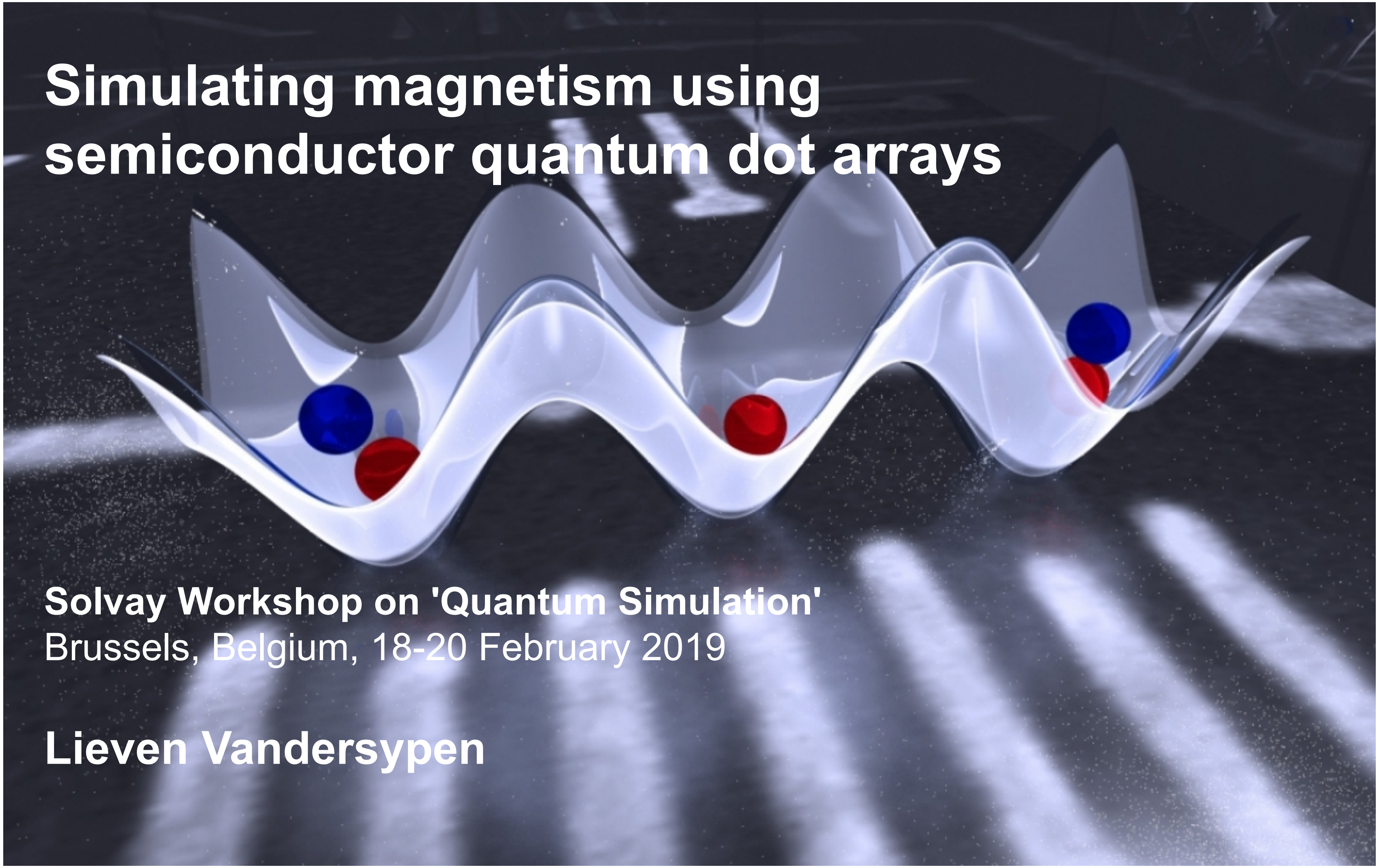
Simulating magnetism using semiconductor quantum dot arrays



Solvay Workshop on 'Quantum Simulation'
Brussels, Belgium, 18-20 February 2019

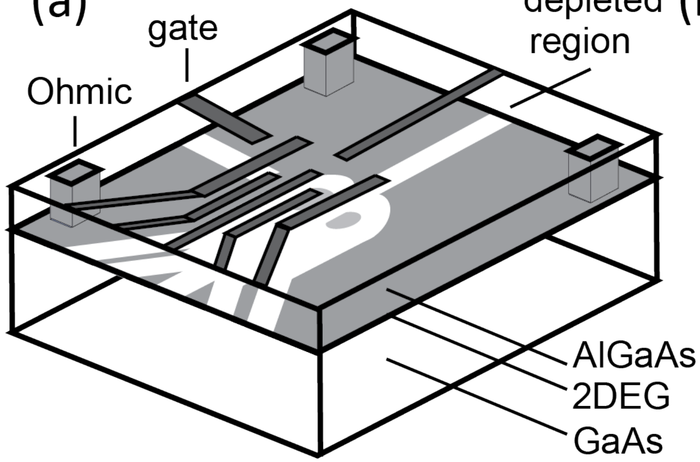
Lieven Vandersypen

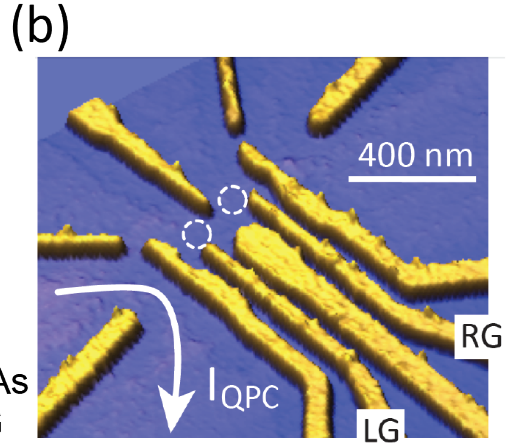
TU Delft
Delft University of Technology

QUTech

KAVLI INSTITUTE
of Nanoscience Delft

All-electrical semiconductor quantum dots



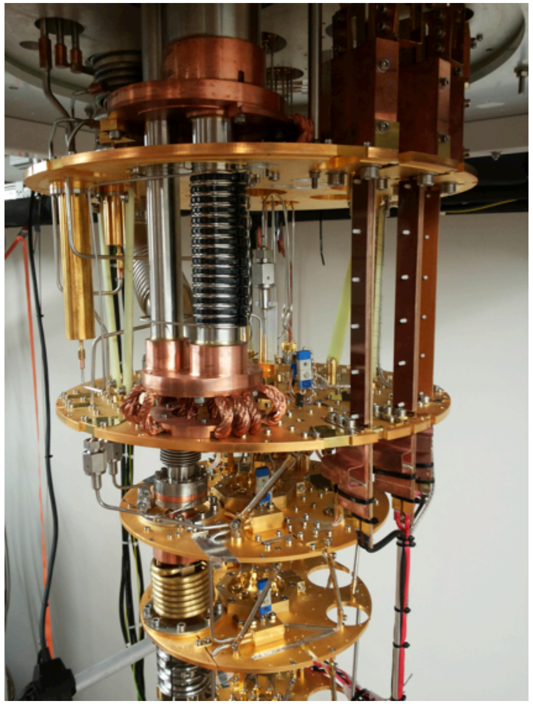


Artificial atoms and molecules

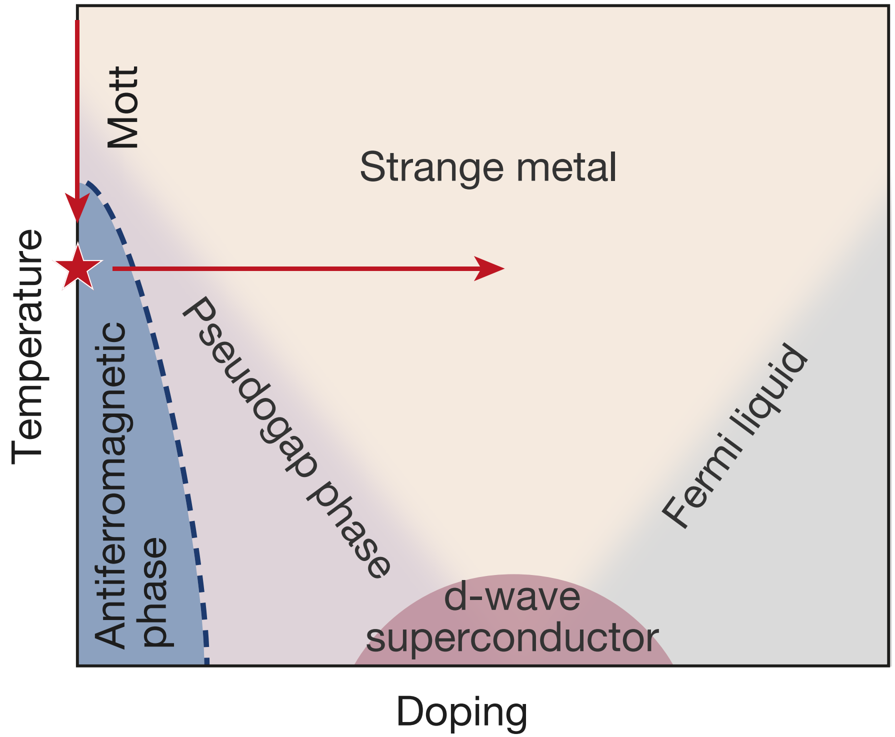
Discrete # charges, quantized orbitals

Electrical control and detection

- Tunable # of electrons and tunnel barriers
- Electrical contacts
- All-electrical spin control and detection

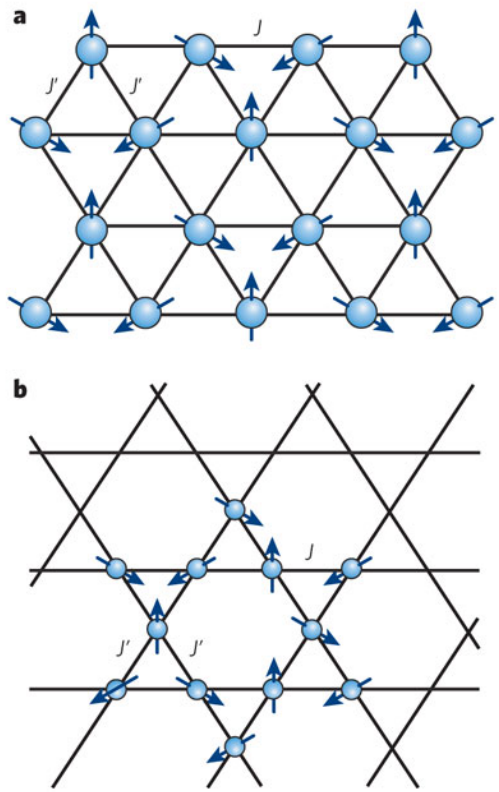


Fermi-Hubbard physics



Mazurenko et al, Nature 2017

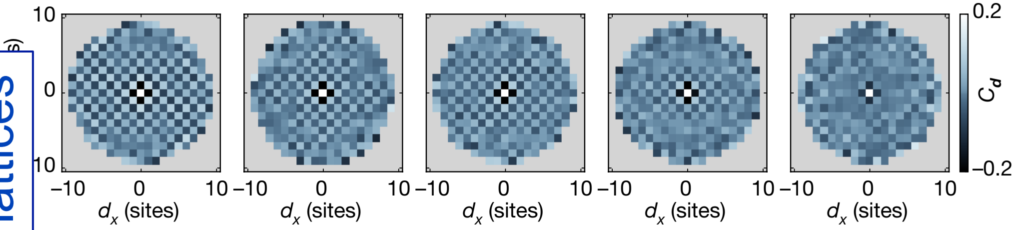
Spin models



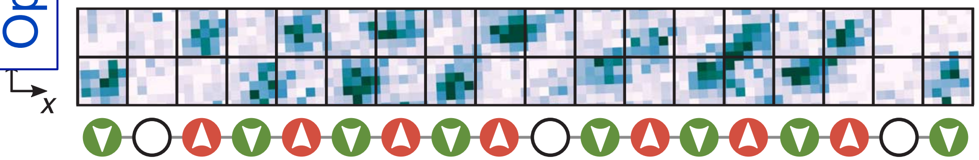
Balents, Nature 2010

Quantum simulation of Fermi-Hubbard and spin models – examples

Optical lattices

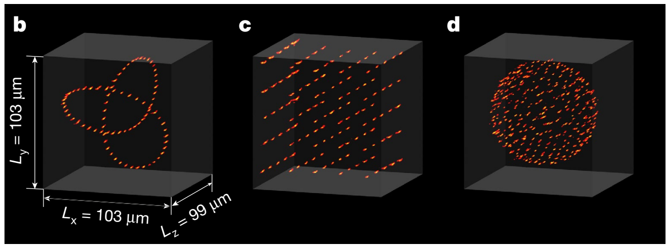


Mazurenko et al, Science 2017

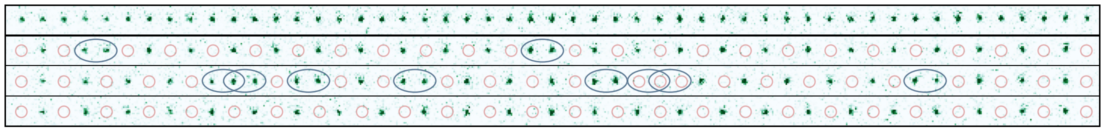


Hilker et al, Science 2017

Optical tweezers

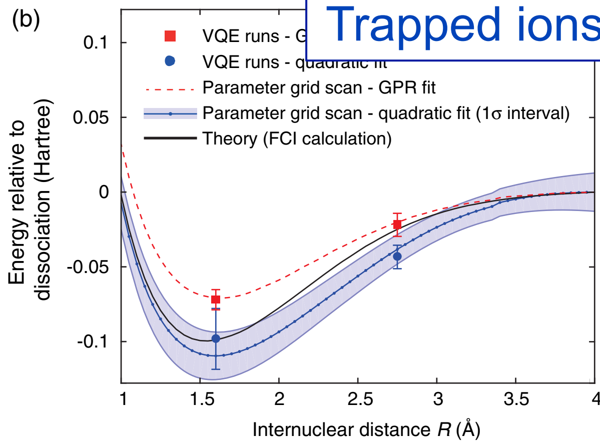


Barredo et al, Nature 2018



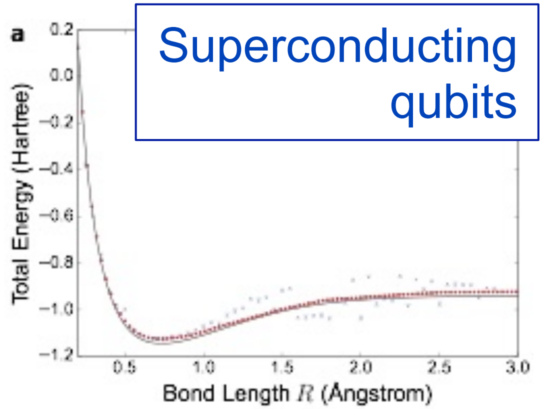
Bernien et al, Nature 2017

Trapped ions



Hempel et al, PRX 2018

Superconducting qubits



O'Malley et al, PRX 2016

Real fermions in the low-temperture regime of the Fermi-Hubbard model

$$H = -\sum_i \epsilon_i n_i - \sum_{<i,j>,\sigma} t_{ij}(c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.}) + \sum_i \frac{U_i}{2} n_i(n_i - 1) + \sum_{i,j} V_{ij} n_i n_j$$

