Encoding quantum information in a dynamical superconducting circuit

Zaki Leghtas

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Mines Paris, Inria, ENS, Université PSL, CNRS


Nature 629, 778–783 (2024)

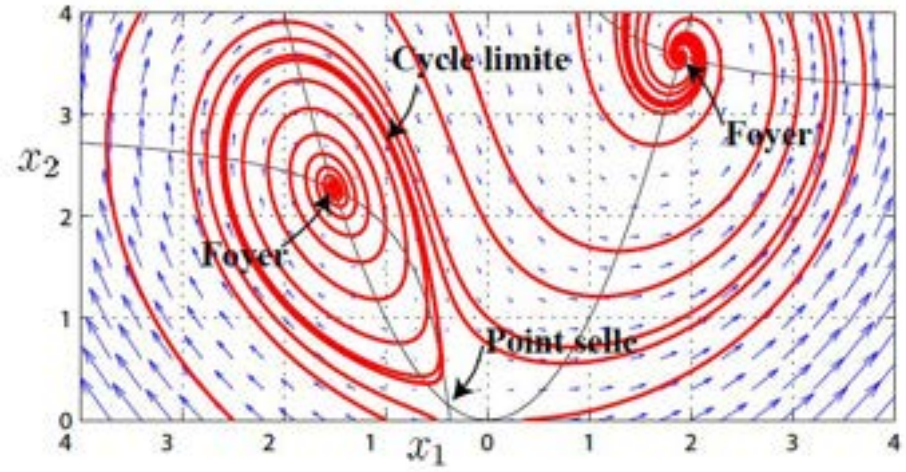
arXiv:2307.06617



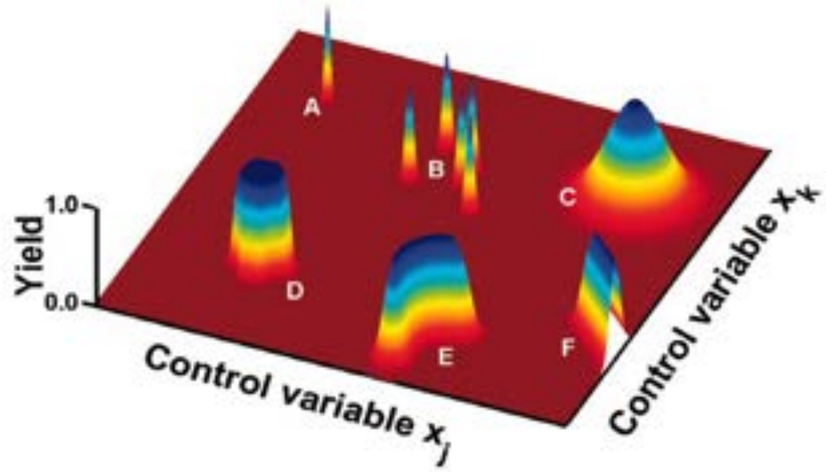
Ulysse Réglade, Adrien Bocquet, Ronan Gautier, Antoine Marquet, Emanuele Albertinale, Natalia Pankratova, Mattis Hallén, Felix Rautschke, Lev-Arcady Sellem, Pierre Rouchon, Alain Sarlette, Mazyar Mirrahimi, Philippe Campagne-Ibarcq, Raphaël Lescanne, Sebastien Jezouin, ZL

Dynamical systems & Schrödinger cat states

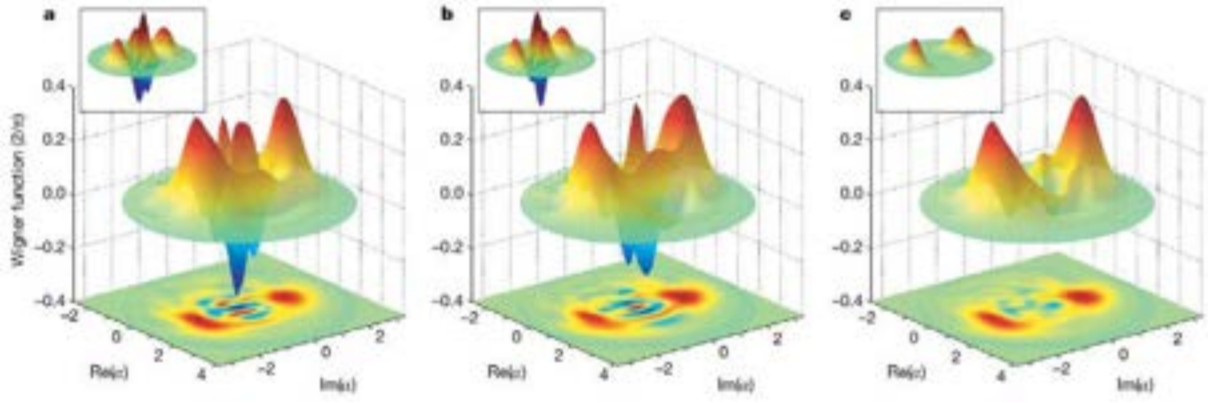
Since 2007 …



Pierre Rouchon & **Nicolas Petit**
Ecole des Mines de Paris

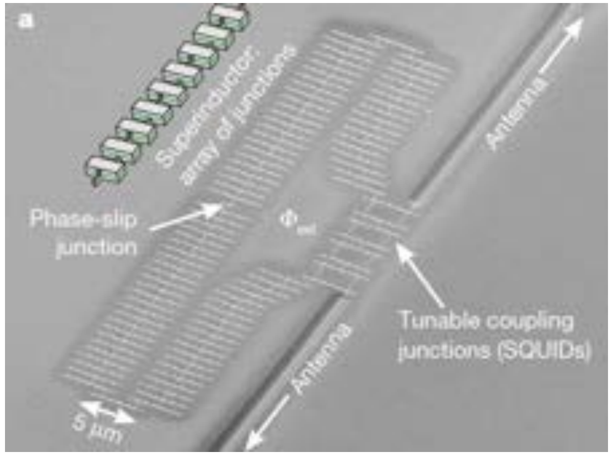


Herschel Rabitz
Princeton University



Deléglise et al. Nature (2008)

