Quantum Measurement for Axion Dark Matter Searches

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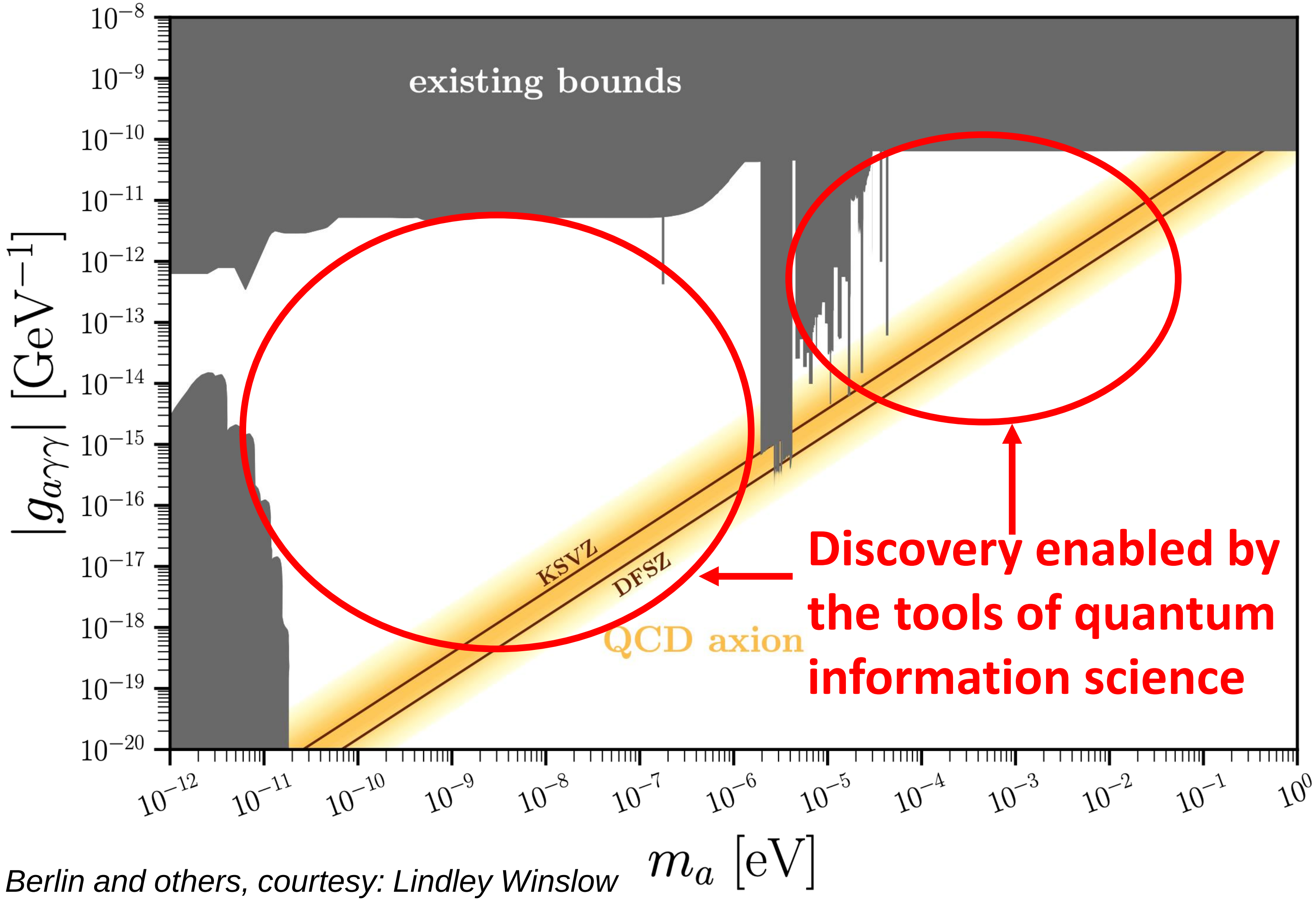
Introduction to QCD axions

- Originally motivated as a solution to strong CP problem (Peccei, Quinn, Weinberg, Wilczek)
  - $U(1)_{PQ}$ symmetry introduced to conserve CP in QCD
  - QCD axion: pseudo-Nambu-Goldstone boson introduced when breaking symmetry
- QCD axions have feeble couplings to photons, nucleons, and electrons -> natural DM candidate
- Sikivie, 1983 and 1985: cavity haloscope to search for QCD axion DM
  - Resonant enhancement often key for searches

