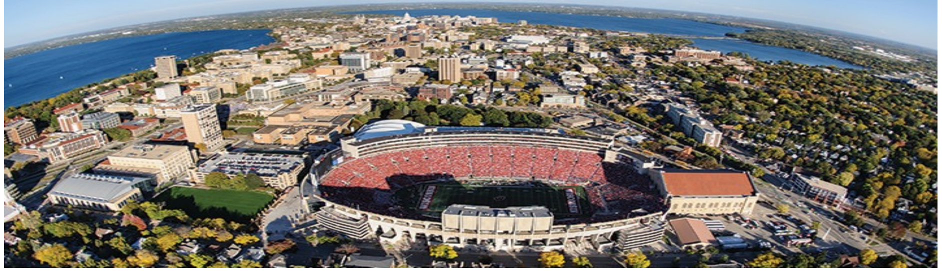


Condensed Matter Theory at UW

PHY701 Research Presentation

Ilya Esterlis, Mark Friesen, Robert Joynt, Alex Levchenko, Micheline Soley, Maxim Vavilov

(October 14, 2022)

Research Interests:

Quantum kinetics, Mesoscopic effects, Nonequilibrium systems, Superconductivity, Topological materials

https://arxiv.org/find/cond-mat/1/au:+Levchenko_A/0/1/0/all/0/1

- Electronic phases and transport in quantum materials at strong coupling

(NSF: single-PI, 2022-2025)

- Modeling, probing, and controlling quantum coherence in materials

(DOE: multi-PI, UWisc+Livermore Nat Lab, 2022-2025)

- Hybrid Quantum Architectures and Networks

(NSF: multi-PI, UWisc+UIUC+Uchicago, 2019-2024)

Group: 2 undergraduate students, 2 graduate students, 1 postdoc

Emil

David

Joy

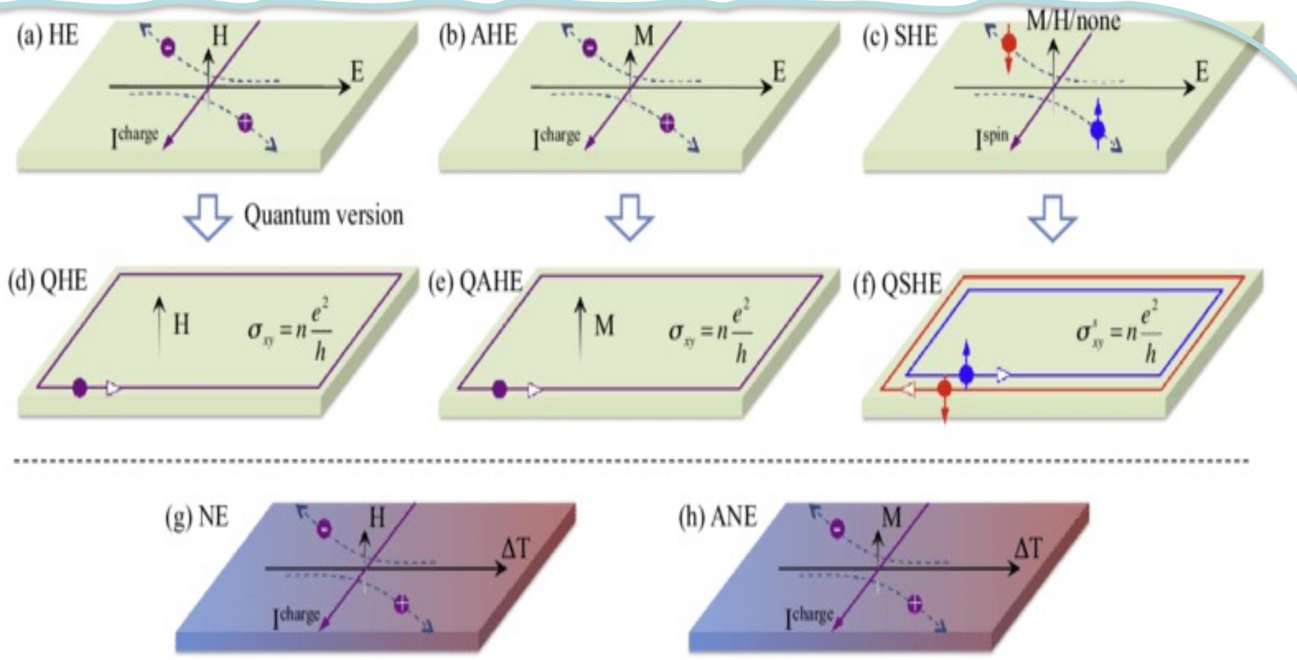
Dmitry

Songci

Electronic phases and transport

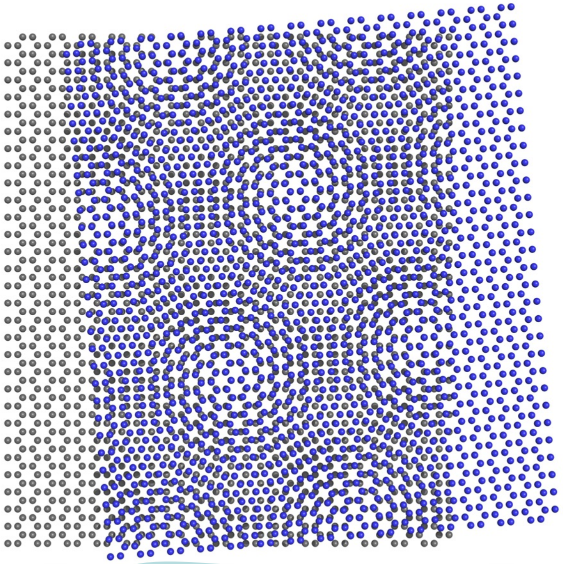
Family of anomalous Hall effects:

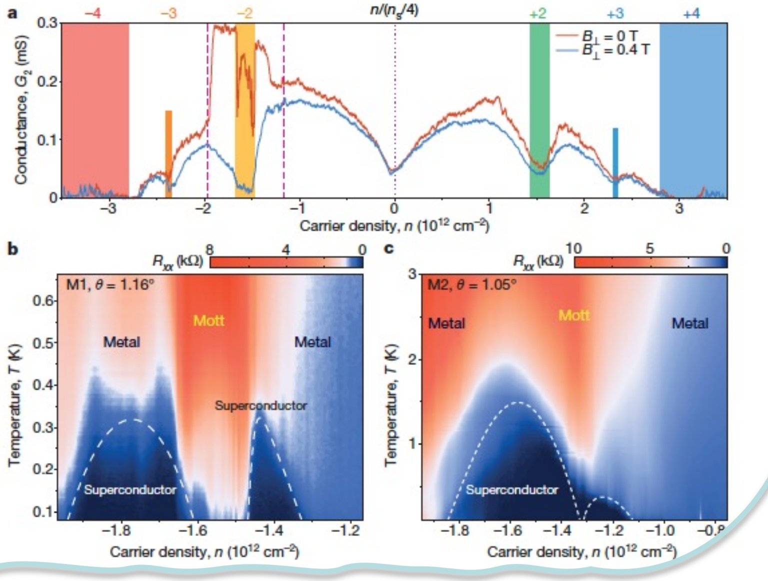
- Spin or valley Hall effect
- Thermal Hall effect
- Spin-torque
- Polar Kerr/Faraday effects
- Chiral magnetic effect
- Nonlinear photogalvanic effect
- Nonlinear Hall effects
- Anomalous Josephson effect



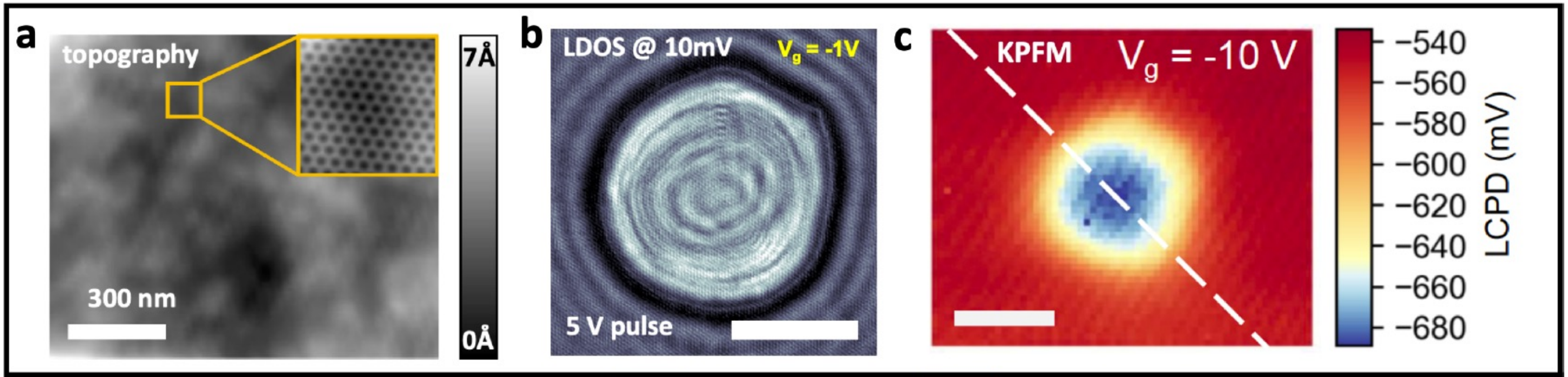
Magic angle twisted bilayer graphen:

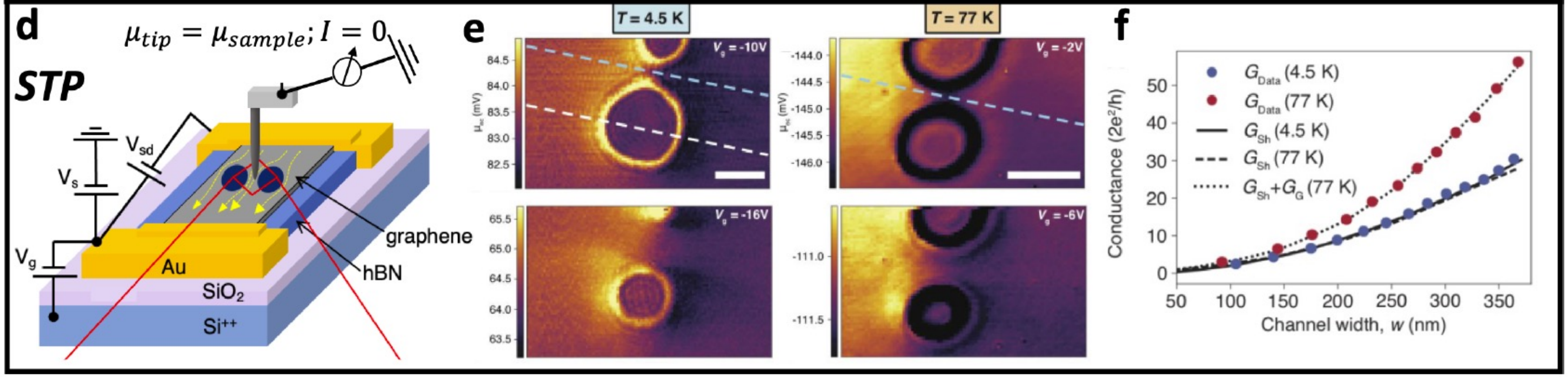
- Correlated normal state
- Superconductivity
- Insulating state
- Topological states
- Unconventional SC

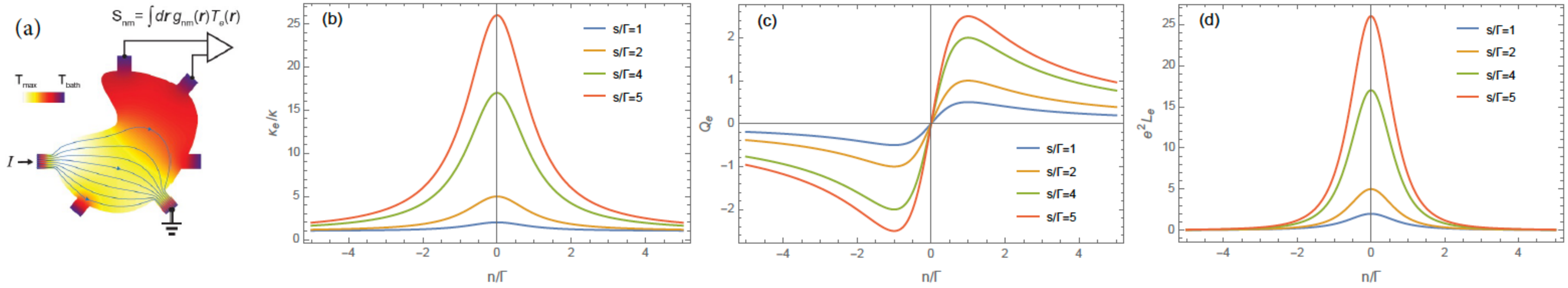




Scanning tunneling potentiometry

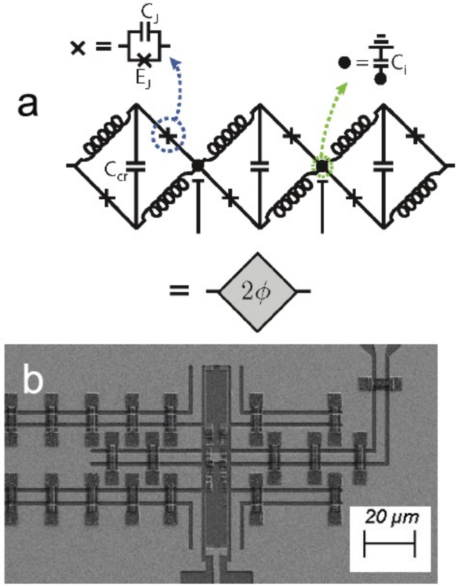




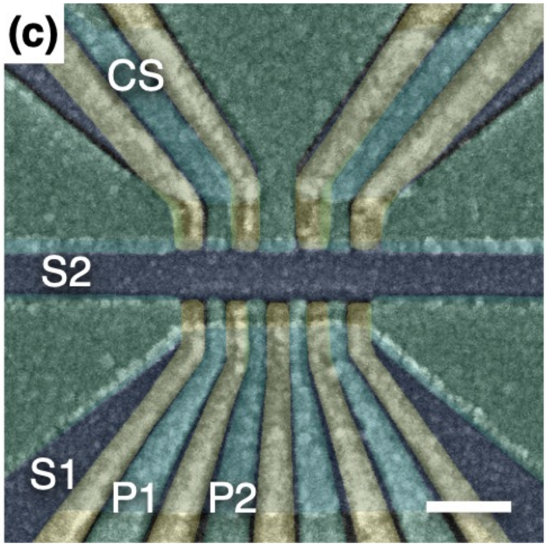


Hybrid superconducting/topological systems

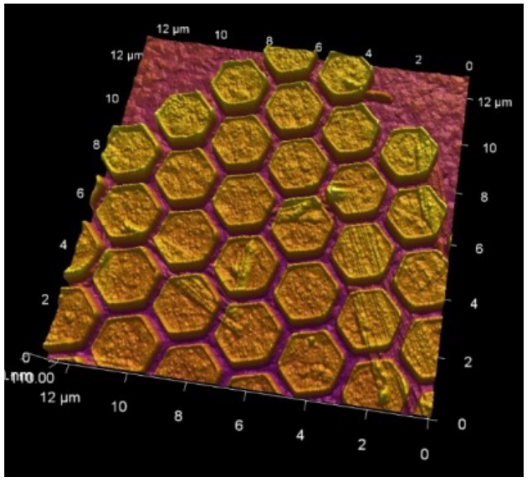
[#1] SC metamaterials platform

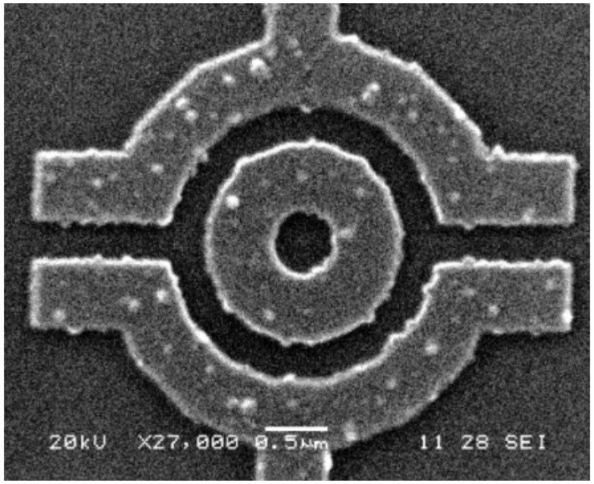


[#2] Super-Semi platform



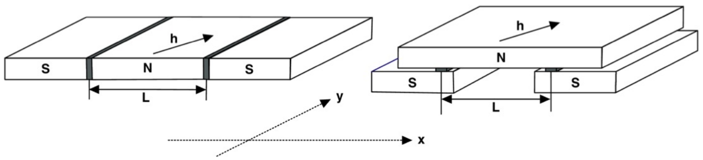
[#3] Superconductor-Topological Insulator platform



