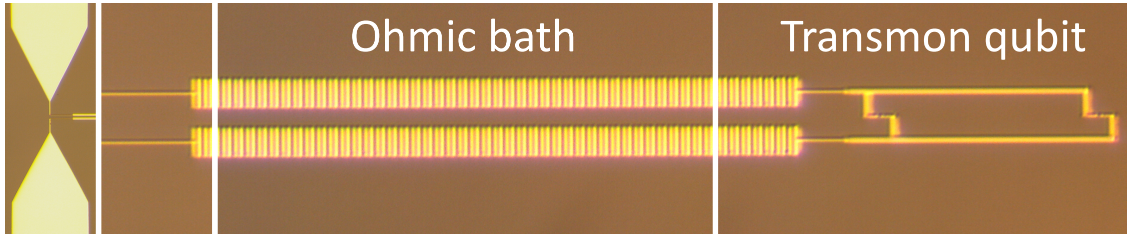
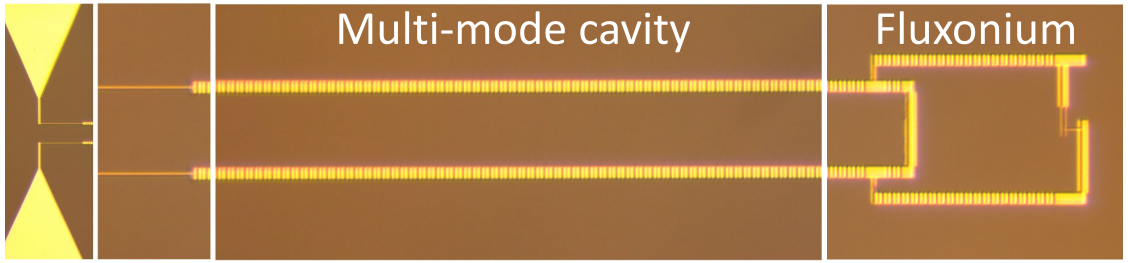
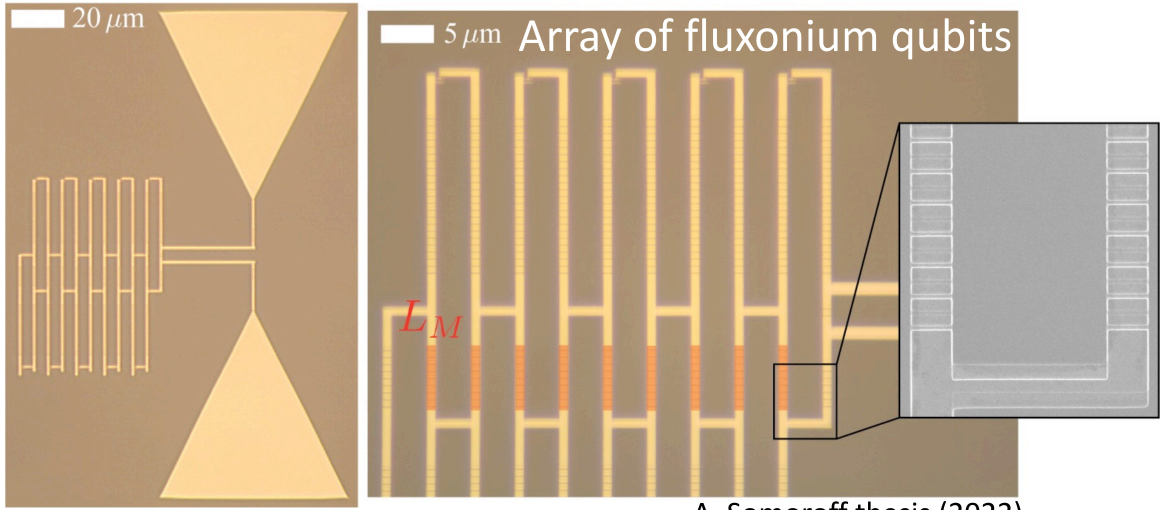
Simulation of Quantum Many-Body Phenomena with Superconducting Qubits

We simulate:

- Quantum phase transitions
- Many-body localization
- The Kondo effect
- Impurities in Luttinger liquid
- Interacting spins
- Strongly-correlated materials



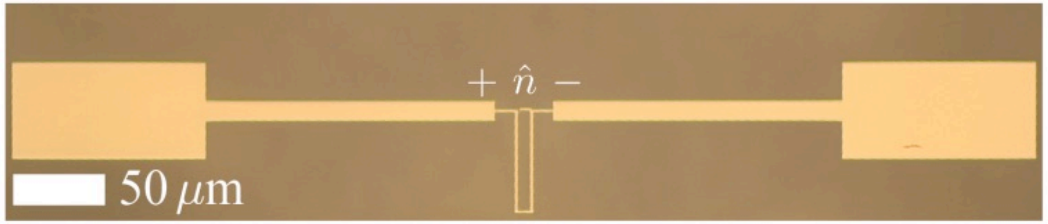


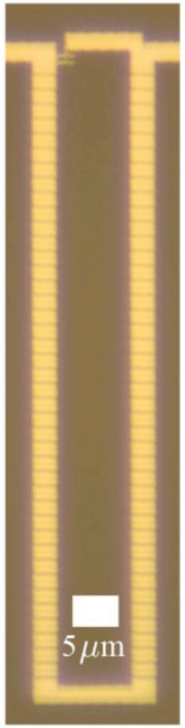


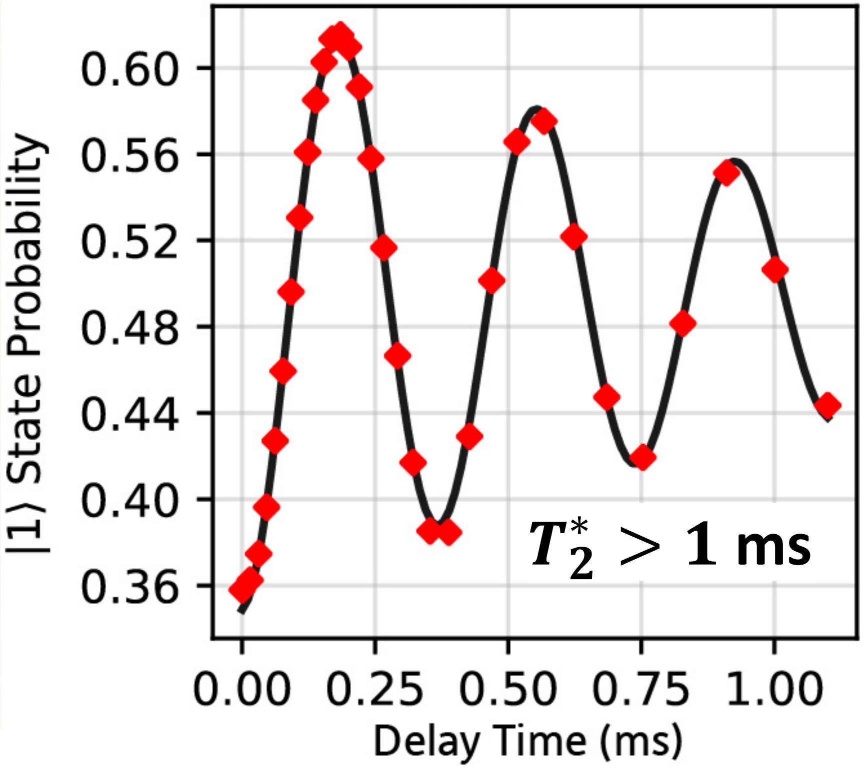
A. Somoroff thesis (2022)

Nature Physics 15, 930 (2019); npj Quantum Information 5, 20 (2019)
PRL 126, 197701 (2021); PRL 126, 137701 (2021)
arXiv:2210.14681 (2022); Nature 613, 650 (2023)

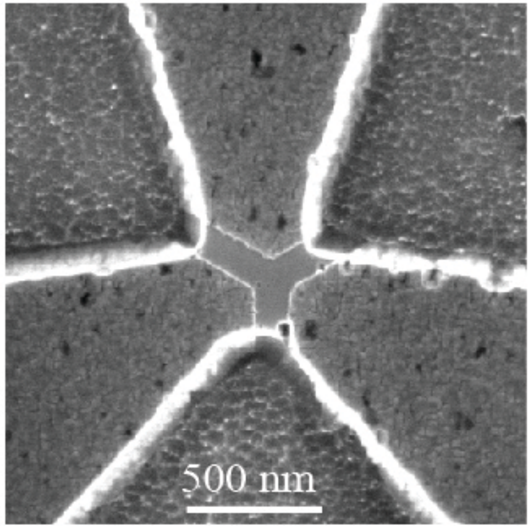
Decoherence in Fluxonium Qubits

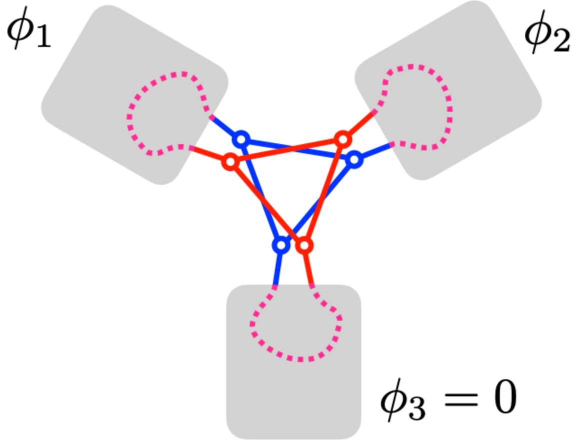




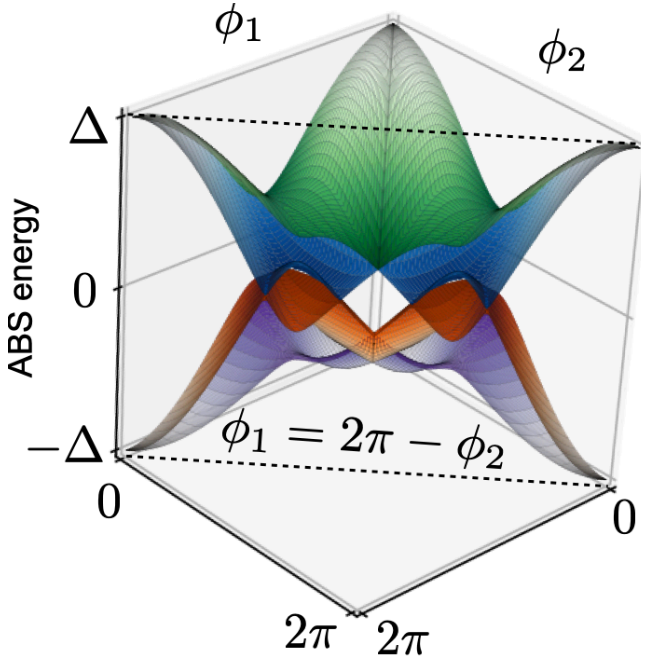


Multi-terminal Josephson Junctions





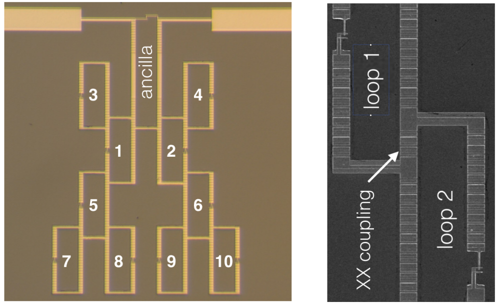
Physics in N dimensions with N+1-terminal junctions



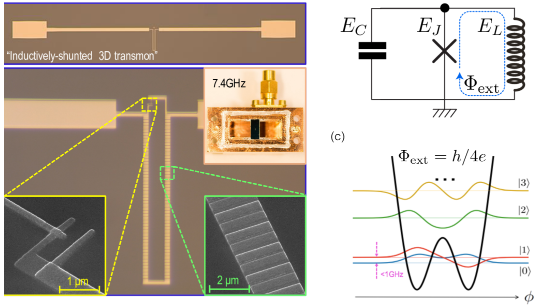
arXiv:2103.08578 (2021); PRX 10, 31051 (2020)

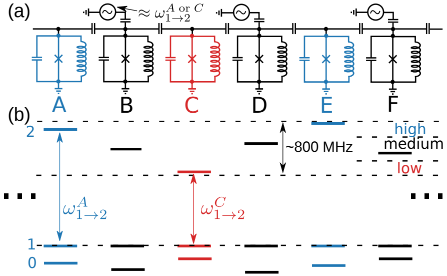
Network of Fluxonium Qubits

10-qubit quantum annealer based on fluxonium devices.

