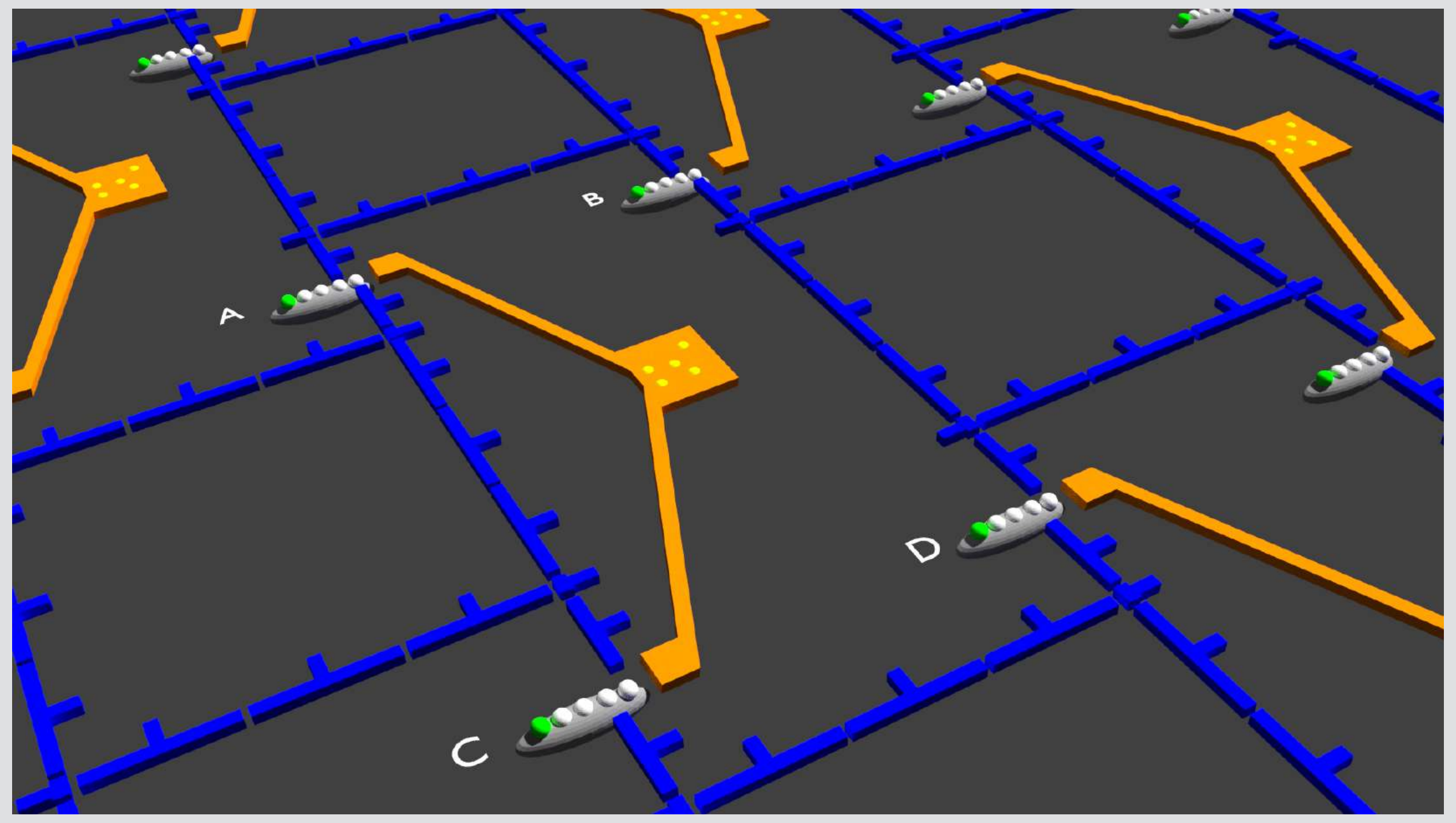
Simulating coherent electron shuttling in silicon quantum dots

B. Buonacorsi[1,2], B. Shaw[1], J. Baugh[1,3]

[1]Institute for Quantum Computing, University of Waterloo, Waterloo, Ontario, Canada
[2]Department of Physics and Astronomy, University of Waterloo, Waterloo, Ontario, Canada
[3]Department of Chemistry, University of Waterloo, Waterloo, Ontario, Canada

