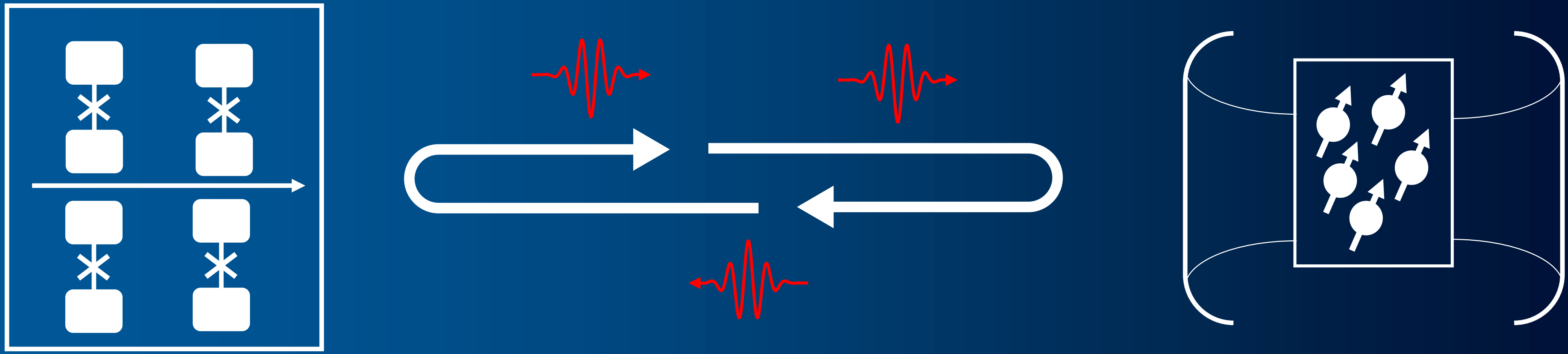
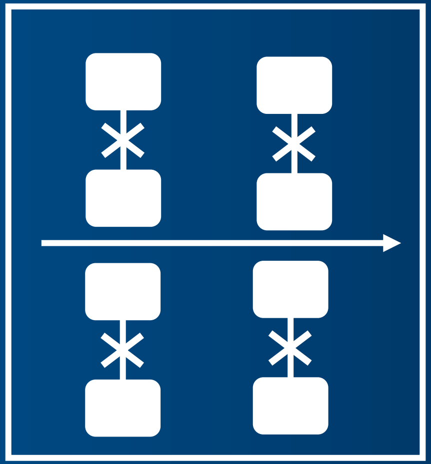
Implementing a quantum memory at microwave frequencies with Bismuth donors in silicon

Tristan Lorriaux & Yutian Wen, V. Ranjan, D. Vion, E. Flurin, B. Huard, P. Bertet, A. Bienfait



Superconducting circuits:
how to implement qubits and gates ?



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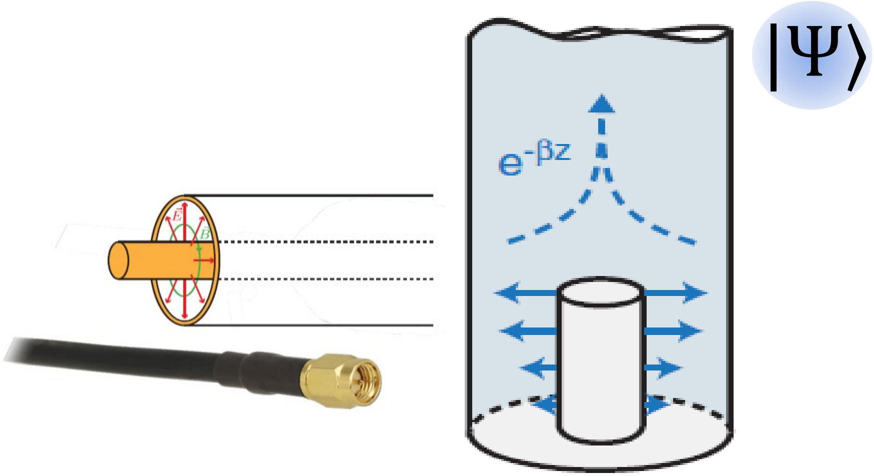
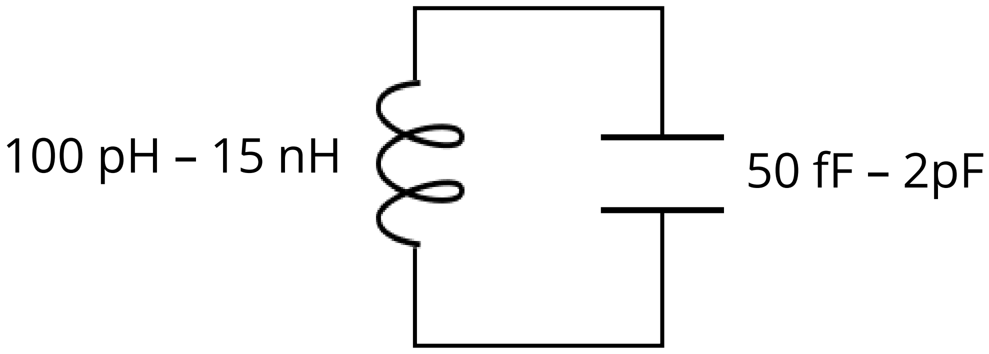
Quantum superconducting circuits

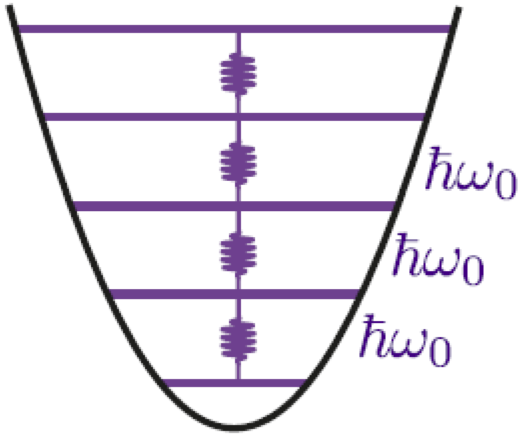
Quantum mechanics
with microwave circuits



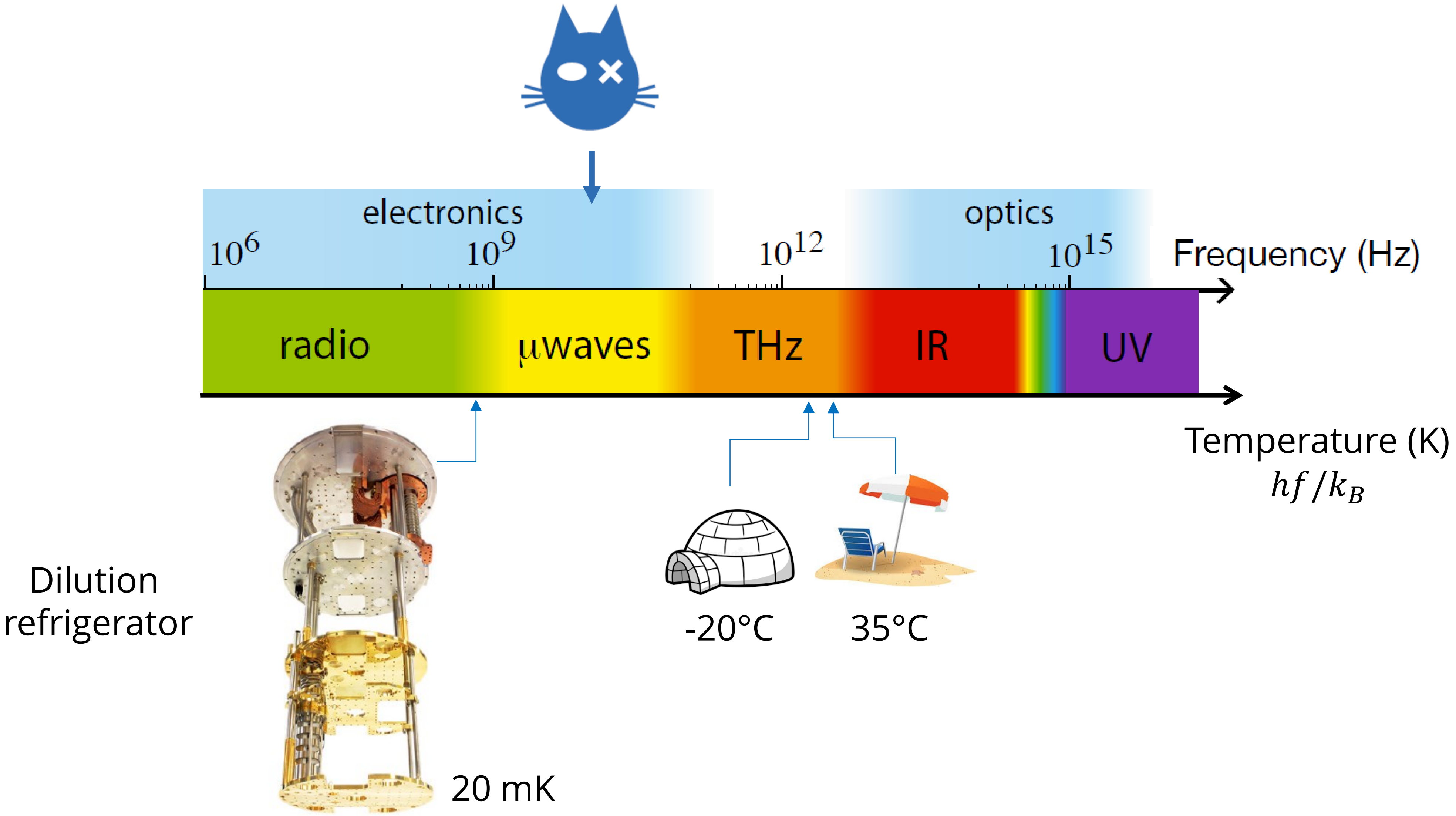
First brick: microwave harmonic oscillator



$\omega_0/2\pi =$ 3-10 GHz



Reaching the quantum regime ?

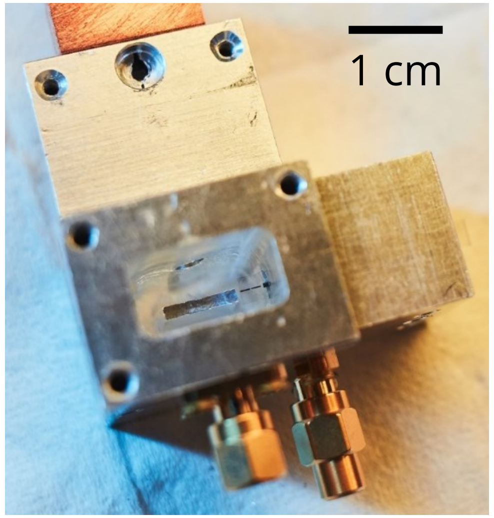


Different flavors of oscillators : bulk type

We need long-lived states

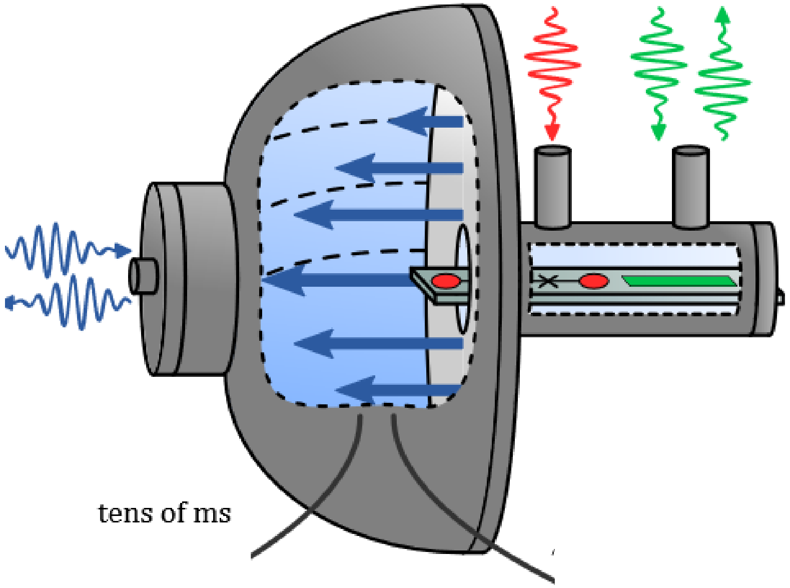
⇒ use superconducting materials
⇒ low temperature for best quality factor

Aluminum 3D cavity (T_c = 1K)
99.999% purity



T_{decay} = 1.6 ms
Q = 5×10^7

Niobium half elliptical cavity (T_c = 9.2K)

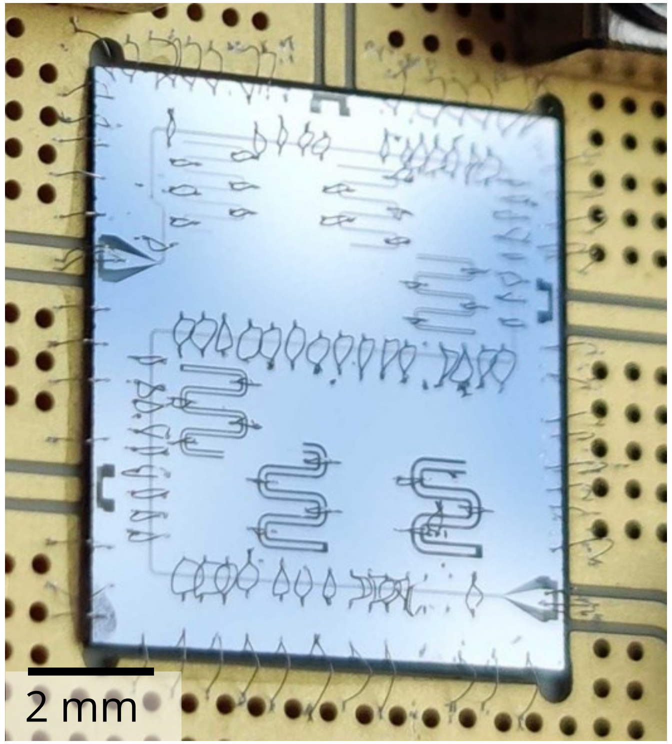


T_{decay} = 25 ms
Q = 1×10^9

O. Milul et al., *arxiv* 2302.06442

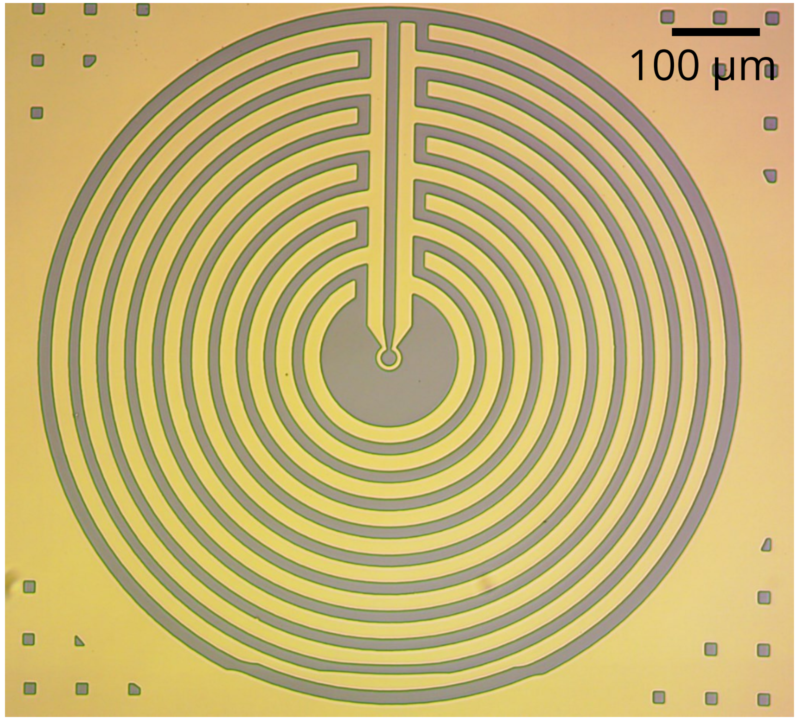
Different flavors of oscillators : planar type

Tantalum distributed
planar resonators (T_c = 4.4 K)



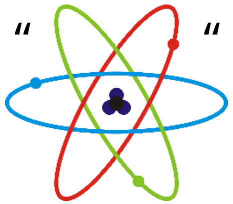
T_{decay} = 19 μs
$Q = 1.1\ 10^6$

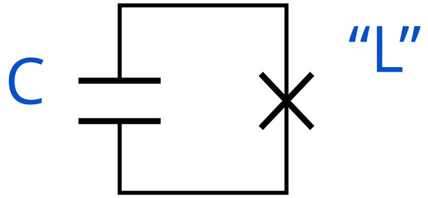
NbTiN lumped resonators
(T_c = 13 K, B_0 = 1 T)



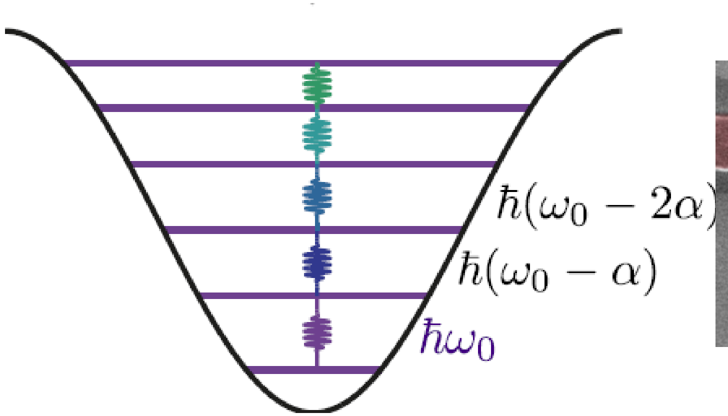
T_{decay} = 16 μs
$Q = 6\ 10^5$

Superconducting qubit



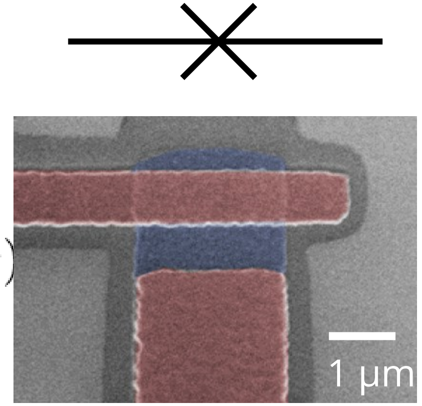


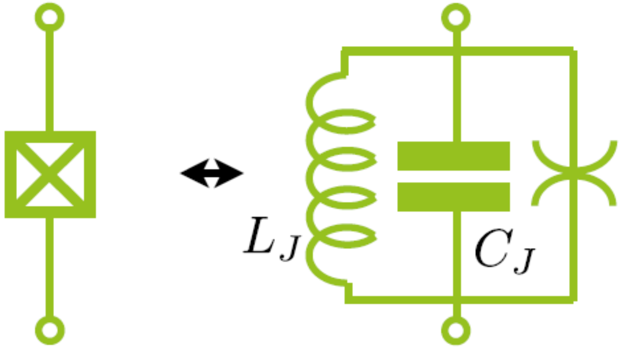
Non-linear LC oscillator



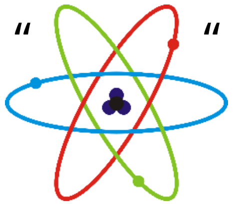
transitions observed in 1980’s [Berkeley & Saclay]
strong coupling regime of CQED in 2004 [Yale]

