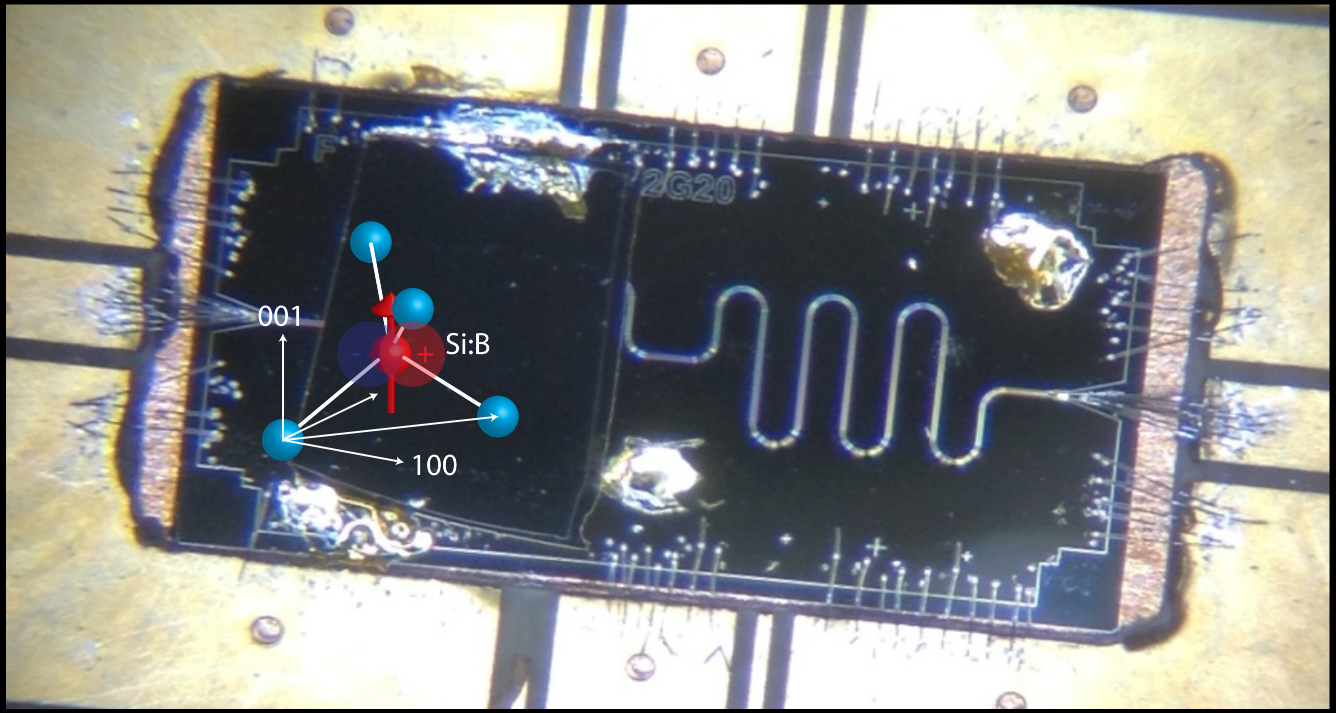
Engineering long coherence times of spin-orbit qubits in 28Si



Asst. Prof. J. Salfi

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The University of British Columbia

RIKEN/Vancouver Joint Workshop

August 24, 2021

Kobayashi, **Salfi**, van der Heijden, Chua, Culcer, House, Johnson, McCallum, Riemann, Abrosimov, Becker, Pohl, Simmons, Rogge, Nature Materials, 20, 38-42 (2021)

Wang, Marcellina, Hamilton, Cullen, Rogge, **Salfi**, Culcer, Nature Partner Journals: Quantum Information, 7, 1-8 (2021)

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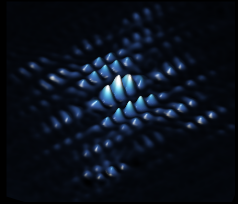


Electron Spin Qubits in Silicon

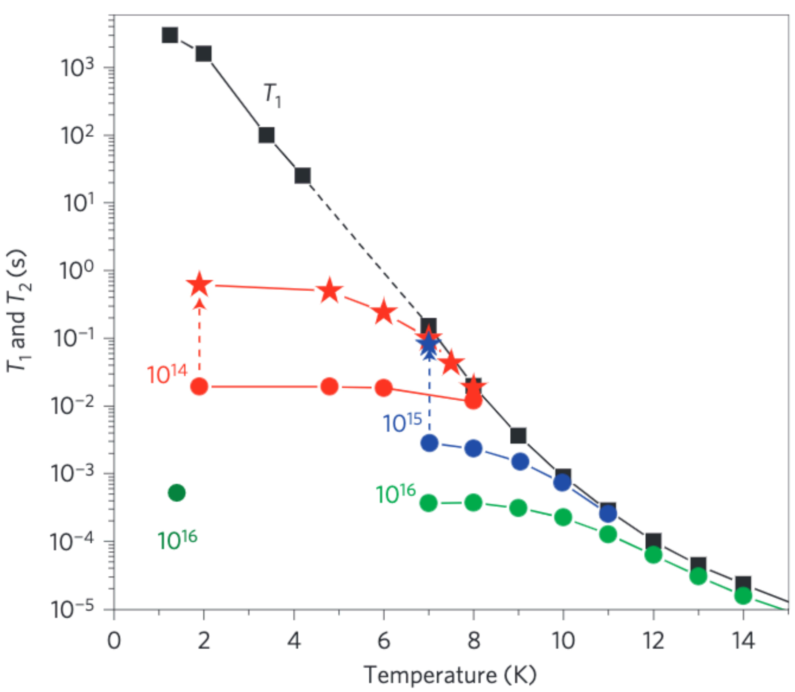
What is special about 28Si?

Solid-state host with very long coherence times

"Atoms in a semiconductor vacuum"

Donor ensembles

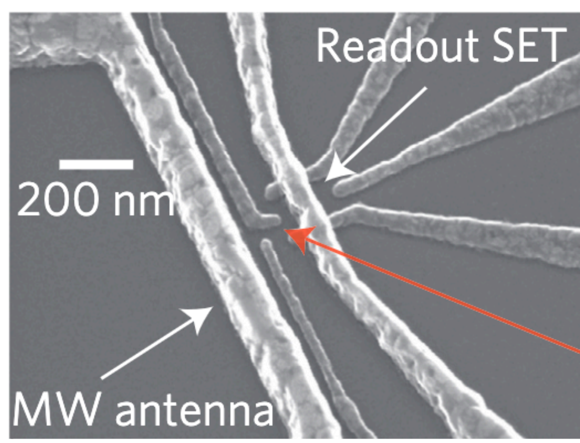
$T_2 \sim$ 10 ms to 100 ms

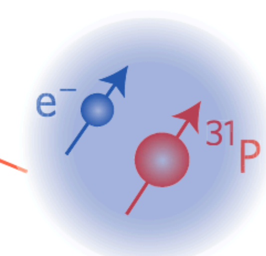


Tyryshkin et al,
Nature Mat, 2011

Single donor

$T_2 \sim$ 100 ms

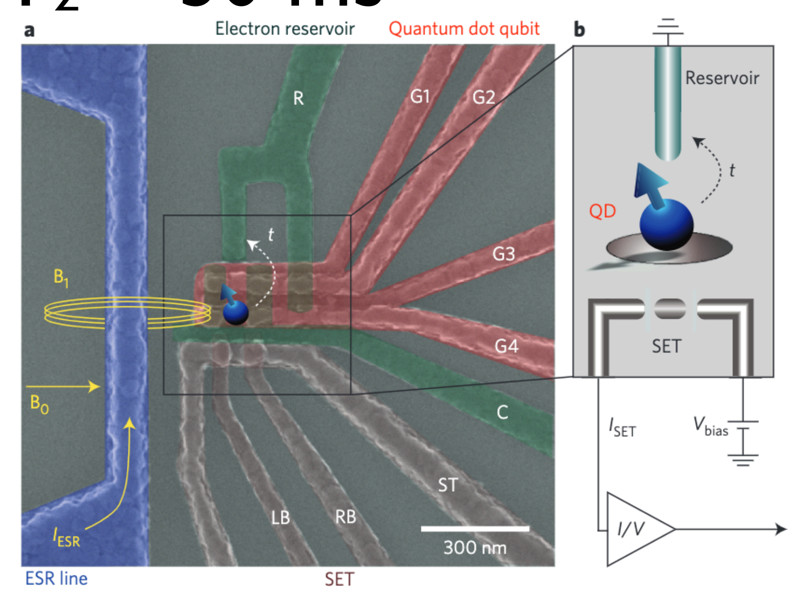




Muhonen et al,
Nature Nano, 2014

Single quantum dot

$T_2 \sim$ 30 ms



Veldhorst et al,
Nature Nano, 2014

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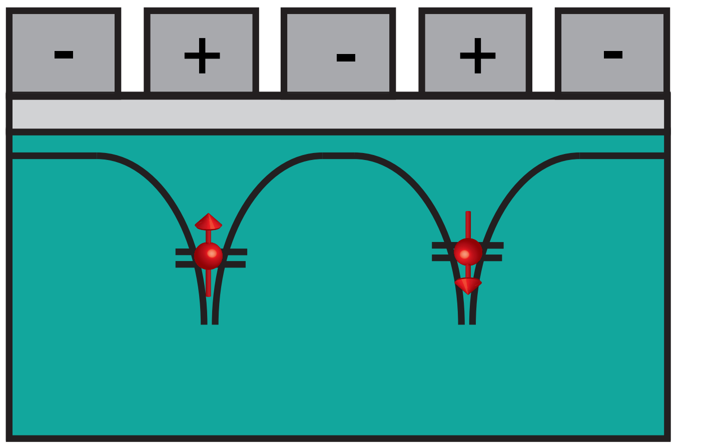
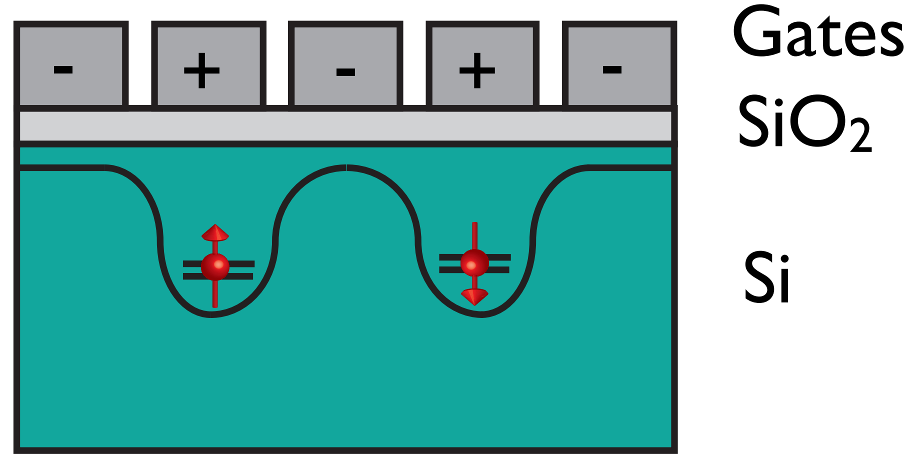
Electron Spin Qubits in Silicon

