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

Audrey Bienfait, Tristan Lorriaux, Yutian Wen, V. Ranjan, Denis Vion, Emmanuel
Flurin, Benjamin Huard, Patrice Bertet

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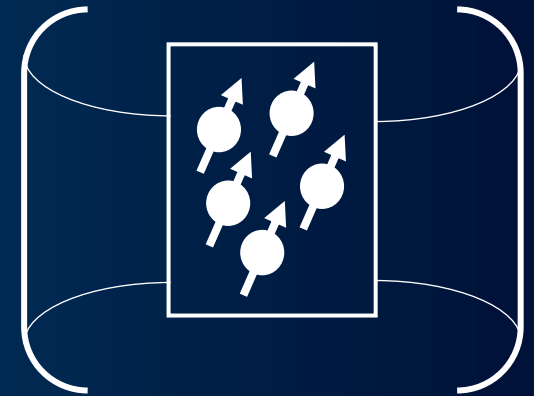
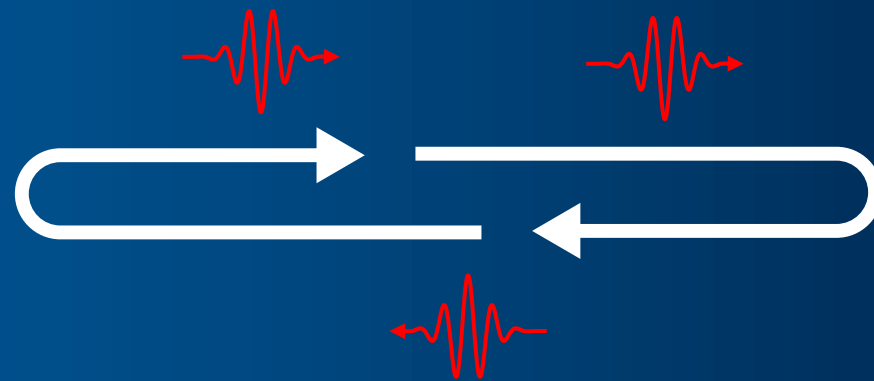
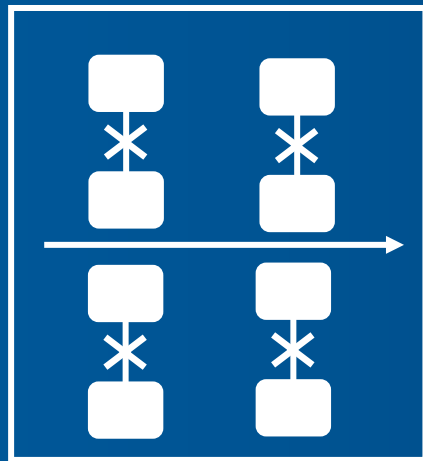
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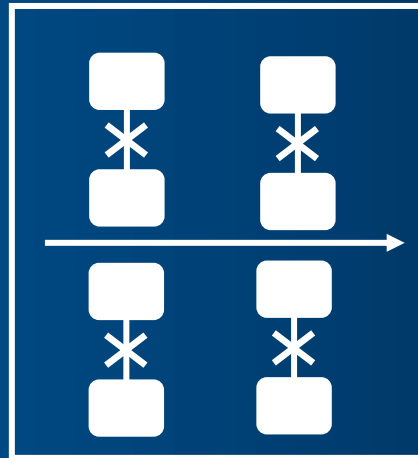
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Implementing a quantum memory at microwave frequencies with Bismuth donors in silicon

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

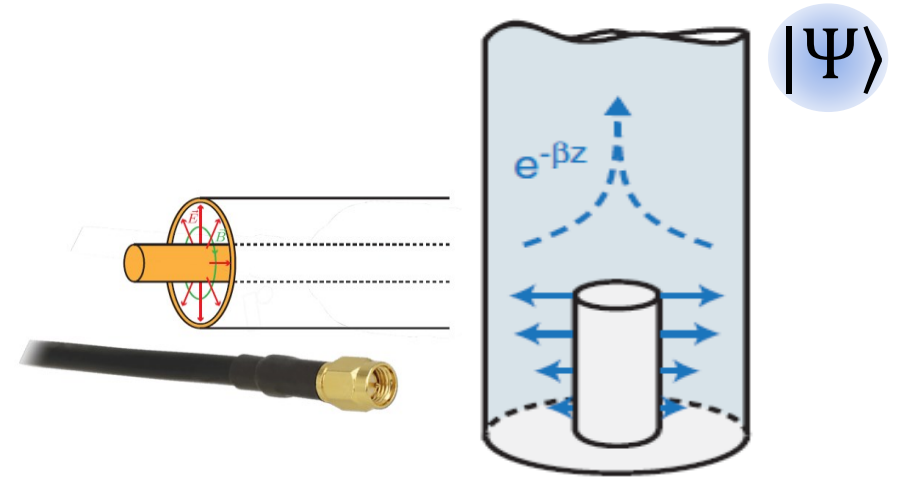


Superconducting circuits: how to implement qubits and gates ?

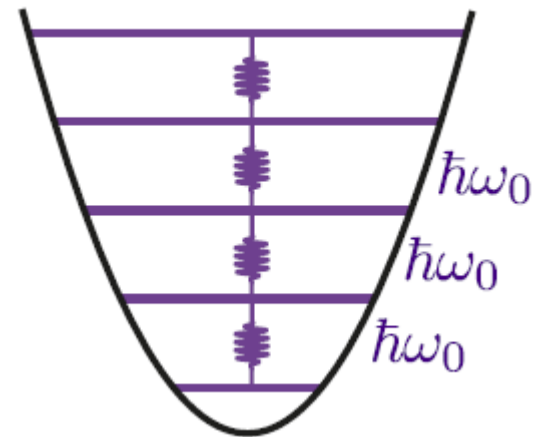
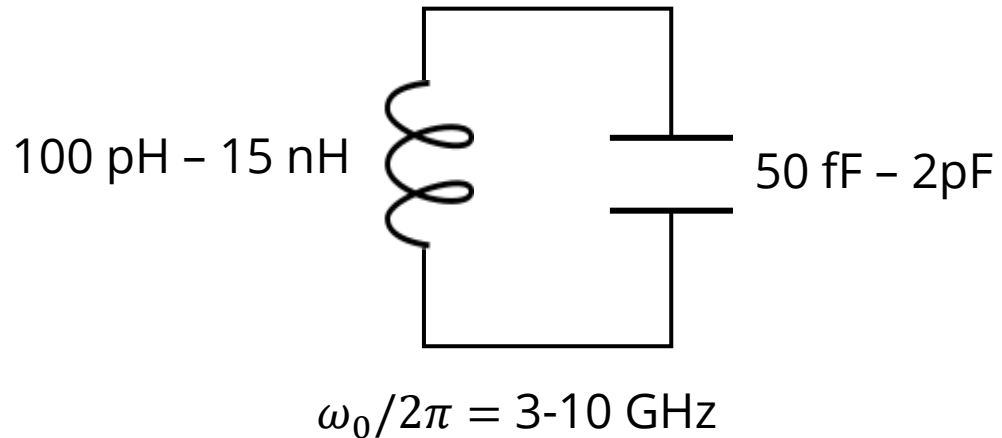


Quantum superconducting circuits

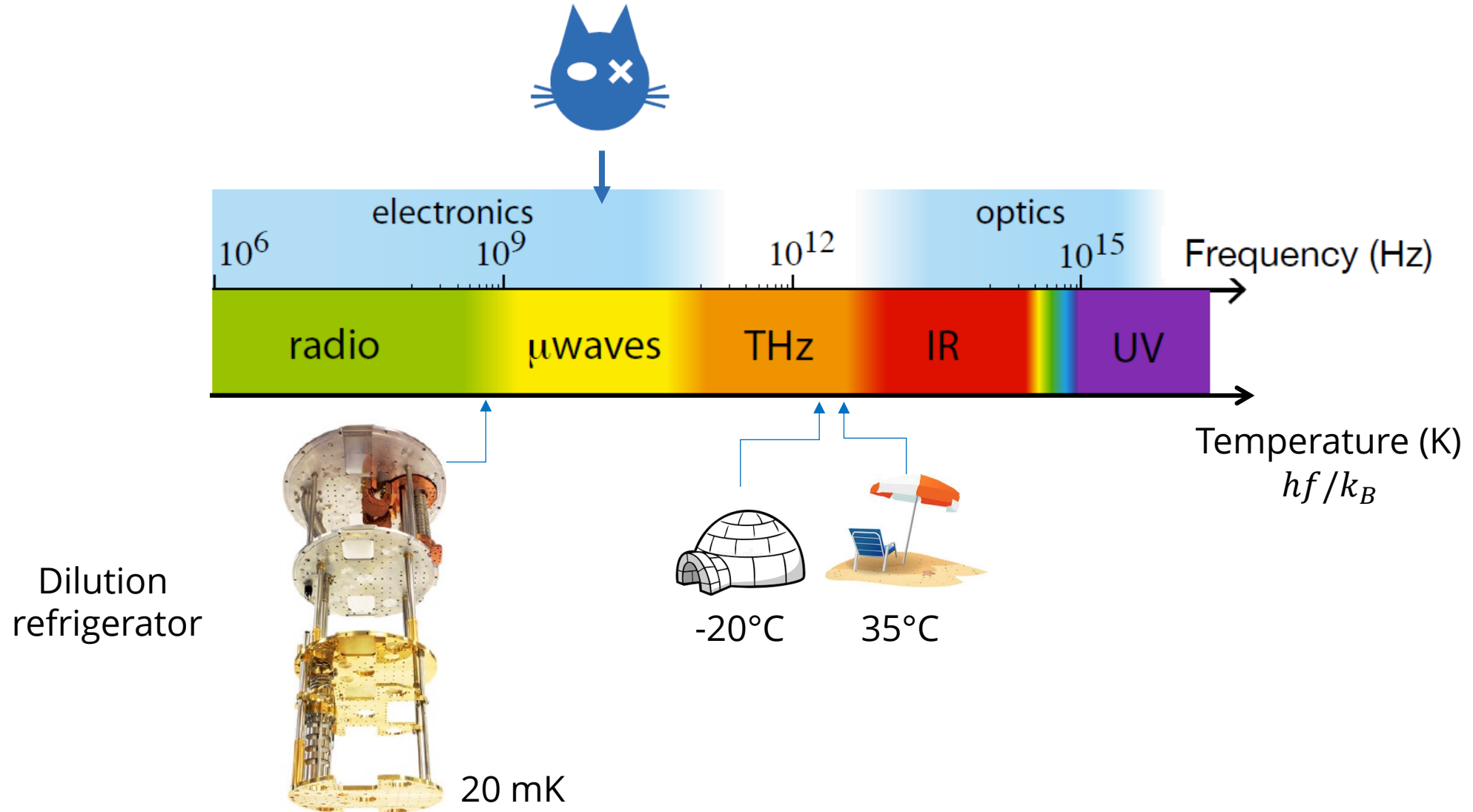
Quantum mechanics
with microwave circuits



First brick: microwave harmonic oscillator



Reaching the quantum regime ?

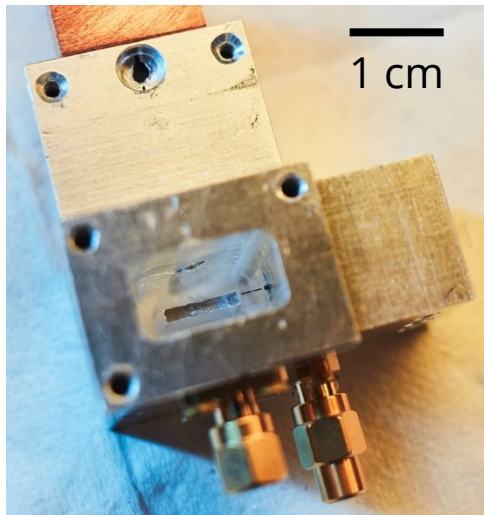


Different flavors of oscillators : bulk type

We need long-lived states

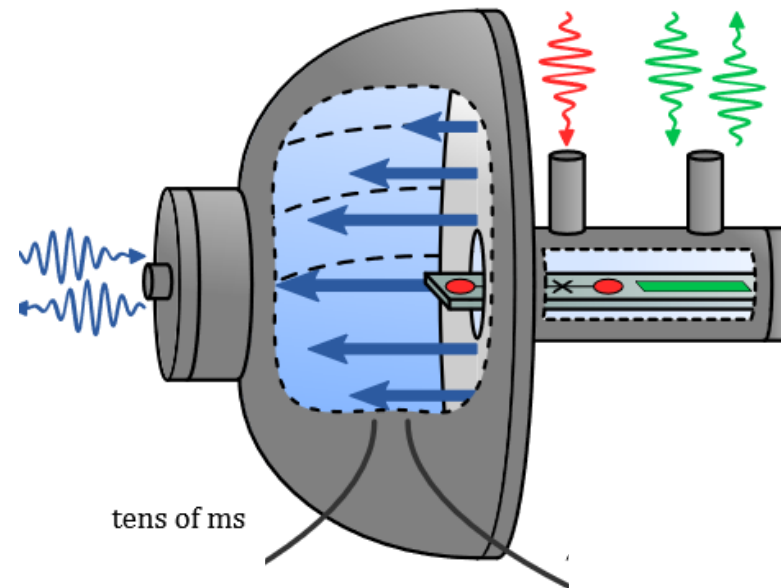
- ⇒ use superconducting materials
- ⇒ low temperature for best quality factor

Aluminum 3D cavity ($T_c = 1\text{K}$)
99.999% purity



$$T_{\text{decay}} = 1.6 \text{ ms}$$
$$Q = 5 \times 10^7$$

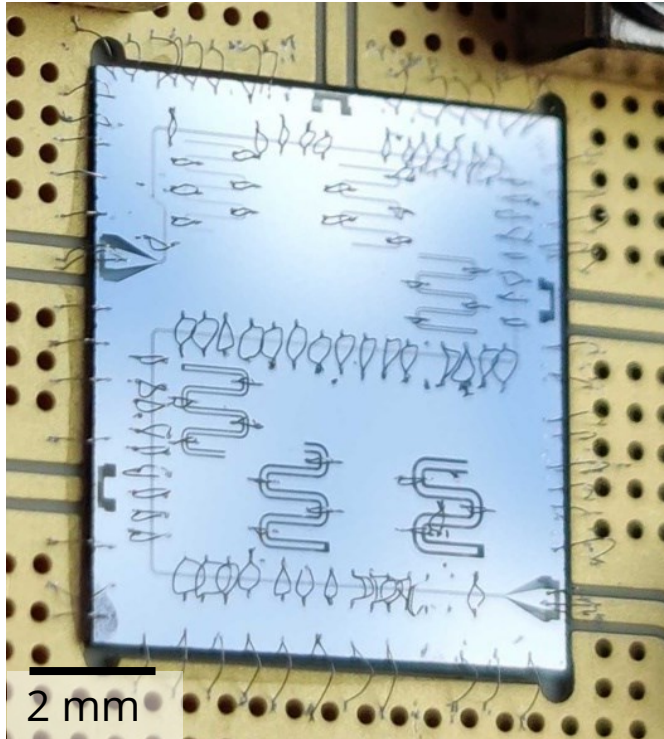
Niobium half elliptical cavity ($T_c = 9.2\text{K}$)



$$T_{\text{decay}} = 25 \text{ ms}$$
$$Q = 1 \times 10^9$$

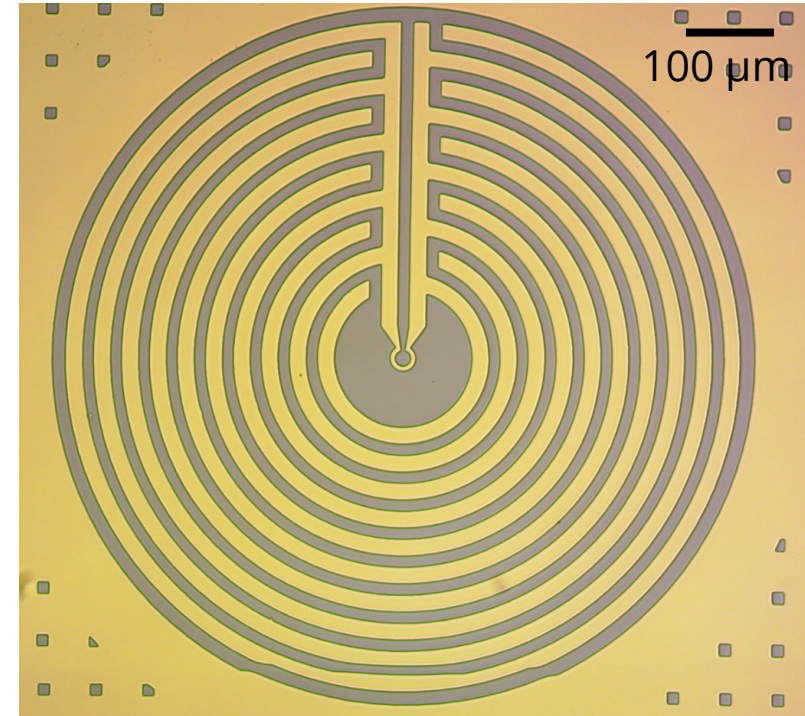
Different flavors of oscillators : planar type

Tantalum distributed
planar resonators ($T_c = 4.4$ K)



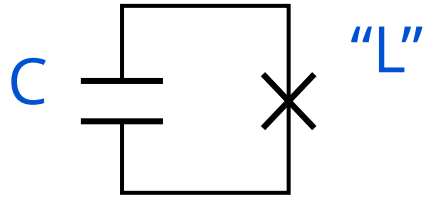
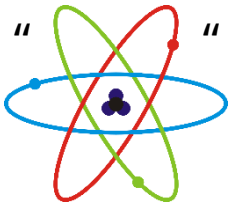
$$\begin{aligned} T_{\text{decay}} &= 19 \mu\text{s} \\ Q &= 1.1 \cdot 10^6 \end{aligned}$$

