Radio-frequency Quantum Upconverters for dc-VHF quantum metrology

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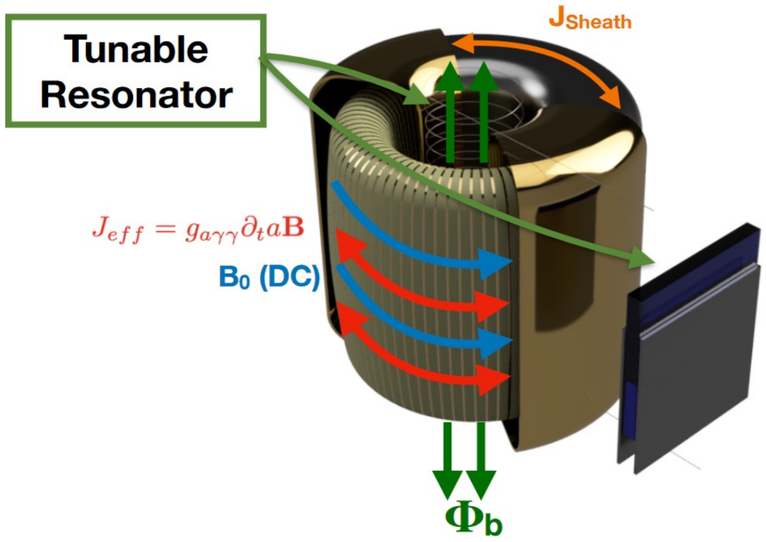
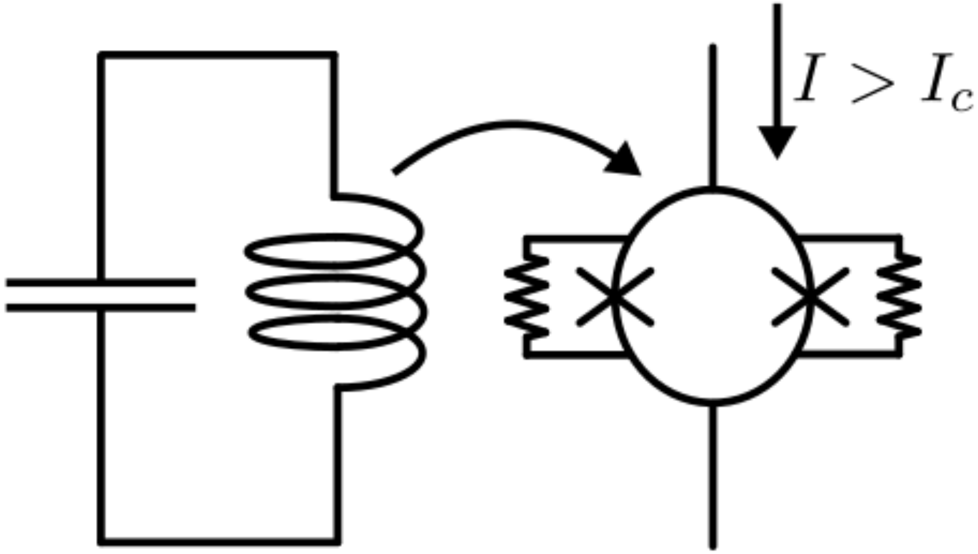
Motivation for lumped element resonators as dark matter detectors

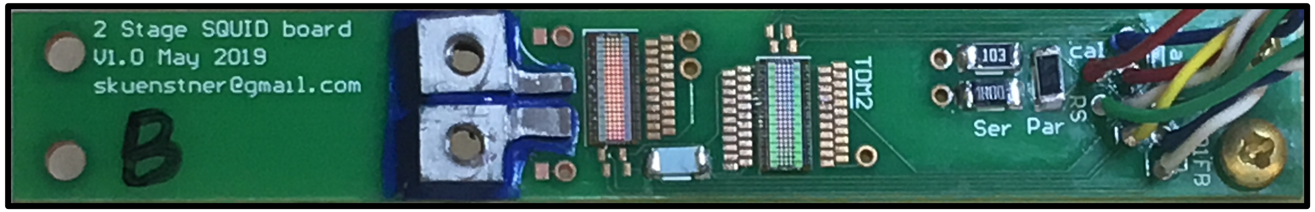
- Most of the matter in the universe is made up of an unknown particle, known as dark matter.
- The axion is a leading dark matter candidate.
- Axions convert to a weak AC magnetic field in the presence of a strong DC magnetic field.
- Low mass particles (peV to μeV) correspond to frequencies in the kHz to high MHz range.
- Lumped element resonators create detectors with a wide tuning range.



