Quantum error correction with superconducting circuits

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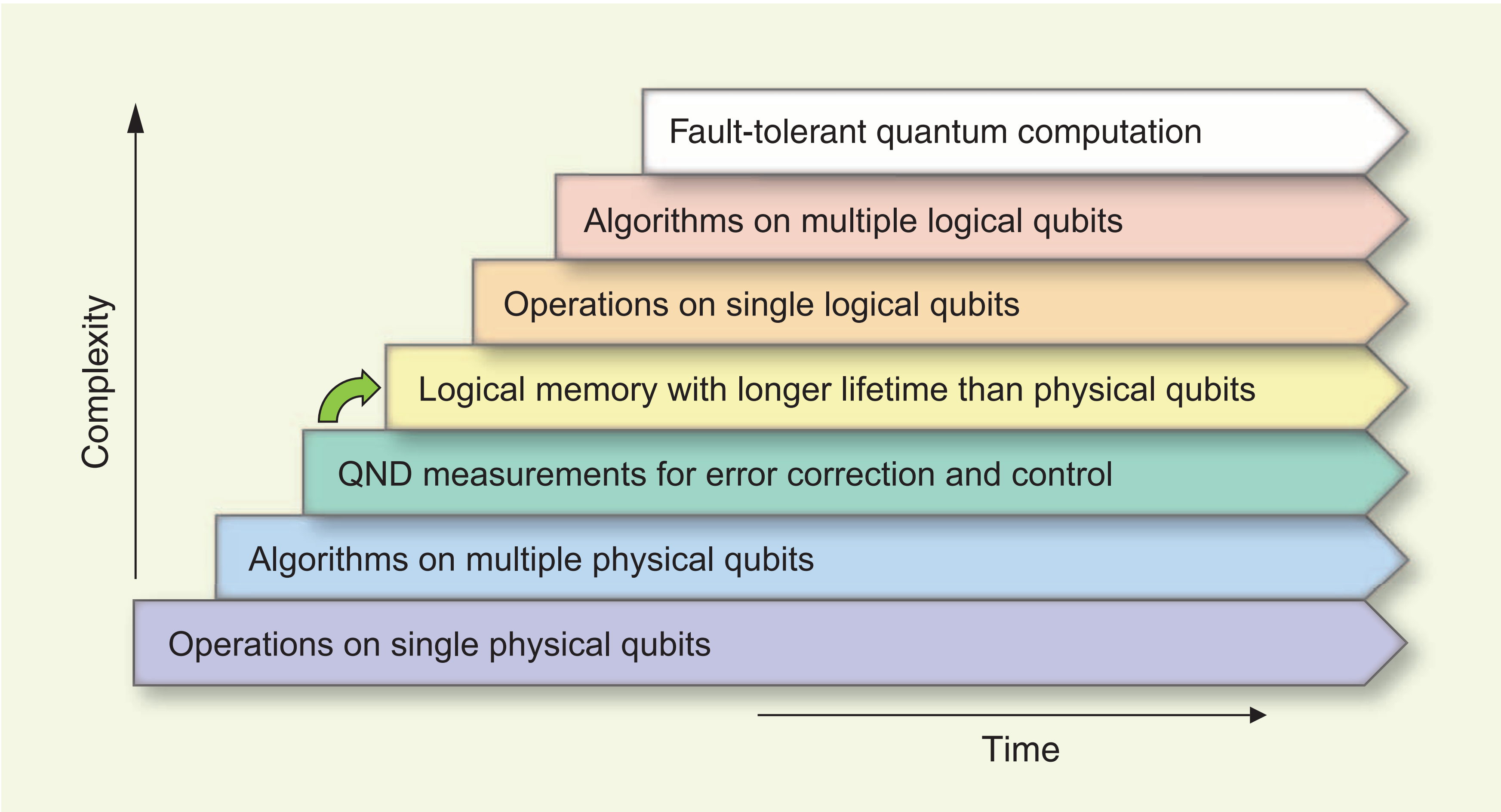
QUANTUM INFORMATION PROCESSING

What is next?

- Interesting quantum devices in the next 10 years:
  = complexity that CANNOT EVER be classically simulated
  (> 50 qubits or equivalent)

- Outstanding questions:
  what level of quantum error correction(QEC) needed?
  how much overhead QEC?
  what's the best architecture?
  what are the useful and achievable (on short term) applications?

ROAD-MAP TOWARDS FAULT-TOLERANT QUANTUM COMPUTATION



M.H. Devoret & R.J. Schoelkopf, Science 339, 1169-1174 (2013).

OUTLINE

- ❑ Introduction to quantum error correction
  - Classical vs quantum error correction
  - Theory of quantum error correction
  - Insights on fault-tolerance

- ❑ A continuous-variable alternative
  - Cat-qubits for protection against photon-loss
  - Nonlinear dissipation paving the way towards fault-tolerance

QUANTUM ERROR CORRECTION

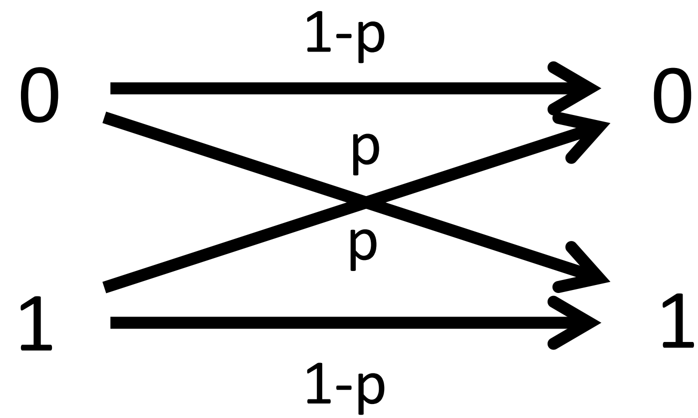
Scheme for reducing decoherence in quantum computer memory

Peter W. Shor*
AT&T Bell Laboratories, Room 2D-149, 600 Mountain Avenue, Murray Hill, New Jersey 07974
(Received 17 May 1995)

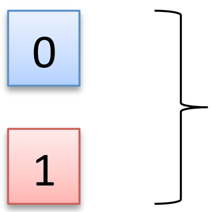
- Decoherence: not a fondamental objection to quantum computation;
- Model continuous decoherence as discrete error channels;
- Redundantly encode quantum information in an entangled state of a multi-qubit system and perform quantum error correction.

CLASSICAL NOISE, CLASSICAL ERROR CORRECTION

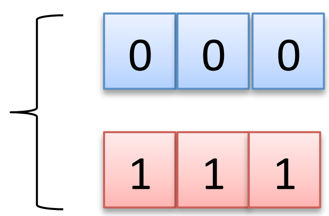
Classical noise: bit-flip errors



Basics of **classical** error correction: redundancy

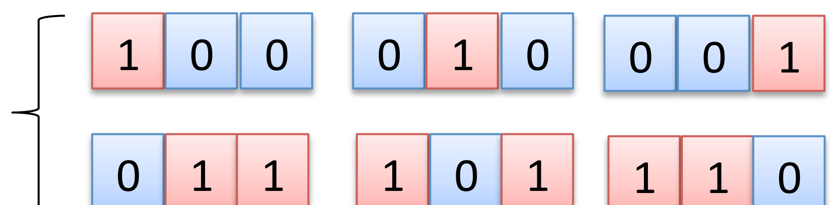


replaced by



« repetition code »

1-bit errors tractable by **majority vote**:



Probability of incorrectible 2-bit errors: $3p^2$ (p error probability per unit time)

QUANTUM VS CLASSICAL ERROR CORRECTION

Objective: Protect any superposition state $c_0|0> + c_1|1>$ without any knowledge of c_0 and c_1.

Quantum error correction: bit-flip errors

$$c_0 \boxed{0} + c_1 \boxed{1} \longleftrightarrow c_0 \boxed{0}\boxed{0}\boxed{0} + c_1 \boxed{1}\boxed{1}\boxed{1}$$

- Majority vote erases the information.
- 1-bit errors tractable by **parity measurement**: Z_1Z_2 and Z_2Z_3
- Four outcomes: (++) No errors, (-+) error on Q1, (+-) error on Q3, (--) error on Q2.

QEC BEYOND BIT-FLIP ERRORS

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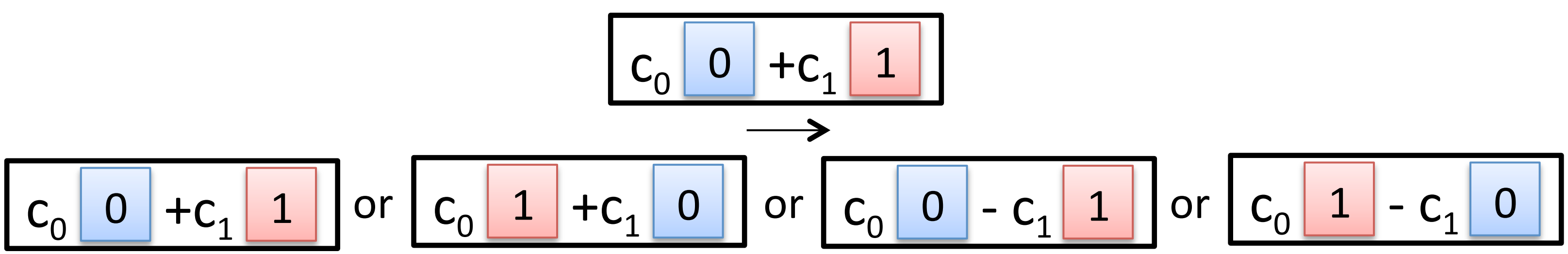
One needs to correct four possible error channels: I,X,Z,Y=iXZ



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  - Fault-tolerant parity measurements

QEC BEYOND BIT-FLIP ERRORS

Quantum noise: interaction with environment

A general error mechanism:

$$\mathcal{E}\left(\rho_{\boldsymbol{s}}\right) = \boldsymbol{tr}_{\text{env}}\left[\boldsymbol{U}_{\tau}\left(\rho_{\boldsymbol{s}} \otimes \rho_{\text{env}}\right)\boldsymbol{U}_{\tau}^{\dagger}\right] = \sum_{\boldsymbol{k}} \boldsymbol{E}_{\boldsymbol{k}} \rho_{\boldsymbol{s}} \boldsymbol{E}_{\boldsymbol{k}}^{\dagger}$$

with $\sum_{\boldsymbol{k}} \boldsymbol{E}_{\boldsymbol{k}}^{\dagger} \boldsymbol{E}_{\boldsymbol{k}} = \boldsymbol{I}.$

EXAMPLES

Pure dephasing

$$\mathcal{E}_{\varphi}\left(\rho\right)=\boldsymbol{E}_0\rho\boldsymbol{E}_0^{\dagger}+\boldsymbol{E}_1\rho\boldsymbol{E}_1^{\dagger},$$

$$\boldsymbol{E}_0=\sqrt{1-p}\boldsymbol{I},\quad \boldsymbol{E}_1=\sqrt{p}\boldsymbol{\sigma}_z,\quad p=\tau/T_{\varphi}$$

T1 Relaxation

$$\mathcal{E}_{T1}\left(\rho\right)=\boldsymbol{E}_0\rho\boldsymbol{E}_0^{\dagger}+\boldsymbol{E}_1\rho\boldsymbol{E}_1^{\dagger},$$

$$\boldsymbol{E}_0=\left|0\right\rangle\left\langle 0\right|+\sqrt{1-p}\left|1\right\rangle\left\langle 1\right|,\quad \boldsymbol{E}_1=\sqrt{p}\left|0\right\rangle\left\langle 1\right|,\quad p=\tau/T1$$

QEC BEYOND BIT-FLIP ERRORS

Theory of QEC

Similarly to an error channel, the error correction (measuement and feedback) can be modeled by a quantum operation:

$$\rho \to \mathcal{R}\left(\rho\right) = \sum_k \boldsymbol{R}_k \rho \boldsymbol{R}_k^\dagger$$

This corrects an error channel $\rho \to \mathcal{E}\left(\rho\right)$ if for any ρ in the code space

$$\mathcal{R} \circ \mathcal{E}\left(\rho\right) = \rho.$$

QEC BEYOND BIT-FLIP ERRORS

Theorem: discretization of error channels

If the operation $\mathcal{R}$ corrects the error channel $\mathcal{E}$, it corrects any other error channel $\mathcal{F}$ whose elements $\boldsymbol{F_k}$ are linear combinations of elements $\boldsymbol{E_k}$ with complex coefficients:

$$\mathcal{R} \circ \mathcal{E}(\rho) = \rho \quad \Rightarrow \quad \mathcal{R} \circ \mathcal{F}(\rho) = \rho$$

Corollary: case of qubits

It sufficies to correct the operations $\{\boldsymbol{I}, \sigma_x, \sigma_z, \sigma_y = \boldsymbol{i}\sigma_x\sigma_z\}$ to correct for any single-qubit errors.

FULL QUANTUM ERROR CORRECTION

Four possible error channels for each qubit: I, X, Z, Y=iXZ

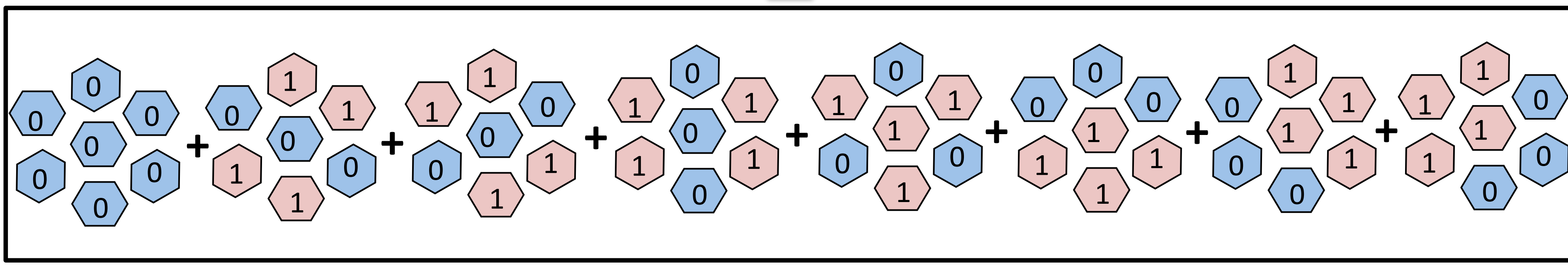
$$c_0\,|0\rangle + c_1\,|1\rangle \longrightarrow$$

c_0 0 $+c_1$ 1 or c_0 1 $+c_1$ 0 or c_0 0 $- c_1$ 1 or c_0 1 $- c_1$ 0

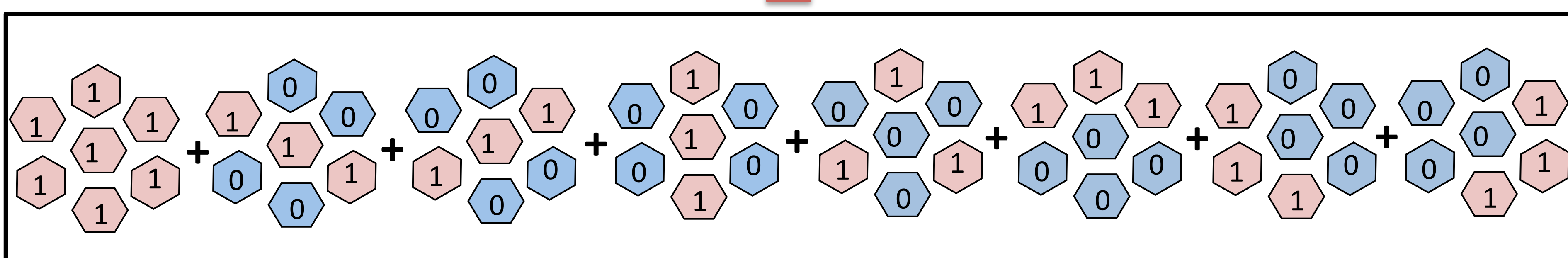
At least five qubits to make all these errors tractable

7-qubit Steane code:

0 ⟶



1 ⟶

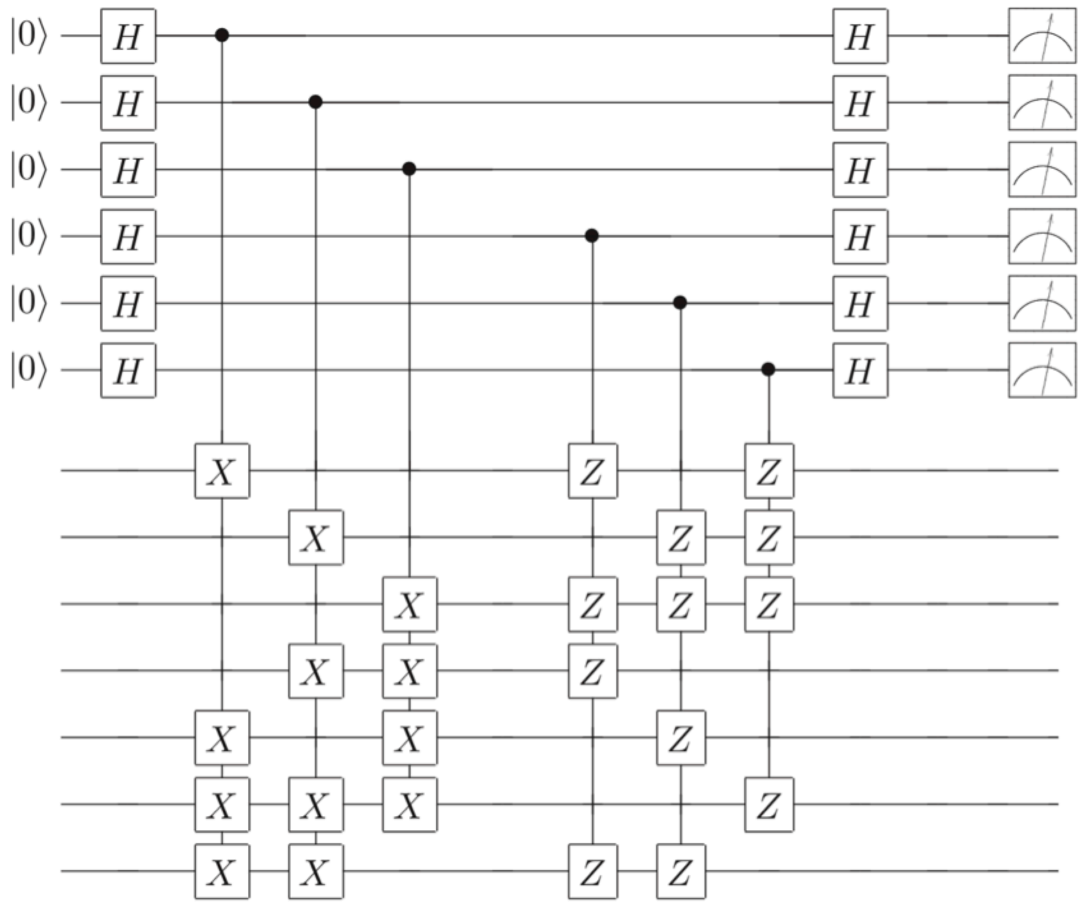


FULL QUANTUM ERROR CORRECTION

$$|0_L\rangle = \frac{1}{\sqrt{8}}\Big[|0000000\rangle + |1010101\rangle + |0110011\rangle + |1100110\rangle + |0001111\rangle + |1011010\rangle + |0111100\rangle + |1101001\rangle\Big]$$

$$|1_L\rangle = \frac{1}{\sqrt{8}}\Big[|1111111\rangle + |0101010\rangle + |1001100\rangle + |0011001\rangle + |1110000\rangle + |0100101\rangle + |1000011\rangle + |0010110\rangle\Big]$$

Single round of error correction



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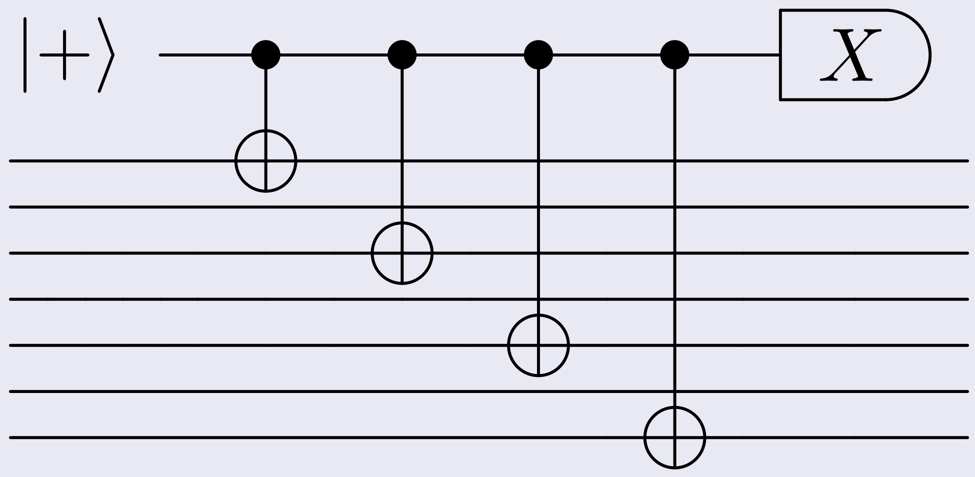
FAULT-TOLERANCE

Central idea: through operations, one should not introduce new error channels not taken into account by QEC. In particular, one should avoid propagation/amplification of errors

Example of parity measurements: simplest circuit to measure the parity $X_1X_3X_5X_7$ for the Steane code.



$$|+\rangle = \left(|0\rangle + |1\rangle\right)/\sqrt{2}$$

NOT FAULT-TOLERANT

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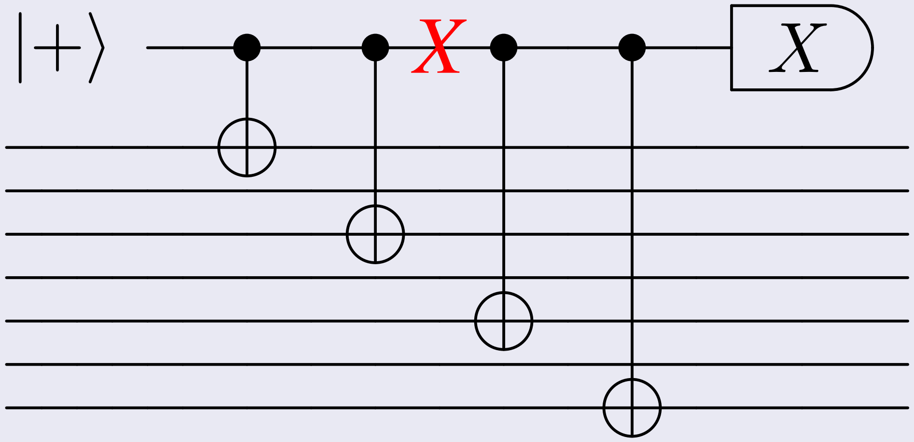

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A bit-flip of the ancilla qubit propagates to memory qubits.

