

This paper describes objective technical results and analysis. Any subjective views or opinions that might be expressed in the paper do not necessarily represent the views of the U.S. Department of Energy or the United States Government.

SAND2019-8092C

# Quantum Science and Engineering at Sandia National Laboratories: Overview and Opportunities

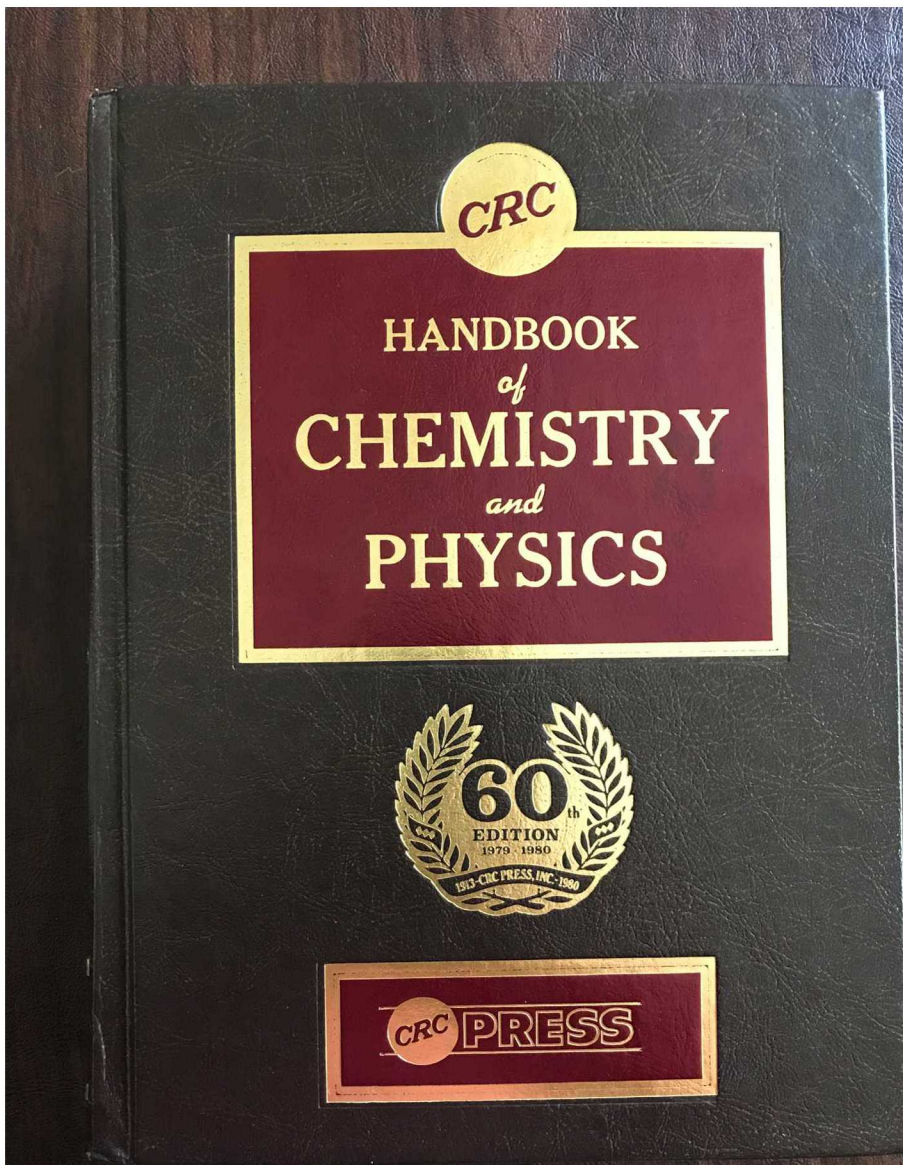


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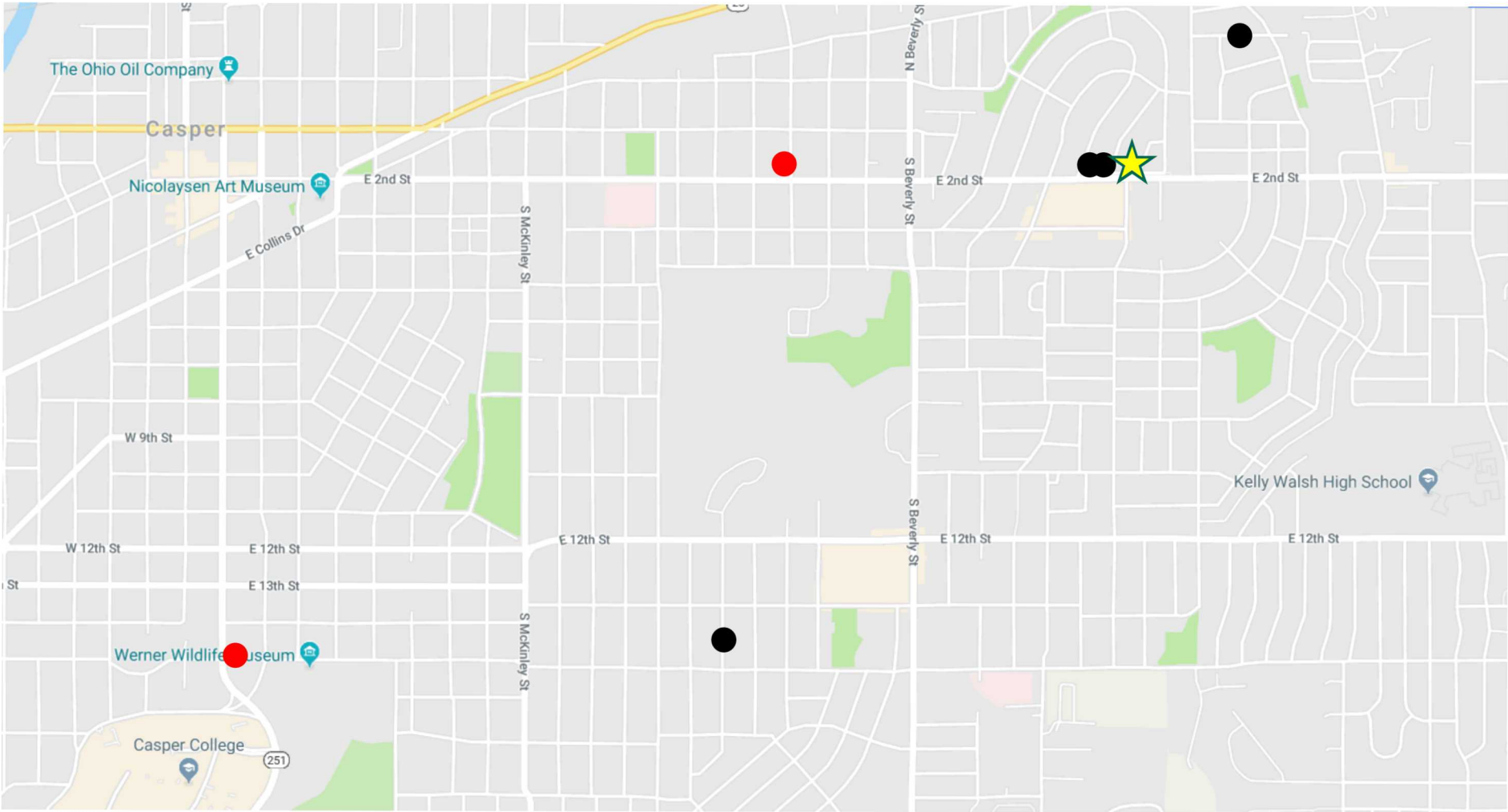
David R. Sandison, Director  
MESA: Microsystems Engineering, Science and Applications