0-20 meV   0-0.5 meV   2-10 meV   0-1 meV

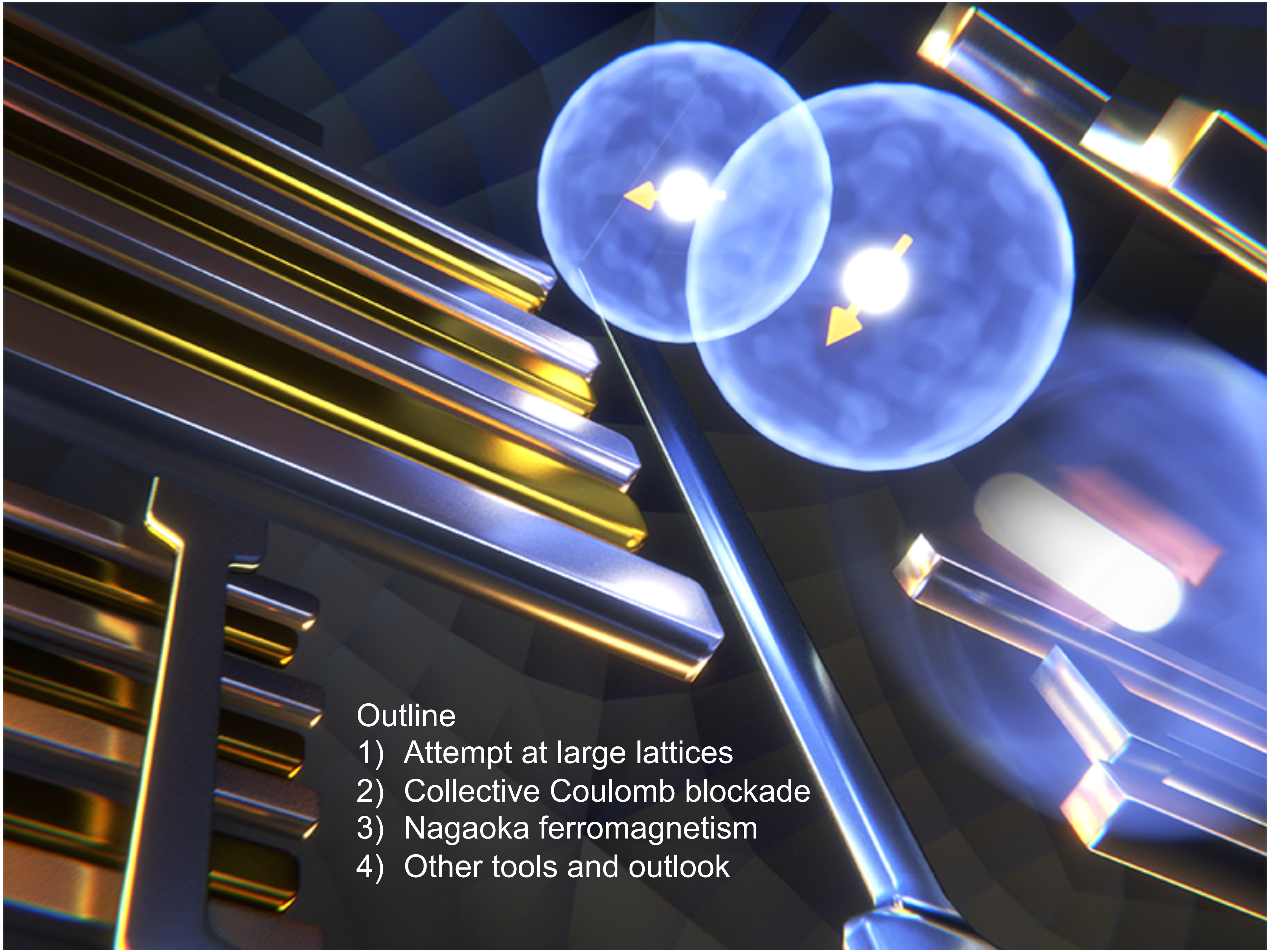
gate controllable

$k_B T$ = 1-10 μeV dilution refrigerator @(10-100 mK)

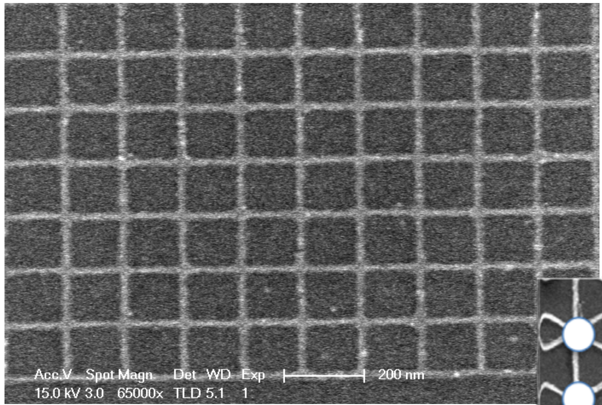
Dots can reach $k_B T << t < U$, with tuneable t/U and μ/U

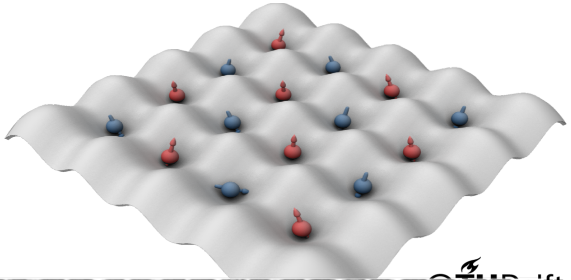
Proposal papers:
Stafford & Das Sarma, PRL 72, 3590 (1994)
Manousakis, J. Low Temp. Phys. **126**, 1501 (2002)
Byrnes *et al.*, Physical Review B **78**, 075320 (2008)
Yang *et al.*, Physical Review B **83**, 161301 (2011)
Barthelemy *et al.*, Annalen der Physik **525**, 808 (2013)

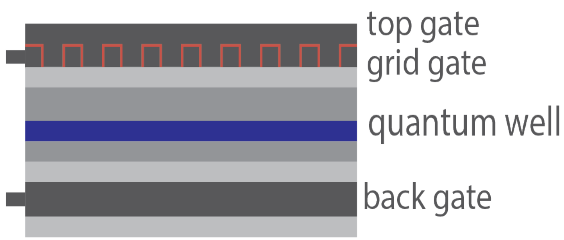
Experimental reviews:
Hanson et al, RMP 2007
Zwanenburg et al, RMP 2013

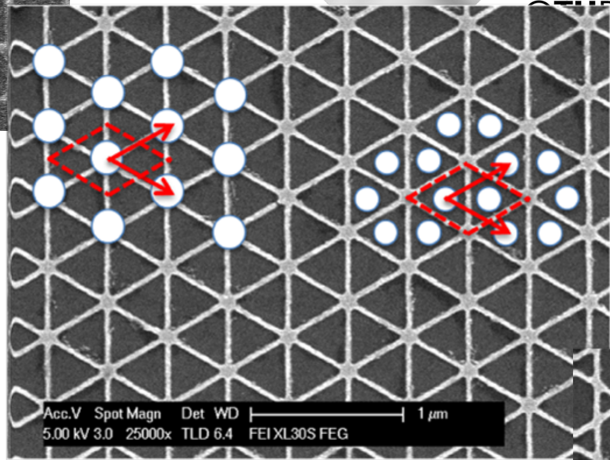

Outline
1) Attempt at large lattices
2) Collective Coulomb blockade
3) Nagaoka ferromagnetism
4) Other tools and outlook

Large periodic lattices

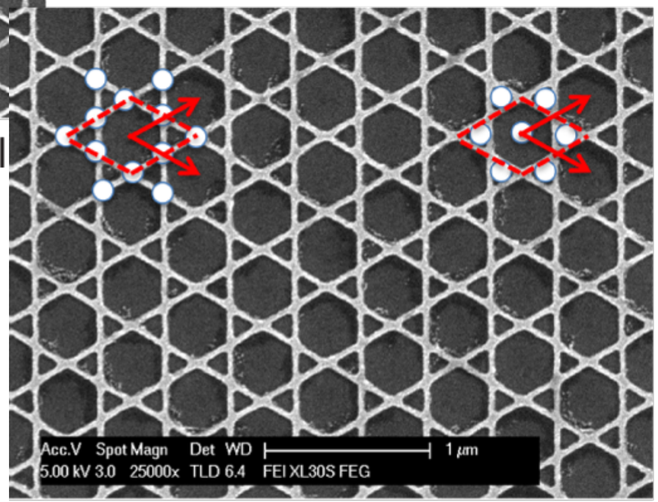






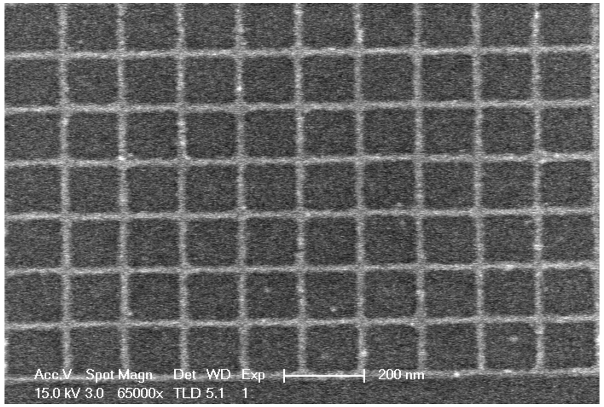


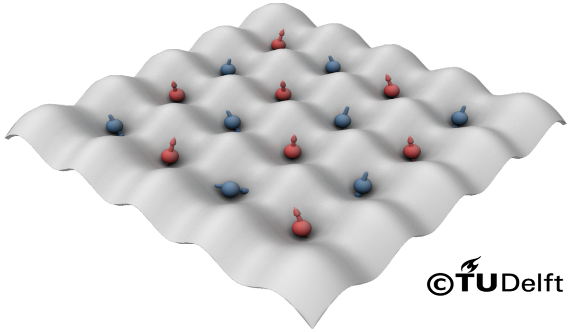
Triangular Hexagonal



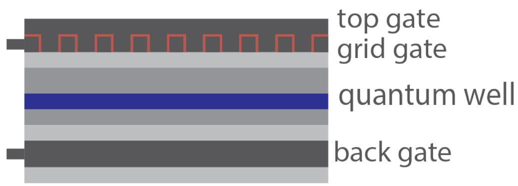
Kagome Dice/T3

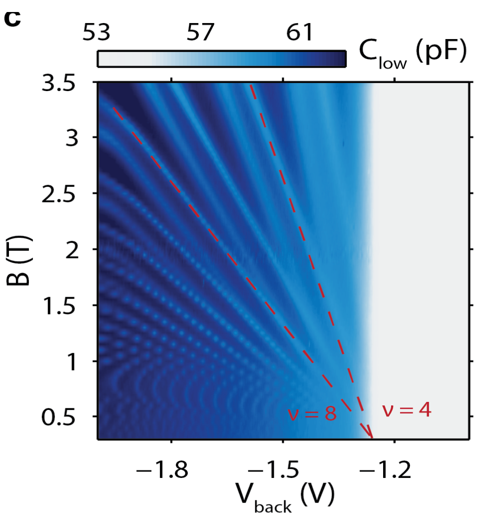
Large periodic lattices – disorder

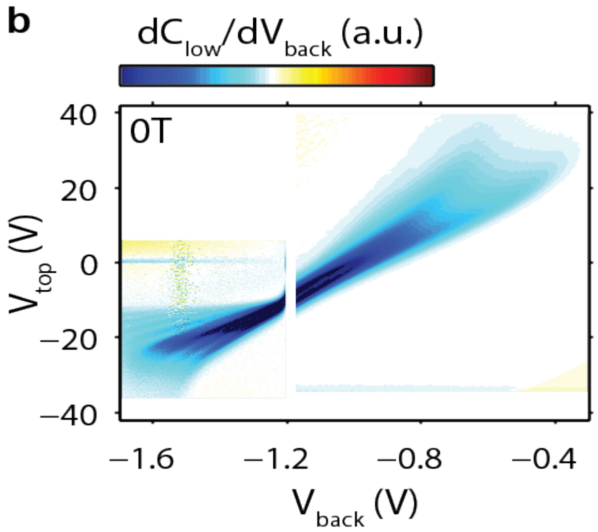




Probe: capacitance spectroscopy (density of states)



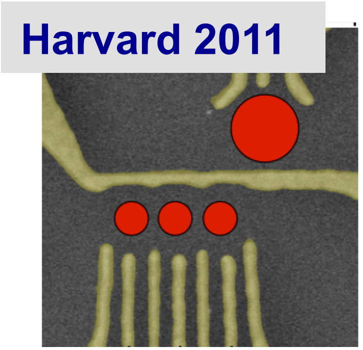


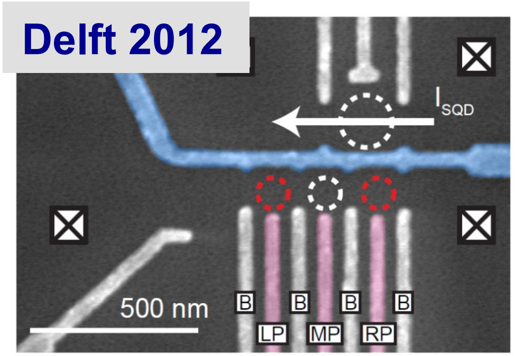


Disorder masks minibands and Mott gap

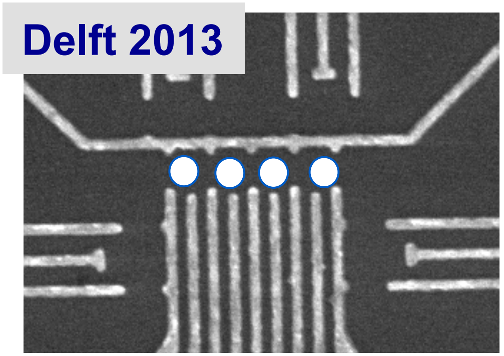
Hensgens et al,
J. Appl. Phys. 2018

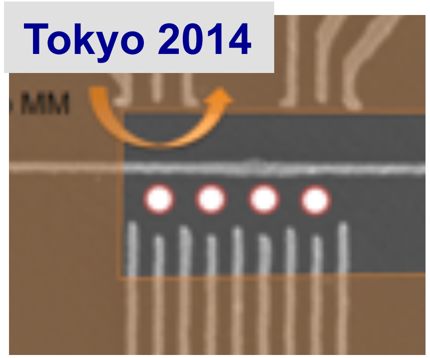
Building lattices from the bottom-up

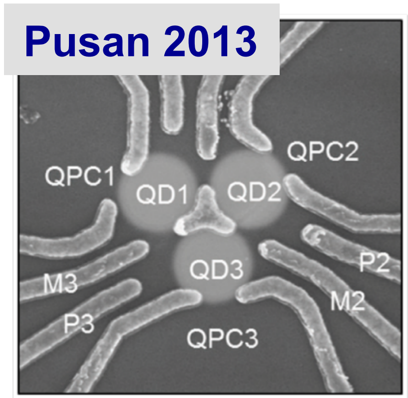


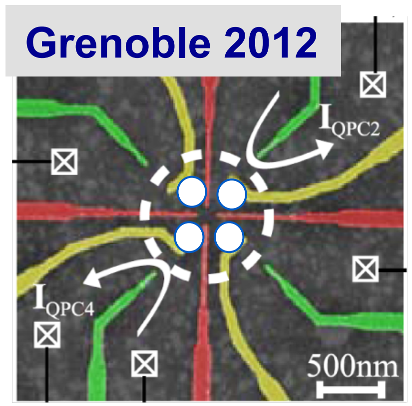


Local electrodes allow individual tunability

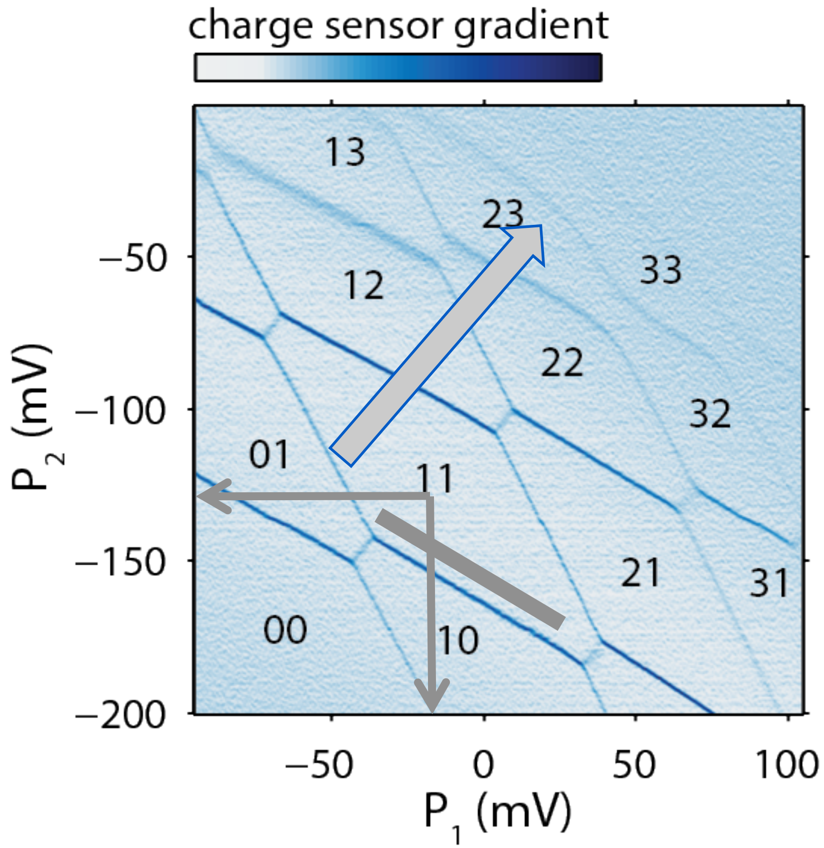








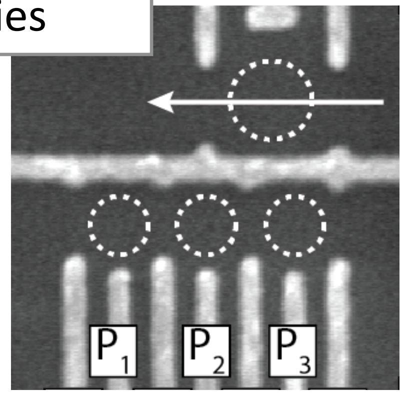
Detailed view of cross-talk and disorder



