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Towards analog quantum simulation of strongly correlated electron systems with lithographic quantum dots

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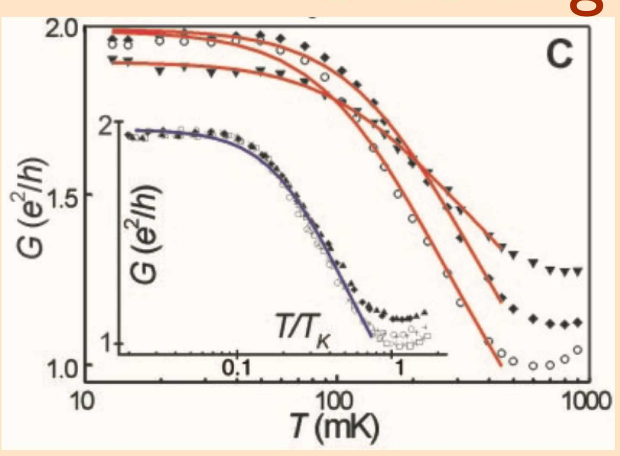
Motivation

Analog Quantum Simulation

Exact simulation of strongly correlated quantum systems is prohibitively difficult. However, fabrication and control of quantum systems has come to the point where we can imitate one quantum system with a precisely controllable engineered one with a similar Hamiltonian.

This is known as analog quantum simulation. [1]

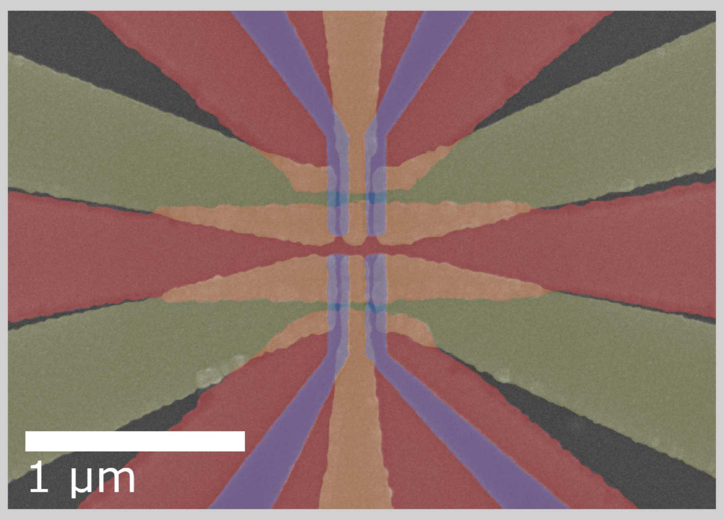
Could quantum dots (QDs) be used for analog simulation of strongly correlated electron systems?



- QDs have already been shown to exhibit the Kondo effect in transport experiments (left, [2])
- Captured by the Anderson impurity model (AIM)
- Can we combine measurement and feedback to simulate the AIM itself, or dynamical mean-field theory?

Model

Devices being modeled



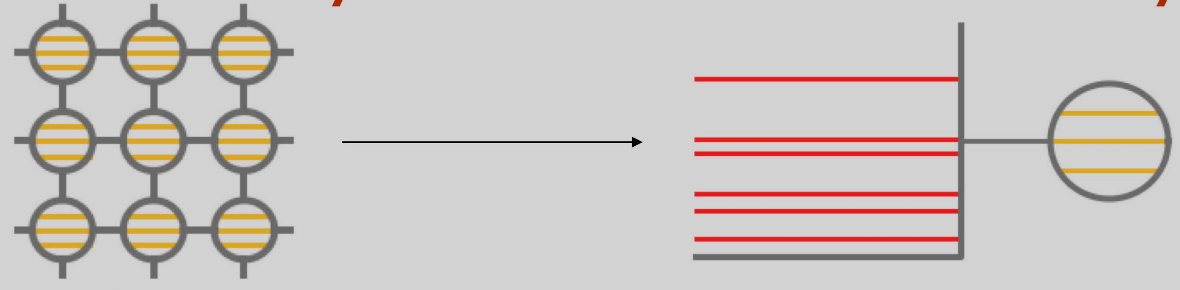
- Calculations here are based on a Ge hole QD design developed at Sandia (left, [3])
- We are developing tools to model these devices so we can implement analog quantum simulation

Anderson Impurity Model

$$\hat{H}_{AIM} = \sum_{\sigma j} \epsilon_{\sigma j} \hat{c}^{\dagger}_{\sigma j} \hat{c}_{\sigma j} + \sum_{j} U_j \hat{n}_{\uparrow j} \hat{n}_{\downarrow j} + \sum_{\sigma jk} t_{\sigma jk} \hat{c}^{\dagger}_{\sigma j} \hat{c}_{\sigma k} + \sum_{\sigma jk} \left(V_{\sigma jk} \hat{c}^{\dagger}_{\sigma j} \hat{d}_{\sigma k} + h.c. \right)$$

The AIM is a natural way to describe quantum dot systems, with fermionic operators of the impurity corresponding to the electrons on the dot, the $\hat{c}_{\sigma j}$s, and the bath operators corresponding to the leads, the $\hat{d}_{\sigma j}$s. Prior to this work, we could compute all the coefficients but the $V_{\sigma jk}$s for most systems – the infinite elements give it this functionality.

