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Coherent coupling between a quantum dot and a donor in silicon

Patrick Harvey-Collard

University of Wisconsin-Madison

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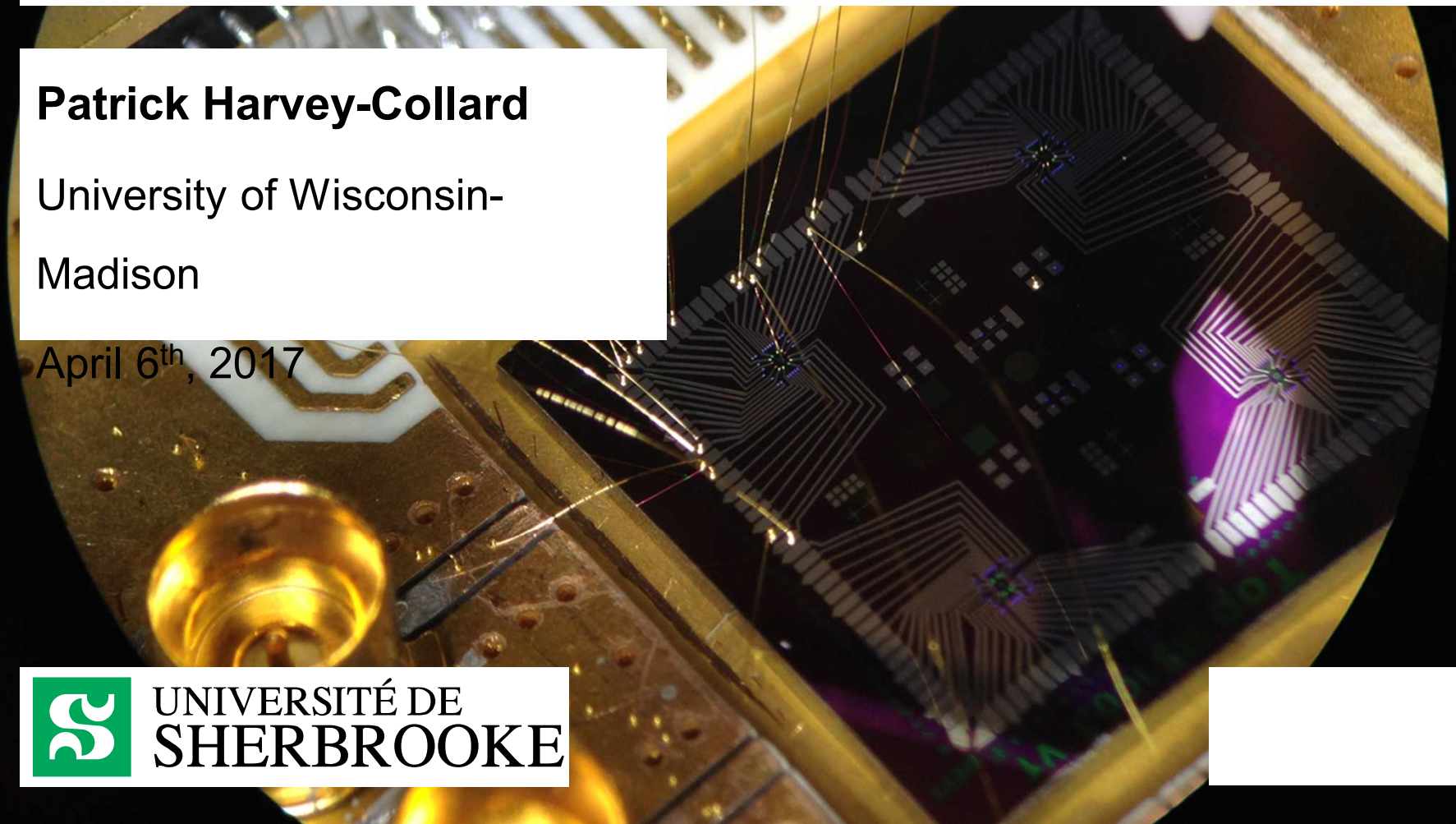

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Plan (for guidance only)

- Spin qubits in semiconductors
  - nice qubits
  - Donors: high fidelity, long coherence times
  - QD: Tunable, easier to engineer, 2 qubit gates demonstrated
  - Us: combine advantages of two systems

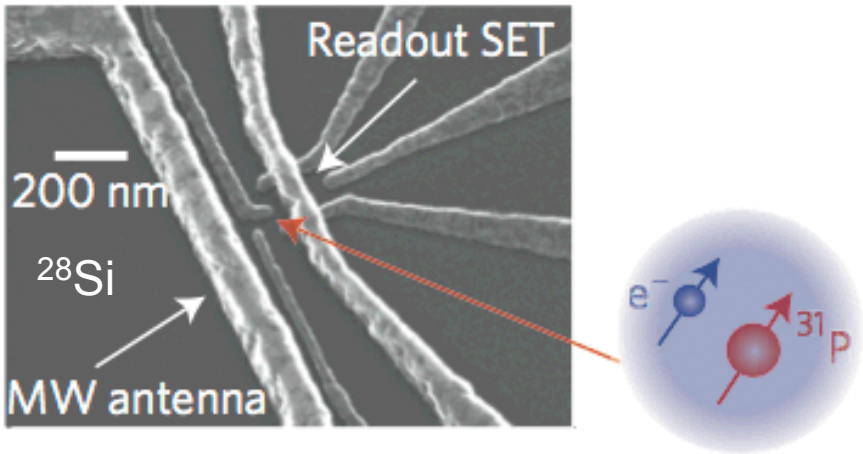
- Outline
  - Announce results:
    - Challenge: valley splitting: Tuning the valley splitting, 4 electron trick for orbitals
    - Challenge: readout: Enhanced latching readout combines best aspects of spin qubit readouts
    - Physics: Electrically driven QD-D qubit
    - ST experiment
- System
  - MOS gate structure, accumulate electrons in 2DEG
  - Few electron QD. CS.
  - ST encoding
- Valley splitting
  - Si valleys. Lifting of degeneracy.
  - Work by Yang et al. Contrast with SiGe. Motivate with SiGe multivalley refs.
  - Own data set. APL paper. Theory model by John G.
  - Interaction with donors: Pick the right coupling.
  - 4-electron trick: play with dot size, boost ST splitting
  - Used at HRL now in SiGe.
- Readout
  - QD-D dipole not always aligned with CS.
  - ELR: bigger signal, independent of dipole
  - Enhanced lifetime, game-changer in GaAs [Tarucha]
  - High fidelity result. Important because faster than high-fidelity ½.

Plan (for guidance only)

- ST MAJIQ
  - ST hyperfine driven rotations physics
  - Hamiltonian, independent of state (mostly)
  - Rotation, 2D plot, exchange
  - Charge noise
- Summary
- Perspectives

Can the best characteristics of qubit systems be combined?

Donor (D) qubits are high fidelity…



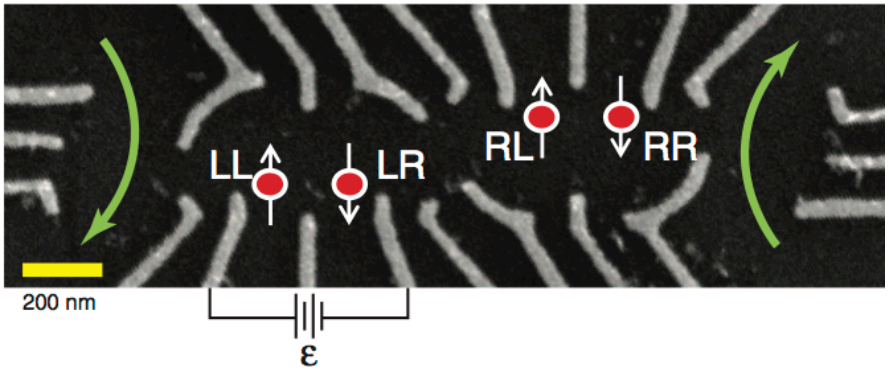
Electron spin 1/2:
T_2^* = 270 μs [1]
$T_{2,\,\mathrm{CPMG}}$ = 0.98 s [3]
$F_{\mathrm{prep/readout}}$ = 97%
F_{control} = 99.95%

Nuclear spin 1/2:
T_2^* = 600 ms
$T_{2,\,\mathrm{CPMG}}$ = 36.5 s
$F_{\mathrm{prep/readout}}$ = 99.995%
F_{control} = 99.99%

But they are not easily coupled together!

[1] Muhonen, J. T. et al. Nat Nano 9, 986–991 (2014).
[2] Muhonen, J. T. et al. Journal of Physics: Condensed Matter 27, 154205 (2015).
[3] A. Morello, unpublished.

Quantum dot (QD) qubits are tunable…



Singlet-triplet spin qubit in GaAs:

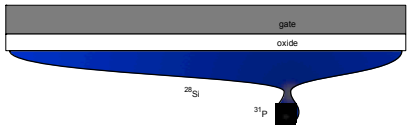
- All-electrical control [2]
- Two-qubit gates realized [1,2]

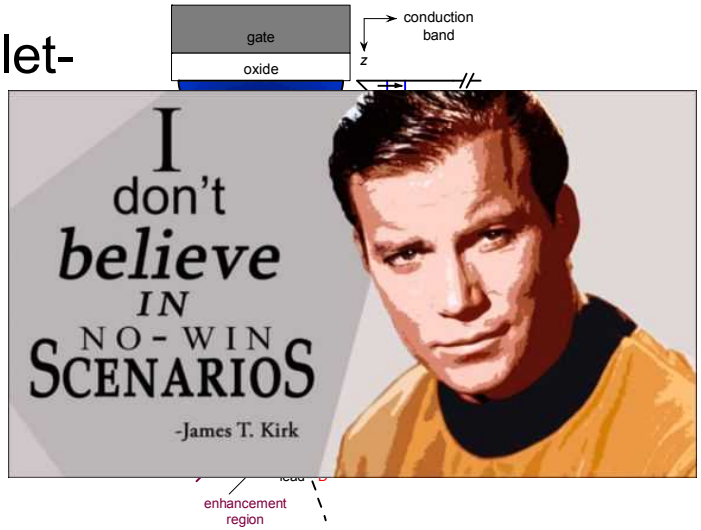
But they are not quite as high fidelity!

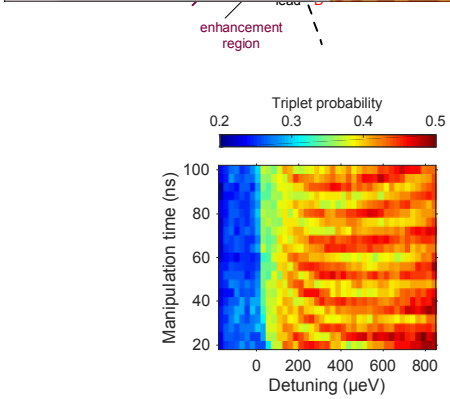
[1] Shulman, M. D. et al. Science 336, 202–205 (2012).
[2] Petta, J. R. et al. Science 309, 2180–2184 (2005).
[3] Veldhorst, M. et al. Nat Nano 9, 981–985 (2014).
[4] Veldhorst, M. et al. Nature 526, 410–414 (2015).
[5] Nichol, J. M. et al. npj Quantum Information 3, 3 (2017).

Outline

- Donor-Quantum dot system
- Valley splitting, singlet-triplet splitting, and coupling to donors
- Enhanced latching readout
- Singlet-triplet qubit (hyperfine-driven rotations)
- Summary and perspectives







References

1. Gamble, J. K., **Harvey-Collard, P.** et al. "Valley splitting of single-electron Si MOS quantum dots" Applied Physics Letters 109, 253101 (2016).

Harvey-Collard, P. et al., "High-fidelity single-shot readout for a spin qubit via an enhanced latching mechanism" arXiv 1703.02651 (2017)

3. **Harvey-Collard, P.** et al. "Coherent coupling between a quantum dot and a donor in silicon" arXiv 1512.01606.v2 (2015).

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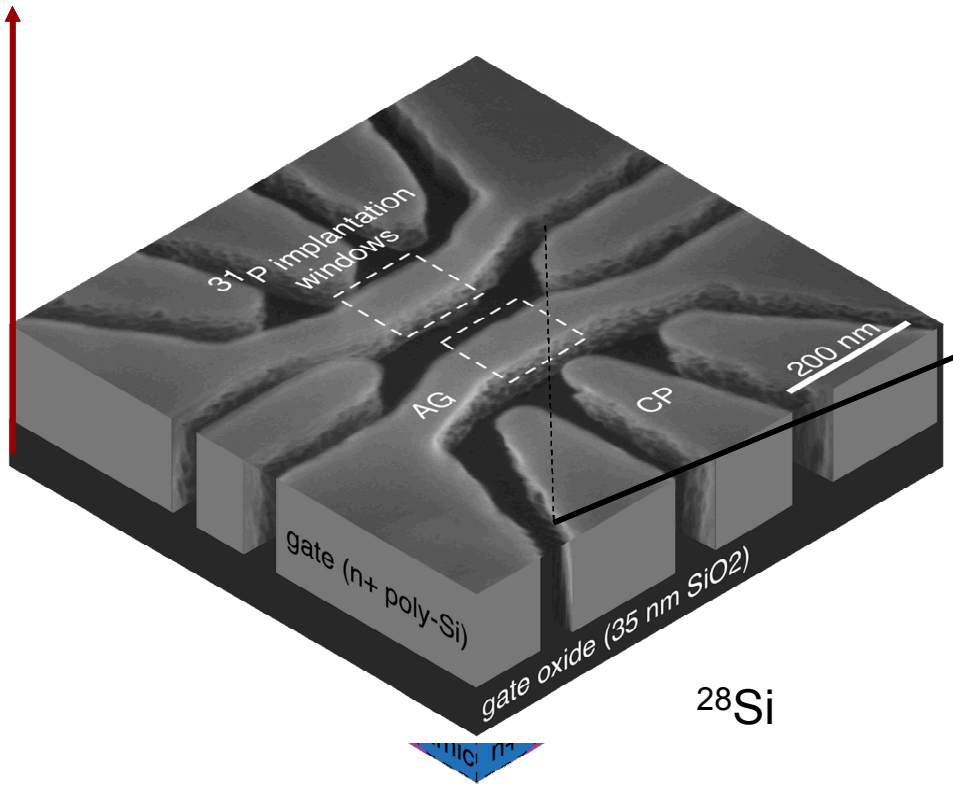
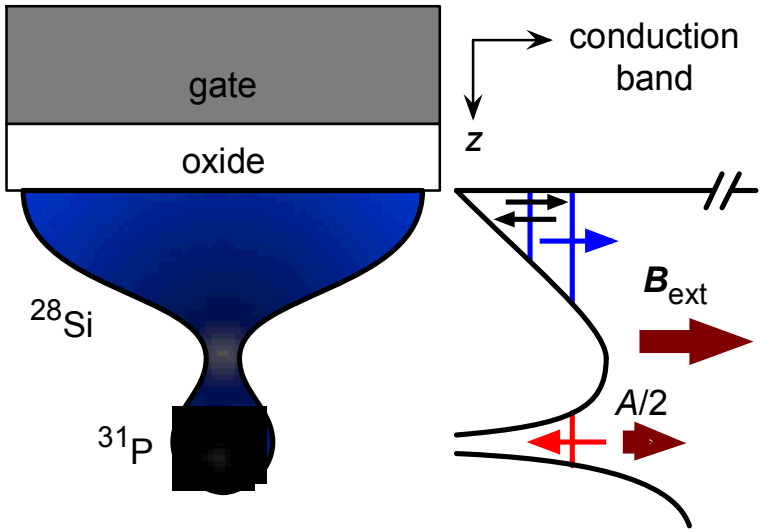
Our silicon MOS nanostructure



Filled-shell valley configuration

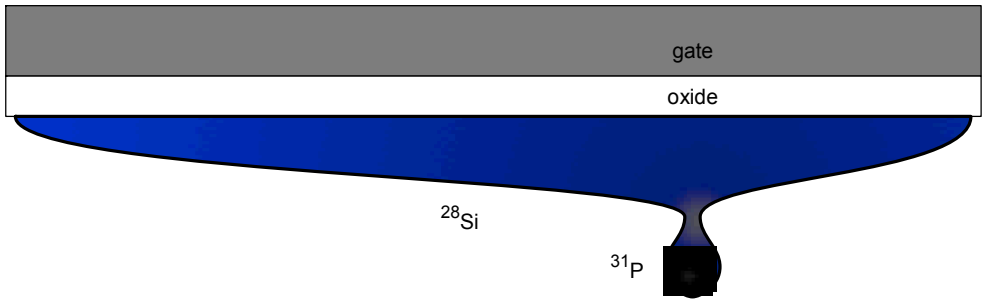


effective (2,0)-(1,1)

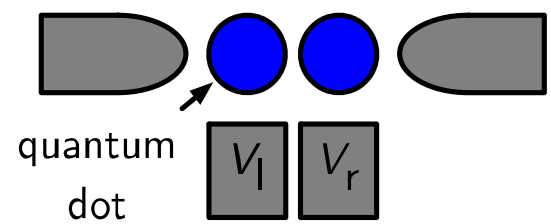
[1] Harvey-Collard, P. et al. “Coherent coupling between a quantum dot and a donor in silicon” arXiv 1512.01606.v2 (2015).
[2] Gamble, J. K. et al. Valley splitting of single-electron Si MOS quantum dots. Applied Physics Letters 109, 253101 (2016).

Singlet-triplet encoding

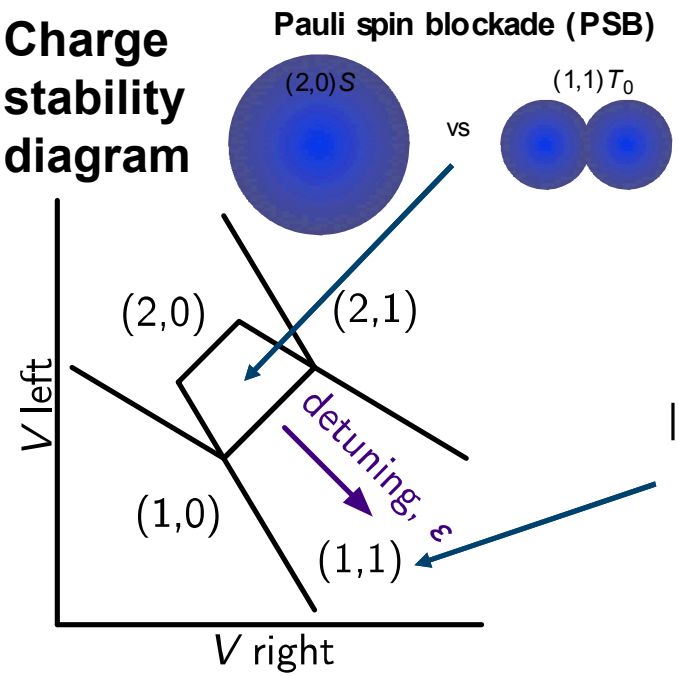
QD-D



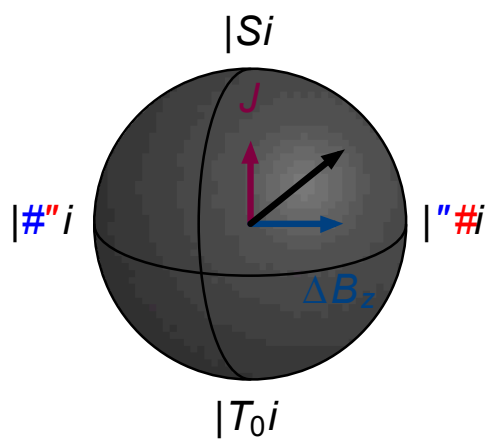
Double QD



Charge stability diagram



Qubit Bloch Sphere



Spin states for two electrons

$$\left.\begin{aligned} |S\rangle &= |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle \\ |T_0\rangle &= |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle \end{aligned}\right\} m = 0$$

$$|T_-\rangle = |\downarrow\downarrow\rangle \qquad m = -1$$

$$|T_+\rangle = |\uparrow\uparrow\rangle \qquad m = +1$$

[1] Harvey-Collard, P. et al. “Coherent coupling between a quantum dot and a donor in silicon” arXiv 1512.01606.v2 (2015).