The grand challenge: QIS-enabled probes of axion dark matter

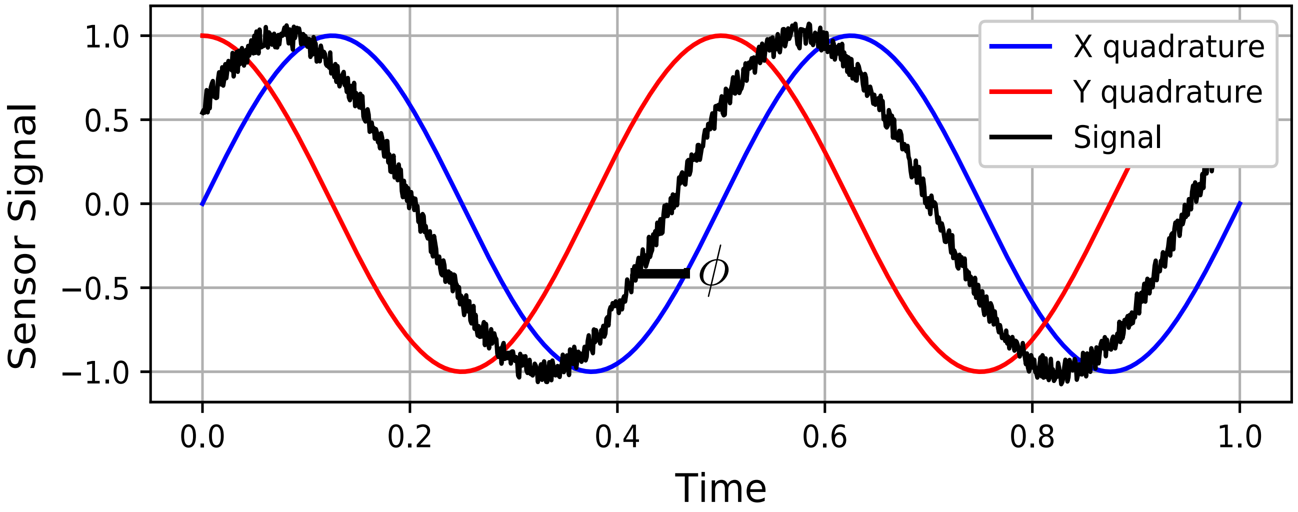


A. Berlin and others, courtesy: Lindley Winslow

- New theoretical understanding of QCD axions has motivated the entire peV-eV mass range
- Rapid growth in quantum information science (QIS) has birthed new techniques with unprecedented sensitivity
- Community effort over the next 20 years to use these techniques for a comprehensive probe of QCD axion dark matter

SQL for electromagnetism

- A generic E&M signal has sine and cosine components which do not commute.
- Heisenberg uncertainty principle: we cannot measure both perfectly, so an amplifier must add noise
- "Standard quantum limit" achieved when both components measured as well as possible, saturating Heisenberg
- Equivalent to one photon of noise



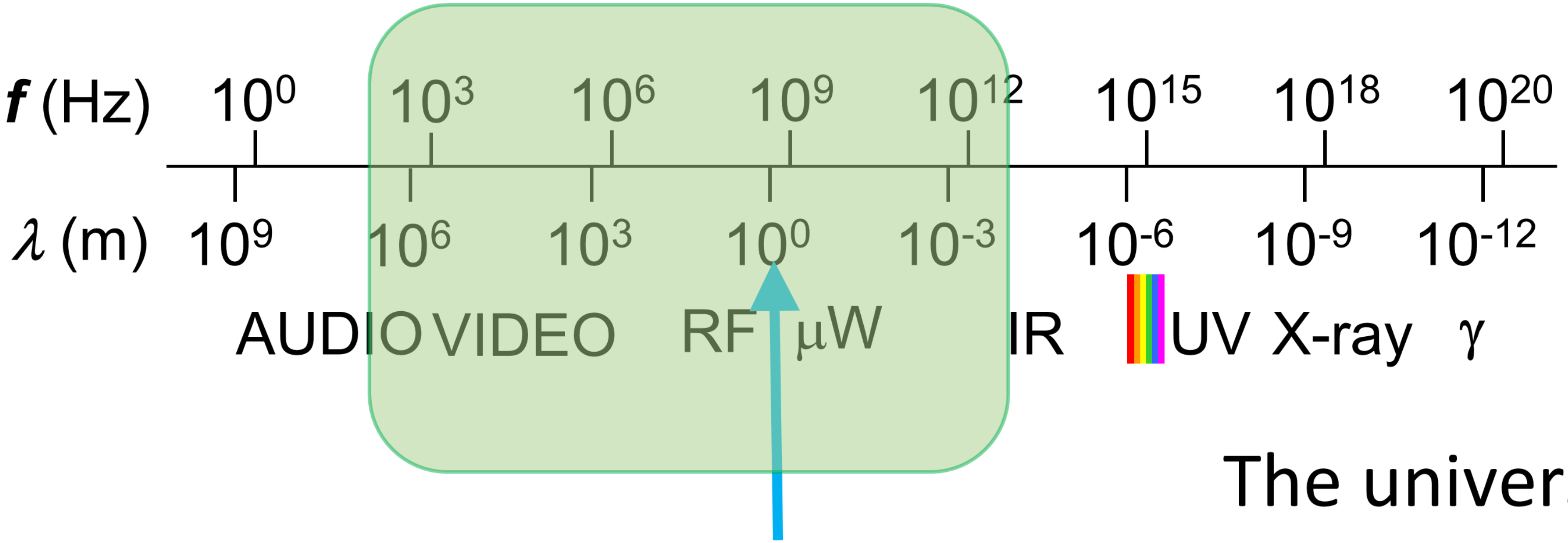
$$[\hat{X}, \hat{Y}] = i$$

Commutator

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

Heisenberg Uncertainty Relation

QCD axion band spans two regions for SQL evasion: smaller-than-human and larger-than-human scale