Serge Haroche
Collège de France



Michel Devoret
Collège de France
Yale University

Mazyar Mirrahimi

Ioan Pop

Philippe Campagne-Ibarcq

Emmanuel Flurin

Nicolas Petit

Gabriel Turinici

Michel Devoret

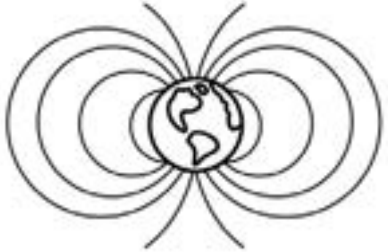
Pierre Rouchon

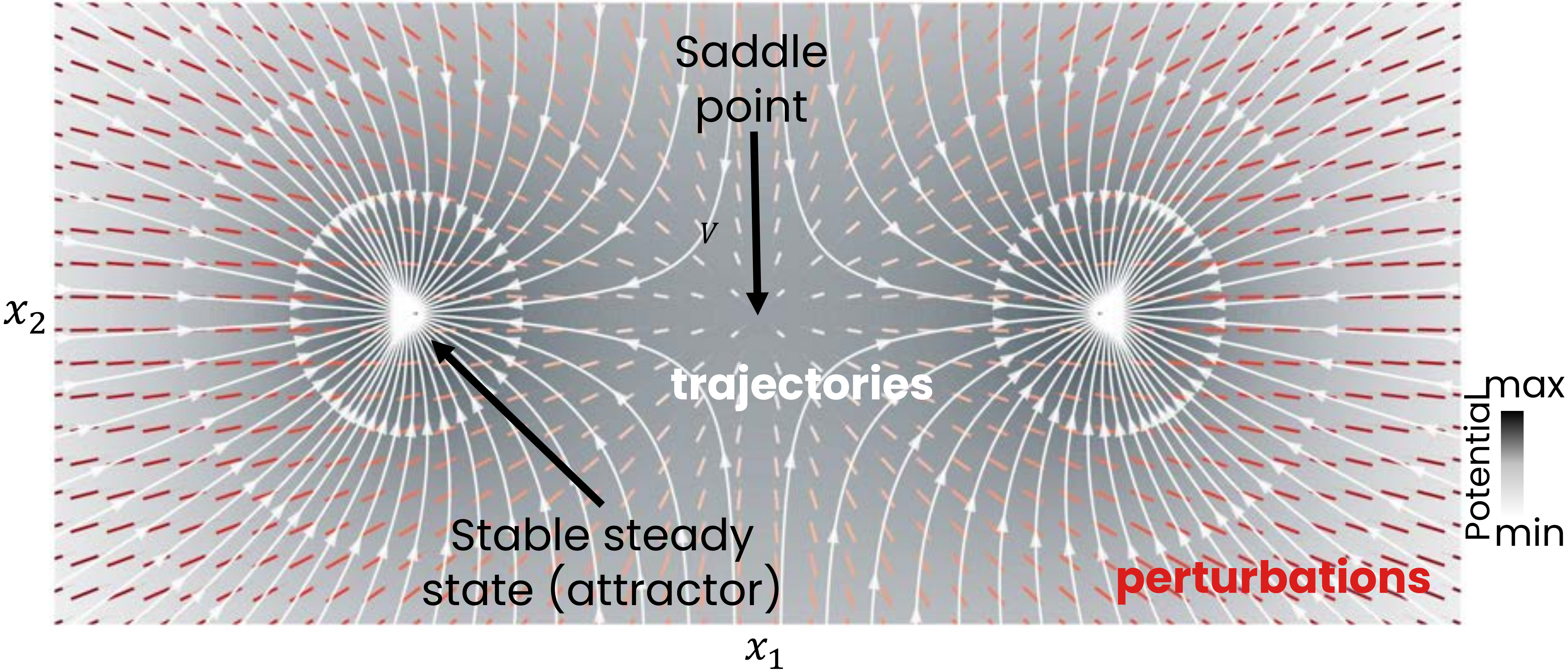
JM Coron

JM Raimond

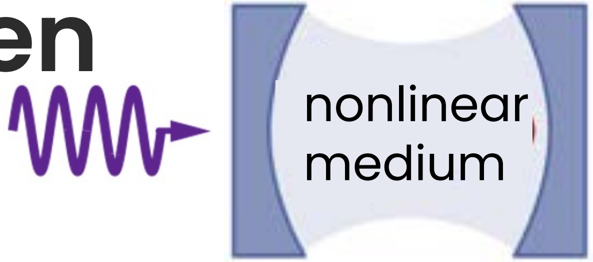
Dynamical systems

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

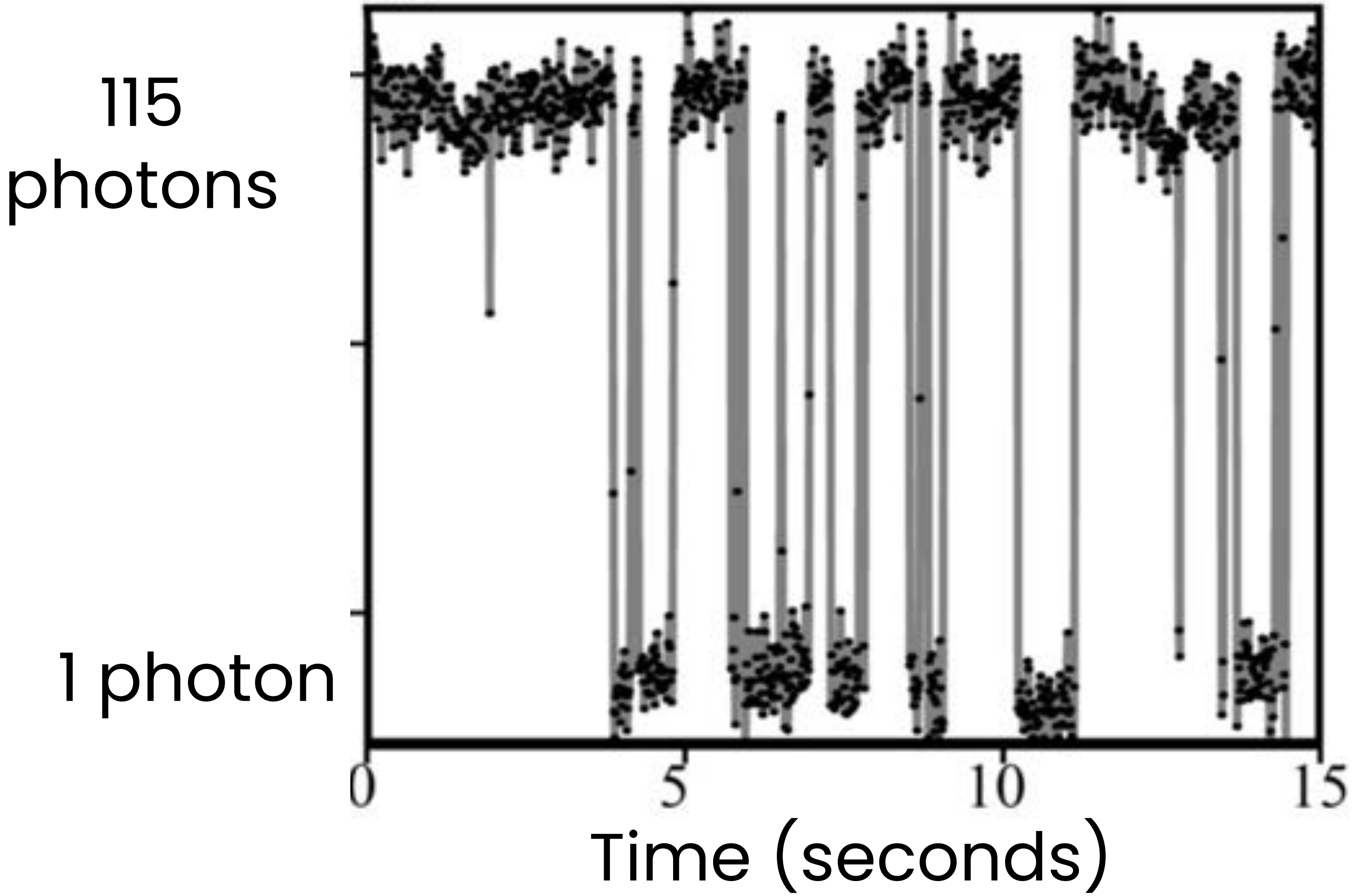




Macroscopic switching times between few-photon dynamical states



Muppalla PRB 2018

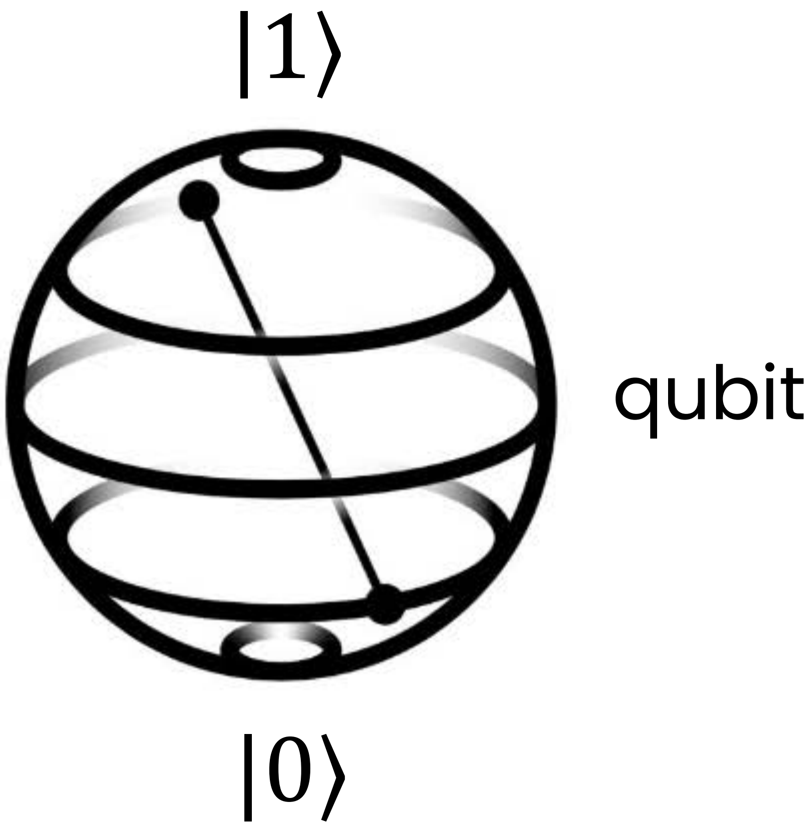


→ Ultra-low power classical logic

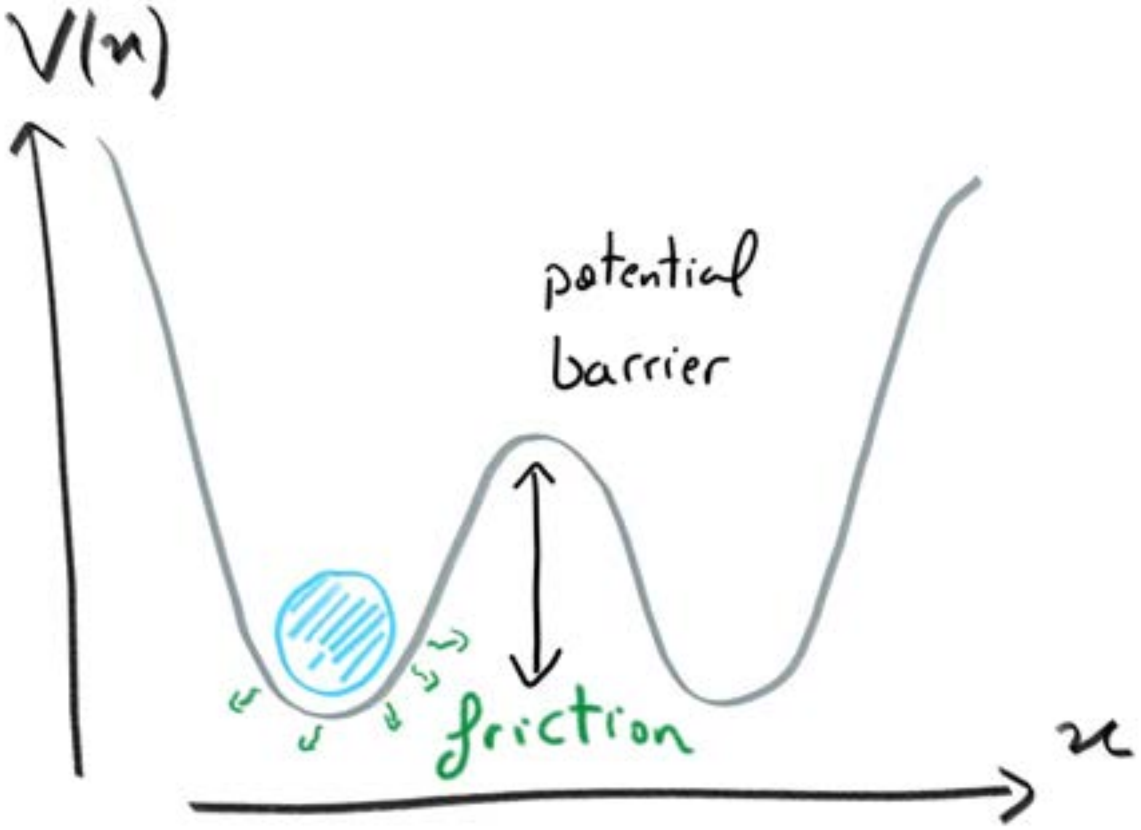
Andersen PRApp 2015

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

From dynamical bits to dynamical qubits

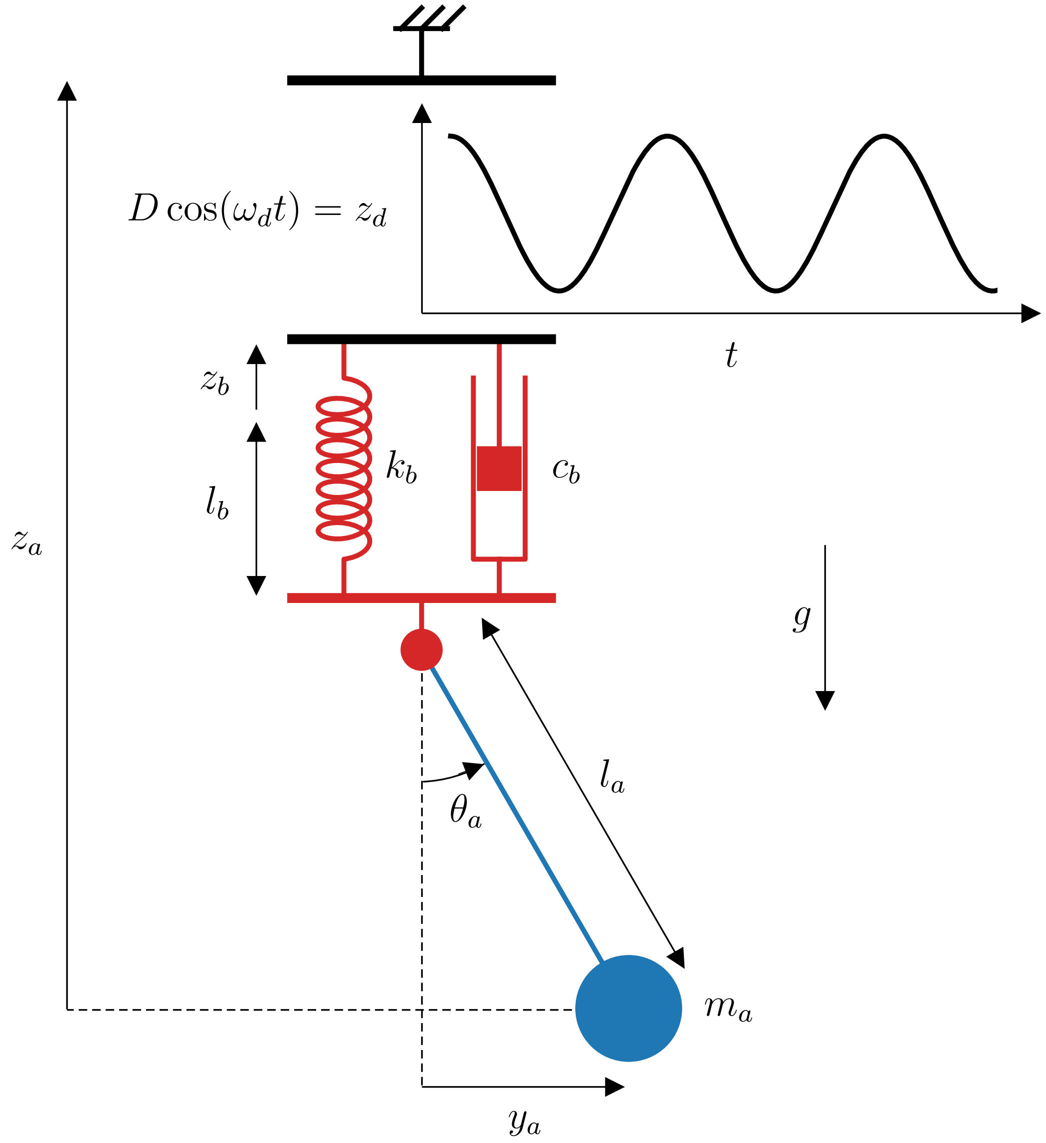


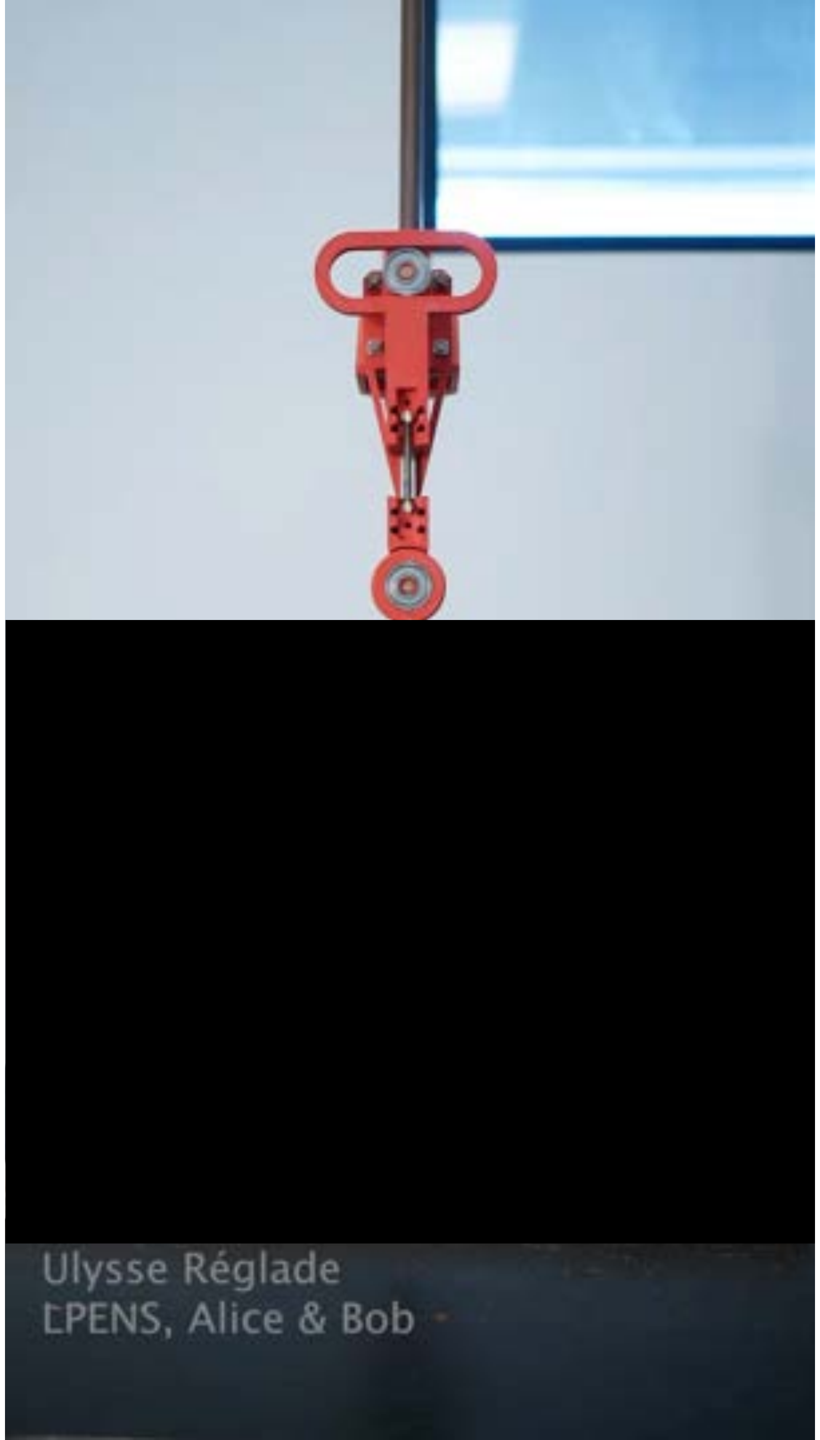
Is dissipation good or bad ?



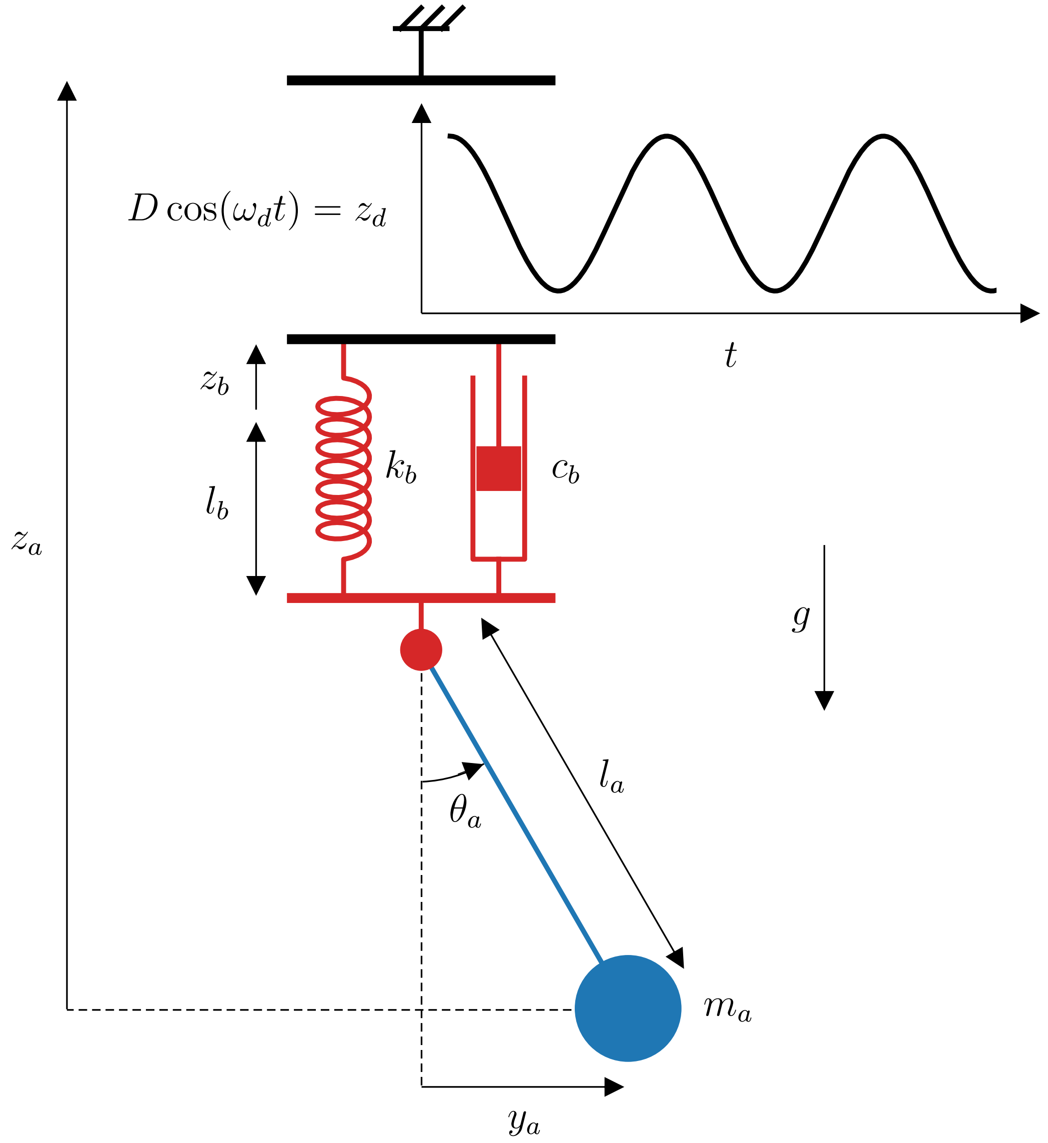
Friction (dissipation)
→ **Stability**
→ **Quantum decoherence**

Agnostic dissipation





Agnostic dissipation



Two-photon dissipation

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

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

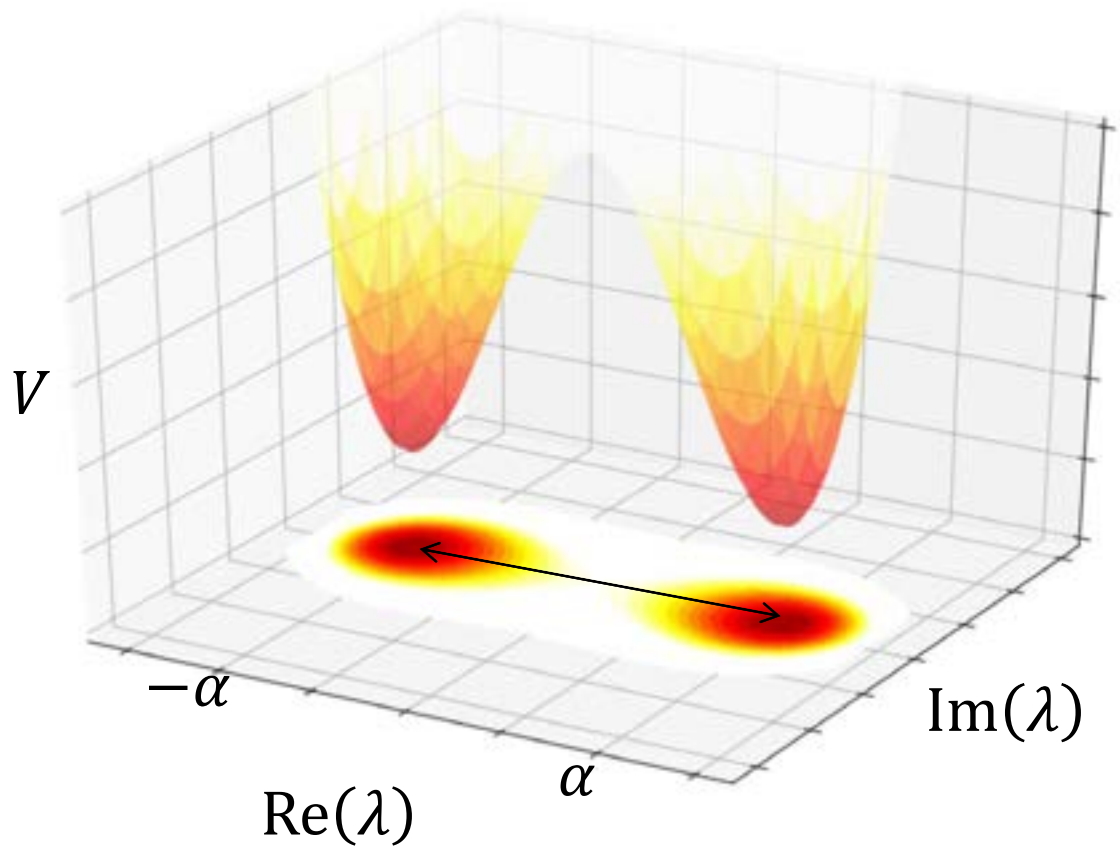
$$\alpha = \left(\frac{2\epsilon_2}{\kappa_2}\right)^{1/2}$$

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

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

Meta−potential $V(\lambda)$

$|\alpha|^2 = 4$

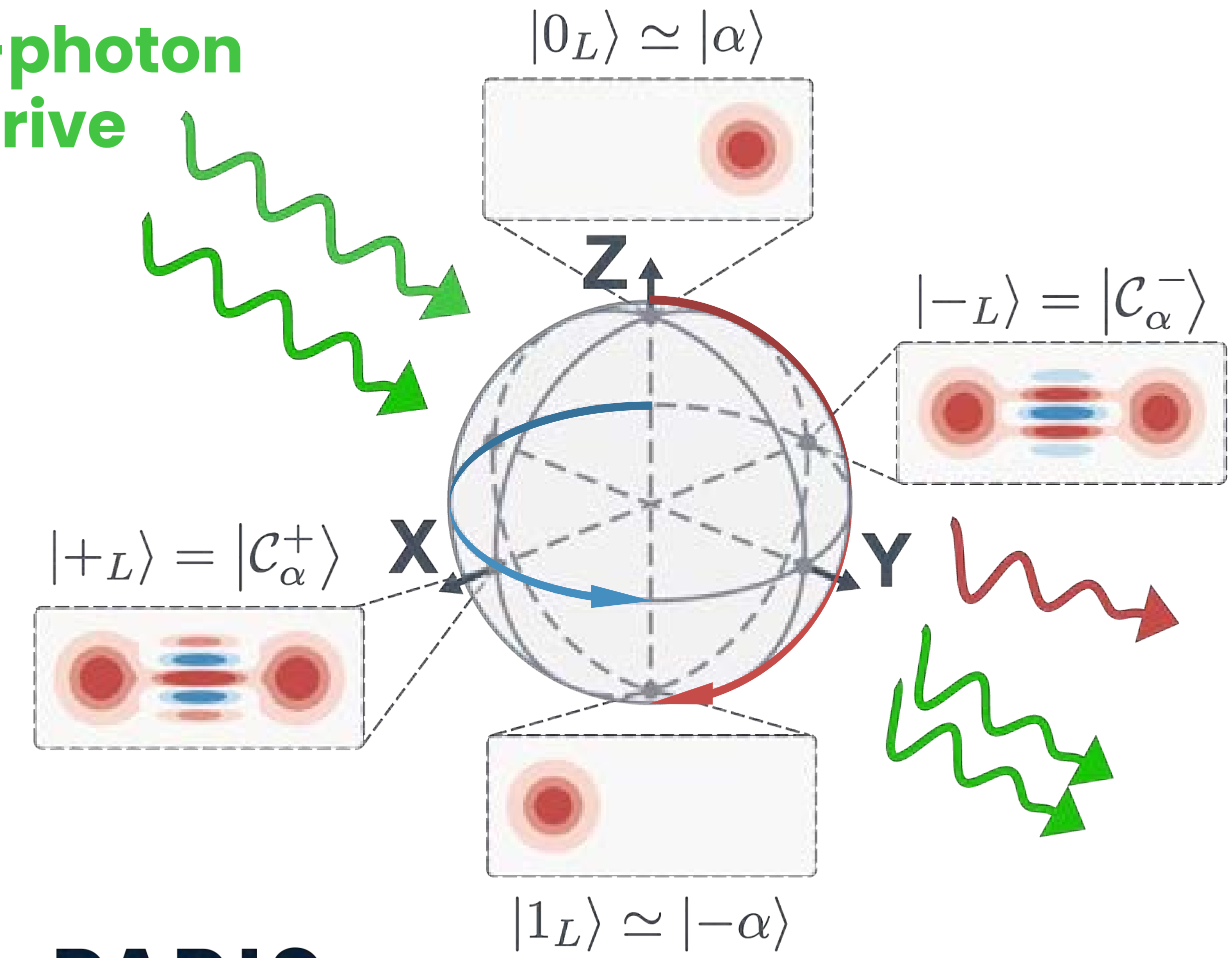


Wolinsky and Carmichael PRL (1998), Leghtas Science (2015)

The cat-qubit

The dissipative cat-qubit

Two-photon Drive



One-photon Dissipation κ_1

Two-photon Dissipation κ_2

Yale
Grimm, Nature 2020
Puri, Science Adv 2019
Touzard, PRX 2018
Leghtas, Science 2015

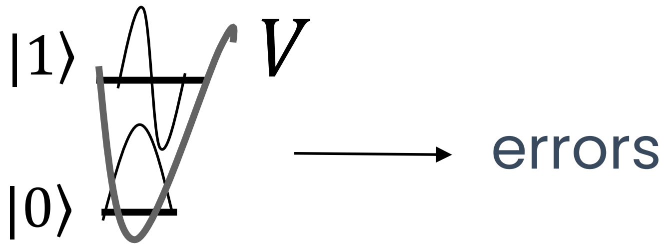
PARIS
Réglade Nature 2025
Lescanne Nature Phys 2020
Mirrahimi NJP 2014

Rousseau 2025
LYON Marquet PRX 2024

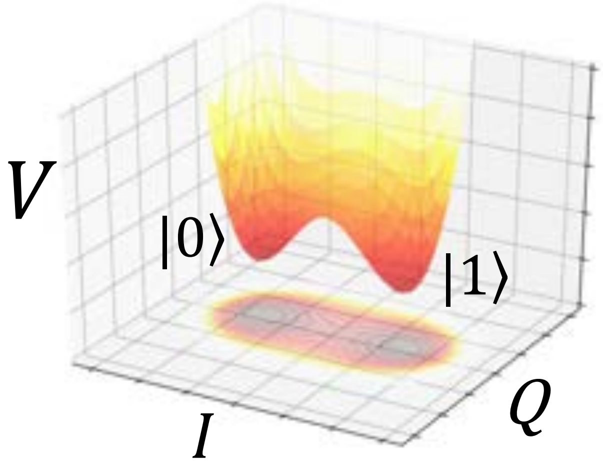
aws
Chamberland PRXQ 2022
Putterman Nature 2025

The dissipative cat-qubit

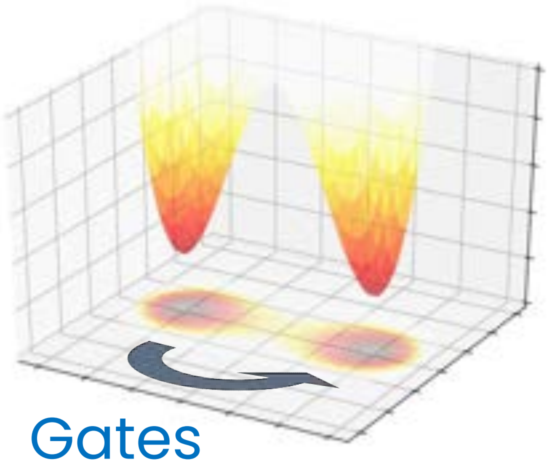
Standard qubit : local



Cat qubit : non-local



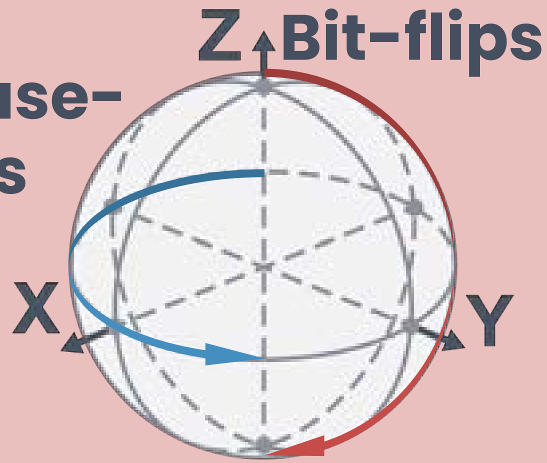
Exponential suppression of bit-flip errors

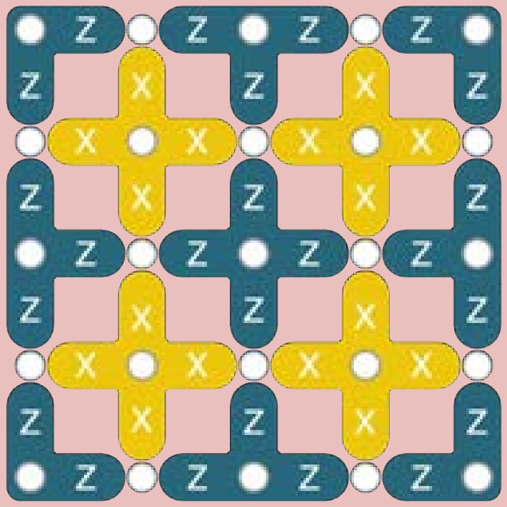


- Linear increase in phase-flip errors
- Gates : rotations in phase-space

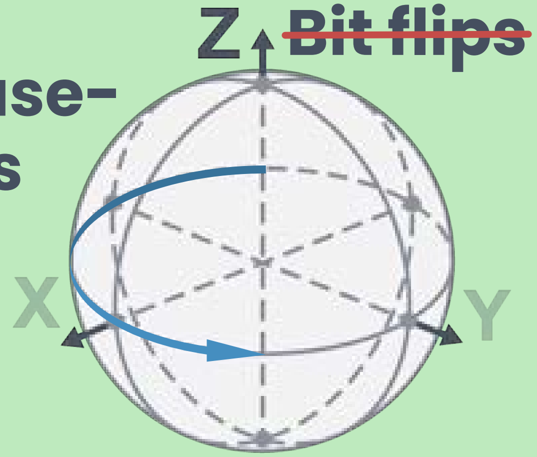
Biased-noise qubits reduce hardware overhead

Standard qubits





Biased-noise qubits



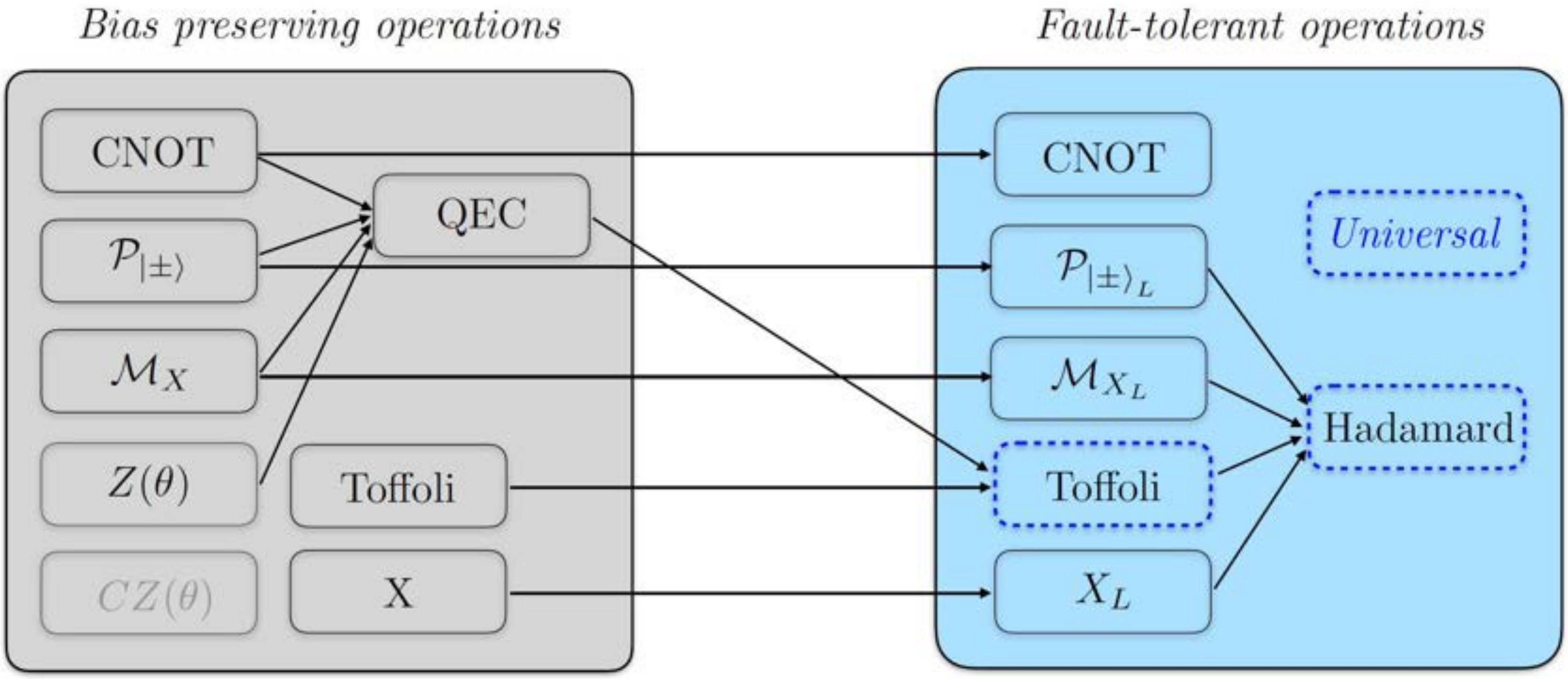
x10-100 less overhead
but requires bias preserving operations

