

Environmental Dependence of Qubit Observables Under Controlled Tuning

Daniel Molenaar

Illinois Institute of Technology

CPAD 2026

Main Collaborator Acknowledgement

This study is the culmination of effort from many people



Arianna H. Colón Cesaní



Dan Baxter

Northwestern



Sara Sussman

Fermilab



Olivia Seidel

UTA



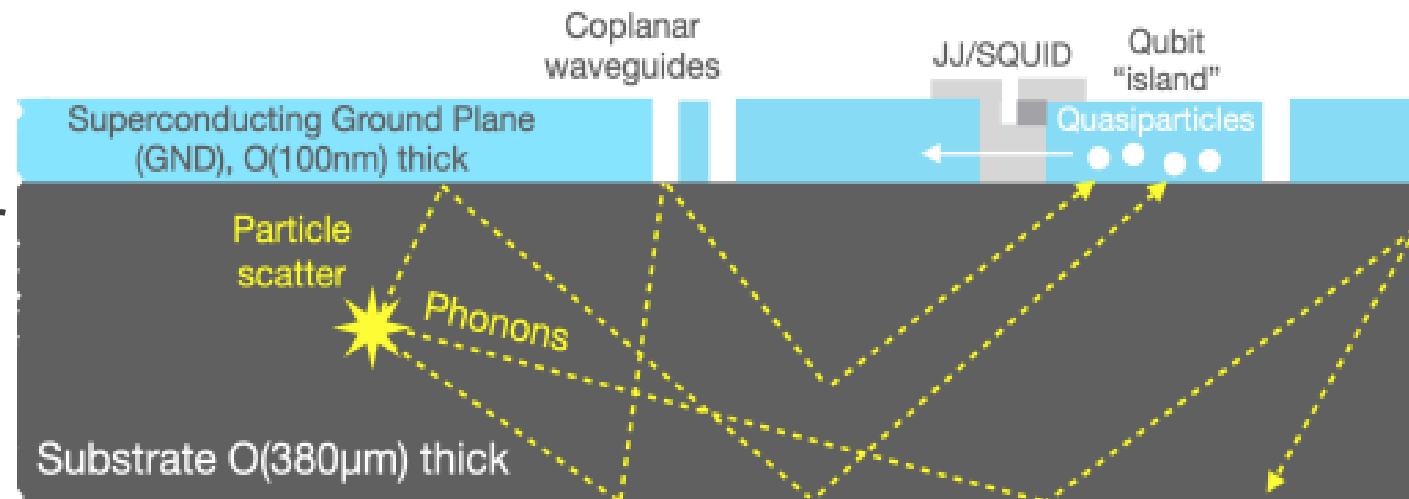
Rakshya Khatiwada

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Qubits For Sensing

- Our group want to use superconducting qubits to look for dark matter interactions
- We want to build a comprehensive understanding of our device backgrounds
- Understand the environmental and hardware level influence on qubit performance

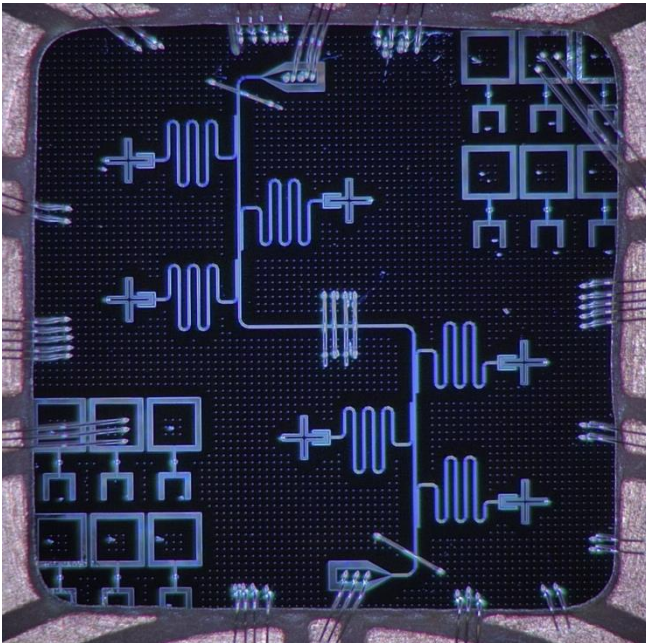
→ inform how to use qubits for dark matter searches



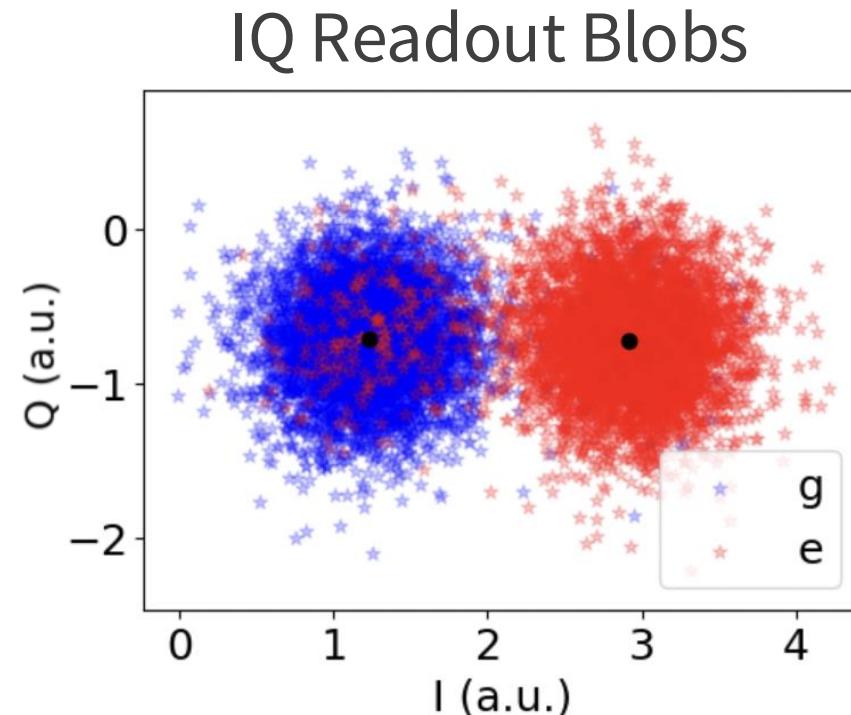
Phys. Rev. D **111**, 063047

Important Sensing Parameters

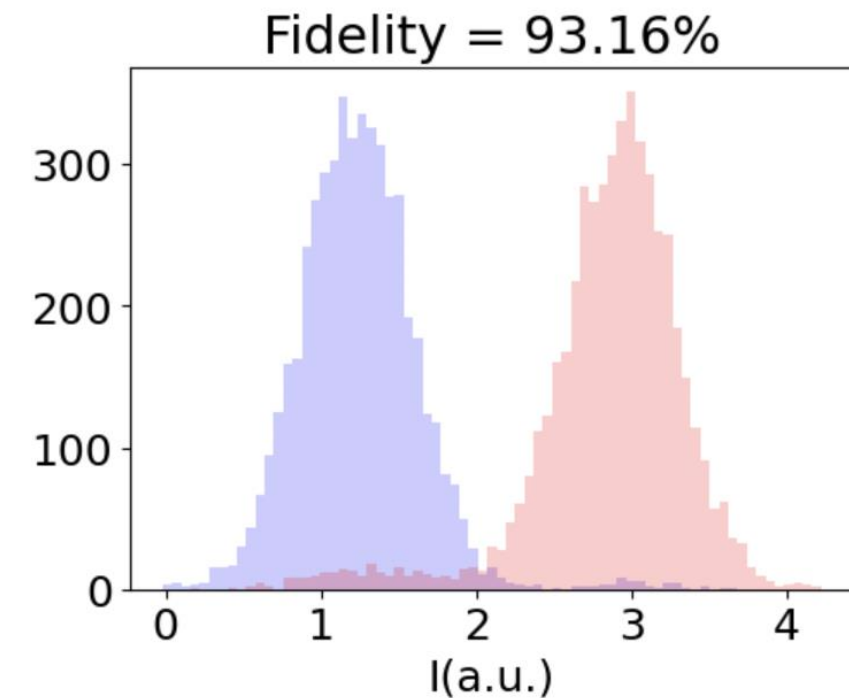
- Important performance metrics for Qubits are T_1 and T_2
 - T_1 describes the lifetime of the first excited state; the coherence time
 - T_2 Is the phase decoherence time
- Two particularly relevant system parameters are single shot fidelity (SSF) and residual excited state: P_e



10/22/2026



CPAD 2026 Daniel Molenaar (IIT)



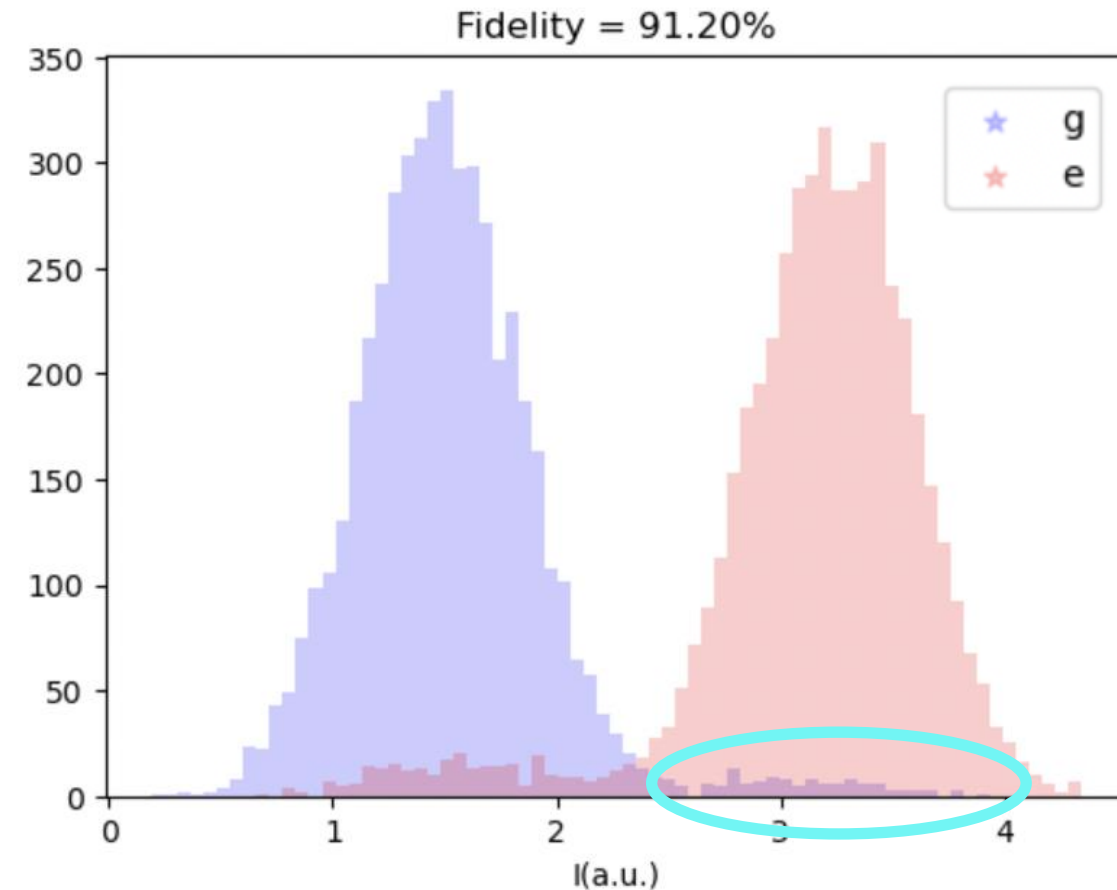
Residual Excited State (P_e)

The residual excited state population is a non vanishing excited state population. The size of this population may vary with time.

Most labs report an excess population from what would be expected from the operating temperature

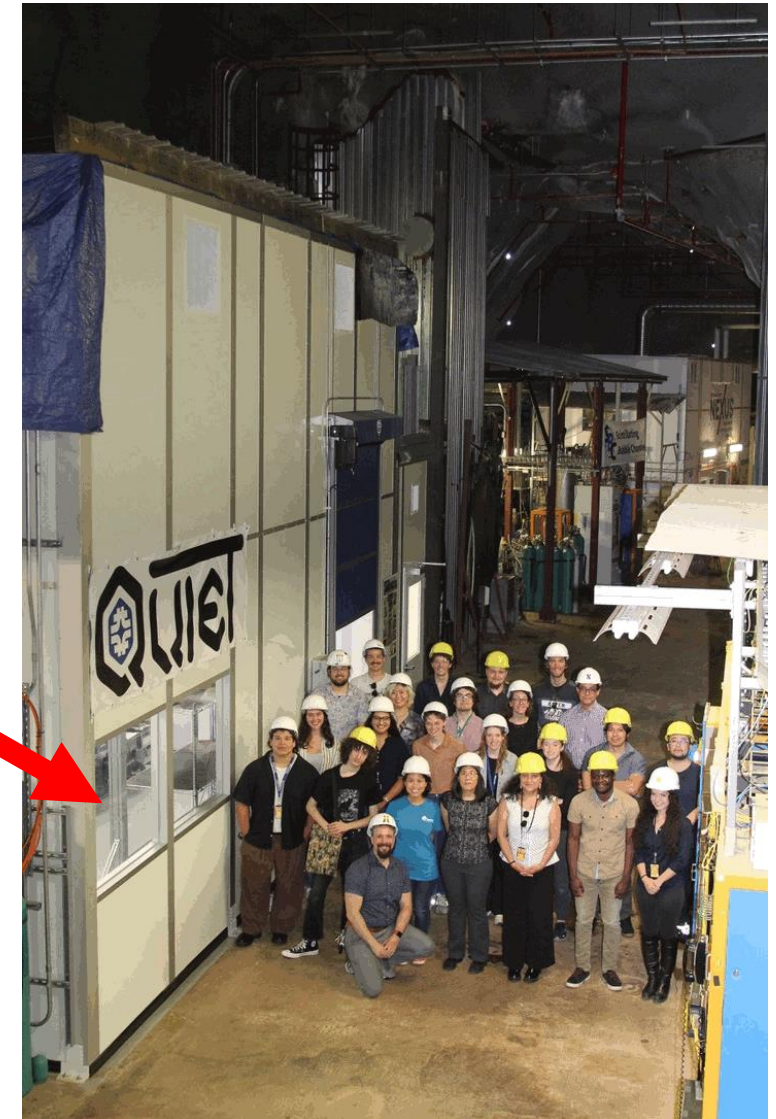
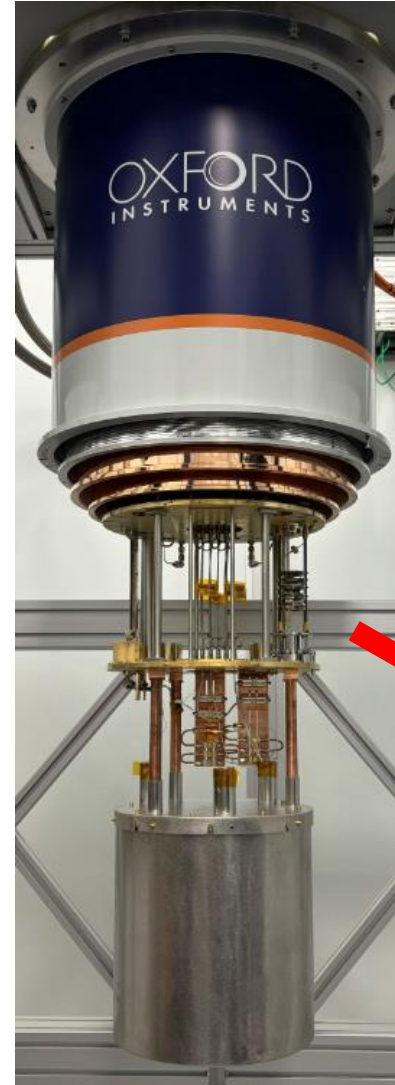
Methods:

- SSF Methods
- EF Rabi (Phys. Rev. Lett. 110, 120501)
- Correlated Measurements (Phys. Rev. Lett. 124, 240501)

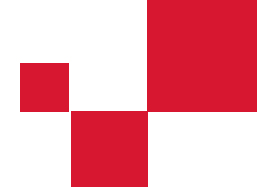


QUIET (Quantum Underground Instrumentation Experimental Testbed)

- Oxford Proteox MX
- Located 100 meters underground in the Minos cavern at Fermilab
- Provides a 100x reduction in cosmic ray muons

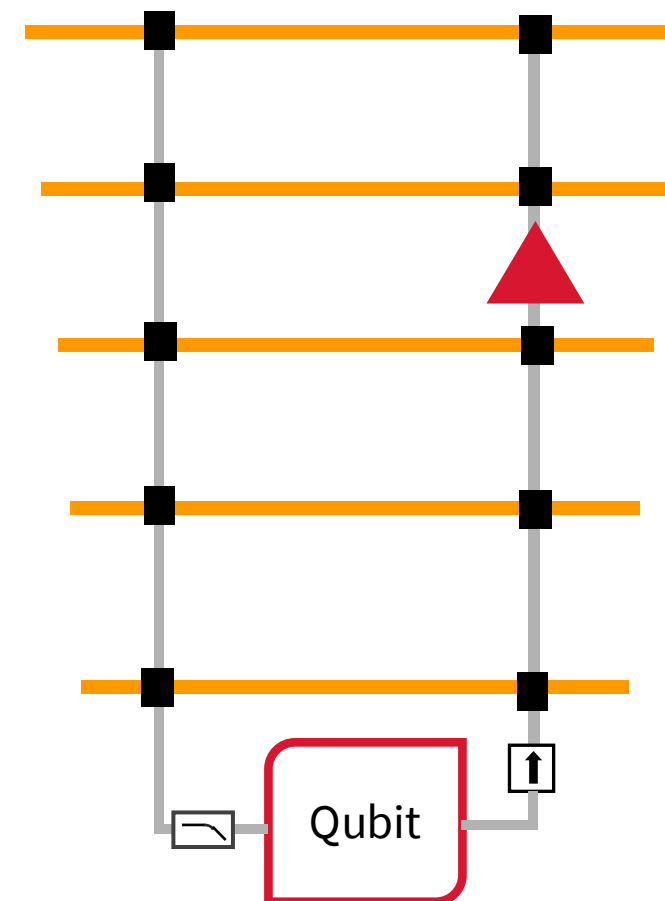


Finding Optimal Qubit Setups



Setups often include attenuation and filtering along their lines

- But how much attenuation is really required?
- What symptoms does a qubit displays when its lines lack sufficient attenuation and filtering?
- How much performance is left on the table when using an under optimized configuration?



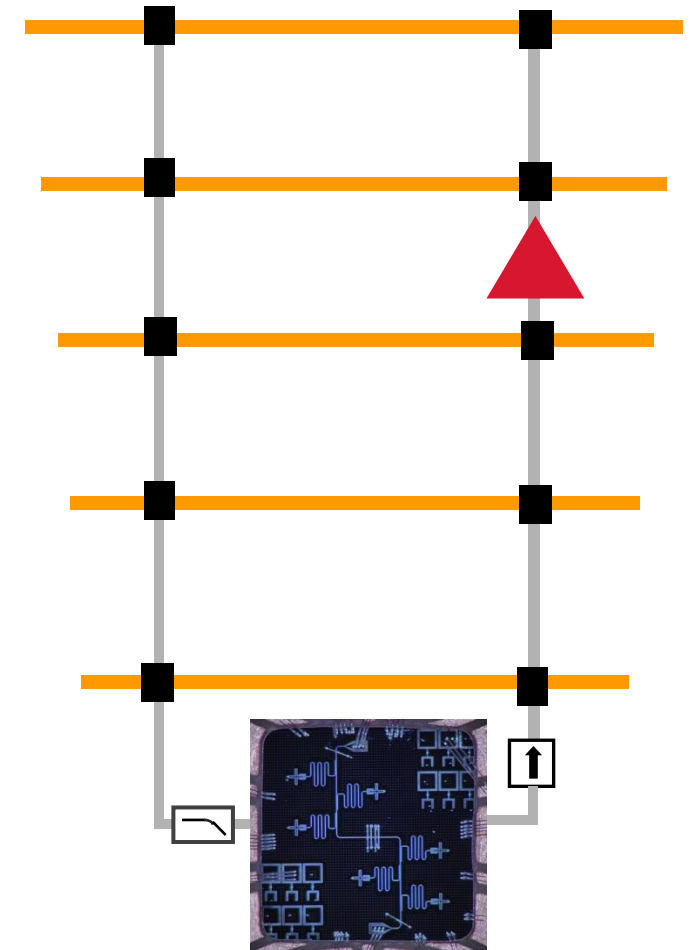
AB Study Framework

Through careful tuning of attenuation and filtering we explore the incremental changes in qubit performance throughout multiple cooldowns

