robust quantum computing
with
Cat Qubits

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an enriching collaboration (I’m just a secondary part)

QUANTIC team theory group

<u>Mazyar Mirrahimi</u>
Pierre Rouchon
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Antoine Tilloy
Alexandru Petrescu
Rémi Robin

QUANTIC team experiments group

Zaki Leghtas
Philippe Campagne-Ibarcq

& many PhD students, postdocs

(inria Paris, ENS Paris, Mines Paris)

Yale University collaboration

Michel Devoret*
Rob Schoelkopf
Steve Girvin
Liang Jiang

Alice & Bob company (since 2020)

Théau Perronin
Raphaël Lescanne

Outline

1. The cat qubits concept

2. Stabilizing cat qubits

3. Computing with cat qubits

M.Mirrahimi et al, « Dynamically protected cat-qubits: a new paradigm for universal quantum computation. » , NJPhys.2014
arXiv:1312.2017

R.Lescanne et al, « Exponential suppression of bit-flips in a qubit encoded in an oscillator. » , Nature Physics 2020
arXiv:1907.11729

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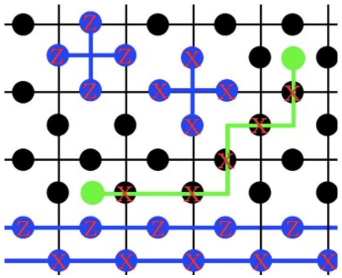
NB: Images are often illustrative and adapted from general webpages, please don't mis-credit me.
The cat-qubit data are from our group & Yale collaboration

Quantum Computing needs Error Correction

protect 1 qubit $a|0\rangle + b|1\rangle$ information in

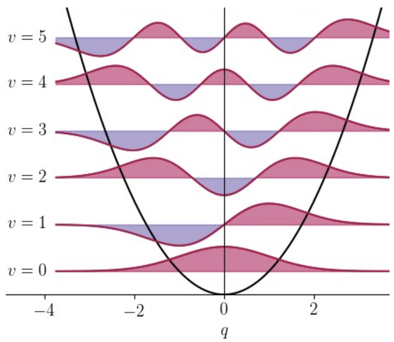
n qubits

$a|000\rangle + b|111\rangle$



one qu-*d*-it

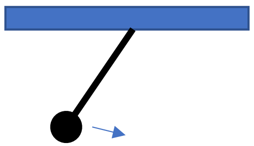
$a|\psi_0\rangle + b|\psi_1\rangle$



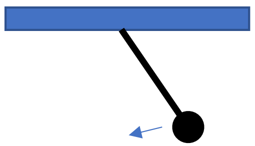
Keep $|0\rangle$, $|1\rangle$ "macroscopically" distinct

qu-*d*-it = quantum harmonic oscillator

$|0_L\rangle = |\alpha\rangle$



$|1_L\rangle = |-\alpha\rangle$



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$|0_L\rangle = |\alpha\rangle$

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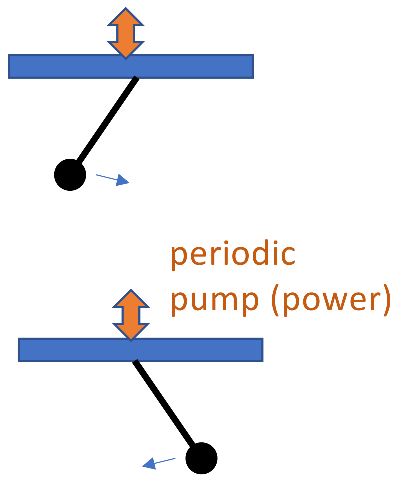
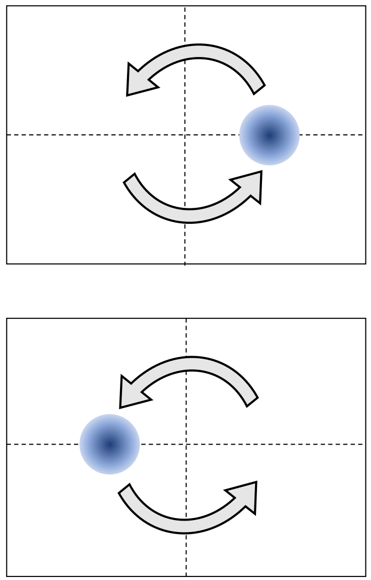
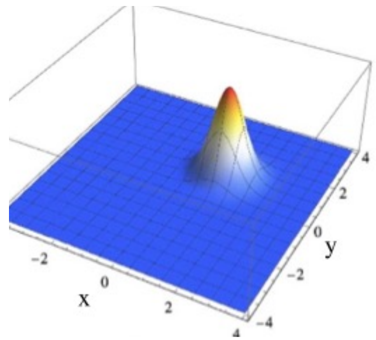
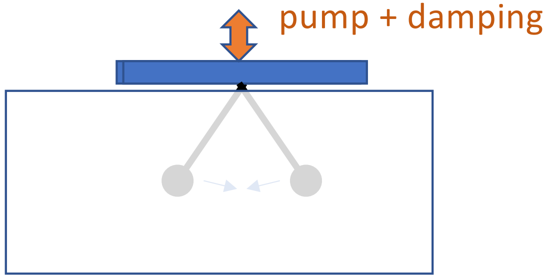