Motivation

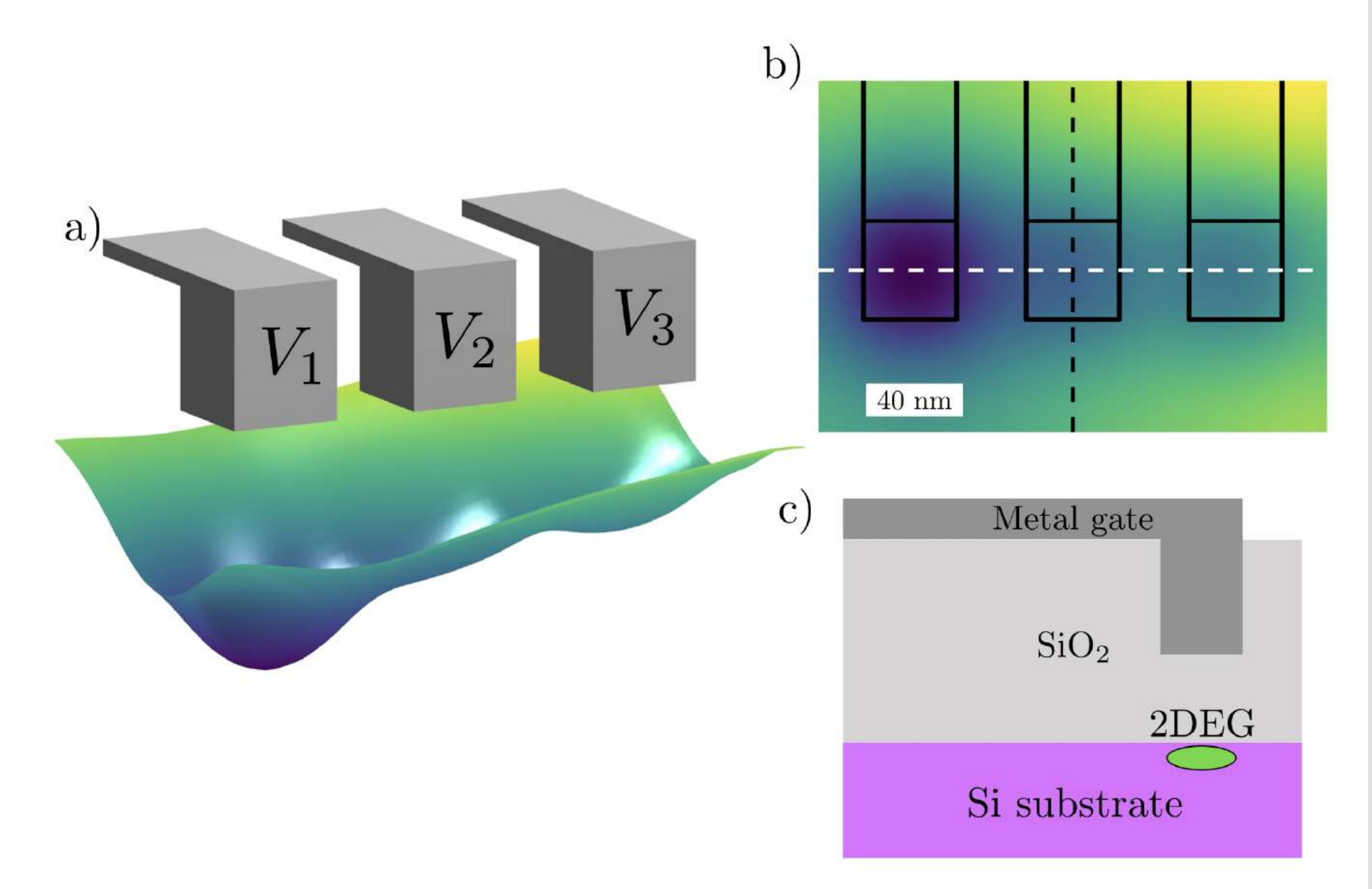
- Electron spins in silicon quantum dots (QDs) are promising qubit candidates for scale-able quantum information processing.
- A network approach for connecting QD qubit 'nodes' spreads out the dense electronic wiring required for qubit control [1].
- Electrons are shuttled between nodes through linear chains of QDs to achieve long distance two-qubit operations.
- We investigate what shuttling fidelities and speeds are achieve-able in silicon QDs.



Schematic of QD network architecture where data qubit 'nodes' (labelled A, B, C, D) are connected by QD chains (blue).

