



**AFRL-AFOSR-VA-TR-2024-0007**

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## Quasiparticles in Superconducting Circuits

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**10/05/2023  
Final Technical Report**

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## REPORT DOCUMENTATION PAGE

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## **AFOSR Deliverable Reporting Format: Final and Interim Reports**

**This document has been developed to provide Principal Investigators (PIs), co-PIs, and research organizations with:**

- A listing of the questions that will be asked in the new AFOSR project reporting format;
- Assistance in planning for the submission of the report

**Overview: There are two main sections of the AFOSR Deliverable Report. Section 1 is filled out in Qualtrics, and Section 2 is uploaded by PDF.**

- Section 1: Structured Survey Questions in Qualtrics
  - This section captures information in a structured survey format as required by the Research Performance Progress Report Format (RPPR) guidance. Information in this section will include publications, participants, and other intellectual property questions. All questions in this section will be asked within Qualtrics.
- Section 2: Technical Report PDF
  - This section captures unstructured technical information not captured in the above section. PI's will upload PDF reports that contain information on awards, changes to scope, and other technical updates. This PDF upload will be very similar to previous AFOSR report uploads. Please contact your individual program officer if you have further questions about what should be contained in this report.

\*\*\*Note: The information being asked in this deliverable report is explicitly defined by the official RPPR guidance which can be found here: <http://www.nsf.gov/bfa/dias/policy/rppr/index.jsp>. We have automated several questions to make the reporting less burdensome on the principal investigator. Your report link, found in the deliverable reminder email, contains individualized information that is specific to your deliverable report. You may edit this information if anything appears to be incorrect.

# Section 1: Structured Survey Questions

## Award Information

You will be asked for the following information in the survey. The majority of these fields will be sent pre-populated, but can be edited if necessary. You will be able to manually edit any of these fields if information needs to be updated.

- Award Number: **Federal Award Identification Number FA9550-19-1-0060**
- Report Type: **Final Performance**
- Principal Investigator: **Prof. Eli Levenson-Falk**
- Principal Investigator Email: **elevenso@usc.edu**
- Principal Investigator Phone: **(213) 740-0163**
- Project Title: **Quasiparticles in Superconducting Quantum Circuits**
- Recipient Organization: **University of Southern California**
- Business Office Email:
- Report Due Date
- Report Period Start Date: **12/01/2018**
- Report Period End Date: **05/14/2023**
- Current Program Officer: **Dr. Grace Metcalfe**
- Please list any other Co-Program Officers (if applicable)

## Publications

Our servers will be contacting the Cross Reference open source database (<https://www.crossref.org/>) to find any publications related to your award number. These publications will automatically populate to your report page and you will be able to select the reports that you would like to submit for the reporting period. Note: for annual/interim reports, you should only report publications that were completed in the current reporting period. For final reports, you should report all publications throughout the entire lifecycle of the grant.

If a publication does not show up in the initial publication search, you will also be able to manually enter publications using the publication's DOI number. Our servers will then contact Cross Reference to see if they can verify your publication information. Lastly, if your publication does not contain a DOI number, you can simply enter the bibliographic information into the text field.

# Participants

You will be asked to provide the information below for: (1) PIs; and (2) each person who worked on and was funded by this grant during the current reporting period. Please include all participants including yourself.

- Provide the name and identify the role the person played in this project.
- Indicate the total number of months (including partial months) that the individual worked on this project.
- If applicable, the participant's ORCID.
- Project role, select the most senior role in which the person worked on the project for any significant length of time.
  - For example, if an undergraduate student graduated, entered graduate school, and continued to work on the project, report that person as a graduate student, preferably explaining the change in involvement.
- Contribution to the project (text field).
- If international business was accomplished during this reporting period
  - Did the individual collaborate with individuals located in a foreign country?
  - Did this individual travel to a foreign country as part of the collaboration?

\*\*If the answer to either question above is yes, you will be expected to report the country that business was conducted in, and the amount of days spent in that country.

# Other Partners or Collaborators

This section will ask you to describe partner organization or collaborators who worked on this grant – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that were involved with the project. Partner organizations may have provided financial or in-kind support, supplied facilities or equipment, collaborated in the project, exchanged personnel, or otherwise contributed.

If you do not have any additional partners to report, please leave this section blank.

# Inventions, patent applications, licenses, and technologies/techniques

Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of an interim or final research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award. You will still have to separately file the appropriate form 882 for your invention/patent.

- Patents
  - You will be asked for Patent Title, Patent Abstract, Patent Number, Country, Patent Application Status, and Date Issued.
- Inventions
  - You will be asked for Invention Title, a description of the invention and the inventors.
- Licenses
  - You will be asked for License Title, Application Date, License Status, Date Issued, and License Assignees
- Technologies or Techniques
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  - You will also be able to report other products such as:
    - Audio/Video
    - Databases
    - Educational Aids/Research Curricula
    - Evaluation Instruments
    - Equipment
    - Models
    - Physical Collections
    - Protocols
    - Software or NetWare
    - Survey Instruments
    - Other

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## Section 2: Technical Report PDF Upload

You will be asked to complete the following questions as part of the report documentation section:

- Distribution Statement –Please verify that the report you are about to upload is cleared for public release through your organization’s processes and procedures.
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Regarding the content of the report, we require the following sections in your PDF technical report upload.

