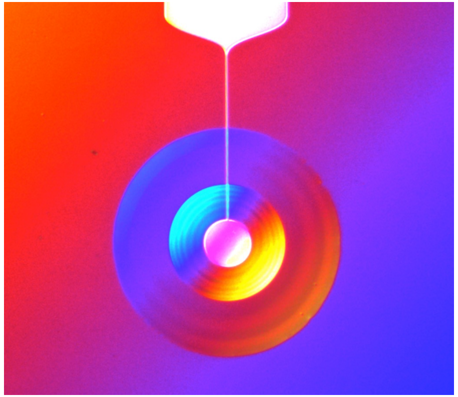
Schrödinger cat states of a 16-μg mechanical oscillator



Yiwen Chu

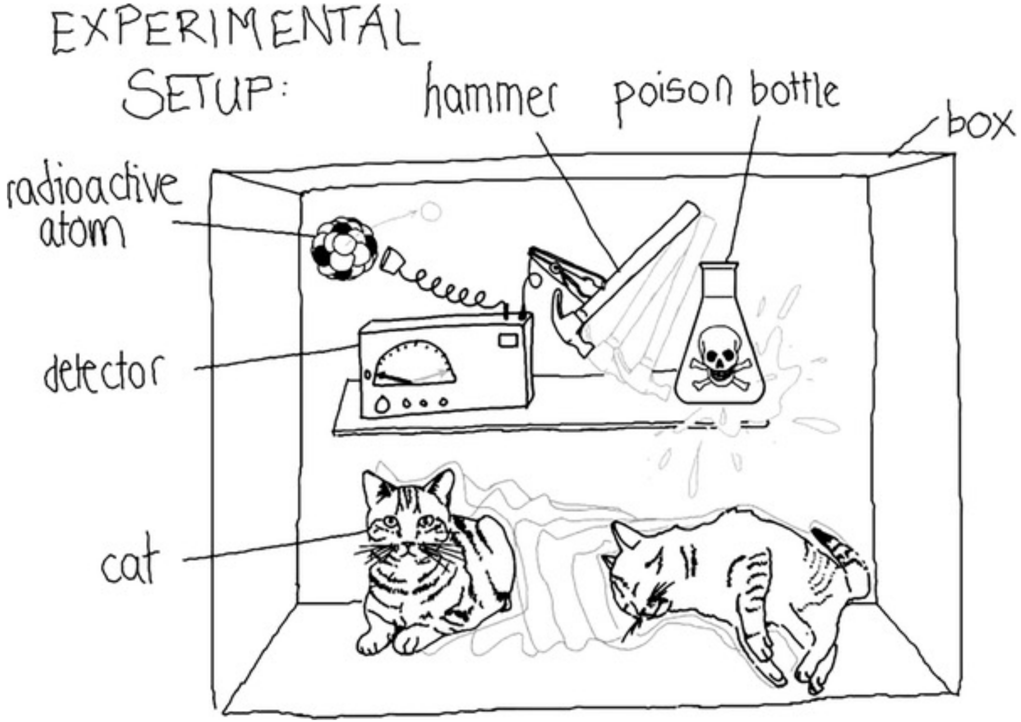
Triangle Quantum Seminar

24 Februrary, 2023

HyQu
www.hyqu.ethz.ch

ETH zürich

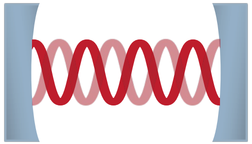
Schrödinger's cat



Macroscopic object in a quantum superposition of **macroscopically distinct states**.

Drawing by Lara Hartjes, from W. P. Schleich et al. Applied Physics B (2016)

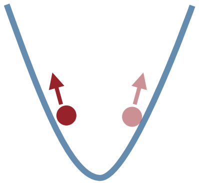
Schrödinger cat states: some examples



Electromagnetic modes

$|\alpha\rangle + |-\alpha\rangle$

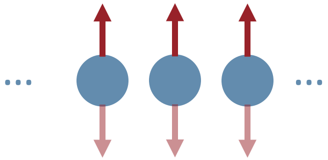
Ourjoumtsev et al. Nature (2007)
Deléglise et al. Nature (2008)
Vlastakis et al. Science (2013)



Motion and internal states of trapped ions

$|\uparrow, \alpha\rangle + |\downarrow, -\alpha\rangle$

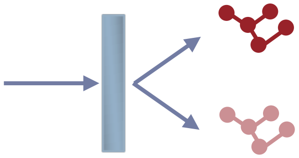
Monroe et al. Science (1996)
Lo et al. Nature (2015)



GHZ states

$|\uparrow\uparrow\uparrow\rangle + |\downarrow\downarrow\downarrow\rangle$

Leibfried et al. Nature (2005)
Gao et al. Nature Physics (2010)



Atom interferometers

$|x\rangle + |-x\rangle$

Fein et al. Nature Physics (2019)

Cat masses

- Photons
- GHZ states of spins
- SQUIDS
- Trapped ions
- Atom/molecular interferometers

- **Solid state mechanical objects**

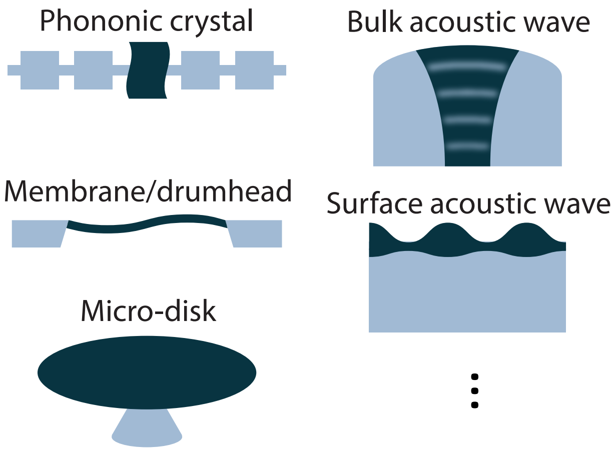
- Schrödinger’s cat

mass (g)