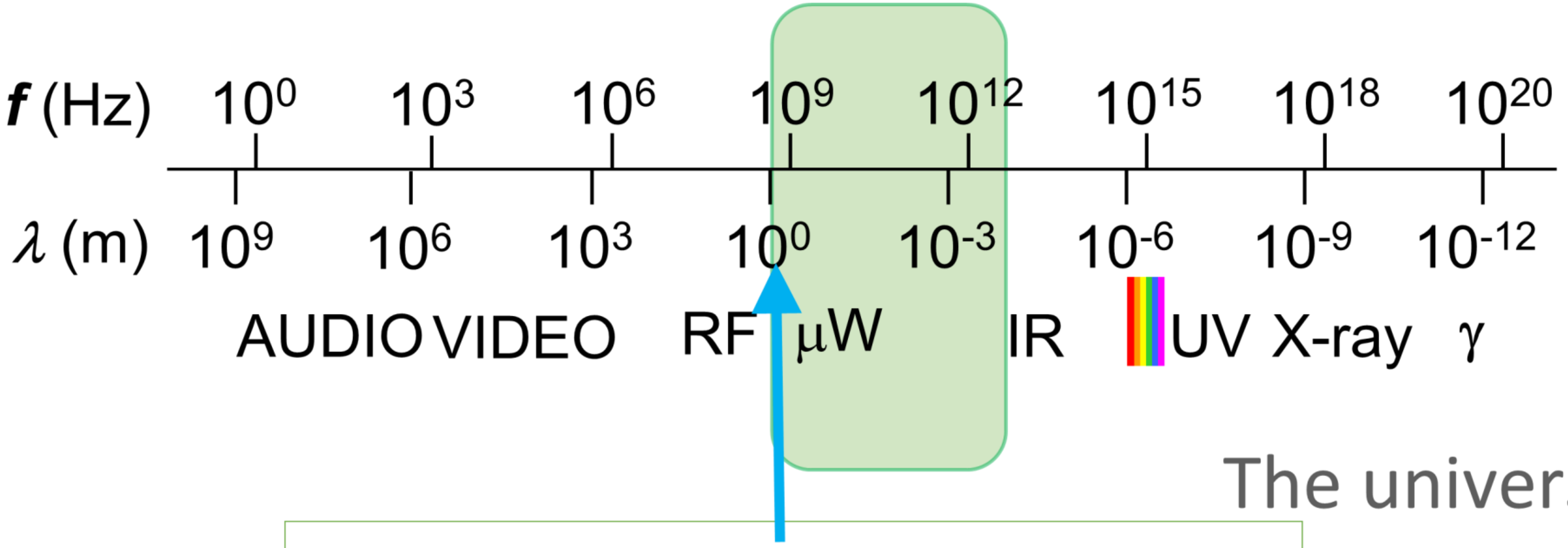


The universe ~ 2.7 K

300 MHz ~ 0.015 Kelvin ~ 1 m

300 MHz ~ human scale ~ dilution refrigerator temperature

Smaller than human: post-inflationary axion



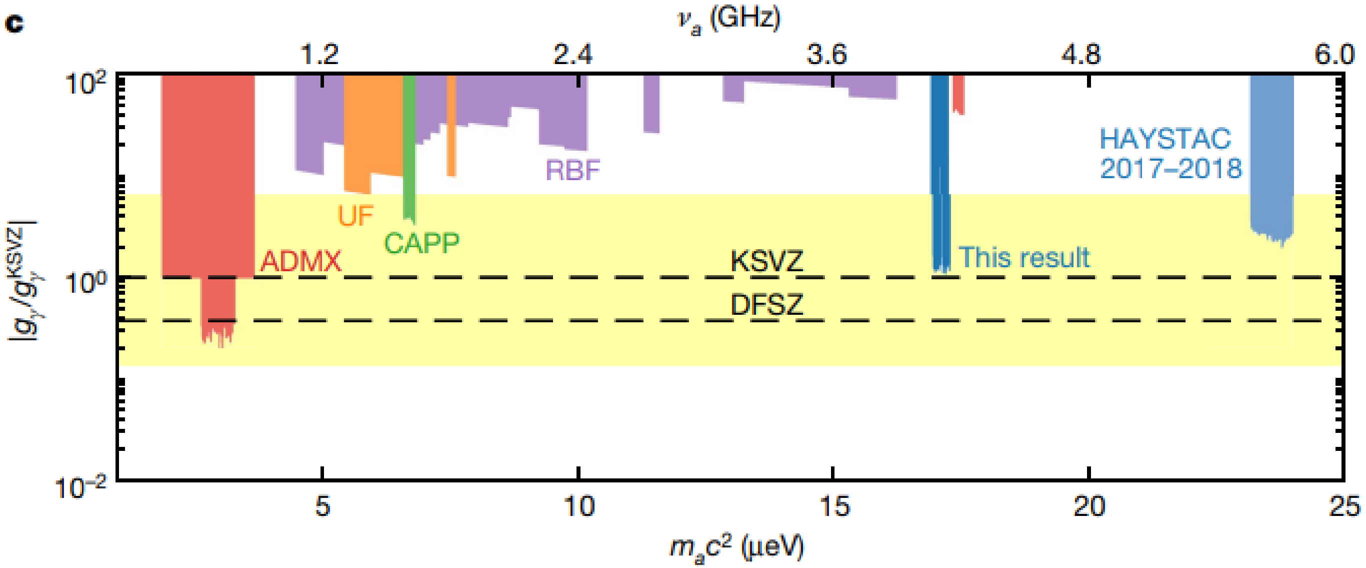
The universe ~ 2.7 K

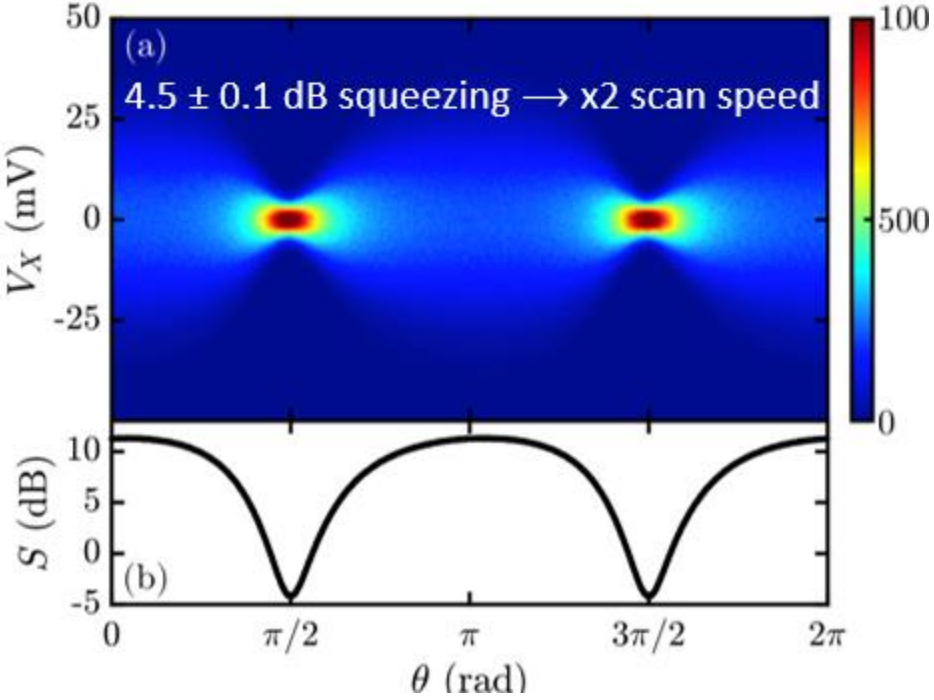
300 MHz ~ 0.015 Kelvin ~ 1 m

- Top ~40% of QCD axion band