(barriers set to same tunnel rate)

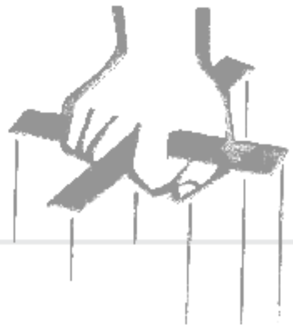
Observations:

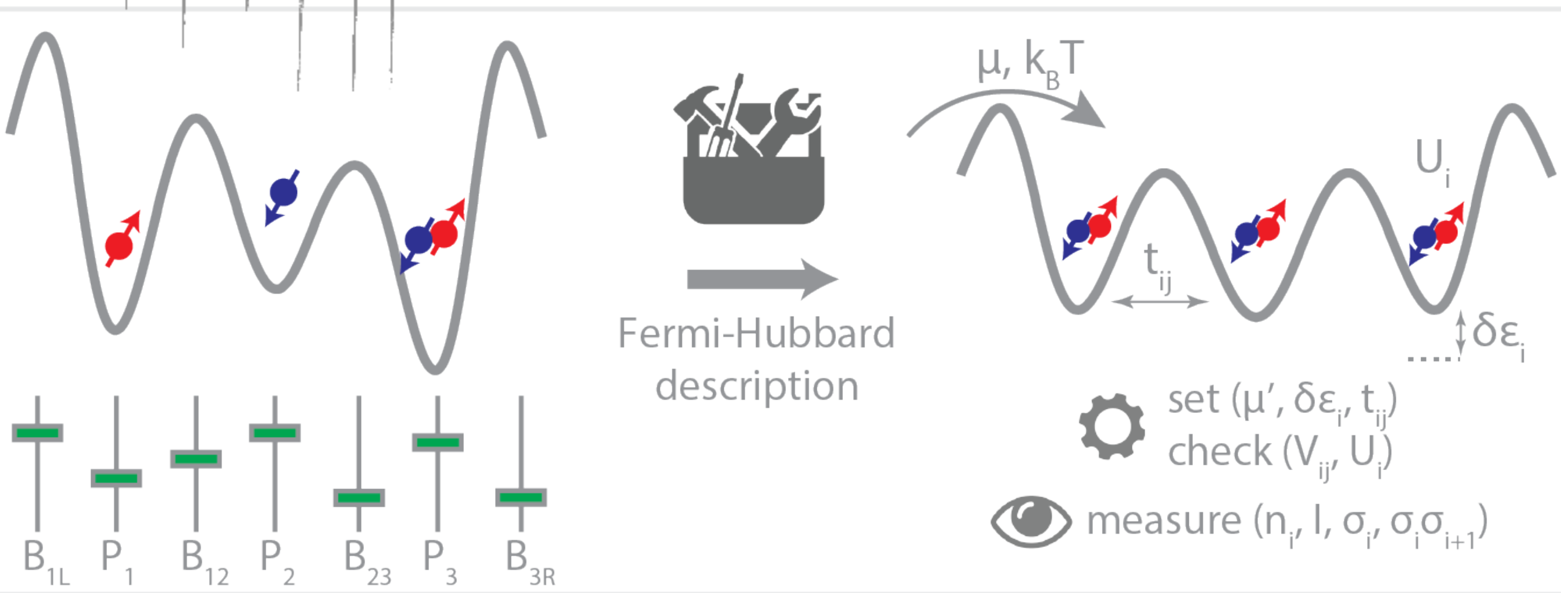
1. Initial disorder
2. Gate cross-talk
3. Nonlinearities



From real gate voltages to virtual gates

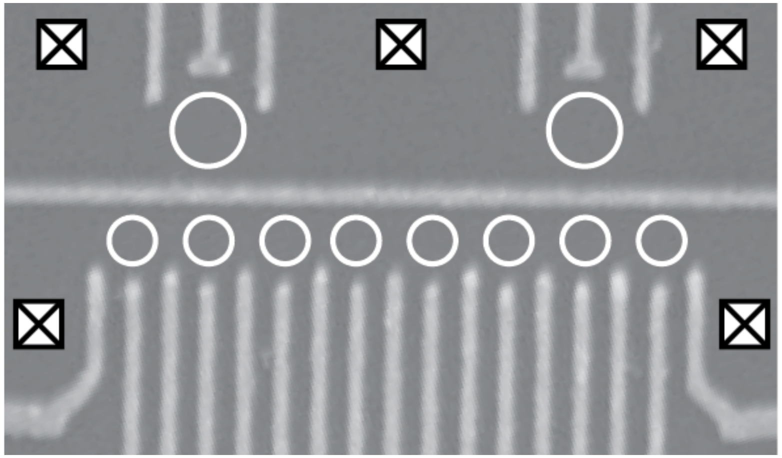
$$\begin{pmatrix} \Delta \mathrm{VP}_1 \\ \Delta \mathrm{VB}_1 \\ \Delta \mathrm{VP}_2 \\ \Delta \mathrm{VB}_2 \\ \Delta \mathrm{VP}_3 \end{pmatrix} = \begin{pmatrix} 1 & \alpha_{12} & \alpha_{13} & \alpha_{14} & \alpha_{15} \\ 0 & 1 & 0 & 0 & 0 \\ \alpha_{31} & \alpha_{32} & 1 & \alpha_{34} & \alpha_{35} \\ 0 & 0 & 0 & 1 & 0 \\ \alpha_{51} & \alpha_{52} & \alpha_{53} & \alpha_{54} & 1 \end{pmatrix} \begin{pmatrix} \Delta P_1 \\ \Delta B_1 \\ \Delta P_2 \\ \Delta B_2 \\ \Delta P_3 \end{pmatrix}$$





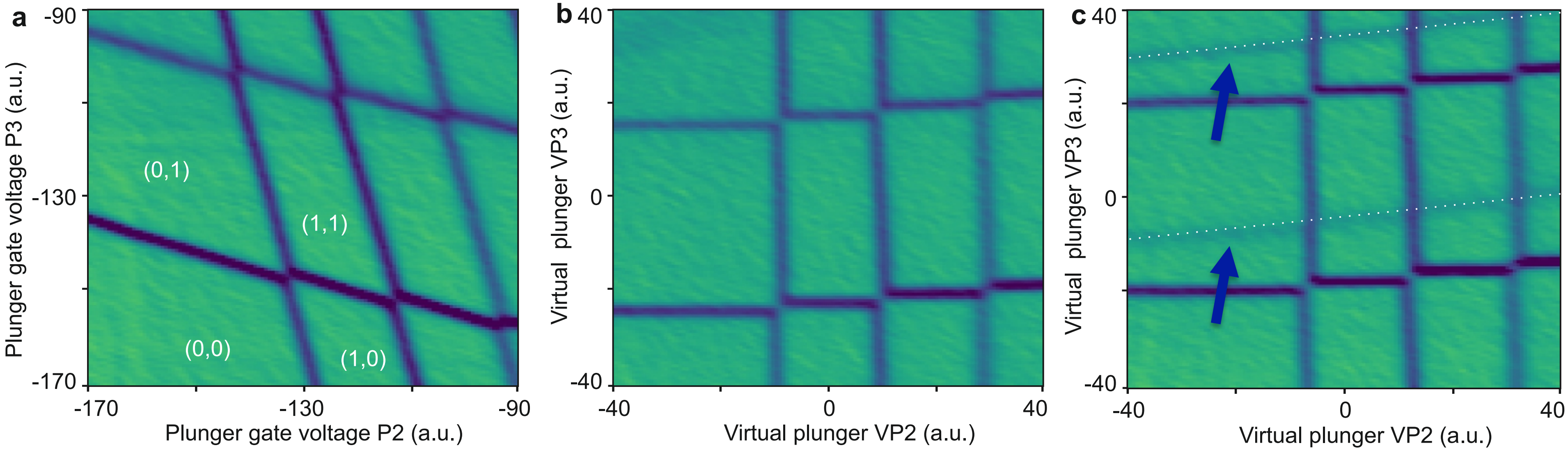
Nowack et al, Science 2011
Hensgens et al, Nature 2017