0

10^{-20} g

~10^{3} g

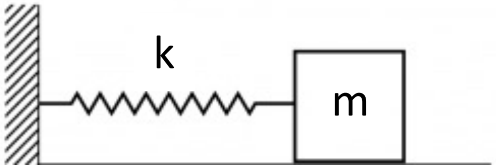


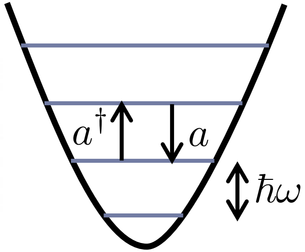
a cat with m = 18 kg →

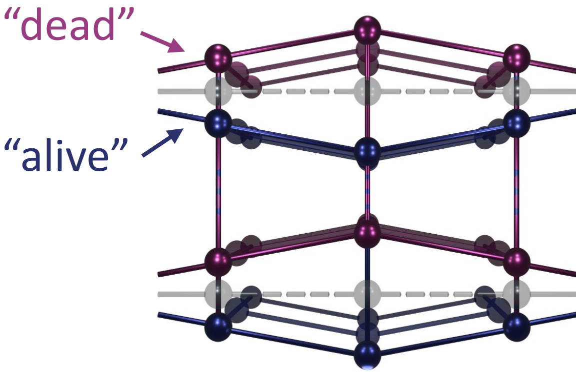
Wikipedia

Macroscopically distinct states

Mechanical modes: harmonic oscillators

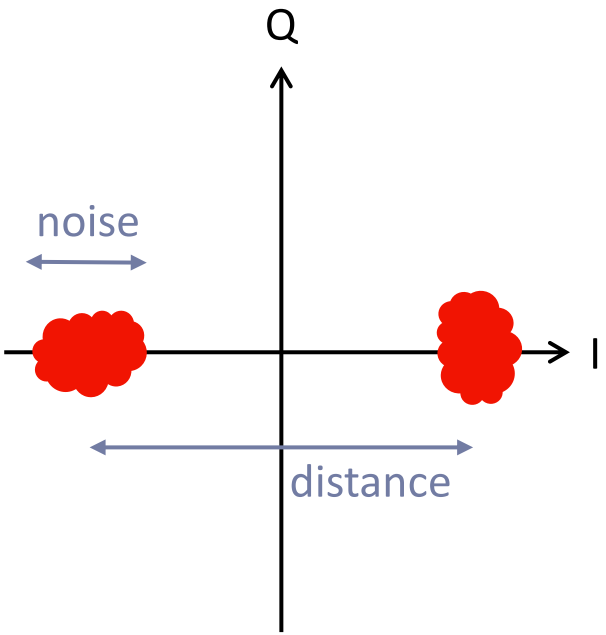




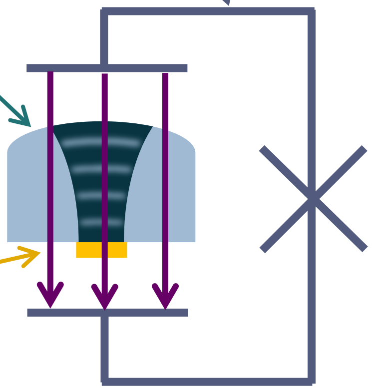


Snapshot of atomic lattice

Phase space picture



Circuit QAD



Piezoelectric tensor

Strain

Electric field

$$H_{int} = \int e \cdot S \cdot E_q \, dV$$

$$= \hbar g_0 (a + a^\dagger)(\sigma_+ + \sigma_-)$$

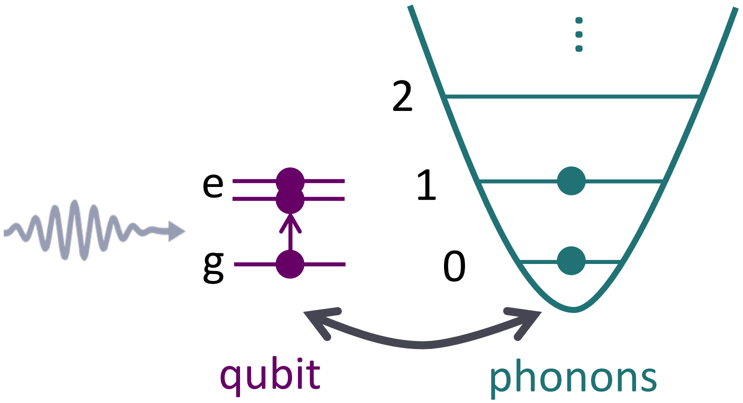
$$\sim \hbar g_0 (a\sigma_+ + a^\dagger \sigma_-)$$

