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EXPERIMENTAL INVESTIGATION OF SUPERCONDUCTING QUBITS AS QUANTUM SENSORS FOR THE DETECTION OF IONIZING RADIATION

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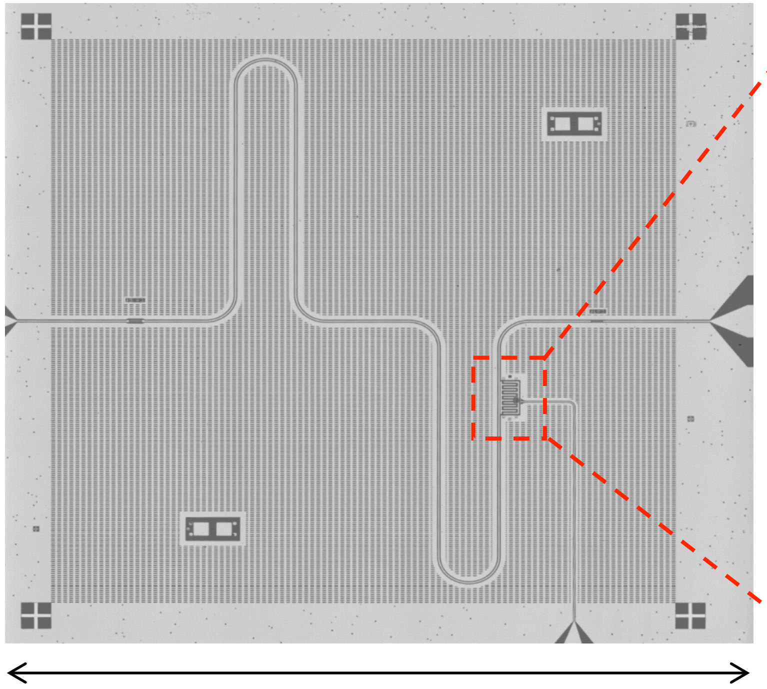
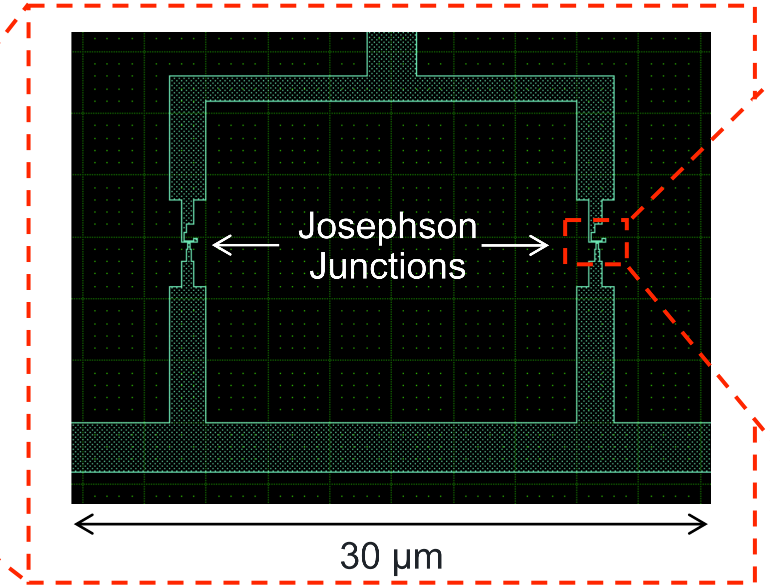
OVERVIEW OF THINGS TO COME

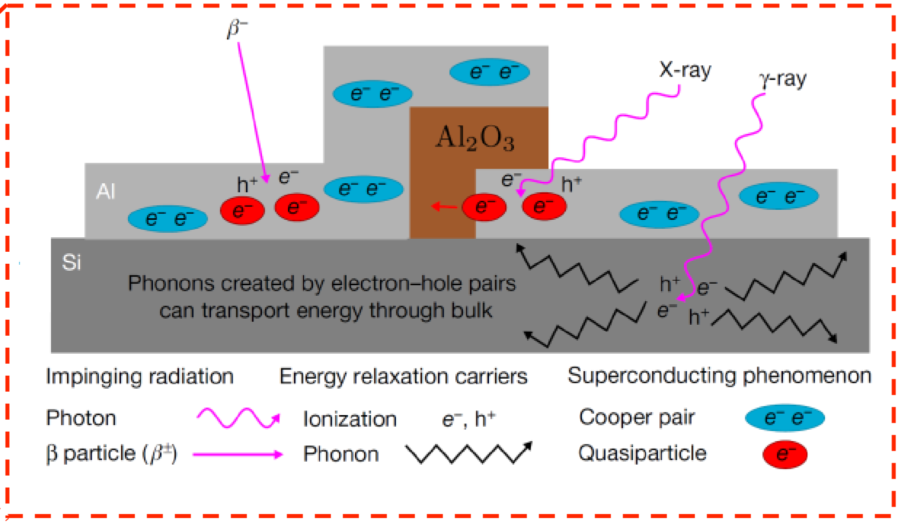
Overview

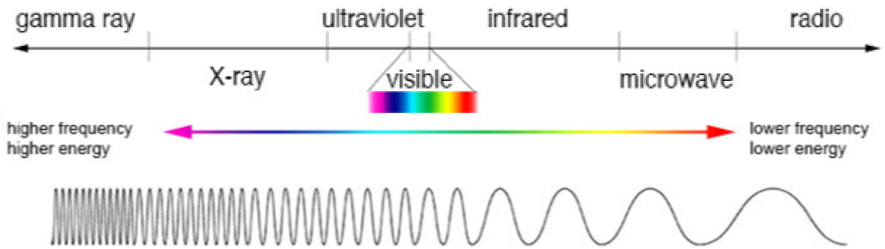
- Define quantum sensing in general independent of a specific implementation.
- Define our specific implementation of quantum sensing using a superconducting qubit.
- Present data *without* ionizing radiation on our current qubit design.
- Proposed measurement configuration *with* a source of ionizing radiation.

