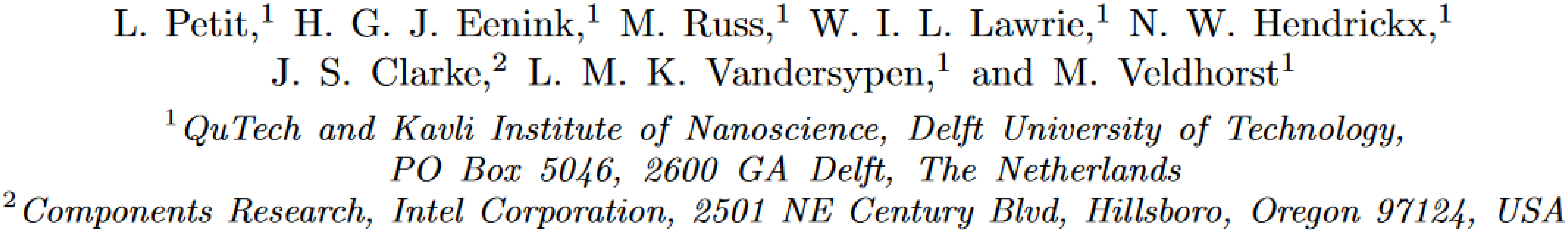
Universal quantum logic in hot silicon qubits



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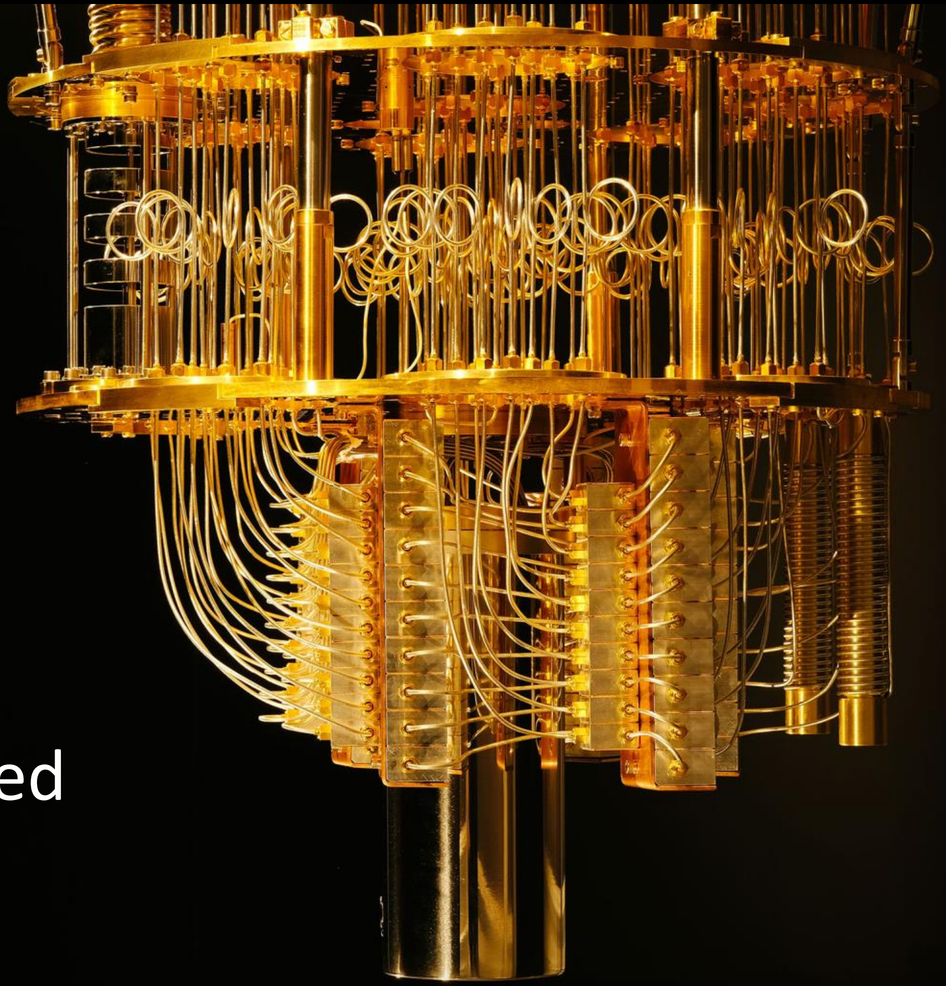
Simon Geyer, group meeting talk 13 Dec 2019

Large-scale quantum computing



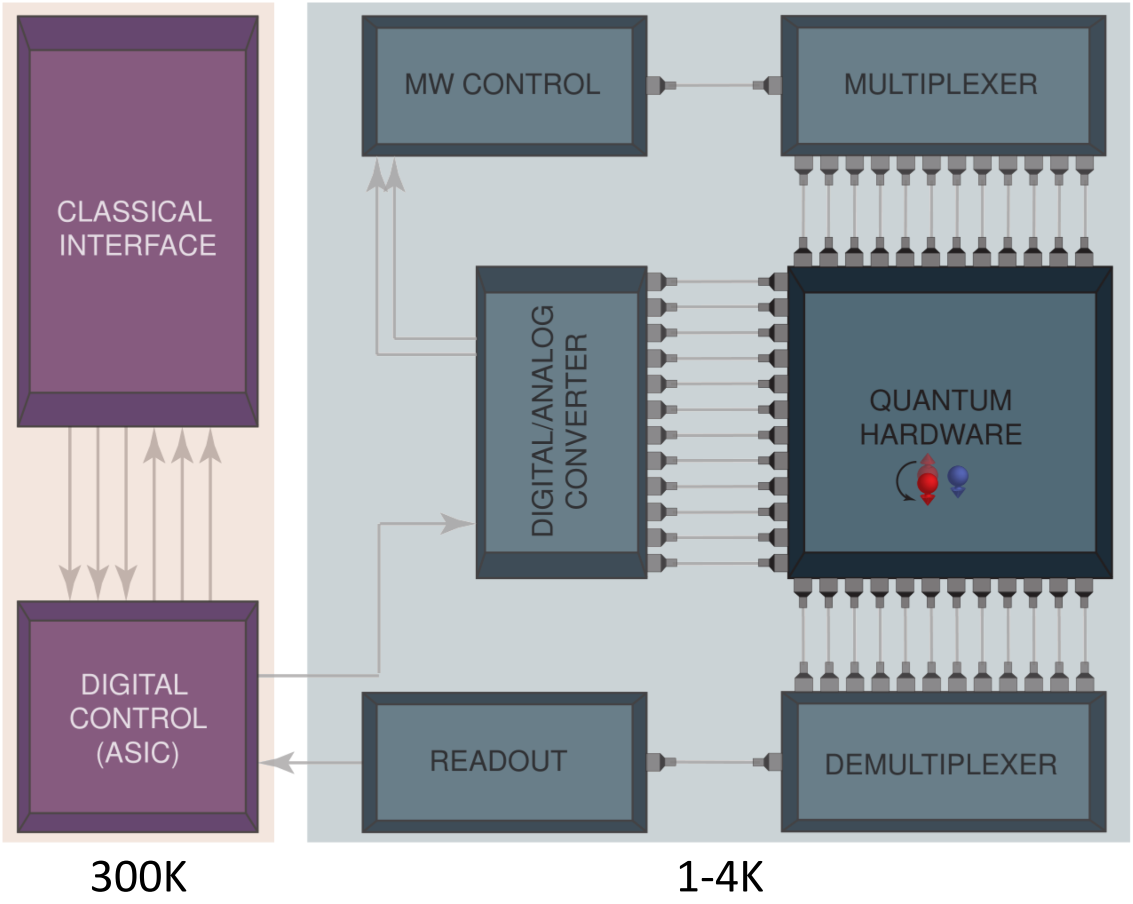
- scalable qubit
- scalable architecture

- problems:
  - bottleneck of interconnections to RT electronics
  - many qubits -> high cooling power needed

https://www.roche.com/quantum-computing.htm

Idea: quantum integrated circuit

- quantum integrated circuit
  - on-chip electronics for qubit-control
  - no interconnection bottleneck
  - dissipates large amount of heat -> more cooling needed



Petit et al., arXiv: 1910.05289v1 (2019)

Idea: quantum integrated circuit

- Why should we operate at 1-4K?
  - on-chip electronic and large number of qubits generate heat
  - cooling power increases with temperature

technology	temperture (K)	typical cooling power (W)
l^{4}He	4.2	
1K pot	1.8	10^{-1}
^{3}He	0.8	10^{-2}
^{3}He/^{4}He-dilution refrigerator	20×10^{-3}	10^{-5}

cooling power increases by factor 10^{4}

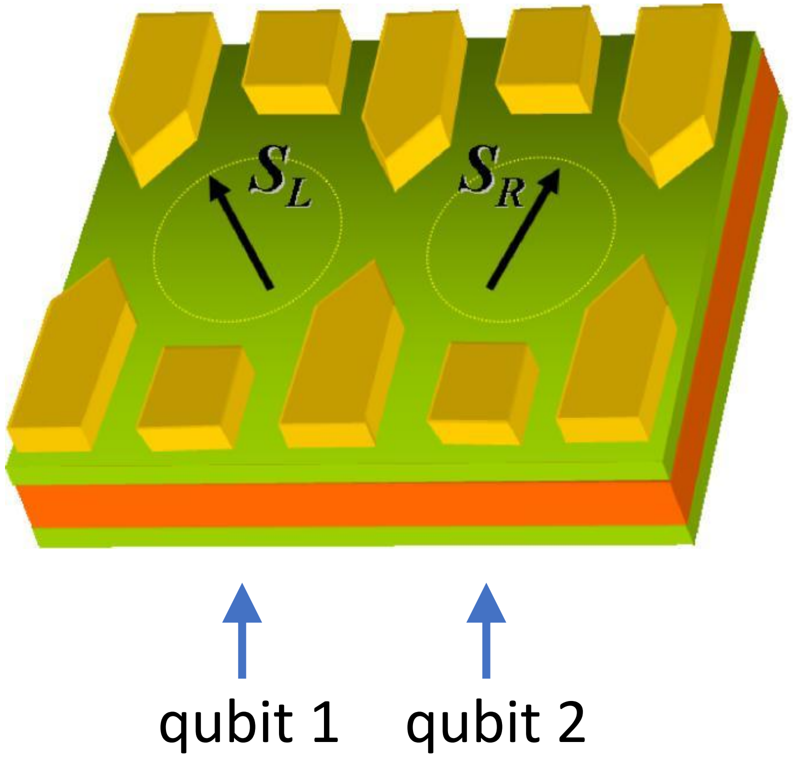
- challange: good qubit properties at high T

