Quantum simulation of a Fermi–Hubbard model using a semiconductor quantum dot array

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Introduction

- Fermi-Hubbard model is a key concept in condensed matter physics and provides crucial insights into electronic and magnetic properties of materials.
- Quantum Simulations:
  - Potential to realize novel electronic and magnetic properties of low-dimensional condensed matter
  - Digital Simulations:
    - Require a large numbers of highly controlled quantum bits
    - Additional error-correction overhead
  - Analog Simulations:
    - Limited by the residual entropy of the initialized system
- Quantum Dots:
  - An array can be naturally described by a Fermi–Hubbard model in the low temperature, strong-interaction regime
  - Pure state initialization of highly entangled states is possible without the use of adiabatic initialization

Fermi-Hubbard model

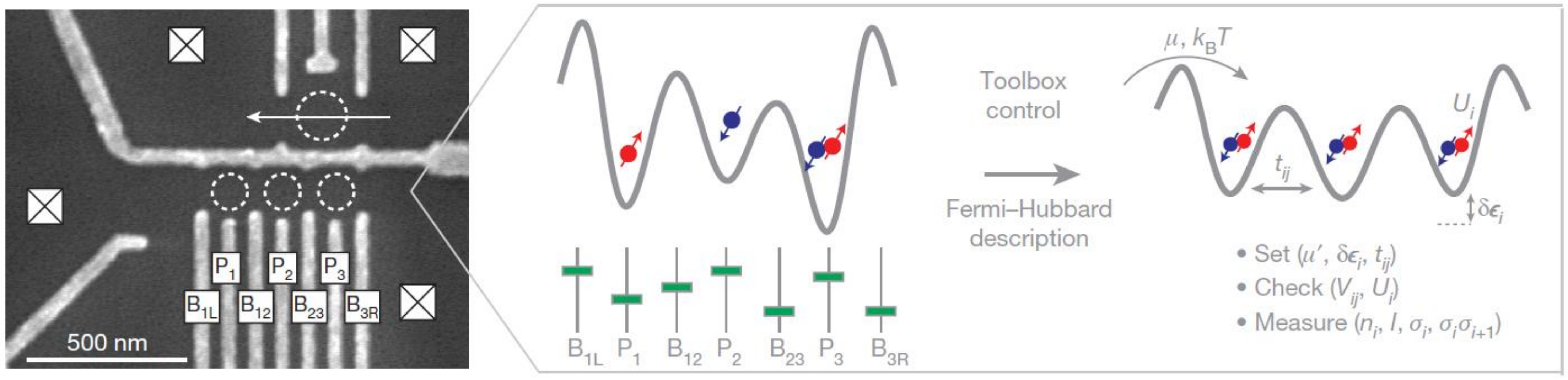
- two species of fermionic particles (spin up, spin down)
  - confined in a lattice
  - move by hopping to neighbours
- extended model, which includes inter-site interaction

$$H = \underbrace{-\sum_i \epsilon_i n_i}_{\text{chemical potential}} \underbrace{- \sum_{<i,j>,\sigma} t_{ij}\left(c_{i\sigma}^{\dagger} c_{j\sigma} + \mathrm{h.c.}\right)}_{\text{tunneling}} + \underbrace{\sum_i \frac{U_i}{2} n_i (n_i - 1)}_{\text{on-site interactions}} + \underbrace{\sum_{i,j} V_{ij} n_i n_j}_{\text{inter-site interactions}}$$

