

Quantum sensing for fundamental physics efforts at SQMS

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FERMILAB-POSTER-24-0274-SQMS

Introduction: One of the areas of research of the Superconducting Quantum Systems and Materials (SQMS) center is the application of quantum sensing to fundamental physics searches, demonstrating that quantum sensors can greatly improve the sensitivity of experiments searching for Beyond the Standard Model (BSM) physics, or performing high-precision measurements. Theorists have developed many ideas for BSM physics that would result in interactions that can in principle be detected, but with signals small enough that they haven't been observed yet.

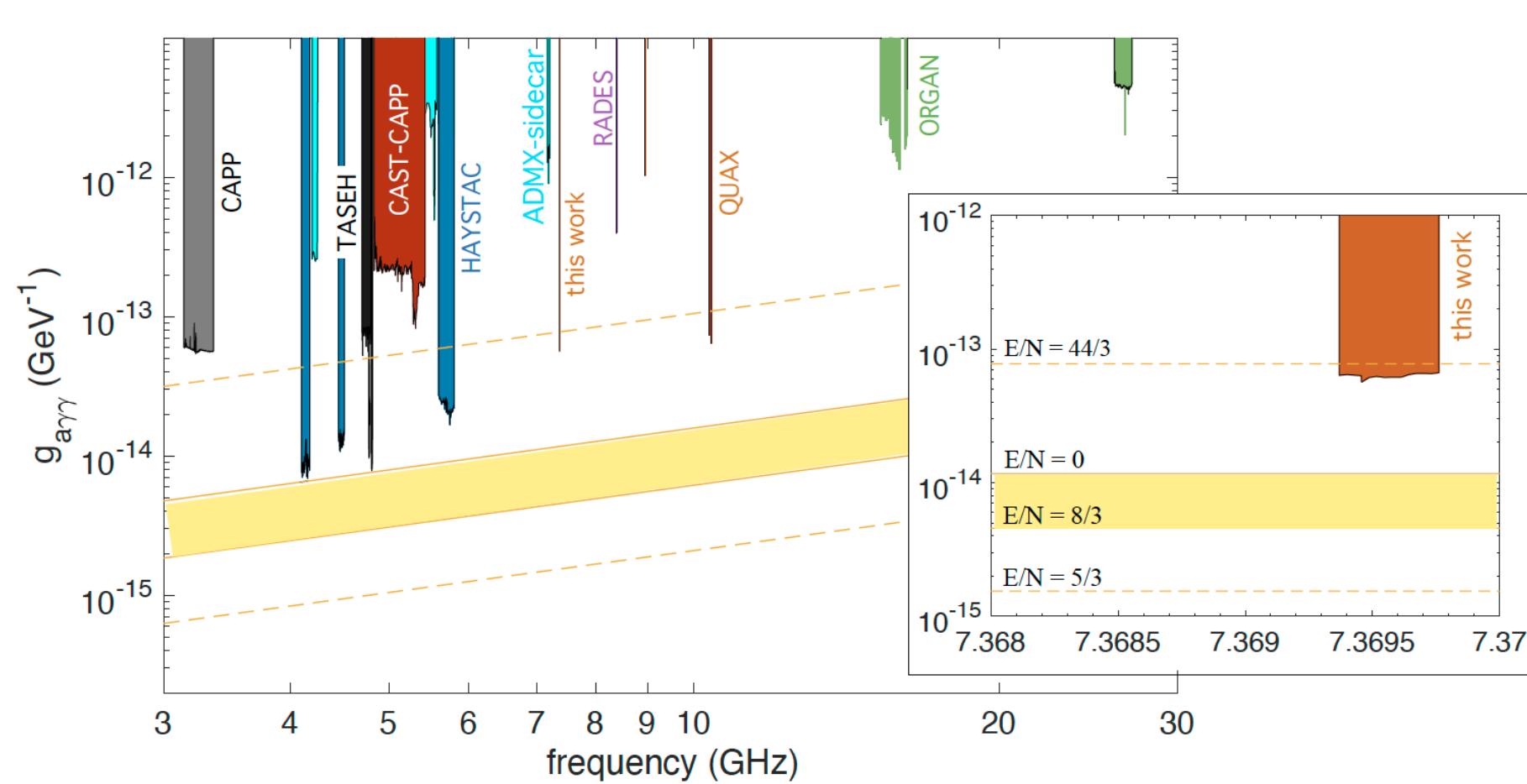
In this field, the capability to lower the detector's thermal noise to few or dozens of mK, and to use QIS technologies such as Josephson Parametric Amplifiers and photon counters (in-situ or itinerant) enable us to reach unprecedented sensitivities and faster scan rates.

