Beating the thermal limit of qubit initialization with a Bayesian "Maxwell's Demon"

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Motivation

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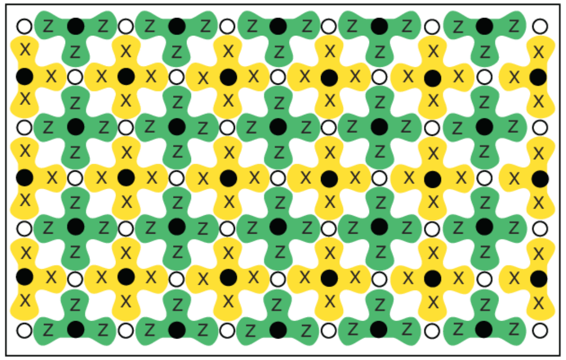
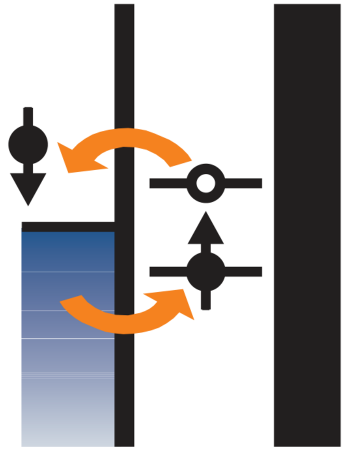
Fidelity requirements of Surface Code

- single- and two qubit gate fidelities:[1] >99%
- state preparation and measurement (SPAM) fidelity:[1] >99%



- systems based on energy-selective tunnelling: ultimatley limited by temperature
- readout fidelity: can be improved by QND measurement[2]
- here: overcome temperature limit of initialization
  - for high-temperature operation
  - or higher fidelity at lower temperature



[1]A. G. Fowler, M. Mariantoni, J. M. Martinis, and A. N. Cleland, Phys. Rev. A **86**, 032324 (2012)
[2]J. Yoneda et al., Nat. Commun. **11**, 1144 (2020)
[3]J. M. Elzerman *et al.*, Nature **430**, 431–435 (2004)

Basic idea

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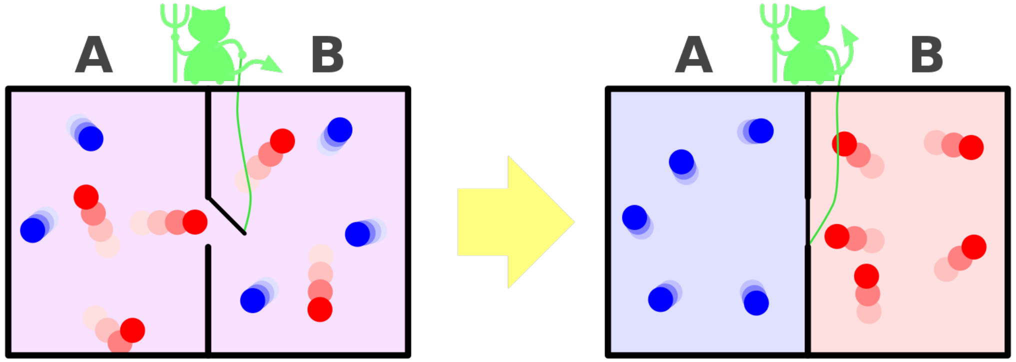
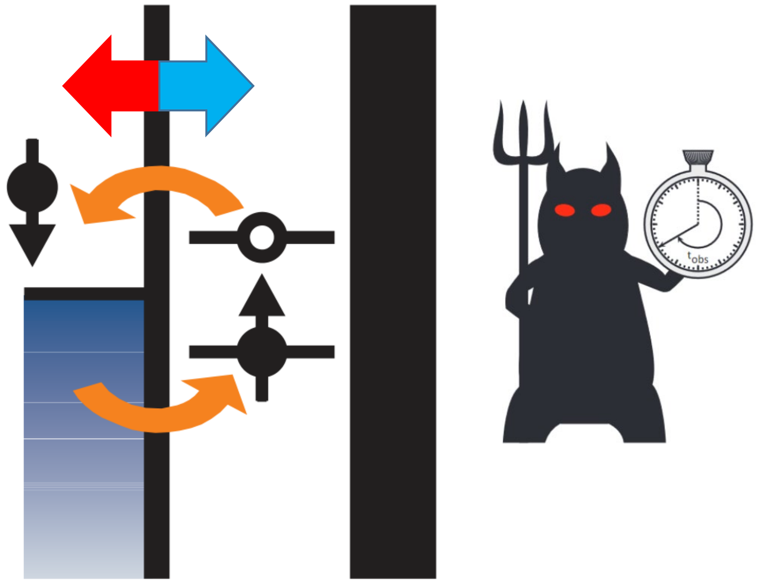
Maxwell‘s Demon

