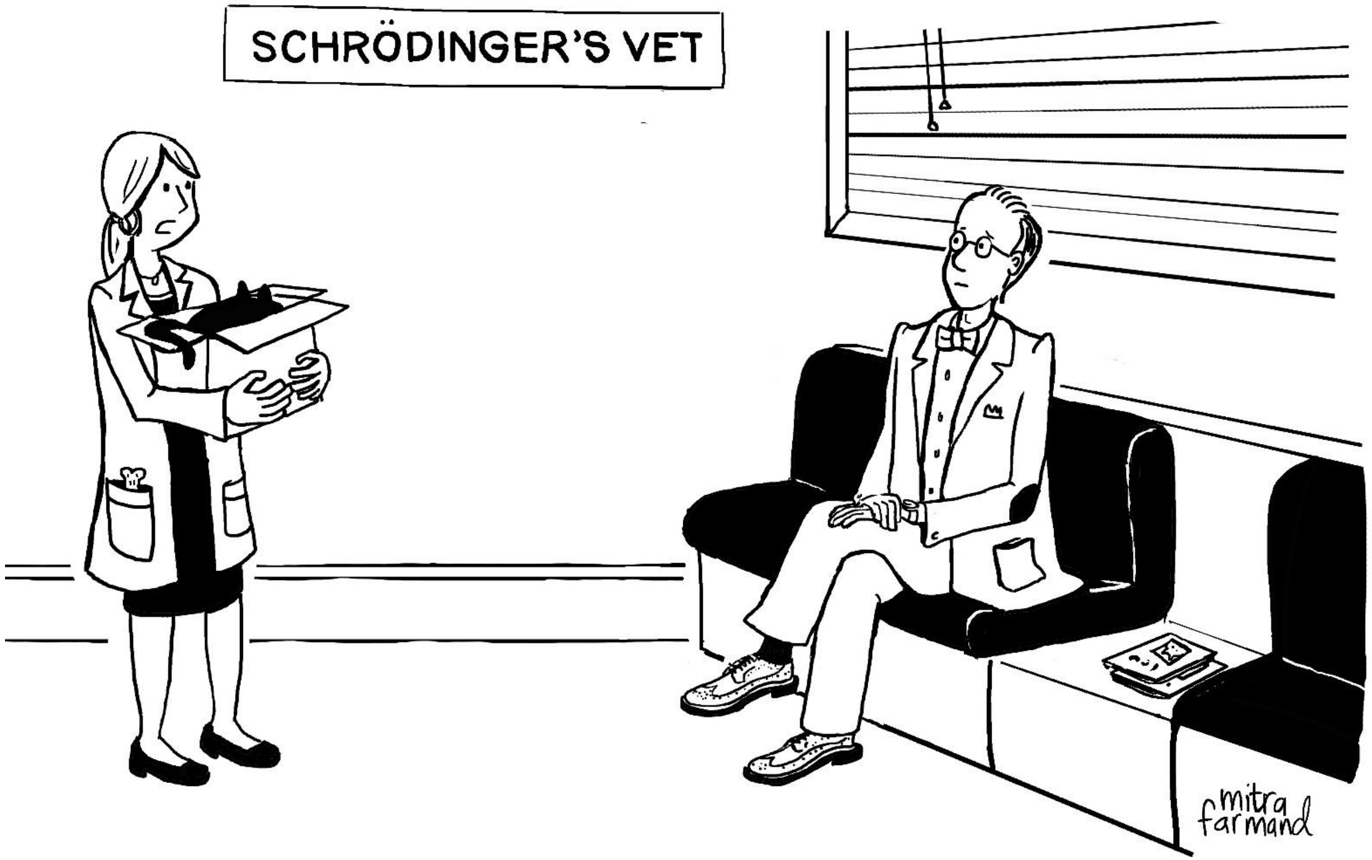
PROTECTING QUANTUM SUPERPOSITIONS IN JOSEPHSON CIRCUITS



“I have good news and bad news”

PROTECTING QUANTUM SUPERPOSITIONS IN JOSEPHSON CIRCUITS

Michel Devoret, Yale University

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Sponsors:

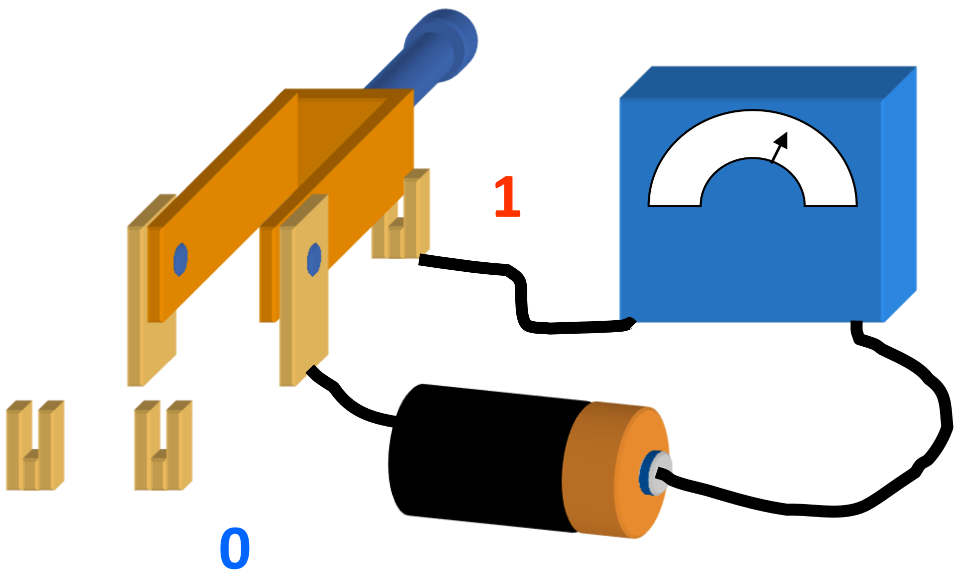
PROTECTING QUANTUM SUPERPOSITIONS IN JOSEPHSON CIRCUITS

LECTURE I: INTRODUCTION AND OVERVIEW

LECTURE II: CAT CODES

LECTURE III: PARITY MONITORING AND CORRECTION

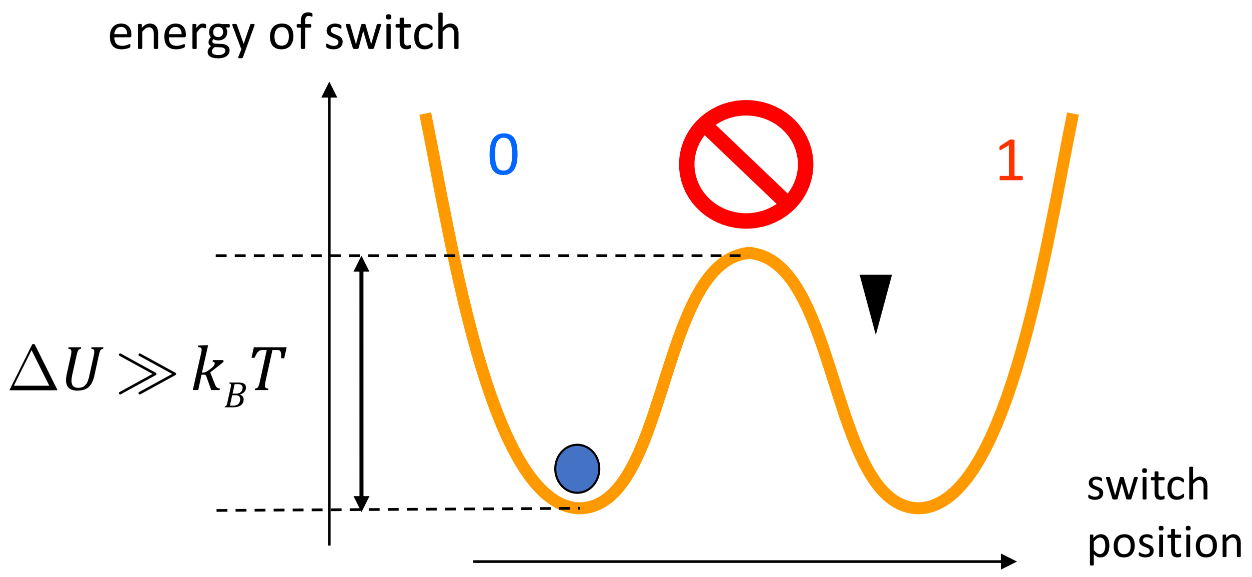
PROTECTING CLASSICAL INFORMATION



ONE BIT OF INFORMATION ENCODED IN A SWITCH

ENERGY BARRIER PROTECTS INFORMATION

$$\Gamma_{\text{error}} \sim \exp\left(-\frac{\Delta U}{k_B T}\right)$$



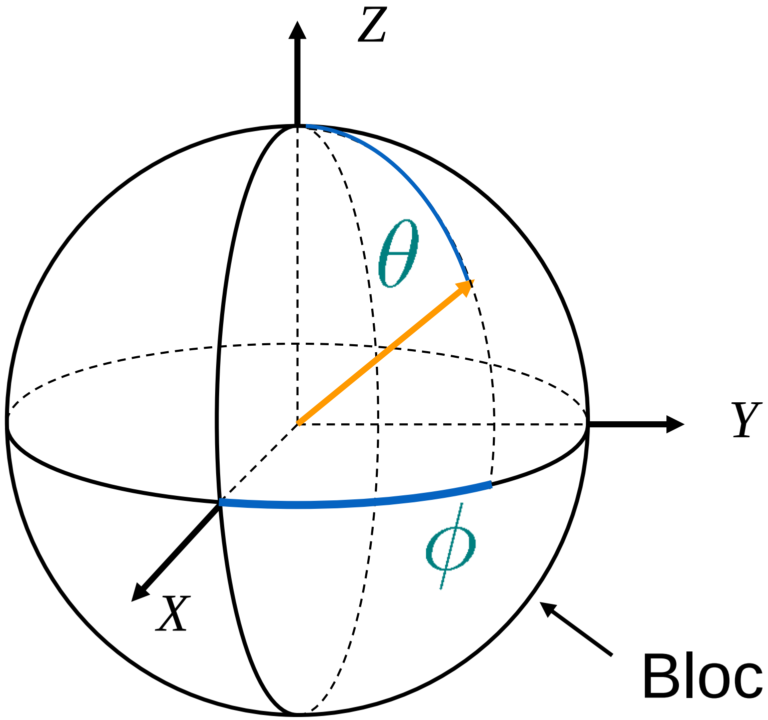
ELEMENT OF QUANTUM INFORMATION: QUBIT

Two basis quantum states:

$$|0\rangle \qquad |1\rangle$$

Generic superposition:

$$|\Psi\rangle = \cos\frac{\theta}{2}|0\rangle + \exp\left(i\phi\right)\sin\frac{\theta}{2}|1\rangle$$



Bloch sphere

MUST PRESERVE ALL SUPERPOSITIONS, I.E. THE ENTIRE SPHERE

CARDINAL POINTS OF THE BLOCH SPHERE

$$|Z=+1\rangle$$

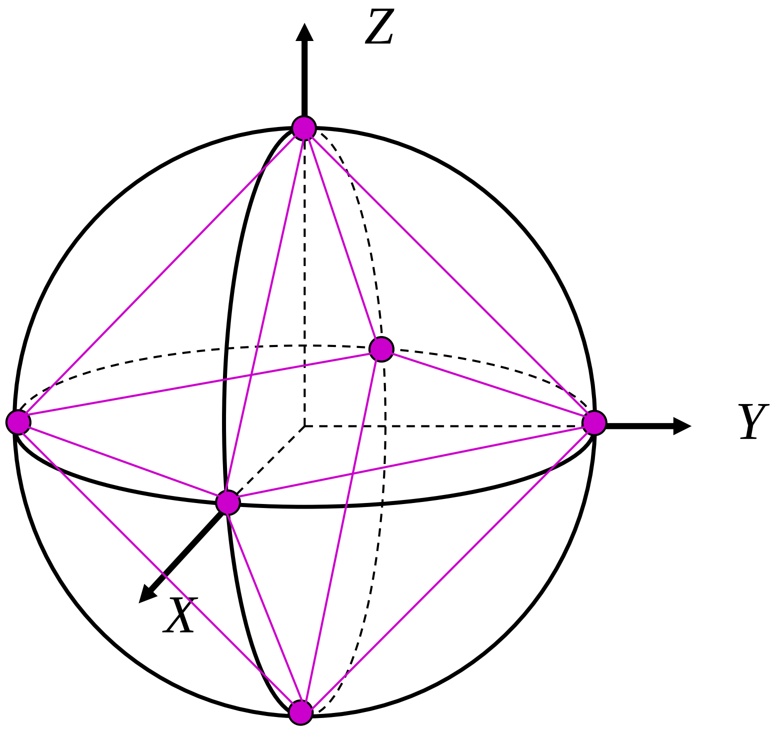
$$|Z=-1\rangle$$

$$|X=+1\rangle$$

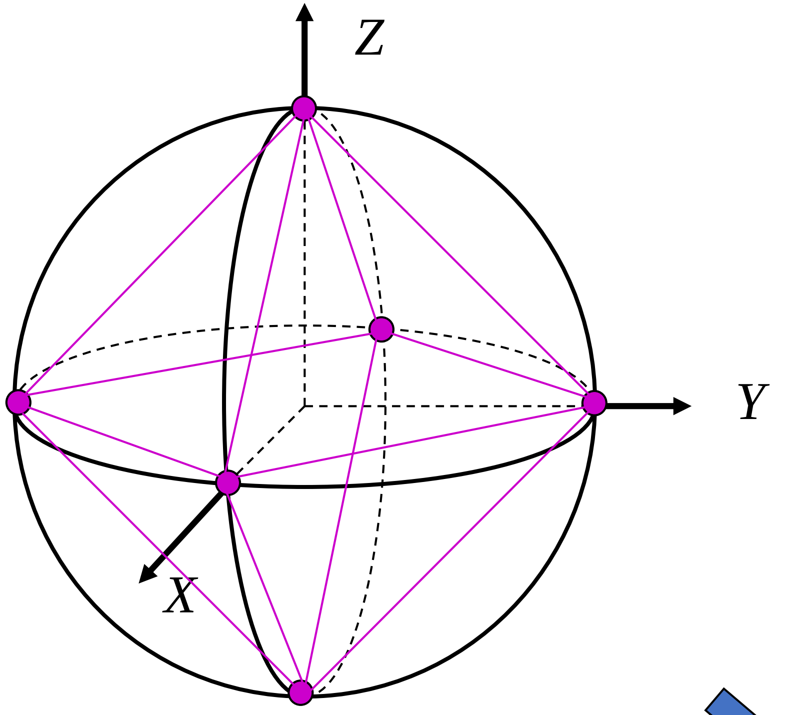
$$|X=-1\rangle$$

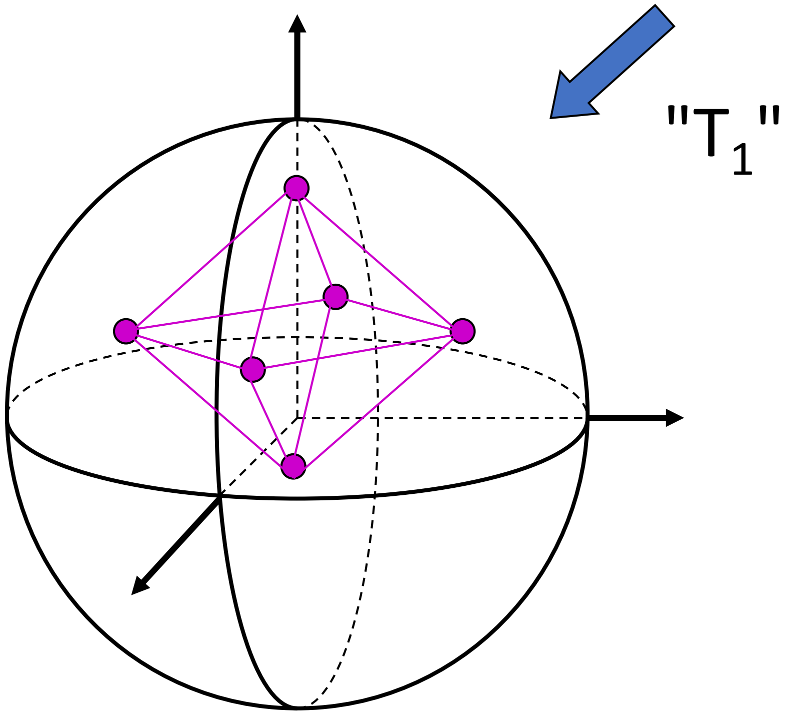
$$|Y=+1\rangle$$

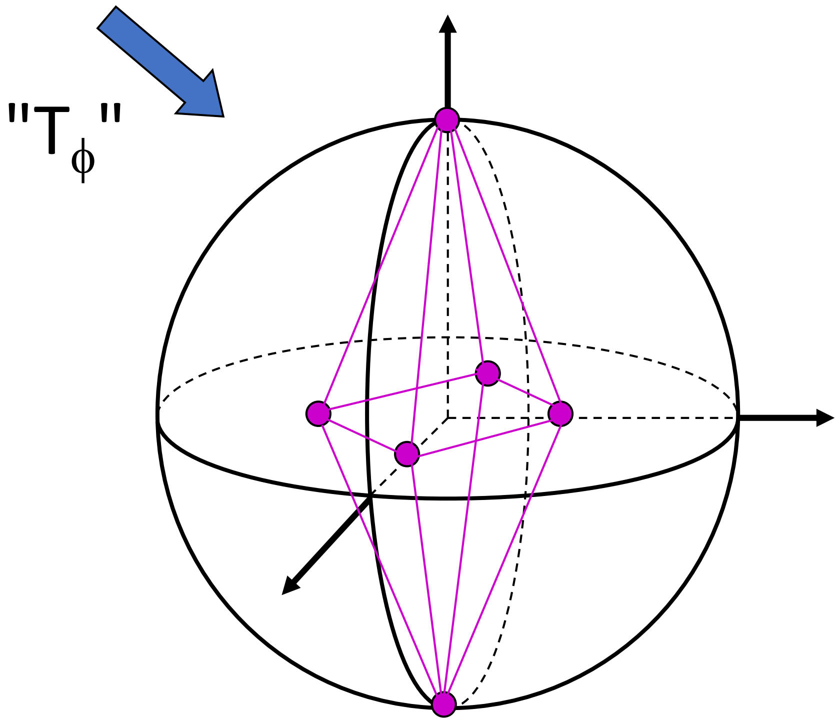
$$|Y=-1\rangle$$



DECOHERENCE: LOSS OF INFORMATION







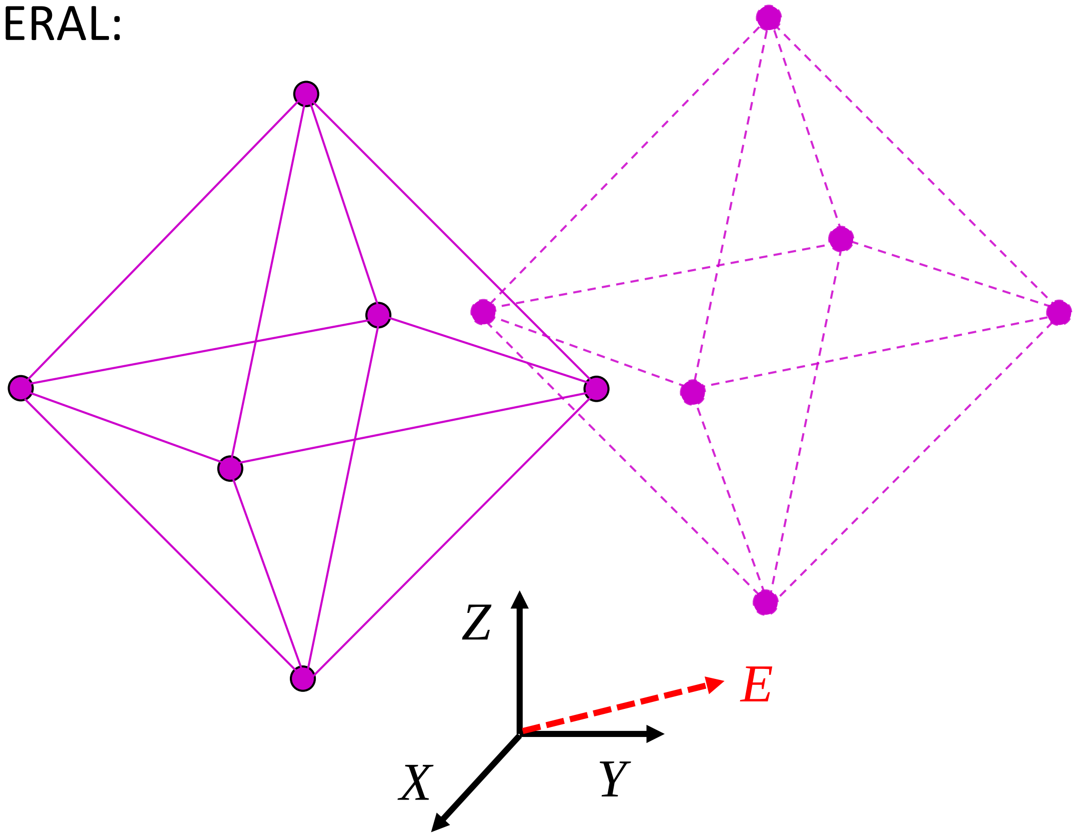
BY CAREFUL ENCODING IN A LARGE ENOUGH SPACE, QUANTUM INFORMATION CAN BE PROTECTED

SIMPLE EXAMPLE:

$$|\Psi\rangle = \cos\frac{\theta}{2}|\uparrow\downarrow\rangle + e^{i\phi}\sin\frac{\theta}{2}|\downarrow\uparrow\rangle$$

X AND Y COMPONENTS IN $M = 0$ MANIFOLD ARE PROTECTED FROM NOISE IN COMMON MODE MAGNETIC FIELD $\boldsymbol{B}$

IN GENERAL:



ELEMENTARY ERRORS $\boldsymbol{E}$ ONLY *MOVE* OCTAHEDRON ALONG A 3+nth *DIMENSION*, WITHOUT CHANGING ITS VOLUME

3 STRATEGIES FOR PROTECTING QUANTUM INFORMATION

- Encode using defects in topological quantum matter

  Example: Majorana fermions

- Encode into a register of qubits, monitor multi-qubit parities

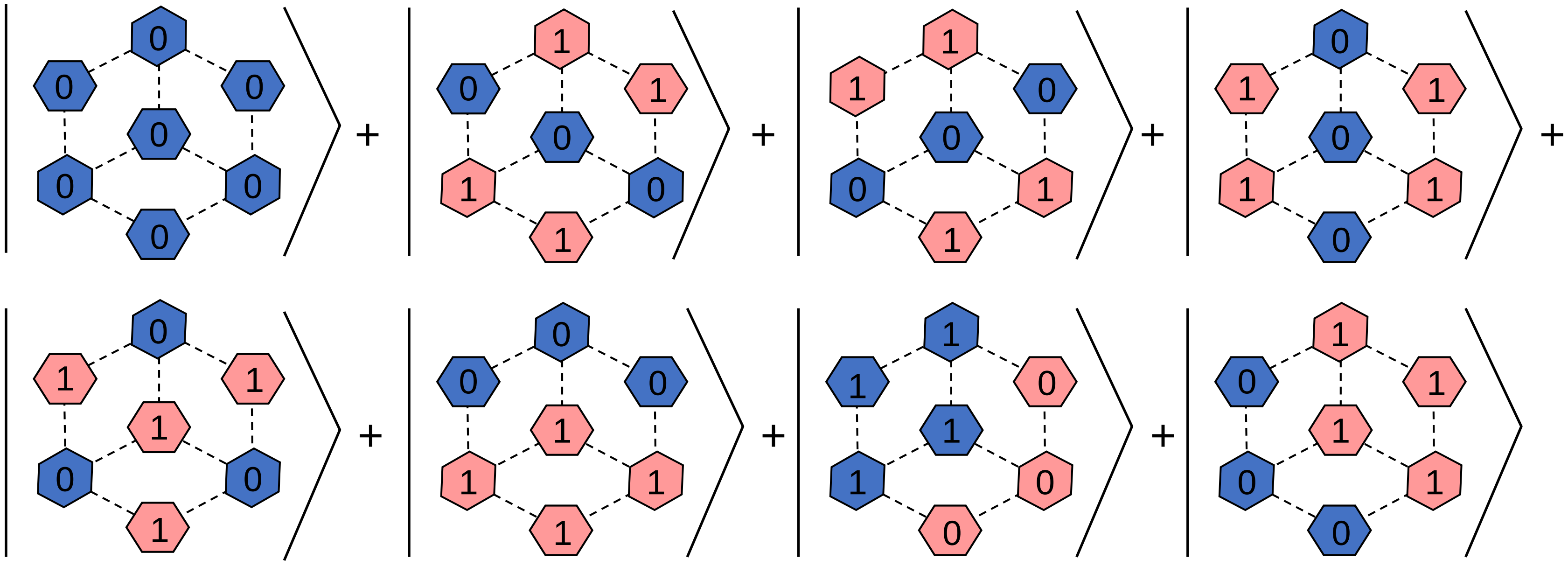
  Examples: Steane & surface codes

- Encode into a quantum cavity resonator and monitor photon number parity

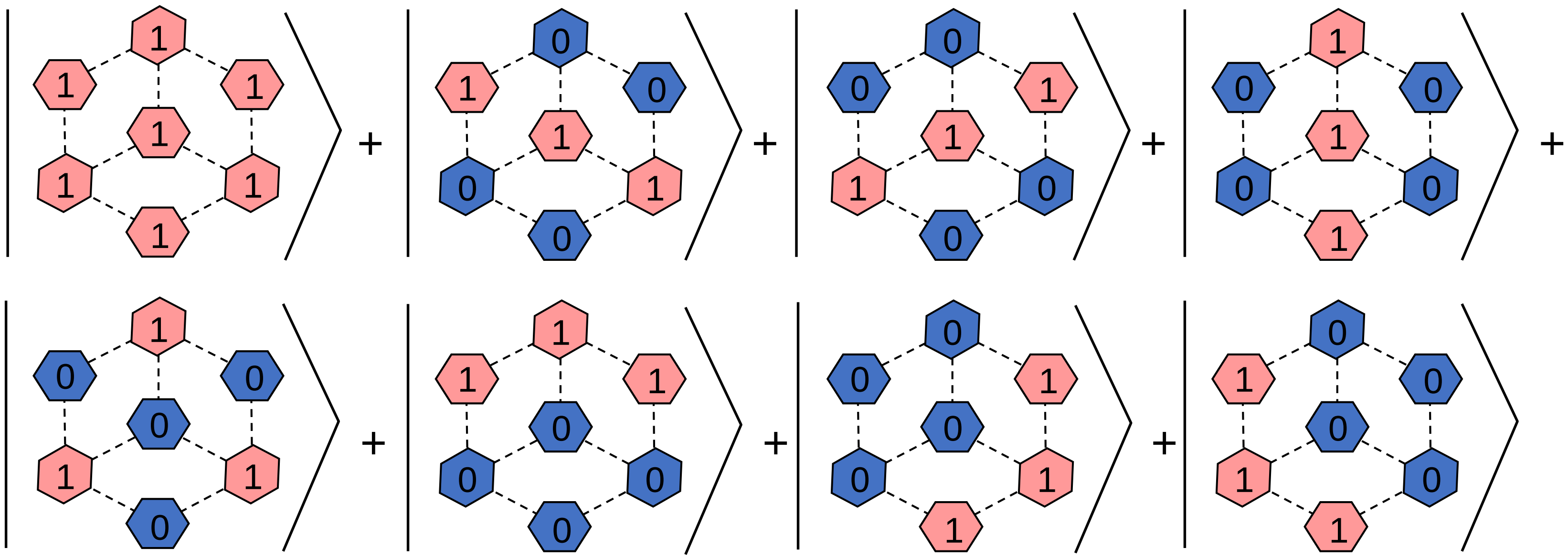
  Example: cat codes

REGISTER ERROR CORRECTION: STEANE CODE

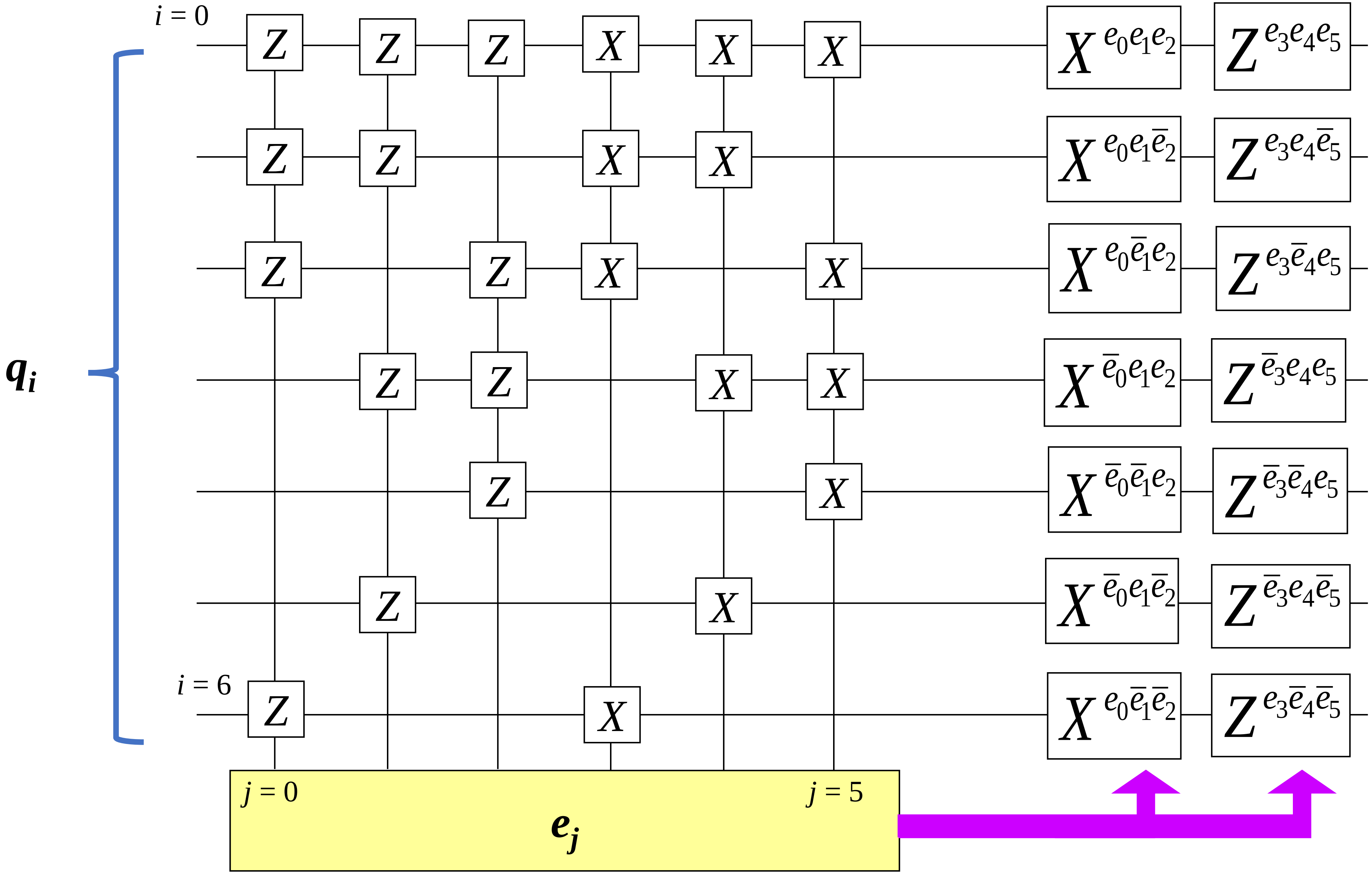
$$|0_L\rangle =$$



$$|1_L\rangle =$$



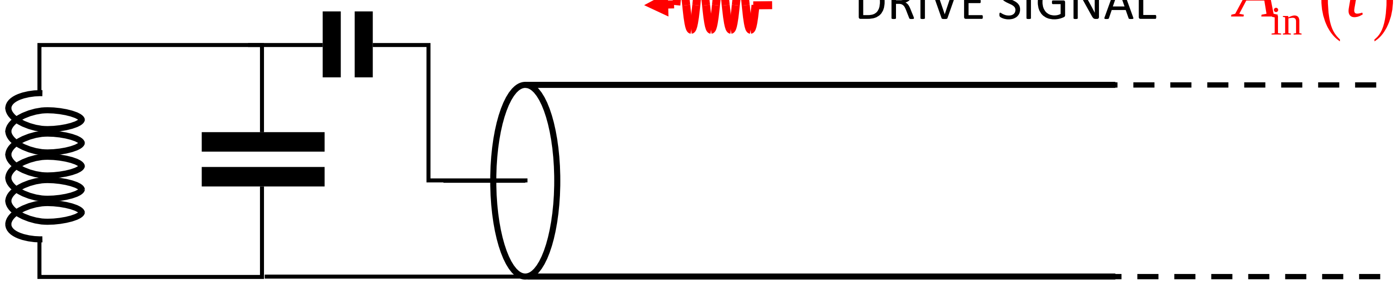
STEANE CODE ERROR CORRECTION PROTOCOL



SUPERCONDUCTING QUBIT PARADIGM:
CONSIDER A SINGLE, DRIVEN ELECTROMAGNETIC MODE...

