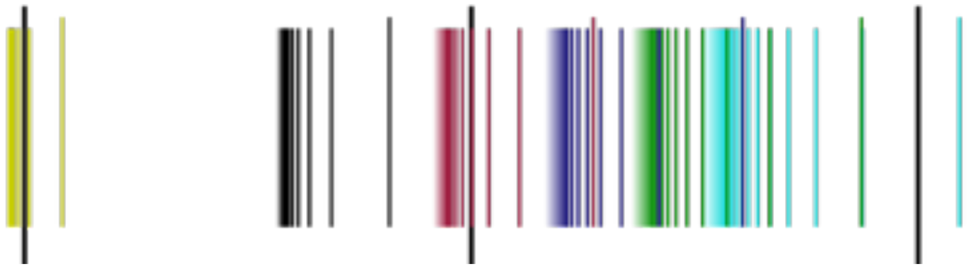
Testing quantum mechanics with 16-microgram Schrödinger cat states

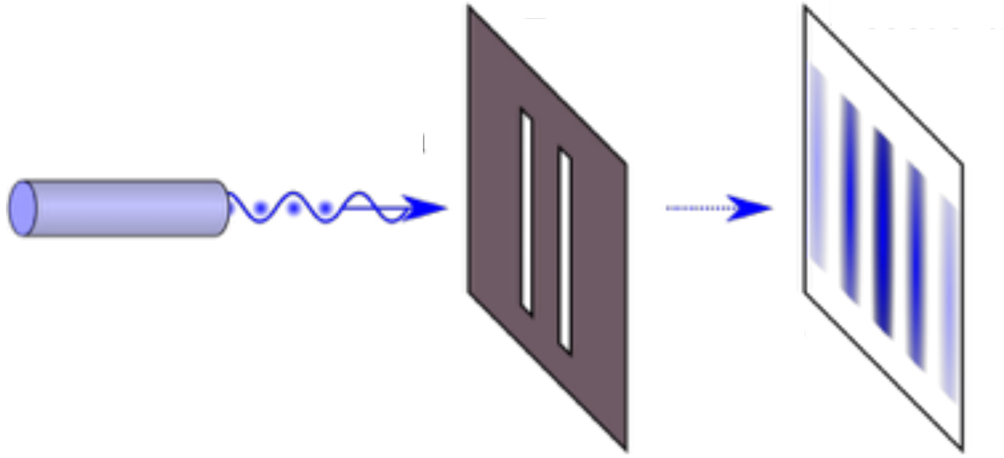
Dr. Matteo Fadel

ETH zürich

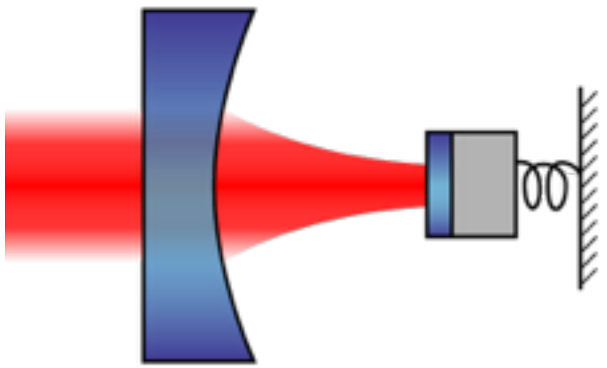
precision spectroscopy

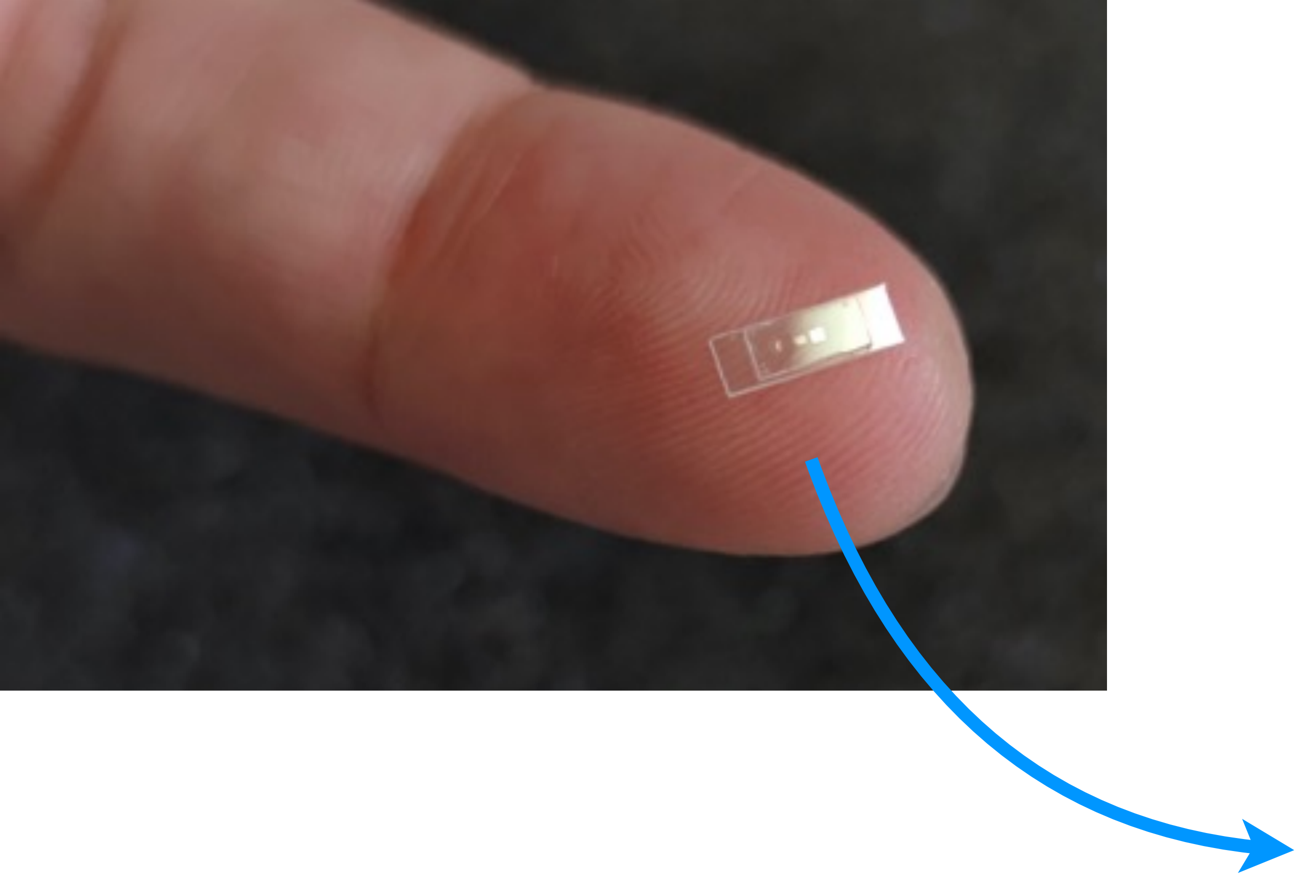


matter-wave interferometry

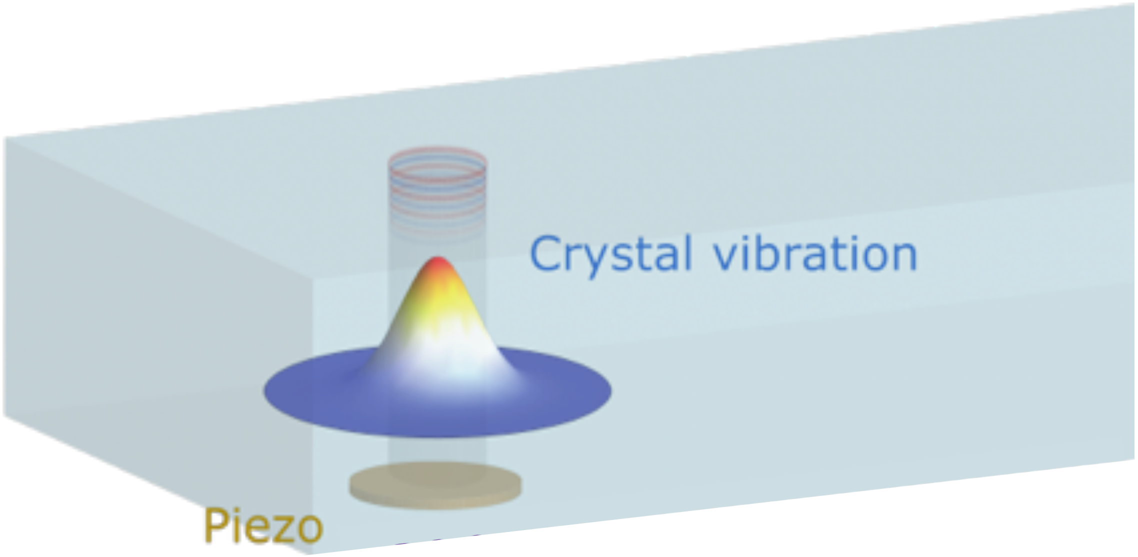


mechanical oscillators





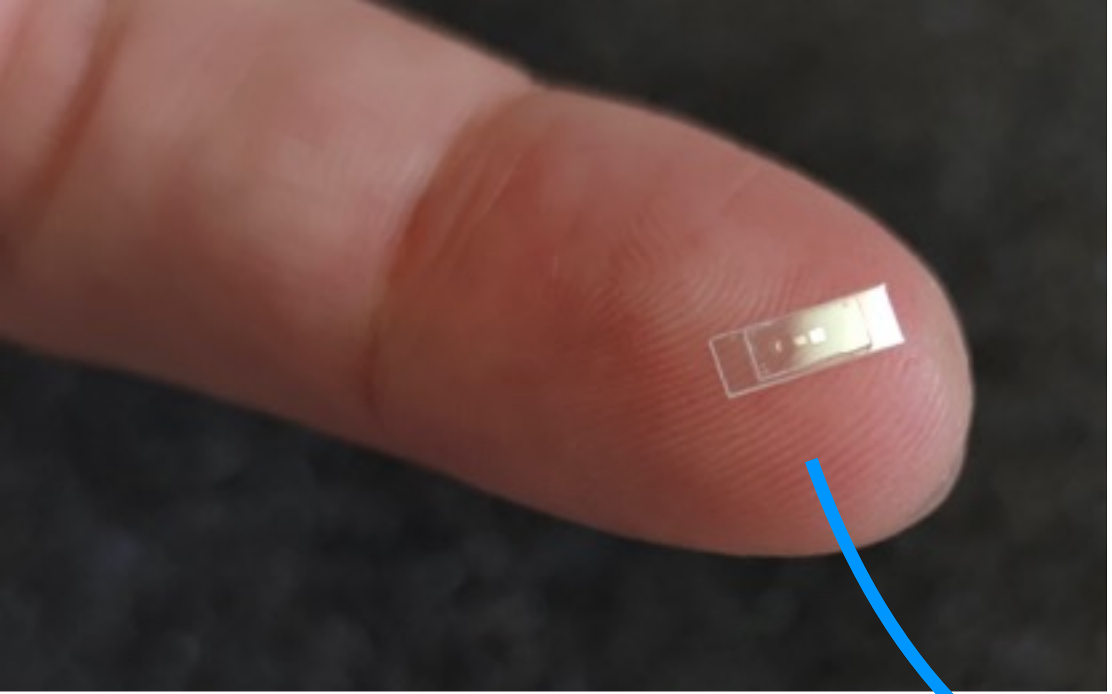
bulk acoustic-wave resonator



frequency $\sim 6\,\mathrm{GHz}$

effective mass $M_{\mathrm{eff}} \approx 16\,\mu\mathrm{g}$

number of atoms $\sim 10^{17}$



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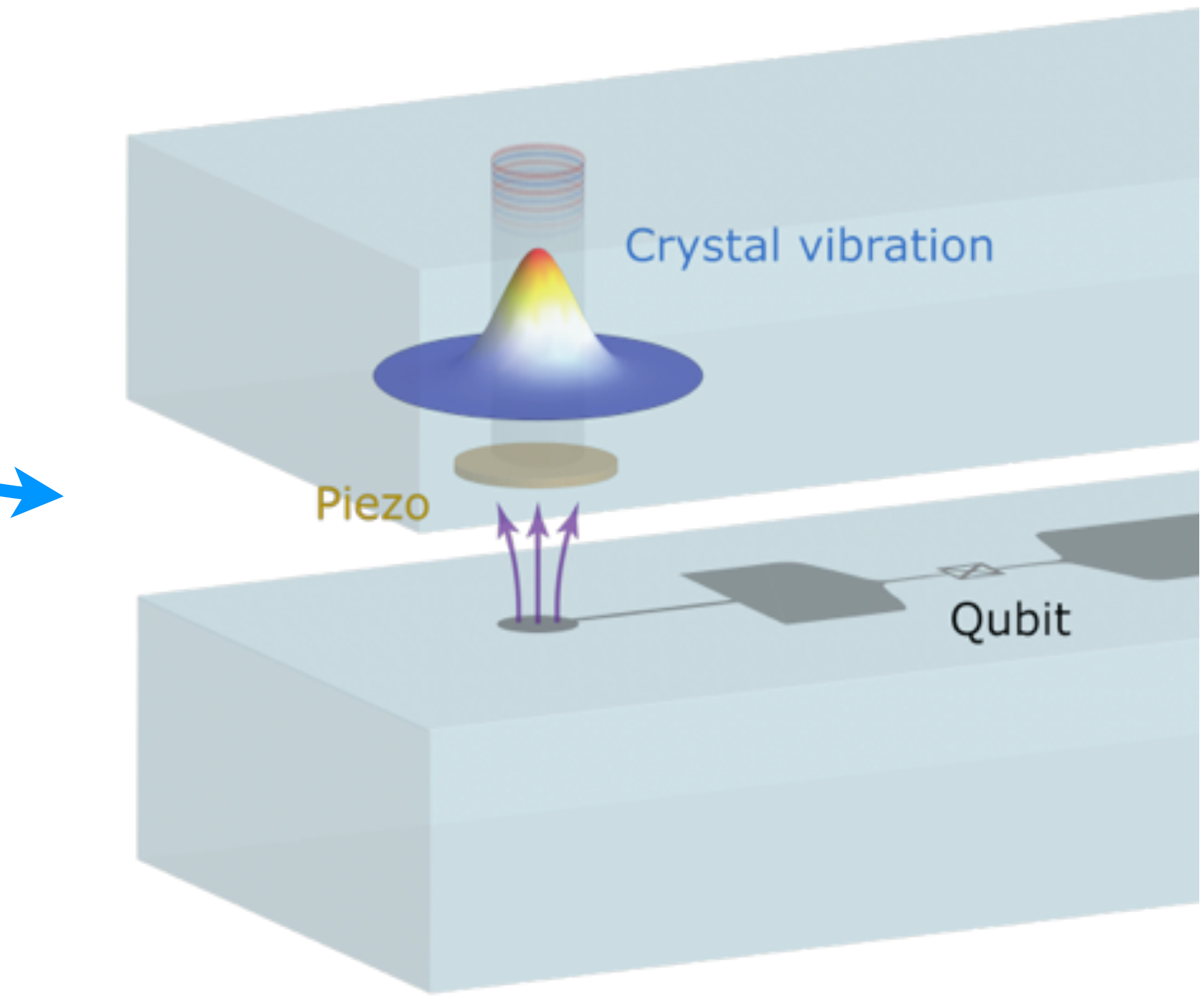

