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QUANTUM SENSING USING A QUBIT FOR THE DETECTION OF IONIZING RADIATION

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PREAMBLE AND OVERVIEW OF THINGS TO COME

Preamble

- There has been tremendous progress with superconducting qubits for quantum information processing. The work presented here was motivated in part by the seminal results from Nature 584, 551 (2020). While Nature 584, 551 (2020) was focused on the impact of ionizing radiation for quantum information processing, it motivates the investigation of superconducting qubits as a quantum sensors for the detection of ionizing radiation. This is a new field that is just beginning.

Overview

- Define quantum sensing in general independent of a specific implementation.
- Define our specific implementation of quantum sensing using a superconducting qubit:
- Proposed measurement configuration *with* a source of ionizing radiation.

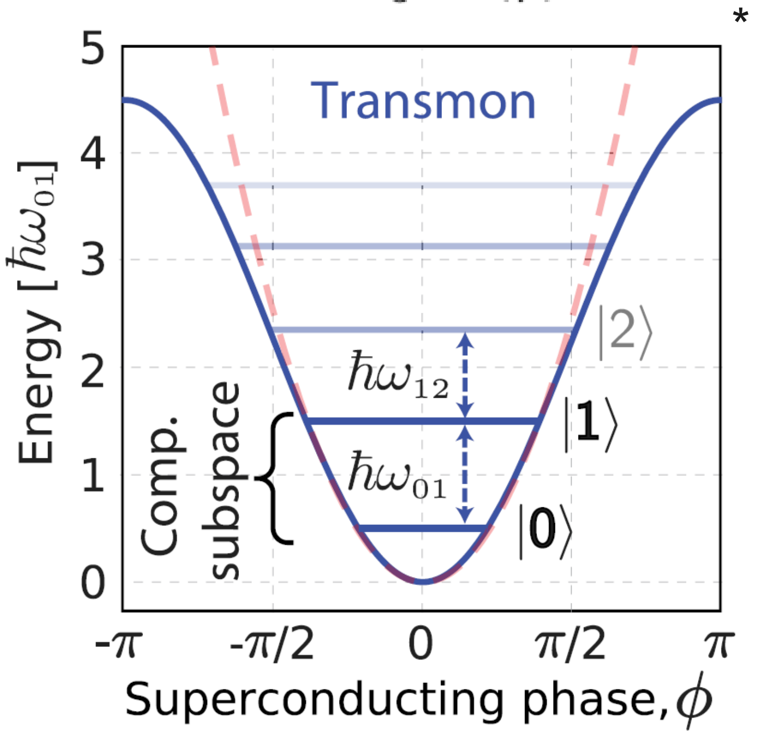
INTRODUCTION TO QUANTUM SENSING

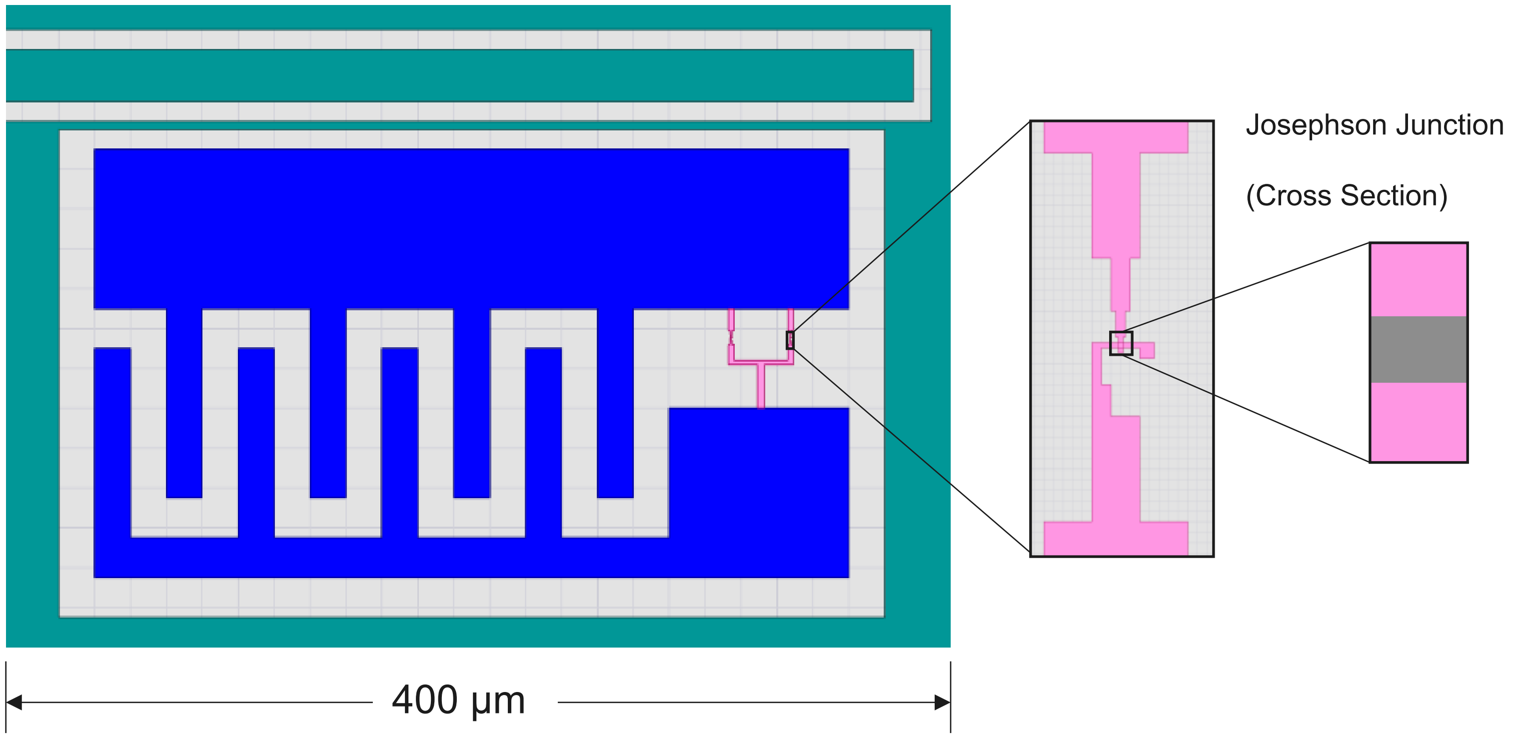
- Quantum sensing describes the use of a quantum system, quantum properties, or quantum phenomena to perform a measurement of a physical quantity.
- Generally in three categories:
  - Use of a quantum object to measure a physical quantity.
  - Use of quantum coherence to measure a physical quantity. 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

