At the edge of perception: a new world visible through quantum sensing

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Signal decomposition

Any signal can be decomposed as

$$A_{\text{in}}(t) = X\cos(\omega_0 t) + Y\sin(\omega_0 t)$$

where X and Y represent 2 quadratures.

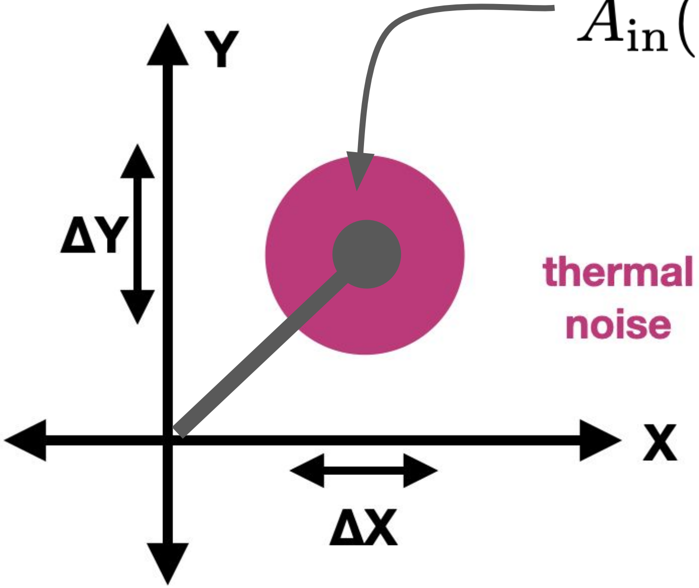
Receiver chain amplifies both quadratures with phase-preserving measurement

$$X \to \sqrt{G}X \qquad Y \to \sqrt{G}Y$$

when accounting for both quadratures: fundamental noise that cannot be mitigated, termed the “Standard Quantum Limit”.

Noise sources

$$A_{\text{in}}(t) = X\cos(\omega_0 t) + Y\sin(\omega_0 t)$$



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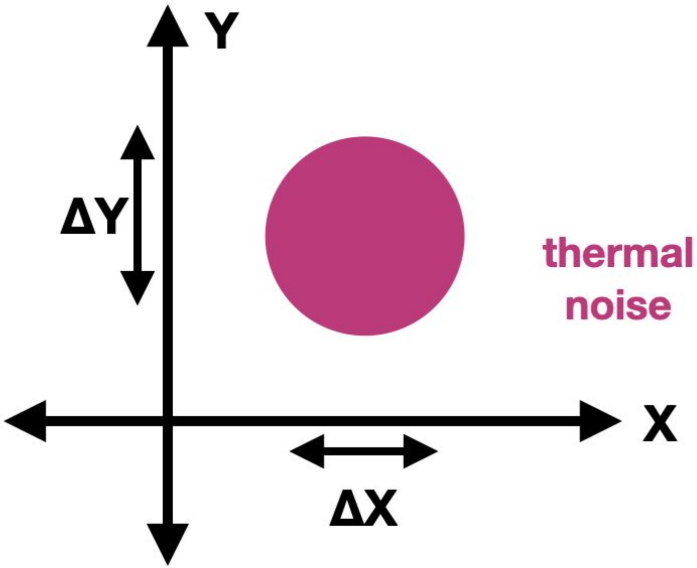
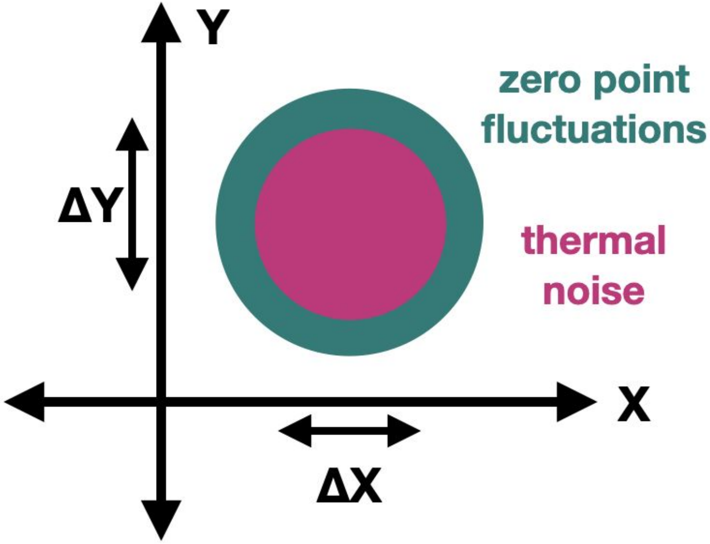


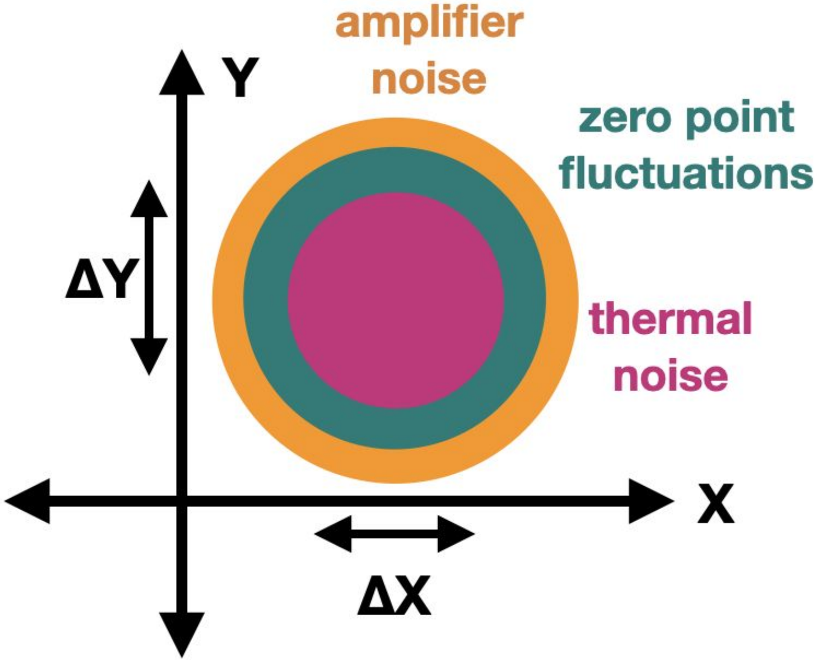
- Thermal noise or Johnson noise

Noise sources



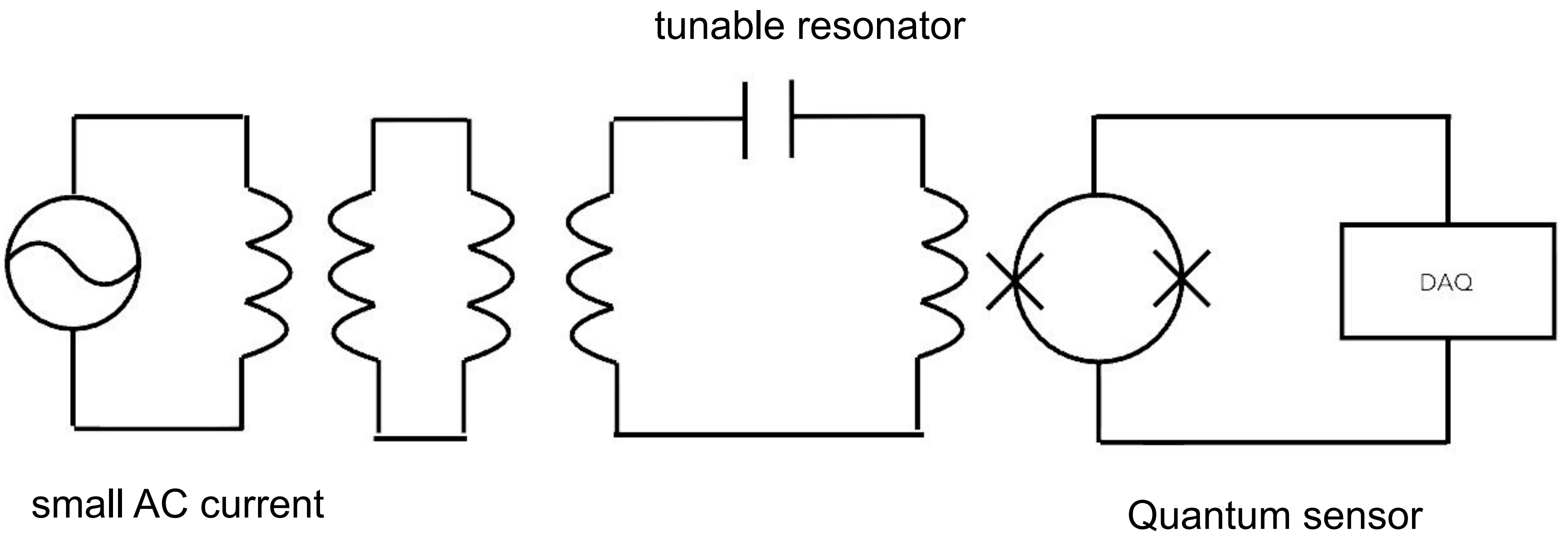
- Thermal noise or Johnson noise
- Zero point fluctuations