- Squeezing, state swapping, photon counting, Fock state engineering…
- ADMX, HAYSTAC, BREAD, MADMAX, etc.

HAYSTAC: squeezing to accelerate axion search

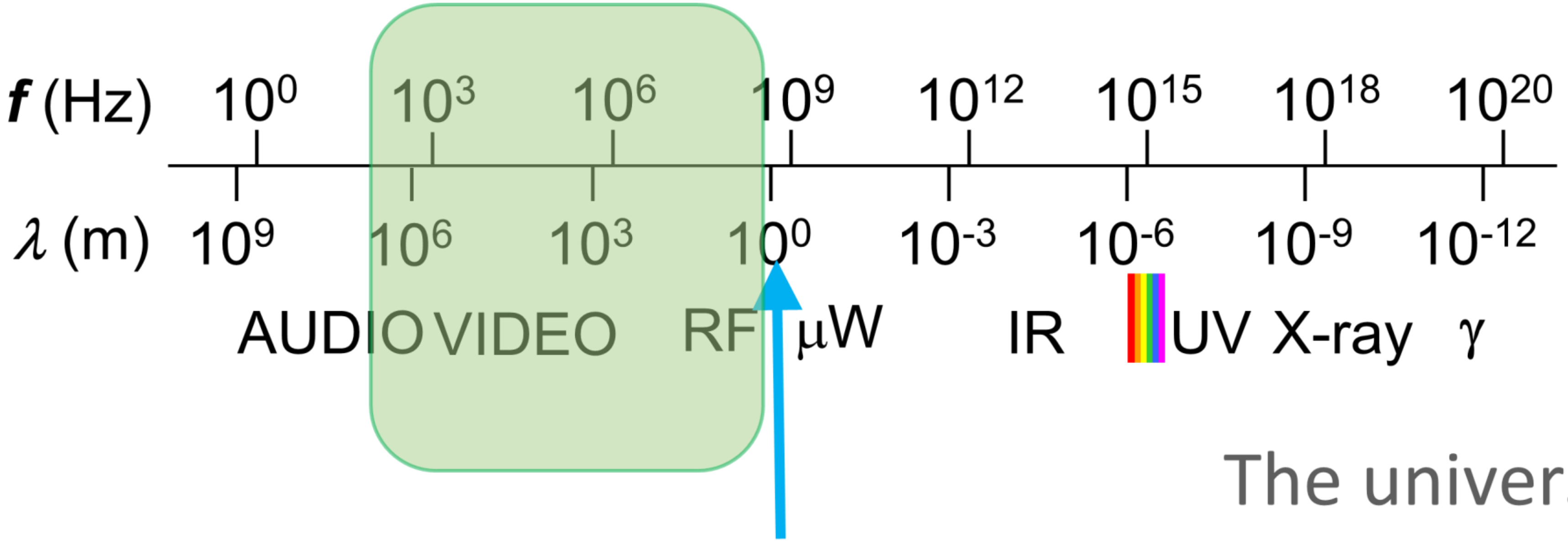
- May evade SQL by measuring one quadrature with lower noise, while increasing noise in the other quadrature
- Squeezing on GHz resonators in vacuum states demonstrated in QCD axion search by HAYSTAC





