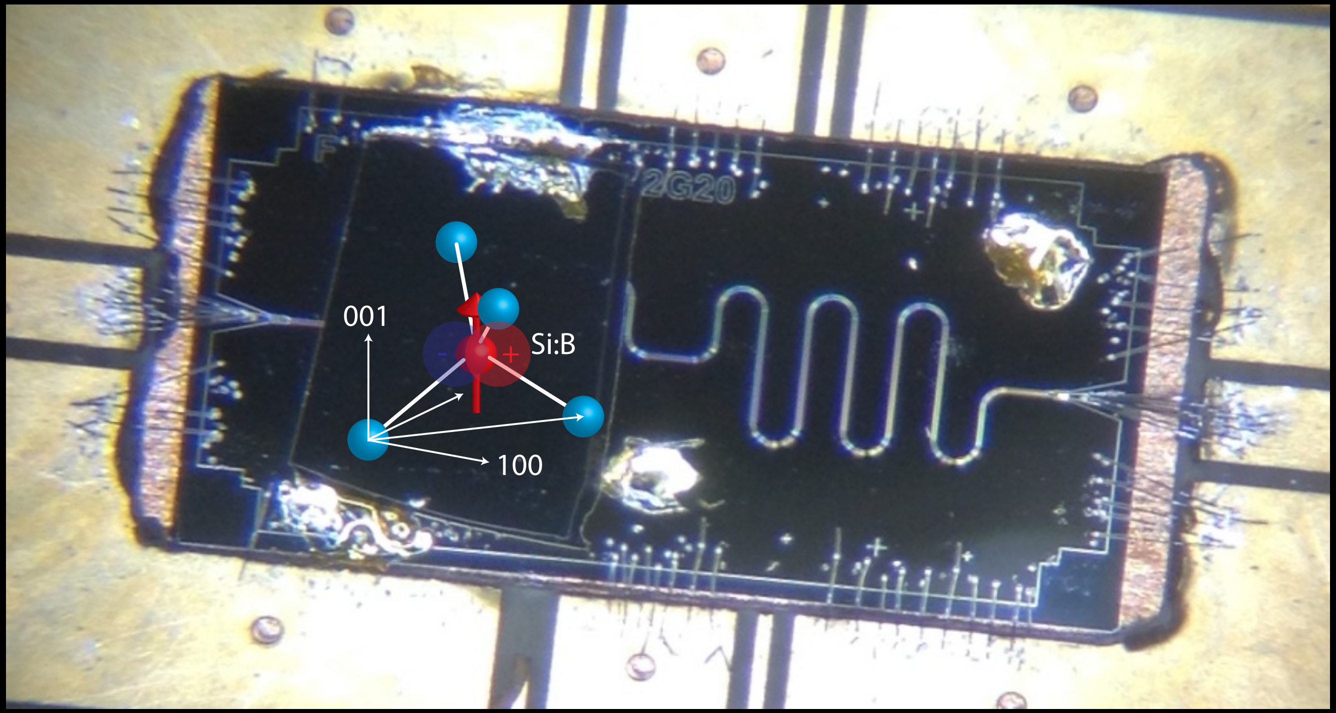
Ultra-long coherence times of spin-orbit qubits



J. Salfi
Asst. Prof.

Dept of Electrical and Computer Eng.
The University of British Columbia

Quantum Information: Quo Vadis?

November 13, 2019

Kobayashi, **Salfi**, van der Heijden, Chua, Culcer, House, Johnson, McCallum, Riemann, Abrosimov, Becker, Pohl, Simmons, Rogge, arxiv:1809.10859.

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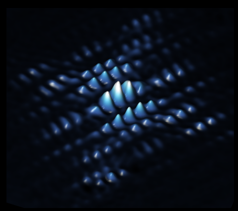


Quantum Computing

Aim: Scalable system of atom-based qubits [this talk]

- Long coherence times ✅
- High fidelity single-qubit operations ✅
- High fidelity long-distance deterministic multi-qubit operations

Frontiers: Building large systems with above properties
Hybrid quantum systems

Aim: Problem-specific success with quantum simulators [a different talk]

- Special purpose problems to address
- ..Ideally that are hard for trapped ion and superconducting qubits
- Fermions [1,2] are hard to simulate using most systems

[1] Salfi et al, Nature Comms 2016
[2] Hensgens et al, Nature 2017

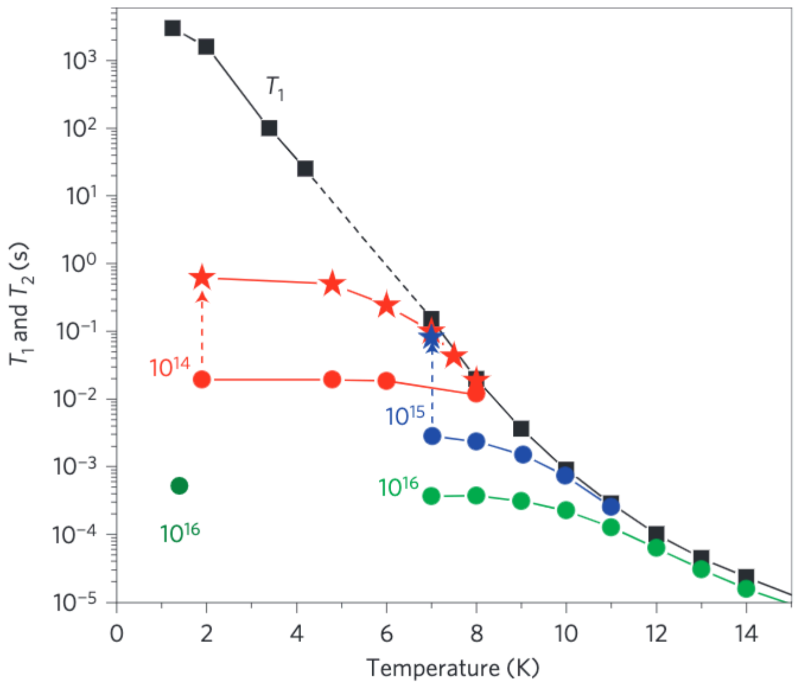
Electron Spin Qubits in Silicon

What is special about 28Si?

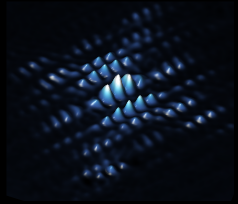
Solid-state system with among the longest coherence times available

Donor ensembles

T_2 ~ 10 ms plus



Tyryshkin et al,
Nature Mat, 2011



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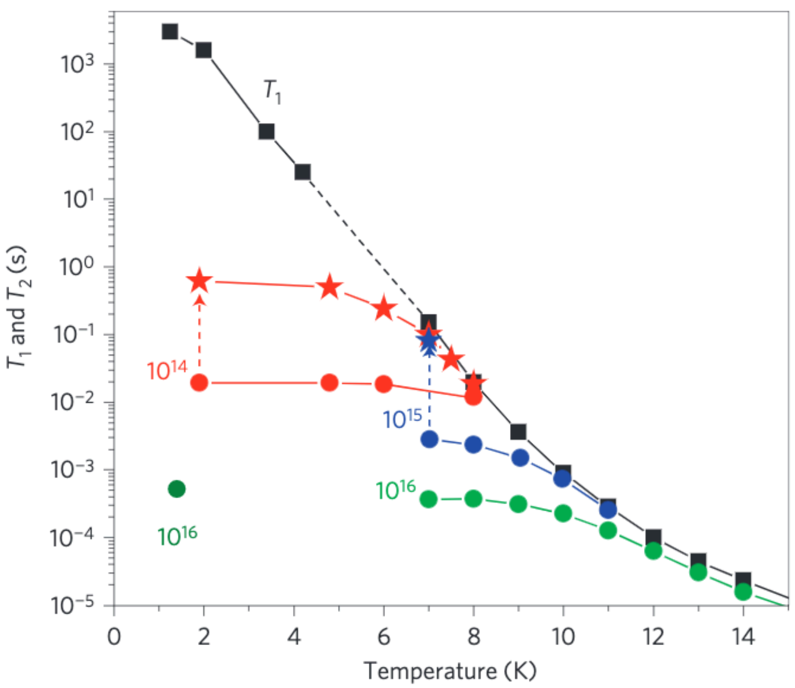
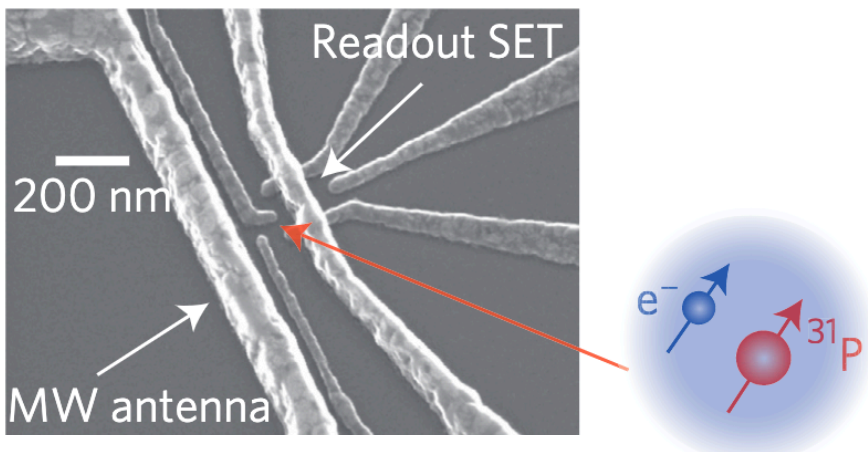


Tyryshkin et al,
Nature Mat, 2011

Single donor

T_2 ~ 100 ms



Muhonen et al,
Nature Nano, 2014

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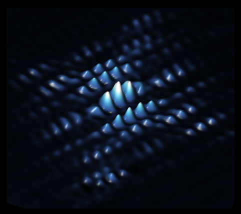

Electron Spin Qubits in Silicon

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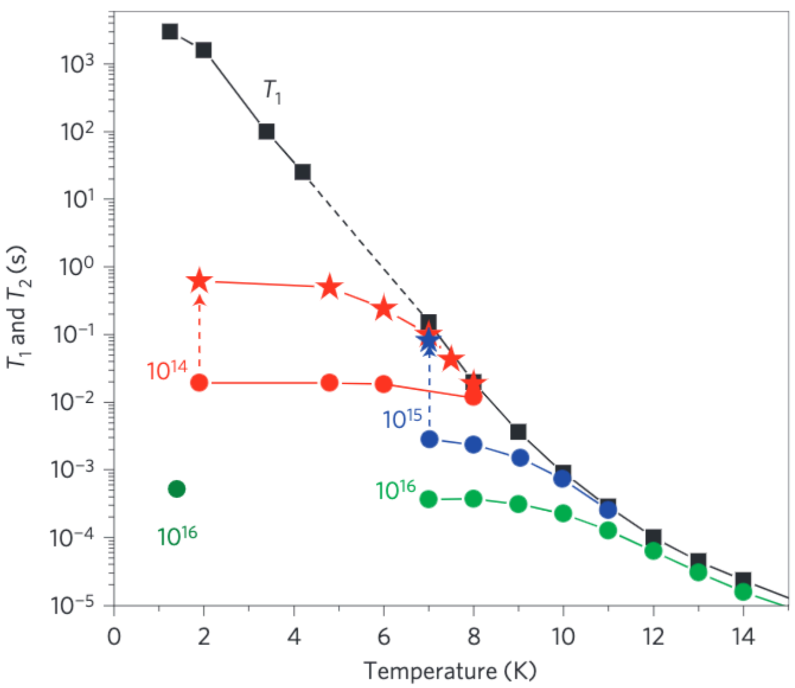

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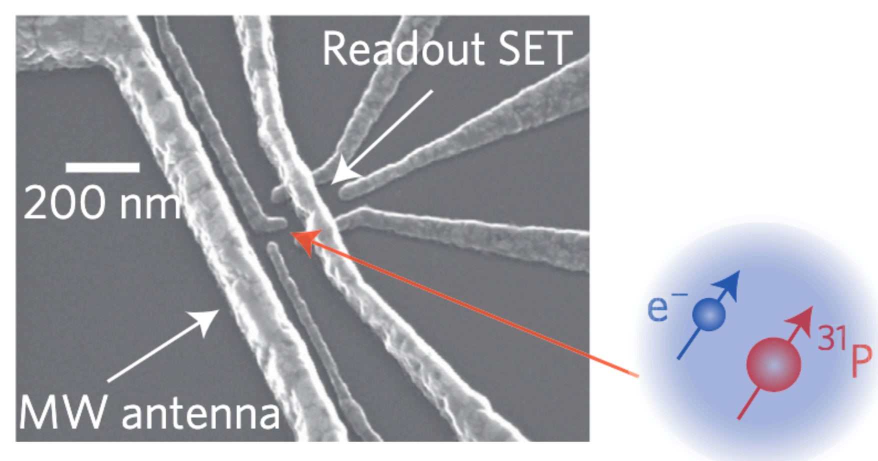
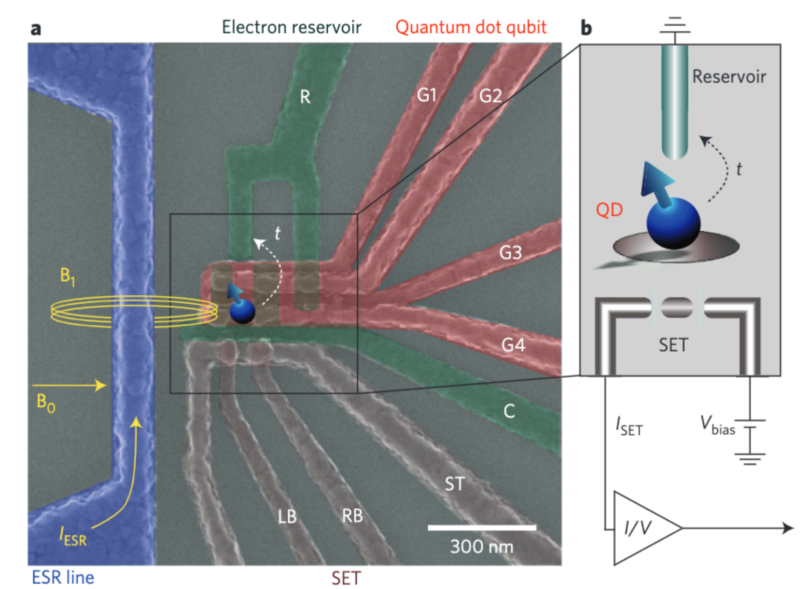