ST qubit theory: Taylor, J. M. et al. Relaxation, dephasing, and quantum control of electron spins in double quantum dots. Phys. Rev. B 76, 035315 (2007).

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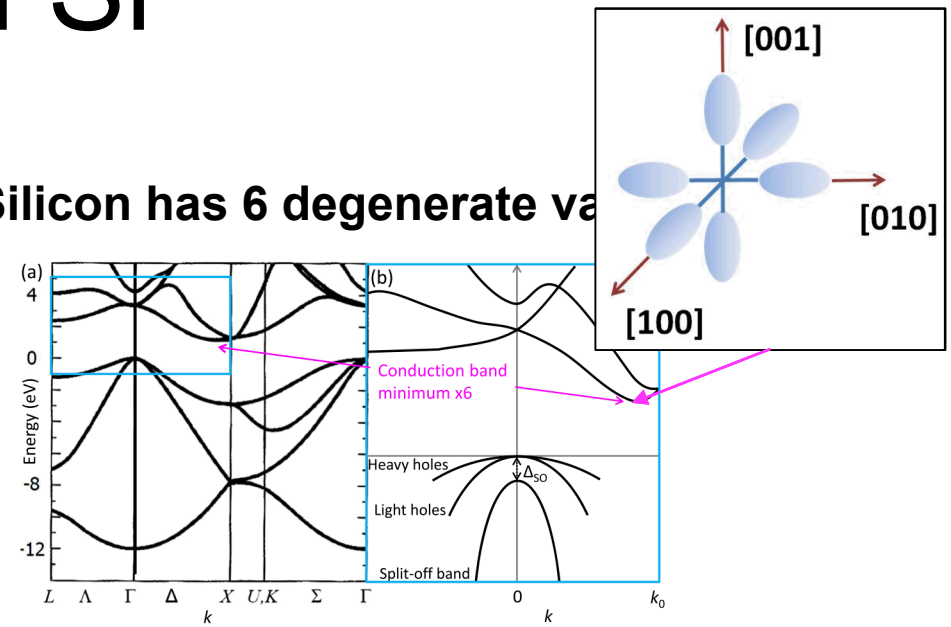
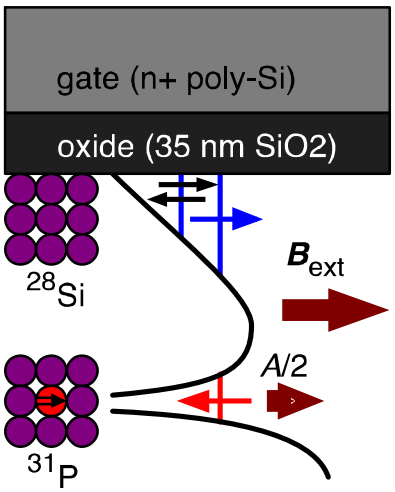
Valley splitting in Si

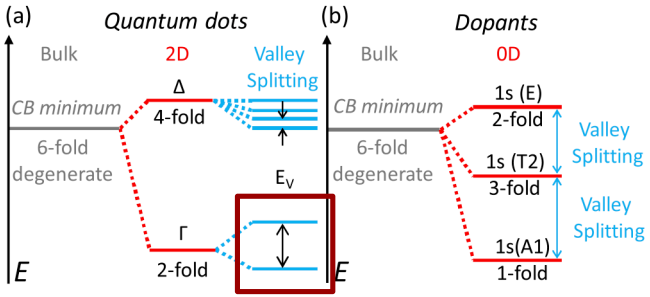
Silicon has 6 degenerate va



Filled-shell valley configuration

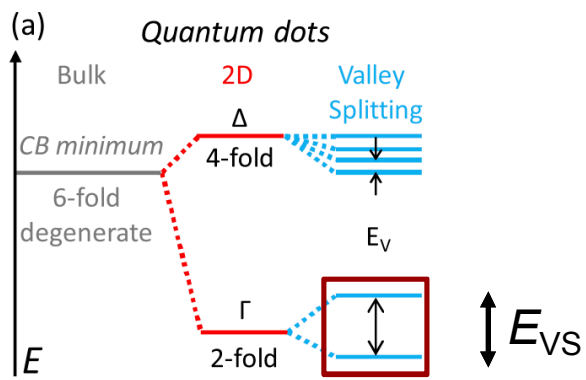


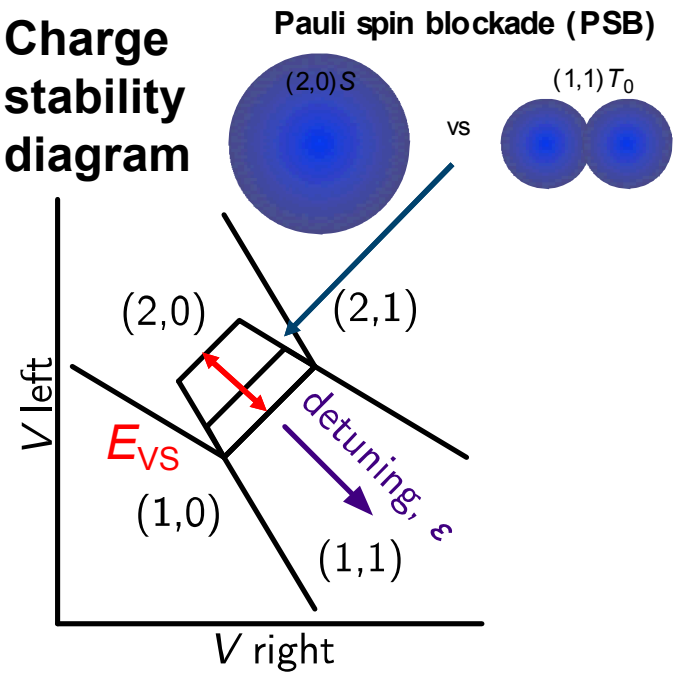
Valley degeneracy is lifted because of the strong confinement at the Si/SiO2 interface



[1] Zwanenburg, F. A. et al. Silicon quantum electronics. Rev. Mod. Phys. 85, 961–1019 (2013).

Small valley splittings are a problem

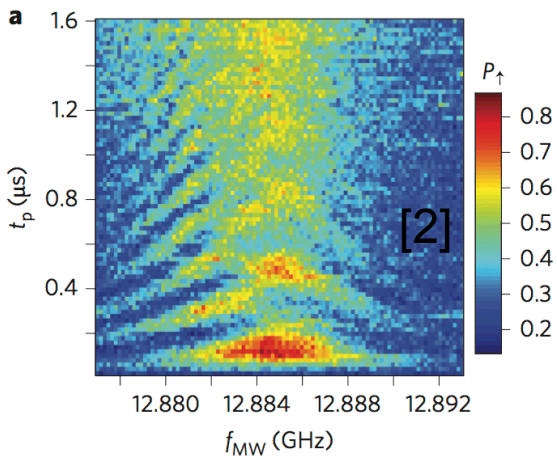




Valley splitting in Si (SiGe and MOS)

If valley splitting is low compared with the temperature, problems can arise.

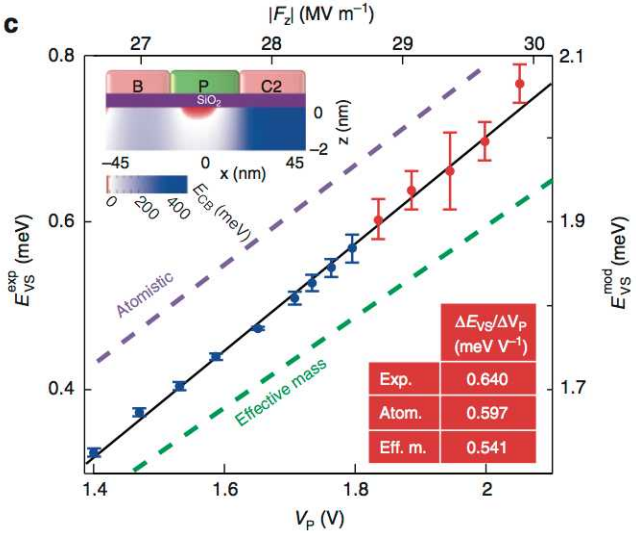
- For electron spin 1/2 qubits, different valleys can have different g-factors (hence different driving frequencies). [1,2]



- For ST qubits, spin blockade window can be unpractically small.

Valley splitting is typically larger and tunable in Si MOS.

- Yang et al. have established the tunability of the valley splitting in MOS QDs [3].



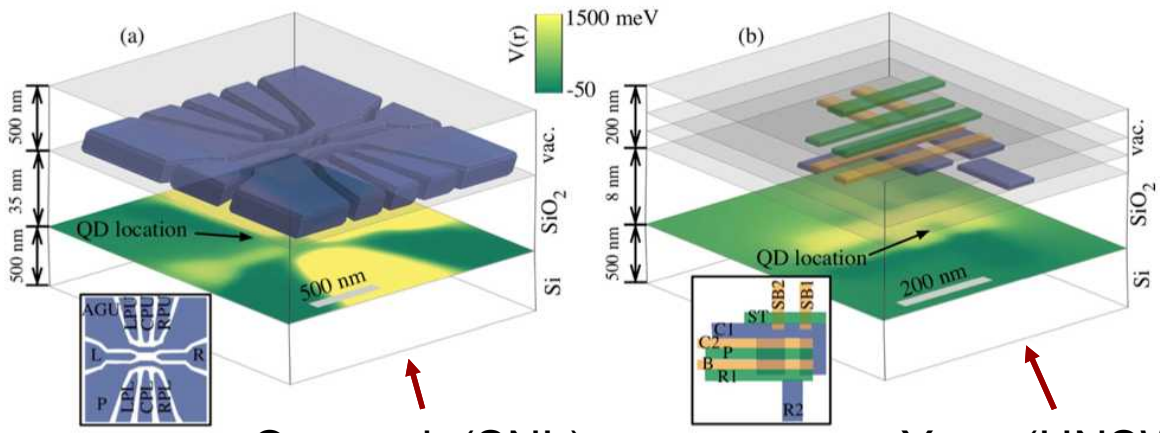
- Not a problem in this case.

[1] Eng, K. et al. Science Advances 1, e1500214 (2015).
[2] Kawakami, E. et al. Nat Nano 9, 666–670 (2014).
[3] Yang, C. H. et al. Nat Commun 4 (2013).

Valley splitting is tunable in MOS

Reproduced in our devices [1].

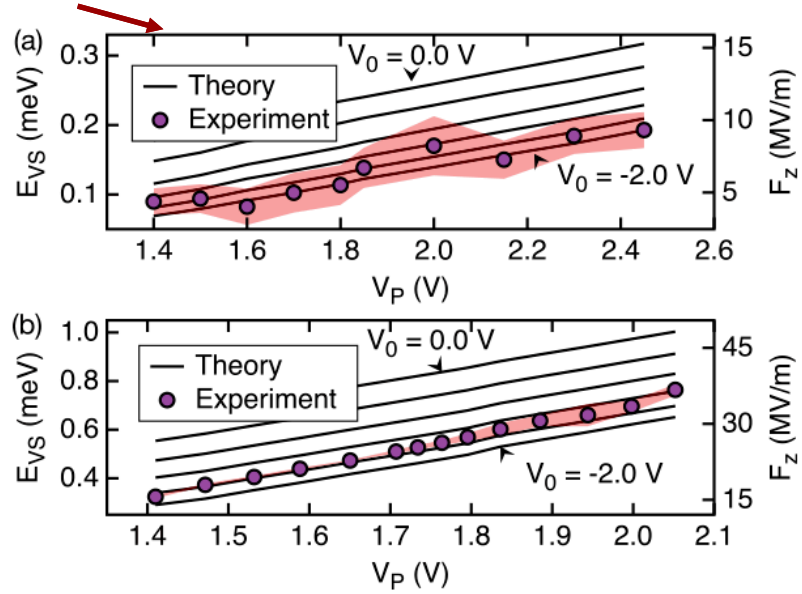
Theoretical understanding [1].



Our work (SNL)

Yang (UNSW)

We find consistently large (>60 μeV) and tunable (60 to >250 μeV) valley splittings in our SNL devices.

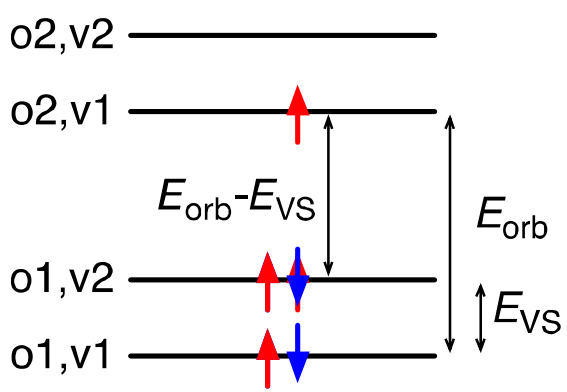


[1] Gamble, J. K., **Harvey-Collard, P.** et al. Valley splitting of single-electron Si MOS quantum dots. Applied Physics Letters 109, 253101 (2016).

Tuning the ST splitting via shell engineering

Give up? Or play some tricks!

- Interaction with donors can restrict the electric field tuning range.
- Electrons are fermions. Spin singlets have a symmetric valley-orbit wavefunction.
- Trick: fill the lowest valley with a singlet. Then forget about it!



4-electron trick

- Introduced in [Harvey-Collard, P. et al. arXiv 1512.01606 (2015)]
- Proposed that this trick can
  - Circumvent small ST splitting
  - Change QD size to adjust tunnel coupling to donors
- Now used by the HRL group too.

Outline

- Donor-Quantum dot system
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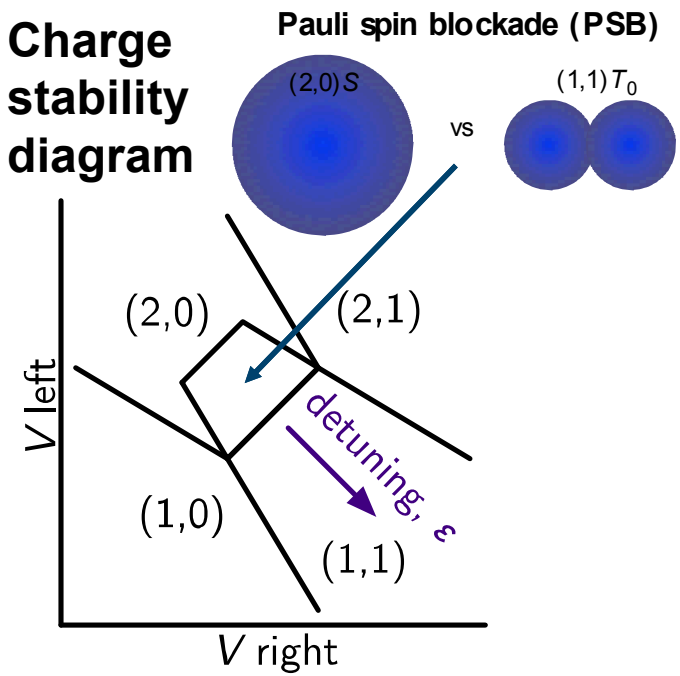
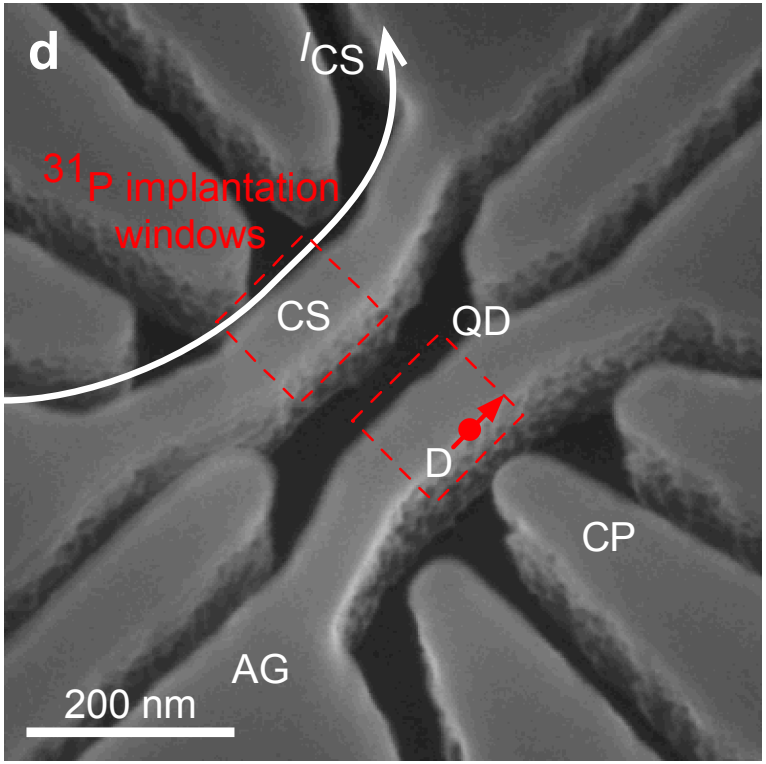
Issues with spin readouts

Charge sensor not necessarily aligned with sensed dipole





Why care about readout?

How to improve readout?