Potential Energy

$$V = \frac{\hbar}{2eI_C\cos(\varphi)}\frac{dI}{dt}$$



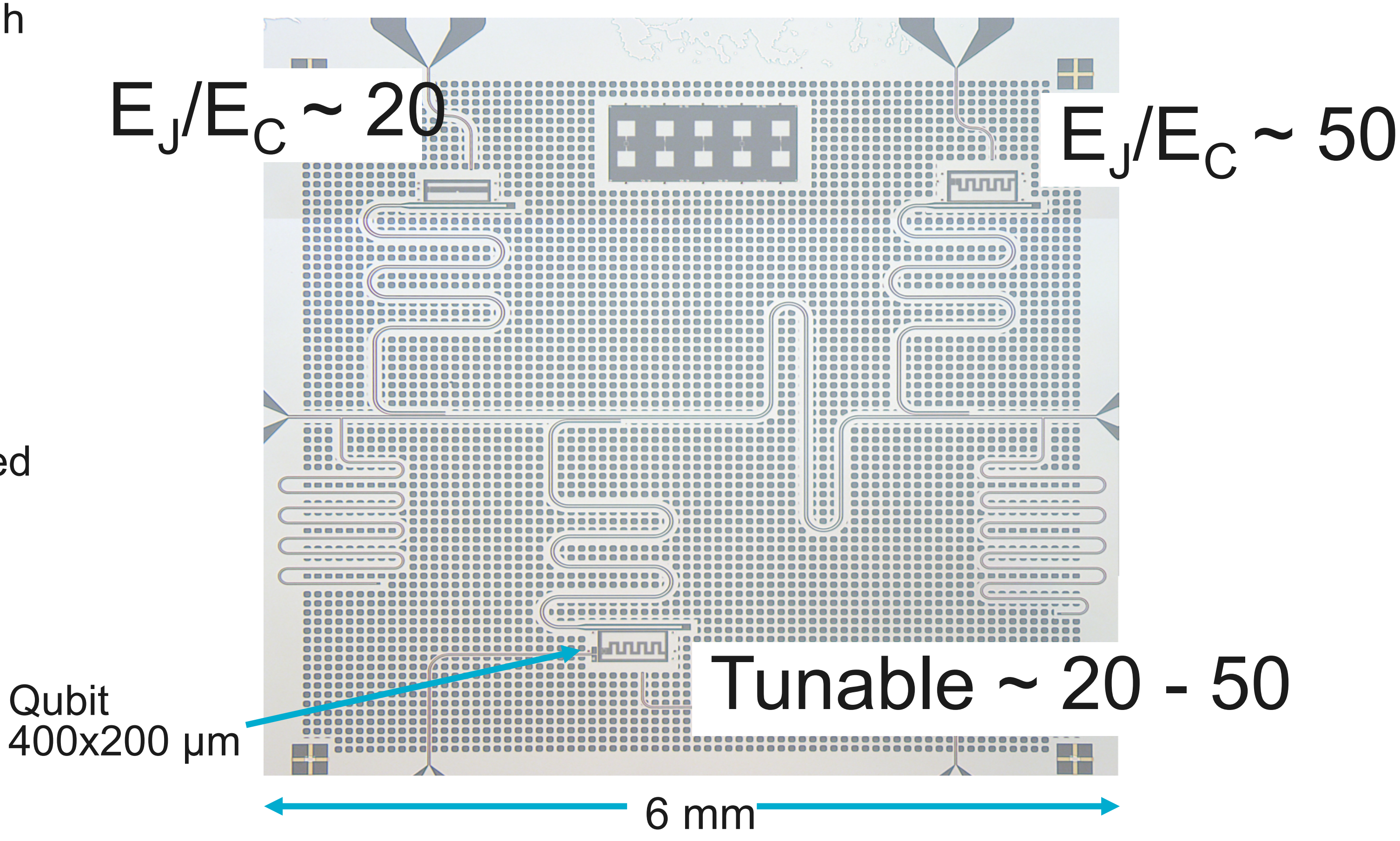


$$\hbar\omega_{01} \approx 5\ GHz = 240\ mK \ll LN_2, HPGe$$

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

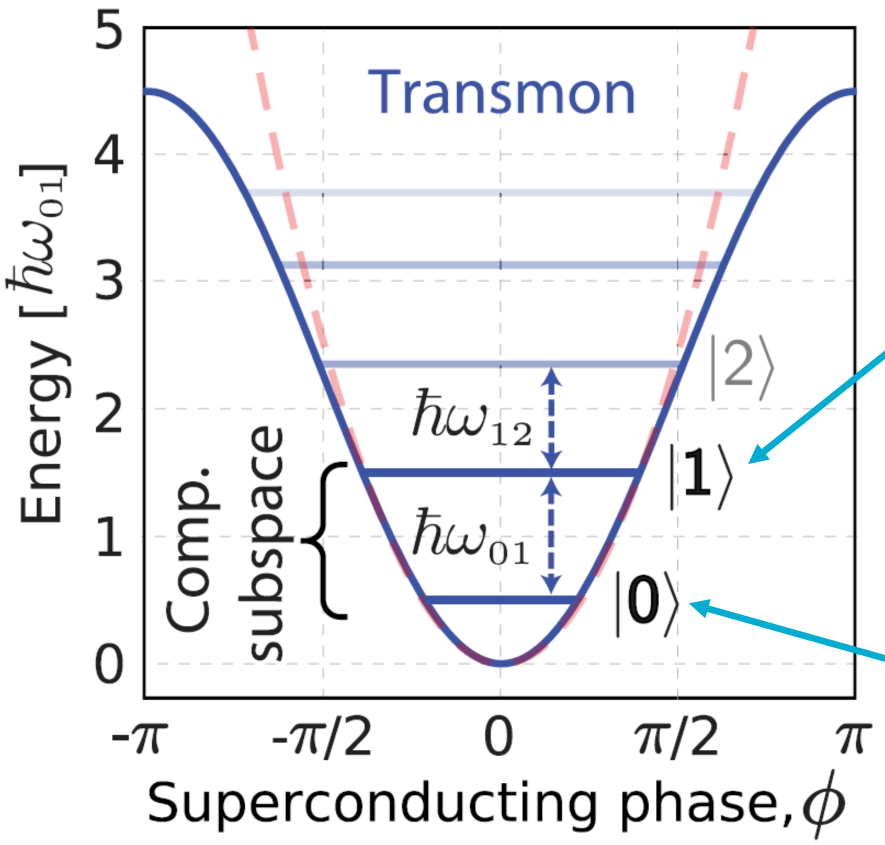
3 QUBIT CHIP FOR A RANGE OF SENSITIVITY

- 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.

