The Northeast Quantum Systems Center (NEQsys) - Research and Services in Support of Real Applications

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BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY

BNL Operates and Supports Many Data-rich Facilities

- Relativistic Heavy Ion Collider (**RHIC**)
- National Synchrotron Light Source II (**NSLS-II**)
- Center for Functional Nanomaterials (**CFN**)
- Accelerator Test Facility (**ATF**)
- LHC **ATLAS US Tier 1 Center**
- Atmospheric Radiation Measurement (**ARM**) program
- **Belle II**: computing for neutrino experiment
- Quantum chromodynamics (**QCD**) computing facilities for BNL, RIKEN, and U.S. QCD communities

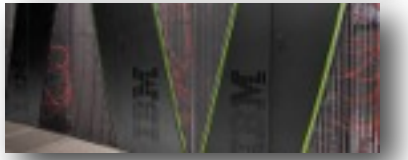
RHIC

NSLS II

CFN

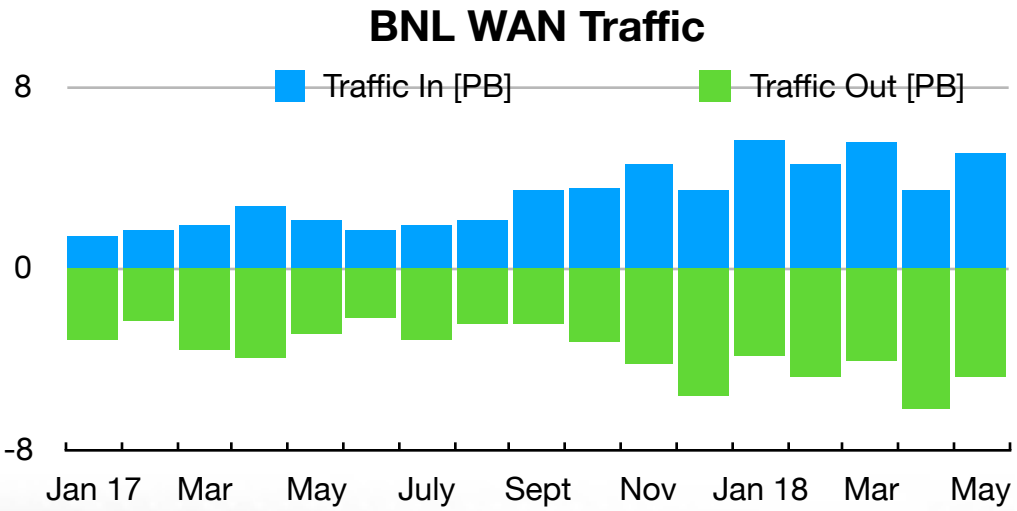
ATLAS

QCD



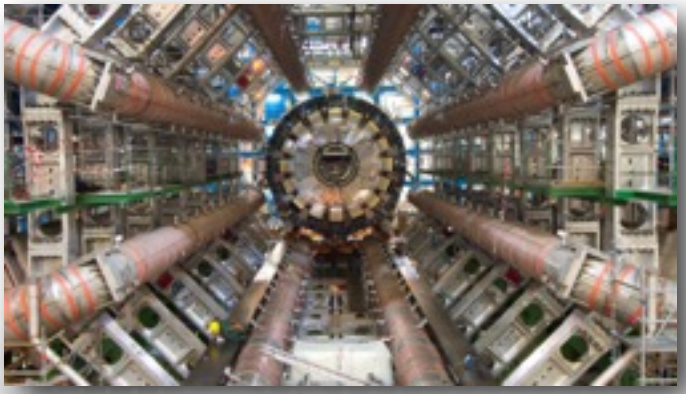
BNL Data by the Numbers

- **Largest scientific archive in the U.S.;** among the top five in the world (ECMWF, UKMO, CERN)
- **~145 PB archived** to date
- **~110PB Data Transfer per Year**



Key Challenge Examples at BNL's Large-scale Facilities

- Real-time Analysis and Steering of Experiments–Challenges:
  - CFN–400 images/sec
  - NSLS II–up to 5TB/s in burst



- Extreme Scale Data Management and Analysis:
  - **690 PB of data analyzed in FY18**
  - Moved data to compute and storage in 2016–1.6 Exabyte

Scalability of Algorithms and Systems is Vital to Meet Our Mission Needs

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History of Systems Design to Optimally Support Mission Critical Applications

- Working with Partner Universities: Columbia and Edinburgh
- Systems specifically for QCD
- Optimally balanced
- Forerunner of successful IBM Blue Gene Series

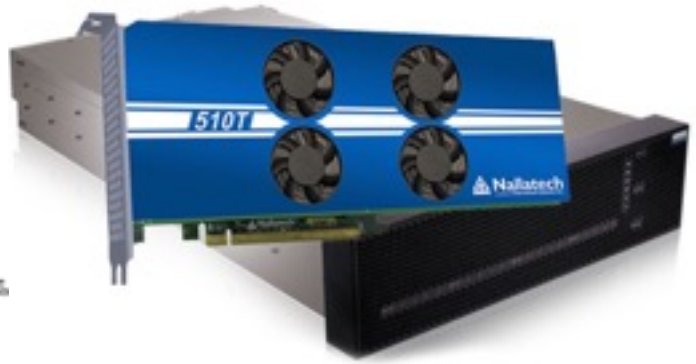
QCDSP

Blue Gene Q

QCDOC

Artificial Intelligence and Machine Learning @ Scale

- Leading experts in Streaming Machine Learning
- Leaders of ExaLearn: Machine Learning at Exascale
- Machine Learning for High Energy Physics: LHC Atlas and SciDAC Resource and Application Productivity through computation, Information, and Data Science (RAPIDS)
- AI-driven Optimal Experimental Design
- Partner University: Carnegie Mellon



