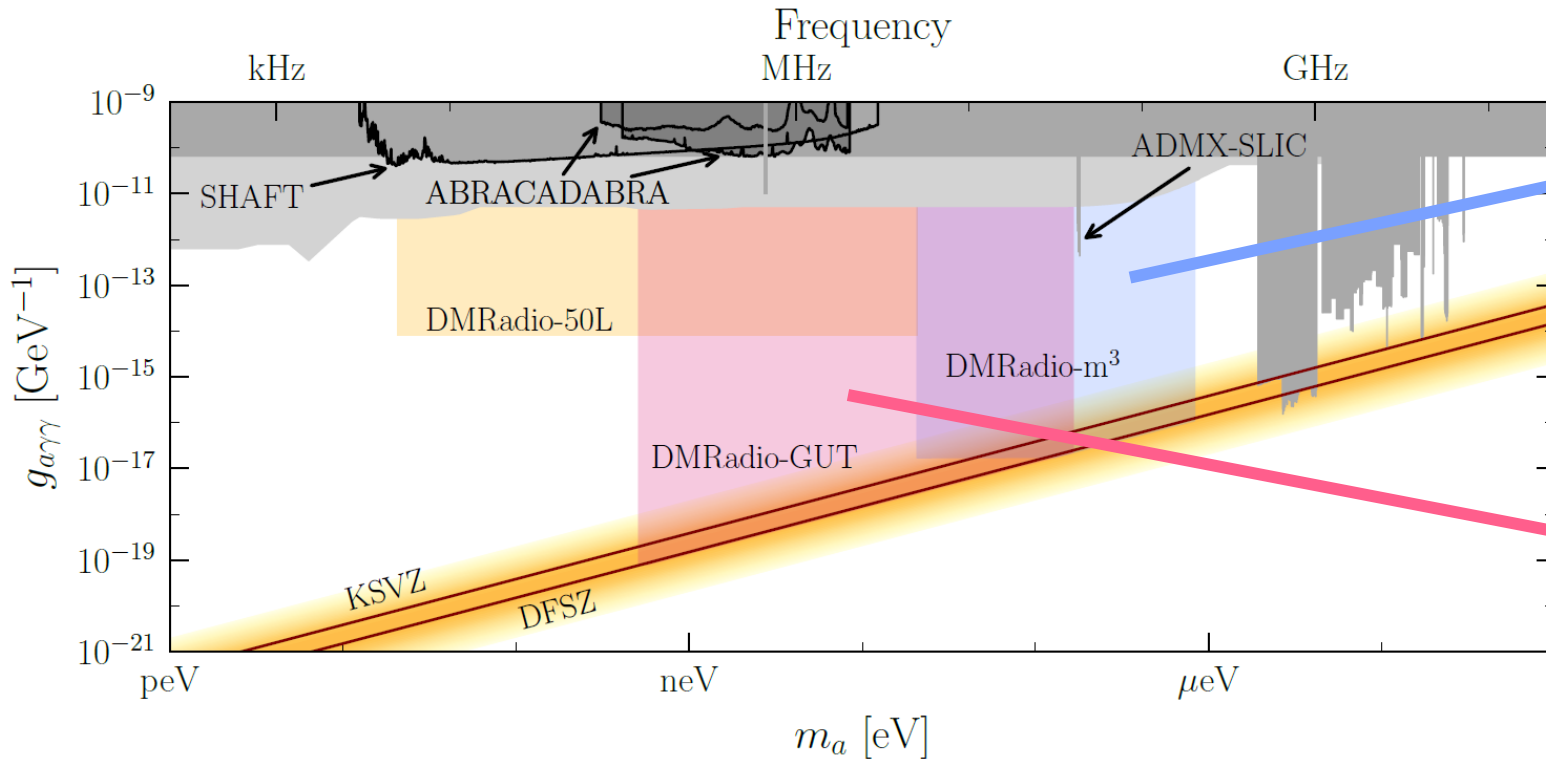


# Quantum Sensing for DMRadio Axion Searches

Elizabeth Cady van Assendelft  
DMRadio Collaboration

# DMRadio suite of experiments



DC SQUIDS are “standard” readout technology and will be used in DMRadio-M3.

For DMRadio-GUT, quantum enhancement necessary to meet science goals.

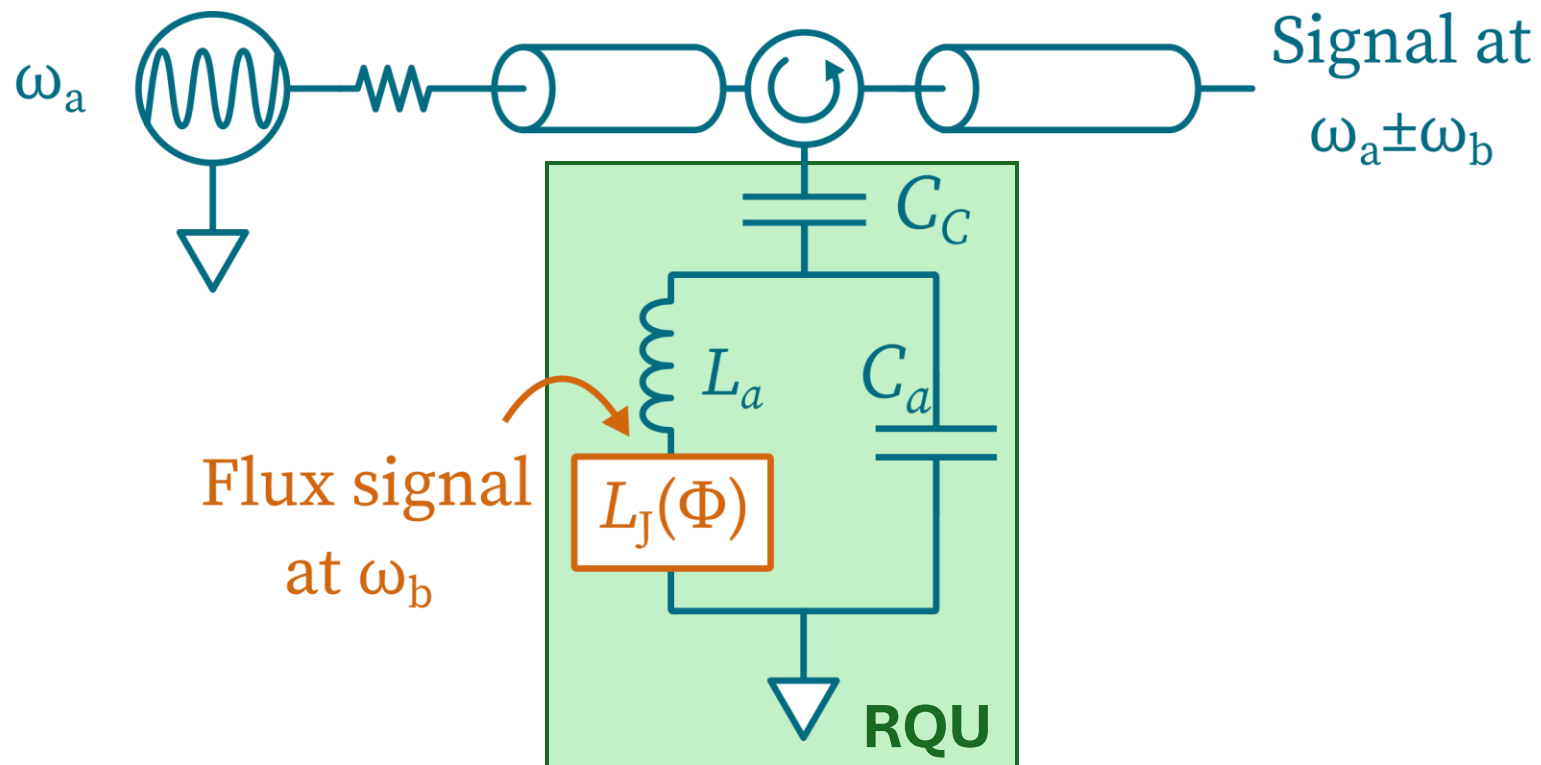
- Axion wavelength  $\gg$  detector size: **lumped element regime**.
- Requires “Op-amp” voltage-state measurements, instead of “Scattering mode” power measurements.
- Large thermal occupation even at cryogenic temperatures.

# Radio-frequency Quantum Upconverter (RQU)

- Continuous-variables quantum sensor to measure axion-induced signals in electromagnetic resonators.
- Phase-preserving measurements (measuring both quadratures) can reach the Standard Quantum Limit (SQL).
  - Dramatically better sensitivity than is possible with existing dc SQUIDs.
- Single-quadrature measurement can perform better than SQL using quantum backaction-evasion (BAE) protocols.