Semiconductor QD-array

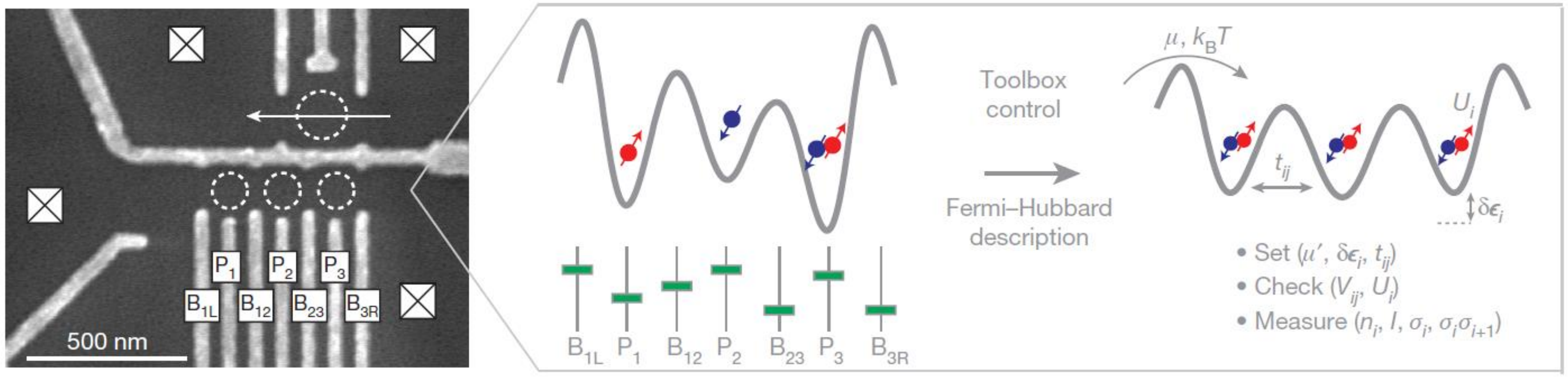
- Coupled semiconducting QD’s act according to the Fermi-Hubbard model naturally at low temperatures
- highly entangled states without adiabatic initialization
- coherent evolution of exitations spans many sites

Semiconductor QD-array: sample



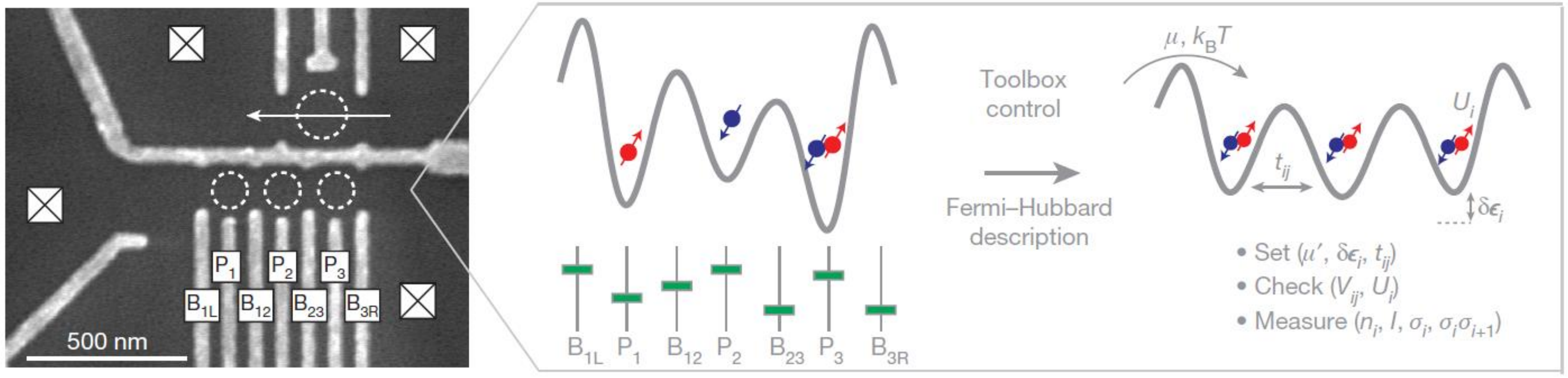
- GaAs/AlGaAs heterostructure
  - creates 2-DEG
  - triple quantum dot device (dashed circles)
  - dashed circle (arrow): sensing channel, real-time charge sensing using radio-frequency reflectance
  - reservoirs (crossed square)

Semiconductor QD-array: sample



- electrostatically defined using voltages applied to gates
  - selectively depletes regions from the 2-DEG
  - 7 gates (barrier and plunger gates)
  - gates control set up Fermi-Hubbard model, using a toolbox, independet calibration of $\{\mu', \delta\epsilon_i, t_{ij}\}$ and measurement of $\{V_{ij}, U_i\}$