INTRODUCTION









- In the left image a superconducting qubit device is shown at the 6 mm x 6 mm die level.
- In the middle zoom-in image the core elements of superconducting qubits, Josephson Junctions, are barely visible at this 30 μm x 30 μm scale.
- In the right zoom-in image [2] a typical Superconductor-Insulator-Superconductor Josephson Junction is schematically shown in cross-section.
- In the lower right image is the electromagnetic spectrum. A superconducting qubit as a quantum sensor for ionizing radiation in the 10 keV to 1 MeV energy range.

[2] A. P. Vepsäläinen et al, Impact of ionizing radiation on superconducting qubit coherence, *Nature* 584, 551 (2020).

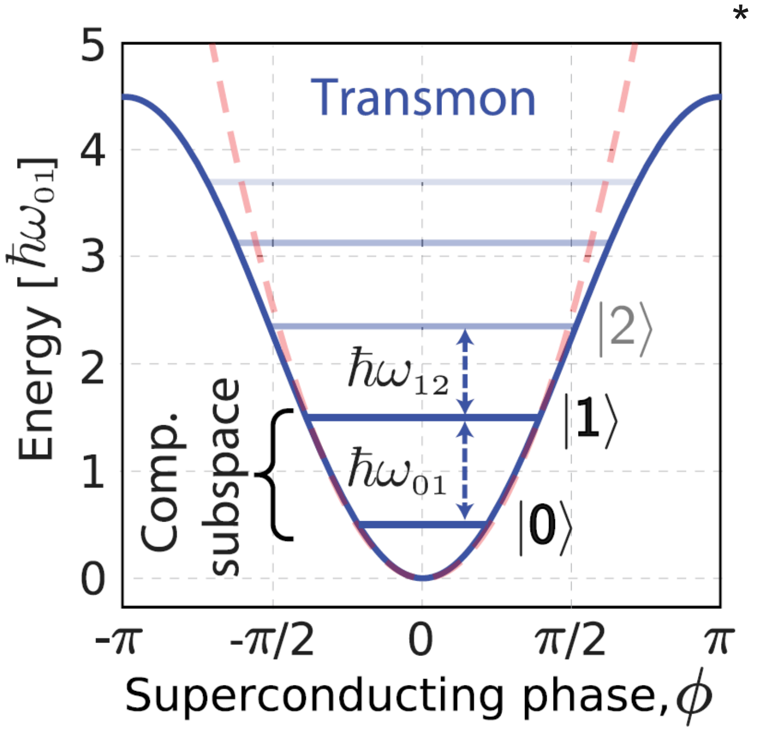
INTRODUCTION TO QUANTUM SENSING

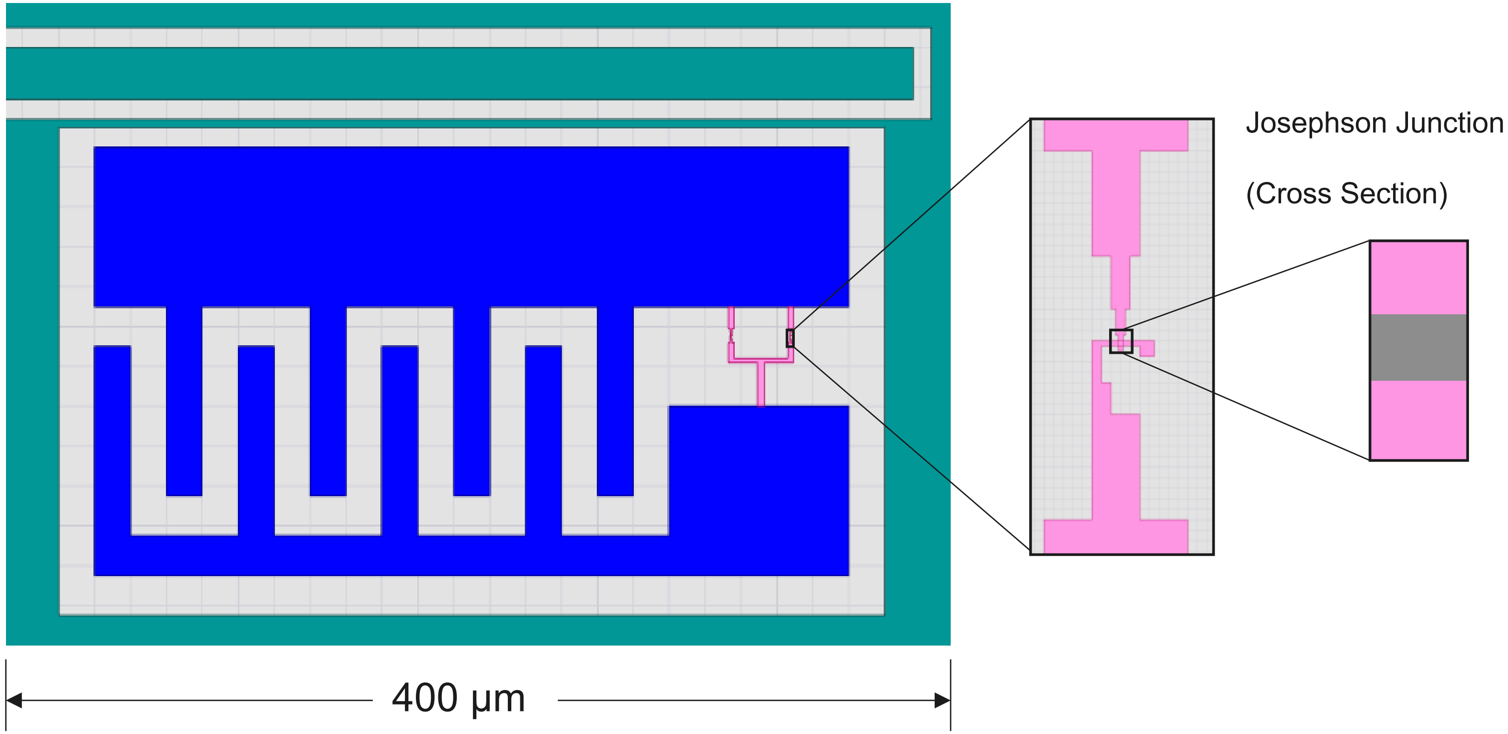
- Quantum sensing describes the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity.
- Generally in three categories:
  - Use of a quantum object to measure a physical quantity.
  - Use of quantum coherence to measure a physical quantity. Such as temporal superposition of states.
  - Use of quantum entanglement to improve measurement sensitivity beyond classical limits.
- Types of quantum sensors:
  - Trapped Ions
  - Rydberg Atoms
  - Superconducting Circuits
    - We are utilizing transmission-line shunted plasma oscillation qubit or "transmon" for short.
  - And many more.