NOT FAULT-TOLERANT

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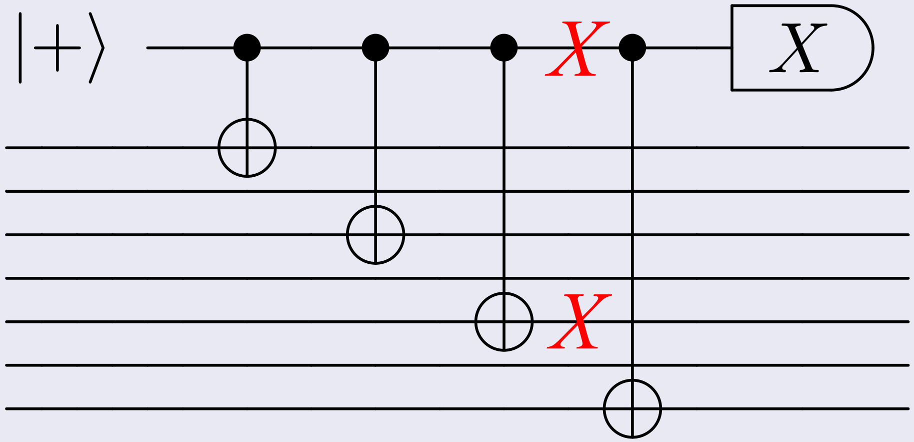

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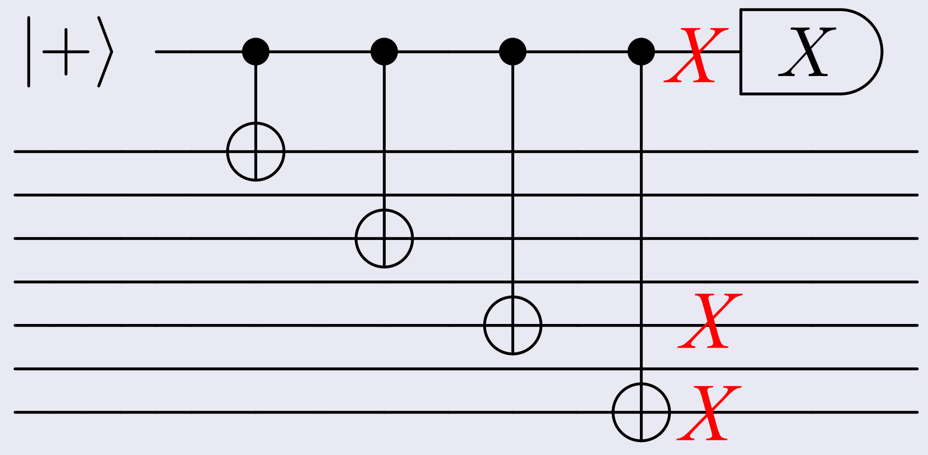
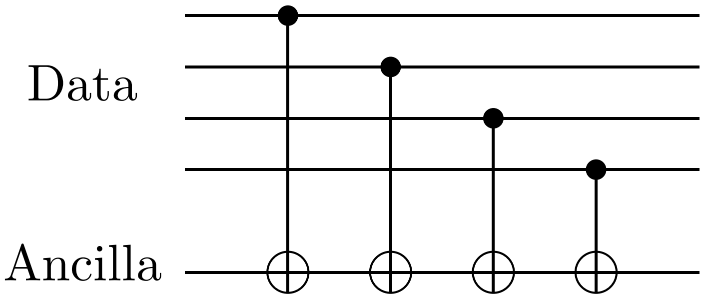


$$|+\rangle = (|0\rangle + |1\rangle)/\sqrt{2}$$

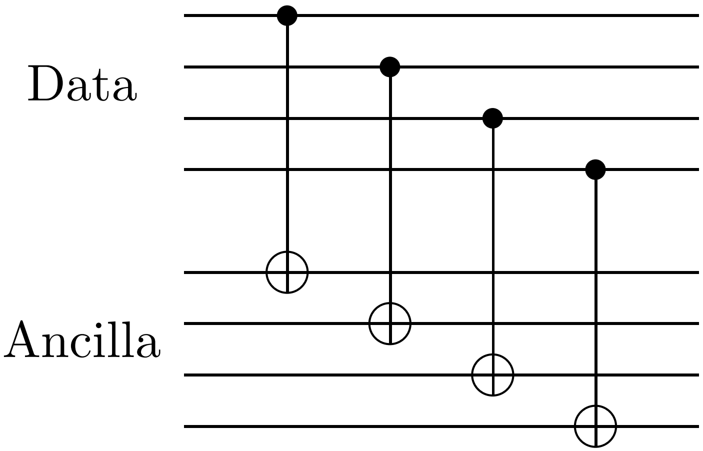
A bit-flip of the ancilla qubit propagates to memory qubits.

TOWARDS A SOLUTION

Idea N1: transversal operations



Bad!



Good!

- Each ancilla qubit couples to no more than one memory qubit.
- We readout more than the required information (ancillas get entangled to the codeword).

J. Preskill, Fault-tolerant quantum computation, 1997.

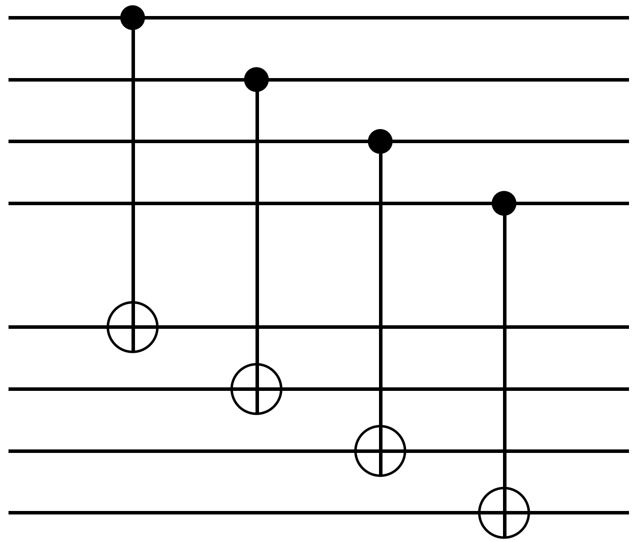
TOWARDS A SOLUTION

Idea N2: encoding ancillas

Data

$$|\mathrm{Shor}\rangle = \frac{1}{\sqrt{8}} \sum_{\text{even } v} |v\rangle \quad \Bigg\{$$

Ancilla

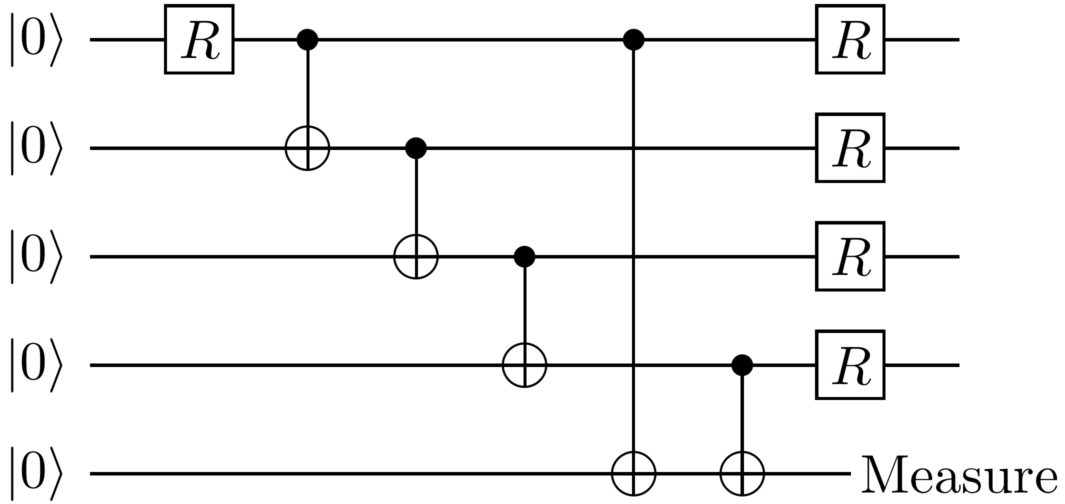


- The parity of the data qubits is mapped on the parity of the Shor state.
- An error in preparation of the Shor state can propagate.

J. Preskill, Fault-tolerant quantum computation, 1997.

TOWARDS A SOLUTION

Idea N3: verification of ancillas



$$R = \frac{1}{\sqrt{2}}\left(X + Z\right)$$

- Parity measurement is launched if the 5th qubit is measured in 0.
- Otherwise repeat the preparation.

J. Preskill, Fault-tolerant quantum computation, 1997.

TOWARDS AN ERROR-CORRECTED QUBIT

Three main strategies for implementing a logical qubit:

- A register of physical qubits with full gate operations

- A fabric of physical qubits with nearest neighbor gates

- A superconducting resonator with non-linear drives, non-linear dissipation and photon parity monitoring. These services are provided by Josephson junctions.

Shor (1995)
Steane (1996)
Gottesman, Kitaev, Preskill (2001)
Kitaev (2006)
M.M. et al. (2014)

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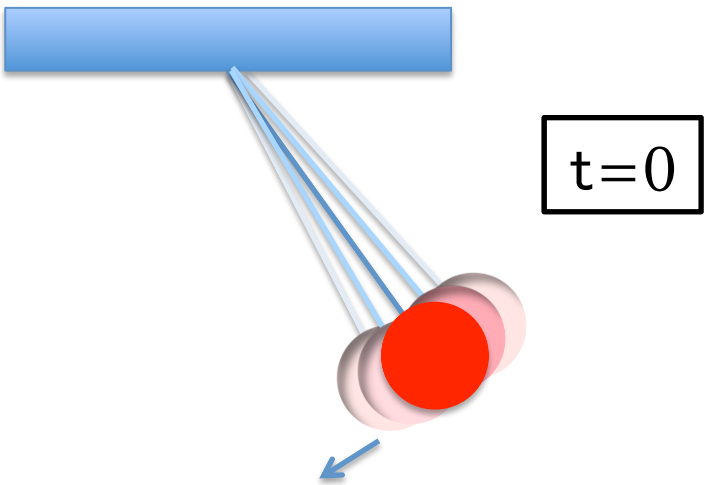
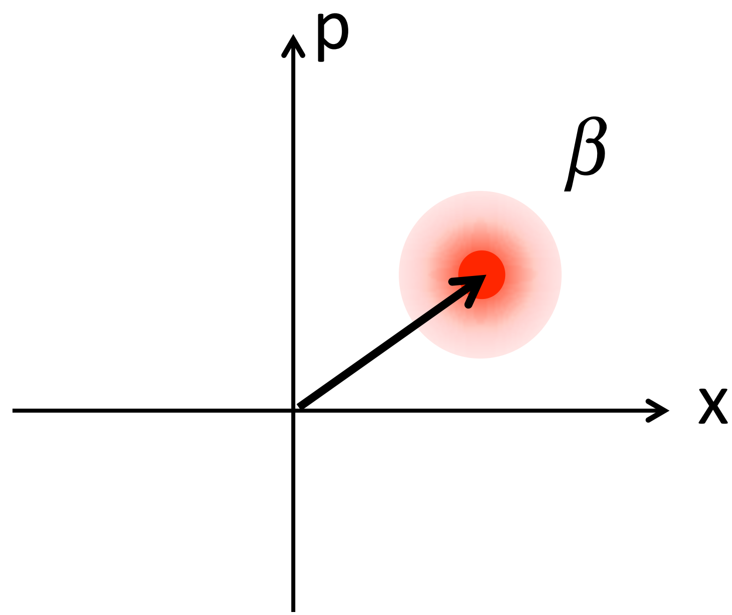
QUANTUM HARMONIC OSCILLATOR AND COHERENT STATES

Using classical control (e.g. laser, force), one can only make coherent displacements

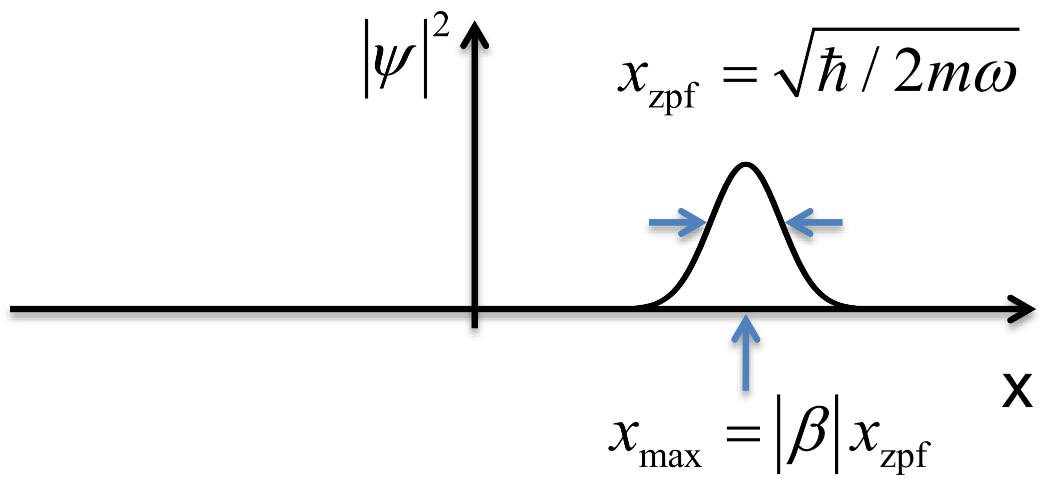




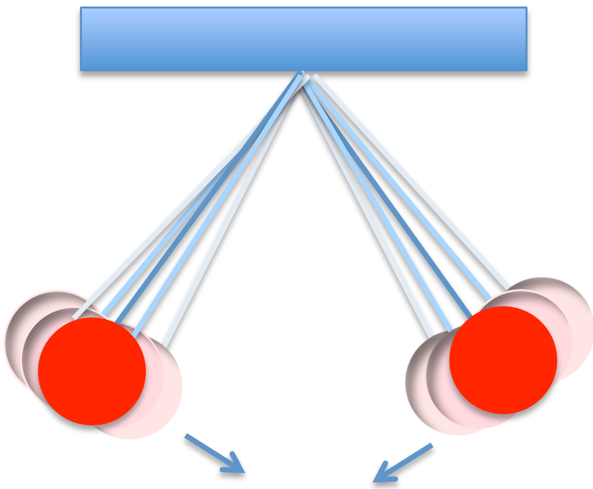
Glauber (coherent) state

$$\left|\beta\right\rangle = e^{-\frac{|\beta|^2}{2}} \sum_{n=0}^{\infty} \frac{\beta^n}{\sqrt{n!}} \left|n\right\rangle$$

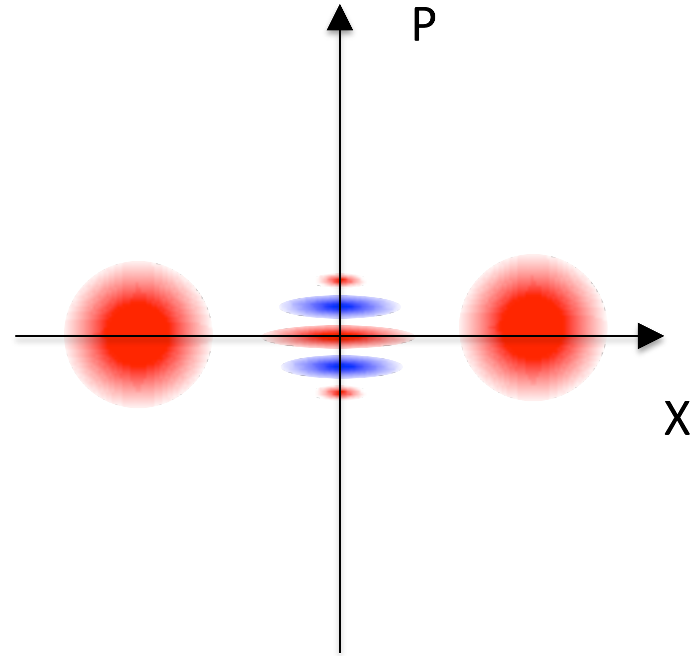
$$\hat{a}\left|\beta\right\rangle = \beta\left|\beta\right\rangle$$



SCHRÖDINGER CAT STATE FOR A HARMONIC OSCILLATOR



t=0

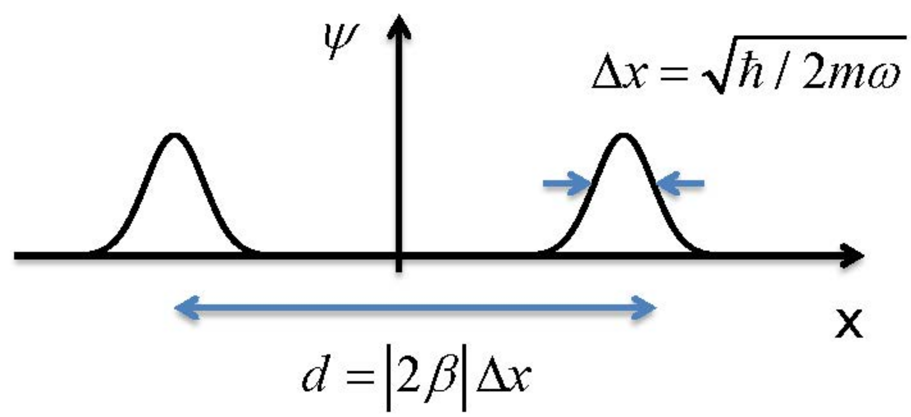


Wigner function W(β)