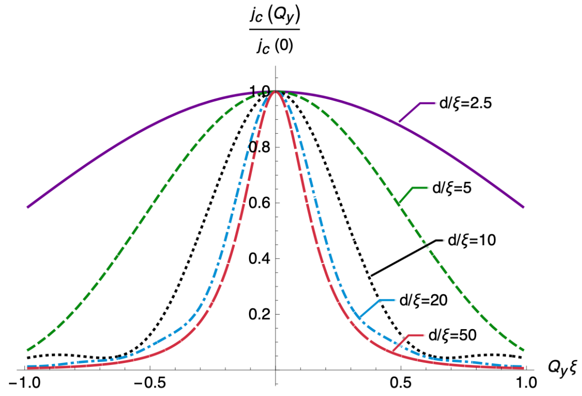


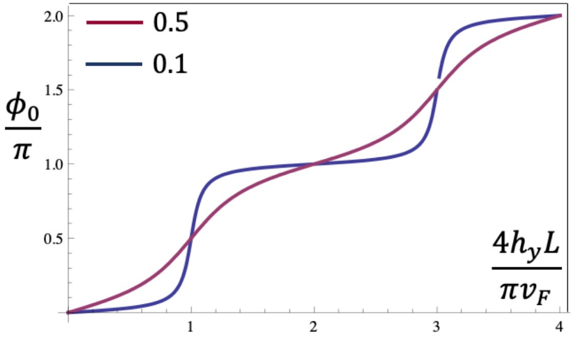
An example from the recent work:

AJE in planar 2D devices



$$j(\phi) = j_c \sin(\phi + \phi_0)$$





Condensed matter theorist, broadly interested in characterizing phases of matter and phase transitions in many-body quantum systems

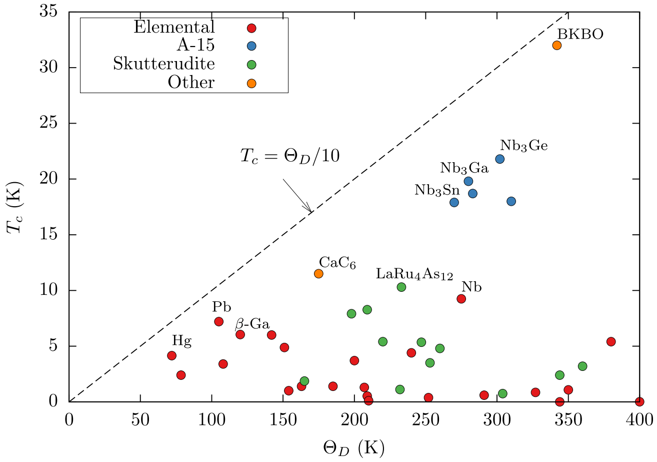
Ilya Esterlis

My work is motivated both by close collaboration with experiment, as well as formal questions regarding the organizing principles governing the phase diagrams of interacting quantum systems. Current lines of investigation include:

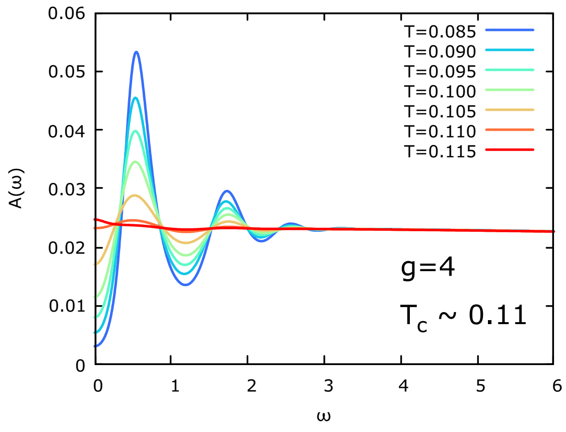
- Superconductivity in conventional and unconventional metals
- Phases of two-dimensional electronic systems
- Characterization of exotic magnetic materials

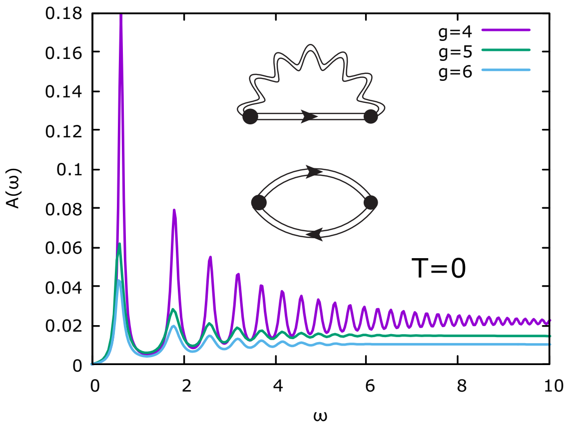
Superconductivity in conventional and unconventional metals

- What limits the superconducting transition temperature in conventional metals?



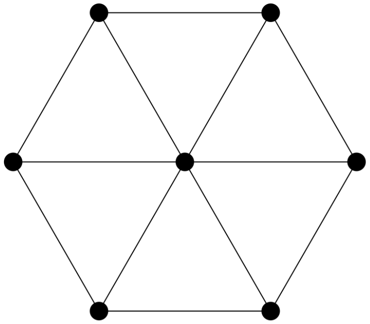
- What is the nature of the superconducting state that emerges from an unconventional metal?

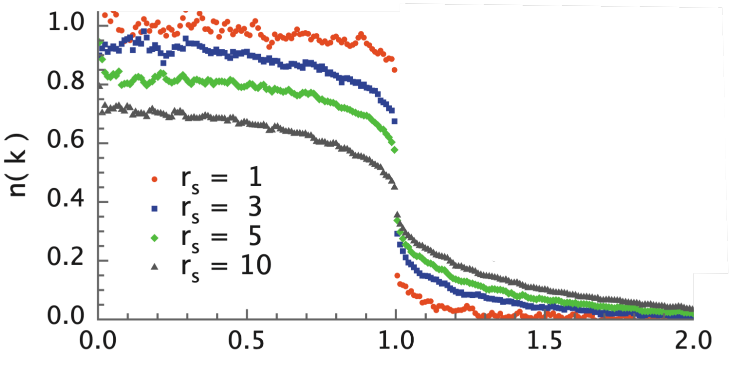


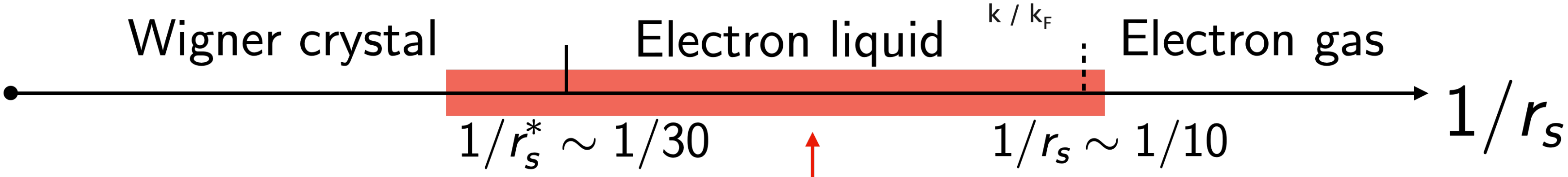


Phases of two-dimensional electronic systems

- What is the behavior of two-dimensional electron systems at intermediate coupling? Are there phases intermediate between the electron liquid and electron solid and how would we probe such a phase?



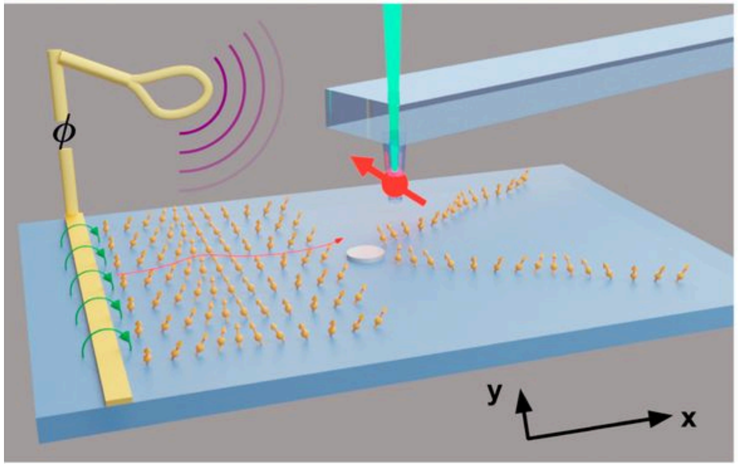


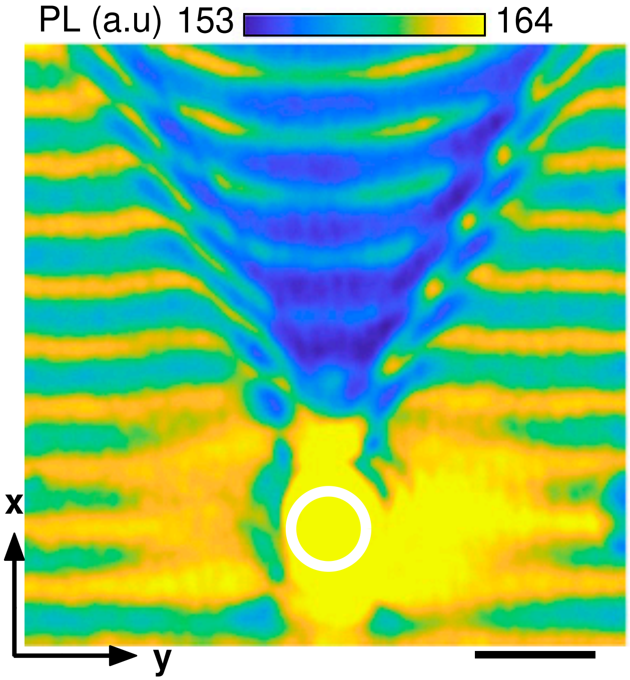


magnetism? intermediate phases (e.g., microemlusions)? ...

Characterization of exotic magnetic materials

- Many magnetic materials of current interest are challenging to probe with conventional techniques – what new techniques can we develop to learn about these interesting systems?



