Vers l'ordinateur quantique

un qubit de chat de Schrödinger à long temps de vie

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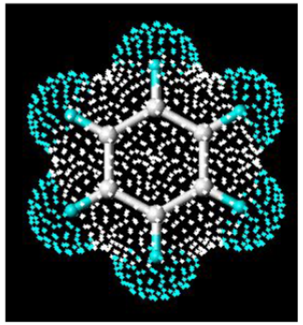
Quantum Mechanics of Many-Electron Systems.

By P. A. M. Dirac, St. John's College, Cambridge.

(Communicated by R. H. Fowler, F.R.S.—Received March 12, 1929.)

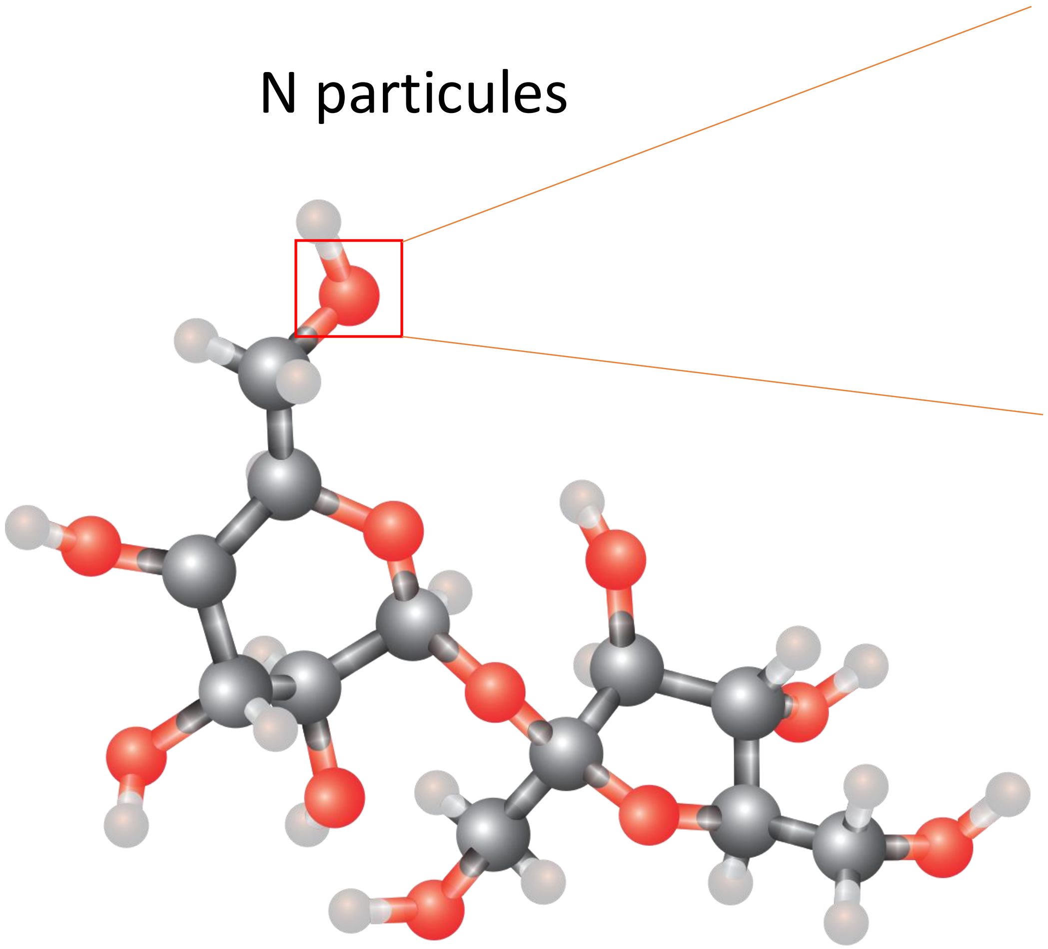
« Ainsi, les lois d'une grande partie de la physique et de toute la chimie sont entièrement connues, et la difficulté est uniquement que l'application de ces lois engendre des équations beaucoup trop compliquées à résoudre. »

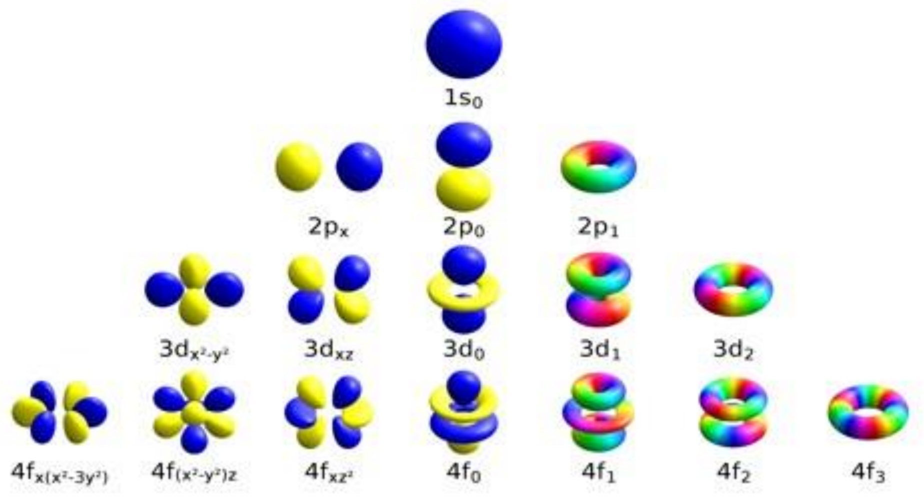


$$\mathcal{H}\left|\psi\right\rangle = E\left|\psi\right\rangle$$

Le problème de la dimension exponentielle

N particules





K orbitales par particule

Espace de Hilbert de dimension $D = K^N$

e.g. $K = 10, N = 20 \;\rightarrow D = 10^{20}$

On aurait besoin de toutes les ressources de stockage d'information existante pour écrire cette fonction d'onde !

La synthèse d'engrais

$N_2 + 3\,H_2 \rightarrow 2\,NH_3$ → Fertilizer

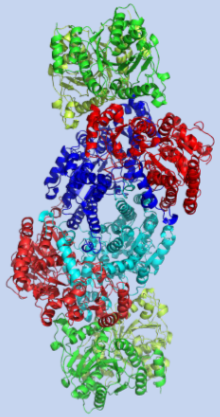
Humans: Haber Process

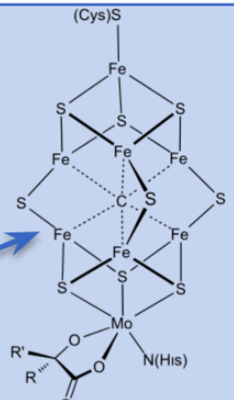
400°C & 200 atm

1-2% of ALL energy on earth, used on Haber process

Nature: Nitrogenase

25° C & 1 atm





"FeMoco"

Beyond all current classical methods

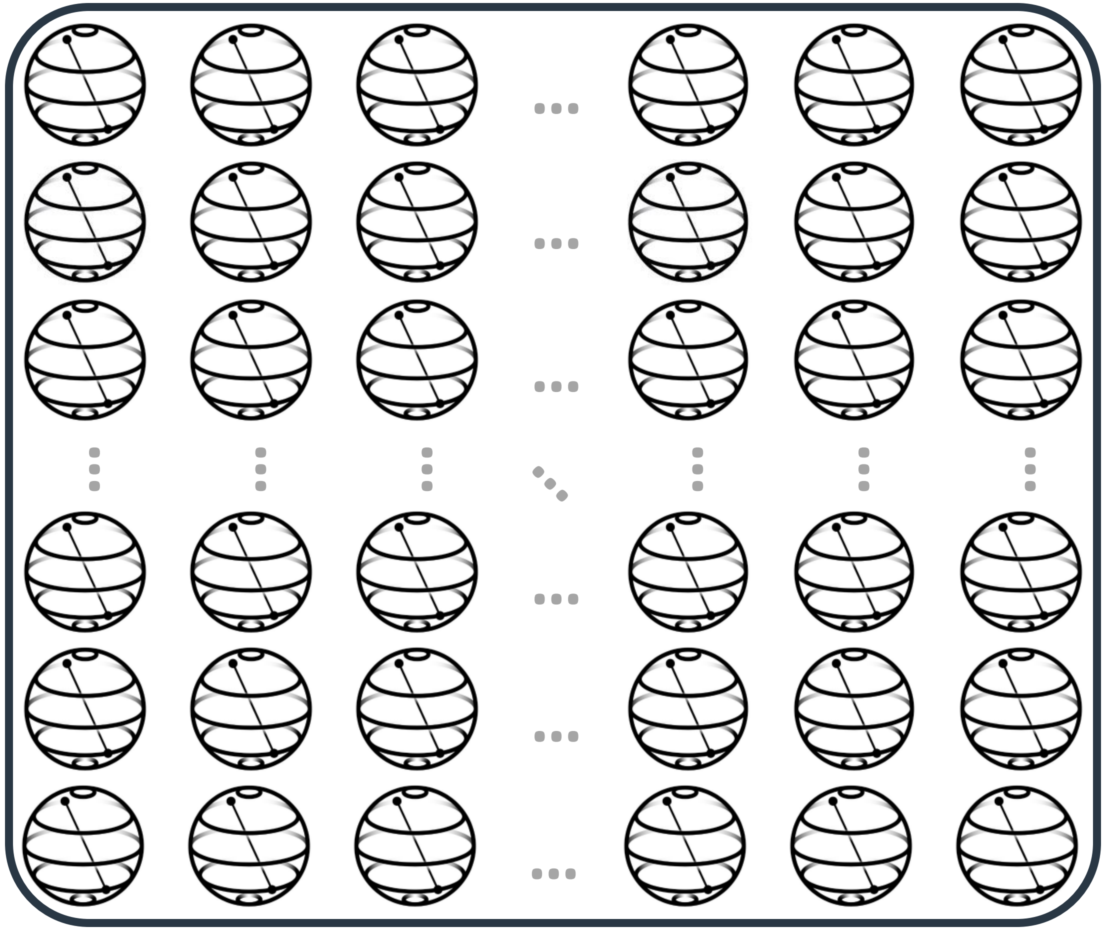
Both electronic structure and substrate attachment almost totally unknown

Classically – No clear path to accurate solution
Quantum Mechanically – 150-200 logical qubits for solution

Jarrod McClean Google Quantum AI, Reiher et al. PNAS vol. 114 no. 29 (2017)

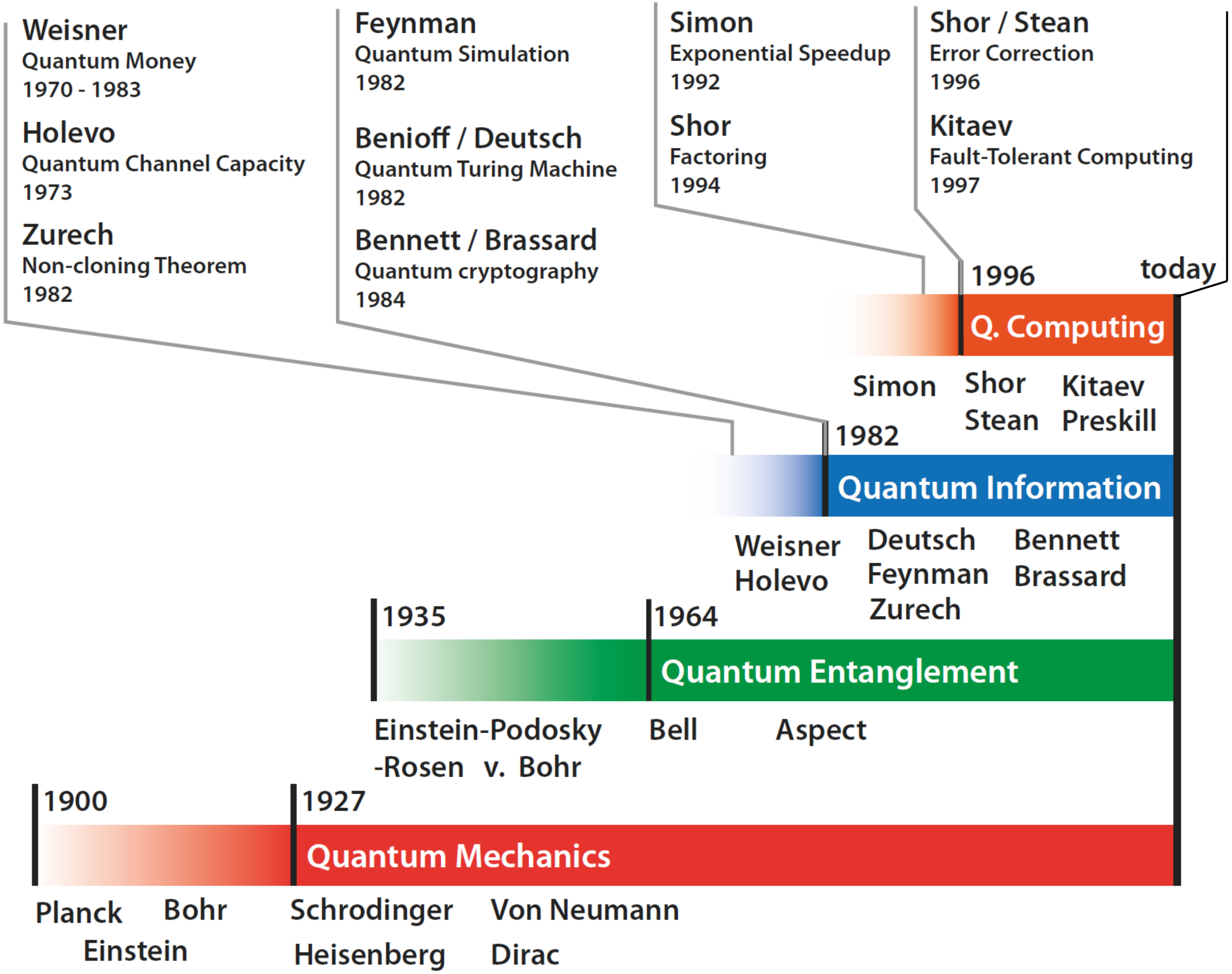
L’ordinateur quantique

Le bit quantique peut prendre toutes les positions d’un point sur une sphère



Ces bits quantiques peuvent être intriqués

A brief history of quantum information



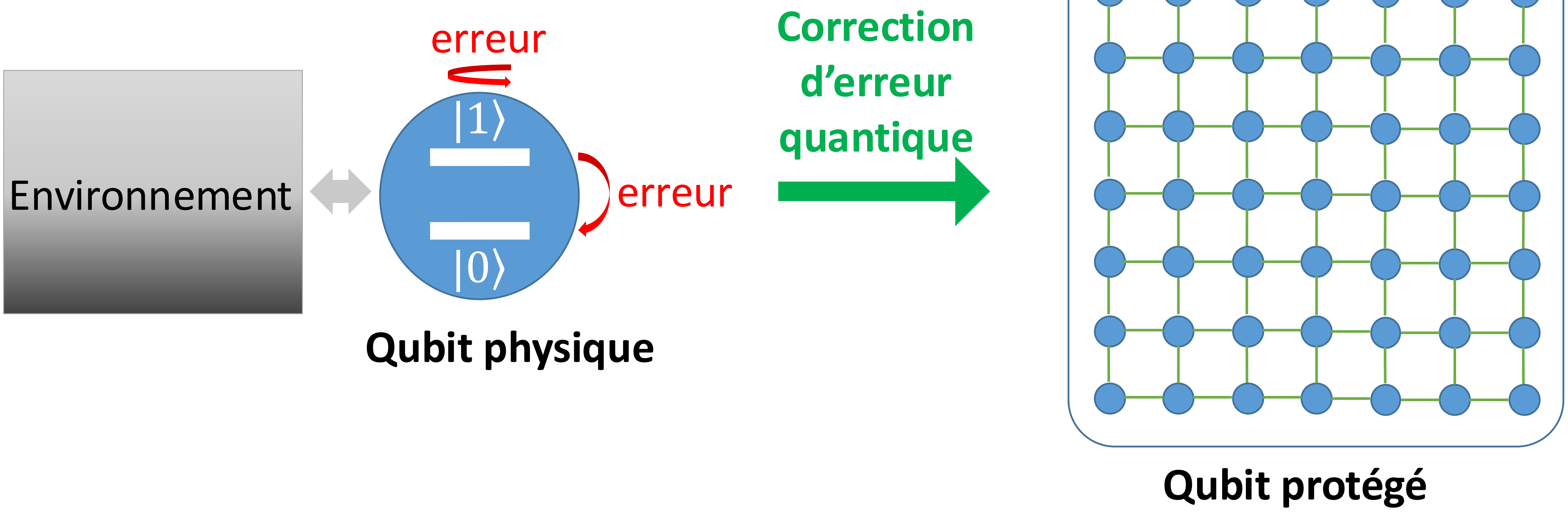
Quantum artificial intelligence
Machine learning
Variational quantum eigensolver

Quantum computing enters a new phase

"Now is an opportune time for a fruitful discussion among researchers, entrepreneurs, managers, and investors who share an interest in quantum computing."