coupling strength

phonon

qubit

The strong coupling regime

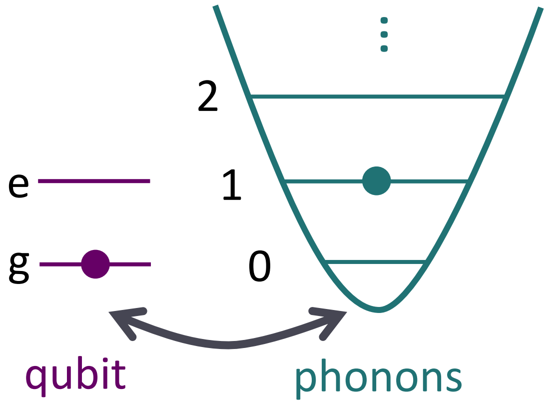


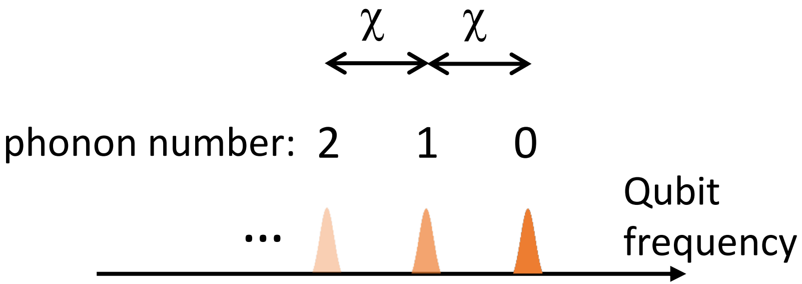
$$H = \hbar g_0 (a\sigma_+ + a^\dagger \sigma_-)$$

Quantum ground state: $\hbar\omega \gg k_B T$

Strong coupling regime: $g_0 \gg \kappa, \gamma$

The strong dispersive regime





$$H = \hbar g_0 (a\sigma_+ + a^\dagger \sigma_-) \xrightarrow[\Delta = \omega_q - \omega_m]{|\Delta| \gg |g_0|} H_{disp} = \hbar \chi a^\dagger a \sigma_z / 2$$

Dispersive shift: $\chi \sim 2g_0^2/\Delta$

Quantum ground state: $\hbar\omega \gg k_B T$

Strong coupling regime: $g_0 \gg \kappa, \gamma$

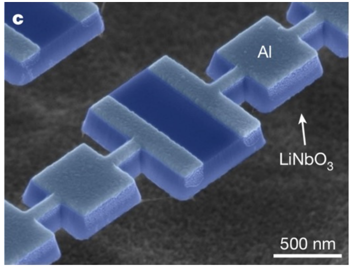
Strong dispersive regime: $\chi \gg \kappa, \gamma$

Circuit QAD devices

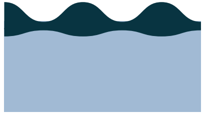
Some examples

Phononic crystal

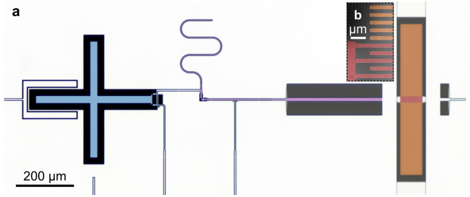
P. Arrangoiz-Arriola et al.
Nature (2019)



Surface acoustic wave

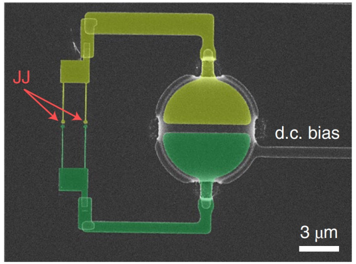


K. Satzinger et al.
Nature (2018)

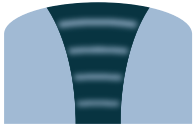


Membrane/drumhead

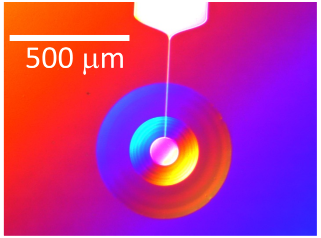
J. Viennot et al., *PRL* (2018)



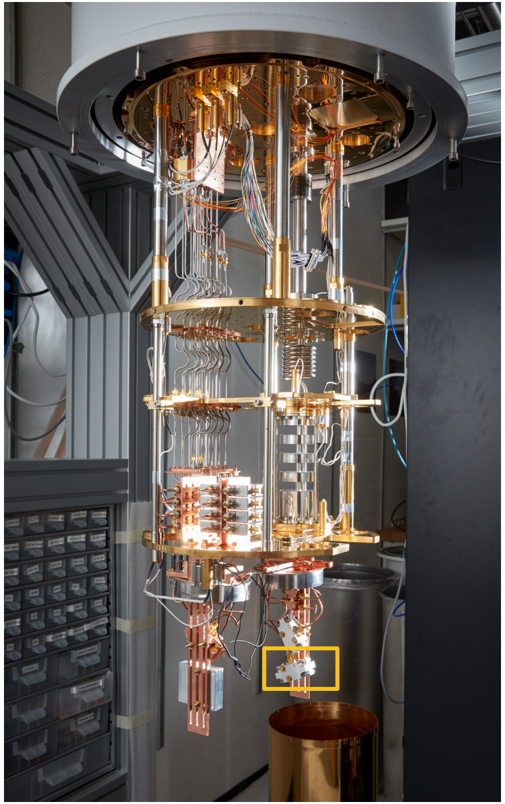
Bulk acoustic wave



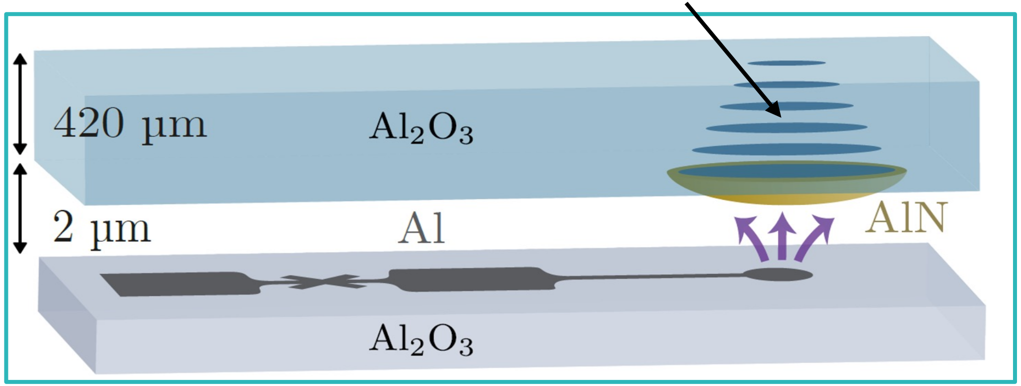
U. von Luepke, Y. Yang, M. Bild et al. Nat. Phys. (2022)