$\kappa \ll \omega_0$

DRIVE SIGNAL $A_{\text{in}}(t) = A\cos(\omega t)$



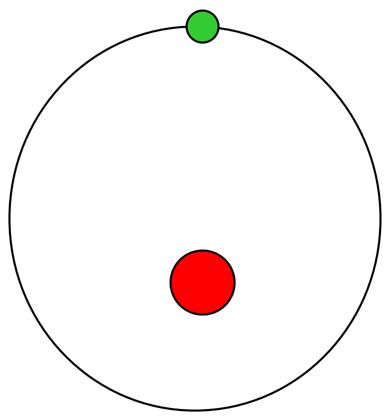
ω_0

REFLECTED SIGNAL $A_{\text{out}}(t) = A\cos(\omega t + \phi)$

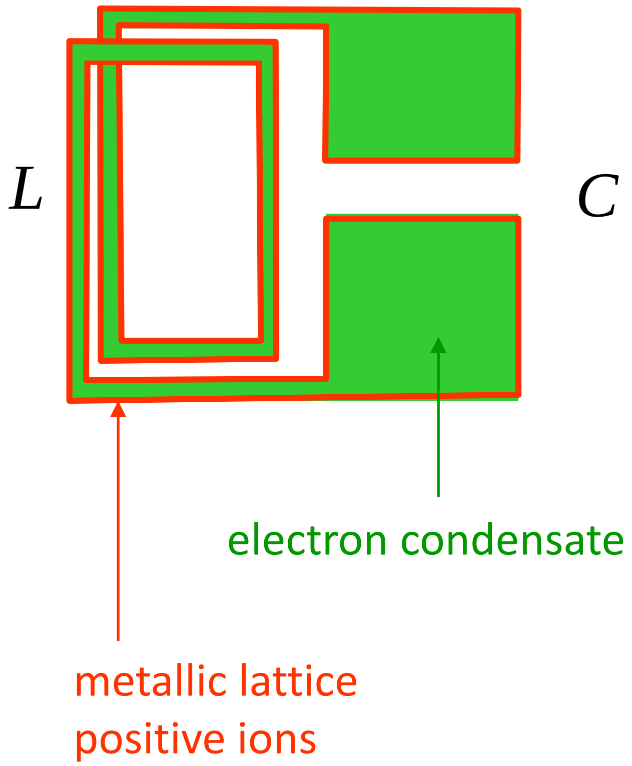
MICROWAVE FREQUENCIES $\hbar\omega_0 \gg k_B T$

ATOM vs CIRCUIT

Hydrogen atom



Superconducting
LC oscillator



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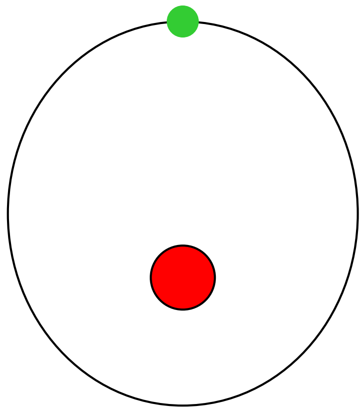

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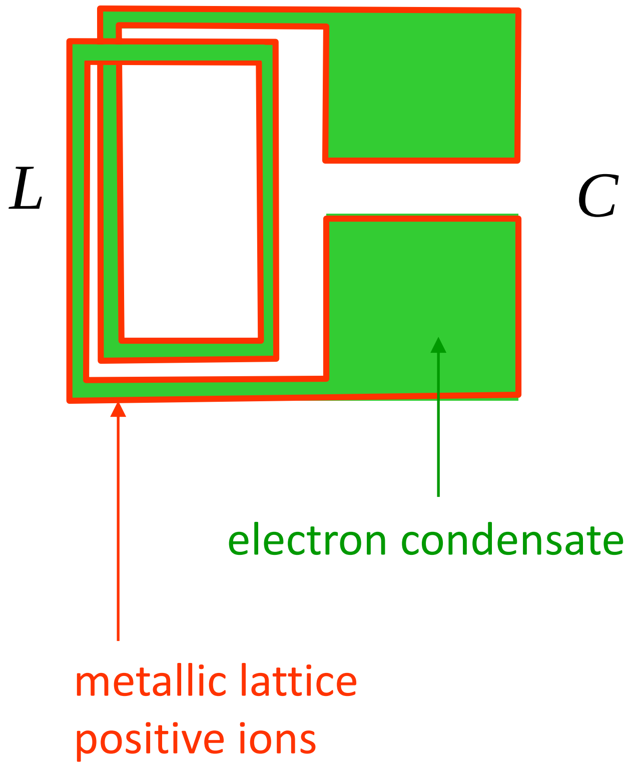

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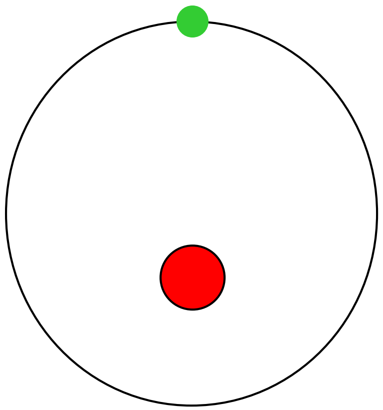

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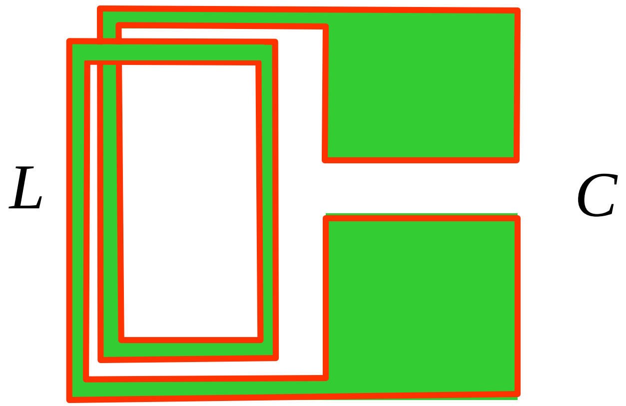
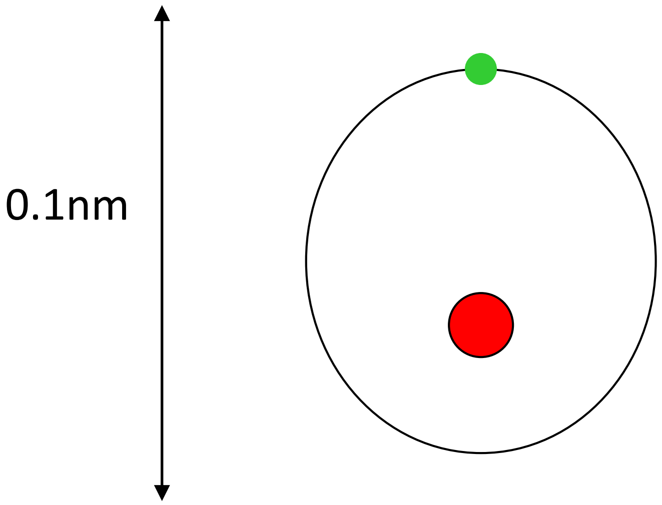


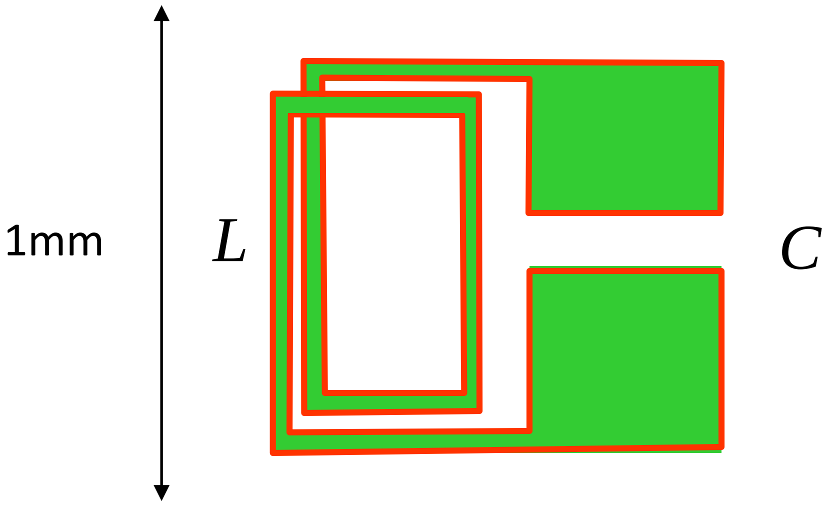
unique electron → whole superconducting condensate
velocity of electron → **current through inductor**
force on electron → **voltage across capacitor**

ATOM vs CIRCUIT

Hydrogen atom

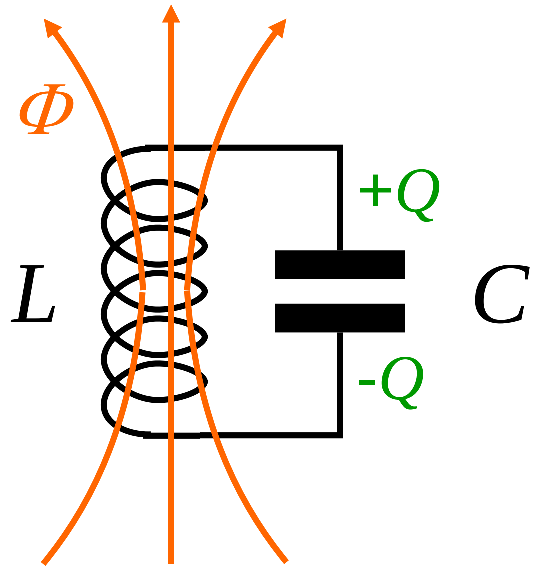


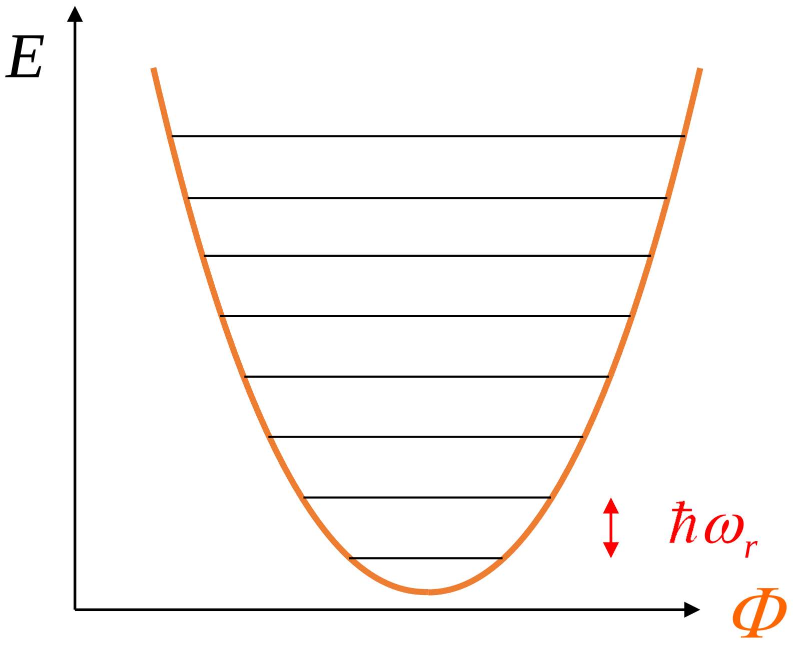
Superconducting
LC oscillator



unique electron → whole superconducting condensate
velocity of electron → **current through inductor**
force on electron → **voltage across capacitor**

LC CIRCUIT AS A QUANTUM HARMONIC OSCILLATOR



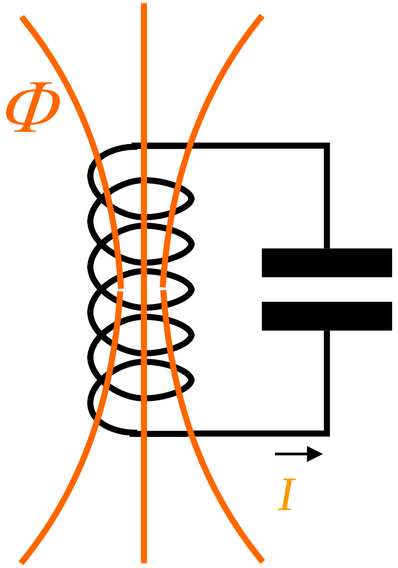


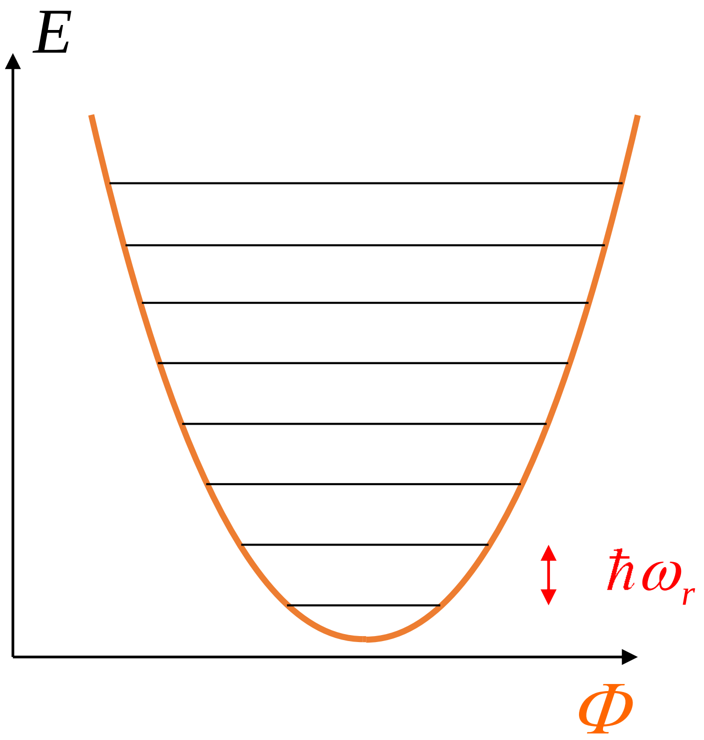
$\Phi = LI$

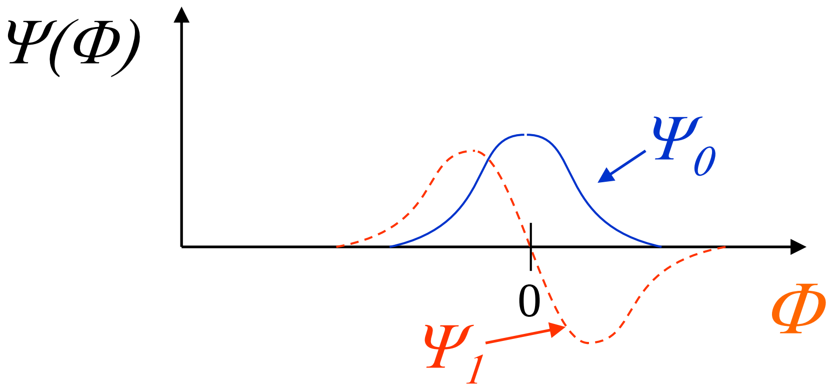
$Q = CV$

$$\left[\hat{\Phi}, \hat{Q}\right] = i\hbar$$

WAVEFUNCTIONS OF LC CIRCUIT

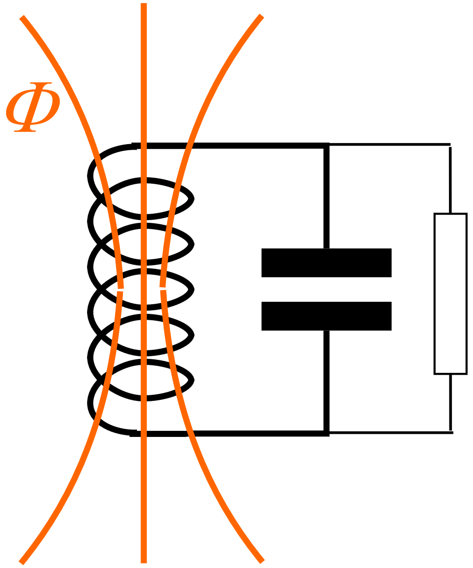


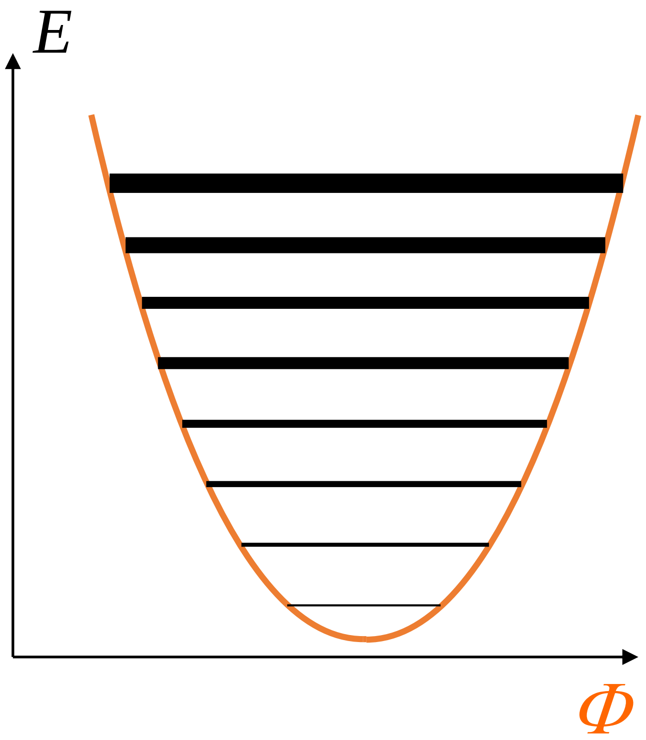




In every energy eigenstate,
(microwave photon state)
current flows in opposite
directions simultaneously!

EFFECT OF DAMPING



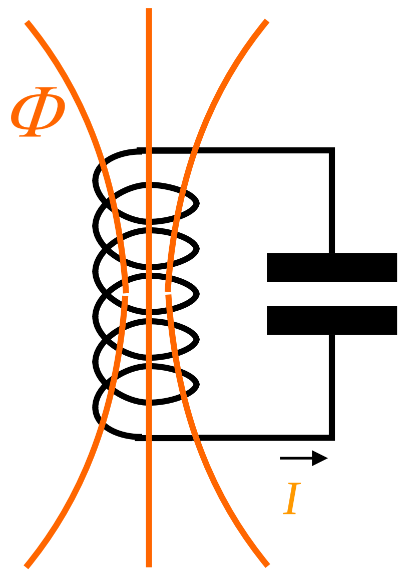


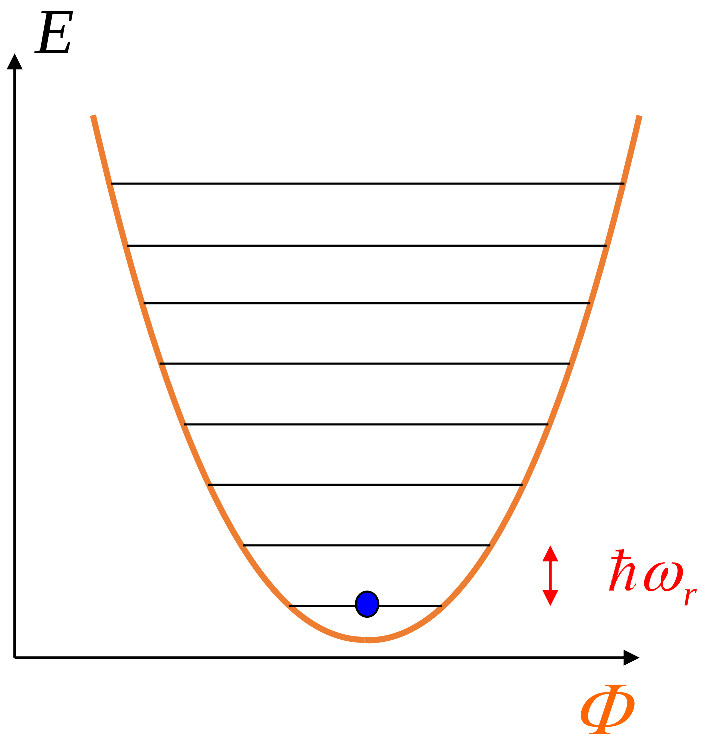
important: as little resistance as possible

dissipation broadens energy levels

$$\left.\begin{aligned} E_n &= \hbar\omega_r \left[n\left(1+\frac{i}{2\mathcal{Q}}\right) + \frac{1}{2} \right] \\ \mathcal{Q} &= RC\omega_r \end{aligned}\right\}$$

CAN PLACE CIRCUIT IN ITS GROUND STATE





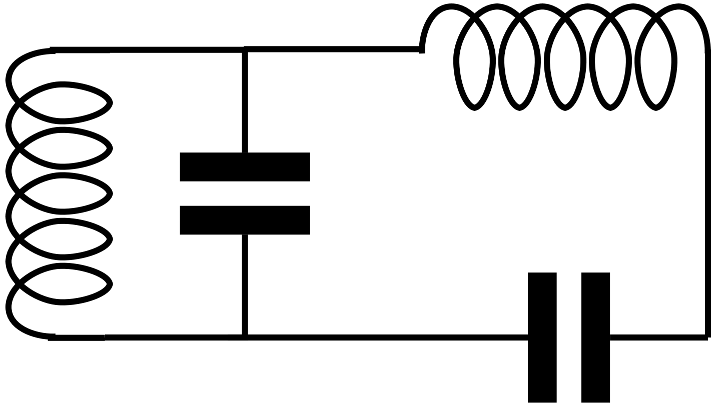
some cold dissipation is actually needed: provides reset of circuit!

$$\hbar\omega_r \gg k_B T$$

10-5 GHz

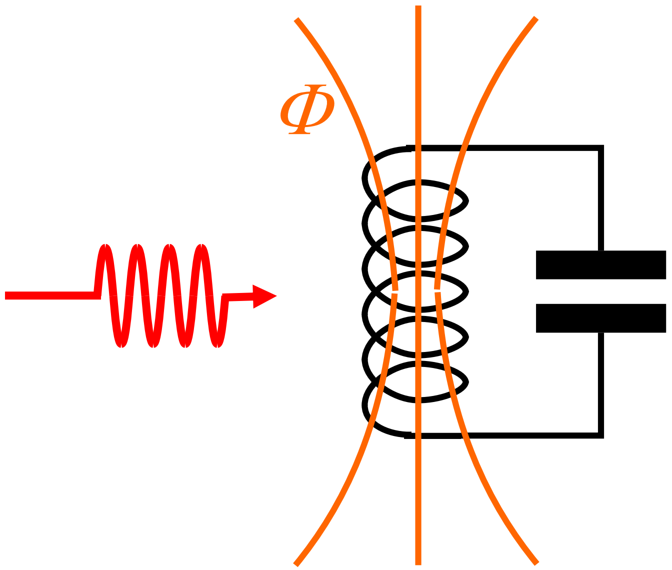
10mK

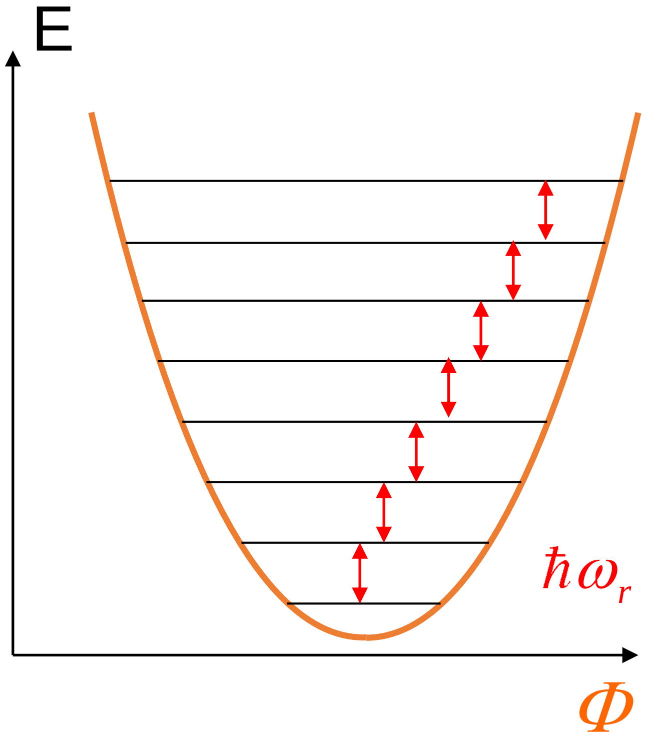
UNLIKE ATOMS IN VACUUM,
TWO CIRCUITS EASILY COUPLE
THROUGH THEIR WIRES:



COUPLING CAN BE ARBITRARILY STRONG!
HAMILTONIAN BY DESIGN!

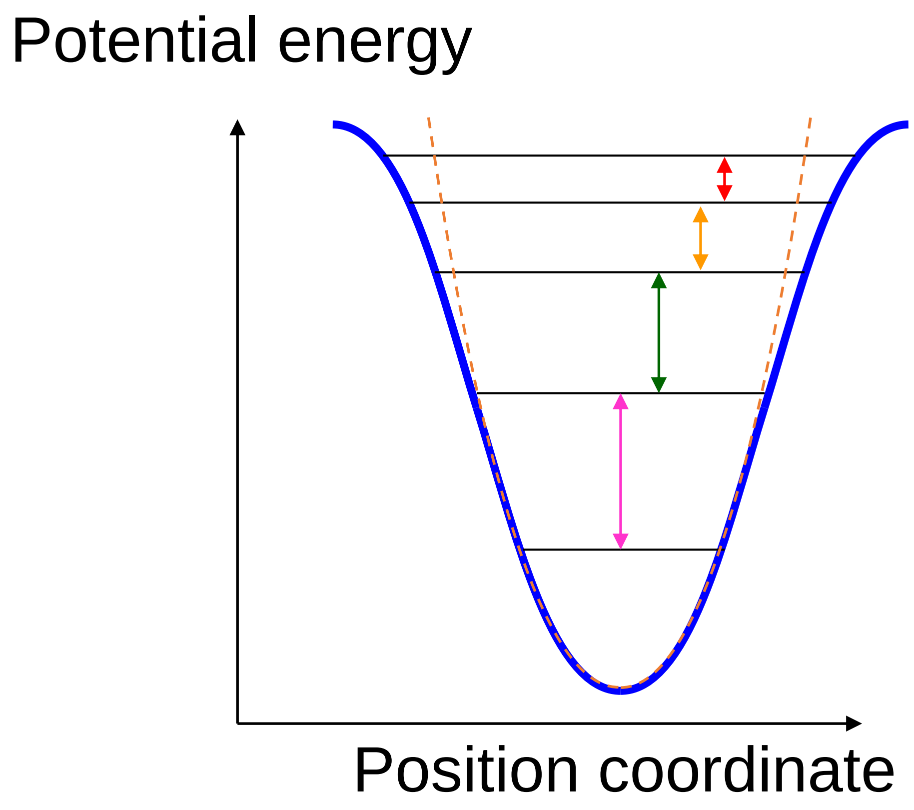
CAVEAT: THE QUANTUM STATES OF A PURELY LINEAR CIRCUIT CANNOT BE FULLY CONTROLLED!





NO STEERING TO AN ARBITRARY STATE IF SYSTEM PERFECTLY LINEAR

NEED NON-LINEARITY TO FULLY REVEAL QUANTUM MECHANICS



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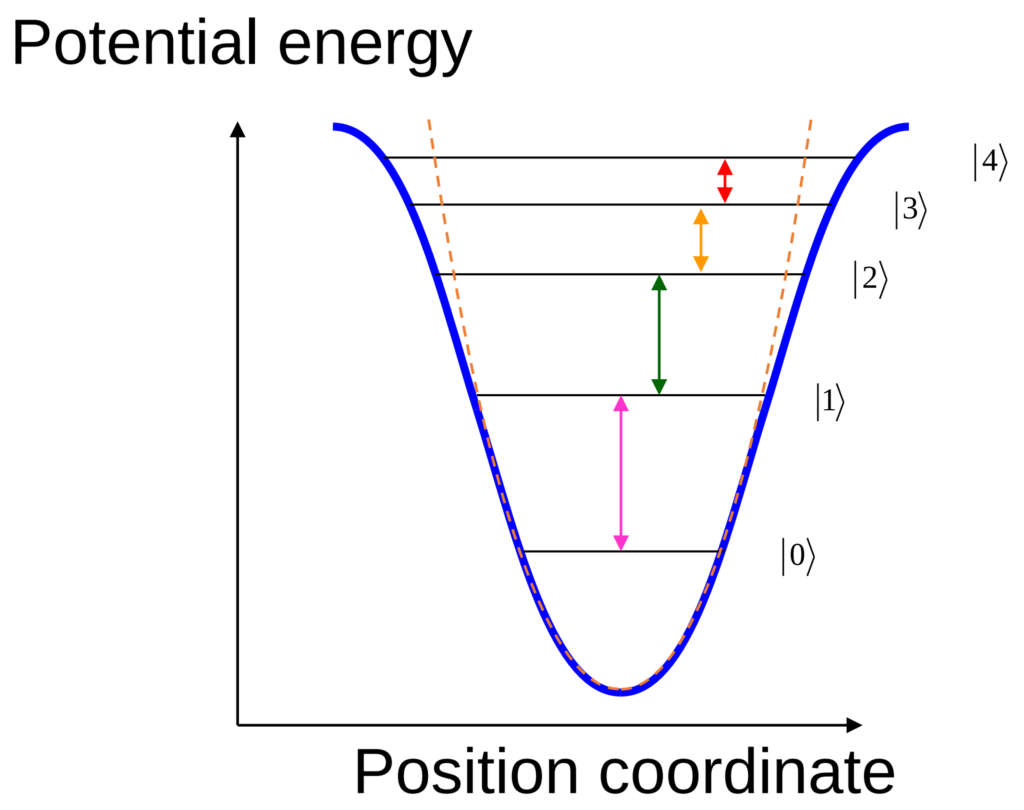

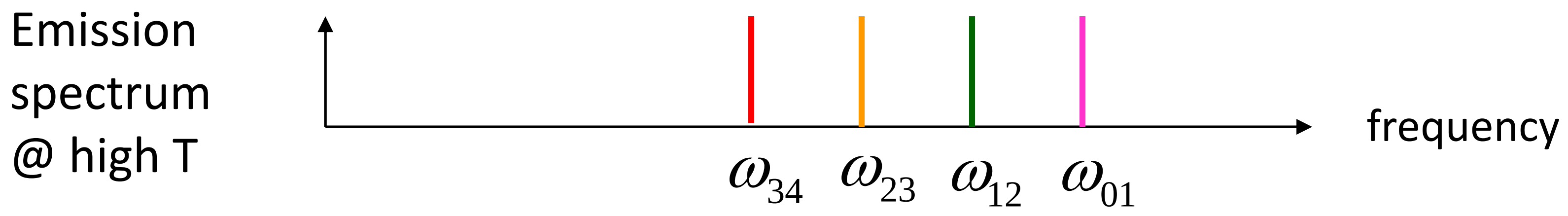

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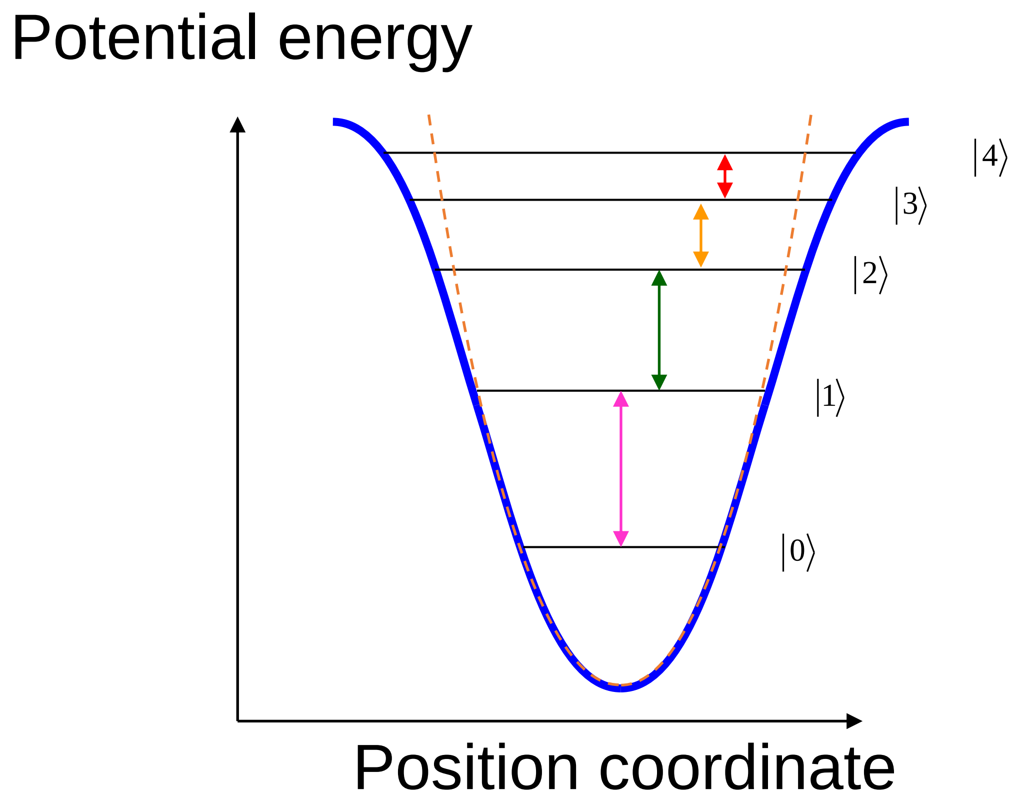
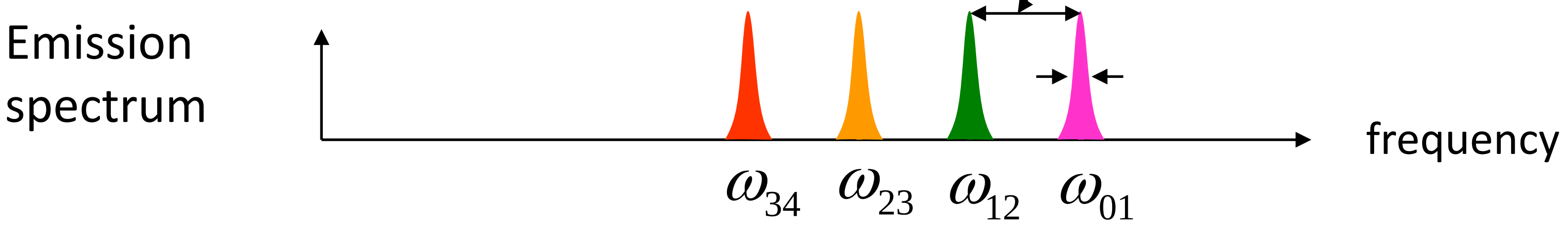
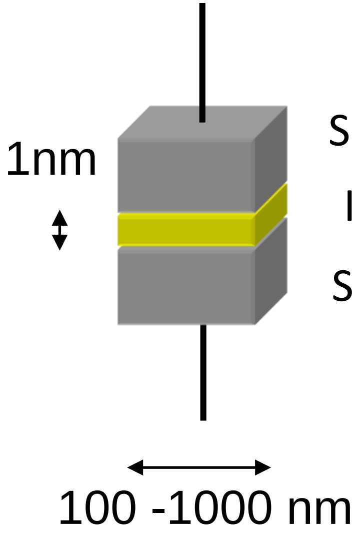


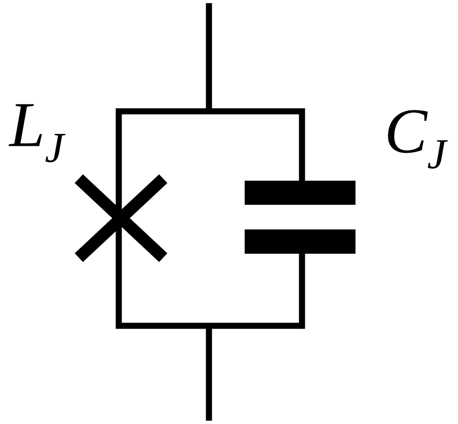
absolute non-linearity is ratio of peak distance to peak width



JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO DISSIPATION

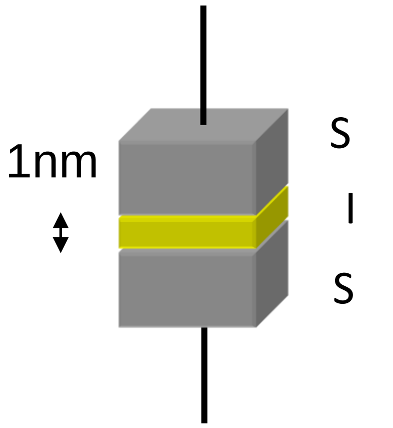


superconductor-
insulator-
superconductor
tunnel junction



MIGHT BE SUPERSEDED SOME DAY BY ANOTHER DEVICE
(BASED ON ATOMIC POINT CONTACTS, NANOWIRES, ???)

