Quantum control and thermometry of surface acoustic wave phonons

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THE UNIVERSITY OF CHICAGO | Institute for Molecular Engineering | Argonne NATIONAL LABORATORY

QT-60
Workshop on thermodynamics, thermoelectrics and Jukka
Hanasaari Swedish-Finnish Cultural Centre
19-21 September 2018

Friday September 21 2018
0900-0930

UC Berkeley: 1985-86

"Team milliKelvin": Packard & Clarke groups
Second basement of Birge Hall

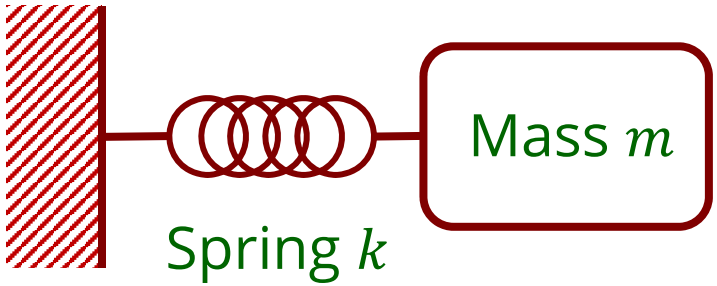
Clarke group:

- Josephson junctions
- SQUIDs
- MQT ⇒ qubits
- Coulomb blockade

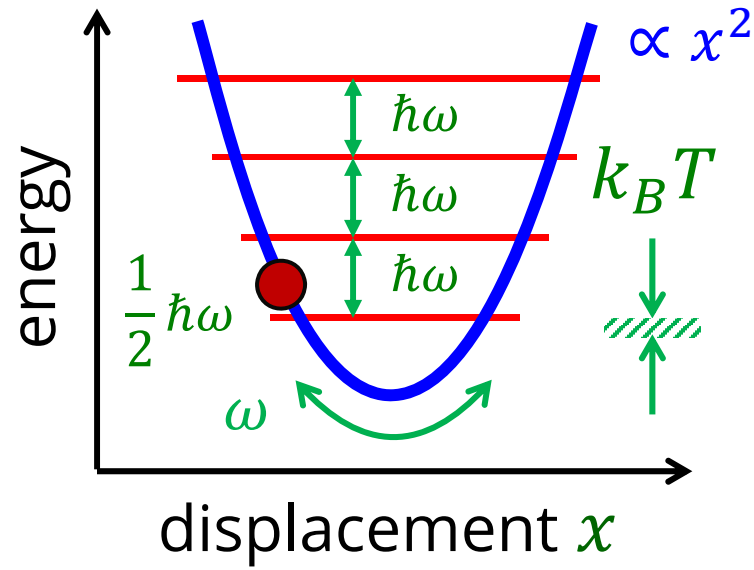
Packard group:

- Superfluid helium
- Josephson junctions
- SQUIDs

Mechanical systems in the quantum regime



Frequency $\omega = \sqrt{k/m}$



- Ground state operation: $k_B T \ll \hbar\omega$
- A resonator with $\omega = 1$ kHz needs $T \ll 10$ nK
- Higher frequencies relaxes temperature requirement

  $\omega = 10$ GHz needs $T \ll 100$ mK – not so hard!

Very hard!

- Need a way to measure/control at the quantum level

  ...using another quantum system

Xmon qubit

Measurement:

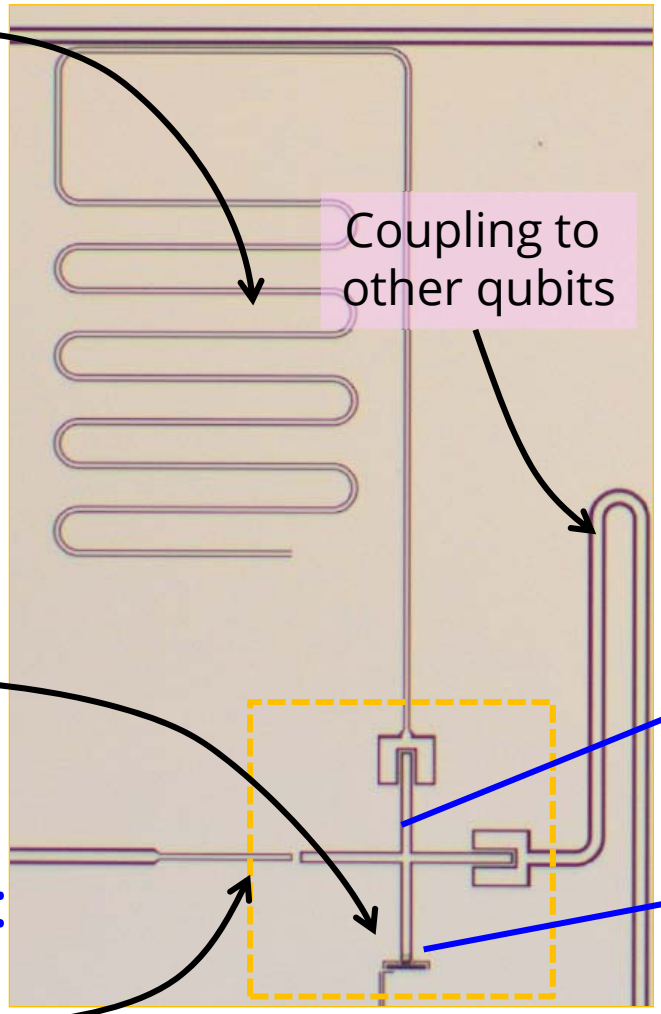
- Dispersive resonator readout
- Measure change in phase of few-photon excitation in readout resonator
- Projective & accurate

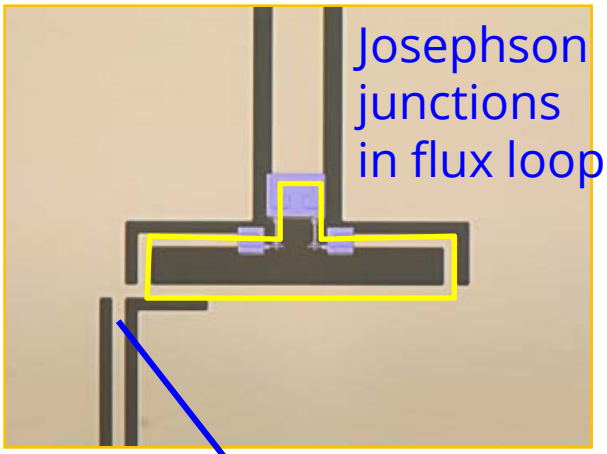
Z rotations:

- Flux tuning L
- Changes qubit frequency

X and Y rotations:

- Microwaves at qubit frequency





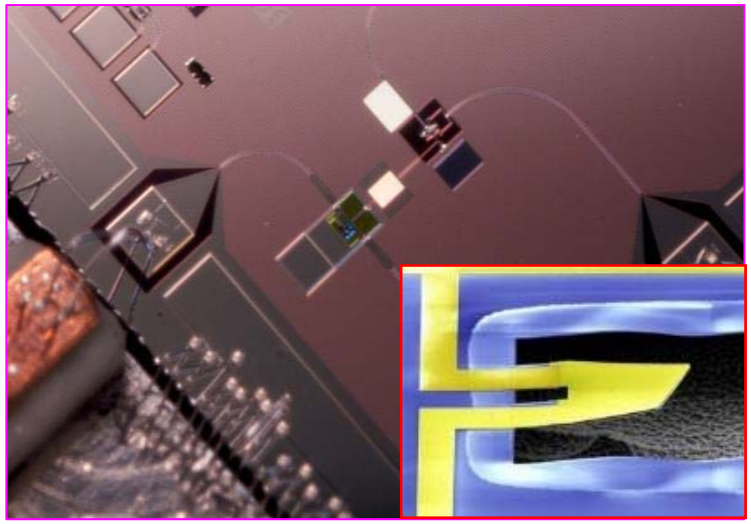
Z control

Capacitance C

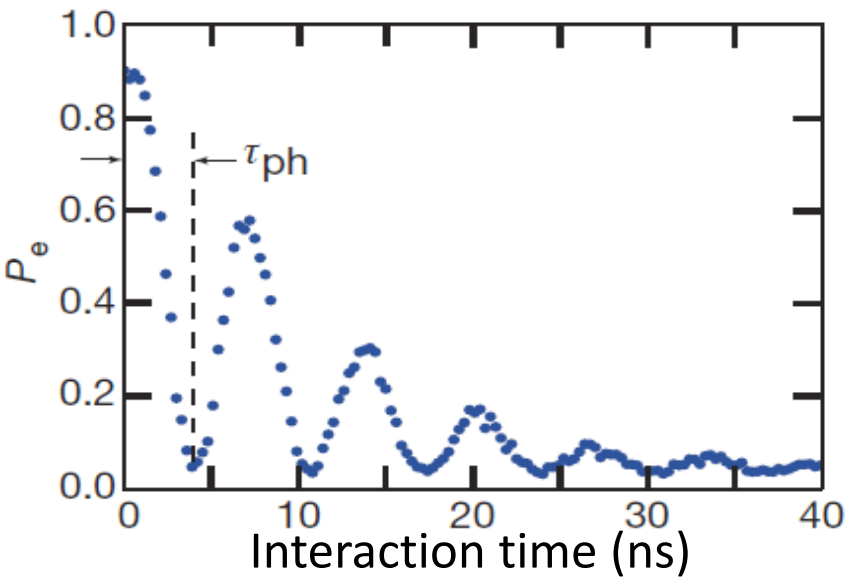
Josephson junctions (tunable inductance L)

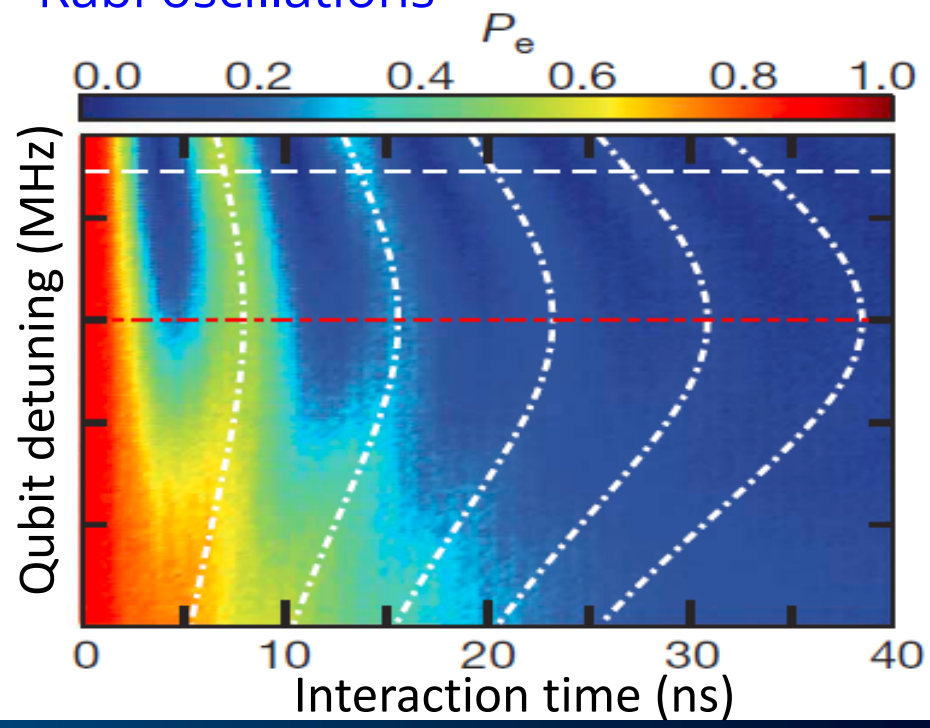
Barends et al. (PRL, 2013)