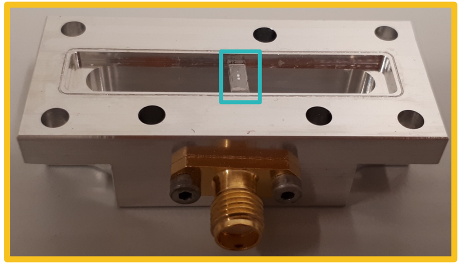


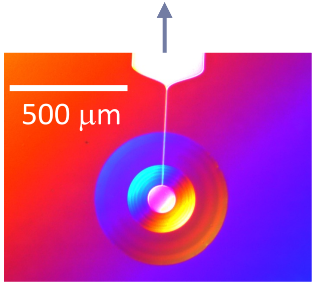
Circuit QAD with bulk acoustic waves



HBAR: high overtone bulk acoustic wave resonator

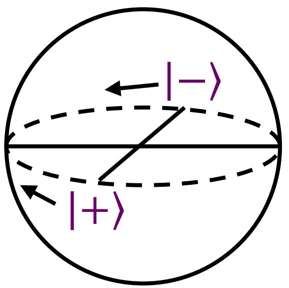






Cat states of a mechanical resonator

Initial state: $|\psi(0)\rangle = |\pm, \alpha\rangle$ $\qquad |\pm\rangle = \frac{|e\rangle \pm |g\rangle}{\sqrt{2}}$

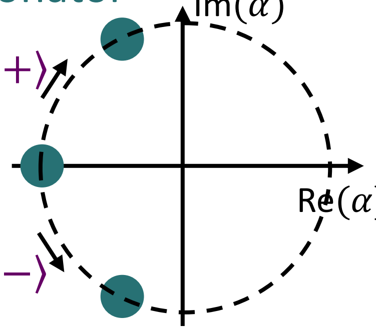


$$H = \hbar g_0\left(a\sigma_+ + a^\dagger\sigma_-\right)$$
$$\approx \hbar g_0 \alpha(\sigma_+ + \sigma_-) = \hbar g_0 \alpha \sigma_x \text{ for } |\alpha| \gg 1 \text{ and real}$$

$\rightarrow |\psi(t)\rangle \approx e^{\mp i g_0 \alpha t}|\pm, \alpha\rangle$ to 0th order in $\frac{n-\alpha^2}{\alpha^2}$

$$\approx e^{\mp i g_0 \alpha t/2} \frac{e^{\mp i g_0 t/2\alpha}|e\rangle \pm |g\rangle}{\sqrt{2}} \left|\alpha e^{\mp i g_0 t/2\alpha}\right\rangle$$

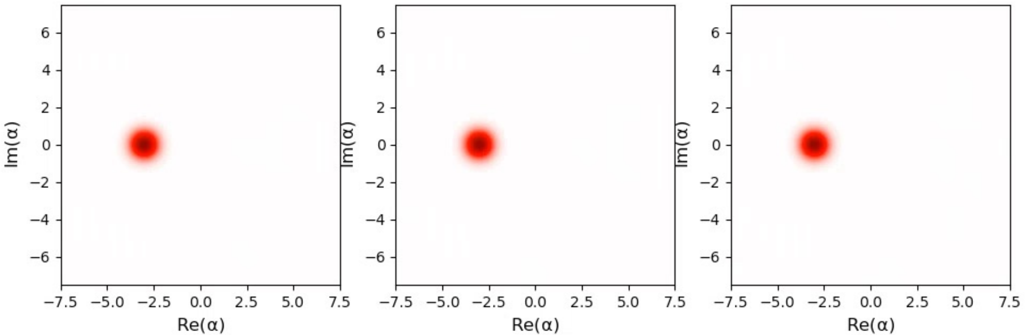
to 1st order in $\frac{n-\alpha^2}{\alpha^2}$

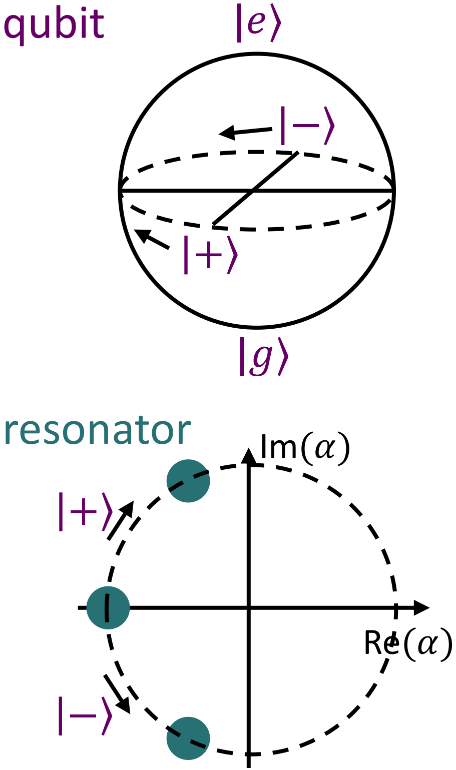


V. Bužek et al. PRA (1992), A. Auffeves et al. PRL (2003)

Cat states of a mechanical resonator

Qubit initial state $|-\rangle$ $|+\rangle$ $|e\rangle = \frac{|+\rangle + |-\rangle}{\sqrt{2}}$