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



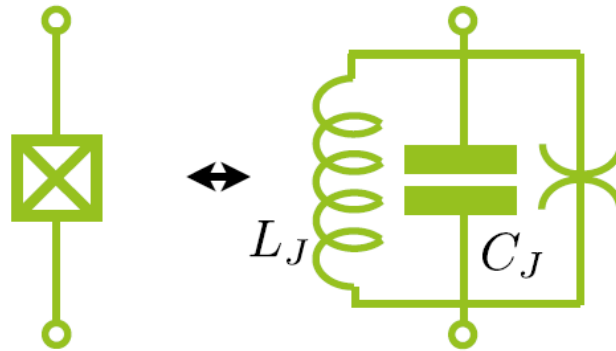
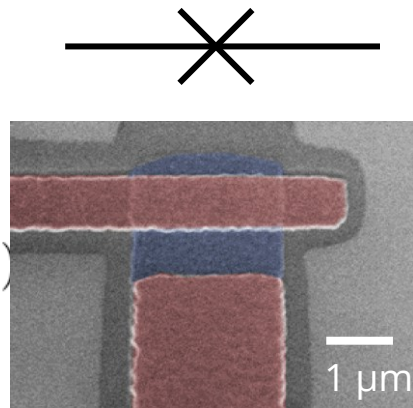
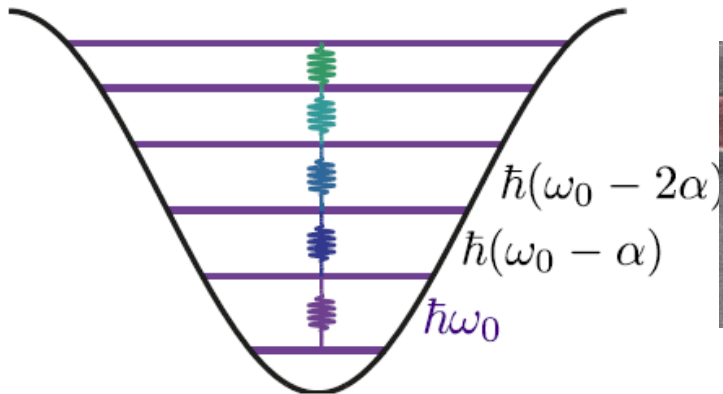
$$\begin{aligned} T_{\text{decay}} &= 16 \mu\text{s} \\ Q &= 6 \cdot 10^5 \end{aligned}$$

Superconducting qubit



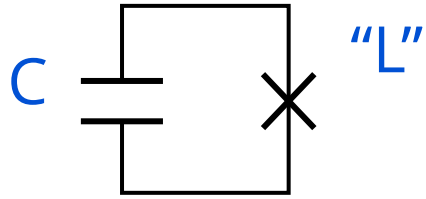
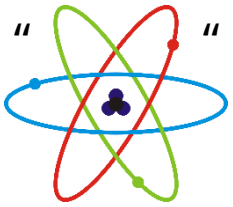
Non-linear LC oscillator

Josephson junction



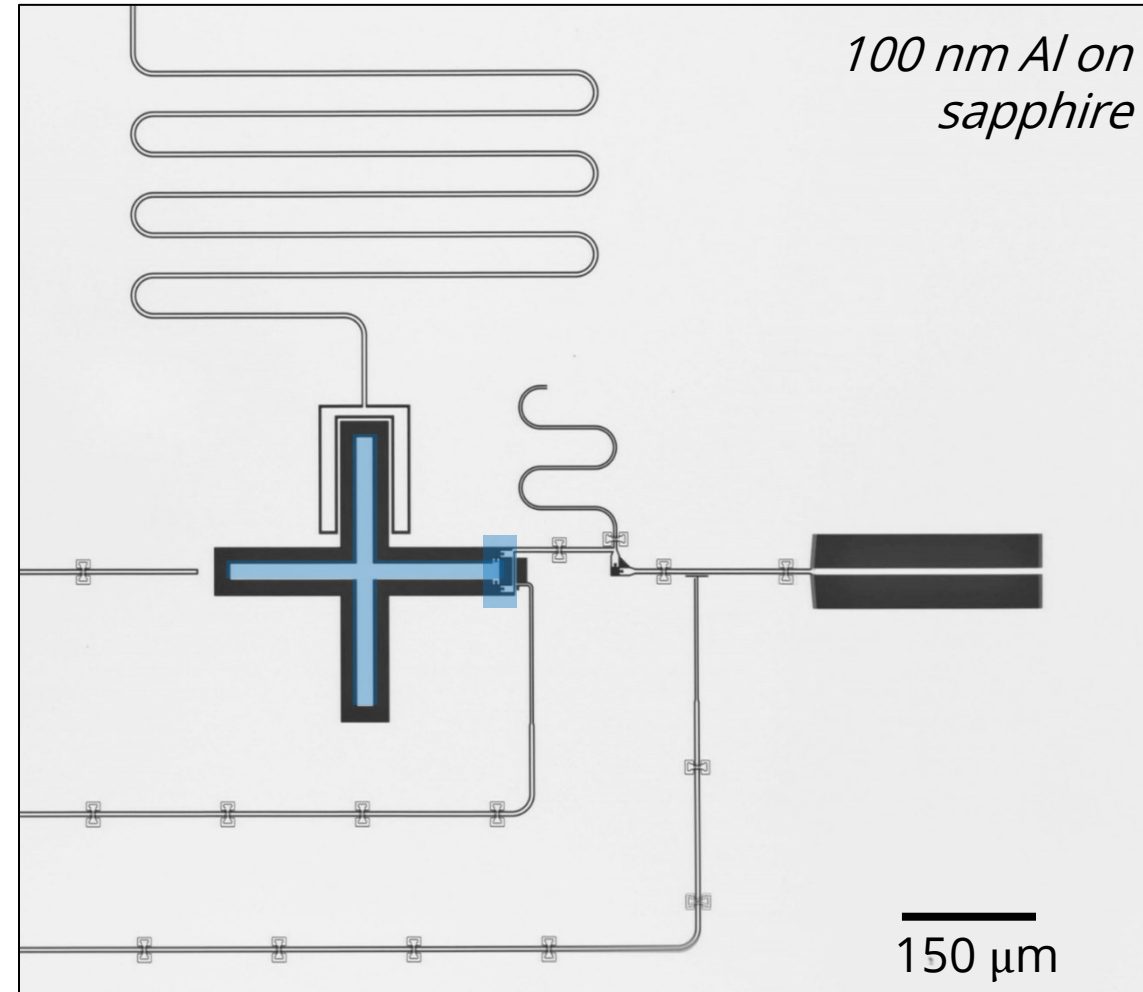
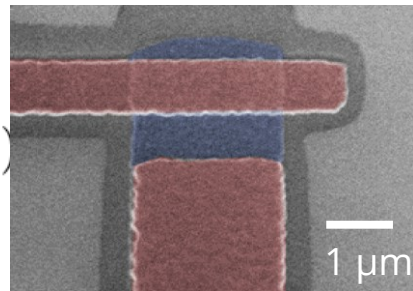
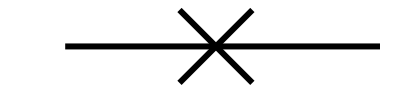
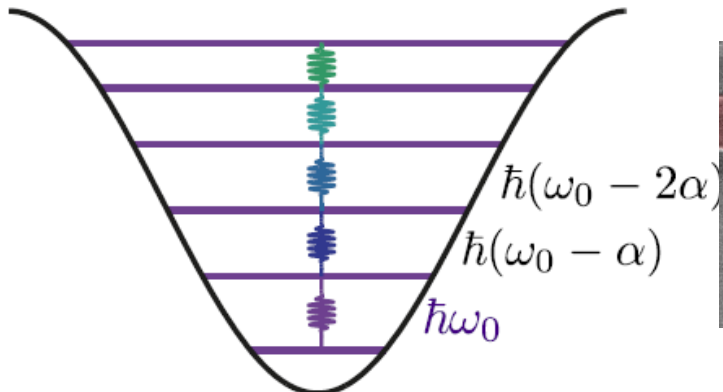
transitions observed in 1980's [Berkeley & Saclay]
strong coupling regime of CQED in 2004 [Yale]

Superconducting qubit



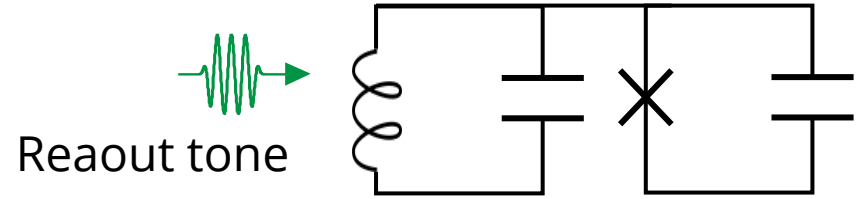
Non-linear LC oscillator

Josephson junction

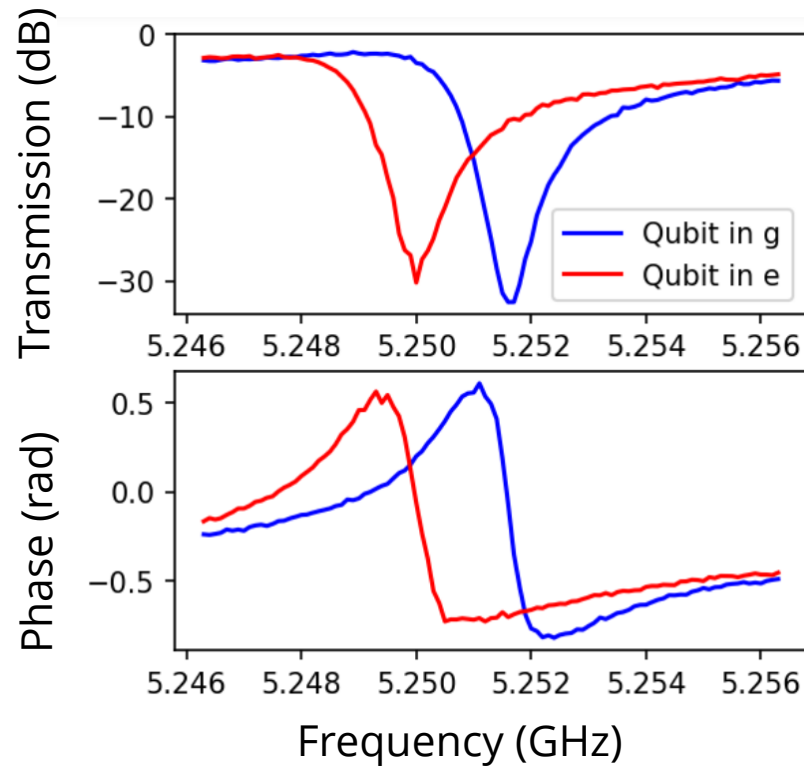
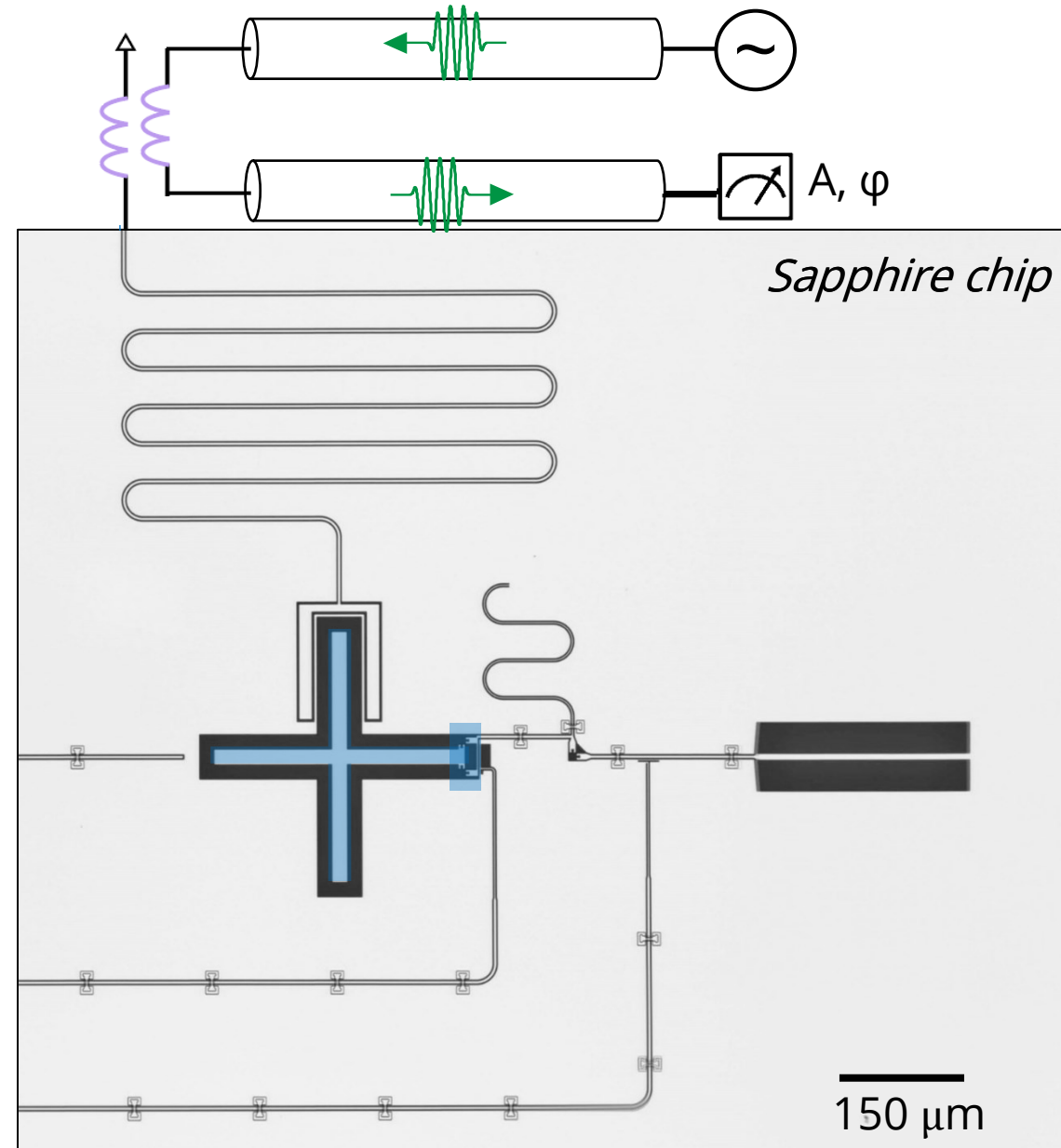


transitions observed in 1980's [Berkeley & Saclay]
 strong coupling regime of CQED in 2004 [Yale]

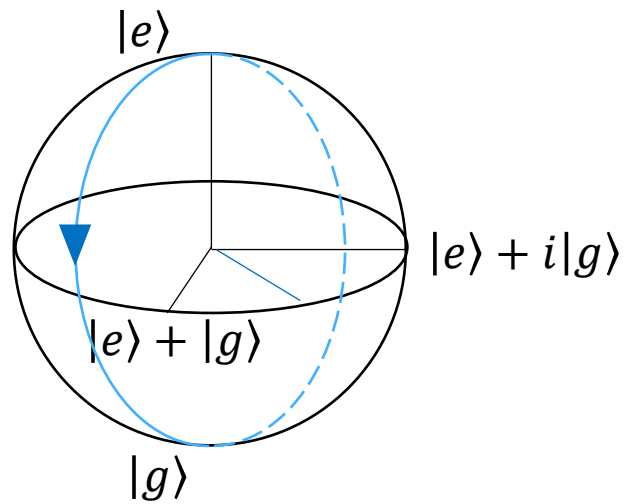
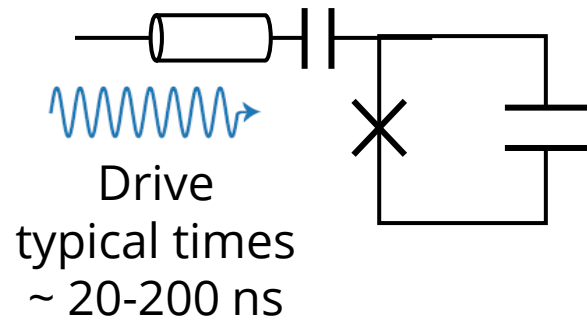
Superconducting qubit