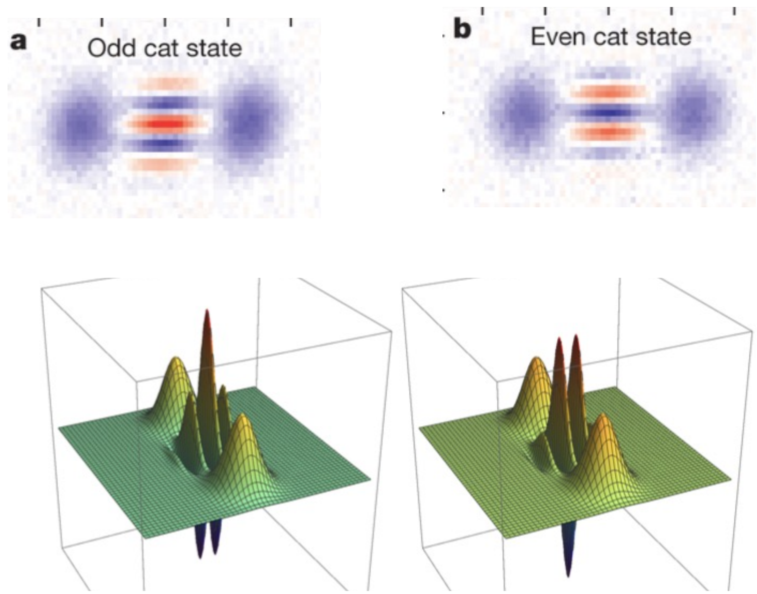




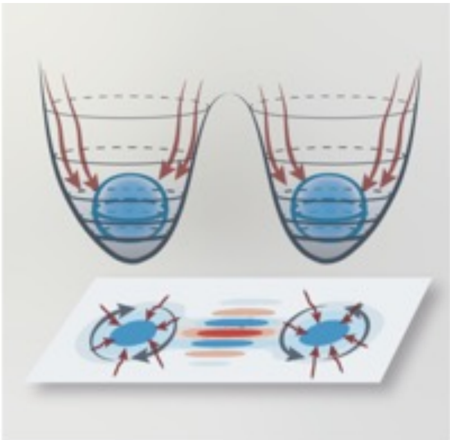
The cat is |dead> ± |alive>



classically bi-stable system



The cat is $|dead\rangle \pm |alive\rangle$



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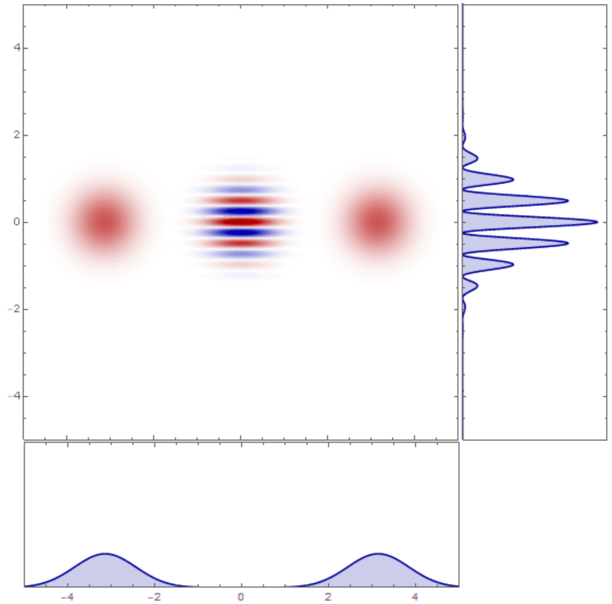
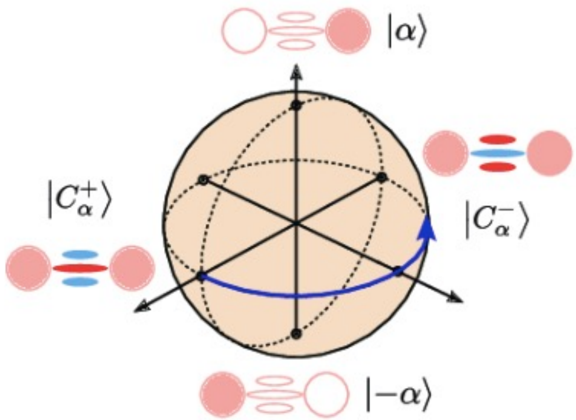
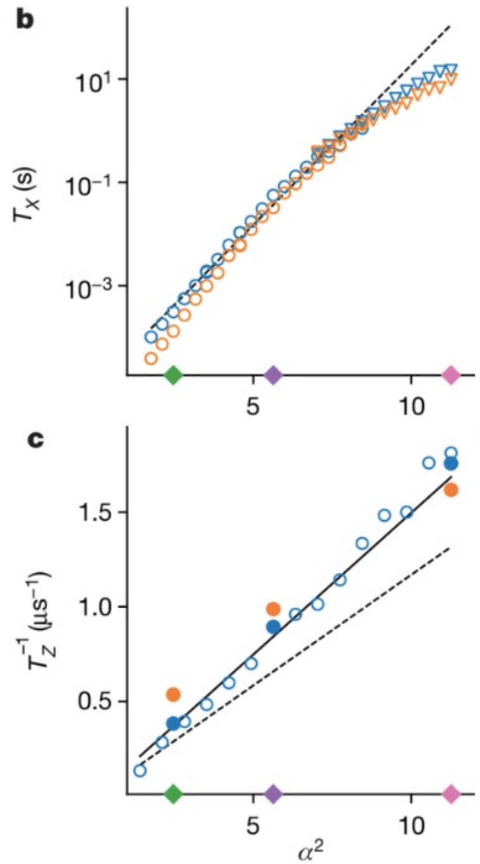


