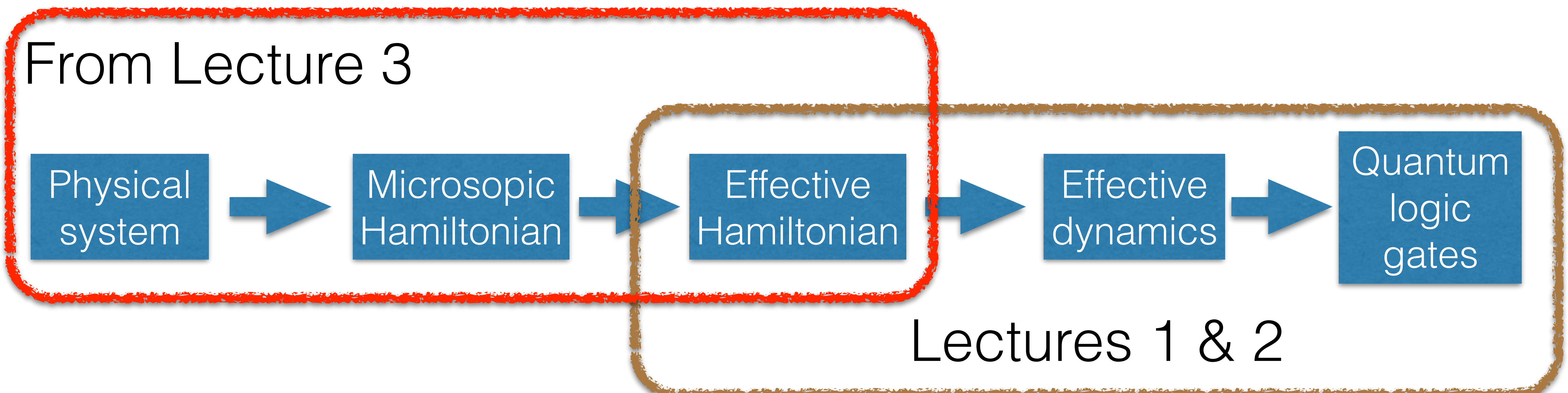
Quantum Computing Architectures

Budapest University of Technology and Economics
2018 Fall

Lecture 3
Qubits based on the electron spin



Schedule of this course

Szerda		
augusztus 29. - Regisztrációs hét -		
szeptember 5.	lecture 01	**Introduction**
szeptember 12.		
szeptember 19.	lecture 02	
szeptember 26. TTK Dékáni szünet		
október 3.	lecture 03 (today)	**Spin qubits** (electron spin)
október 10.		
október 17.	lecture 04	
október 24.	lecture 05	
október 31.	lecture 06	**Superconducting qubits** (transmon)
november 7.	lecture 07	
november 14. TDK konferencia		
november 21.	lecture 08	
november 28.	lecture 09	
december 5.	lecture 10	

Qubit Checklist

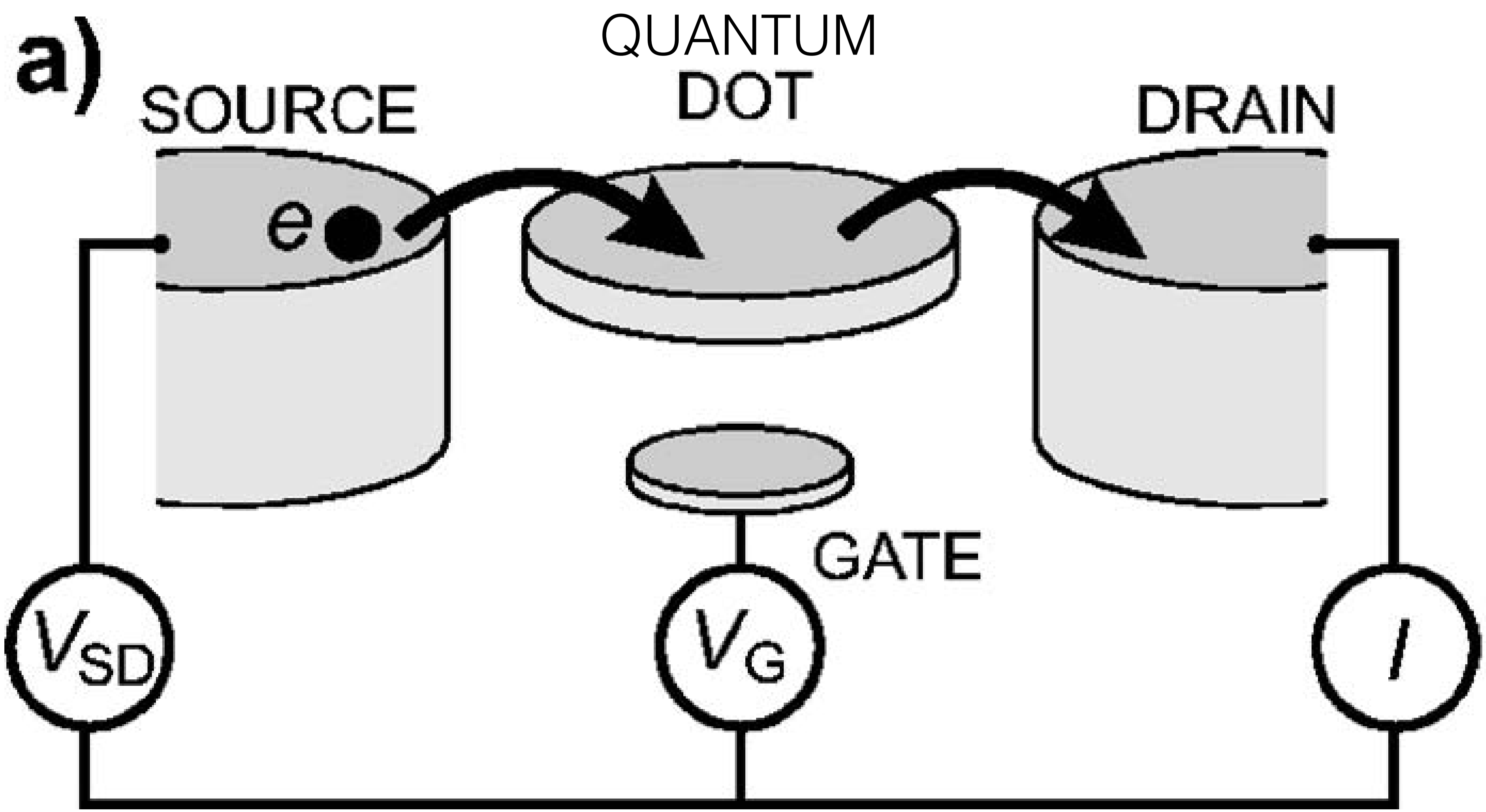
1. make a few qubits
2. initialize
3. control (1-qubit gate, 2-qubit gate)
4. read out
5. understand and reduce information loss

today

Qubits based on the electron spin (Spin qubits)

review papers: Hanson et al., Rev. Mod. Phys. (2007), Zwanenburg et al., Rev. Mod. Phys. (2013)