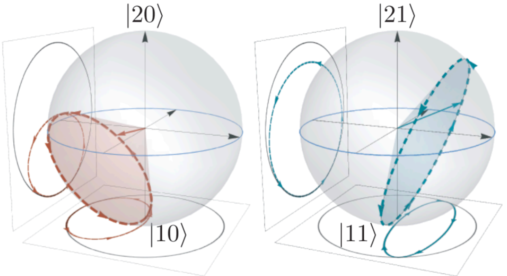


A single Fluxonium qubit and two qubit gates





Two qubit gates between fluxoniums

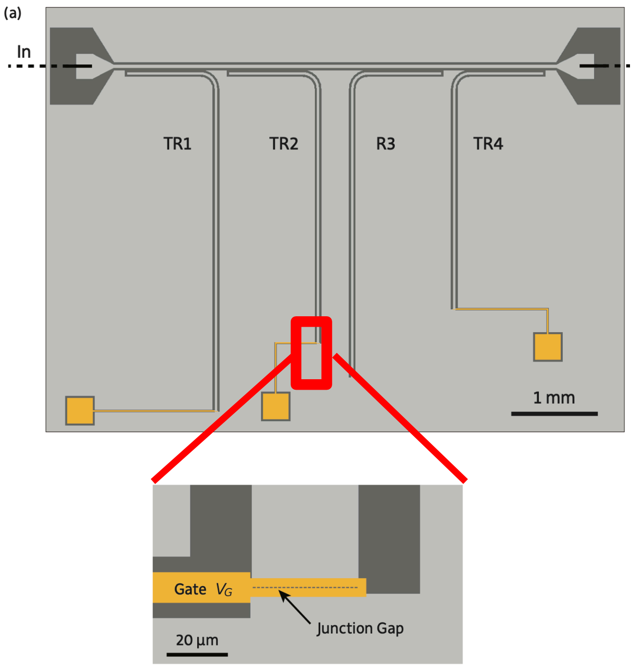


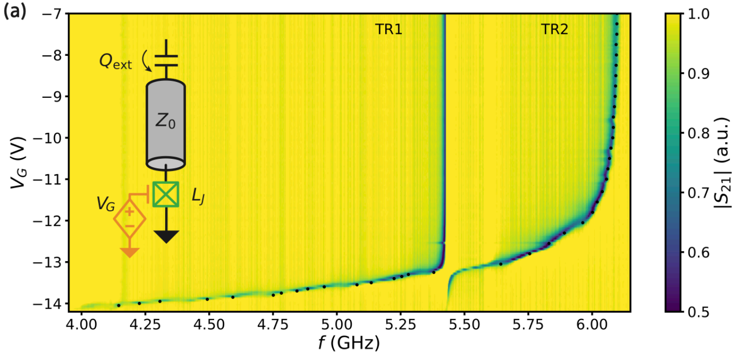
Nesterov et al. *PRA* 98, 030301 (2018)
Ficheux, Q et al. *PRX*, *11*, 021026 (2022)

in collaboration with Univ of MD

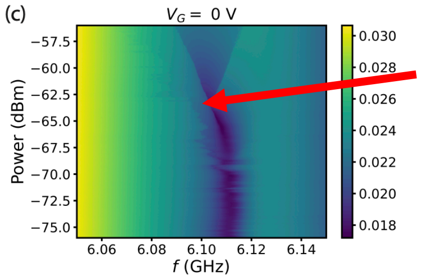
Super-Semi Josephson junctions

Microwave resonator with tunable Josephson junction at one of its terminals: gate voltage changes the frequency of tunable resonator 2





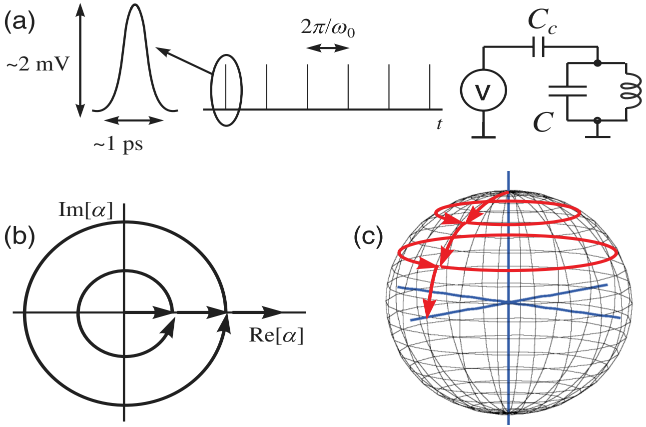
The junction also introduces non-linearity of the resonator and leads to bifurcation regime



bifurcation

in collaboration with NYU (to appear in Phys. Rev. Applied, arXiv:2210.02491)

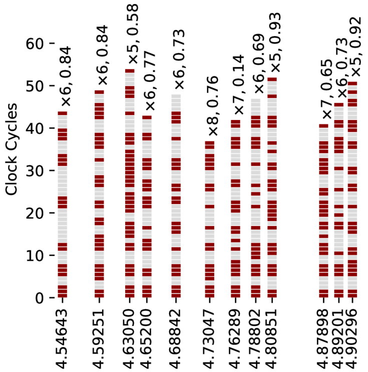
Single Flux Quantum Pulse for Qubit Control

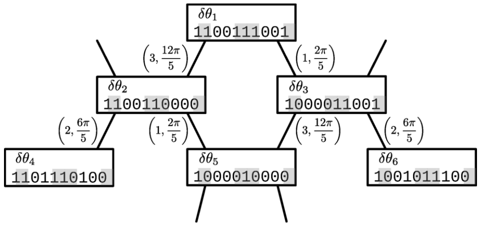


Single Quantum Flux control of superconducting qubits

- Single qubit gates: Ed Leonard et al, Phys. Rev. Appl. (2018)
- Two qubit gates;
- Parity measurements Quantum Error correction
- SFQ optimal control

Optinmal SFQ pulses with gate error <1e-4: Kangbo Li et al, Phys. Rev. Applied (2019)



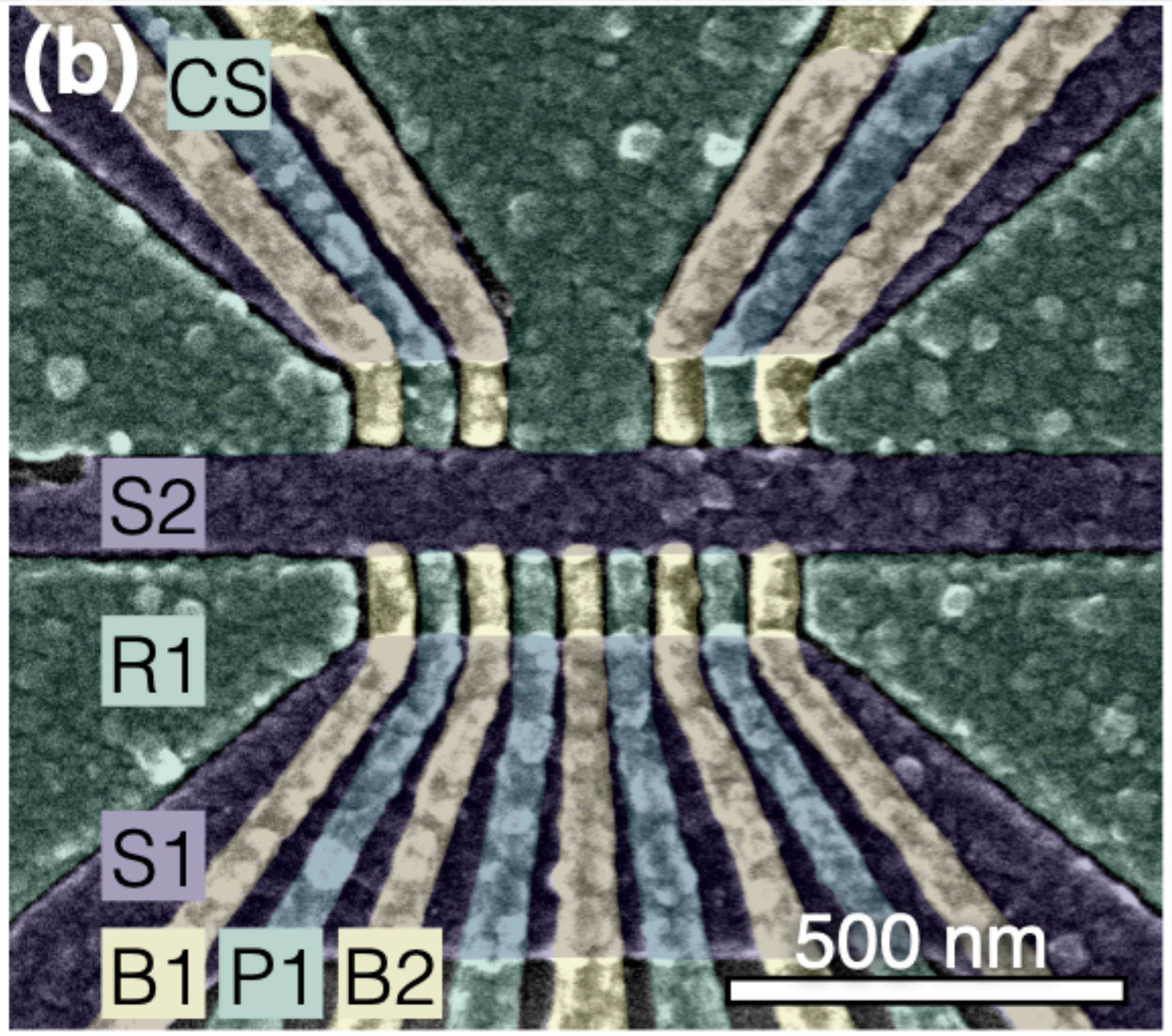


in collaboration with Prof. McDermott

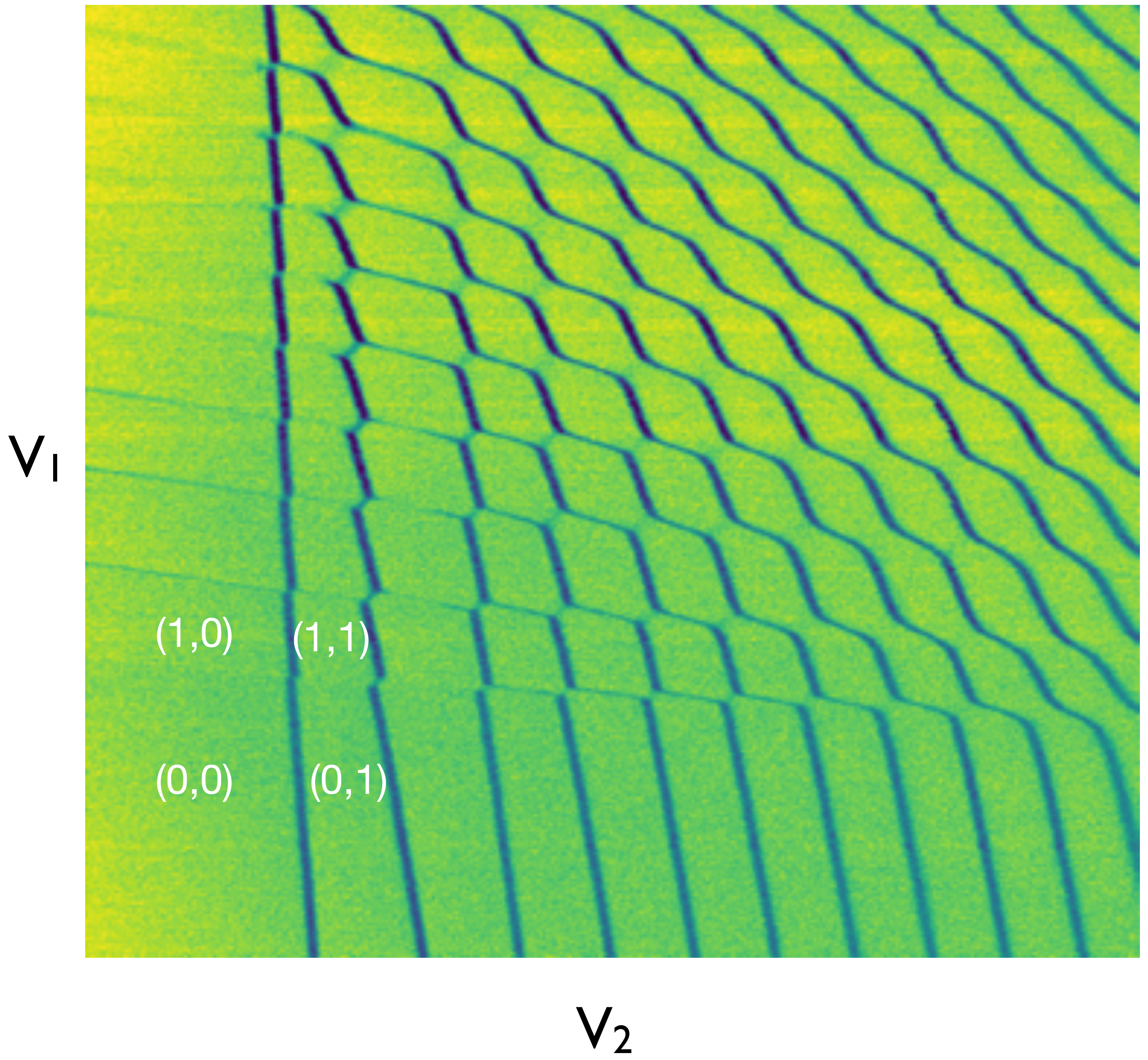
Quantum Computing Using Electron Spins in Silicon