Hardware shortcut: blocking bit-flips (at scale)





exponentially low bit-flip

linear increase in phase-flip

Outline

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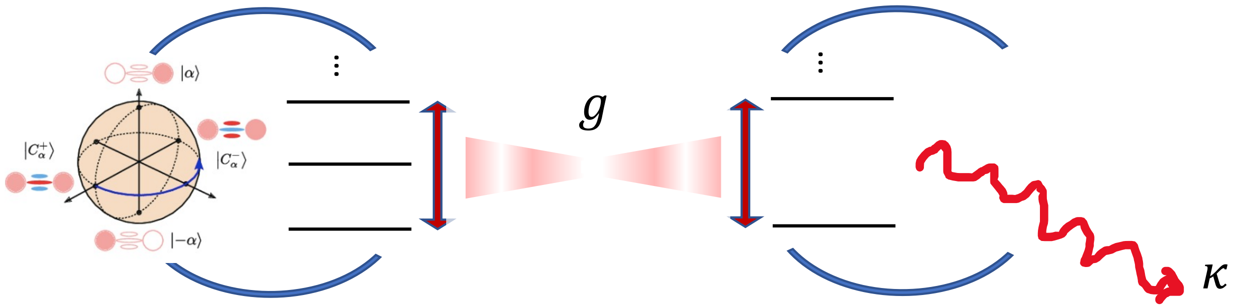
Creating a bi-stable quantum system

$$\frac{d}{dt}\boldsymbol{\rho} \;=\; (a^2-\alpha^2)\boldsymbol{\rho}(a^2-\alpha^2)^+ - \;\frac{1}{2}\{\,(a^2-\alpha^2)^+(a^2-\alpha^2)\,,\boldsymbol{\rho}\,\}$$