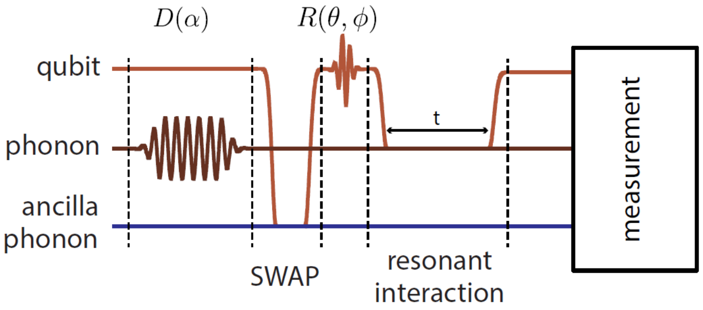




At time $t_C = \frac{\pi\alpha}{g_0}$, a "Schrödinger cat" state forms

Cat states of a mechanical resonator

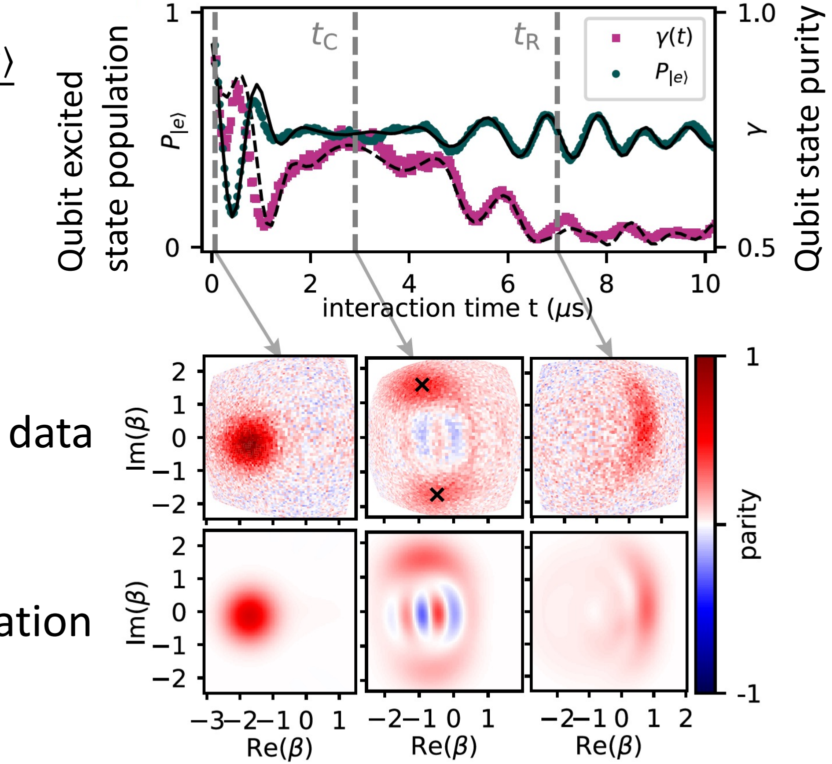
Initial state: $|\psi(0)\rangle = |e, \alpha\rangle = \frac{|+,\alpha\rangle + |-,\alpha\rangle}{\sqrt{2}}$



Wigner function:

$$\frac{\pi}{2} W(\beta) = \mathrm{Tr}(\hat{D}(-\beta)\rho\hat{D}(\beta)\hat{\Pi})$$