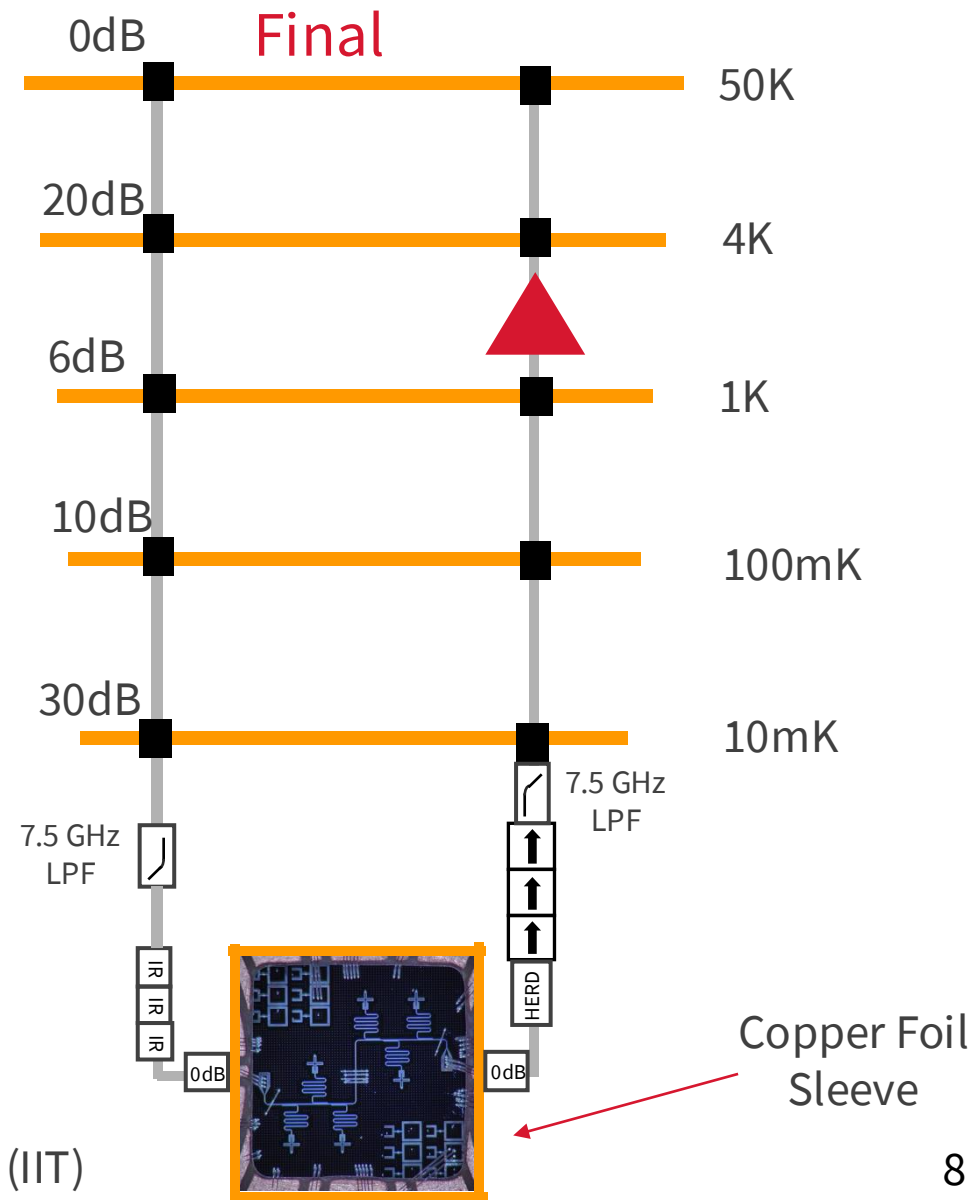
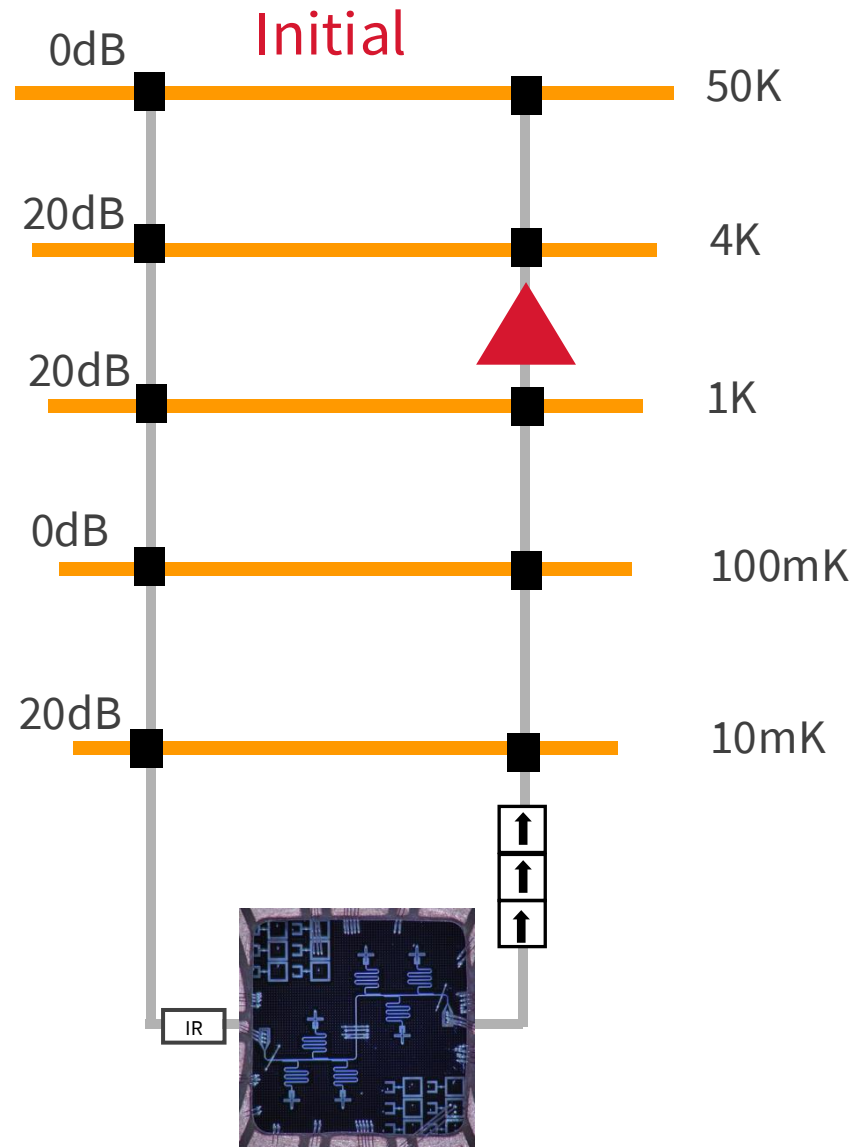
We progressively improve Qubit performance metrics of a 6 transmon chip throughout 6* cooldowns.

Monitored metrics included frequencies, coherence, readout fidelity, and effective temperature

* 7th run currently going



AB Study Framework

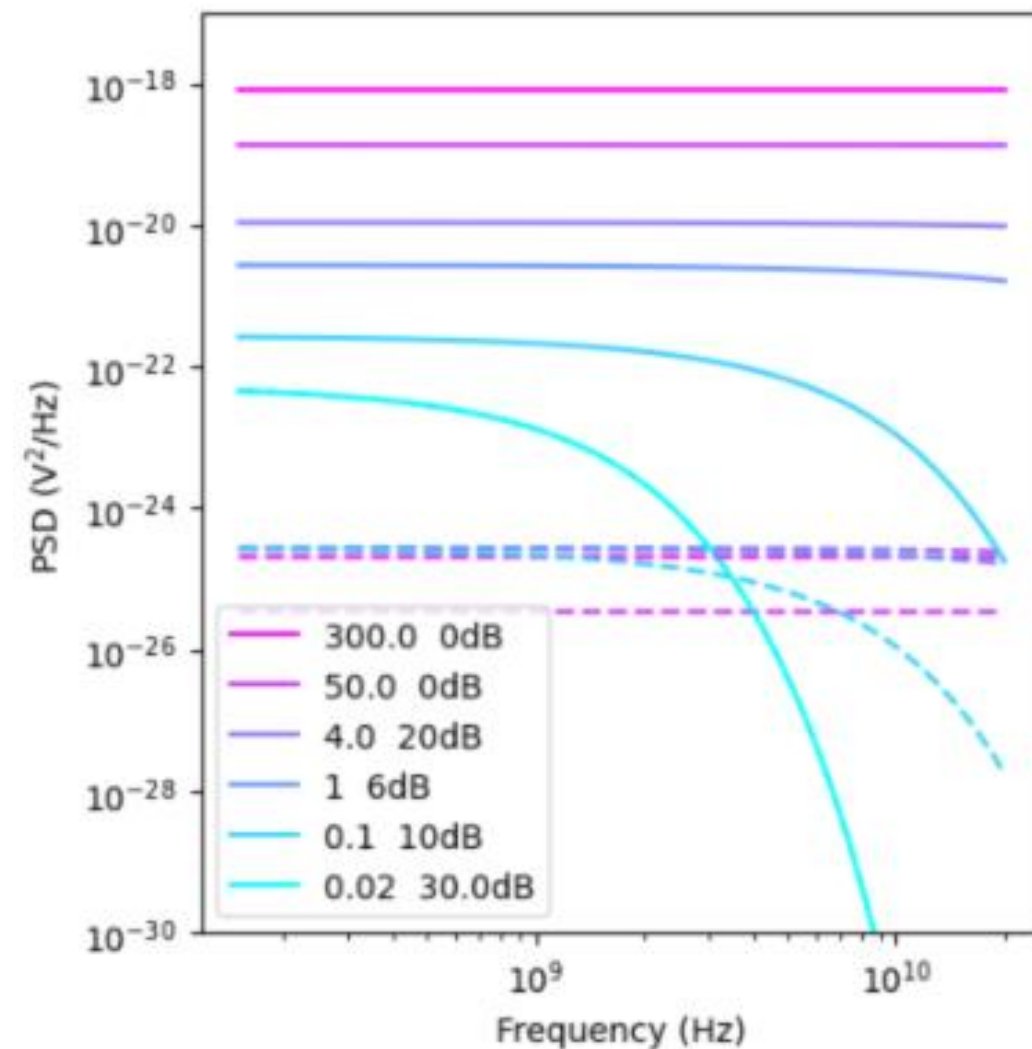


Double Layer
Amuneal Not
Visualized

Johnson-Nyquist noise

From Johnson-Nyquist Noise we can estimate the thermal noise contribution from each fridge stage on our lines.

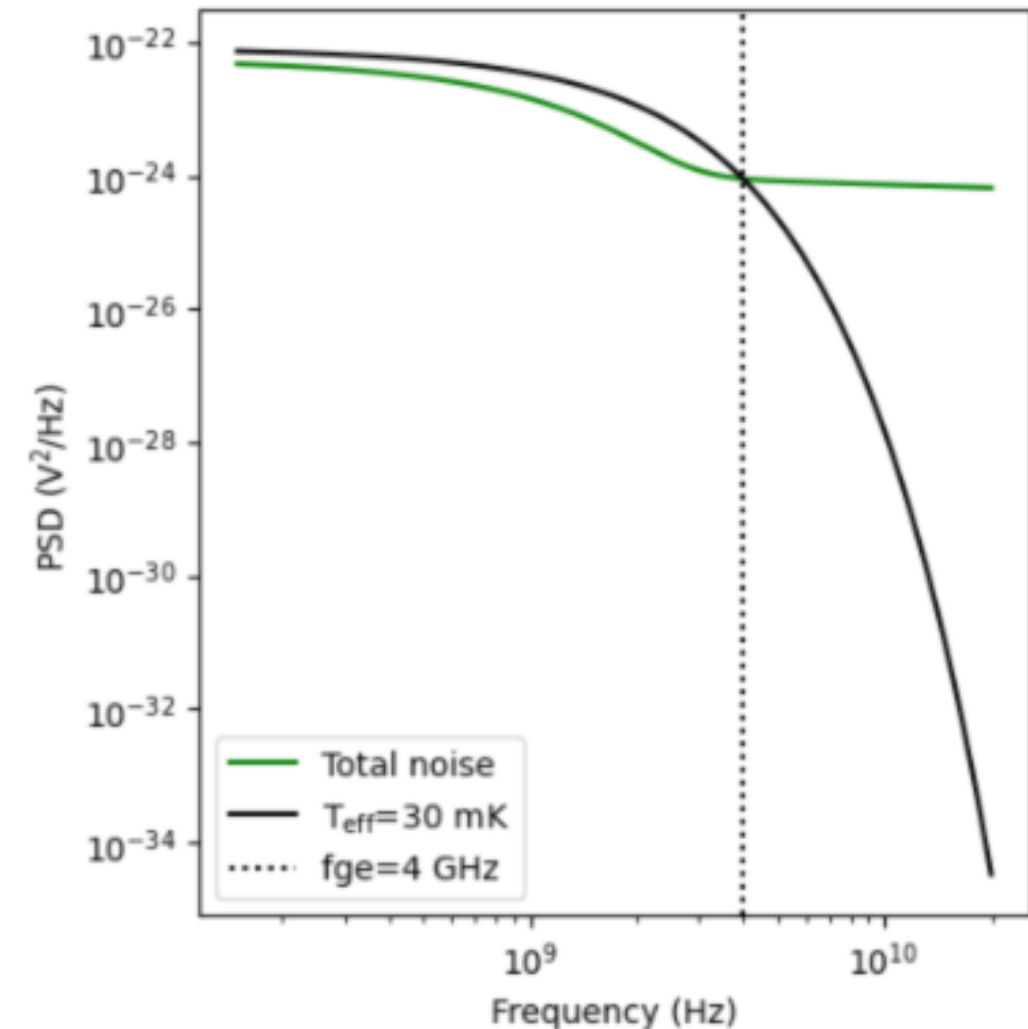
We can then propagate this noise with respect to our attenuation scheme



Johnson-Nyquist noise

Summing these contributions, we can estimate the power spectral density at our qubit frequency

This allows for the prediction of a noise temperature for our device (I.e. a performance floor)



IR Filters

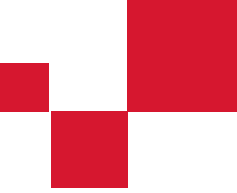
Some recent work have shown reductions in quasiparticle populations with increasing IR filter length. Using these works as a reference point, we land on using 3 IR filters.

shield \ filter	0 mm	9 mm	26 mm	36 mm	63 mm
open-top shield	10,000*	360*	560*		
aluminum tape seal	25,000	59 53 [▽]	22		
indium O-ring seal			9.1	1.9 0.7 [□]	1.3 [×] 1.2 [×] 0.14

<https://link.aps.org/doi/10.1103/PhysRevLett.132.217001>



QMC-CRYOIRF-002

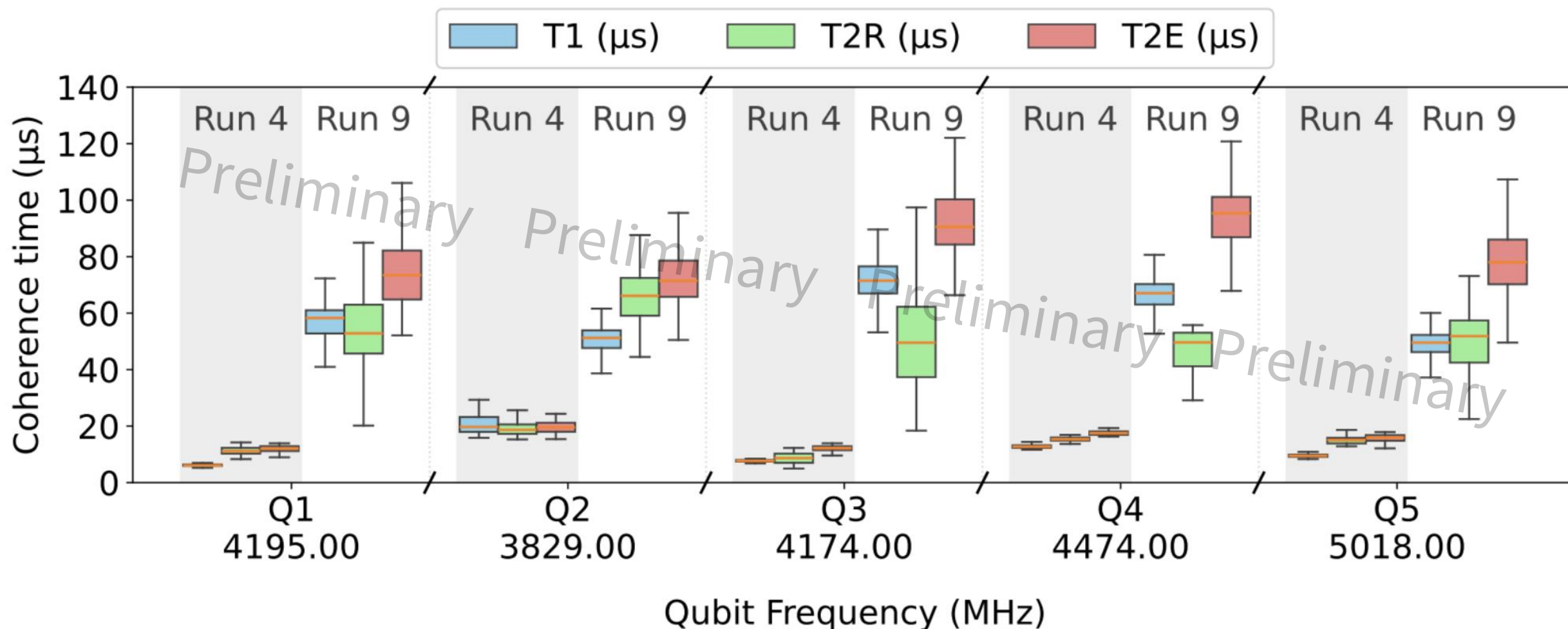


Early Result

The following are some preliminary results from this study. We're currently in the process of taking another dataset. These results should not be taken as final. A publication is currently in the works and is hoped to be submitted as soon as possible.

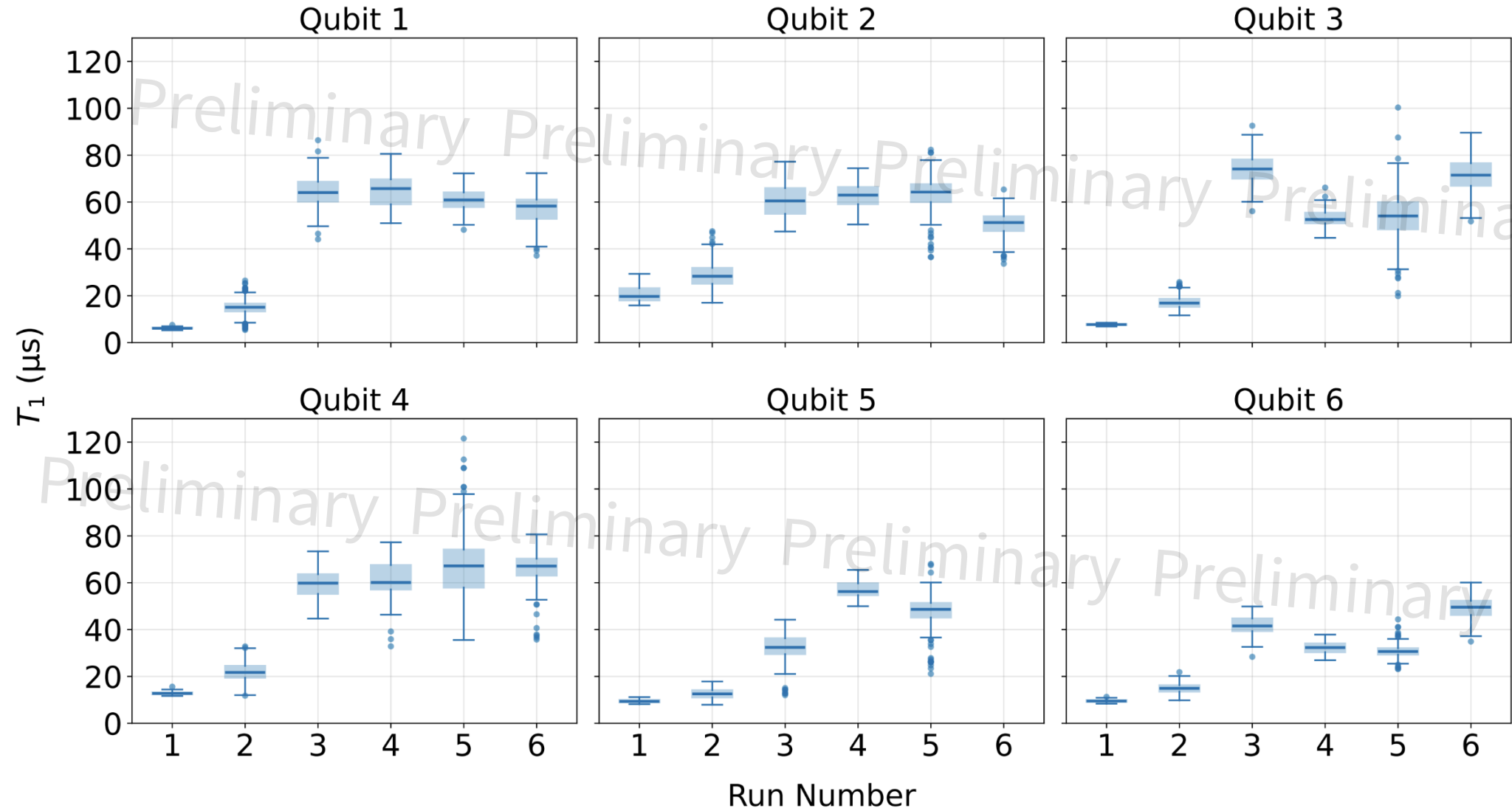
Throughout cooldowns occasionally TLS's and other phenomena would disrupt data collection. As a result, some plots may only show 5 qubits.