Muhonen et al,
Nature Nano, 2014

Single quantum dot

T_2 ~ 30 ms



Veldhorst et al,
Nature Nano, 2014

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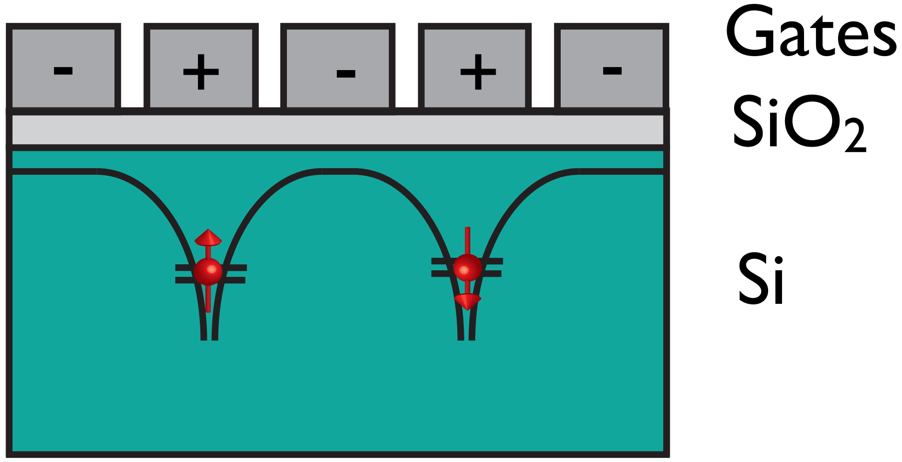
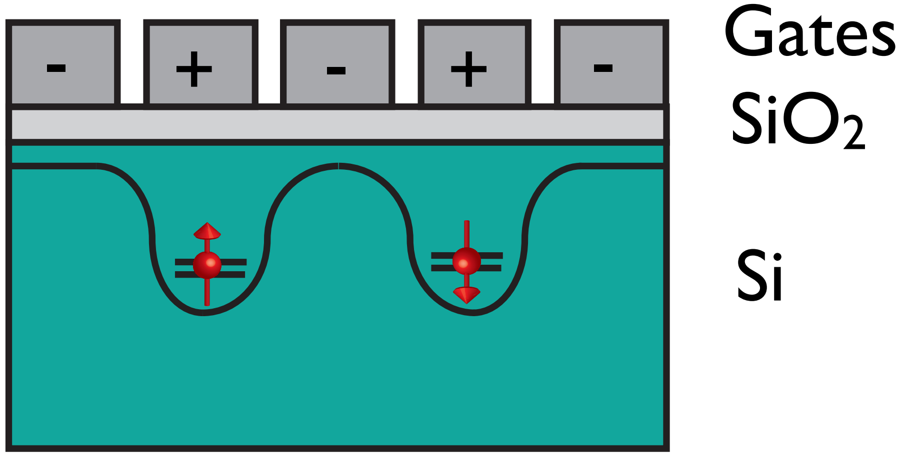
Electron Spin Qubits in Silicon

Donors $T_2 \sim 100$ ms



Muhonen et al Nature 2014

Quantum dots $T_2 \sim 30$ ms



Veldhorst et al Nature Nano 2014

Donor qubit measurement (spin to charge conversion)

Watson et al, Science Advances, 2016 $p_{\mathrm{e}} = 2 \times 10^{-3}$

High accuracy single qubit gates (magnetic resonance)

Dehollain et al NJP 2016 $p_{\mathrm{e}} = 5 \times 10^{-4}$

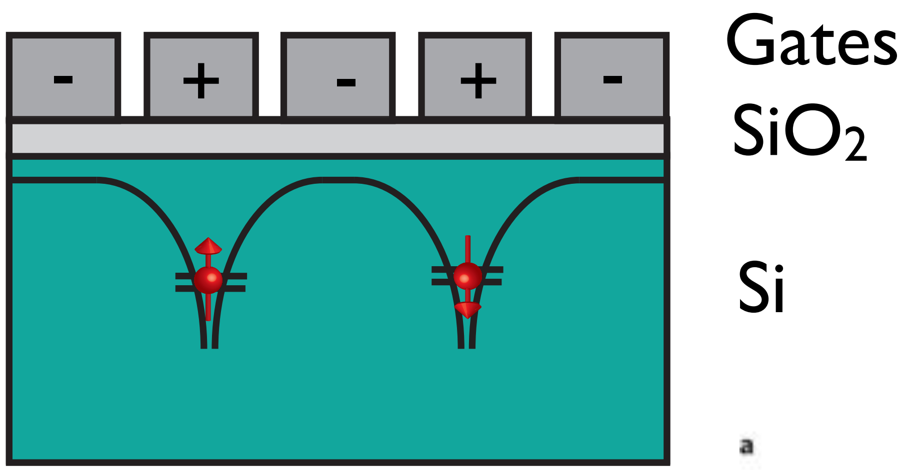
Two-qubit gates (exchange interaction)

Huang et al Nature 2019 $p_e \sim 4 \times 10^{-2}$

Challenges: short-range interactions: electric noise, circuit density

Electron Spin Qubits in Silicon

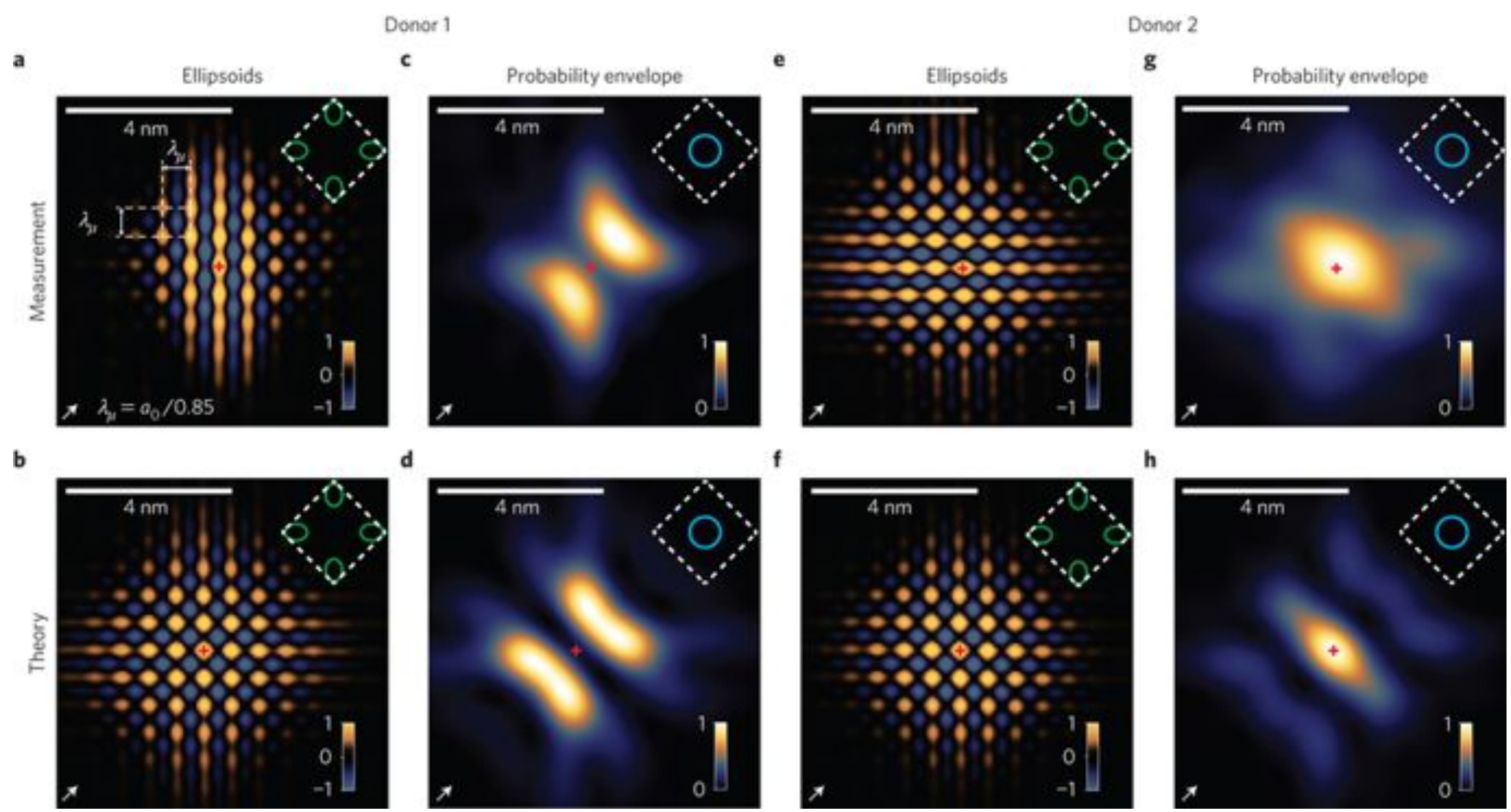
Donors $T_2 \sim 100\ \text{ms}$



Muhonen et al Nature 2014

Direct quantum state measurements

Salfi Nature Materials 2014



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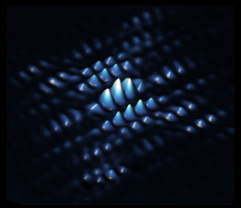


Scalability

Objective

Coherence of atomic qubits in ^{28}Si

Long-range noise-insensitive interconnects

1. Quantum electrodynamics (microwave photons)
2. Acoustic phonons
3. Capacitive interactions

How to accomplish this?

Activate the electric dipole for spin

Maintain qubit coherence

Why is this hard in Silicon?

Si electron spin has weak intrinsic coupling to electric fields

Mechanisms to engineer coupling this usually lead to decoherence

Electric Control

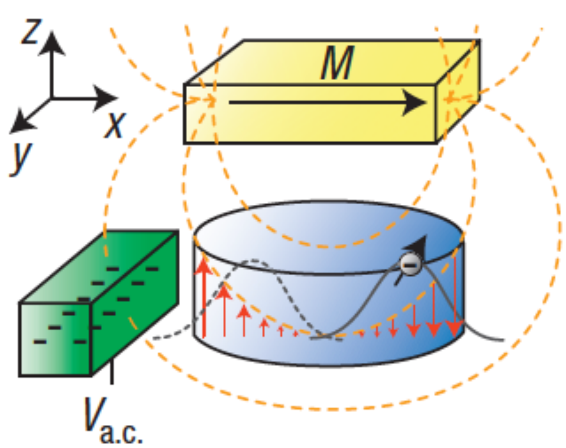
Intrinsic electric dipole: Electric field E(t) moves electron, and it experiences time-varying B(t) [special relativity]   Thomas, Nature 1926

Strong spin decoherence [1-6] $T_2 \sim 0.1 \text{ to } 1\ \mu\text{s}$

For electrons in Si, the effect is far too weak

[1] Nowack et al Science 2007
[2] Nadj-Perge et al Nature 2010
[3] Maurand Nature Comm 2016
[4] Watsinger Nature Comm 2018
[6] Hendrickx, arxiv:1904.11443

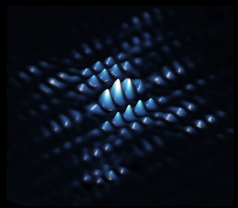
Artificial electric dipole? E(t) moves electron x(t), B(x(t)) from magnet