K. Backes et al, *Nature* (2021), figure courtesy of Karl van Bibber of HAYSTAC collaboration

Larger than human: pre-inflationary axion

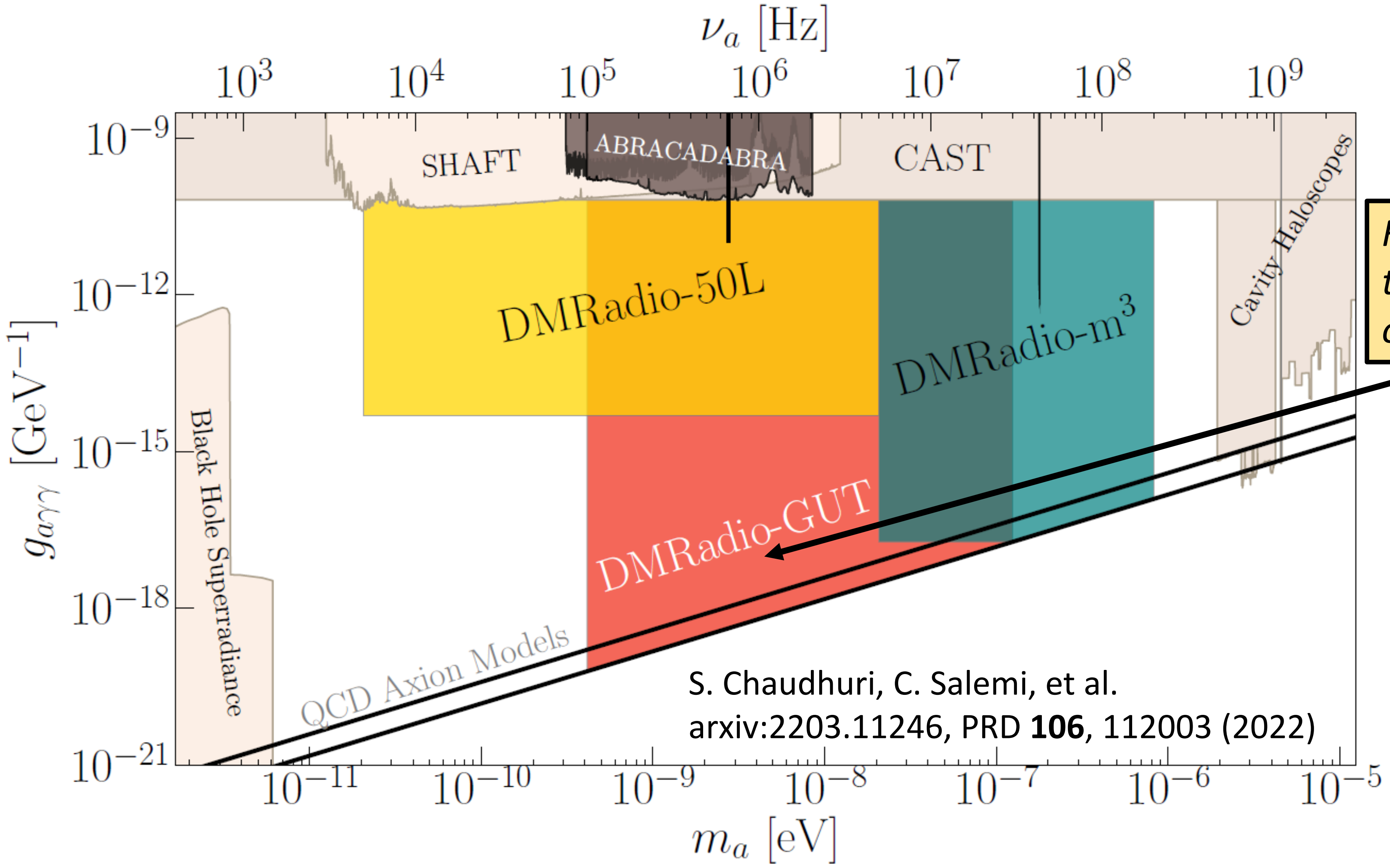


The universe ~ 2.7 K

300 MHz ~ 0.015 Kelvin ~ 1 m

- Bottom ~60% of QCD axion band
- Photon counting of resonator thermal state not advantageous
- DMRadio, CASPEr-Electric, etc

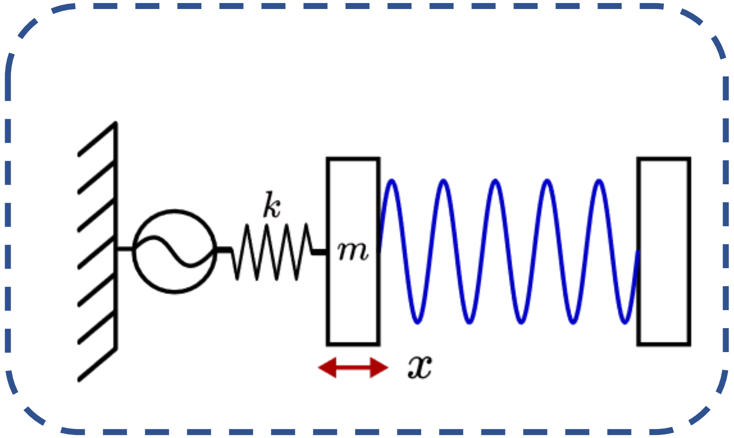
DMRadio-GUT: ambitious, long-term goal for GUT-scale axion search