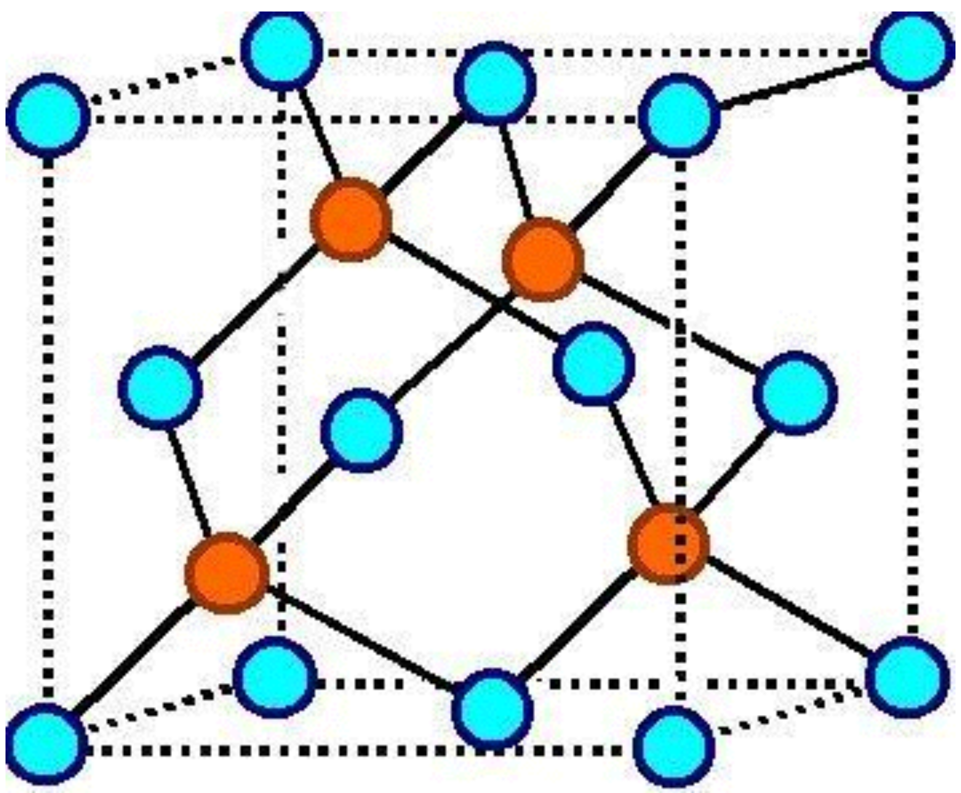
Make a qubit



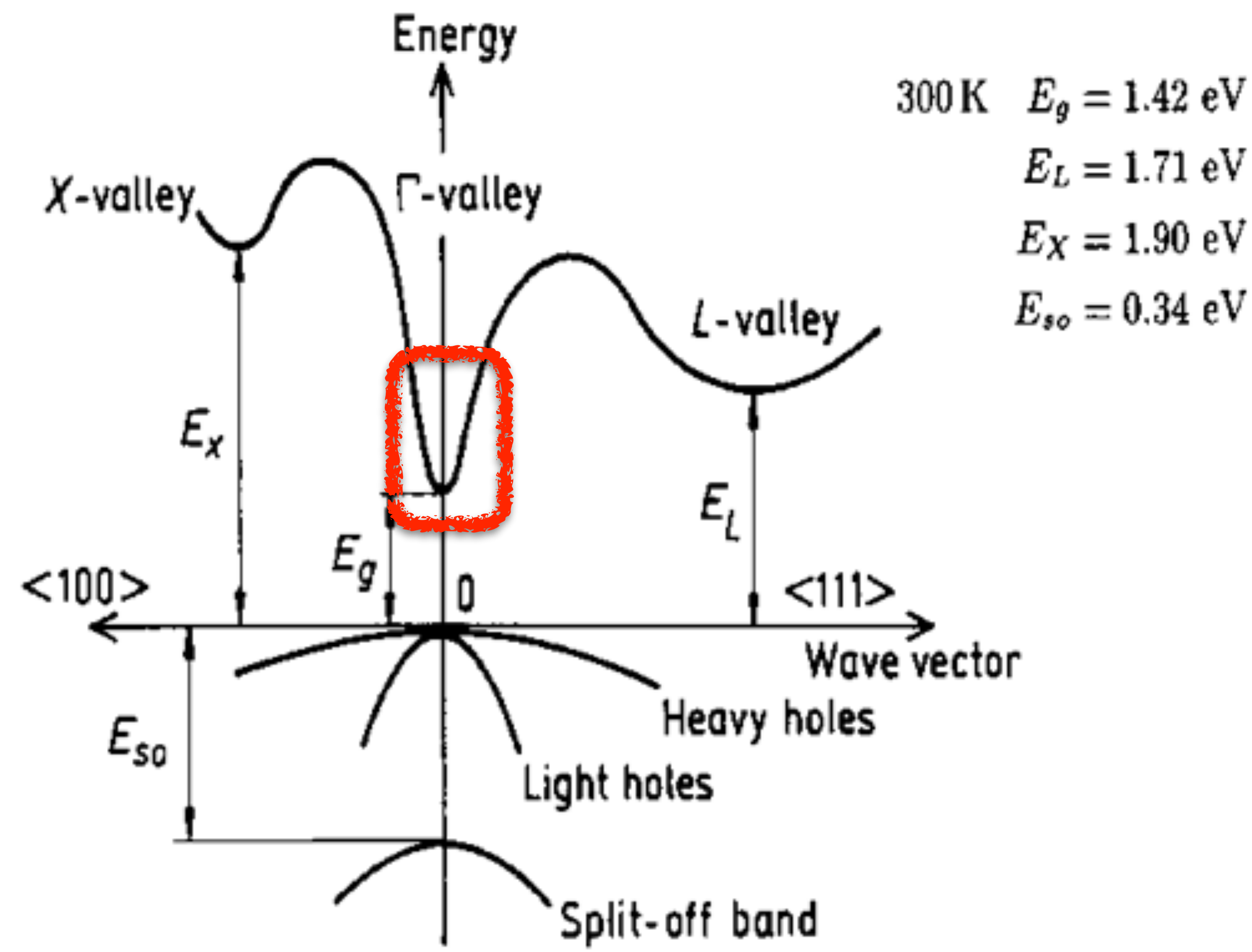
Gate voltage tunes the number of electrons in the quantum dot