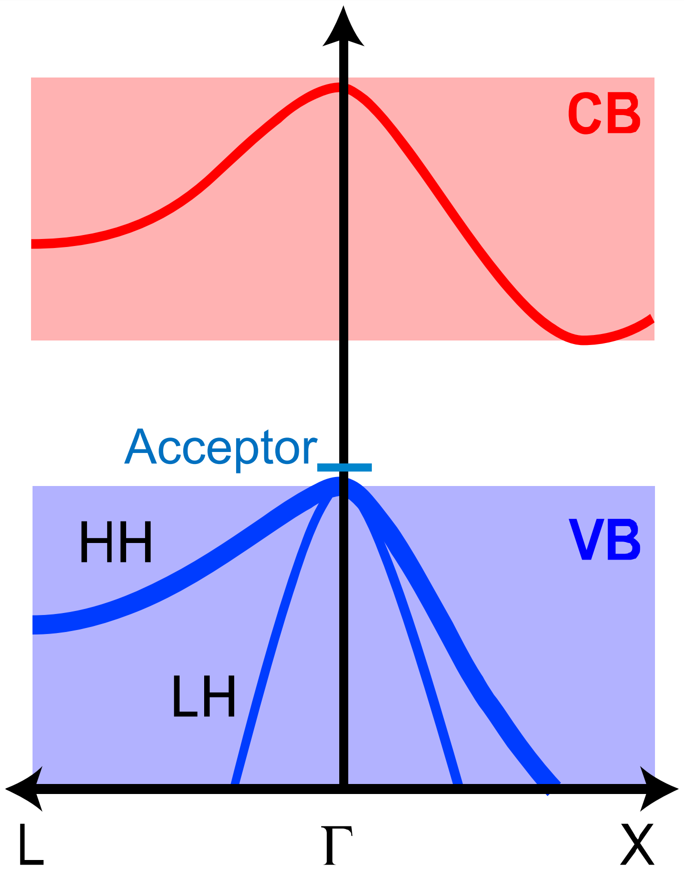
First demonstrated in GaAs [7]

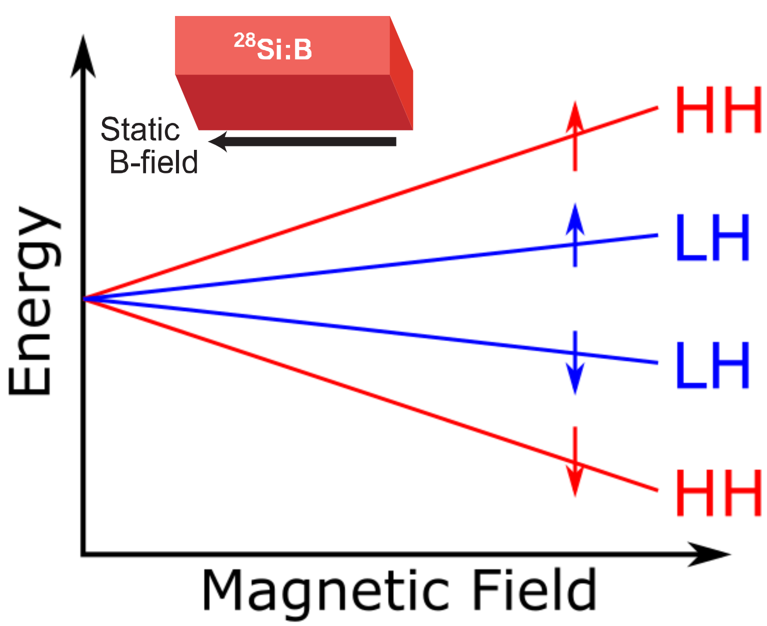
Suppressed coherence for Si [9,10] $T_2 \sim 1\ \mu\text{s}$

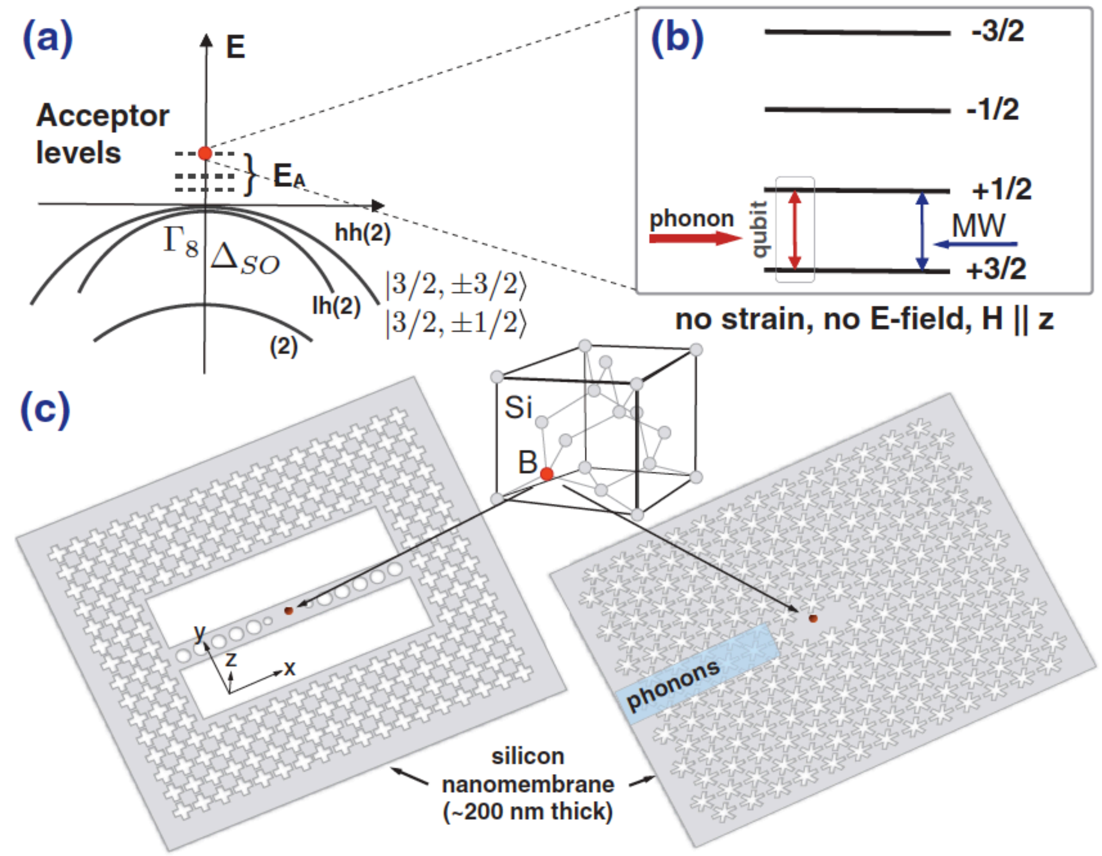
[7] Pioro-Ladrière et al Nature Physics 2008
[8] Kawakami et al Nature Nanotech 2014
[9] Mi et al Nature 2018
[10] Samkharadze et al Science 2018



Si:B acceptors







Long-ranged interactions
2Qbit gate with phonons
Long relaxation times

Ruskov PRB 2013

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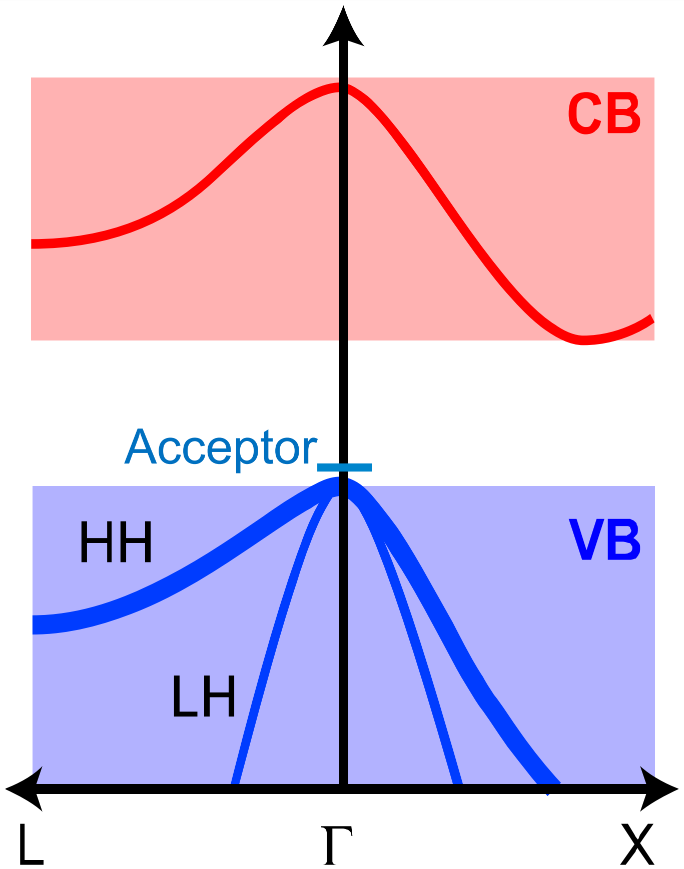
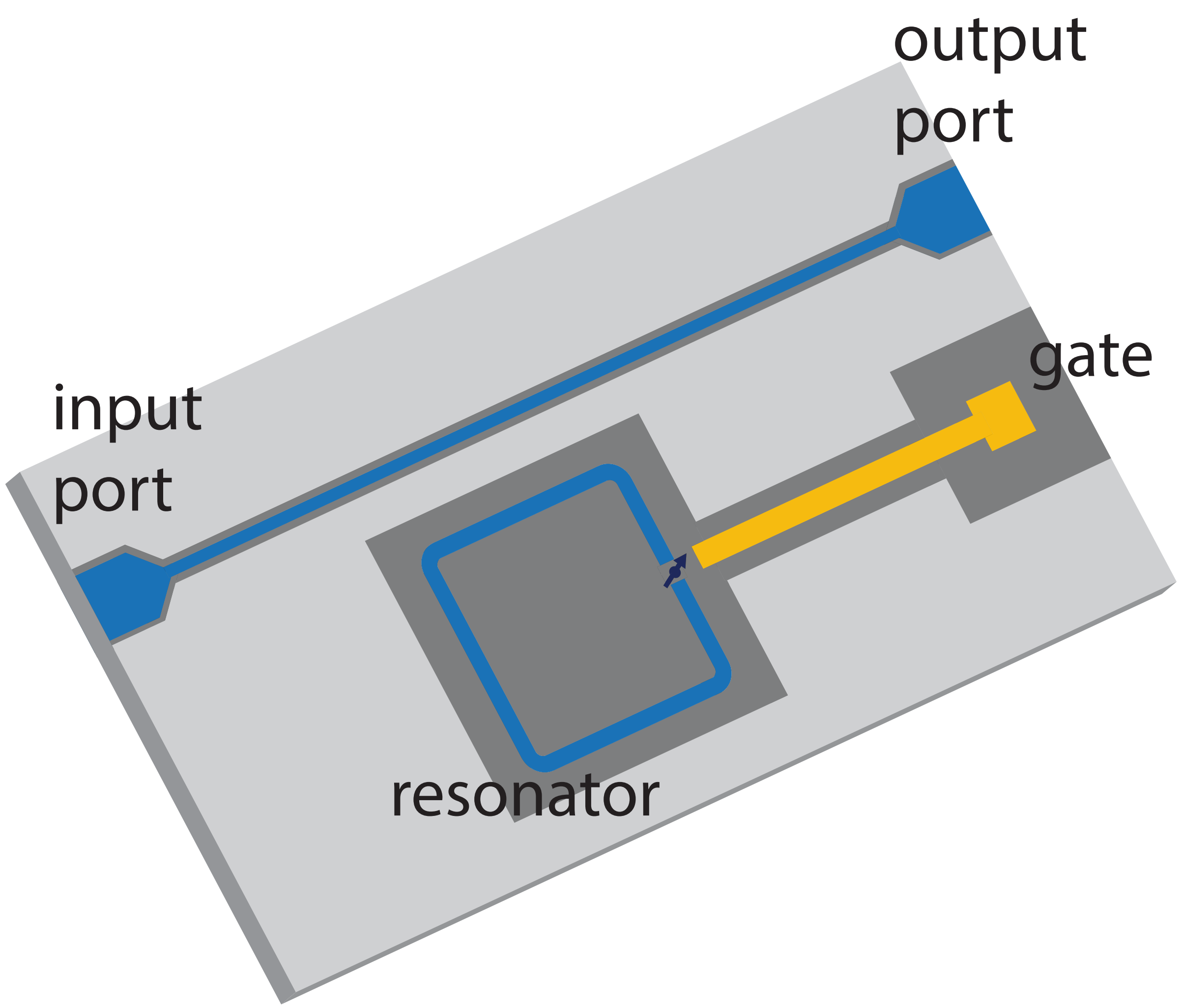
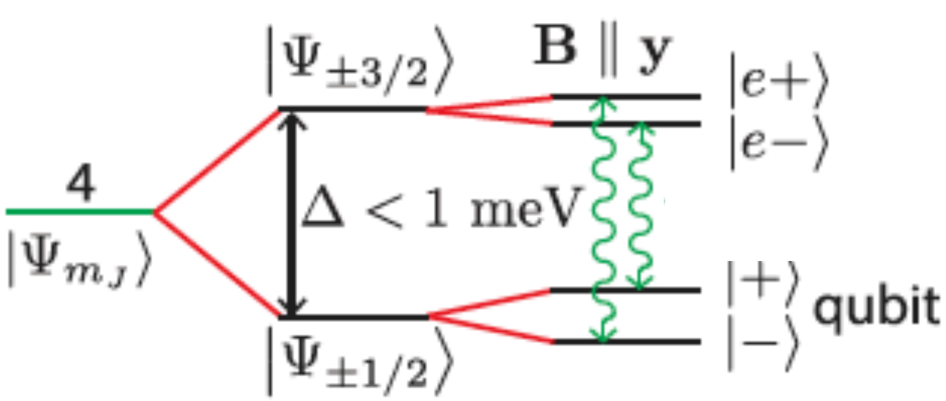
Si:B acceptors