Initial to Final* Qubit Coherence



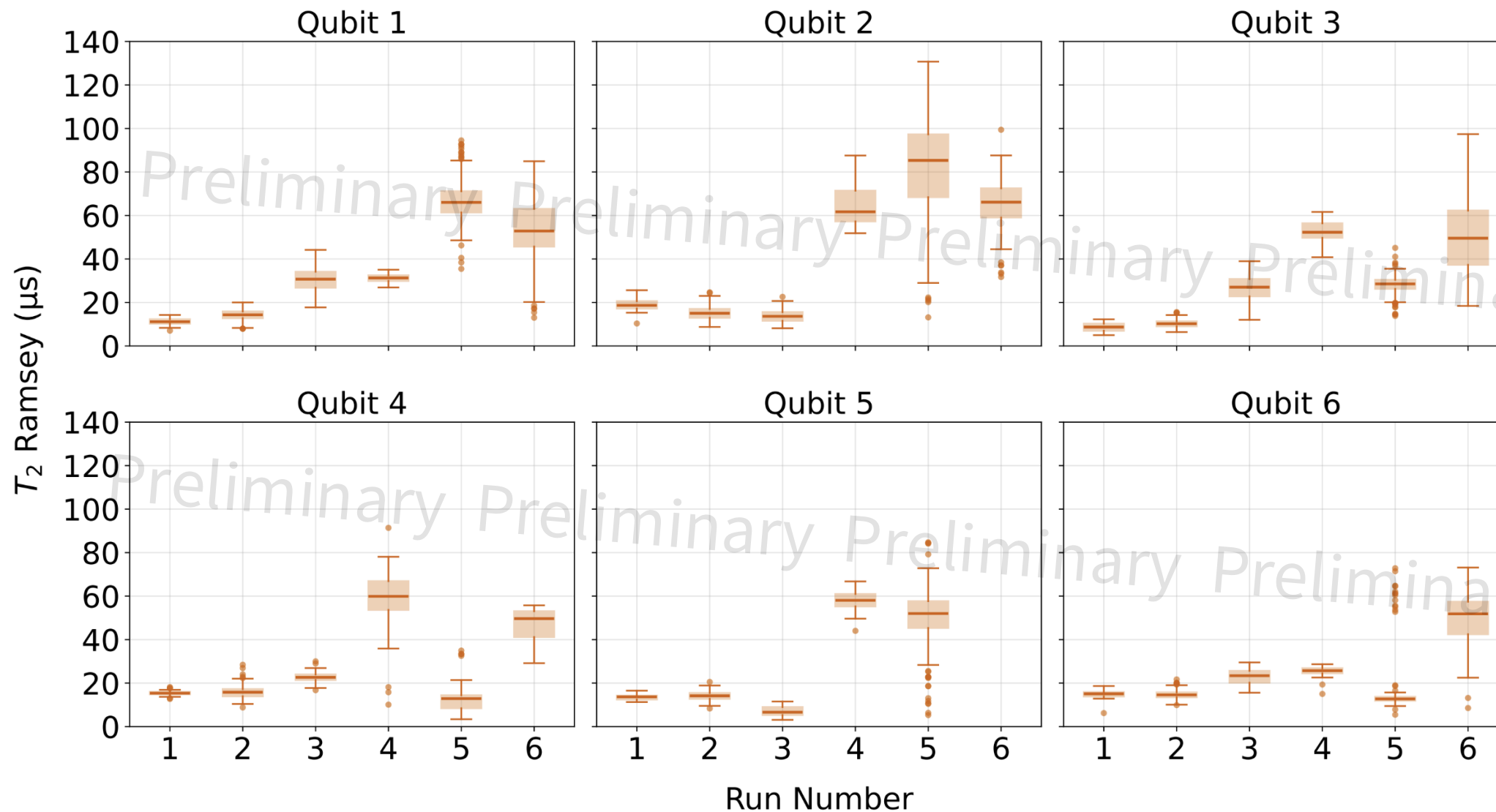
*Last Dataset currently going, coherence is not expected to change

Initial to Final* T1



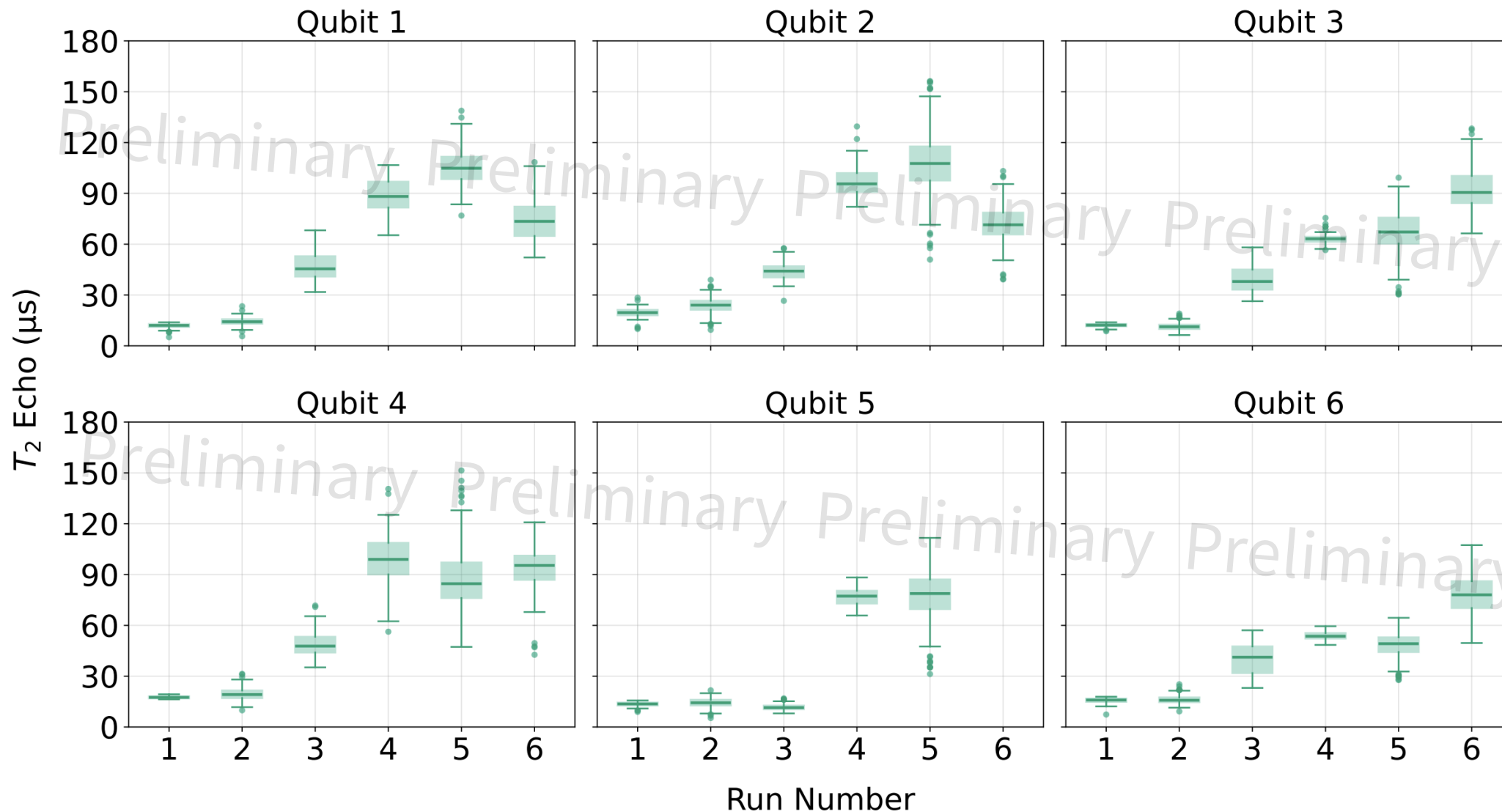
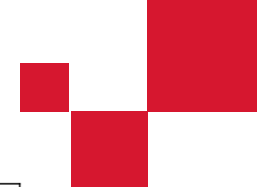
Saturates prior to final attenuation profile, after terminator + 0dB

Initial to Final* T2R



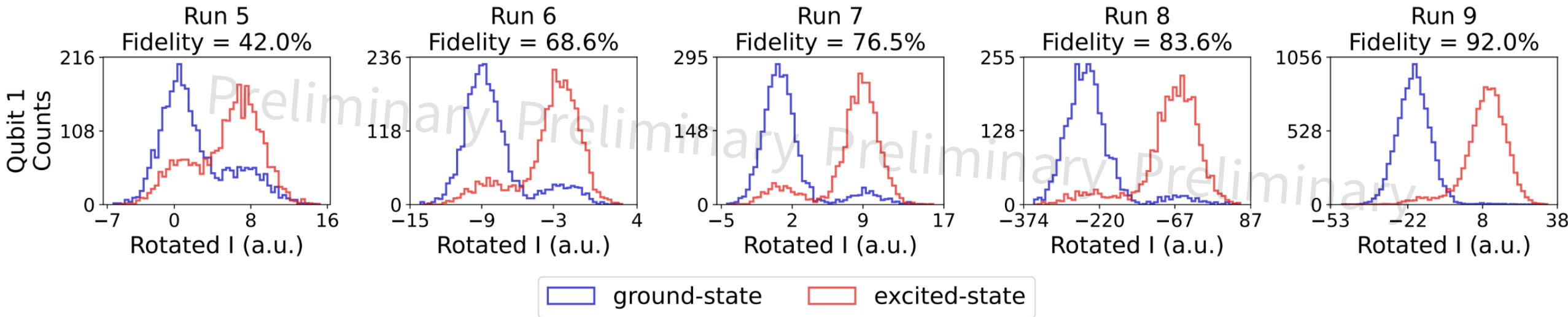
“Saturates” after final attenuation profile and thermal upgrades

Initial to Final* T2E



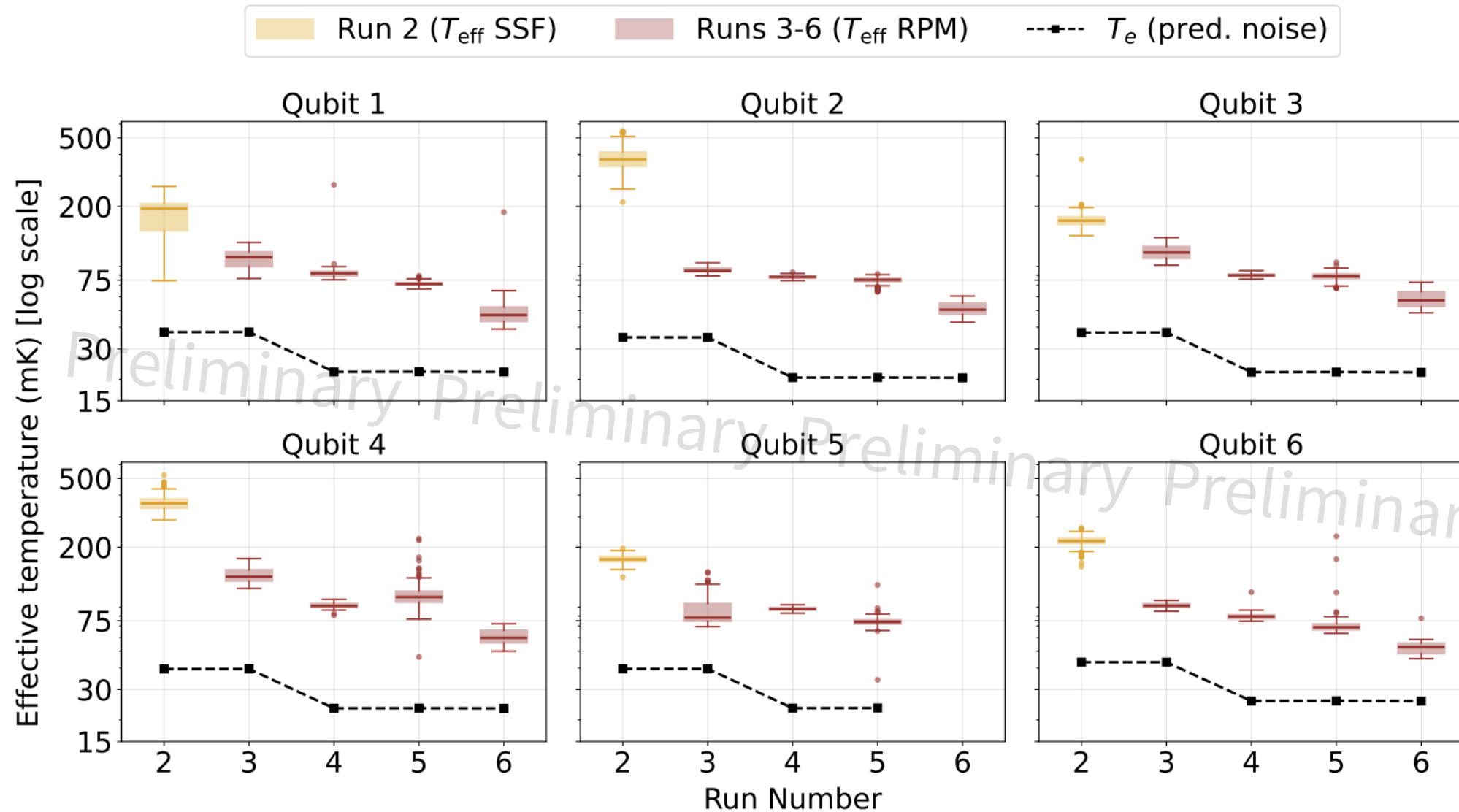
Improves with shielding + Thermal efforts

Single Shot Fidelity Throughout Runs

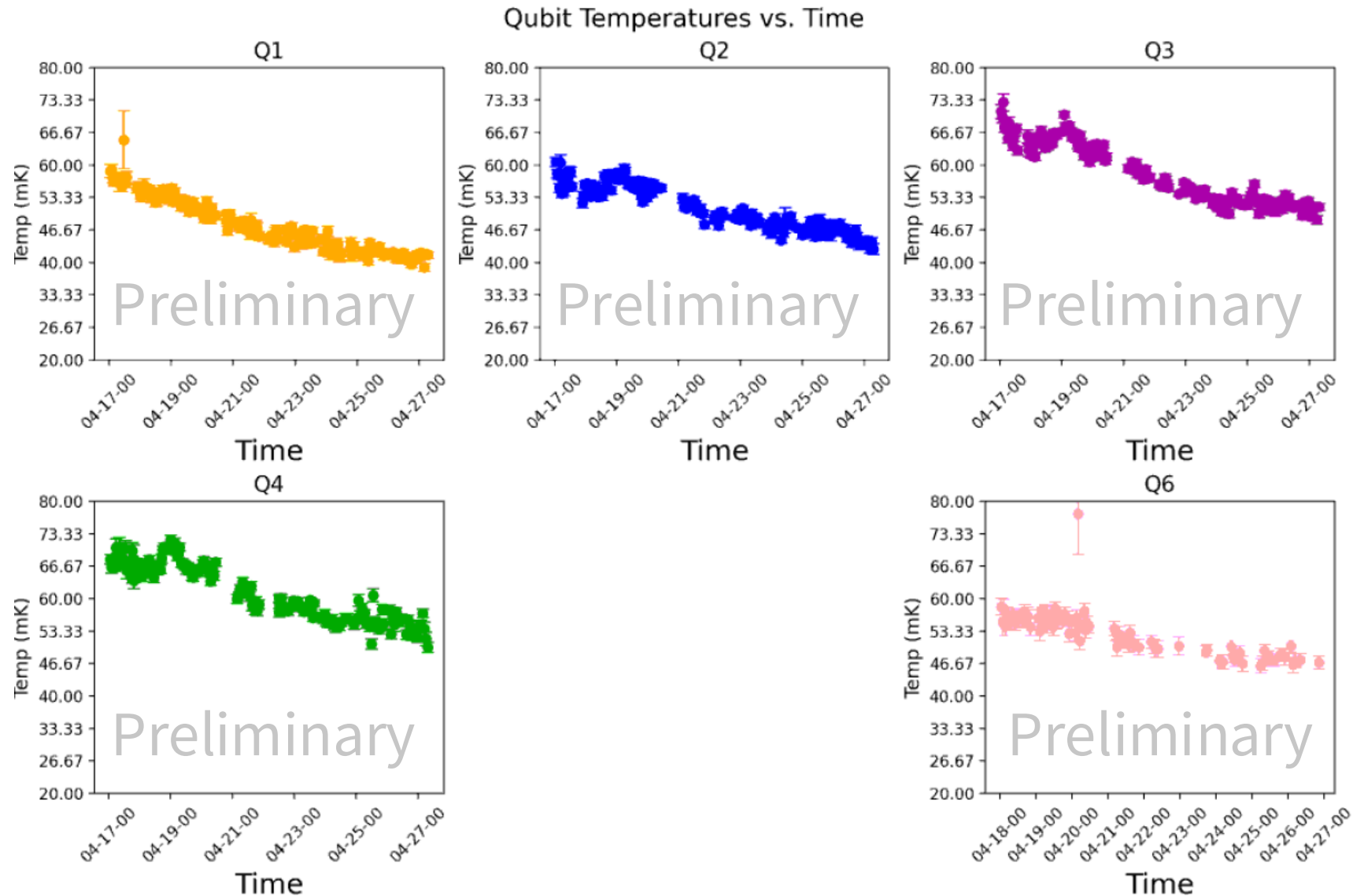
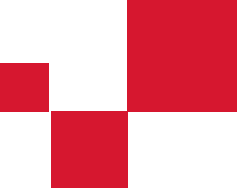


- Minimizing excess connections was found to improve SNR (expected)
- Improved line filter and environmental shielding was found to reduce excited state population, boosting SSF
- Similar trends observed in all qubits

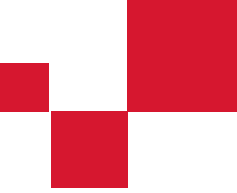
Effective Temperatures



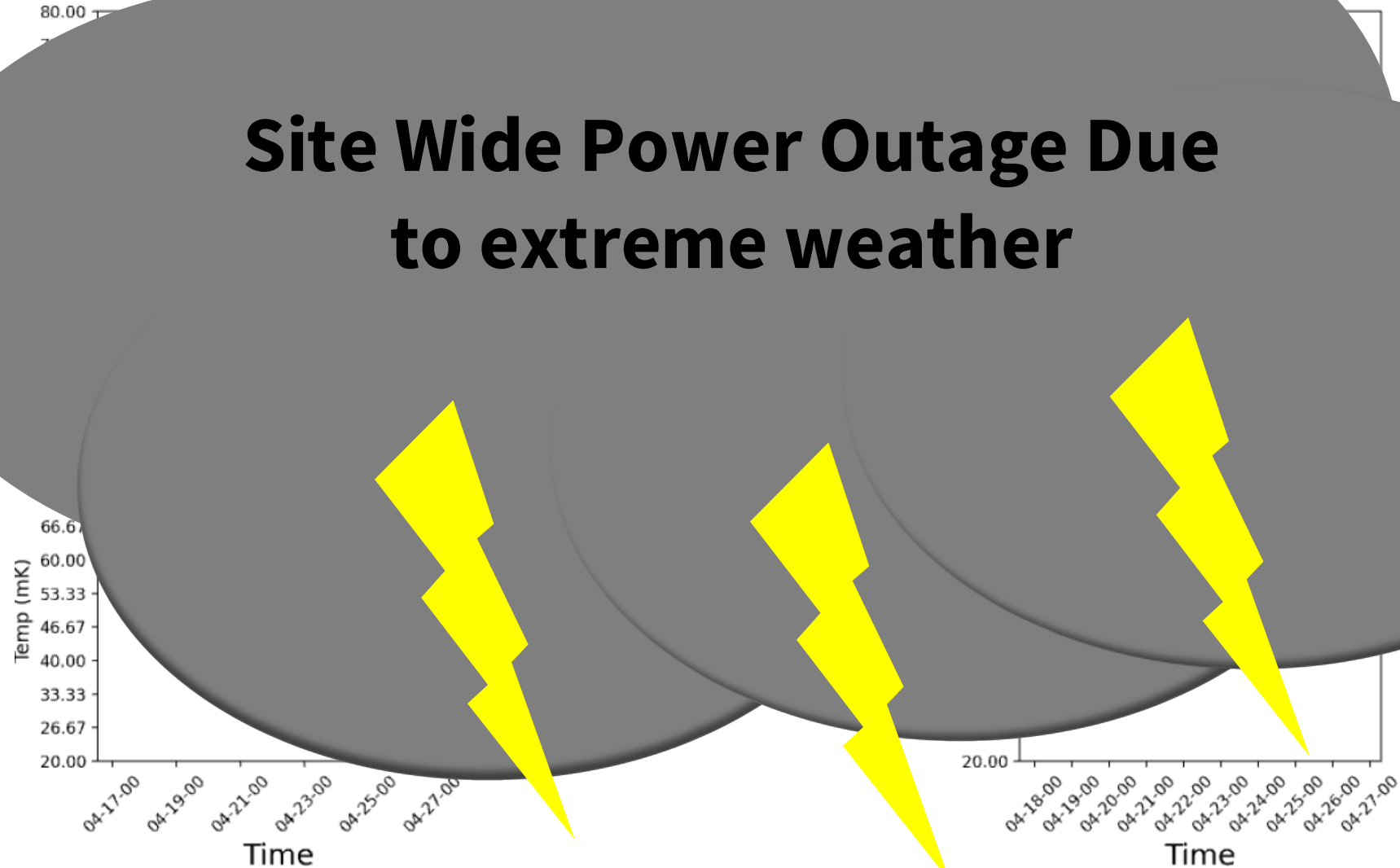
Effective Temperatures Continued



Effective Temperature



Site Wide Power Outage Due to extreme weather

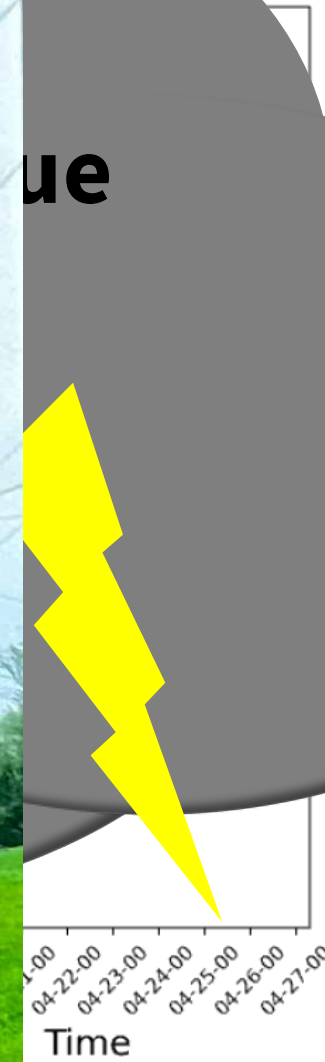
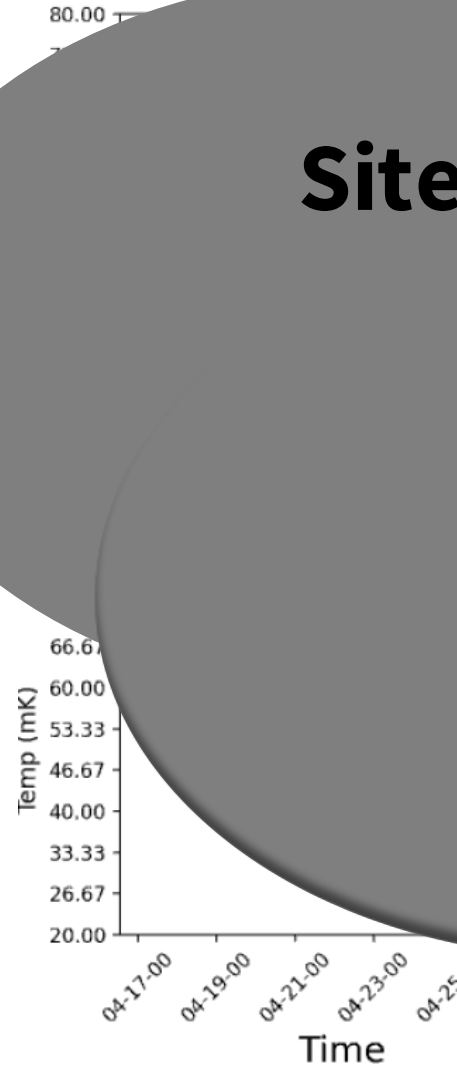