Current state of the art: DC SQUIDs

- The DC SQUID readout has been proven in prototype haloscope experiments, including the DMRadio Pathfinder.
- DC SQUIDs are mature, with good bandwidth and dynamic range, and reasonably good noise.
- 2 stage SQUID systems are proven and relatively easy to implement.

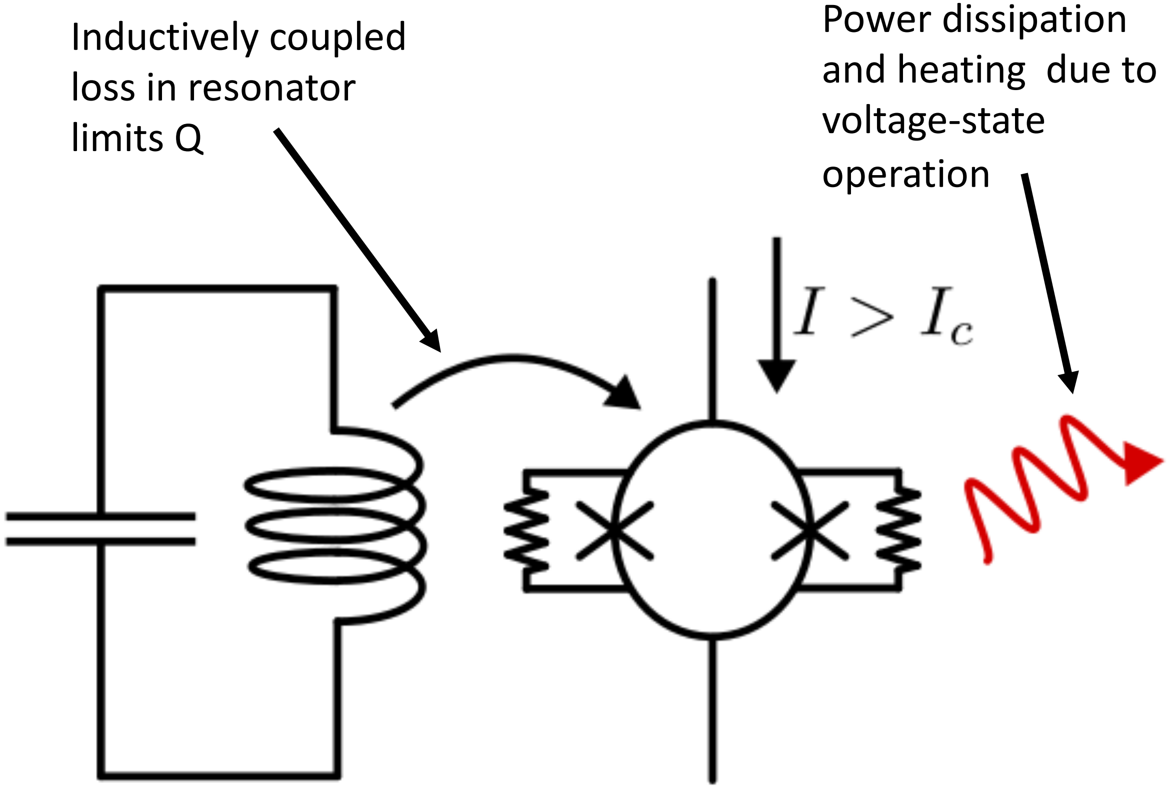




Limitations of DC SQUIDs

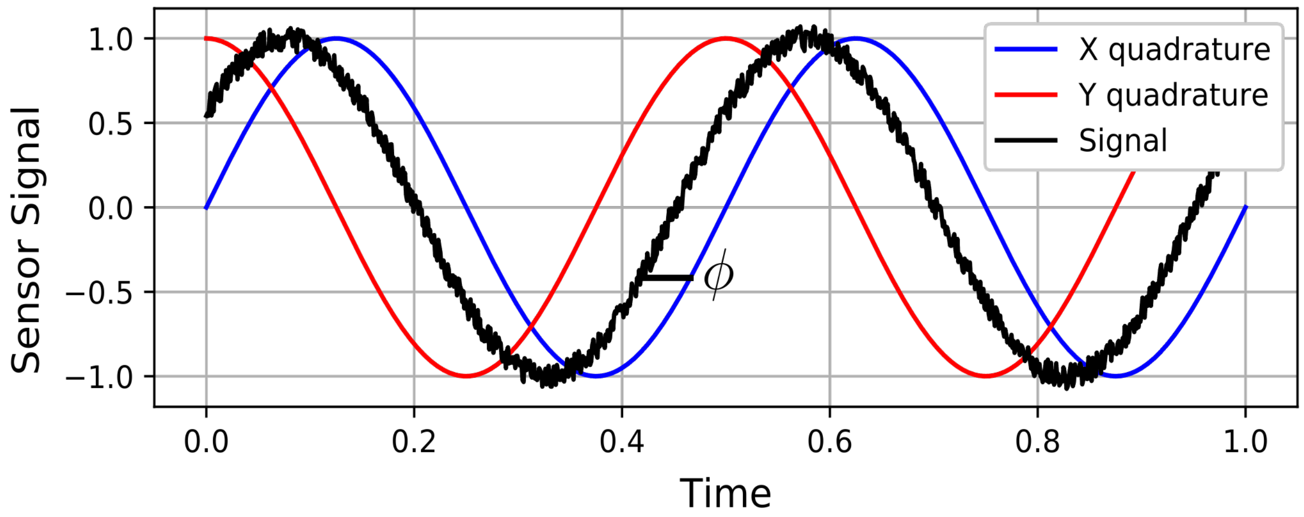
DC SQUIDs have issues that limit their ultimate performance:

- Inductively coupled loss,
- Heating due to power dissipation,
- **They can approach, but never exceed, the Standard Quantum Limit.**



The Standard Quantum Limit

- A generic signal has ‘sine’ and ‘cosine’ components, which do not commute.
