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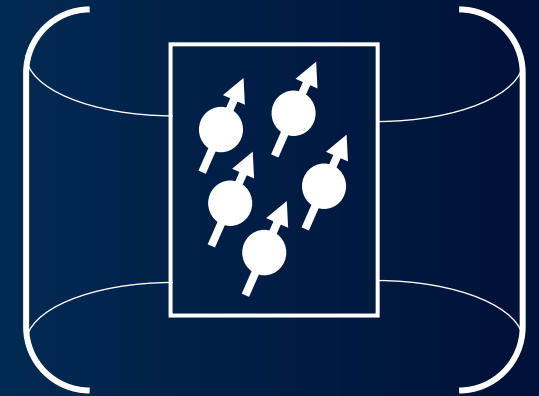
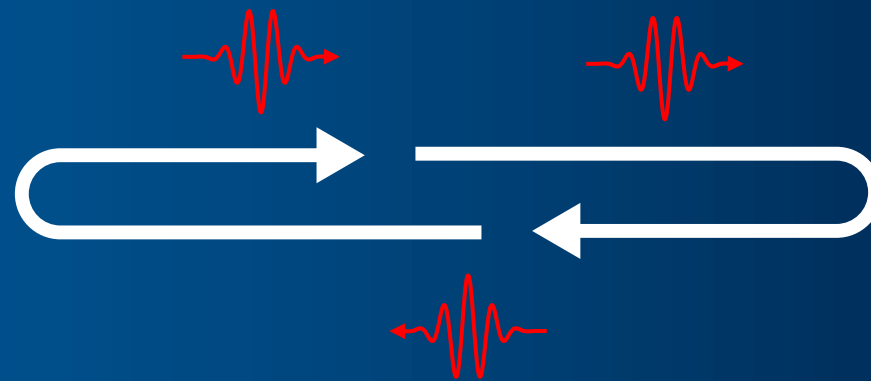
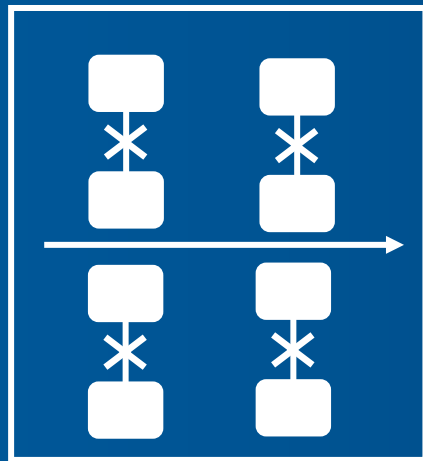
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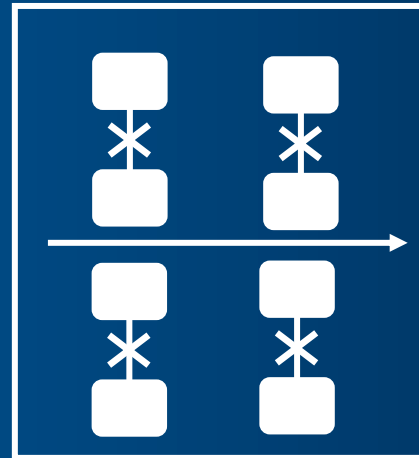
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# Implementing a quantum memory at microwave frequencies with Bismuth donors in silicon

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

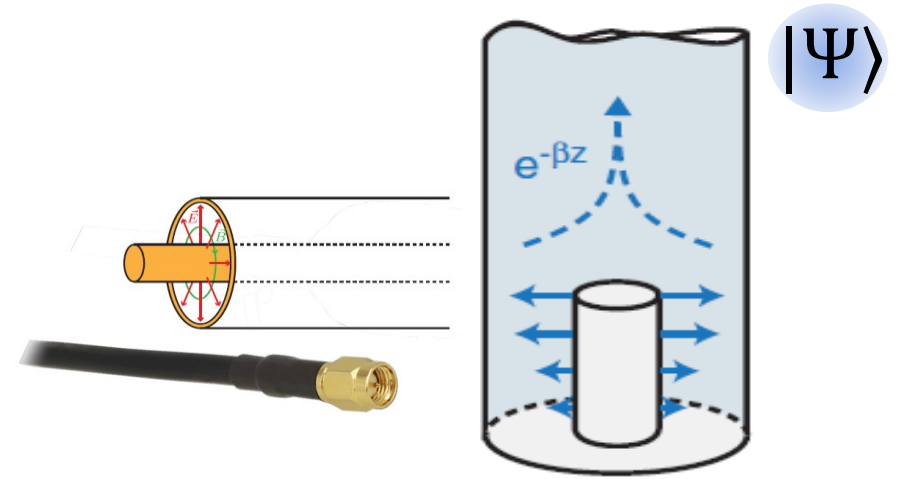


# Superconducting circuits: how to implement qubits and gates ?

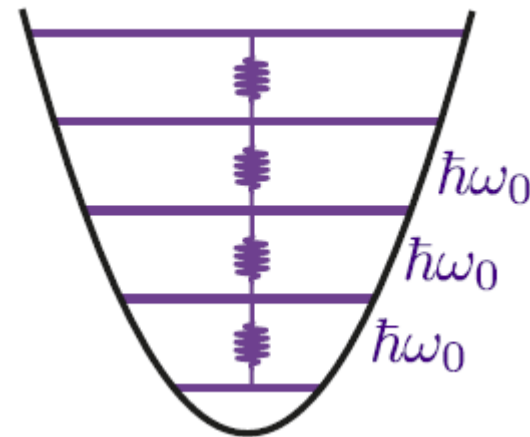
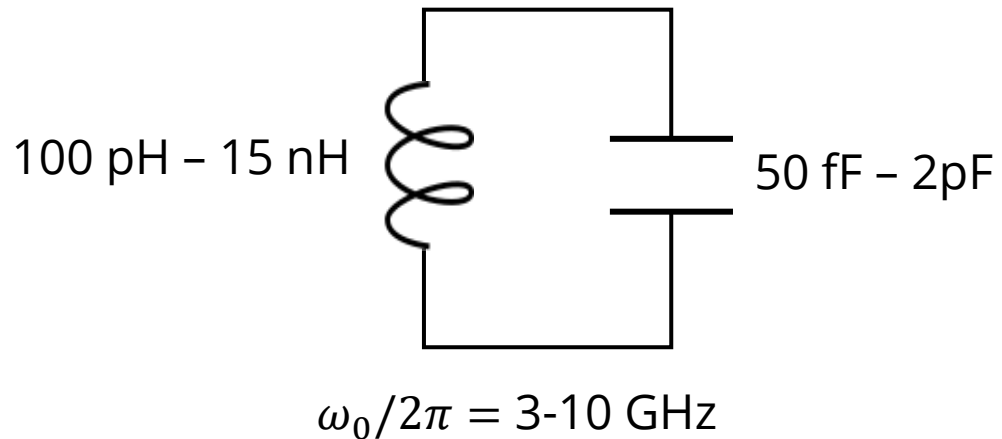


# Quantum superconducting circuits

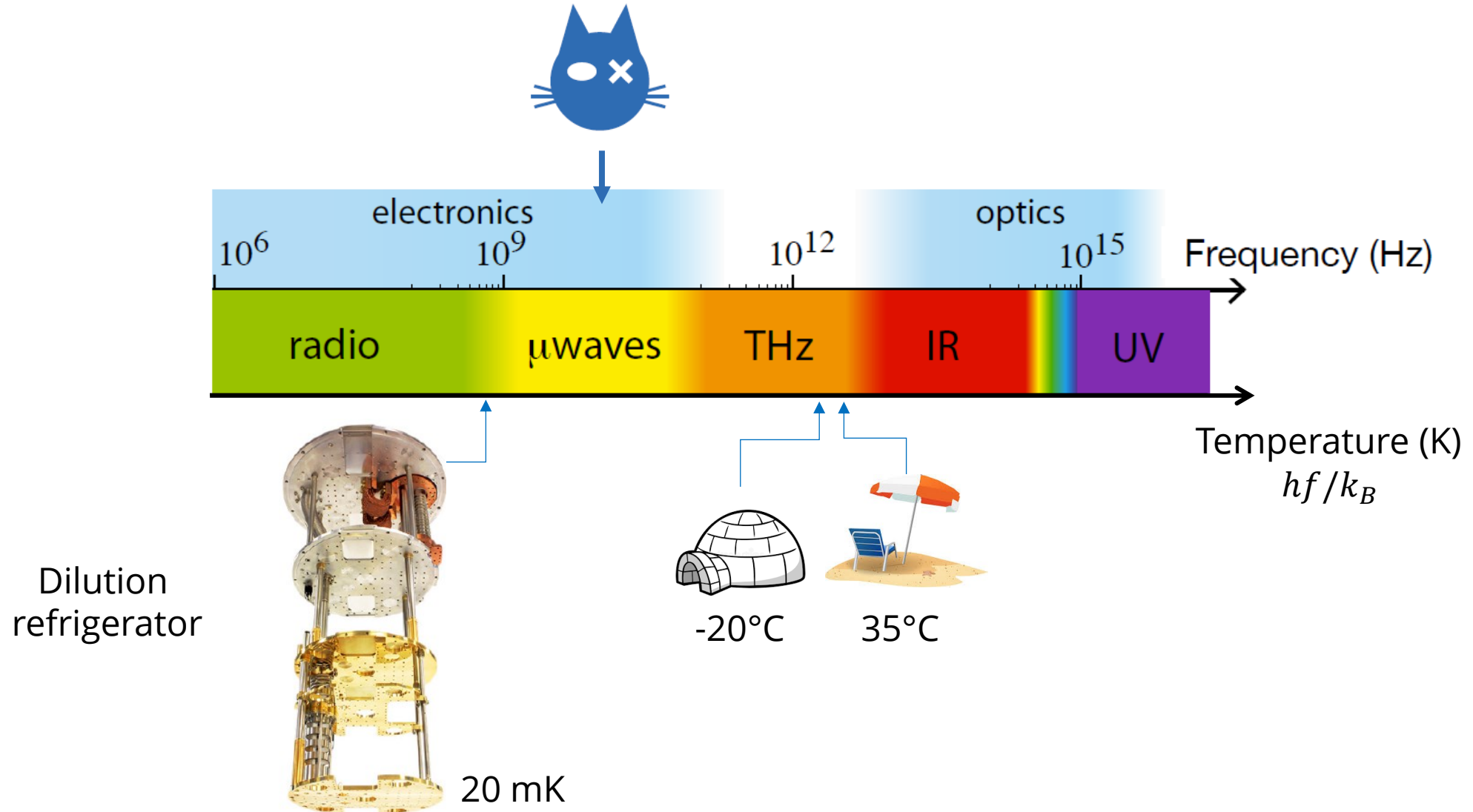
Quantum mechanics  
with microwave circuits



First brick: microwave harmonic oscillator



# Reaching the quantum regime ?

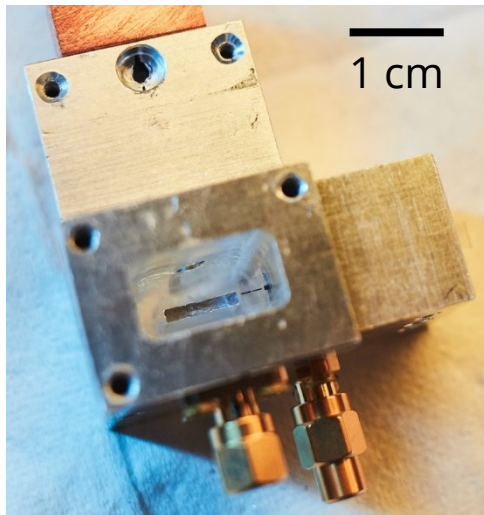


# Different flavors of oscillators : bulk type

We need long-lived states

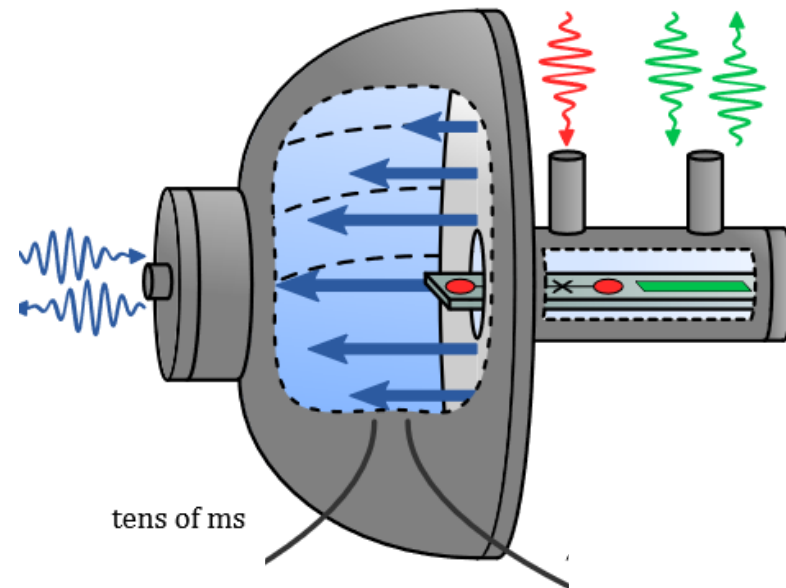
- ⇒ use superconducting materials
- ⇒ low temperature for best quality factor

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



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

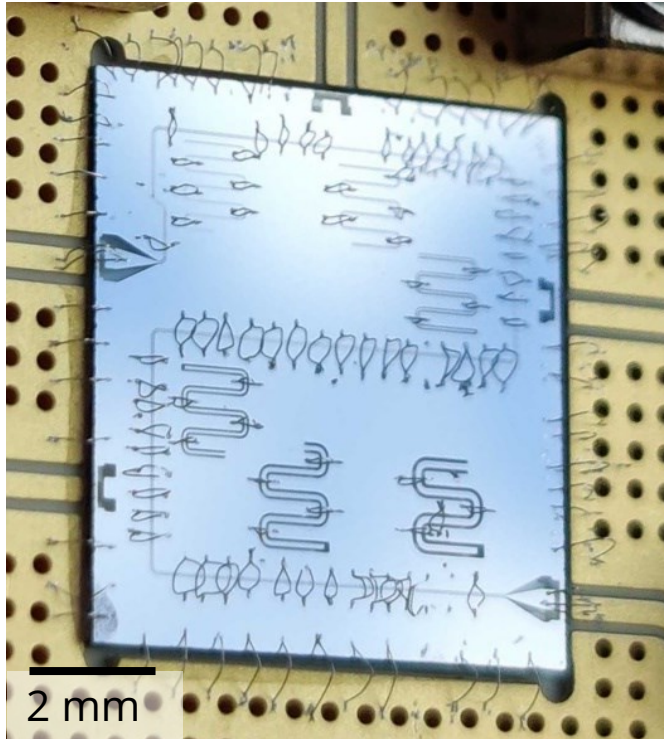
Niobium half elliptical cavity ( $T_c = 9.2\text{K}$ )



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

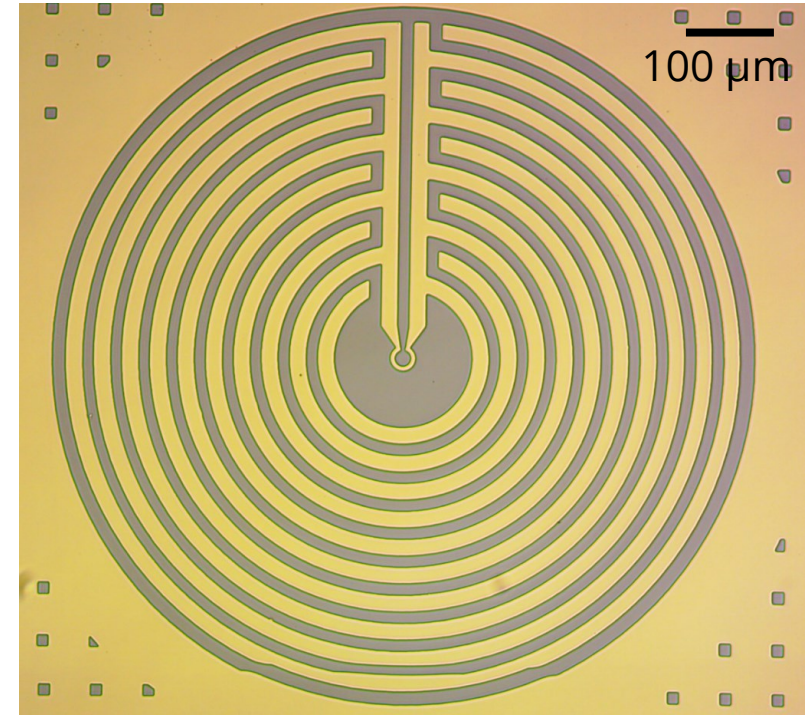
# Different flavors of oscillators : planar type

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



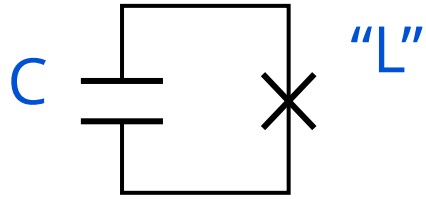
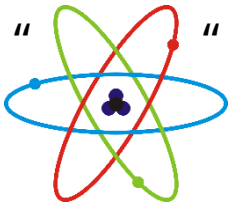
$$T_{\text{decay}} = 19 \mu\text{s}$$
$$Q = 1.1 \cdot 10^6$$