Loss-DiVincenzo spin qubit

- confine electrons in QDs
- encode information in spin of a single electron[1]
- qubit states $|0\rangle$ and $|1\rangle$:

$$|0\rangle = |\uparrow\rangle$$

$$|1\rangle = |\downarrow\rangle$$



https://upload.wikimedia.org/wikipedia/commons/7/7a/DoubleQuantumDot.jpg

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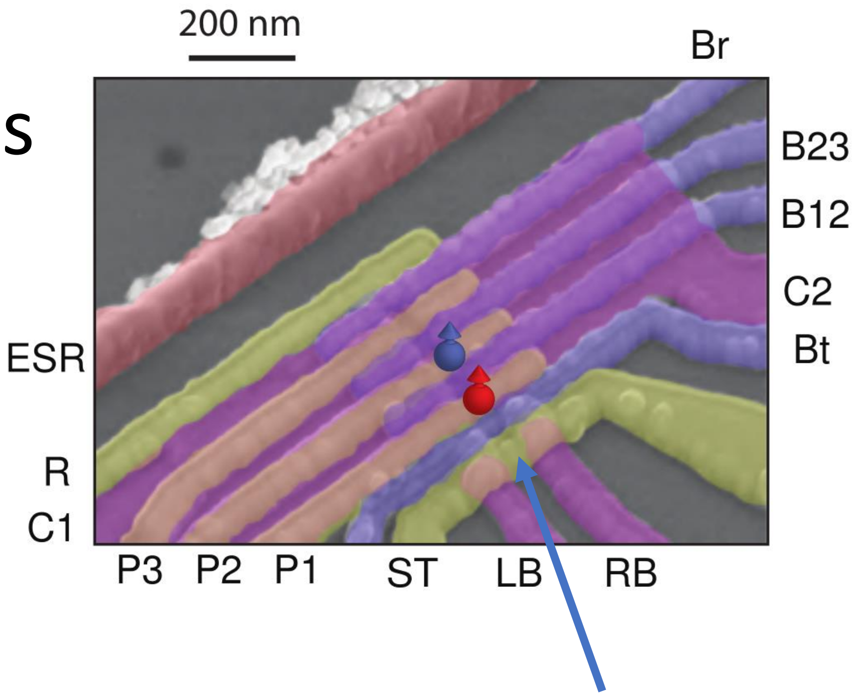
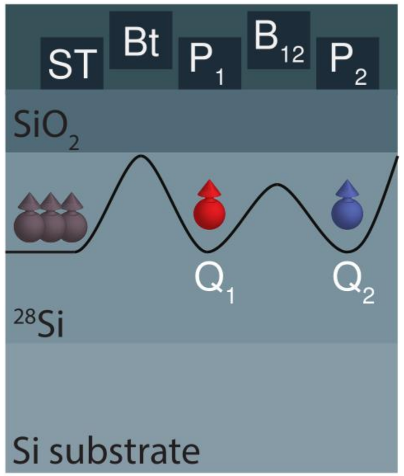
[1] Loss & DiVincenzo, Phys. Rev. A 57, 120 (1998)

Device

- ^{28}Si substrate (spins-free)
- P-gates accumulate e^{-}-QDs at Si-SiO$_2$ interface
- B-gates tune tunnel barriers
- charge sensor
- MW antenna for ESR