Semiconductor QD-array: sample

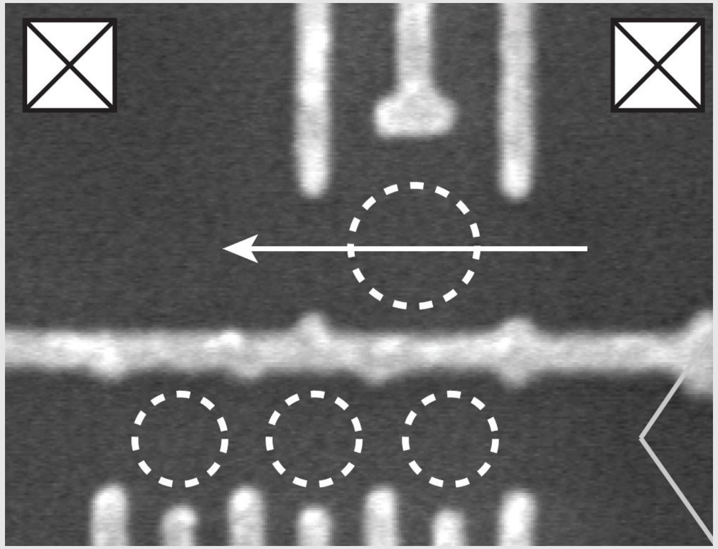


measurable observables, sample @ 45 mK

- local charge occupation
- global charge transport
- degrees of freedom of the spin
- nearest-neighbour singlet-triplet spin correlations

Sensing

- Using a SQD instead of QPC
- can also be operated as QPC
- usually operated at rf and not dc
- compare reflected amplitude with transmitted/sent amplitude
- advantages over QPCs
  - 30 times more sensitive
  - 3 times signal-to-noise ratio



Toolbox

Goals:

- Independent control of the Fermi–Hubbard parameters $\{\mu', \delta\varepsilon_i, t_{ij}\}$ to within several $k_B T$ and over a wide range of fillings and tunnel couplings.
  - =>Need according gate voltages P_i, B_{ij}
- Measurements

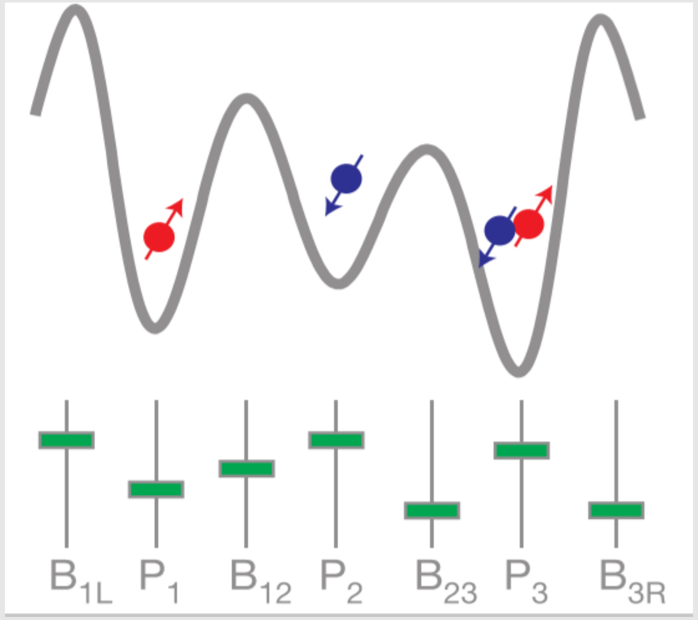
Nonidealities:

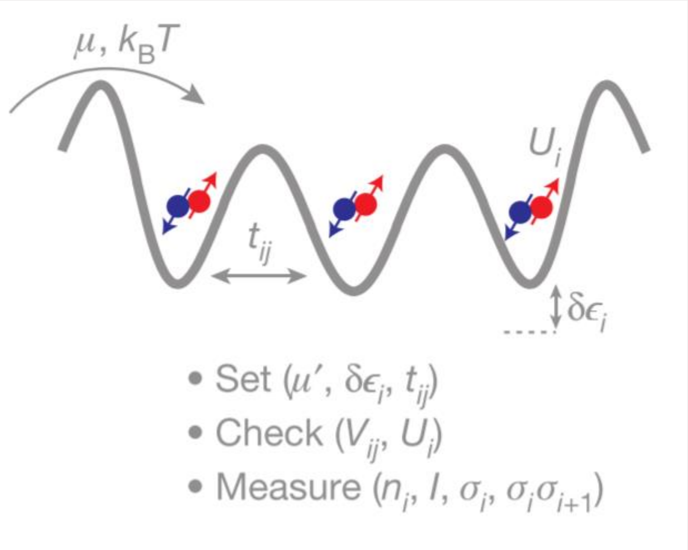
- Cross Talk
- Finite size of the array and inhomogeneity in interaction terms:

