Identifying and mitigating errors in hole spin qubit readout

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Presented by Aakash Shandilya
Thursday, 03/07/2025

Spin Readout

How do we do it?

Spin to Charge conversion

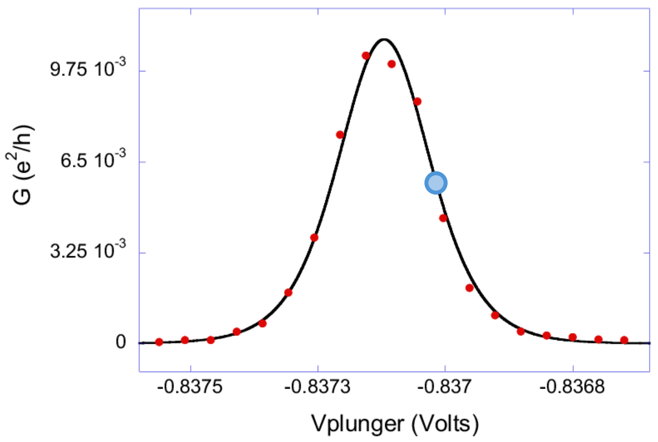
+

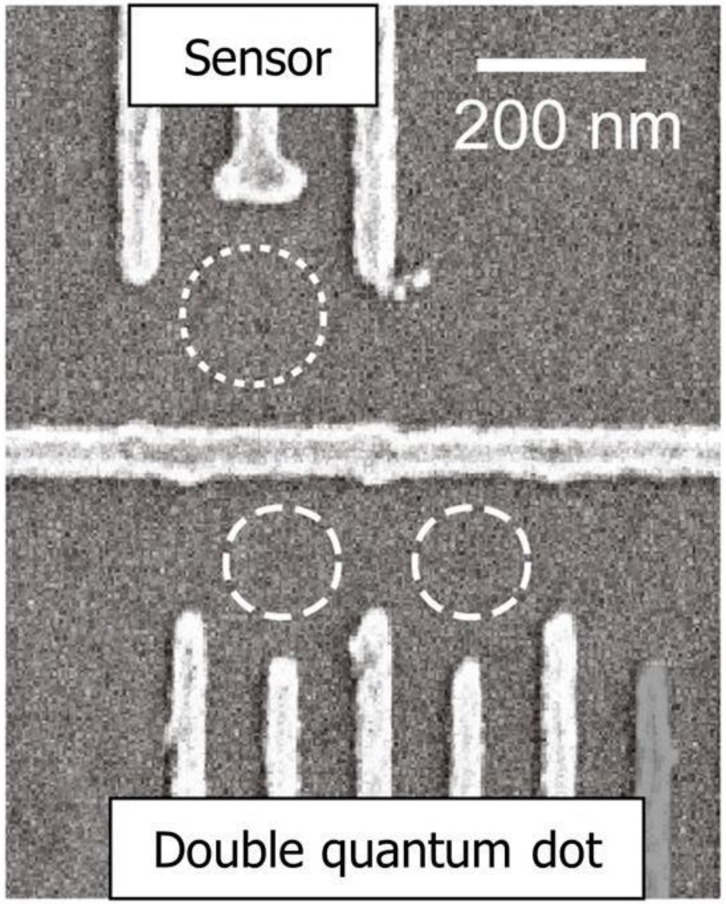
Charge readout

Charge readout

Charge sensor

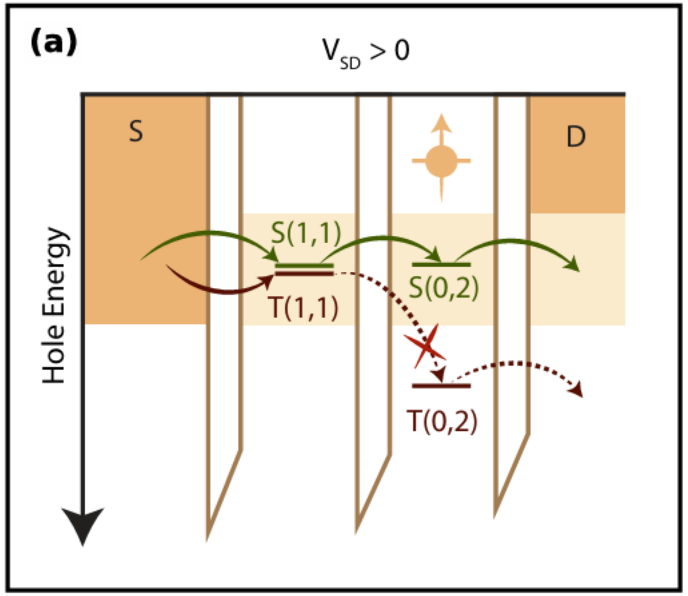
- Different coupling capacitances enable sensitivity to charge distribution.

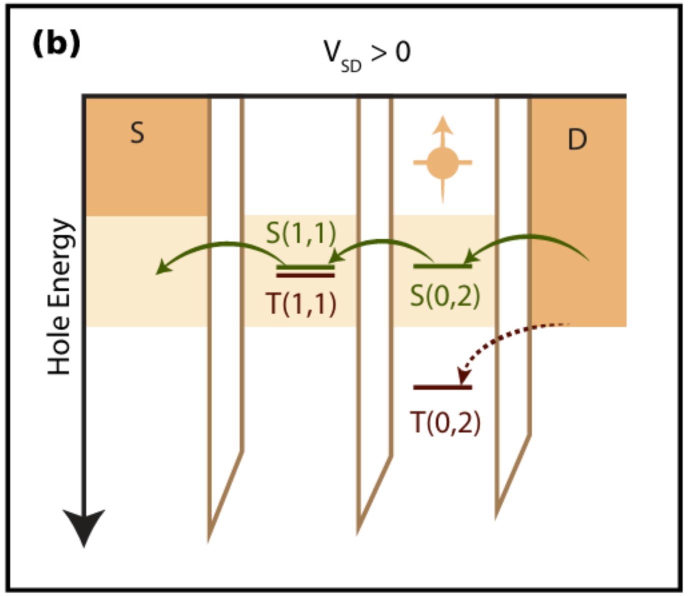


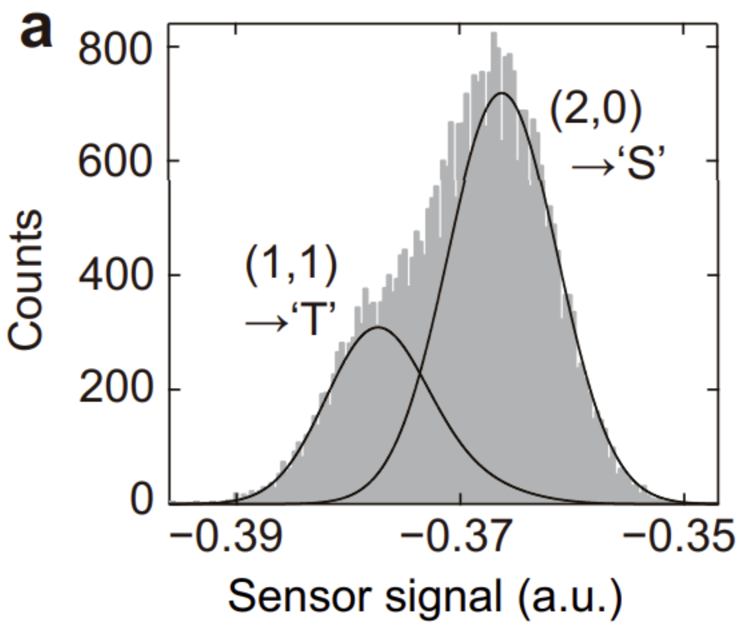


Spin to Charge conversion

Pauli spin blockade







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High-fidelity spin readout via the double latching mechanism

Haruki Kiyama, Danny van Hien, Arne Ludwig, Andreas D. Wieck & Akira Oiwa

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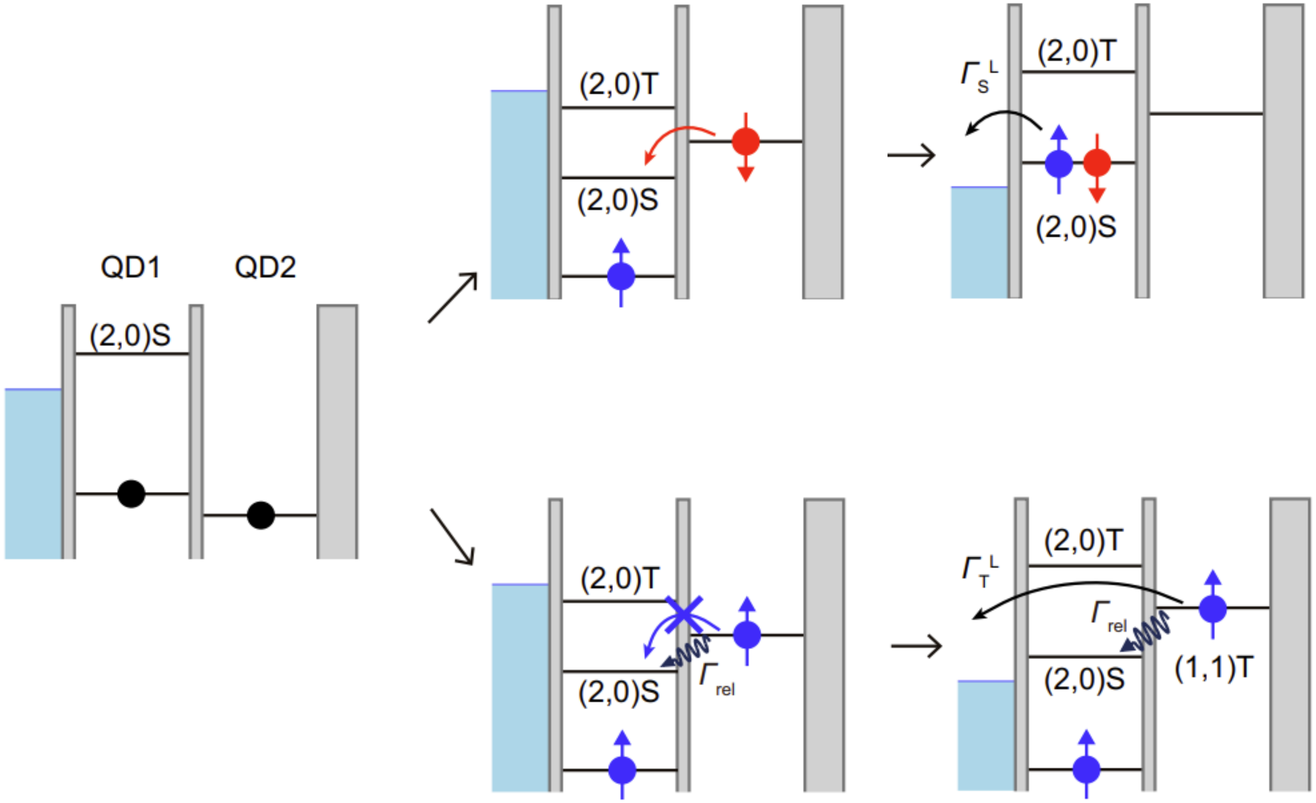
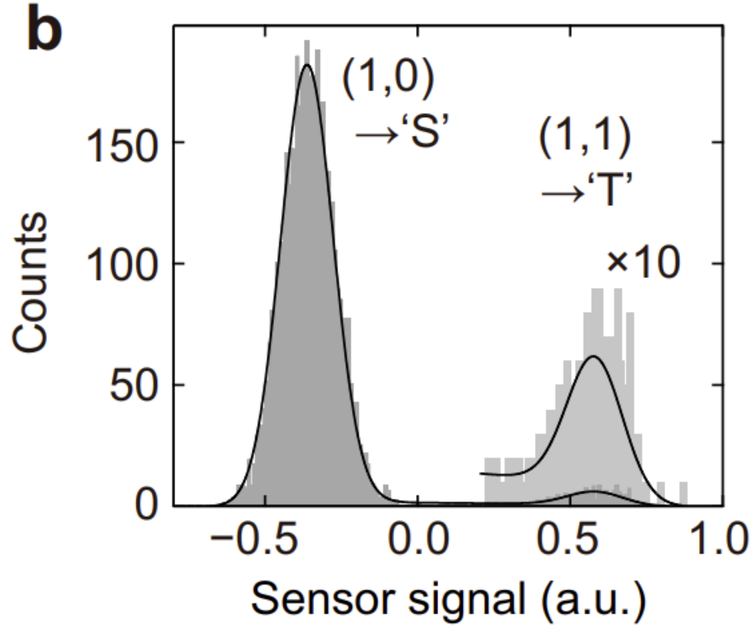
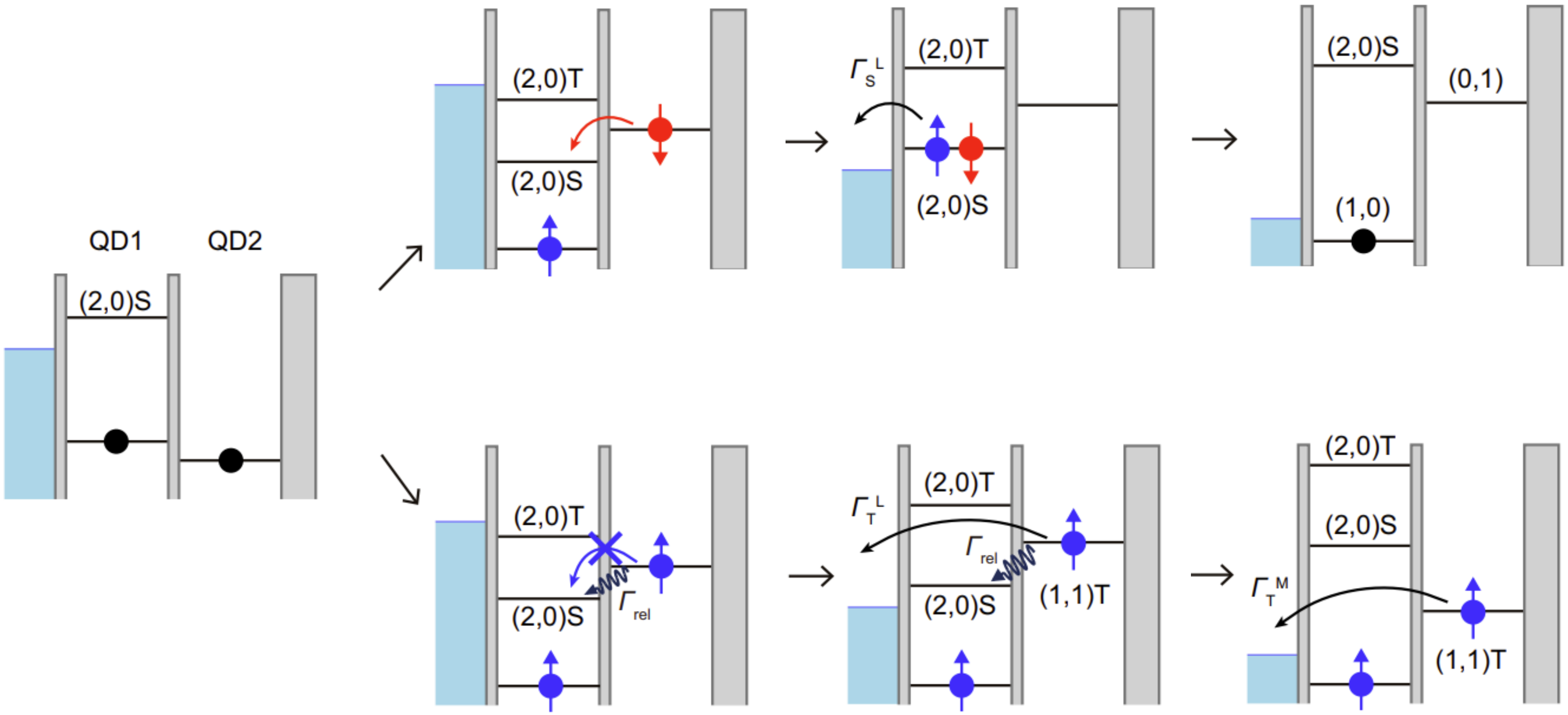
Single Latching