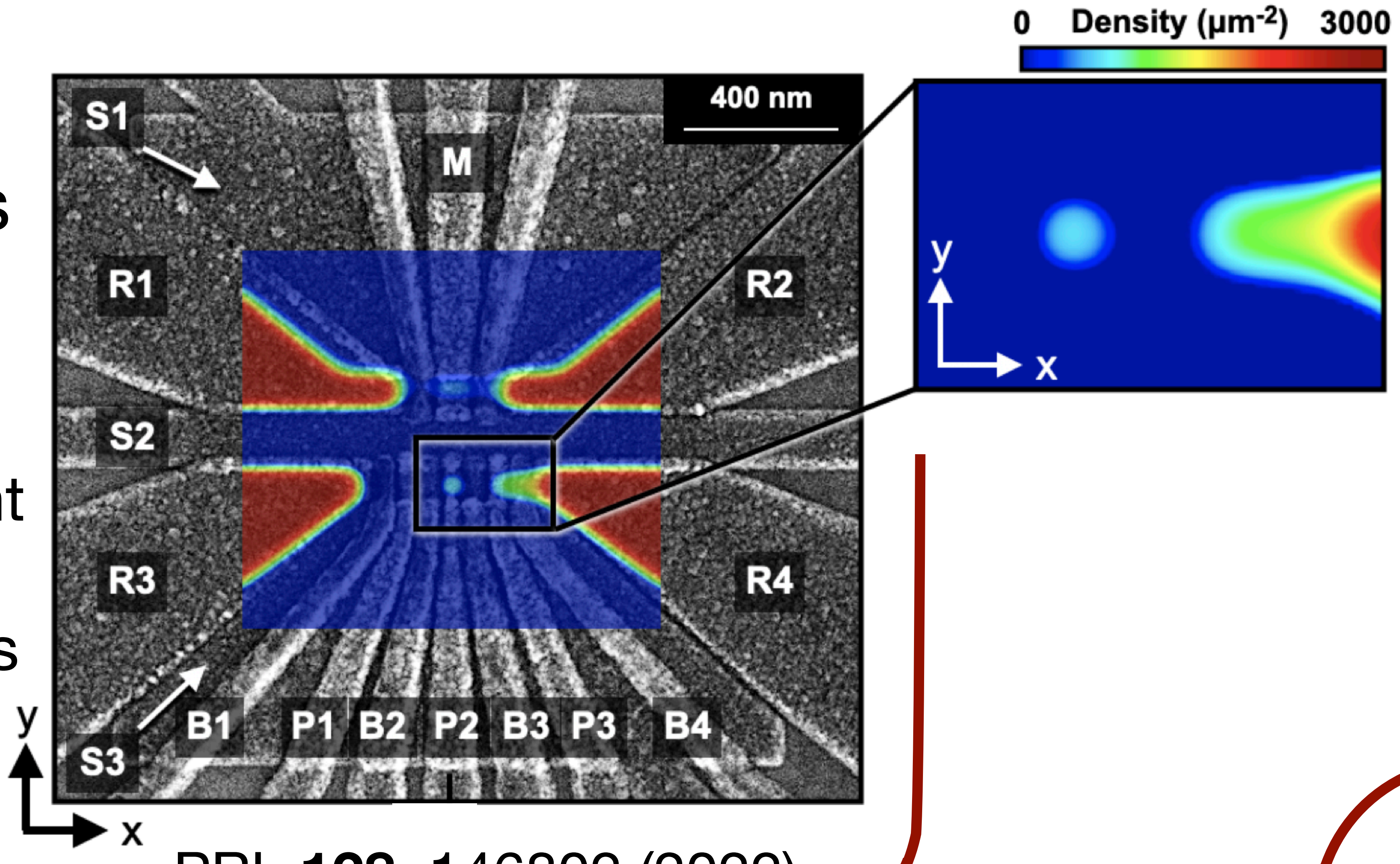


Mark Friesen

https://pages.physics.wisc.edu/~friesen/

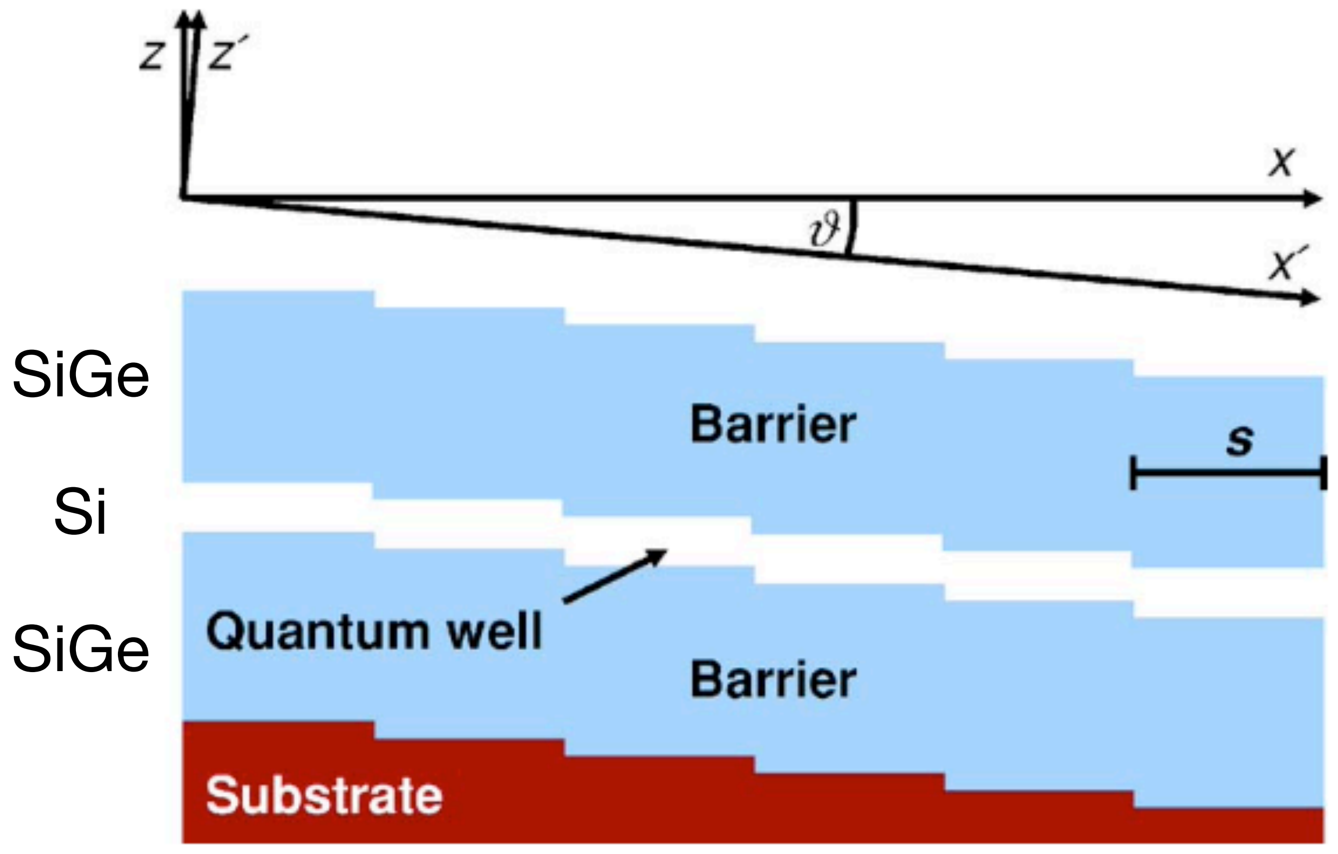
Device simulations to explore…

- Quantum confinement
- Electrostatics
- Multi-electron physics



PRL **128**, 146802 (2022)

Materials physics of quantum dot qubits



Silicon quantum well

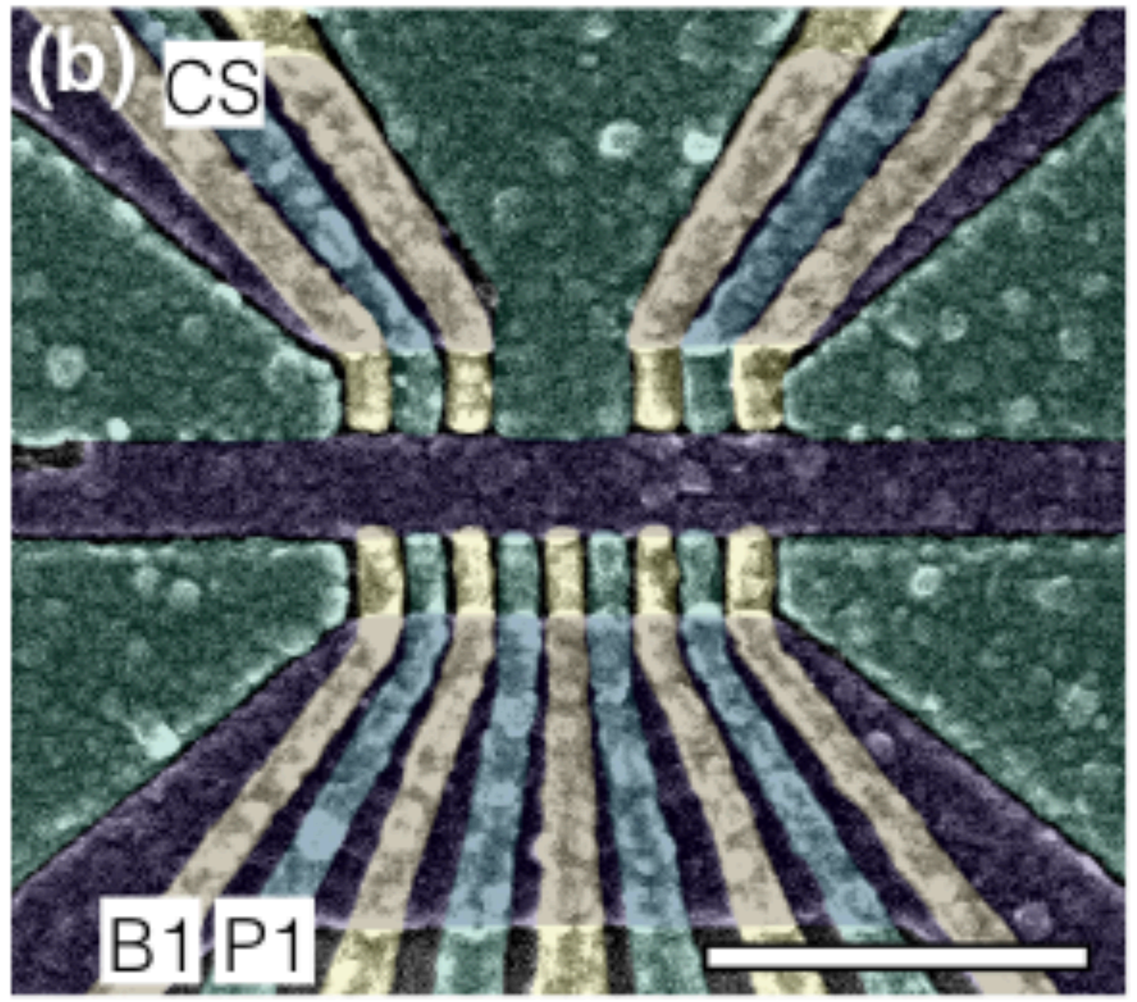
- DISORDER!
- Specially engineered heterostructures
- Novel qubits enabled by novel materials

Other ongoing projects:

- Topological qubits based on super-semi hybrids
- Charge defects and charge noise that affects quantum dot qubits

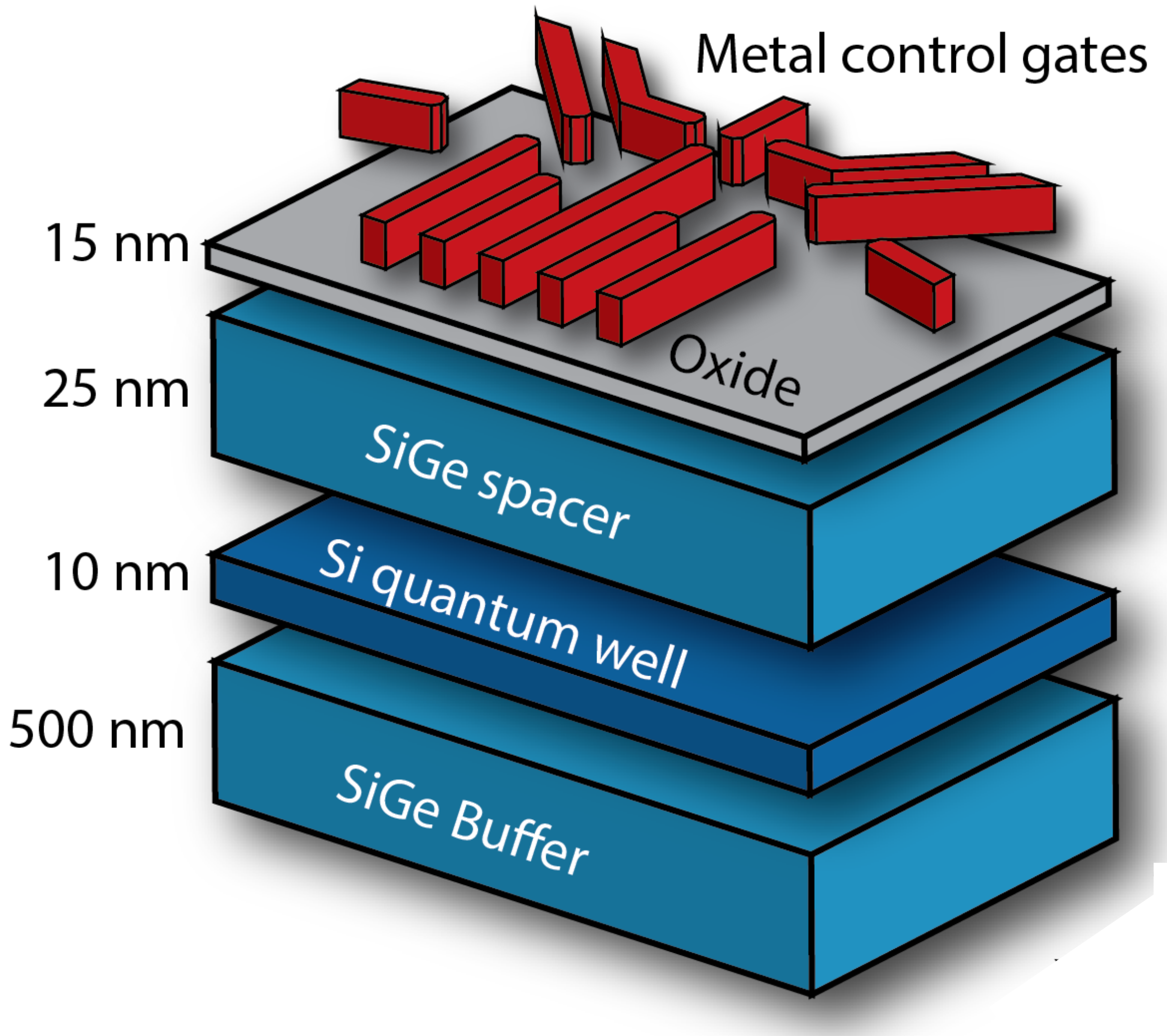
Fast qubit initialization using excited states of a quantum dot