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



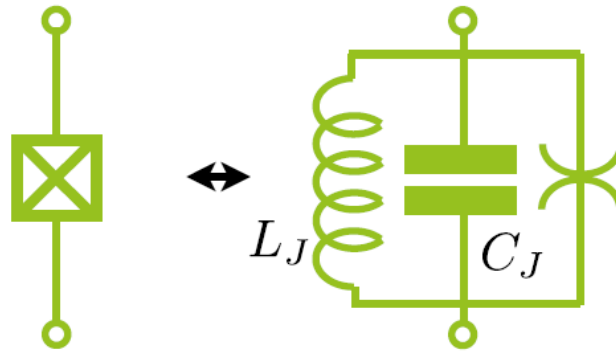
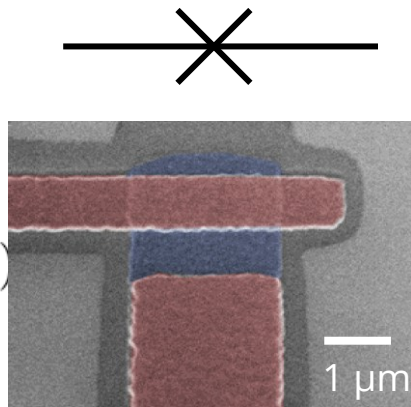
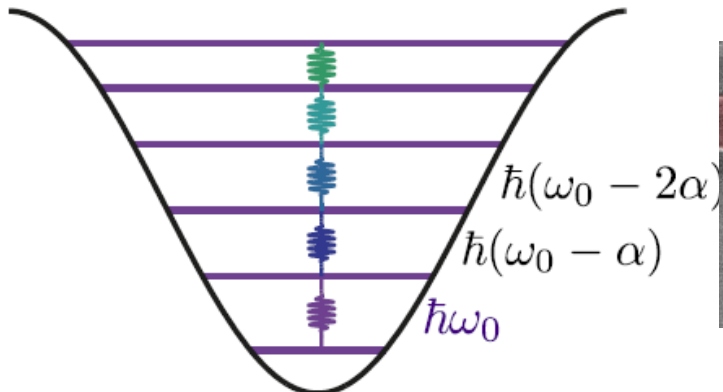
$$T_{\text{decay}} = 16 \mu\text{s}$$
$$Q = 6 \cdot 10^5$$

# Superconducting qubit



Non-linear LC oscillator

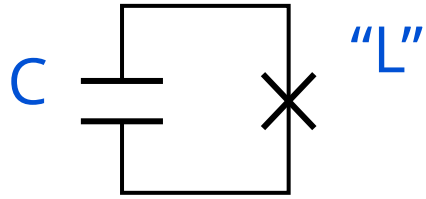
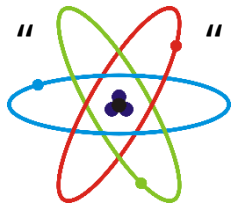
Josephson junction



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

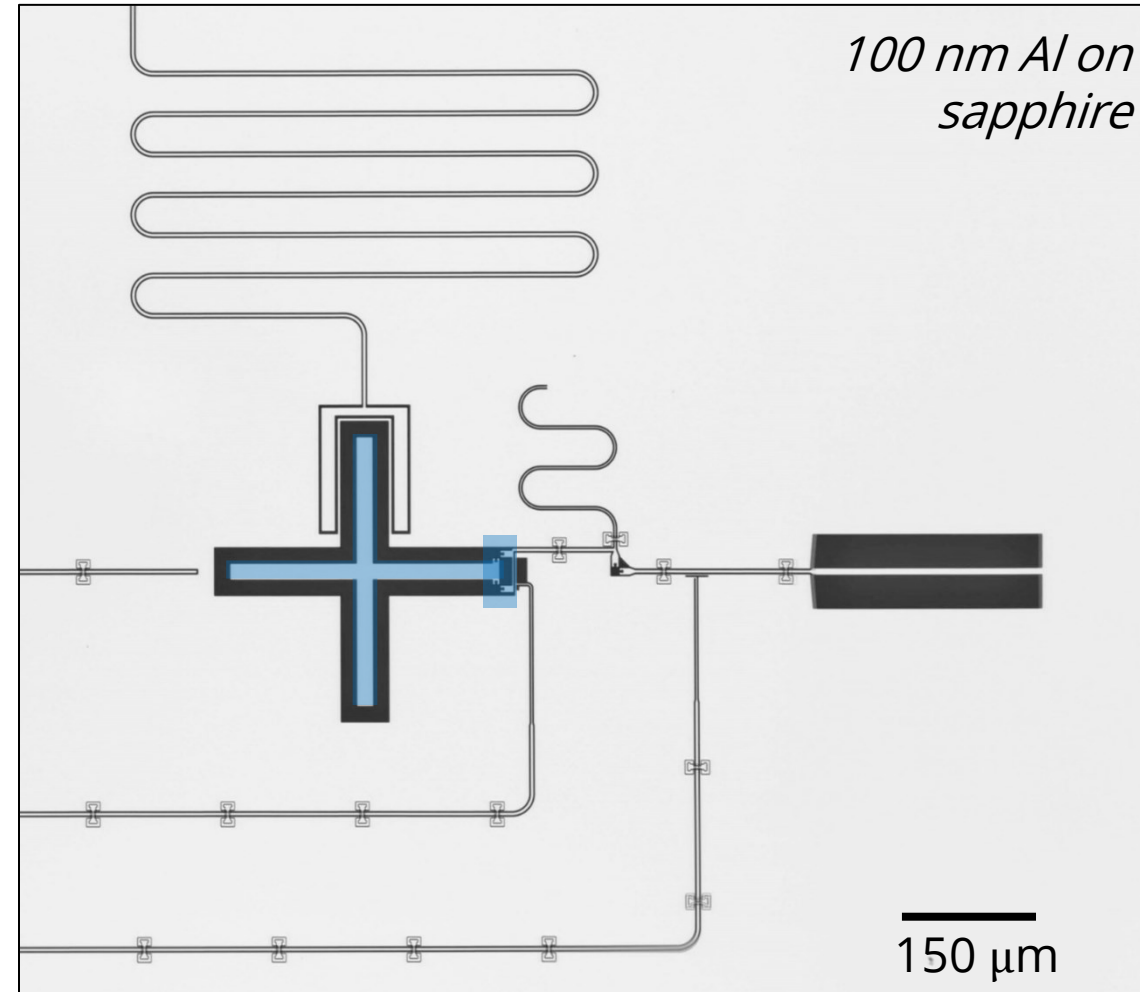
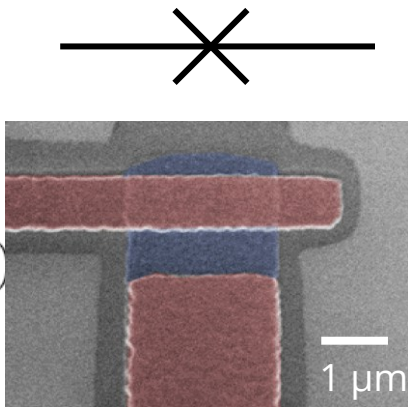
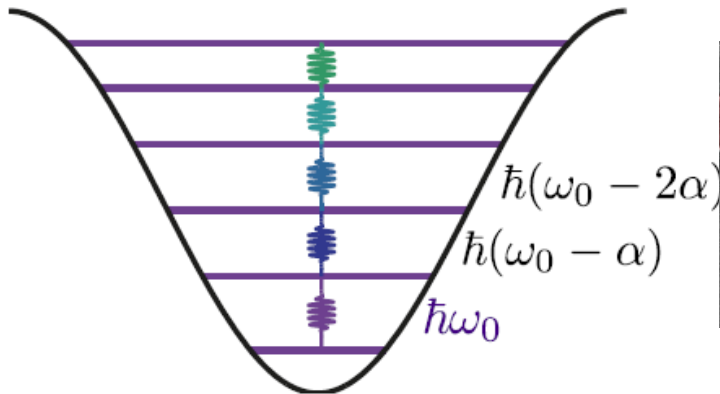


# Superconducting qubit



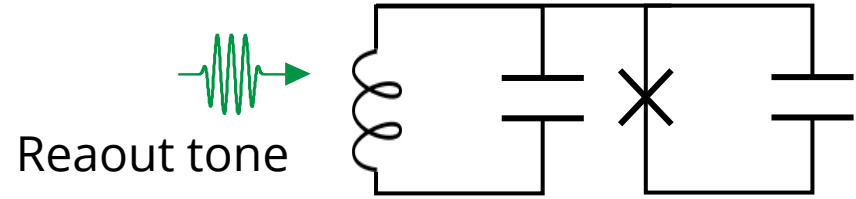
Non-linear LC oscillator

Josephson junction

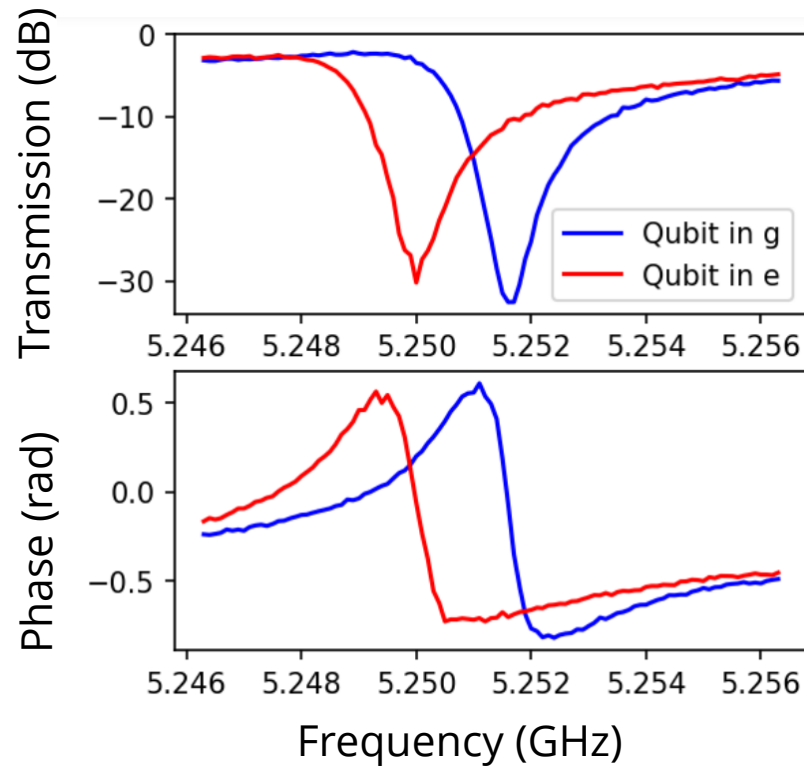
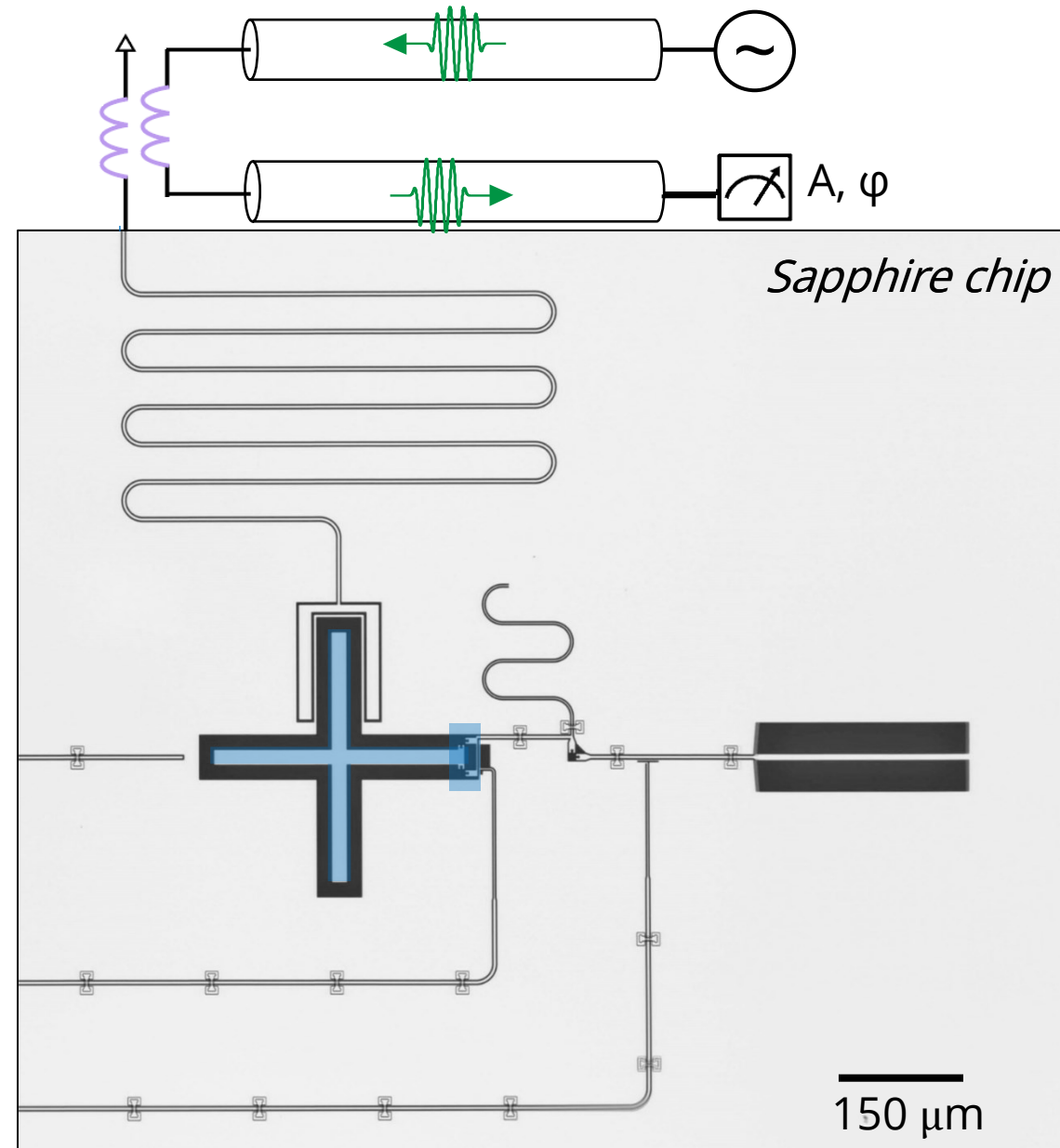


transitions observed in 1980's [Berkeley & Saclay]  
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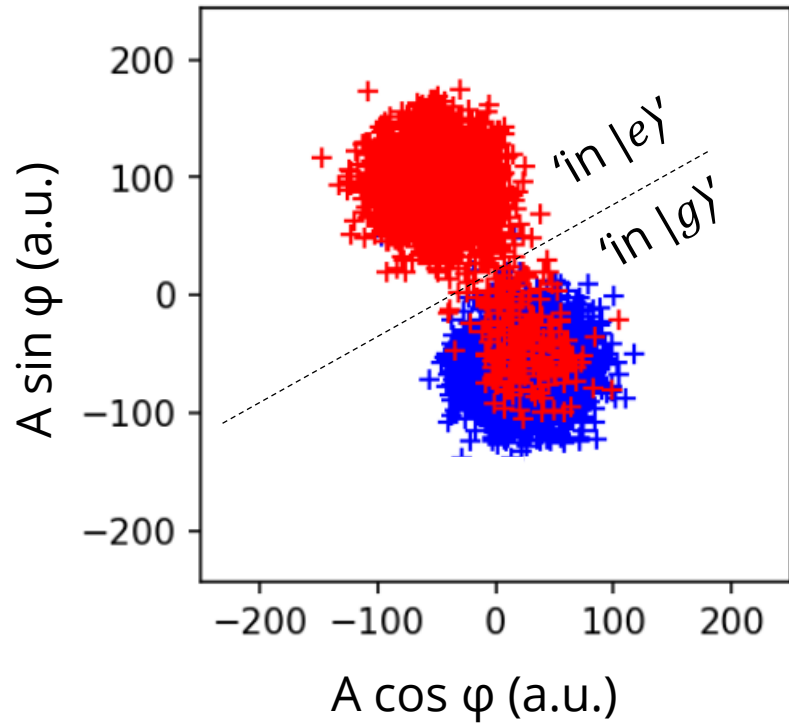
# Superconducting qubit



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



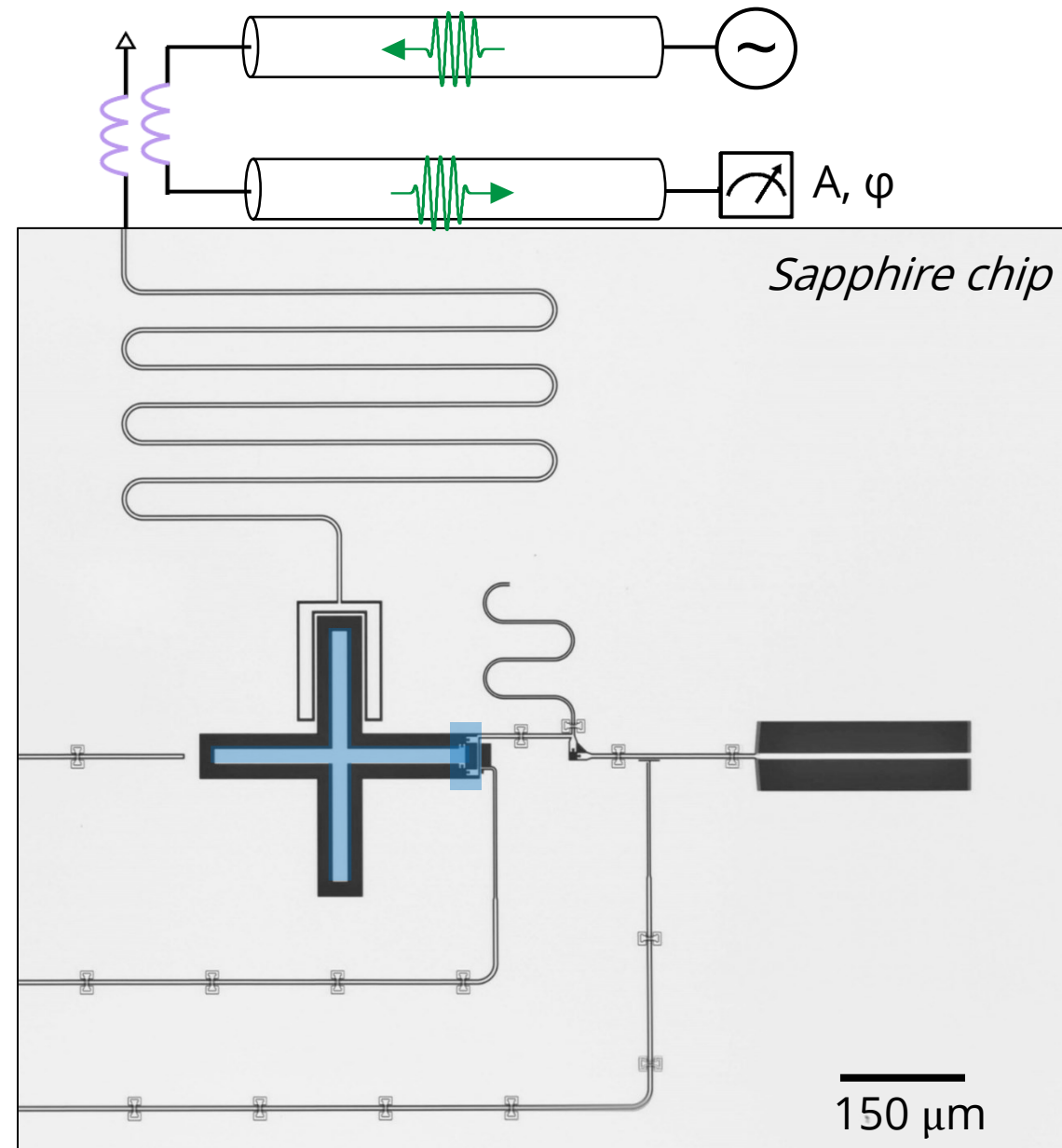
# Superconducting qubit



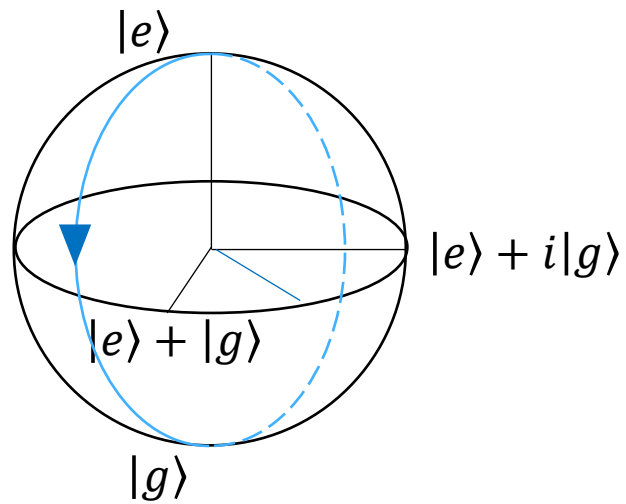
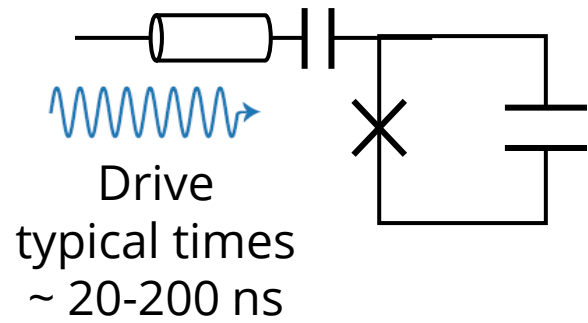
Capacitively coupled to **readout** resonator