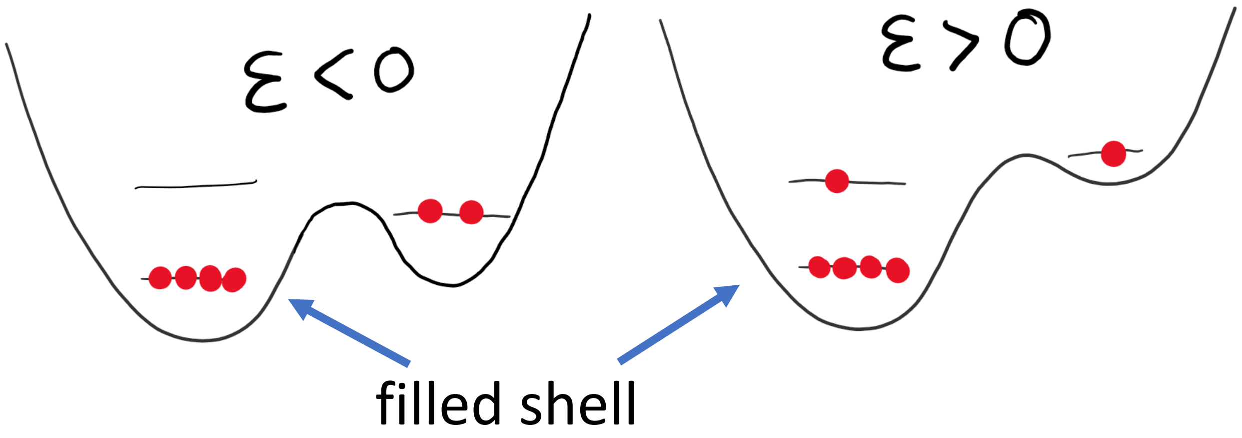


charge sensing SET

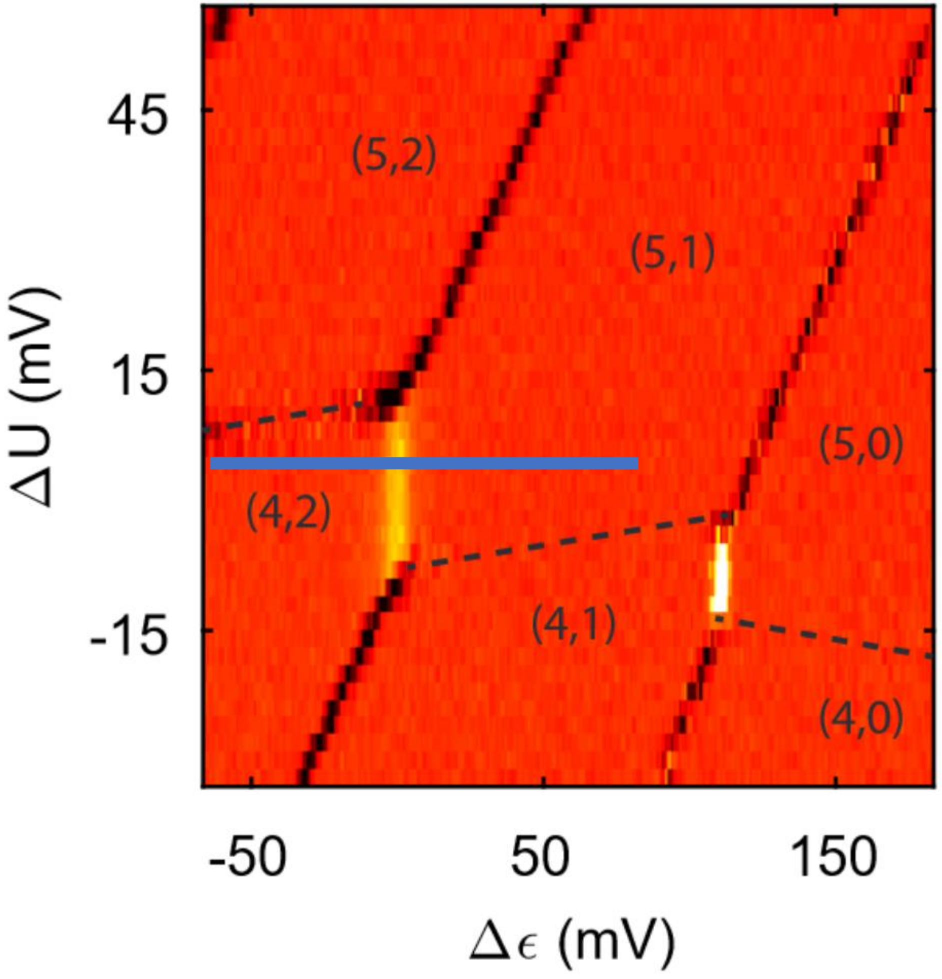


Double QD

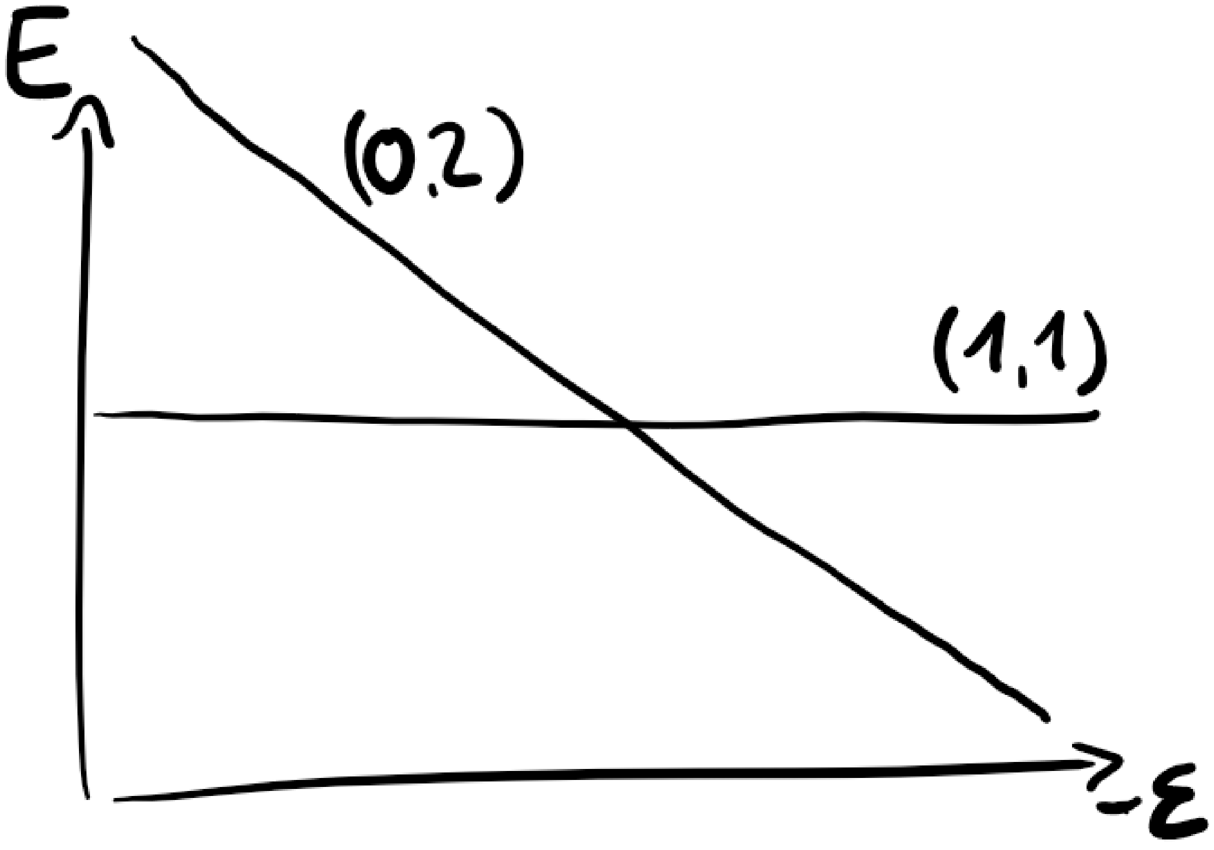
- 4 electrons in left dot fill shell
  -> only use valence electrons