$$U_i + \sum_{i \neq j} V_{ij}$$

  =>non-homogeneous filling

- When multiple electrons in array:
  - Higher wavefunction overlap of higher electron fillings have an effect on the tunnel couplings





Toolbox: Methods

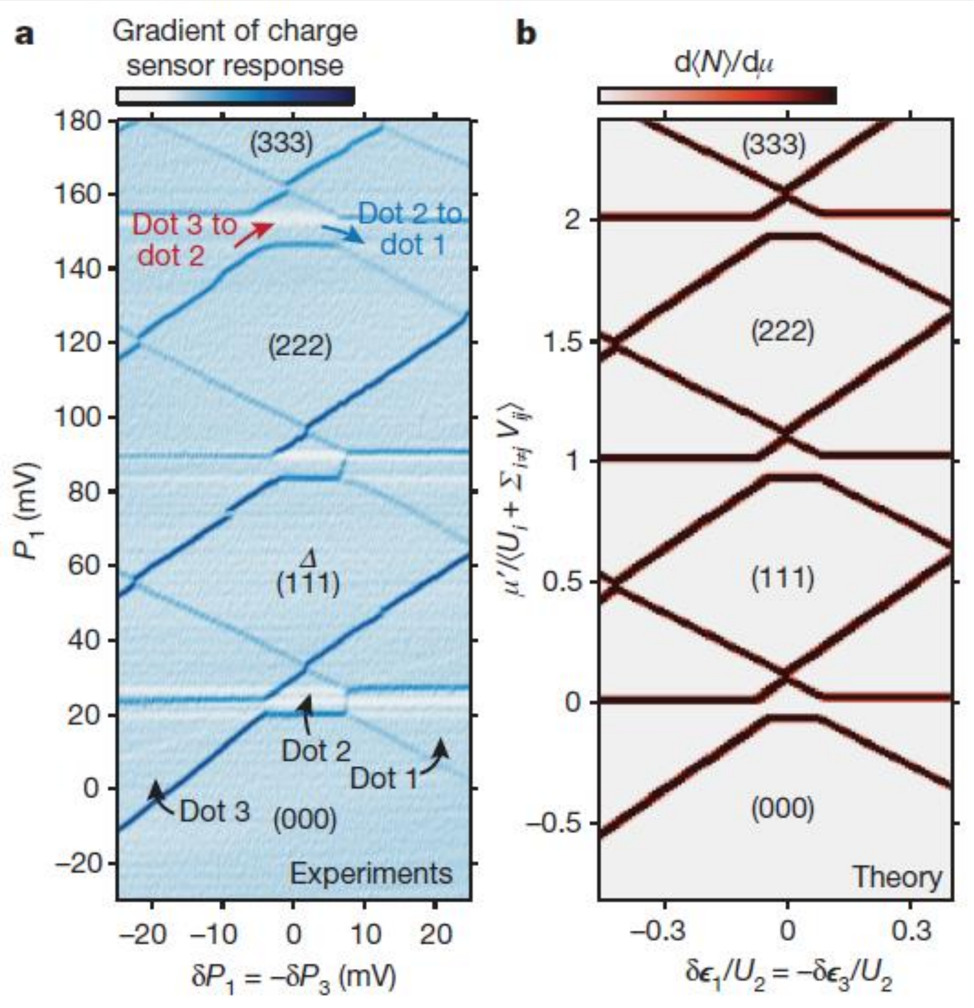
- Linear combinations of gate voltages:

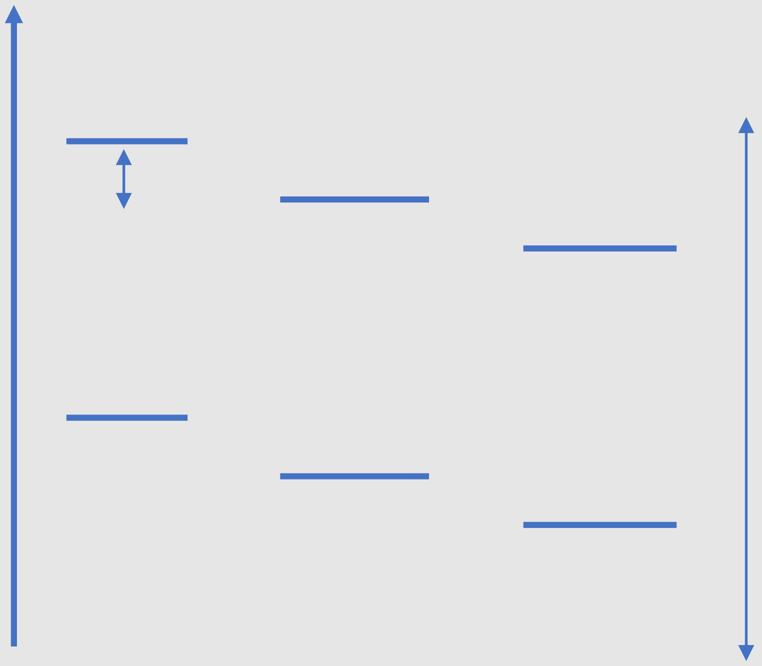
$$\delta\begin{pmatrix}\epsilon_1\\ \epsilon_2\\ \epsilon_3\end{pmatrix}=\begin{pmatrix}\alpha_{11} & \alpha_{12} & \alpha_{13} & \alpha_{14} & \alpha_{15} & \alpha_{16} & \alpha_{17}\\ \alpha_{21} & \alpha_{22} & \alpha_{23} & \alpha_{24} & \alpha_{25} & \alpha_{26} & \alpha_{27}\\ \alpha_{31} & \alpha_{31} & \alpha_{33} & \alpha_{34} & \alpha_{35} & \alpha_{36} & \alpha_{37}\end{pmatrix}\ \delta(P_1\ P_2\ P_3\ B_{1L}\ B_{12}\ B_{23}\ B_{3R})^{\mathrm{T}}\cdot$$

  - α_{ii}: Coupling of P_i to the energy offset ε_i
  - α_{ij}: Cross Terms
  - All elements known → Can deterministically control the on-site energies ε_i
- Matrix has been measured multiple times for different fillings and tunnel couplings
- In between these points: Linear interpolation
- Simplify the tuning process: Virtual Gates
  - Virtual barrier gates: Change specific tunnel couplings without changing the energy offsets ε_i of any of the dots
  - Virtual $\delta\varepsilon_i$ gate: Changing $\delta\varepsilon_i$ without changing the tunnel couplings

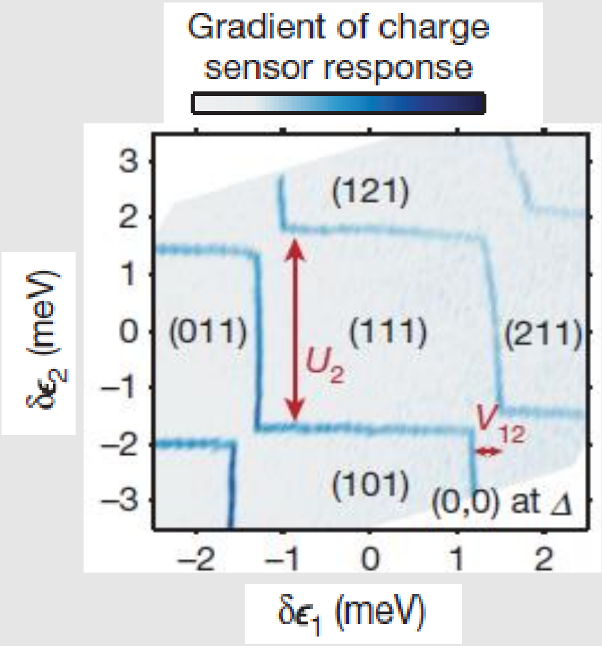
$$\delta B_{12} \rightarrow \delta B'_{12} = \delta(P_1, P_2, P_3, B_{12})$$