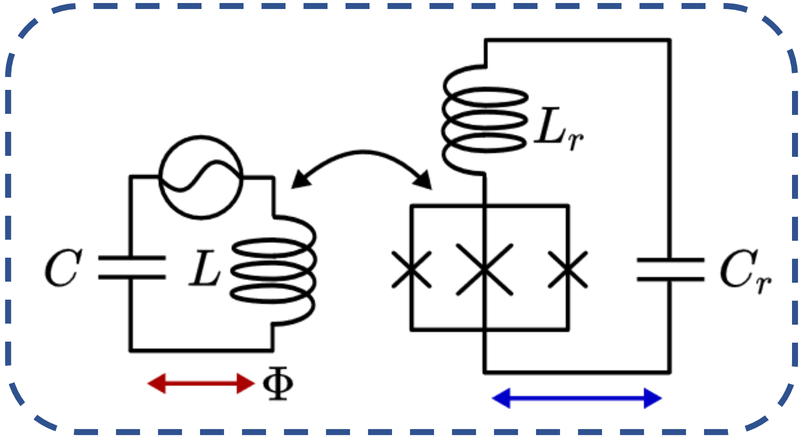
Requires techniques evading the Standard Quantum Limit of amplification

RF Quantum Upconverters: Analogous to optomechanical systems

LIGO:



Axion detector with RQU:



$$\omega_b = \sqrt{\frac{k}{m}} \qquad \omega_a = \frac{\pi c}{l(x)} \qquad \omega_b = \sqrt{\frac{1}{LC}} \qquad \omega_a = \sqrt{\frac{1}{L_r(\Phi)C_r}}$$

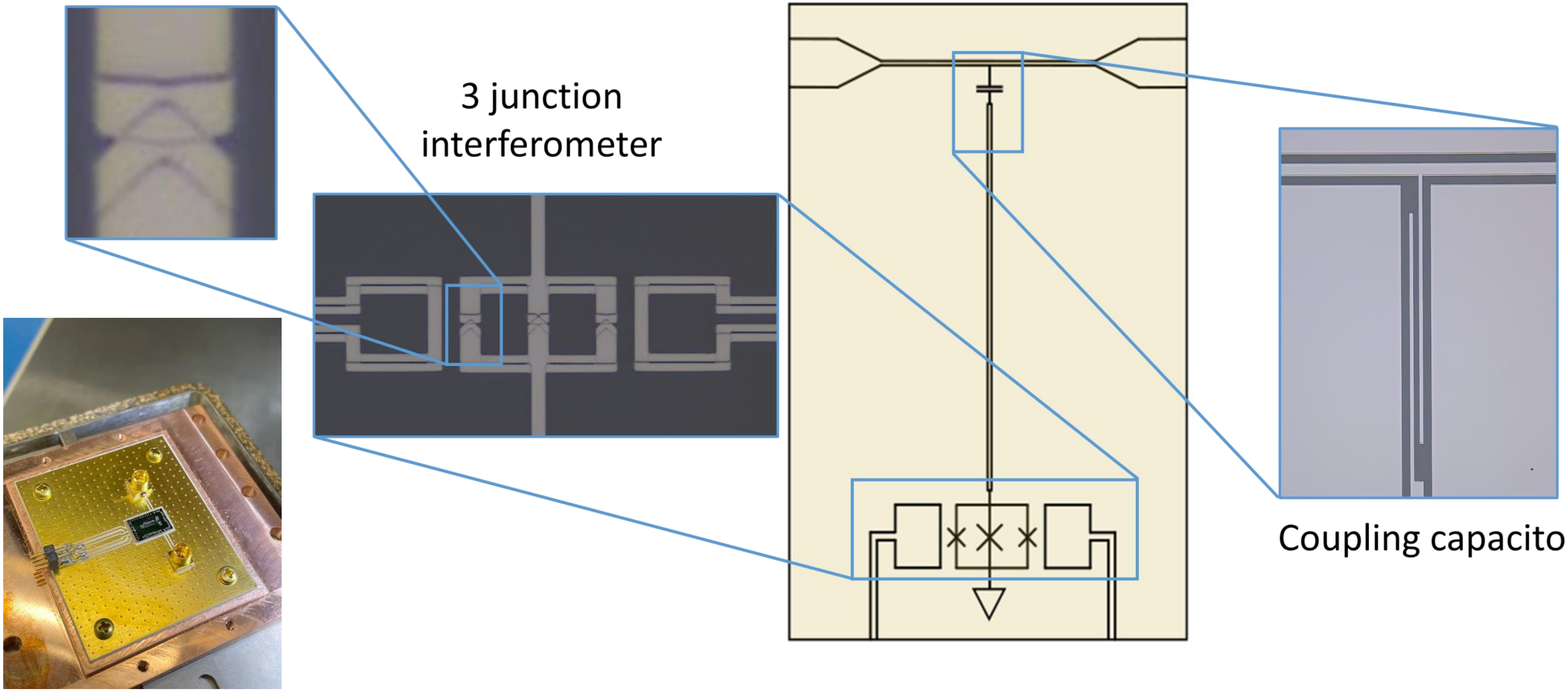
Exploit mature microwave quantum technologies and mimic existing optomechanical protocols to enhance sensitivity in DMRadio at kHz-MHz frequencies.