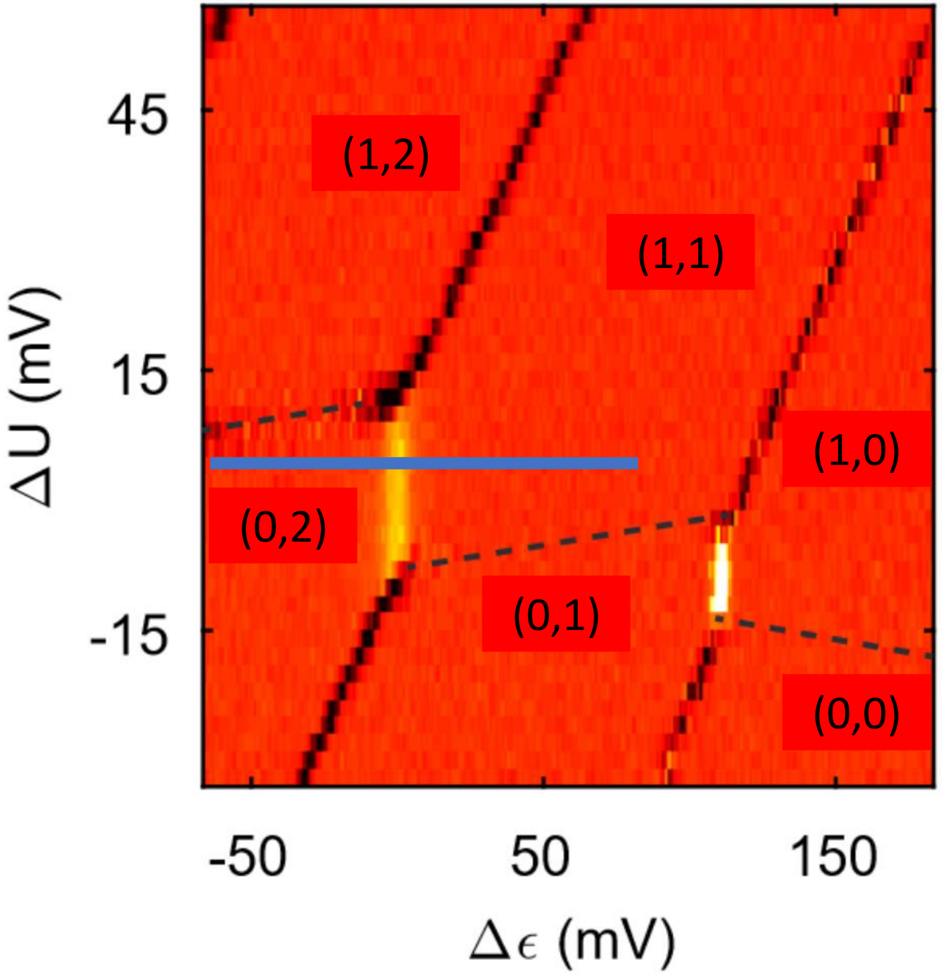
filled shell



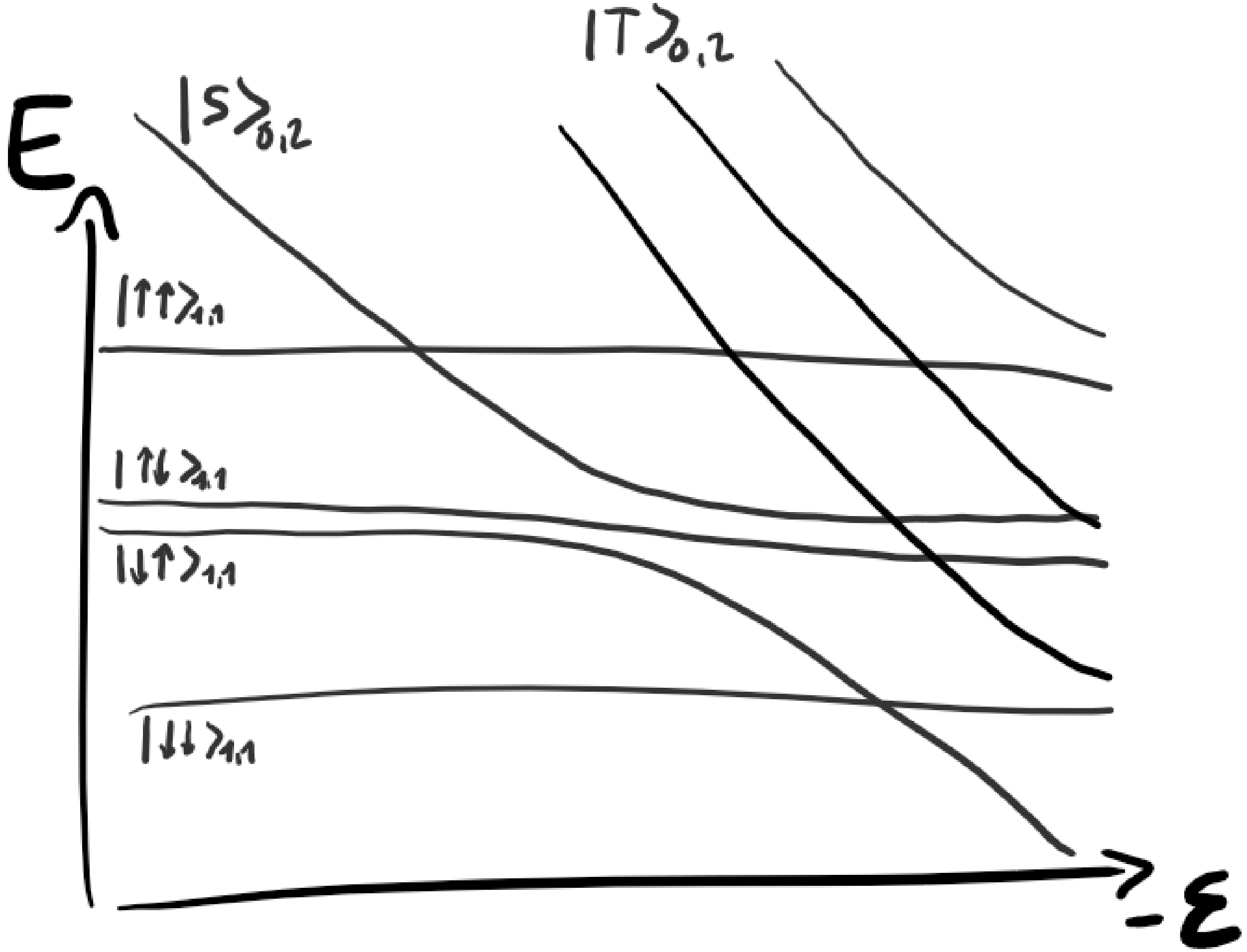
Double QD – states



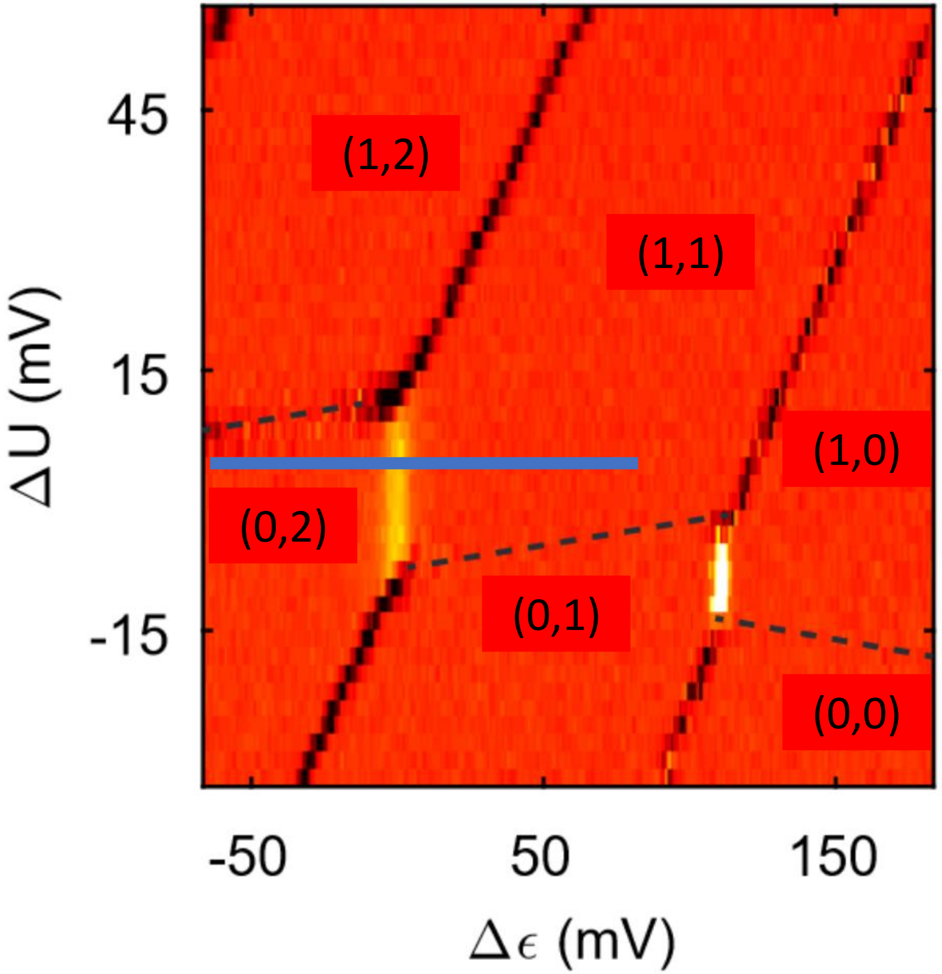
equivalent:



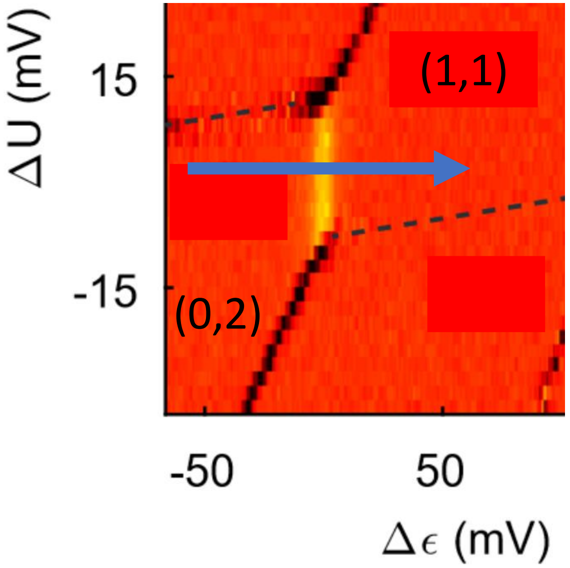
Double QD – states



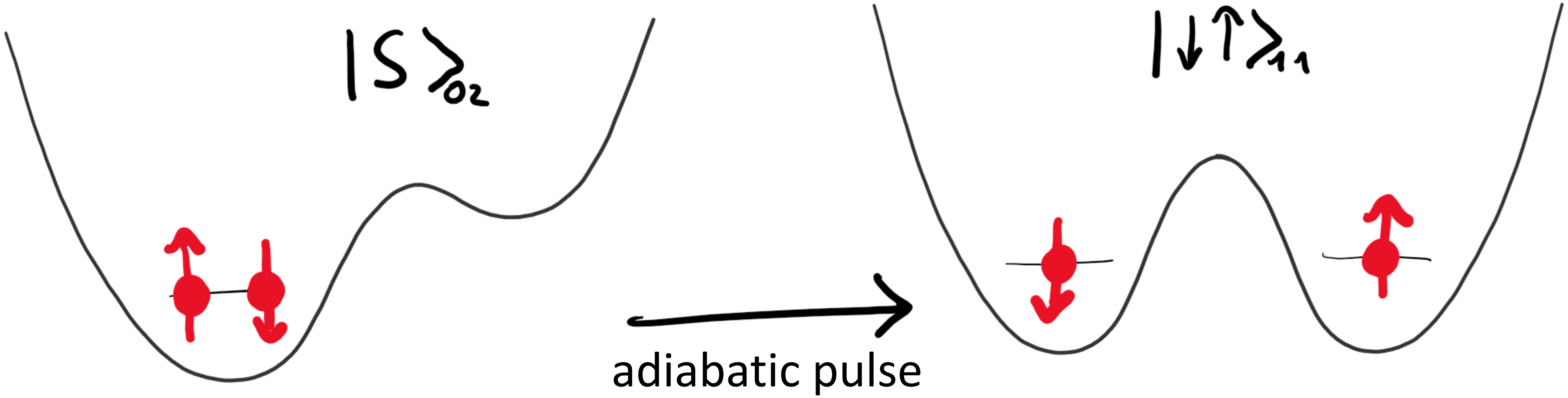
equivalent:



Initializing the qubit

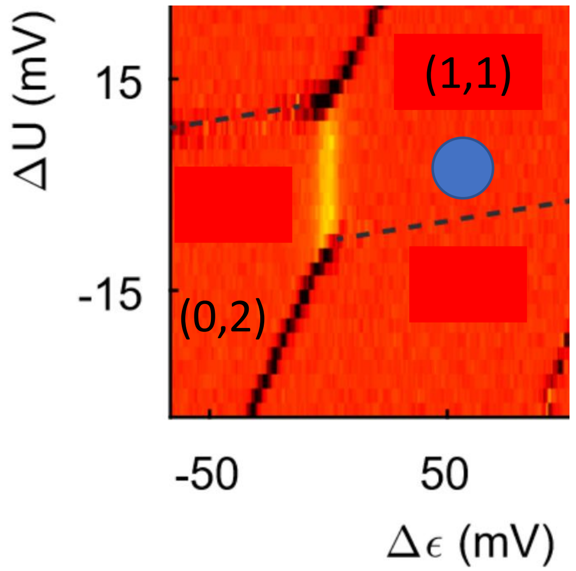


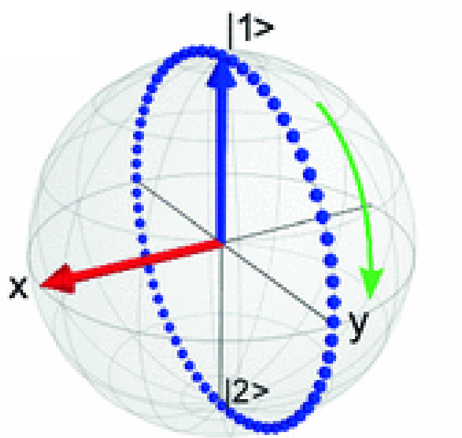
- goal: well-defined state, e.g. $|du\rangle_{11}$
- use fast spin relaxiation in (0,2) charge state to populate $|S\rangle_{02}$ ground state
- adiabatic pulse to (1,1) gives $|du\rangle_{11}$

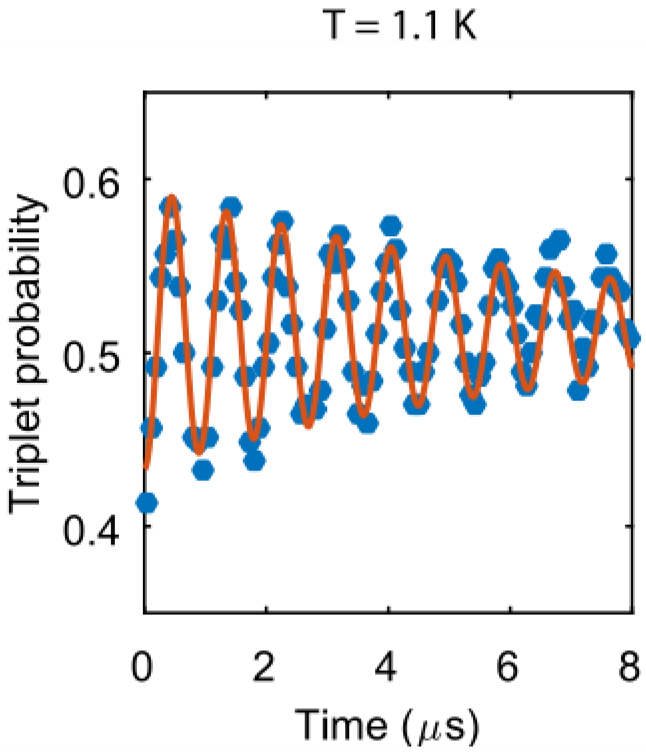


Manipulation

- MW signal -> oscillating B-field rotates spin -> arbitrary single-qubit rotations
- slightly different resonance frequency ->allows to address qubits individually