- equilibria
- convergence
- information protection

Engineering a bi-stable quantum system (1)



$$\frac{d}{dt}\boldsymbol{\rho} = -i\, g[a^2 b^+ + a^{+2} b, \boldsymbol{\rho}] - i\, u[b + b^+, \boldsymbol{\rho}]$$

$$+ \kappa\, (b\boldsymbol{\rho} b^+ - \tfrac{1}{2}\{ b^+ b\, , \boldsymbol{\rho}\, \})$$

Engineering a bi-stable quantum system (2)

$$H_{coupling} \;=\; -i\; g[a^2 b^+ + a^{+2} b, \boldsymbol{\rho}]$$

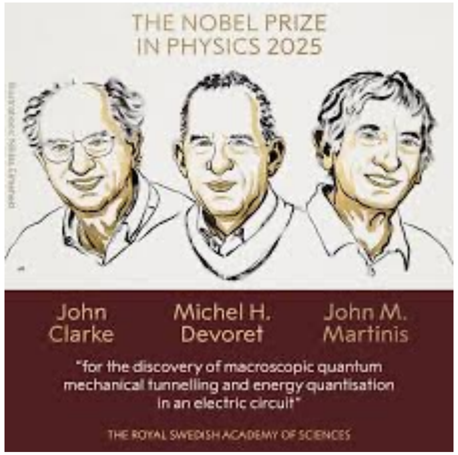
$$\approx\;\; \omega_a\, a^+ a \;\;+\;\; \omega_b\, b^+ b \;\;+\;\;\; f_{nl}(\,(a^+ + a), (b^+ + b),\;\, u(t)\,)$$

Frequency-selective activation
(resonance ≈ Rotating Wave Approximation ≈ averaging)

Building a bi-stable quantum system

$$H_{coupling} = -i\, g[a^2 b^+ + a^{+2} b, \boldsymbol{\rho}]$$

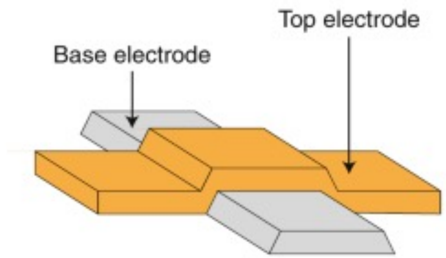
$$\approx \; \omega_a\, a^+ a \; + \; \omega_b\, b^+ b \; + \; f_{nl}(\,(a^+ + a), (b^+ + b), \; u(t)\,)$$