# RQU circuit model

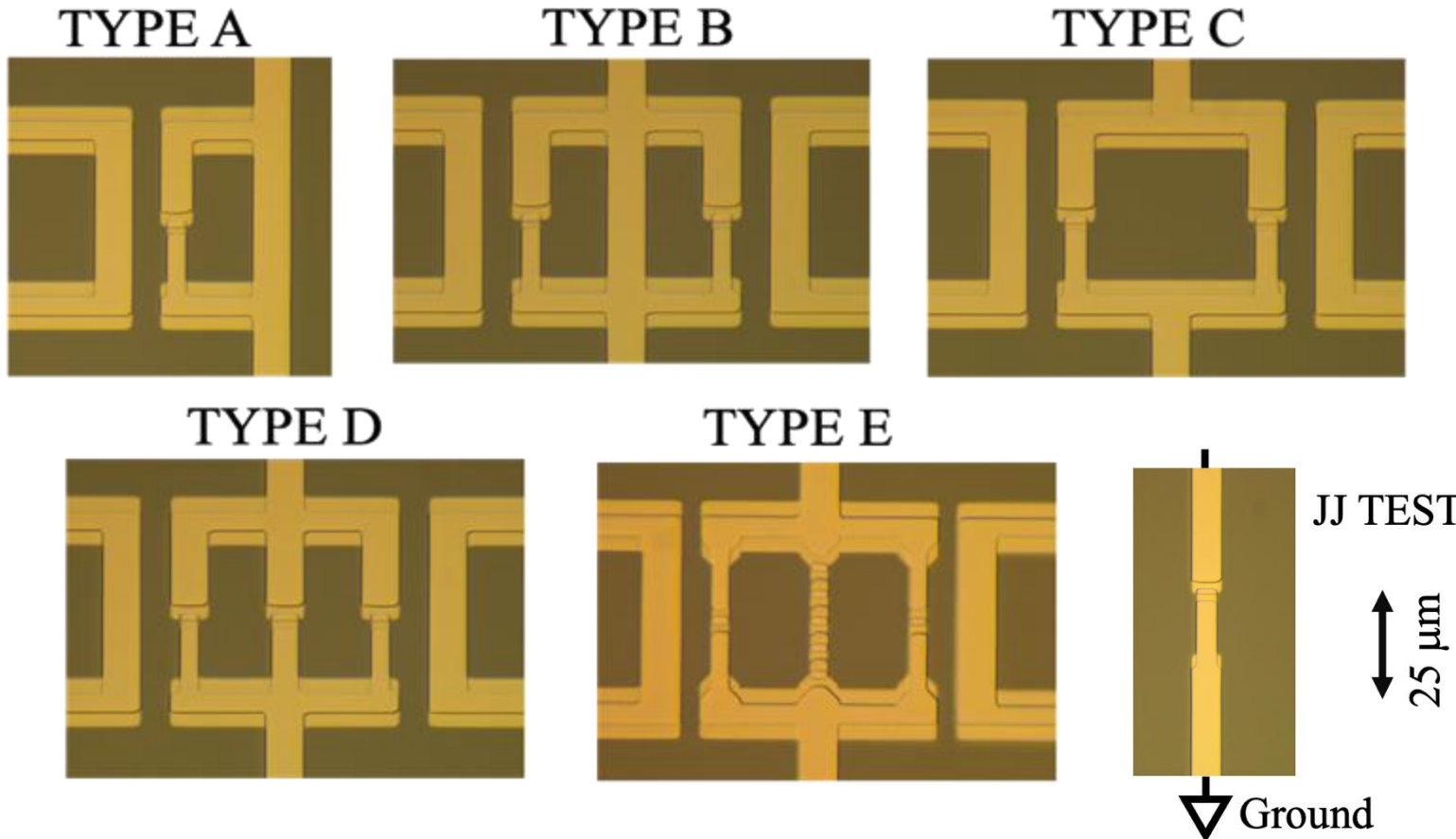
- Tunable inductance modifies electrical length of GHz resonator.
- Analogous to optomechanics– three-wave mixing upconverts signal mode to sidebands around microwave drive tone.



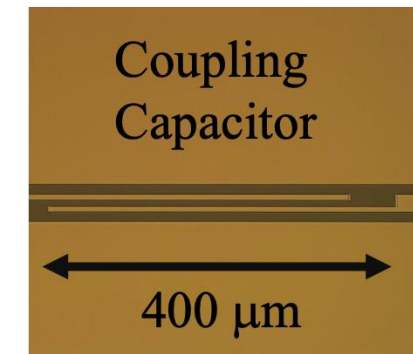
# Aluminum RQU fabrication

- Fab process is fast and flexible, enabling a range of designs.

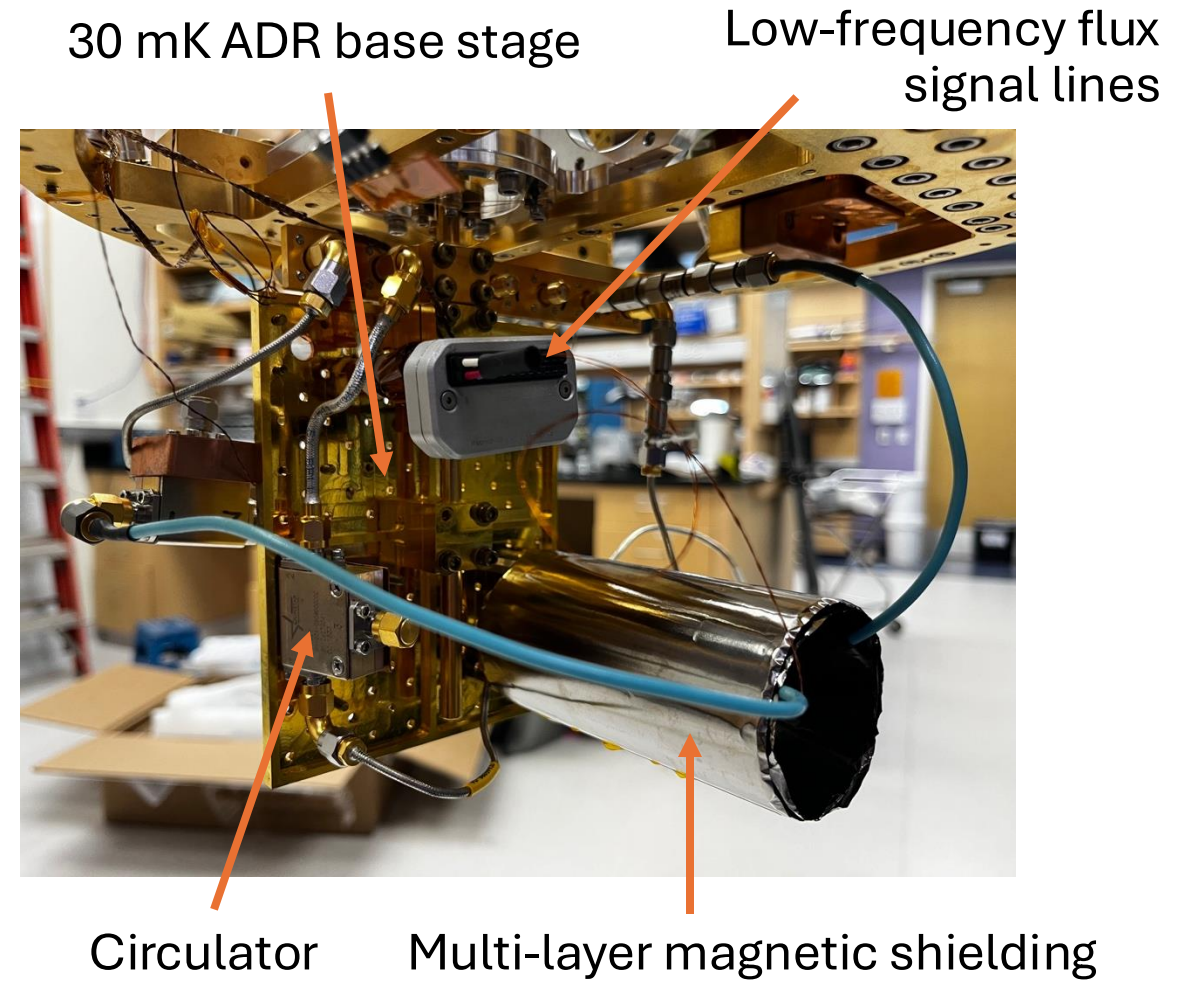
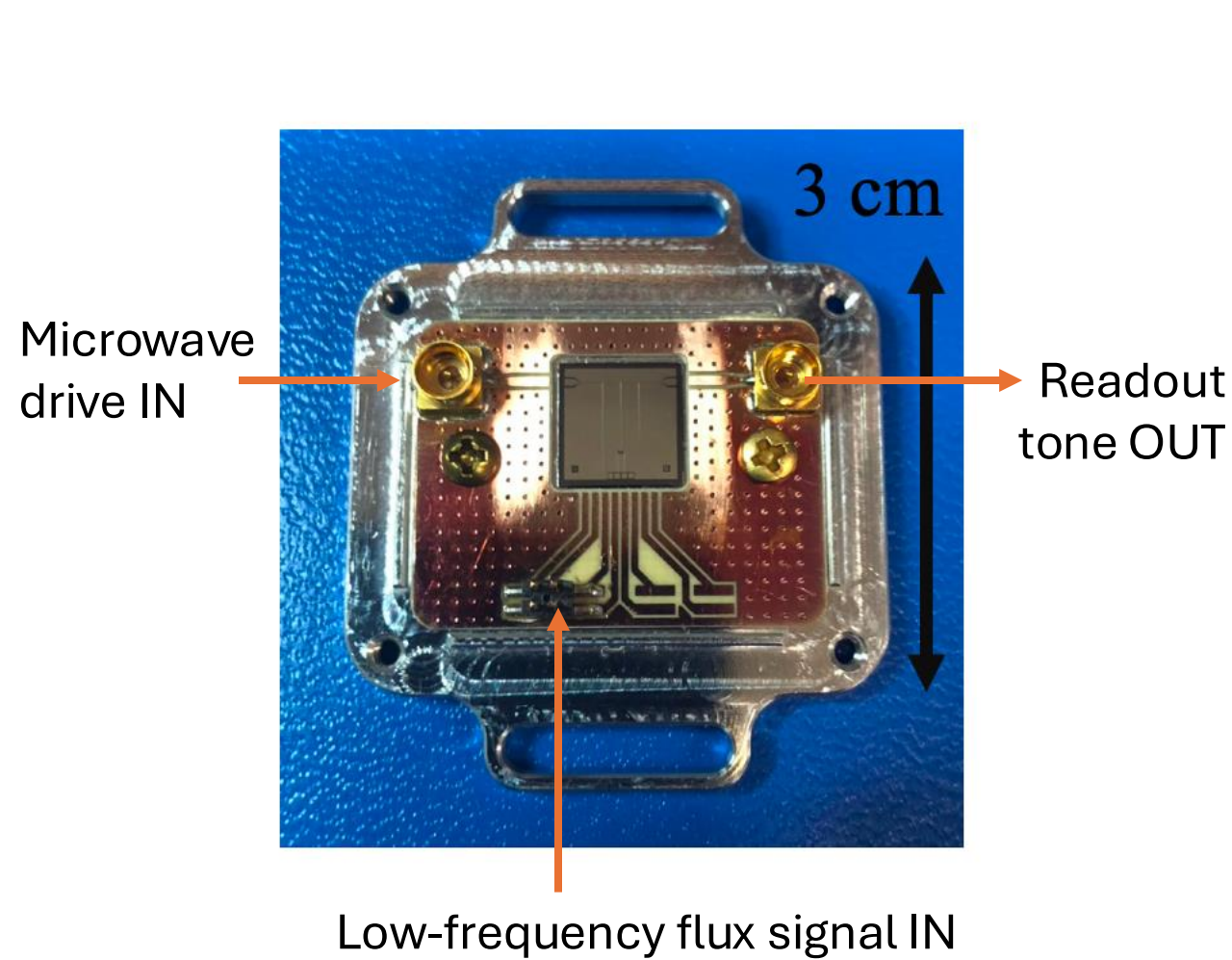
## Tunable inductance designs