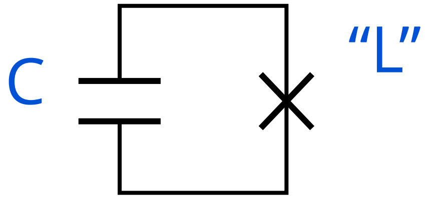
Josephson junction



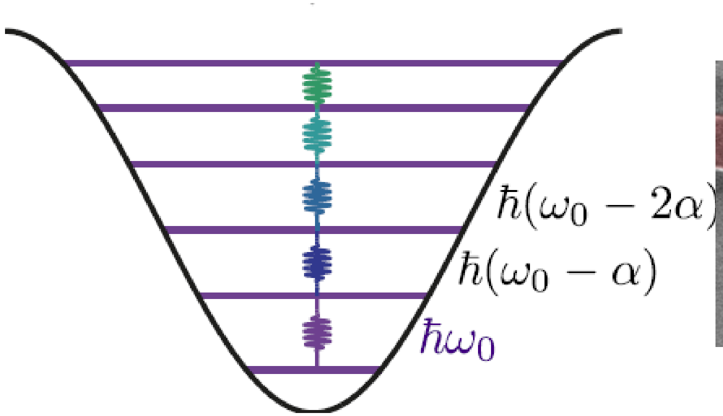


Superconducting qubit





Non-linear LC oscillator



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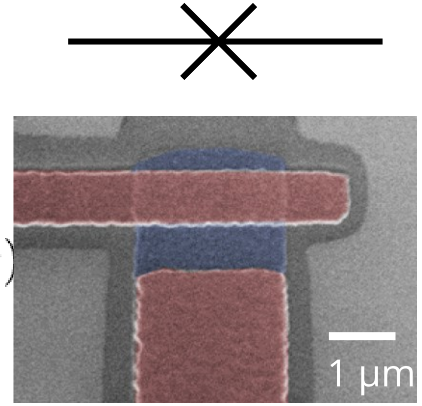
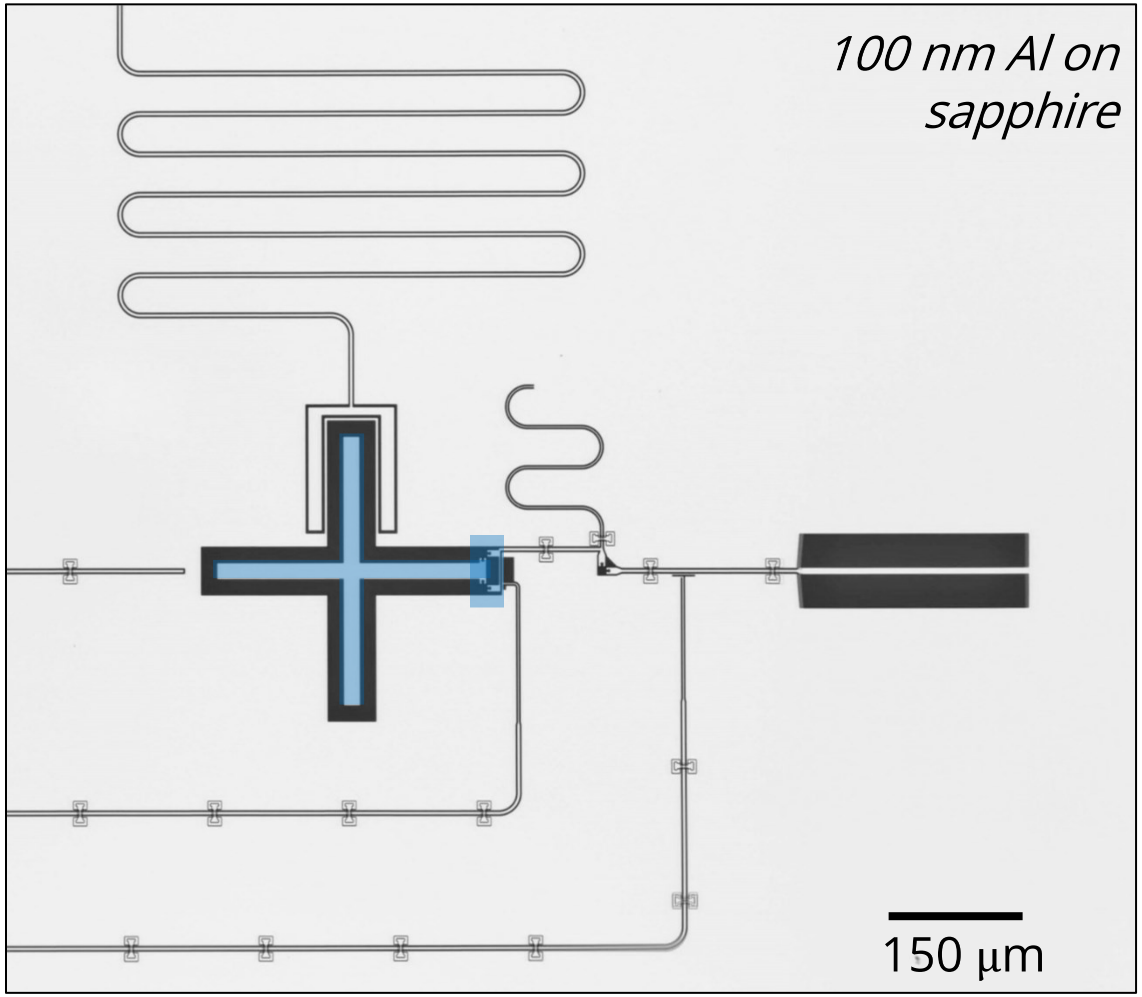
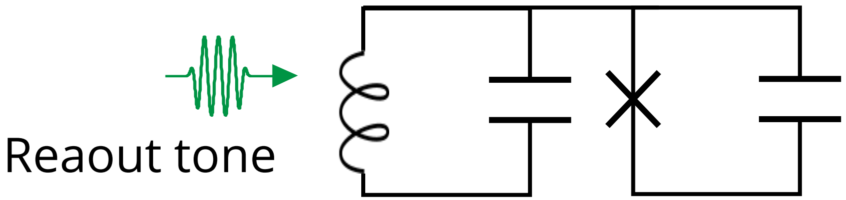
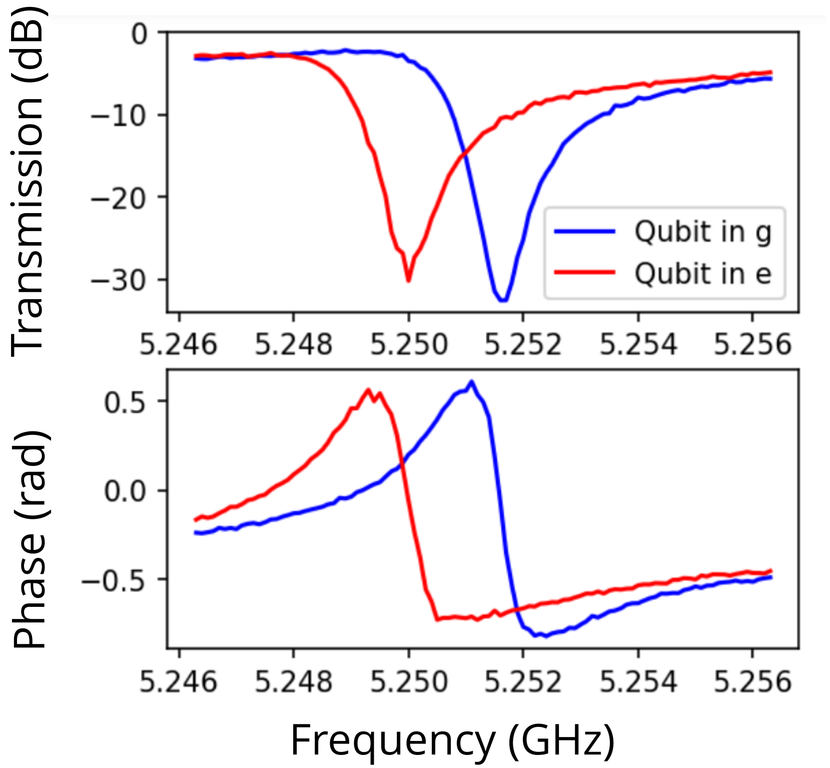


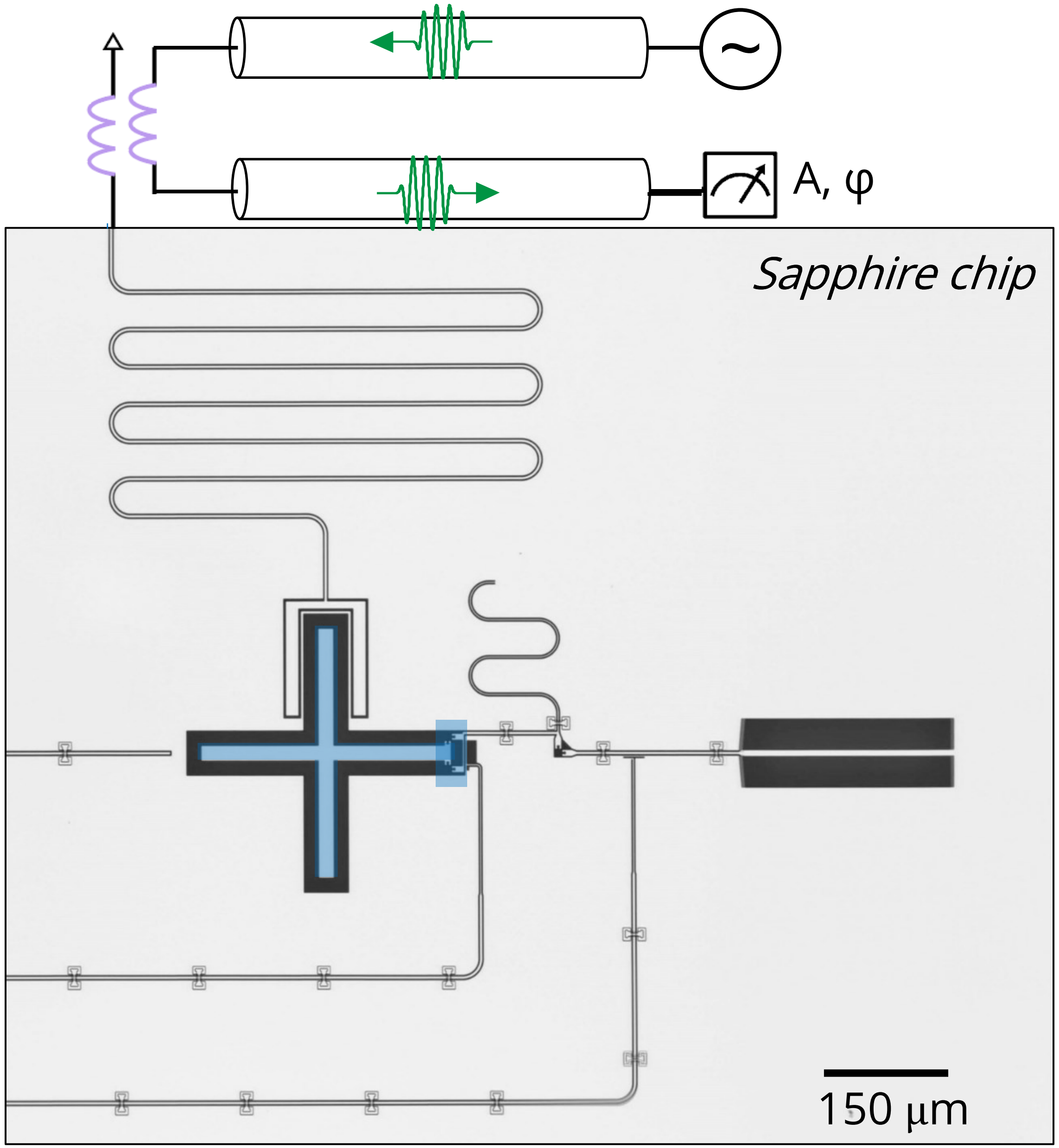


Superconducting qubit



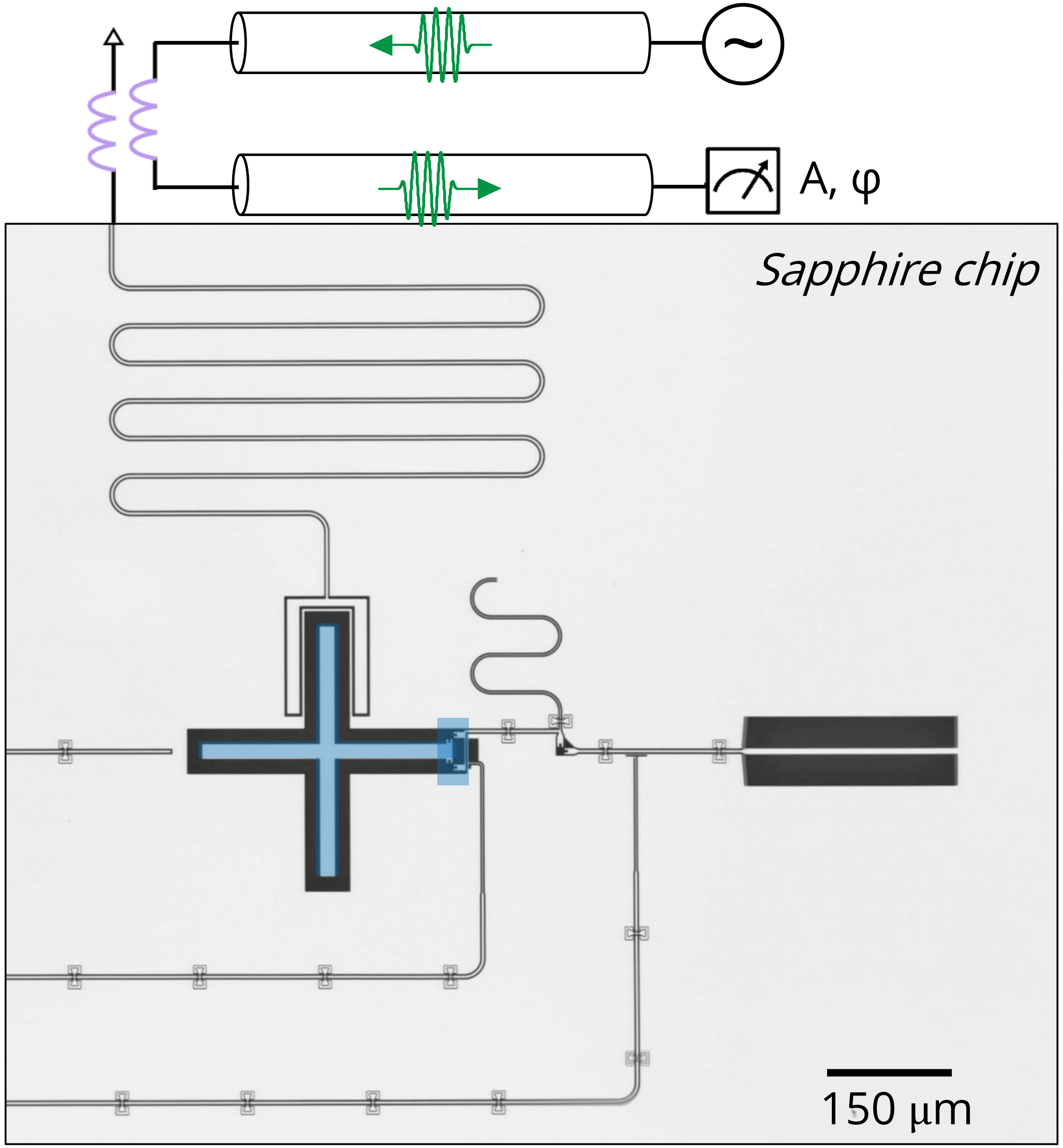
Capacitively coupled to **readout** resonator to measure P_e and P_g.