Effective

Site

ued

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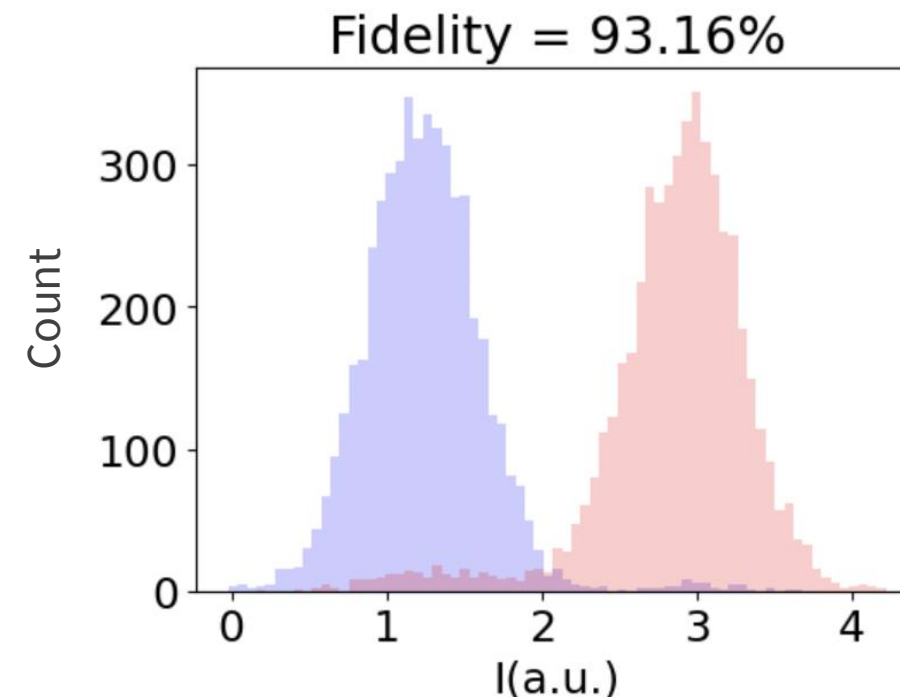
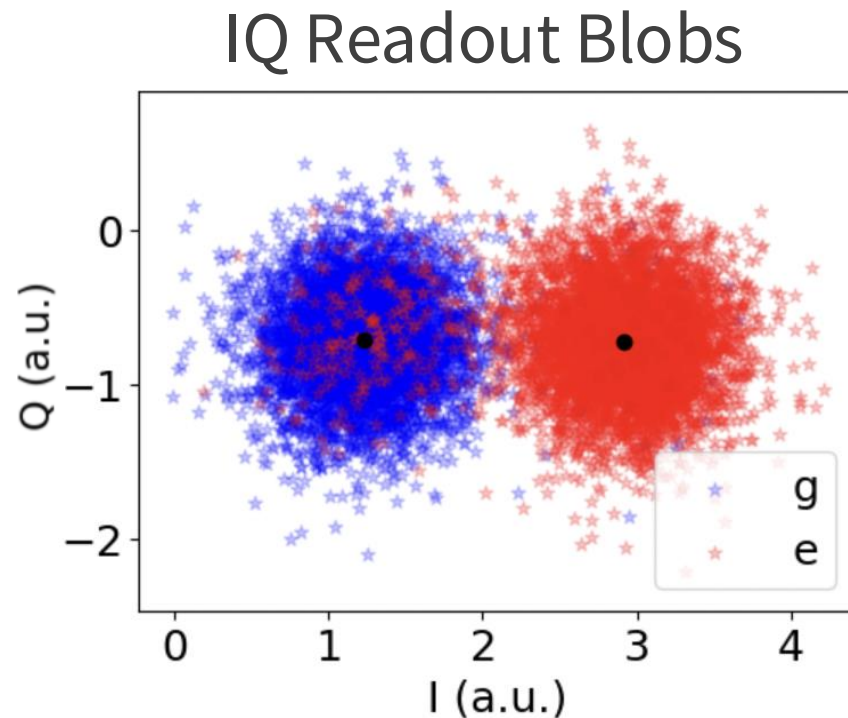
Transferability With LOUD

- LOUD is an above ground fridge (same model: Oxford Proteox MX)
- Proof of concept handmade IR shielding demonstrated and incorporated into AB study
- LOUD is our testbed for a MEMs guided laser for qubit energy deposition studies



LOUD Device

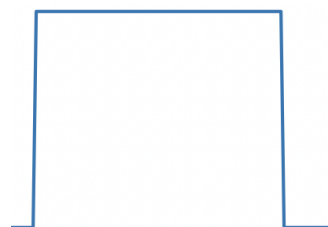
- Using the same configuration as our AB test we established good SNR and low effective temperatures in a different device.
- No quantum amplifier!



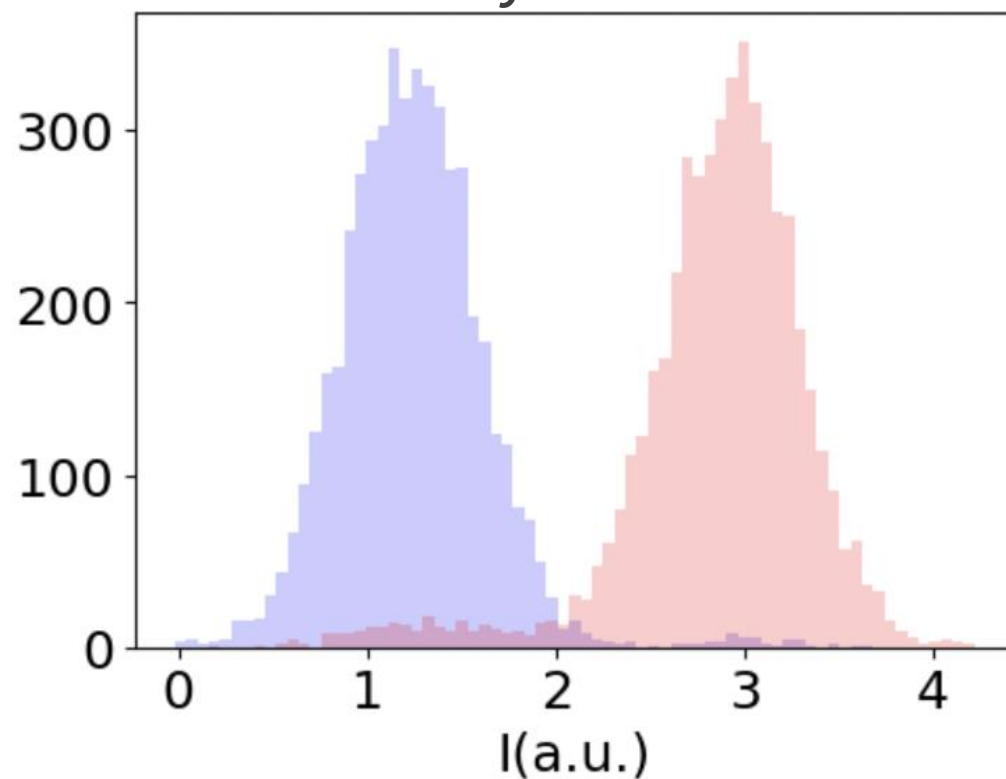
Readout Pulse Shape Refinement

Square

Readout Length
~1 μs

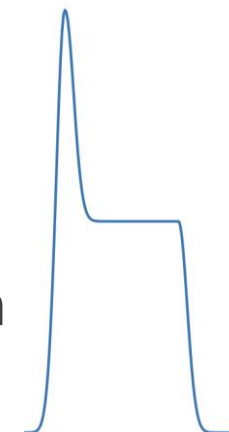


Fidelity = 93.16%



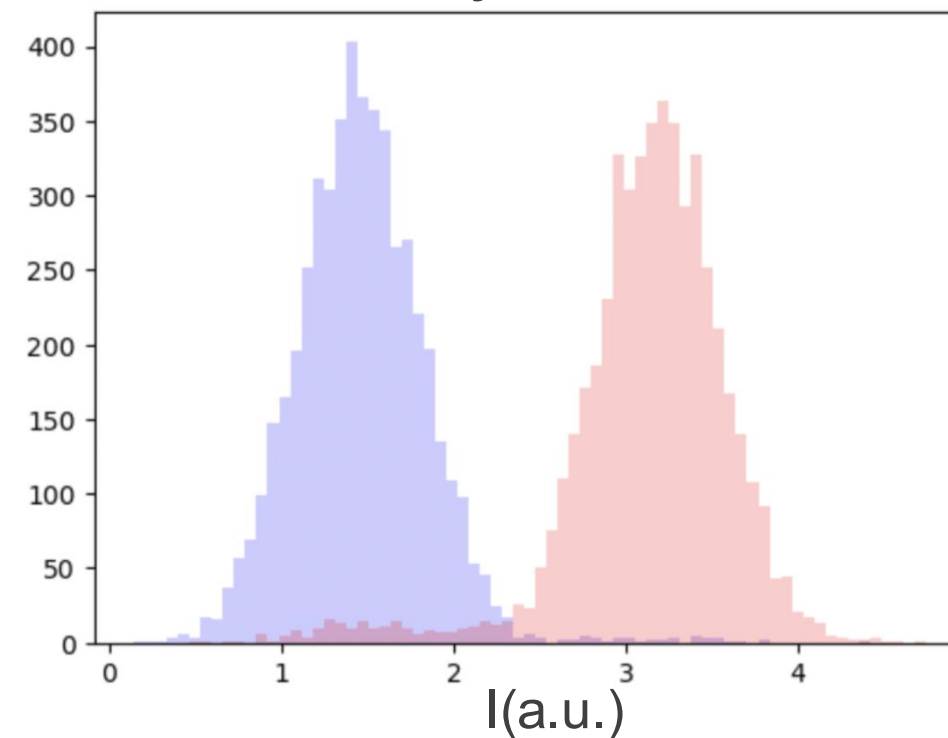
Two-Step

Readout Length
~0.6 μs

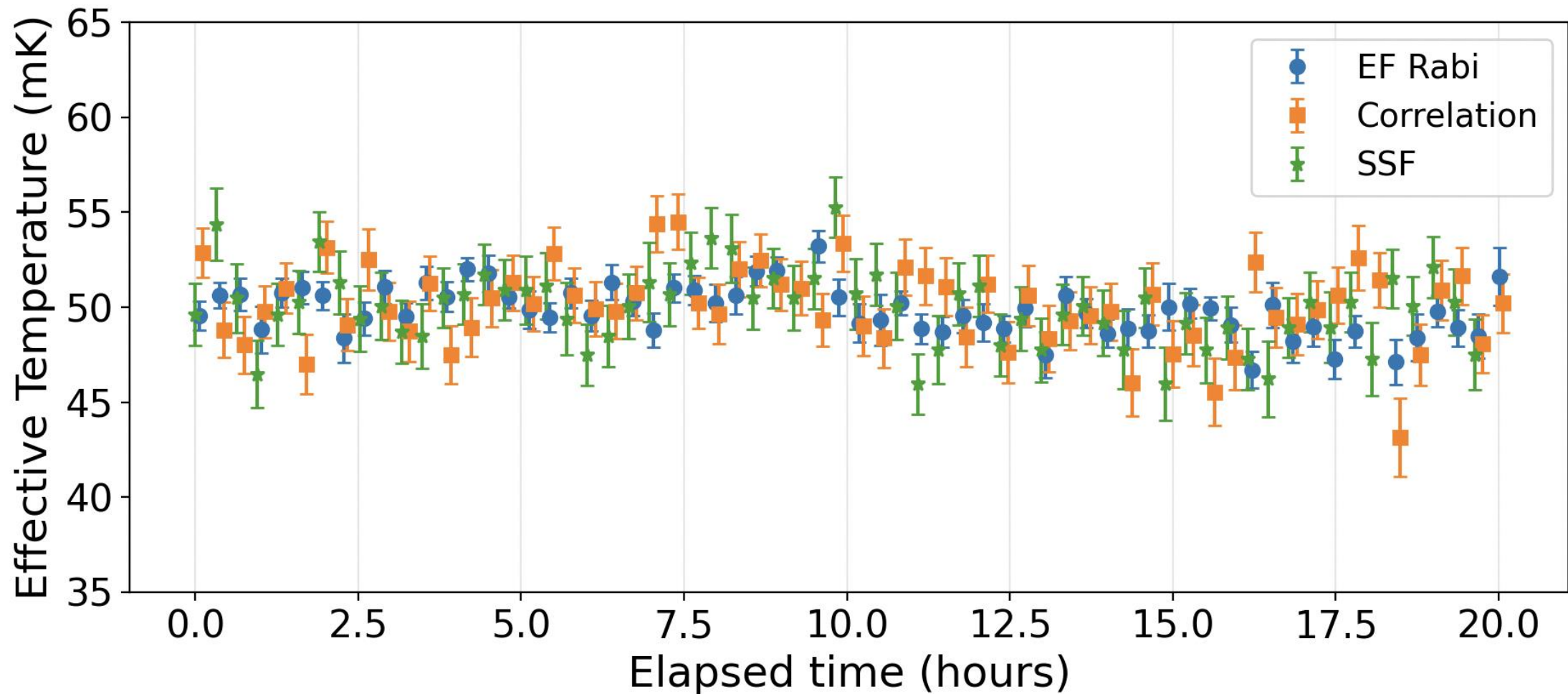


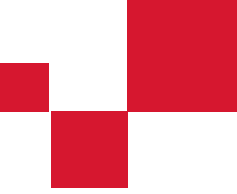
*Scale Exaggerated for
visualization

Fidelity = 94.40%



Excited State Population Studies





Next Steps

- Conclude & Publish our Study
- Implement Improved Packaging and shielding
- Leverage these results to continue optimizing our setup for our future qubit detector efforts

Acknowledgements

•**IIT:** Rakshya Khatiwada (joint w/ FNAL), Kester Anyang, Israel Hernandez, Ziyu Cai

•**FNAL:** Gustavo Cancelo, Lauren Hsu, Daniel Baxter, Dylan Temples, Ryan Linehan, Sara Sussman, Sho Uemura, Olivia Seidel, Joyce Christiansen-Salameh, Tilly Schaaf,

•**Northwestern University:** Enectali Figueroa-Feliciano (joint w/ FNAL), Emmanuela Celi, Grace Bratrud, Firas Abouzahr, Arianna Colón Cesaní

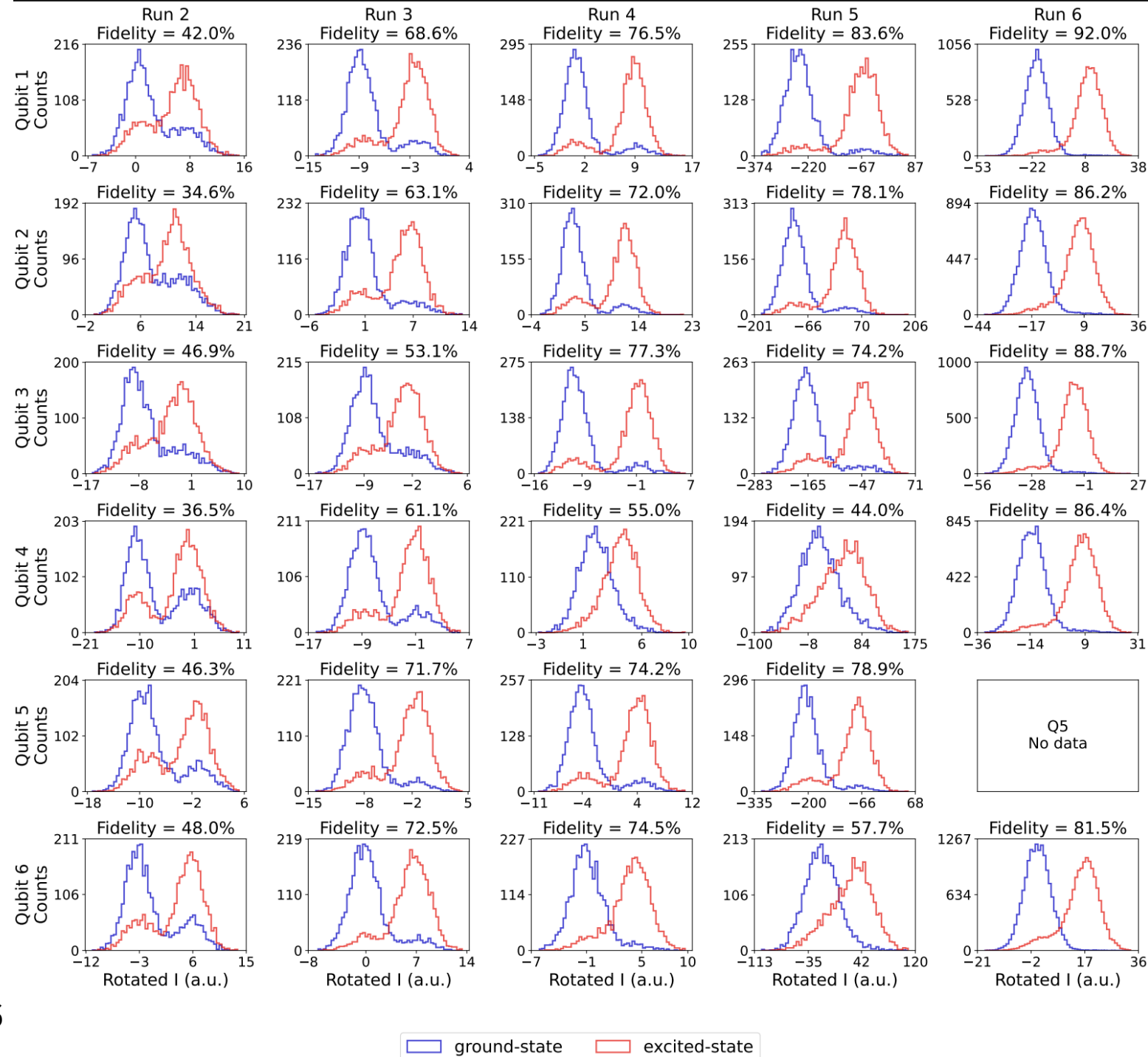
DOE QuantiSED 2.0



This presentation is based upon work that is supported by the Visiting Scholars Award Program of the Universities Research Association, QuantiSED 2.0, Quantum Science Center (QSC), and Illinois Institute Of Technology Physics Department, National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-2234667. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the Universities Research Association, Inc or views of the national science foundation.

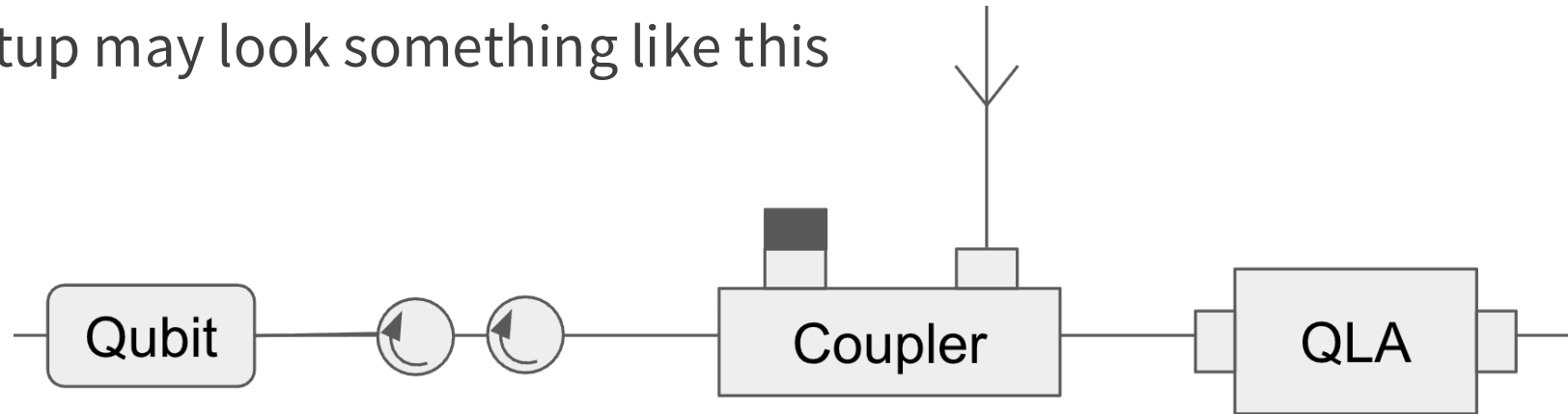
Thank you!