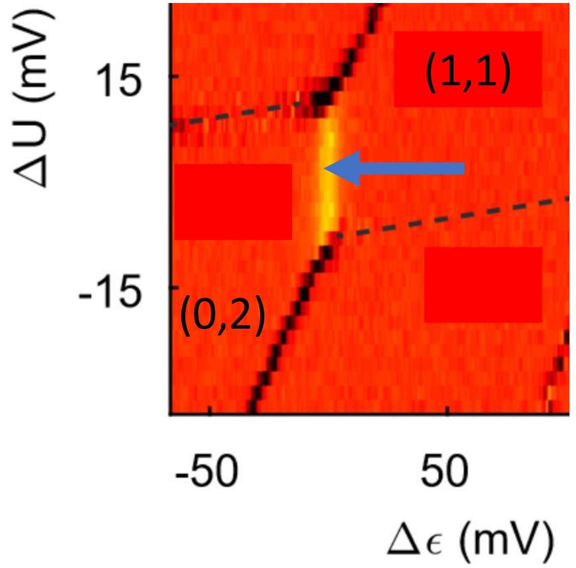




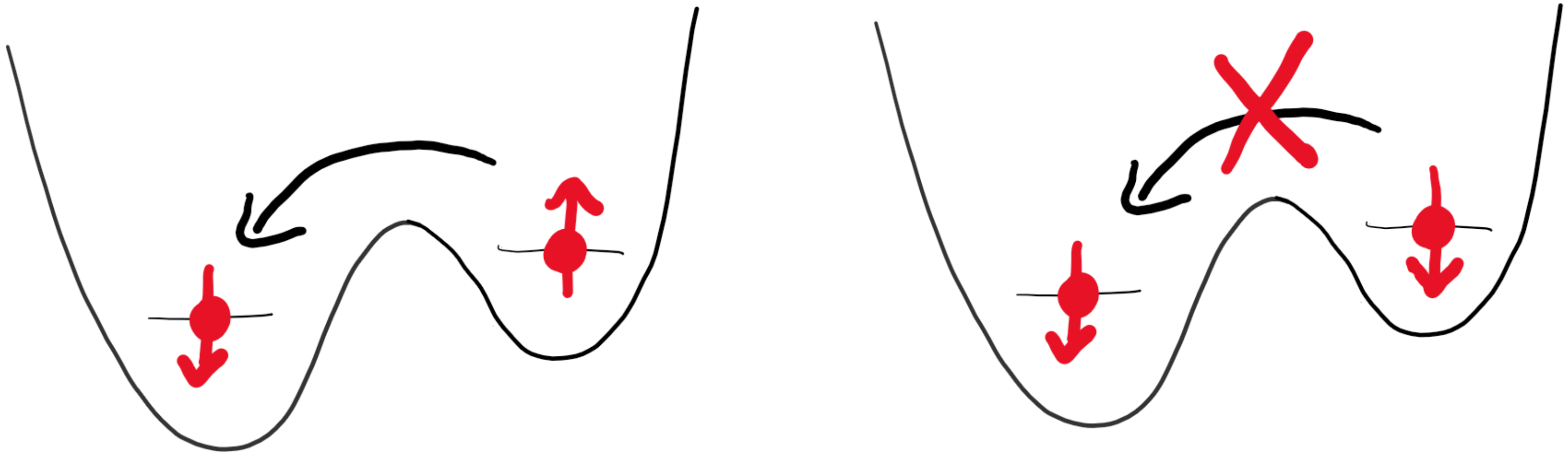


Alexander J. Dunning, *Coherent Manipulation and Interferometry* (2015)

Readout

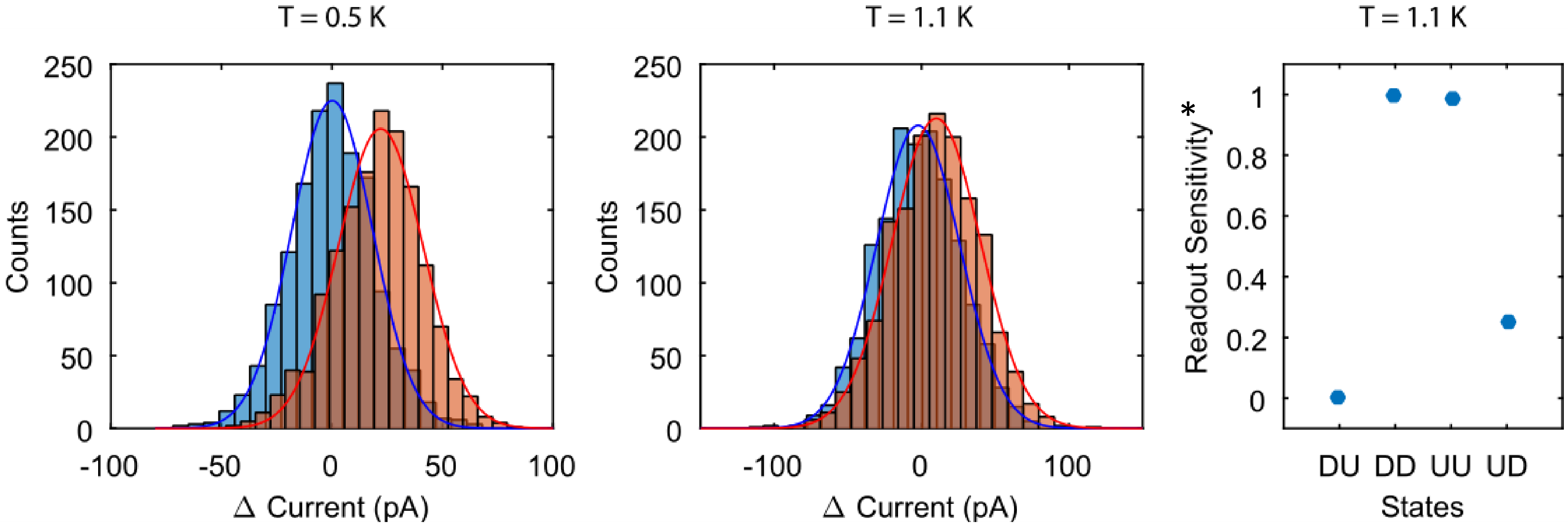


- spin-to-charge conversion:
  - singlet -> current
  - triplet -> no current
- only one qubit can be read out



Yang et al., arXiv: 1902.09126 (2019)

Readout

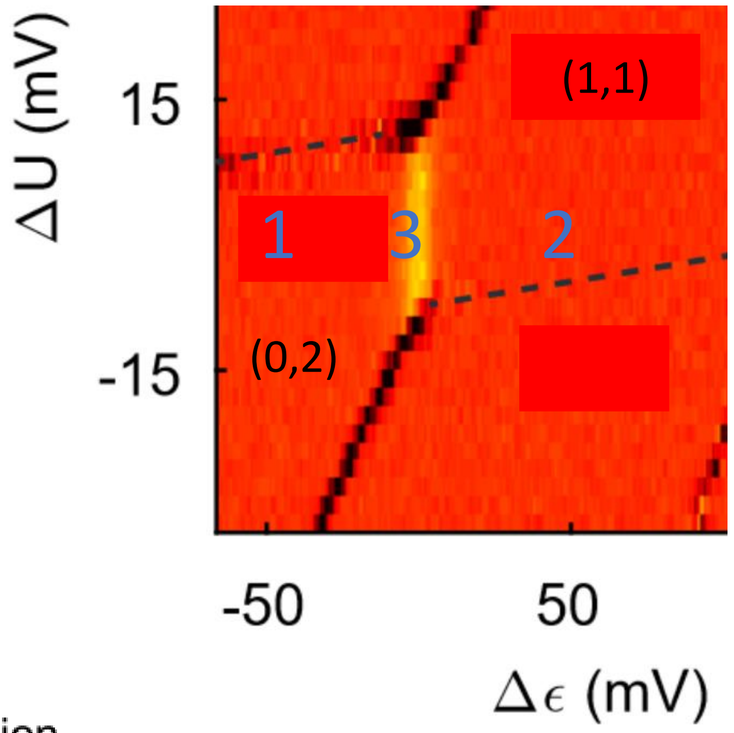


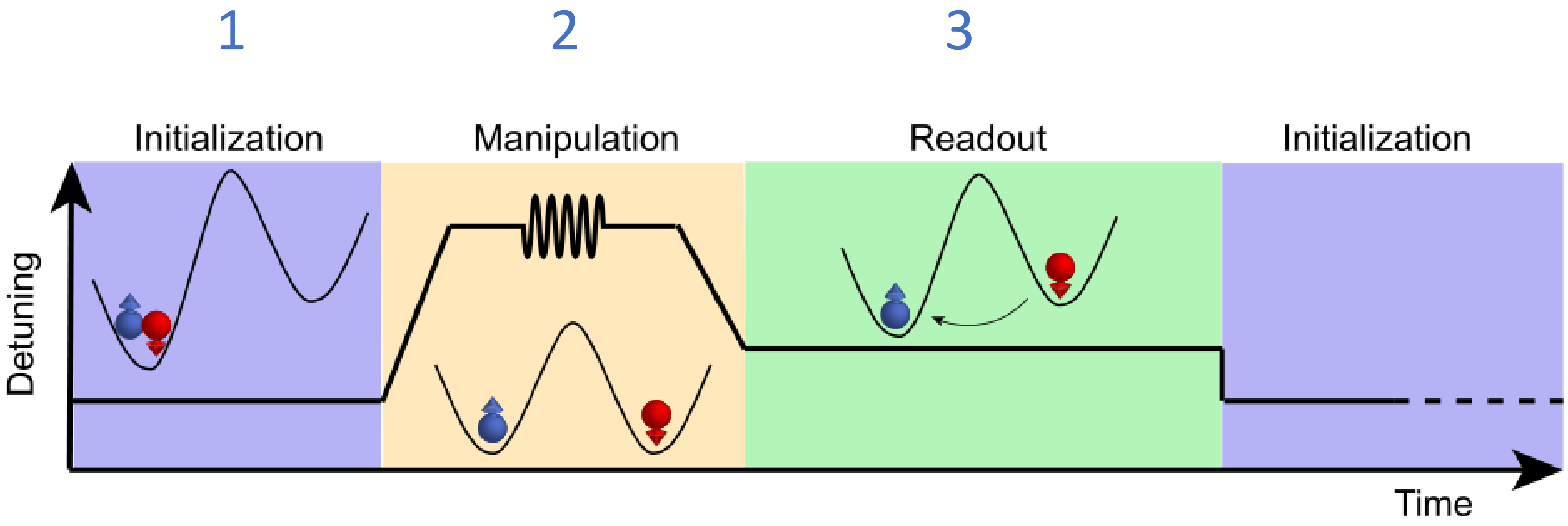
- different current measured for singlet and triplet states
- $|ud\rangle_{11}$ mixes with singlet -> hard to distinguish
- alternative: parity-readout[1]