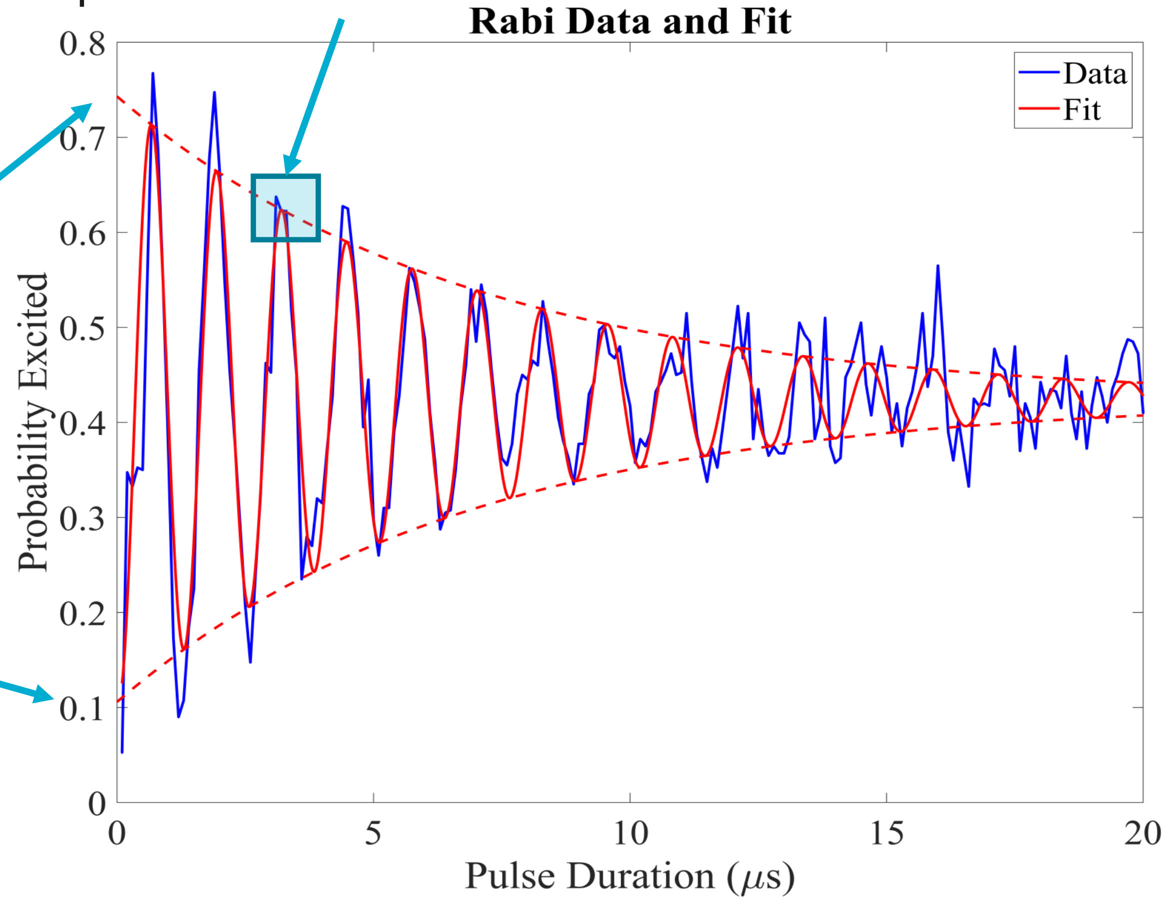


EXAMPLE OF A QUBIT MEASUREMENT – RABI OSCILLATIONS