JOSEPHSON TUNNEL JUNCTION: A NON-LINEAR INDUCTOR WITH NO DISSIPATION



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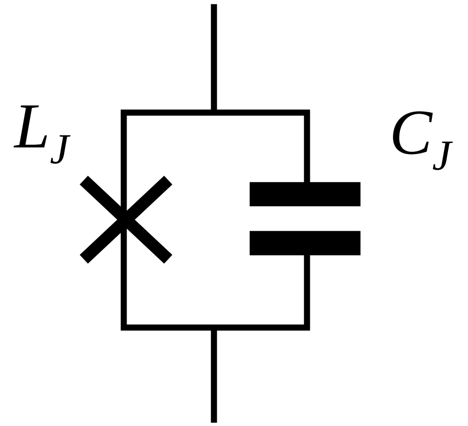
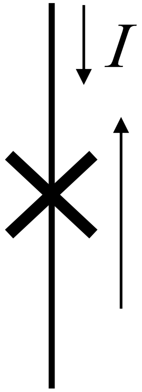
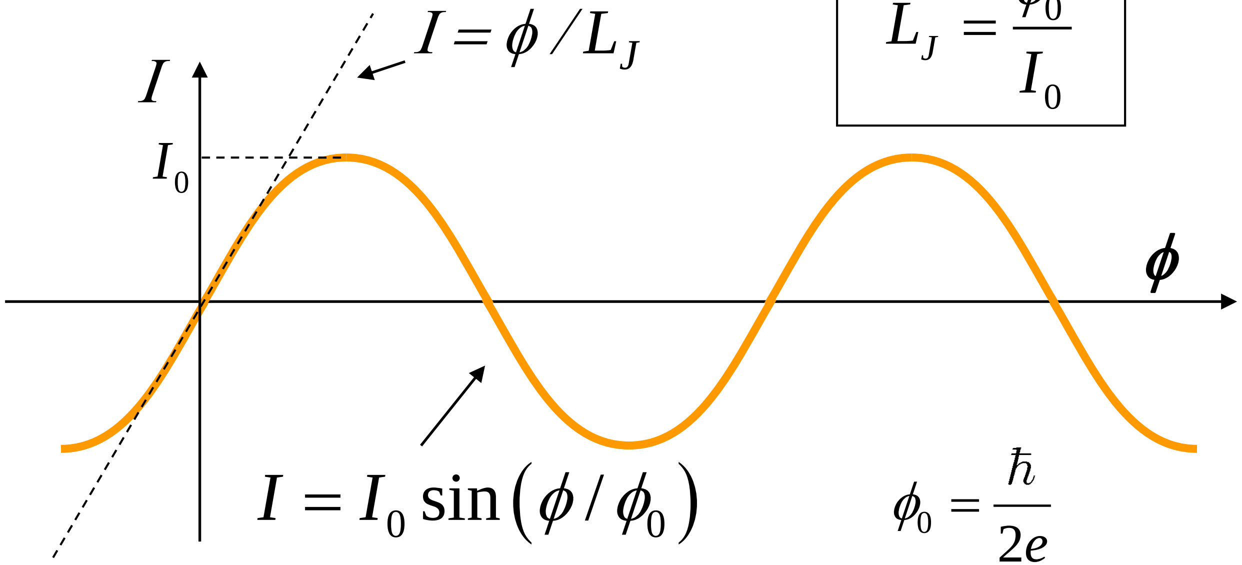


$$L_J = \frac{\phi_0}{I_0}$$



$$\phi = \int_{-\infty}^{t} V(t')\,dt'$$



$$\phi_0 = \frac{\hbar}{2e}$$

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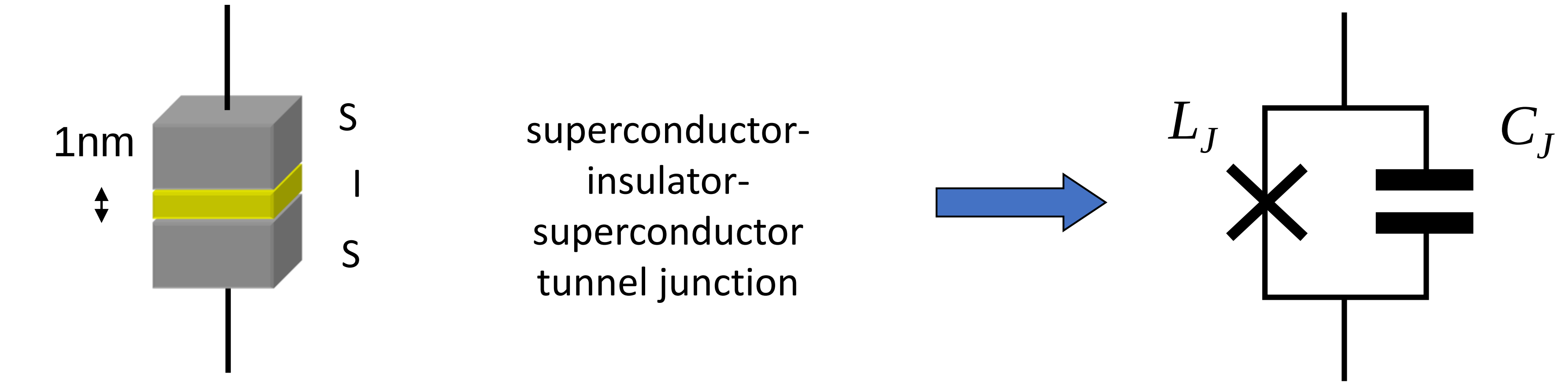
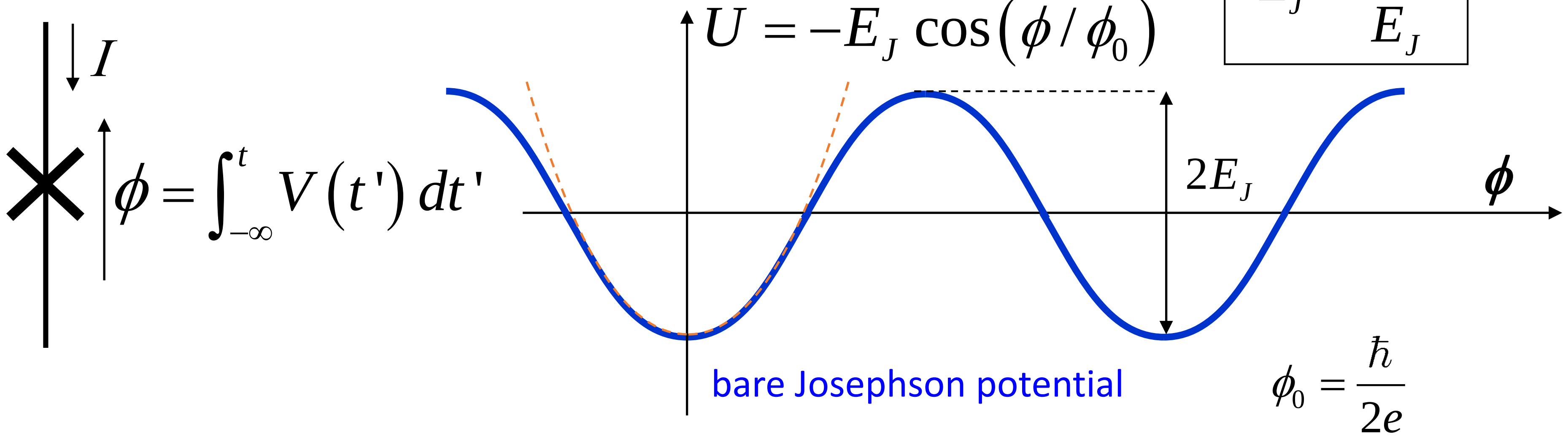
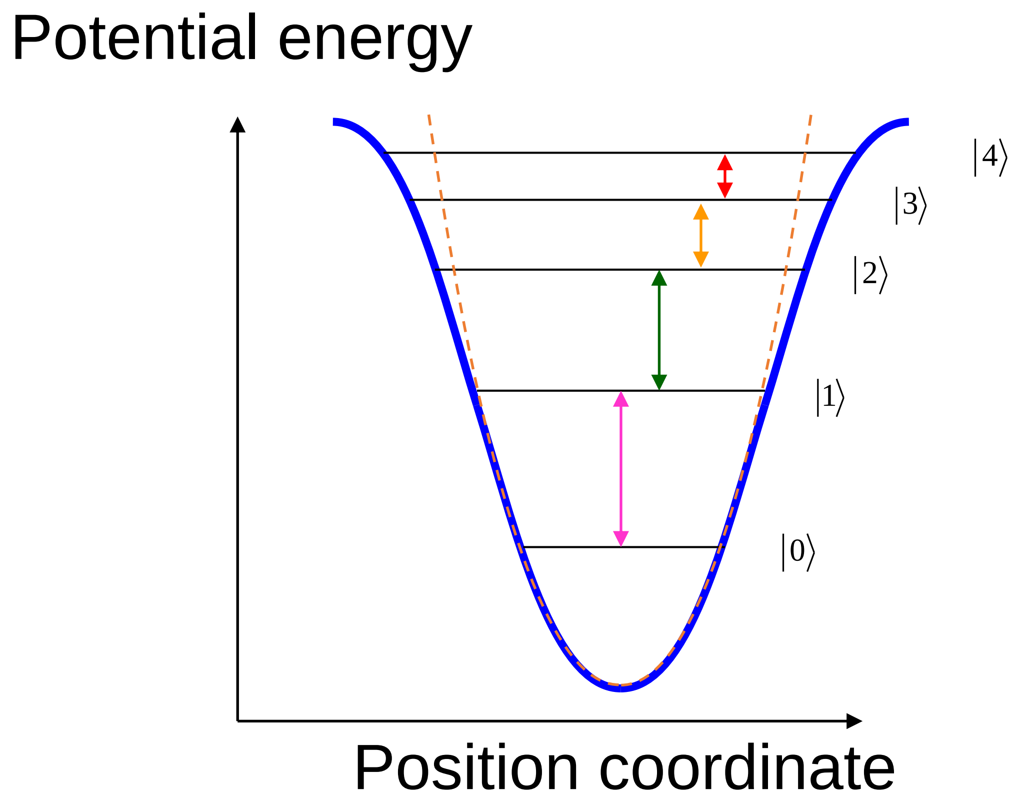
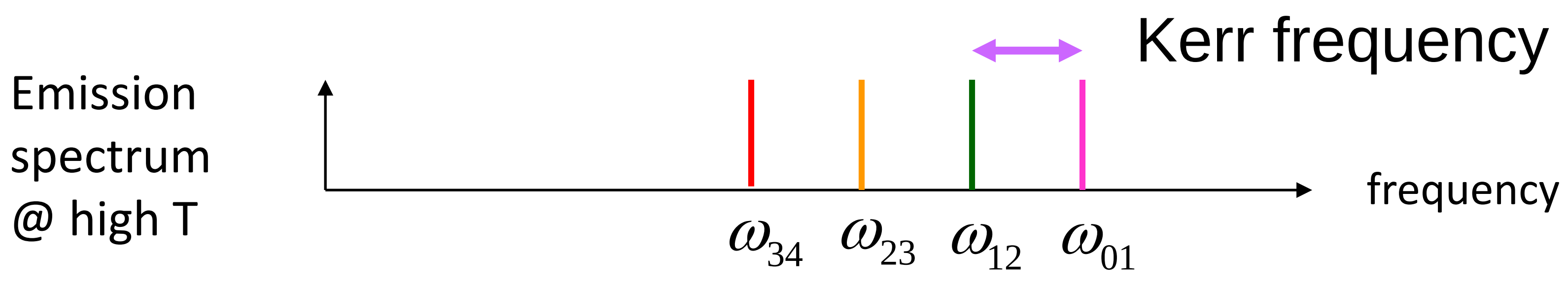


$$L_J = \frac{\phi_0^2}{E_J}$$



ELECTROMAGNETIC OSCILLATOR ENDOWED WITH JOSEPHSON NON-LINEARITY

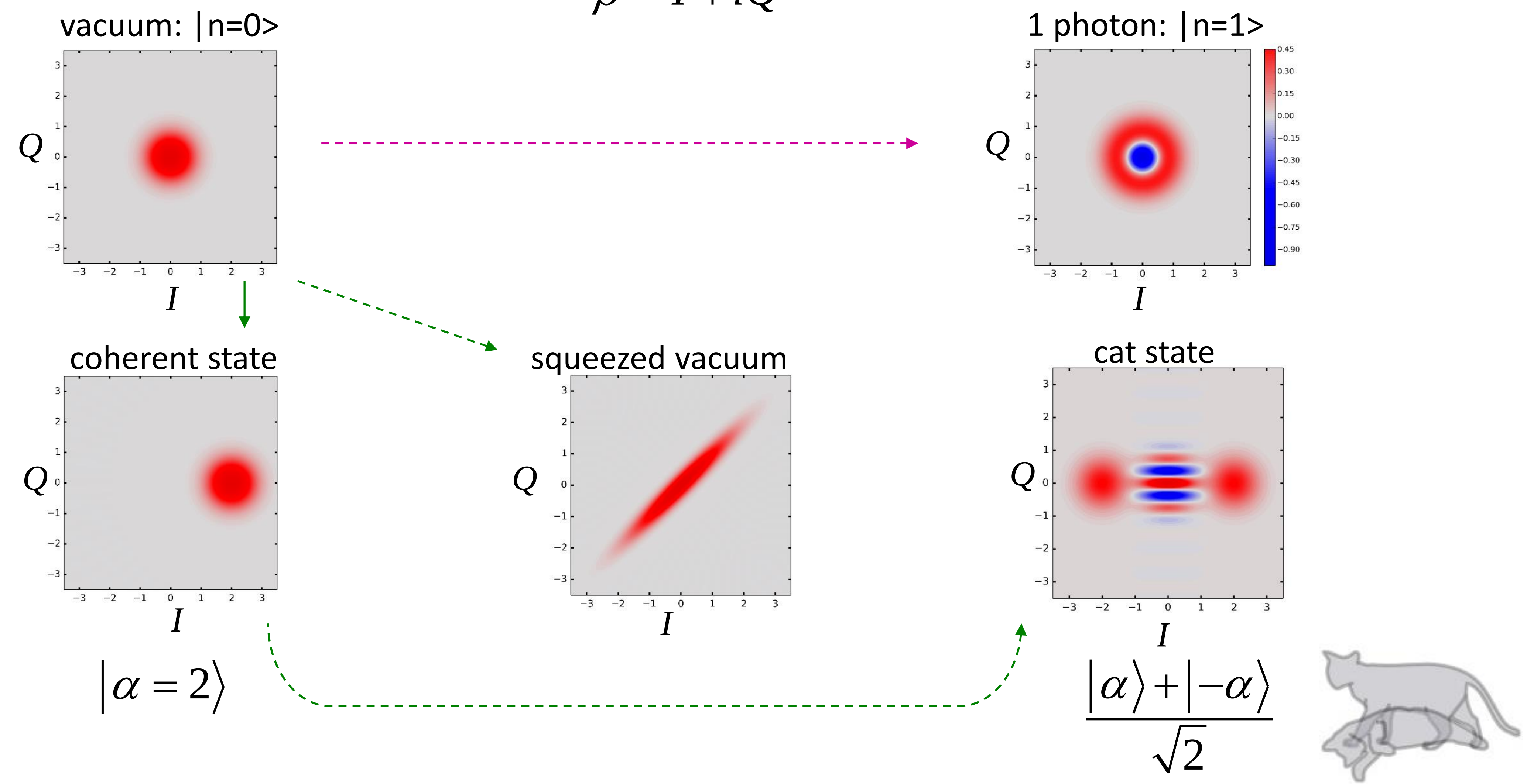




QUANTUM STATES OF A HARMONIC OSCILLATOR

REPRESENTED BY THEIR QUASI-PROBABILITY WIGNER FUNCTION IN PHASE SPACE $W(\beta) = \langle D_{-\beta} P D_{\beta} \rangle ; P = (-1)^{a^\dagger a}$

$$\beta = I + iQ$$



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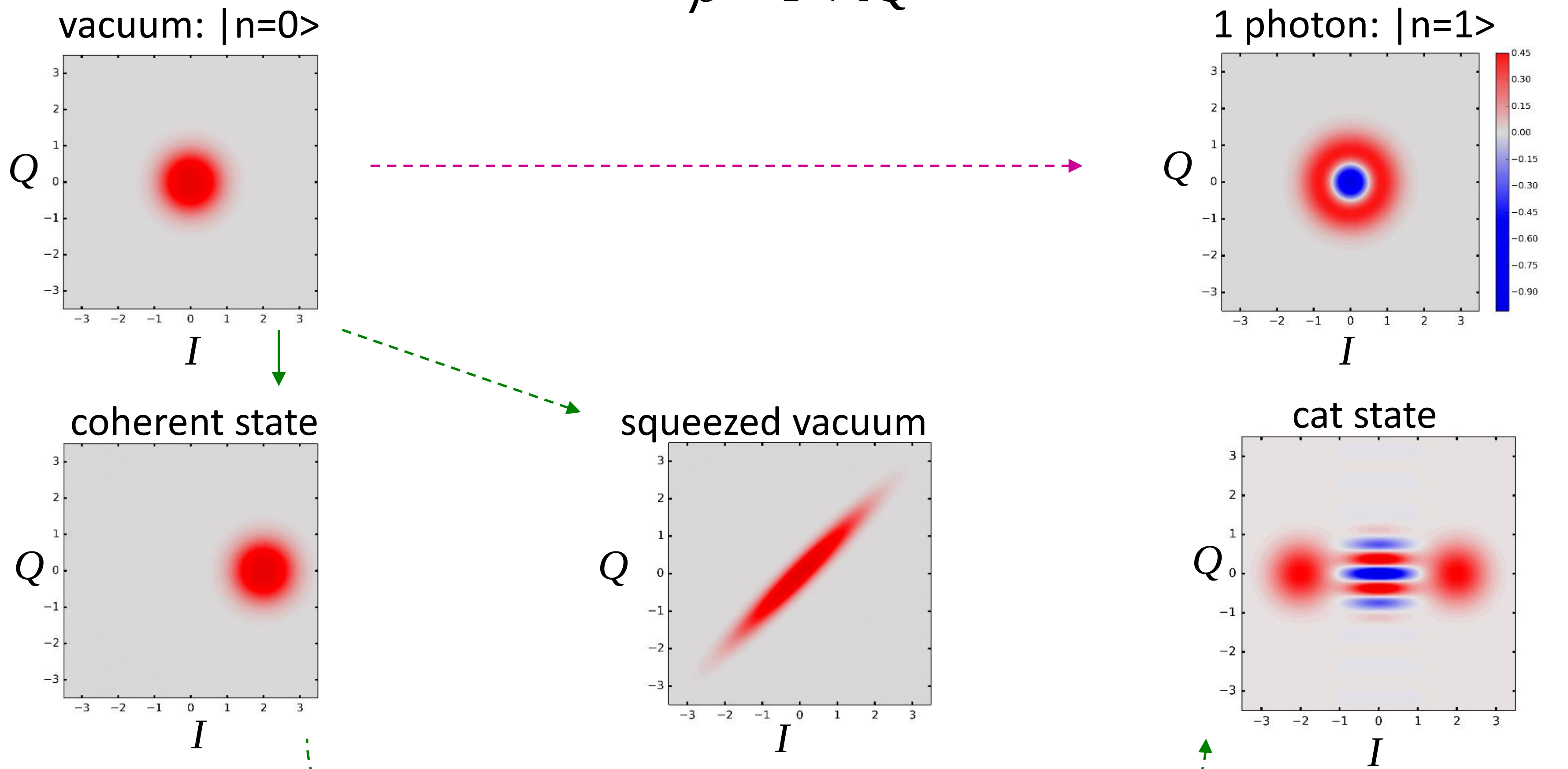
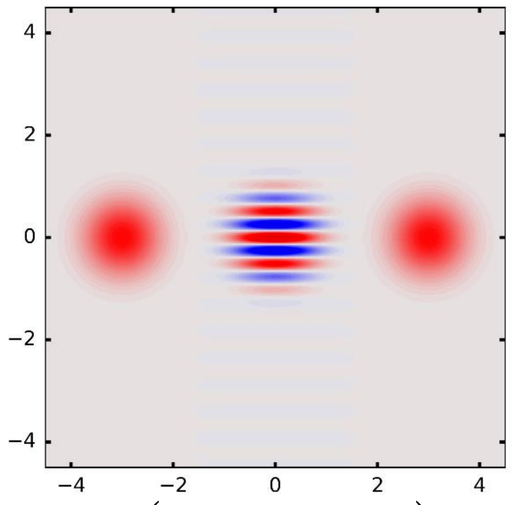


$$|\alpha = 2\rangle$$

$$\frac{|\alpha\rangle - |-\alpha\rangle}{\sqrt{2}}$$

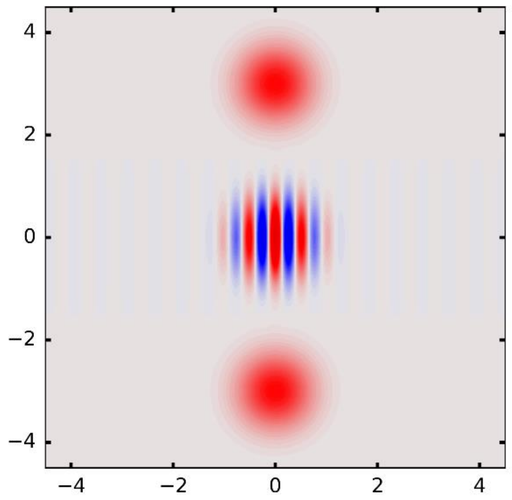
CAT ENCODING, AND INFORMATION DECAY

even



$$|0\rangle_L = \mathcal{N}\left(|\alpha\rangle + |-\alpha\rangle\right)$$

even



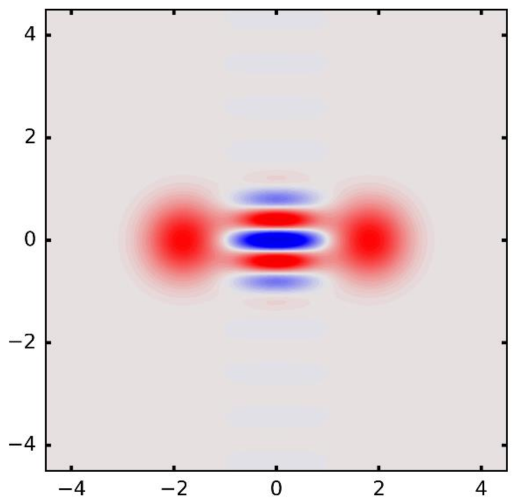
$$|1\rangle_L = \mathcal{N}\left(|i\alpha\rangle + |-i\alpha\rangle\right)$$

$$|\alpha = 3\rangle$$

typical time evolution

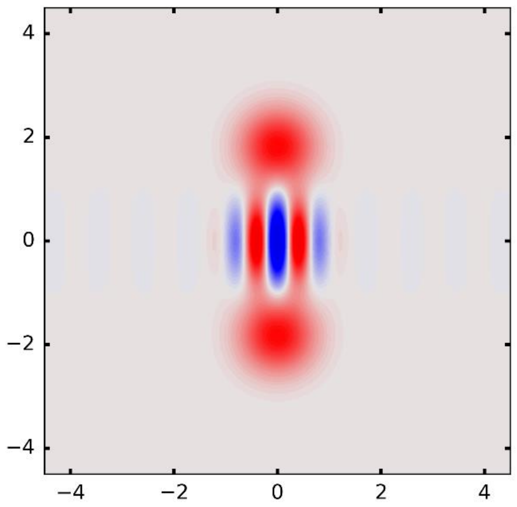
$$\Delta t = \kappa^{-1}$$

$$\hat{a}|\alpha\rangle = \alpha|\alpha\rangle$$



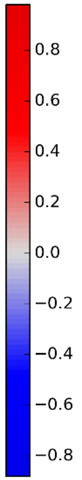
odd

$$\mathcal{N}\left(|\alpha'\rangle - |-\alpha'\rangle\right)$$

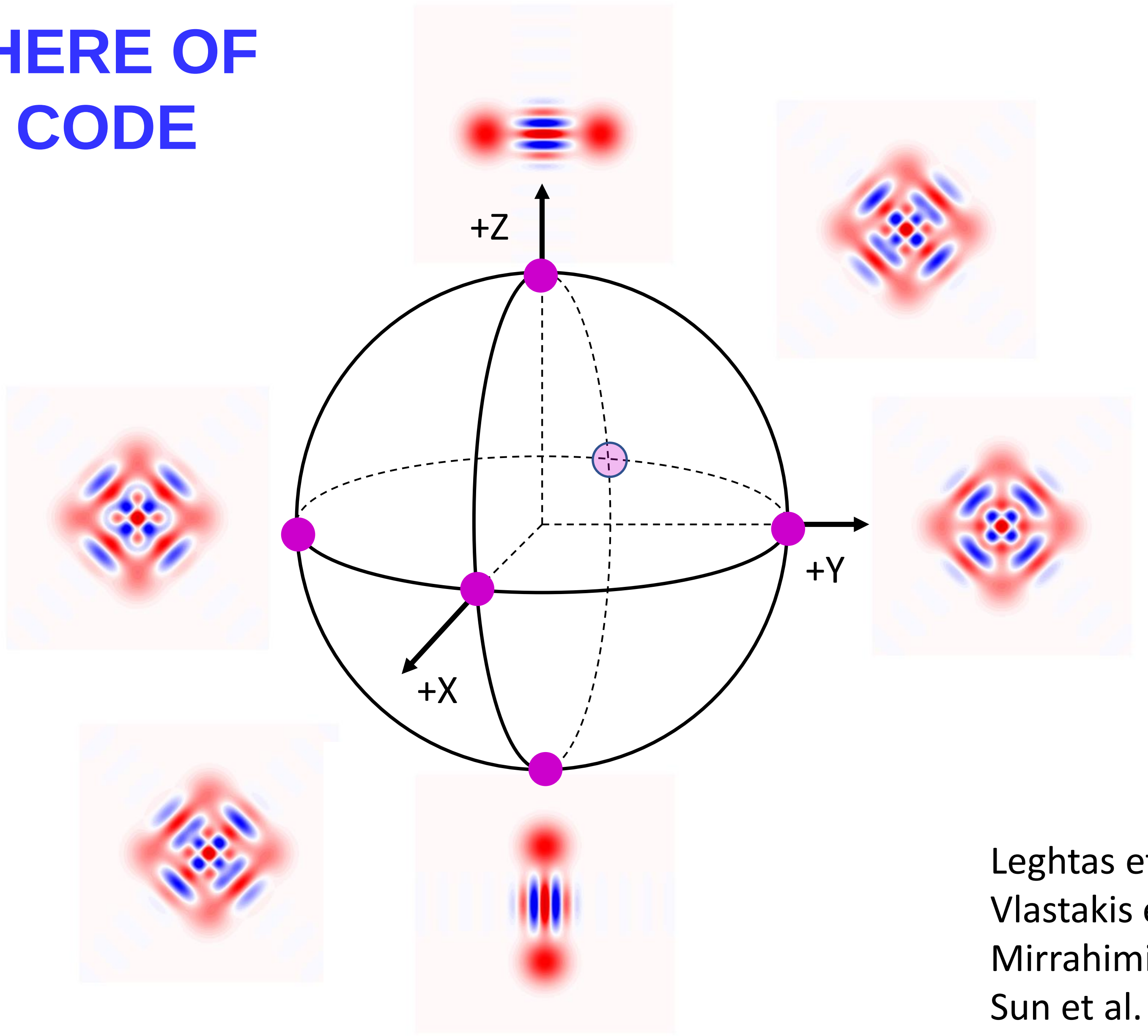


odd

$$i\mathcal{N}\left(|i\alpha'\rangle - |-i\alpha'\rangle\right)$$



BLOCH SPHERE OF 4-LEG CAT CODE



Leghtas et al. PRL (2013)
Vlastakis et al. Science (2013)
Mirrahimi et al. NJP (2014)
Sun et al. Nature (2014)

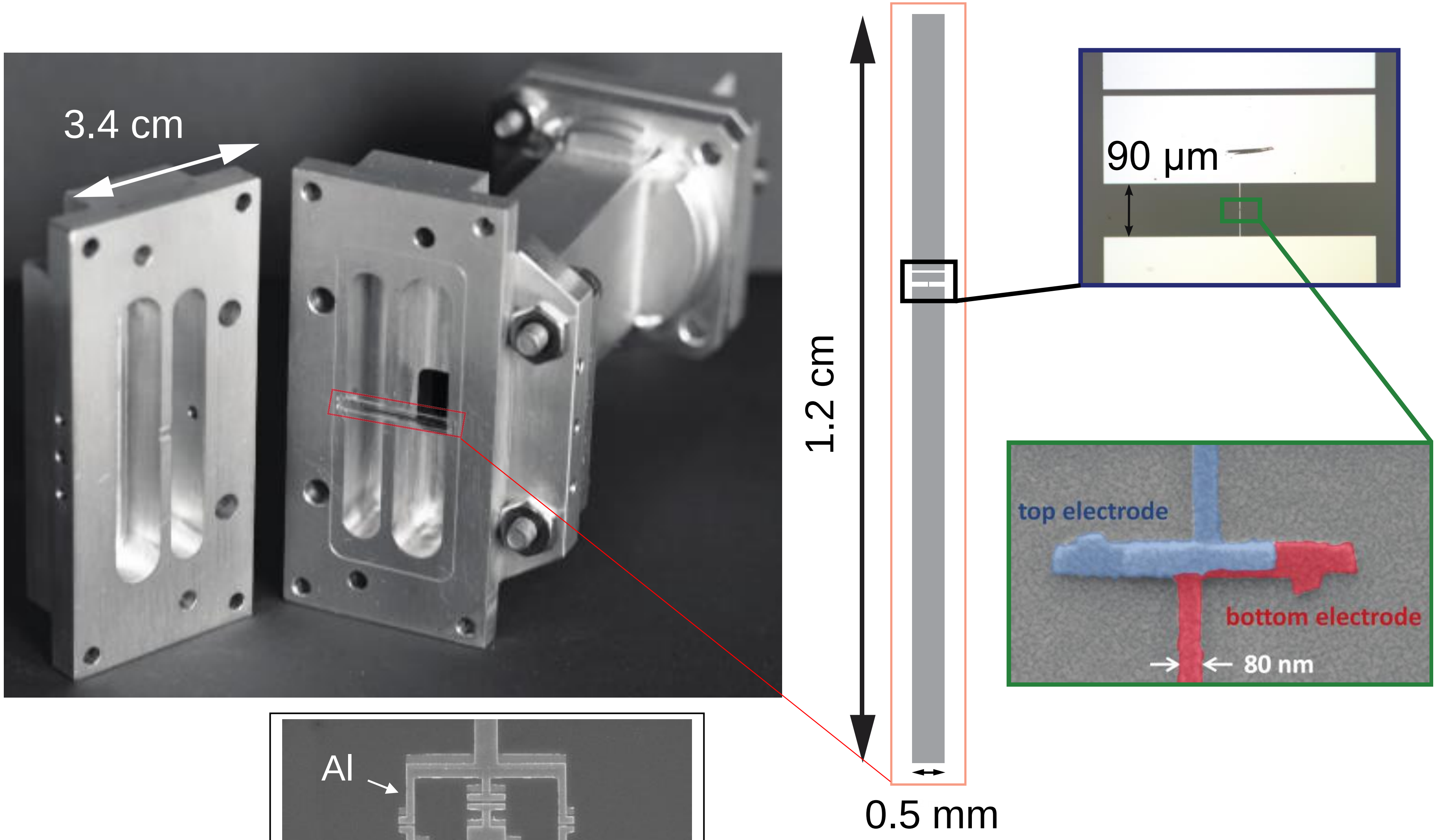
TWO TYPES OF CAT ERROR MUST BE ADDRESSED:

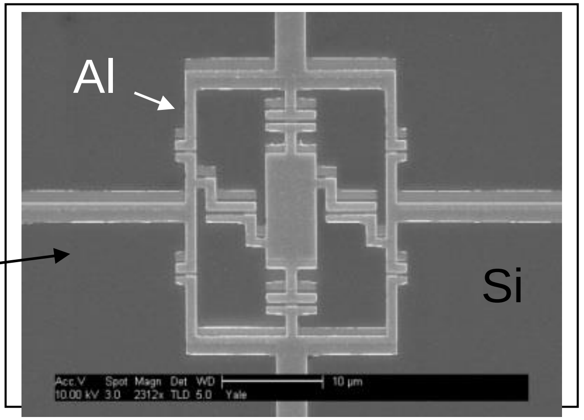
- COHERENT STATE SHRINKING, DEPHASING & DEFORMING

- PHOTON NUMBER PARITY JUMPING

HOW DO WE FULLY CONTROL THE RESONATOR?