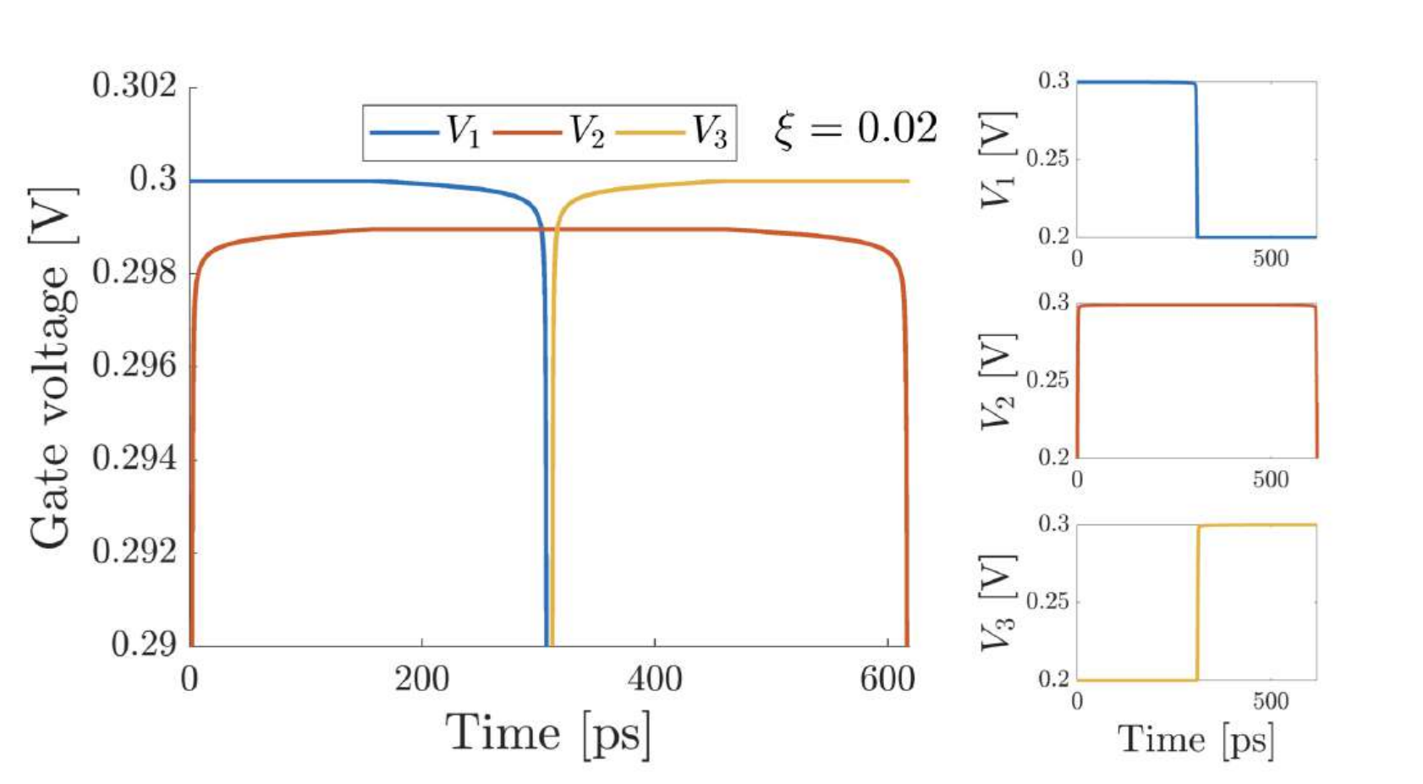
3D Device Modelling

- A triple QD linear chain for electron shuttling is modelled in **nextnano++** to find how the electrostatic potential varies with plunger gate voltages $\{V_1, V_2, V_3\}$.