- thougth experiment: use a „demon“ to separate hot and cold gas particles



„qubit initialization“ demon

- load cold electrons into the QD and leave warm electrons in the reservoir
- beat theoretical limit for qubit initialization fidelity



[1]J. M. Elzerman *et al.*, Nature **430**, 431–435 (2004)

Setup

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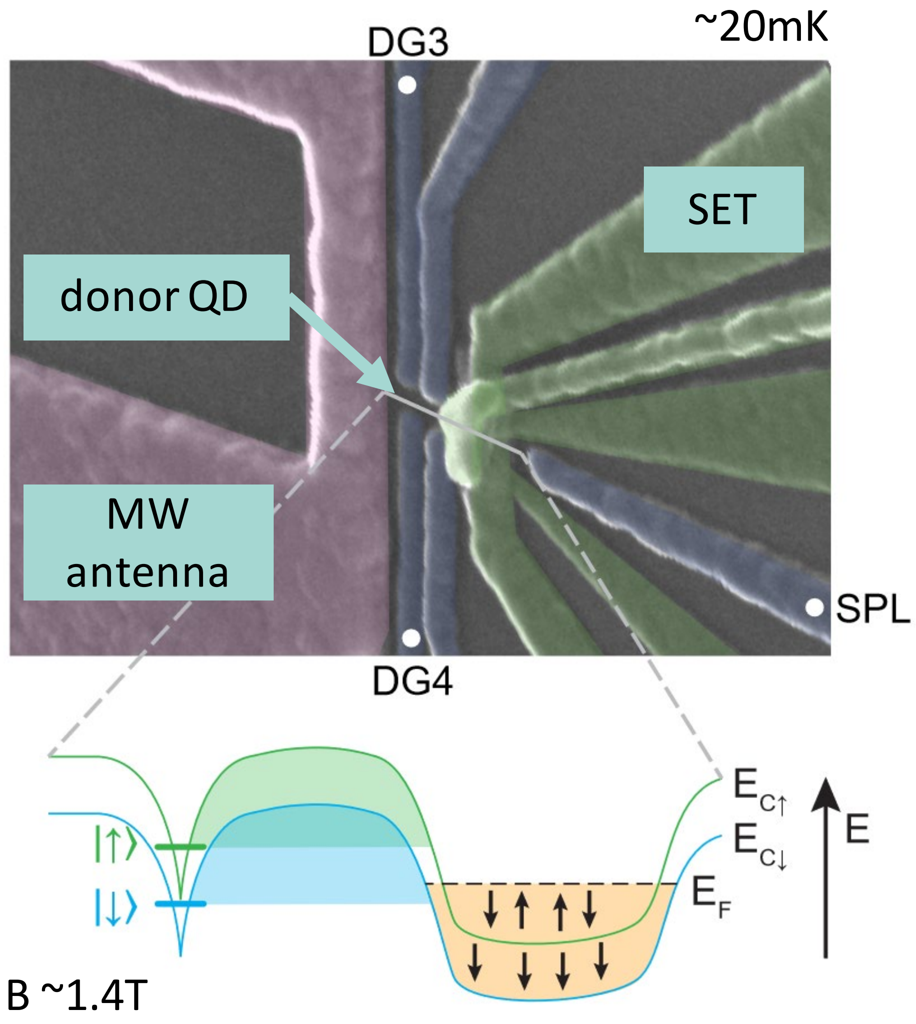
Device: donor QD

