New Mexico is a Quantum State:

Development of Sandia's QIS program

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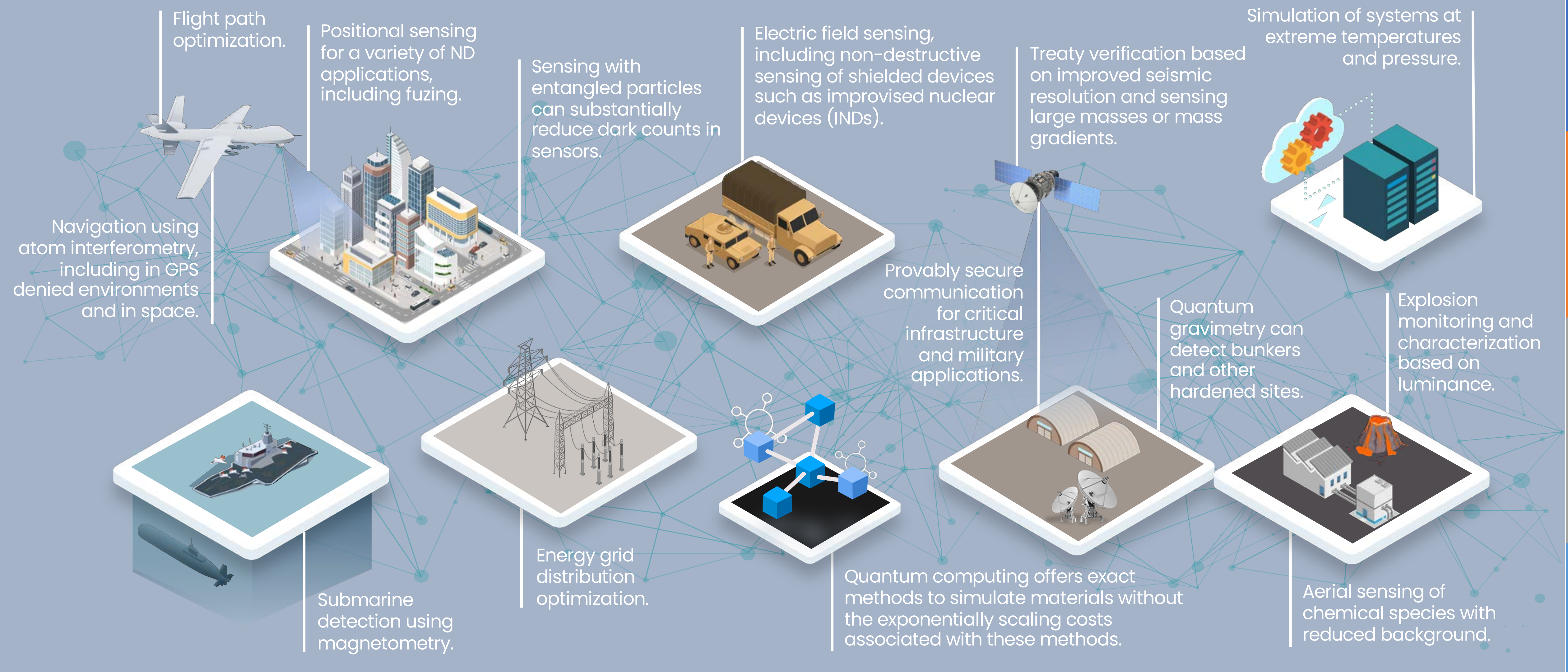
QIS Impacts Many Key Areas of National and Economic Security

Prevent strategic technological surprise associated with quantum sensing, computation, and communications



INDUSTRY AND GOVERNMENT QIS TIMELINE

Estimated Timeframes of Industry and Government QIS activities and programs

1980s

Simulating physics with computers, R.P. Feynman, Int J Theo Phys 21 *(1982)*

1990s

Deutsch/Jozsa Bernstein/Vazirini *(1992)*

Shor's Algorithm, P.W. Shor, IEEE *(1994)*

Quantum error correction, P.W. Shor, Phys Rev A 52 *(1995)*

2000s

US launches QIS R&D program (early 2000s)

China launches QIS R&D program (early 2000s)

