A vision for large-scale quantum computation with semiconductor spins

MOONSHOT GOAL INTERNATIONAL SYMPOSIUM
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LIEVEN VANDERSYPEN

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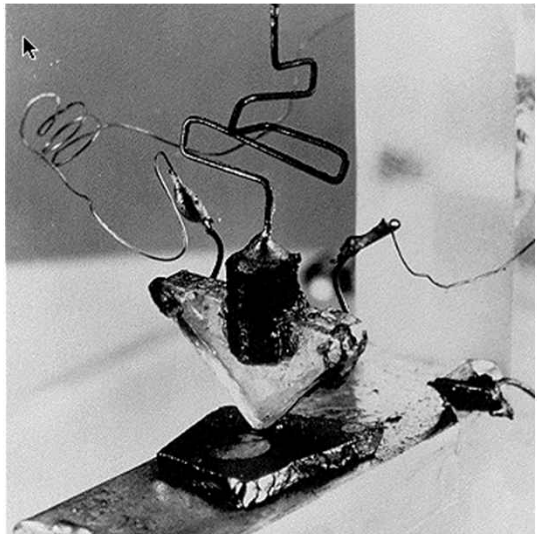
QuTech is a collaboration between TU Delft TNO

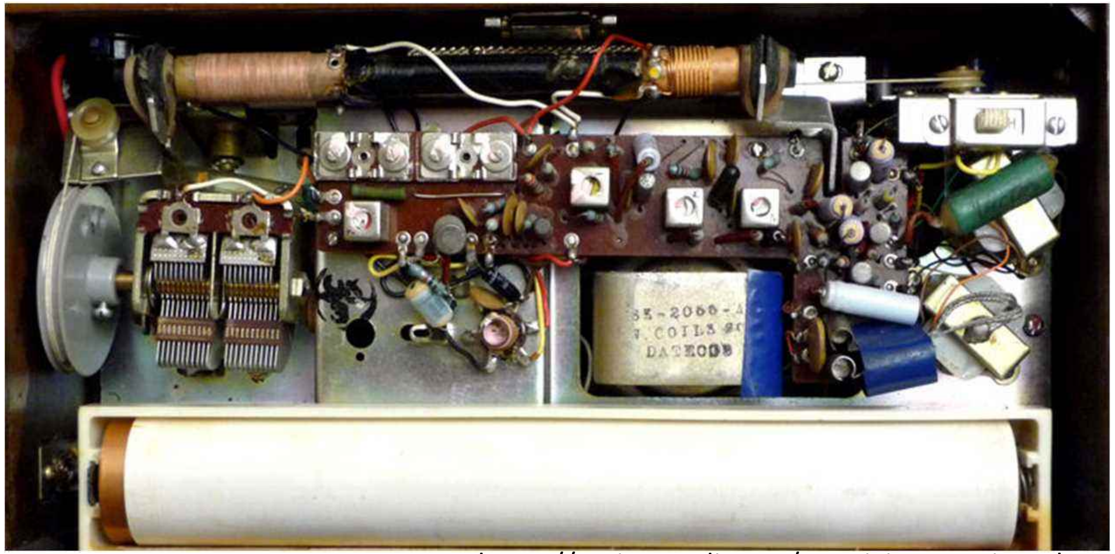
Transistors and early technology

1947 First transistor



http://www.don-lindsay-archive.org/

From 1954 Transistor radio's



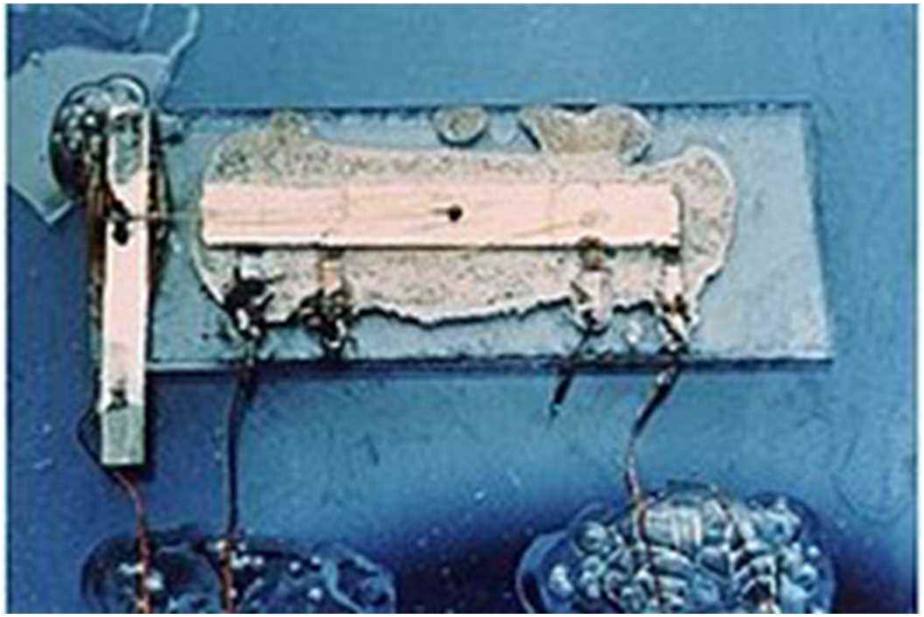
https://antiqueradio.org/JVCNivicoTransistor.htm

Simple circuits are of commercial value

Brute forcing known methods only goes so far

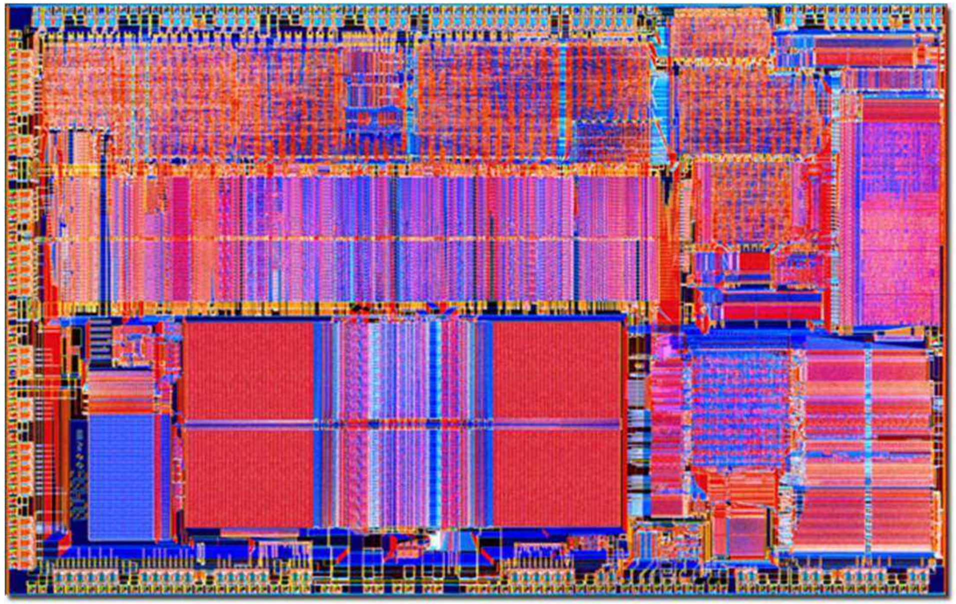
Integrated circuits

1958 First integrated circuit



https://en.wikipedia.org/wiki/Integrated_circuit

1989 Intel 486 processor



https://regmedia.co.uk/2011/11/14/80486_die_large.jpg

Enabling highly complex, powerful electronics

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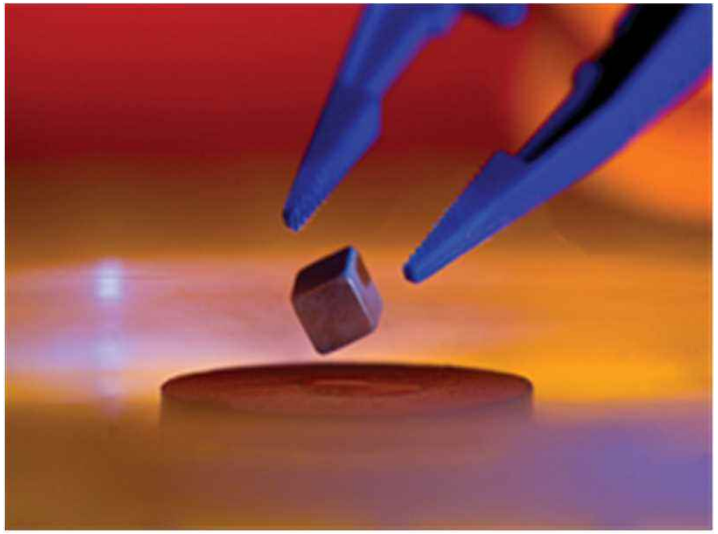
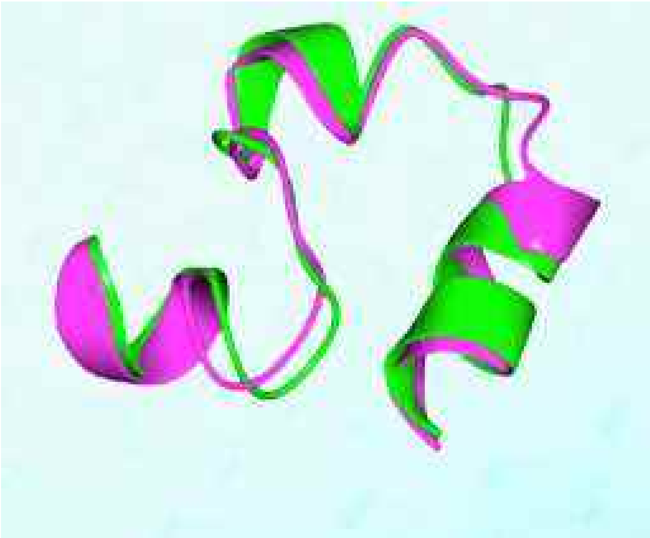
Quantum computing applications and requirements



Energy



Health

Security

Challenge: solving *real-world* problems with *real-world* qubits requires quantum error correction and millions of qubits

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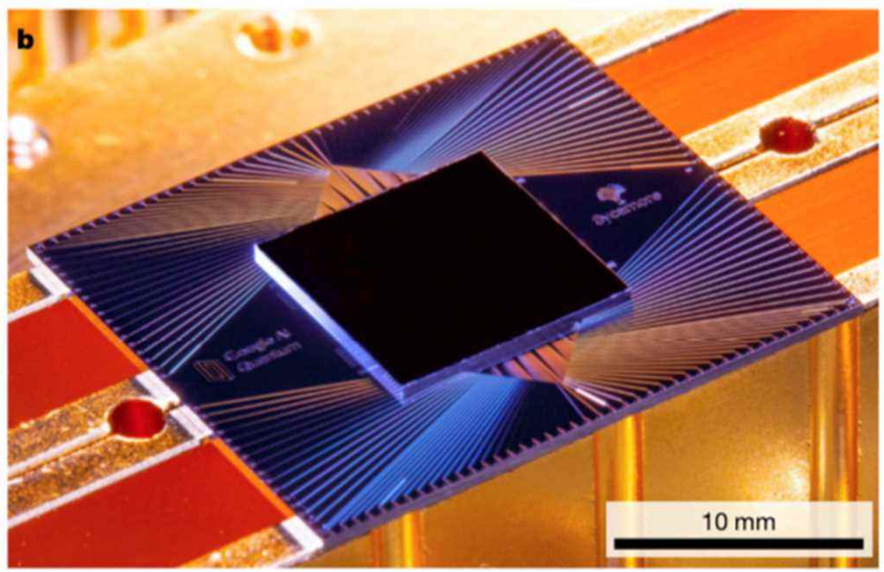
From quantum supremacy to quantum practicality



Arute et al, Nature 2019
Zhong et al, Science 2020, PRL 2021
Wu et al, PRL 2021

?

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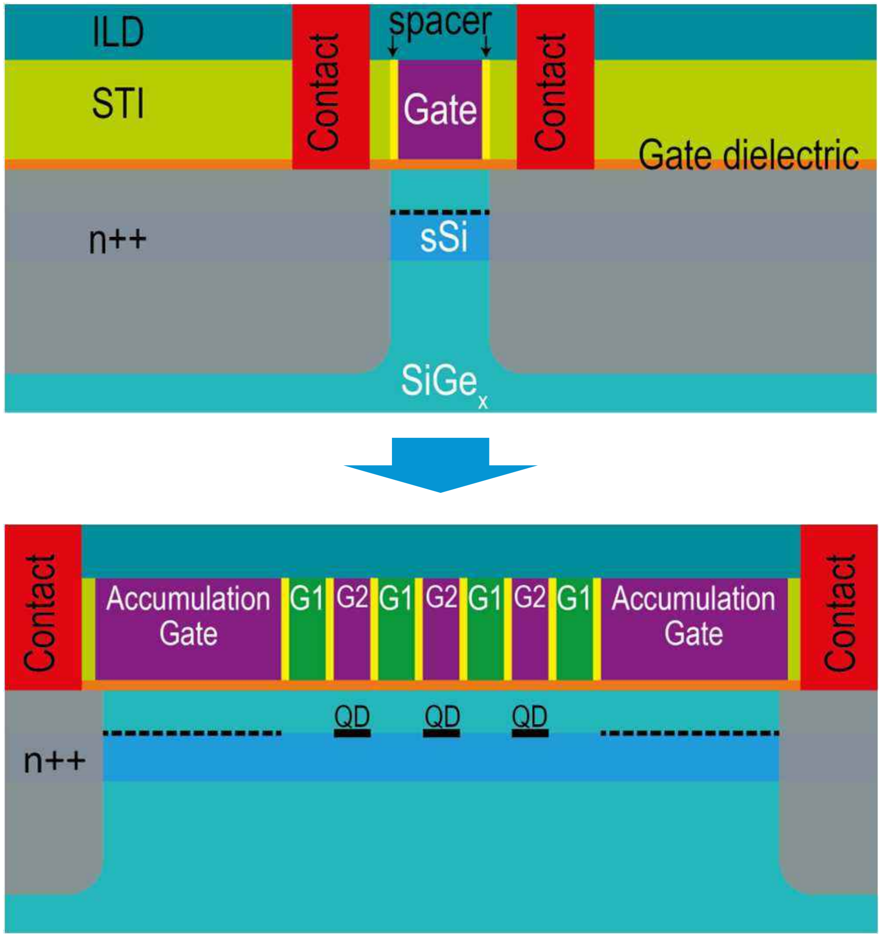
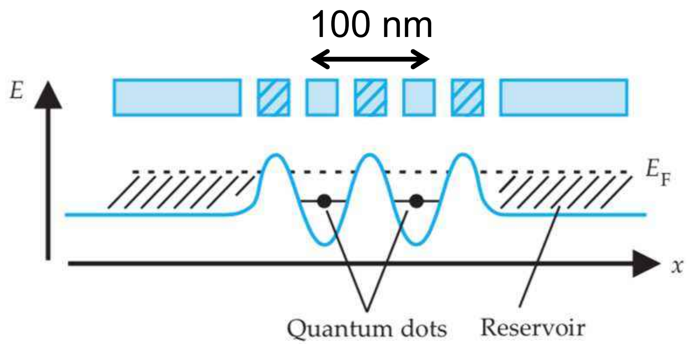
Quantum computing with semiconductor spins –
an excellent starting point for scaling



1 electron spin = 1 qubit

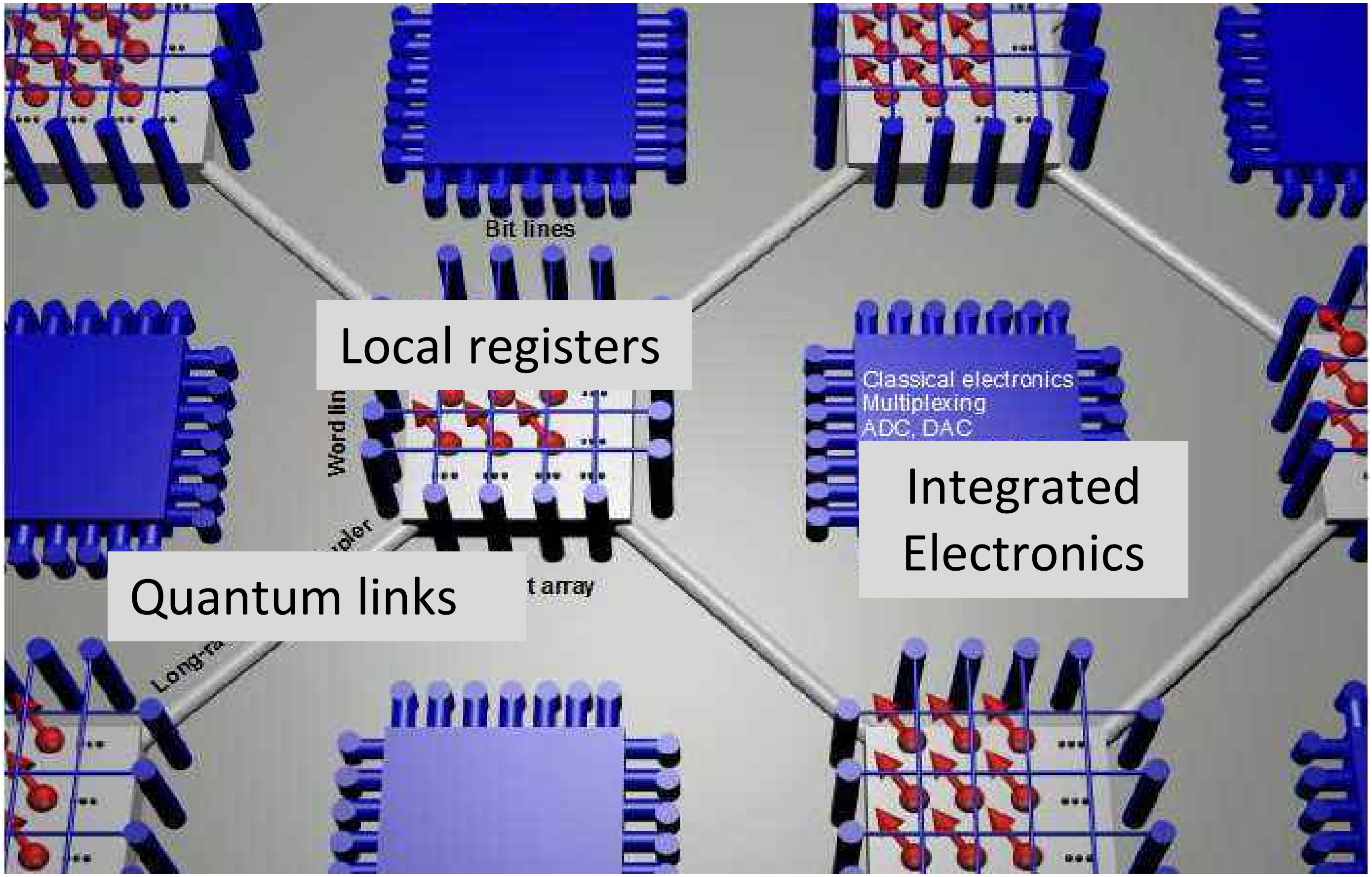
individual electrons stored in semiconductor quantum dots

Loss and DiVincenzo, PRA 1998



Vandersypen and Eriksson, Physics Today, August 2019

Our vision of a scalable semiconductor spin qubit processor – hot, dense and coherent



L.M.K. Vandersypen, H. Bluhm, J.S. Clarke, A.S. Dsurak, R. Ishihara, A. Morello, D.J. Reilly, L.R. Schreiber, and M. Veldhorst., npj Q Info 2017