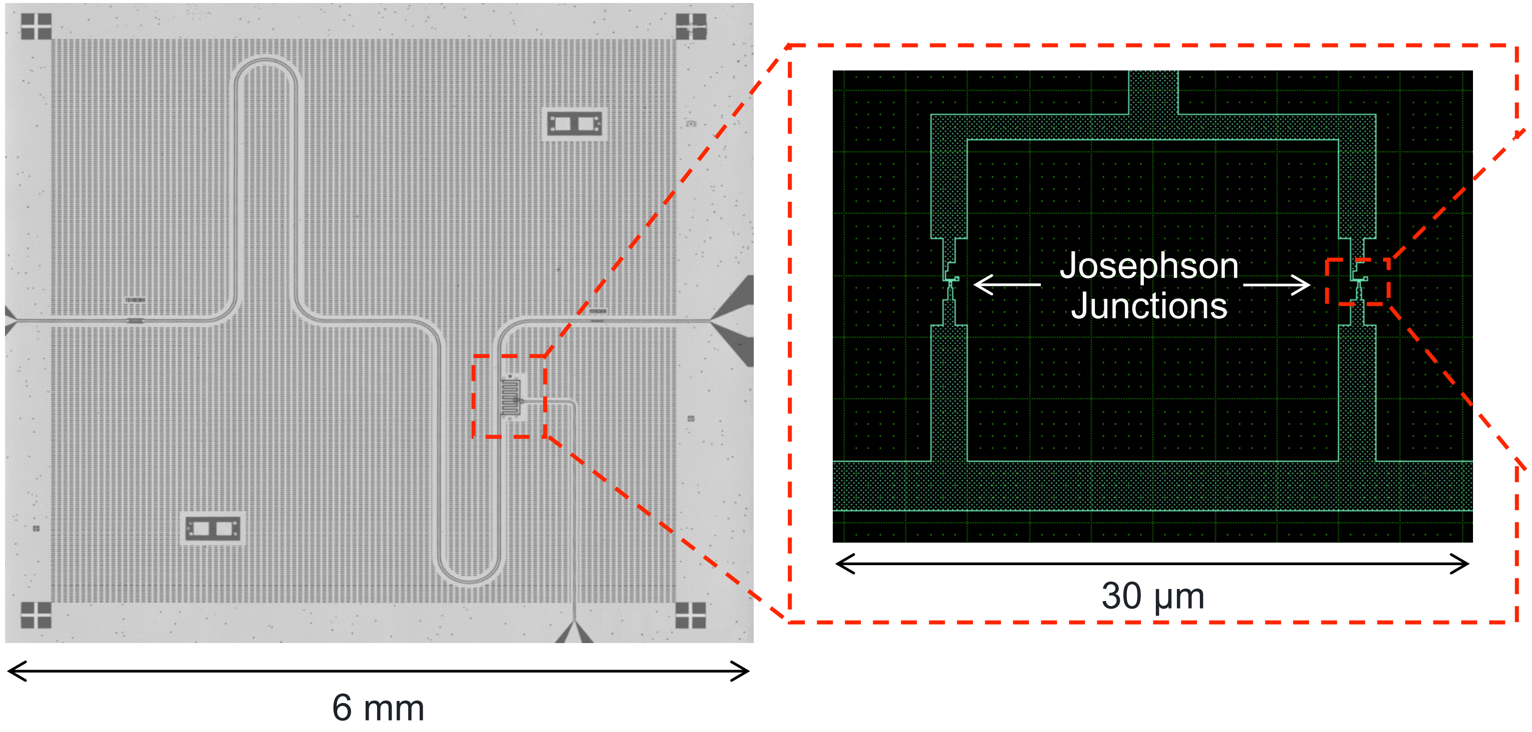
- Rabi Oscillations, $P(Excited) \propto \sin^2\left(\frac{\omega t}{2}\right)$