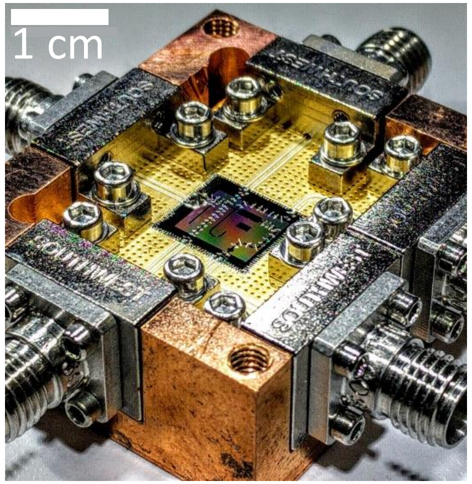
\- John Preskill 2018

Le défi majeur: protéger l'information quantique contre les erreurs

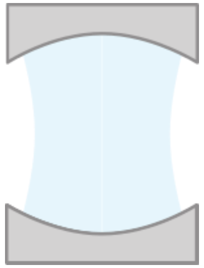


Circuits supraconducteurs

Circuits Supraconducteurs

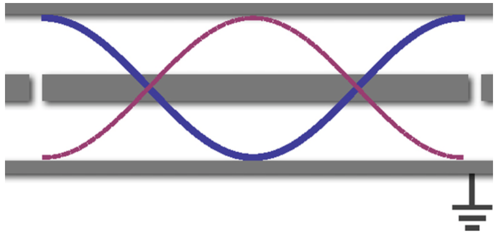


Cavité

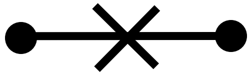


=

$f \approx 5\ \text{GHz}, \ \ Q \approx 10^{6-8}$

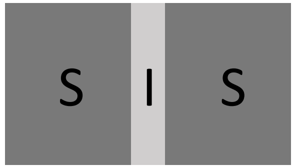


Elément non-linéaire

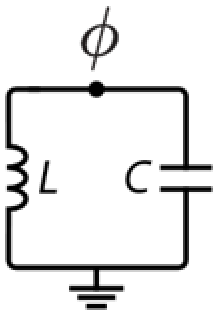


=

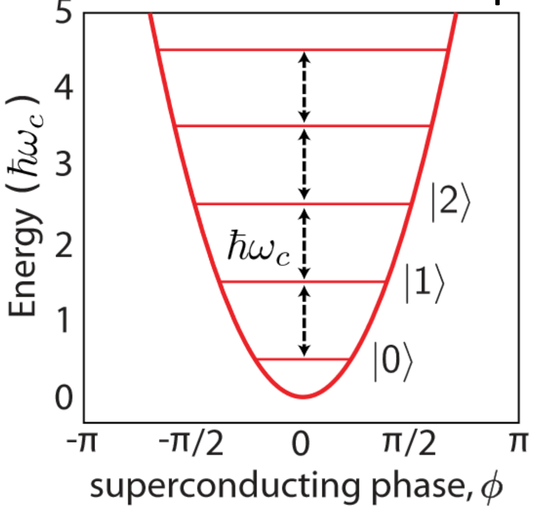
$100\ \text{nm} \times 100\ \text{nm}$



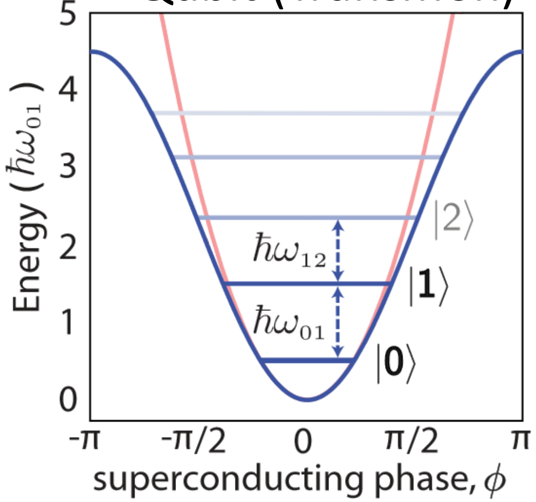
Jonction Josephson

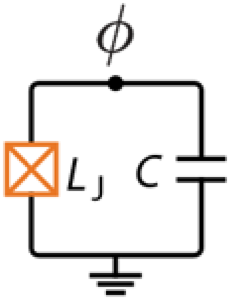


Oscillateur harmonique

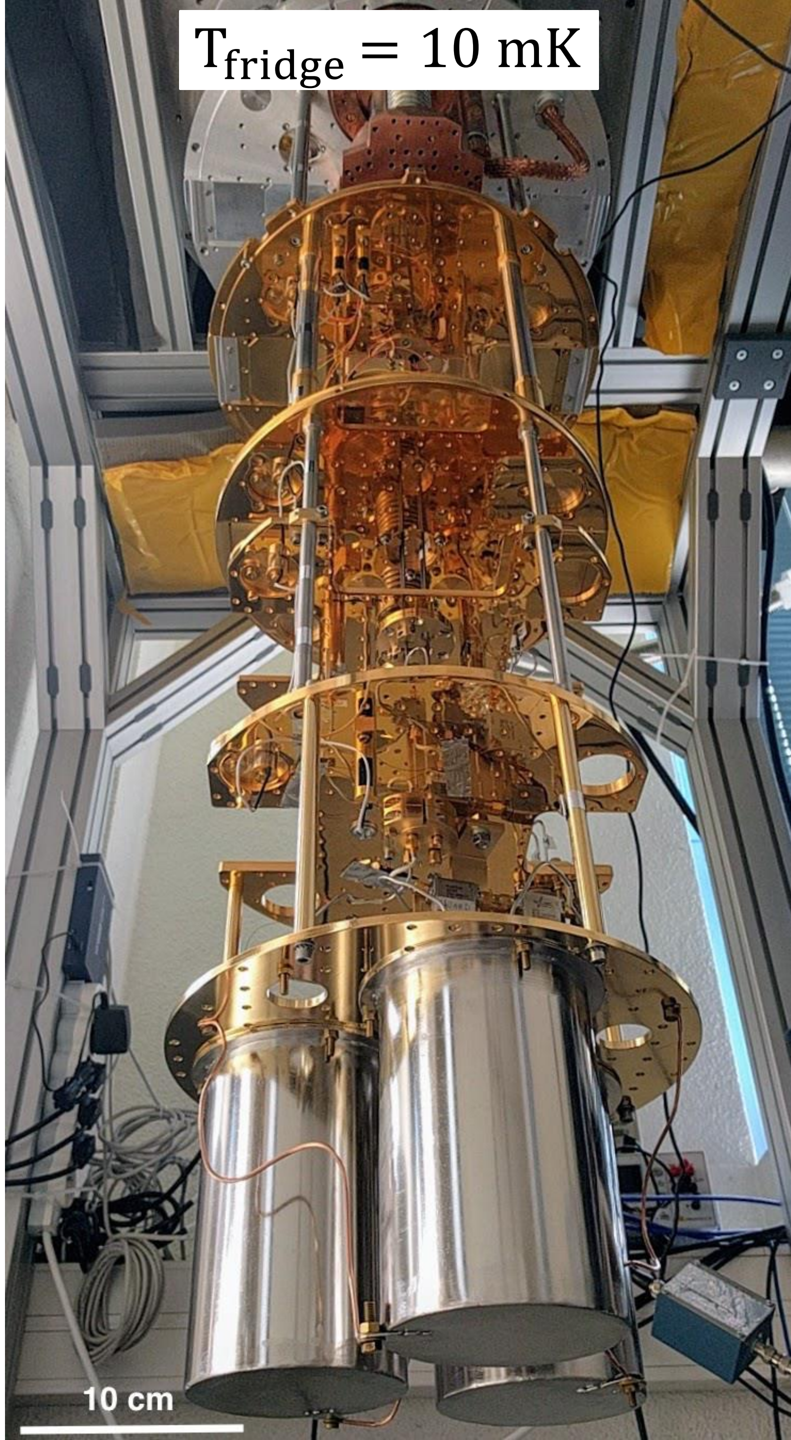


Qubit (Transmon)



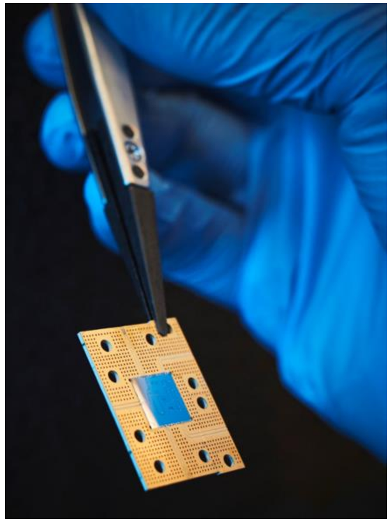


Applied Physics Reviews 6, 021318 (2019)