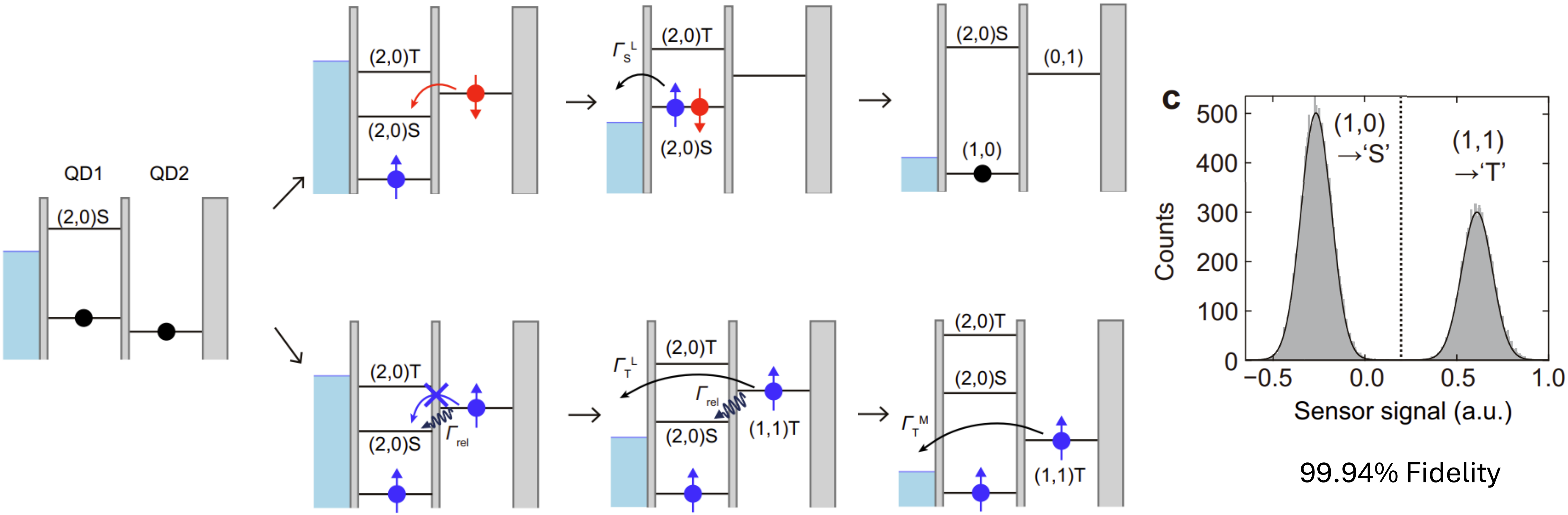




Double Latching



Double Latching

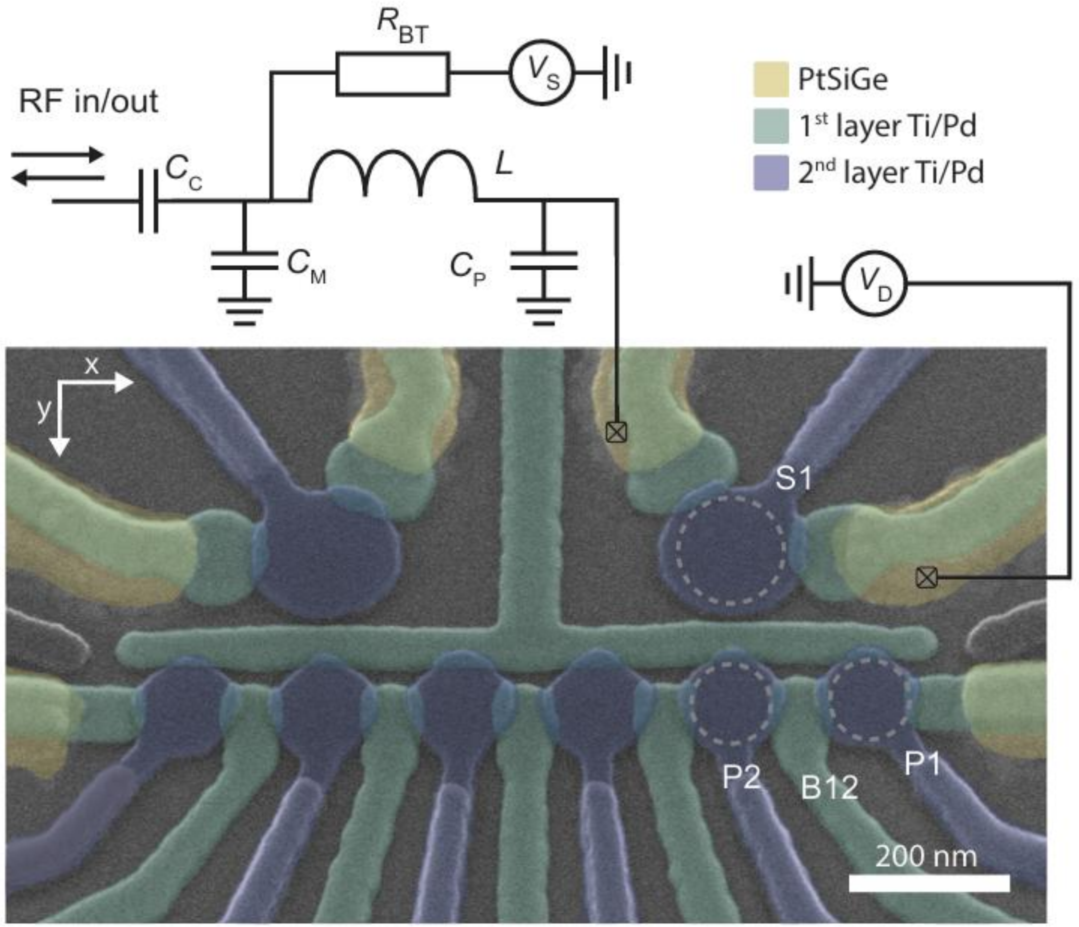


99.94% Fidelity

Takeaway

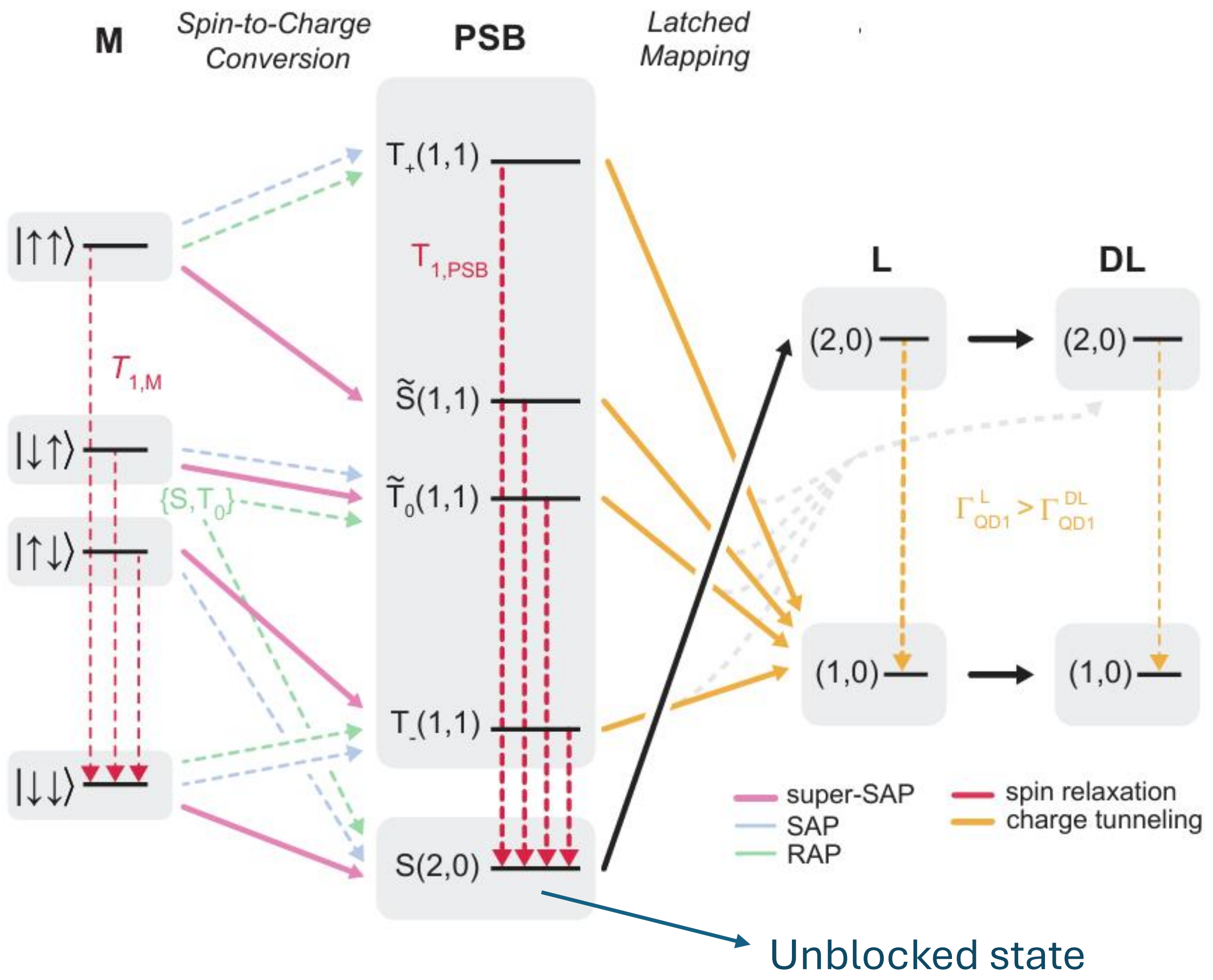
- Single latching improves the contrast of the sensor signal. Because it differentiates between 1e and 2e charges, as opposed to 2e(1,1) and 2e(2,0) charges with just PSB readout.
- Double latching prevents the decay of the 2e charge configuration to 1e.

Coming back to the original paper



All measurements performed with $V_{SD} = 0$

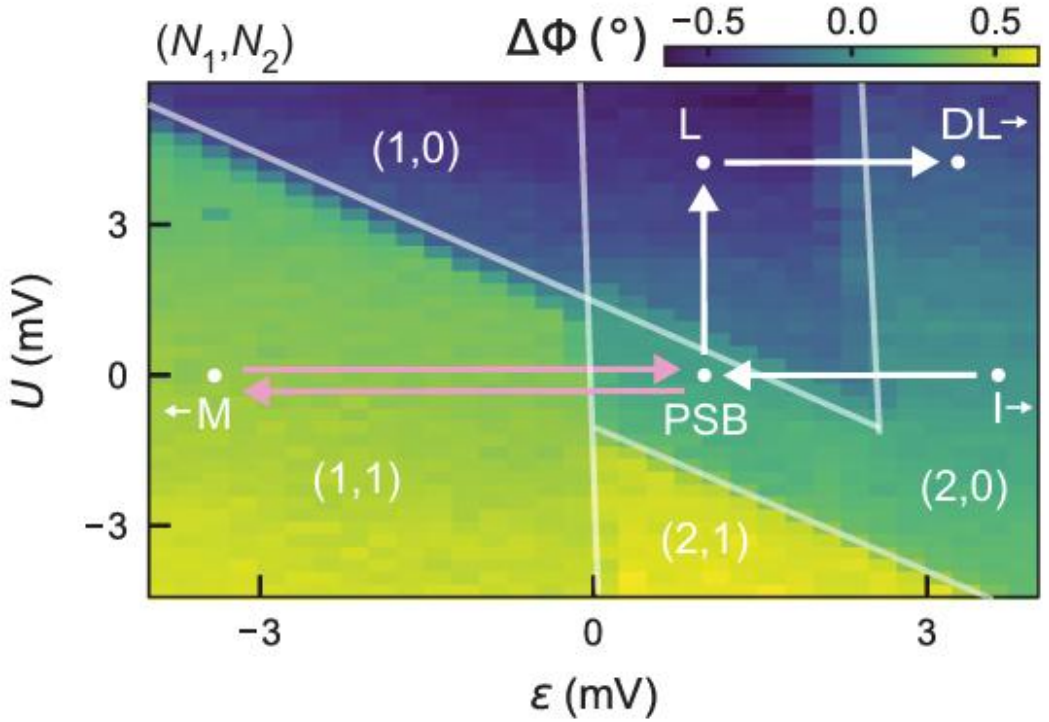
How do they do the spin readout



Avenues for errors:

- Spin to charge conversion.
- Reading out the charge.