ANATOMY OF A TRANSMON

Hamiltonian

$$H = 4E_C n^2 - E_J \cos\varphi$$



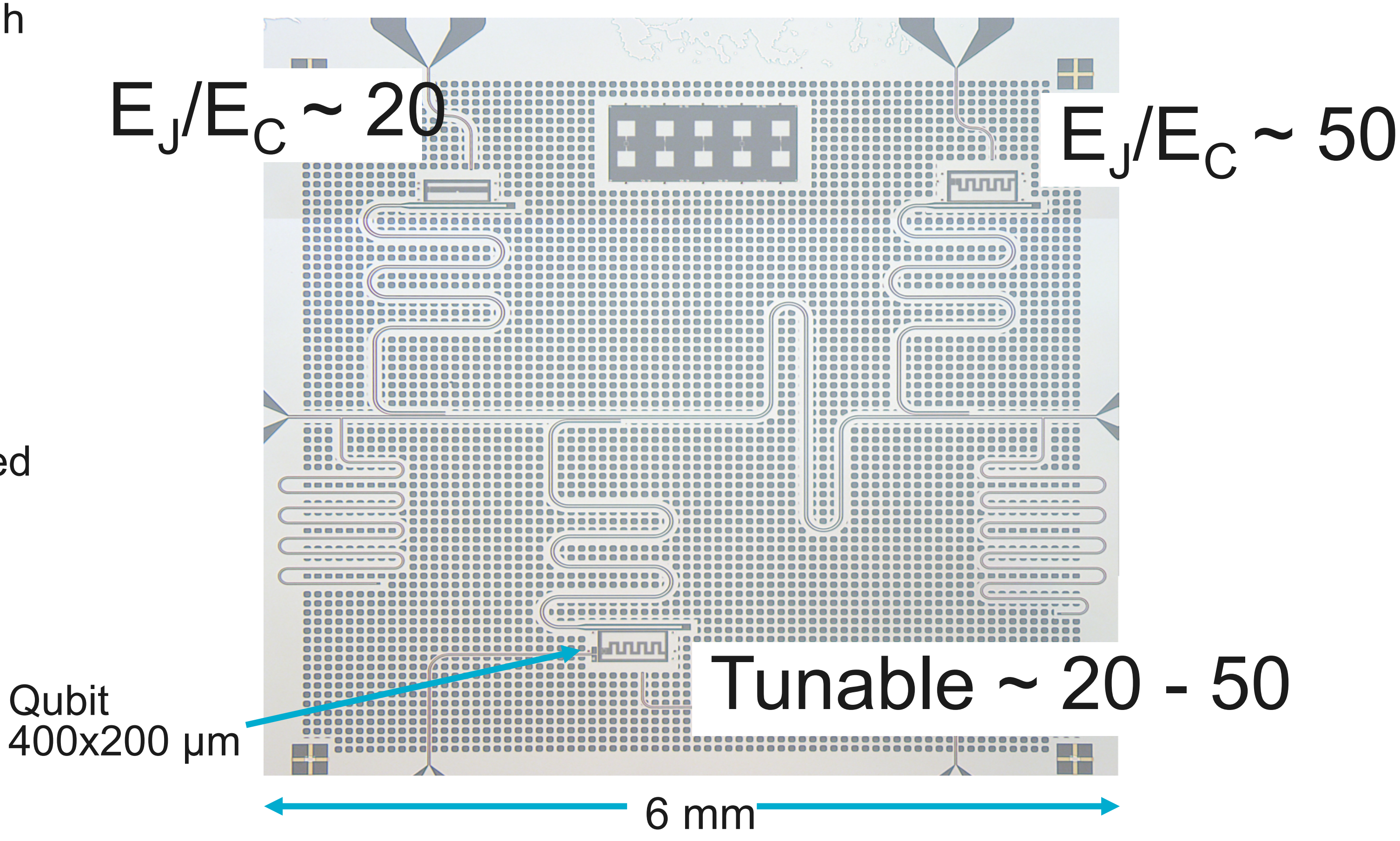


$$\hbar\omega_{01} \approx 5\ GHz = 240\ mK > 10\ mK \text{ (operating temperature)}$$

*Krantz, P. et. el., A quantum engineer's guide to superconducting qubits, Apl. Phys. Rev., 2019