- ^{31}P donor in enriched ^{28}Si
- MW antenna for ESR and NMR
- SET as reservoir and charge sensor (50kHz)
- control setup via FPGA at 100MHz



Qubit initialization

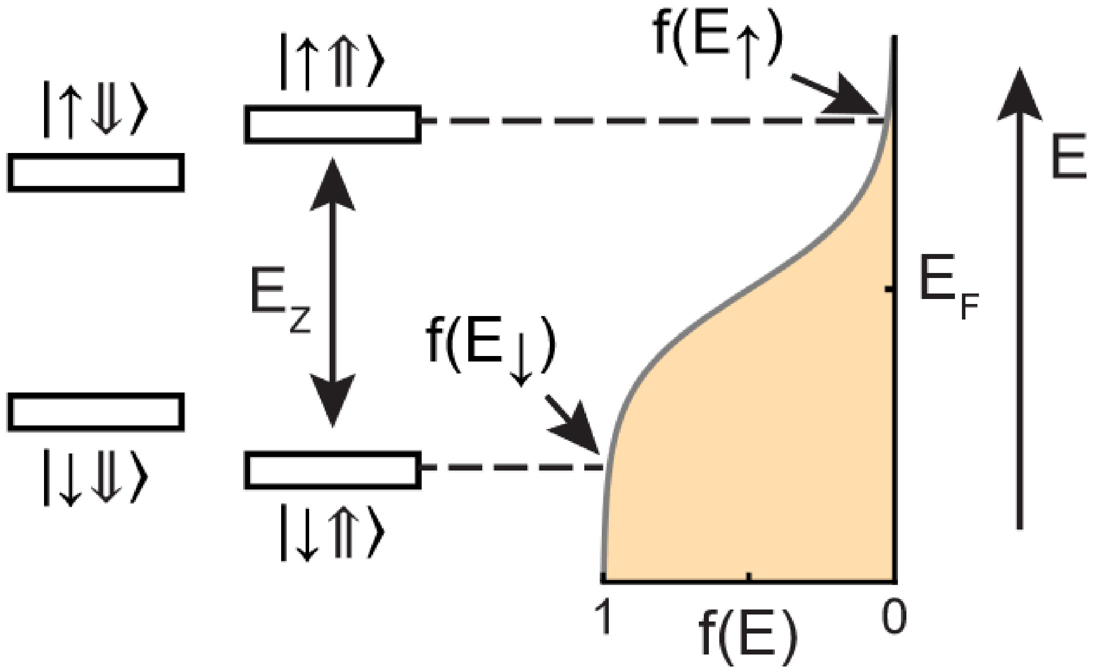
Spin-dependent tunneling

- probablility for loading $|\downarrow\rangle$ or $|\uparrow\rangle$ is given by Fermi distribution:

$$f(E) = \left(1 + \exp\left(\frac{E - E_\mathrm{F}}{k_B T_\mathrm{e}}\right)\right)^{-1}$$

- if $E_Z >> k_B T$ → mostly $|\downarrow\rangle$ is loaded
- probability to load $|\downarrow\rangle$ is limited by finite T