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) $e = 2 \times 10^{-3}$

Watson et al, Science Advances, 2016

Donor single qubit gates (magnetic resonance) $e = 5 \times 10^{-4}$

Dehollain et al NJP 2016

Two-qubit gates (exchange interaction) $e = 2 \times 10^{-2}$

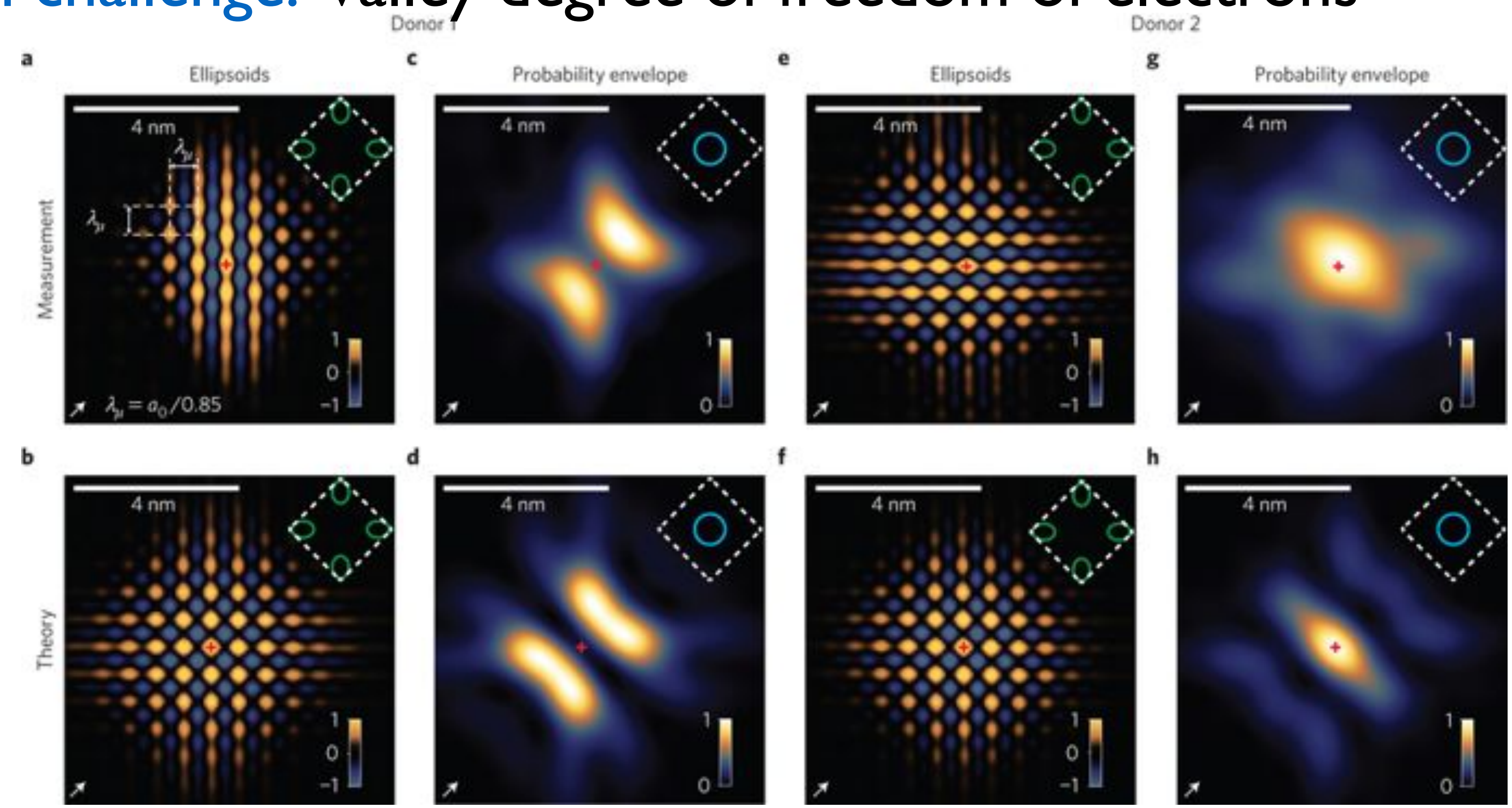
Huang et al Nature 2019

Electron Spin Qubits in Silicon

Summary: Small, clean qubits, manufacturable

Challenges with short-range interactions: electric noise (isotropic), cross-talk, density, range: ~20 nm (donor), ~100 nm (electron QD)

Additional challenge: Valley degree of freedom of electrons



Salfi et al Nature Materials 2014

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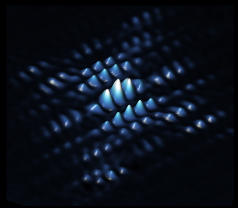


Desiderata

Desiderata

Maintain long coherence time of spin qubits in ^{28}Si

Build long-range noise-insensitive multi-qubit gates

1. Capacitive interactions
2. Quantum electrodynamics (Q.E.D.) with microwave photons [or acoustic phonons]

How to accomplish this?

***Enable electric control* [or elastic control] for spin**

Without spoiling coherence

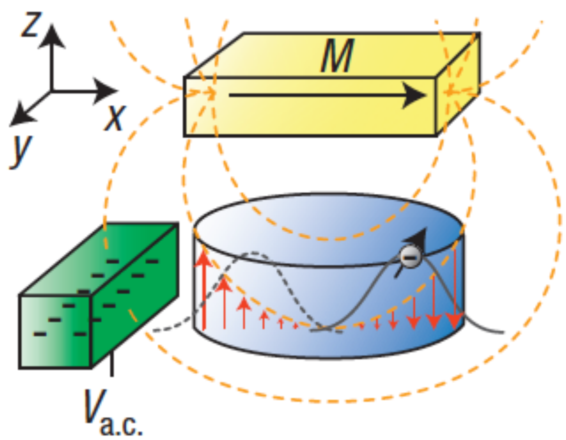
Why is this hard?

Si electron spin has weak intrinsic coupling to electric fields

Electric coupling is normally associated with fast decoherence

Electric Control

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



First demonstrated in GaAs [1]
Later shown for electrons in Si [2-5]

[1] Pioro-Ladrière et al NPhys. 2008
[2] Kawakami et al NNano. 2014
[3] Mi et al Nature 2018
[4] Samkharadze et al Science 2018
[5] Yoneda et al, NNano 2018

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

Strong spin decoherence [6-10] $T_2 \sim 0.1 \text{ to } 1\ \mu s$
For electrons in Si, the effect is far too weak

[6] Nowack et al Science 2007
[7] Nadj-Perge et al Nature 2010
[8] Maurand NComm 2016
[9] Watsinger NComm 2018
[10] Hendrickx, arxiv:1904.11443

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Existential Question

Question: Is 1 μs coherence time the best we can do with intrinsic spin orbit?

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Better question: How do we
[1] keep spin qubit coherence
[2] with strong intrinsic spin-orbit coupling

This would make hole spin a simple candidate for scalable quantum computation.

Existential Question

Question: Is 1 μs coherence time the best we can do with intrinsic spin orbit?

Better question: How do we
[1] keep spin qubit coherence
[2] with strong intrinsic spin-orbit coupling

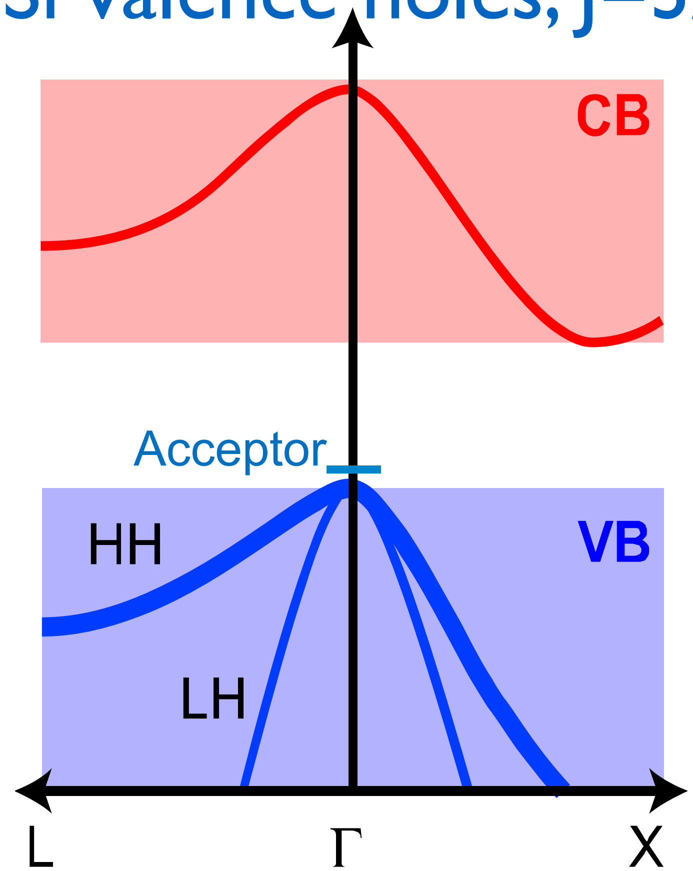
This would make hole spin a simple candidate for scalable quantum computation. The conventional wisdom: this is not possible with intrinsic spin-orbit coupling

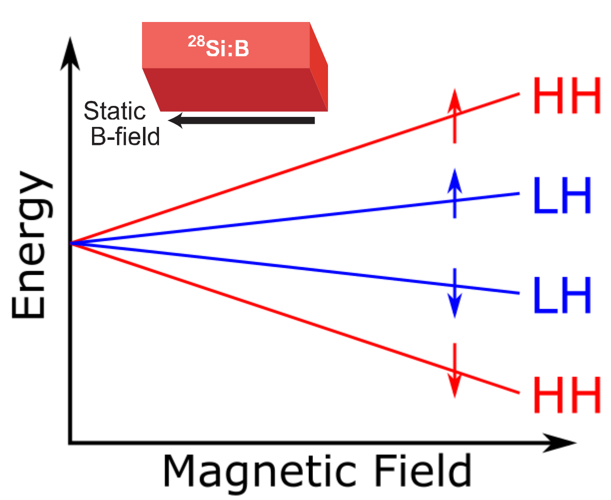
I will show you experiments demonstrating very long coherence times in a strong spin-orbit coupled system (spin is not a good quantum number).