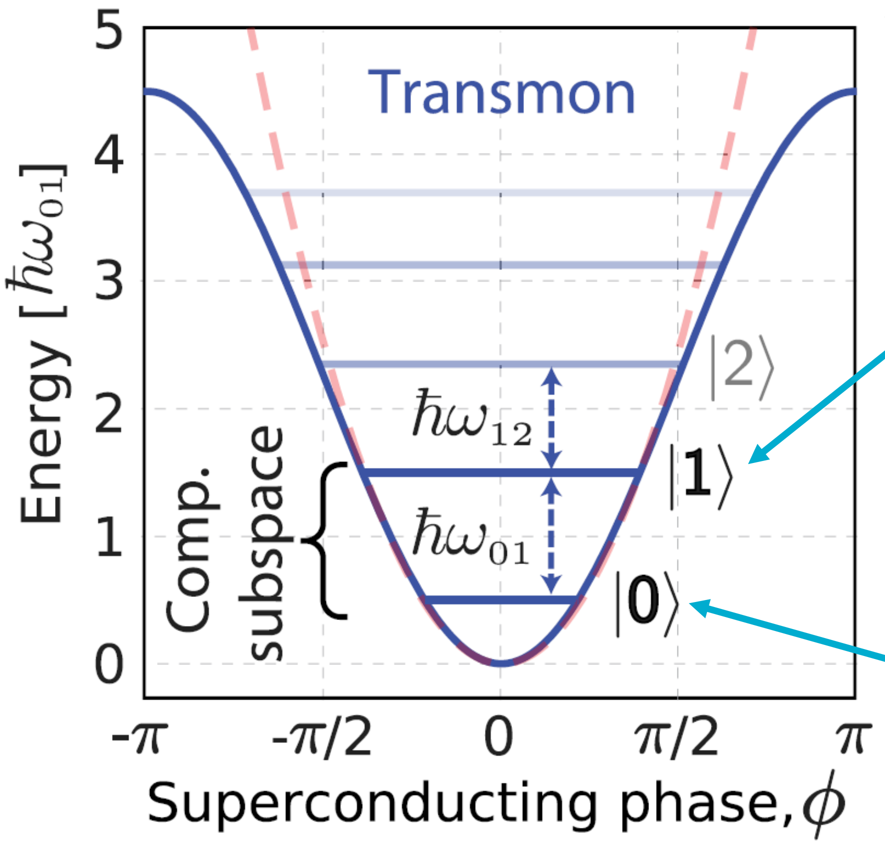
THREE QUBIT CHIP FOR A RANGE OF SENSITIVITY

- E_J =Josephson Energy
  - Ability of Cooper pair to tunnel through the junction.
  - Measure of energy stored in the junction.
- E_C = Charging energy of junction.
- E_J/E_C = A measure of sensitivity to charge noise.
- By having a multi-qubit die the range of sensitivity to charge noise can be increased by having a range of E_J/E_C.