Nallatech 510T field-programmable gate array (FPGA) card:
- 2.8 TeraFLOPs
- 290 GB/s Peak Aggregate Memory Bandwidth

- Exploration of new architectures to better support high-throughput, high-volume data analysis - FPGA/ CPU systems, DGX-2, Neuromorphic, Quantum

The Same Principle Applies: Leverage and Adapt Quantum Computing to Optimally Support Our Core Missions

North East Quantum Systems Center (NEQsys)

- Collaborative environment for research and integration across the spectrum of activities, from theoretical and experimental materials science and condensed matter physics to devices/ systems and system software to algorithms and computational applications
- University Partners: **Harvard, MIT, Princeton, Stony Brook, Columbia, Toronto, Tufts, Yale,**
- Industry Partners: **Raytheon**

Yale University

HARVARD UNIVERSITY

Stony Brook University

PRINCETON UNIVERSITY

UNIVERSITY OF TORONTO

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Tufts UNIVERSITY

Raytheon BBN Technologies

NEQsys: Focus

Potential Activities

- Collaborative Projects
- Joint Appointments
- Visiting Faculty
- Student/postdoc exchanges REs
- Workshops
- Colloquia
- Summer School
- University inter-movement
- Masters Degree in quantum computing
- Problem market

Why NEQsys?

- Bringing together and leveraging wealth of research at leading universities and in industry.
- Collaboration with BNL at its center can provide knowledge integration across the hardware/software stack to impact work across institutions.
- Cross-cutting effort will adapt algorithm and software stack developments, quantum system size and architectures, enhance connectivity, and measure fidelity, impacting the entire quantum ecosystem.
- Moderately sized system (5-20 qubit) at BNL.
- Unique characterization capabilities at BNL.

Quantum Simulations

Some of our application drivers, and support tool research

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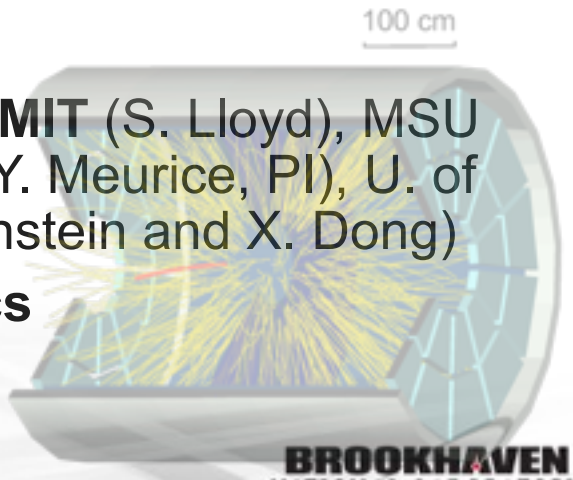
Foundations of Quantum Computing for Gauge Theories and Quantum Gravity

- Develop fundamental building blocks of quantum computing relevant to problems in high energy physics that are beyond the reach of classical computing

- **Scalable Quantum Codes in four Space-Time for the Evolution of Hadrons in Collider Experiments, the Early Universe and New Models of Gravity**

- Partners: **BNL** (M. McGuigan), **BU** (R. Brower), **MIT** (S. Lloyd), MSU (A. Bazavov), Syracuse (Catterall), U. of Iowa (Y. Meurice, PI), U. of Maryland/Microsoft (S. Jordan), UCSB (D. Berenstein and X. Dong)
- **Funded by DOE office of High Energy Physics**

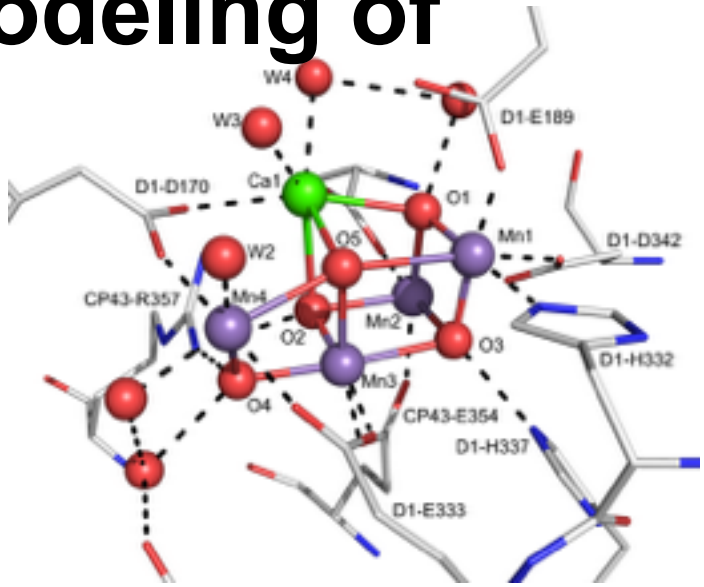


Accelerating State Preparation in Quantum Field Theory Calculations on a Universal Quantum Computer

- One of the profound problems in applications of quantum computing for Quantum Field Theory (QFT) involves the preparation of quantum states used in matrix elements and further time evolution
- **Broad research program to study optimal ways to prepare states for simple QFTs**
- Partners: **BNL** (Hooman Davoudiasl, Christoph Lehner) , RIKEN (Taku Izubuchi)
- **Funded by BNL**