Here is presented an overview of the quantum sensing efforts at SQMS [1], focusing on theoretical advancements and experimental searches for Dark Sector particles (as dark matter candidates and not), gravitational waves, and precision measurements. The experiments conducted, or under preparation, include axion dark matter (DM) [2,3], dark photon DM searches [4,5], light-shining-through-wall experiments [6], cavity-based searches for high frequency gravitational waves [7], and measurements of the electron magnetic moment [8].

Dark Sector Searches

Axion Dark Matter

Itinerant photon counting for axion DM [2]: **quantum enhanced search in high B field using single microwave photon detector and Cu cavity with NbTi film** → demonstrated acceleration by orders of magnitude in the search scan rate and simplification of the data acquisition and analysis.



Figures taken from Ref. [2]

SHADE (Superconducting Heterodyne Axion Dark matter Experiment) [3,9]: one SRF cavity, no applied $\vec{B}$. **Leverages two-nearly degenerate modes to search for ultralight axion DM in heterodyne scheme** → $m_{axion} \approx \Delta f$.

Cavity temperature limited to 1.4-2K due to high field in pump mode, but **reducing temperature of readout quantum electronics would enable to approach or subvert the SQL.**

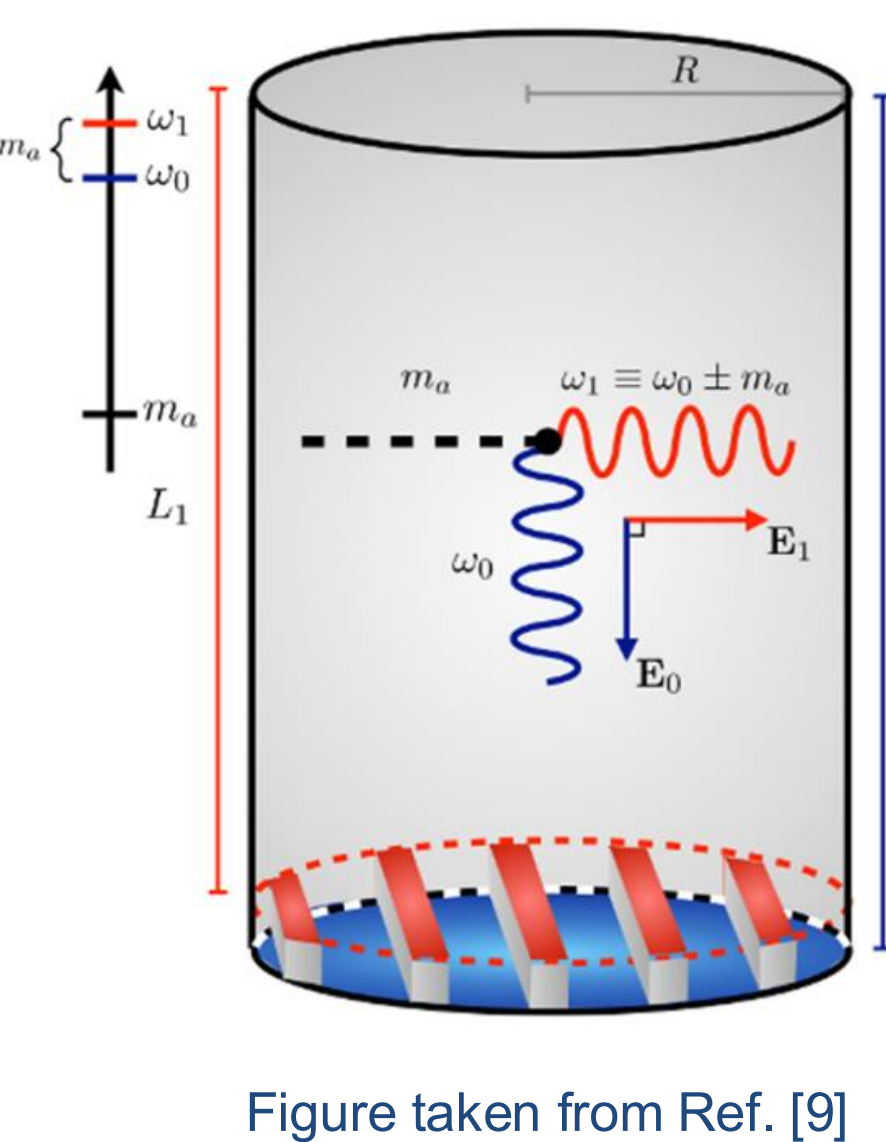
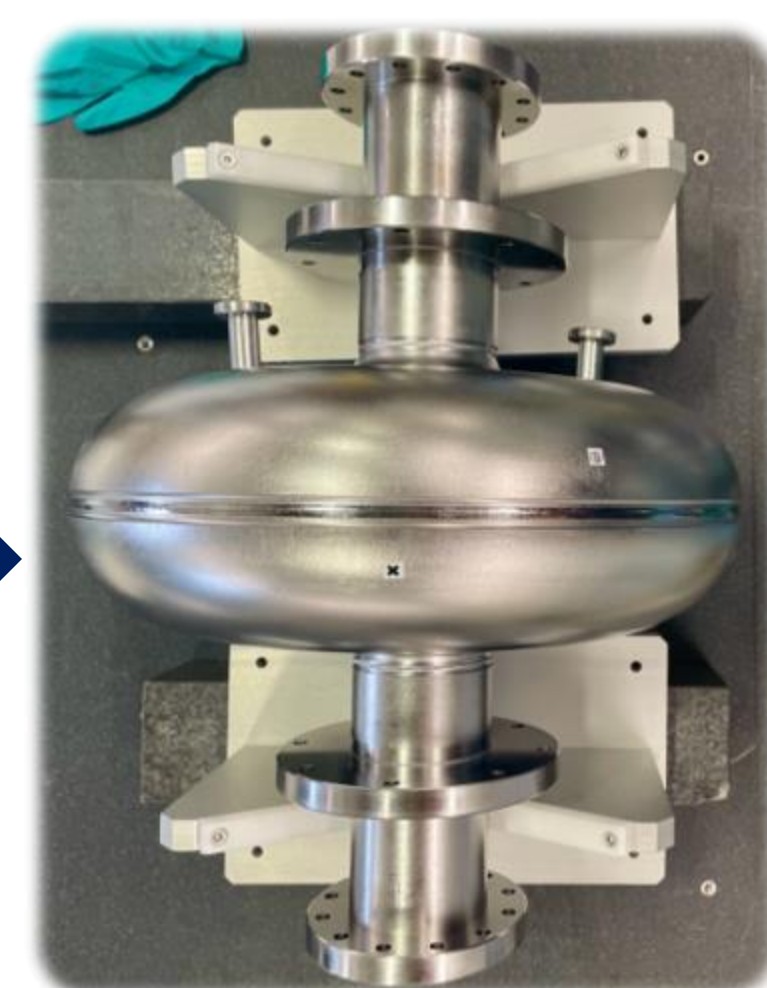
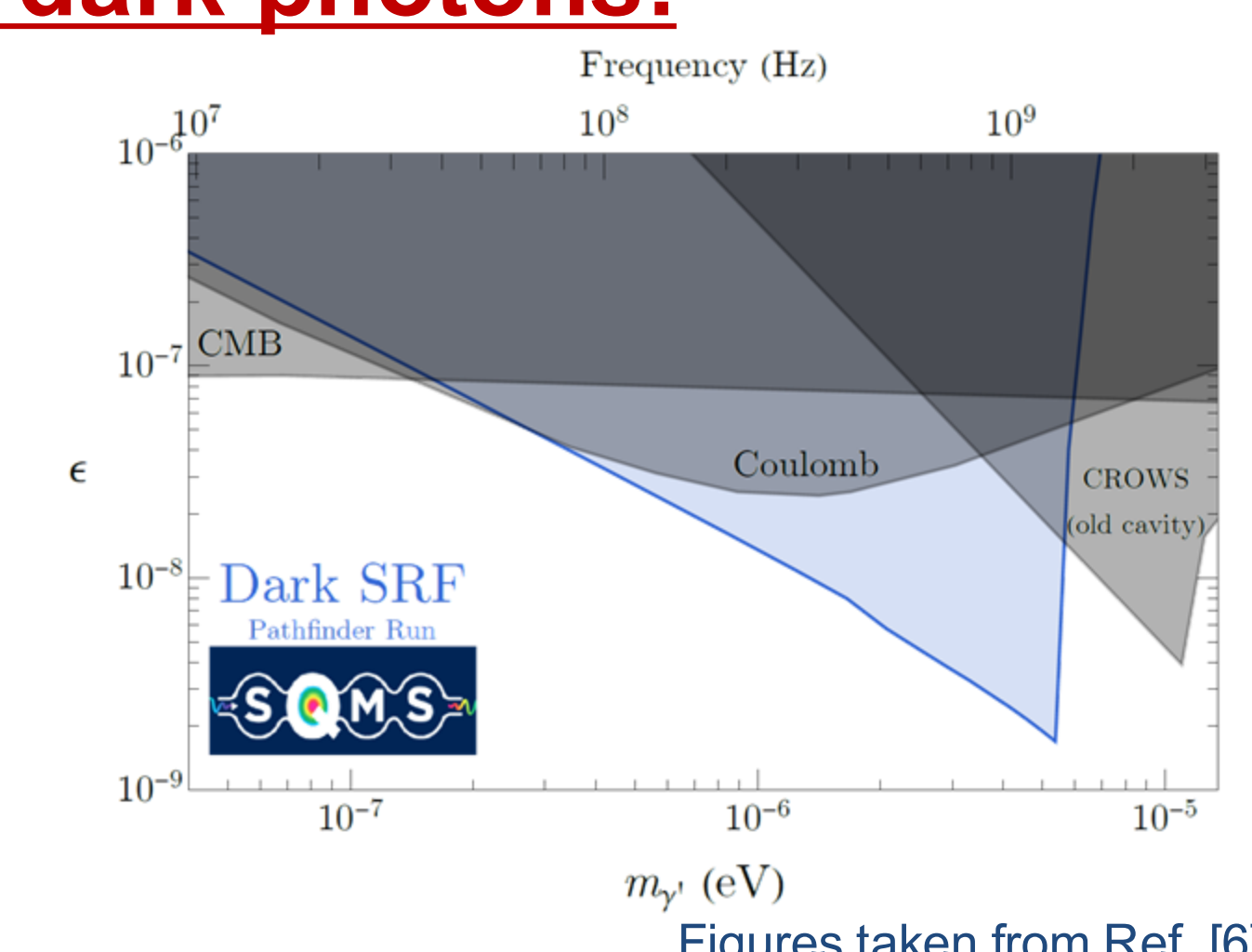