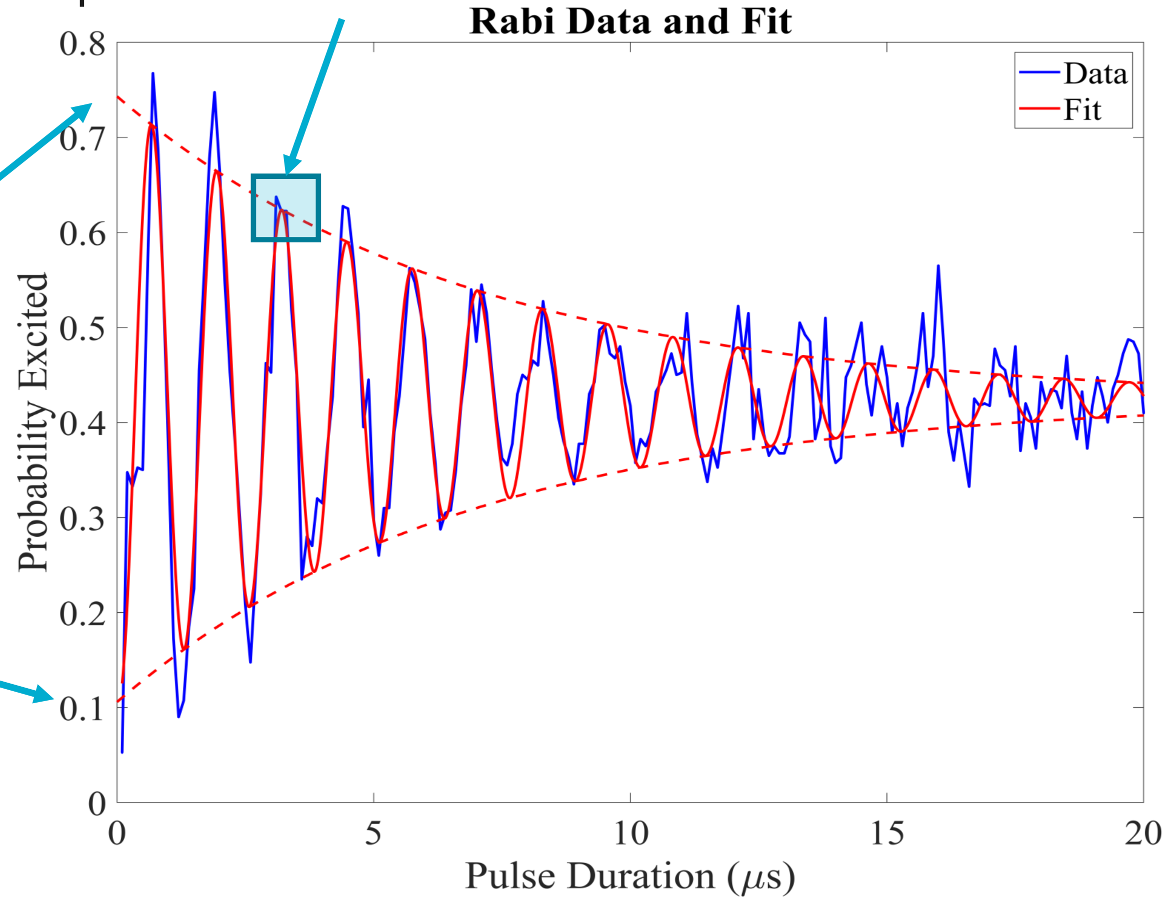


EXAMPLE OF A QUBIT MEASUREMENT – RABI OSCILLATIONS ON E_J/E_C = 50 QUBIT

- Rabi Oscillations, $P(Excited) \propto \sin^2\left(\frac{\omega t}{2}\right)$

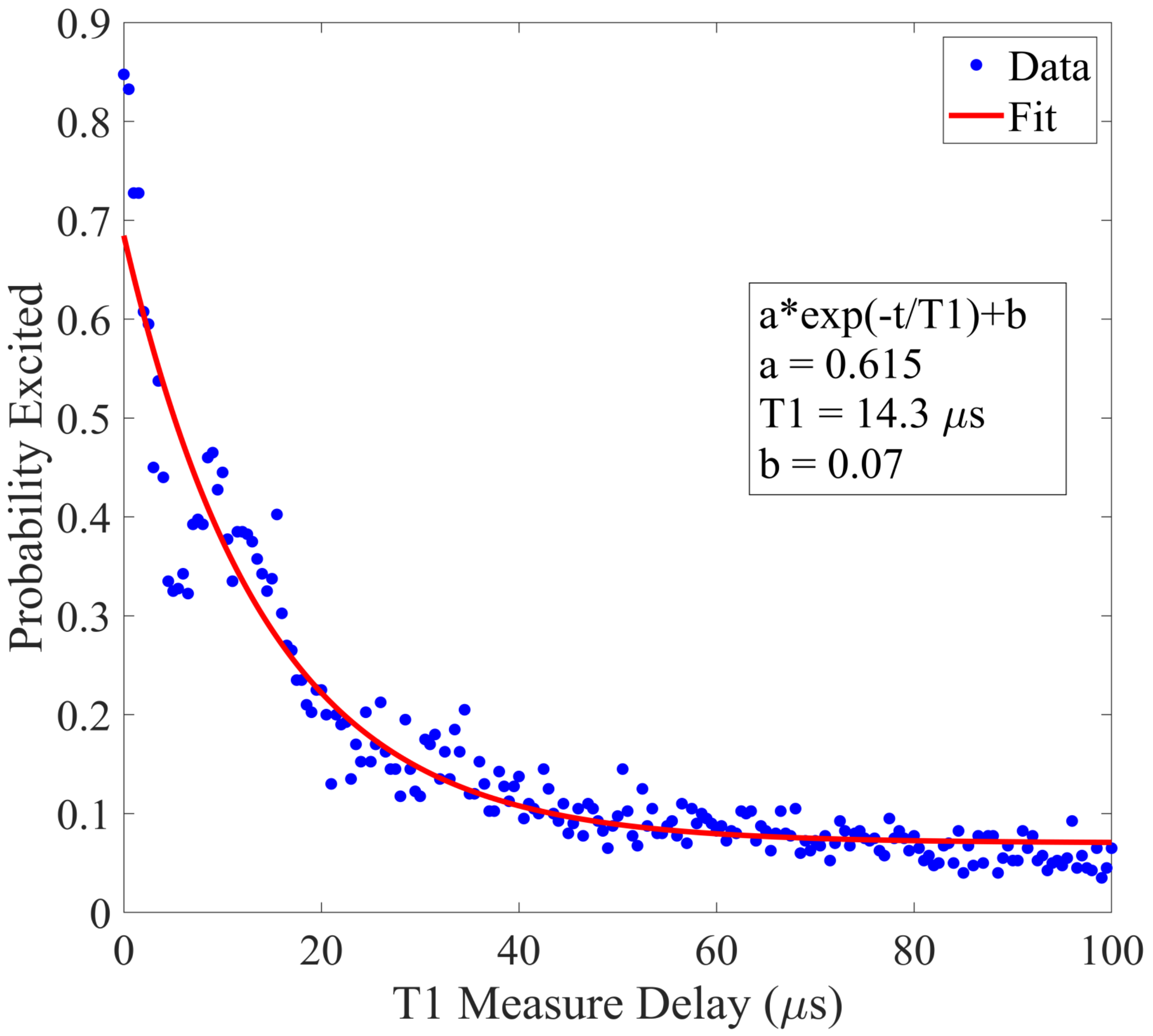


Repeatedly measure a single point in the curve, such as this peak.