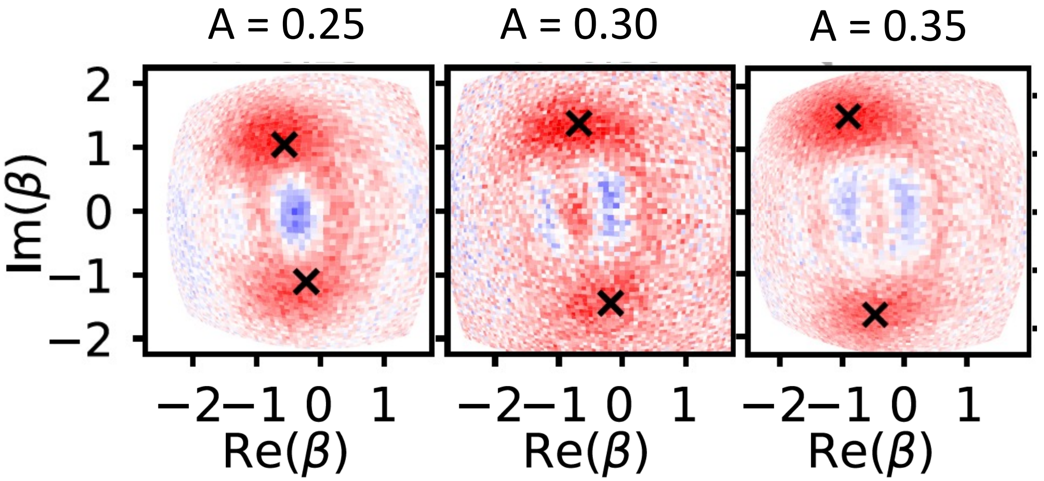
$\hat{\Pi}$: Parity operator

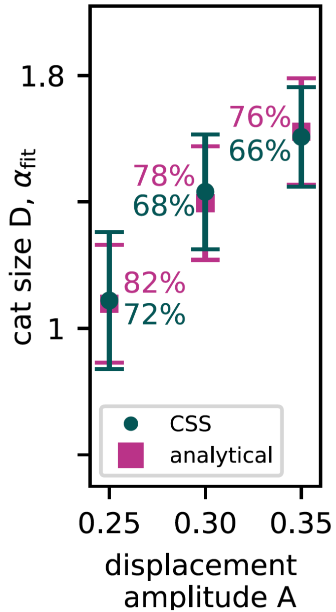


Cat size

- CSS: coherent state superposition
- analytical: full Hamiltonian simulation

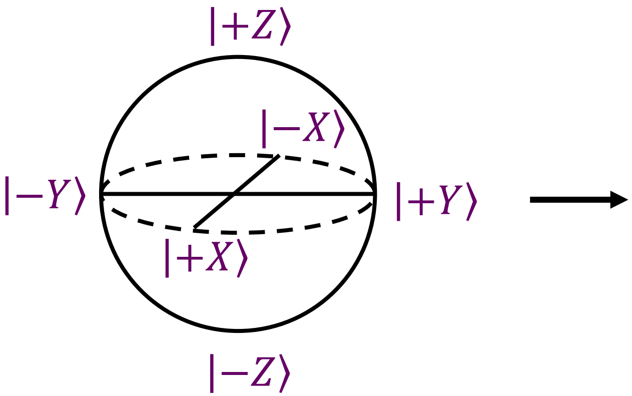
A: Displacement drive amplitude



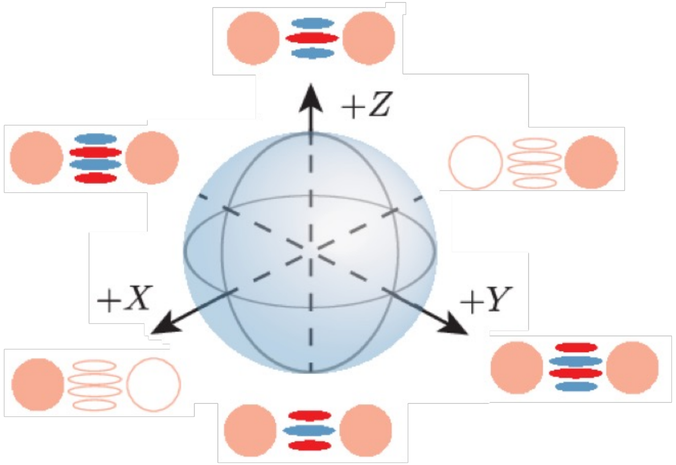


Mapping of qubit states

qubit

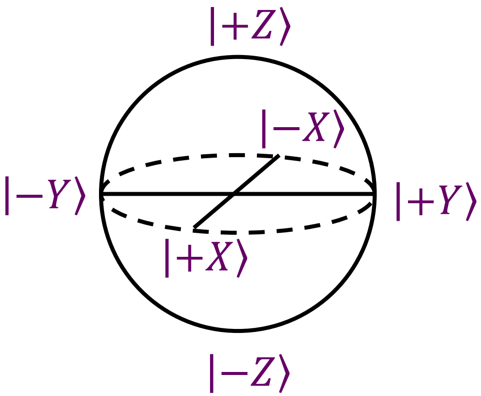


resonator

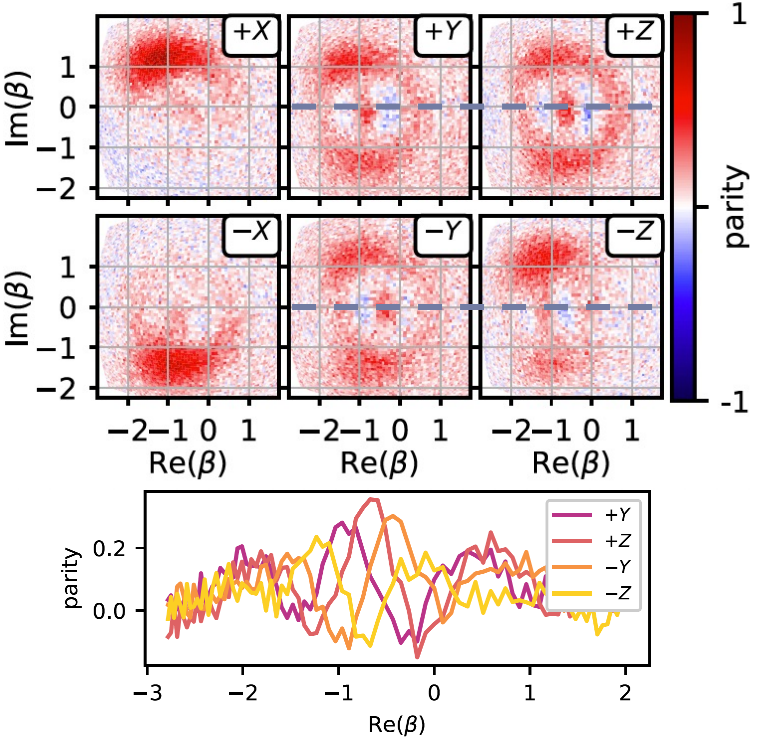


Mapping of qubit states

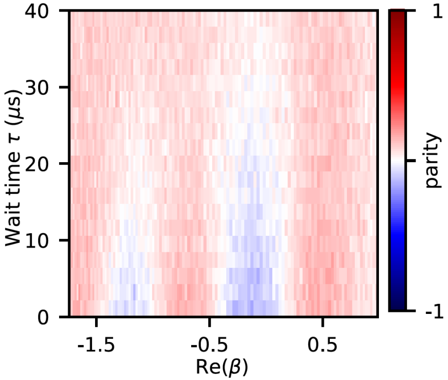
qubit



resonator

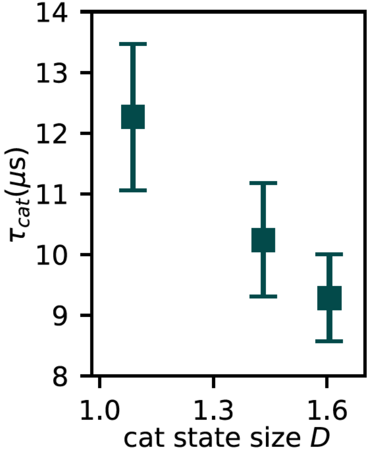