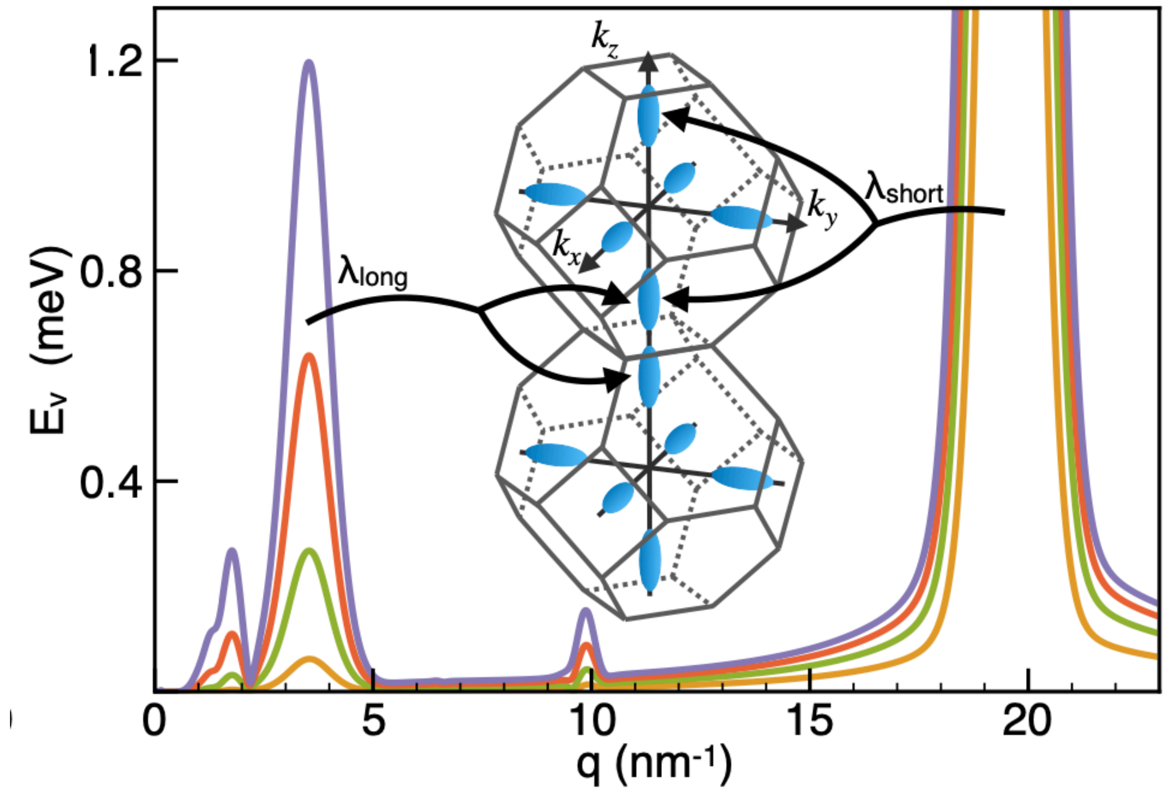
Mark A. Eriksson
Department of Physics & Wisconsin Quantum Institute
University of Wisconsin-Madison

Mark Eriksson: Silicon and Germanium-based Quantum Science



Our group nanofabricates quantum dots in the UW-Madison clean room (the NFC)

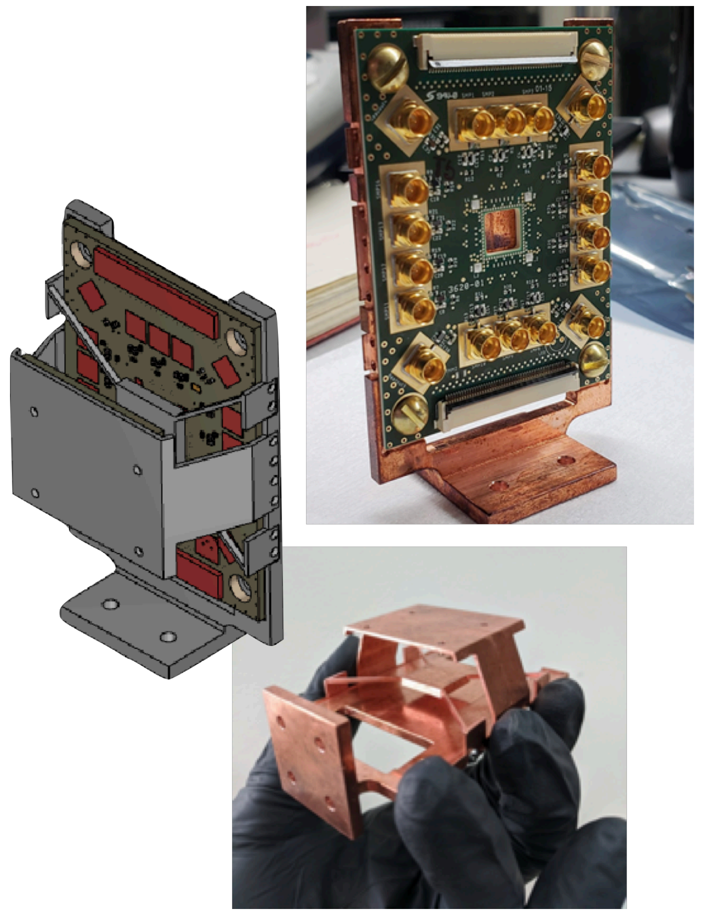


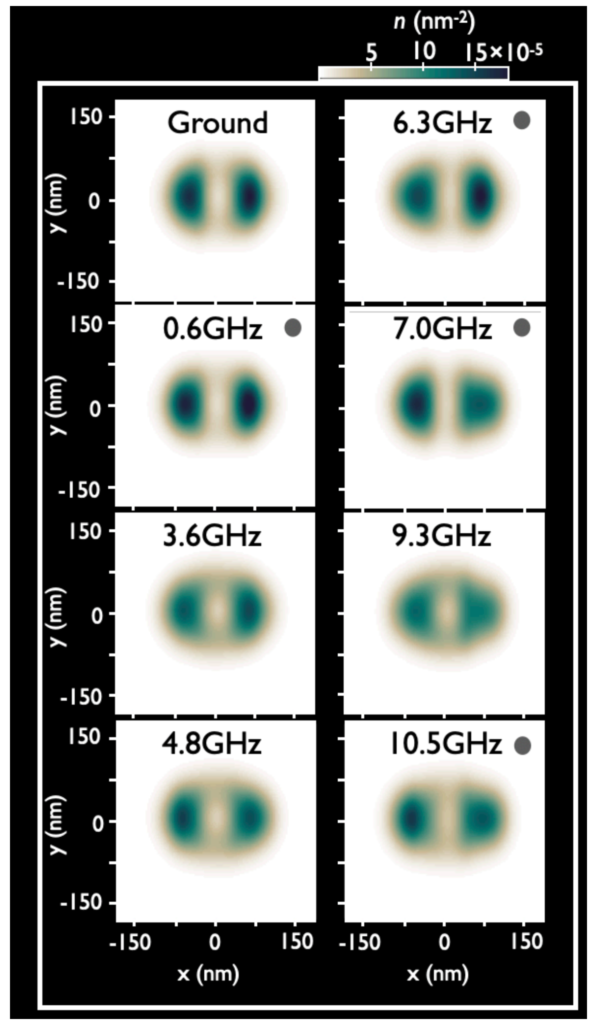


We design and build structures to generate desired quantum states out of which we form qubits.

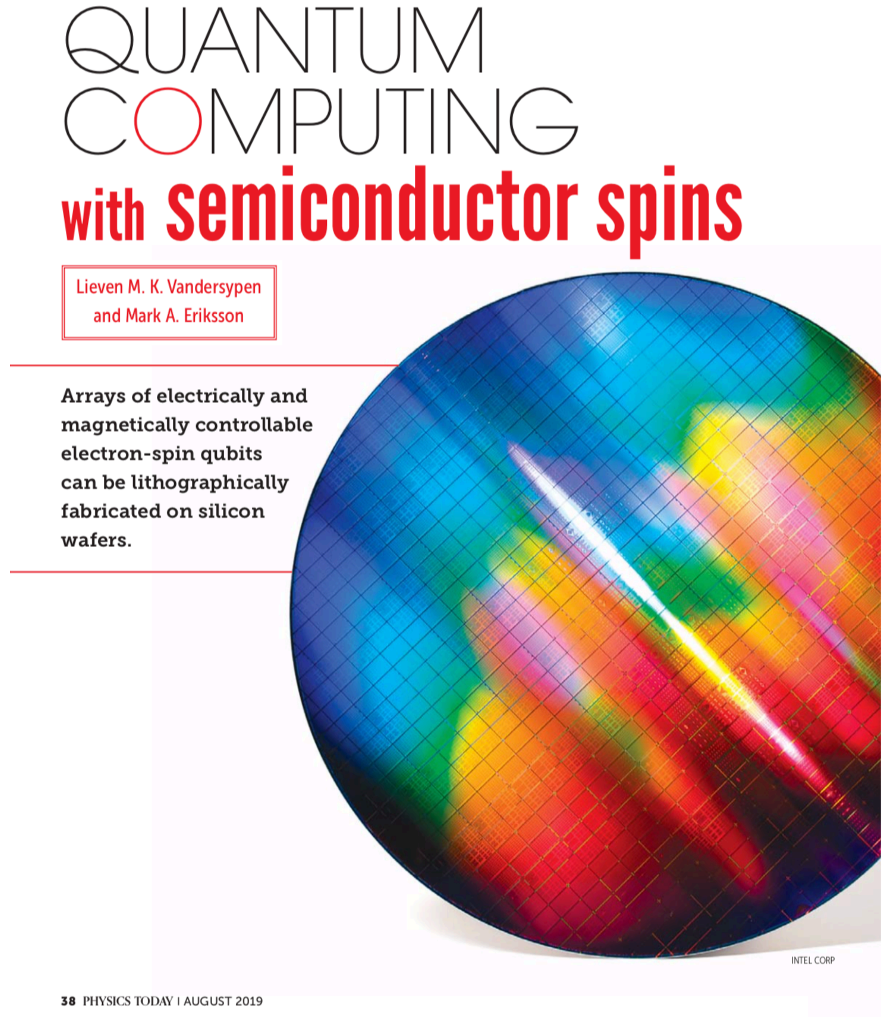
Anticipating openings for two new Ph.D. students this coming year.