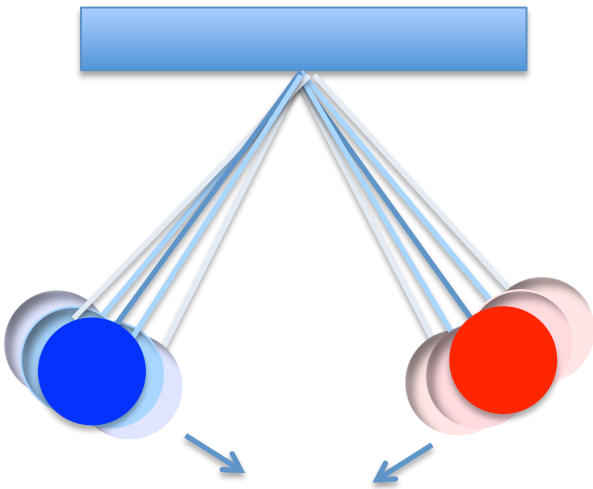
Cat state of an oscillator

$$\left|C_\beta^+\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\beta\right\rangle + \left|-\beta\right\rangle\right)$$

$$= \frac{1}{\sqrt{\cosh\left|\beta\right|^2}} \sum \frac{\beta^{2n}}{\sqrt{(2n)!}}\left|2n\right\rangle$$



SCHRÖDINGER CAT STATE FOR A HARMONIC OSCILLATOR



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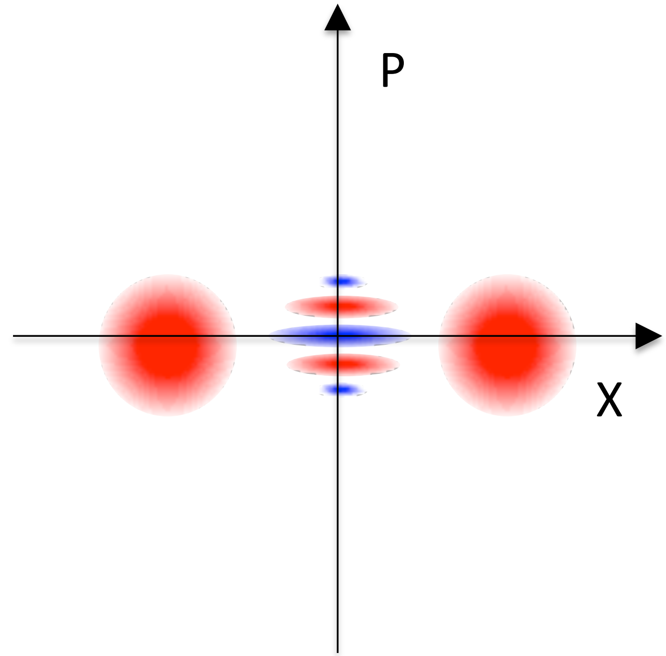
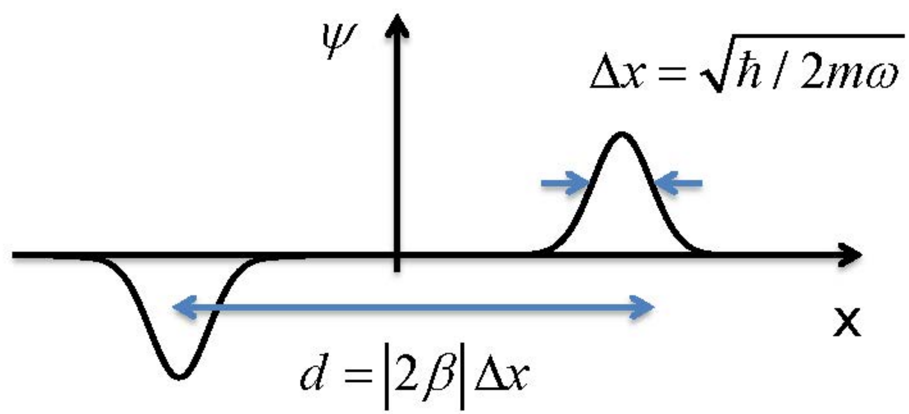


Wigner function W(β)

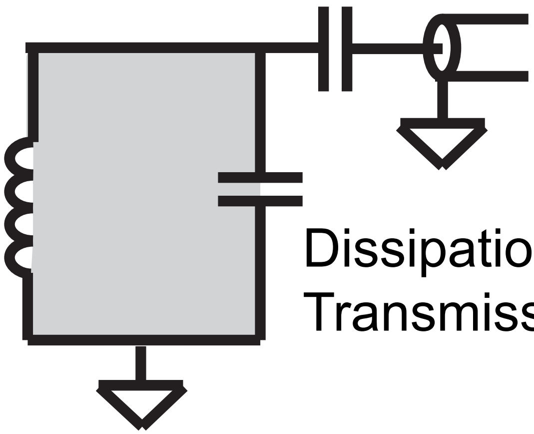
Cat state of an oscillator

$$\left|C_\beta^-\right\rangle = \frac{1}{\sqrt{2}}\left(\left|\beta\right\rangle - \left|-\beta\right\rangle\right)$$

$$= \frac{1}{\sqrt{\sinh|\beta|^2}} \sum \frac{\beta^{(2n+1)}}{\sqrt{(2n+1)!}} \left|2n+1\right\rangle$$



PHOTON LOSS: MAJOR DECAY CHANNEL OF A H.O.



$$\frac{d}{dt}\rho = \kappa D[\boldsymbol{a}]\rho,$$

$$D[\boldsymbol{a}]\rho = \boldsymbol{a}\rho\boldsymbol{a}^{\dagger} - \frac{1}{2}\boldsymbol{a}^{\dagger}\boldsymbol{a}\rho - \frac{1}{2}\rho\boldsymbol{a}^{\dagger}\boldsymbol{a}.$$

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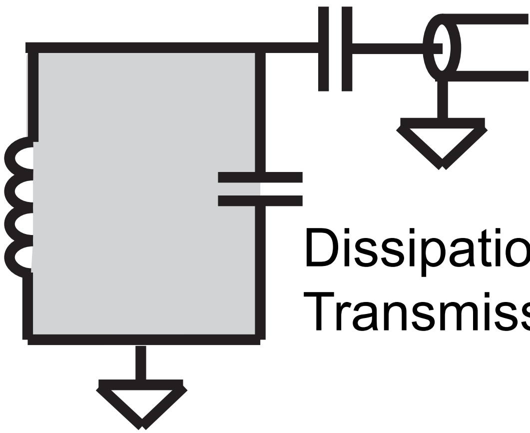

$$\frac{d}{dt}\rho = \kappa D[\boldsymbol{a}]\rho,$$

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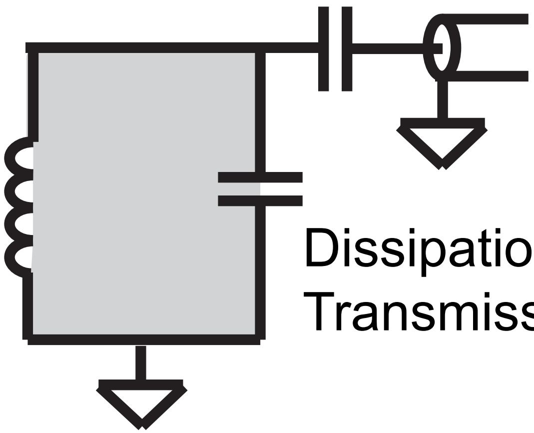
Formulation with error channels:

$$\rho_{\delta t} = \mathcal{E}(\rho_0) = \sum_{l=0}^{\infty} \mathbf{E}_l \rho_0 \mathbf{E}_l^{\dagger}, \quad \mathbf{E}_l = \sqrt{\frac{\left(1 - e^{-\kappa\delta t}\right)^l}{l!}}\, e^{-\frac{\kappa\delta t}{2}\boldsymbol{a}^{\dagger}\boldsymbol{a}}\boldsymbol{a}^l$$

I.L. Chuang et al., PRA 56, 1997.

PHOTON LOSS: MAJOR DECAY CHANNEL OF A H.O.



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Formulation with error channels:

$$\rho_{\delta t} = \mathcal{E}(\rho_0) = \sum_{l=0}^{\infty} \mathbf{E}_l \rho_0 \mathbf{E}_l^{\dagger}, \quad \mathbf{E}_l = \sqrt{\frac{\left(1 - e^{-\kappa\delta t}\right)^l}{l!}} e^{-\frac{\kappa\delta t}{2}\boldsymbol{a}^{\dagger}\boldsymbol{a}} \boldsymbol{a}^l$$

Up to first order in $\kappa\delta t$:

$$\rho_{\delta t} = \mathbf{E}_0\rho_0\mathbf{E}_0^{\dagger} + \mathbf{E}_1\rho_0\mathbf{E}_1^{\dagger}, \ \mathbf{E}_0 = e^{-\frac{\kappa\delta t}{2}\boldsymbol{a}^{\dagger}\boldsymbol{a}}, \ \mathbf{E}_1 = \sqrt{\kappa\delta t}\, e^{-\frac{\kappa\delta t}{2}\boldsymbol{a}^{\dagger}\boldsymbol{a}} \boldsymbol{a}$$

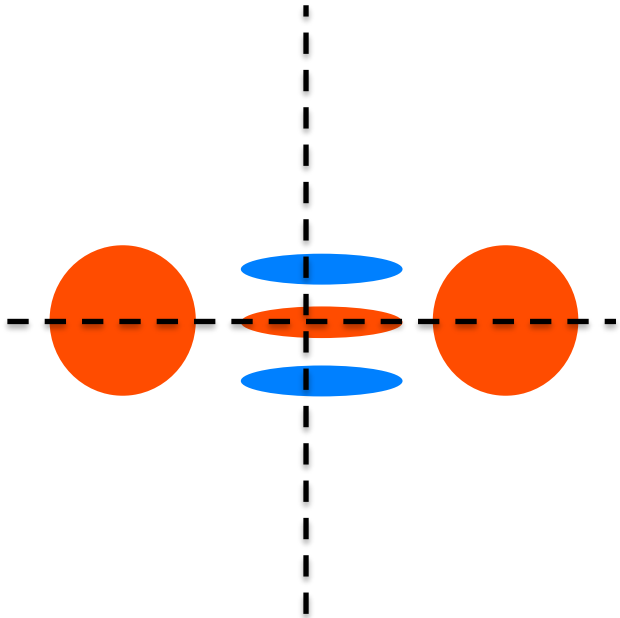
HARDWARE-EFFICIENT QUANTUM ERROR CORRECTION

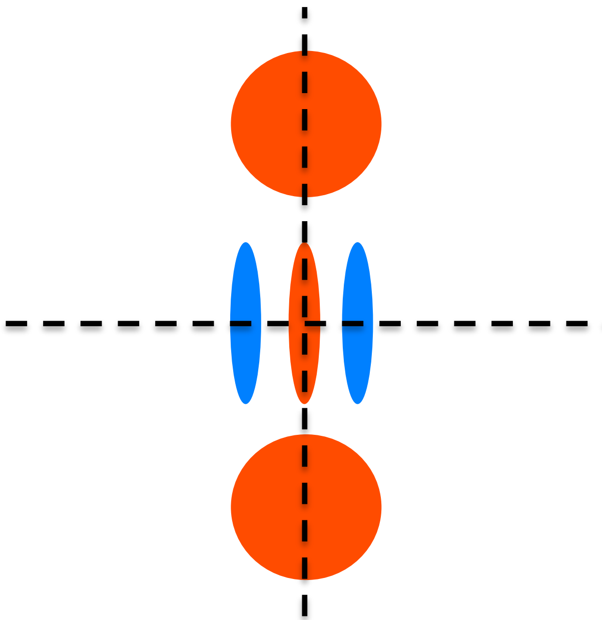
- **Encoding and protecting information on a single cavity mode**

- **Minimal QEC hardware :** protecting a single high-Q cavity mode (memory), using a single qubit (providing non-linearity), one low-Q mode (entropy evacuation).

Idea:

$$|0_L\rangle = |C_\alpha^+\rangle = \frac{1}{\sqrt{2}}(|\alpha\rangle + |-\alpha\rangle) \qquad |1_L\rangle = |C_{i\alpha}^+\rangle = \frac{1}{\sqrt{2}}(|i\alpha\rangle + |-i\alpha\rangle)$$





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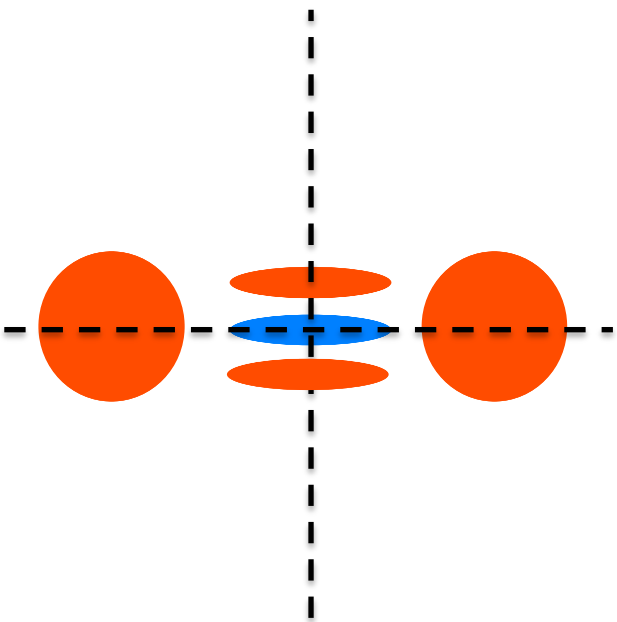
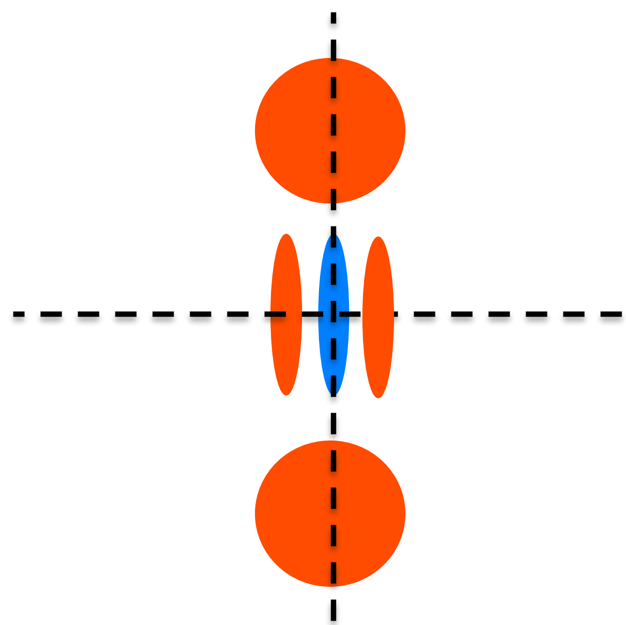
- **Encoding and protecting information on a single cavity mode**

- **Minimal QEC hardware :** protecting a single high-Q cavity mode (memory), using a single qubit (providing non-linearity), one low-Q mode (entropy evacuation).

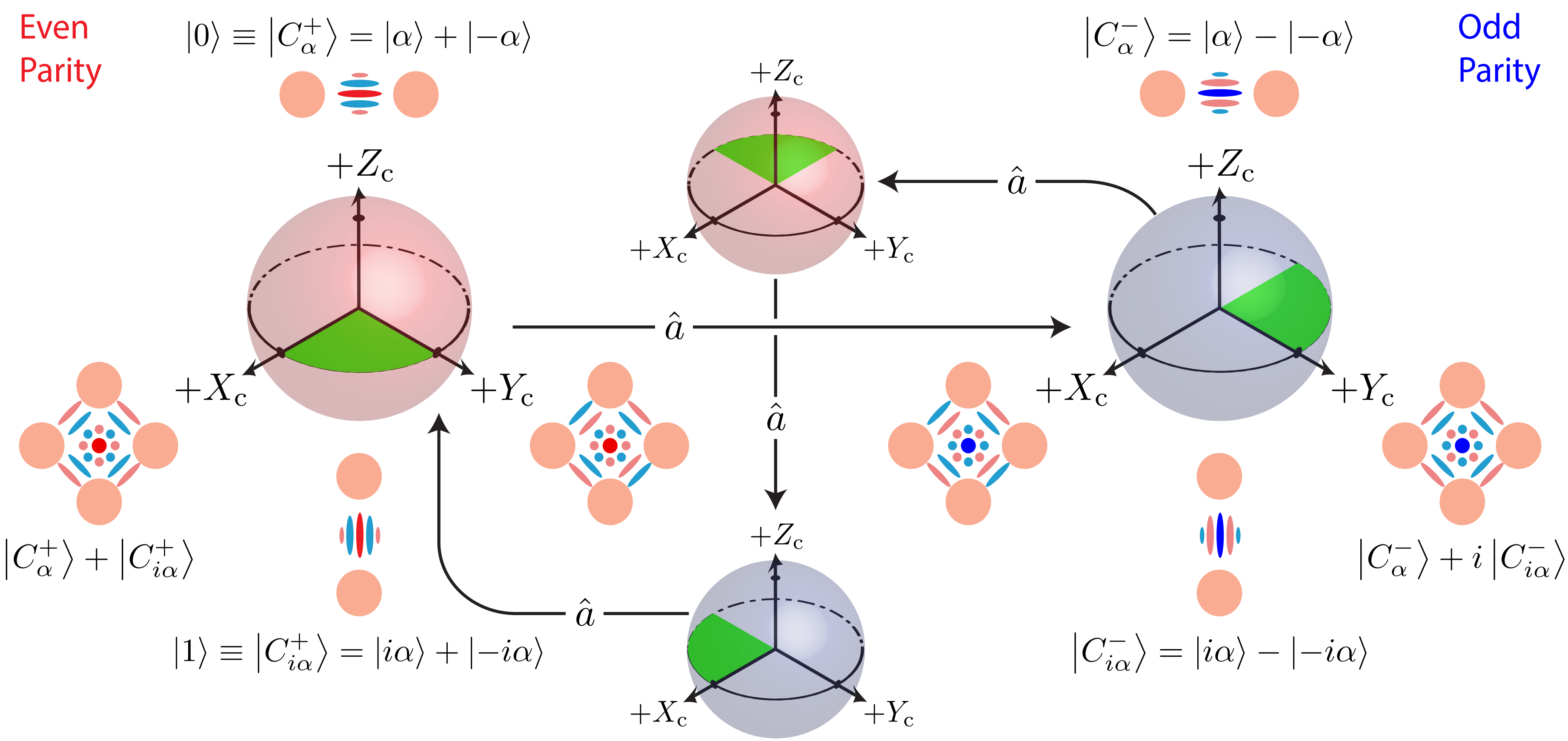
Another possibility:

$$|0_L\rangle = |C_\alpha^-\rangle = \frac{1}{\sqrt{2}}(|\alpha\rangle - |-\alpha\rangle) \qquad |1_L\rangle = |C_{i\alpha}^-\rangle = \frac{1}{\sqrt{2}}(|i\alpha\rangle - |-i\alpha\rangle)$$