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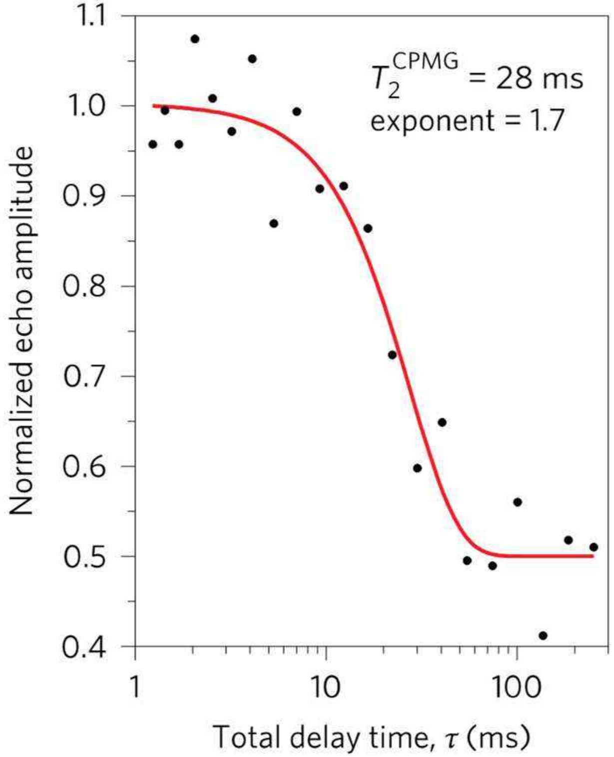
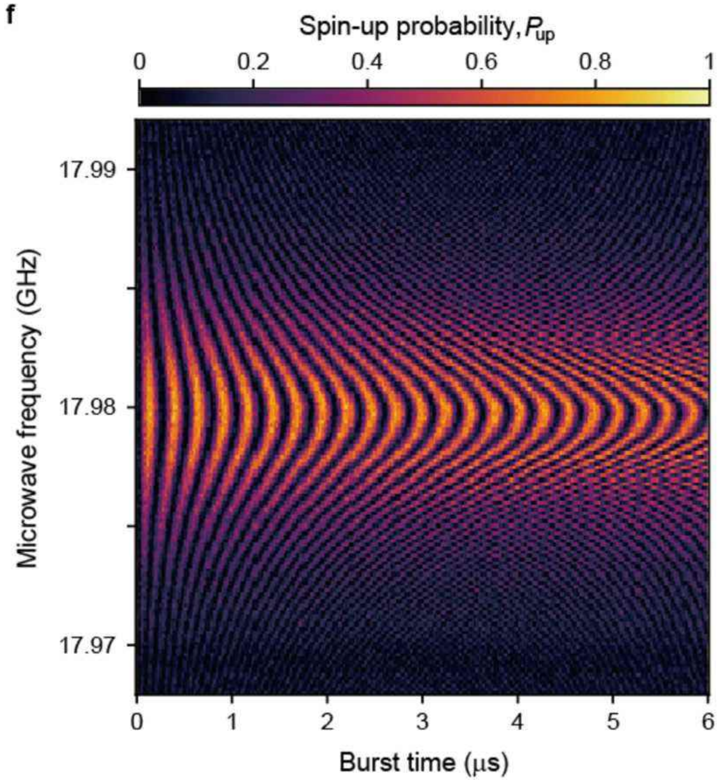
Single electron spin control and coherence

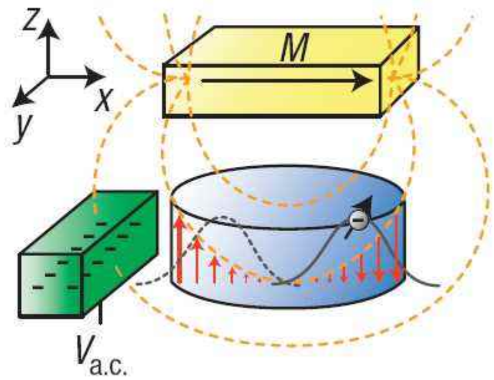
Long-lived coherence
$T_2^* \sim 100\ \mu s,\ T_{2,DD} \sim 28$ ms



Veldhorst et al, Nat Nano 2014

Single-qubit fidelity > 99.9%

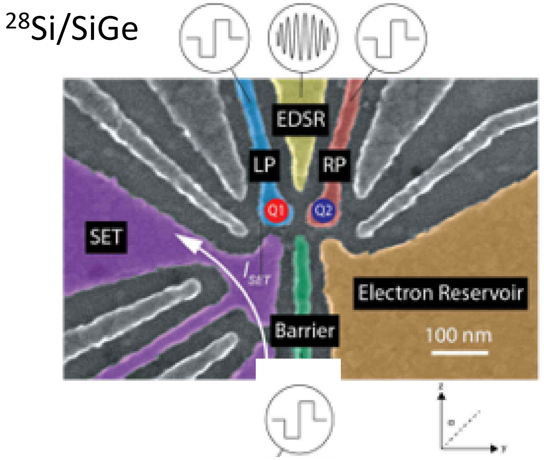


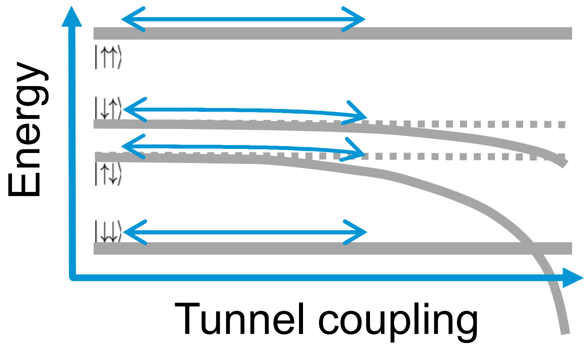


Yoneda et al Nature Nano 2018

Aiming at > 99% fidelity CZ operation

X. Xue, M. Russ et al, Nature 2022





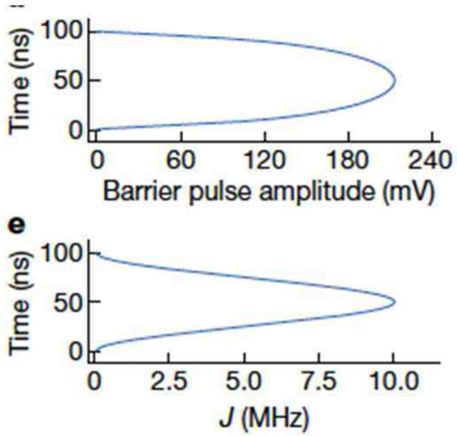
Heisenberg exchange

$H \sim X_1X_2 + Y_1Y_2 + Z_1Z_2$

Δf

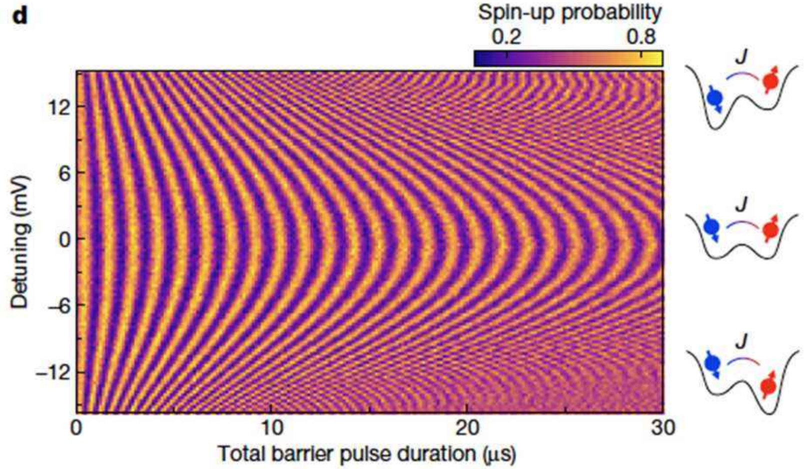
Ising $H_{eff} \sim Z_1Z_2$

Ensure adiabaticity
invert relationship J vs V_g

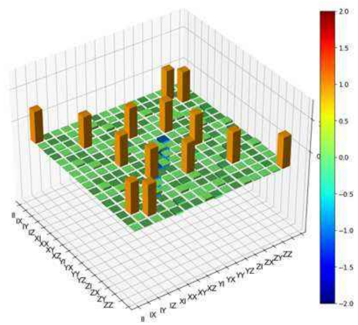


Maintain symmetry condition

After Reed et al, PRL 2016, Martins et al, PRL



Gate set tomography to tweak calibration



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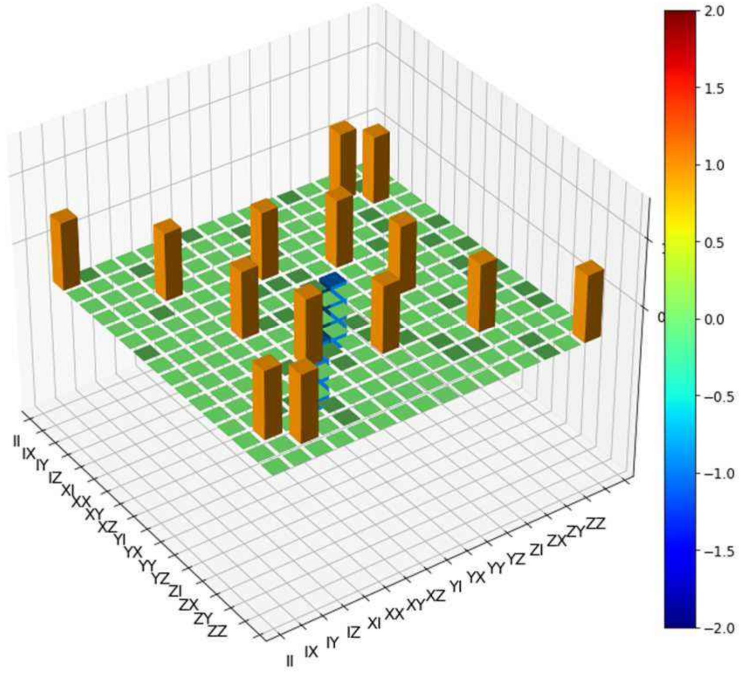
Two-qubit gate fidelity up to 99.65% ± 0.15%

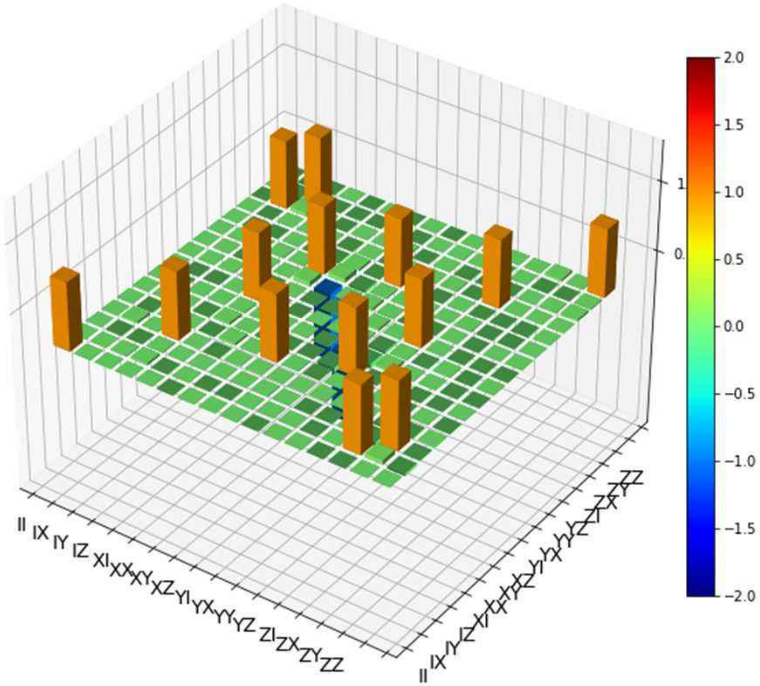
X. Xue, M. Russ et al, Nature 2022

see also A. Noiri et al, Nature 2022
A. Mills et al, Sci. Adv. 2022
^{31}P donors: Madzik et al, Nature 2022

Ideal CPhase



Measured CPhase



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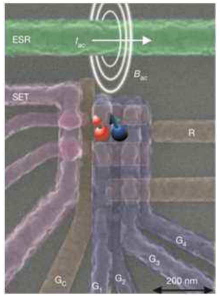
CPhase fidelity is limited by incoherent errors

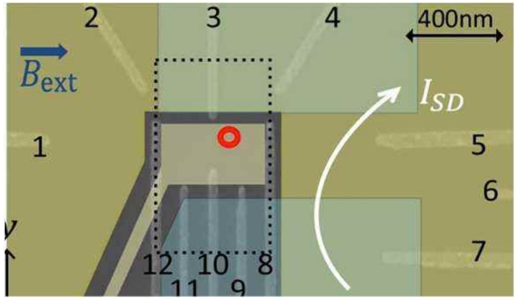
Scaling spin qubit arrays

2-qubit gate in SiMOS



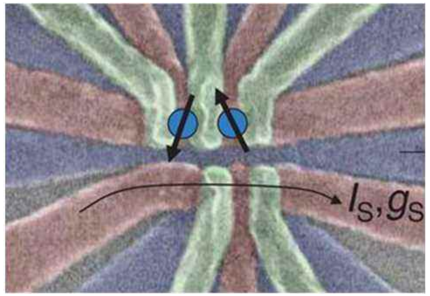
M. Veldhorst et al,
Nature 2015

2-qubit entanglement (fid. 90%) in Si/SiGe



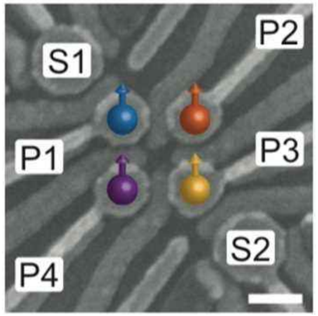
T. Watson et al,
Nature 2018

2-qubit entanglement (fid. 78%) in Si/SiGe



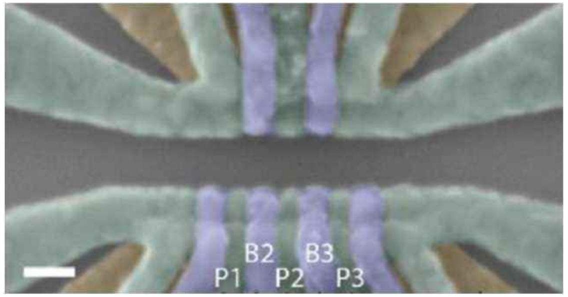
D. Zajac et al,
Science 2018

full control of 4 Ge/SiGe spins



N. Hendrickx et al,
Nature 2020

entanglement of 3 Si/SiGe spins



K. Takeda et al,
Nature Nano 2021

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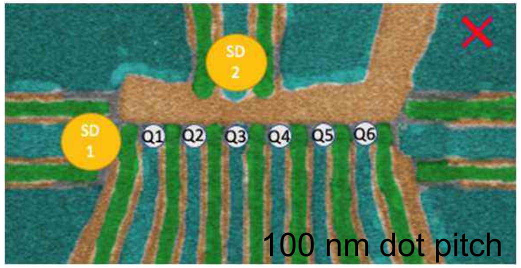
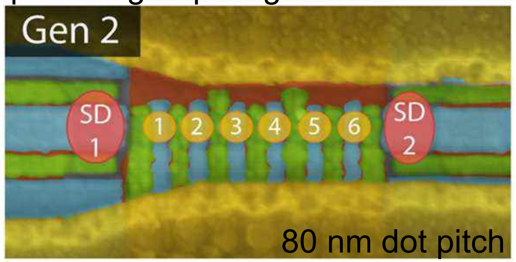
A linear Si/SiGe six-dot array

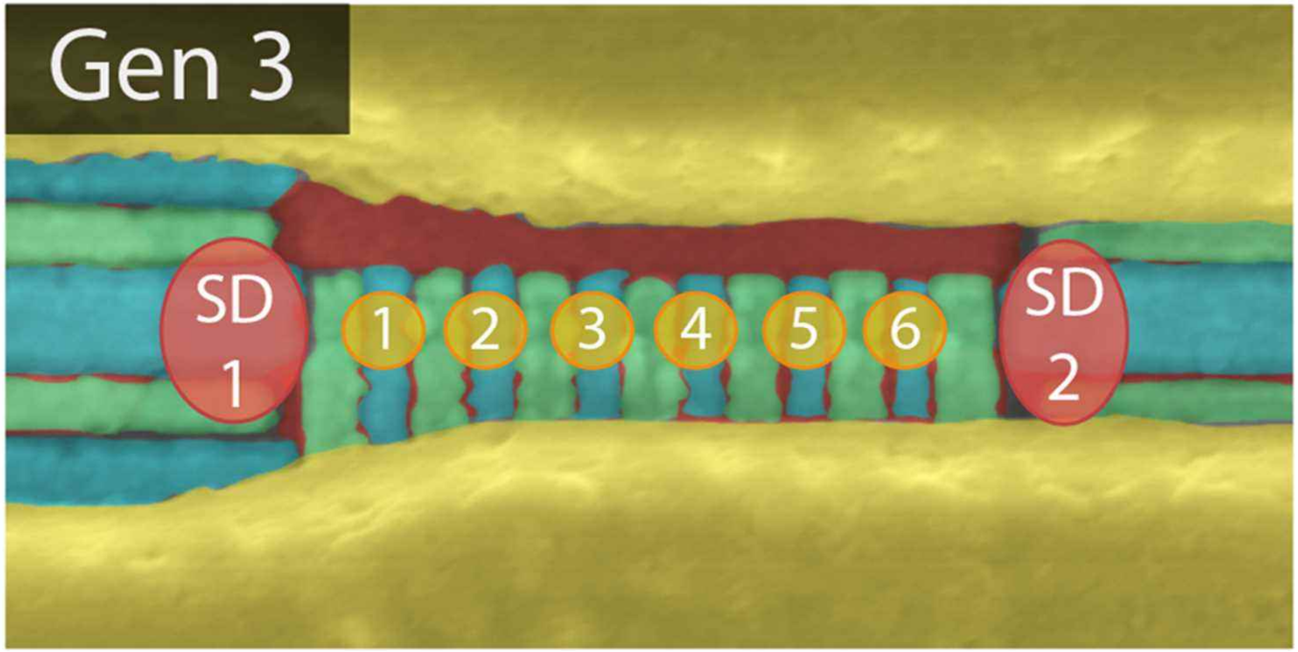
S. Philips, M. Mądzik, et al, Nature 2022

Gen1: 4 qubits working, one small E_v



Gen2: 6 qubits working, slow and poor single-qubit gates





90 nm dot pitch

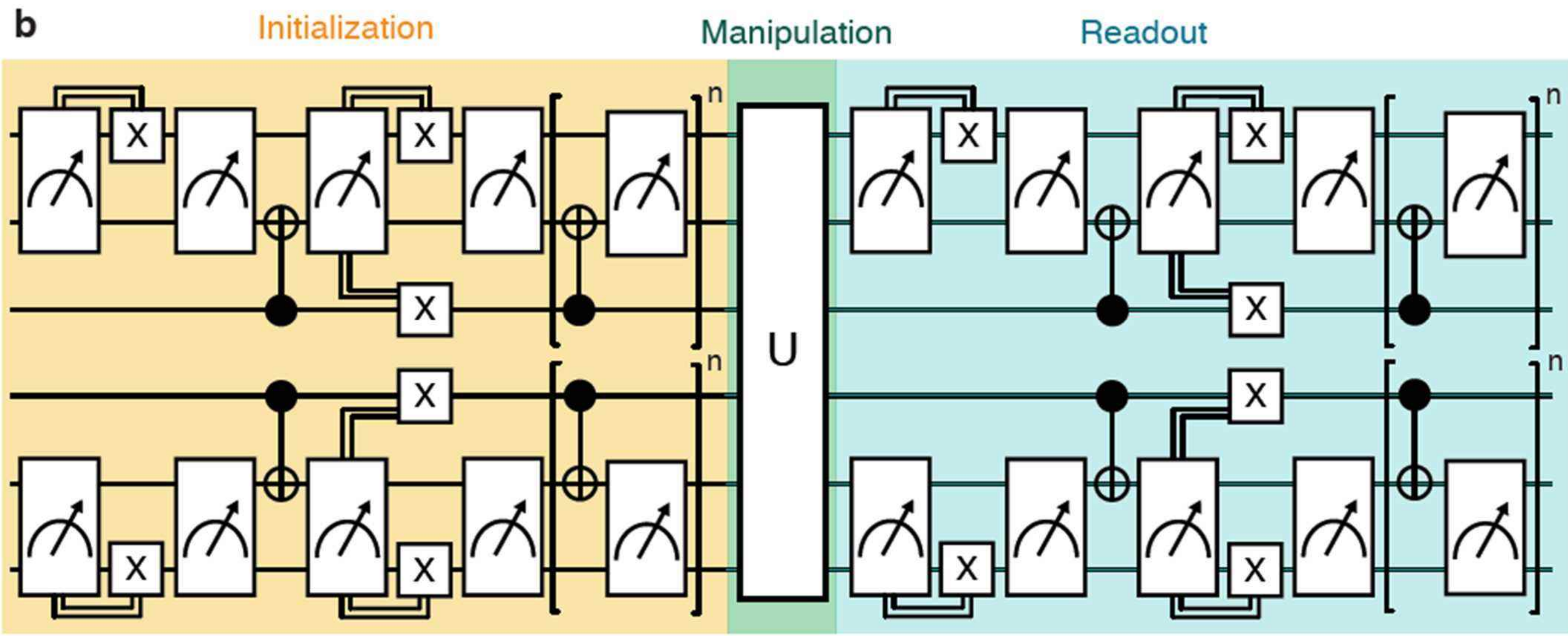
Initialized in (311131)