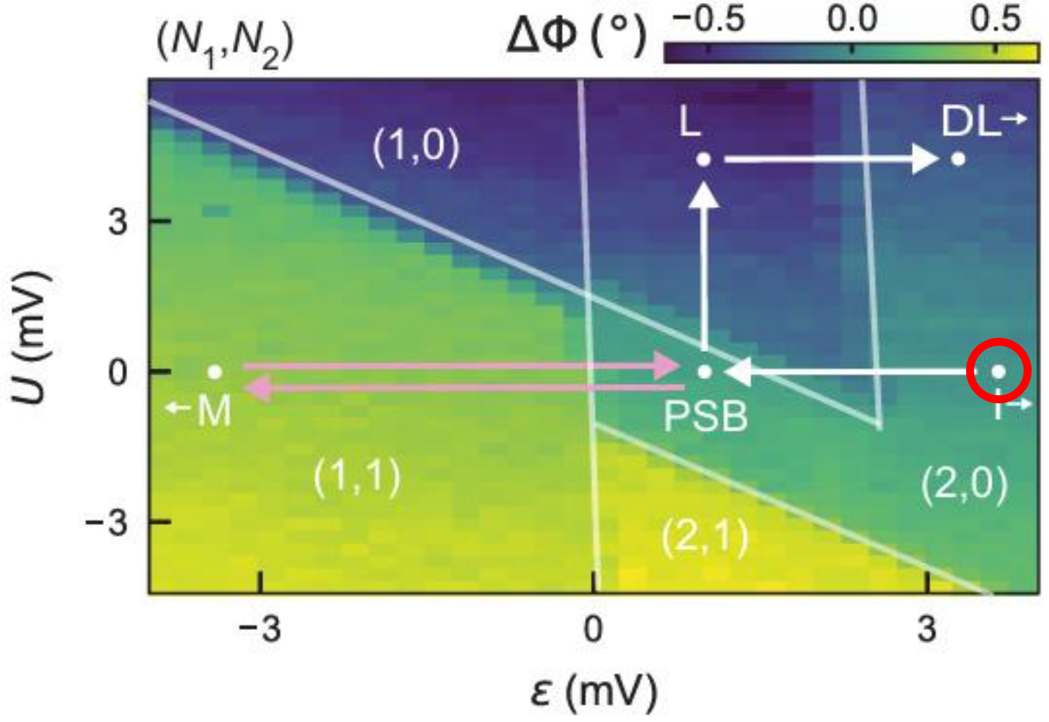
In more detail

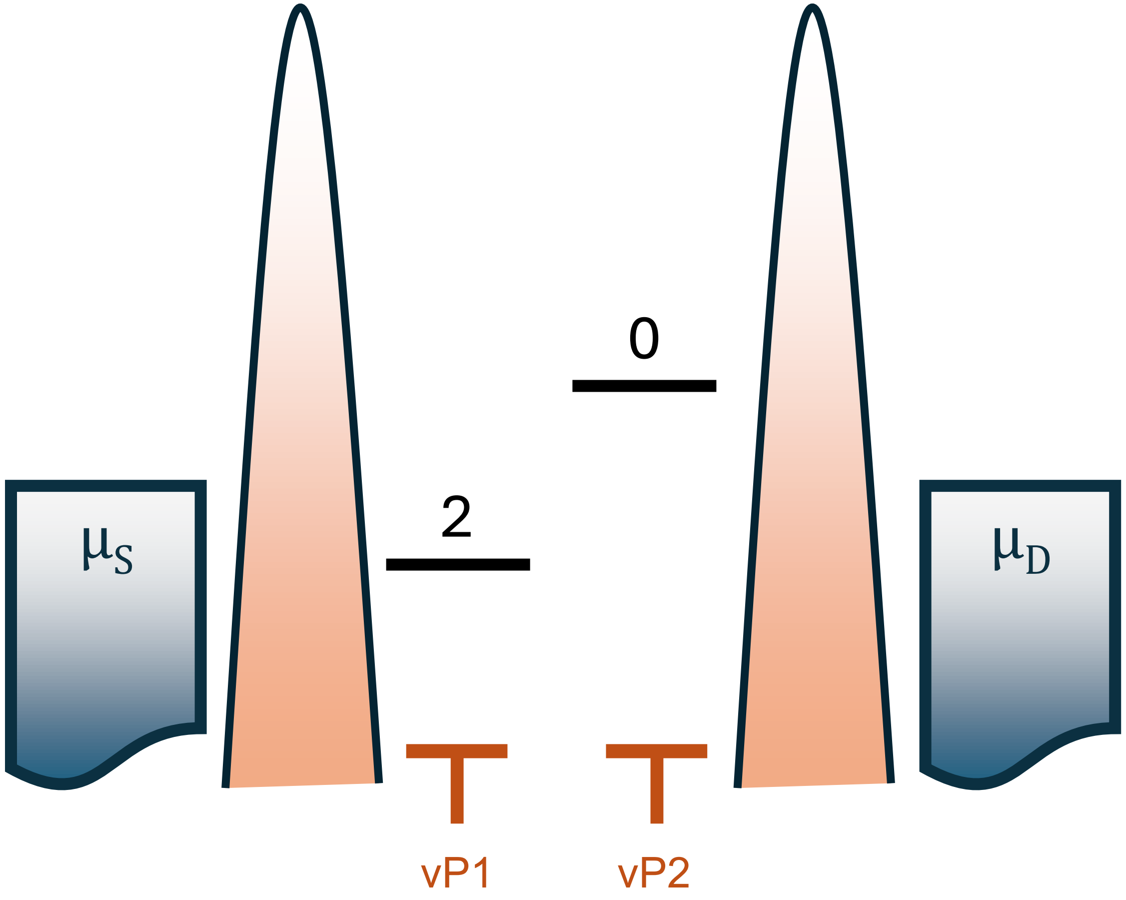


$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$

Point I

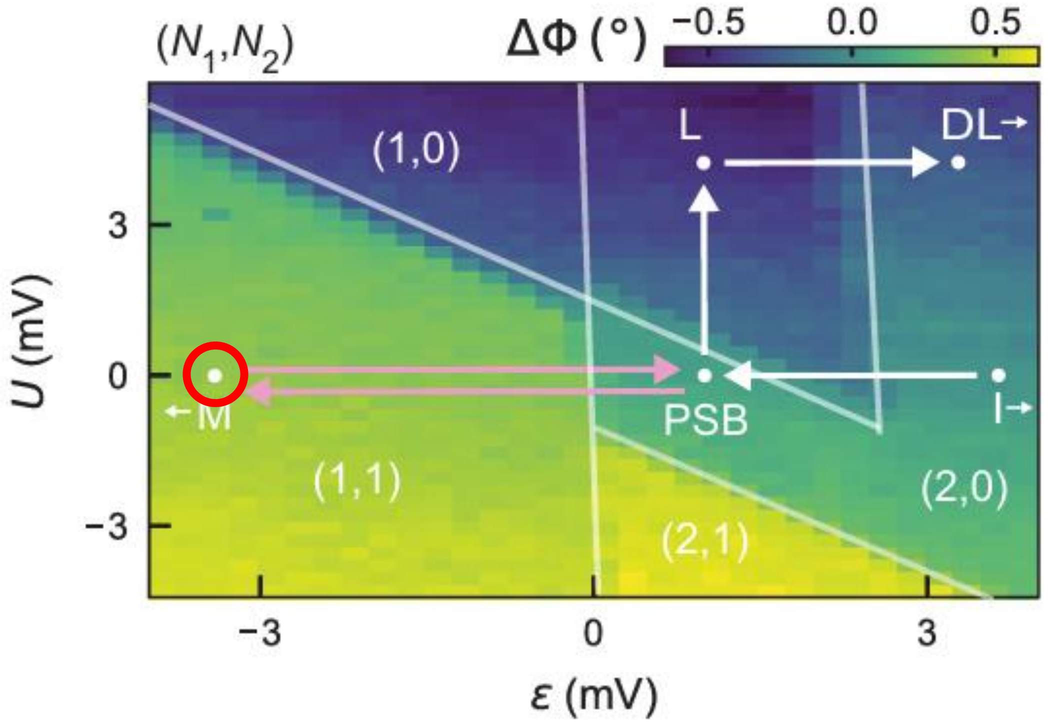
$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$

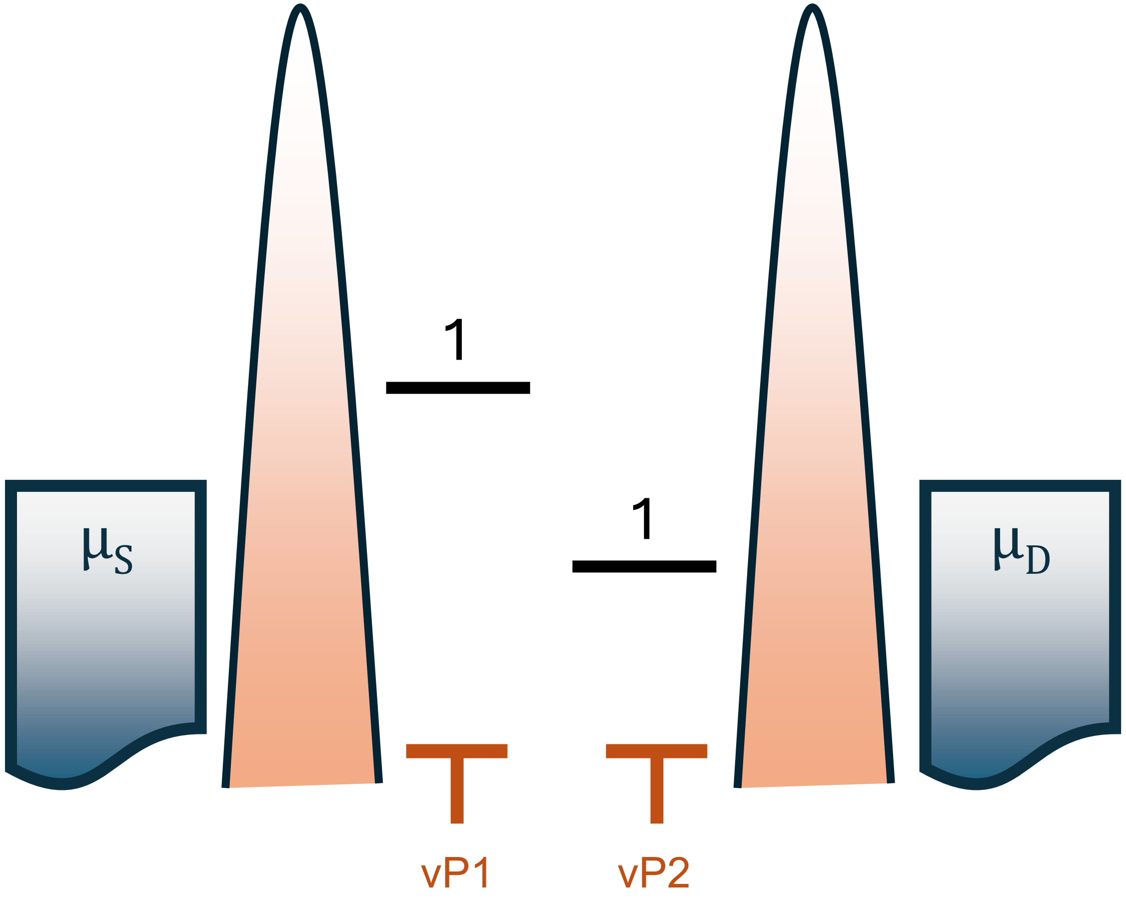




Point M

$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$

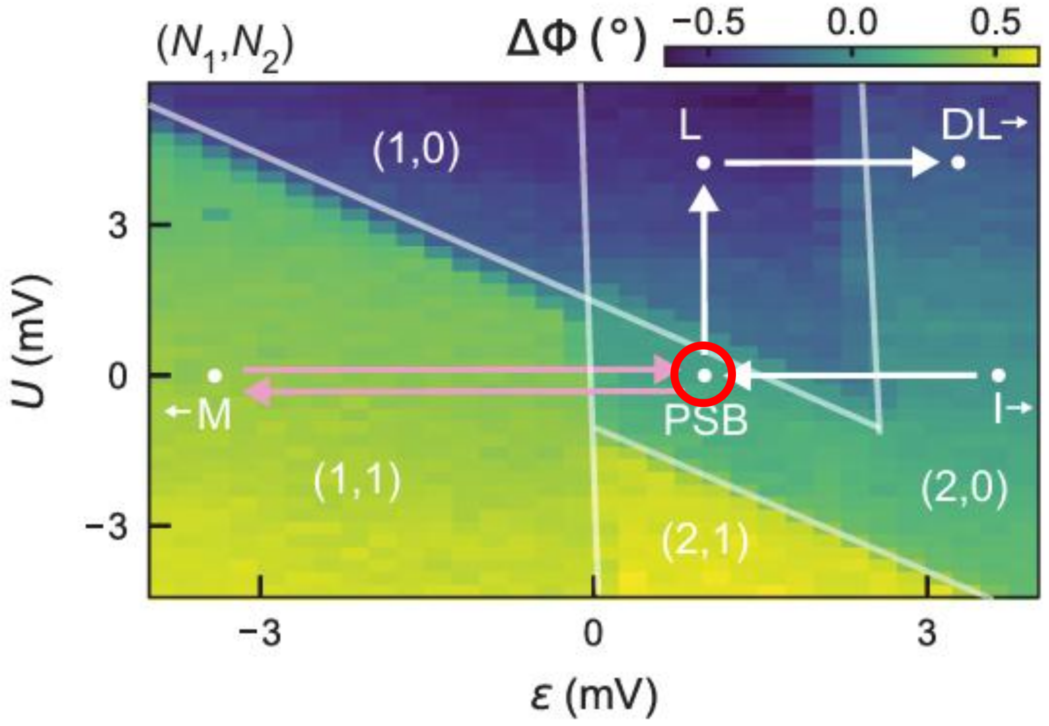


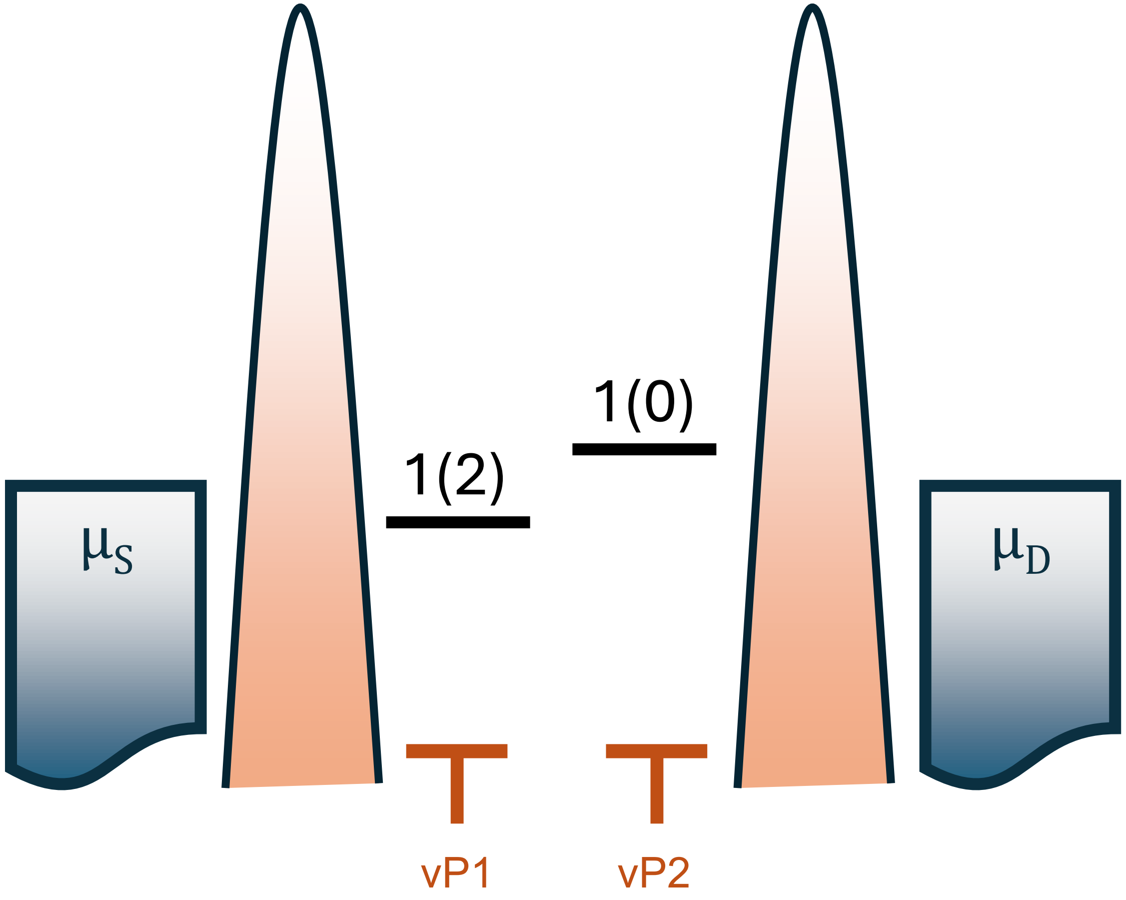


Apply RF pulses
to flip spins

Point PSB

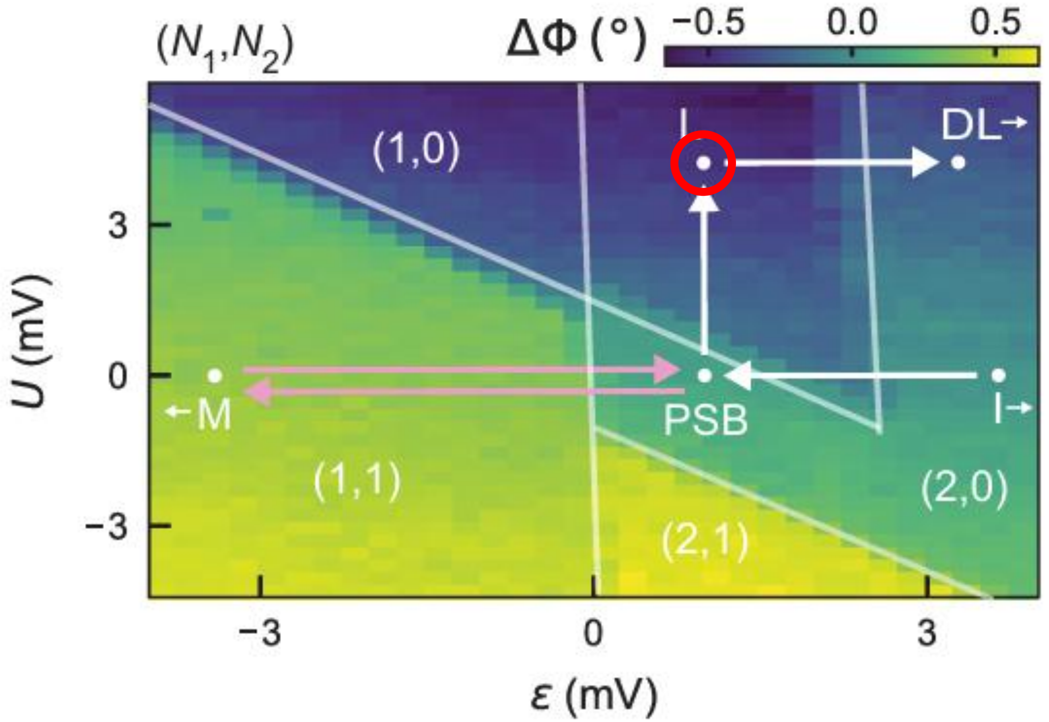
$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$