Actual device

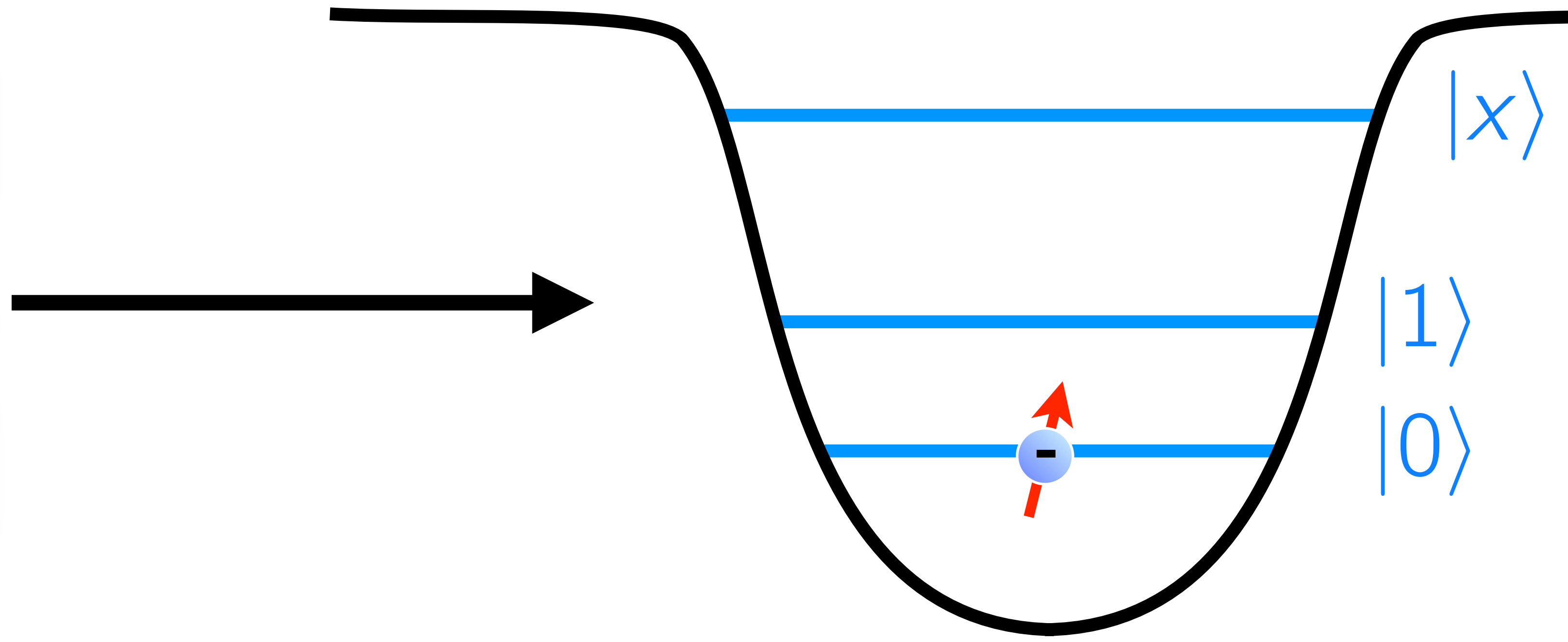


Courtesy: Eriksson lab

Cartoon device

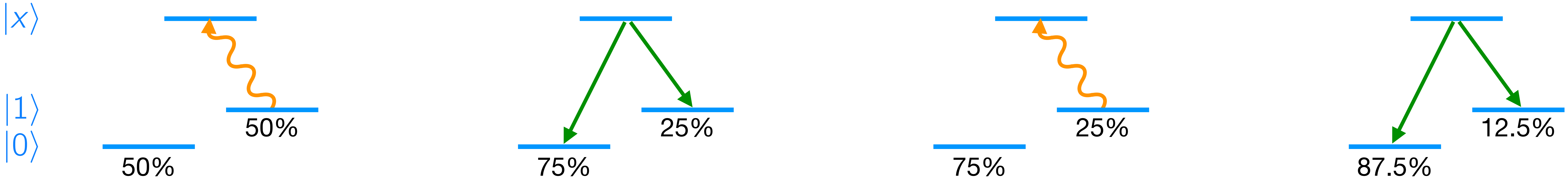


Theorists' view of a quantum dot



- 3D confinement
- Spin qubit

Proposed "microwave cooling" experiment



Selective microwave excitation

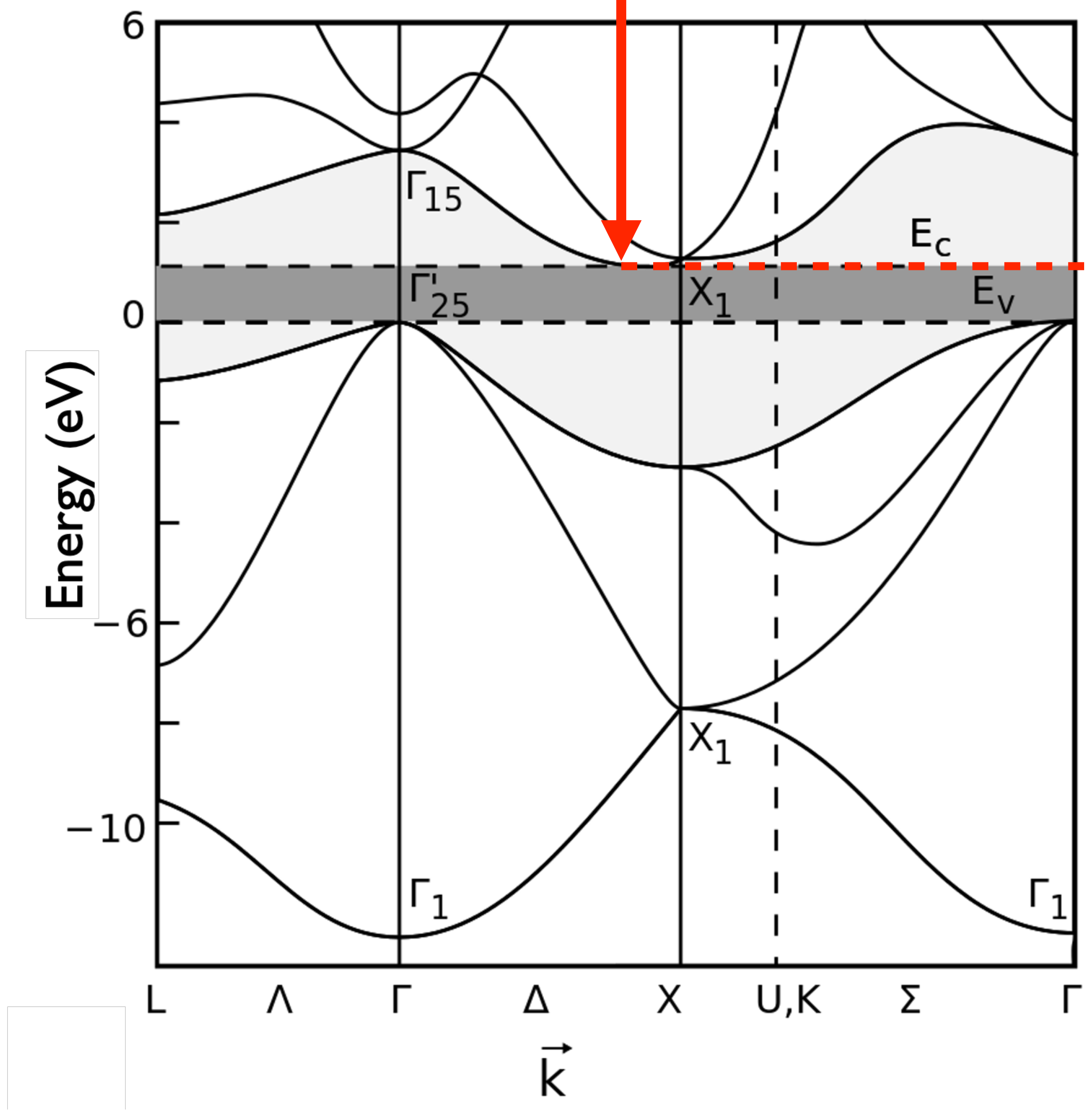
Fast decay

Selective microwave excitation

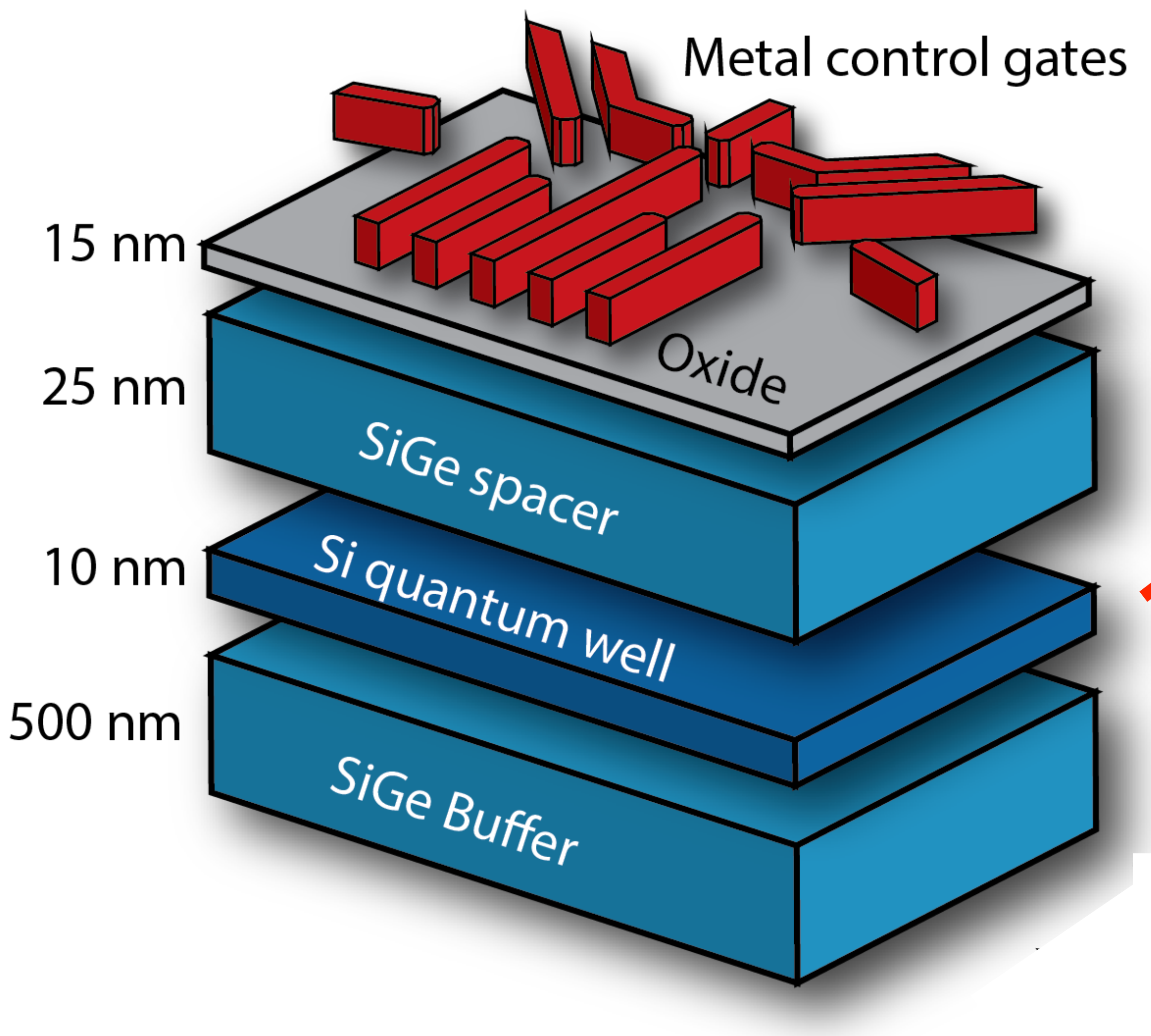
Fast decay

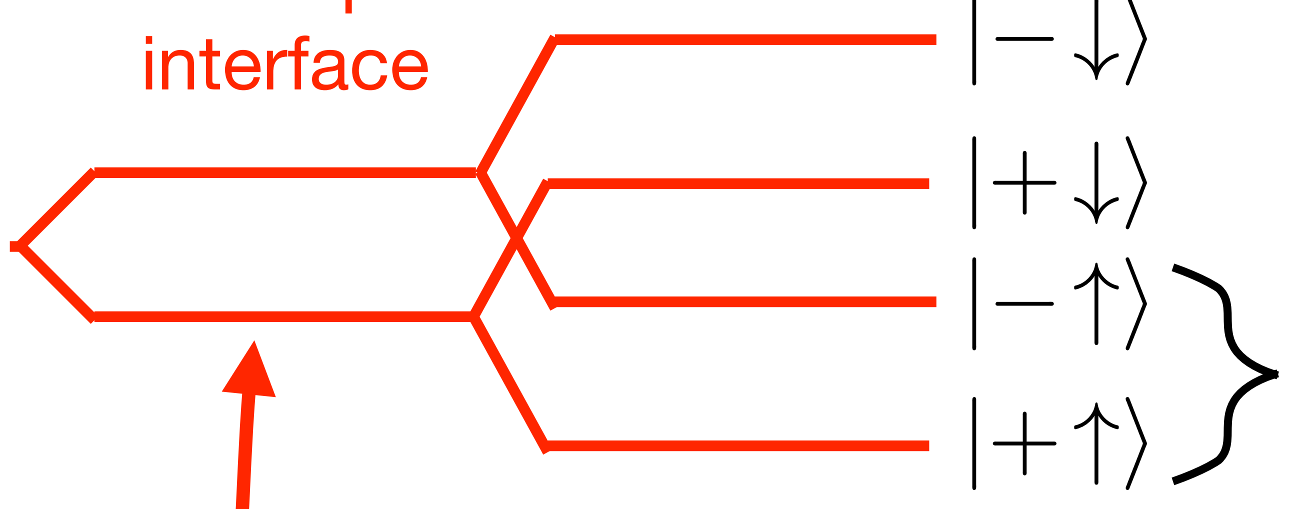
Theoretical simulations of quantum dot excited states: valleys

Conduction band minimum (“valley”)



2x2-fold energy level degeneracy in a quantum well





Sharp interface

Magnetic field

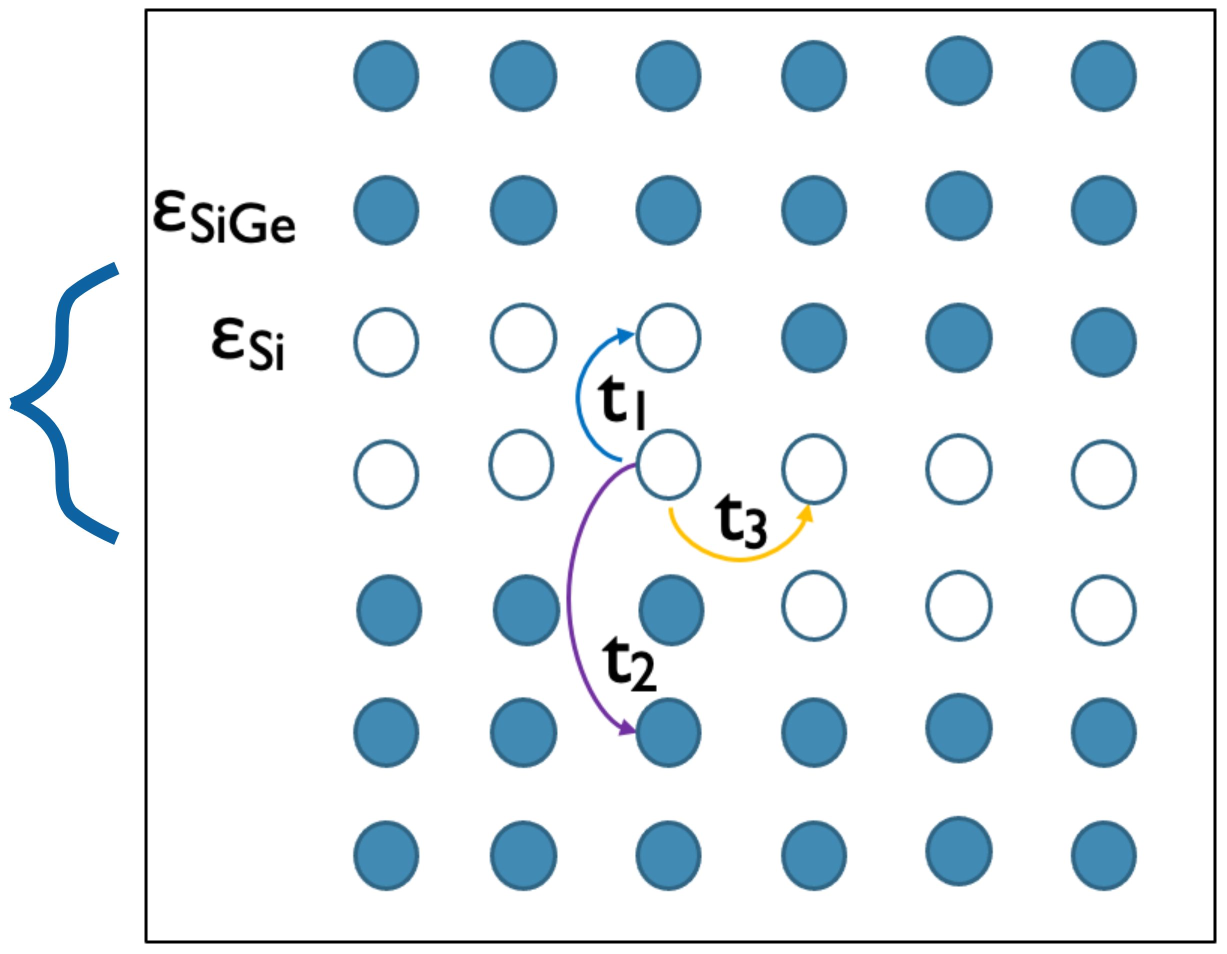
$|-\downarrow\rangle$

$|+\downarrow\rangle$

$|-\uparrow\rangle$

$|+\uparrow\rangle$

Valley qubit or spin qubit?

