ALICE & BOB

Teratec

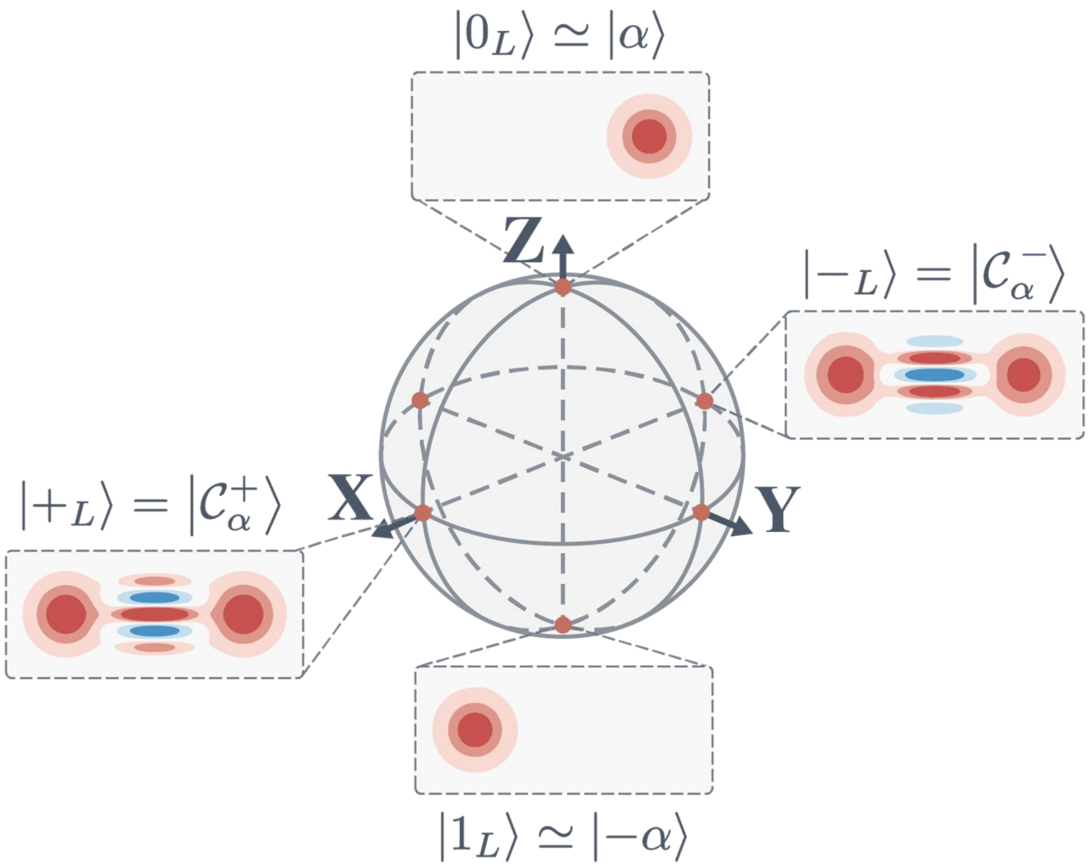
ASSESSING THE PERFORMANCE OF DISSIPATIVE CAT QUBITS

E. Albertinale, T. Assoui, D. Banys, A. Bocquet, N. Bourdaud, G. Campanaro, L. Carde, G. Cardoso, A. Célarier, H. Cisaruk, J. Cohen, N. Cottet, C. Cullip, L. Devanz, A. Devulder, S. Dupouy, A. Essig, P. Février, R. Gautier, A. Gicquel, A. Gras, J. Guillaud, P. Guilmin, E. Gumus, M. Hallen, A. Jacob, R. Lescanne, A. Marquet, A. May, A. Murani, N. Pankratova, G. Paris, T. Peronnin, S. Polis, J. Pruszkowska, F. Rautschke, U. Réglade, J. Roul, R. Rousseau, J. Solard, J. Stevens, A. Thomas, B. Vignon, J.L. Ville, P. Wan-Fat

Paul Magnard

5th June 2024

Presentation outline



01. Introduction to Dissipative Cat Qubits

02. Benchmarking Cat Qubits

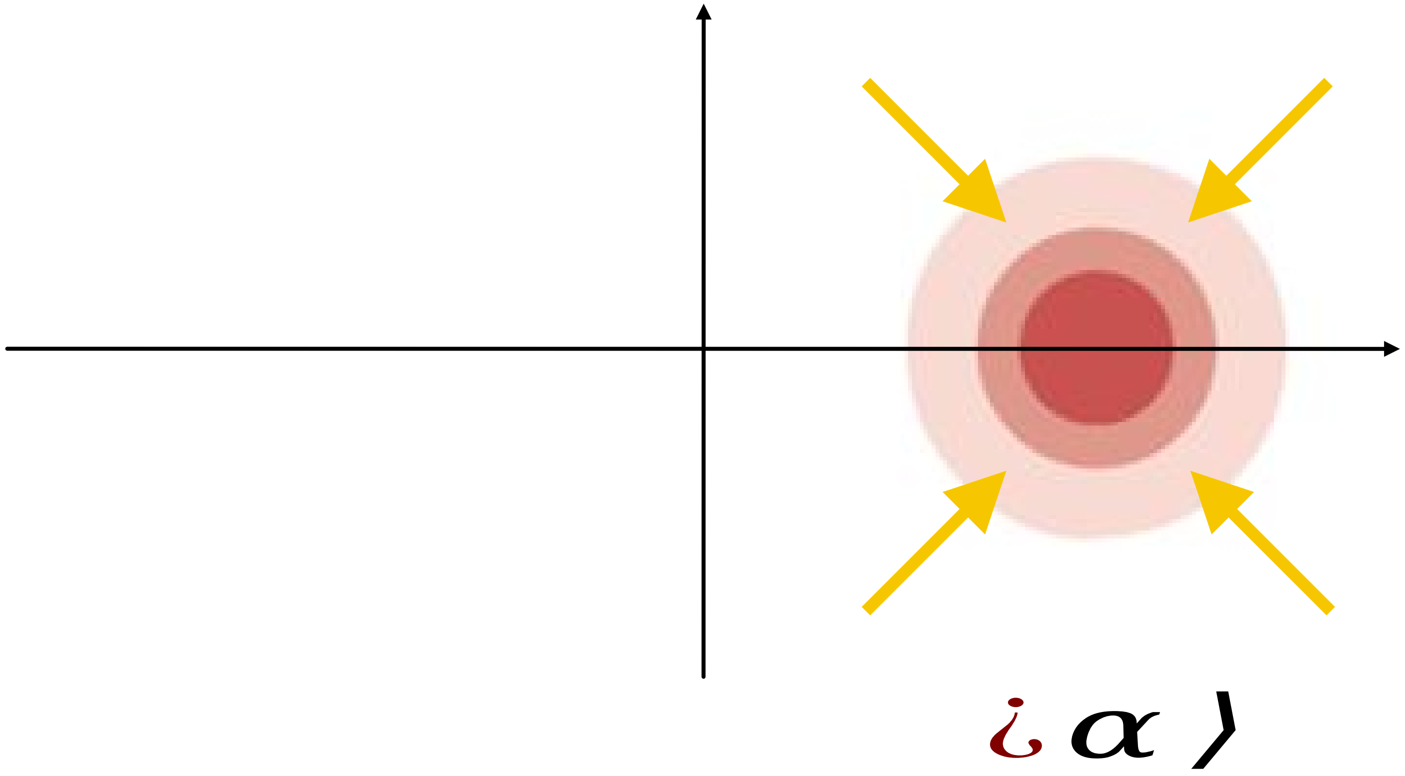
03. Key mertics of Cat Qubits in a repetition code context

01

INTRODUCTION TO DISSIPATIVE CAT QUBITS

Dissipative stabilization of a cat-qubit

Stabilize



Leghtas *et al.*, Science (2015)

Mirrahimi *et al.*, NJP (2014)

Dissipative stabilization of a cat-qubit

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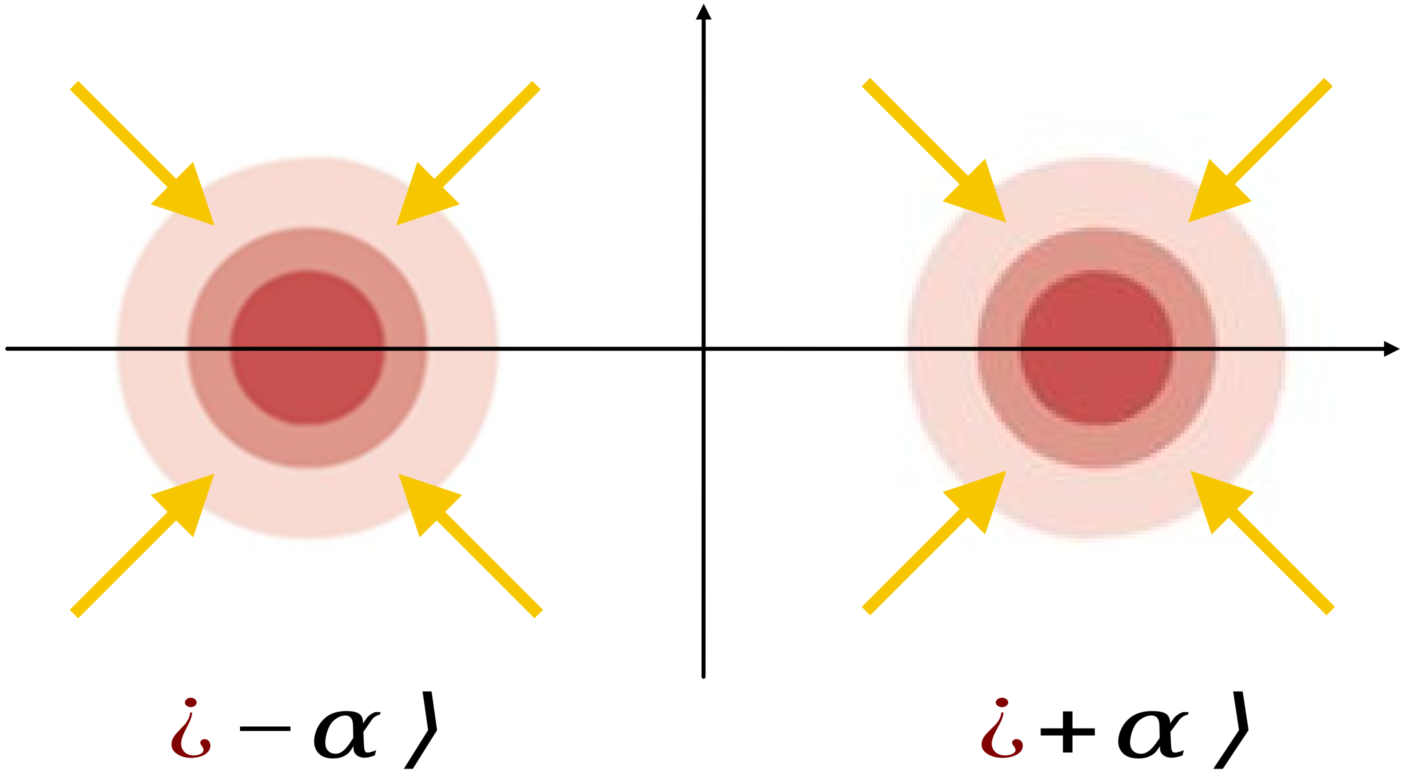

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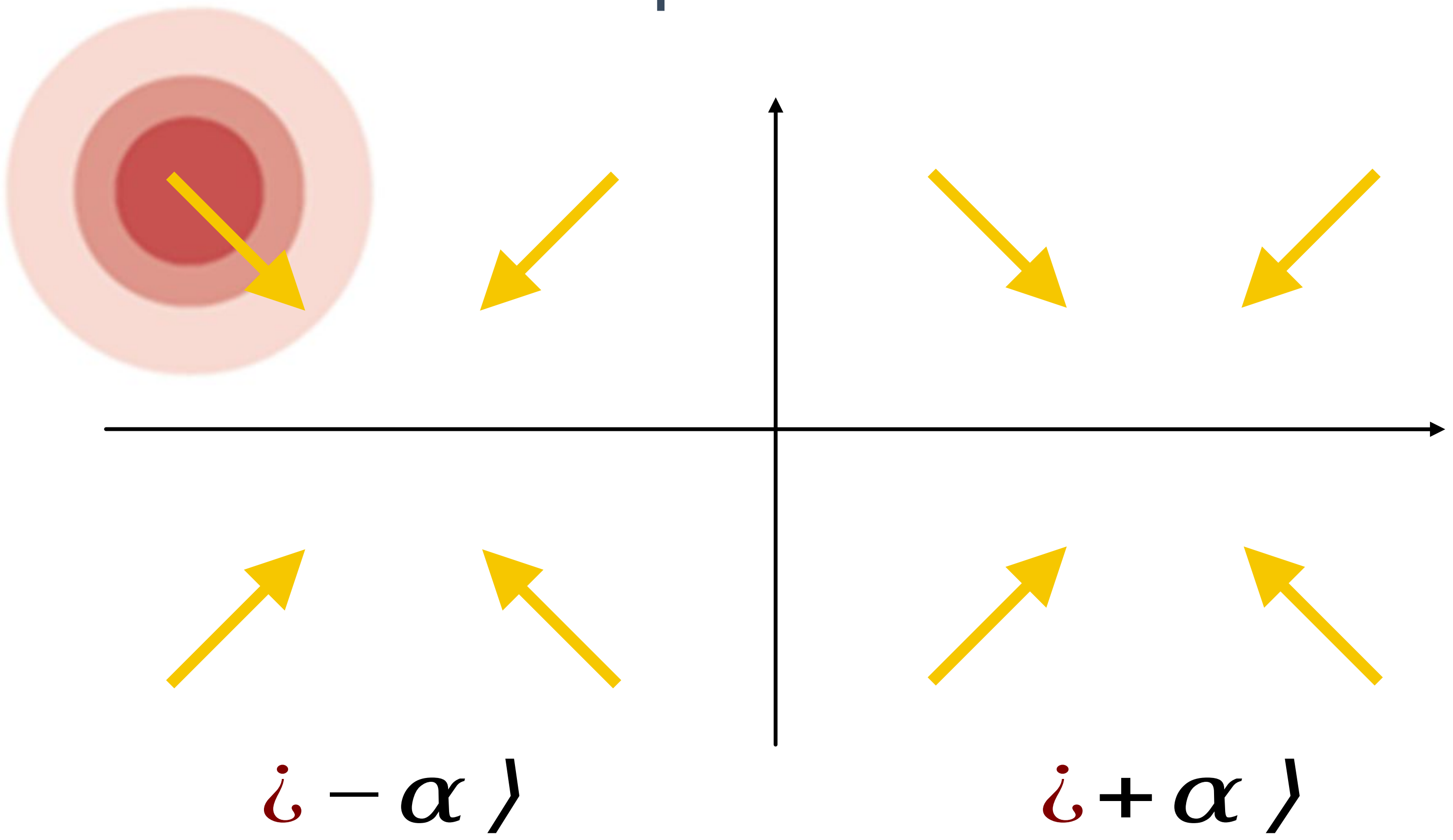