Workhorse material: GaAs

crystal structure:
zinc-blende



electronic
band structure

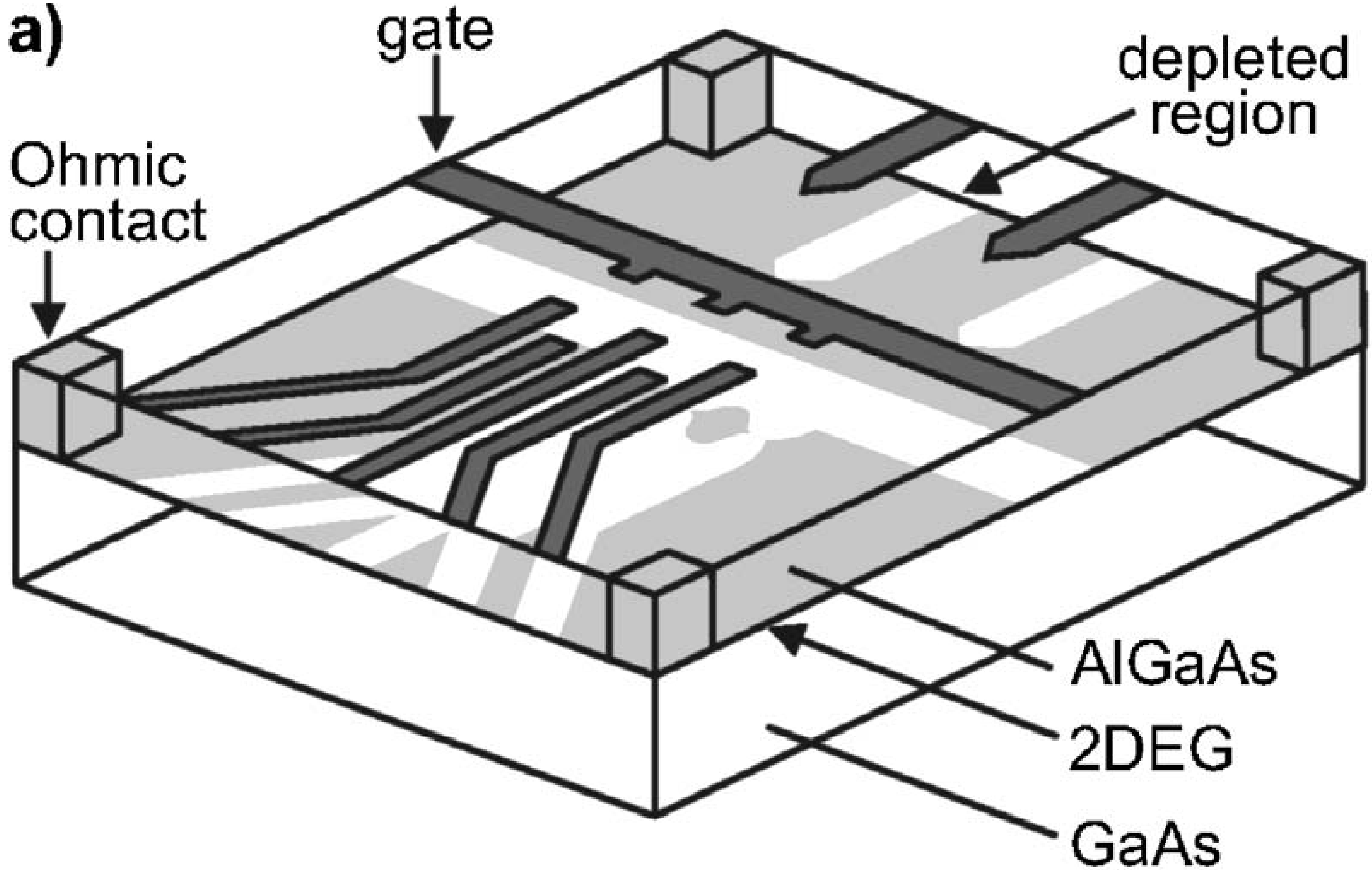


conduction-band effective mass: $m = 0.063\, m_\mathrm{e}$

static dielectric constant: $\epsilon_r = 12.9$

effective g-factor $g^* = -0.4$

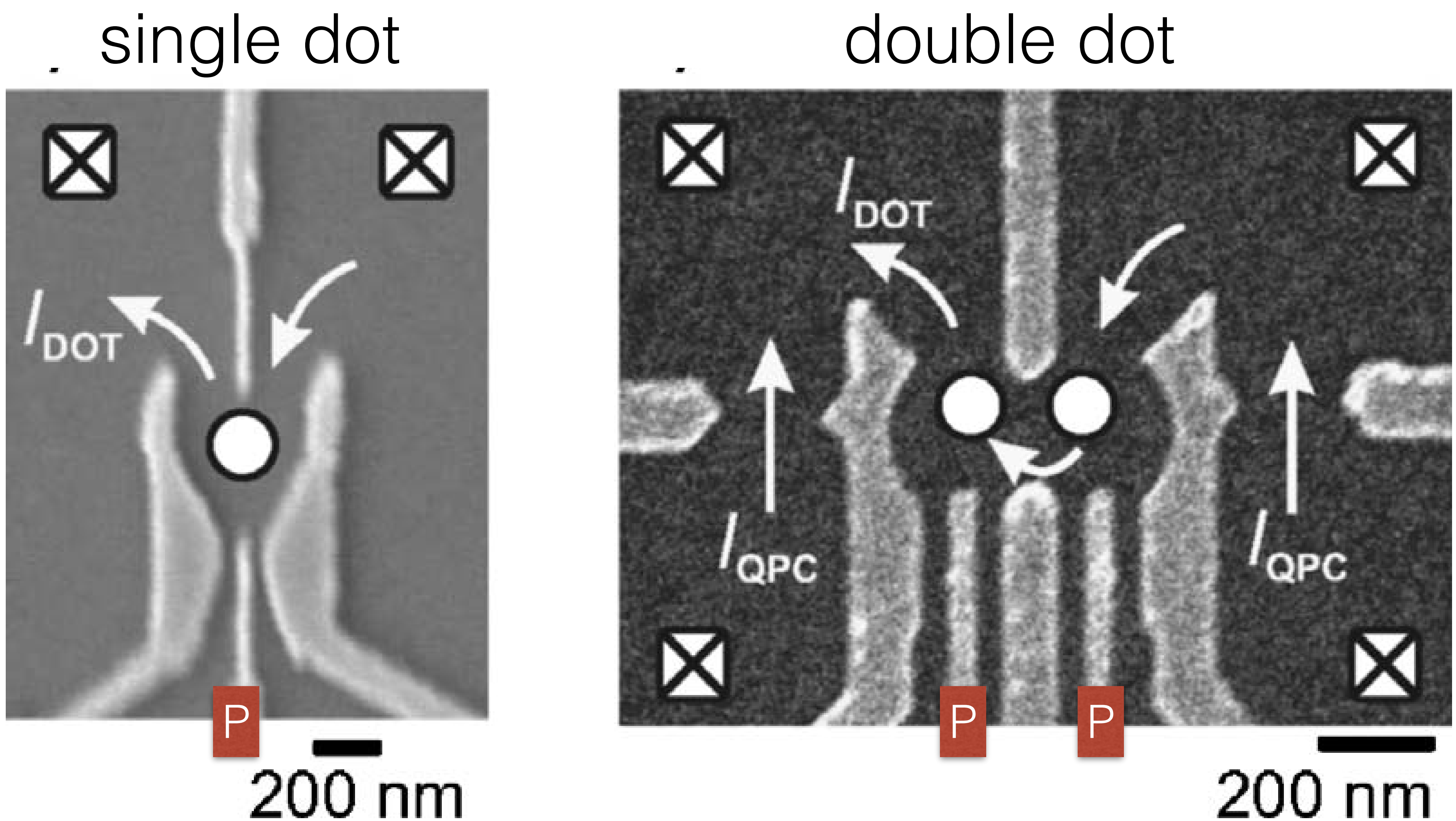
A double quantum dot in a semiconductor heterostructure



2DEG (2D electron gas) confined in GaAs at the GaAs/AlGaAs interface

AlGaAs layer height ~ 30 nm, gate features ~ 50 nm

Top view of the gate structure

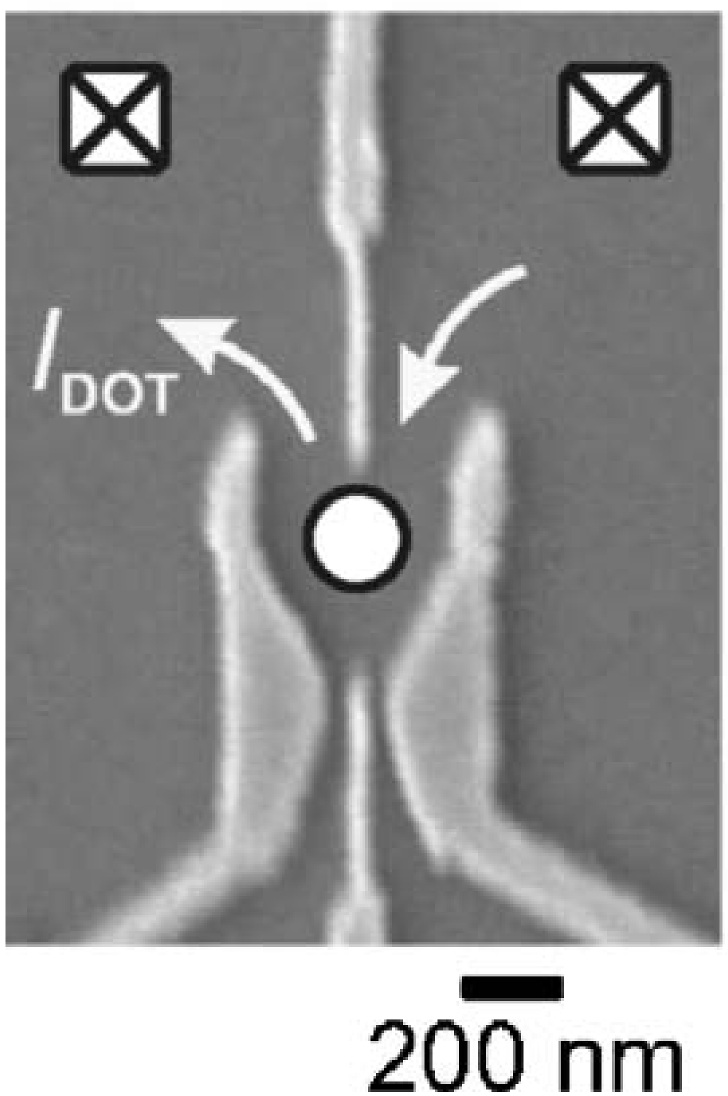


P: Plunger gates: tune (mostly) the on-site potential energy

QPC: Quantum Point Contact; used as a charge sensor

Energy scales

confinement energy, charging energy, thermal energy



Assume circular confinement:

$$H = \frac{p_x^2 + p_y^2}{2m} + \frac{1}{2} m\omega_0^2 (x^2 + y^2)$$

Energy spectrum: $E_{n,m} = \hbar\omega_0 (n + m + 1)$

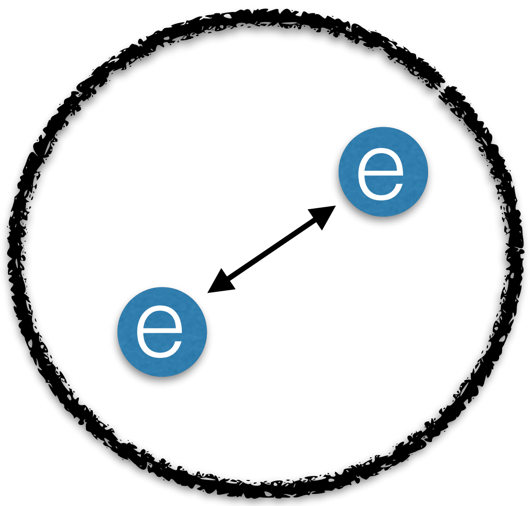
Orbital level spacing:
(a.k.a. *confinement energy*) $E_{\rm orb} = \hbar\omega_0$

Spatial extension of ground state:
(a.k.a. *oscillator length*)
(a.k.a. *confinement length*) $\ell = \sqrt{\frac{\hbar}{m\omega_0}}$

Homework: assume 50 nm confinement length in GaAs;
then, what is the confinement energy? It is ~0.5 meV.

Energy scales

confinement energy, charging energy, thermal energy



charging energy estimate: $U \sim \frac{e^2}{4\pi\epsilon_0\epsilon_r\ell}$

for GaAs, with $\ell = 50$ nm, $U \approx 2.2$ meV

thermal energy at 300 K: $k_B T \approx 30$ meV

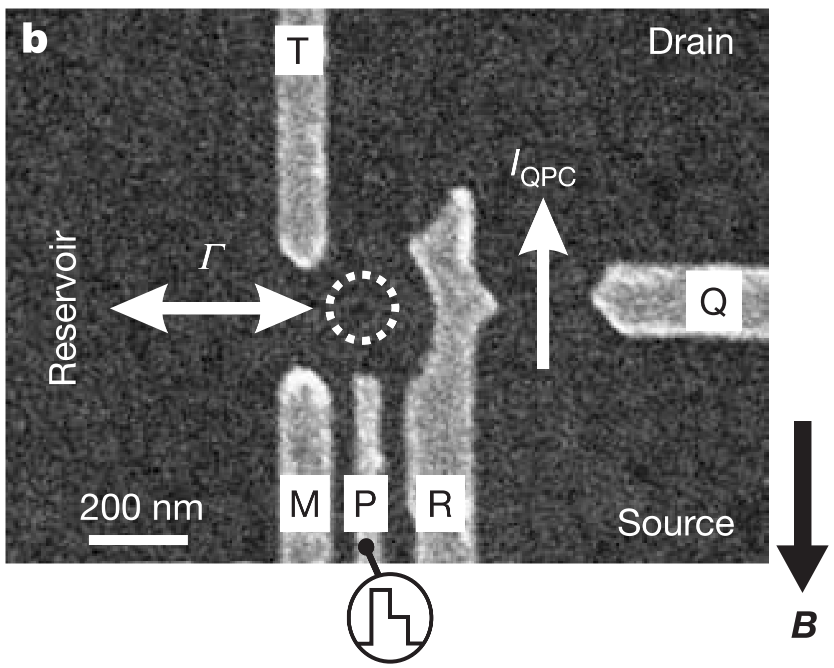
thermal energy at 100 mK: $k_B T \approx 10\,\mu$eV