Δ from strain

Long-ranged interactions
2Qbit gate with microwave photons
Long coherence times

Salfi, Mol, Culcer, Rogge PRL 2016
Salfi, in IOP Quantum Nanotechnology Roadmap (2019, submitted)

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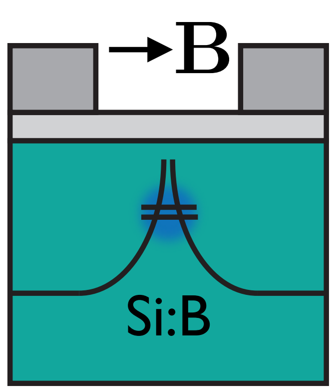
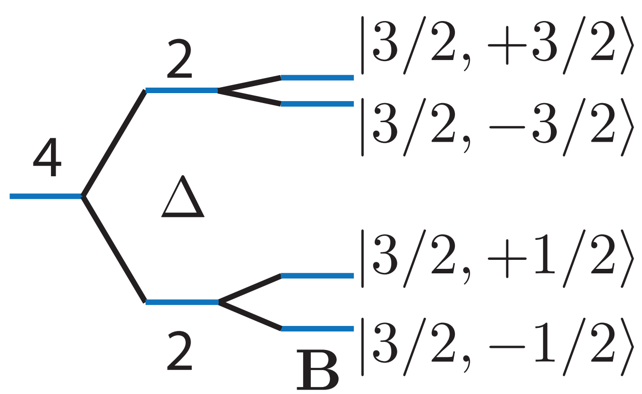
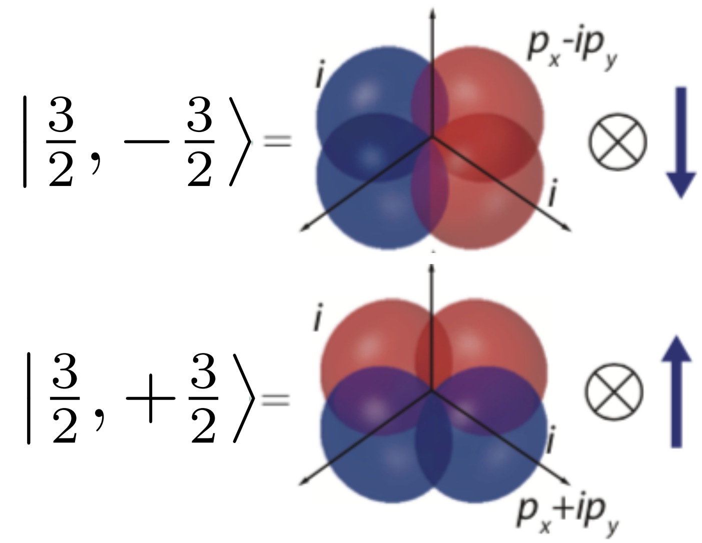
Si:B acceptors

Si valence holes, J=3/2 ~~and~~ L.S







HH

Spin-3/2 system in silicon, with electric quadrupole

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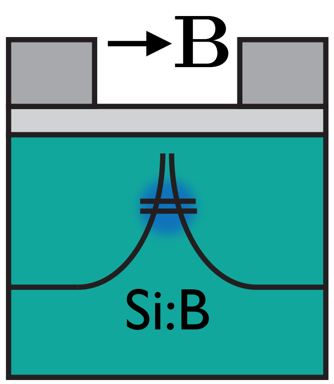
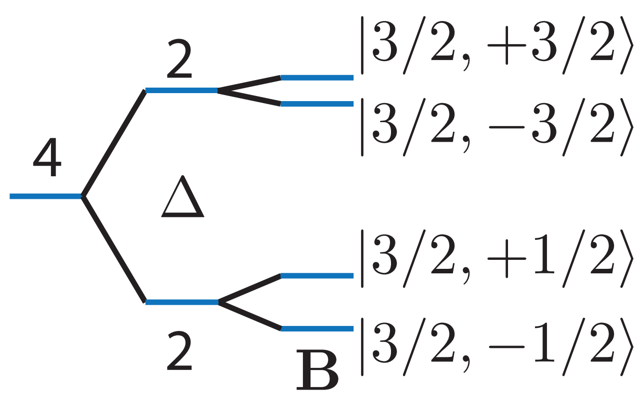
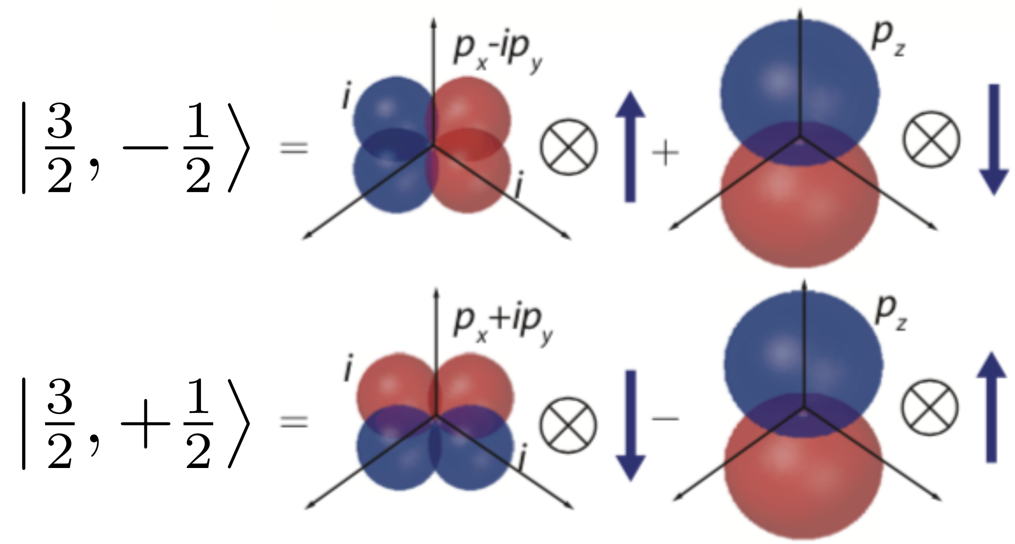
Si:B acceptors

Si valence holes, J=3/2 ~~and~~ L.S

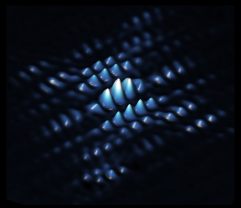




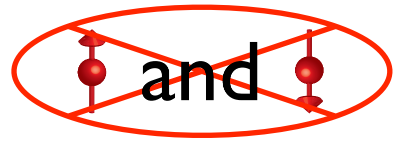


LH

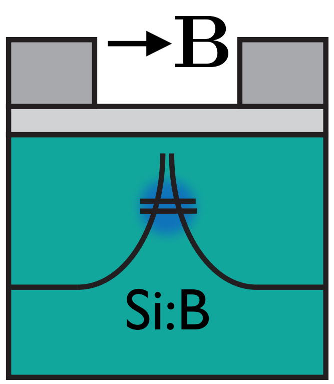
Spin-3/2 system in silicon, with electric quadrupole

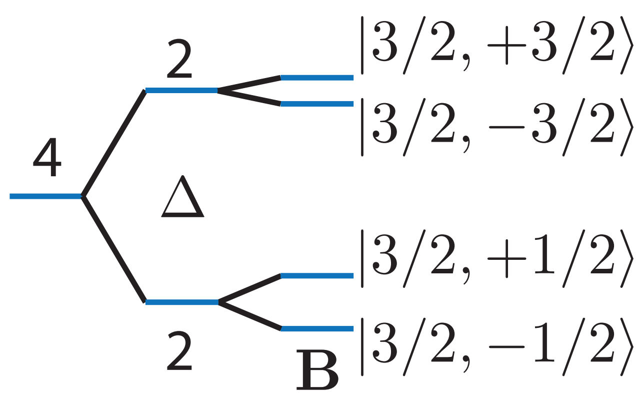


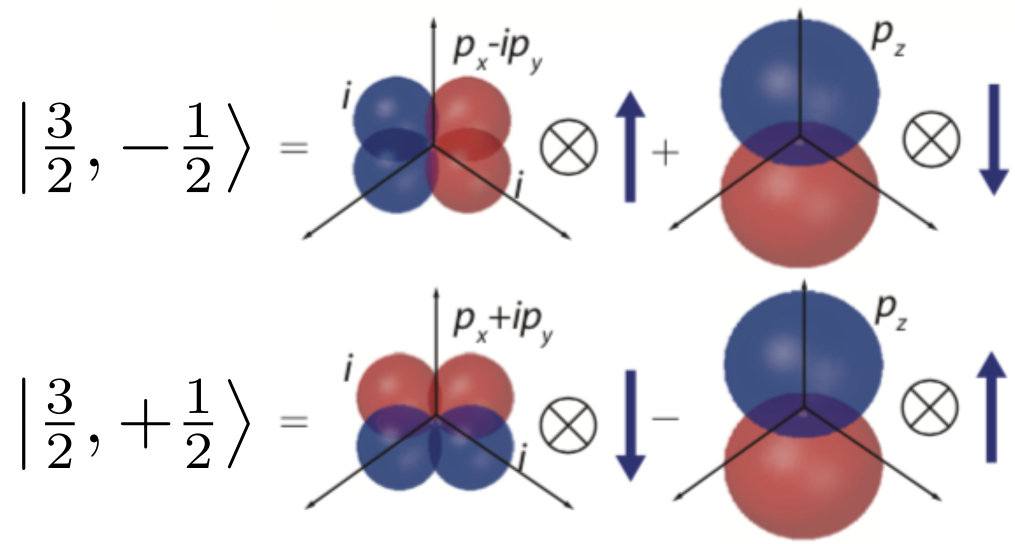
Si:B acceptors

Si valence holes, J=3/2 

L.S







LH

Spin-3/2 system in silicon, with electric quadrupole

Our findings

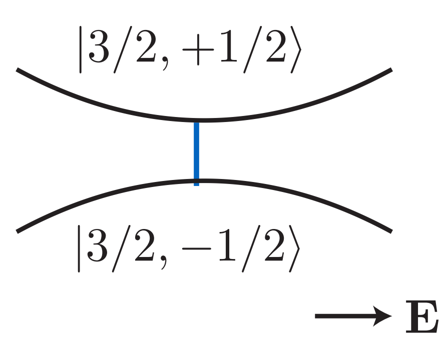
1-qubit, 2-qubit gates:

Strong electric dipole coupling

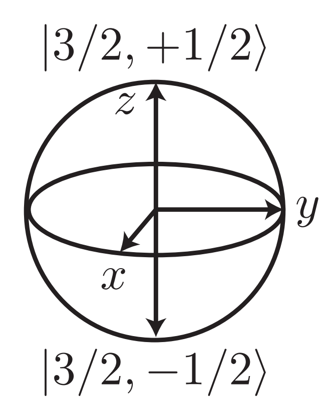
Coherence:

Robust to *E* field noise

Salfi et al PRL 2016



electric clock transition!!