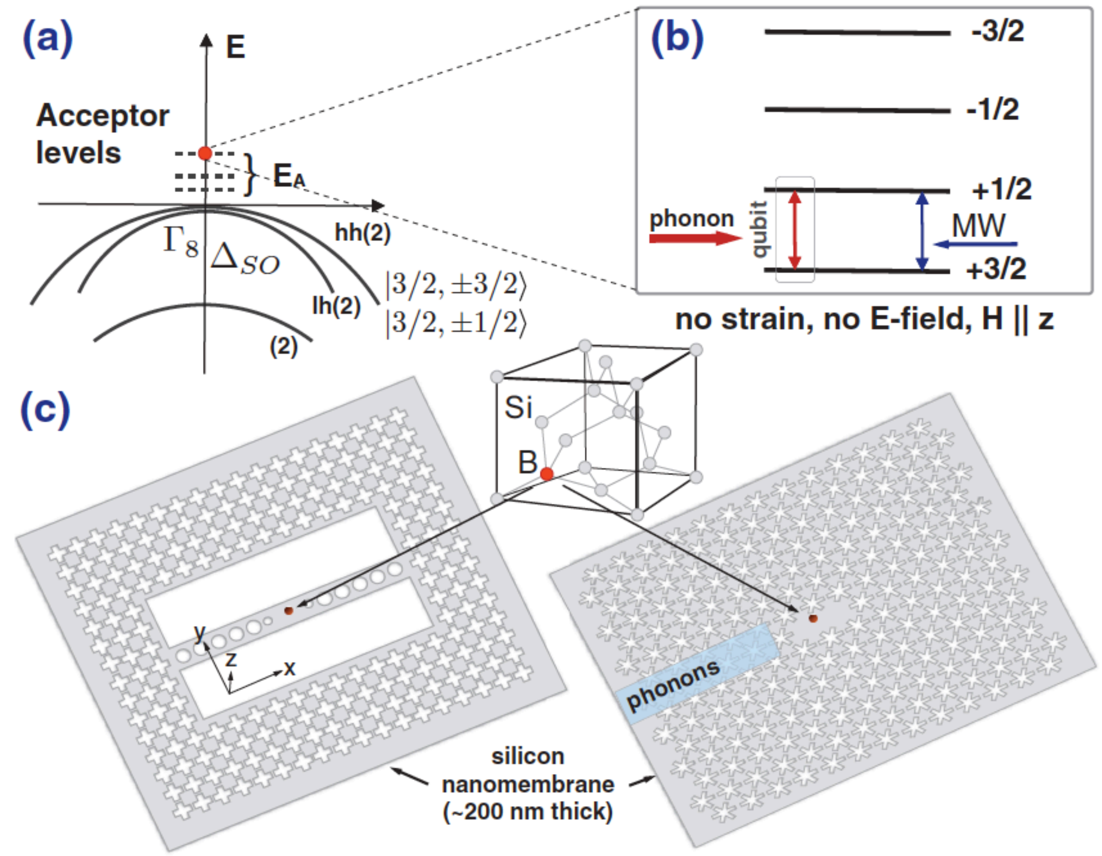
Our model system: hole spin bound to Si:B

Si:B hole spin

Si valence holes, J=3/2 and L.S → Quantized total angular momentum



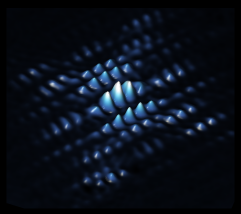




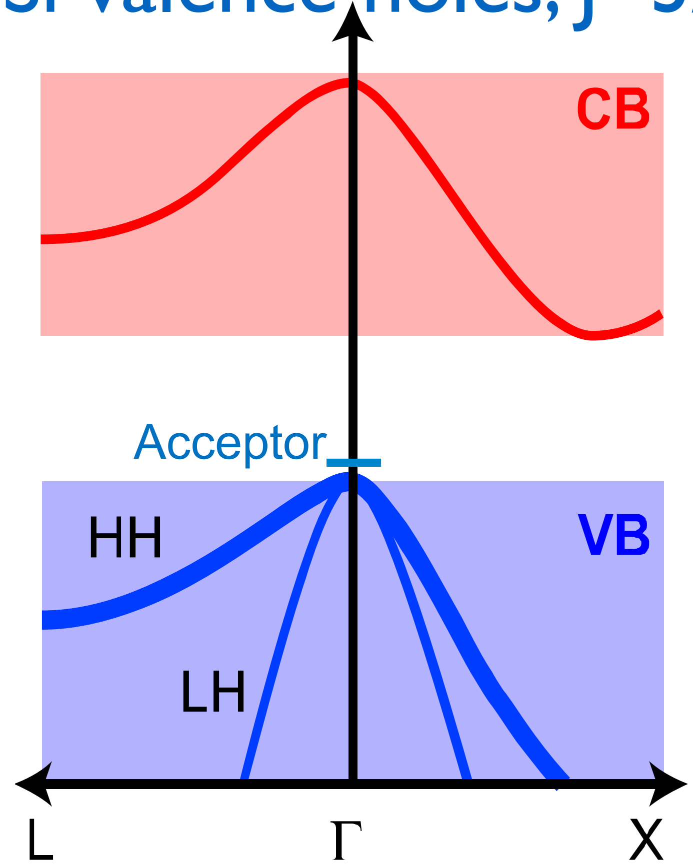
Long-ranged interactions
Mediated by phonons
Long relaxation times

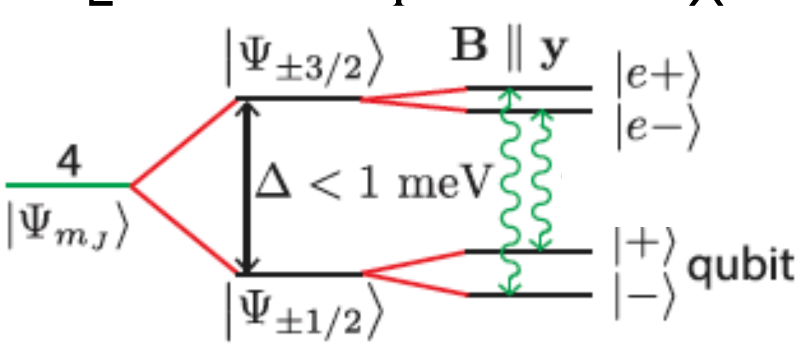
Ruskov and Tahan PRB 2013

Si:B hole spin

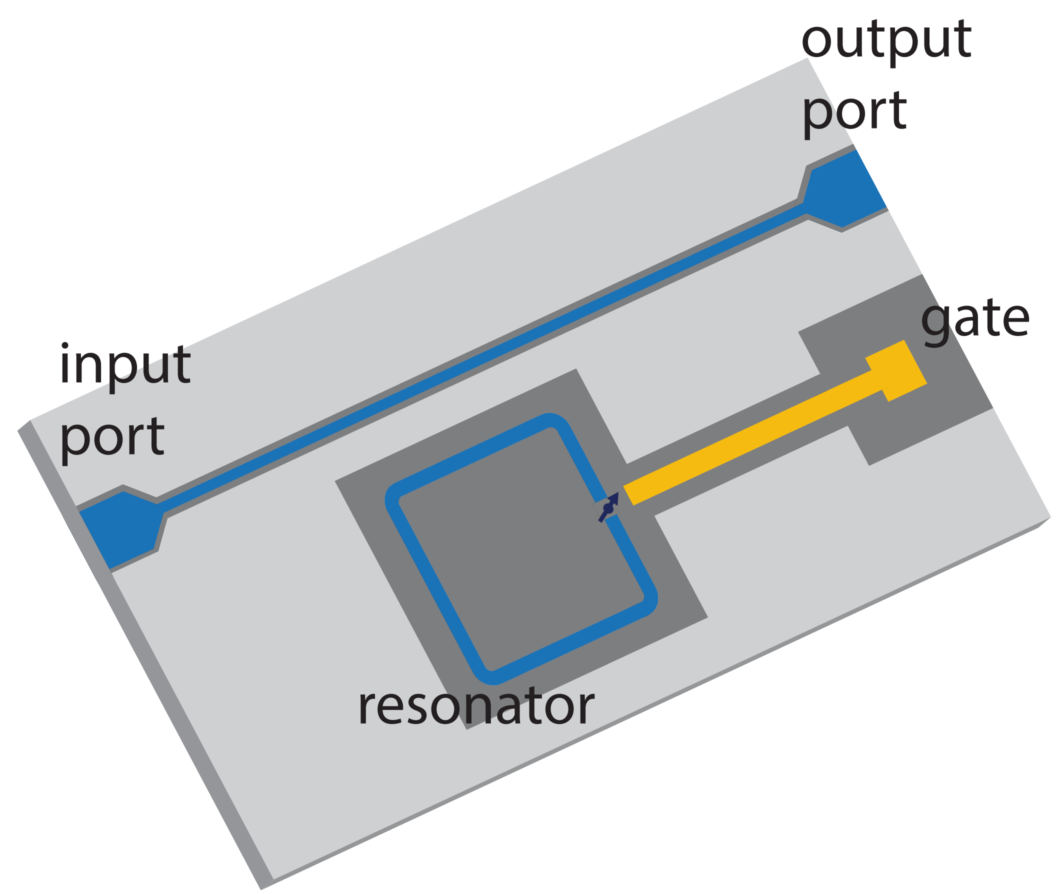


Si valence holes, J=3/2 ~~and~~ L.S → Quantized total angular momentum





Δ e.g. from strain



Long-ranged interactions
Mediated electrically (or by photons)
Long coherence times