DEVICES

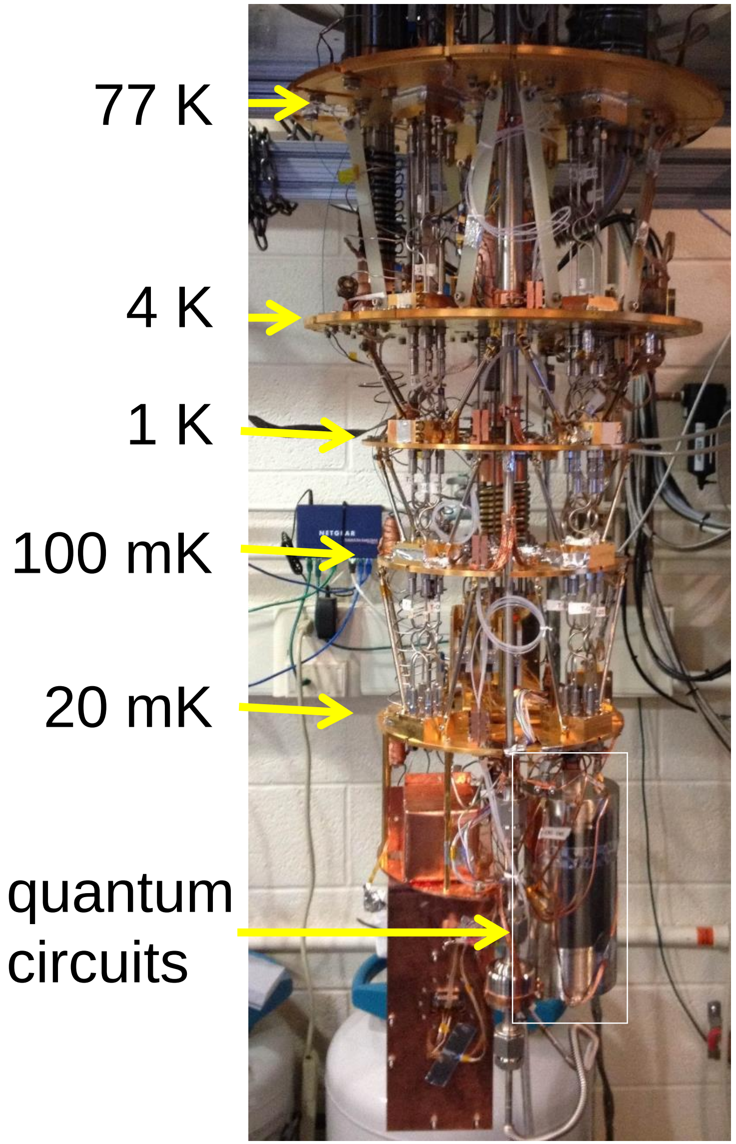




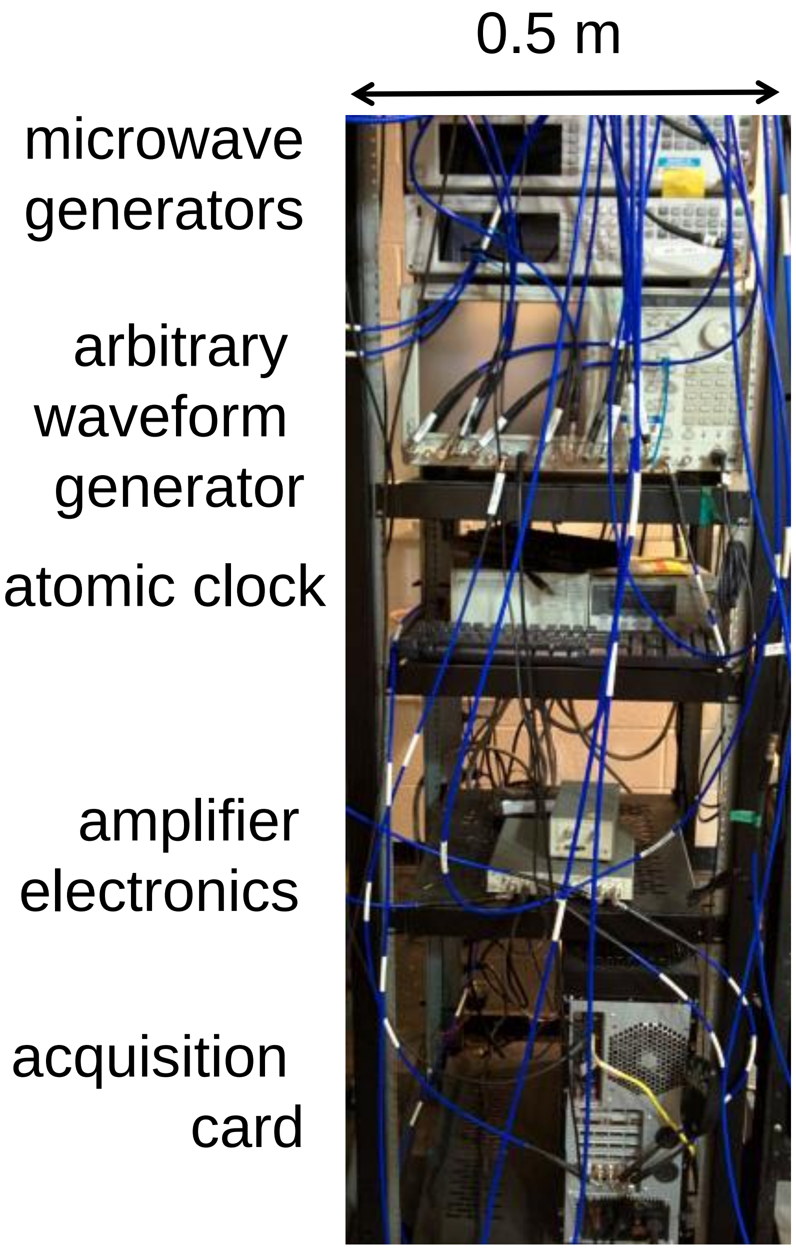
Josephson Ring Modulator

N. Bergeal *et al.* Nature (2008)
H. Paik *et. al.* PRL (2011)
G. Kirchmair *et. al.* Nature (2013)

EXPERIMENTAL SETUP

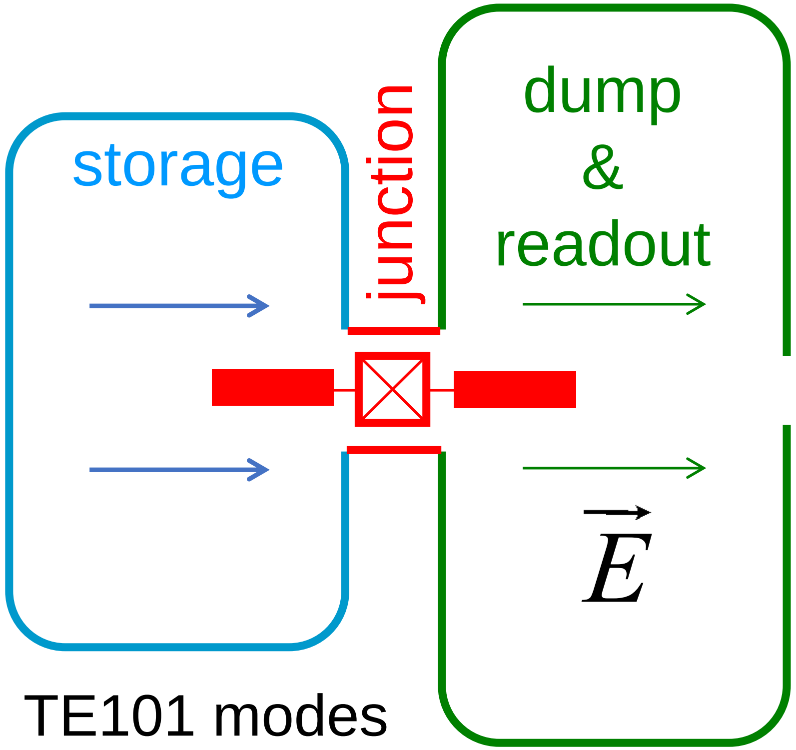


dilution refrigerator



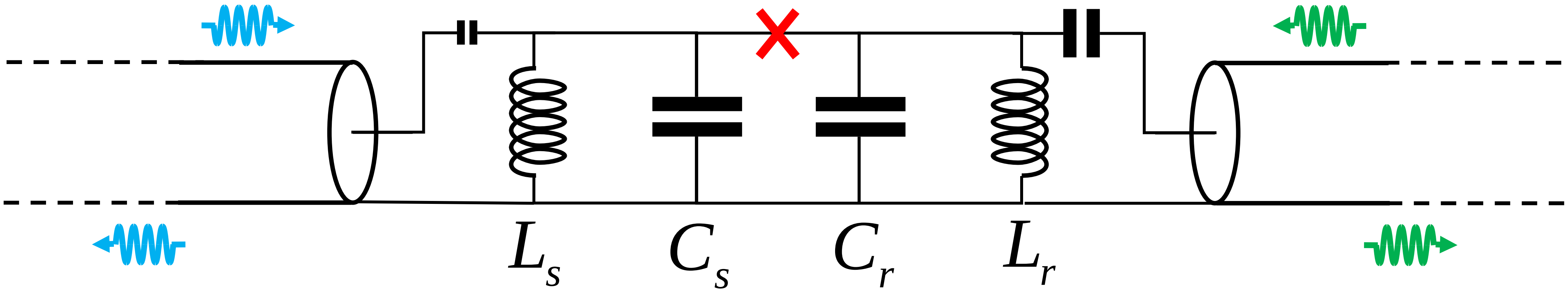
instrument rack

2 OSCILLATORS COUPLED THROUGH A TUNNEL JOSEPHSON JUNCTION



SIMPLIFIED MODEL

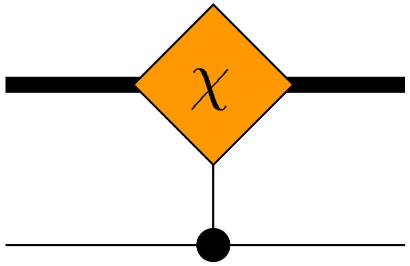
$$H = \frac{Q_s^2}{2C_s} + \frac{\Phi_s^2}{2L_s} + \frac{Q_r^2}{2C_r} + \frac{\Phi_r^2}{2L_s} - E_J \cos\left[\left(\Phi_r - \Phi_s\right)/\phi_0\right] \qquad \omega^0_{r,s} = \sqrt{L_{r,s} C_{r,s}}$$



A POWERFUL DETERMINISTIC GATE COMBINING MICROWAVE LIGHT AND A QUBIT

cavity oscillator

superconducting qubit



$$H = \chi a^{\dagger} a \, \sigma_z$$

$$\omega_c - \omega_q \gg \chi \gg \kappa \gg T_2^{-1}$$

strong dispersive regime: Stark shift per photon > 1000 linewidths

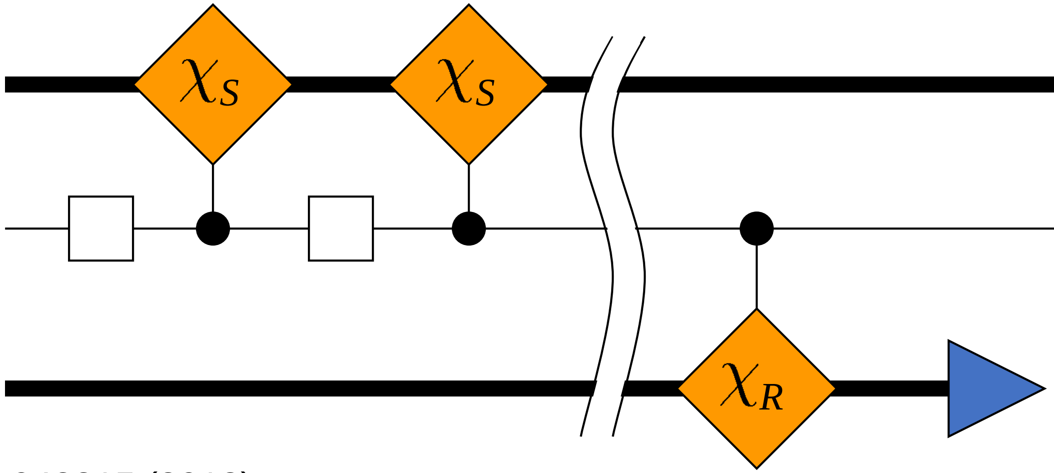
---

Can combine two cavities, a qubit and a quantum limited Josephson amplifier:

storage cavity

superconducting qubit

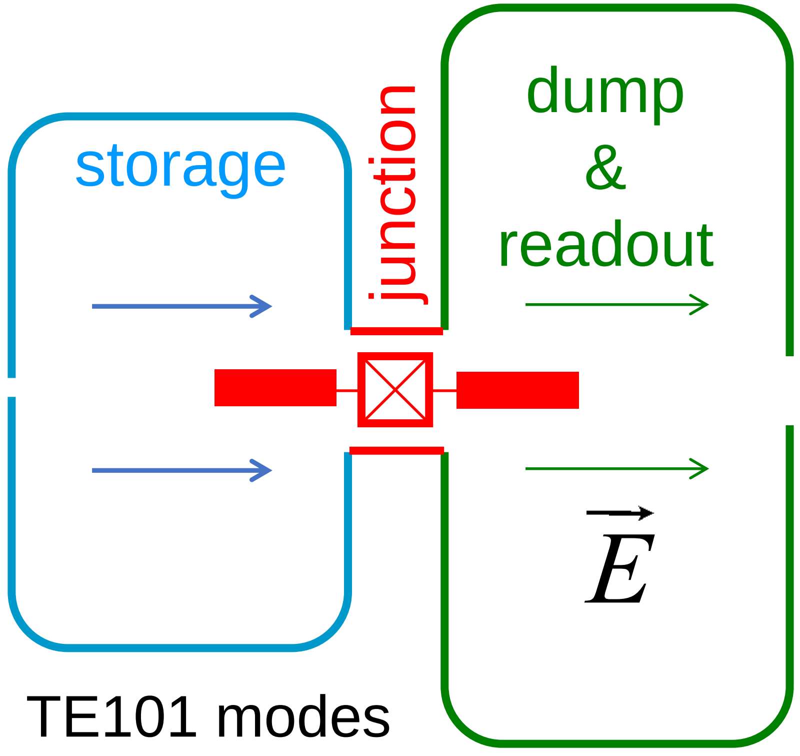
readout cavity

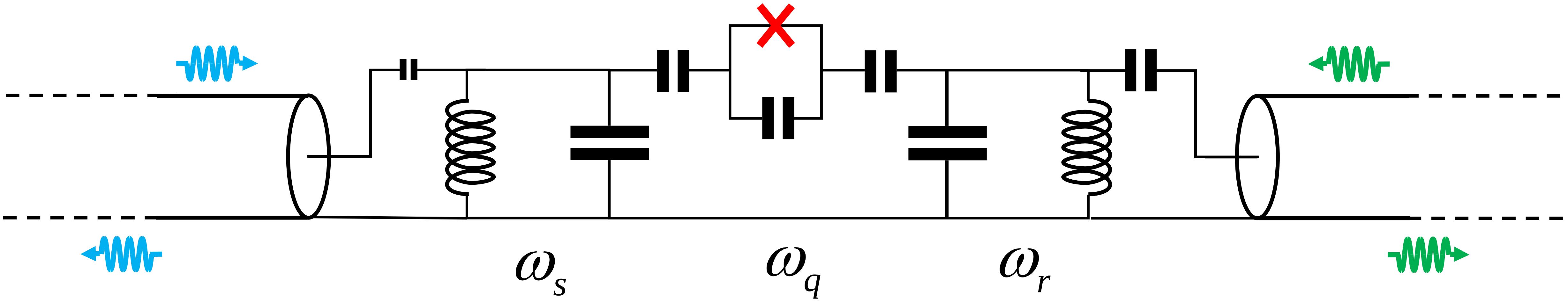


amplification chain

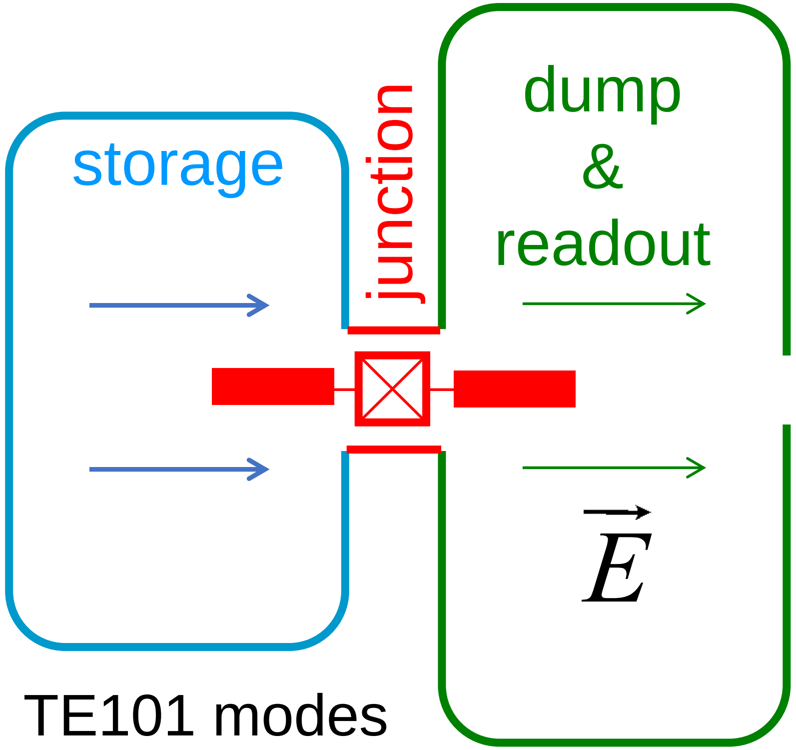
Leghtas et al., Phys. Rev. A87, 042315 (2013)

2 OSCILLATORS COUPLED THROUGH A TUNNEL JOSEPHSON JUNCTION





2 OSCILLATORS COUPLED THROUGH A TUNNEL JOSEPHSON JUNCTION



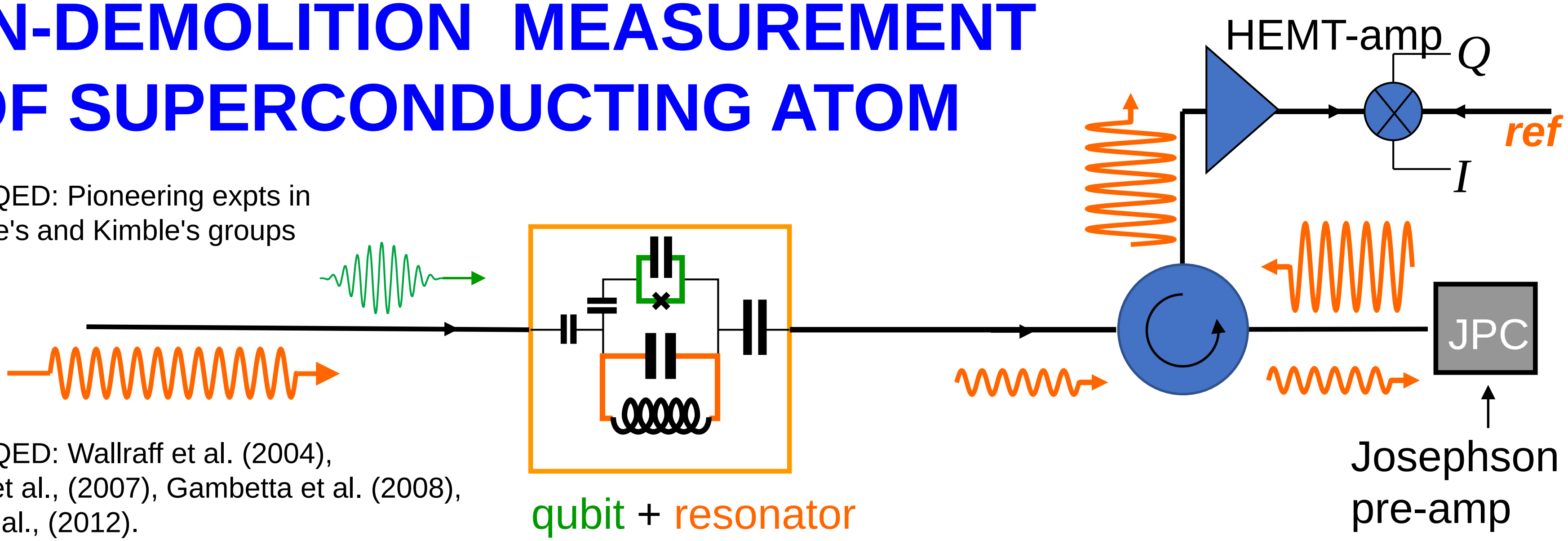
$$H/\hbar = \omega_s a_s^\dagger a_s + \omega_r a_r^\dagger a_r + \omega_q a_q^\dagger a_q - \frac{c_{qq}}{2}\left(a_q^\dagger\right)^2\left(a_q\right)^2 - c_{qs} a_q^\dagger a_q a_s^\dagger a_s - c_{qr} a_q^\dagger a_q a_r^\dagger a_r + \ldots$$

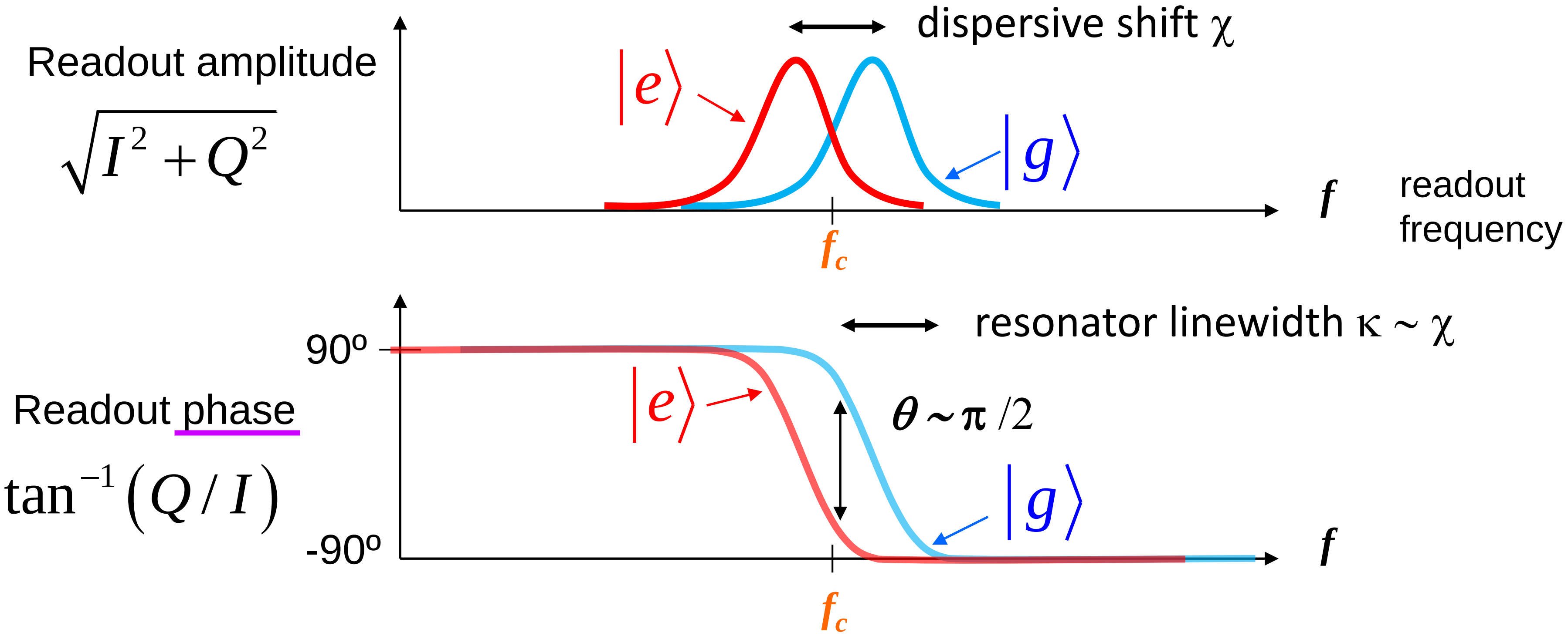
$$- \frac{c_{rs}}{4}\left(a_s\right)^2\left(a_r^\dagger\right)^2 + \text{h.c.} + \ldots$$

NON-DEMOLITION MEASUREMENT OF SUPERCONDUCTING ATOM

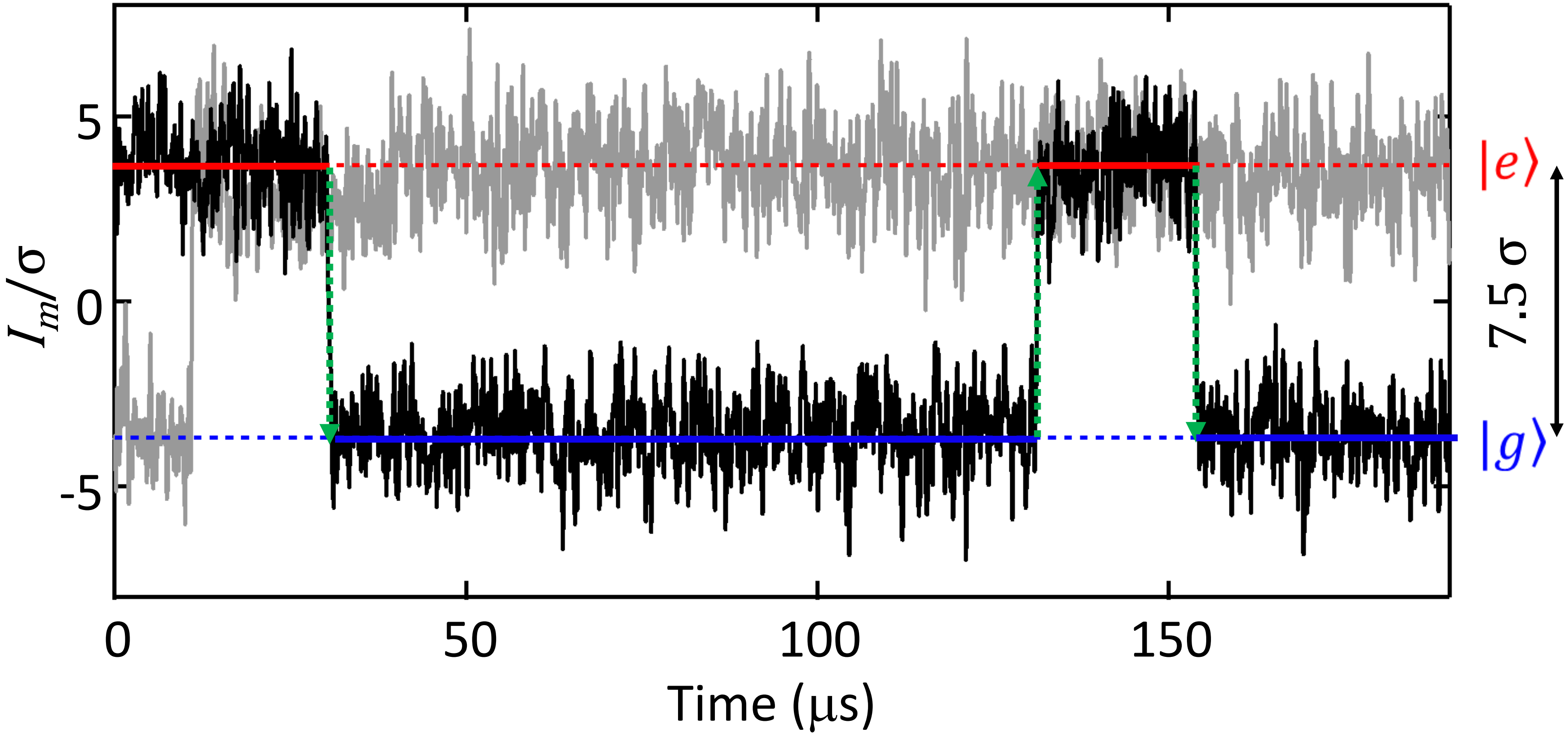
Cavity QED: Pioneering expts in
Haroche's and Kimble's groups

Circuit QED: Wallraff et al. (2004),
Houck et al., (2007), Gambetta et al. (2008),
Vijay et al., (2012).





QUANTUM JUMPS OF QUBIT STATE



~ 90% of fluctuations of signal at 300K are quantum noise!

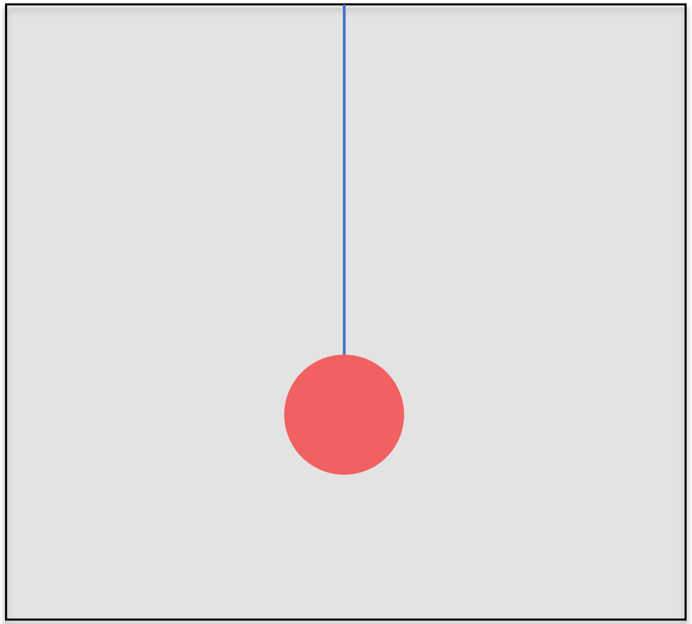
~2000 bits per qubit lifetime

TWO TYPES OF CAT ERRORS MUST BE ADDRESSED:

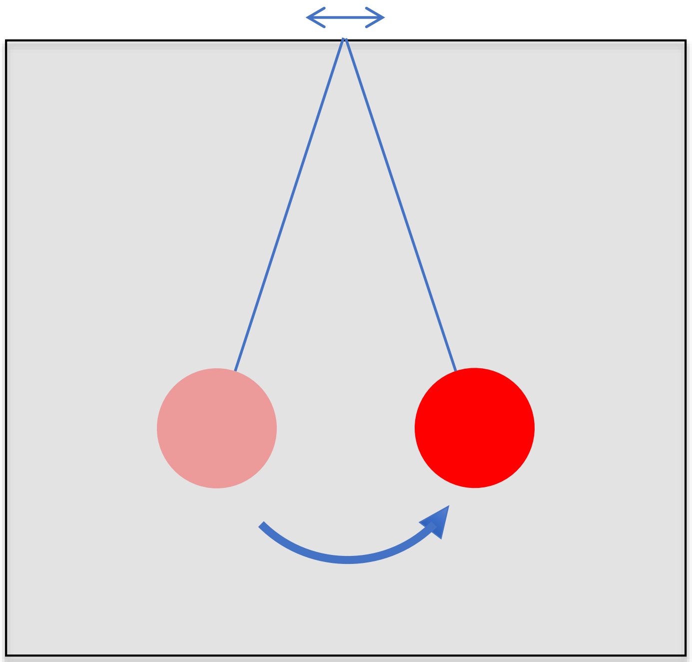
- COHERENT STATE SHRINKING, DEPHASING & DEFORMING

- PHOTON NUMBER PARITY JUMPING

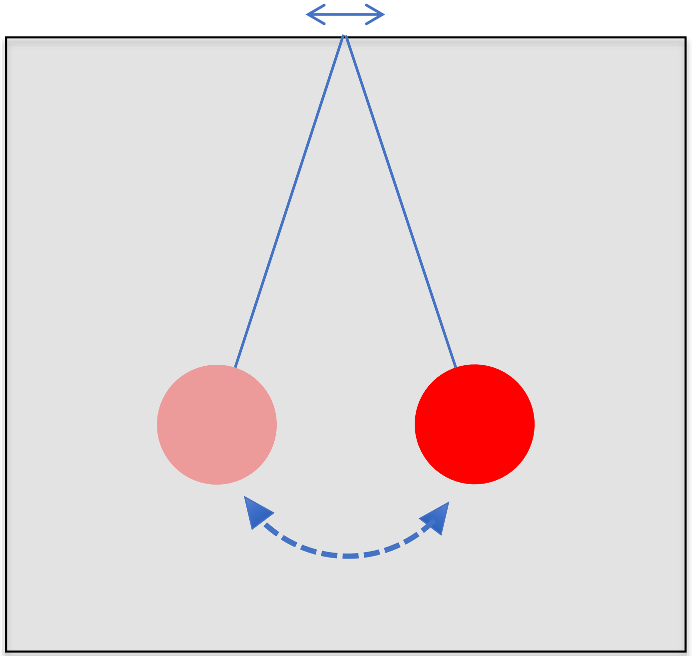
REVIEW THE USUAL DRIVEN-DAMPED HARMONIC OSCILLATOR

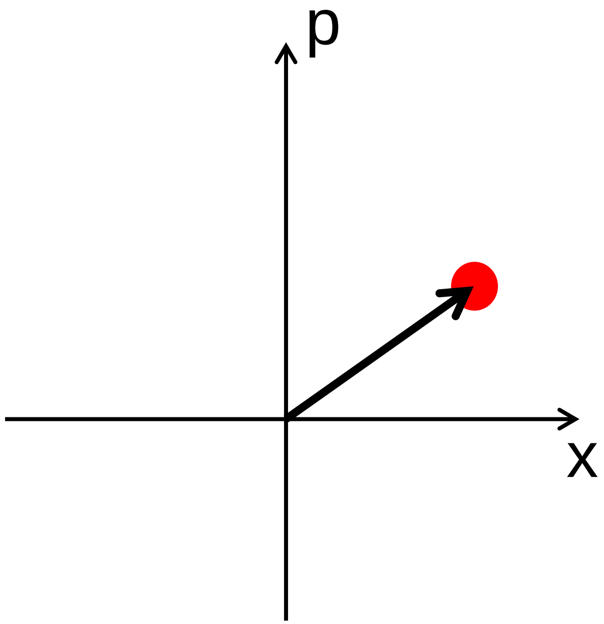


REVIEW THE USUAL DRIVEN-DAMPED HARMONIC OSCILLATOR

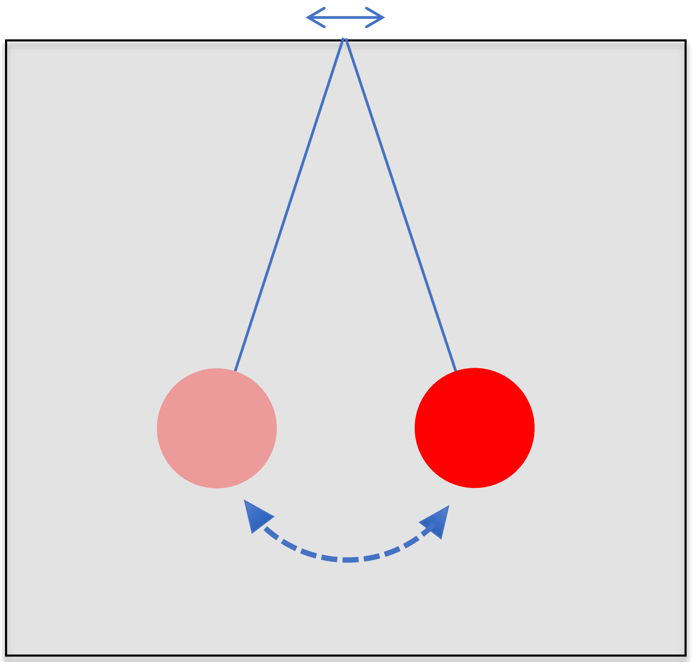


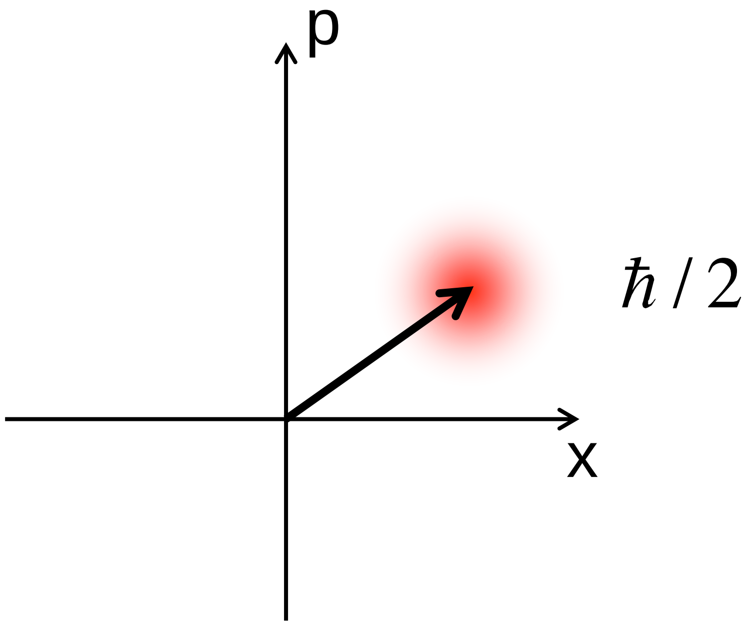
REVIEW THE USUAL DRIVEN-DAMPED HARMONIC OSCILLATOR



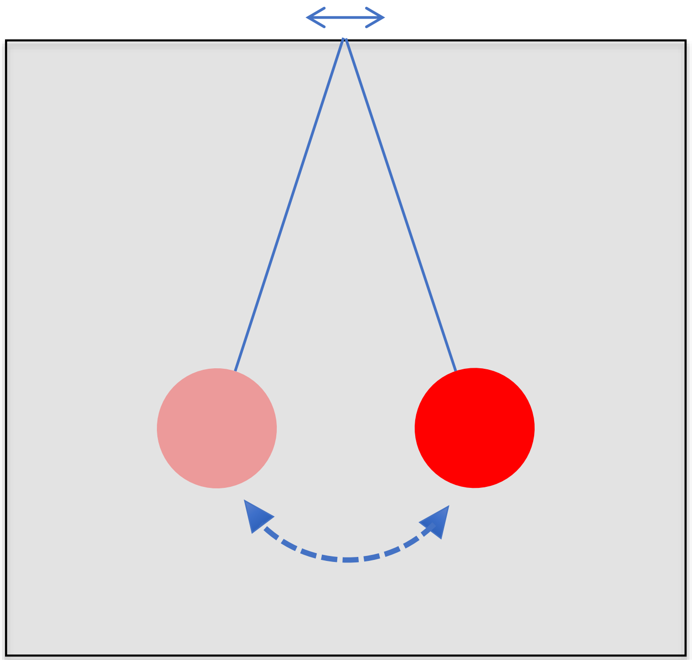


REVIEW THE USUAL DRIVEN-DAMPED HARMONIC OSCILLATOR

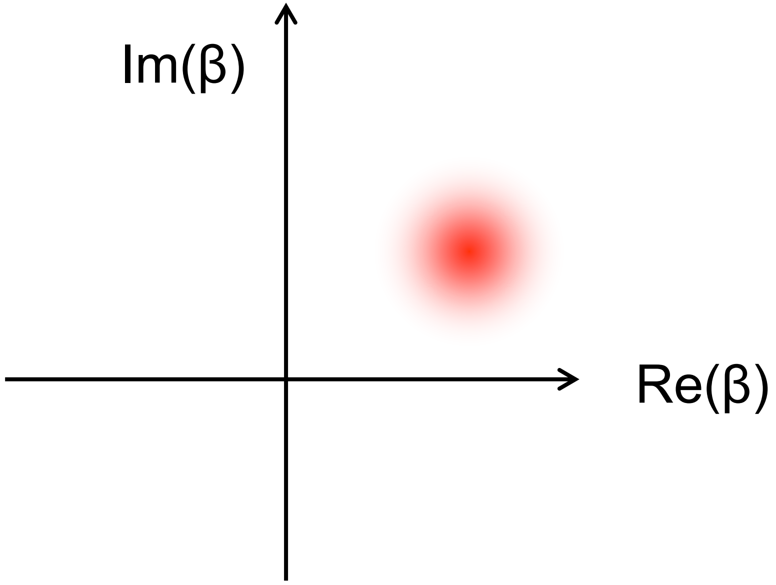




REVIEW THE USUAL DRIVEN-DAMPED HARMONIC OSCILLATOR



Wigner function W(β)