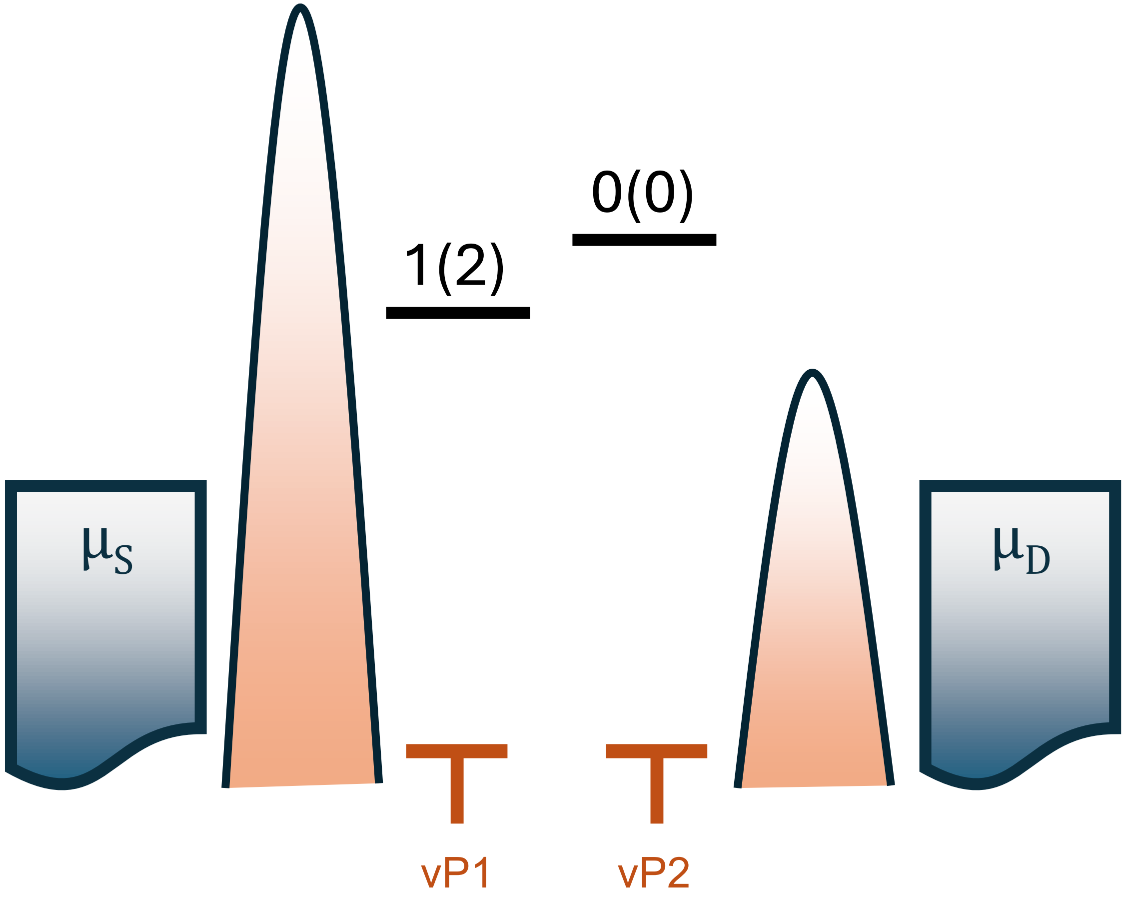




Point L

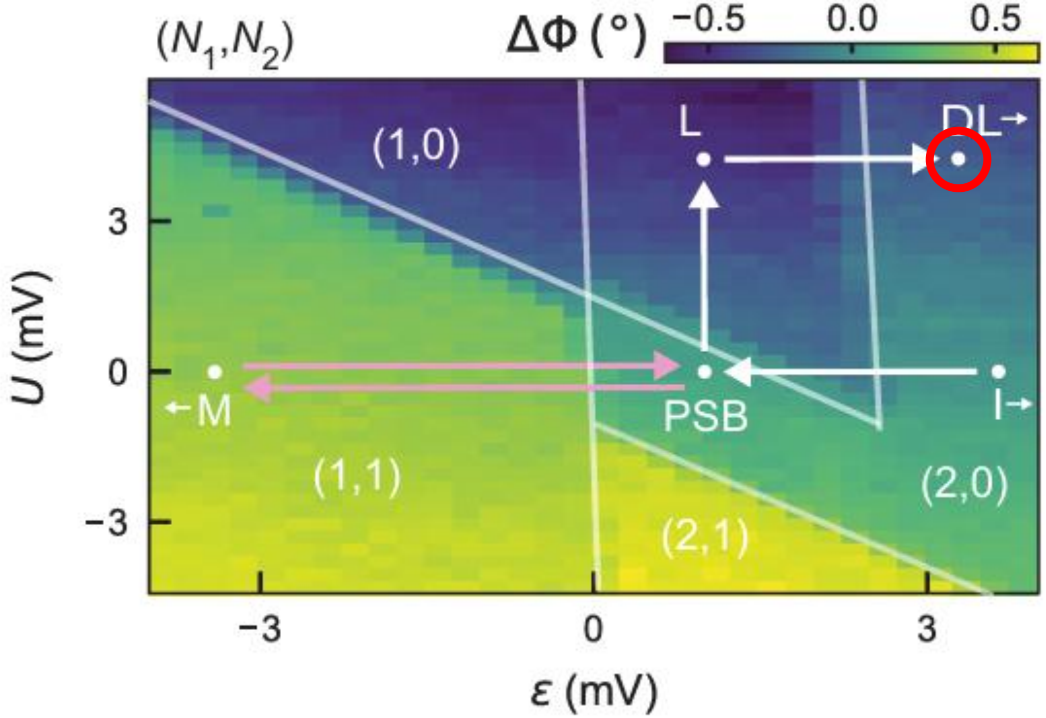
$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$

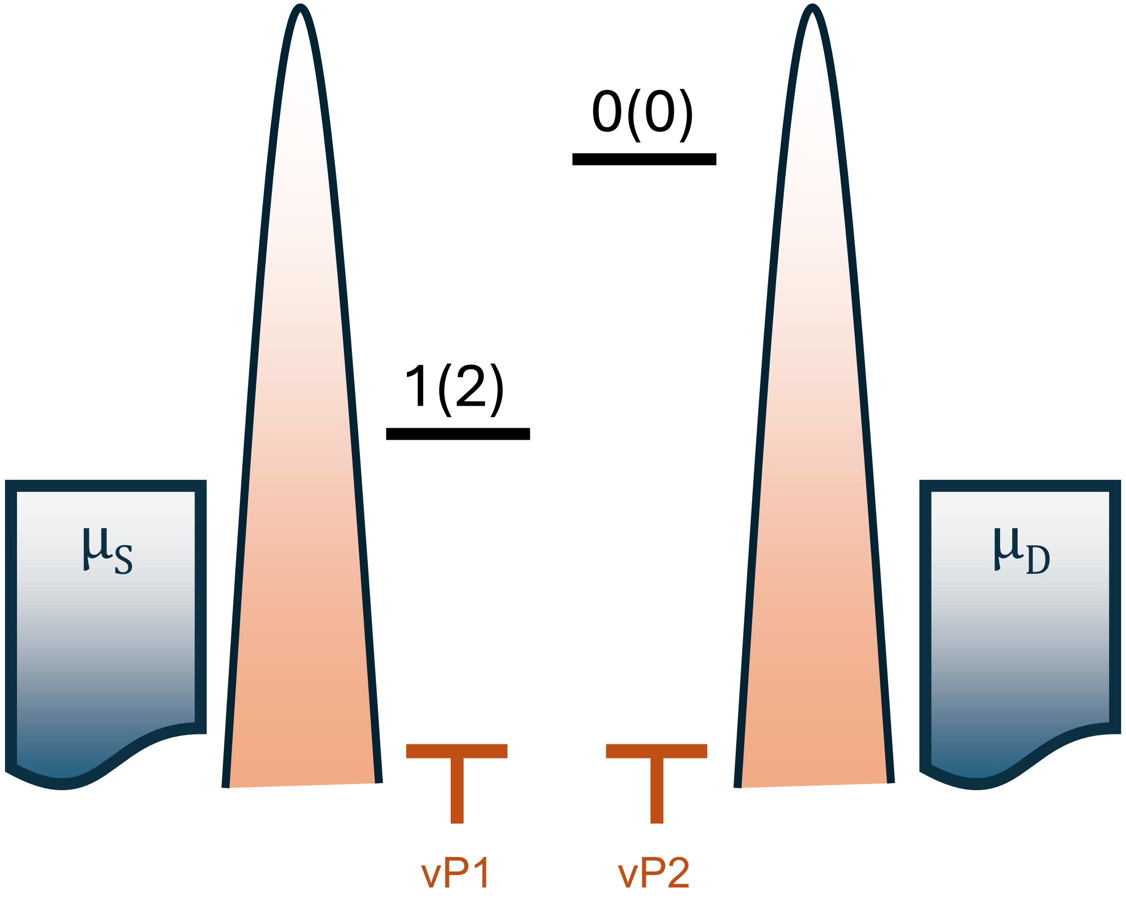




Point DL

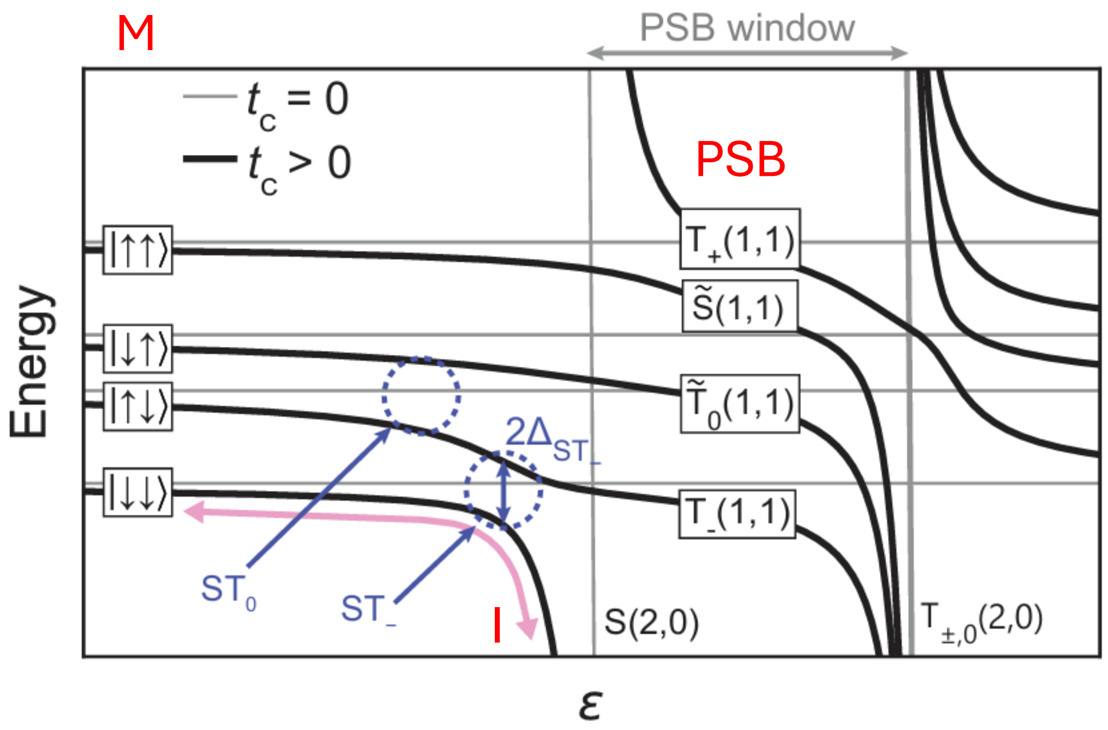
$$\begin{pmatrix} \mathrm{vP1} \\ \mathrm{vP2} \end{pmatrix} = \begin{pmatrix} -0.5 & 0.5 \\ 0.5 & 0.5 \end{pmatrix} \begin{pmatrix} \varepsilon \\ U \end{pmatrix}$$





Spin to Charge conversion

Evolution of energy from M to PSB



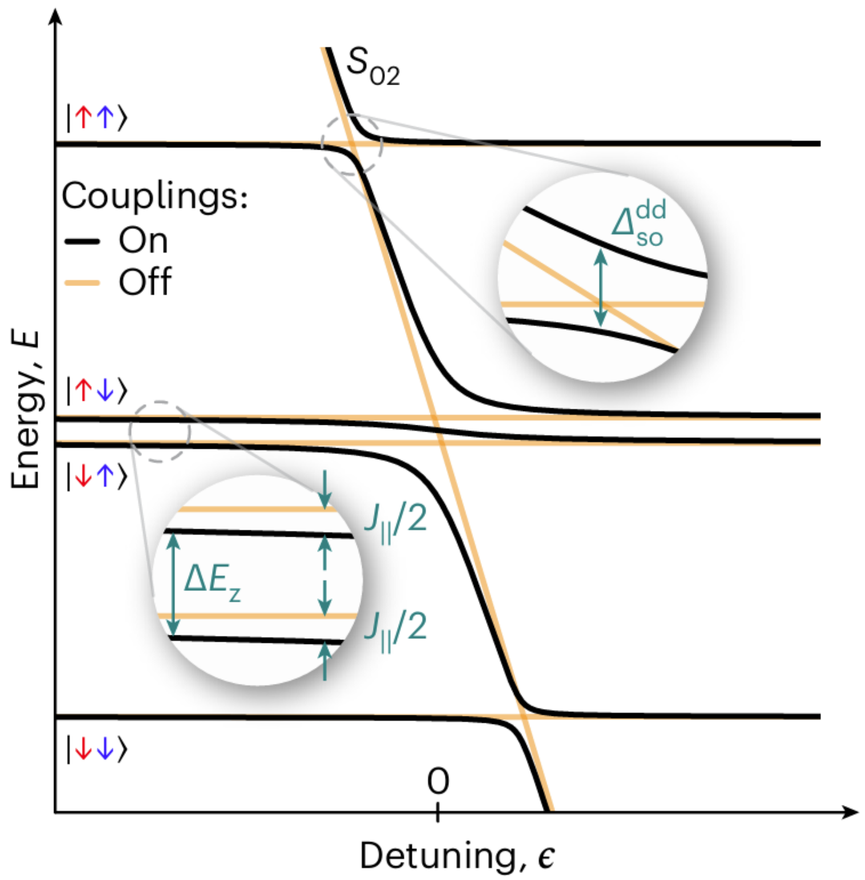
Adiabaticity of ramps at ST_- and ST_0 anticrossings

- **Super-SAP** (Super slow adiabatic passage):
  - ST_- Adiabatic (slow)
  - ST_0 Adiabatic (slow)

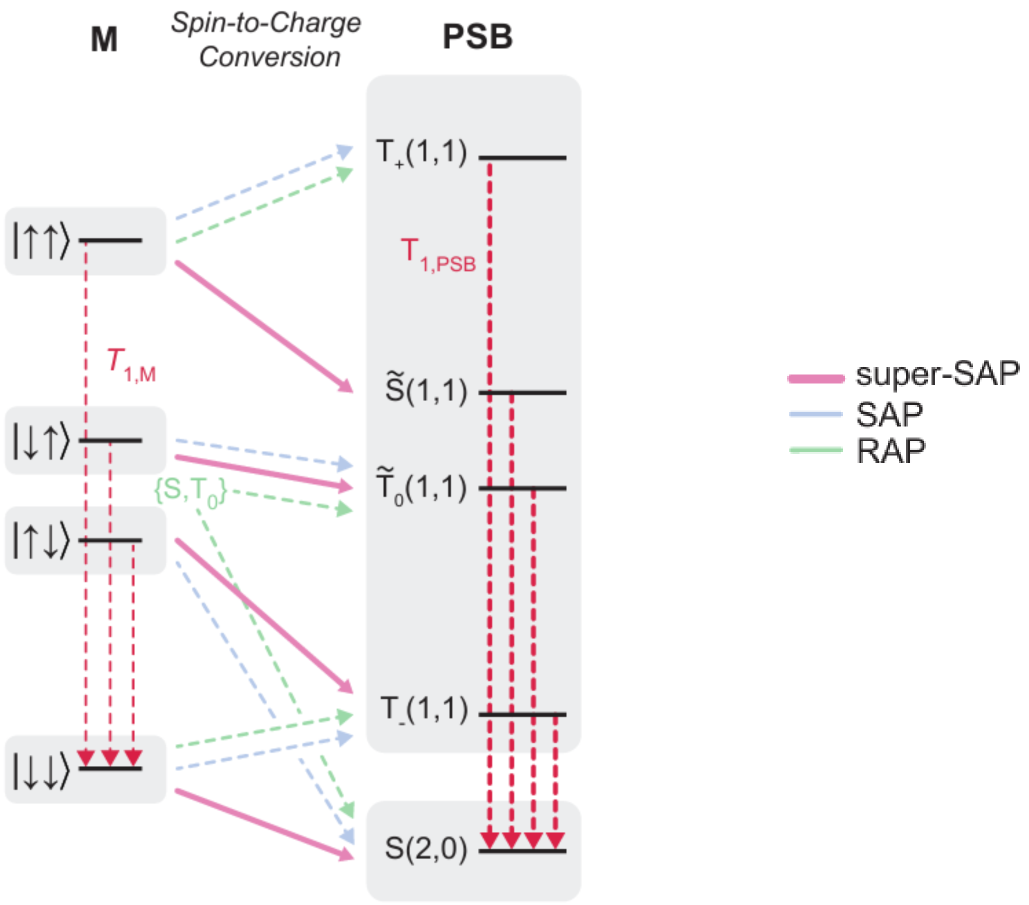
- **SAP** (Slow adiabatic passage):
  - ST_- Adiabatic (slow)
  - ST_0 Diabatic (fast)

- **RAP** (Rapid adiabatic passage):
  - ST_- Diabatic (fast)
  - ST_0 Diabatic (fast)