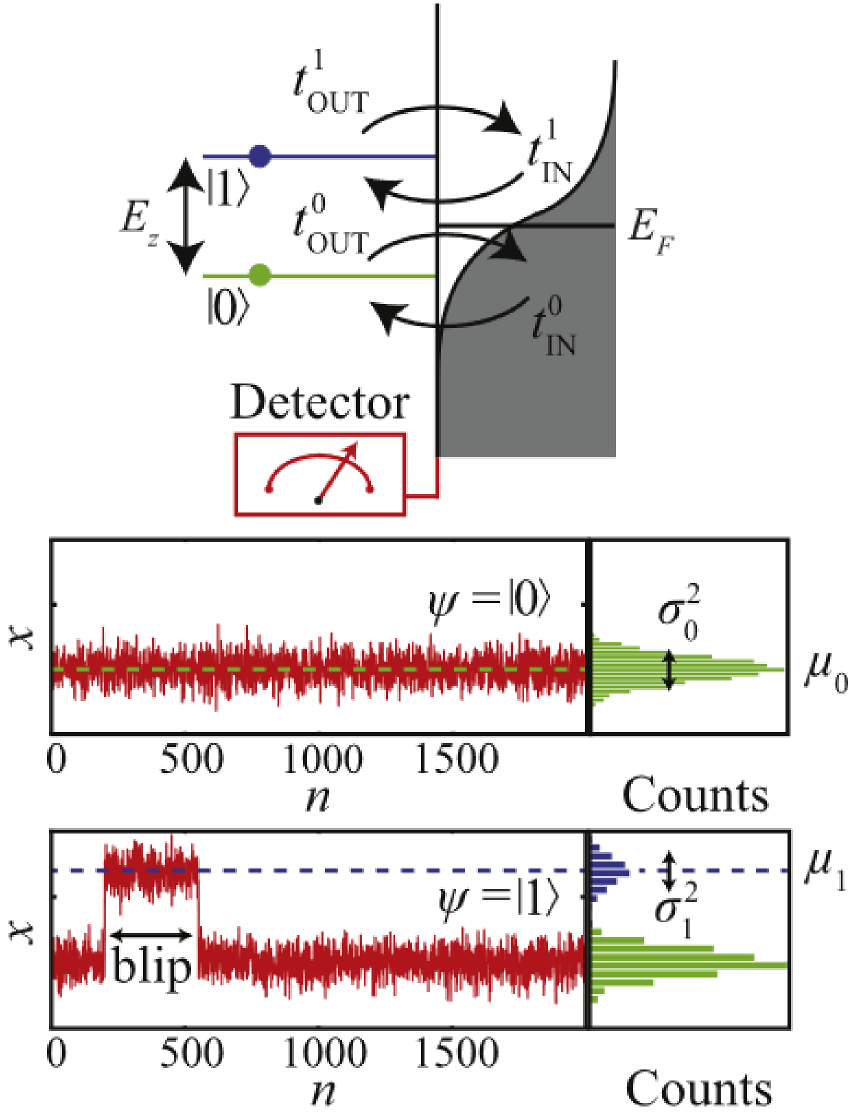
$P(\downarrow) = f(E_\downarrow)$



Bayesian Maxwell's Demon

Negative-outcome measurement

- if $|\uparrow\rangle$ is loaded, electron tunnels out fast since $\Gamma_{\uparrow,\text{out}} \gg \Gamma_{\downarrow,\text{out}}$
- absence of a tunneling event provides information on spin state without destroying the state



[1]D. Keith *et al.*, New J. Phys. **21** 063011 (2019)

Bayesian Maxwell's Demon

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Discrete Bayesian model

- integration time T_S = 10µs
- N number of measurements
- measurement outcome
  - B = tunneling detected
  - ¬B = no tunneling detected
- prior probablility $P(\downarrow) = f(E_\downarrow)$
- probability to not observe a tunneling event:

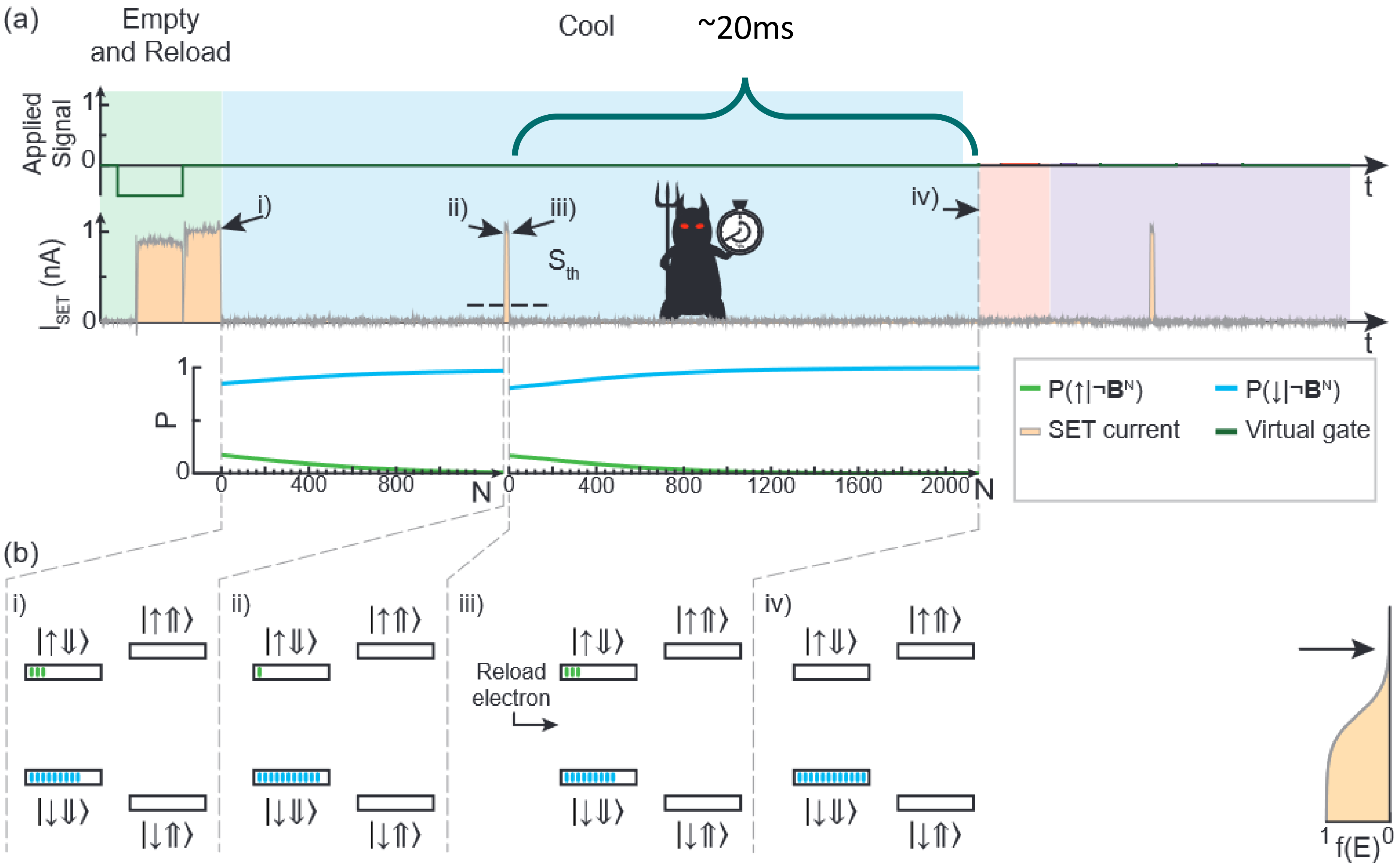
$$\mathcal{L}(\neg B_1 \,|\!\uparrow) = e^{-T_s \Gamma_{\uparrow,\text{out}}}$$
$$\mathcal{L}(\neg B_1 \,|\!\downarrow) = e^{-T_s \Gamma_{\downarrow,\text{out}}}$$