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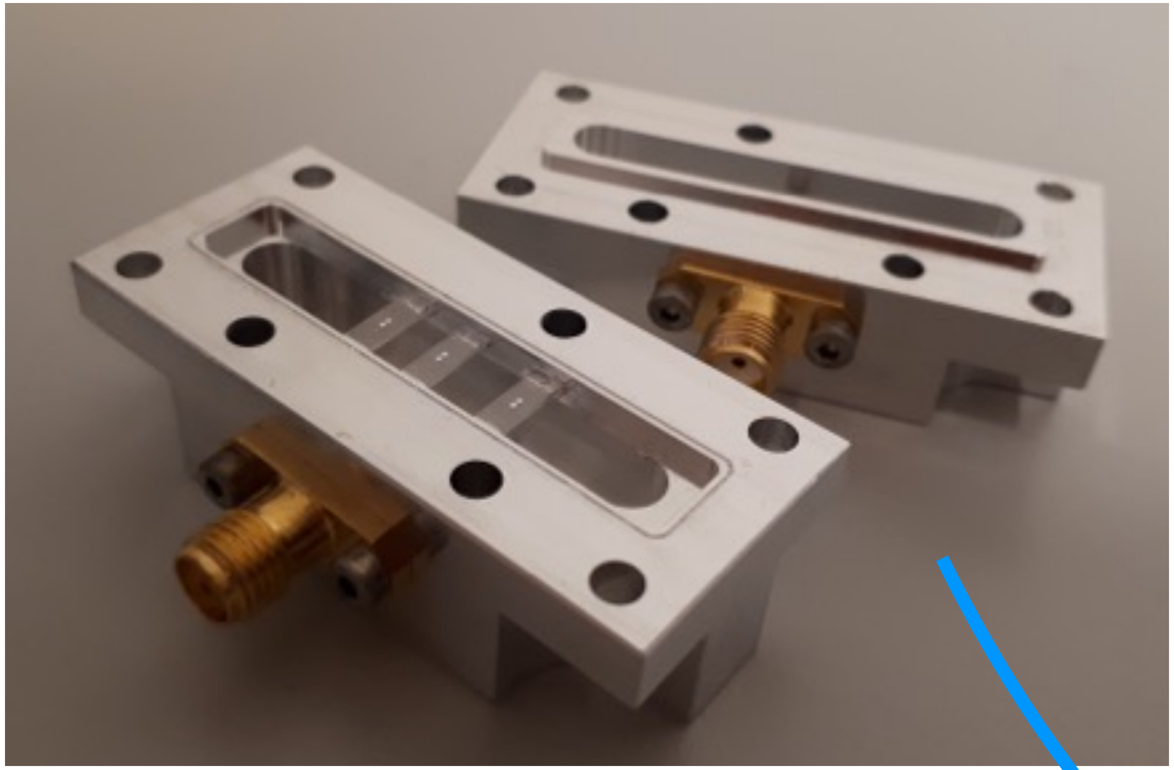
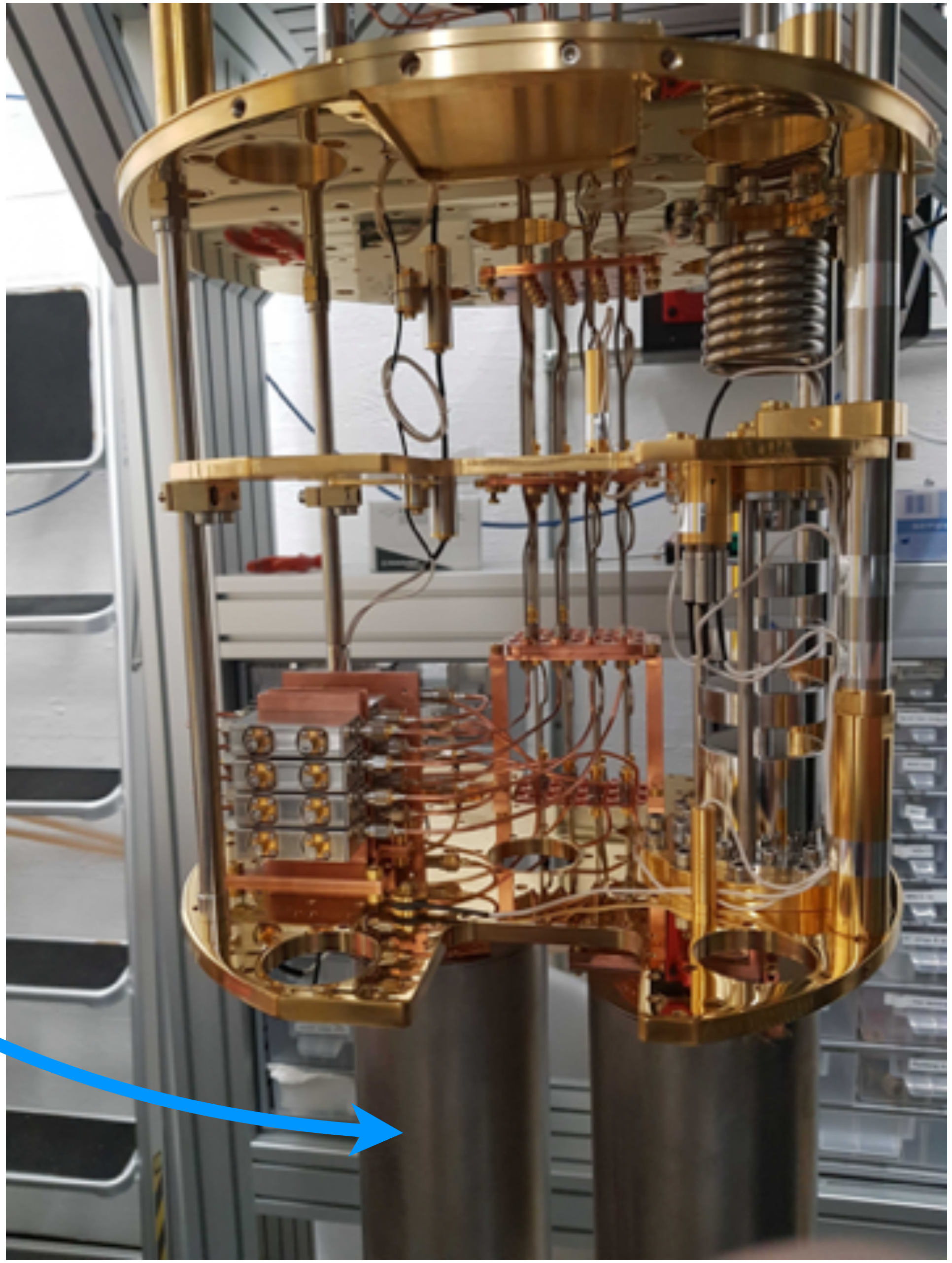
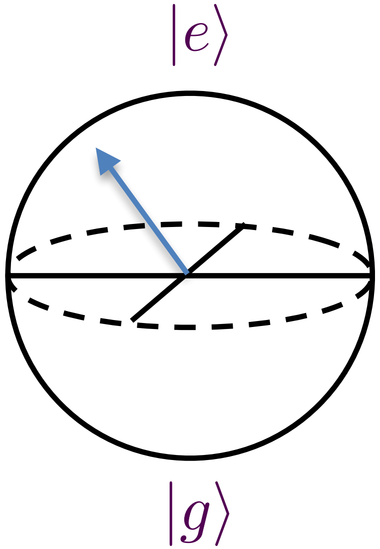


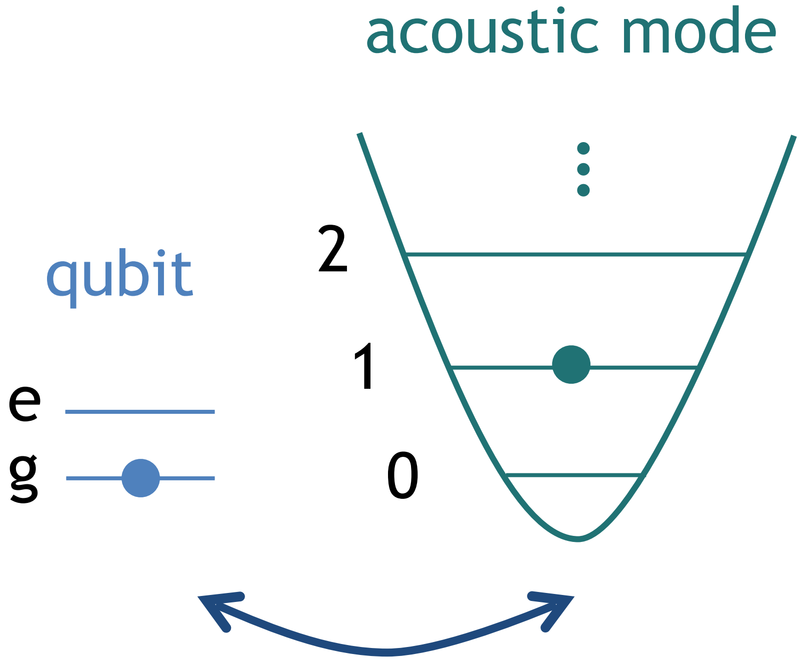


$T \approx 10$ mK

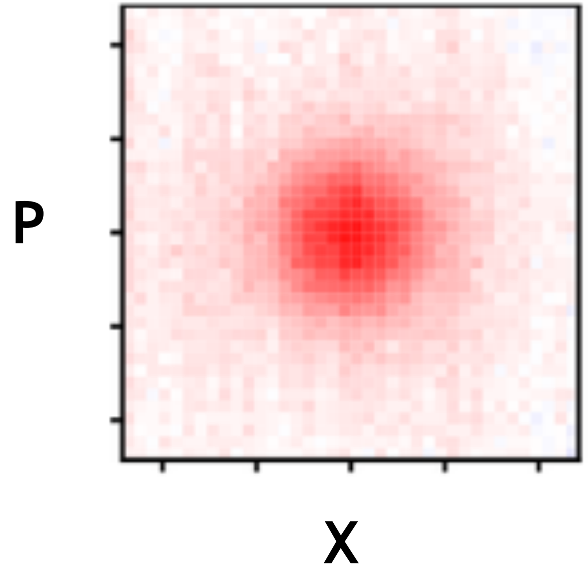
$$k_B T \ll \hbar\omega$$

ground state cooling “for free”