## Microwave components

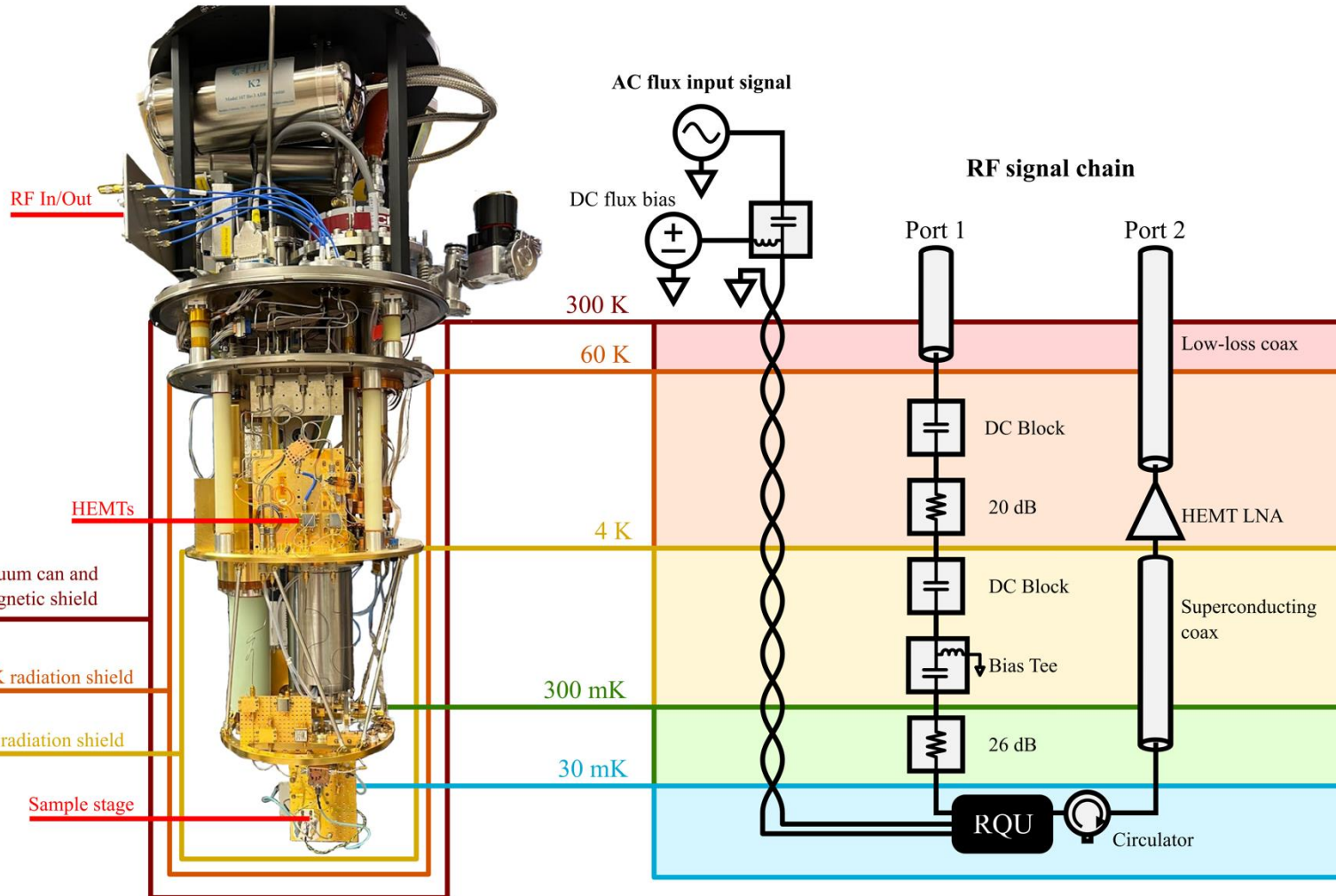


# Packaging and test setup



# Readout chain

HPD He-3 backed  
Adiabatic Demagnetization Refrigerator



E. C. van Assendelft

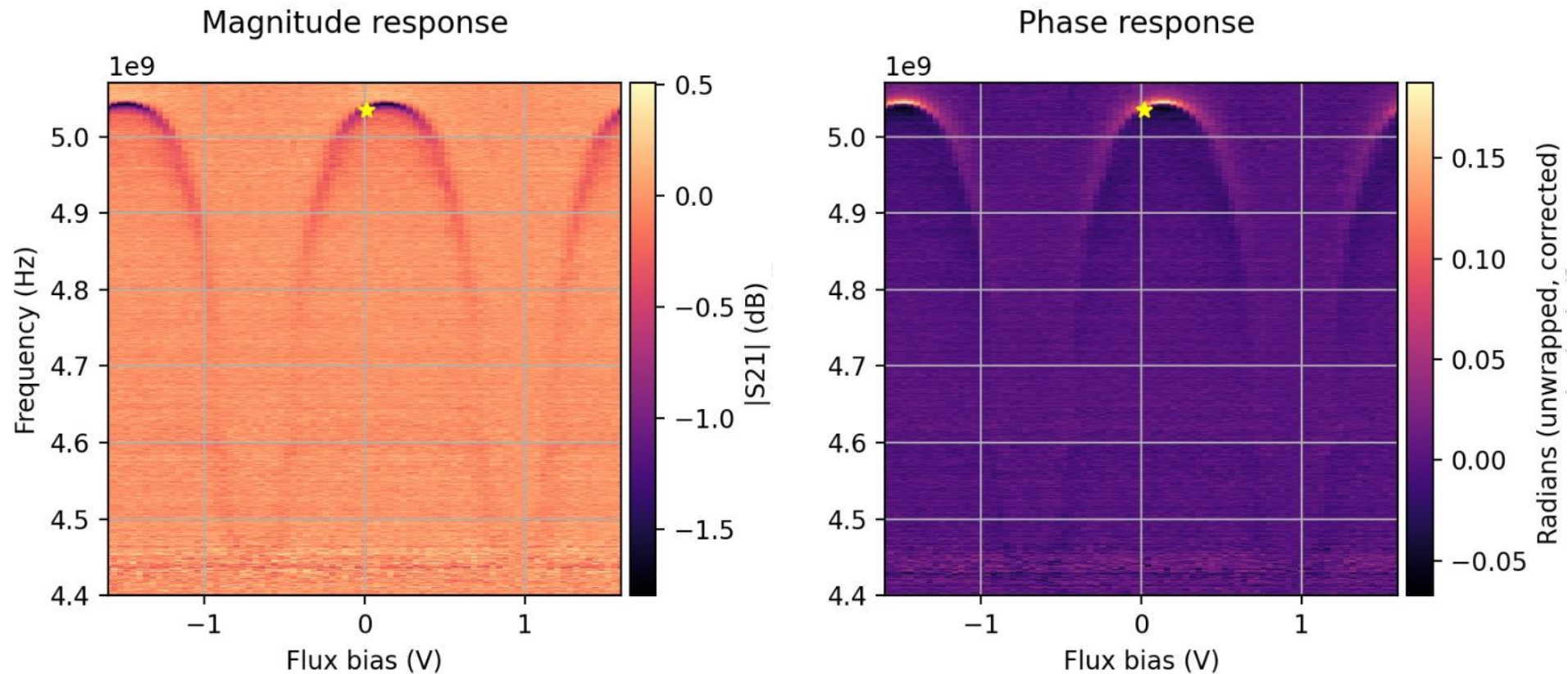
3EOr1A-04

- Room-temperature microwave chain configurable based on desired measurement

Port 1	Port 2
VNA Port 1	VNA Port 2
Signal Generator	Spectrum Analyzer
Signal generator	Homodyne down-mix and digitizer
Lock-in amplifier output	Lock-in amplifier input