Hamiltonian : $H = \epsilon_1^* a + \epsilon_1 a^\dagger$

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

$\alpha = -2i\epsilon_1 / \kappa_1$

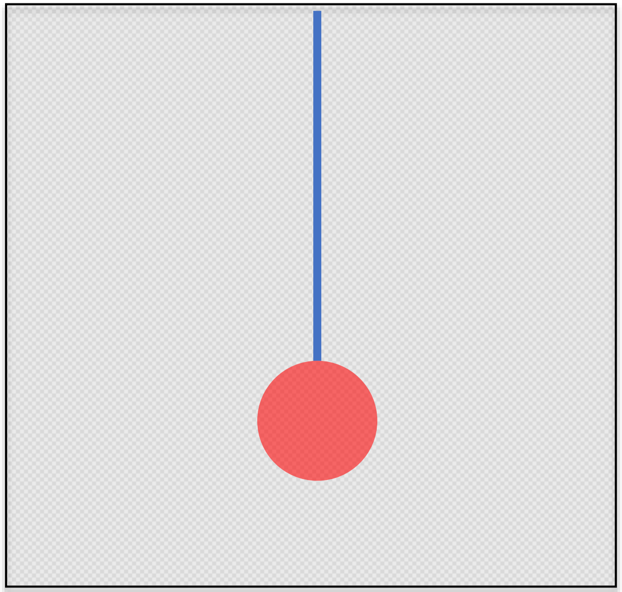
AVERAGE EVOLUTION OF DENSITY MATRIX FOR AN OPEN SYSTEM

$$\frac{d}{dt}\rho = -i\left[H,\rho\right] + \mathcal{D}\left[c\right]\rho$$

$$\mathcal{D}\left[c\right]\rho = c\rho c^{\dagger} - \frac{1}{2}\left(c^{\dagger}c\rho + \rho c^{\dagger}c\right)$$

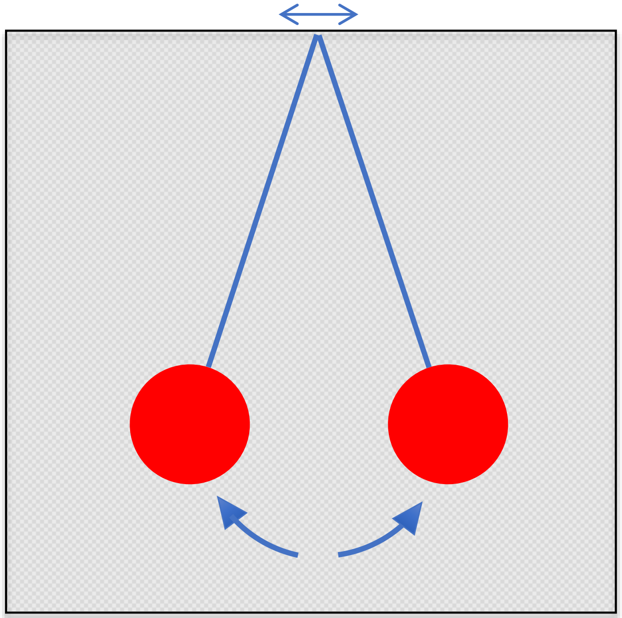
loss operator

A SPECIAL DRIVEN-DAMPED OSCILLATOR



A SPECIAL DRIVEN-DAMPED OSCILLATOR

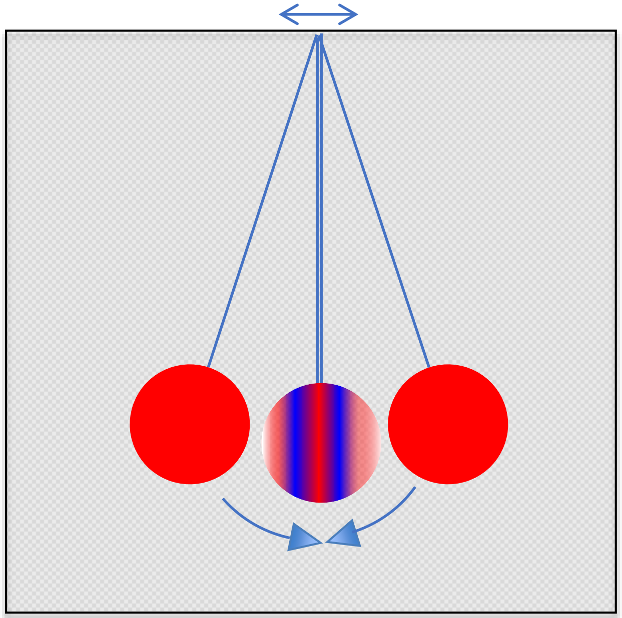
Force ~ X^2



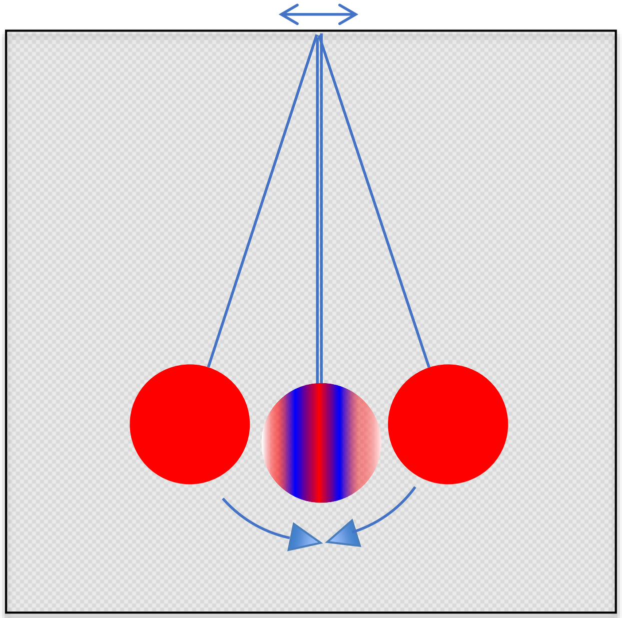
A SPECIAL DRIVEN-DAMPED OSCILLATOR

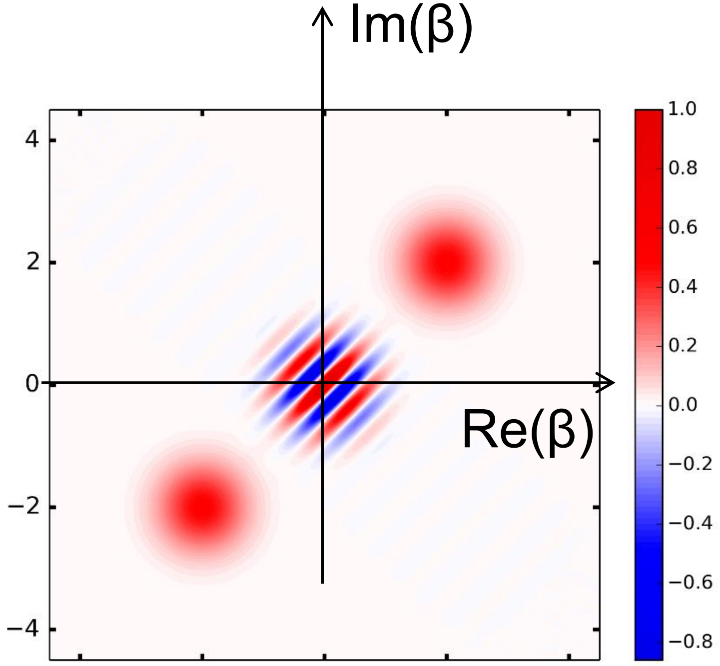
Force ~ X^2

Damping ~ V^2



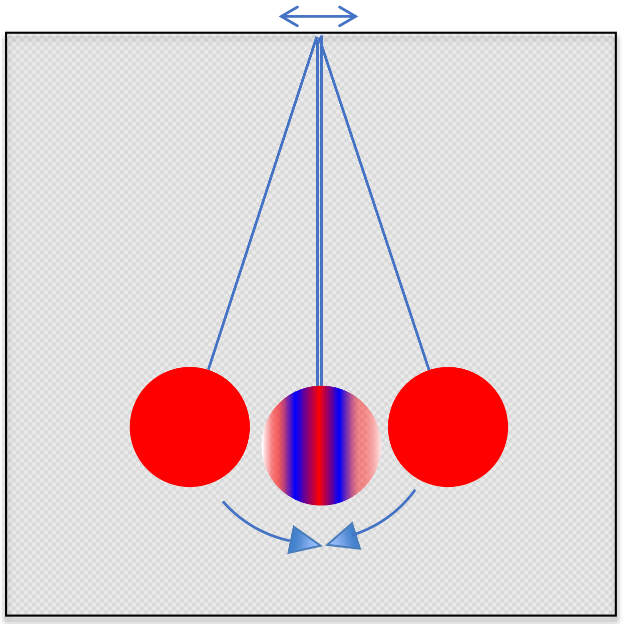
A SPECIAL DRIVEN-DAMPED OSCILLATOR

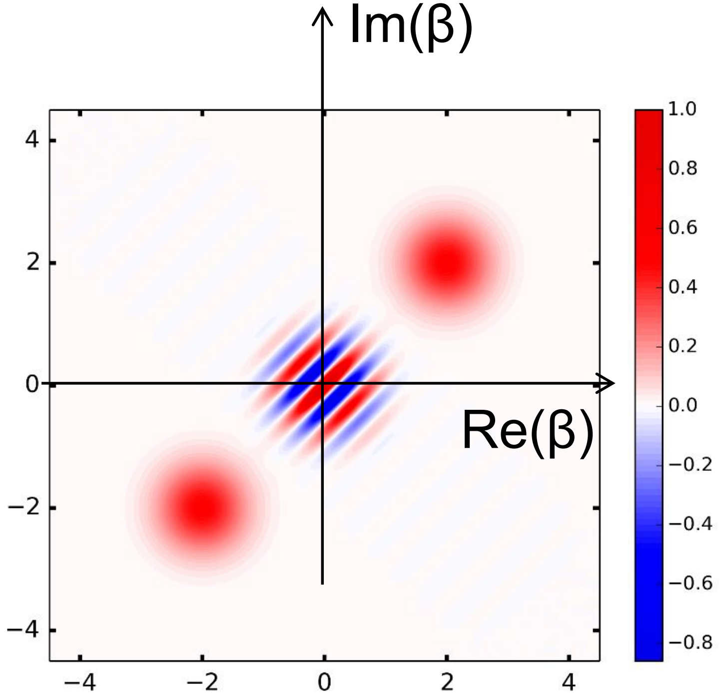




Wigner function W(β)

A SPECIAL DRIVEN-DAMPED OSCILLATOR





Wigner function W(β)

Hamiltonian : $H = \epsilon_2^{*} a^2 + \epsilon (a^{\dagger})^2$

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

$$\alpha = \pm\sqrt{-2i\epsilon_2 / \kappa_2}$$

PROTECTING QUANTUM SUPERPOSITIONS IN JOSEPHSON CIRCUITS

LECTURE I: INTRODUCTION AND OVERVIEW

LECTURE II: CAT CODES

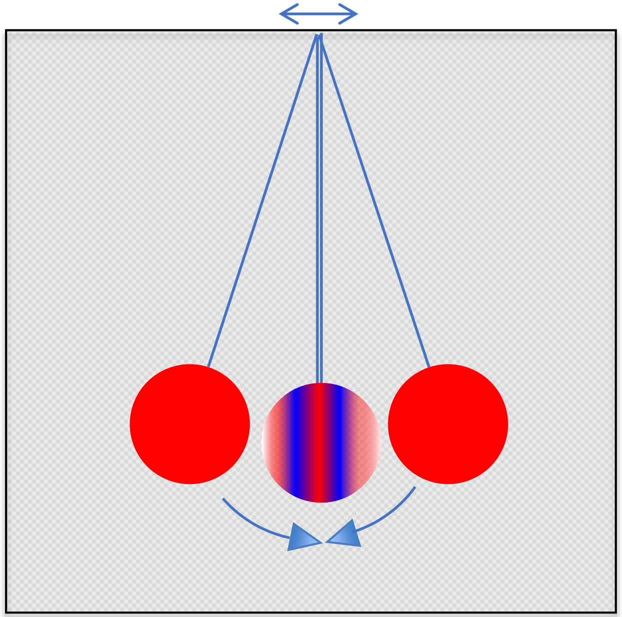
LECTURE III: PARITY MONITORING AND CORRECTION

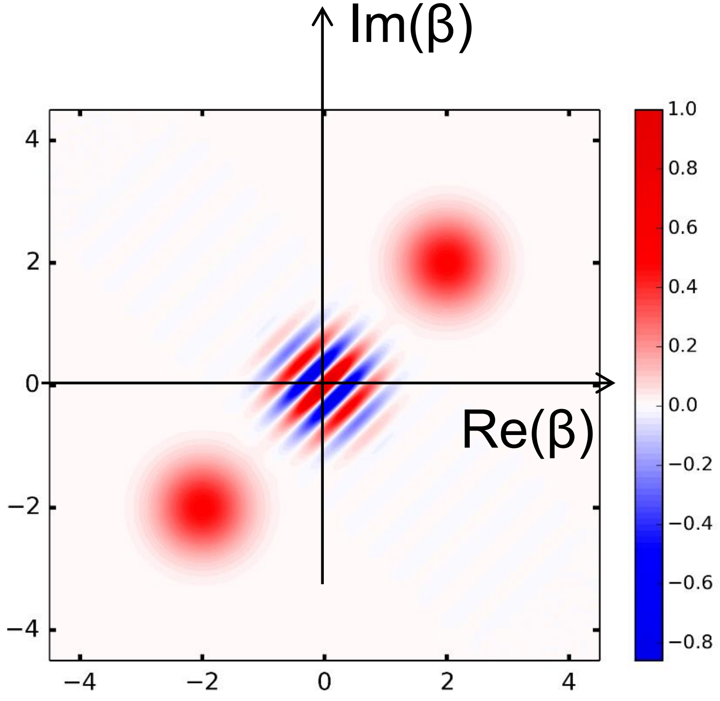
A SPECIAL DRIVEN-DAMPED OSCILLATOR

Force $\sim X^2$

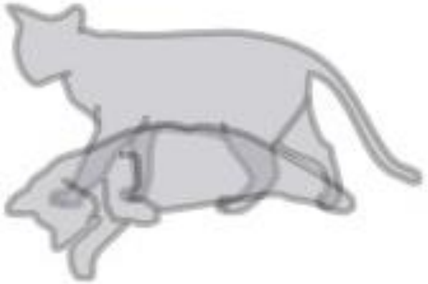
Damping

$\sim \dot{X}^2$





Wigner function W(β)



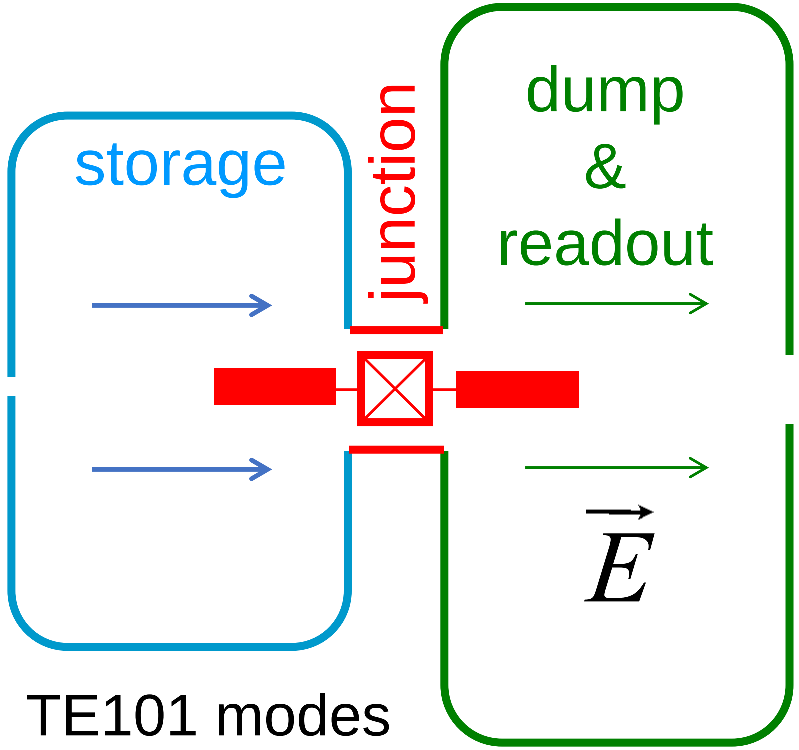
Hamiltonian : $H = \epsilon_2^* a^2 + \epsilon(a^\dagger)^2$

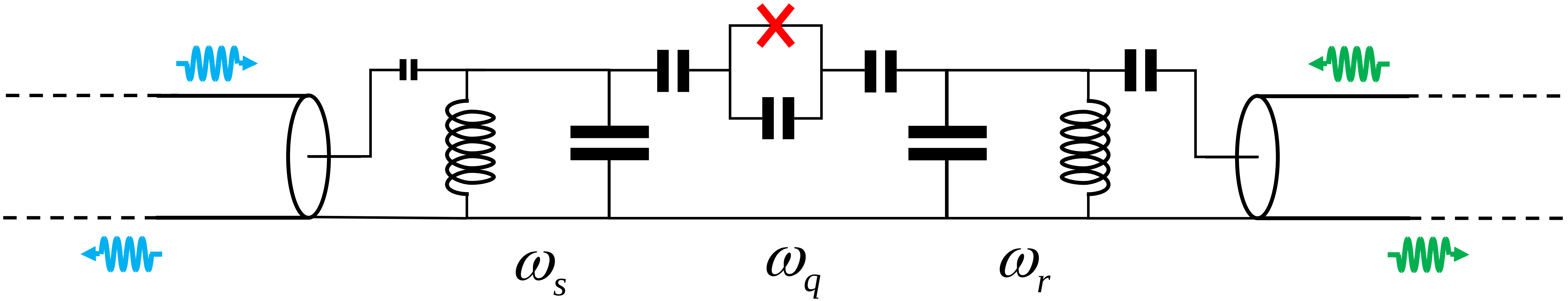
loss operator : $\sqrt{\kappa_2}\, a^2$

$$\alpha = \pm\sqrt{-2i\epsilon_2 / \kappa_2}$$

Mirrahimi et al., New J. Phys. 16, 045014 (2014)

2 OSCILLATORS COUPLED THROUGH A TUNNEL JOSEPHSON JUNCTION





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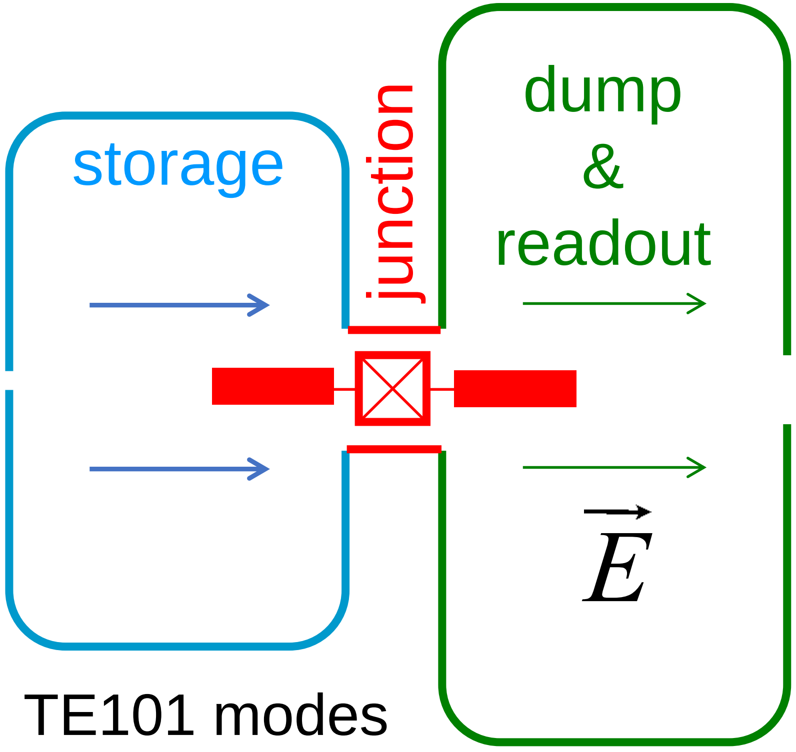
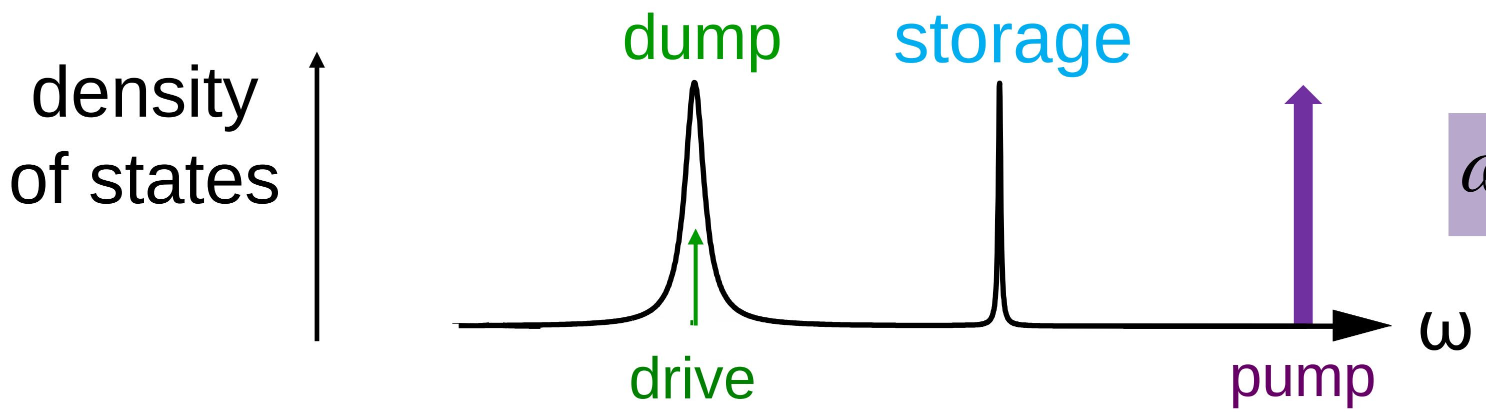


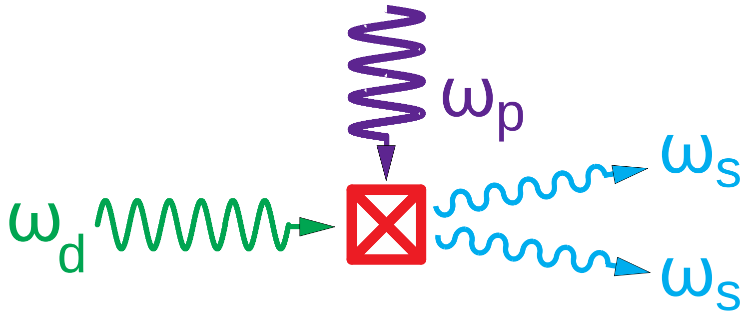
$$H/\hbar = \omega_s a_s^\dagger a_s + \omega_r a_r^\dagger a_r + \omega_q a_q^\dagger a_q - \frac{c_{qq}}{2}\left(a_q^\dagger\right)^2\left(a_q\right)^2 - c_{qs} a_q^\dagger a_q a_s^\dagger a_s - c_{qr} a_q^\dagger a_q a_r^\dagger a_r + \ldots$$

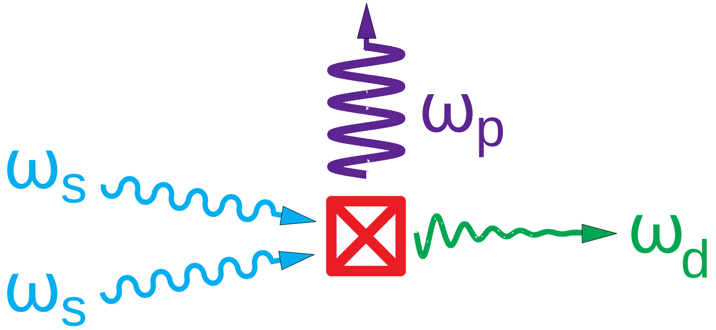
$$- \frac{c_{rs}}{4}\left(a_s\right)^2\left(a_r^\dagger\right)^2 + \mathrm{h.c.} + \ldots$$

TWO-PHOTON EXCHANGE BETWEEN THE 2 CAVITIES



$$\omega_p = 2\omega_s - \omega_d$$

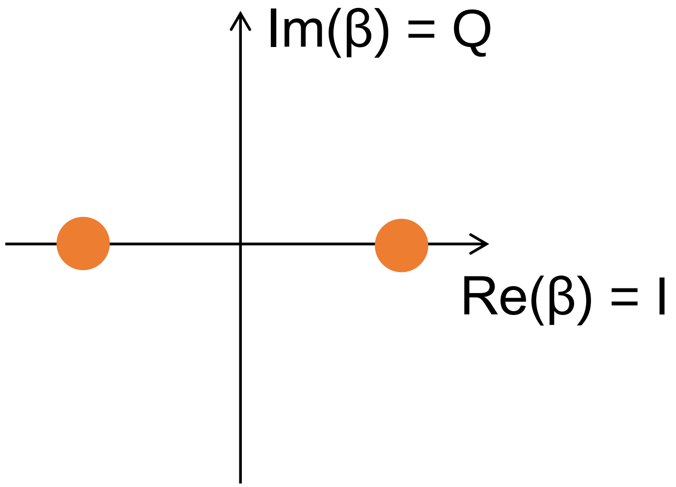




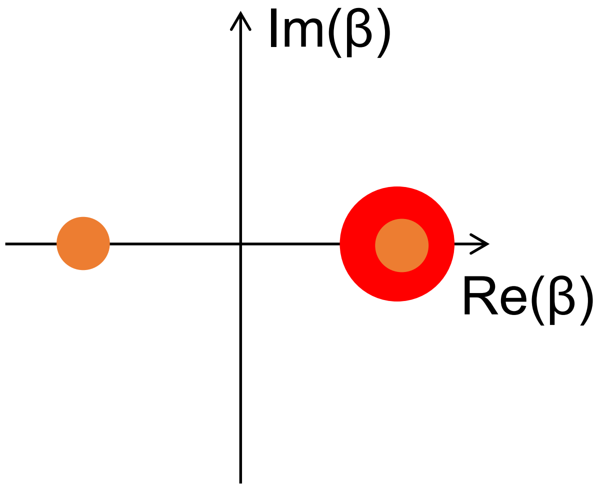
effective drive Hamiltonian: $\epsilon_2 \left(a_s^\dagger\right)^2 + \mathrm{h.c.}$

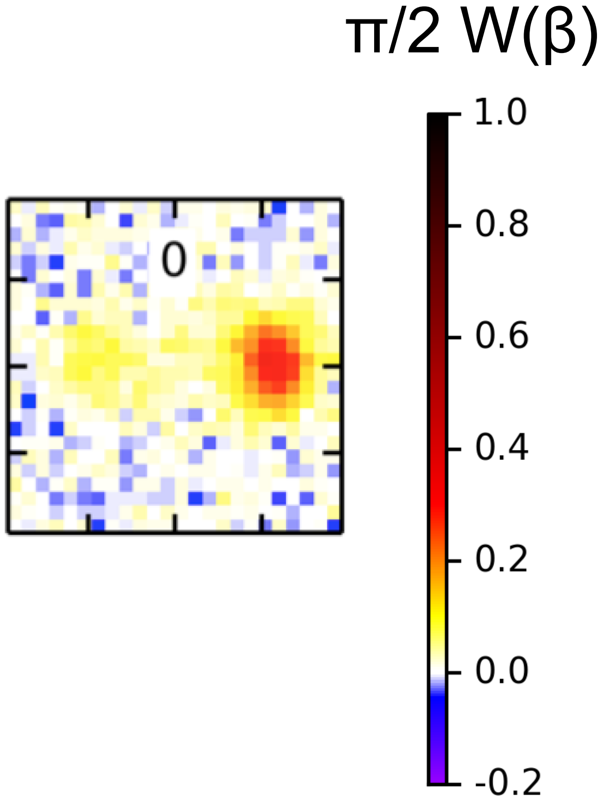
effective loss operator: $\sqrt{\kappa_2}\, a_s^{\,2}$

CAVITY BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



CAVITY BI-STABLE BEHAVIOR (SEMI-CLASSICAL)





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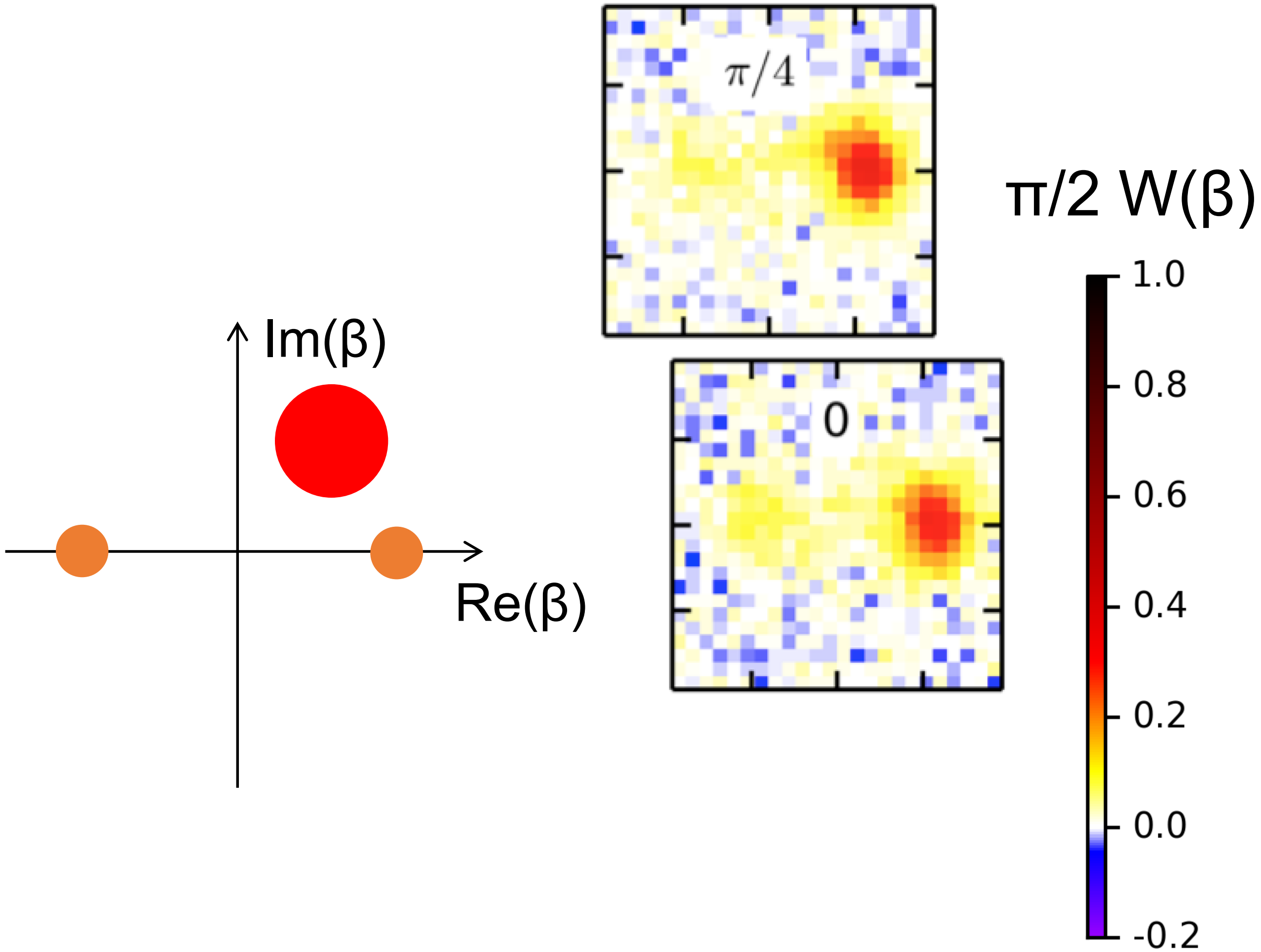

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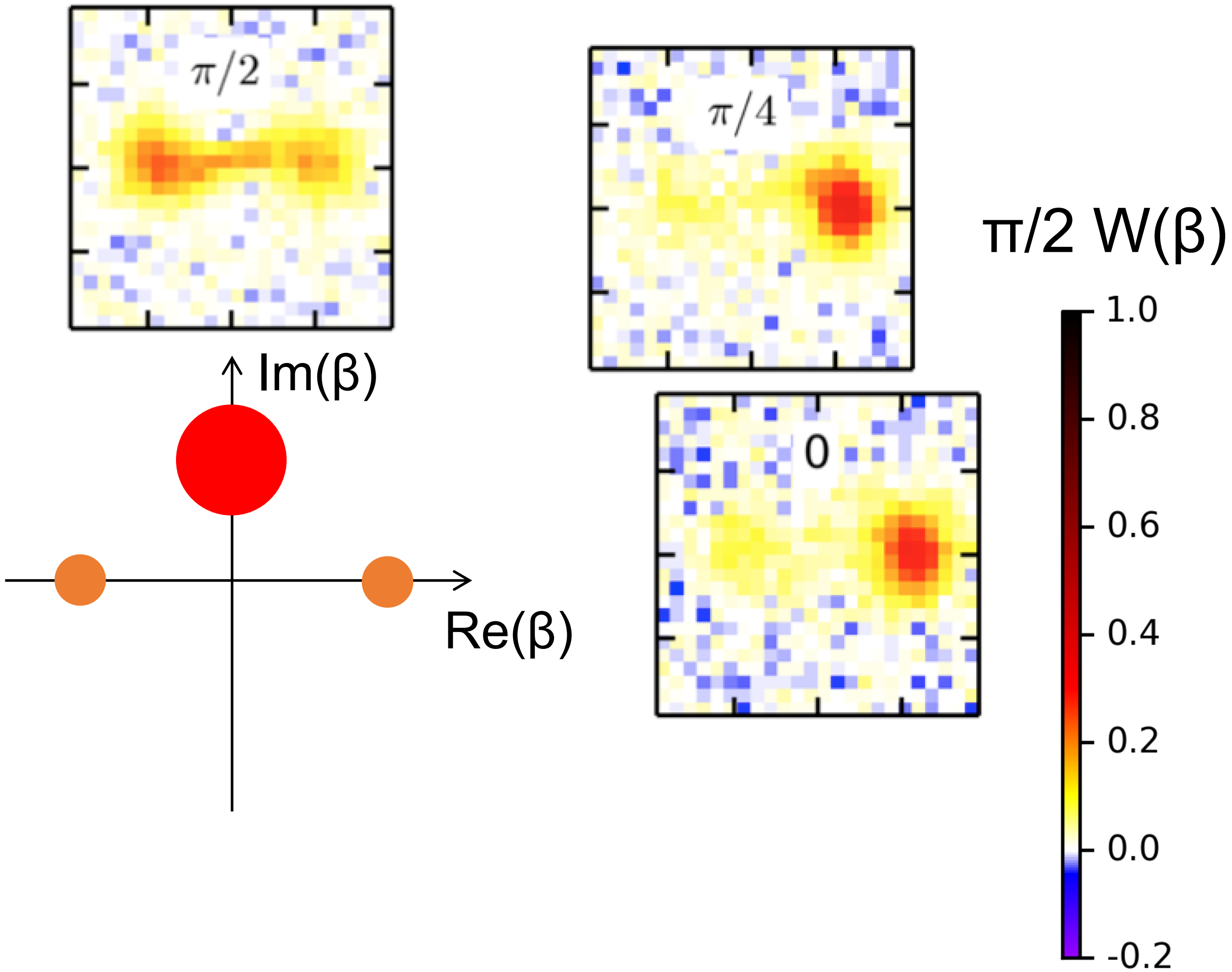