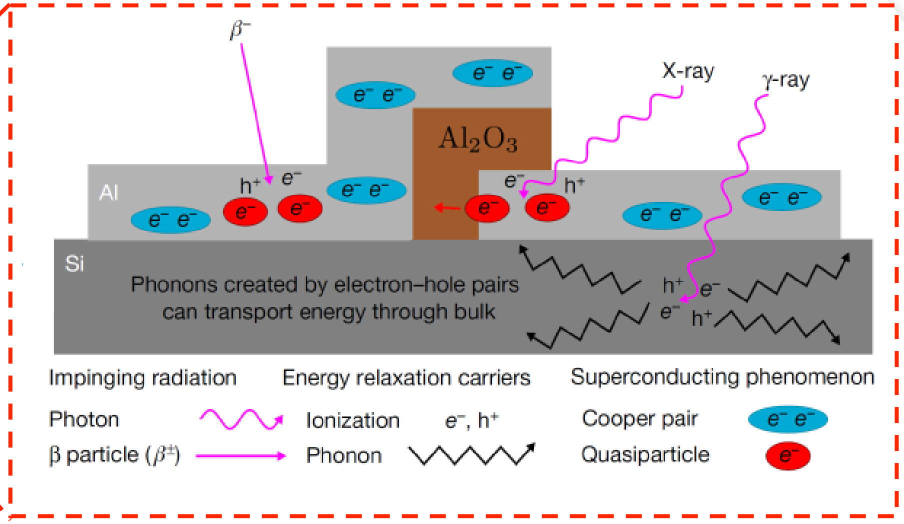


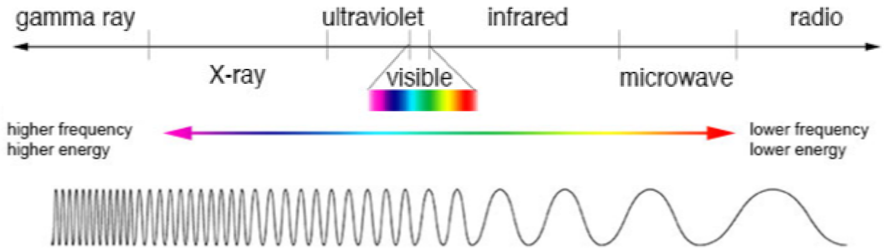
Repeatedly measure a single point in the curve, such as this peak.



WHAT HAPPENS WHEN RADIATION IMPACTS A SUPERCONDUCTING QUBIT?