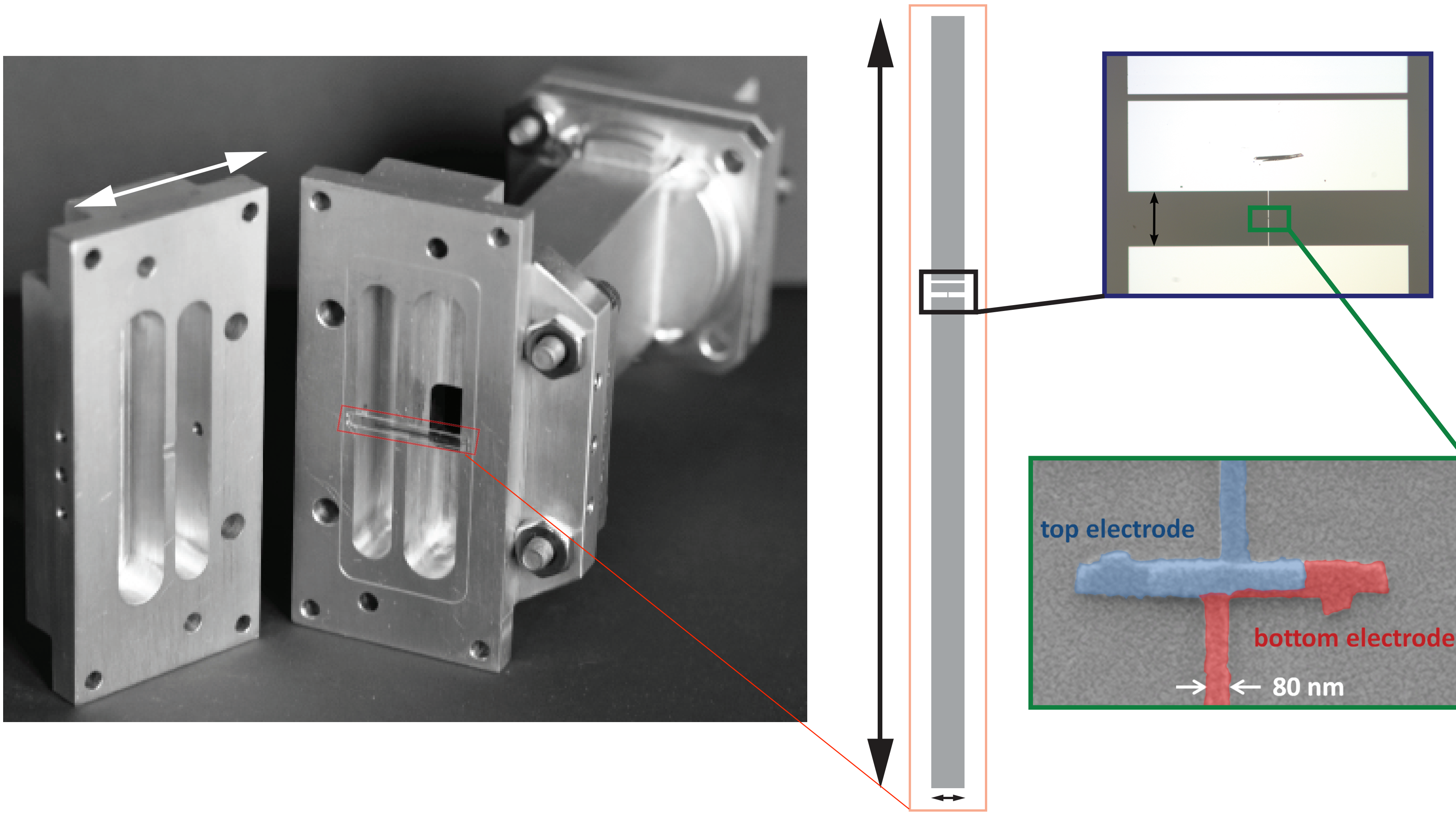


TO LIVE AND DIE IN A CAVITY



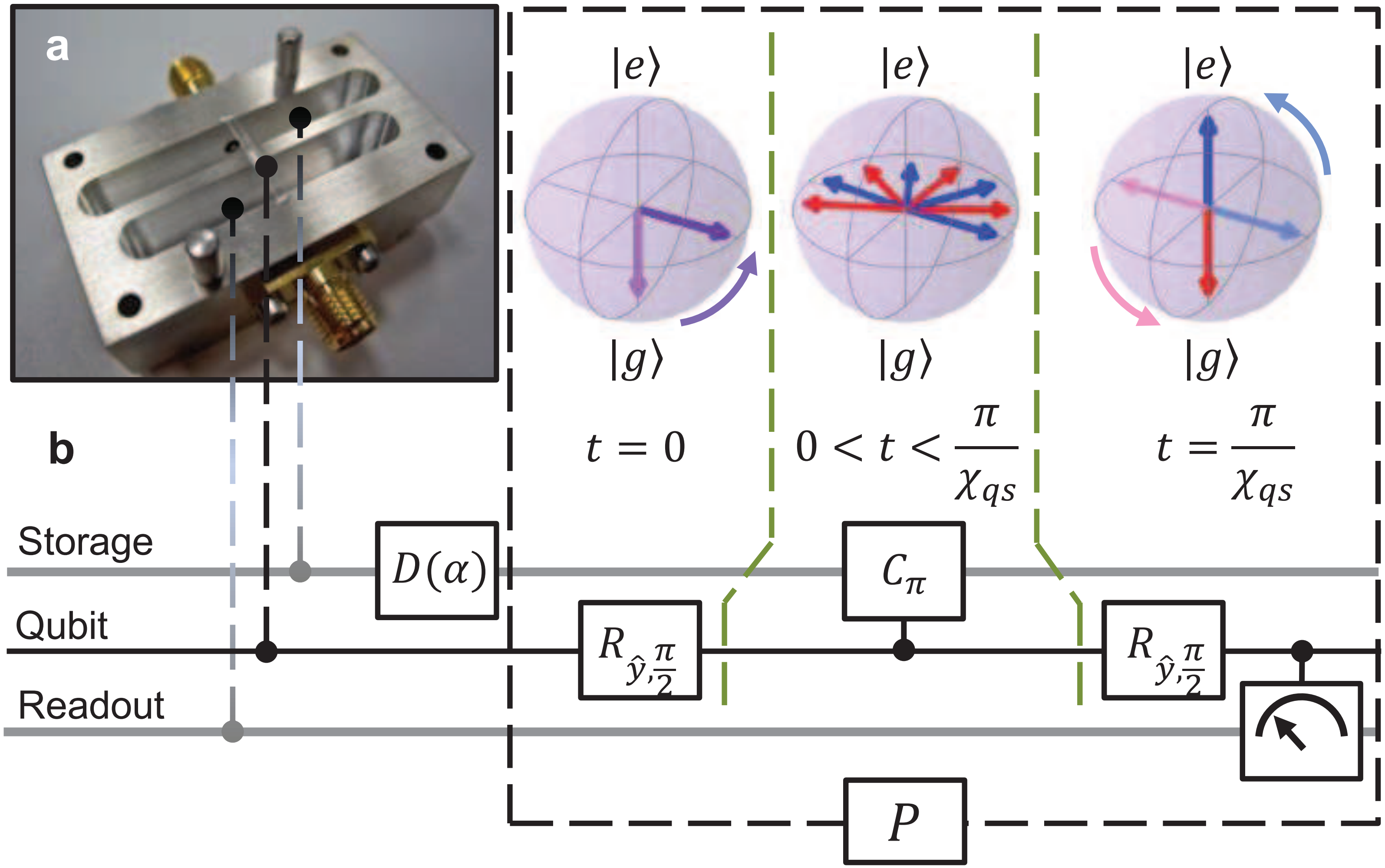
*Ofek et al., Nature 536, 441-445, 2016.

DEVICE



H. Paik *et. al.* PRL (2011),
G. Kirchmair *et. al.* Nature (2013)

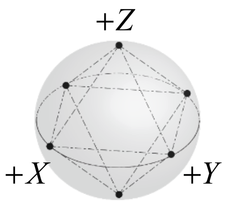
MEASURING PHOTON-NUMBER PARITY



Bertet et al. PRL 89, 200402 (2002)
Sun et al. Nature 511, 444-448 (2014)

ERROR CORRECTION START-TO-FINISH

Initialize

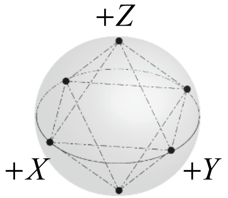


$$|g\rangle|0\rangle \rightarrow |\psi\rangle = \left(c_g|g\rangle + c_e|e\rangle\right)|0\rangle$$

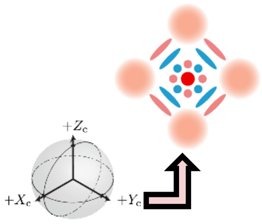
Courtesy of A. Petrenko and R. Schoelkopf

ERROR CORRECTION START-TO-FINISH

Initialize



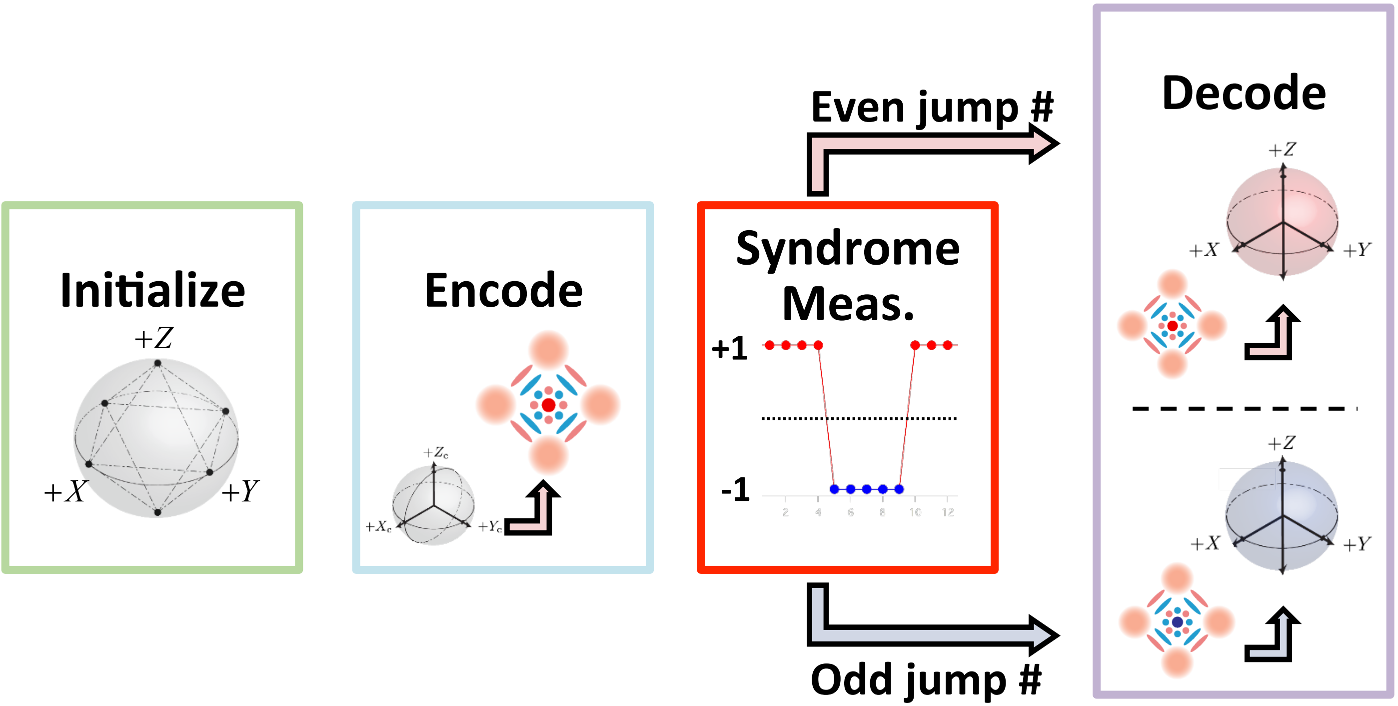
Encode



$$\left|\psi_L\right\rangle = \left(c_g\left|\mathcal{C}_\alpha^+\right\rangle + c_e\left|\mathcal{C}_{i\alpha}^+\right\rangle\right)\left|g\right\rangle$$

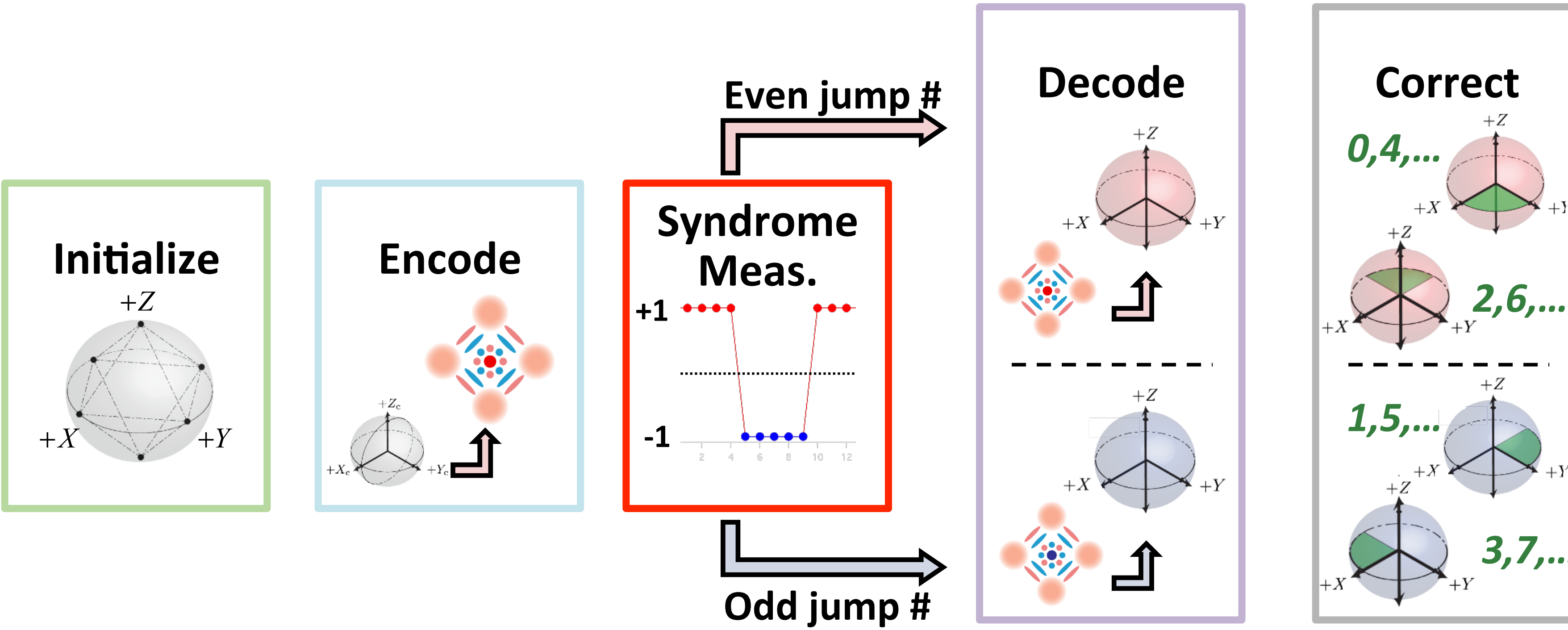
Courtesy of A. Petrenko and R. Schoelkopf

ERROR CORRECTION START-TO-FINISH



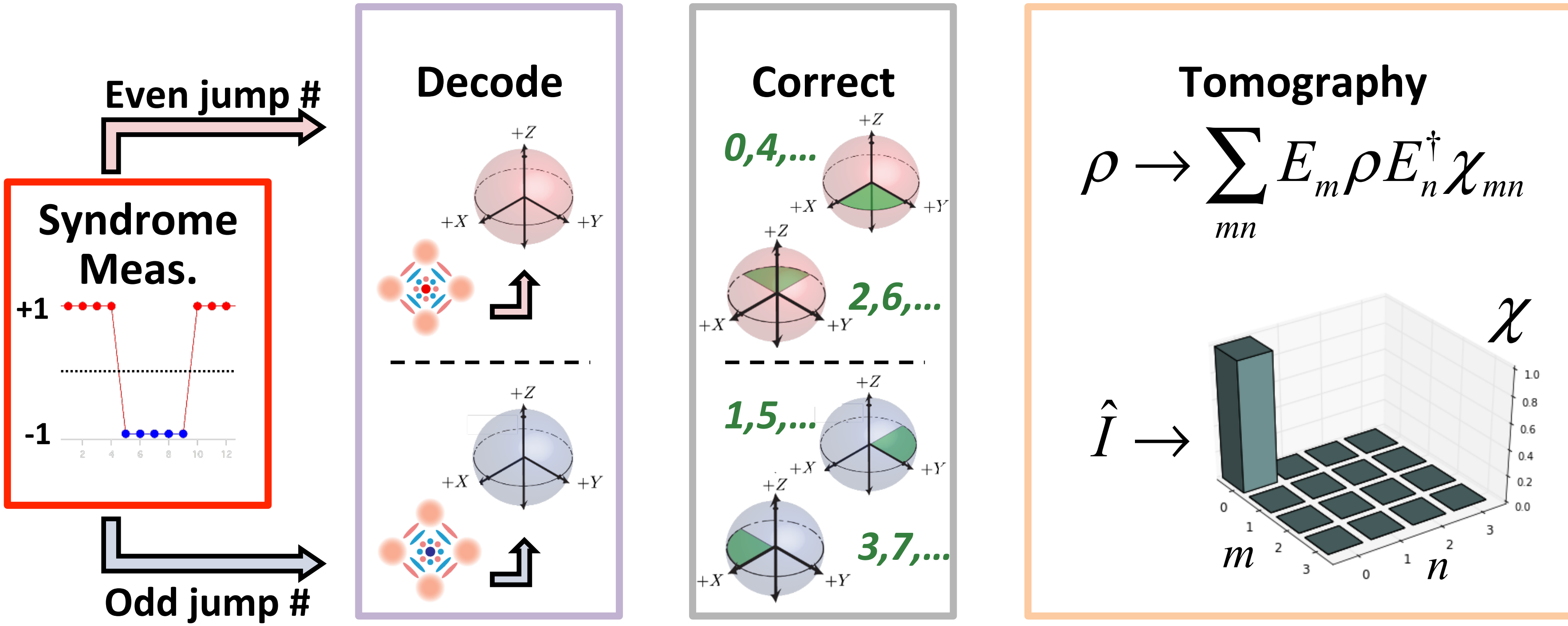
Courtesy of A. Petrenko and R. Schoelkopf