Qubits and “bulk” mechanics



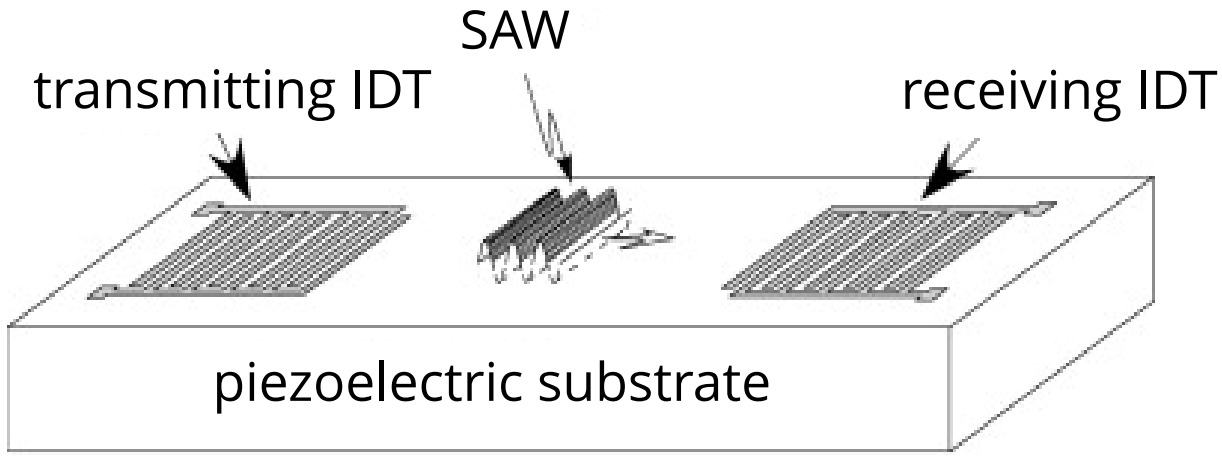
- Phase qubit coupled to microwave dilatational mechanical resonator
- Measurement of mechanical quantum ground state
- Measurement of mechanical-qubit Rabi oscillations





O’Connell et al (Nature 2010)

Surface acoustic waves

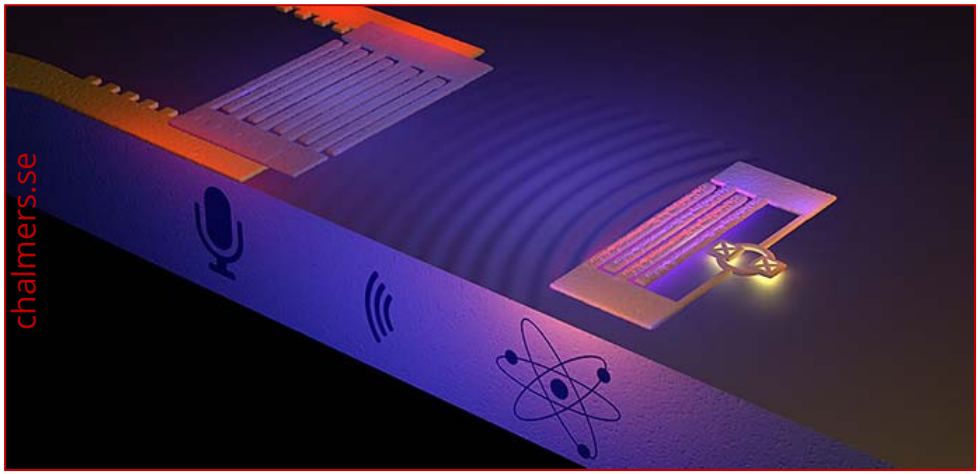


J.K. Na et al, Sensors & Actuators (2008)

- Compact
- Tailorable
- MHz-GHz frequencies
- Low power

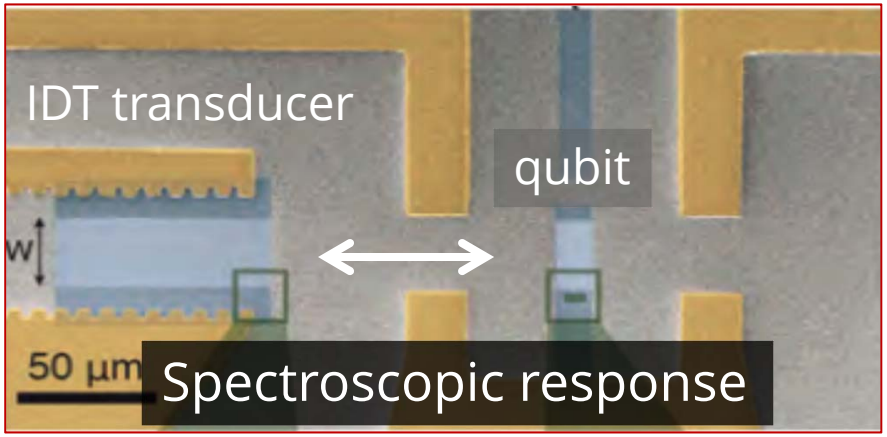
- Phonons travel **100,000** times slower than photons
- Delay lines, pulse shaping, pulse compression
- Resonators
- Can phonons be used as flying qubits?
- Phonons to couple disparate quantum systems?

Quantum surface acoustics



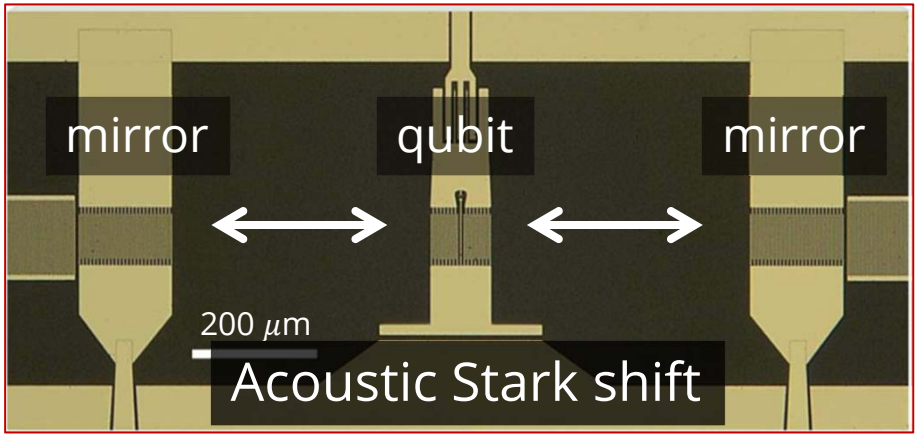
- Interdigitated transducer on piezoelectric substrate
- GHz transition frequencies
- Electromechanical coupling
- Superconducting qubit

Gustafsson et al. (2014) Chalmers



Send-receive IDTs on GaAs

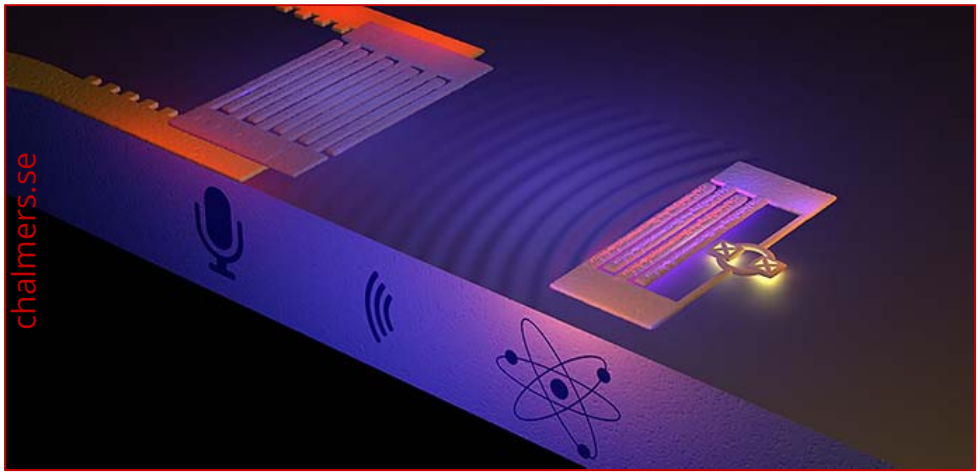
Manenti et al. (2017) Oxford



SAW resonator on ST-X quartz

Gustafsson et al. Science (2014)
Manenti et al. Nat Comm (2017)

Quantum surface acoustics



Gustafsson et al. (2014) Chalmers

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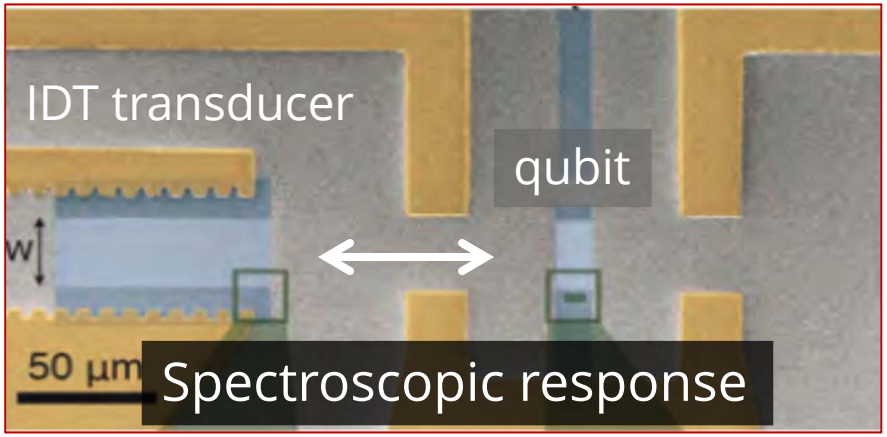
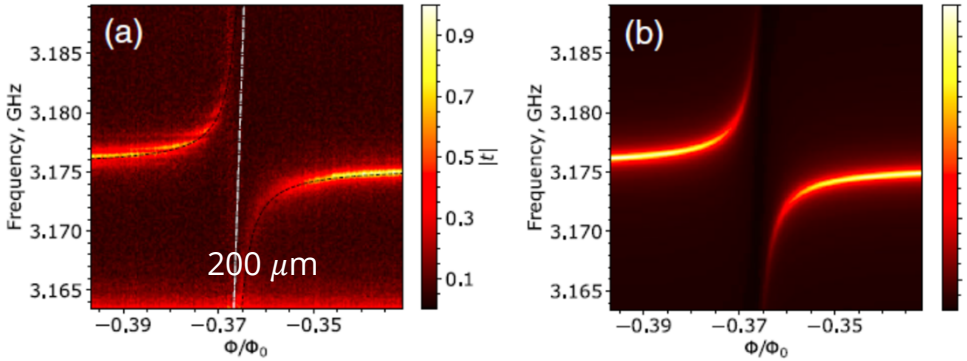