Noise sources

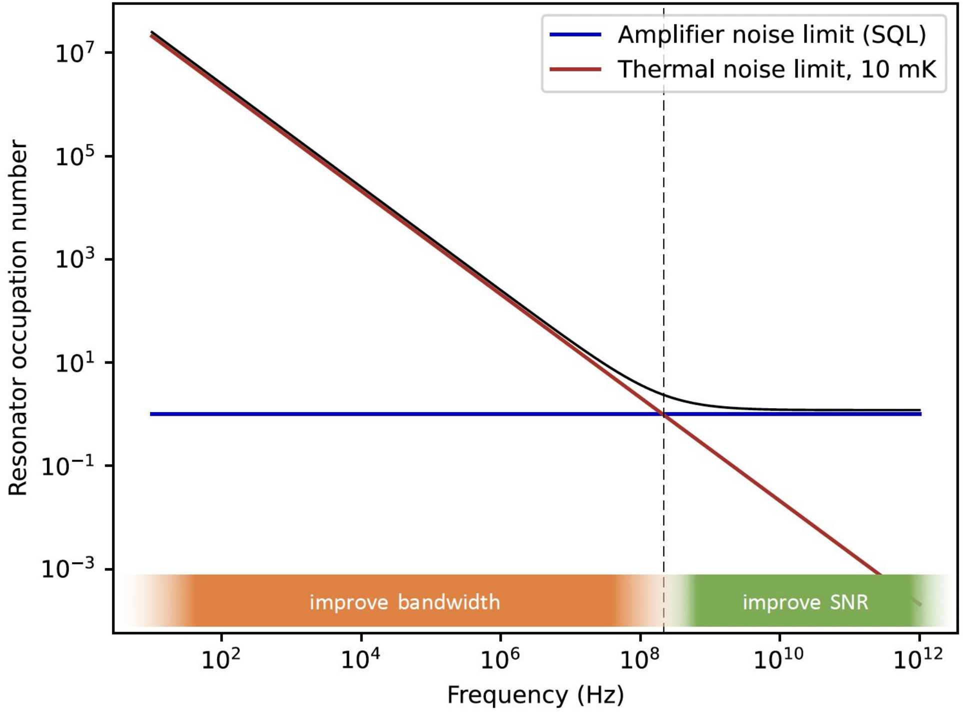


- Thermal noise or Johnson noise
- Zero point fluctuations
- Amplifier noise

Detector regimes



Quantum sensing for axion searches

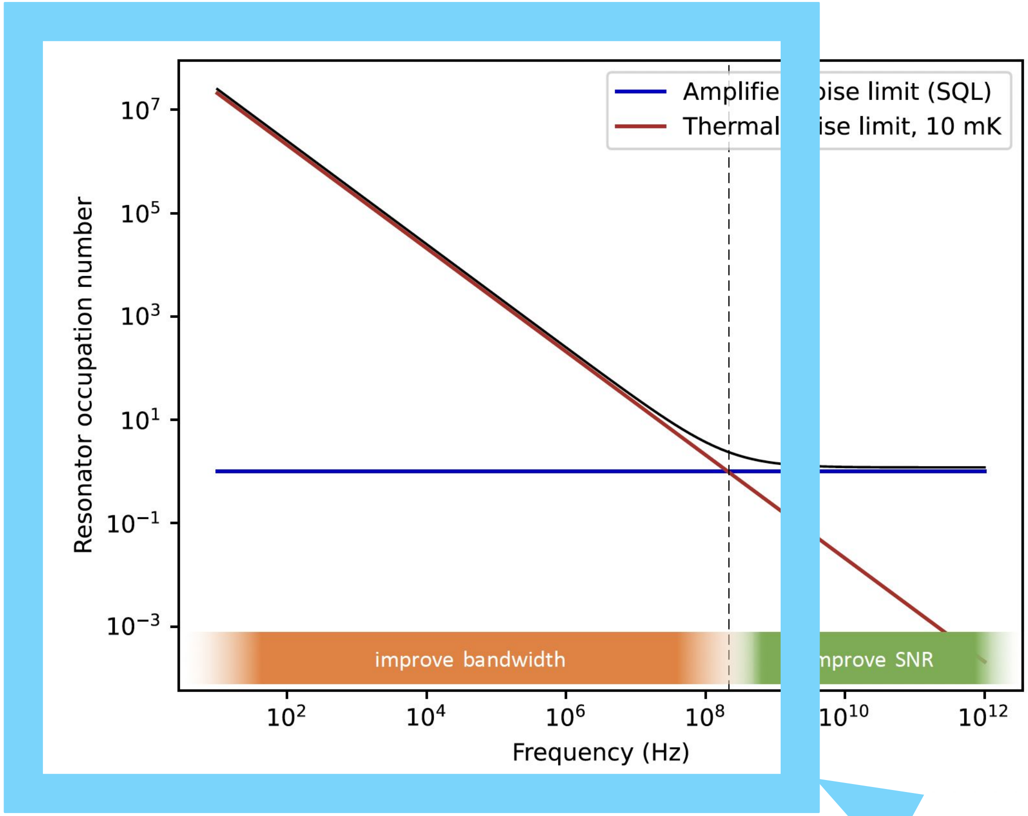


Detector has an associated thermal noise with frequency dependence

Assuming your detector can reach 10 mK, this frequency dependence will look like the plot on the left

At some point the photon occupation number for the thermal noise is equal to that of the amplifier noise set by the SQL.

Quantum sensing for axion searches



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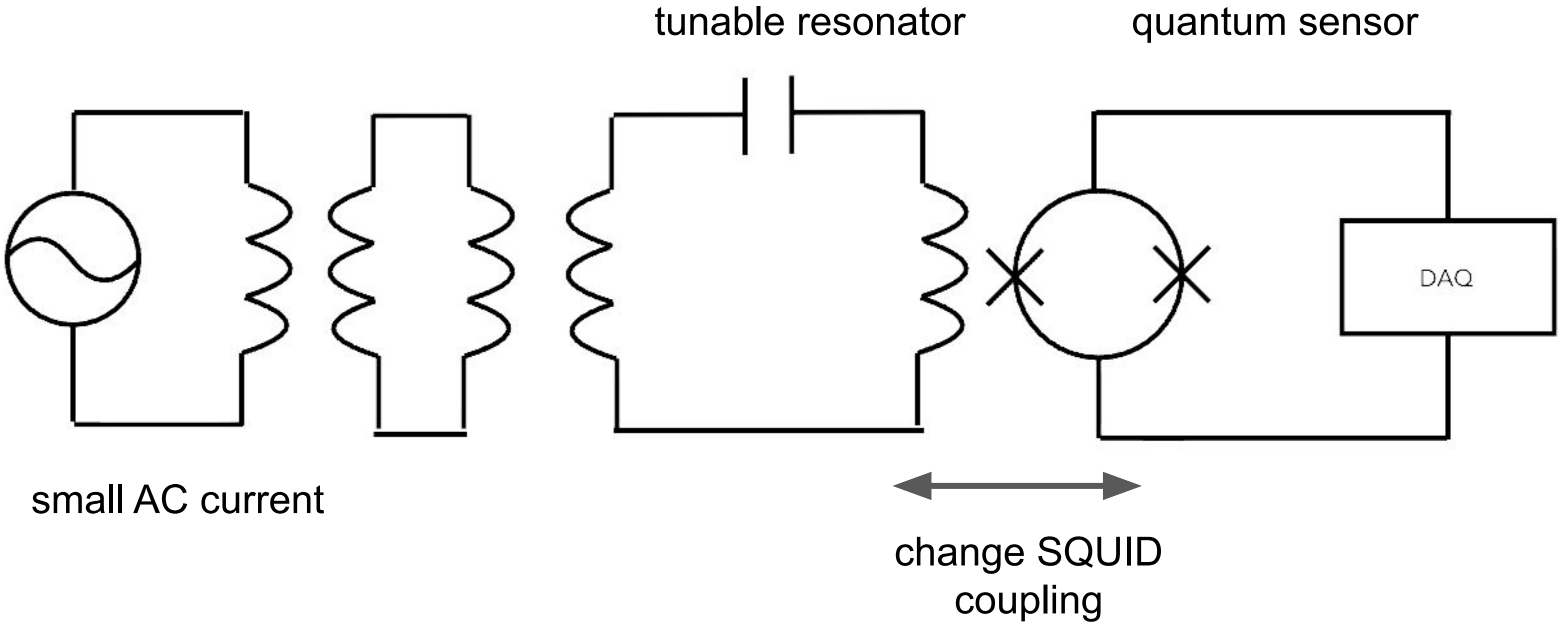
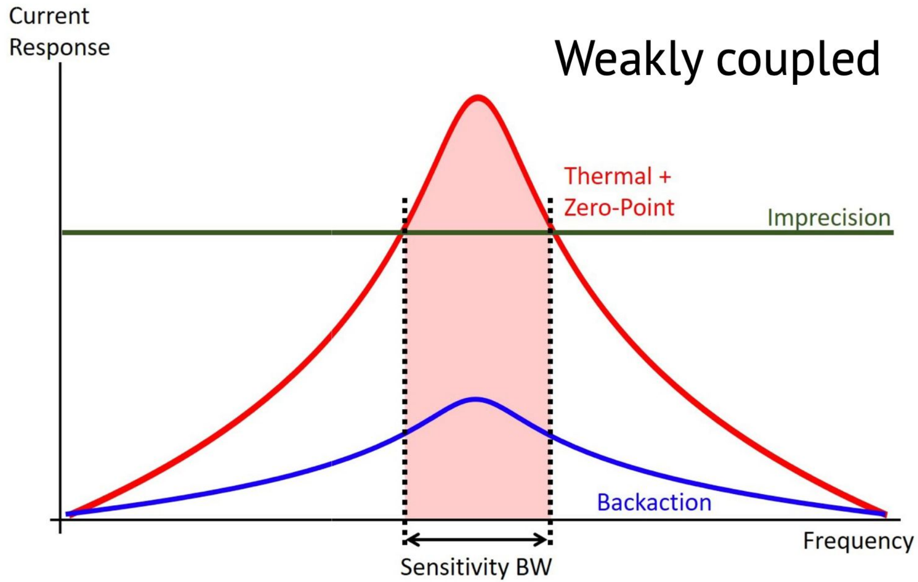
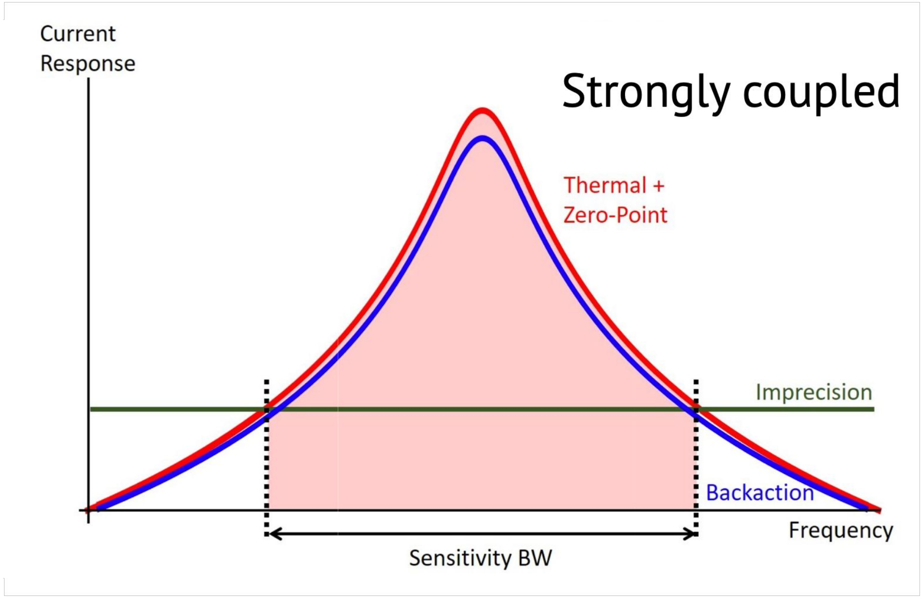
Let's start at the lower frequencies…