### Accomplishments

The information provided in this section allows AFOSR to assess whether satisfactory progress has been made during this reporting period. The PI is reminded that the recipient organization is required to obtain prior written approval from the awarding agency grants official whenever there are significant changes in the project or its direction. See agency specific instructions for submission of these requests.

- Research Objectives: Please list the main research objectives of this project
  - List the major goals of the project including the scientific or technological objectives of this effort. Describe the proposed technical approach to obtain those goals. If the application listed milestones/target dates for important activities or phases of the project, identify these dates and show actual completion dates or the percentage of completion.

*The objectives of this project were to study the behavior of Bogoliubov quasiparticles in superconducting quantum circuits. These quasiparticles are a key source of decoherence for superconducting qubits, and can cause correlated errors in quantum processors which are particularly hard to correct. The project aimed to study quasiparticle behavior with the goal of finding and testing ways to reduce quasiparticle-induced decoherence.*

*The technical approach taken was to make a quasiparticle sensor device capable of detecting quasiparticles entering and leaving “trap” states in real time. This device was based on superconducting aluminum nanobridge Josephson junctions, which houses internal Andreev bound states. Quasiparticles can trap in these bound states, altering the junction properties and producing a detectable signal. By carefully optimizing device parameters and signal analysis, we were able to achieve continuous readout of quasiparticle trapping with good signal-to-noise ratio. We then studied quasiparticle trapping and untrapping behavior under a range of conditions to*

*carefully analyze how quasiparticle interactions with other excitations lead to their behavior. Through collaborations, we also began studying quasiparticle trapping in semiconductor Josephson junctions which also contain Andreev bound states. Finally, we began developing and testing novel low-pass filters aimed at removing quasiparticle-generating infrared light from propagating down microwave coaxial cables.*

*The original proposal also included studying quasiparticle behavior with tunneling measurements in offset-charge-sensitive transmon qubits. Between the time of the proposal and the beginning of the project, other groups published significant progress towards similar measurements, and so the decision was made to focus entirely on trapping measurements rather than competing with colleagues.*

- Please provide details of accomplishments during this reporting period.
  - For this reporting period describe: 1) major activities; 2) specific objectives; 3) significant results or key outcomes, including major findings, developments, or conclusions (both positive and negative); and/or 4) other achievements. Include a discussion of stated goals not met.

*We had several key accomplishments in this reporting period. First, we successfully fabricated and tested a nanobridge junction resonator device capable of detecting trapped quasiparticles. We developed robust detection techniques for analyzing quasiparticle detection data based on a hidden Markov model analysis, and demonstrated the effectiveness of these techniques under conditions such as poor signal-to-noise ratio and a breakdown of the Markovian approximation.*

*Once the detector device and the detection techniques were well-developed, we began studying quasiparticle behavior under a range of environmental conditions. By sweeping the Andreev state energy and the thermal bath temperature, we were able to quantitatively describe the electron-phonon interactions that are key to quasiparticle thermalization and recombination. By sweeping drive tone amplitude, we were able to begin characterizing quasiparticle-photon interactions that cause decoherence in qubits. Finally, we successfully developed and tested a novel filter based on a Stycast dielectric that should provide more infrared attenuation than traditional eccosorb filters.*

*Originally, we had planned to study quasiparticle temporal and spatial correlations. However, we saw no sign of such correlations, likely because the background Markovian quasiparticle density was too high. We had also planned to test mitigation techniques based on circuit design, but fabrication delays prevented us from making the devices required for this.*

- How were the results disseminated to communities of interest? If there is nothing significant to report during this reporting period, state “Nothing to Report.”
  - Describe how the results were disseminated to communities of interest for this reporting period. Include any outreach activities that were undertaken to reach members of communities who are not usually aware of these project activities, for the purpose of enhancing public understanding and increasing interest in learning

and careers in science, technology, and the humanities.

*Results were disseminated in 3 journal articles (one of which is undergoing the final stages of review) and posted for free access on the arXiv preprint repository. Regular talks were given at the yearly APS March Meeting updating the community on the latest results in the project; a total of 6 such talks were given over the course of the project. Results were also presented at the South Carolina Quantum Technology Forum, and in 8 seminars and colloquia at various institutions.*

- (Interim Reports Only) What do you plan to do during the next reporting period to accomplish the goals and objectives? If there are no changes to the agency-approved application or plan for this project or if this is the final report, state “Nothing to Report.”
  - Describe briefly what you plan to do during the next reporting period to accomplish the goals and objectives.