Efficient formation and loading of quantum dot arrays



C. Volk, A-M. Zwerver et al,
arXiv:1901.00426

Central idea:
Add dots while preserving existing dots

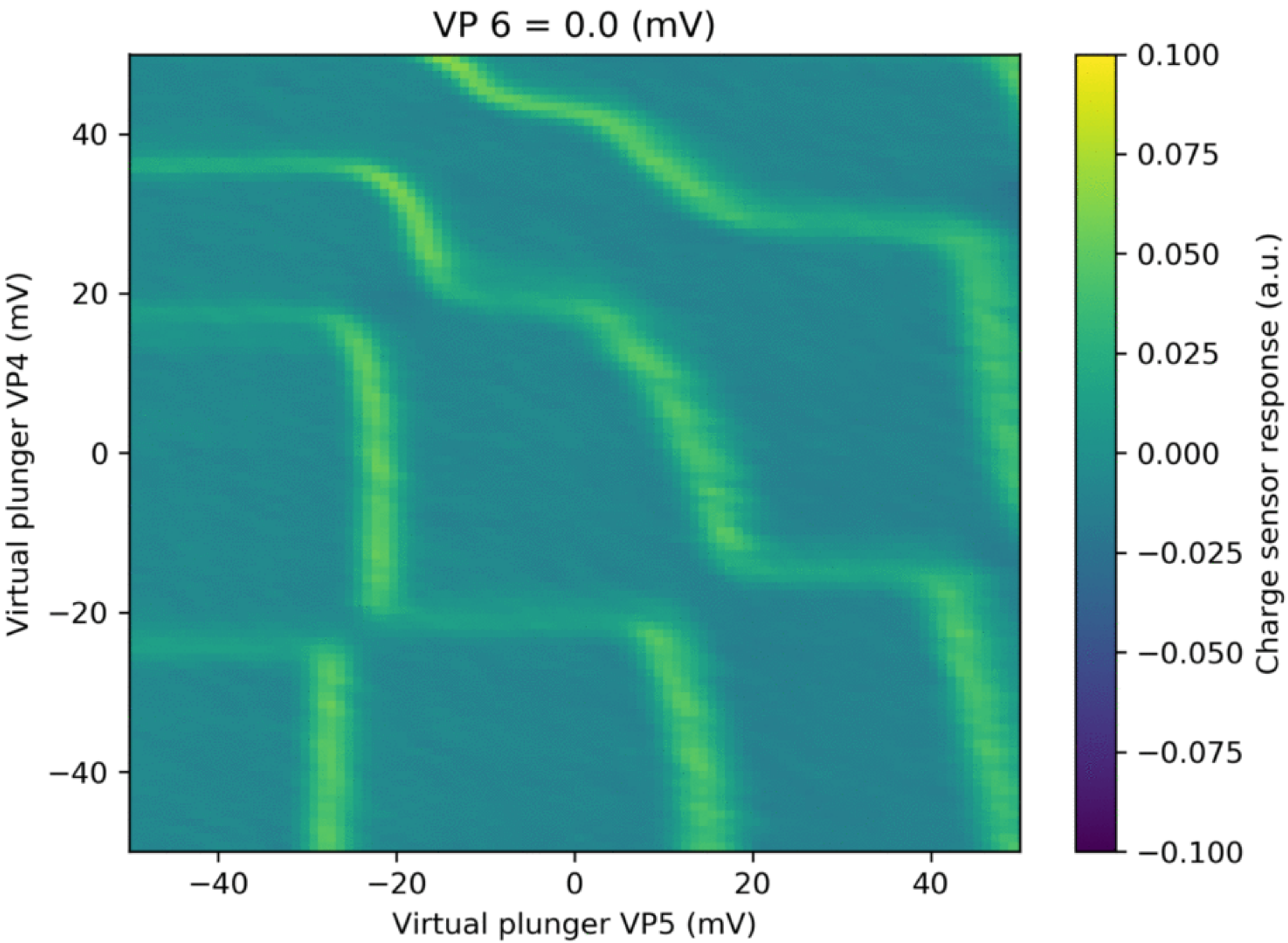


No crosstalk compensation

Compensation using virtual gates

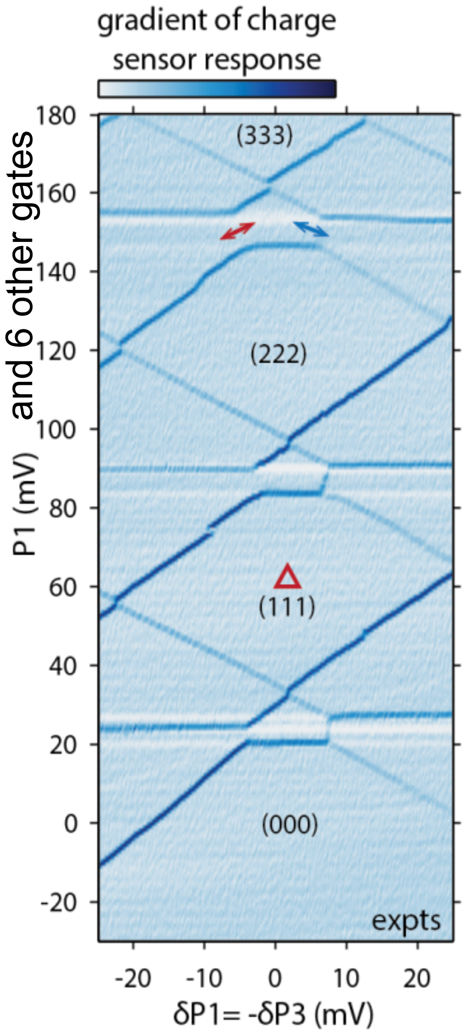
Adding a neighboring dot

Real-time tuning of dot arrays

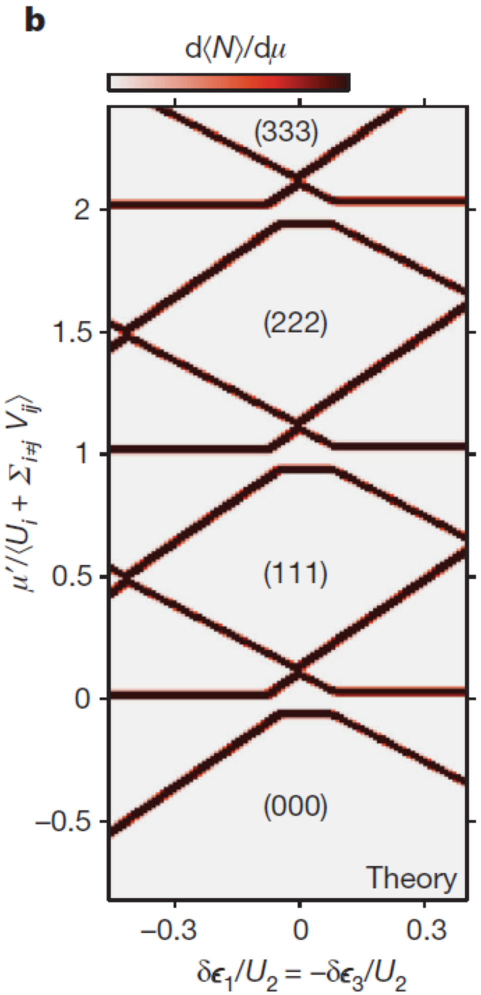


Hamiltonian engineering

Hensgens et al, Nature 2017



Set local potentials



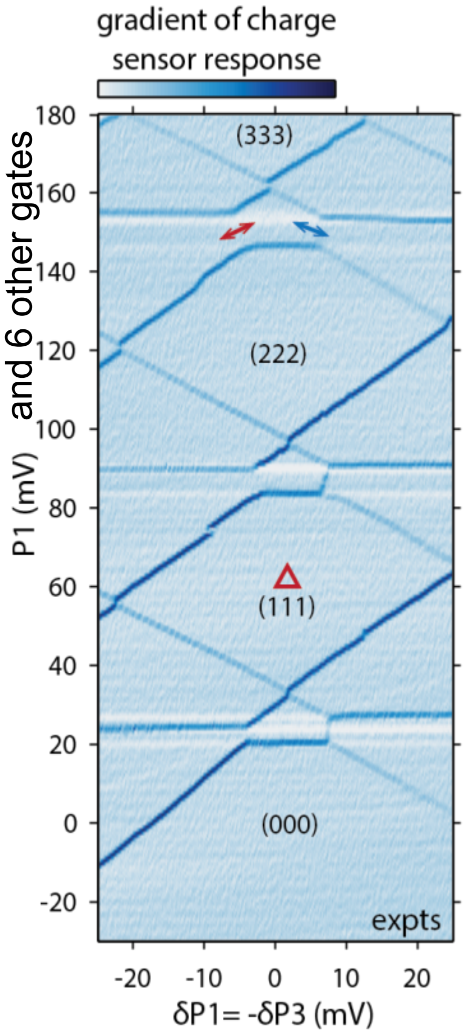
Simulation

$$H = -\sum_i \epsilon_i n_i$$

Hamiltonian engineering

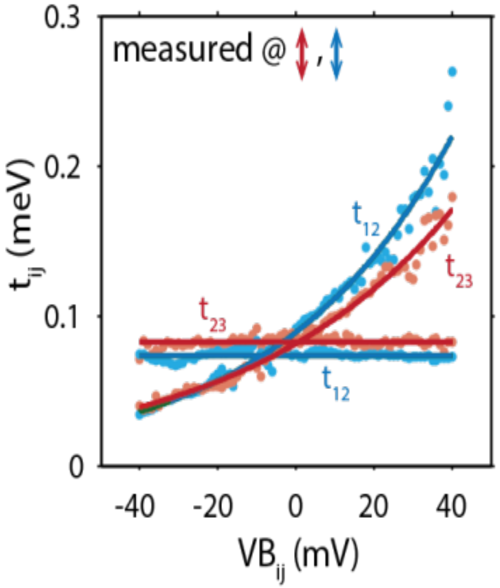
Dialing in individual terms or combined terms

Hensgens et al, Nature 2017



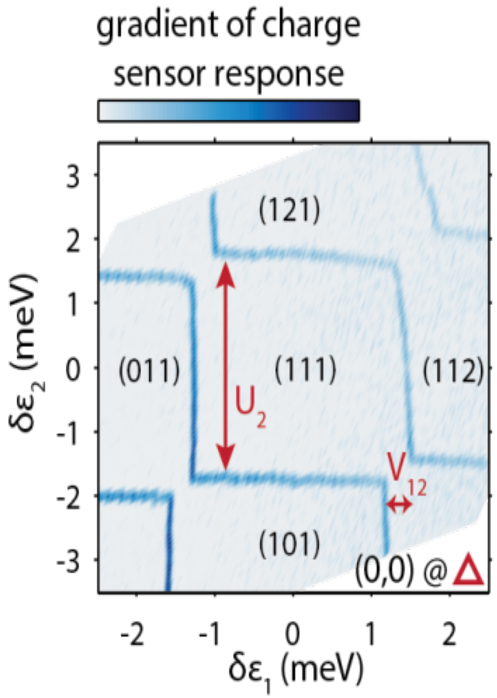
Set local potentials

$$H = -\sum_i \epsilon_i n_i$$



Set tunnel rates

$$\sum_{<i,j>,\sigma} t_{ij}(c^\dagger_{i\sigma} c_{j\sigma} + \mathrm{h.c.})$$

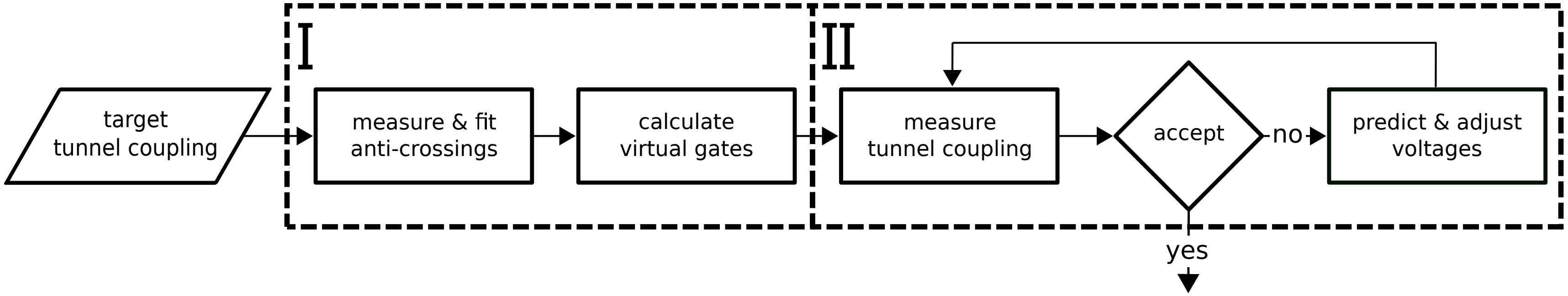


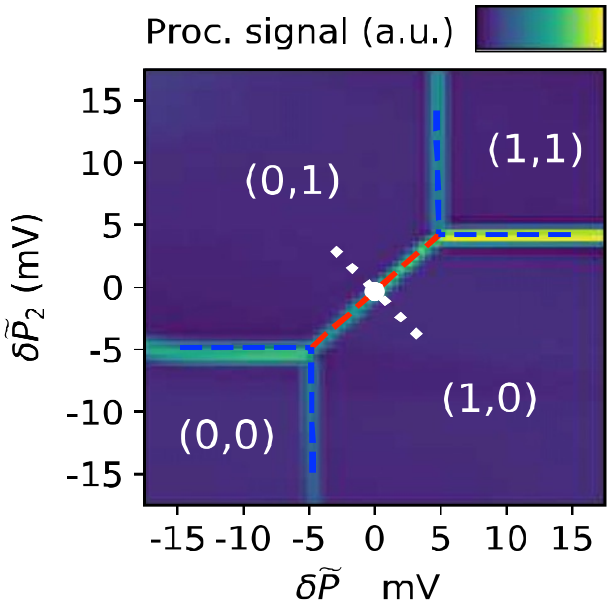
Determine interaction energies

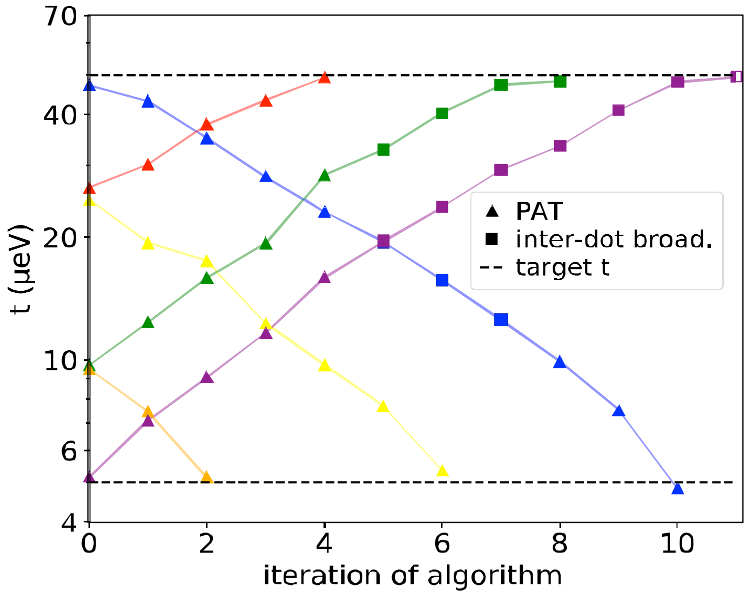
$$\sum_{i,j} V_{ij} n_i n_j + \sum_i \frac{U_i}{2} n_i(n_i - 1)$$

Automating Hamiltonian engineering

Example: setting interdot tunnel coupling







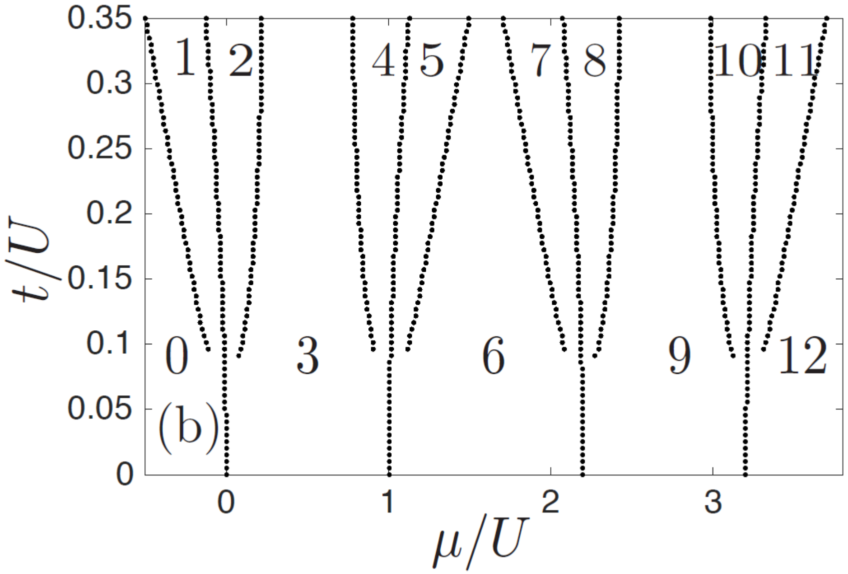
van Diepen *et al.* APL 2018

First proof-of-principle experiment

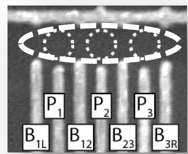
VOLUME 72, NUMBER 22 PHYSICAL REVIEW LETTERS 30 MAY 1994

Collective Coulomb Blockade in an Array of Quantum Dots: A Mott-Hubbard Approach

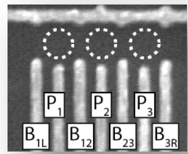
C. A. Stafford and S. Das Sarma
Center for Superconductivity Research, Department of Physics, University of Maryland, College Park, Maryland 20742
(Received 26 August 1993)



← Collective Coulomb blockade



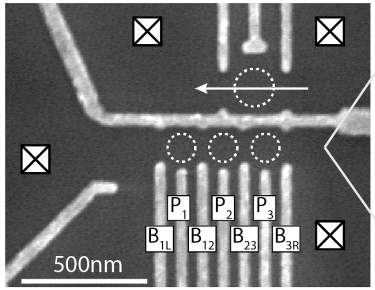
← Classical Coulomb blockade

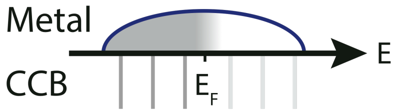


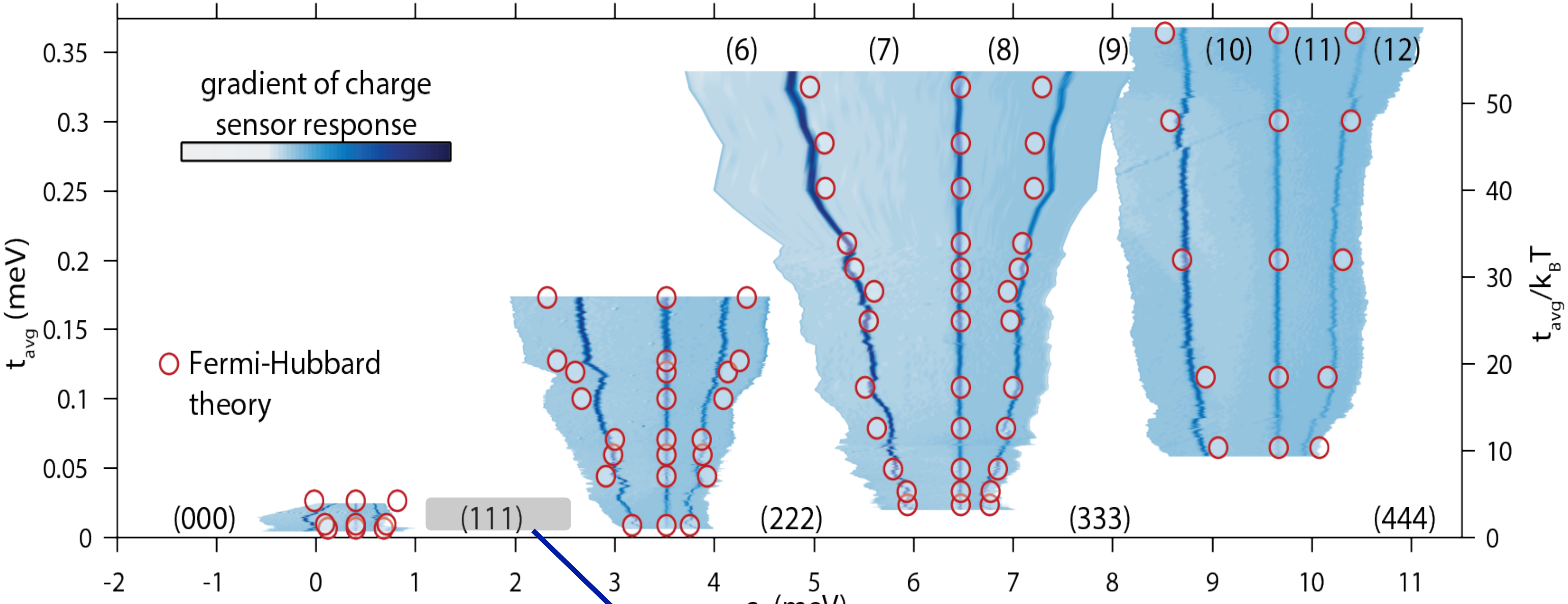
Collective Coulomb blockade transition

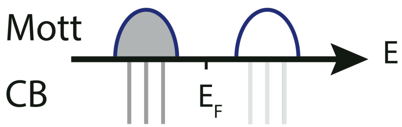
Finite size analogue of the Mott insulator transition