Multiple dilution refrigerators, 4 in Eriksson lab, 2 shared with McDermott and Kolkowitz labs





Collaborate with theorists to understand the detailed quantum dot electronic states



QUANTUM COMPUTING with semiconductor spins

Lieven M. K. Vandersypen and Mark A. Eriksson

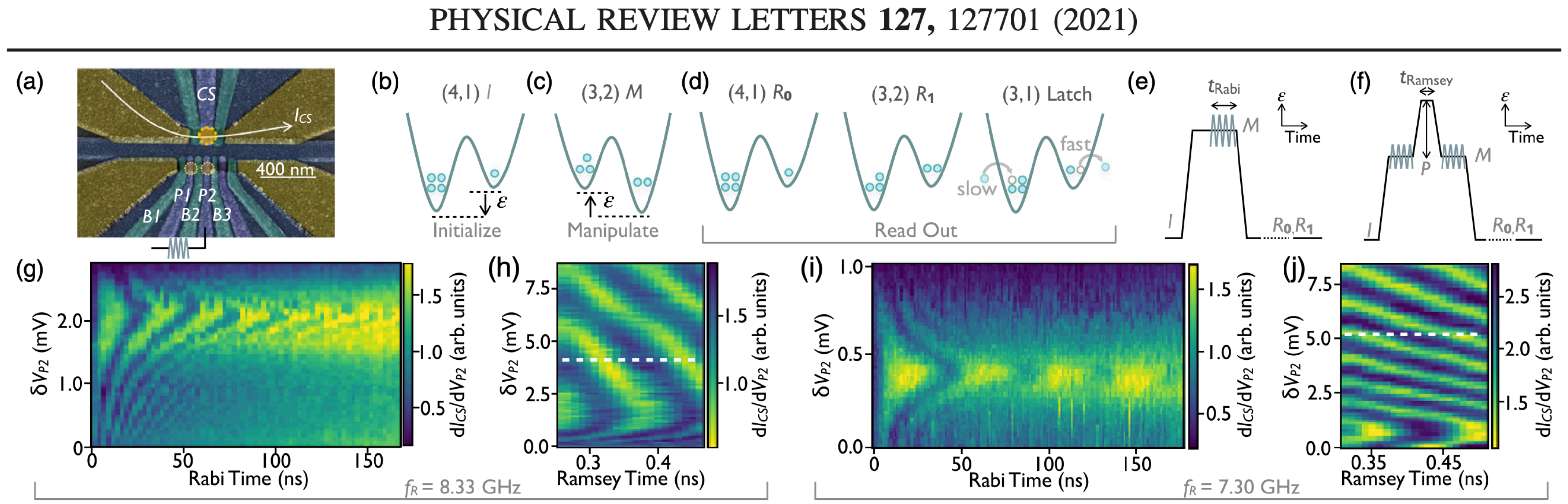
Arrays of electrically and magnetically controllable electron-spin qubits can be lithographically fabricated on silicon wafers.

38 PHYSICS TODAY | AUGUST 2019

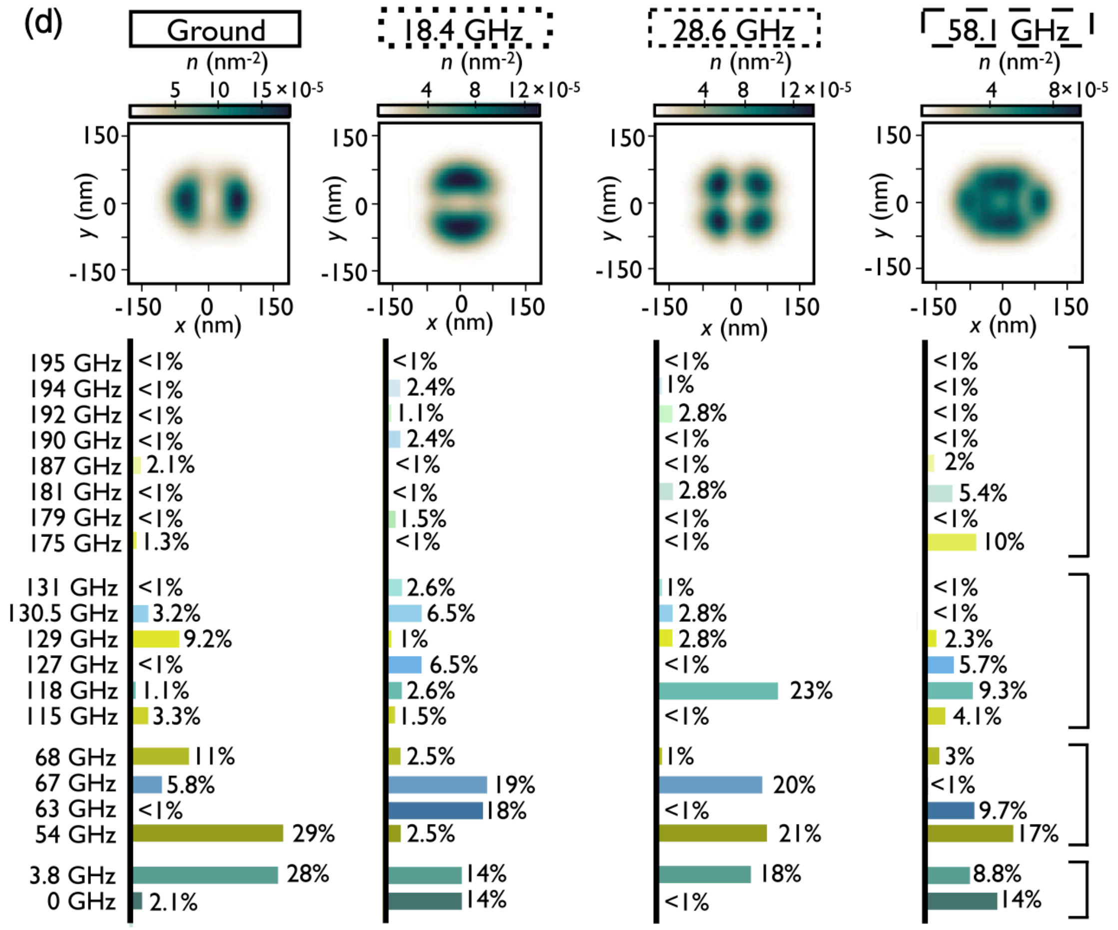
August, 2019 issue of Physics Today

Coherent Control and Spectroscopy of a Semiconductor Quantum Dot Wigner Molecule

J. Corrigan, J. P. Dodson, H. Ekmel Ercan, J. C. Abadillo-Uriel, Brandur Thorgrimsson, T. J. Knapp, Nathan Holman, Thomas McJunkin, Samuel F. Neyens, E. R. MacQuarrie, Ryan H. Foote, L. F. Edge, Mark Friesen, S. N. Coppersmith, and M. A. Eriksson
Phys. Rev. Lett. **127**, 127701 – Published 16 September 2021


PHYSICAL REVIEW LETTERS **127,** 127701 (2021)

This publication in *Phys. Rev. Lett.* from September, 2021 reported the first demonstration of coherent control between multiple different pairs of quantum states in a semiconductor quantum dot.



Work with our theory collaborators enabled us to identify those states as Wigner-molecule states of two electrons within a single quantum dot.

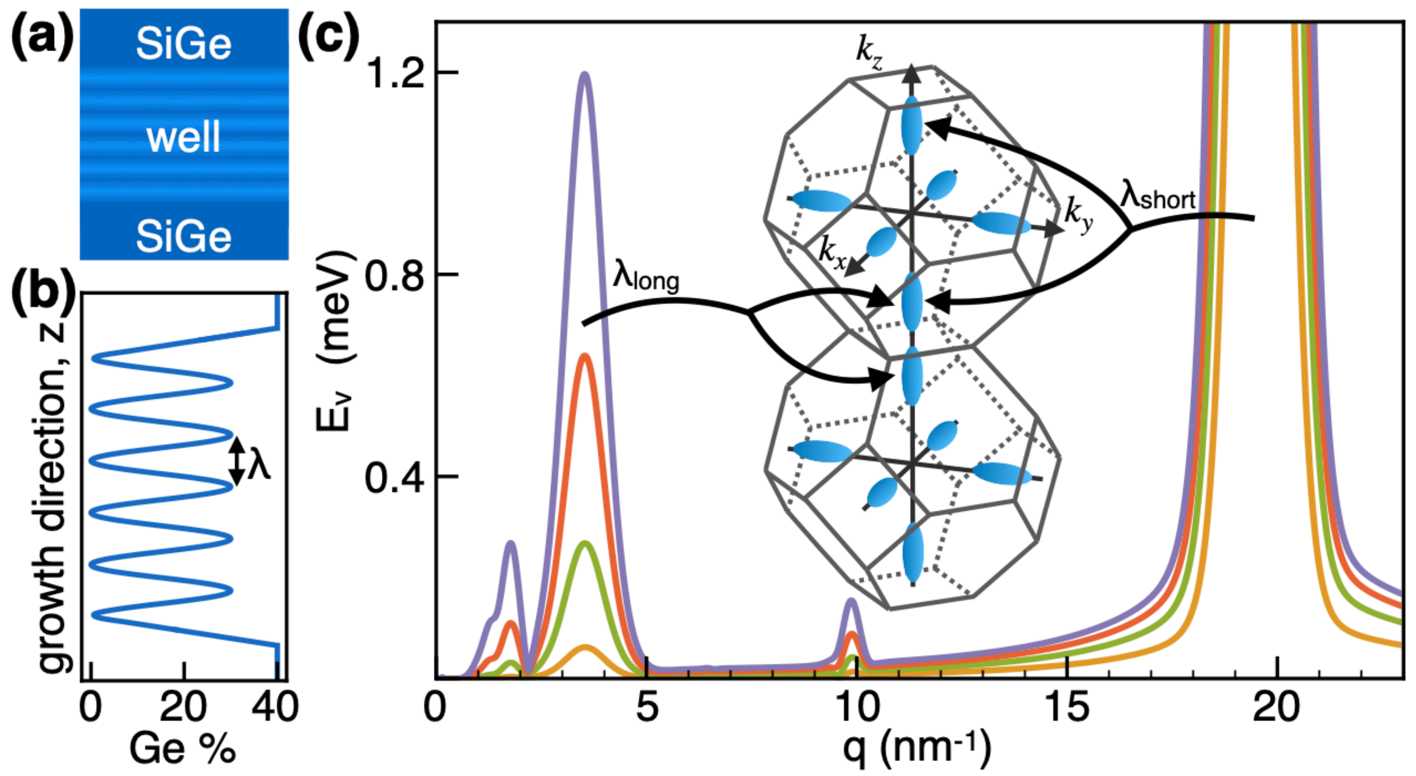
Article | Open Access | Published: 15 December 2022

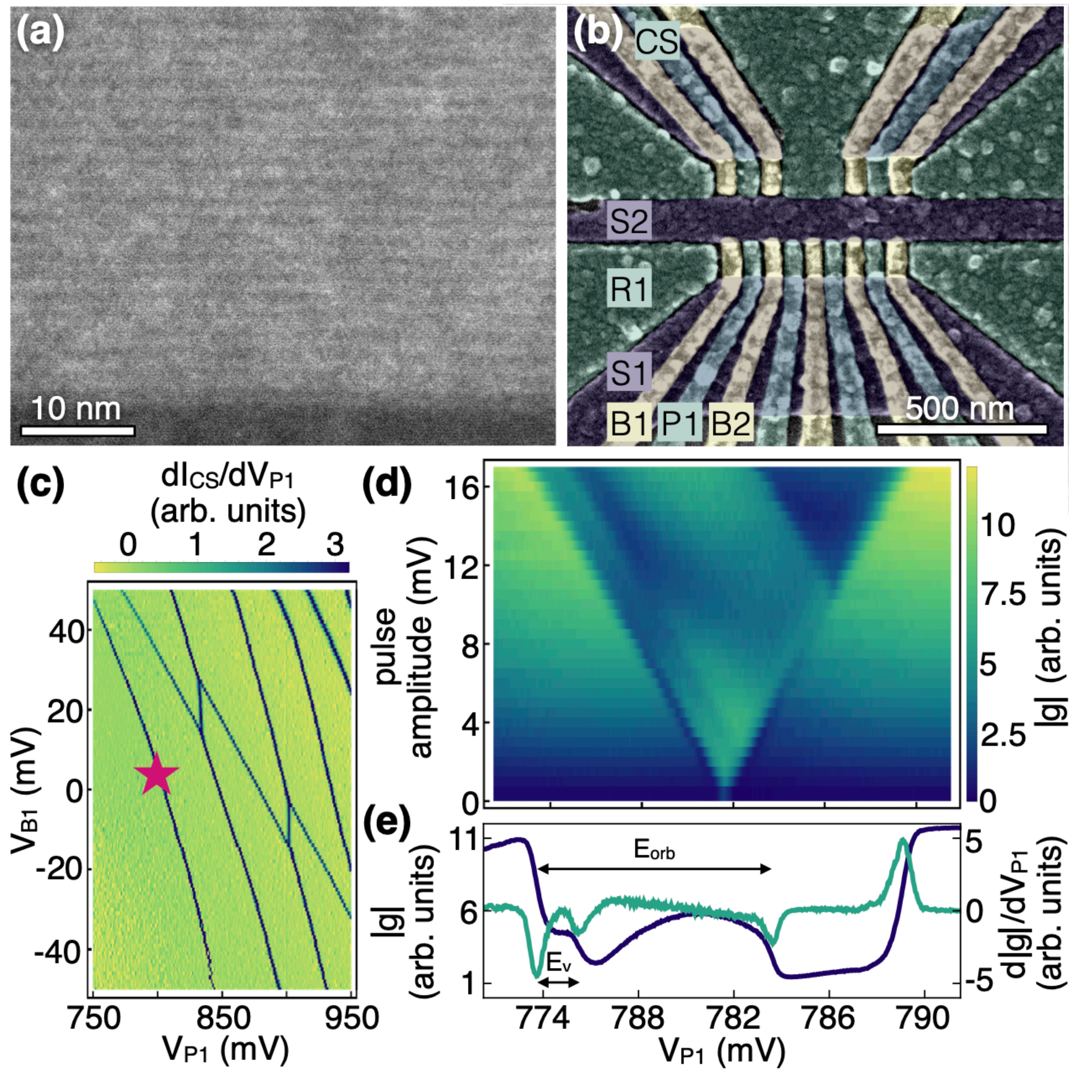
SiGe quantum wells with oscillating Ge concentrations for quantum dot qubits