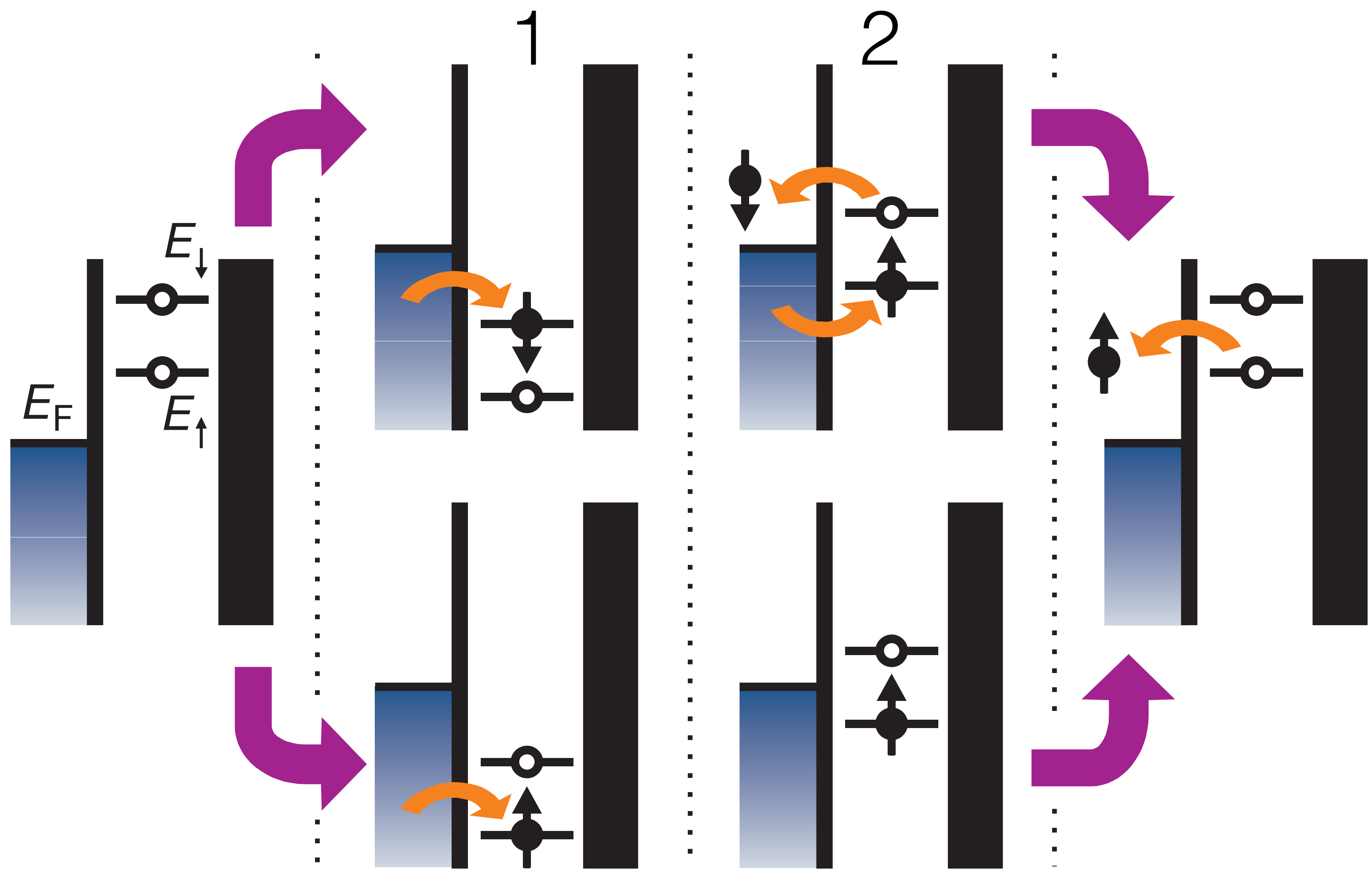
thermal E << confinement E, charging E
required to confine a single electron on a single level

Experiments are done at T ~ 100 mK

Readout of a spin qubit

Γ: tunnel rate





Zeeman splitting:

$$E_\downarrow - E_\uparrow = g^* \mu_B B \approx 230\mu\text{eV for } B = 10 \text{ T}$$

Step 1: load an electron (up or down)

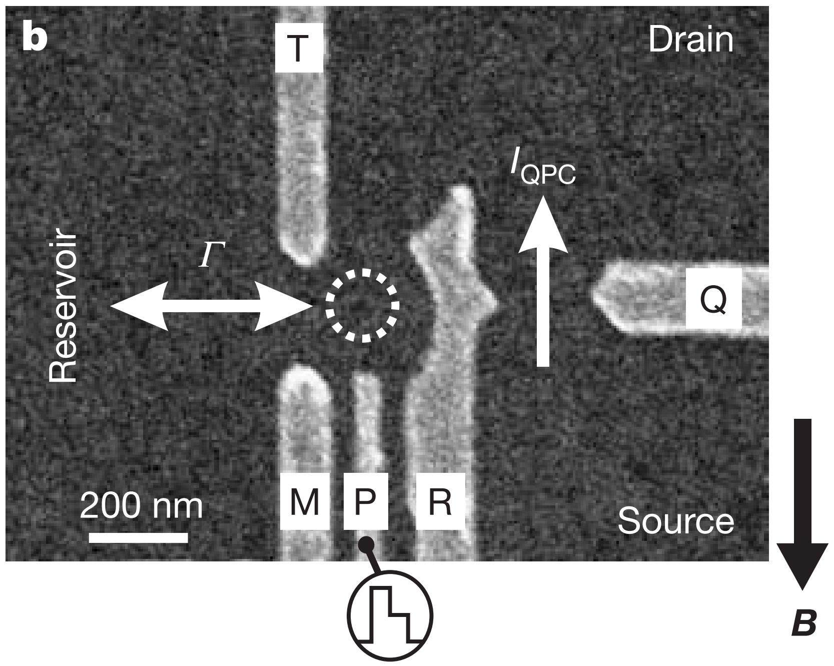
Goal = Readout = Distinguish between up and down

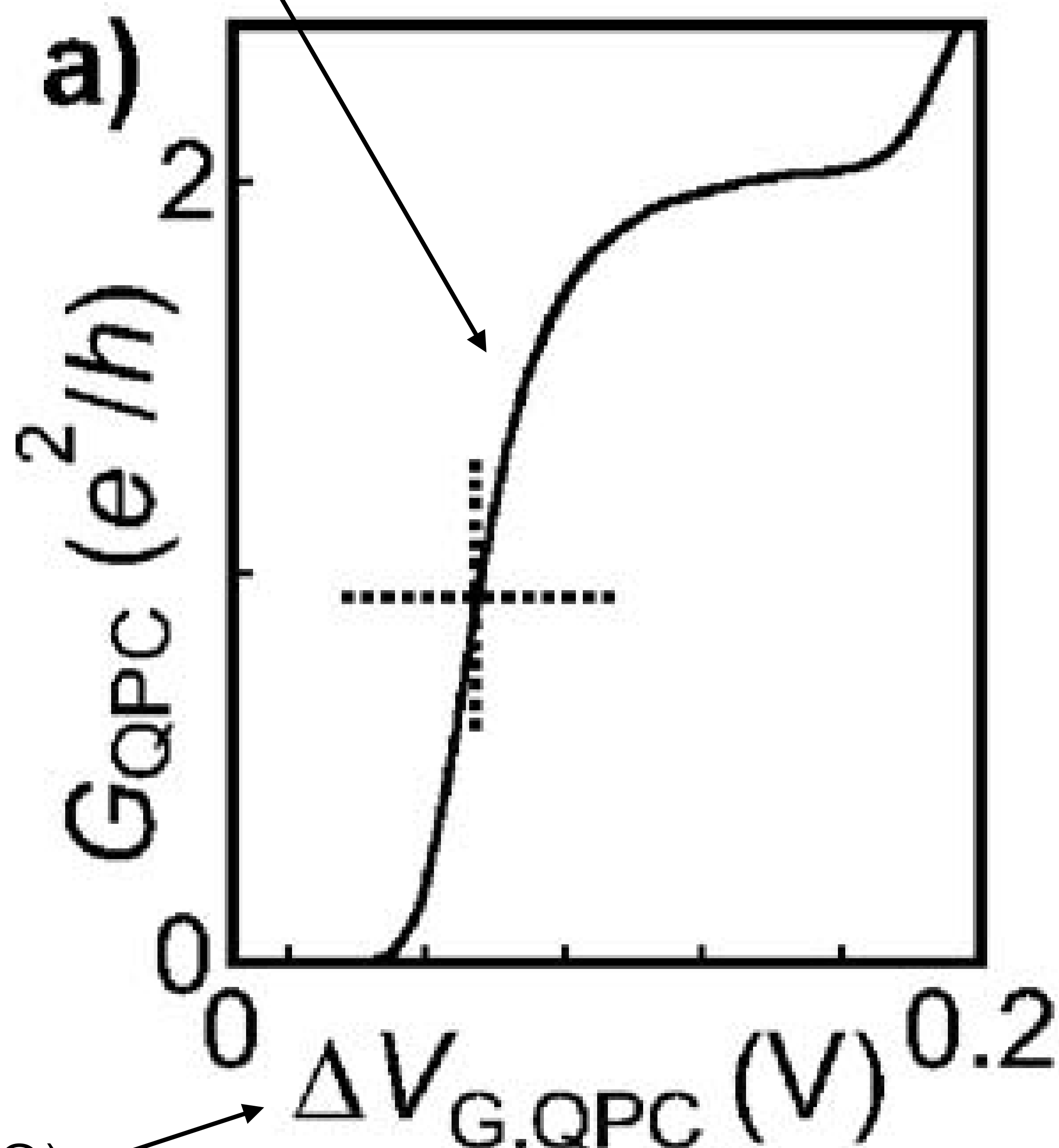
Step 2: spin is converted to charge

`Elzerman-style spin readout': Elzerman et al., Nature (2004)