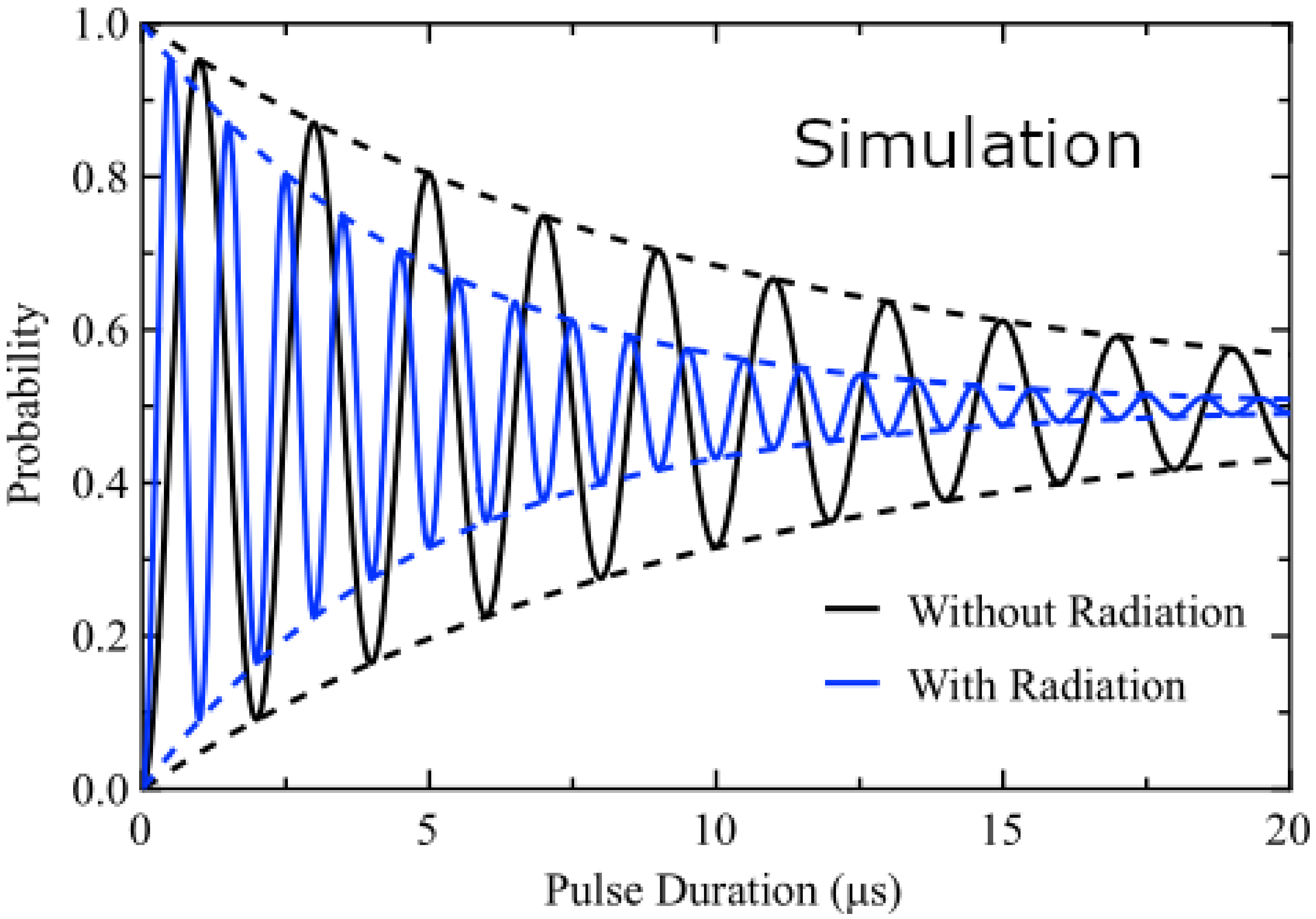




- In the left image a superconducting qubit device is shown at the 6 mm x 6 mm die level.
- In the middle zoom-in image the core elements of superconducting qubits, Josephson Junctions, are barely visible at this 30 µm x 30 µm scale.
- In the right zoom-in image [2] a typical Superconductor-Insulator-Superconductor 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).

DETECTION PRINCIPLE

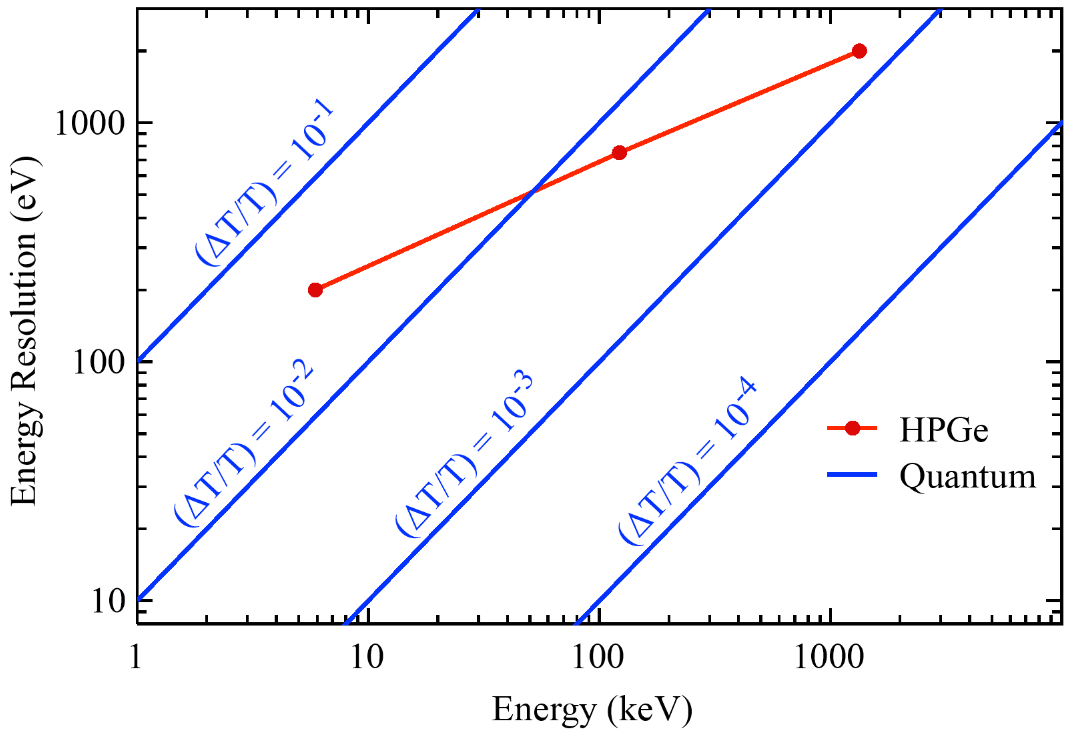


WHY WOULD WE WANT TO USE A QUANTUM SENSOR?

Why might we want to use a superconducting qubit for radiation detection?