## Impacts

This component is used to describe ways in which the work, findings, and specific products of the project have had an impact during this reporting period. Describe distinctive contributions, major accomplishments, innovations, successes, or any change in practice or behavior that has come about as a result of the project. You can report on the following impact categories, but you are not required to report on all categories. Please only report in the categories that are relevant to your project:

### **Development of the principal discipline(s) of the project**

Describe how findings, results, techniques that were developed or extended, or other products from the project made an impact or are likely to make an impact on the base of knowledge, theory, and research in the principal disciplinary field(s) of the project. Summarize using language that a lay audience can understand (e.g., Scientific American style).

*Our results show another set of techniques for studying quasiparticle behavior in quantum devices which is complementary to the typical tunneling measurements used. We have tested and validated theoretical models of how quasiparticles interact with other excitations in these devices, which will allow future researchers to further develop mitigation techniques and to avoid pitfalls in developing devices where quasiparticles may play a role. Our results are especially impactful in the nascent field of Andreev-based qubits, where trapped quasiparticles themselves function as qubits. In these devices, quasiparticle-phonon and quasiparticle-photon interactions are crucial, and our results quantitatively describe these interactions.*

### **Other disciplines:**

Describe how the findings, results, or techniques that were developed or improved, or other products from the project made an impact or are likely to make an impact on other disciplines.

*Our results give more insight into the behavior of quasiparticles in general, not just in quantum*

*information devices. This will be useful for condensed matter researchers studying the mechanisms of superconductivity, for astronomers using detectors based on quasiparticle generation, and for all fields which use low-temperature superconducting devices.*

**Describe the impact in this reporting period on the development of human resources**

For example, how has the project provided opportunities for research and teaching in the relevant fields; improved the performance, skills, or attitudes of members of underrepresented groups that will improve their access to or retention in research, teaching, or other related professions; provided scholarships; provided exposure to science and technology for practitioners, teachers, young people, or other members of the public?

*As part of this project, we have trained and graduated 1 physics PhD student, 1 physics MS student, and trained 1 postdoc. We have additionally trained and graduated 3 physics BS students and 1 electrical engineering BS student. An additional 1 physics PhD student and 2 electrical engineering BS students have been working on the project and are progressing towards graduation. In all cases care was given to encourage participation from underrepresented groups in physics, which has been demonstrated in the roughly equal gender ratio of participating students.*

**Describe the impact on teaching and educational experiences**

For example, has the project: Developed and disseminated new educational materials; led to ideas for new approaches to course design or pedagogical methods; or developed online resources that will be useful for teachers and students and other school staff?

**Describe the impact in this reporting period on physical, institutional, and information resources that form infrastructure.**

For example: Physical resources such as facilities, laboratories, or instruments; institutional resources (such as establishment or sustenance of societies or organizations); or information resources, electronic means for accessing such resources or for scientific communication, or the like.

**Impact on society beyond science and technology:**

Describe how results from the project made an impact, or are likely to make an impact, beyond the bounds of science, engineering, and the academic world on areas such as: improving public knowledge, attitudes, skills, and abilities; changing behavior, practices, decision making, policies (including regulatory policies), or social actions; or improving social, economic, civic, or environmental conditions.

# Changes

In this section, please incorporate any and all changes that you would like your program officers to know about the grant. The principal investigator is reminded that the recipient organization is required to obtain prior written approval from program officers whenever there are significant changes in the project or its direction. Sections may include:

## **Changes in approach**

Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the agency.

*Early in the project, other groups published results indicating significant progress towards the tunneling measurements planned in the original proposal. Because of this, the decision was made to focus solely on trapping measurements.*

## **Problems or delays**

Describe problems or delays encountered during the reporting period and actions or plans to resolve them.

*The COVID-19 pandemic caused major delays in nanofabrication—broken equipment went several months without repair, and the planned commissioning of a new campus cleanroom was pushed back more than a year. To address these delays, the program provided a no-cost extension and later a cost extension, and we obtained amplifier devices from our collaborators who had not experienced significant fabrication disruptions.*

## **Expenditure Impacts**

Describe changes during the reporting period that may have had a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.

*The COVID-19 pandemic caused significant delays in all project activities, as in-person research was virtually stopped for several months and the nanofabrication facility on campus was shut down for an extended period. The main costs incurred due to these delays were additional personnel expenses. These were covered by additional funding provided by the program.*

## **Significant changes in the use or care of human subjects, vertebrate animals and/or biohazards**

Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, biohazards, and/or select agents during the reporting period. If required, were these changes approved by the applicable institution committee (or equivalent) and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.

**Changes to the primary place of performance from that originally proposed**

Identify any change to the primary performance site location identified in the proposal, as originally submitted.