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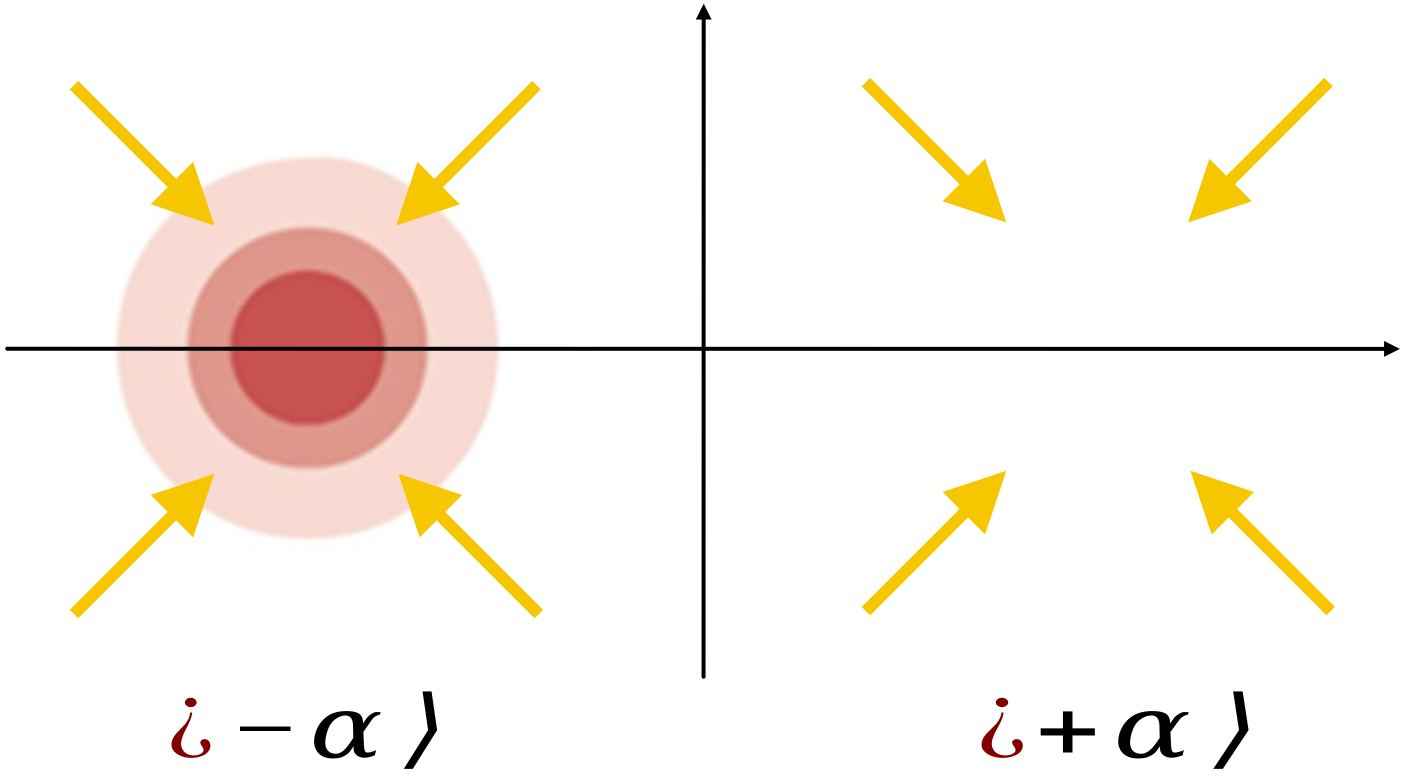

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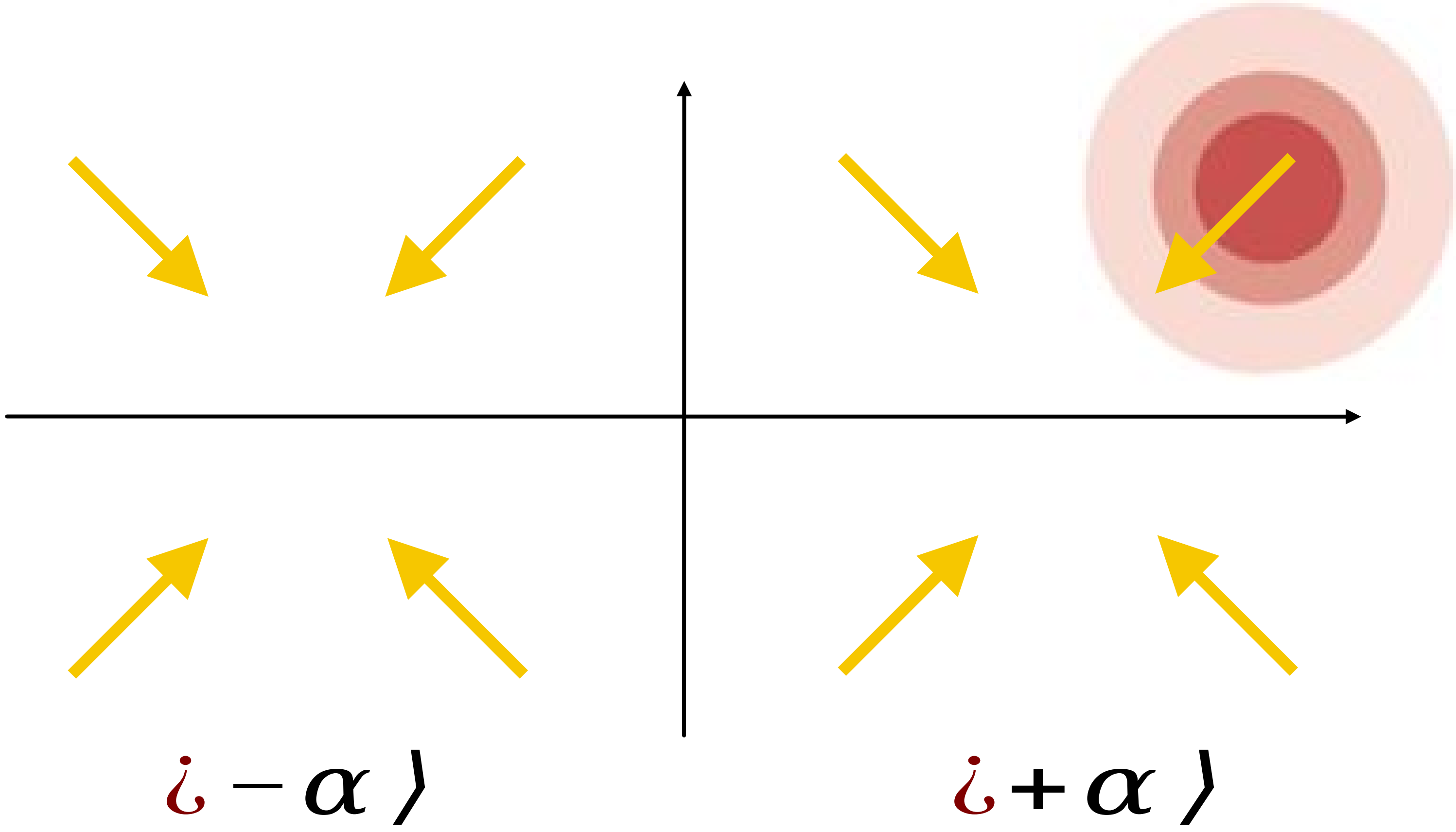

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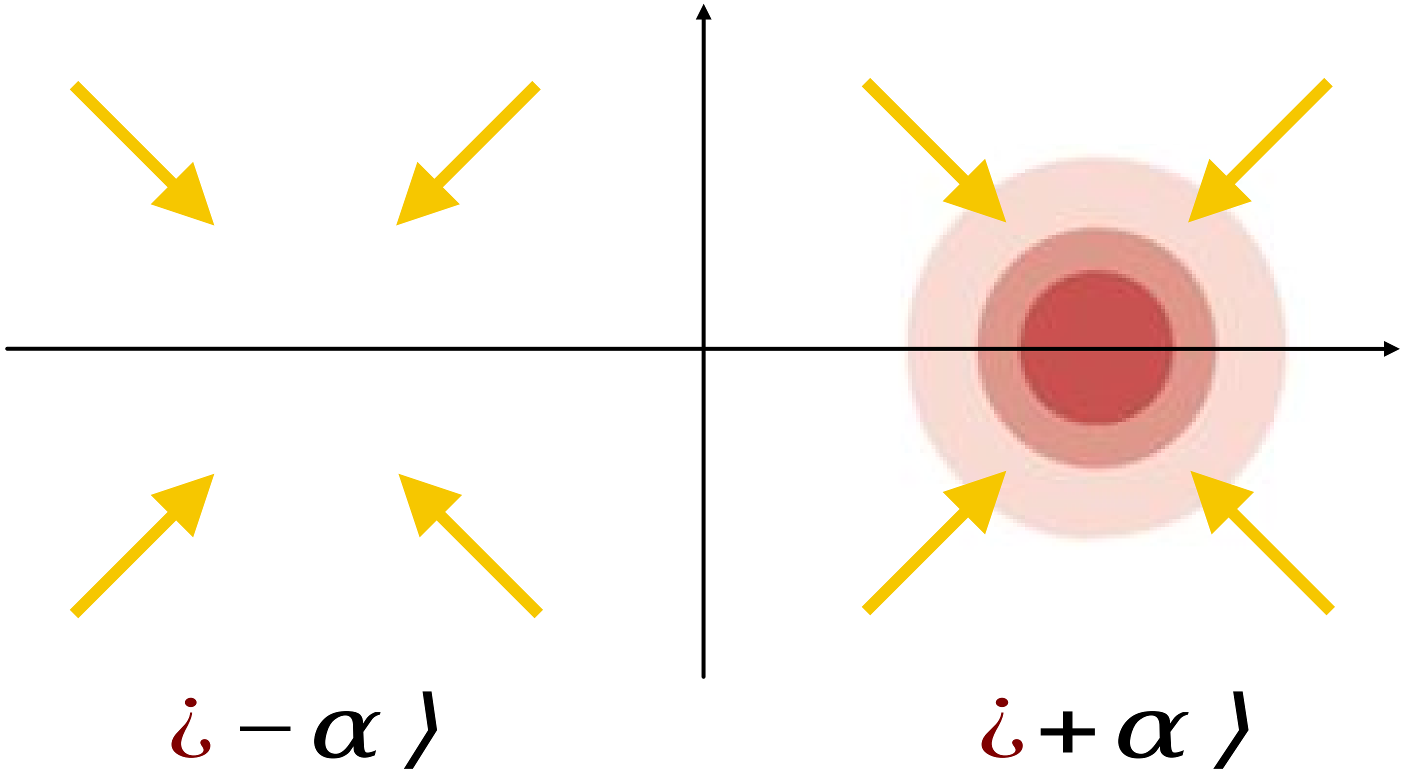

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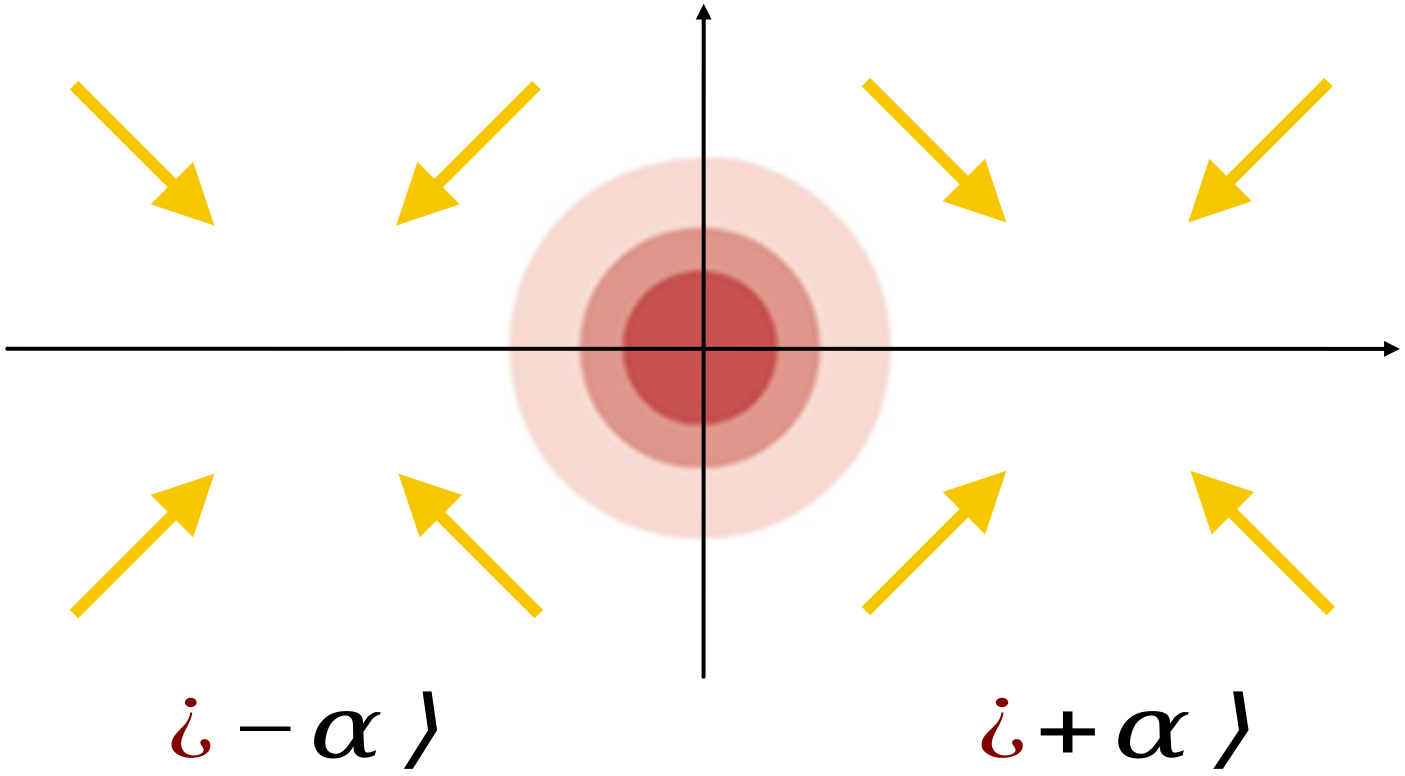