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

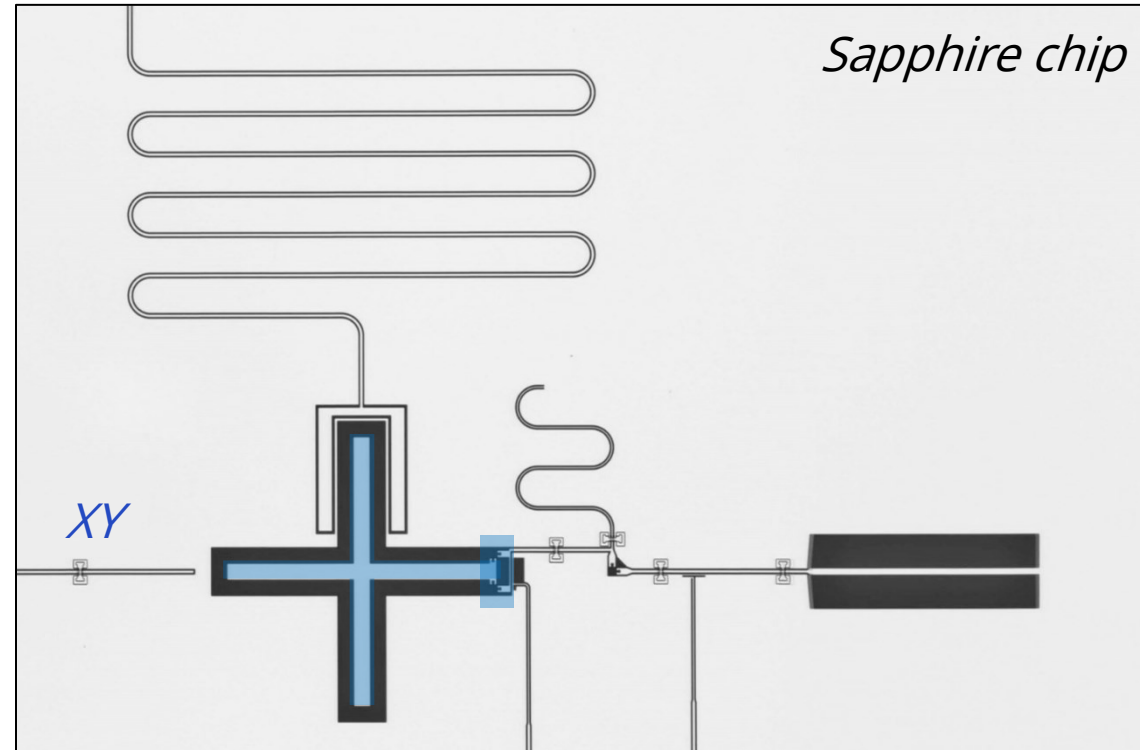


Superconducting qubit: control



Readout

Excitation and control



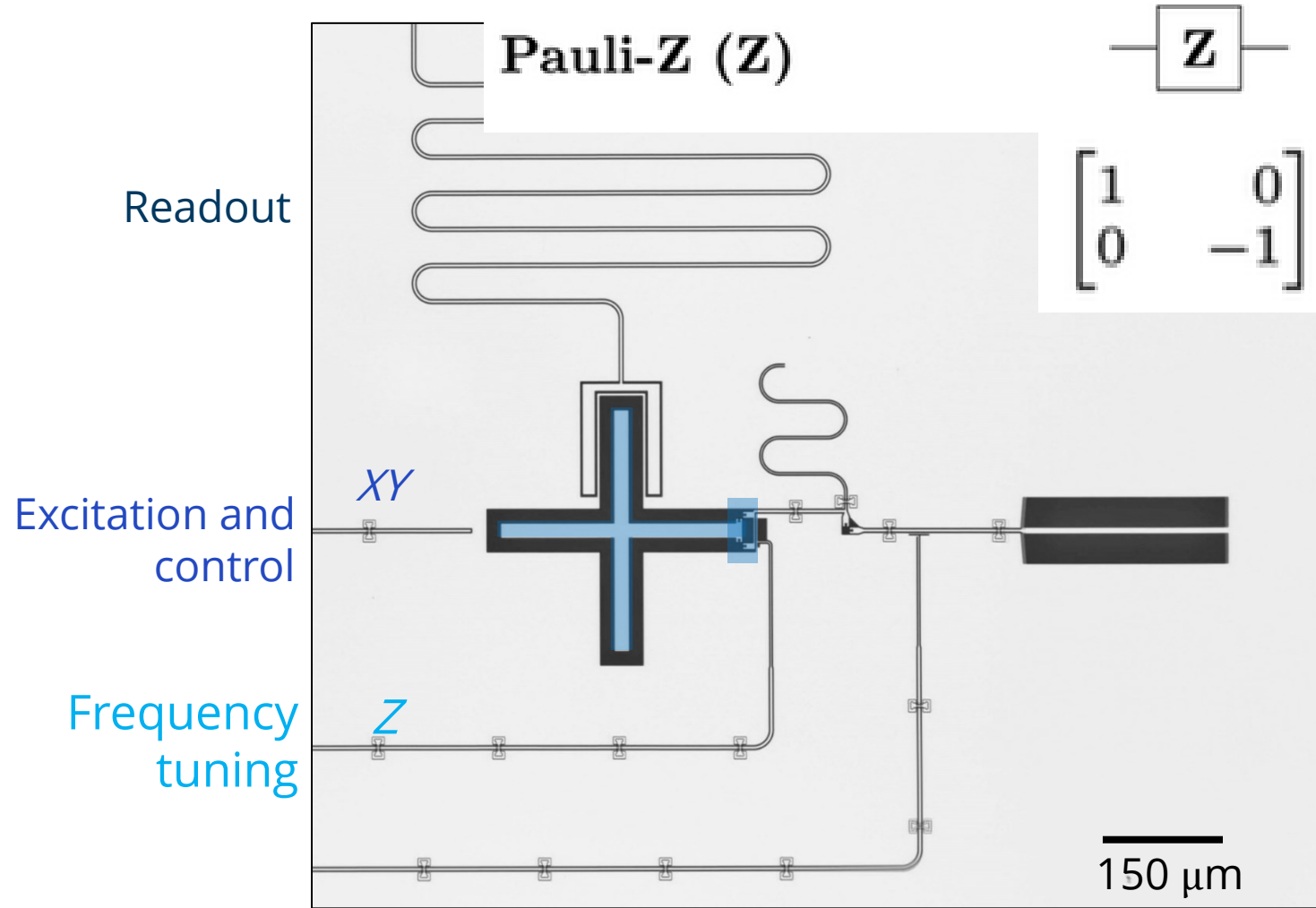
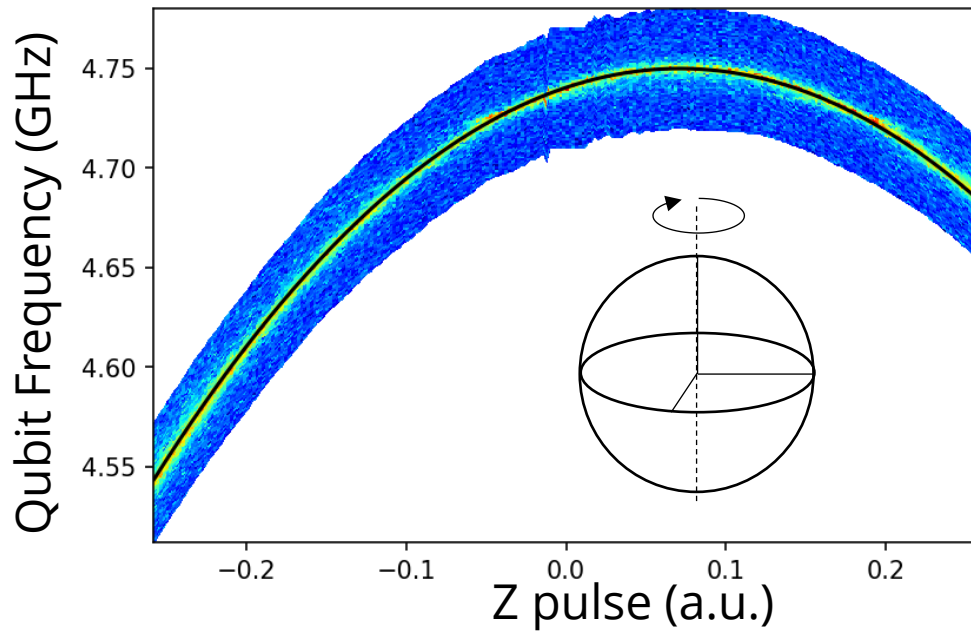
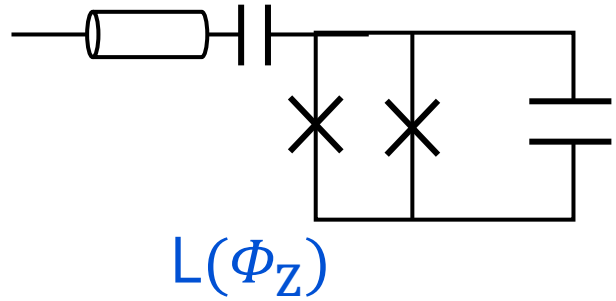
Pauli-X (X)

$$\text{---} \boxed{\text{X}} \text{---} \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}$$

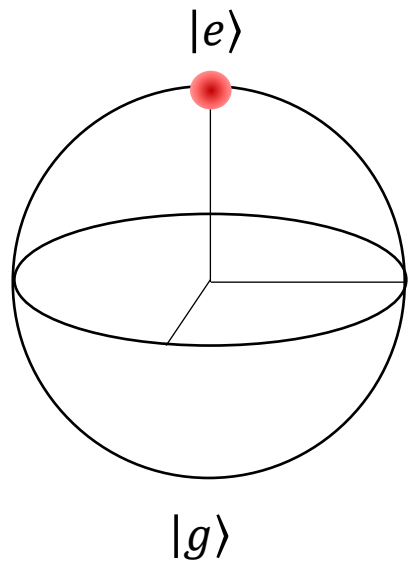
Pauli-Y (Y)

$$\text{---} \boxed{\text{Y}} \text{---} \begin{bmatrix} 0 & -i \\ i & 0 \end{bmatrix}$$

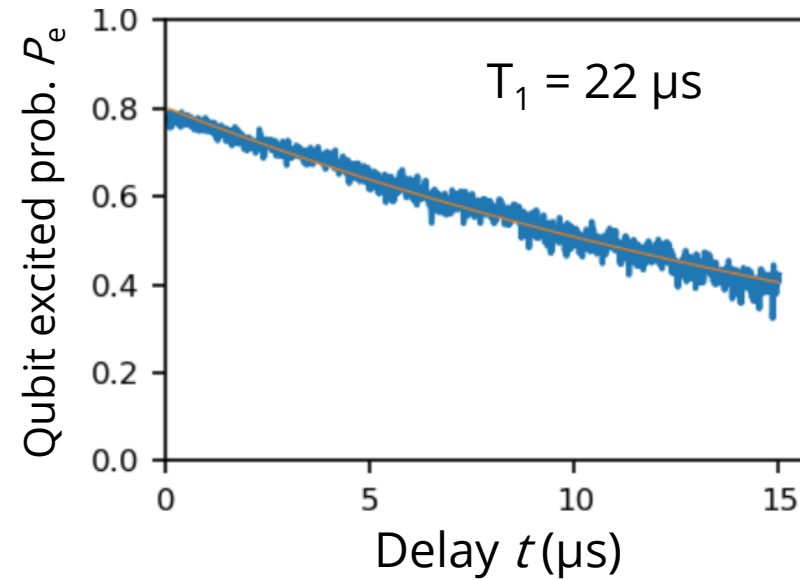
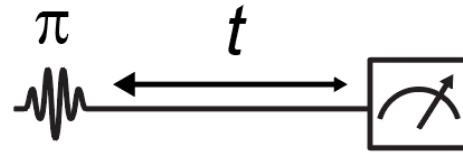
Superconducting qubit: control



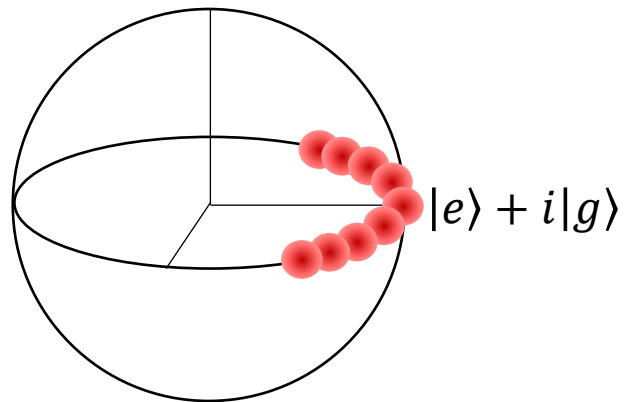
Superconducting qubit: coherence



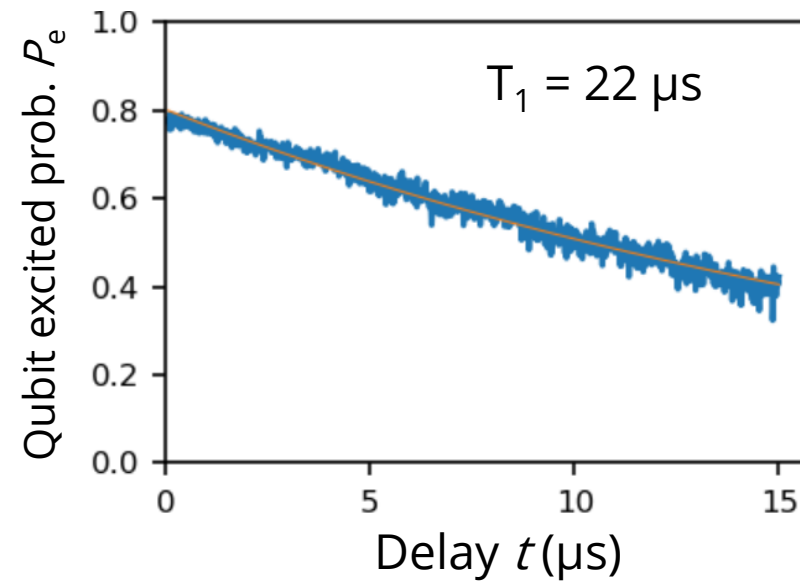
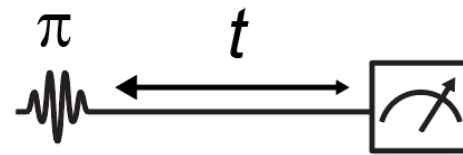
Energy relaxation (T_1)



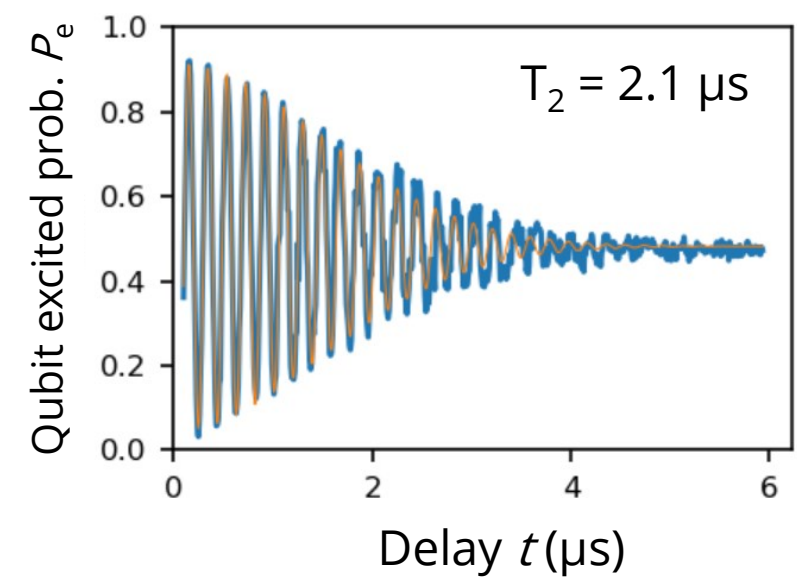
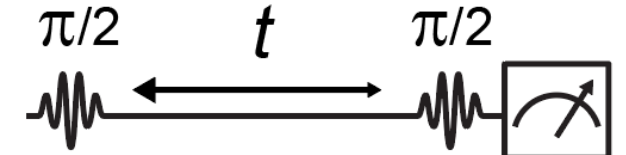
Superconducting qubit: coherence