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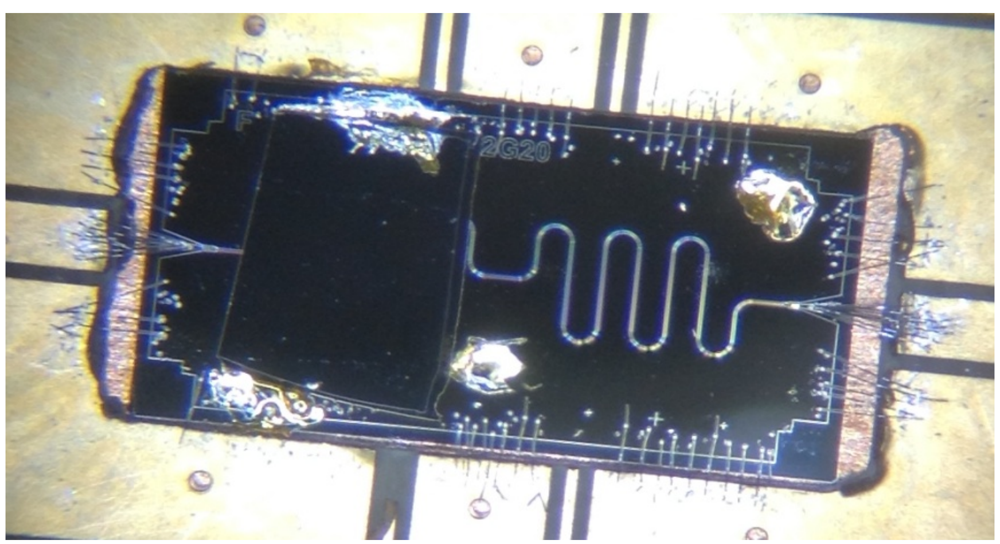
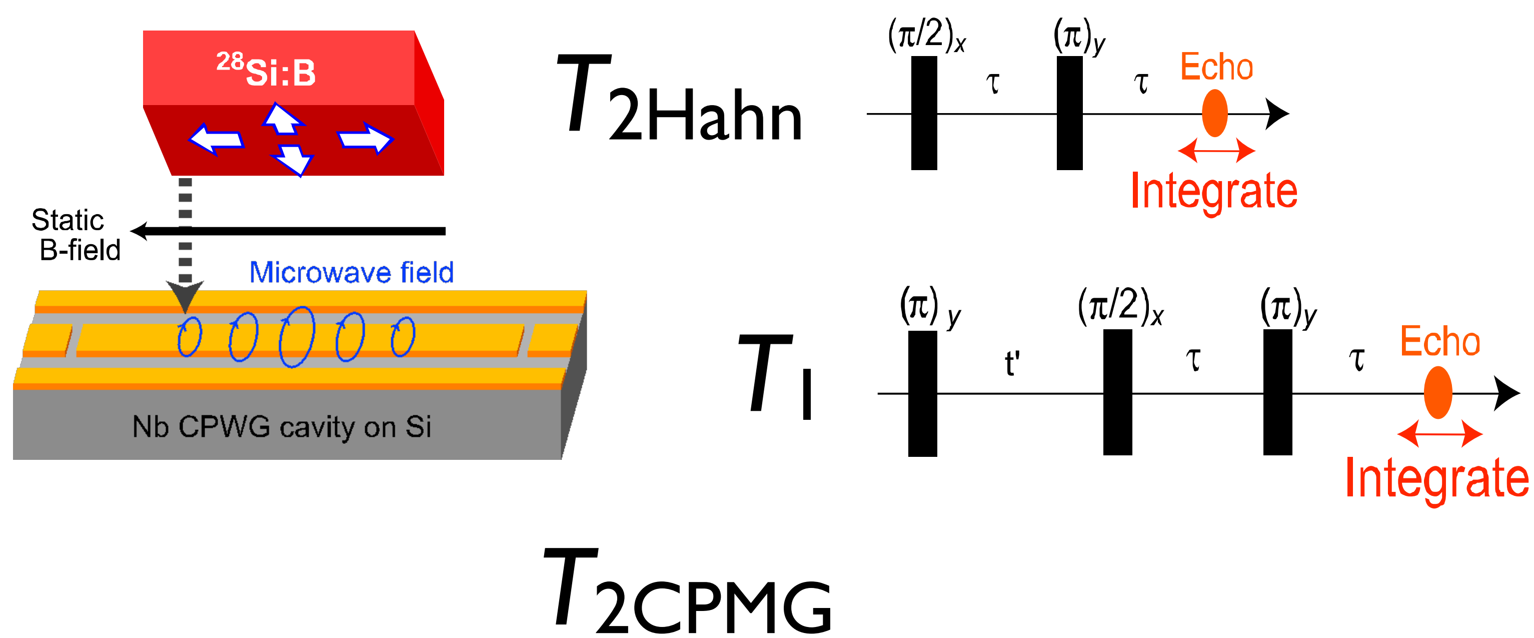
Hole spin coherence

Objective: Investigate and engineer hole spin coherence in Si:B atoms
^{28}Si, strain to engineer coherence and relaxation

Methodology: Planar superconducting resonator
Technology to couple/measure/control superconducting qubits
We use NbN rather than Aluminum (tolerates **B** field)





Kobayashi, **Salfi** et al, arxiv:1809.10859

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Hole spin coherence

Superposition preparation

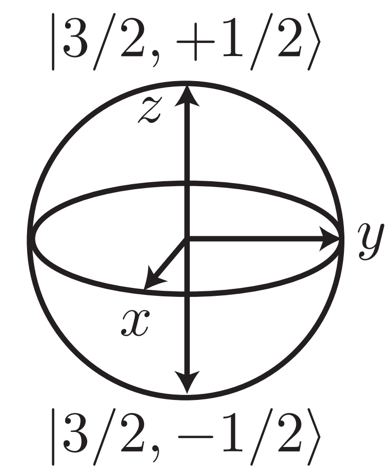
Apply X(π/2) pulse (input)

Refocusing

After time t, apply X(π) pulse

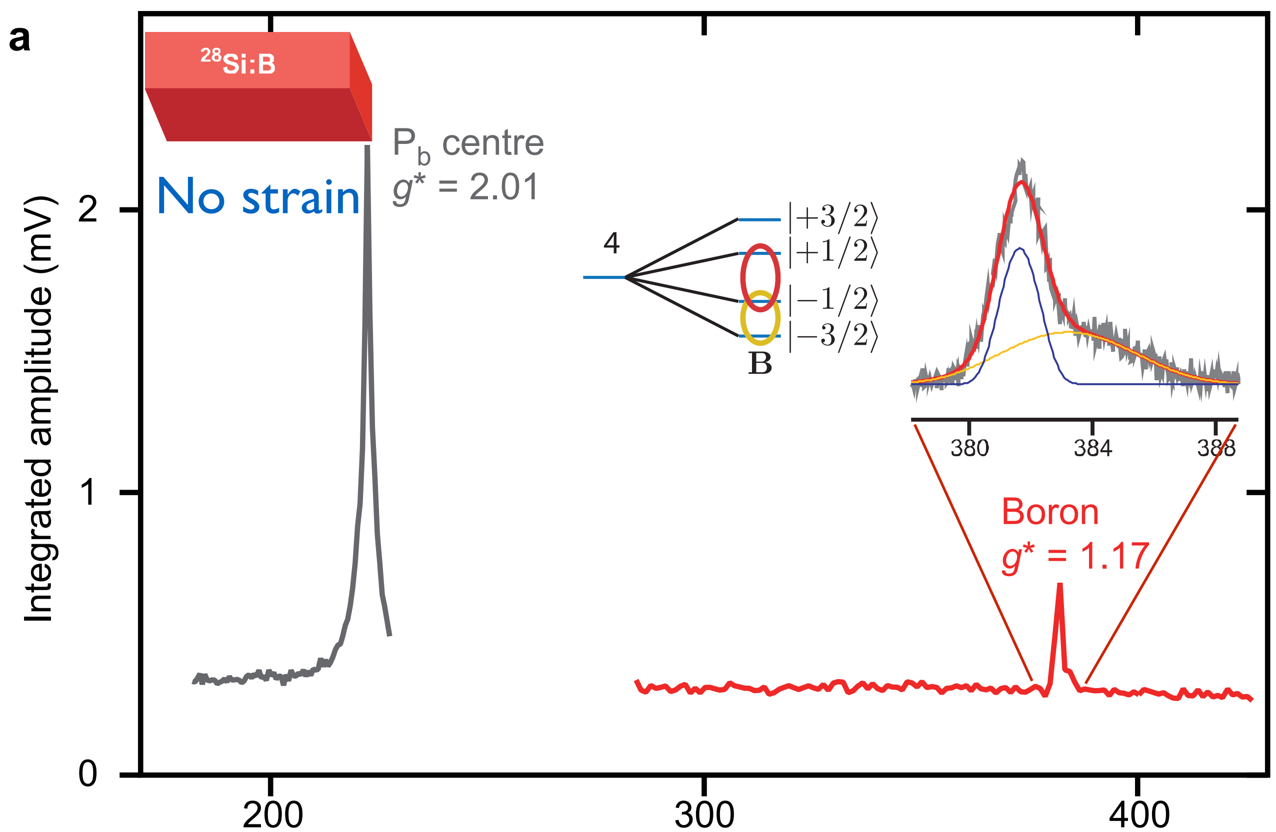
Measurement

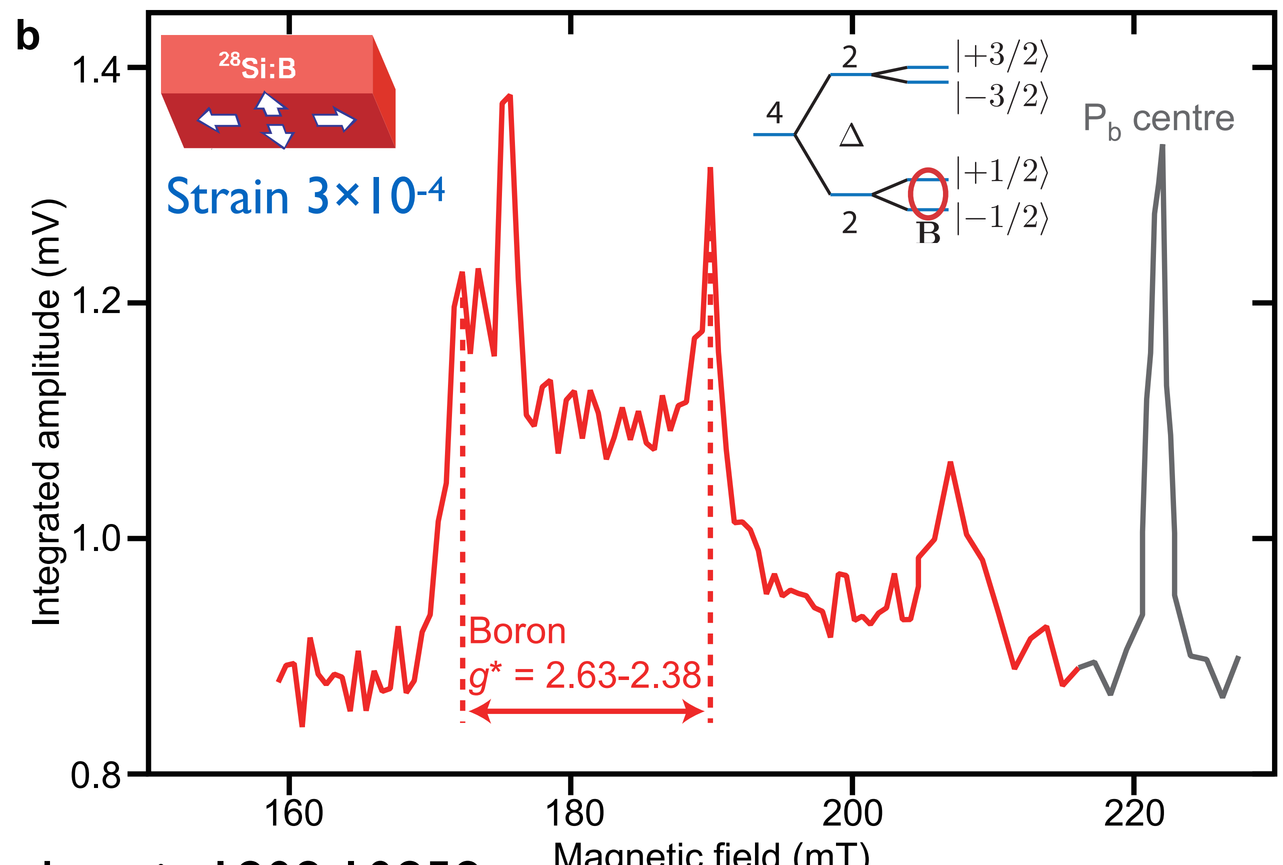
After time 2t, refocusing occurs, photons can be emitted into cavity



$$hf = g^* \mu_B B$$

$$f = 6.6 \text{ GHz}$$





Kobayashi, **Salfi** et al, arxiv:1809.10859

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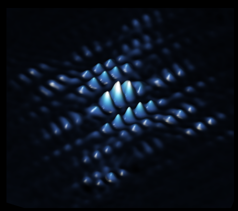
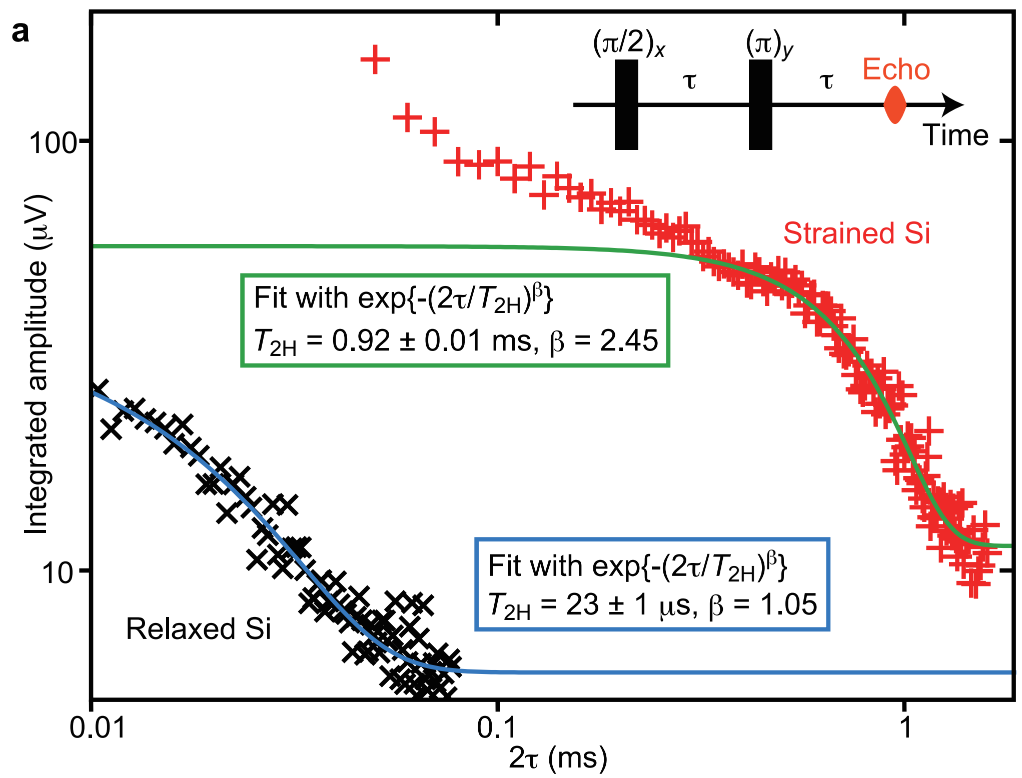