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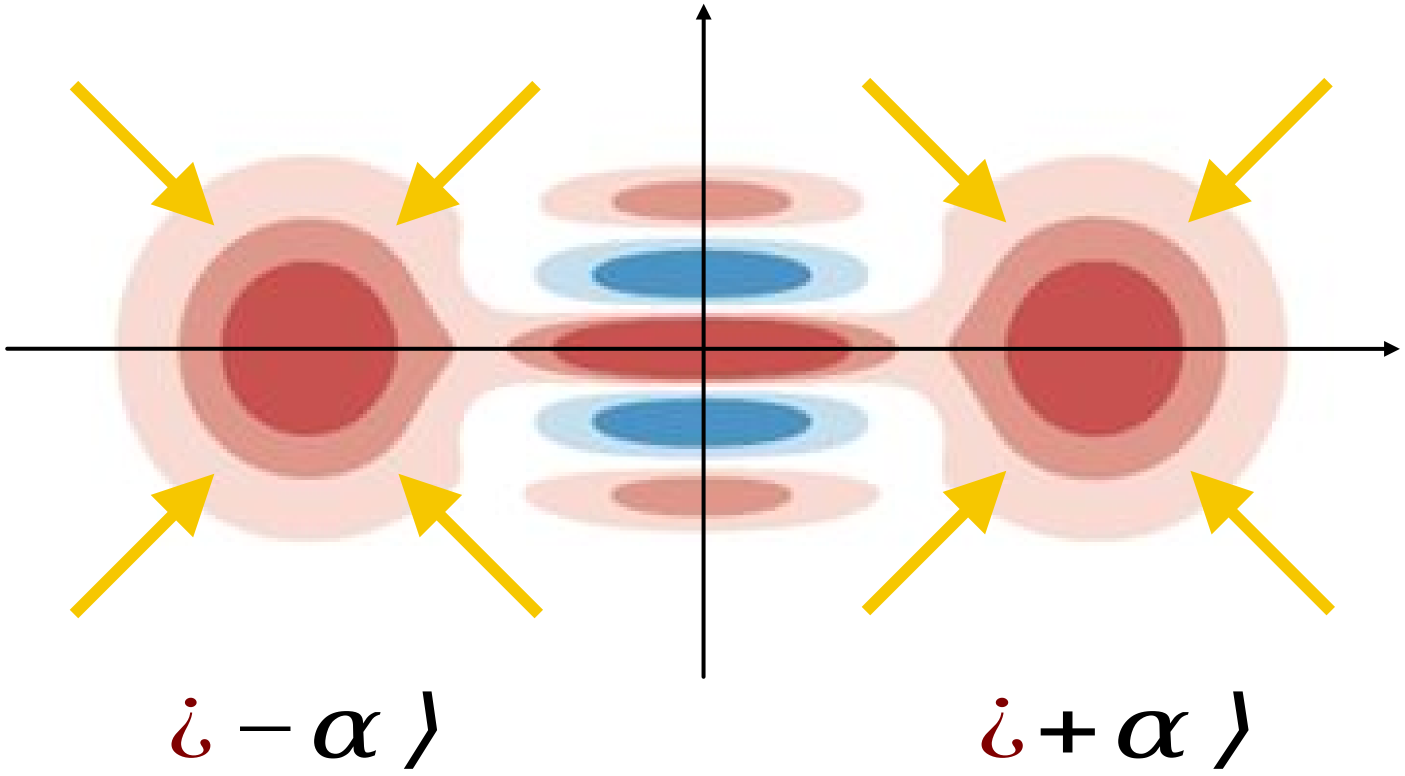
Dissipative stabilization of a cat-qubit

Stabilize

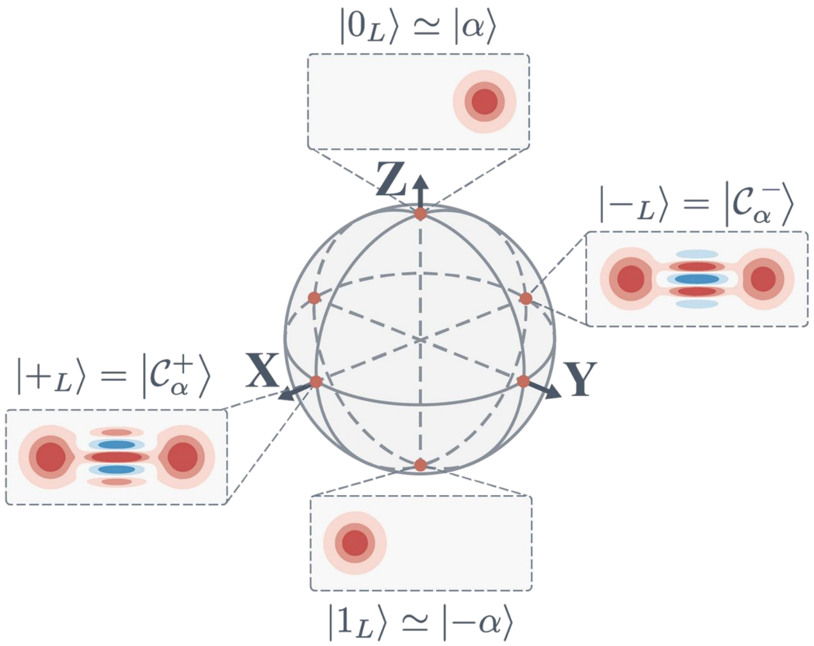


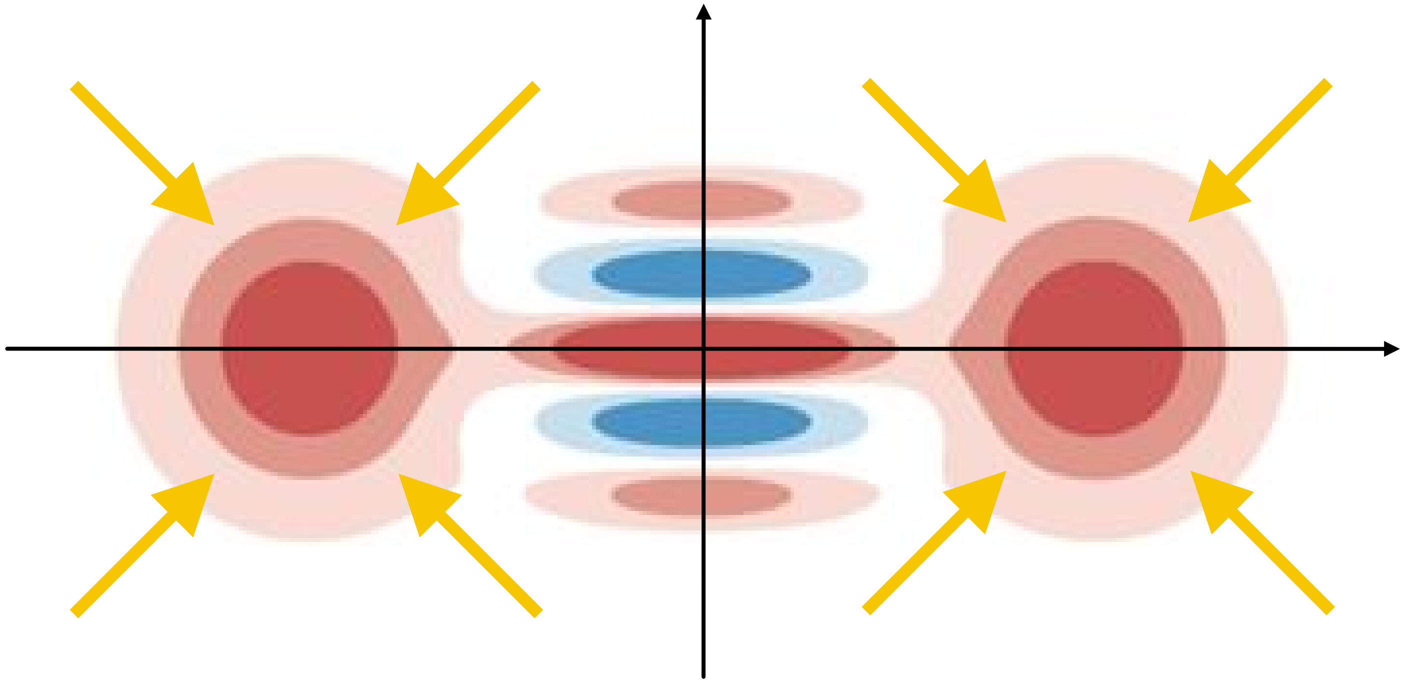
Leghtas *et al.*, Science (2015)

Mirrahimi *et al.*, NJP (2014)

Dissipative stabilization of a cat-qubit

Stabilize the whole cat-qubit **subspace**





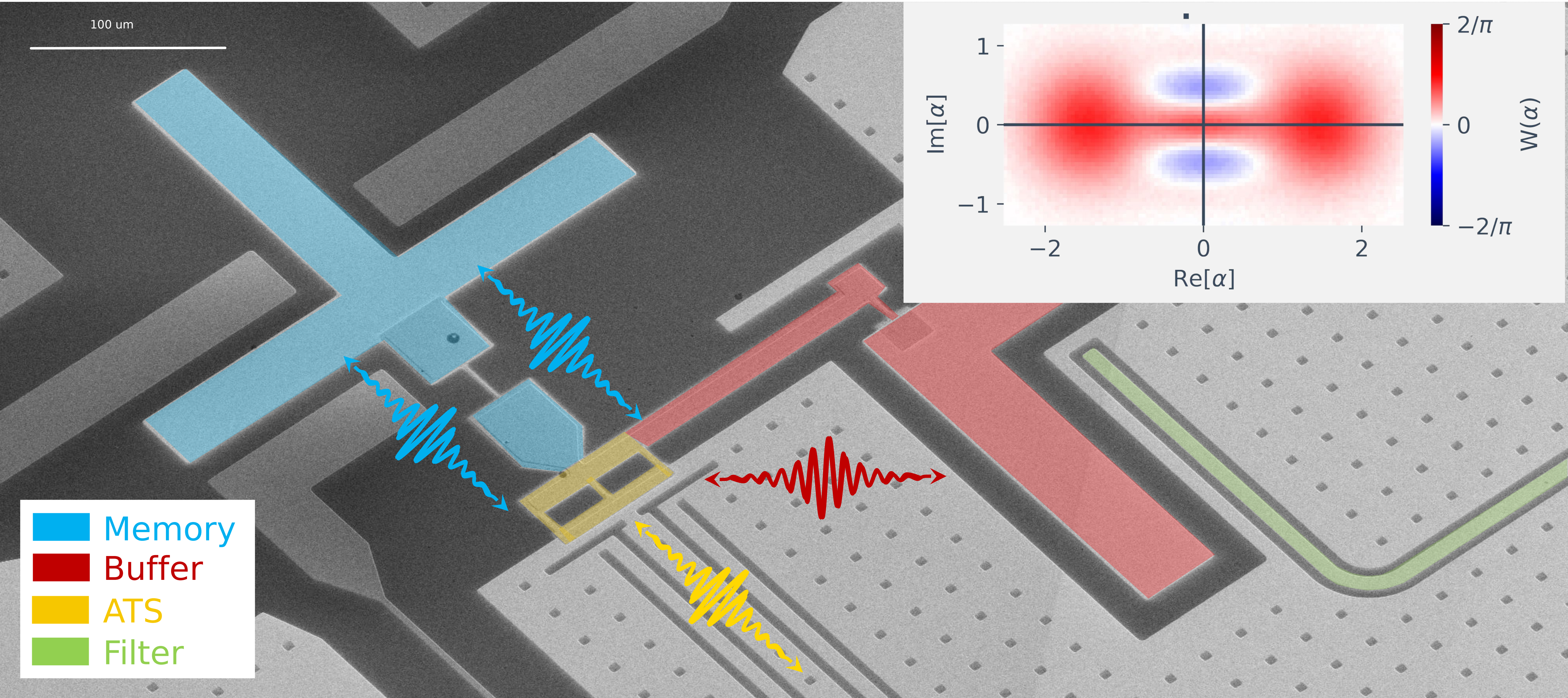
¿ − α ⟩

¿+α ⟩

Leghtas *et al.*, Science (2015)

Mirrahimi *et al.*, NJP (2014)

Experimental realization



Exponentially asymmetric noise

BIT FLIPS

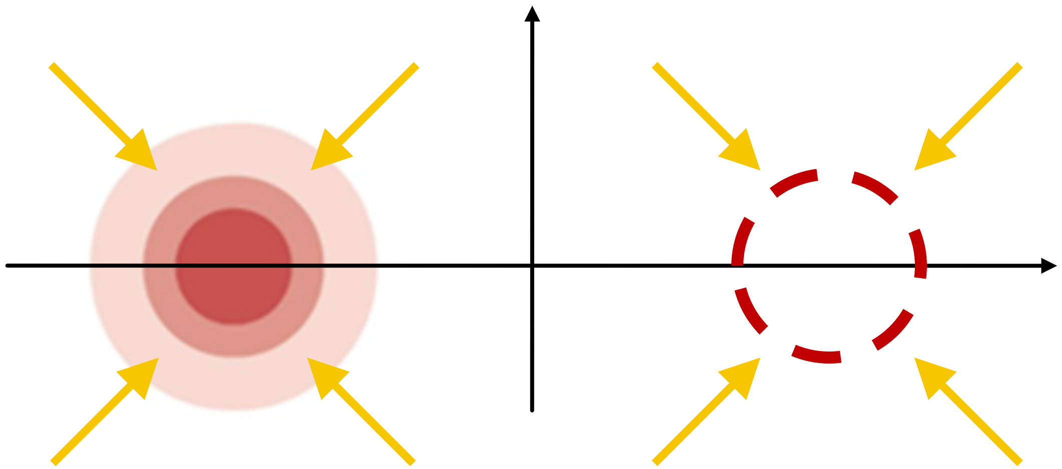
$$|0_L\rangle \approx |-\alpha\rangle \longleftarrow\!\!\!-\!\!-\!\!\!\longrightarrow |\alpha\rangle \approx |1_L\rangle$$

Expnonentially asymmetric noise

BIT FLIPS

$$|0_L\rangle \approx |-\alpha\rangle \leftarrow - - \rightarrow |\alpha\rangle \approx |1_L\rangle$$

Tunneling at rate , with



Expnonentially asymmetric noise

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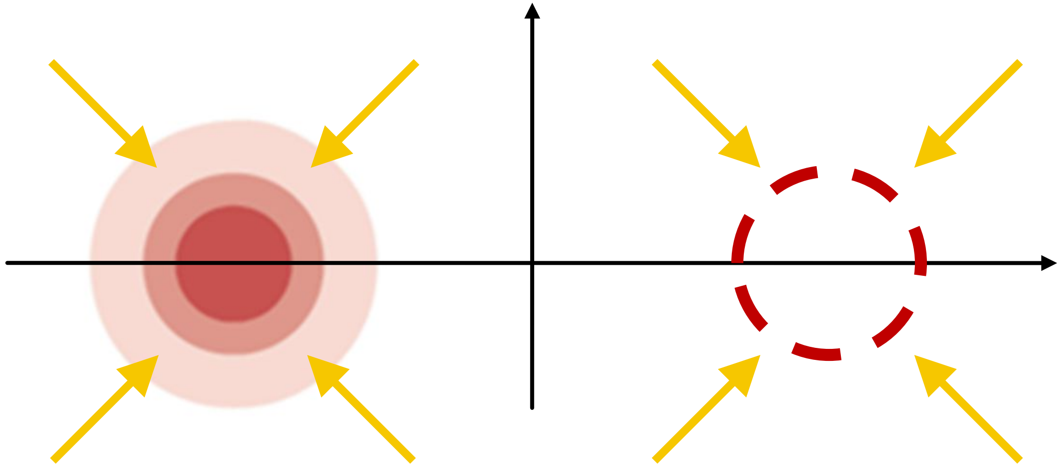
EXPONENTIALLY SUPPRESSED