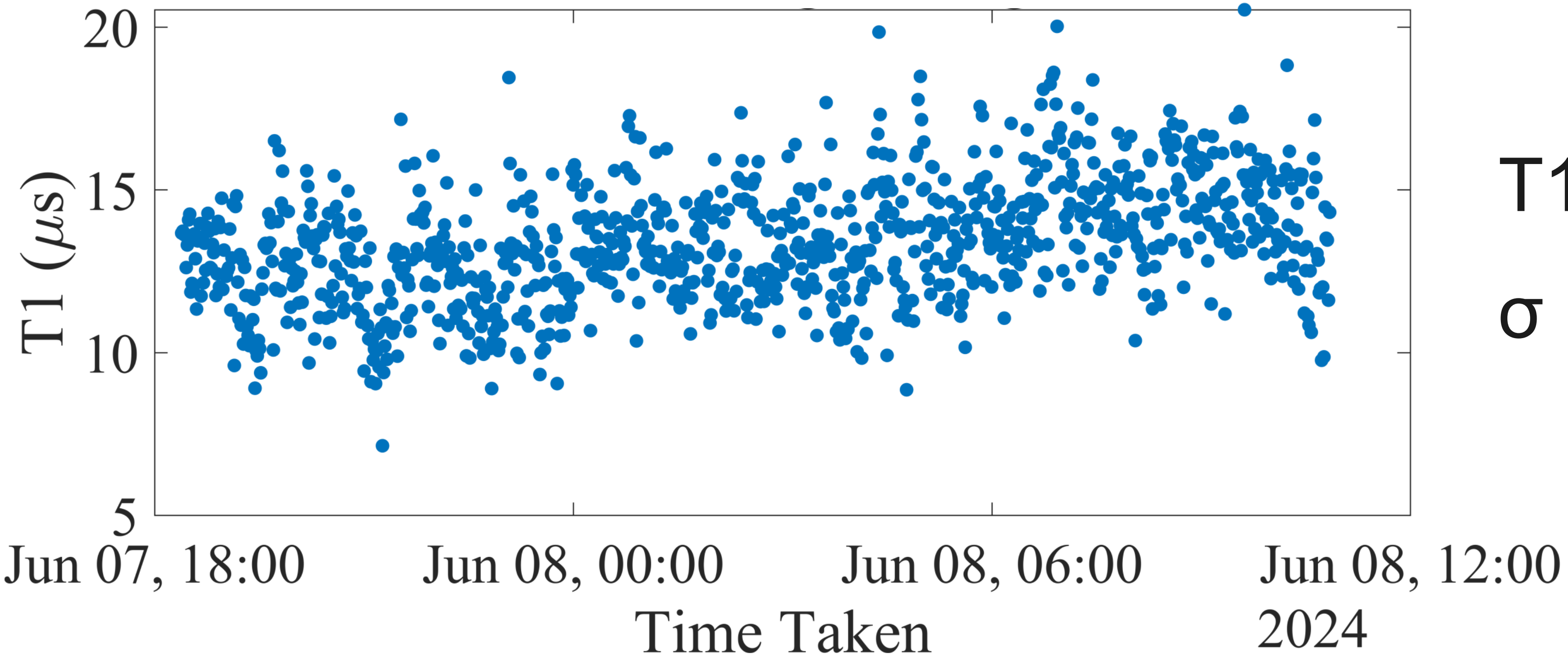


HIGH E_J/E_C = 50, T1

- T_1 measures the time for the qubit to relax from the first excited state into the ground state.
- T_1 is fit by an exponential.