Microsoft launches **station Q** to investigate QIS *(2005)*

Japan launches early efforts in QIS *(mid-2000s)*

IBM starts to explore **SC Qubits** *(mid-2000s)*

Australia launches the **Centre for Quantum Computer Technology** CQCT *(mid-2000s)*

Singapore launches the **Center for Quantum Technologies** *(2007)*

2010s

D-Wave one released; 128-qubit chipset using quantum annealing *(2011)*

UK announces 5 year, £385m investment for **QIS** *(2015)*

IBM Quantum Experience launches, granting QC access to the public *(2016)*

China launches **Q comm satellite** for QKD *(2016)*

Intel announces **17-qubit** SC test chip *(2017)*

Australia announces two new **QIS Centres of Excellence** *(2017)*

Microsoft announces QC programming language *(2017)*

D-Wave two released; 2000Q chipset using q annealing *(2017)*

EU commits $1.1 billion to **quantum R&D** *(2018)*

Japan launches **Q-LEAP** initiative to advance QIS *(2018)*

Google announces **72-qubit quantum chip** *(2018)*

Germany launches **QIS program**, allocating € 650m for R&D *(2018)*

Google announces 49-qubit SC chip Tangle Lake *(2018)*

IonQ introduces first **trapped Ion computer** *(2018)*

Russia announces **50b roubles** ($663m) for QIS *(2019)*

US passes **National Quantum Initiative** Act, authorizing $1.2B *(2019)*

Google **Quantum Supremacy Paper** *(2019)*

2020s

IBM announces new record for **quantum volume** *(2020)*

Honeywell releases 10 qubit TI QC *(2020)*

Japan announces **$14 billion quantum** cryptography project *(2020)*

India allocates **$1.12 billion** for QIS *(2020)*

Taiwan announces $282M for QIS *(2020)*

SANDIA QIS R&D TIMELINE

Estimated Timeframes Sandia QIS activities and programs

1980s

- **Strained-layer superlattices** from Lattice mismatched materials, *Journal of Applied Physics* 53, 1586 *(1982)*

1990s

- **Fractional quantum Hall effect**, J.A. Simmons, et al., Phys Rev B 44 *(1991)*
- **Functional single electron transistor**, J.A. Simmons, T. Eiles *(1997/98)*

2000s

- **LDRD: "Quantum Computing Accelerator** I/O," C.P. Tigges, N. Modine *(2003)*
- **1st QIS presentation by SNL**: Microfabricated ion traps for QC architectures, M. Blain, et al. *(2004)*
- **16th Electronic Properties** of 2D Electronic Systems in Albuquerque *(2005)*
- **LDRD**: Traps for QC & Qsim *(2005)*
- **DOE SC National User Facility** CINT founded *(2006-Present)*
- **3 LDRD**: Ion qubits; Si qubits; QC architecture *(2007)*
- **QIST Grand Challenge LDRD**: Si quantum bits & logical qubits *(2008-10)*
- **DARPA IMPACT**: Ion microwave atomic clock *(2009-14)*