- after N measurements with outcome ¬B posterior probability is

$$\begin{aligned} P(\downarrow | \neg \boldsymbol{B}^N) &= \frac{\mathcal{L}(\neg \boldsymbol{B}^N \,|\!\downarrow) P(\downarrow)}{\mathcal{L}(\neg \boldsymbol{B}^N \,|\!\downarrow) P(\downarrow) + \mathcal{L}(\neg \boldsymbol{B}^N \,|\!\uparrow) P(\uparrow)} && (2) \\ &= \frac{1}{1 + \frac{\mathcal{L}(\neg \boldsymbol{B}^N \,|\!\uparrow) P(\uparrow)}{\mathcal{L}(\neg \boldsymbol{B}^N \,|\!\downarrow) P(\downarrow)}} && (3) \\ &= \left(1 + \frac{1 - P(\downarrow)}{P(\downarrow)} e^{-N T_s (\Gamma_{\uparrow,\text{out}} - \Gamma_{\downarrow,\text{out}})}\right)^{-1}, && (4) \end{aligned}$$

→ goes towards 1 for large N

Bayesian Maxwell‘s Demon



Initialization fidelity

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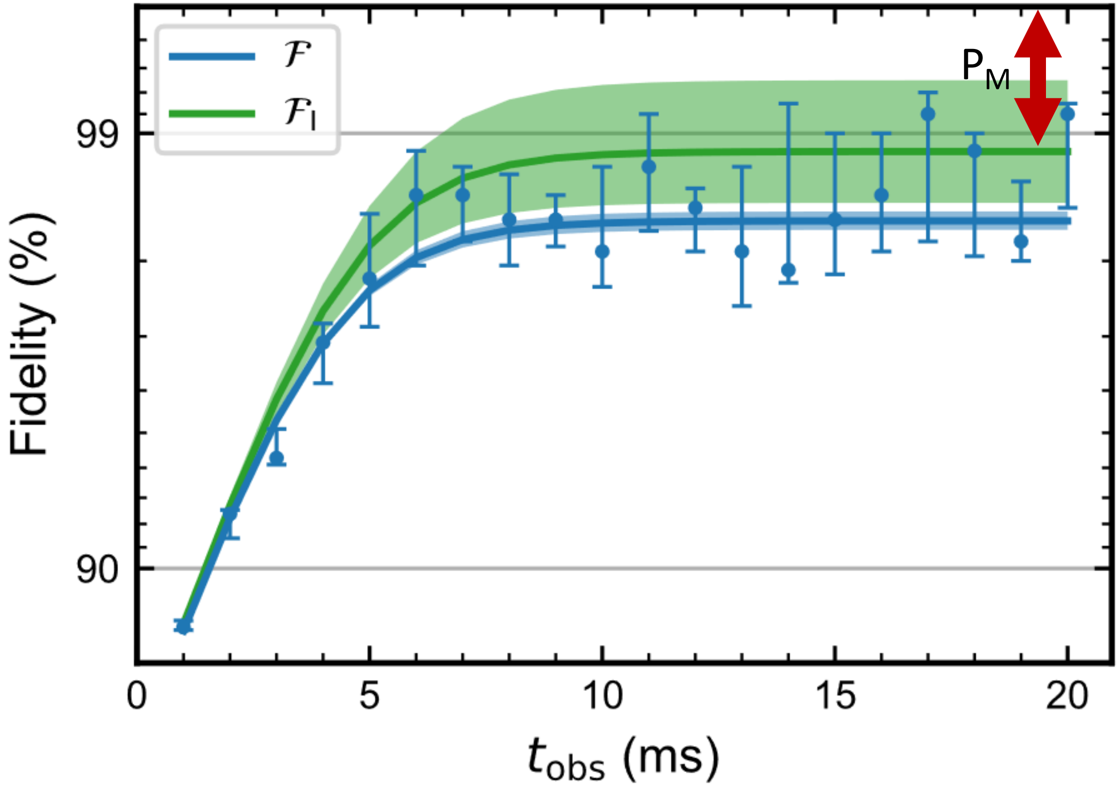
Total fidelity $F = F_I F_C F_R$