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

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

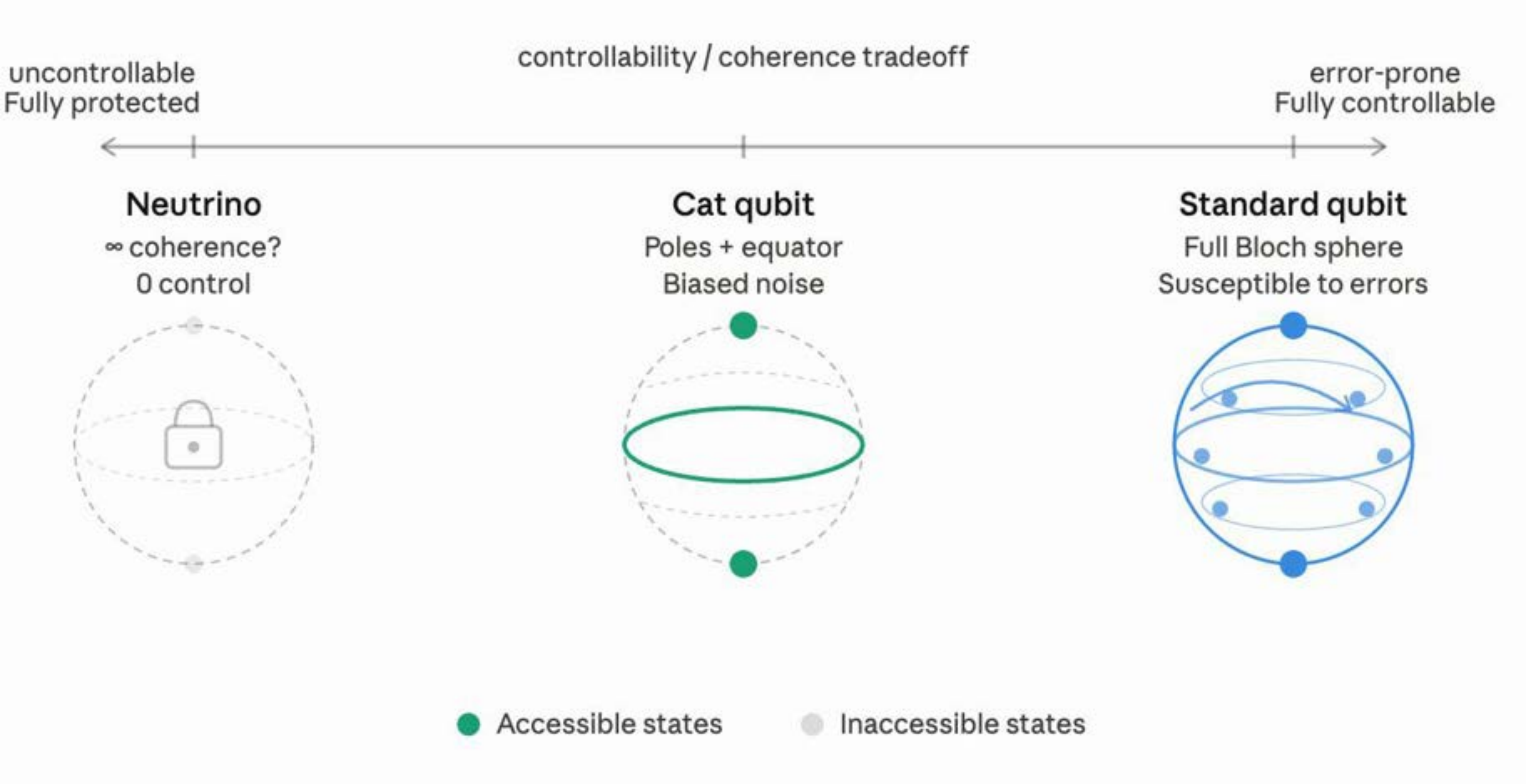
Puri, Science Adv, 2023
Ruiz, 2023

Universal set of fault-tolerant gates



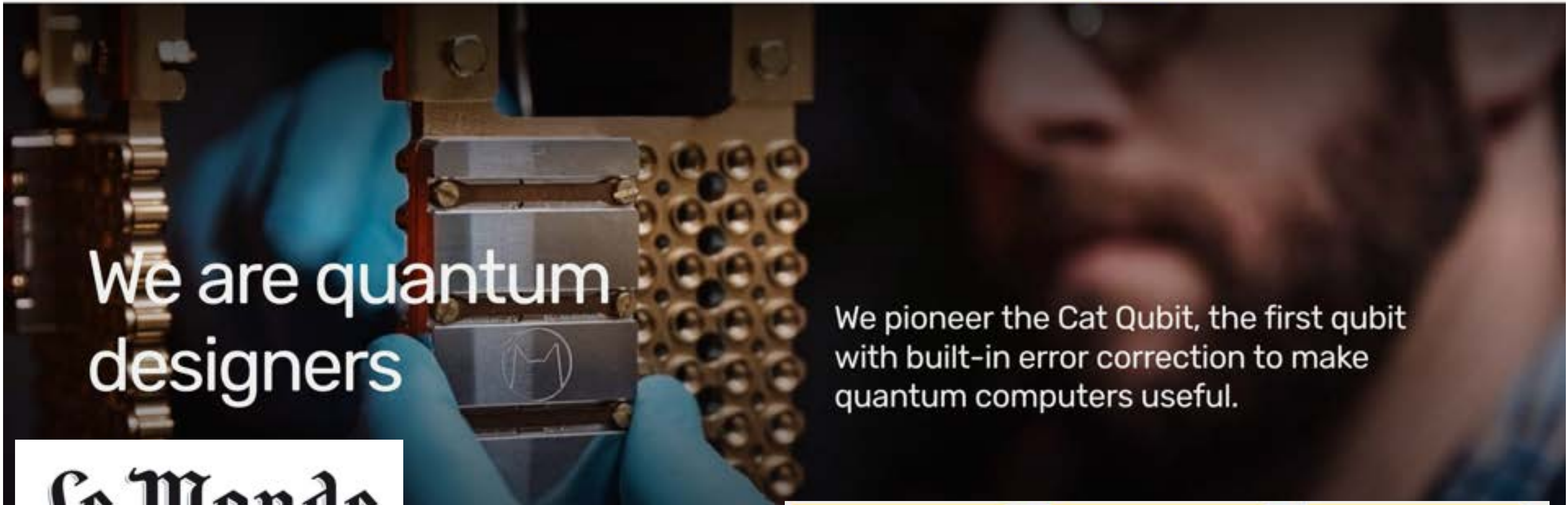
Guillaud, Mirrahimi, PRX 2019

Controllability versus coherence



ALICE & BOB

SCIENCE · TECH · SOLUTIONS · CLOUD · THAT'S US · ROADMAP · RESOURCES · JOIN US



Le Monde

ÉCONOMIE · ENTREPRISES

Alice & Bob lève 100 millions d'euros pour développer son ordinateur quantique

La jeune start-up française, fondée en 2020, prévoit de sortir son premier modèle abouti d'ici à 2030.

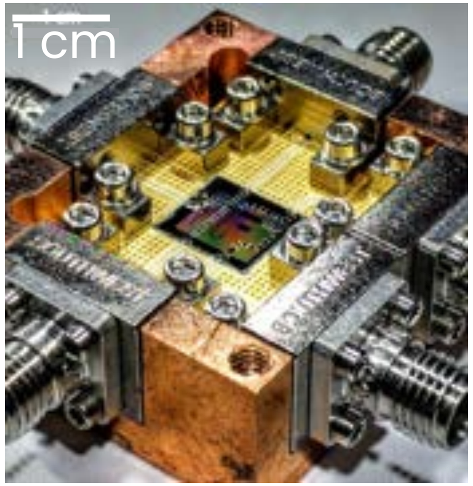
Par Vincent Fagot

Publié le 28 janvier 2025 à 20h20, modifié le 29 janvier 2025 à 11h52 · Lecture 1 min.

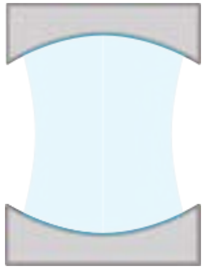
Employees	Offices	Money raised
250+	4	€130M+
PhD holders	**Nationalities**	**Gender Parity (EgaPro index)**
79	35	54/100

Circuit QED

Superconducting circuits

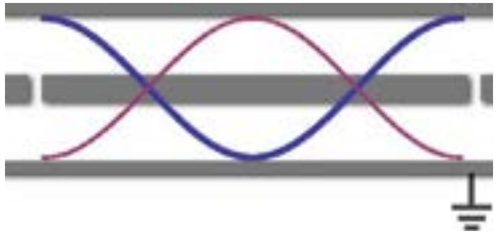


High quality cavity



=

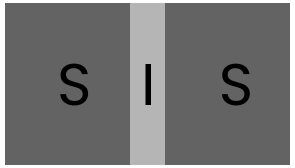
$f \approx 5\ \text{GHz},\ \ Q \approx 10^{6-8}$



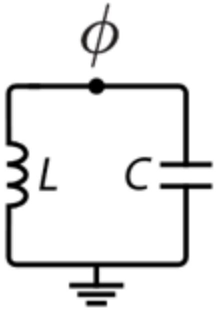
Non-linear element

=

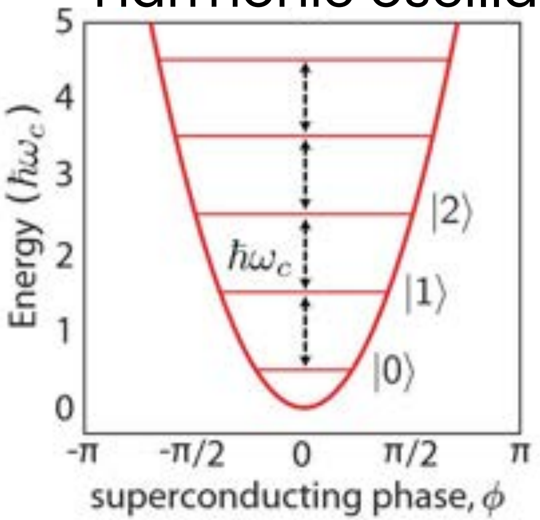
$100\ \text{nm} \times 100\ \text{nm}$



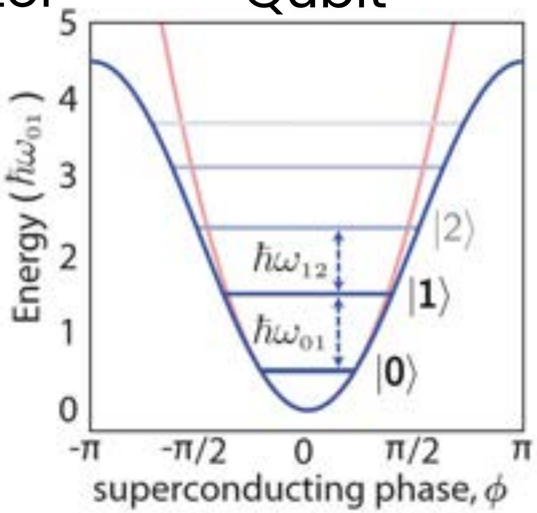
Josephson junction

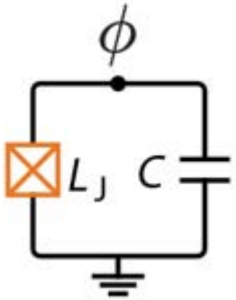


Harmonic oscillator



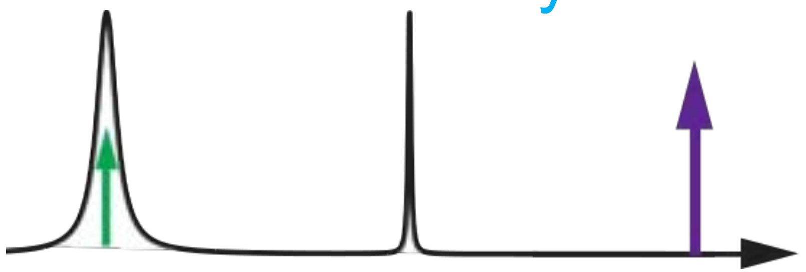
Qubit



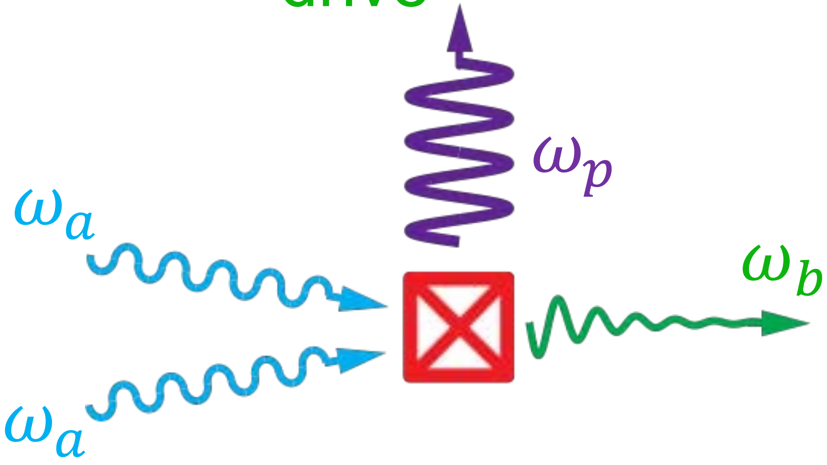


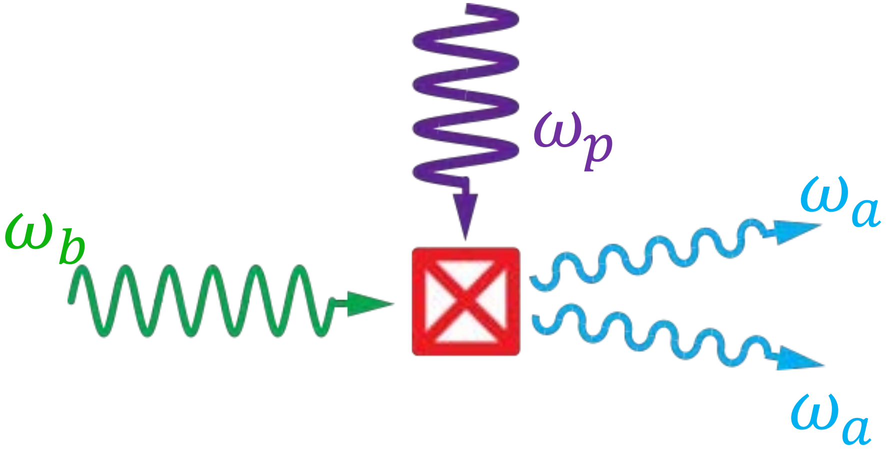
Applied Physics Reviews 6, 021318 (2019)

Engineering 2-photon exchanges



$$\omega_p = 2\omega_a - \omega_b$$



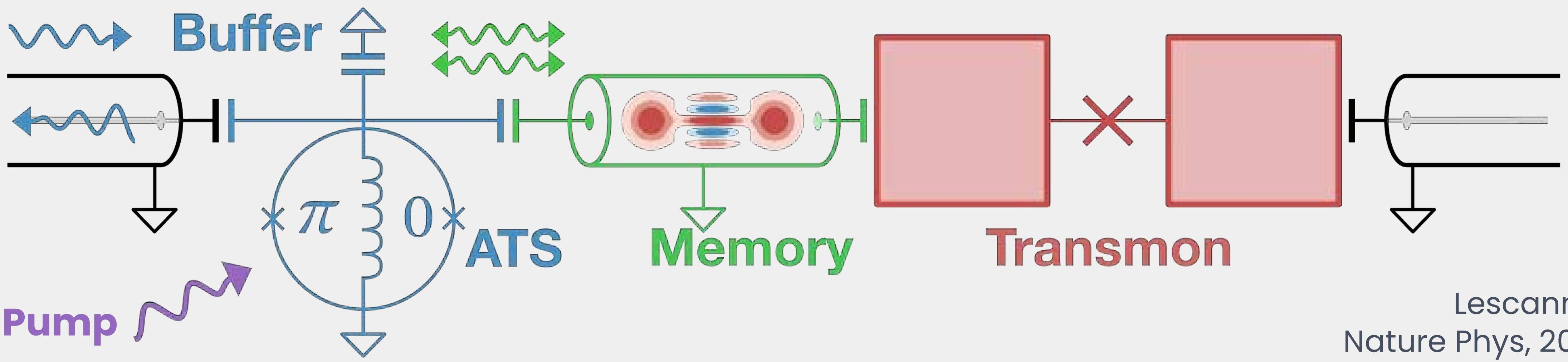


$$H = g_2 a^2\, b^\dagger + \text{h.c} \quad + \quad \epsilon\, b + \text{h.c}$$

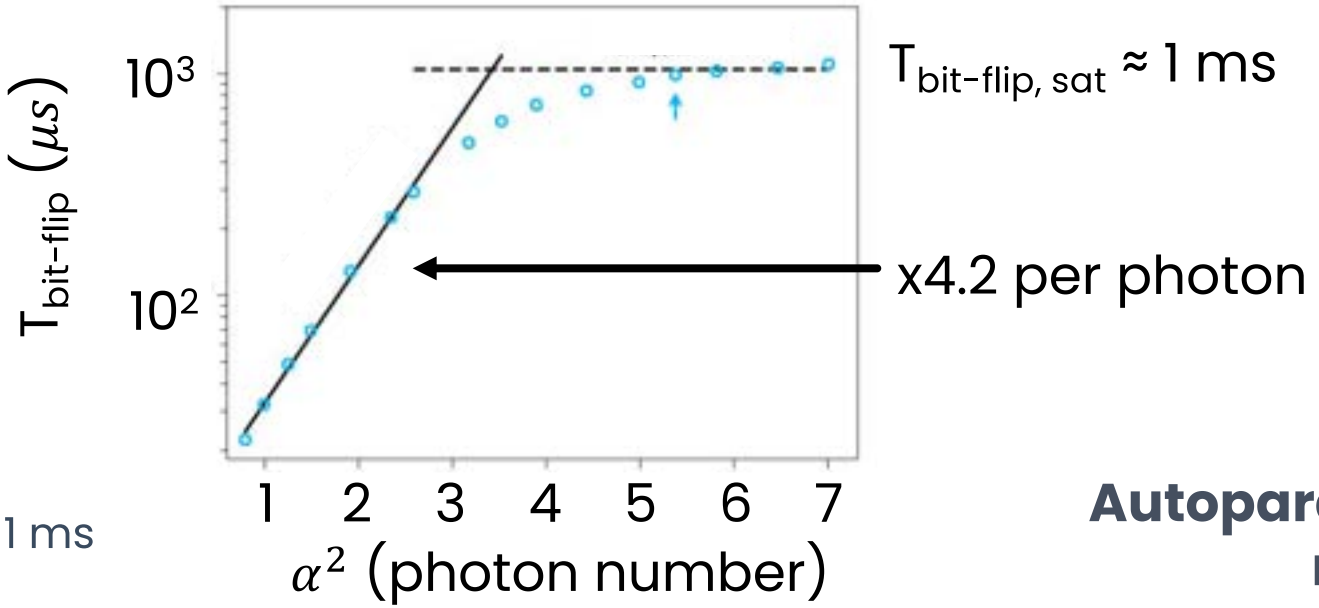
Effective loss $\sqrt{\kappa_2}a^2$

Effective drive $i\epsilon_2 {a^\dagger}^2 + \text{h.c}$

Previous experiments plateaued around 1 ms



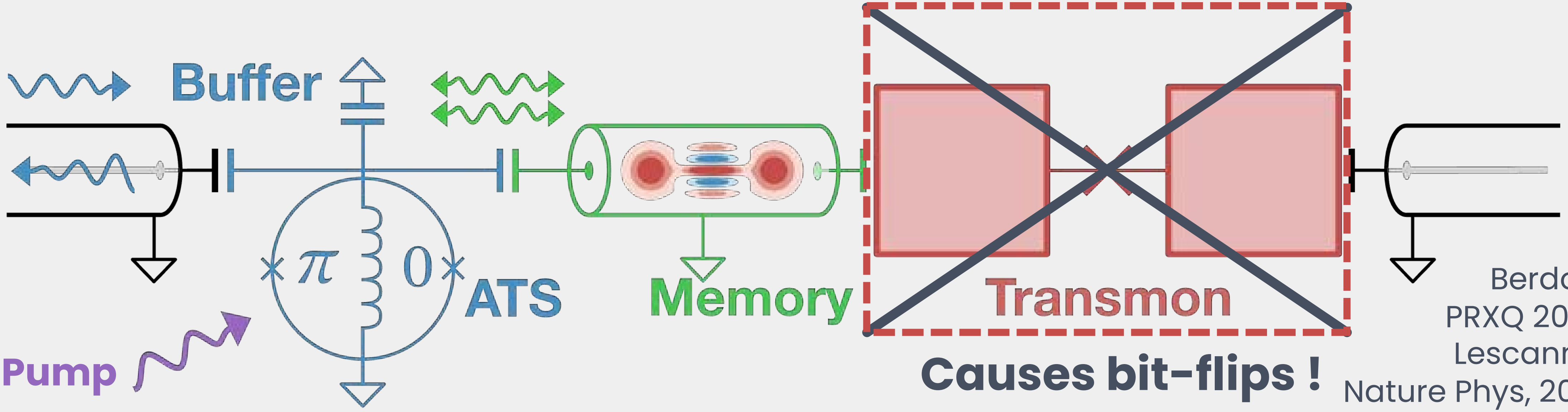
Lescanne,
Nature Phys, 2019



Kerr-cats also limited to about 1 ms
Grimm, Frattini, Nature, 2020
Frattini, Cortiñas, 2022

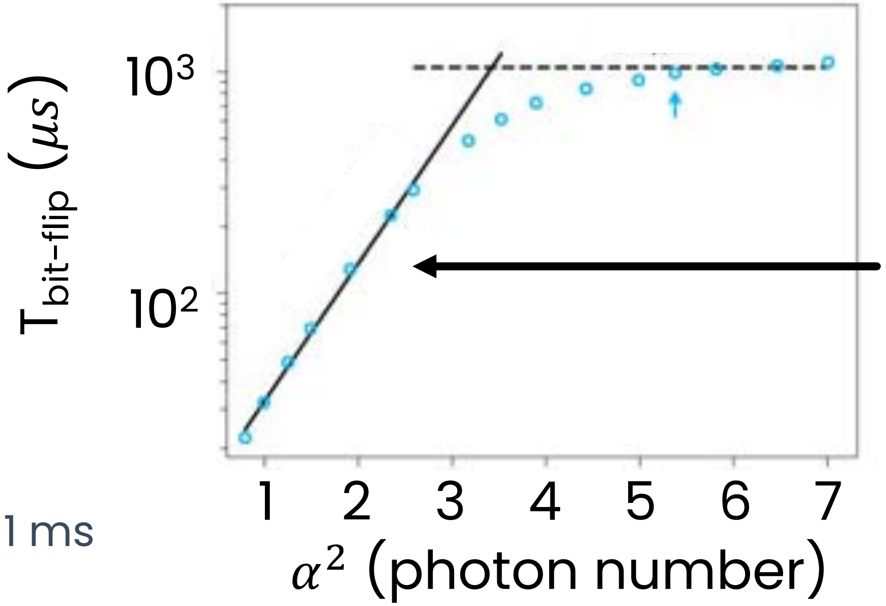
Autoparametric cats reached 0.3s
Marquet, …, Huard, 2023

Transmon limits the bit-flip time



Causes bit-flips !