- Energy Resolution
- Active Area
- Dynamic (Energy or Spectral) Range

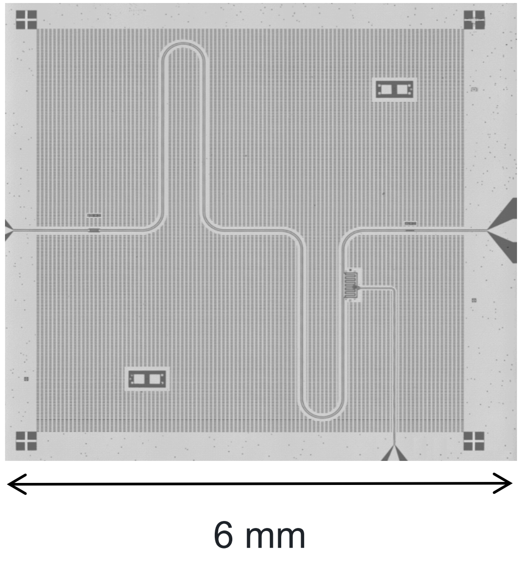
DETECTION RESOLUTION

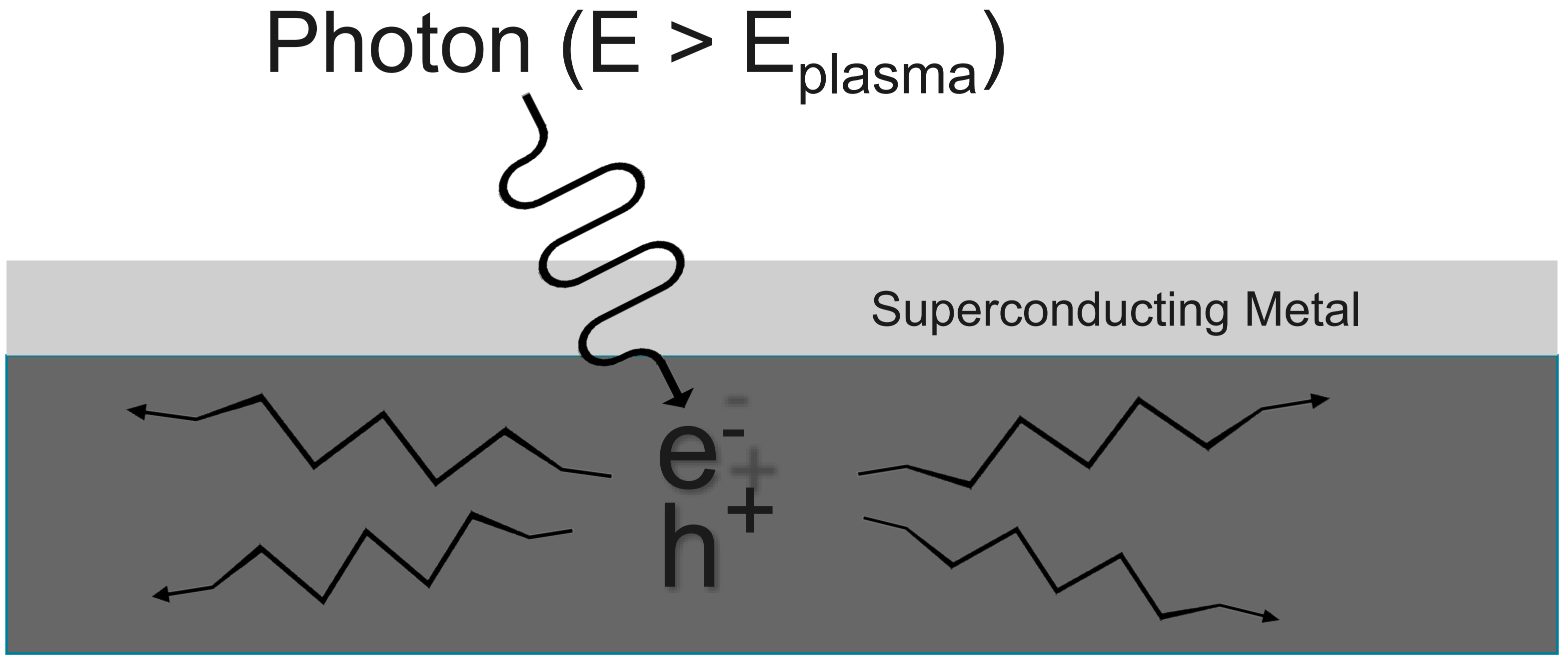


- Above is a plot of energy resolution versus energy for our proposed principle of detection using quantum sensing (blue).
- The state-of-the-art is defined by a reverse biased semiconductor diode detector referred to as High-Purity Germanium (HPGe, red).
- For fixed temporal resolution ΔT the calculated improvement of quantum sensing (blue) versus HPGe (red) increases with increasing quantum coherence time T.