Salfi, Mol, Culcer, Rogge PRL 2016
Rogge, Salfi, Mol, US Patent 9,691,033

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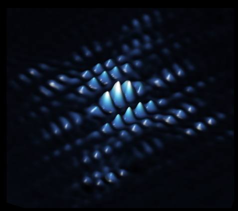
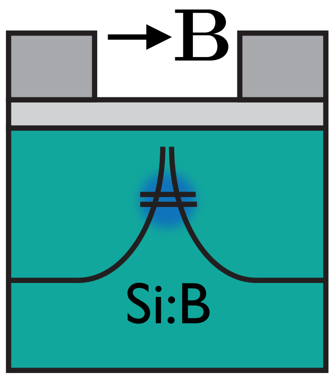
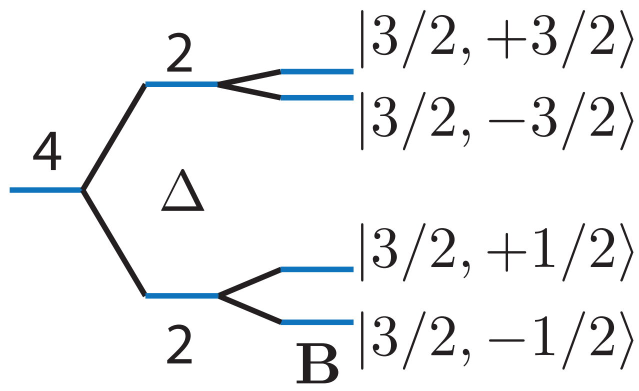
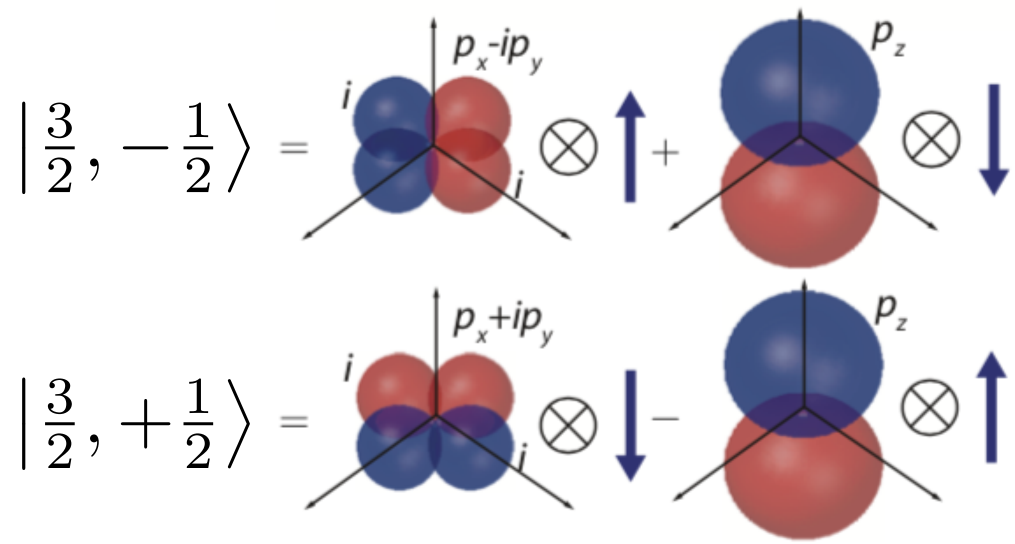


Si:B hole spin

Si valence holes, J=3/2 ~~and~~ L.S → Quantized total angular momentum







LH

Electric & elastic quadrupole + Zeeman —— Electric & elastic dipole

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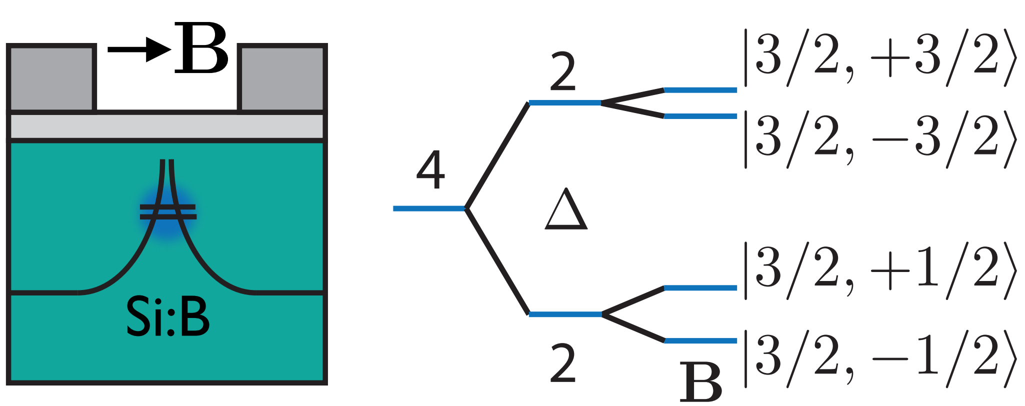
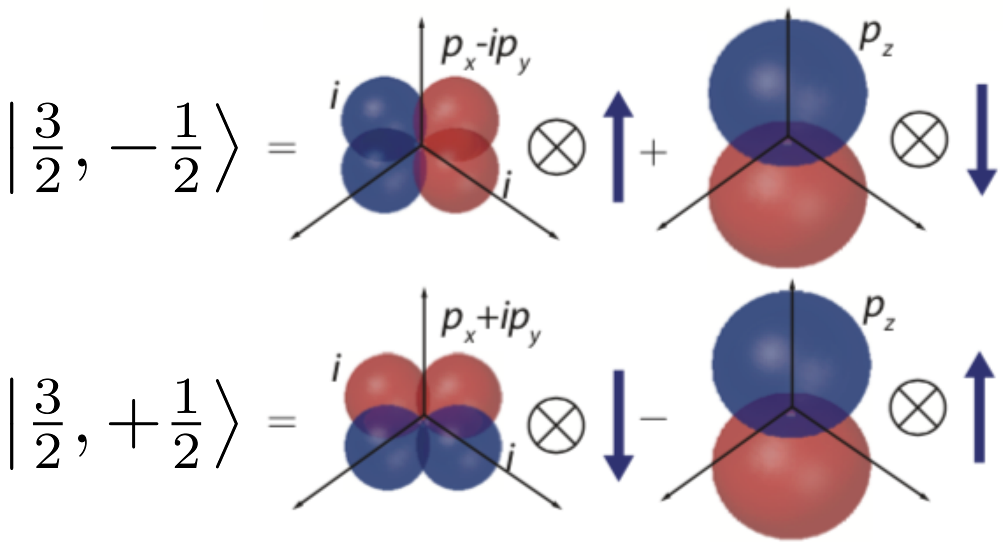
Si:B hole spin

Si valence holes, J=3/2 ~~and~~ L.S → Quantized total angular momentum





LH

Electric & elastic quadrupole + Zeeman —— Electric & elastic dipole

Theory findings

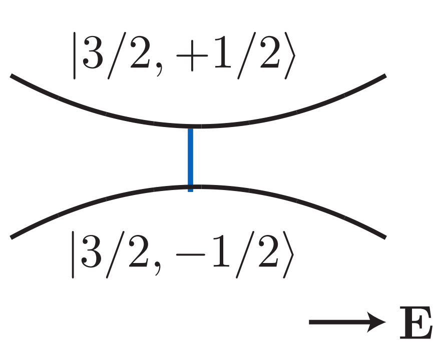
1-qubit, 2-qubit gates:

Strong electric dipole coupling

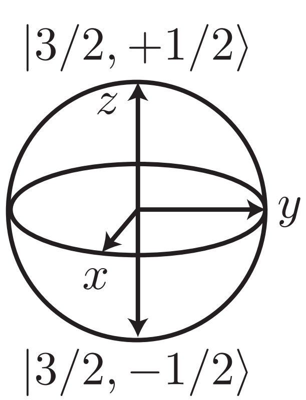
Coherence:

Robust to *E* field noise

Salfi et al PRL 2016



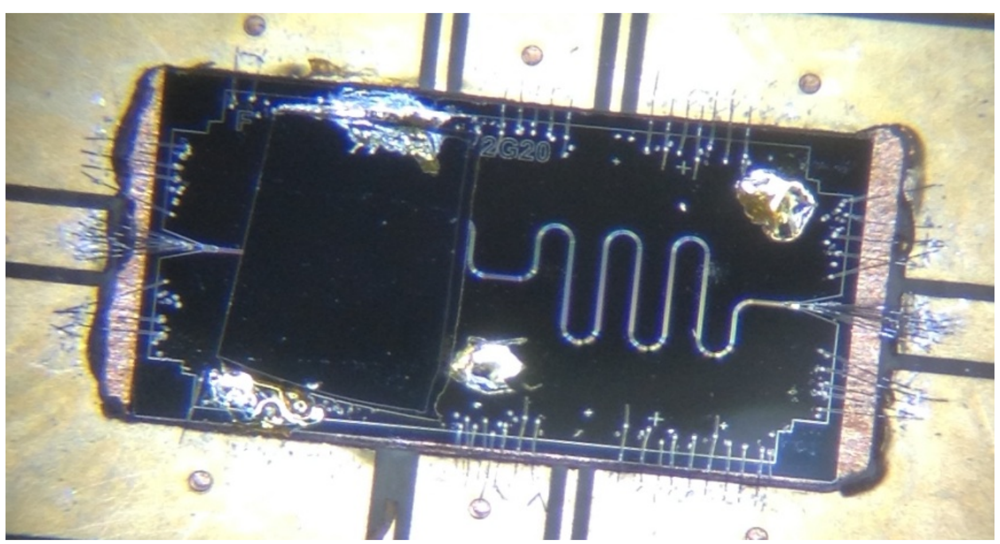
electric clock transition!!