Figure taken from Ref. [9]



Light-Shining-Through-Wall search for dark photons:

Dark SRF 1.3GHz [6] → 1st proof of concept SC LSW search. In LHe, cavities matched to same frequency; emitter cavity excited to high field, receiver: silent, searching for power excess. **Dark SRF 2.6GHz** → deploy setup in dilution refrigerator to leverage low thermal background and quantum amplification for receiver cavity.



Figures taken from Ref. [6]

Dark Photon Dark Matter (DPDM)

SERAPH: Ultra-high Q SRF cavities for DM searches → demonstration of haloscope scan rate $\propto$ loaded quality factor, even with cavity bandwidth much narrower than DM halo line shape & **demonstration of deepest sensitivity to DPDM** [4]. **SERAPH 2.0:** Widely Tunable SRF cavity with high Q and subverting Standard Quantum Limit (SQL) with photon counting

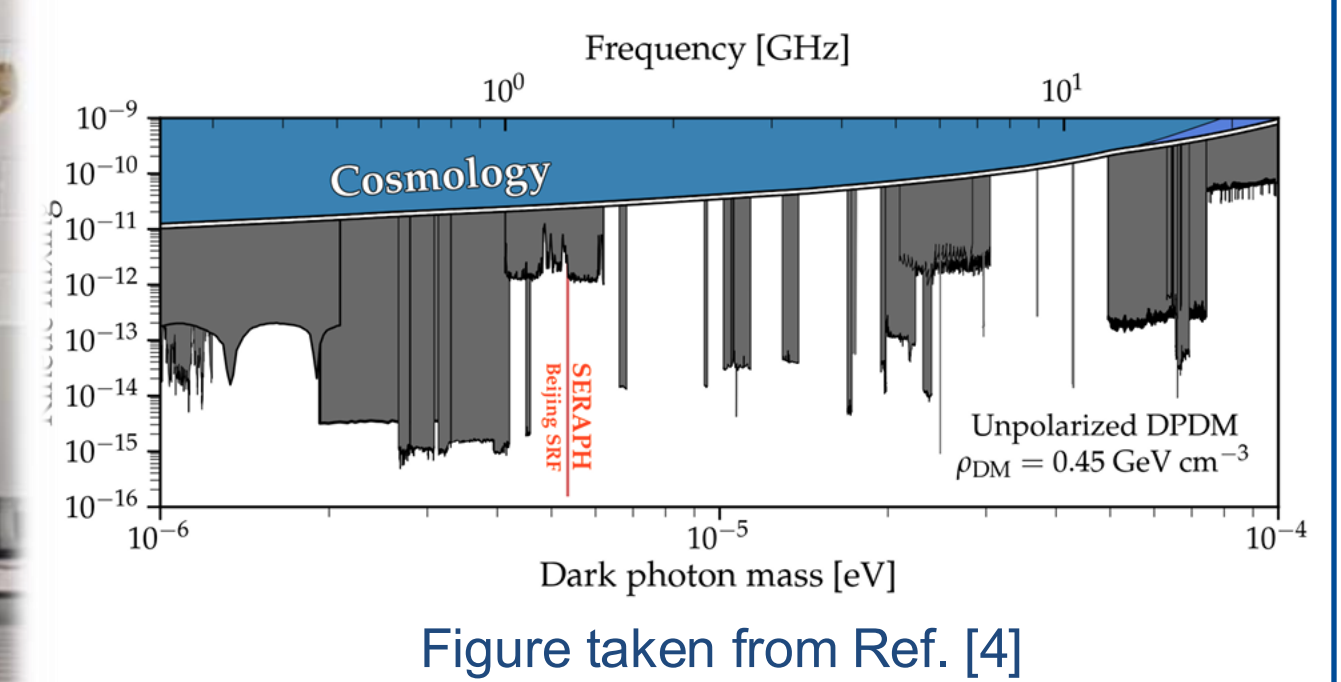
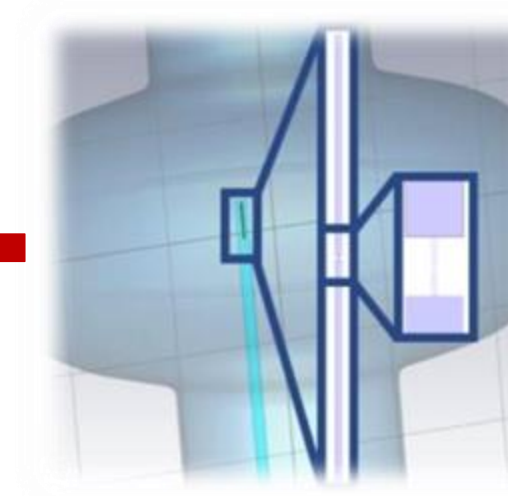
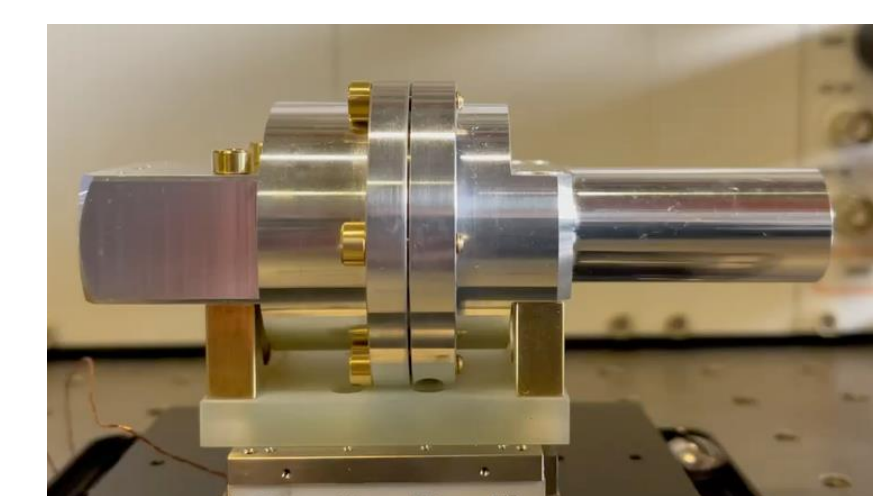