Quantum *Ab Initio* Modeling of Photosynthesis

- Catalysis
  - Poses an NP hard problem
- Approach
  - Combine conventional and quantum computers for even more power
- Methods to be explored
  - Embedding combined with variational quantum eigensolver (VQE)
  - Quantum subspace expansion (QSE) extends VQE for properties in the linear response regime
  - Witness-assisted variational eigenspectra solver (WAVES) extends VQE for excited states

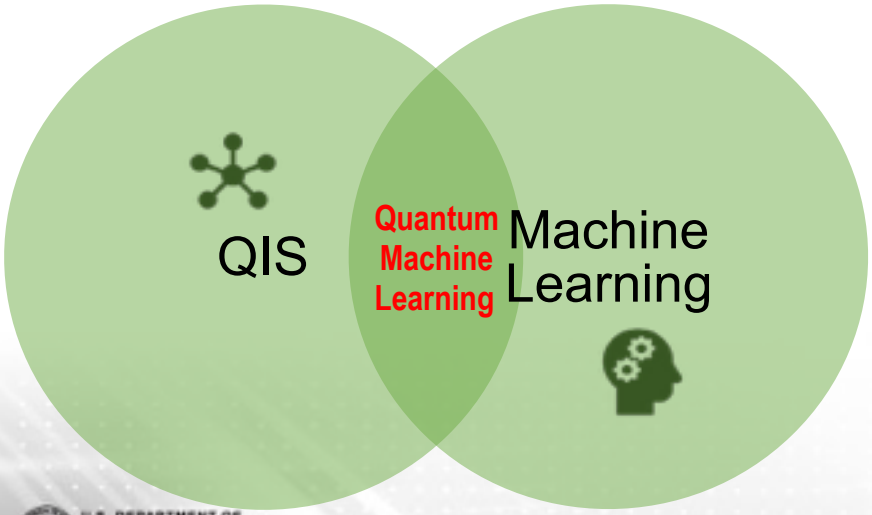


Partners: **BNL** (Mehmed Ertem, Huub van Dam),**Harvard** (Prineha Narang), LBNL (Bert de Jong), **MIT** (Seth Lloyd), **Toronto** (Alán Aspuru-Guzik), **Tufts** (Peter J. Love)

Initial Funding by New York State

Input/Output Efficient Quantum Machine Learning

- Initial work showed state of the art machine learning models face two key challenges - data loading and encoding
- Need to improve ML algorithms and QS I/O hardware through new qRAM designs.

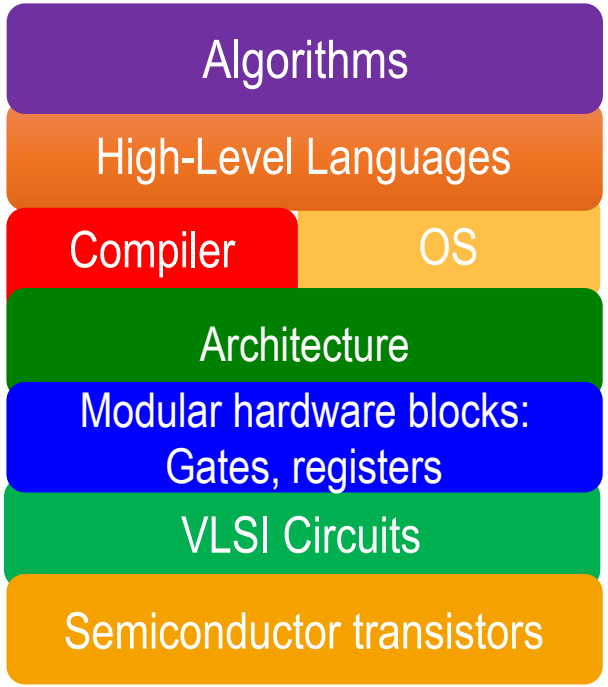


- Plans
  - Self error-correcting machine learning algorithms with redundancy
  - Compress input data into better representation for QIS using classical machine learning techniques
  - Improve representation power during compression by incorporating latest advances in deep representation learning
- Partners: **BNL**, CMU, **Stony Brook**
- **Funded by New York State**

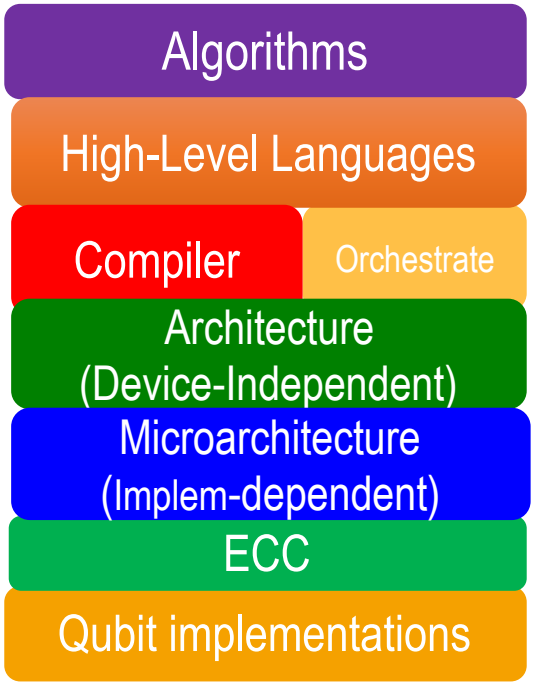
Better Support For Quantum System Programming

