devices, on Google Play and at the Apple AppStore. On Google Play alone the game already has 1000+ installs.

Jeffrey Schenker: “Localization and Diffusion in Open and Many Body Quantum Systems”, $250,000, 08/01/19-07/31/22 **Intellectual merit** To prove the existence, and clarify the nature, of Anderson localization in many-body and open quantum systems and to prove diffusion in open quantum systems and quantum systems subject to noise. **Broader impacts** include support for two Ph.D students.

Ilya Kachkovskiy: NSF DMS 1758326, “Spectral Theory of Periodic and Quasiperiodic Quantum Systems” $71,837.00, 9/1/2017-06/30/2019, **Intellectual merit**: Developing new methods for studying localization for single- and multi-particle quasiperiodic Schrodinger operators. **Broader impacts**: Co-mentoring a postdoctoral scholar and supervision of an undergraduate research group of six students, and publication.

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