ERROR CORRECTION START-TO-FINISH



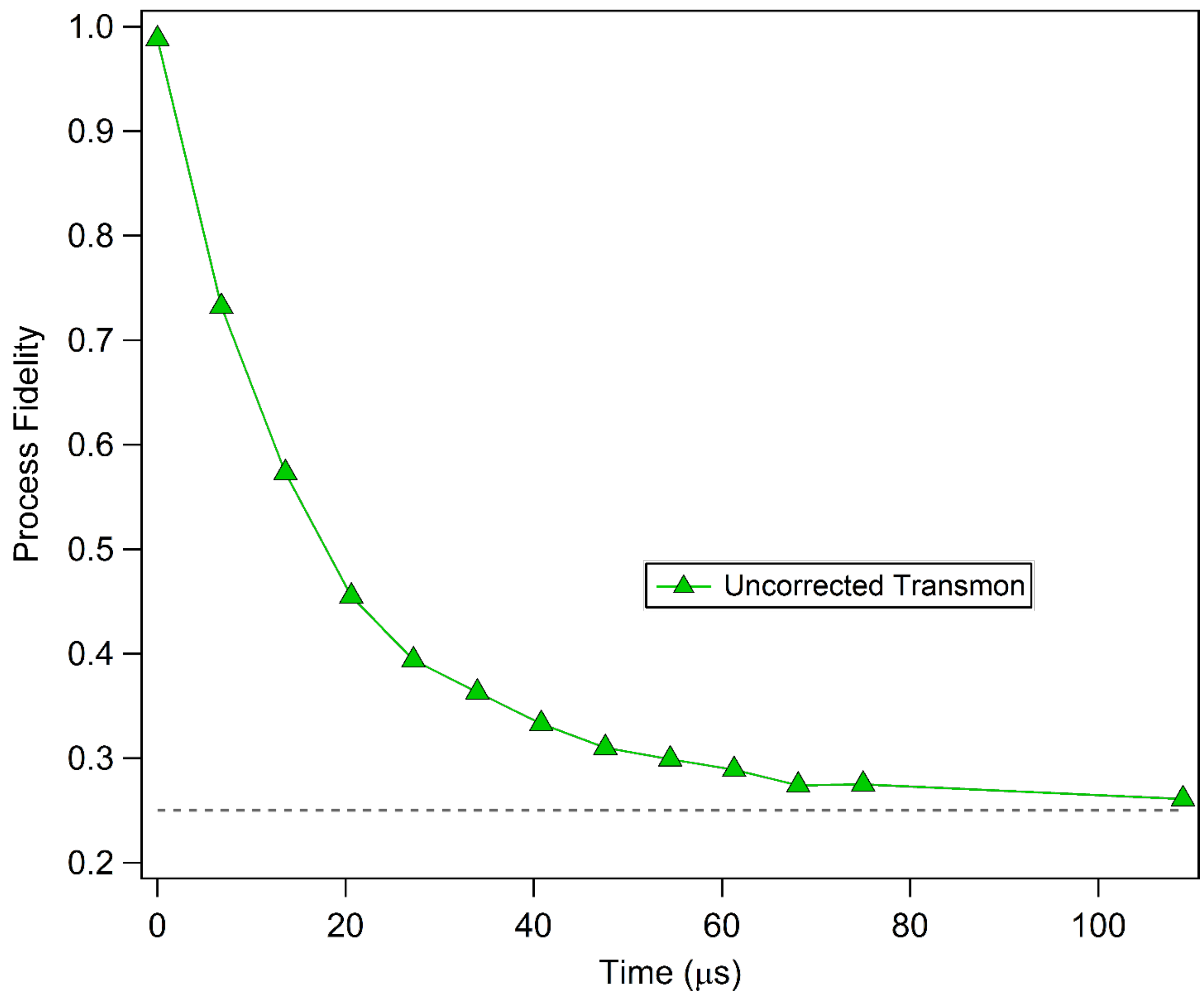
Courtesy of A. Petrenko and R. Schoelkopf

ERROR CORRECTION START-TO-FINISH



Courtesy of A. Petrenko and R. Schoelkopf

ERROR CORRECTION START-TO-FINISH

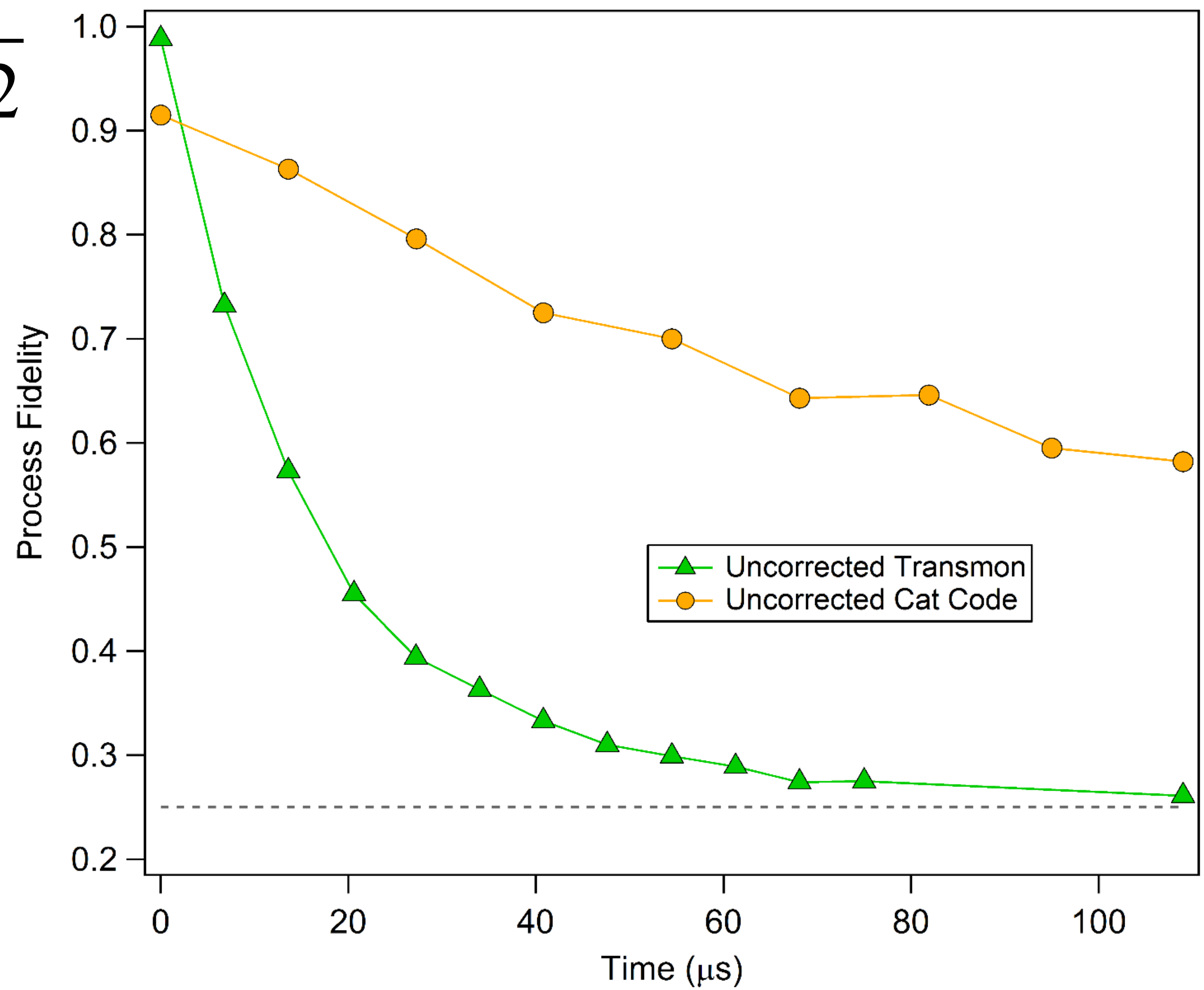


$\tau \approx 15\mu s$

*Ofek et al., Nature 536, 441-445, 2016.

ERROR CORRECTION START-TO-FINISH

$\alpha = \sqrt{2}$



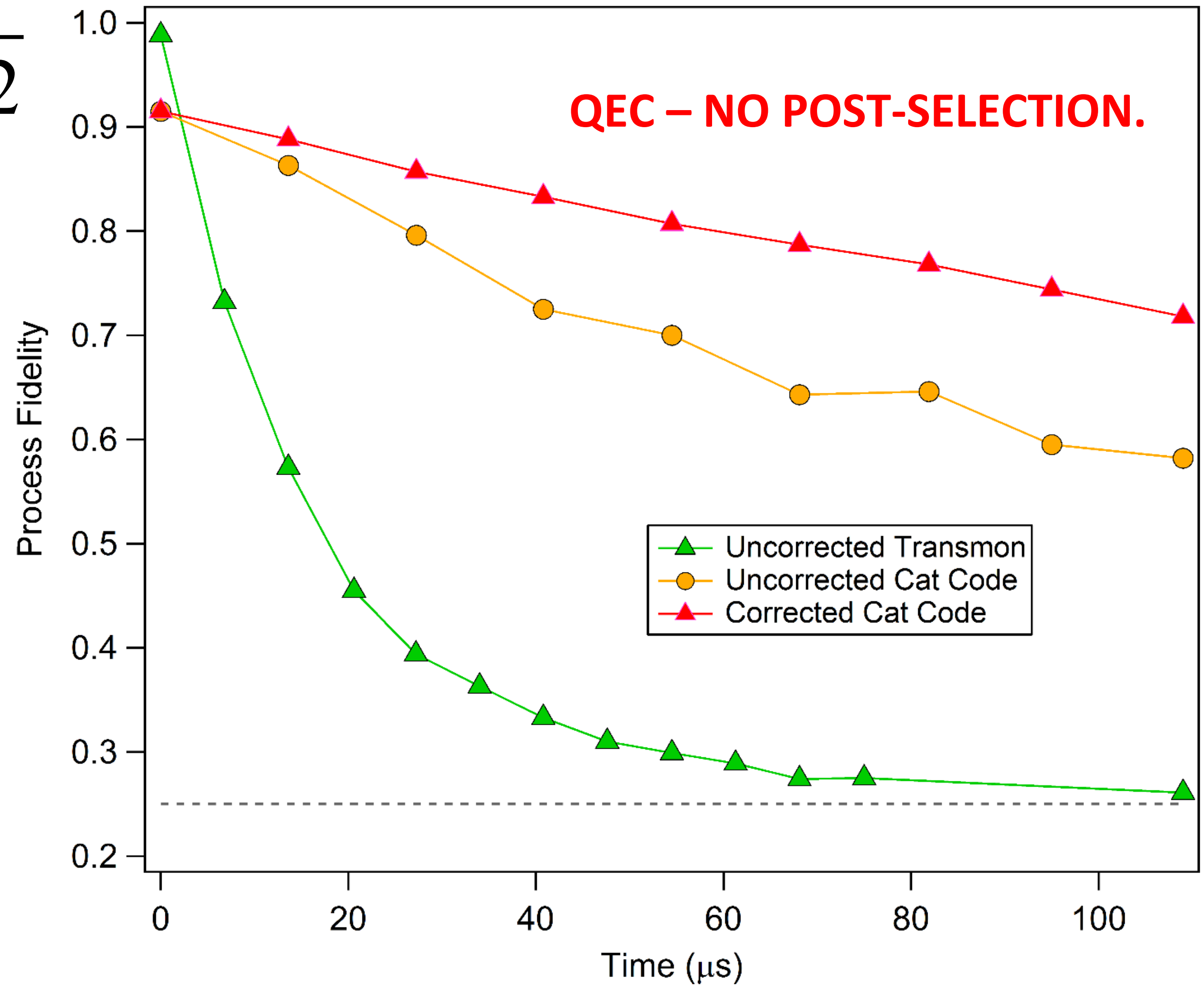
$\tau \approx 130\mu s$

$\tau \approx 15\mu s$

*Ofek et al., Nature 536, 441-445, 2016.

ERROR CORRECTION START-TO-FINISH

$\alpha = \sqrt{2}$



$\tau \approx 320\mu s$

$\tau \approx 130\mu s$

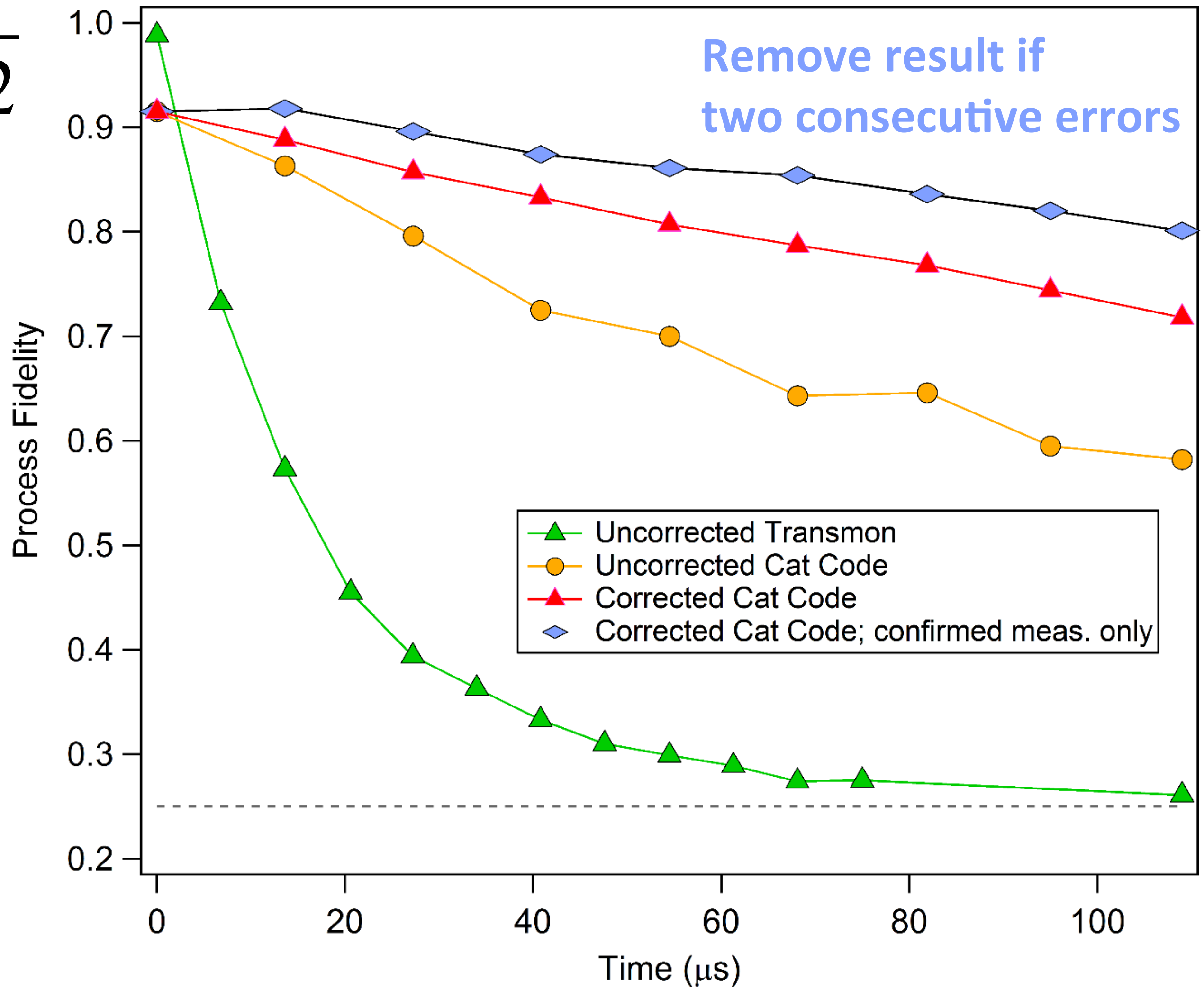
$\tau \approx 15\mu s$

*Ofek et al., Nature 536, 441-445, 2016.

ALLOW POSTSELECTION?

Throwing out ~ 20% of data
which are probably msmt. errors…

$\alpha = \sqrt{2}$



$\tau \approx 560\mu s$

$\tau \approx 320\mu s$

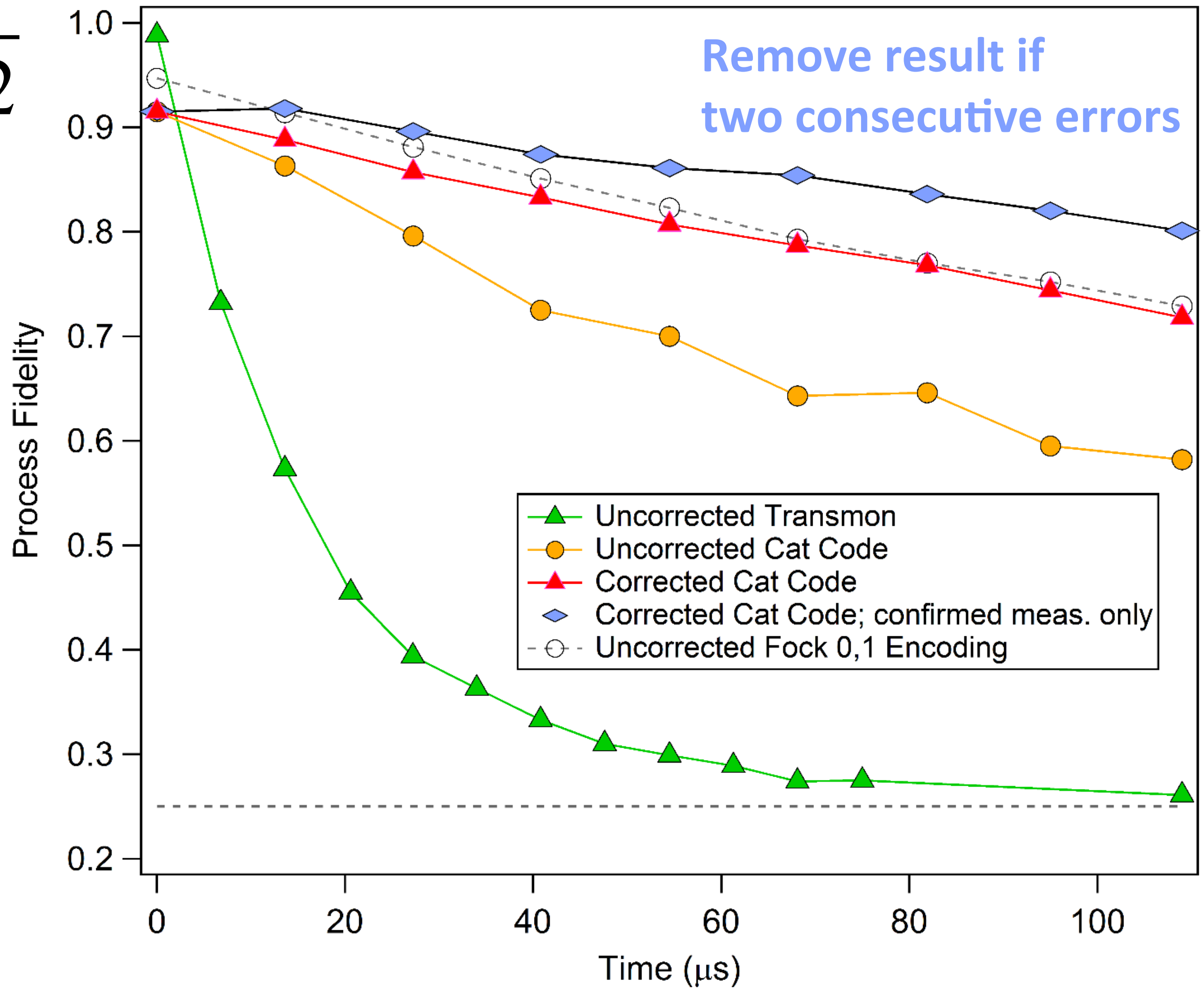
$\tau \approx 130\mu s$

$\tau \approx 15\mu s$

*Ofek et al., Nature 536, 441-445, 2016.

COMPARING TO SINGLE PHOTON ENCODING

$$\alpha = \sqrt{2}$$



$\tau \approx 560 \mu s$

$\tau \approx 290 \mu s$

$\tau \approx 320 \mu s$

$\tau \approx 130 \mu s$

$\tau \approx 15 \mu s$

*Ofek et al., Nature 536, 441-445, 2016.

TOWARDS FAULT-TOLERANT QC

Most important limitations:

- Energy decay.
- Uncorrected errors: dephasing due to combination of Kerr and decay.
- Non fault-tolerance: propagation of errors.

Rest of this talk: parametric methods to achieve fault-tolerance.

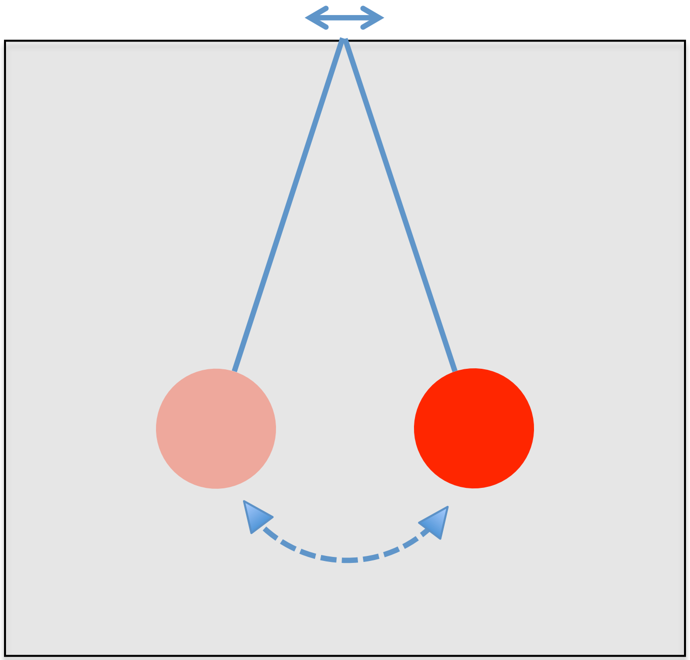
Idea: driven-dissipative mechanism to restrict the dynamics to 2- or 4-dimensional manifolds $\mathrm{Span}\{|\pm\alpha\rangle\}$ and $\mathrm{Span}\{|\pm\alpha\rangle, |\pm i\alpha\rangle\}$.