Axion search: DMRadio



DMRadio



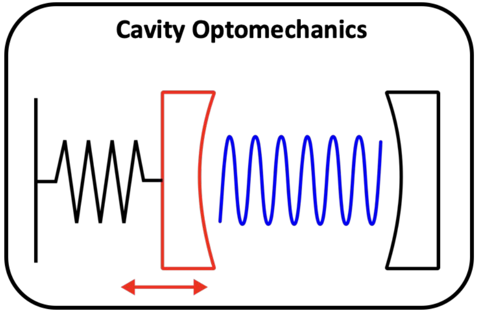


Improves scan rate; fewer mechanical tuning steps (tuning is hard)

Radiofrequency Quantum Upconverters

Device borrows concept from cavity optomechanics

- Two modes at different frequencies
- High frequency EM mode (a)
- Low frequency mechanical mode (b)
- Quantized with ladder operators

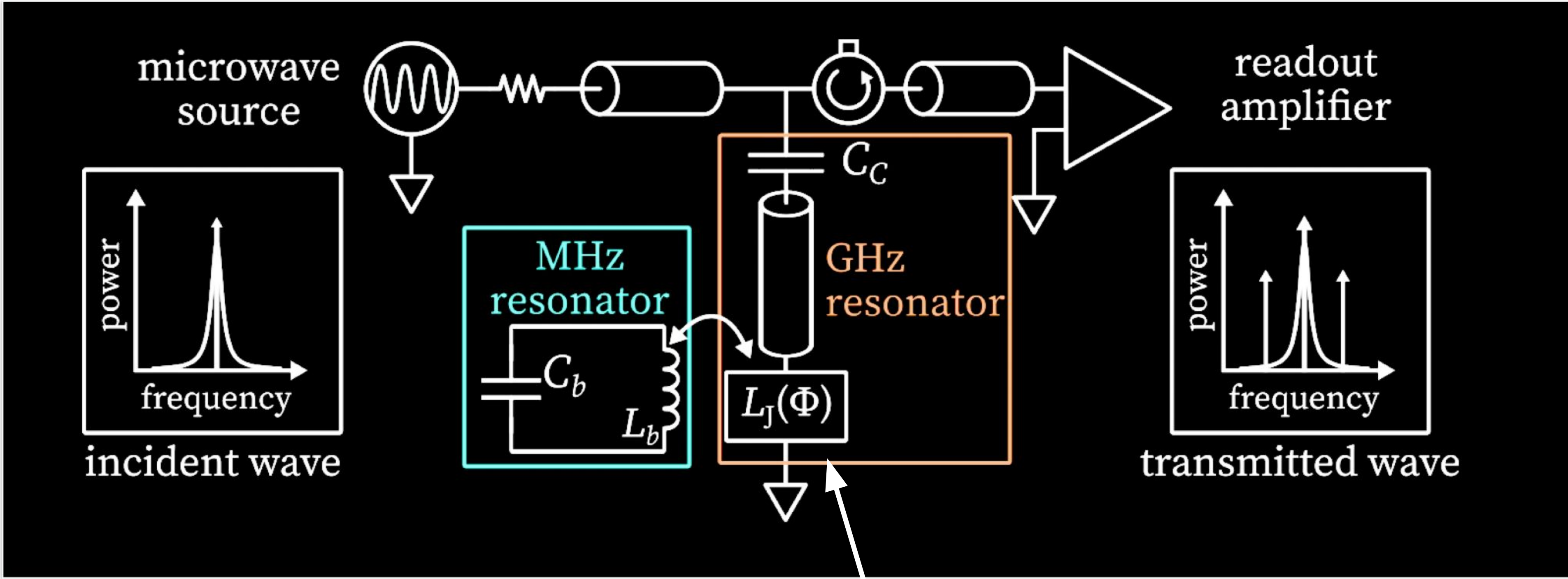


$$\hat{H} = \hbar\omega_a\left(\hat{a}^\dagger a + \frac{1}{2}\right) + \hbar\omega_b\left(\hat{b}^\dagger b + \frac{1}{2}\right) + \hbar g_0 \hat{a}^\dagger \hat{a}\left(\hat{b}^\dagger + \hat{b}\right)$$

Kuenstner, Stephen E., et al. "Quantum metrology of low frequency electromagnetic modes with frequency upconverters." arXiv preprint arXiv:2210.05576 (2022).

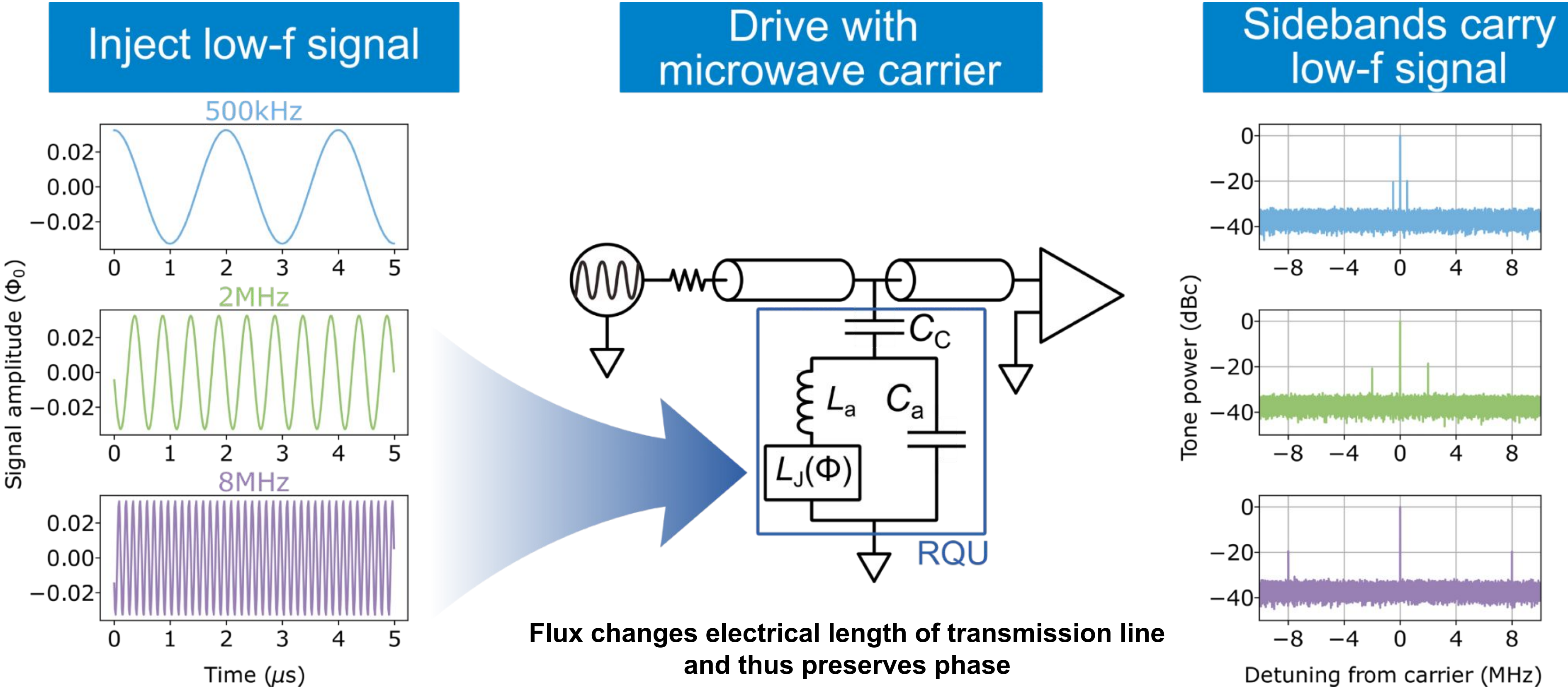
Radiofrequency quantum upconverters (RQUs)