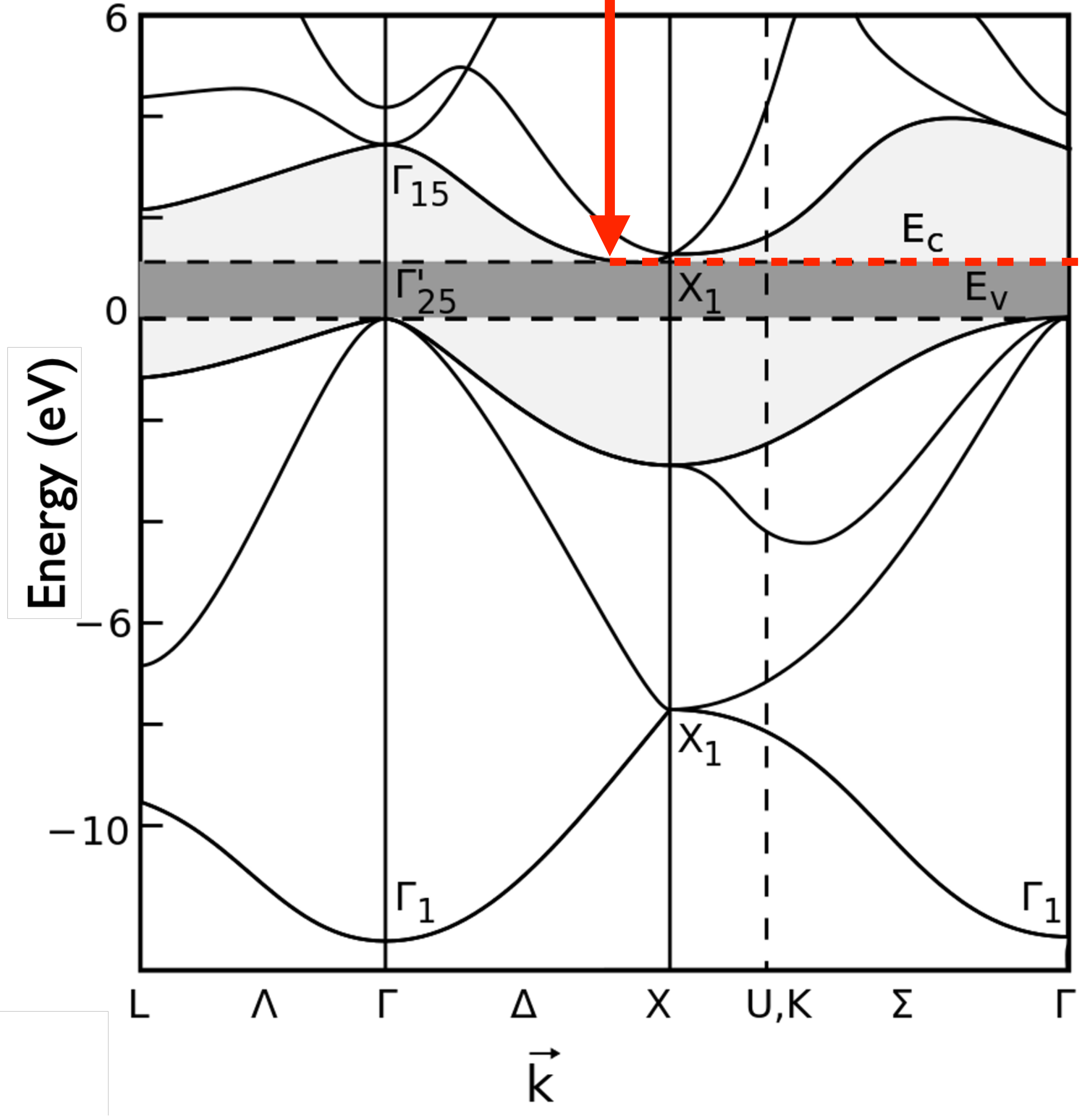


Tight-binding models can describe valley splitting in disordered quantum wells

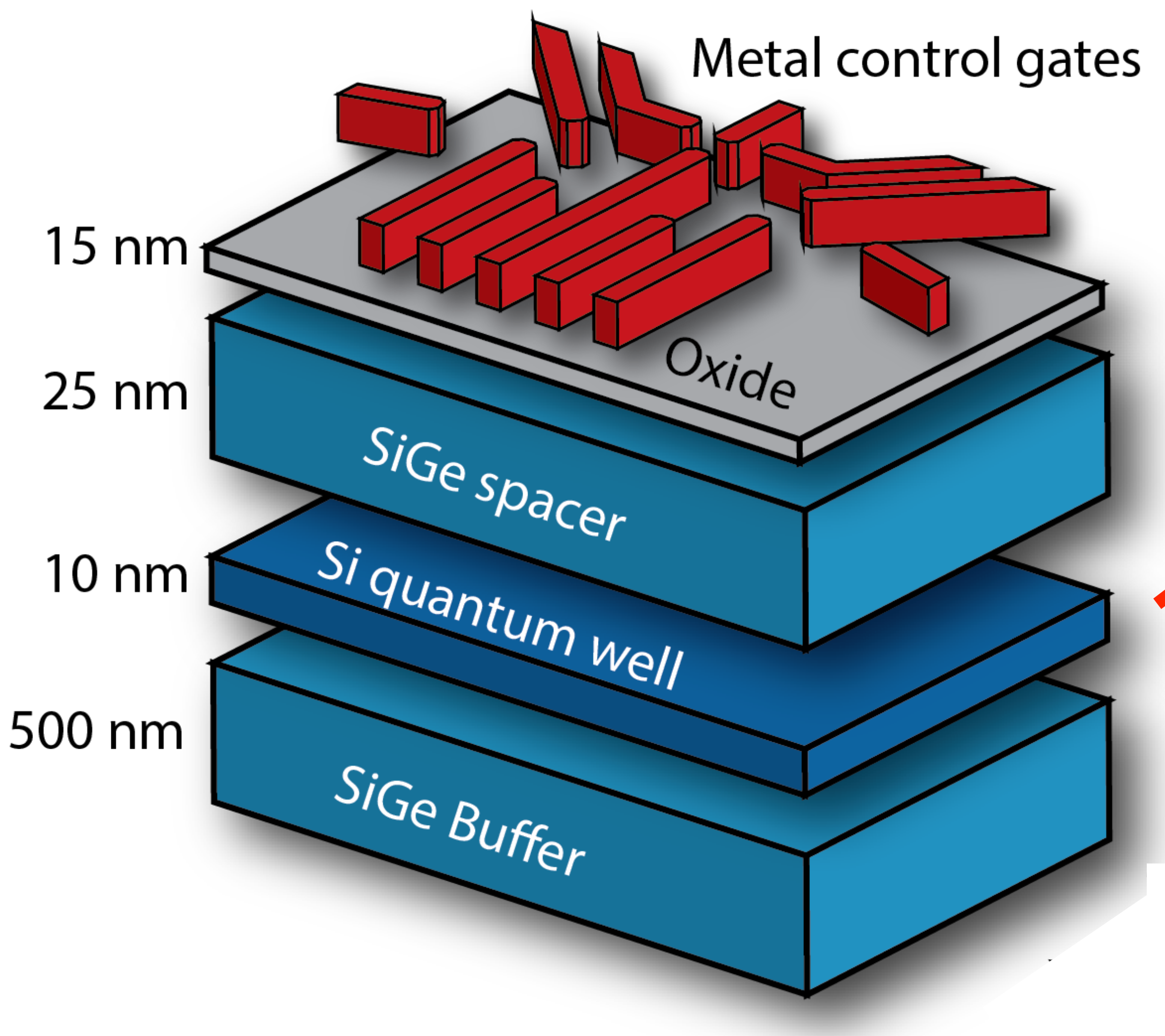
PRL **128**, 247701 (2022)

Theoretical simulations of quantum dot excited states: valleys

Conduction band minimum ("valley")



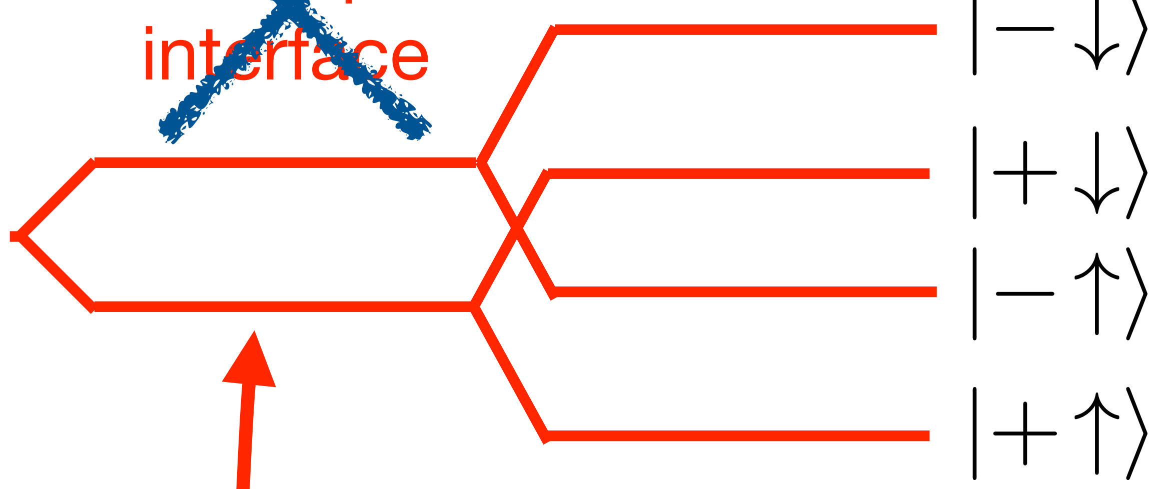
2x2-fold energy level degeneracy in a quantum well



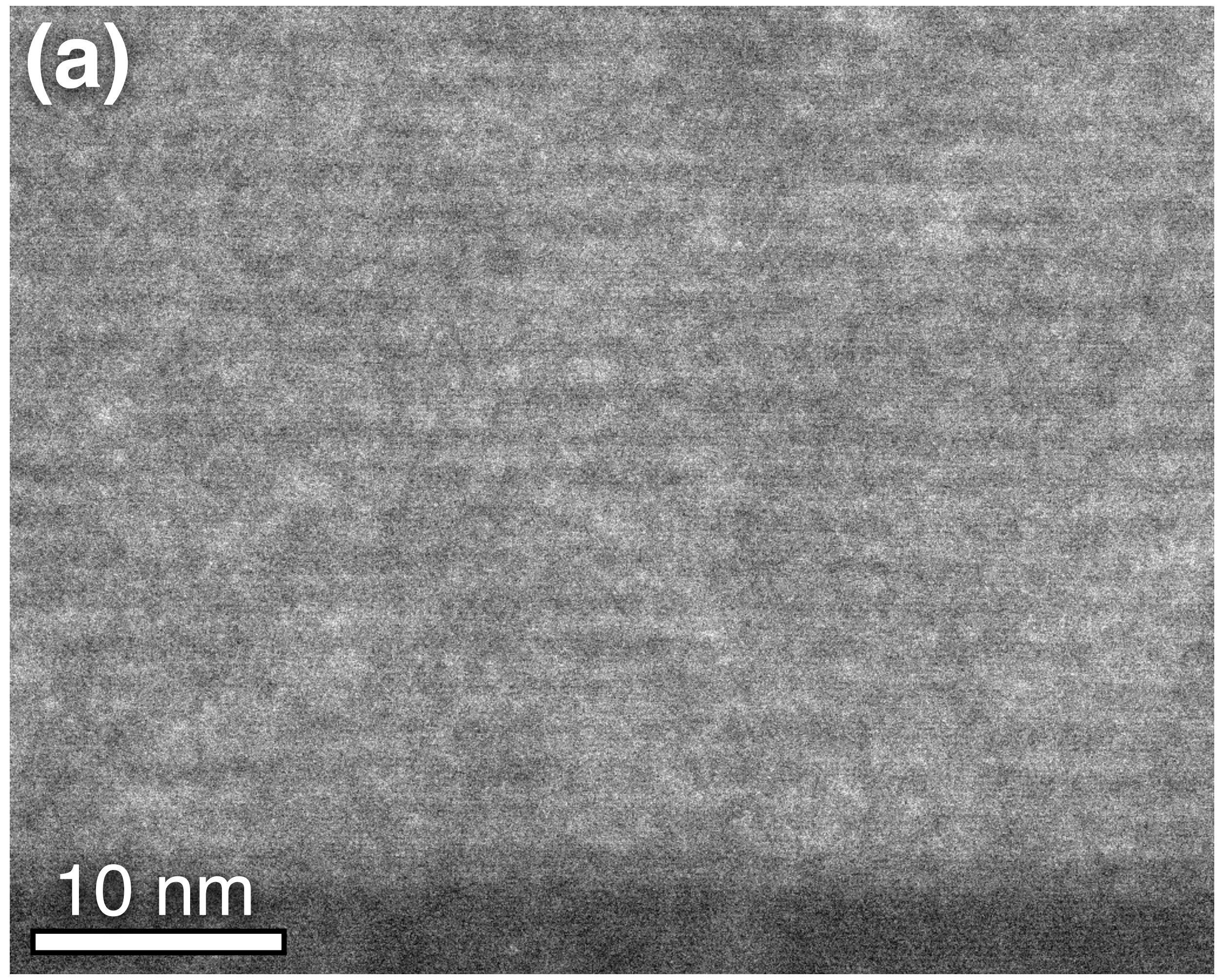
"Wiggle Well"

~~Sharp interface~~

Magnetic field



Valley qubit or spin qubit?



1.8 nm germanium concentration oscillations

arXiv:2112.09765

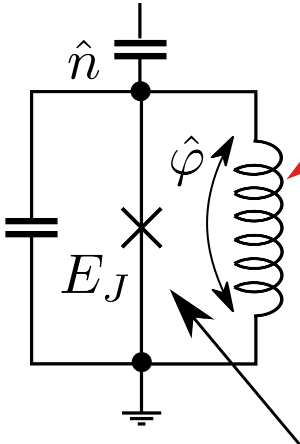
Maxim Vavilov – Quantum hardware simulations

Research Interests: superconducting quantum devices, mesoscopic superconductivity, quantum simulations, machine learning

Current group: Yinqi Chen (5th year PhD), Rafael Alapisco (1st year PhD)

Most recent group members:
- Kostya Nesterov (postdoc, now at Blexio Inc – QC startup),
- Baris Ozguler (PhD 2020, intern at LANL, now postdoc at Fermilab)
- Zhenyi Qi (PhD 2019, intern at NASA, Google AI + quantum)

Fluxonium Qubit



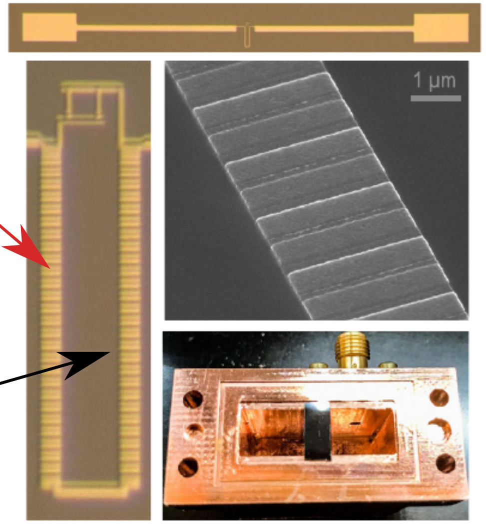
$$E_C = \frac{e^2}{2C}$$

superinductance
(many JJs)

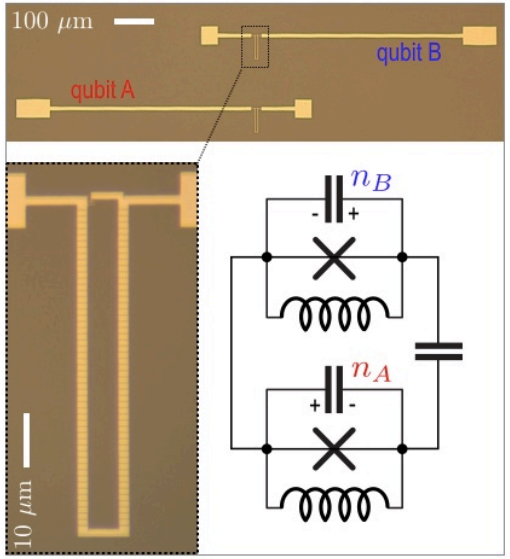
$$E_L = \left(\frac{\hbar}{2e}\right)^2 \frac{1}{L}$$

$$\Phi_{\text{ext}} = \frac{\hbar}{2e}\phi_{\text{ext}}$$

(external flux threading the loop)



Y.-H. Lin, et. al., PRL 120, 150503 (2018)



Superinductor – large superconducting inductor formed by an array of Josephson Junctions or dirty superconductor with large kinetic inductance.

