Quantum non-demolition readout of an electron spin in silicon

J. Yoneda, Nat Commun 11, 1144 (2020)

Qubit

whiskers

Copy-Cat

Journal-Club

MJC, April 3rd, 2020

Outline

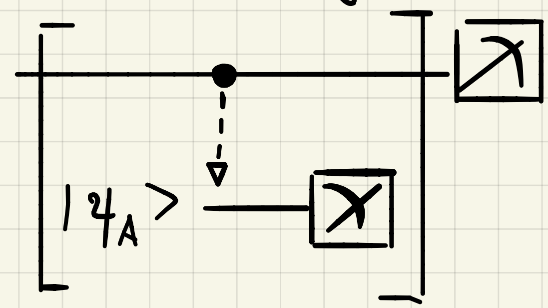
- Brief intro
- Device setup & readout calibration
- Results of repetitive readout
- Fidelities of QND, measurement & preparation
- Bonus, : „Surface code, a crash course"

QND-Measurements...

- allow for high fidelities when reading out (spin) information due to numerous averaging.

Qubit $|\psi\rangle$

Ancilla (little helper)



$20 \times t_{QND} < T_1$

- enable fast initialization of states because you can „peak" & see the state & flip it if required w/o having to wait for the spin to relax.

- are essential for implementation of quantum error-correcting protocols, such as the planar/surface code.

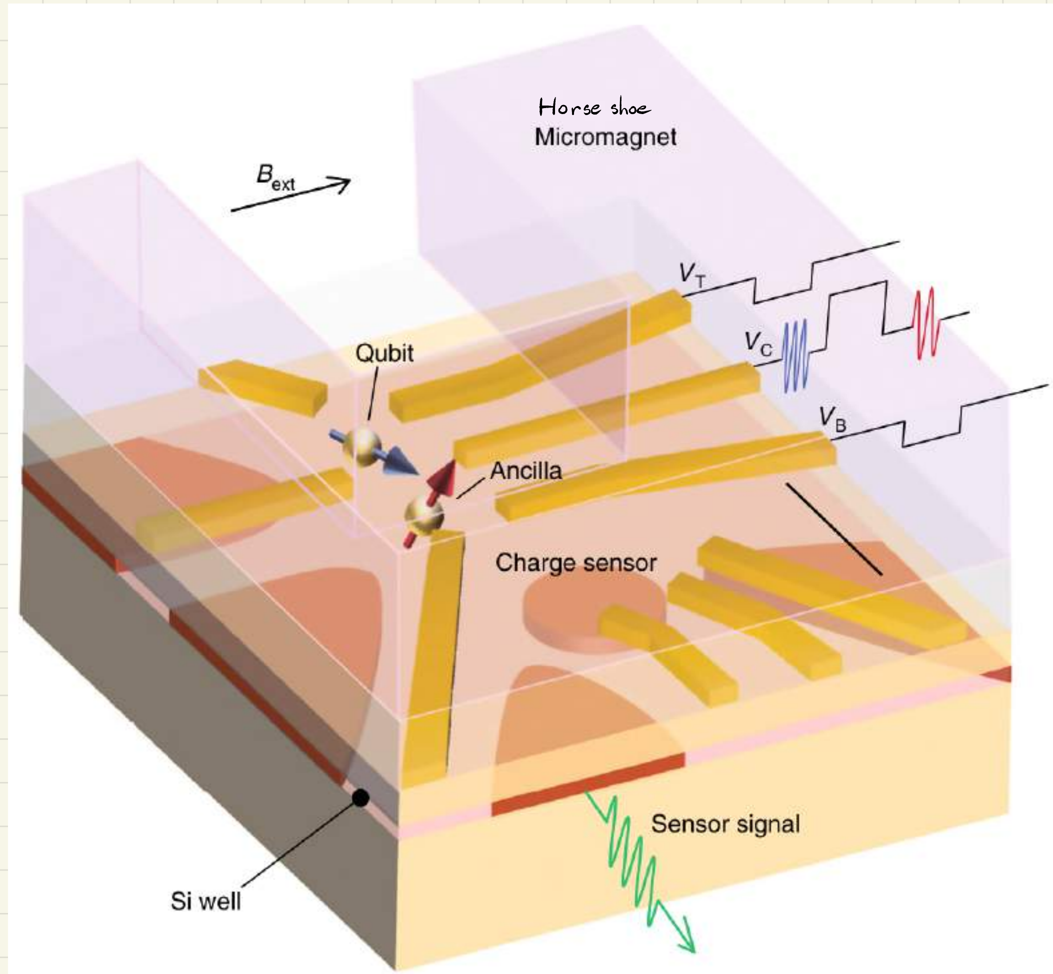
Device

- e^- spins confined in double Si/SiGe QD

- Spin states are discriminated & re-initialized (30 μs) w/ energy selective spin to charge conversion.

- Micro magnet ($B_{ext} = 0.51\,T$) → separates resonance freqs. of q & a. Freq. selective EDSR.

$-640\,MHz \quad 16.3\,GHz \quad +640\,MHz$



- changing V_T & V_B modulates the exchange coupling between q & a

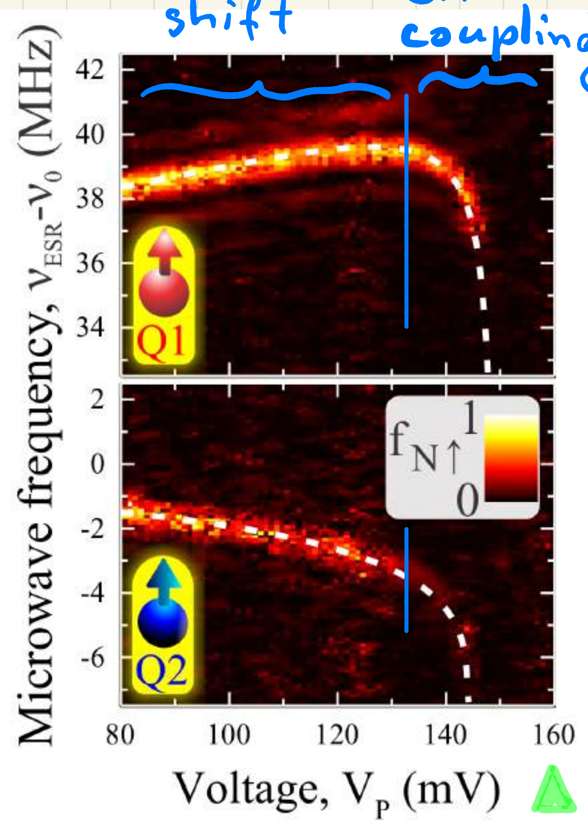
Qubit-spin dependent precession frequency of the ancilla

- According to Veldhorst, when inside the enhanced exchange coupling regime, the system can be tuned s.t. the resonance freq. of a is double when q is |↑>. MJC ?!