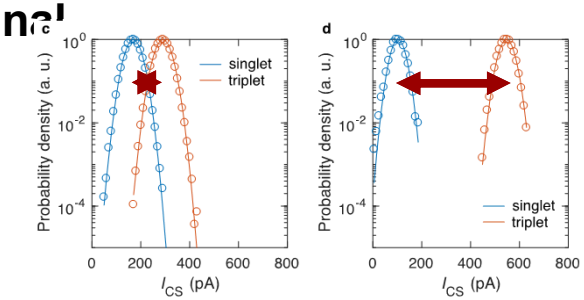
- **Goal:** Gates, readout < 0.1% error.
- Spin qubit readouts typically have a stochastic decay time:
  $T_{\mathbf{lifetime}}$
- The measurement can be done in time
  $T_{\mathbf{measurement}}$
- $T_{\text{measurement}}$: depends on the **signal** and **noise**.
- When $T_{\text{lifetime}} \gg T_{\text{measurement}}$:
  $\mathbf{P(error)} \approx T_{\mathbf{measurement}}/T_{\mathbf{lifetime}}$
  $\lesssim$ **1/1000**

Enhanced latching readout

- Change relaxation mechanism → improve lifetime

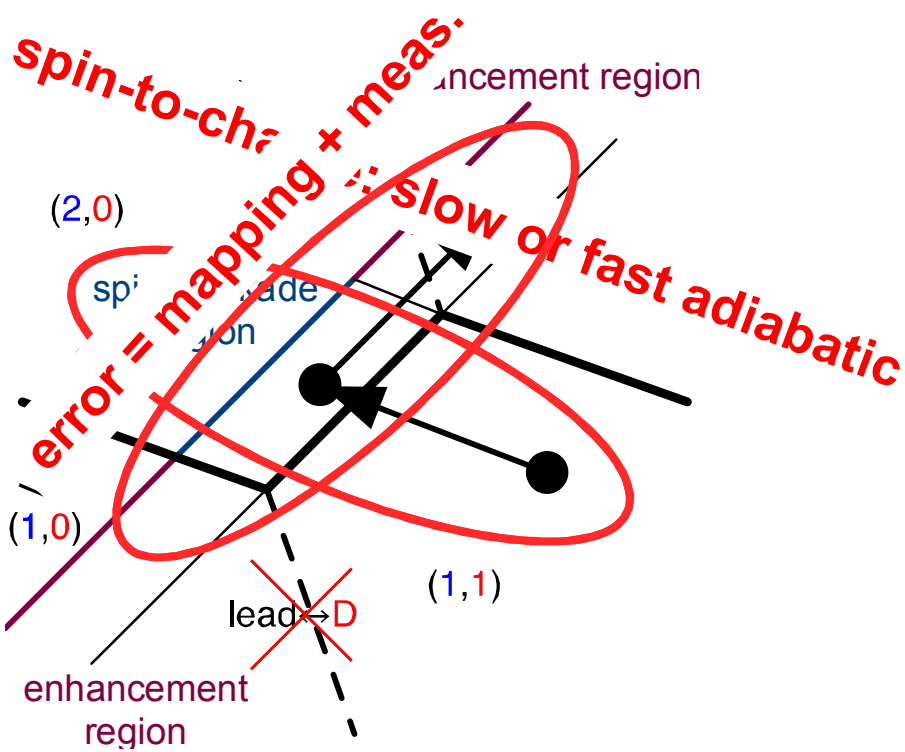
spin + phonon → metastable charge
300 µs → 31 000 µs

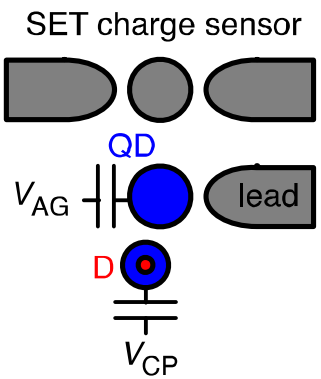
- Improved spin-to-charge mapping
  ~0.2 electron signal → 1 electron signal



- **Average single-shot readout fidelities > 99.86%**
- Works with ST/all-exchange qubits.
- Not dependent on (2,0)-(1,1) dipole

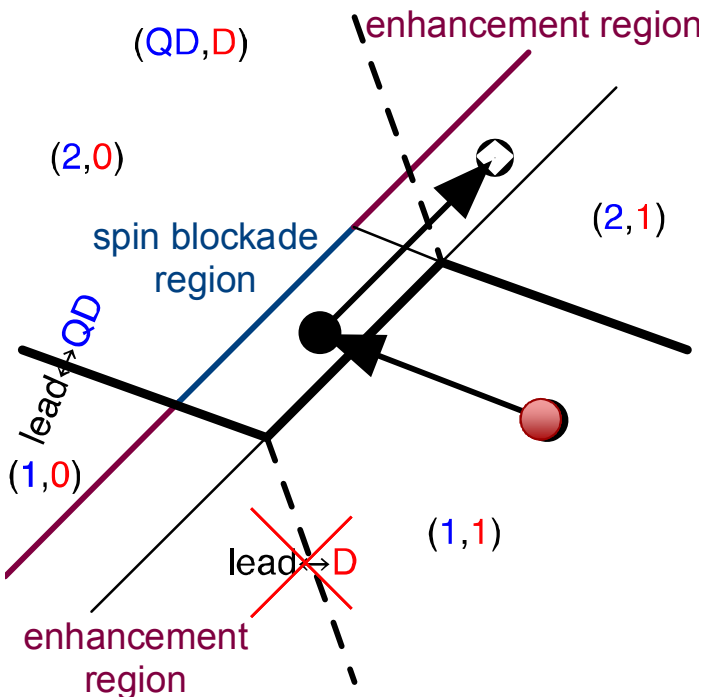
Readout concept (illustrated)

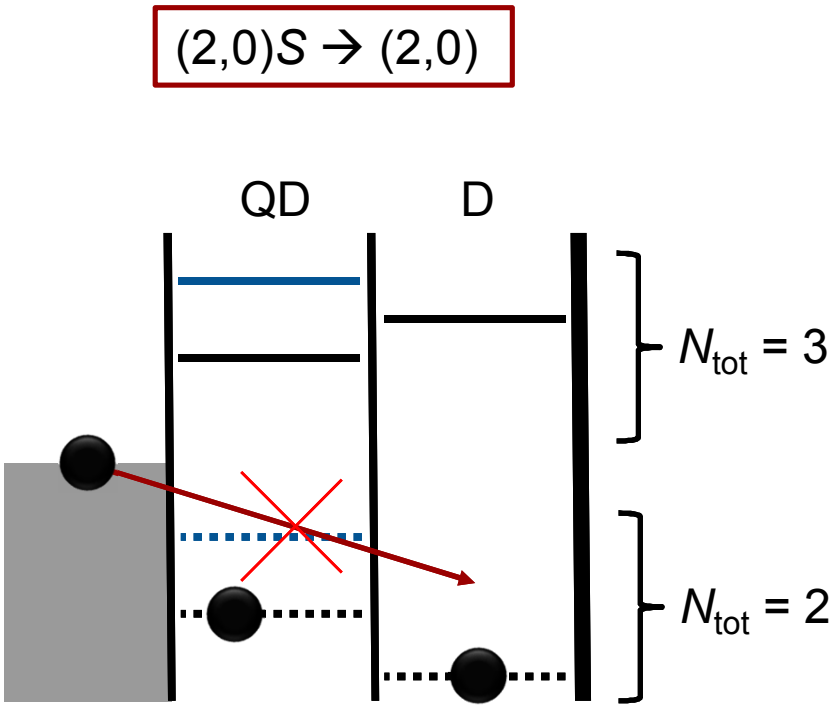




Inspired from: S. A. Studenikin, J. Thorgrimson, G. C. Aers, A. Kam, P. Zawadzki, Z. R. Wasilewski, A. Bogan, and A. S. Sachrajda, “Enhanced charge detection of spin qubit readout via an intermediate state,” Applied Physics Letters 101, 233101 (2012).
Other work: Mason, J. D. et al. Role of metastable charge states in a quantum-dot spin-qubit readout. Phys. Rev. B 92, 125434 (2015).
Petersson, K. D., Petta, J. R., Lu, H. & Gossard, A. C. Quantum coherence in a one-electron semiconductor charge qubit. Phys. Rev. Lett. 105, 246804 (2010).

Readout concept (illustrated)





[1] **Harvey-Collard, P.** et al., "High-fidelity single-shot readout for a spin qubit via an enhanced latching mechanism" arXiv 1703.02651 (2017)

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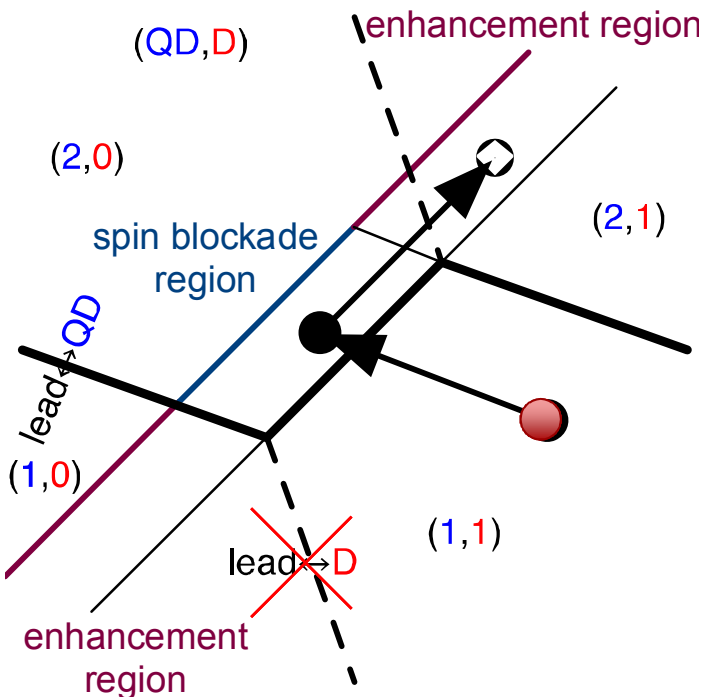
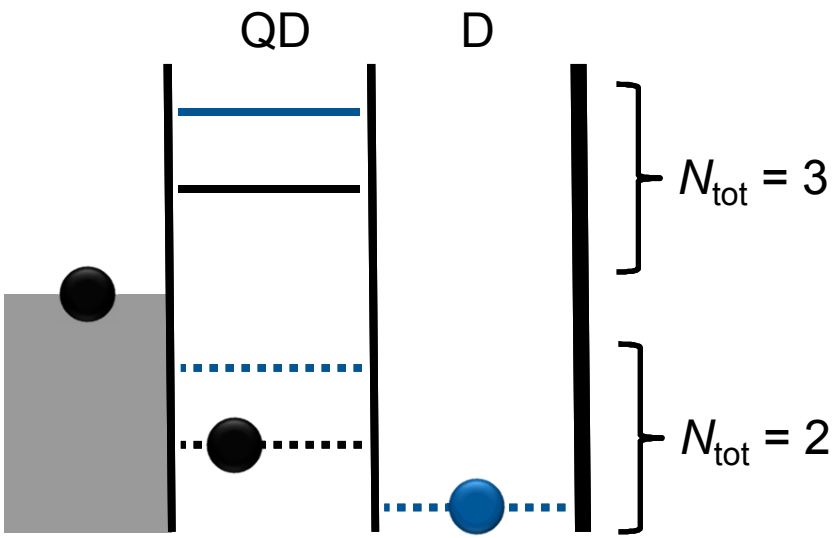


(1,1)T_0 → (2,1)
(2,0)S → (2,0)



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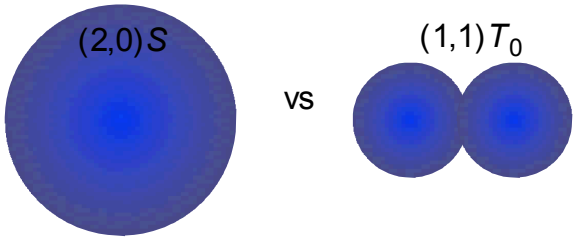
State of the art (ST qubits)

Reference	Material	Readout fidelity (%)	Notes
bertrand2015	GaAs	80	
eng2015 (HRL)	Si/SiGe	>99.5	Estimate.
higginbotham2014b	GaAs	~90	Worked out from supplementary.
prance2012	Si/SiGe	~95?	Not stated but this is my estimate.
barthel2009	GaAs	90	
shulman2012a	GaAs	98 and 97	For two qubits.
nakajima2017	GaAs	99.7	Using reverse ELR **(game changer for GaAs)**
This work	**Si MOS**	**99.86**	**Direct ELR**

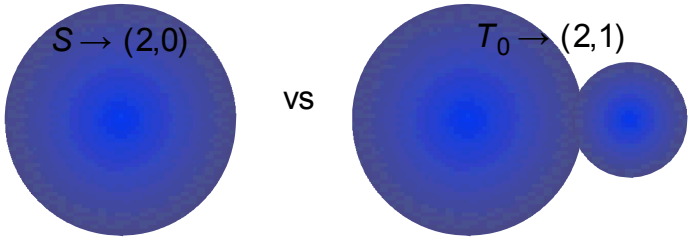
[1] **Harvey-Collard, P.** et al., “High-fidelity single-shot readout for a spin qubit via an enhanced latching mechanism” arXiv 1703.02651 (2017)

ELR relaxes layout constraints

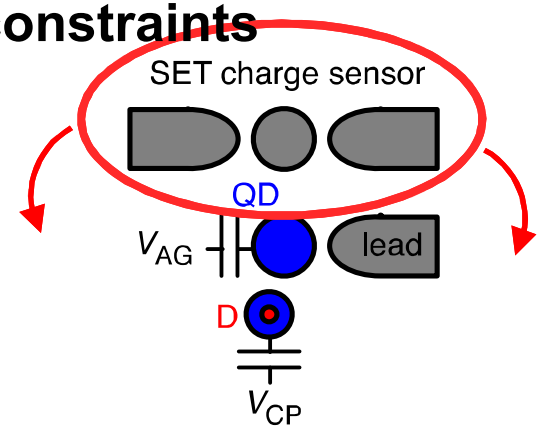
Pauli spin blockade (PSB)



Enhanced latching readout



Relaxes layout constraints



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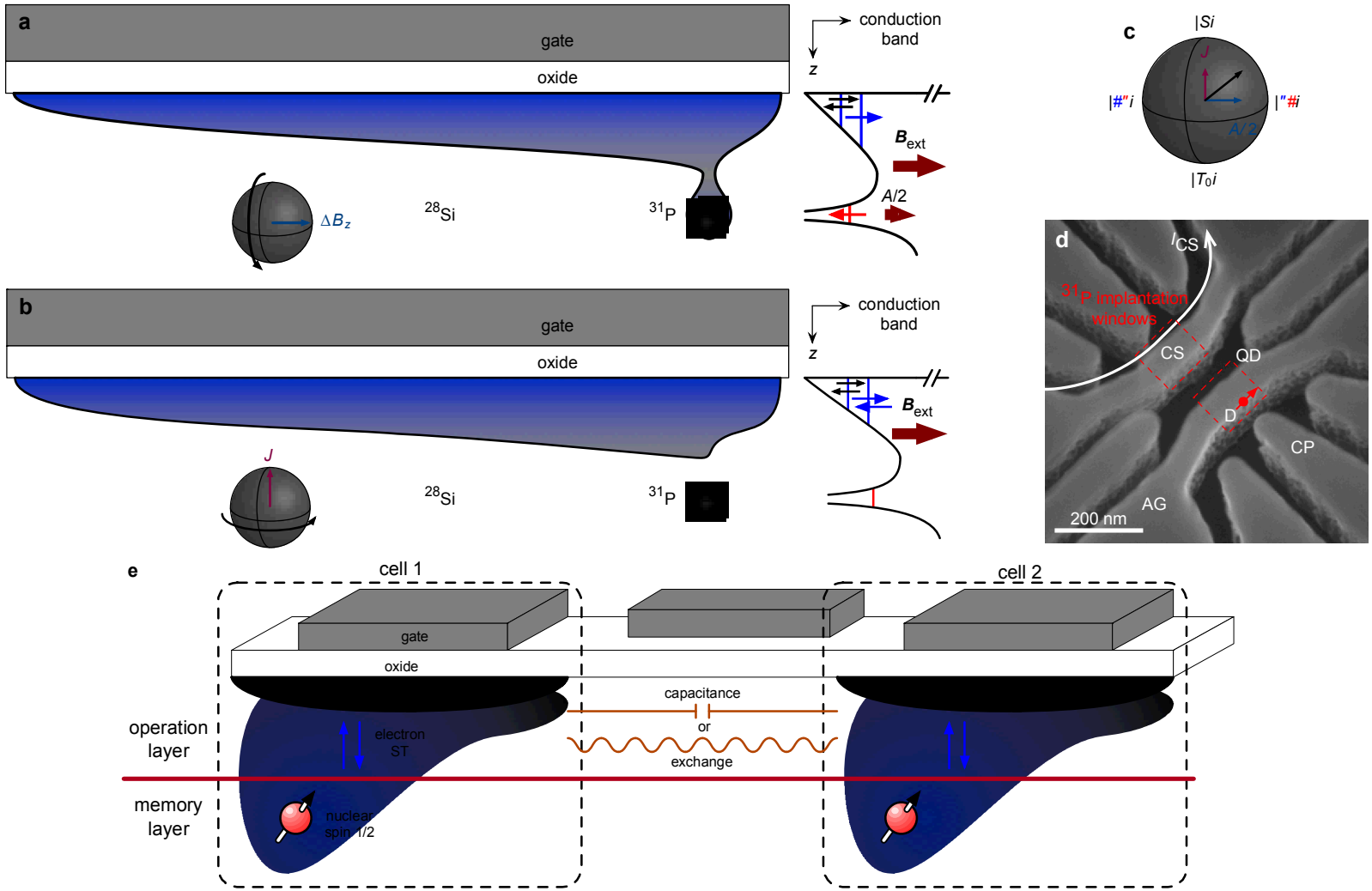
The MAJIQ system

MOS (M) hyperfine (A) exchange (J) nuclear spin (I) qubit (Q)



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QD-D physics

Question: What is ΔB_z for the QD-D ST qubit?

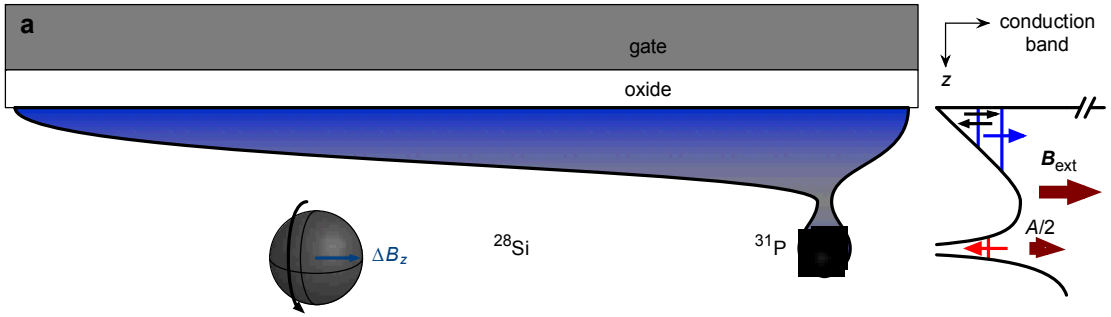
- Hand waving:
  - For electron on donor, $H = (g\mu_B/\hbar)\boldsymbol{S}\cdot\boldsymbol{B} + A\boldsymbol{S}\cdot\boldsymbol{I}$
  - Trace out nuclear spin: $\langle\Uparrow| A\boldsymbol{S}\cdot\boldsymbol{I}\,|\Uparrow\rangle = \frac{A}{2}S_z$
  - Effective B field:

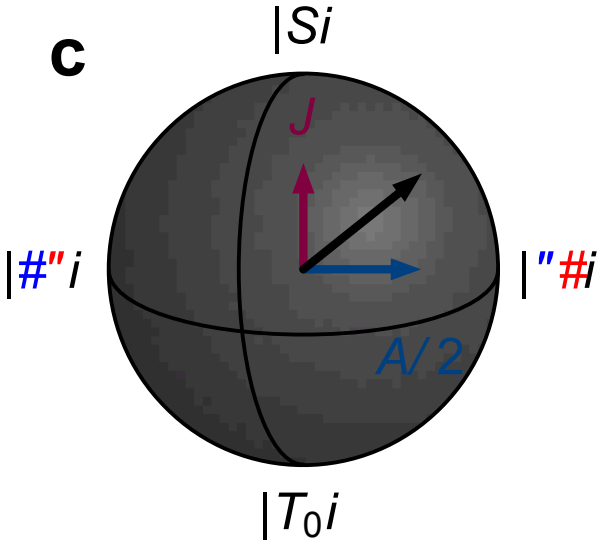
$$H = (g\mu_B/\hbar)\boldsymbol{S}\cdot(B + \hbar A/2g\mu_B)\hat{\boldsymbol{B}}$$

- Classical nucleus approx.:

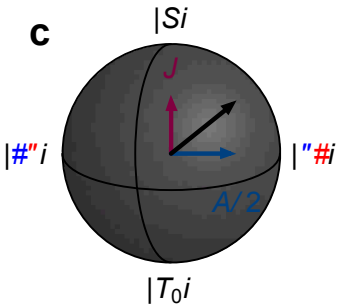
$$H = -J(\epsilon)\frac{\sigma_z}{2} - \frac{A(\epsilon)}{2}\frac{\sigma_x}{2}$$

Analog to GaAs.