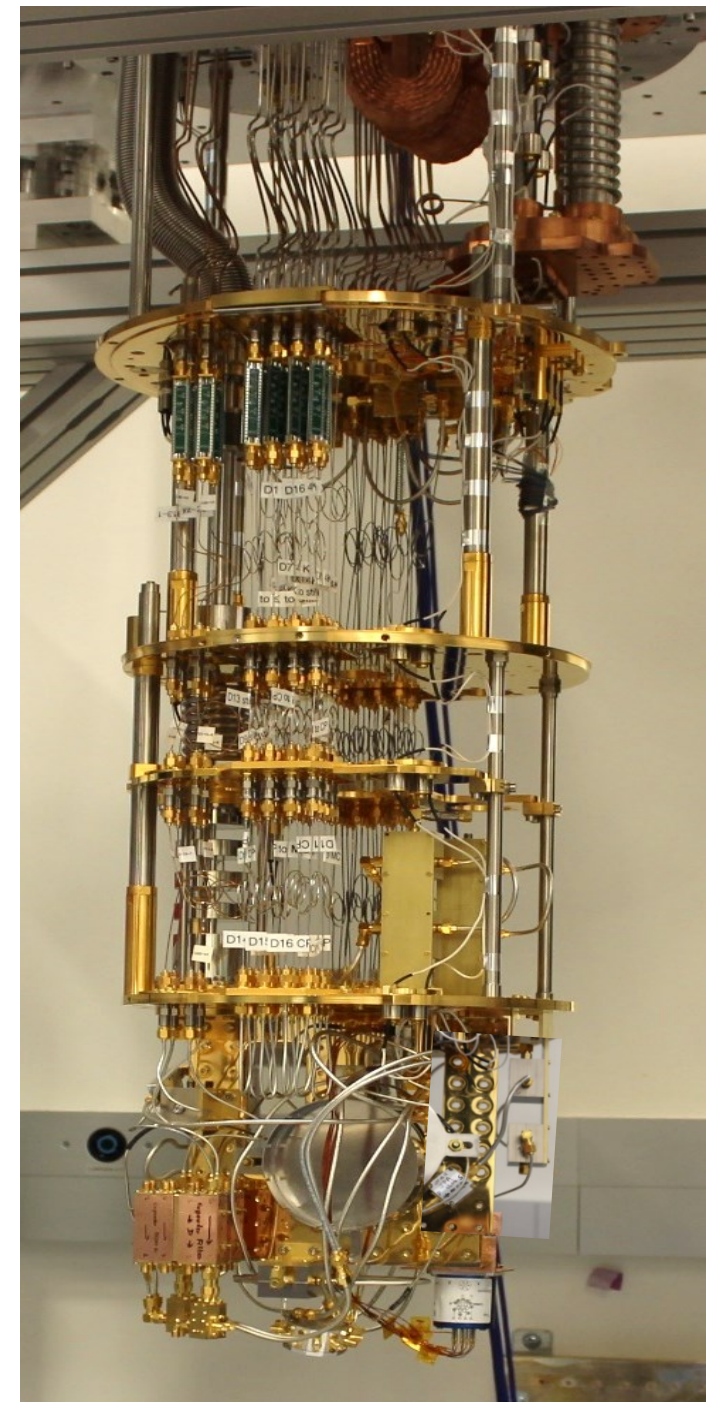
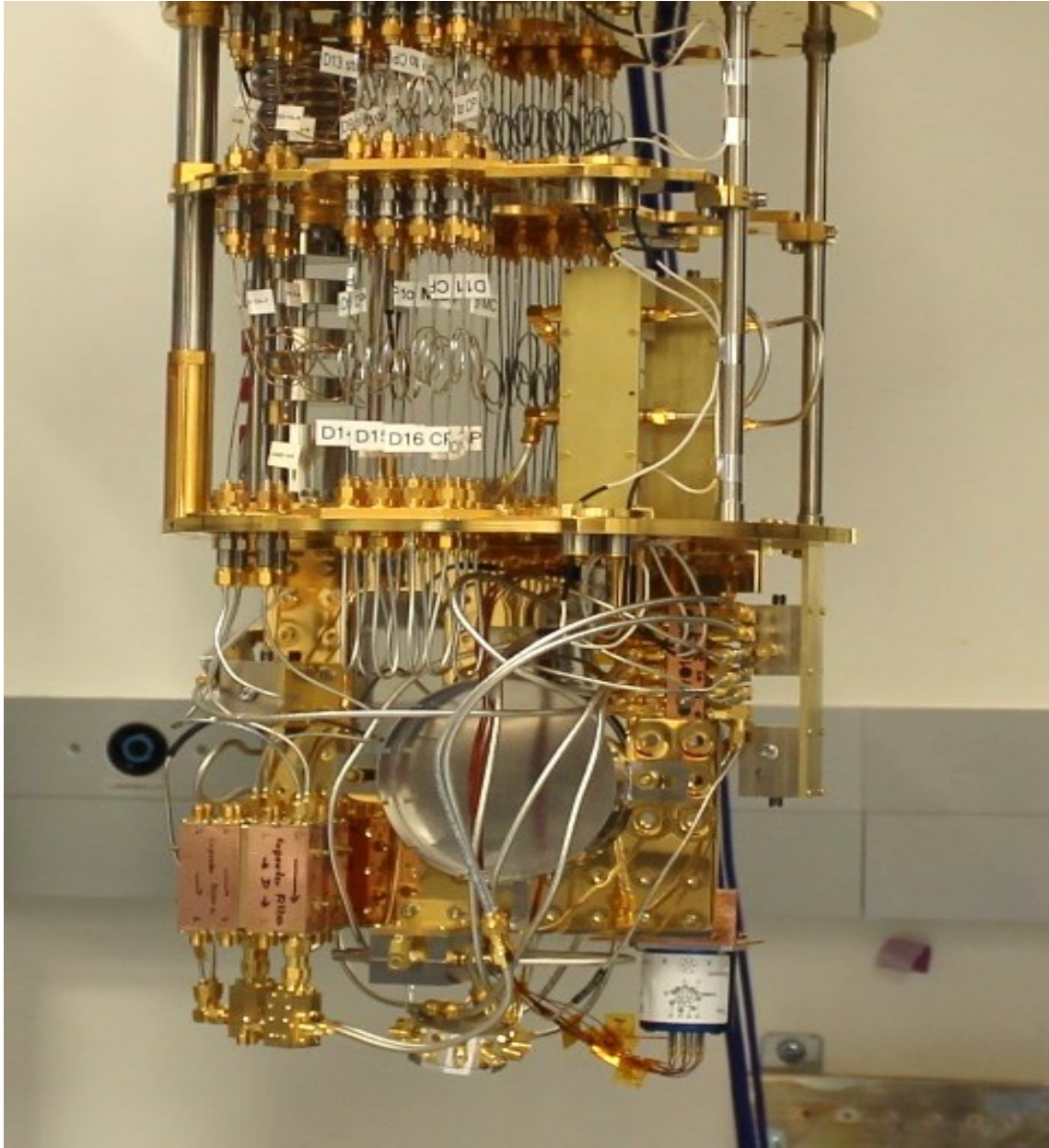
Energy relaxation (T_1)



Phase coherence (T_2)

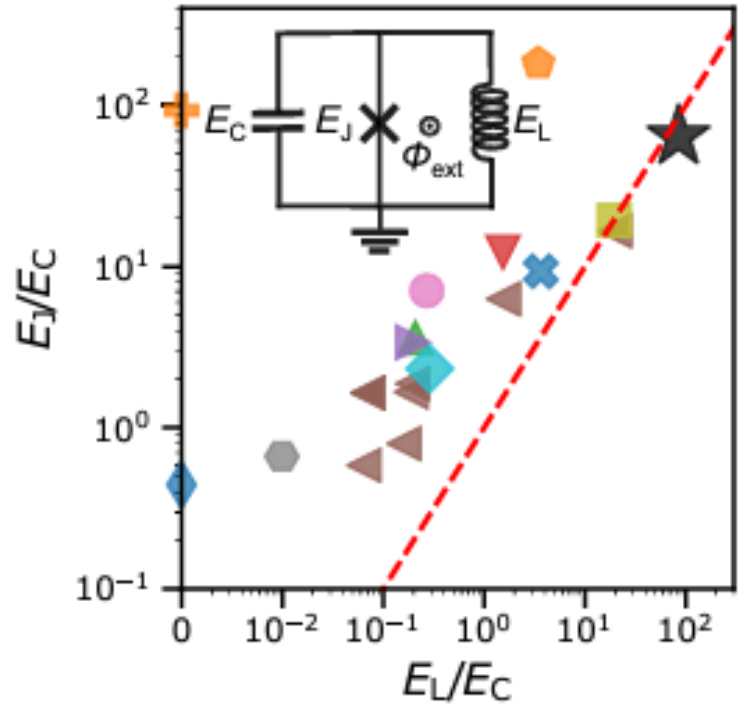



Typical setup

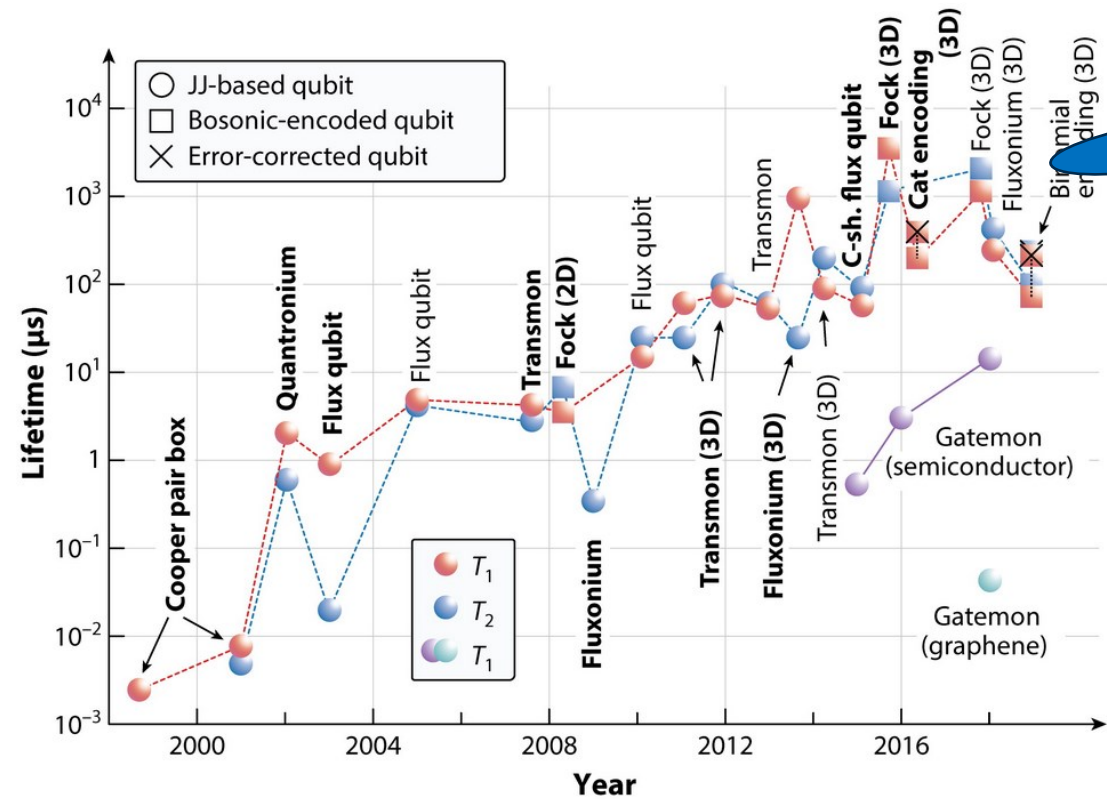


Zoology and lifetimes

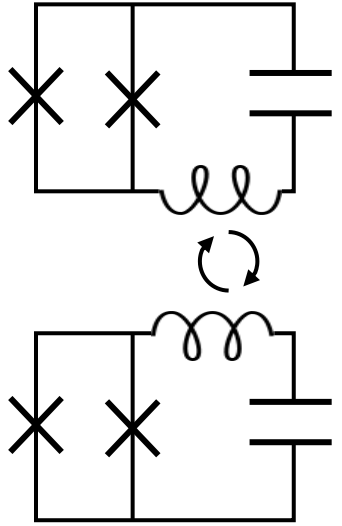
 **Transmon**
Popularity



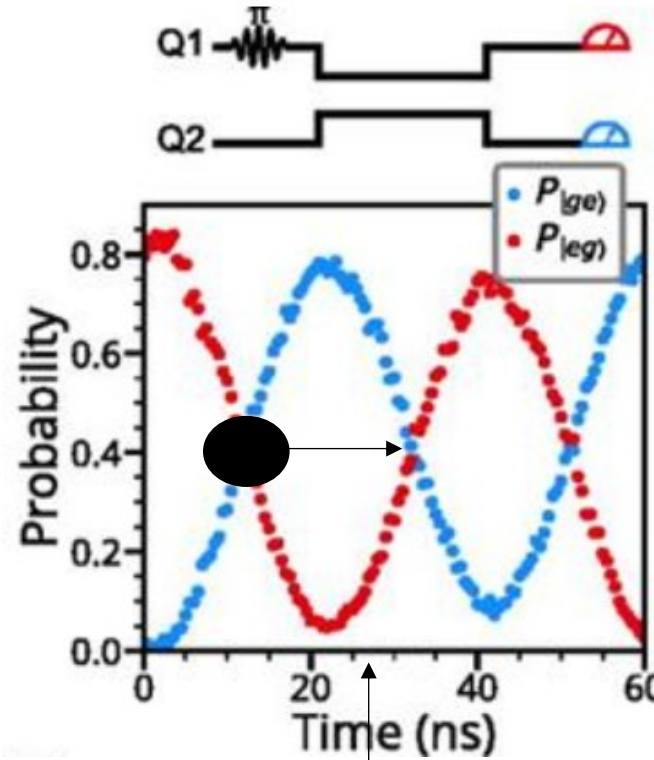
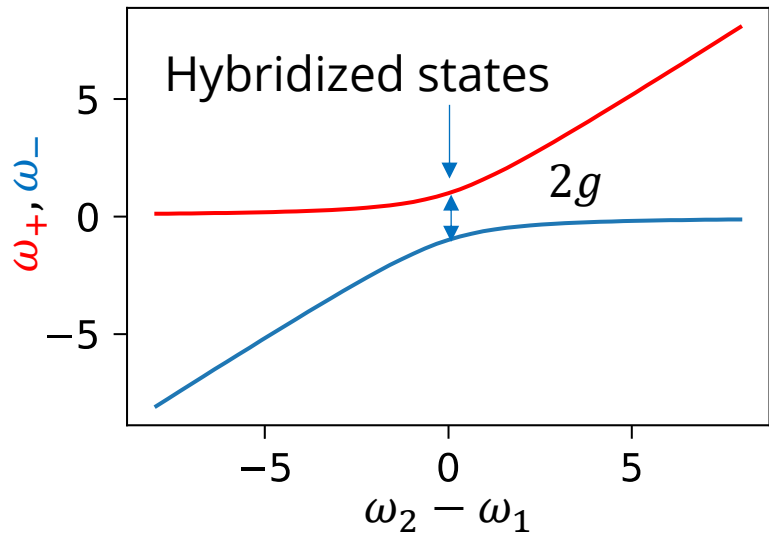
Fluxonium
 Lifetime & gate errors



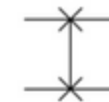
Examples of two qubit gates : SWAP gate



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

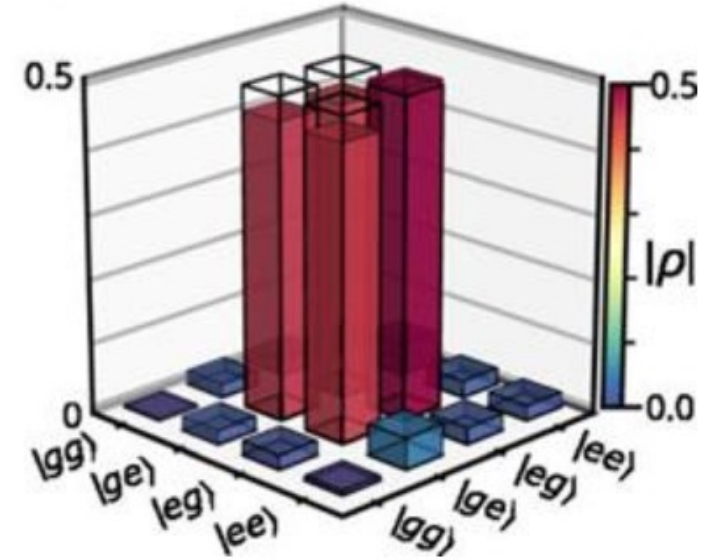


SWAP

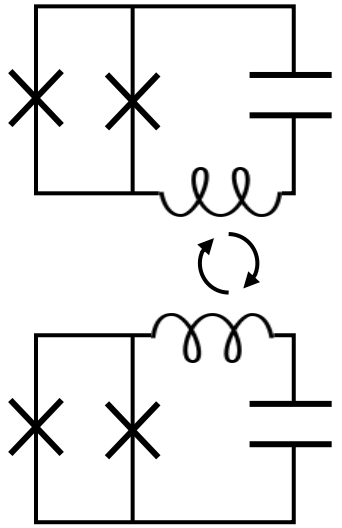


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

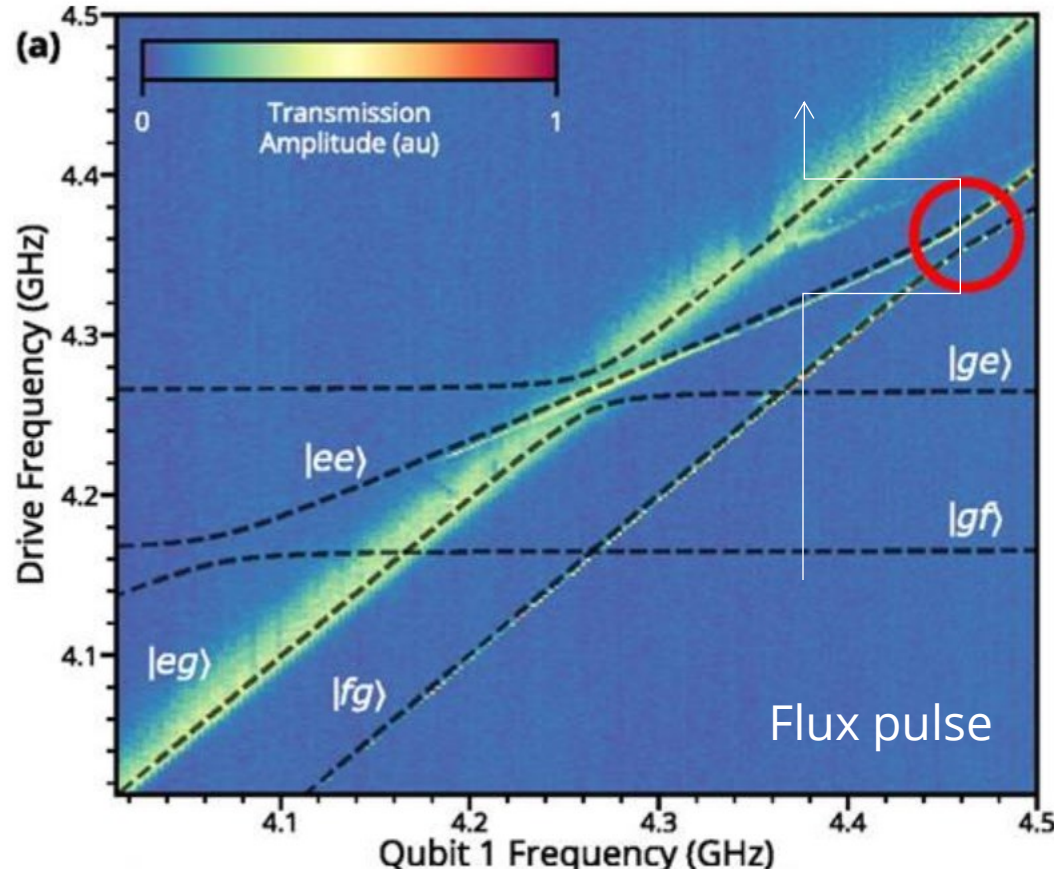
Half swap



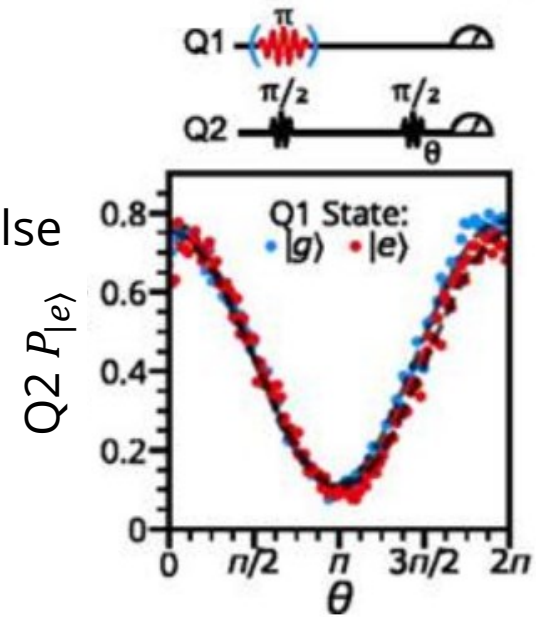
Examples of two qubit gates : CZ gate



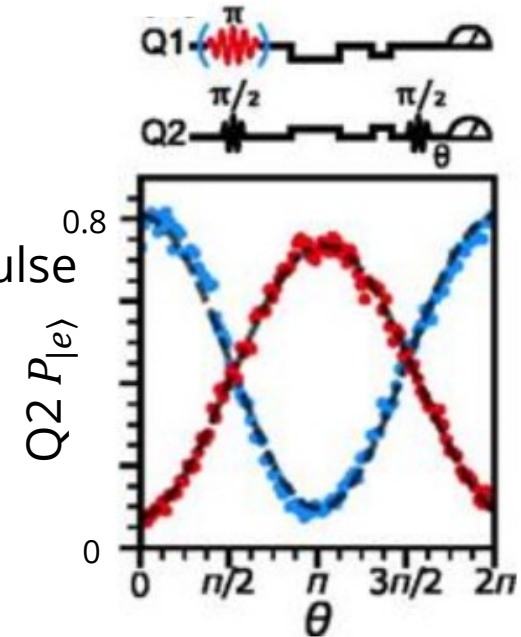
$|gg\rangle \rightarrow |gg\rangle$
 $|ge\rangle \rightarrow |ge\rangle$
 $|eg\rangle \rightarrow |eg\rangle$
 $|ee\rangle \rightarrow |fg\rangle \rightarrow e^{i\phi}|ee\rangle$