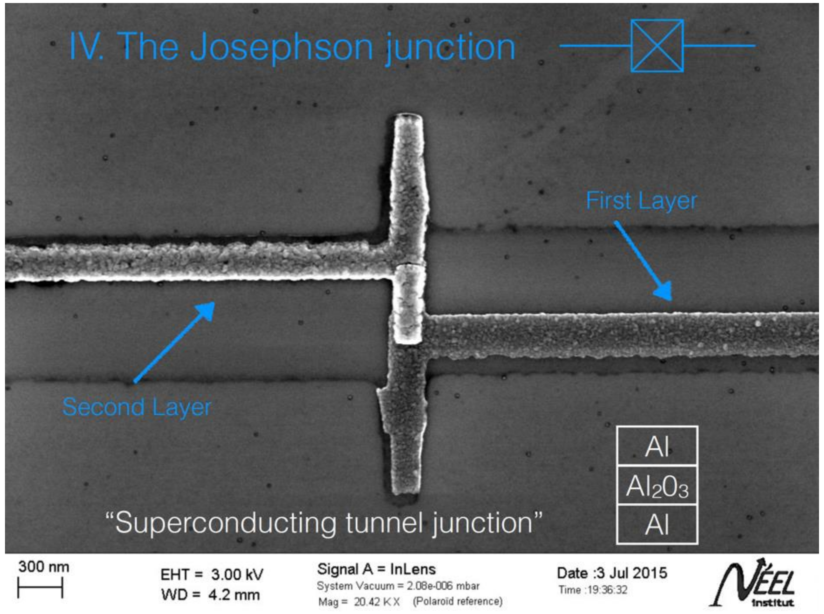


Nano fabrication

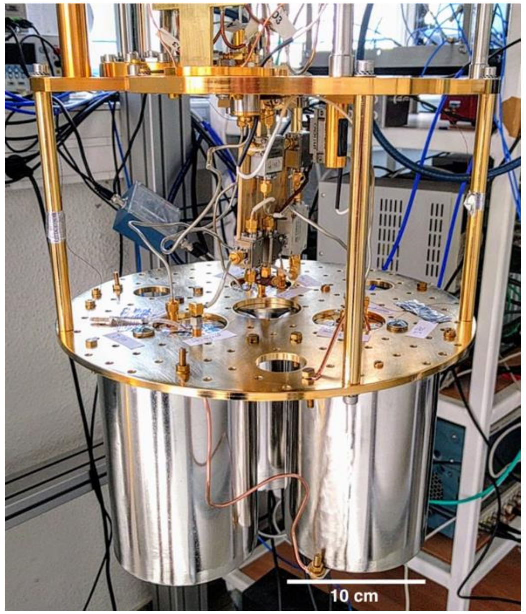
puce



Jonction Josephson



Cryogénie



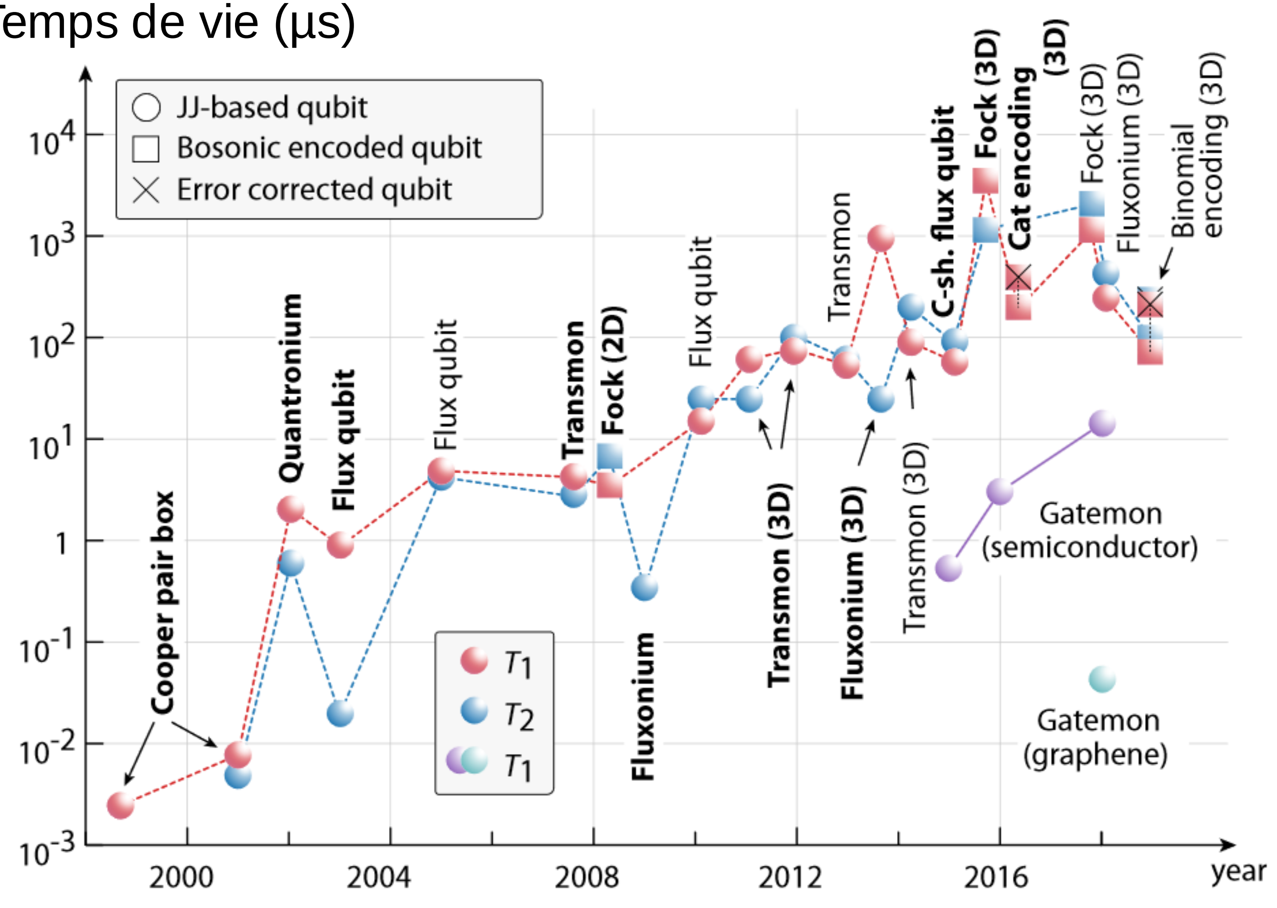
Ingénierie microondes

Circuits surpaconducteurs

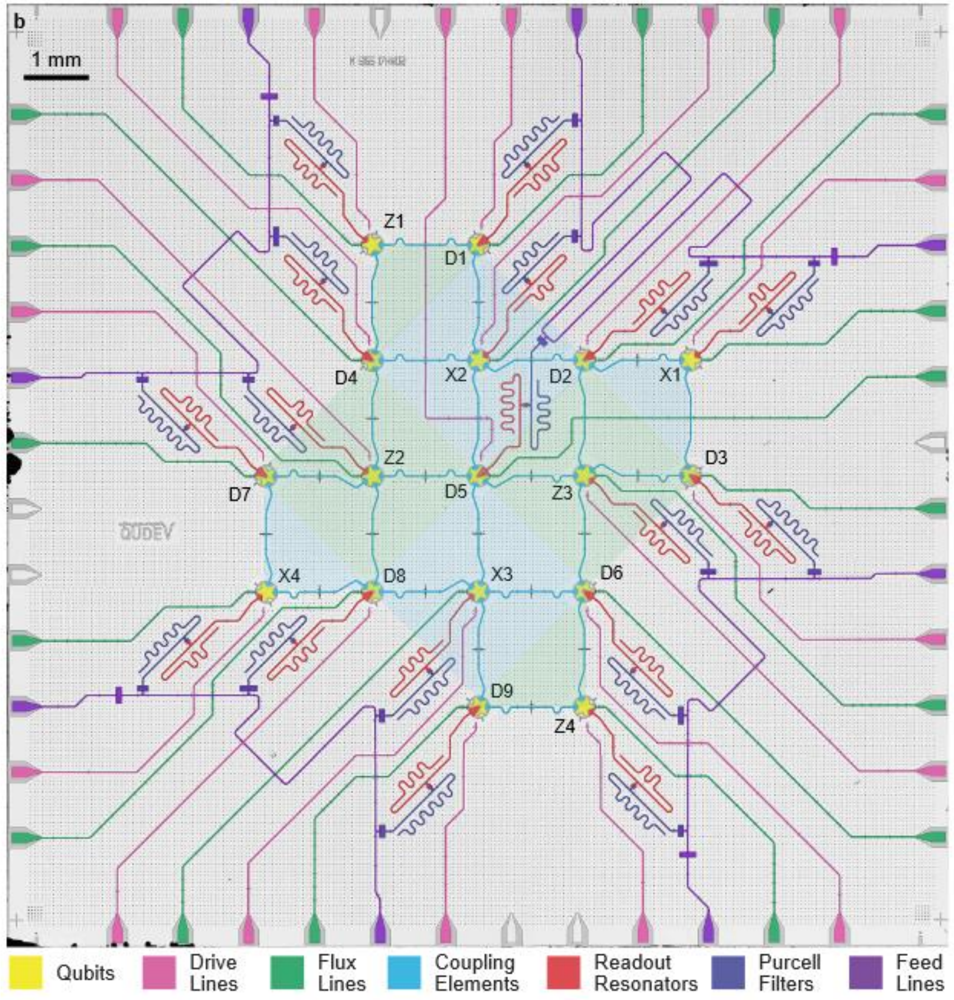
Supraconductivité → Longs temps de vie
Effet Josephson → Forte non-linéarité
Industrie télécom → Control des qubits

Industrie semi-conductrice
→ Architectures complexes

Temps de vie (µs)



Kjaergaard Annual Review of Cond Matt Phys 11 (2020)

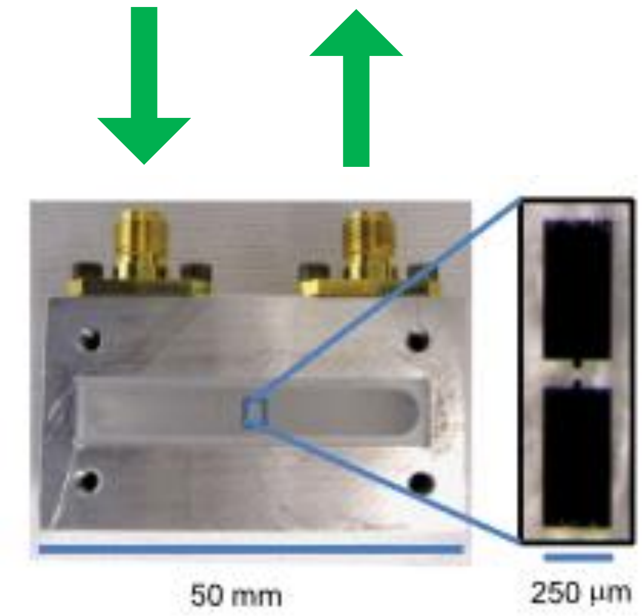


Krinner et al. Nature (2022)

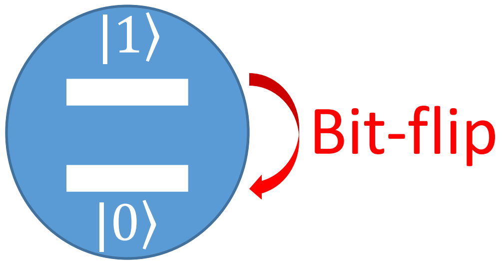
Contrôle d’un qubit supraconducteur

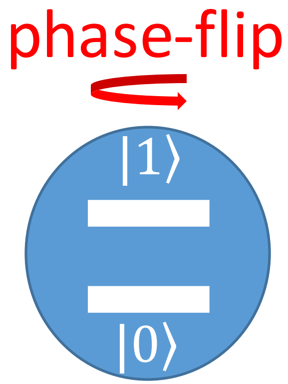
Signals IN

Signals OUT

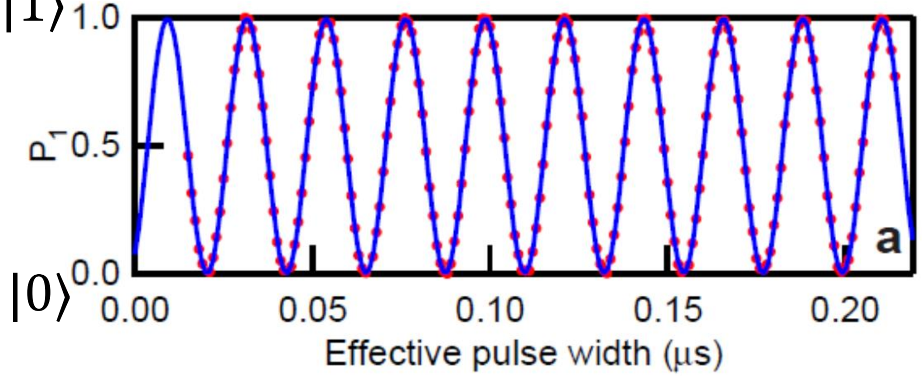


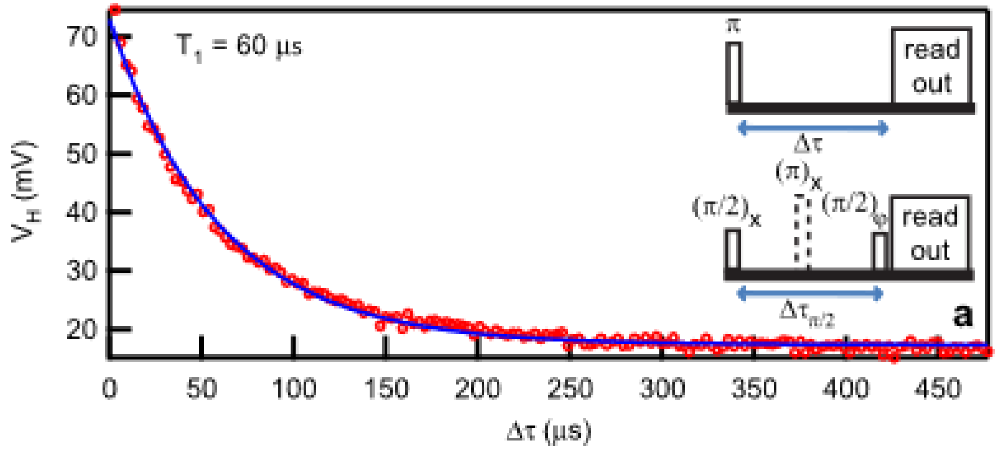
Paik, PRL (2011)

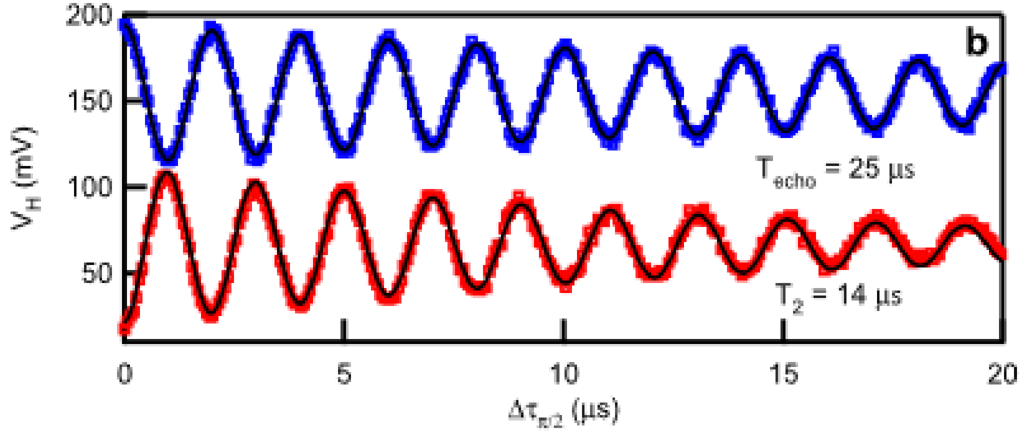




Rabi oscillations

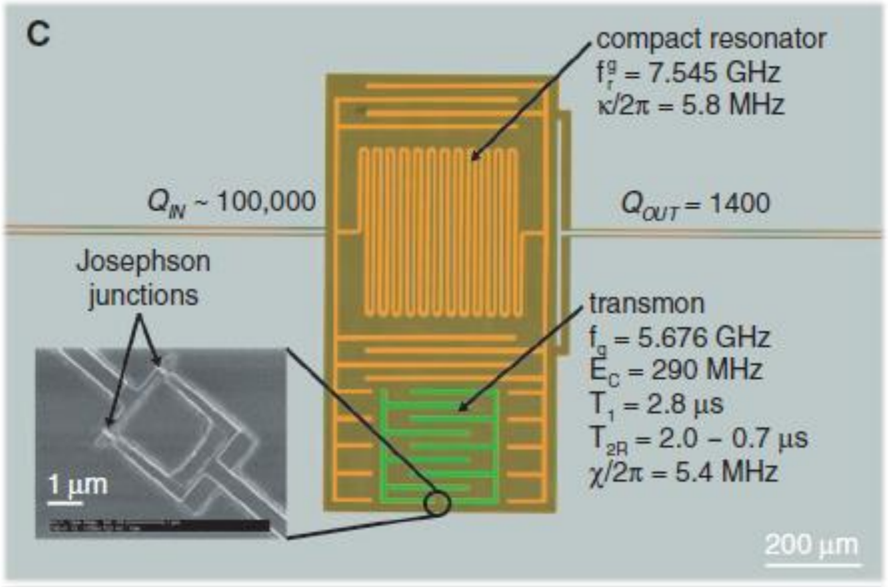






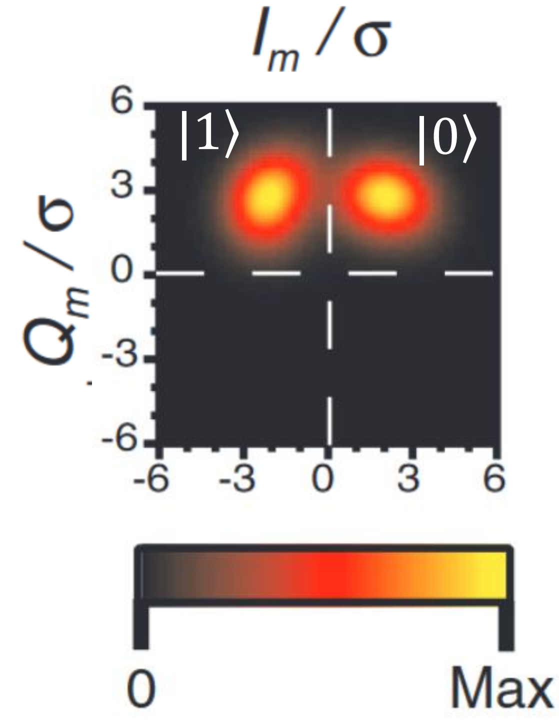
Mesure d'un qubit supraconducteur

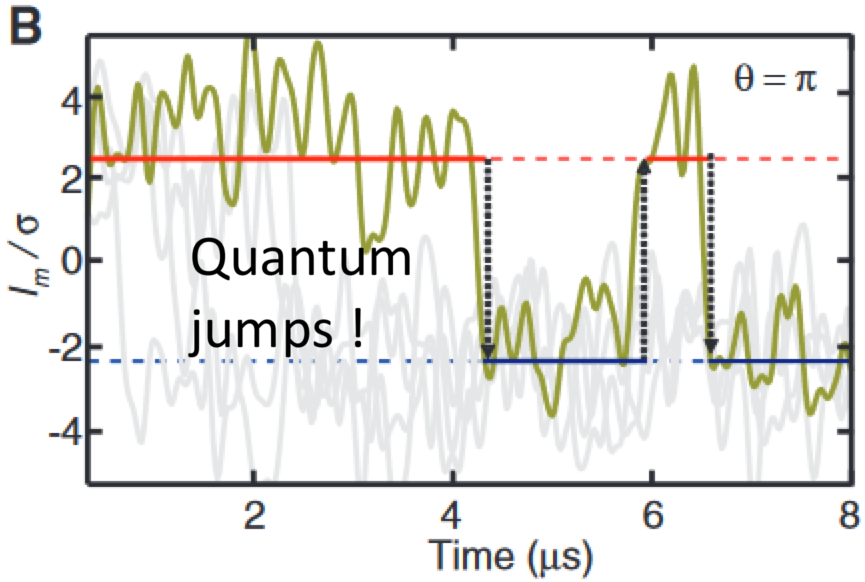
Signals IN



Signals OUT

Hatridge, Science (2013)





Our approach :
The Schrödinger cat-qubit

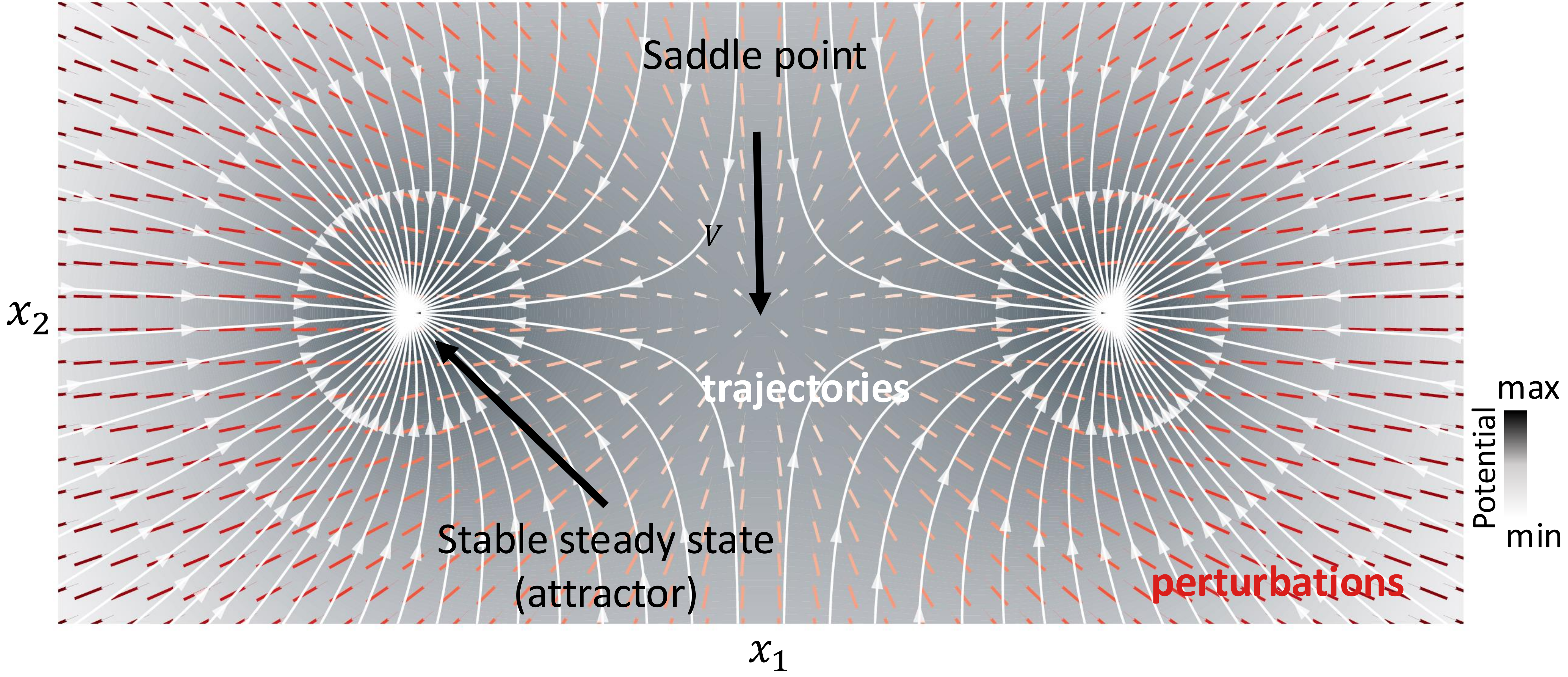
Mirrahimi, NJP, 2014
Leghtas, Science 2015
Touzard, PRX 2018
Lescanne, Nature Physics 2020
Réglade & Bocquet, Nature 2024