Phase-preserving: single microwave tone injection (upconversion)



Josephson junction based array

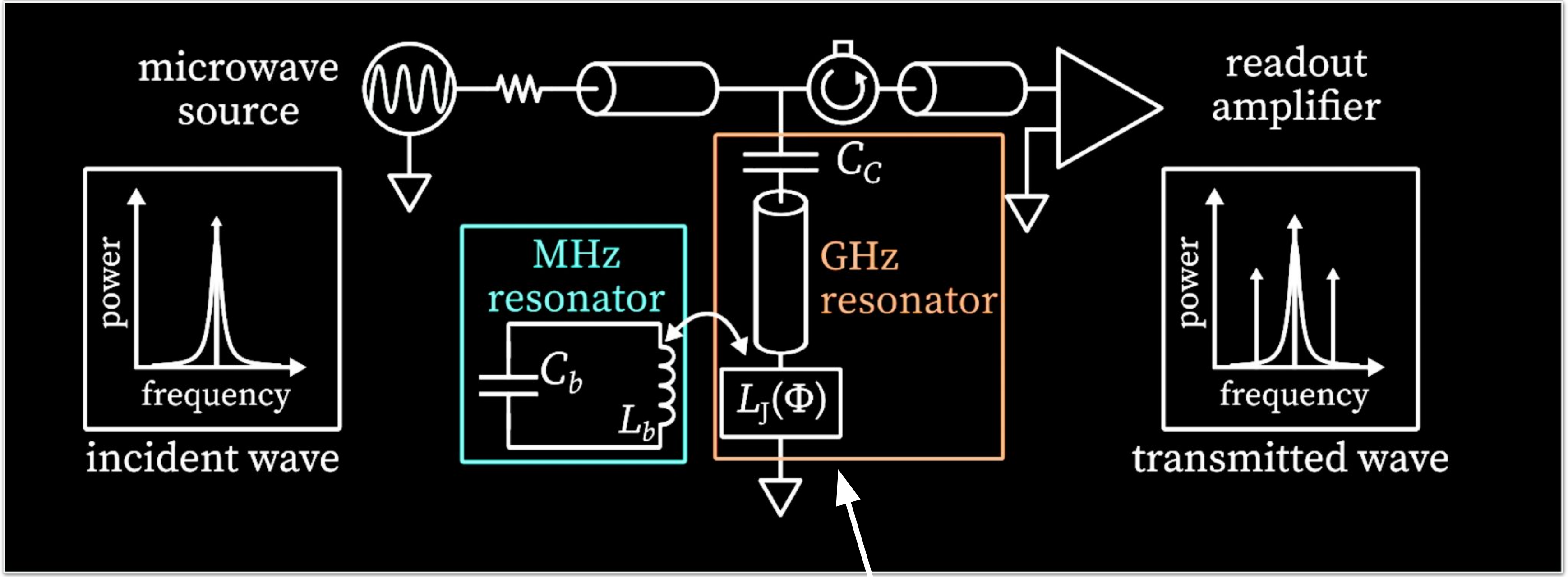
Radiofrequency quantum upconverters (RQUs)



Flux changes electrical length of transmission line and thus preserves phase

Radiofrequency quantum upconverters (RQUs)

Phase-sensitive readout: inject two tones in the microwave

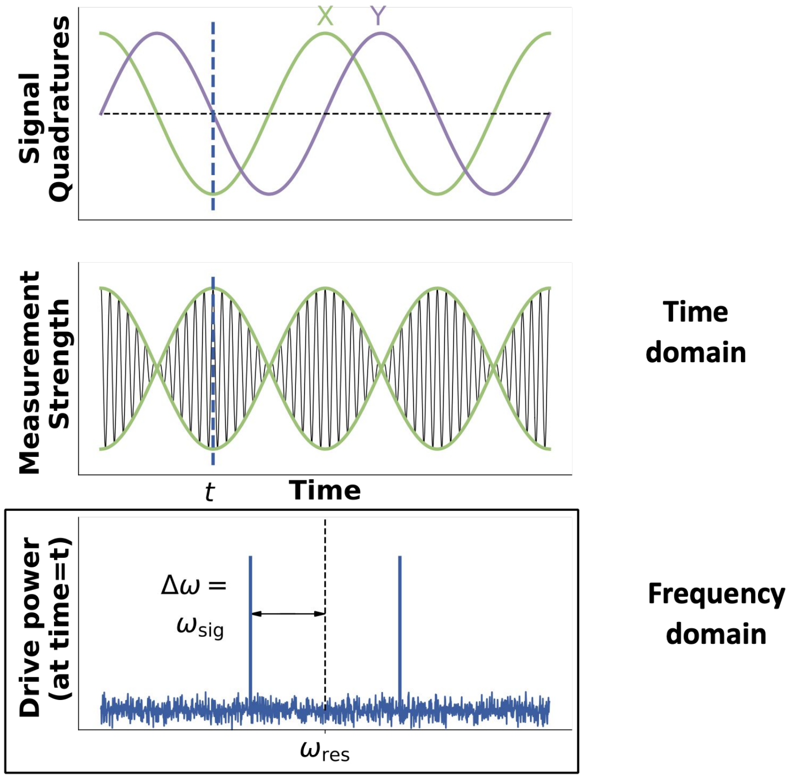


Josephson junction based array

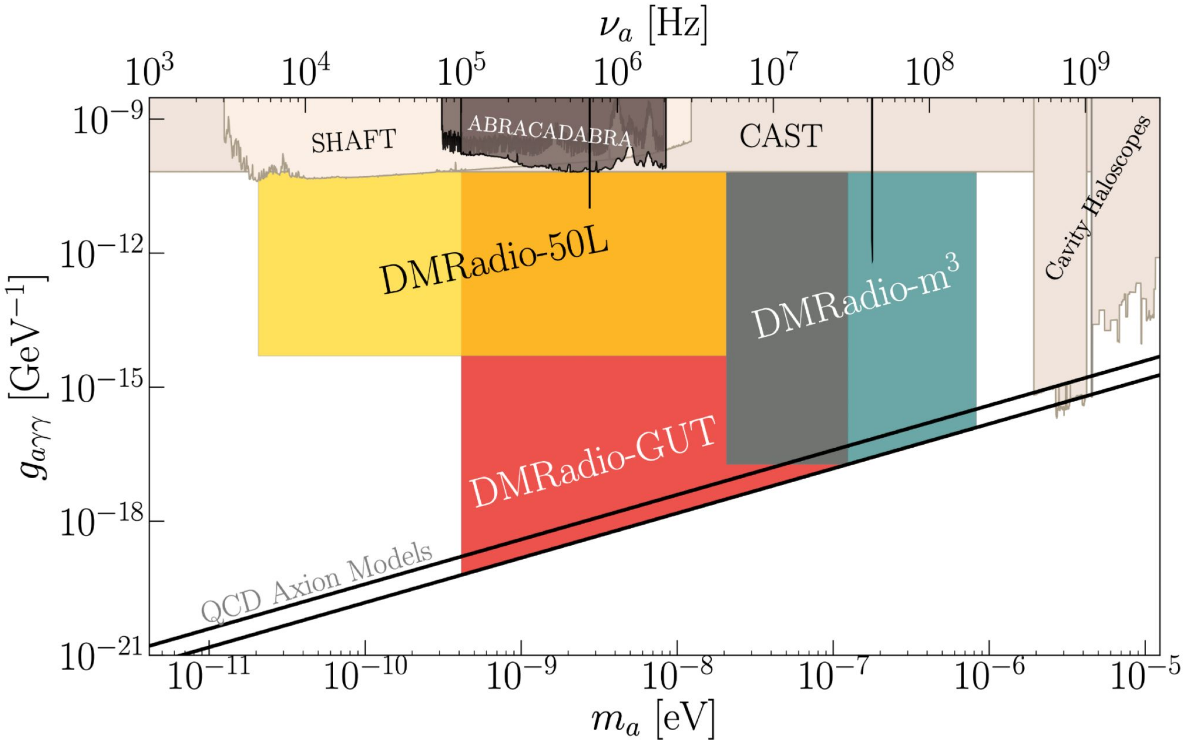
Radiofrequency quantum upconverters (RQUs)

$$A_{\text{in}}(t) = X\cos(\omega_0 t) + Y\sin(\omega_0 t)$$

- Microwave drive tone determines strength of the measurement
- Can use two drive tones to amplify and therefore measure the signal in only one quadrature
- Selectively measure when X quadrature is at maximum and Y quadrature is at minimum