QD-D physics with nuclear spin



Reduced model*

*Ignoring T_-/T_+ states.

- ST qubit alone, $\{|S\rangle,|T_0\rangle\}$ basis:

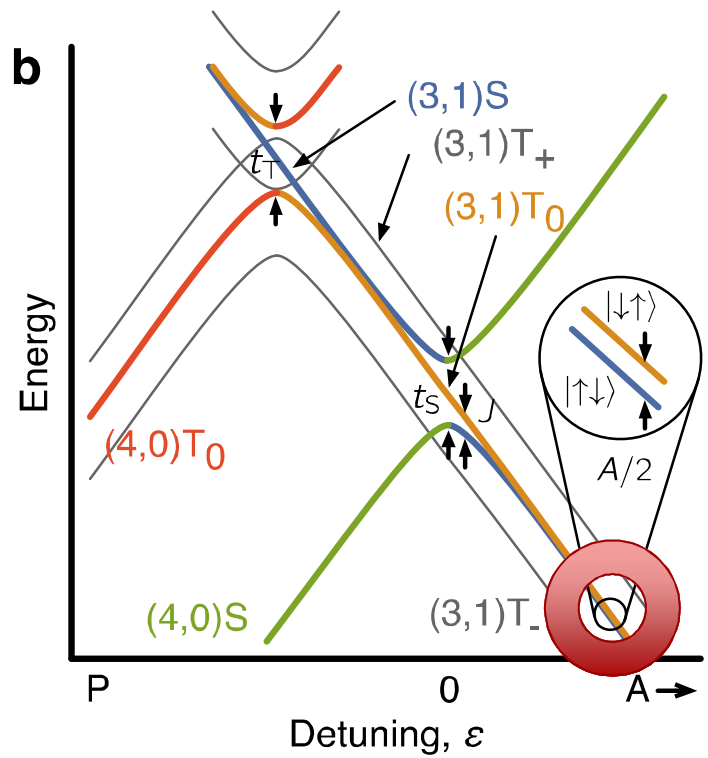
$$H = -J(\epsilon)\frac{\sigma_z}{2} - \frac{A(\epsilon)}{2}\frac{\sigma_x}{2}$$

- With nuclear spin, $\{|\Uparrow\rangle,|\Downarrow\rangle\}$ basis:

$$H = -J(\epsilon)\frac{\sigma_z}{2}\otimes\mathbb{I} - \left(\frac{A(\epsilon)}{2}\sigma_x + \gamma_n B\mathbb{I}\right)\otimes\frac{\sigma_z}{2}$$

$$(\text{ST qubit})\otimes(\text{nuc. spin})$$

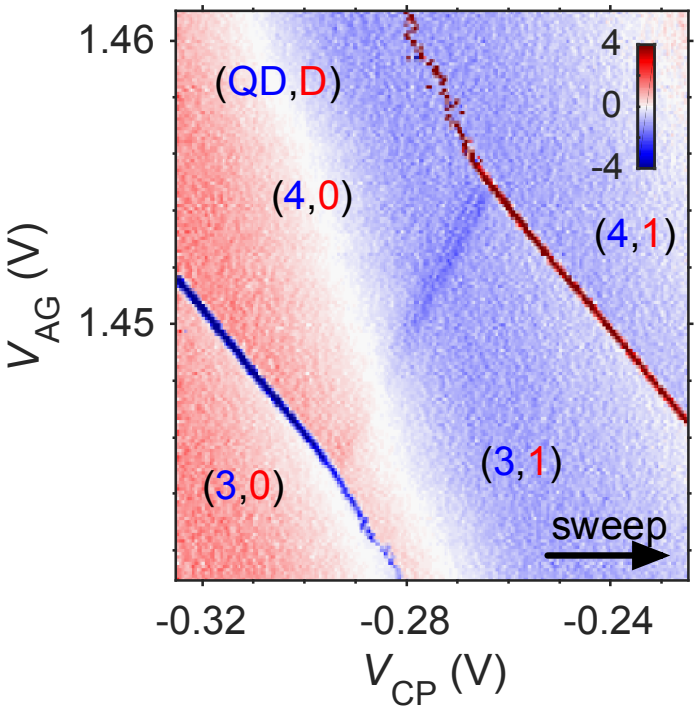
- The nuclear spin state does not affect the S-T_0 qubit (~mostly).
- Including polarized triplets gives access to the nuclear spin state!



Complete theory by A. D. Baczewski & N. T. Jacobson

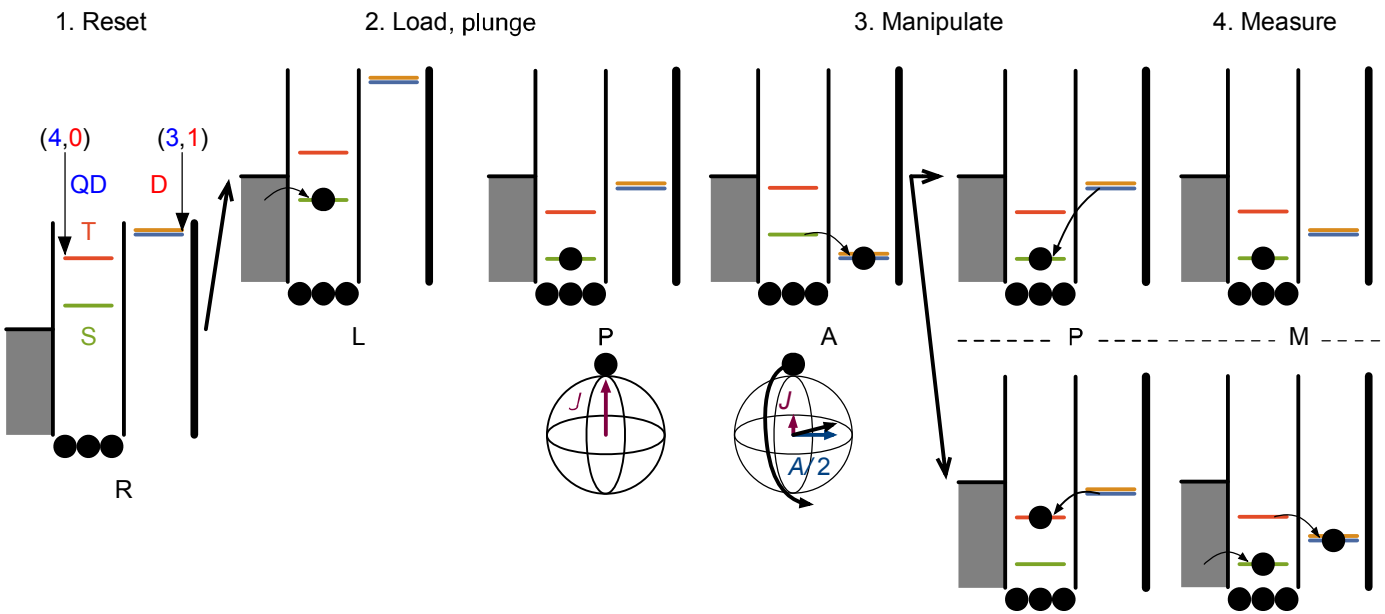
Quantum dot-donor anti-crossing

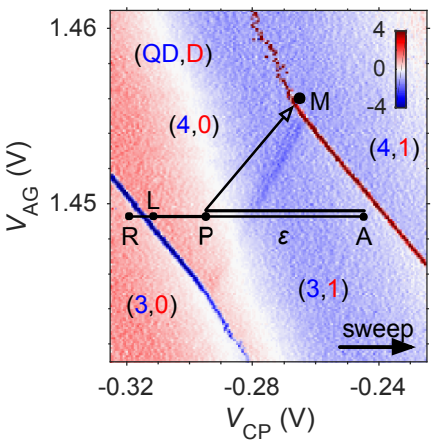
Forms an effective (2,0) ↔ (1,1) transition

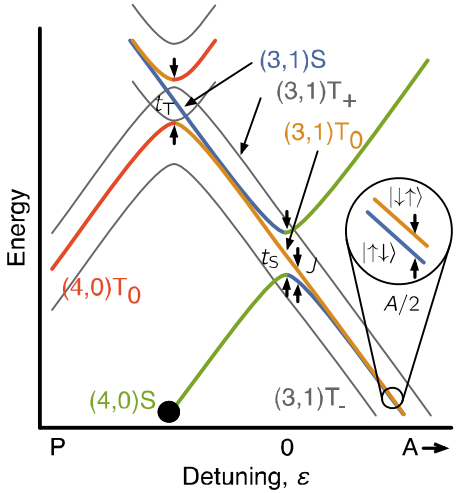


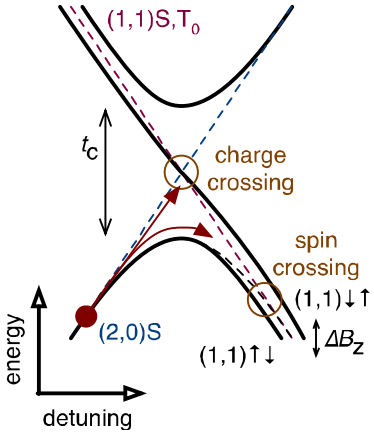
Charge hysteresis: [1] Yang, C. H. et al. Applied Physics Letters 105, 183505 (2014).

State manipulation



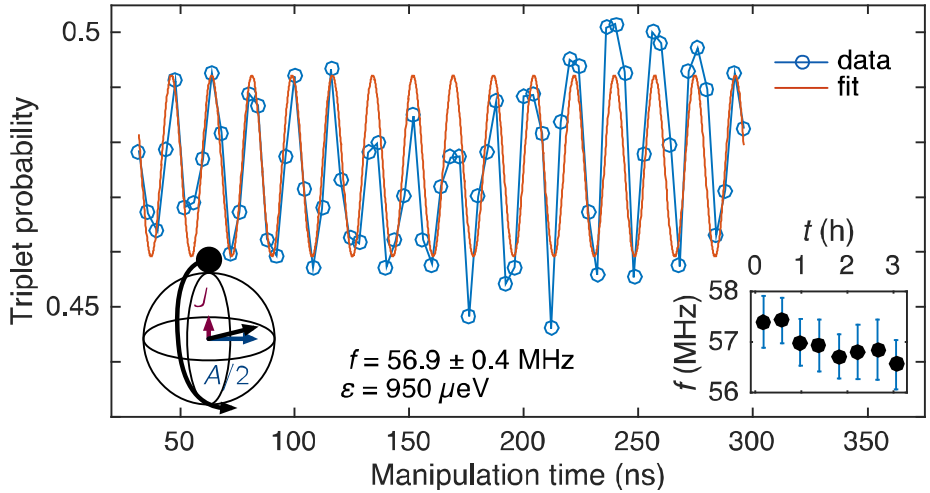


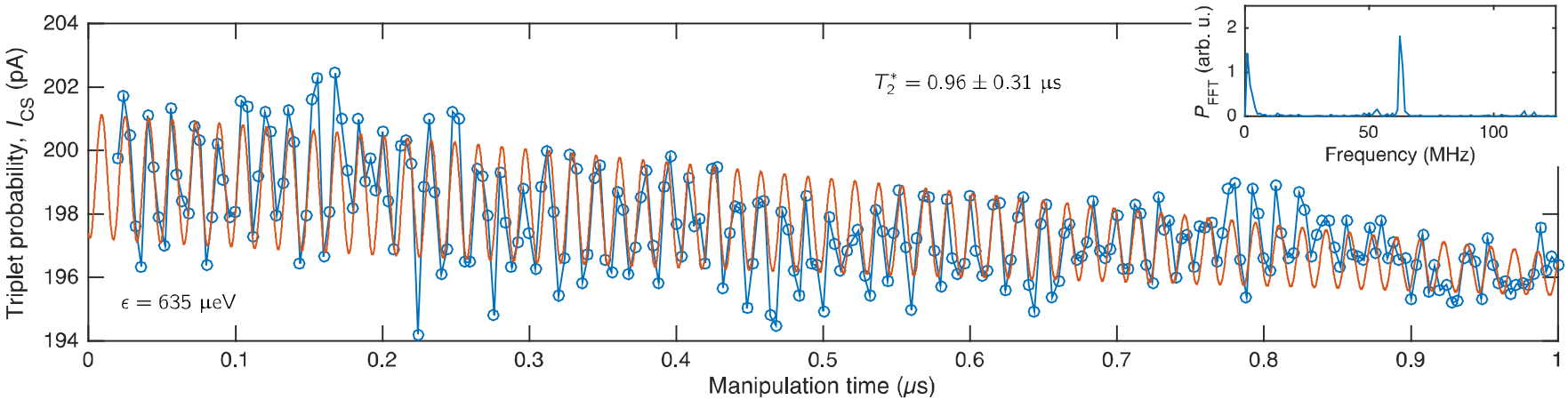




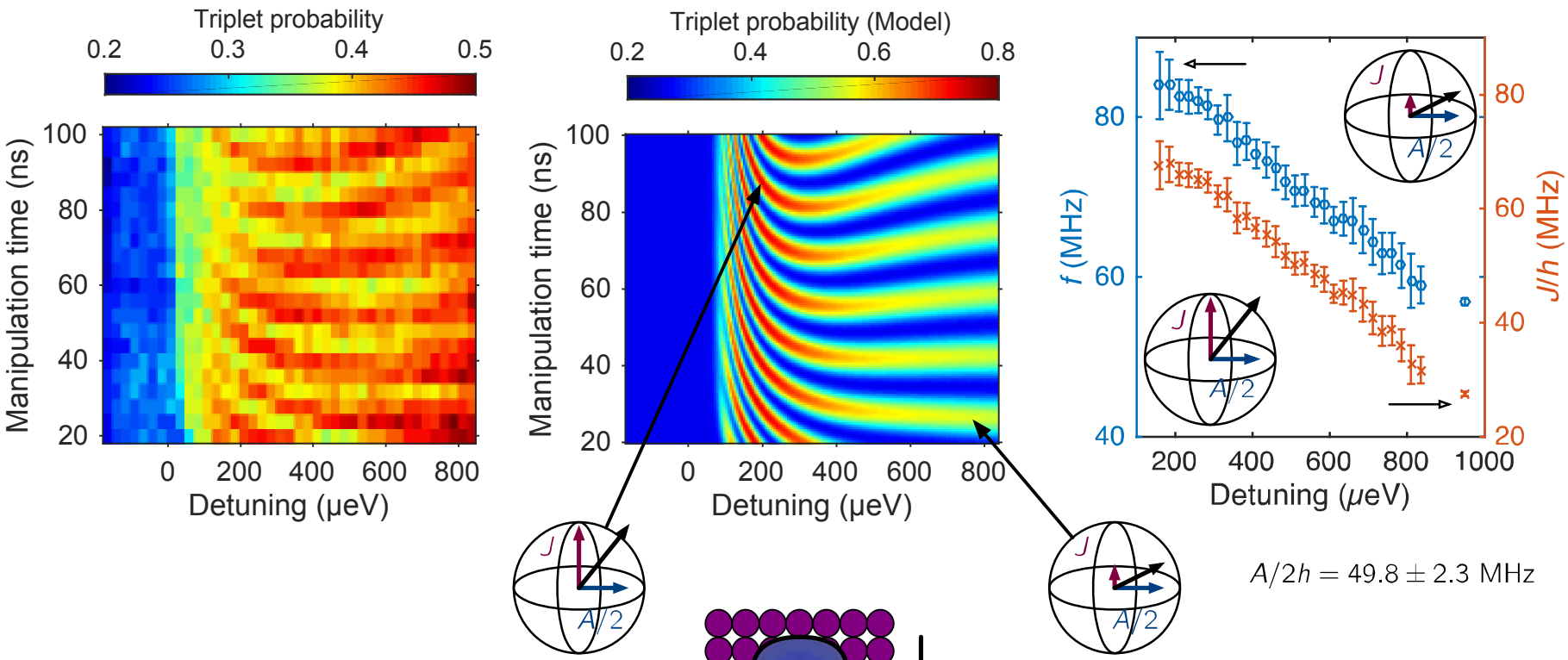
State manipulation

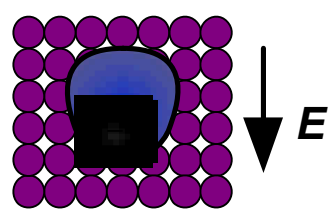
Singlet-triplet rotations driven by a single ^{31}P nucleus





Detuning dependence of exchange interaction

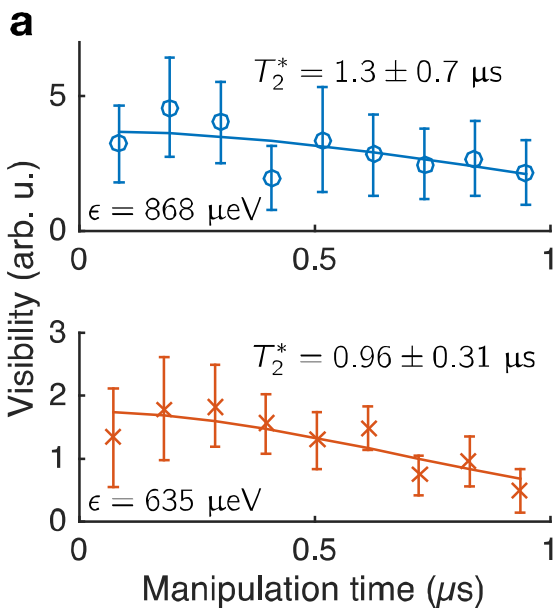


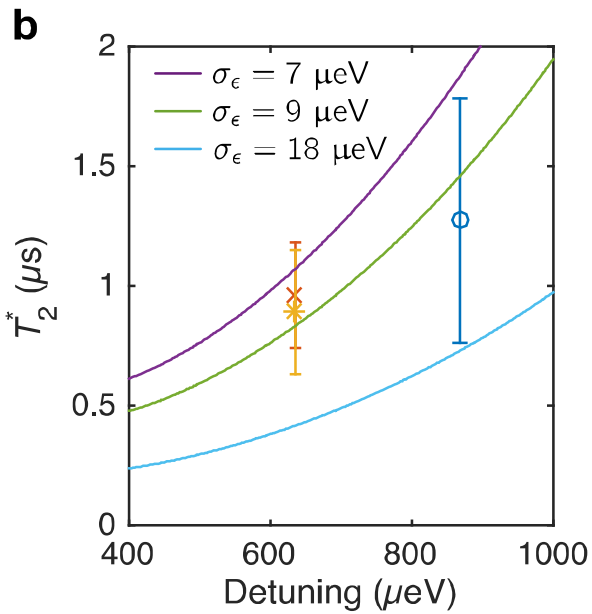


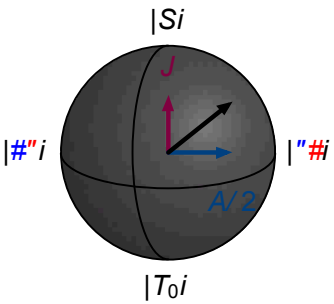
Bulk: A/h = 117 MHz

Our exp.: A/h = 100 MHz

Coherence time and charge noise







$J \rightarrow J(\epsilon + \text{noise})$

Reference	Petersson *et al.*	Shi *et al.*	Eng *et al.*	This work
Material	GaAs/AlGaAs	Si/SiGe	Si/SiGe	Si (MOS)
$2\sigma_\varepsilon$ (μeV)	7.4	10	9.2	18
$k_B T_e$ (μeV)	6.9	12	6.9 — 8.6	18

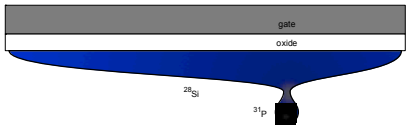
[1] Harvey-Collard, P. et al. “Coherent coupling between a quantum dot and a donor in silicon” arXiv 1512.01606.v2 (2015).
See also: Rudolph, M. et al. In 2016 IEEE International Electron Devices Meeting (IEDM), 34.1.1–34.1.4 (2016).