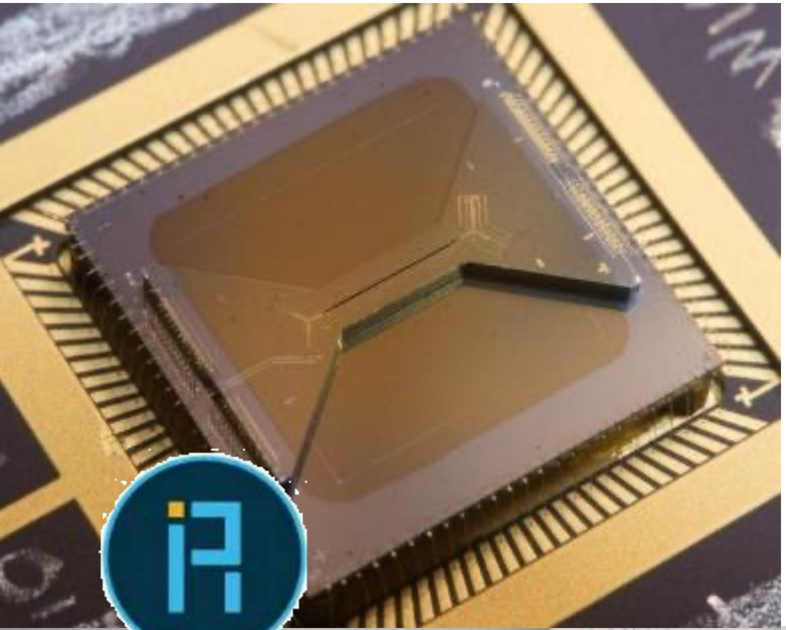
2010s

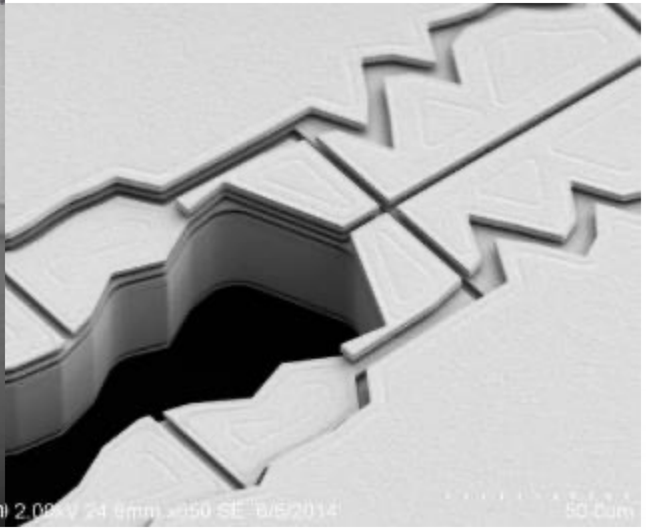
- Sandia publishes paper on **Magnetoencephalography** (MEG) *(2010)*
- **IARPA MQCO**: Microfabricated surface traps for multiple qubits *(2010 – 2015)*
- **AQUARIUS GC LDRD**: Adiabatic QC *(2011-13)*
- Sandia observes entanglement of remote **superconducting qubits** *(2014)*
- **SECANT GC LDRD**: QKD *(2016-18)*
- **IARPA LOGIQ**: Microfabricated traps for a logical qubit *(2016-2021)*
- **Quantum Performance Lab** established for QC assessment *(2017 – present)*
- DOE/SC **Quantum Science Open User Testbed (QSCOUT)** – trapped ion testbed *(2018-22)*
- **SIGMA GC LDRD**: AI for inertial Guidance *(2018-20)*
- **DOE/SC OVER-QC**: developing tools for extracting QC utility *(2018-22)*
- **DARPA TICTOC**: Ion optical clock *(2019-21)*
- **FAIR DEAL GC LDRD**: Atomic precision advanced manufacturing *(2019-22)*
- **NIH MEGs**: atomic sensors for wearable brain-scanning *(2019-current)*
- **FAR-QC:** Algorithmic Development for QC *(2019-current)*
- **TOQN**: transduction between microwave and optical systems *(2019-current)*

2020s

- **DOE/SC Quantum Systems Accelerator**: developing next gen quantum systems *(2020-current)*

IARPA Ion Trap Foundry





- Sandia is the world leader in design and realization of microfabricated (MEMS) ion traps, used by the leading ion trapping groups worldwide
  - Development of surface trap by Tigges and Blain
  - Two key IARPA projects: MQCO & LOGIQ
- "Plug and Trap" - standardized package compatible with many chambers
- "known good trap" - eases deployment

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BE THE FUTURE

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universität innsbruck
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AFRL
UNIVERSITY OF MARYLAND
MIT LINCOLN LABORATORY

Sequential GCs Built Sandia QIS Foundations

QIST
Quantum Information S&T

FY08 – FY10
Si-based qubits

- Silicon quantum dot qubits
- Architecture & logical qubit design

AQUARIUS™
Adiabatic quantum architectures in ultracold systems

FY11-FY13
Alt. Architecture

- Adiabatic architecture assessment
- Atomic precision lithography development
- Neutral atom computation