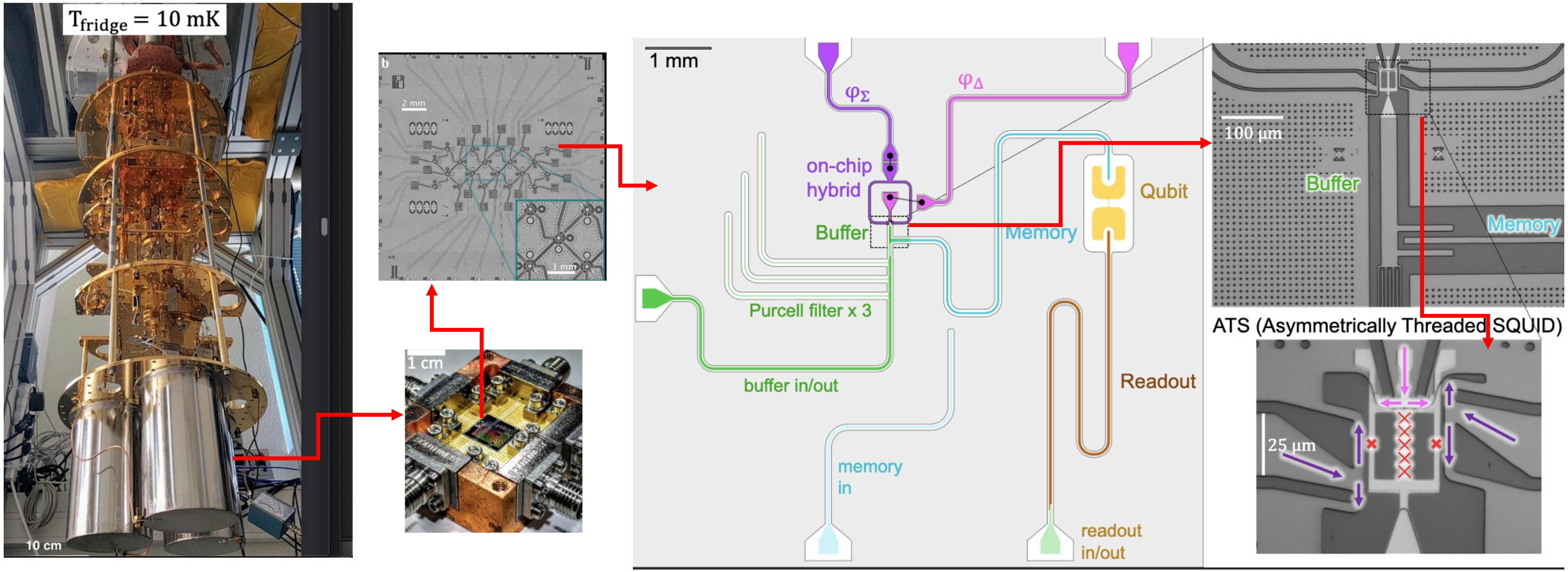
superconducting circuits

Josephson Junction

$f_{nl}(\dots) = \cos(\dots)$



Building a bi-stable quantum system



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Operations on a quantum computer

- Read-out (measuring the qubit in at least 1 basis)
- Input (initialize the qubit in at least 1 state)
- Operations: - on single qubit
  - coupling qubits
  - non-Clifford
- Quantum Error Correction

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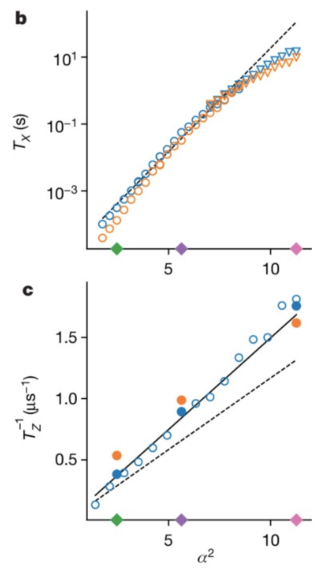
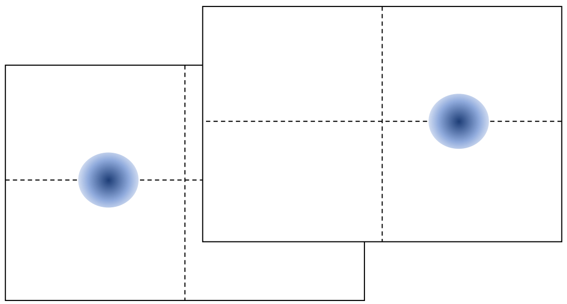
! keep perfect handling of bit value



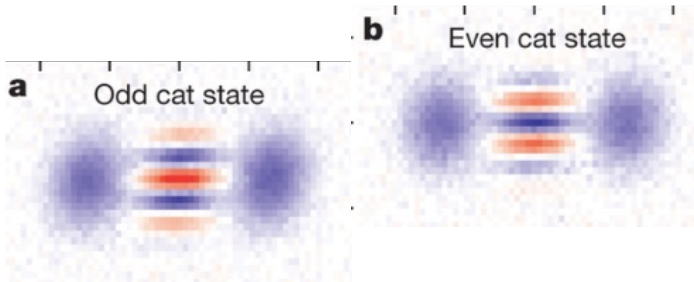
Reading out a cat-qubit value

|0> ,|1> basis



pendulum position
« easy »