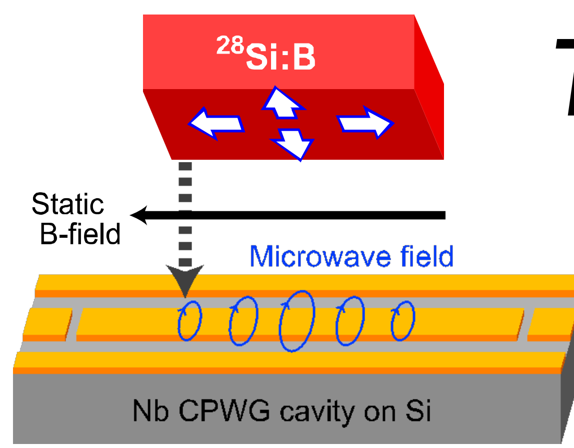


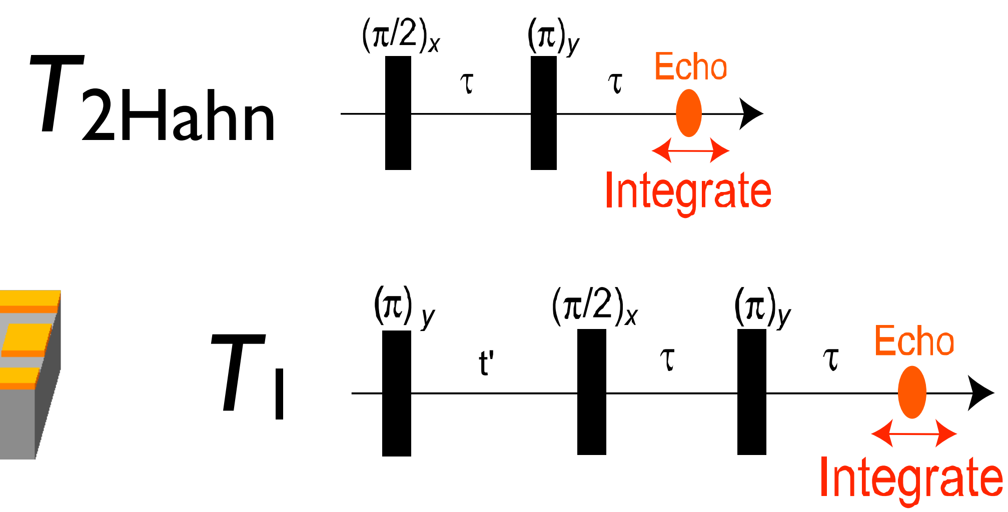
Hole spin coherence

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

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







T_{2CPMG}

Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)

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Hole spin coherence

Prepare superposition

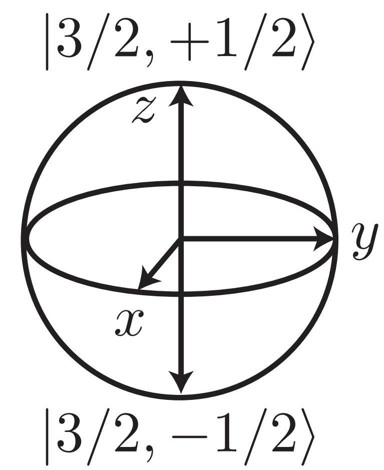
Apply X(π/2) pulse (input)

Invert to enable refocusing

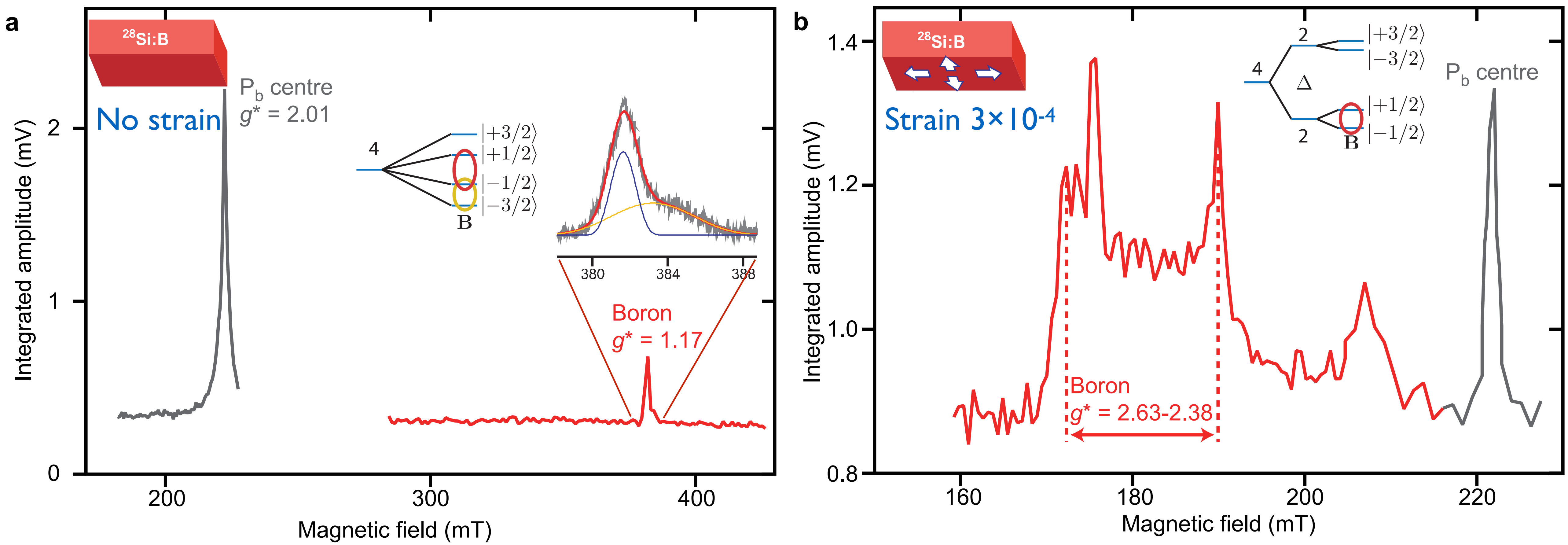
After time t, apply X(π) pulse

Hahn-echo

After time 2t, refocusing (Hahn echo) is emitted into the resonator



$$hf = g^* \mu_B B$$
$$f = 6.6\ \text{GHz}$$



Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)

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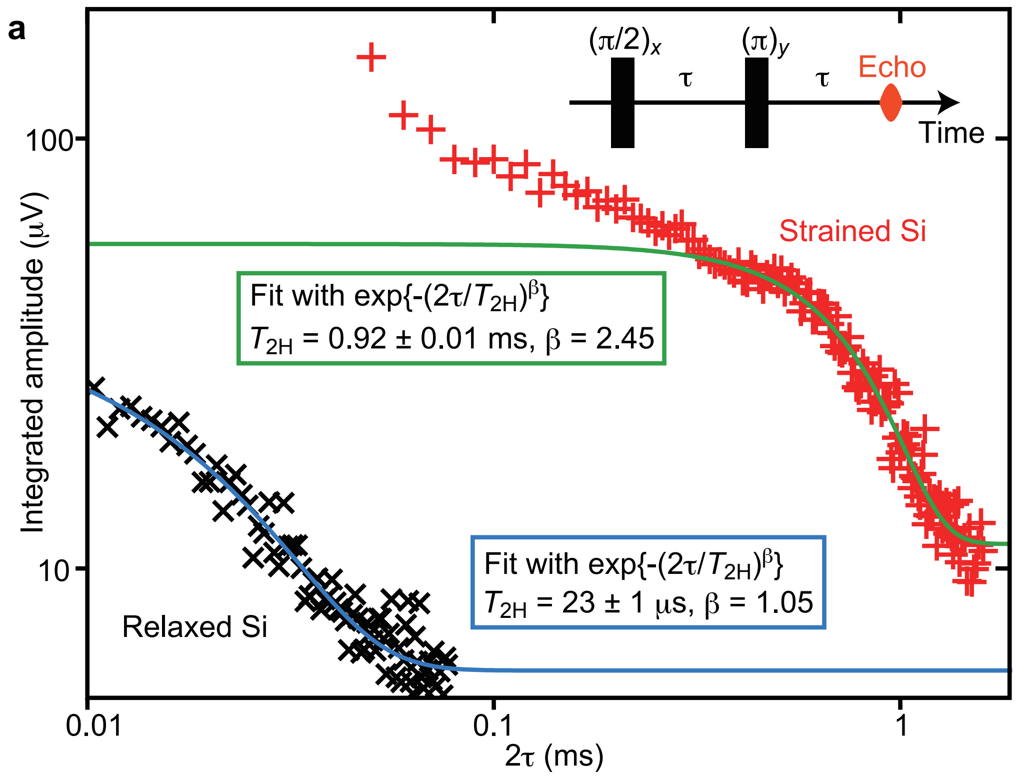
Hole spin coherence