Same Hamiltonian for both systems (to first order in coupling)

$$\hat{\mathrm{H}} = \hbar\omega_a\left(\hat{a}^\dagger\hat{a} + 1/2\right) + \hbar\omega_b\left(\hat{b}^\dagger\hat{b} + 1/2\right) + \hat{\mathrm{H}}_{\mathrm{INT}}$$

$$\hat{\mathrm{H}}_{\mathrm{INT}} = -\hbar g_0 \hat{a}^\dagger\hat{a}\,(\hat{b} + \hat{b}^\dagger)$$

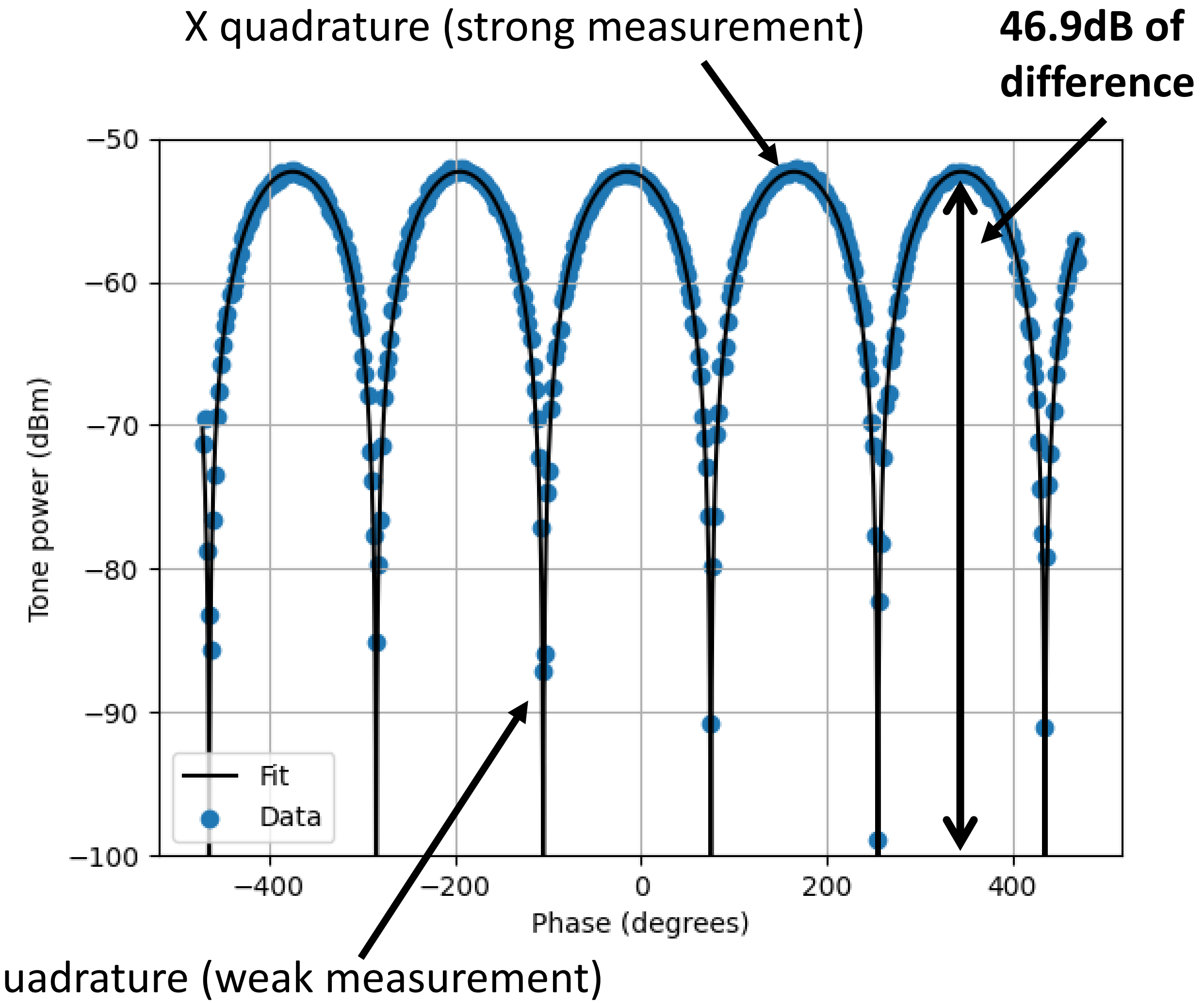
First RQUs fabricated!



Credit: E.C. van Assendelft, Irwin Group, Stanford

Phase-sensitive amplification with the RQU

- Backaction evasion (BAE): reduce backaction in one quadrature at expense of increased backaction in the other.
- Demonstrated first step toward realizing BAE: phase-sensitive amplification with amplitude modulated drive (Clerk et al, *NJP*, 2008)
    - Fit to ~50 dB extinction ratio
    - Robustly measure >30 dB
- Will be testing protocols in DMRadio-50L