No flux pulse



With flux pulse



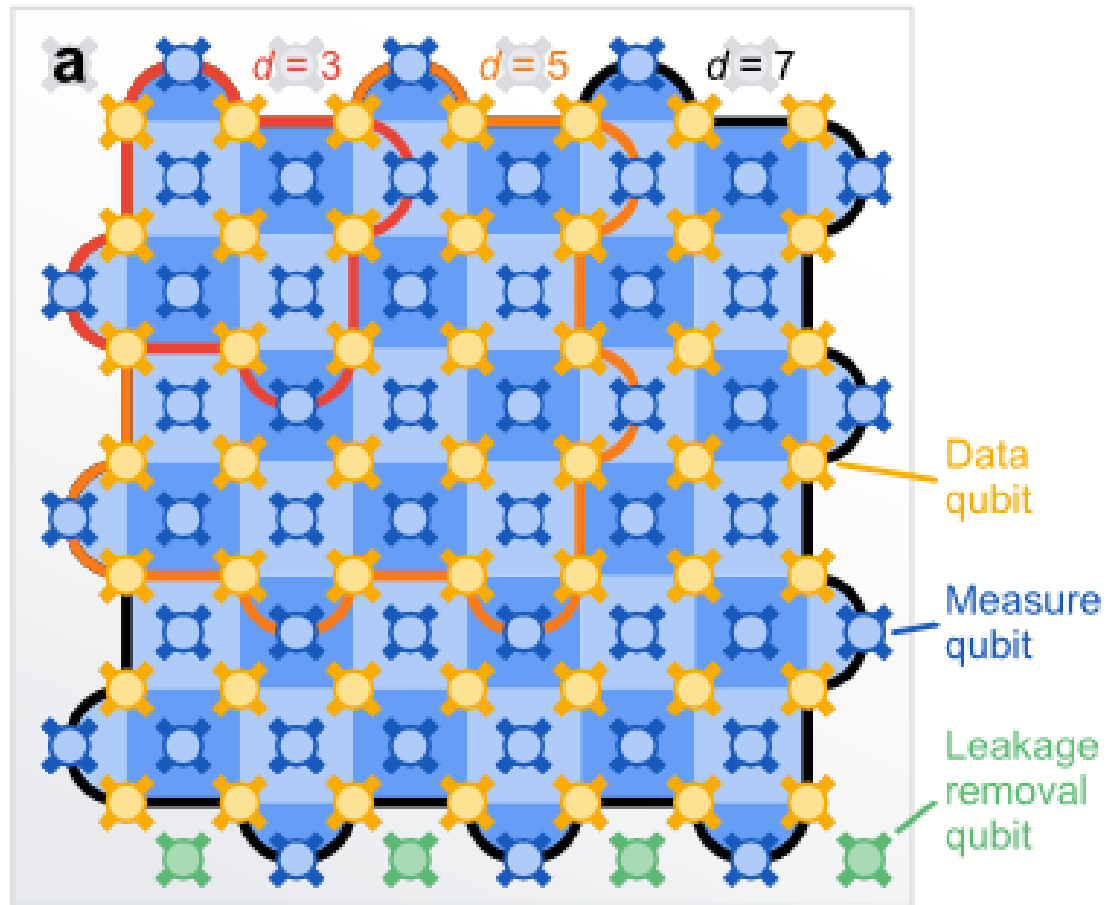
Controlled Z (CZ)



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

Only hope for viability : quantum error correction

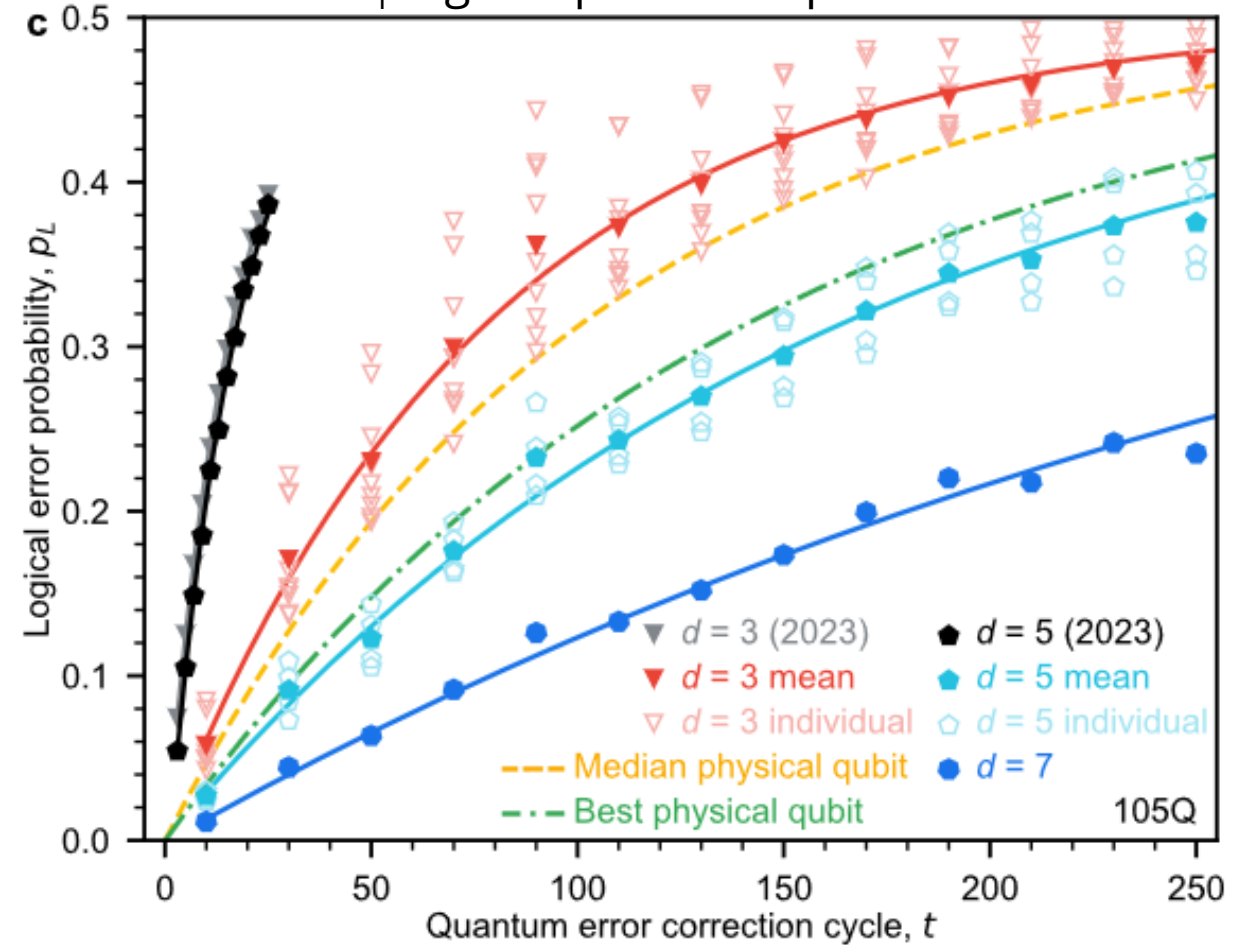
Processor with 105 qubits
≡ 1 logical qubit



Use stabilizers for error decoding on data qubits

T_1 physical qubit : 89 μs

T_1 logical qubit : 290 μs

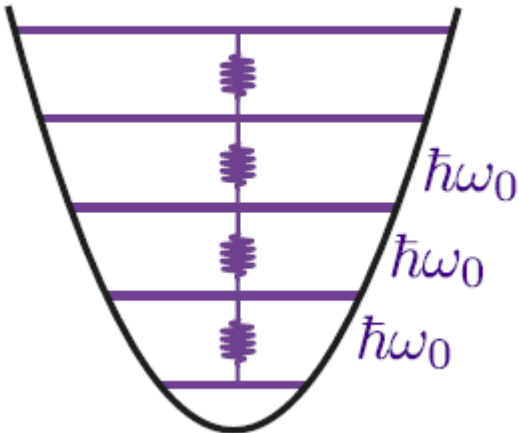


arXiv:2408.13687,
Google Quantum AI

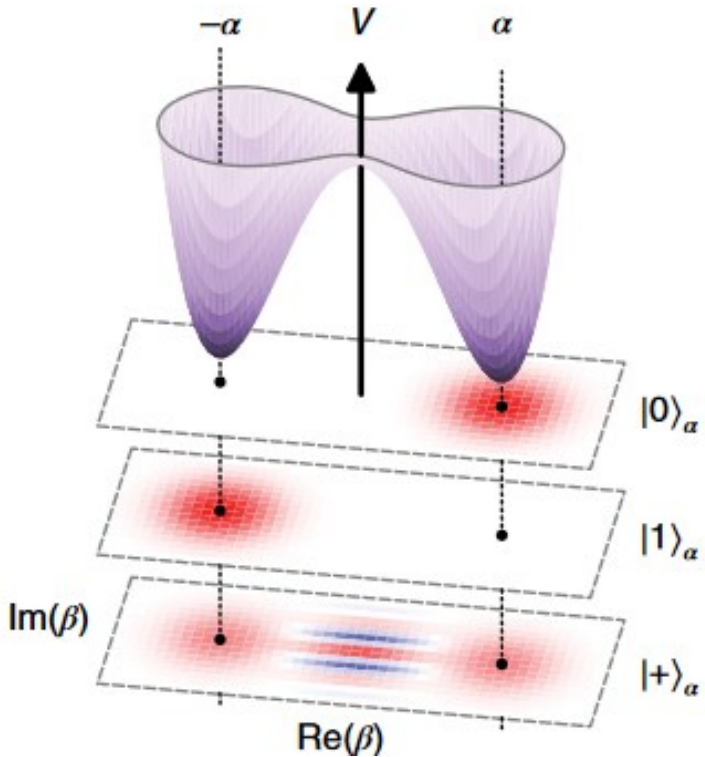
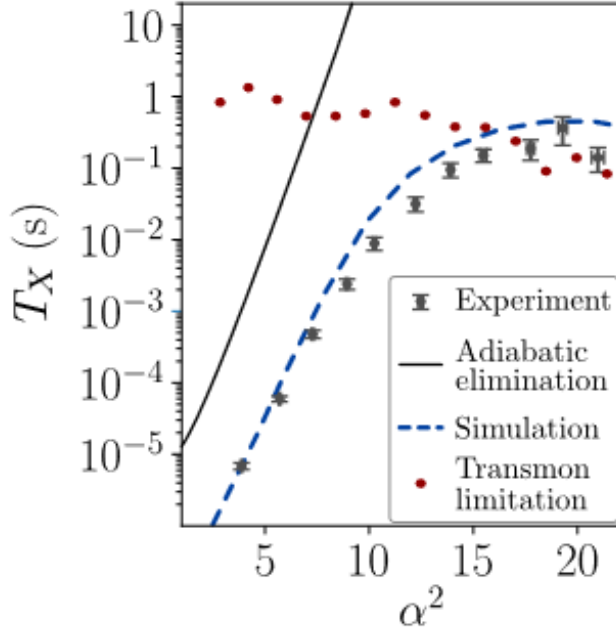
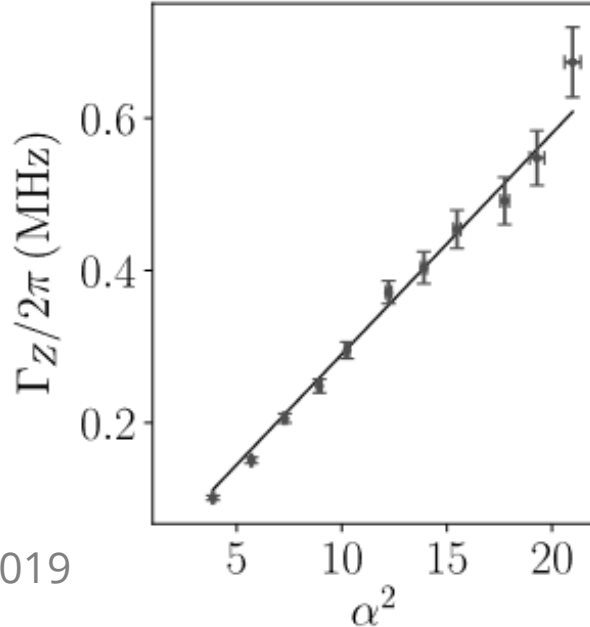
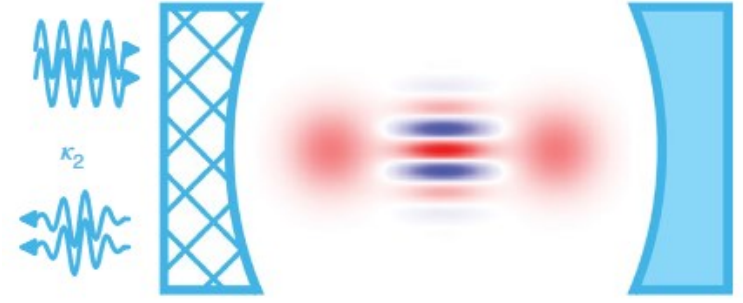
1 cycle = 1.1 μs

Bosonic codes

Redundancy given by usage of multiple Fock states

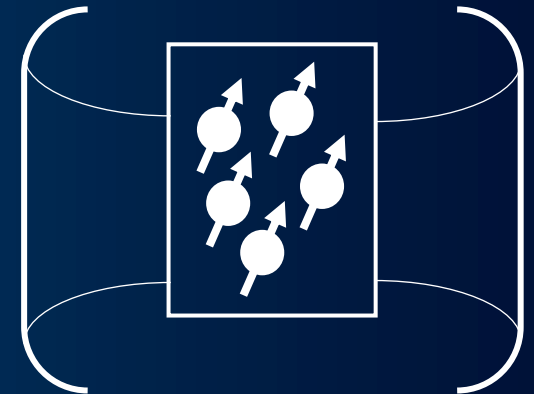
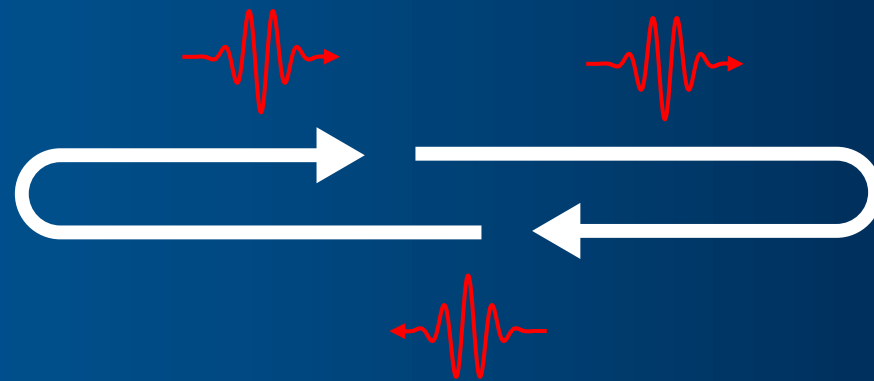
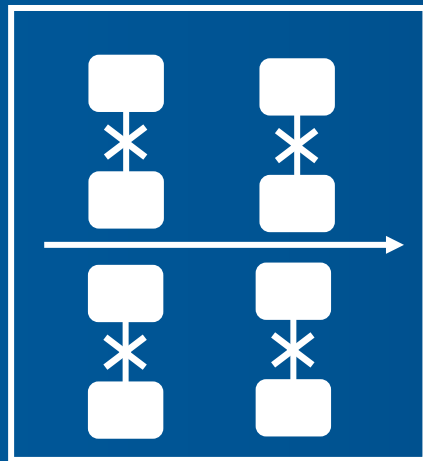


One example of encoding:
 $|0\rangle_L = |\alpha\rangle$
 $|1\rangle_L = |-\alpha\rangle$
 $|+\rangle_L = |\alpha\rangle + |-\alpha\rangle = \sum_i c_i |2i\rangle$
 $|-\rangle_L = |\alpha\rangle - |-\alpha\rangle = \sum_i c_i |2i + 1\rangle$



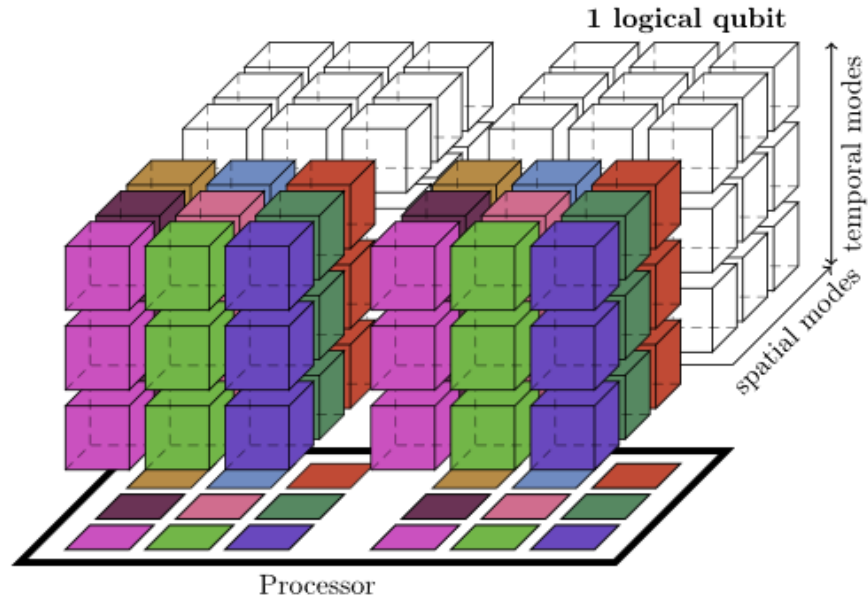
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Storing qubits' quantum states

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)

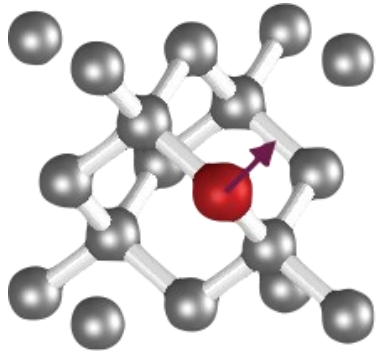
Quantum memory hierarchies: Efficient designs to match available parallelism in quantum computing, Thaker et al., Symposium on Computer Architecture (2006).