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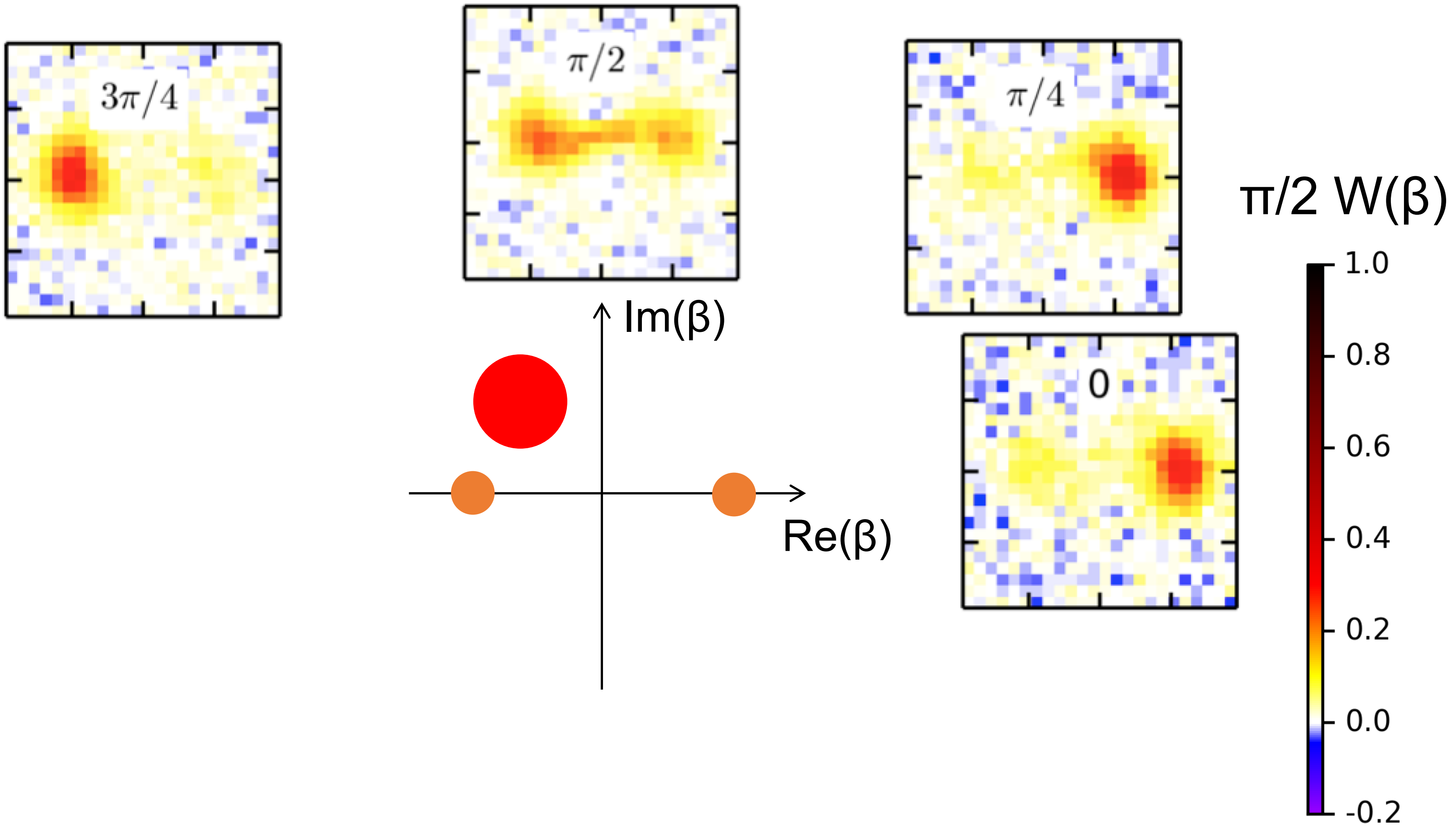

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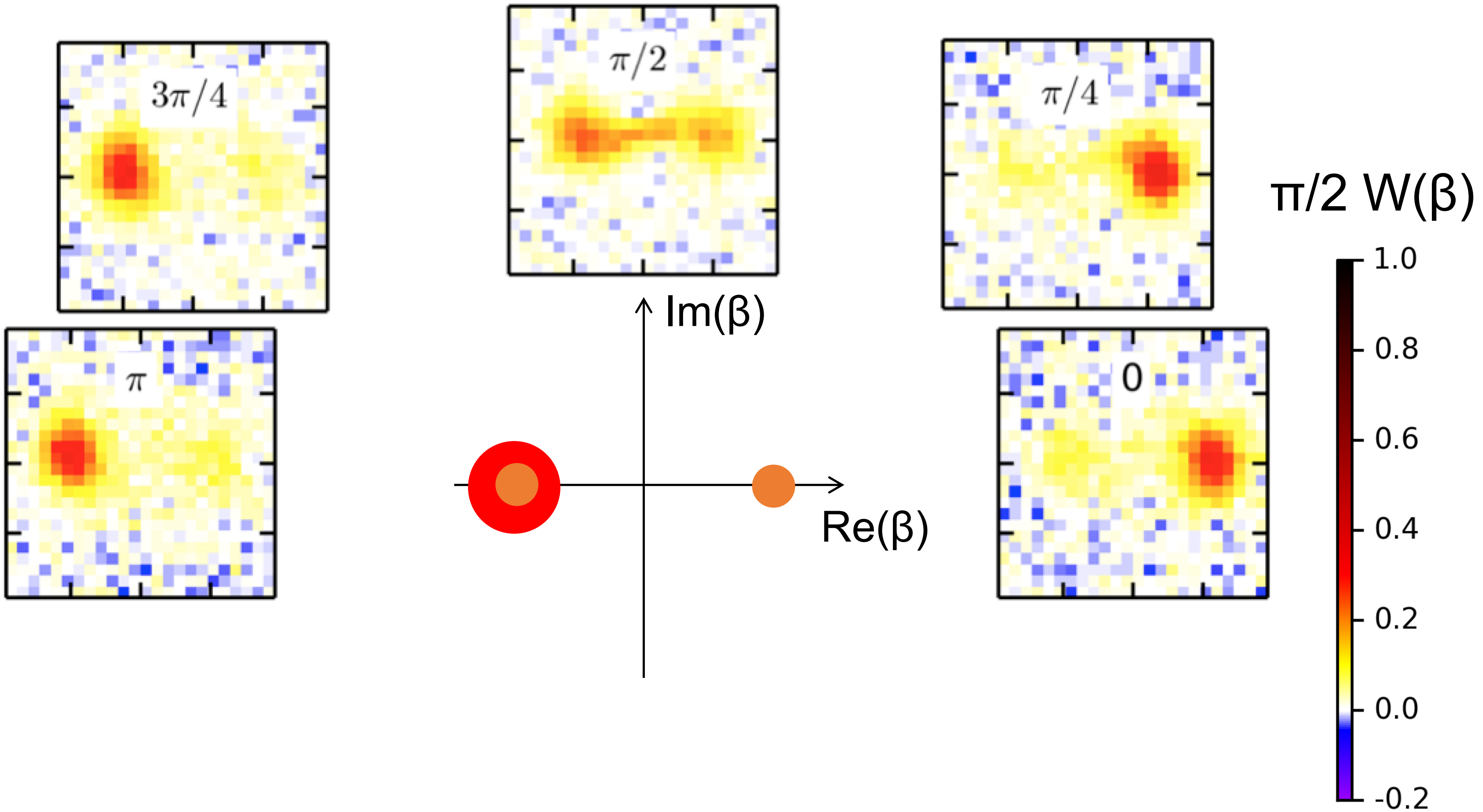

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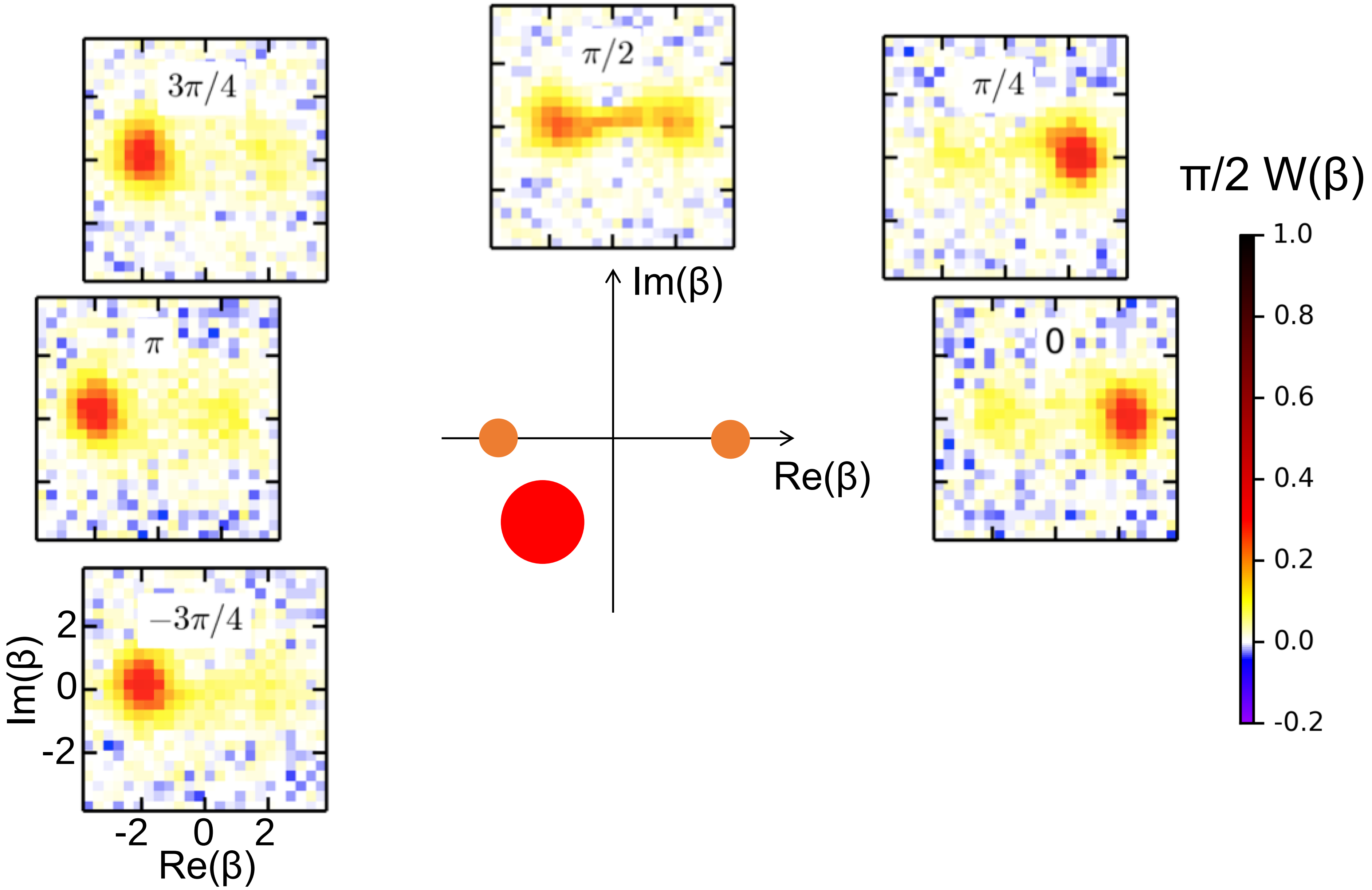

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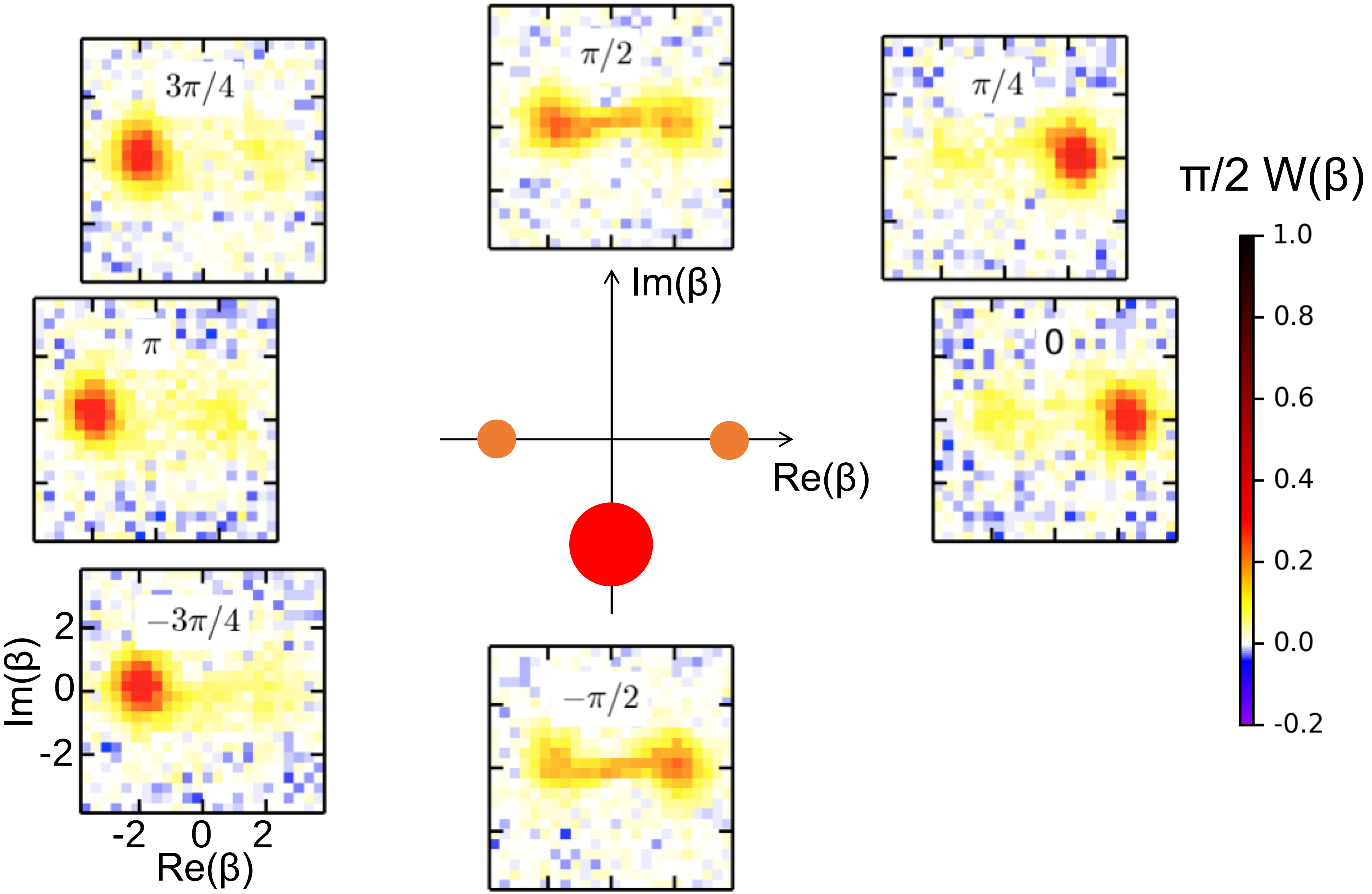

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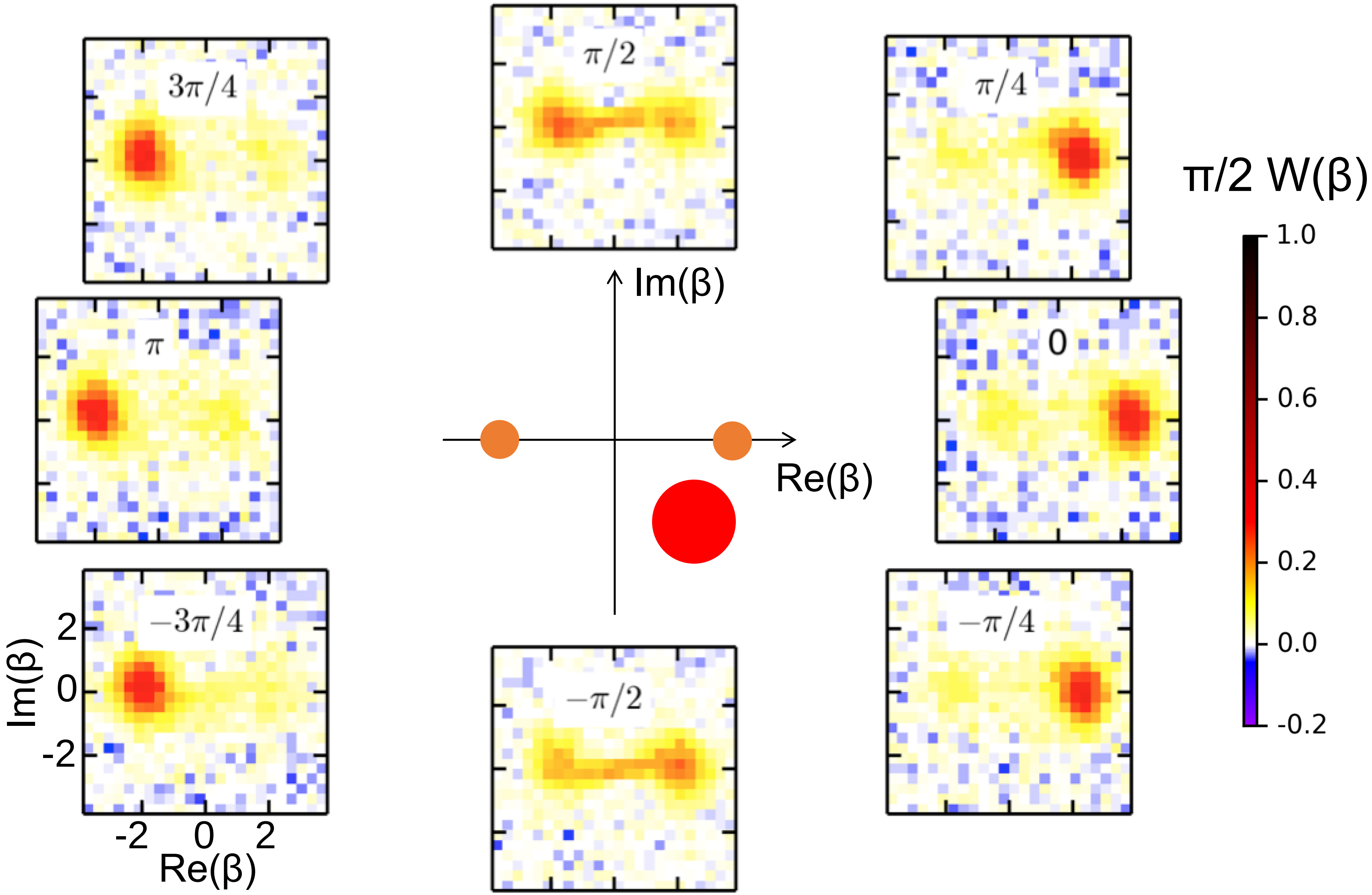

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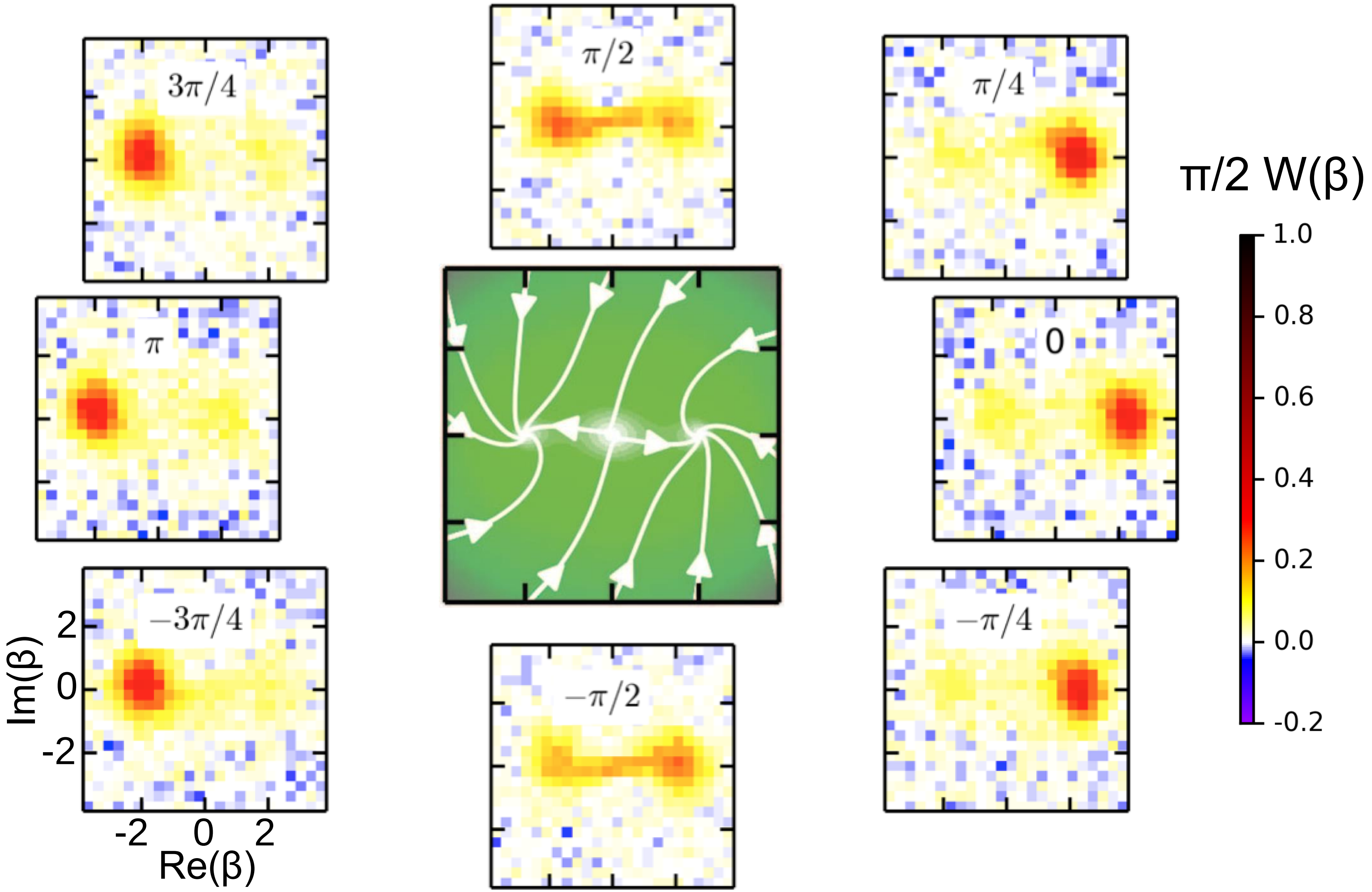
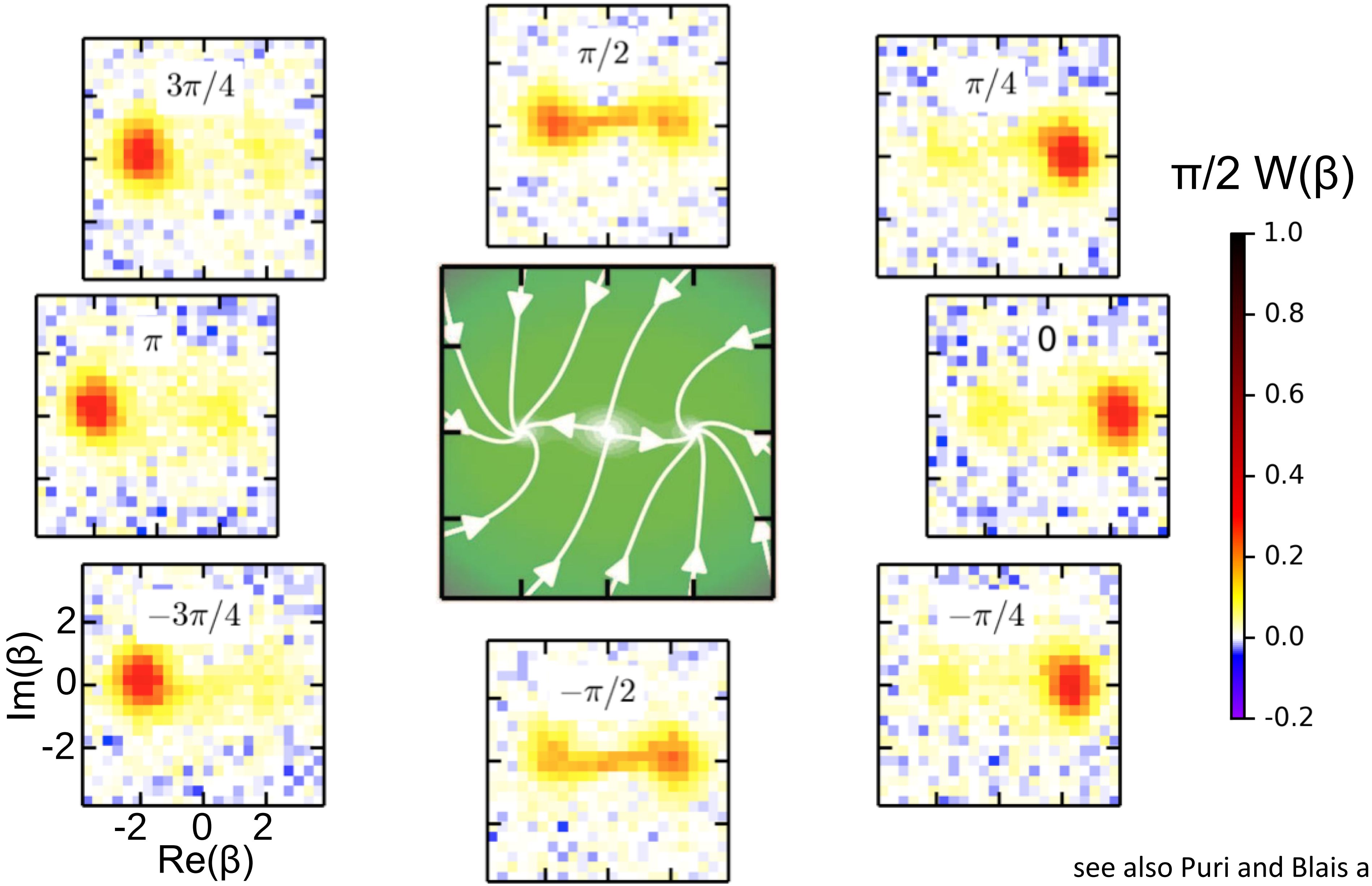
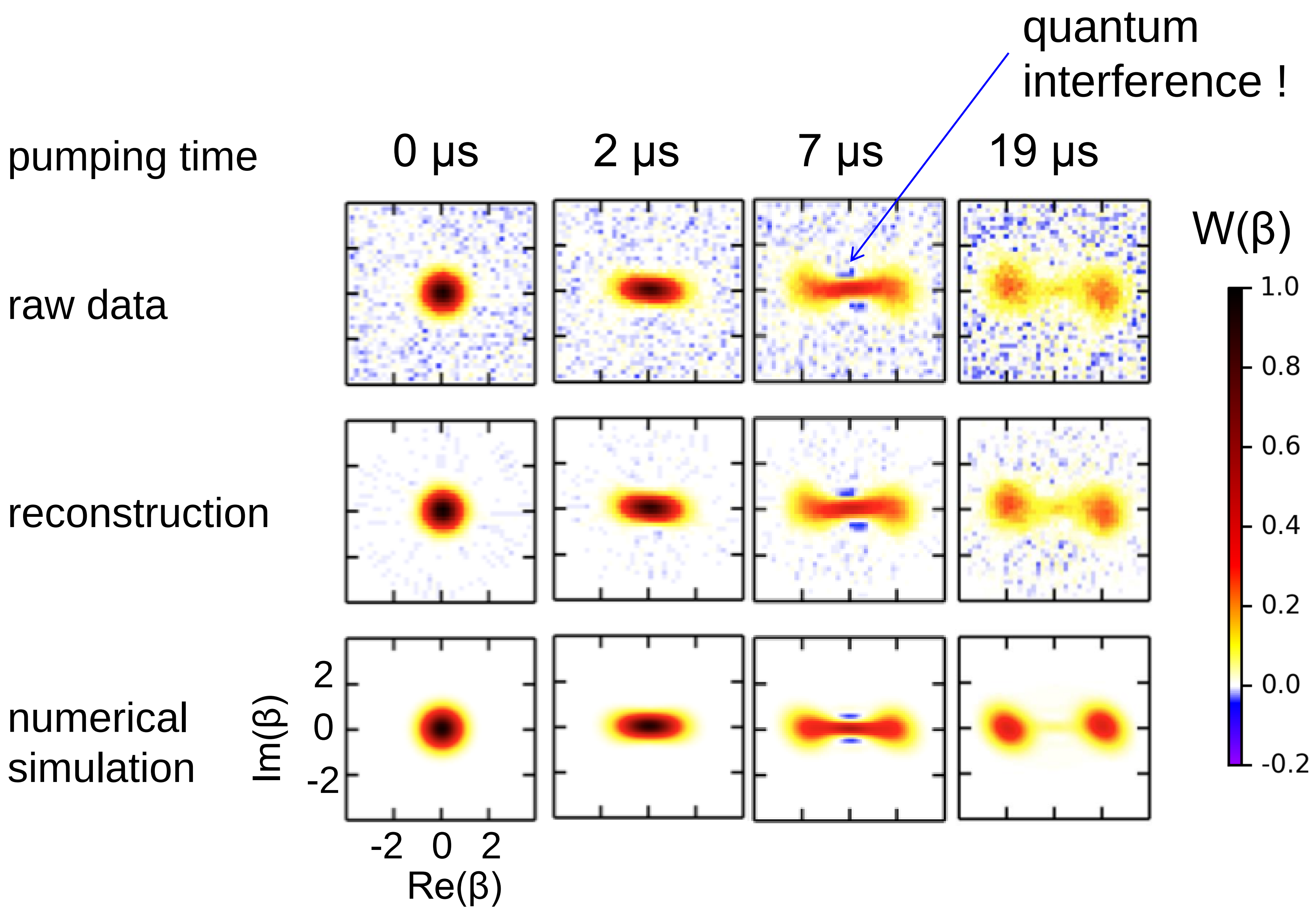


CAVITY BI-STABLE BEHAVIOR (SEMI-CLASSICAL)



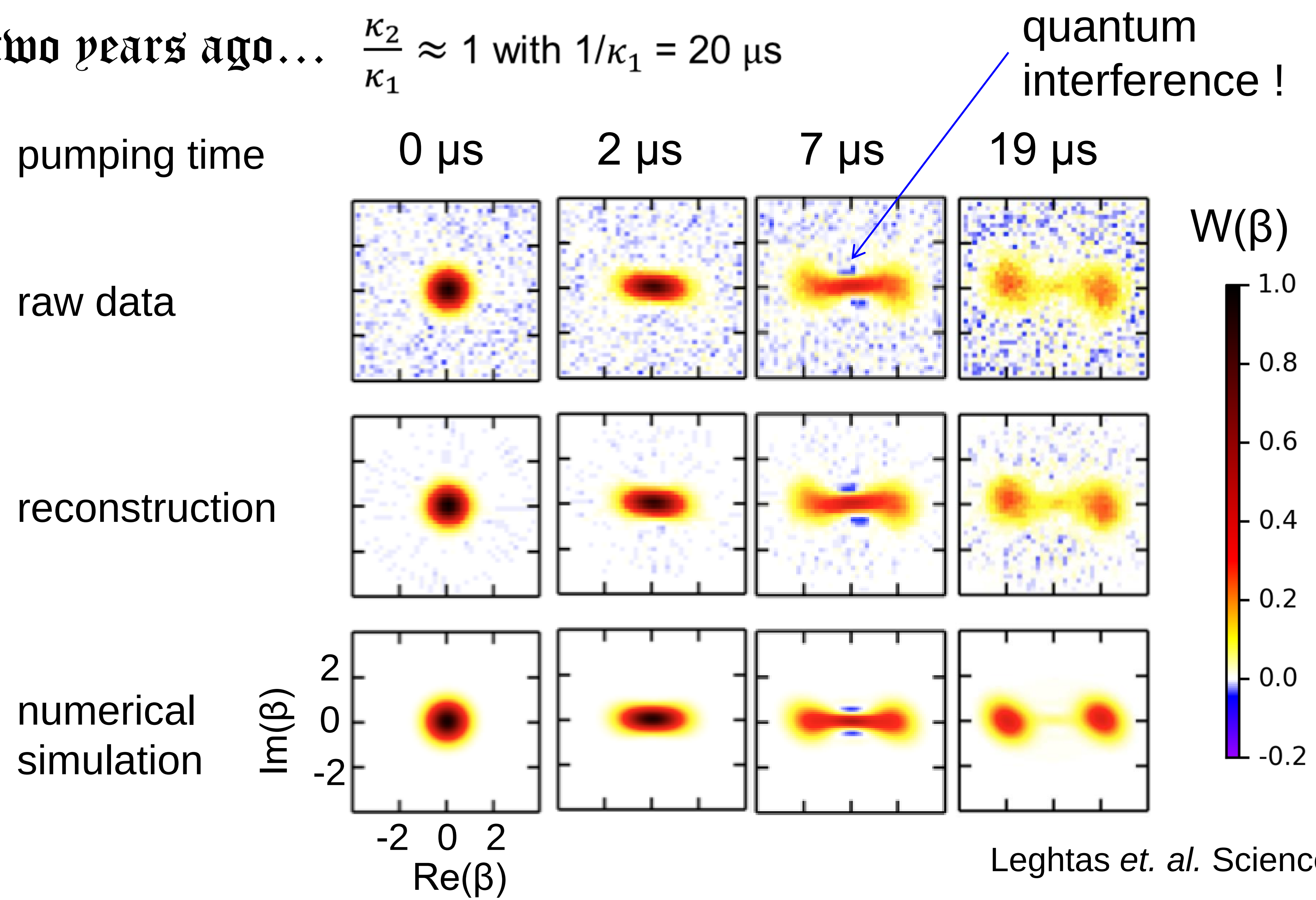
see also Puri and Blais arXiv:1605.09408

CAT SQUEEZES OUT OF VACUUM !



CAT SQUEEZES OUT OF VACUUM !