Berdou, PRXQ 2023
Lescanne, Nature Phys, 2019



$T_{\text{bit-flip, sat}} \approx 1$ ms

x4.2 per photon

Kerr-cats also limited to about 1 ms
Grimm, Frattini, Nature, 2020
Frattini, Cortiñas, 2022

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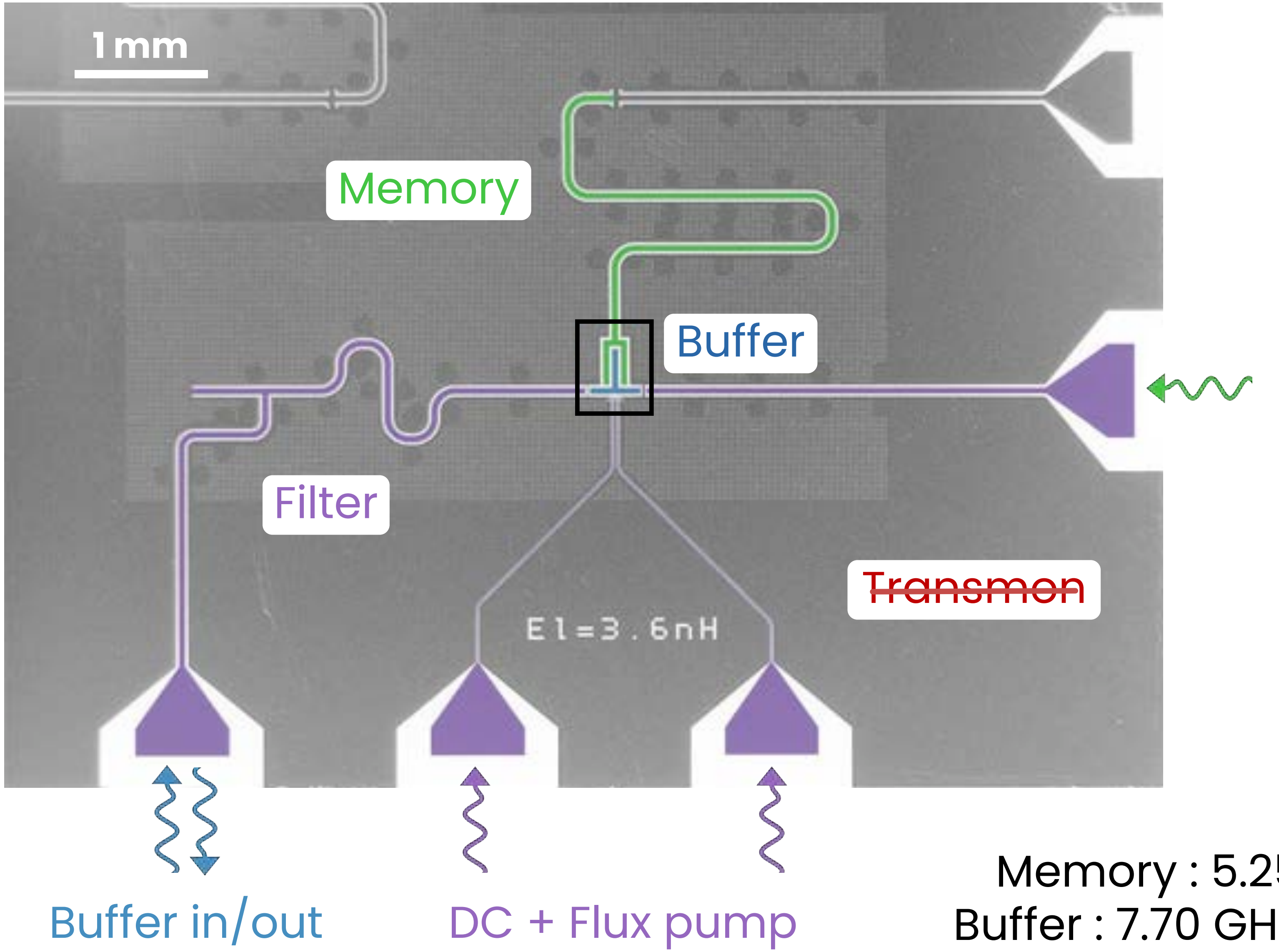
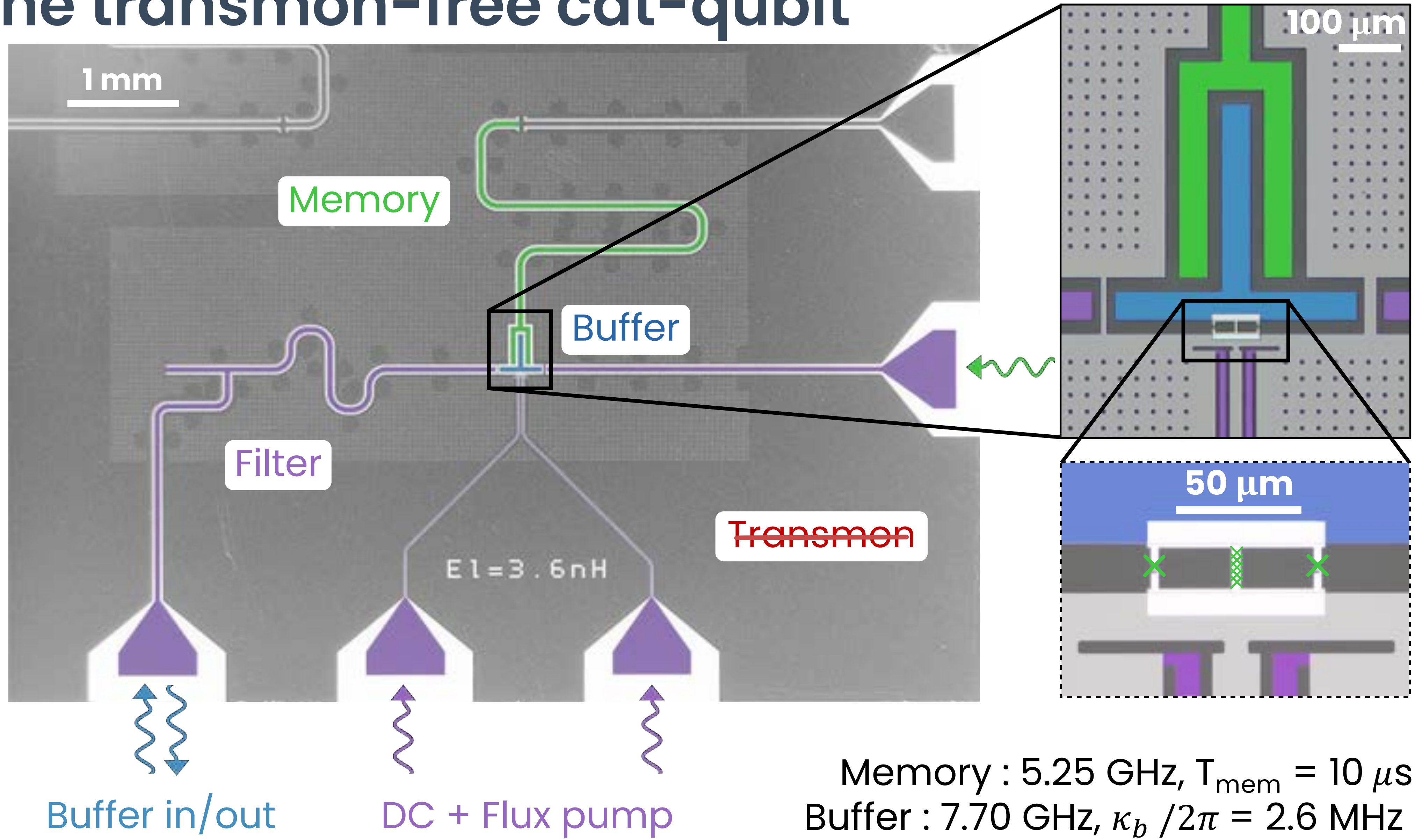
The transmon-free cat-qubit



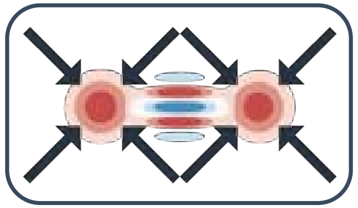
Memory : 5.25 GHz, T_{mem} = 10 μs
Buffer : 7.70 GHz, κ_b /2π = 2.6 MHz

The transmon-free cat-qubit



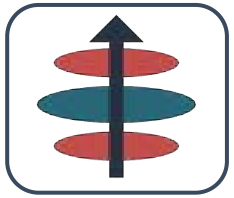
Memory : 5.25 GHz, T_{mem} = 10 μs
Buffer : 7.70 GHz, $\kappa_b /2\pi$ = 2.6 MHz

4 gadgets to replace the transmon



Inflate

Pump + buffer drive



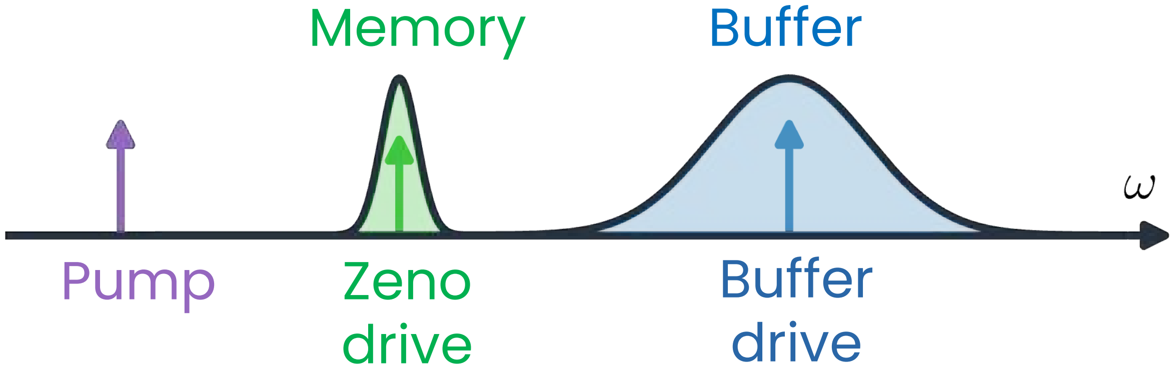
Zeno gate

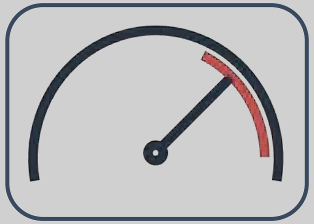
Pump + buffer & Zeno drives

Deflate

Pump

$$\omega_p = 2\omega_a - \omega_b$$

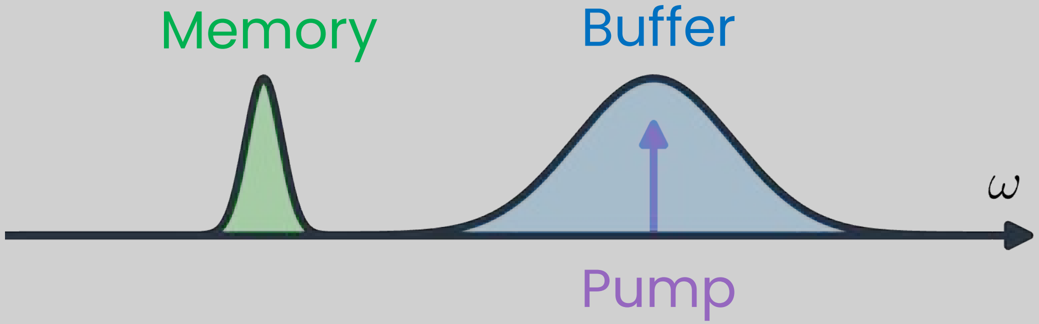




Count number of photons

$$H = g_l a^\dagger a \, (b + b^\dagger)$$

$$\omega_p = \omega_b$$



Count number of photons

$H = g_l a^\dagger a\,(b + b^\dagger)$

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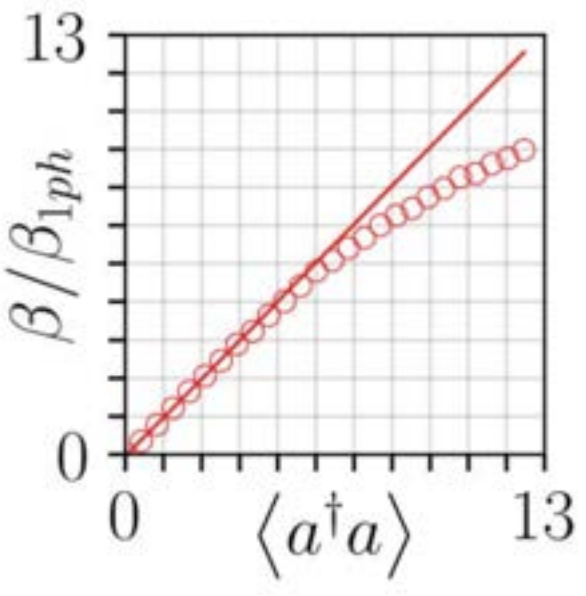
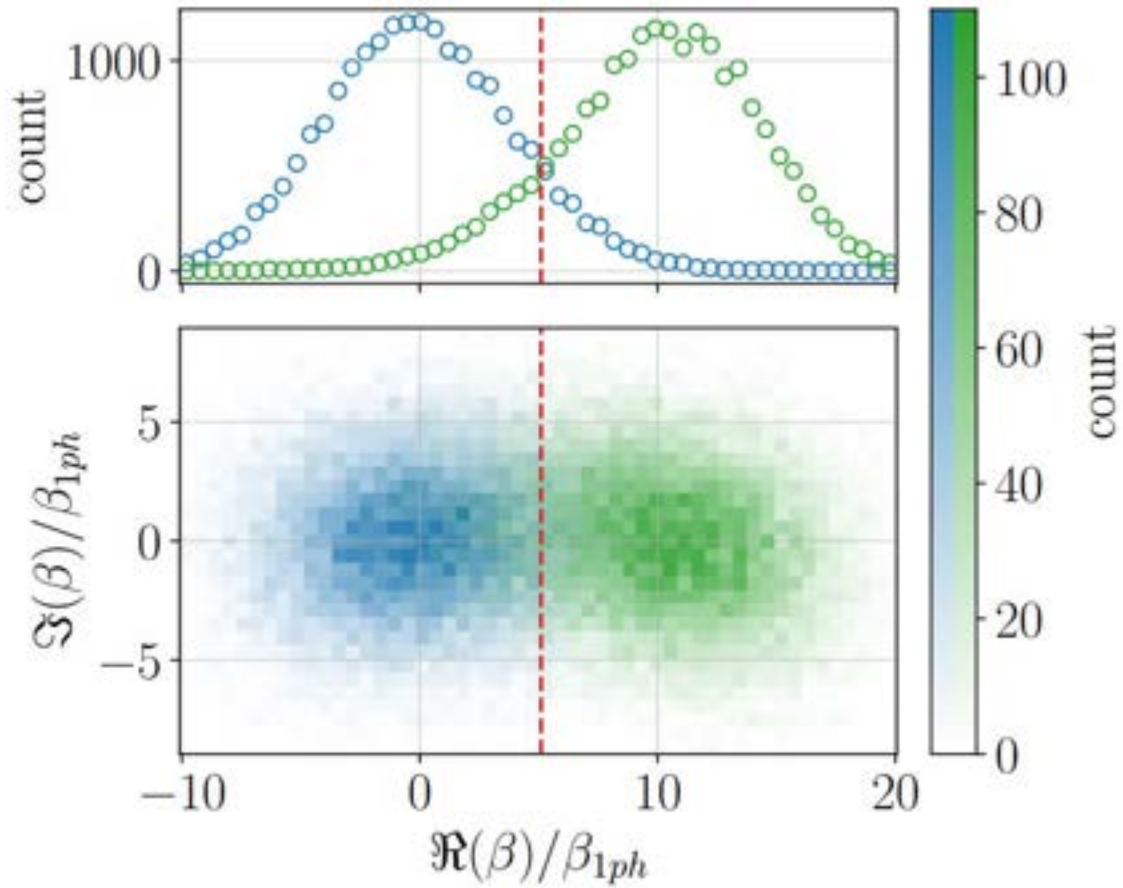
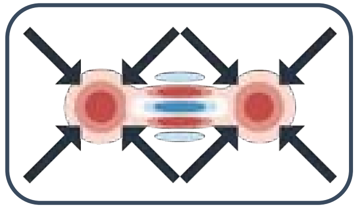