Figure taken from Ref. [4]

Trapped electrons as high-Q resonators for detecting ~ meV DPDM [5]:

if the rest energy of the DP matches the energy splitting of the two lowest cyclotron levels, the first excited state of the electron cyclotron will be resonantly excited → **proof-of-principle demonstration at 148 GHz (0.6 meV) with 75 times improvement compared to previous limits.**

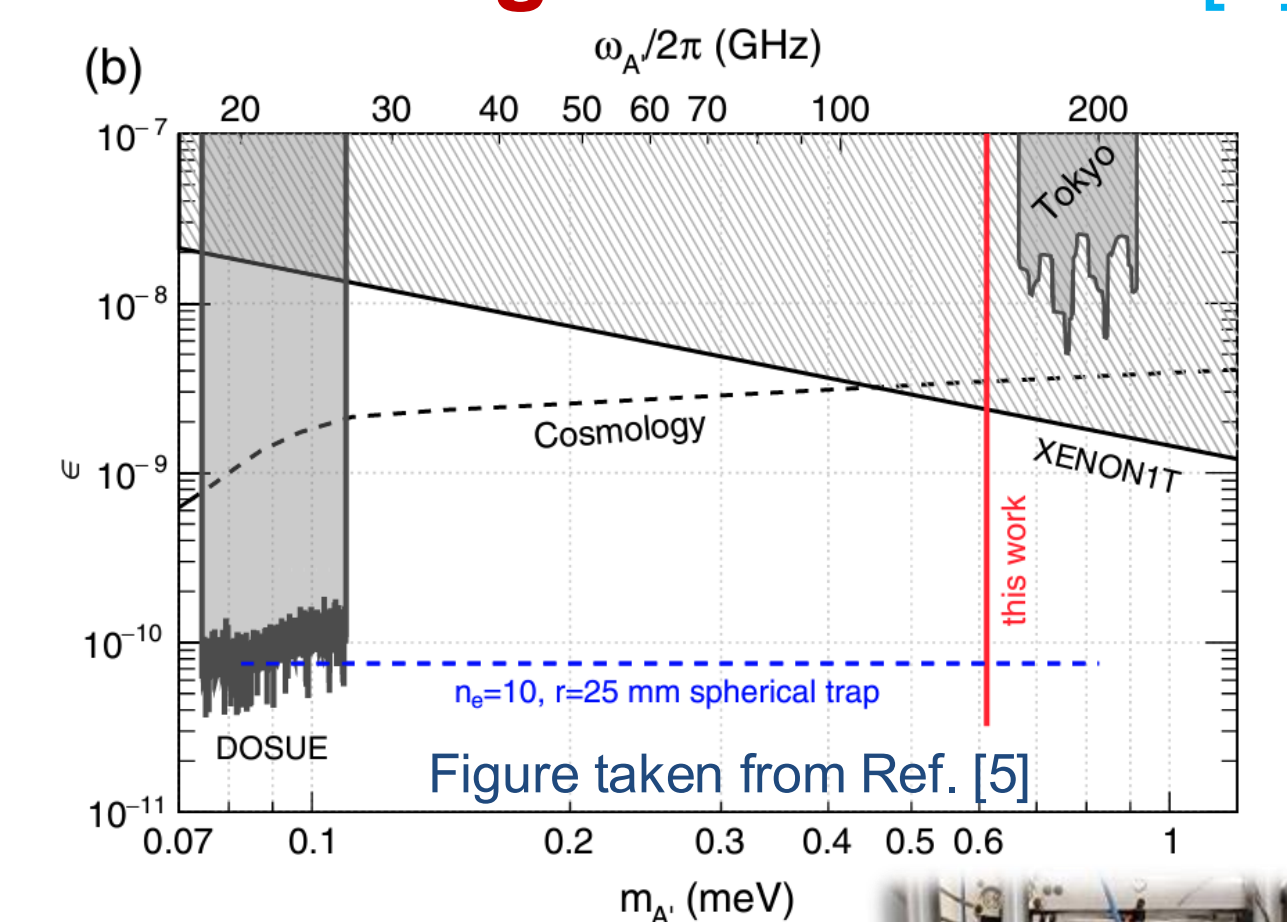


Figure taken from Ref. [5]

High Frequency Gravitational Waves Searches with SRF Cavities

Theoretical work [7, 10] to correct and build upon previous work [11] on formalism for **GW-EM cavity interaction**. Current axion experiments have sensitivity to GHz gravitational waves. Dedicated cavity experiment: significant reach at KHz-MHz. Fermilab-DESY collaboration: investigating physics reach and new readout methods using existing MAGO cavity [11].