$$P_e = \frac{N_{\text{in } |e\rangle}}{N_{\text{in } |e\rangle} + N_{\text{in } |g\rangle}}$$

$$P_g = 1 - P_e$$

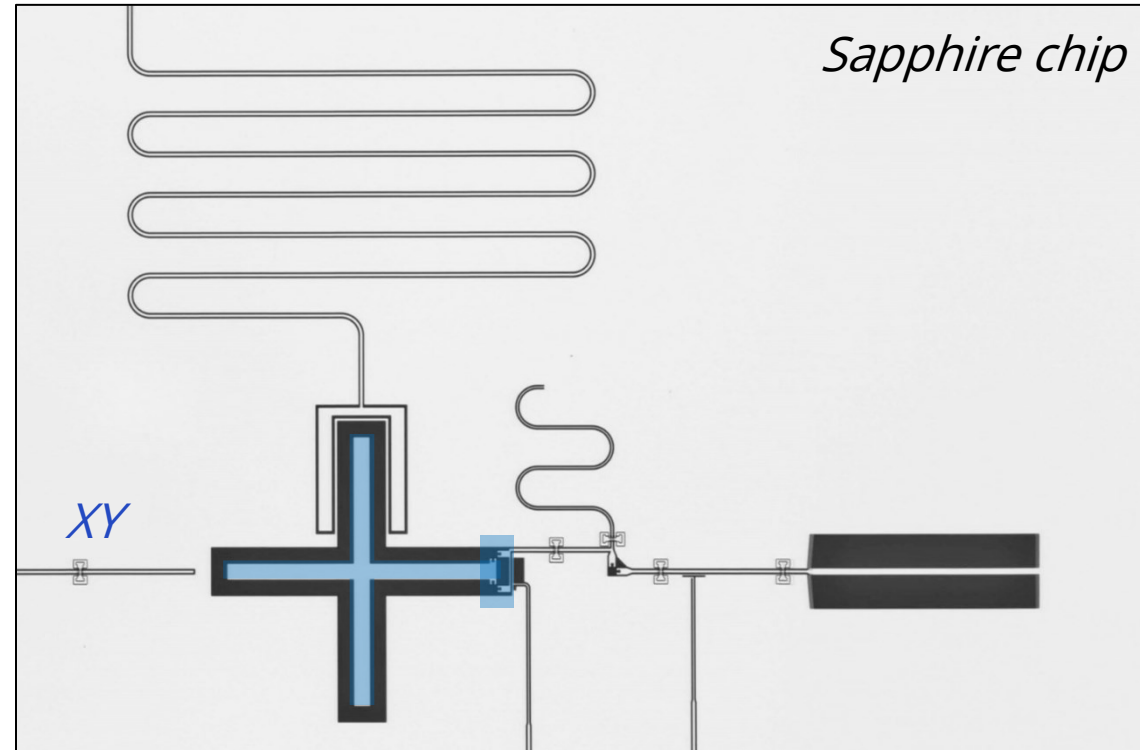


# Superconducting qubit: control



Readout

Excitation and control



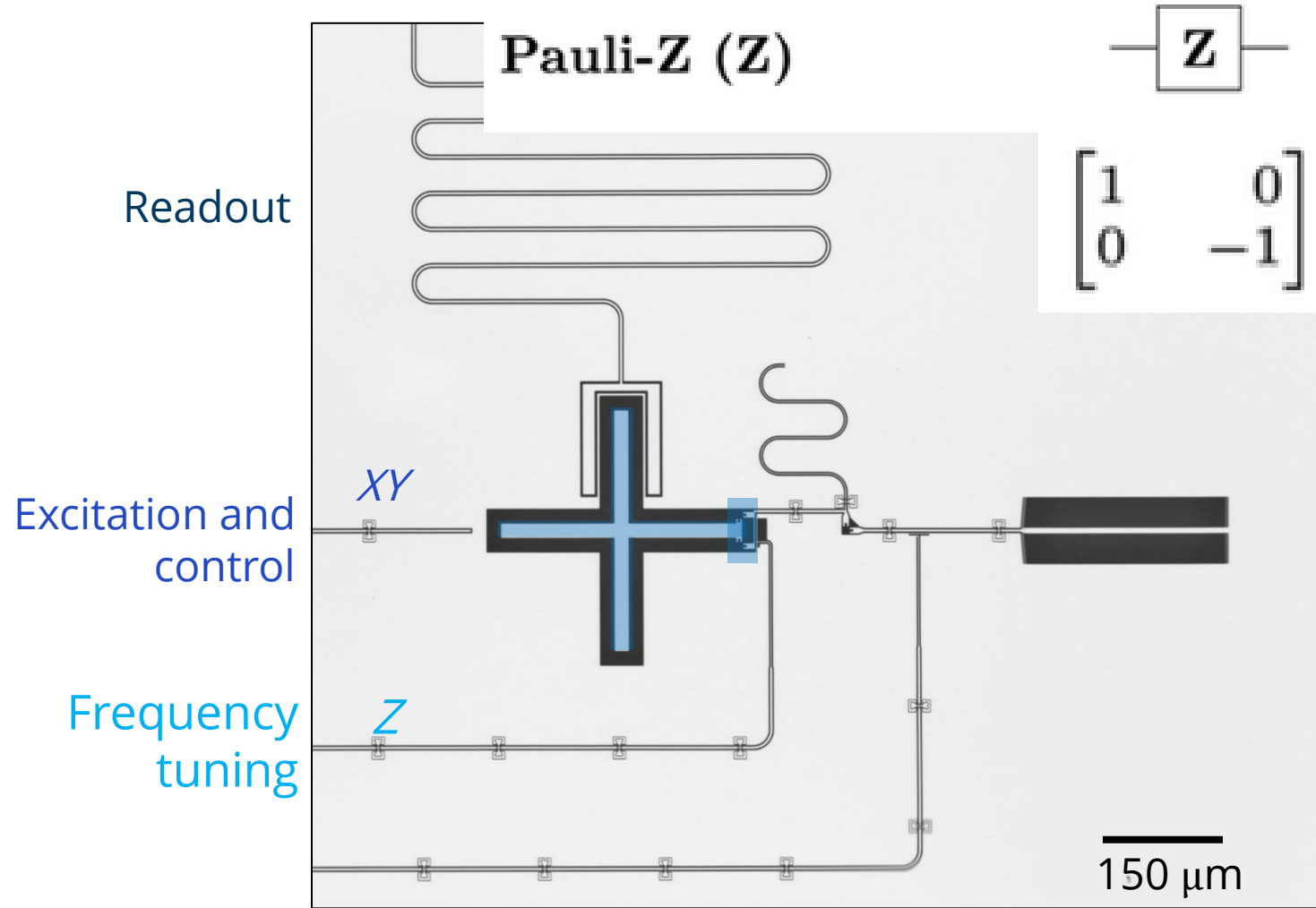
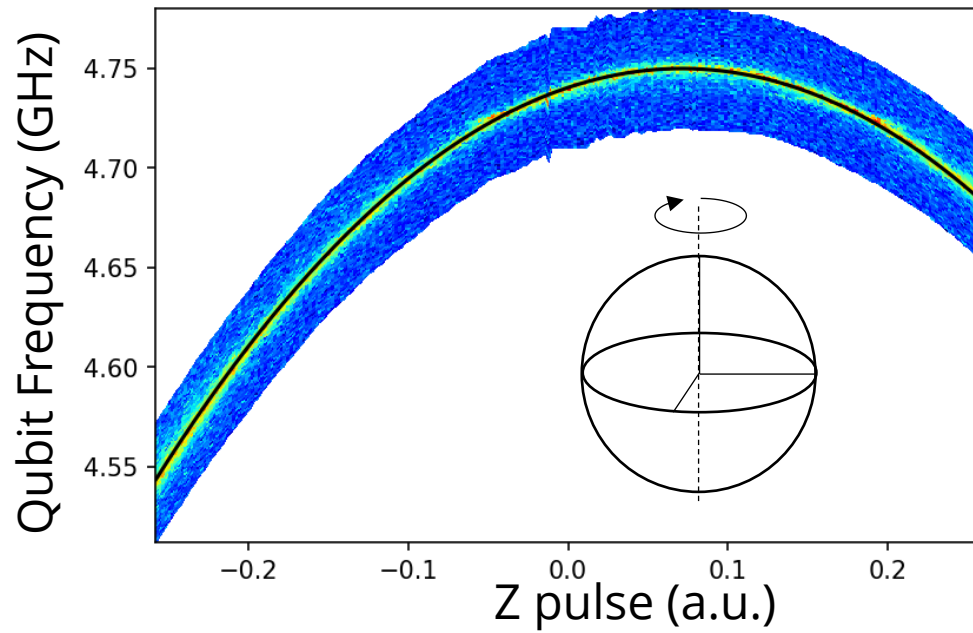
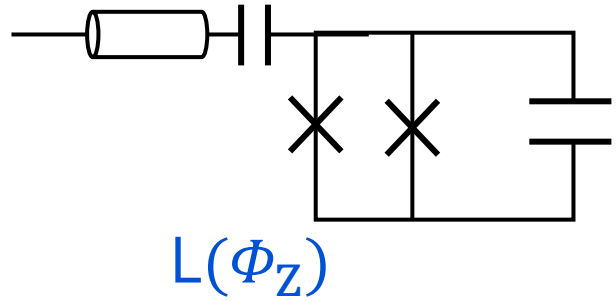
**Pauli-X (X)**

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

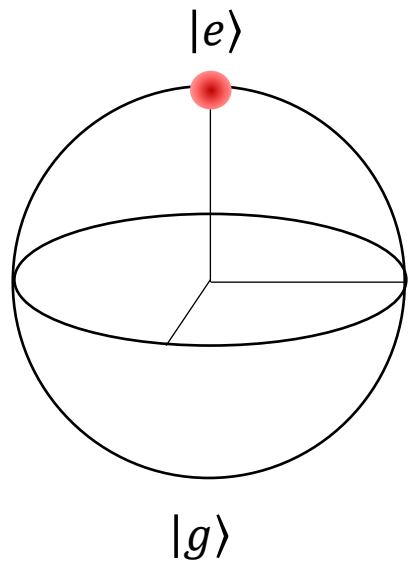
**Pauli-Y (Y)**

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

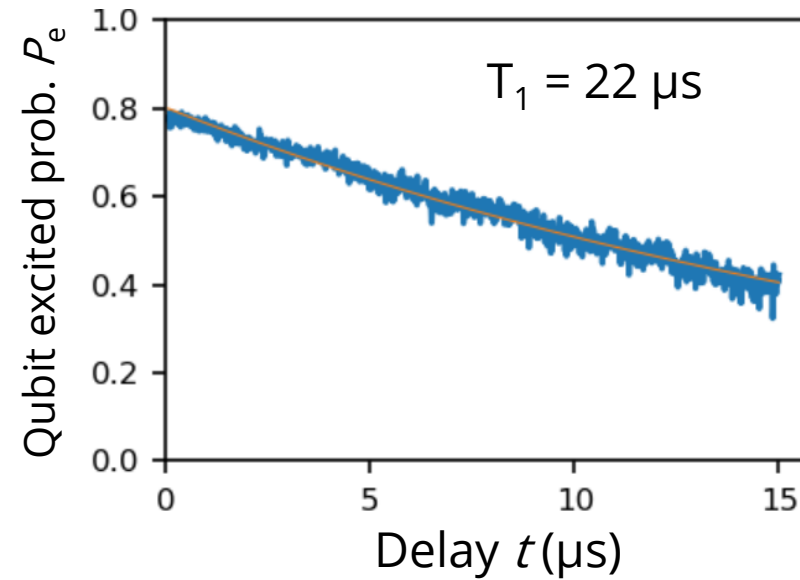
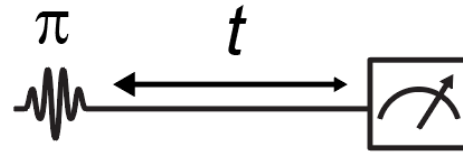
# Superconducting qubit: control



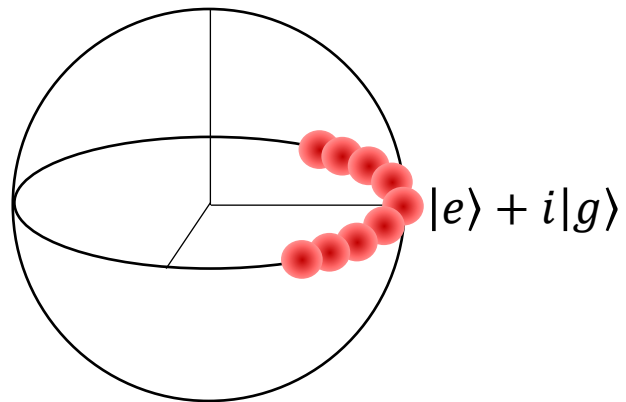
# Superconducting qubit: coherence



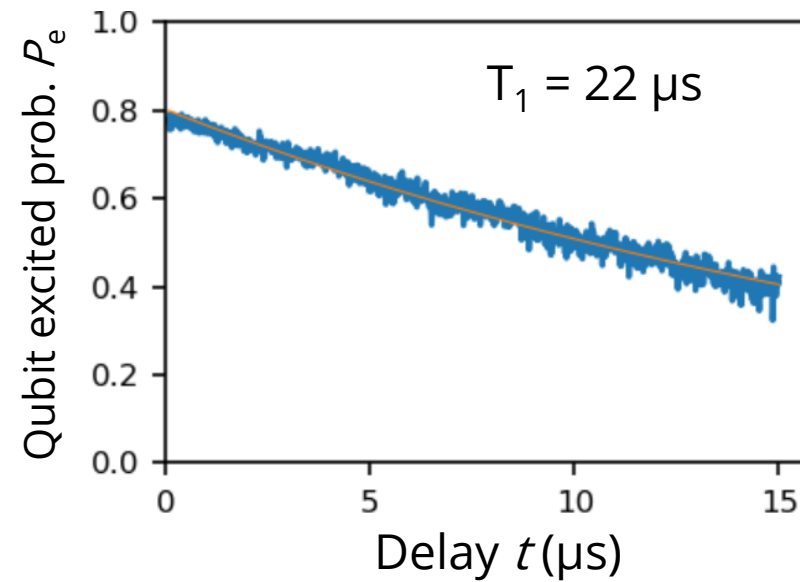
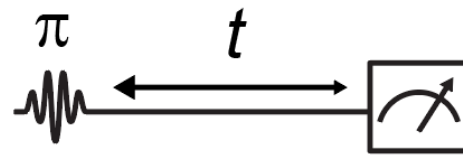
Energy relaxation ( $T_1$ )



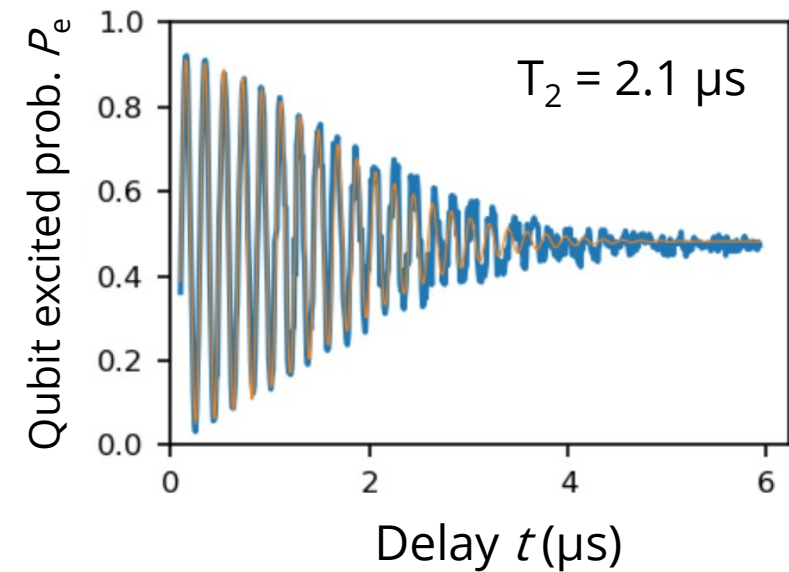
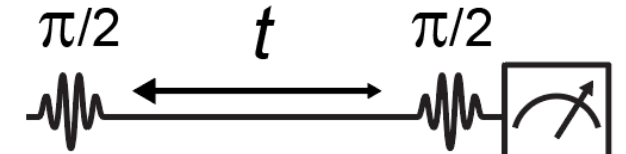
# Superconducting qubit: coherence