Small detour

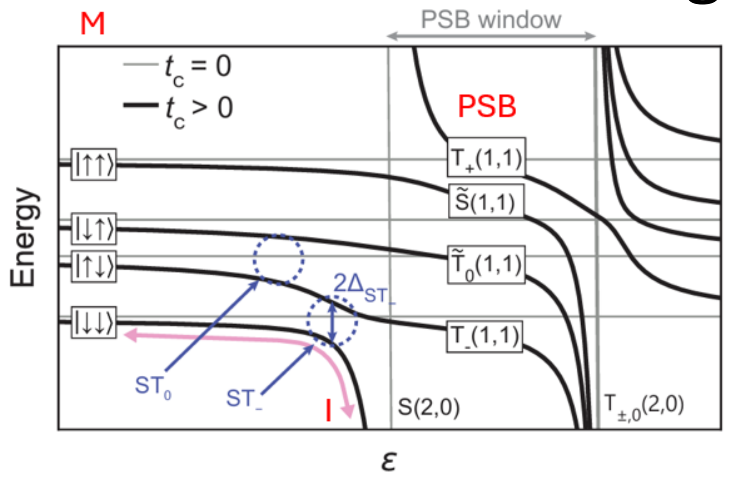


Adiabaticity of ramps at ST_- and ST_0 anticrossings



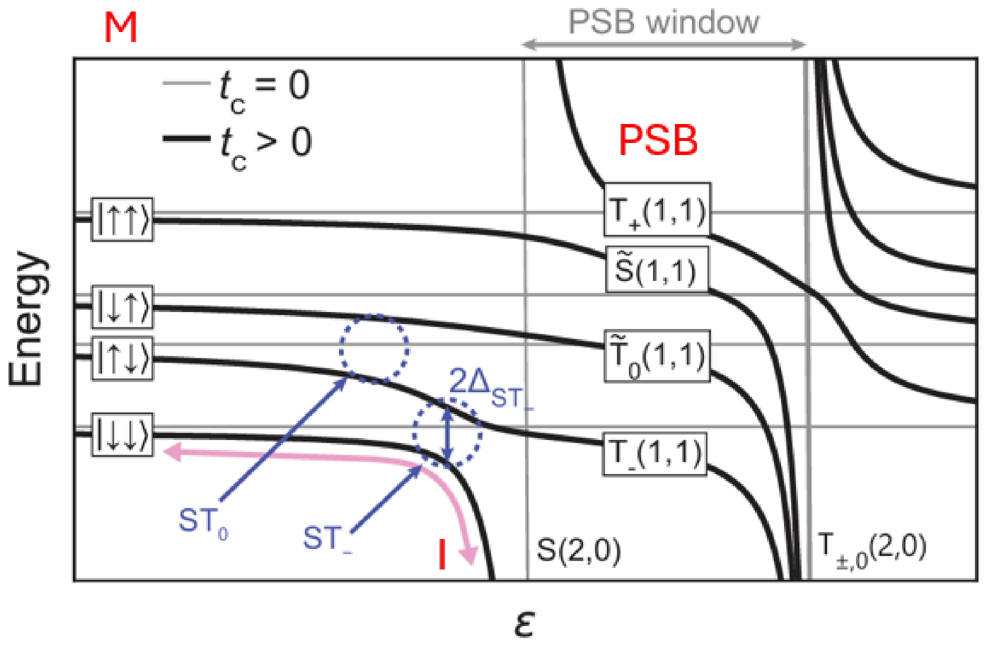
Choosing between Super-SAP/SAP/RAP

- Ideally going as fast as possible is desired to minimise errors due to relaxation and dephasing of the qubit.
- So, RAP should be the best.
- But is it achievable in this setup.
- Note that two different ramps to address the two different anticrossings is not possible in this setup as the two anticrossings have significant overlap.



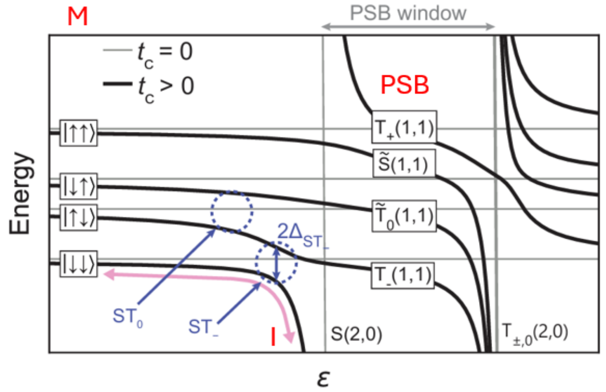
Choosing between Super-SAP/SAP/RAP

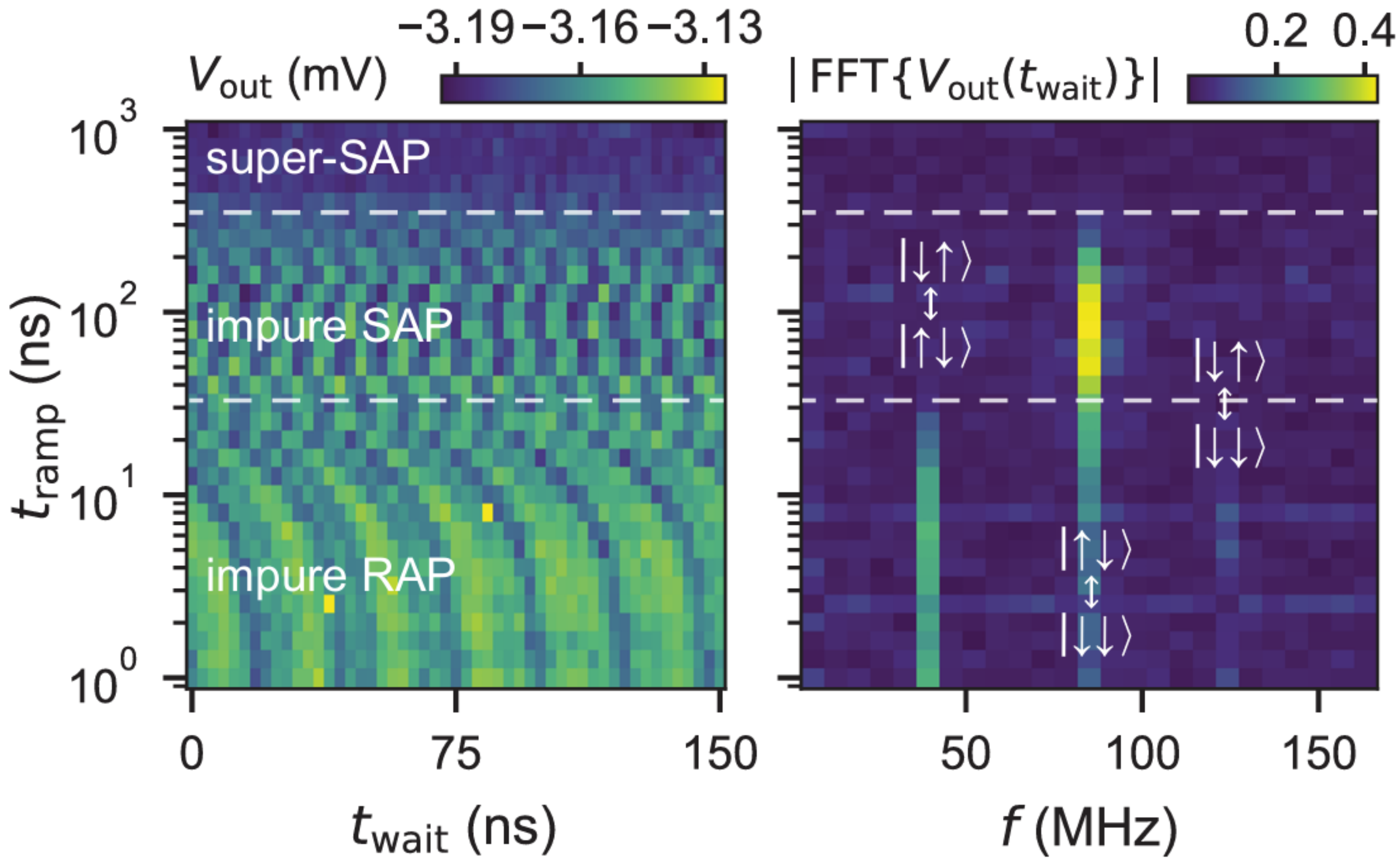
- $t_{ramp\ in}$ – Ramp time to the point M.
- Wait for t_{wait} at point M.
- $t_{ramp\ out}$ – Ramp time from the point M.
- They set $t_{ramp\ in} = t_{ramp\ out} = t_{ramp}$
- Also set $B = 40$ mT



Choosing between Super-SAP/SAP/RAP

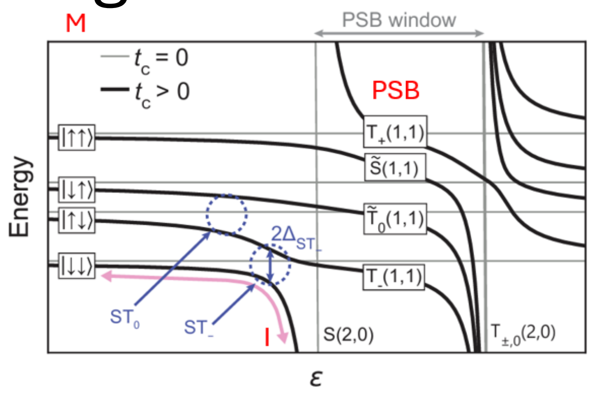
- Oscillations due to mixing of different spin states.
- Observable in fast ramp times.
- Super-SAP is the only option.



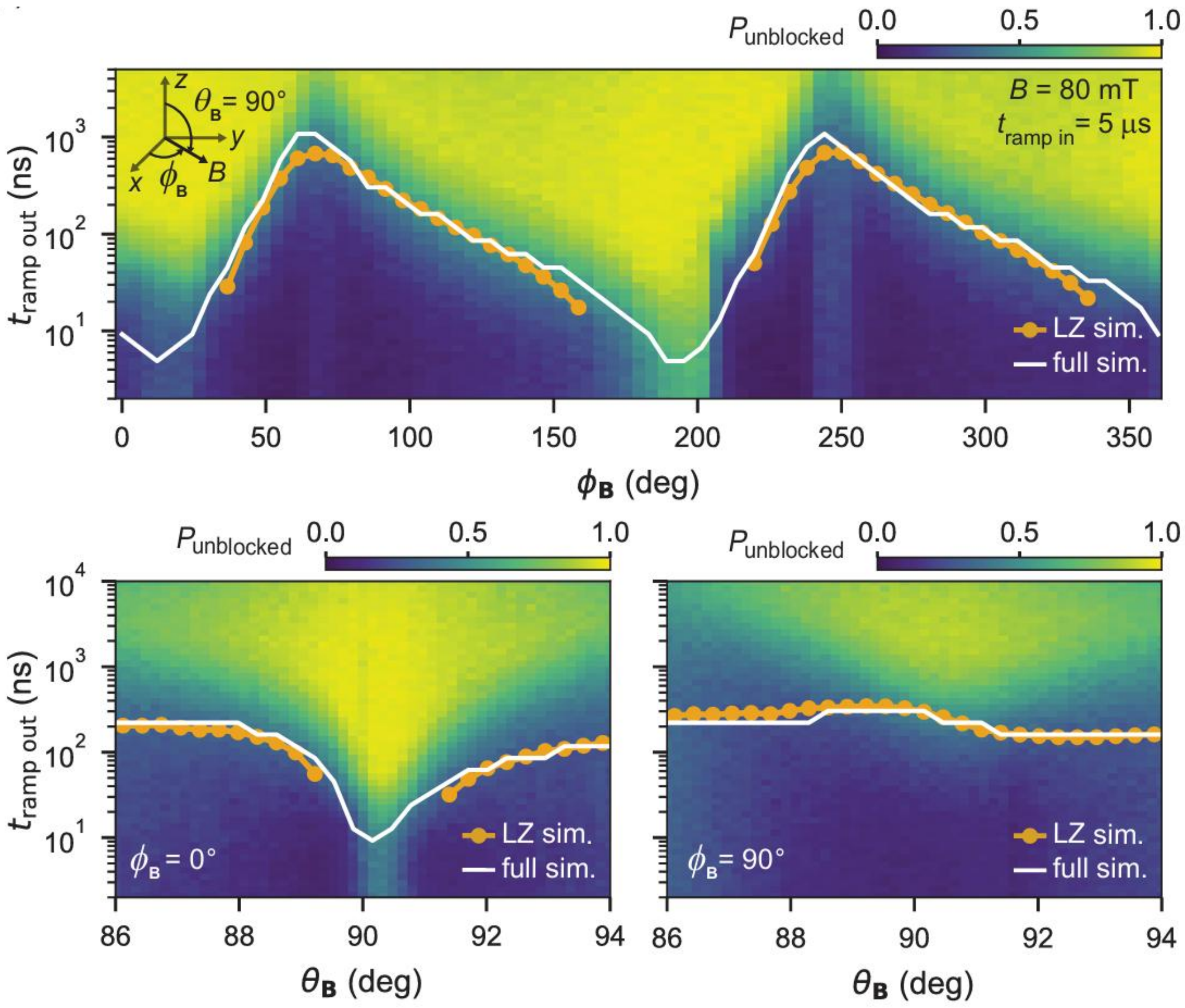


Variation of t_{ramp} with $\vec{B}$ field orientation

- Optimum points of qubit coherence exist at certain magnetic field orientations due to the highly anisotropic nature of hole-g tensors in Ge.
- Fix $t_{ramp\ in}$ to a large value to start with $|\downarrow\downarrow\rangle$.
- Plot $t_{ramp\ out}$ vs $\varphi_{\mathbf{B}}$ and $\theta_{\mathbf{B}}$, the azimuthal and polar angles for the magnetic field.
- Z axis is $P_{\mathrm{Unblocked}}$, which is the probability of measuring the unblocked (2,0) state.



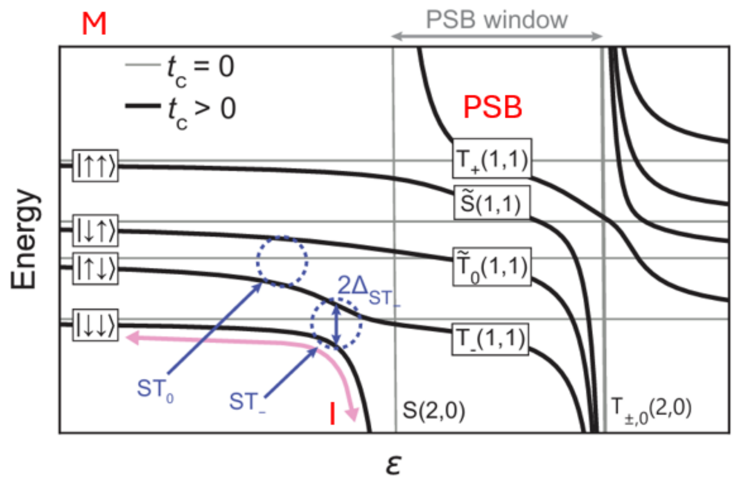
Variation of t_{ramp} with $\vec{B}$ field orientation



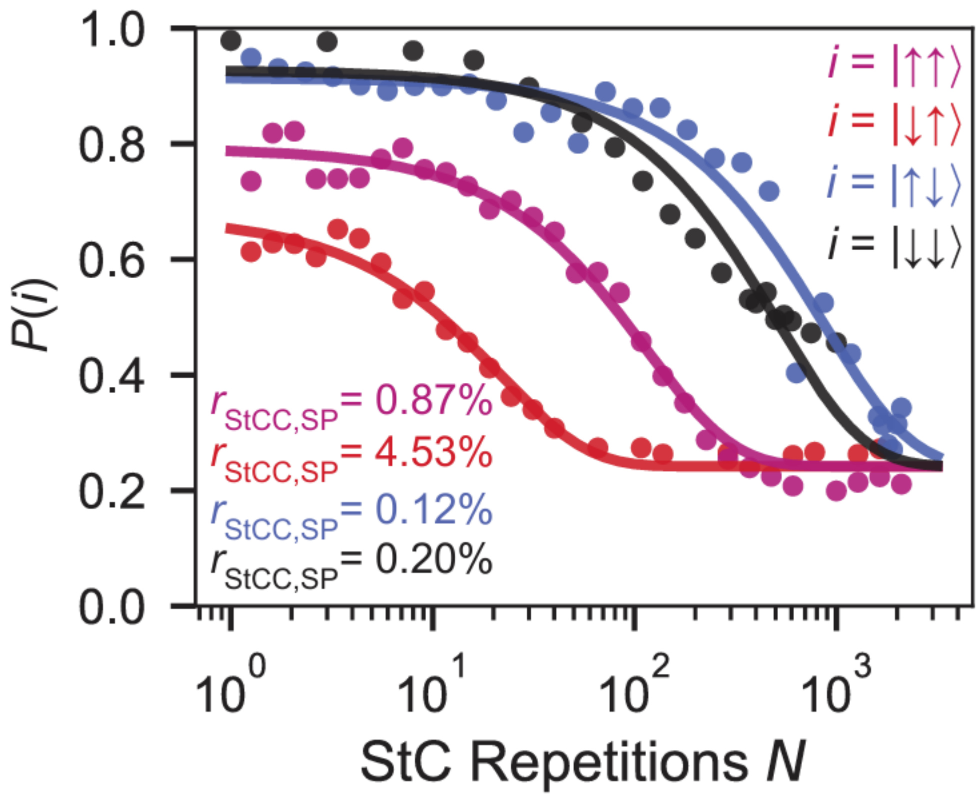
- They operate at $(\varphi_{\mathbf{B}}, \theta_{\mathbf{B}}) = (194°, 90°)$ orientation to minimise spin decay errors during spin-to-charge conversion.