LARGE ACTIVE AREA AND SPECTRAL RANGE

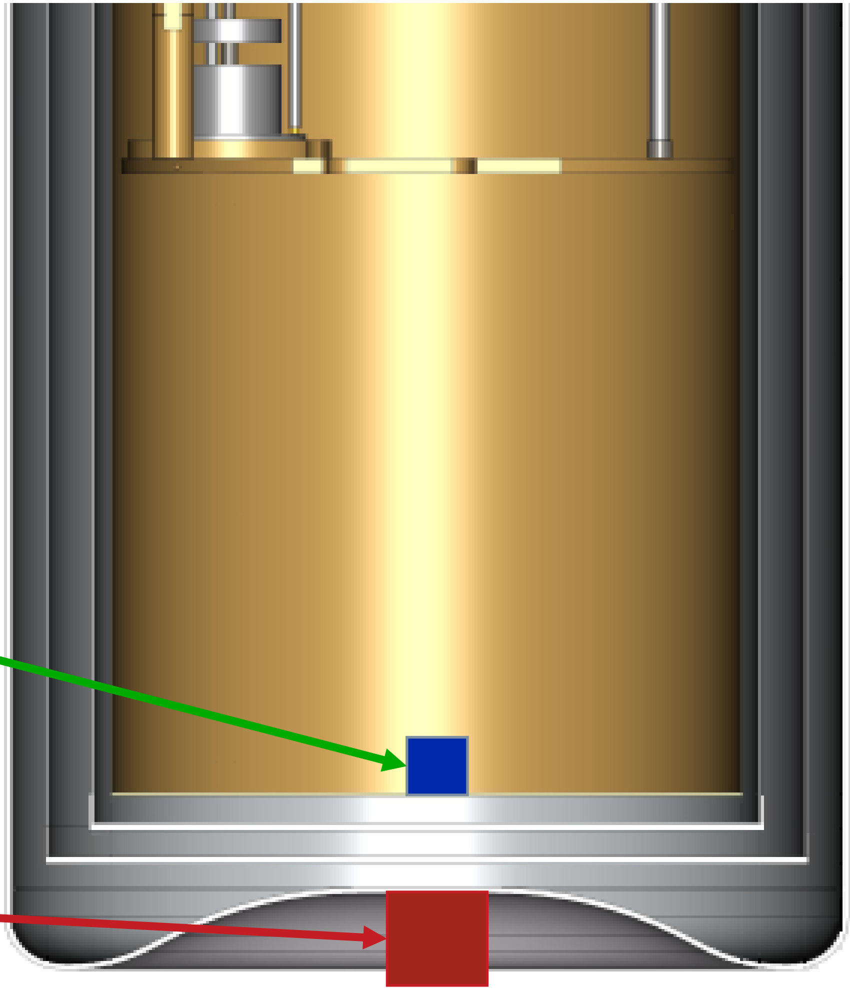
- Superconducting Tunnel Junctions detect radiation impacting an absorber that is on the micron scale.
- A quantum sensor made from superconducting qubits detect radiation on the millimeter scale.
- No a priori for a spectral response except near the superconducting gap.





PROPOSED MEASUREMENT CONFIGURATION

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



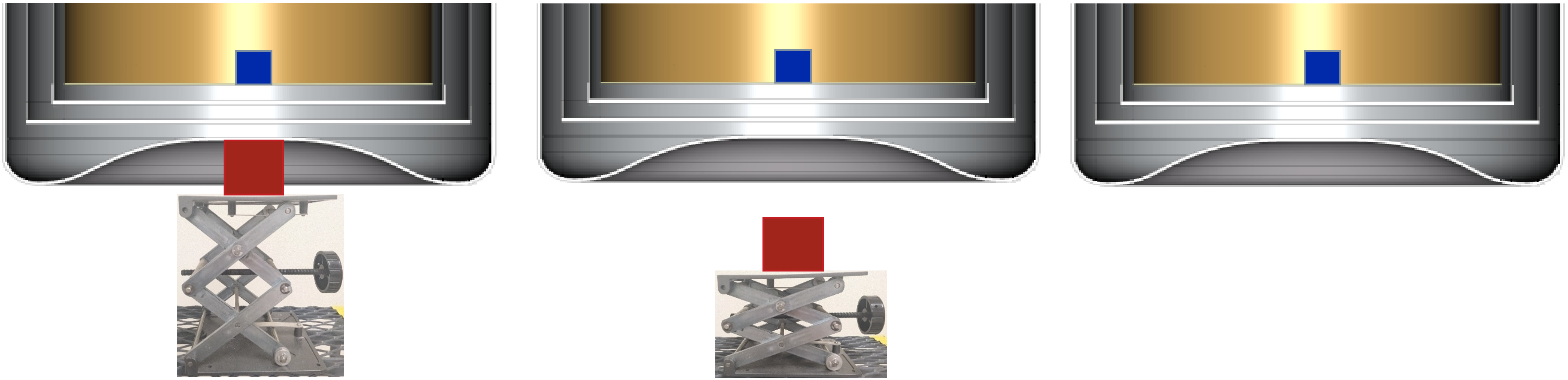
Quantum Sensor
(Transmon Qubit)
10 mK

Source
295 K
Co^{60} or Cs^{137}

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.
- The quantum sensor is expected to have a large active area, dynamic range, and energy resolution.
- 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.