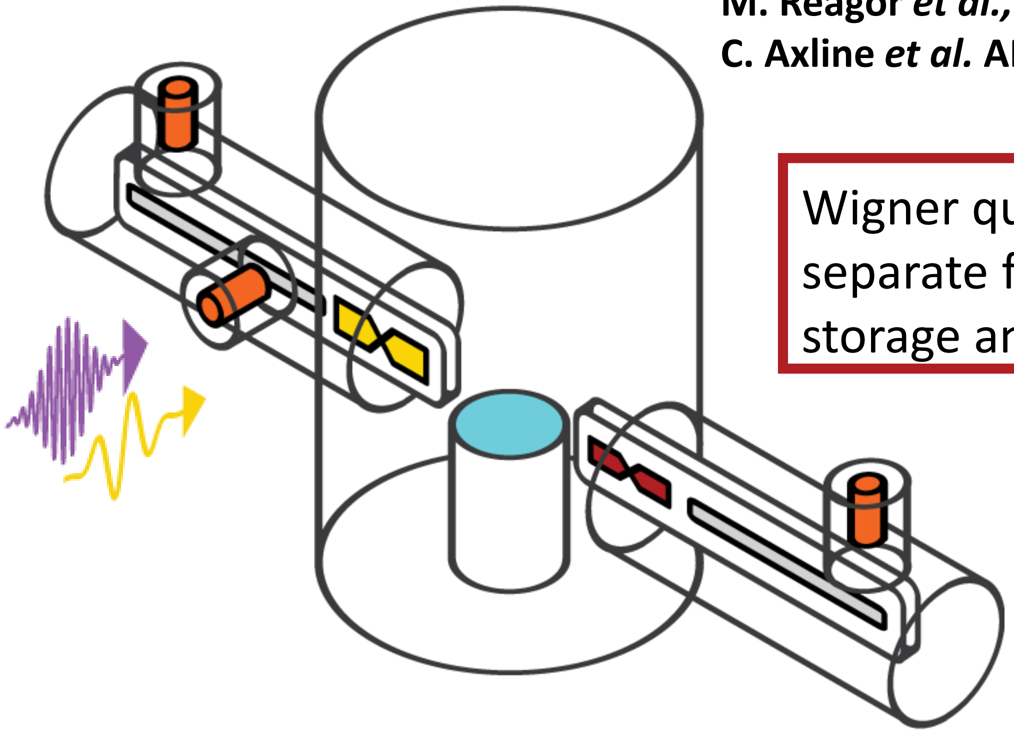
Data of two years ago… $\frac{\kappa_2}{\kappa_1} \approx 1$ with $1/\kappa_1$ = 20 μs



Leghtas *et. al.* Science (2015)

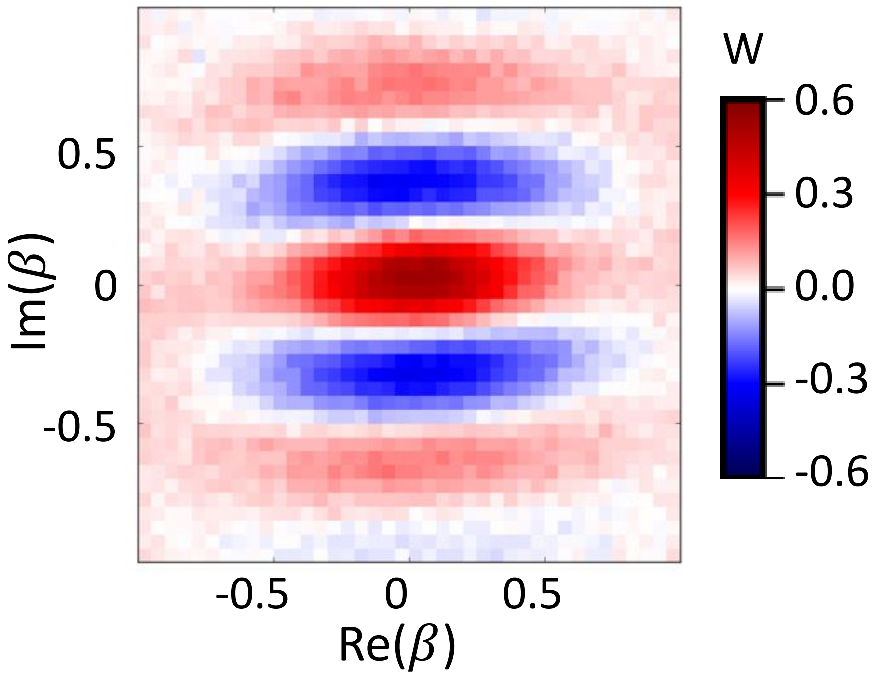
PRESENT “CAT-PUMPING” COHERENCE

NOW: $\boxed{\frac{\kappa_2}{\kappa_1} = 100 \text{ with } 1/\kappa_1 = 92\ \mu\text{s}}$



M. Reagor *et al.*, APL (2013),
C. Axline *et al.* APL (2016)

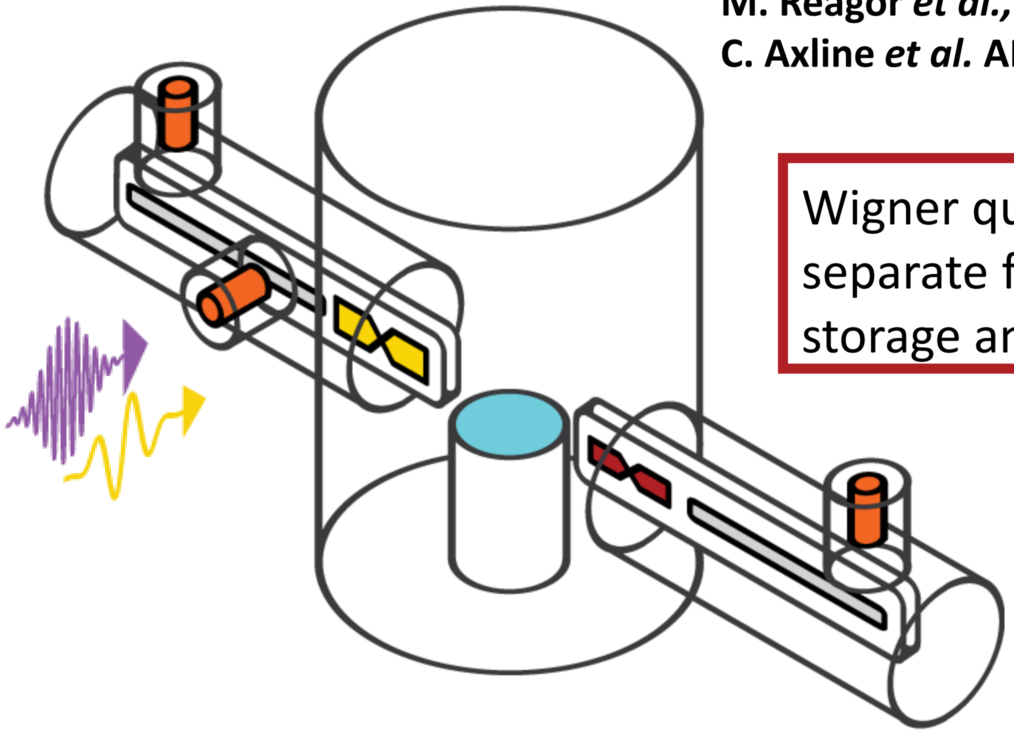
Wigner qubit separate from storage ancilla



Touzard, Grimm, et al. arXiv:1705.02401

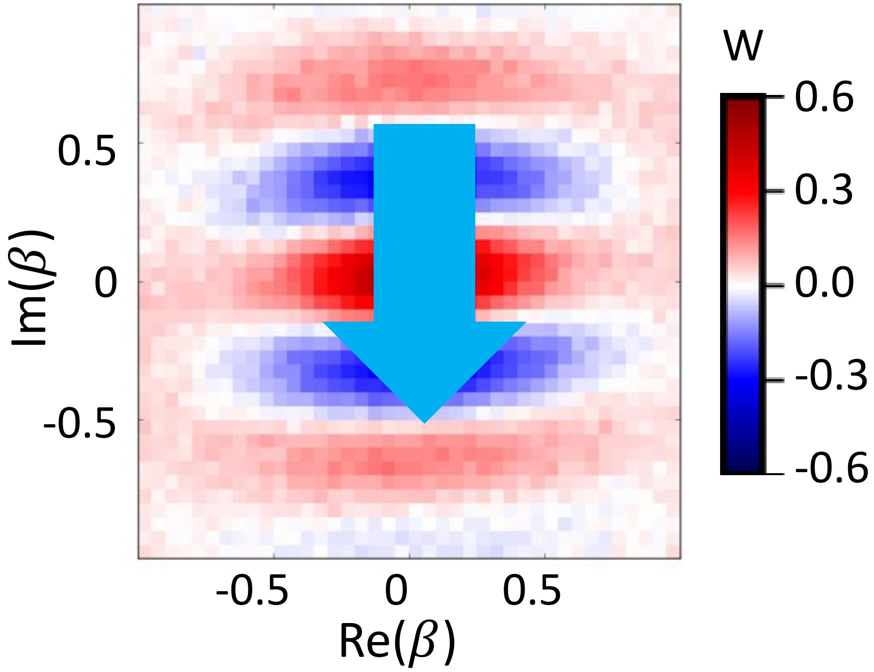
PRESENT “CAT-PUMPING” COHERENCE

NOW: $\boxed{\frac{\kappa_2}{\kappa_1} = 100 \text{ with } 1/\kappa_1 = 92\ \mu s}$



M. Reagor *et al.*, APL (2013), C. Axline *et al.* APL (2016)

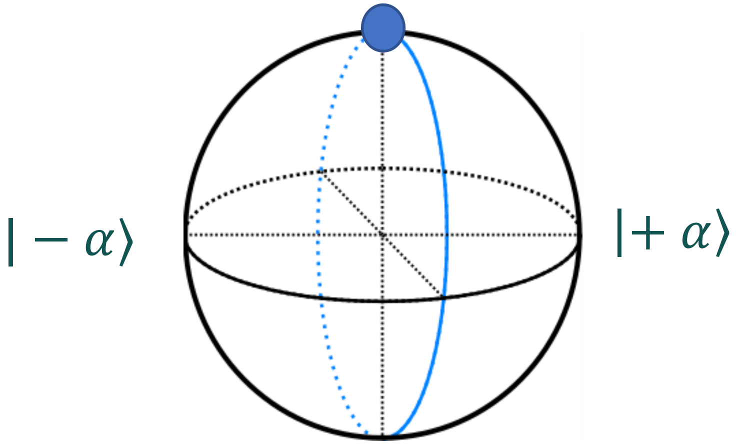
Wigner qubit separate from storage ancilla



Touzard, Grimm, et al. arXiv:1705.02401

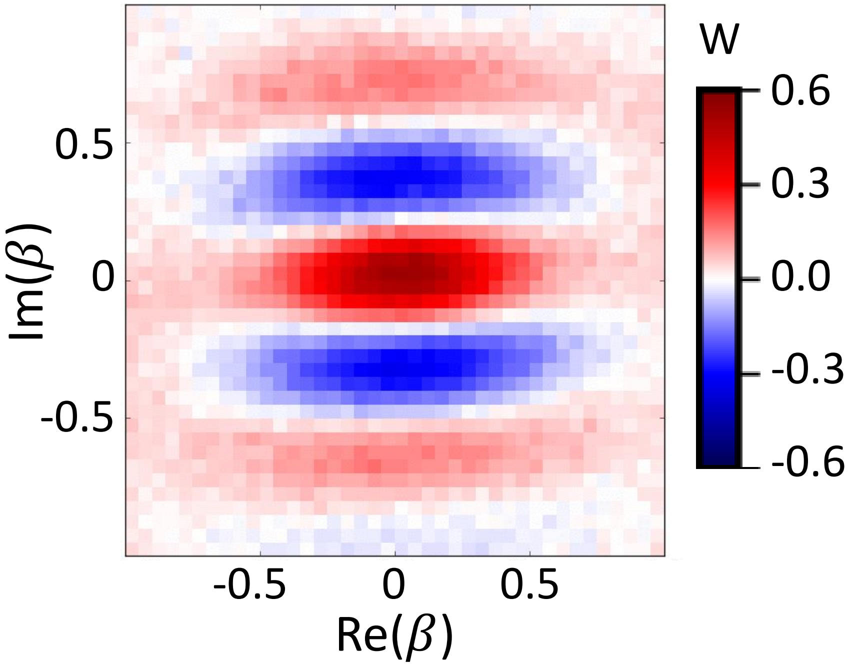
RABI OSCILLATIONS OF CAT WHILE PUMPING

$$|0\rangle_L = \frac{|\alpha\rangle + |{-\alpha}\rangle}{\sqrt{2}}$$



$$|1\rangle_L = \frac{|\alpha\rangle - |{-\alpha}\rangle}{\sqrt{2}}$$

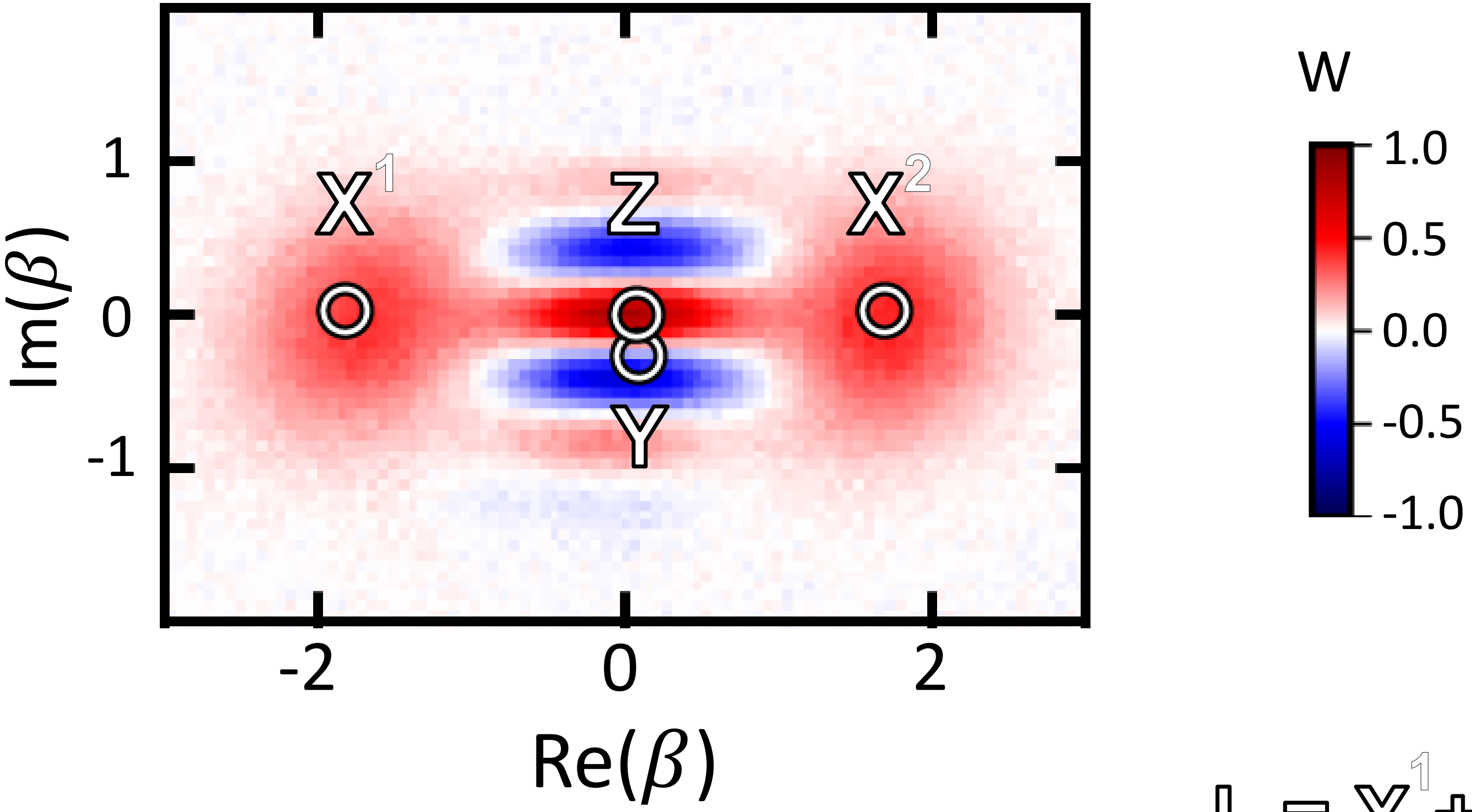
Movie slowed down by 10^{-6}



observation of quantum Zeno dynamics of <u>protected</u> information!

Misra & Sudarshan (1977); Itano et al., (1990); Fisher, Gutierrez-Medina & Raizen (2001); Facchi & Pascazio (2002); Raimond et al., (2012)

MEASUREMENT OF THE 4 PAULI OPERATORS OF THE PROTECTED QUBIT MANIFOLD

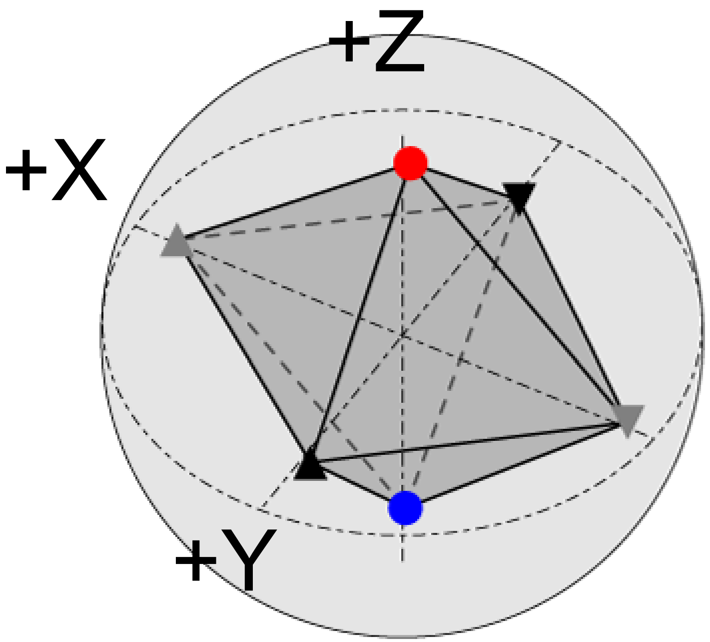


$$I = X^1 + X^2$$

$$X = X^2 - X^1$$

PROCESS TOMOGRAPHY OF QUANTUM ZENO RABI ROTATION

Encode

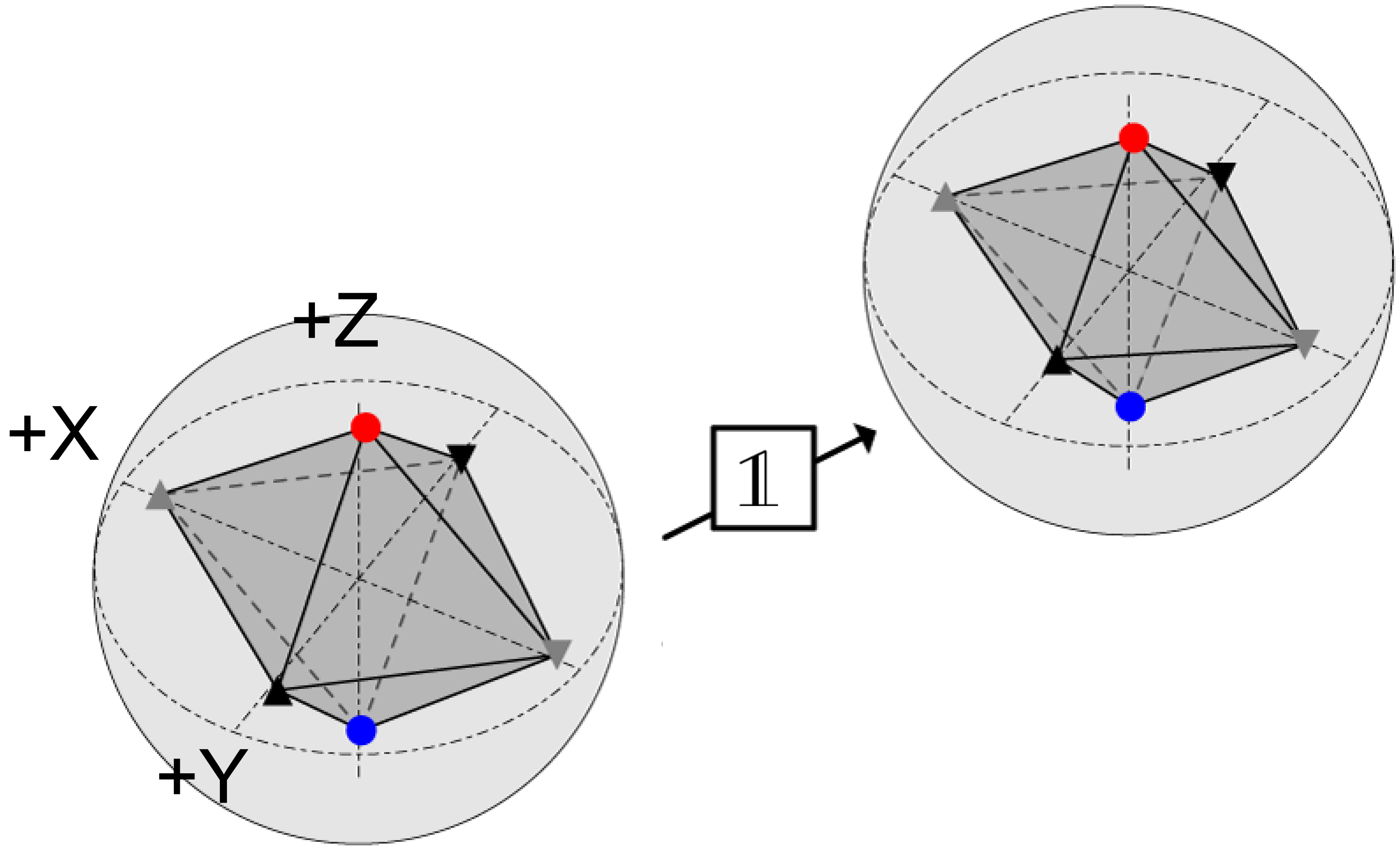


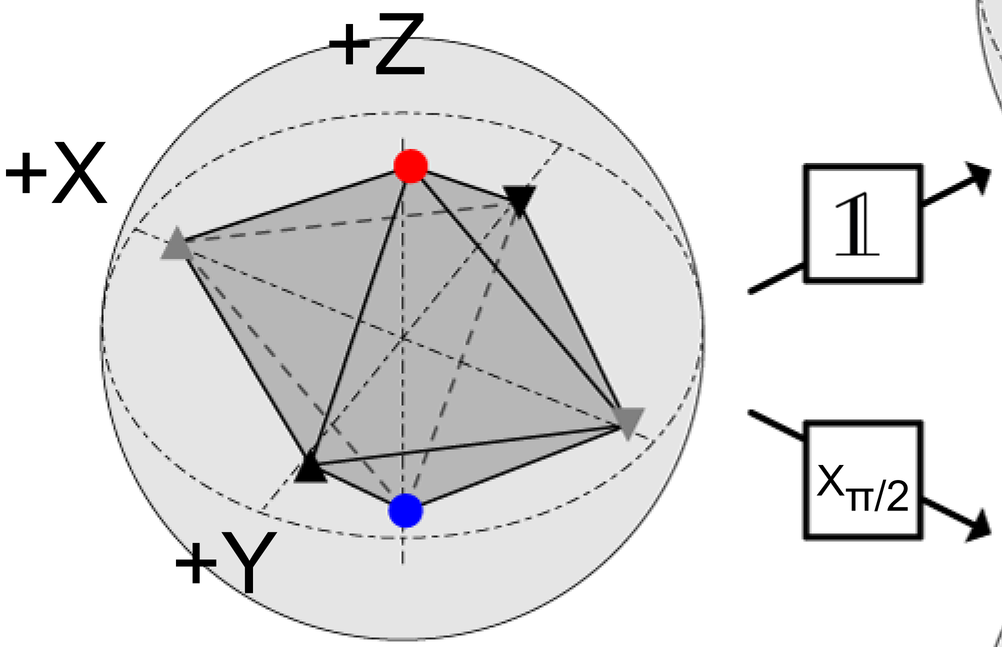
●/● : $N(|\alpha\rangle \pm |-\alpha\rangle)$

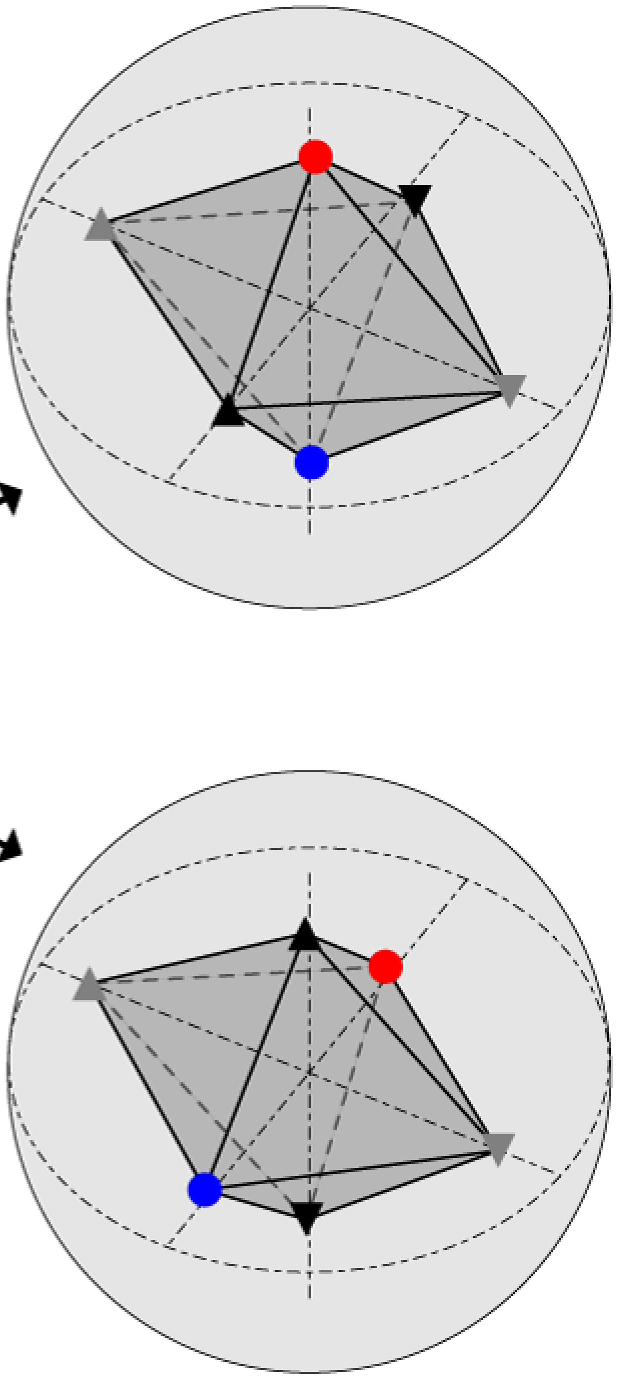
▲/▼ : $N(|\alpha\rangle \pm i|-\alpha\rangle)$

▲/▼ : $|\pm\alpha\rangle$

Identity







DURATION OF LOGICAL GATES: 1.8 μs

GATE DONE WHILE CORRECTING!

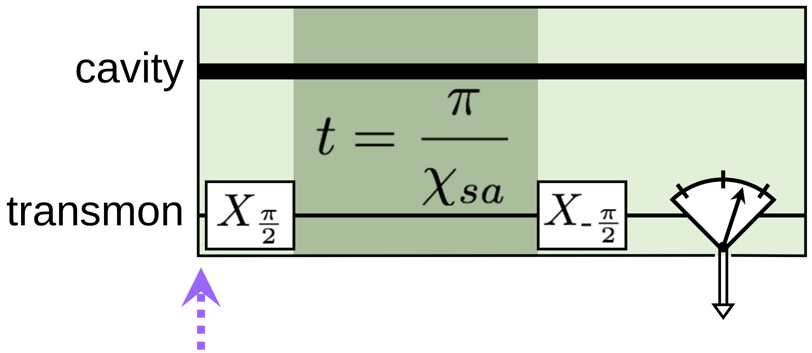
Zeno $\pi/2$ rotation around X

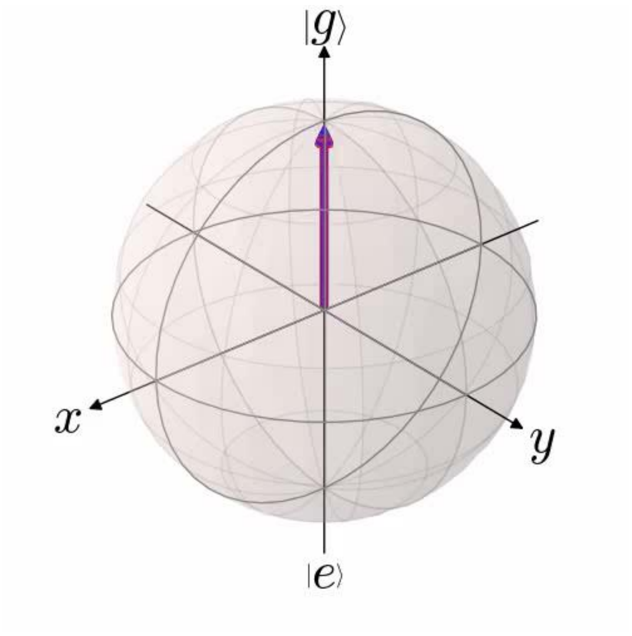
TWO TYPES OF CAT ERRORS MUST BE ADDRESSED:

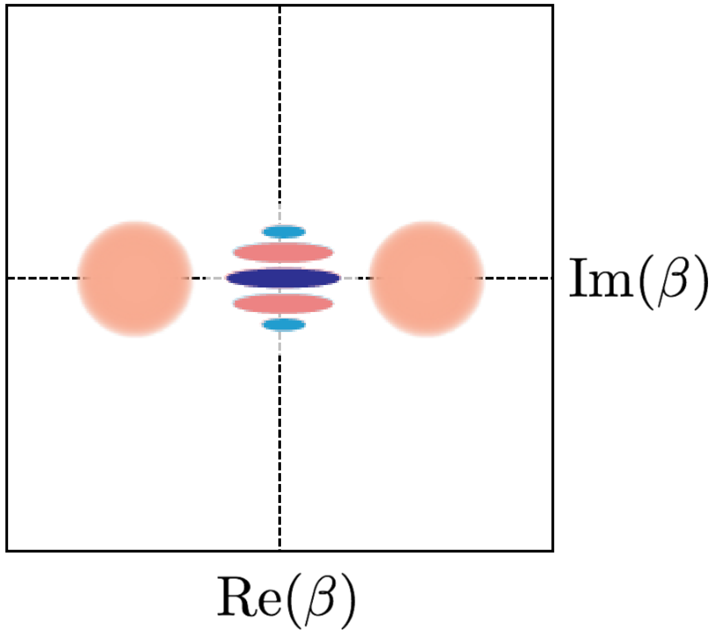
- COHERENT STATE SHRINKING, DEPHASING & DEFORMING