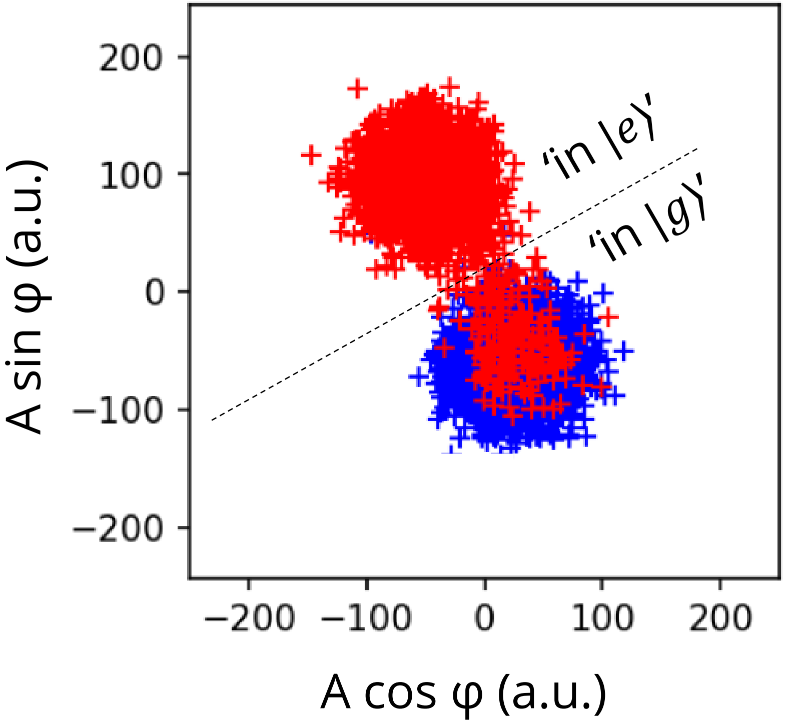




Superconducting qubit

Capacitively coupled to
readout resonator

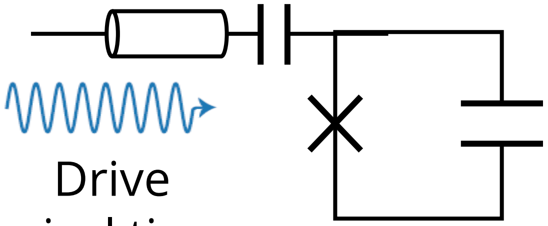




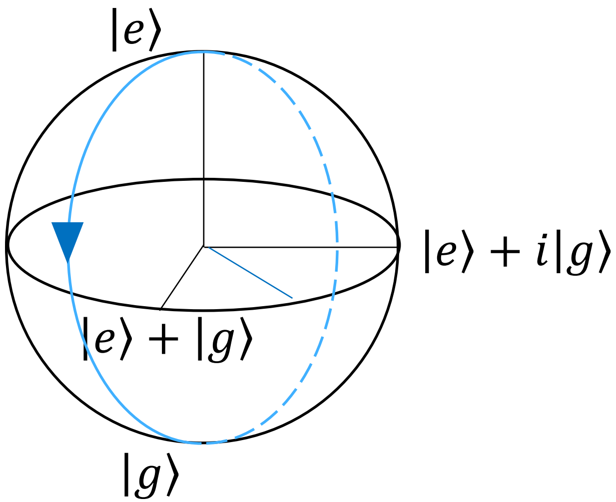
$$P_{\mathrm{e}} = \frac{N_{\mathrm{in}\,|e\rangle}}{N_{\mathrm{in}\,|e\rangle} + N_{\mathrm{in}\,|g\rangle}}$$

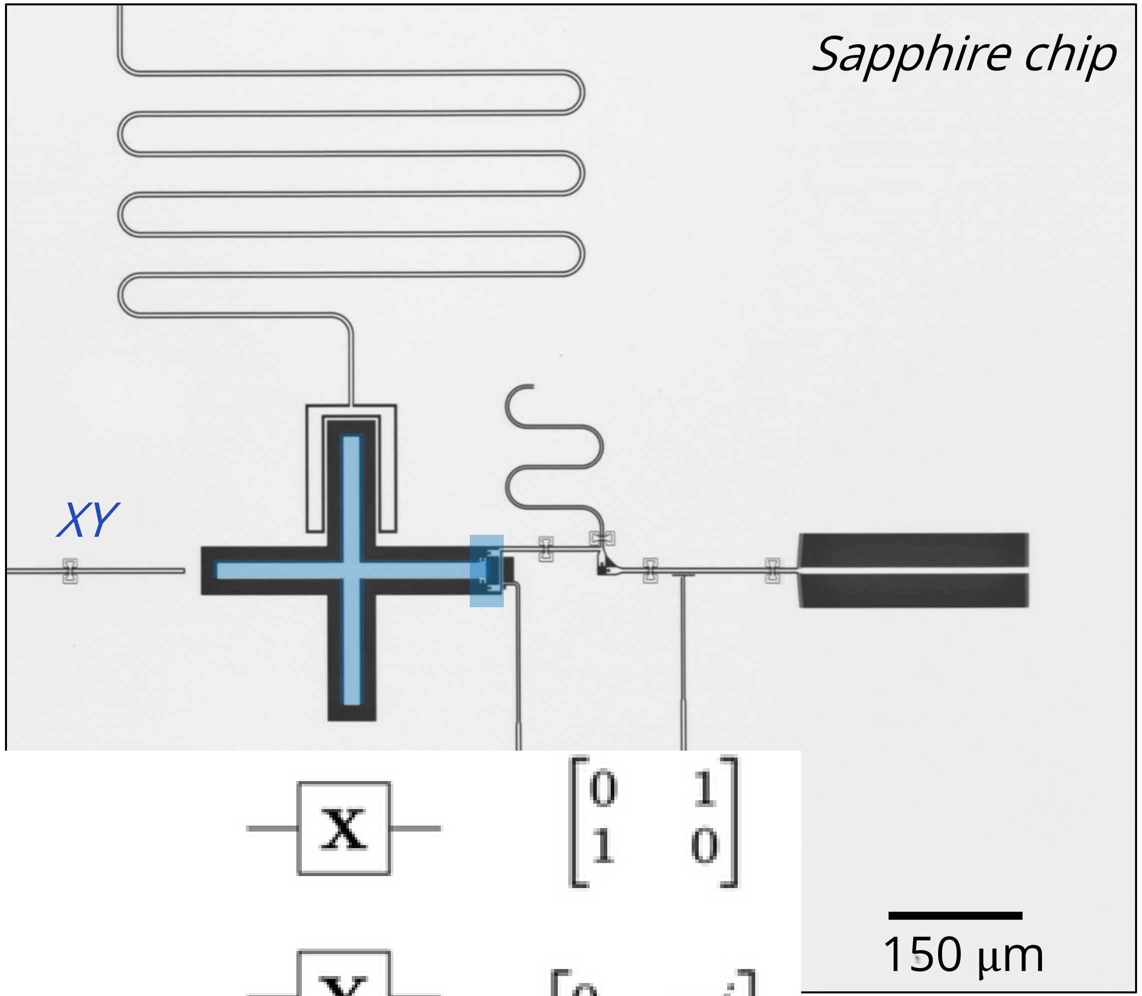
$$P_{\mathrm{g}} = 1 - \mathrm{P}_{\mathrm{e}}$$

Superconducting qubit: control



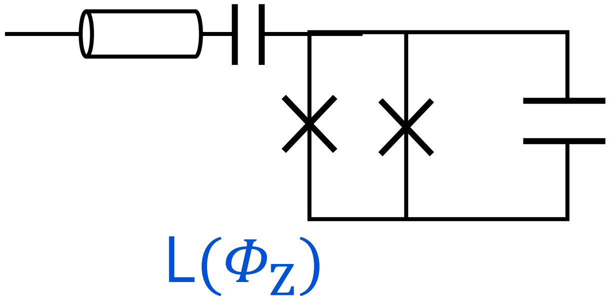
Drive
typical times
~ 20-200 ns

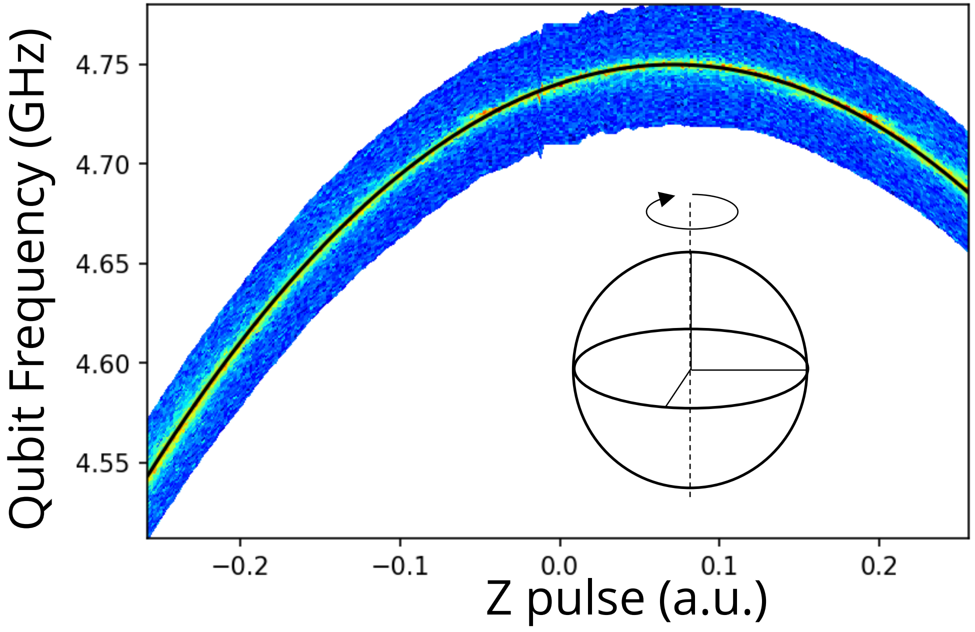




Pauli-X (X)	$\boxed{X}$	$\begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$
Pauli-Y (Y)	$\boxed{Y}$	$\begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$

Superconducting qubit: control

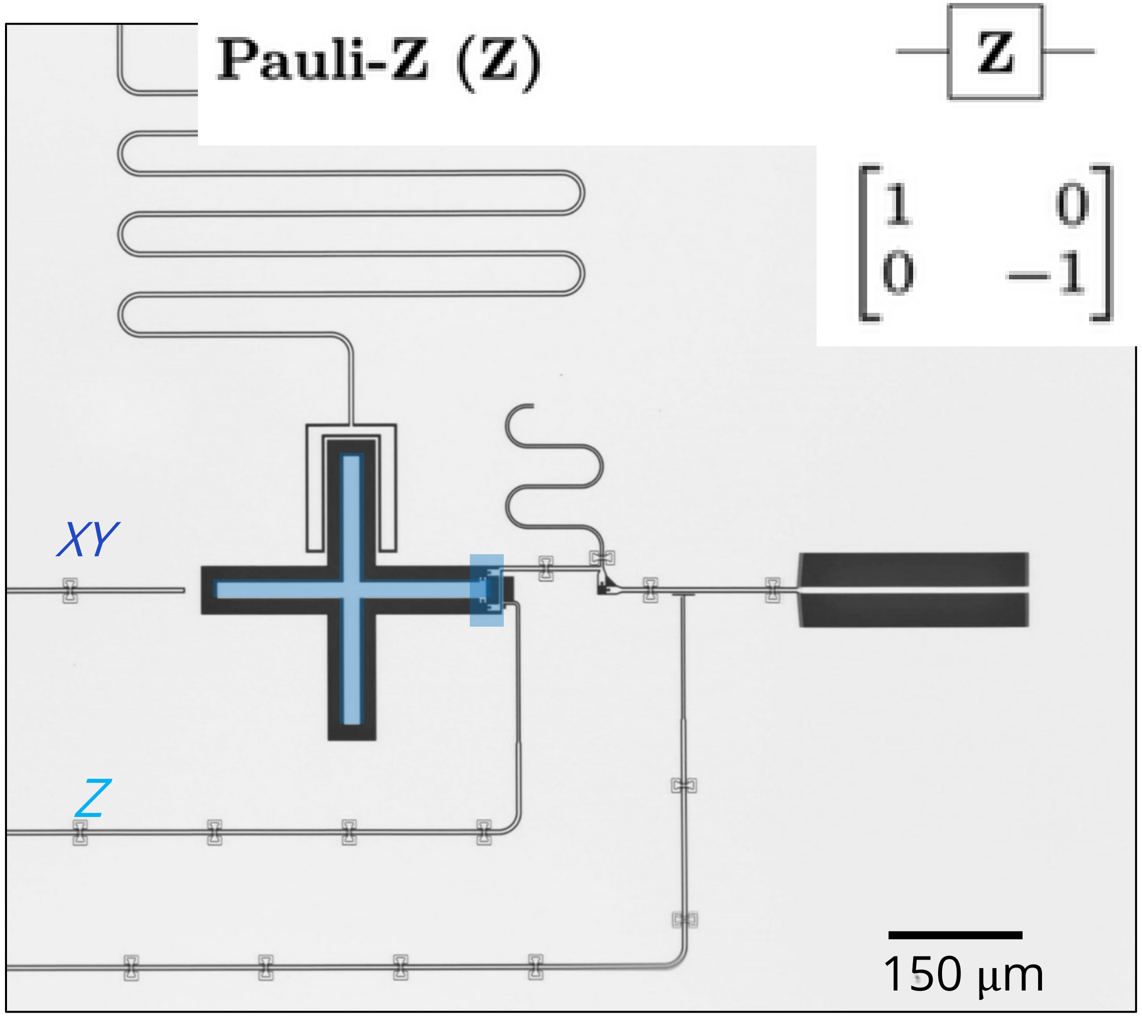




Readout

Excitation and control

Frequency tuning

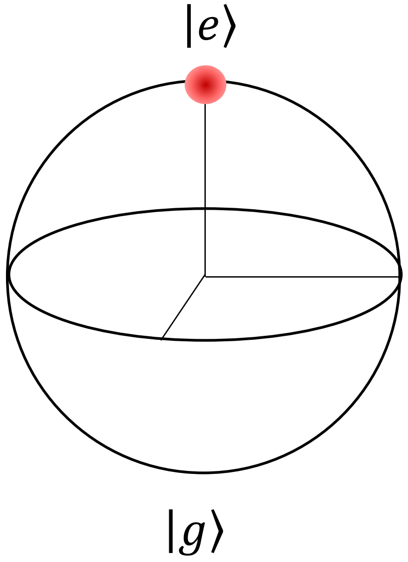


Pauli-Z (Z)

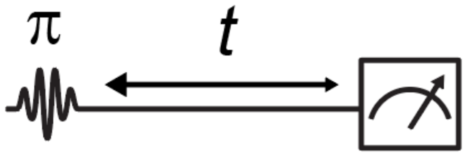
$$\boxed{Z}$$

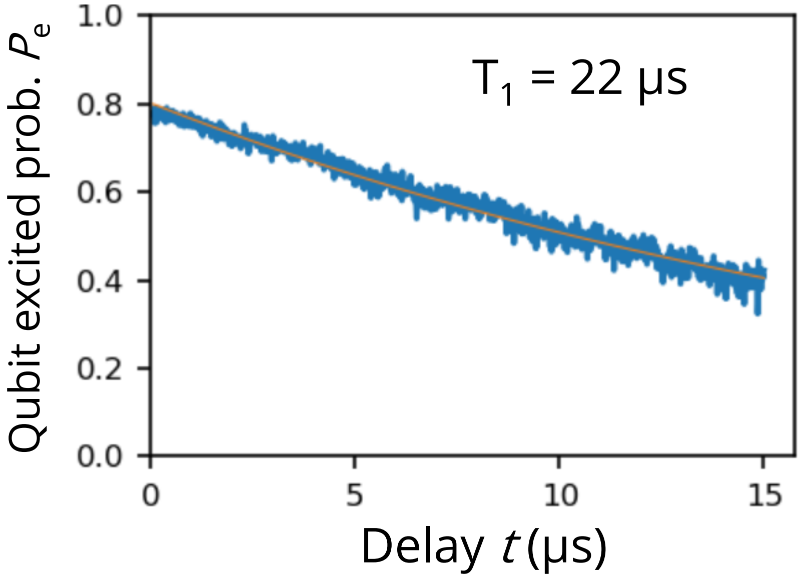
$$\begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}$$

Superconducting qubit: coherence

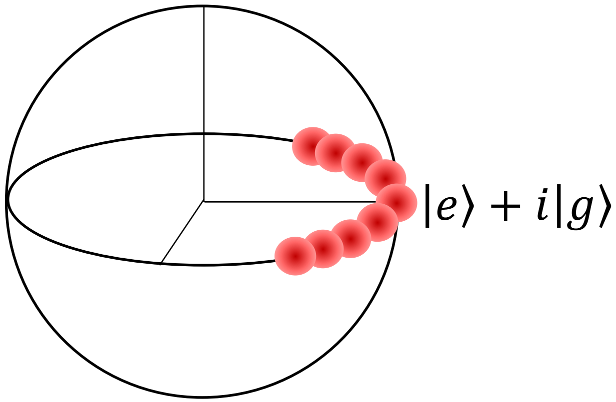


Energy relaxation (T_1)