Red: qubit

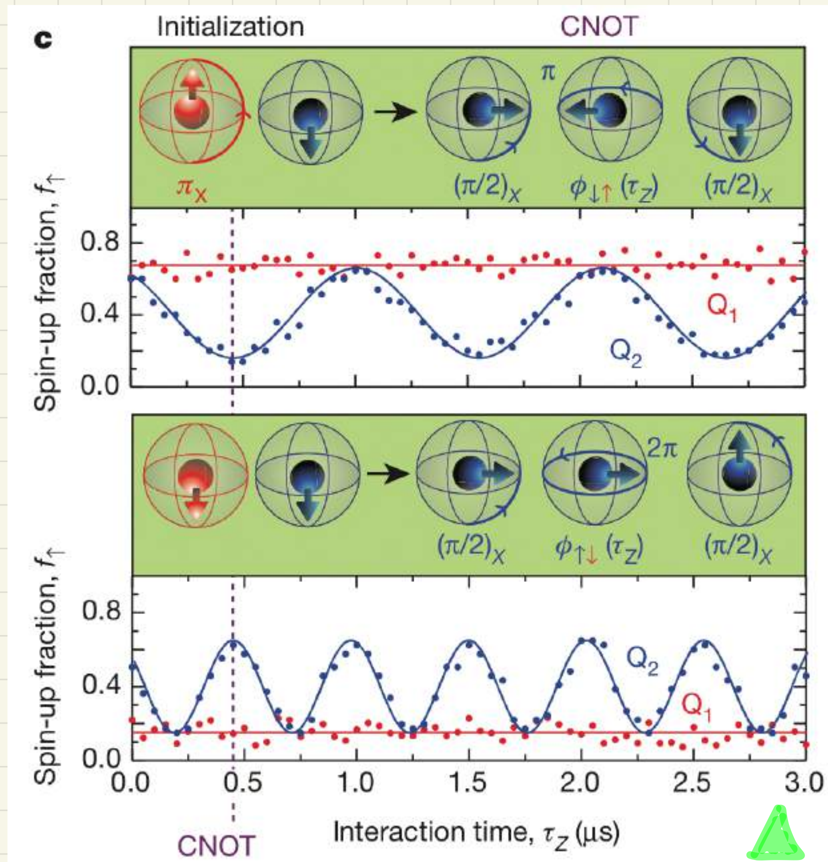
Blue: ancilla

stark shift   exchange coupling



qubit

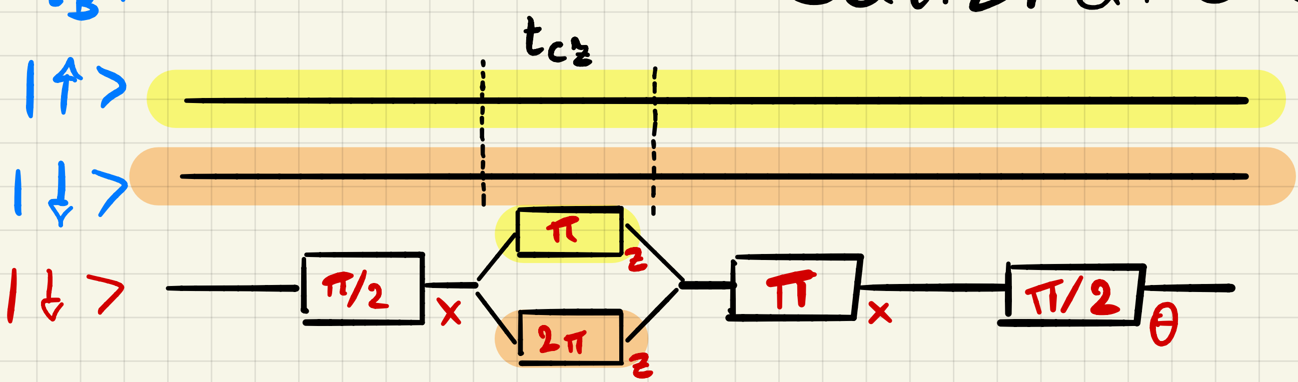
ancilla

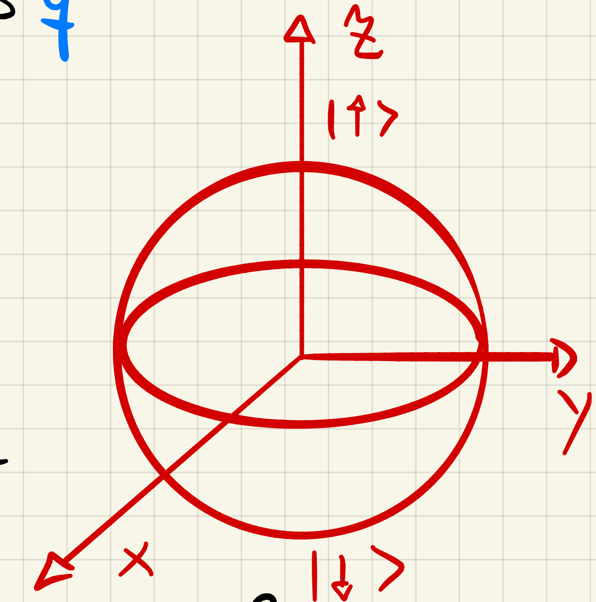


Ref (3) M. Veldhorst, Nature 526, 410-414 (2015)