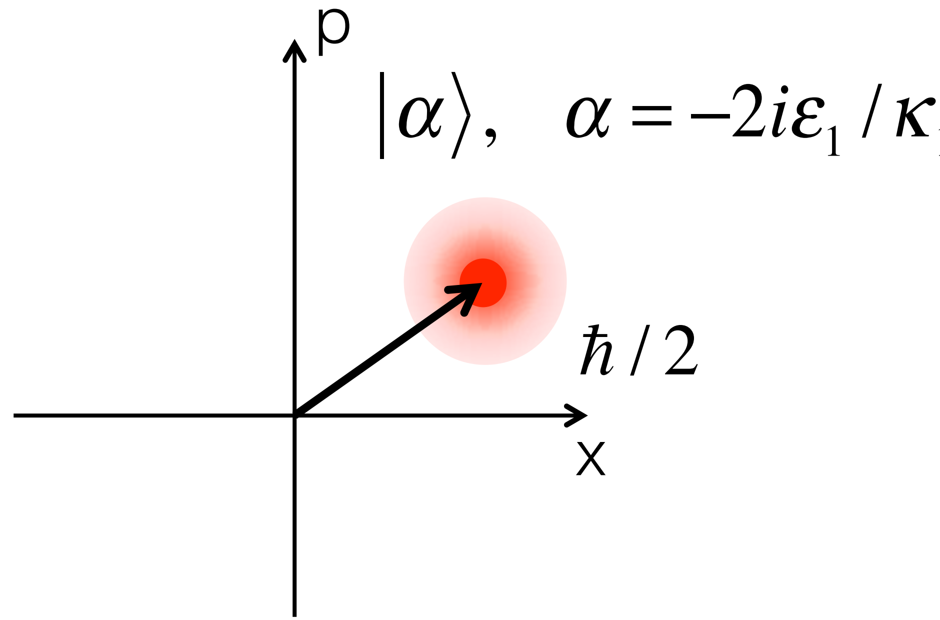
OUTLINE

- Introduction to quantum error correction
  - Classical vs quantum error correction
  - Theory of quantum error correction
  - Insights on fault-tolerance

- A continuous-variable alternative
  - Cat-qubits for protection against photon-loss
  - Nonlinear dissipation paving the way towards fault-tolerance

DRIVEN-DAMPED HARMONIC OSCILLATOR

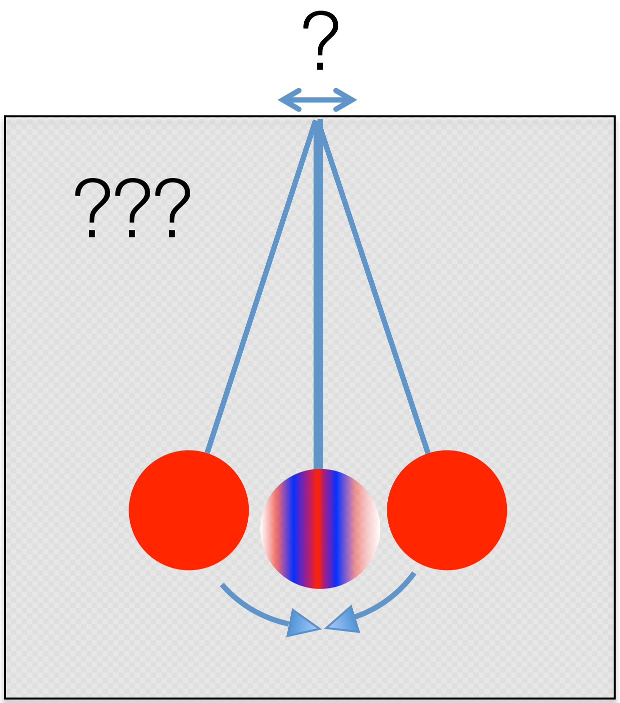


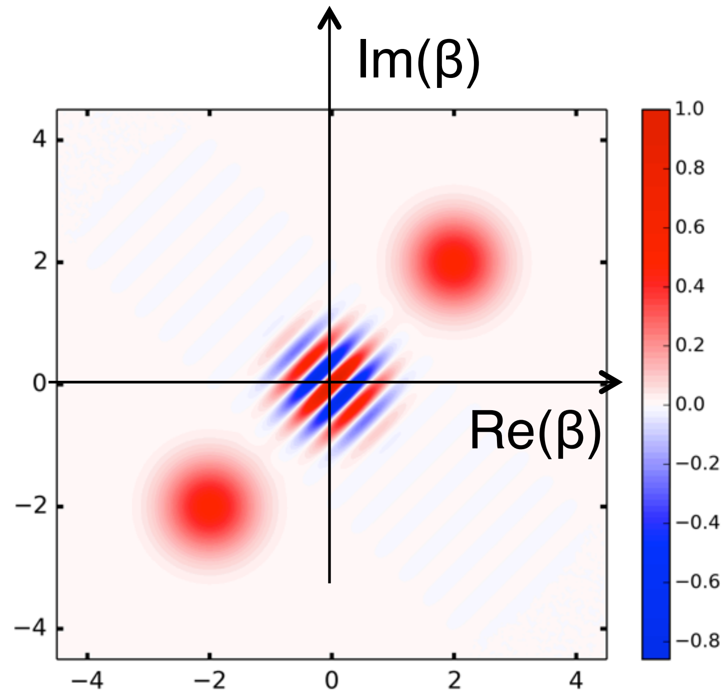


Hamiltonian : $H = \varepsilon_1^* \hat{a} + \varepsilon_1 \hat{a}^\dagger$

loss operator : $\sqrt{\kappa_1}\hat{a}$

A SPECIAL DRIVEN-DAMPED OSCILLATOR





Wigner function W(β)

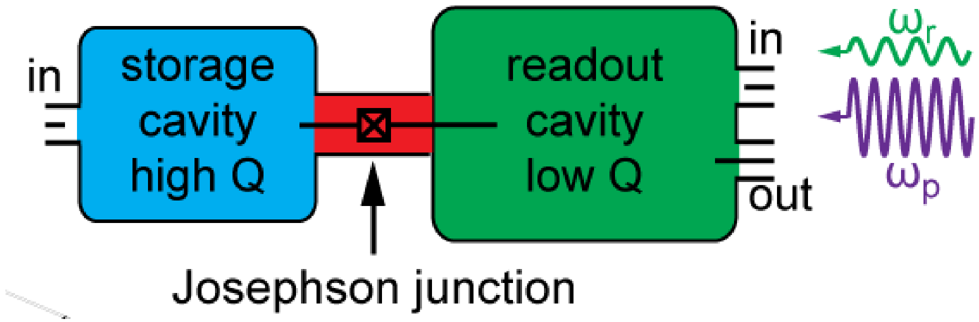
Hamiltonian : $H = \varepsilon_2{}^* \hat{a}^2 + \varepsilon_2 (\hat{a}^\dagger)^2$

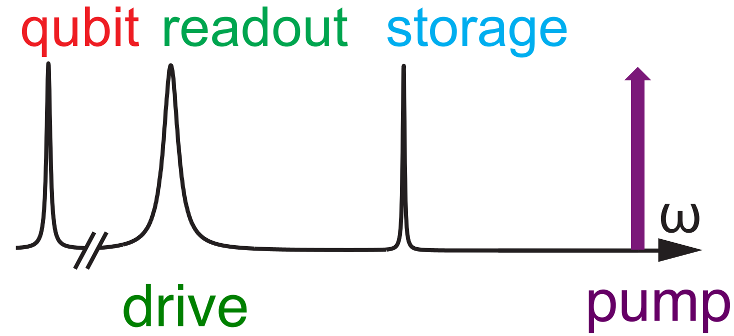
loss operator : $\sqrt{\kappa_2}\hat{a}^2$

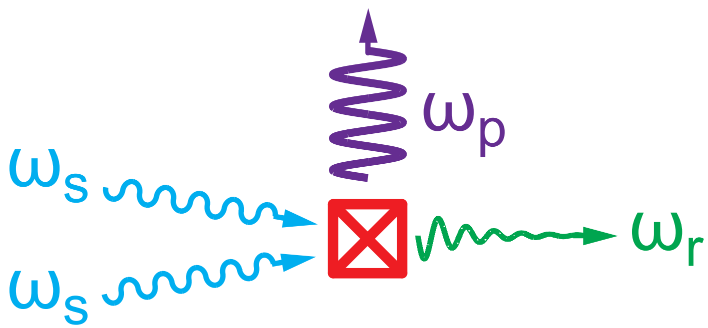
$$\alpha = \pm\sqrt{-2i\varepsilon_2 / \kappa_2}$$

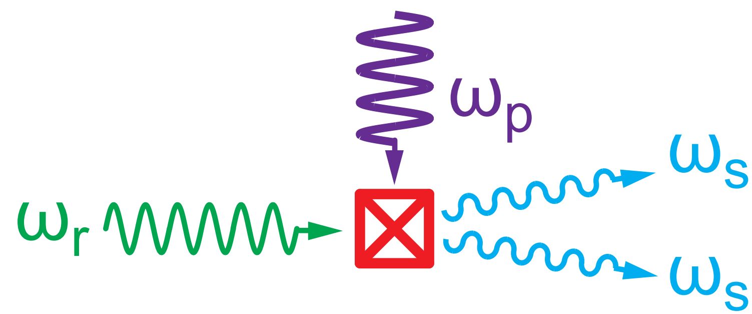
TWO-PHOTON EXCHANGE

$$\omega_p = 2\omega_s - \omega_r$$







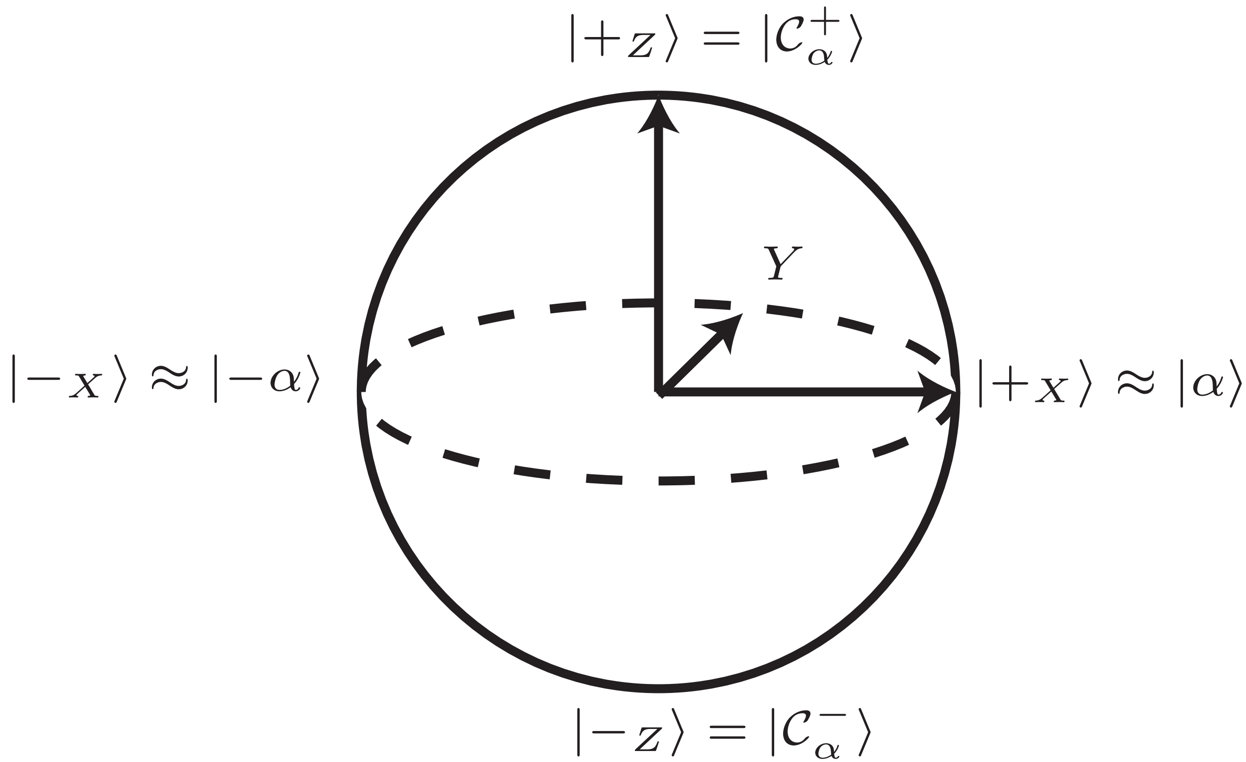


$$H_{sr} = \left(g_2^{\,*}\hat{a}_s^{\,2}\hat{a}_r^{\,\dagger} + \text{h.c.}\right) \quad + \quad \varepsilon\hat{a}_r^{\,\dagger} + \text{h.c.}$$

effective loss operator: $\sqrt{\kappa_2}\,\hat{a}_s^{\,2}$

effective drive : $\varepsilon_2\left(\hat{a}_s^{\,\dagger}\right)^2 + \text{h.c.}$

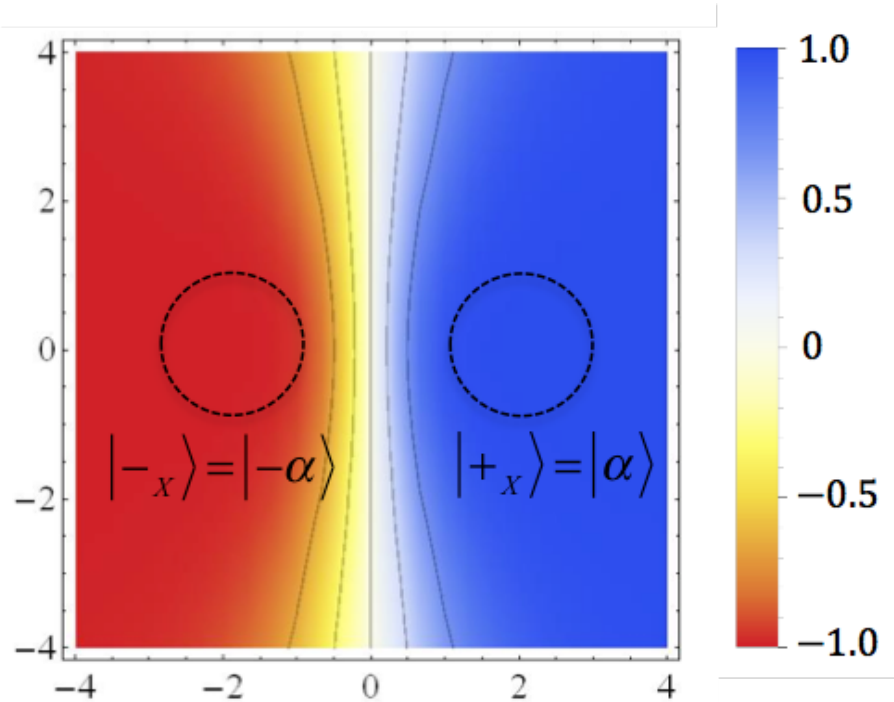
CHOICE OF QUBIT BASIS

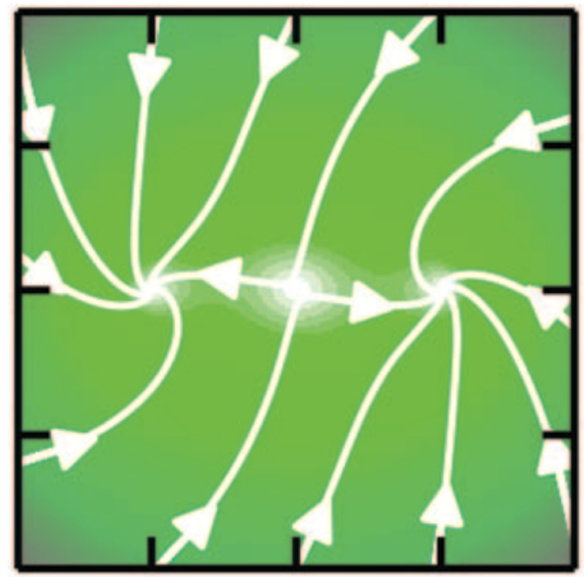


$$\left|+_Z\right\rangle = \left|C_\alpha^+\right\rangle = N_+(\left|\alpha\right\rangle + \left|-\alpha\right\rangle) = \sum c_{2n}\left|2n\right\rangle$$

$$\left|-_Z\right\rangle = \left|C_\alpha^-\right\rangle = N_-(\left|\alpha\right\rangle - \left|-\alpha\right\rangle) = \sum c_{2n+1}\left|2n+1\right\rangle$$

A QUBIT WITHOUT PHASE-FLIPS

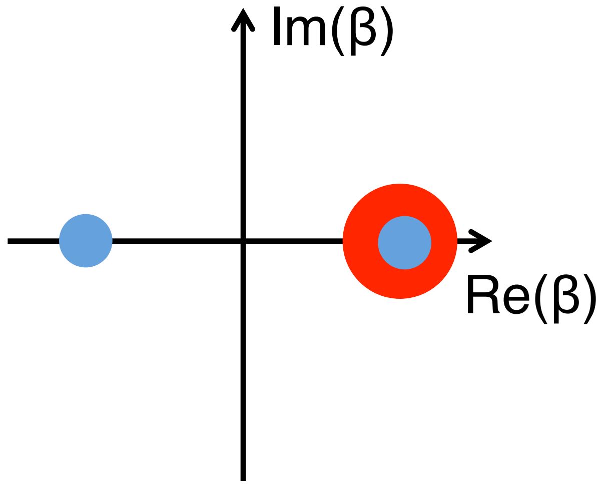


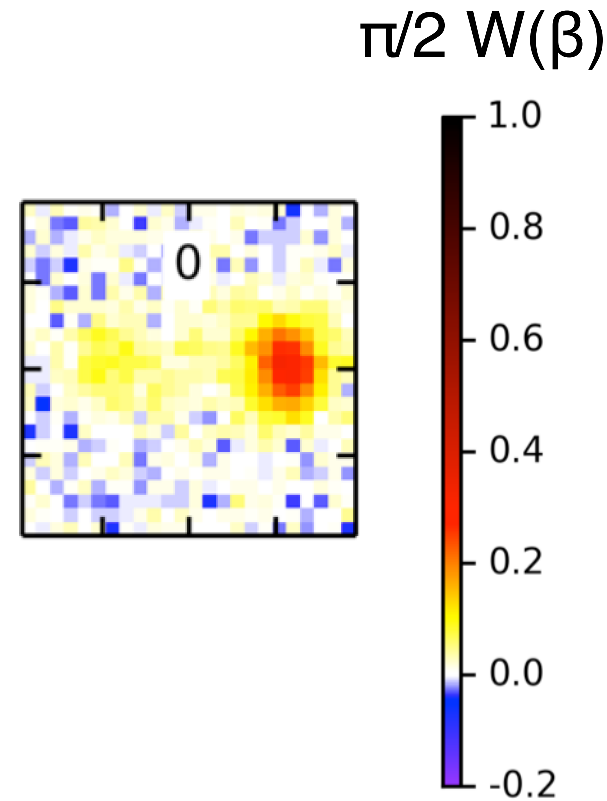


$\mathrm{Tr}(\sigma_X^L \rho_\infty)$ for $\rho_0 = |\beta\rangle\langle\beta|$

Phase-flip errors induced by reasonable (local in the phase space) errors are suppressed exponentially in $|\alpha|^2$.