Hole spin coherence

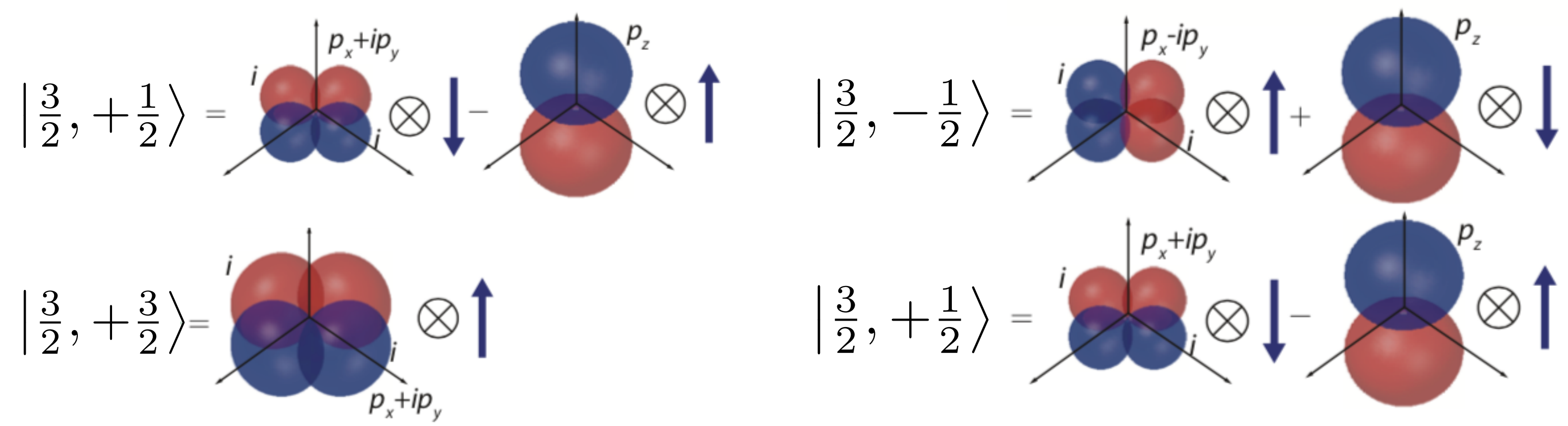


Unstrained sample:

T_2=23 μs, β=1.05

Strained sample:

T_2=0.9 ms, β=2.45



Strained sample with m_J=1/2 eigenstates and J=3/2 has longer lifetime

These states are time-reversal symmetric

Change in β from ~1 to > 2?

τ_c=correlation time of the fluctuator is changing

Kobayashi, **Salfi** et al, arxiv:1809.10859

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Hole spin coherence

Strained sample:

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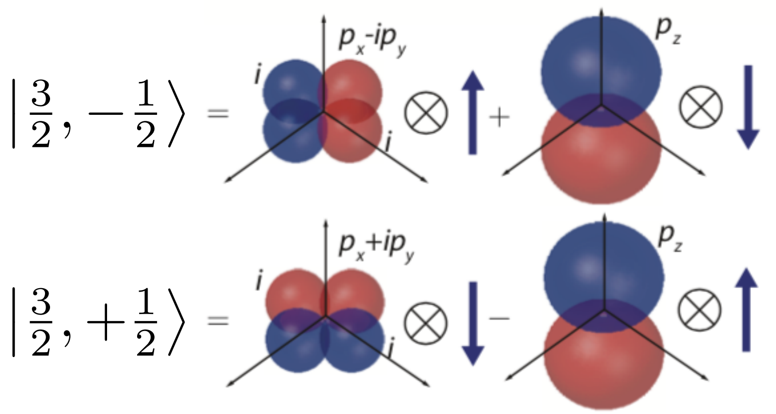
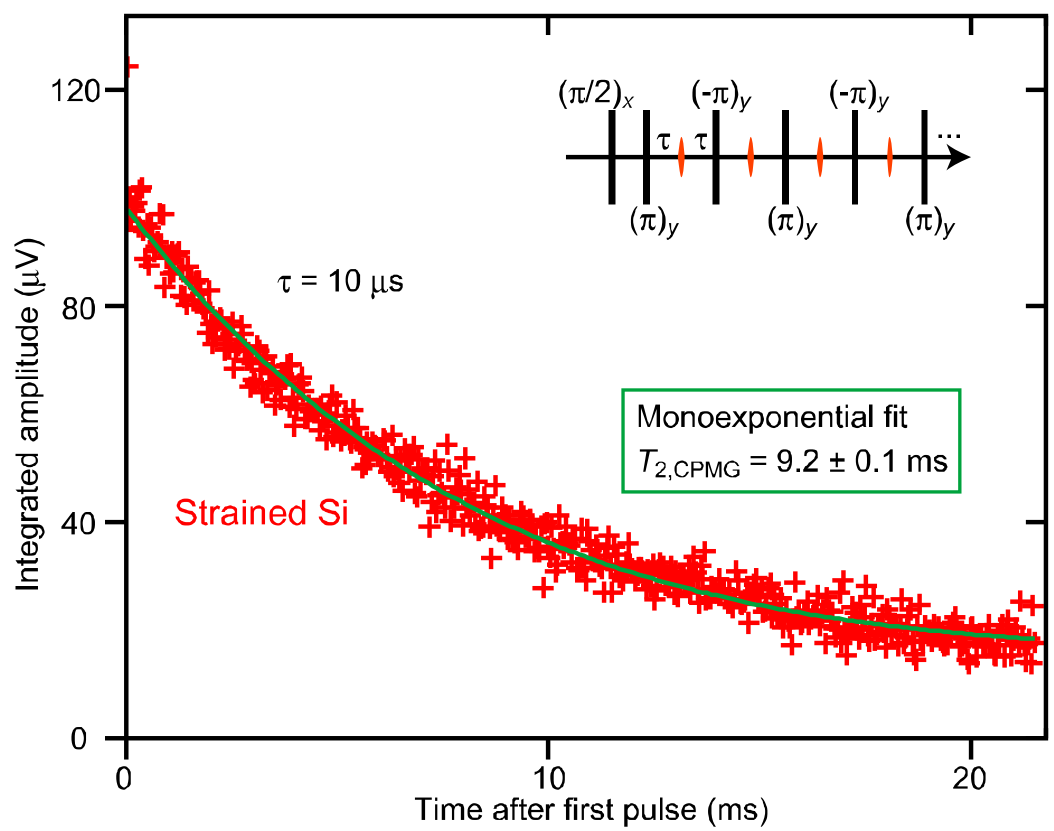


Exponent β=2.45

Spectral diffusion

Dynamical decoupling

$T_{2,\mathrm{CPMG}}$ = 9.2 ms



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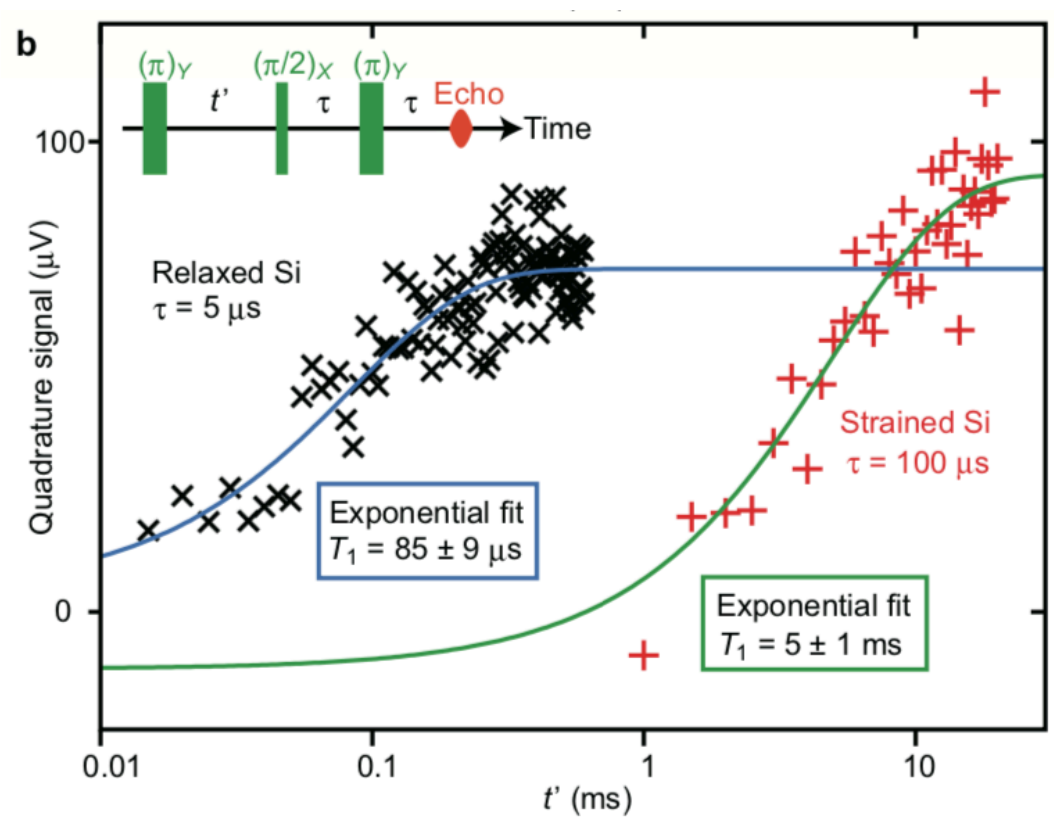
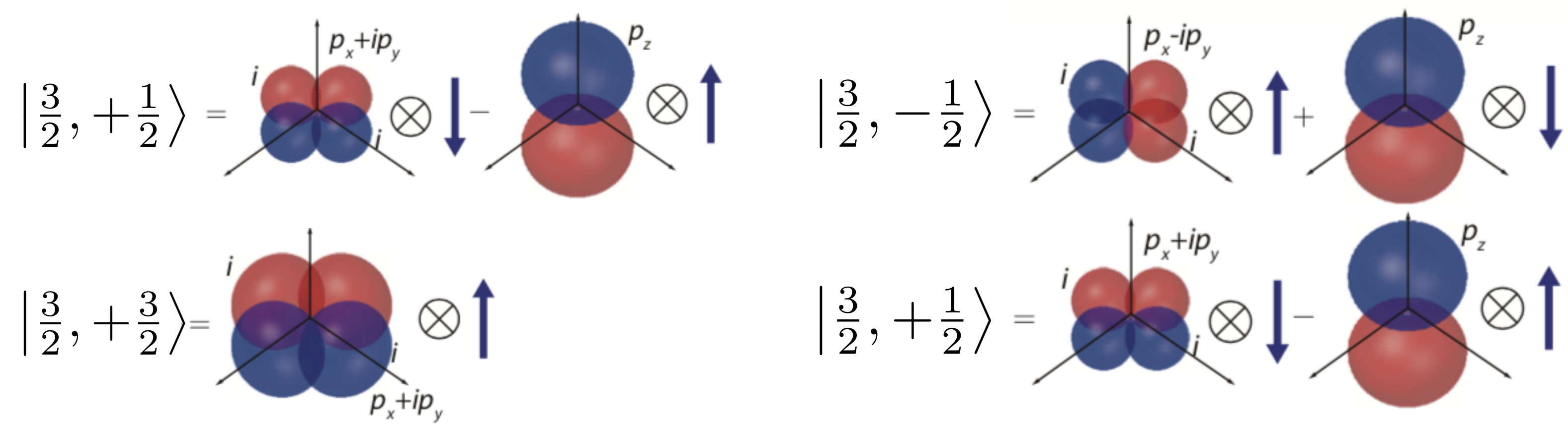
Hole spin coherence



Unstrained sample:
T_1=85 μs

Strained sample:
T_1=5 ms



Strained sample with m_J=1/2 eigenstates and J=3/2 has longer T_1

Reduced spin-phonon coupling

10 ms T_{2CPMG} is a close to T_1-limited spin coherence time

T_1 reasonably long but can be increased further

Kobayashi, **Salfi** et al, arxiv:1809.10859

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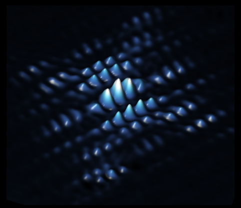

Comparison to state-of-the-art

System	T_{2H}	T_{2CPMG}
Si:P e- [1]	4 ms	-
Si:P e- [2]	0.95 ms	~100 ms
Si e- QD [3]	1.2 ms	~28 ms
Si h+ QD [4]	0.25 μs	-
Si:B h+ no strain	23 μs	-
Si:B h+ strain	0.9 ms	9 ms

this work

~100 ms T_2 of electrons
no electric dipole

[1] Tyryshkin Nature Mat 2011
[2] Muhonen Nature Nanotech 2013
[3] Veldhorst Nature Nanotech 2014
[4] Maurand Nature Comms 2016