- initialization fidelity: F_I
- NMR control[1] fidelity: $F_C \sim 99.5\%$
- QND readout[2] fidelity: $F_R \sim 99.99\%$
- additionally: missed blips on detector P_M

Fidelity increase:
$F_I(0) \sim 78\%$-80%
$F_I = 98.9\%$



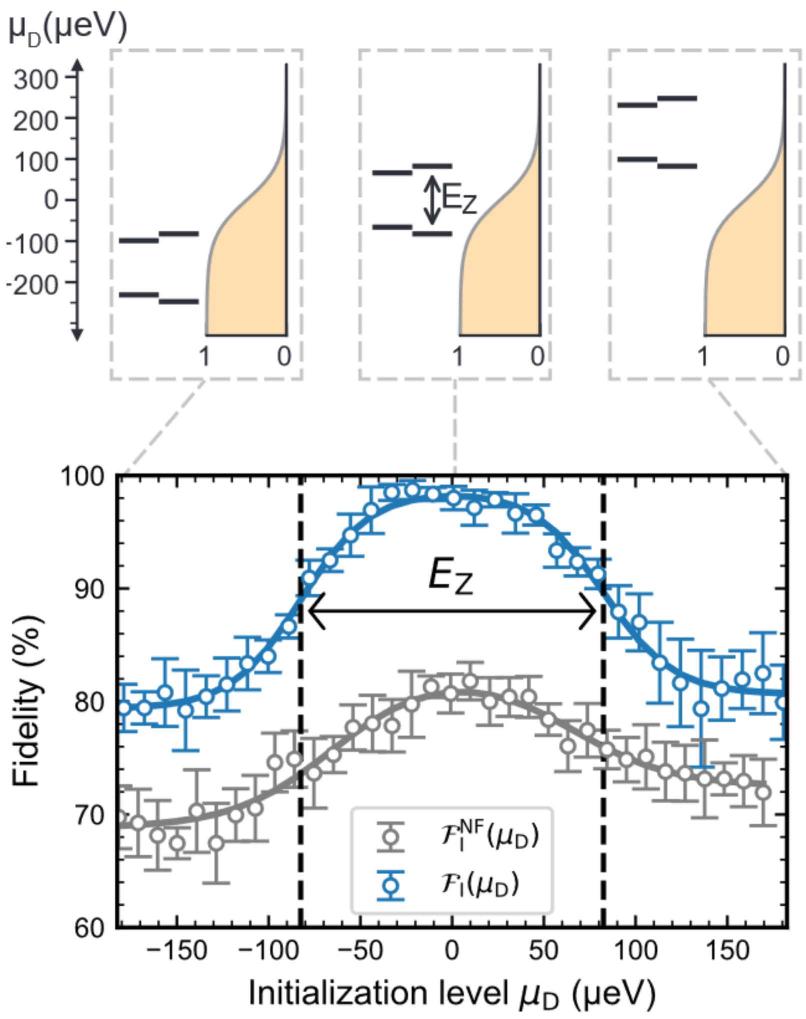
[1]S. Freer *et al.*, Quantum Science and Technology **2**, 015009 (2017)
[2]J. J. Pla *et al.*, Nature **496**, 334 (2013)

Initialization fidelity

Fidelity robustness

- detune initiaization level μ_D
- initialization with feedback shows plateau of width ~$E_Z/2$