T. Hensgens et al., Nature 2017



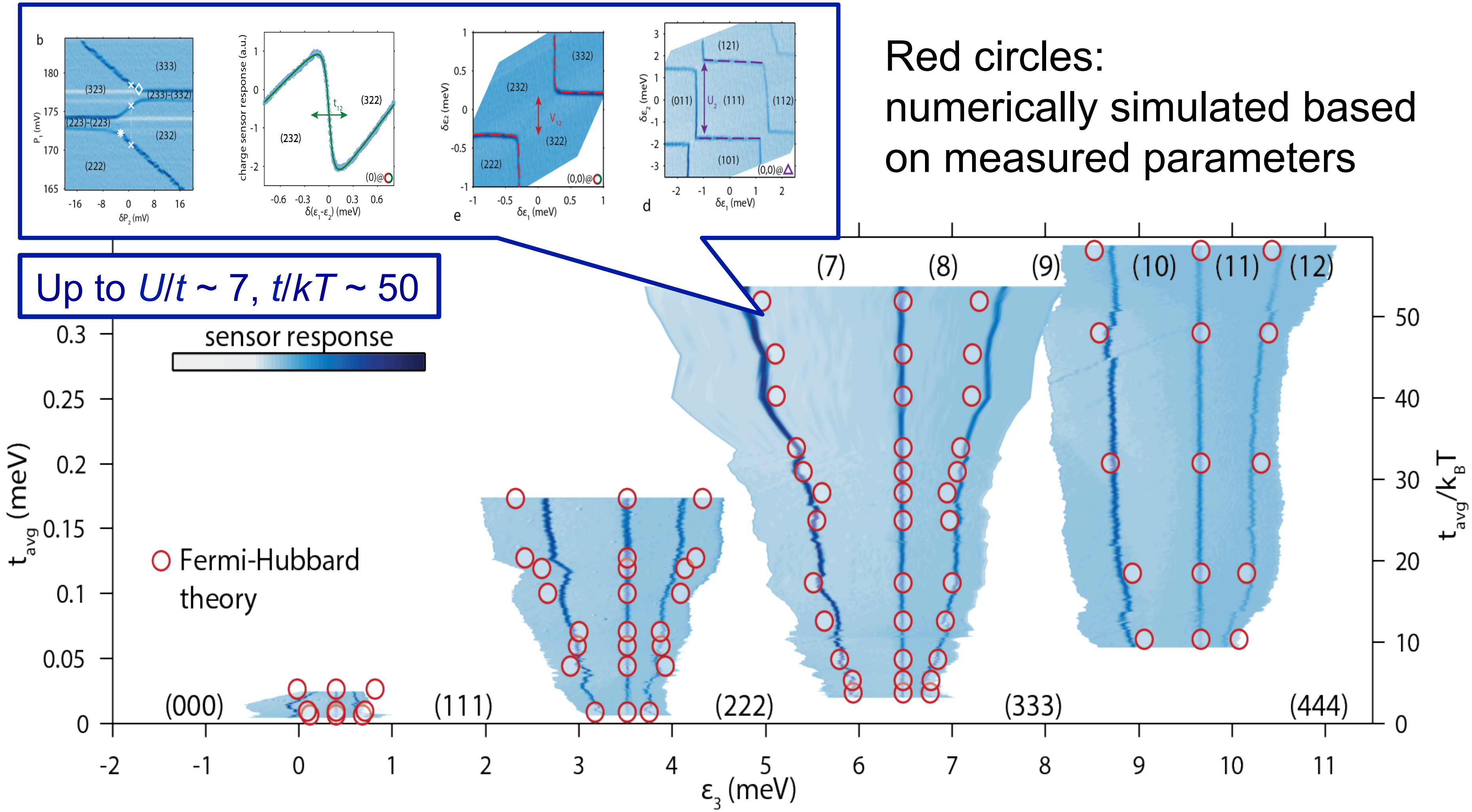






Spin qubit experiments
(1 electron per dot, *t* ~ 1-10 μeV)

Collective Coulomb blockade transition

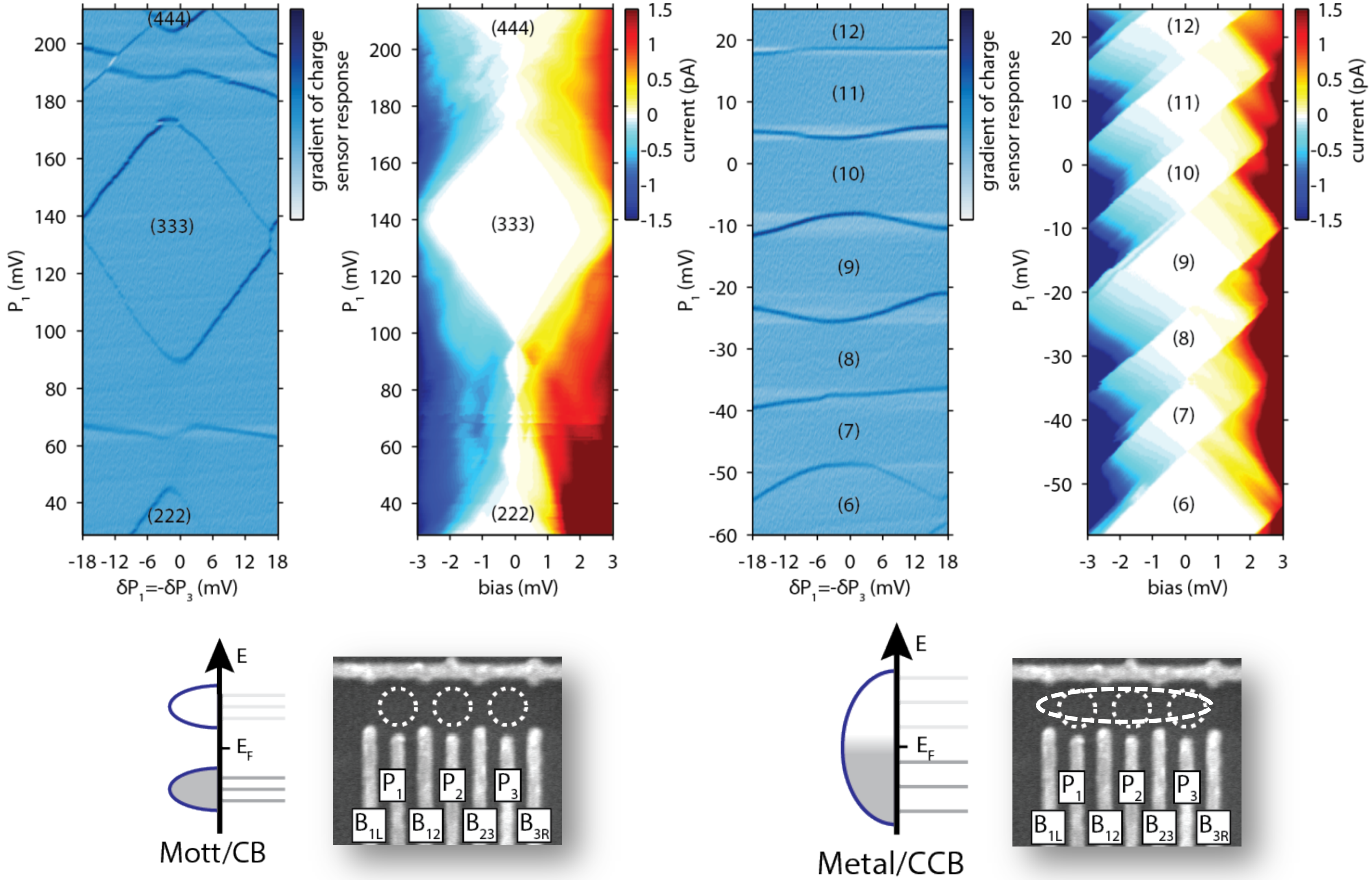


Red circles: numerically simulated based on measured parameters

Simulations: Xiao Li and S. Das Sarma

T. Hensgens et al., Nature 2017

Probing the (collective) Coulomb blockade gap via non-equilibrium transport



Nagaoka Ferromagnetism

PHYSICAL REVIEW VOLUME 147, NUMBER 1 8 JULY 1966

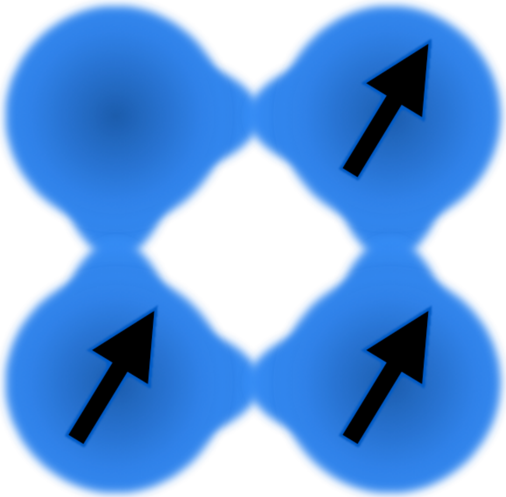
Ferromagnetism in a Narrow, Almost Half-Filled s Band*

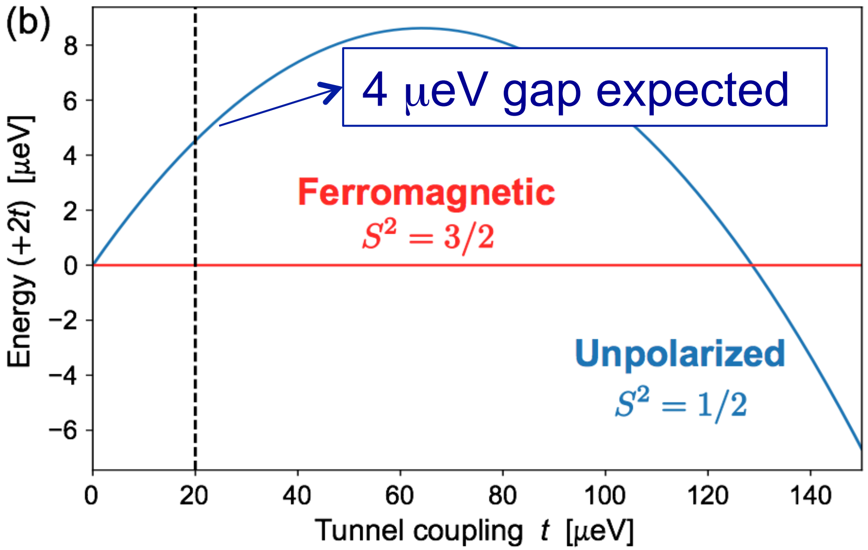
YOSUKE NAGAOKA†
Department of Physics, University of California, San Diego, La Jolla, California
(Received 17 January 1966)

EIGENVALUES AND MAGNETISM OF ELECTRONS ON AN ARTIFICIAL MOLECULE

International Journal of Nanoscience
Vol. 2, No. 3 (2003) 165–170

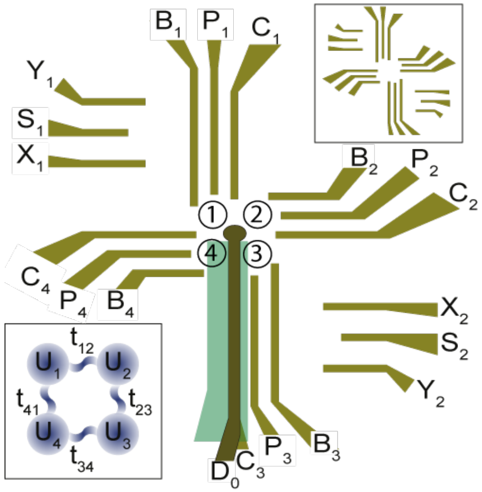
D. C. MATTIS
Department of Physics, University of Utah