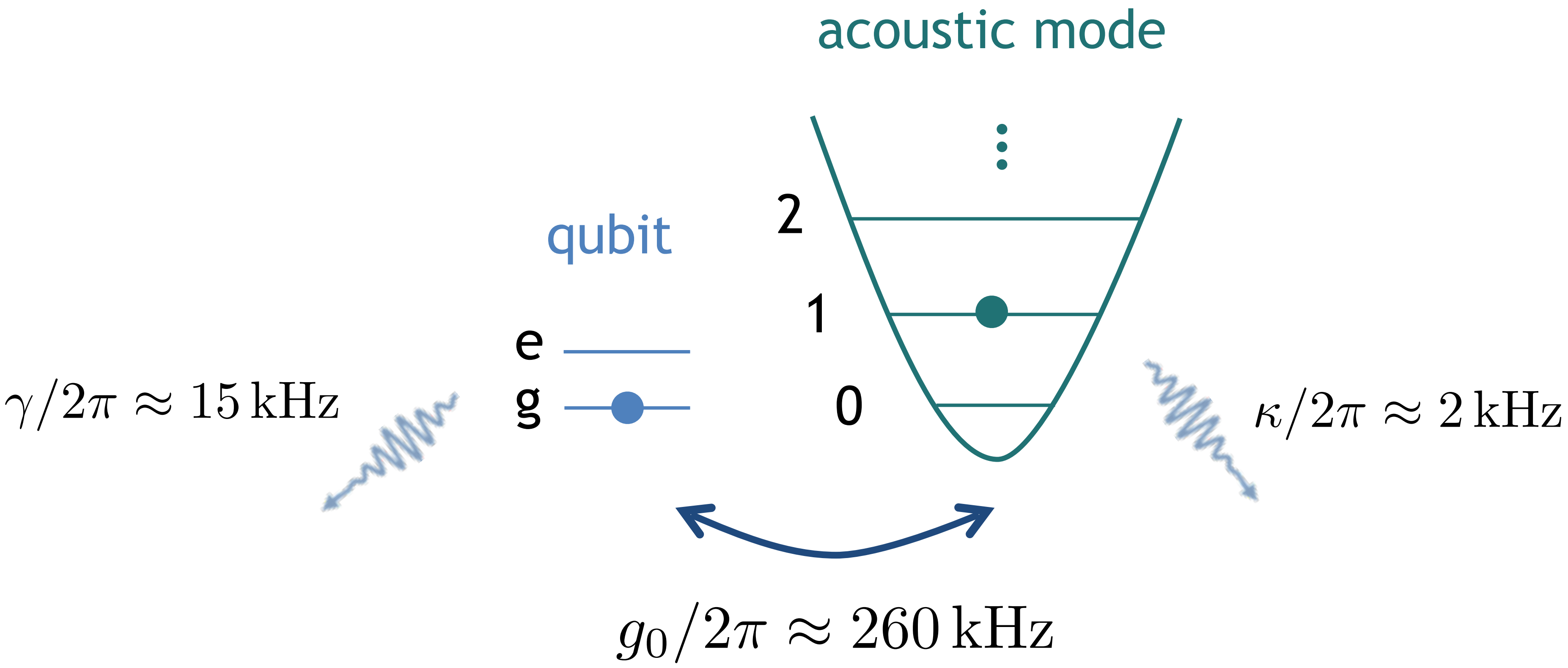




$$g_0/2\pi \approx 260\,\mathrm{kHz}$$



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

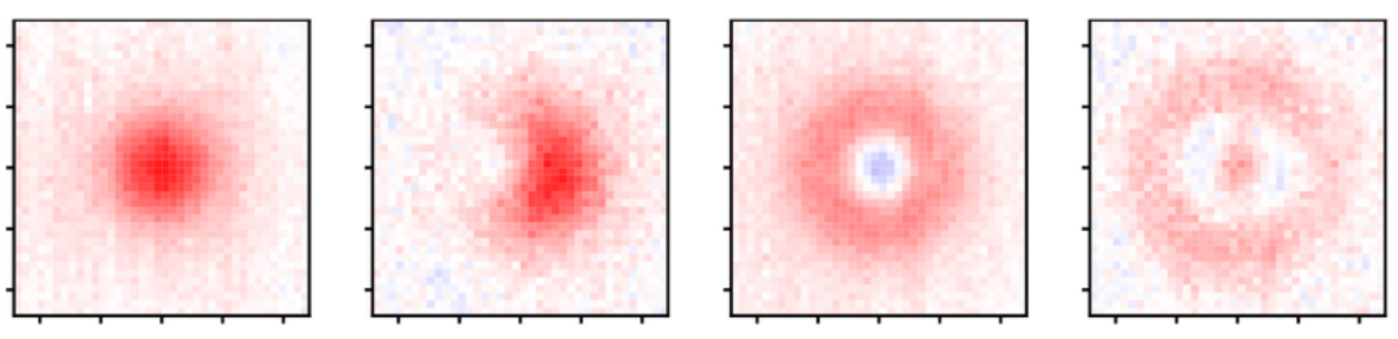


$$H/\hbar = g_0(\sigma^+ a + \sigma^- a^\dagger)$$

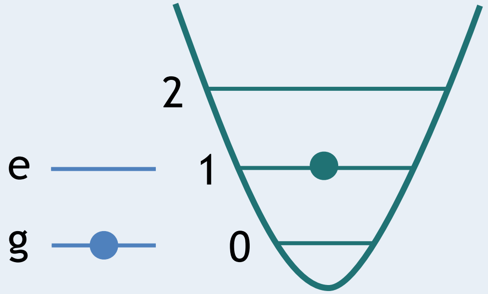
Jaynes-Cummings interaction in the **strong coupling** regime $g_0 \gg \kappa, \gamma$

preparation of the resonator state

Fock states



$|0\rangle$ $\quad$ $|0\rangle + |1\rangle$ $\quad$ $|1\rangle$ $\quad$ $|2\rangle$



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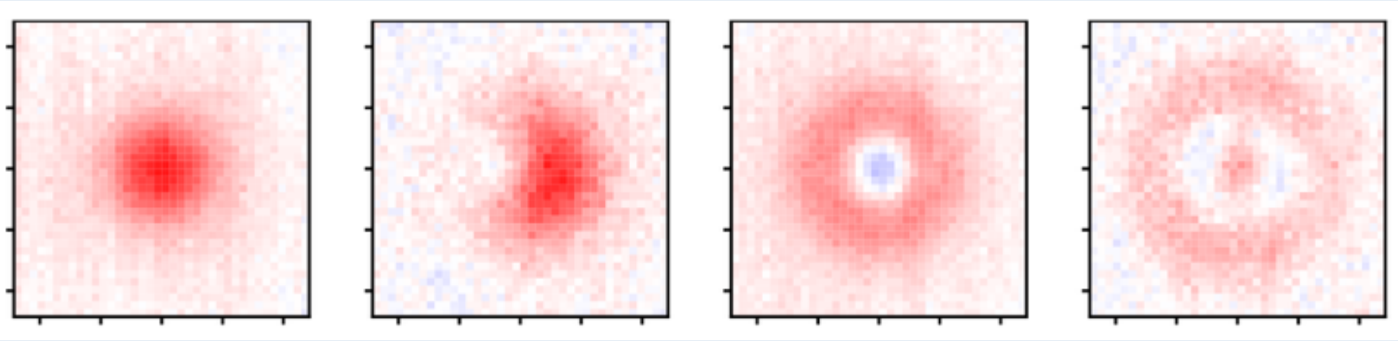

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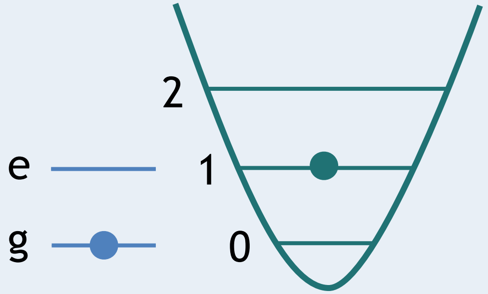
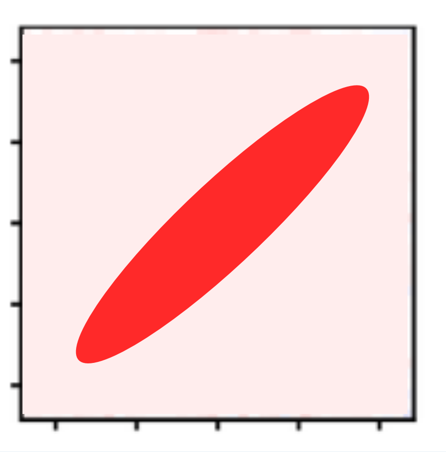


Squeezed states

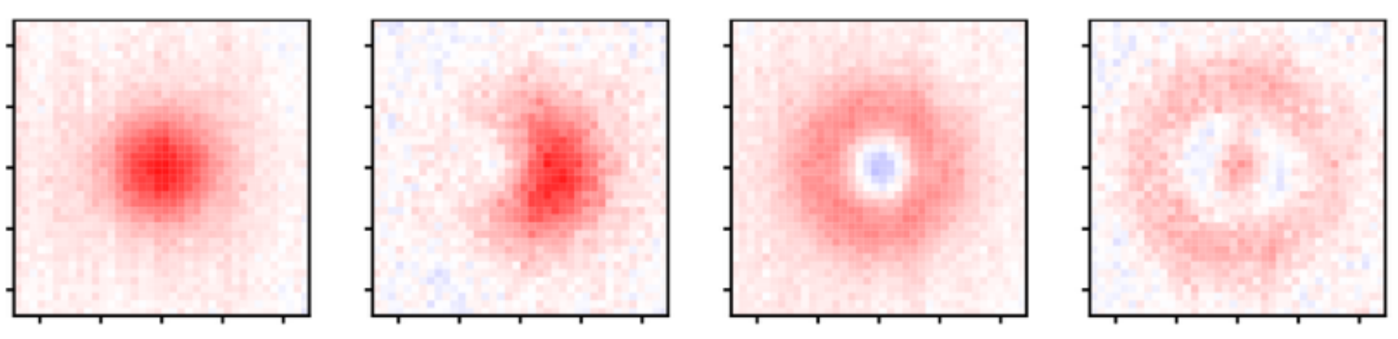
use the qubit as a four-wave mixer



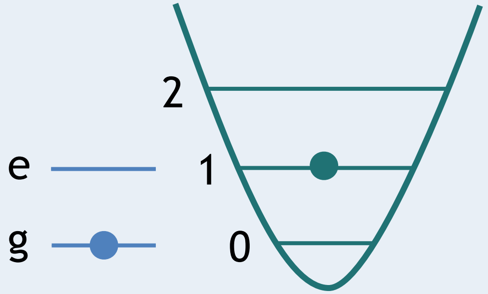
work in progress!

preparation of the resonator state

Fock states



$|0\rangle$ $|0\rangle + |1\rangle$ $|1\rangle$ $|2\rangle$



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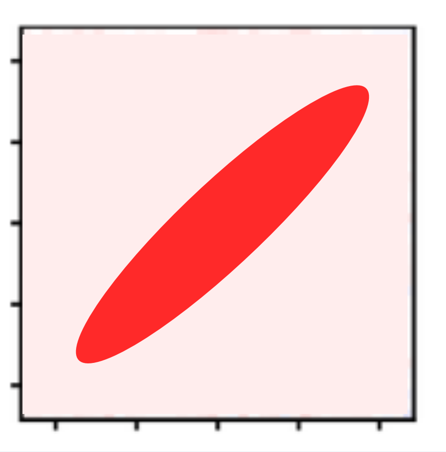
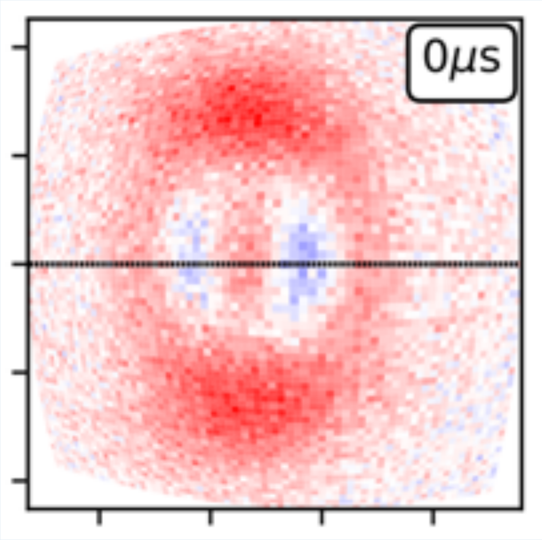


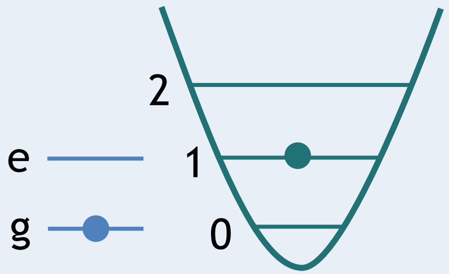
work in progress!