Kobayashi, **Salfi** et al, arxiv:1809.10859

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this work

~0.25 μs T_2 of hole QD with electric dipole

[1] Tyryshkin Nature Mat 2011
[2] Muhonen Nature Nanotech 2013
[3] Veldhorst Nature Nanotech 2014
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Si:B h+ no strain	23 μs	-
Si:B h+ strain	0.9 ms	9 ms

this work

Si:B holes
~ 1 ms T_2
~ 10 ms T_{2CPMG}
with electric dipole

[1] Tyryshkin Nature Mat 2011
[2] Muhonen Nature Nanotech 2013
[3] Veldhorst Nature Nanotech 2014
[4] Maurand Nature Comms 2016

Intrinsic electric dipoles are compatible with long coherence times

10^4 to 10^5 times improvement over previous spin-orbit systems

Kobayashi, **Salfi** et al, arxiv:1809.10859

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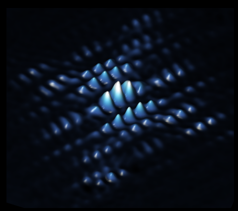
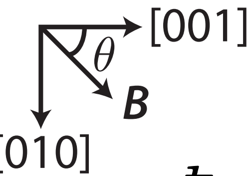
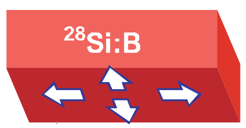


Hole spin coherence

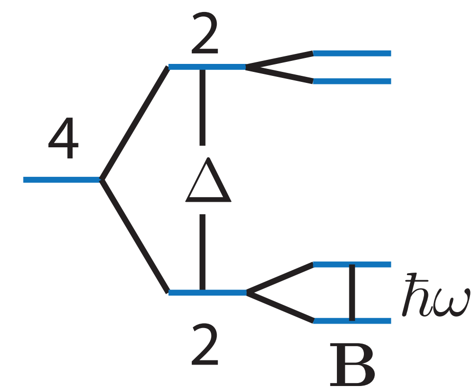
How does the strain improve coherence? $\mathcal{H} = \left(\hbar\omega + \frac{d\hbar\omega}{\delta E_z}\delta E_z \right)\sigma_z + \nu E_x \sigma_x$

Decoherence is suppressed by the gap

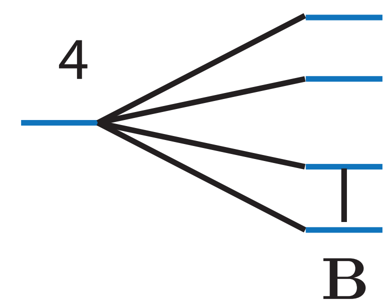




$$\frac{\delta\hbar\omega}{\delta E_z} = \boxed{\frac{\hbar\omega}{2\Delta}} \sin(2\theta)\sqrt{3}p \qquad \text{for small } \frac{\hbar\omega}{\Delta}$$



c.f. $$\frac{\hbar\delta\omega}{\delta E_z} = \sin(2\theta)\sqrt{3}p \qquad \text{for big } \frac{\hbar\omega}{\Delta}$$



Experiment: Reduced longitudinal coupling enhances T_2

[1] Decoherence from electric fluctuations

[2] Decoherence from electric dipole-dipole interaction

Conveniently, T_1 is a good measure of the strain-induced gap $\frac{\hbar\omega}{\Delta} \sim \frac{1}{5}$

Kobayashi, **Salfi** et al, arxiv:1809.10859

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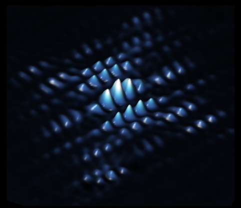
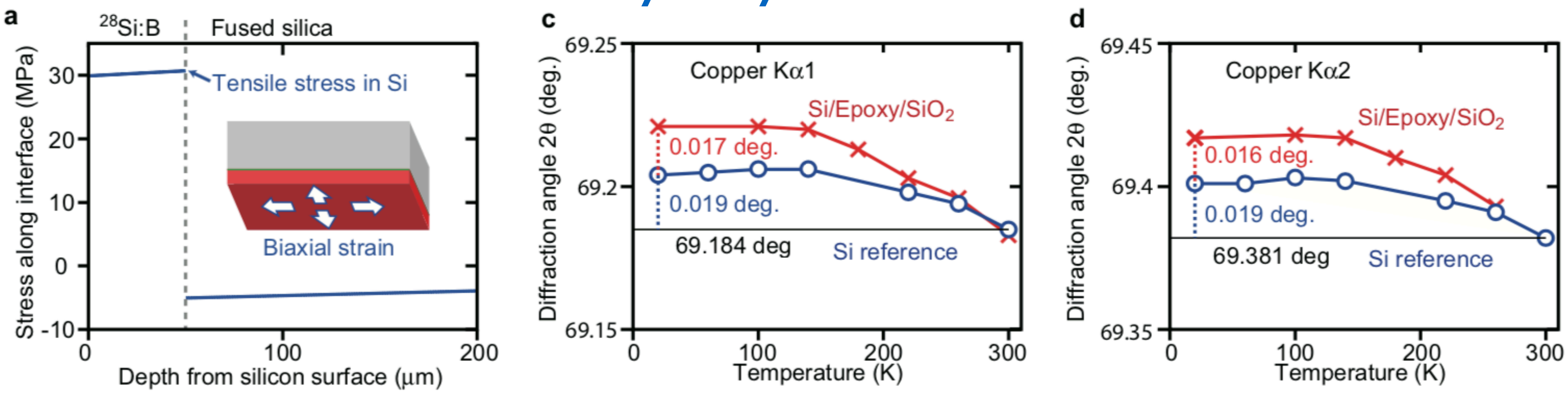
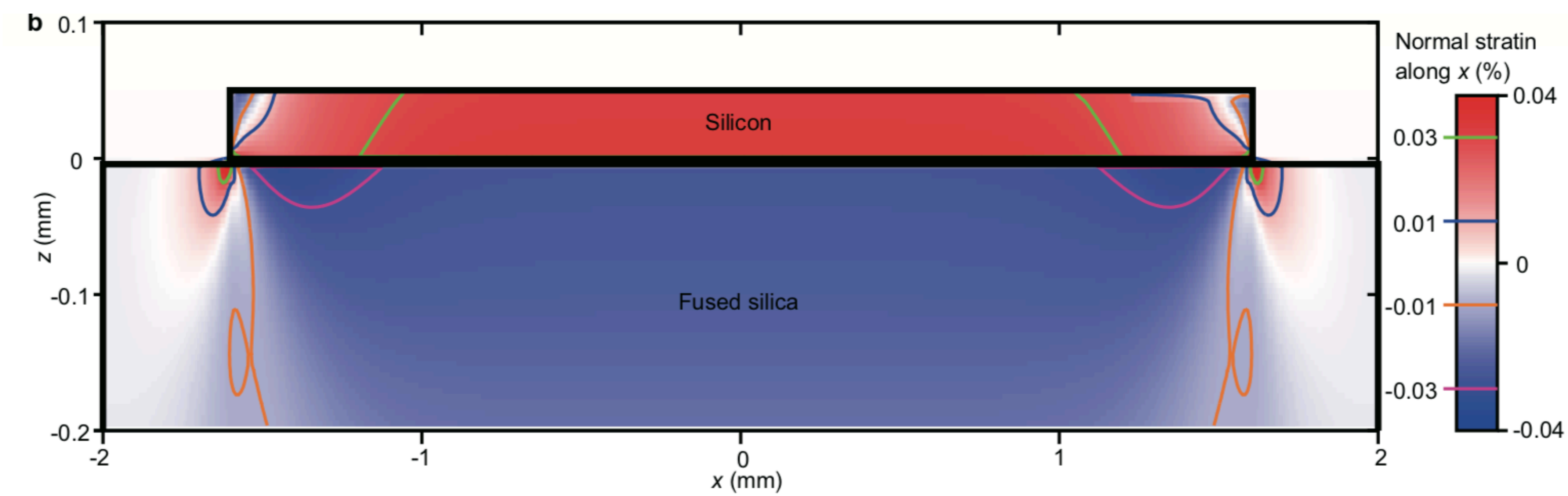


Hole spin coherence

Direct strain measurement by Cryo-XRD



Strain inhomogeneity simulation



Kobayashi, **Salfi** et al, arxiv:1809.10859

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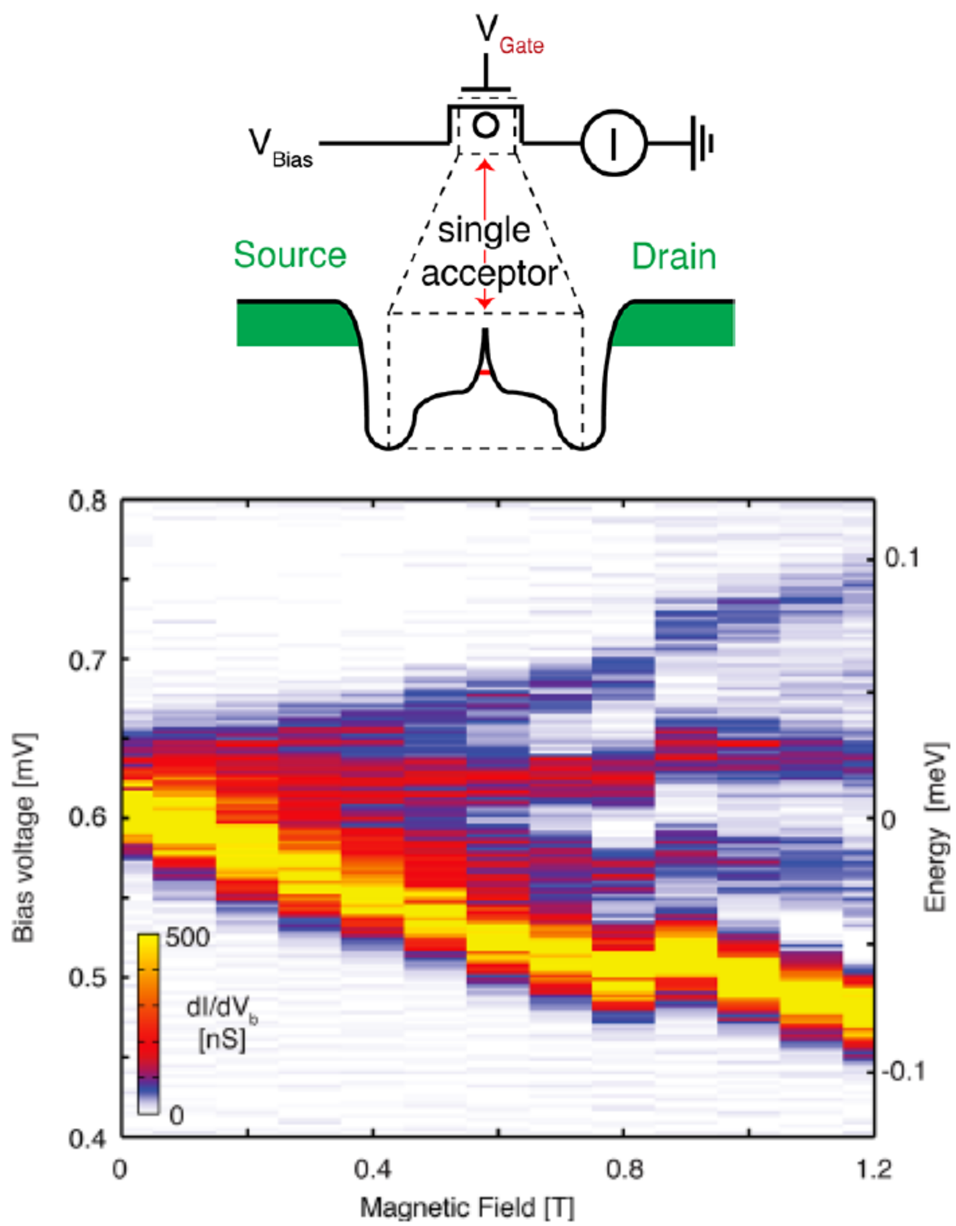
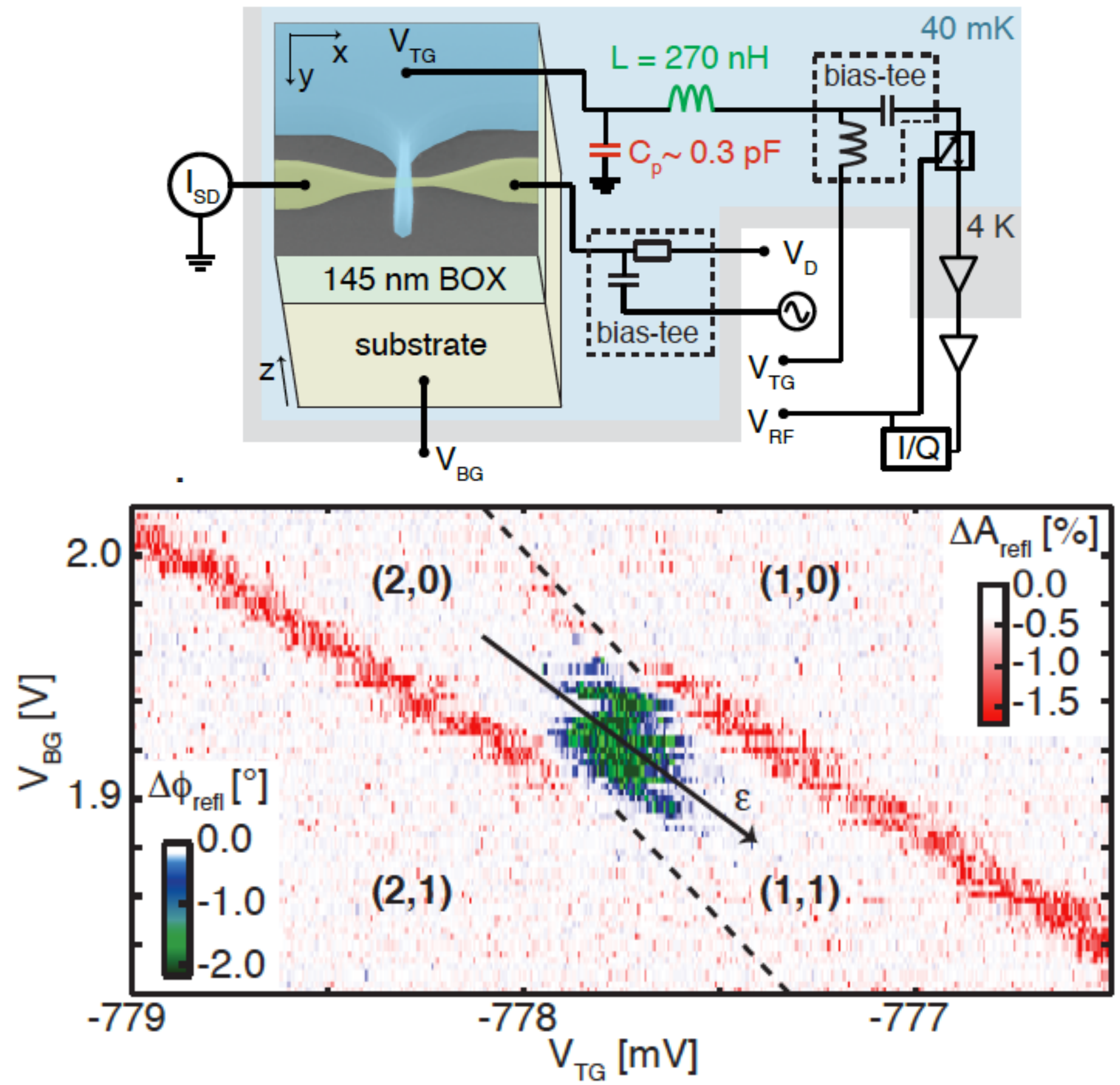
Si:B devices : single and coupled atoms