- The Heisenberg uncertainty principle says we cannot measure both perfectly, so an amplifier must add noise.
- When ΔX = ΔY = ½, the amplifier is said to be operating at the Standard Quantum Limit (SQL).



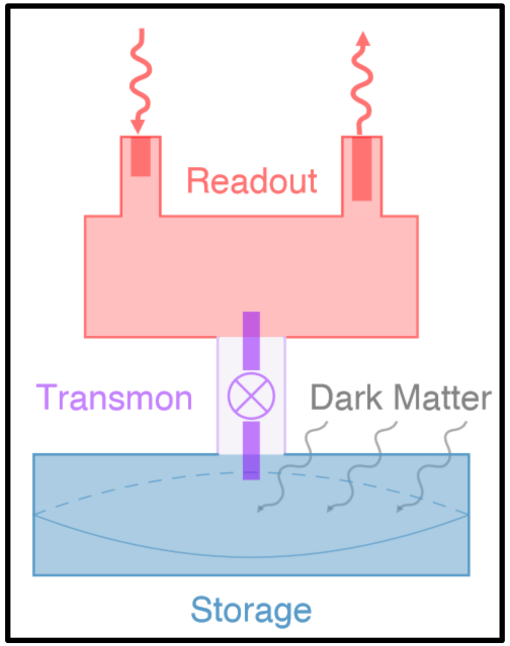
$$[\hat{X}, \hat{Y}] = i$$

$$\Delta X \Delta Y \geq \frac{1}{4}$$

Evading the SQL: techniques for high frequencies

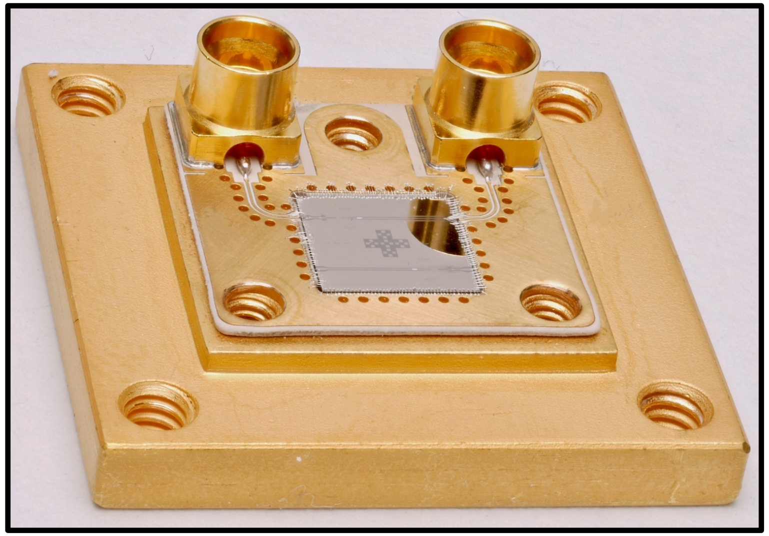
- Experiments at higher frequency implemented SQL-evading techniques to improve the sensitivity of real dark matter searches.
- However, these techniques do not directly apply to experiments in the DM Radio frequency range:
  - DM Radio does not have a well-defined photon number to count,
  - It is challenging to generate squeezing at DM Radio's frequency.