Inflate

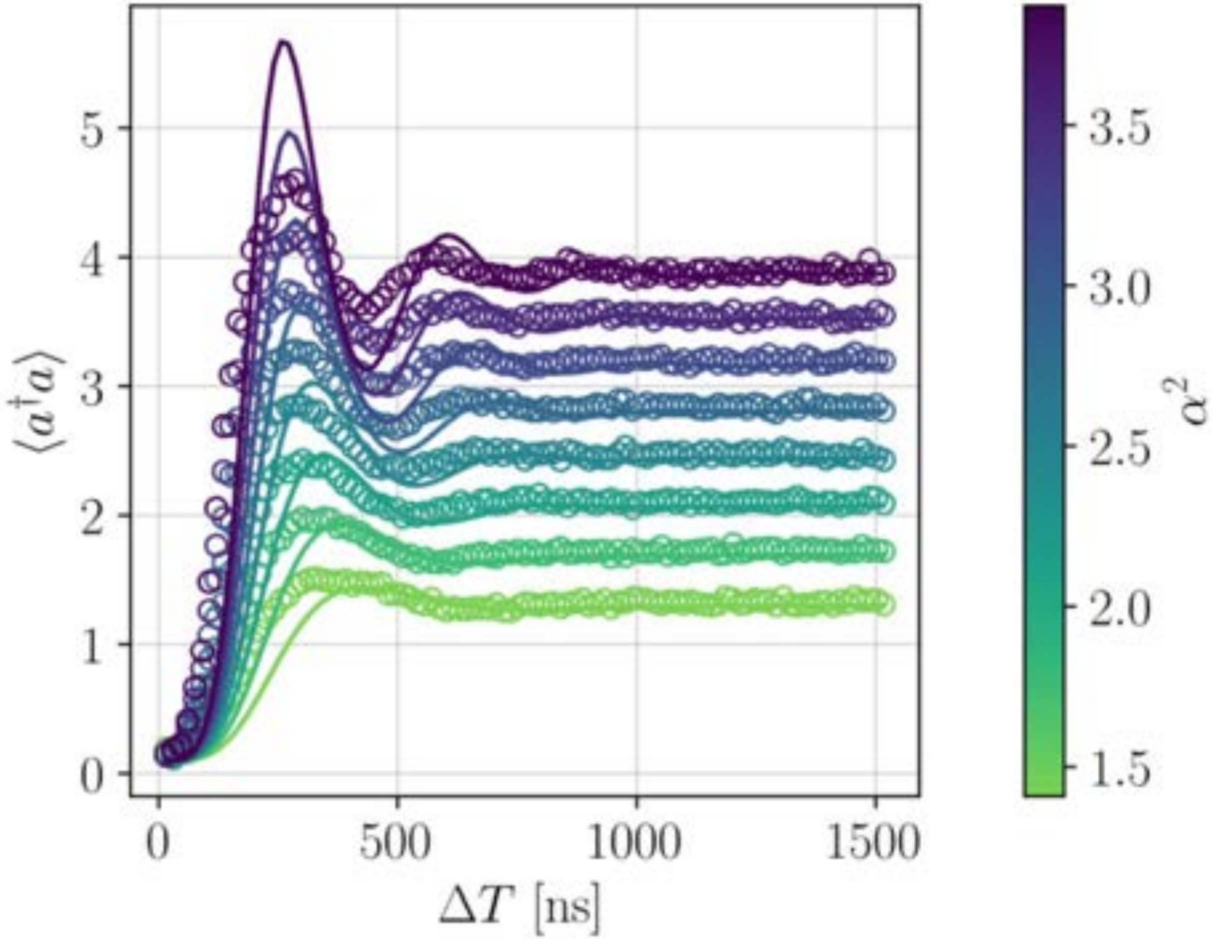


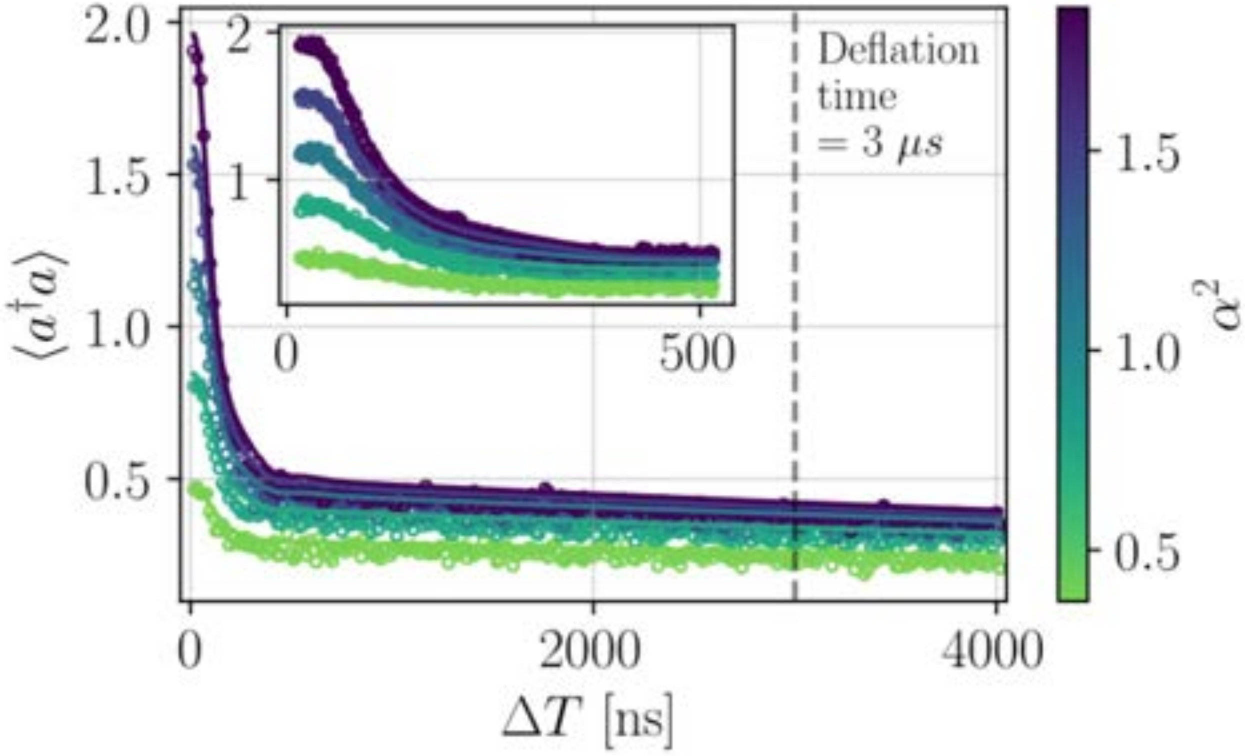
Drive ON

$\omega_p = 2\omega_a - \omega_b$

Deflate

Drive OFF



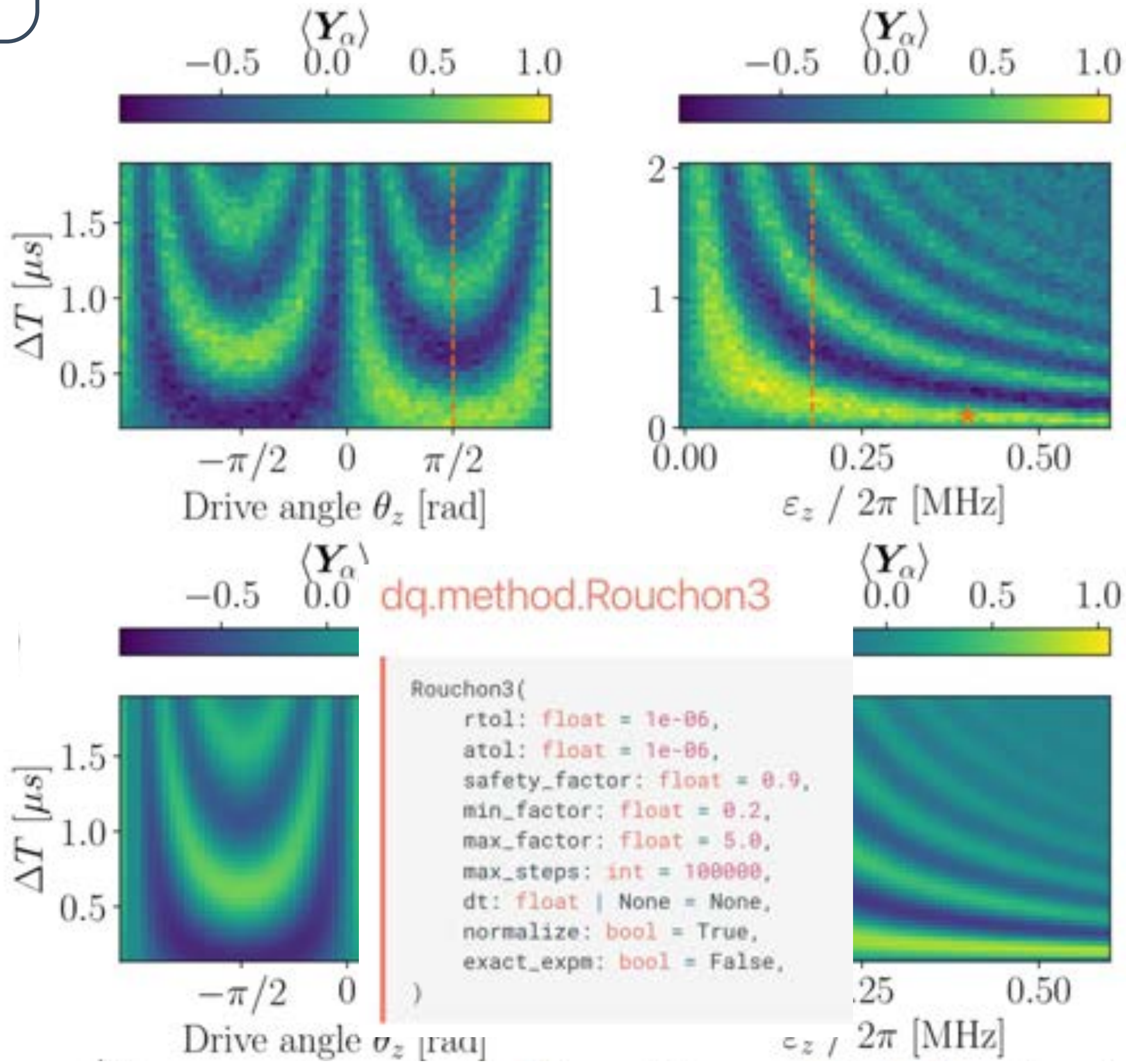


Zeno gate

$\omega_p = 2\omega_a - \omega_b$

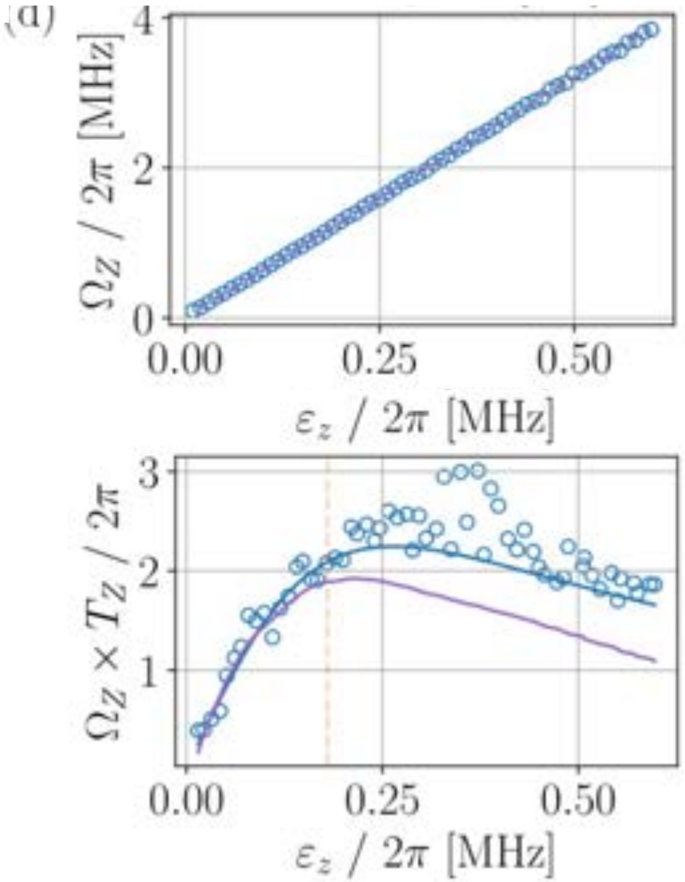
Data

Theory



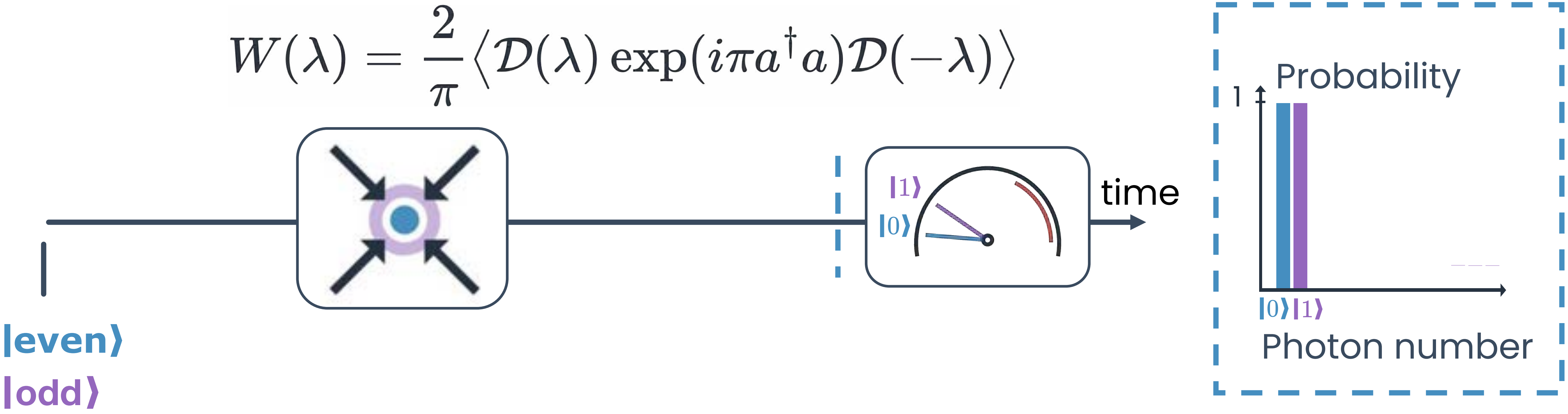
dq.method.Rouchon3

```
Rouchon3(
    rtol: float = 1e-06,
    atol: float = 1e-06,
    safety_factor: float = 0.9,
    min_factor: float = 0.2,
    max_factor: float = 5.0,
    max_steps: int = 100000,
    dt: float | None = None,
    normalize: bool = True,
    exact_expm: bool = False,
)
```



Transmon-free tomography protocols

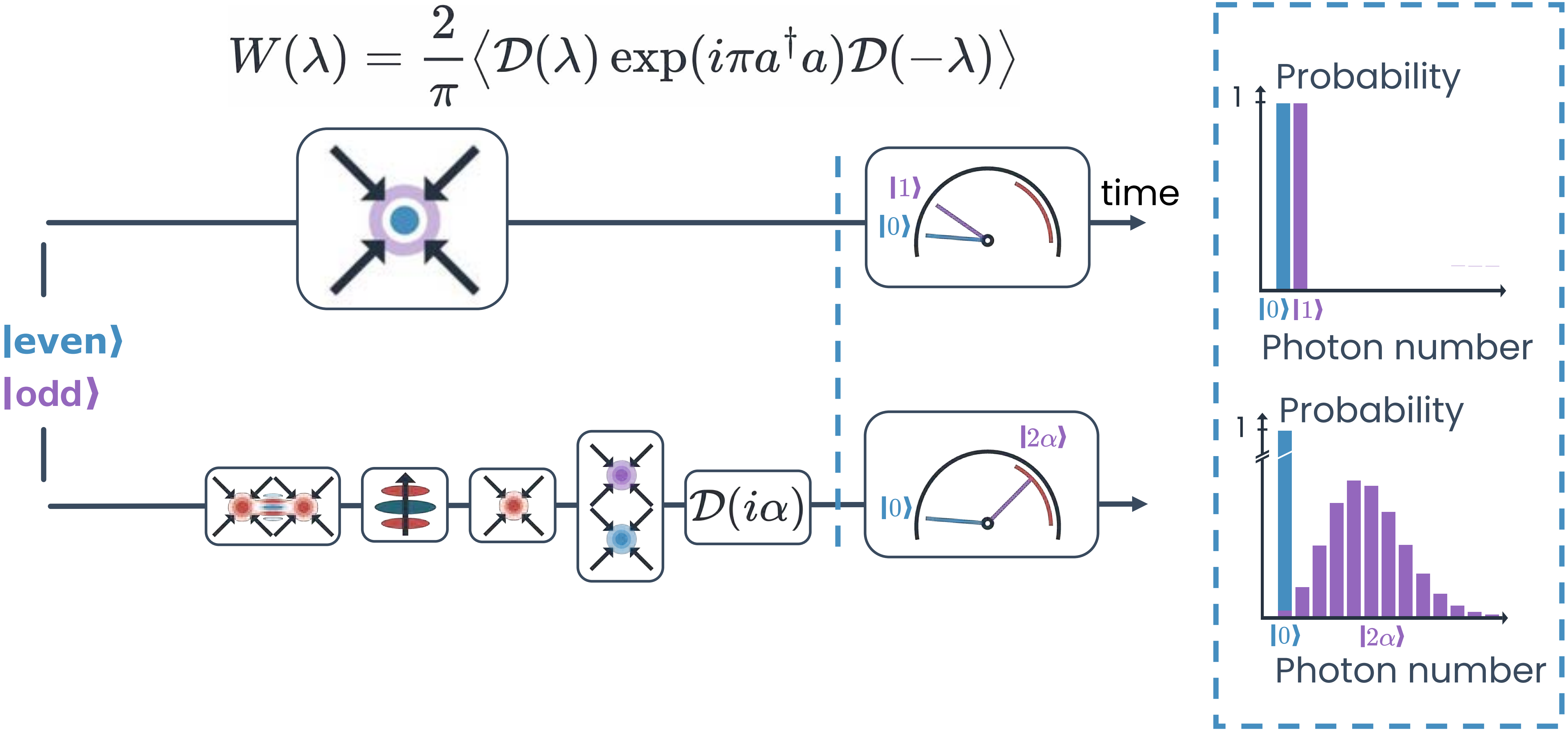
$$W(\lambda) = \frac{2}{\pi}\langle \mathcal{D}(\lambda)\exp(i\pi a^\dagger a)\mathcal{D}(-\lambda)\rangle$$



Albert PRL 2016
Grimm, Frattini, Nature, 2020

Transmon-free tomography protocols

$$W(\lambda) = \frac{2}{\pi}\langle \mathcal{D}(\lambda)\exp(i\pi a^\dagger a)\mathcal{D}(-\lambda)\rangle$$



Albert PRL 2016
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Transmon-free tomography protocols

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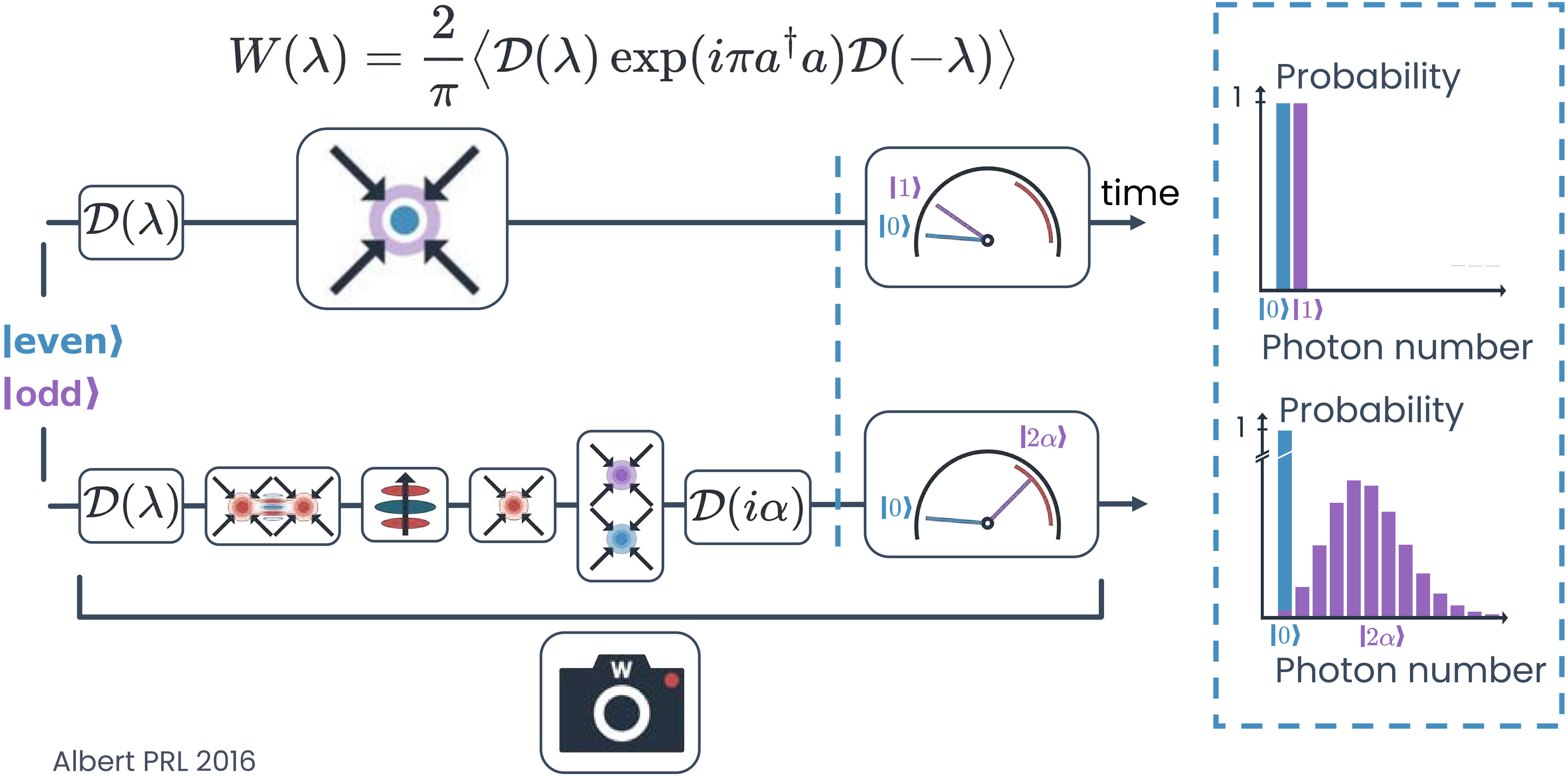
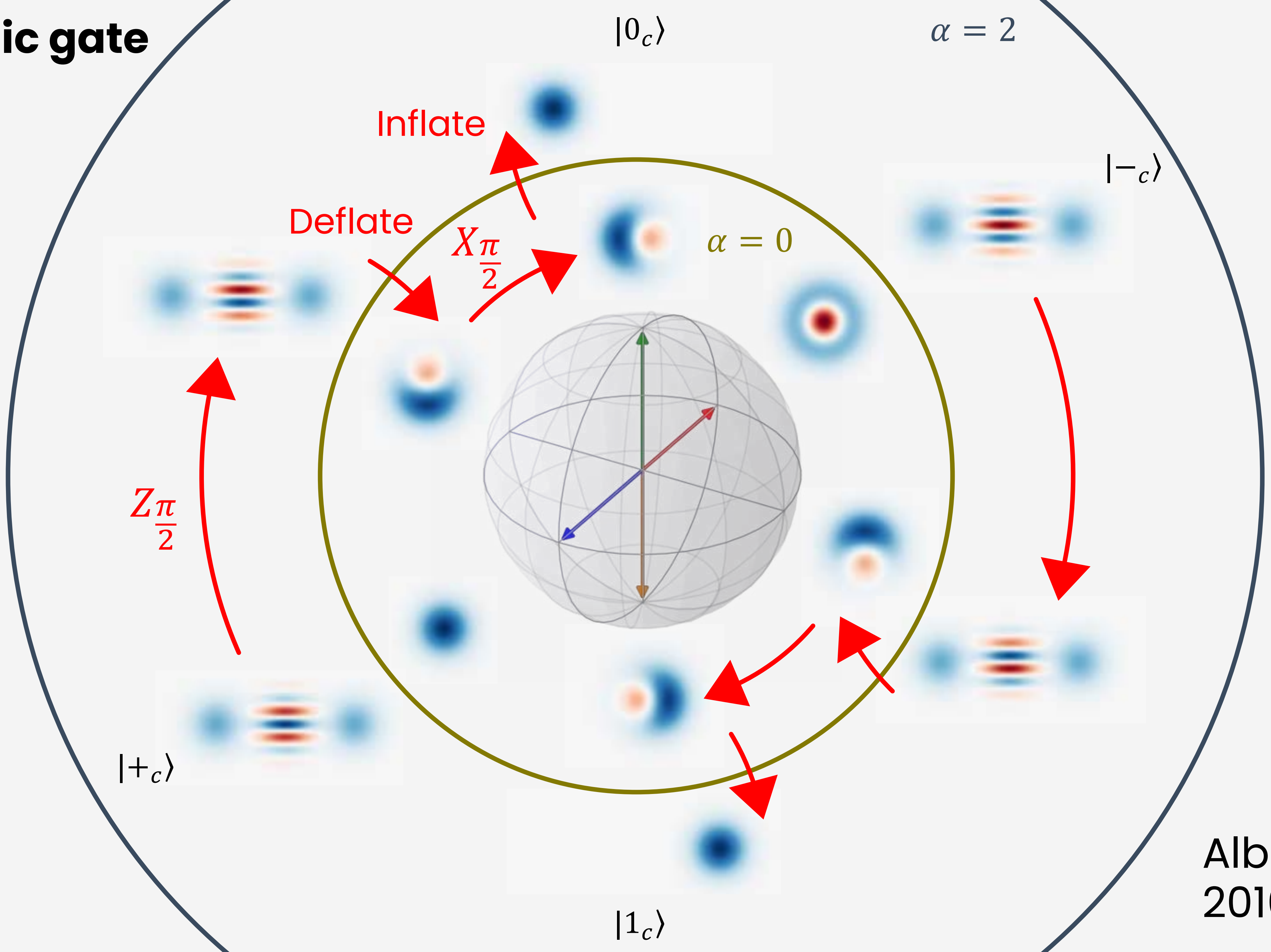