Send-receive IDTs on GaAs

Bolgar et al. (2018) MIPT & NPL



SAW resonator on ST-X quartz

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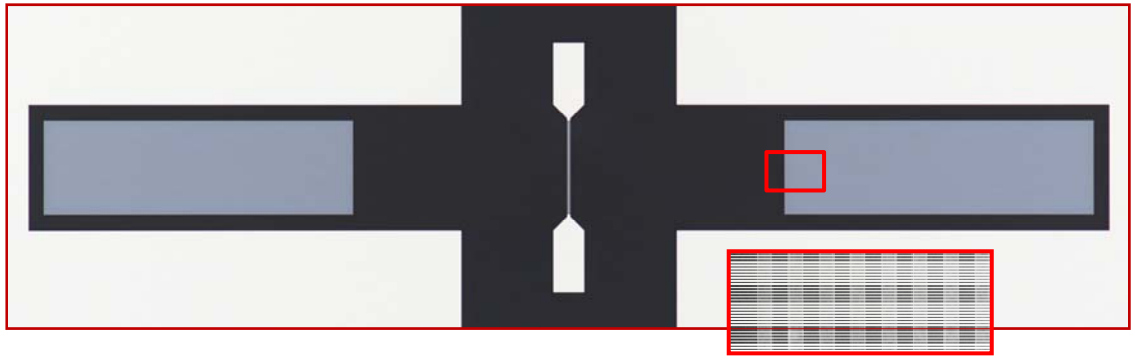
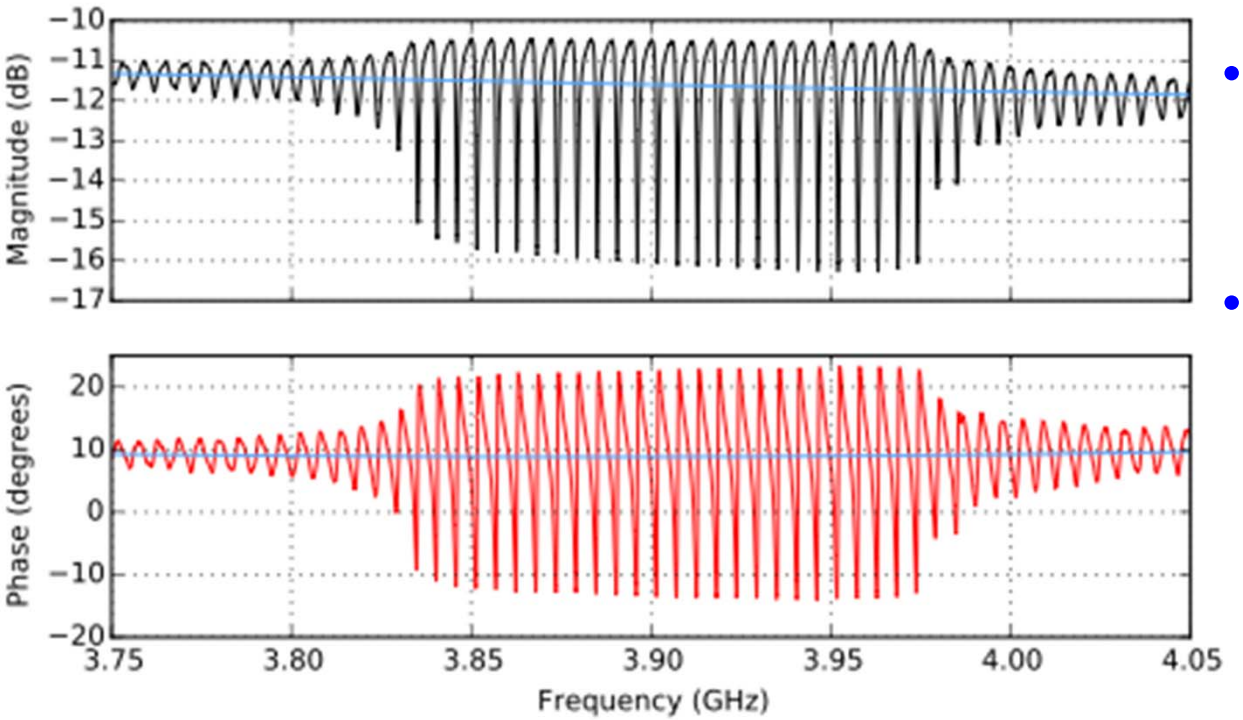
SAW resonator on $LiNbO_3$

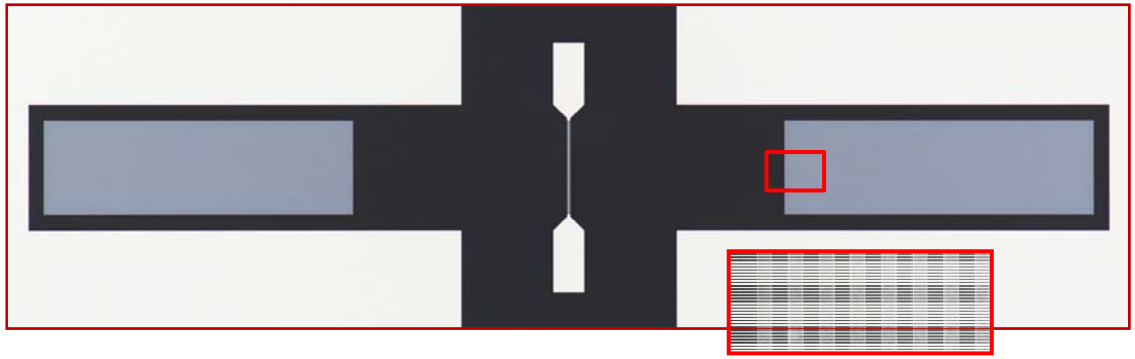


$LiNbO_3$ substrate
1 μm finger pair spacing
4 GHz center frequency



- Measure transmittance S_{21} (magnitude & phase)
- Model embedding circuit (C_{stray} and L_{stray})

SAW resonator on $LiNbO_3$



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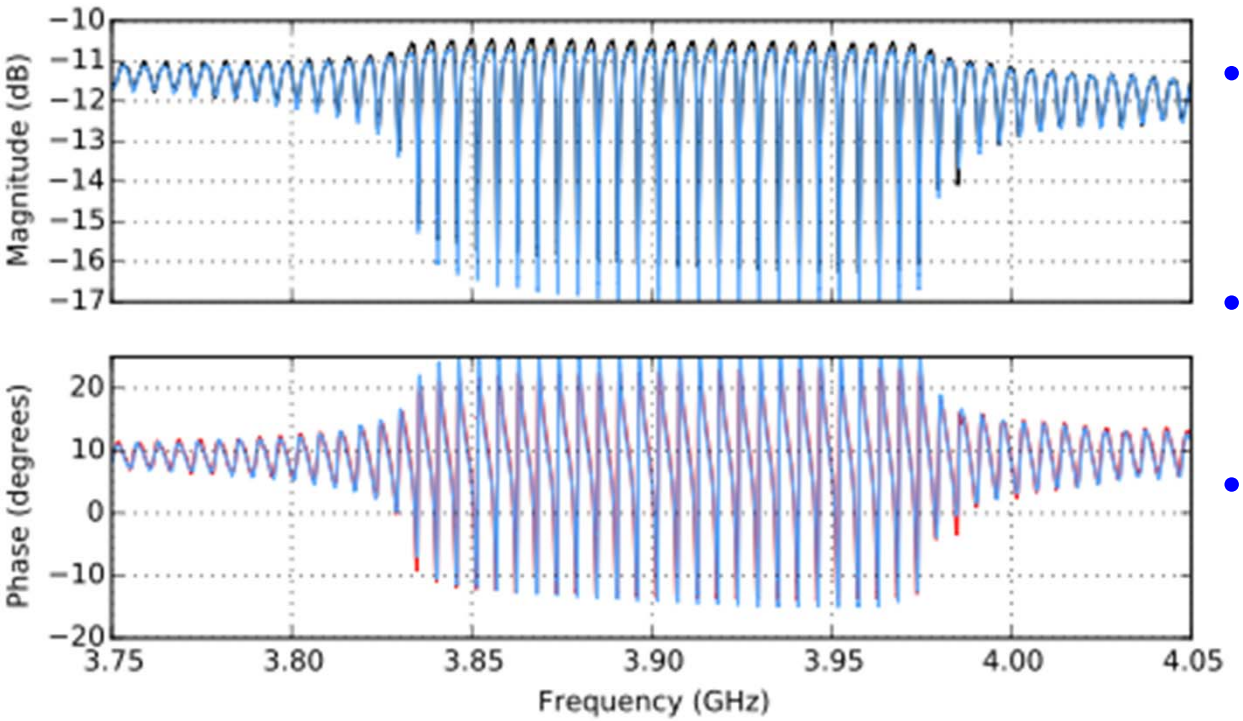
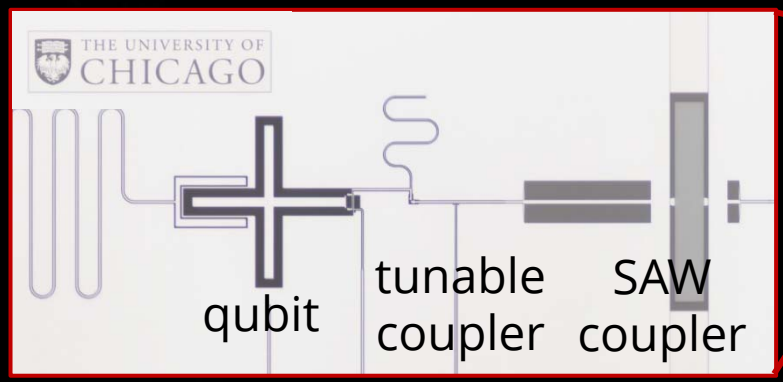
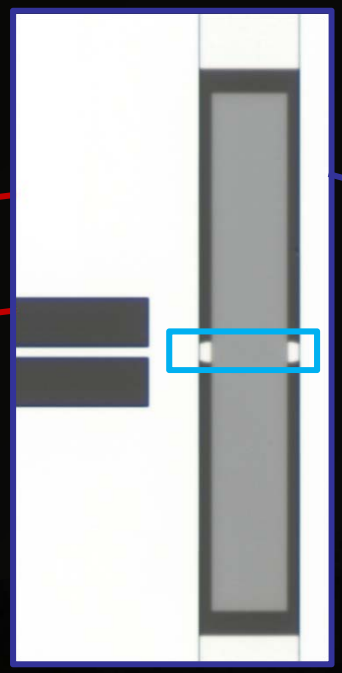
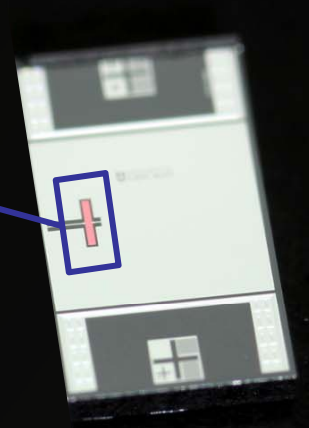