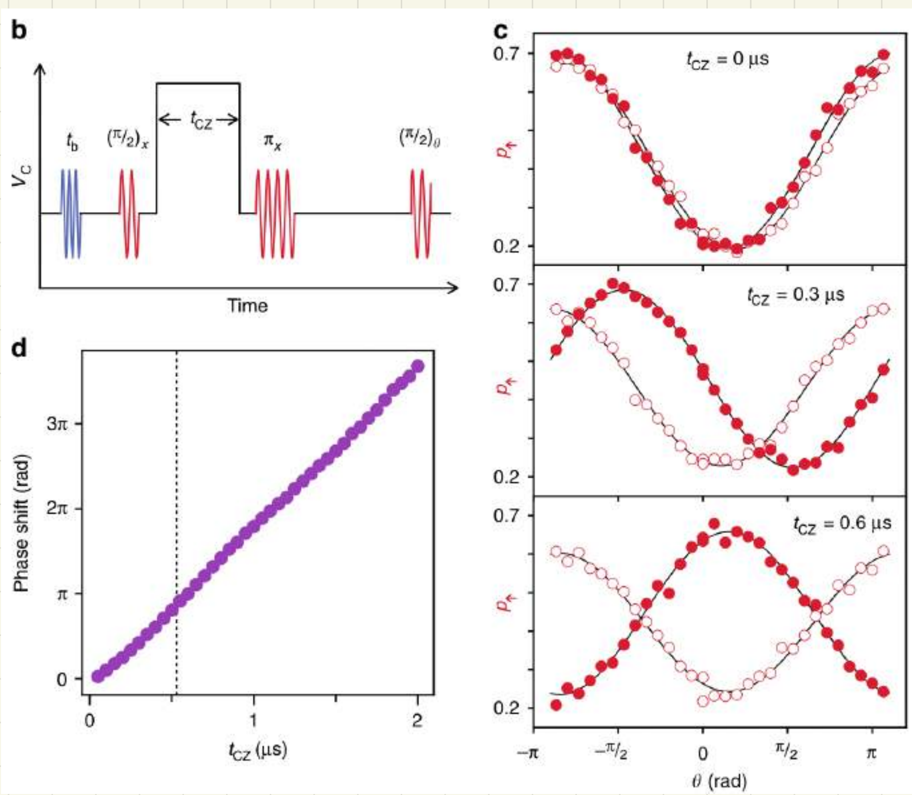
Calibration α vs q

t_B init



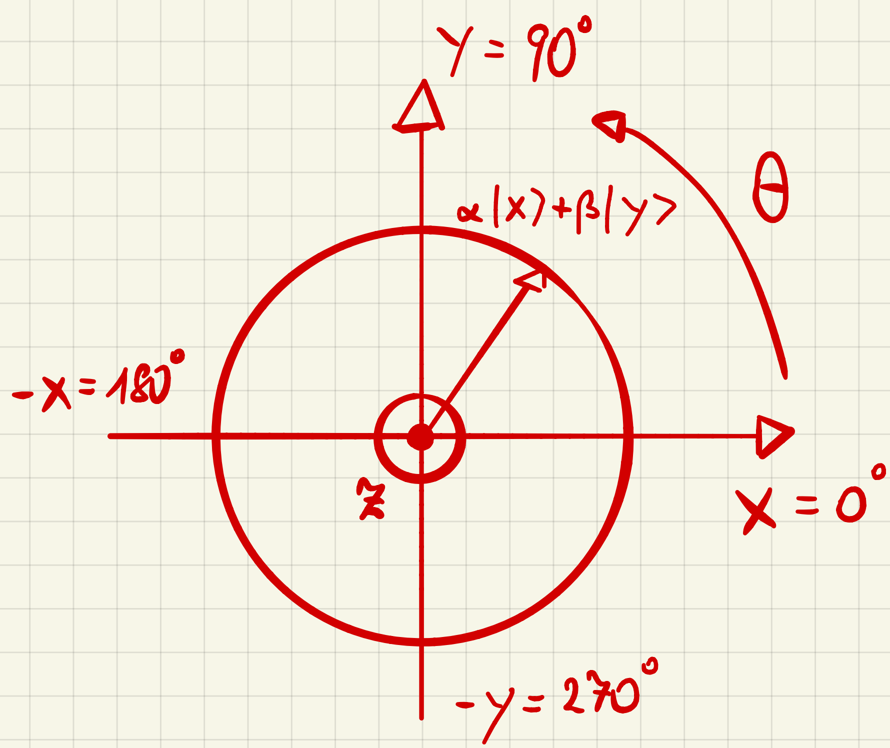


Aim to have π, 2π precession, hence max projection at $\theta = 0°$.



optimal $t_{cz} = 0.53\,\mu s$

Birdseye view of equatorial plane

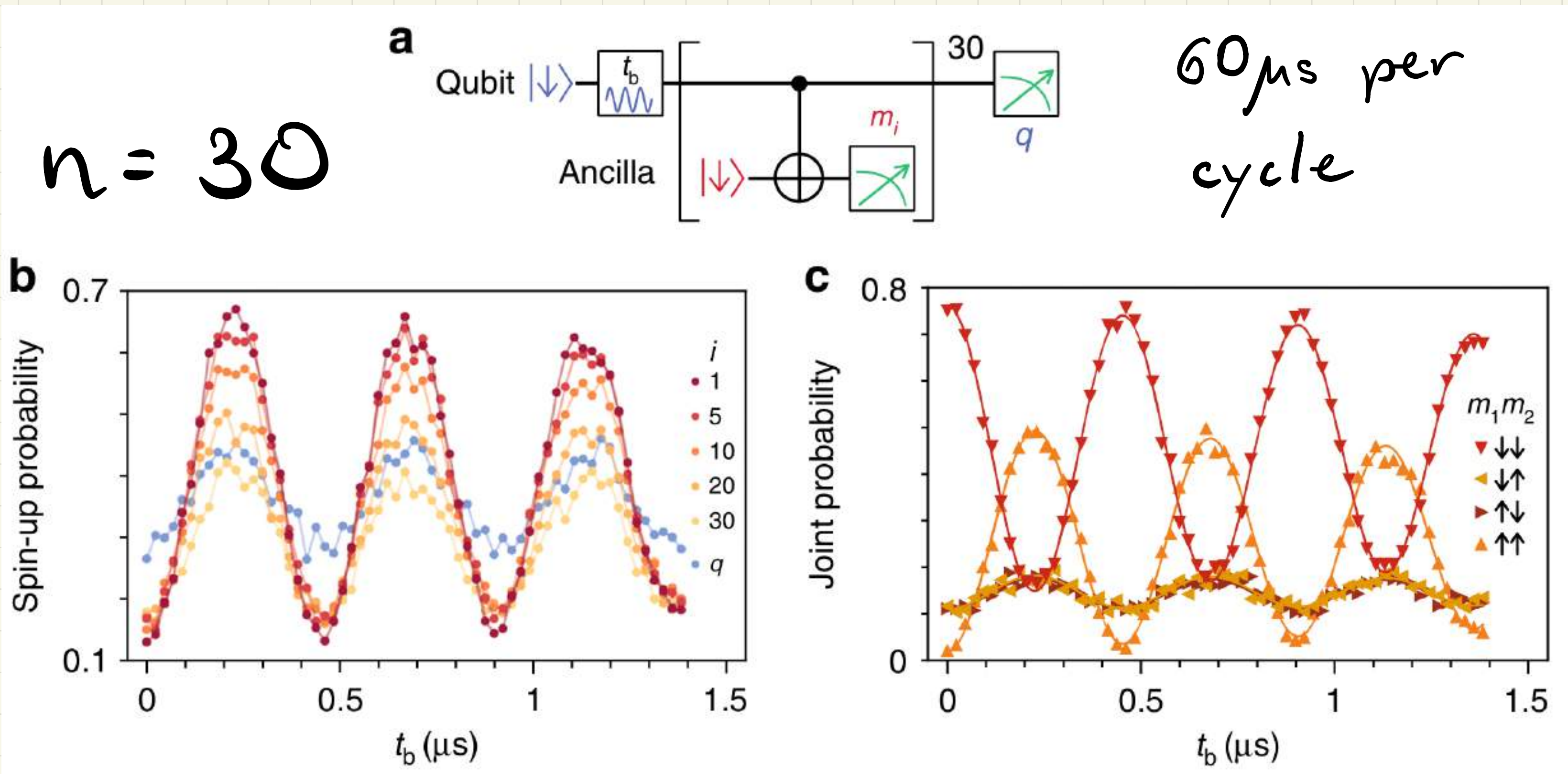


● $|\uparrow\rangle$ $(=|\downarrow\rangle + \pi_x)$ ○ $|\downarrow\rangle$

Repetitive readout

- Measuring Rabi oscillations of q on a. With increasing n, $P(\uparrow)$ decreases since spin decoheres. The n a-readouts (QNDs) must happen within T_1. This already indicates how $F_{QND} \to 0$ for $n \to \infty$.