Photon-counting hidden photon detector (~6GHz)



Dixit (2021)

Squeezed-state axion receiver (HAYSTAC, ~4GHz)

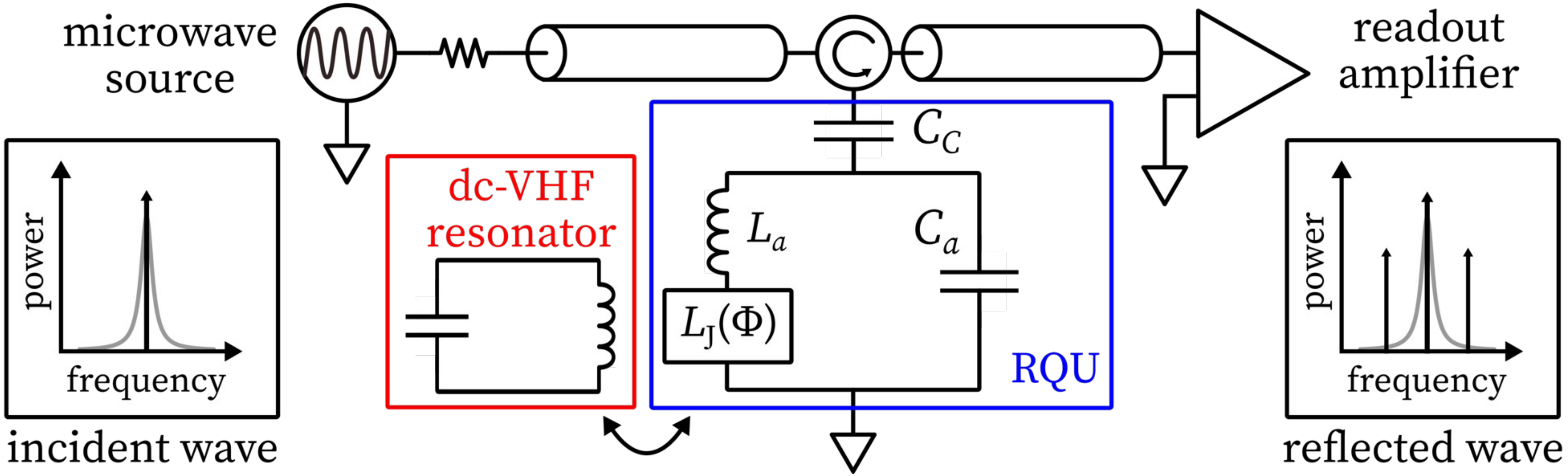


M. Malnou and D. Schmidt, (2021)

Evading the SQL at low frequency: Radio-frequency Quantum Upconverter

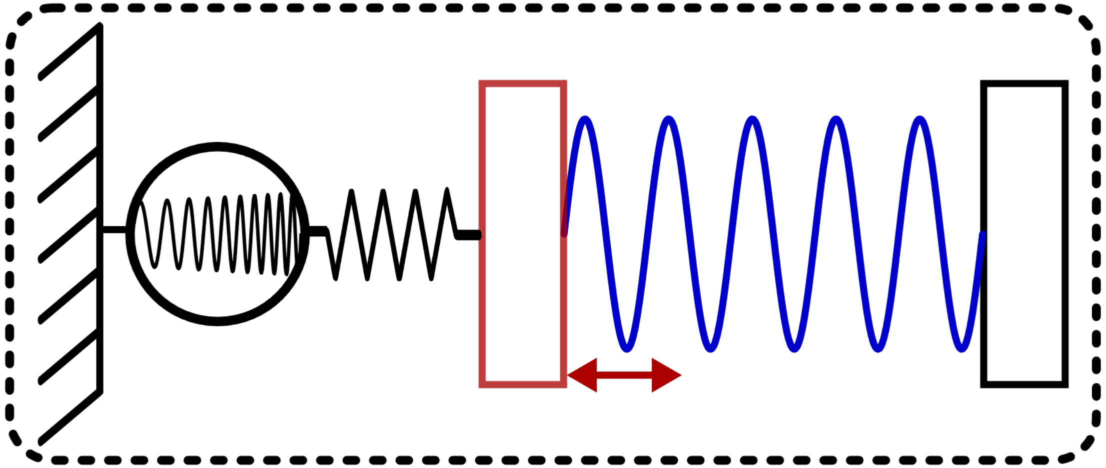
Idea: convert information from low frequencies to higher frequencies, where quantum metrology techniques are more mature.

Implementation: embed a flux-tunable inductor in a microwave resonator, so that the low-frequency dark matter signal modulates the microwave resonant frequency