Tunneling at rate , with



Expnonentially asymmetric noise

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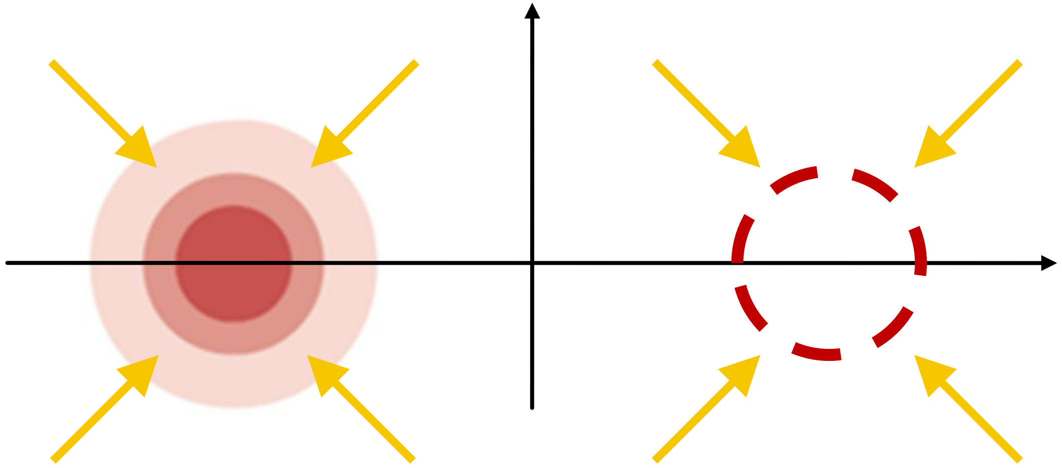

PHASE FLIPS

Mirrahimi *et al.*, NJP (2014)

Expnonentially asymmetric noise

BIT FLIPS

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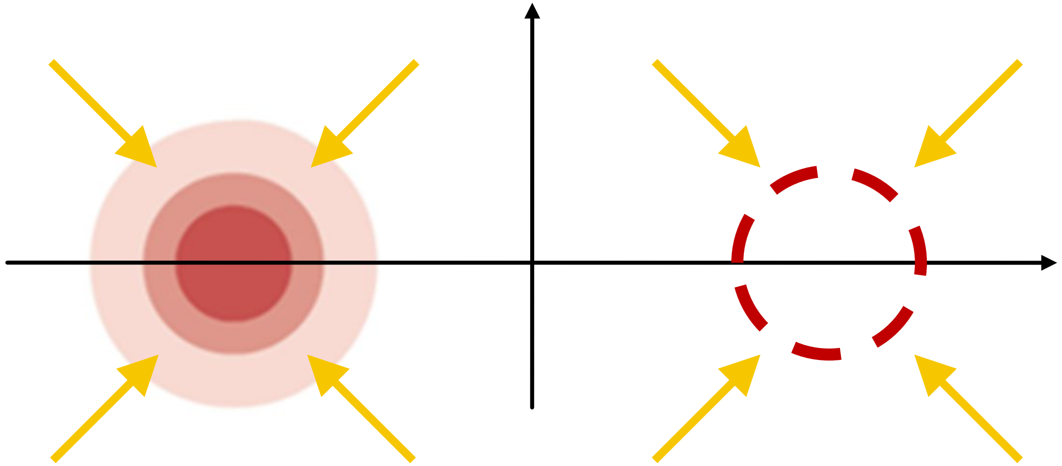
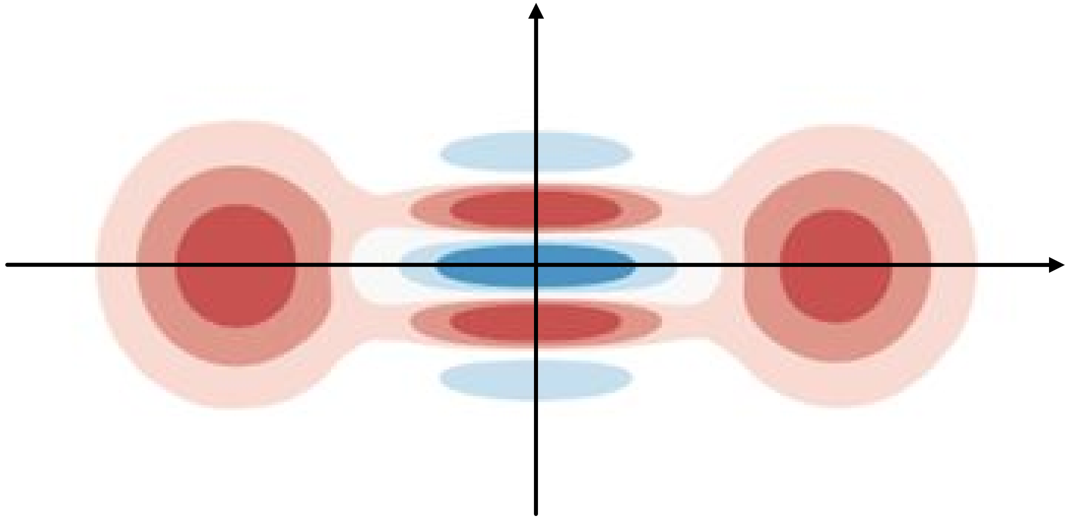
EXPONENTIALLY SUPPRESSED

Tunneling at rate , with



PHASE FLIPS

Losing any photon flips the parity



Mirrahimi *et al.*, NJP (2014)

Expnonentially asymmetric noise

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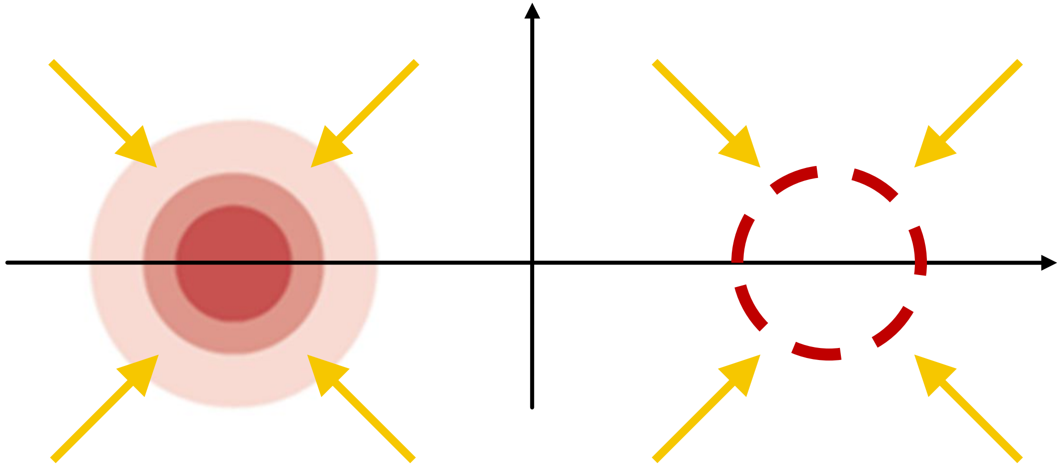
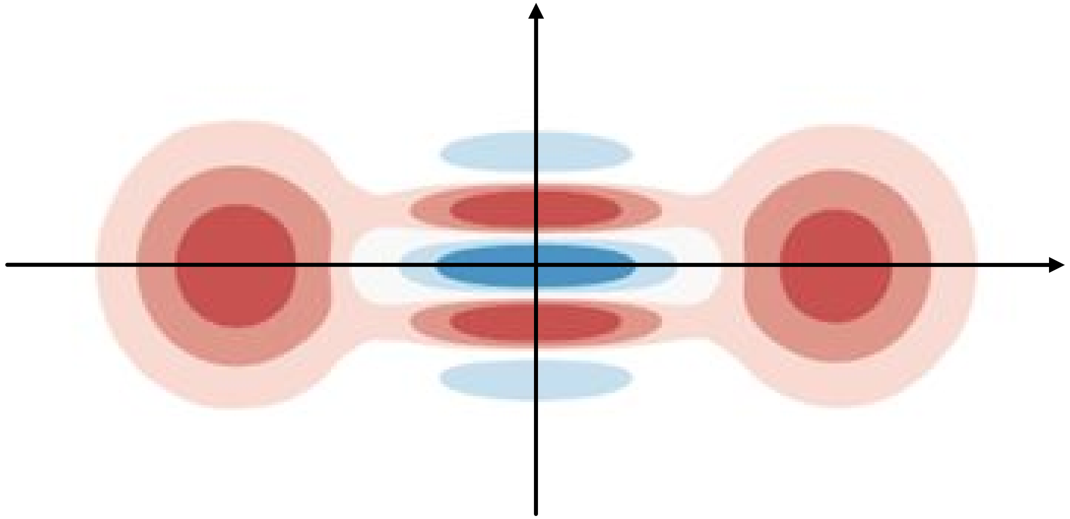
Tunneling at rate , with



PHASE FLIPS

LINEAR INCREASE

Losing any photon flips the parity



Mirrahimi *et al.*, NJP (2014)

Expnonentially asymmetric noise

BIT FLIPS

EXPONENTIALLY SUPPRESSED

VS

PHASE FLIPS

LINEAR INCREASE

Is the Cat qubit really getting better ?

How to quantify that ?

Mirrahimi *et al.*, NJP (2014)

02

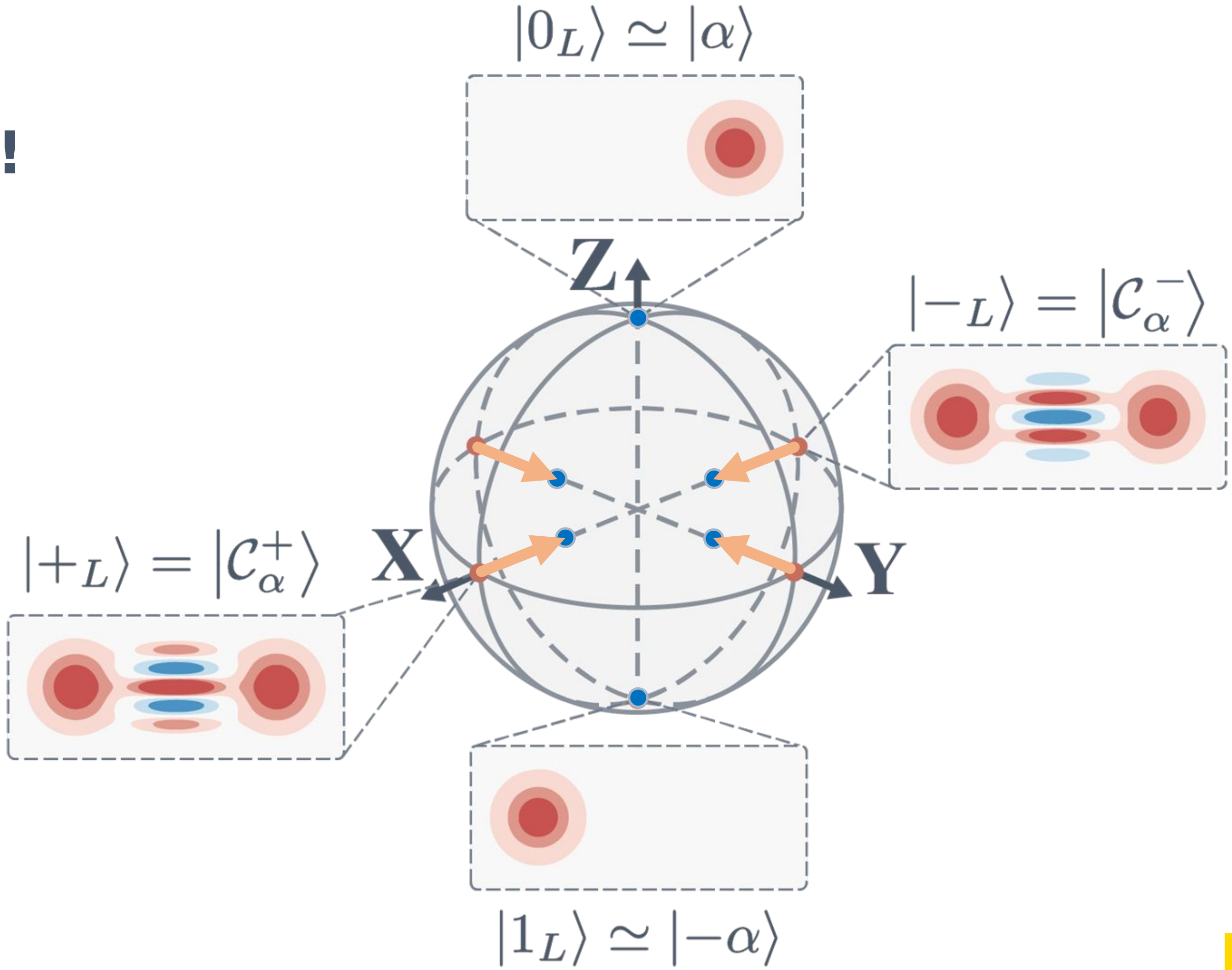
BENCHMARKING CAT QUBITS

Traditional Benchmarks on Cat qubits

Randomized Benchmarking !!

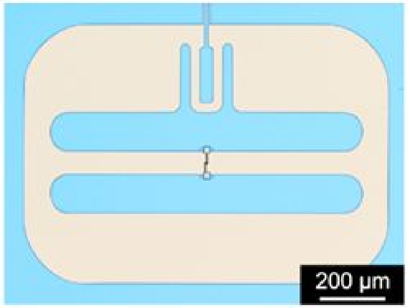
- Operation error is **averaged** over Bloch sphere
- Insensitive to noise bias
- Bigger cat ✉ bigger RB noise…

… does not capture the performance of a cat qubit.



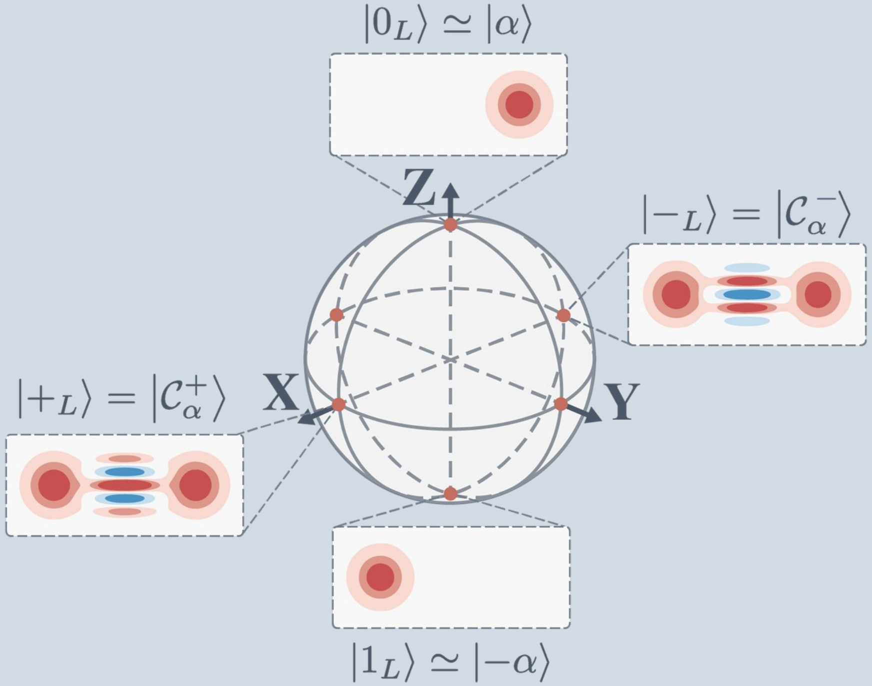
How to compare a Cat qubit to other qubits?