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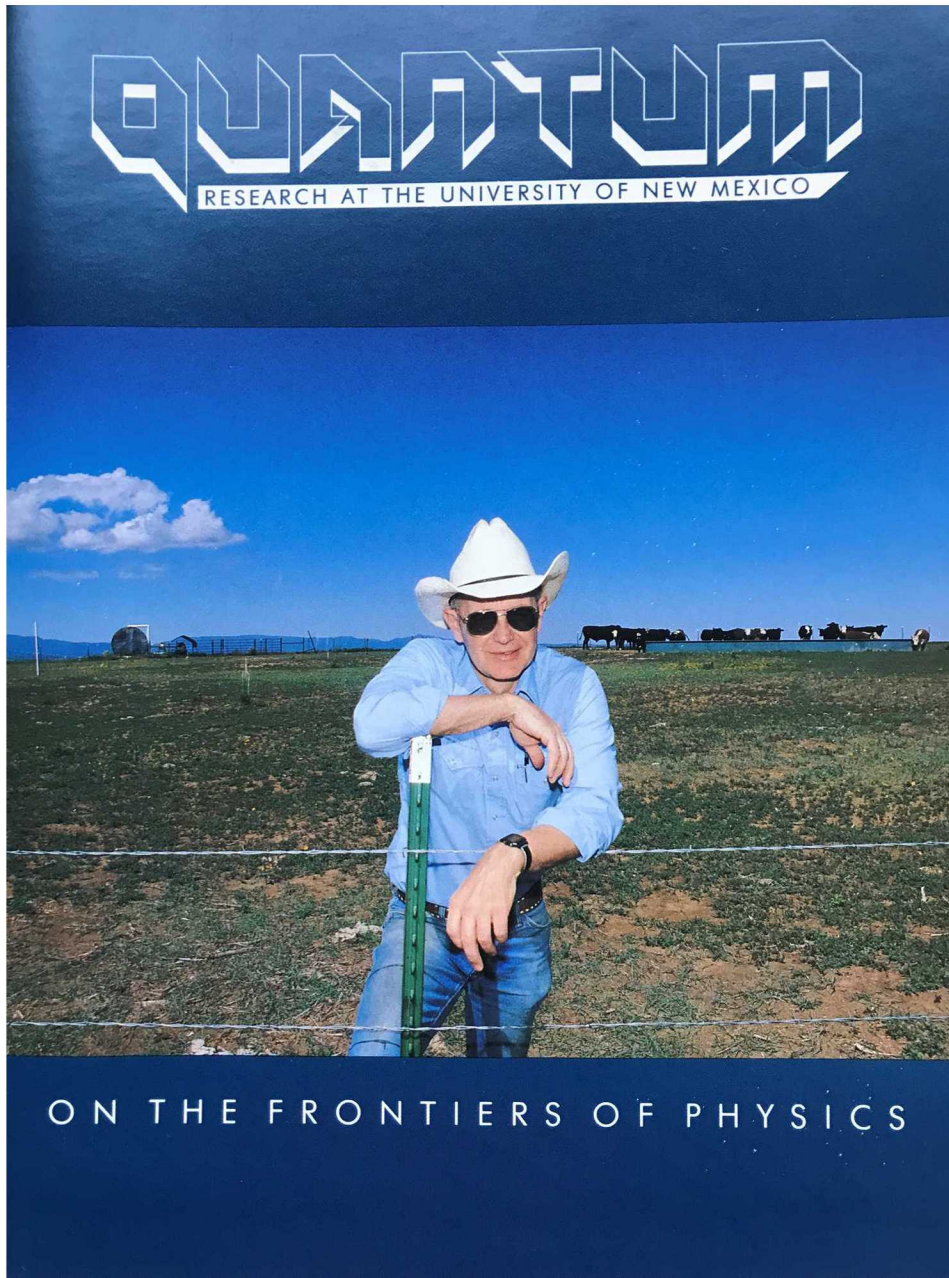
David Sandison  
Chemistry - 2nd Place  
College Days 1981  
Casper College