Enable long-distance communication



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

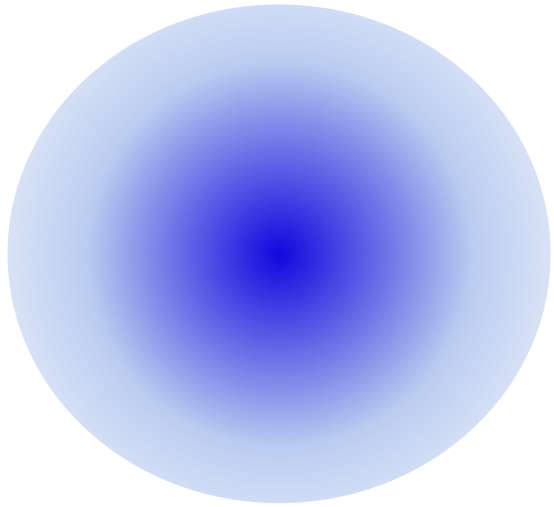
Ideal candidate : Bismuth donors in silicon



^{209}Bi

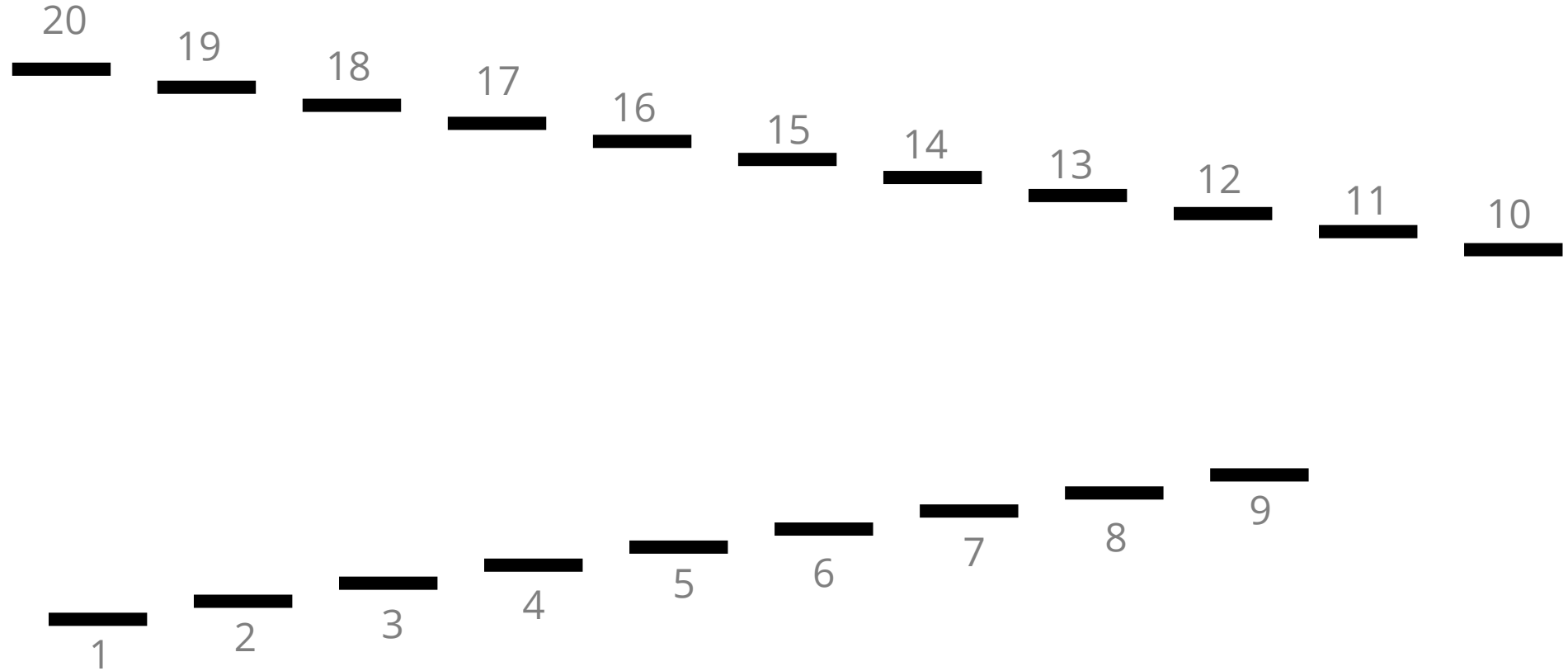
Nuclear spin
 $I = 9/2$

Ideal candidate: Bismuth donors in silicon



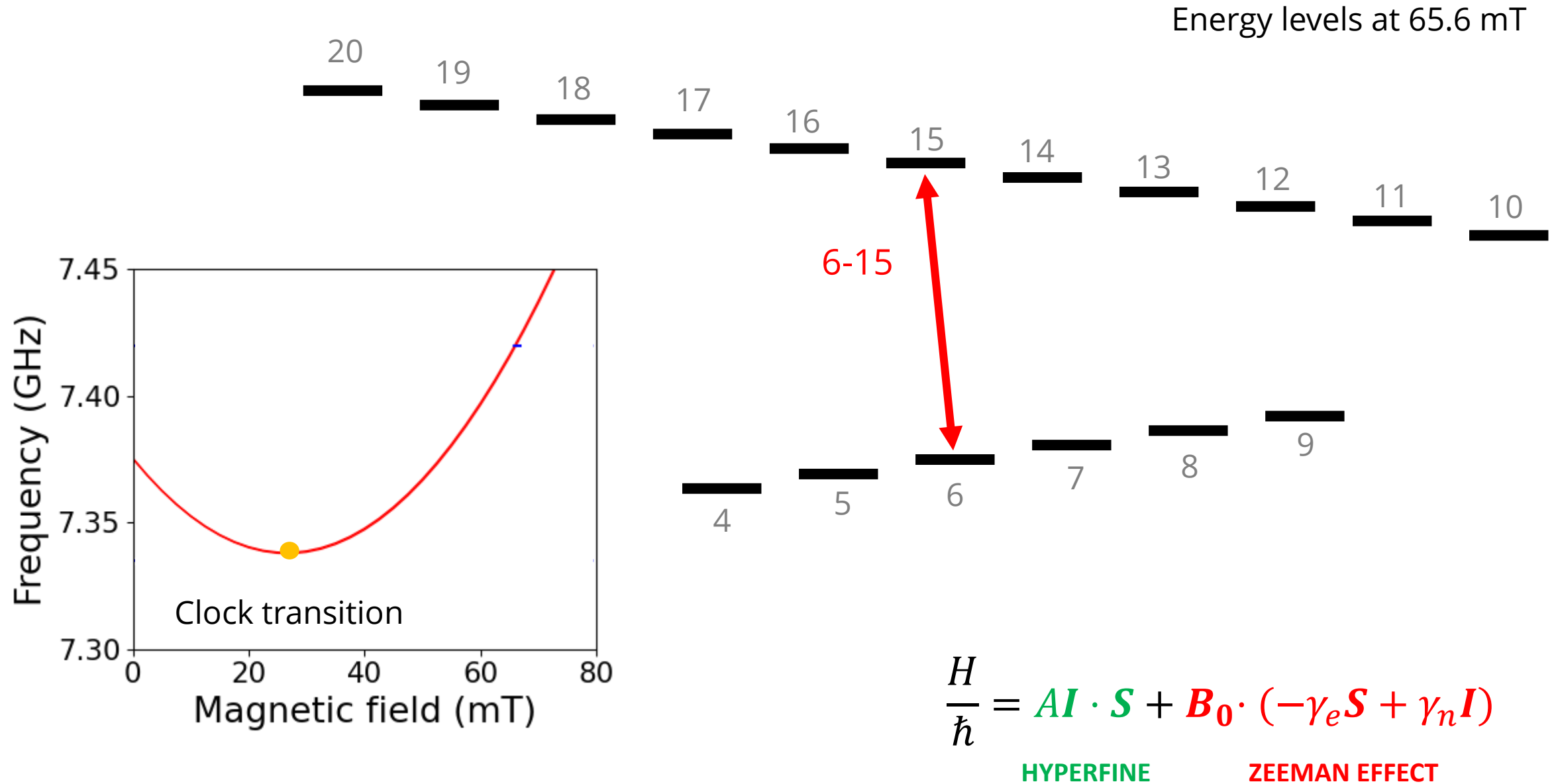
Nuclear spin
 $I = 9/2$

Electronic spin
 $S = 1/2$

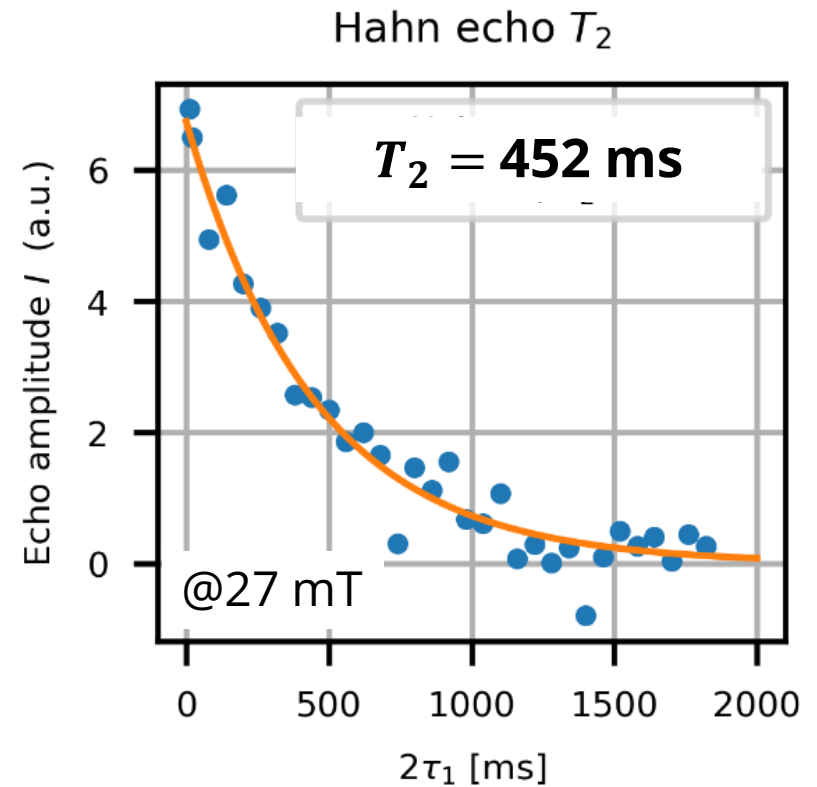
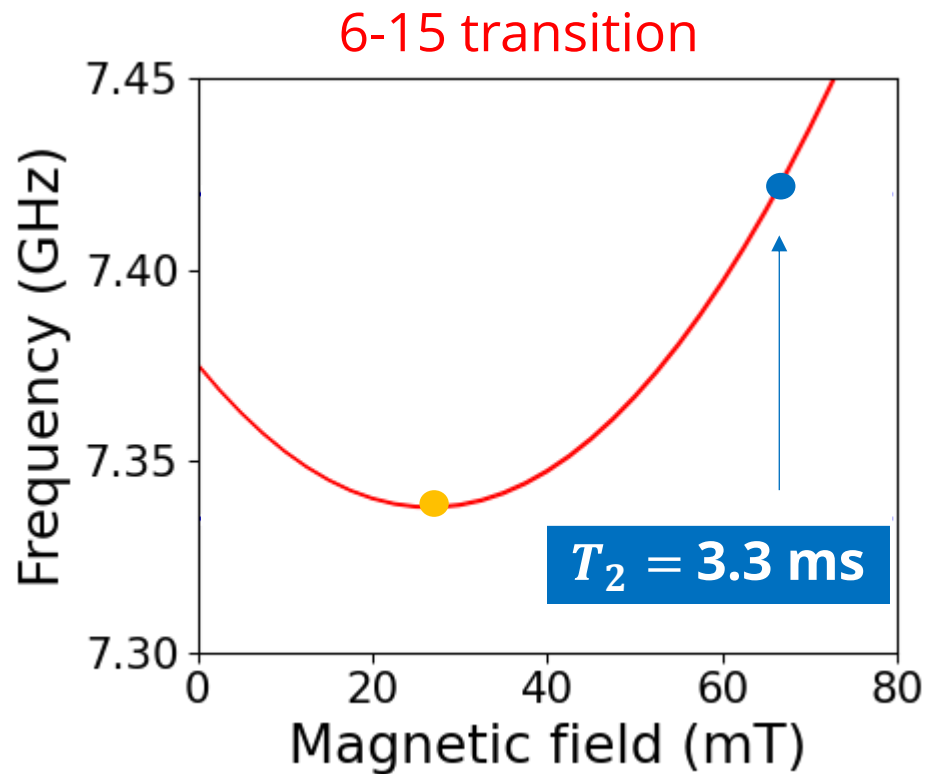
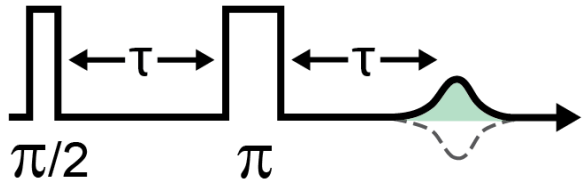


$$\frac{H}{\hbar} = \underbrace{AI \cdot \mathbf{S}}_{\text{HYPERFINE}} + \underbrace{\mathbf{B}_0 \cdot (-\gamma_e \mathbf{S} + \gamma_n \mathbf{I})}_{\text{ZEEMAN EFFECT}}$$

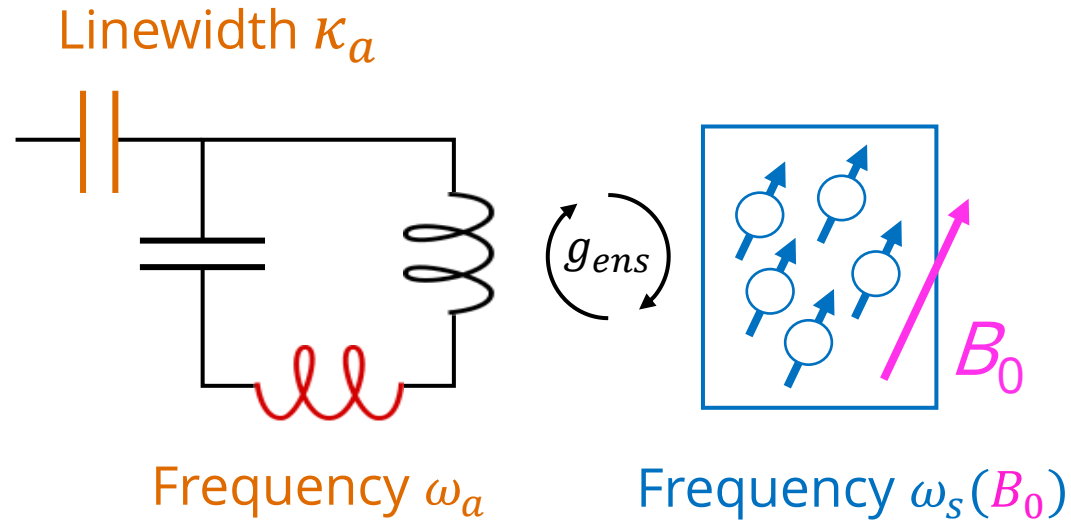
Ideal candidate: Bismuth donors in silicon