Thomas McJunkin, Benjamin Harpt, Yi Feng, Merritt P. Losert, Rajib Rahman, J. P. Dodson, M. A. Wolfe, D. E. Savage, M. G. Lagally, S. N. Coppersmith, Mark Friesen ✉, Robert Joynt & M. A. Eriksson ✉

Nature Communications **13**, Article number: 7777 (2022) | Cite this article

1164 Accesses | **2** Citations | **19** Altmetric | Metrics

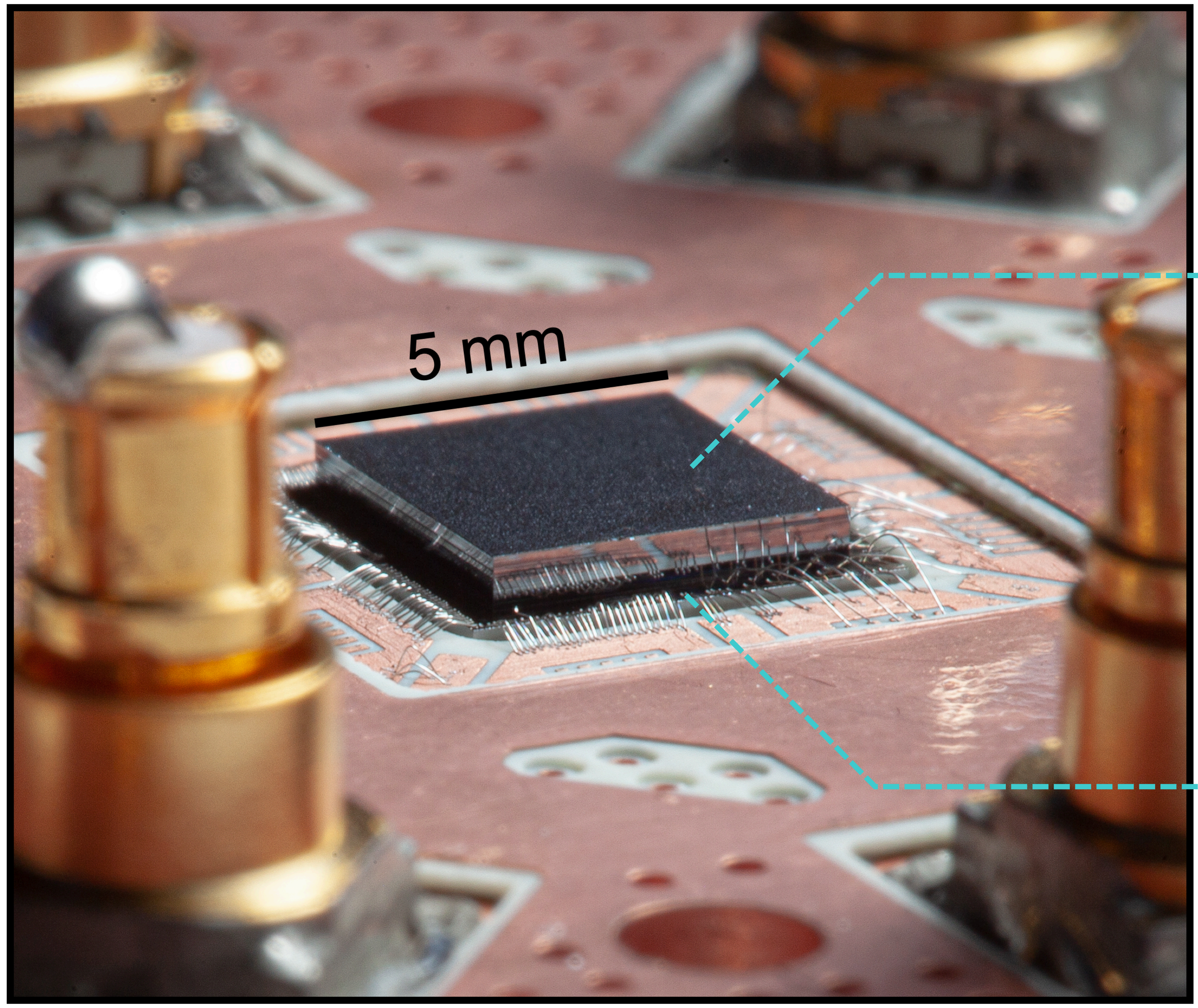


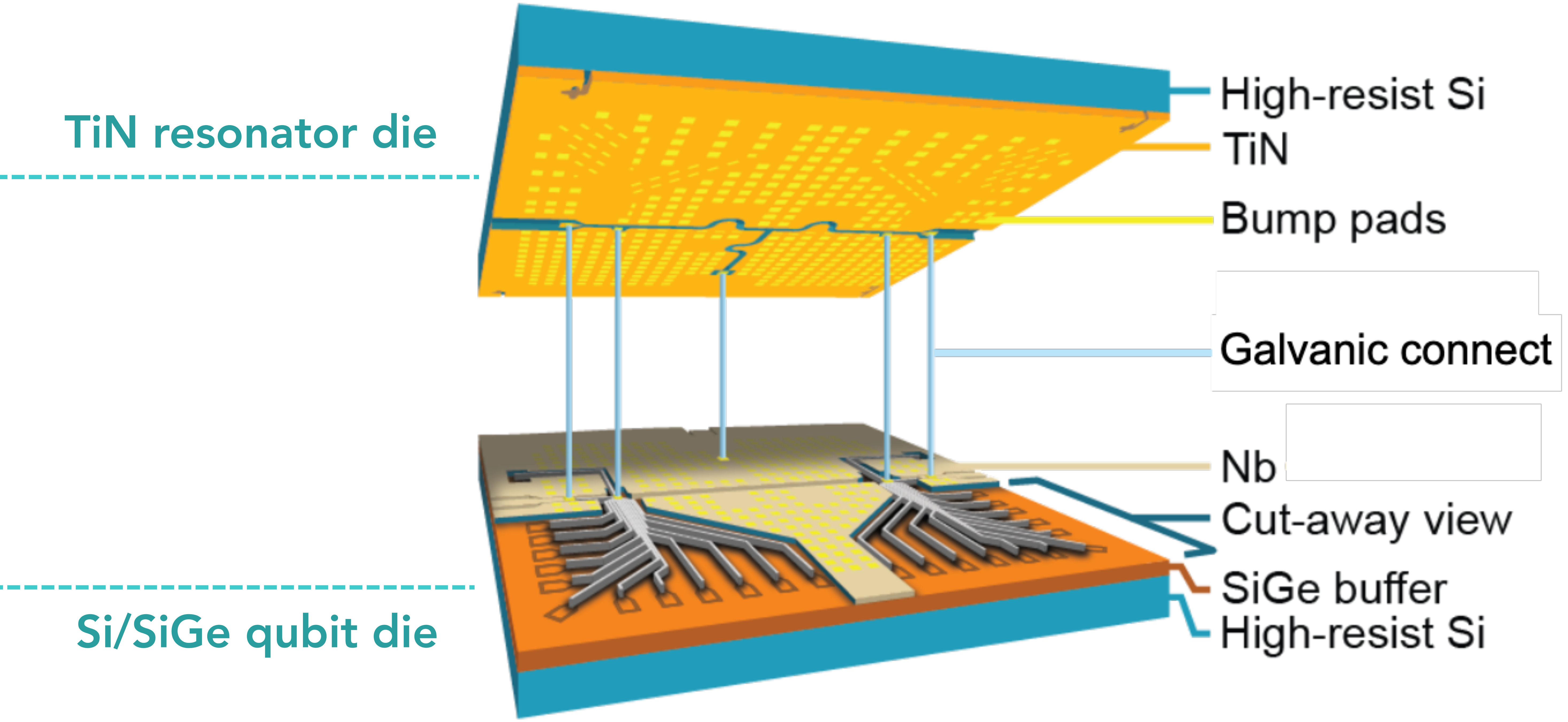


We showed that a Si quantum well containing a small, oscillatory concentration of Ge enhances the coupling between two otherwise degenerate states that are called valley states, because they sit at the minimum energy of the conduction band.

The method is to choose a wavelength for the oscillation that produces a wavevector q = 2π/λ matching the distance between the valleys in k-space. The wavevector can connect valley minima both within and between Brillouin zones.