$n = 30$

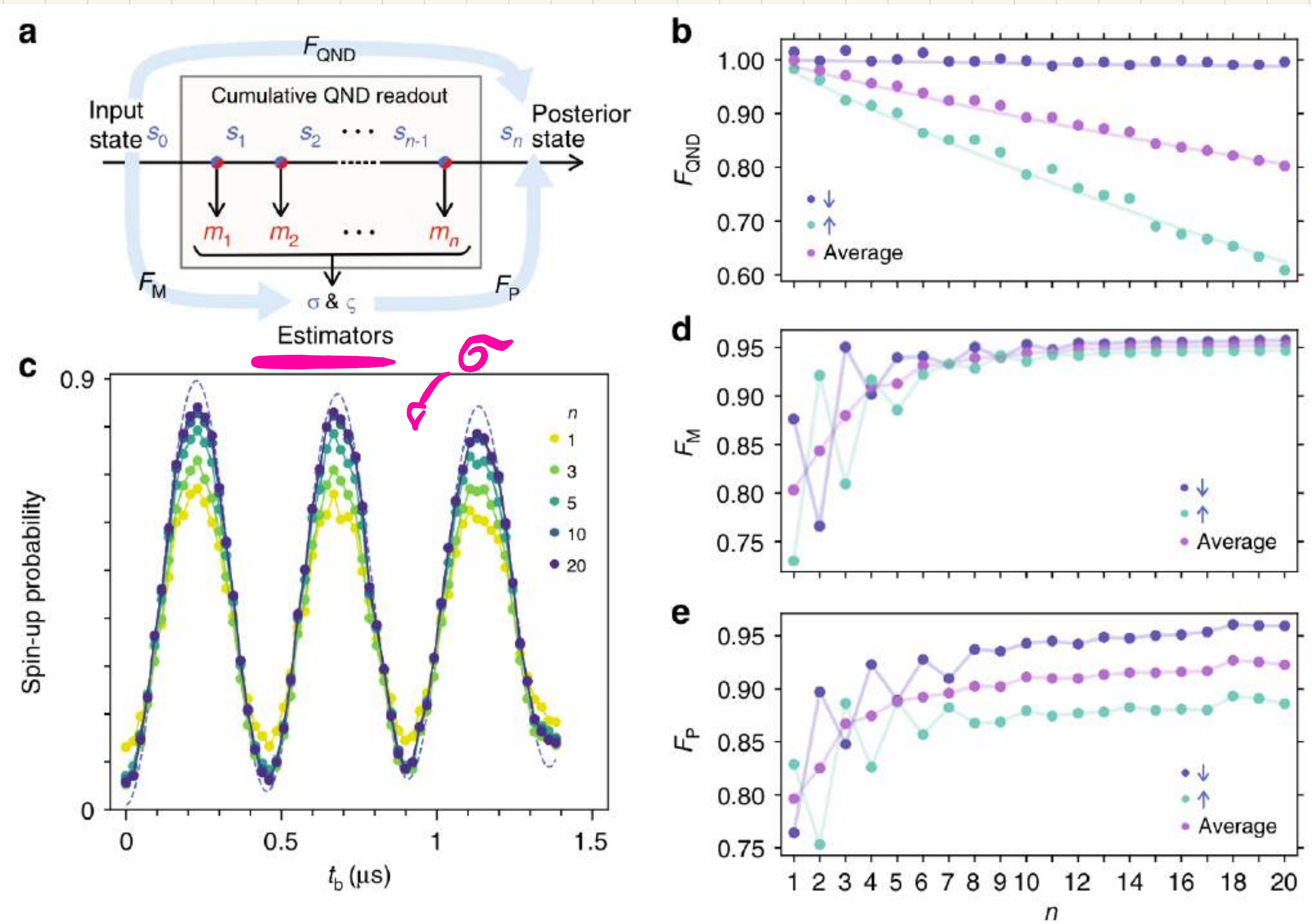


60 μs per cycle

Fidelities: F_{QND}, F_M, F_P (map, measure, prepare)

- Expect $F_{QND} \xrightarrow{n\to\infty} 0$. $F_{QND}^{\uparrow(\downarrow)} = P(s_n = s_0 \mid s_0 = \downarrow(\uparrow))$, from $p_n^{\downarrow} = F^{\downarrow}_{QND\,(M)}\, p_0^{\downarrow} + (1 - F^{\uparrow}_{QND\,(M)})\, p_0^{\uparrow} = P(\sigma = \downarrow)$
- $F_M \xrightarrow{n\to\infty} 1$, $F_M^{\downarrow(\uparrow)} = P(\sigma = s_0 \mid s_0 = \downarrow(\uparrow))$, σ is estimator for input state s_0
- $F_P^{\downarrow(\uparrow)} = P(s_n = \varsigma \mid \varsigma = \downarrow(\uparrow))$, ς estimator for post. qubit. To estimate ς from m_n compare $P(m_n \mid s_n = \downarrow)$ vs -"- $\uparrow$

$n = 20$



$\hat{=}$ GS

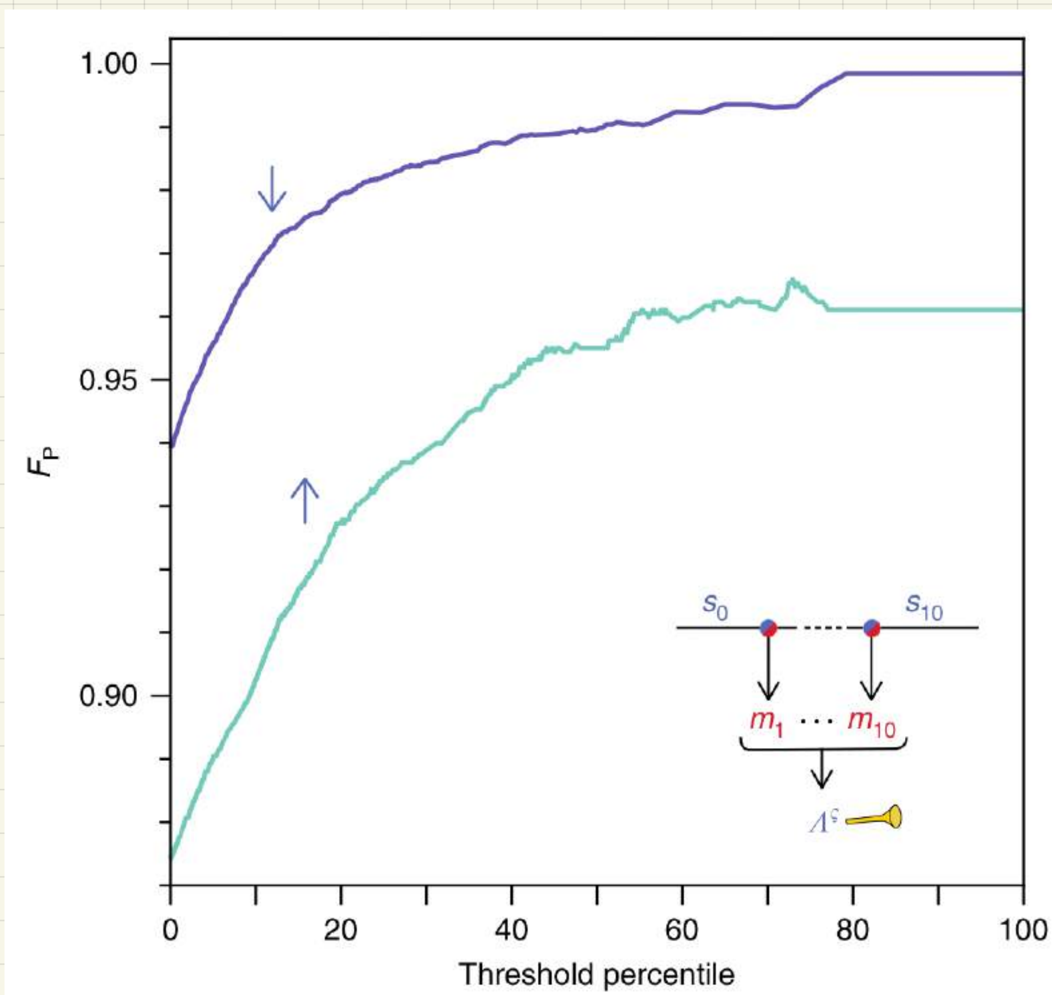
$T_1^{\downarrow(\uparrow)} = 78\,ms\ (2.5\,ms)$

$\hat{=}$ EX, can relax

Bottleneck is readout of α

Heralded enhanced preparation fidelity

?