SECANT QKD

FY14-FY16
Comms/QKD

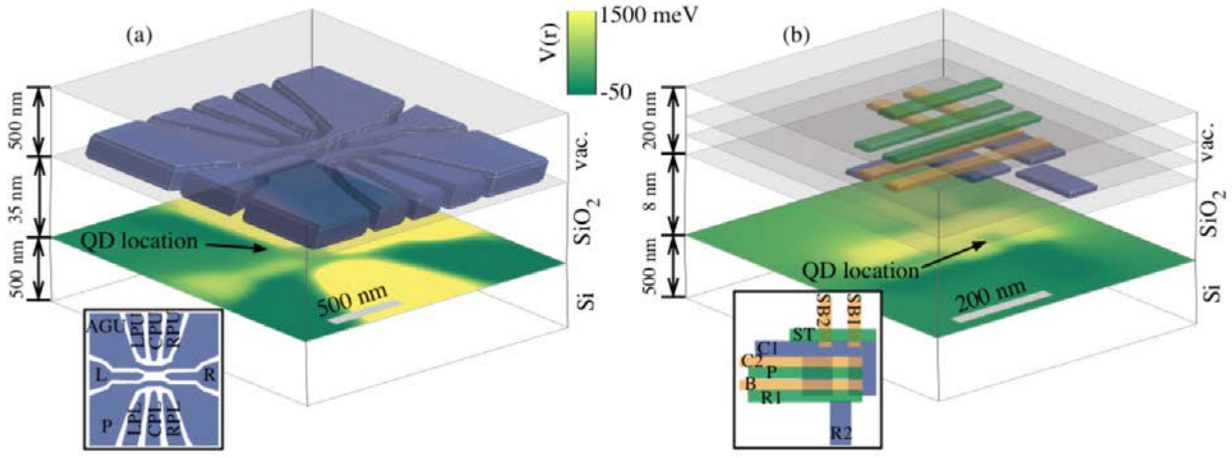
- Quantum key distribution development
- Photonic communications/networking development

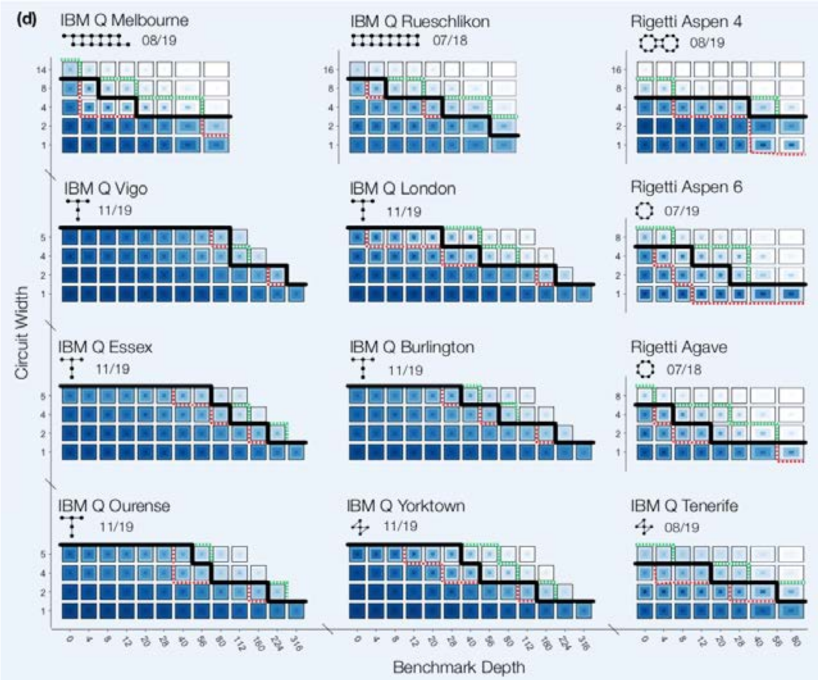
Strategic Inertial Guidance
ΣΙΓΜΑ
with MAtterwaves

FY18-FY20
Atom Interferometer

- Develop deployable quantum devices
- Quantum sensing based location determination

Modeling and Characterizing Quantum Processors





Sandia has developed an extensive quantum device modeling effort for different platforms and at different levels of operations that guides the development of quantum devices and the interpretation of quantum experiments.