^{28}Si/SiGe from Scappucci group
Fab by D. Brousse & S. Amitonov et al

Six-spin initialization by measurement and real-time feedback

S. Philips, M. Mądzik, et al, Nature 2022

Total duration of each cycle 2-3 ms (incl 10 us per PSD readout)



In addition, we also postselect to further enhance the initialization fidelity

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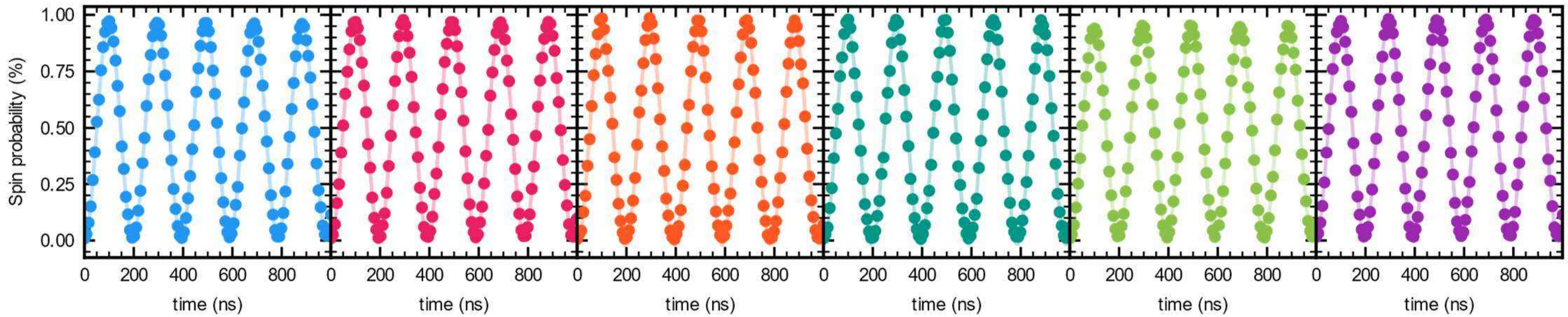
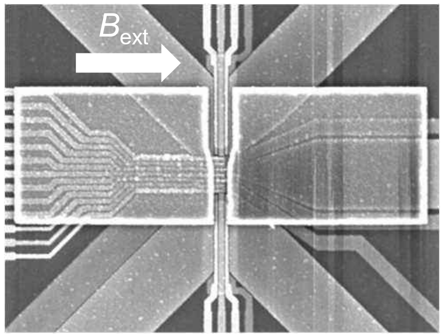
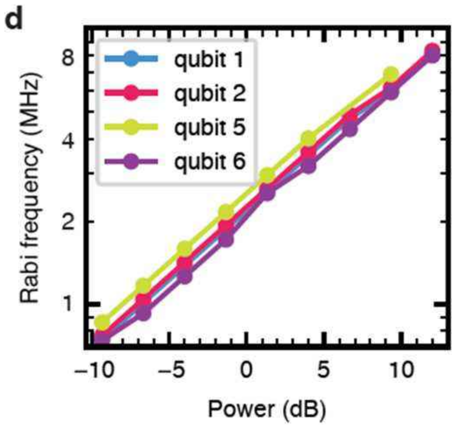
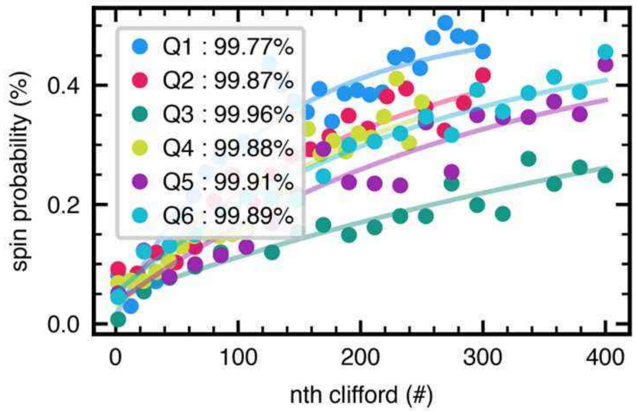
Single-qubit control (EDSR)

S. Philips, M. Mądzik, et al,
Nature 2022









Qubit	T_2^*(us)	T_2^h(us)	Vis(%)
1	3.0	14.0	96
2	2.5	21.1	97
3	3.7	40.1	97
4	3.7	37.2	97
5	5.9	44.7	93
6	5.1	26.7	95

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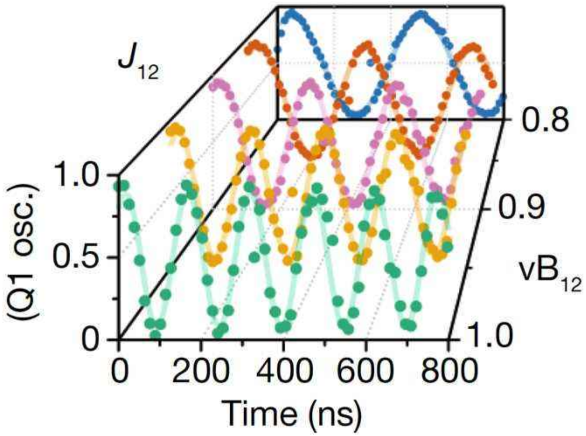
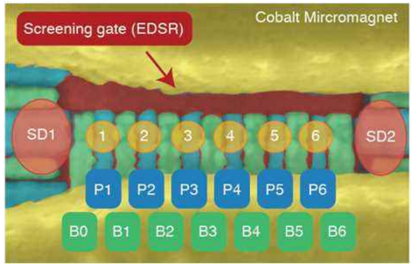
Entangled pairs across the array

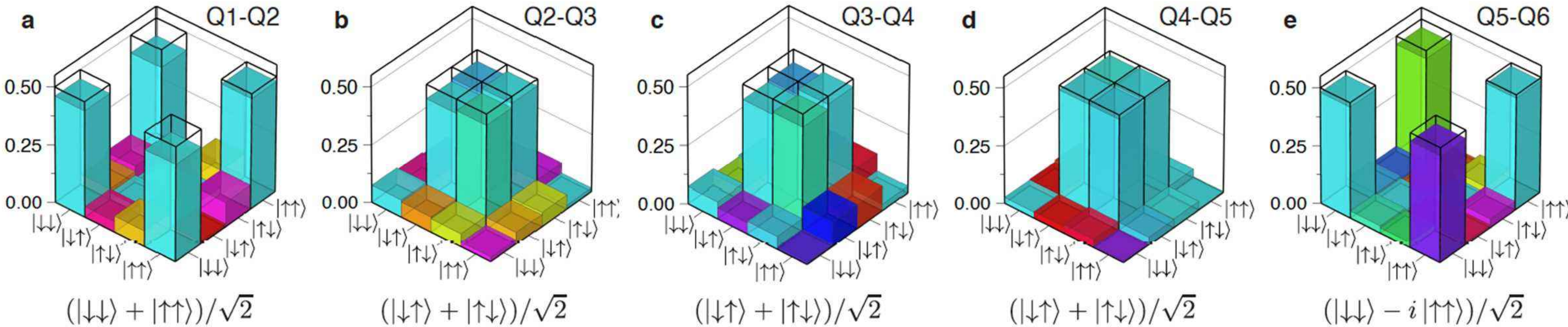
S. Philips, M. Mądzik, et al, Nature 2022





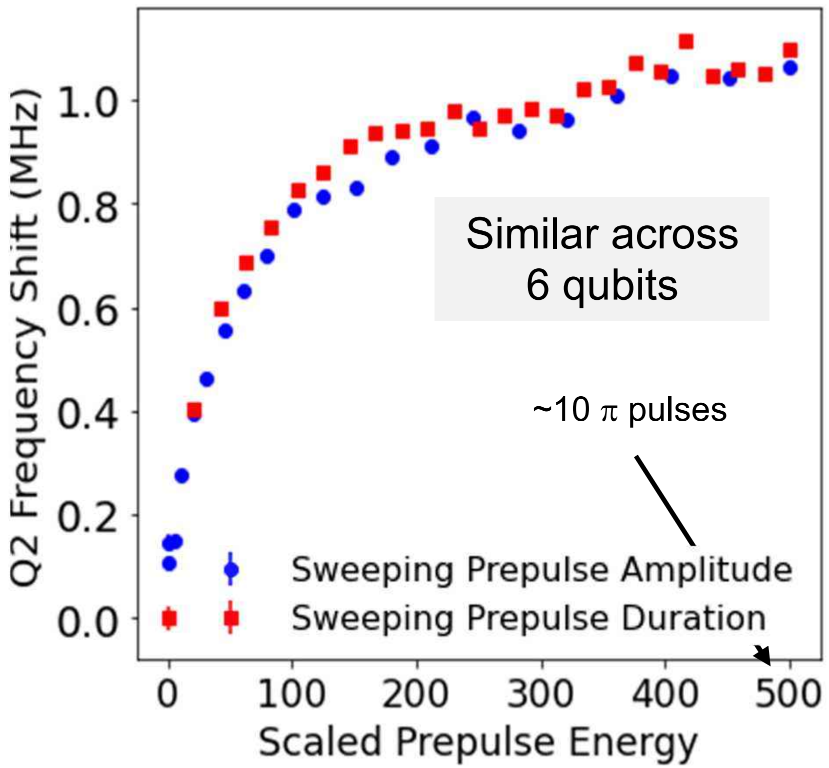
coupling on/off ratios $\gtrsim$ 100

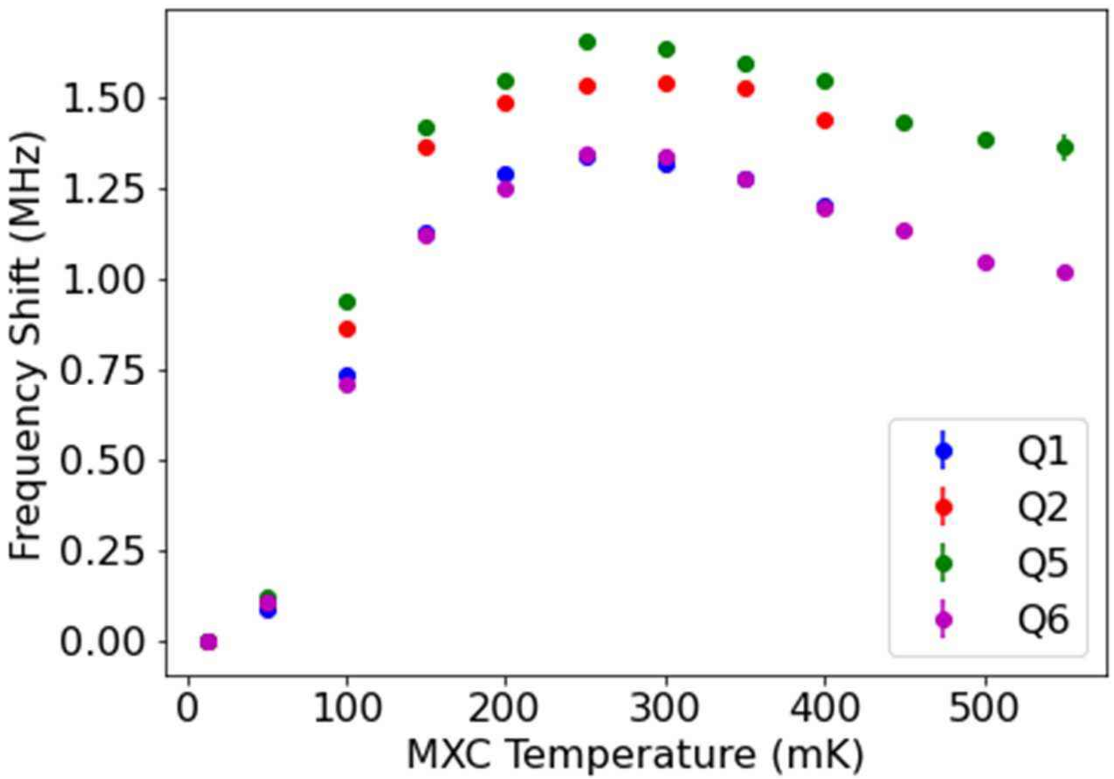
Qubits	Fidelity (%)
1-2	89.2 ± 2.2
2-3	90.1 ± 2.2
3-4	88.3 ± 3.6
4-5	95.6 ± 2.0
5-6	94.1 ± 1.4



Surprise: Spin resonance frequency shifts with microwave driving … and with temperature

B. Undseth, O. Pietx I Casas,
arXiv:2304.12984





See also Watson et al, Nature 2018
Takeda et al, npj Q Info 2018

Non-monotonous temperature dependence

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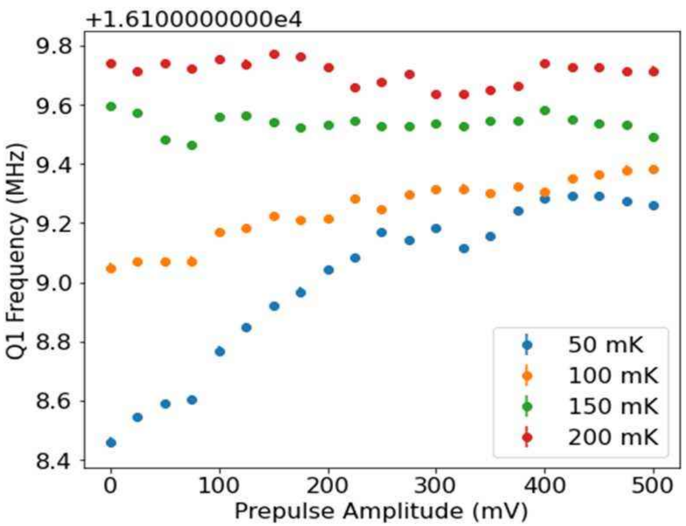
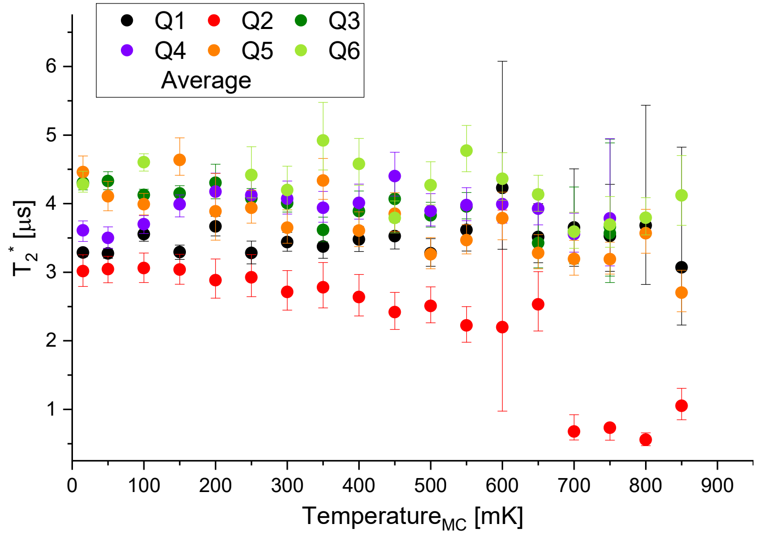
Operating at 200 mK makes life easier!

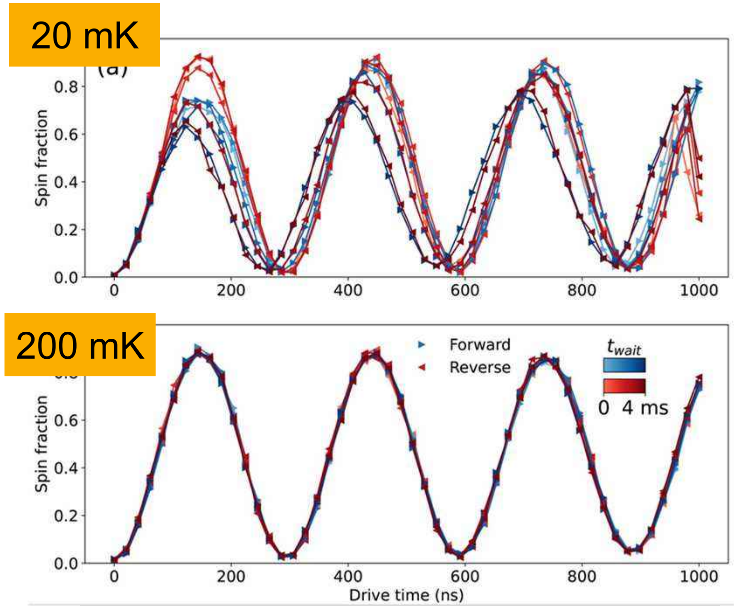
B. Undseth, O. Pietx I Casas, arXiv:2304.12984



No more ”RF heating” effects



T_2* barely reduced at 200 mK



Contextuality of Rabi oscillations disappears

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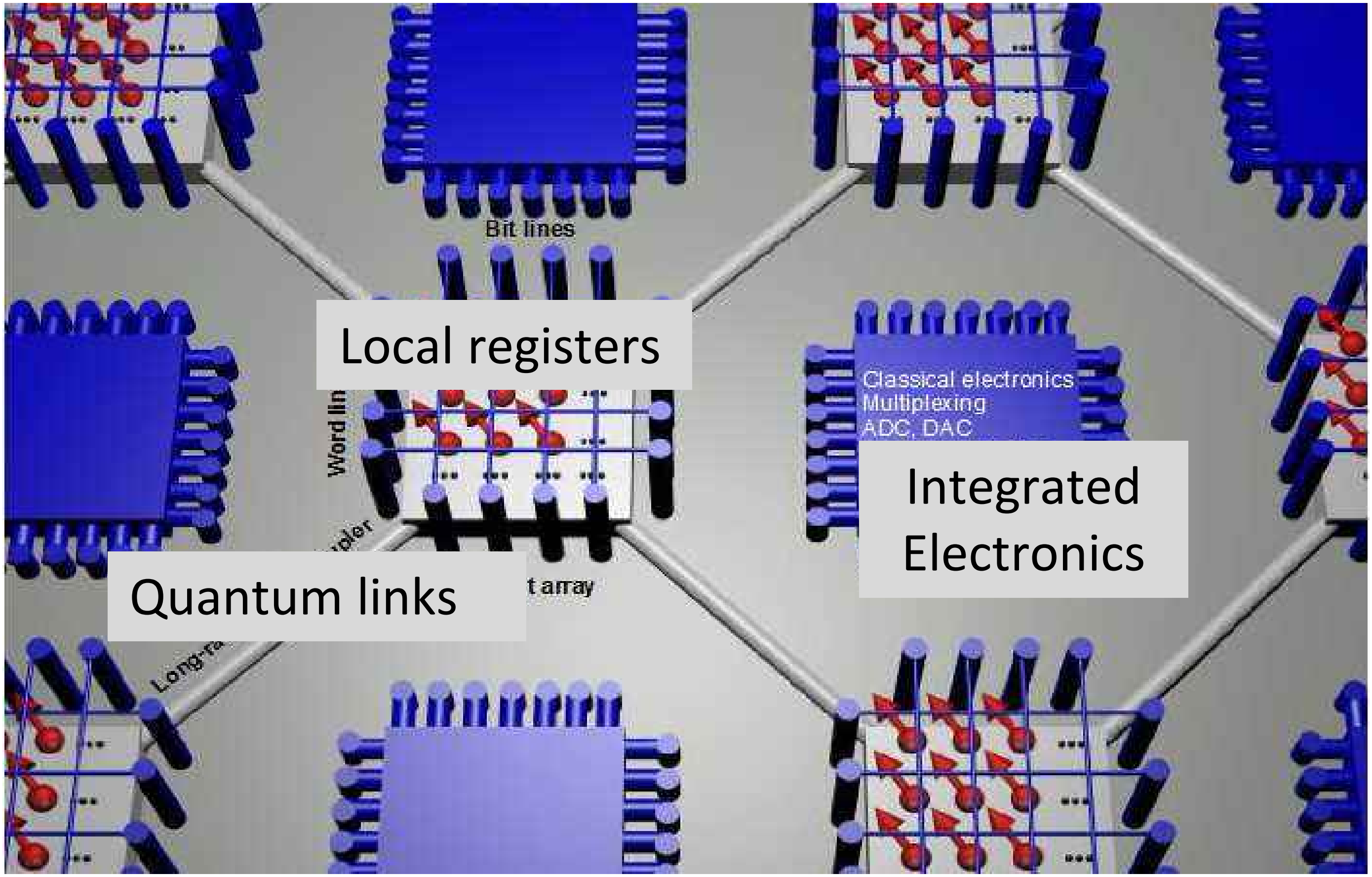
Our vision of a scalable semiconductor spin qubit processor – hot, dense and coherent