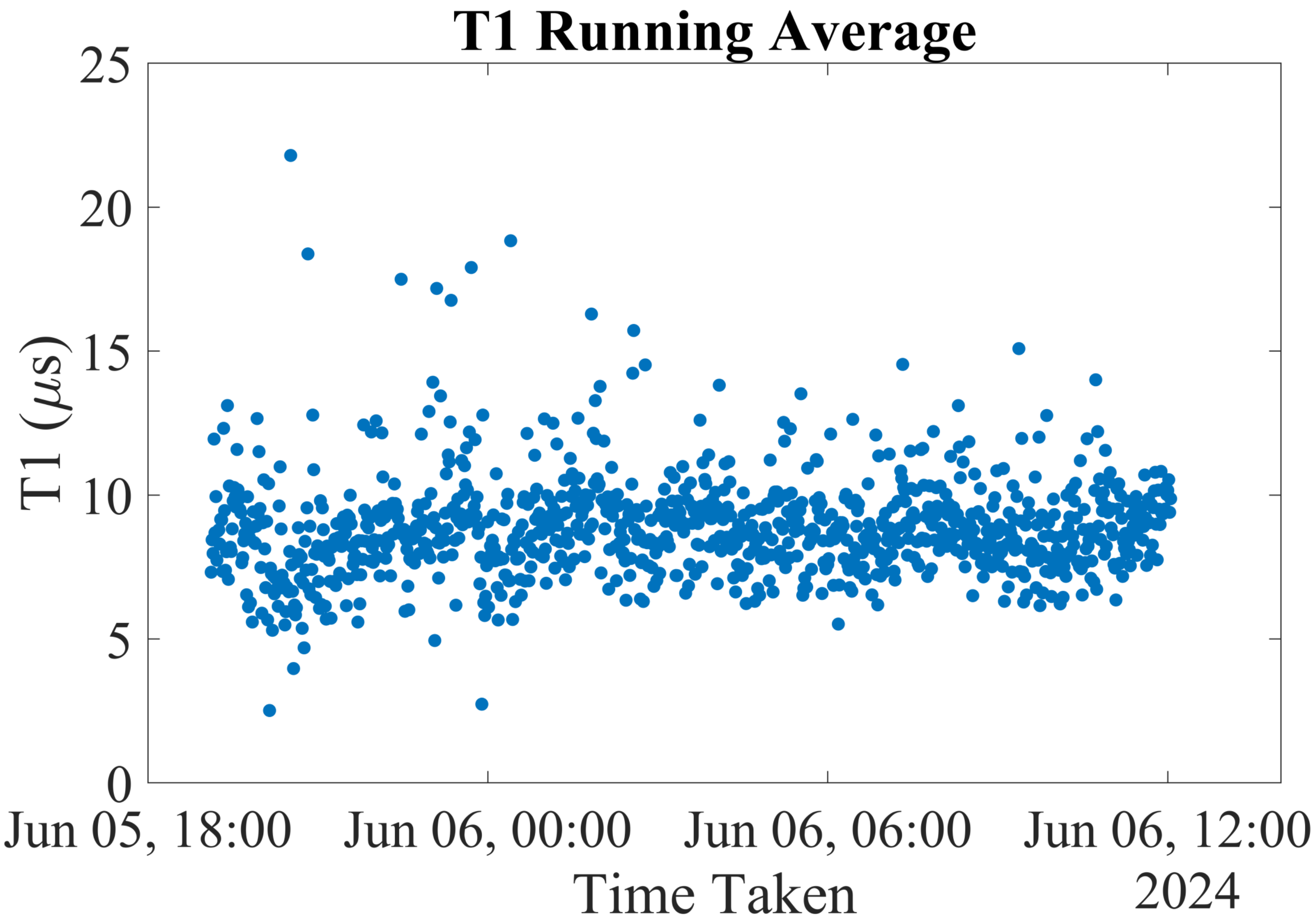
HIGH E_J/E_C = 50, T1 AVERAGE



T1 = 13.4 μs

σ = 1.9 μs

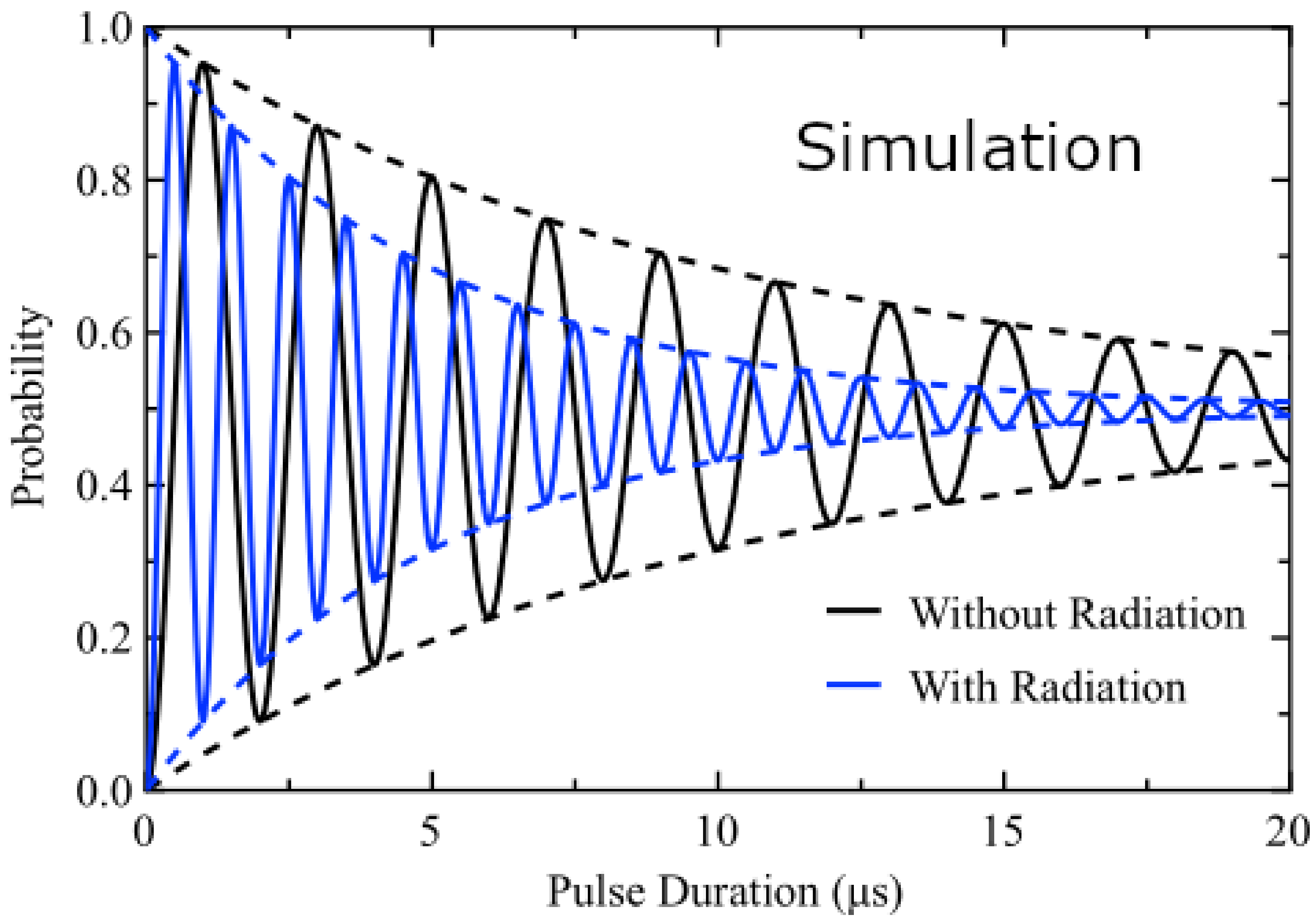
TUNABLE QUBIT, $E_J/E_C = 50$, T1 AVERAGE