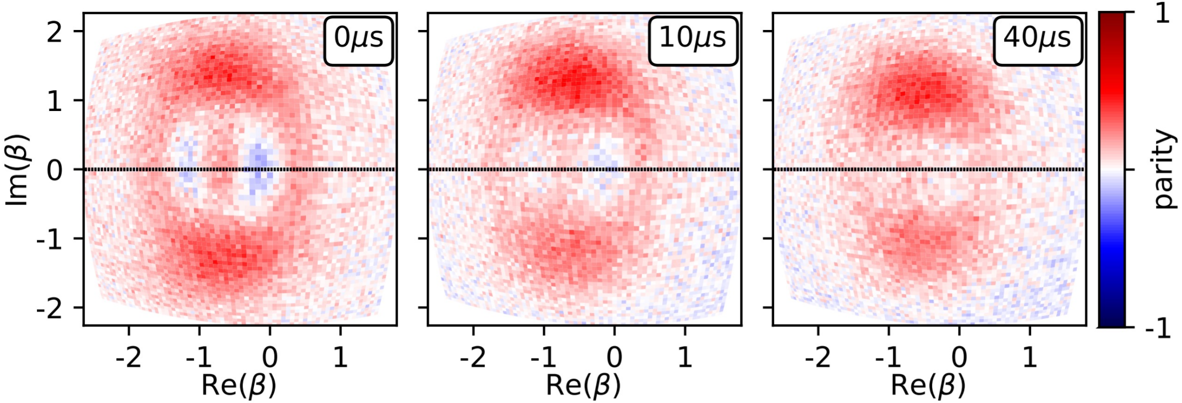
The fate of a cat



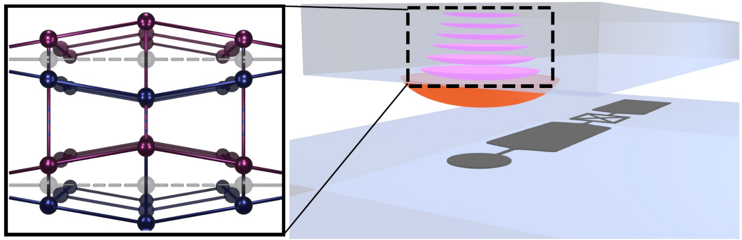
negativity $= \int d\beta \, [|W(\beta, t)| - W(\beta, t)]$

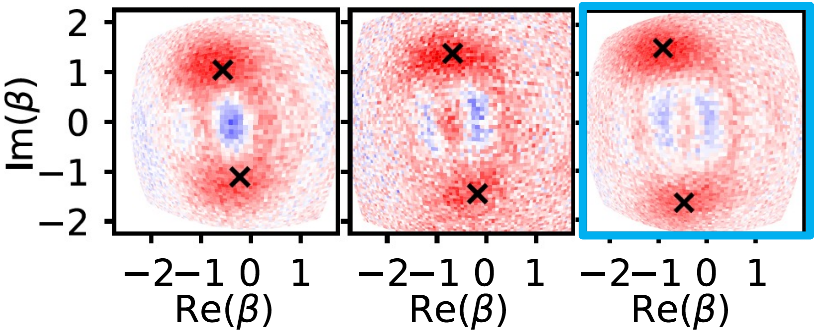
negativity decay constant





Cat facts



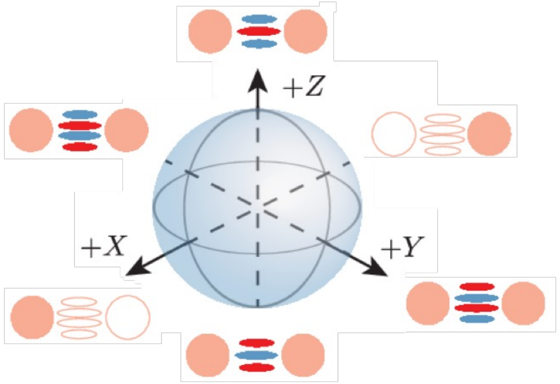


Effective mass: 16 μg
Number of atoms: ~ 10^{17}
Phase space distance: D = 1.61 (D^2 = 2.6)
Physical delocalization: 2×10^{-18} m

M. Bild, M. Fadel, Y. Yang et al. arXiv:2211.00449 (2022)

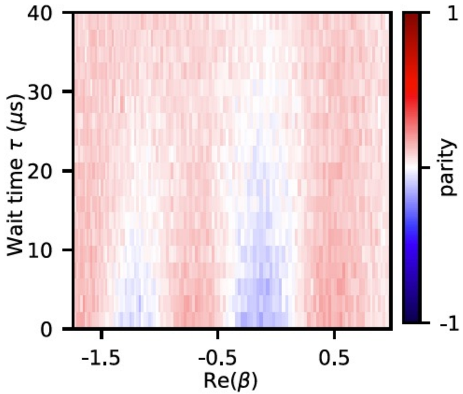
What are cat states good for?