Back Up Slides



Quantum Amplifiers

Quantum Amplifiers typically use 3 wave or 4 wave mixing processes. A general setup may look something like this



Depending on your amplifier your pump tone may lay within the typical qubit band. This may act as a noise source. Additionally depending on your circulator/isolators the pump tone may be at a non trivial power. As a result outcomes with this type of a system may obscure study results (especially across cooldowns)

Quantum Amplifiers Continued

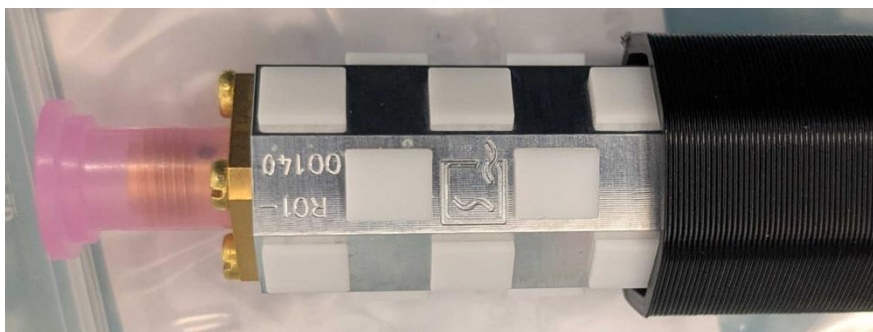
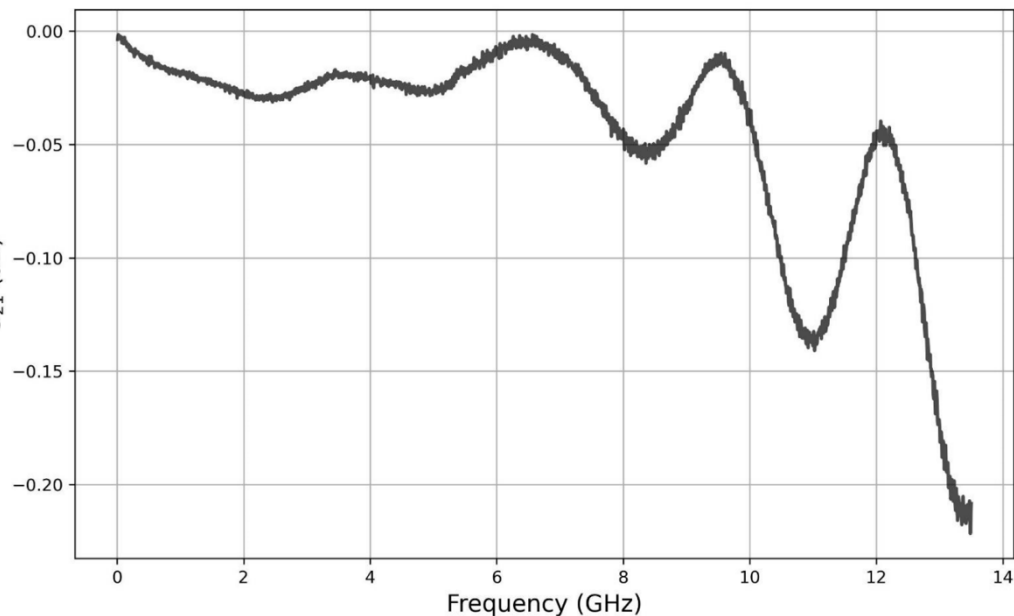
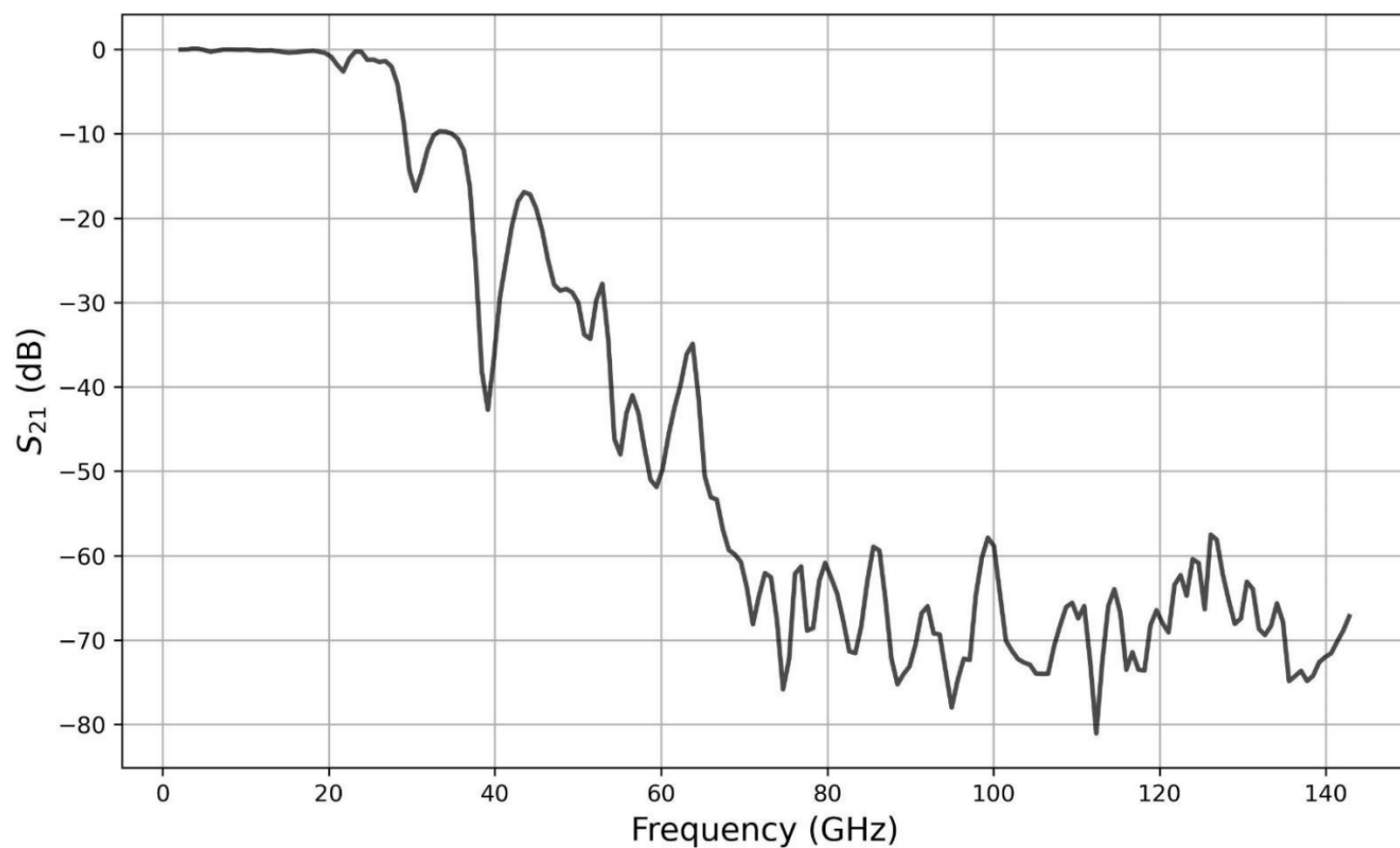
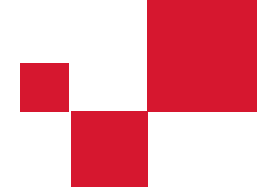
We're currently in the process of implementing Quantum limited amplifiers and will investigate their influence on our devices

Because of the variety of QLA implementations the transferability of these results may vary significantly

HERD

Extremely low loss filter

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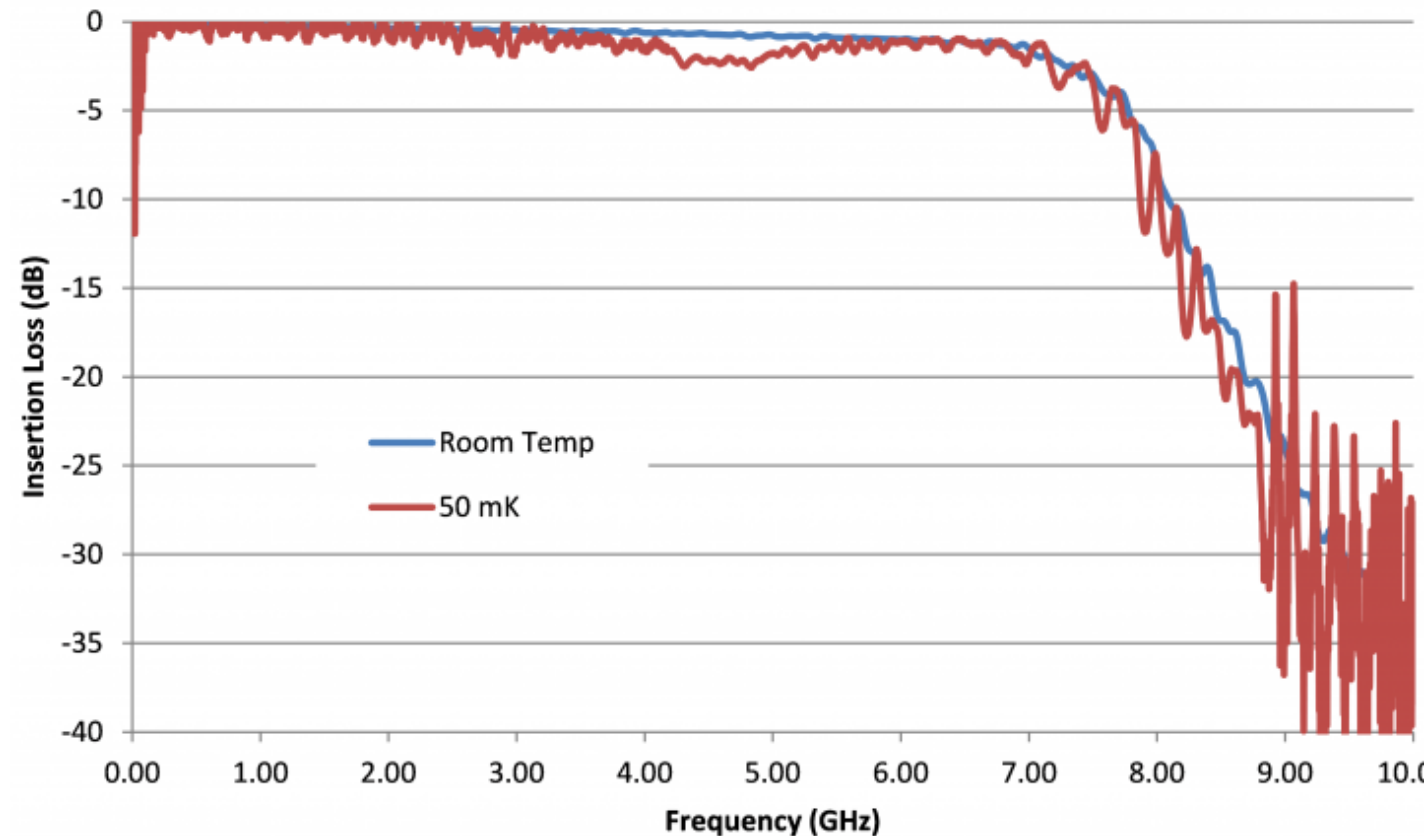
<https://arxiv.org/abs/2205.03941>

Low pass Vs Band pass



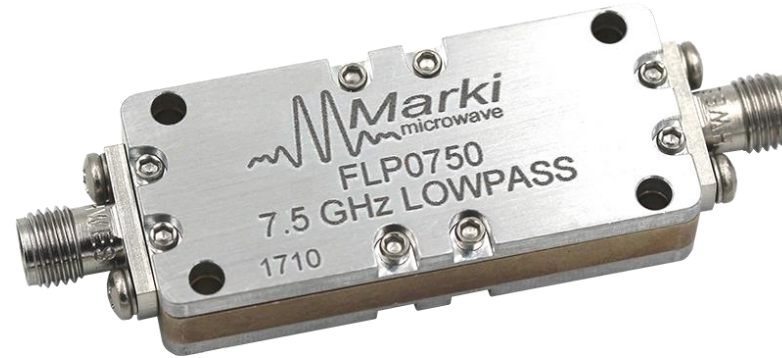
We use the Marki FLP0750 as our filter of choice. This filter has been used in multiple cryo setups and seems to be reasonably low loss

Cryogenic Performance of FLP-0750



https://markimicrowave.com/technical-resources/application-notes/cryogenic_performance_of_marki_microwave_products/

Low pass Vs Band pass

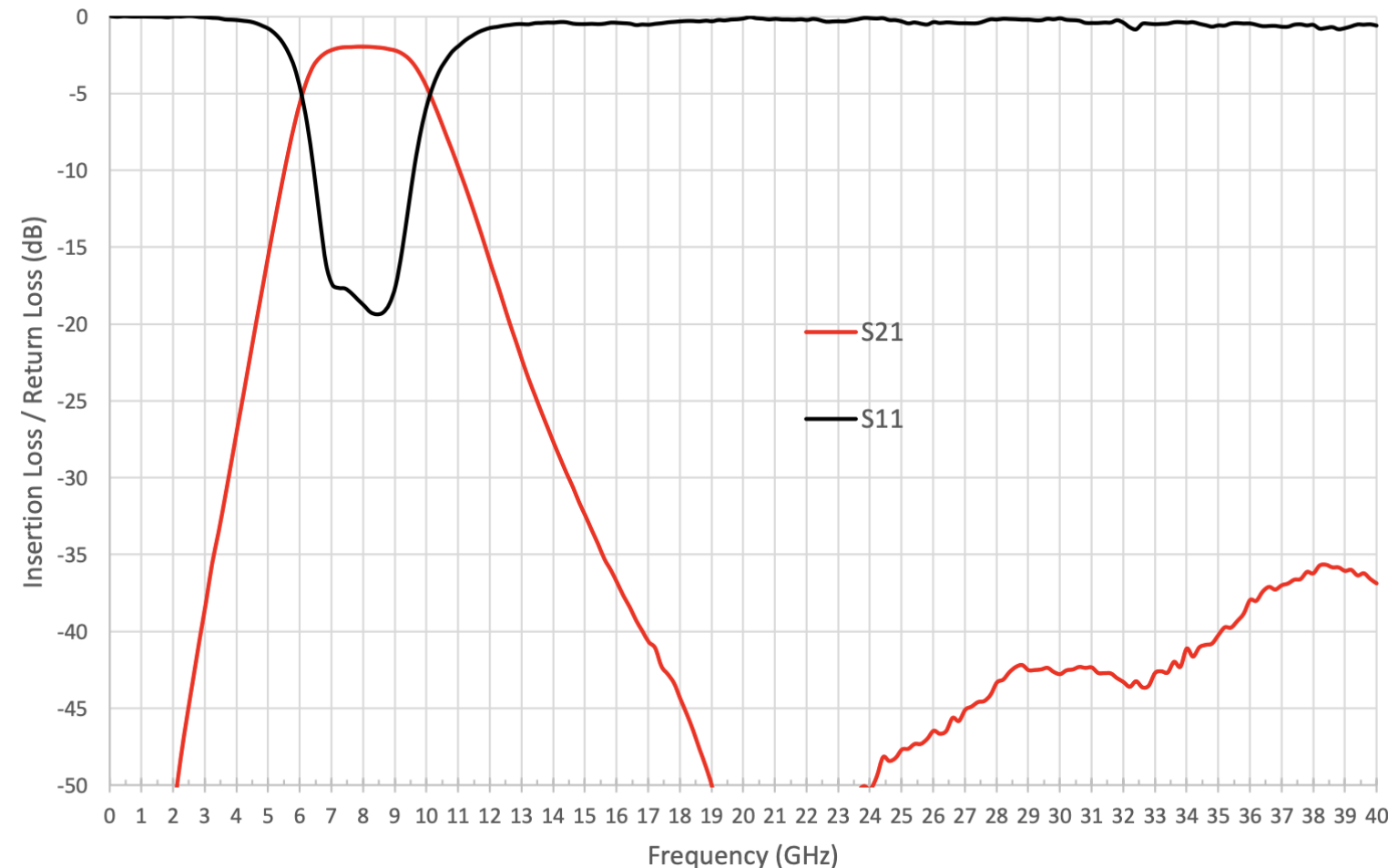


Low pass Vs **Band pass**

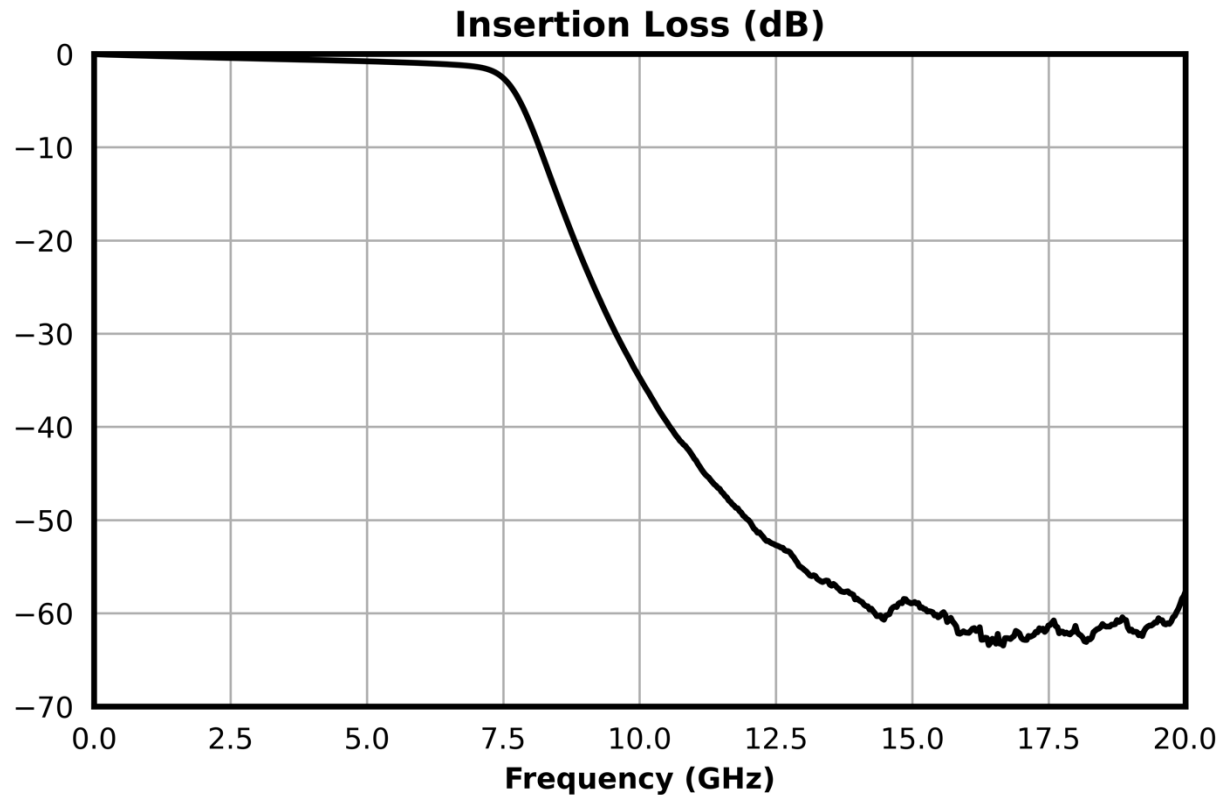


Few bandpass filters have been battle proven at cryo. Many of the cryo rated options seem fairly lossy (fine on the input problematic on the output)

Room Temperature Measured Data



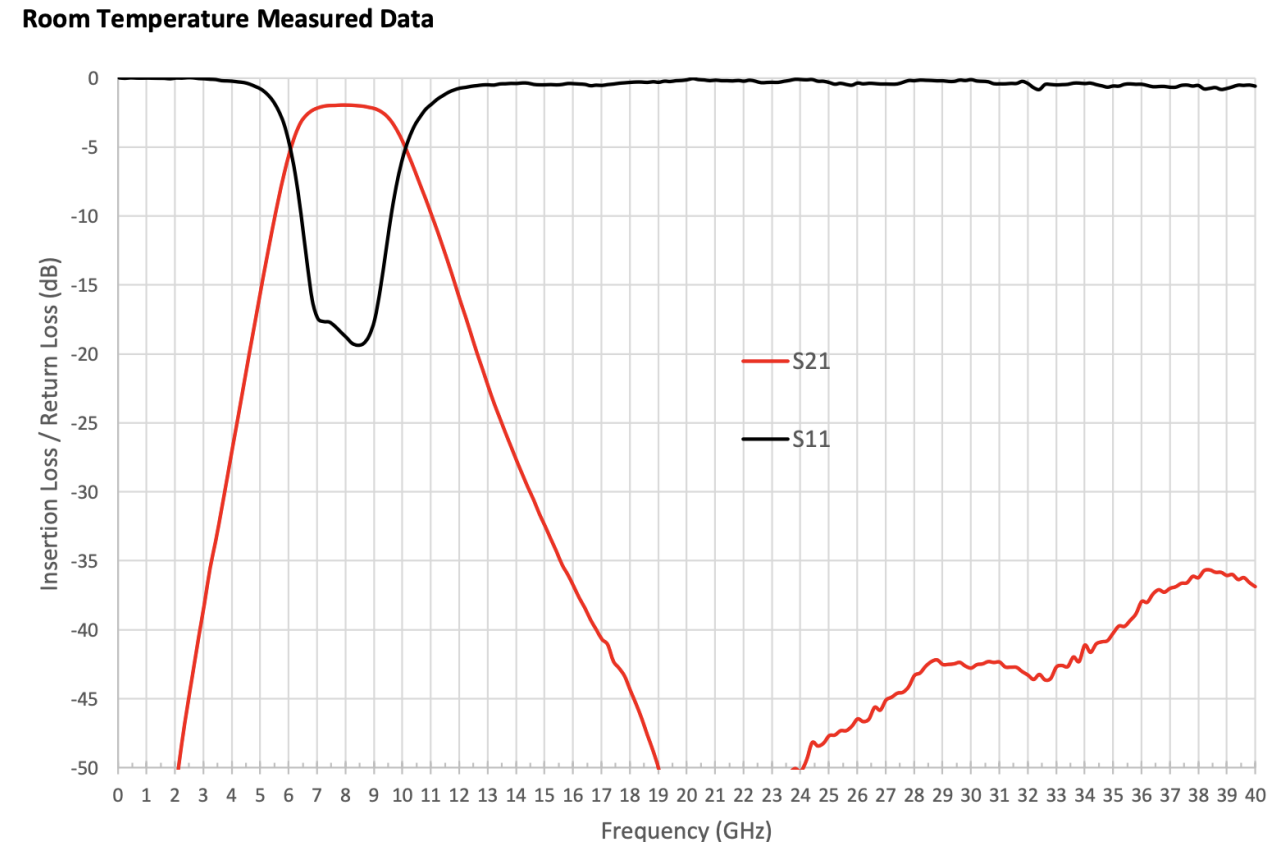
Low pass Vs Band pass



At 10GHz: -35dB

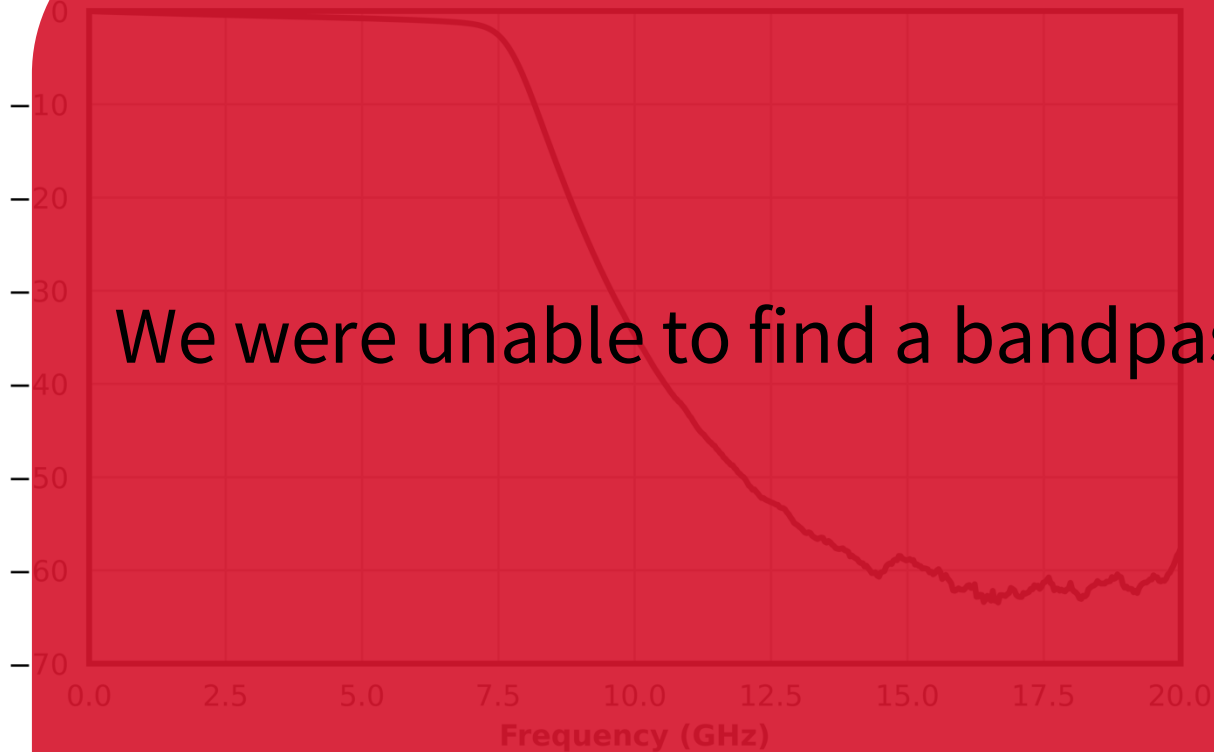
vs

-5dB



Low pass Vs Band pass

Insertion Loss (dB)