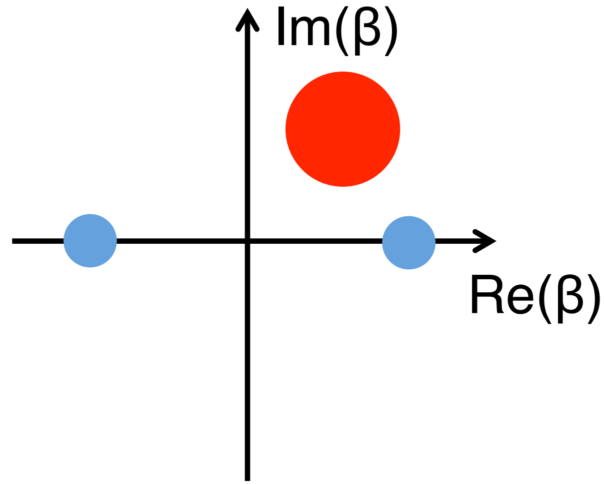
BI-STABLE BEHAVIOR (SEMI-CLASSICAL)

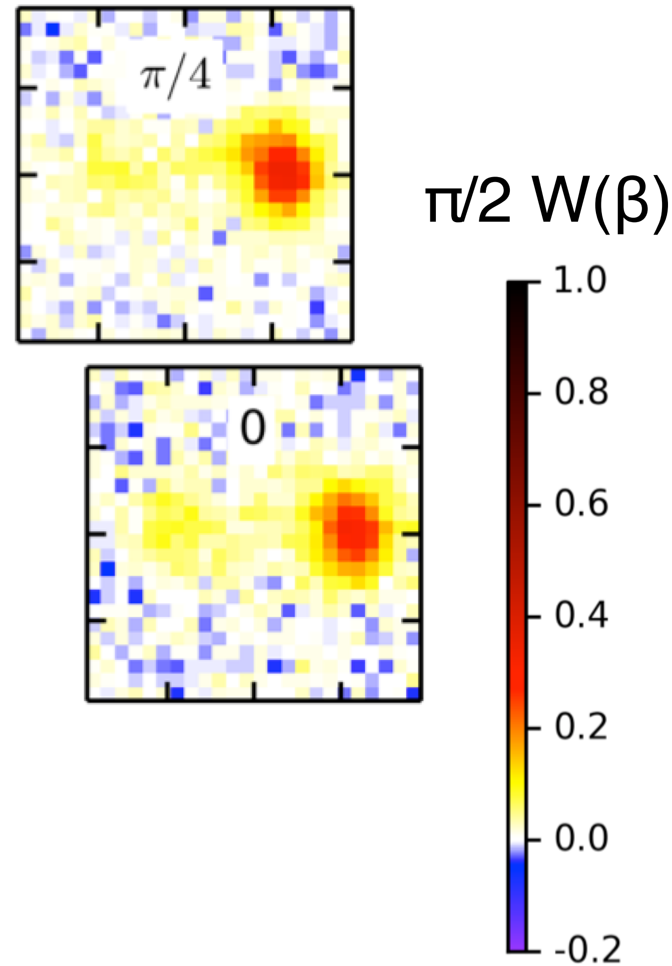




Leghtas *et. al.* Science (2015)

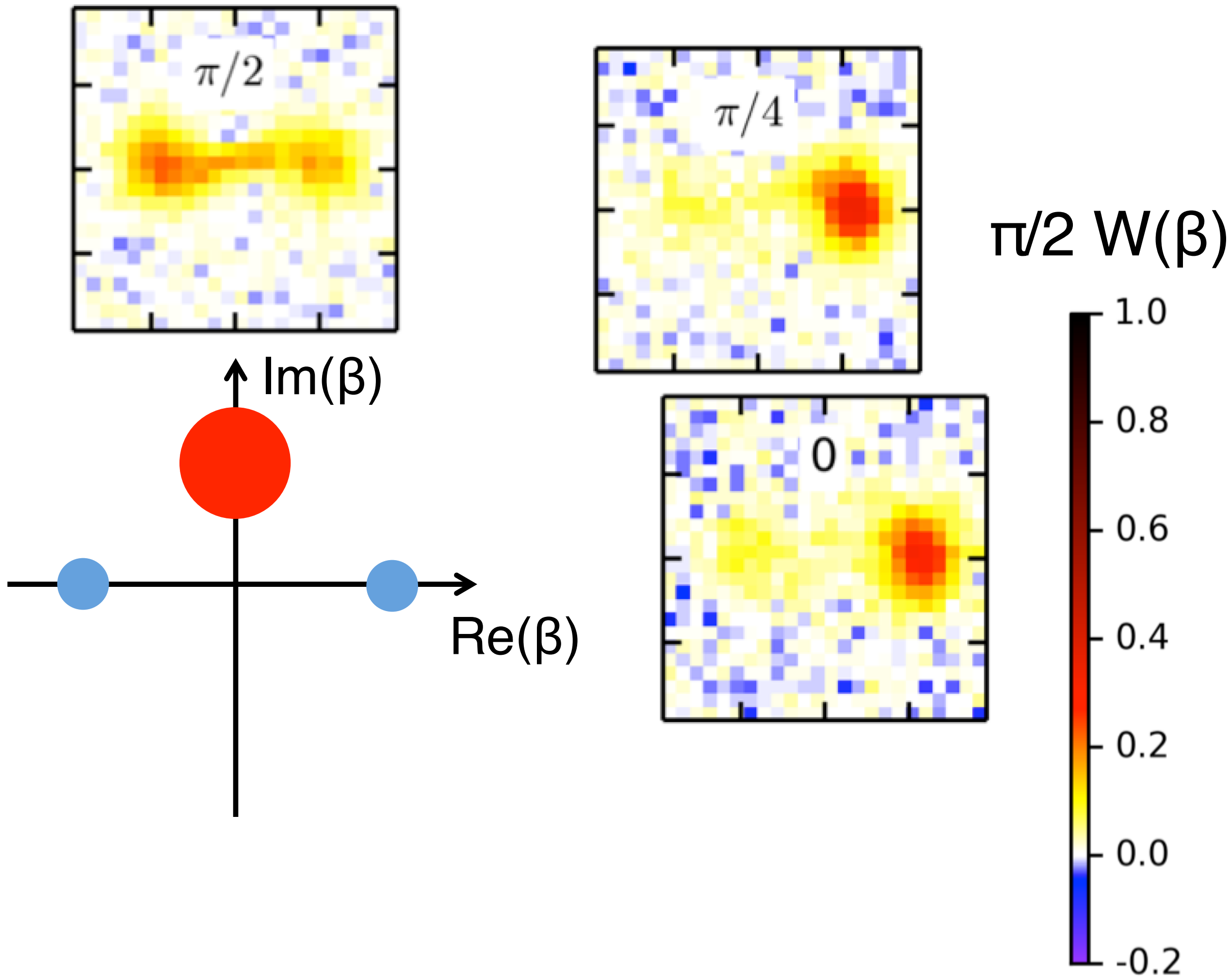
BI-STABLE BEHAVIOR (SEMI-CLASSICAL)





Leghtas *et. al.* Science (2015)

BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



Leghtas *et. al.* Science (2015)

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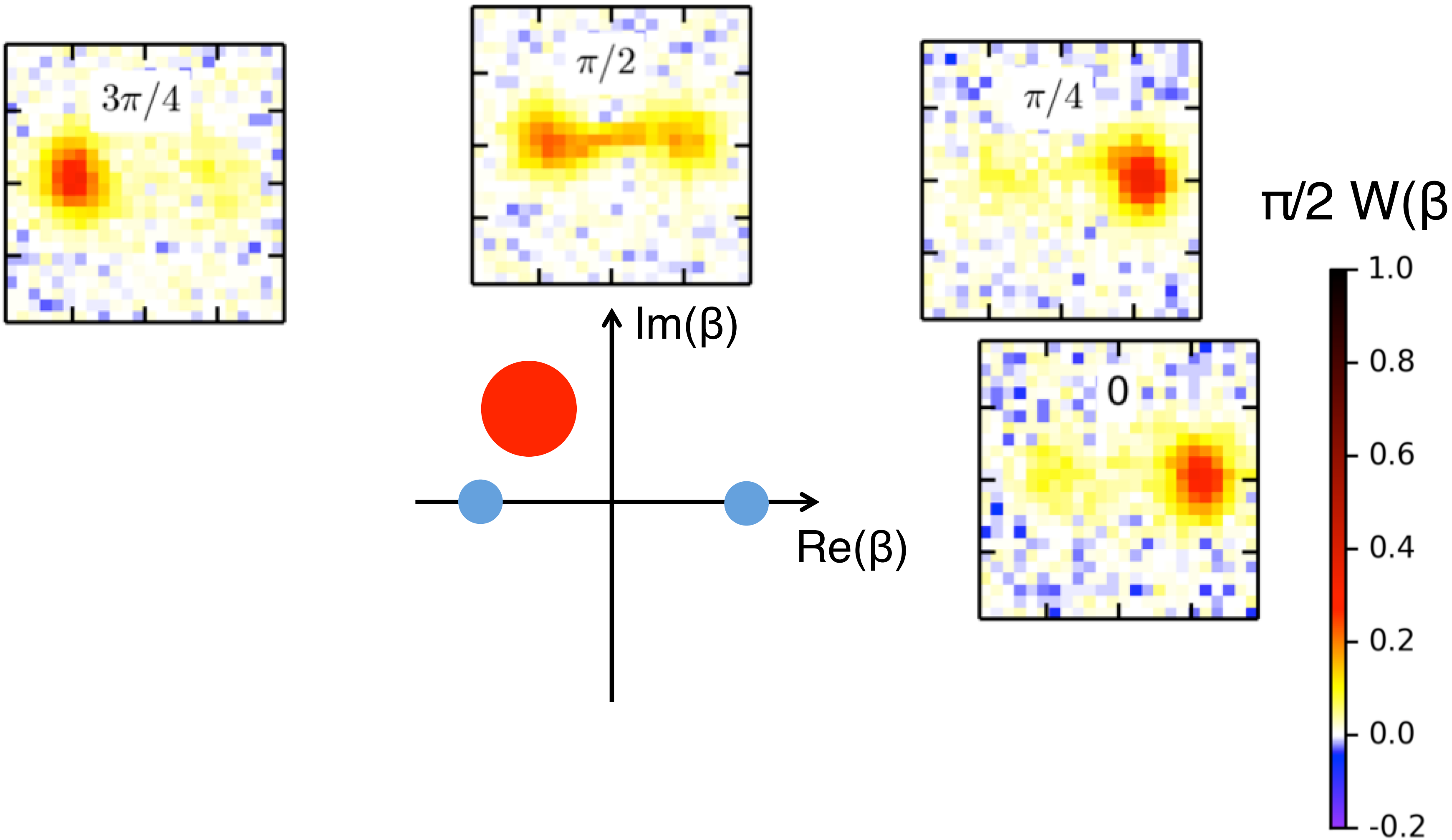
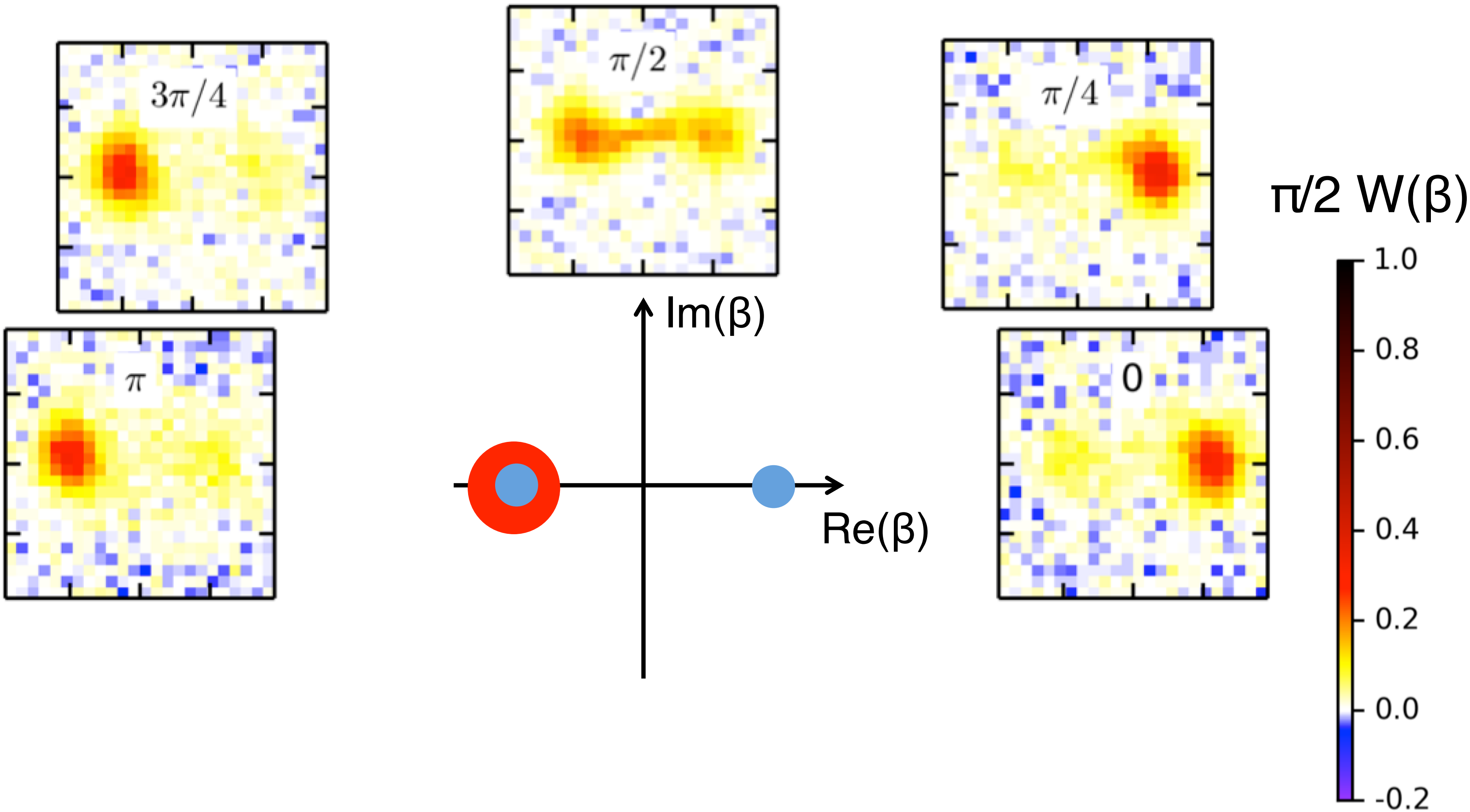


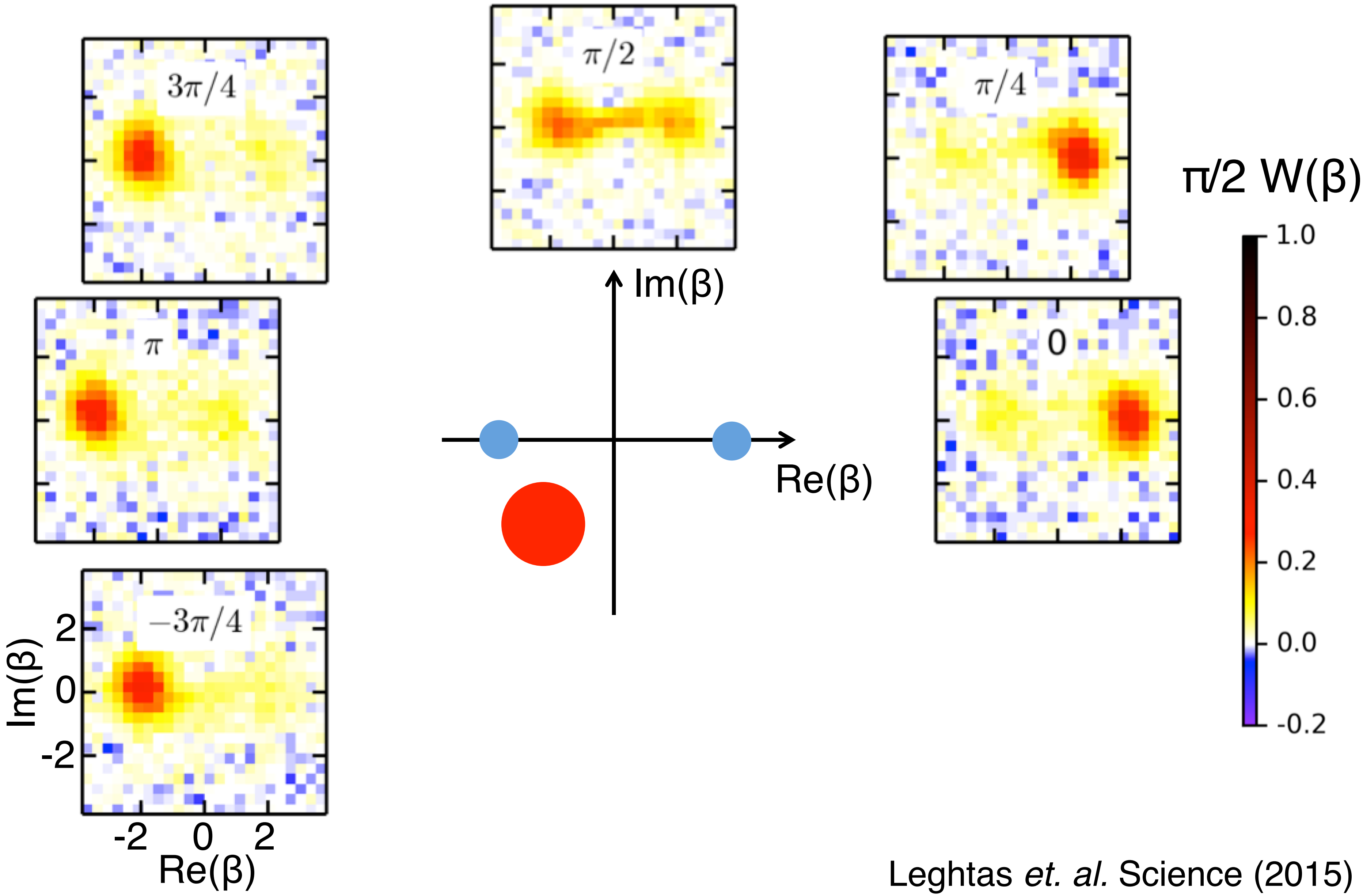
Leghtas *et. al.* Science (2015)

BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



Leghtas *et. al.* Science (2015)

BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



Leghtas *et. al.* Science (2015)