PRINCETON UNIVERSITY

Classical Layering



Quantum Toolflows

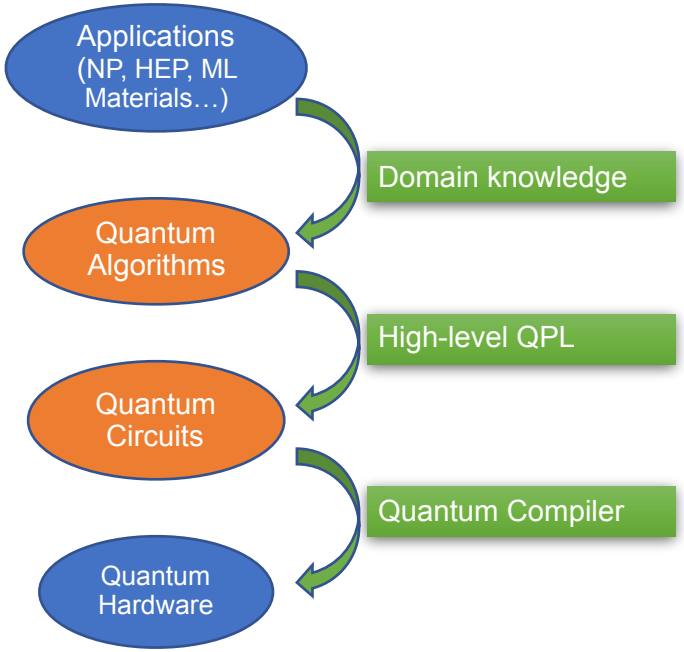


High-level QC Languages.
Compilers.
Optimization.
Error Correcting Codes
Orchestrate classical gate control,
Orchestrate qubit motion and manipulation.

Margaret Martonosi, Princeton, NSF funded

NISQ-era Quantum Algorithms and Compiling Support

- The applications of existing and near-term quantum computers are limited by
  - Small number of qubits
  - Short decoherence time
  - Lack of error correction.
- To broaden the range of applications accessible on near-term quantum computers, we will need to make use of the available qubits effectively by developing
  - Algorithms that require fewer qubits
  - Compiling tools that map quantum algorithms into shorter circuits.
- This project aims to
  - Optimize high-level algorithms to reduce the number of gate counts for potential high energy physics applications
  - Translate the optimized quantum circuit to low-level pulse sequences guided by physics and qubit topology.
- Partners: **BNL** (Meifeng Lin, Leo Fang)



Funded by BNL Laboratory Directed Research Development #19-002

Integrated Quantum Communication and Computation Research and Testbed Facility

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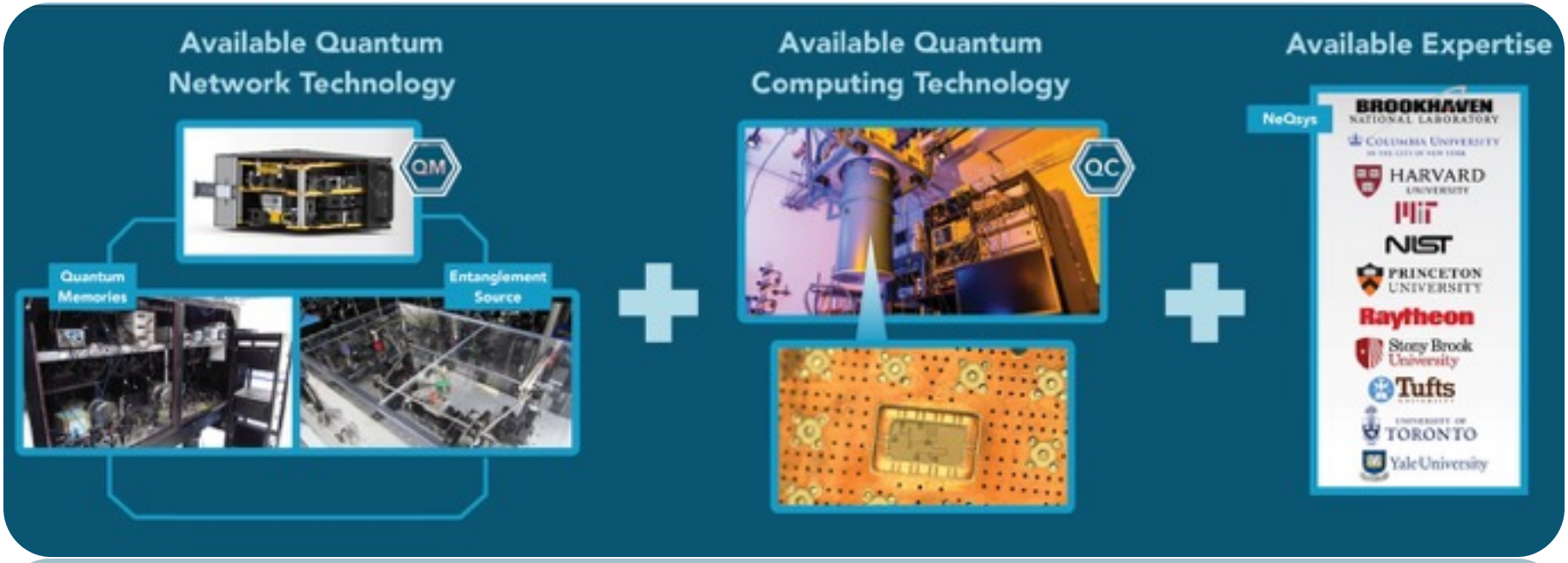
Developing the First Integrated Quantum Network and Computing Infrastructure