Cat states



measurement of the resonator state

Resonant **swap** to the qubit (limited to the $|0\rangle, |1\rangle$ subspace)



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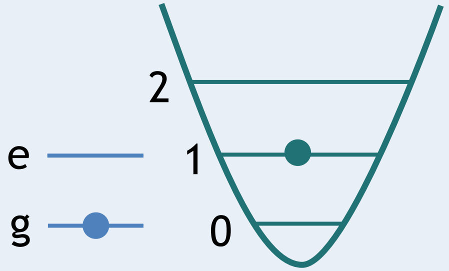
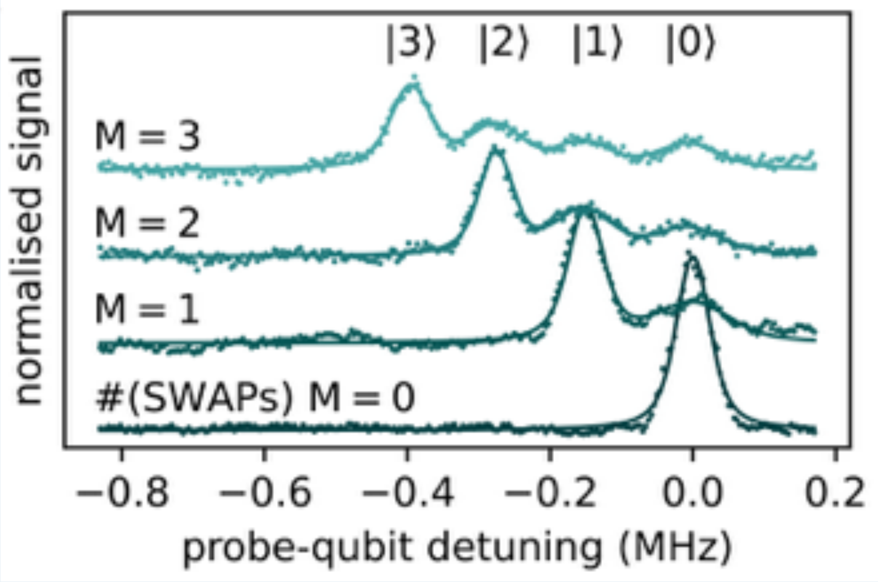
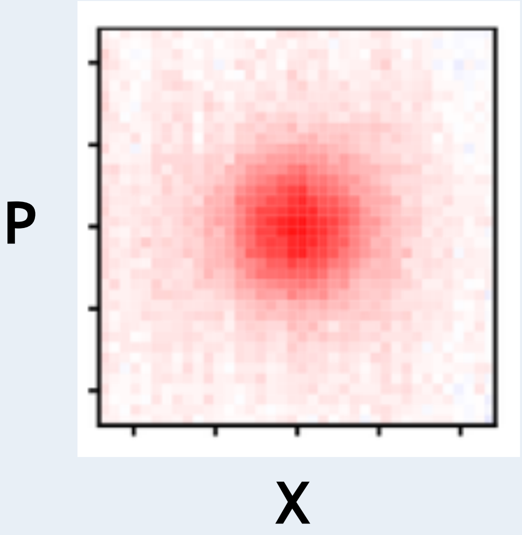


Off-resonant **dispersive interaction** with the qubit





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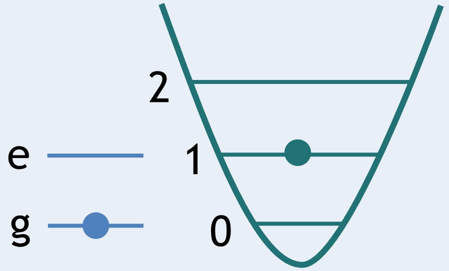

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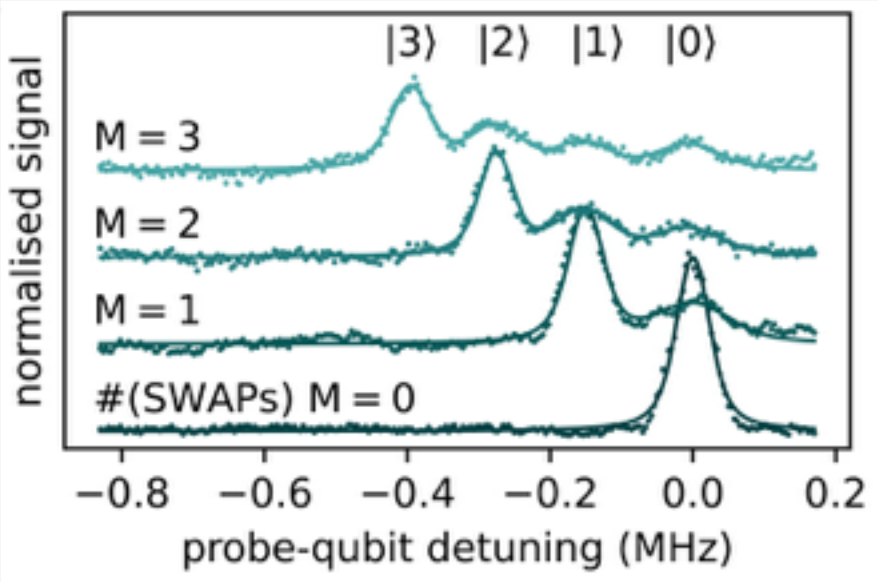
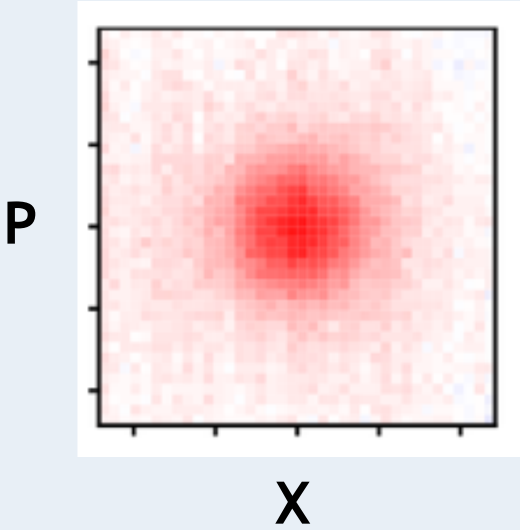
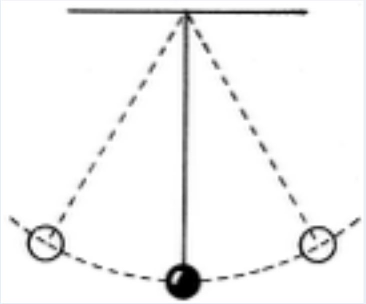
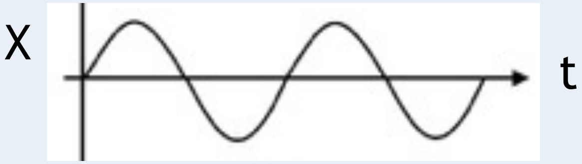




***X*, *P* measurement**





work in progress!

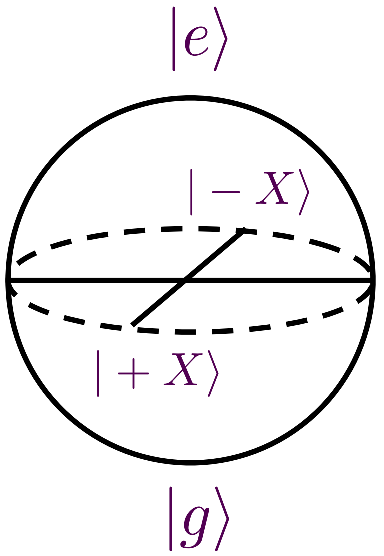
initial state: $|\psi(0)\rangle = |\pm X, \alpha\rangle$

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

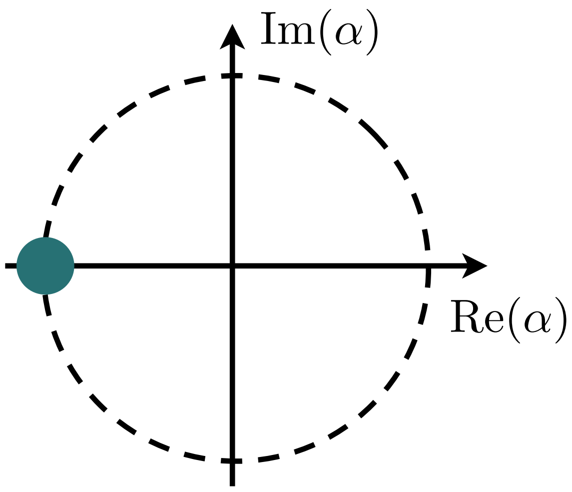
$$\approx \hbar g_0 \alpha \sigma_x \qquad \text{for } |\alpha| \gg 1 \text{ and real}$$

qubit

$$|\pm X\rangle = \frac{|e\rangle \pm |g\rangle}{\sqrt{2}}$$



resonator



J. Gea-Banacloche, PRL 65, 3385 (1990)

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

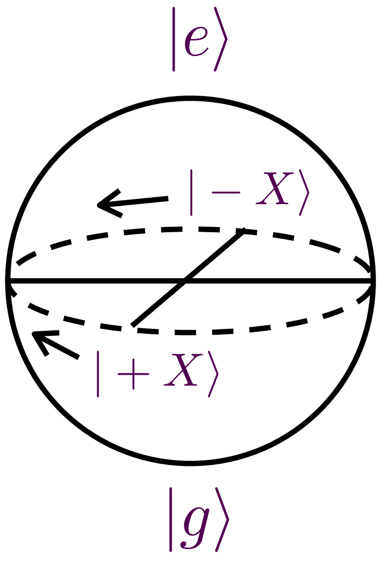
$\approx \hbar g_0 \alpha \sigma_x$ for $|\alpha| \gg 1$ and real

to first order the state evolution is

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

qubit

$$|\pm X\rangle = \frac{|e\rangle \pm |g\rangle}{\sqrt{2}}$$



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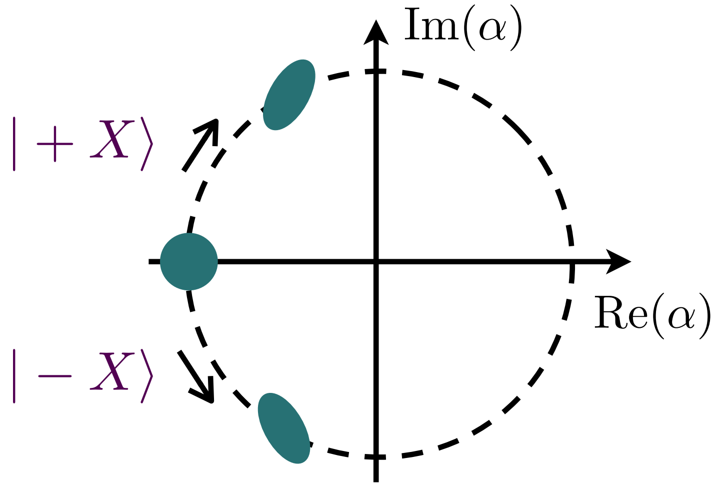

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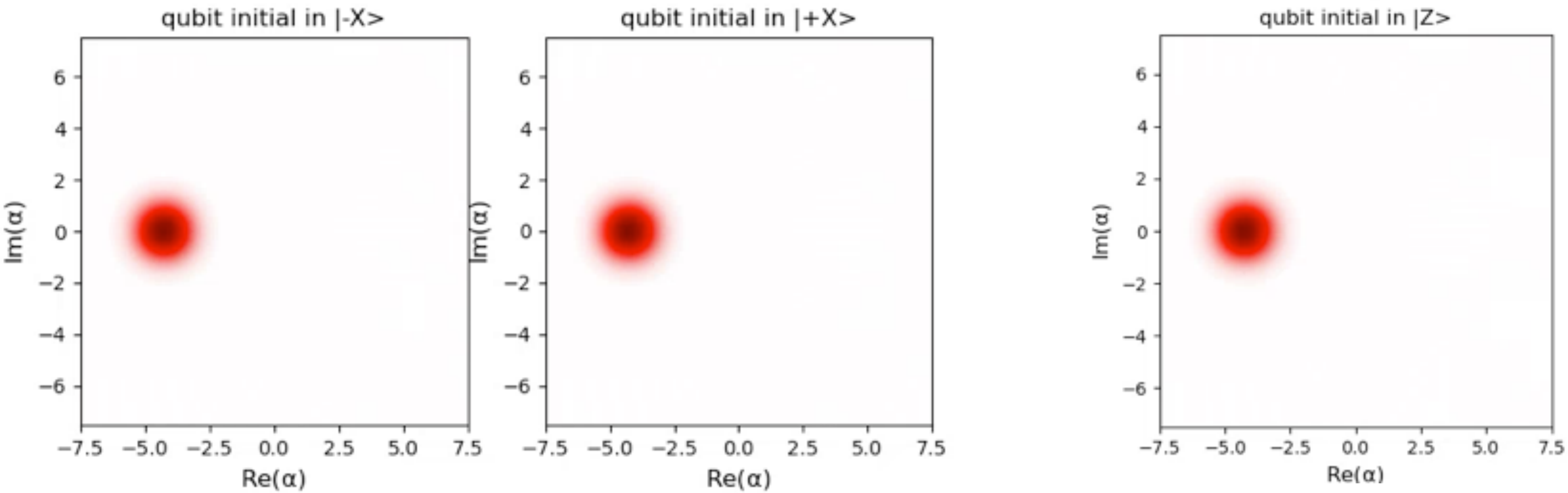
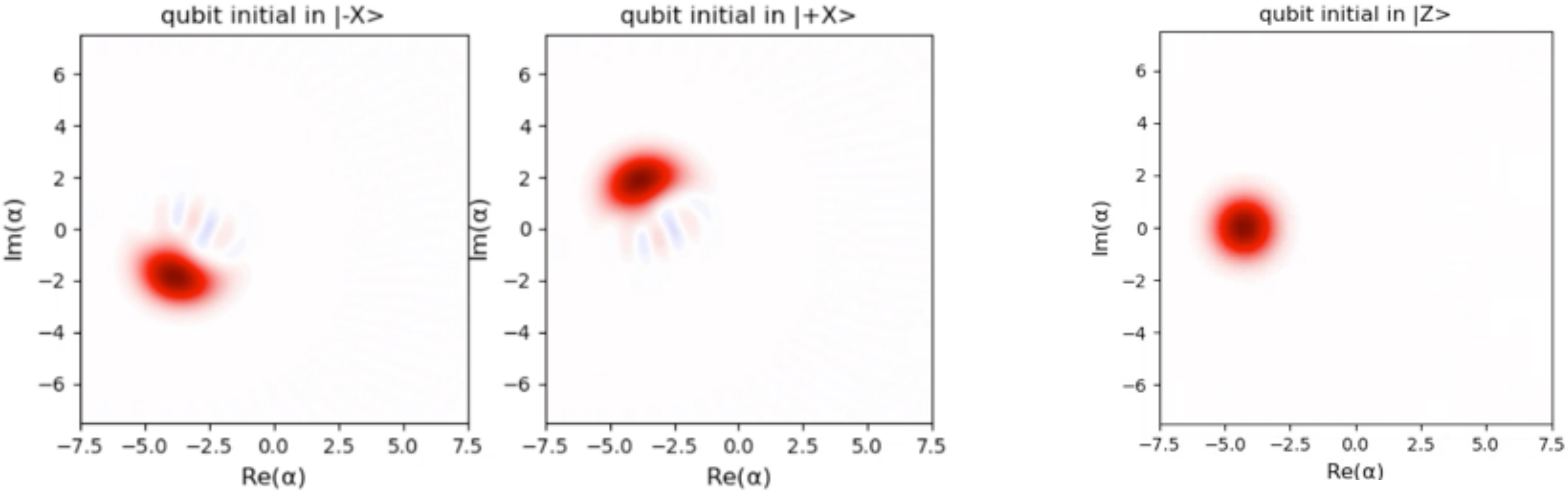
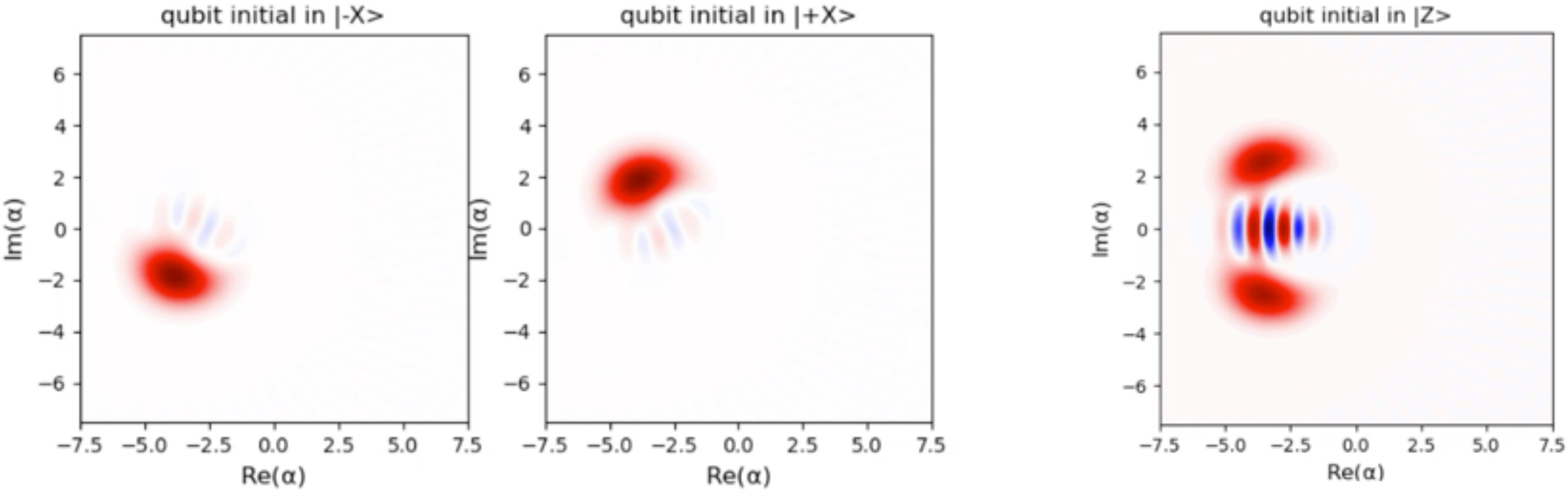