Dot charge is detected by Quantum Point Contact

conductance or current
through QPC



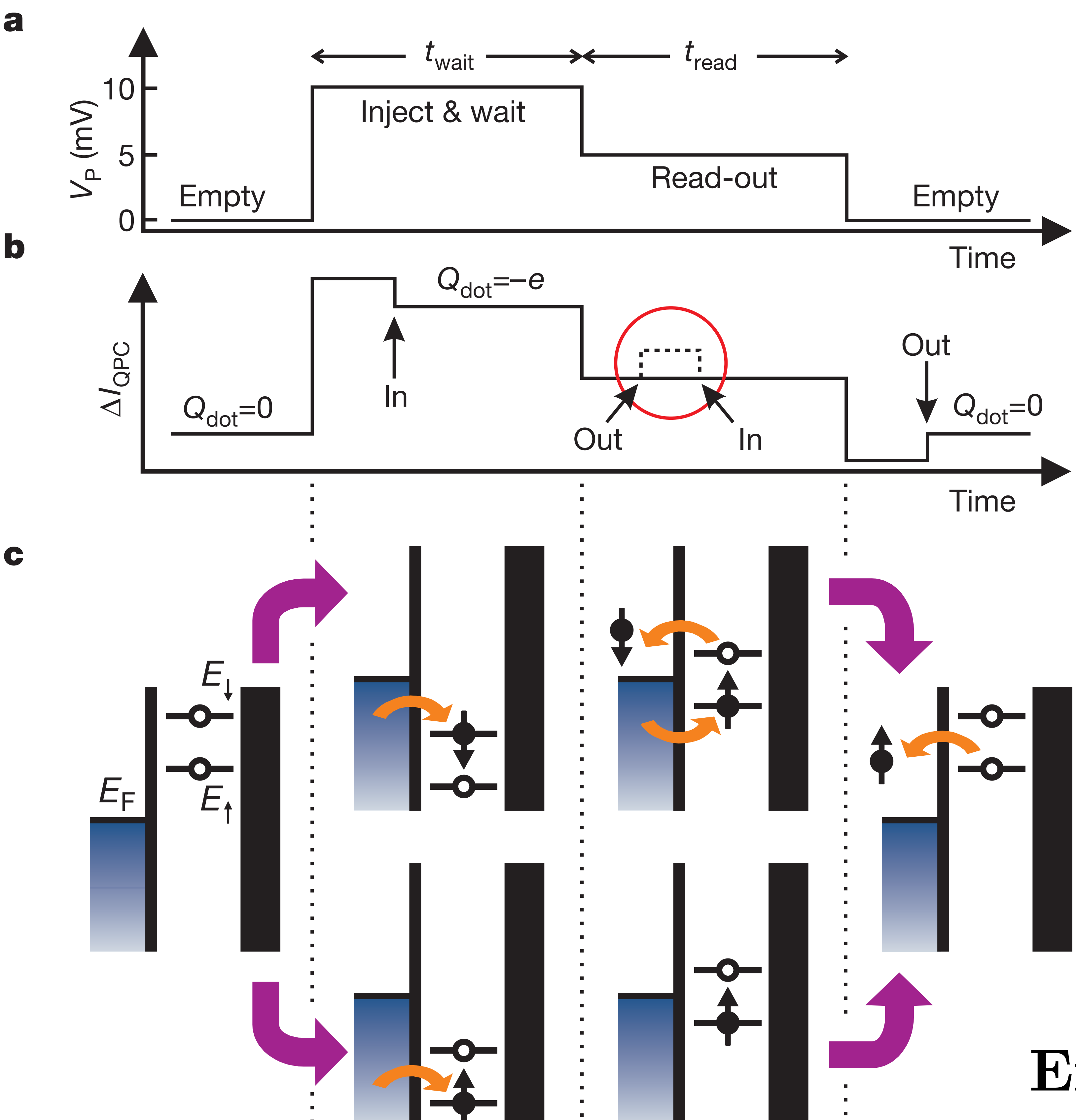


QPC current is sensitive to

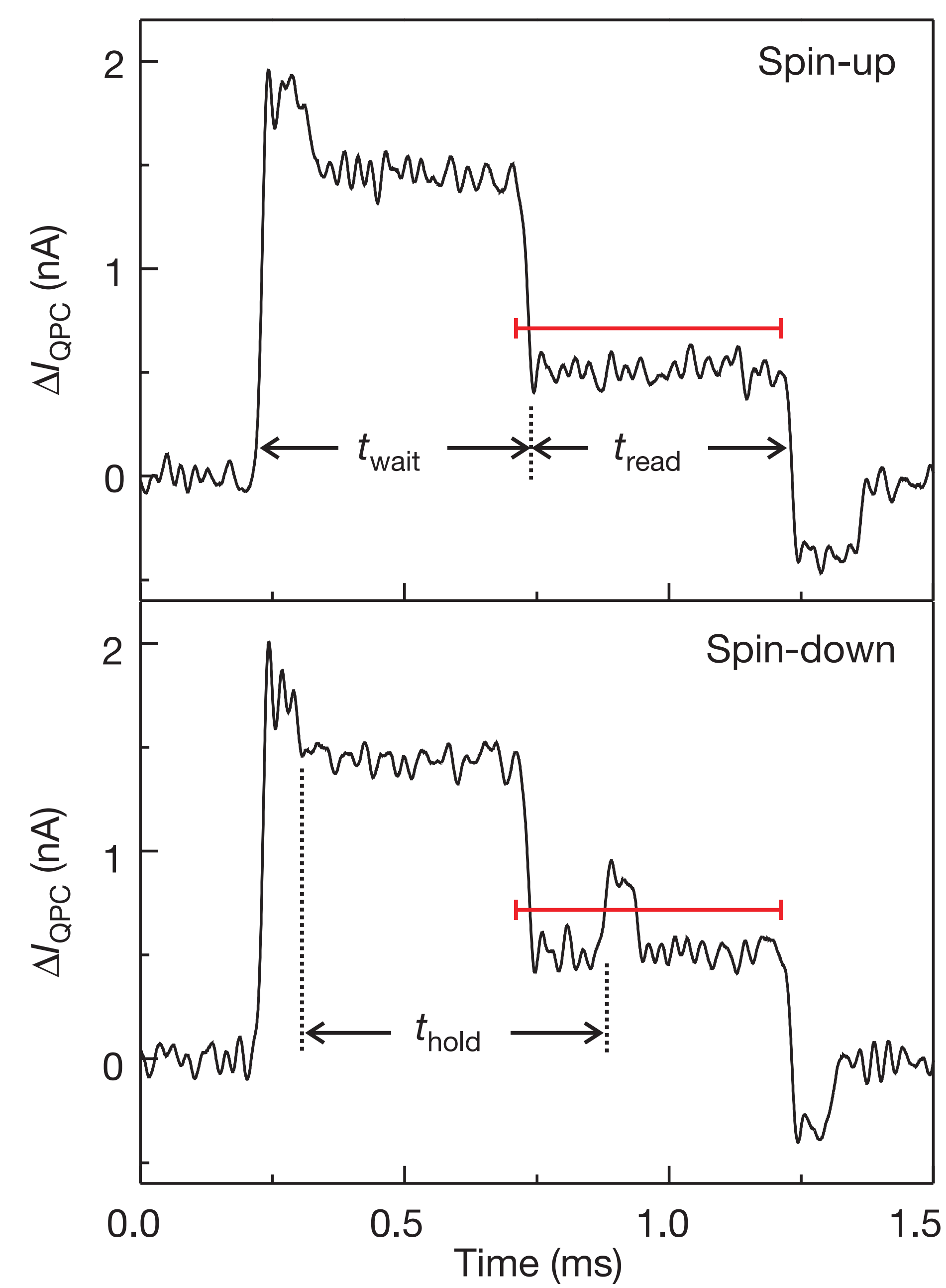
- its own gate voltage Q
- any other gate voltage M, P, R, T
- <u>number of electrons in the dot</u>

QPC gate voltage (Q)

Spin Down: blip in the current (dashed).
Spin Up: no blip (solid).