ALICE & BOB

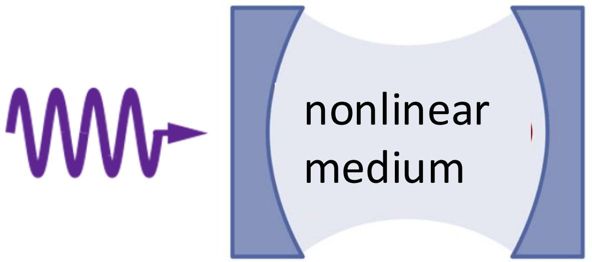
amazon

Dynamical systems

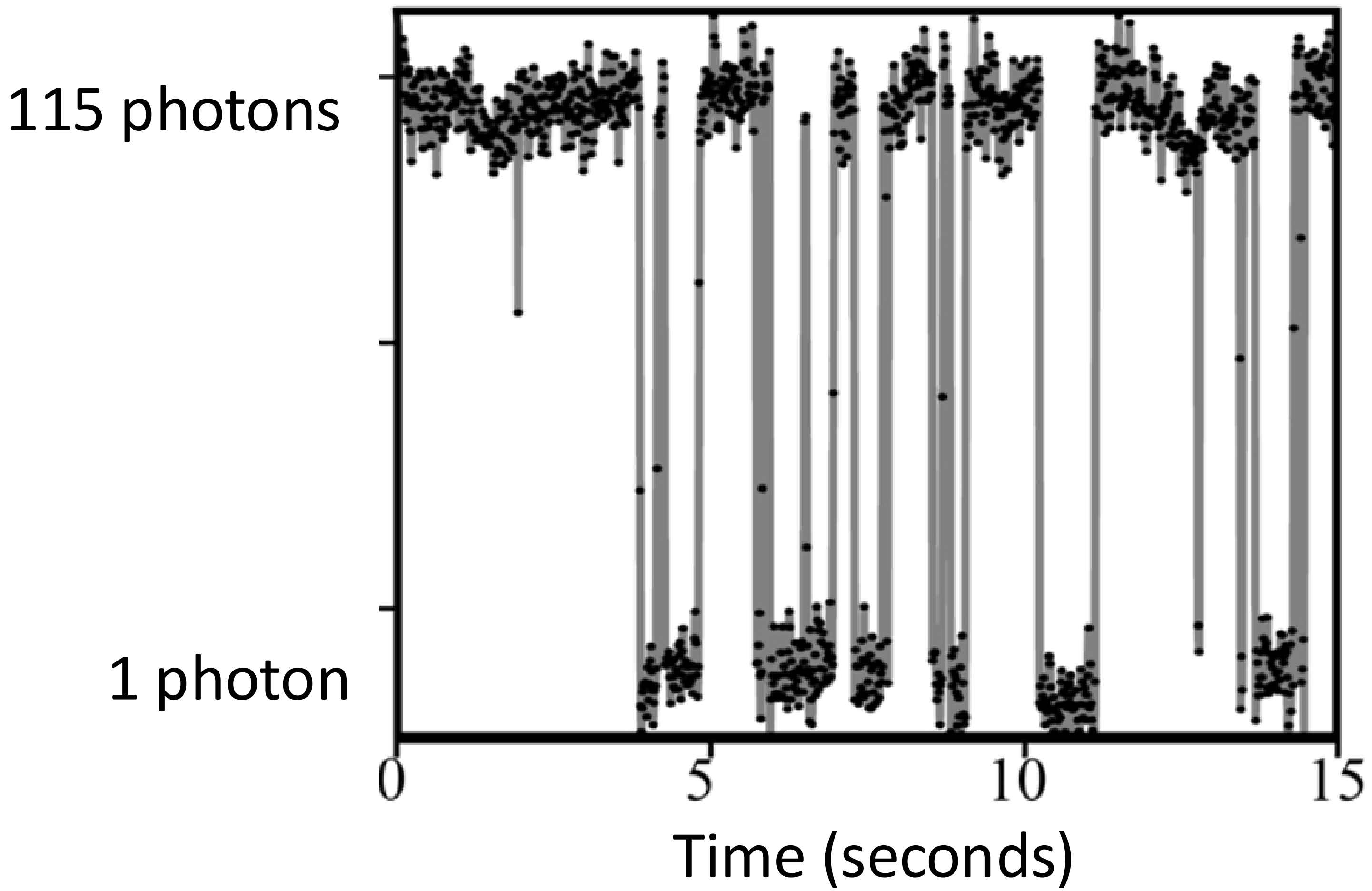
$$\frac{d}{dt}x = f(x)$$



Macroscopic switching times between few-photon dynamical states



Muppalla PRB 2018

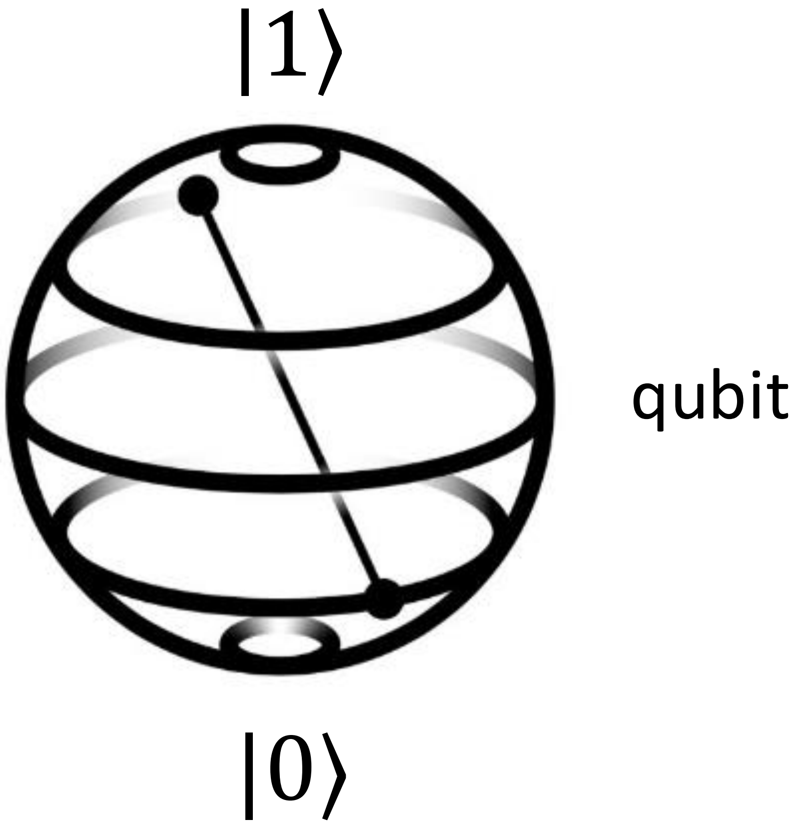


→ Ultra-low power classical logic

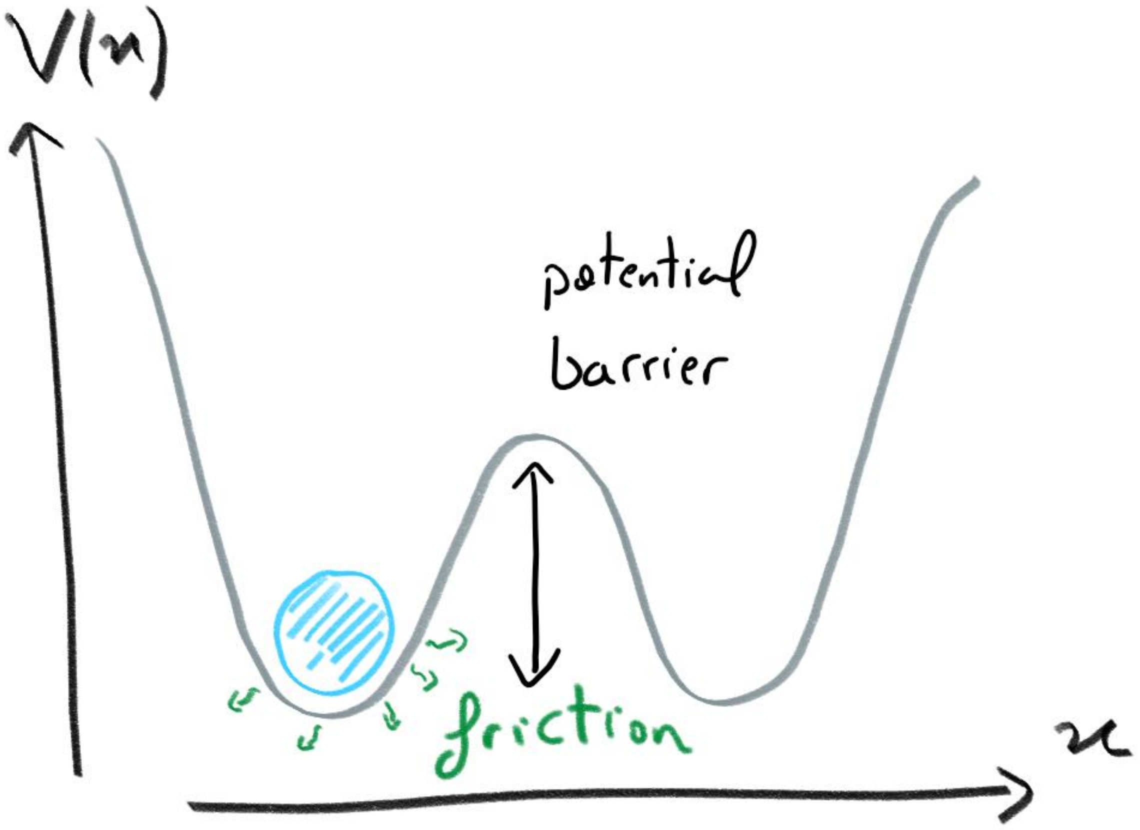
Andersen PRApp 2015

Berdou PRXQ 2023, Krantz NatComm 2016, Siddiqi PRL 2004 …

From dynamical bits to dynamical qubits

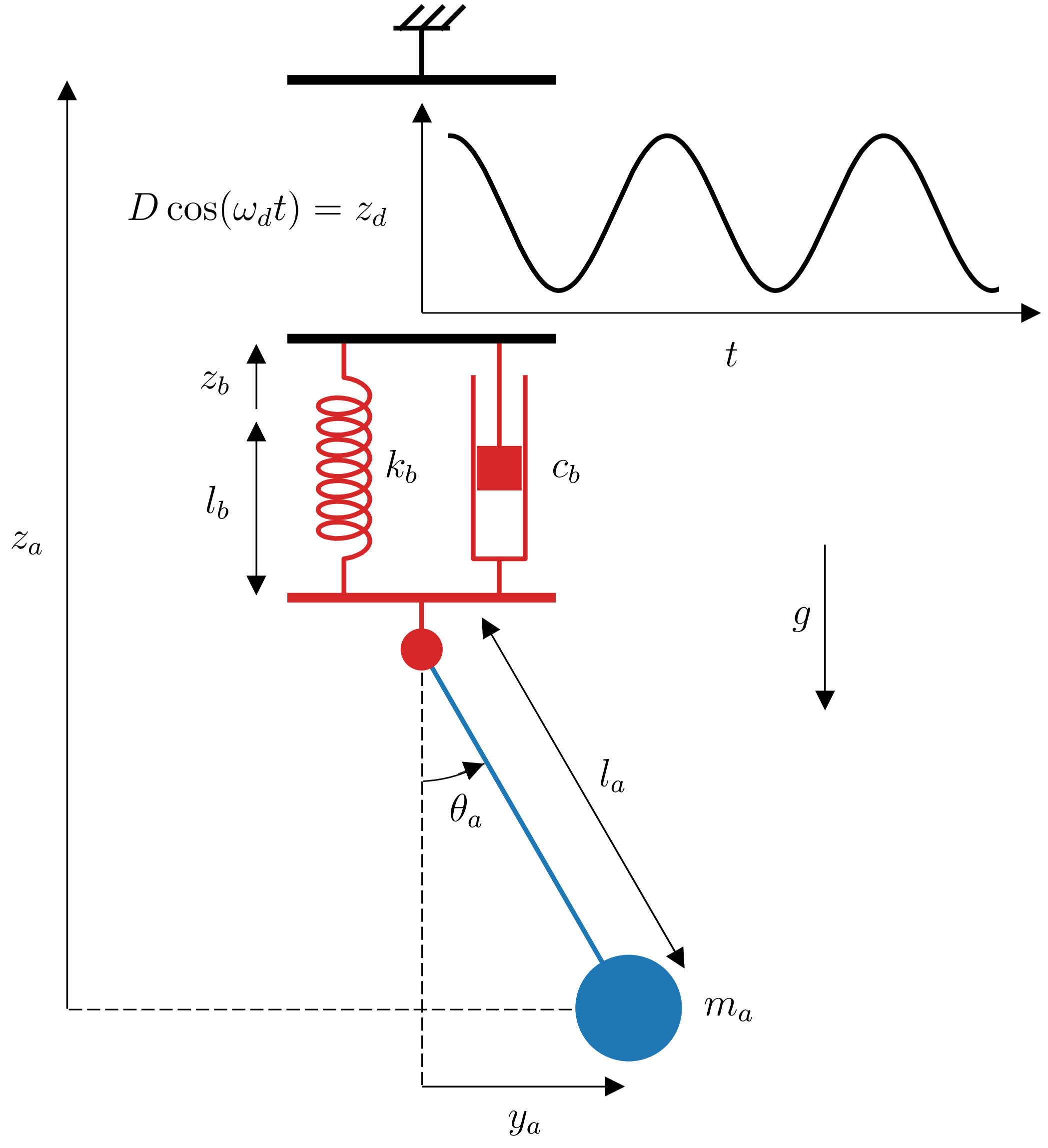


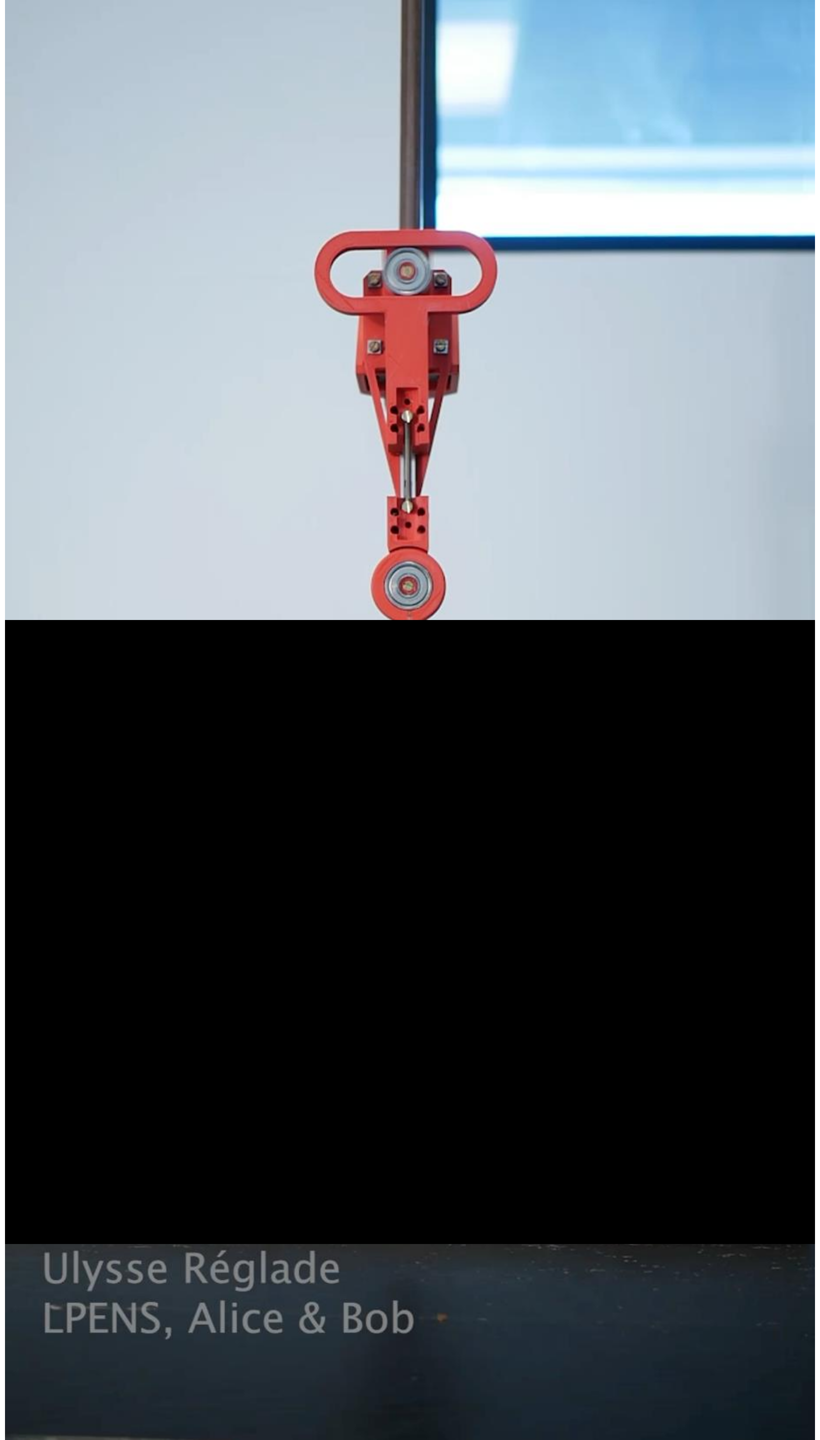
Is dissipation good or bad ?



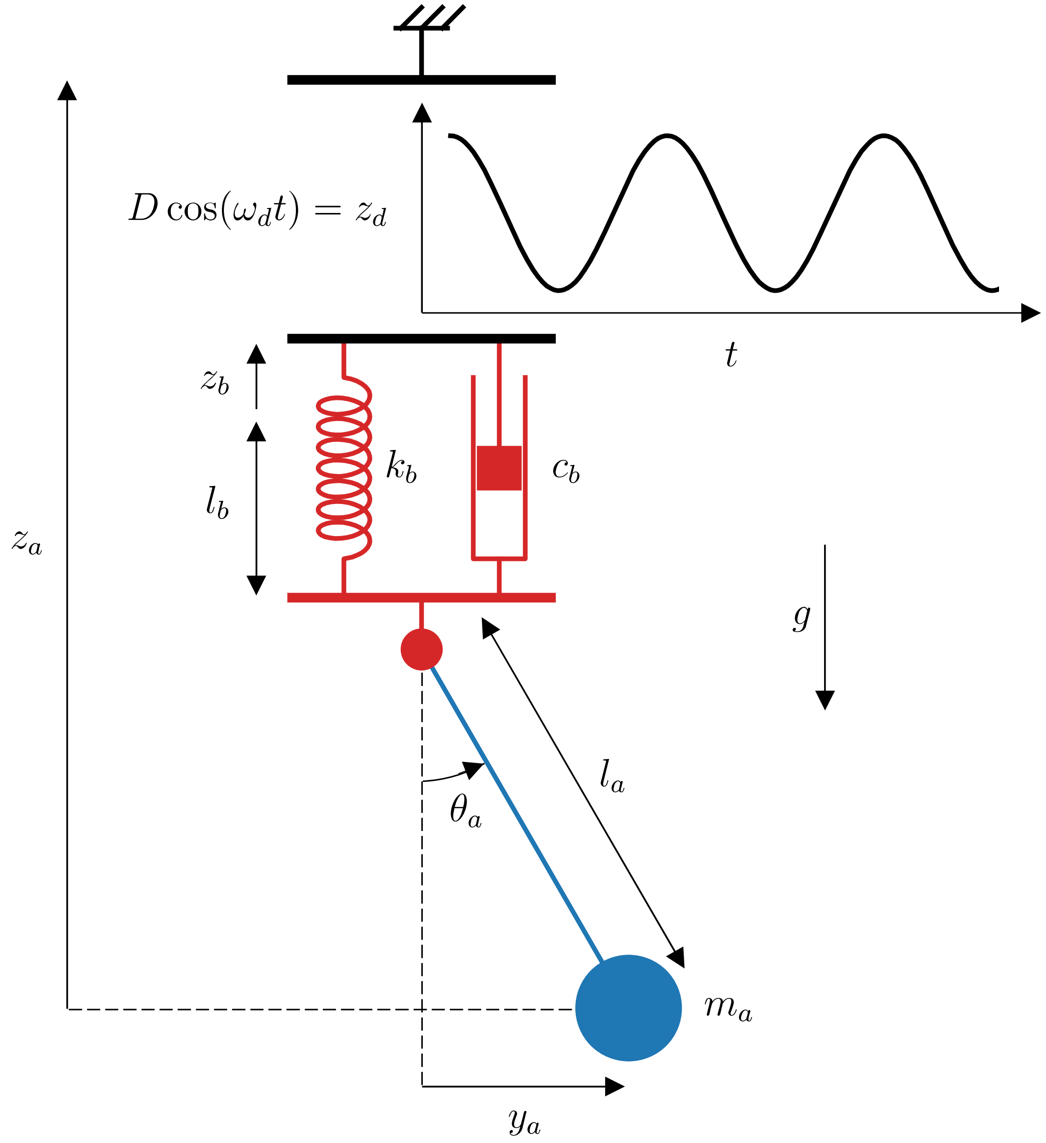
Friction (dissipation)
→ **Stability**
→ **Quantum decoherence**

Agnostic dissipation





Agnostic dissipation



Two-photon dissipation

Hamiltonian $H/\hbar = i\epsilon_2 a^{\dagger 2} - i\epsilon_2^* a^2$

Loss operator $L = \sqrt{\kappa_2} a^2$