Outline

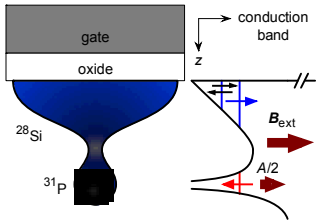
- Donor-Quantum dot system
- Valley splitting, singlet-triplet splitting, and coupling to donors
- Enhanced latching readout
- Singlet-triplet qubit (hyperfine-driven rotations)
- Summary and perspectives

Summary

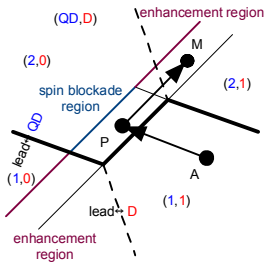
- First coherent **donor-quantum dot** system



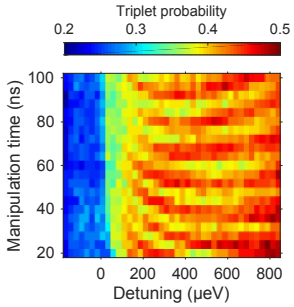
- Valley splitting is **tunable**, **4-electron** trick



- Enhanced latching readout, **>99.68%** single shot readout



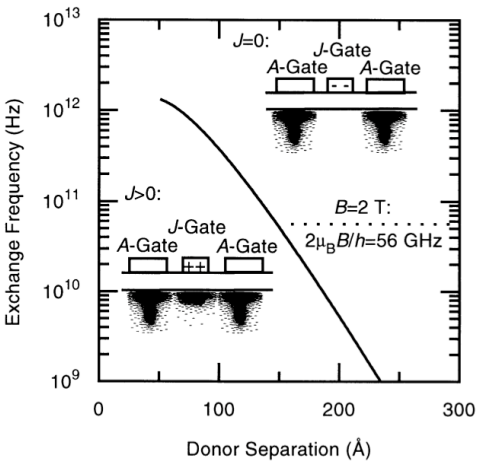
- Singlet-triplet qubit: **hyperfine-driven rotations**, measure of **exchange**



First ST qubit in MOS.

Perspectives

Modern implementation of Kane's original vision

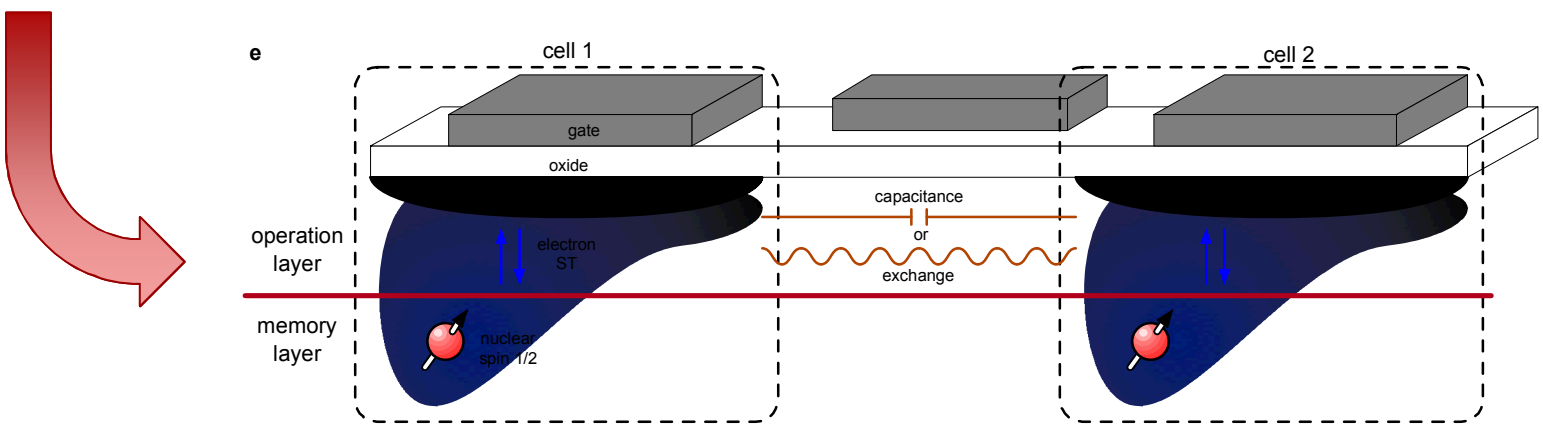


[1] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).

Over 19 years of QD-D schemes!

Future work:

- High-fidelity qubit operation (AC, etc.)
- Strong hyperfine donors species
- Two-MAJIQ coupling
- Nuclear spin addressing



Acknowledgements & Team

Experiments

- Malcolm S. Carroll (SNL advisor)
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- Martin Rudolph
- Ryan M. Jock
- Matthew J. Curry
- Lisa A. Tracy (Staff, fridge)

Fabrication

- Jason Dominguez
- Gregory A. Ten Eyck
- Joel R. Wendt
- Tammy Pluym

Theory

- Benjamin D'Anjou (McGill U.)
- William A. Coish (McGill U.)
- N. Tobias Jacobson
- John King Gamble
- Andrew D. Baczewski
- Erik Nielsen
- Richard Muller

Université de Sherbrooke

- Michel Pioro-Ladrière (academic advisor)

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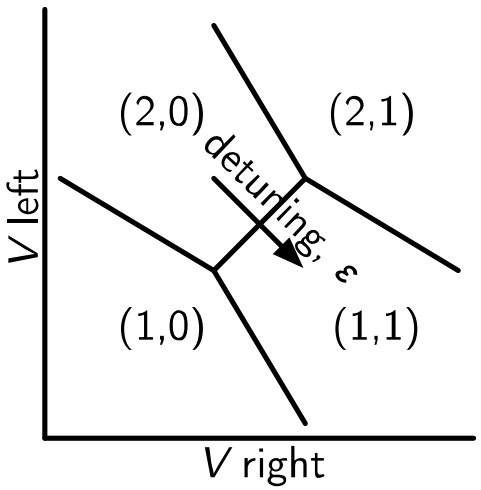
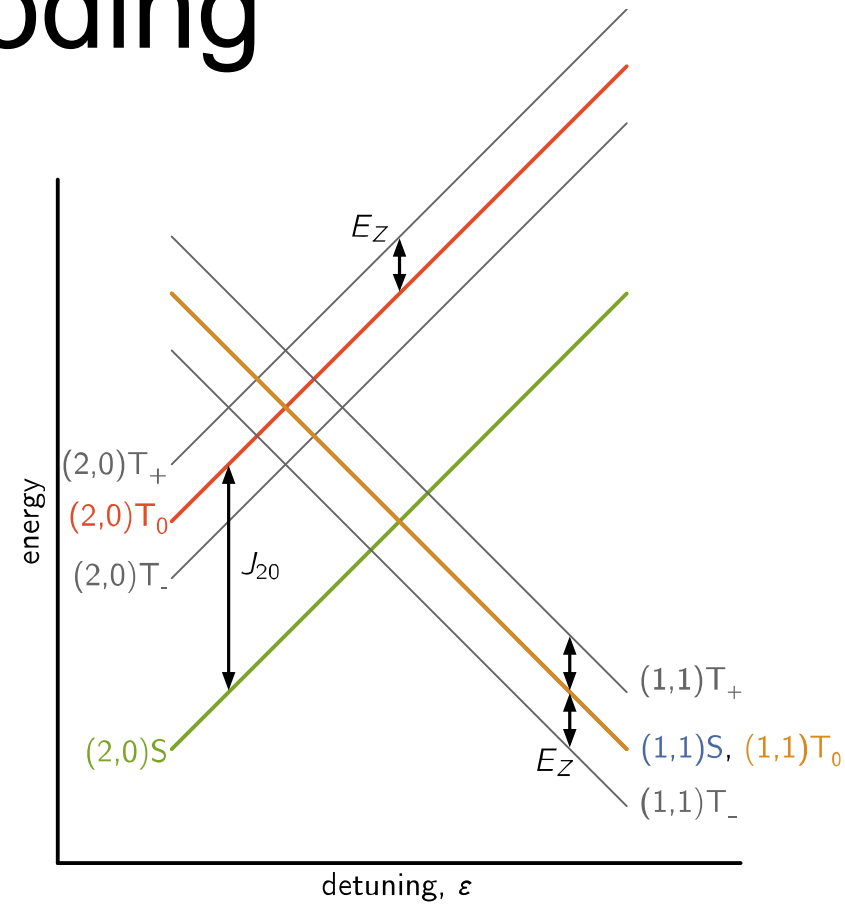
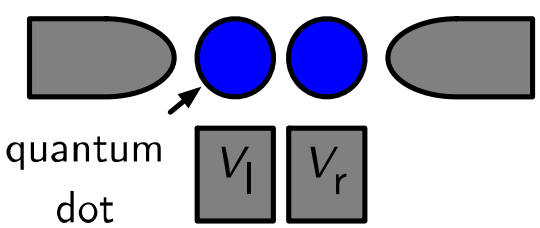
Singlet-triplet encoding

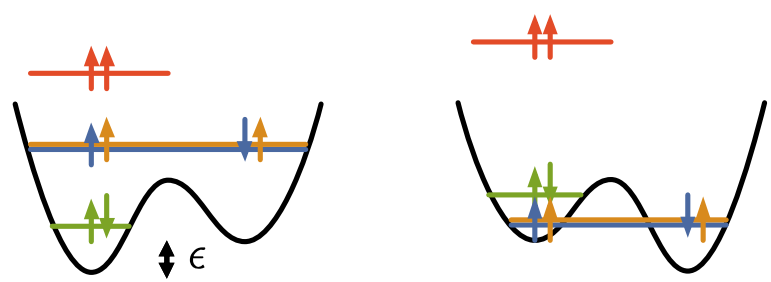
Charge stability diagram





Double QD

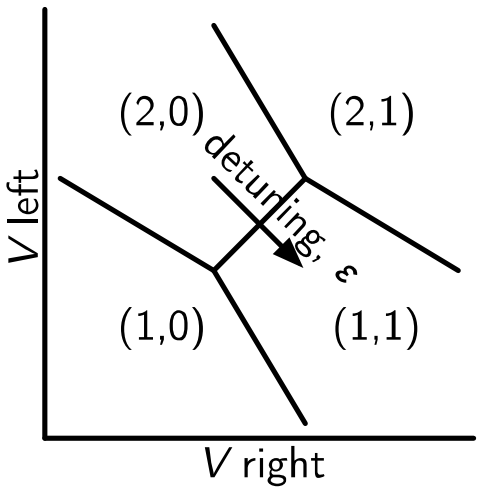


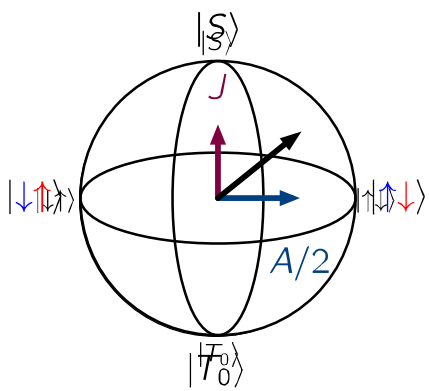


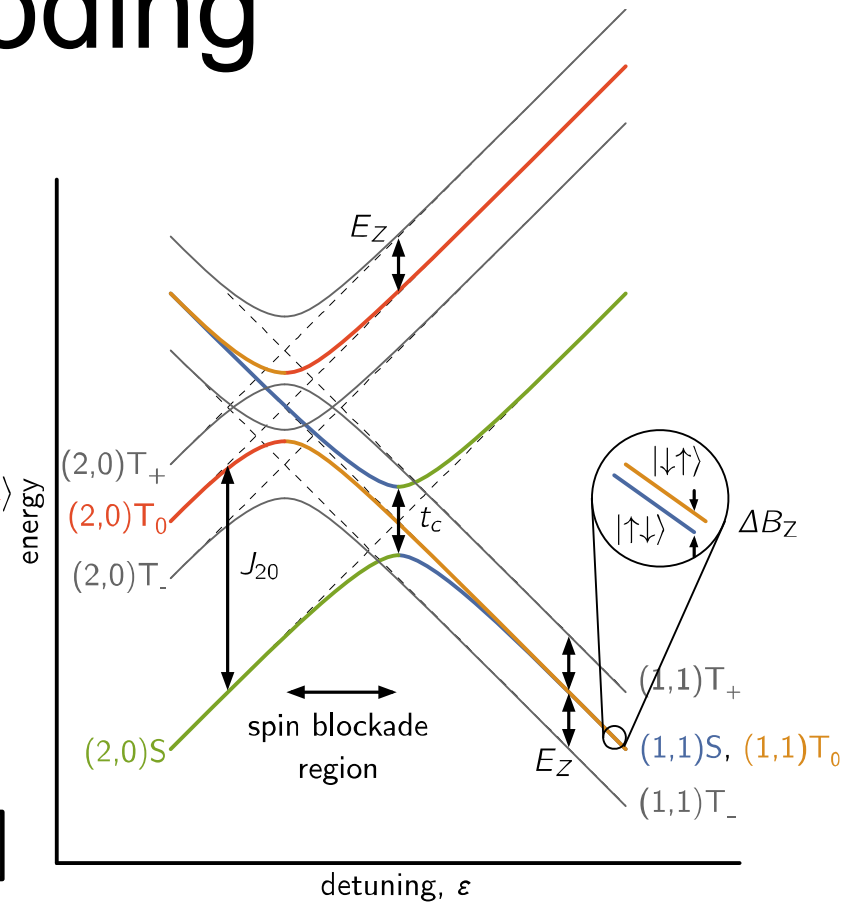
[1] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, “Relaxation, dephasing, and quantum control of electron spins in double quantum dots,” Phys. Rev. B 76, 035315 (2007).

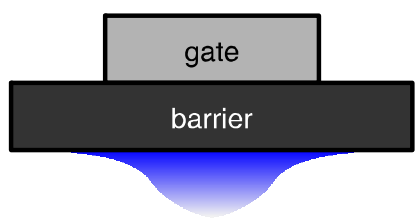
Singlet-triplet encoding

Charge stability diagram

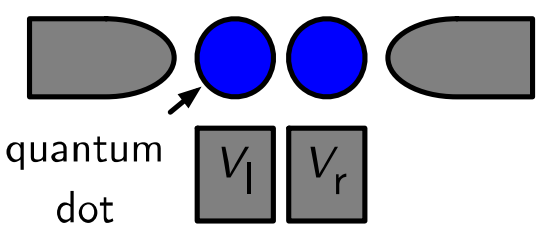


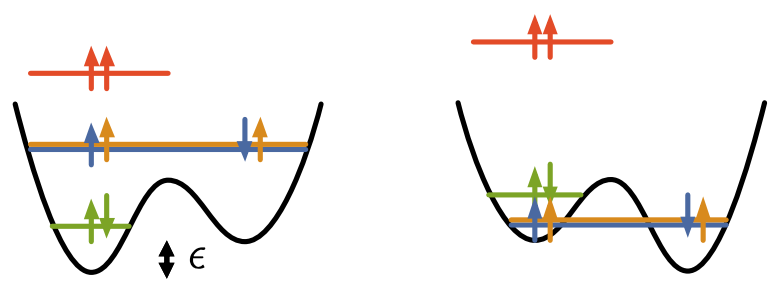






Double QD



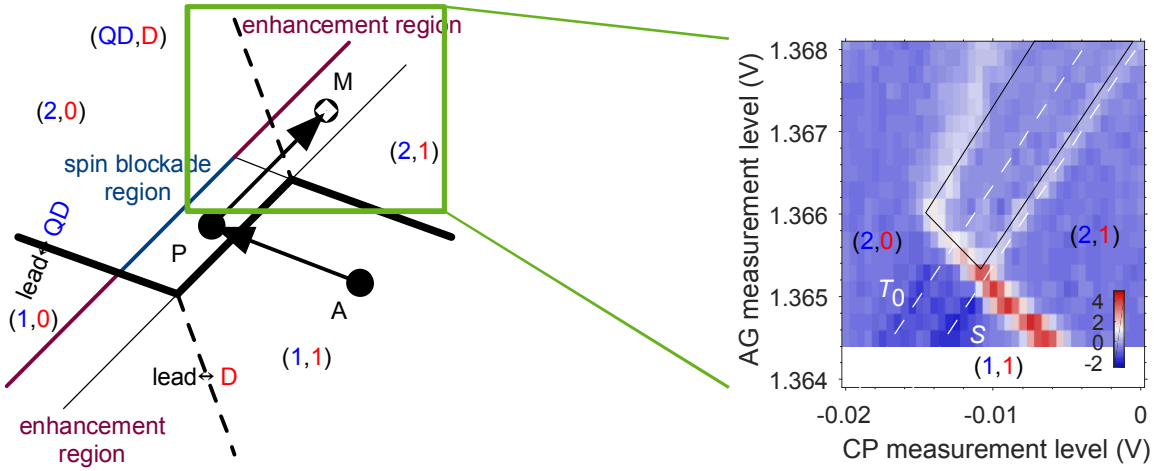


[1] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, “Relaxation, dephasing, and quantum control of electron spins in double quantum dots,” Phys. Rev. B 76, 035315 (2007).

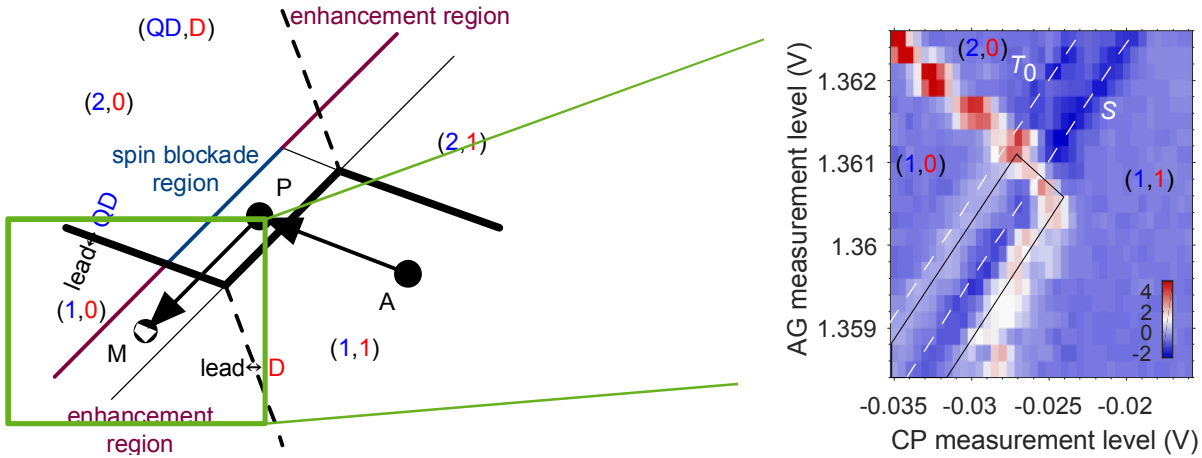
Variations of the enhanced dout

See our preprint for details!