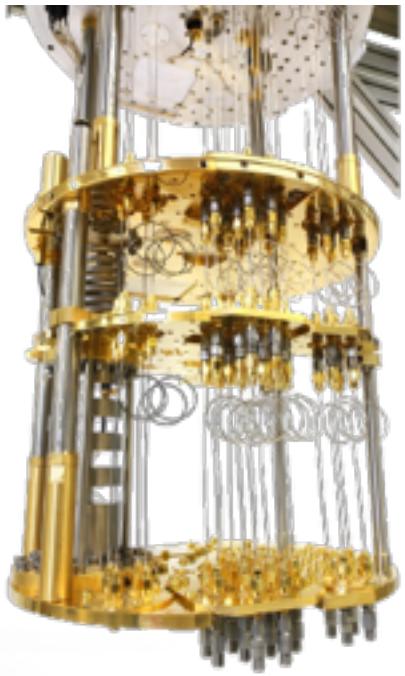


Quantum Computing System at BNL

- CSI has formed a collaboration with **Raytheon-BBN Technologies** and the **National Institute of Standards and Technology** (Boulder, CO) to build a Quantum Information Science (QIS) system at BNL.
- Initial system will include a 5-qubit superconducting quantum processor (5QP), the required cryo and room temperature management and readout electronics, and will be housed in a dilution fridge. Expect to upgrade to 20-qubits in year one.
- We will work with Stony Brook University on integrating Quantum Networking directly into the QIS system.
- Partners: **BNL** (Nick D'Imperio, Adolfy Hoisie, Layla Hormozi)

NIST (David Pappas), **Raytheon** (Thom Ohki)

- **Funded by New York State**



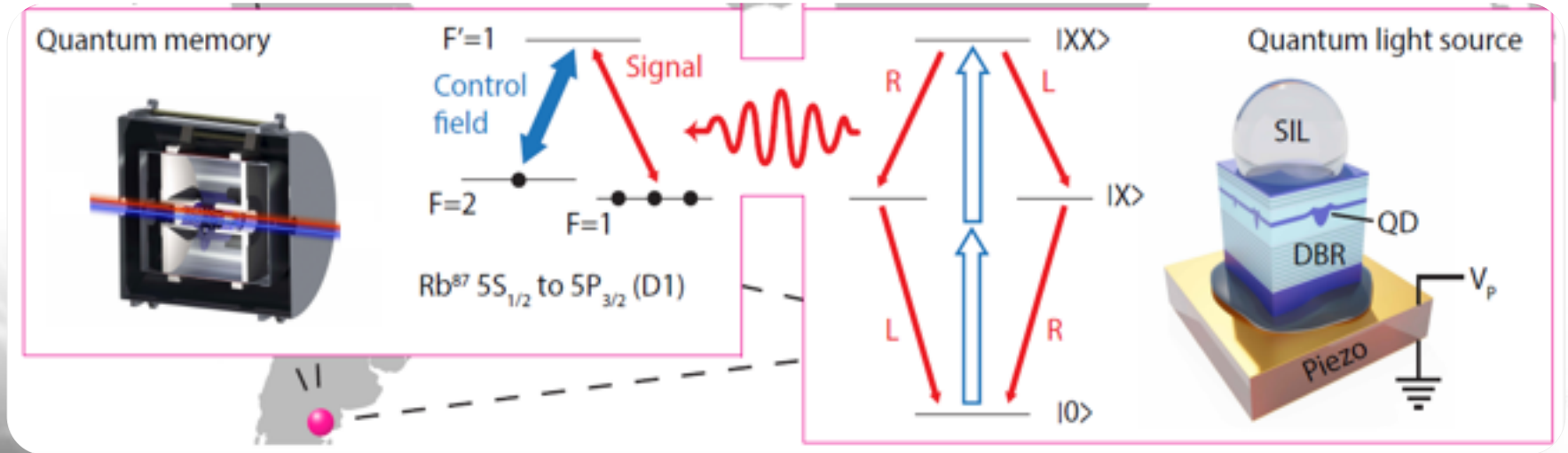
U.S. DEPARTMENT OF ENERGY NIST Raytheon BBN Technologies BROOKHAVEN NATIONAL LABORATORY

Scalable Room Temperature Quantum Networks

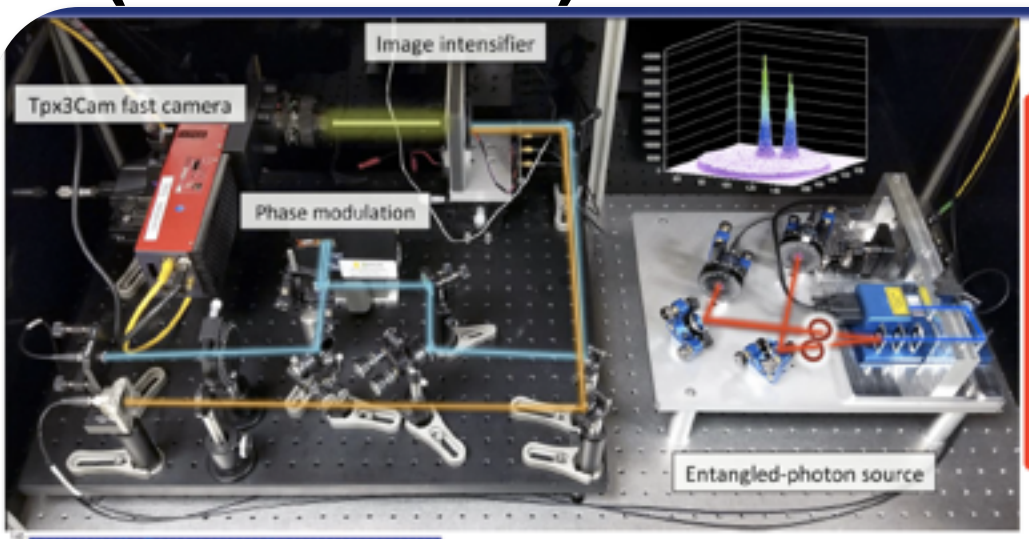
- Quantum memories for light qubits
- Room-temperature operation
- Laboratory based and fully portable
- Miniaturized for real networks and outside lab storage
- Interaction with entangled photons from Quantum Dots (SBU/ KTH)
- Electromagnetically Induced Transparency with Quantum Dot Photons