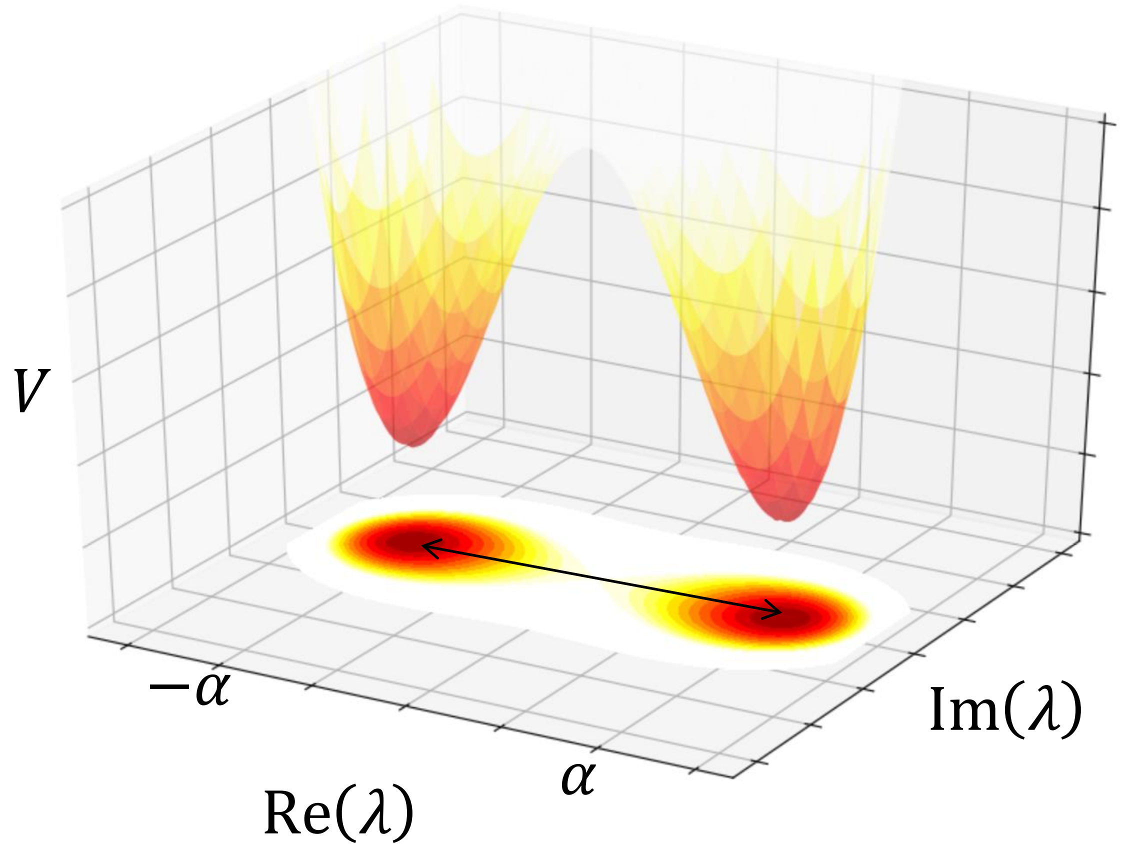
$$\alpha = \left(\frac{2\epsilon_2}{\kappa_2}\right)^{1/2}$$

Steady states in $\text{span}\{|-\alpha\rangle, |\alpha\rangle\}$

$$\frac{d\langle a\rangle}{dt} = -\nabla V(\langle a\rangle)$$

Meta−potential $V(\lambda)$

$|\alpha|^2 = 4$

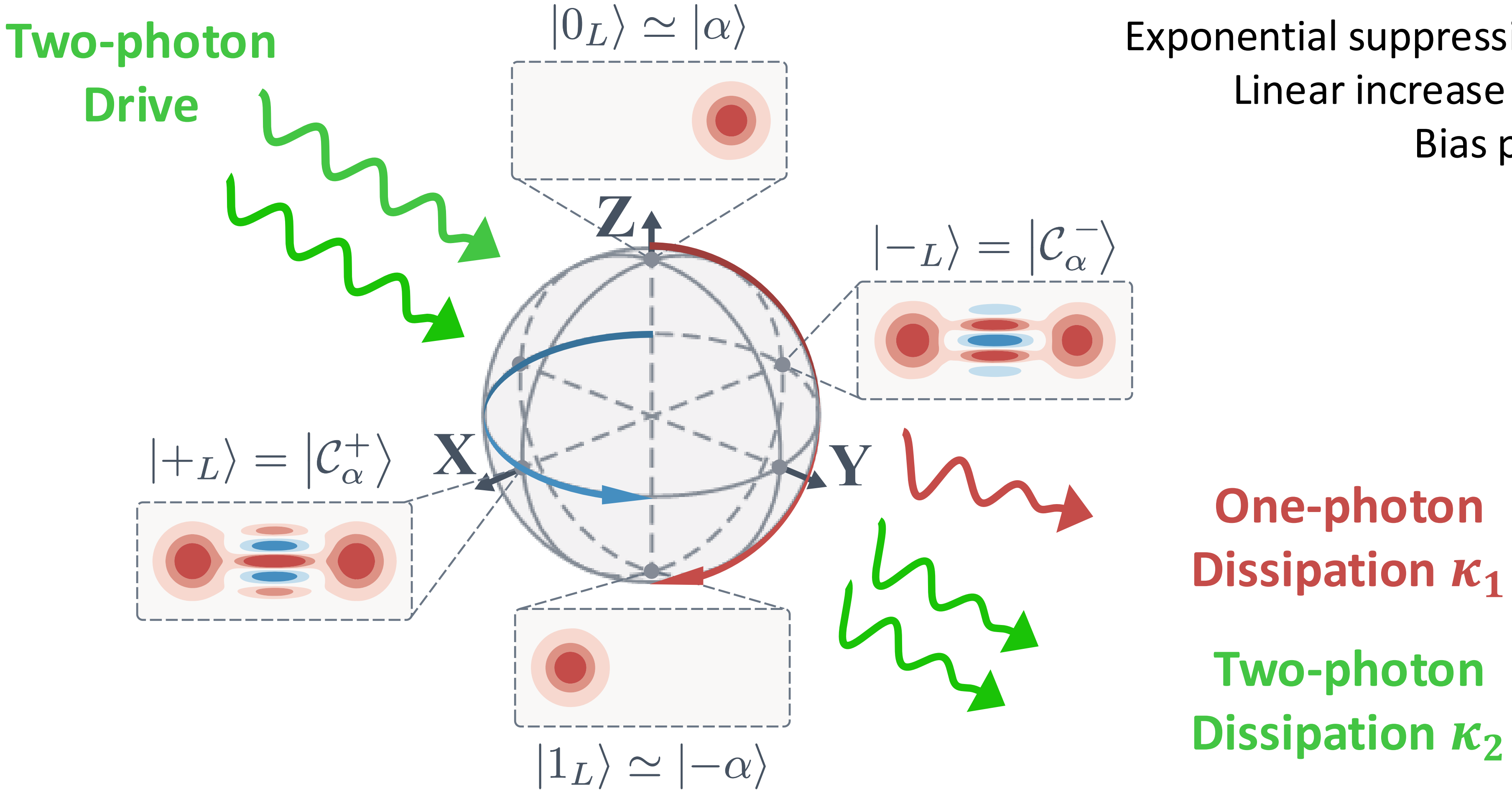


Wolinsky and Carmichael PRL (1998)

The dissipative cat-qubit

$$H = \varepsilon_2 a^2 + \varepsilon_2^* (a^\dagger)^2; L_2 = \sqrt{\kappa_2}\, a^2$$

Exponential suppression of bit-flip with α^2
Linear increase of phase-flip with α^2
Bias preserving operations

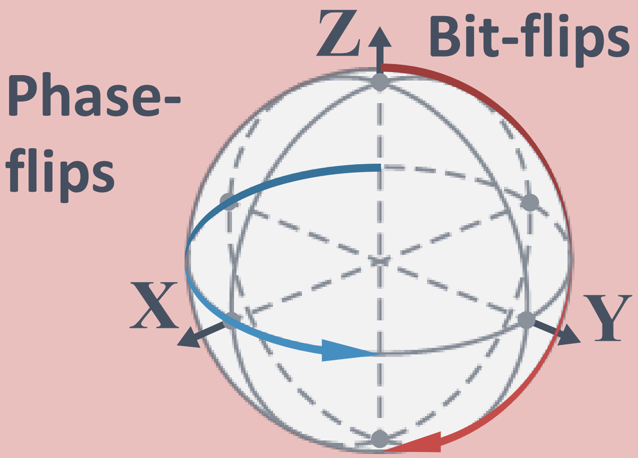


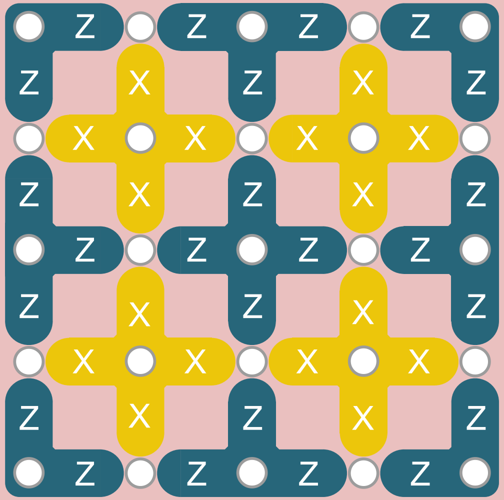
Mirrahimi, NJP, 2014
Touzard, PRX 2018

Lescanne, Nature Physics 2020
Leghtas, Science 2015

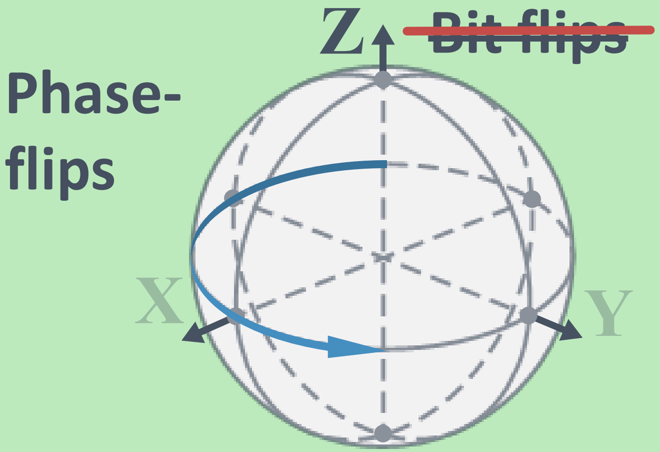
Biased-noise qubits reduce hardware overhead