# Deep Wyoming roots



# “The Quantum Cowboy”

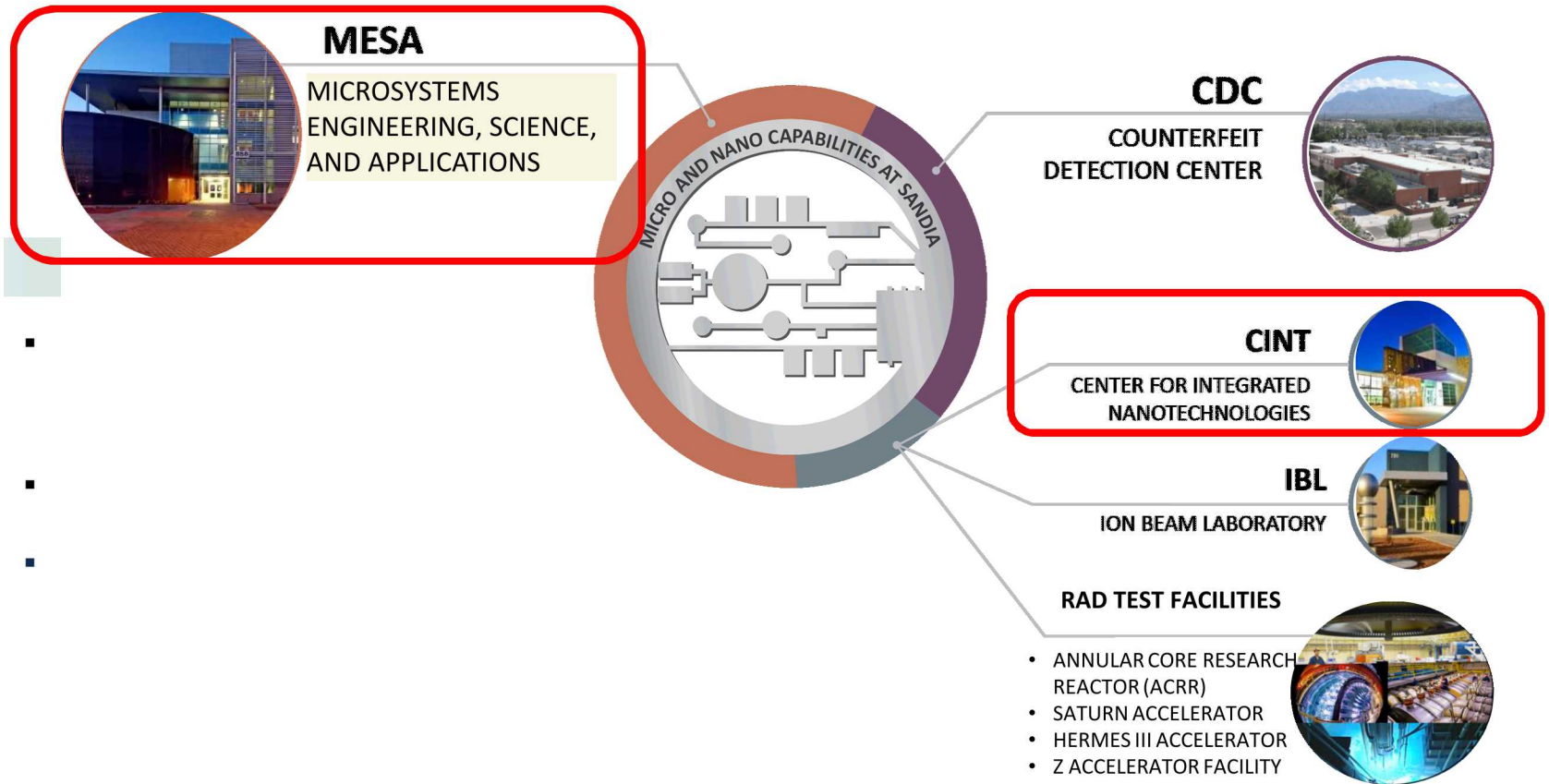


1980 – Center for Modern Optics  
198X – Center for Advance Studies



2009 – Center for Quantum  
Information and Control

# Sandia's Micro & Nano Capabilities: Strategic National Resource



- 
- 
-

# Sandia has a long history in Microelectronics and Microsystems



1960s

Microelectronics and Microsystems

Present

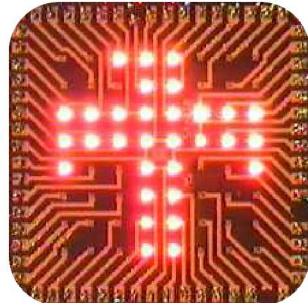
Laminar Flow Clean Room



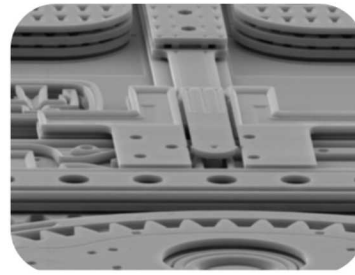
Design/Build Galileo ICs



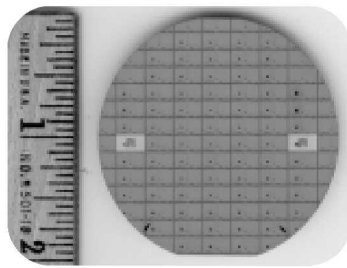
High Efficiency VCSEL



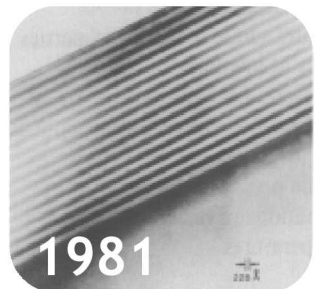
5-Level Surface Micromachining



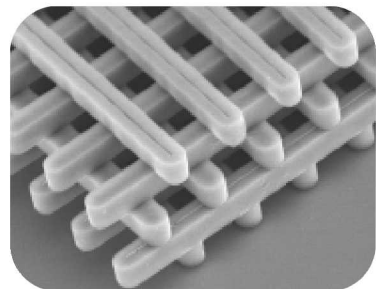
Microsystems-Enabled Photovoltaics



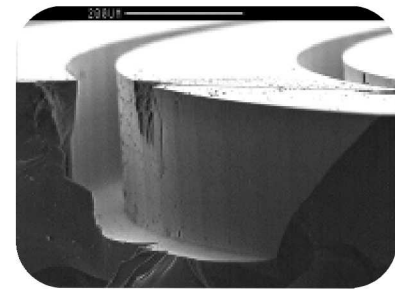
Radiation-Hardened CMOS



Strained-layer Superlattices



Photonic Lattice



MicroChemLab



Quantum Computing

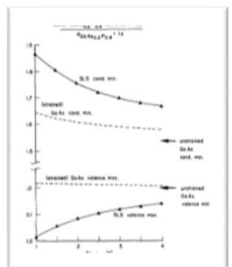
1980s

Quantum Engineering

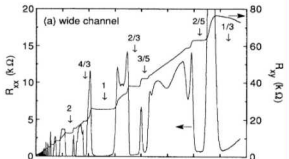
Present



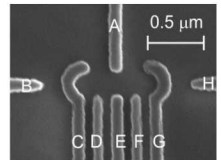
Strained-layer superlattices from lattice mismatched materials, *Journal of Applied Physics* 53, 1586 (1982)