Quantum dot-resonator vertical integration benefits scalability

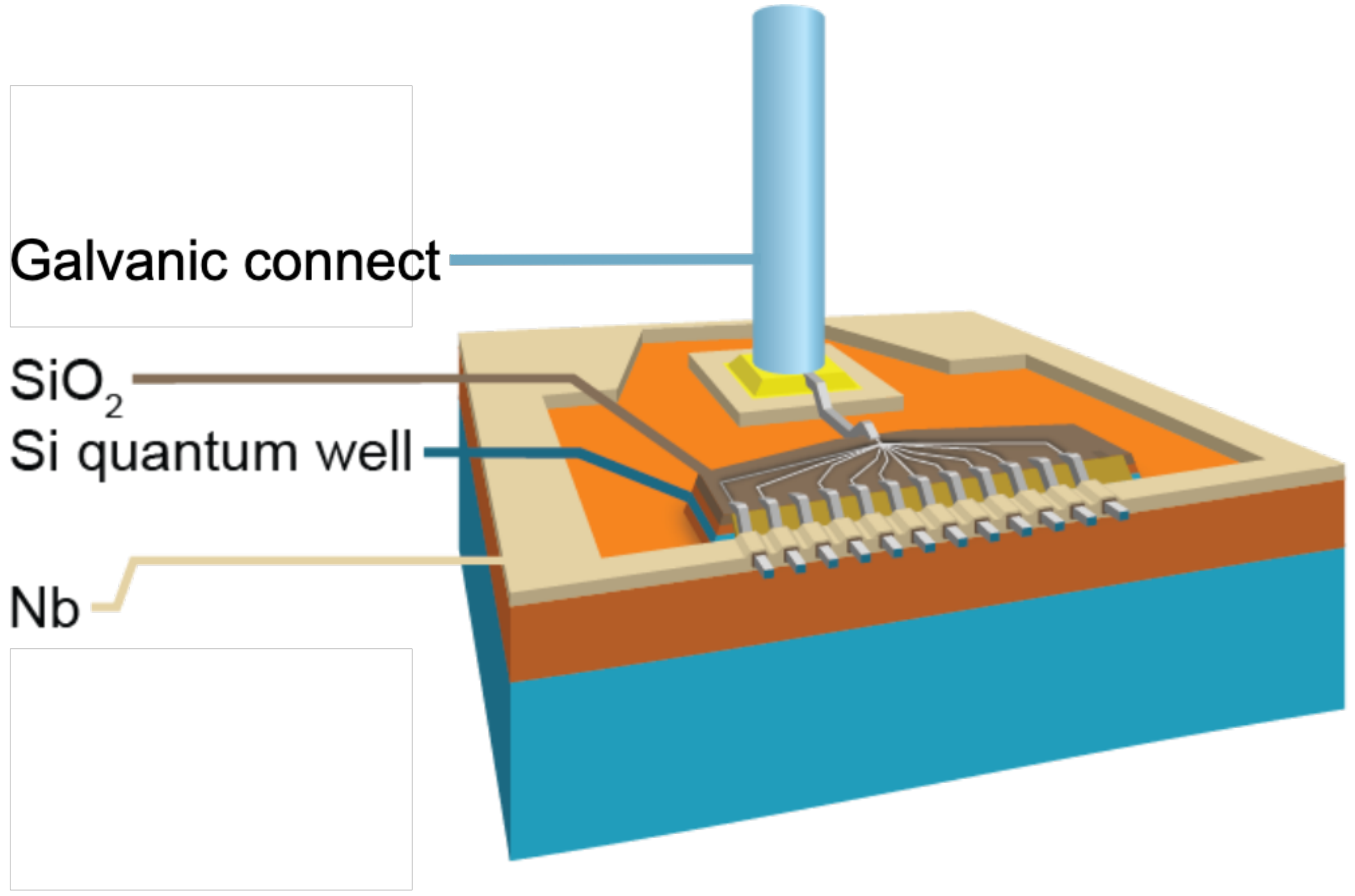


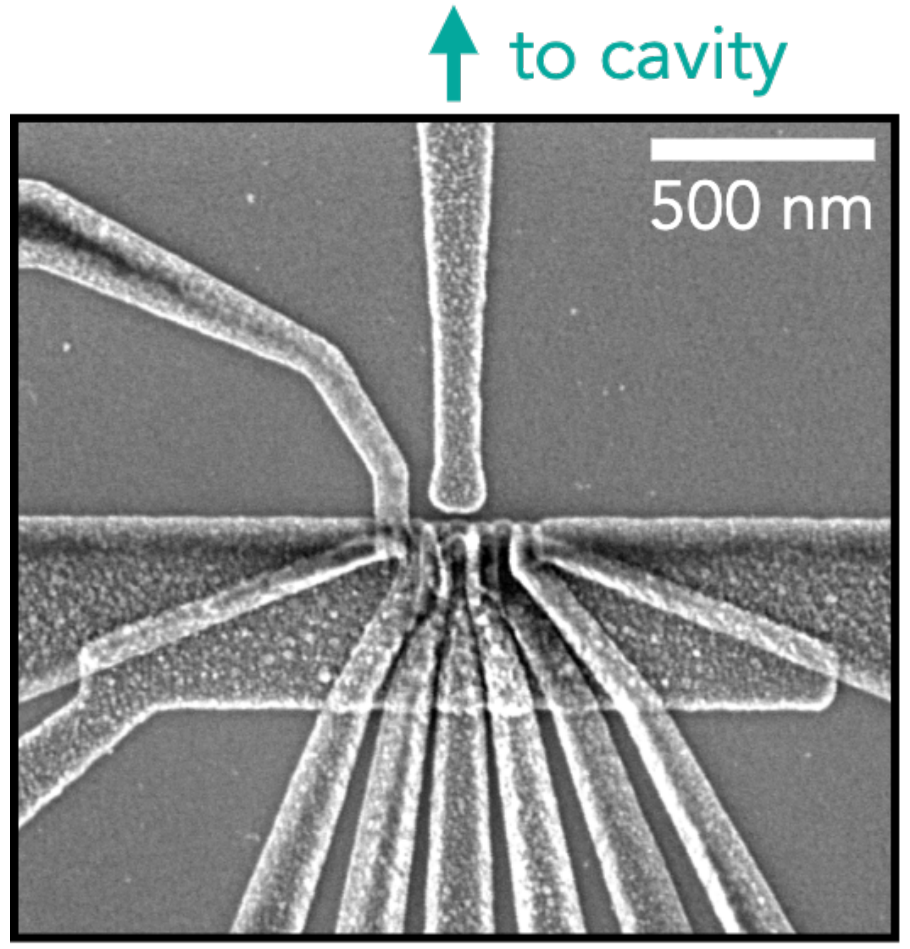


Quantum dot device and microwave resonator fabricated on separate samples

Vertically integrated in flip-chip package

3D design relieves fabrication and wiring constraints, improves scalability





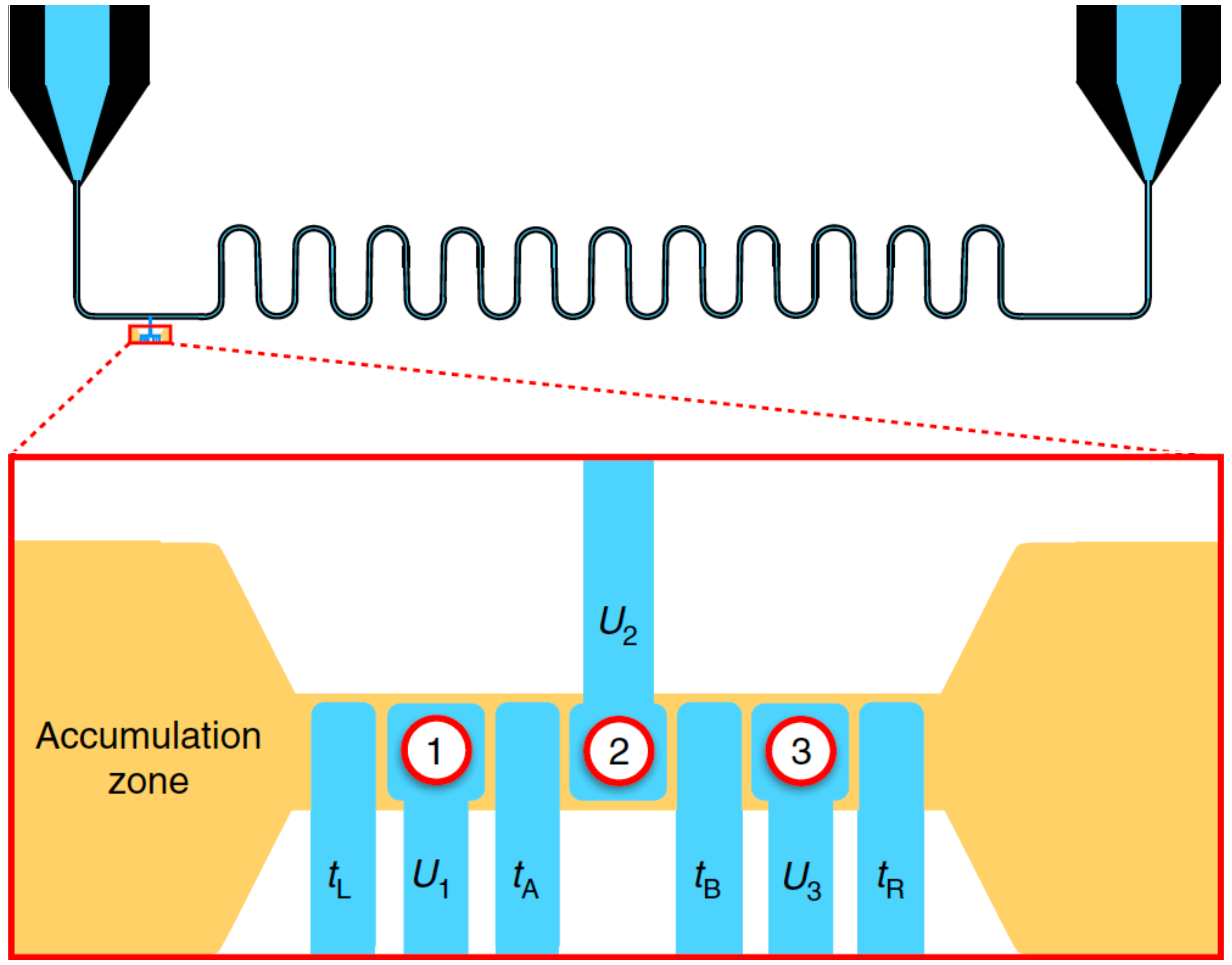
Fabrication collaboration with MIT Lincoln Laboratory; see Holman et al. npj Quantum Inf **7** (2021). for further details

Friesen Group:

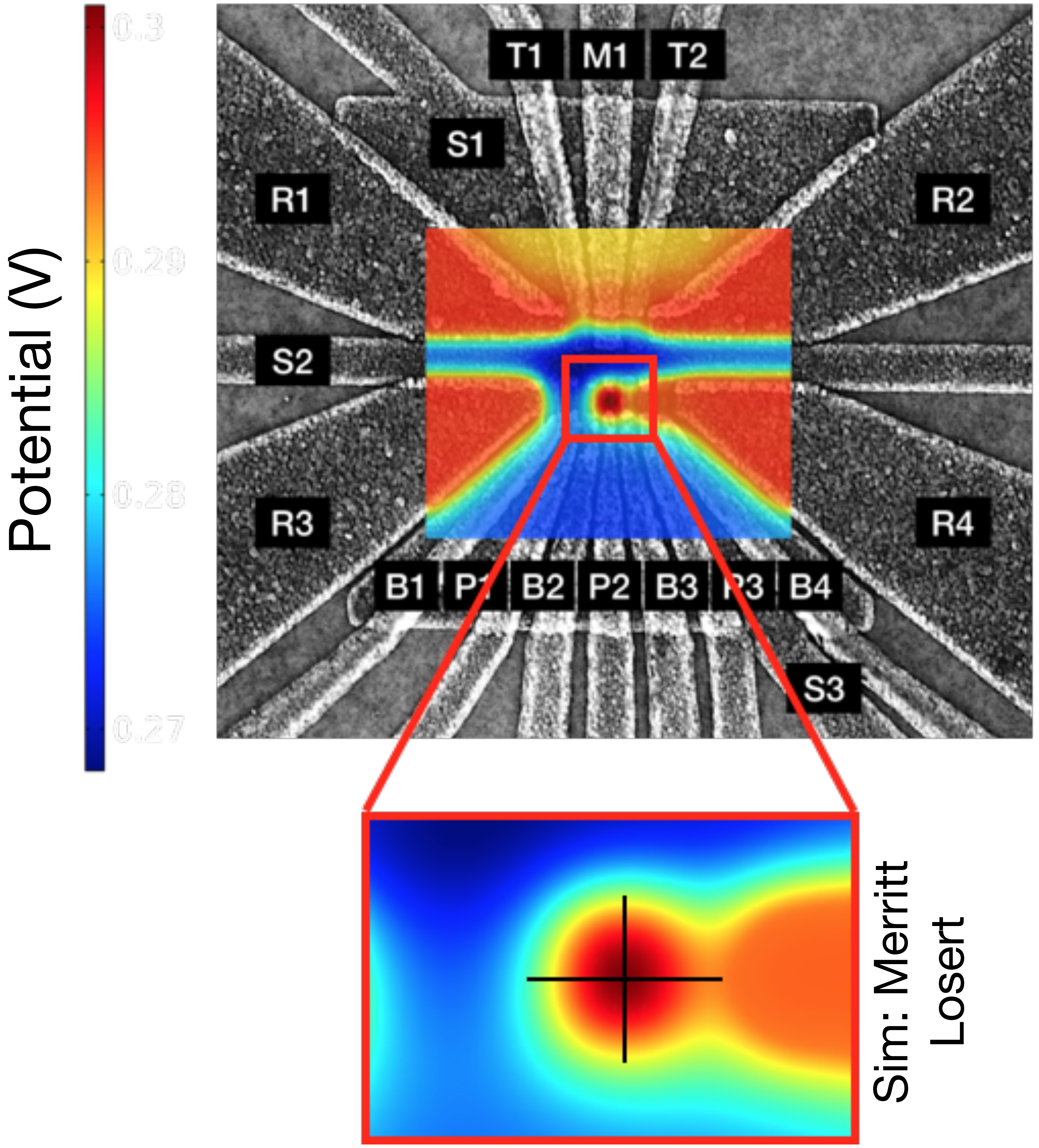
Theory of quantum computing in semiconductor quantum dots

Current projects:

- Topological qubits
- Semiconductor-superconductor hybrids
- Device simulations
- Spins coupled to photons
- Materials science of Si & Ge
- Theory of decoherence
- Investigation of defects that cause charge noise



Novel qubits: ("Quadrupole qubit")