Standard qubits





Biased-noise qubits



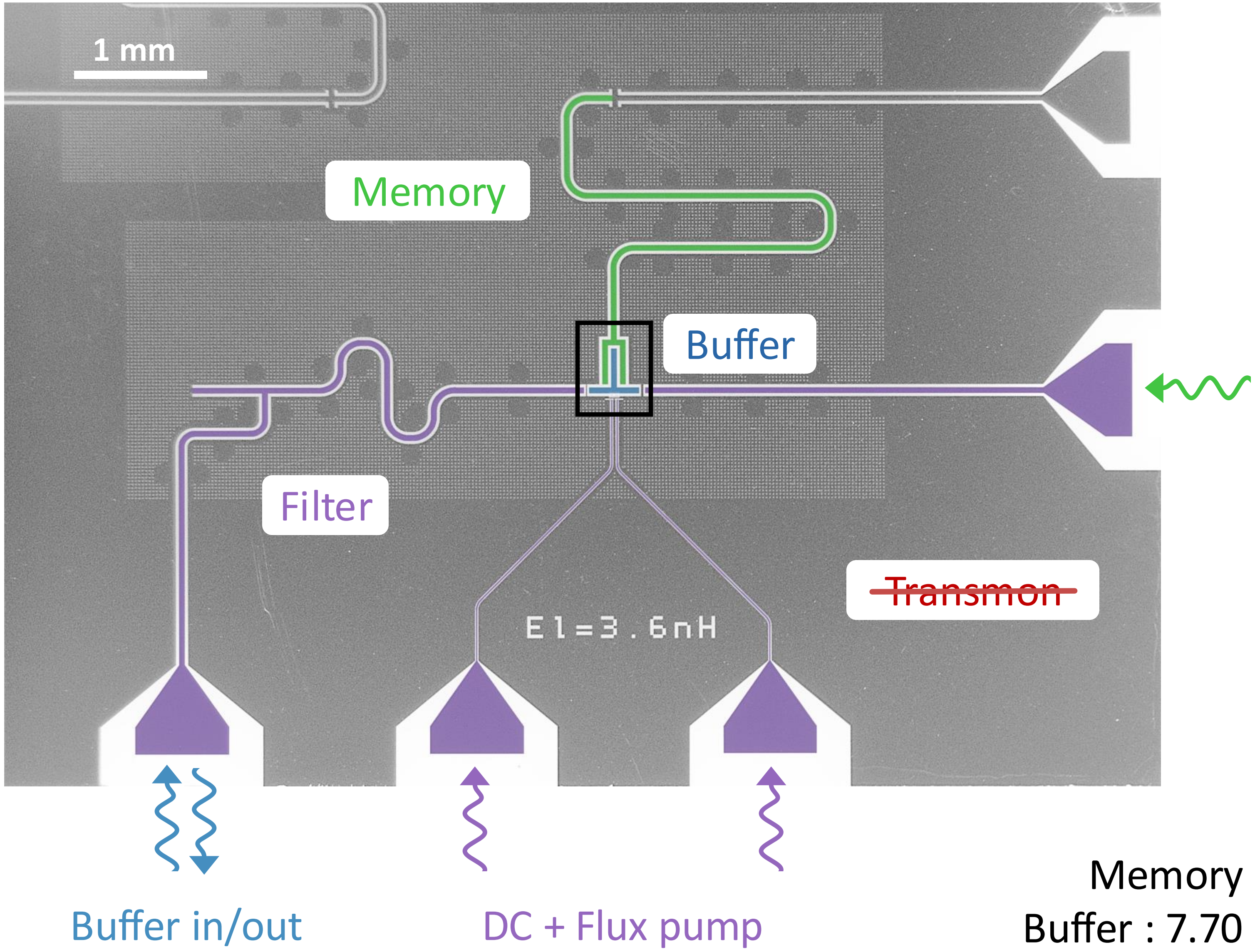
x10-100 less overhead
but requires bias preserving operations

Chamberlan, 2023
Webster, Bartlett, Poulin. PRA, 2015.

Aliferis, Preskill, PRA 2008
Tuckett, Bartlett, Flammia. PRL 2018

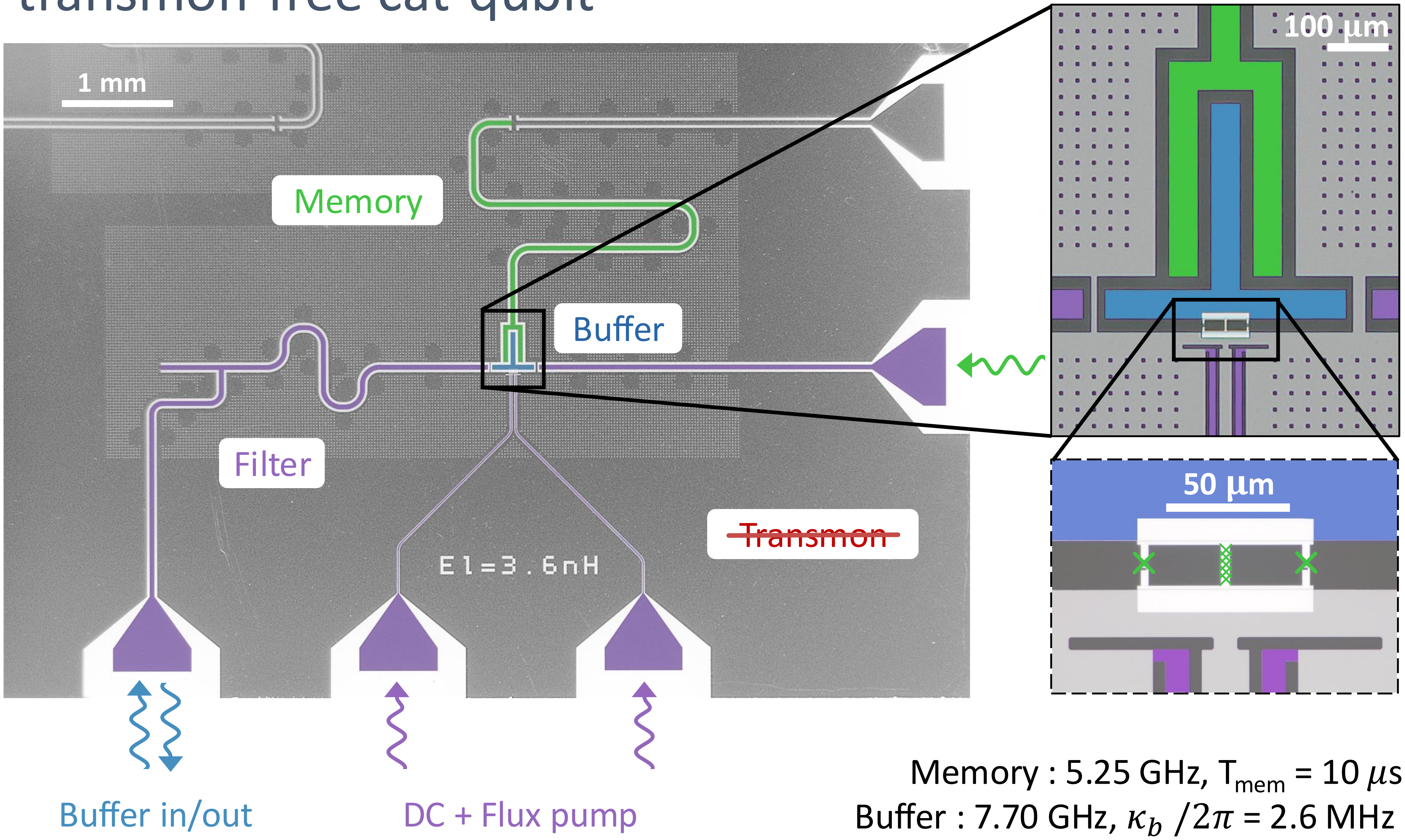
Puri, Science Adv, 2023
Ruiz, 2023

The transmon-free cat-qubit



Memory : 5.25 GHz, T_{mem} = 10 μs
Buffer : 7.70 GHz, $\kappa_b\ /2\pi$ = 2.6 MHz

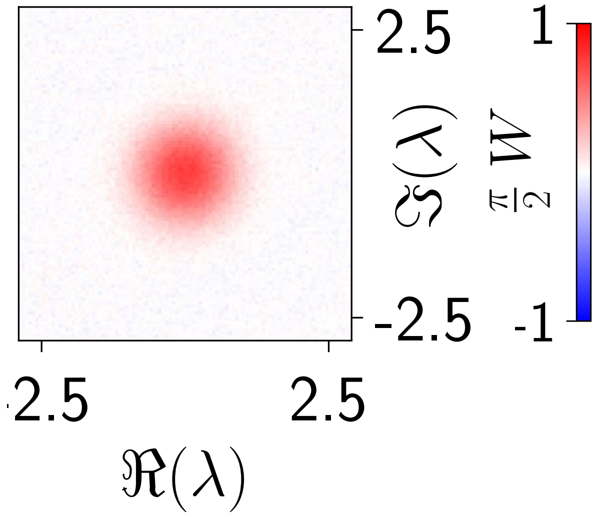
The transmon-free cat-qubit



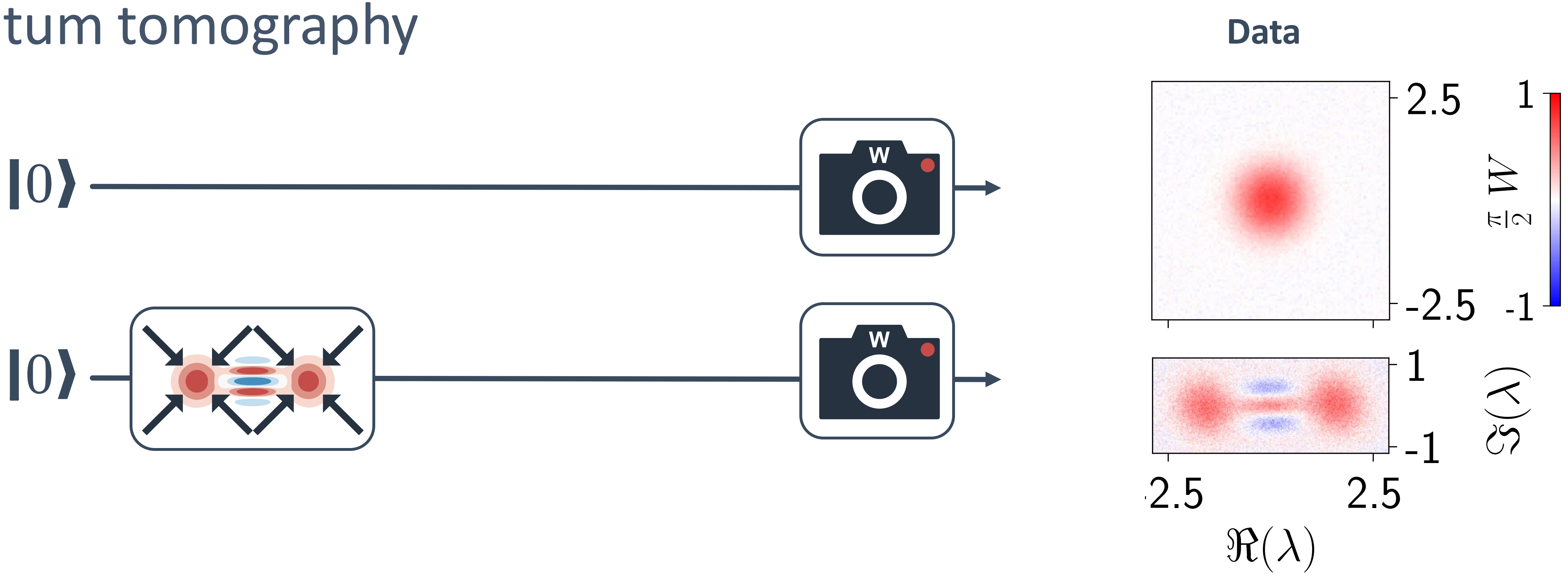
Memory : 5.25 GHz, T_{mem} = 10 μs
Buffer : 7.70 GHz, κ_b $/2\pi$ = 2.6 MHz