Stony Brook University

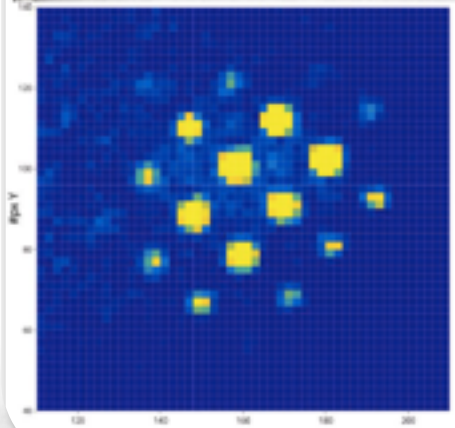
Eden Figueroa

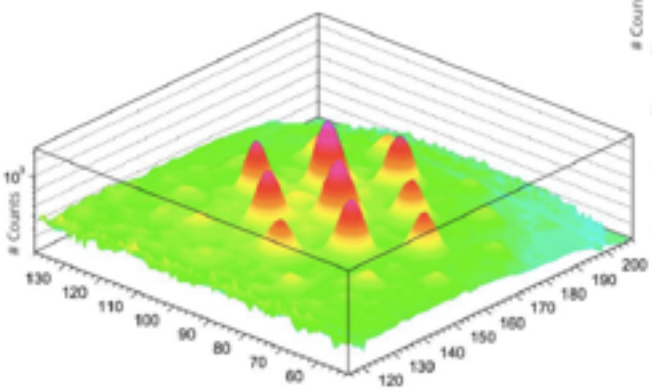


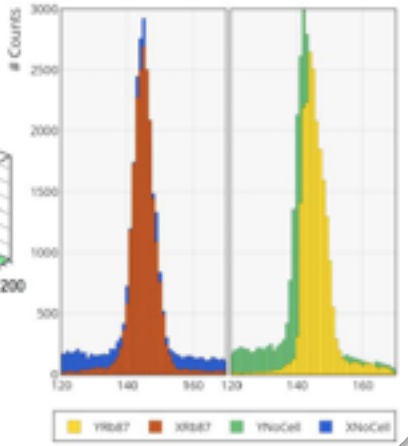
Scaling and Multiplexing: A Quantum Grid (SBU/BNL)



- TimePix camera with intensifier.
- Single photon level detection in time and space.
- 16-rail system created.
- Rubidium interaction.