- Measure transmittance S_{21} (magnitude & phase)
- Model embedding circuit (C_{stray} and L_{stray})
- Model admittance: 4 add'l parameters

Qubit coupled to SAW resonator





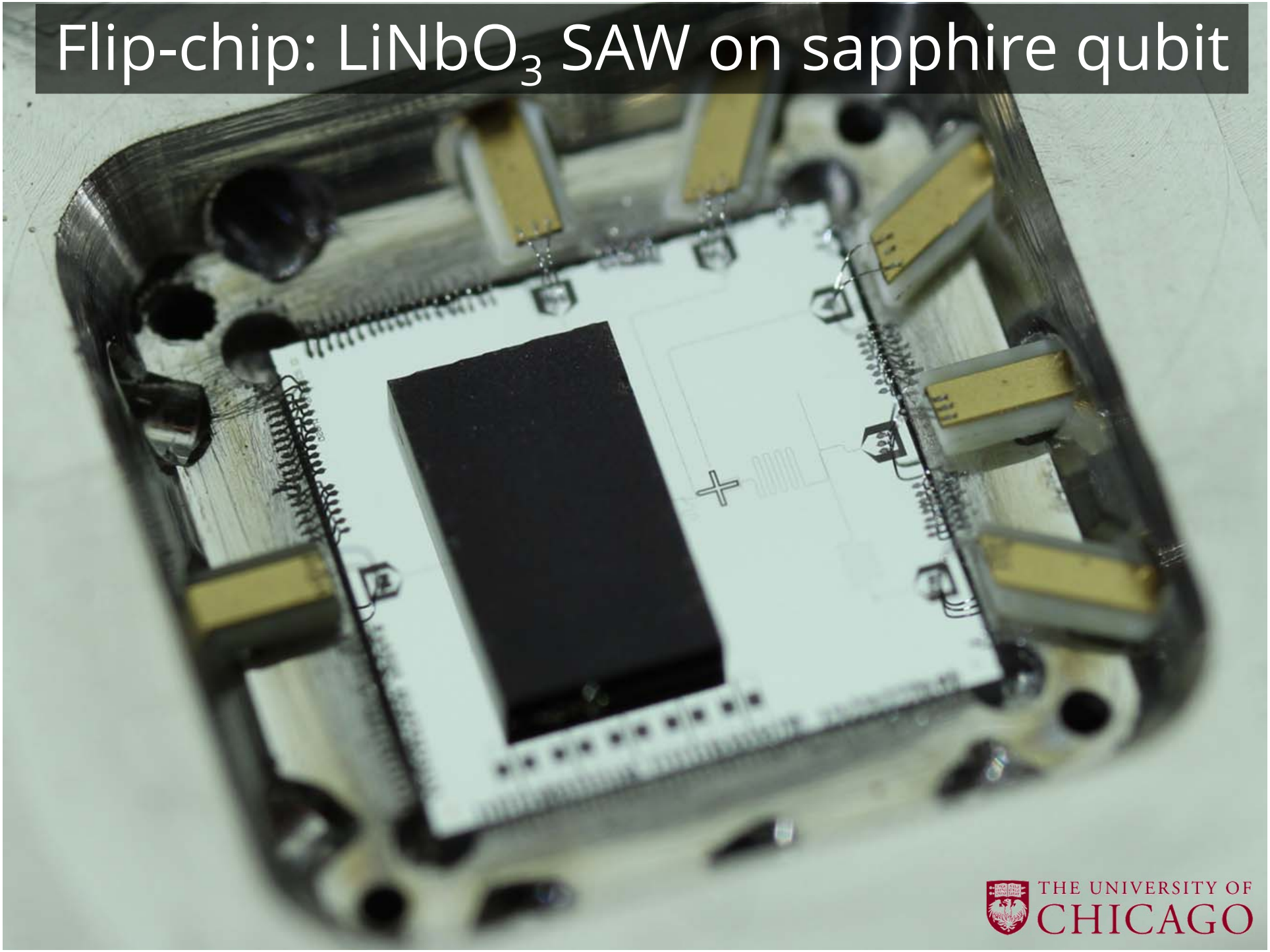


SAW
resonator

- Tunable coupler : electronic control of qubit-SAW coupling

- Mirrors as close as possible to transducer
- Single SAW mode

Flip-chip: $LiNbO_3$ SAW on sapphire qubit



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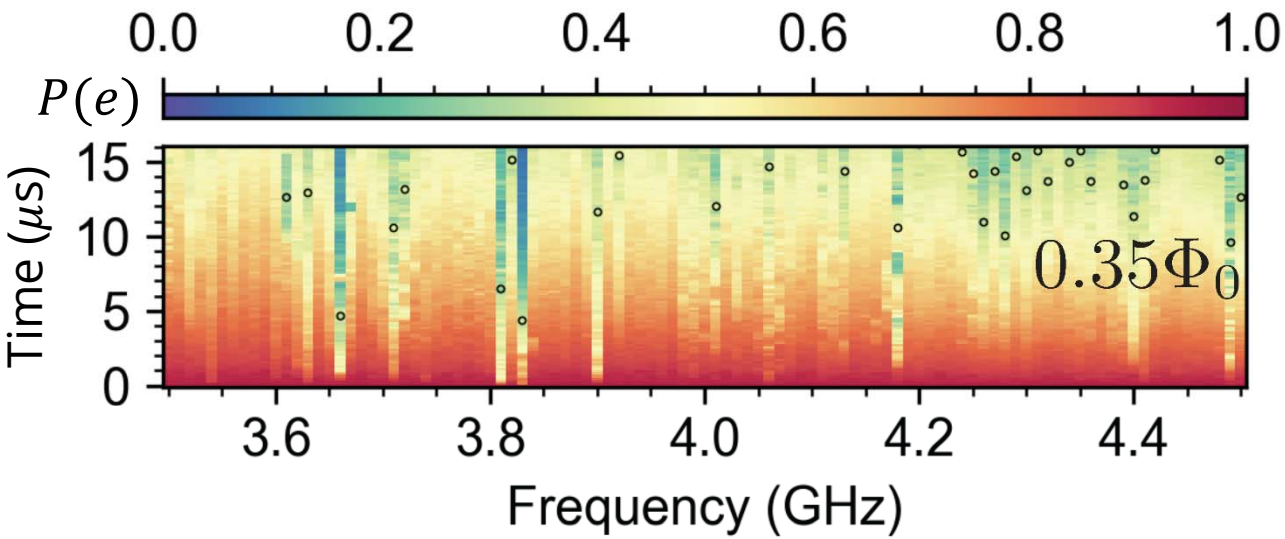
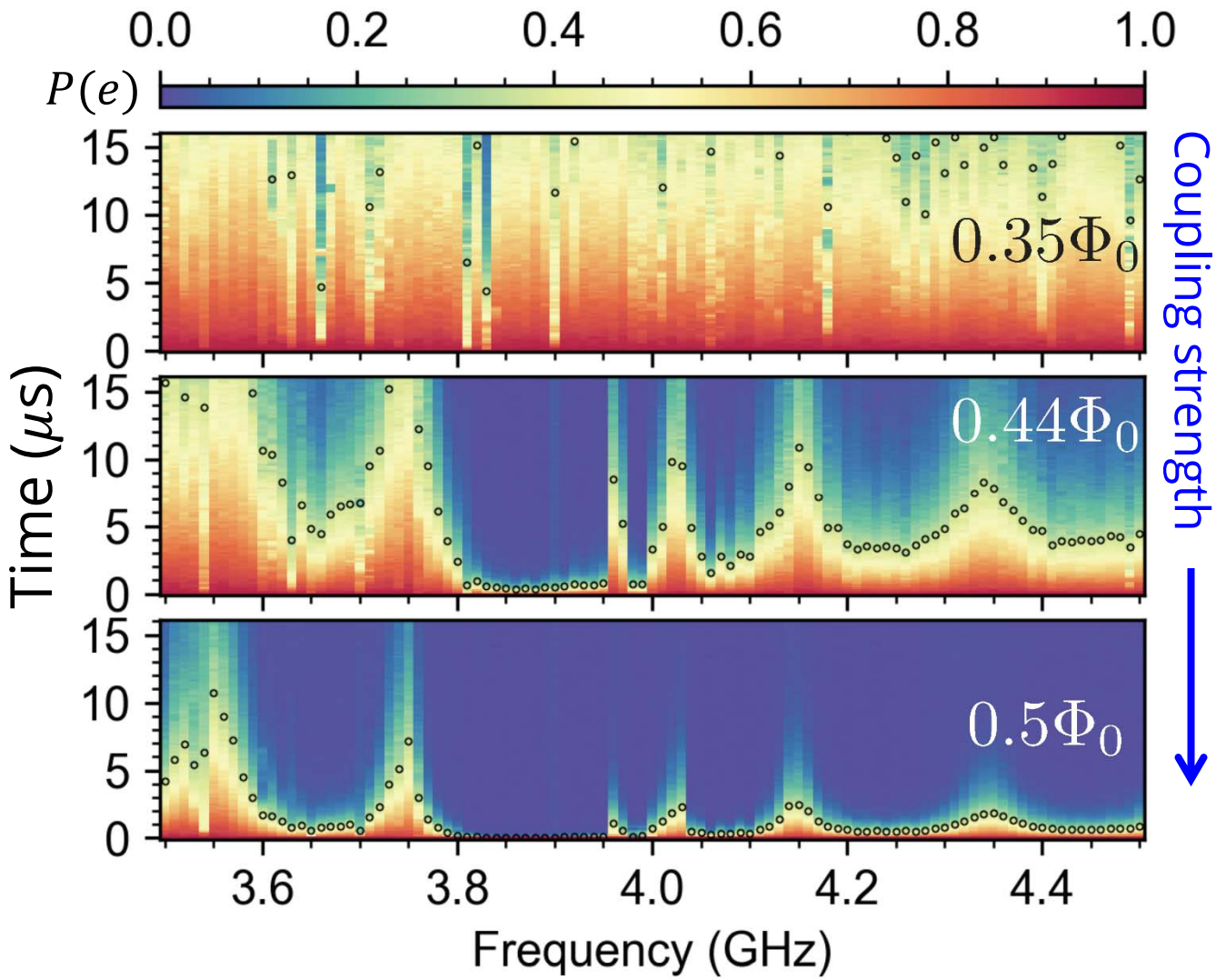
Qubit probes environment