T1 = 8.7 μs

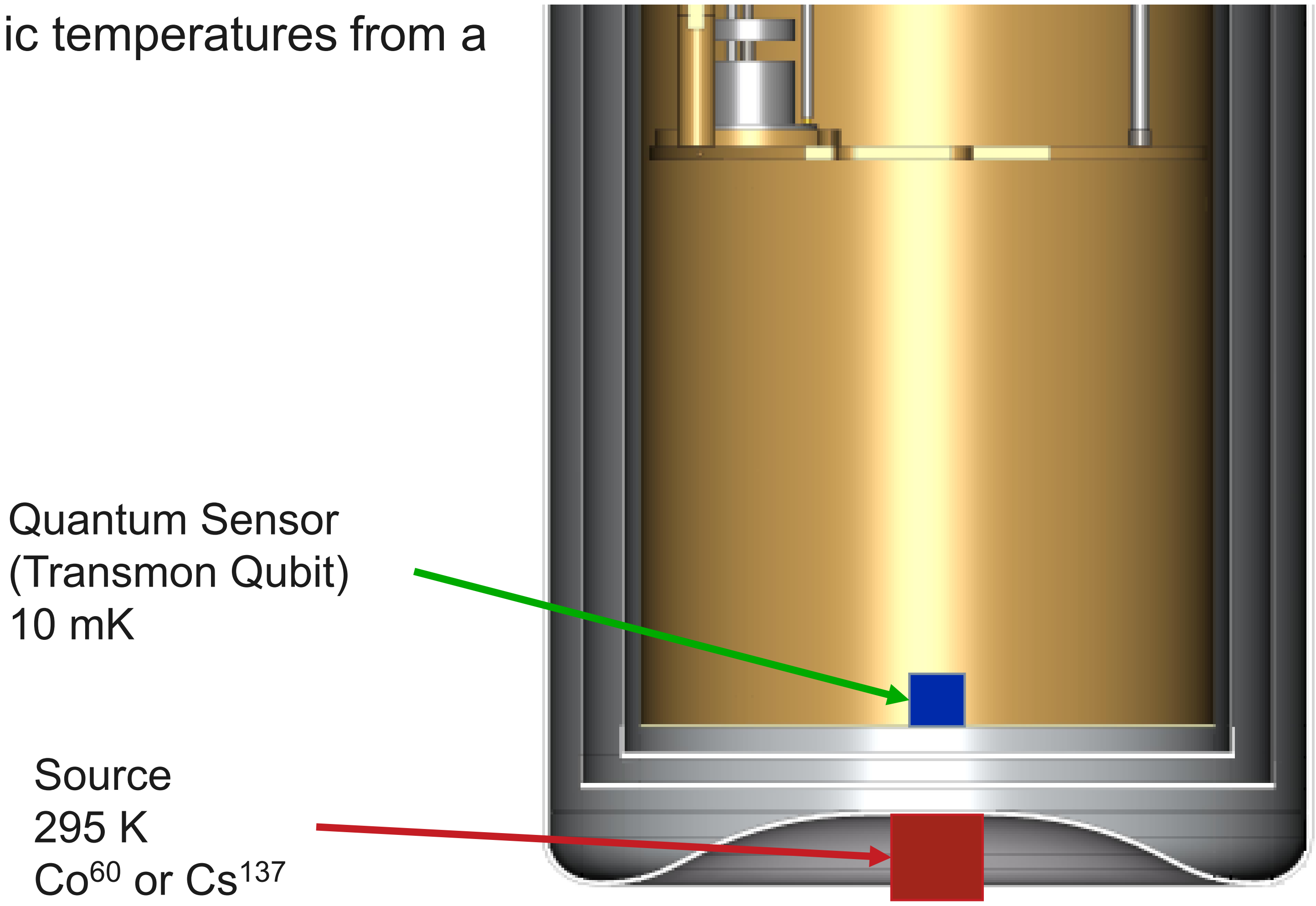
σ = 1.8 μs

DETECTION PRINCIPLE



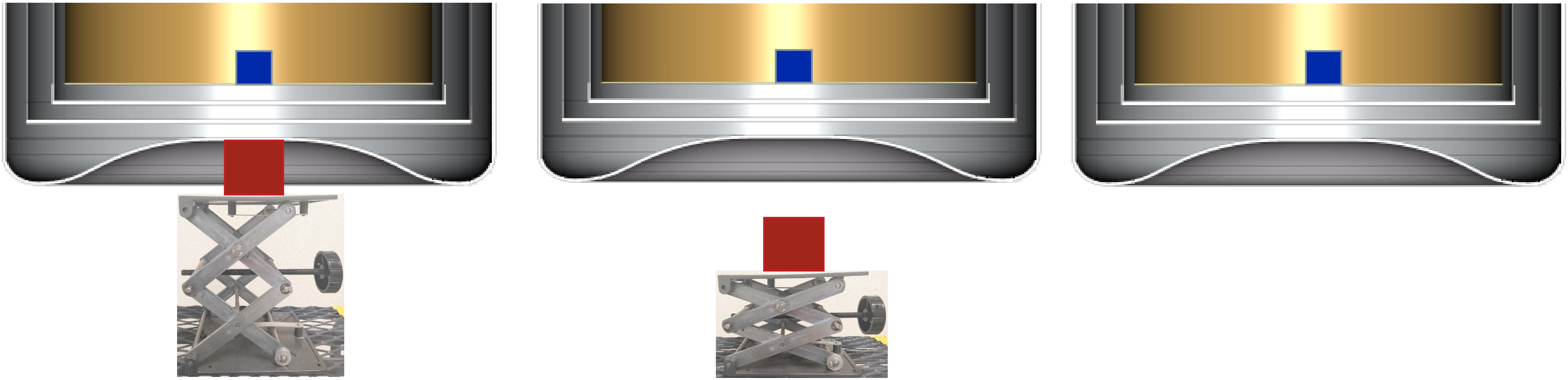
PROPOSED MEASUREMENT CONFIGURATION

Measurement of a source at cryogenic temperatures from a source at room temperature.



CONTROL OVER RADIATION

- By having the radiation source external to the cryostat we can control the exposure strength and duration.
- Allows use of different sources without thermal cycling.



SUMMARY

- We propose to utilize a transmon qubit as a quantum sensor for ionizing radiation.
- To increase sensitivity range, we are developing a multi-qubit chip housing a range of E_J/E_C.
- Work to characterize our device is currently on going.
- Impacting radiation is expected to be seen as a decrease in coherence.
- We propose to measure a radiation source at RT with a sensor at ~10 mK.