Summary & Conclusion

- 30 ancilla measurements are possible before $F_{QND}^{1} \lesssim 50\%$ (uncorrelated IN vs OUT)
  Limited by T_1.
- T_2 doesn't affect fidelity since meas. of a are projected on z-axis.
- For $n \to \infty$, $F_M, F_P \to 1$ whereas $F_{QND} \to 0$ impacting overall performance.
- Overall QND readout of single e^- spin in Si was demonstrated.
- Next step, make surface code. Approx 2-5 weeks.

Outlook

Error Correction

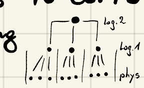
& Surface Code

... a crash course

Backed by the 2016 - chronicles by J. Wootton

Error Corr. & Surface Code, Crash Course

Idea:
- Need redundancies
- Check if they all agree (parity)
- Map that parity to a „sacrificial" ancilla,
  which you can read-out & therefore decide
  to perform an error correction or not.

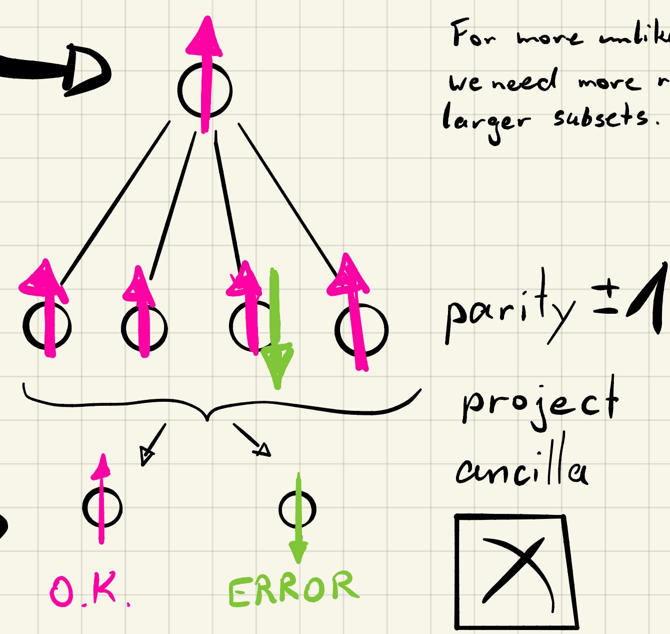
(consider 1^{st} ord. errors:
So we correct only „likely" errors.
For more unlikely errors e.g. 2x flip,
we need more redundancies to correct
larger subsets. → Stacking 

)

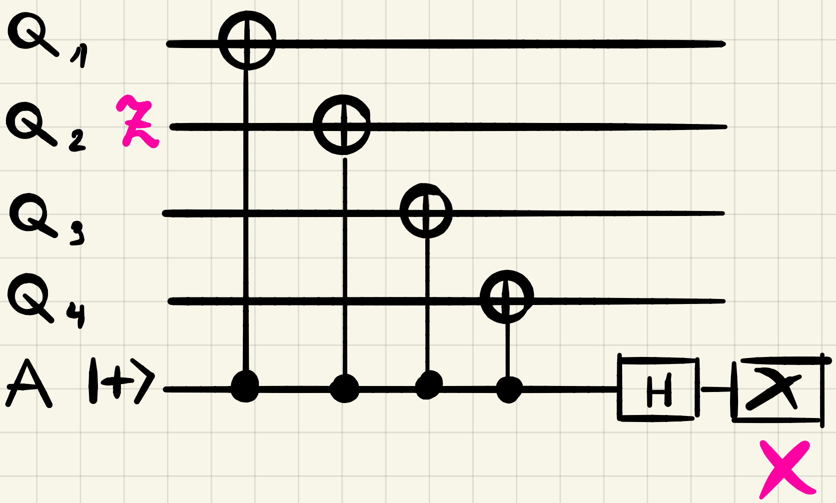
logical qubit →

Stabilizer consisting of
4 phys. qubits →

one phys. qubit →

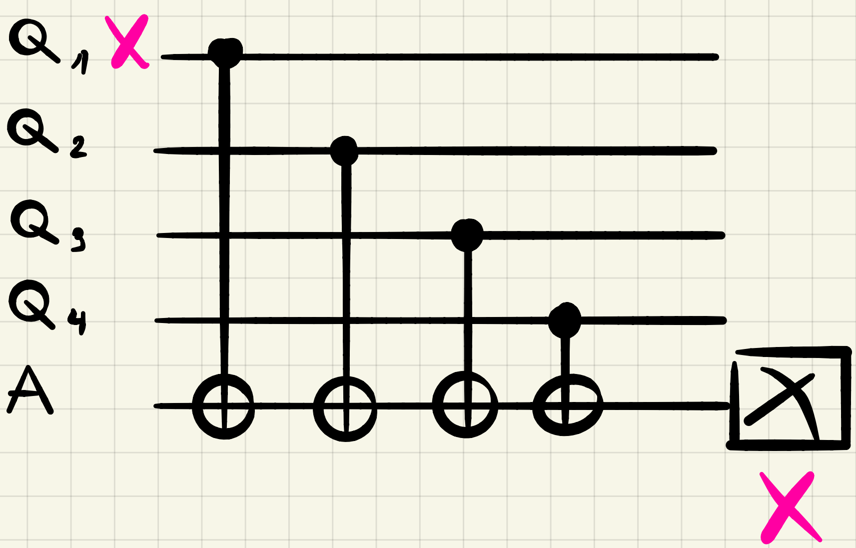


Stabiliser Code /w parity check



ancilla flips if Z error

Z-parity check, stabilizer S_Z



ancilla flips if X error

X-parity check, Stabilizer S_X

Define Stabilizer Code

$XZ = -ZX$

Def: Set of code states

e.g. $s_x = \sigma_x \sigma_x \sigma_x \sigma_x$

$$\boxed{|\psi\rangle \in C : s|\psi\rangle = |\psi\rangle \ \forall \text{ operators } s \in \mathcal{S}}$$

We say s „stabilizes" $|\psi\rangle$ because $|\psi\rangle$ is the $+1$ Eigenstate of s.