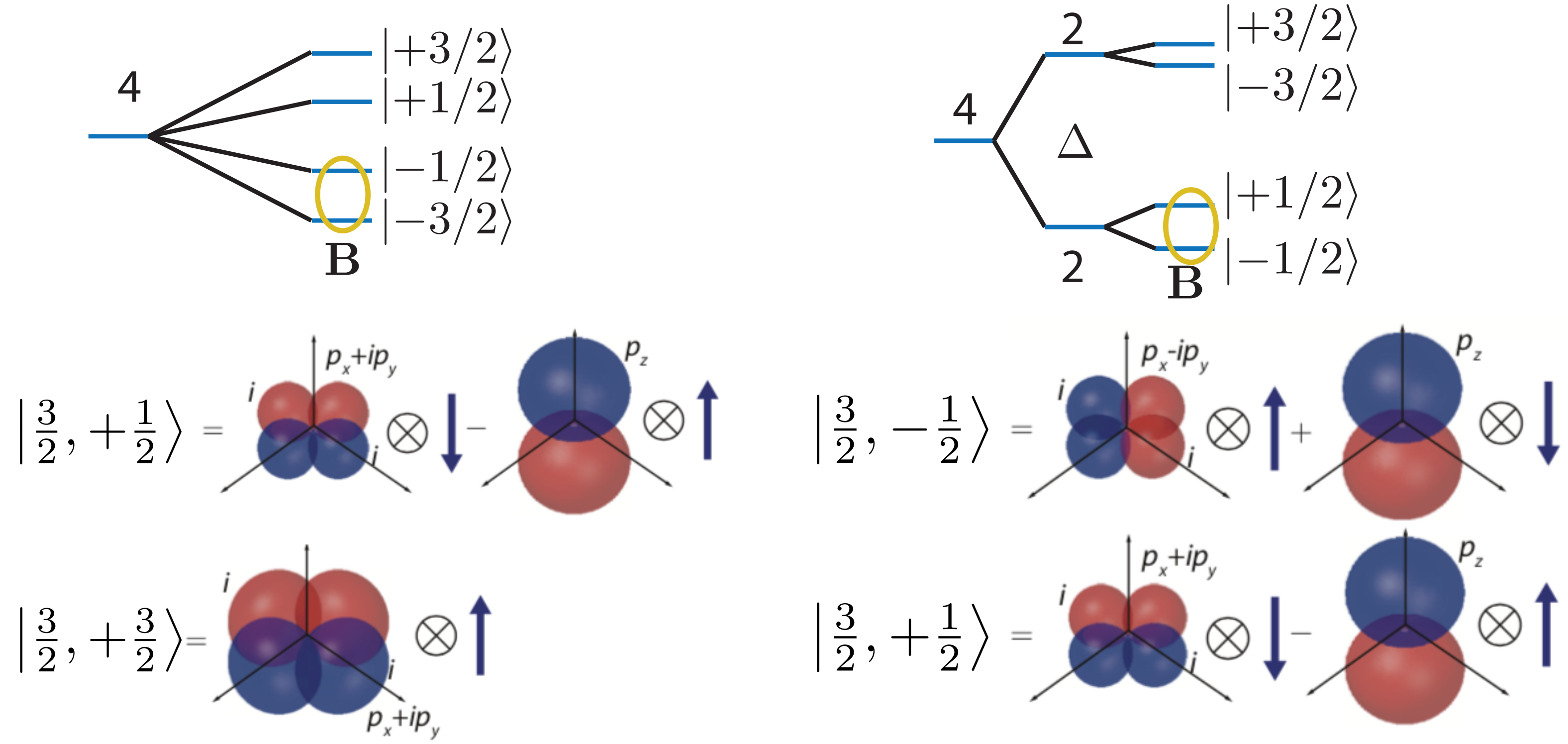


Unstrained 28Si:

T_2=23 μs, β=1.05

Strained 28Si:

T_2=0.9 ms, β=2.45



Change in β from ~1 to > 2?

τ_c=correlation time of the fluctuator is changing

Unstrained : τ_c fast compared to coherence time

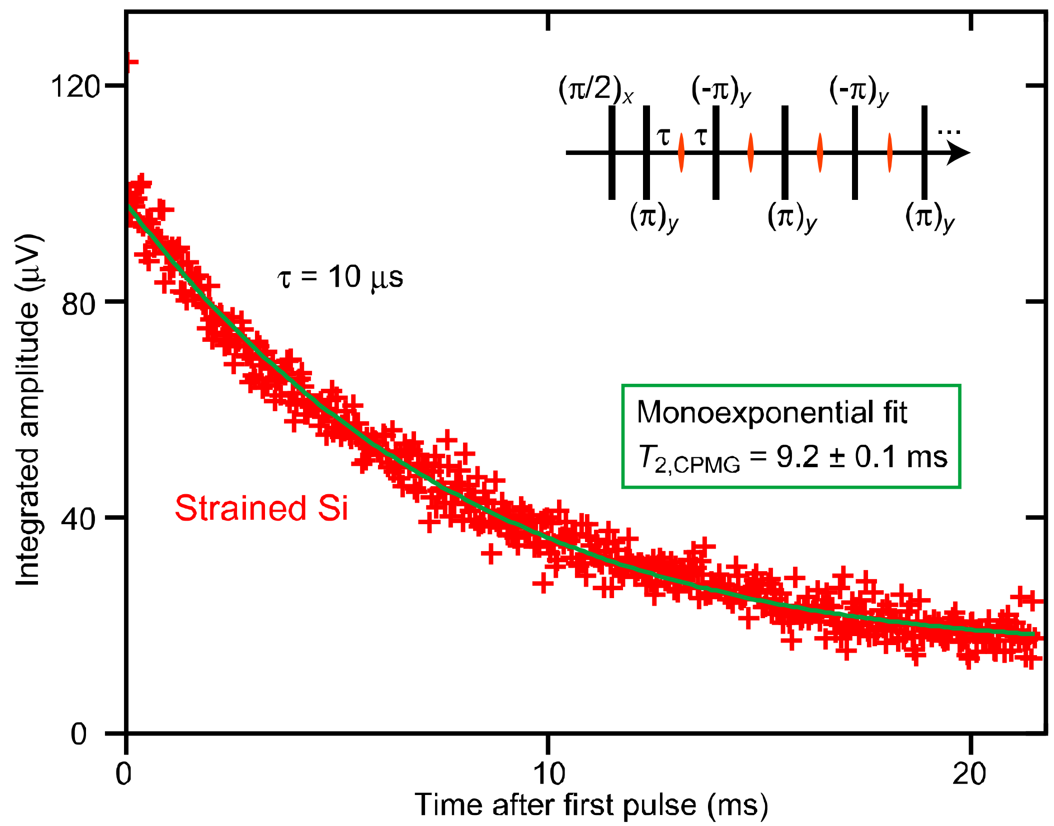
Strained: τ_c slow compared to coherence time

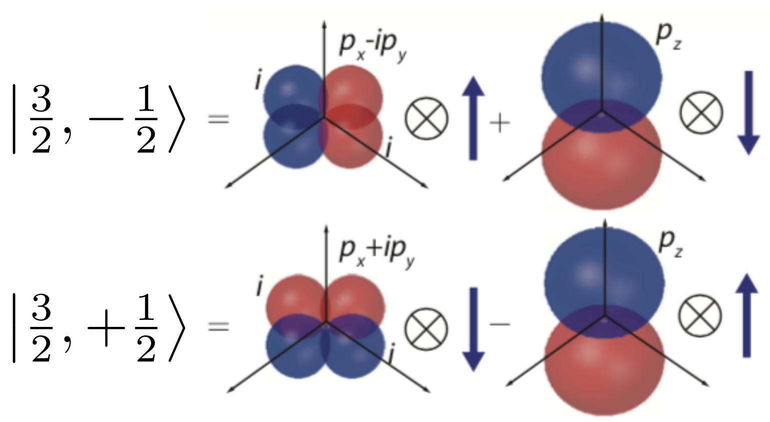
Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)

Hole spin coherence

Dynamical decoupling extends coherence time to $T_{2,\mathrm{CPMG}}$ = 9.2 ms

Confirms slow fluctuators are limiting coherence in the ensemble





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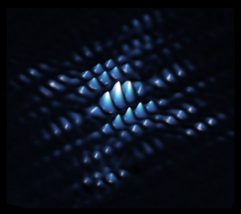
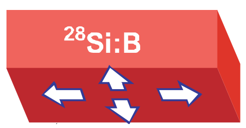


Hole spin coherence

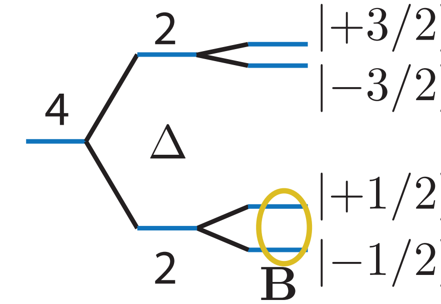
How does the strain improve coherence? $\mathscr{H} = \hbar\left(\omega_0 + \frac{\partial\omega}{\partial E}\delta E\right)\sigma_z + vE_z\sigma_x$

Decoherence is suppressed by the gap



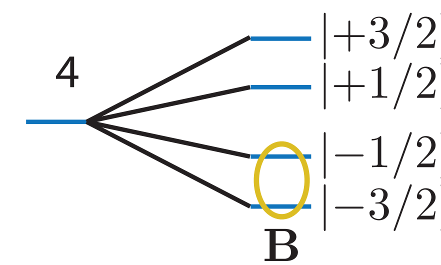
Strain

$$\frac{\partial\omega}{\partial E} = \frac{\hbar\omega_0}{2\Delta}p \quad \text{for} \quad \frac{\hbar\omega_0}{\Delta} \ll 1$$



No strain

c.f. $$\frac{\partial\omega}{\partial E} = p \quad \text{for} \quad \Delta = 0$$



Experiment: Reduced longitudinal coupling enhances T_2

[1] Suppress decoherence from electric fluctuations

[2] Suppress decoherence from electric dipole-dipole interaction

Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)

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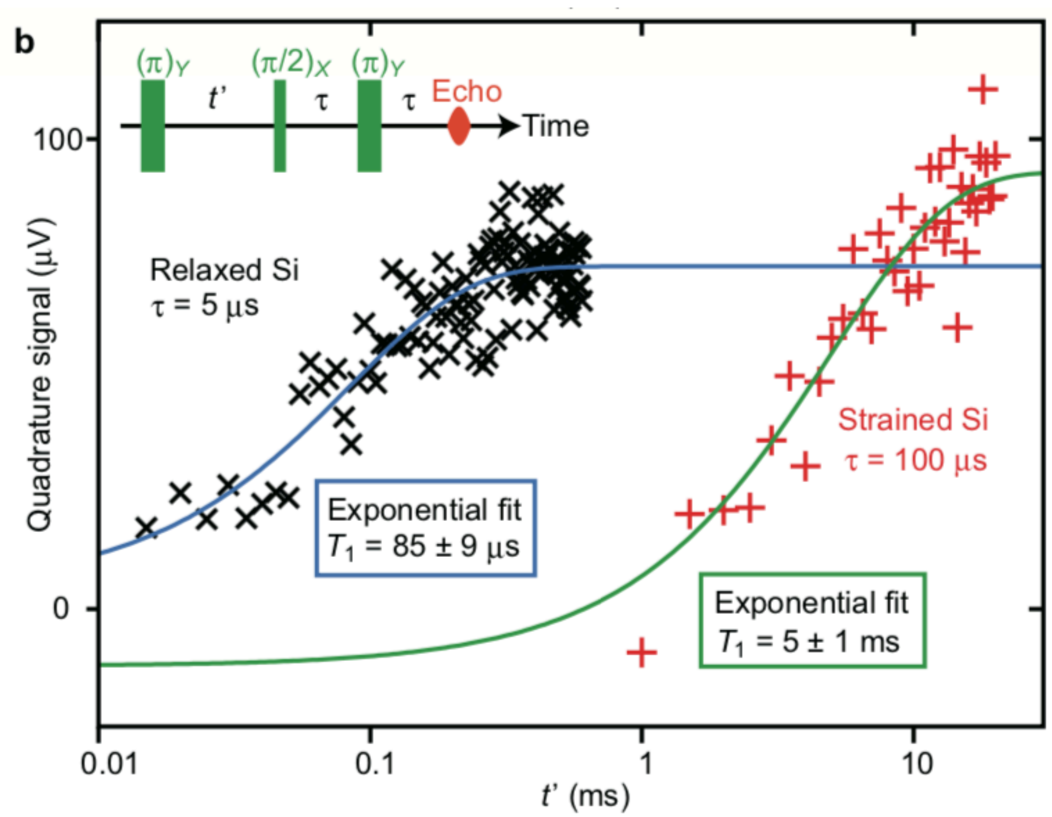
Hole spin coherence