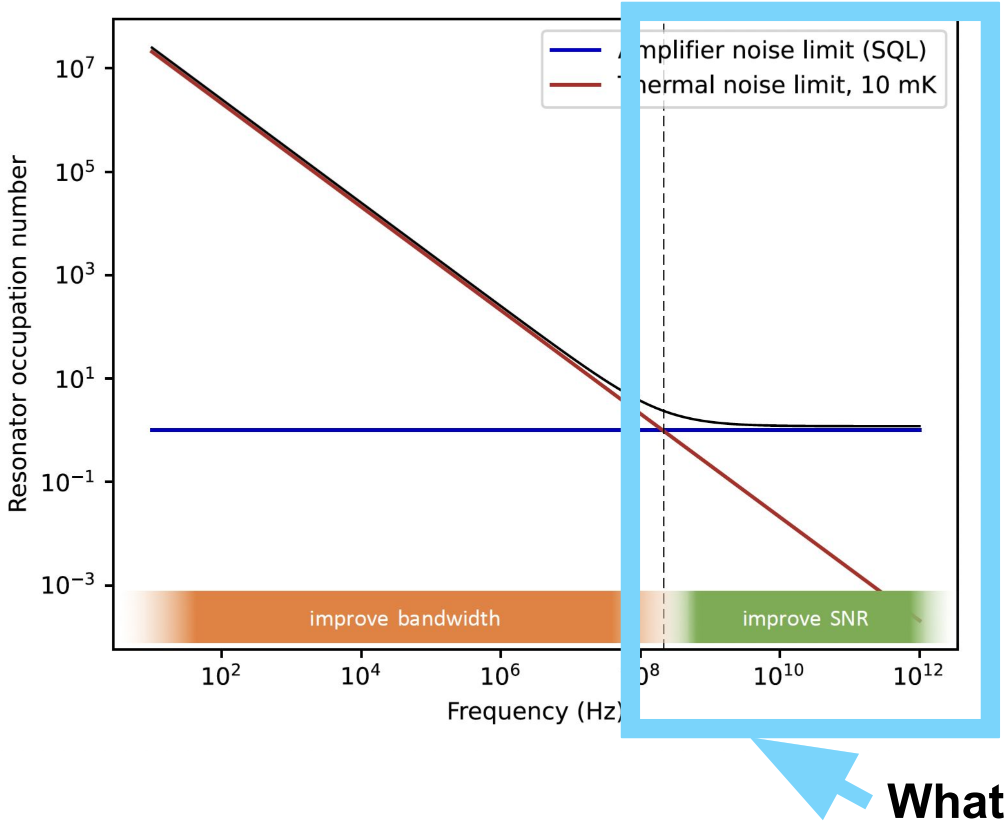
Sensitivity projection for pre-inflationary axion search



Sensitivity to the QCD axion requires the development of beyond SQL sensing at these frequencies

RQUs most promising technology so far

Quantum sensing for axion searches



Detector has an associated thermal noise with frequency dependence

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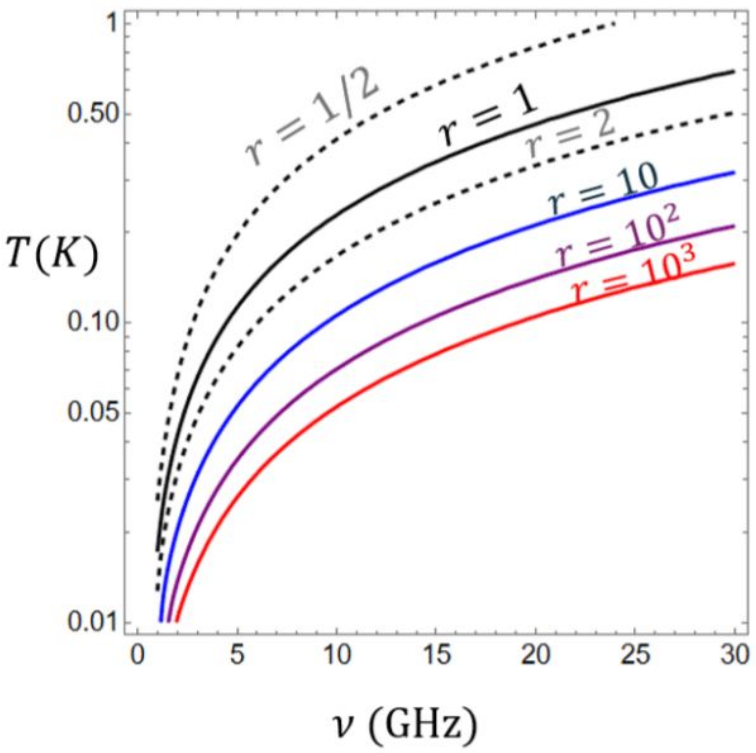
At some point the photon occupation number for the thermal noise is equal to that of the amplifier noise set by the SQL.

What about higher frequencies?

What are the options?



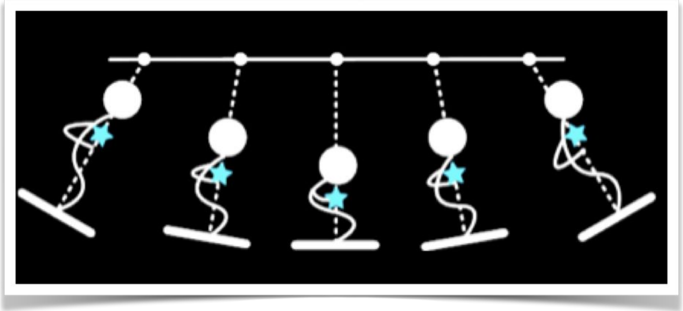
- Continuous wave amplifiers
  - Better at high temperature / low frequencies
- Photon counters
  - Better at low temperatures / high frequencies

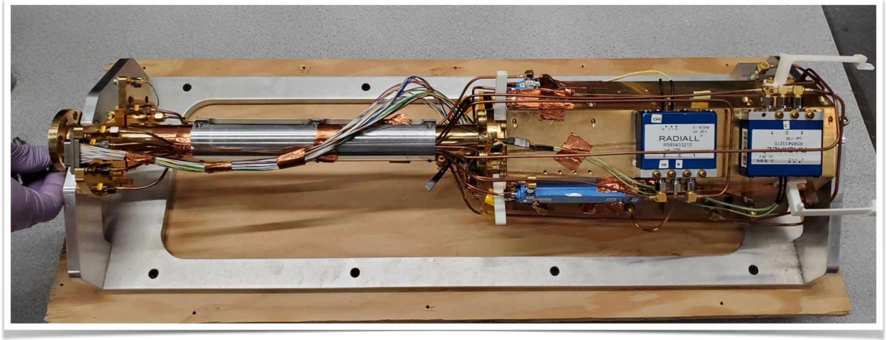
$$r = \frac{\text{photon counting scan rate}}{\text{amplifier scan rate}}$$

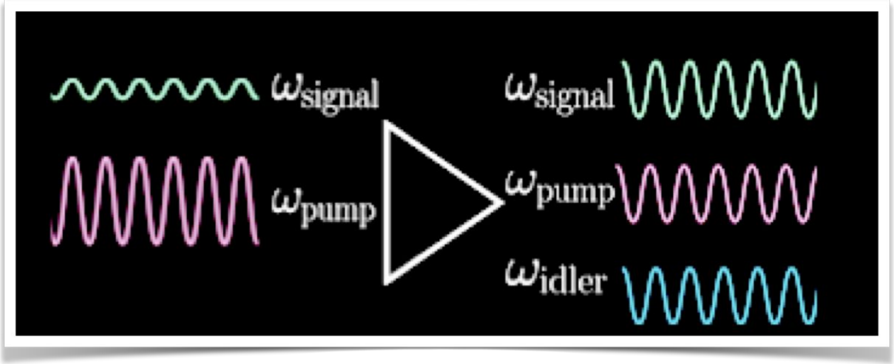
Kuo, Chao-Lin, et al. "Maximizing quantum enhancement in axion dark matter experiments." *Physical Review D* 111.12 (2025): 123018.