L.M.K. Vandersypen, H. Bluhm, J.S. Clarke, A.S. Dsurak, R. Ishihara, A. Morello, D.J. Reilly, L.R. Schreiber, and M. Veldhorst., npj Q Info 2017

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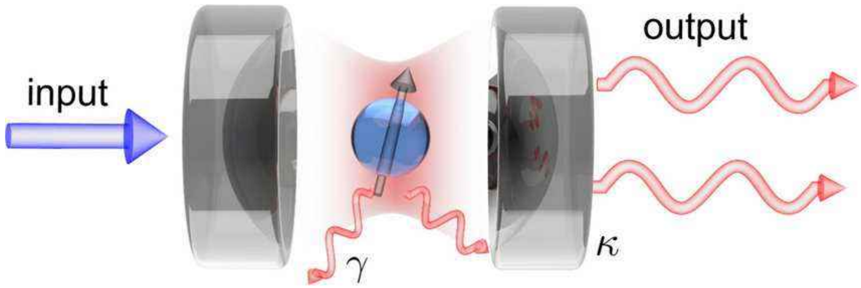
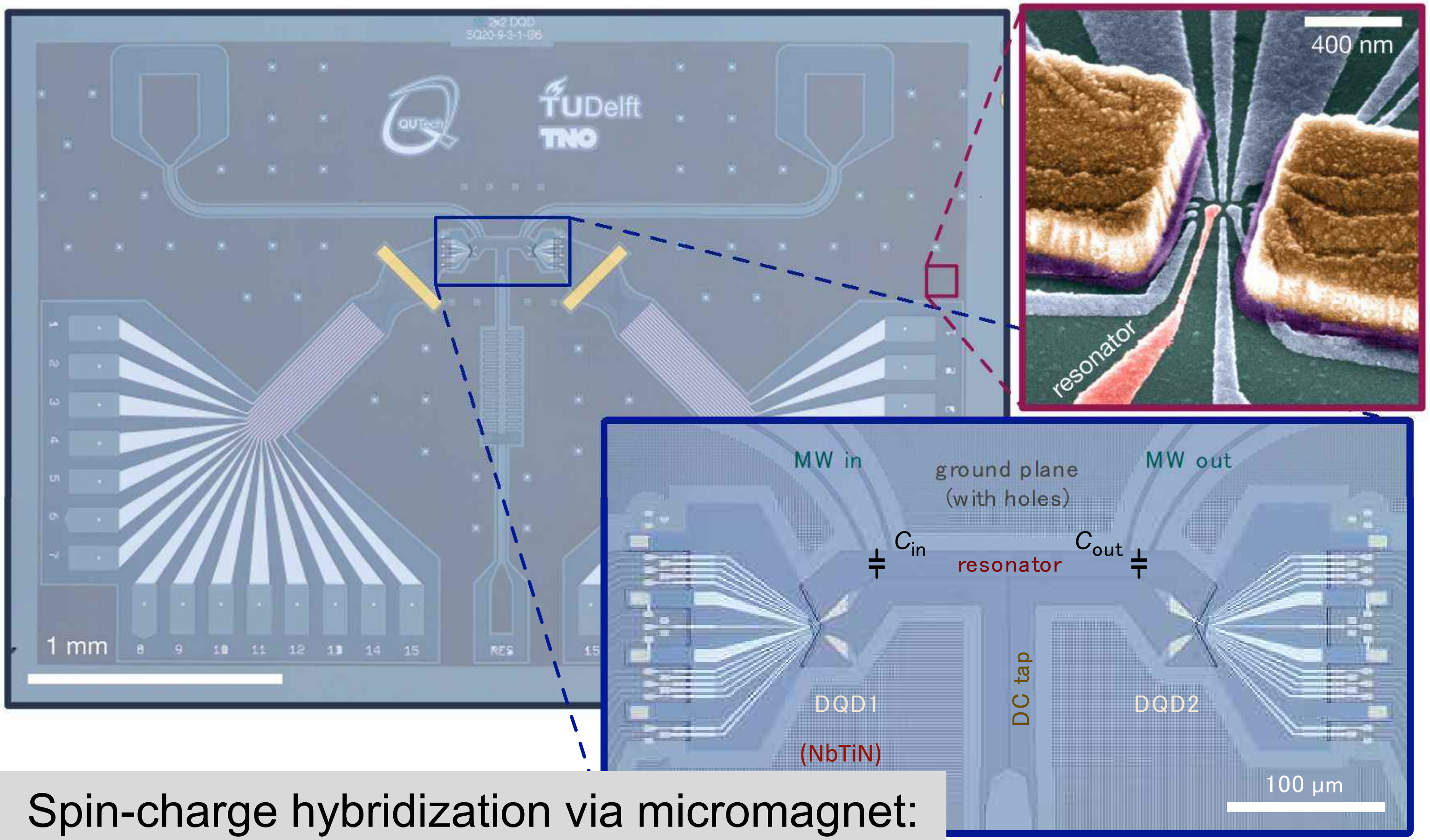
Hybrid quantum dot-resonator proposals



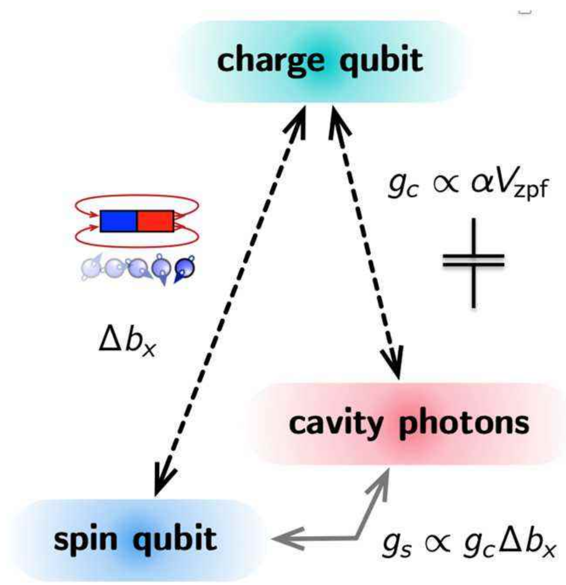
L. Childress, et al, Phys. Rev. A 69, 042302 (2004).
G. Burkard, et al Phys. Rev. B 74, 041307 (2006)
M. Trif, V. N. Golovach, D. Loss, Phys. Rev. B 77, 045434 (2008)
A. Cottet, T. Kontos, Phys. Rev. Lett. 105, 160502 (2010).
C. Kloeffel, et al, Phys. Rev. B 88, 241405 (2013).
F. Beaudoin, et al, Nanotechnology 27, 464003 (2016).
Hu *et al.*, *Phys. Rev. B* 86, 035314 (2012)
Beadoin *et al.*, *Nanotechnology* 27, 464003 (2016)
Benito *et al.*, *Phys. Rev. B* 96, 235434 (2017)
…

Coupling distant spins via (virtual) microwave photons

P. Harvey-Collard, et al, PRX 2022



Spin-charge hybridization via micromagnet:
Photon interacts indirectly with spin.

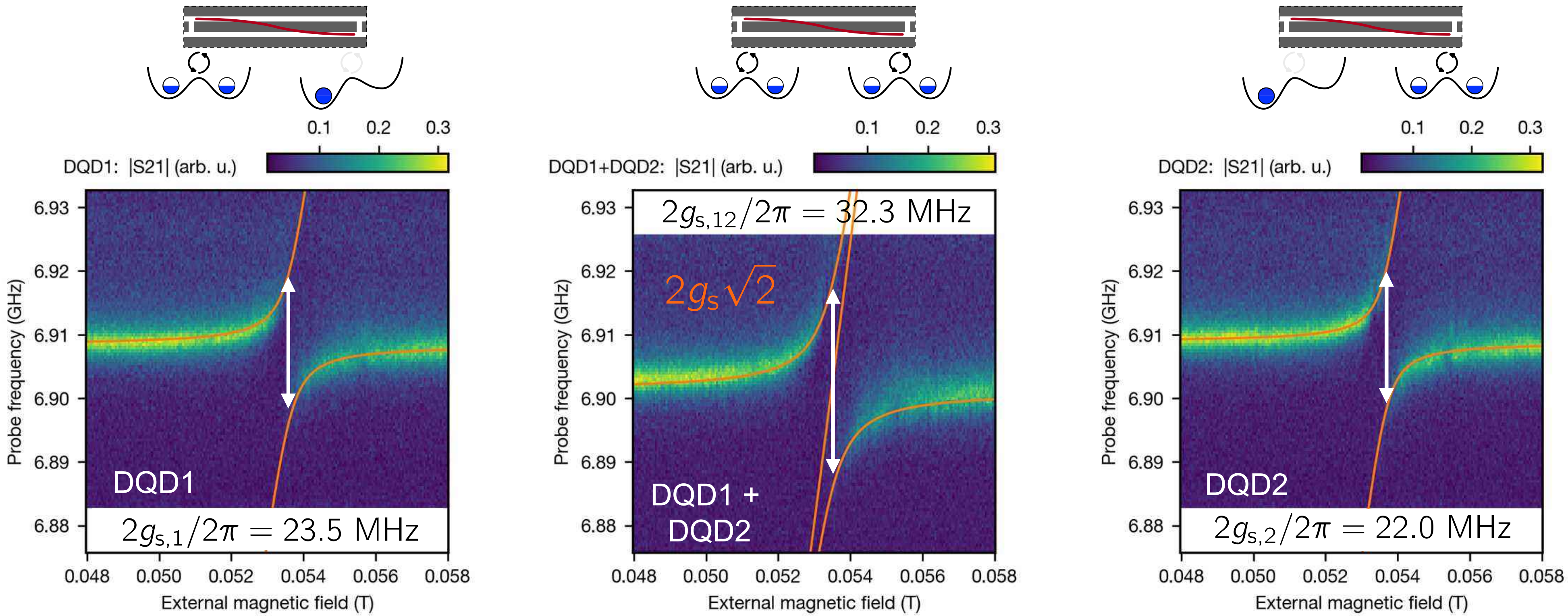


novel filters
P. Harvey-Collard et al, PRAppl 2020

Simultaneous resonant spin-photon interaction at both sites

P. Harvey-Collard, et al, PRX 2022

See also Borjans et al, Nature 2020



Enhanced vacuum Rabi splitting
Indicates coherent spin-spin-photon interaction

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Dispersive spin-spin coupling

P. Harvey-Collard, et al, PRX 2022

$$2J = g_{s1} g_{s2} \left(\frac{1}{\Delta_{s1}} + \frac{1}{\Delta_{s2}} \right)$$

$g_{si}/2\pi$ ~ 32 MHz

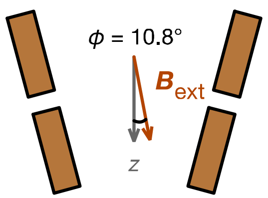
$\Delta_{si}/2\pi$ = -112 MHz

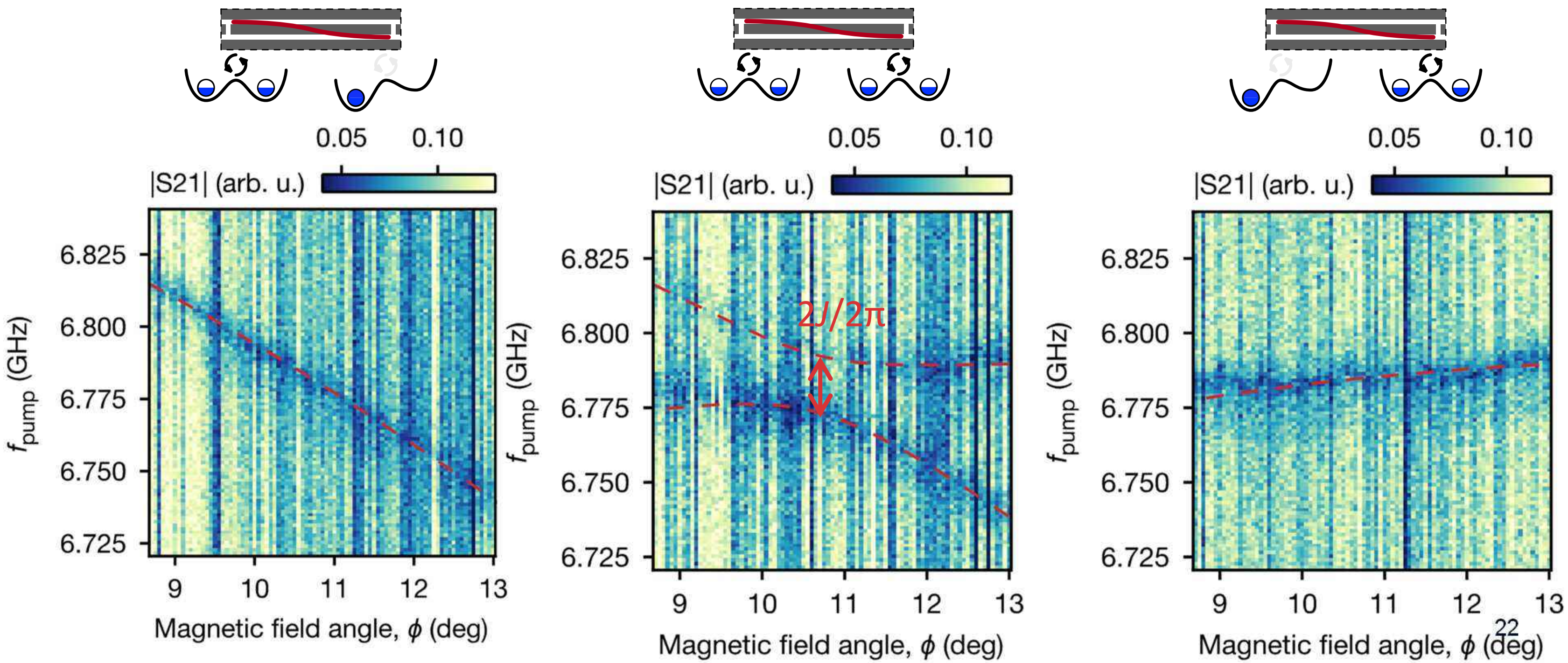
"Strong spin-spin coupling regime"

$\gamma_{s1}/2\pi$ = 6 MHz $J/2\pi$ = 9.5 MHz $\gamma_{s2}/2\pi$ = 6 MHz

Two-tone spectroscopy reveals the spin qubit frequencies

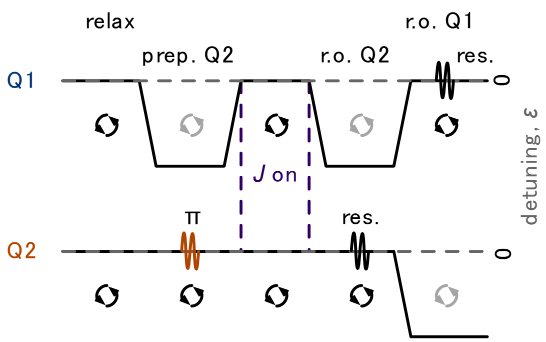
B_{ext} orientation tunes spin frequencies



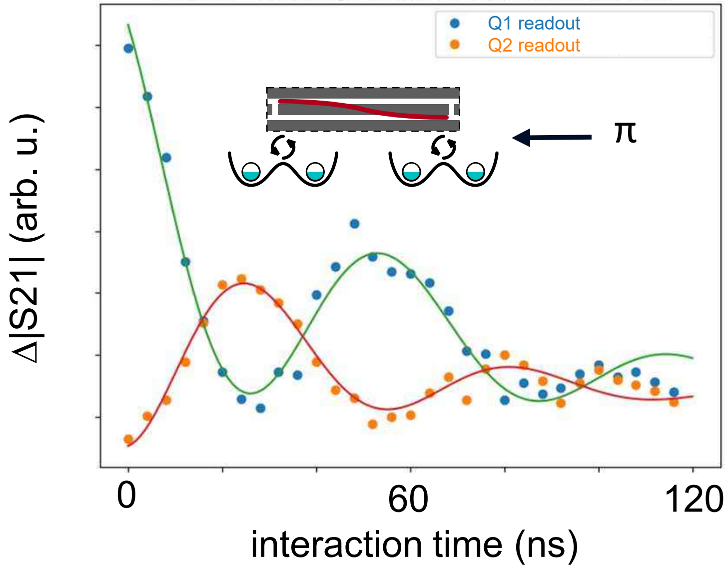


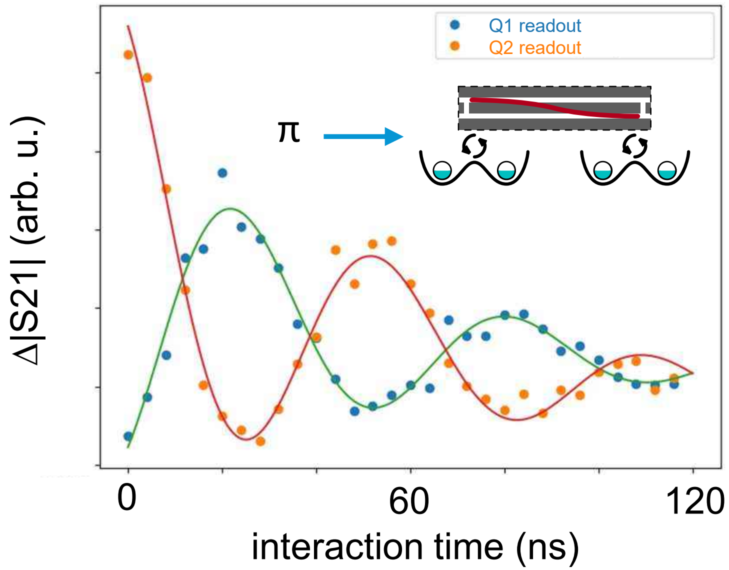
Two-qubit logic of distant spins

J. Dijkema, X. Xue, unpublished



iSWAP evolution under the Jaynes-Cummins Hamiltonian





Spin-photon coupling:
Spin-cavity detuning 120 MHz:
$2J \sim 17.5$ MHz

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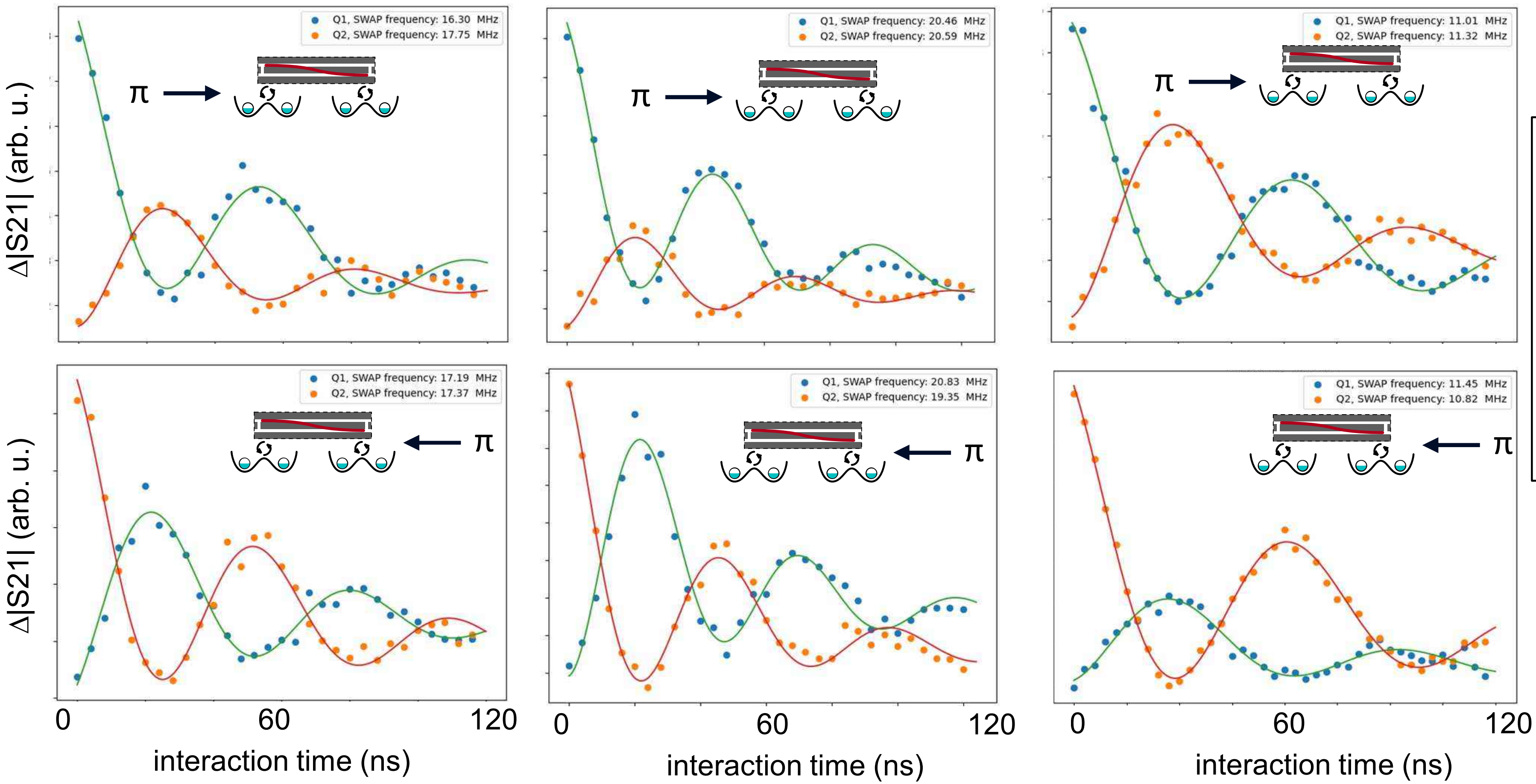
Controlling the spin exchange rate