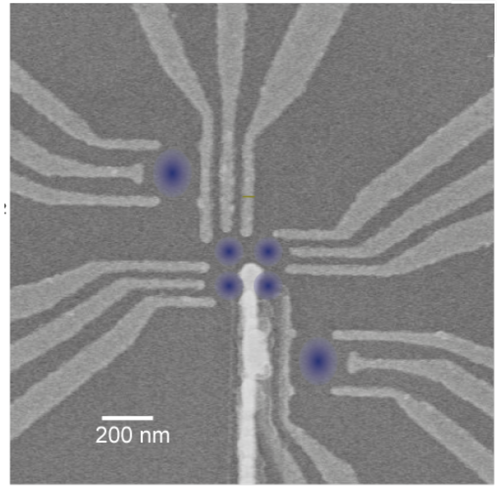




Quantum dots plaquette:
B. Wunsch,
M. Rudner,
LMKV,
E. Demler

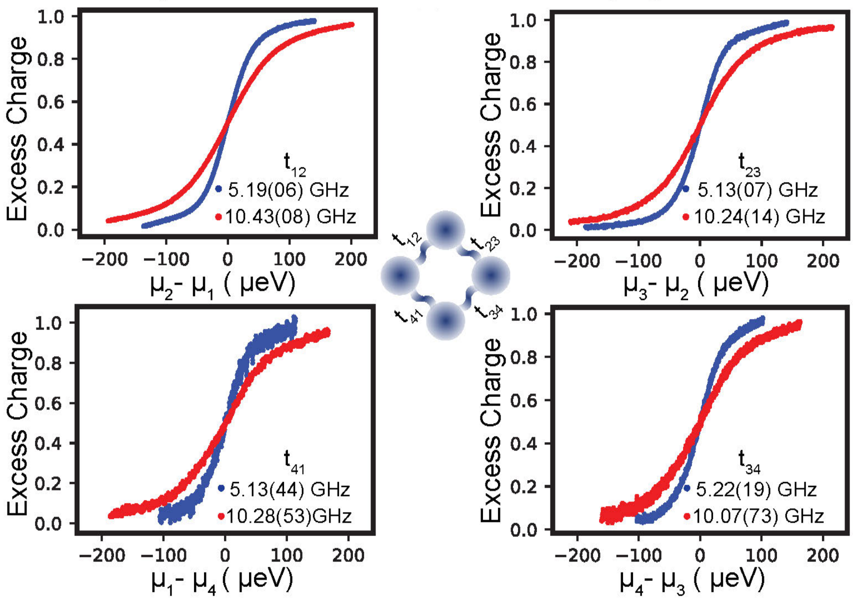
Quantum dot plaquette

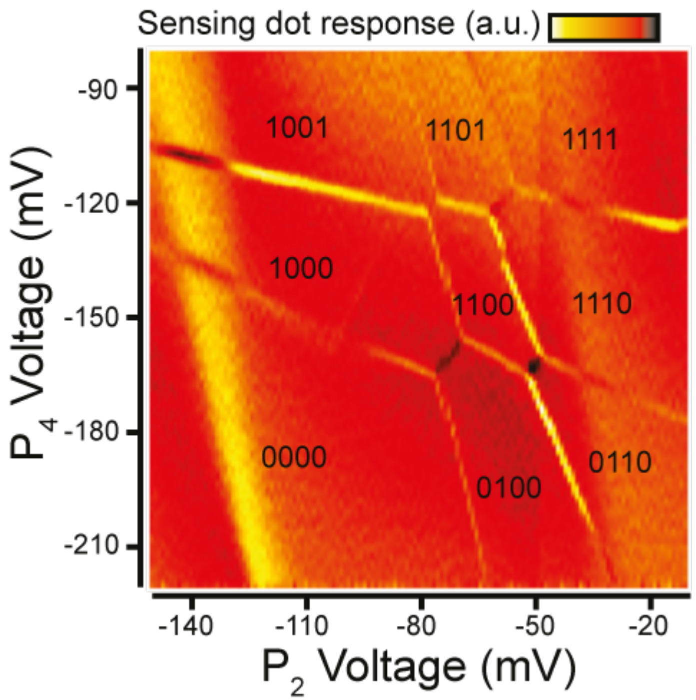




Mukhopadhyay, Dehollain et. al. APL 2018

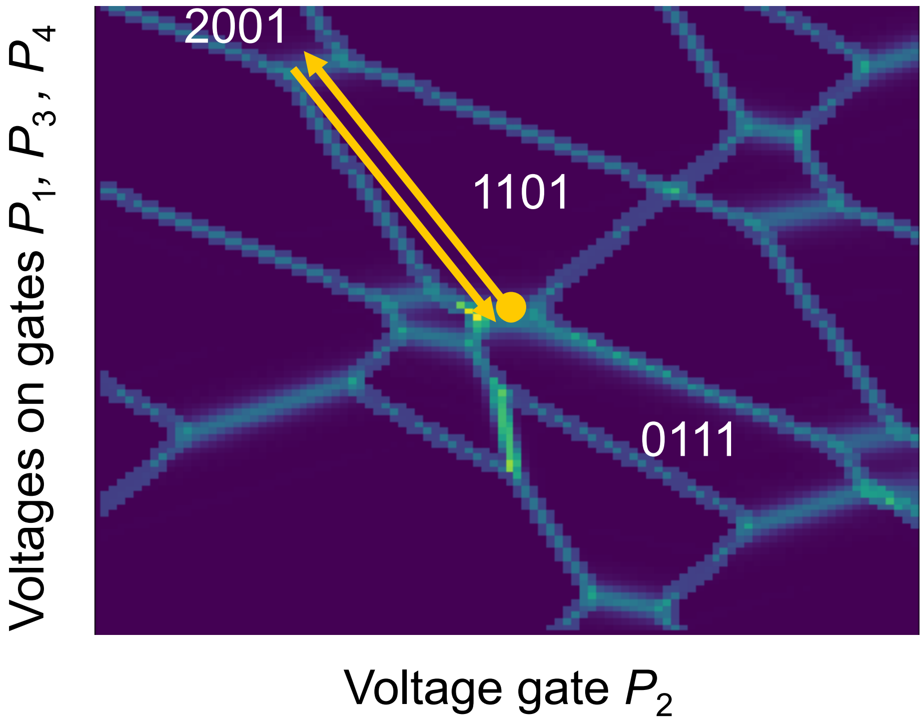
See also Thalineau et al, APL 2013

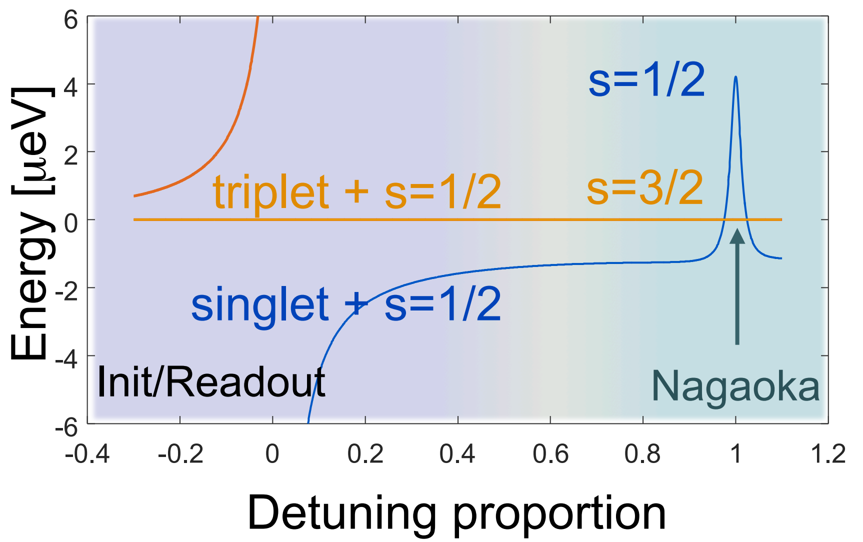


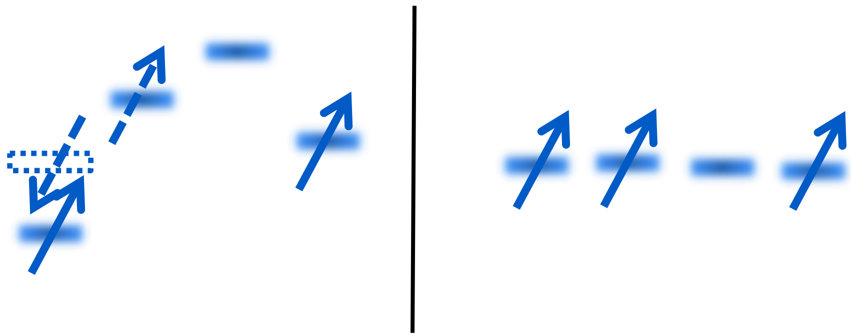


Experimental procedure

Dehollain, Mukhopadhyay, et. al., unpublished

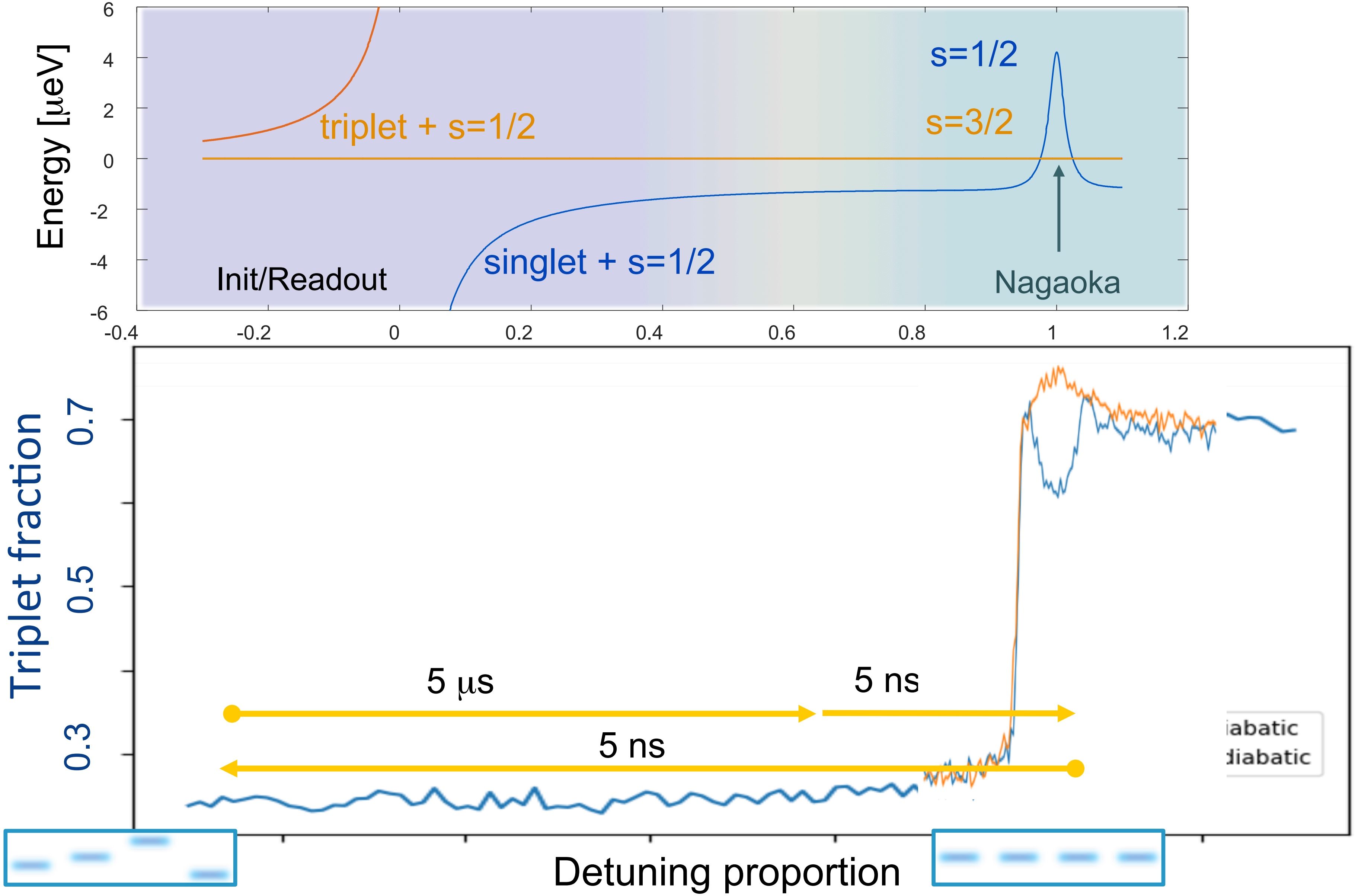




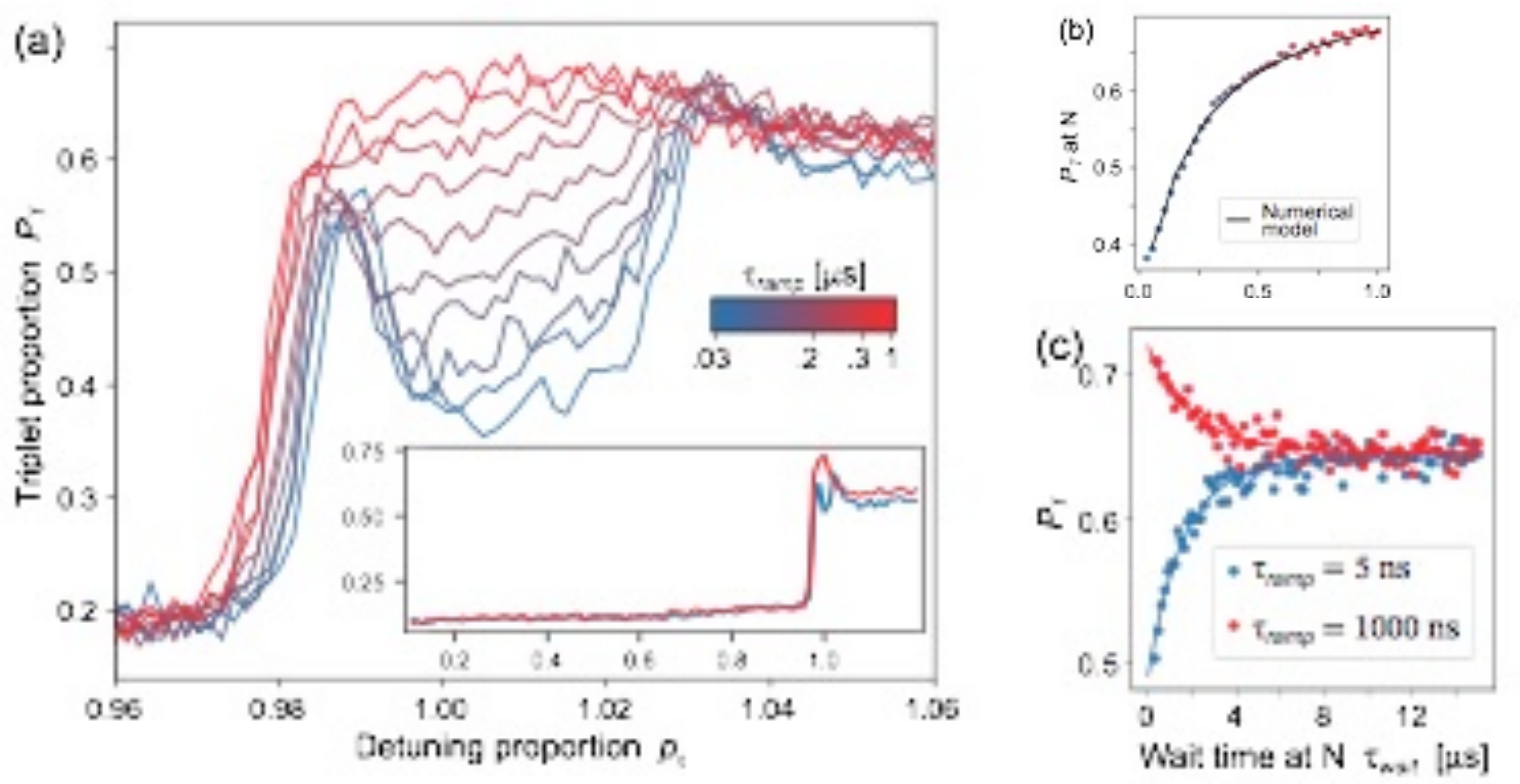


Protocol and main observation

Dehollain, Mukhopadhyay, et. al., unpublished



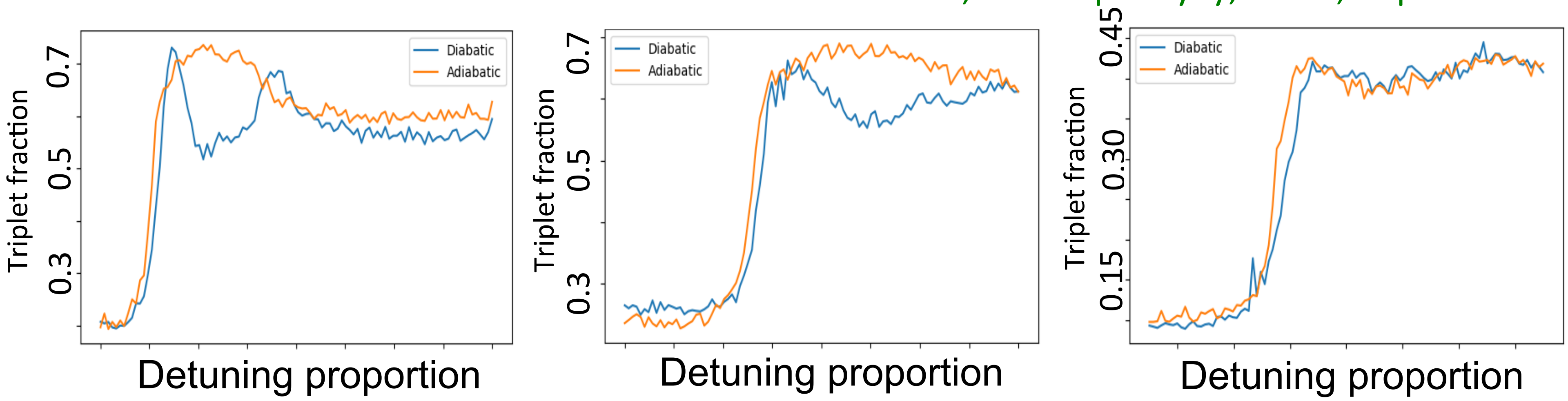
Adiabatic to diabatic transition, and equilibration



Dehollain, Mukhopadhyay, et. al., unpublished

Test 1: Change topology

Dehollain, Mukhopadhyay, et. al., unpublished



[19, 15, 17, 19] μeV

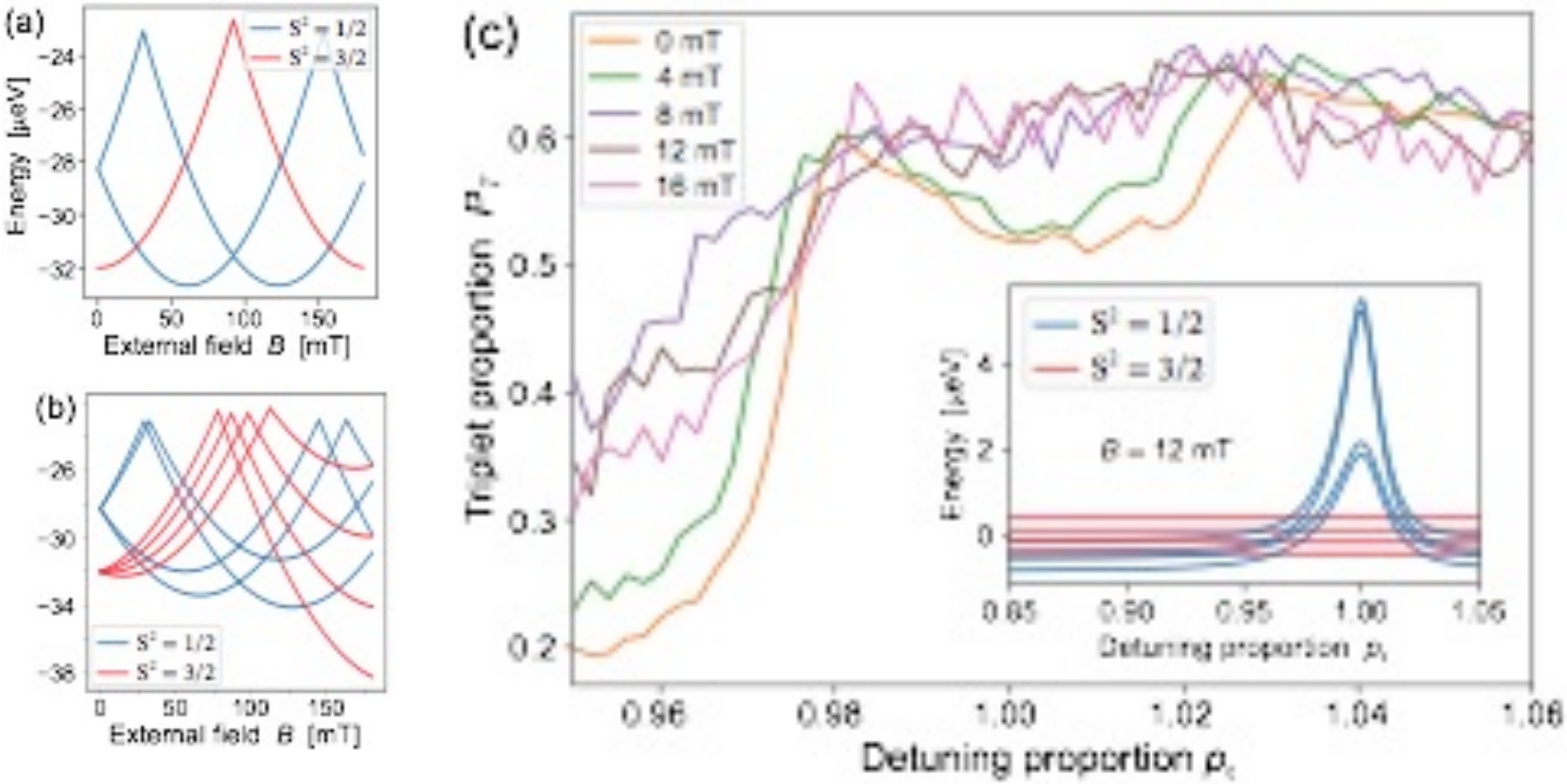
[16, 8, 20, 19] μeV

[18, 0, 21, 21] GHz

Magnetic GS disappears for a linear chain (consistent with Lieb-Mattis)