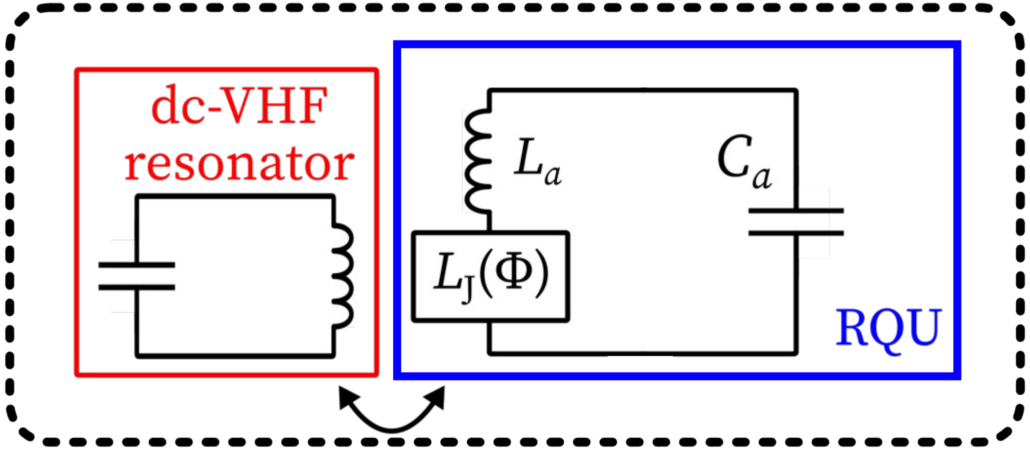


Analogous to optomechanics

Cavity Optomechanics



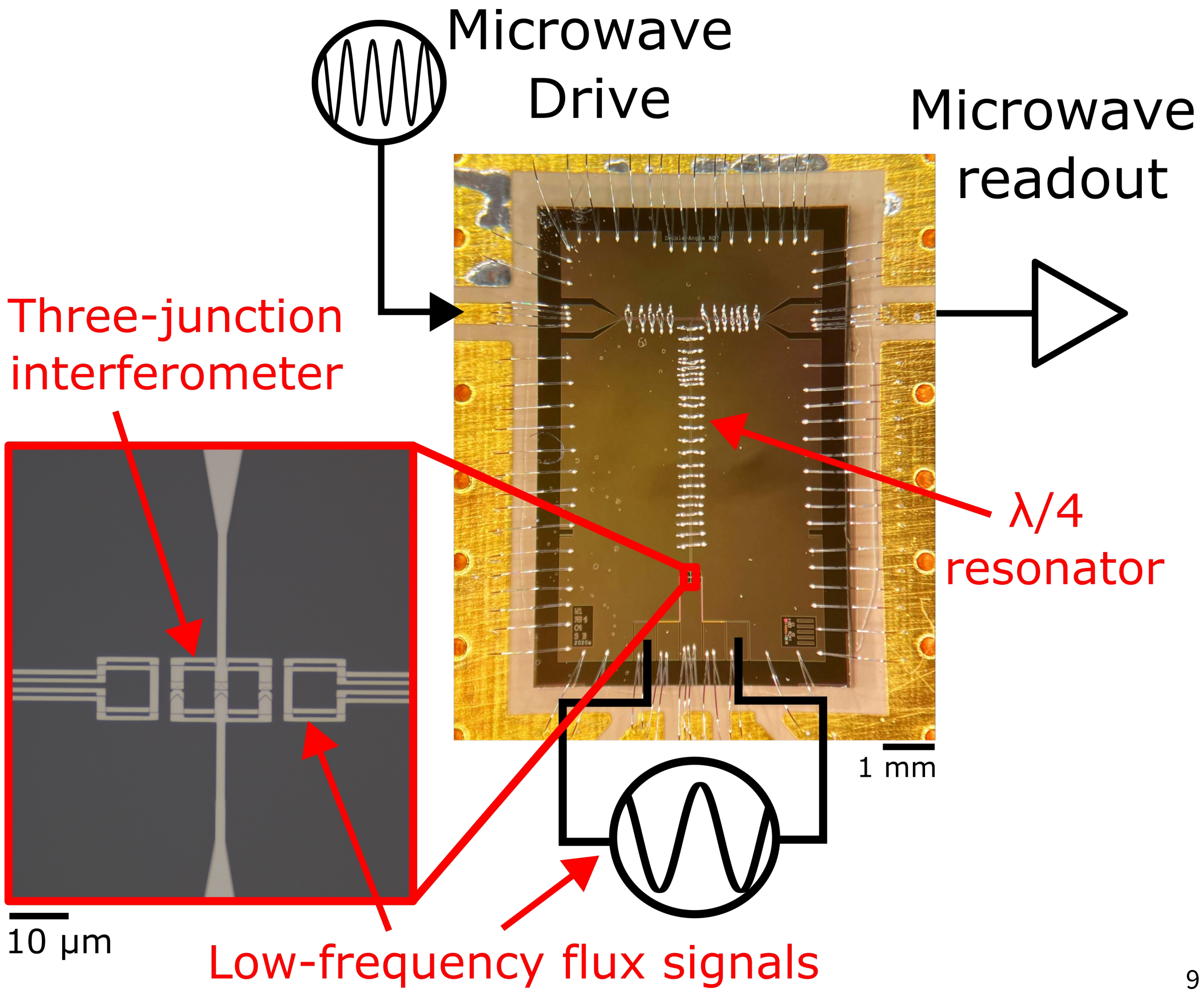
LC + RQU



$$\hat{H} = \hbar\omega_a(\hat{a}^\dagger\hat{a} + \frac{1}{2}) + \hbar\omega_b(\hat{b}^\dagger\hat{b} + \frac{1}{2}) + \hbar g\hat{a}^\dagger\hat{a}(\hat{b}^\dagger + \hat{b})$$