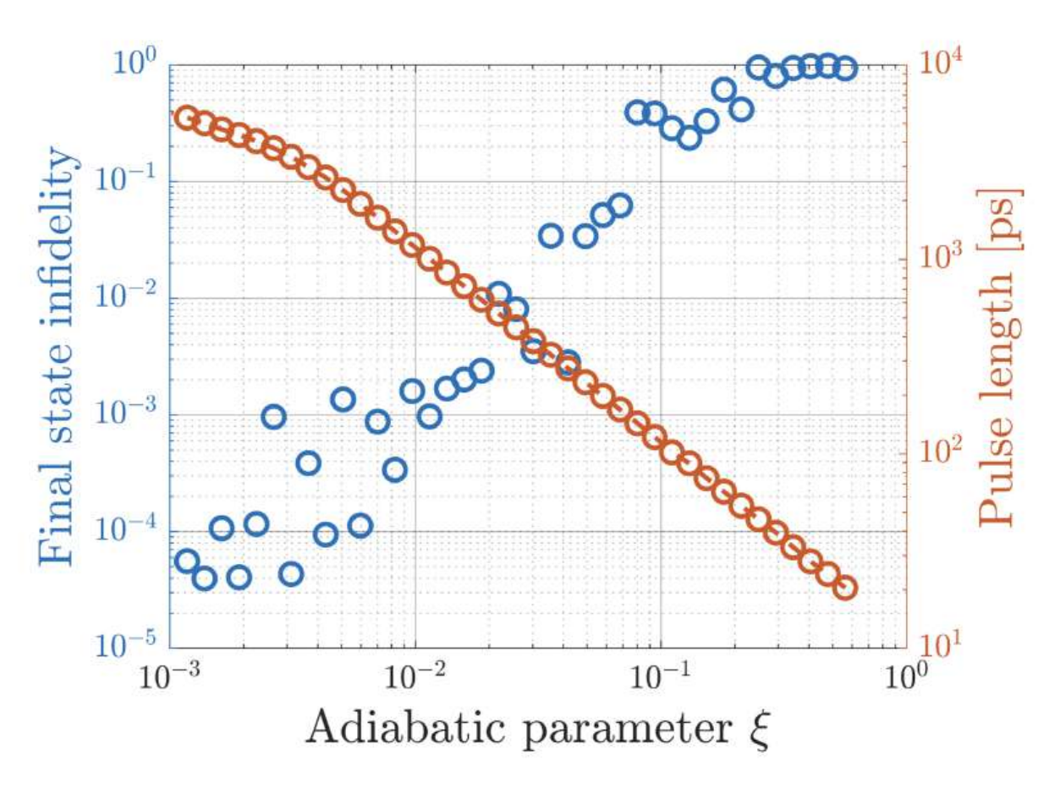


a) 3D schematic of a triple linear QD chain and an example electrostatic potential taken 1 nm below the Si/SiO$_2$ interface. **b)** 2D view of the gate geometry. White dashed line indicates where a 1D slice of the potential is taken for shuttling simulations. **c)** Schematic slice along the black dashed line in **b)** showing the use of 'via' gates to confine electrons at the head of the plunger gate.

Adiabatic Control of Shuttling



Adiabatic voltage control pulse for electron shuttling through a linear triple QD chain. For this pulse, $\xi = 0.02$.