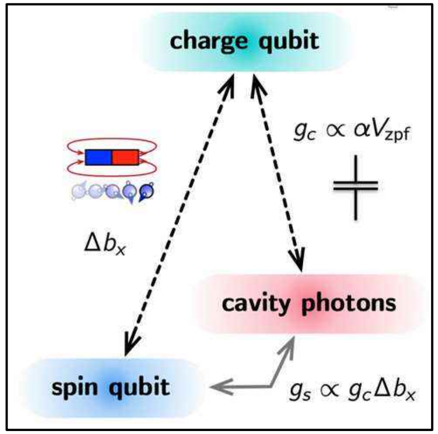
J. Dijkema, X. Xue, unpublished

Spin-cavity detuning 120 MHz: $2J \sim 17.5$ MHz

Spin-cavity detuning 95 MHz: $2J \sim 20.5$ MHz

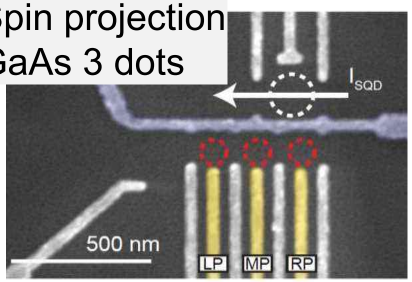
Increase charge-photon detuning: $2J \sim 11$ MHz





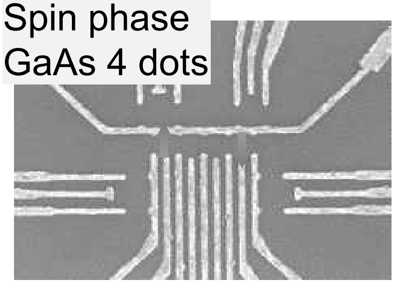
Shuttling charges and spins

Spin projection
GaAs 3 dots



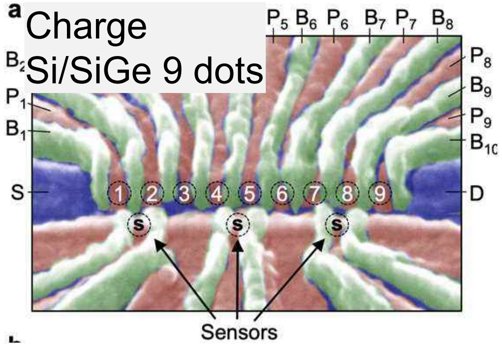
Baart, Shafiei et al,
Nat Nano 2016

Spin phase
GaAs 4 dots



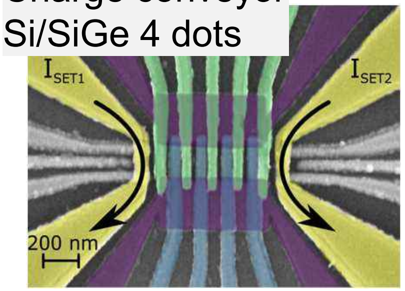
Fujita et al, npj Q Info 2017

Charge
Si/SiGe 9 dots



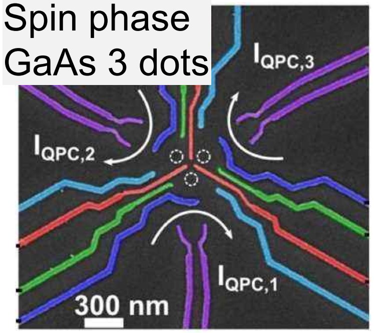
Mills et al, Nat Comm 2019

Charge conveyor
Si/SiGe 4 dots



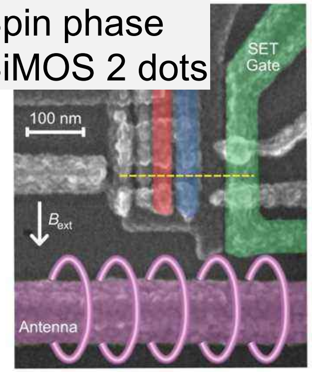
Seidler et al, npj Q Info, 2022

Spin phase
GaAs 3 dots



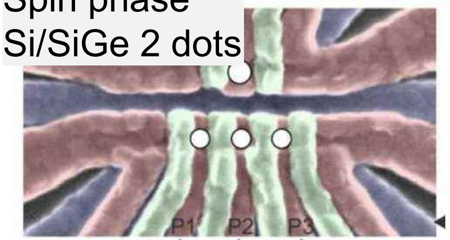
Flentje et al,
Nat Comm 2017

Spin phase
SiMOS 2 dots



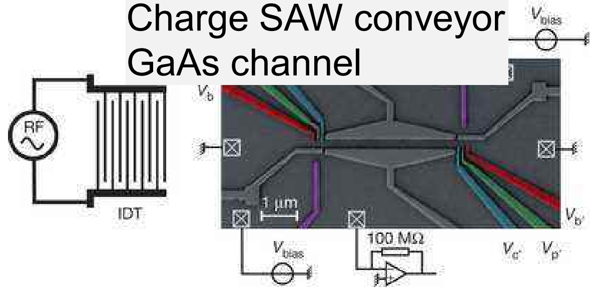
Yoneda et al, Nat Comm 2021

Spin phase
Si/SiGe 2 dots



Noiri et al, arXiv:2202.01357

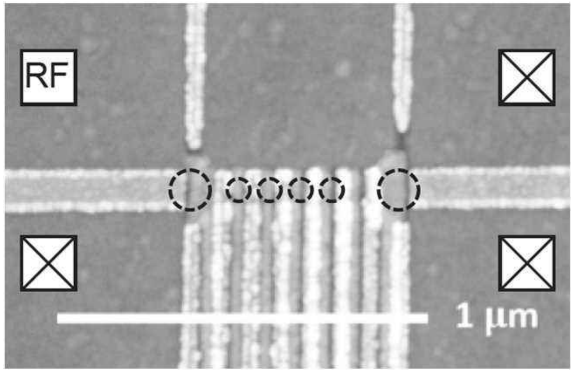
Charge SAW conveyor
GaAs channel

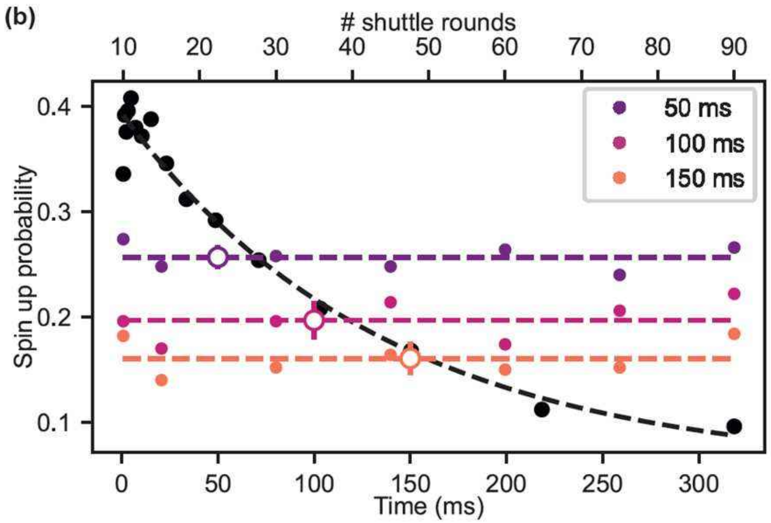


Hermelin et al, Nature 2011
McNeil et al, Nature 2011

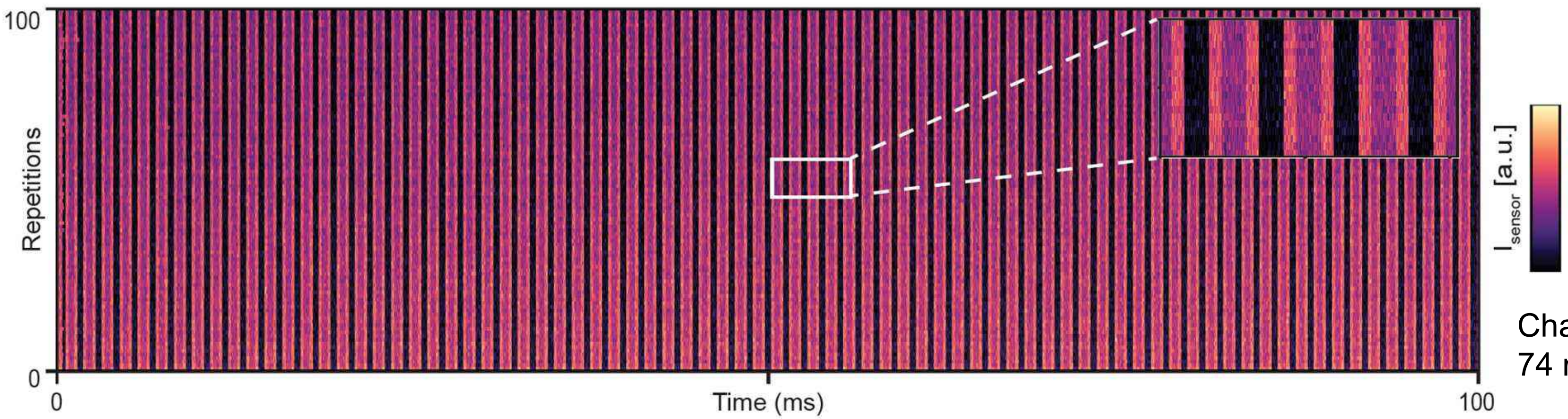
Spin shuttling in silicon quantum dot arrays

A.M. Zwerver et al, arXiv:2209.000920





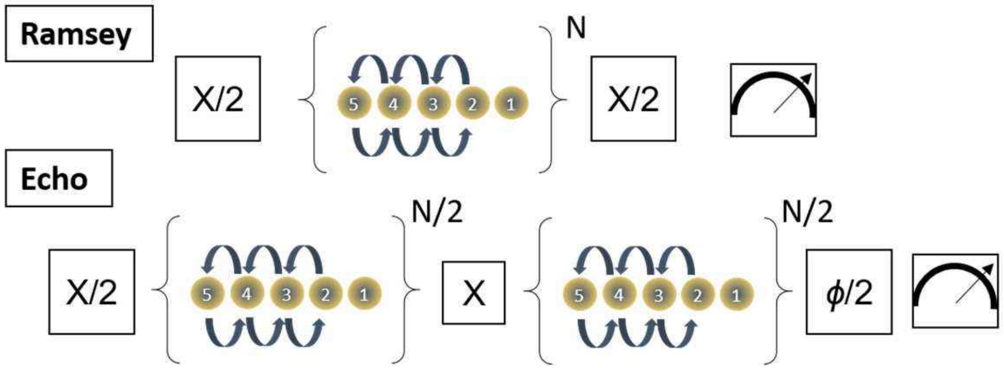
No detectable impact of shuttling on spin polarization over > 500 hops

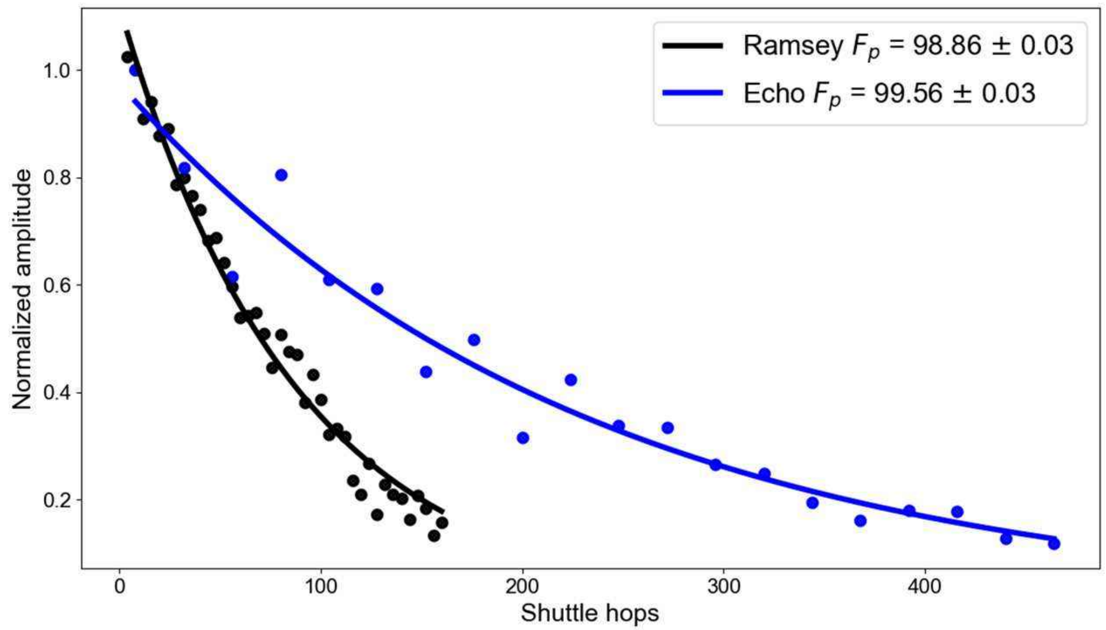


Charge shuttling
74 rounds across the first 3 dots

Coherent spin shuttling
Preliminary data

M. De Smet, Y. Matsumoto, et al, unpublished





	Q2-3	Q2-4	Q2-5
Ramsey	98.41	98.86	98.97
Echo	98.99	99.56	99.62

Low-frequency noise can be echoed out.
Zeeman energy differences impact spin coherence.

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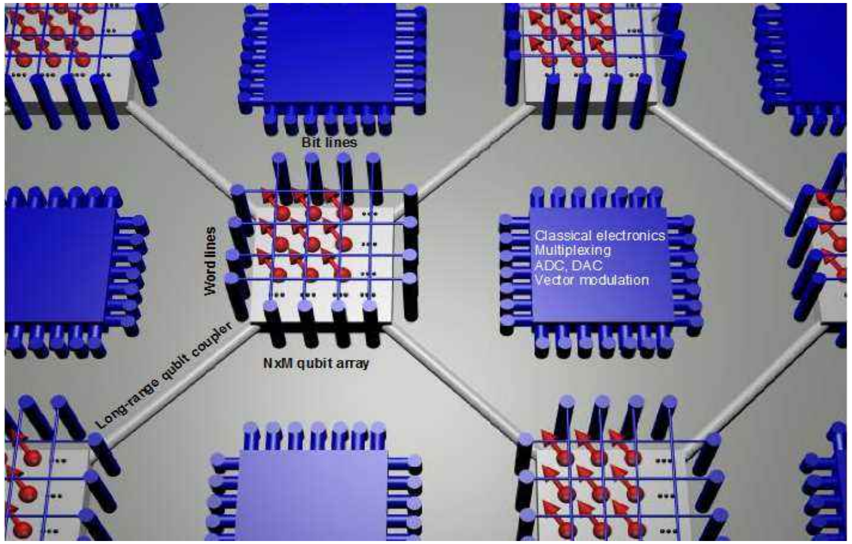
Advancing the realization of our vision



Single- and two-qubit control with >99.5 fidelity

Small-scale quantum algorithms shown, 6-qubit control

Distant spin-spin coupling, path to on-chip qubit networks

Fully industrial qubits match quality of academic devices

Qubits function above 1 K, modest coherence degradation

CryoCMOS 2-qubit control matches quality of RT control

Not only the pieces are coming together,
but also the prospects of large-scale integration of qubits (and electronics)

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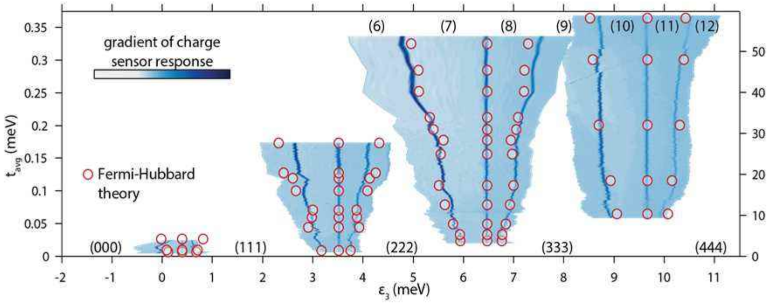
Analog quantum simulation of Fermi-Hubbard physics

$$H = -\sum_i \epsilon_i n_i - \sum_{<i,j>,\sigma} t_{ij}(c^\dagger_{i\sigma} c_{j\sigma} + \text{h.c.}) + \sum_i \frac{U_i}{2} n_i(n_i - 1) + \sum_{i,j} V_{ij} n_i n_j$$

Dots can reach $k_B T$ << *t* < U, with tuneable *t*/*U* and *μ*/*U*

U dominated



T. Hensgens et al., Nature 2017

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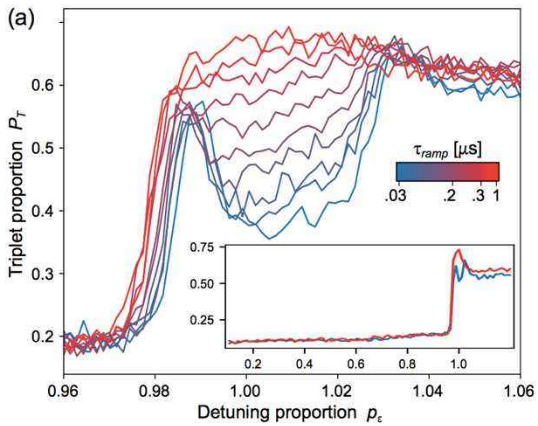
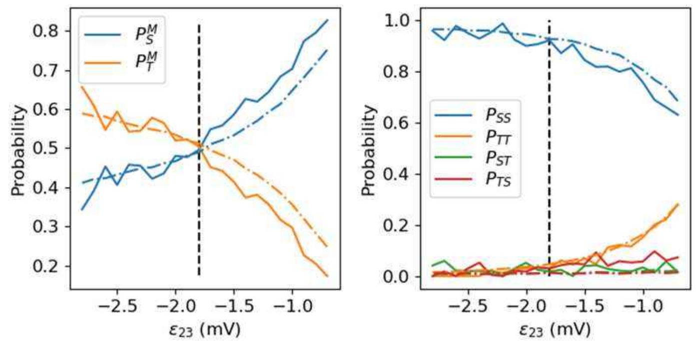
t dominated