## **Technical Updates**

This section will include any and all technical updates that you would like to provide to your program officer. You are encouraged to upload graphs and other visualizations that highlight the work done during this reporting period. Program Officers may request additional information that is specific to your research topics

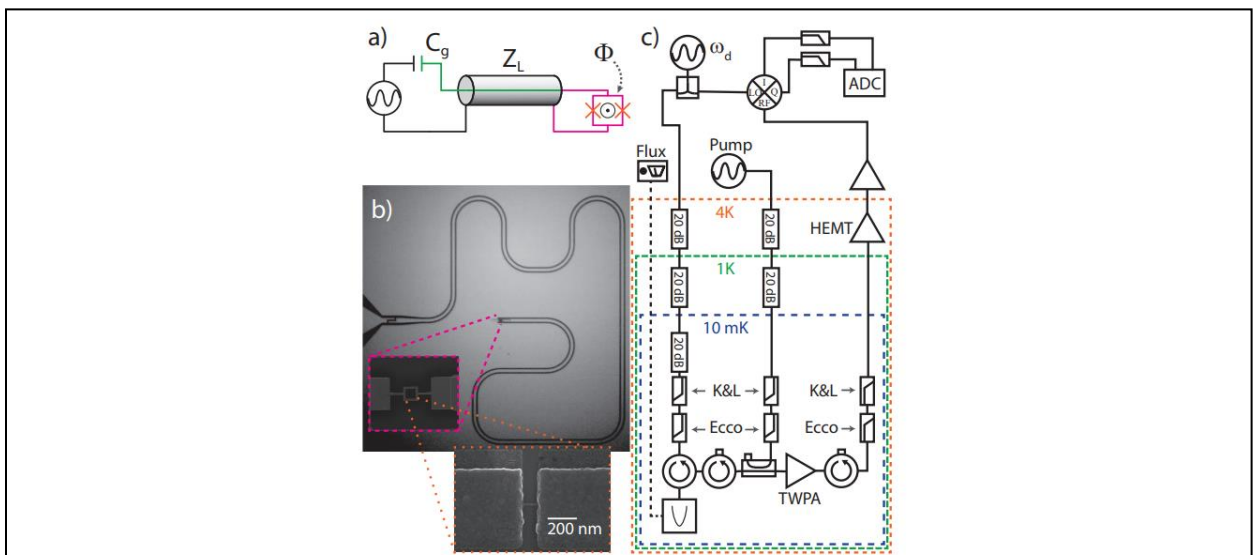
In this project we had a few key accomplishments:

- We developed a quasiparticle detector device based on aluminum nanobridge Josephson junctions, and developed analysis techniques for robustly detecting quasiparticle trapping in the junctions' internal Andreev bound states with real-time resolution.
- We used our detector device to quantitatively characterize quasiparticle-phonon and quasiparticle-photon interactions, and fit the former to first-principles models to explain the behavior.
- With our collaborators at NYU, we demonstrated quasiparticle trapping in superconductor-semiconductor-superconductor (super-semi) Josephson junctions, characterizing a key noise mechanism in this nascent technology.
- We simulated and tested initial prototypes for next-generation infrared filters to remove quasiparticle-generating radiation.

### Detector device

Our device is a section of coplanar waveguide (CPW), open at one end and terminated with a two-junction nanobridge SQUID at the other end; see Figure 1. This forms a resonator with the waveguide length equal to  $\frac{1}{4}$  of the wavelength at the fundamental mode with a resonant frequency  $\sim 4.3$  GHz. This quarter-wave resonator has a resonant frequency which shifts when the SQUID inductance changes, which occurs when a quasiparticle traps in one of the junctions' internal Andreev bound states (ABS). When the SQUID is biased with an external flux, it causes a phase bias on the junctions, which brings the ABS energies inside the superconducting gap. It is therefore energetically favorable for quasiparticles to trap in the ABS.