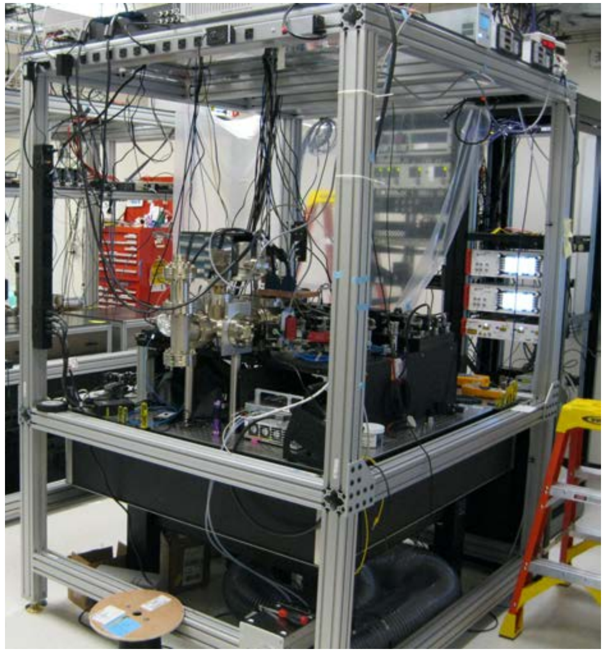
The Quantum Performance Laboratory provides tools and technologies to characterize qubits, benchmark quantum processors, and analyze the sources and types of errors that occur in quantum devices.

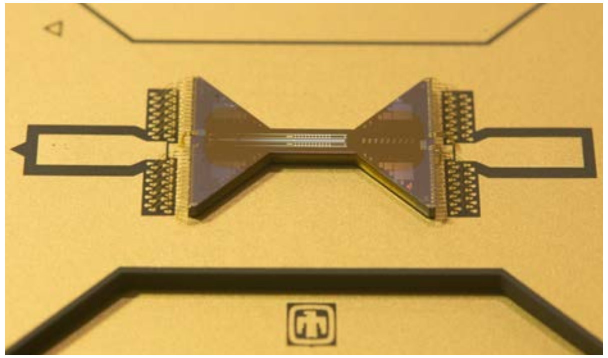
Quantum Scientific Computing Open User Testbed

PI: Susan Clark

- DOE/ASCR quantum testbed to understand promise of quantum computing platforms for DOE science problems
- Low-level access provided by QSCOUT is not available in existing commercial systems and enables researchers to study the behavior of quantum hardware
- Access to high-fidelity quantum operations
  - Qubit coherence time ≈ 14s
  - Parallel single qubit gates on all qubits, target fidelity 99.5%
  - Serial two-qubit gates between any pair of qubits, target fidelity 98%
- Jaqal Quantum Assembly Language offers low-level access, control of gate scheduling and execution, and extensible native gates.
- QSCOUT serving users:
  - 5 projects for first round (2021), 5 projects for second (2022)