"reverse" ELR

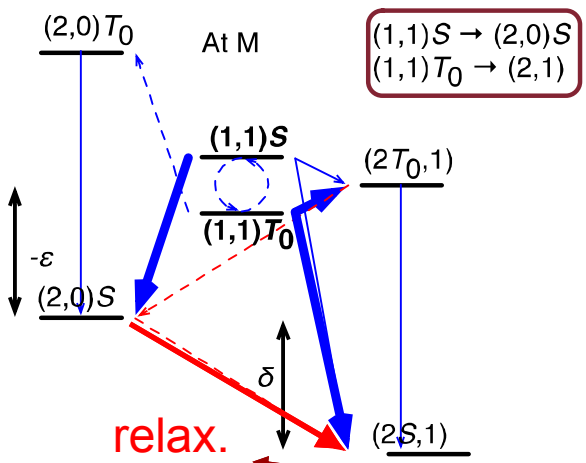


"direct" ELR

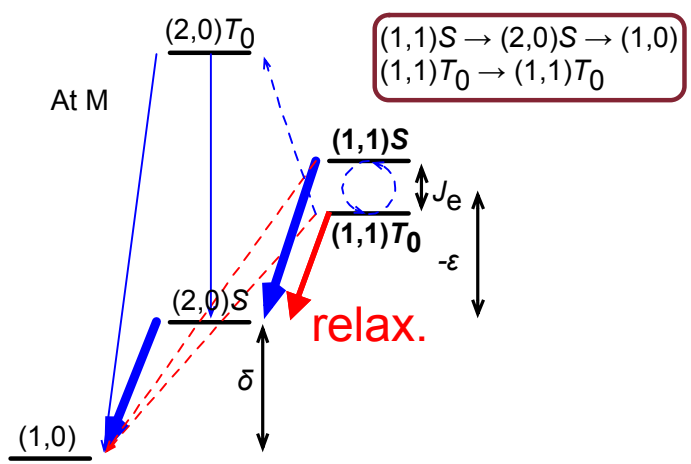


Reverse ELR enhances the lifetime of the signal by changing the relaxation mechanism

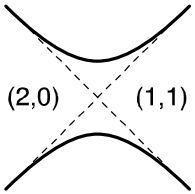
"reverse" ELR



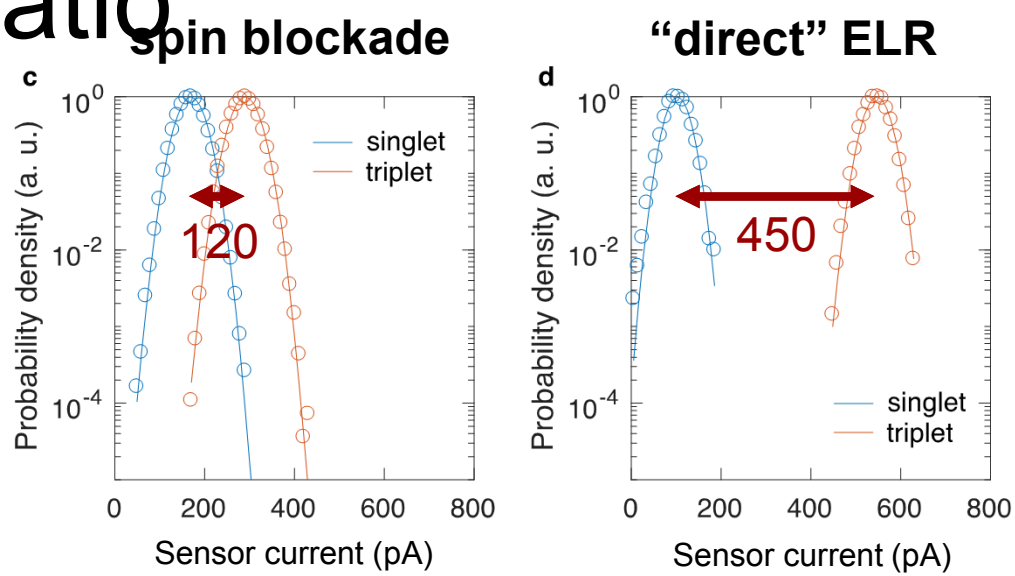
"direct" ELR



limiting factor: (2,0)-(1,1) hybridization near degeneracy point

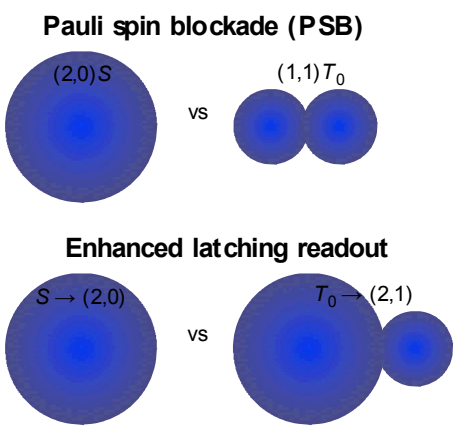


ELR enhances the signal-to-noise ratio

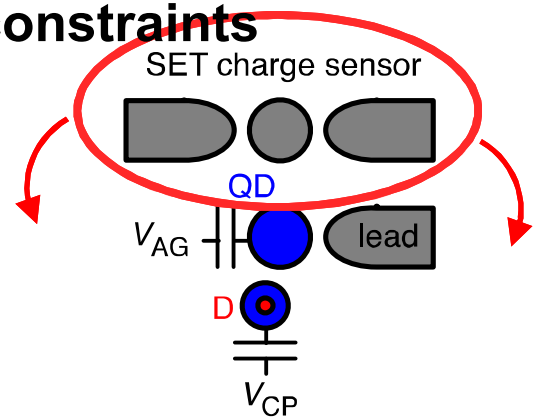


	Signal (pA)
PSBR	120
ELR	450
Enhancement factor	**3.8 x**

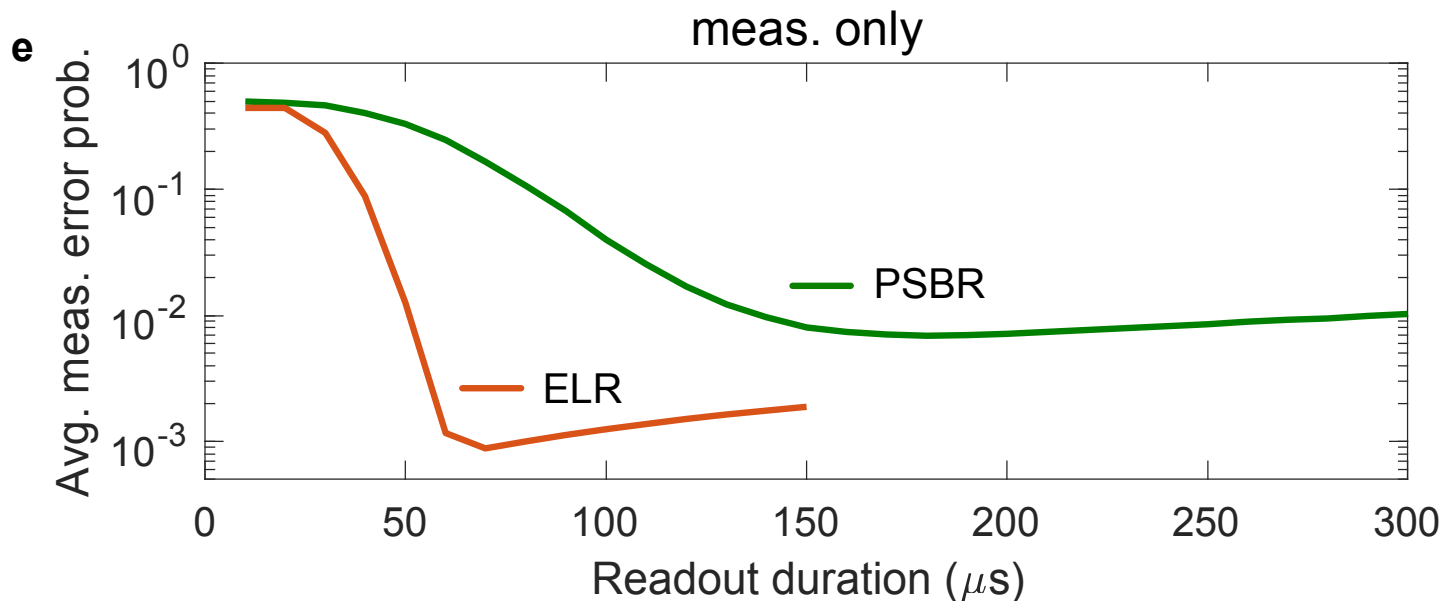
Noise is the same.

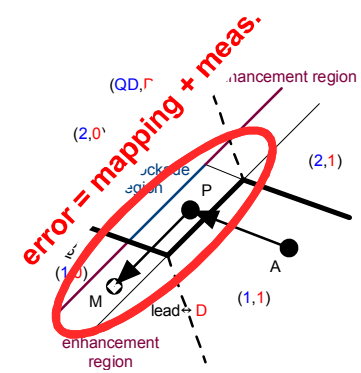


Relaxes layout constraints



ELR enhances fidelity and readout time





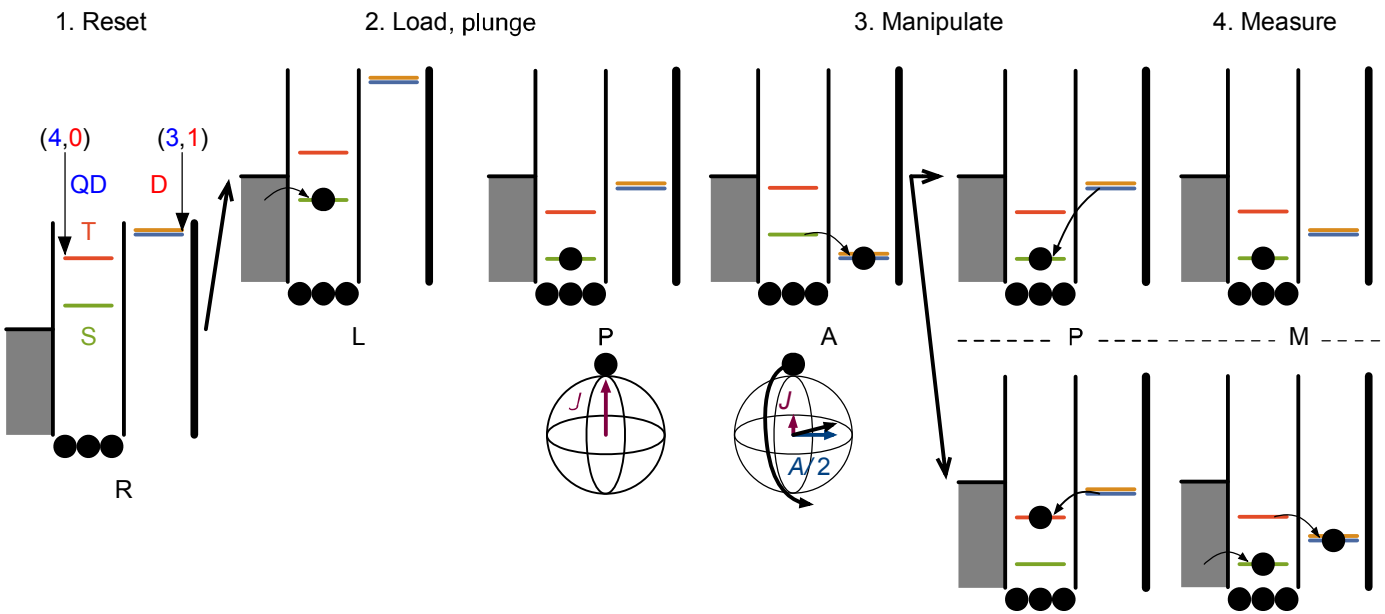
	Avg. Fidelity (%)	Time (μs)
PSBR	99.3 ± 0.1	150
ELR	99.912 ± 0.008	65
Enhancement factor	**8 x**	**2.3 x**

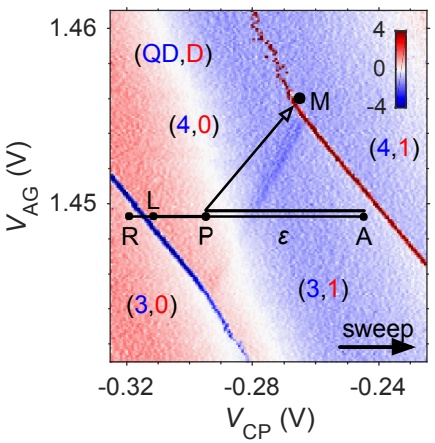
Average fidelity, accounting for *all* error sources:
> 99.86 %

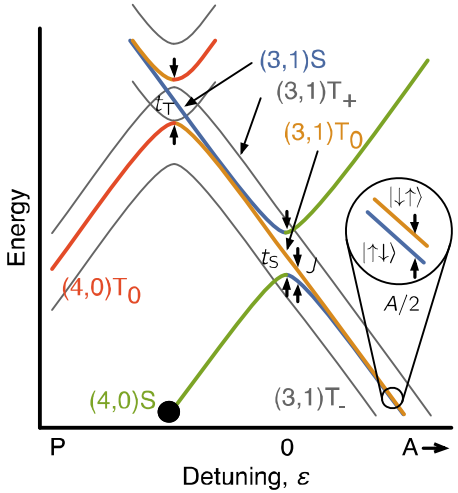
Error sources accounted for:

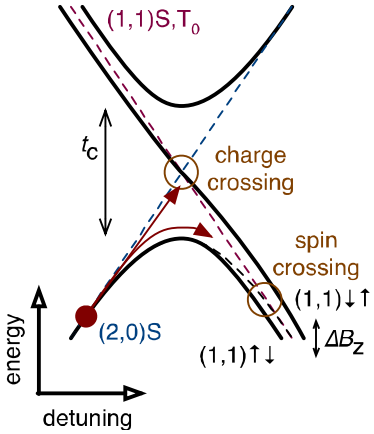
- Diabatic (2,0)<->(1,1) passage
- Slow (2S,0)->(1,0) transition
- (1,1)T0 decay before measurement
- Finite temperature

State manipulation





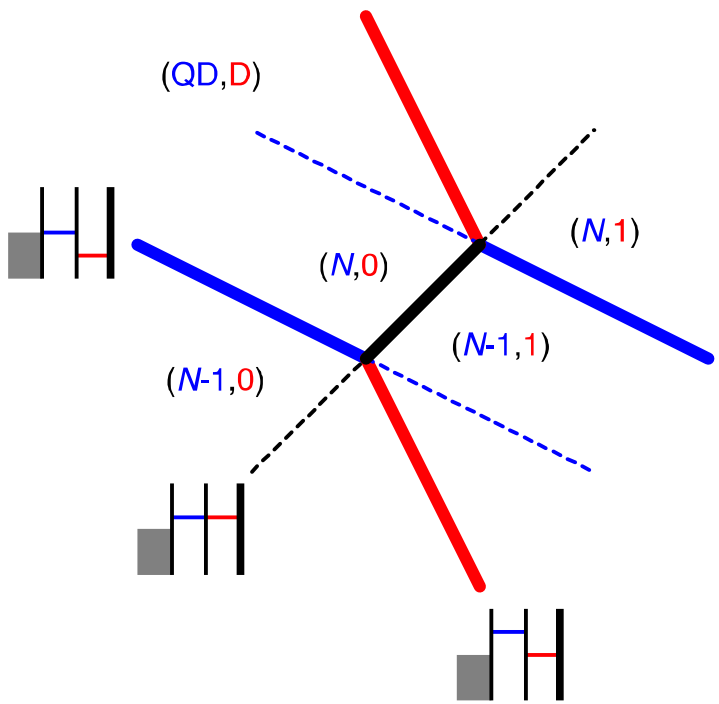




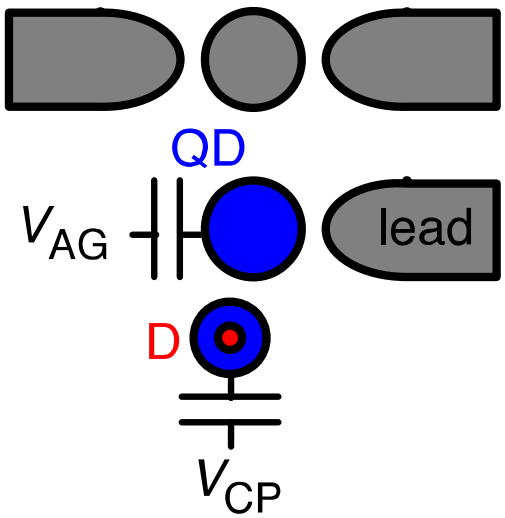
QD-D system has latching charge transitions

Charge stability diagram

equilibrium

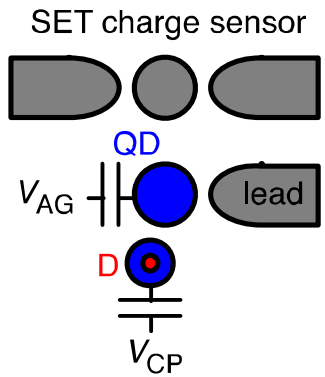


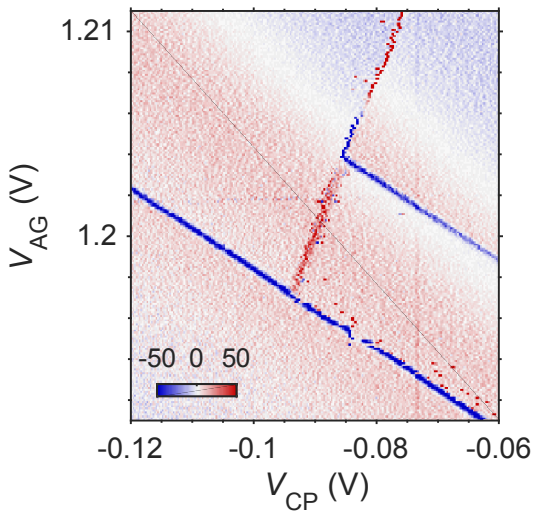
SET charge sensor



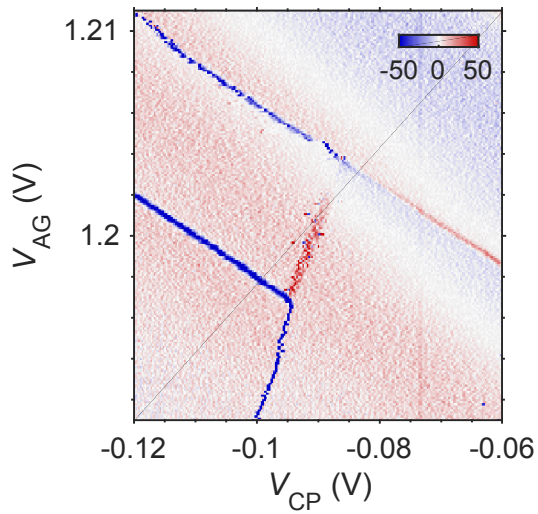
For DQD version: C. H. Yang, A. Rossi, N. S. Lai, R. Leon, W. H. Lim, and A. S. Dzurak, “Charge state hysteresis in semiconductor quantum dots,” Appl. Phys. Lett., vol. 105, p. 183505, 2014.