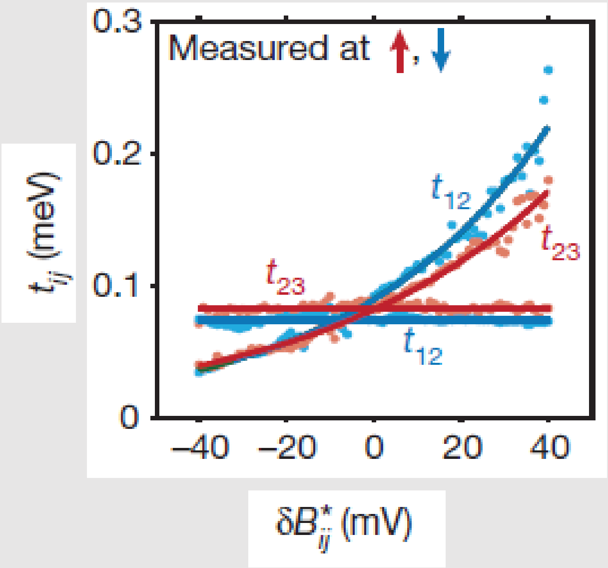
Toolbox: Verification





Toolbox: Measurements

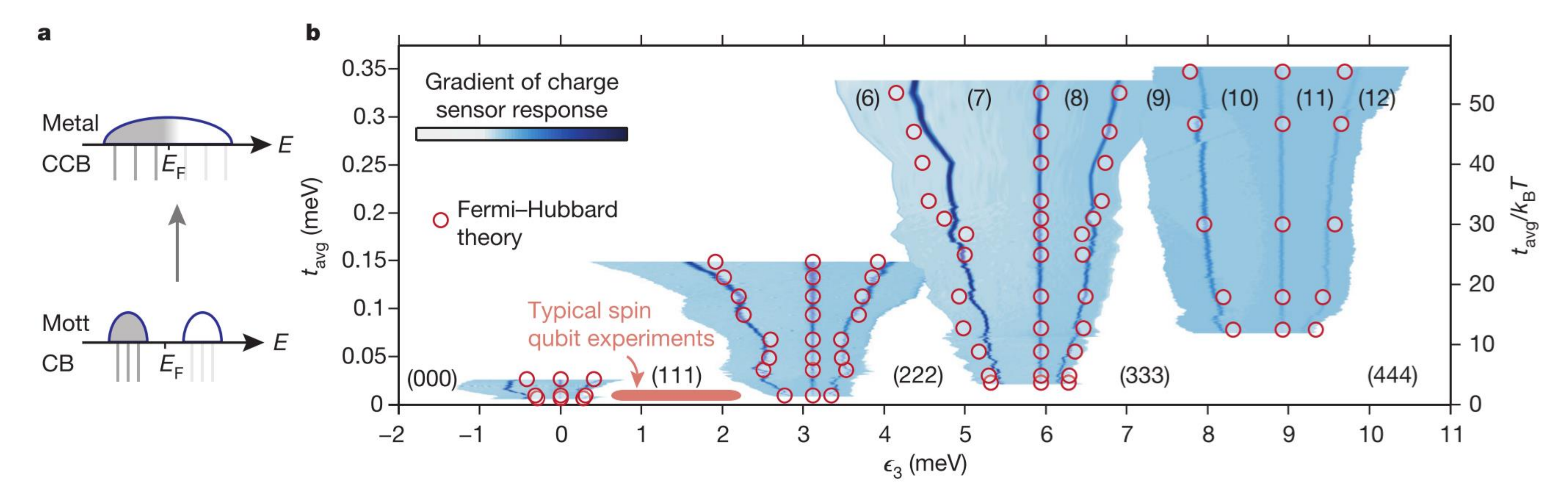




Measurements

- use toolbox to emulate Fermi-Hubbard physics
- realization of coulomb blockade physics (Mott insulator)
- only tunneling, degeneration lifts → minibands

Results



Minibands widen at expense of collective gap.

Agreement between measurements and numerical calculation

Conclusion

- accurate calibration and characterization of QD parameters
- large energy scales compared to temperature
  - strong quantum correlations
- larger QD-arrays require automation of used methods
- realize many-body physics
- possible extension to multiple dimensions