Superinductor provides protection of the fluxonium qubit against:

- Flux noise due to large inductance;
- Low-frequency charge noise by screening all offset charges;
- We demonstrated high fidelity fast two qubit gates (PRX 11, 021026; PR Research 4, 023040)
- Next step - multiqubit systems

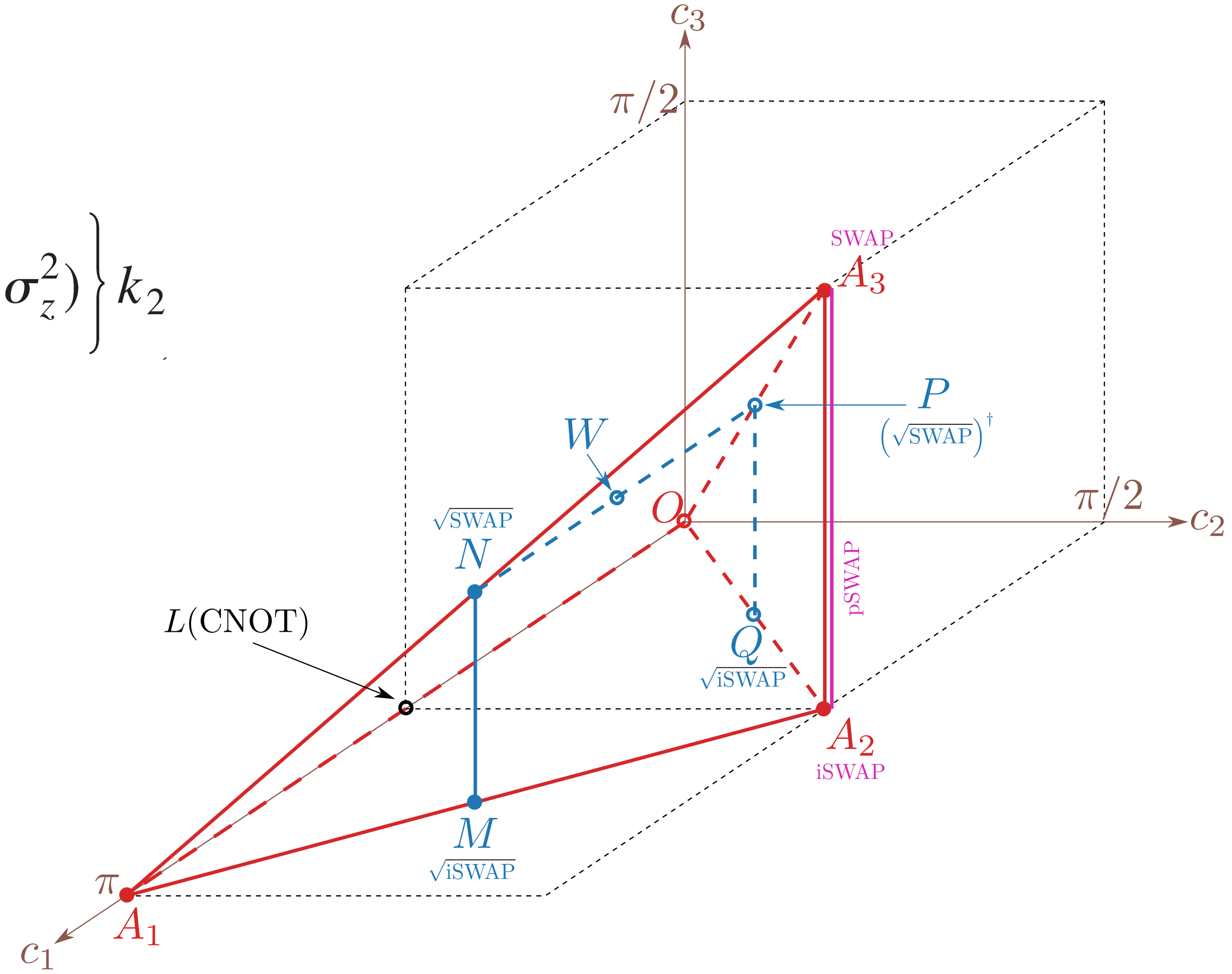
Two qubit gates

Any two qubit gate is characterized by three rotation angles $\{c_1, c_2, c_3\}$ and single qubit rotations

$$U = k_1 A k_2 = k_1 \exp\left\{ \frac{i}{2} \left(c_1 \sigma_x^1 \sigma_x^2 + c_2 \sigma_y^1 \sigma_y^2 + c_3 \sigma_z^1 \sigma_z^2 \right) \right\} k_2$$

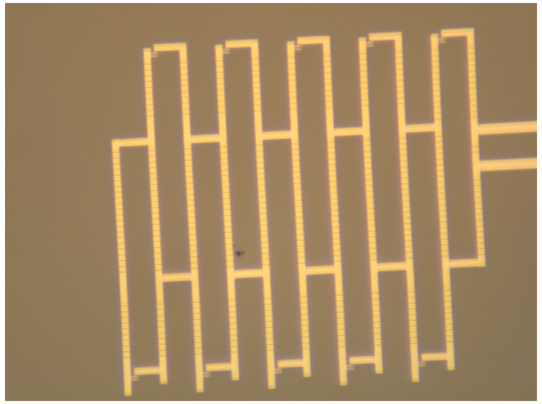
Gates are characterized by local invariants that define unique points in the **Weyl chamber**.

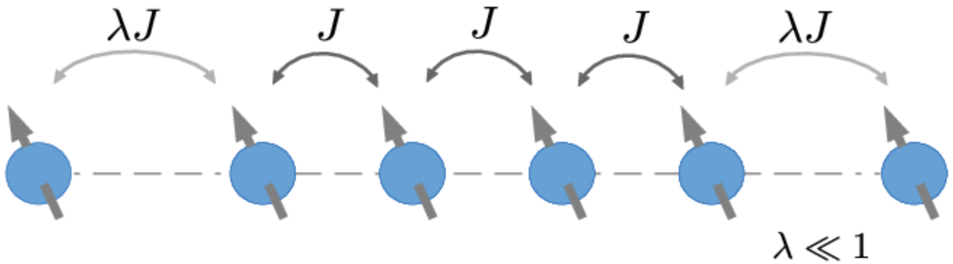
What are suitable two-qubit gates for specific hardware?



Quantum simulations using chain of fluxonium qubits

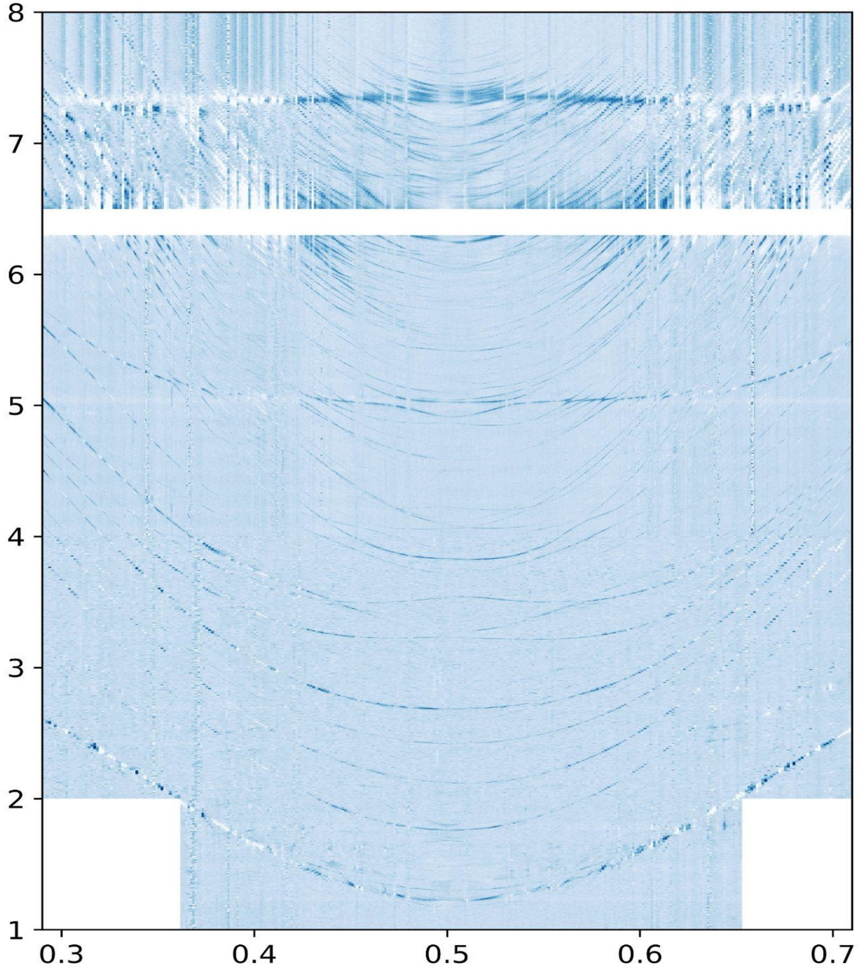
Transverse-field Ising model: what are effects of higher energy states, interaction with resonator modes, effect of disorder.



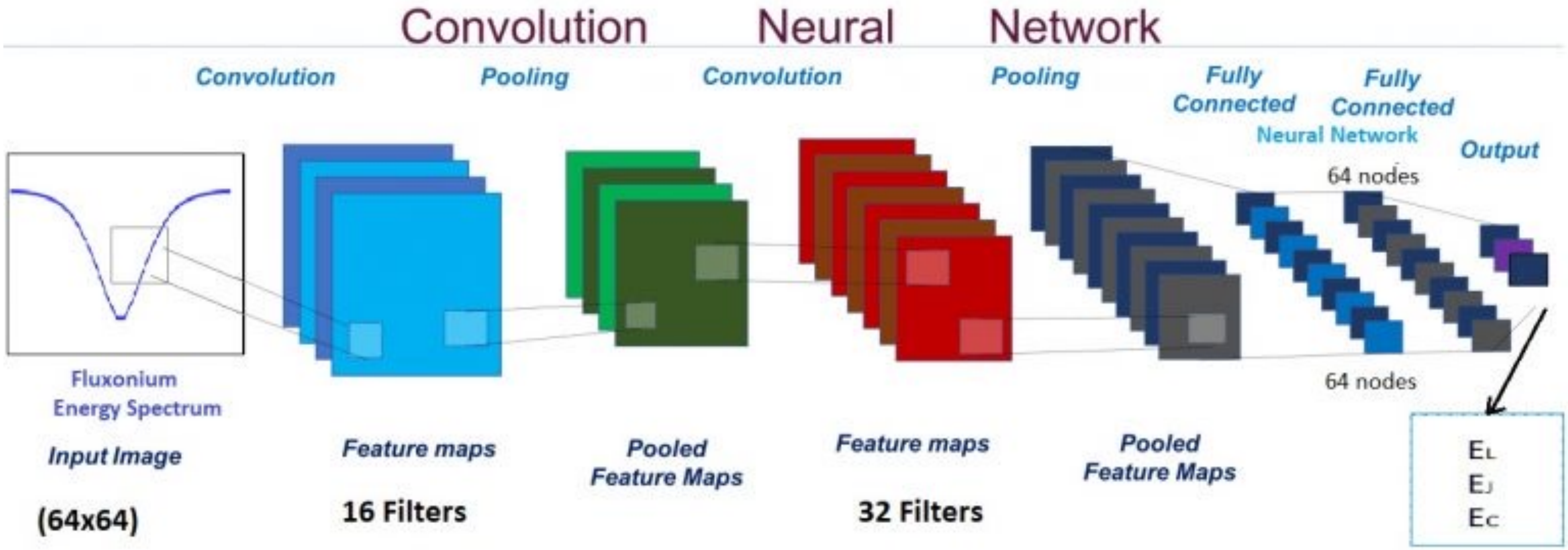


$$H = \sum_i (h_{z_i}\sigma_{z_i} + h_{x_i}\sigma_{x_i}) + \sum_i J_{x_i x_{i+1}} \sigma_{x_i} \sigma_{x_{i+1}}$$

Earlier work with Baris (arxiv:2104.03300)



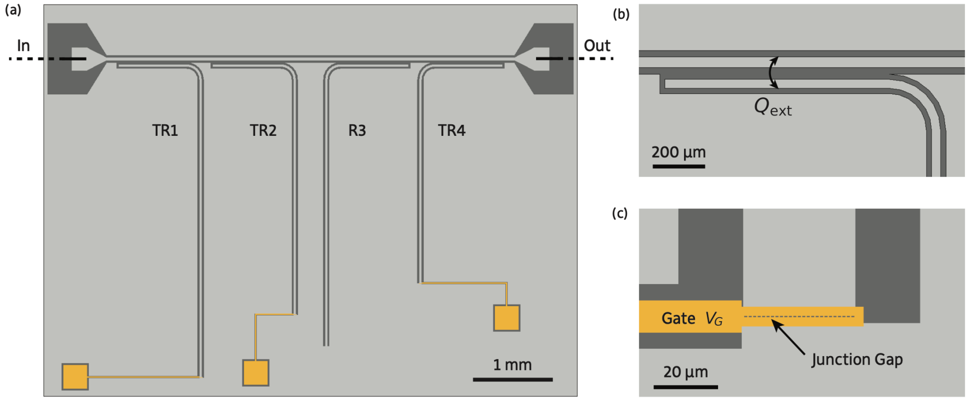
Machine learning applications to characterization and control of quantum systems

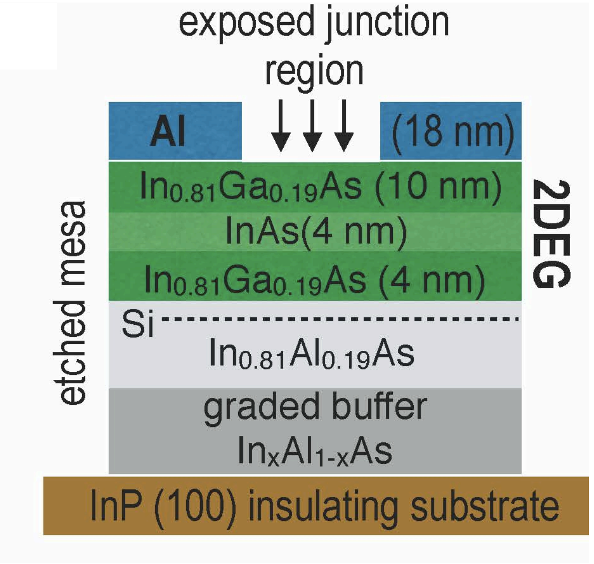


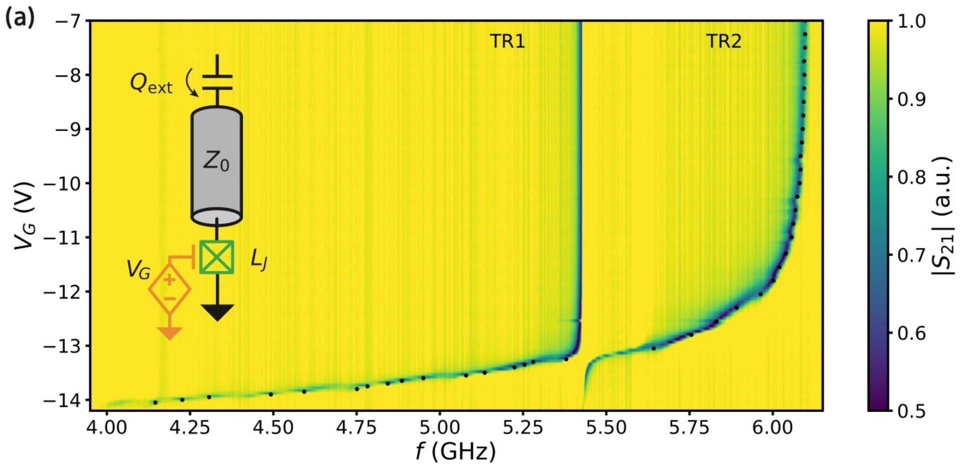
Thanks to Rafael!