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)



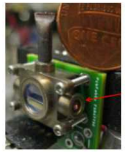
QIST Grand Challenge LDRD: Si quantum bits & logical qubits (2008-10)



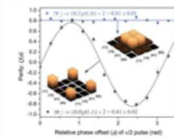
16th Electronic Properties of 2D Electronic Systems in Albuquerque (2005)



DARPA IMPACT: Ion microwave atomic clock (2009-14)



AQUARIUS GC LDRD: Adiabatic QC (2011-13)



SECANT GC LDRD: QKD (2016-18)



IBM Quantum Experience: 1<sup>st</sup> public access to QC (2016)



DOE/SC Quantum Science Open User Testbed (QSCOUT) (2018-22)



1980s

1990s

2000s

2010s

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

Simulating Physics with Computers  
Richard P. Feynman

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

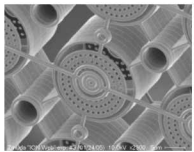
$$|0\rangle \rightarrow \frac{1}{2\sqrt{2}}(|000\rangle + |111\rangle)(|000\rangle + |111\rangle)(|000\rangle + |111\rangle),$$

$$|1\rangle \rightarrow \frac{1}{2\sqrt{2}}(|000\rangle - |111\rangle)(|000\rangle - |111\rangle)(|000\rangle - |111\rangle). \quad (3.1)$$

LDRD: "Quantum Computing Accelerator I/O," C.P. Tigges, N. Modine (2003)



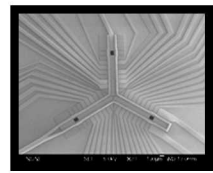
1<sup>st</sup> QIS presentation by Sandia: Microfabricated ion traps for QC architectures, M. Blain, *et al.* (2004)



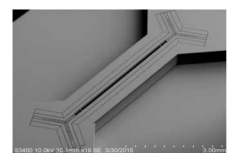
1<sup>st</sup> external QIS funding at Sandia: Trap foundry, M. Blain, *et al.* (2005); LDRD: Traps for QC & Qsim (2005)



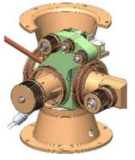
3 LDRD: Ion qubits; Si qubits; QC architecture (2007)



IARPA MQCO: Microfabricated surface traps for multiple qubits (2010-2015)



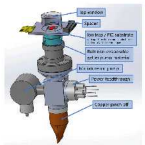
IARPA LOGIQ: Microfabricated traps for a logical qubit (2016-2021)



SIGMA GC LDRD: AI for inertial guidance (2018-20)



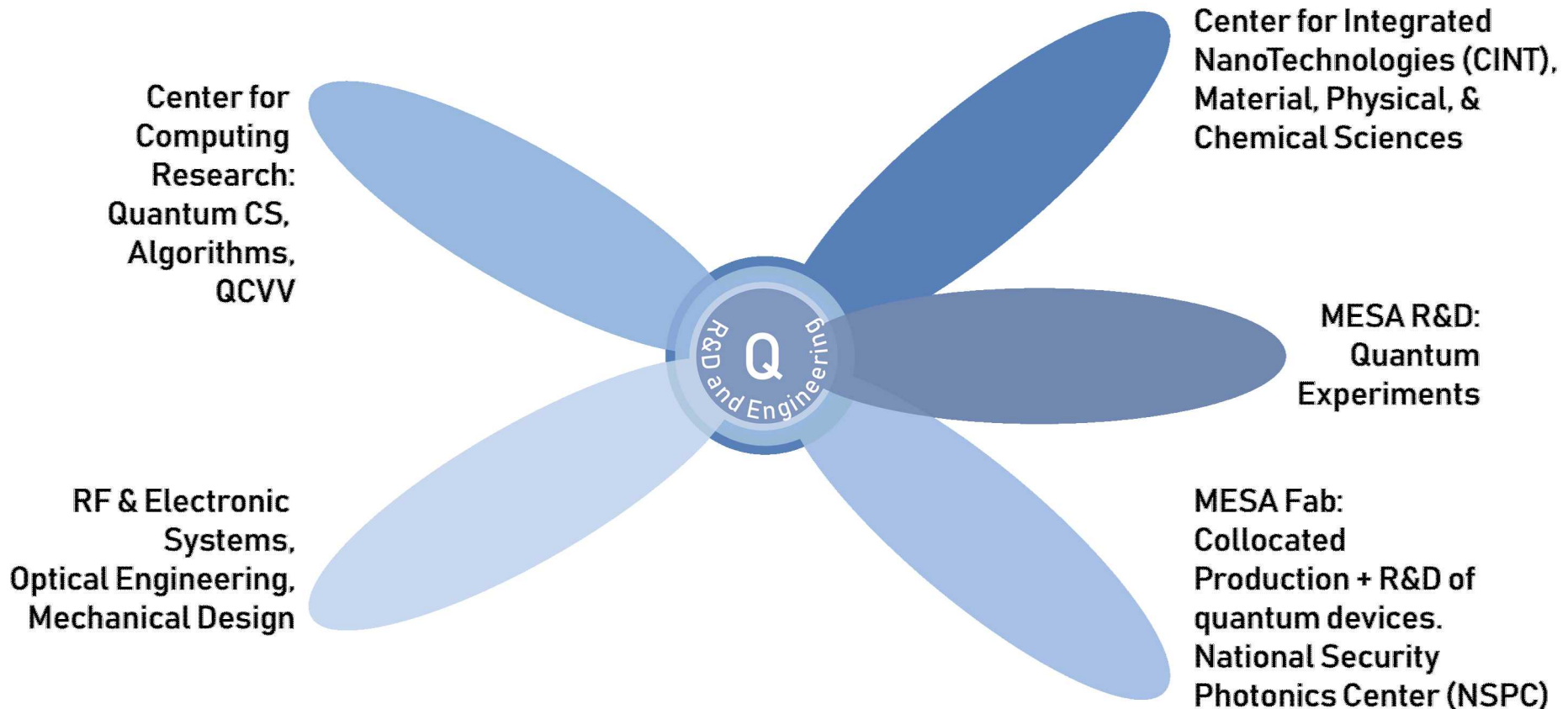
DARPA TICTOC: Ion optical clock (2019-21)