Dehollain, Mukhopadhyay, et. al., Nature 2020
Kiczynski et al, Nature 2022

J~*t*²/*U* dominated



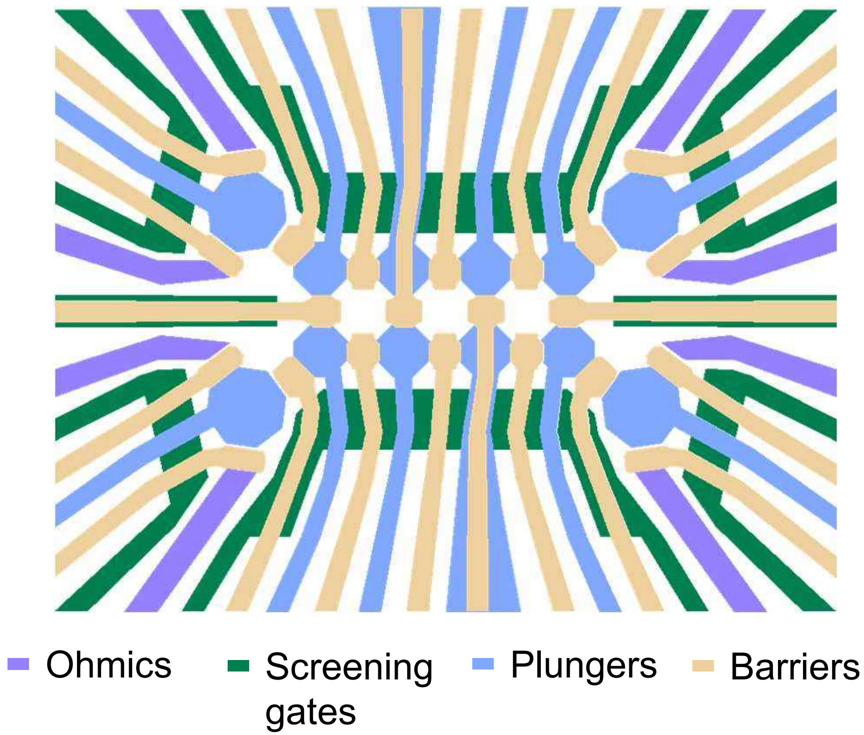
van Diepen, Hsiao, et. al., PRX 2021
See also H. Qiao, PRX 2020
Salfi, et al, Nat Comm 2016
Wang et al, arXiv:2208.11505

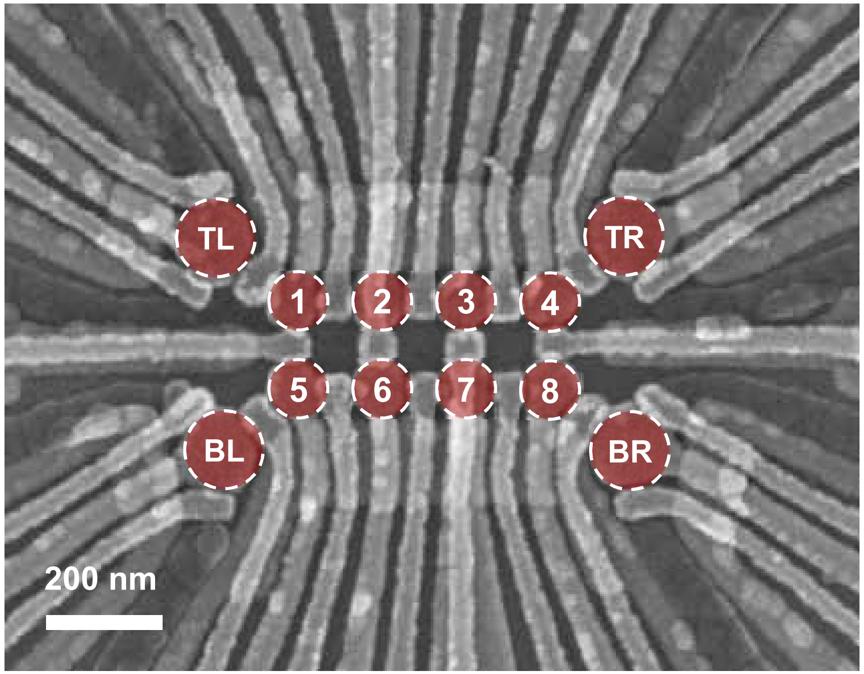
Exciton physics in 4x2 ladder

V dominated

T.K. Hsiao, P. Cova Fariña, et al
arXiv:2307.02401

Multi-layer fabrication



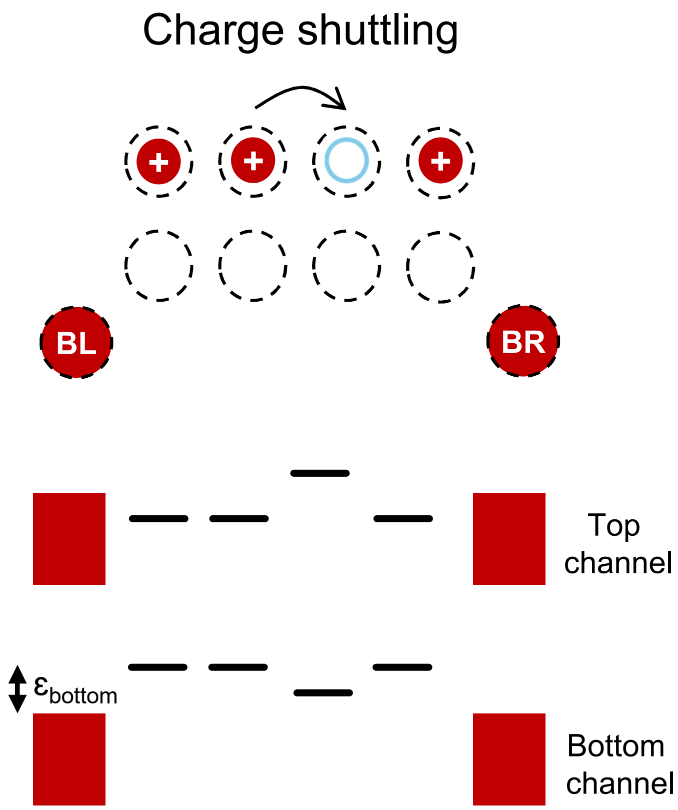


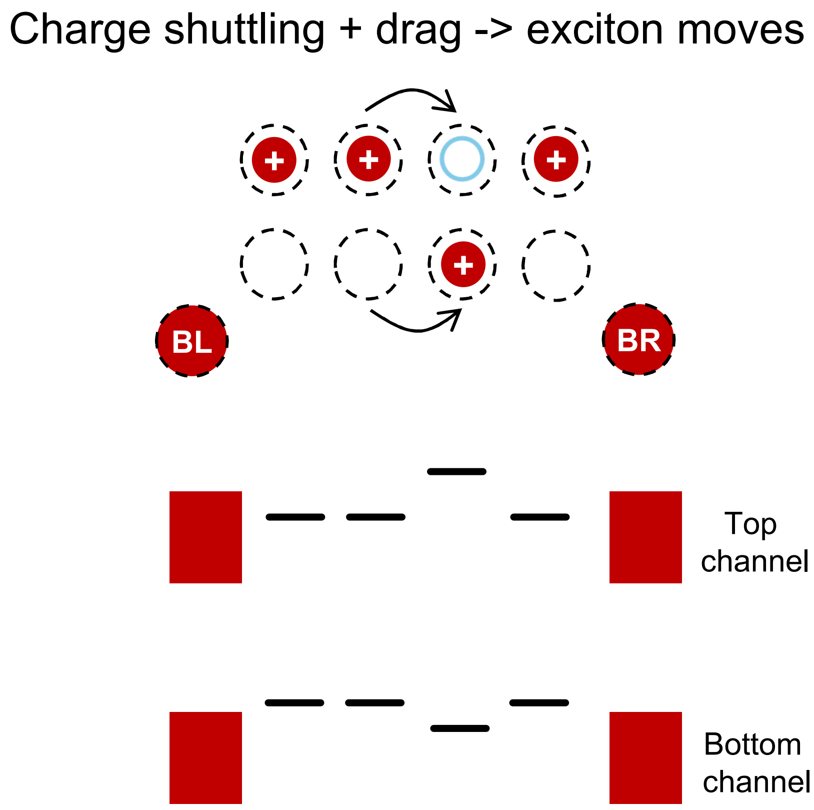
Fabrication: Stefan Oosterhout with Veldhorst group

Ge/SiGe qwell: Amir Sammak Scappucci group

Exciton formation from long-range Coulomb interaction

T.K. Hsiao, P. Cova Fariña, et al
arXiv:2307.02401





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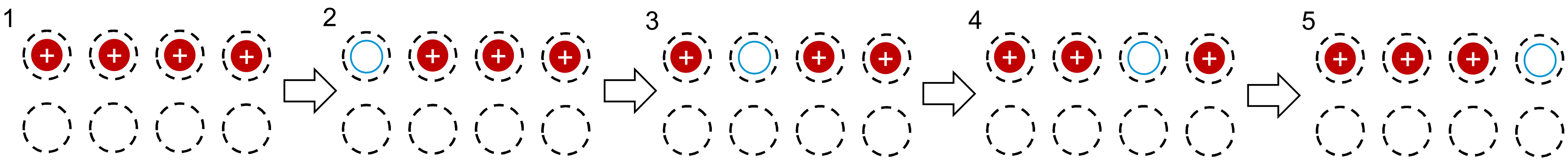
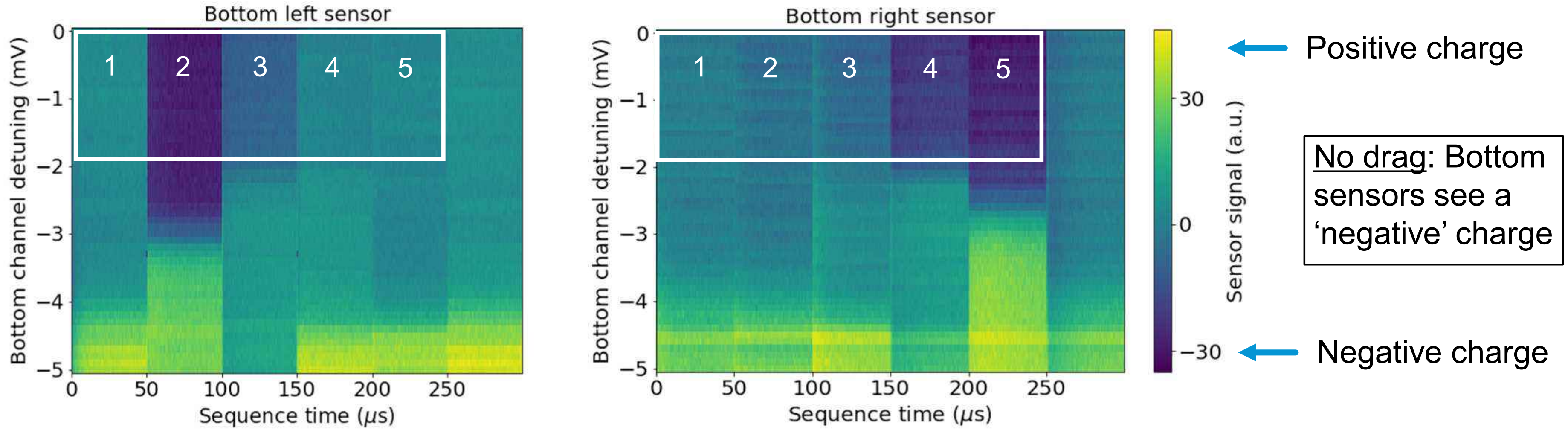
Note: gate voltage pulses applied in virtual gate space

Results no-drag regime

T.K. Hsiao, P. Cova Fariña, et al
arXiv:2307.02401





No drag: Bottom sensors see a 'negative' charge

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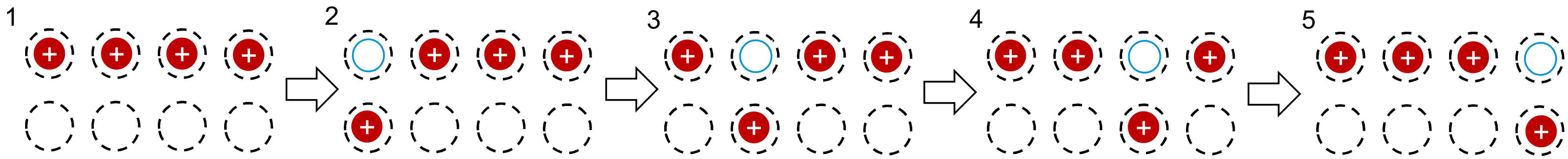
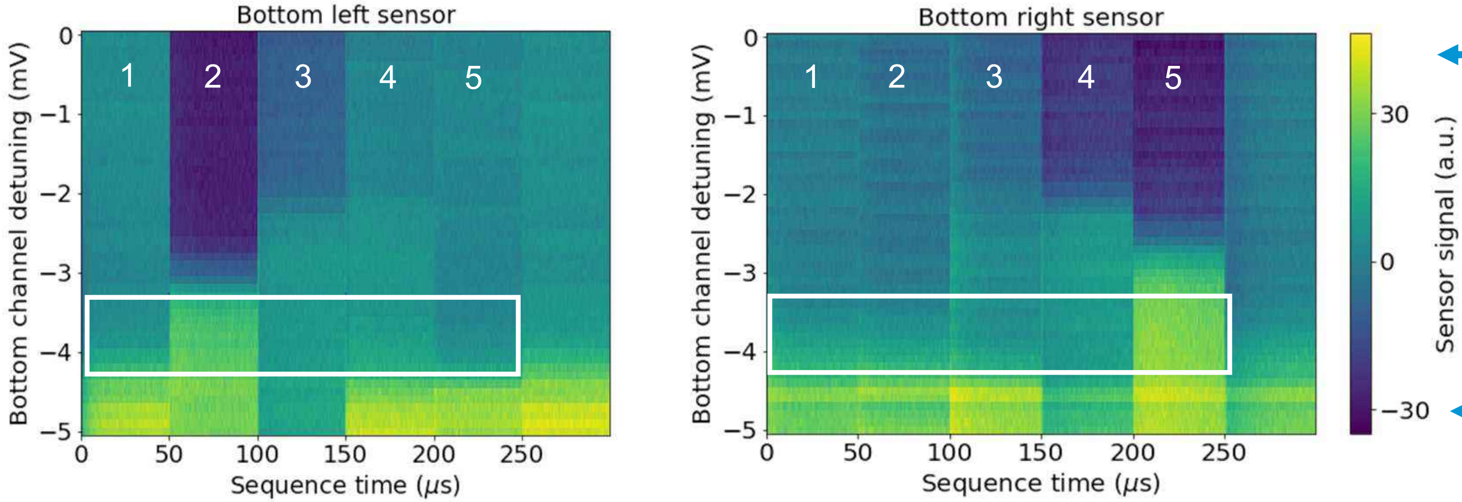
Results drag regime

T.K. Hsiao, P. Cova Fariña, et al
arXiv:2307.02401





Positive charge

Negative charge

Drag: Bottom sensors see a net 'positive' charge

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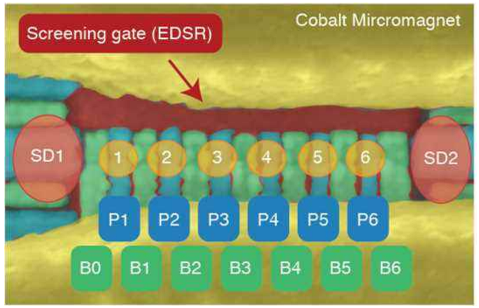
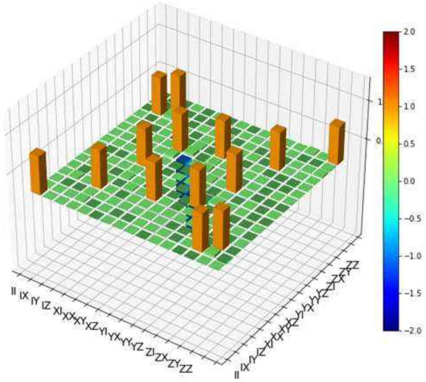
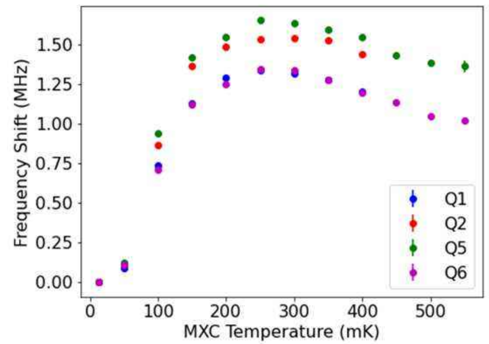
Summary



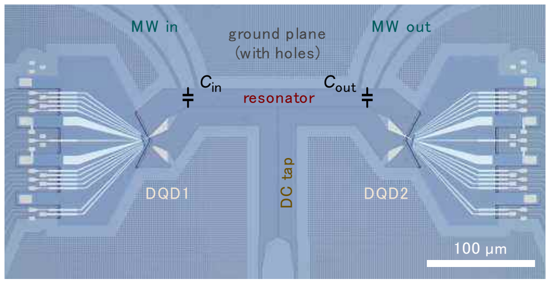
Universal control of 6 qubits



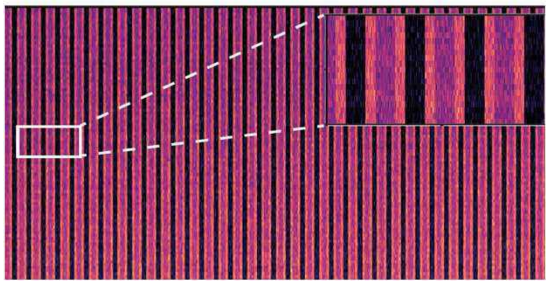
> 99.5% 2-qubit gate fidelity



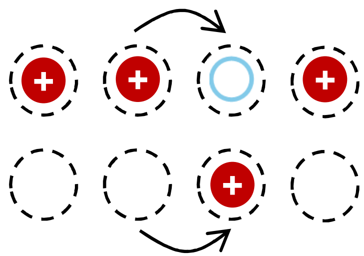
Surprising T dependence



Universal control of distant spins



Shuttling spins



Exciton formation and transport

Acknowledgements

https://qutech.nl/lab/vandersypen-lab

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G. Scappucci

W. Lawrie
M. Meyer
S. Oosterhout (TNO)
M. Veldhorst

M. Mehmandoost
S. Dobrovitski

Si/SiGe (U Wisconsin)
M. Eriksson
S. Coppersmith, M. Friessen

GaAs Heterostructures (ETH)
C. Reichl, W. Wegscheider

U. Maryland (theory)
Xiao Li, S. Das Sarma

Harvard U. (theory)
B. Wunsch, Y. Wang, E. Demler

U. Sherbrooke (theory)
U. C. Mendes, A. Blais

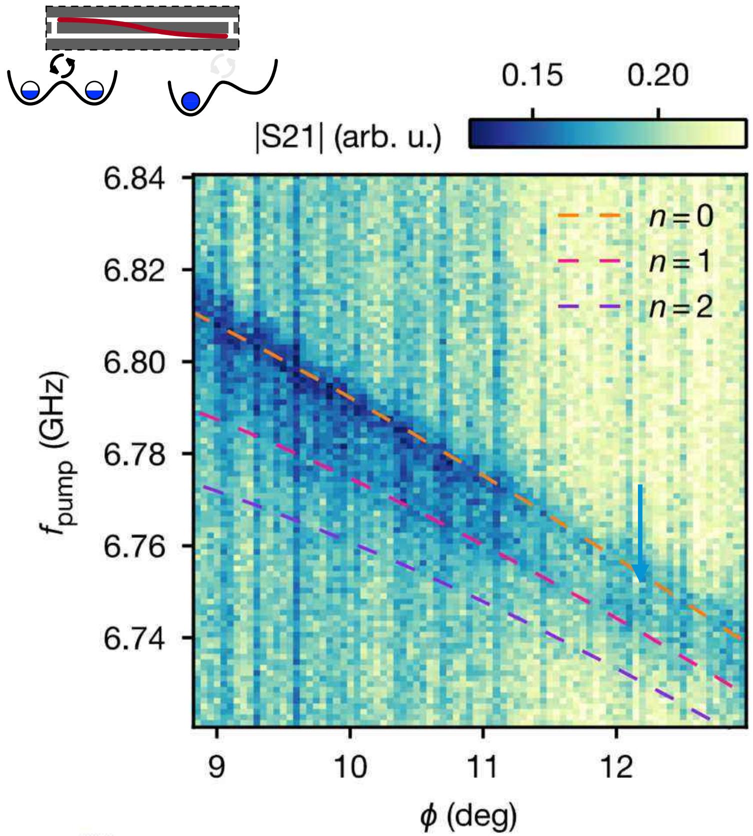
Intel qubits
P. Amin
S. Bojarski
R. Caudillo
D. Corras-Serrano
H.C. George
E. Henry
R. Kotlyar
L. Lampert
F. Luthi
D. Michalak
B. Mueller
S. Neyens
R. Pillarisetty
J. Roberts
T. Watson
O. Zietz
J.S. Clarke