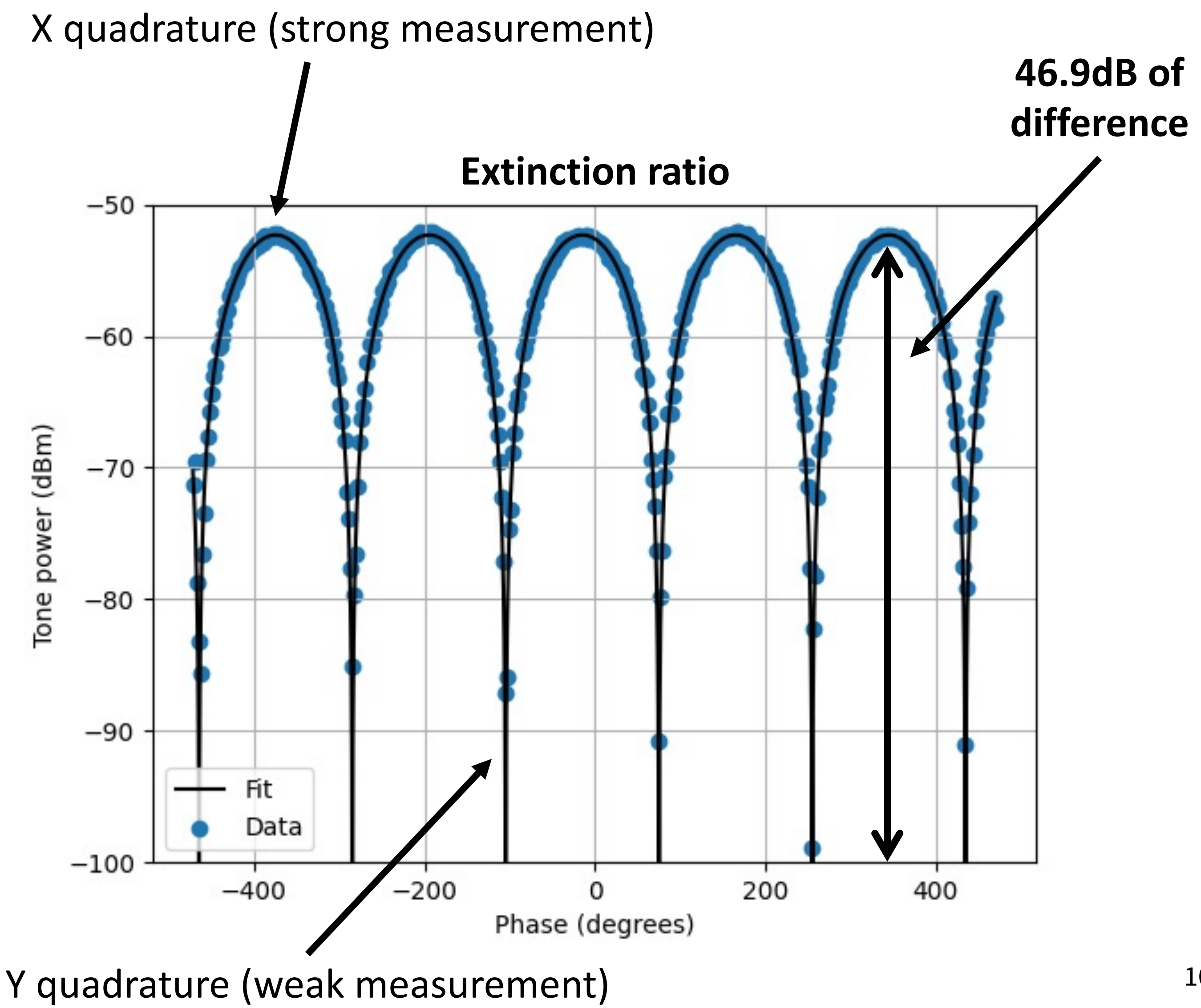
Implementing the RQU

- The tunable inductor is made of an interferometer with three Josephson junctions and two loops.
- The microwave resonator is a quarter wave stub of coplanar waveguide.
- Flux inputs couple a low-frequency input signal into the interferometer.
- A microwave transmission line allows us to detect the state of the microwave resonator.



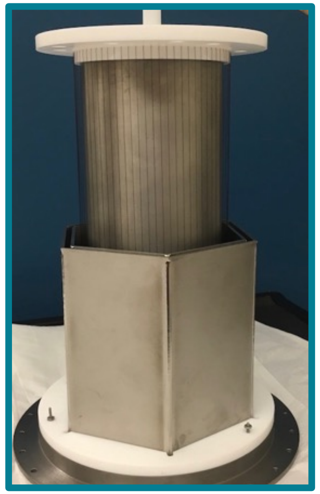
First results: phase-sensitive amplification

- To evade the SQL, the RQU needs to operate as a **phase-sensitive** amplifier.
- Readout using amplitude-modulated microwaves allows us to selectively measure only one quadrature.
- We can test the phase-sensitivity of the RQU when we pump it with amplitude-modulated microwaves, and there is a high phase-sensitive extinction ratio.