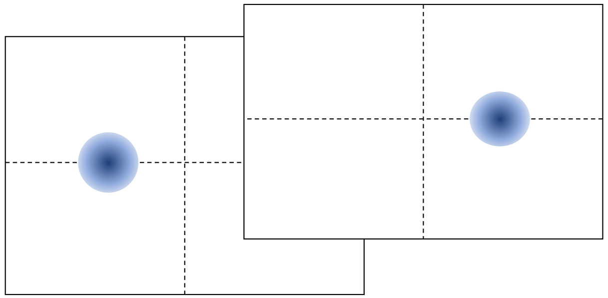
|+> ,|–> basis



photon number parity
« harder »

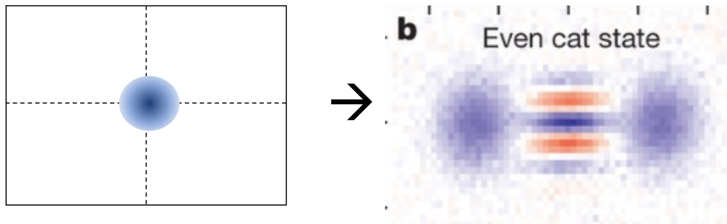
Initializing a cat qubit

|0> ,|1> basis



put it roughly
left or right

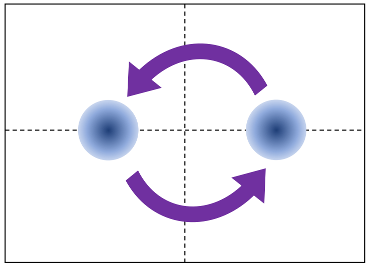
|+> ,|−> basis



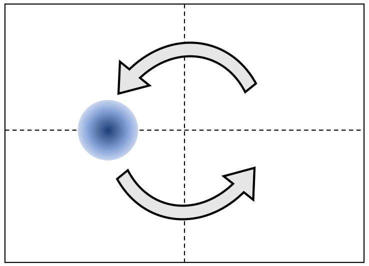
0 (vacuum) is
an even number

Cat-qubit X gate

π rotation



OR



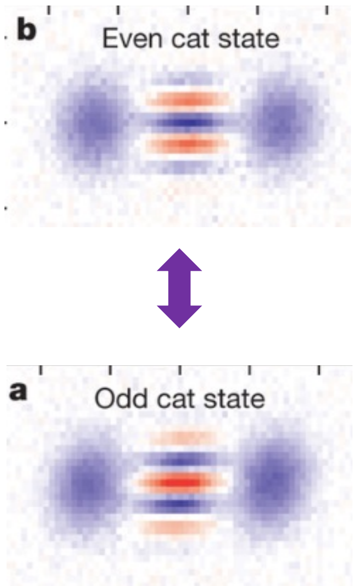
$$H = a^{+}a$$

& stabilize $\pm\alpha\, e^{it}$

delay by half a period

(purely control software)

Cat-qubit Z gate (imperfect)



$H = (a^{+} + a)$ & stabilize $\pm\alpha$

- Zeno dynamics
- $\approx$ position-dependent energy

Alternatives:

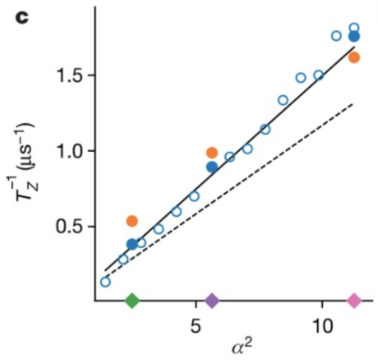
other H , subtract 1 photon , …

Cat-qubit H gate ; X(θ) gate

- Hadamard (H) transforms |+> → |0> i.e.