Measuring the errors during the StCC ramps

- Super-SAP state preparation of $|\downarrow\downarrow\rangle$ with $t_{ramp\ in} = 120\ \mathrm{ns}$.
- Application of spin-flip pulses.
- Super-SAP back-and-forth ramp (M→PSB→M), repeated N times.
- Mapped back down to $|\downarrow\downarrow\rangle$ with spin-flip pulses.
- A final StCC mapping followed by double-latched readout.



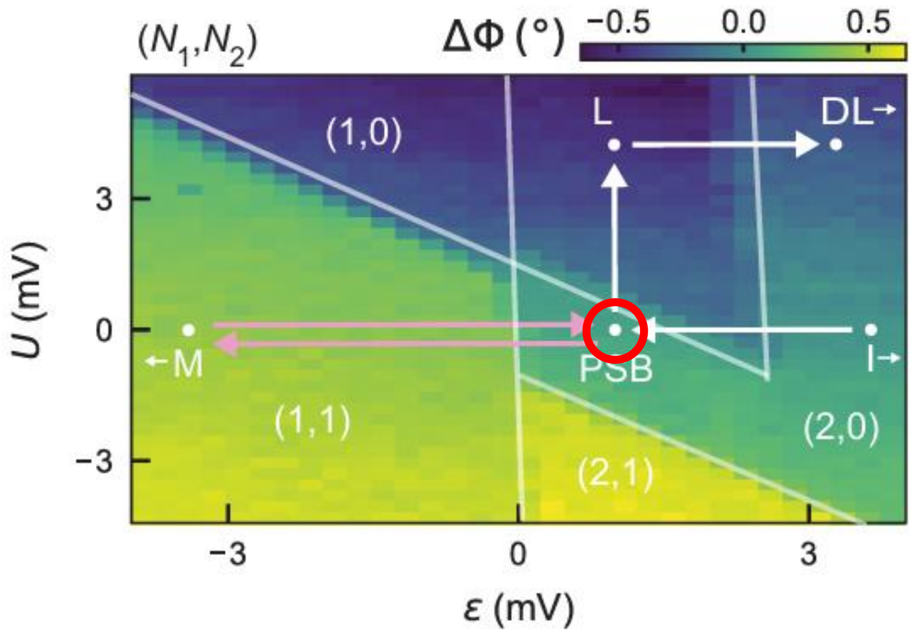
Measuring the errors during the StCC ramps



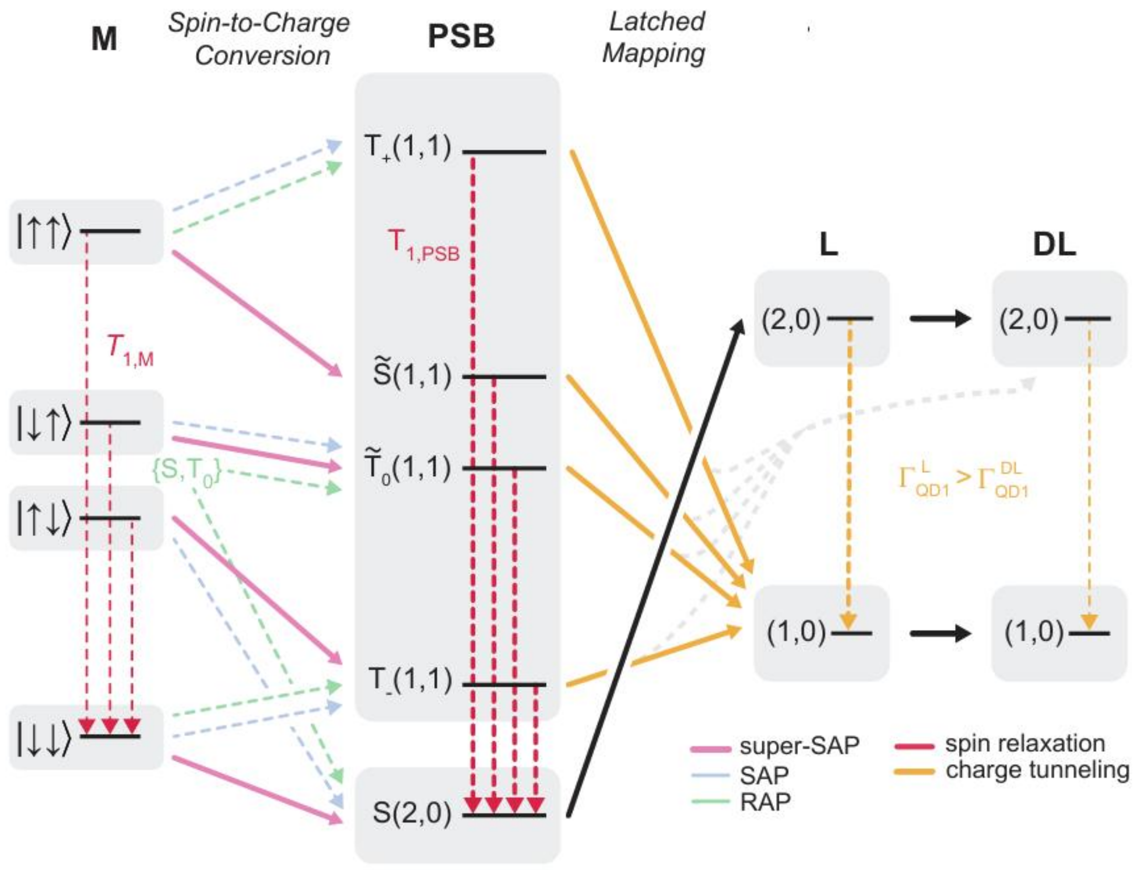
- Define r_{StCC} as the probability of not detecting the signal of the prepared state after one back-and-forth.

Charge readout

To refresh

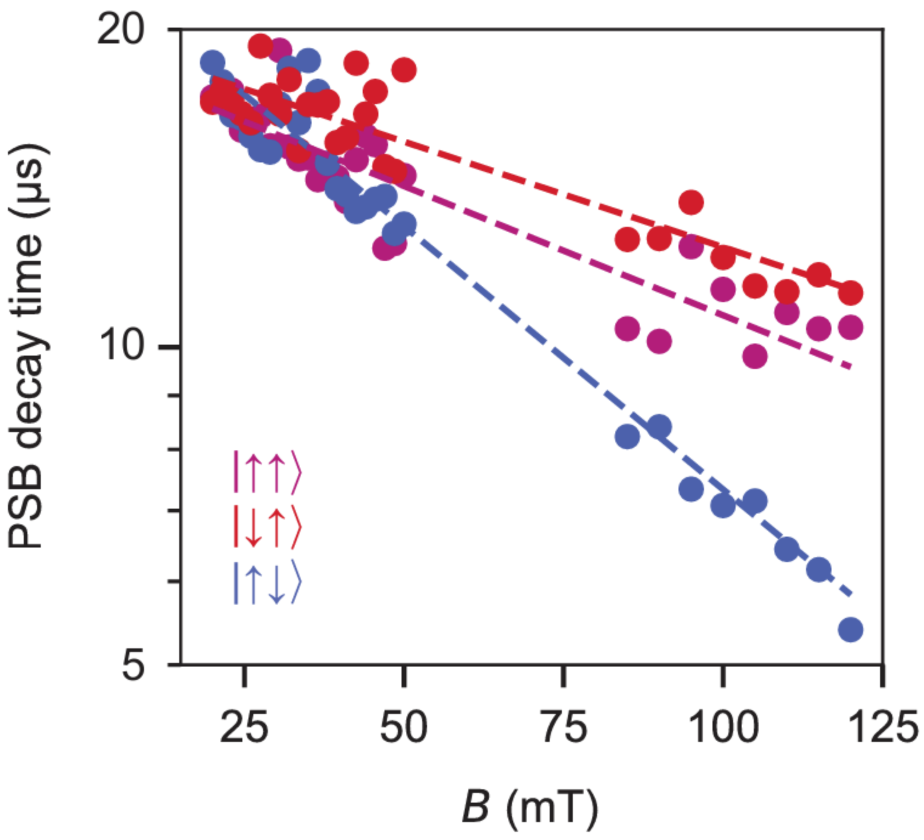


(N_1,N_2)
$\Delta\Phi$ (°)
−0.5
0.0
0.5
(1,0)
L
DL→
3
0
−3
←M
PSB
I→
(1,1)
(2,1)
(2,0)
−3
0
3
ε (mV)
U (mV)



M
Spin-to-Charge Conversion
PSB
Latched Mapping
$T_+(1,1)$
$|\uparrow\uparrow\rangle$
$T_{1,PSB}$
$T_{1,M}$
$\tilde{S}(1,1)$
$|\downarrow\uparrow\rangle$
$\{S,T_0\}$
$\tilde{T}_0(1,1)$
$|\uparrow\downarrow\rangle$
$T_-(1,1)$
$|\downarrow\downarrow\rangle$
S(2,0)
L
DL
(2,0)
(2,0)
$\Gamma^{L}_{QD1} > \Gamma^{DL}_{QD1}$
(1,0)
(1,0)
super-SAP
SAP
RAP
spin relaxation
charge tunneling

Spin decay errors at point PSB

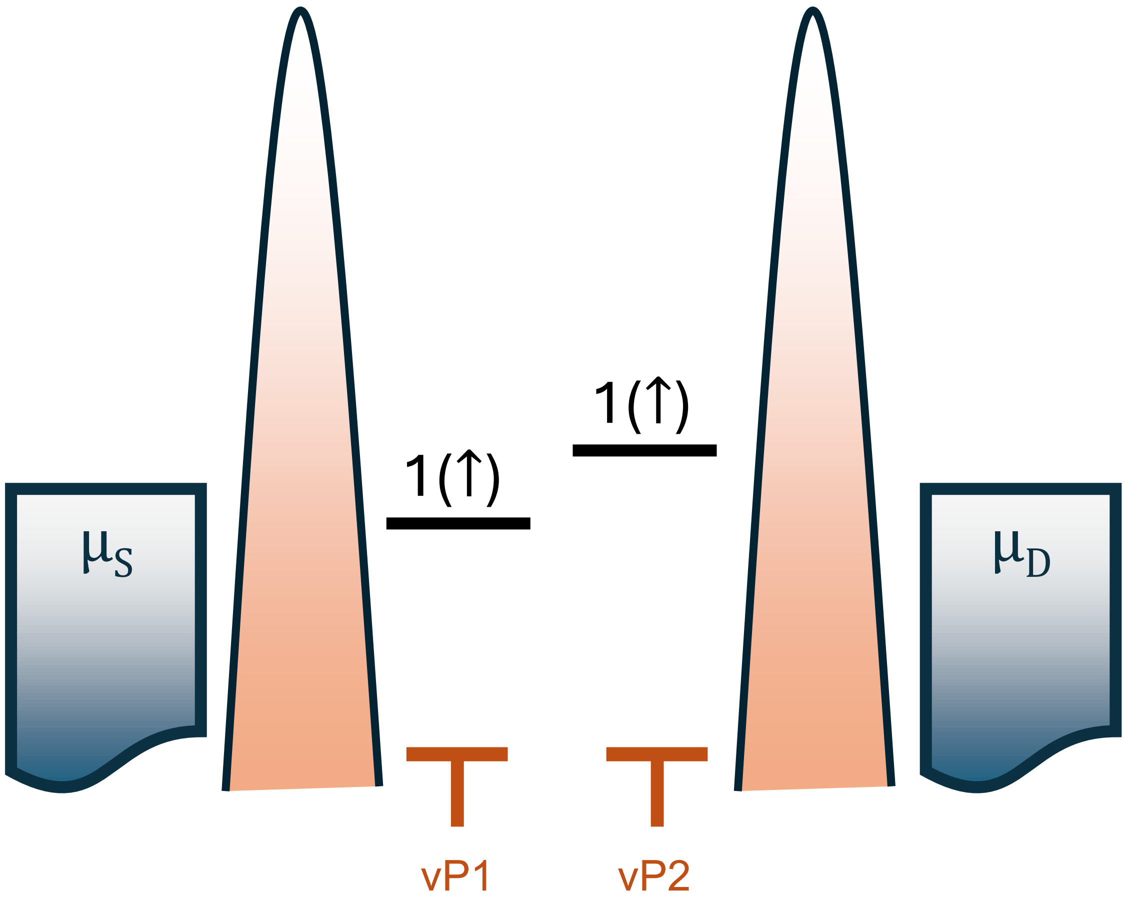


- Spin decay times for the blocked spin states at the PSB points as a function of B with $(\varphi_{\mathbf{B}}, \theta_{\mathbf{B}}) = (196°, 90°)$.
- So, operating at low B is beneficial for readout, in addition to qubit coherence.
- But the spin still decays at low B in 20 μs.

Latching

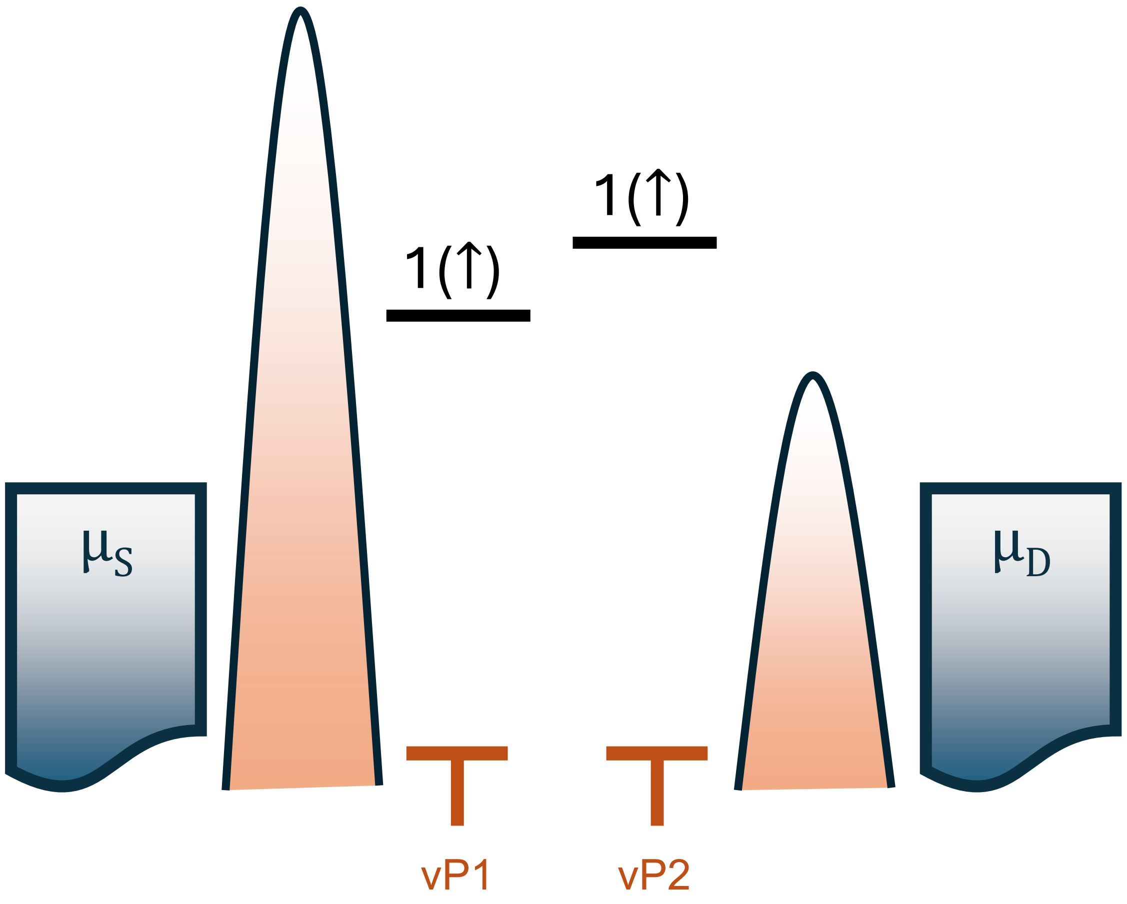
- Minimise the time spent at PSB by performing latching.
- It also improves the contrast of the sensor signals.