Energy relaxation ( $T_1$ )

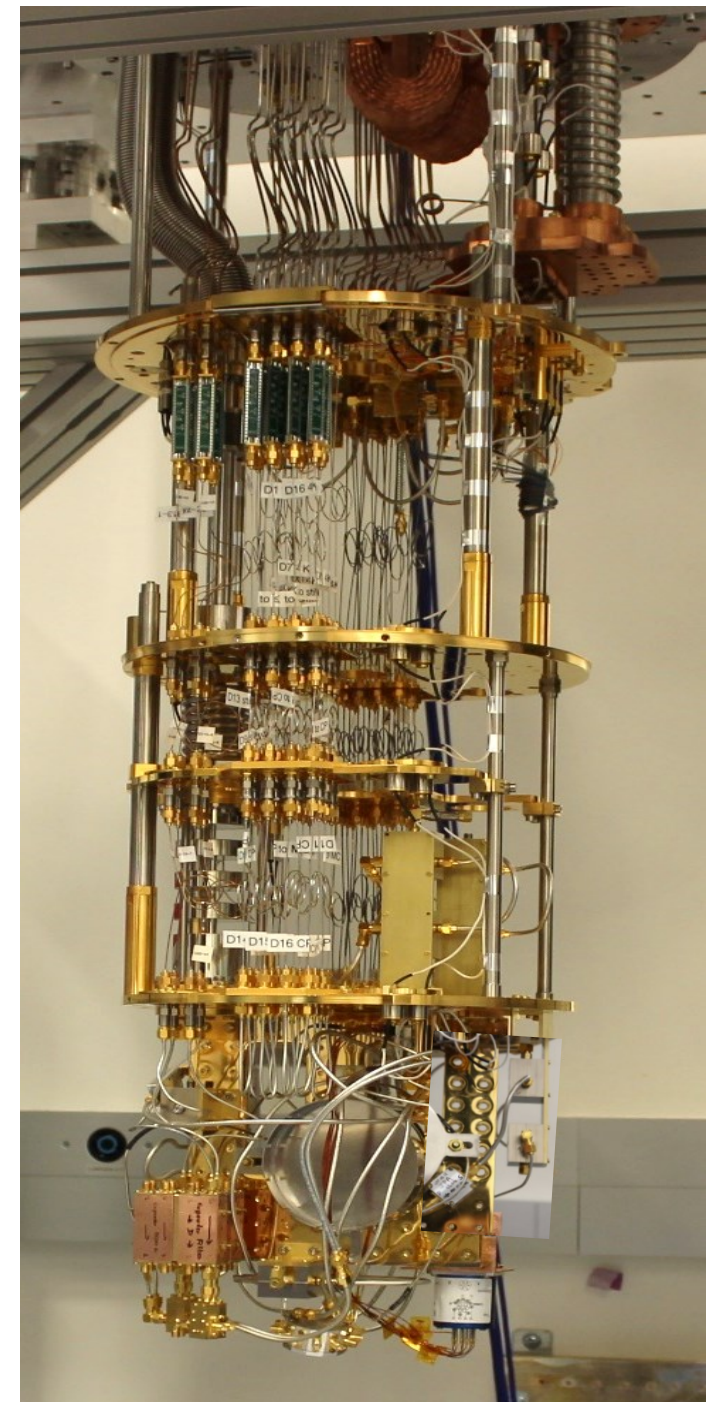
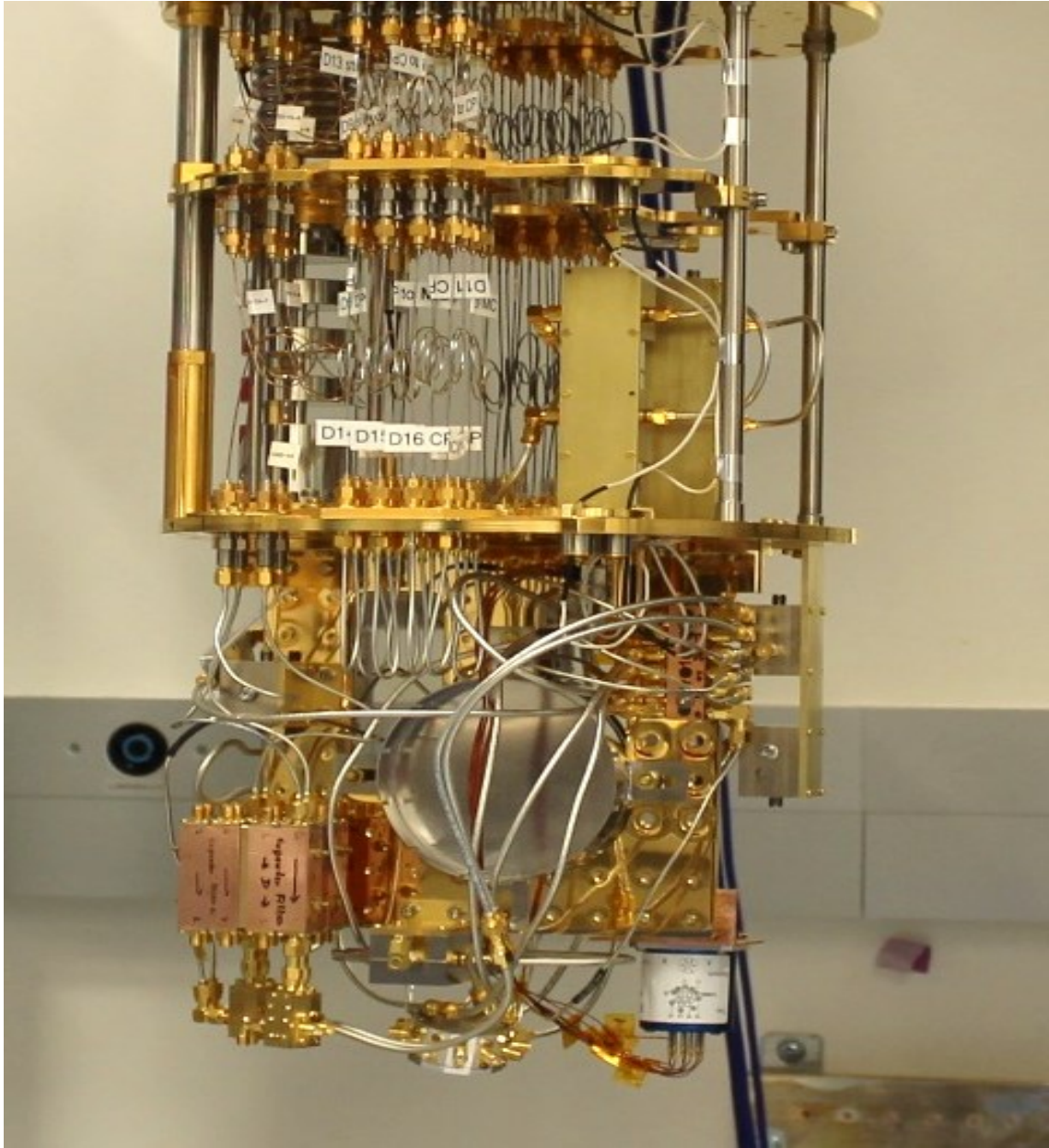


Phase coherence ( $T_2$ )





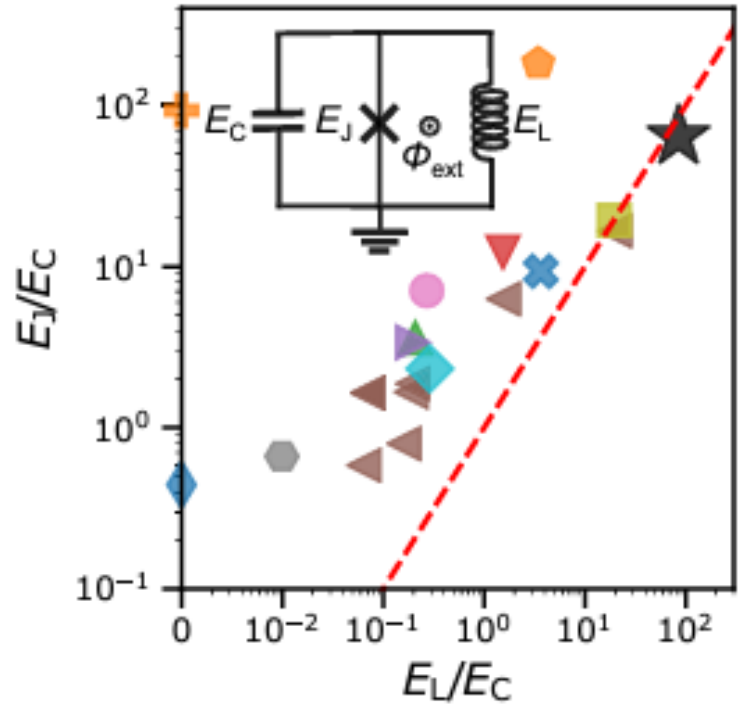
# Typical setup




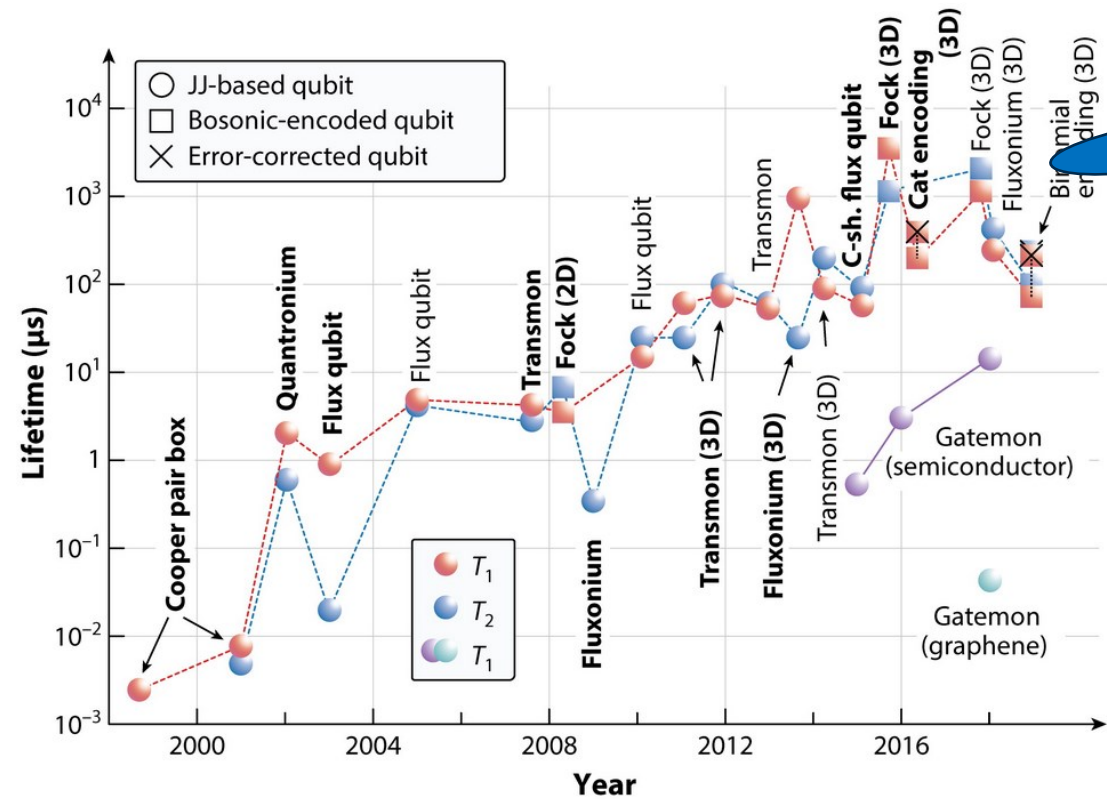


# Zoology and lifetimes

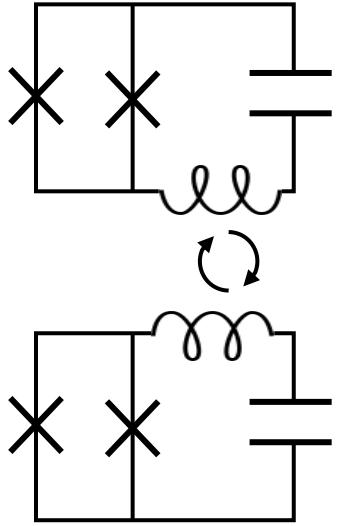
 **Transmon**  
Popularity



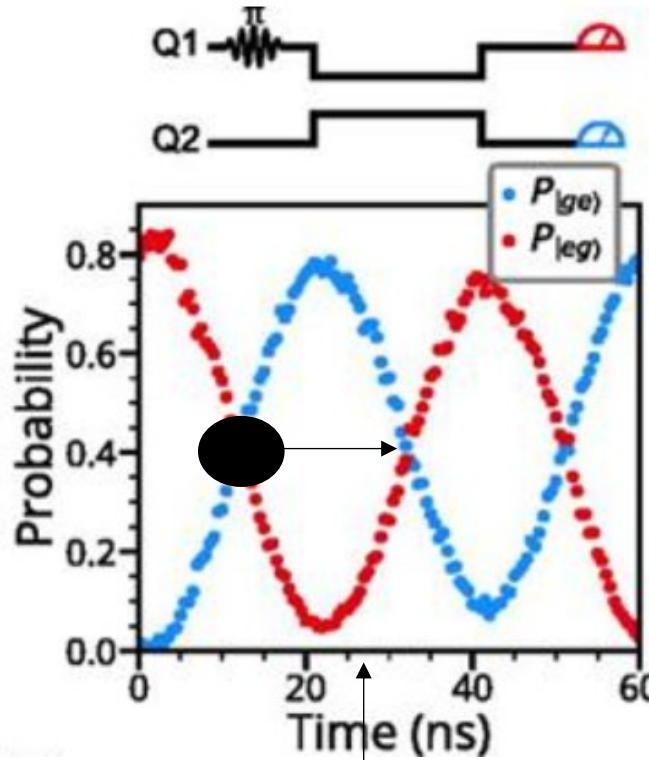
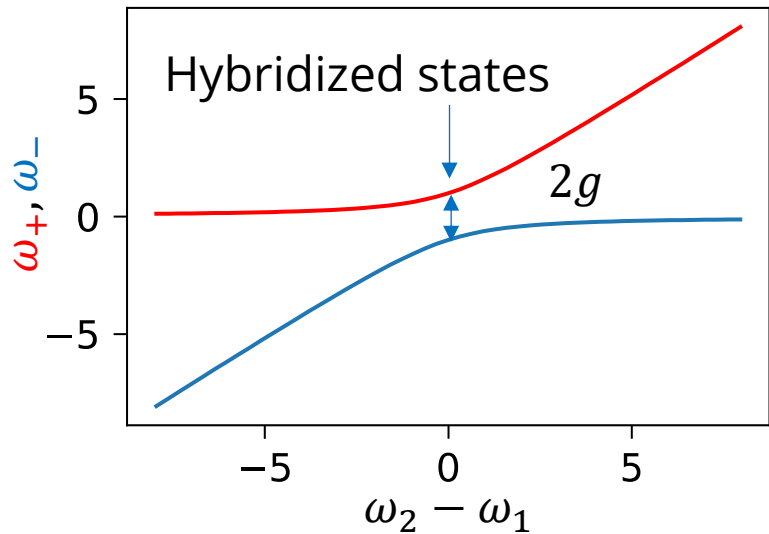
**Fluxonium**  
 Lifetime & gate errors



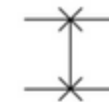
# Examples of two qubit gates : SWAP gate