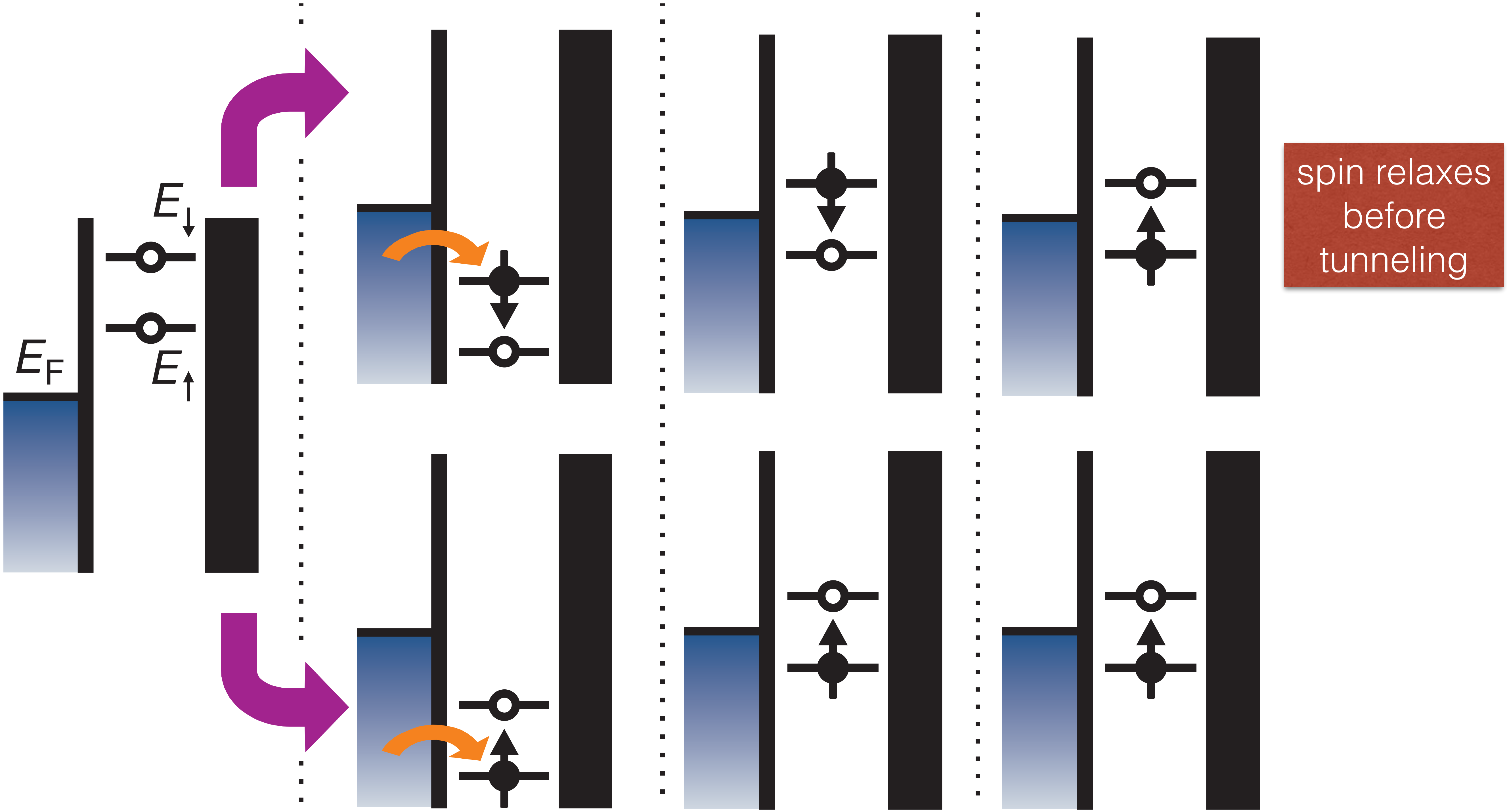
Data from the experiment:



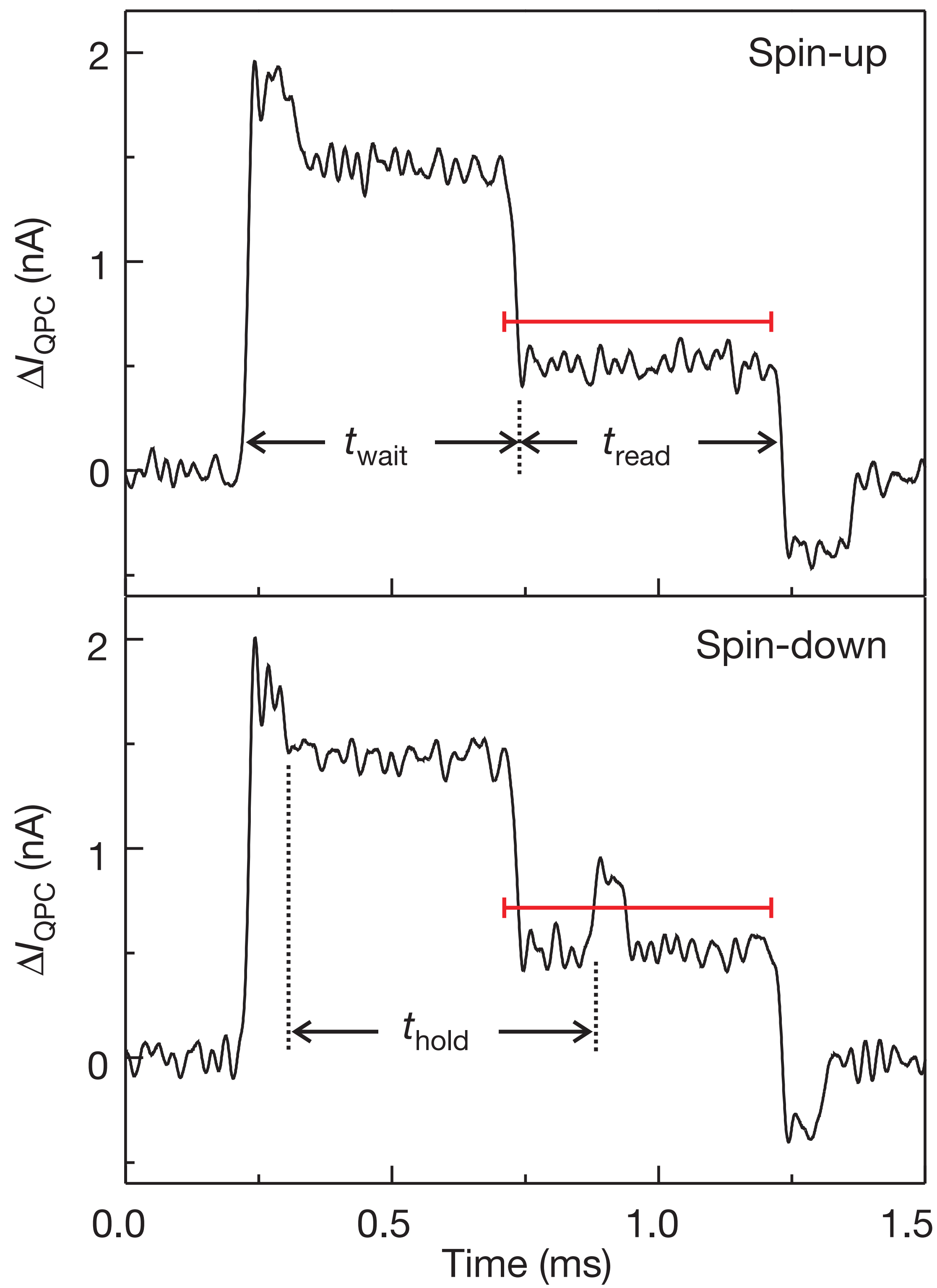
Exercise: estimate the tunnel rate Γ from the data.