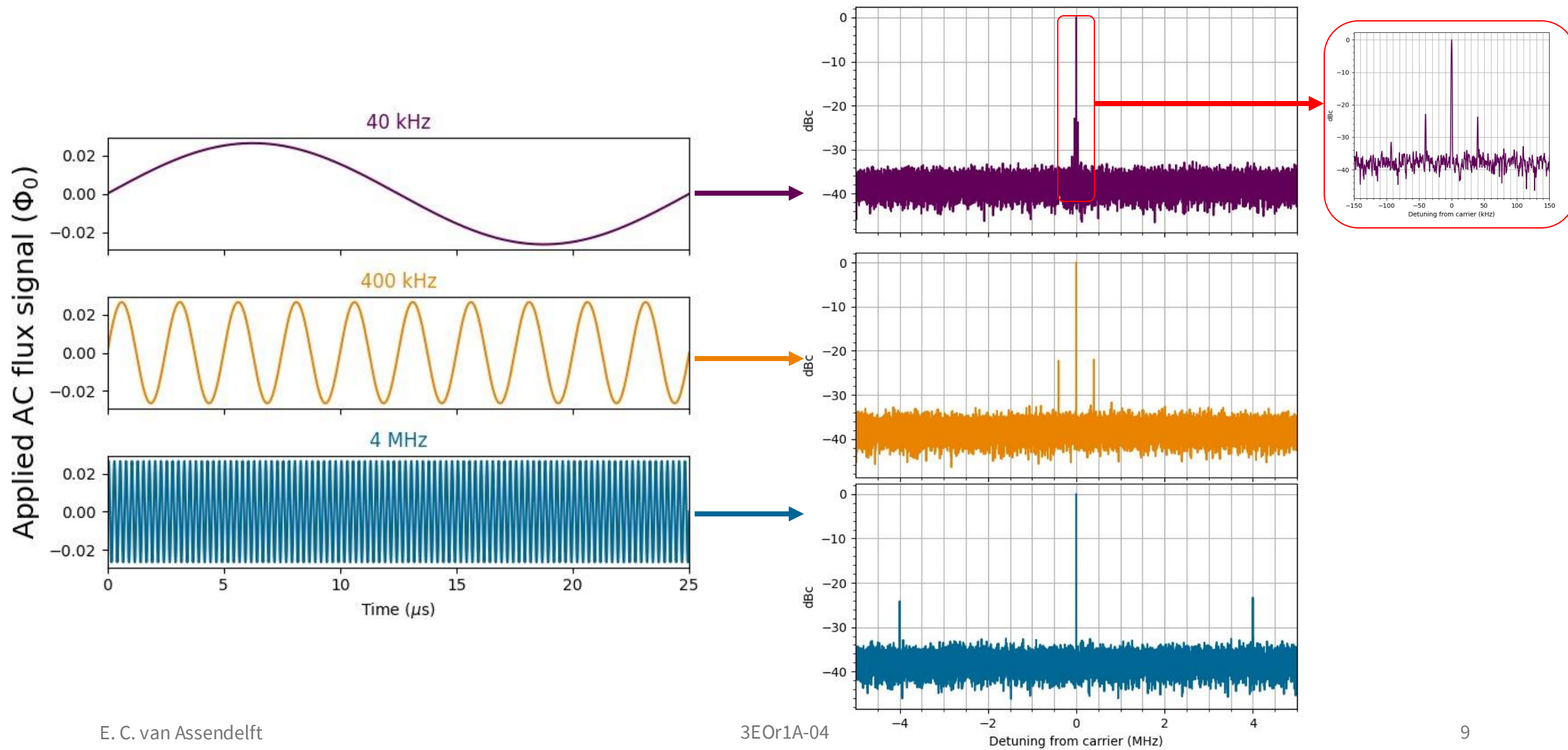
# RQU resonance and operating point

- Type D (3JJ) devices show tuning of  $\sim 600\text{MHz}$  with applied DC flux.
- Microwave resonator centered in 4.5-5GHz, in C-Band frequency.

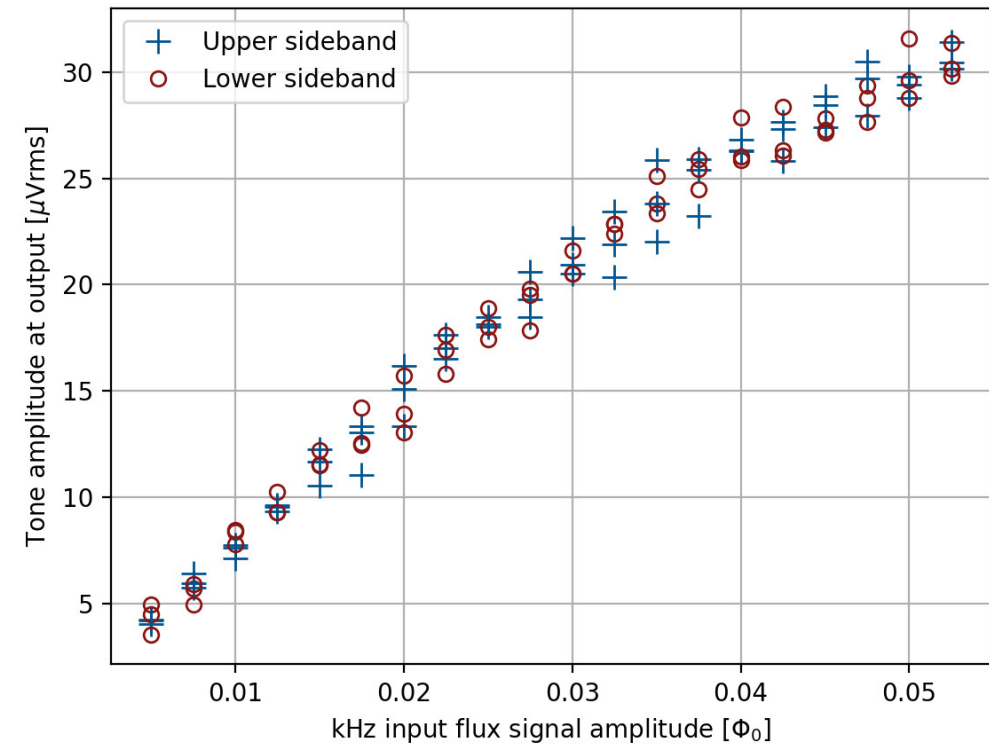
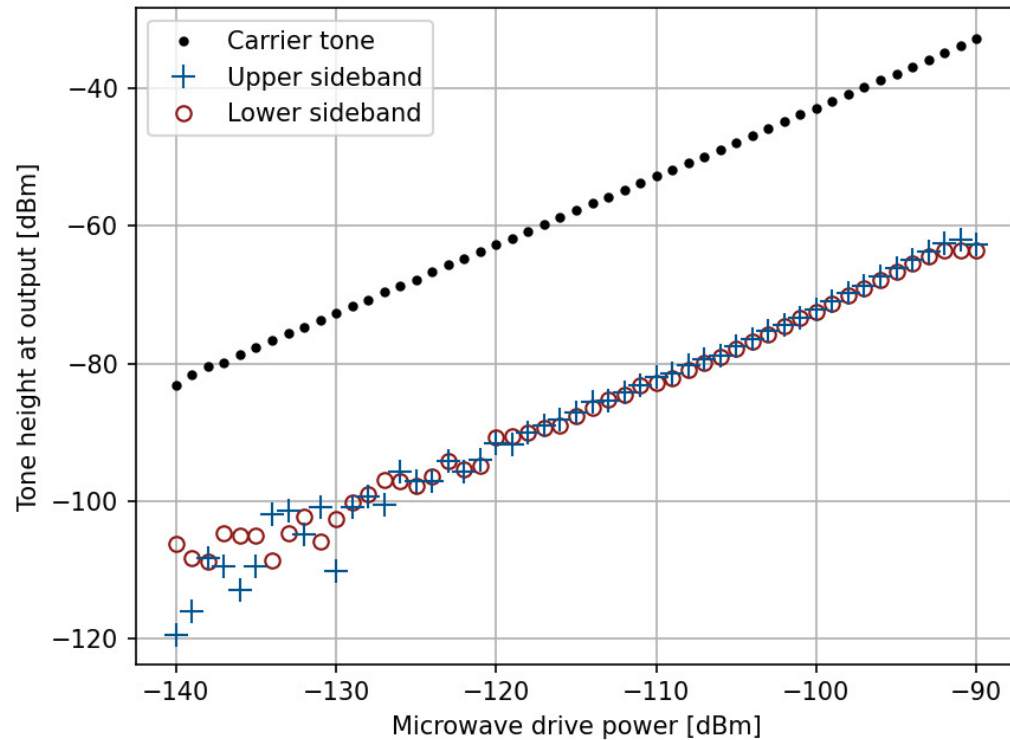