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

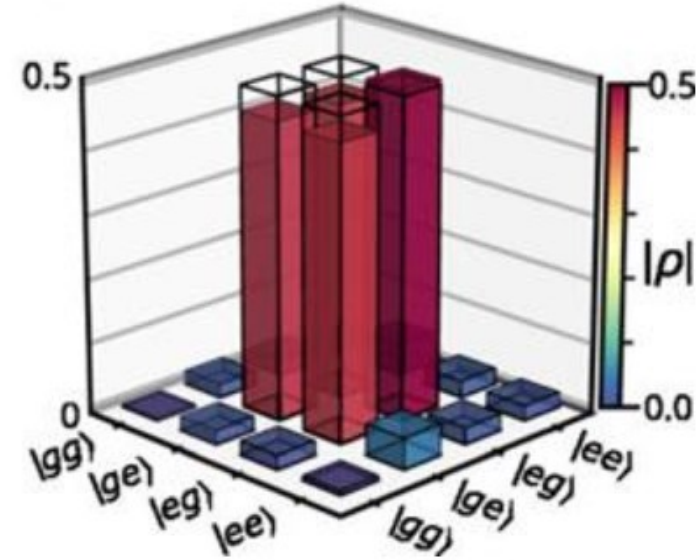


SWAP

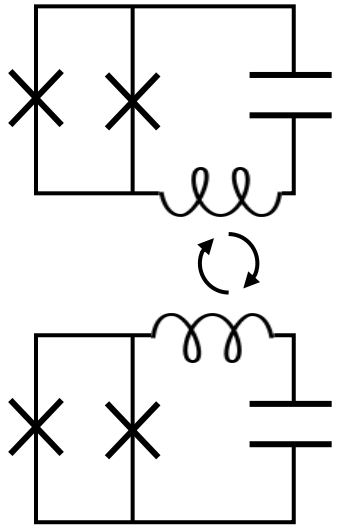


$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

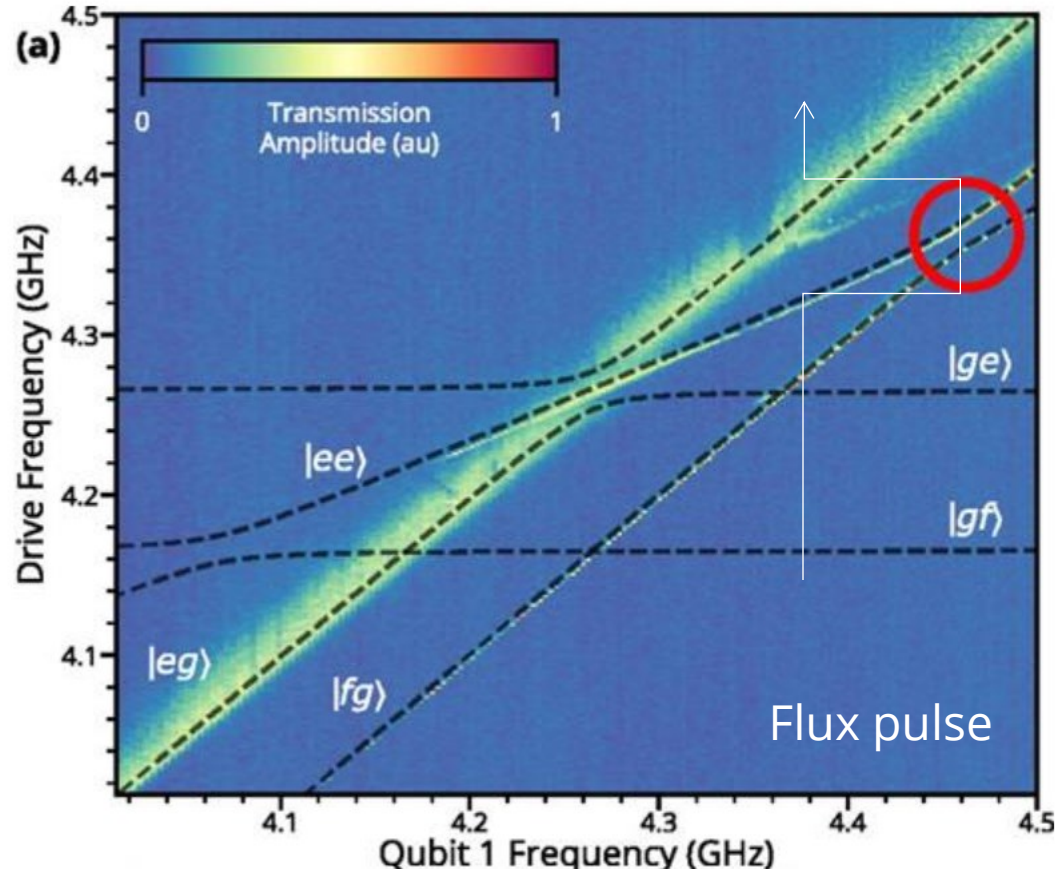
Half swap



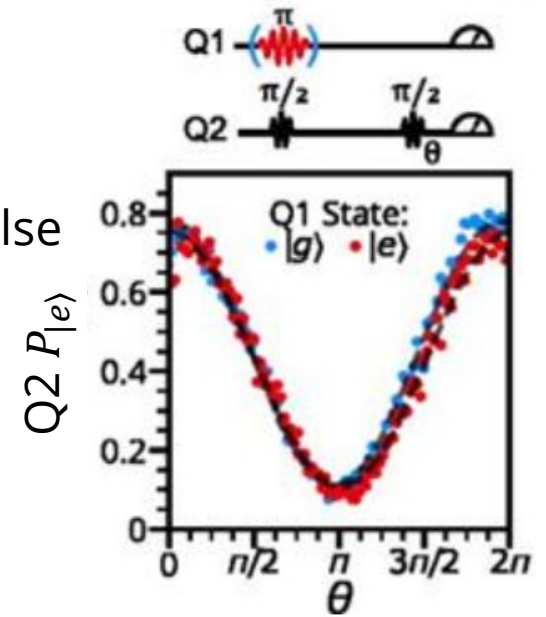
# Examples of two qubit gates : CZ gate



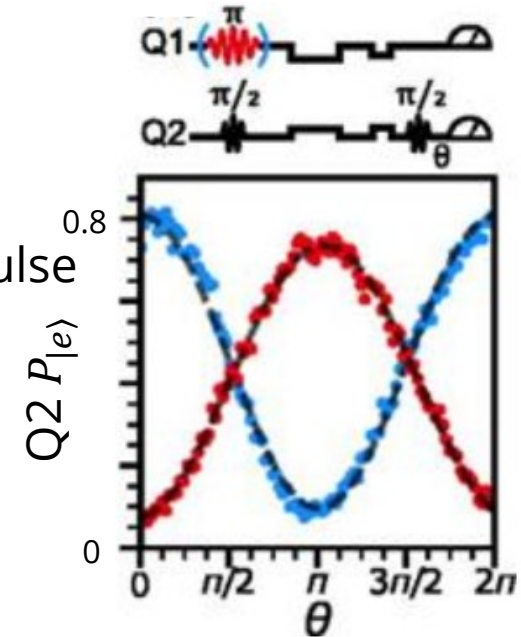
$|gg\rangle \rightarrow |gg\rangle$   
 $|ge\rangle \rightarrow |ge\rangle$   
 $|eg\rangle \rightarrow |eg\rangle$   
 $|ee\rangle \rightarrow |fg\rangle \rightarrow e^{i\phi}|ee\rangle$



No flux pulse



With flux pulse



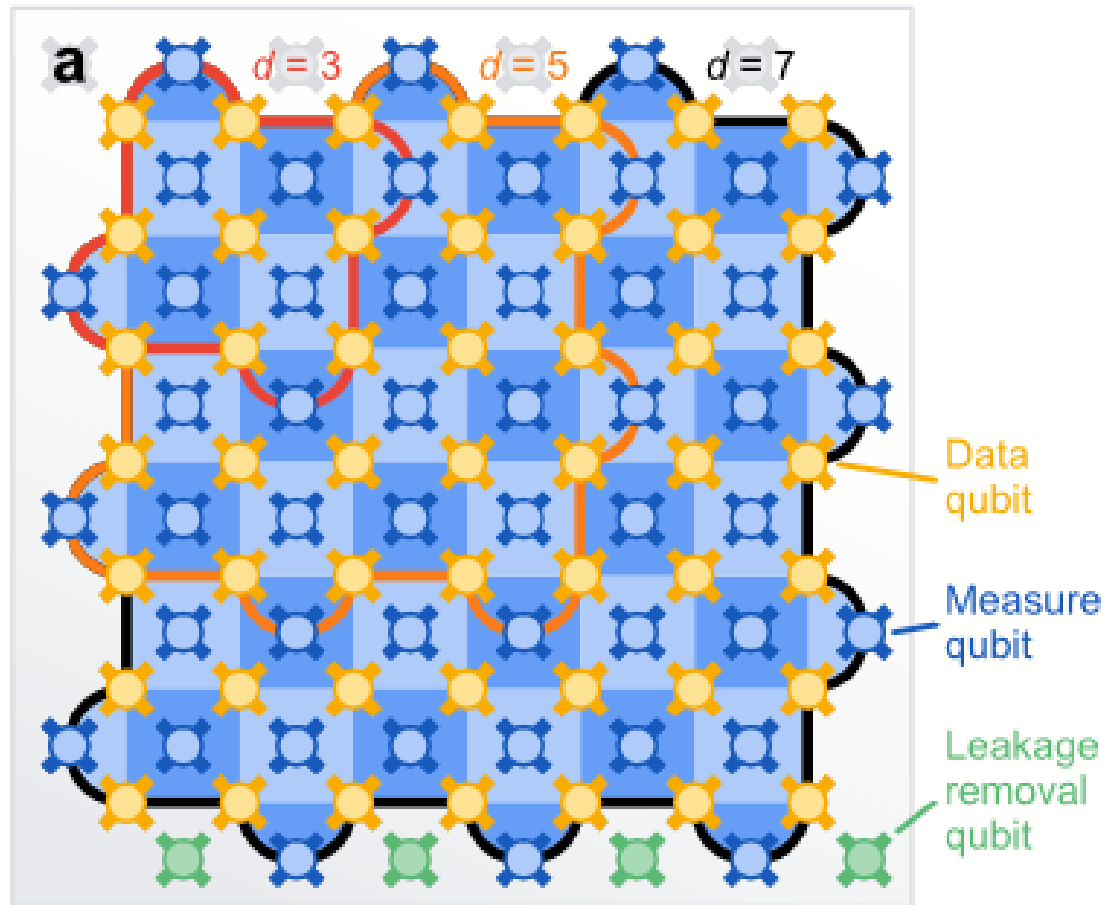
**Controlled Z (CZ)**



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

# Only hope for viability : quantum error correction

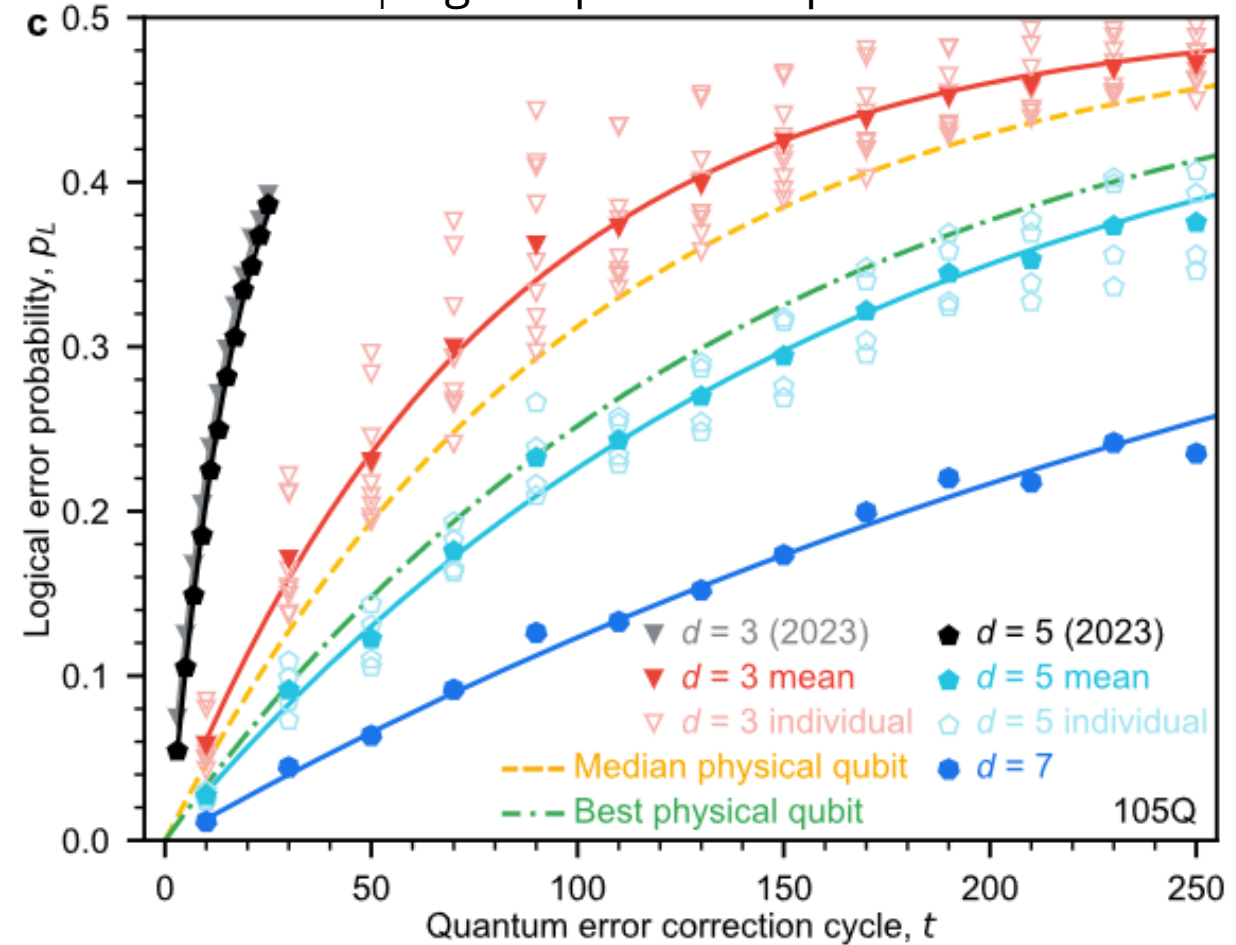
Processor with 105 qubits  
≡ 1 logical qubit



Use stabilizers for error decoding on data qubits

$T_1$  physical qubit : 89  $\mu$ s

$T_1$  logical qubit : 290  $\mu$ s



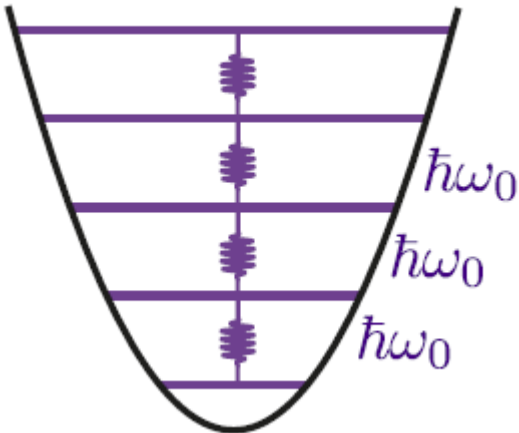
arXiv:2408.13687,  
Google Quantum AI

1 cycle = 1.1  $\mu$ s

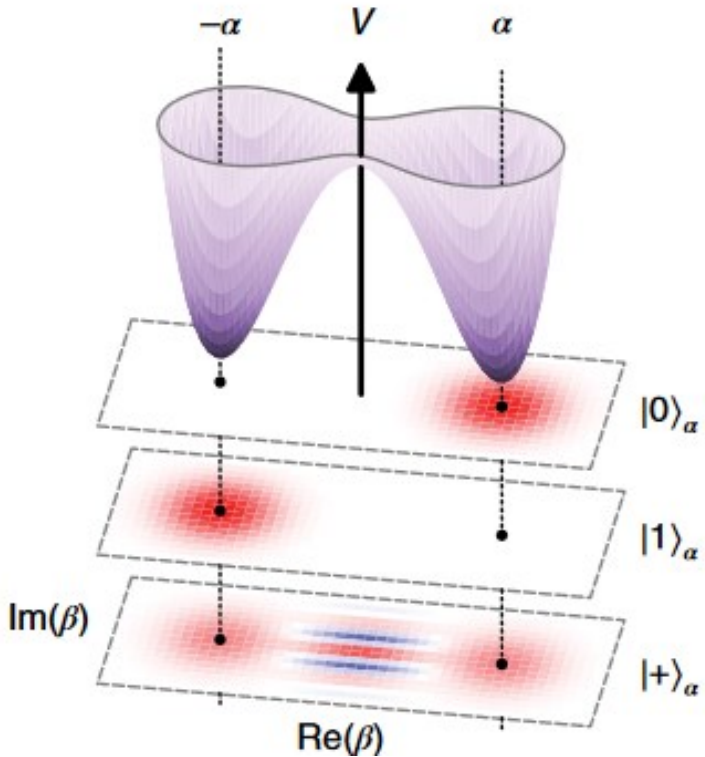
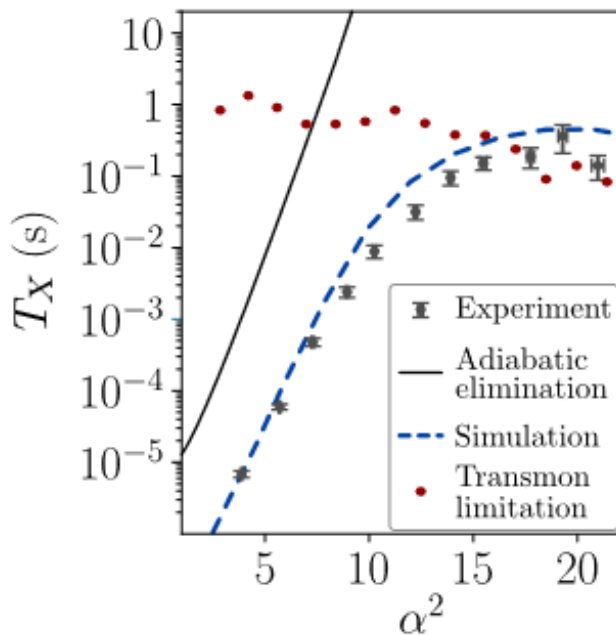
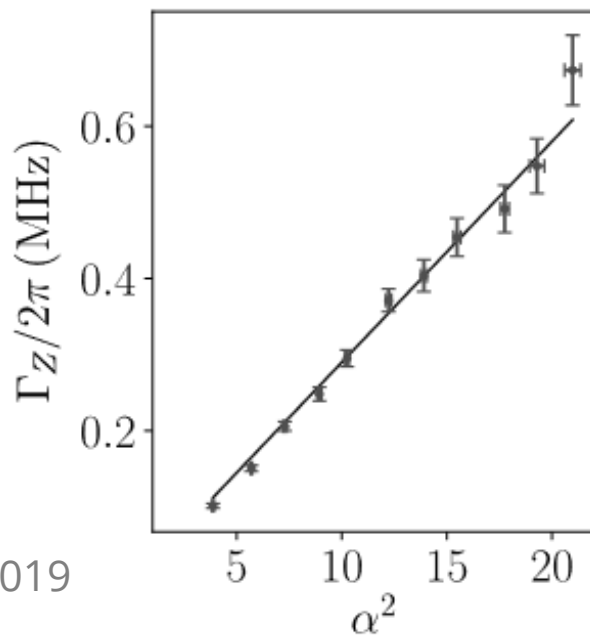
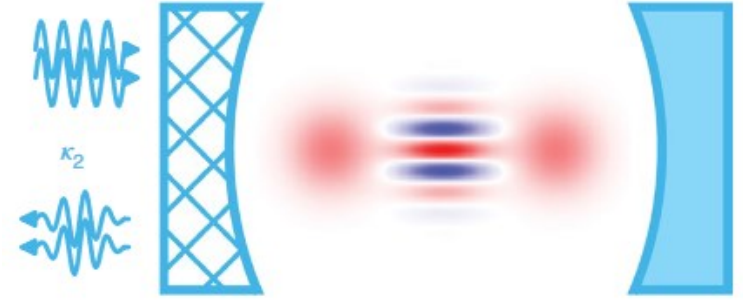