# Sandia Quantum Information Science Organization Chart

## QIS work at Sandia draws on skills and resources from across the Labs

- QIS is an exciting opportunity for Sandia's engineers and scientists
- QIS benefits from decades of collective experience in all relevant domains at Sandia
- Examples of results: QSCOUT, SIGMA (coming up later in talk)



## DOE funded nano-science user center

- Free access to staff expertise and equipment for open science
- Two proposal calls per year - short-term projects proposals accepted continuously

## In-situ characterization & nanomechanics

- Dynamic response of materials and nanosystems to mechanical, electrical, or other stimuli.

## Nanophotonics & optical nanomaterials

- Synthesis, excitation, and energy transformations of optically active nanomaterials and electromagnetic phenomena

## Soft, biological & composite nanomaterials

- Synthesis, assembly, and characterization of soft, biomolecular, and composite nanomaterials that display emergent functionality.

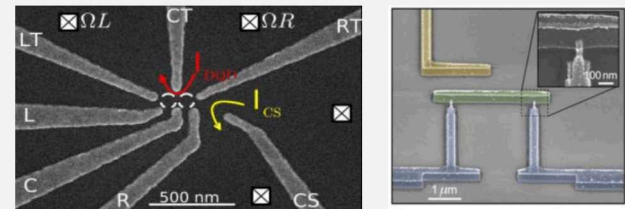
## Quantum material systems

- Understanding and controlling quantum effects of nanoscale materials and their integration into systems spanning multiple length scales.

## Quantum material systems details:

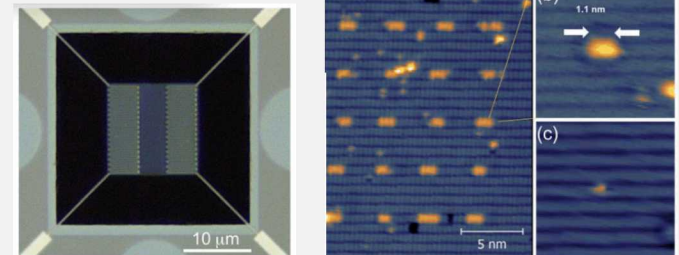
### Quantum information science

- Quantum transport & qubits
- Quantum sensing
- Focused ion implantation



### Forefront lithography

- Atomic-precision lithography
- Nanoscale devices



### Materials synthesis

- Ultra-high mobility MBE
- Complex oxide PLD
- CVD nanowire growth

### Correlated systems

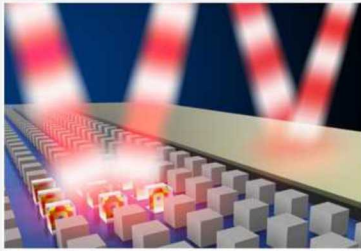
- Mean-field modeling for quantum materials
- Many-body approaches

# DOE/Office of Science (SC) Project (CINT & MESA)

Light-matter interaction phenomena using subwavelength engineering of material properties (PI: Igal Brener, Sr. Scientist, MESA; DOE/SC BES)

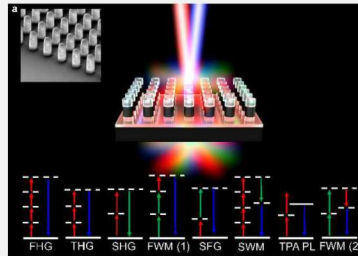
*Approach: Combining nanostructures and metamaterials with state-of-the-art compound semiconductors to achieve new behaviors*

## Optical Magnetic Mirror

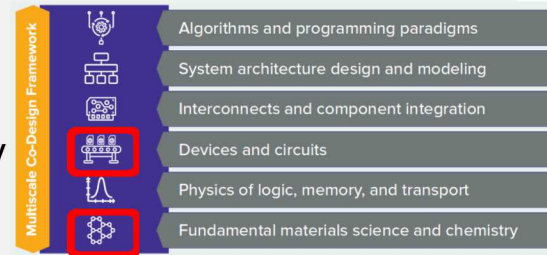


Enhances light field interactions at the mirror surface for absorbers & emitters

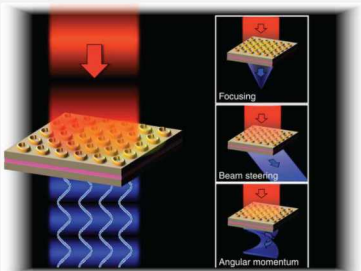
## Optical Nonlinear Mixer



Eleven new frequencies (colors) simultaneously generated

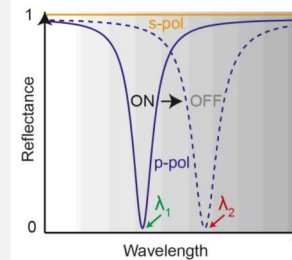
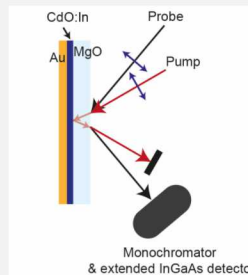