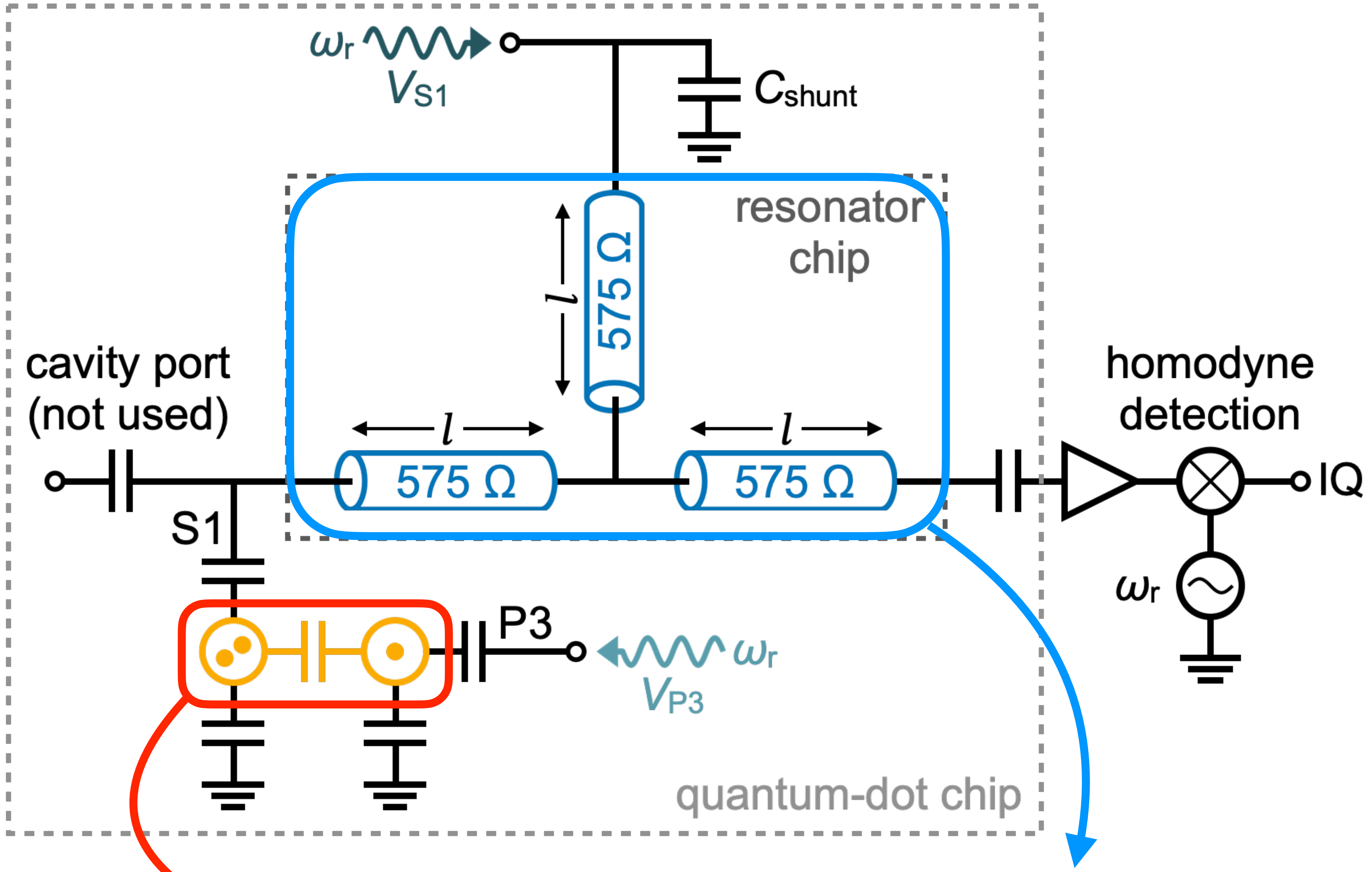
Courtesy: Eriksson lab

Sim: Merritt Losert

Device physics (double quantum dot)

Friesen Group:

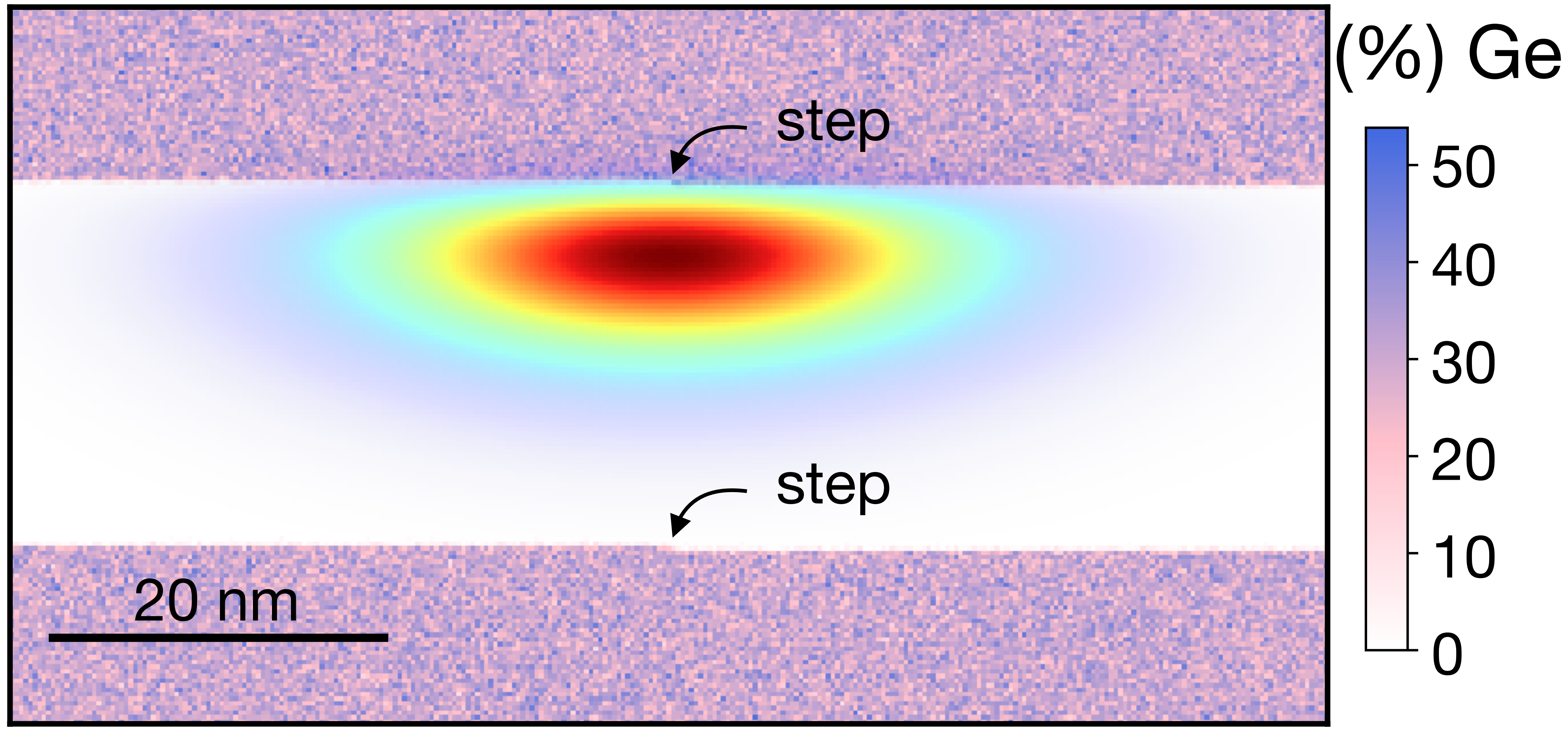
Theory of quantum computing in semiconductor quantum dots



Quantum-dot "hybrid" qubit

Longitudinal coupling to a microwave resonator

Novel qubit gate operations



Atomic-scale simulation of a quantum dot in the presence of step and alloy disorder

Materials science of qubit systems

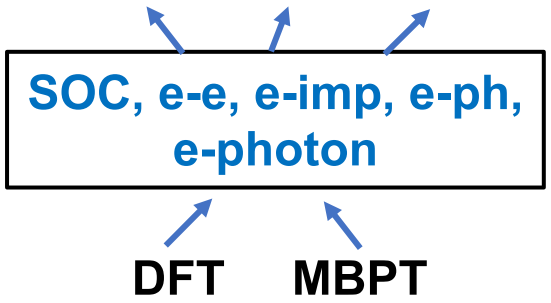
PING GROUP

ALFRED P. SLOAN
FOUNDATION

GORDON AND BETTY
MOORE
FOUNDATION

Theory Development: Ab-initio Open Quantum Dynamics[2]

$$i\hbar\dot{\rho} = [H,\rho] + F[\rho]$$



SOC, e-e, e-imp, e-ph, e-photon

DFT **MBPT**

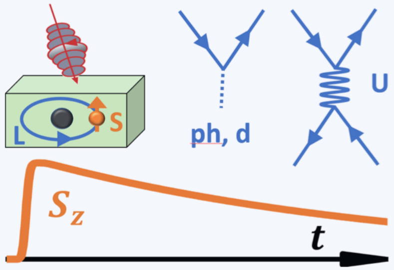
Quantum Dynamics

Non-Markovian

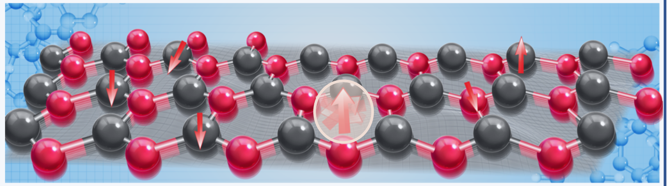
Markovian (Lindblad)

Boltzmann Equation

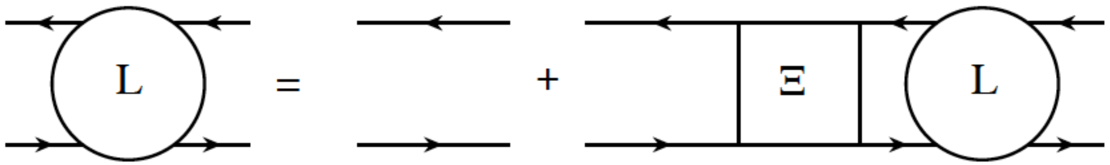
Spin Dynamics and Transport[2,4]



Spin Qubit T_1 and T_2

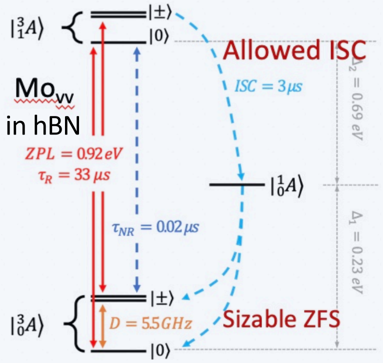


Many-Body Perturbation Theory (MBPT) for Excited States[1]

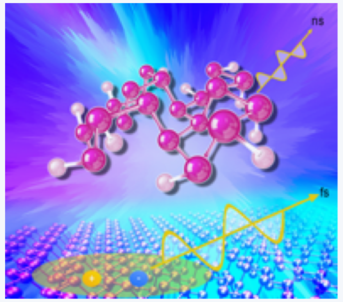


We develop new theory and ab-initio computational methods for quantum information science and spintronics applications

Quantum Defects Optical Readout[3]



Exciton Dynamics[5]



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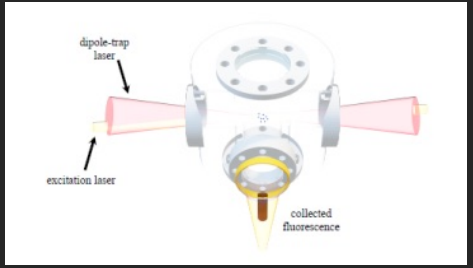
1. Y. Ping et al, *Chem. Soc. Rev.*, 2013. 2. J. Xu, ..Y.P., *Nat. Commun.* 2020. J. Xu, Y.P., PRB, 2021. Editor's Suggestions and Highlight: "**A universal model of spin relaxation**".
3. T. Smart, Y. Ping, *npj Comp. Mater*. 2021. Y. Ping, T. Smart, *Nat. Comput. Sci.* 2021. 4. J. Xu, ..Y.P., *Nano Lett.* 2021 5. F. Wu, D. Rocca, Y.P., JMCC, 2019. 6. T. Smart.. Y.P., *npj Comp. Mater.* 2018.