# Bosonic codes

Redundancy given by usage of multiple Fock states

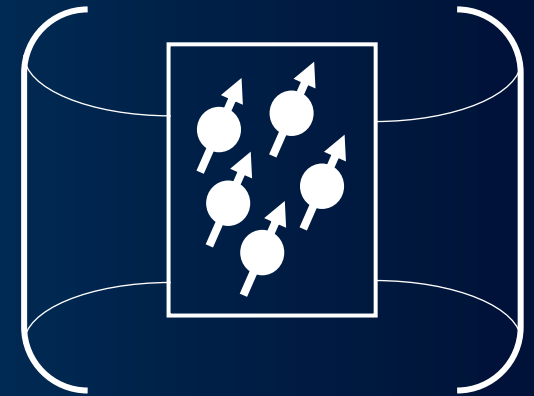
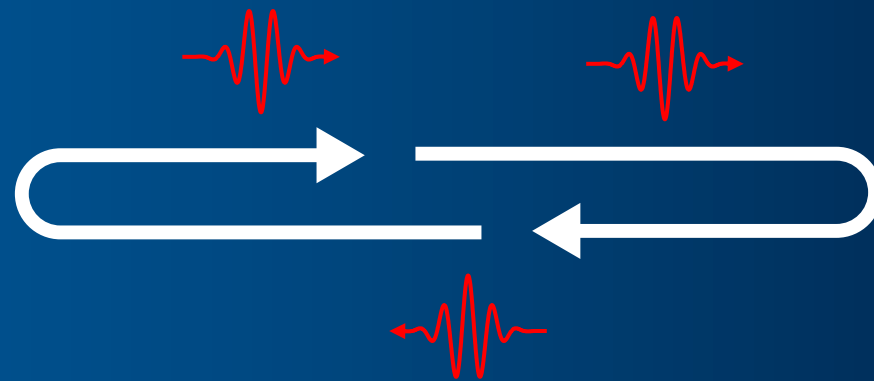
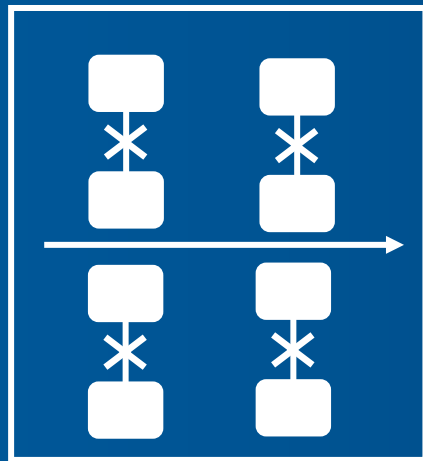


One example of encoding:  
 $|0\rangle_L = |\alpha\rangle$   
 $|1\rangle_L = |-\alpha\rangle$   
 $|+\rangle_L = |\alpha\rangle + |-\alpha\rangle = \sum_i c_i |2i\rangle$   
 $|-\rangle_L = |\alpha\rangle - |-\alpha\rangle = \sum_i c_i |2i + 1\rangle$



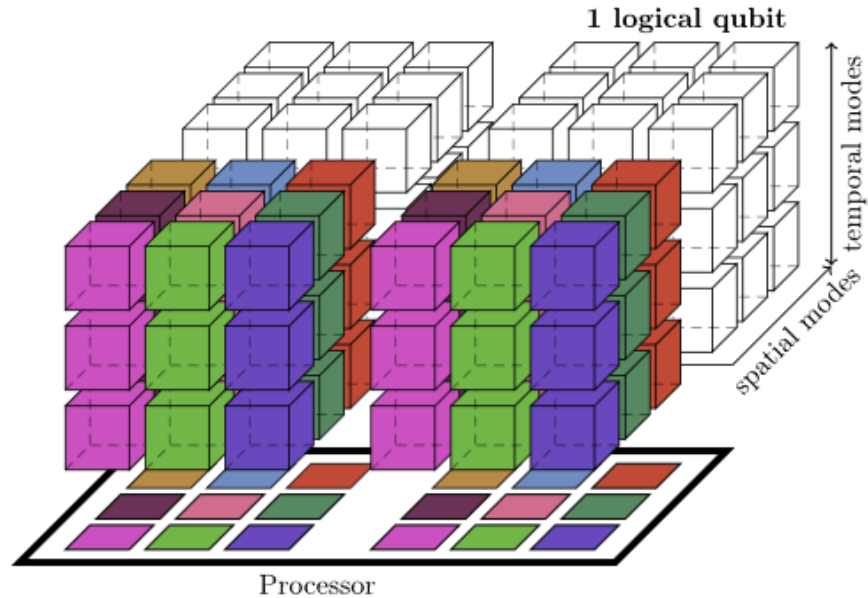
# Implementing a quantum memory at microwave frequencies with Bismuth donors in silicon

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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)

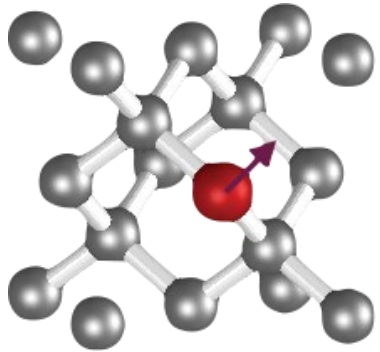
Quantum memory hierarchies: Efficient designs to match available parallelism in quantum computing, Thaker et al., Symposium on Computer Architecture (2006).

Enable long-distance communication



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

# Ideal candidate : Bismuth donors in silicon

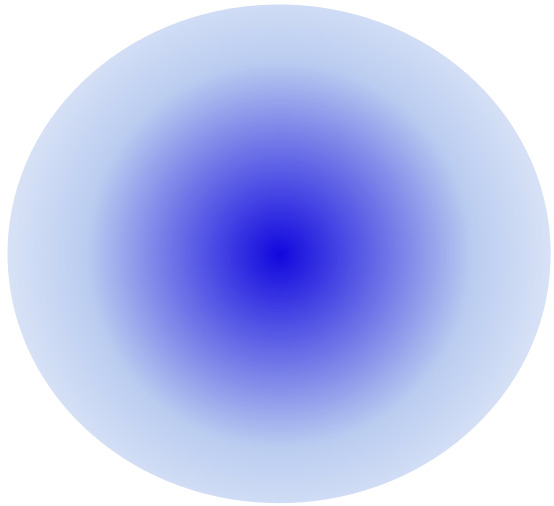


$^{209}\text{Bi}$

Nuclear spin  
 $I = 9/2$

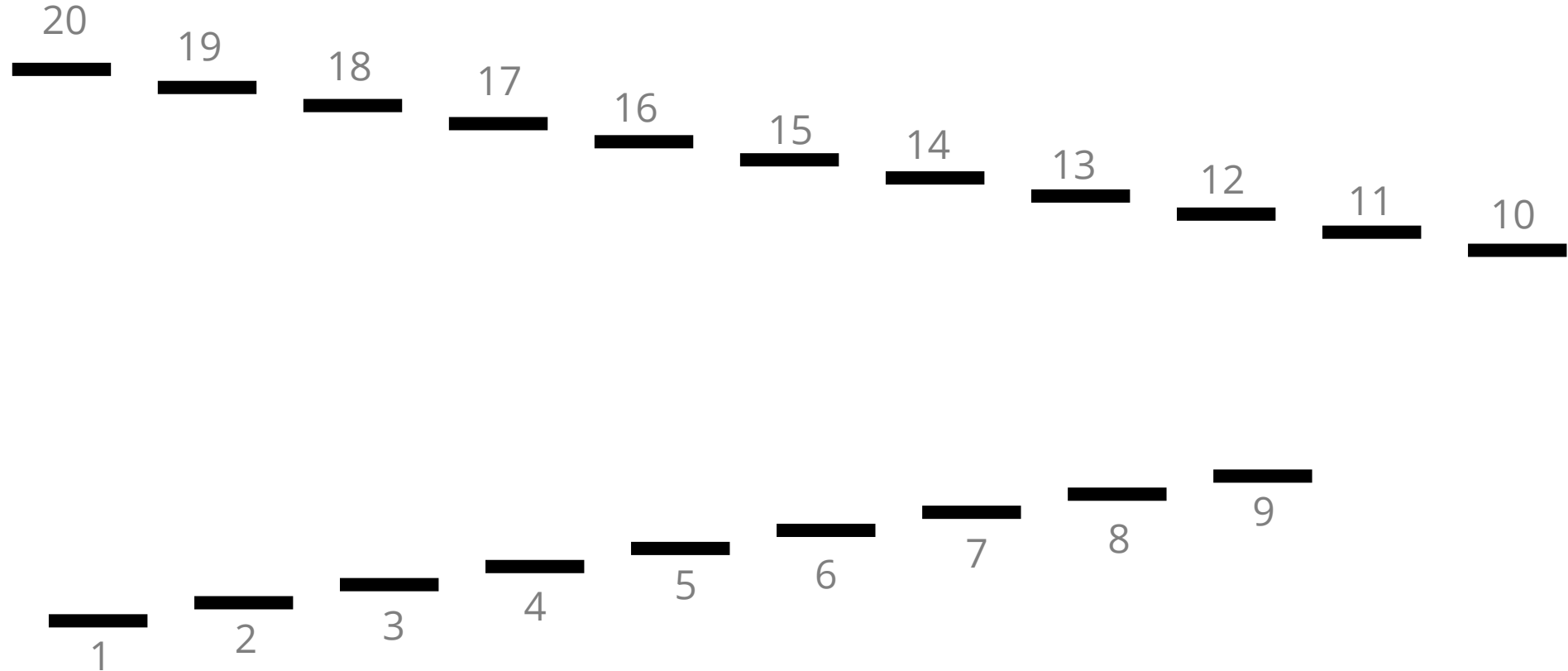


# Ideal candidate: Bismuth donors in silicon



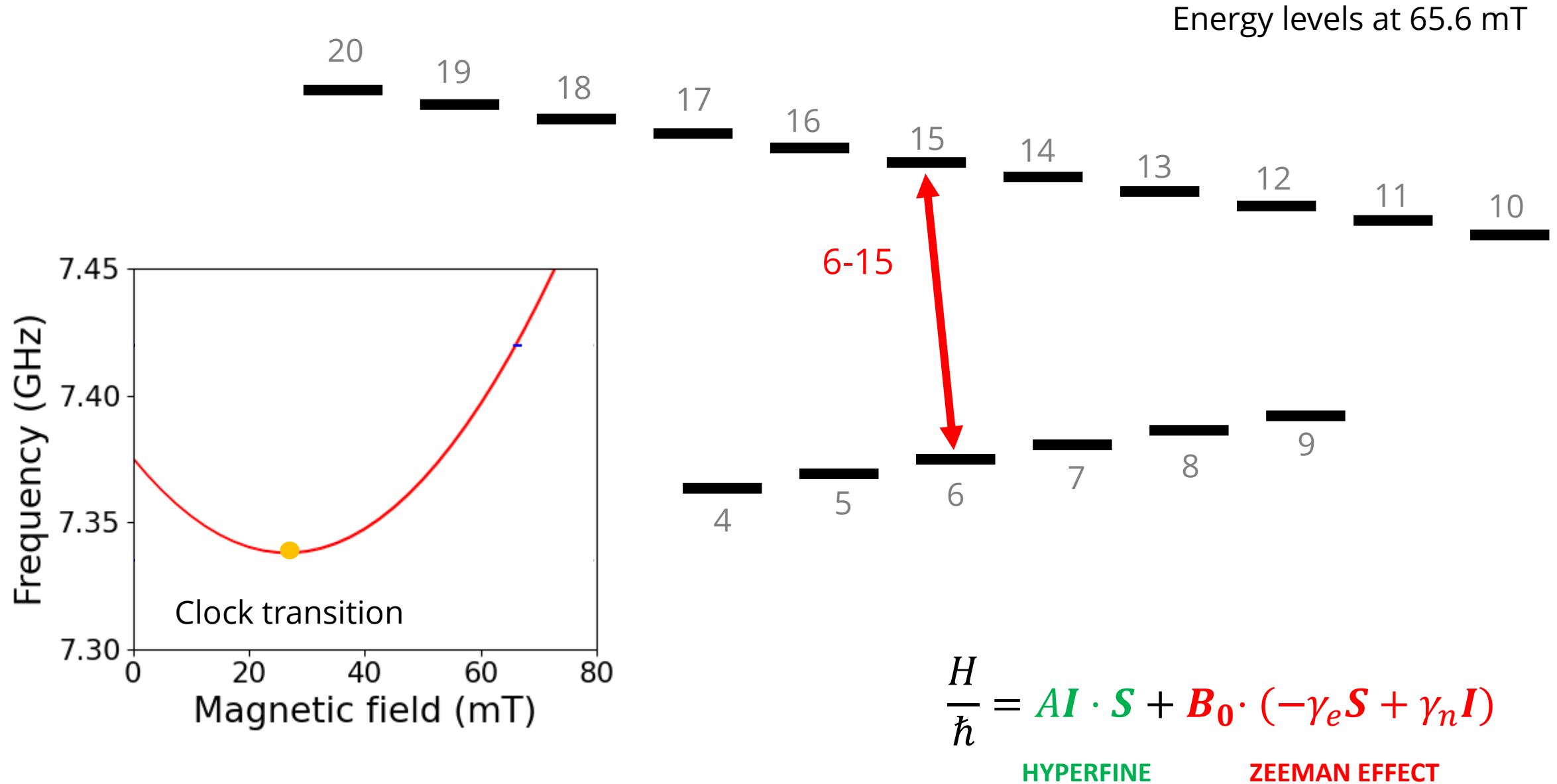
Nuclear spin  
 $I = 9/2$

Electronic spin  
 $S = 1/2$

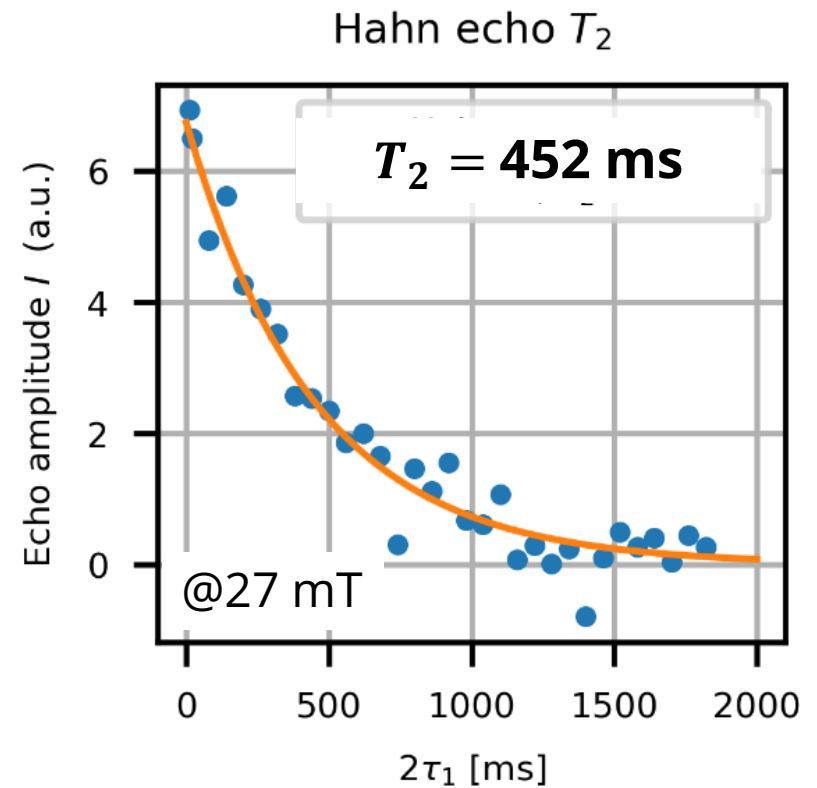
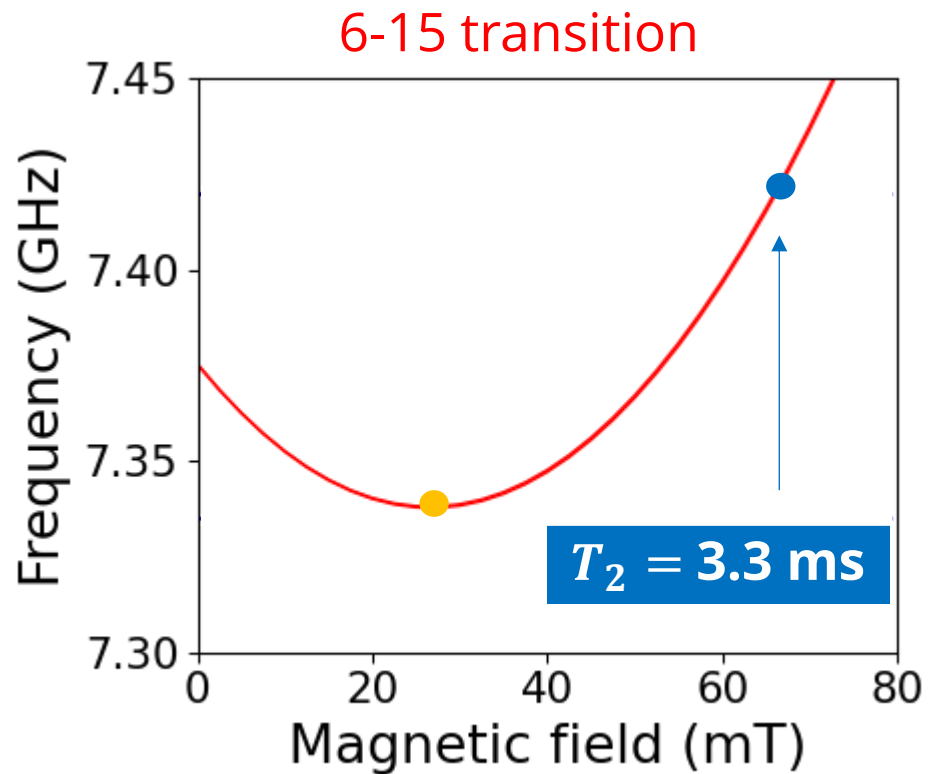
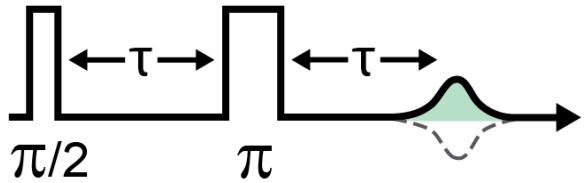


$$\frac{H}{\hbar} = \underbrace{AI \cdot \mathbf{S}}_{\text{HYPERFINE}} + \underbrace{\mathbf{B}_0 \cdot (-\gamma_e \mathbf{S} + \gamma_n \mathbf{I})}_{\text{ZEEMAN EFFECT}}$$