# Frequency upconversion across relevant DMRadio range



# Demonstration of device responsivity

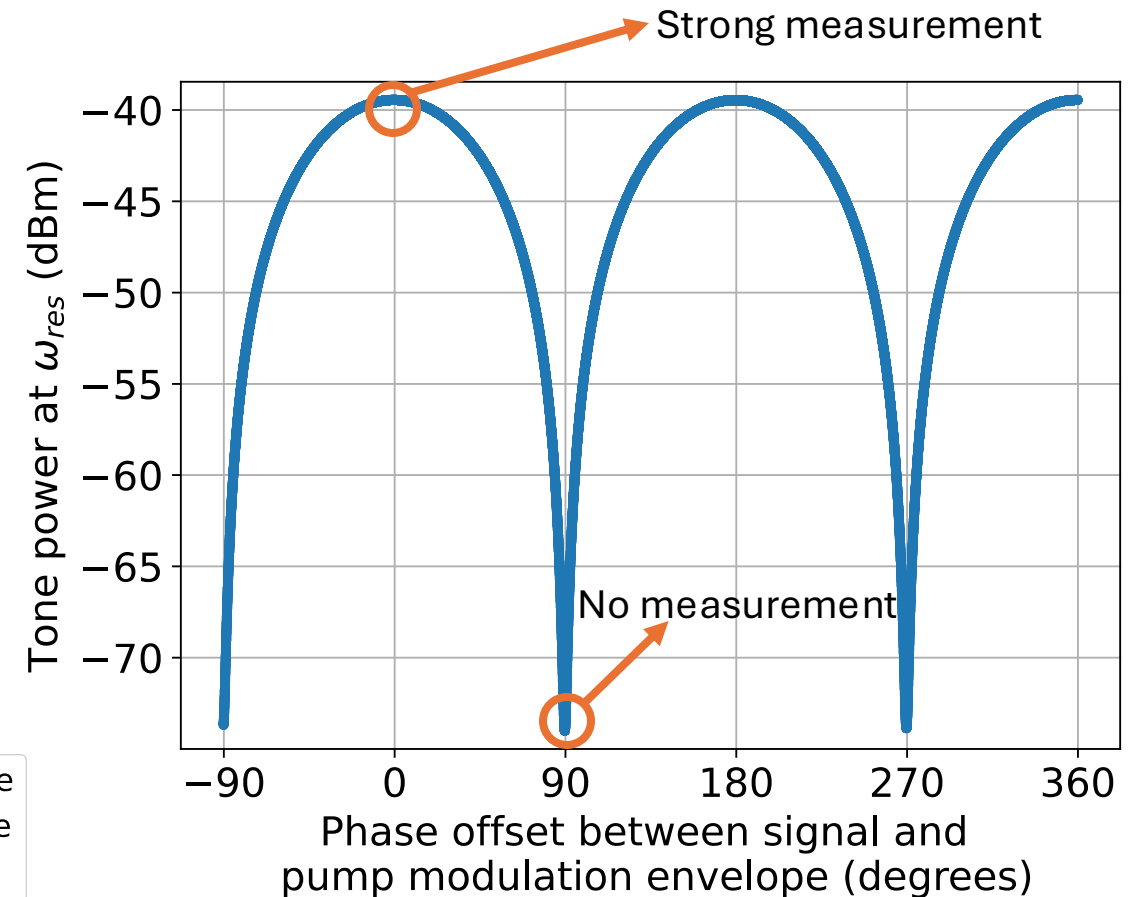
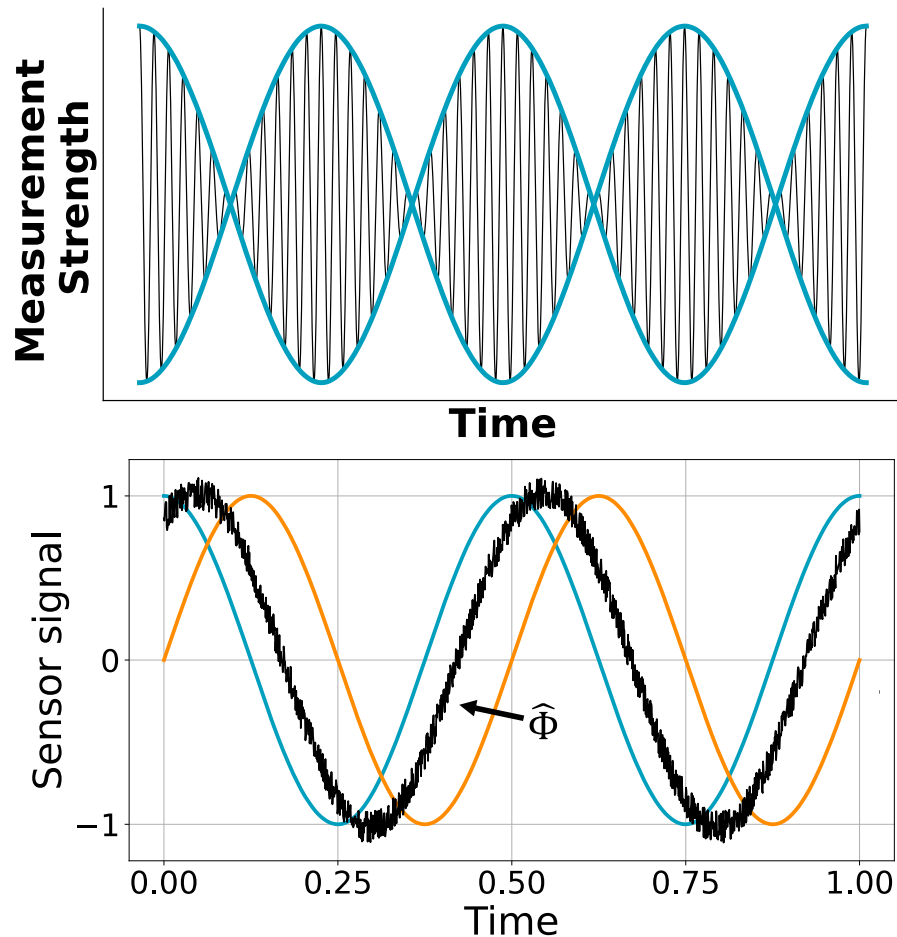


- Measurement strength of input signals depends on device bias parameters and microwave drive power.

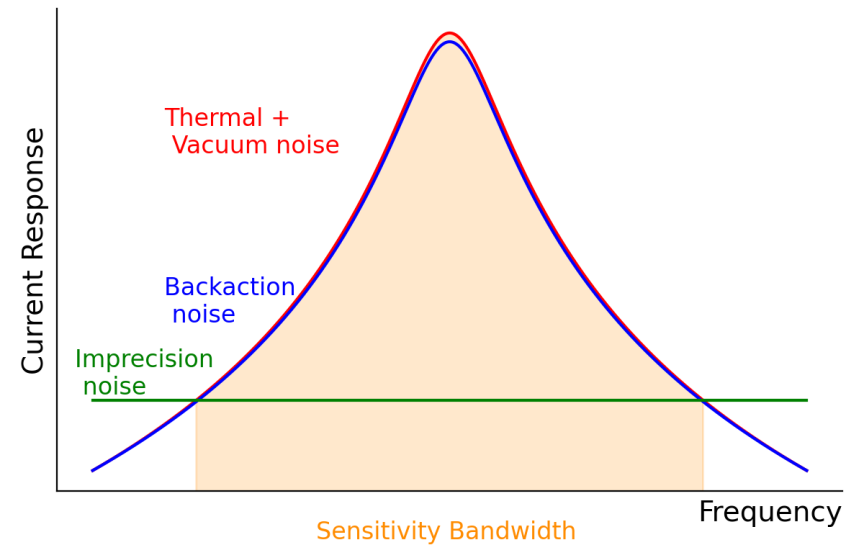
- RQU operates as an op-amp mode linear amplifier of input flux signals.

# Demonstration of phase-sensitive gain

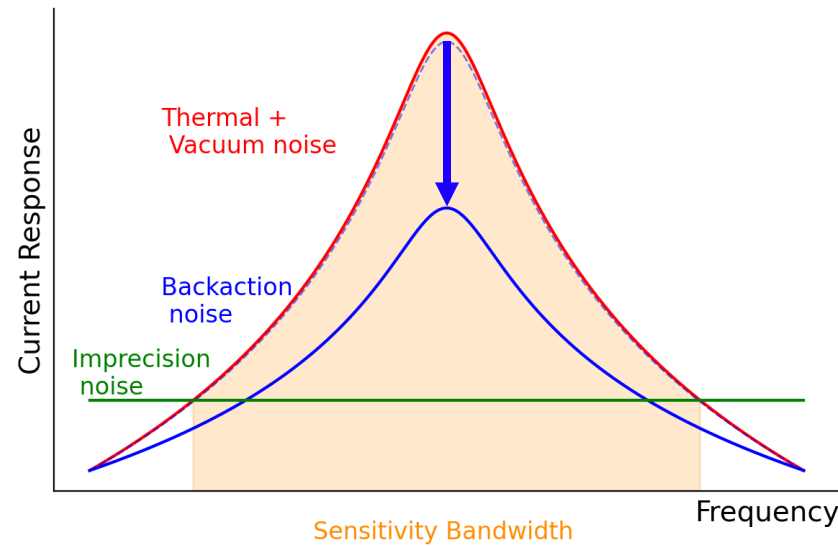
- An amplitude-modulated readout with an envelope that matches the MHz flux signal selectively amplifies one quadrature.