Readout is wrong if spin relaxation is too fast

fast spin relaxation: $\Gamma \ll \Gamma_{\mathrm{spin}}$

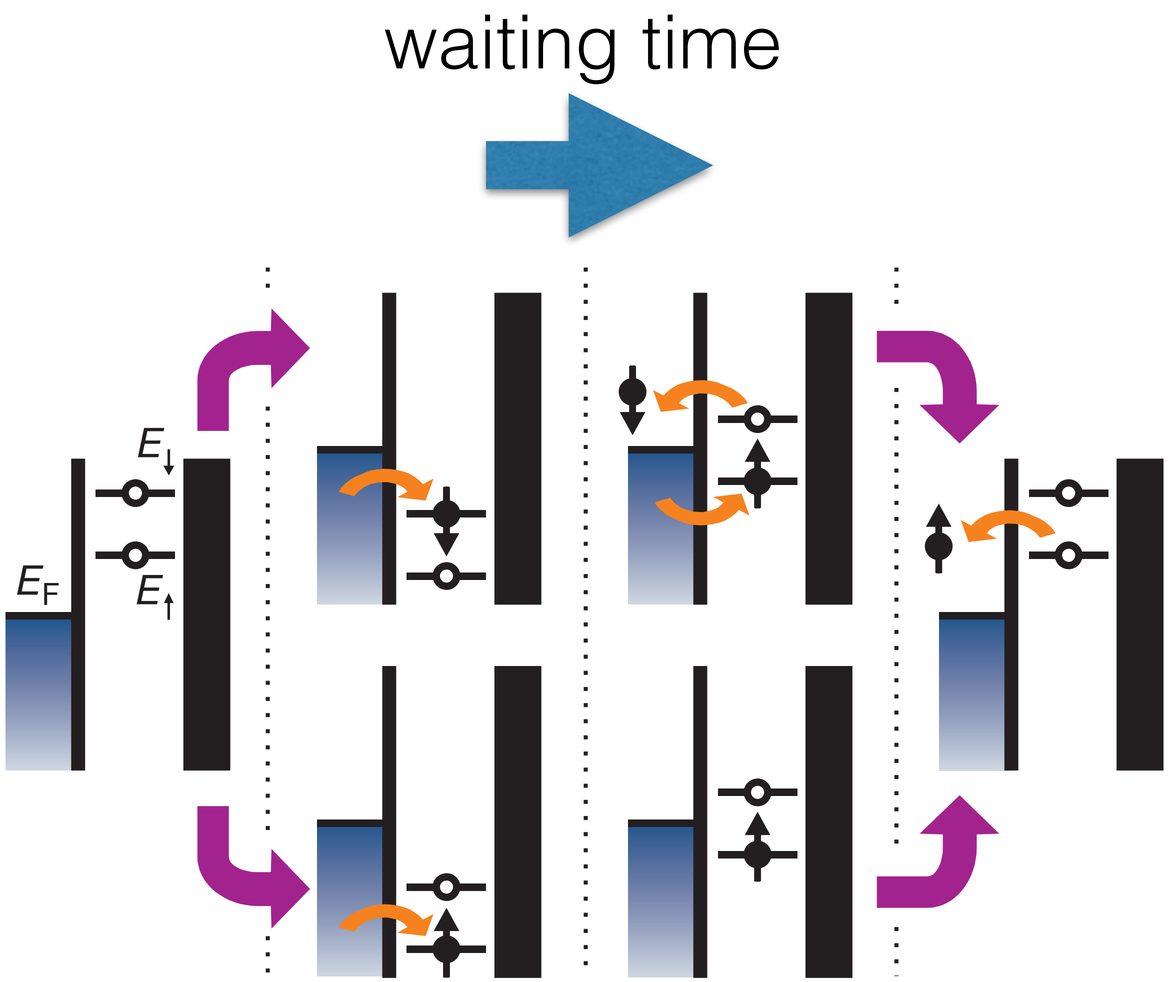


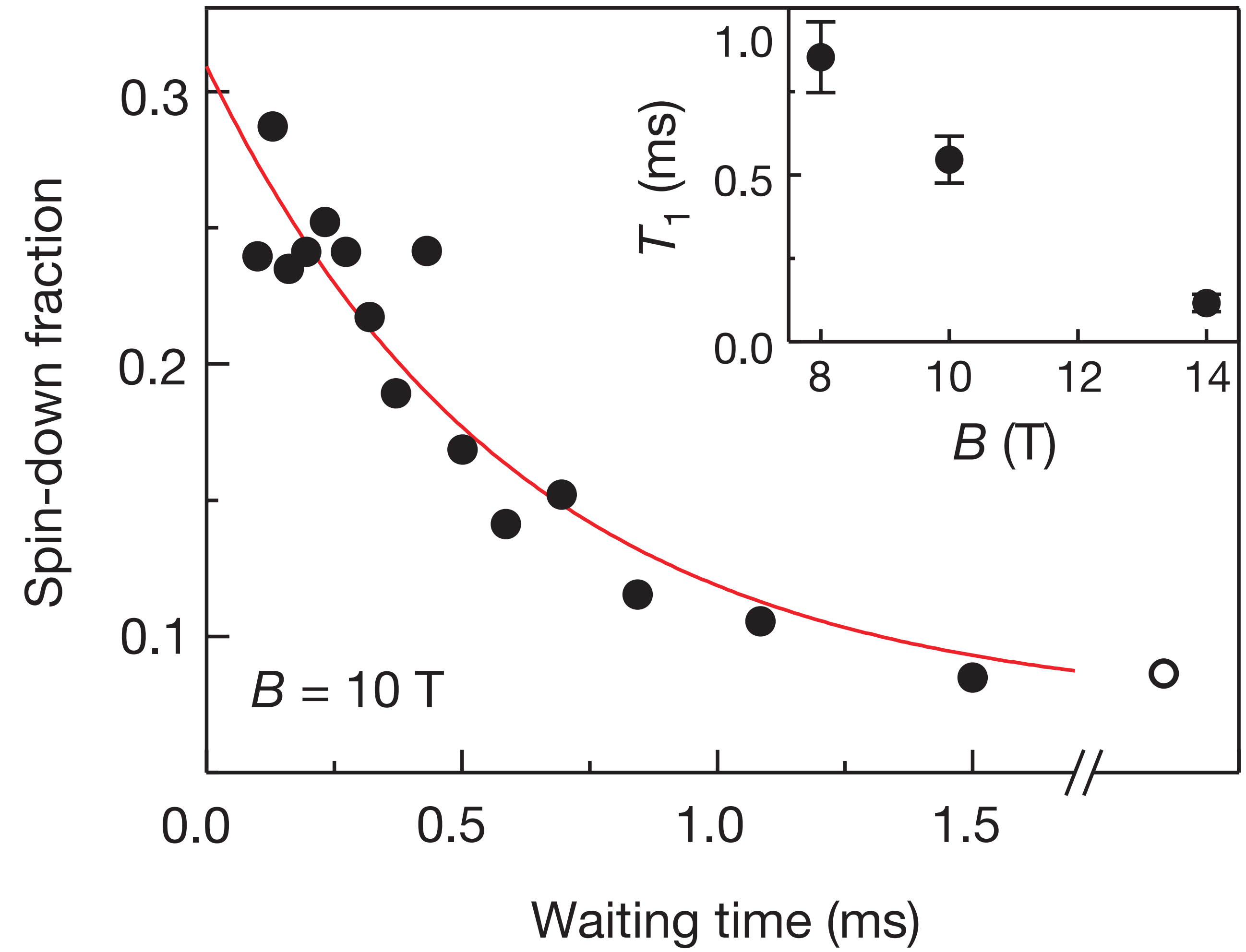
Elzerman-style spin readout is rather slow



Readout time scale: millisecond. Control time scale (q-gates): microsecond.

A basic application: measurement of spin relaxation time

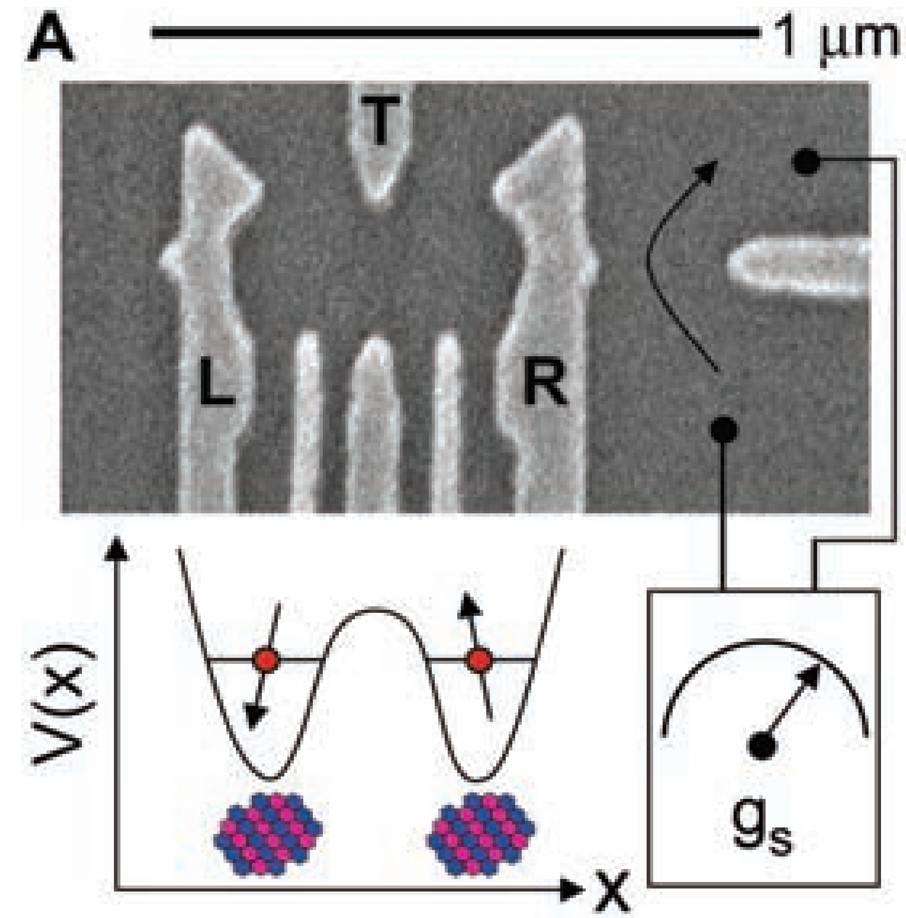




spin relaxation: exponential decay, $P_\downarrow(t_\text{wait}) \approx \frac{1}{2} e^{-\frac{t_\text{wait}}{T_\text{spin}}} = \frac{1}{2} e^{-\Gamma_\text{spin} t_\text{wait}}$

For increasing B-field, spin relaxation gets faster.

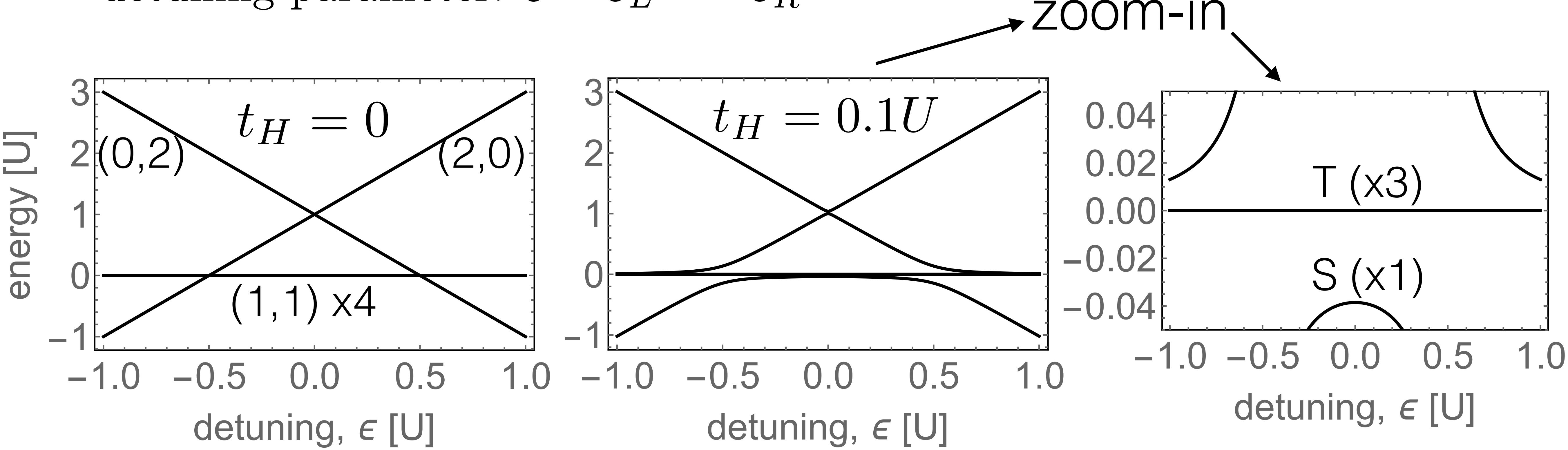
Spin-to-charge conversion in a double dot