Albert PRL 2016
Grimm, Frattini, Nature, 2020

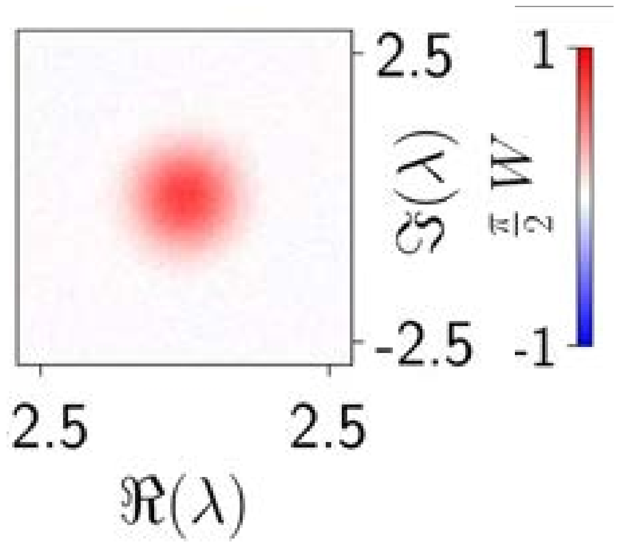
Holonomic gate



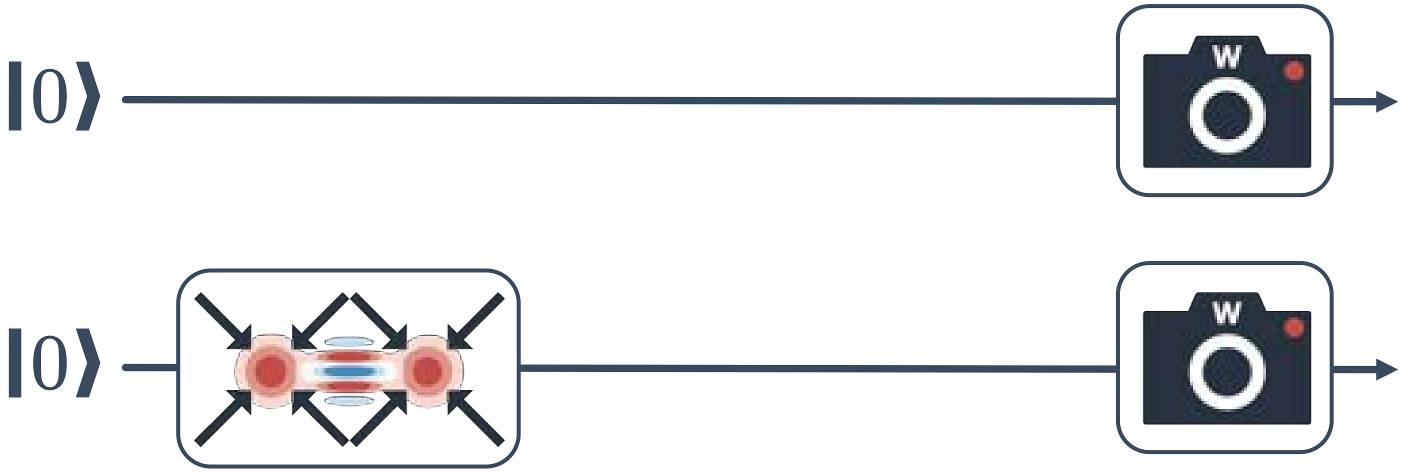
Albert PRL 2016

Transmon-free tomography examples

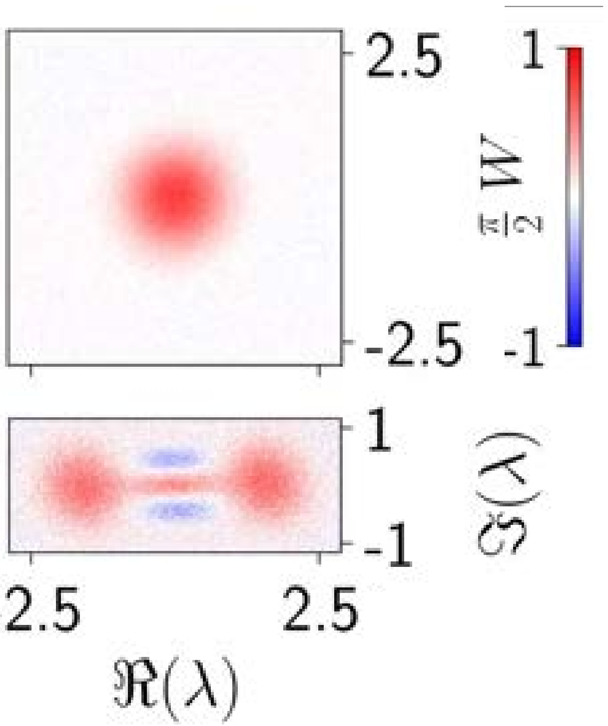
Data



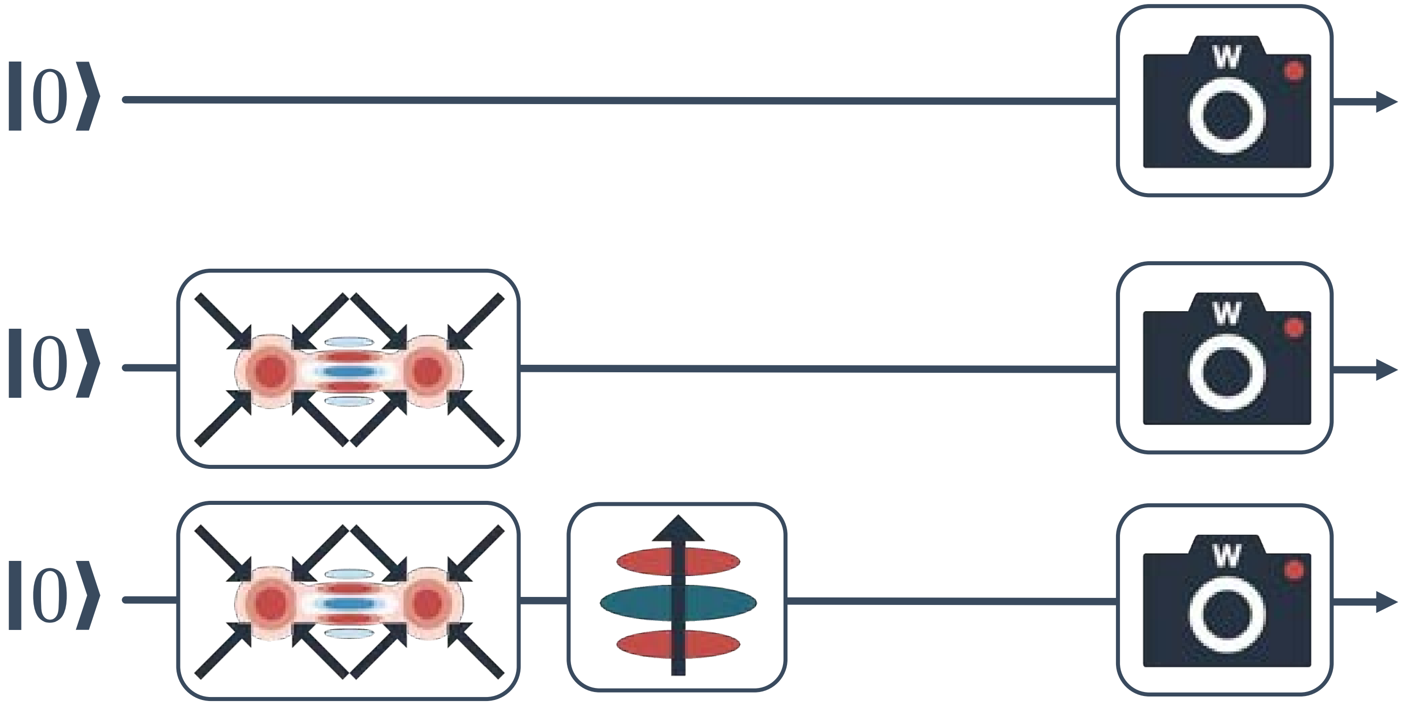
Transmon-free tomography examples



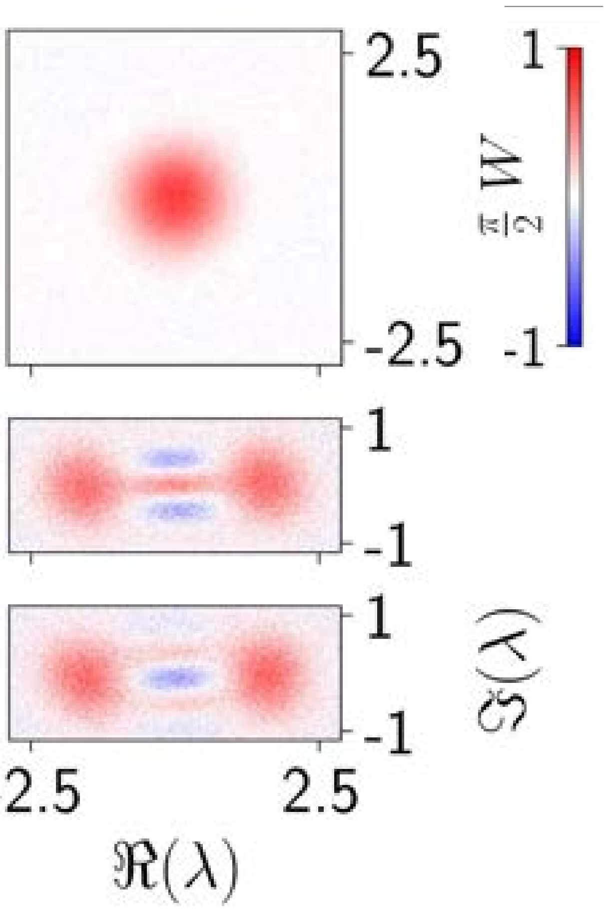
Data



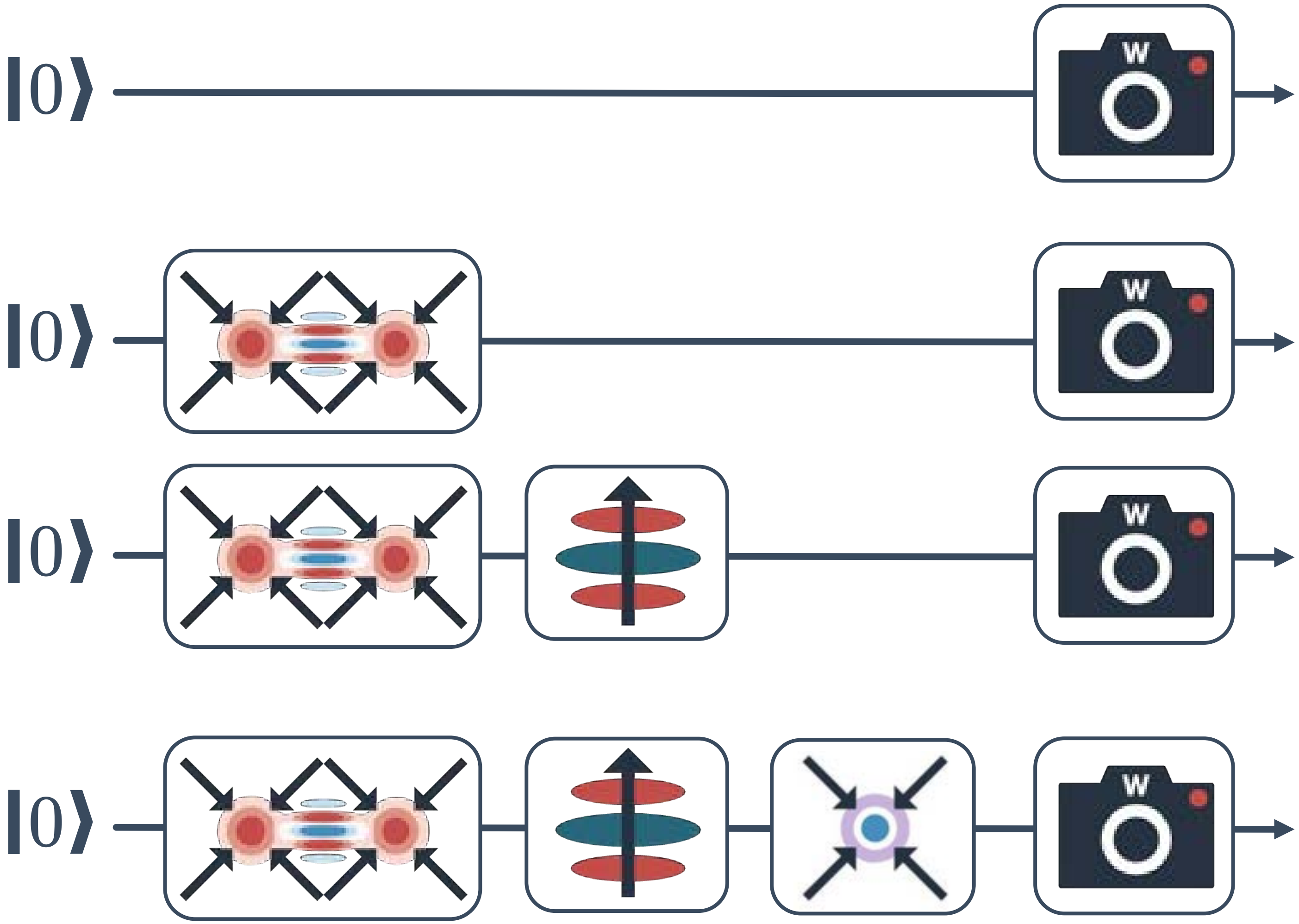
Transmon-free tomography examples

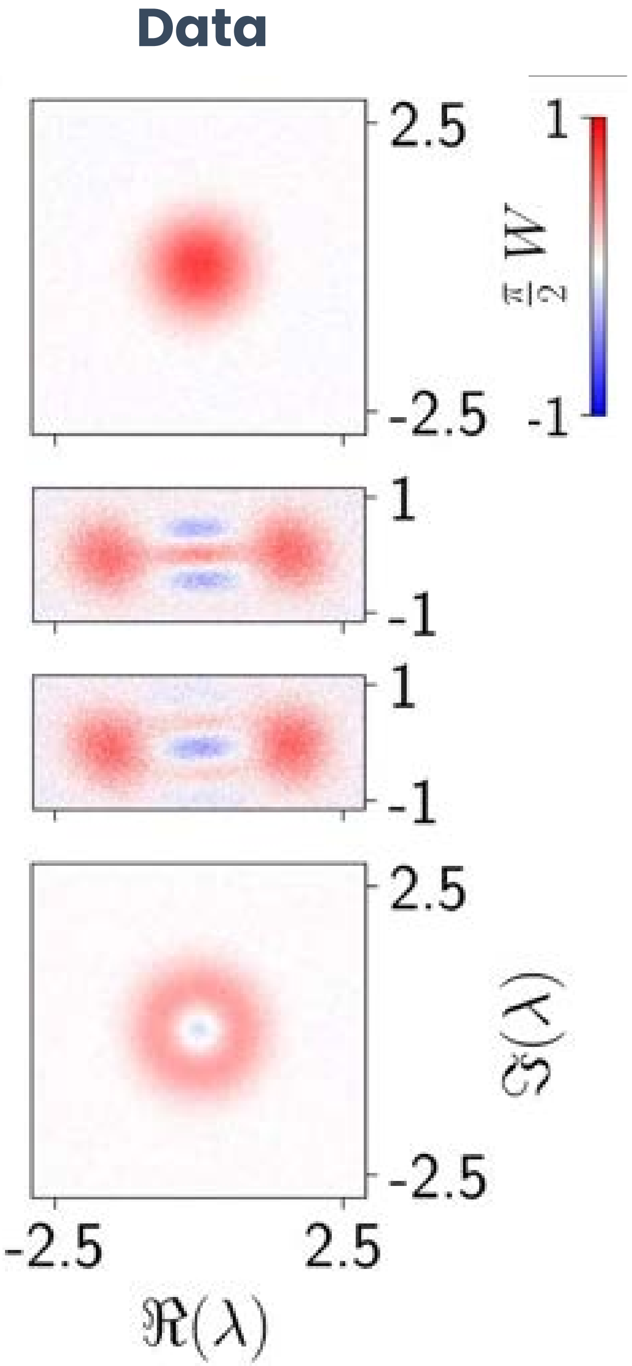


Data

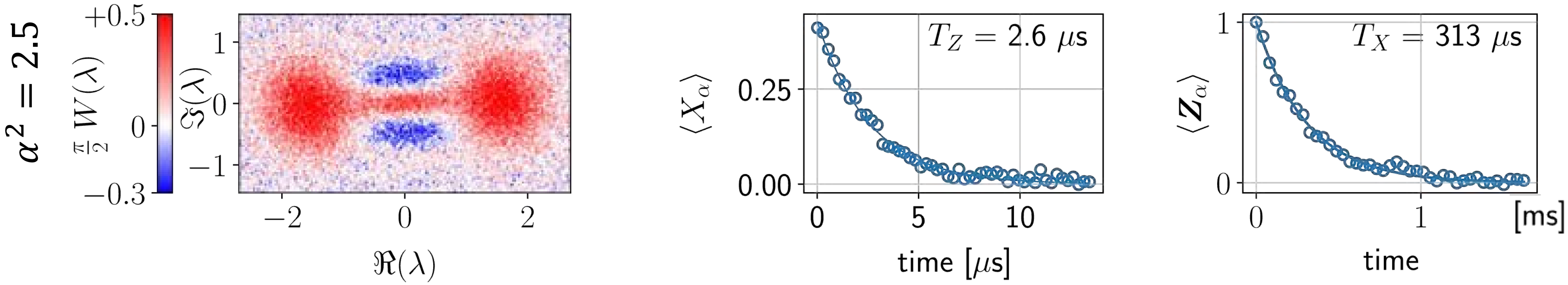


Transmon-free tomography examples

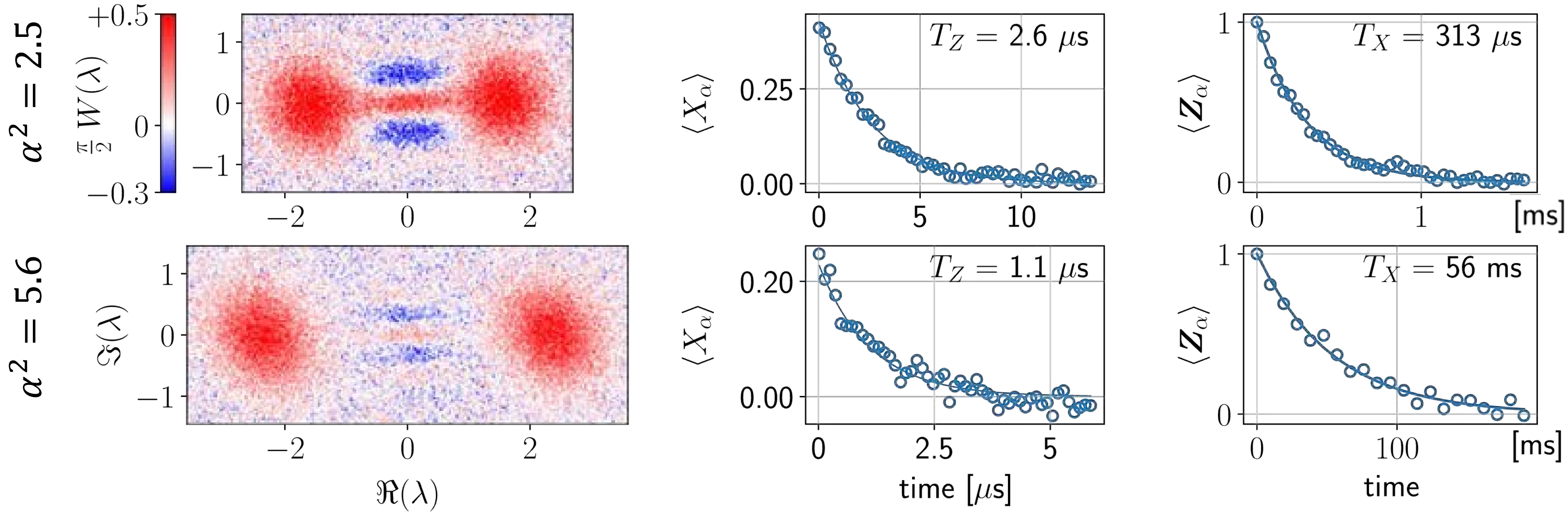




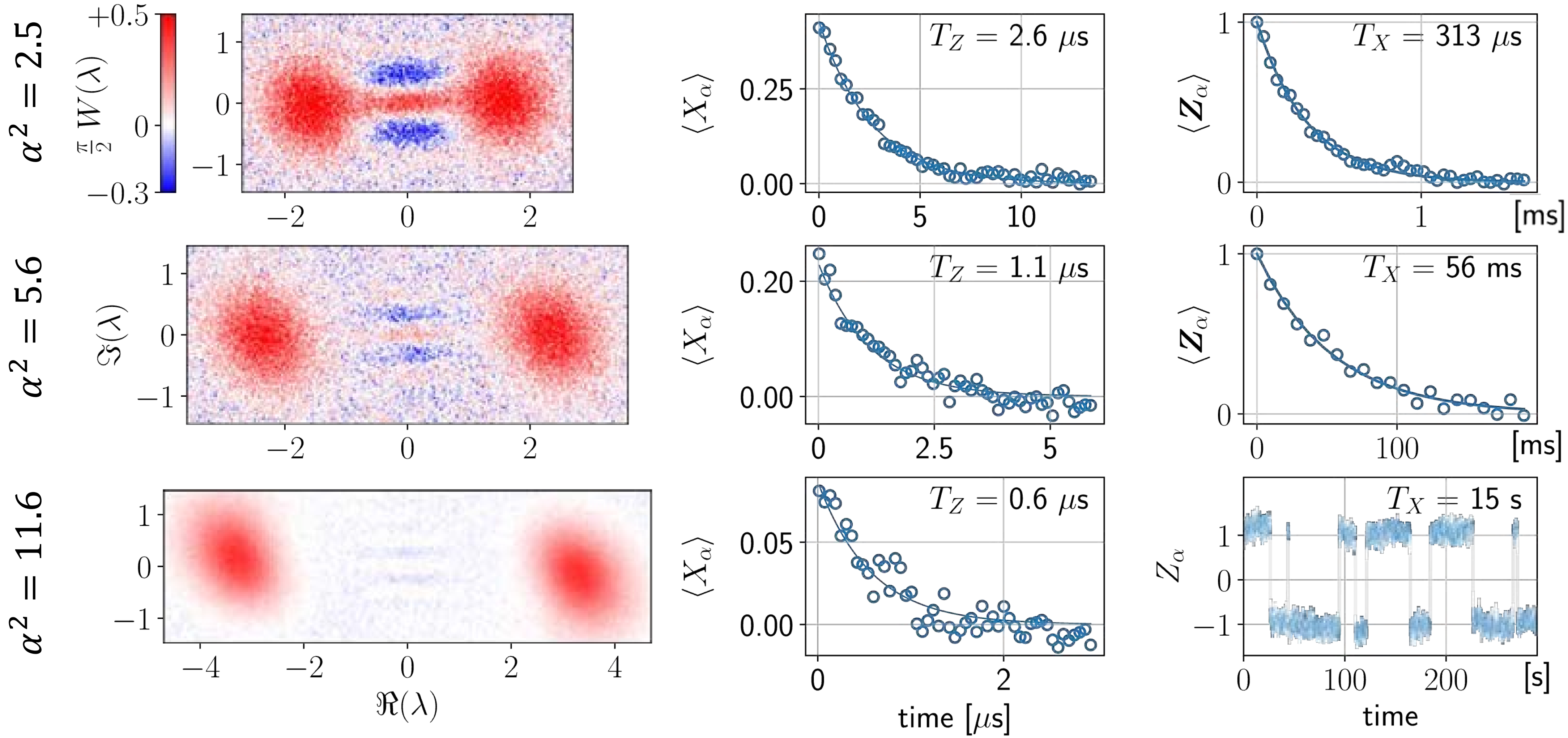
Our qubit is noise-biased



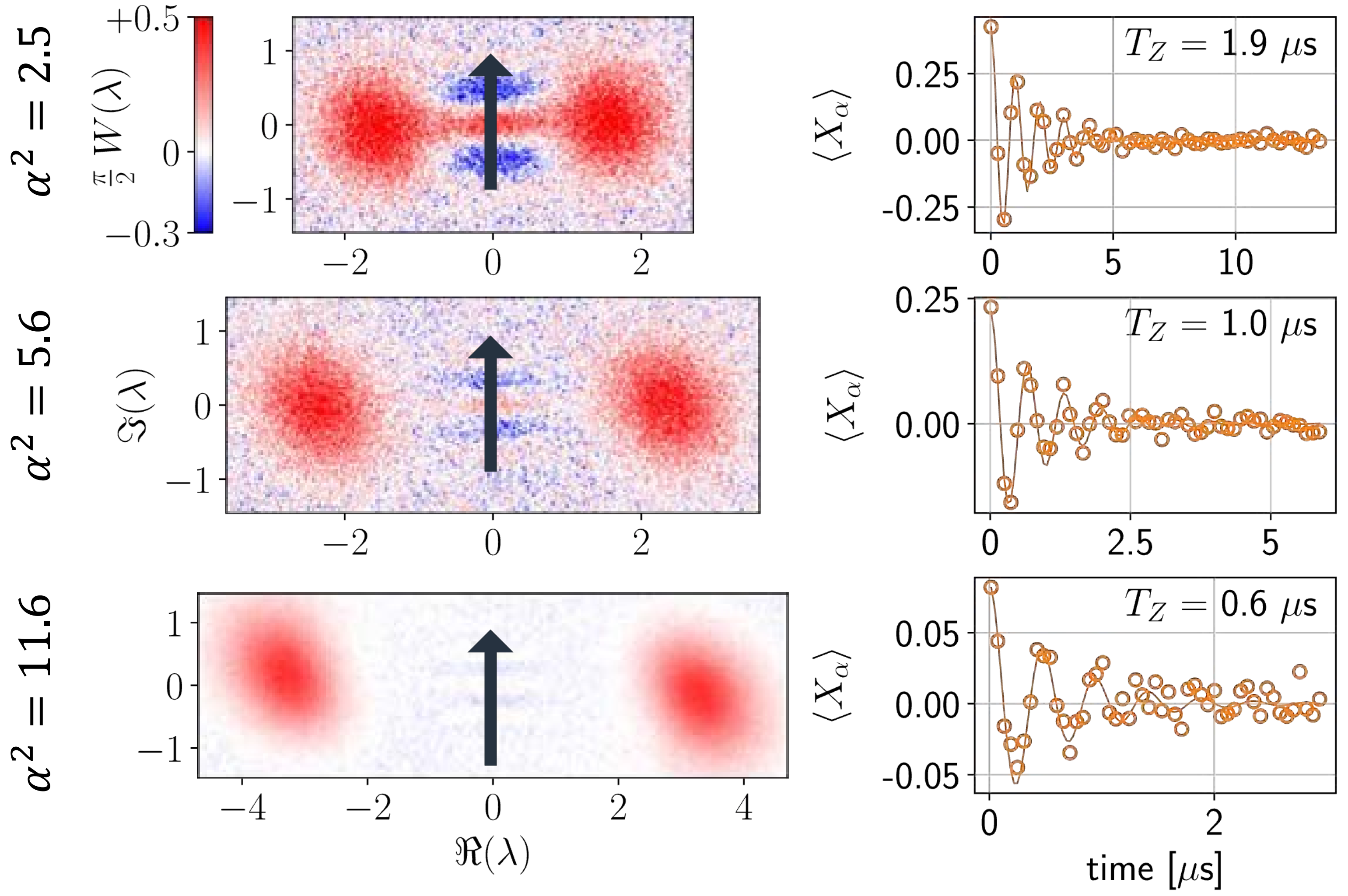
Our qubit is noise-biased



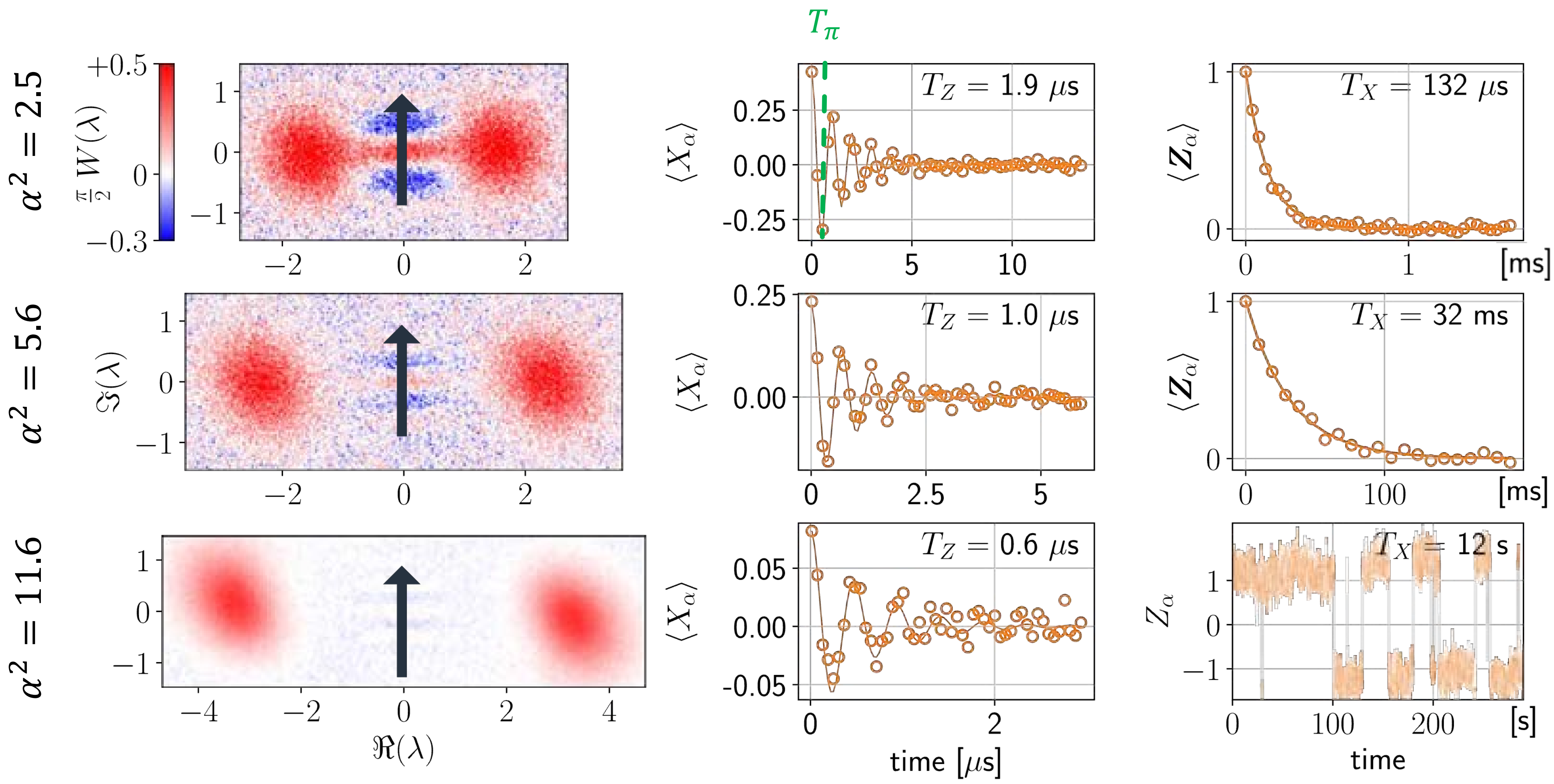
Our qubit is noise-biased



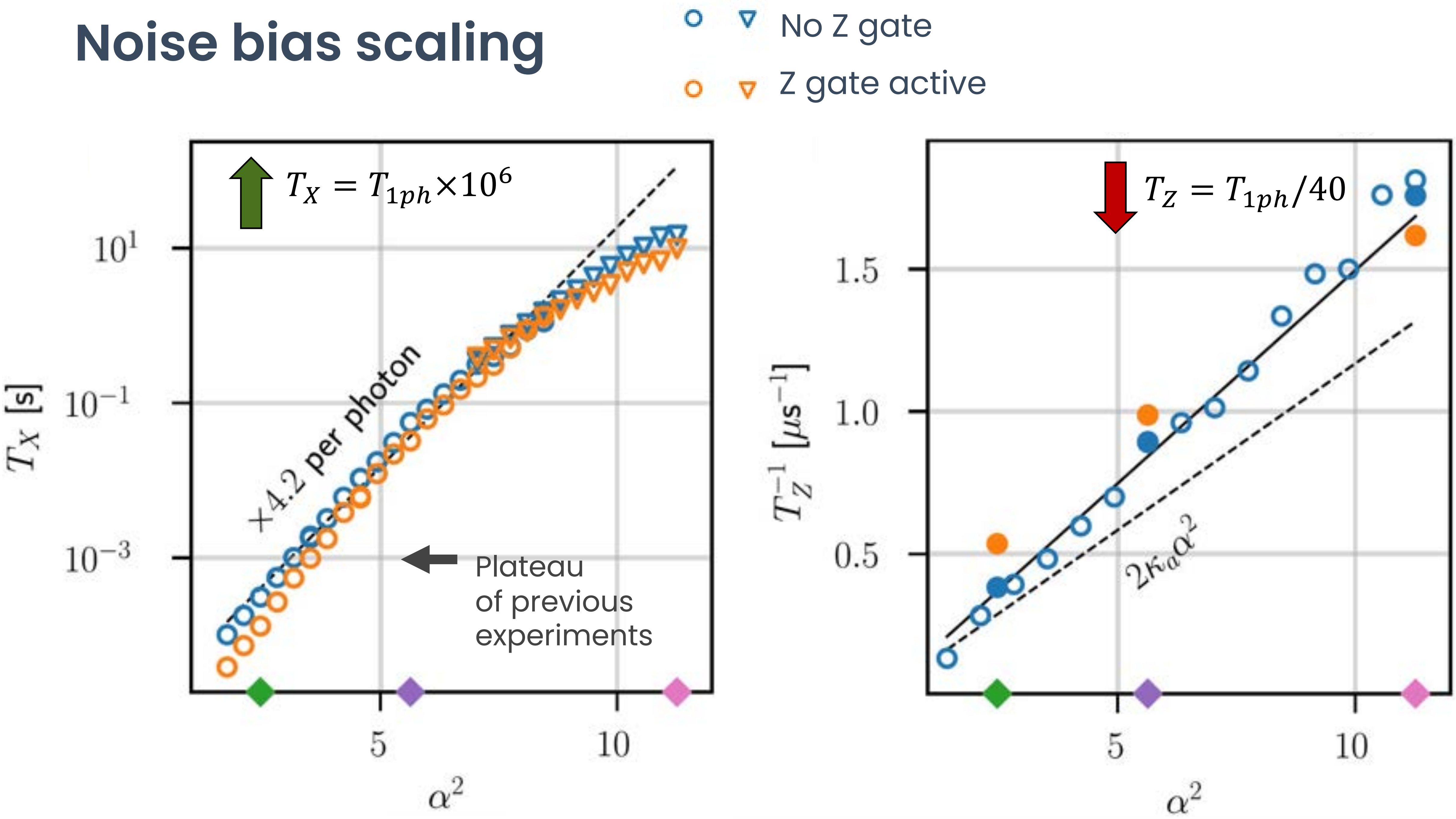
Our qubit is noise-biased under control



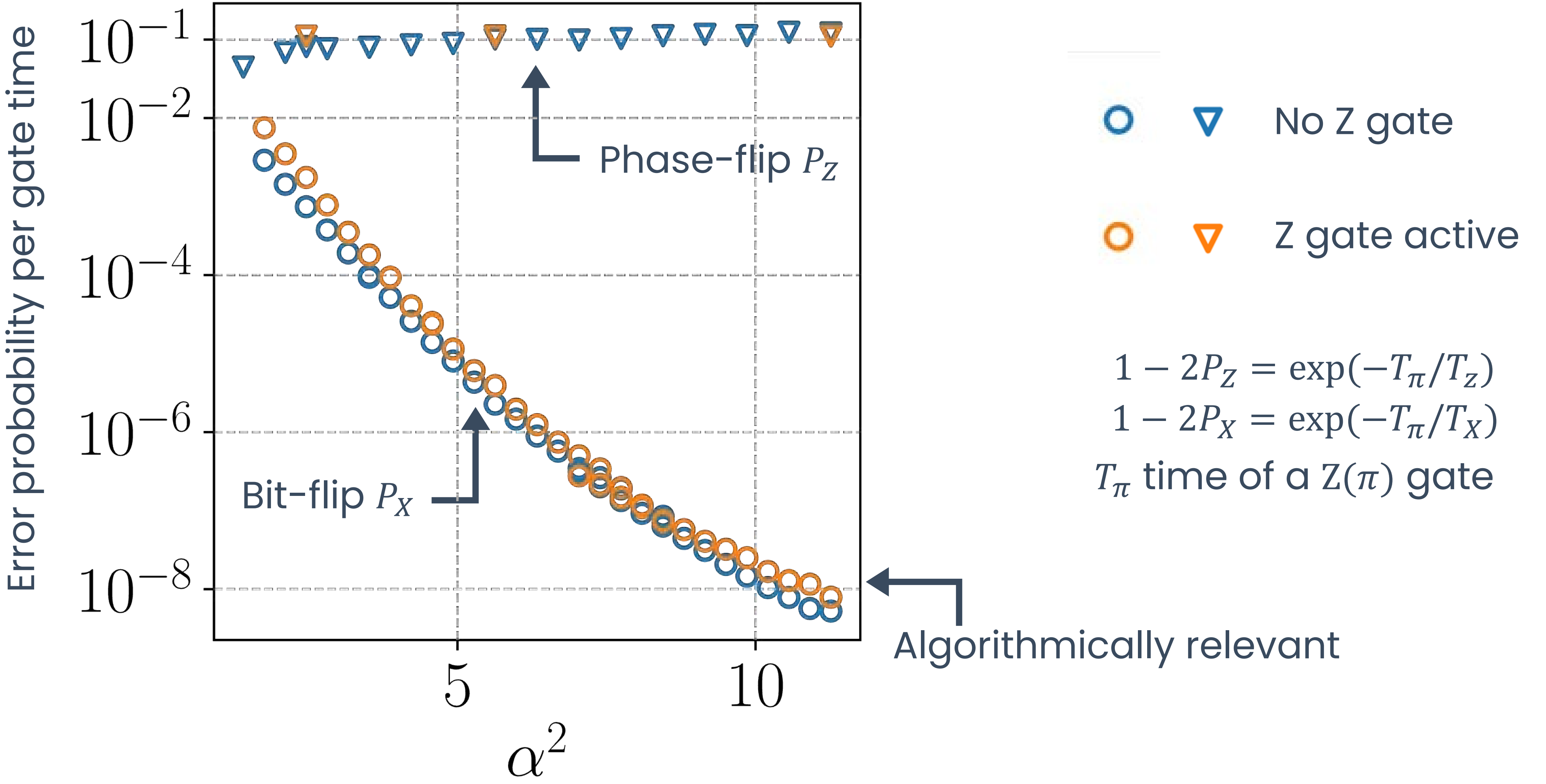
Our qubit is noise-biased under control