Assume an error $E \in$ Paulis, $|\psi\rangle \longmapsto E|\psi\rangle$

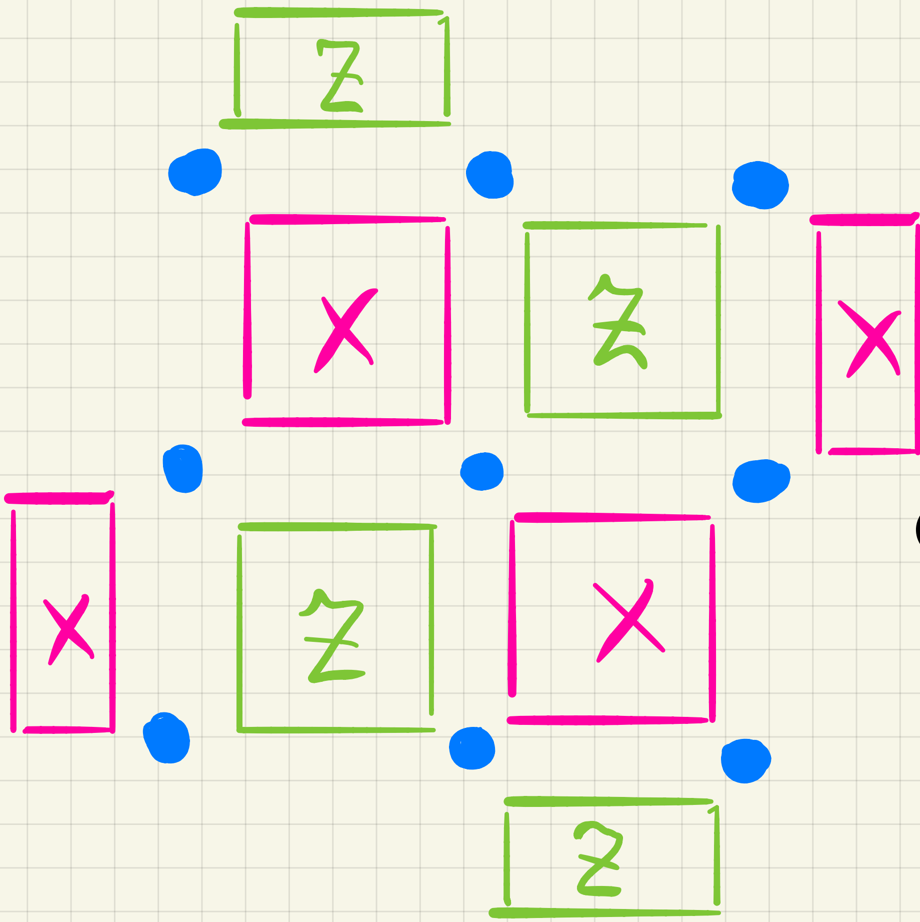
$Es = -sE$

$E^2 = \mathbb{1}$

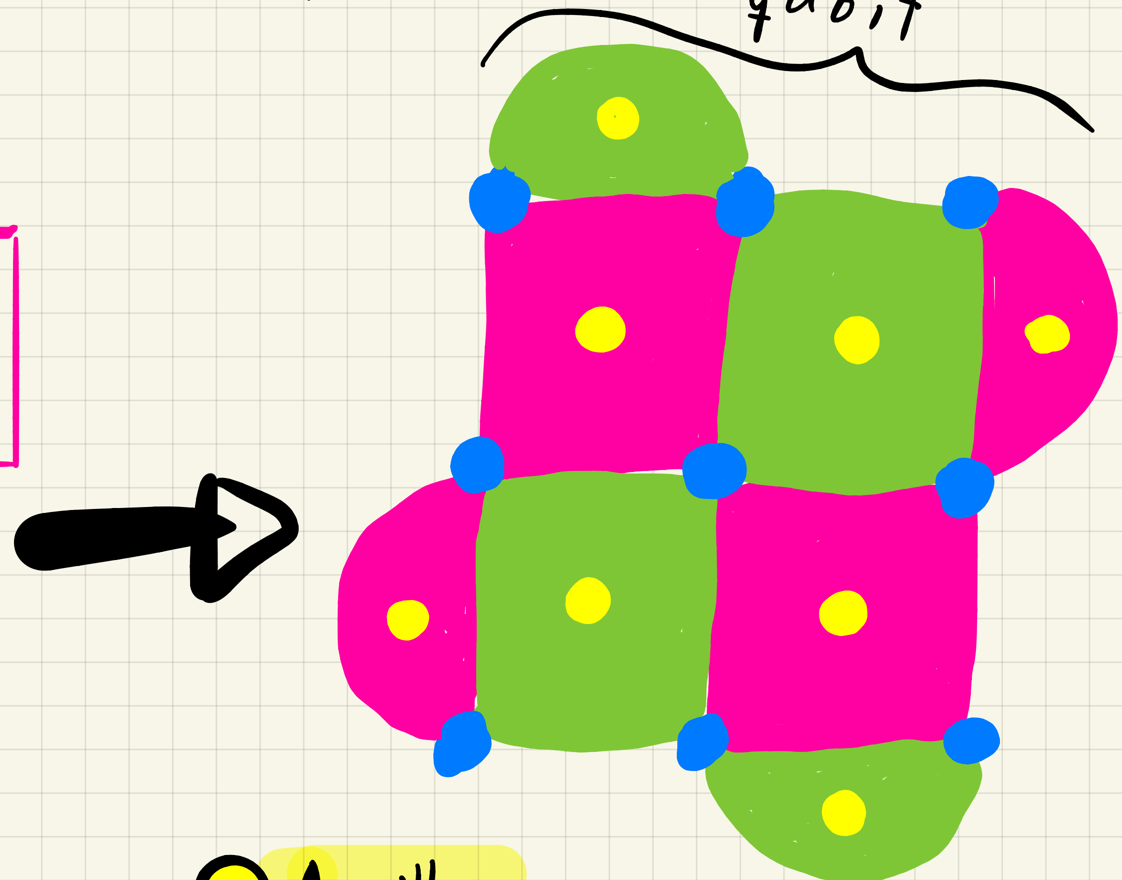
$$\left.\begin{aligned} \therefore \langle\psi|EsE|\psi\rangle &= -1 \\ \langle\psi|s|\psi\rangle &= +1 \end{aligned}\right\} \text{E has phys measurable effect.}$$