Two-site dynamical mean-field theory

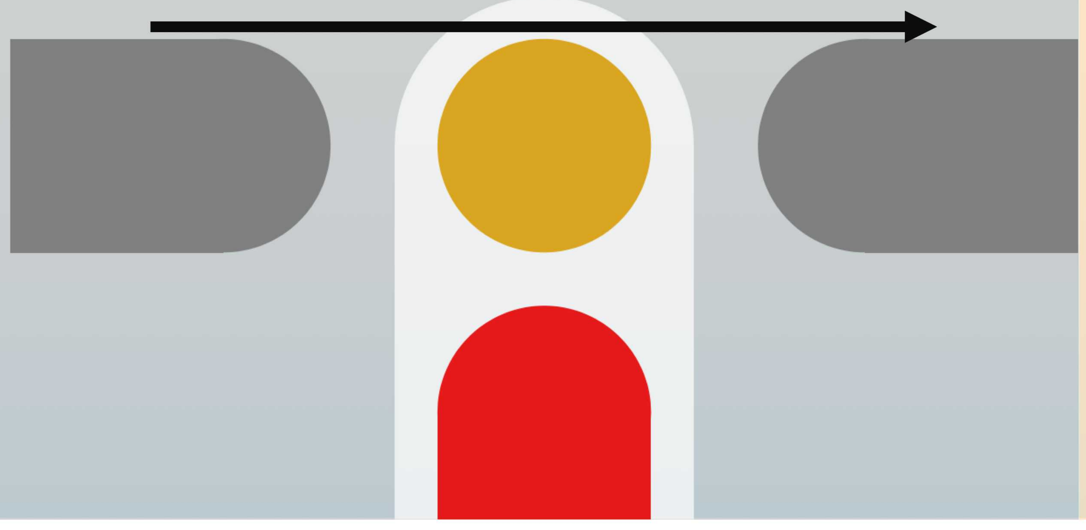


Dynamical mean-field theory approximates Hubbard Hamiltonians with an AIM. For example, the Bethe lattice can be mapped to a two-site AIM through an iterative process which we can simulate with a quantum dot (impurity) coupled to a lead (bath). The Green's function for the dot-bath system acts as an approximation to that of the Bethe lattice.

Measuring the Green's function

Connecting a QD to nearby leads at differing chemical potentials, e.g. by applying a bias, V, yields a current, I. This is proportional to the integral of the spectral function of the QD, A_{00}, between the chemical potentials.

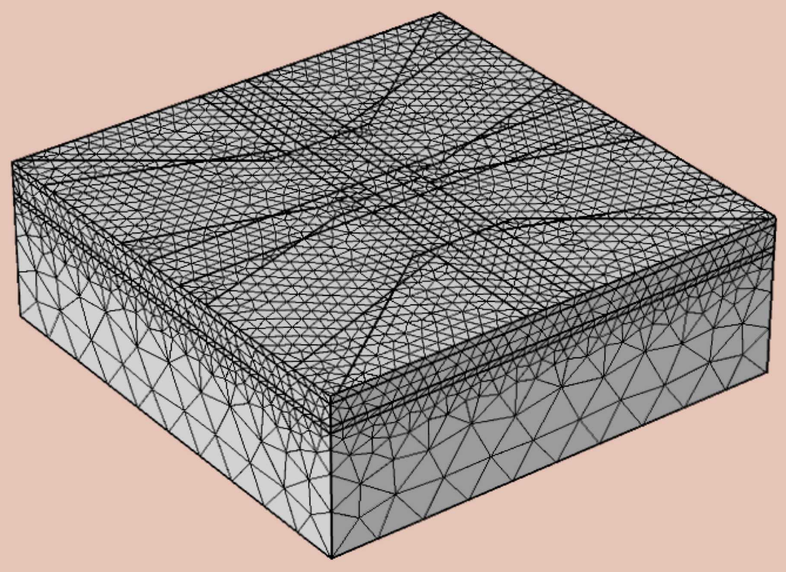
Diagram of the proposed two-site DMFT simulation. The QD (yellow) is strongly connected to a bath lead (red) to form the two-site Hamiltonian. A current (black) through nearby leads (grey) provides a measurement of the system.