QD-D latching charge transitions





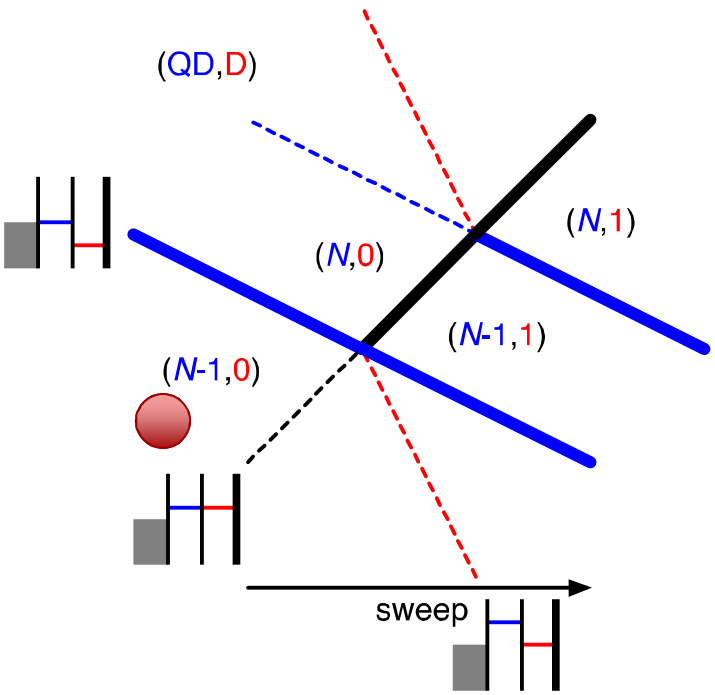
sweep

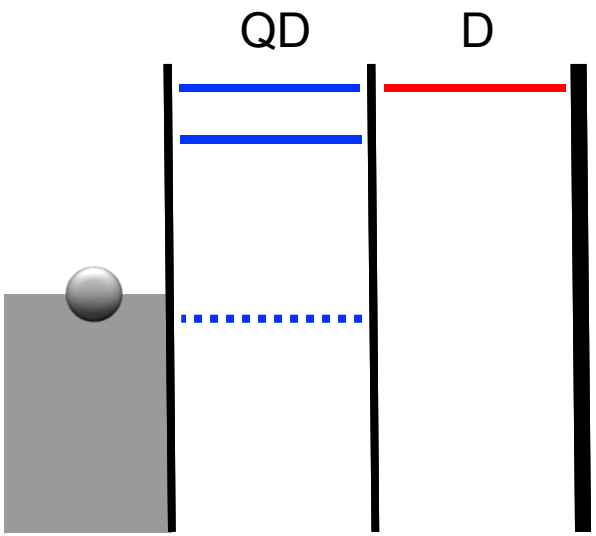


sweep

QD-D system has latching charge transitions

Charge stability diagram

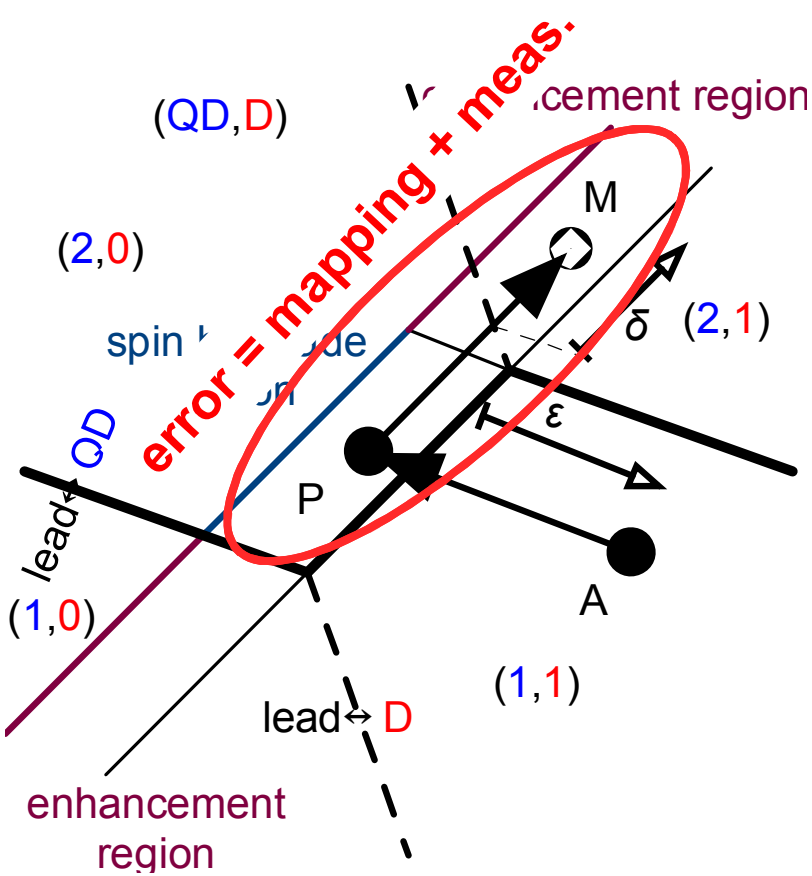




For DQD version: C. H. Yang, A. Rossi, N. S. Lai, R. Leon, W. H. Lim, and A. S. Dzurak, “Charge state hysteresis in semiconductor quantum dots,” Appl. Phys. Lett., vol. 105, p. 183505, 2014.

Enhanced Latching Readout (ELR)

Mechanism



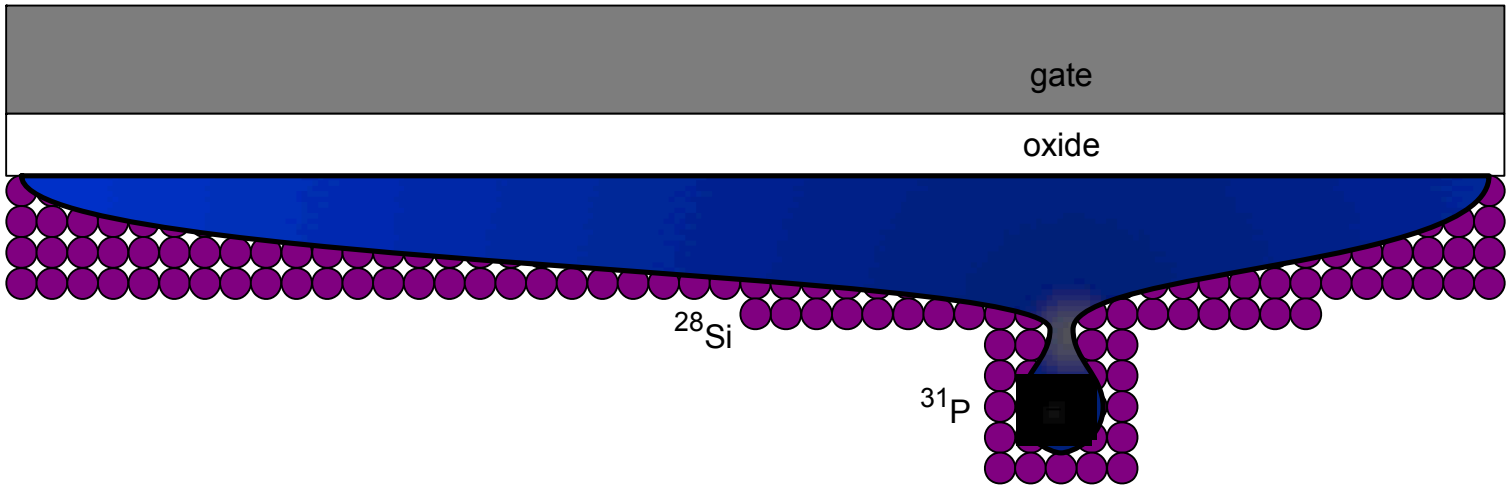
Comparison of electron readouts

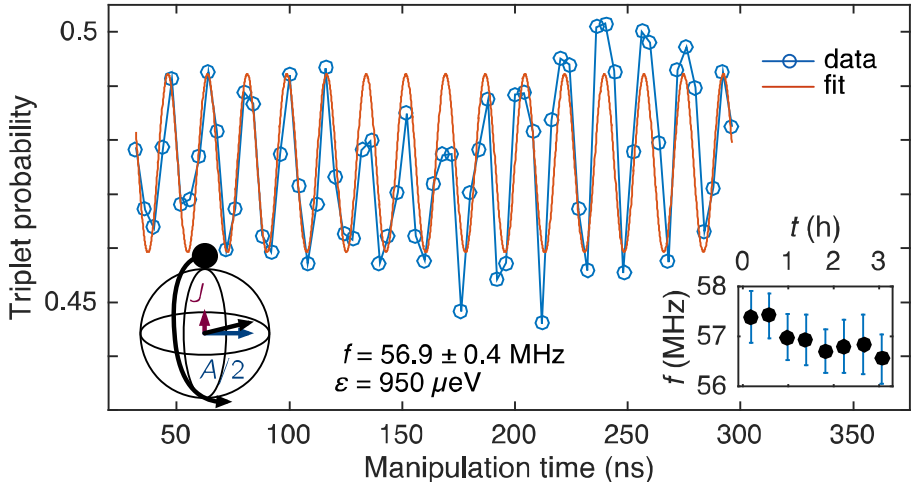
	Spin 1/2	Singlet-triplet	This work
Signal	1 e	~0.2 e	1 e
Lifetime	Good, but long waits	Ok (Si), Bad (GaAs)	Good
Fixed readout window	Poor	Good	Good

If you have **any** singlet-triplet system, this can work!

In this presentation:

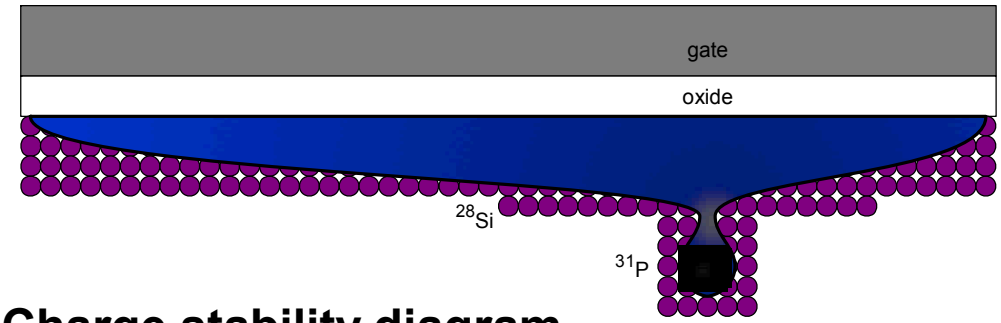
First *coherent* coupling and control between a quantum dot (QD) and a donor (D)



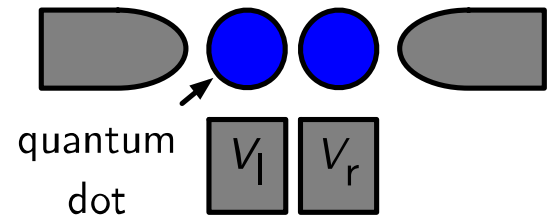


Singlet-triplet encoding

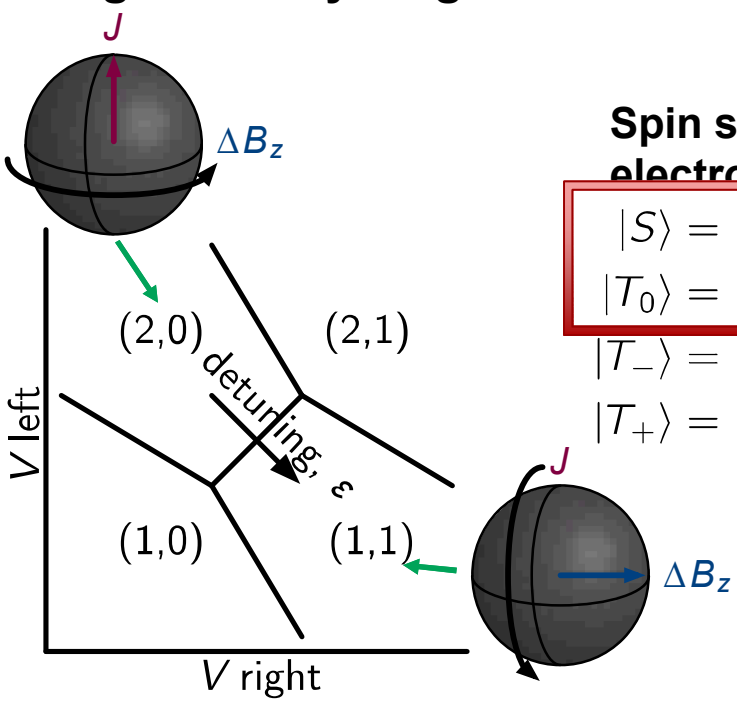
QD-D



Double QD



Charge stability diagram

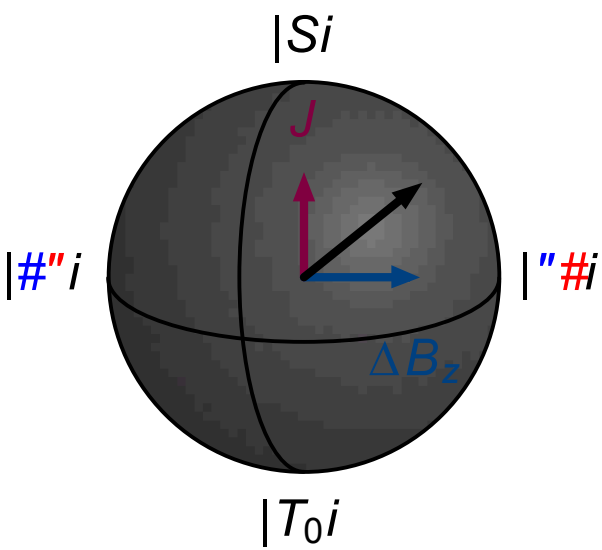


Spin states for two electrons

$$|S\rangle = |\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle$$
$$|T_0\rangle = |\uparrow\downarrow\rangle + |\downarrow\uparrow\rangle$$
$m = 0$

$$|T_-\rangle = |\downarrow\downarrow\rangle \qquad m = -1$$
$$|T_+\rangle = |\uparrow\uparrow\rangle \qquad m = +1$$

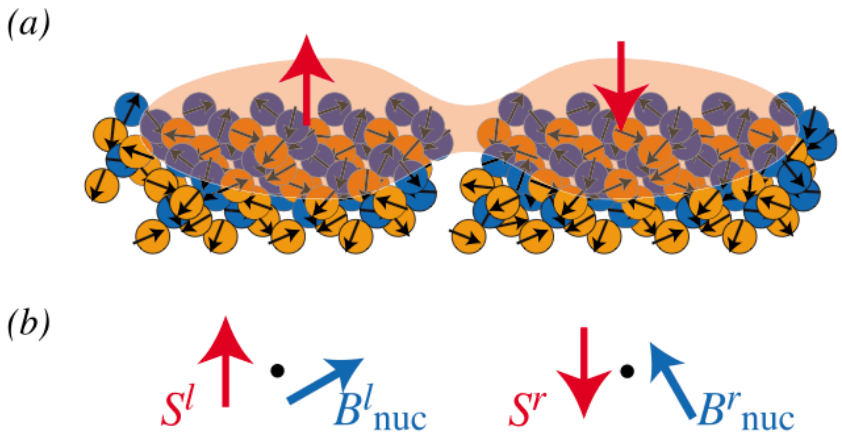
Qubit Bloch Sphere



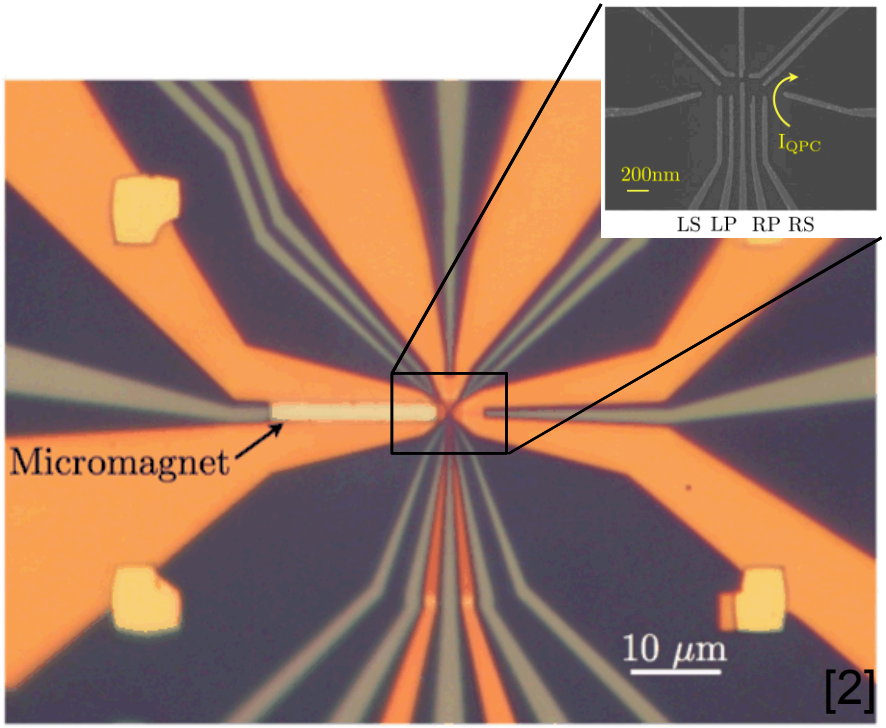
ST qubit theory: J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, “Relaxation, dephasing, and quantum control of electron spins in double quantum dots,” Phys. Rev. B 76, 035315 (2007).