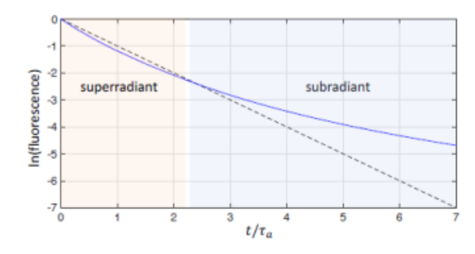
QPAL Quantum Physics with Atoms and Light

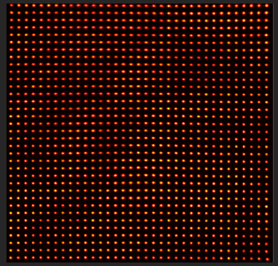
hexagon.physics.wisc.edu

Atom arrays: atom-light interactions

with Prof. Walker, Prof. Yavuz

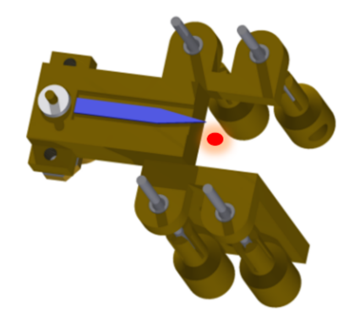


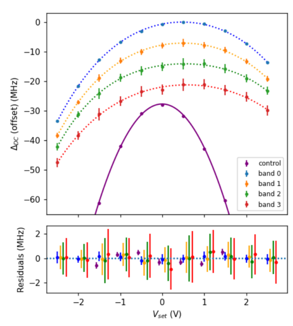




Atom-superconductor quantum interface

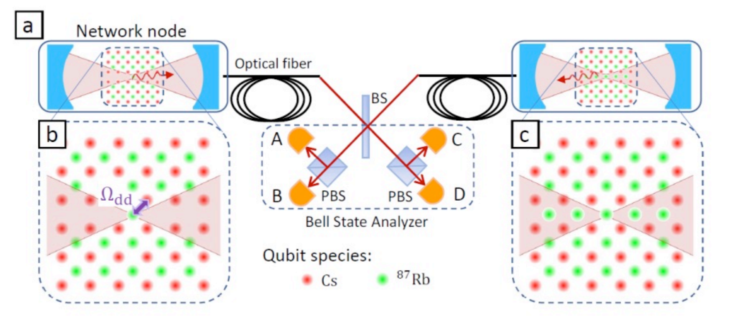
with Prof. McDermott



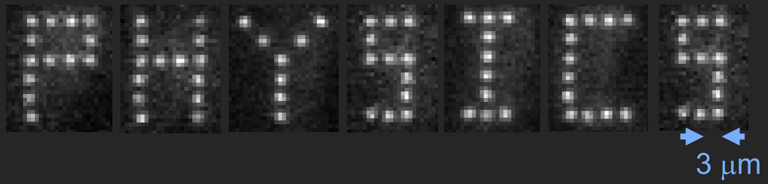


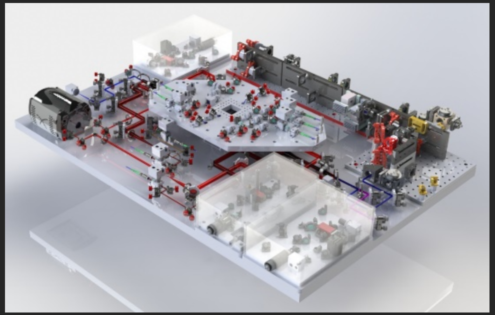
Quantum networking

with Prof. Goldsmith(Chemistry), Prof.Kats (ECE)

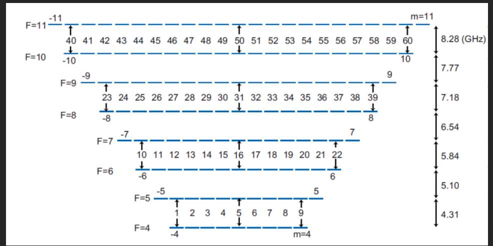


Quantum computing



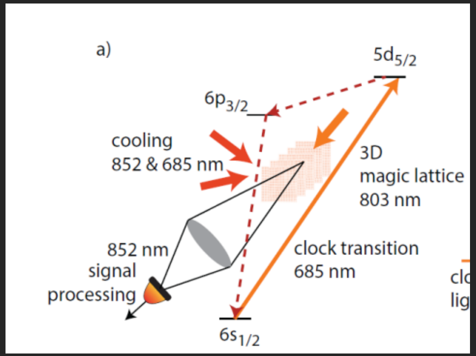


Qudits – Ho atoms



Atomic clocks

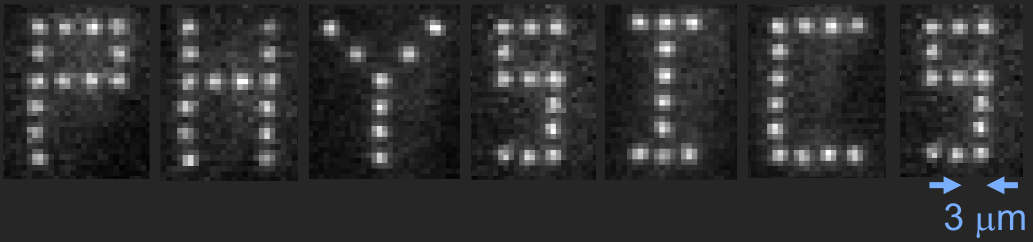
with Prof. Kolkowitz



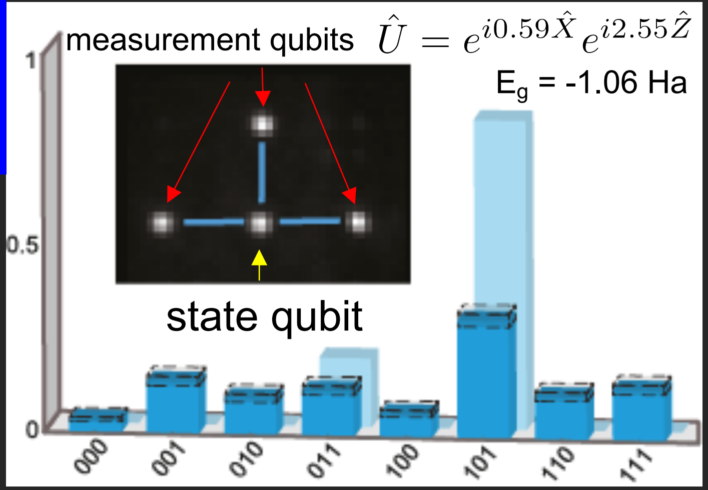
Quantum computing

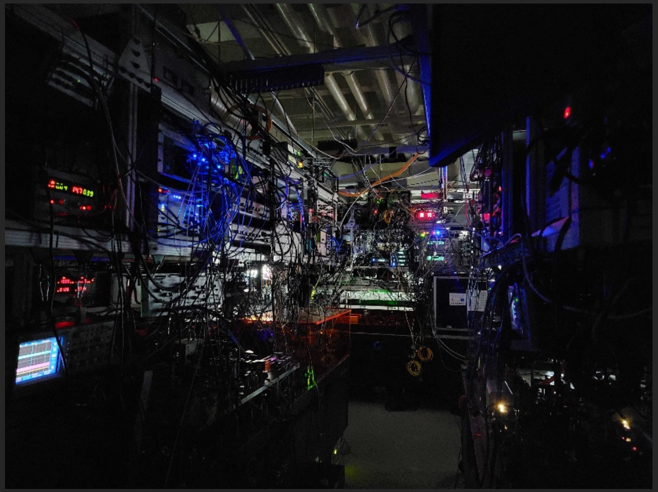
- Quantum mechanics was originally developed to understand the structure of atoms.
- Almost 100 years later we have come full circle and are using individual atoms to develop quantum computers to help us explore some of the mysteries of quantum mechanics.

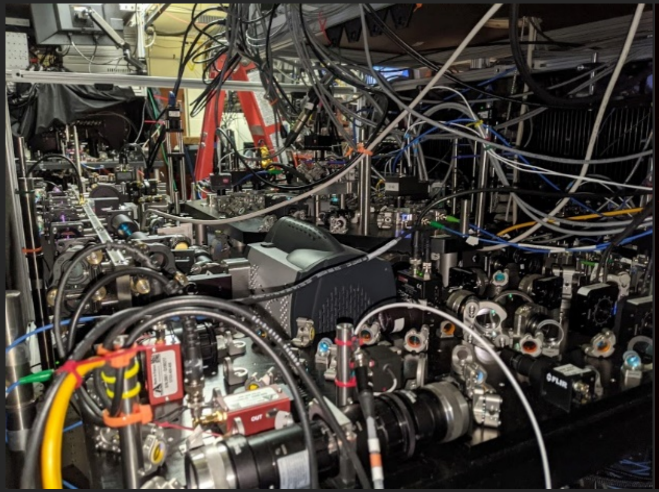
Individual Cs atoms cooled, arranged, and trapped by light.

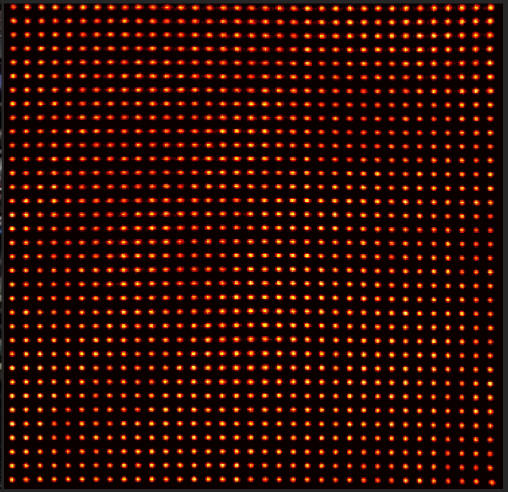


H_2 molecular energy









Nature **604**, 467 (2022)

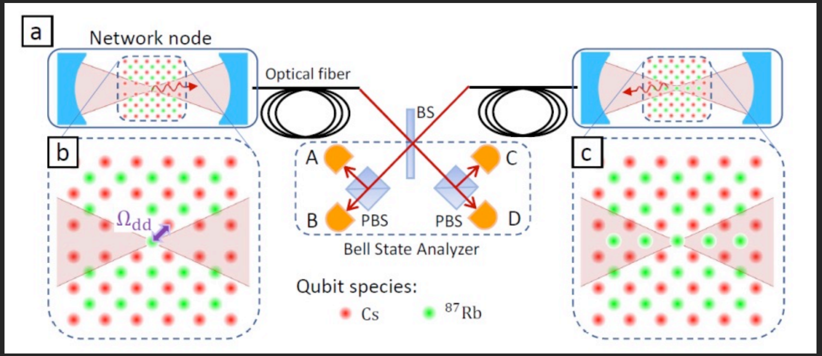
1225 Cs atoms
(averaged image)

PRA **105**, 063111(2022)

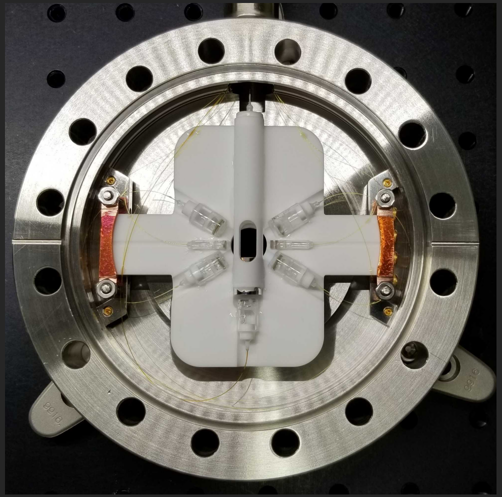
Quantum networking

- To reach very large scale, modules can be connected optically
- Optically connected small-medium scale processors will form the backbone of a quantum repeater enabled network
- Also relevant for quantum processor enhanced sensors

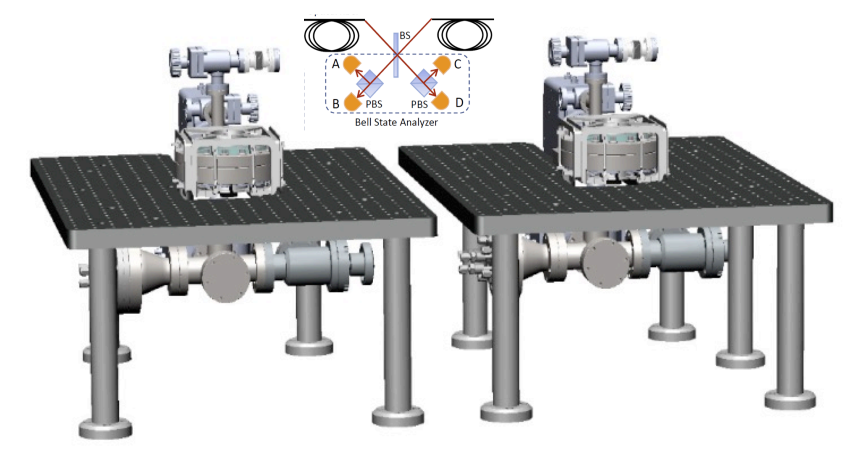
Two-species architecture



Atomic network node

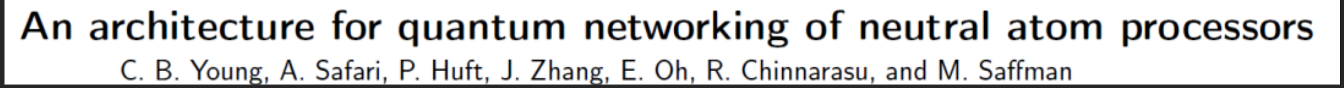


Two node setup



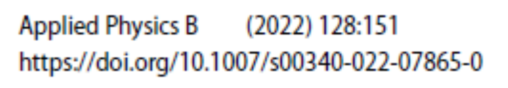
er

tube for
parabolic
mirror



An architecture for quantum networking of neutral atom processors

C. B. Young, A. Safari, P. Huft, J. Zhang, E. Oh, R. Chinnarasu, and M. Saffman



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