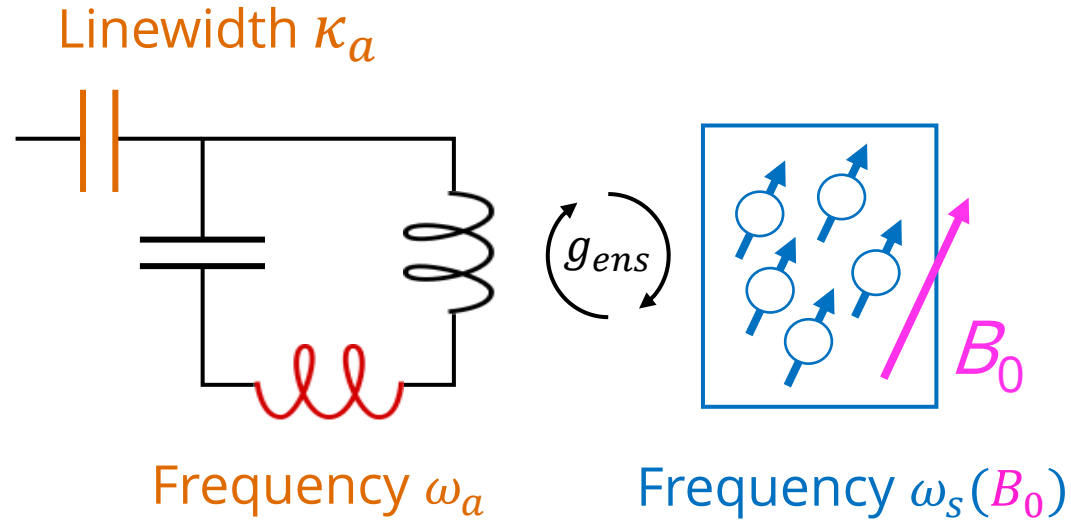
# Ideal candidate: Bismuth donors in silicon



# Bismuth donors in silicon



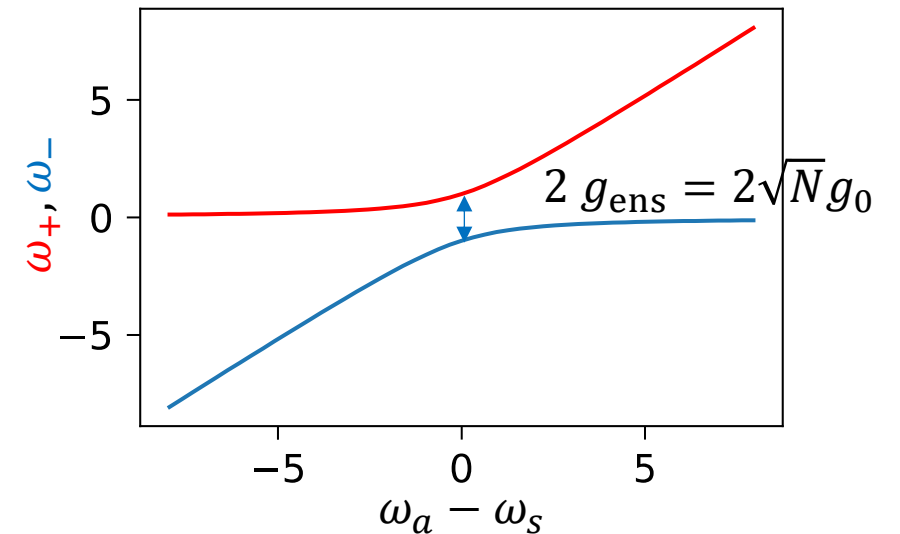
# Spin ensemble coupled to a superconducting resonator



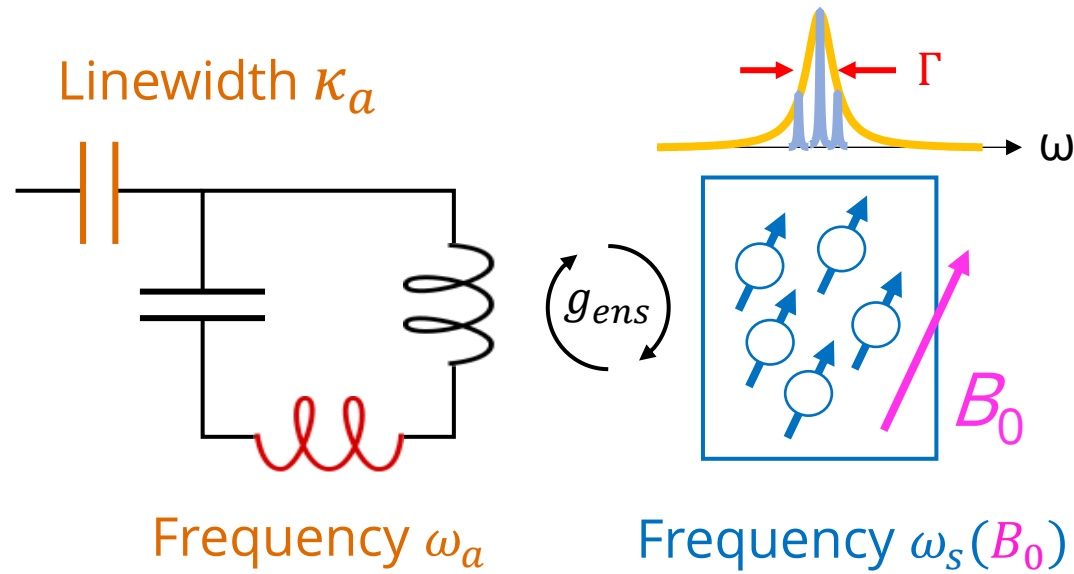
$$H = \mu (\vec{B}_0 + \vec{B}_1) \cdot \vec{S}$$

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

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

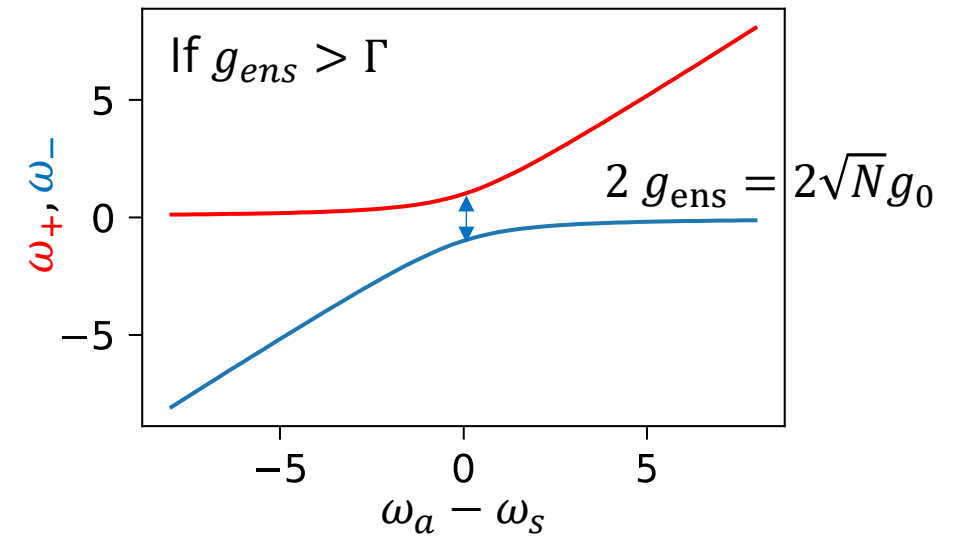


# Spin ensemble coupled to a superconducting resonator

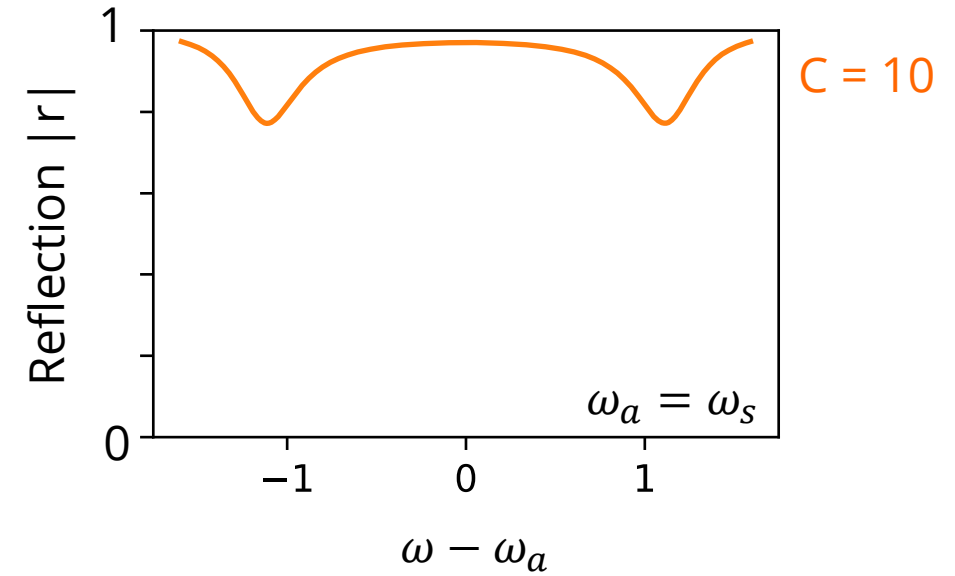
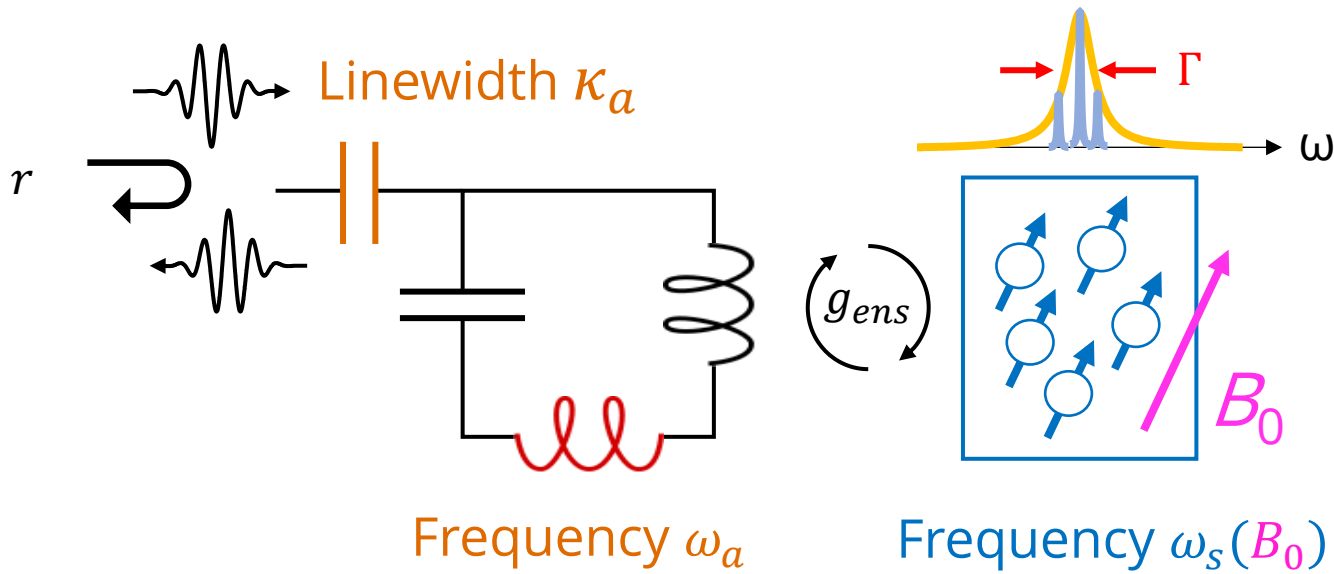


Regime of interaction given by cooperativity

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



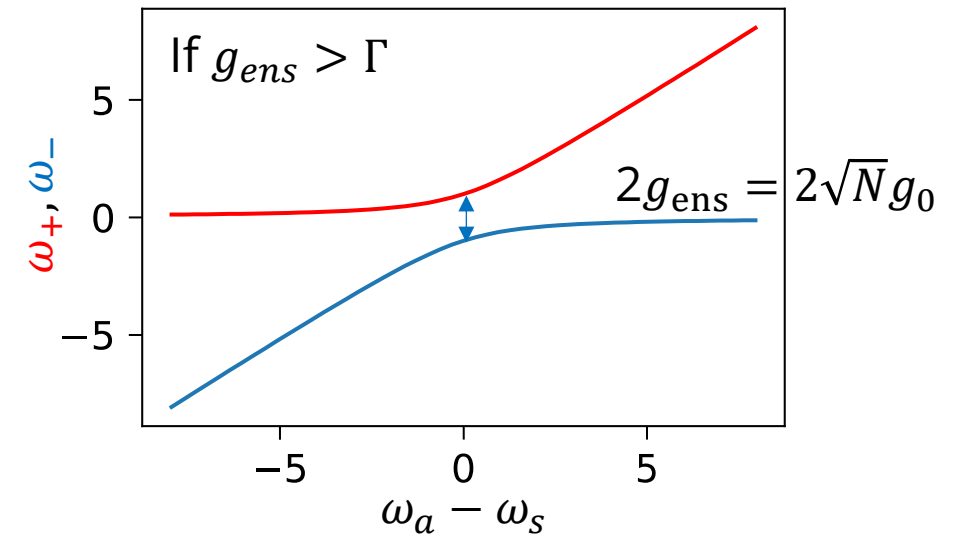
# Spin ensemble coupled to a superconducting resonator



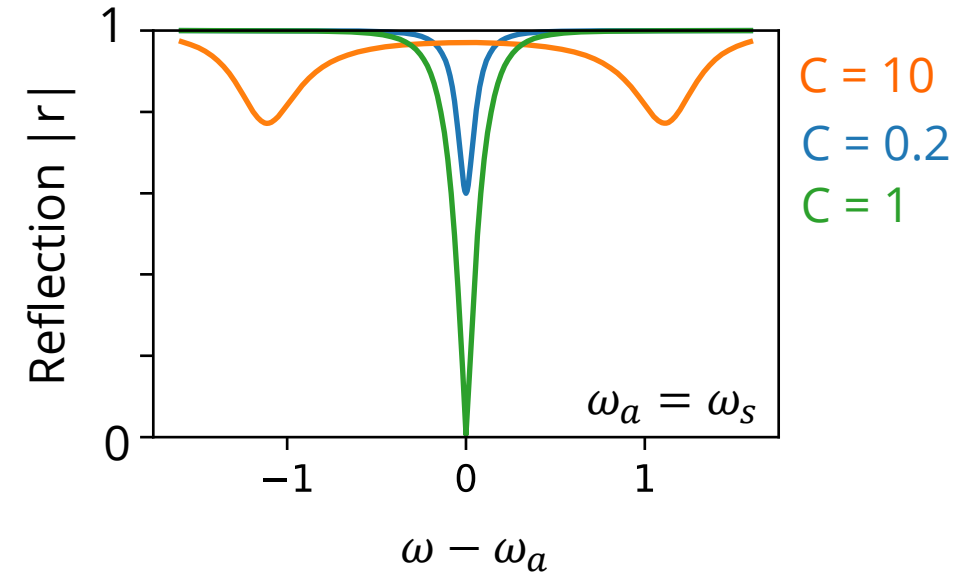
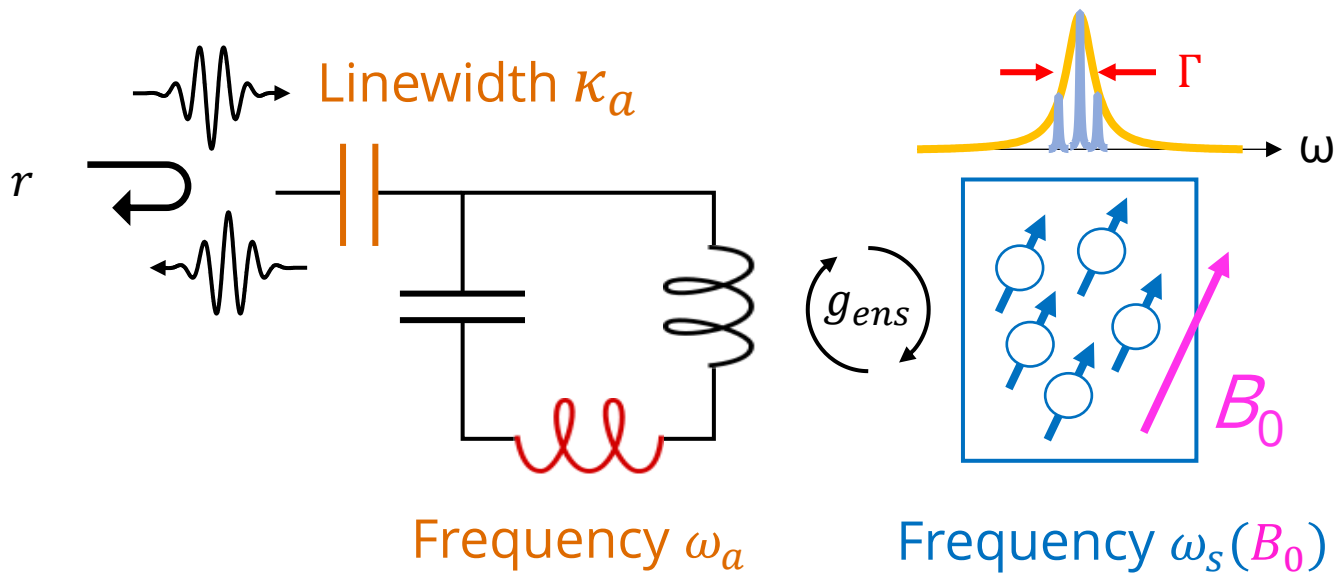
High cooperativity