Driving ΔB_z rotations in the singlet-triplet qubit

GaAs: nuclear field gradient



Si: micromagnets



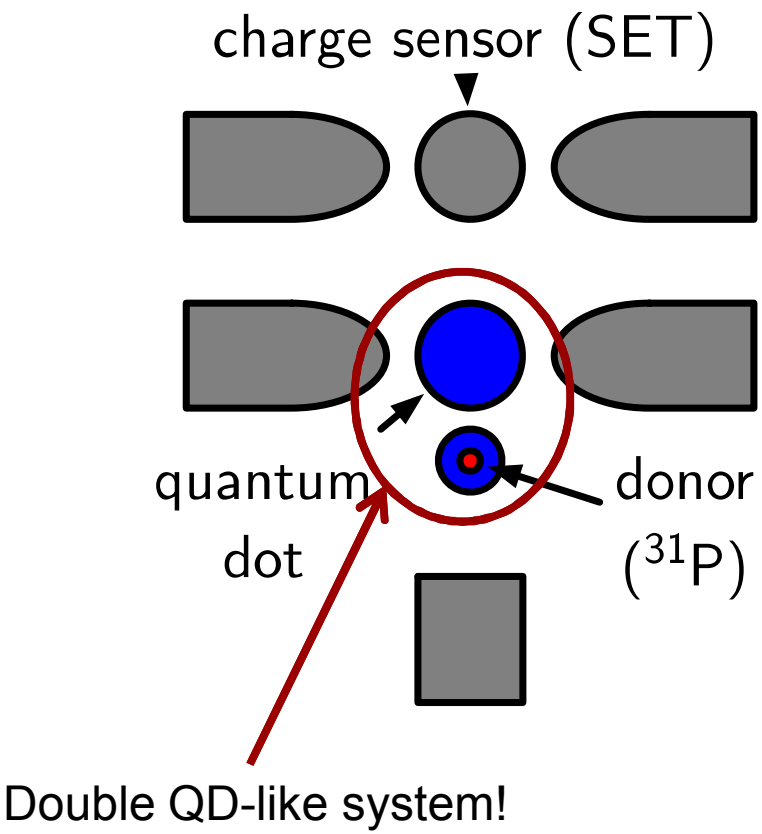
[1] J. M. Taylor, J. R. Petta, A. C. Johnson, A. Yacoby, C. M. Marcus, and M. D. Lukin, "Relaxation, dephasing, and quantum control of electron spins in double quantum dots," Phys. Rev. B 76, 035315 (2007).

[1] Pioro-Ladrière, M. et al. Nat Phys 4, 776–779 (2008).
[2] Wu, X. et al. Proceedings of the National Academy of Sciences 111, 11938–11942 (2014).

New key idea: use contact hyperfine interaction with ***single donor*** to rotate the spin

$$\langle \Downarrow | A\boldsymbol{S} \cdot \boldsymbol{I} | \Downarrow \rangle = \frac{A}{2}\boldsymbol{S}$$

Hybrid QD-D singlet-triplet qubit



For electron on donor:

$$\hat{H} = (g\mu_B/\hbar)\boldsymbol{S} \cdot \boldsymbol{B}_{\text{ext}} + A\boldsymbol{S} \cdot \boldsymbol{I}$$

Singlet-Triplet Hamiltonian:

$$\hat{H}_{\text{ST}} = J(\epsilon)\hat{\sigma}_z + \Delta B_Z(\epsilon)\hat{\sigma}_x$$

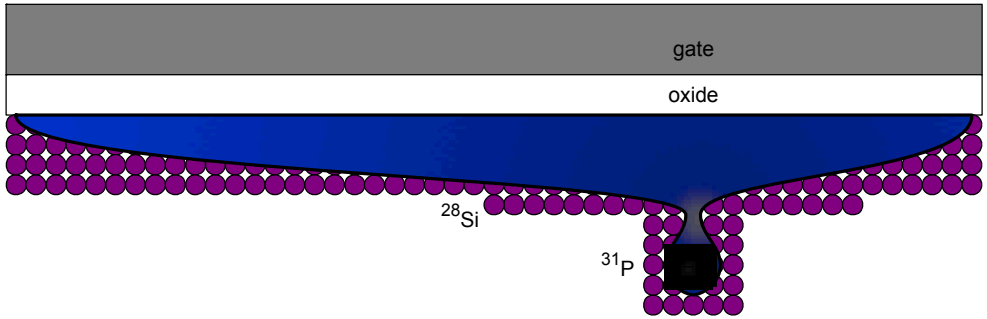
Advantages

- **Fast** and **stable** rotation speed: Contact hyperfine interaction $A/2$ = 57 MHz gives **9 ns π rotation (potentially faster).**
- Compact design: No need for **nuclear field bath**, **spin-orbit int.**, **micromagnet**. Just **one QD**.
- ST states: good probe of coherence between the QD and the D.
- **Get nuclear spin** for free.

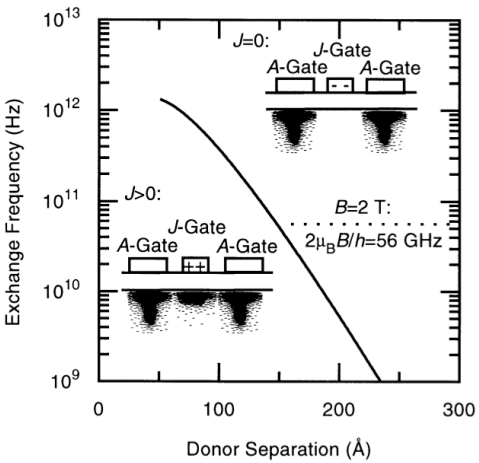
For details: N. Tobias Jacobson and Andrew D. Baczewski

Perspectives

This work: First coherent coupling between a quantum dot (QD) and a donor (D)

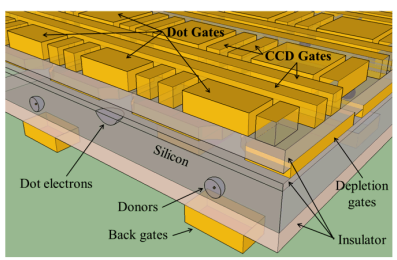


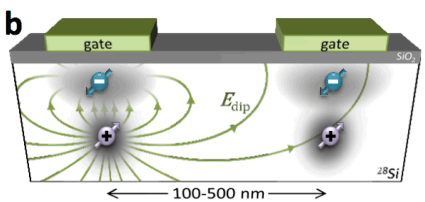
Kane's original exchange "*J*" gate



[1] Kane, B. E. A silicon-based nuclear spin quantum computer. Nature 393, 133–137 (1998).

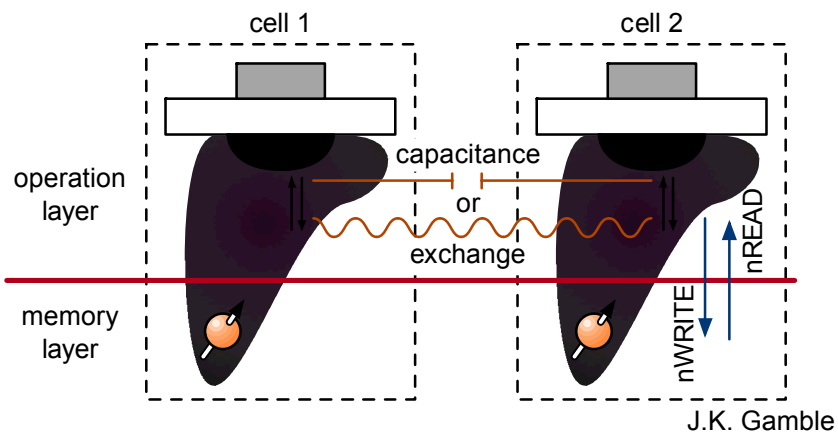
"Modern" proposals involve QDs





[1] Pica, G., Lovett, B. W., Bhatt, R. N., Schenkel, T. & Lyon, S. A. Phys. Rev. B 93, 035306 (2016).
[2] Tosi, G. et al. ArXiv e-prints (2015). 1509.08538.

Future work



John Gamble: "*Designing a flying qubit at a silicon interface*"
Andrew Baczewski: "*What can I do with a singlet-triplet qubit coupled to a nuclear spin qubit?*"
Toby Jacobson: "*A singlet-triplet qubit coupled to the nuclear spin of a single phosphorus donor*"

System Hamiltonian

States

- Charge states:

$$v_{(2,0)} = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad v_{(1,1)} = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- Spin states:

$$u = \begin{pmatrix} 1 \\ 0 \end{pmatrix} \qquad d = \begin{pmatrix} 0 \\ 1 \end{pmatrix}$$

- Ordering: {charge c, electron 1, electron 2, nuclear spin j}

- Spin operators (so that s and j are dimensionless)

$$\boldsymbol{S} = \hbar \boldsymbol{s} \qquad \boldsymbol{I} = \hbar \boldsymbol{j}$$

Hamiltonian

- Zeeman energy: $\gamma_e = \hbar g \mu_B$

$$H_B = \gamma_e \boldsymbol{s}_1 \cdot \boldsymbol{B} + \gamma_e \boldsymbol{s}_2 \cdot \boldsymbol{B} - \gamma_n \boldsymbol{j} \cdot \boldsymbol{B}$$

- Exchange in (2,0)

$$H_J = \left| v_{(2,0)} \right\rangle \left\langle v_{(2,0)} \right| \otimes J_{20} \boldsymbol{s}_1 \cdot \boldsymbol{s}_2 \otimes I_j$$

- Detuning, tunnel coupling

$$H_t = \left(\frac{\epsilon}{2} Z_c + \frac{t}{2} X_c \right) \otimes I_1 I_2 I_j$$

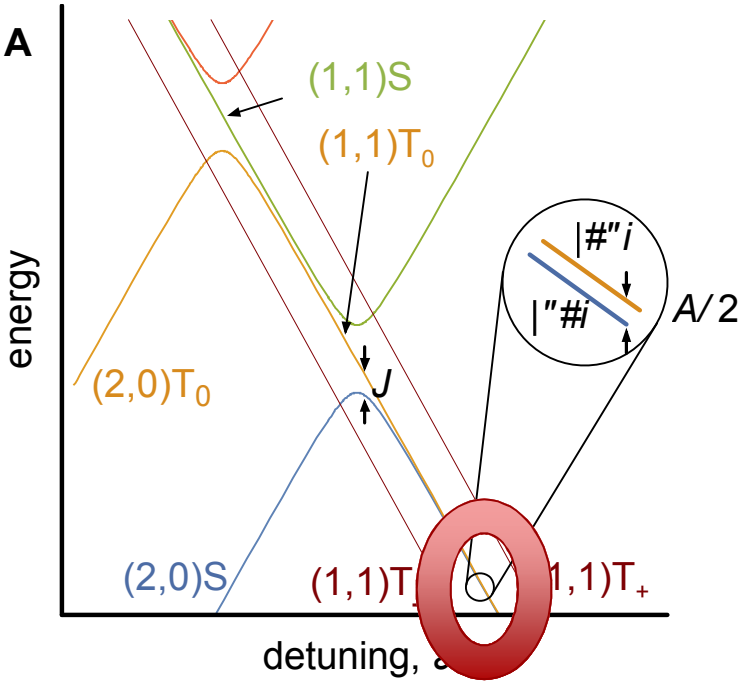
- Hyperfine interaction

$$H_{HF} = A \boldsymbol{s}_2 \cdot \boldsymbol{j}$$

$$H = H_t + H_B + H_J + H_{HF}$$

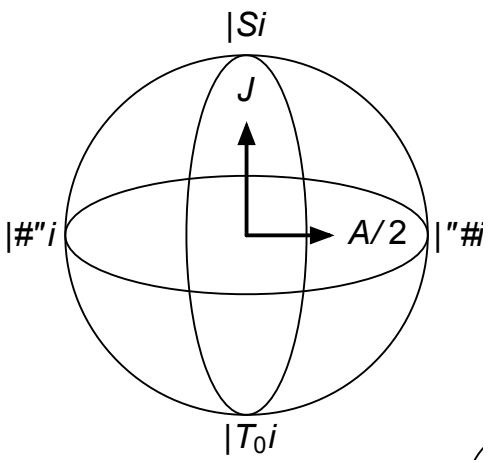
dim H = 2x2x2x2 = 8

Hamiltonian, in (1,1), S and T_0



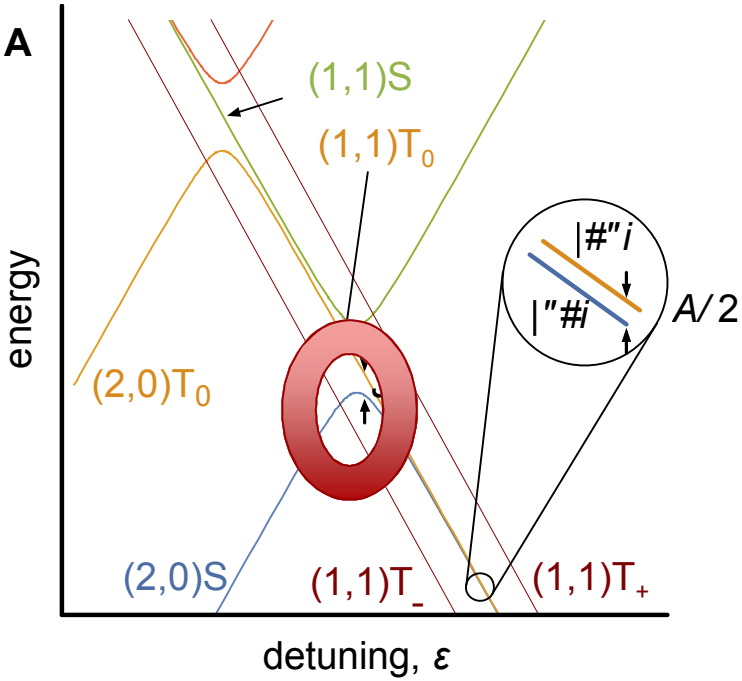
ST qubit Nuclear spin

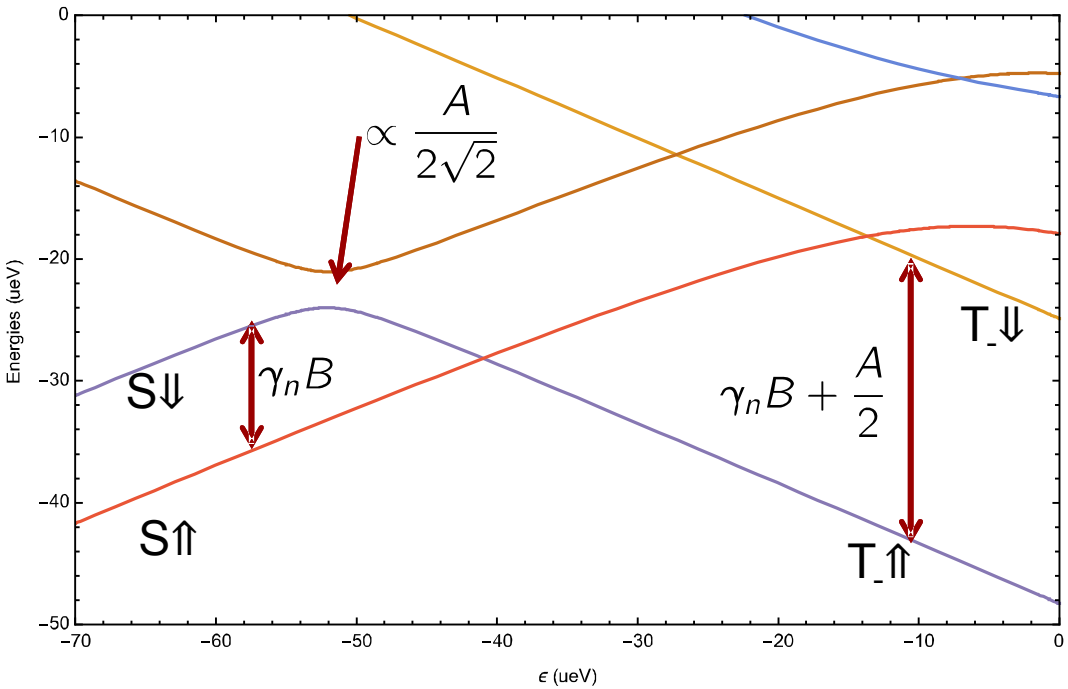
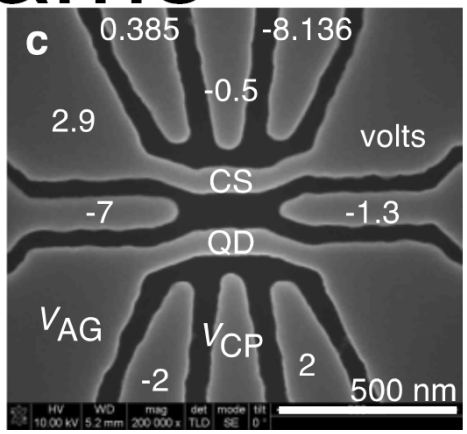
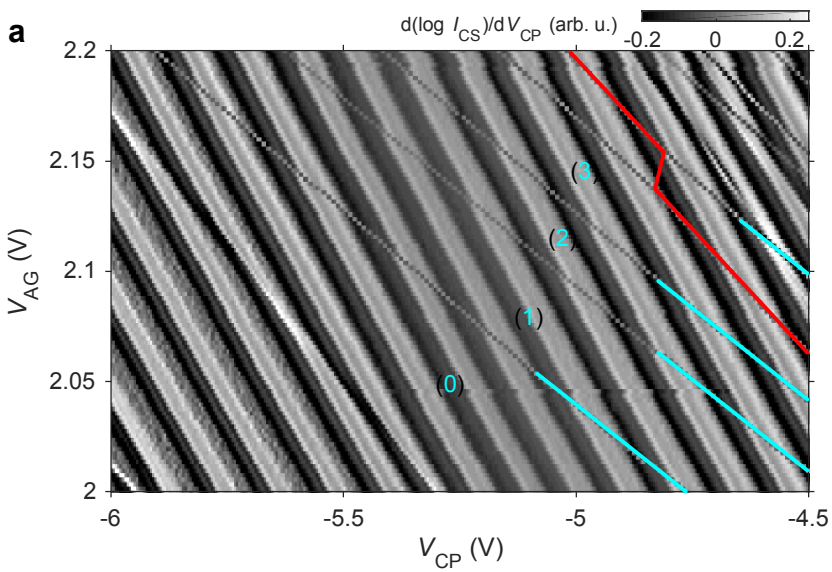
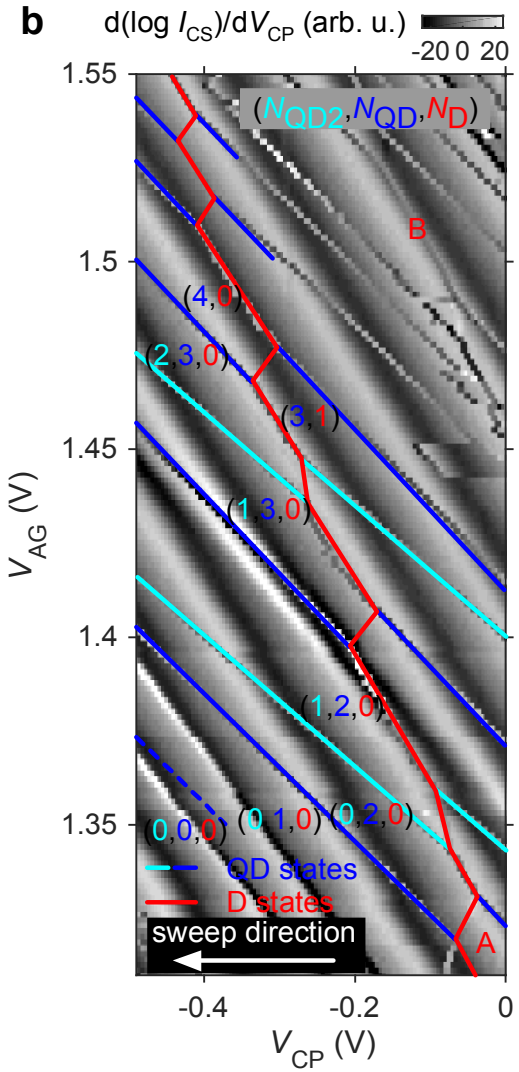
$$H = -\left(\frac{A}{2}X + \gamma_n B\mathbb{I}\right) \otimes \frac{Z}{2}$$



The nuclear spin state does not affect the S-T_0 qubit

Hamiltonian, in (1,1), S and T-





Donors in charge stability diagrams