## Phased Array Nonlinear Source



Directional Control of Nonlinear ( $2\omega$ ) beams

## Terahertz-Speed Optical Switch Using Epsilon-Near-Zero Materials



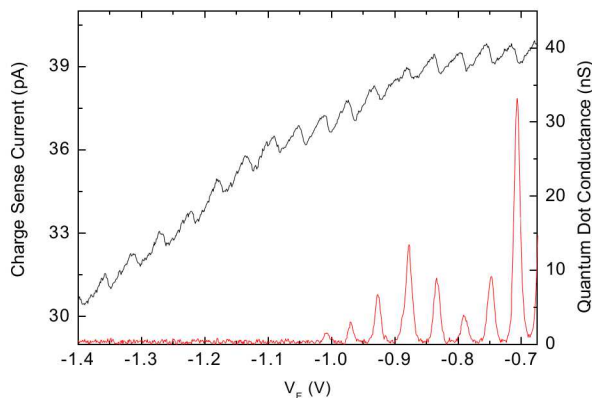
Near-complete beam switching with femtosecond speed

Enabling III-V growth, sample processing, and subject matter expertise from MESA



## Project accomplishments:

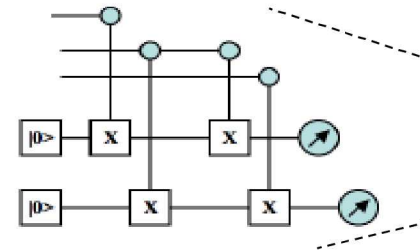
- **Fabrication and measurement techniques for silicon quantum bit (qubit) using double quantum dots**
- **End-to-end design (qubits to quantum circuit) for error corrected logical qubit with Si double quantum dot hardware**
- **Modeling tools to guide the fabrication, measurement, and assessment of Si qubit and circuits.**



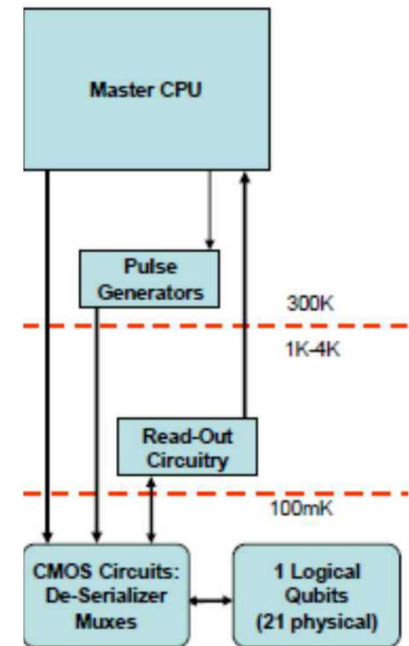
*World's first single electron charge sensing in Si MOS system*



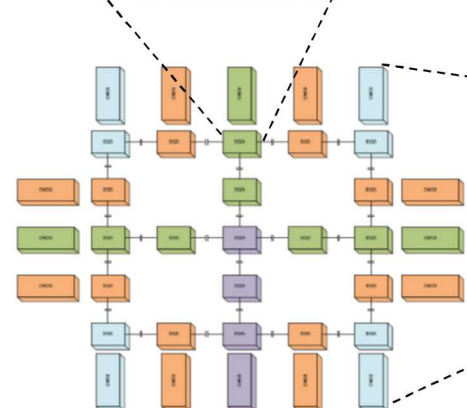
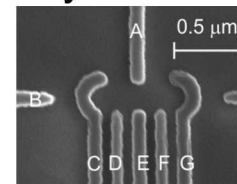
Quantum Circuit



Classical Interface



Physical Qubit



Logical Qubit

# QSCOUT: An open quantum testbed at Sandia

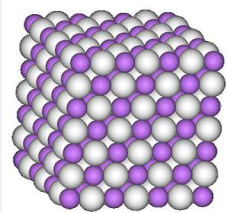
DOE/SC Advanced Scientific Computing Research (ASCR) **QSCOUT** (PI: P. Maunz)

- Quantum processor with **5-15 trapped-ion qubits**
- Goal: **Available to the DOE/SC computing community** in 2020
  - Access to quantum processor with high-fidelity operations
  - Low-level access to gate & quantum circuit implementations
  - Full information on implementation of quantum operations
  - Ability to run any testing circuits

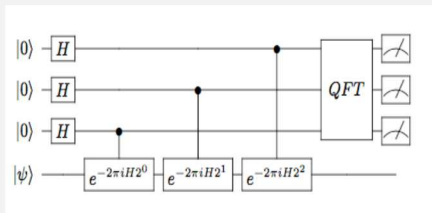
## Design approach

- Build on established qubits ( $^{171}\text{Yb}^+$ )
- Use Sandia microfabricated traps
- Use established qubit manipulation tools (e.g. pulsed laser as demonstrated at UMD, Duke, Sandia)

## Example QSCOUT workflow:



Lithium hydride example

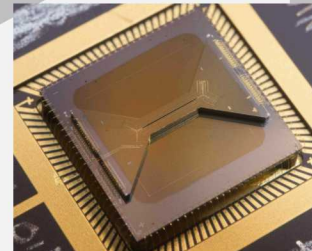


Textbook digital quantum simulation circuit

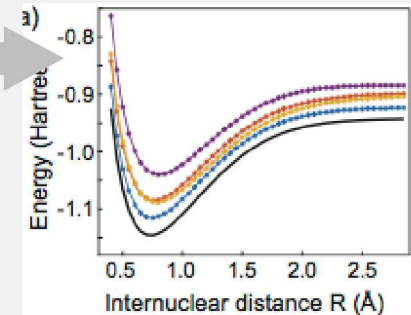
```
In [8]: circuits = ['alegret']
print(Q_program.get_name(circuits[0])

OPENQASM 2.0;
include "qelib1.inc";
qreg q[3];
creg c[3];
creg c[1];
creg c[2];
h q[1];
cx q[1],q[2];
ry(0.785398163397448) q[0];
cx q[0],q[1];
h q[0];
barrier q[0],q[1],q[2];
measure q[0] -> c[0];
measure q[1] -> c[1];
if(c[0]==1) x q[2];
if(c[1]==1) x q[2];
measure q[2] -> c[2];
```

QSCOUT code/  
microcode



Implement on hardware/trapped ions



Results

## QSCOUT's main interdisciplinary tasks

Qubit hardware

Gate modeling

QCVV

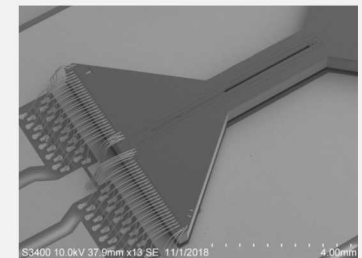
Hardware controllers

Software stack

Exemplar apps

## QSCOUT collaborations

- Duke University (K. Brown)
- Tufts University (P. Love)
- LBNL
- Open to others...