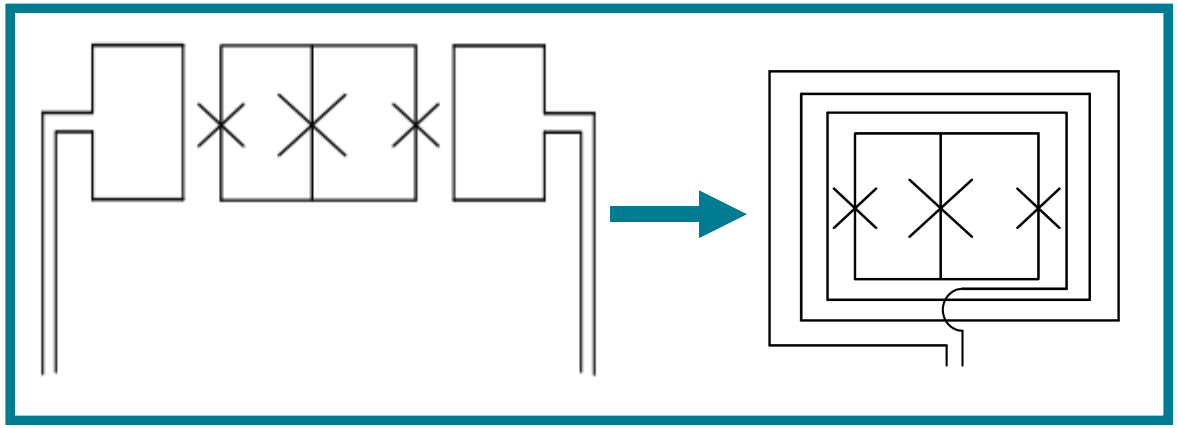


Next steps

High-Q resonator on input



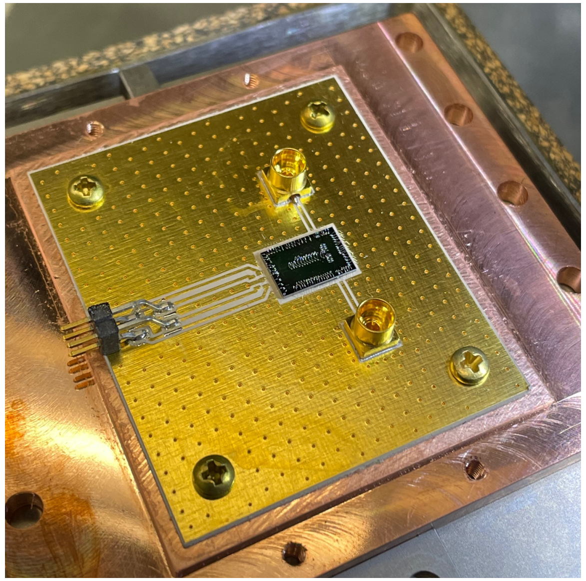
Stronger input coupling with efficient input coil

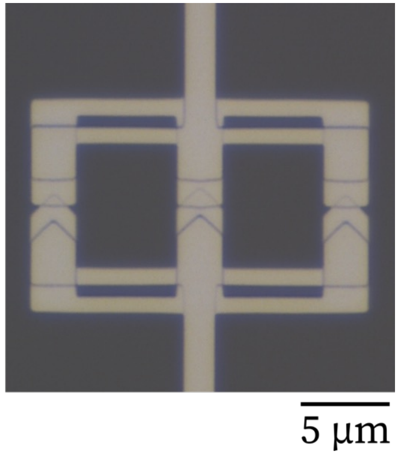


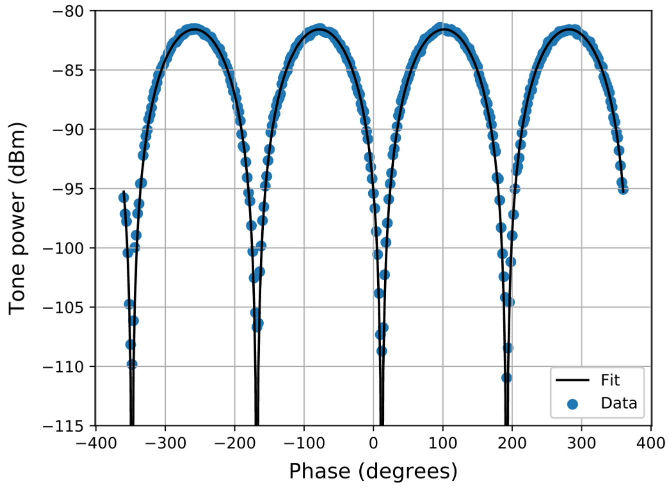
Follow-on amplification with JPA

Conclusion

- Quantum sensing is a powerful tool to improve the science reach of dark matter haloscopes.
- Initial measurements show successful upconversion and high gain contrast.
- We hope to measure phase-sensitive noise as the next step towards backaction evasion and other quantum metrology techniques.







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DMRadio Collaboration

DARK MATTER RADIO

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Berkeley University of California
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MIT
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Berkeley Lab
The University of North Carolina at Chapel Hill
Santa Clara University
TUNL Triangle Universities Nuclear Laboratory
Cal State East Bay
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