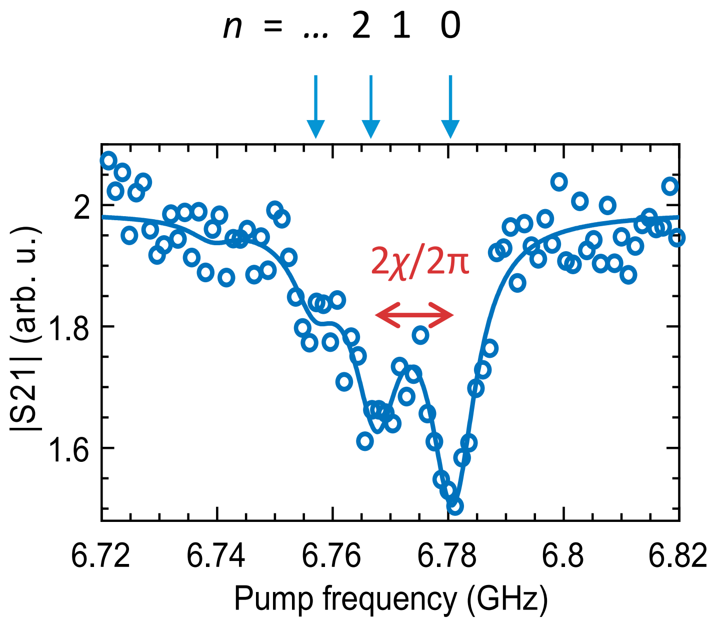
CryoCMOS @ QuTech
B. Patra
J. van Dijk,
M. Babaie
E. Charbon,
F. Sebastiano

CryoCMOS @ Intel
S. Subramanian
C. Jeon,
F. Sheikh
S. Pellerano

Counting microwave photons with an electron spin

P. Harvey-Collard, et al, PRX 2022





AC Stark shift at the single-photon level

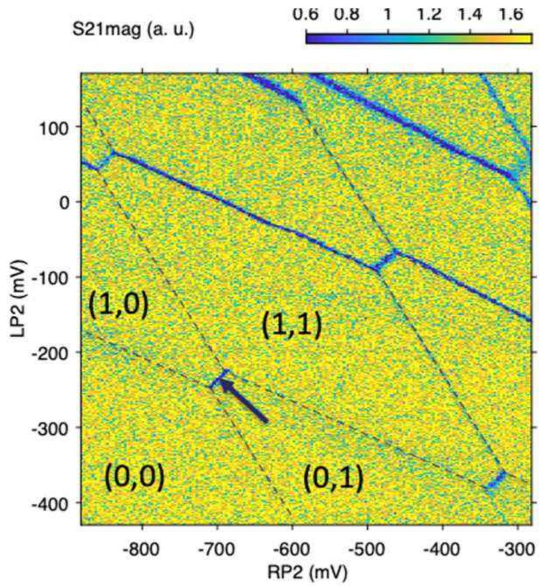
$$2\chi_s = 2\frac{g_s^2}{\Delta_s}$$

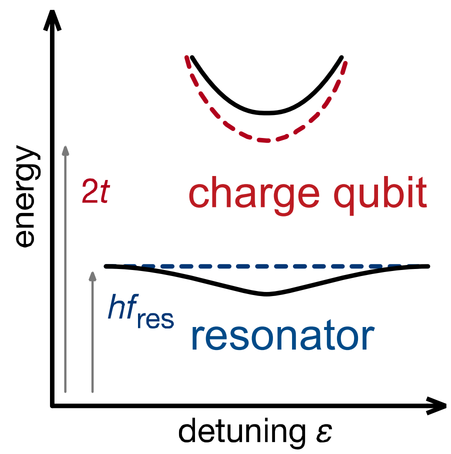
Compare dispersive spin-spin coupling

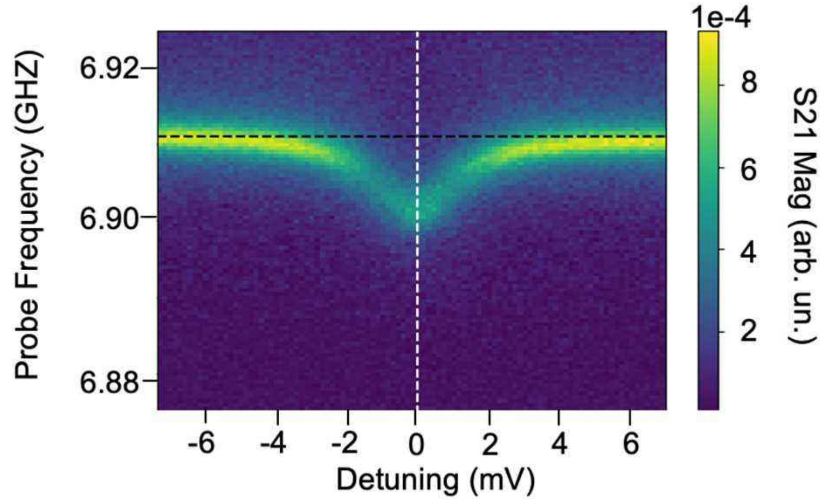
$$2J = g_{s1}g_{s2}\left(\frac{1}{\Delta_{s1}} + \frac{1}{\Delta_{s2}}\right)$$

Photon counting with a superconducting qubit: D. I. Schuster et al Nature (2007)

Dispersive charge sensing







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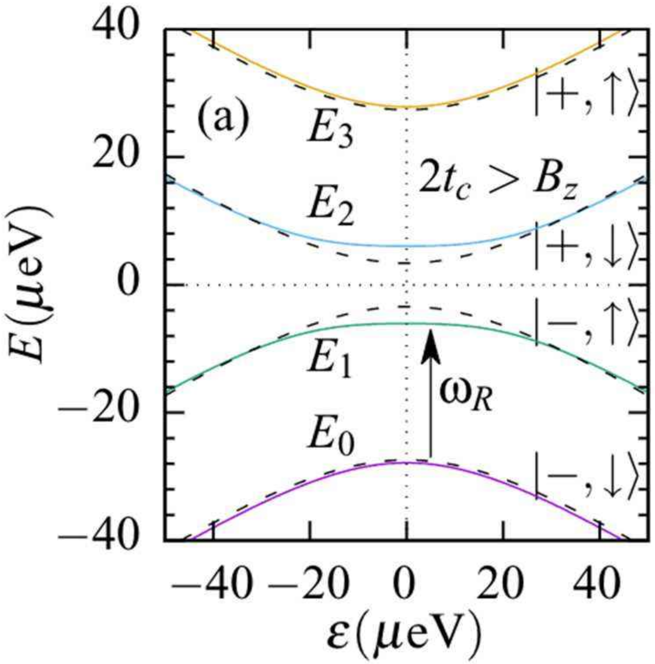
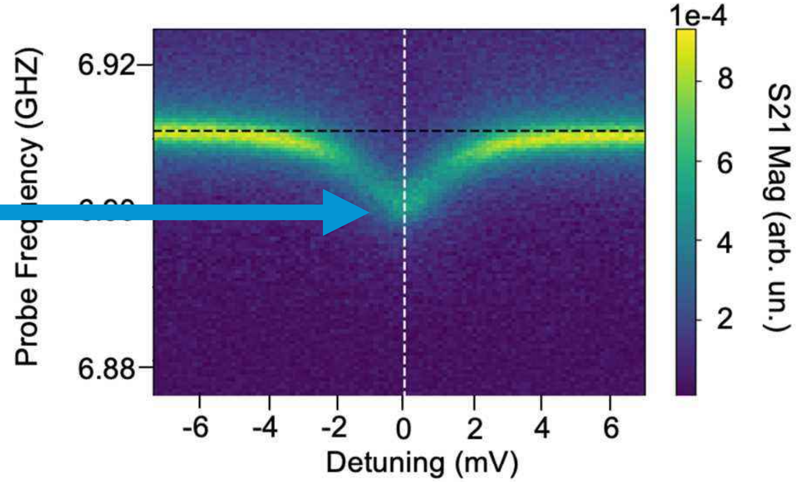
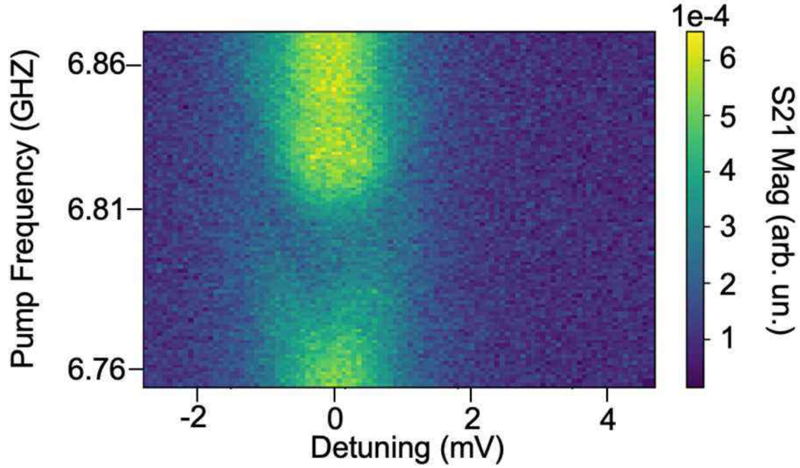
Dispersive spin sensing

[M. Benito... Phys. Rev. B **96** (2017)]



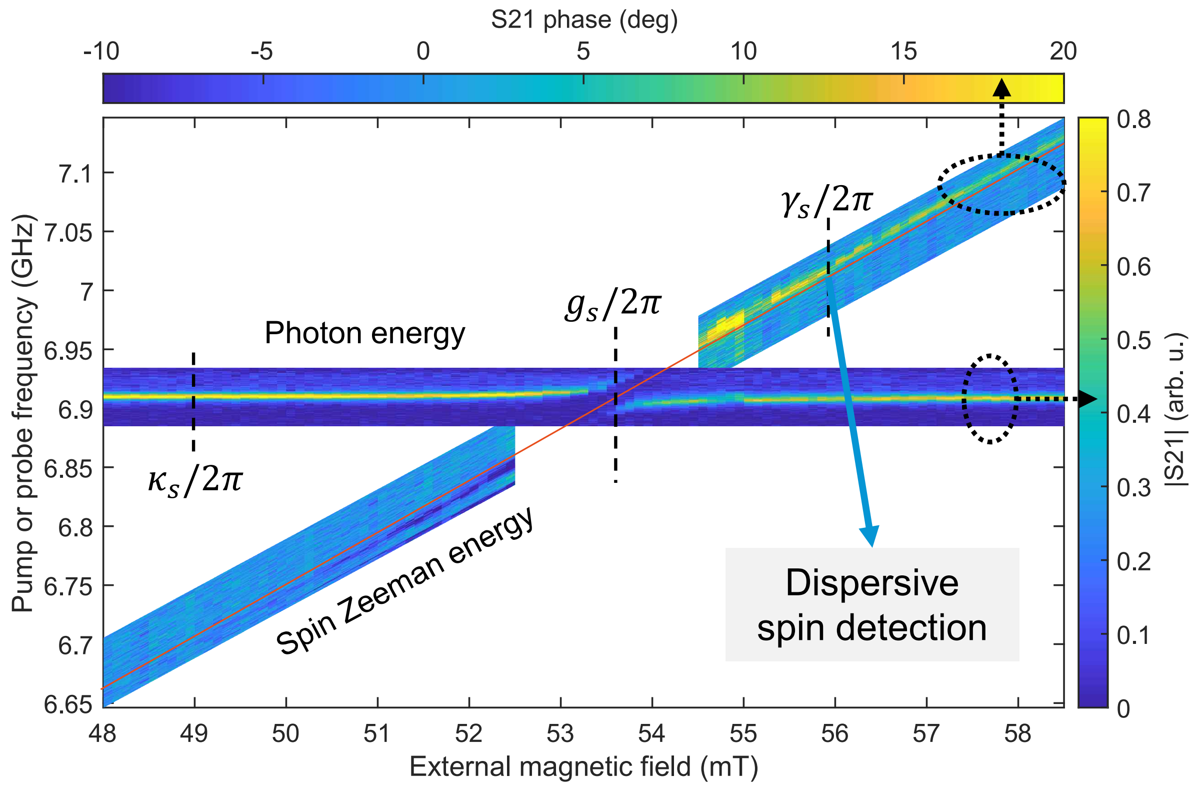
Probe here





Spin-photon coupling at each double dot

P. Harvey-Collard, et al, PRX 2022



	DQD1	DQD2
$g_s/2\pi$	13 MHz	12.5 MHz
$\gamma_s/2\pi$	6.2 MHz	3.3 MHz
$\kappa_s/2\pi$	2.6 MHz	2.3 MHz

Strong-coupling regime reached independently for both sides
$g_s > (\kappa_s, \gamma_s)$

Other parameters:
$2t_c/h$ = 12.7 GHz
$g_c/2\pi$ = 192 MHz

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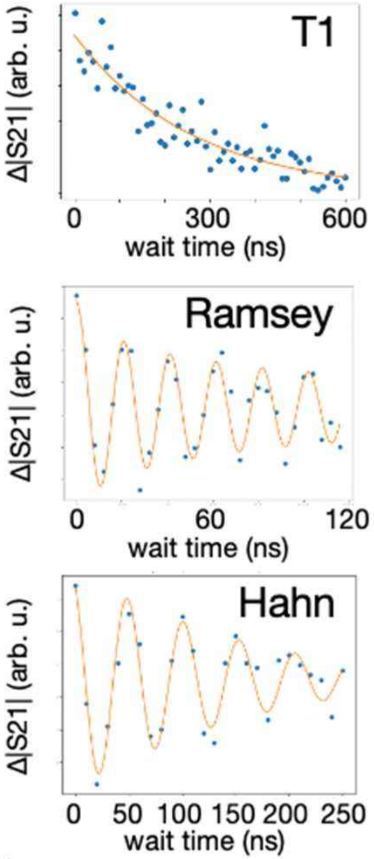
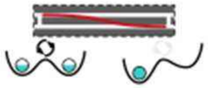
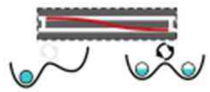
Decoherence metrics

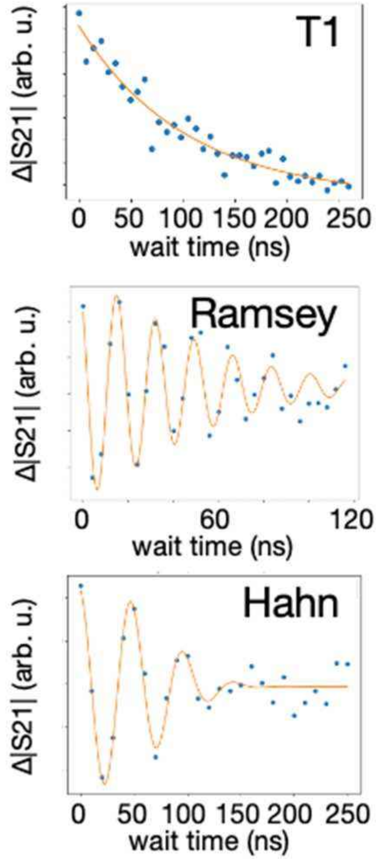


Q1





Q2



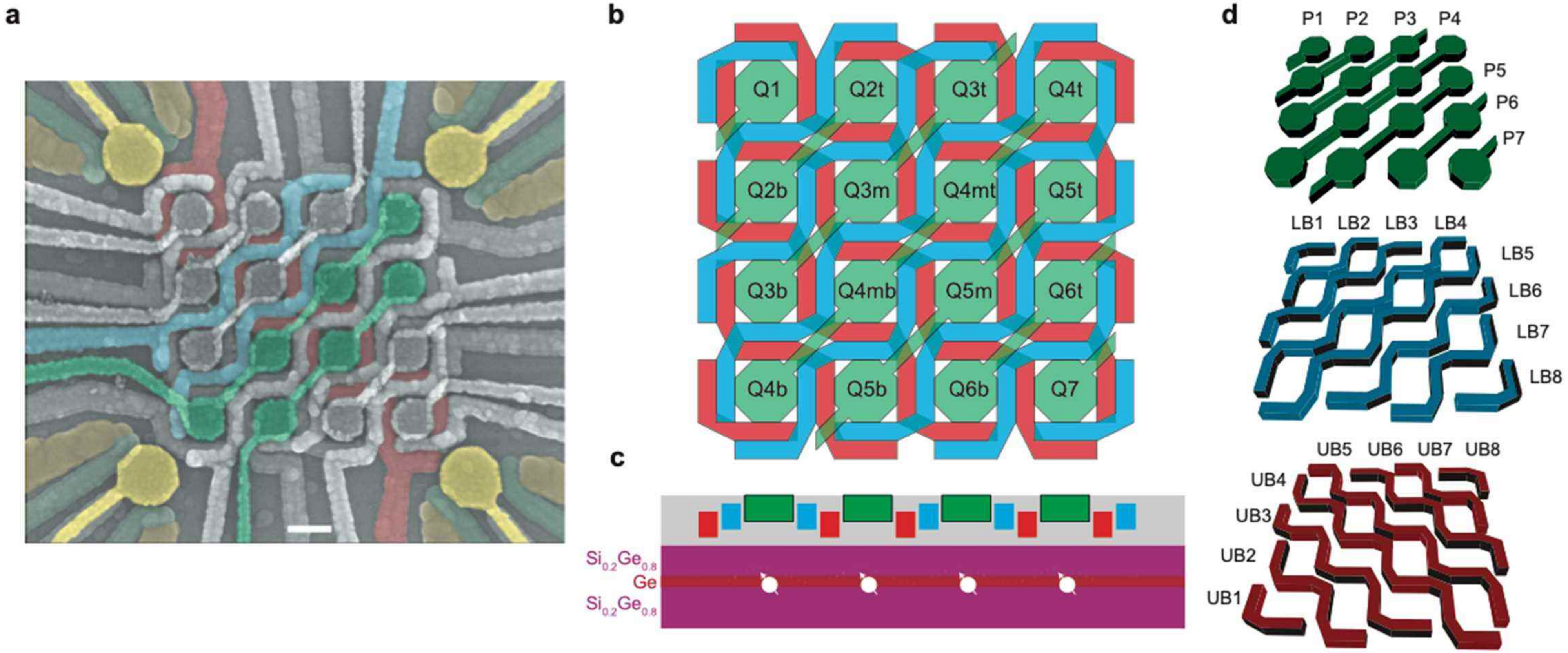
Decoherence times at zero detuning (spin-charge hybridization)

$\Delta_{s1,2}$ ~ 120 MHz , $g_{s1,2}$ ~ 30 MHz, 2J ~ 18 MHz

	Q1	Q2
T_1	260 ns	100 ns
T_2^*	60-80 ns	40-60 ns
T_2^H	160 ns	90 ns
T_2^{Rabi}	100 ns	100 ns