Latching vs Decay



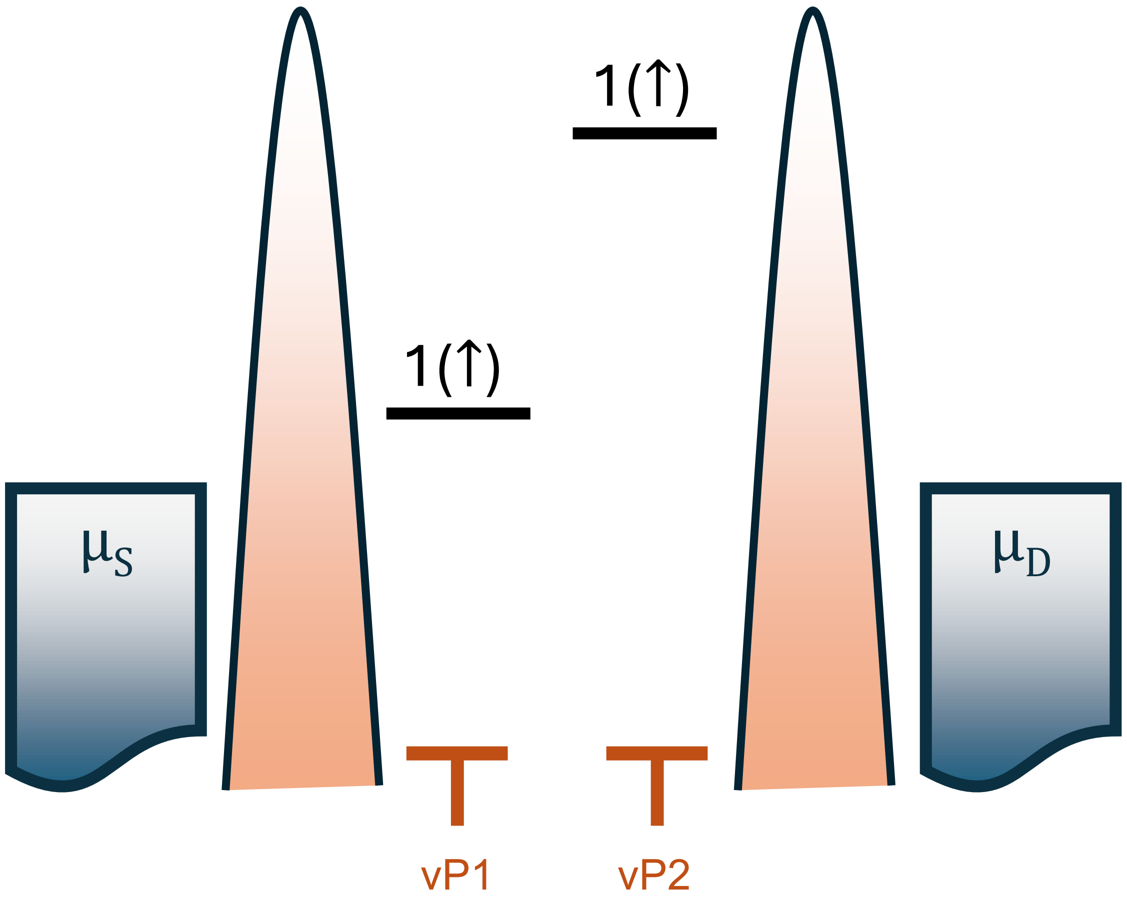
- Point PSB

Latching vs Decay



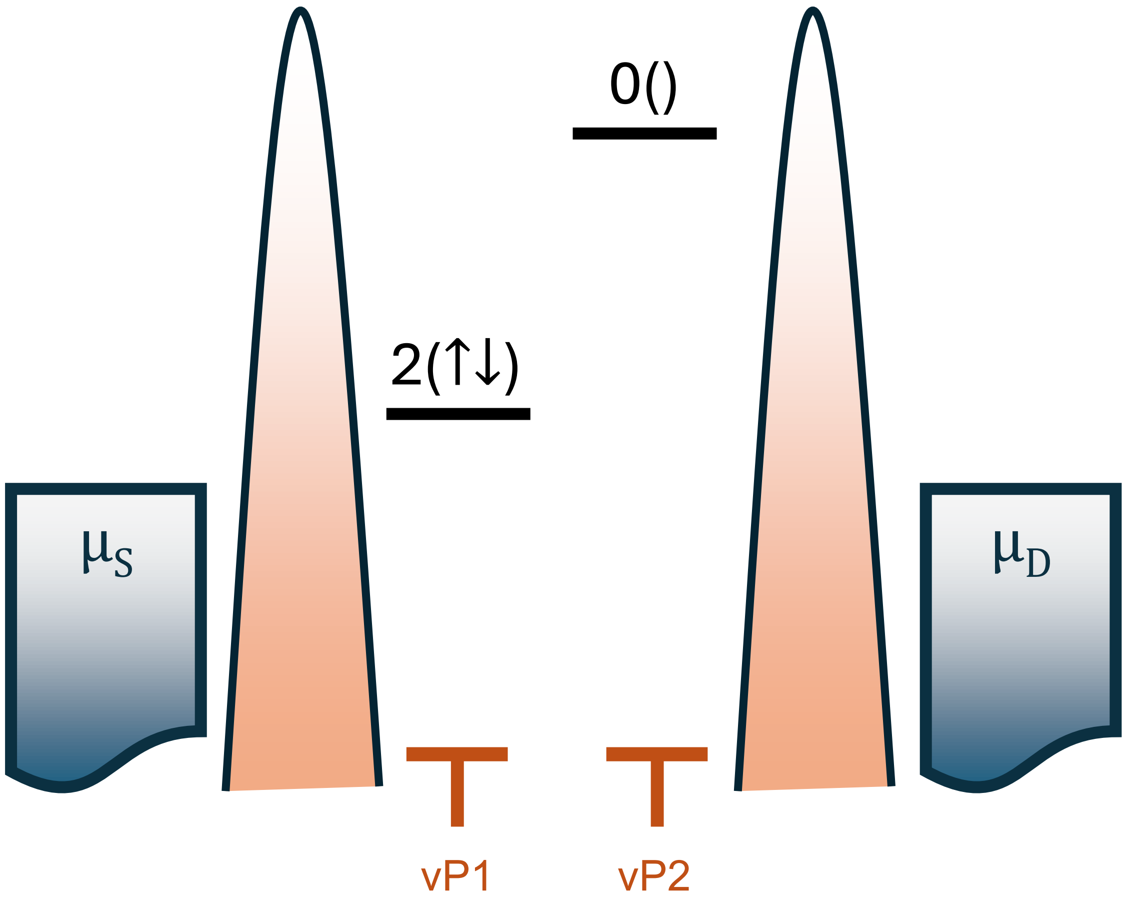
- Point L
- The right dot decaying to the drain is faster than it decaying to the left dot.
- Wait here for time t_L
- If t_L is too short, then (1,1) stays (1,1).

Latching vs Decay



- Point DL
- Perform readout with an integration time of 50 μs.
- Note that this is longer than the spin decay time of 20 μs at lowest B.
- So, the spin decays to (2,0) during readout.

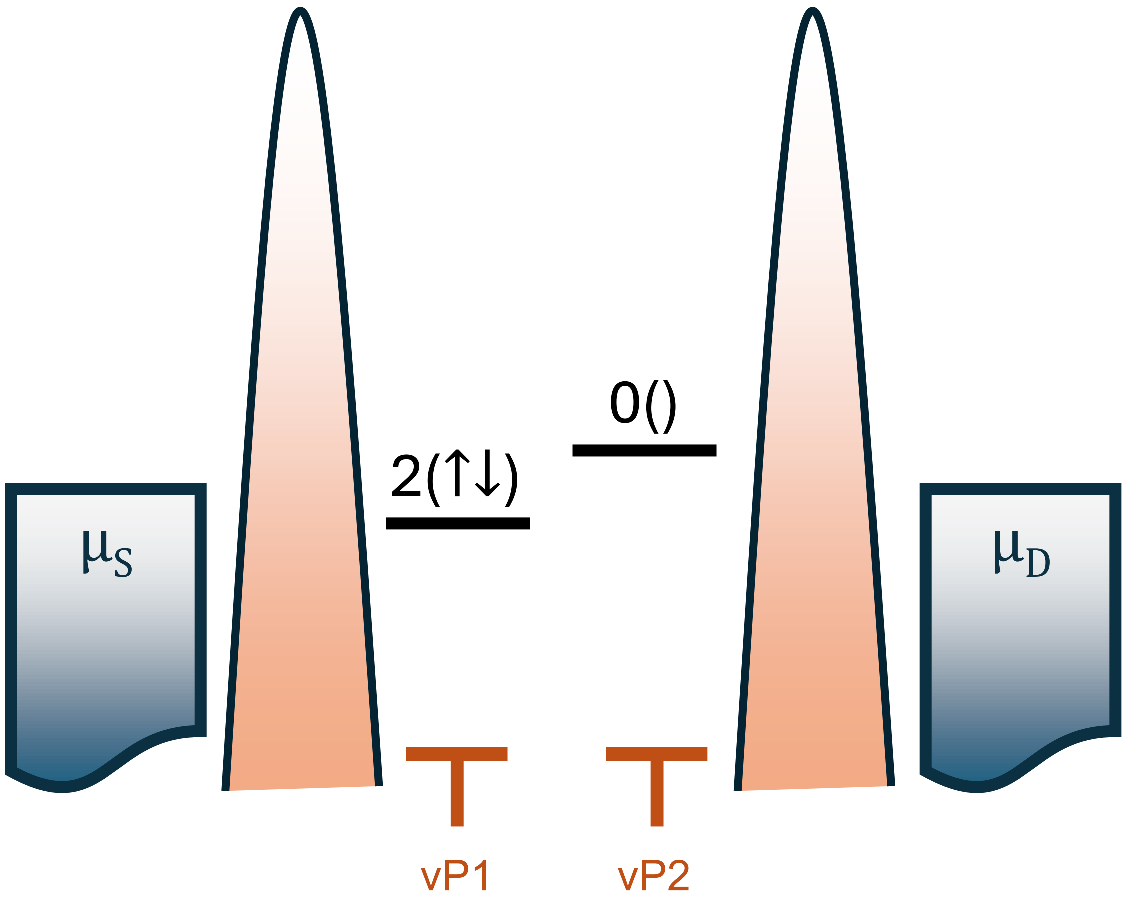
Latching vs Decay



- Point DL
- Perform readout with an integration time of 50 μs.
- Note that this is longer than the spin decay time of 20 μs at lowest B.
- So, the spin decays to (2,0) during readout.
- We readout (2,0) instead (1,0)

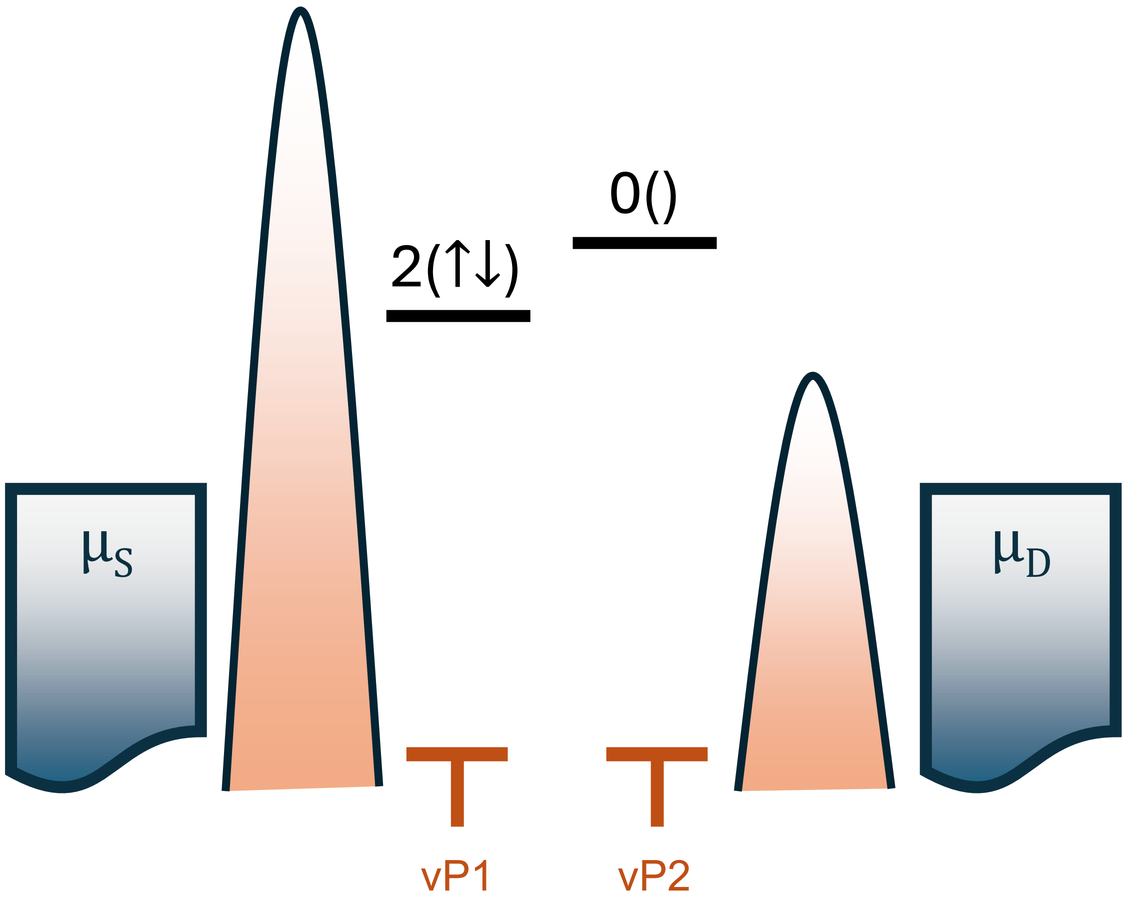
The other case

Latching vs Decay



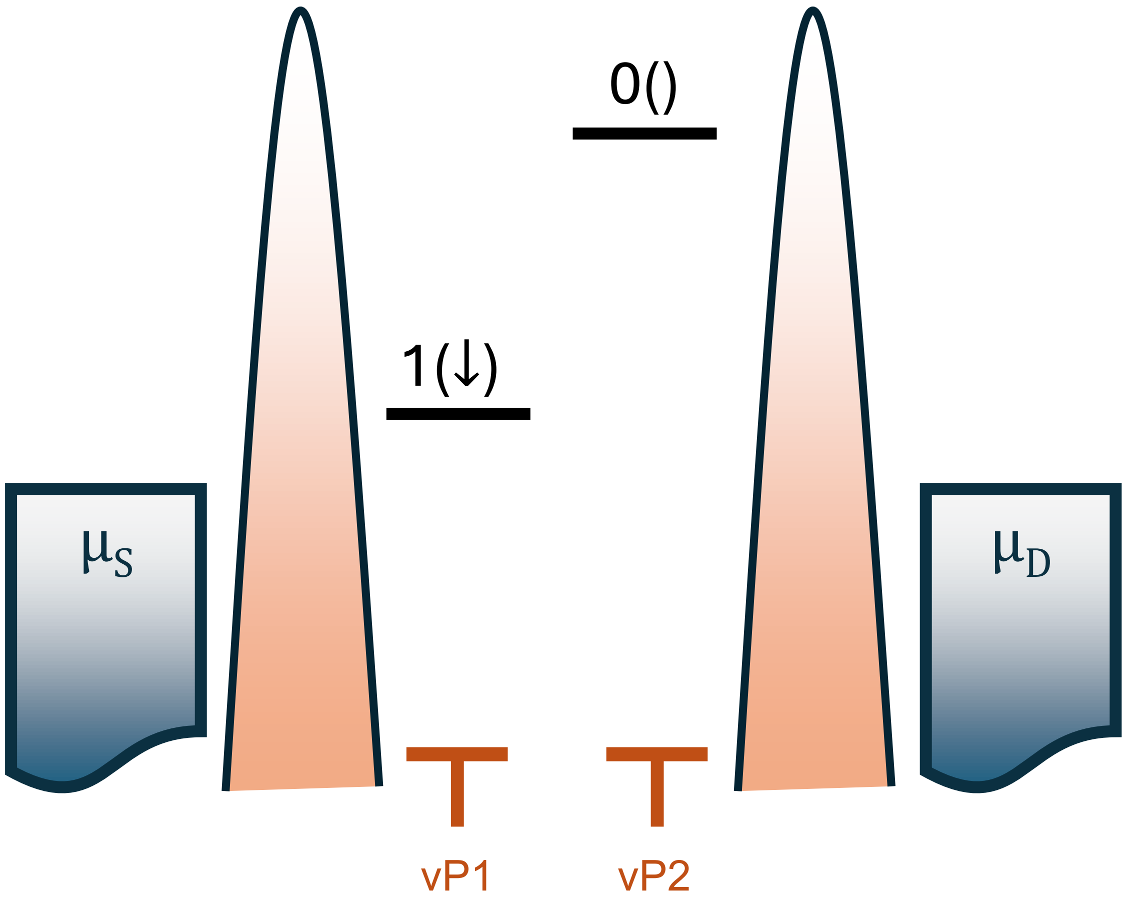
- Point PSB

Latching vs Decay



- Point L
- Wait here for time t_L
- If t_L is too long, then (2,0) becomes (1,0).