Noise bias scaling



Noise bias scaling



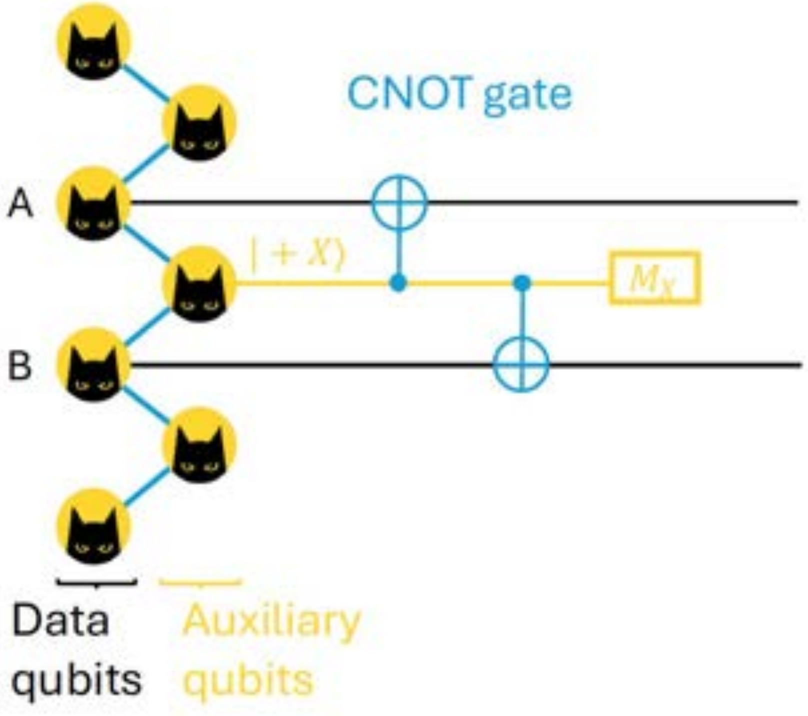
$$1 - 2P_Z = \exp(-T_\pi/T_z)$$
$$1 - 2P_X = \exp(-T_\pi/T_X)$$

T_π time of a Z(π) gate

Parity measurements

Single-shot high-fidelity parity measurements

Repetition code with cat qubits



Was there a phase-flip on A or B ?

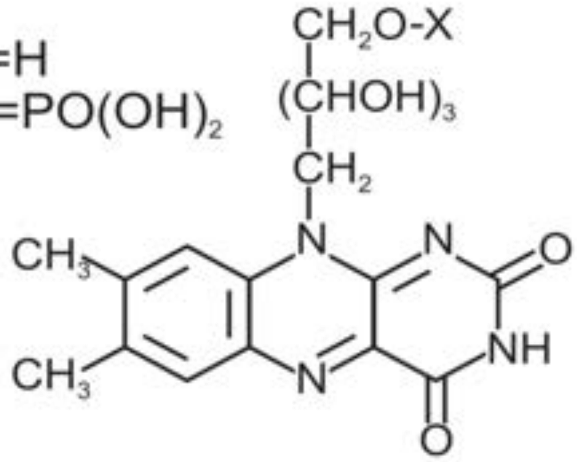
- ✓ Macroscopic bit-flip times
- ✓ $Z(\theta)$ gate
- ✓ Measure of Z
- ➡ **Measure of the parity M_X**
- Bias-preserving CNOT

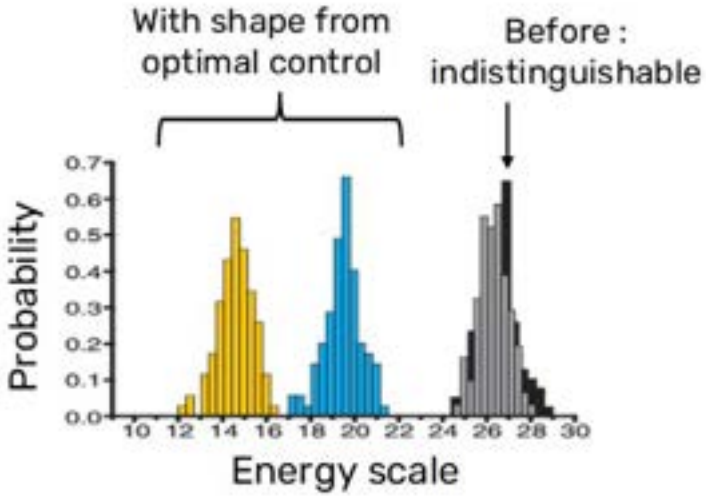
Selected for a Viewpoint in *Physics*
PRL **102**, 253001 (2009) PHYSICAL REVIEW LETTERS week ending 26 JUNE 2009

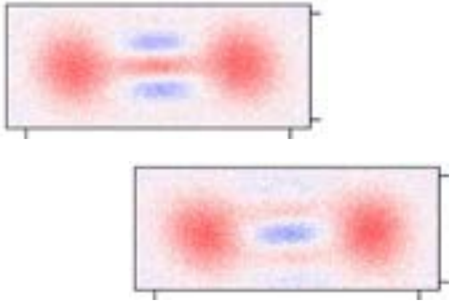
Quantum Control of Tightly Competitive Product Channels

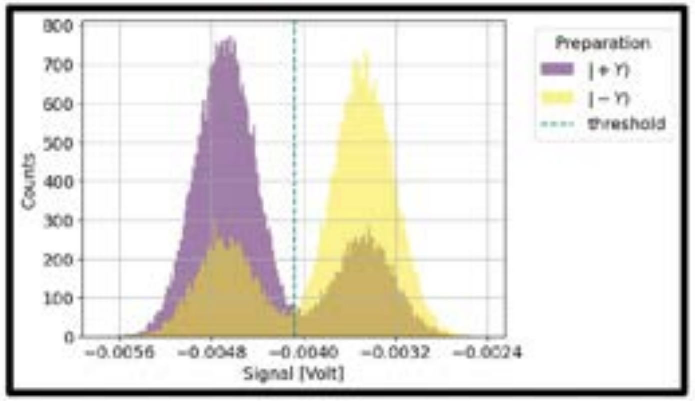
Matthias Roth,[1] Laurent Guyon,[2] Jonathan Roslund,[1] Véronique Boutou,[2] Francois Courvoisier,[2,3] Jean-Pierre Wolf,[3] and Herschel Rabitz[1,*]
[1]*Department of Chemistry, Princeton University, Princeton, New Jersey 08544, USA*