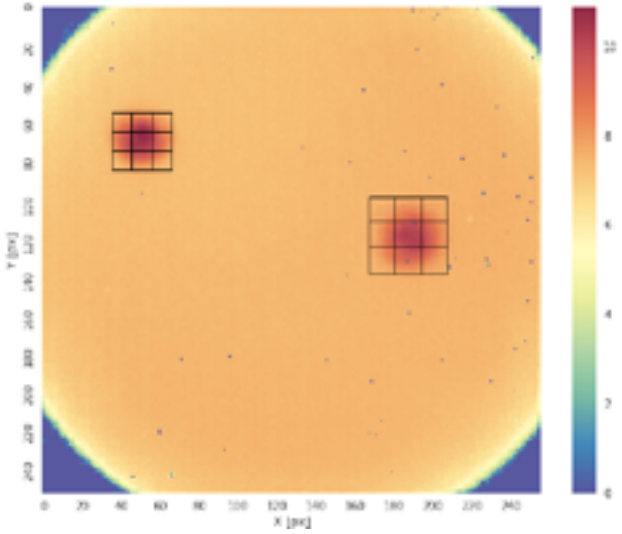


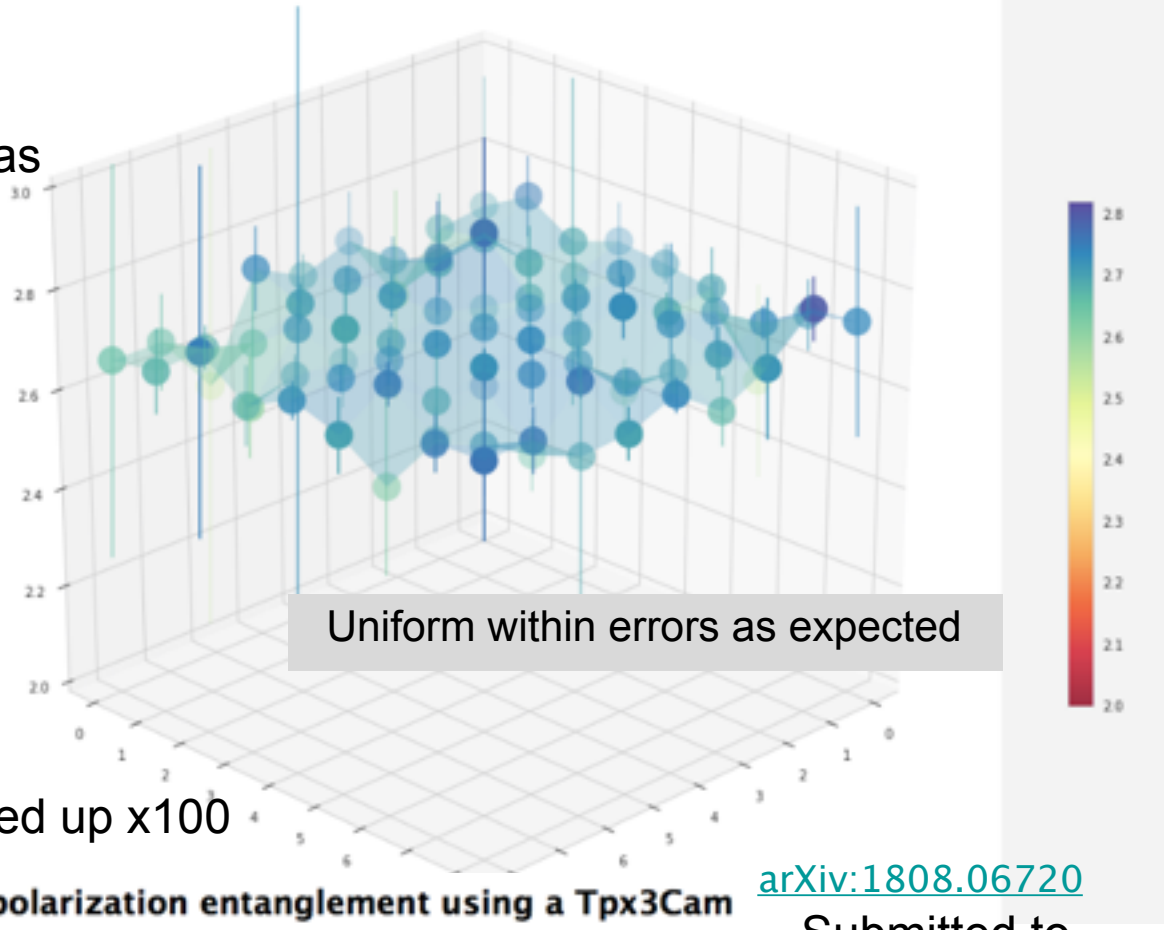




High-dimensional spatial entanglement

Measure S-value
for 81 combinations of subareas





Uniform within errors as expected

Photon throughput can be scaled up x100

Spatial characterization of photonic polarization entanglement using a Tpx3Cam intensified fast-camera

Christopher Ianzano, Peter Svihra, Mael Flament, Andrew Hardy, Guodong Cui, Andrei Nomerotski, Eden Figueroa

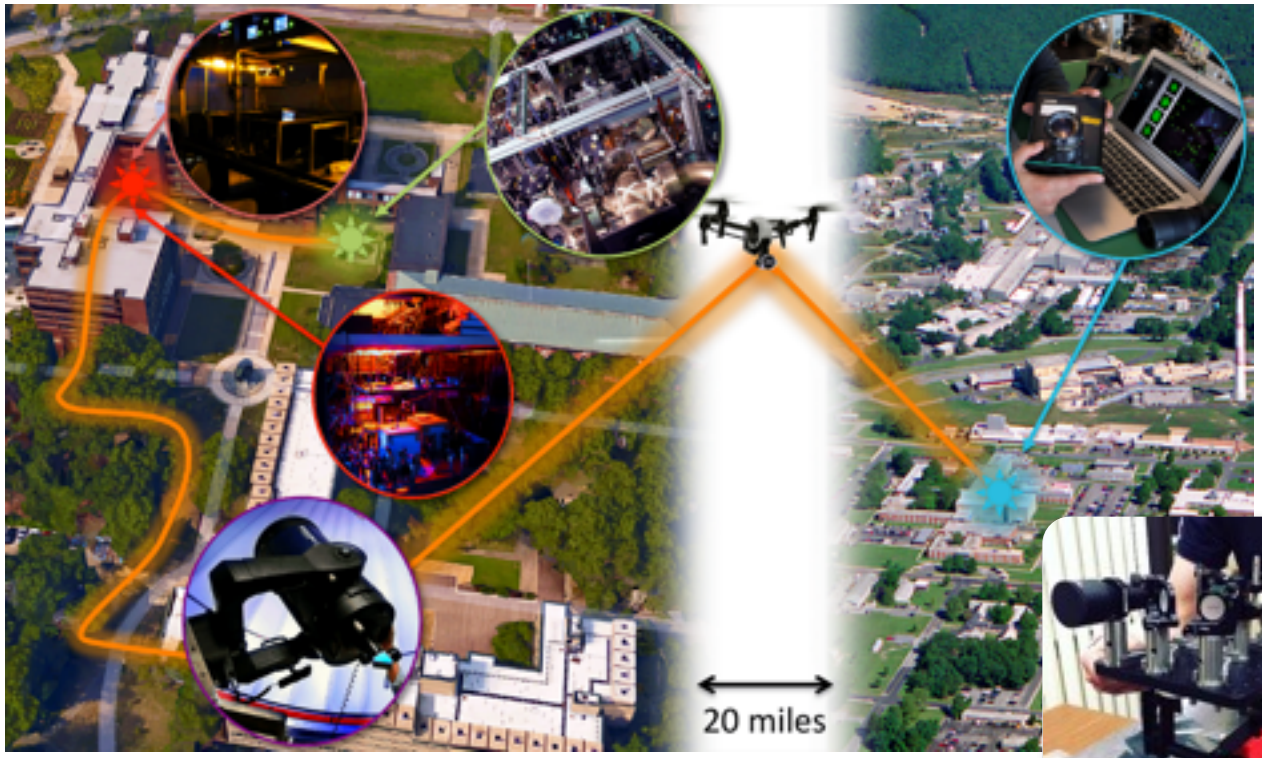
arXiv:1808.06720

Submitted to

nature > communications physics

COMMUNICATIONS PHYSICS

In Development: Quantum Network Connecting SBU and BNL



- Large quantum network connecting SBU and BNL
  - Quantum imaging of photons
  - Quantum cryptography
  - Entanglement over long distances