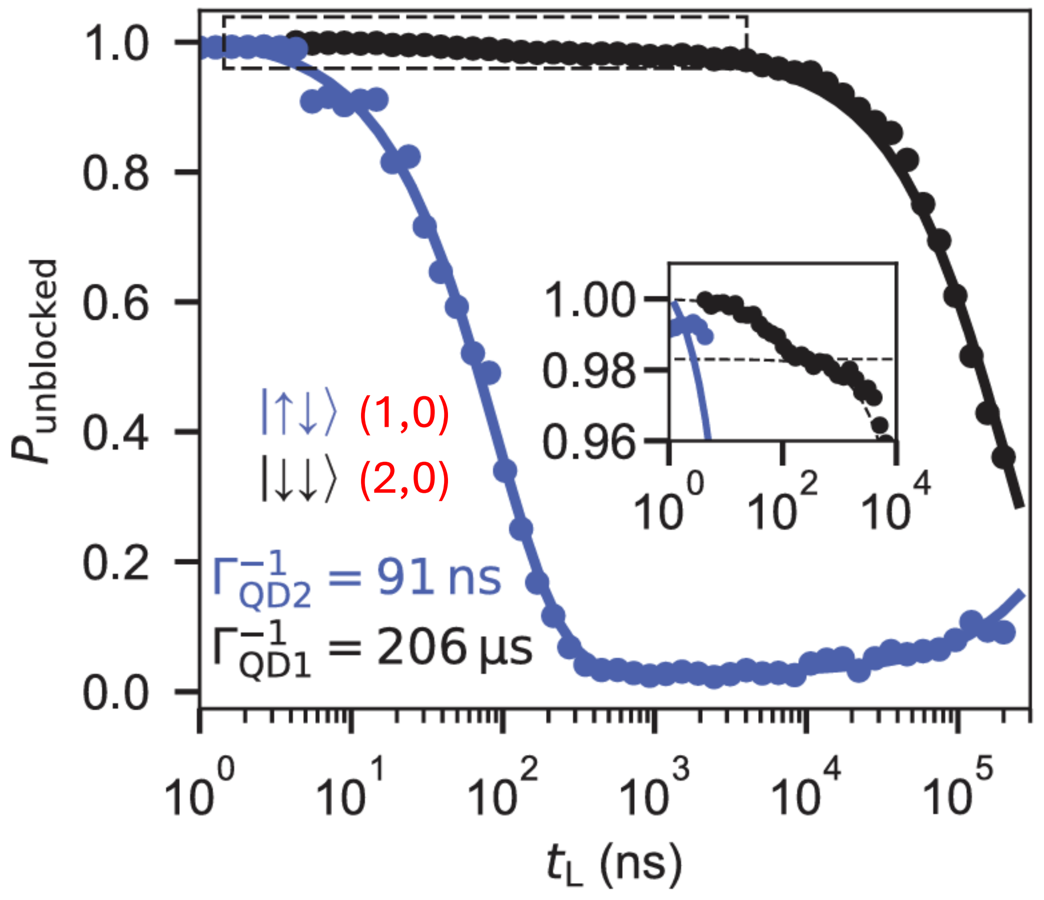
Latching vs Decay



- Point DL
- We readout (1,0), instead of (2,0).

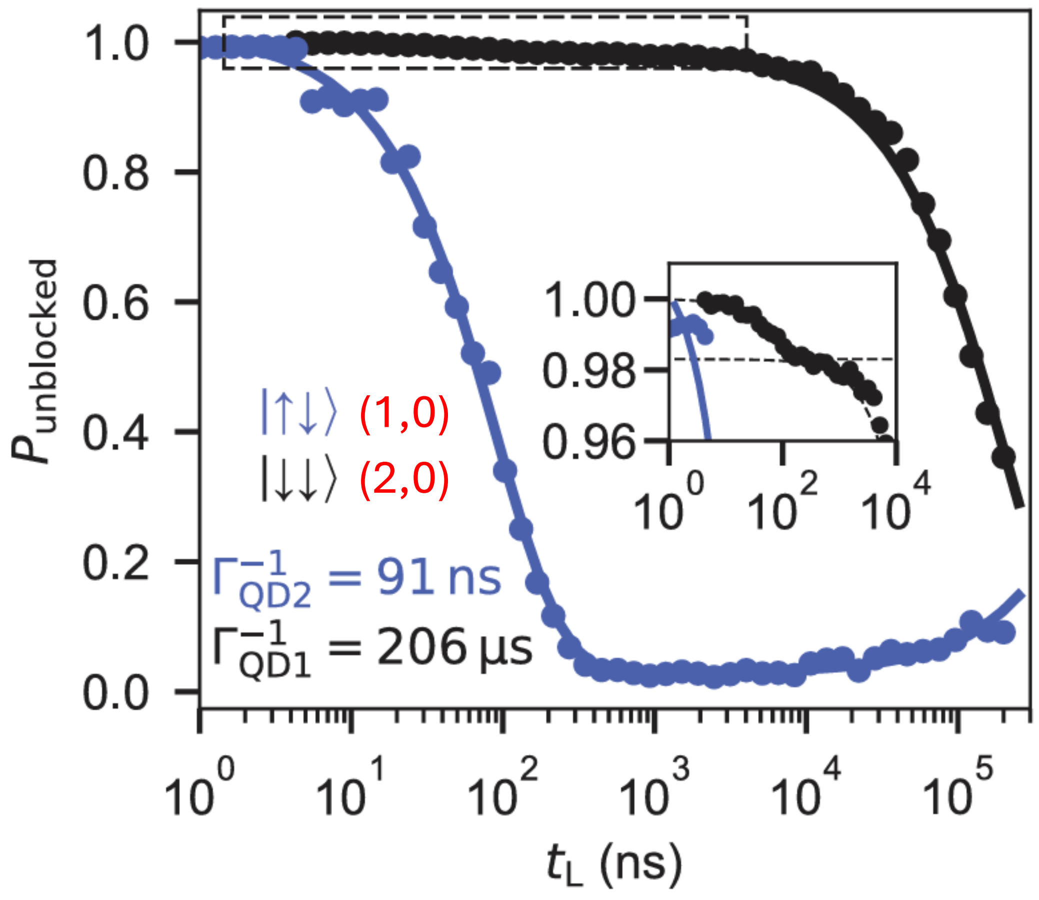
To remedy this

- $P_{\mathrm{Unblocked}}$ is measured, after preparing $|\uparrow\downarrow\rangle$ and $|\downarrow\downarrow\rangle$ separately, as a function of t_{L}



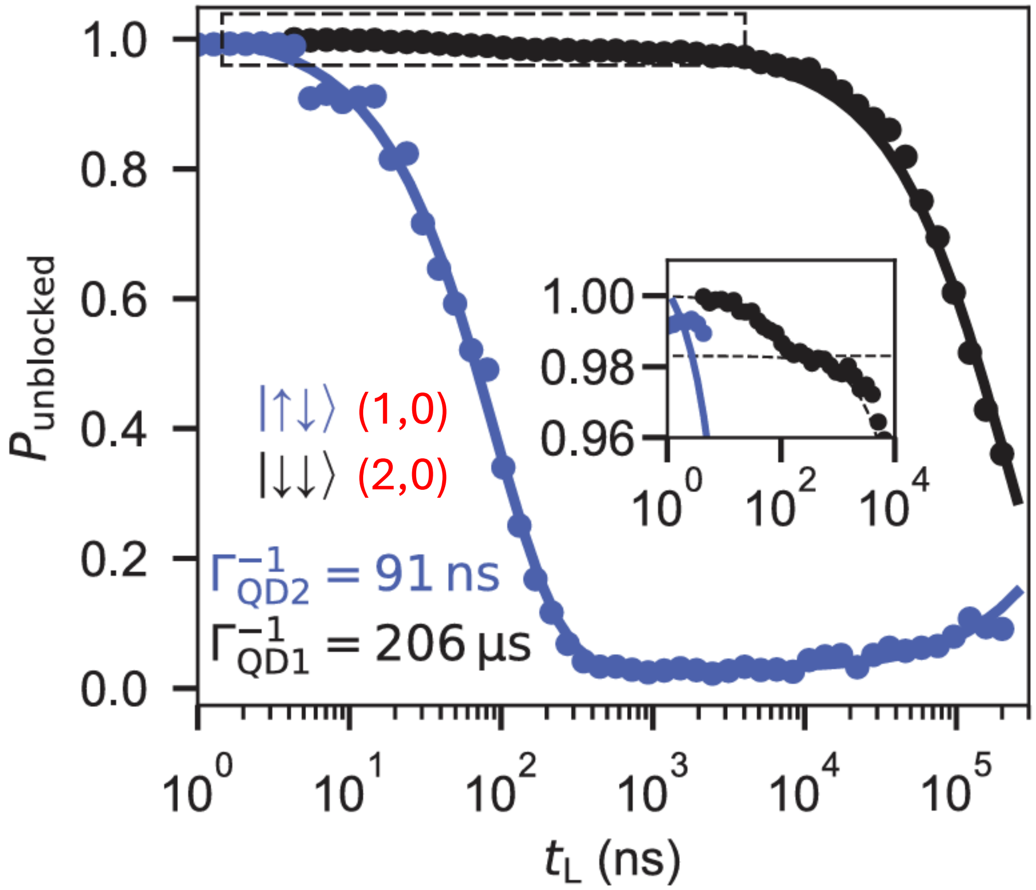
To remedy this

- $P_{\mathrm{Unblocked}}$ is measured, after preparing $|\uparrow\downarrow\rangle$ and $|\downarrow\downarrow\rangle$ separately, as a function of t_{L}
- $|\uparrow\downarrow\rangle$ relaxes from (2,0) to (1,0) exponentially with a characteristic time of 91 ns.
- $|\downarrow\downarrow\rangle$ relaxes from (2,0) to (1,0) with a characteristic time of 206 μs.



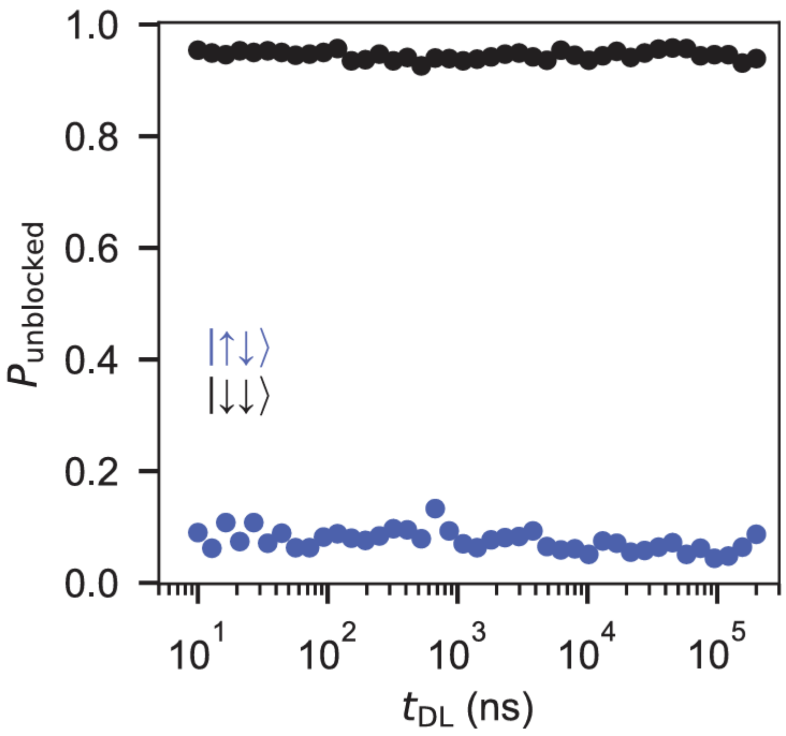
Why do the DL, still?

- Being somewhere in between 91 ns and 206 μs should be enough to distinguish between (2,0) and (1,0) without any unwanted relaxations.
- But the measurement is still limited by the integration time t_{int}, which is not much faster than 206 μs.
- With $t_{\text{int}} = 50$ μs, there is still an error of 11.4% in the readout.



DL saves the day!

- Waiting for an optimal time at point L and then pulsing to DL prevents further decay of the (2,0) state entirely.
- With $t_{\mathrm{L}} = 2\ \mu\mathrm{s}$, the (2,0) decay error during integration is reduced to 0.97%.

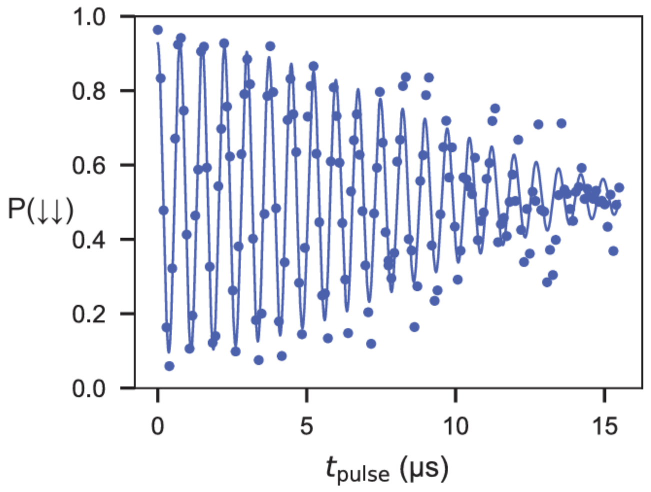


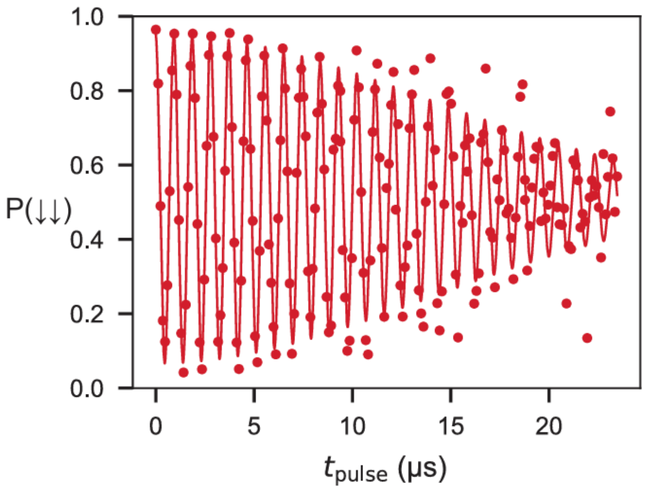
Conclusion

- **Super-SAP is chosen as the StCC regime**, because it accommodates the relatively large ΔST_- and circumvents the challenges of using double ramps that make SAP difficult in this hole system.
- $\overrightarrow{\boldsymbol{B}}$ **field orientation** is chosen such that it **minimises the time required to reach the Super-SAP regime**, to prevent spin-decay during StCC.
- **Spin decay at the PSB point is extended by operating at low $\overrightarrow{\boldsymbol{B}}$.** This relaxation alone would yield an average readout fidelity of 64% for the PSB readout without latching, assuming the same $t_{\mathrm{int}} = 50$ μs.

Conclusion

- The enhanced **latching readout (without double latching) increases this fidelity to 92.5%** under the same measurement conditions.
- After double latching, average single-qubit SPAM fidelity of 97.0(5)% is achieved, only limited by $|\downarrow\downarrow\rangle$ initialization errors (1.7%) as well as SNR errors ($\lesssim$ 1.3%).





Rabi decay times of $T_2^R = 10.8(7)$ μs for the left dot,
and $T_2^R = 19.6(13)$ μs for the right dot.

Thank you