Two-site Hubbard model:

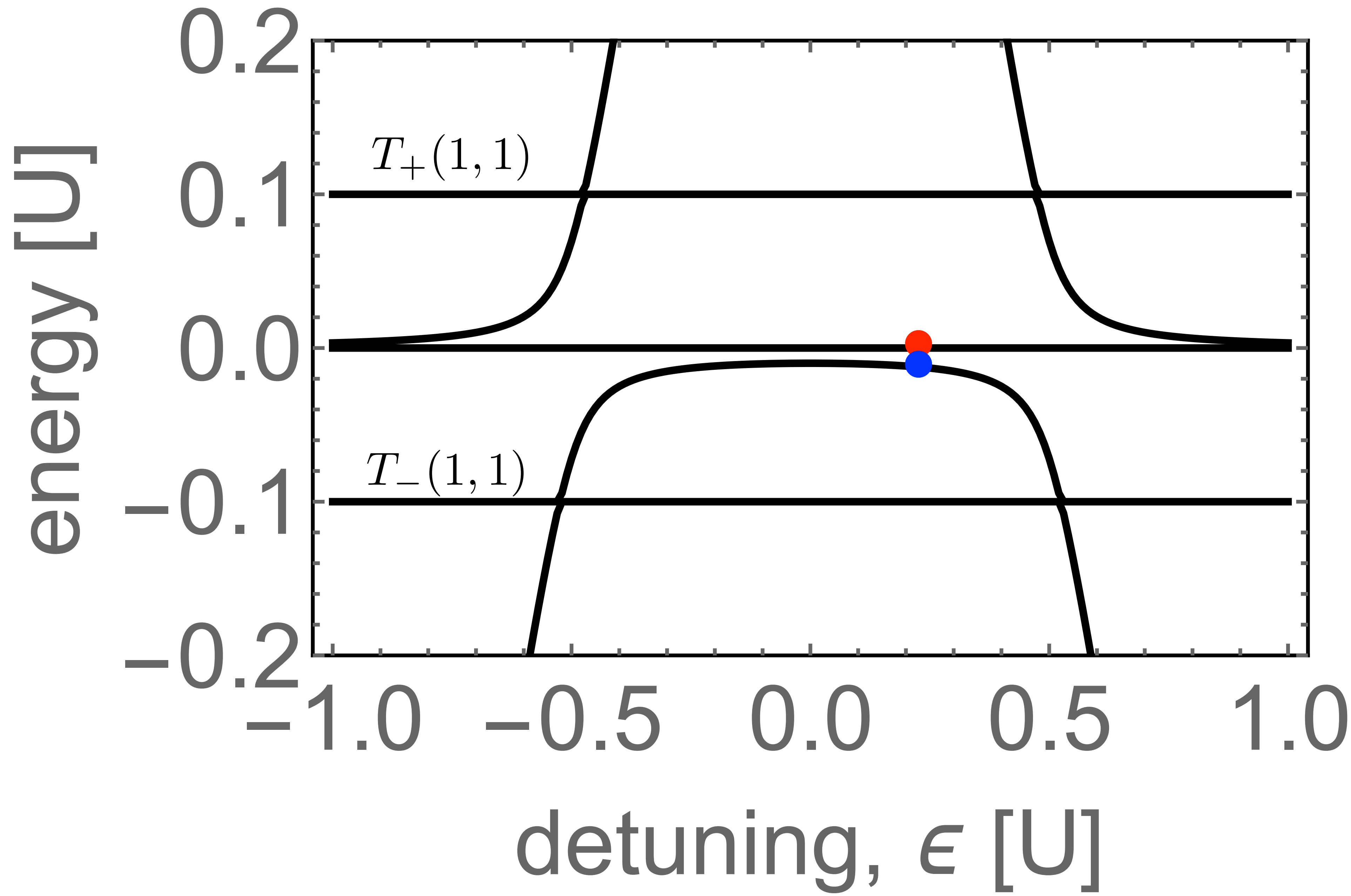
$$H_{\text{Hubbard}} = H_{\text{on-site}} + H_{\text{tun}} + H_{\text{Coulomb}}$$
$$H_{\text{on-site}} = \varepsilon_L n_L + \varepsilon_R n_R$$
$$H_{\text{tun}} = t_H \left(a^\dagger_{L\uparrow} a_{R\uparrow} + a^\dagger_{L\downarrow} a_{R\downarrow} + h.c. \right)$$
$$H_{\text{Coulomb}} = U(n_{L\uparrow} n_{L\downarrow} + n_{R\uparrow} n_{R\downarrow})$$

detuning parameter: $\varepsilon = \varepsilon_L = -\varepsilon_R$



Spin-to-charge conversion in a double dot

add magnetic field:

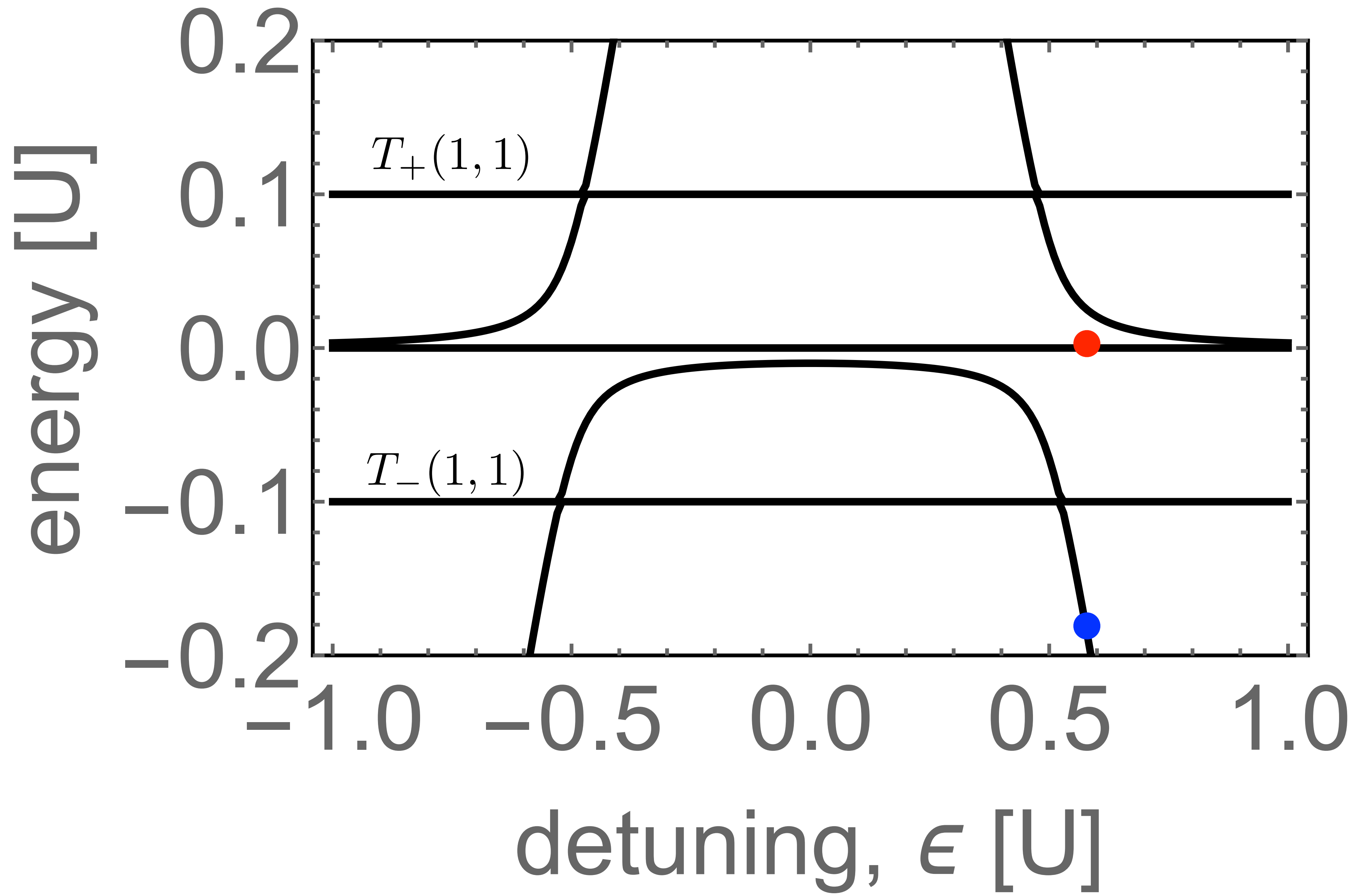


$$\psi_i = \alpha \, |S(1,1)\rangle + \beta \, |T_0(1,1)\rangle$$

Task: do a measurement in the S-T_0 basis.

Spin-to-charge conversion in a double dot

add magnetic field:



Solution: sweep ϵ 'slowly' and then measure charge in right dot.

$$\psi_f = \alpha\,|S(0,2)\rangle + \beta e^{i\varphi}\,|T_0(1,1)\rangle$$

Summary of key results

1. a spin qubit can be defined in a quantum dot
2. Elzerman readout of a spin qubit
3. the relaxation of a spin qubit can be measured
4. two electrons can be used to define a singlet-triplet qubit
5. Pauli blockade readout of a singlet-triplet qubit

Potential extensions

1. Pauli blockade: thermal $<<$ Zeeman not required
2. Pauli blockade readout for a spin qubit
3. readout based on gate reflectometry
4. ways to reduce the readout time
5. how to control the singlet-triplet qubit