  200 miles, through NY, utilizing existing fibre (ESNET, LIMAN)

Partners: **BNL (**A. Nomerotski, G. Carini, D. Aisner, D. Katramatos), **SBU** (E. Figuaroa, D. Schneble, A. von der Linden)

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Stony Brook University

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Research and Support for the Development of Future Quantum Computation Systems

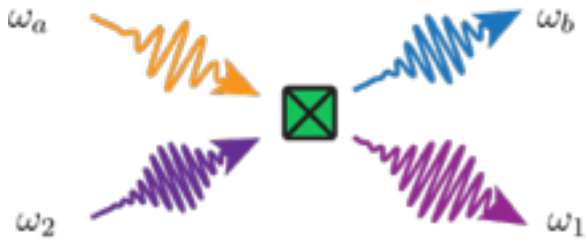
New Cryo Electronic Solutions for Faster and Easier Readout and Control

- Commercial CMOS processes can be used to design circuits that operate at Temperatures << 4K
- This allows the tight integration of existing electronics concepts and interface with qubits
- Has potential to support the implementation of various types of qubit
- Scaling advantages compared to other approaches due to:
  - Proven high density and high speed connections to warm electronics
  - Integrated electronics allows easier interfaces to readout and control at << 4K
  - Small parasitics and high bandwidth enable fast readout and control
- Leverage our experience with cryogenic electronics for HEP
- **Funded by BNL**

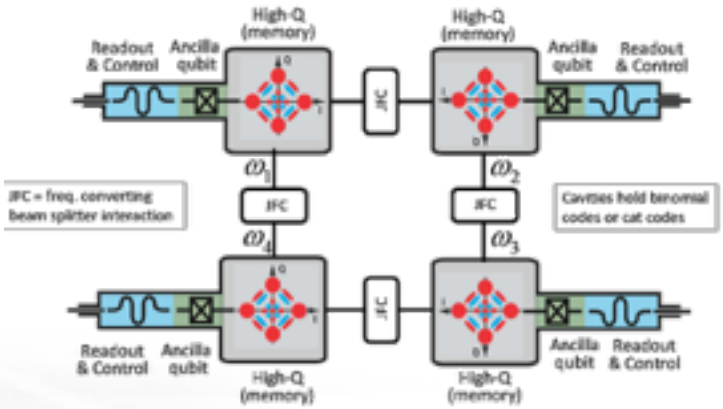
Building "Native" Quantum Error-corrected Qubits

Yale University

- Simple, repeatable modules based on Photonic Qubits
- Error correction built into lowest level
  - Hardware-efficient logical data qubits
- Intermodule Coupling
  - Error correctable quantum communication
  - Remote teleportation of gate operations



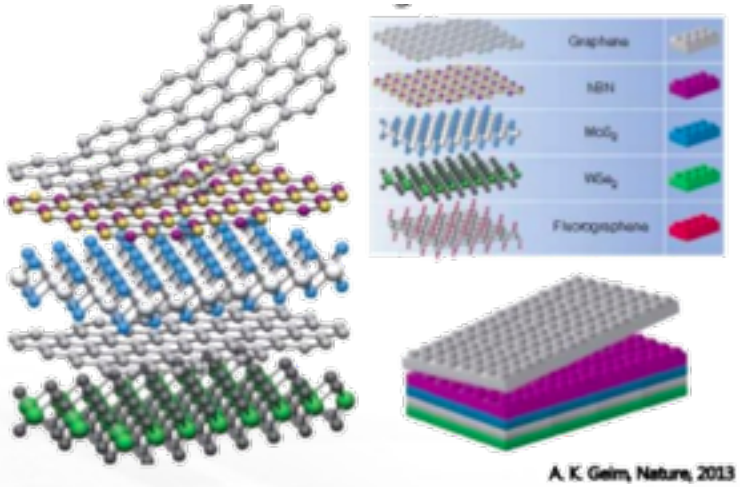
- Replace physical qubits with photon states stored in high, High-Q cavities
- Three code-independent, on-demand operations between two bosonic modes in cQED:
  - SWAP
  - First deterministic C-SWAP
  - First E-SWAP
- Useful ingredients for universal quantum computation, quantum machine learning, etc.
- Funded by NSF



Steve Girvin
QuantumInstitute.Yale.edu
NSF funded

Quantum Material Press: Unique Facility for Automated Synthesis of Layered 2D Material Heterostructures

- CFN awarded $5.7 million to construct the Quantum Material Press.
- Atomically-thin 2D materials are well-known candidates for next-generation QIS.
- Layered heterostructures can be designed to support exotic electronic excitations for novel QIS schemes.
- Condensed Matter Physics & Materials Science Department (CMPMSD) has robust expertise in synthesis of bulk crystals for use as QPress feedstocks.
- Existing and planned NSLS-II beamlines particularly well suited for characterizing 2D materials.
- **Funded by DOE Basic Energy Sciences**

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Thank You!

New OASIS: Integrated Synthesis, Characterization, and Visualization Instrument to Address Fundamental QIS Questions

- Strong-correlated oxide materials can be high-temperature superconductors, or high-T_c, and topological materials
- CMPMSD: world-leaders in synthesis and characterization of these materials
- Synergistic with NSLS-II beamlines
- **Funded by DOE Basic Energy Sciences**

Oxide MBE ARPES

SISTM