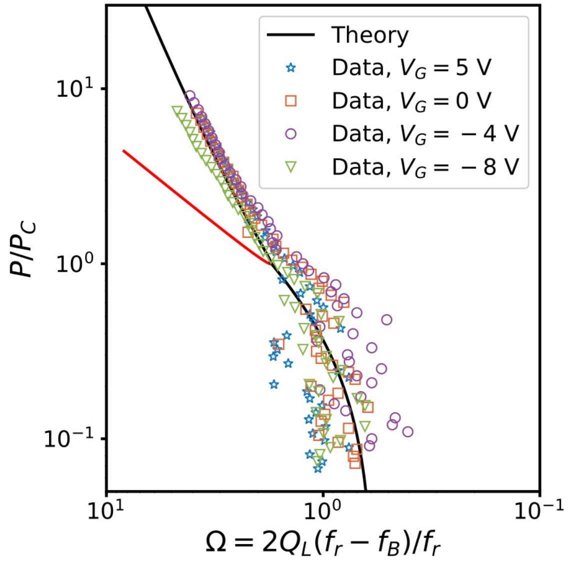
Epitaxial Super-Semi devices

A system of coupled resonators. One terminal of tunable resonators (1,2,and 4) are shunted by super-semi Josephson contact



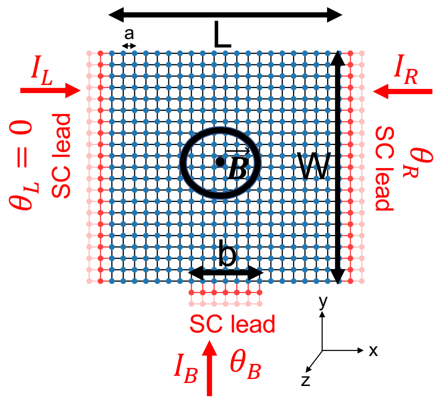






Strickland et al, arXiv:2210.02491, see also arXiv:1806.01880 – tunable resonators

Josephson Effect in Epitaxial Super-Semi junctions



The scattering region is a ballistic normal metal

$$H = \frac{(\boldsymbol{p} - e\boldsymbol{A})^2}{2m} - \mu$$

We use the lattice model

$$H = \sum_{<i,j>} t_{ij} c_i^\dagger c_j - \mu \sum_i c_i^\dagger c_i$$

with $t_{ij} = t_0 e^{i\phi_{ij}}$, $t_0 = \hbar^2/(8ma^2)$,
and $\phi_{ij} \propto B$ is the magnetic factor.

- **Beenakker's determinant equation**

Defines ABS energies in terms of the full scattering matrix S
(valid for short wires, *L*,*W*<<ξ)

$$\det[1 - \exp(-2i\gamma)\, \hat{r}\hat{S}^* \hat{r}^* \hat{S}] = 0$$

Here, $\gamma = \arccos(E/\Delta)$ for $E < \Delta$;
$\hat{r} = \mathrm{diag}\{e^{i\phi_1}, \ldots, e^{i\phi_N}\}$ and
ϕ_j are the SC phases in the leads.

- **Finite size system**

(microscopically accurate model, finite size effects)

Kwant package is used for simulations, combined with own software and high throughput computing at UW-Madison (UW-CHTC).

Micheline Soley

Physics
Department—
Affiliate

Chemistry
Department

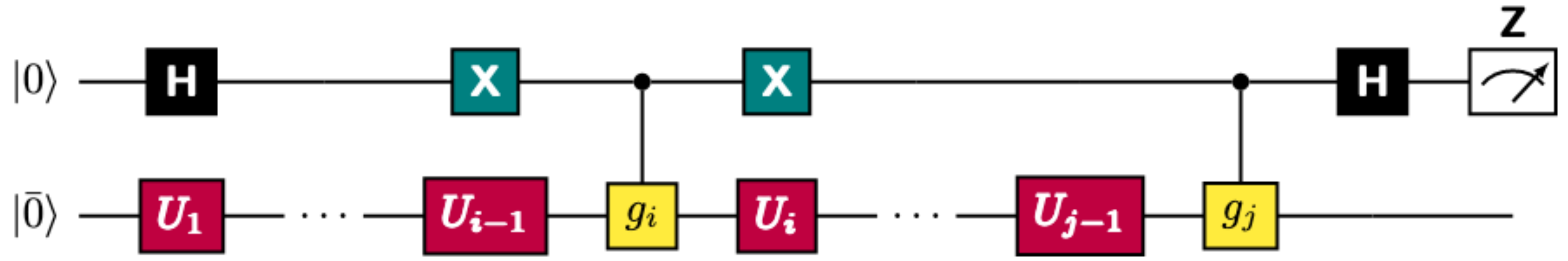
Theorist interested in research at the intersection between physics, chemistry, applied mathematics, and computer science with a particular focus on:

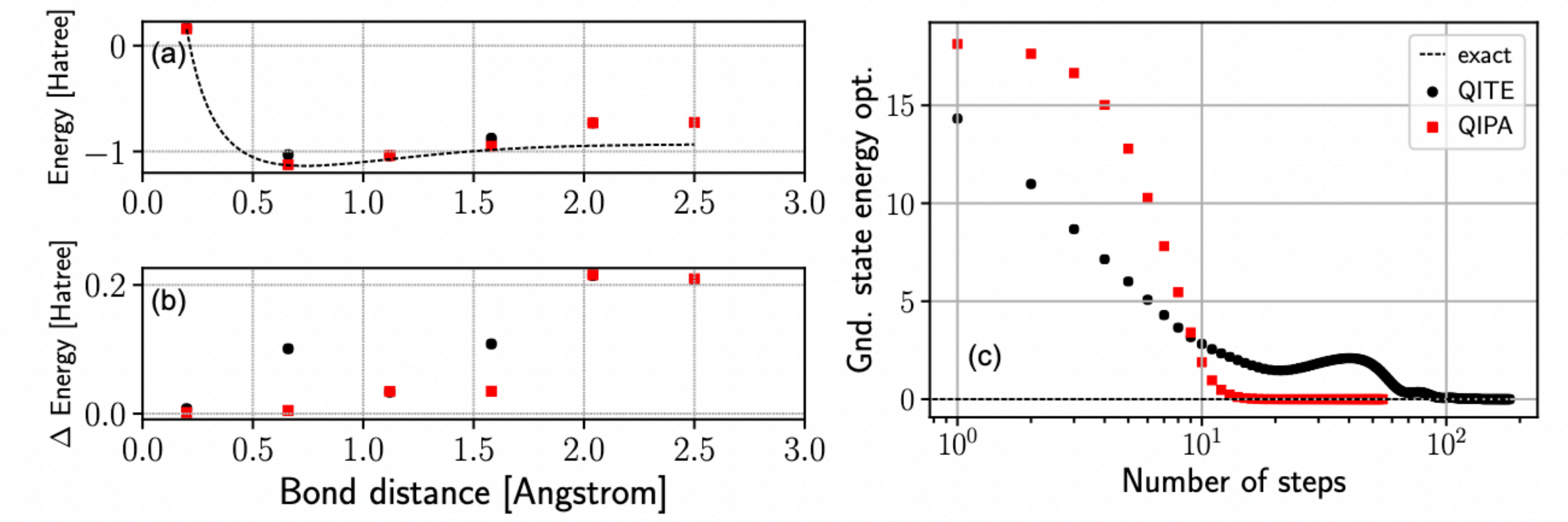
- Quantum computing algorithm development
- Simulation, analysis, and quantum control of ultracold collisions and near-threshold systems
- Investigation of $\mathscr{PT}$-symmetry behavior in fundamental quantum-mechanical systems

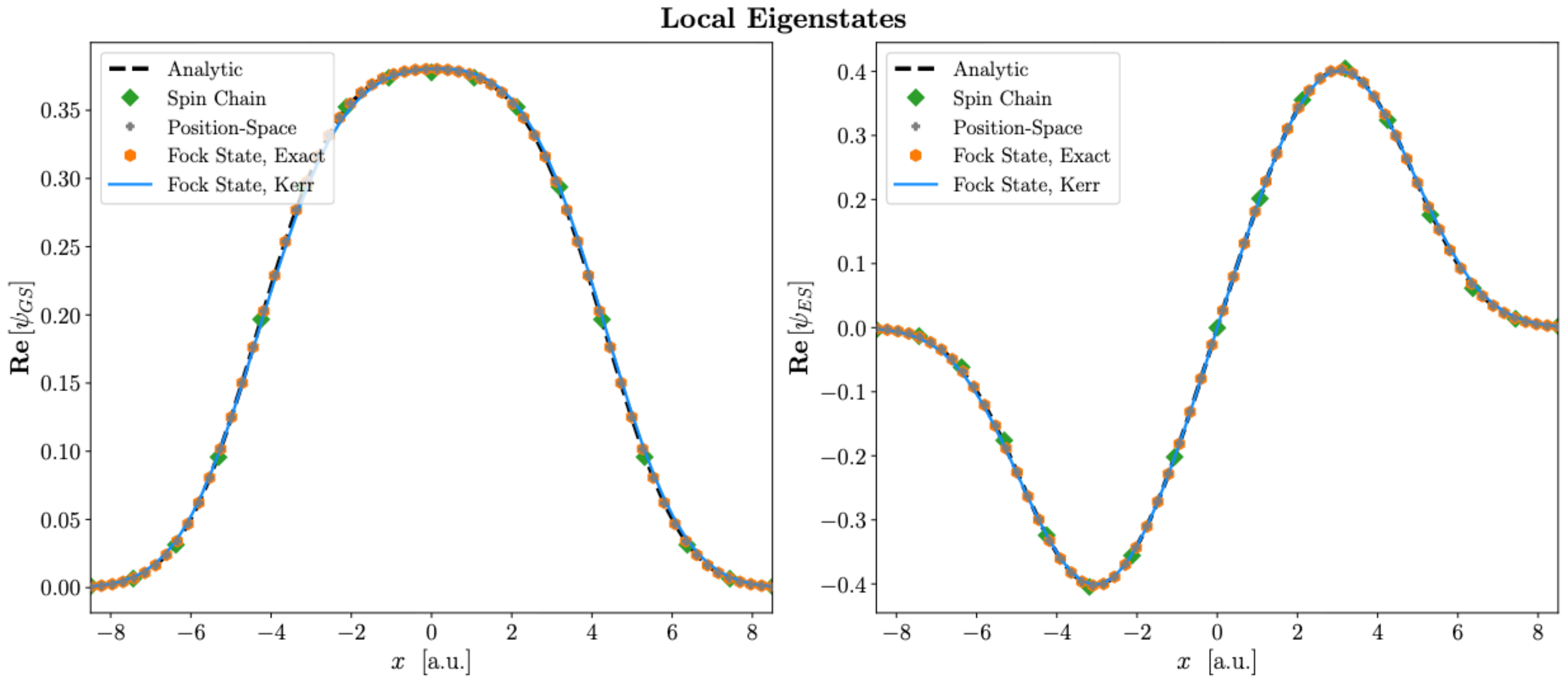
Quantum computing algorithm development

- Algorithmic design for quantum computation on discrete qubit- and continuous qudit-based quantum architectures, collaboration with experimental groups

- Simulation of molecular dynamics, near-threshold scattering, and global optimization informed by matrix product state/tensor network approaches