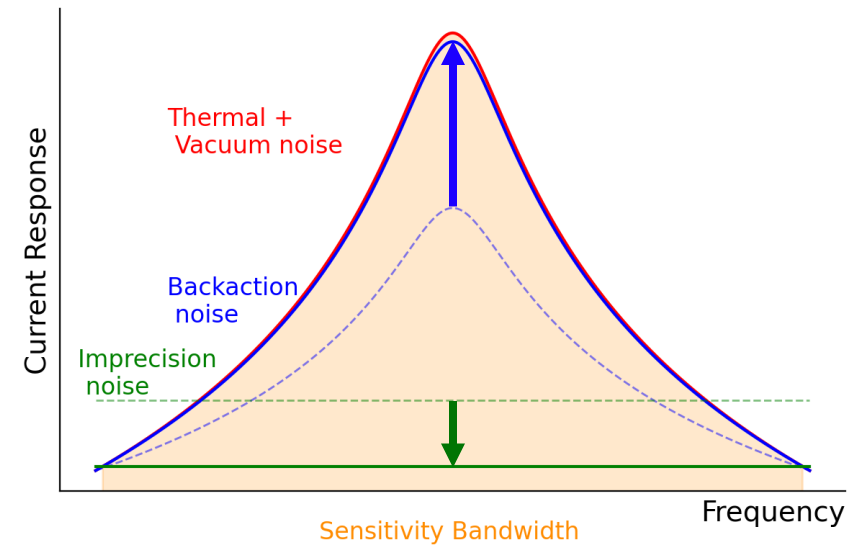
# Axion scan rate improvement from quantum BAE protocols



Without BAE, sensitivity bandwidth is limited by Standard Quantum Limit.



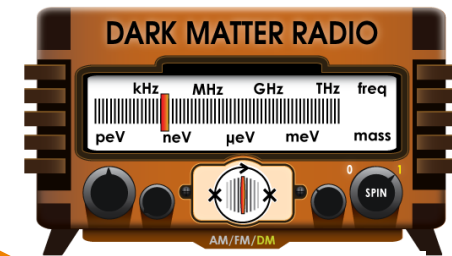
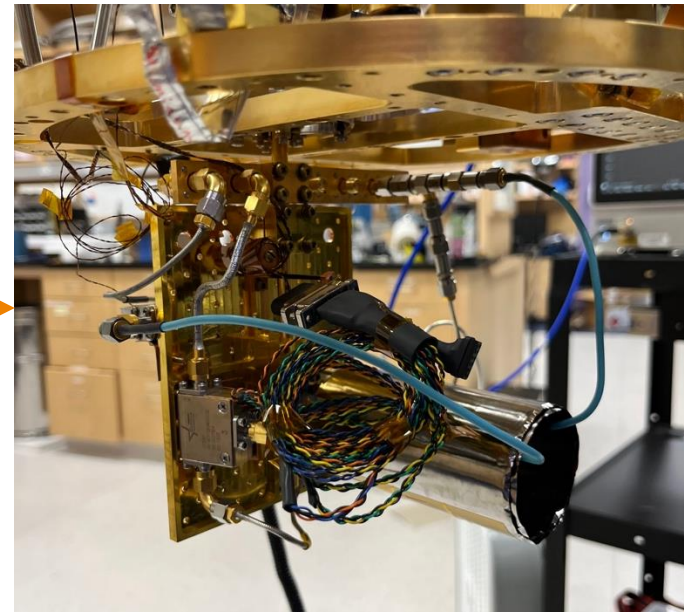
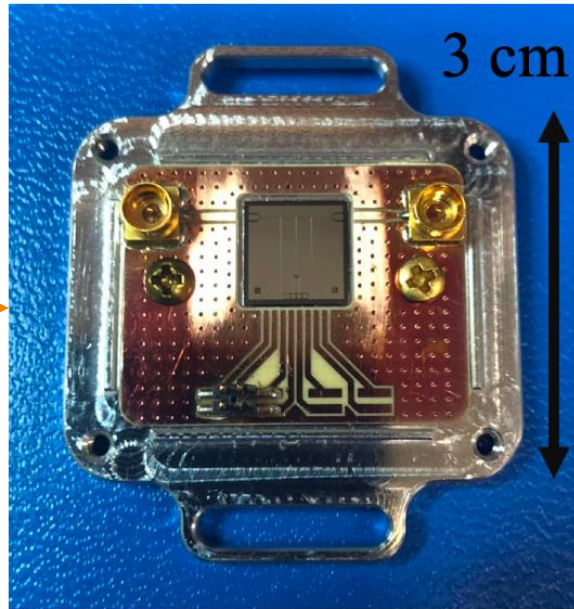
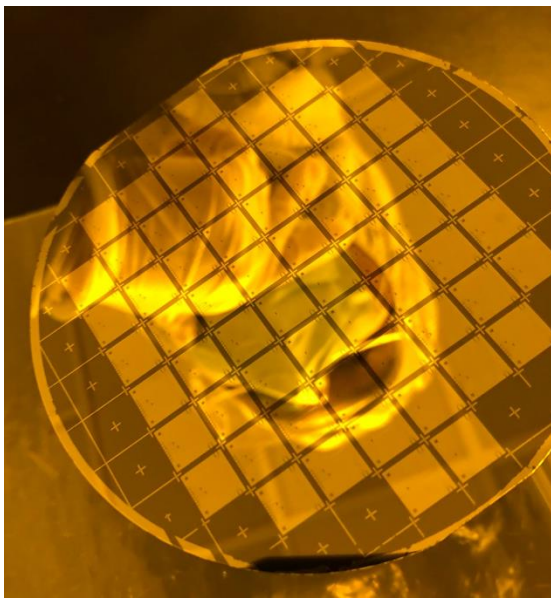
BAE protocol suppresses backaction noise in measured quadrature.



Stronger coupling lowers imprecision noise, increasing the sensitivity bandwidth.

# Next steps

- Fabrication iterations to improve robustness, increase microwave resonator quality factor, and readout method (reflection mode).
- Full demonstration of backaction-evasion and sub-SQL sensitivity.