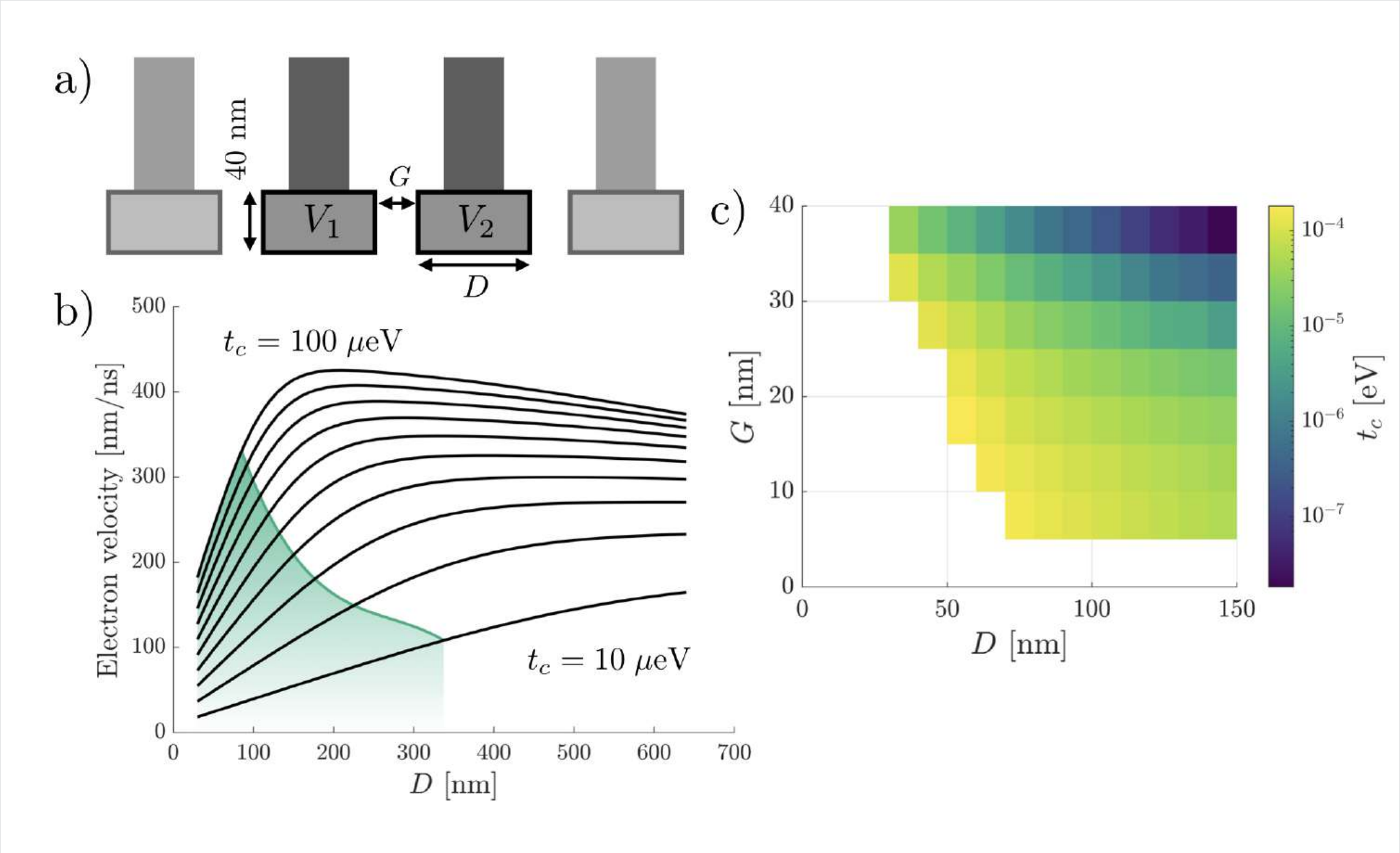
Relationship between ξ and both the electron shuttling fidelity (blue) and the pulse length (orange). Lower ξ results in higher fidelity pulses while reducing their speed.

- To prevent unwanted excitations of the electron state during shuttling, the electron must tunnel adiabatically through the QDs.
- Adiabicity of a ground state electron is governed by the approximate adiabatic parameter

$$\xi(t) = \sum_{m \neq 0} \hbar \left| \frac{\langle \psi_m(t) | \frac{d}{dt} | \psi_0(t) \rangle}{E_0(t) - E_m(t)} \right| \tag{1}$$

- Developed an algorithm to find smooth adiabatic control pulses with constant adiabicity ξ.