Quantum tomography

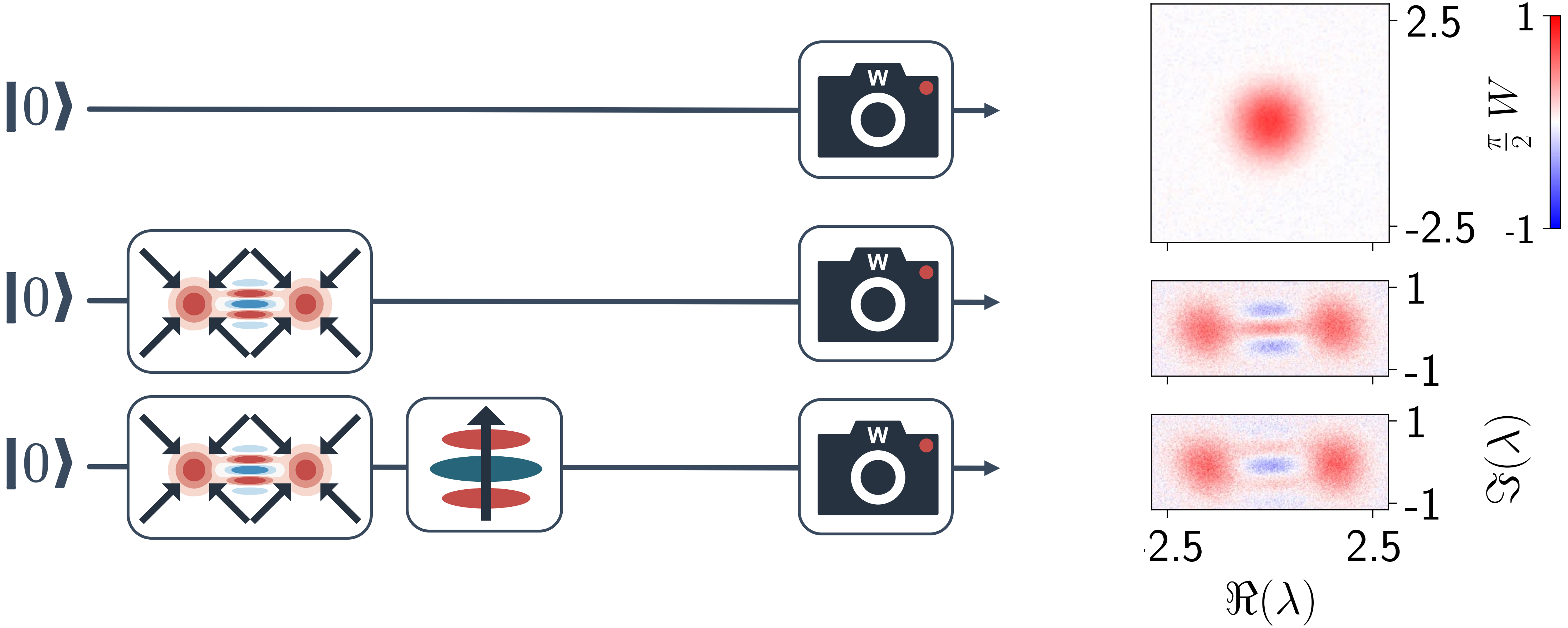
Data



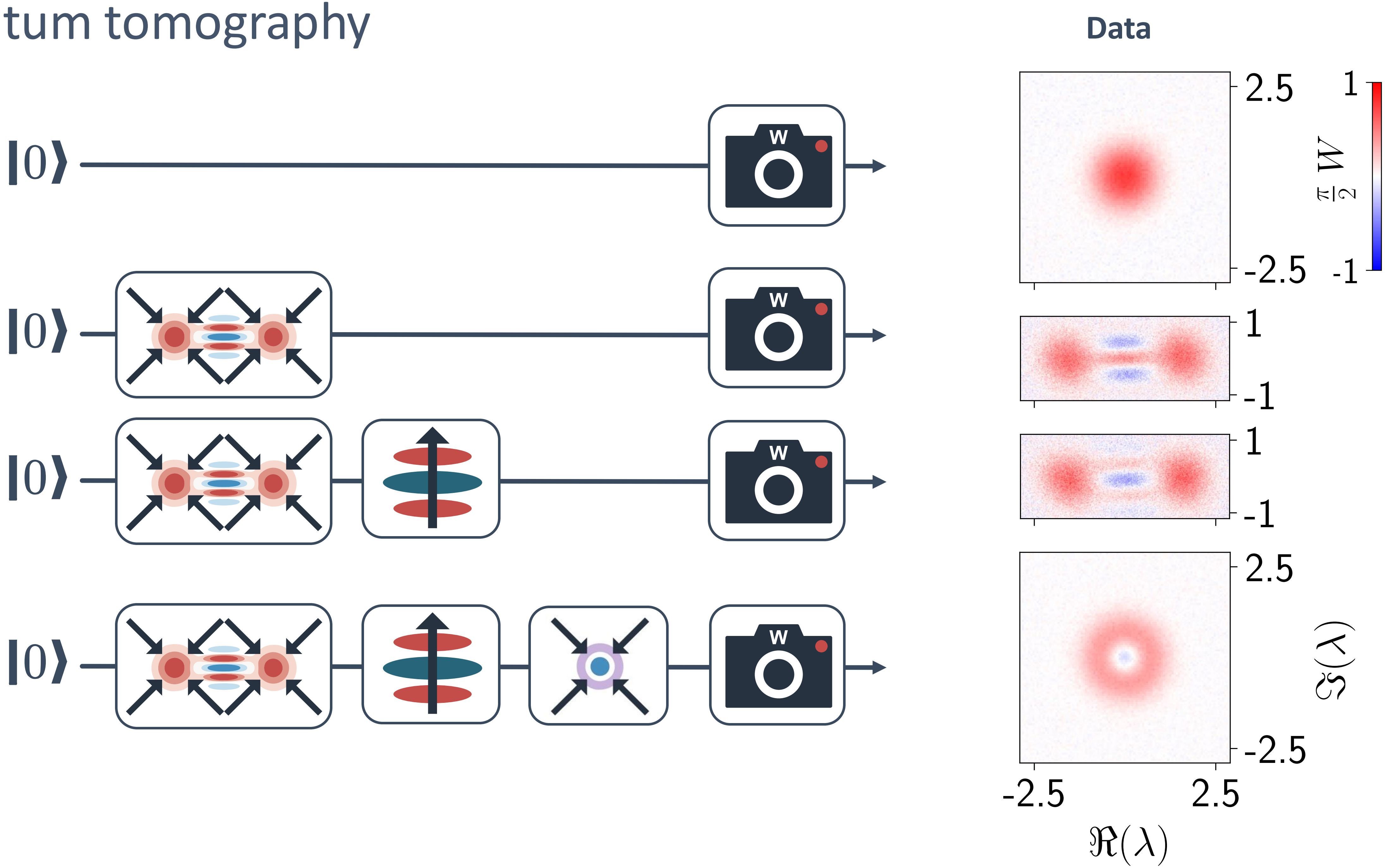
Quantum tomography



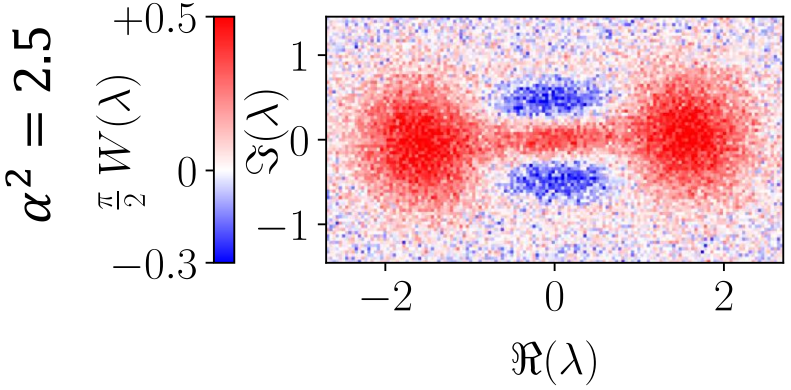
Quantum tomography

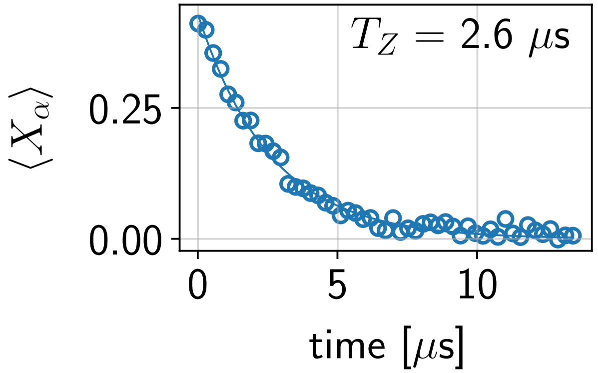


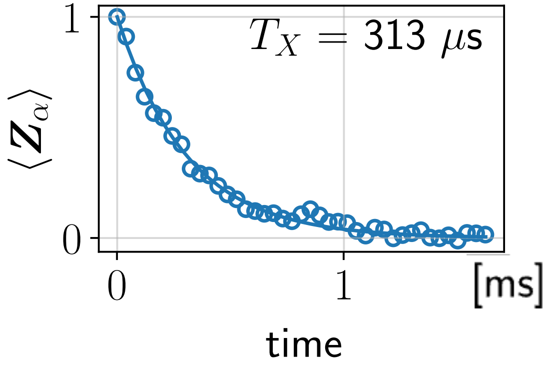
Quantum tomography



Our qubit is noise-biased







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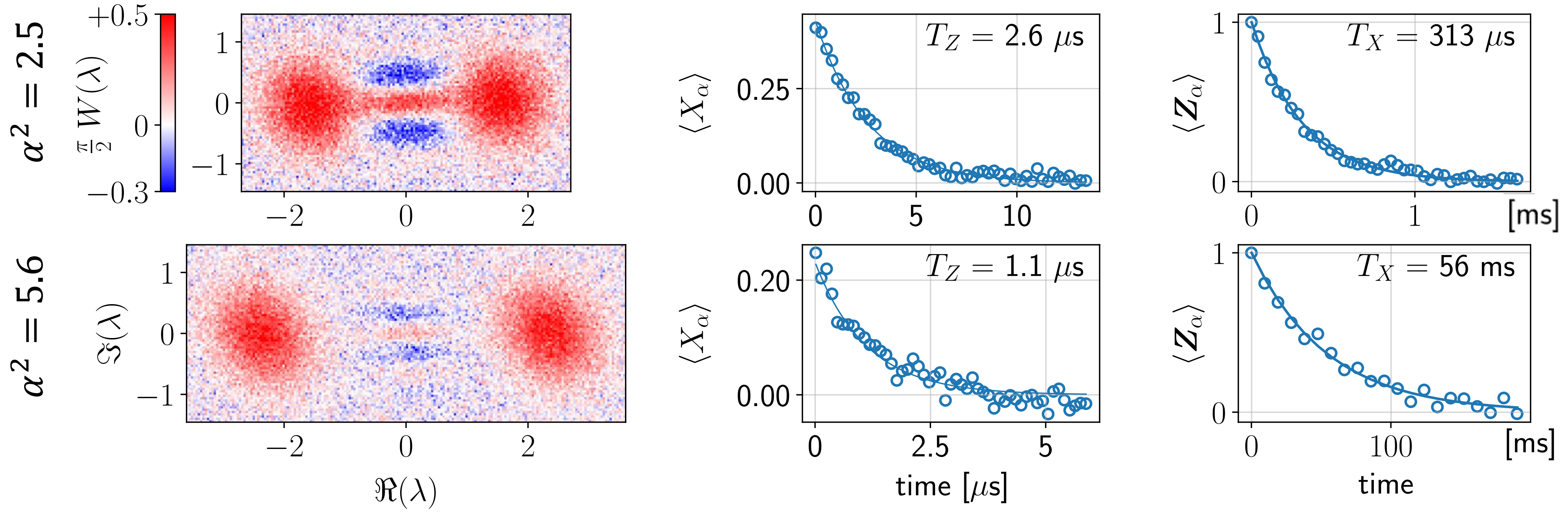
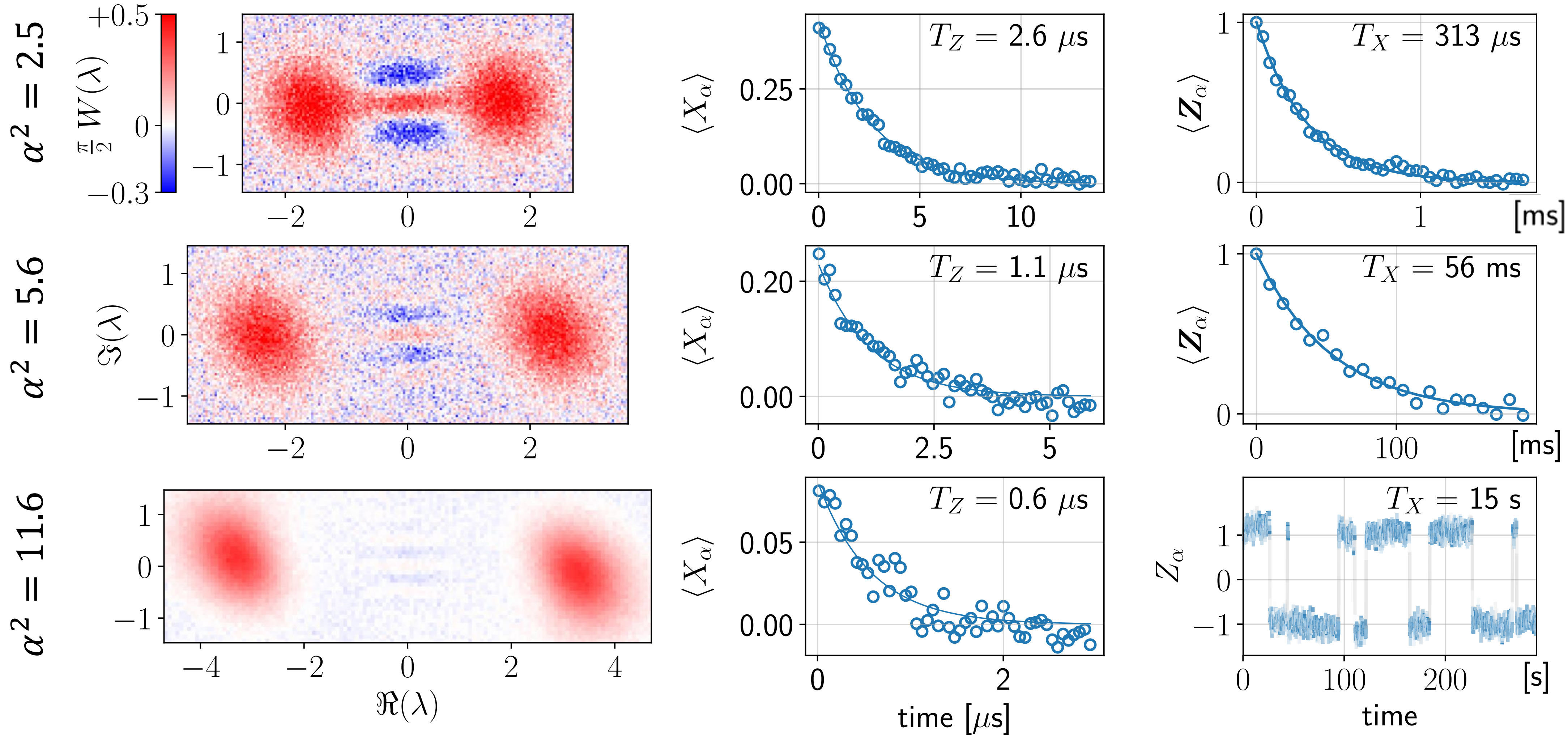
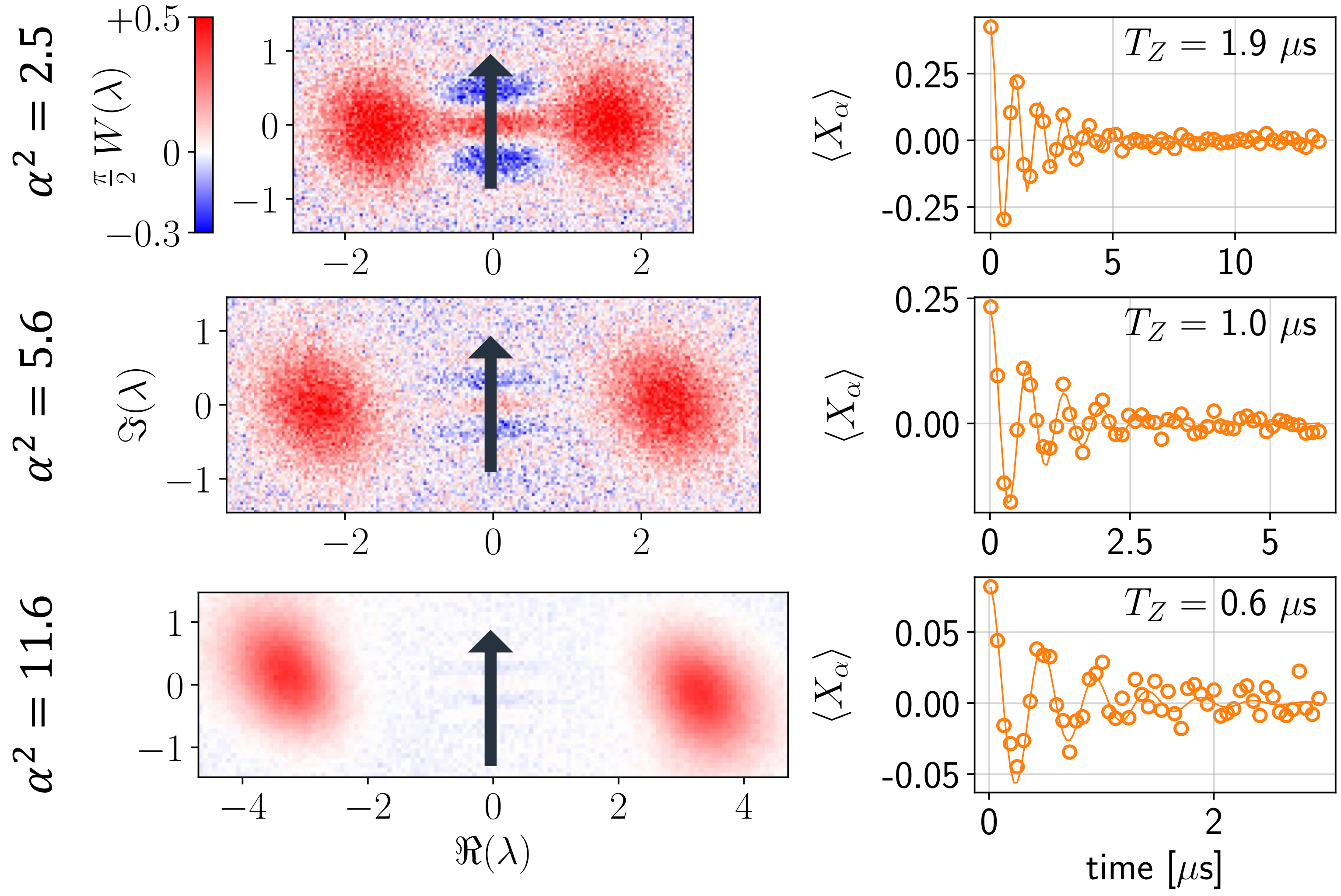