  phase error → bit error

  avoid native implementation

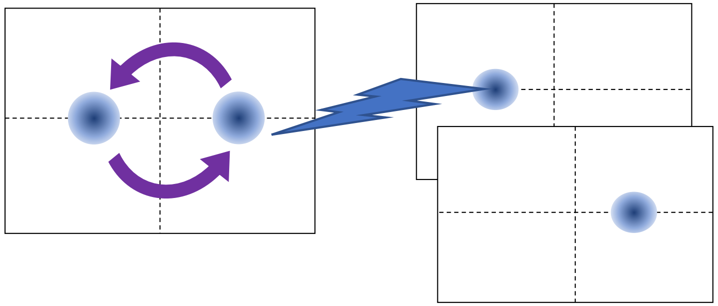


- X(θ) requires fine weighting of bit transfer by θ

  avoid native implementation

Cat-qubit CNOT gate

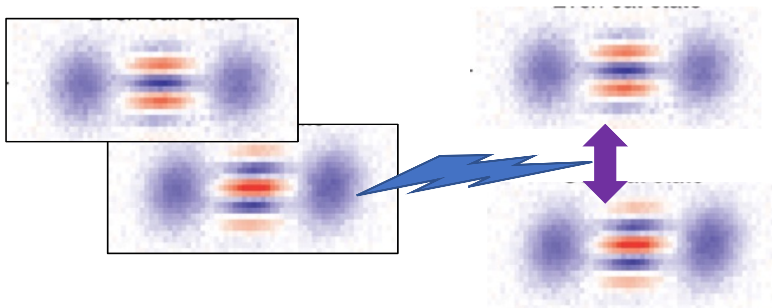
|0> ,|1> basis viewpoint



$$H = a^{+}a \ \ (b + b^{+} - 2\alpha)$$

& stabilize $\pm\alpha\ (t\ , b)$

|+> ,|–> basis viewpoint



$$H = (a^{+}a\ - (..4..))\ \ f\,(b + b^{+})$$

see Z gate

Non-Clifford gate (universality)

bit-preserving options

- Toffoli = ControlControl-NOT
- Z(θ) gate (e.g. T gate)
- Magic-State injection

main issue: compatibility with Quantum Error Correction

Cat-qubits (quantum) Error-Correction

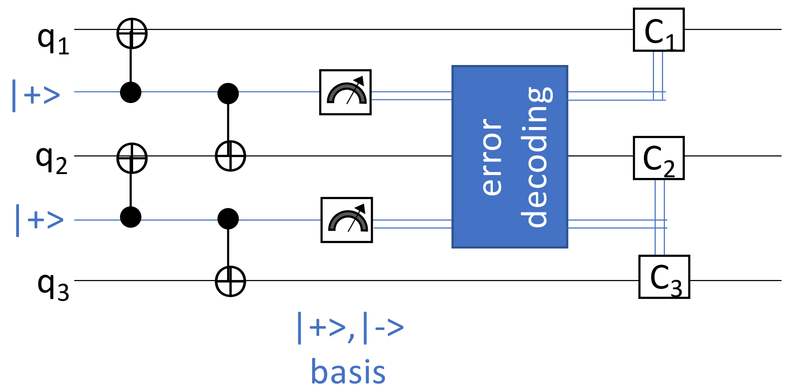
bit-flip rate ≈ 0 → **only correct phase-flips**

Classical error correction in |+>,|–> basis

Example: repetition code

|$+_L$> = |++…+>

|$-_L$> = |– – … –>



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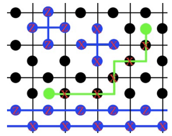
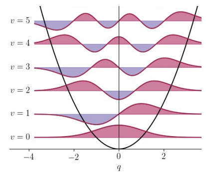
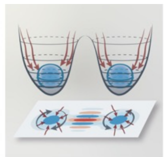
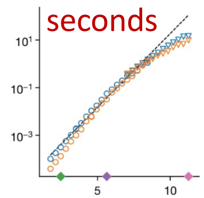




2. Stabilizing cat qubits





3. Computing with cat qubits

ongoing development

M.Mirrahimi et al, *arXiv:1312.2017*

R.Lescanne et al, *arXiv:1907.11729*

Concluding Remarks

- Well-established paradigm, logic-level operational options translated
- Serious investment, patents: Alice&Bob but also e.g. AmazonWS
- <u>Challenges:</u> get all operations as fast & accurate as on other qubits

  <u>Payoff:</u> no need to correct any bit-flips → much smaller QEC codes

- Competitors: Kerr-cats ; other bosonic codes e.g. GKP codes