Continuous wave amplification

- Parametric amplification
  - Classic example is child on a swing
- Anharmonicity leads to energy transfer from the pump tone to the signal tone
- Requires some non-linear element
  - Josephson Junction
  - Kinetic inductance



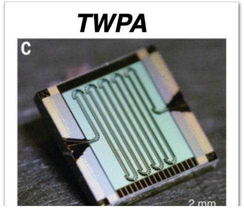


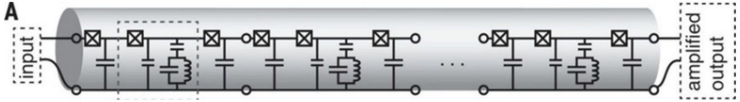


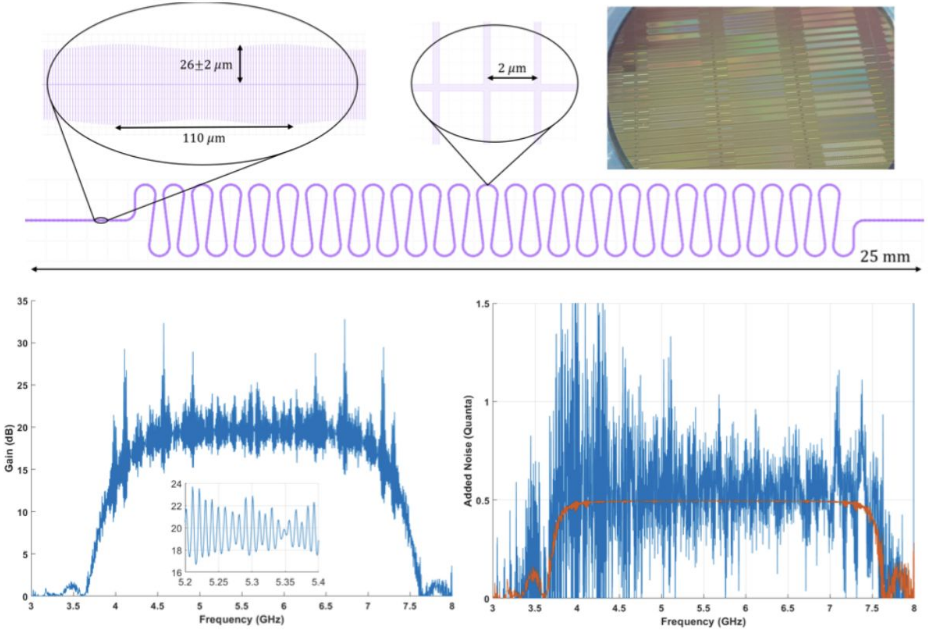
Continuous wave amplification

- Josephson parametric amplifiers (JPAs)
- Josephson traveling wave parametric amplifiers (JTWPAs)
- Kinetic Inductance traveling wave parametric amplifiers (KI-TWPAs)

O(100) Josephson junctions



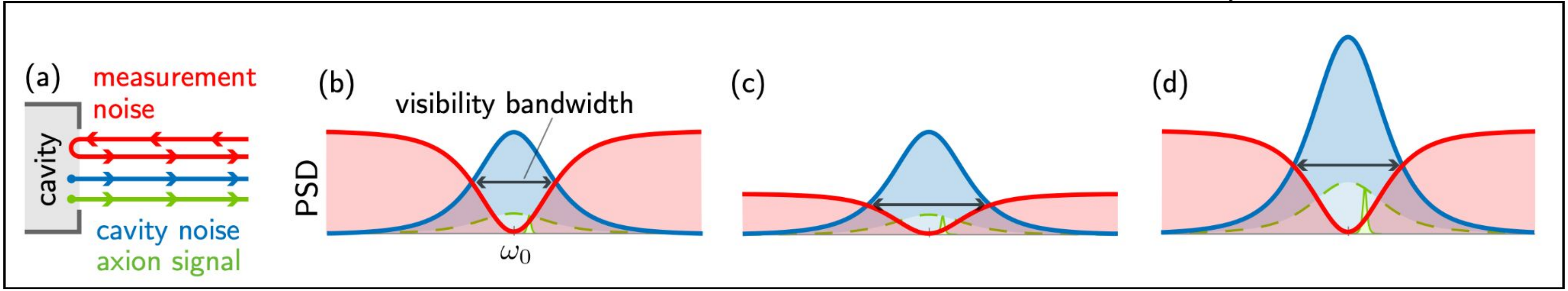




KI-TWPA chip and performance
Klimovich, N. et al. (2023).
arXiv:2306.11028

Squeezing: noise is ‘squeezed’ into one quadrature

Courtesy of Konrad Lehnert



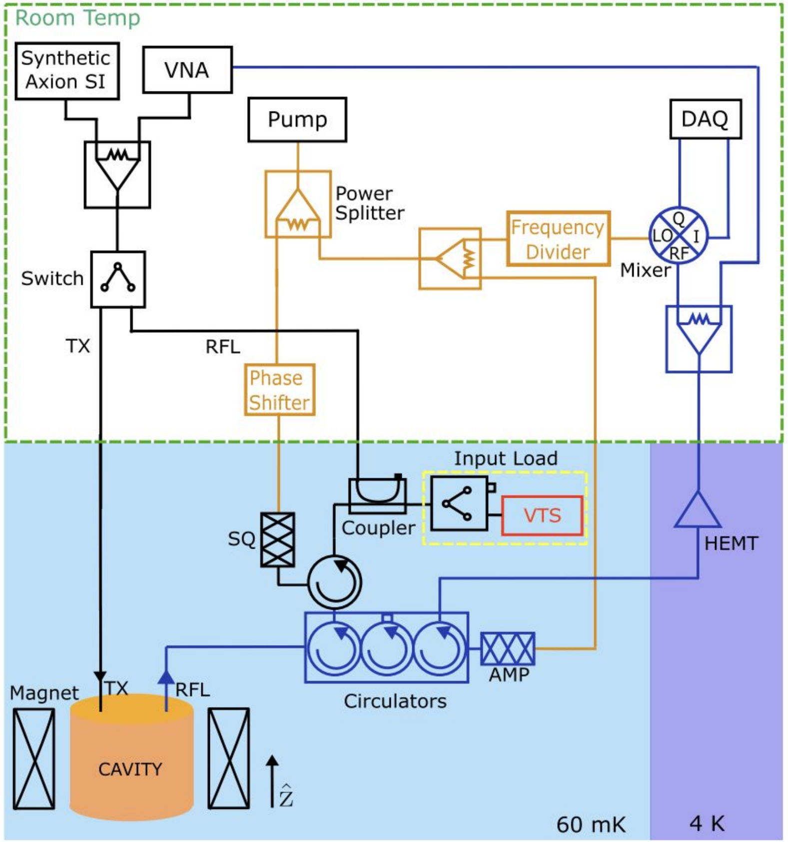
(a) Measurement noise originates outside and reflects off the cavity

(b) The signal, detector noise and measurement noise all contribute to the power spectrum

(c) The measurement noise is prepared in a squeezed state. Signal + detector noise are unchanged.

(d) Signal + detector noise are amplified together before being polluted by measurement noise

Squeezed state receiver in an axion dark matter search



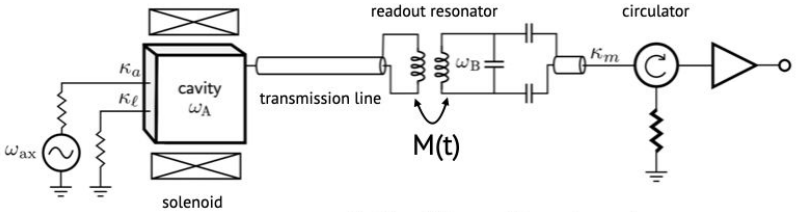
Bai, Xiran, et al. "Dark matter axion search with HAYSTAC phase II." *Physical Review Letters* 134.15 (2025): 151006.

- Haystac experiment uses two Josephson parametric amplifiers (JPA) in a squeezed state receiver setup.

- Dominant loss mechanism is the circulators.

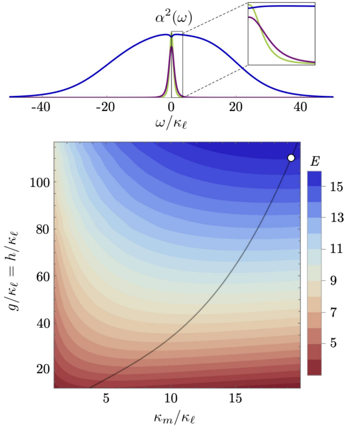
- Conceptual solution: “CEASEFIRE” concept.
    - Wurtz, K., et al. "Cavity entanglement and state swapping to accelerate the search for axion dark matter." *PRX Quantum* 2.4 (2021): 040350.

Entanglement in an axion dark matter search

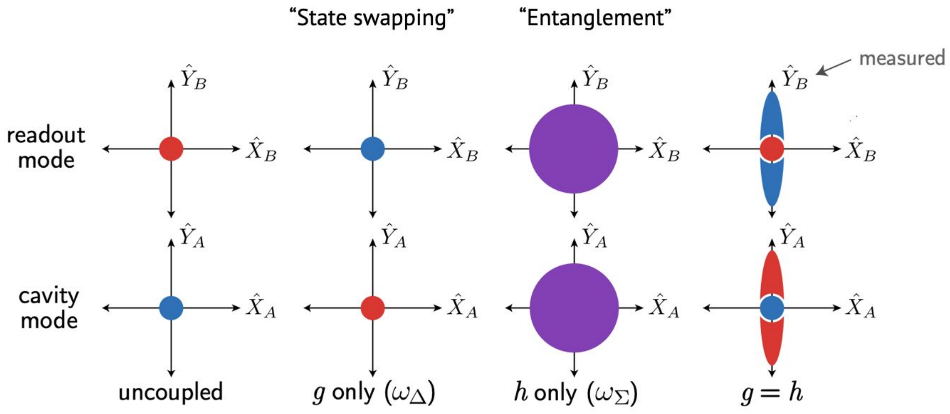


Modulate M(t) at two different frequencies

$$\omega_\Sigma = \omega_B + \omega_A$$
$$\omega_\Delta = \omega_B - \omega_A$$



Predicts scan rate enhancements between 10 and 15



Uncoupled vacuum states of the readout resonator and cavity are represented by circles