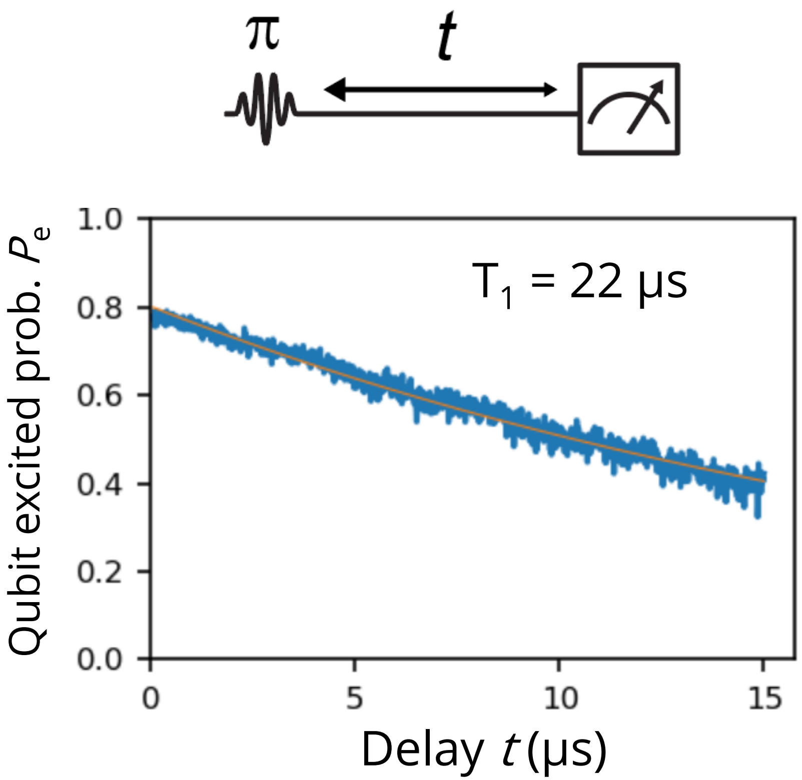




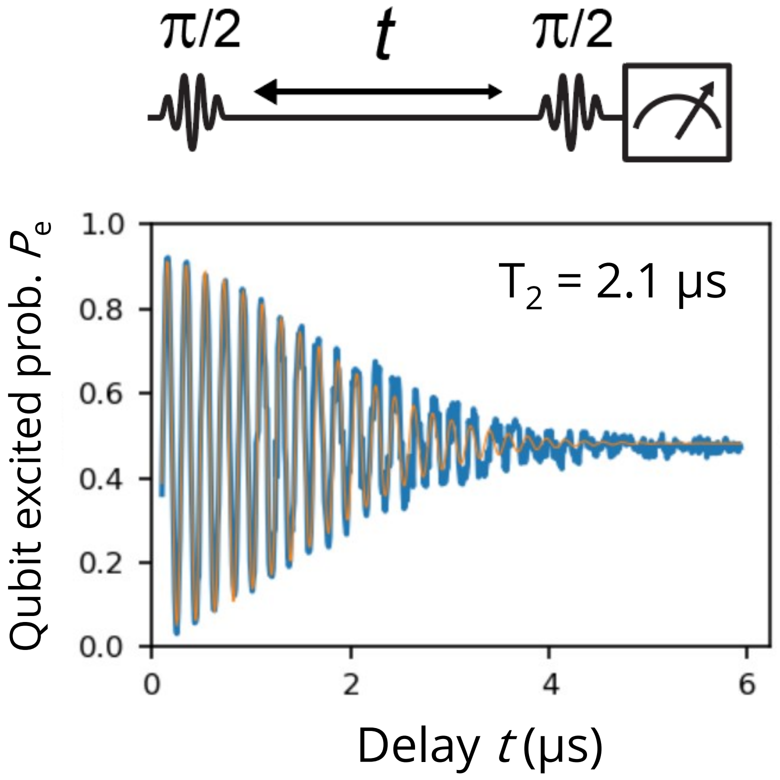
Superconducting qubit: coherence



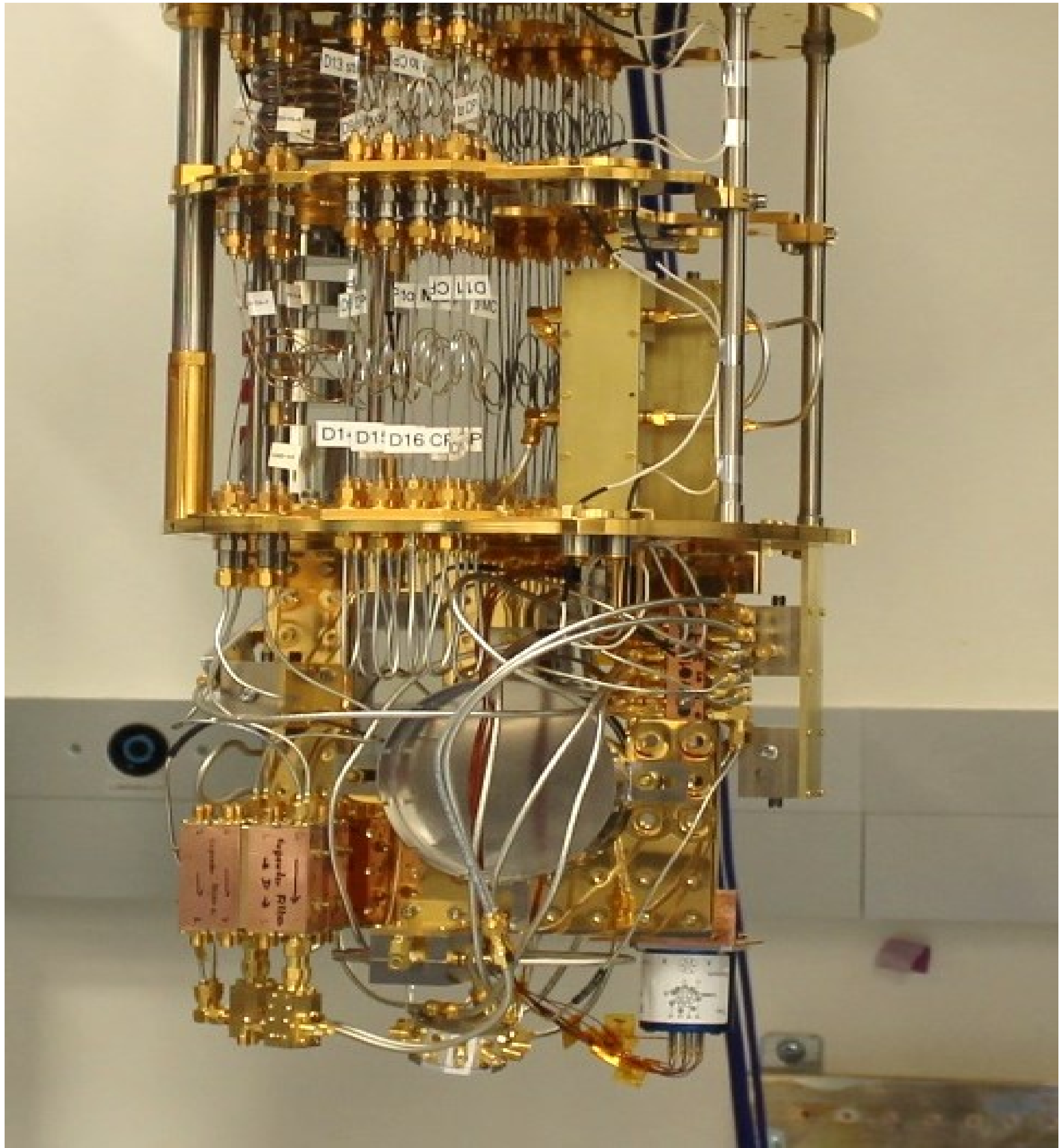
Energy relaxation (T_1)

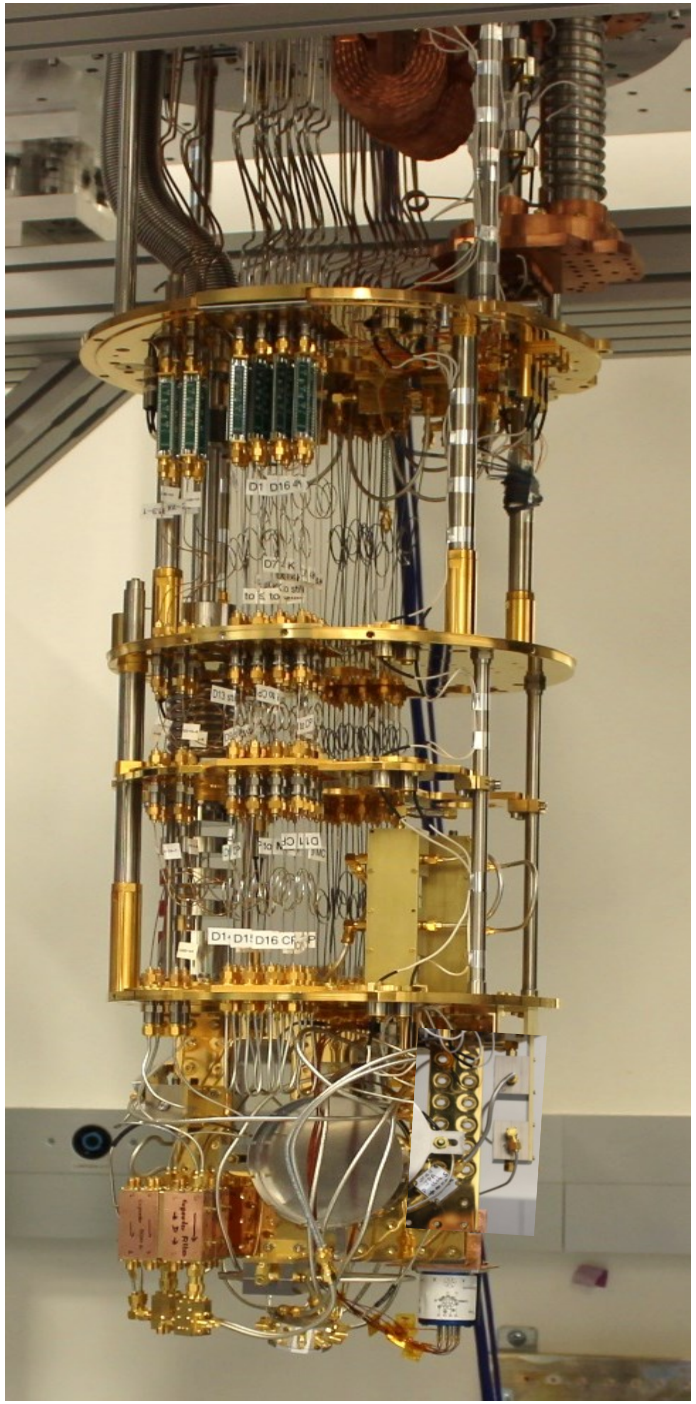


Phase coherence (T_2)



Typical setup

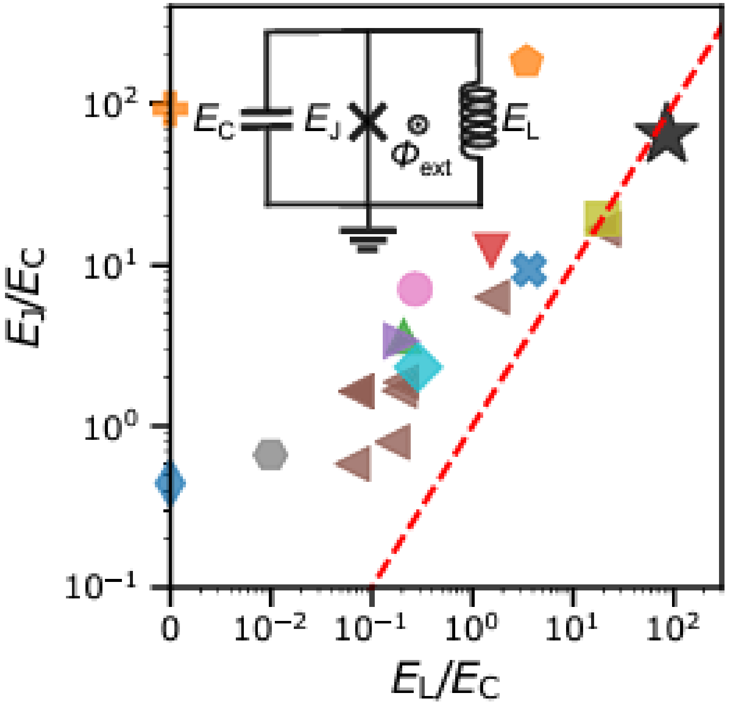




Zoology and lifetimes

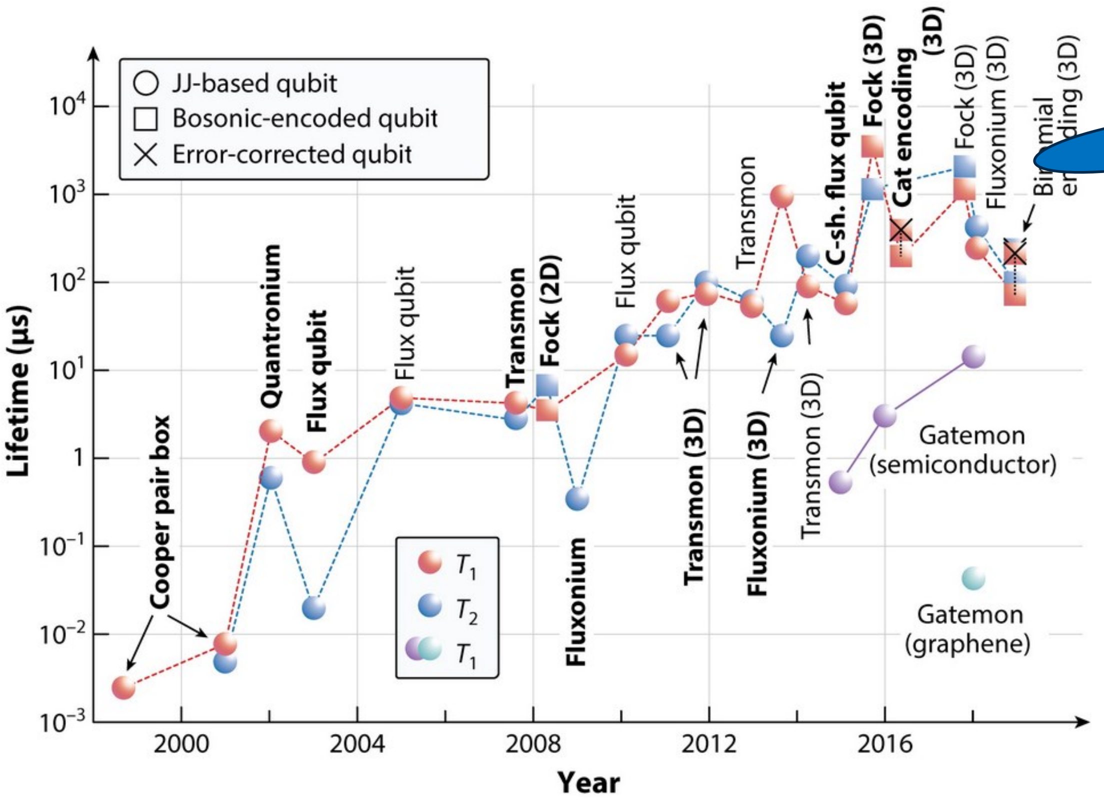
Transmon

Popularity



Fluxonium

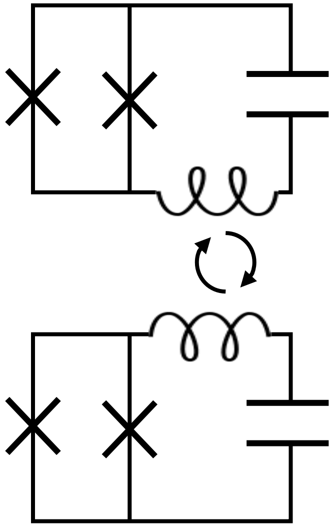
Lifetime
& gate errors



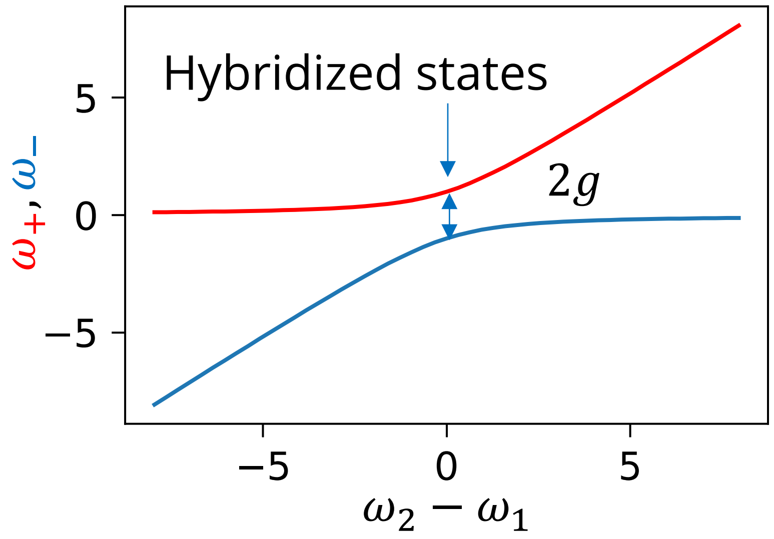
E. Hyyppä et al., *Nat. Comm.*, 2022

Kjaergaard et al., *Ann Rev Cond Matt Phys*, 2020

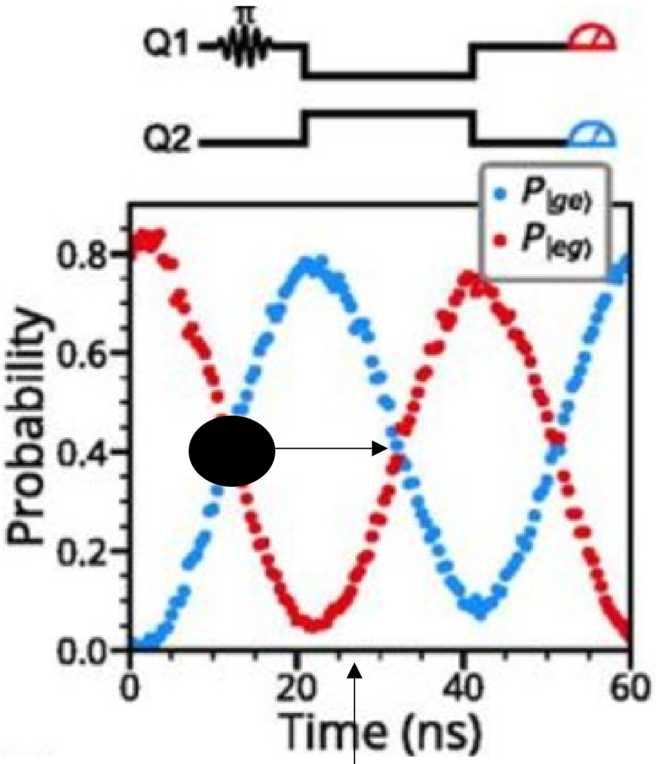
Examples of two qubit gates : SWAP gate



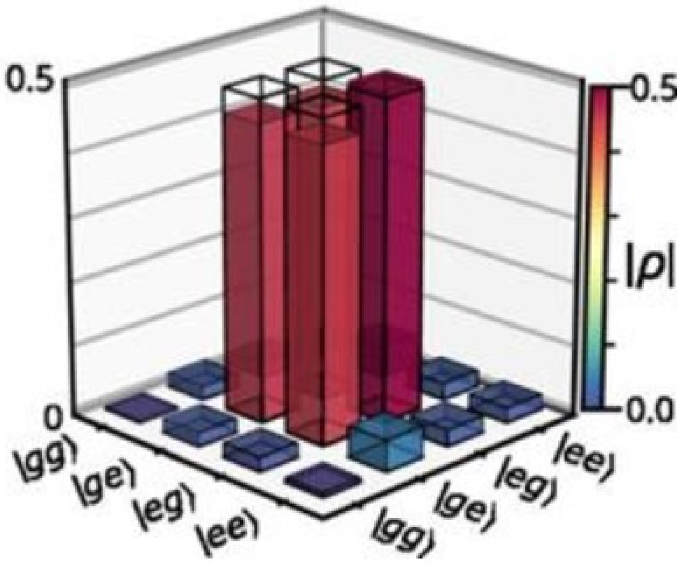
$$H_{\text{int}} = \hbar g(\sigma_+^1\sigma_-^2 + \sigma_-^1\sigma_+^2)$$



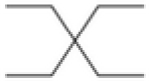
Conner et al., *Appl. Phys. Lett.* (2021)