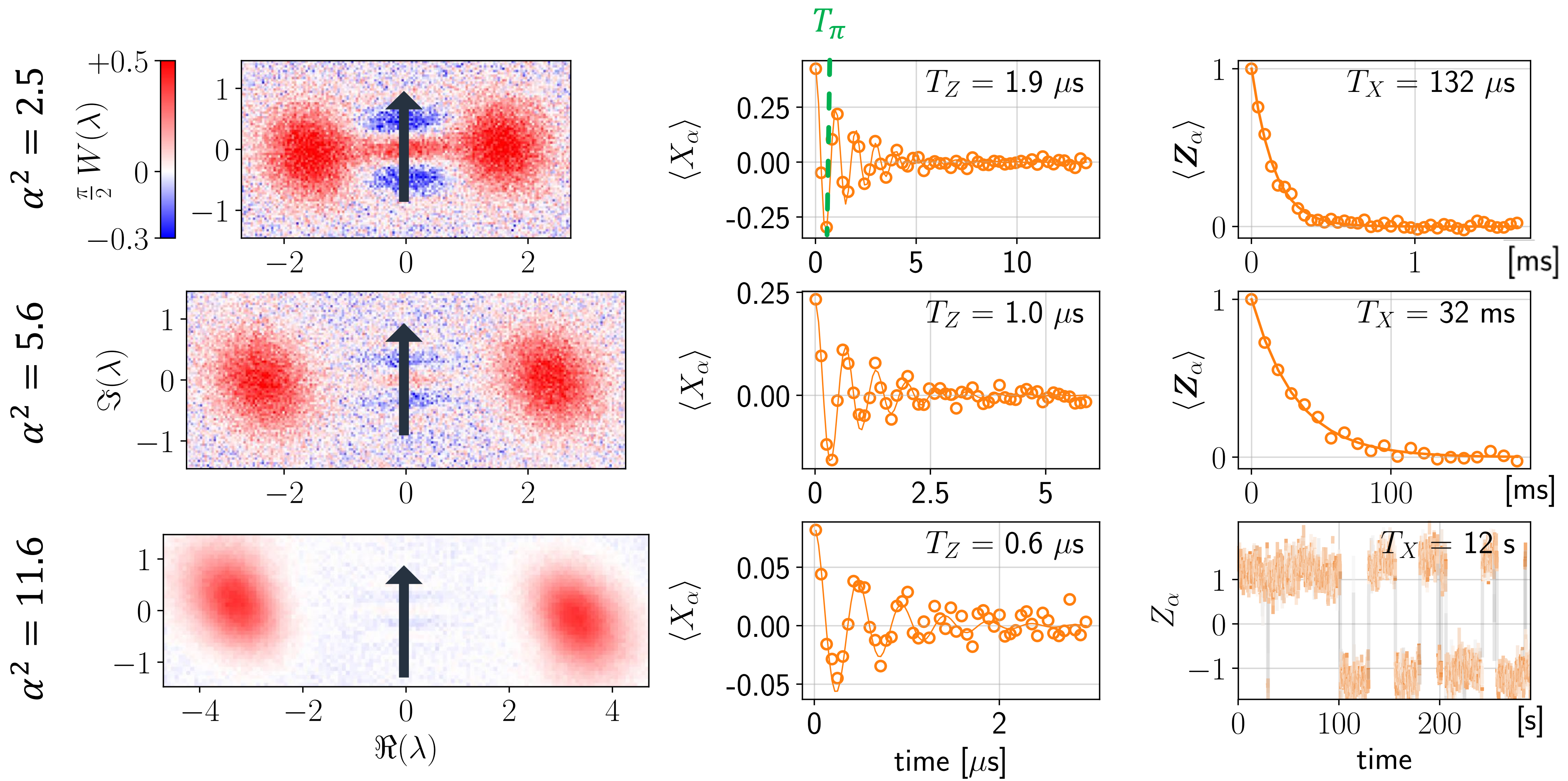
Our qubit is noise-biased



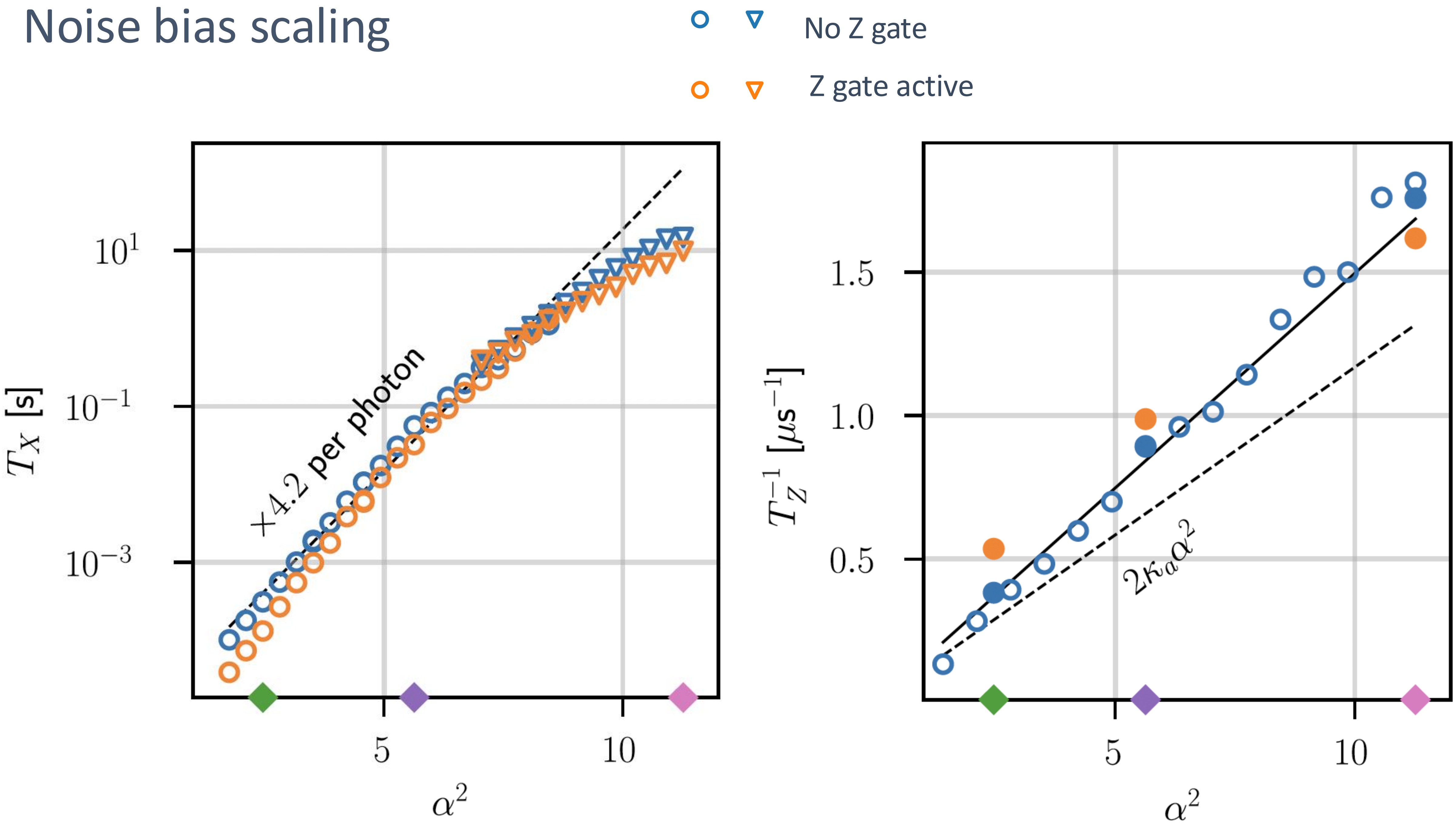
Our qubit is noise-biased under control



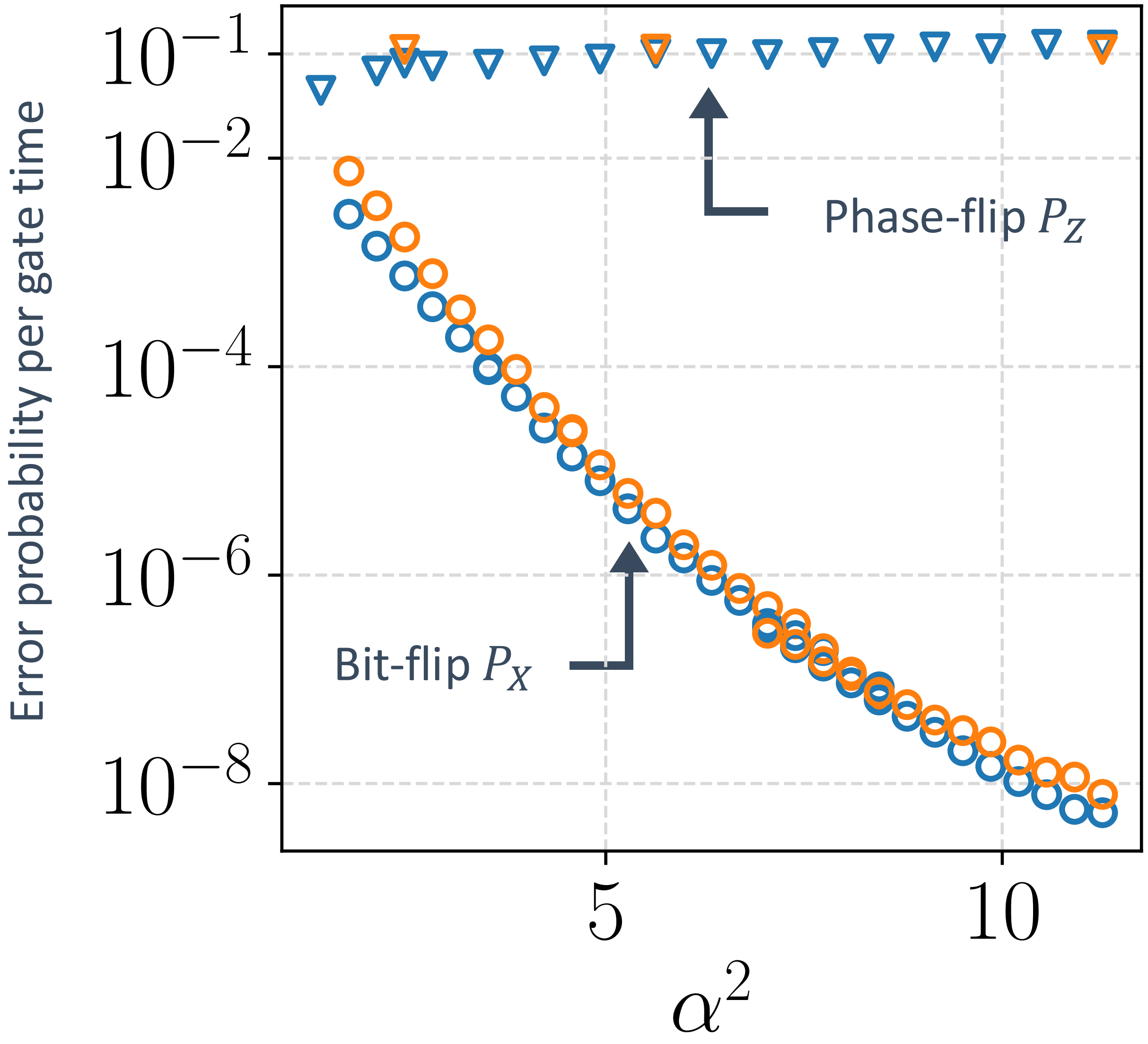
Our qubit is noise-biased under control



Noise bias scaling



Noise bias scaling



No Z gate

Z gate active

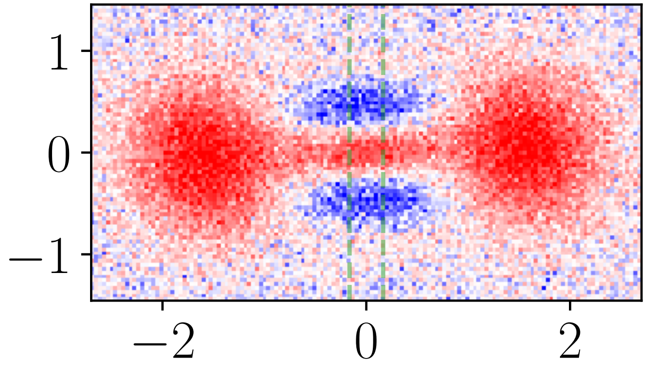
$1 - 2P_Z = \exp(-T_\pi/T_Z)$

$1 - 2P_X = \exp(-T_\pi/T_X)$

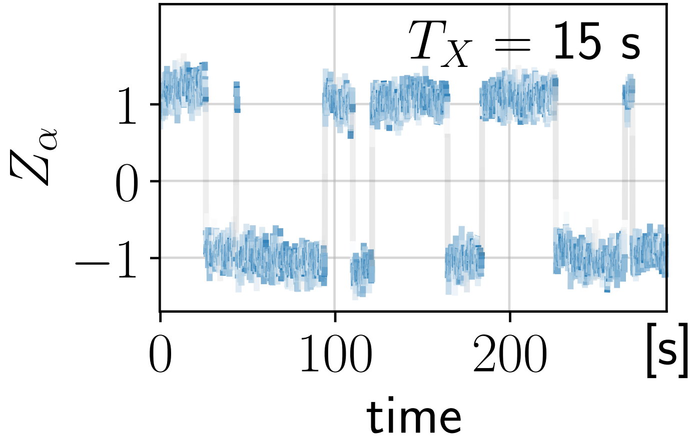
T_π time of a Z(π) gate

Conclusion

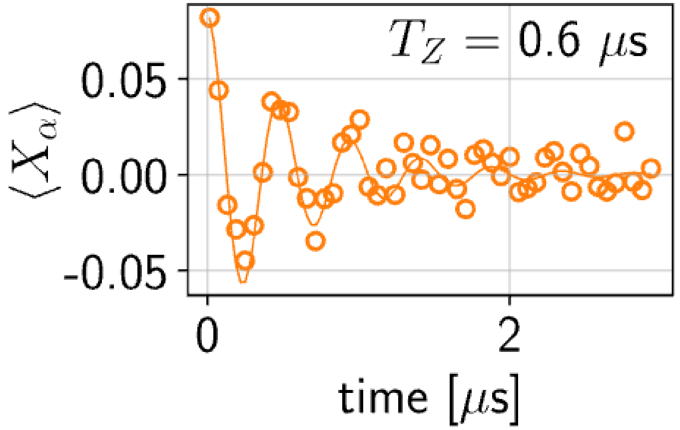
Tomography ✅



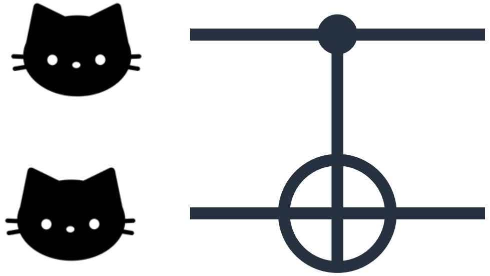
Macroscopic bit-flip time ✅



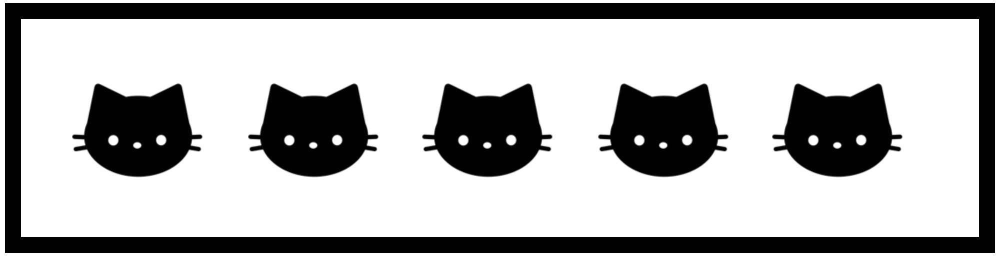
Coherent control ✅



CNOT Gate 🚧



Repetition code 🚧



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