Excite qubit to $|e\rangle$
Monitor decay

Satzinger et al *in press*

Qubit probes environment

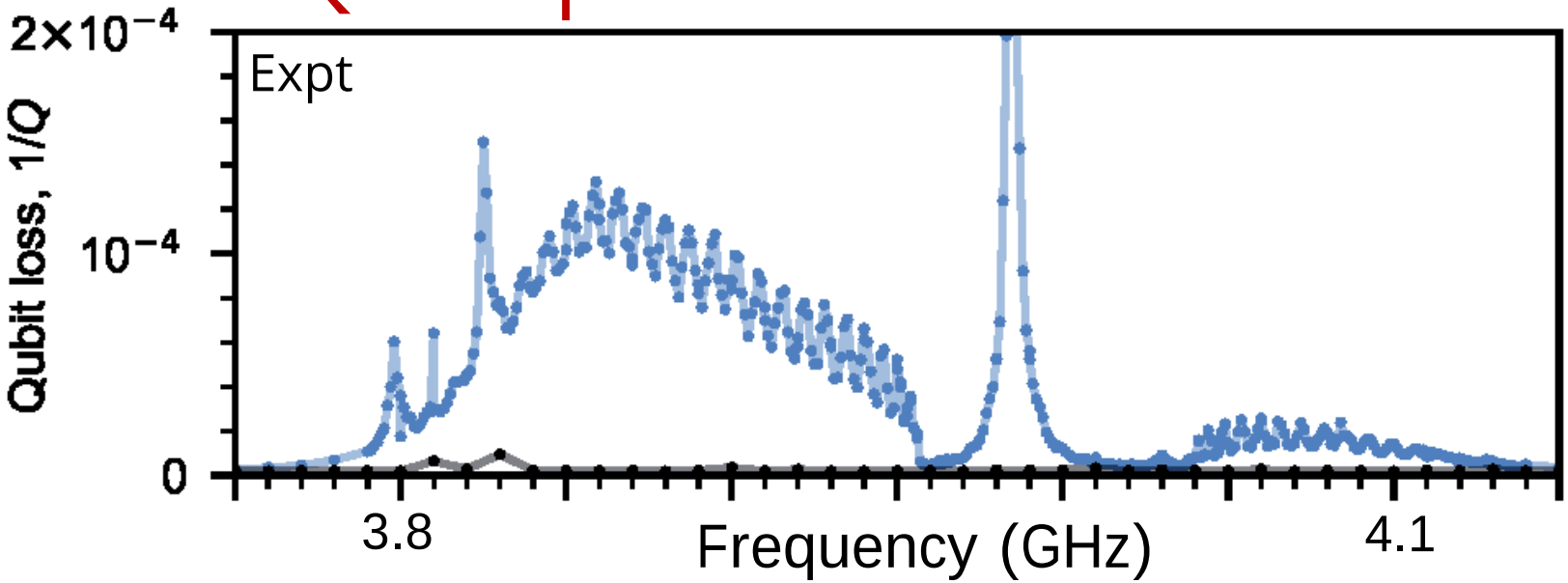


Excite qubit to $|e\rangle$
Monitor decay

- Frequency-dependent T_1
- Strong interaction with SAW resonator
- Coupled T_1 reveals SAW admittance