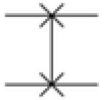


Half swap



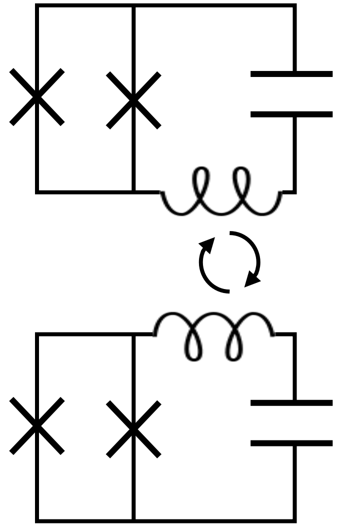
SWAP



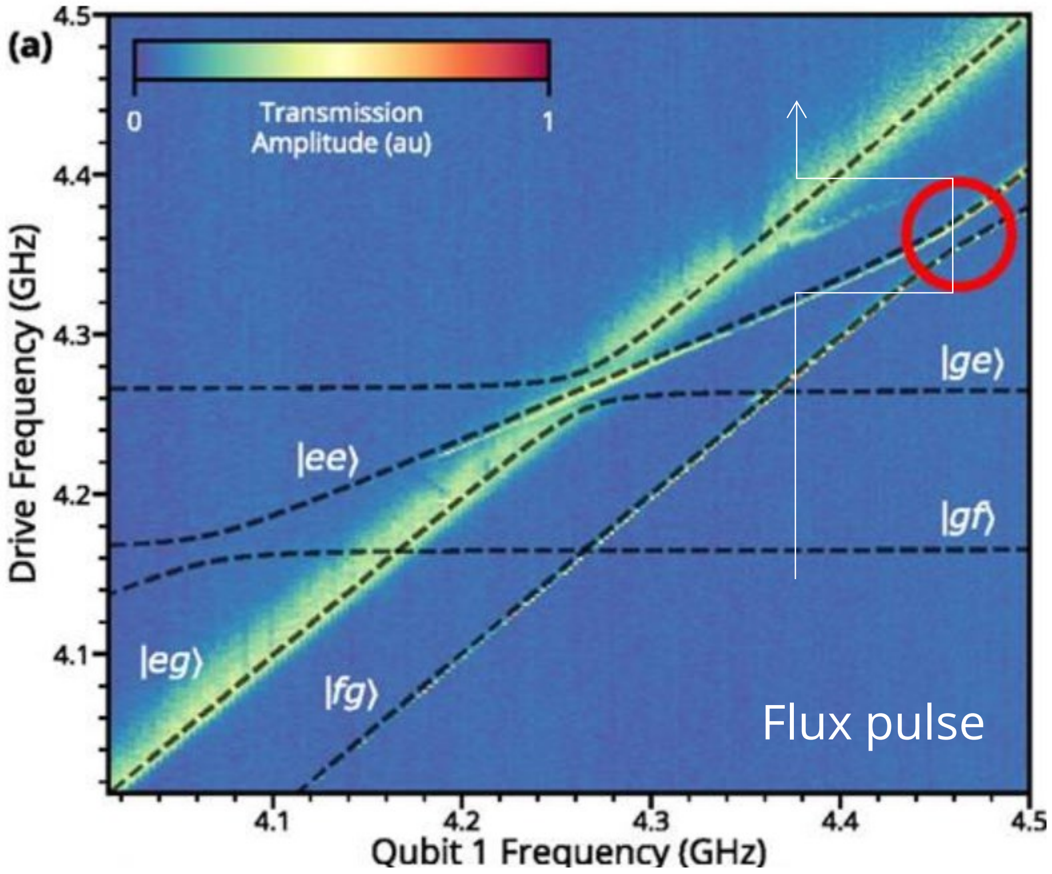


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

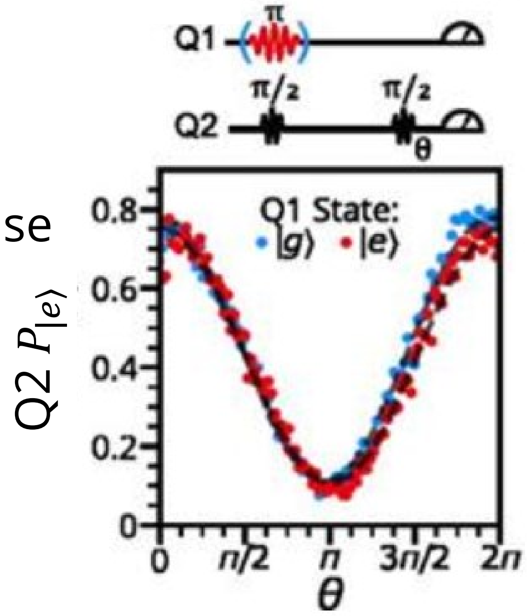
Examples of two qubit gates : CZ gate



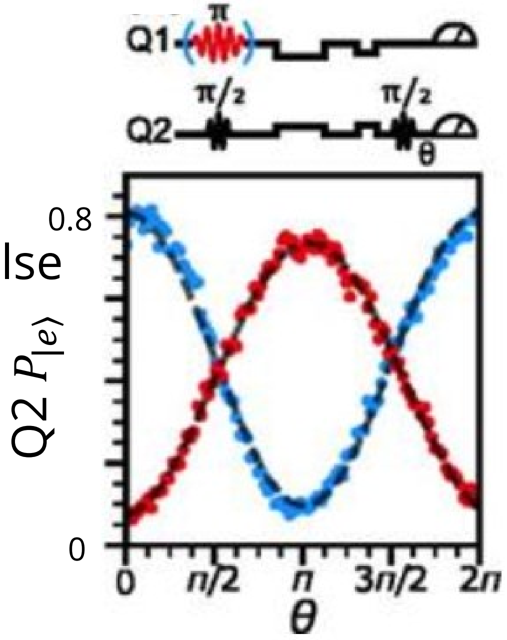
$$|gg\rangle \rightarrow |gg\rangle$$
$$|ge\rangle \rightarrow |ge\rangle$$
$$|eg\rangle \rightarrow |eg\rangle$$
$$|ee\rangle \rightarrow |fg\rangle \rightarrow e^{i\phi}|ee\rangle$$



No flux pulse



With flux pulse



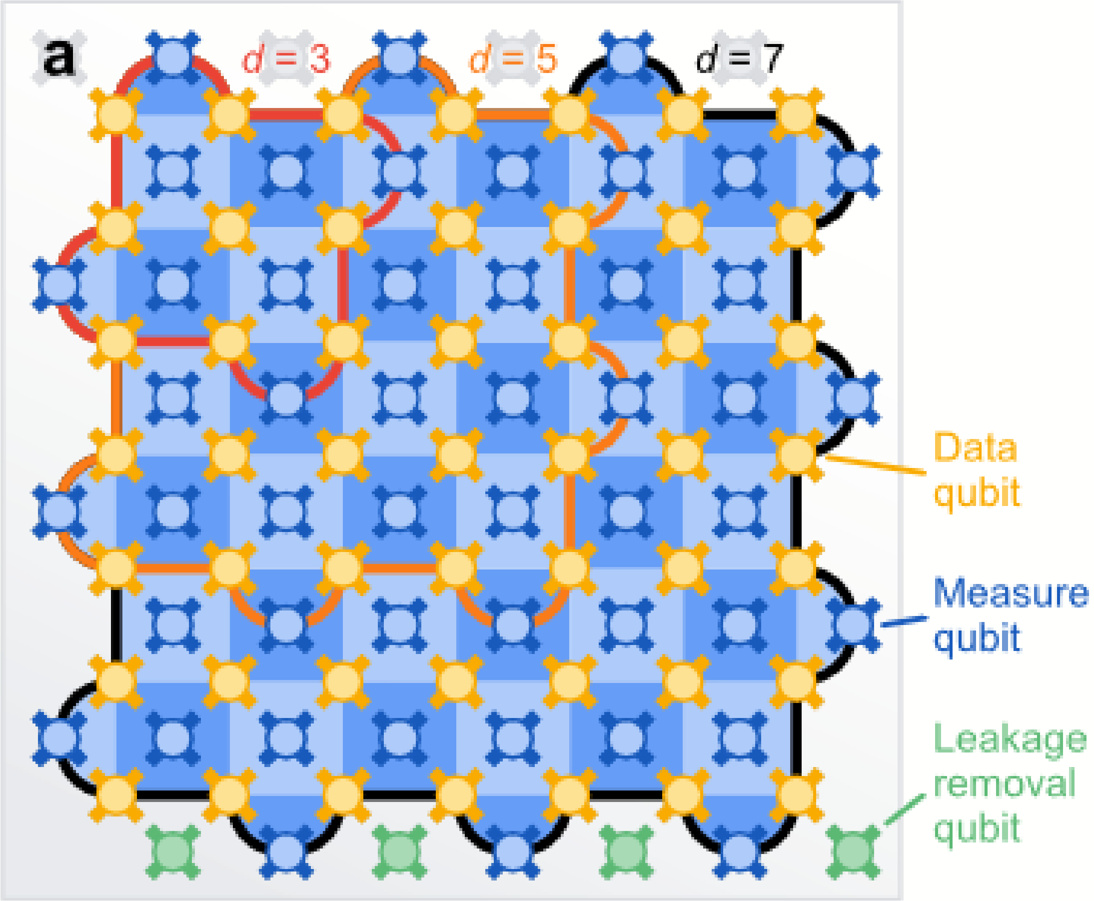
Controlled Z (CZ)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -1 \end{bmatrix}$$

Conner et al., *Appl. Phys. Lett.* (2021)

Only hope for viability : quantum error correction

Processor with 105 qubits
≡ 1 logical qubit

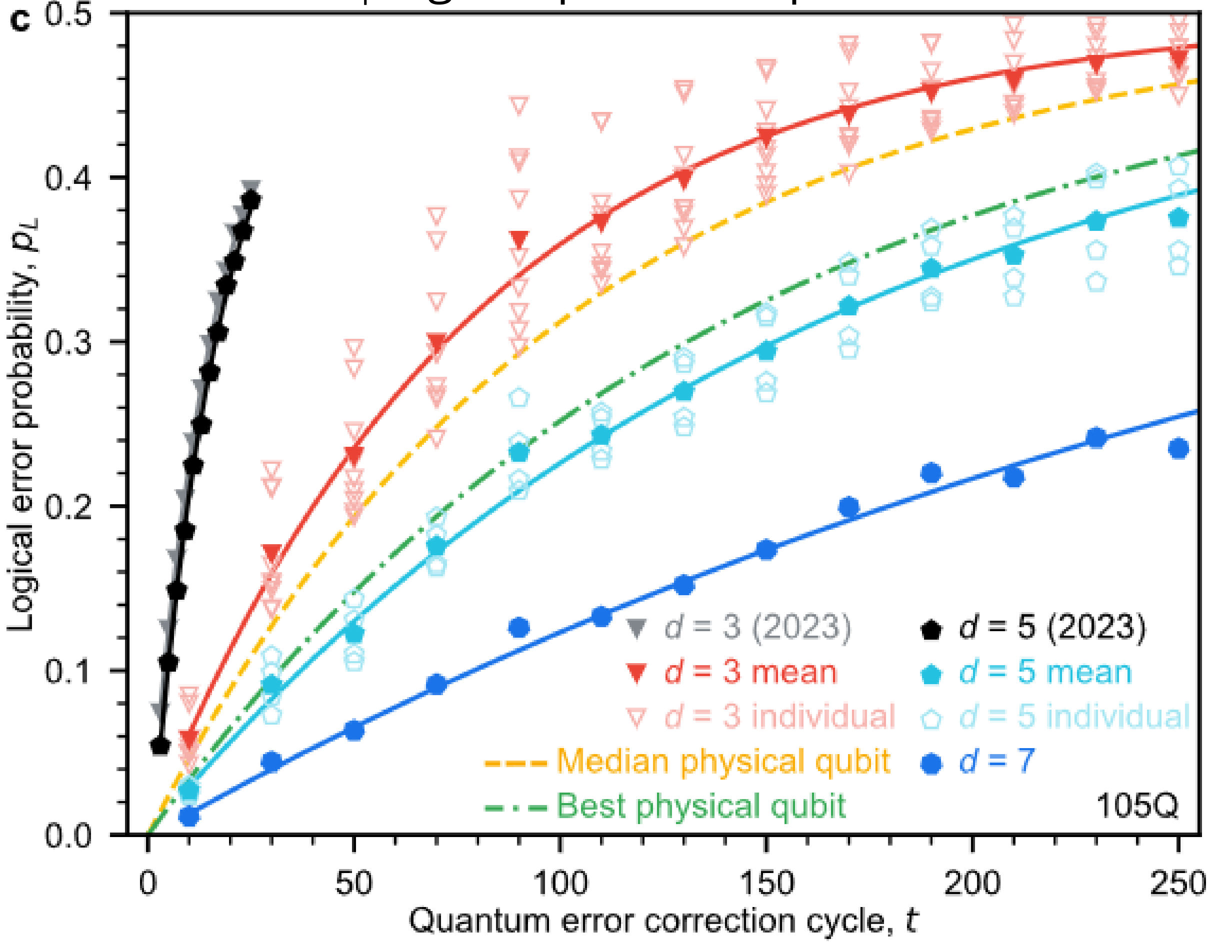


arXiv:2408.13687,
Google Quantum AI

Use stabilizers for error decoding on data qubits

T_1 physical qubit : 89 μs

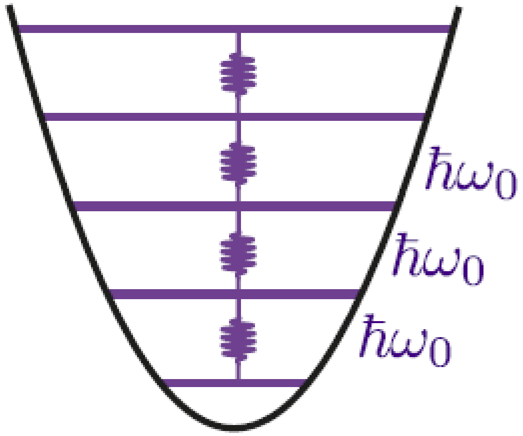
T_1 logical qubit : 290 μs



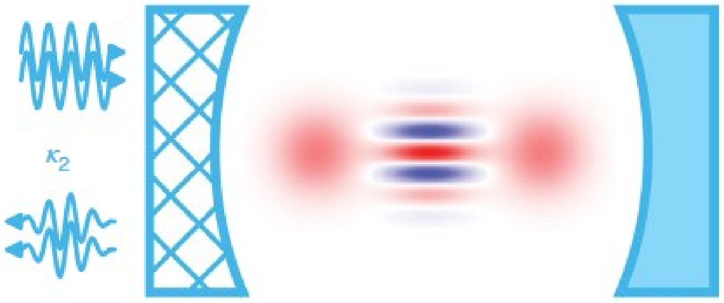
1 cycle = 1.1 μs

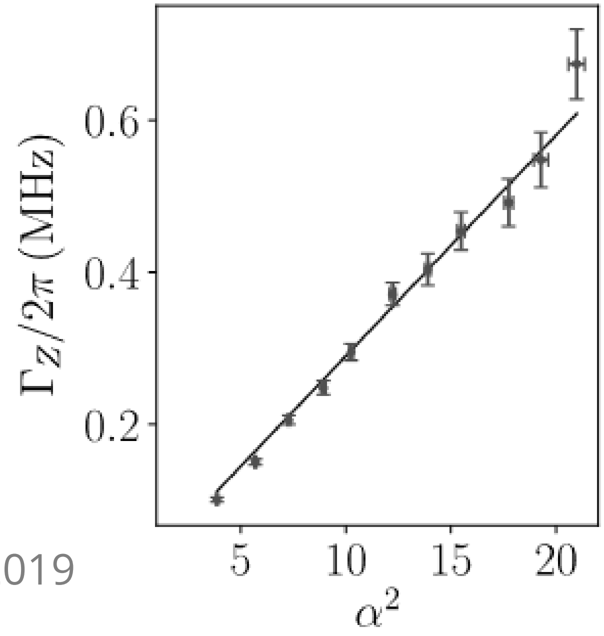
Bosonic codes

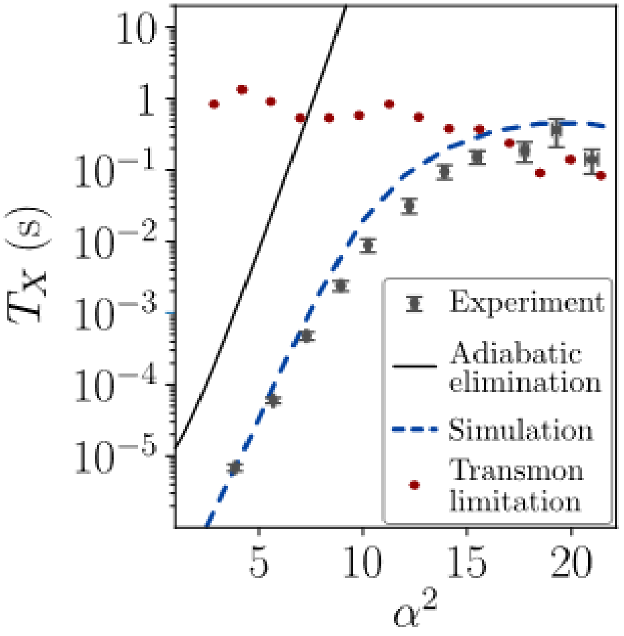
Redundancy given by usage of multiple Fock states

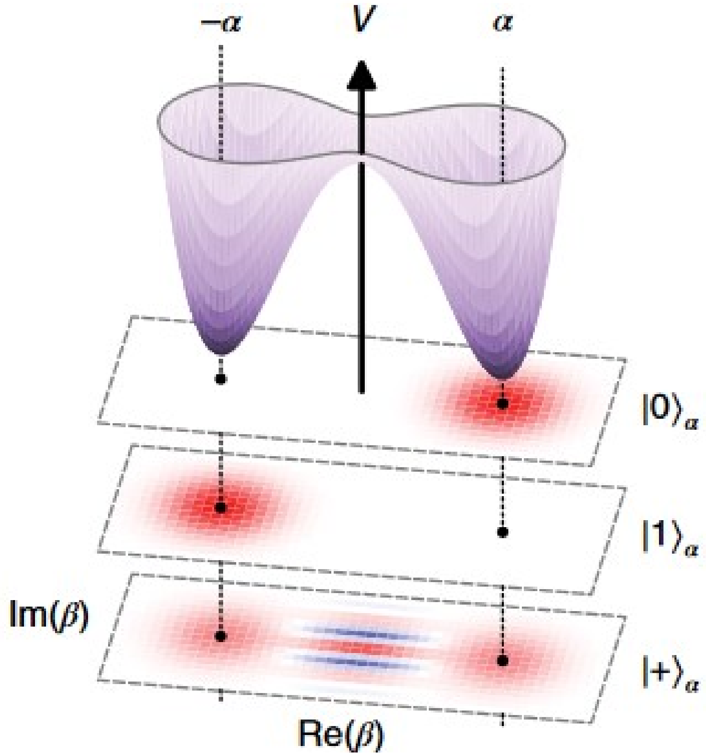


One example of encoding:
$|0\rangle_L = |\alpha\rangle$
$|1\rangle_L = |-\alpha\rangle$
$|+\rangle_L = |\alpha\rangle + |-\alpha\rangle = \sum_i c_i\, |2i\rangle$
$|-\rangle_L = |\alpha\rangle - |-\alpha\rangle = \sum_i c_i\, |2i+1\rangle$