[1] Yang et al., arXiv: 1902.09126 (2019)

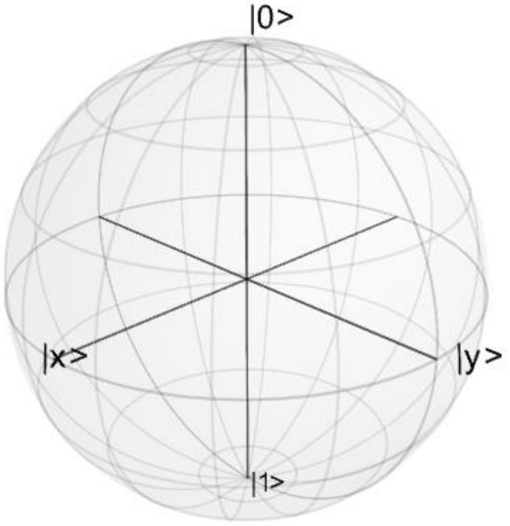
*normalized

Qubit operation cycle

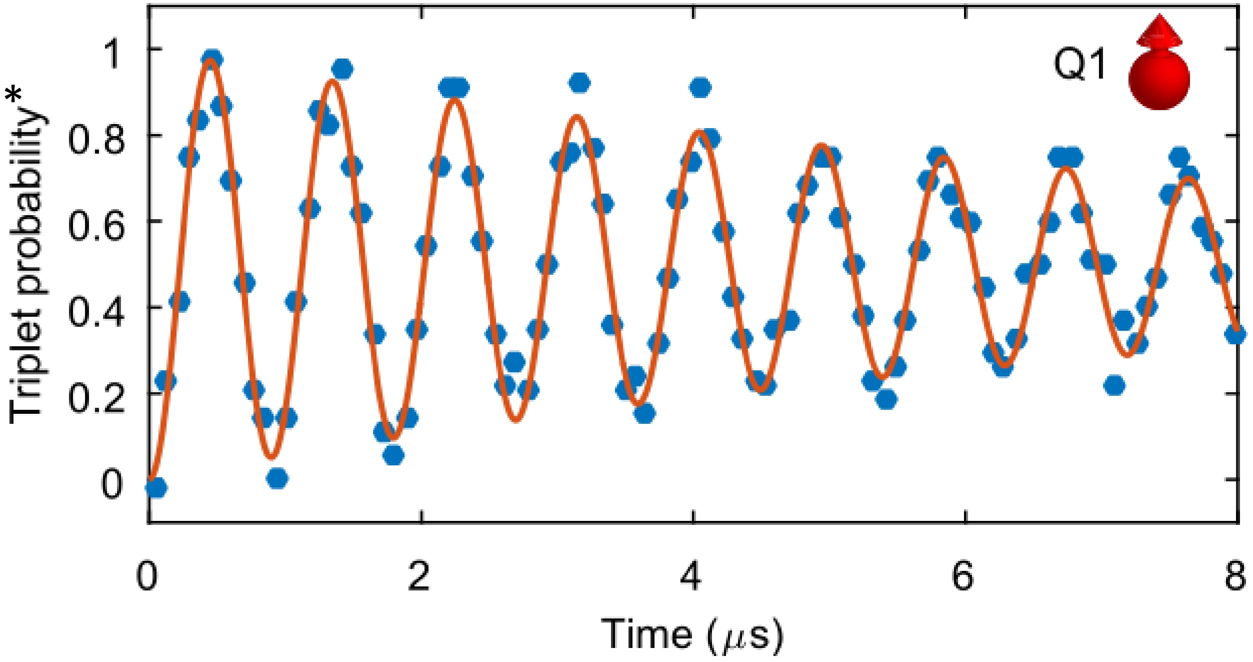


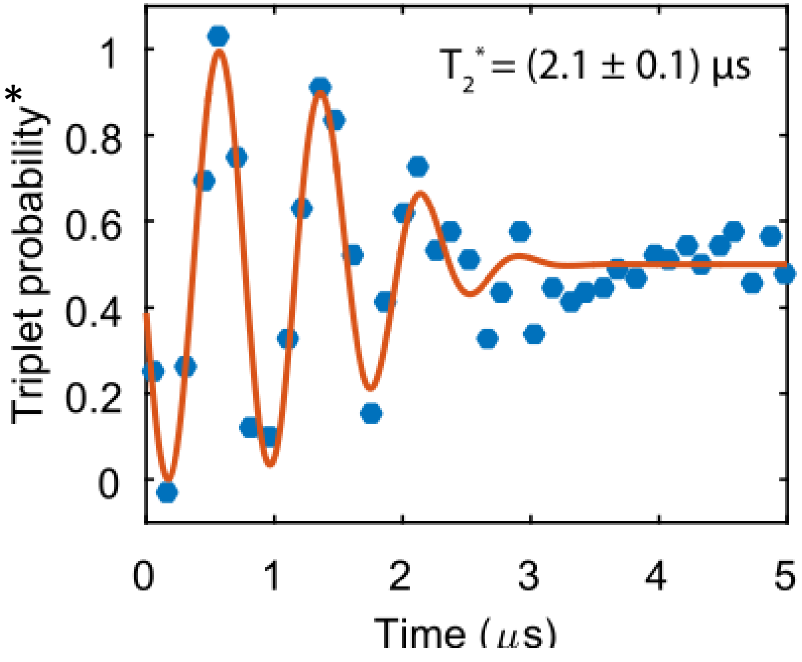


Single-qubit characterization



- Rabi oscillations: constant drive
- Ramsey sequence: dephasing at equator

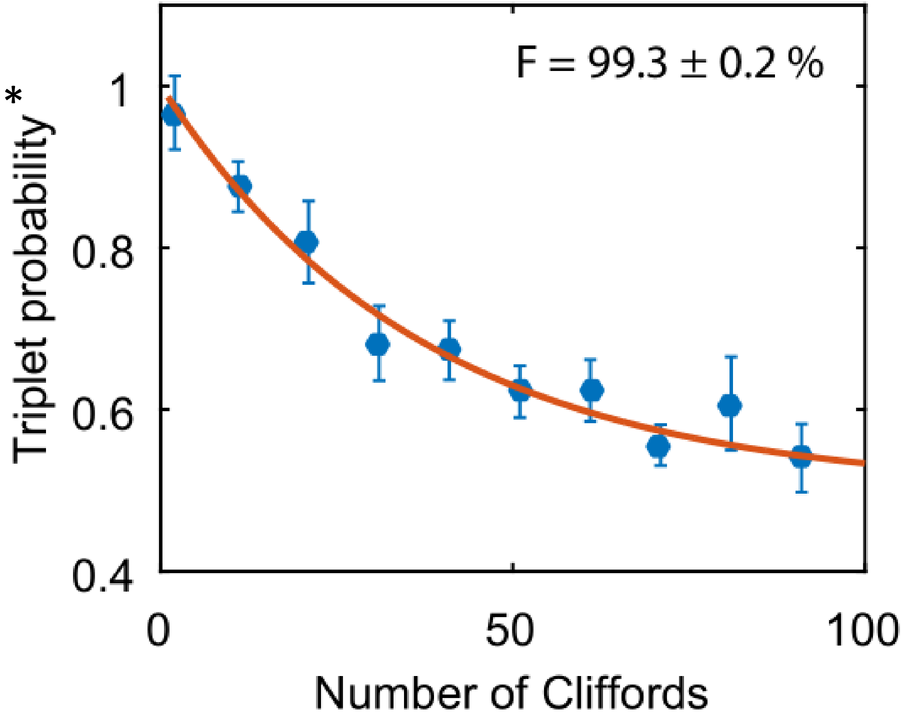




*normalized

Single-qubit gate fidelity

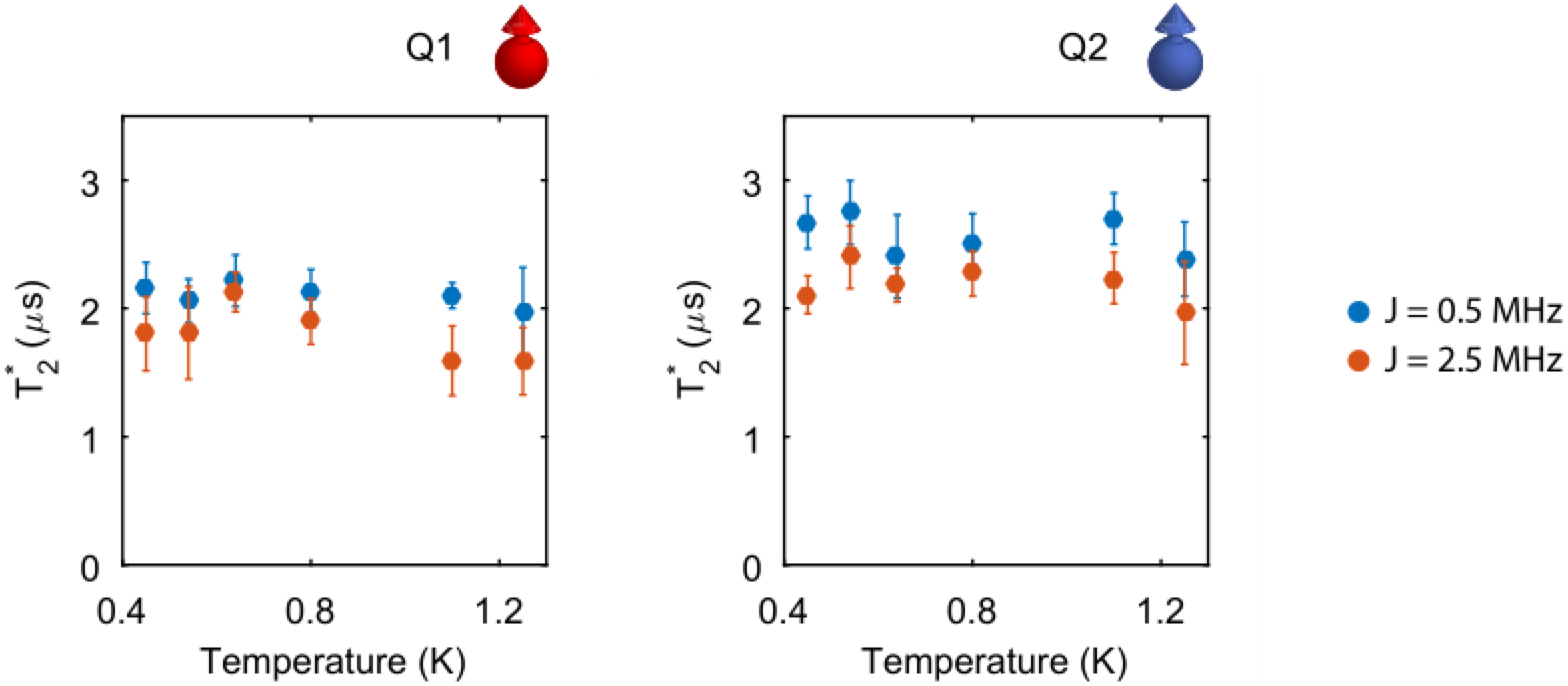
- randomized benchmarking:
  - apply certain number of random Clifford gates
  - go to triplet state
  - read out
- fit yields fidelities ~99% for one single-qubit gate
- readout errors have no influence on this method



*normalized

Hot spin qubits

- so far: T = 1.1K
- T_2^* only weakly dependent on T