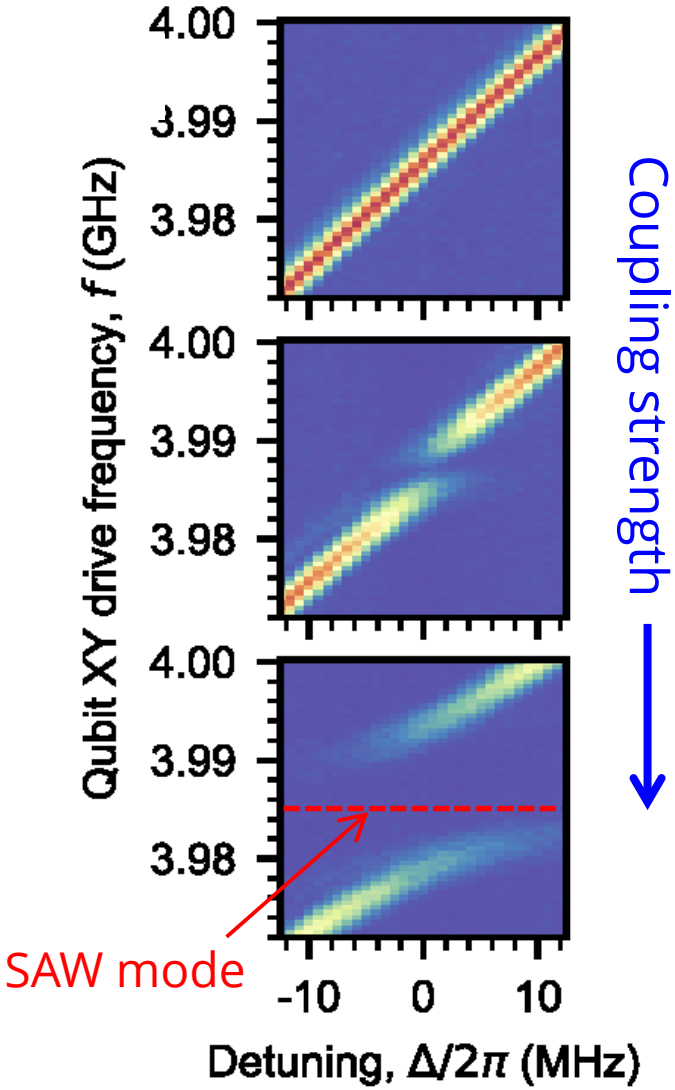
Satzinger et al *in press*

Qubit probes environment

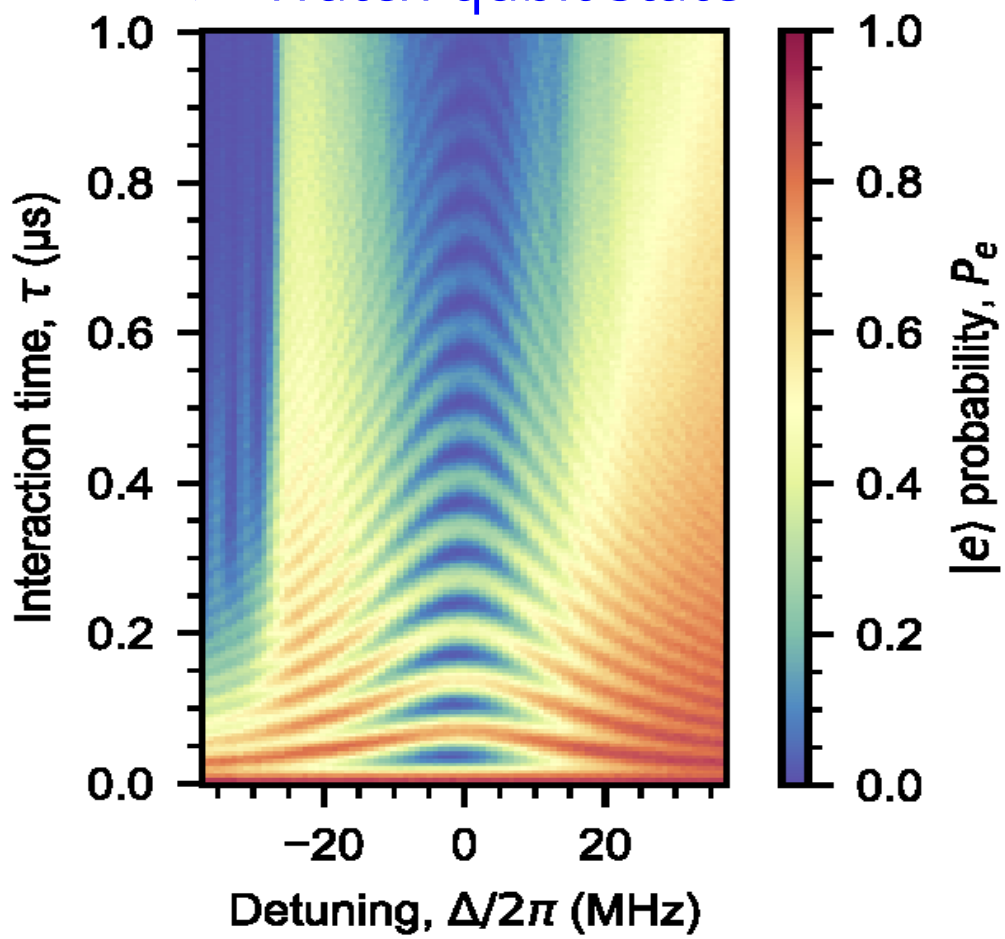


Satzinger et al *in press*

Quantum surface acoustics

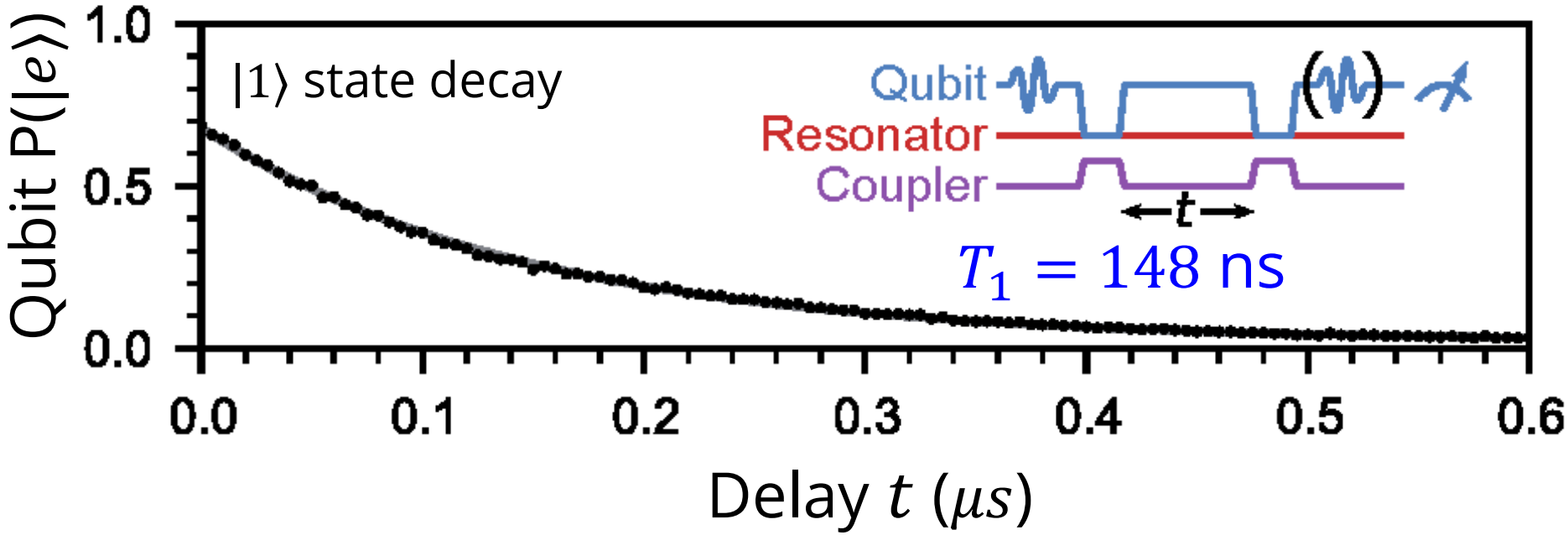


- Excite qubit
- Turn on coupling
- Watch qubit state



Satzinger et al *in press*

SAW coherence times



Satzinger et al *in press*

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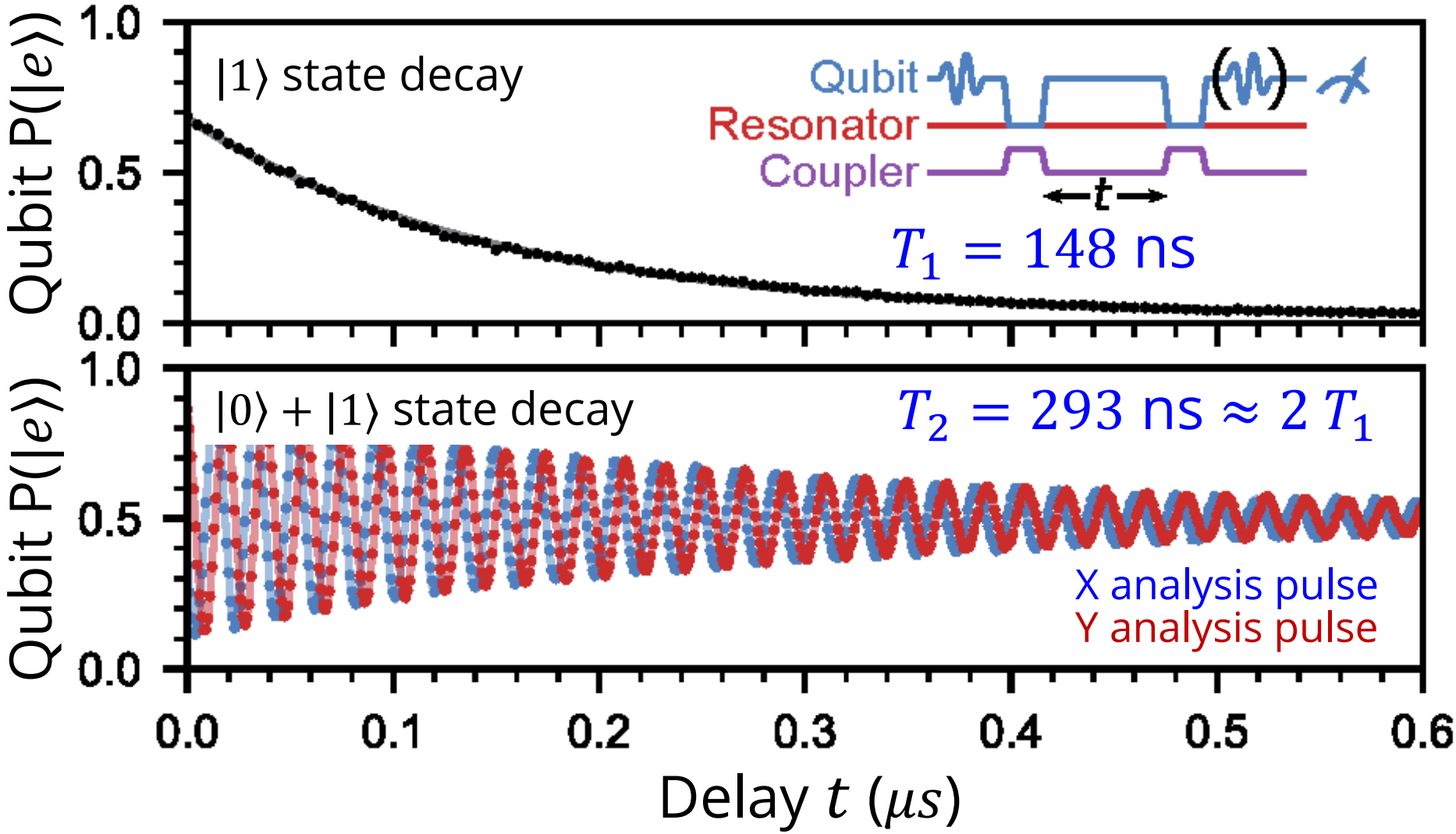


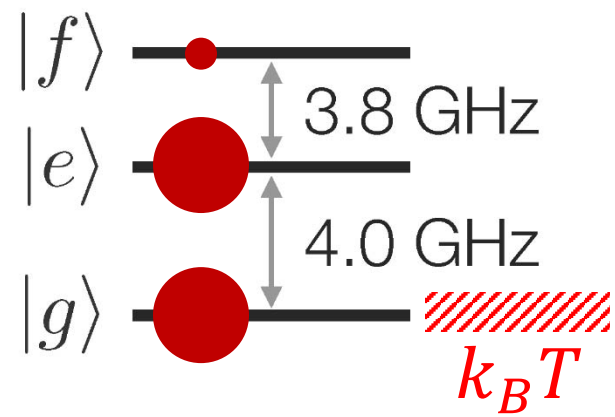
Satzinger et al *in press*

Qubit thermometry

Small $|e\rangle$ population

1. Drive $e-f$ transition
2. Swap $e-g$ populations
3. Measure $|g\rangle$ population

Qubit states:



- "zero" limited by readout error
- variation in final $P(|g\rangle)$ with $e-f$ drive gives $|e\rangle$ population

Geerlings et al. PRL (2013)
Satzinger et al *in press*

Qubit thermometry

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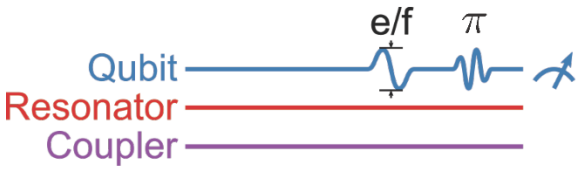

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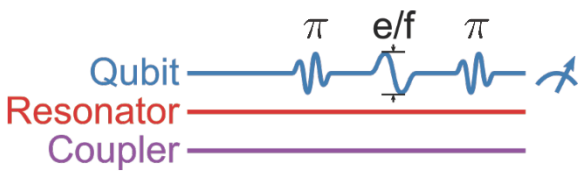
Large $|g\rangle$ population



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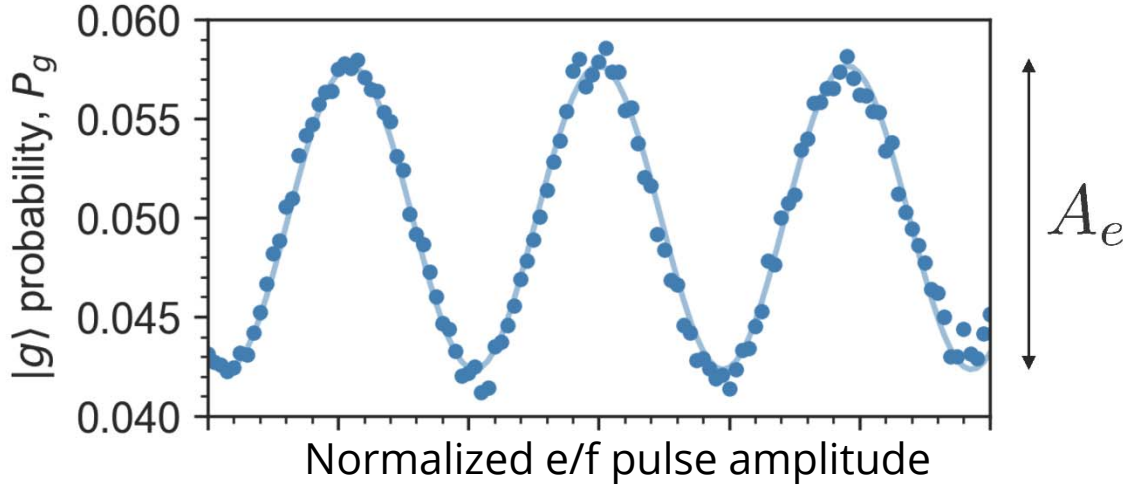


Geerlings et al. PRL (2013)

Qubit thermometry

Excited state population:

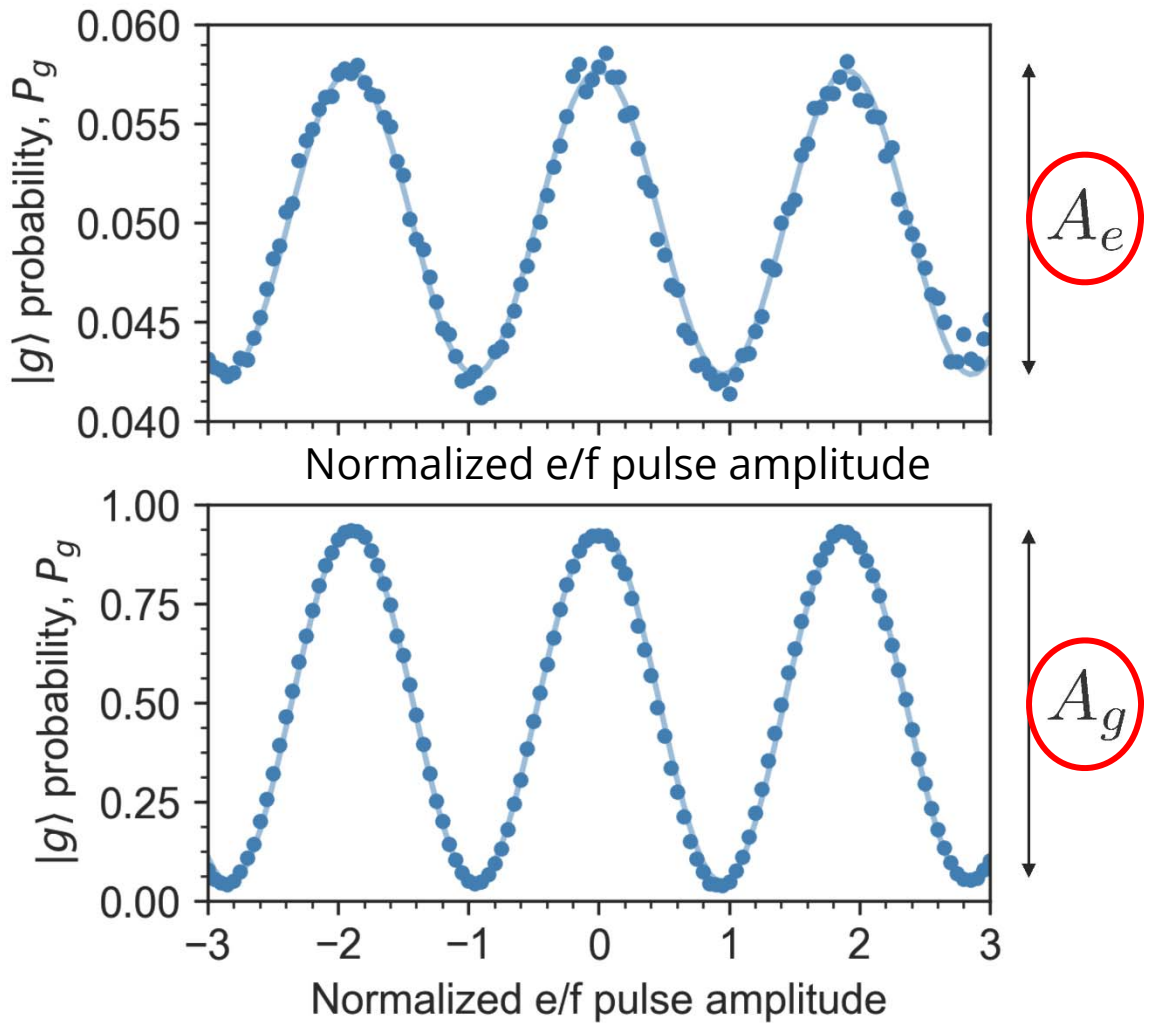
$$P_e = \frac{A_e}{A_e + A_g}$$

Result:

$$P_e = 0.0169 \pm 0.0002$$

Qubit temperature:

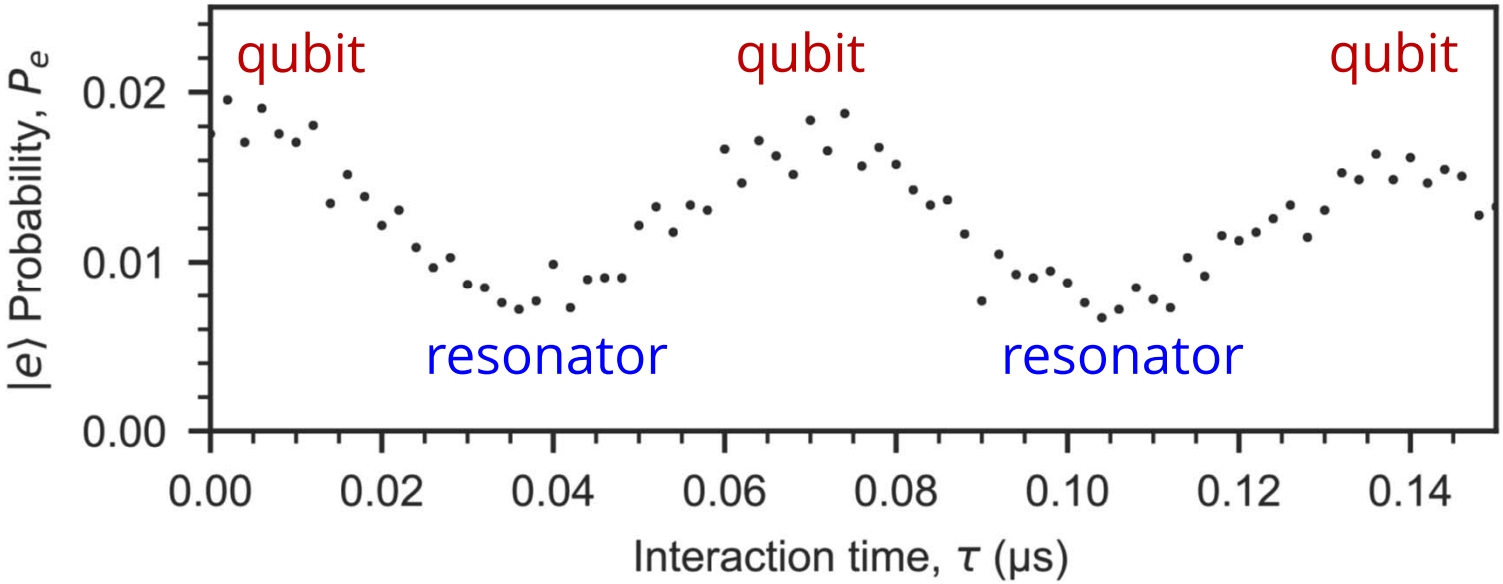
$$T_q \approx 47 \text{ mK}$$



Geerlings et al. PRL (2013)

Resonator thermometry

Measure qubit $|e\rangle$ population while swapping qubit and resonator states

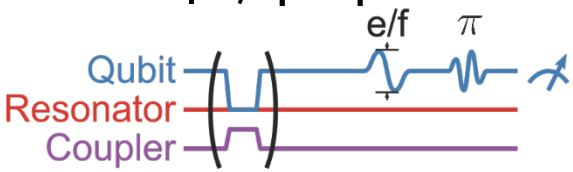


- Resonator is colder than qubit

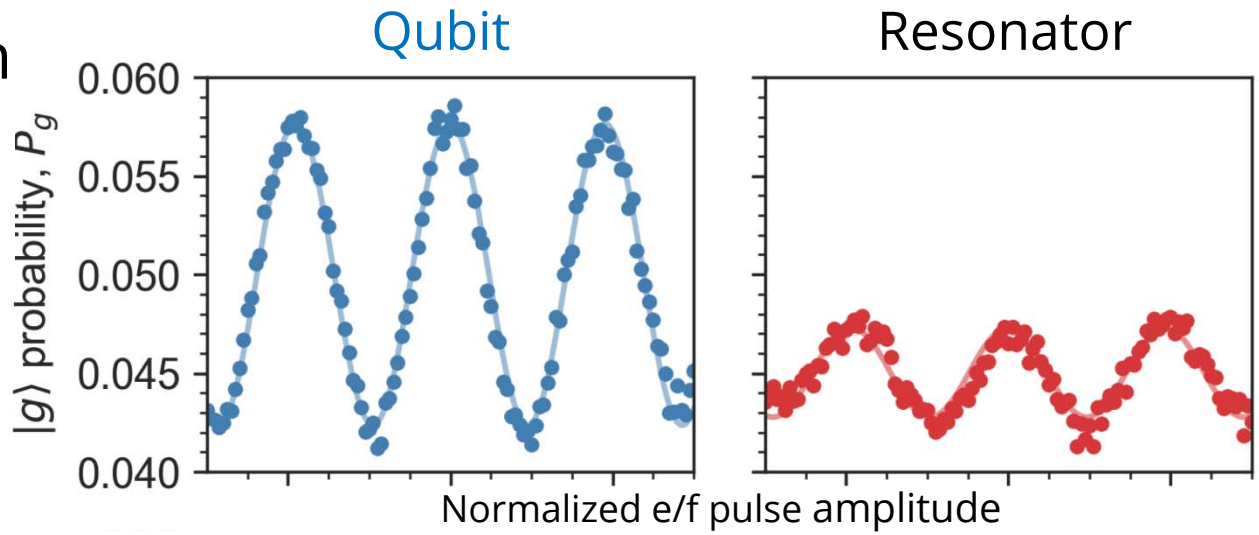
Geerlings et al. PRL (2013)

Resonator thermometry

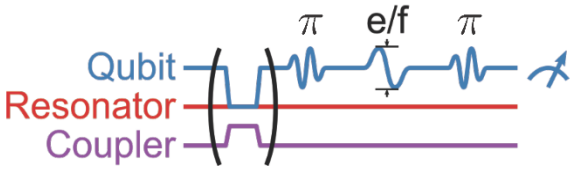
Small $|e\rangle$ population



1. (Swap qubit-resonator)
2. Drive $e - f$ transition
3. Swap $e - g$ populations
4. Measure $|g\rangle$ population



Large $|g\rangle$ population



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Geerlings et al. PRL (2013)

Resonator thermometry

Qubit

$P_e = 0.0169$

Resonator

$P_1 = 0.0049$

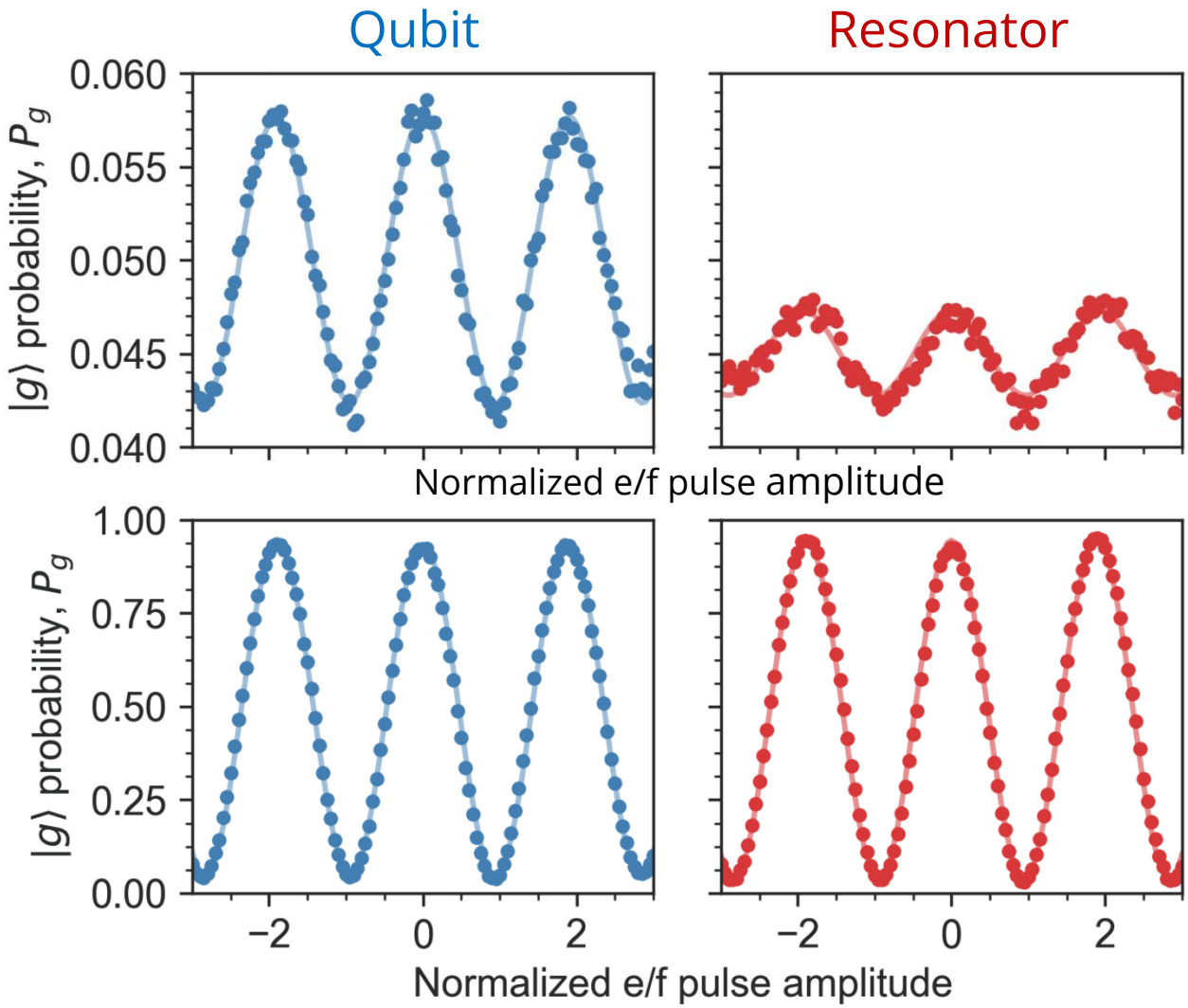
- 99.5% in ground state

Qubit temperature:

$T_q \approx 47\ \mathrm{mK}$

Resonator temperature:

$T_r \approx 36\ \mathrm{mK}$

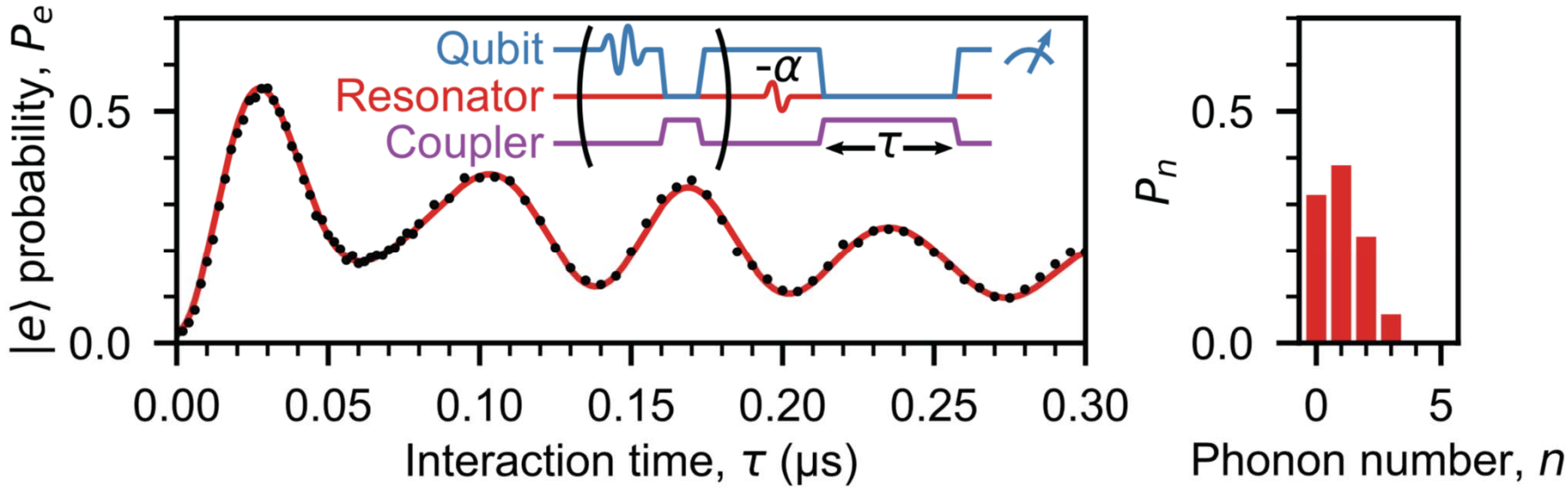


Geerlings et al. PRL (2013)

Wigner tomography

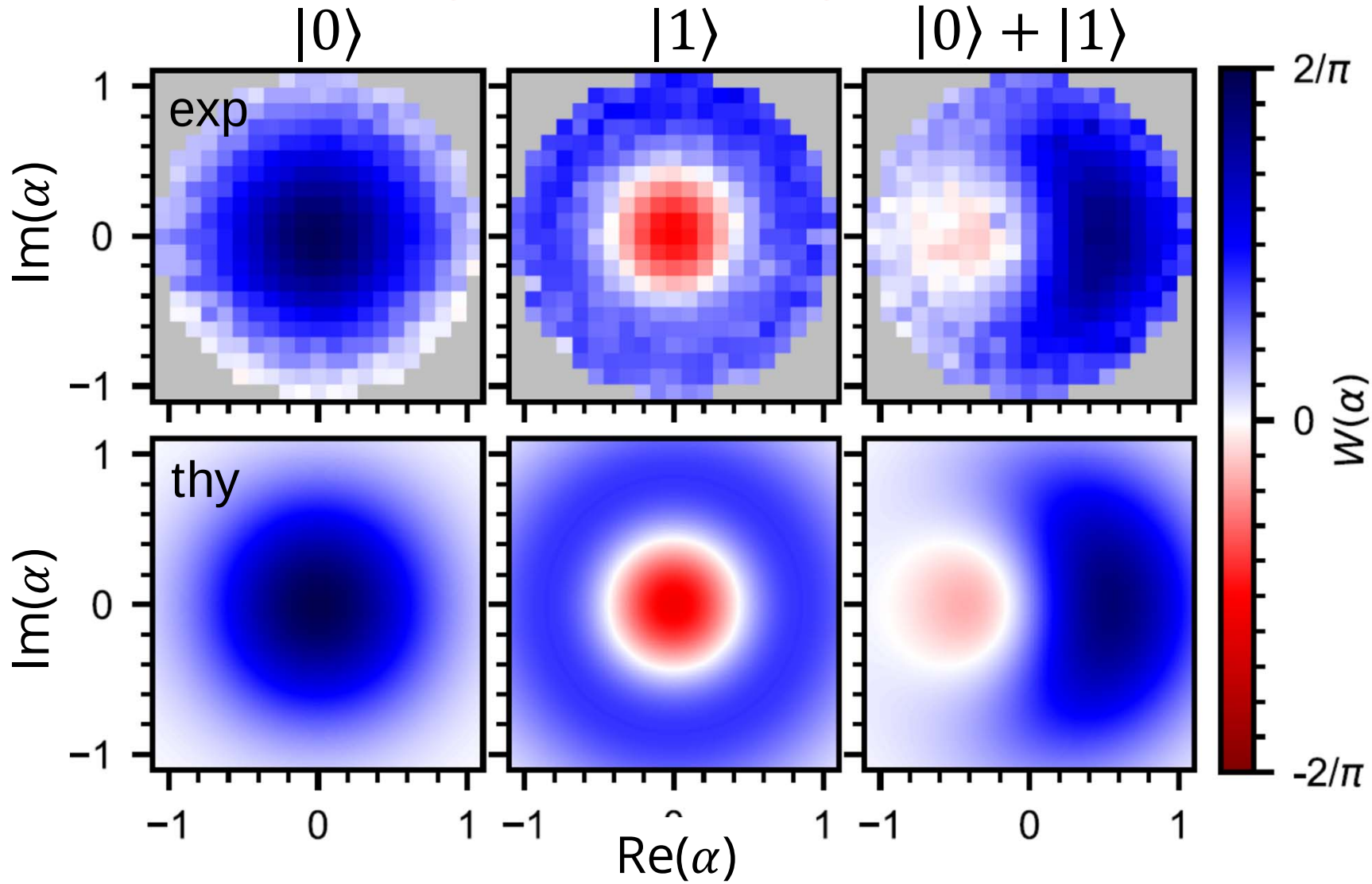
1. Swap qubit⇔resonator state: $|\psi\rangle$ in resonator
2. Displace resonator state in phase space ⇒ $D_\alpha|\psi\rangle$
3. Interact with qubit over time
4. Extract phonon number distribution $P_n(D_\alpha|\psi\rangle)$
5. Calculate parity ⇒ $W(\alpha) = \sum_n (-1)^n P_n\,(D_\alpha|\psi\rangle)$

Example: Analysis of $D_\alpha\,|2\rangle$



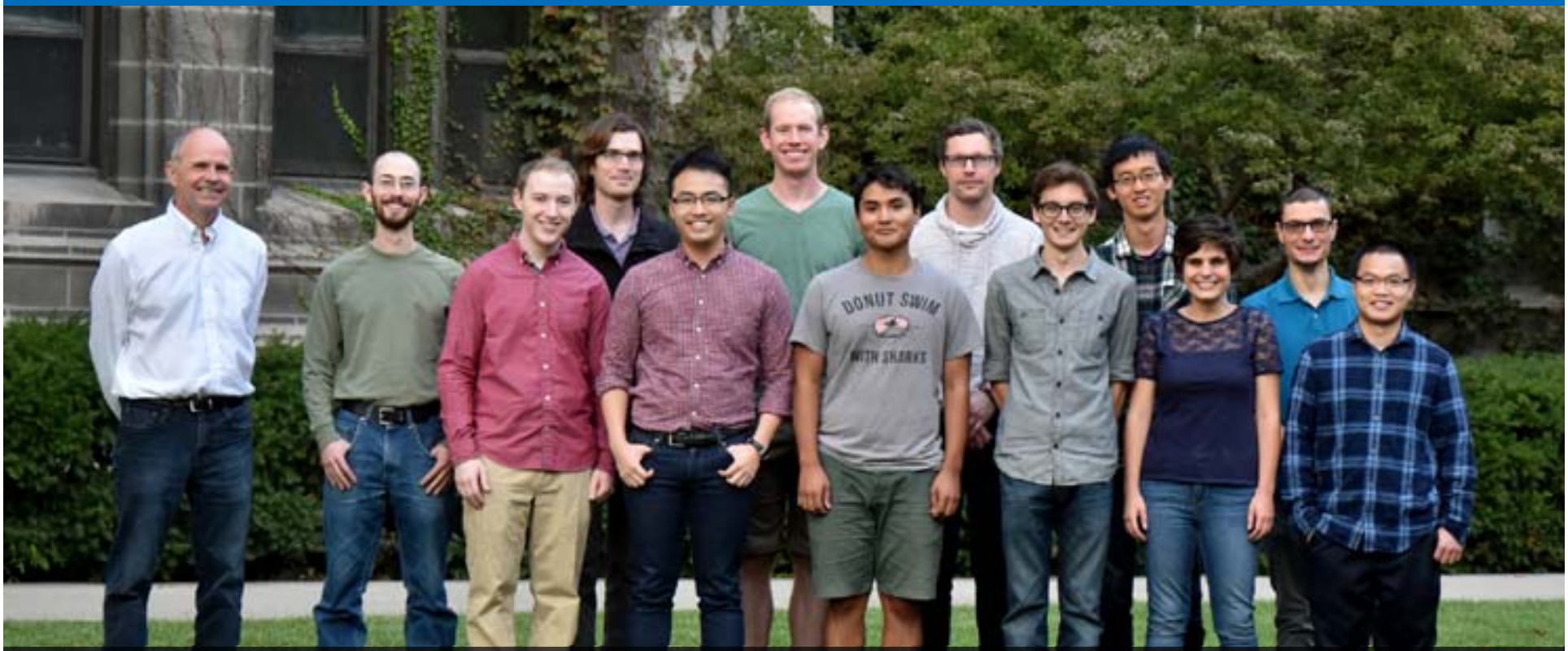
Satzinger et al *in press*

Wigner tomography



Satzinger et al *in press*

Cleland group



Audrey Bienfait
Hung-shen Chang
Ming-han Chou
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Etienne Dumur
Josh Grebel
Ivan Gutierrez
Ben November
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Kevin Satzinger
Youpeng Zhong

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Happy birthday Jukka!