Transmon qubit



VS

Cat qubit



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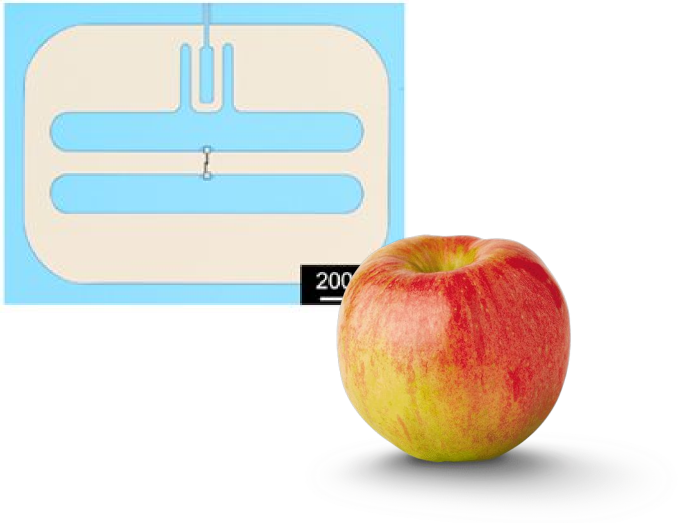

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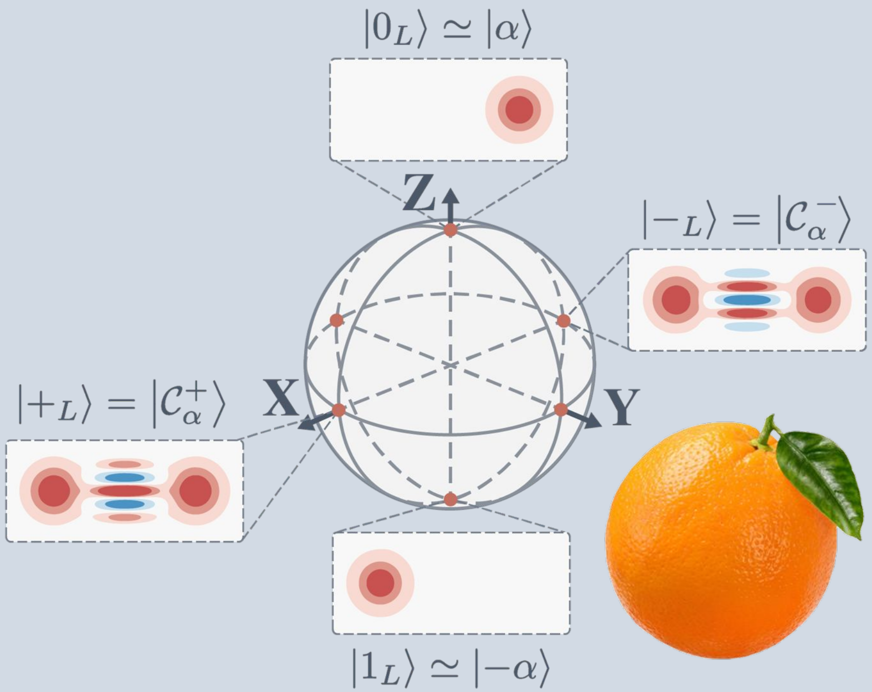

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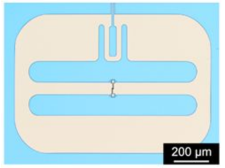
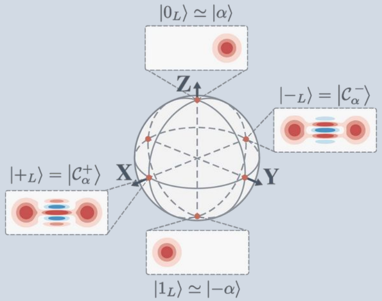
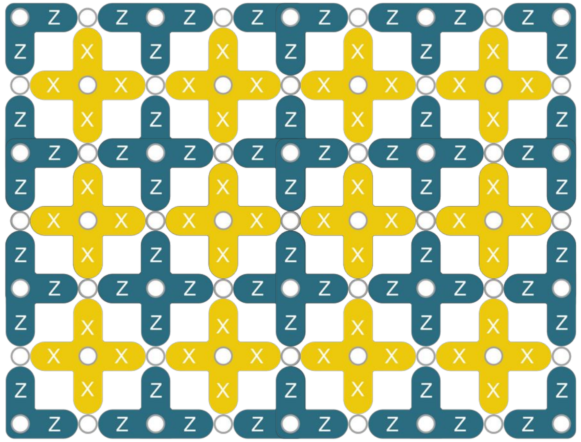


Cat qubit

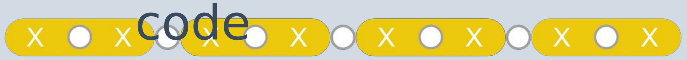


in 2D surface code



VS

in 1D repetition code



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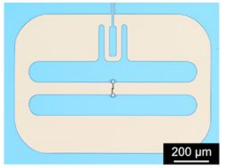

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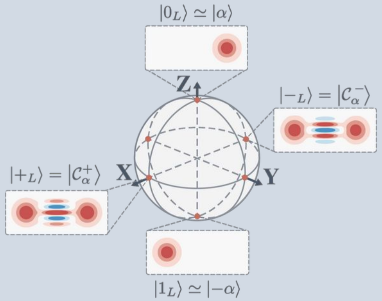

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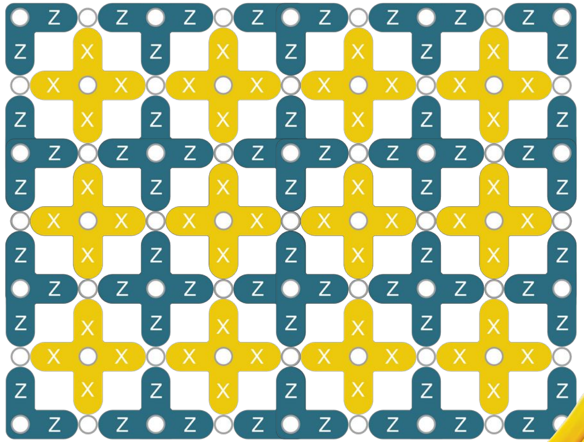
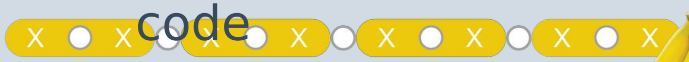
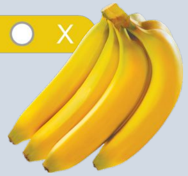


VS

in 1D repetition code

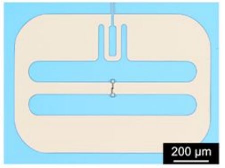




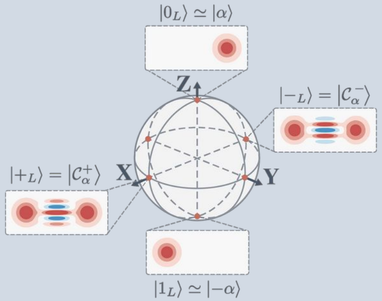
How to compare a Cat qubit to other qubits?

EASY
to benchmark

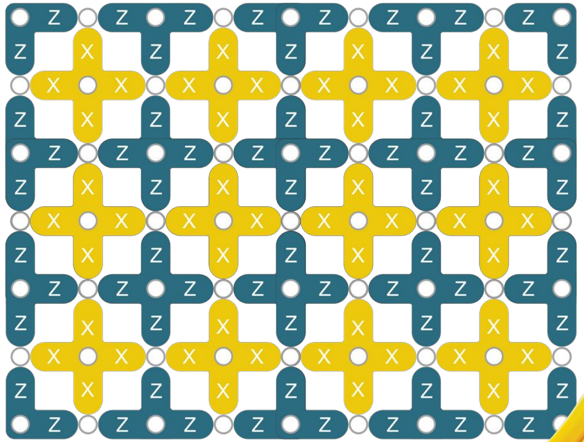
Transmon qubit



Cat qubit

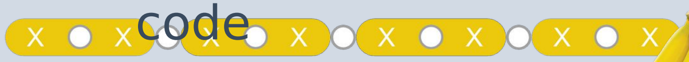


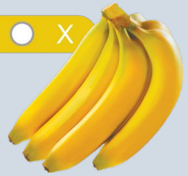
in 2D surface code



VS

in 1D repetition code





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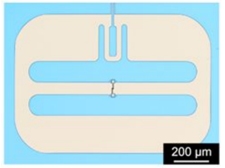

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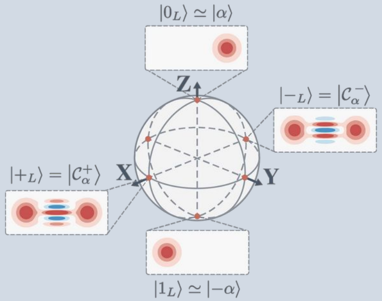
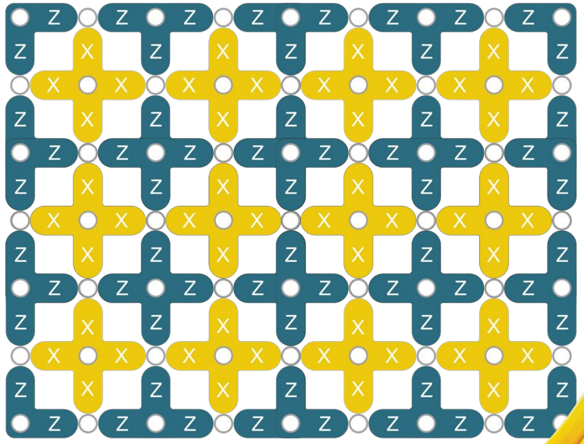
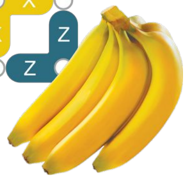


HARD
to benchmark

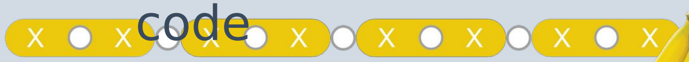
in 2D surface code

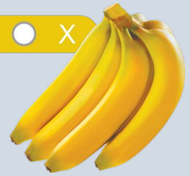




VS

in 1D repetition code

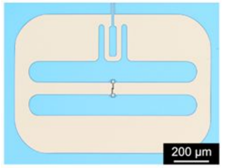




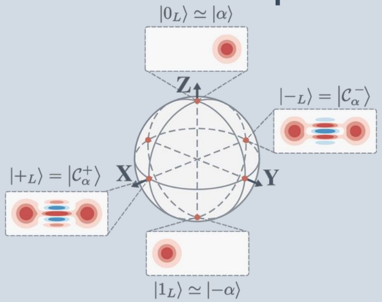
How to compare a Cat qubit to other qubits?

EASY
to benchmark

Transmon qubit



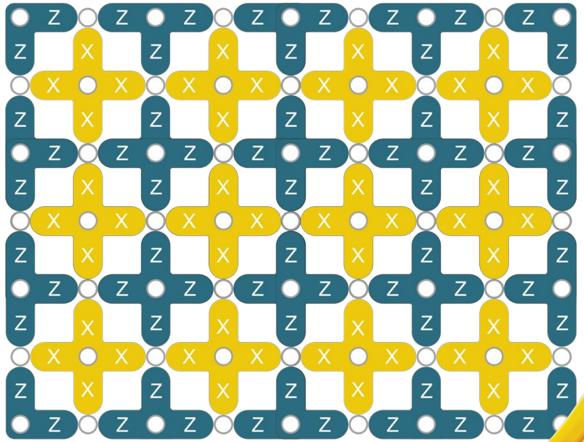
Cat qubit



MEASURE KEY METRICS HERE

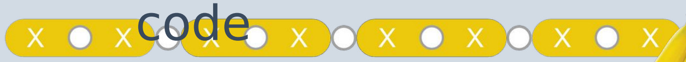
HARD
to benchmark

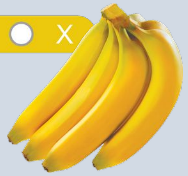
in 2D surface code



VS

in 1D repetition code



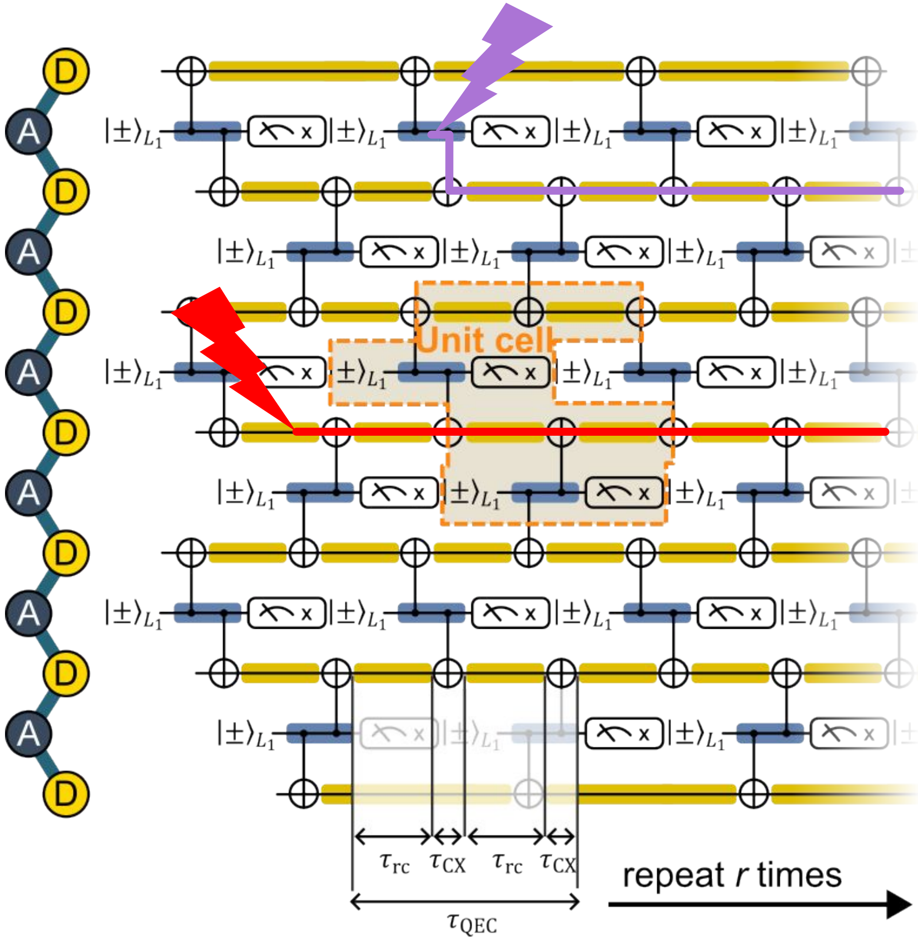


ESTIMATE LOGICAL PERFORMANCE

03

KEY CAT QUBIT METRICS IN REPETITION CODE CONTEXT

How to get to logical errors



BIT FLIPS

Two type of errors:

- **Data bit flip**
- **Ancilla bit flip** in between CNOTs

1 bit-flip error --> 1 logical error

Le Régent *et al.*, Quantum 7, 1198 (2023)