We probe the device resonance by sending in a microwave tone near the resonant



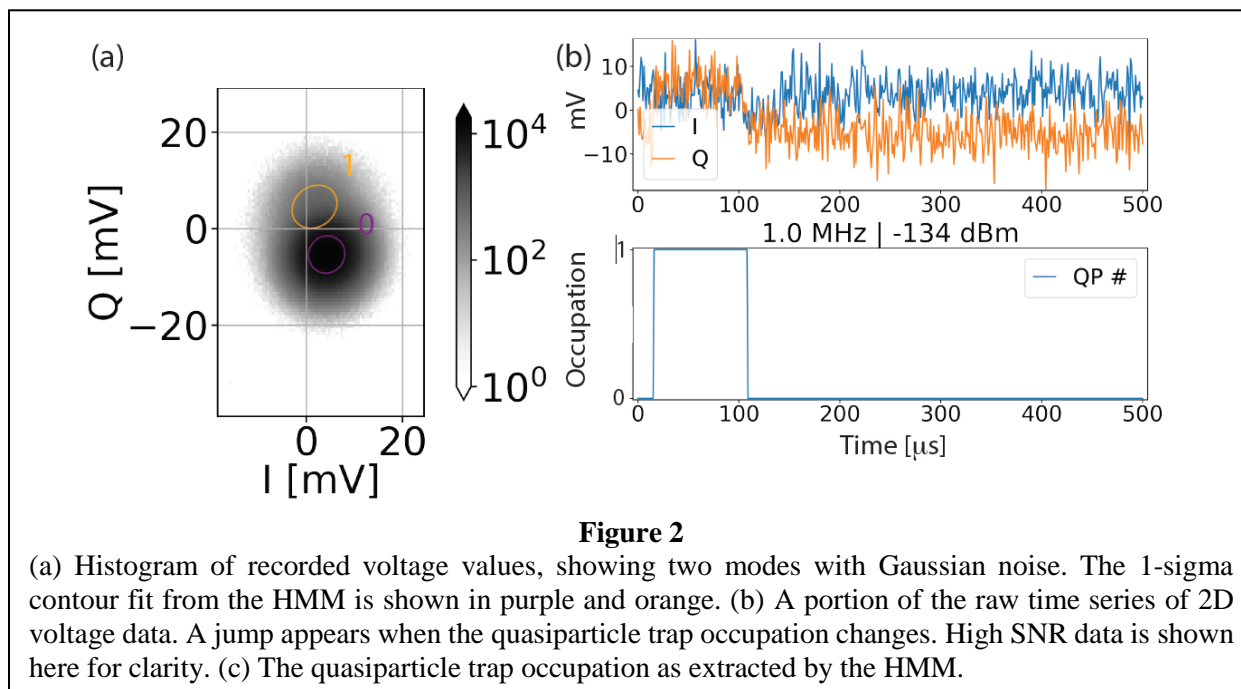
**Figure 1**

(a) Schematic of quasiparticle detector device, showing a quarter-wave section of transmission line terminated by a nanobridge SQUID. (b) SEM image of the device, showing zoom-ins of the SQUID and a single nanobridge junction. (c) Measurement setup schematic.

frequency, which reflects off the device and is sent back to room temperature through an ultra-low-noise amplification chain. When a quasiparticle traps, the resonance shifts to a lower frequency by  $\sim 200\text{-}300$  kHz (depending on bias parameters), which shows up as a change in the reflection coefficient of the device. We demodulate the probe tone at room temperature and digitize it at 300 MS/s to extract the real and imaginary parts of the reflection coefficient. We are thus left with 2D voltage data showing the real and imaginary parts of the reflection as a function of time, continuously probed for time periods from a few seconds up to several hours.

### Data analysis: hidden Markov model

Extracting the quasiparticle trap occupation from the time series data is nontrivial, as there is no way to initialize a particular occupation and thus calibrate the readout signal. Instead, we use the well-developed technique of fitting the data to a hidden Markov model (HMM) with Gaussian emissions. This model describes a system which can transition between hidden states (which correspond to the number of trapped quasiparticles), each of which emits random data with its own Gaussian probability distribution. The system can transition between hidden states in a Poisson process, with different characteristic rates for each transition. The HMM fitting forms a self-consistent model that maximizes the likelihood of the observed data using a Bayesian maximum likelihood estimation. See Figure 2.



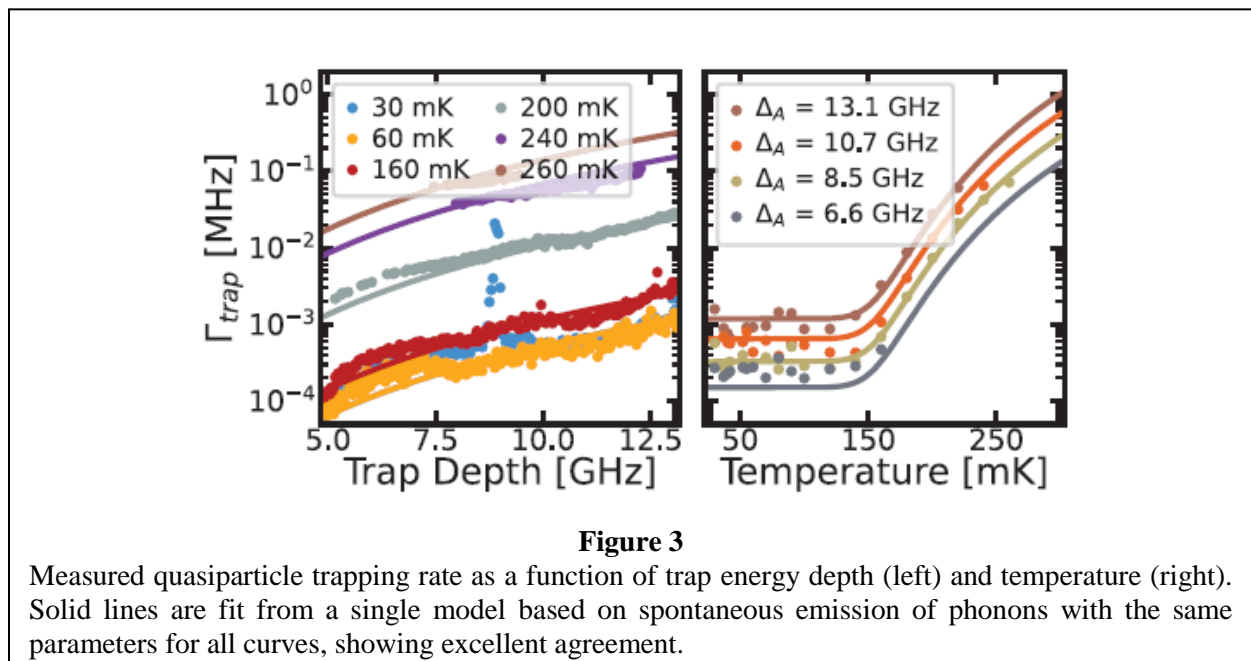
We have tested the robustness of the HMM under conditions of finite SNR and a breakdown of the Markovian approximation (i.e. a non-Poisson process for state transitions). We first created simulated data where a quasiparticle trapping process generates noisy voltage time series data. The trap occupation is known to the scientist but hidden from the model. We find that the model accurately reproduces the true occupation time series and accurately fits the transition