Bismuth donors in silicon



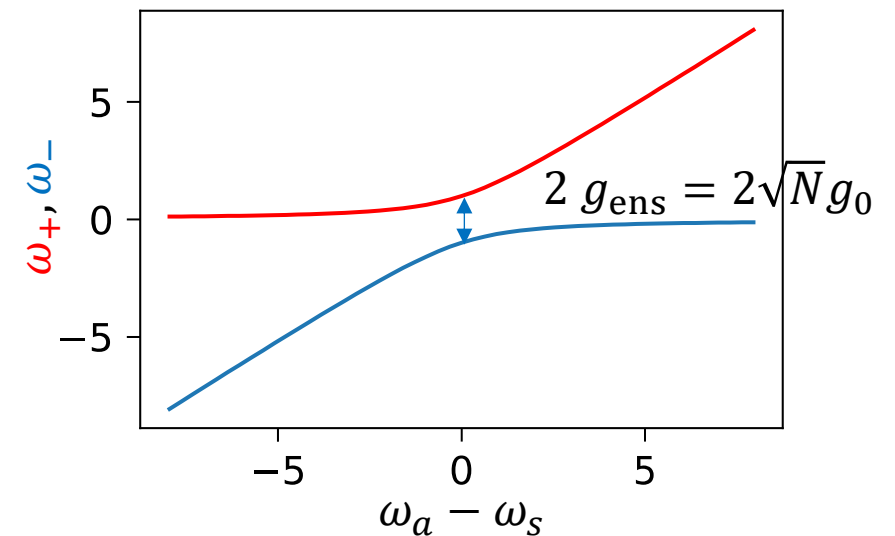
Spin ensemble coupled to a superconducting resonator



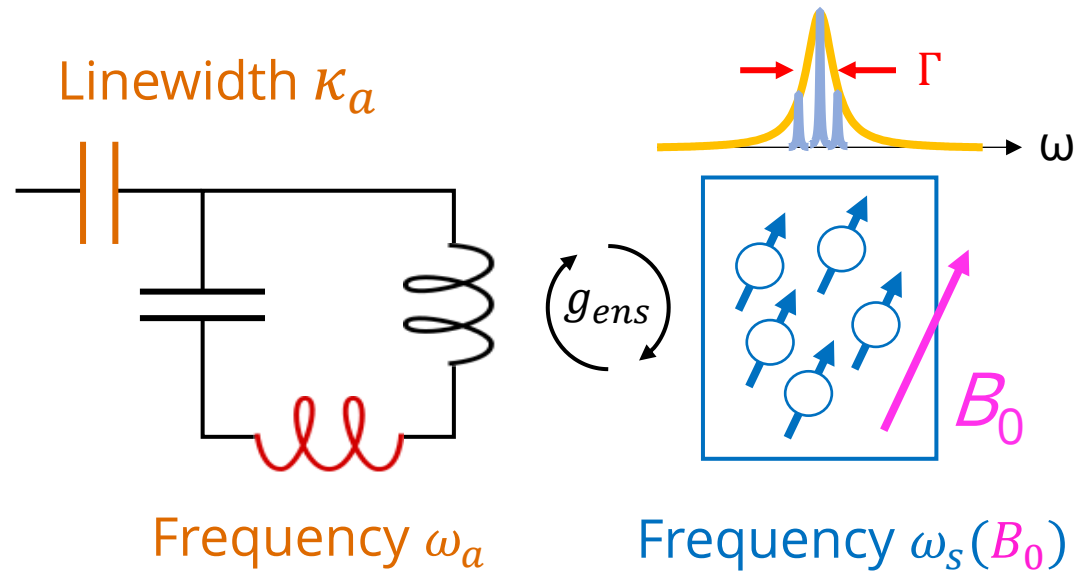
$$H = \mu (\vec{B}_0 + \vec{B}_1) \cdot \vec{S}$$

$$H_{\text{int}} = \underbrace{\mu \delta B_1}_{\text{Coupling constant}} (a + a^\dagger) (\sigma_+ + \sigma_-)$$

Coupling constant $\frac{g_0}{2\pi} = 1 \text{ mHz} - 5 \text{ kHz}$

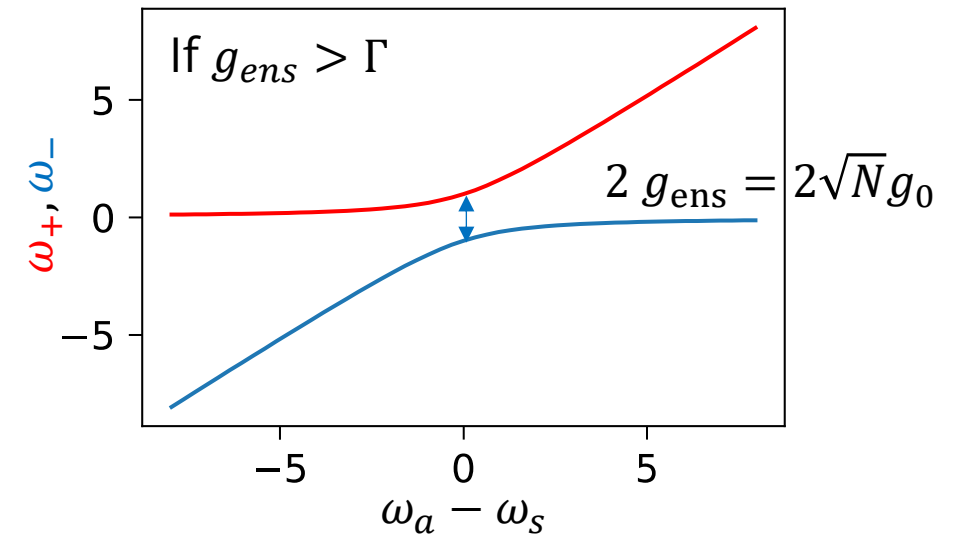


Spin ensemble coupled to a superconducting resonator

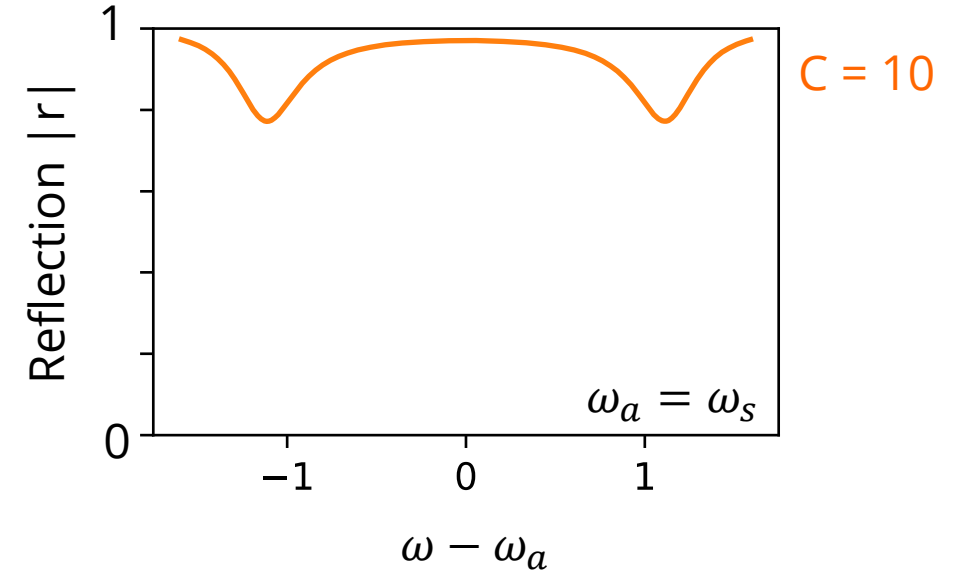
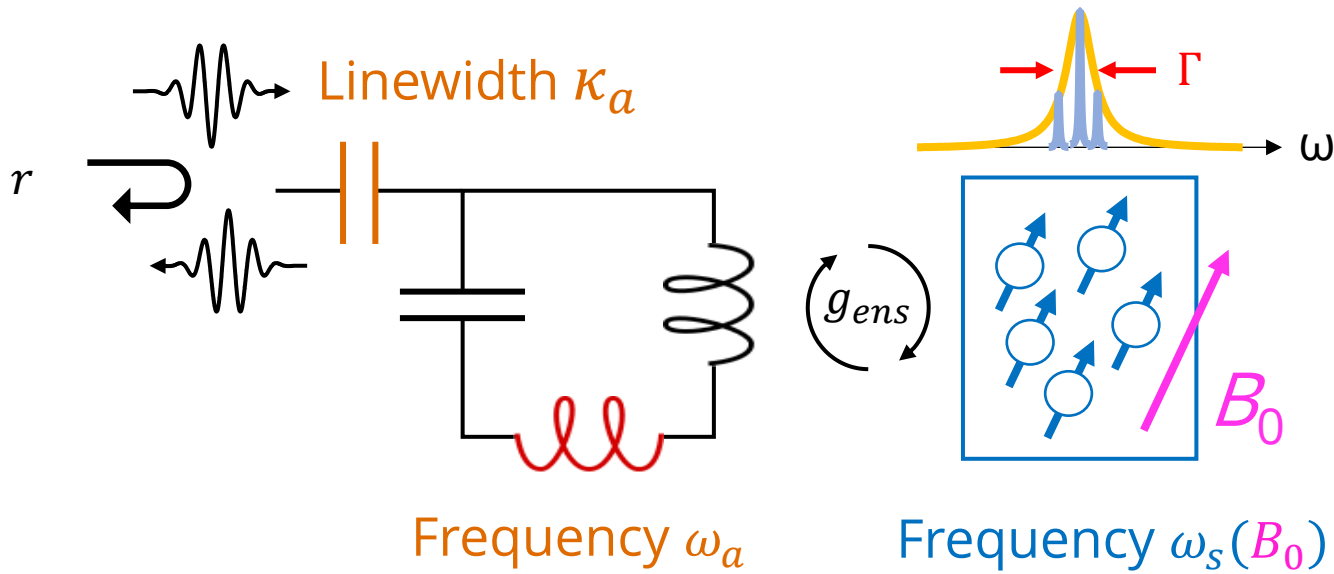


Regime of interaction given by cooperativity

$$C = \frac{4 g_{ens}^2}{\kappa_a \Gamma} = \frac{4 N g_0^2}{\kappa_a \Gamma}$$



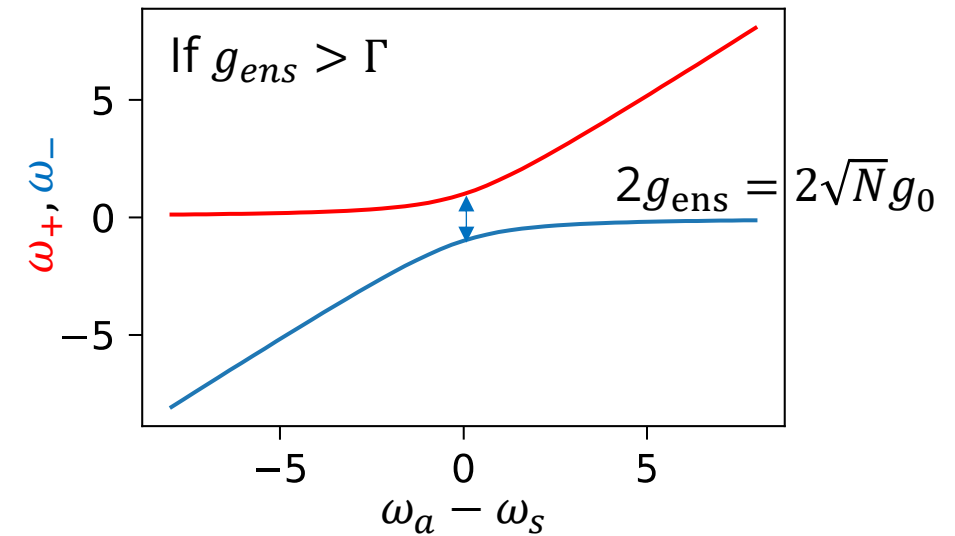
Spin ensemble coupled to a superconducting resonator



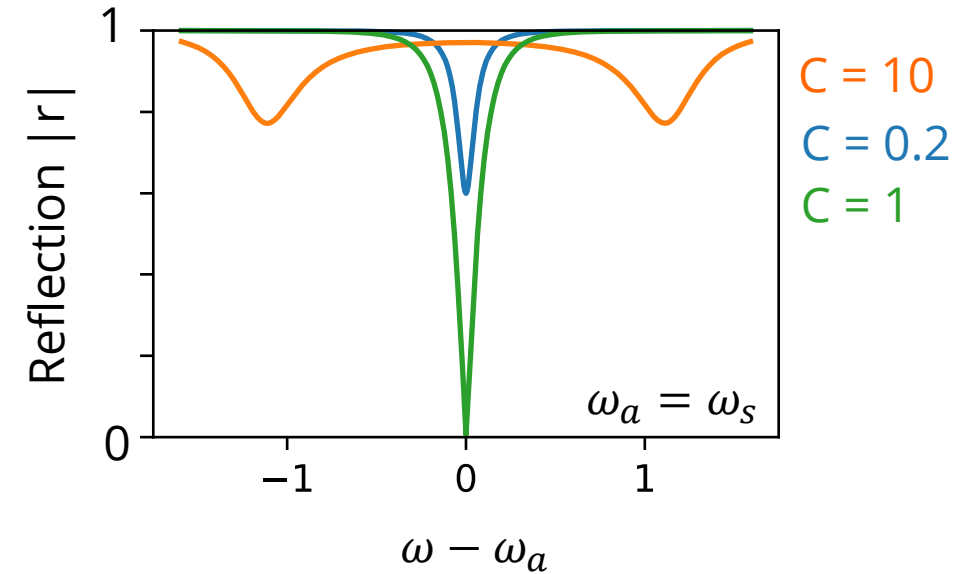
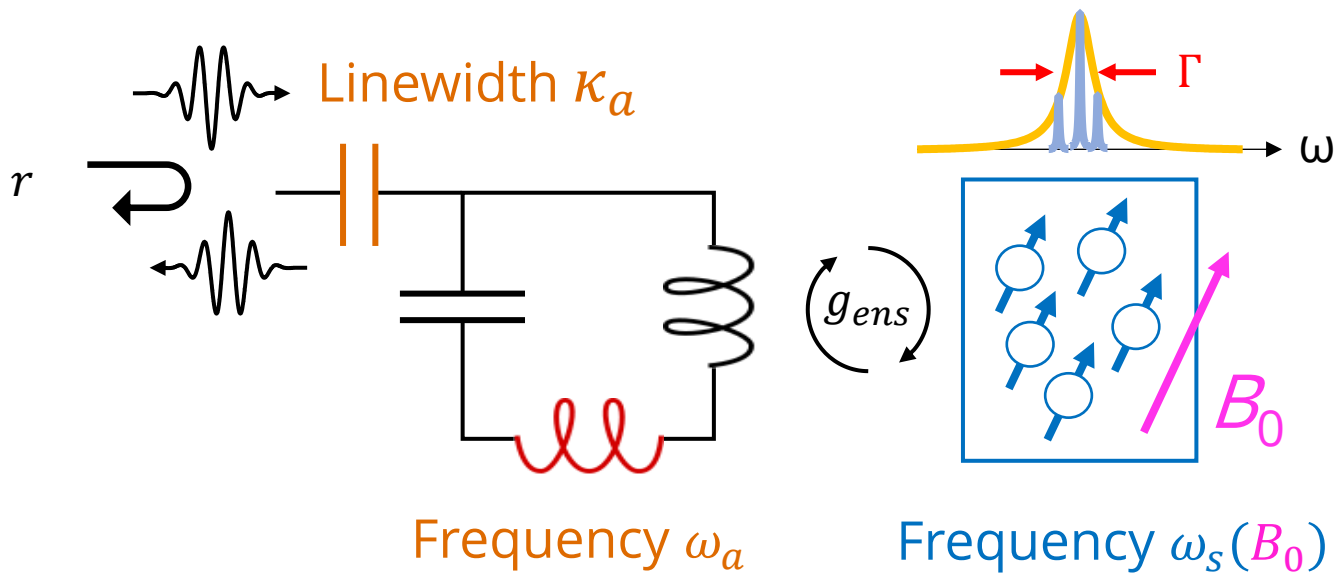
High cooperativity

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

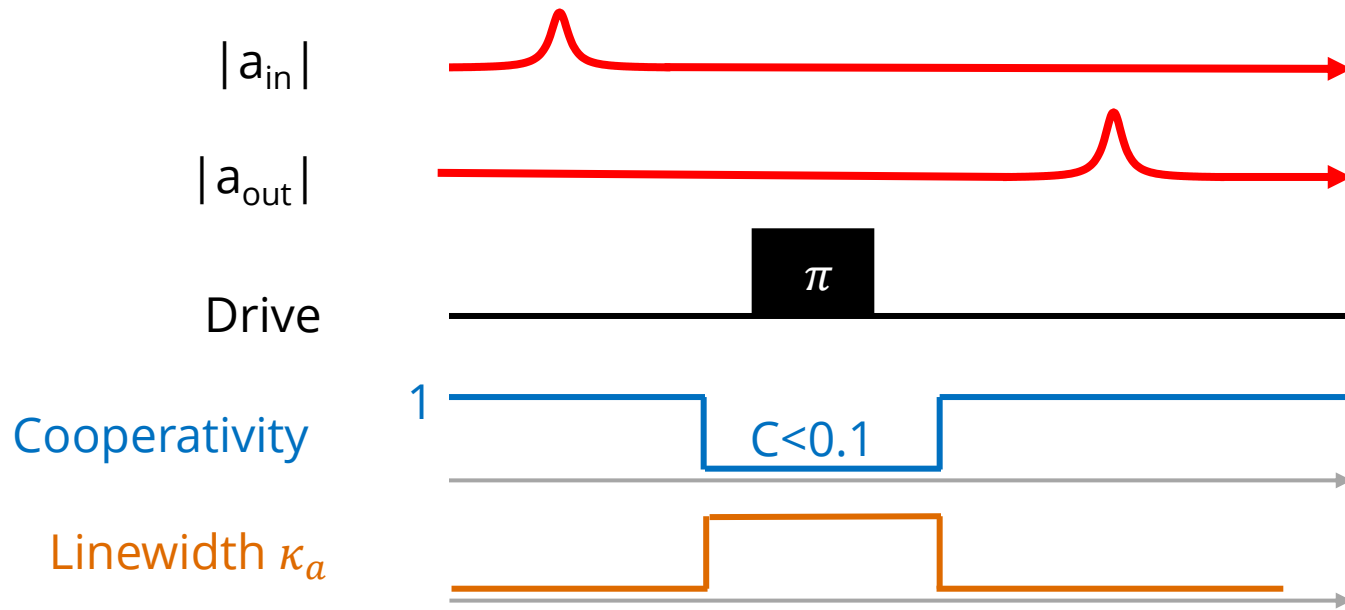
No coherent swapping

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

Spins can deexcite via the resonator (Purcell effect)