Fidelity robustness against detuning increases



Temperature

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„Effective“ temperature

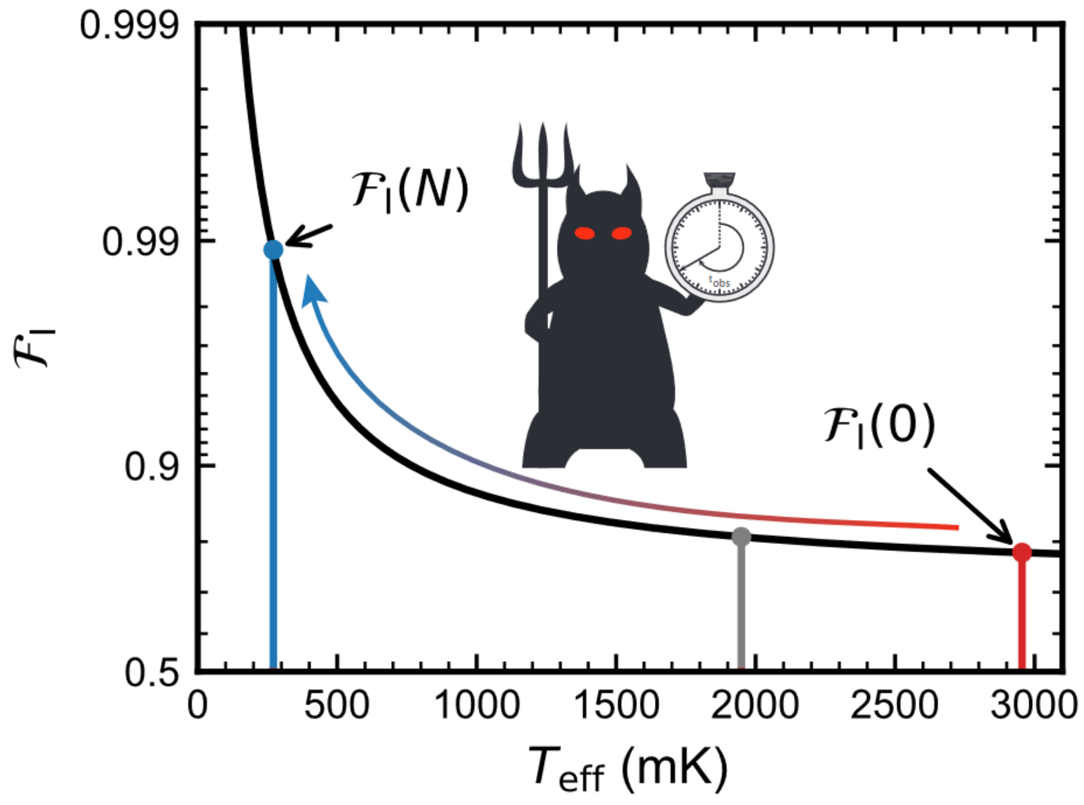
$$\Gamma_{\uparrow,\mathrm{in}}(T_{\mathrm{eff}}) = \frac{2\pi}{\hbar} \left|\langle\uparrow| H' |0\rangle\right|^2 n(E_\uparrow) f(E_\uparrow)$$

$$\Gamma_{\downarrow,\mathrm{in}}(T_{\mathrm{eff}}) = \frac{2\pi}{\hbar} \left|\langle\downarrow| H' |0\rangle\right|^2 n(E_\downarrow) f(E_\downarrow)$$

- fails to reproduce fidelity $\mathcal{F}_{\mathrm{I}}^{\mathrm{NF}} = \frac{\Gamma_{\downarrow,\mathrm{in}}}{\Gamma_{\downarrow,\mathrm{in}} + \Gamma_{\uparrow,\mathrm{in}}}$
- phenomenological parameter

$$\chi = \frac{n(E_\uparrow) \left|\langle\uparrow| H' |0\rangle\right|^2}{n(E_\downarrow) \left|\langle\downarrow| H' |0\rangle\right|^2}$$ ~ 0.388

→ $$\mathcal{F}_{\mathrm{I}}^{\mathrm{NF}} = \frac{1}{1 + R_{\mathrm{in}}} = \frac{1}{1 + \chi \frac{f(E_\uparrow)}{f(E_\downarrow)}}$$



Limitations

Limiting factors of the detector[1]

- sample rate: 100MS/s
- signal-to-noise: >>1
- LP filter: 50kHz

- 99.9% initialization fidelity possible with
  ~300kHz bandwidth
  or ~880Hz electron tunneling rate

[1]D. Keith *et al.*, New J. Phys. **21** 063011 (2019)