rates so long as the SNR is larger than  $\sim 2.5$ . We also simulated circumstances such as correlated and anticorrelated trapping processes, and found that the model still accurately captures the occupation time series as long as SNR is above  $\sim 2.5$ . Finally, we took real experimental data with high SNR, where the trap occupation is quite obvious to the eye and the model is clearly accurate. We then artificially degraded the SNR by adding Gaussian noise to the data, thus producing low-SNR data with a known trap occupation time series. We again found that the model accurately analyzed the data so long as SNR was above  $\sim 2.5$ .

### Quasiparticle-phonon interactions

We expect that, in the absence of drive tones, phonons are the main excitation that quasiparticles emit/absorb when they trap/untrap in an ABS. To quantitatively characterize quasiparticle-phonon interactions, we measured the average quasiparticle trapping rate, untrapping rate, and trap occupation as a function of ABS energy and device temperature. We then fit our data to first-principles models describing the interaction rates. For the trapping rate, we expect a rate which is proportional to the number of quasiparticles and to the rate of spontaneous emission of a phonon. We expect a temperature-independent background density of nonequilibrium quasiparticles plus a temperature-dependent thermal density. The spontaneous emission rate should be temperature-independent but depend on the trap depth as given by Fermi's golden rule, which gives a rate proportional to the trap depth  $\Delta_A \equiv \Delta - E_A$  cubed. This gives an overall trap rate

$$\Gamma_{trap} = \beta \Delta_A^3 \left( x_{ne} + \sqrt{\frac{2\pi k_B T}{\Delta}} \exp\left(\frac{-\Delta}{k_B T}\right) \right)$$