# DMRadio Collaboration

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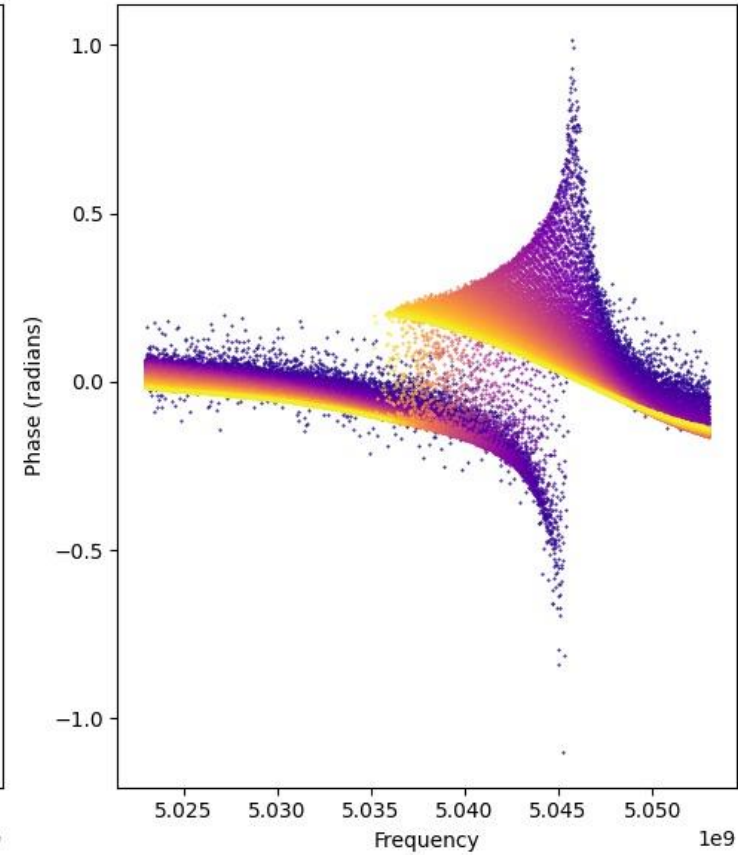
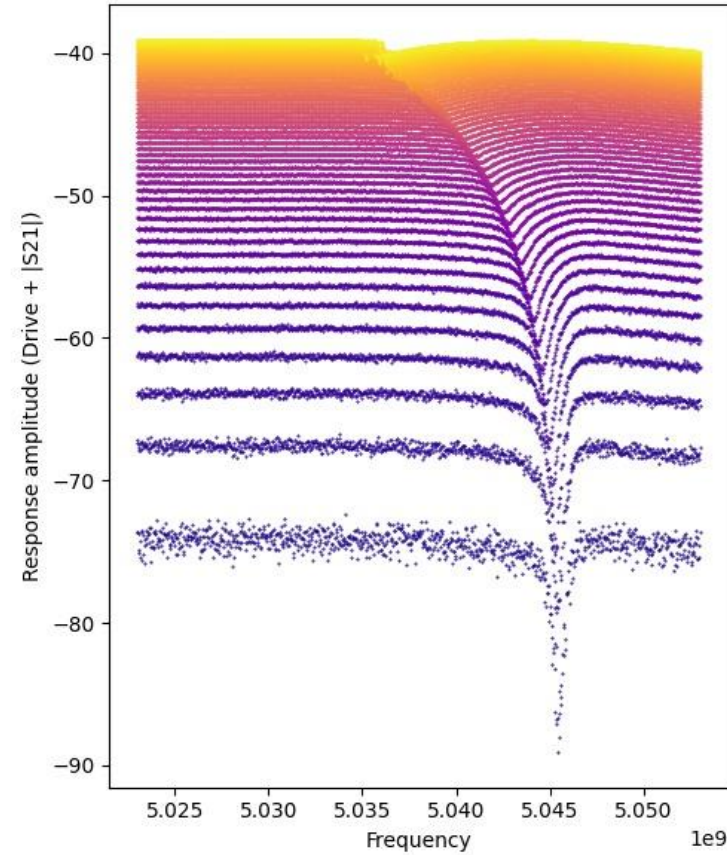
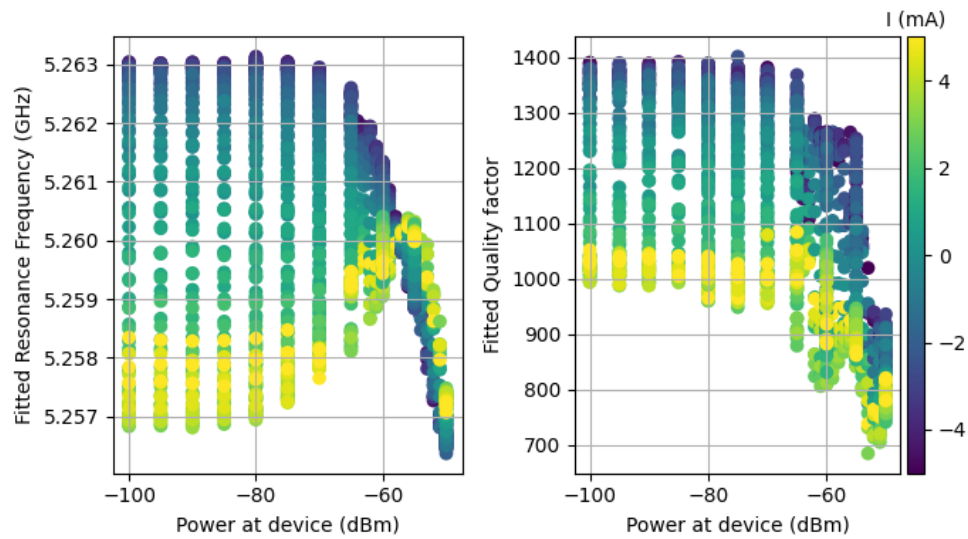
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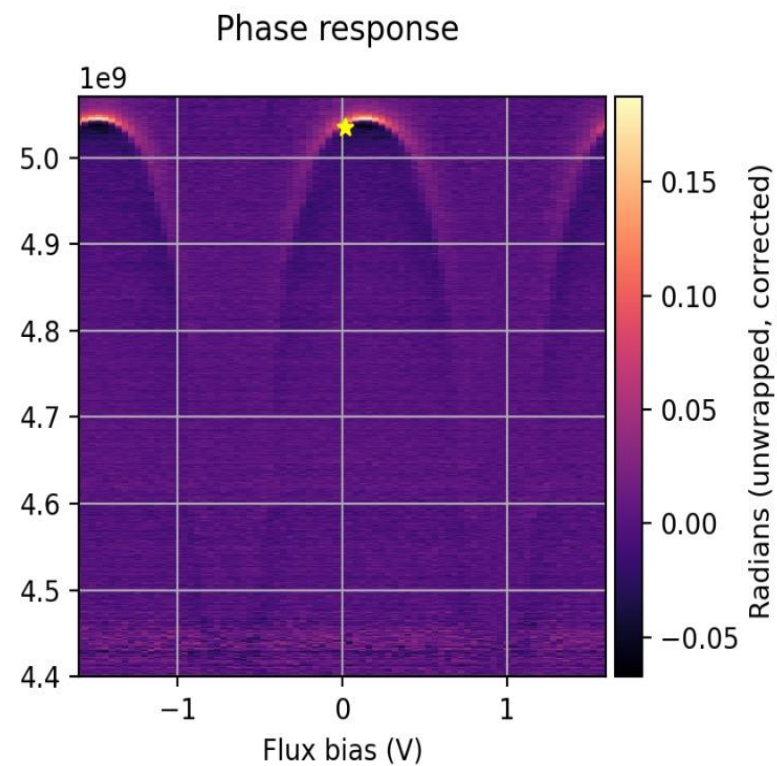
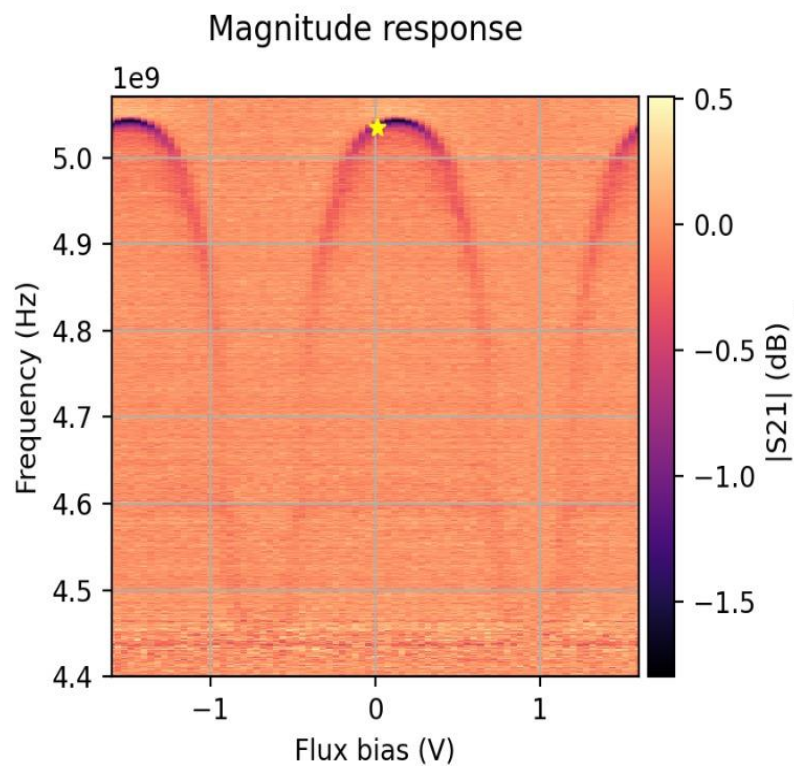
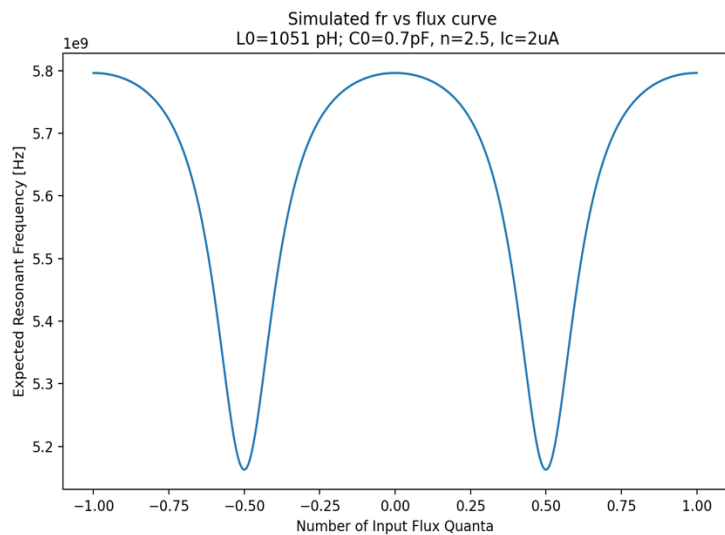