RBF: X=H
FMN: X=PO(OH)$_2$

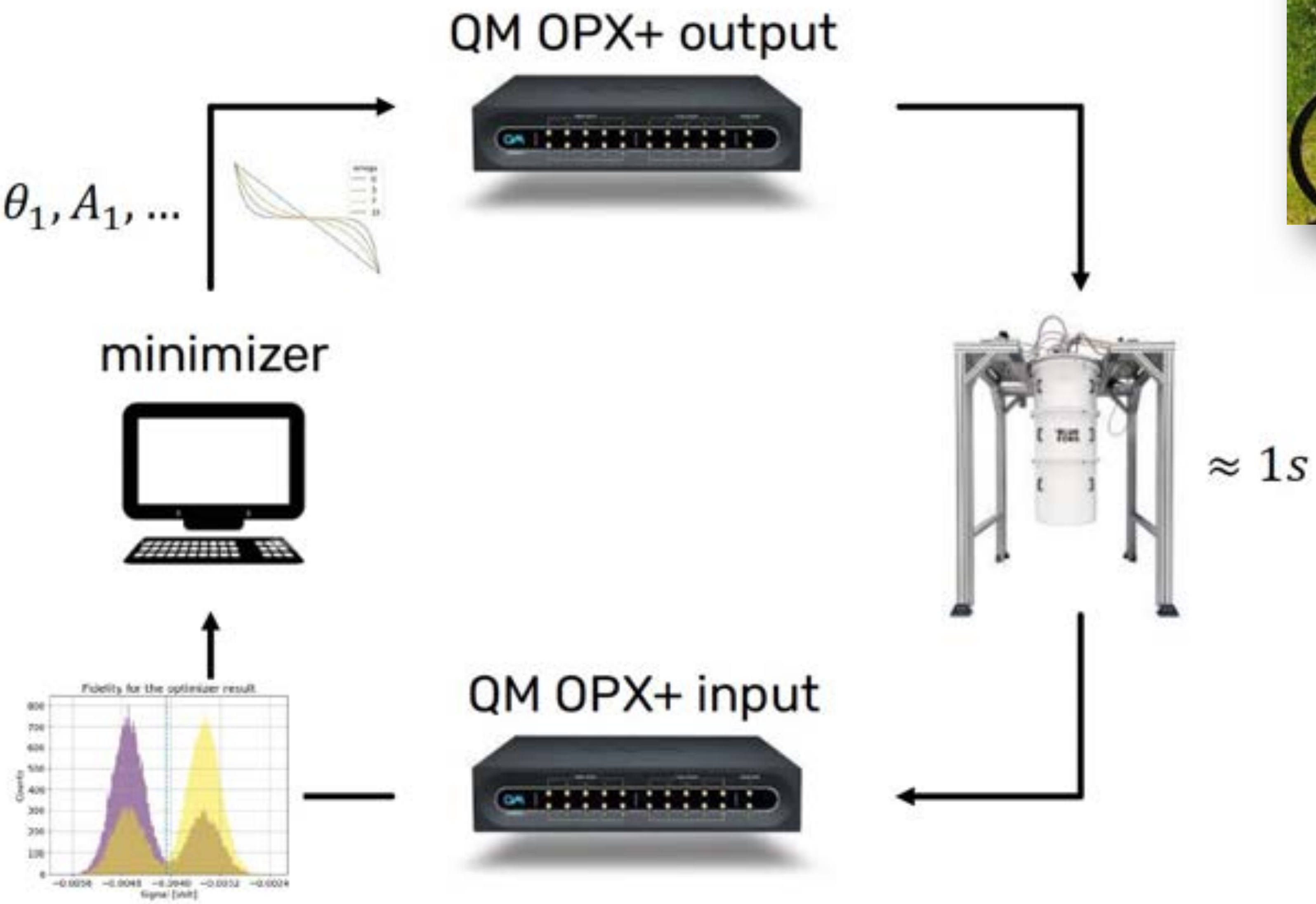








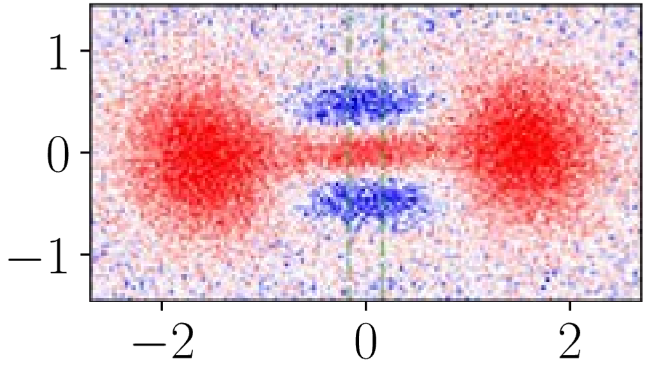
Optimal control



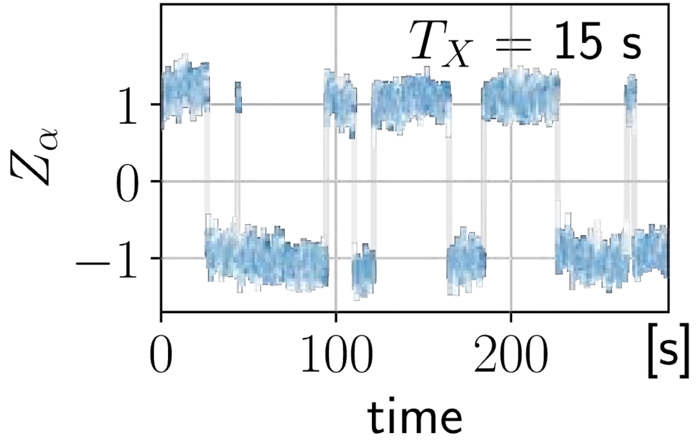
Rémi Robin

Conclusion

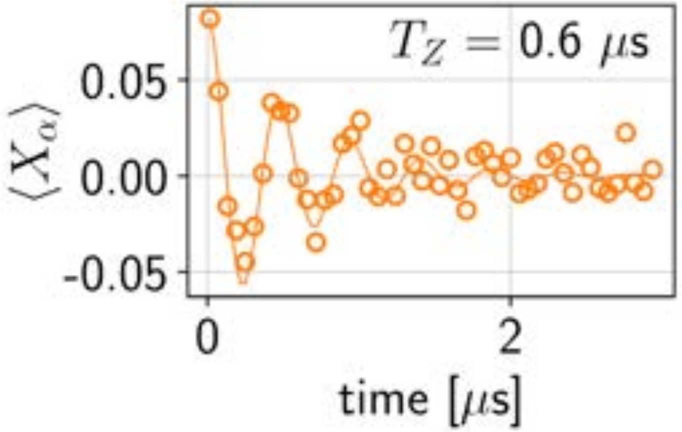
Tomography ✅



Macroscopic bit-flip time ✅

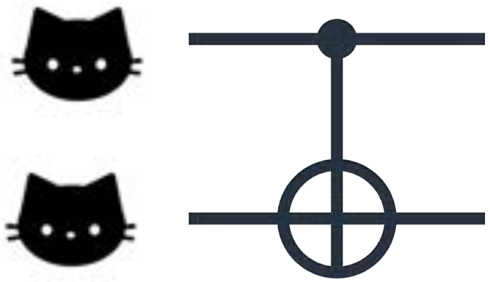


Coherent control ✅

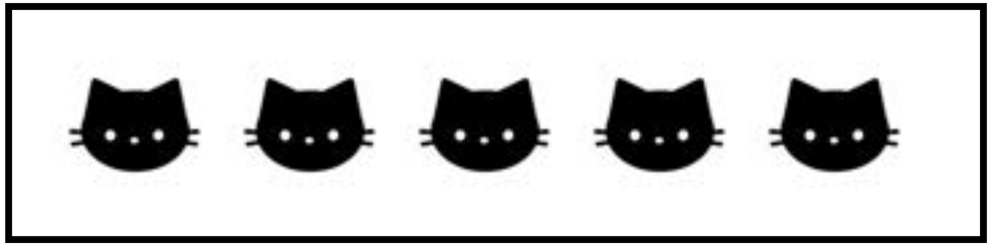


MX 🚧

CNOT 🚧



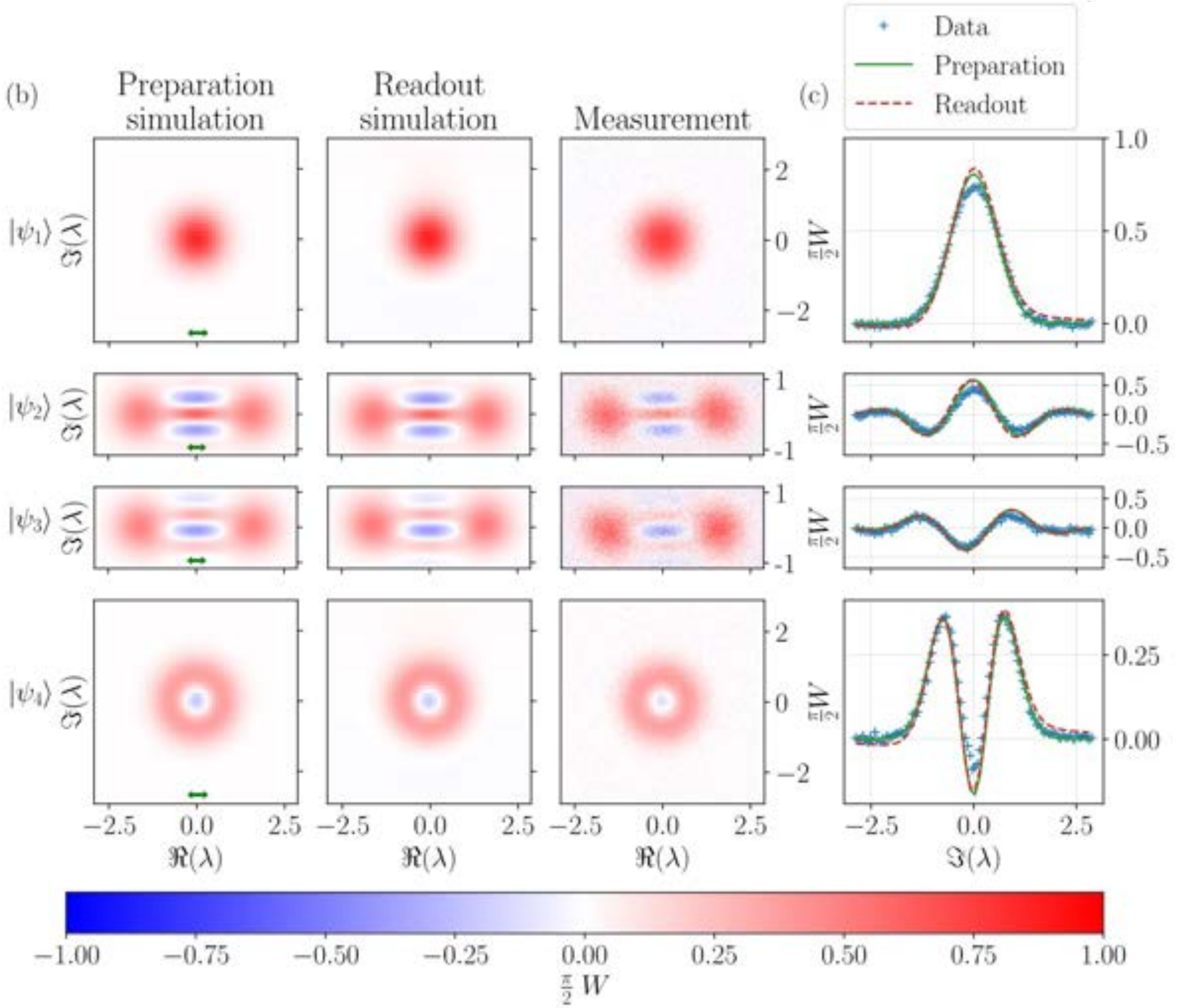
Repetition code 🚧



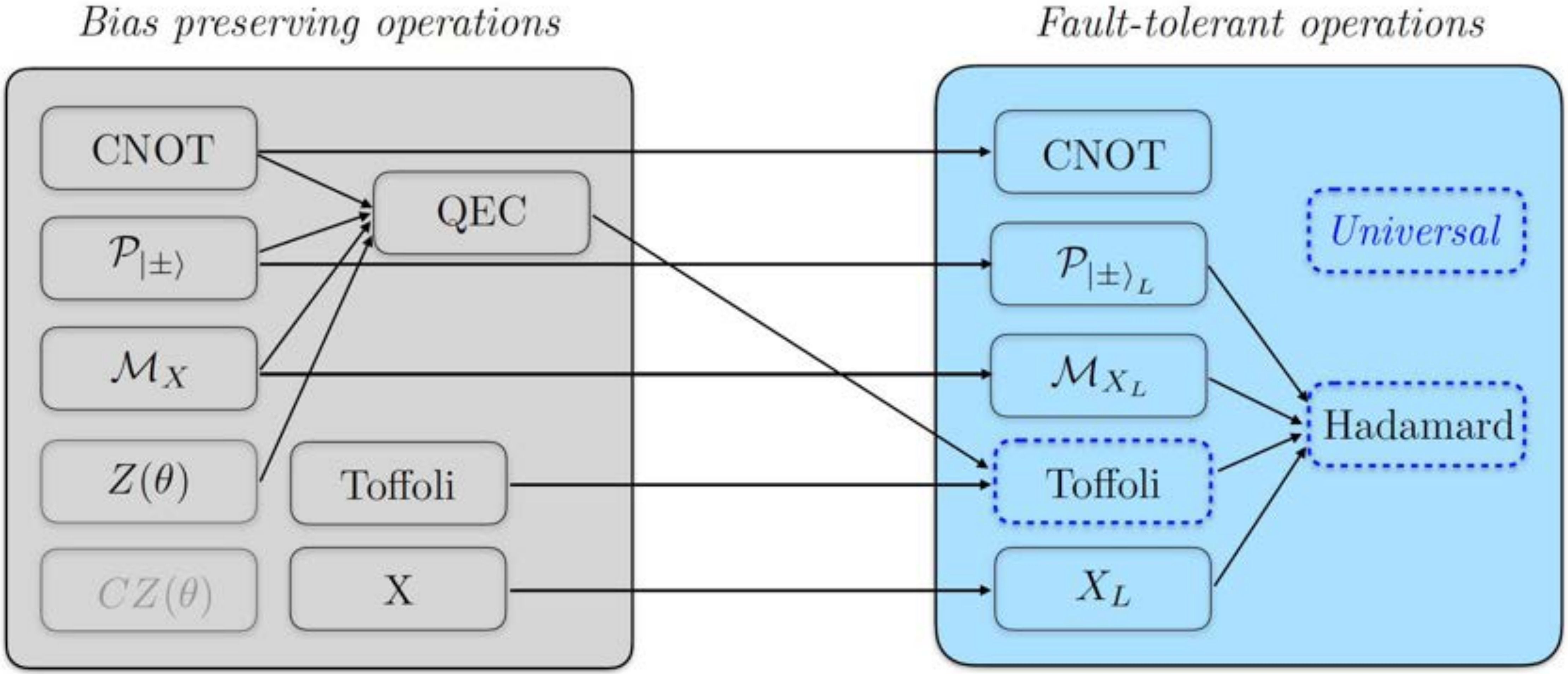
Nature 629, 778–783 (2024)
arXiv:2307.06617

Supplementary materials

Comparision to numerical simulations

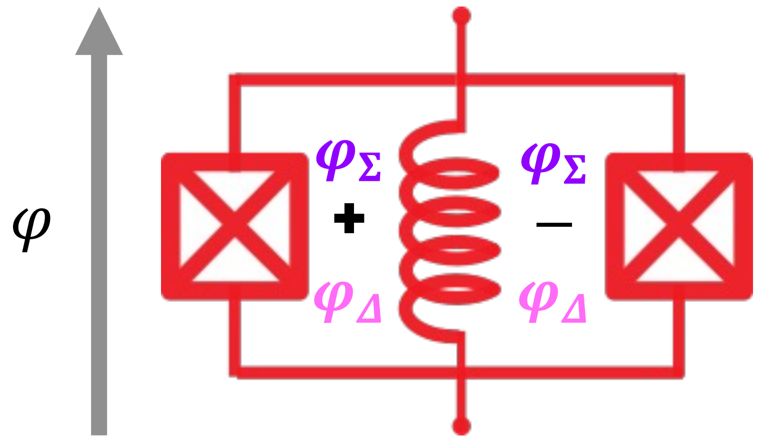


Fault-tolerant gates



Guillaud, Mirrahimi, PRX 2019

ATS (Asymmetrically threaded SQUID)



$$U(\varphi) = -2E_J \cos(\varphi_\Sigma)\cos(\varphi + \varphi_\Delta) + \frac{1}{2}E_L\varphi^2$$

$$U\Big|_{\varphi_\Sigma = \frac{\pi}{2} + \epsilon_\Sigma(t),\, \varphi_\Delta = \frac{\pi}{2}} = -2E_J \sin\big(\epsilon_\Sigma(t)\big)\sin(\varphi) + \frac{1}{2}E_L\varphi^2$$

$$U^{NL}\Big|_{\varphi_\Sigma = \frac{\pi}{2} + \epsilon_\Sigma(t),\, \varphi_\Delta = \frac{\pi}{2}} \approx -2E_J\epsilon_\Sigma(t)\varphi^3/6$$

$$\hat{\varphi} = \varphi_a\left(\hat{a} + \hat{a}^\dagger\right) + \varphi_b\left(\hat{b} + \hat{b}^\dagger\right)$$

$$\epsilon_\Sigma(t) = \epsilon_\Sigma \cos\left(\omega_p t\right)$$

$\omega_p = 2\omega_a - \omega_b$

$\omega_p = \omega_b$

$$\overline{U}_{NL} \propto \hat{a}^2\hat{b}^\dagger + \hat{a}^{\dagger 2}\hat{b}$$

$$\overline{U}_{NL} \propto \hat{a}^\dagger\hat{a}(\hat{b} + \hat{b}^\dagger)$$

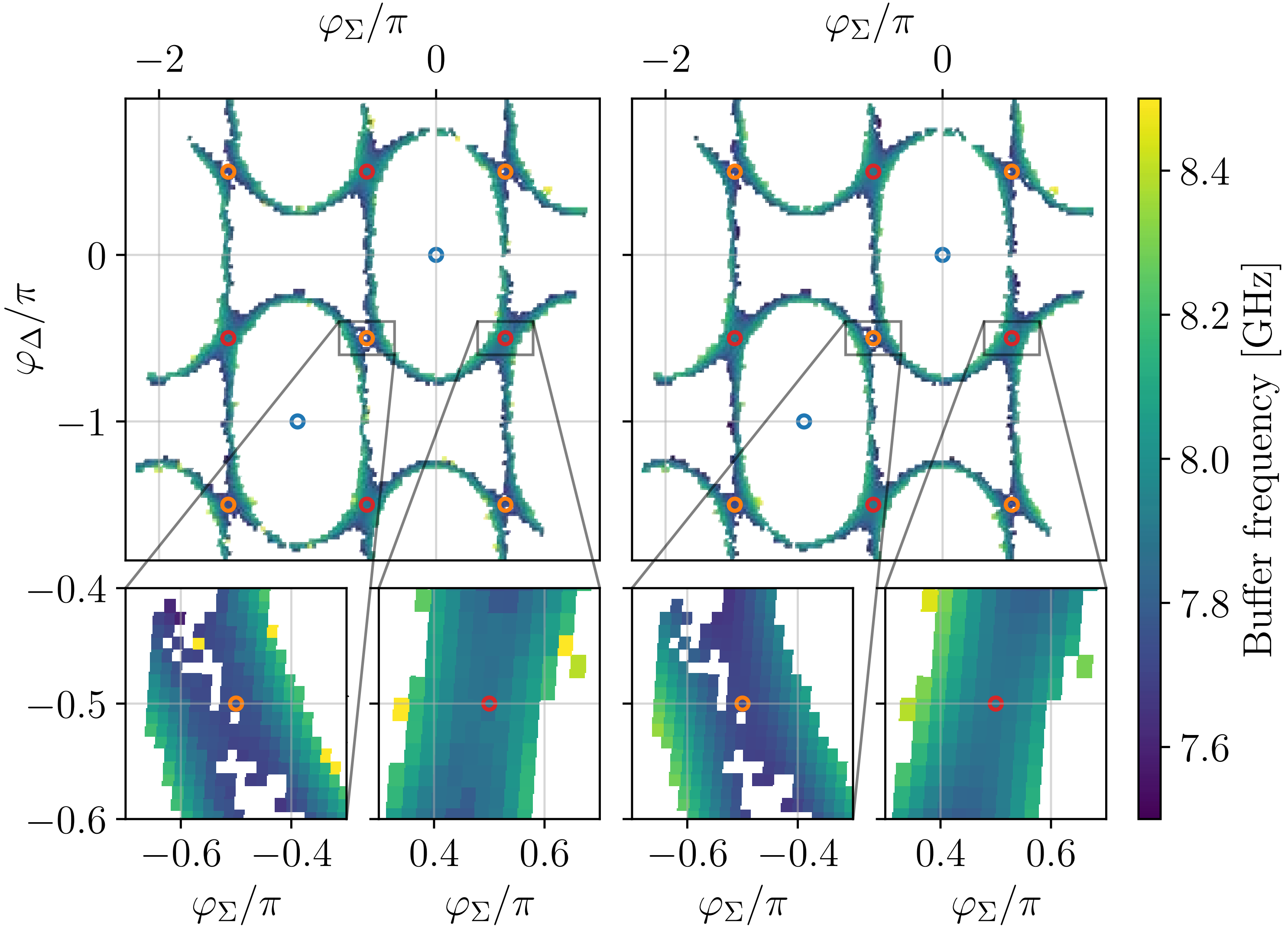
Chip specs

$\omega_{b,0}/2\pi$	7.70 GHz
φ_b	0.29

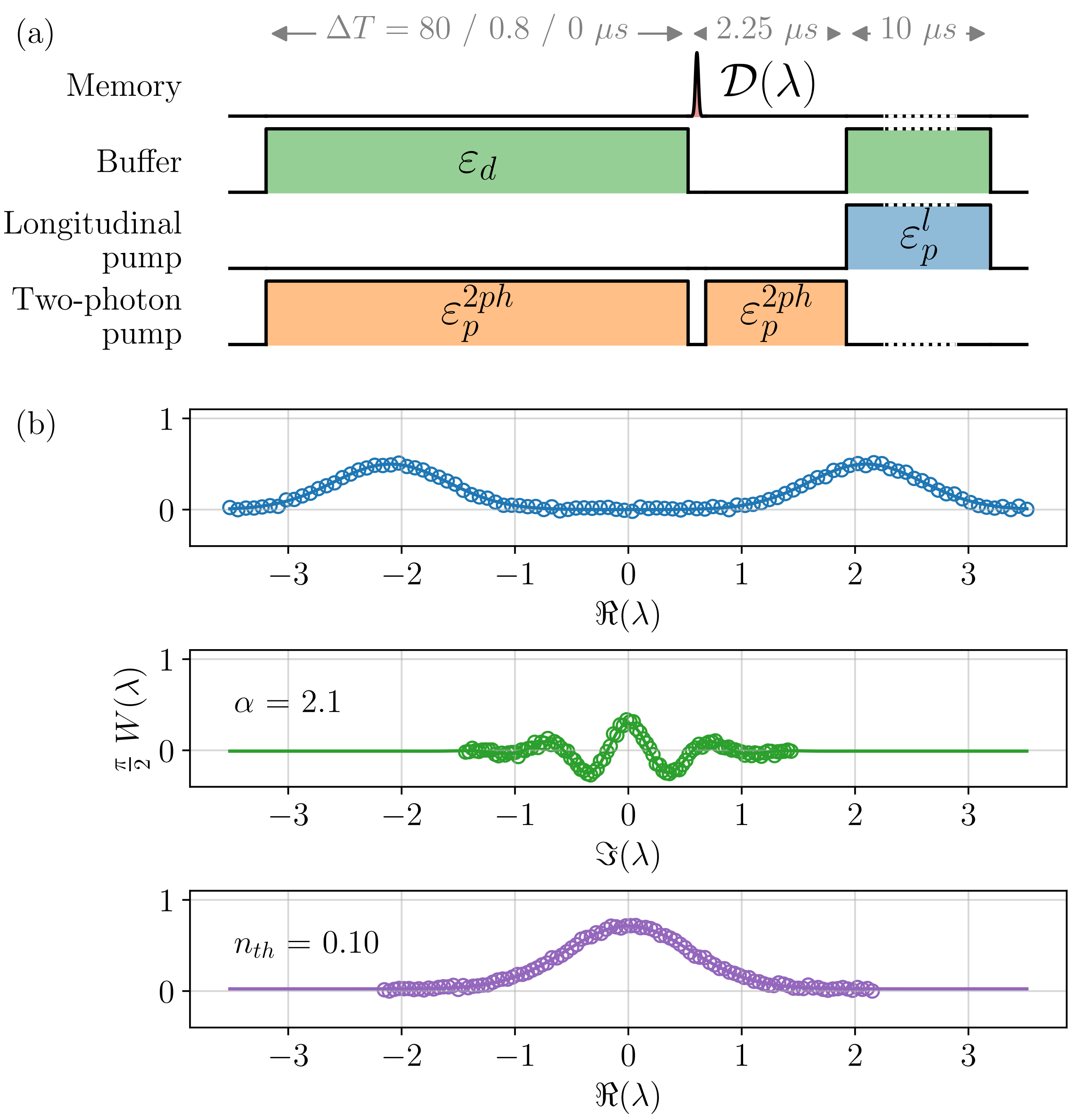
$\omega_{a,0}/2\pi$	5.26 GHz
φ_a	0.06

E_L/h	42.76 GHz
E_J/h	12.03 GHz
$\Delta E_J/h$	0.47 GHz

$g_2/2\pi$	0.763 MHz
$\kappa_b/2\pi$	2.6 MHz
$\kappa_a/2\pi$	9.3 kHz
n_a^{th}	10%
n_b^{th}	1.1%



φ_Σ/π
-2
0
φ_Δ/π
0
-1
-0.4
-0.5
-0.6
-0.6
-0.4
0.4
0.6
φ_Σ/π
8.4
8.2
8.0
7.8
7.6
Buffer frequency [GHz]


(a)
ΔT = 80 / 0.8 / 0 μs
2.25 μs
10 μs
Memory
D(λ)
Buffer
ε_d
Longitudinal pump
ε_p^l
Two-photon pump
ε_p^2ph
ε_p^2ph
(b)
ℜ(λ)
π/2 W(λ)
α = 2.1
ℑ(λ)
n_th = 0.10
ℜ(λ)