# SIGMA Grand Challenge LDRD

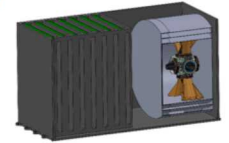


## Quantum Sensing GC LDRD SIGMA (PI: G. Biedermann)

- Miniaturized atom interferometer to enable **sub-100 ng sensing** performance in **1000x smaller package**



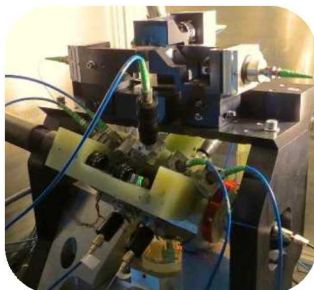
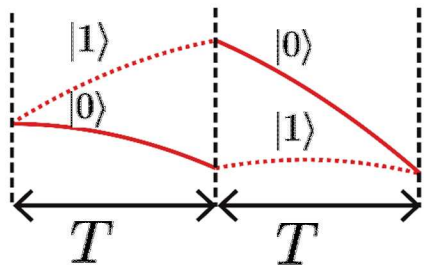
UC San Diego  
Yale



- Atom interferometers operate spectacularly well in laboratory environments
- Fielding is challenging in a compact form and in all but the most benign environments
- Result of: system reliability issues, system size, and dynamic range

### What will it take?

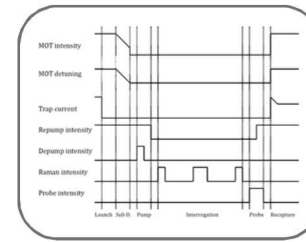
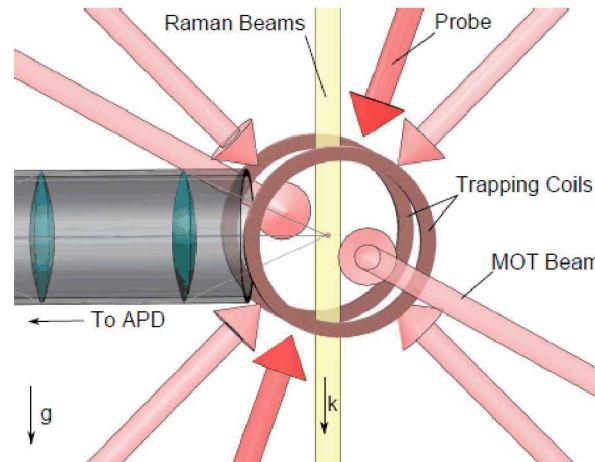
#### Atom interferometer physics



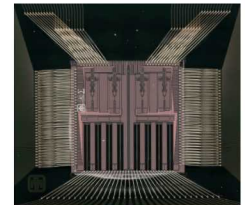
Custom optomechanics



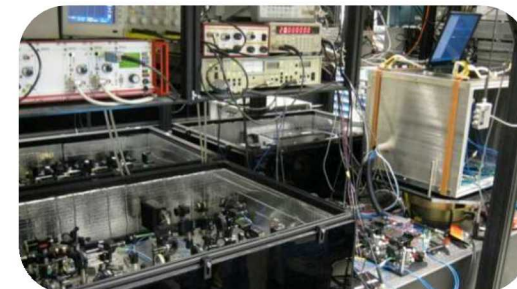
UHV system



Control electronics



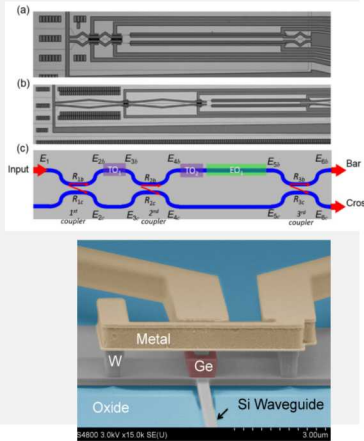
Photonics



Agile & stable laser system

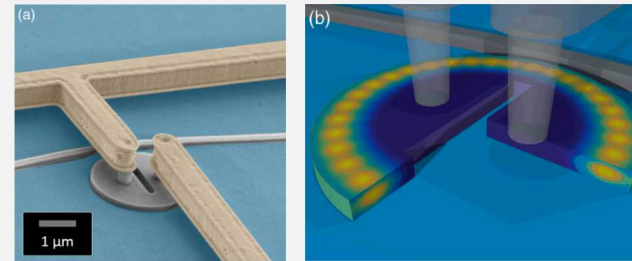
## Integrated photonics for quantum communications

Sandia's silicon, III-V, alumina, lithium niobate heterogeneously integrated photonic platforms: compact microsystems for telecom and visible wavelengths



## Cryogenic optical interconnects

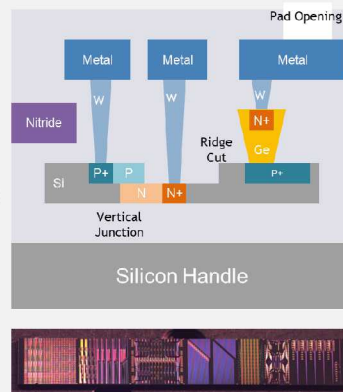
High-speed low-power resonant modulator operating at cryogenic temperatures ( $\leq 4$  K)



*Optica* 4,  
374-382 (2017)