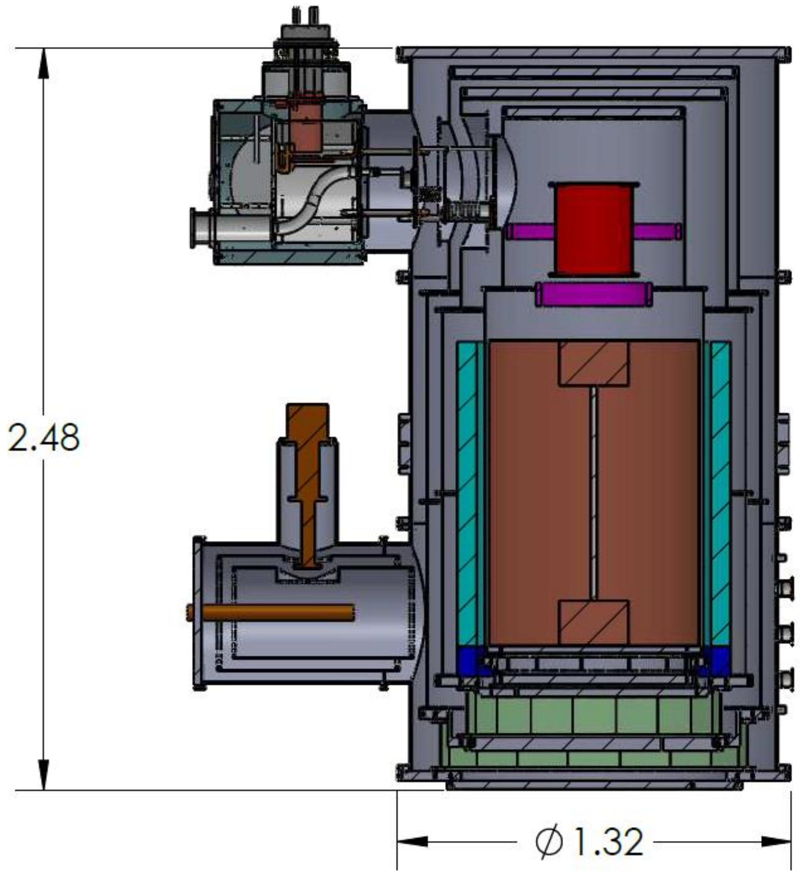


S. Kuenstner et al *arXiv:2210.05576* (2022)

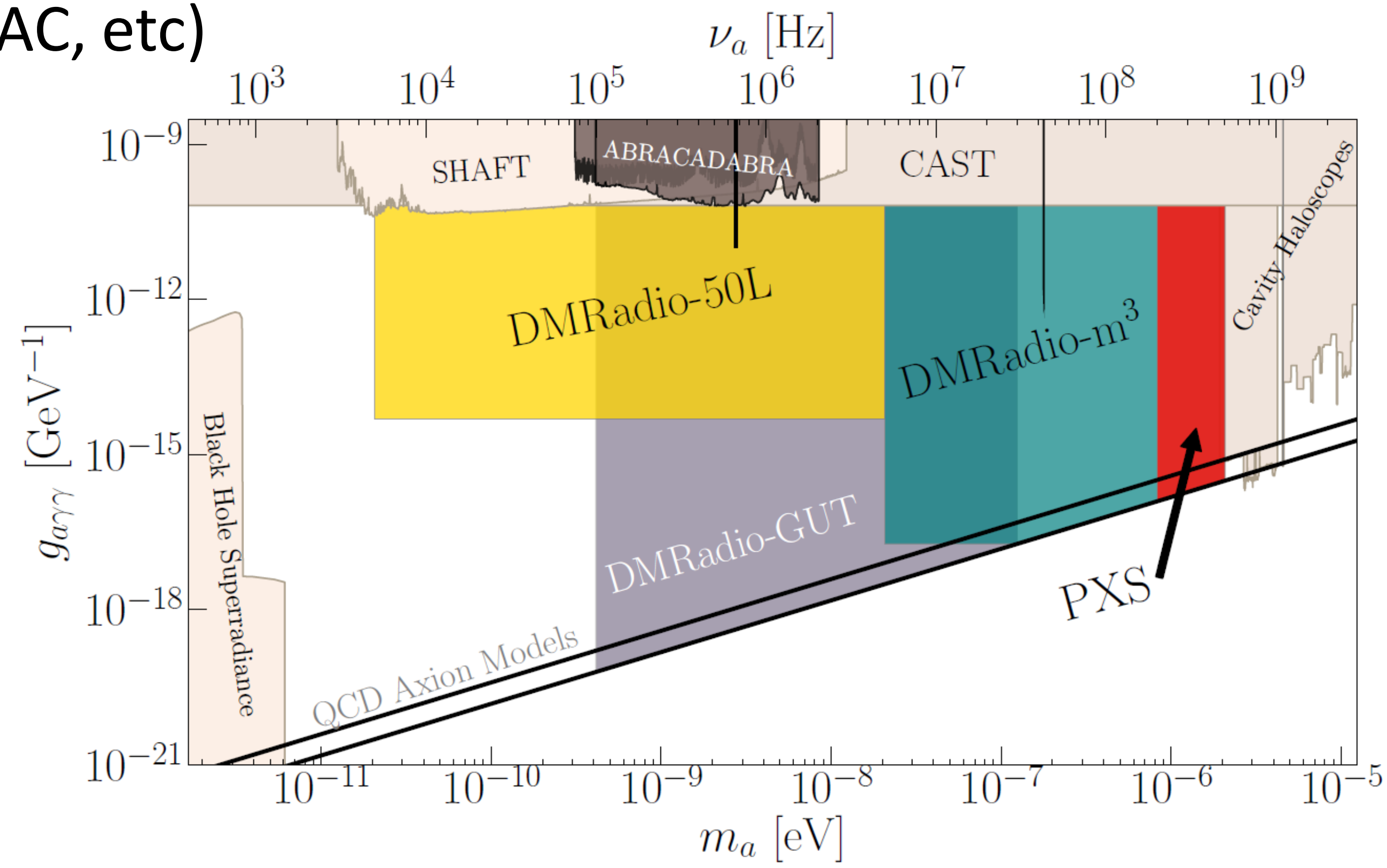
Significant step toward full SQL evasion

Princeton Axion Search (PXS): probing 200-500 MHz QCD axions

- Supported by Simons Foundation, in collaboration with DOE PPPL
- Addressing critical transitional mass range between DMRadio program and cavity haloscopes (ADMX, HAYSTAC, etc)



PXS Cryostat Drawing



Summary

- Exciting convergence of quantum measurement technologies and axion dark matter detection, promising breakthrough capabilities in fundamental physics.

- Different approaches being tailored to the different mass/frequency ranges.