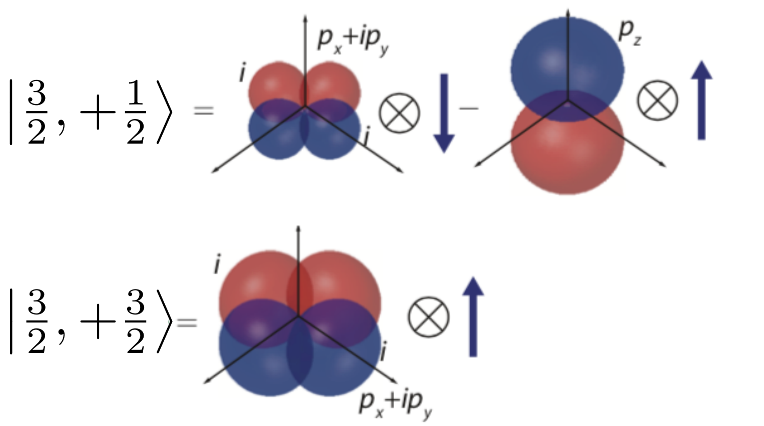
Strained sample also has longer T_1

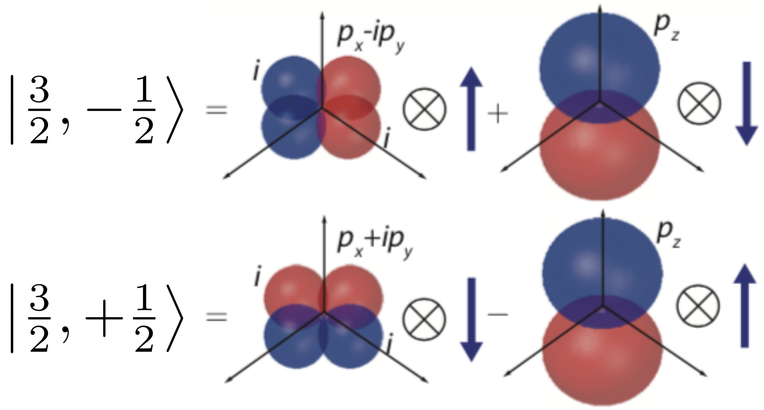
Time-reversal symmetric system inhibits phonon relaxation



Unstrained sample: T_1=85 μs

Strained sample: T_1=5 ms





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

This is not a limitation and T_1 can be improved

Salfi et al, PRL 2016
Abadillo-Uriel et al, APL 2018

Conveniently, T_1 is a good measure of the strain-induced gap

$$\frac{\hbar\omega}{\Delta} \sim \frac{1}{5}$$

Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)

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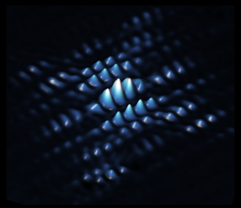


Comparison to state-of-the-art

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

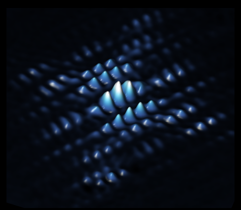
Electron: Donor and QD

~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, Nature Materials, 20, 38-42 (2021)



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this work

Hole: QD

~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
[4] Maurand Nature Comms 2016

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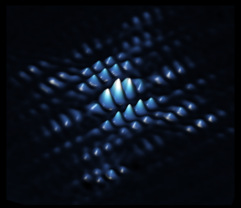

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Si h+ QD [4]	0.25 μs	-
Si:B h+ no strain (this work)	23 μs	-
Si:B h+ strain (this work)	0.9 ms	9 ms

this work

Hole: acceptor

~ 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, Nature Materials, 20, 38-42 (2021)

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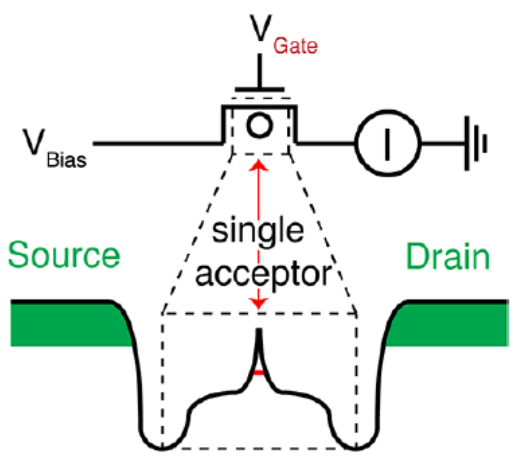
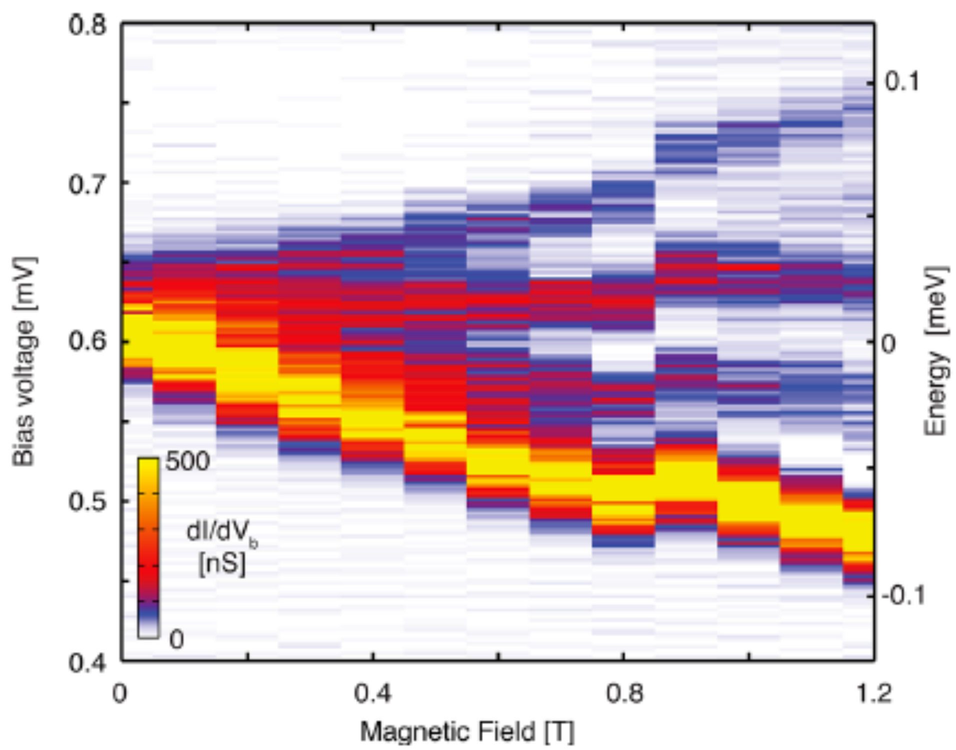
Si:B devices : single and coupled atoms