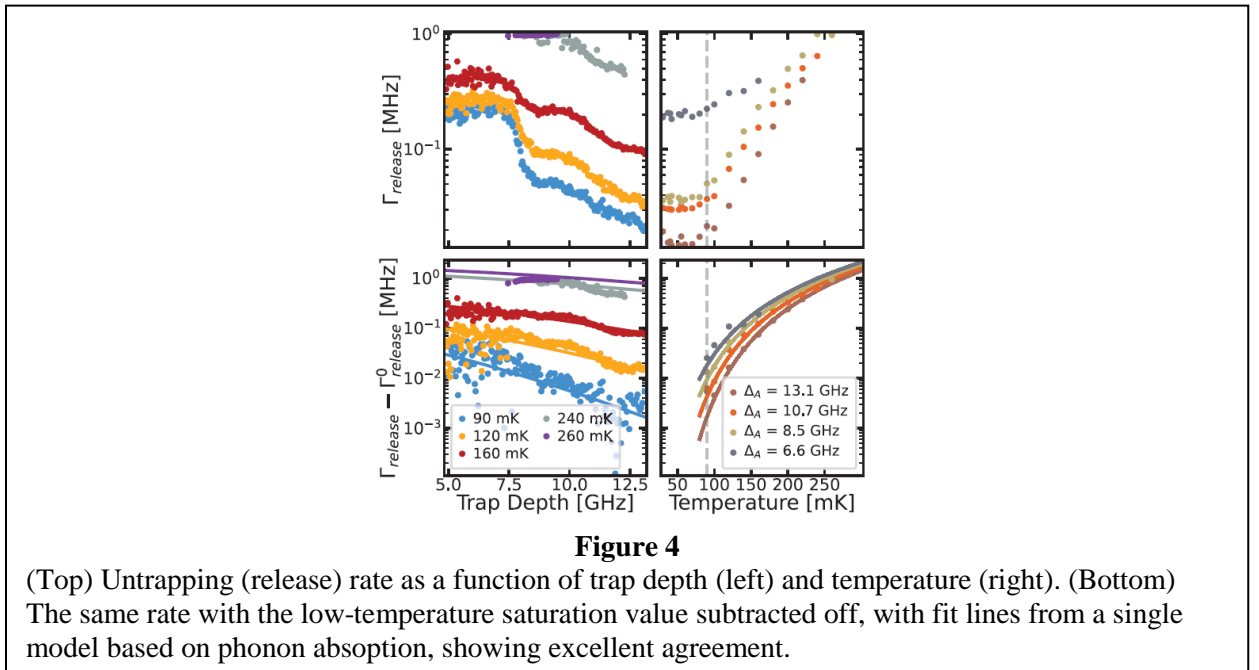


Here  $x_{ne}$  is the background nonequilibrium quasiparticle density,  $\Delta$  is the superconducting gap, and  $\beta$  is a scaling constant. To fit the data we first take advantage of the fact that the trap rate saturates at low temperature, and subtract the low-temperature trap rate  $\Gamma_{trap}^0(\Delta_A)$  from the data. This removes  $x_{ne}$  from the expression, and so we fit to extract  $\beta$  and  $\Delta$ . We then divide the trap rate by  $\Gamma_{trap}^0(\Delta_A)$ , which removes  $\beta$ , and fit the result with fixed  $\Delta$  to extract  $x_{ne}$ . We find excellent agreement between our model and the data, as shown in Figure 3. We note that this provides a method for measuring the background quasiparticle density which is completely independent of typical qubit tunneling measurements and makes only minimal physical assumptions. We further note that we see no evidence for stimulated emission processes in our data, which would have a different temperature dependence and ABS energy dependence.

For the untrapping rate, we expect a background which is dependent on ABS energy but independent of temperature, representing untrapping due to absorption of e.g. measurement tone photons. Once again we can subtract off the low-temperature saturation of the untrapping rate to eliminate this background. We then expect a temperature-dependent rate representing the absorption of a thermal phonon, proportional to the number of phonons with energy greater than the trap depth. This gives an expression

$$\Gamma_{phonon}(\Delta_A, T) = \alpha T^3 \left[ - \left( \frac{\Delta_A}{k_B T} \right)^2 \ln \left( 1 - e^{-\frac{\Delta_A}{k_B T}} \right) + \frac{2\Delta_A}{k_B T} \text{Li}_2 \left( e^{-\frac{\Delta_A}{k_B T}} \right) + 2\text{Li}_3 \left( e^{-\frac{\Delta_A}{k_B T}} \right) \right]$$

Here only the overall strength  $\alpha$  is a free parameter, as we use the superconducting gap previously extracted from the trap rate fits. We fit our data to this model and find excellent agreement, indicating that no other temperature-dependent untrapping processes are significant; see Figure 4.



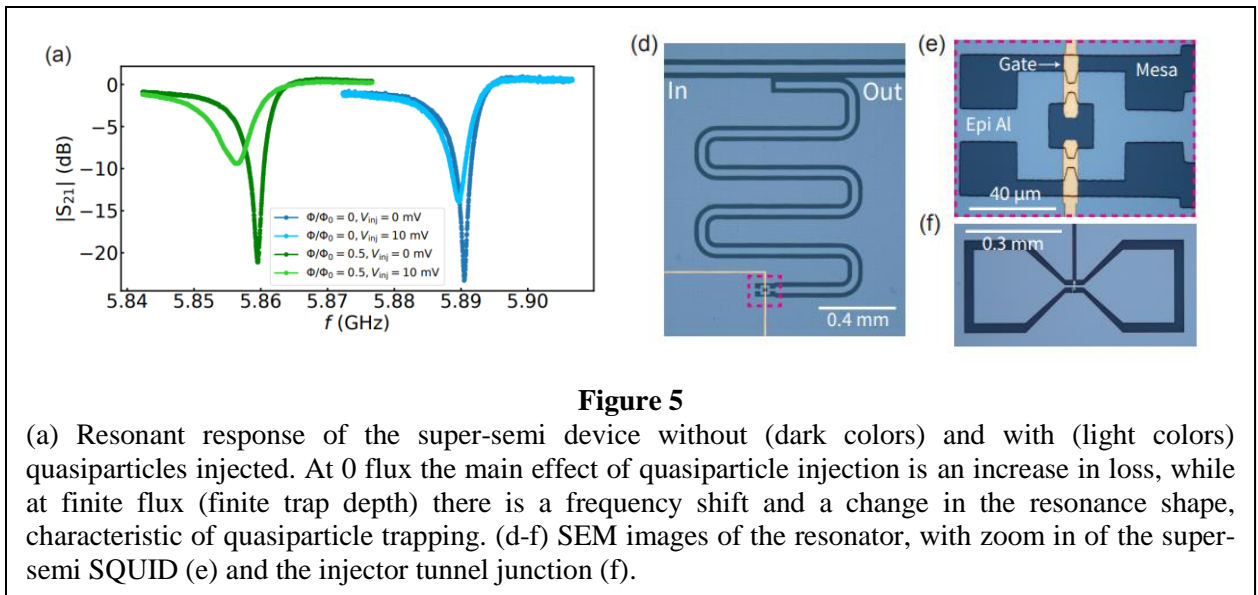
We finally fit the quasiparticle trap occupation, which we expect to be given by the detailed balance between trapping and untrapping rates. We take a ratio of the expressions used to fit these rates and fit again, allowing the fit parameters to vary independently from the prior fits. Again we find excellent agreement with the data, and the fit parameters agree closely with the prior fits. We note that this data is obtained somewhat independently: the mean occupation is extracted from the quasiparticle trap occupation time series, while the trapping and untrapping rates are taken from the HMM used to analyze and extract the time series.