qubit initial in |-X>
qubit initial in |+X>
qubit initial in |Z>
Im(α)
Re(α)



qubit initial in |-X>
qubit initial in |+X>
qubit initial in |Z>
Im(α)
Re(α)
6
4
2
0
−2
−4
−6
−7.5
−5.0
−2.5
0.0
2.5
5.0
7.5



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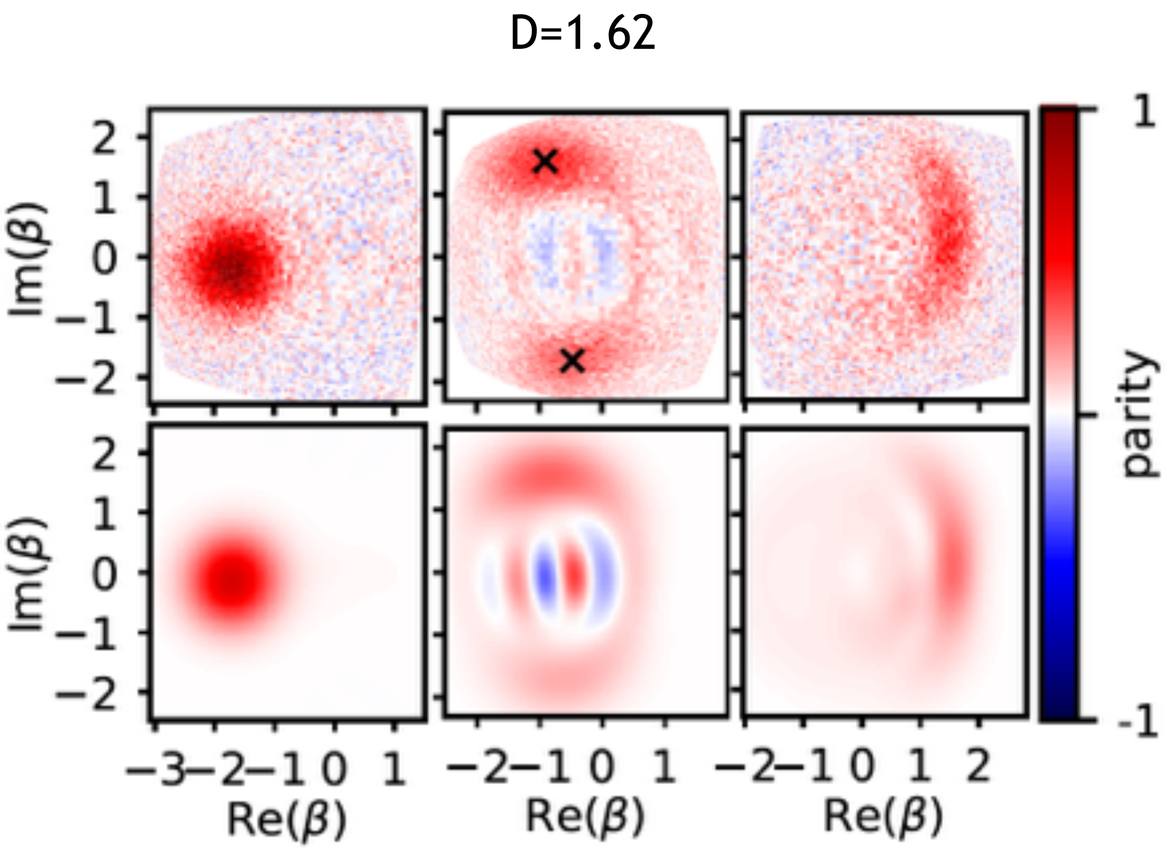
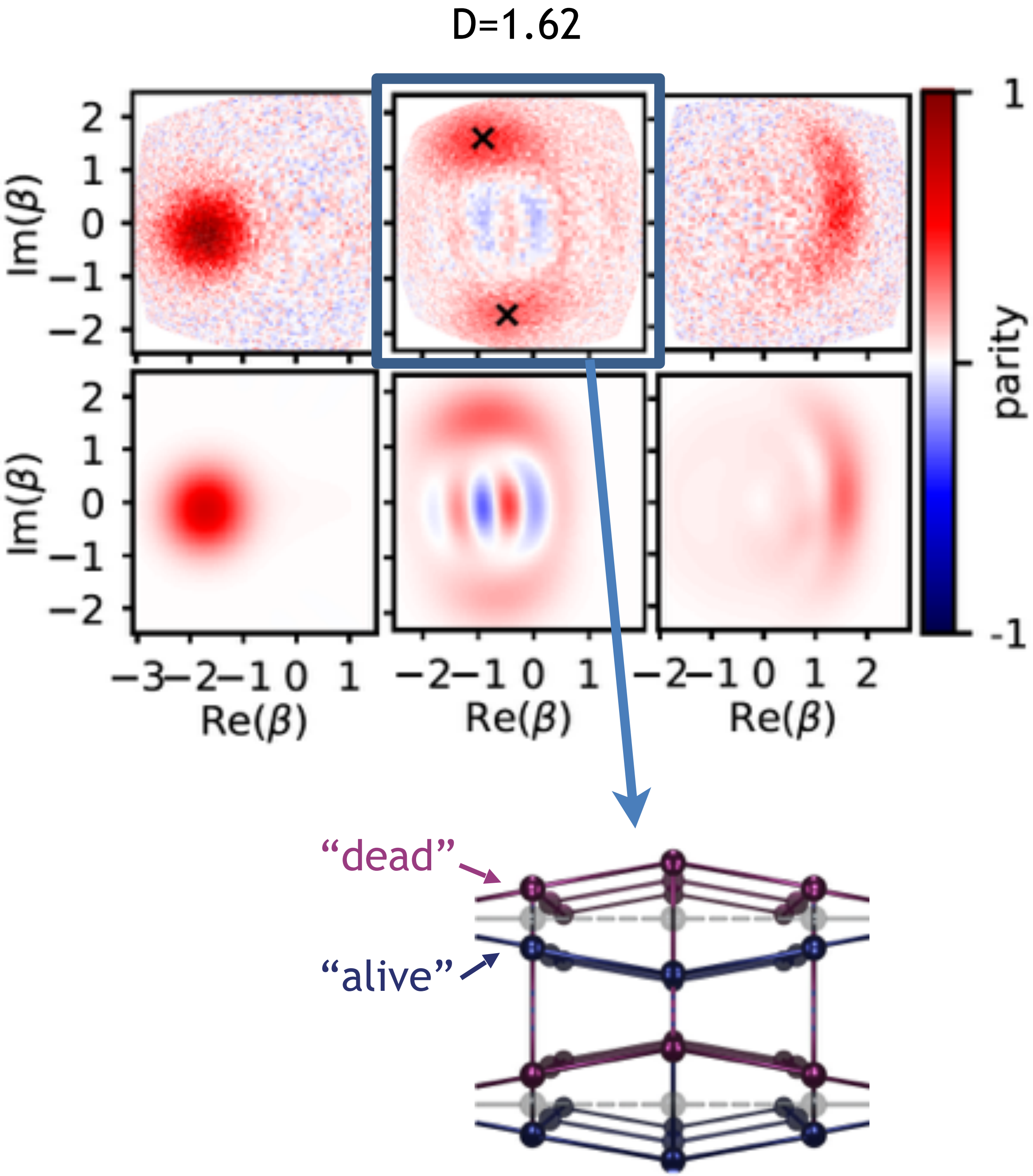
Im(α)
Re(α)

$$D = |\alpha_1 - \alpha_2|/2$$



M. Bild*, MF*, Y. Yang*, et al. Science 380 (2023)



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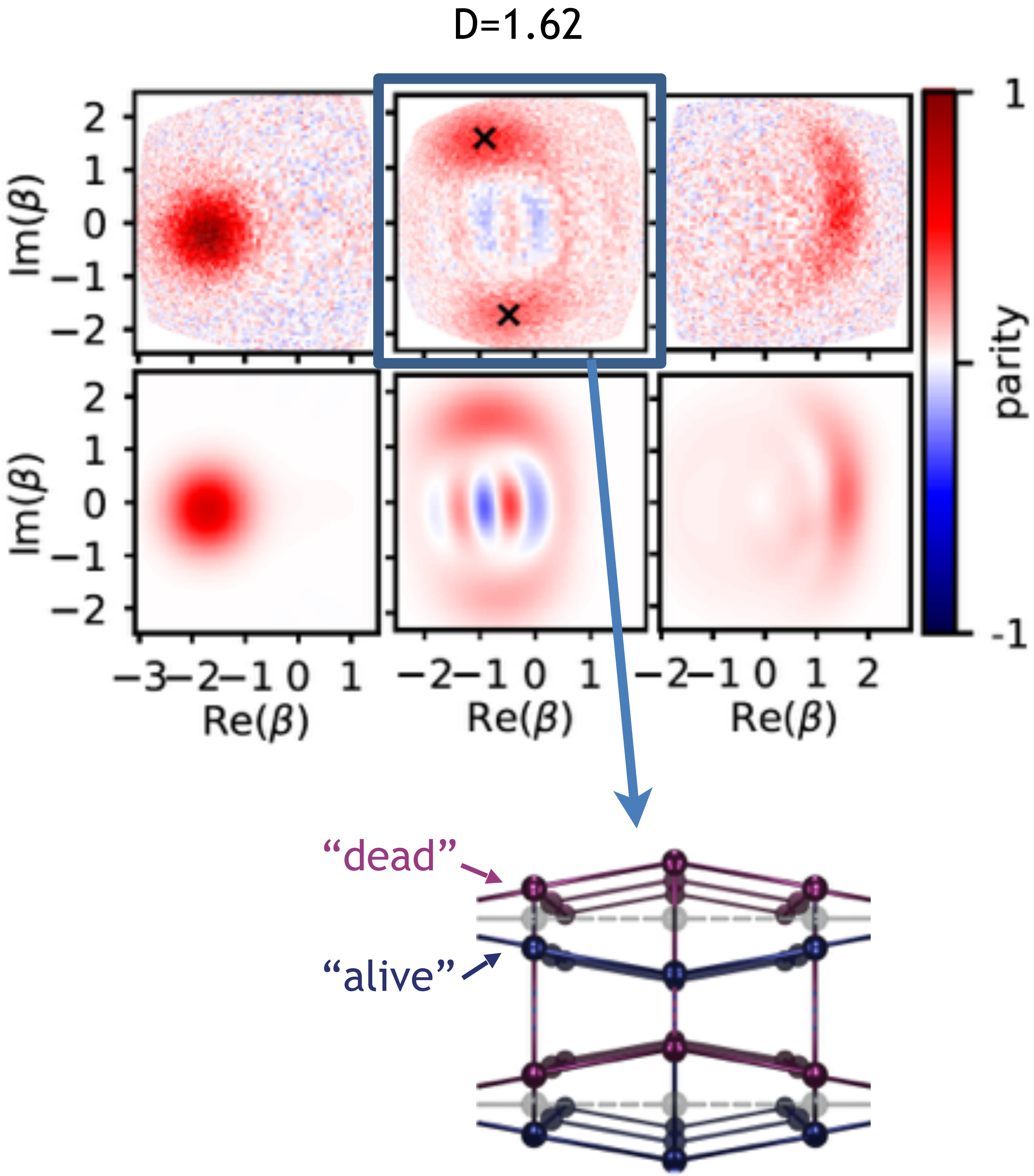