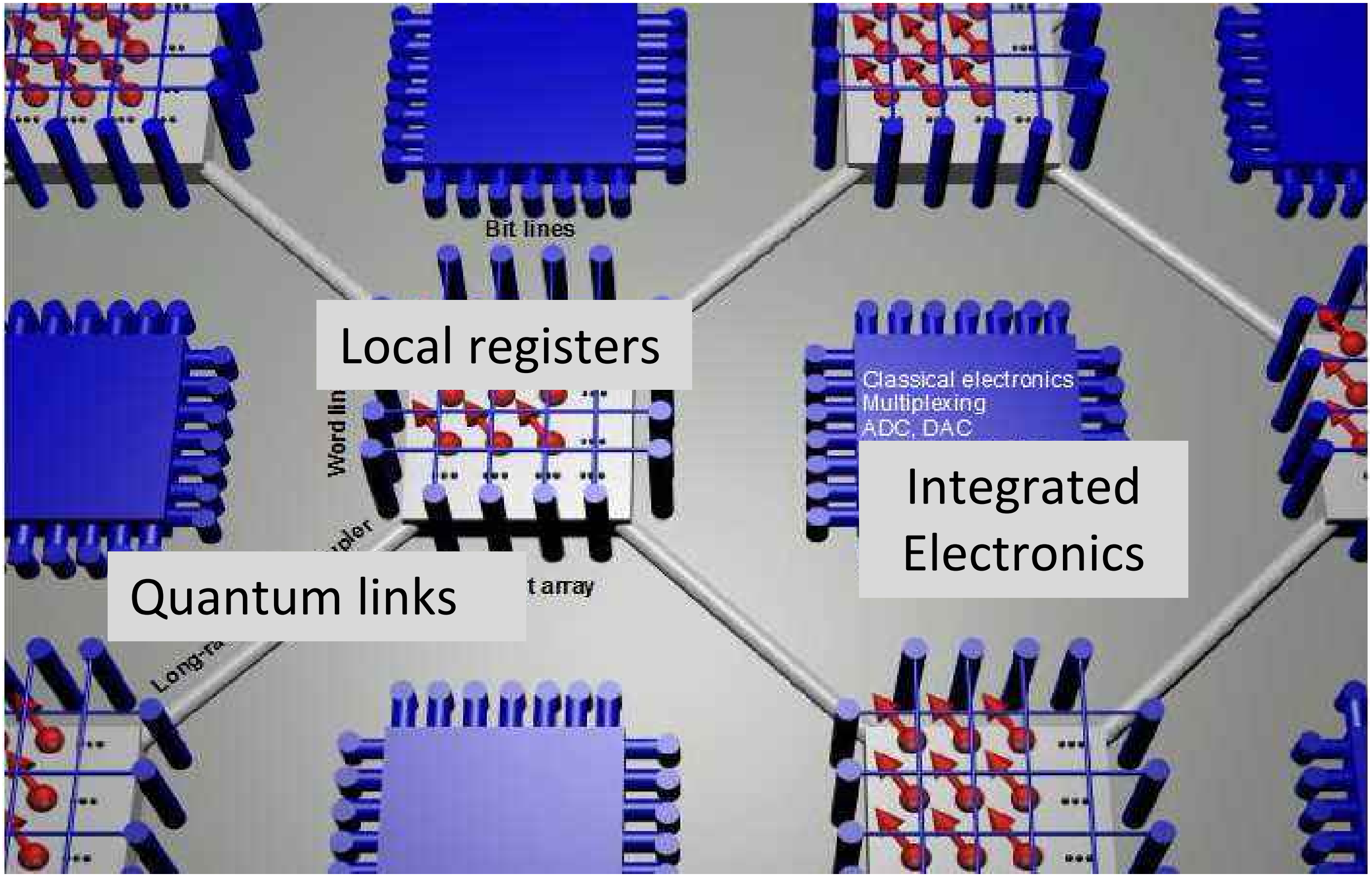
4x4 quantum dot array with cross-bar addressing

F. Borsoi, … , M. Veldhorst
arXiv:2209:06609



Tuned to odd number of holes per site, demonstration of local tunnel coupling control

Our vision of a scalable semiconductor spin qubit processor – hot, dense and coherent



L.M.K. Vandersypen, H. Bluhm, J.S. Clarke, A.S. Dsurak, R. Ishihara, A. Morello, D.J. Reilly, L.R. Schreiber, and M. Veldhorst., npj Q Info 2017

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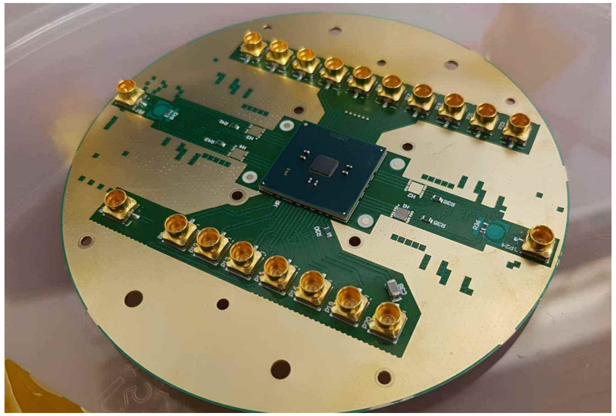
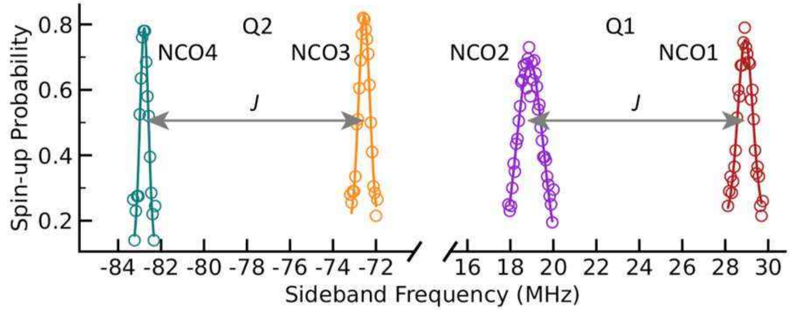
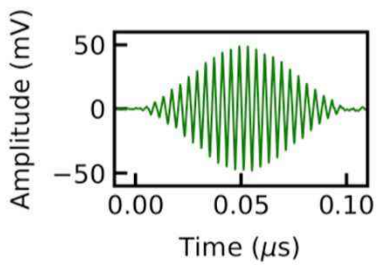
Cryogenic “Horseridge” chip for qubit control

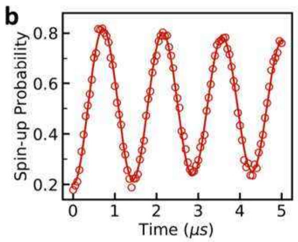
X. Xue, B. Patra, J. van Dijk,
Nature 2021

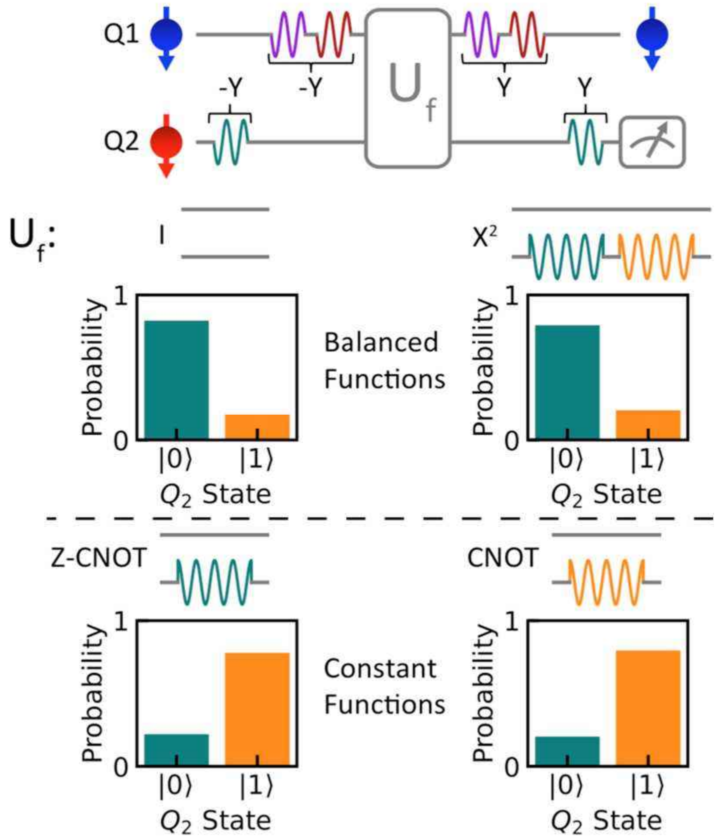


99,7% gate fidelities matching those using RT instruments







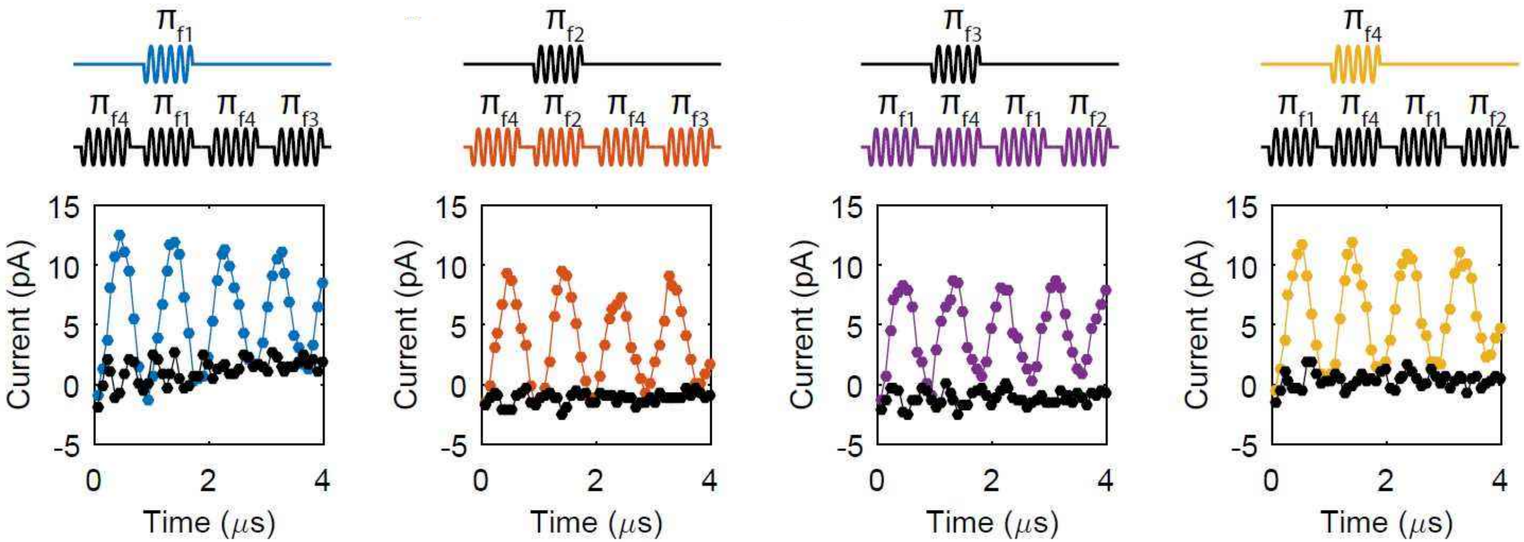


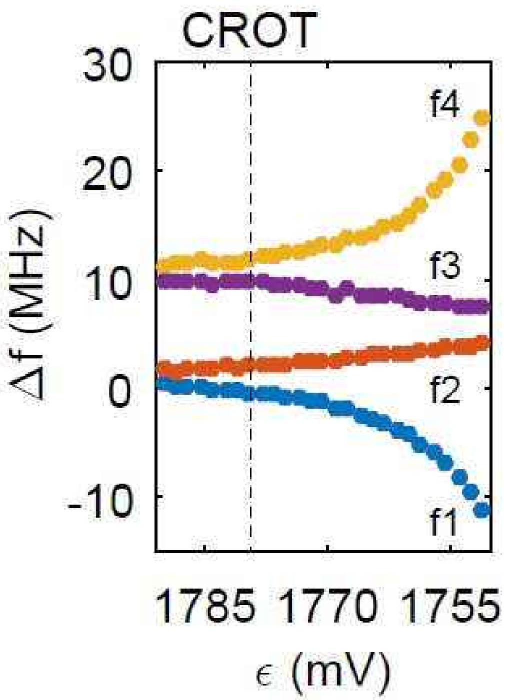
with Charbon & Sebastiano groups at QuTech
and with Intel Quantum

QuTech

Universal quantum logic on “hot” qubits

Petit, Eenink et al. Nature 2020





99/86% single/two-qubit gate fidelities at 1.1K

Se also “hot” single-qubit control Huang et al. Nature 2020

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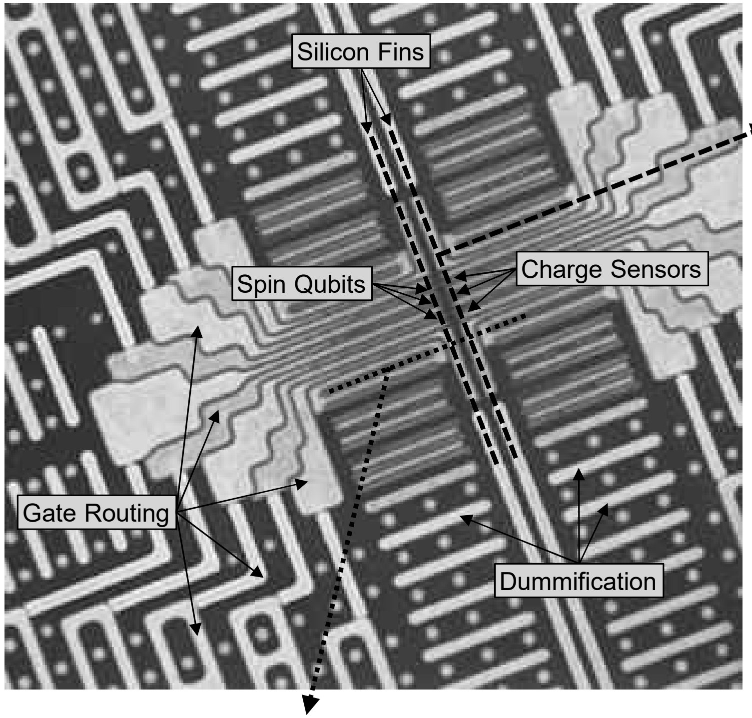
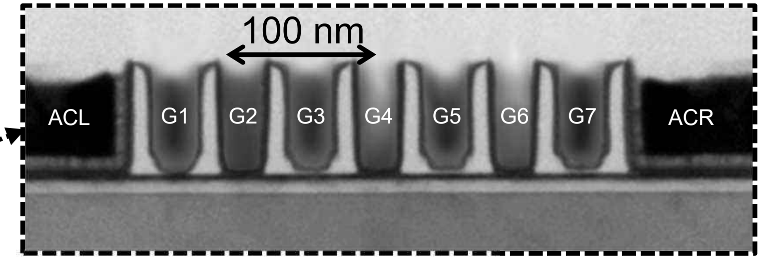
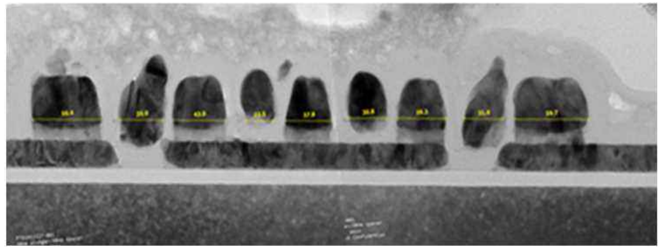
Industrial quantum dot arrays fabricated in an Intel 300 mm processing line

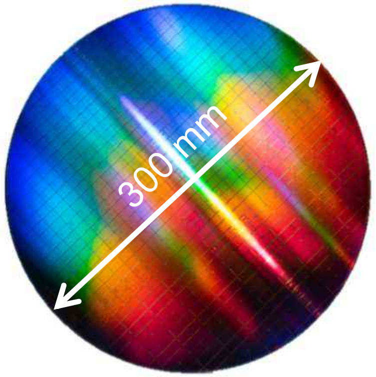
A.M. Zwerver et al,
Nature Electronics 2022

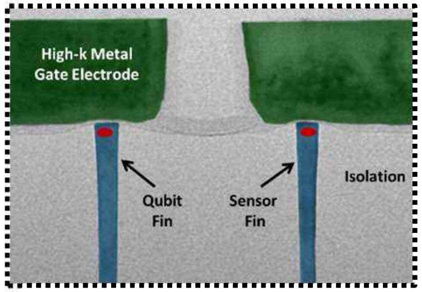


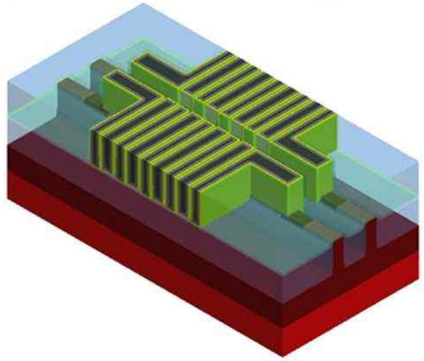




For comparison, made @ Delft







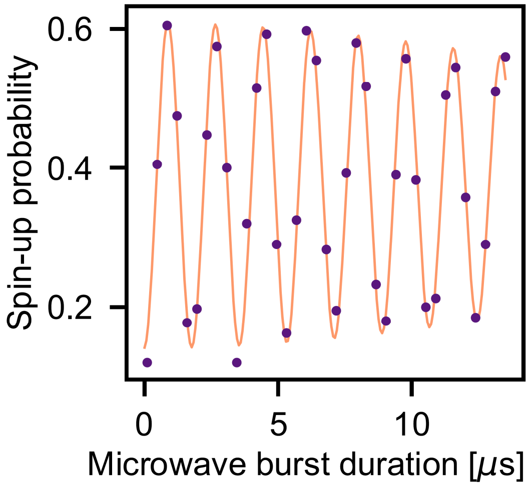
QuTech

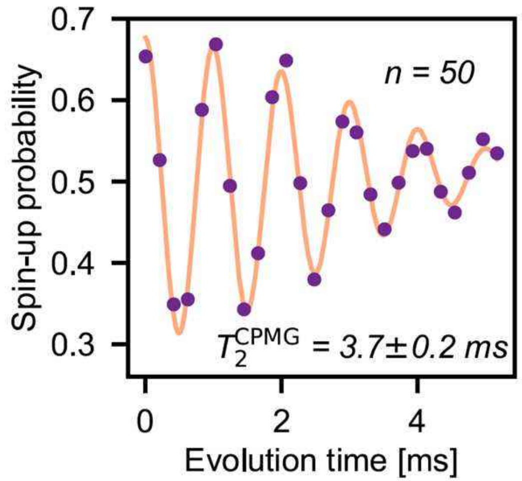
Optical lithography, subtractive processing and chemical mechanical polishing.

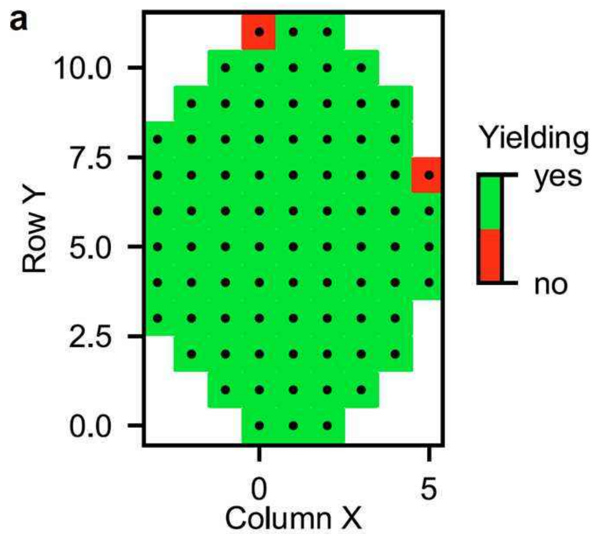
with Intel Quantum
see Pillarisetty et al, IEDM 2018, 2019
Compare Maurand ea, Nat Comm 2016

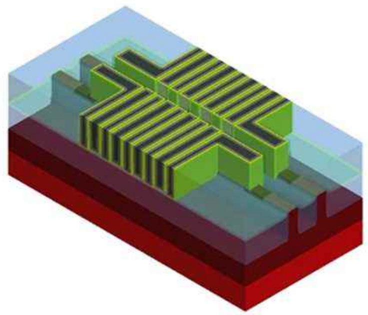
Respectable fidelity and coherence…
with an unprecedented device yield

A.M. Zwerver et al,
Nature Electronics 2022









Spin dephasing time T_2^* ~ 28 μs (100 s avg.)
Spin coherence > 3 ms (50 pulse CPMG)
Gate fidelity > 99% (RB)

98% fully functional devices
across a 300 mm wafer
(18 gates, 4 contacts)

QuTech

with Intel Quantum