Quantum information



P. Cochrane, G. Milburn, and W. Munro, PRA (1999)
M. Mirrahimi et al. New J. Phys. (2014)
R. Lescanne et al., Nat. Phys. (2020)
A. Grimm et al., Nature (2020)
C. Chamberland et al. PRX Quantum (2022)

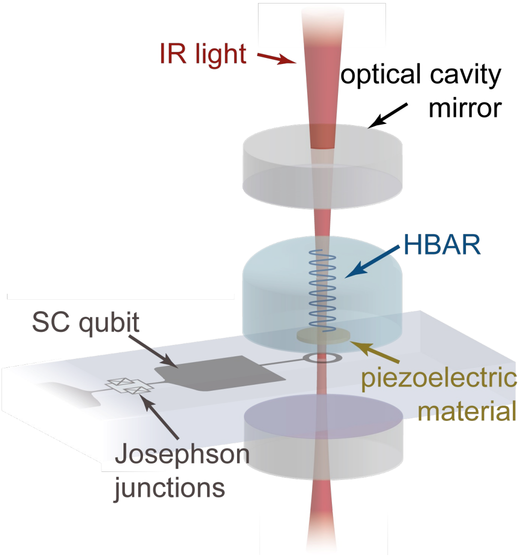
Quantum sensing/metrology



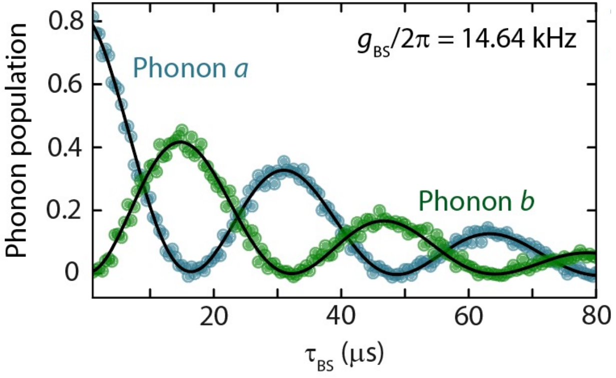
W. Munro et al., PRA (2002)
A. Bassi et al., Rev. Mod. Phys (2013)
M. Gely and G. Steele, AVS Quantum Science (2021)
B. Schrinski et al. arXiv:2209.06635 (2022)

Hybrid quantum systems with BAWs

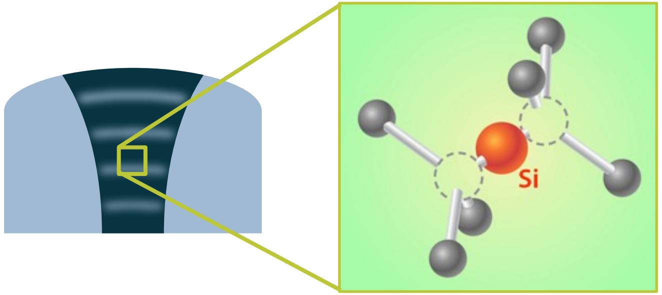
Quantum microwave - optical transduction



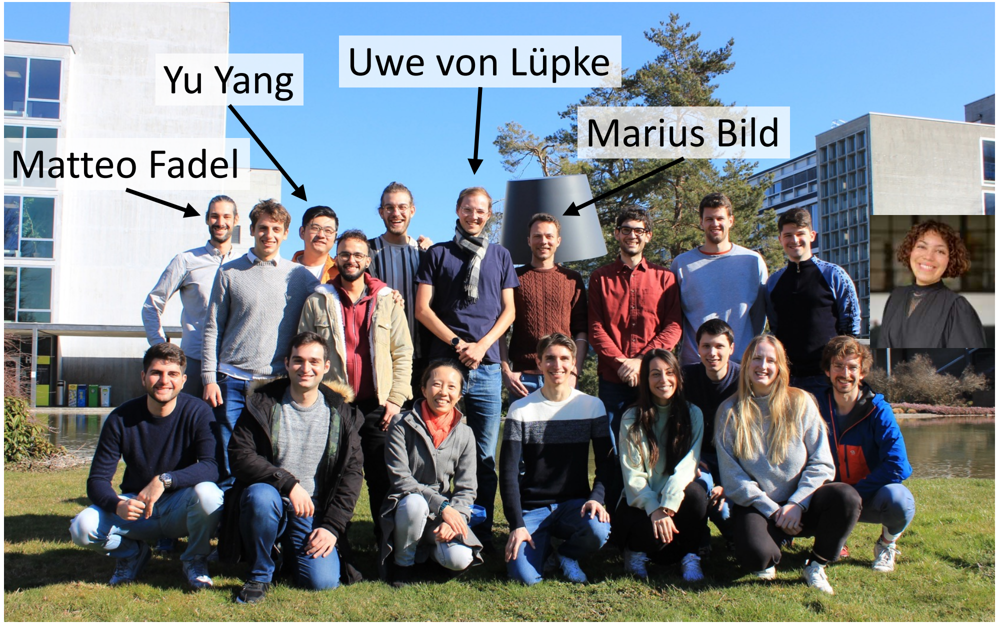
Circuit QAD for quantum information processing



Phonon-spin interface



We're working on it!



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Michael Vanner (Imperial College London)
Yaxing Zhang (Google)

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Debdeep Jena, John Wright (Cornell)
Brian Downey, Vikrant Gokhale (NRL)
Luis Guillermo Villanueva (EPFL)