Def: Stabilizers X, Z

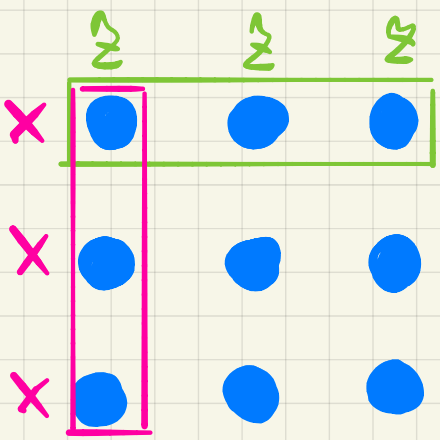
• qubits



One logical qubit



$$\left(X \otimes X \cdot Z \otimes Z = Z \otimes Z \cdot X \otimes X\right)$$



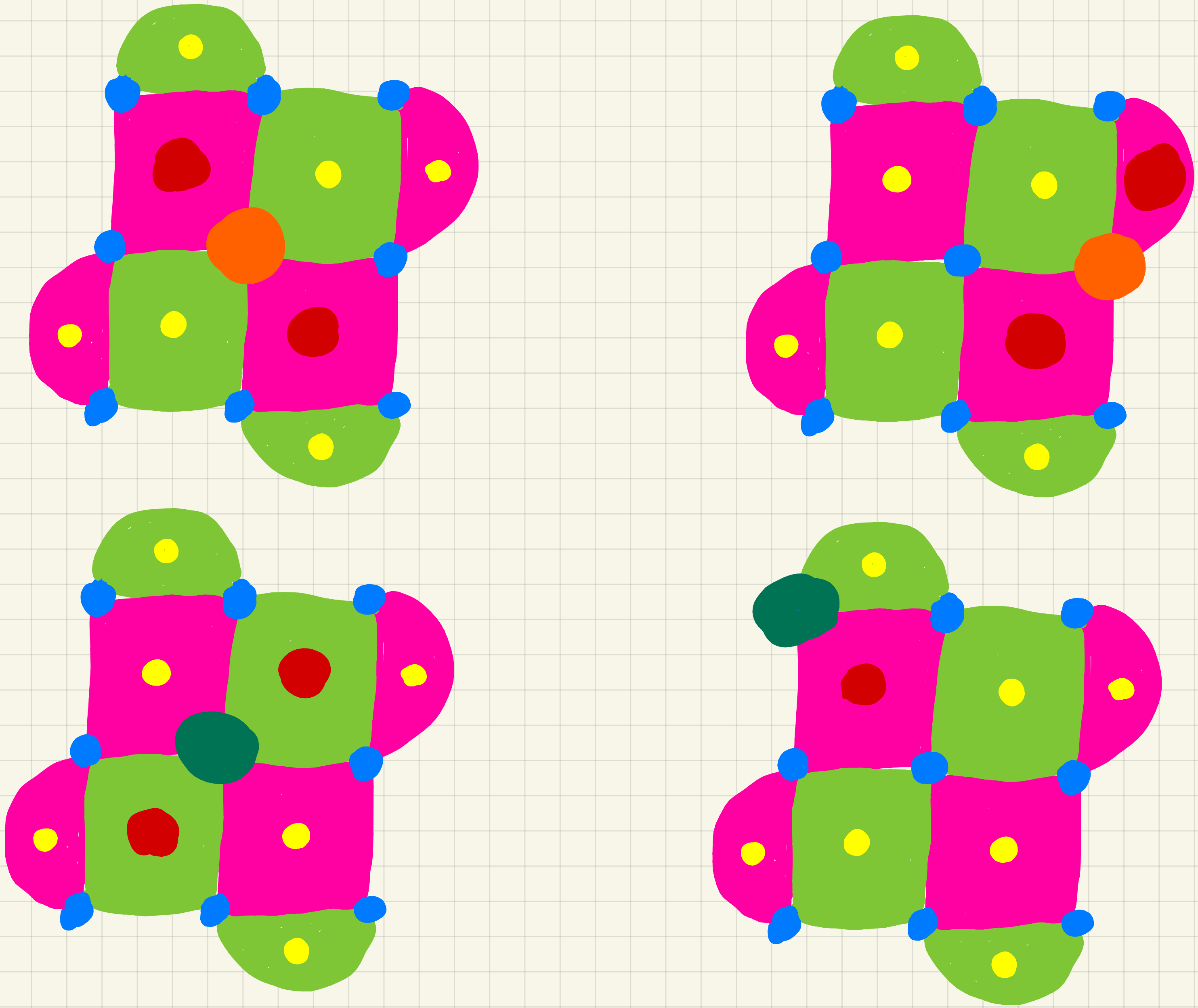
L_z & L_x mutually anticommute on same qubit but commute with stabilizer S_z & S_x respectively. Note $L_i^2 = 1$

This example has 9 qubits, hence:

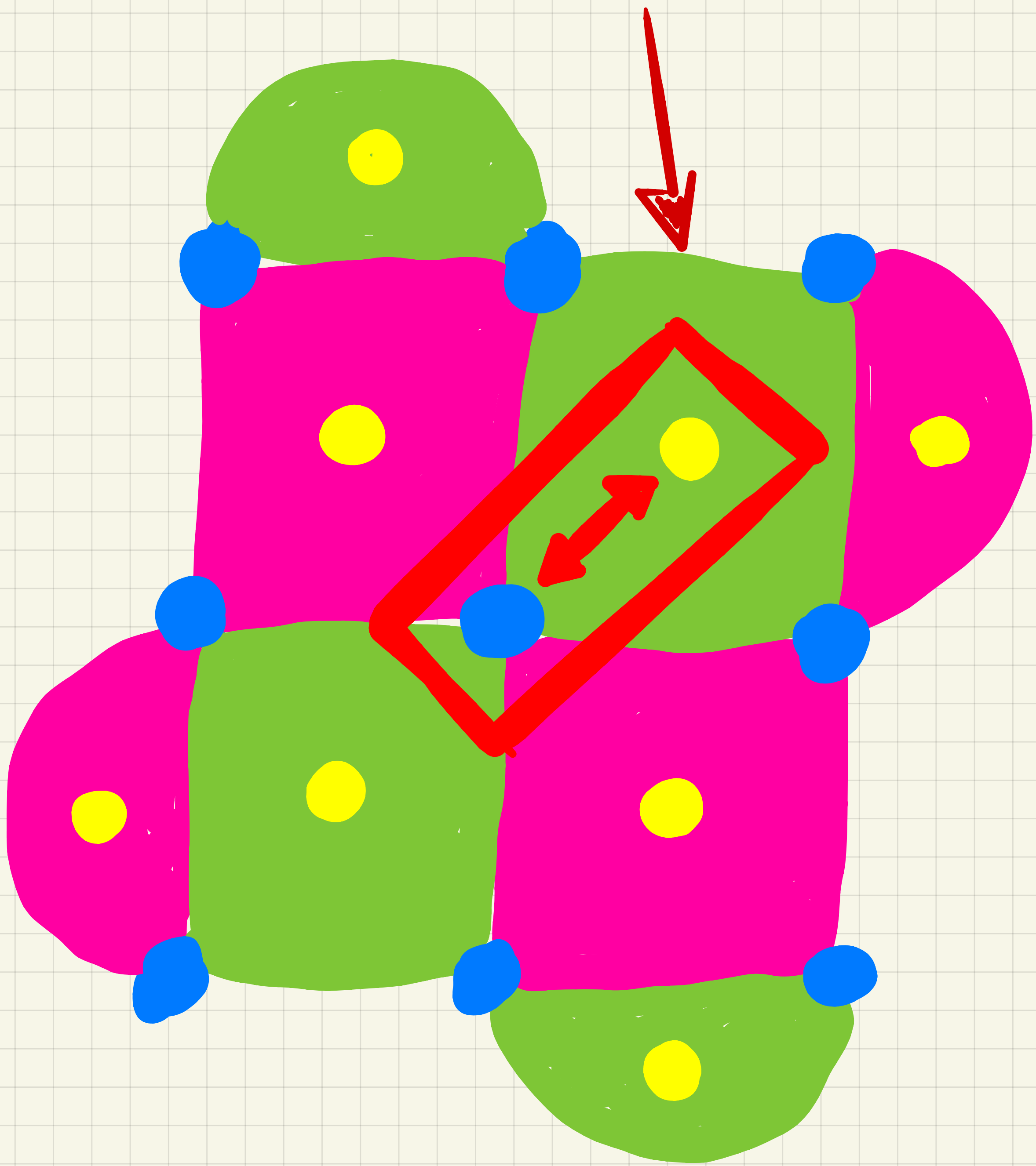
- distance $d = 3$, can correct almost $d/2$ errors
- $k = 1$: # logical qubits
- $n = 9$: # physical qubits