Lescanne, *Nature* 2019
Marquet, *PRX* 2024

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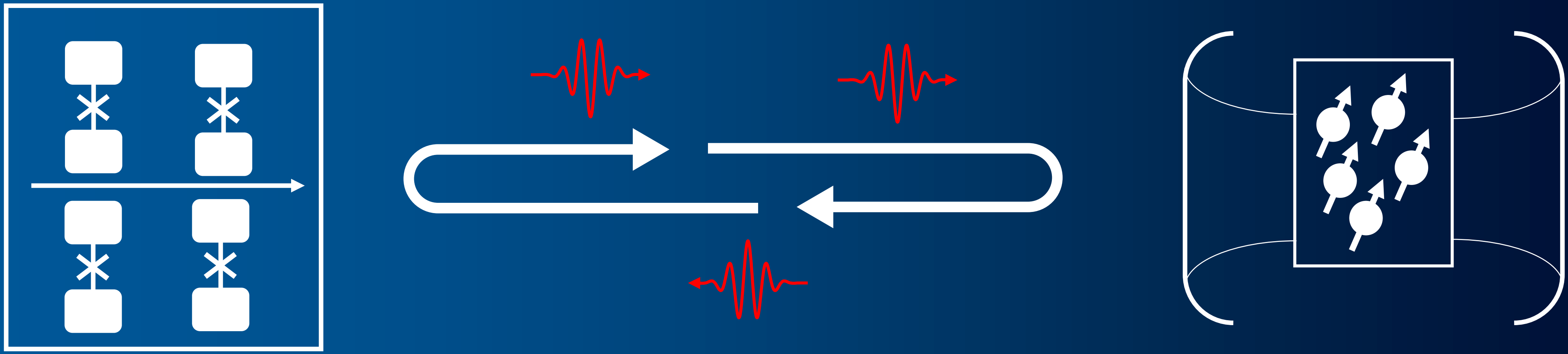
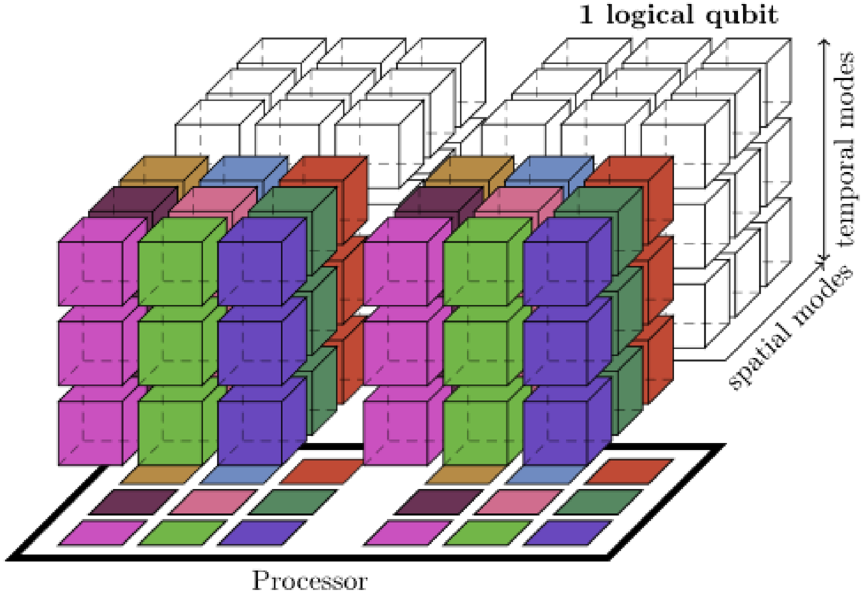


Storing qubits' quantum states

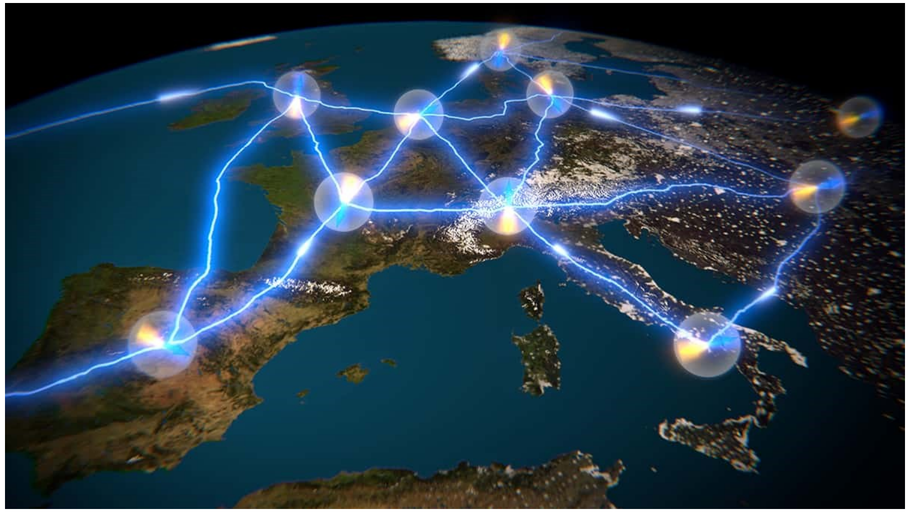
Reduce the number of processing qubits in a quantum computer



Factoring 2048-bit RSA Integers in 177 Days with 13 436 Qubits and a Multimode Memory, Gouzien & Sangouard, *PRL* (2021)

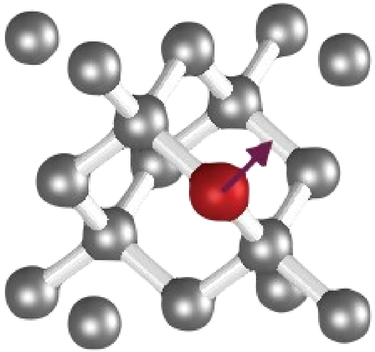
Quantum memory hierarchies: Efficient designs to match available parallelism in quantum computing, Thaker et al., Symposium on Computer Architecture (2006).

Enable long-distance communication



The quantum internet, H. J. Kimble, Nature (2008)

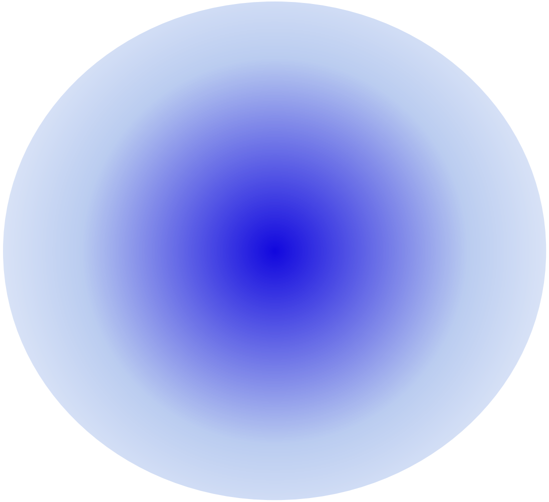
Ideal candidate : Bismuth donors in silicon

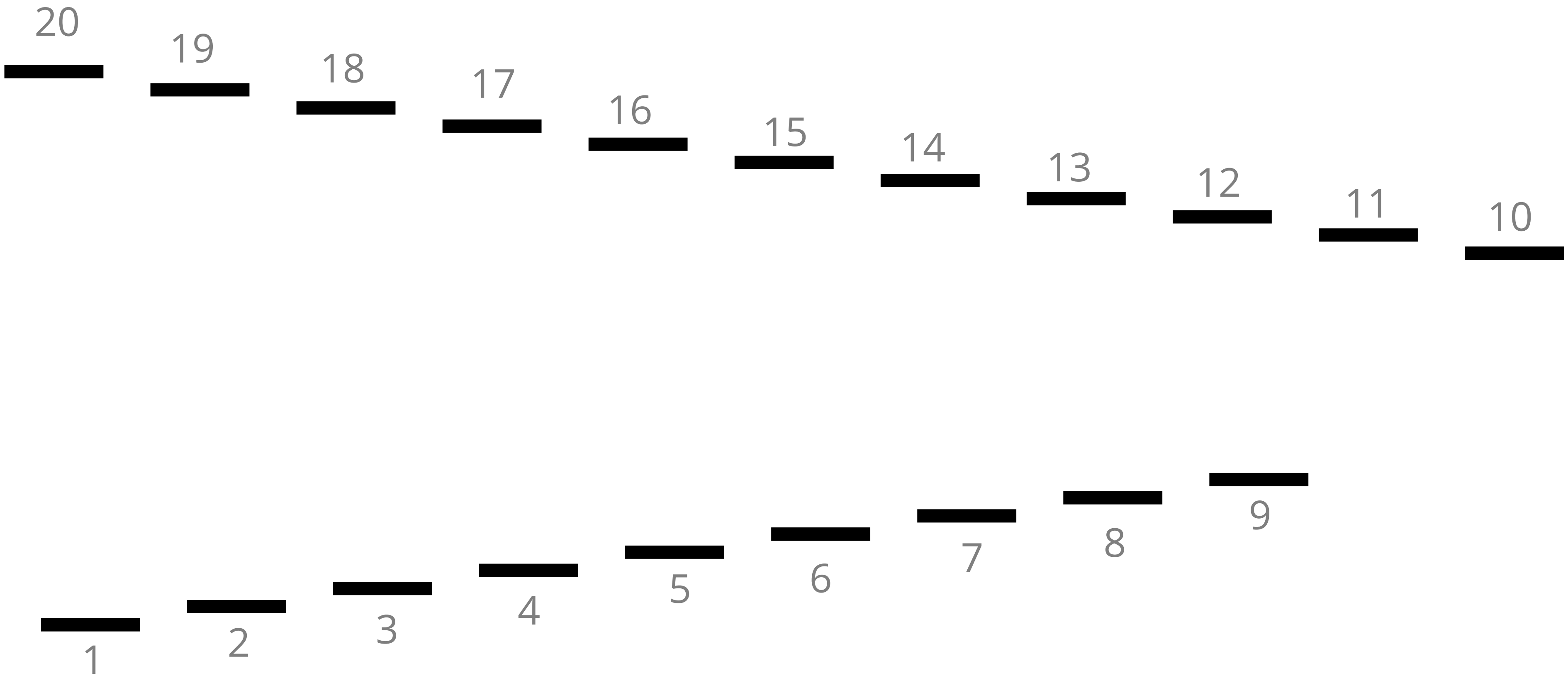


^{209}Bi

Nuclear spin
I = 9/2

Ideal candidate: Bismuth donors in silicon





Nuclear spin
I = 9/2

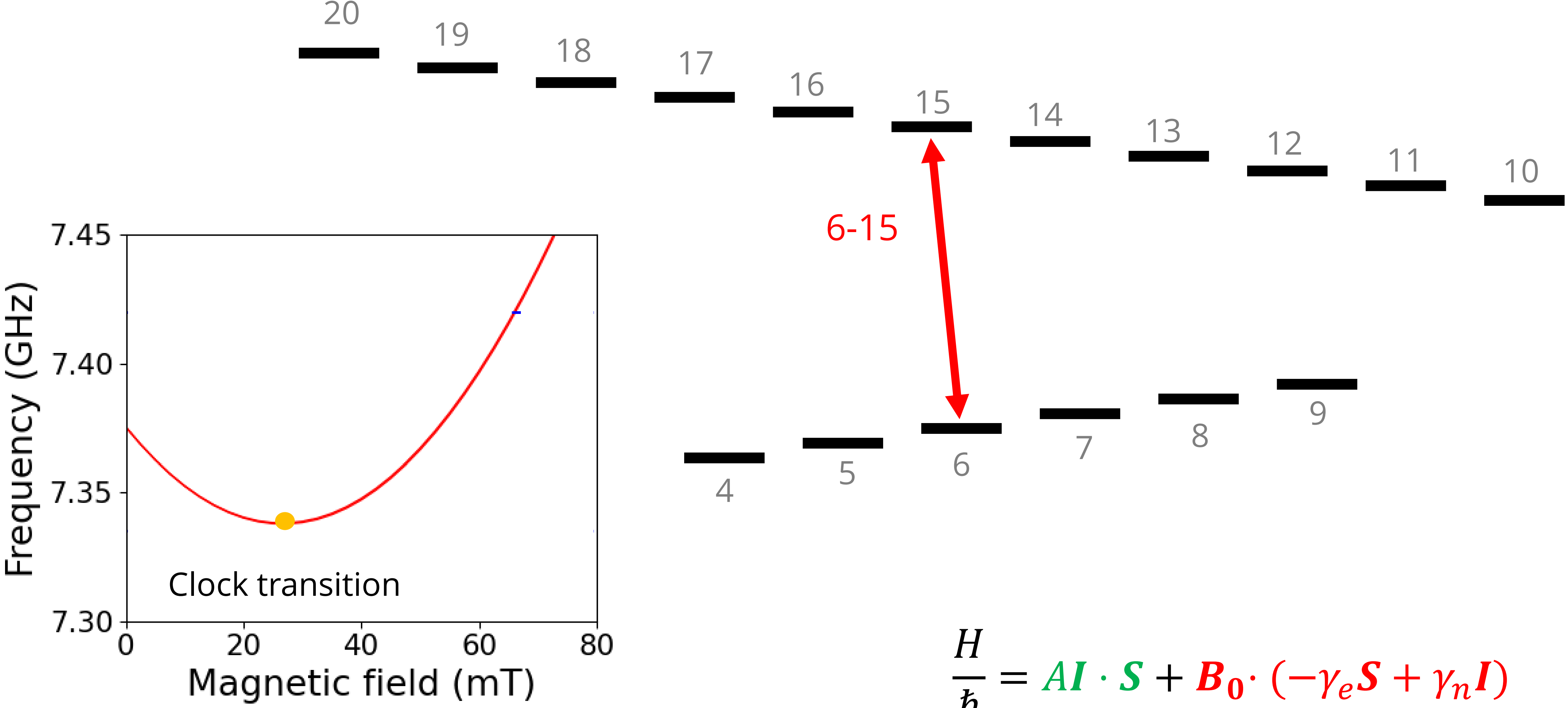
Electronic spin
S= ½

$$\frac{H}{\hbar} = A\boldsymbol{I}\cdot\boldsymbol{S} + \boldsymbol{B_0}\cdot\left(-\gamma_e\boldsymbol{S} + \gamma_n\boldsymbol{I}\right)$$

HYPERFINE **ZEEMAN EFFECT**

Ideal candidate: Bismuth donors in silicon

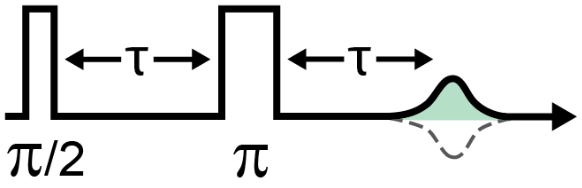
Energy levels at 65.6 mT

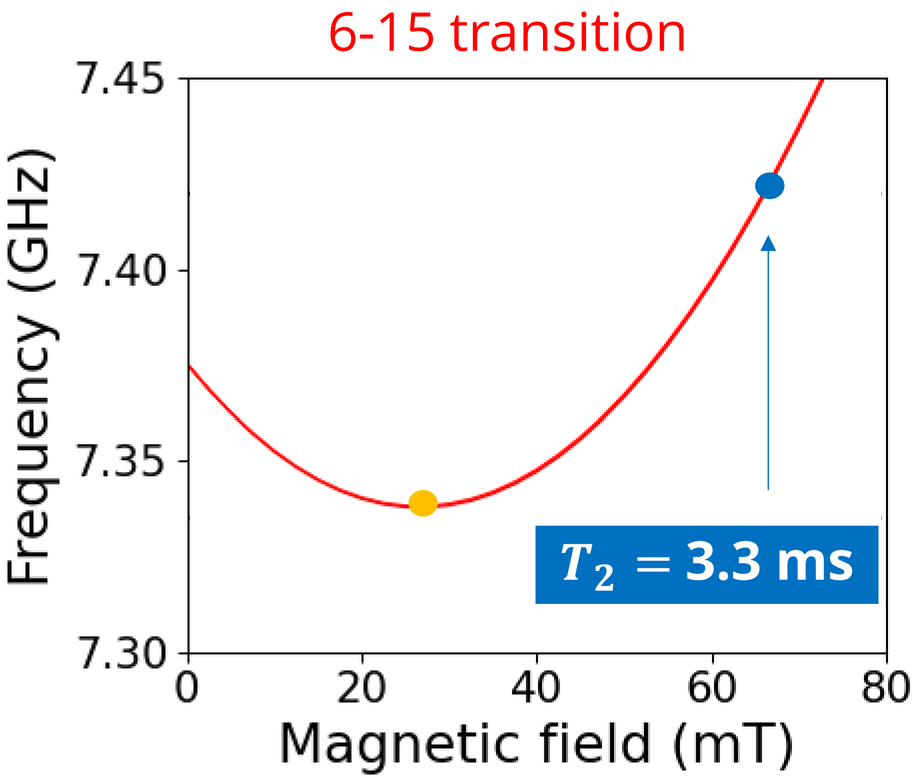


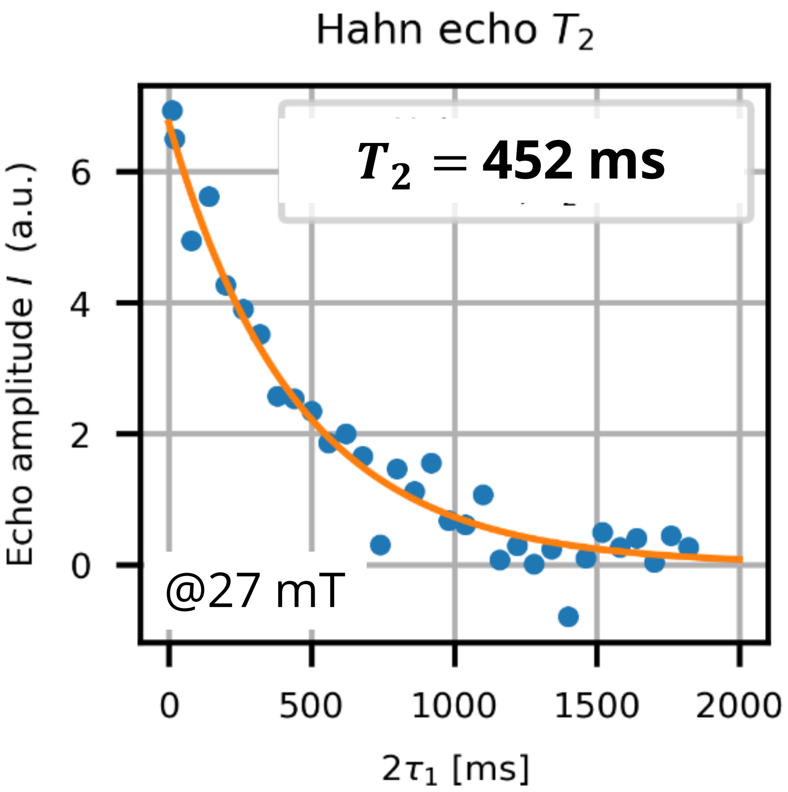
$$\frac{H}{\hbar} = AI \cdot S + B_0 \cdot (-\gamma_e S + \gamma_n I)$$