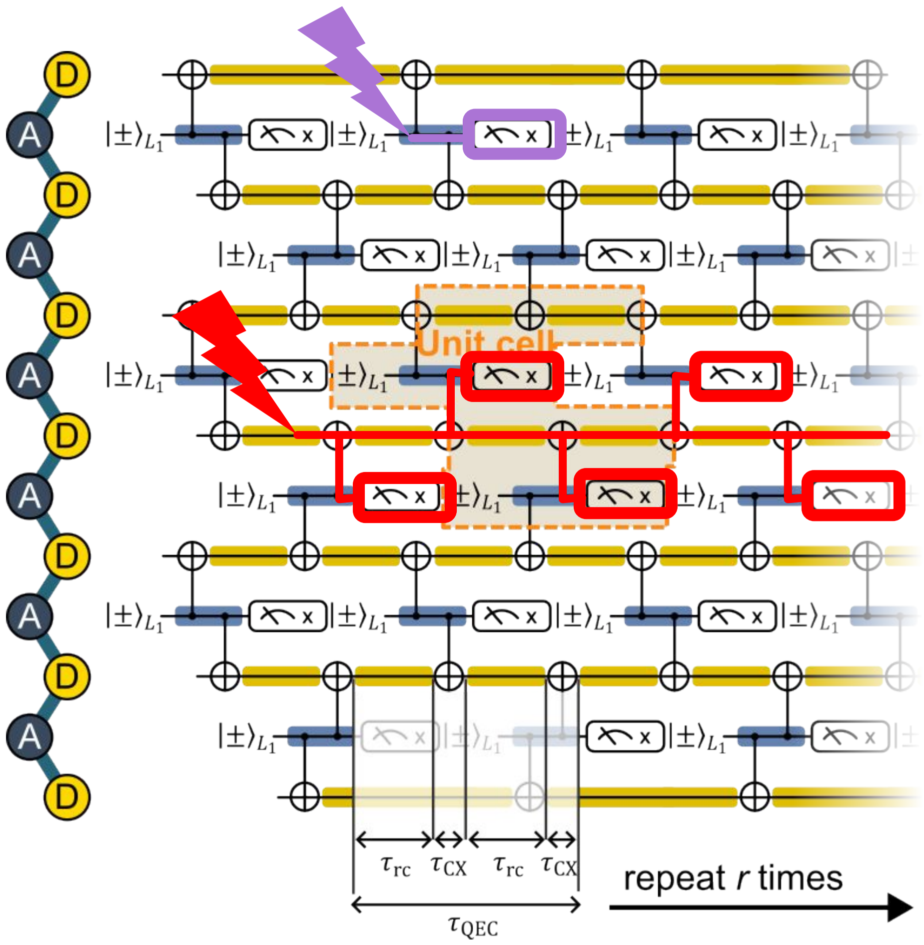
How to get to logical errors

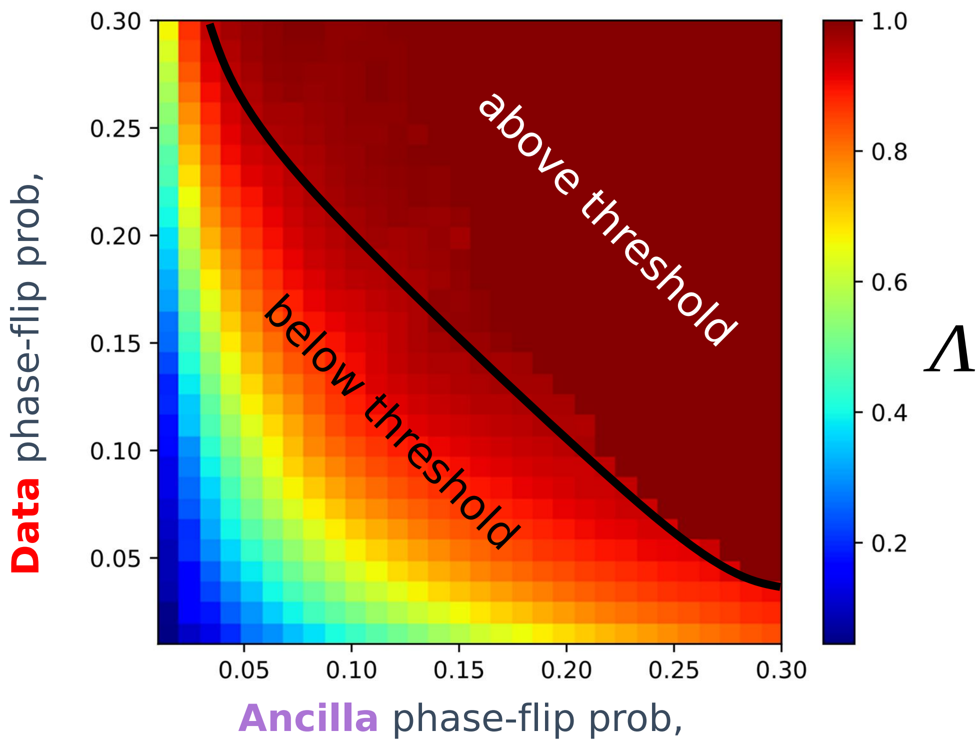
PHASE FLIPS

Two type of errors:

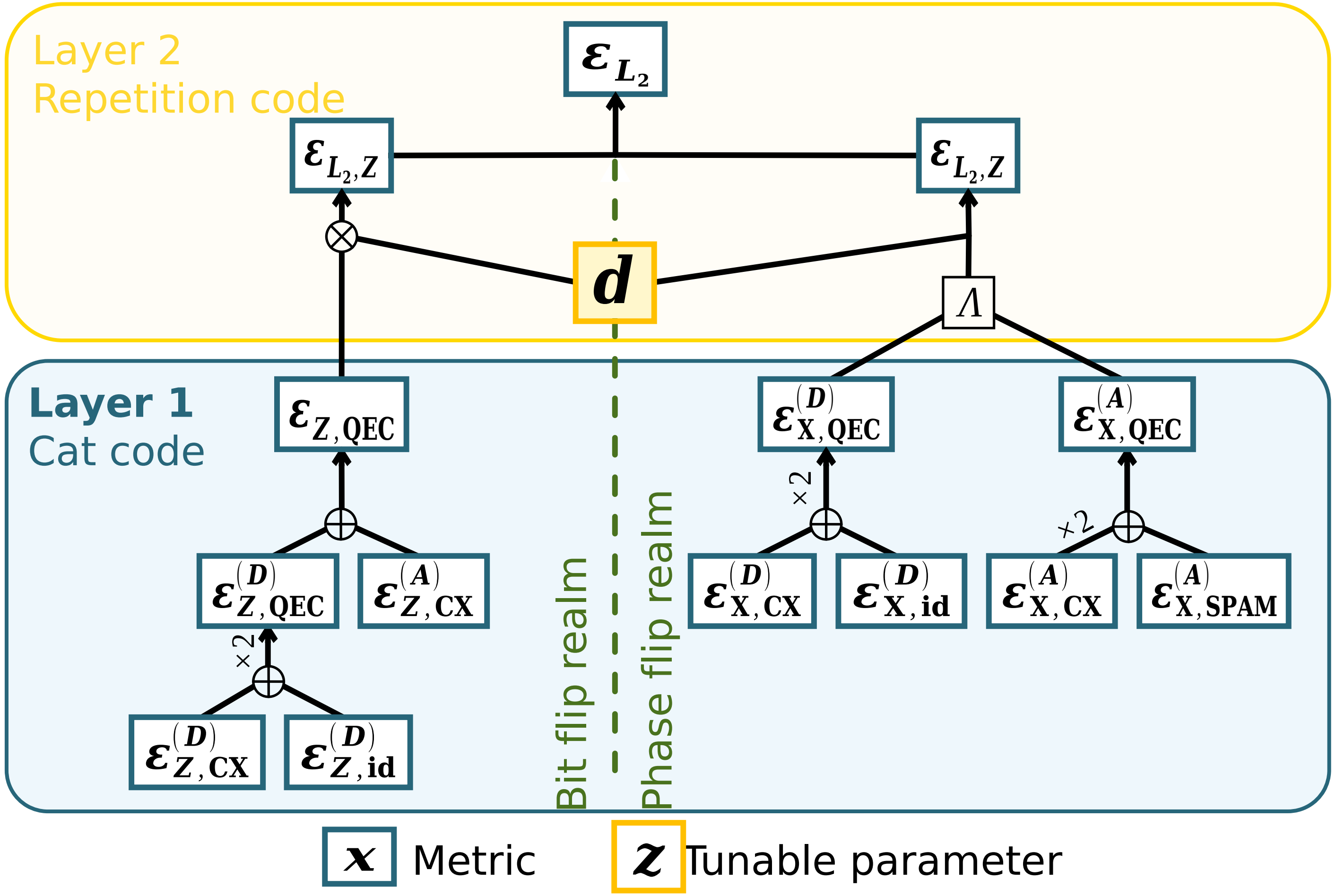
- **Data phase flip** - propagate – detectable
- **Ancilla phase flips** – do not propagate – MXX error

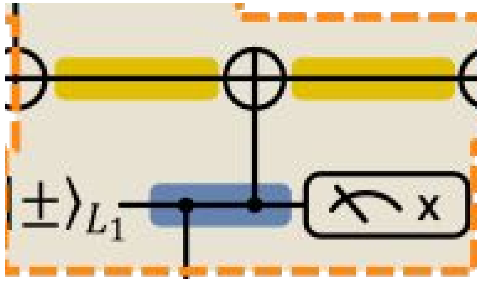
Results in predictable logical error





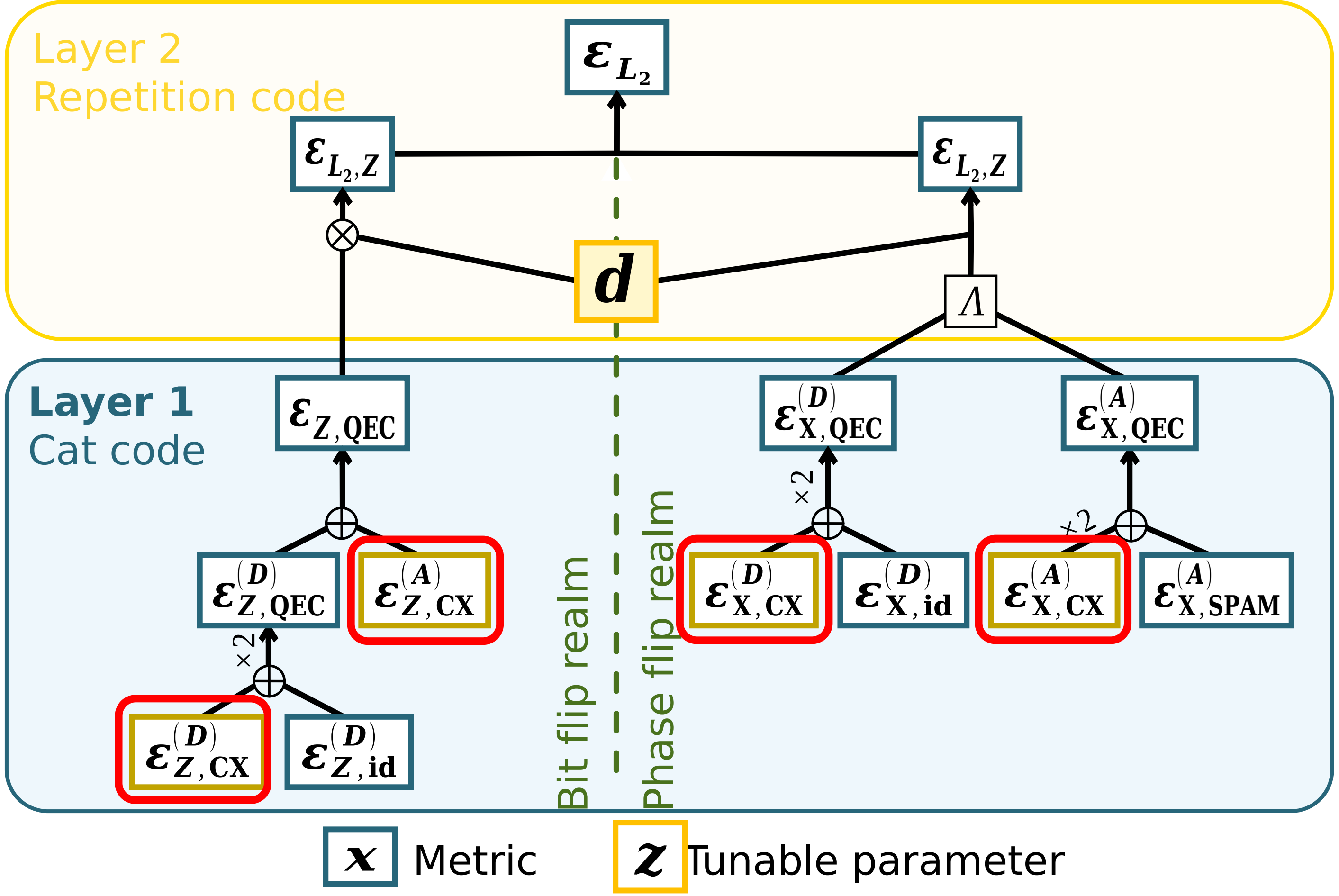
Metrics graph to map key metrics to logical error

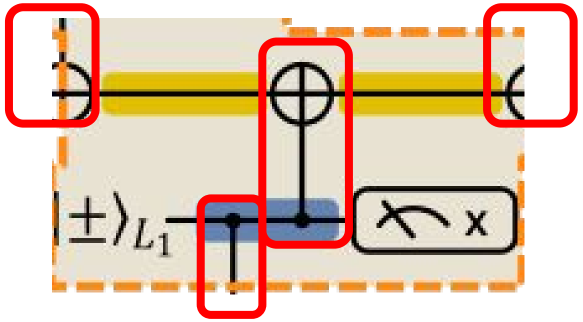




Three types of measurements

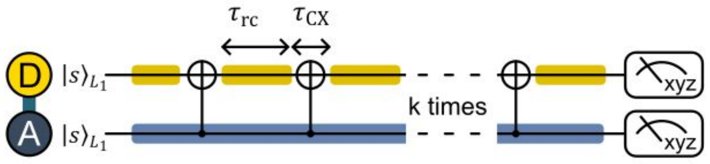
Metrics graph to map key metrics to logical error