ERRORS

alarmed ancilla   Z error   X error

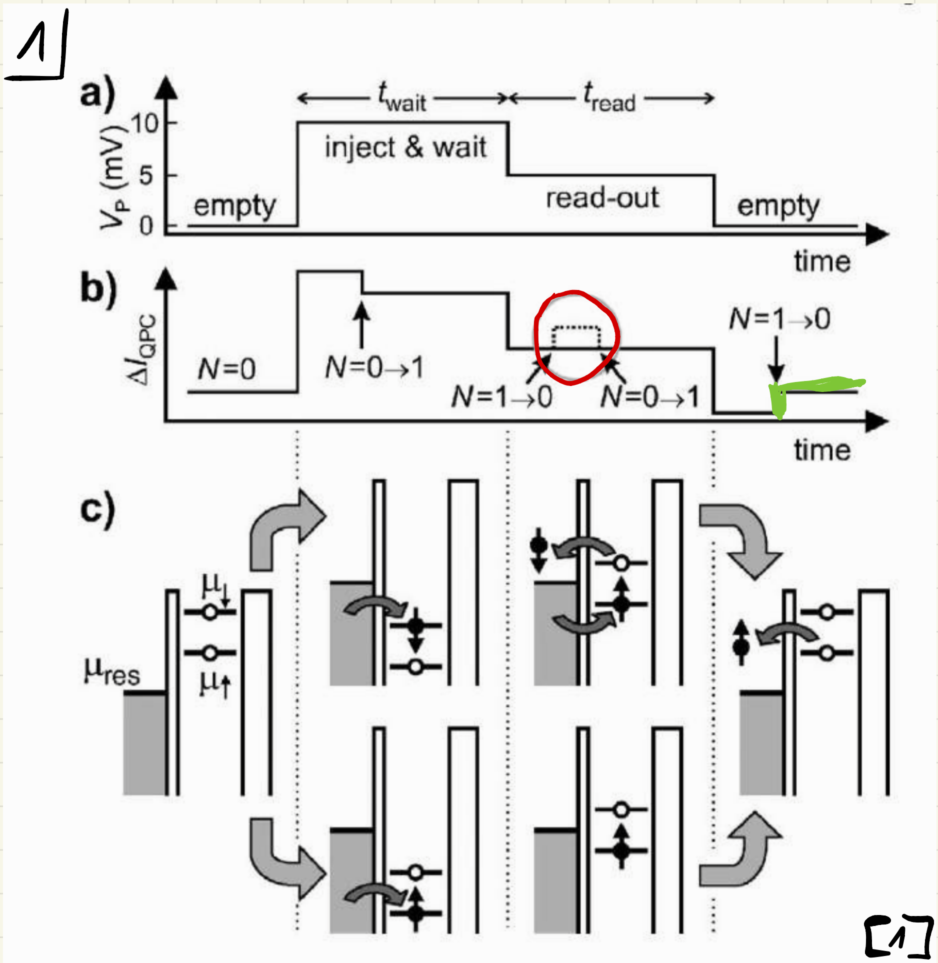


Yaneda et al.

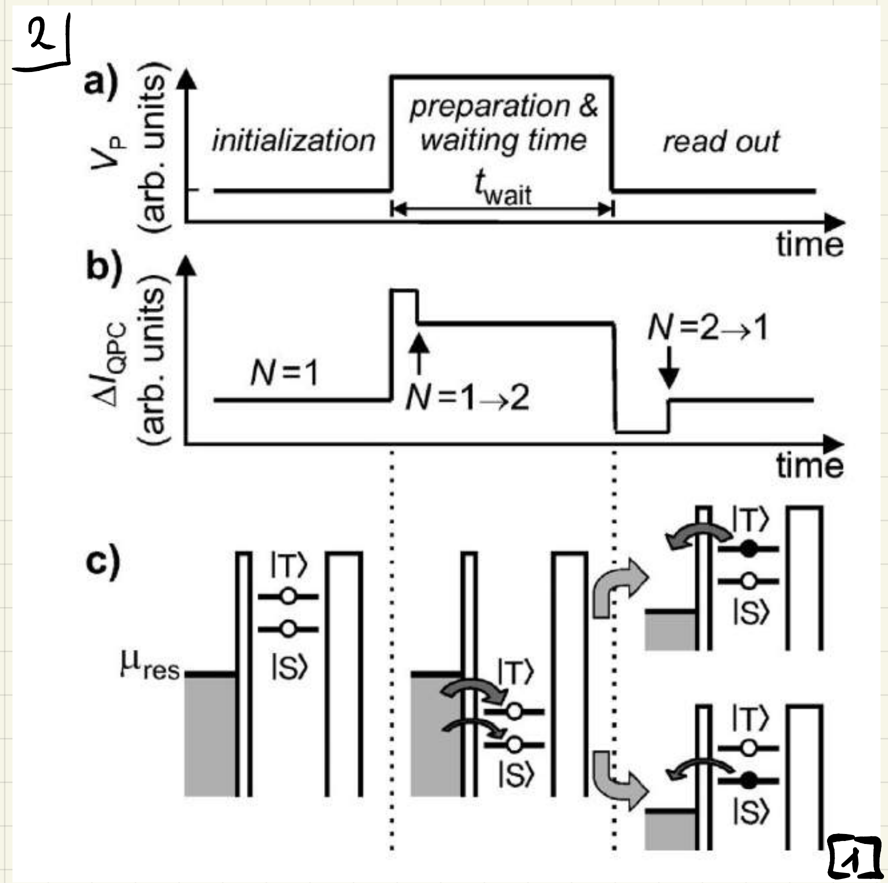


Spin to Charge Readout, Refresh

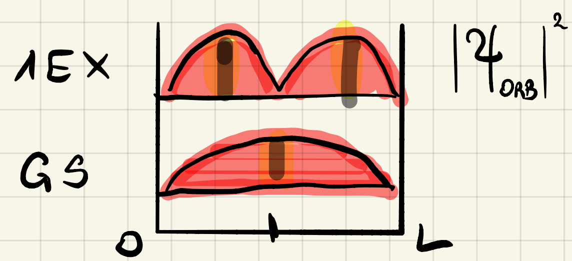
Energy selective readout (Elzerman)



Tunnel-rate selective readout



- Both methods loose the state through the lead.



$|T_{spin}\rangle \rightarrow$ sym.

$|S_{spin}\rangle \rightarrow$ anti-sym.

[1] R. Hanson, Rev. Mod. Phys., 79, 1217 (2007)