Modulate M(t) at difference frequency

Modulate M(t) at sum frequency

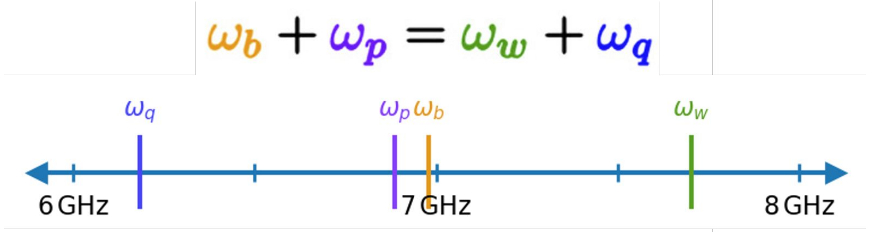
"amplified linear combination of uncoupled states"

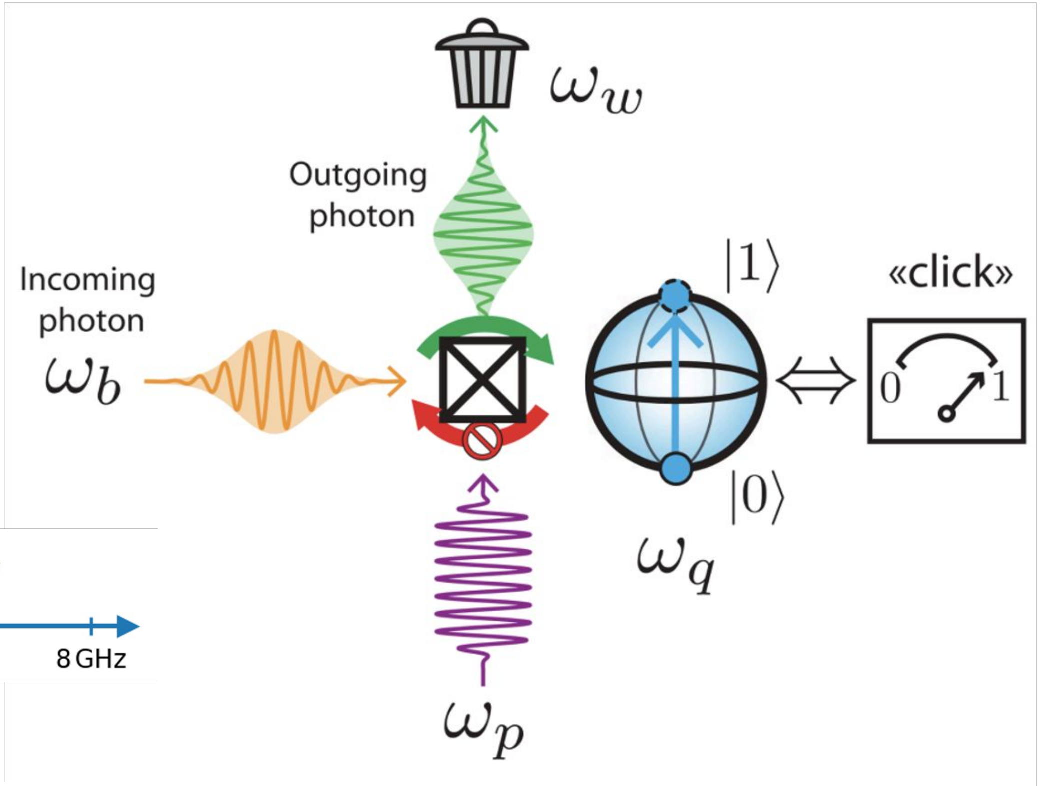
Both

Measured readout mode quadrature has only measurement noise (reflected with unit magnitude) and amplified cavity noise

Photon counters in the microwave are possible

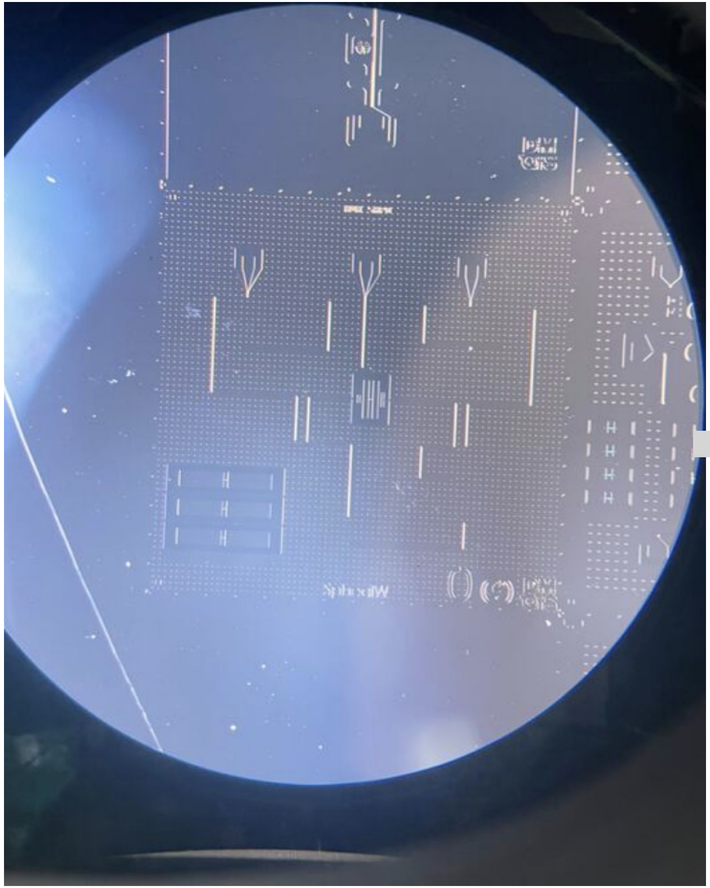
- Single Microwave Photon Detectors
- Four wave mixing due to the Josephson Effect



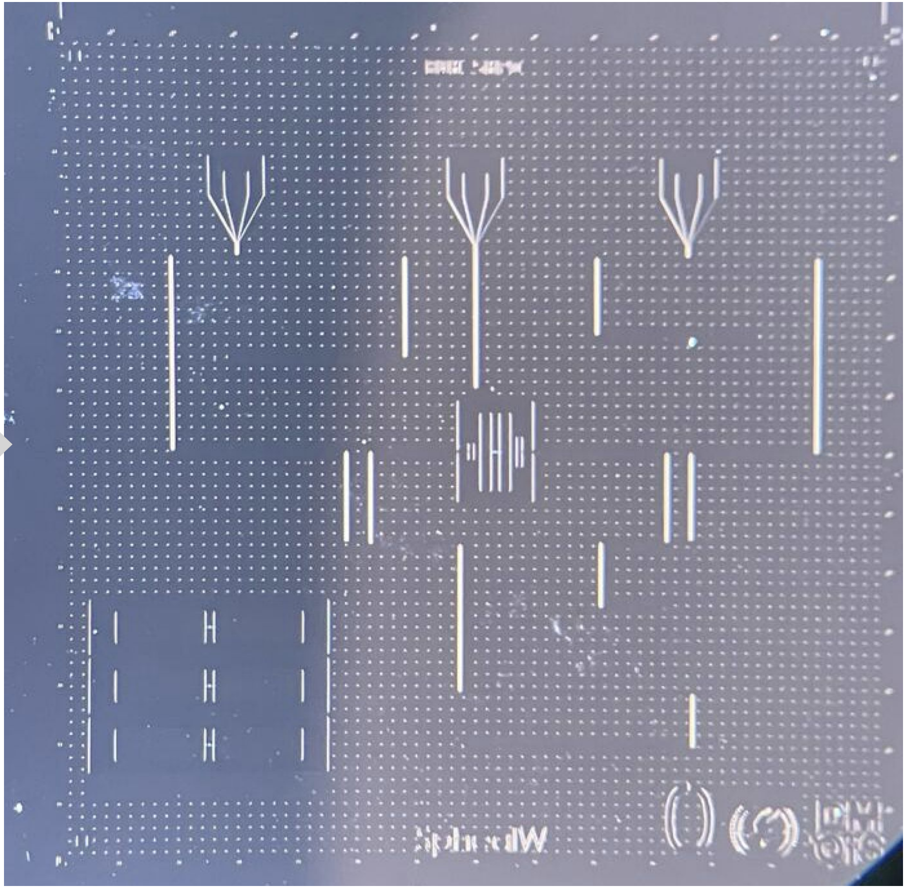


Lescanne, Raphaël, et al. "Irreversible qubit-photon coupling for the detection of itinerant microwave photons." *Physical Review X* 10.2 (2020): 021038.