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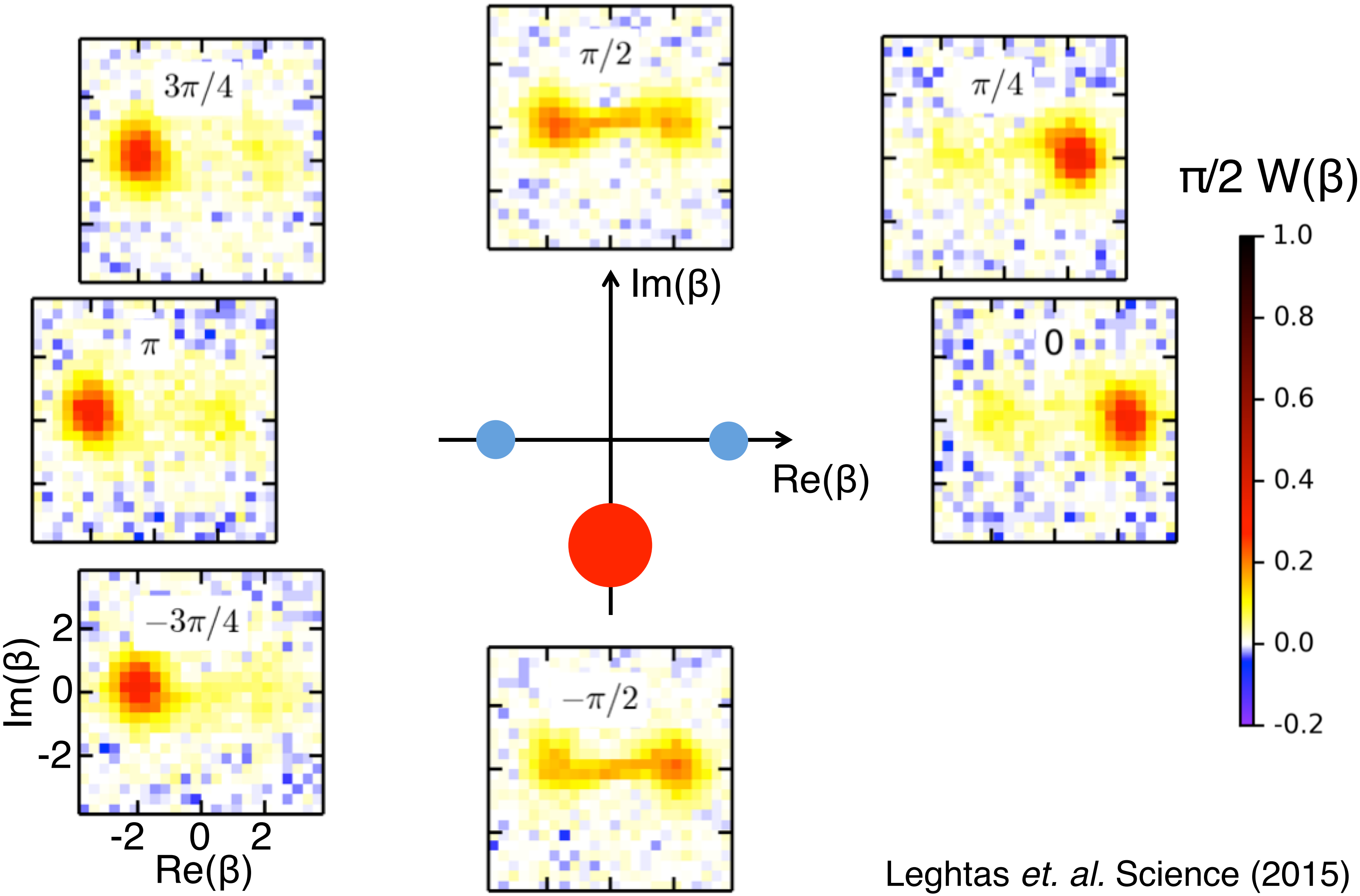

Leghtas *et. al.* Science (2015)

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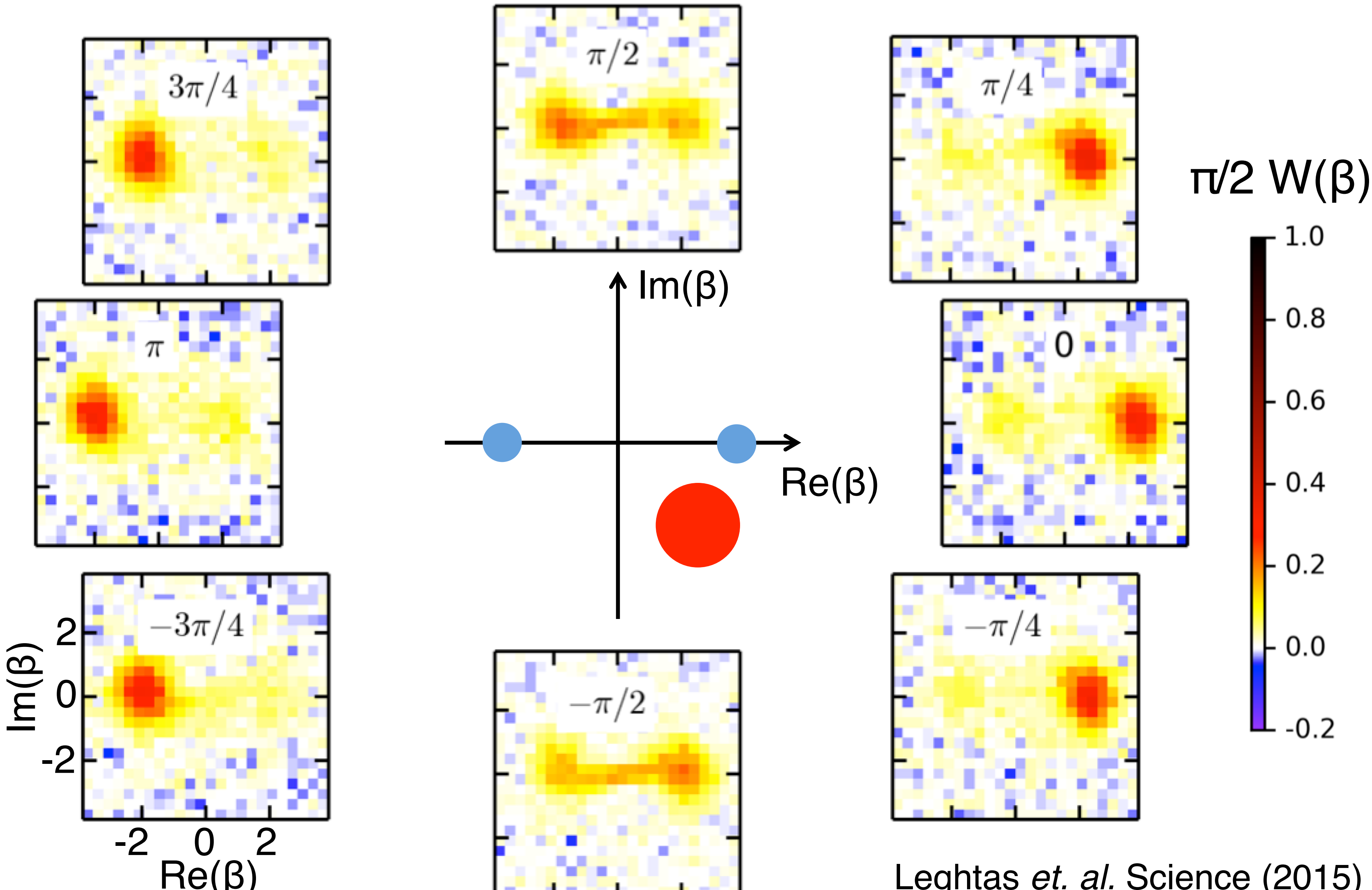
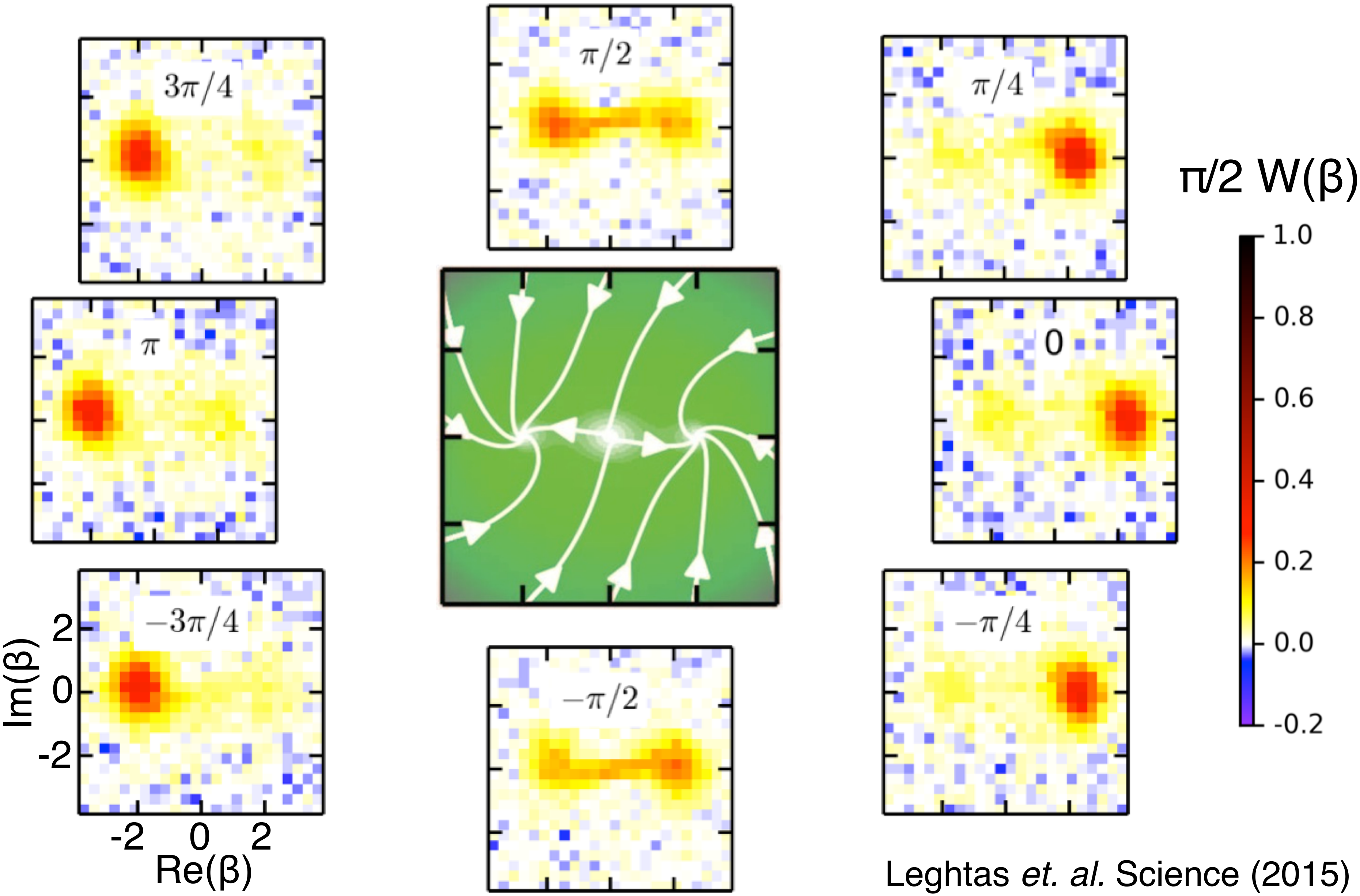


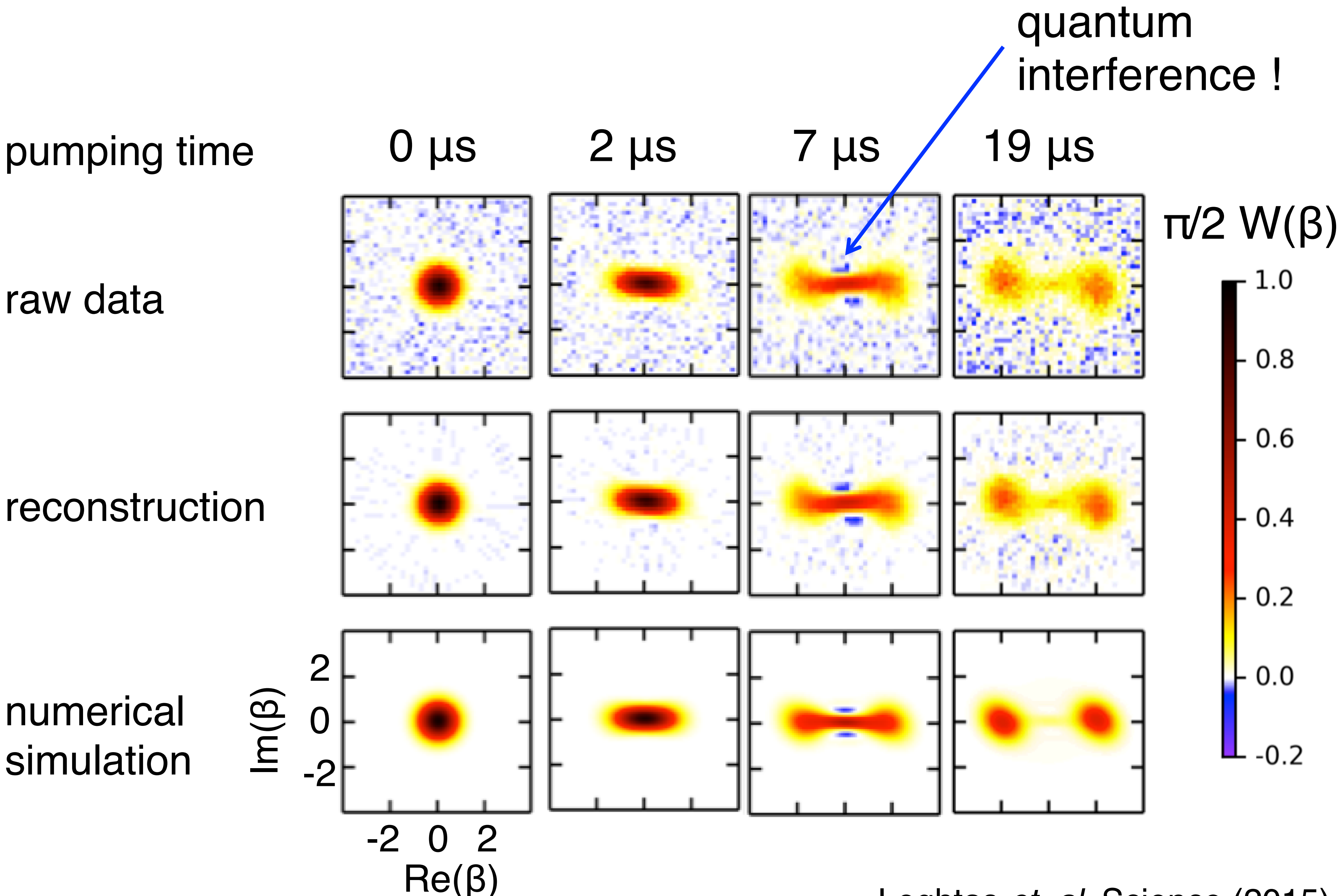
Leghtas *et. al.* Science (2015)

BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



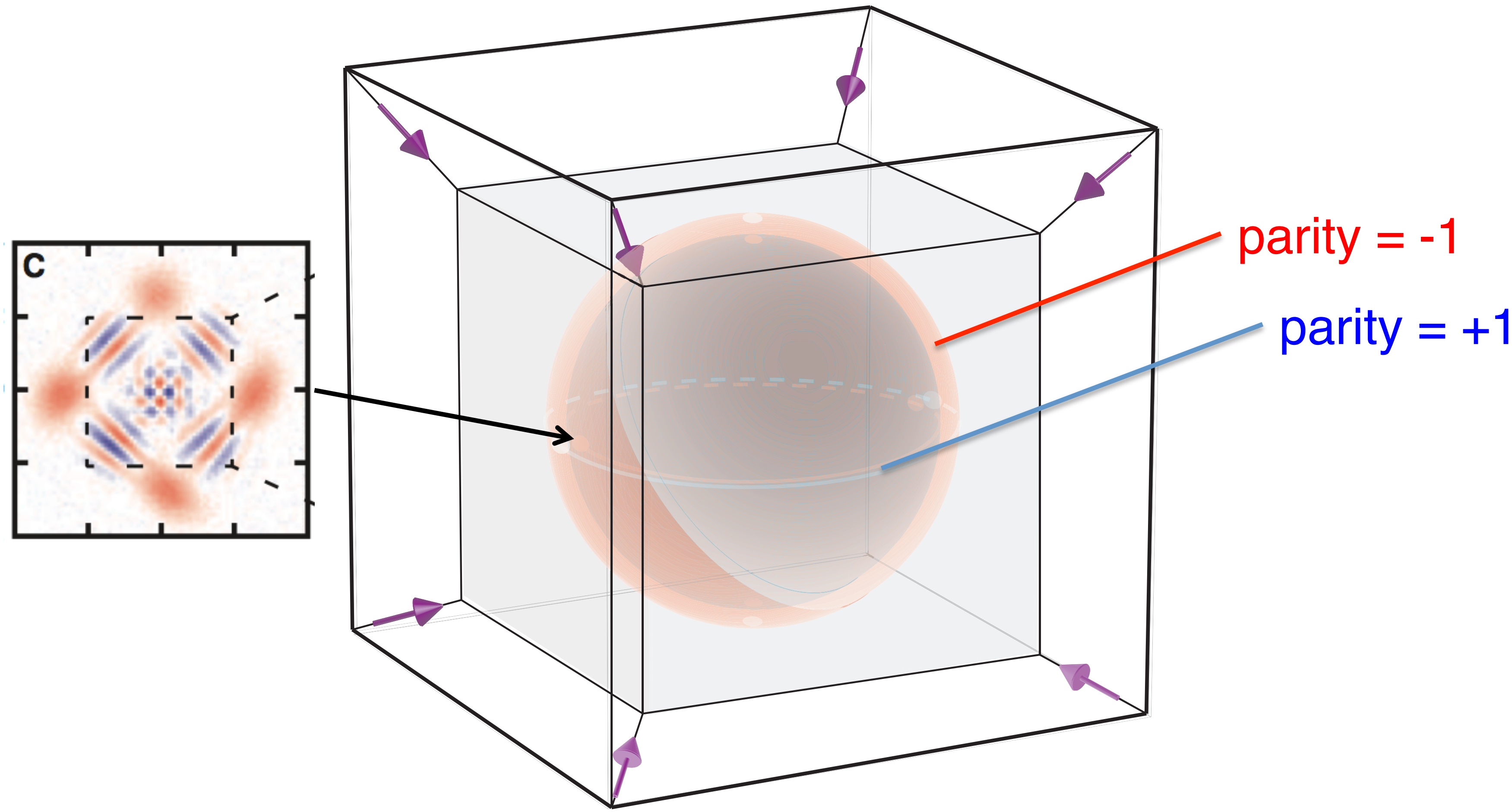
Leghtas *et. al.* Science (2015)

CAT SQUEEZES OUT OF VACUUM



Leghtas *et. al.* Science (2015)

FUTURE: FULL QUANTUM ERROR CORRECTION

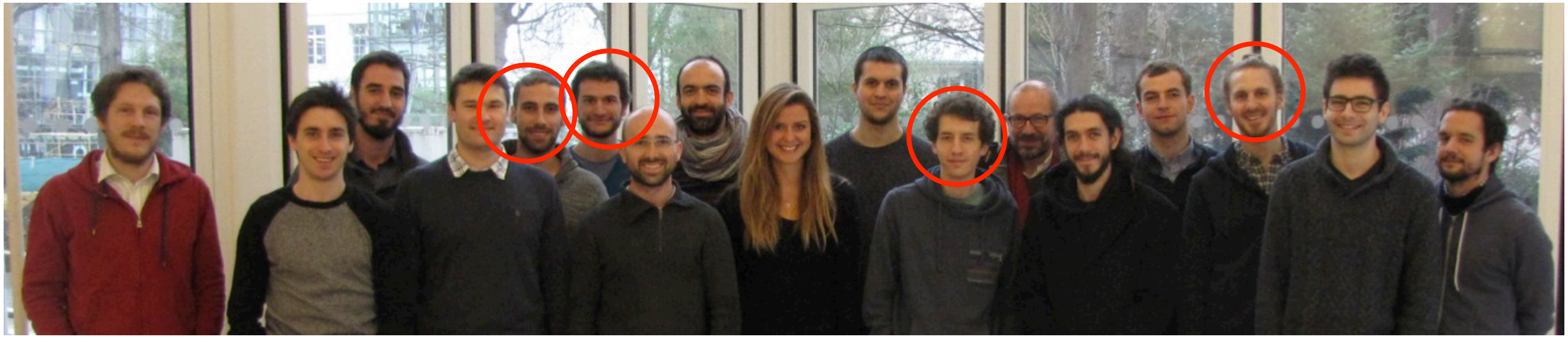


loss operator $\sqrt{\kappa_4}\hat{a}^4$

$$H = \varepsilon_4 \left(\hat{a}^\dagger\right)^4 + \varepsilon_4{}^* \hat{a}^4$$

M.M. *et. al.* NJP (2014)
S. Mundhada *et. al.* in prepation.

COLLABORATORS



QUANTIC, Paris (Zaki Leghtas, Joachim Cohen, Lucas Verney, Raphael Lescanne)

Devoret's group, (Steven Touzard, Alexander Grimm, Shantanu Mundhada, Clarke Smith)

Schoelkopf's group, (Nissim Ofek, Andrei Petrenko)