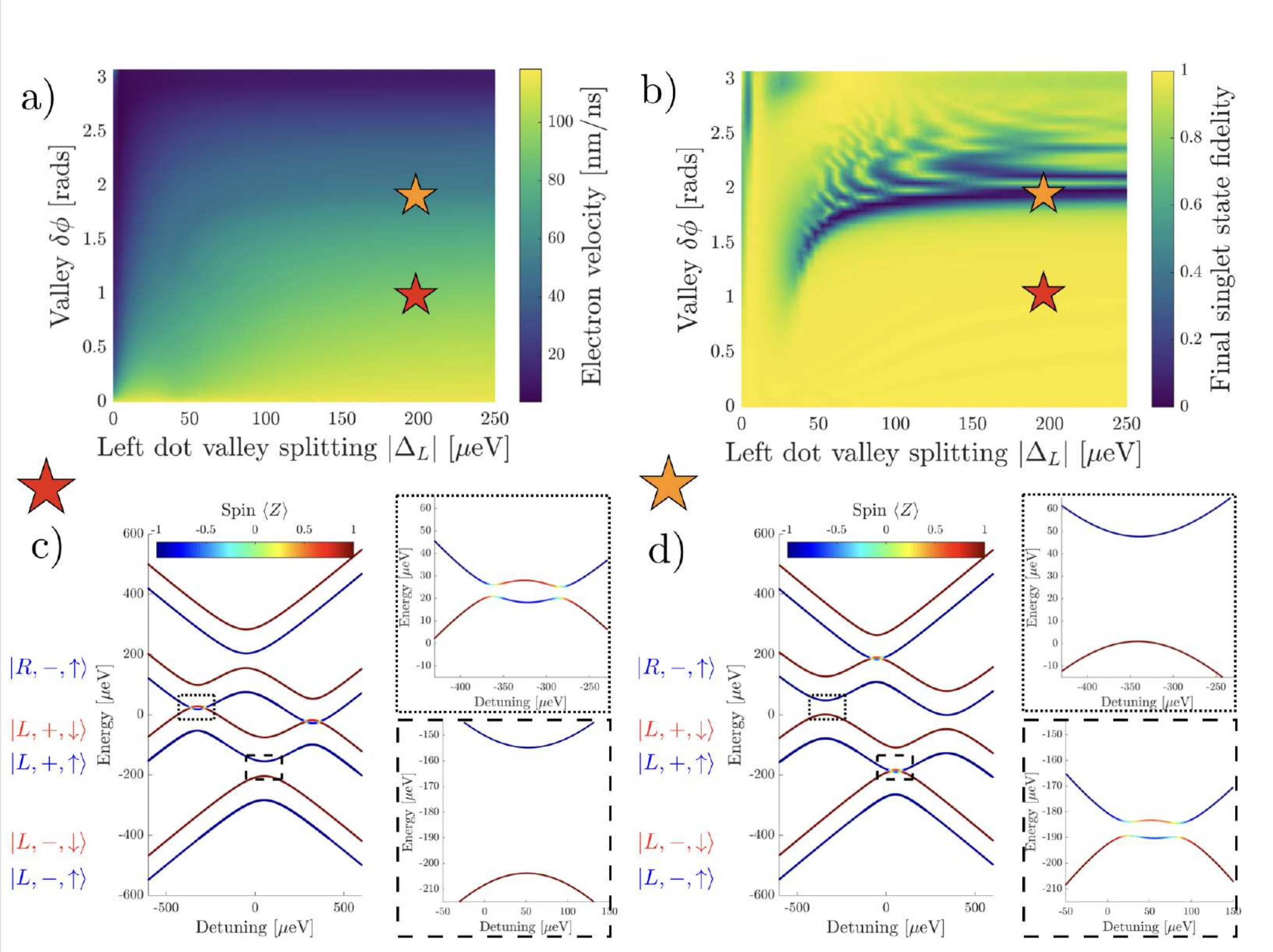
Optimal Device Geometry



a) Top view of the device structure simulated to extract orbital energy spacings. **b)** Shuttling velocity as a function of QD size for varying tunnel couplings t_c. The green shaded region corresponds to a QD separation $G \geq 10$ nm. Smaller separations would be difficult to fabricate. c Tunnel coupling versus QD size D and separation G.

- As the QD size increases, the orbital energy spacing decreases and suppresses the shuttling velocity.
- Used adiabatic pulses and **nextnano++** to find optimal QD geometries that simultaneously maximize shuttling velocity and adiabicity.
- Velocity is mainly determined by the inter-dot tunnel coupling t_c.

Effective Hamiltonian Simulations



Shuttling velocity **a)** and final singlet state fidelity **b)** versus the left QD valley splitting $|\Delta_L|$ and the valley phase difference $\delta\phi$. The shuttled electron's energy spectra at $|\Delta_L| = 200\ \mu$eV for $\delta\phi = 1$ **c)** and $\delta\phi = 2$ **d)**.

- Performed shuttling simulations with an effective double QD Hamiltonian to include valley splitting, valley phase, spin-orbit coupling, and Zeeman splitting.
- The inter-dot valley phase difference $\delta\phi$ strongly affects shuttling speed and fidelity.
- When the inter-dot tunnel coupling t_c is less than the Zeeman splitting E_z, high fidelity shuttling is possible for smaller $\delta\phi$.

Summary and Future Work

- High fidelity and fast electron orbital shuttling simulations using adiabatic pulses are done using realistic electrostatic potentials.
- Shuttling simulations with an effective Hamiltonian including valley and spin physics show coherent electron spin transfer is possible.
- In the future, orbital shuttling simulations can be extended to include charge noise and investigate the shuttling performance of alternative device geometries.

Acknowledgments and References

We are grateful to the Waterloo Institute for Nanotechnology and Defence Research and Development Canada.

1. B. Buonacorsi et al, *Quantum Sci. Technol.* **4**, 025003 (2019)

Mail: baugh@iqc.ca