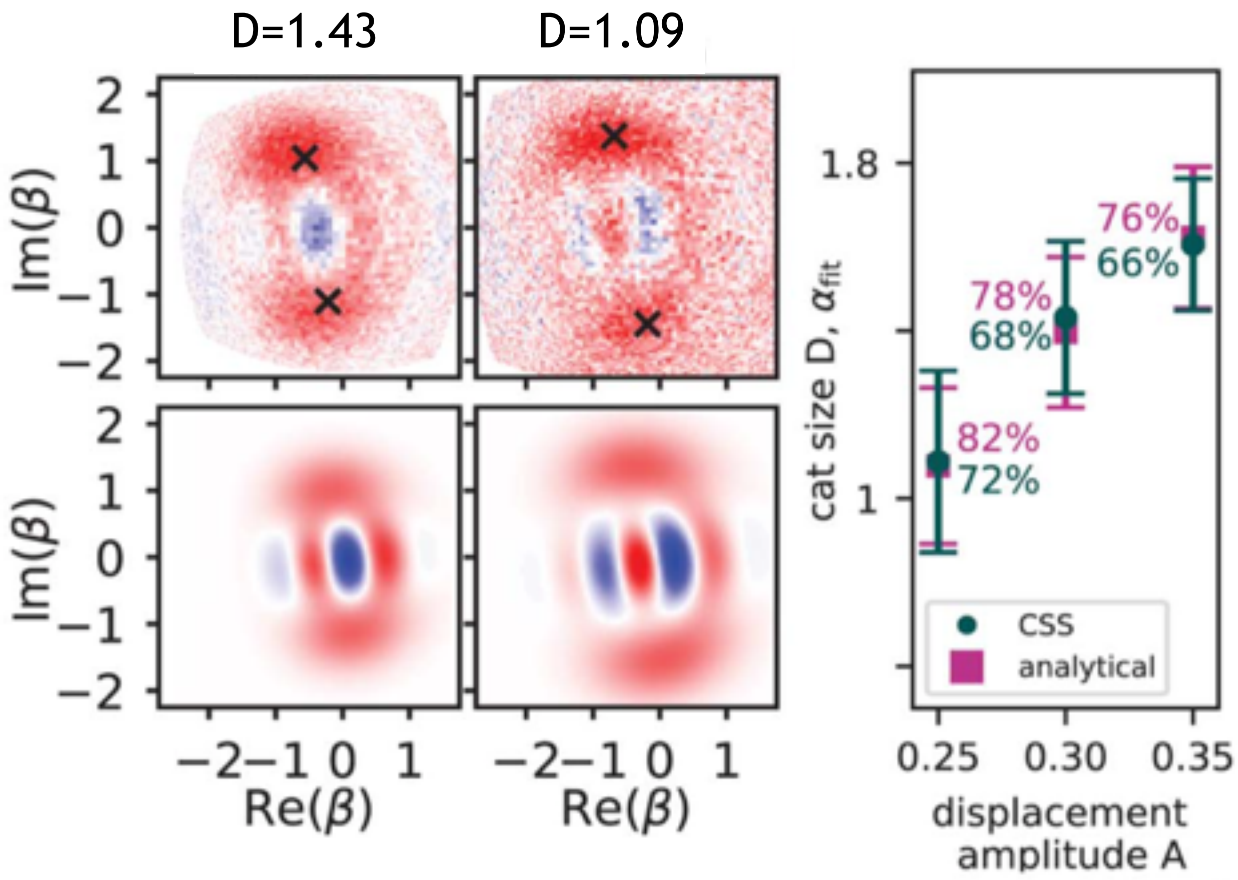

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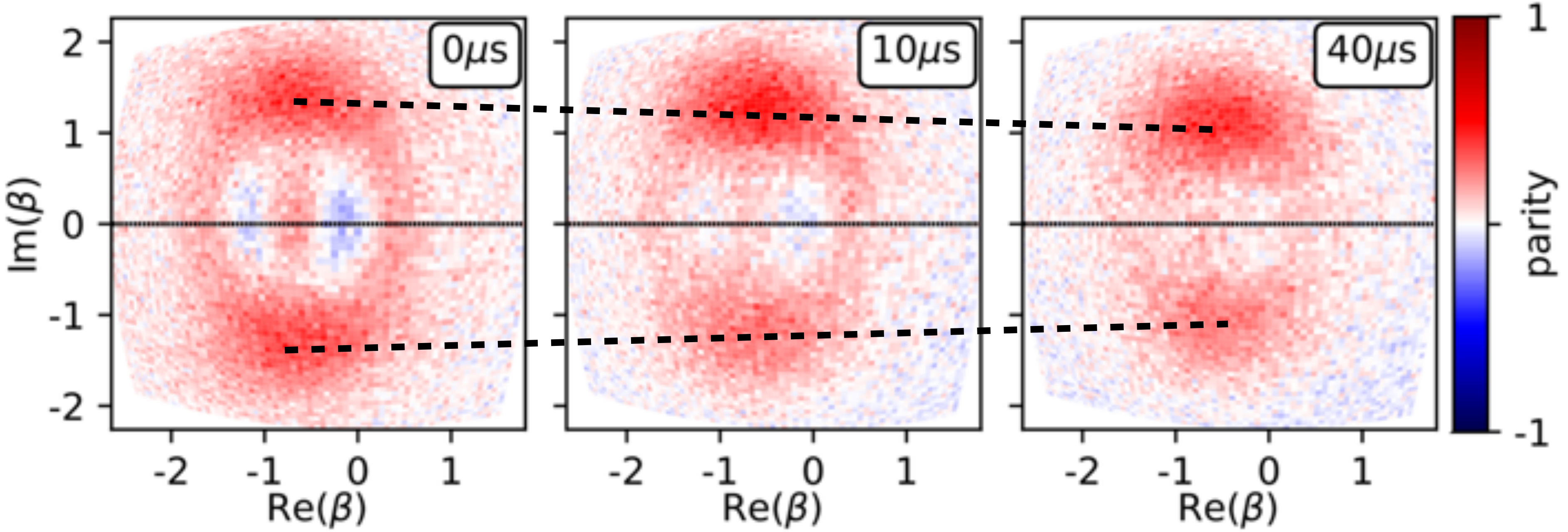
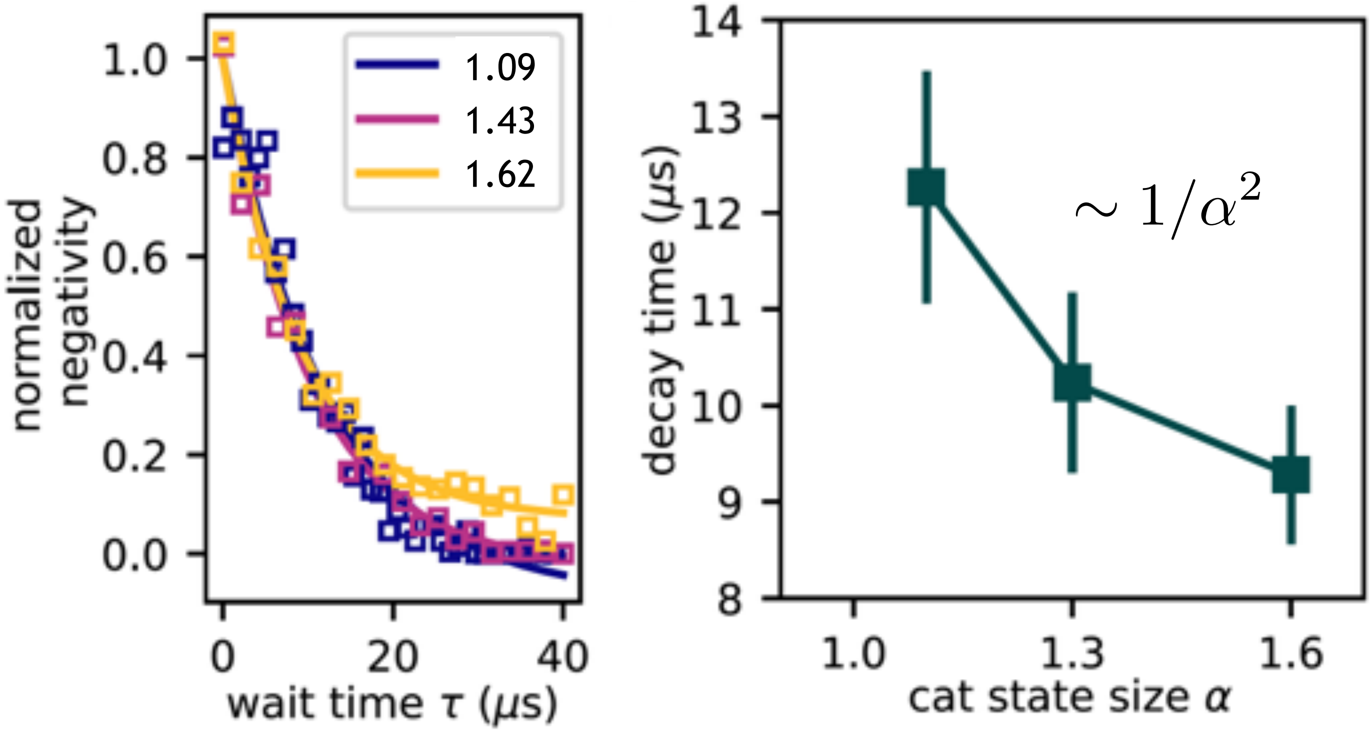
decoherence



M. Bild*, MF*, Y. Yang*, et al. Science 380 (2023)

decoherence

$$\text{negativity} \;= \int d\beta \left[|W(\beta,t)| - W(\beta,t) \right]$$



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standard QM

nonlinear modification

$$\partial_t \rho_t = \mathcal{L}\rho_t + \frac{1}{\tau_e}\mathcal{M}_\sigma \rho_t$$

B. Schrinski, et al. PRL 130 (2023)

standard QM

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example of modification: $2\Gamma\mathcal{D}[X]\rho$

$$\mathcal{D}[X]\rho = X\rho X - \{X^2, \rho\}/2$$

B. Schrinski, et al. PRL 130 (2023)

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which gives: $$\partial_t \rho_t \approx \left(\Gamma + \frac{1}{T_1}\right)\mathcal{D}[\mathrm{a}]\rho + \Gamma\mathcal{D}[\mathrm{a}^\dagger]\rho$$