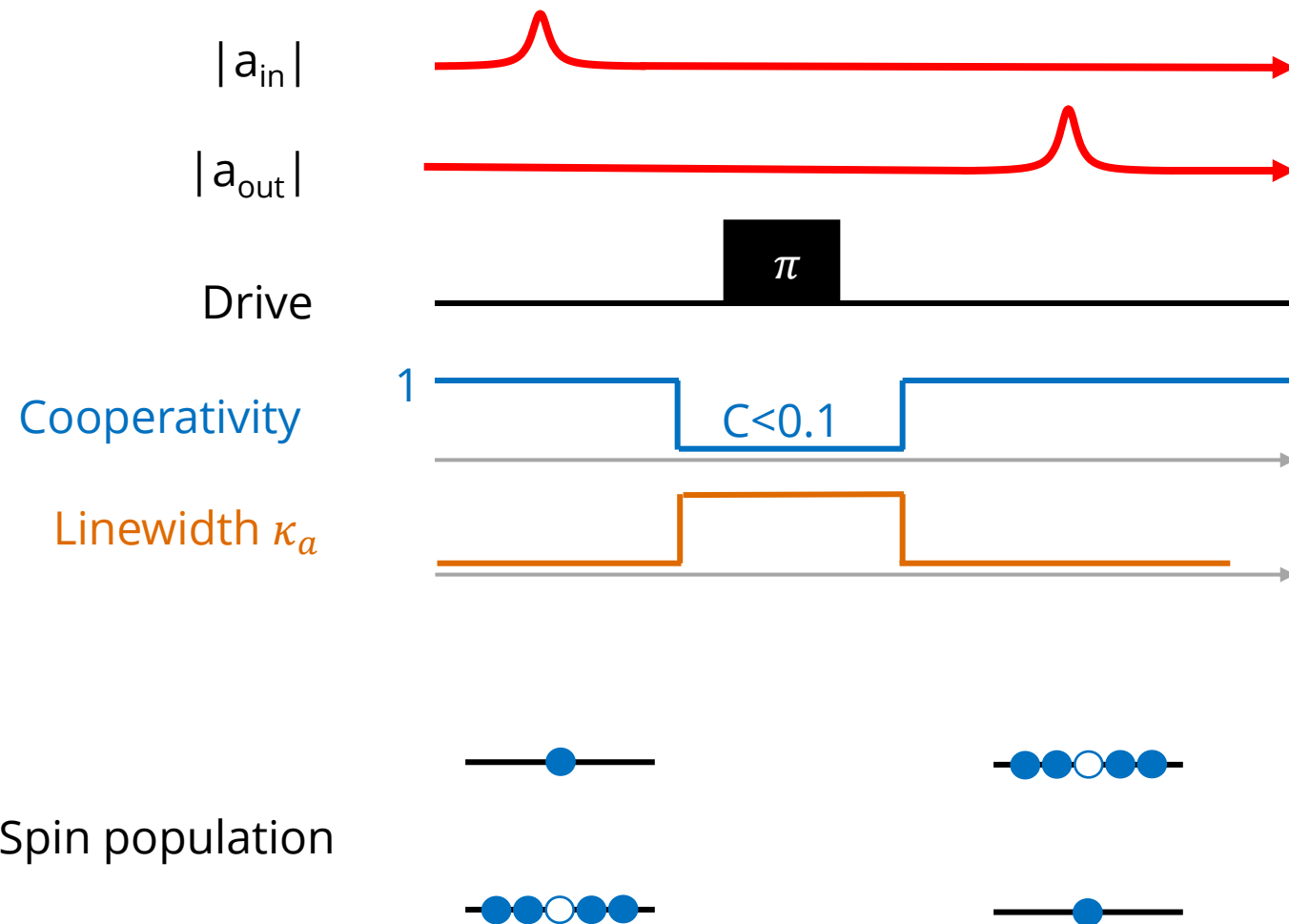
Spin ensemble as a memory: protocol

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



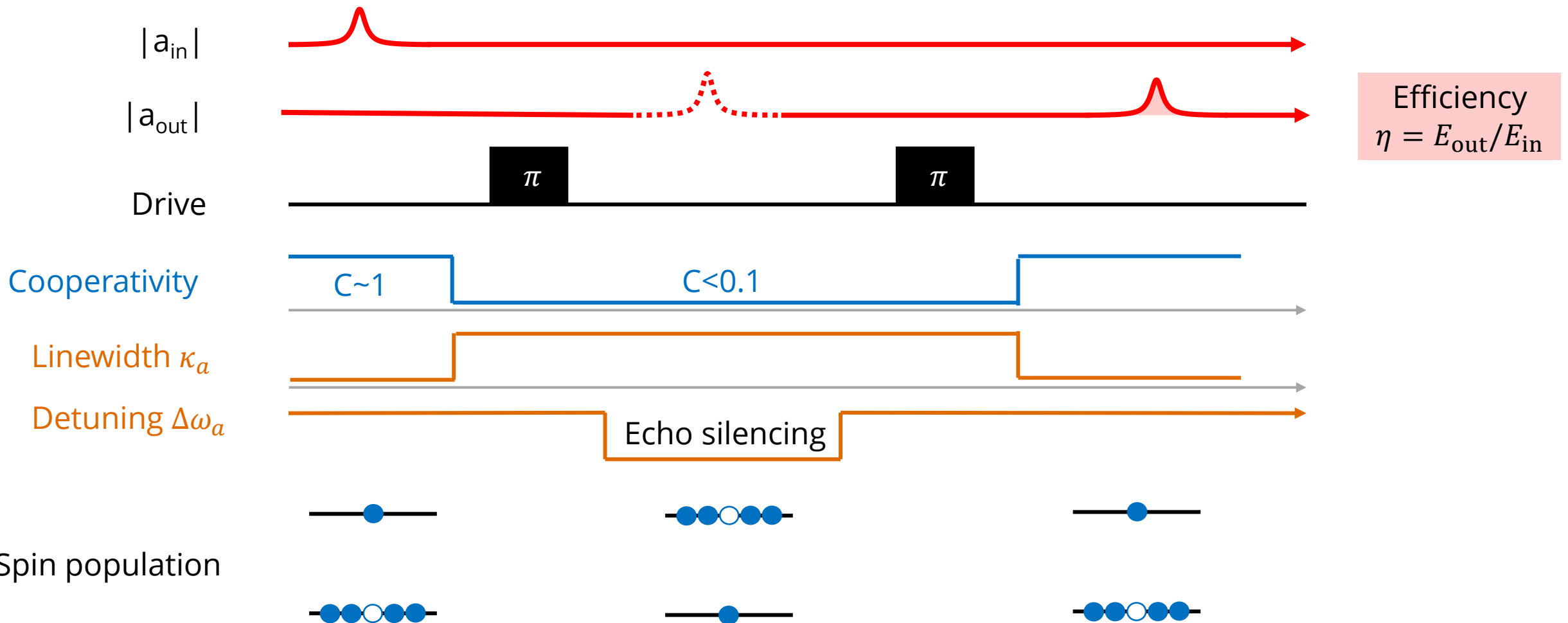
Spin ensemble as a memory: protocol

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



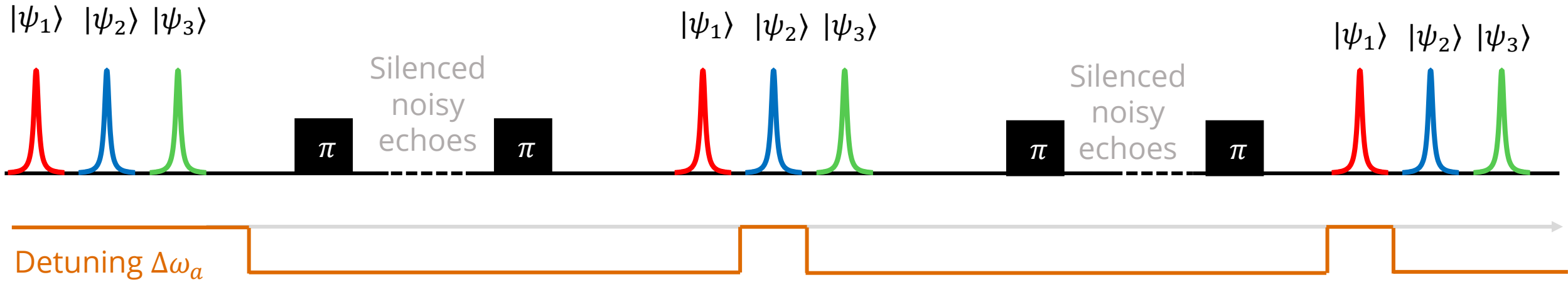
Spin ensemble as a memory: protocol

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



Multimode?

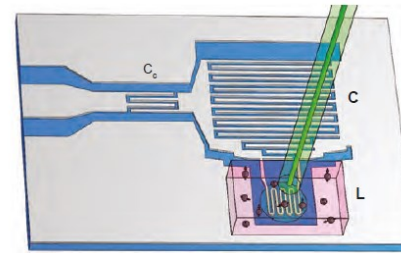
Random access to multiple stored states by echo silencing... except on retrieval !



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



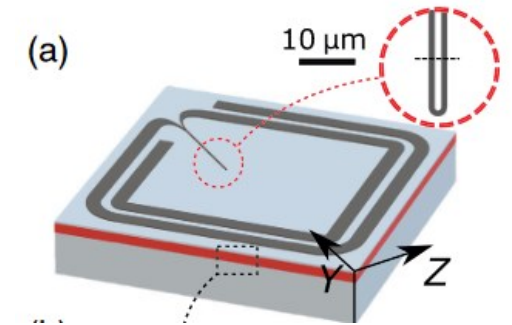
Grezes et al., *PRA* (2015)

Efficiency 0.3 %

$$C = 0.22$$

$$T_2 = 84 \text{ us}$$

Bismuth donors in silicon



Ranjan
PRL (2020)

Efficiency 0.1 %

$$C = 0.04$$

$$T_2 = 0.3 \text{ s}$$

O'Sullivan
PRX (2022)

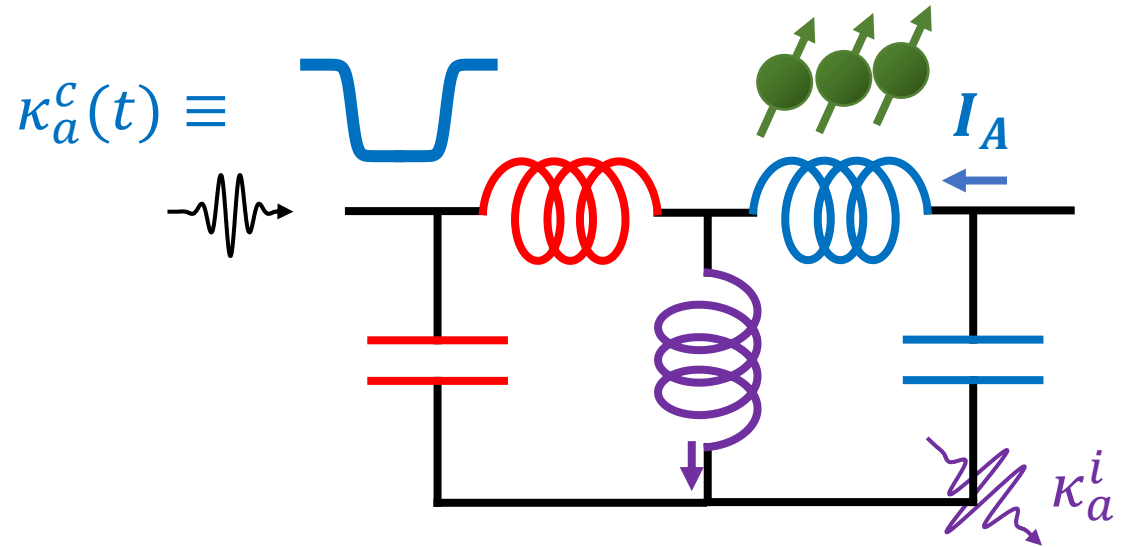
Efficiency 3 %

$$C = 0.06$$

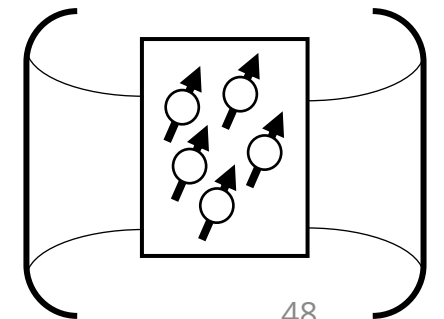
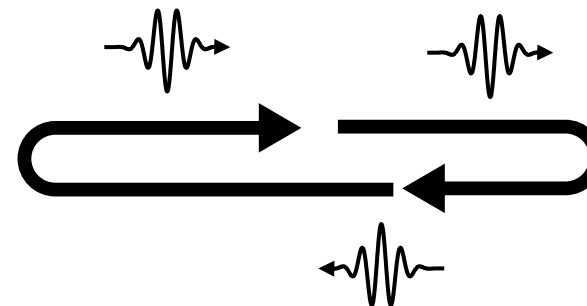
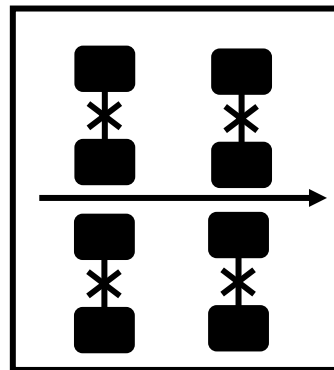
$$T_2 = 2 \text{ ms}$$

Perspective

Running a protocol maximizing efficiency for classical pulses

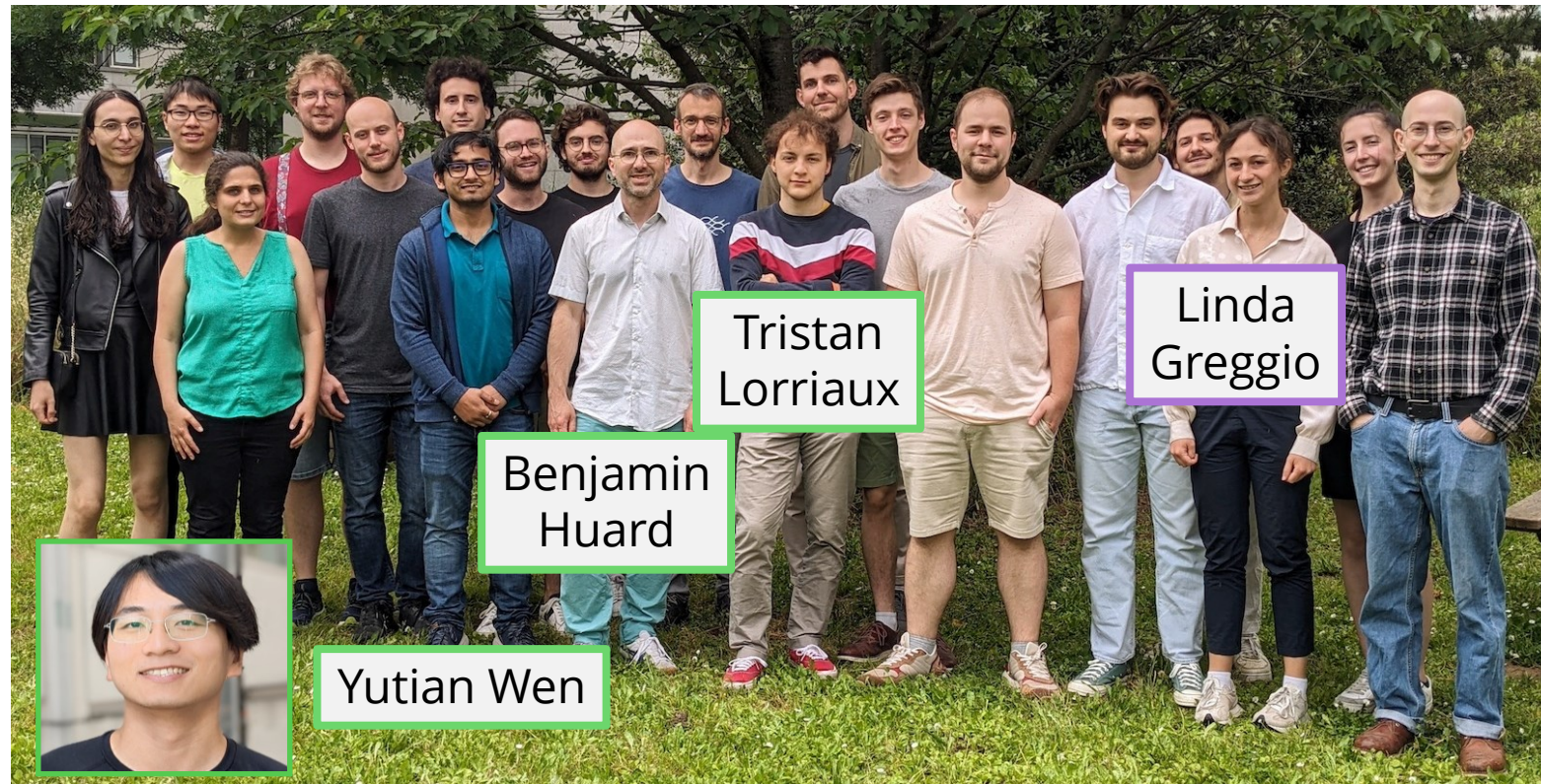


Building a bidirectional link between qubit and processor



Acknowledgments

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M. Mirrahimi
Inria Paris



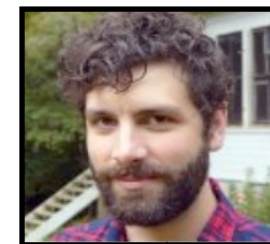
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