Single-atom transistor



van der Heijden et al, Nano Letters 2014

Gate-based spin readout



van der Heijden et al, Science Advances 2018

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Summary

Summary of experiment: Holes in 28Si

A J=3/2 system nearly as coherent as a S=1/2 (28Si) or S=1 (Diamond)

Nontrivial: L.S coupling

10^4 to 10^5 coherence improvement over other spin-orbit systems

Strain increases T_1 by reducing spin-lattice coupling

Strain increases T_2 by reducing sensitivity to electric noise

Opportunities: long-range coupling, electric control + coherence

New experiments

CQED : deterministic gates, cavity optimized for atom qubits

Aim: 5 MHz spin-photon coupling, <1 kHz linewidth, sweet spot

Kobayashi, **Salfi** et al, arxiv:1809.10859
van der Heijden et al, Science Advances, 2018
Salfi et al, PRL 2016

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Thank you!

@UNSW
Takashi Kobayashi
Cassandra Chua
Sven Rogge

Materials
H Riemann
N Abrosimov
P Becker
HJ Pohl

New Lab @ UBC (QMI)

Theory
Dimi Culcer (UNSW)
Bill Coish (hyperfine) (McGill)

B Johnson (Melbourne)
J McCallum (Melbourne)

Kobayashi, **Salfi** et al, arxiv:1809.10859
van der Heijden et al, Science Advances, 2018
Salfi et al, PRL 2016

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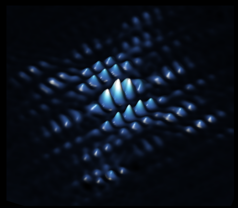

Thank you!

@UNSW

Takashi Kobayashi
Cassandra Chua
Sven Rogge

Materials

H Riemann
N Abrosimov
P Becker
HJ Pohl

Postdoctoral openings

1. Hybrid spin-3/2 devices”
2. “Quantum simulators”

Theory

Dimi Culcer (UNSW)
Bill Coish (hyperfine) (McGill)

B Johnson (Melbourne)
J McCallum (Melbourne)

Kobayashi, **Salfi** et al, arxiv:1809.10859
van der Heijden et al, Science Advances, 2018
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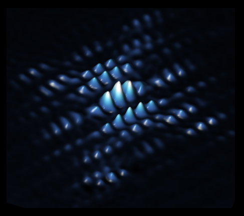
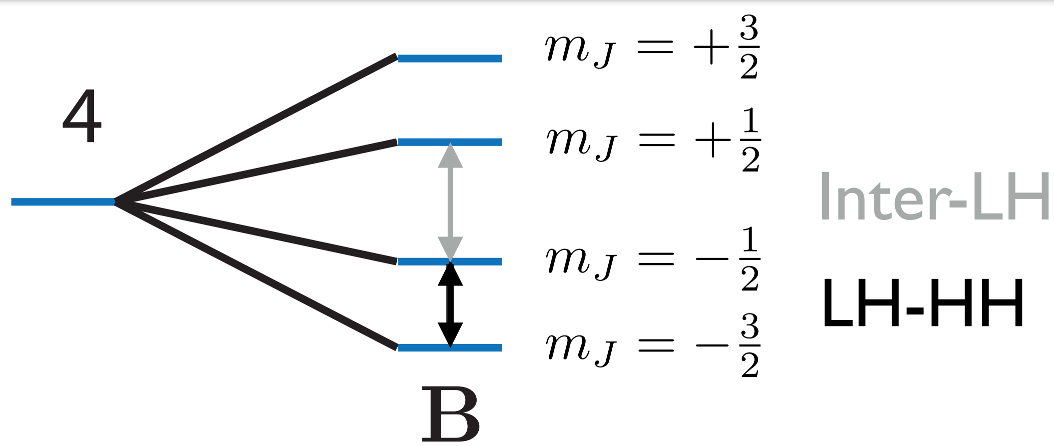


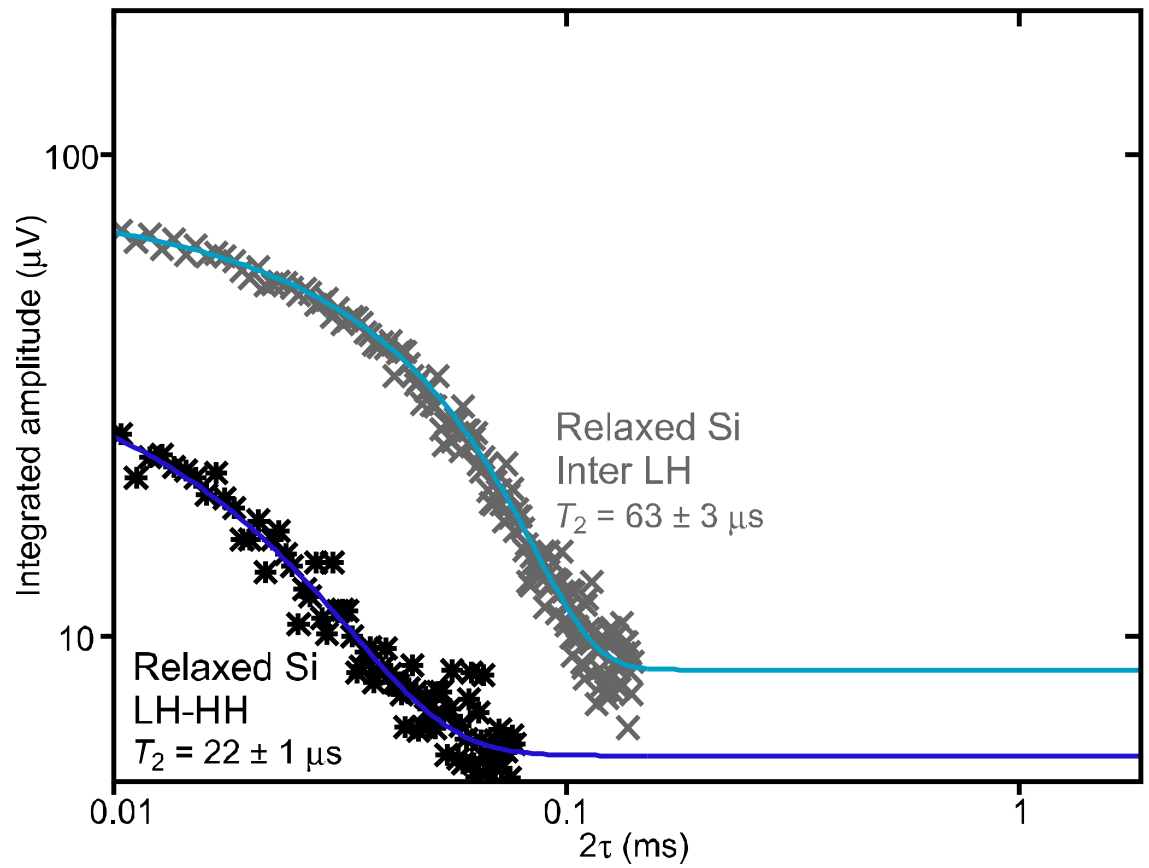
Engineering hole spin coherence

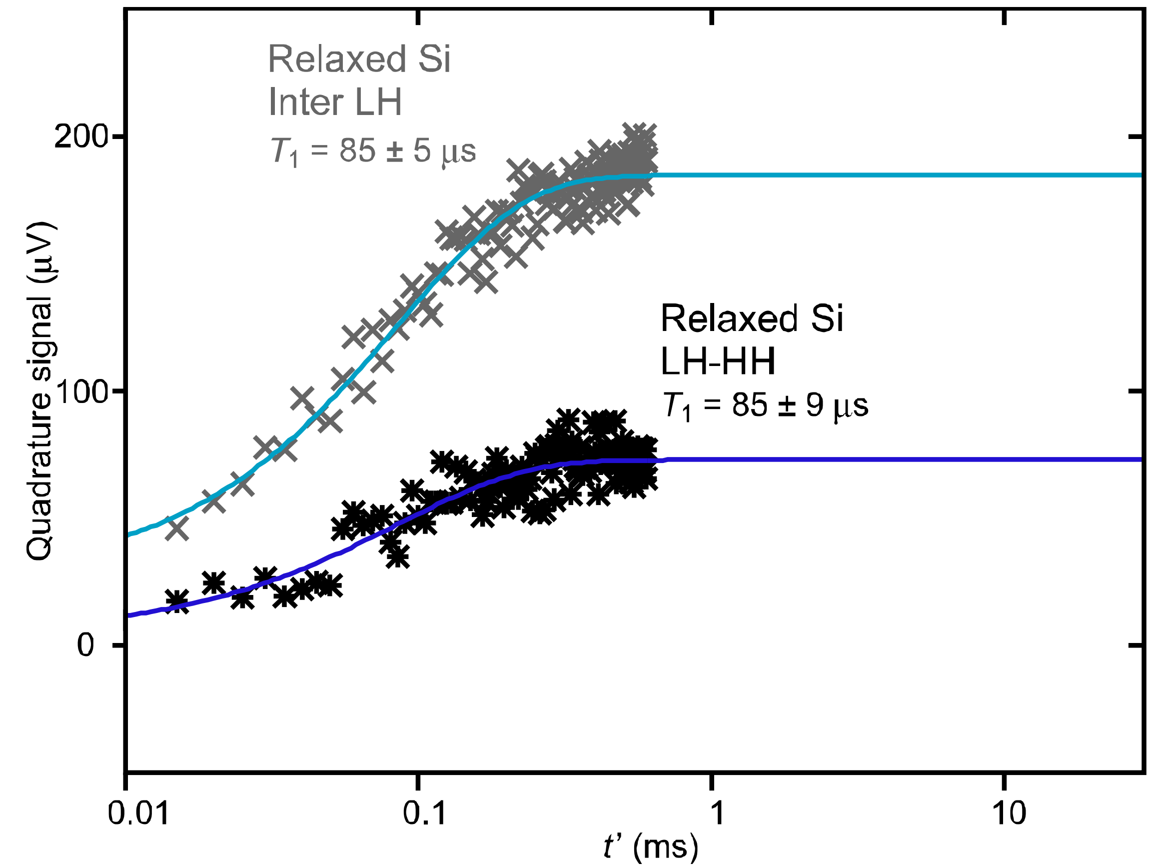
The four-fold degenerate J=3/2 system

Inter-LH: $m_J = \pm 1/2$

LH-HH: m_J=-3/2 to -1/2







Comparison: same T_1, better T_2 for time-reversed system

Kobayashi, **Salfi** et al, arxiv:1809.10859

Australian Government
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