Three types of measurements

1. CNOT



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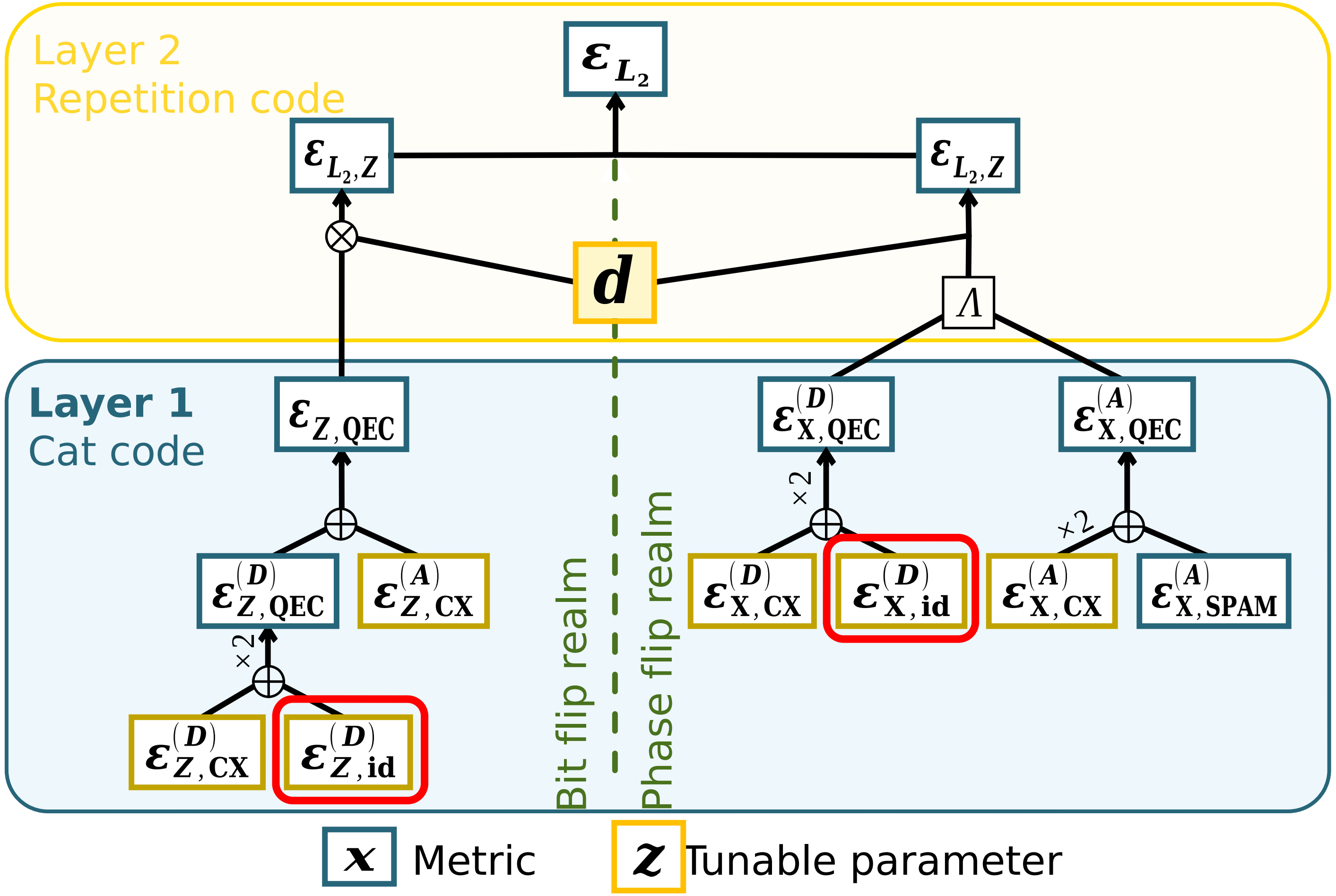
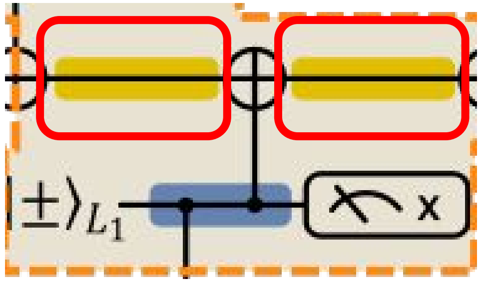
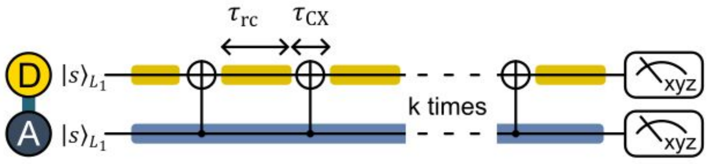




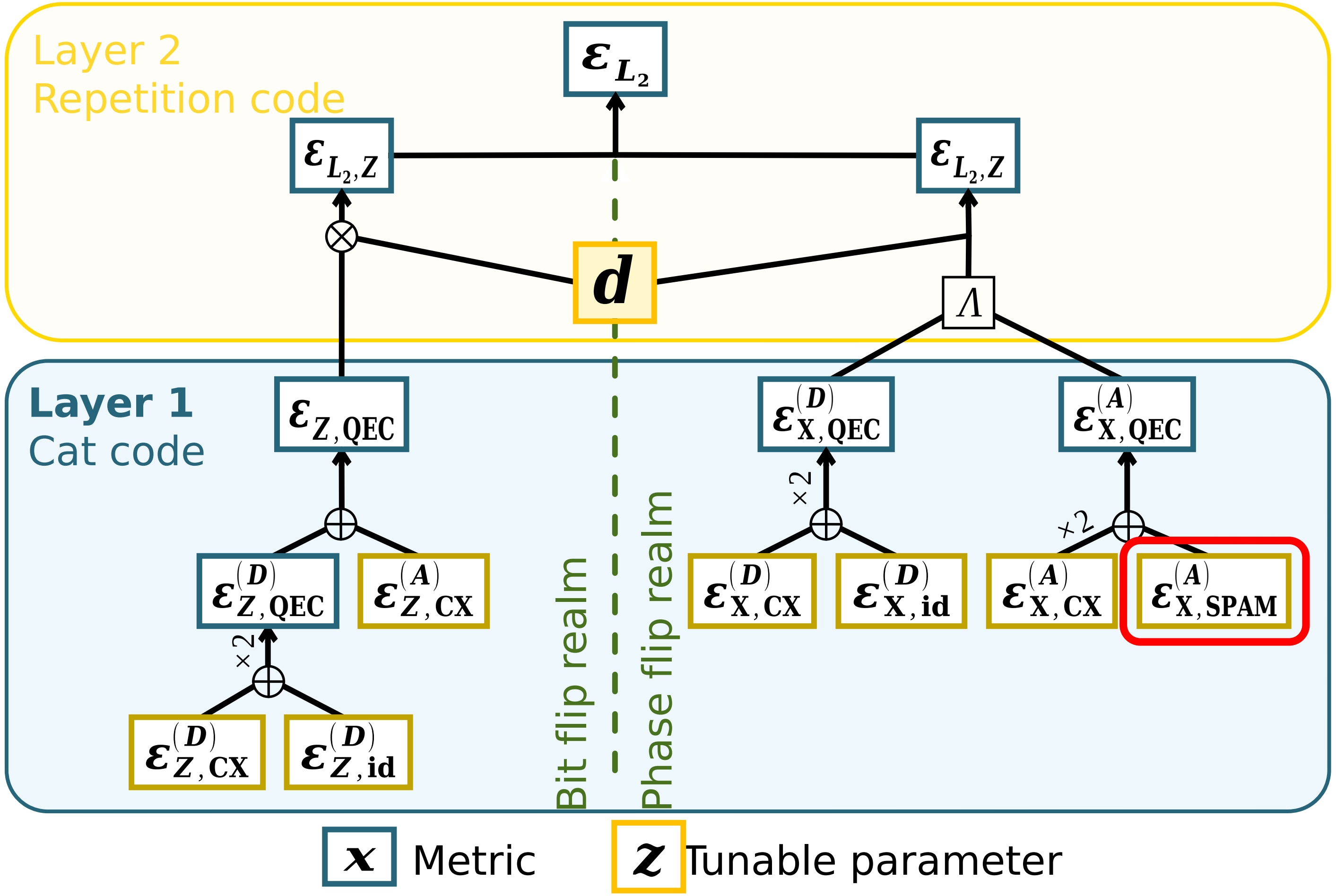
Three types of measurements

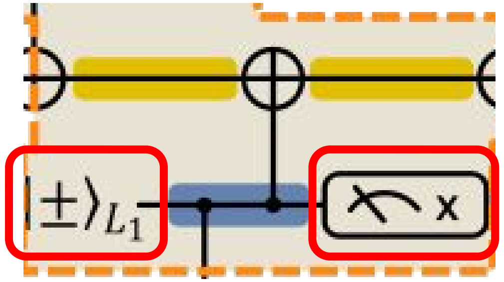
1. CNOT



2. Idle

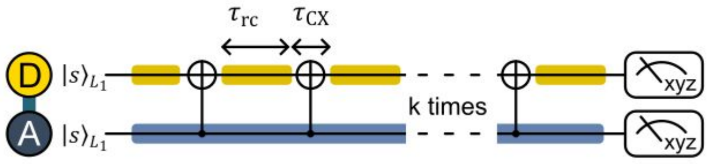
Metrics graph to map key metrics to **logical error**





Three types of measurements

1. CNOT



2. Idle

3. SPAM $|\pm\rangle_{L_1}$ — x

A glimpse of experiment – CNOT phase flips

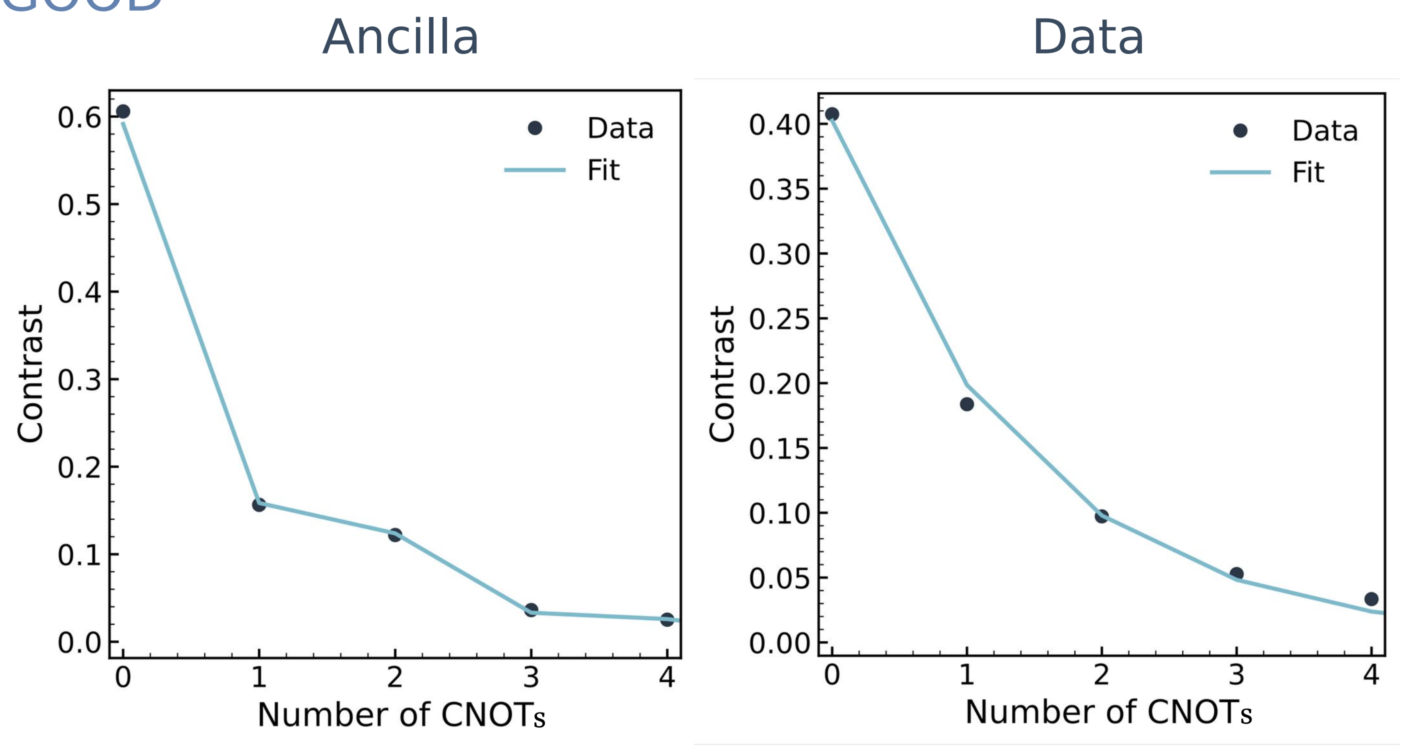
SEEMS BAD on current standard metric but just a factor 2 away from threshold, which IS ACTUALLY GOOD

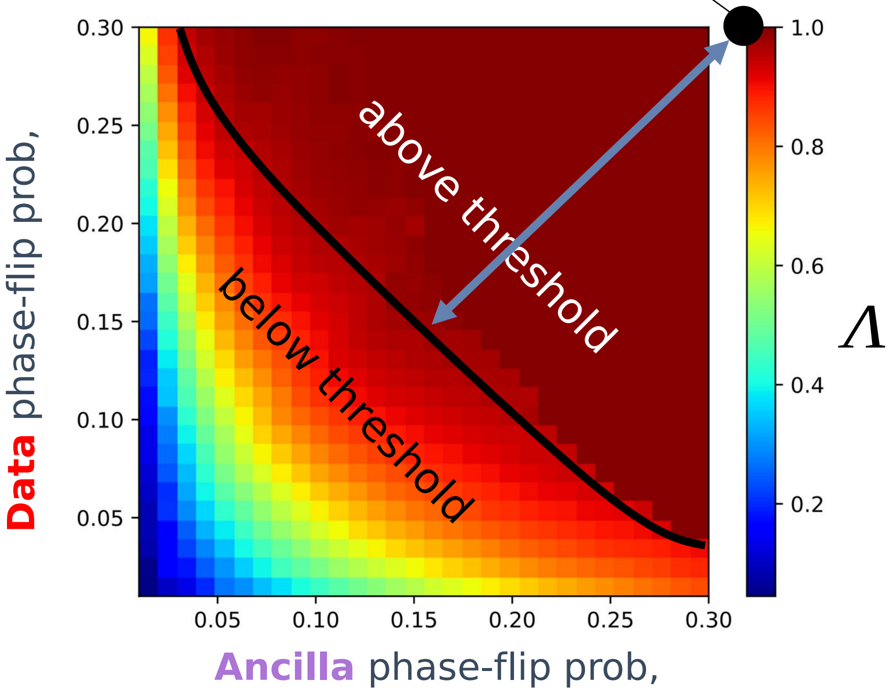
We are here...