# Kerr nonlinearity at high microwave drives

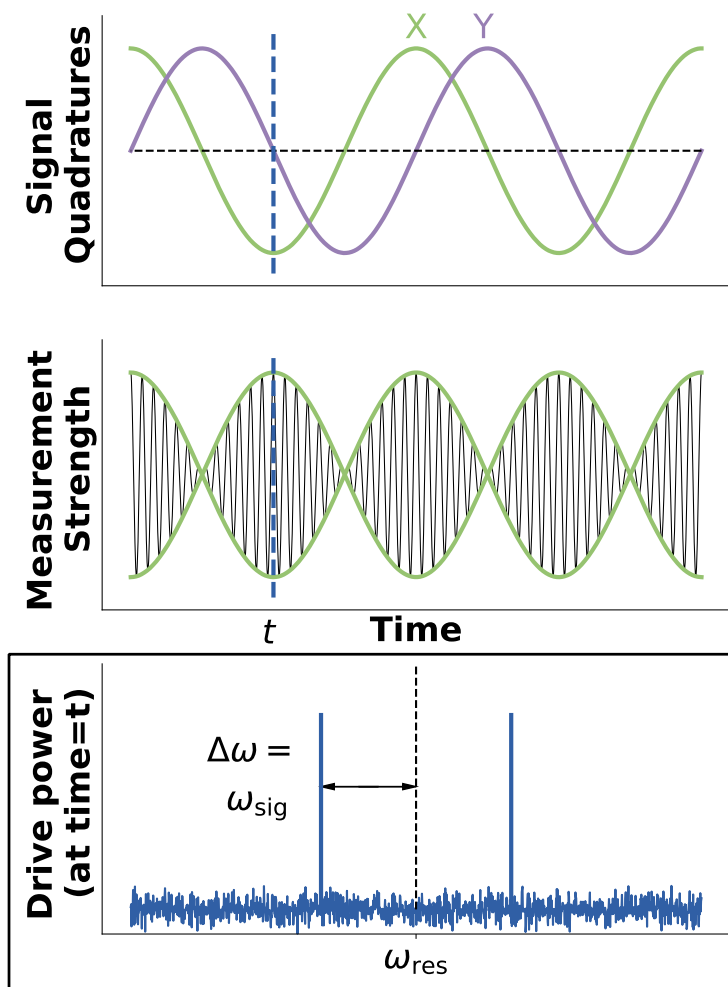




# Simulated data and S21 data

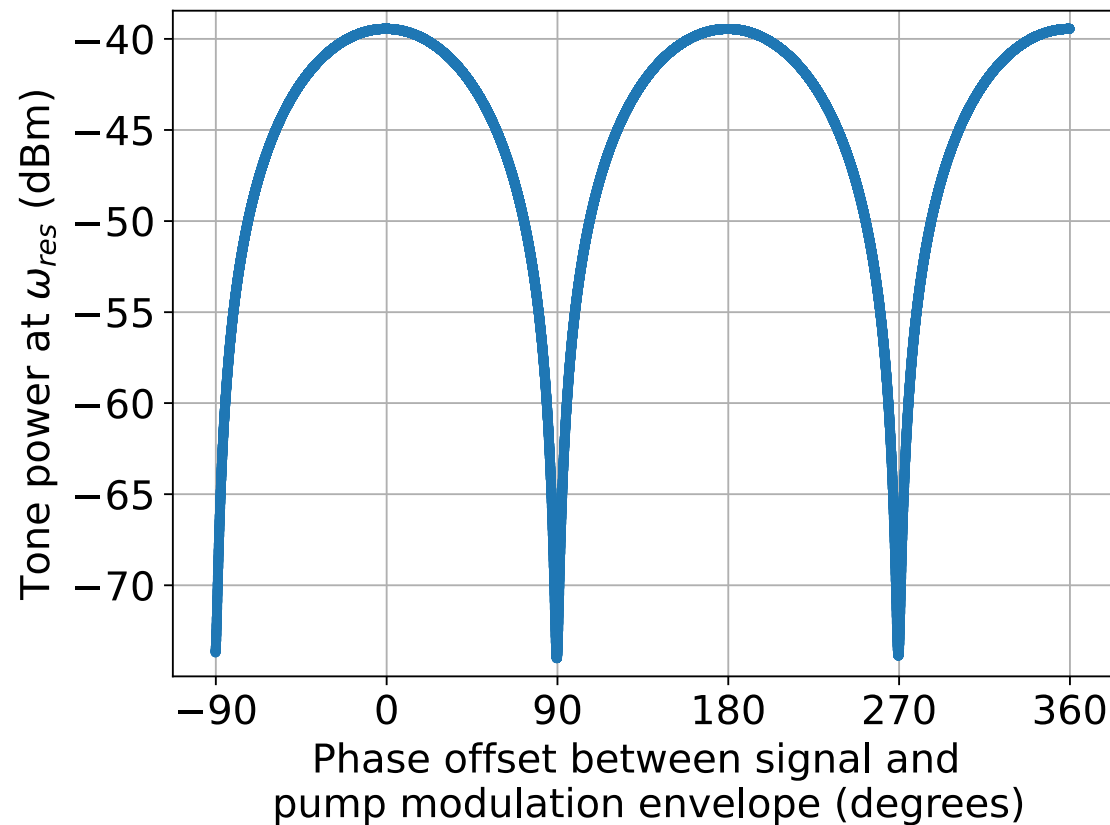


# Phase sensitive measurement



**Time domain**

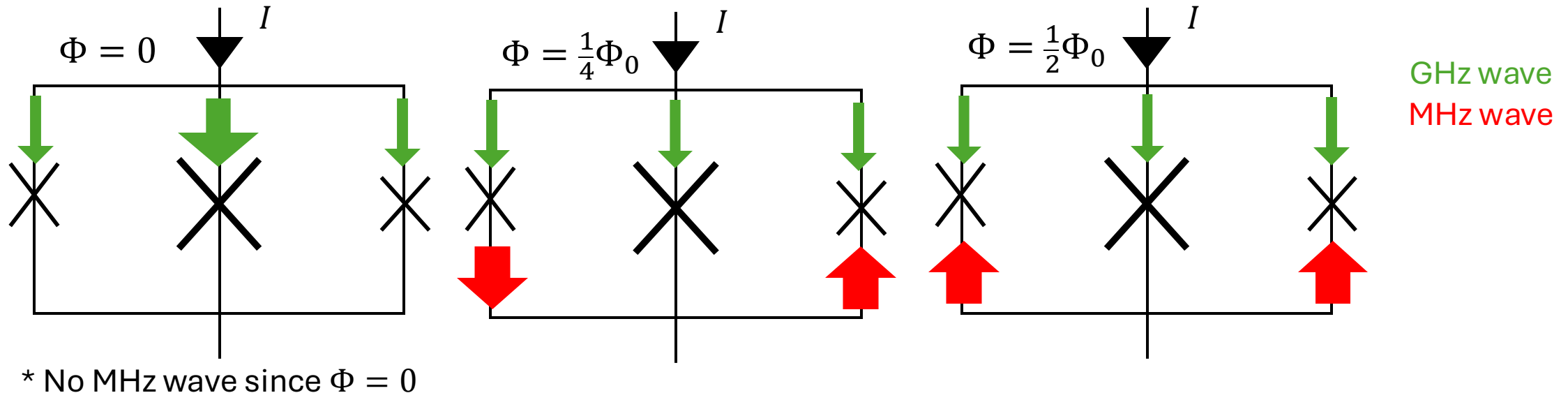
**Frequency domain**



# Why 3-junctions for RQUs?

- Normally, a resistive element would be used to kill higher frequency modes in the MHz resonator
- By tracking currents at different fluxes, however, we can see the usefulness of a 3-junction RQU

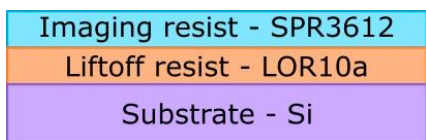
Currents at:



# Fabrication – Shadow Evaporation

Bridge junctions with triangular overlap fabricated as shown below:

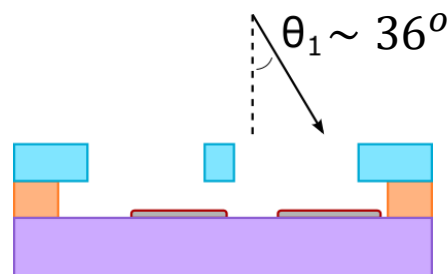
Side view:



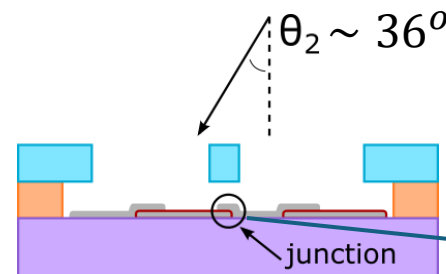
A liffoff resist and imaging resist are applied to a Si substrate.



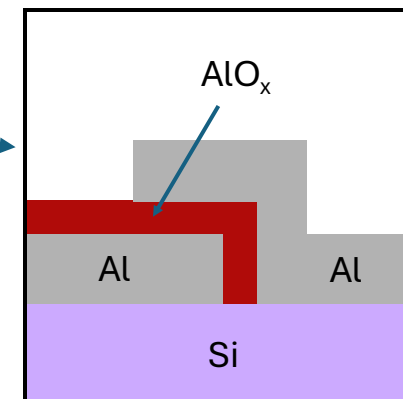
Developer removes exposed imaging resist and a slightly greater area of underlying liffoff resist.



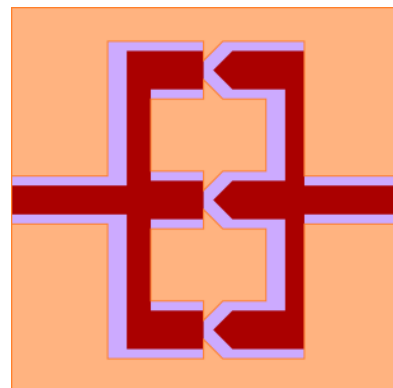
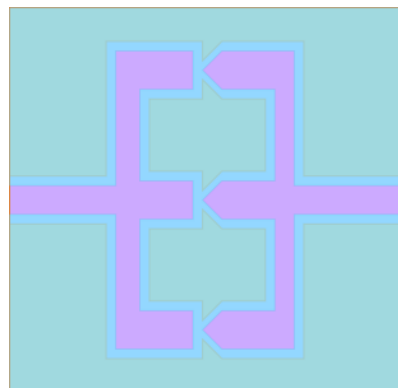
Al is deposited at the 1<sup>st</sup> angle. Oxygen is flowed to create a layer of oxide.



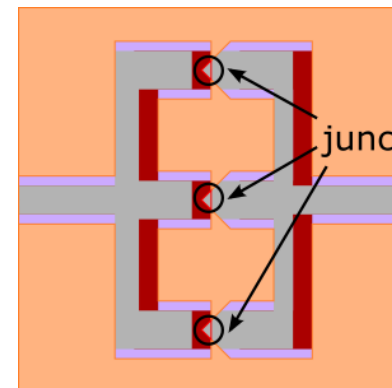
Al is deposited at the 2<sup>nd</sup> angle. Areas of overlap form junctions.



Top view:



\*imaging resist omitted



\*imaging resist omitted

$$J_{ideal} \approx 1.26 \frac{\mu A}{\mu m^2}$$

(based on data from an existing process on the same deposition tool)

# Fabrication – Extra Photos

Imaging resist - SPR3612  
Liftoff resist - LOR10a  
Substrate - Si