B. Schrinski, et al. PRL 130 (2023)

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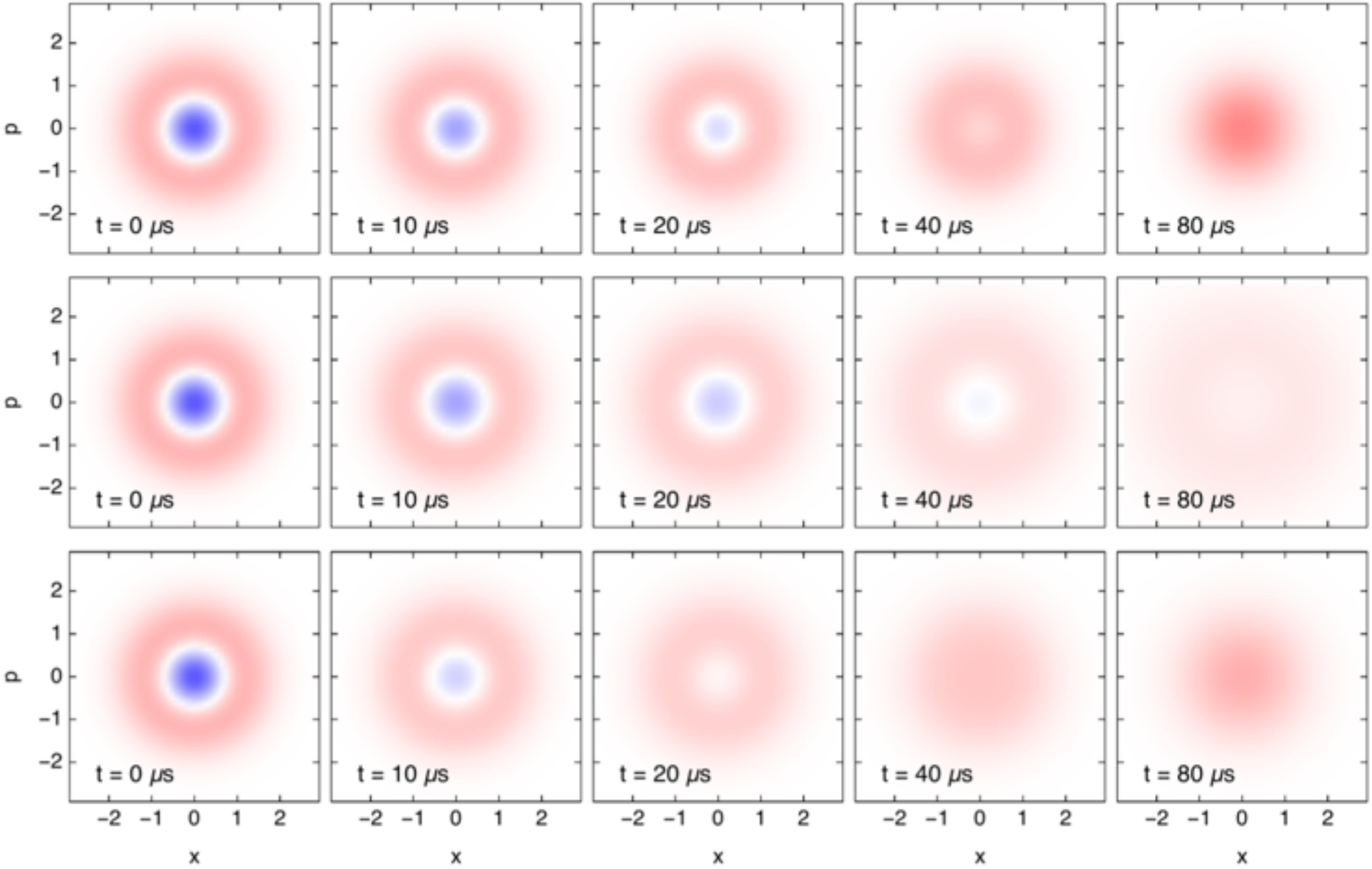
which gives: $$\partial_t \rho_t \approx \left(\Gamma + \frac{1}{T_1}\right)\mathcal{D}[\mathrm{a}]\rho + \Gamma\mathcal{D}[\mathrm{a}^\dagger]\rho$$

analytical solution: $$W(X, P, t) = f[W(X, P, 0)]$$

B. Schrinski, et al. PRL 130 (2023)



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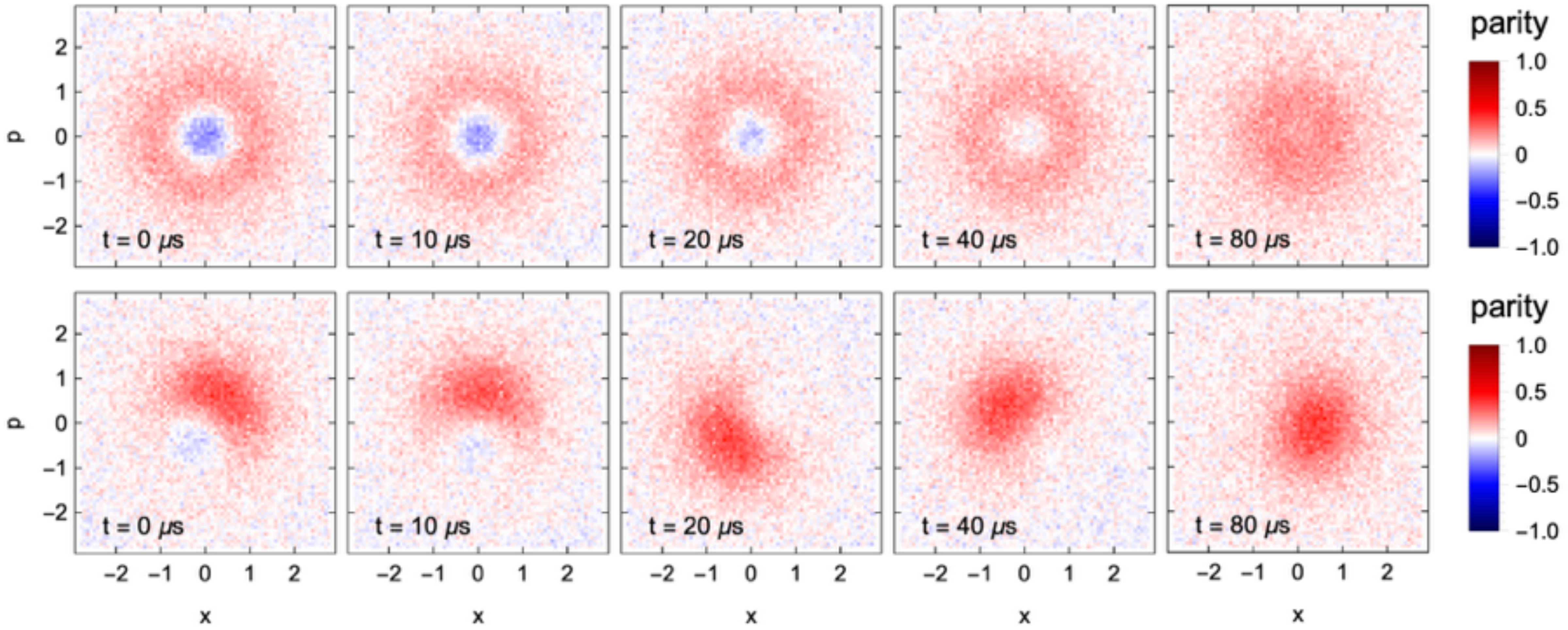
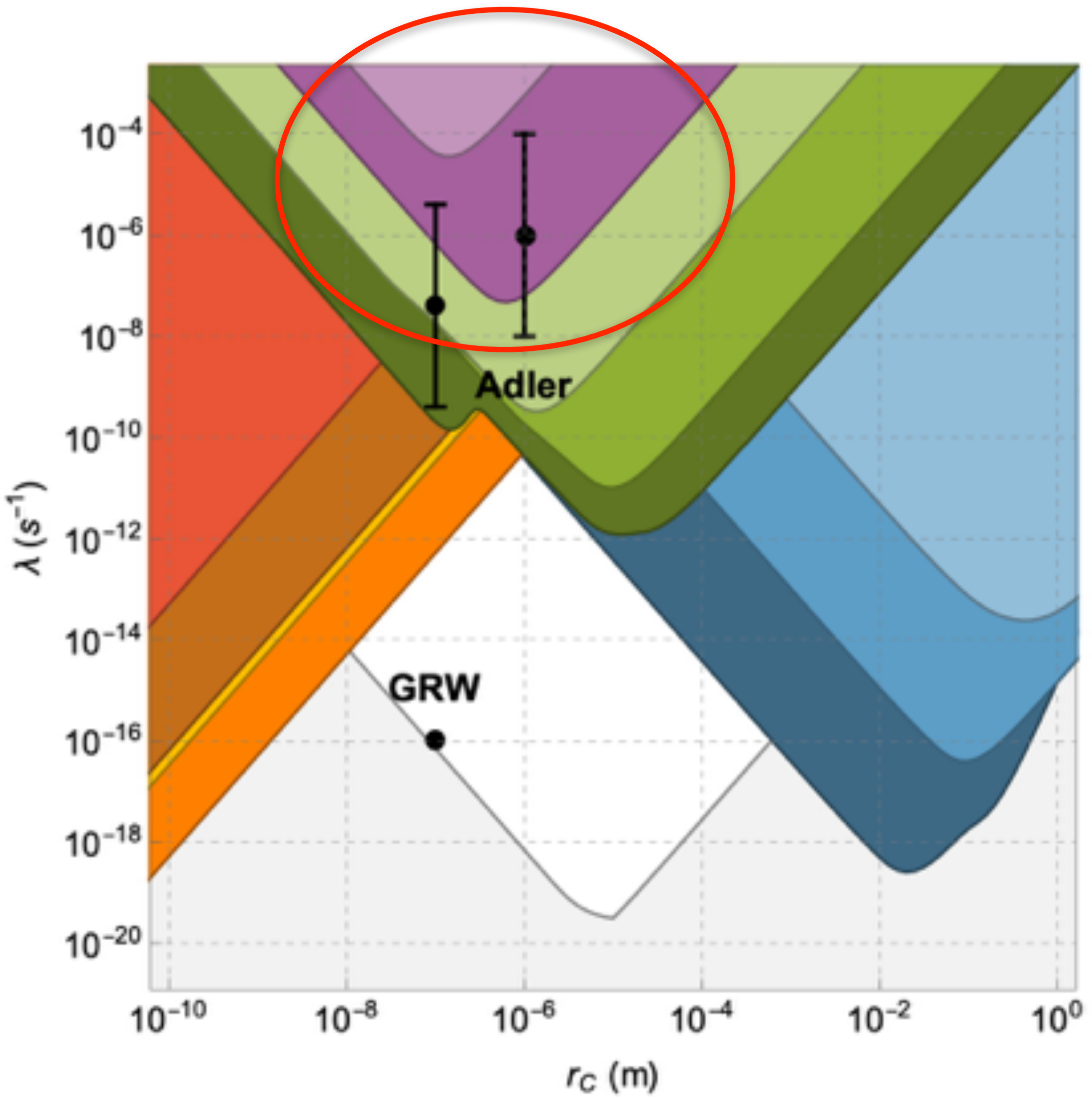
$\Gamma = 120$ Hz



$\Gamma = 640$ Hz

B. Schrinski, et al. PRL 130 (2023)



for DP model: $R_0 > 6.2 \cdot 10^{-17}$

M. Fadel, arXiv:2305.04780

standard QM

nonlinear modification

$$\partial_t \rho_t = \mathcal{L}\rho_t + \frac{1}{\tau_e}\mathcal{M}_\sigma \rho_t$$

macroscopicity μ: measure how well an experiment can exclude a generic set of nonlinear extensions to QM

$$\mu = \log_{10} \frac{\tau_e}{1\,\mathrm{s}}$$

B. Schrinski, et al. PRL 130 (2023)

standard QM — nonlinear modification

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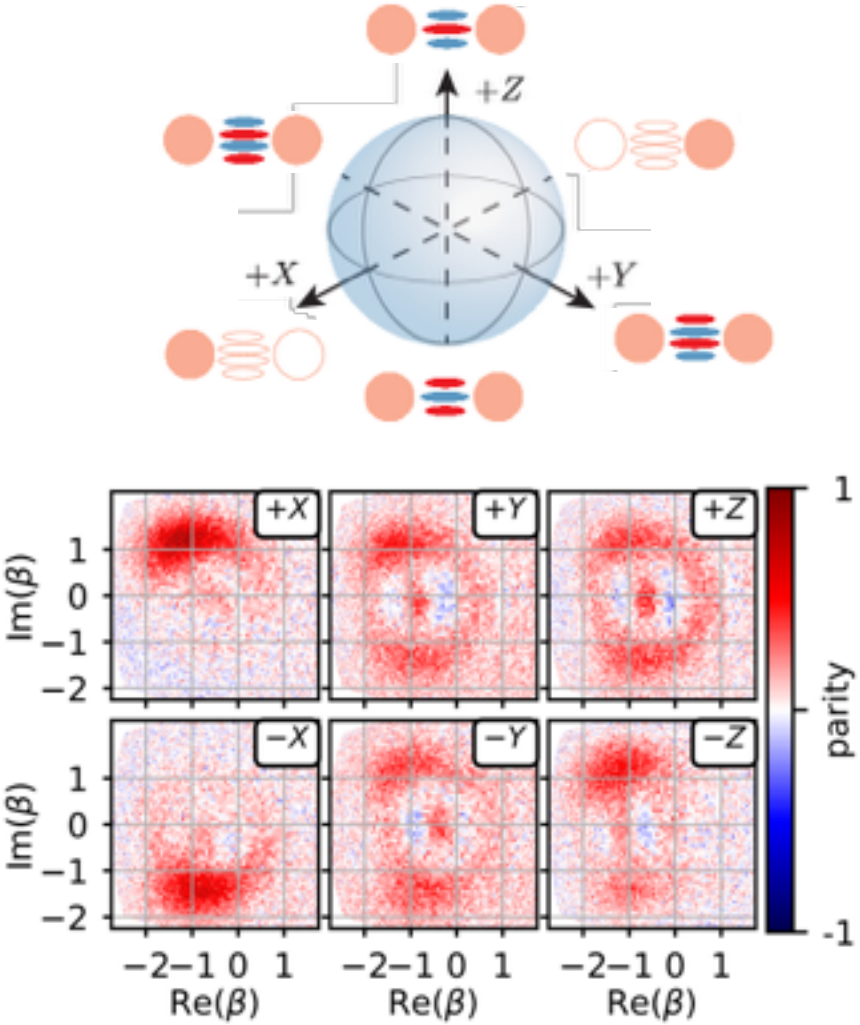
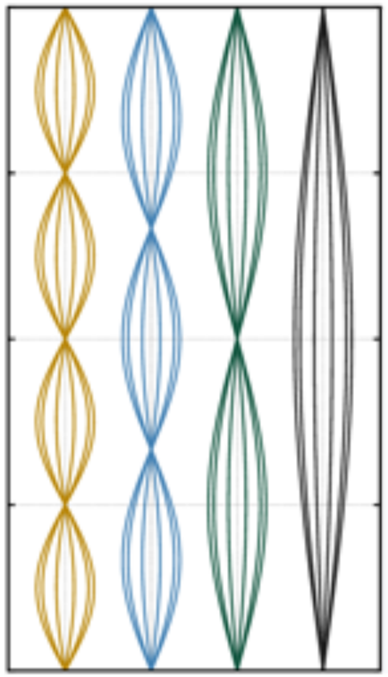
$$\mu = \log_{10} \frac{\tau_e}{1\,\mathrm{s}}$$