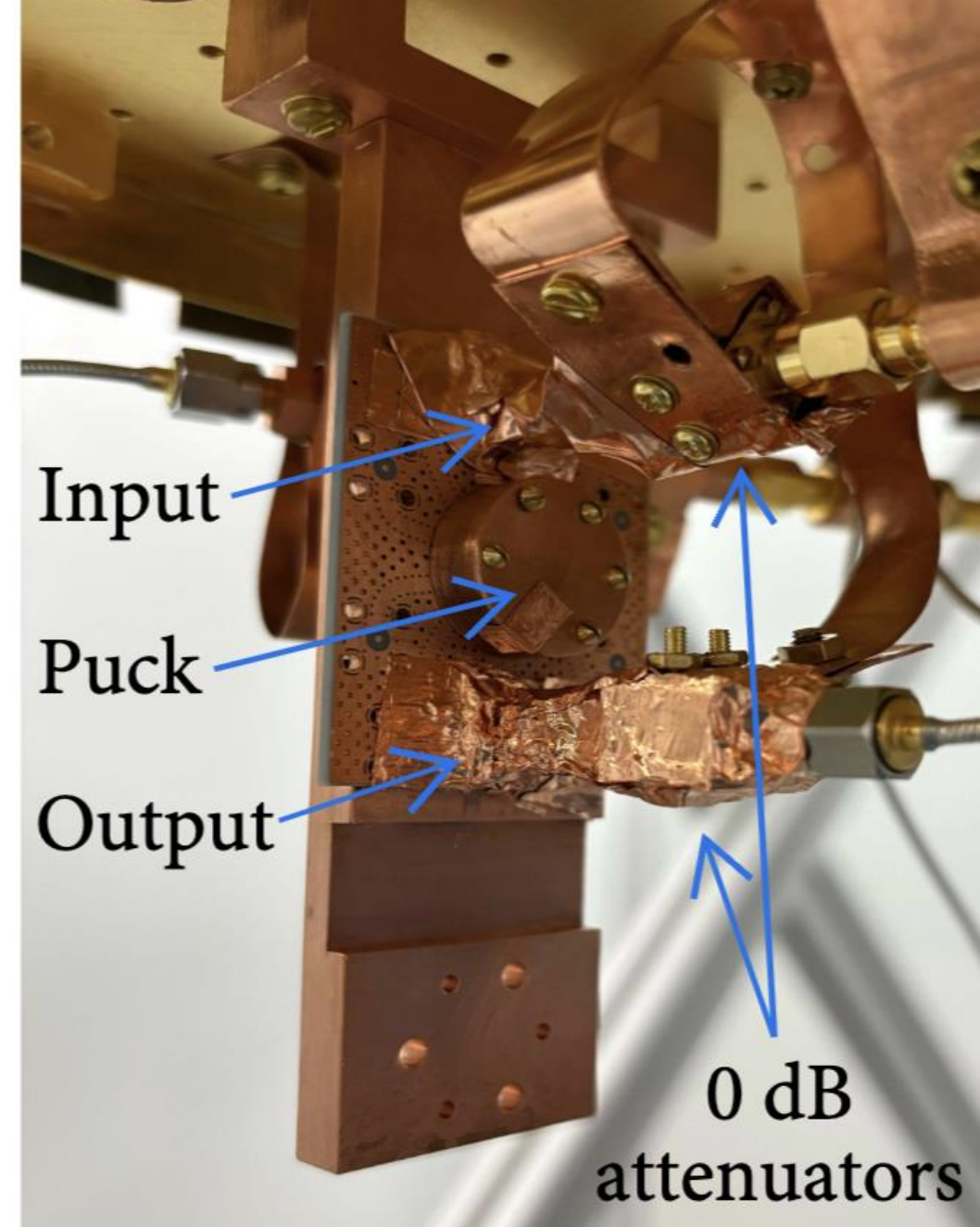
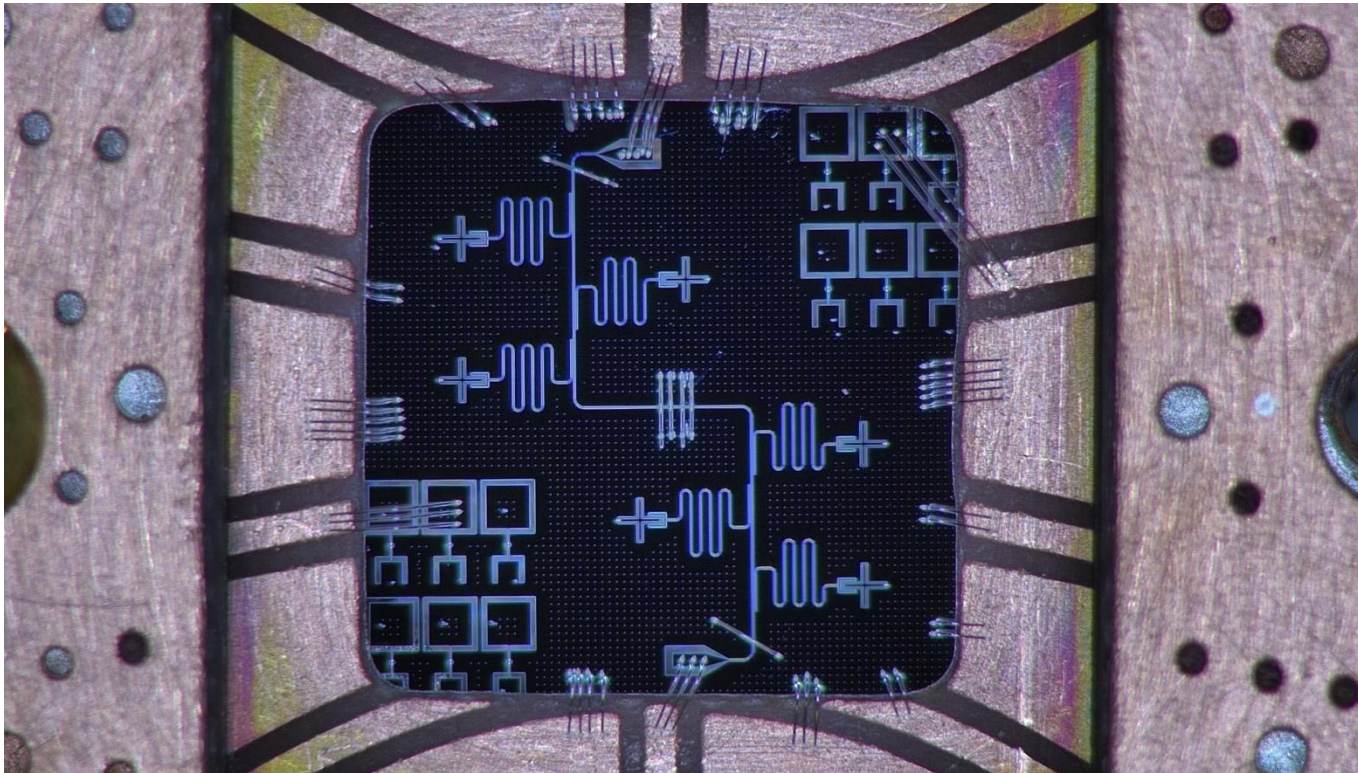
Room Temperature Measured Data

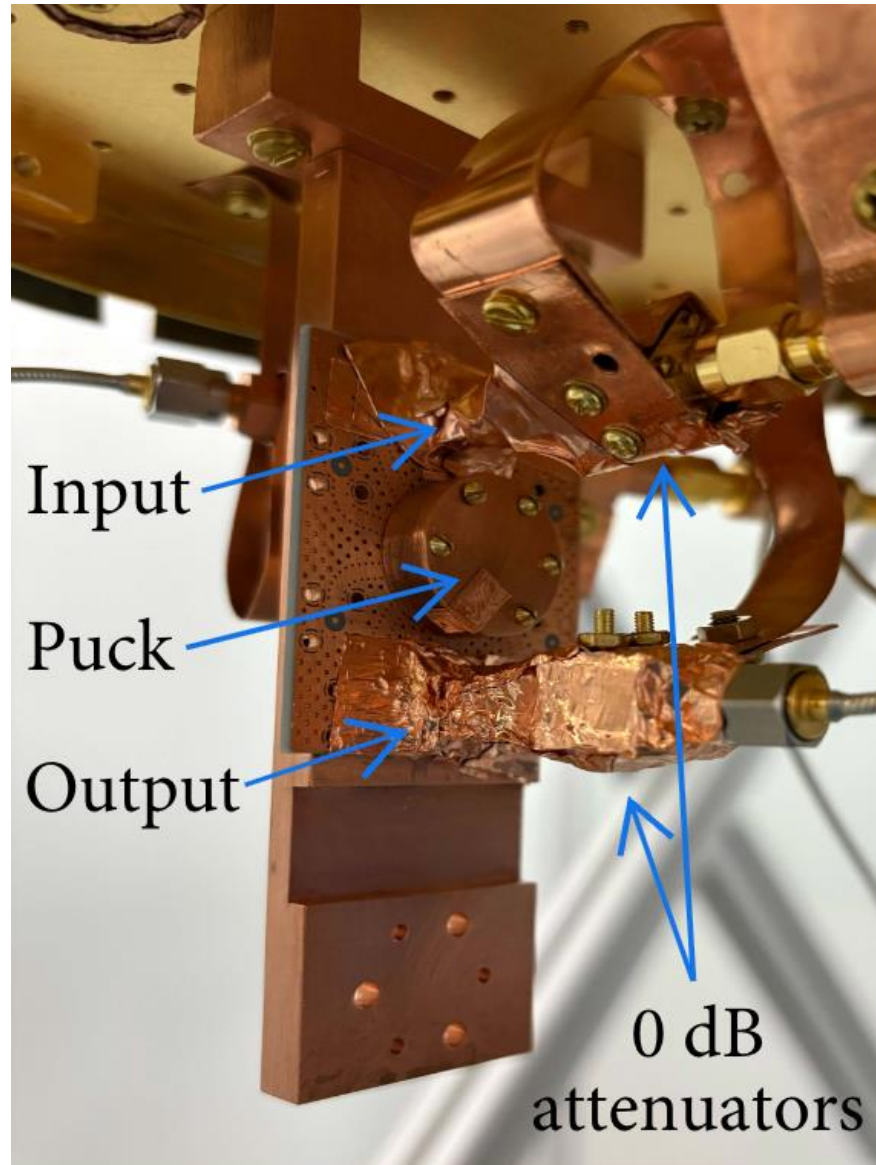


We were unable to find a bandpass filter with satisfactory performance

Packaging

- This study used a PCB style packaging
- 4 layer PCB, Copper Metalization
- Box Mode >10GHz







Fixed Frequency vs Tunable Transmons

- One argument for fixed frequency being used in this study was that line configurations to bias can vary significantly (coax vs twisted pair, bias tees, fast flux vs “slow”, accidental ground loops, etc)
- As a result of this what reduced flux noise in one system may not be directly applicable to another
- Despite these architecture differences what improved the performance of a fixed frequency transmon will be generally applicable to a tunable transmon
- A similar study on noise in flux tunable systems would also be extremely valuable but challenging to realize

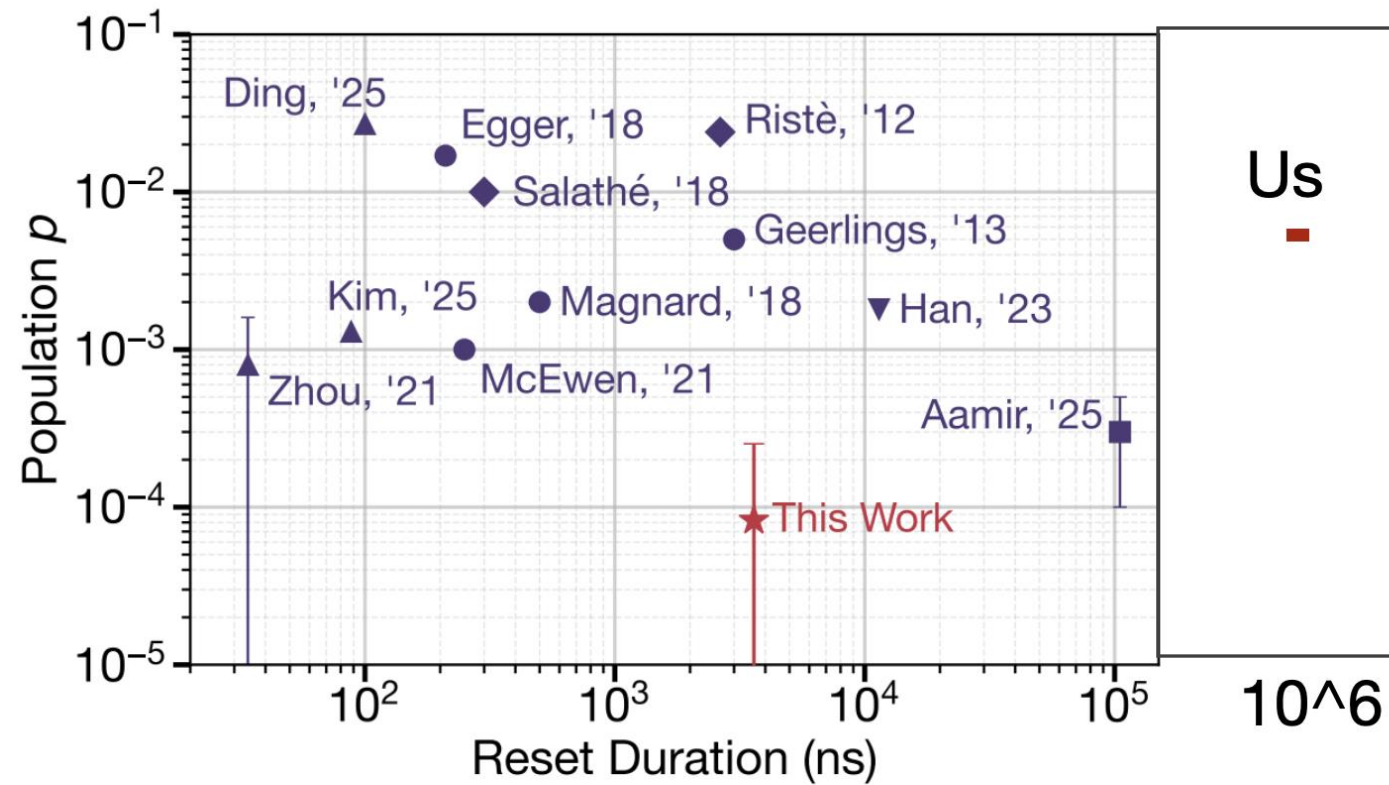
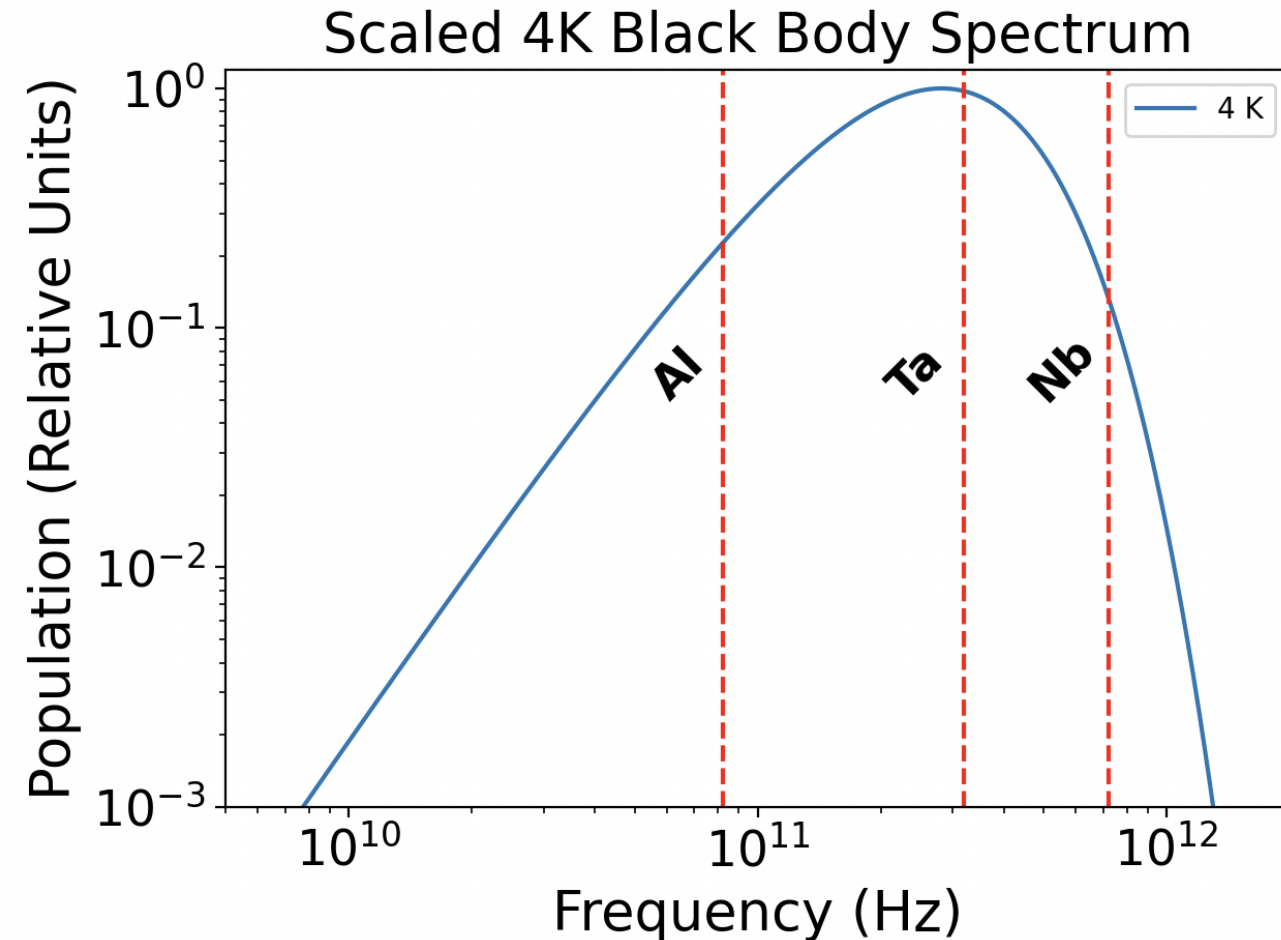


FIG. 4. Comparison of transmon qubit reset protocol performance. The plot markers indicate the reset strategy: measurement-based reset schemes (diamonds) [14, 20]; reset through engineered dissipation using microwave resonators (disks) [15–17, 32]; reset using additional active, on-chip microwave elements (upwards triangles) [18, 19, 33] and external RF components (triangle down) [21]; reset through microwave bath engineering (square) [22]; and reset using a physically different bath (star; this work).