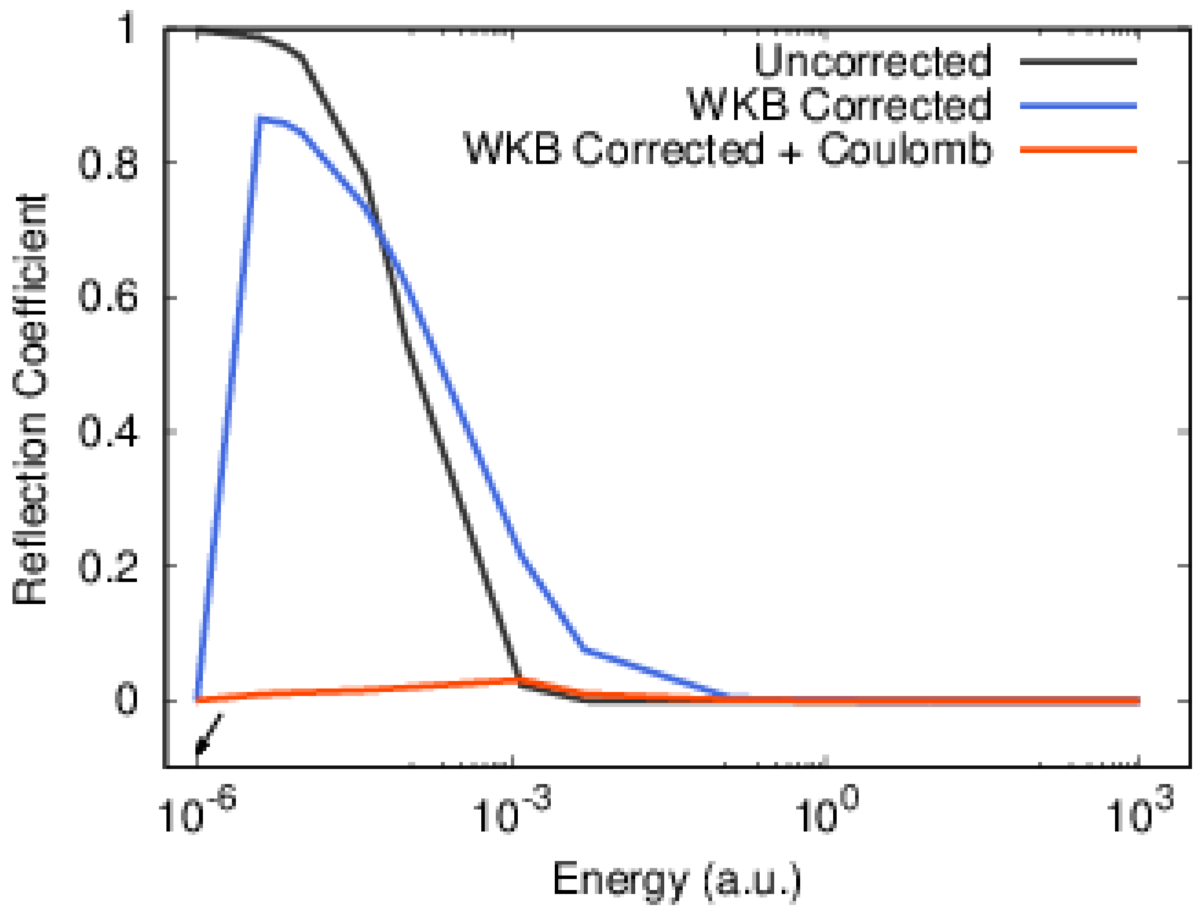


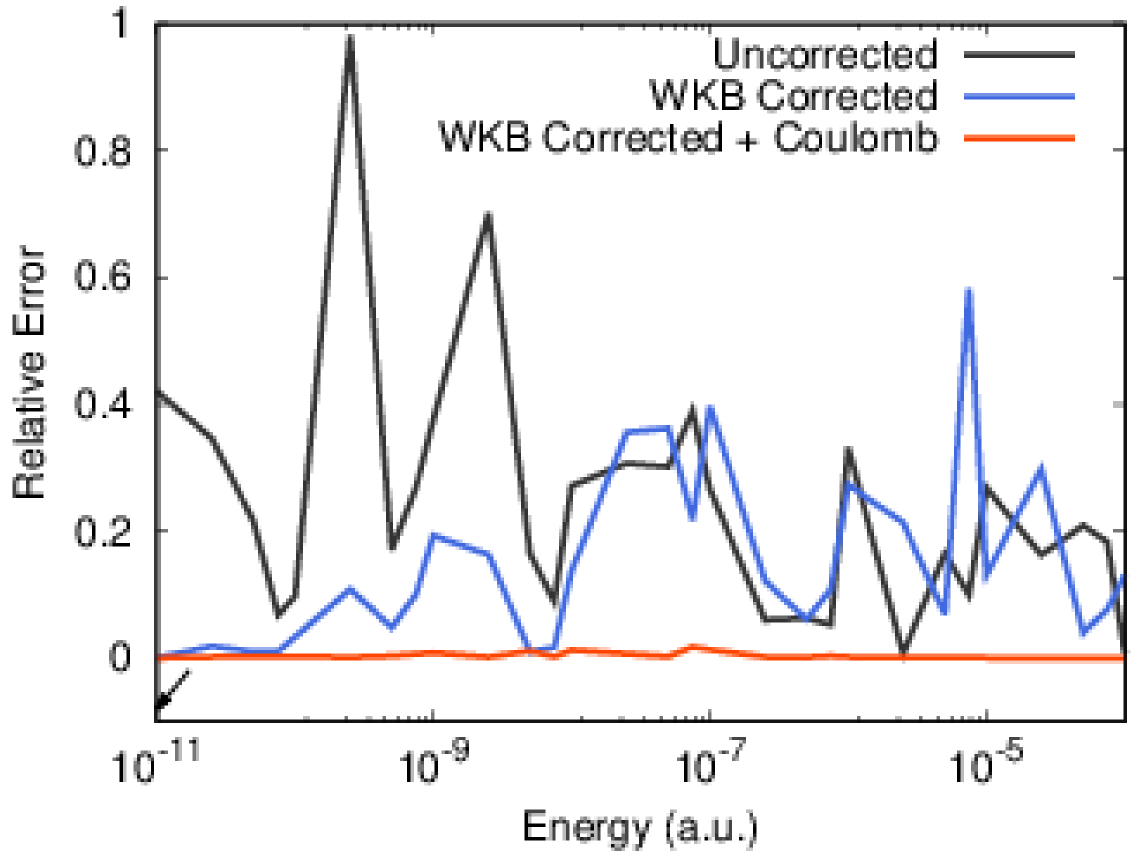


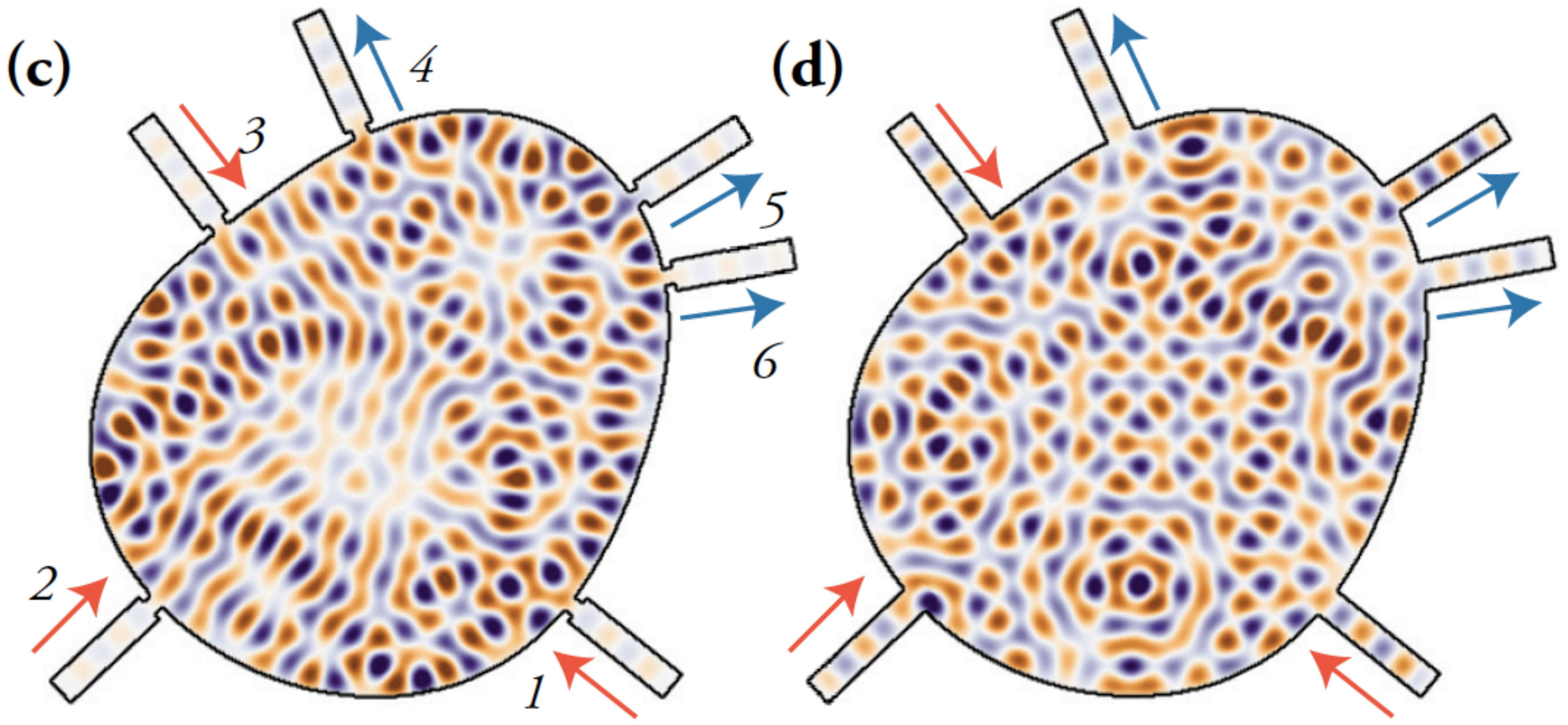
Simulation, analysis, and quantum control of ultracold collisions and near-threshold systems

- What role does quantum reflection play in ultracold collisions (universal laws, computational simulations, product formation, quantum-classical correspondence)?

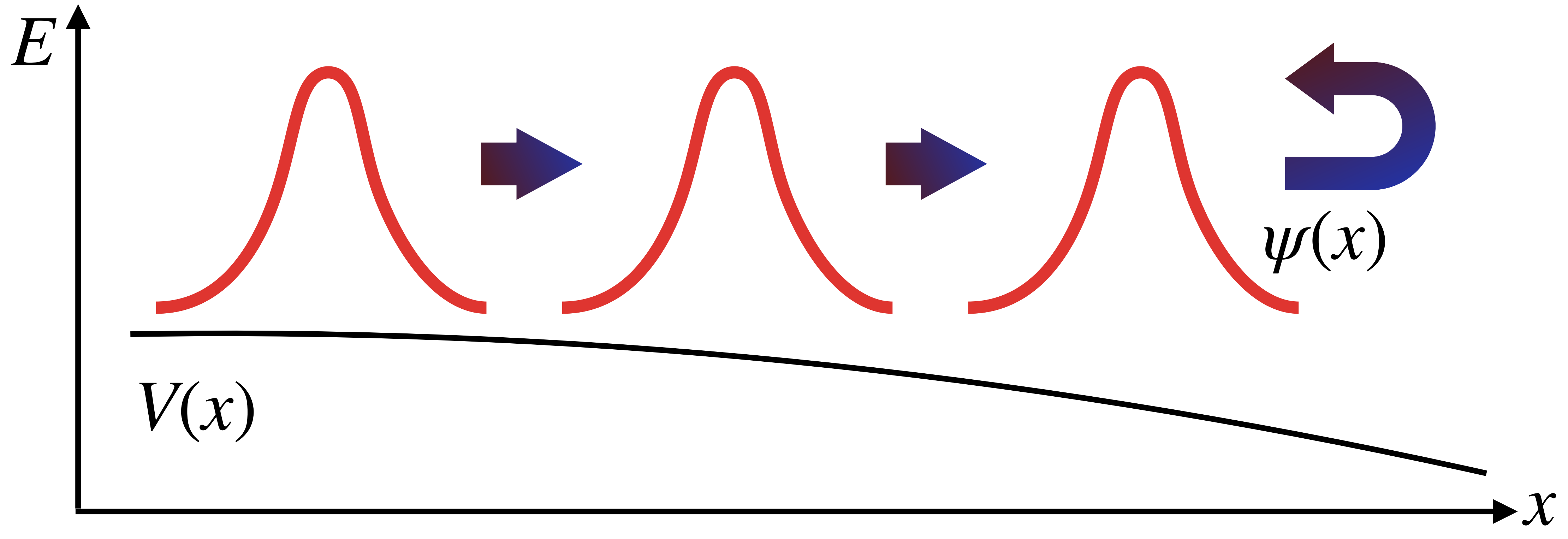
- How can molecular collisions be controlled quantum mechanically via preparation of coherent superposition states and external field parameters?





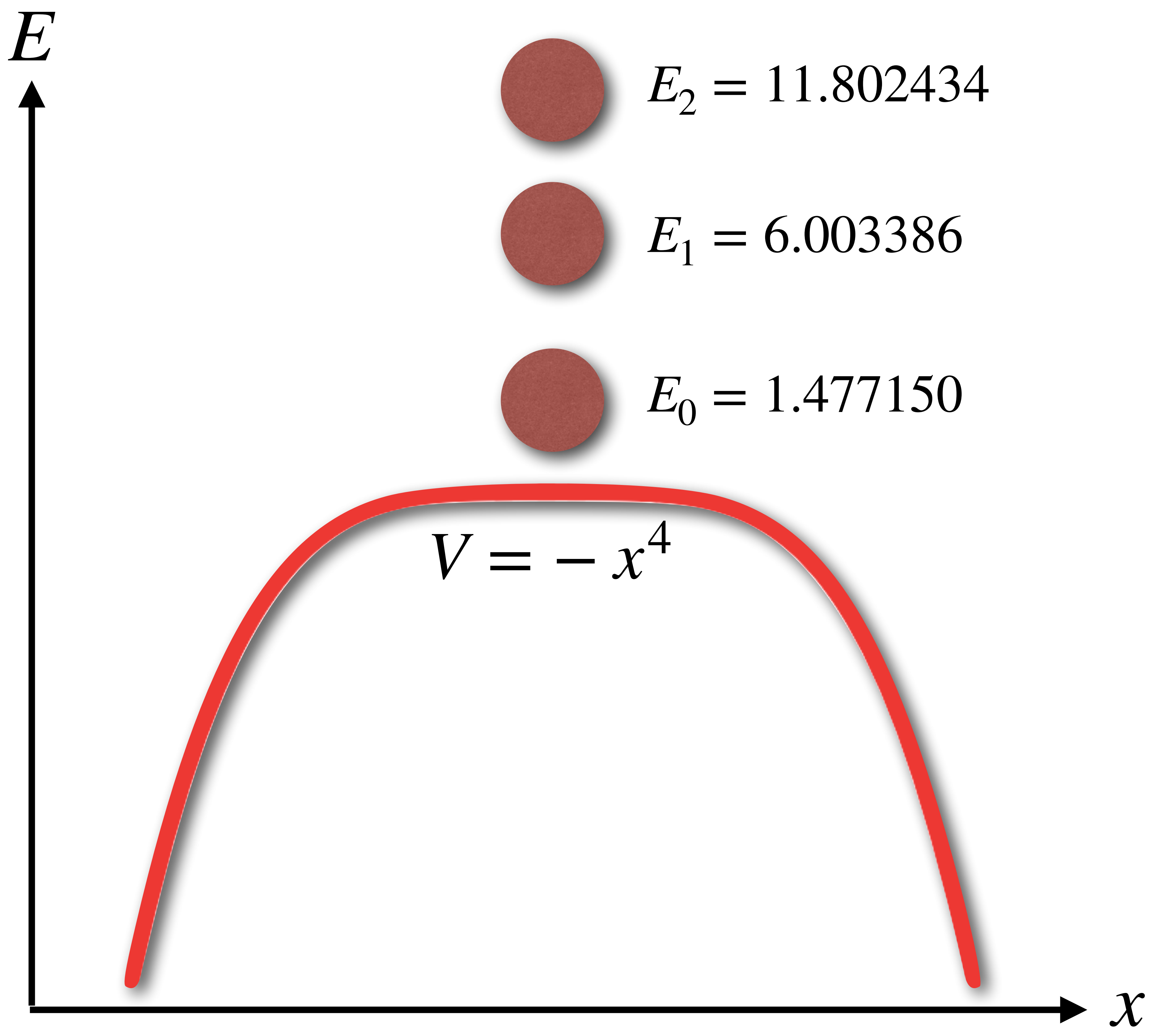


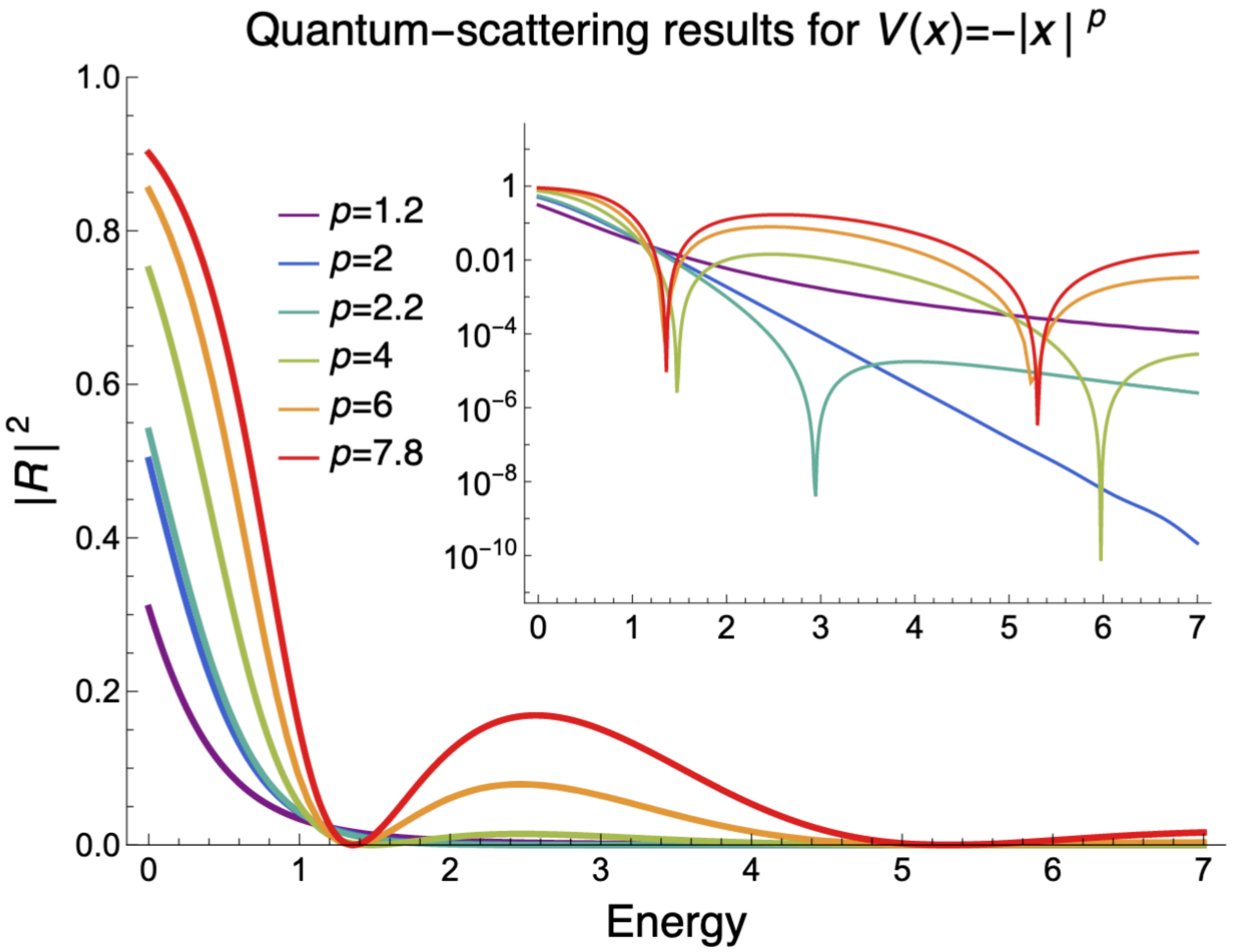
A. D. Stone, et al. Nanophotonics, 10 (2020) 343.



Investigation of $\mathscr{PT}$-symmetry behavior in fundamental quantum-mechanical systems

Search for non-Hermitian, $\mathscr{PT}$-symmetry behavior in near-threshold quantum mechanics via quantum scattering theory and the application of reflectionless scattering mode theory from optics to chemistry and quantum mechanics





Interested in the pursuit of $\mathscr{PT}$-symmetric technologies and experimental realization