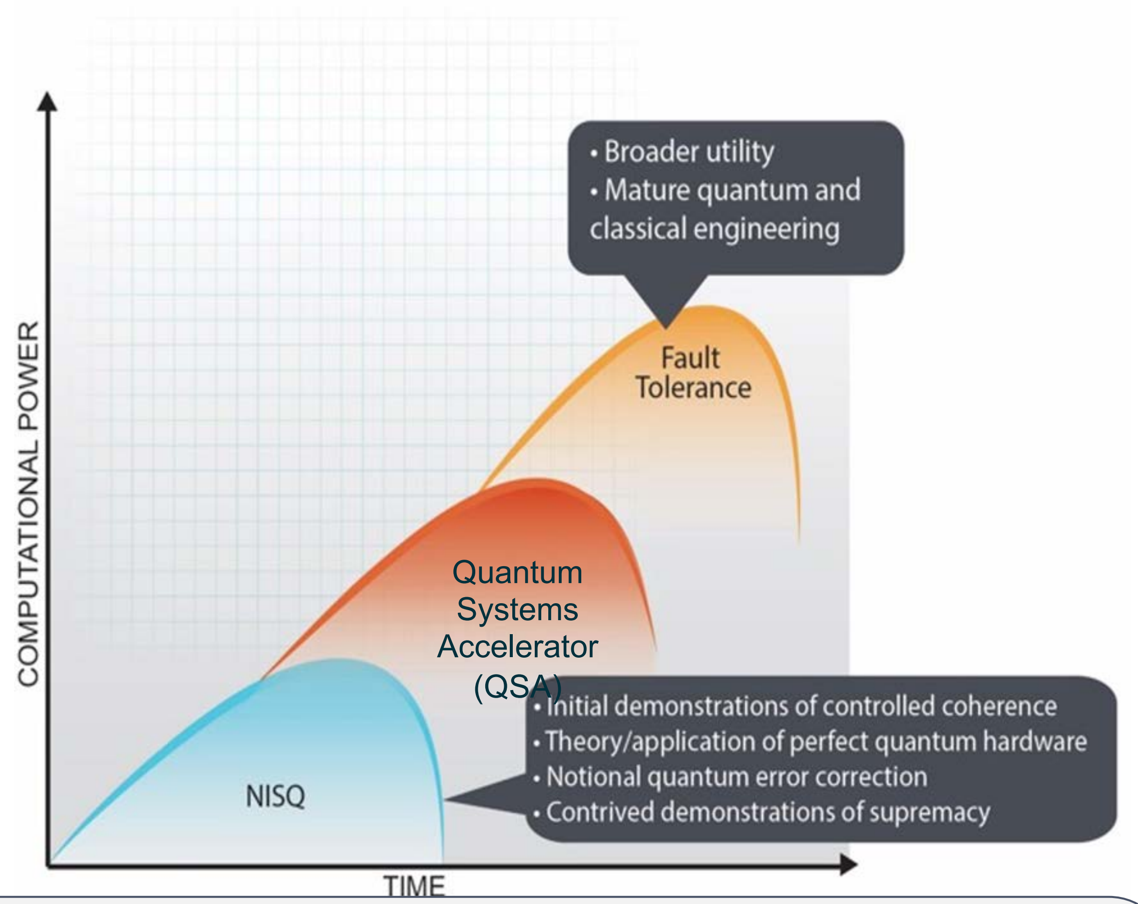
2021 R&D 100 WINNER





Peregrine Trap

Quantum Systems Accelerator



Catalyzing national leadership in quantum information science to co-design the algorithms, quantum devices, and engineering solutions needed to deliver certified quantum advantage in Department of Energy scientific applications.

BERKELEY LAB Lawrence Berkeley National Laboratory

Sandia National Laboratories

Berkeley UNIVERSITY OF CALIFORNIA

Caltech

CU Boulder

Duke UNIVERSITY

HARVARD UNIVERSITY

MIT

UNIVERSITY OF MARYLAND 1856

THE UNIVERSITY of NEW MEXICO

USC

THE UNIVERSITY OF TEXAS AT AUSTIN

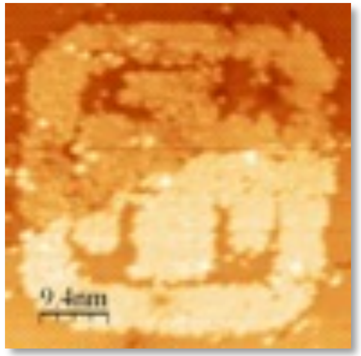
UNIVERSITÉ DE SHERBROOKE

Tufts UNIVERSITY

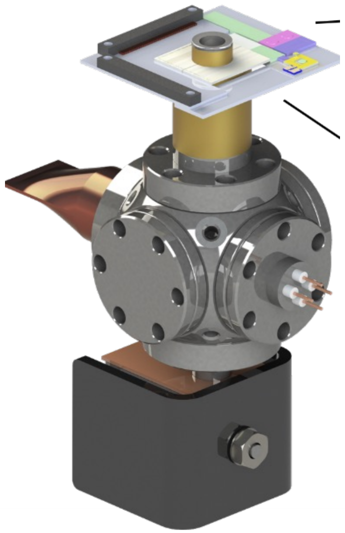
9

Sandia's Future Vision is Integrated Quantum Science

- The critical bottleneck to achieving quantum goals is *integration.*
  - The only way to simultaneously increase qubit capacity and fidelity is to modularize and integrate repeatable units.
  - Challenge: what *capabilities* can be integrated for hybrid quantum devices?
  - Challenge: how to we create, distribute, and maintain quantum resources?
  - Challenge: what opportunities are available with integrated computing and sensing?
- 5 Year Vision: Quantum device integration for national impact.
  - Build on the high fidelity and full connectivity available with trapped ions
  - Integrate chip-based photonic elements and electronics with existing physics devices.
  - Develop algorithms and protocols to deal with connectivity limitations
  - Extend to other Sandia quantum systems



Advanced fabrication



Advanced Integration

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