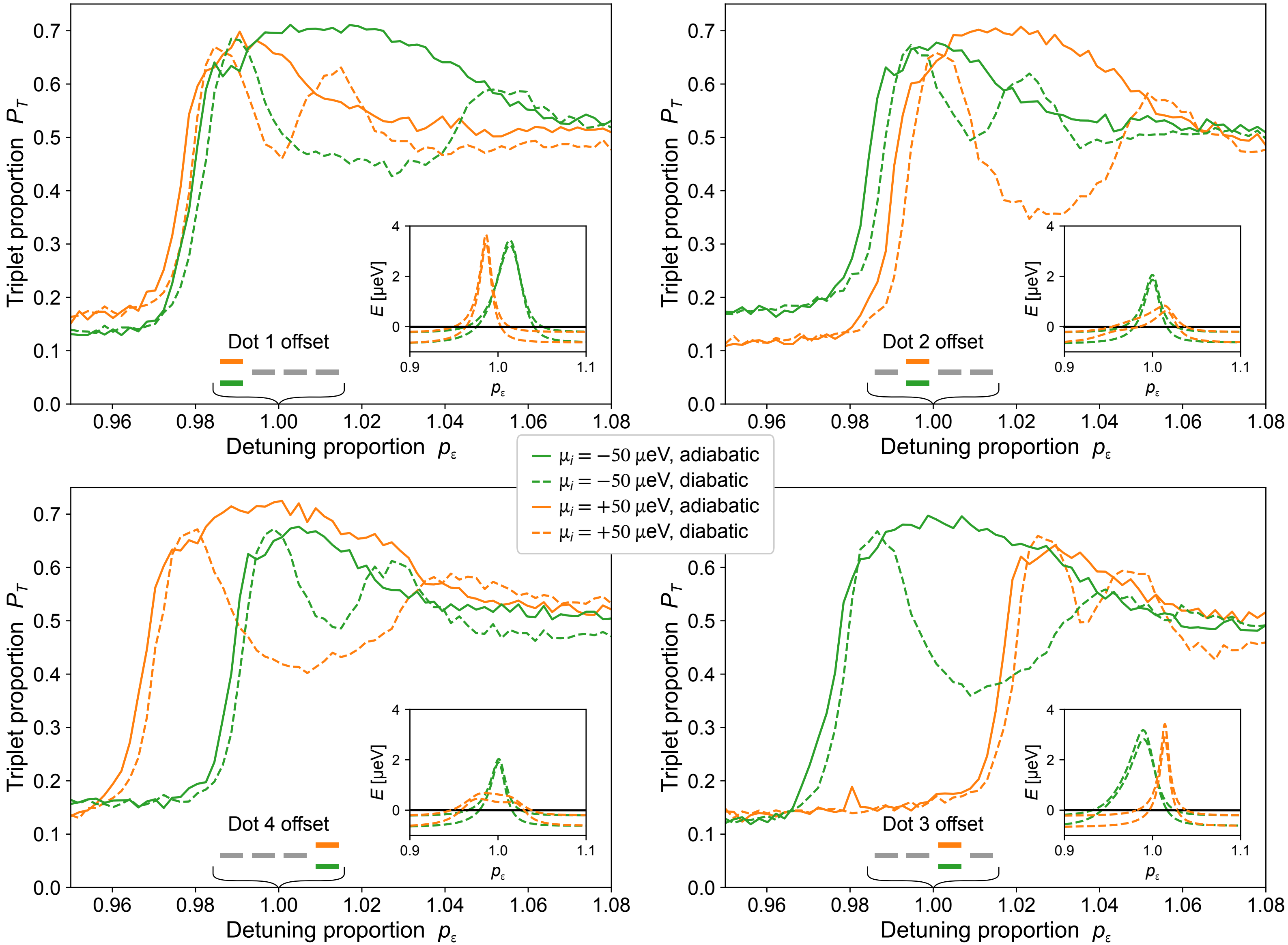
Test 2: Introduce Aharonov-Bohm phase (*B*-field)

Dehollain, Mukhopadhyay, et. al., unpublished



Weak B-field destroys magnetization

Test 3: Offset local potentials



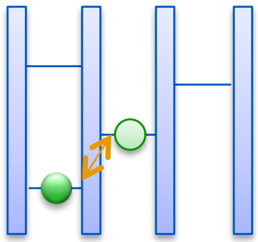
Magnetic ground state survives potential offsets exceeding hopping

What can we do in the time domain?

- Time dynamics
- Quenches
- Variational quantum eigensolvers
- Digital quantum simulation
- …

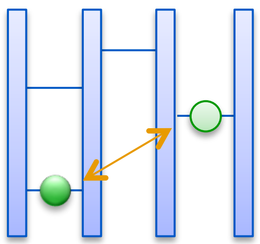
Coherent superexchange between "distant" spins

Short range exchange
(nearest neighbours)



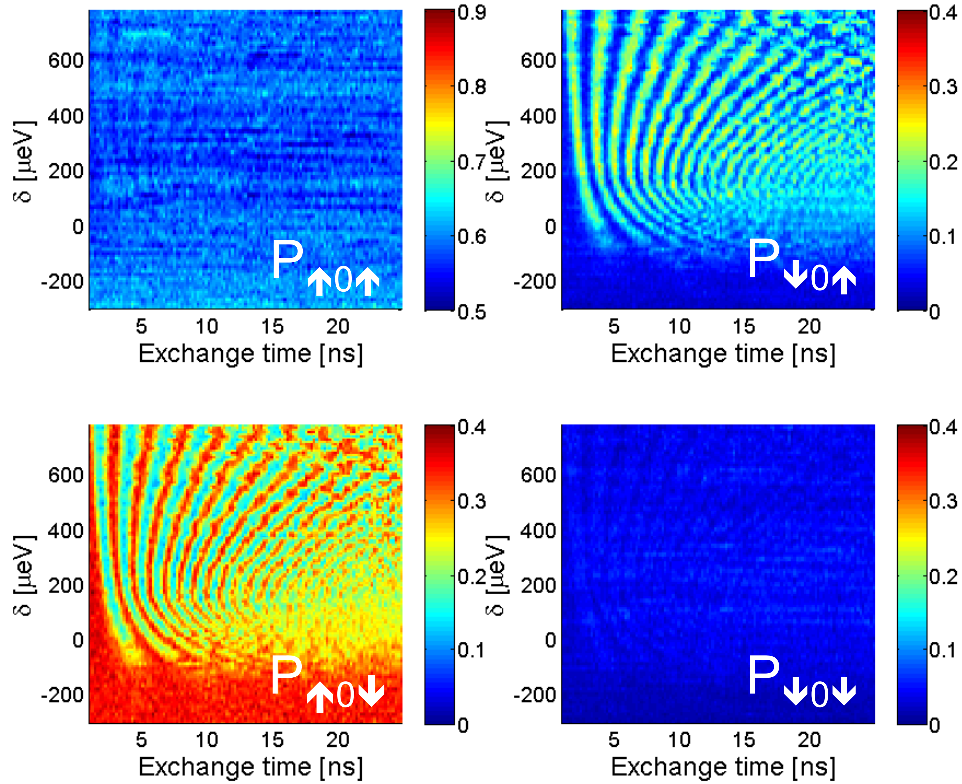
t^2/U

Long range exchange
(next-nearest neighbours)



t^4/U^3

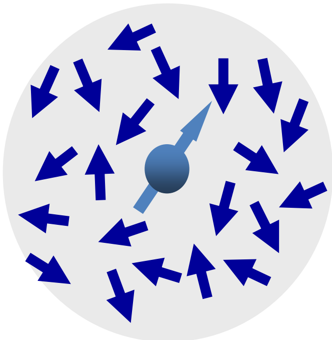
Baart, Fujita, et al, Nature Nano 2016



Spin coupling at a distance mediated by
virtually occupied intermediate level

Materials impact on coherence time

GaAs

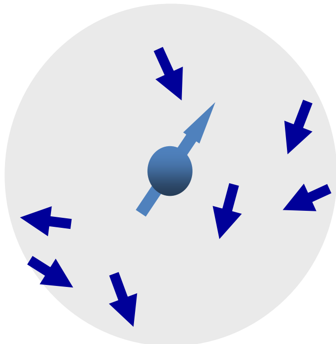


$T_2^* \sim 10$ ns

$T_2^{DD} < 0.2$ ms

Petta et al,
Science 2005

Si

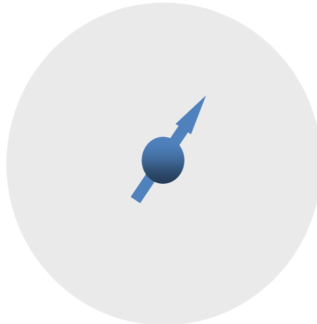


$T_2^* \sim 1$ μs

$T_2^{DD} > 0.5$ ms

Kawakami, Scarlino, et al,
Nature Nano 2014

^{28}Si



$T_2^* \sim 100$ μs

$T_2^{DD} \sim 28$ ms

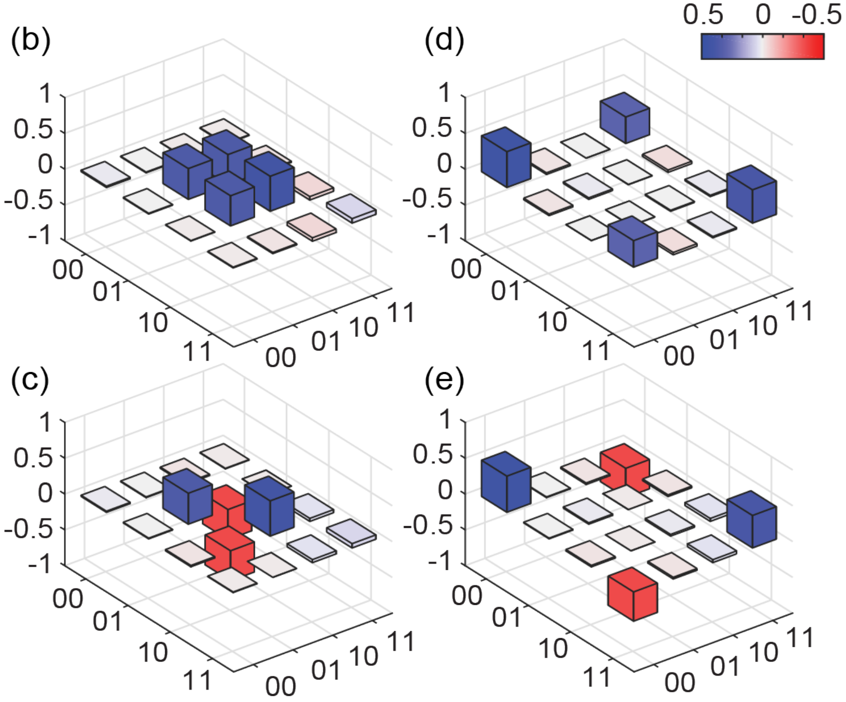
Veldhorst, et al,
Nature Nano 2014

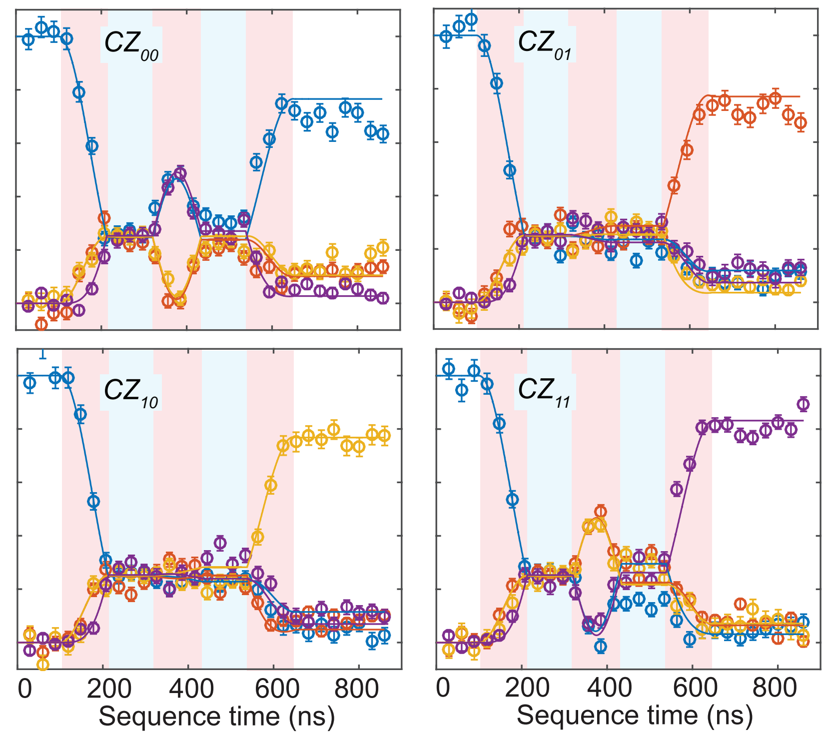
A programmable two-qubit Si/SiGe device

Watson *et al.*, Nature 2018

Bell state fidelity: 85-89%
Concurrence: 73-80%

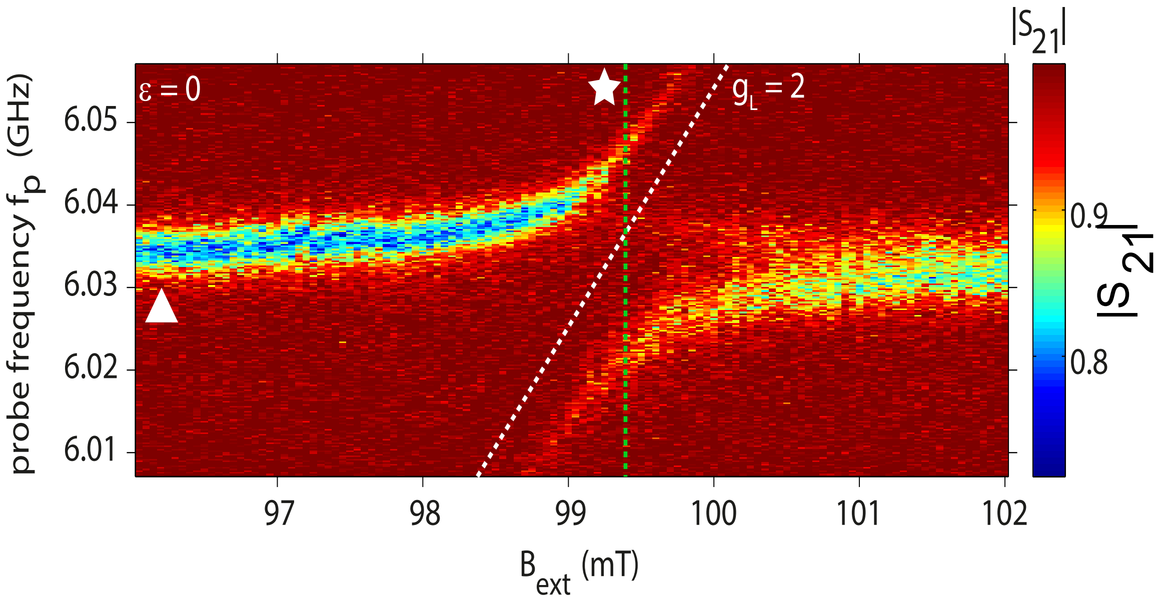
Implemented all instances of the Deutsch-Jozsa and Grover algorithms