- limiting factor[1]: $T_1 \propto T^{-5}$



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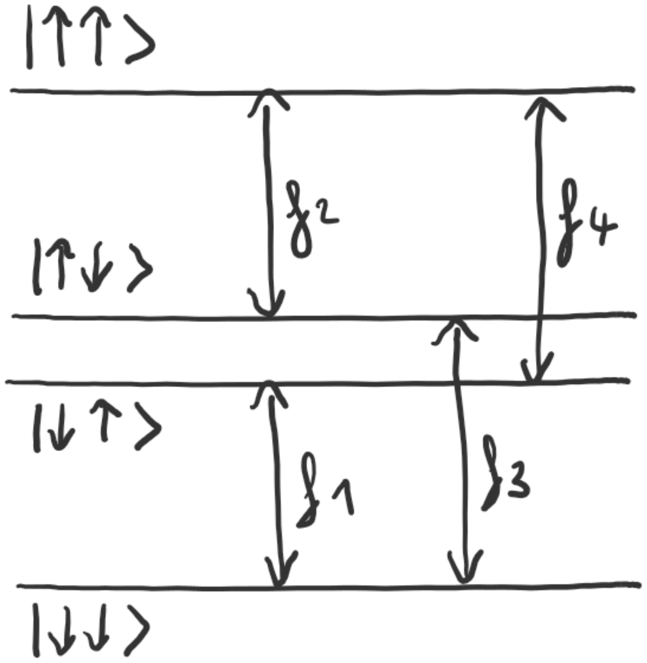
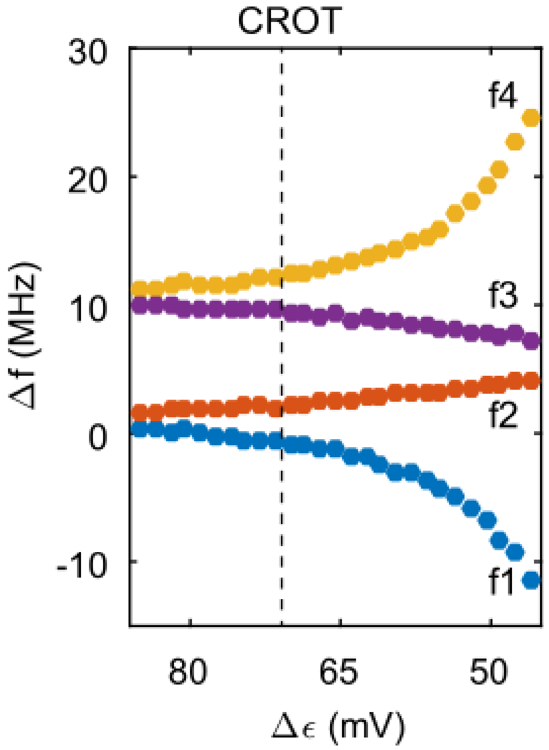
[1] Yang et al., arXiv: 1902.09126 (2019)

Two-qubit characterization

- exchange interaction couples spins
- qubit 1 changes resonance frequency depending on state of qubit 2 and vice versa

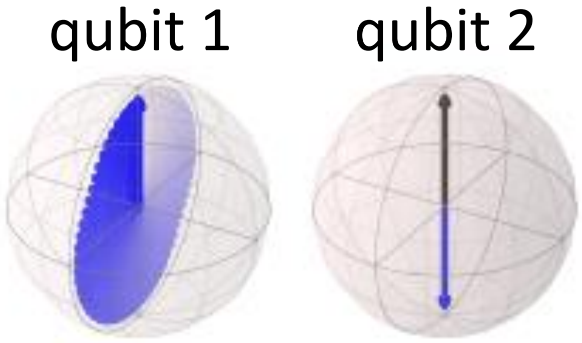


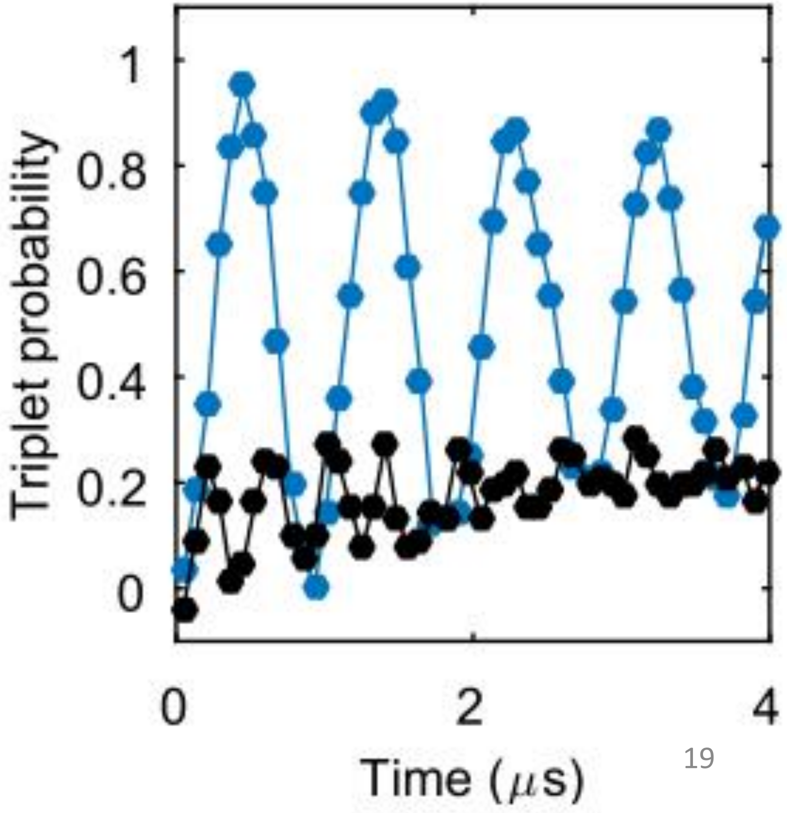
$$H = J\,\vec{S}_1 \cdot \vec{S}_2 + \sum_i \mu_B g_i \vec{B}_i \cdot \vec{S}_i$$



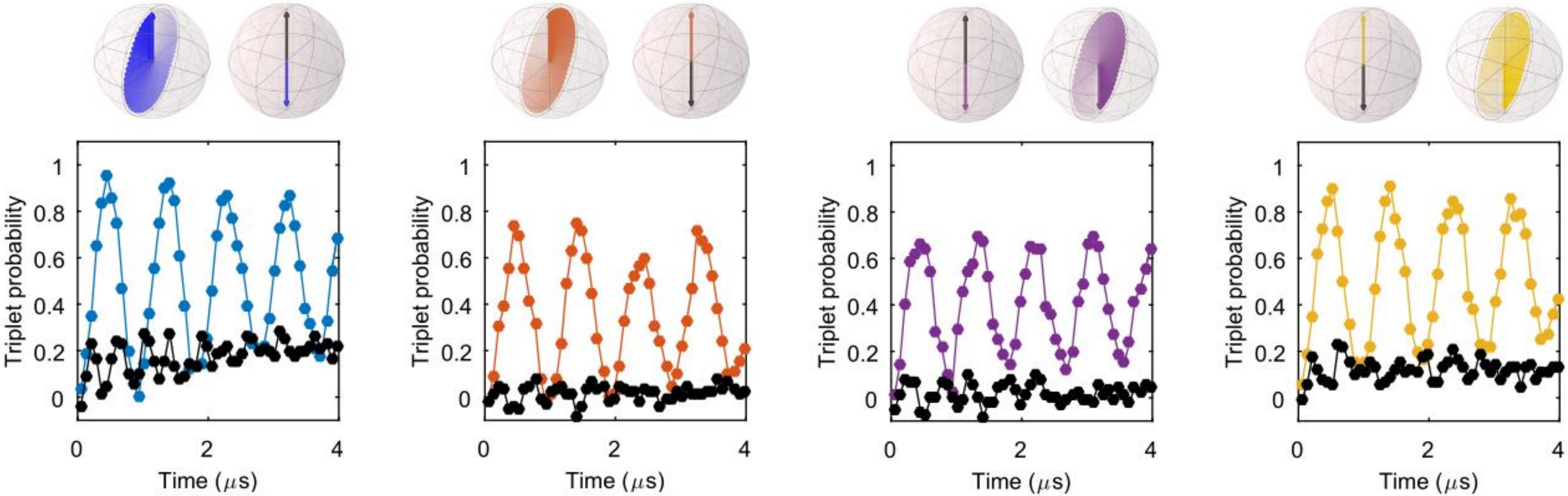
Two-qubit characterization

- CROT gate (conditional rotation)
- qubit 1 is driven only if qubit 2 is in a certain state
- CROT + single-qubit gates = CNOT
- coherent manipulation
- scalable?