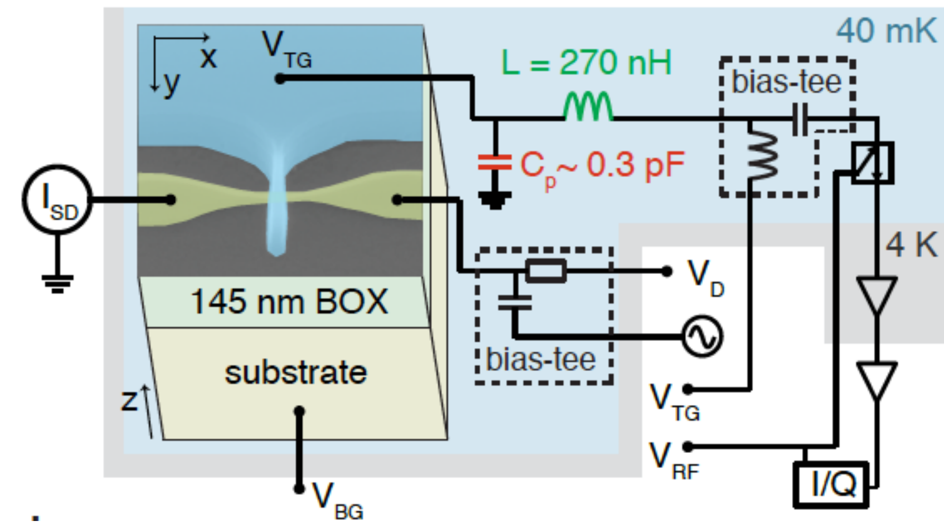
Single-atom transistor

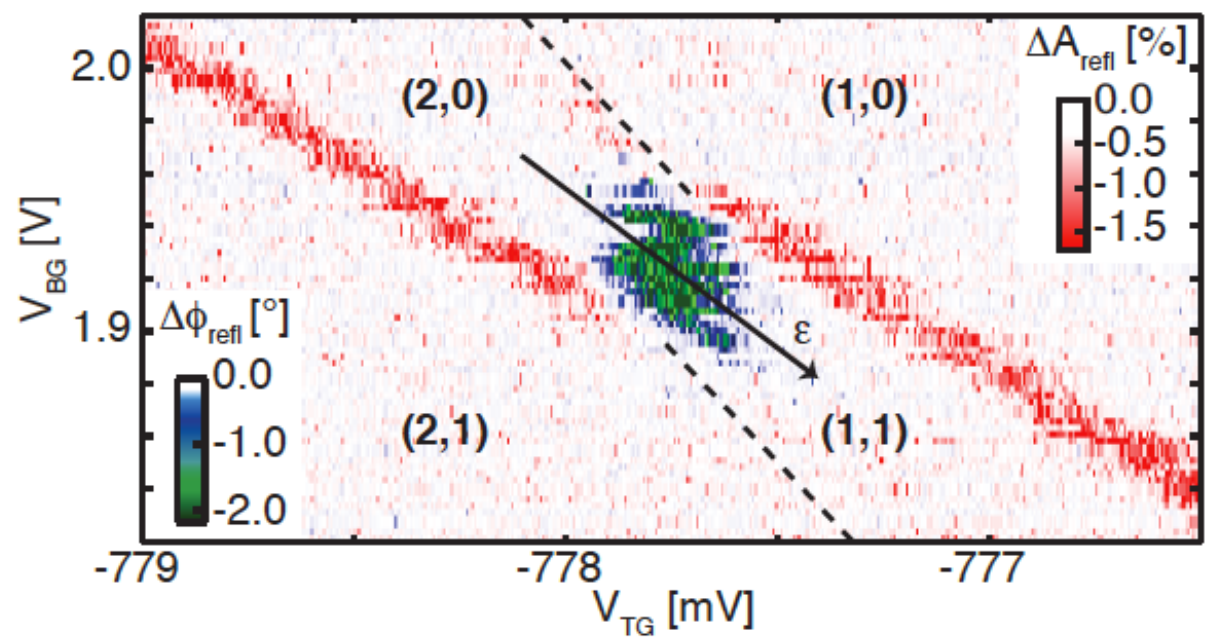




van der Heijden, **Salfi** et al, Nano Letters 2014

Gate-based spin readout





van der Heijden, Kobayashi, House, **Salfi** et al,
Science Advances 2018

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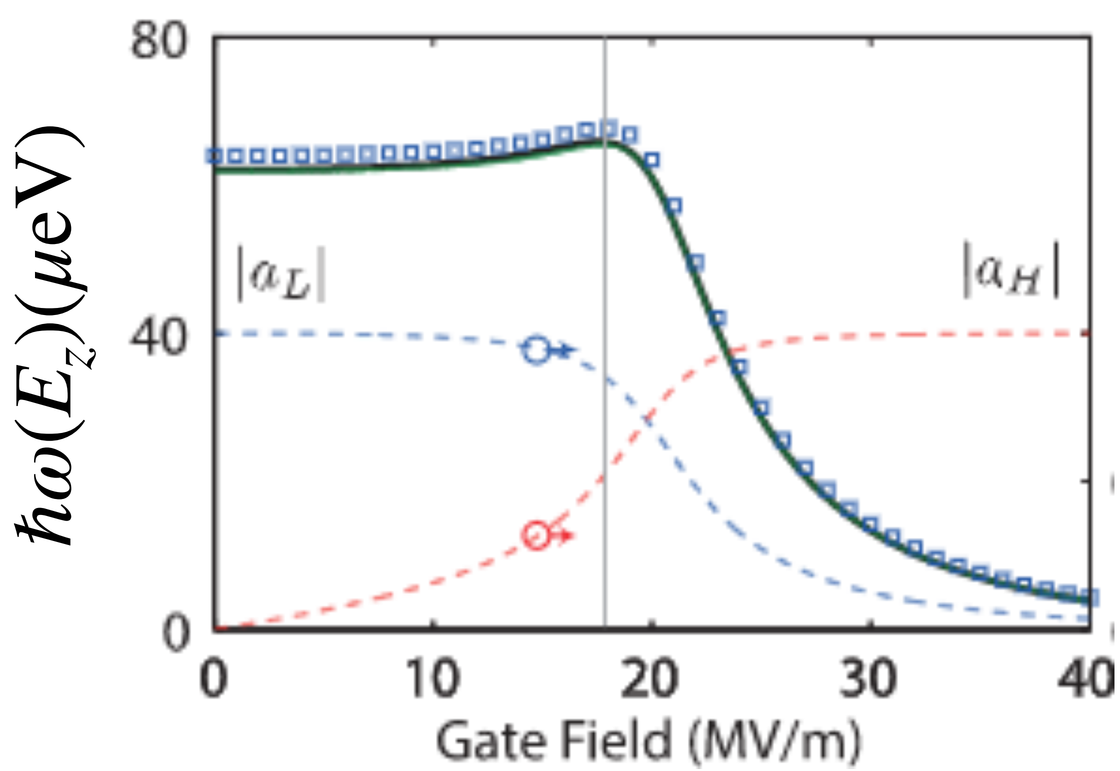
Universality of Group-IV Hole Physics

The theoretical result of long T_1 and long T_2 (robustness to electric fluctuations) with electric control are generic

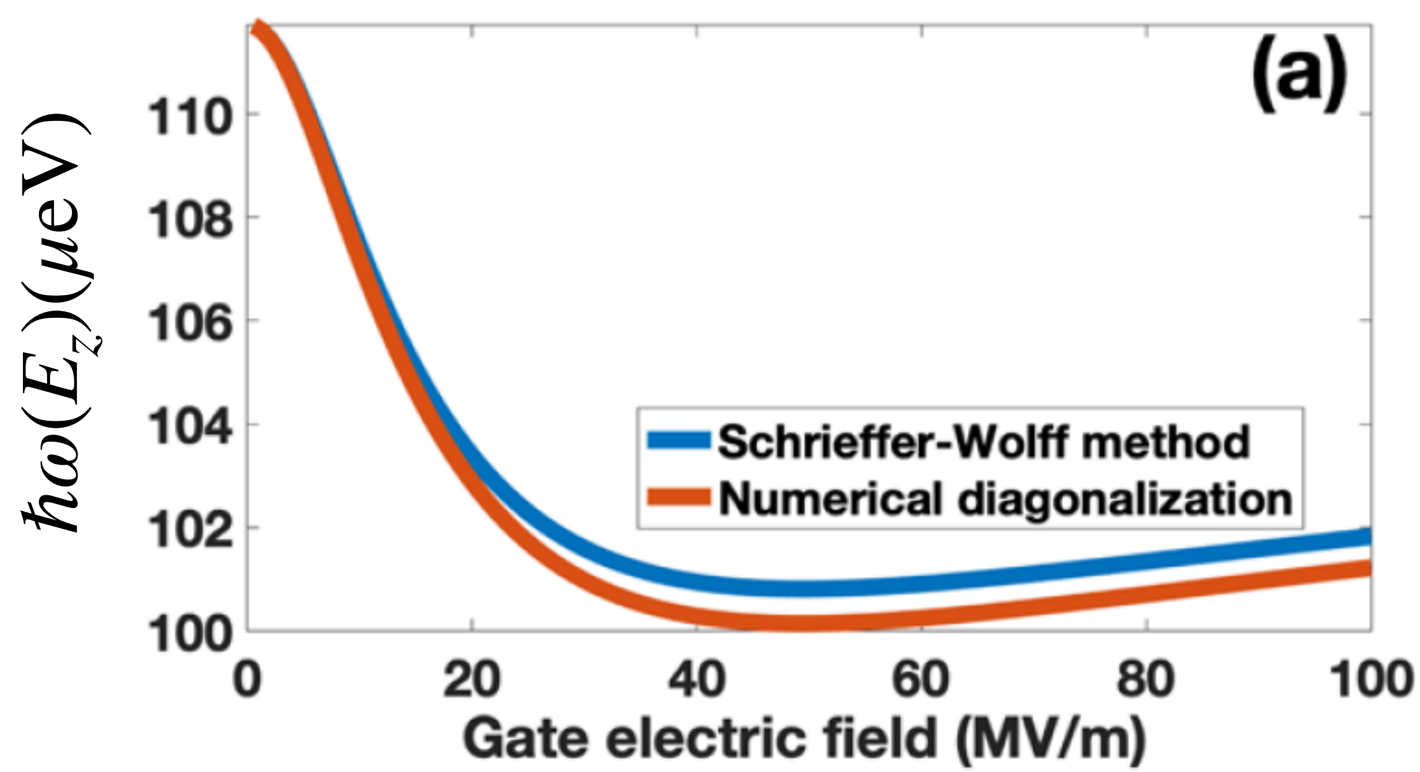
[1] Group IV materials (Rashba, no Dresselhaus SOC): Si or Ge

[2] Confinement potential: impurity (left) or quantum dot (right)

$$\mathscr{H} = \frac{1}{2}\hbar\omega(\mathbf{E})\sigma_{\mathbf{z}} + (\mathbf{v}\cdot\mathbf{E})\,\sigma_{\mathbf{x}}$$



Salfi et al, Phys. Rev. Lett. 2016



Wang, Marcellina, Hamilton, Cullen, Rogge, **Salfi**, Culcer Nature PJ Quantum Information, 7, 1-8 (2021))

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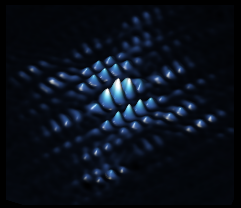


Summary

Summary of experiment: Holes in 28Si

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

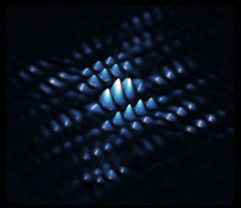
Nontrivial: L.S coupling, 10^4 to 10^5 coherence improvement

Strain increases T_1 and T_2

Opportunity: Electric & elastic quadrupole to build long-distance gates

Clock transition to maintain qubit coherence

Kobayashi, **Salfi** et al, Nature Materials, 20, 38-42 (2021)
van der Heijden et al, Science Advances, 2018
Salfi et al, PRL 2016



Thank you!

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B Johnson (Melbourne)
J McCallum (Melbourne)

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Kobayashi, **Salfi** et al, Nature Materials, 2021
Wang et al Nature PJ Quantum Information, 2021
van der Heijden, Kobayashi, House, **Salfi** et al, Science Advances, 2018
Salfi et al, Phys. Rev. Lett. 2016

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Thank you!

New Lab @ UBC (QMI)

Current projects on spin qubits

Quantum simulation (Fermionic)

Spin based quantum computation

- Gate-based hole-spin quantum dots
- Assisted by superconducting technology

More interesting projects coming soon…

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