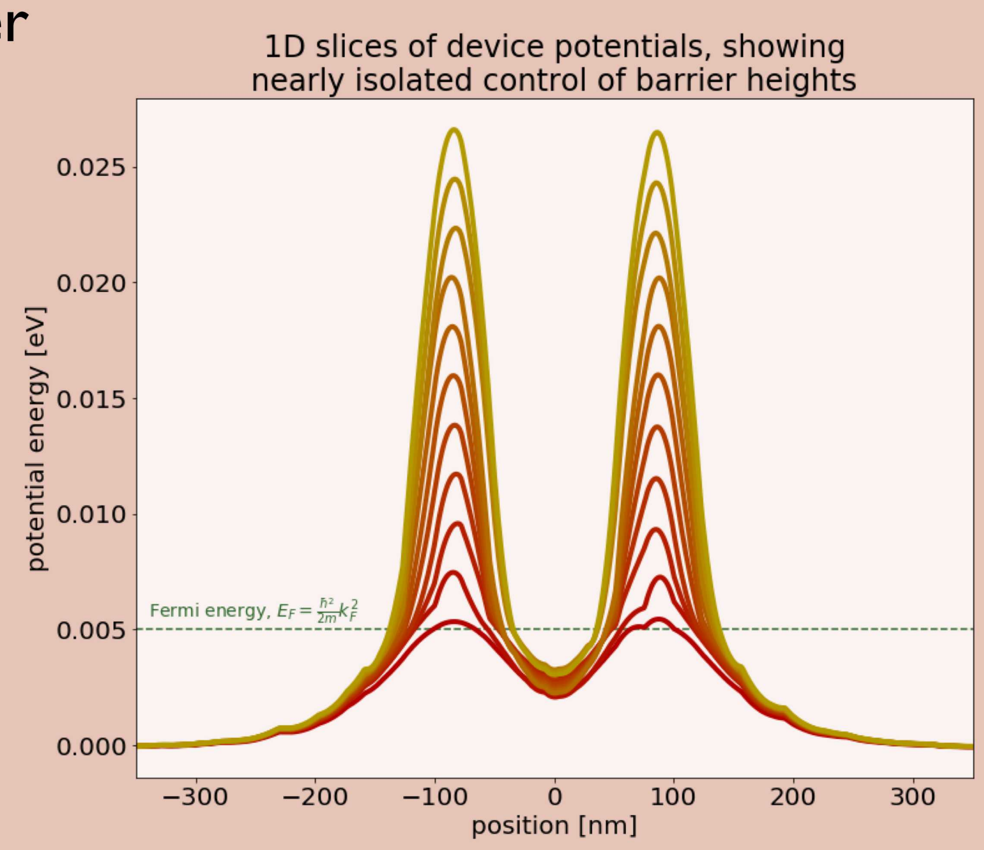


Results

Device control

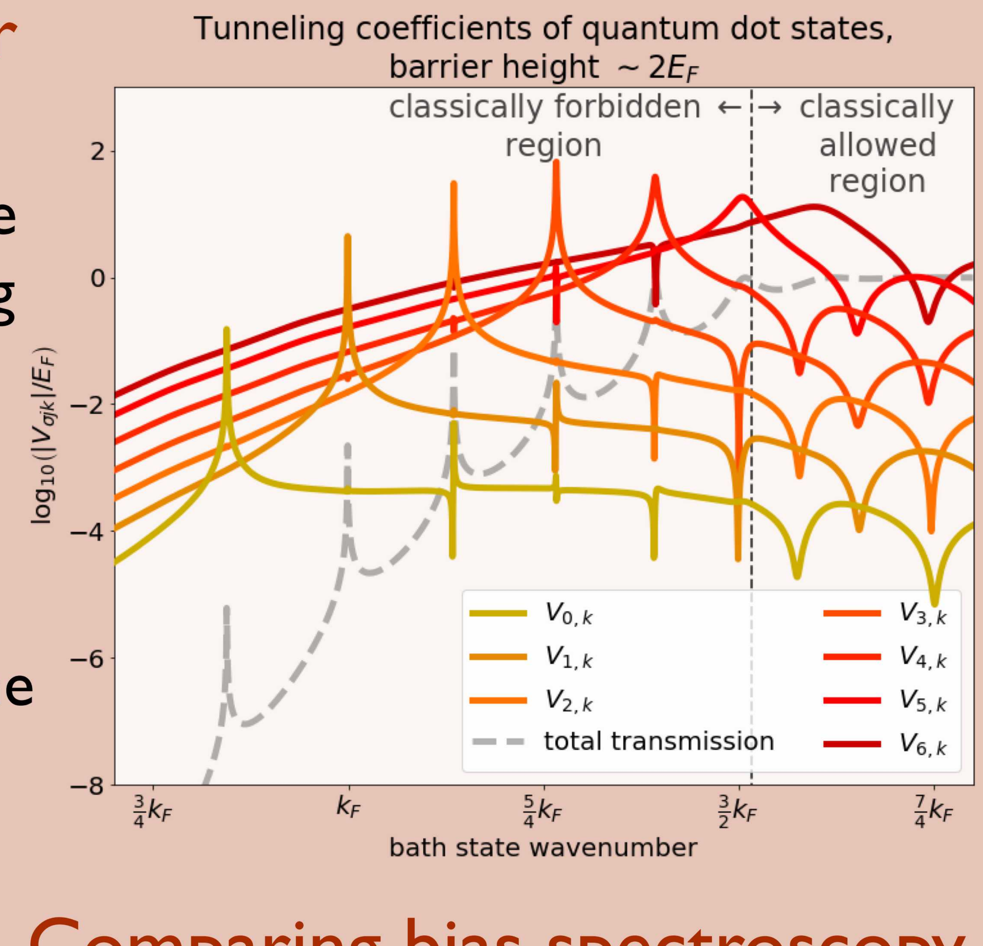
- Can we adjust AIM parameters of a quantum dot separately?
- Device potentials are calculated using COMSOL
- Sweeps of gate voltages showed aspects of the potential could be controlled nearly independently
  - Dot to lead potential difference
  - Dot occupation number
  - Barrier heights