IR Photons

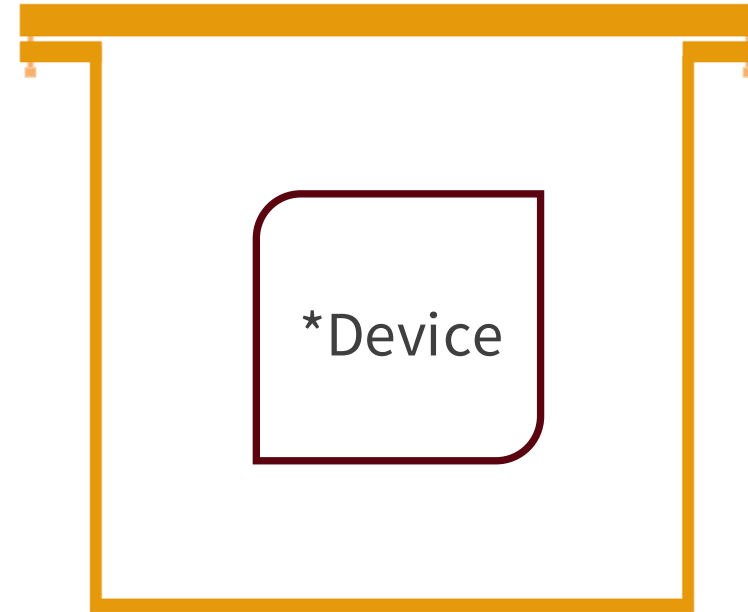
- Black body radiation may leak down from higher temperature stages
- IR photons have a small wavelength and can slip through cracks effectively
- The 4K stage has significant blackbody emission from ~ 10 GHz $\rightarrow$ THz ($\sim$ IR band)



Optimal Shielding

Effective shielding is tough to achieve. In general shields strive to be:

- Light tight
- Vacuum compatible
- Non-device specific (reusable)
- Not radioactive
- Non-magnetic
- Well Thermalized

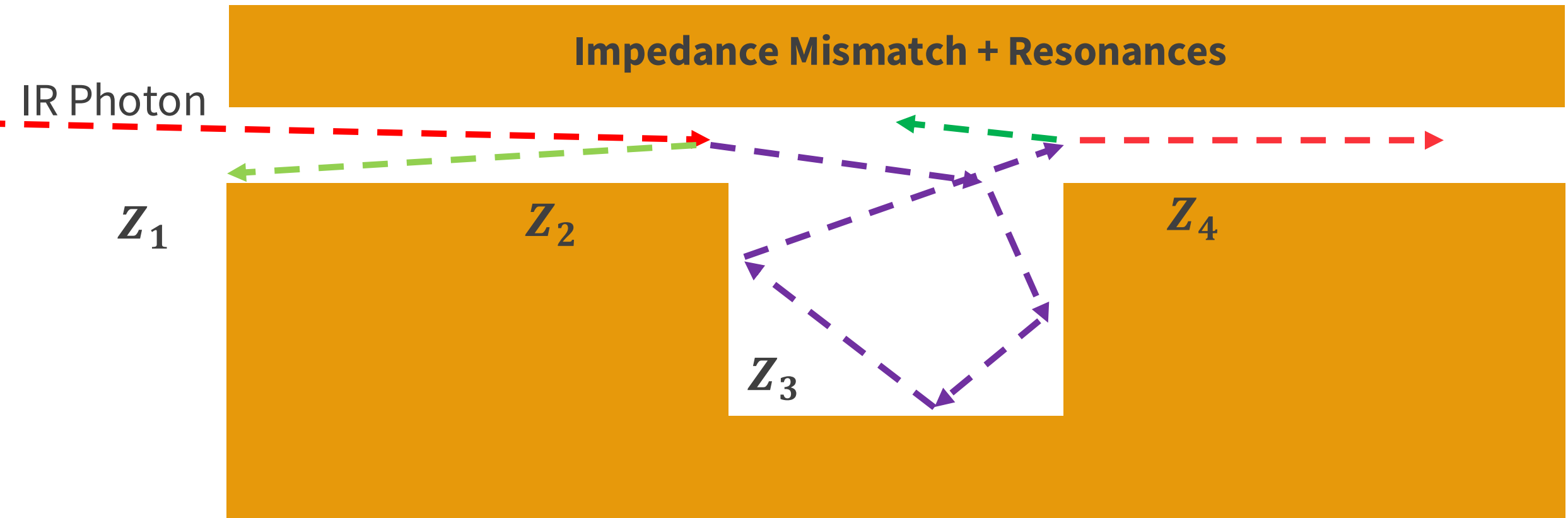


*Generalized Shielding visualization

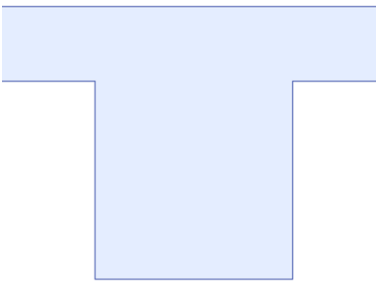
Many of these criteria seem “easy” to achieve but at closer inspection are very challenging or mutually exclusive

Let's look into “Light Tightness”

Stub Filter Basics

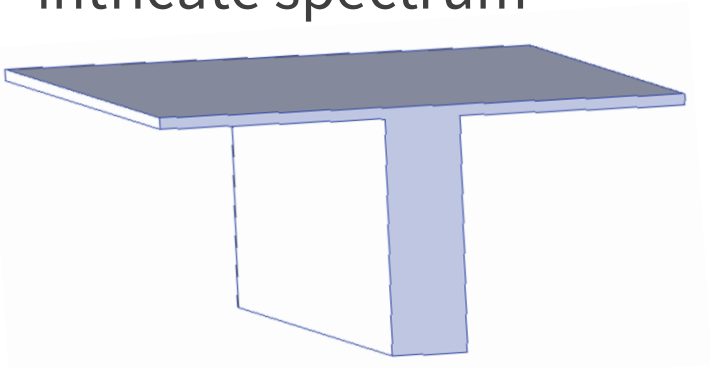


Small (<1mm) and Larger Stubs (>1mm)

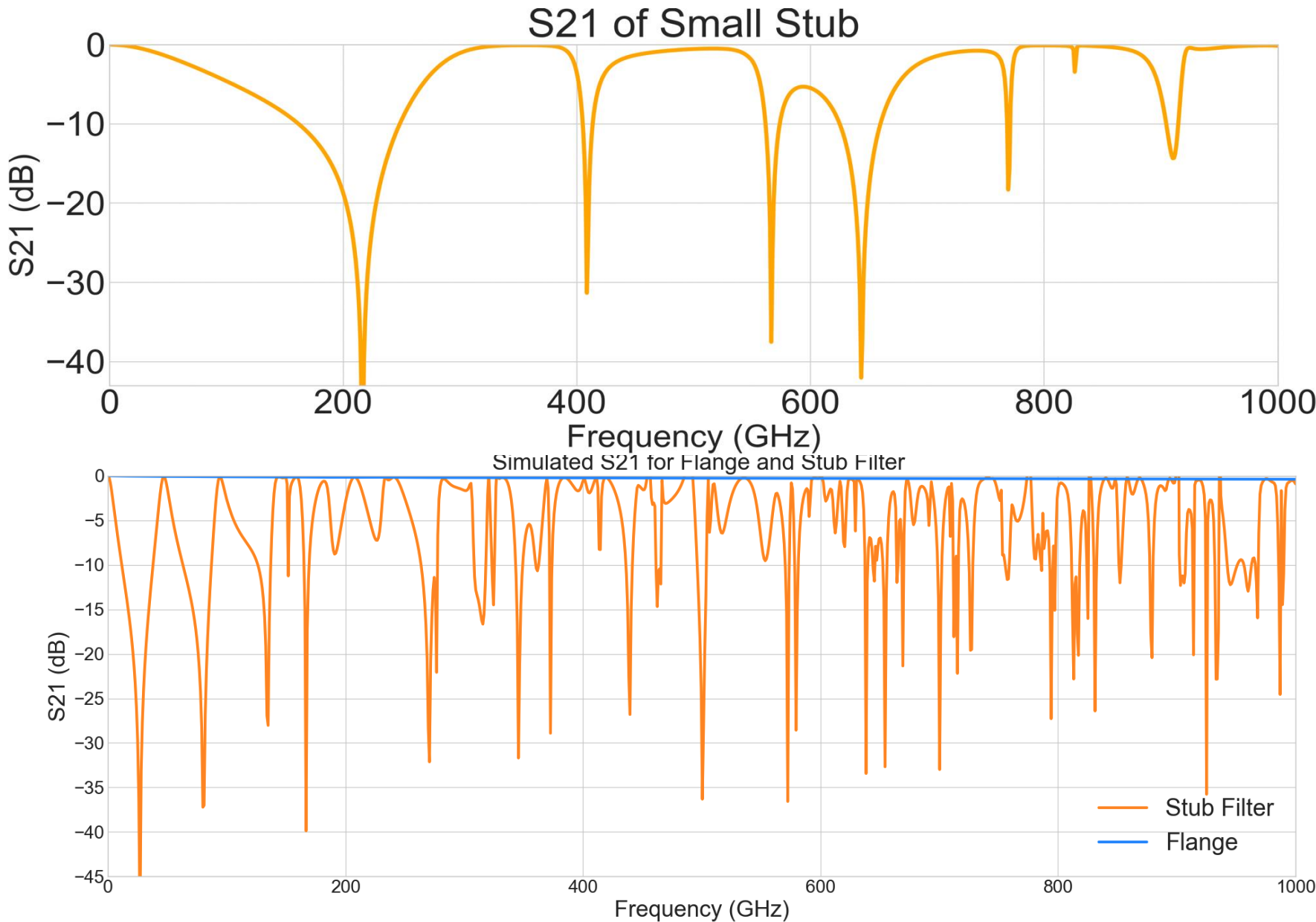


~0.4mm Square Stub

- Larger stubs have a more intricate spectrum

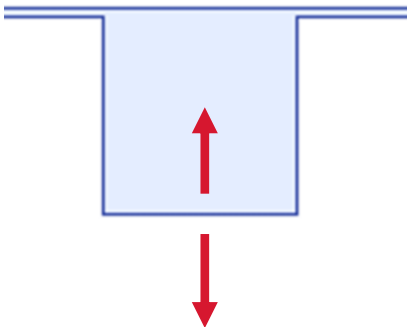
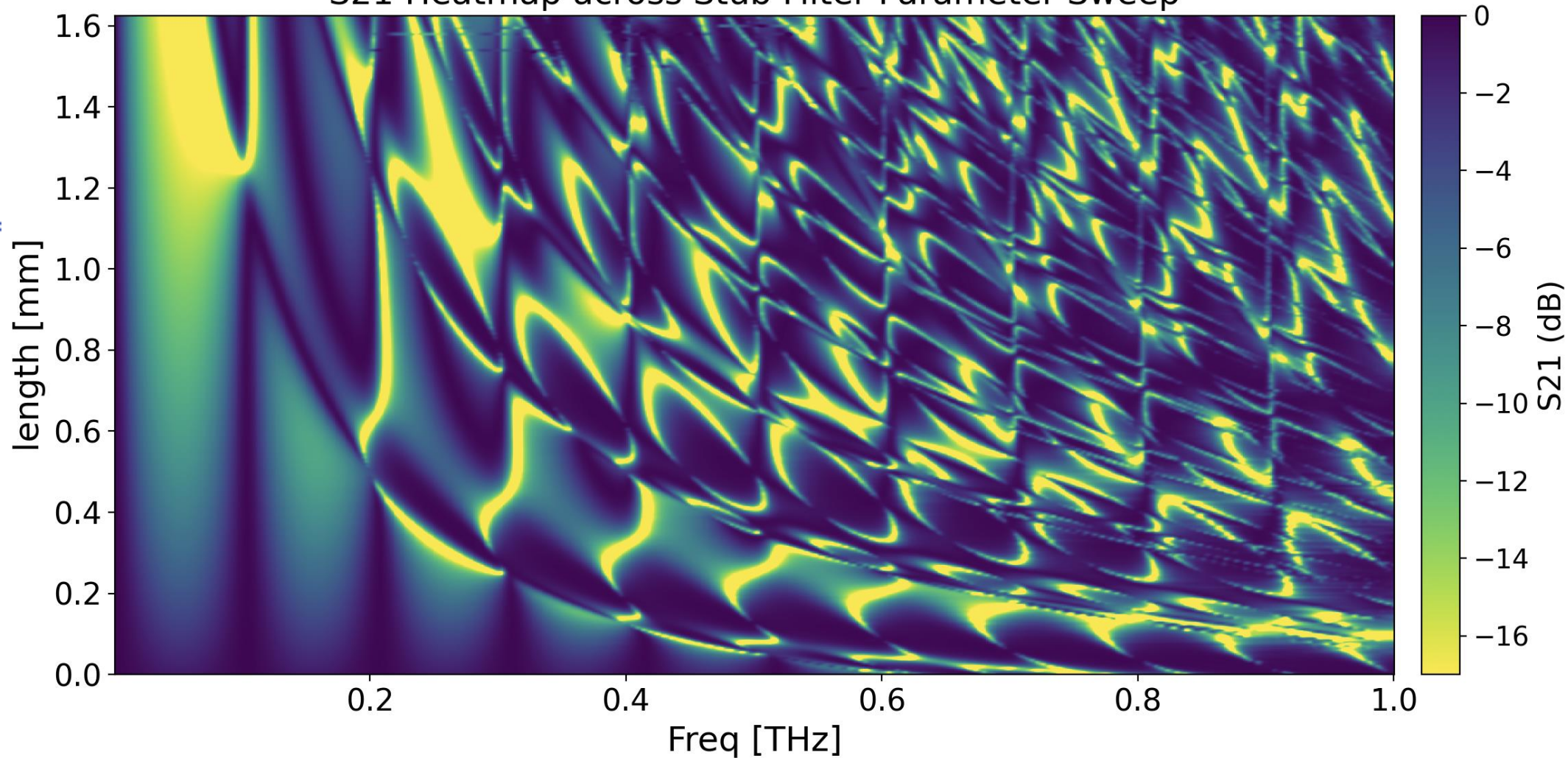


~3.1 x 1 mm Stub

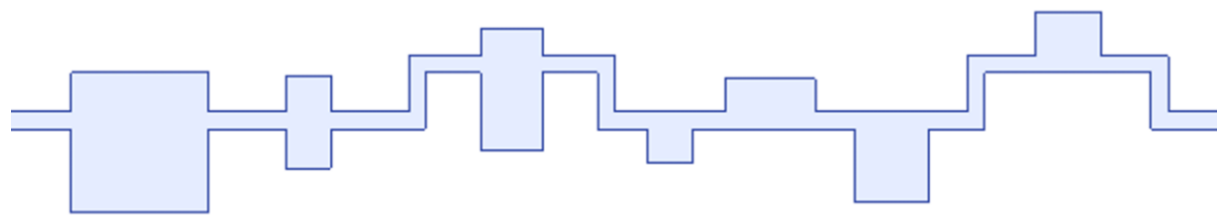


Stub Filter Parameter Space

S21 Heatmap across Stub Filter Parameter Sweep

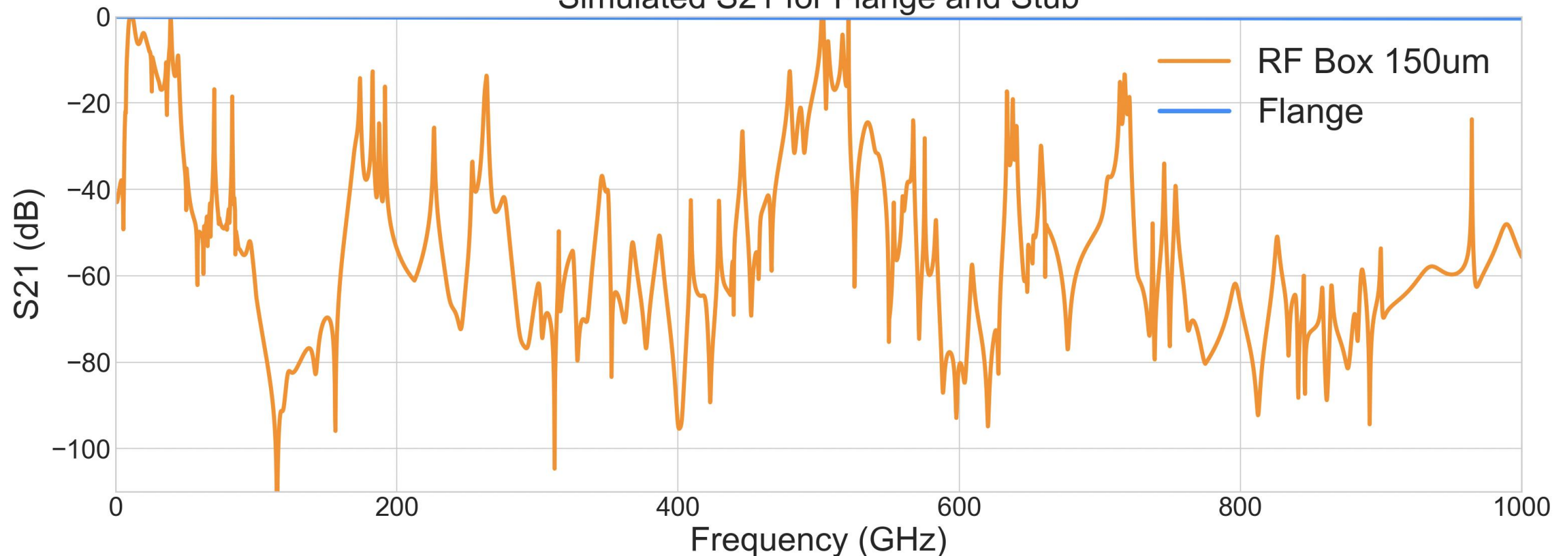


Stub Filter

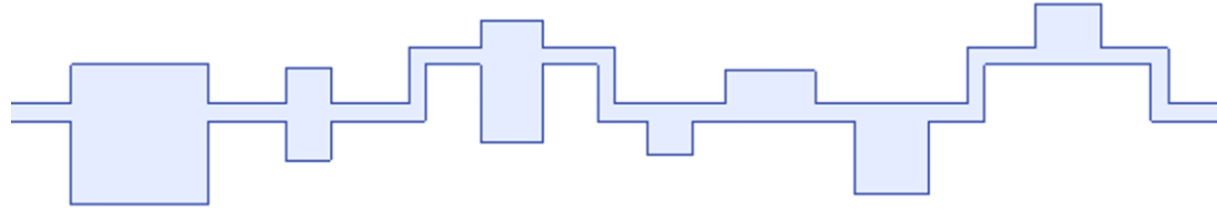


Design made for the RF Box Consortium, Design in Production Currently!

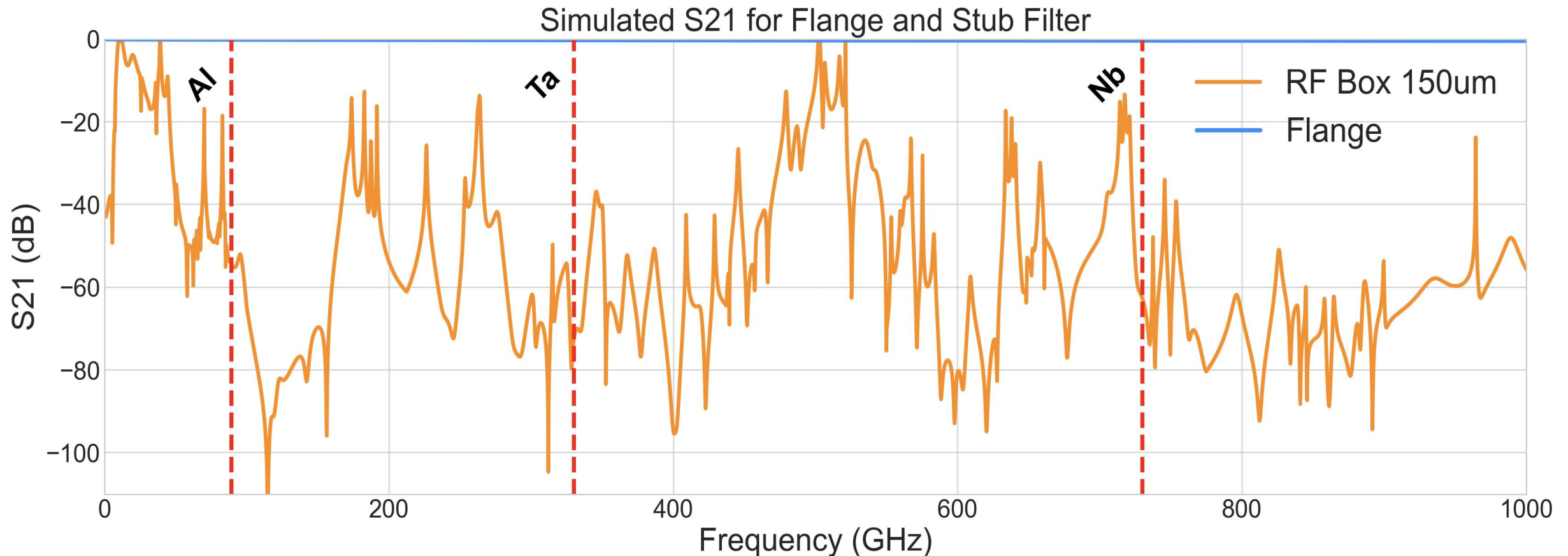
Simulated S21 for Flange and Stub



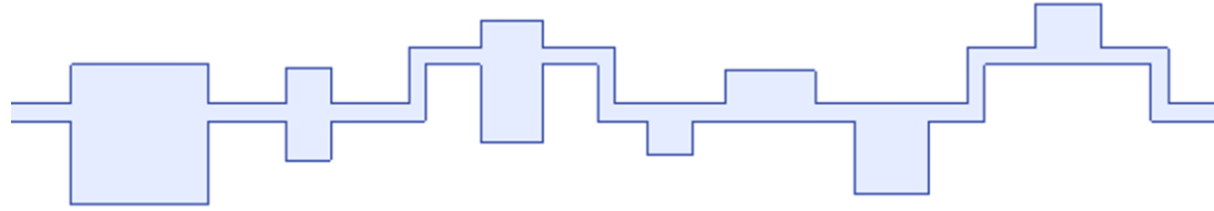
Stub Filter



Design made for the RF Box Consortium, Design in Production Currently!