### **Quasiparticle-photon interactions**

We designed our device with a resonant frequency  $\sim 4.3$  GHz which is much less than the typical trap depth. We therefore expected that, at low measurement drive power, trapped quasiparticles would not be cleared by the absorption of a single measurement photon; at high measurement power, multi-photon processes would clear the quasiparticles with a rate proportional to  $P^n$  where  $n$  is the number of photons absorbed. Instead, when we measured the untrapping rate as a function of measurement power, we saw a nearly linear power dependence. Our HMM robustness tests (see above) confirmed that this was not merely an effect of the changing SNR but in fact a real physical change in the untrapping rate. We further confirmed this with pulsed measurements where the measurement SNR was kept constant but an additional tone was used to clear the quasiparticles from the traps. We are currently finalizing our experimental investigation of this effect and already have a satisfying theoretical explanation provided by our collaborator Leonid Glazman at Yale. In this model, intermediate-energy ABS exist sparsely in the energy spectrum. These ABS exist at trap depths less than 4.3 GHz, and so a single photon can clear a quasiparticle trapped in one of these states. This causes the states to have a very short lifetime and to be broadened, smearing out into a continuum rather than a discrete spectrum. A quasiparticle trapped in a deep ABS can then be excited up into this intermediate continuum before absorbing another photon and clearing into the bulk. This is thus a process that requires absorption of multiple photons but not simultaneously, and therefore has the linear power scaling of a typical single-photon process.

### **Super-semi junction trapping**

We worked with the Shabani Lab at NYU to study quasiparticle trapping in their super-semi Josephson junctions. Again the device is a quarter-wave resonator terminated in a SQUID, this time formed from super-semi junctions instead of nanobridge junctions; see Figure 5. In order to show the quasiparticle trapping effect clearly, we deliberately inject quasiparticles by pulsing a voltage bias on a nearby tunnel Josephson junction—a voltage above the superconducting gap causes quasiparticle generation at that tunnel junction. When the super-semi SQUID is flux-biased (junctions are phase-biased) we observe the resonance shift down in frequency, broaden, and take on a non-Lorentzian lineshape, with the magnitude of this effect growing as the number of injected quasiparticles is increased. These are all characteristic signatures of quasiparticle trapping, as shown in our previous work. By injecting a microwave tone at high frequency ( $\sim 20$  GHz), we can then clear quasiparticles out of the traps, recovering the initial line shape. We characterized the timescales of this trapping and clearing. While SNR was too low for the kind of single-shot



continuous measurements performed on the nanobridge device, we were able to extract significant information from ensemble-averaged measurements.

### Infrared filter prototyping

A main source of quasiparticle generation is far-infrared light propagating down microwave cables. Such photons can impact a superconducting device and break Cooper pairs. The standard technique to suppress far-infrared light is to use a low-pass filter formed by a section of coaxial waveguide with a lossy Eccosorb CR-110 dielectric. Unfortunately, Eccosorb has a loss that does not grow very quickly with frequency; it is thus quite difficult to create a filter that does not cause too much attenuation of wanted microwave signals ( $\sim 10$  GHz) but does heavily attenuate unwanted far-infrared ( $\sim 100$  GHz). To solve this challenge, we have prototyped filters made instead with a Stycast 2850 FT dielectric. While Stycast is 20x less lossy than Eccosorb at 100 GHz, it is approximately 200x less lossy at 10 GHz, and so simply using a longer filter allows for more infrared attenuation with less microwave attenuation. Our prototype Stycast filters are well-matched in the microwave regime and show lower loss at 10 GHz than comparable Eccosorb filters. In our current work we are developing techniques for testing the attenuation of these filters above 100 GHz at cryogenic temperatures.

We also prototyped a coaxial filter with a borosilicate glass dielectric, as such glass is nearly lossless in the microwave regime but has a loss that grows very quickly with frequency. While our prototypes were successfully manufactured and showed very low loss at microwave frequencies, later numerical analysis showed us that they would also have quite low loss even up to 300 GHz. While this is nominally solvable using a longer filter, a filter with sufficient attenuation at 100 GHz would end up being more than 20 cm long, which is impractical in a cryogenic system. We instead shifted our focus to a filter design based on a meandering co-planar waveguide sandwiched between two planes of glass dielectric. Provided we can ensure that infrared light remains confined to the waveguide, this design should allow for a filter with more than 50 cm electrical length to be confined in a package only 2 cm long and wide. We are currently

simulating this filter and, once we find an appropriate design, we will create a prototype.



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