Two-qubit characterization

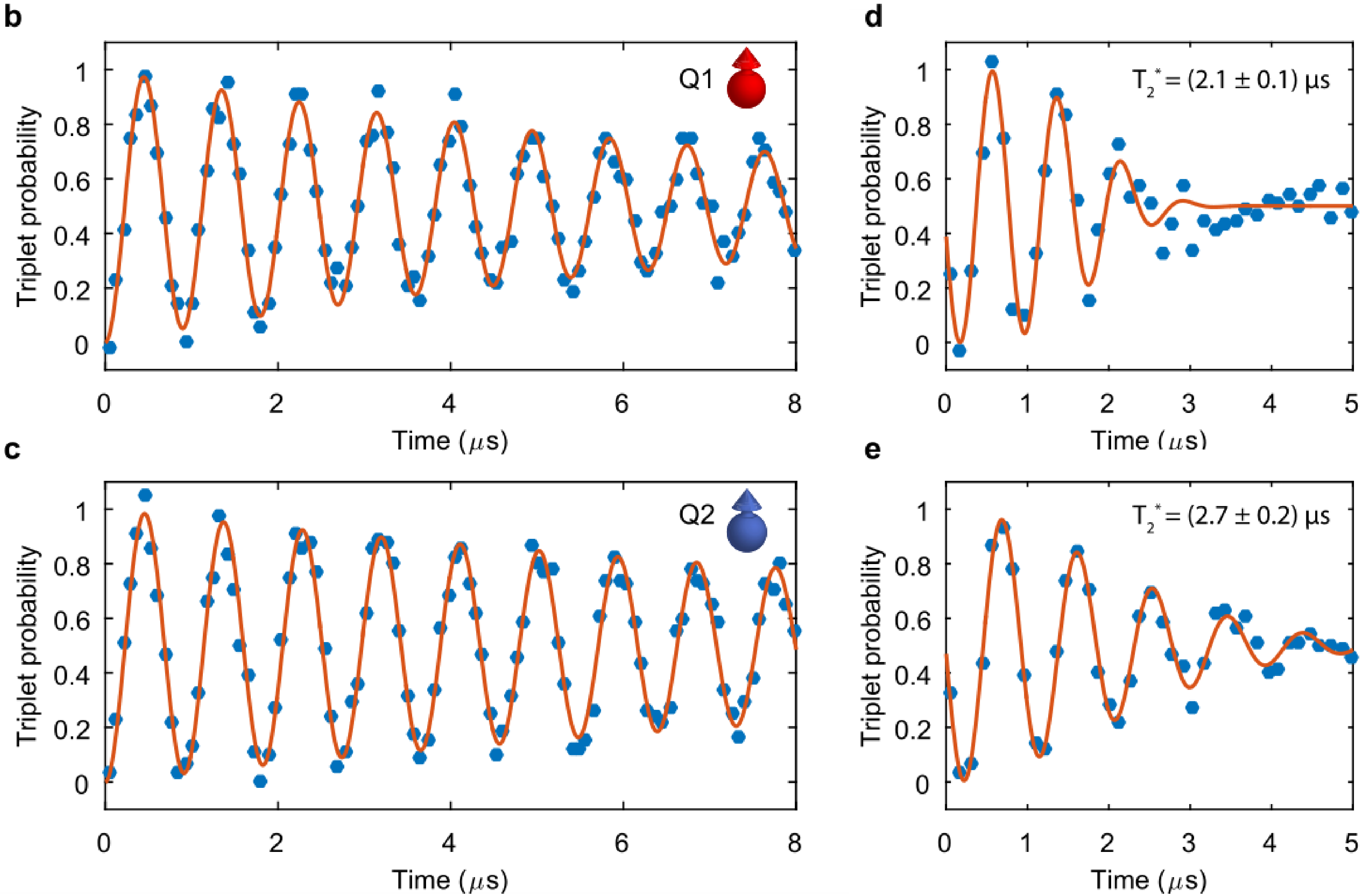


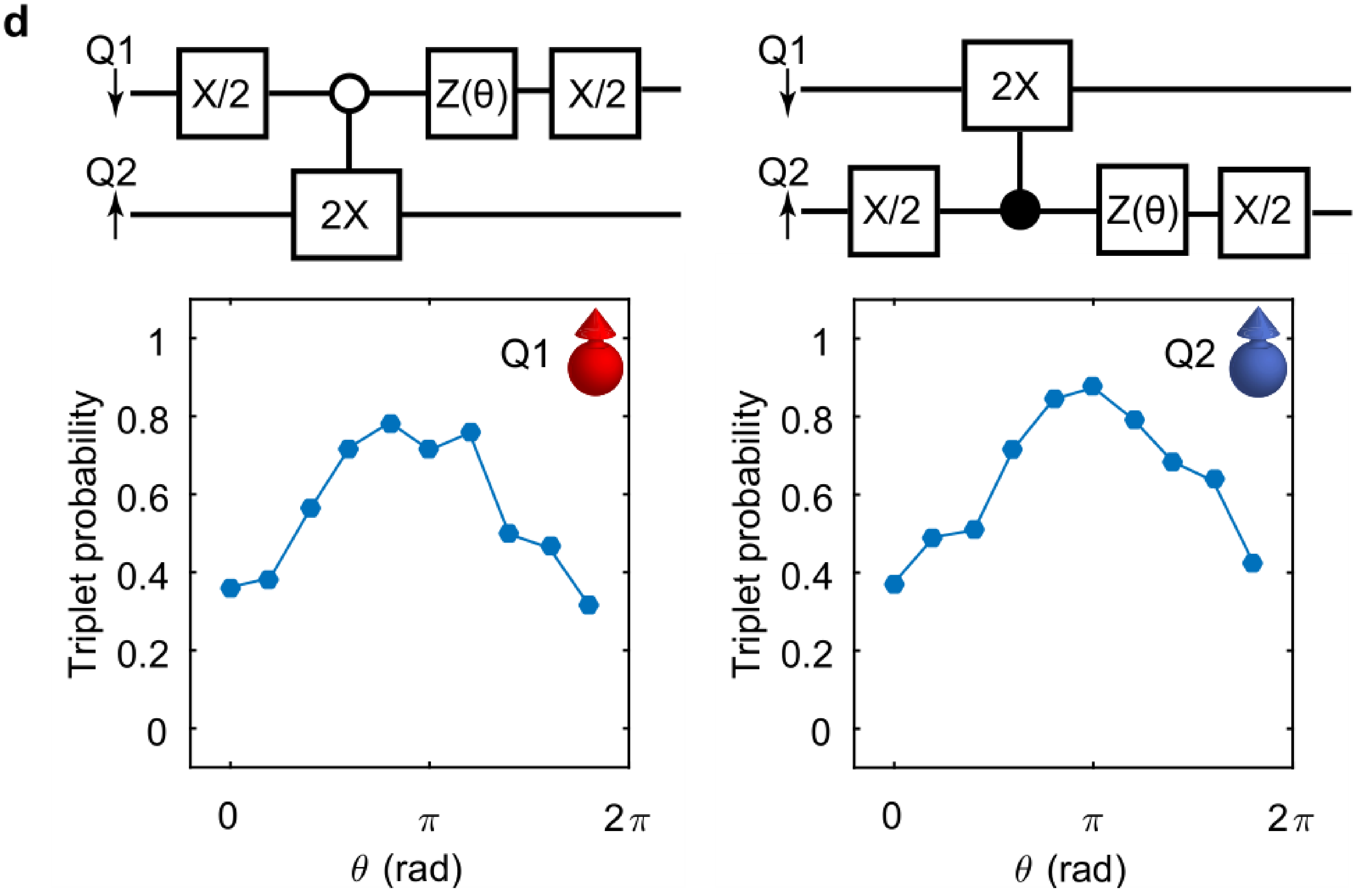
- CROT is realized at all 4 transitions

Conclusion

- single-qubit gates at 1.1K with high fidelity (99%)
- CROT gate for universal quantum computing at 1.1K
- T_2^* independent of temperature
- 2 qubit readout? readout fidelity at high T?
- scalability of qubit-interactions?

Appendix


b
Q1
Triplet probability
0
0.2
0.4
0.6
0.8
1
0
2
4
6
8
Time (μs)
c
Q2
Triplet probability
Time (μs)
d
$T_2^* = (2.1 \pm 0.1)$ μs
Triplet probability
0
1
2
3
4
5
Time (μs)
e
$T_2^* = (2.7 \pm 0.2)$ μs
Triplet probability
Time (μs)


d
Q1
Q2
X/2
2X
Z(θ)
X/2
Q1
Q2
2X
X/2
Z(θ)
X/2
Triplet probability
1
0.8
0.6
0.4
0.2
0
0
π
2π
θ (rad)
Q1
Triplet probability
1
0.8
0.6
0.4
0.2
0
0
π
2π
θ (rad)
Q2