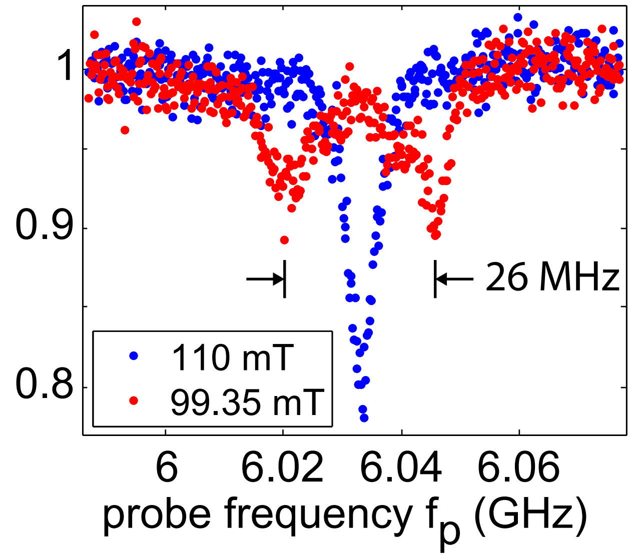


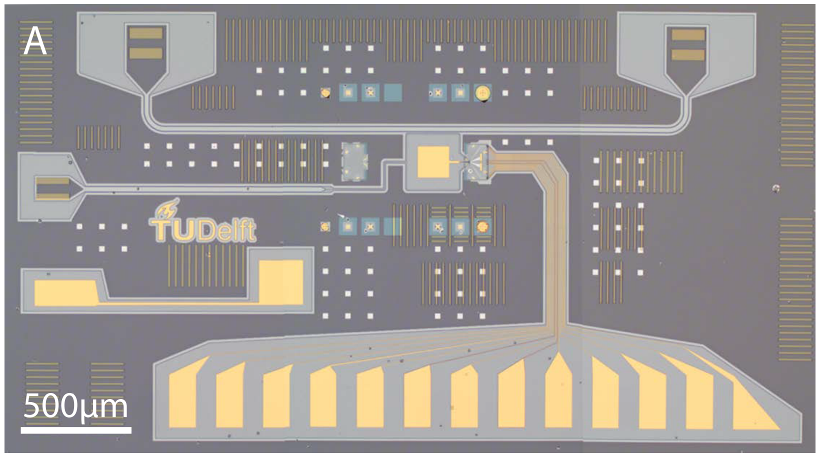


See also Zajac et al, Science 2018
Huang et al, arXiv:1805.05027

Strong spin-photon coupling







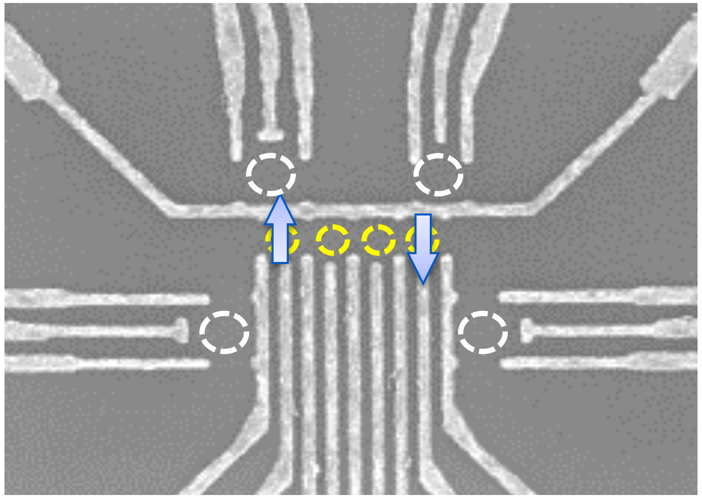
Samkharadze, Zheng, *et al.,* Science 2018

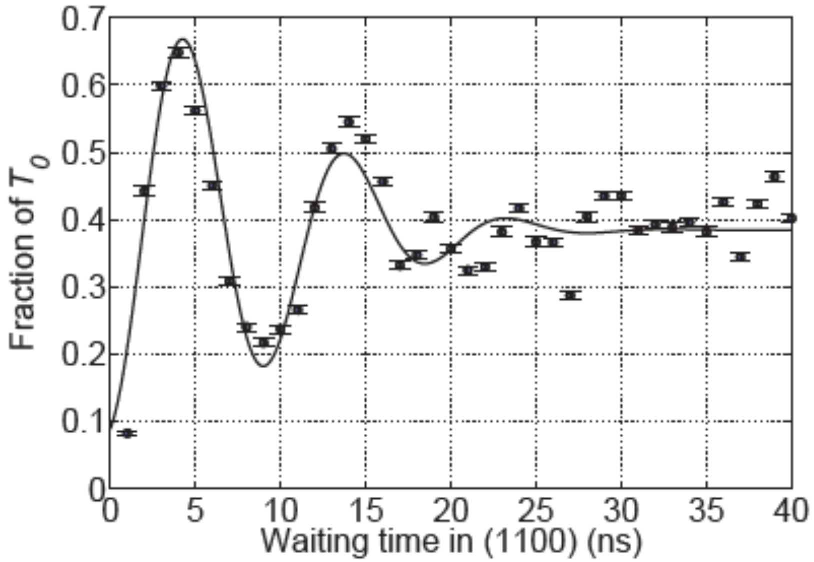
Materials: Scappucci, Theory: A. Blais

See also: X. Mi *et al*., Nature 2018
Landig, Koski, *et al*., Nature 2018

Coherent electron spin shuttling

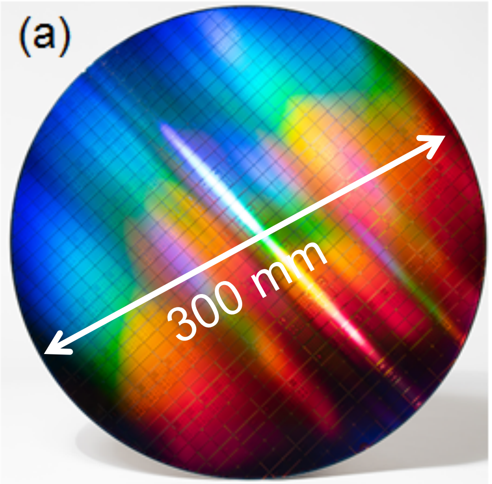
Fujita et al, npj Q Info 2017
See also Flentje et al, Nature Comm 2017

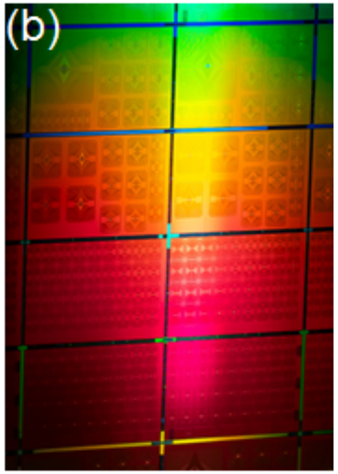


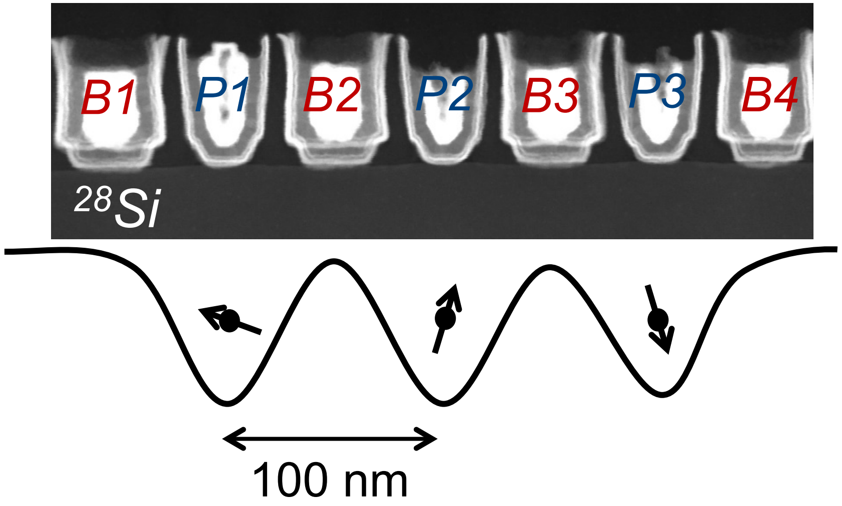


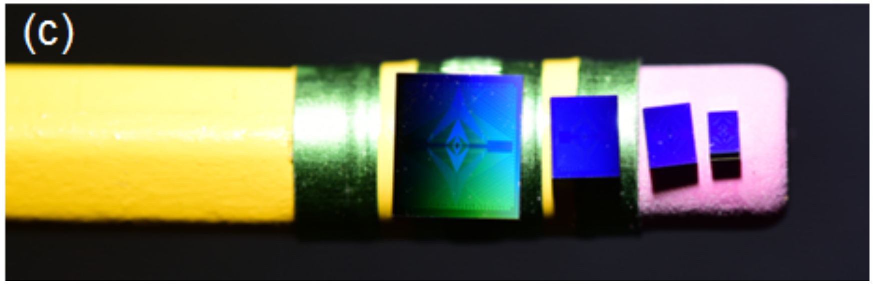
Protocol: separate spin singlet and try to bring back together

Si quantum dots made in Intel 300mm cleanroom



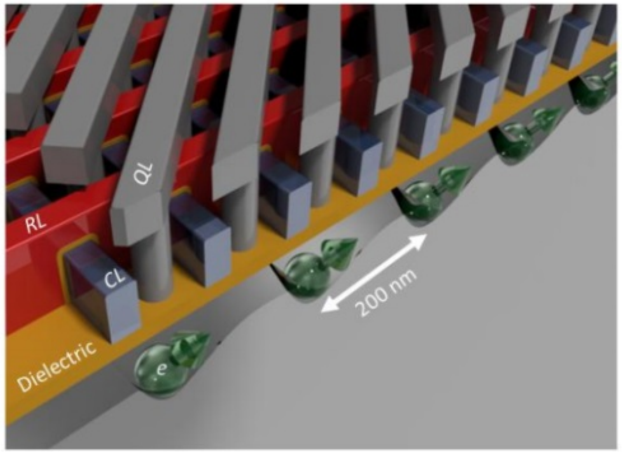






R. Pillarisetty et al., IEDM 2018

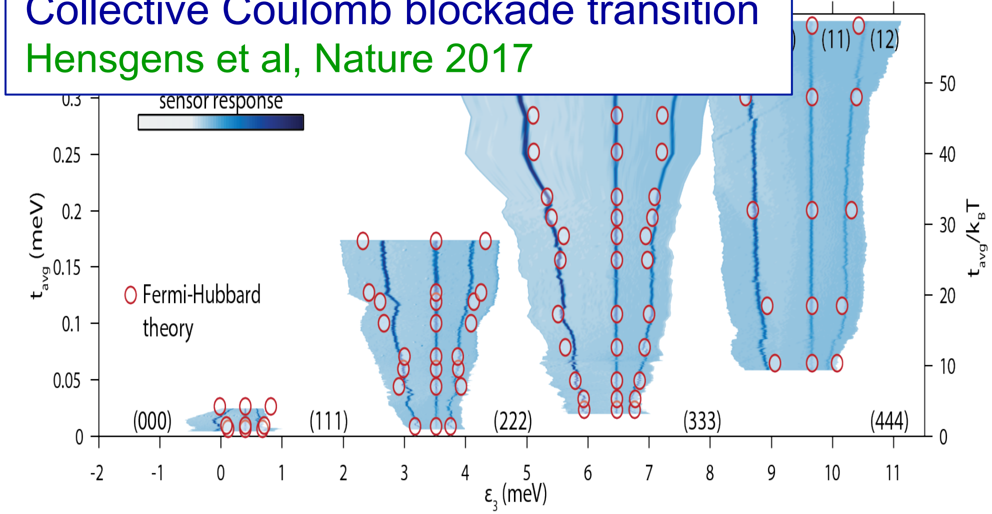
Future: Crossbar architecture



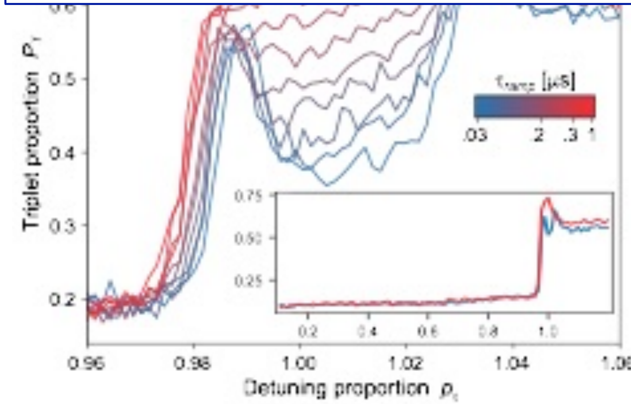
Li *et al.* Sci. Adv. (2018)

Summary and outlook on analog quantum simulation

Collective Coulomb blockade transition
Hensgens et al, Nature 2017

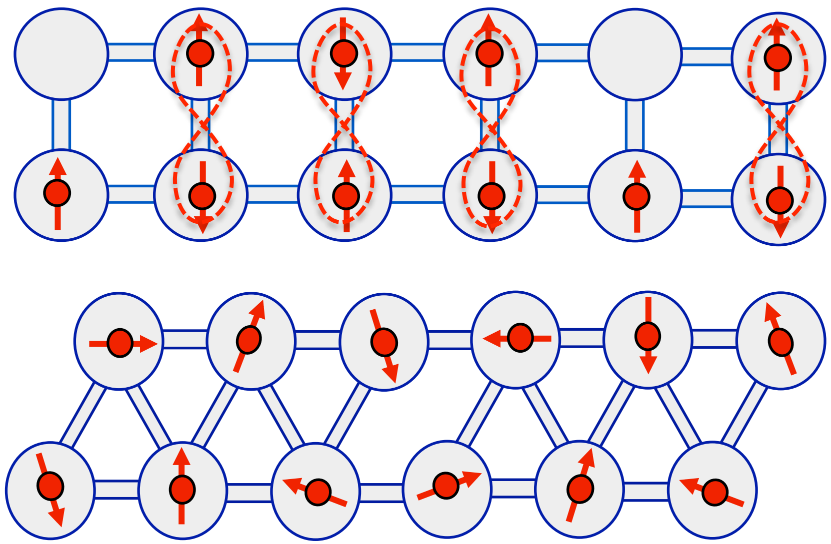


Nagaoka ferromagnetism
Dehollain, Mukhopadhyay, ea, unpublished



Opening up a new platform for simulation

- Fermi-Hubbard physics
- Quantum magnetism
- Many-body localization?
- Topological states
- …



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