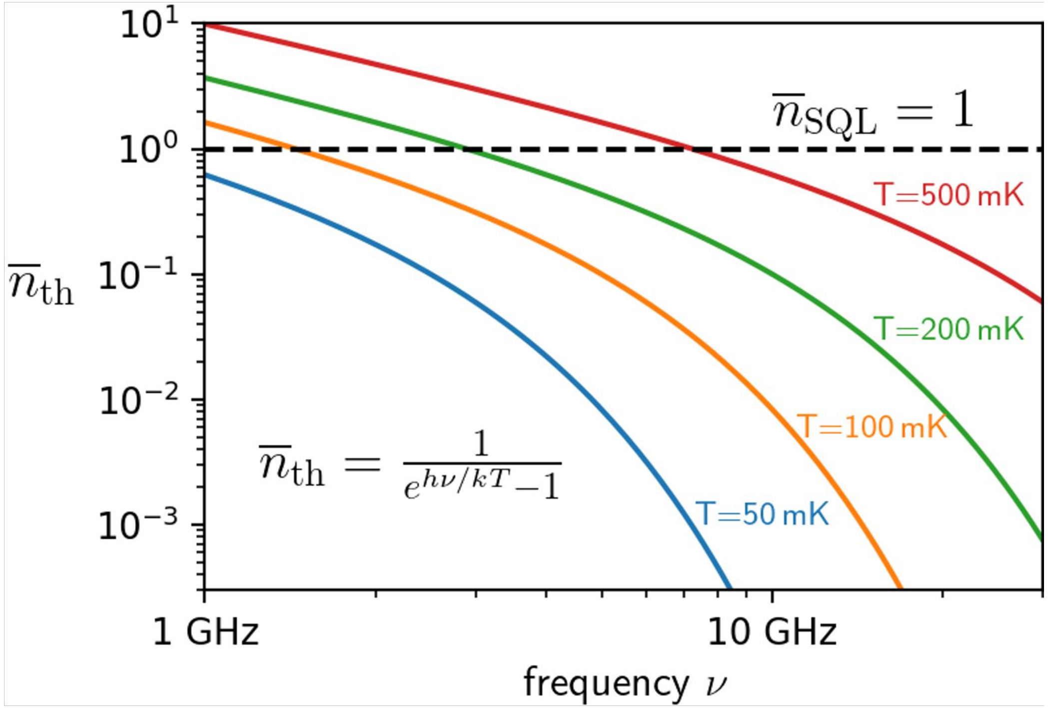
Photon counters in the microwave are possible



Zoom



What are the options?



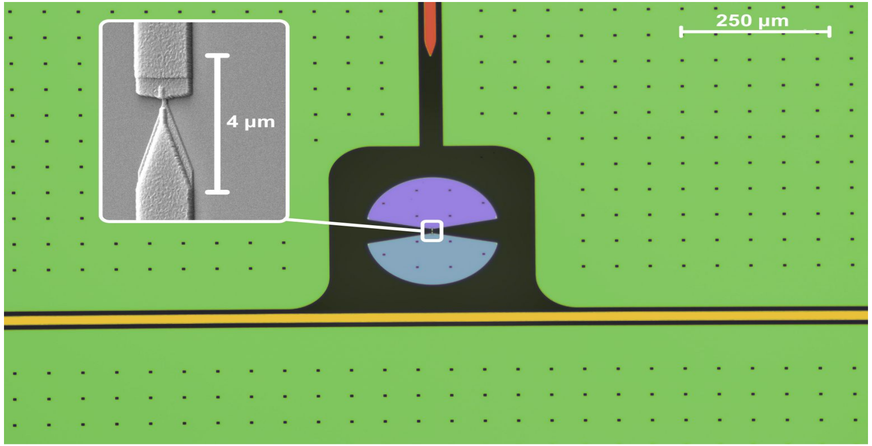
- Photon counting when limited by thermal dark counts can do orders of magnitude better than the SQL.

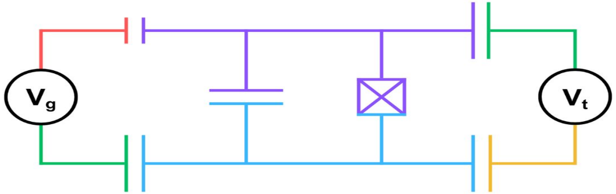
Kuo, Chao-Lin, et al. "Maximizing quantum enhancement in axion dark matter experiments." *Physical Review D* 111.12 (2025): 123018.

SQUATS

Superconducting Quasiparticle Amplifying Transmons

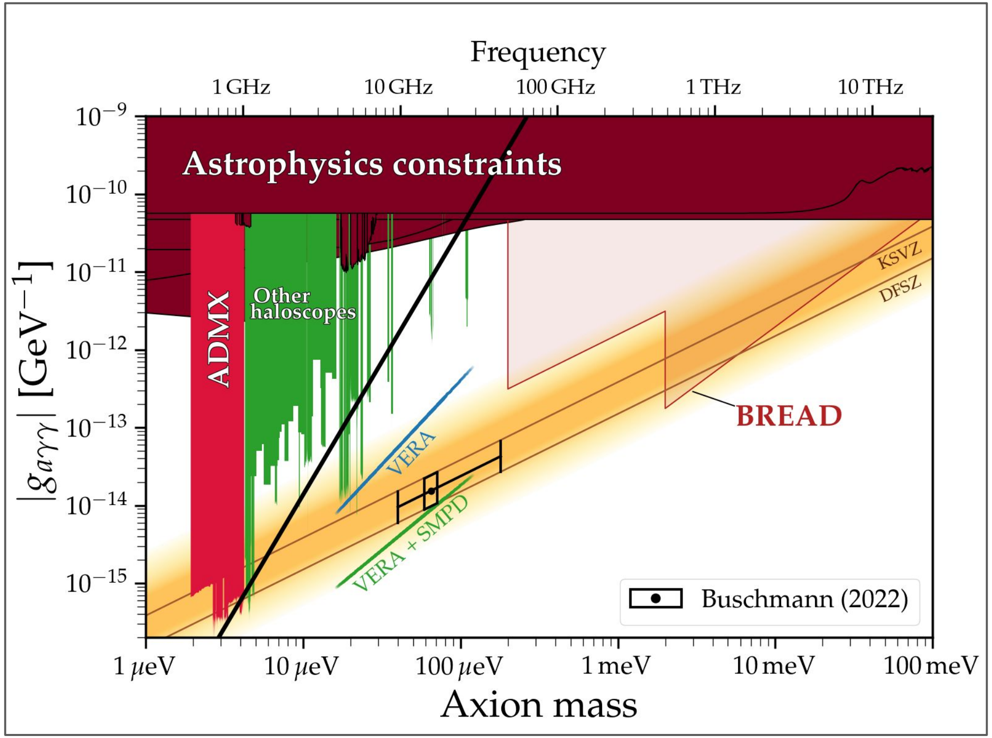
- Photons directly absorbed by the large capacitor “fins” (designed to operate as antennas)
- Phonons produced in the substrate can be absorbed by those same fins
- Photon/phonon energy breaks Cooper-pairs in the superconducting fins
- Increased quasiparticle density increases tunneling rate
- Tunneling rate measured using RF probe signal in CPW transmission line





Courtesy of Taylor Aralis and Noah Kurinsky

Sensitivity projection of post-inflationary axion space



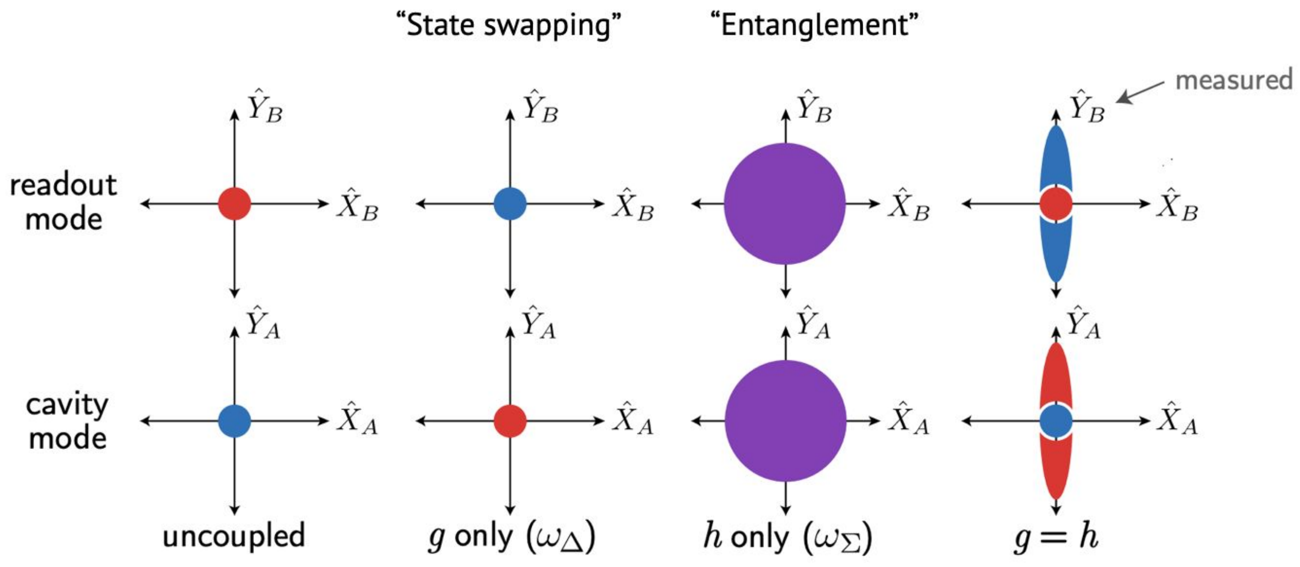
Assuming the use of state of the art quantum sensing techniques such as SMPDs and SQUATS

Able to achieve sensitivity to the QCD axion over a wide range with typical integration times

Conclusion

- Exciting time for the field of quantum measurement!
- Implications for particle and nuclear physics
- Propelled the field of particle physics in the context of axion dark matter (suddenly a new particle may be within reach!)
- Related applications such as spin measurement, neutrino mass measurement, and any measurement requiring detection of small EM signal.

Thank you!



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