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

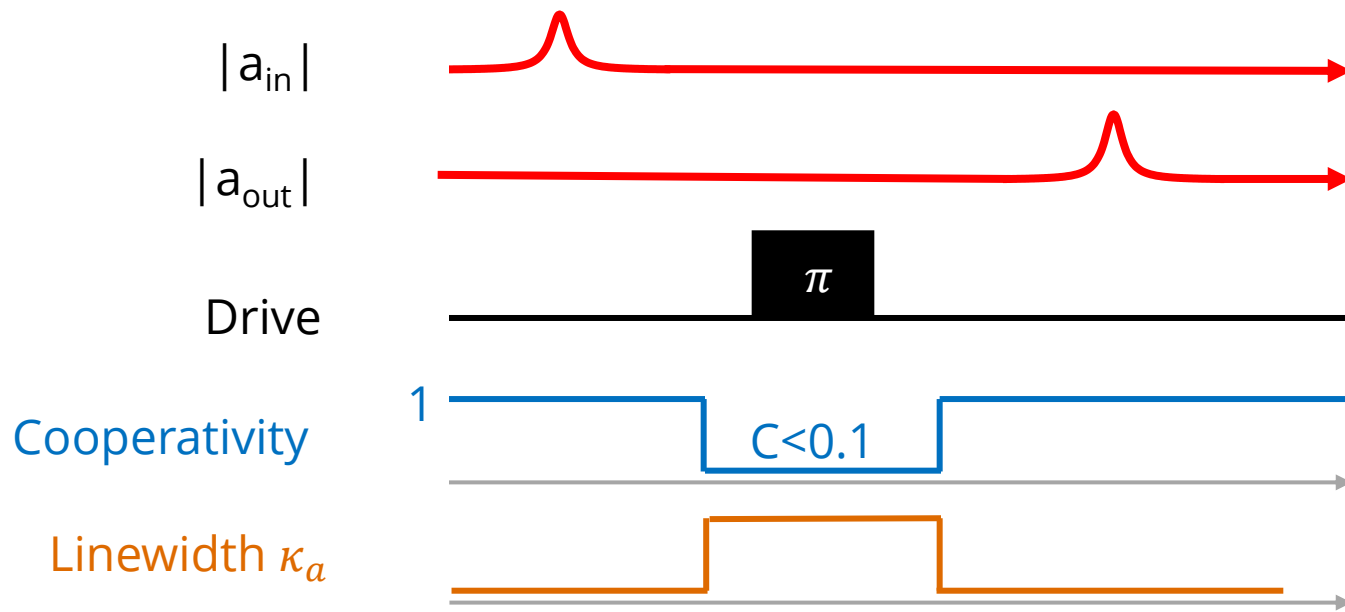
No coherent swapping

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

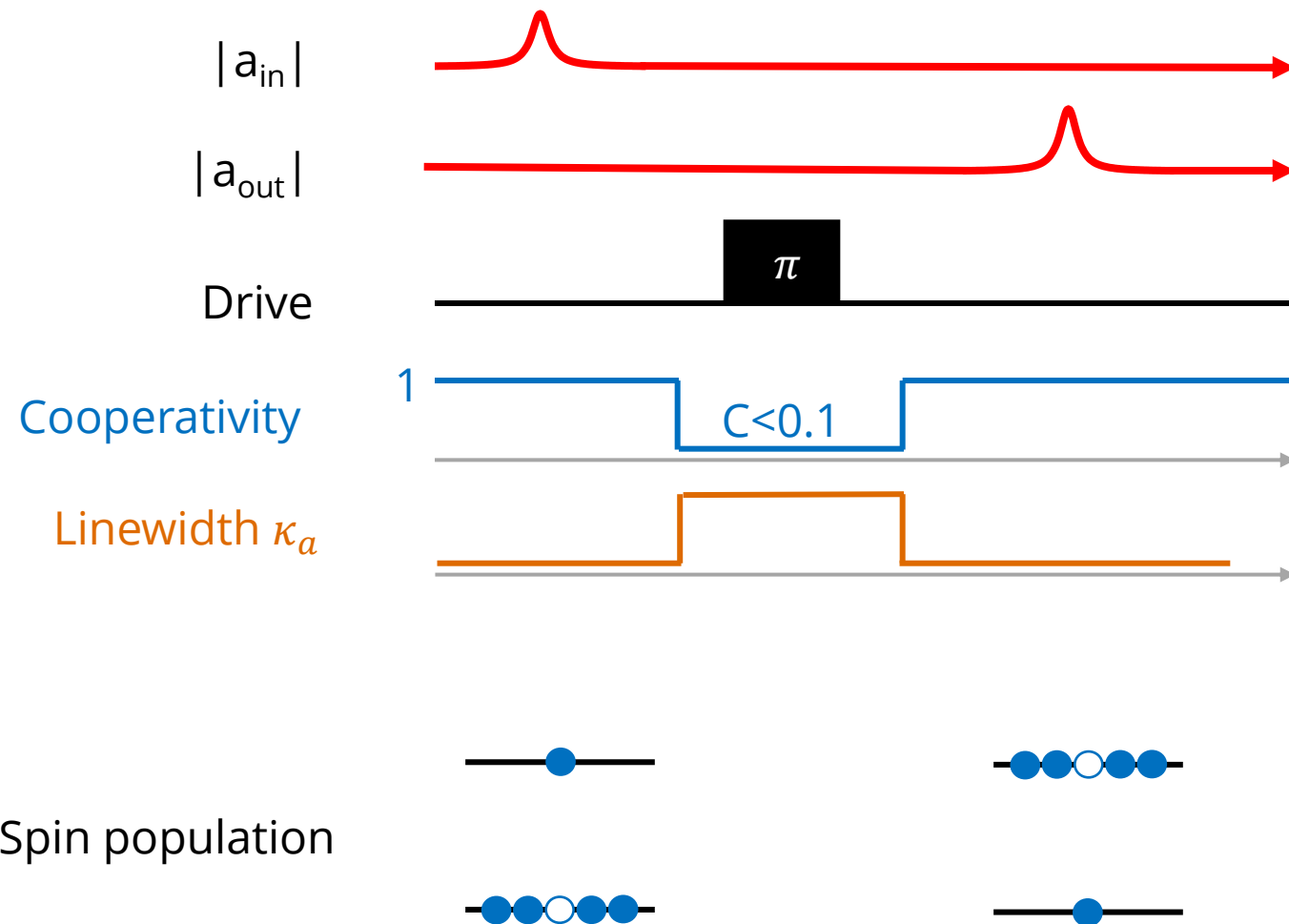
How to store an incoming arbitrary wave packet and retrieve it?





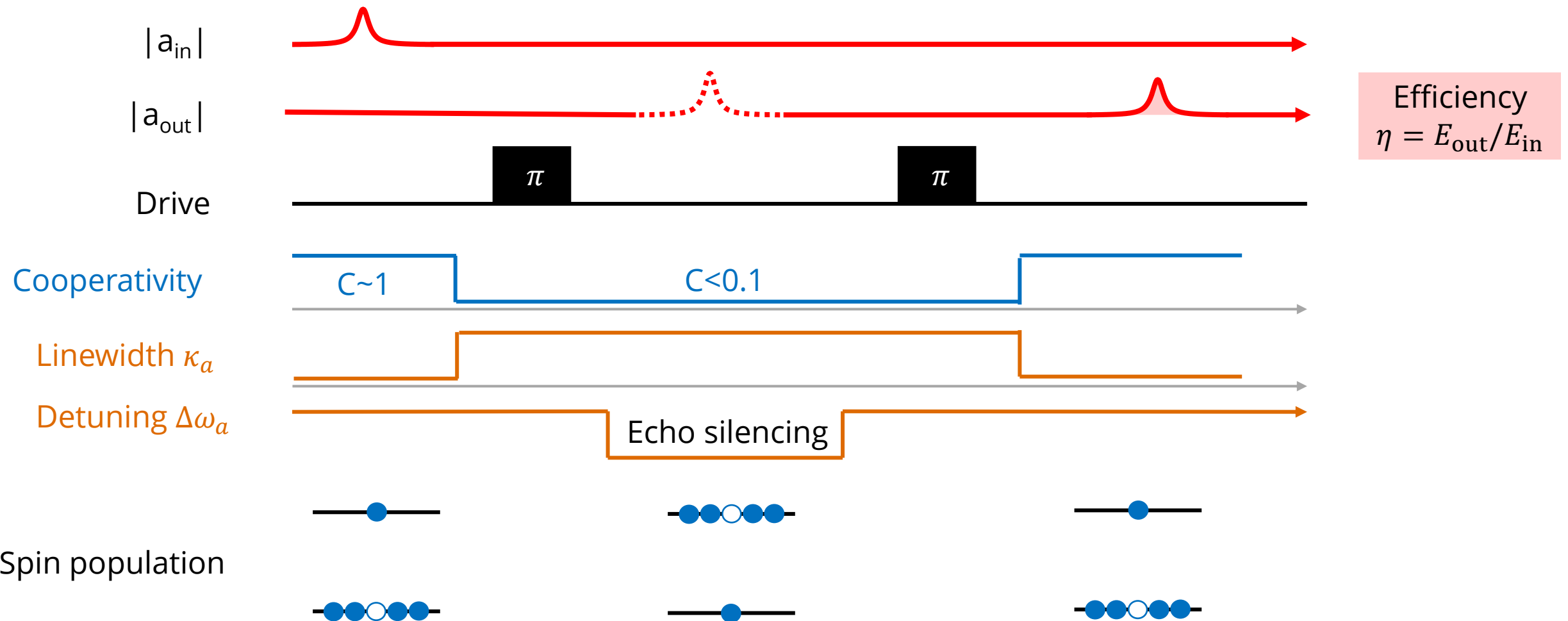
# Spin ensemble as a memory: protocol

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



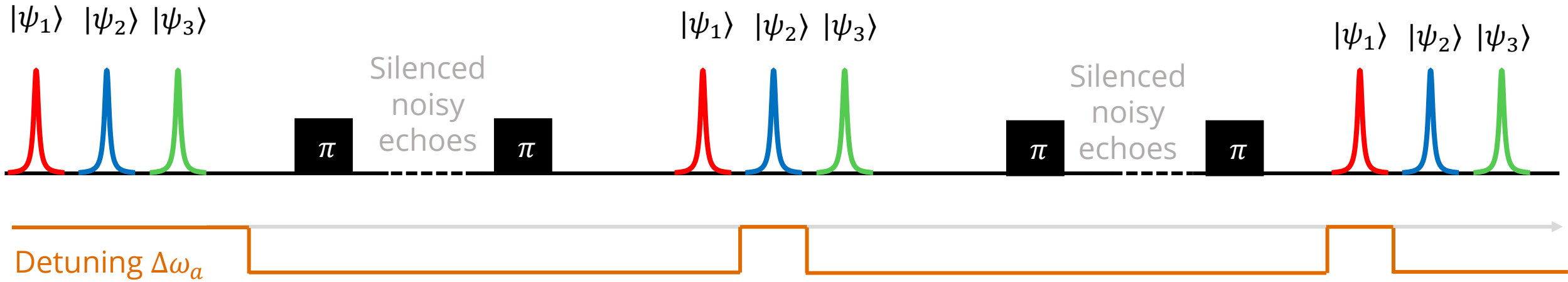
# Spin ensemble as a memory: protocol

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



# Multimode?

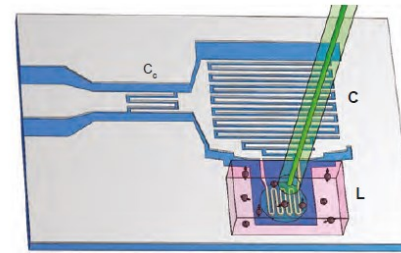
Random access to multiple stored states by echo silencing... except on retrieval !



# 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



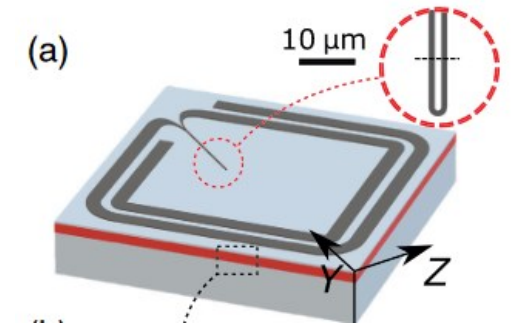
Grezes et al., *PRA* (2015)

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)

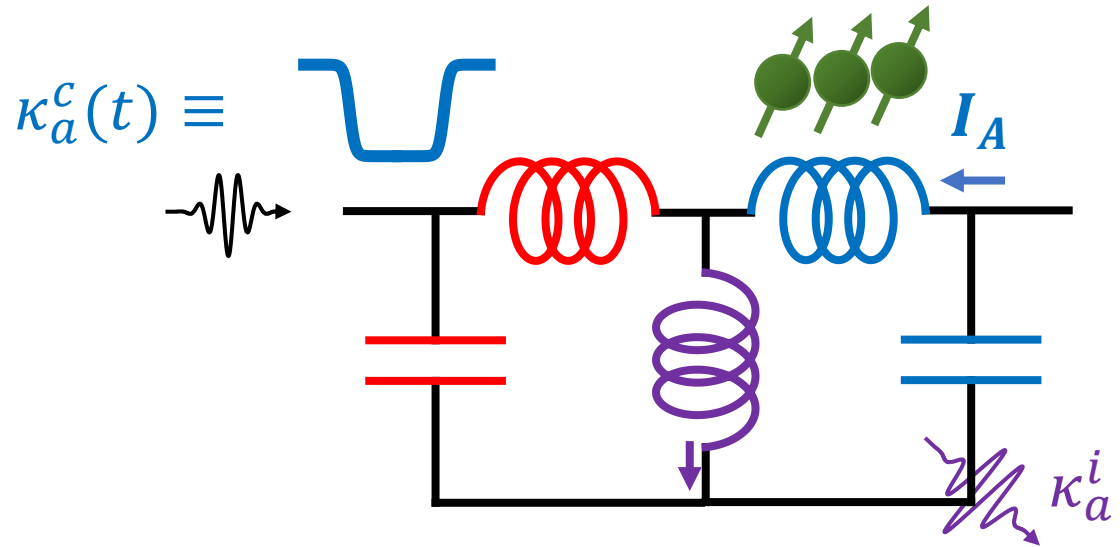
Efficiency 3 %

$$C = 0.06$$

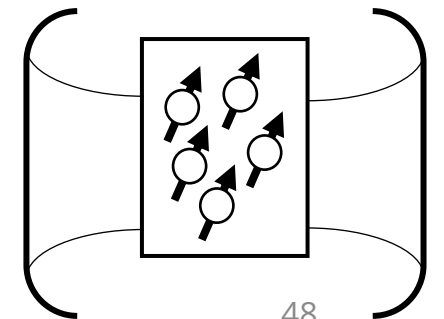
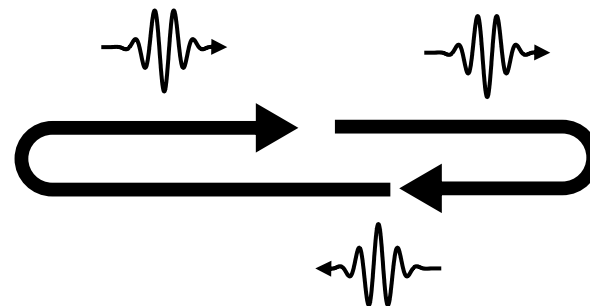
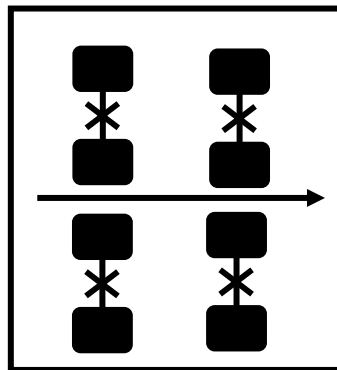
$$T_2 = 2 \text{ ms}$$

# Perspective

Running a protocol maximizing efficiency for classical pulses



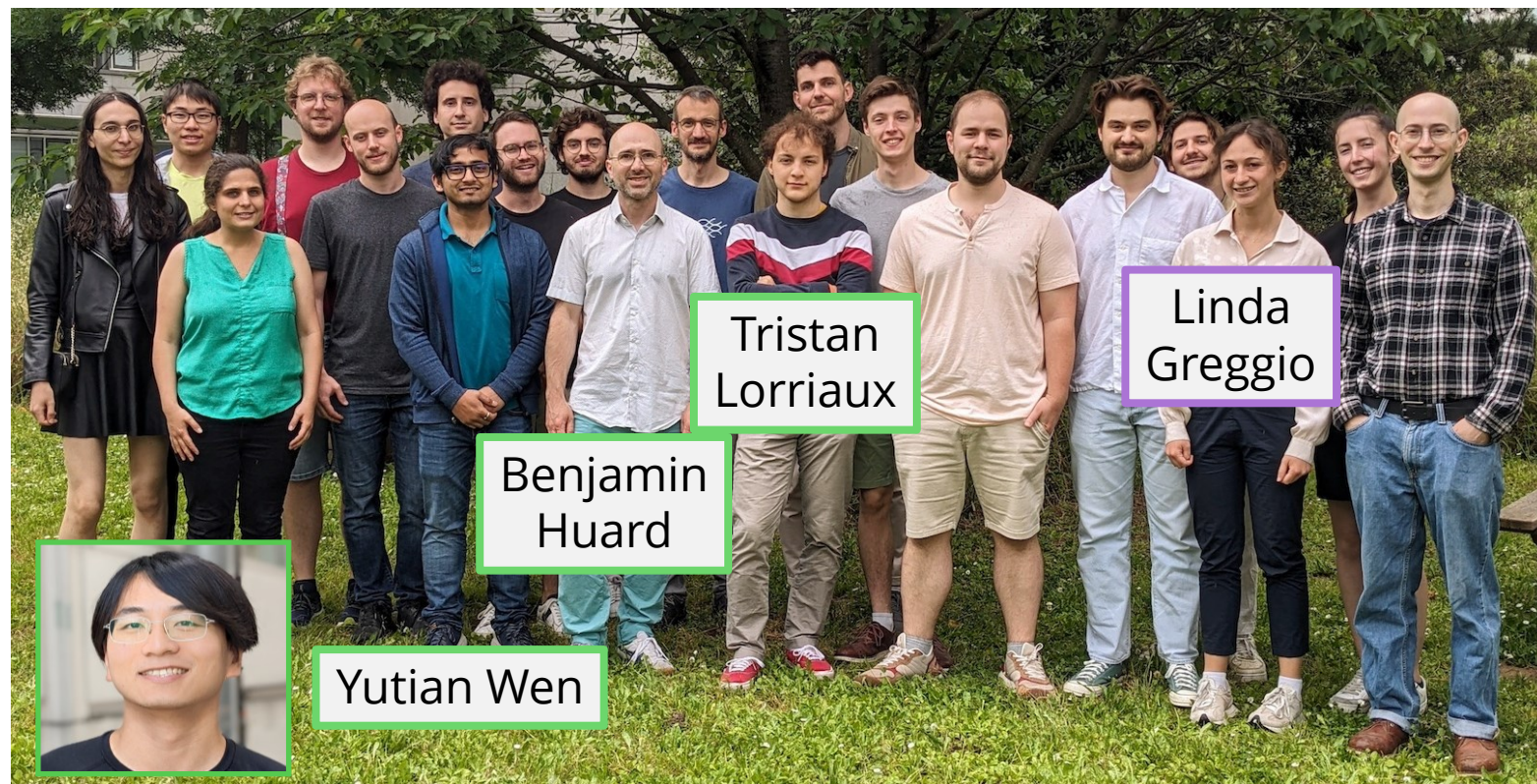
Building a bidirectional link between qubit and processor





# Acknowledgments

Quantum circuit group, summer 2024



M. Mirrahimi  
Inria Paris



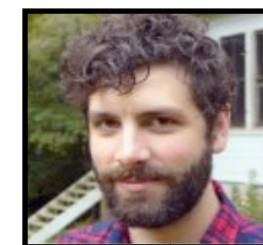
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