$\varepsilon^{A}_{X,CX} \approx \varepsilon^{D}_{X,CX} \approx 0.15$

$\varepsilon^{A}_{X,SPAM} \approx 0.2$

$\varepsilon^{D}_{X,id} \approx 0.09$





ASSESSING THE PERFORMANCE OF DISSIPATIVE CAT QUBITS

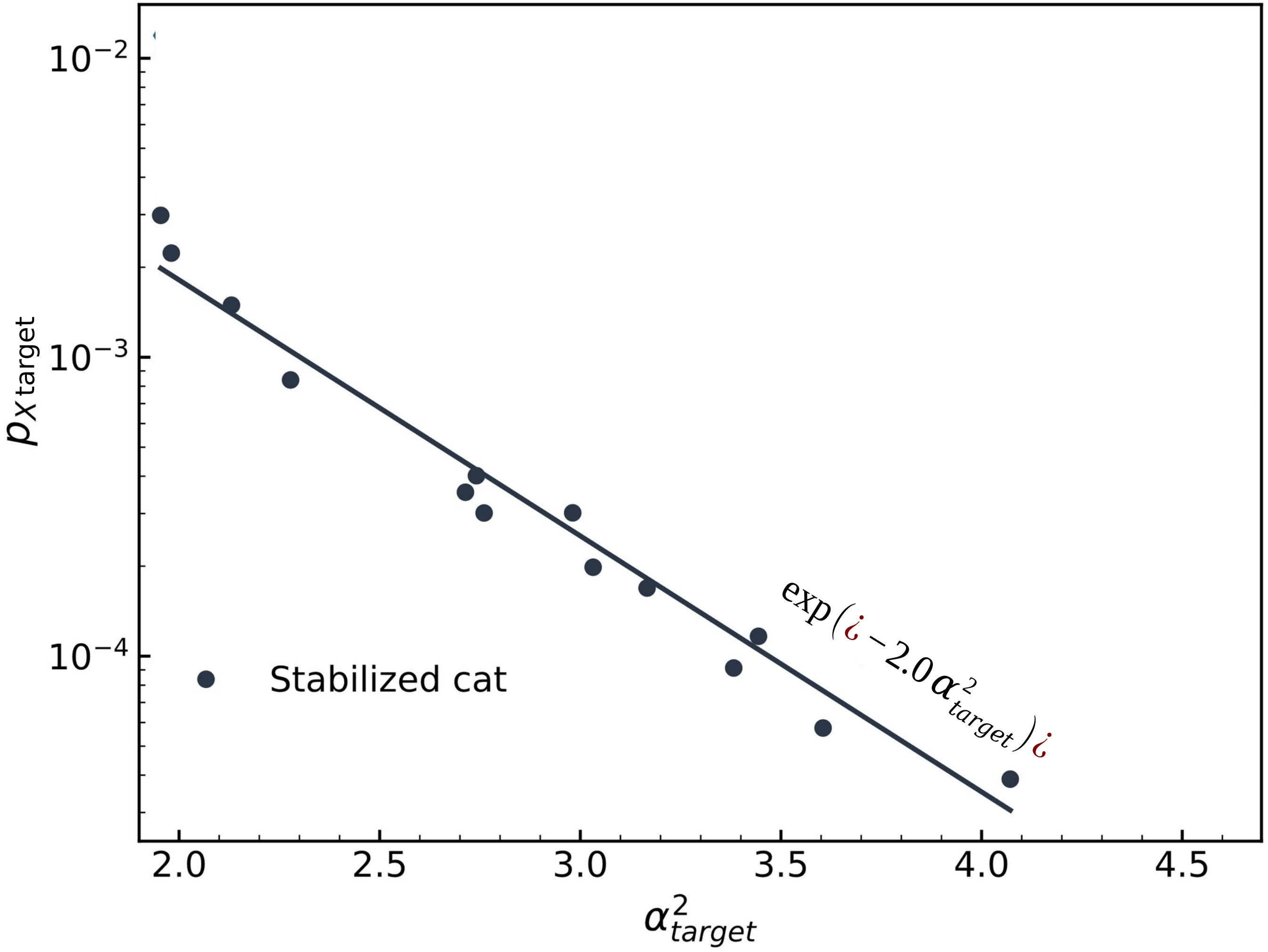
01. Cat qubits give **exponential** bit-flip suppression against a **linear** increase of phase flips.

02. **Existing benchmarks** like RB lack of **relevance** - insufficient to estimate logical performance - and **universality** – not suited to cat qubits.

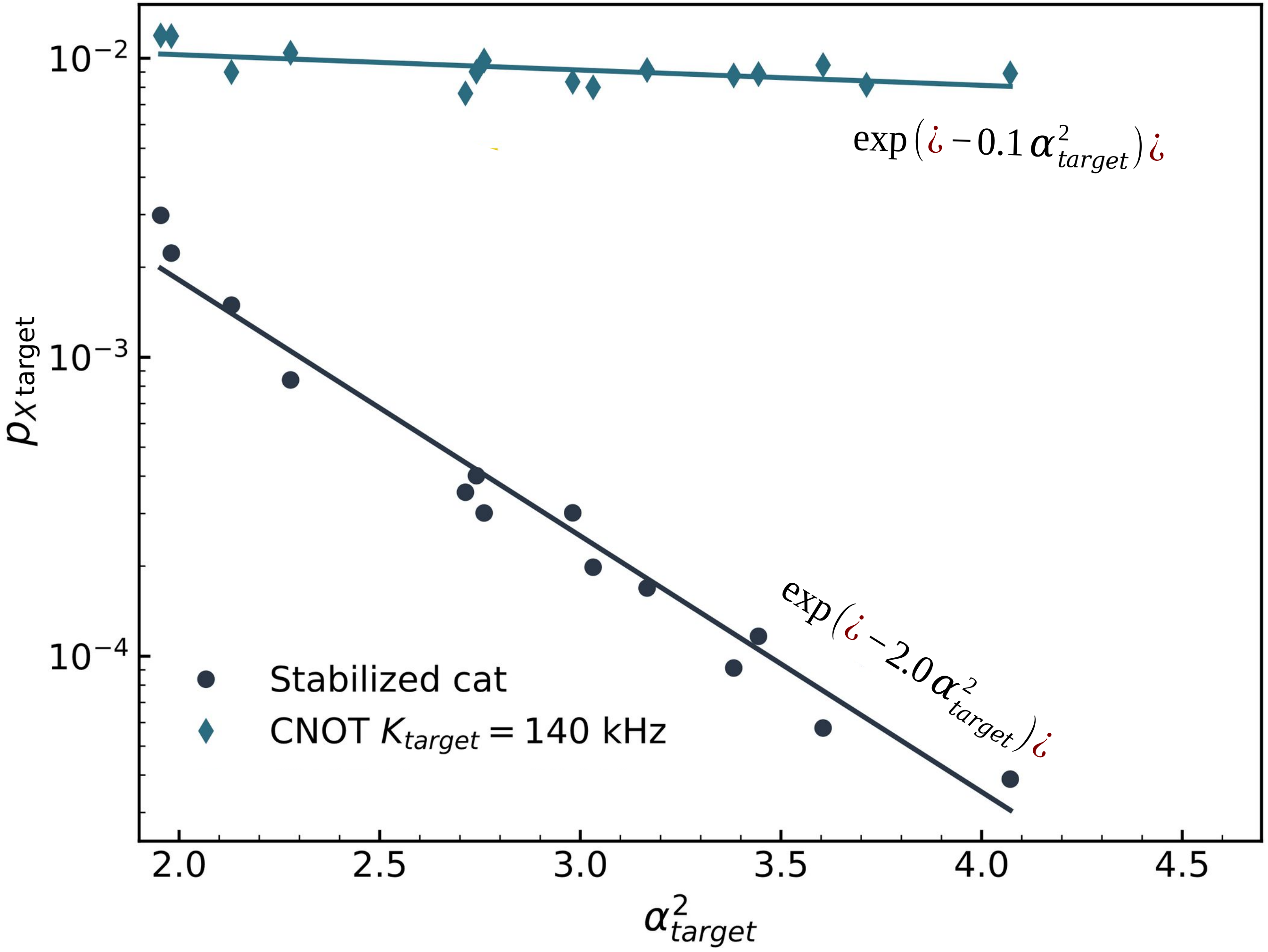
03. Instead, we measure the **key metrics** on cat qubits operations which allow to estimate **logical performance**, allowing **relevant and universal comparison**.

ALICE & BOB

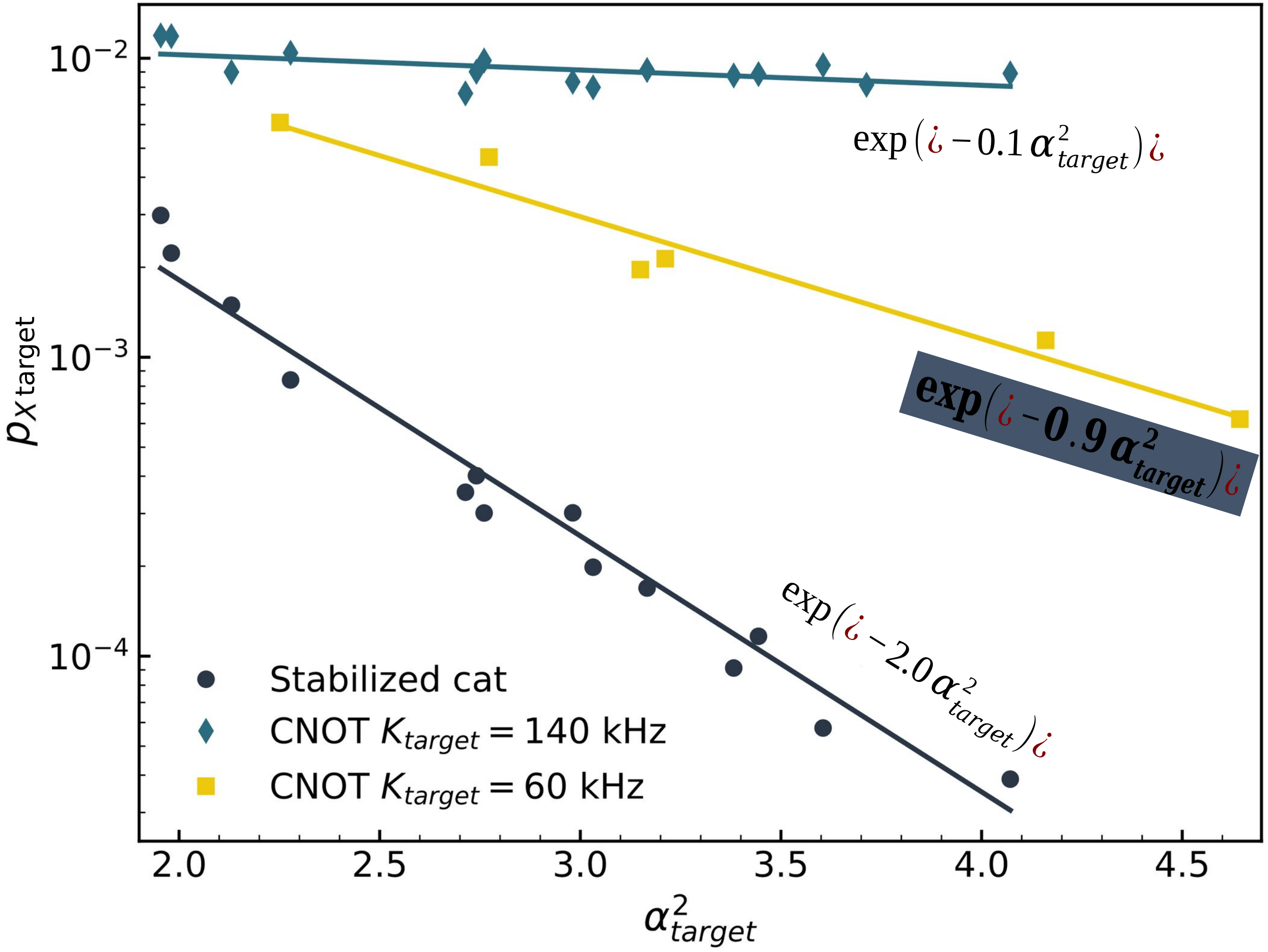
Characterizing bit-flips



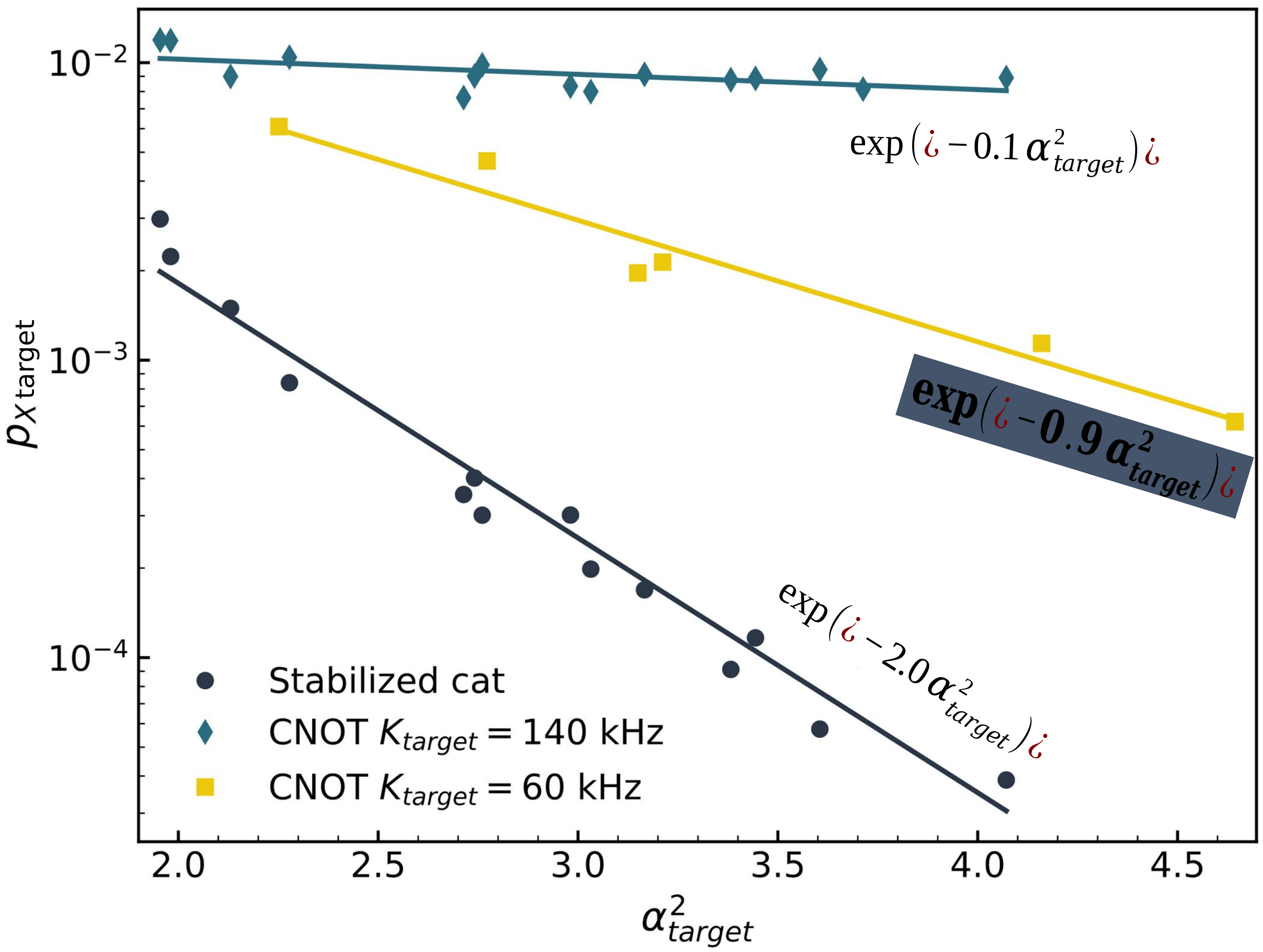
Characterizing bit-flips



Characterizing bit-flips



Characterizing bit-flips



Bit-flip scaling of the target is **limited by leakage** while the stabilization is turned off

Solutions

- Further reduce Kerr (and dephasing)
- Engineer **conditional** rotation of the two-photon dissipation on the target

Guillaud & Mirrahimi, PRX 9, 041053 (2019)