- $\boxed{\text{PHOTON NUMBER PARITY JUMPING}}$

SYNDROME MEASUREMENT

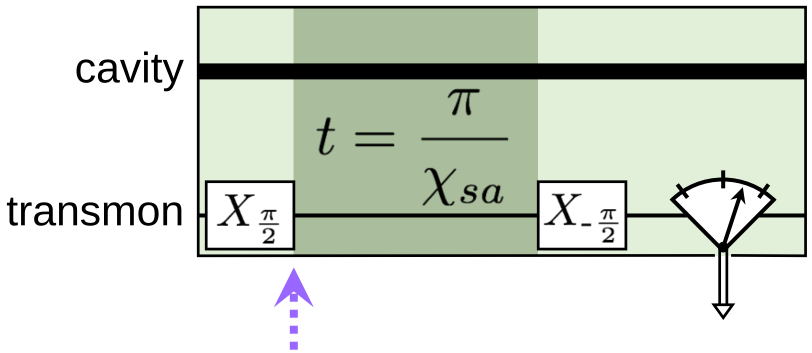


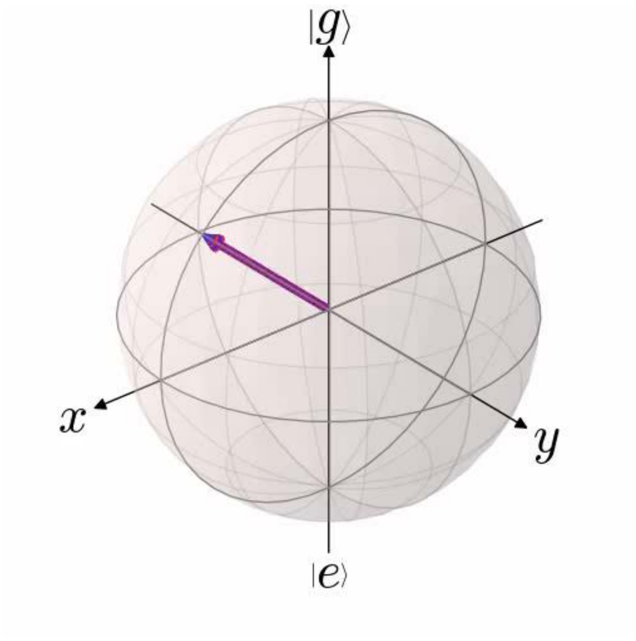


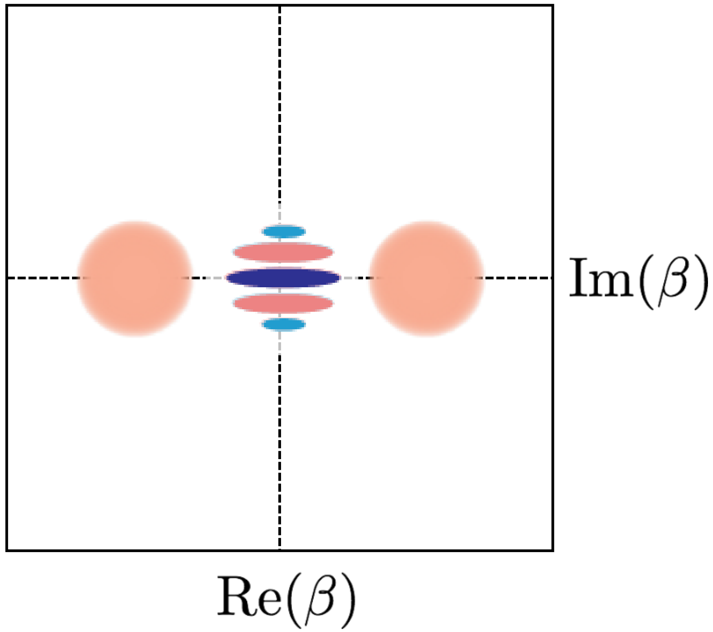


transmon **cavity**

SYNDROME MEASUREMENT

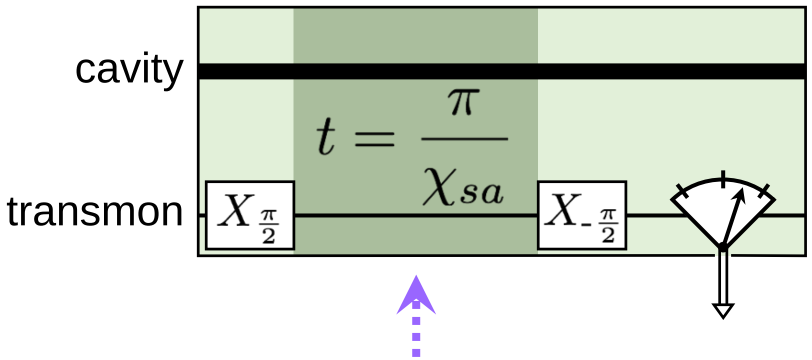


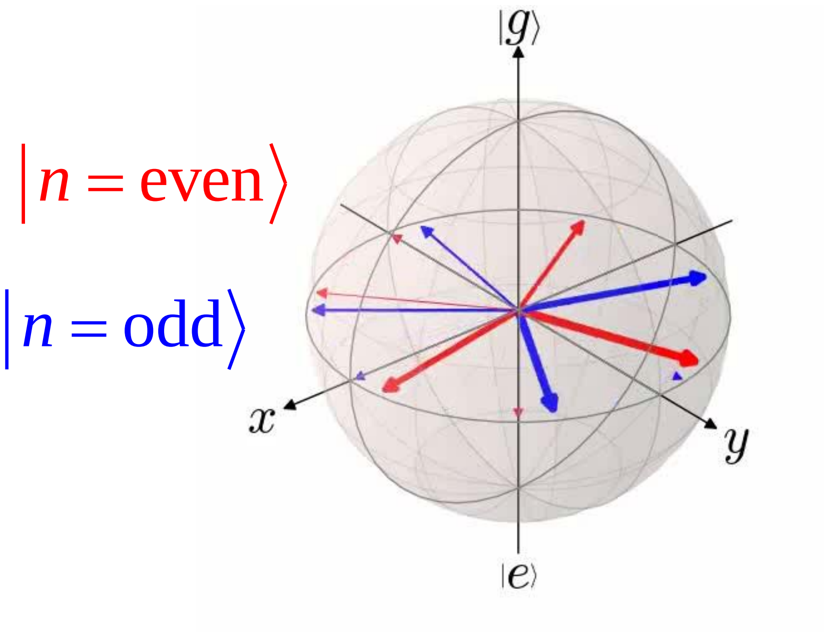


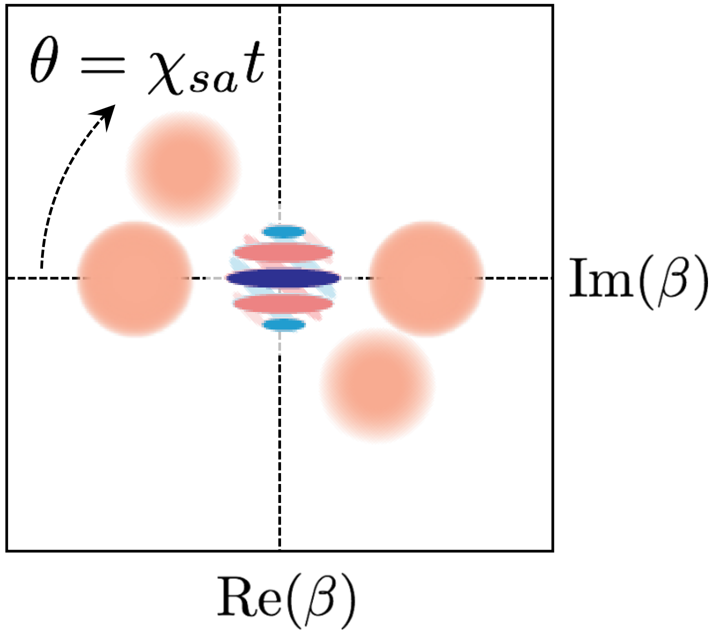


transmon **cavity**

SYNDROME MEASUREMENT

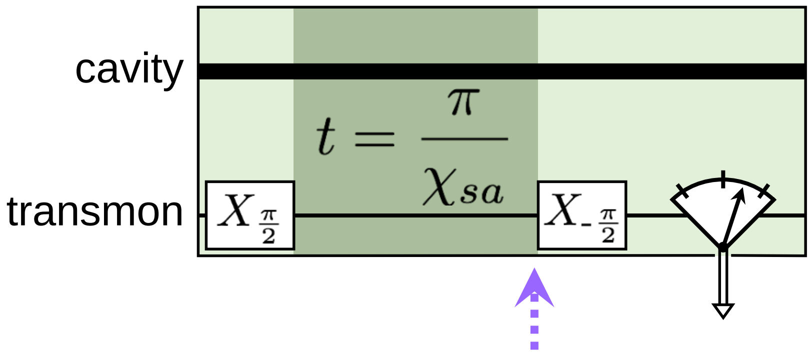


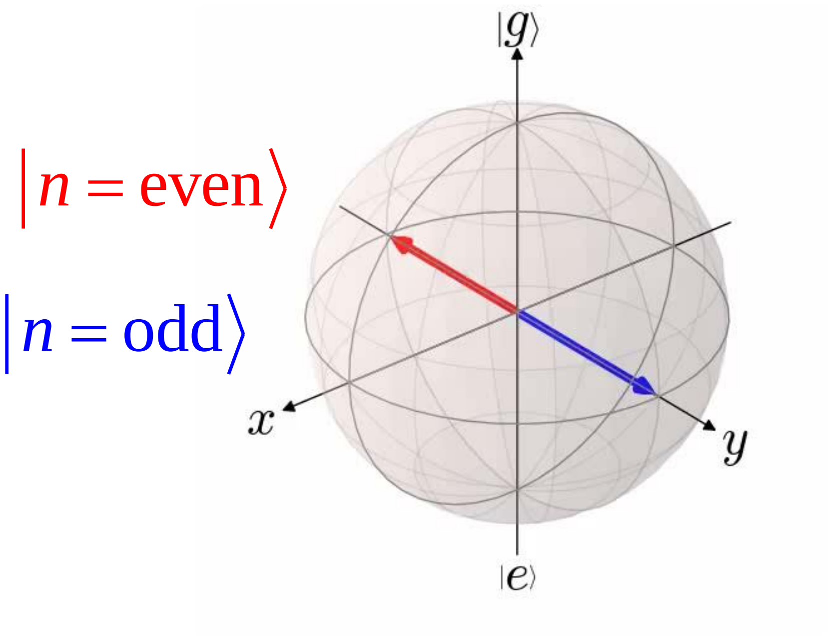


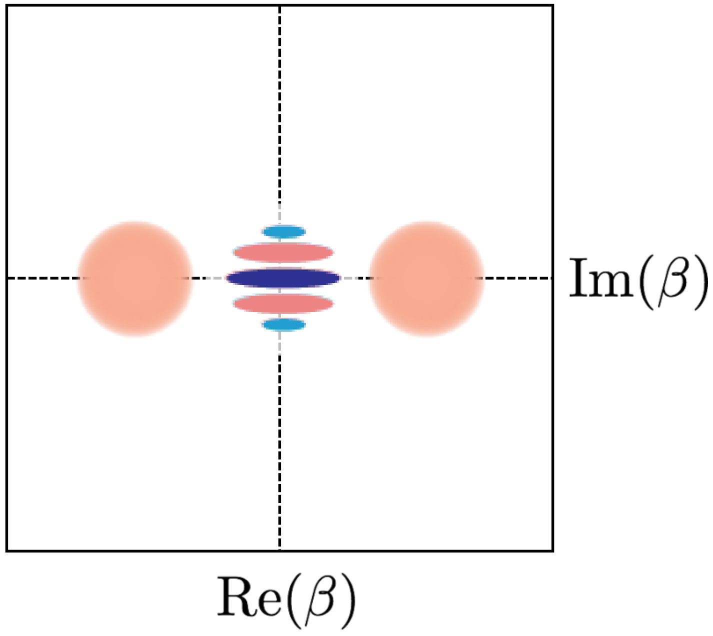


transmon **cavity**

SYNDROME MEASUREMENT

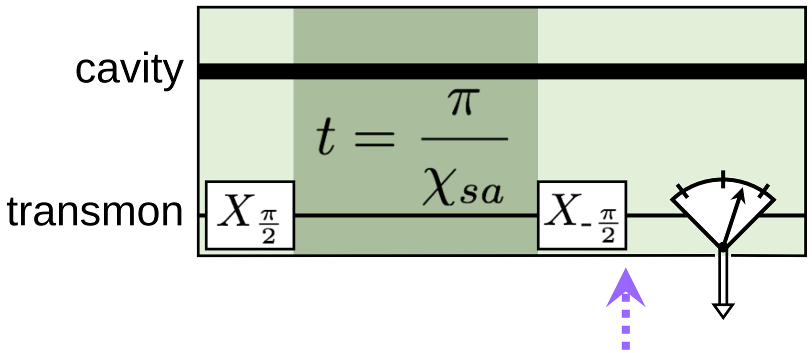






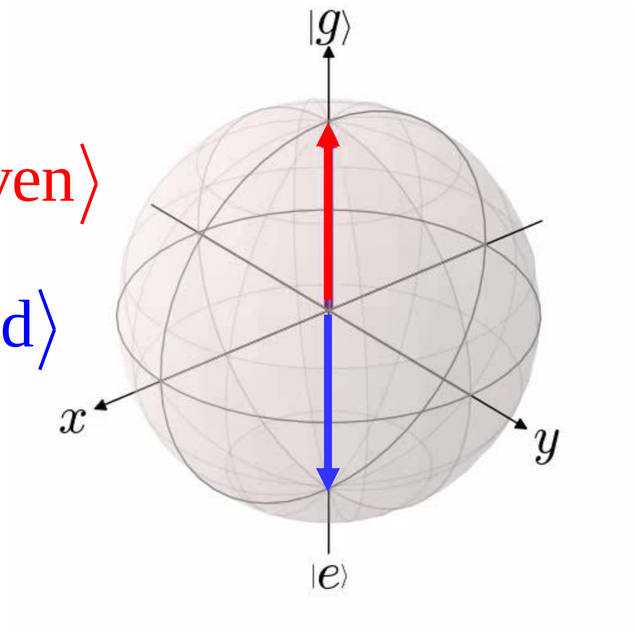
transmon **cavity**

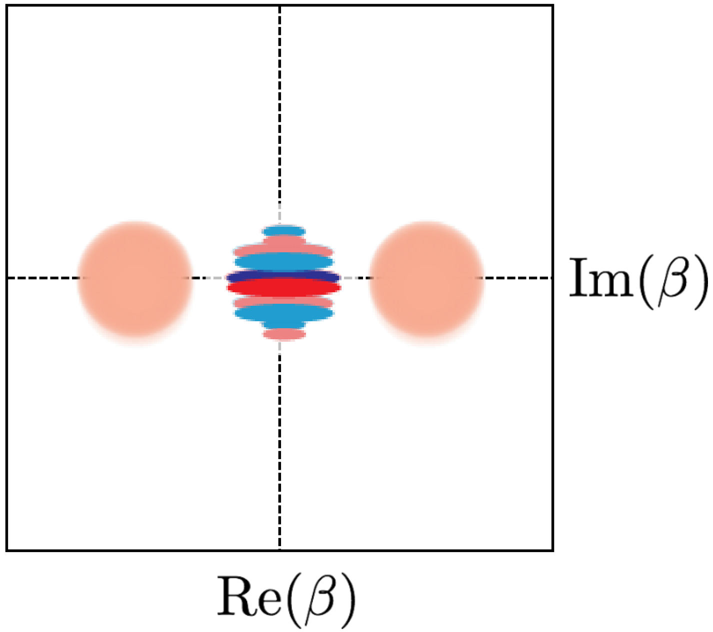
SYNDROME MEASUREMENT



$|n = \text{even}\rangle$

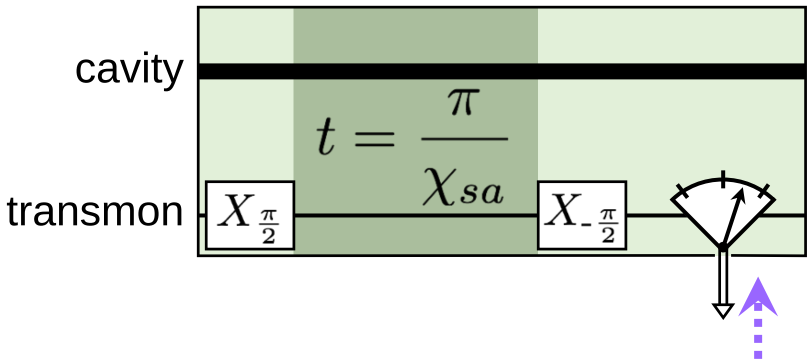
$|n = \text{odd}\rangle$

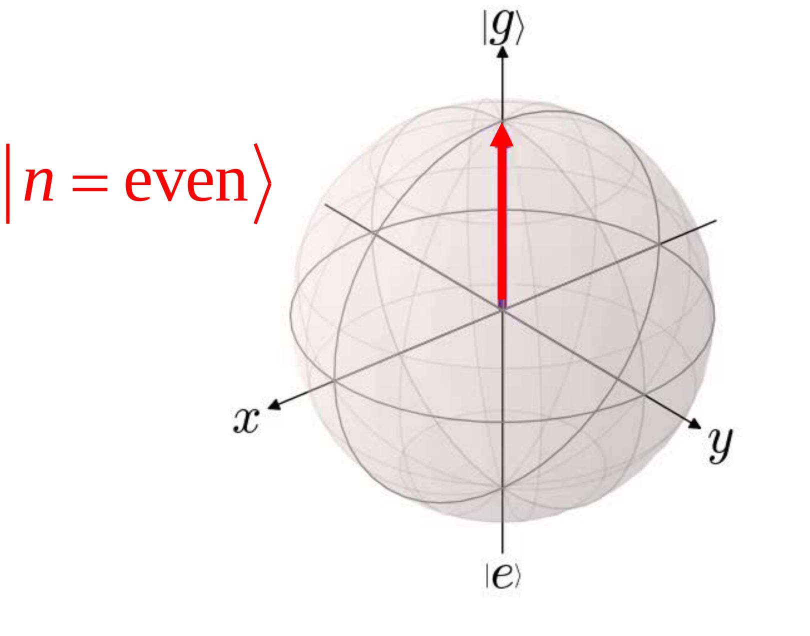


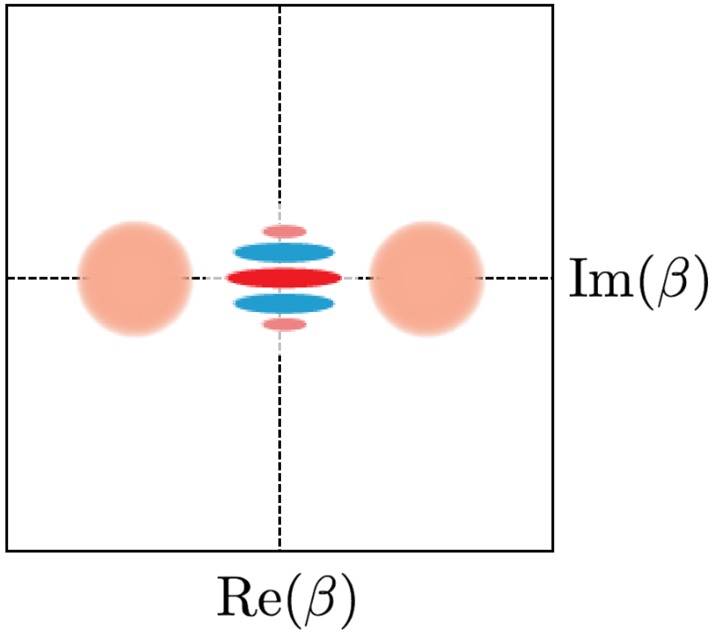


transmon **cavity**

SYNDROME MEASUREMENT

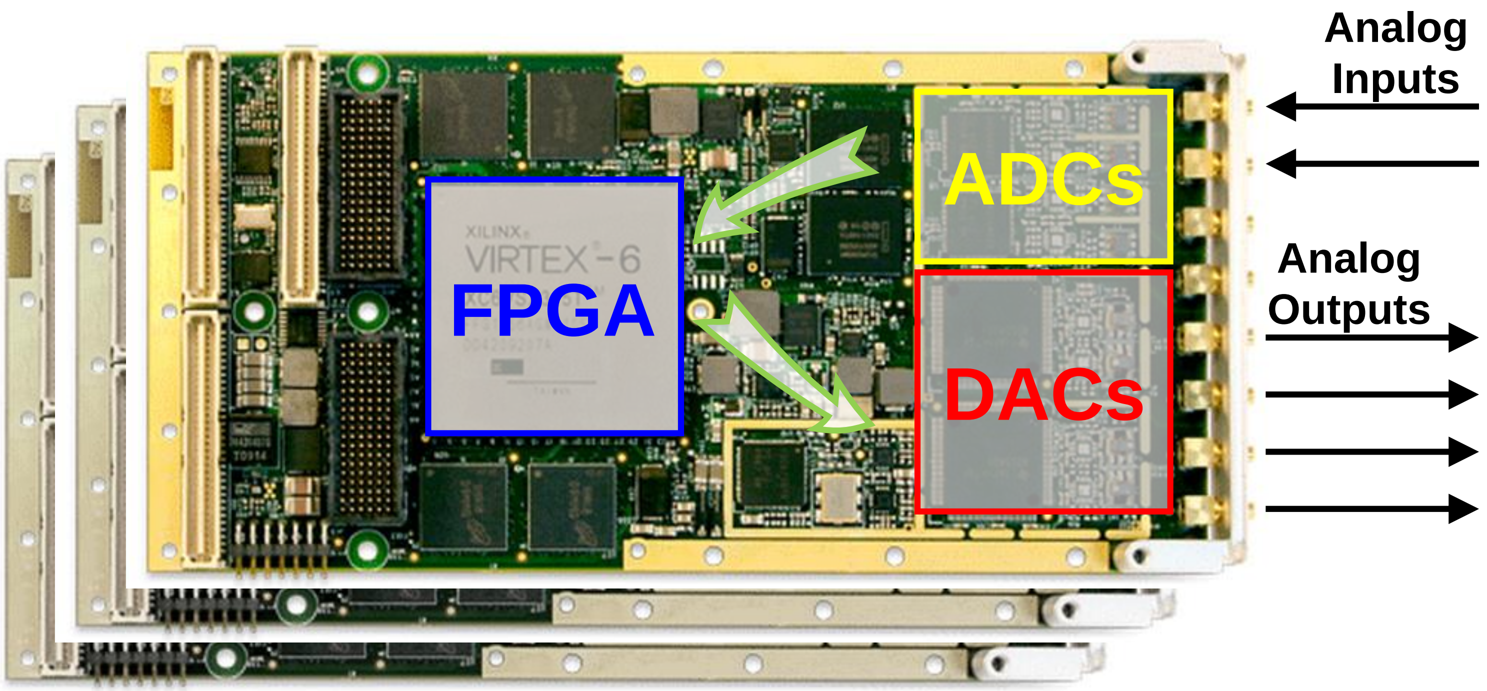






transmon **cavity**

REAL-TIME QUANTUM CONTROLLER FOR FEEDFORWARD CORRECTION



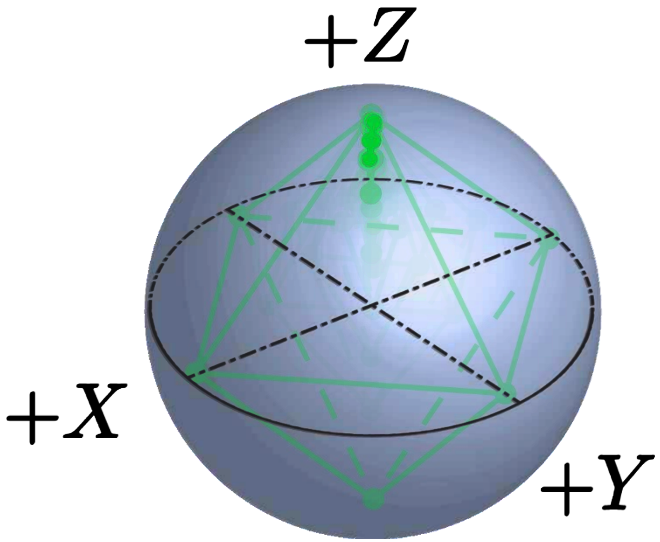
- Commercial FPGA with custom software developed at Yale
- Single system performs all measurement, control, & feedback (latency$\sim$200ns)
- Real-time decision making and on-the-fly pulse generation → essentially infinite program/sequence length

4-CAT ENCODING SLOWS DOWN QUANTUM INFORMATION DECAY

Ofek & Petrenko et al., Nature (2016)

slide courtesy of R. Schoelkopf and A. Petrenko

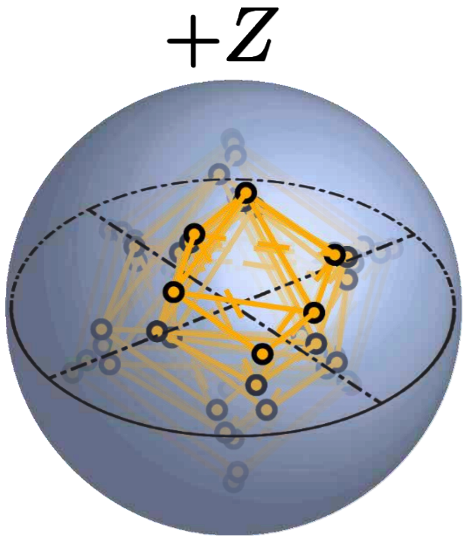
Bare Transmon



Qubit after $109\ \mu s$

Fidelity = 0.26

4Cat Code **NO QEC**

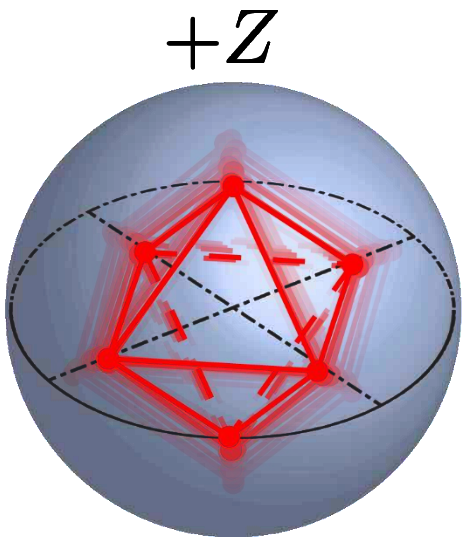


Qubit after $109\ \mu s$

$\alpha = \sqrt{2}$

Fidelity = 0.58

4Cat Code **W/ QEC**



Qubit after $109\ \mu s$

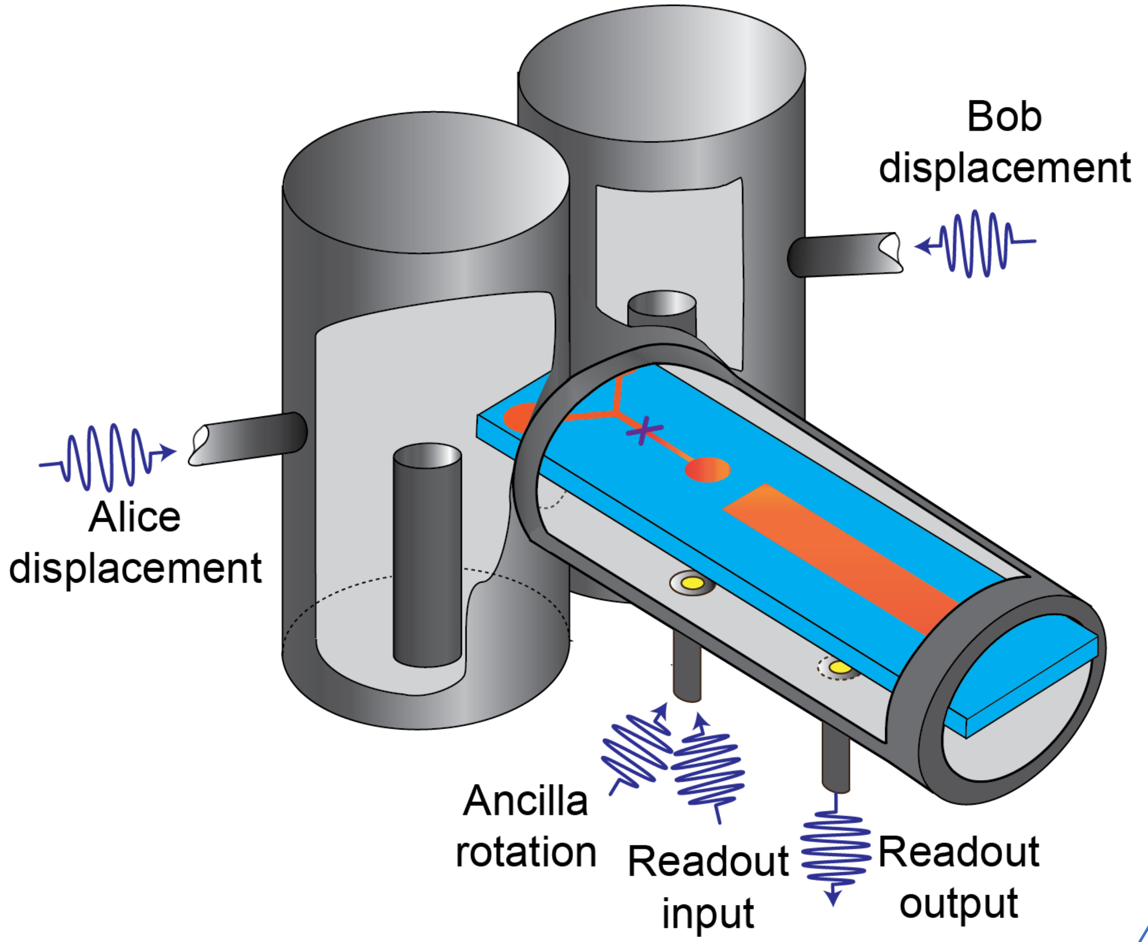
$\alpha = \sqrt{2}$

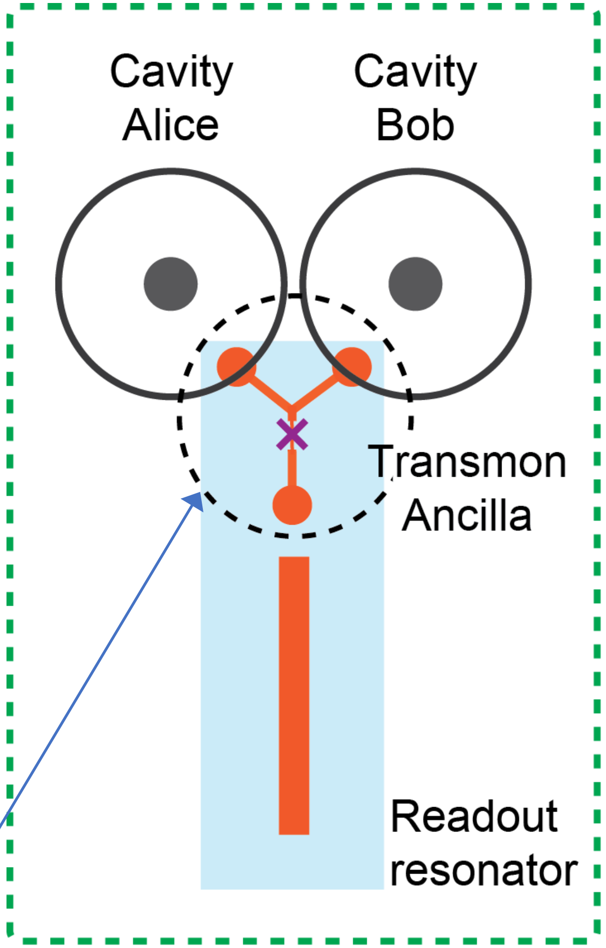
Fidelity = 0.72

QEC = Quantum Error Correction from Parity Monitoring using Field Programmable Gate Array

MULTI-CAVITY ARCHITECTURES

M. Reagor *et al.*, APL (2013),
C. Axline *et al.* (in preparation)
Wang and Gao et al., Science (2016)





The "Y-mon"!!

other experiments currently
underway in the lab with
5 to 10 qubits and 5 to 10 cavities

JOINT WIGNER FUNCTION OF THE TWO-MODE CAT

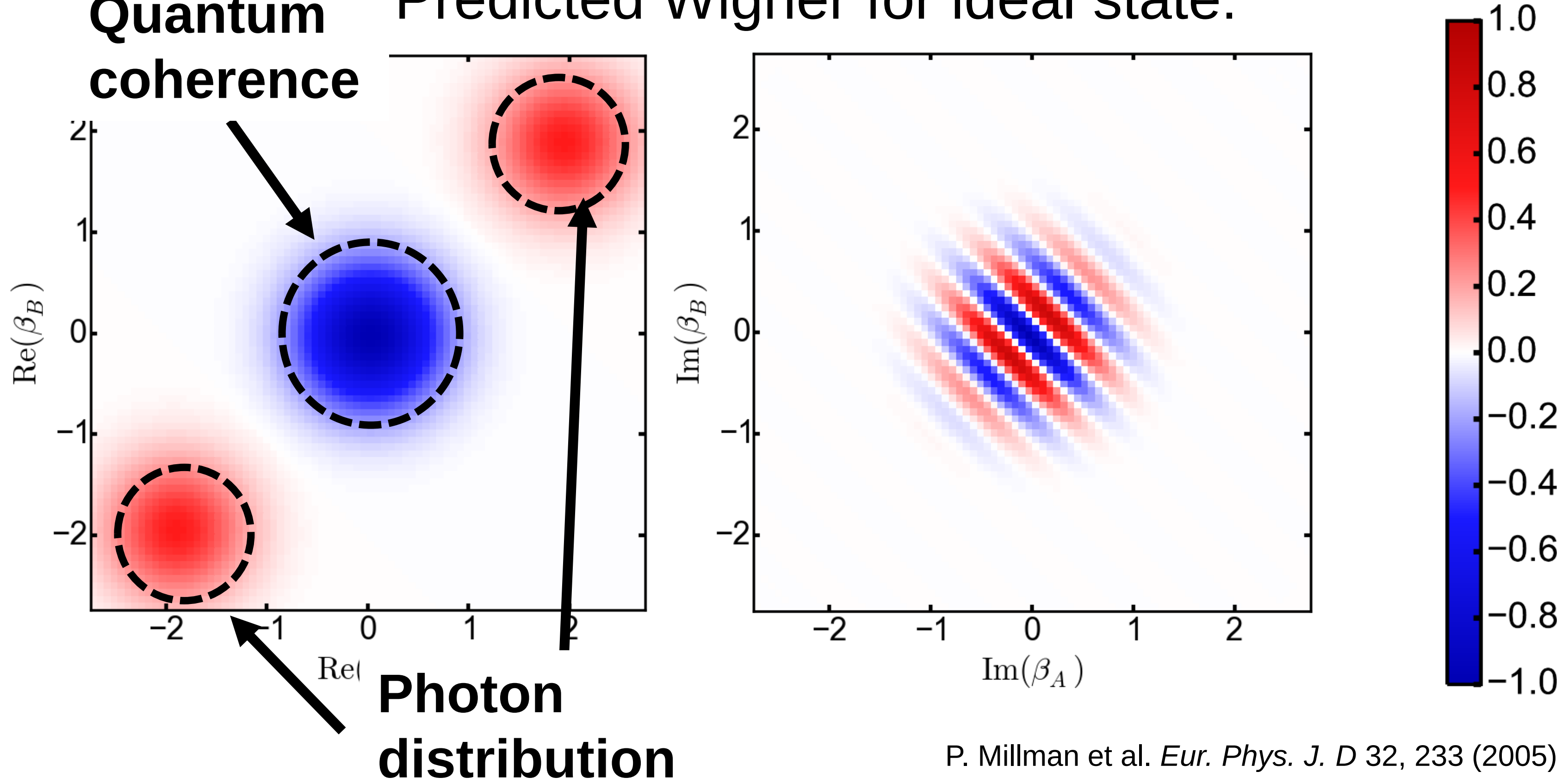
$W_J(b_A, b_B)$: a function in a 4D space

States live in Hilbert space of dimension ~ 150!

$$|y_-\rangle = |a\rangle_A |a\rangle_B - |-a\rangle_A |-a\rangle_B$$

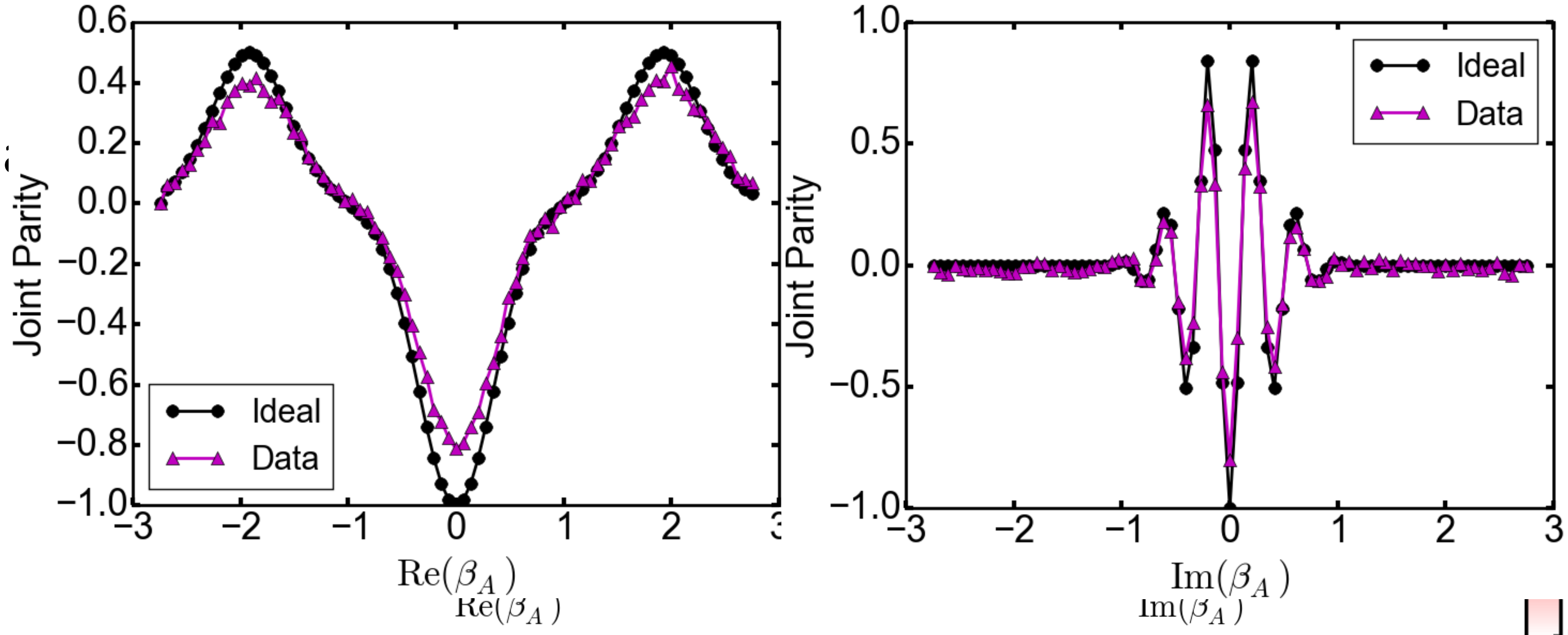
$$(a = 1.92)$$

Predicted Wigner for ideal state:

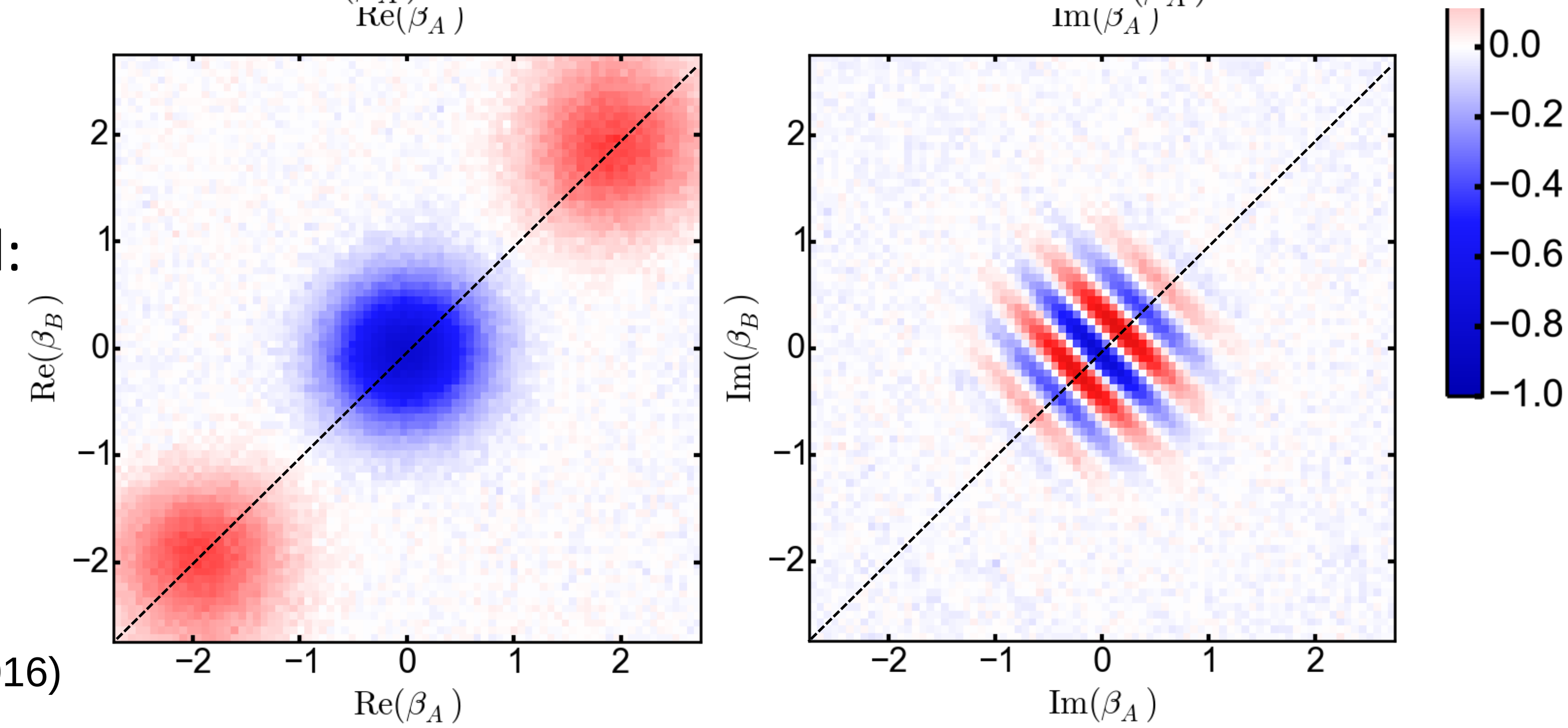


P. Millman et al. *Eur. Phys. J. D* 32, 233 (2005)

Idea



Measured:



Wang and Gao et al., Science (2016)

SUMMARY AND PERSPECTIVES

- Quantum information protection can be static and/or dynamic
- Cat code encodes information in dynamical states: hardware efficiency
- Demonstration of operation while protecting
- Attained break-even point in quantum error correction
- Entanglement of two logical qubits

- Combine protection of cat energy loss and parity monitoring
- Demonstrate hierarchical layers of quantum error correction

MEET THE TEAM!

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L. Frunzio

M. Mirrahimi

L. Glazman

L. Jiang

S. Girvin