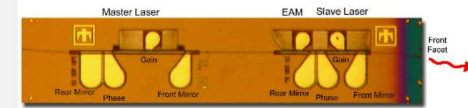
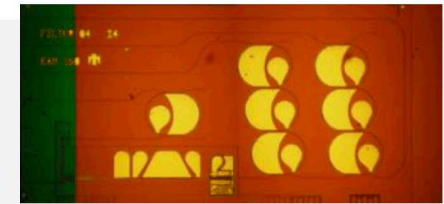
## Silicon photonics integrated circuits

- Leverage CMOS (200 mm SOI)
- 22 passive devices, 20 active devices, design guide and library
- **MPW runs available**, up to passive+active+Ge devices



## III-V photonic integrated circuits (PICs)

- InP, GaAs, GaN
- Elements: Waveguides, lasers, amplifiers, modulators, detectors, phase shifters
- **MPW runs available**



## More information on photonics MPW opportunities:

- National Security Photonics Center: [sandia.gov/mesa/nspc](http://sandia.gov/mesa/nspc)
- Contact [photonics@sandia.gov](mailto:photonics@sandia.gov)

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# National Quantum Initiative (NQI)

## Sandia Center for Integrated Quantum Sciences

The critical bottleneck to achieving quantum goals is **integration**. CIQS attacks this obstacle by addressing an array of **critical S&T challenges**:

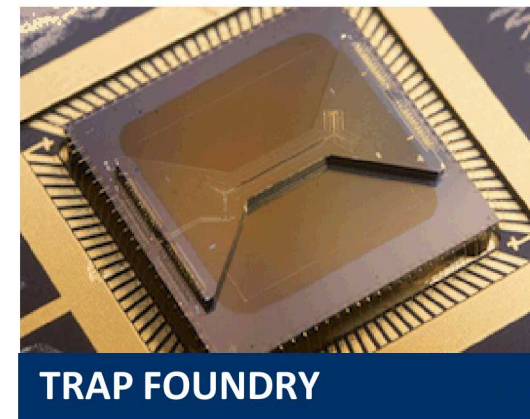
- How do we simultaneously increase qubit capacity and fidelity?
- Can we integrate multiple qubit technologies to reap the benefits of hybrid devices?
- What efficiencies can be achieved from vertical integration of control stacks?
- What system engineering optimizations can enable key applications?

### 5 Year Vision: Integrating Ions and Photons for Science Impact

- Build on the high fidelity and full connectivity available with trapped ions
- Enable improved devices making use of shuttling and photonics coupling
- Integrate chip-based photonic elements and electronics with existing physics devices.
- Develop algorithms and protocols to deal with connectivity limitations
- Extend to other AMO systems such as quantum sensing with trapped atoms
- ***Driven-by and impacting key science applications***

*Beyond 5 years:*

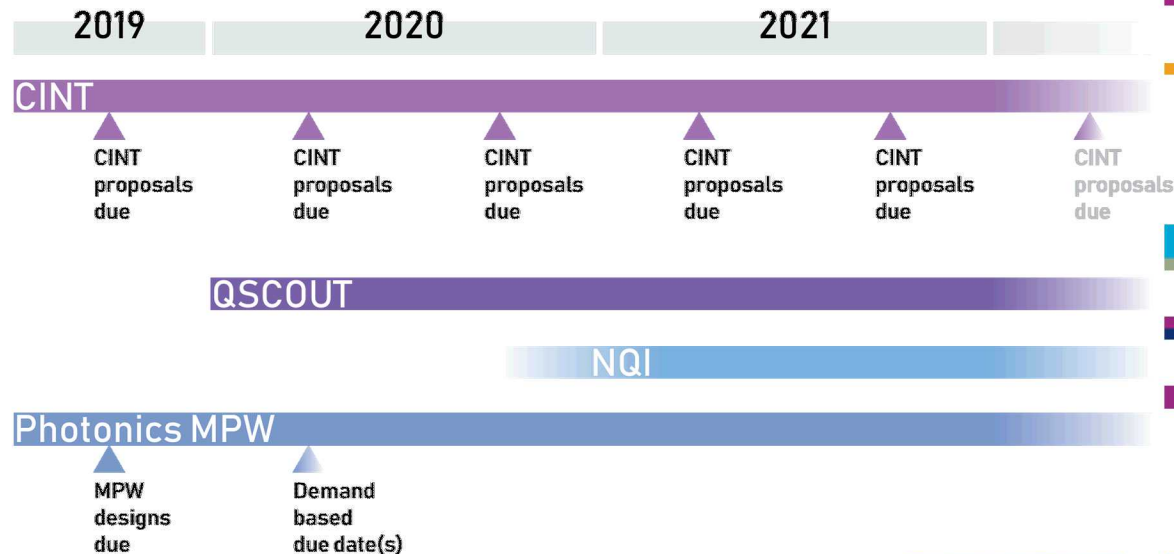
- Extend capabilities to heterogeneously integrate multiple complementary quantum technologies
- Develop and demonstrate an agile platform for chiplets representing different computing, communications, and sensing capabilities.



# How to work and partner with Sandia

Numerous technical **partnerships** in place today:

- Academic institutions, industry, & Government
- CINT**: semi-annual proposals cadence: [cint.lanl.gov](http://cint.lanl.gov)
- QSCOUT**: coming in 2020
- NQI**: in progress
- Contact [quantum@sandia.gov](mailto:quantum@sandia.gov)
- National Security Photonics Center**: [sandia.gov/mesa/nspc](http://sandia.gov/mesa/nspc)
- Contact [photonics@sandia.gov](mailto:photonics@sandia.gov)

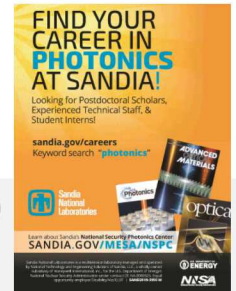


## Recruiting (IDs):

- 668199 – Integrated Photonic Researcher/Optical Engineer
- ...and 7 Post-doc postings

7/11/2019

- contact [quantumjobs@sandia.gov](mailto:quantumjobs@sandia.gov)
- check out [sandia.gov/careers](http://sandia.gov/careers), “photonics”





Questions?