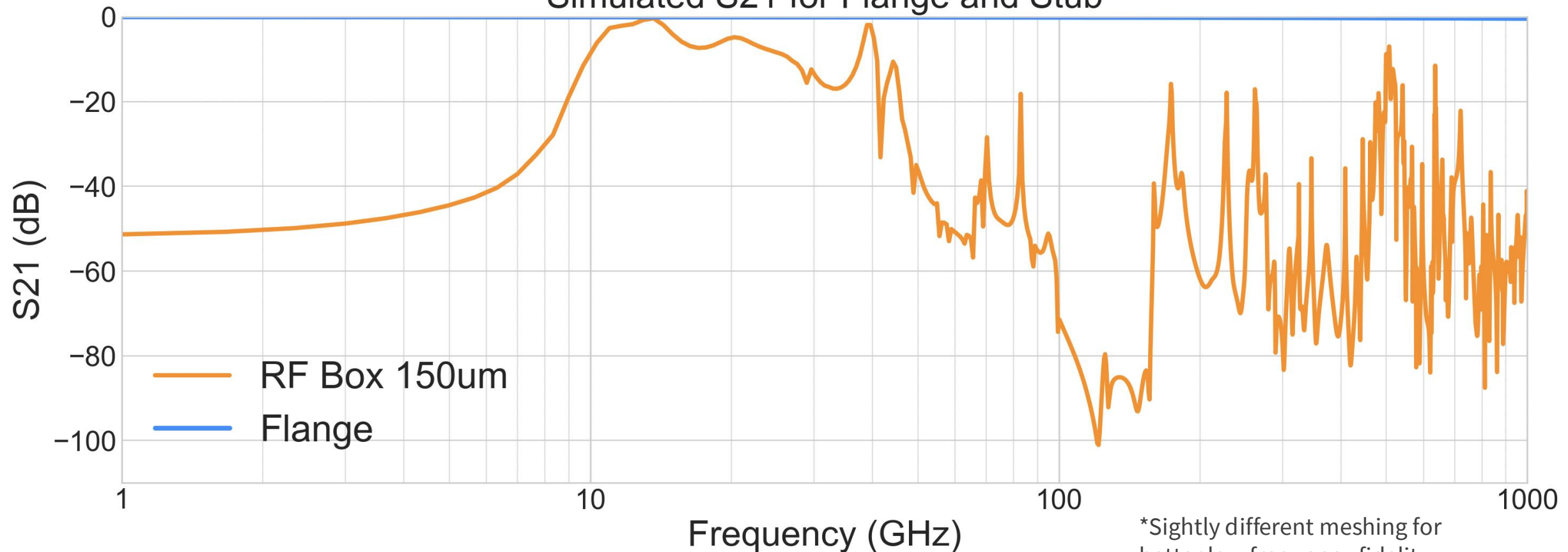


Stub Filter



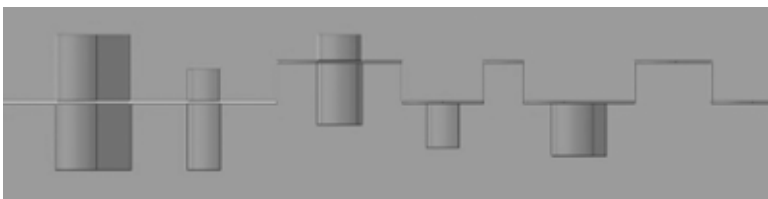
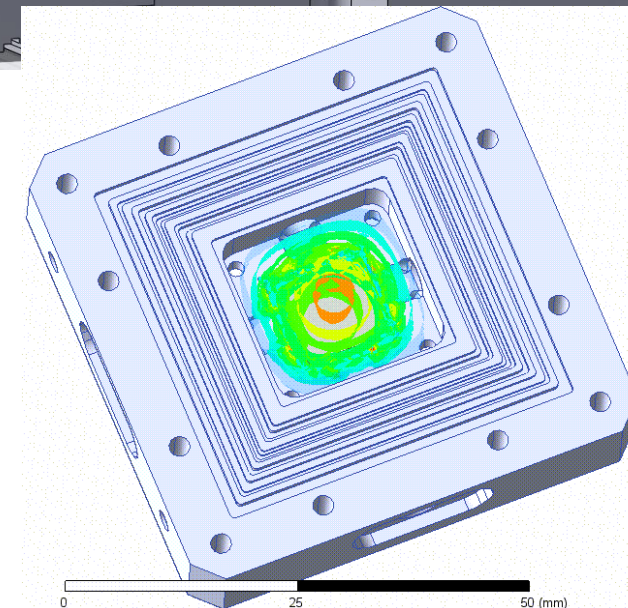
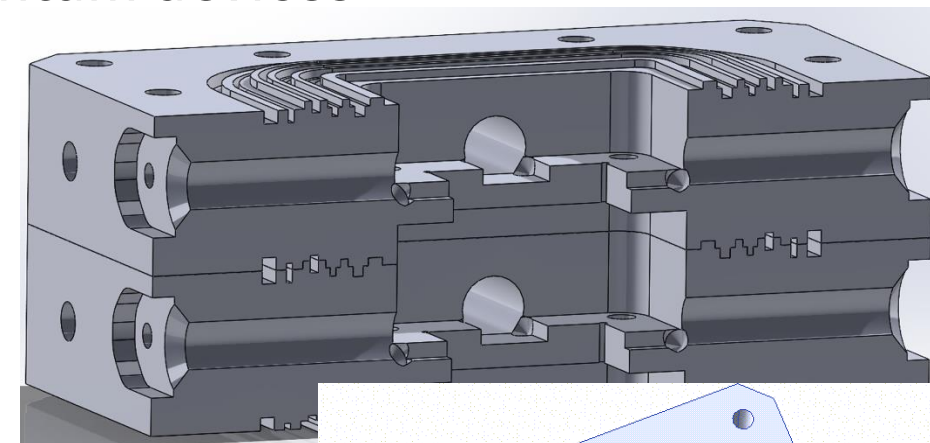
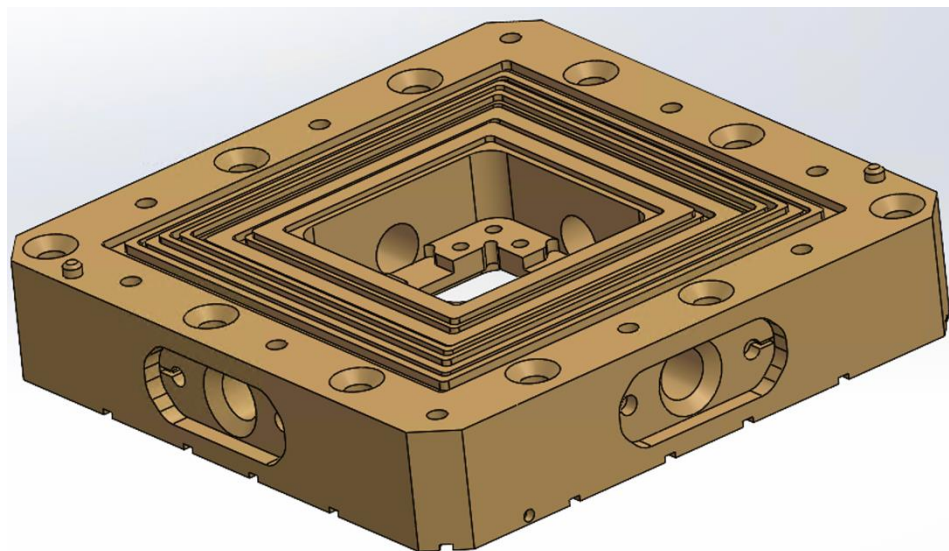
Design made for the RF Box Consortium, Design in Production Currently!

Simulated S21 for Flange and Stub



RF Box Consortium

Through this group we're hoping to create a general device enclosure compatible with TES, Qubits, MKIDs, and other superconducting/quantum devices

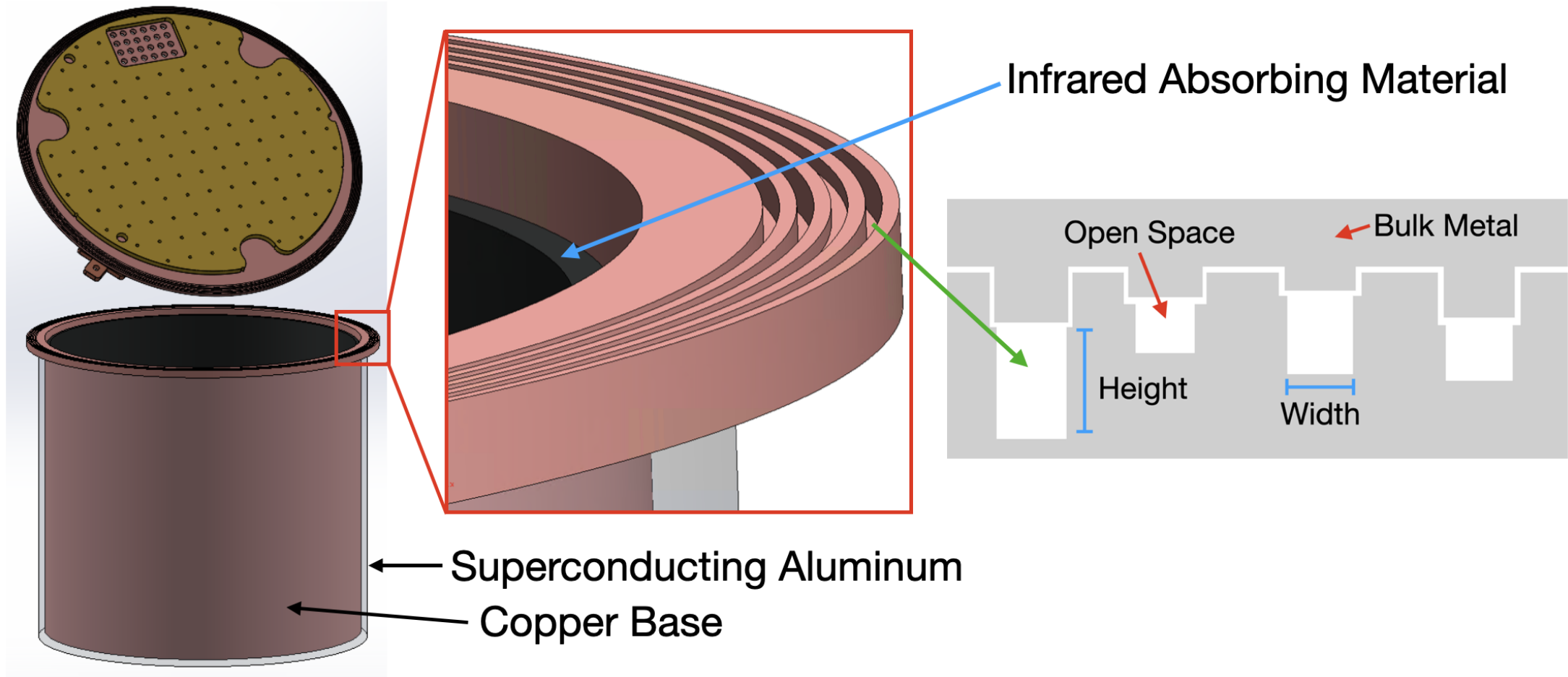


$$g^{(1)}(0) = P_g V_g^2 + P_e V_e^2.$$

$$P_e = \frac{1}{2} - \frac{1}{2\sqrt{1 + 4\bar{g}^{(1)}(0)}}.$$

Stub Implementation

- The scale of these filters is well suited for shielding and device enclosure
- These filters can be retrofitted into an existing shield



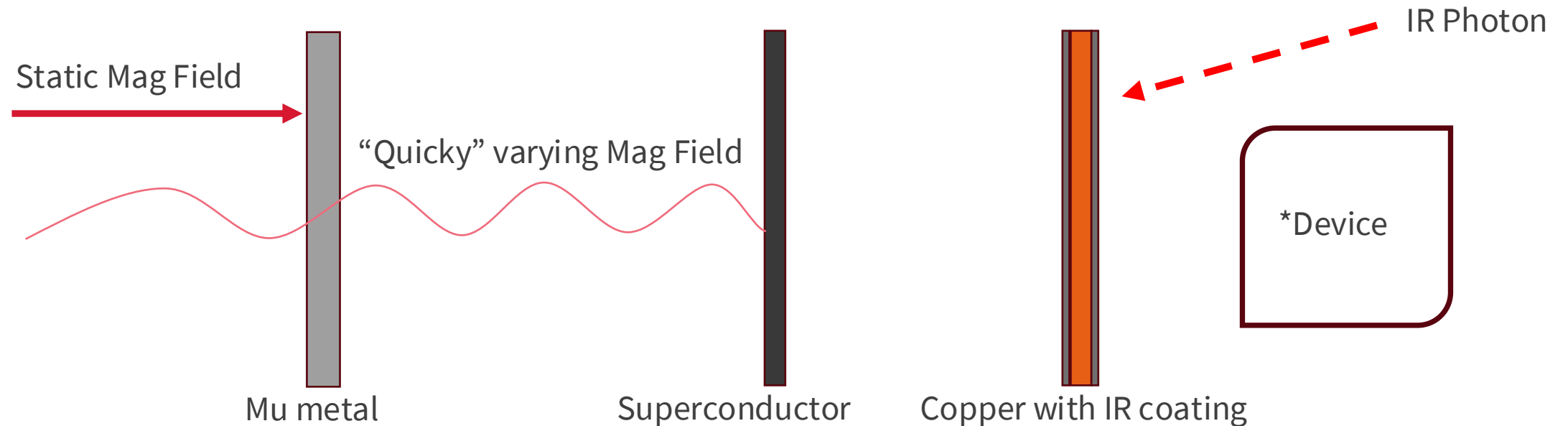
Optimal Shielding

Ideal shielding will generally follow the structure of:

Mu metal -> Superconducting -> IR shield

See 2505.14274 for details

1. Mu metal is fantastic at redirecting static magnetic fields
2. Superconductors are good for more dynamic magnetic fields
3. IR shield Absorbs and thermalized IR radiation

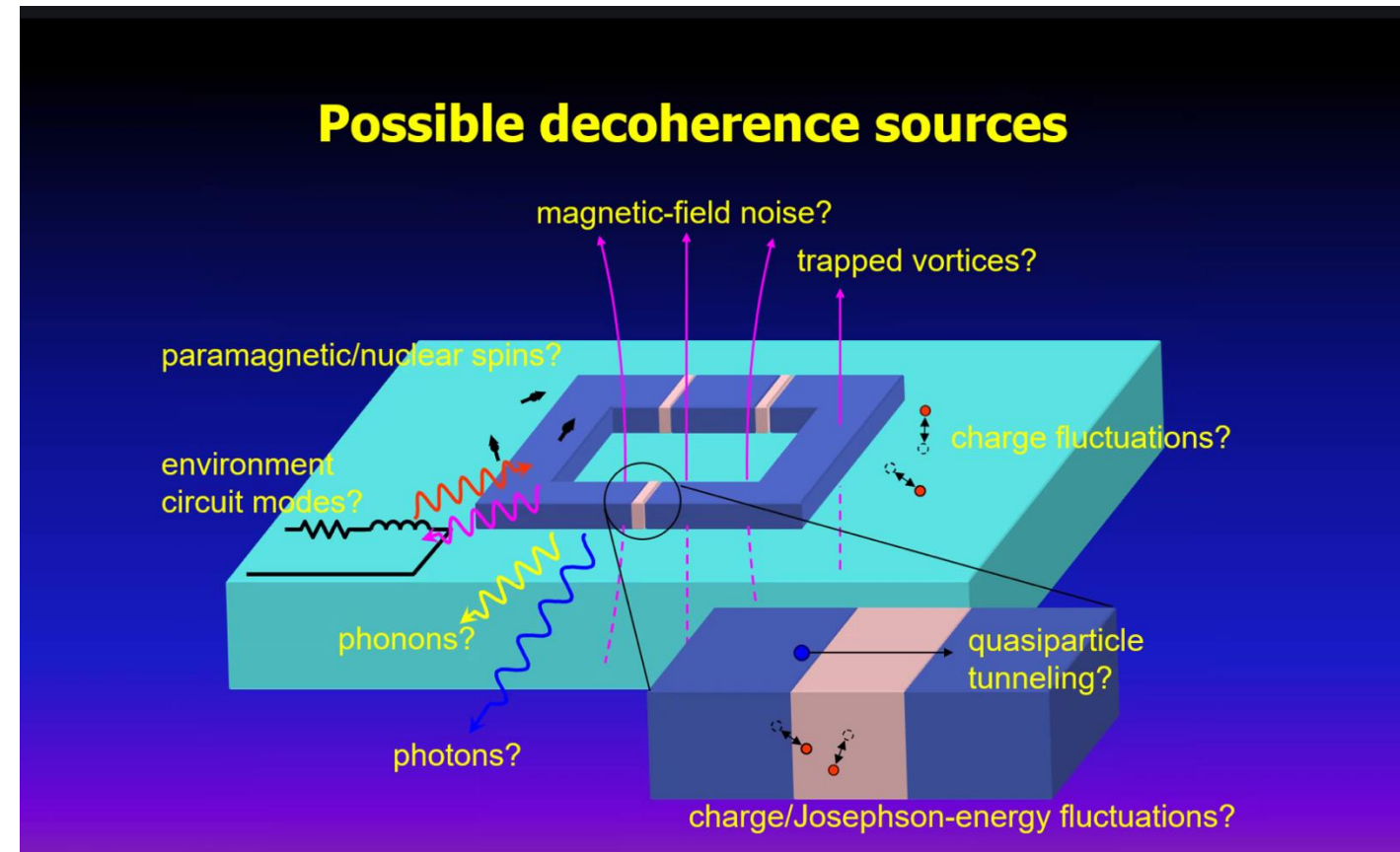


Environmental Background Sources

Problematic Backgrounds:

- Temperature Fluctuations
- Gamma Rays
- Cosmic Rays
- Vibrations
- B(H) – Fields
- IR Photons

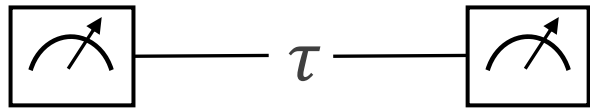
+And many more!



Schematic from Yasunobu Nakamura's Talk
University of Tokyo, RIKEN

Correlation Method

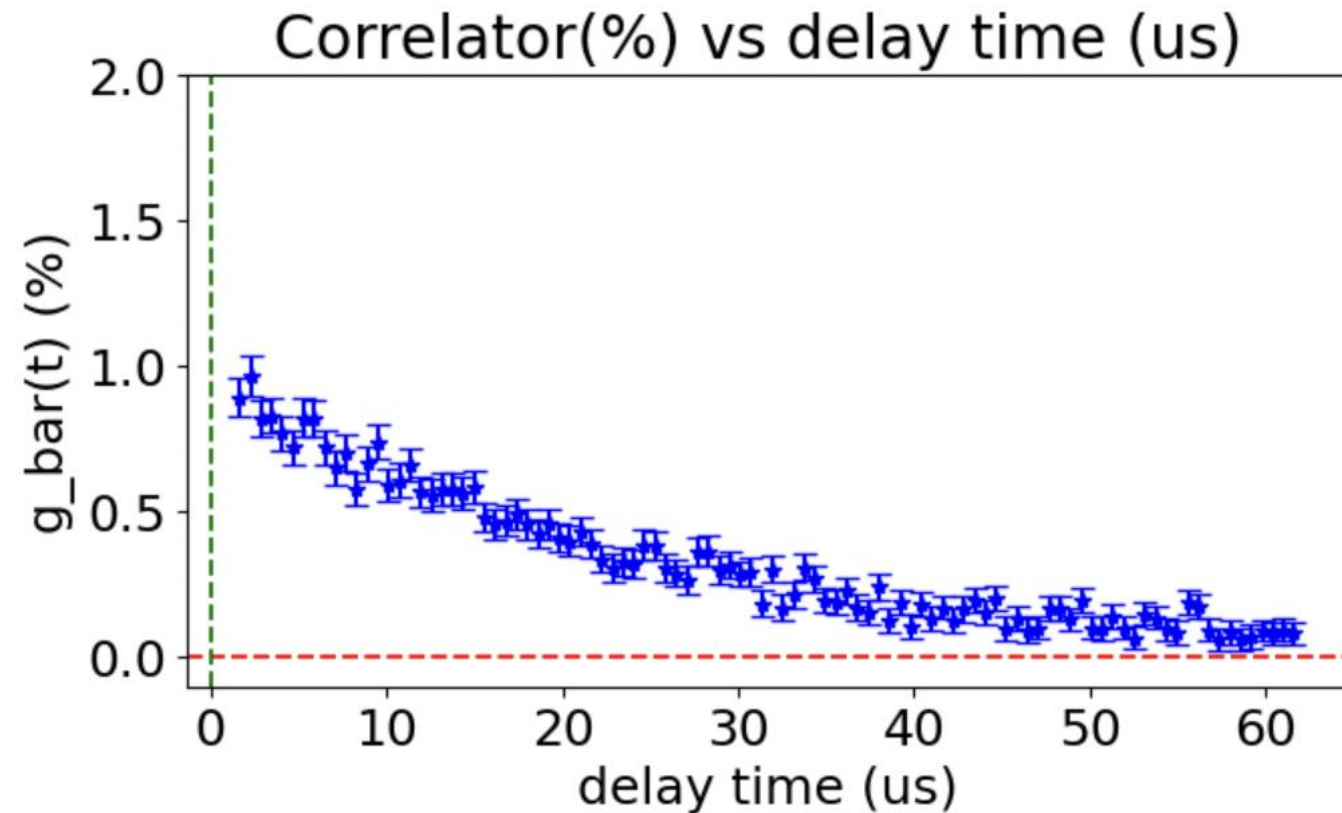
The Correlation Method uses correlated QND of the ground state



A correlation function is then constructed allowing the excited state population to be extracted

$$P_e = \frac{1}{2} - \frac{1}{2\sqrt{1 + 4\bar{g}^{(1)}(0)}}$$

Derivation show in: <https://arxiv.org/pdf/2001.00323>



Qubit T1: ~20 μs