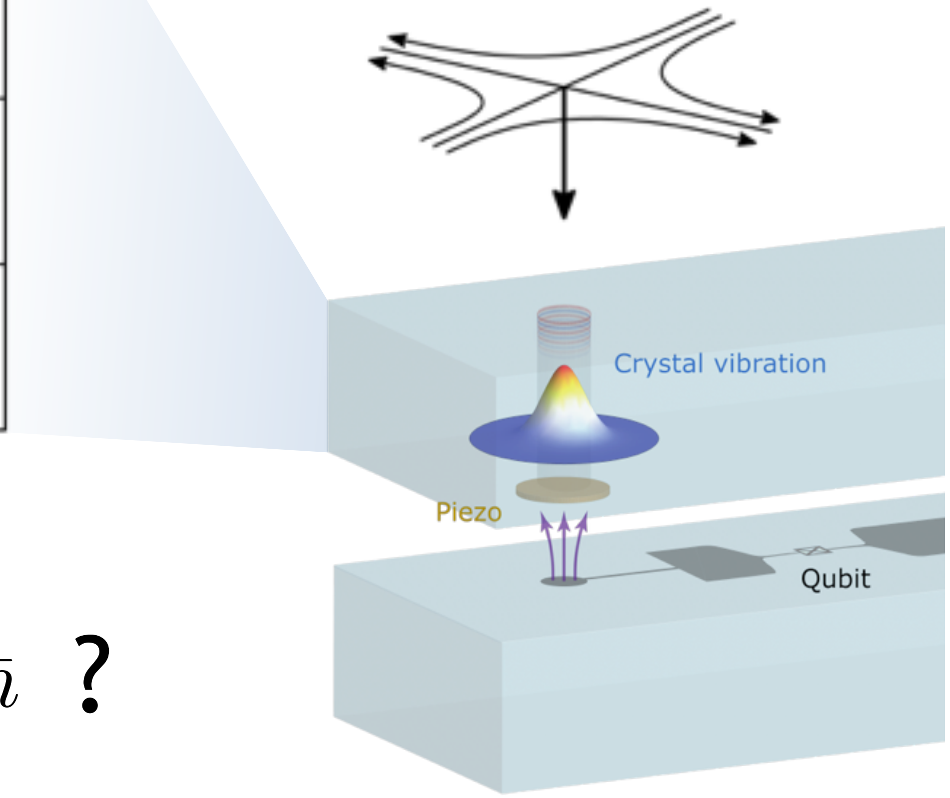
	experiment	year	μ
mechanical resonators	**Bulk acoustic waves [this work]**	**2022**	**11.3**
	Phononic crystal resonator [13]	2022	~ 9.0*
	Surface acoustic waves [12]	2018	~ 8.6*
matter-wave interference	Molecule interferometry [8]	2019	14.0
	Atom interferometry [6]	2019	11.8
	BEC interferometry [5]	2017	12.4

B. Schrinski, et al. PRL 130 (2023)

outlooks

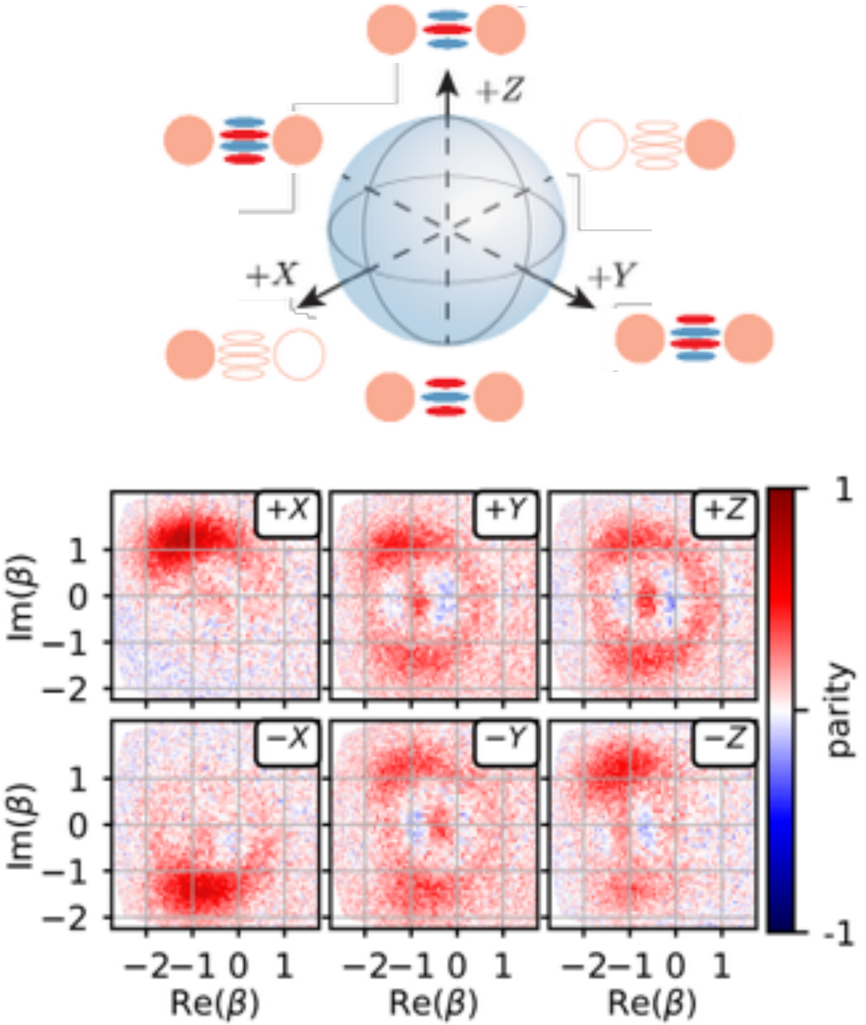


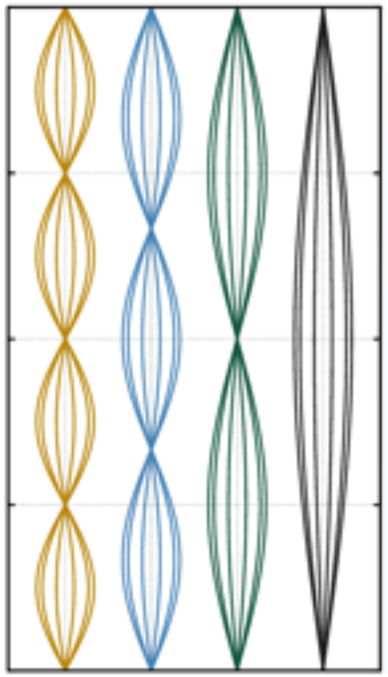


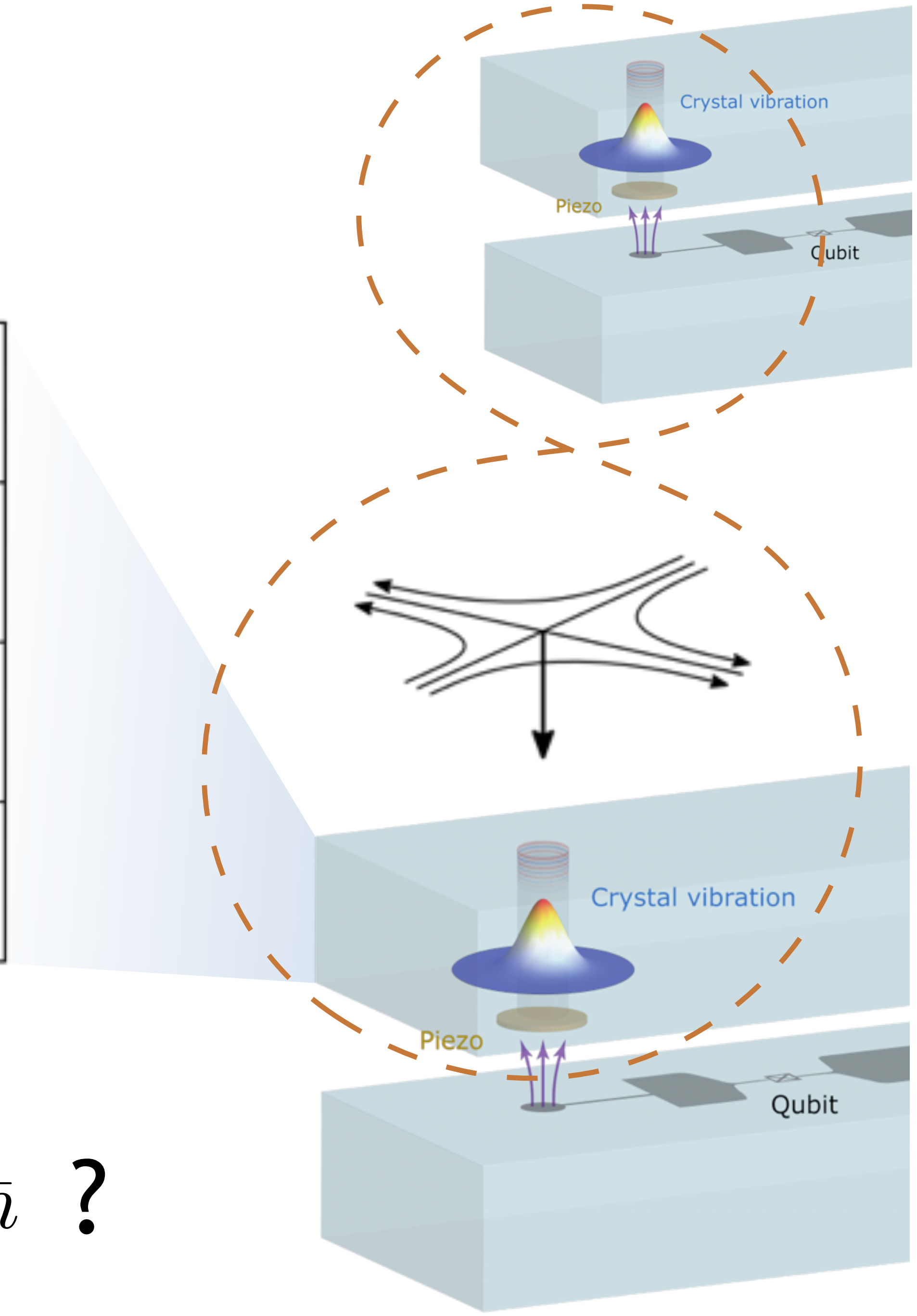


$$[X, P] = i\hbar \quad ?$$

outlooks

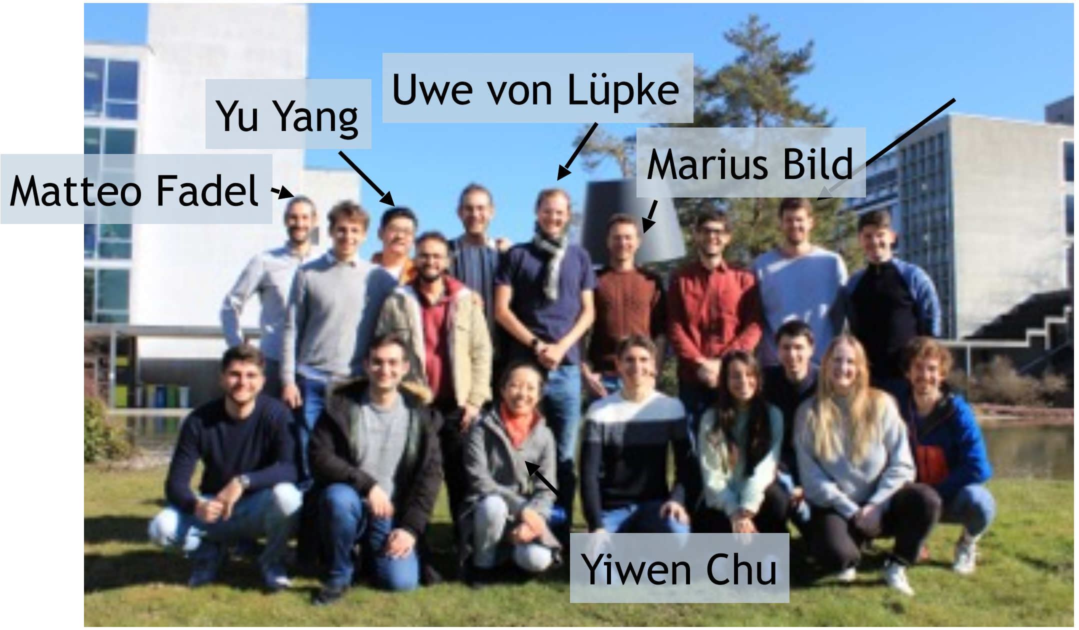






$$[X, P] = i\hbar \quad ?$$

HyQu ETH zürich erc European Research Council Swiss National Science Foundation The Branco Weiss Fellowship Society in Science



Theory collaborators:

Björn Schrinski
Klaus Hornberger
Stefan Nimmrichter

Works discussed here:

- M. Bild, M. Fadel, Y. Yang, *et al.,* Science 380 (2023)
- B. Schrinski, … and M. Fadel, PRL 130 (2023)
- M. Fadel, arXiv:2305.04780