HYPERFINE **ZEEMAN EFFECT**

Bismuth donors in silicon

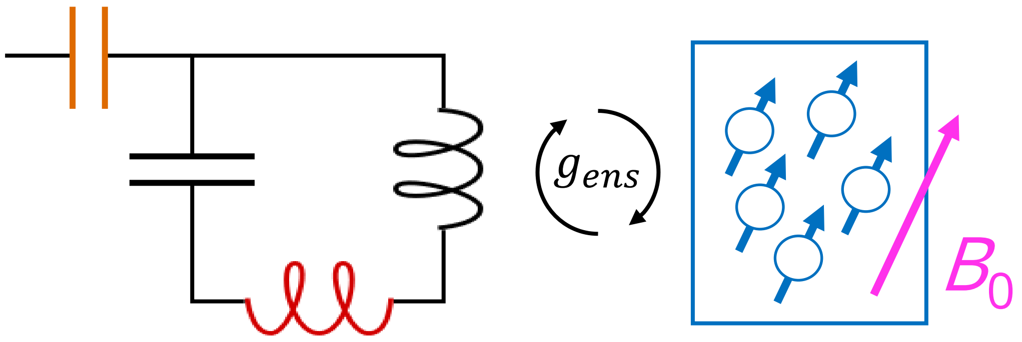






Spin ensemble coupled to a superconducting resonator

Linewidth κ_a



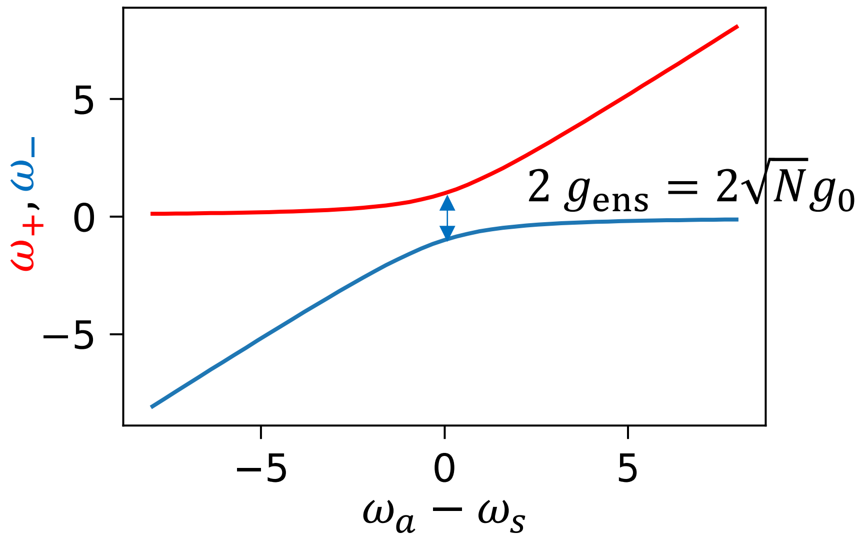
Frequency ω_a

Frequency $\omega_s(B_0)$

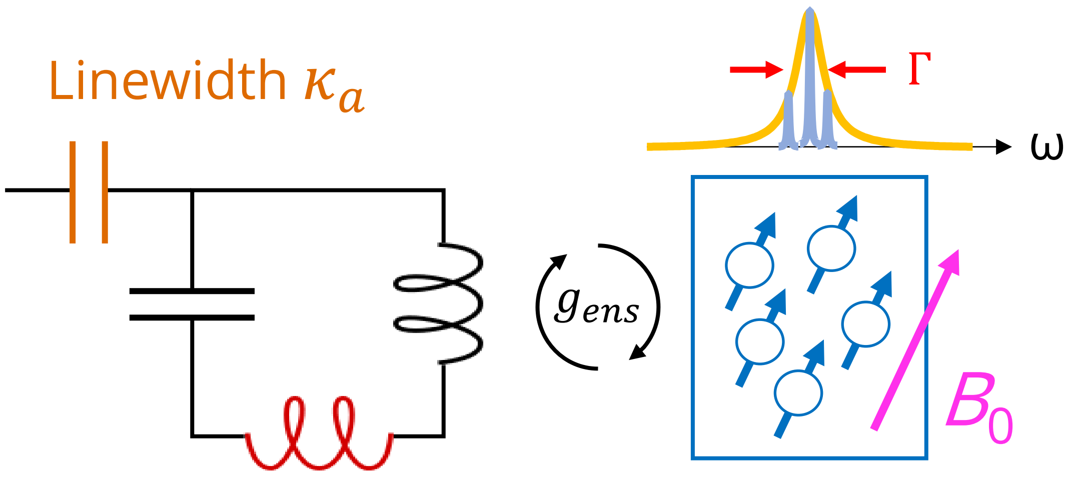
$$H = \mu\,(\vec{B}_0 + \vec{B}_1).\vec{S}$$

$$H_{\text{int}} = \underbrace{\mu\,\delta B_1}(a + a^+)(\sigma_+ + \sigma_-)$$

Couping constant $\frac{g_0}{2\pi}$ = 1 mHz – 5 kHz



Spin ensemble coupled to a superconducting resonator



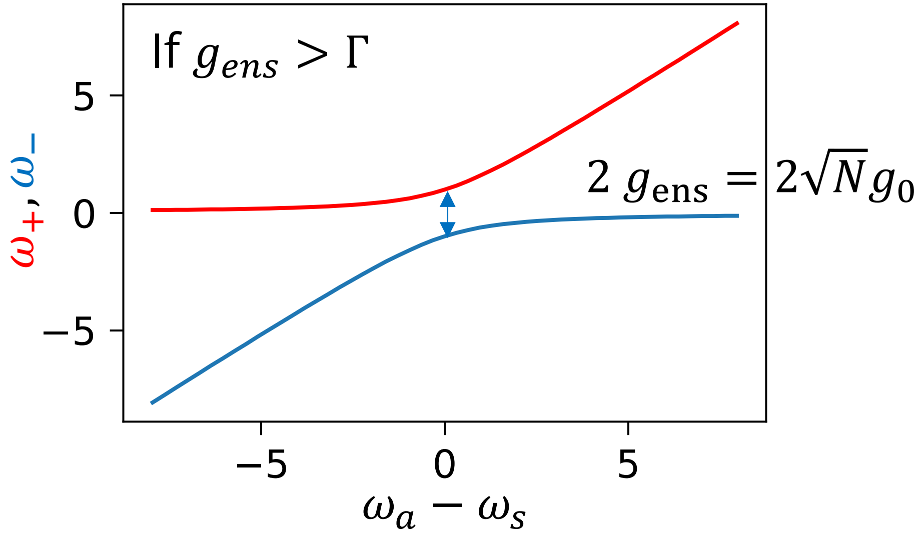
Linewidth κ_a

Frequency ω_a

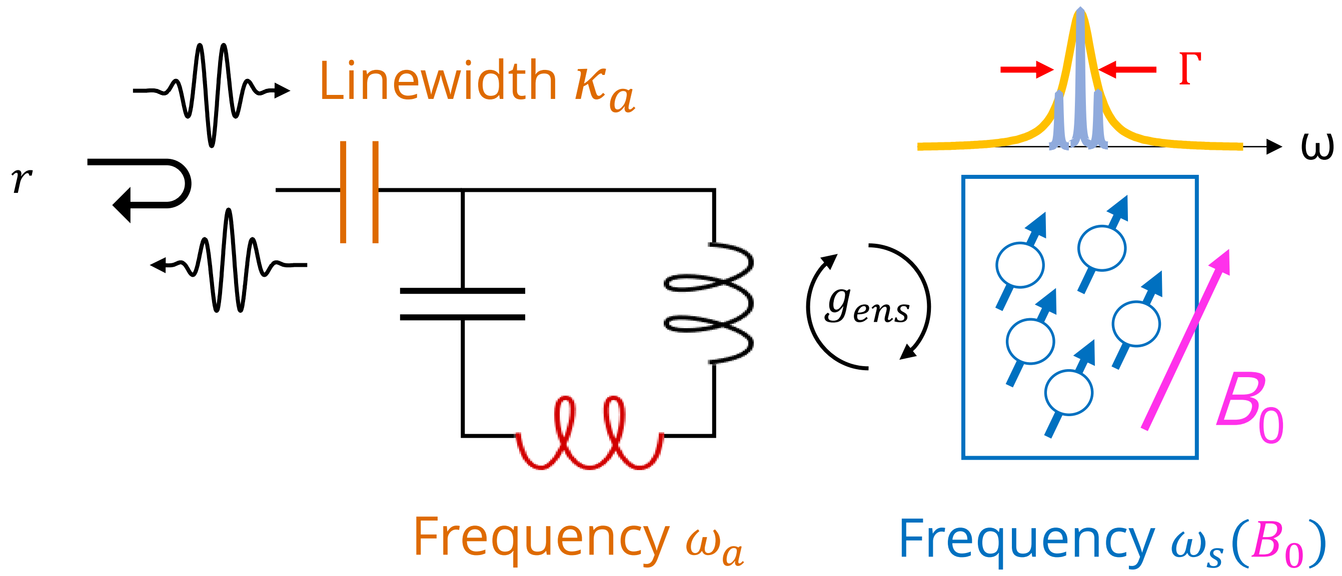
Frequency $\omega_s(B_0)$

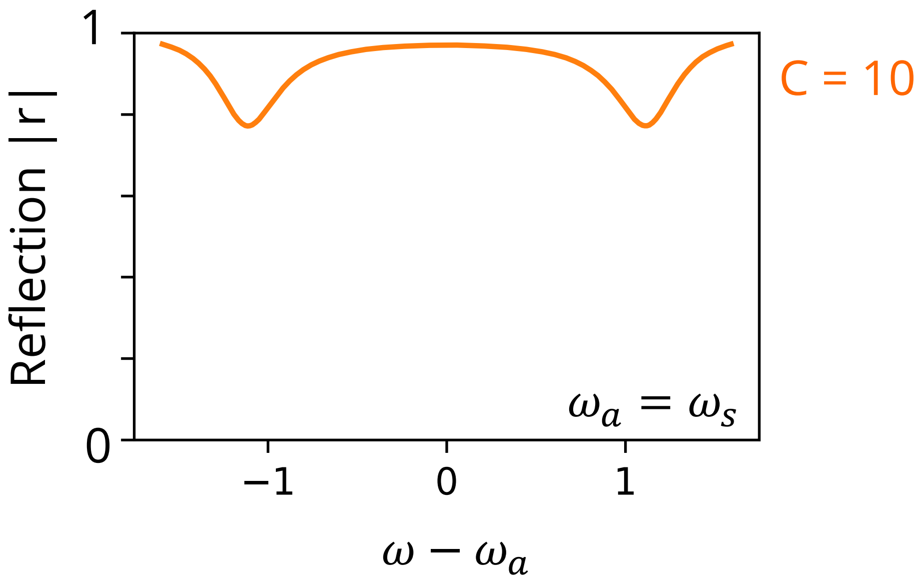
Regime of interaction given by cooperativity

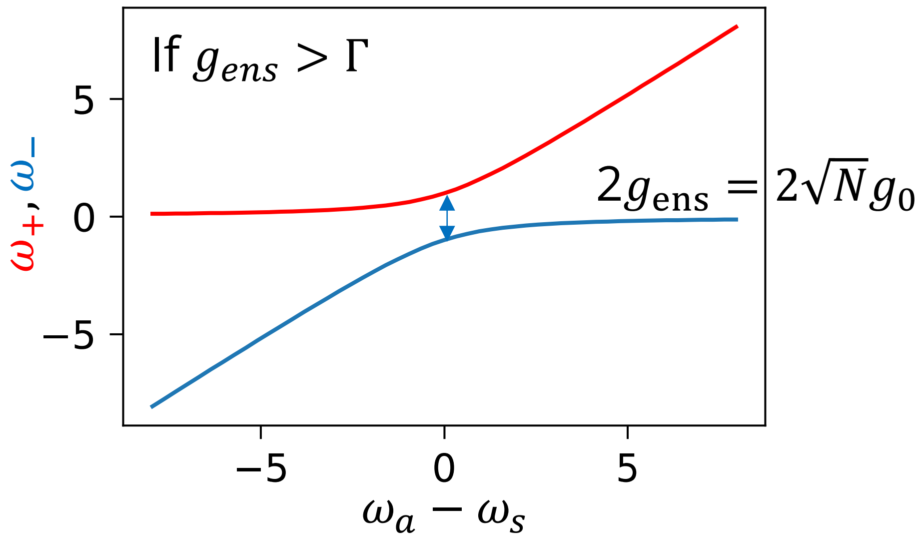
$$C = \frac{4\, g_{\mathrm{ens}}^2}{\kappa_{\mathrm{a}}\Gamma} = \frac{4\, N\, g_0^2}{\kappa_{\mathrm{a}}\Gamma}$$



Spin ensemble coupled to a superconducting resonator





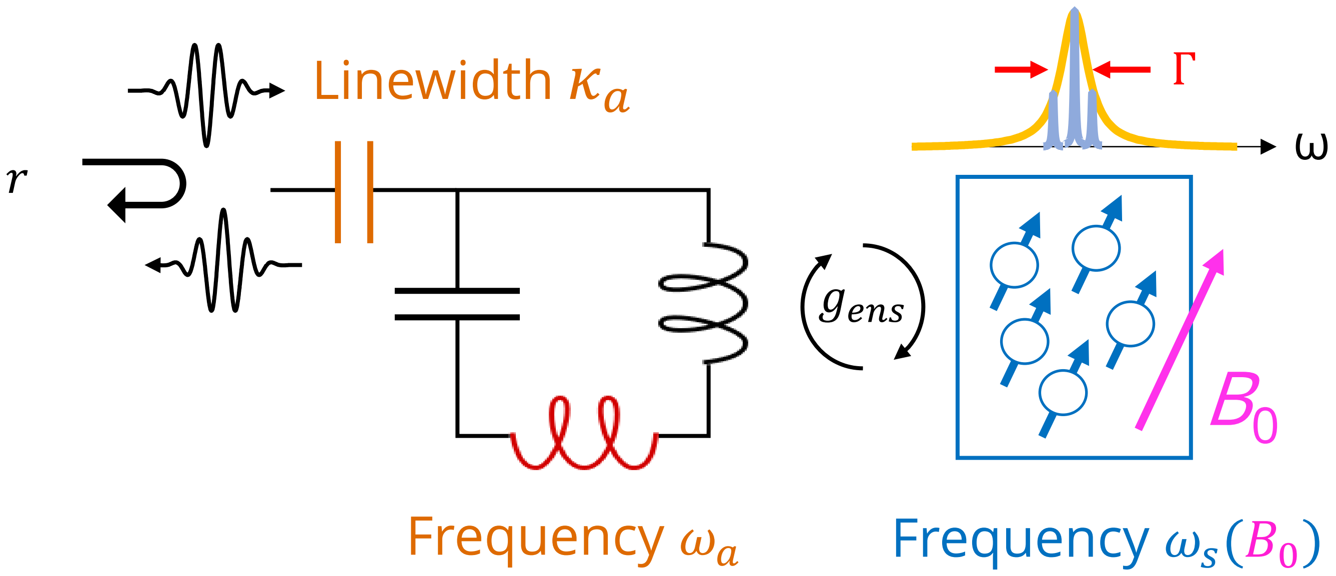


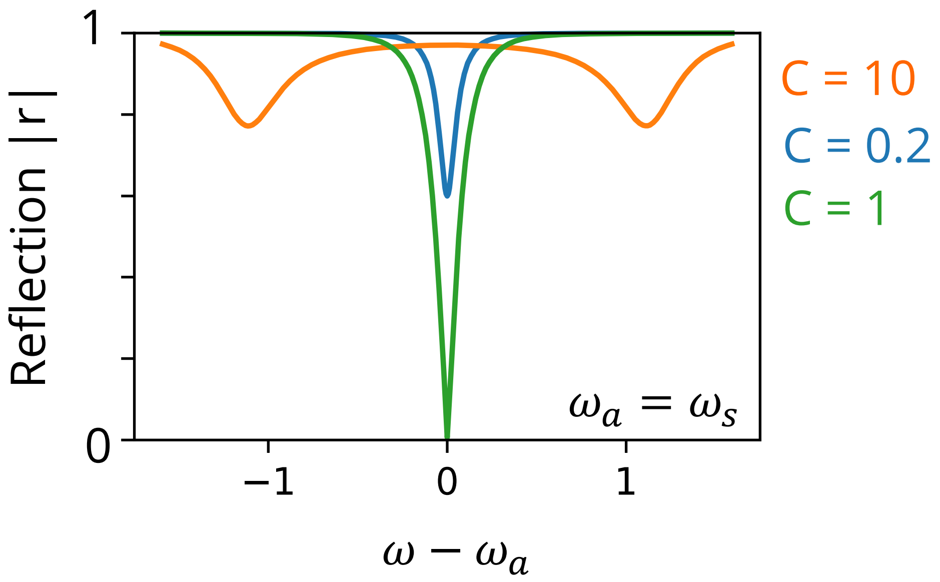
High cooperativity

Signature of avoided level crossings

Coherent swaps between resonators and spins, with exchange time limited by $1/\Gamma$

Spin ensemble coupled to a superconducting resonator





High cooperativity

Signature of avoided level crossings

Coherent swaps between resonators and spins, with exchange time limited by $1/\Gamma$

Unit cooperativity

Perfect absorption into the spins

No coherent swapping

Low cooperativity

Spins act as a loss channel

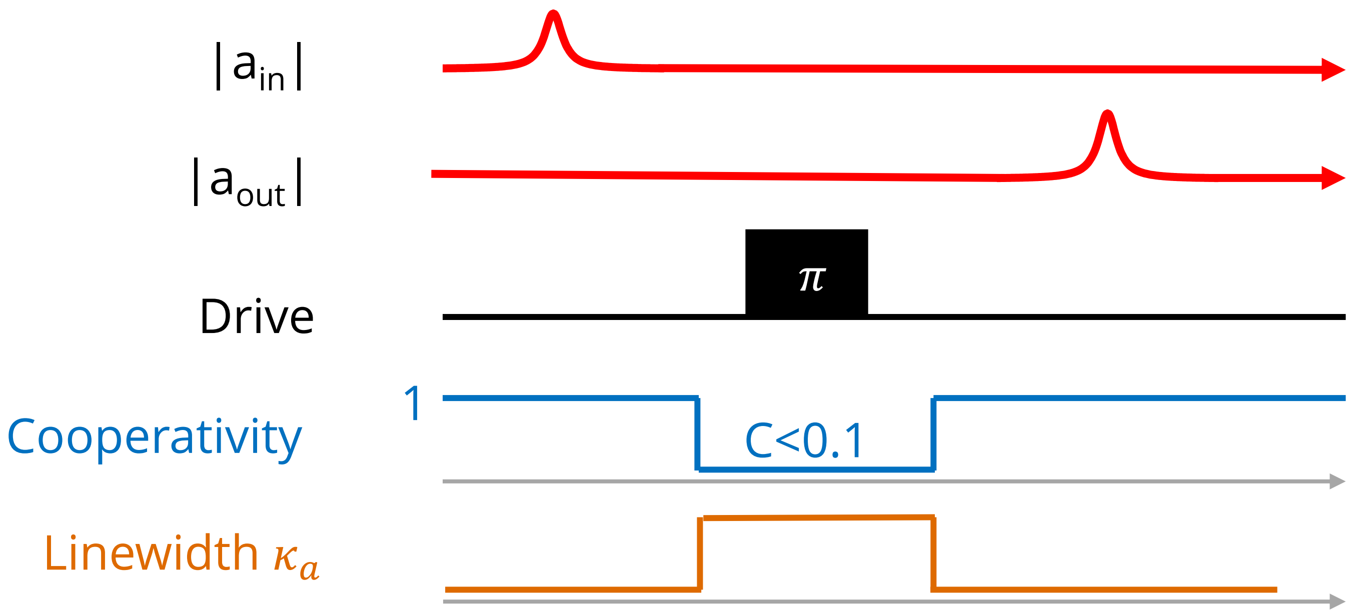
No coherent swapping

Possible to drive the spins classically by applying a coherent drive on the resonator

Spins can deexcite via the resonator (Purcell effect)

Spin ensemble as a memory: protocol

How to store an incoming arbitrary wave packet and retrieve it?