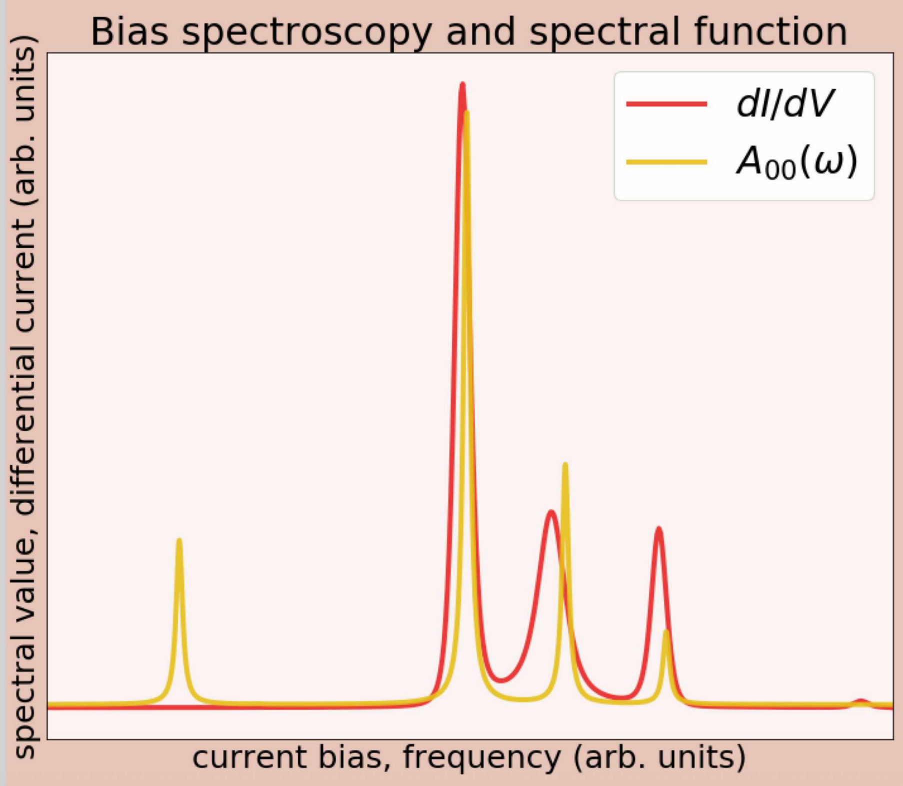




Calculate tunneling rates for quasi-bound states

- Transmission calculations can be done in Laconic to get tunneling between QD and leads ($V_{\sigma jk}$)
- Spikes in tunneling coefficients correspond to resonances with specific states
- Dips in tunneling coefficients line up with resonances of higher level states of similar parity





Comparing bias spectroscopy to the QD spectrum

- The differential conductivity, dI/dV, across the QD is a measure of the spectral function convolved with hybridization of the leads
- An example calculation compares the two – how can we extract A_{00} from dI/dV?
- The two-site DMFT problem will allow us to explore ways to extract information about the QD+bath

References

[1] I. M Georgescu et al, *Rev. Modern Phys.* 86 (2014)

[2] W. G. van der Wiel et al, *Science* 289 (2000)

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[8] H. Ness et al., *Phys. Rev. B* 82 (2010)

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