Julsgaard, et al. (2012), Yin et al. (2013), Ranjan et al. (2020), phase encoding: O'Sullivan et al. (2022)

Spin ensemble as a memory: protocol

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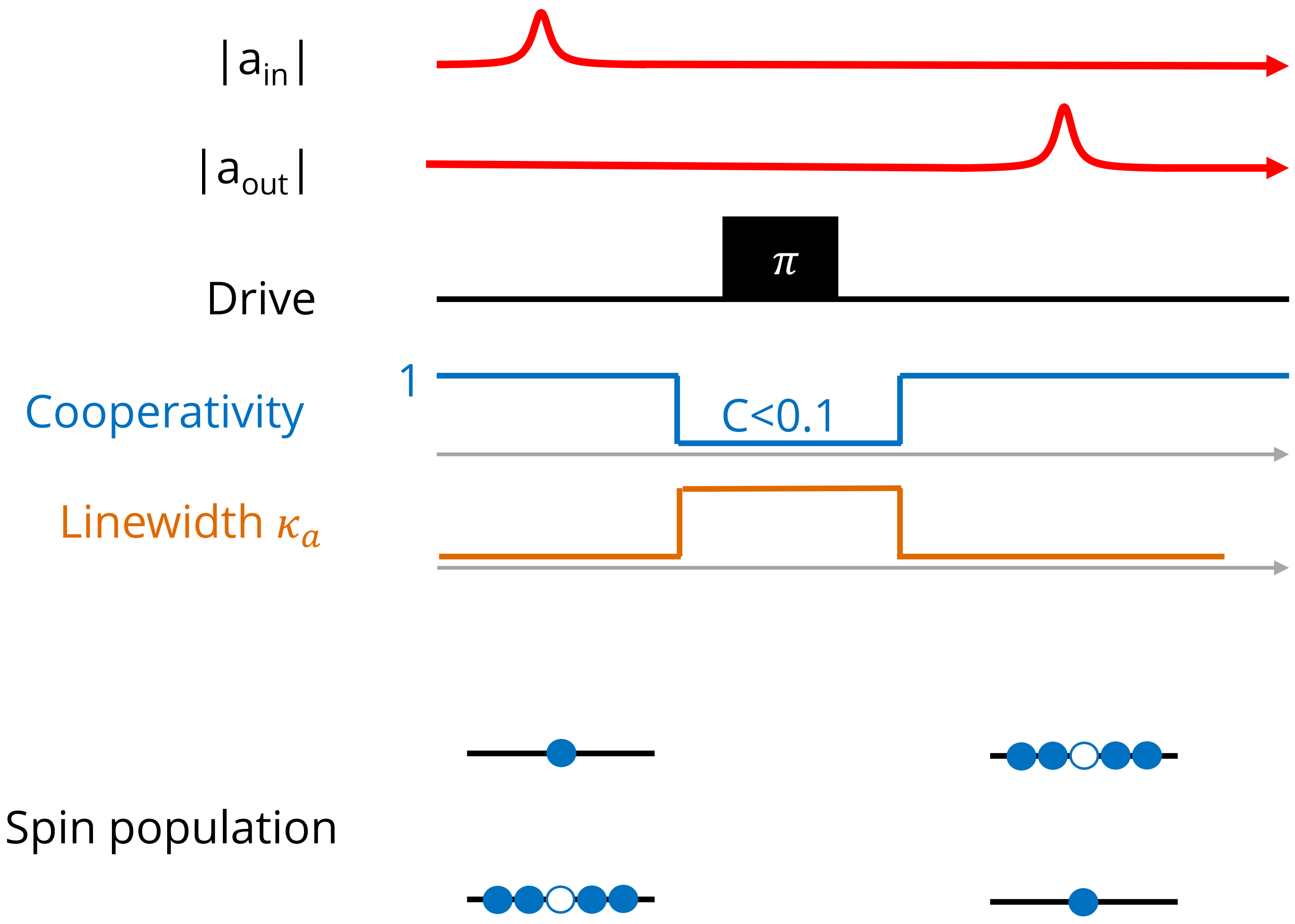

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Spin ensemble as a memory: protocol

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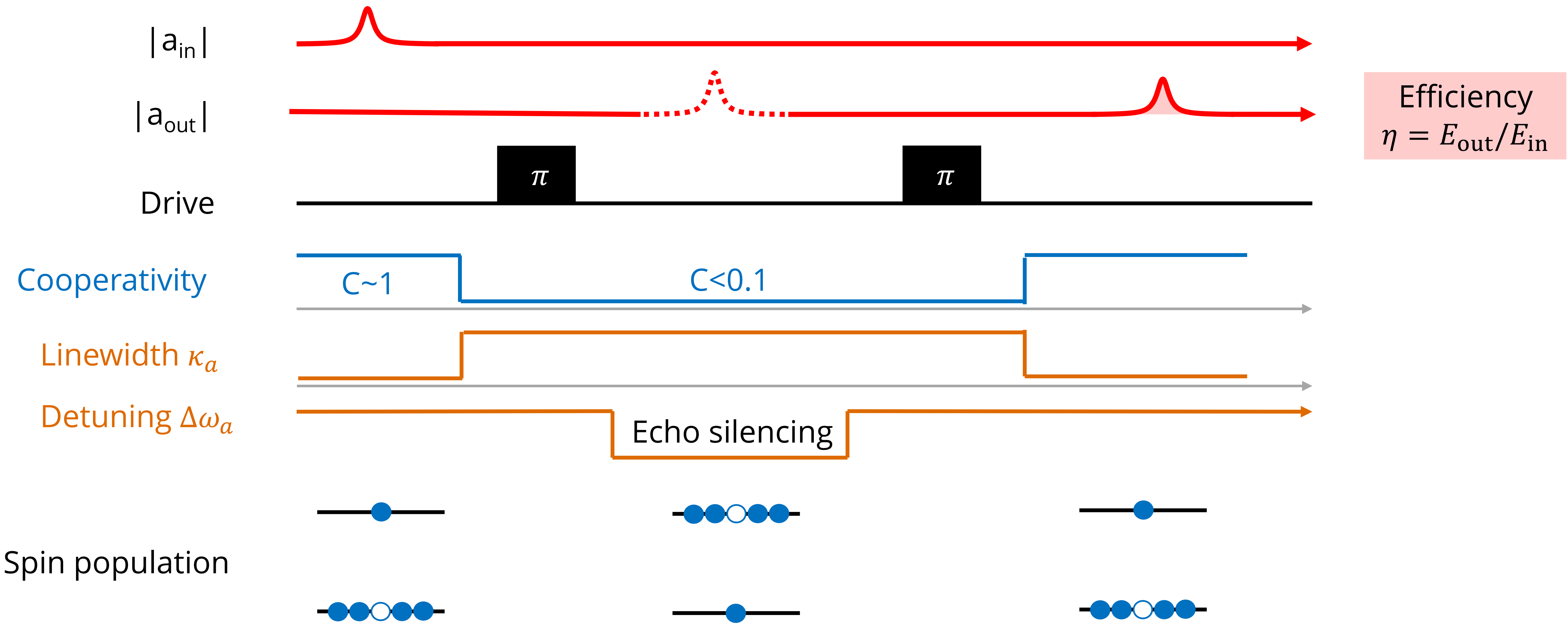
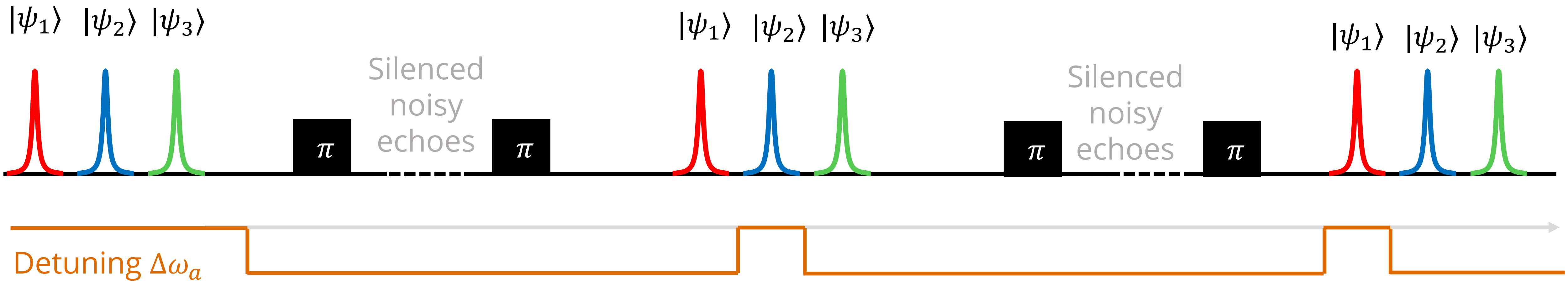


Julsgaard, et al. (2012), Yin et al. (2013), Ranjan et al. (2020), phase encoding: O'Sullivan et al. (2022)

Multimode?

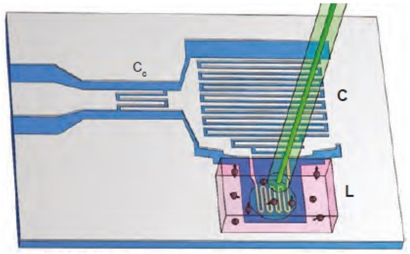
Random access to multiple stored states by echo silencing… except on retrieval !



Spin-ensemble as a memory : requirements & state of the art

- ✓ Long spin coherence
  - ✓ Aim for clock transitions
- ✓ Tunable resonator frequency
  - ✓ For echo silencing
  - ✓ For aiming for clock transitions
- X Tunable linewidth
- X Reach unit cooperativity

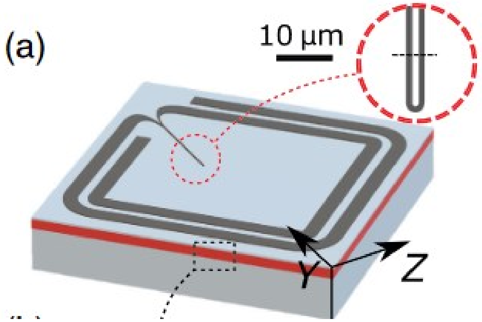
NV centers in diamond



Grezes et al., *PRA* (2015)

Efficiency 0.3 %
C = 0.22
T_2 = 84 us

Bismuth donors in silicon



Ranjan
PRL (2020)

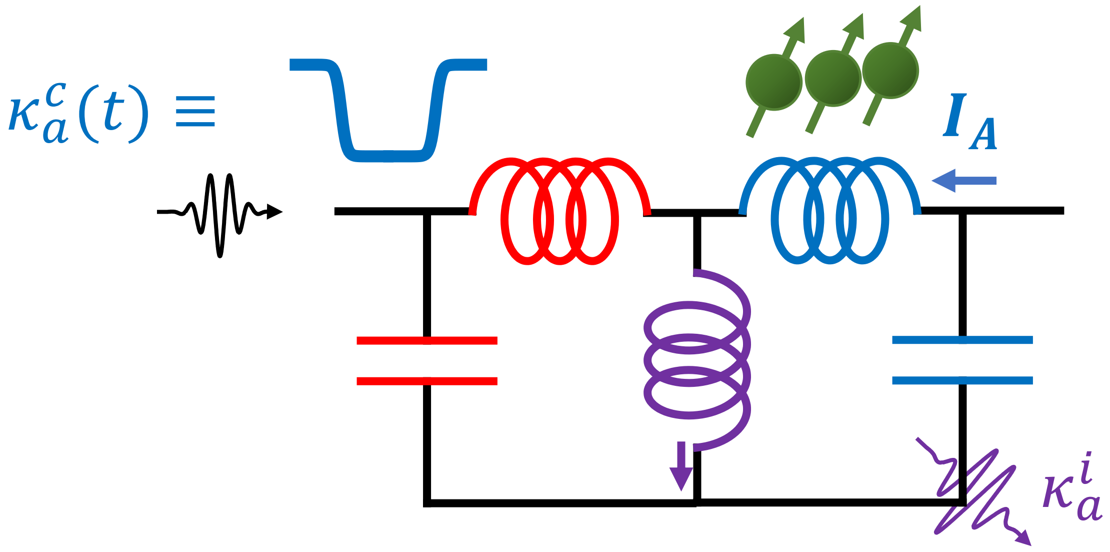
Efficiency 0.1 %
C = 0.04
T_2 = 0.3 s

O'Sullivan
PRX (2022)

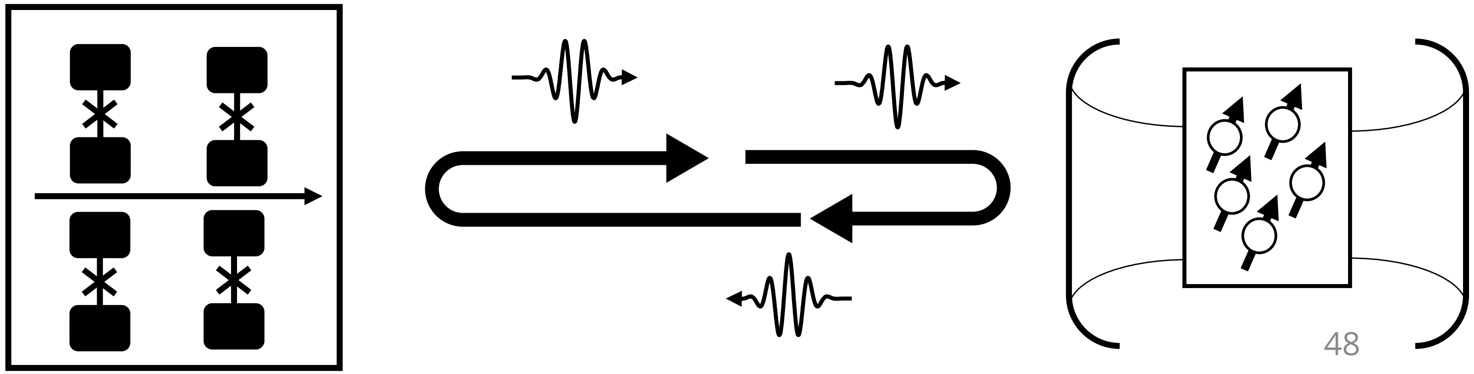
Efficiency 3
C = 0.06
T_2 = 2 ms

Perspective

Running a protocol maximizing efficiency for classical pulses

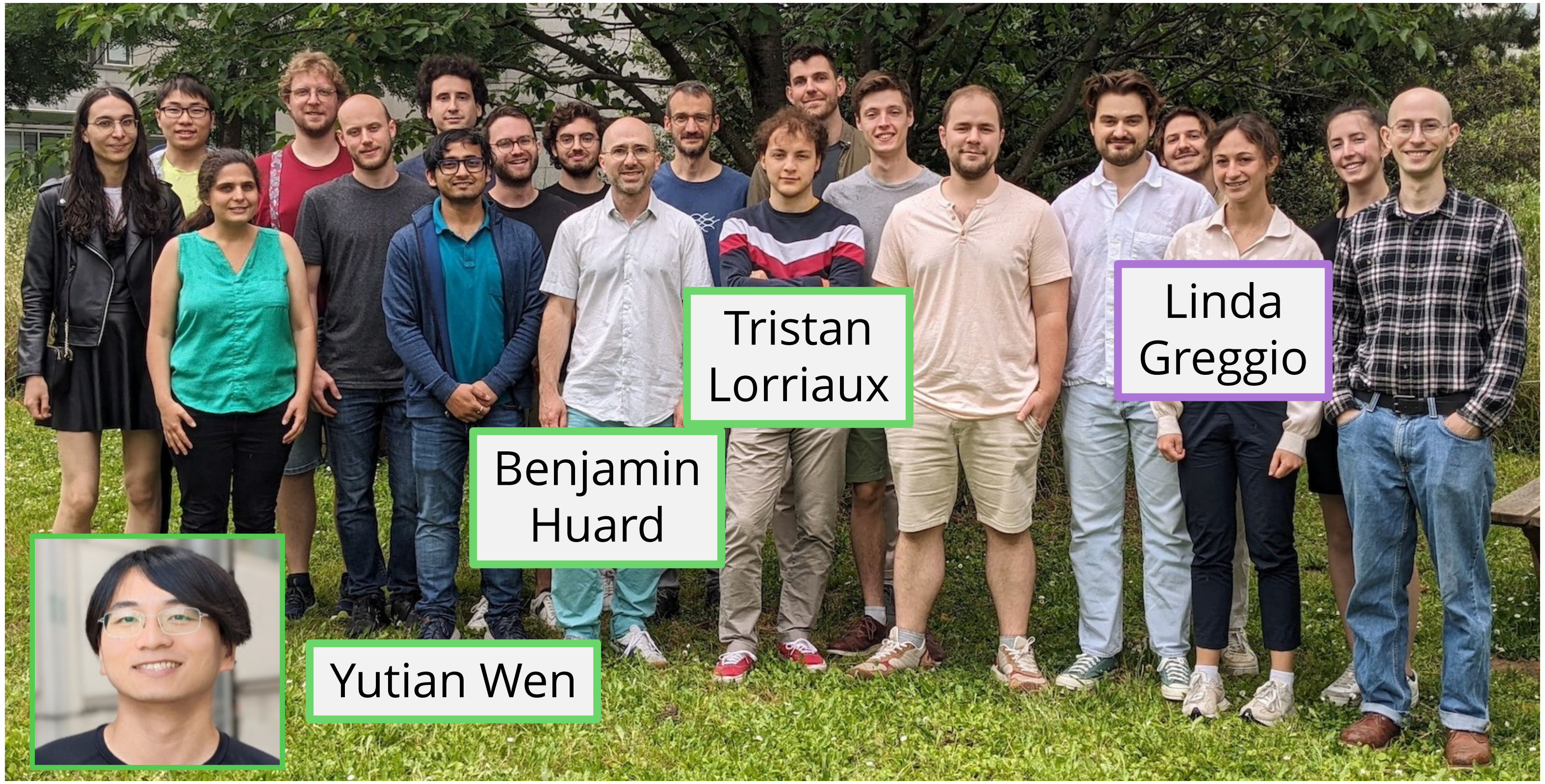


Building a bidirectional link between qubit and processor



Acknowledgments

Quantum circuit group, summer 2024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