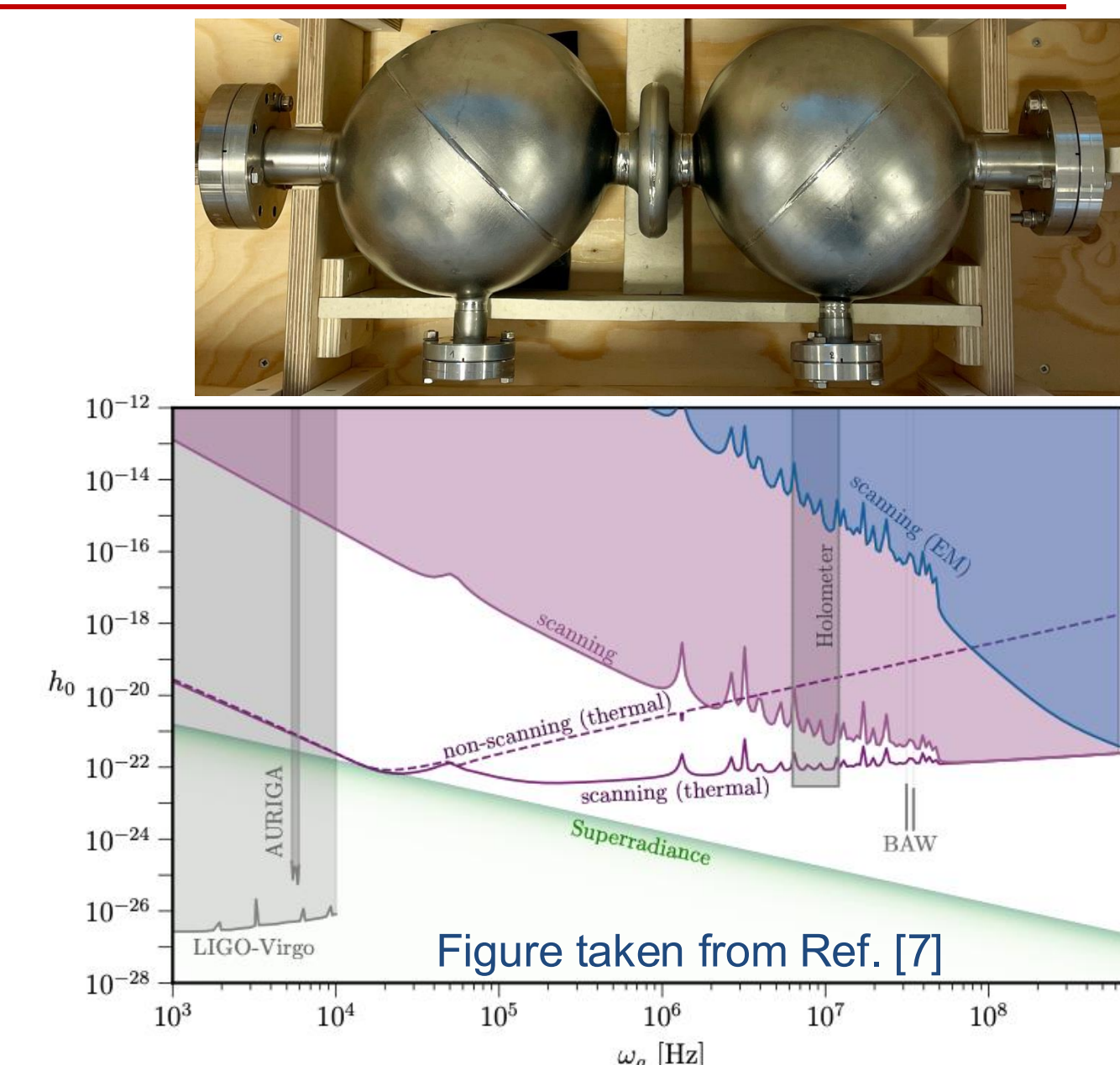
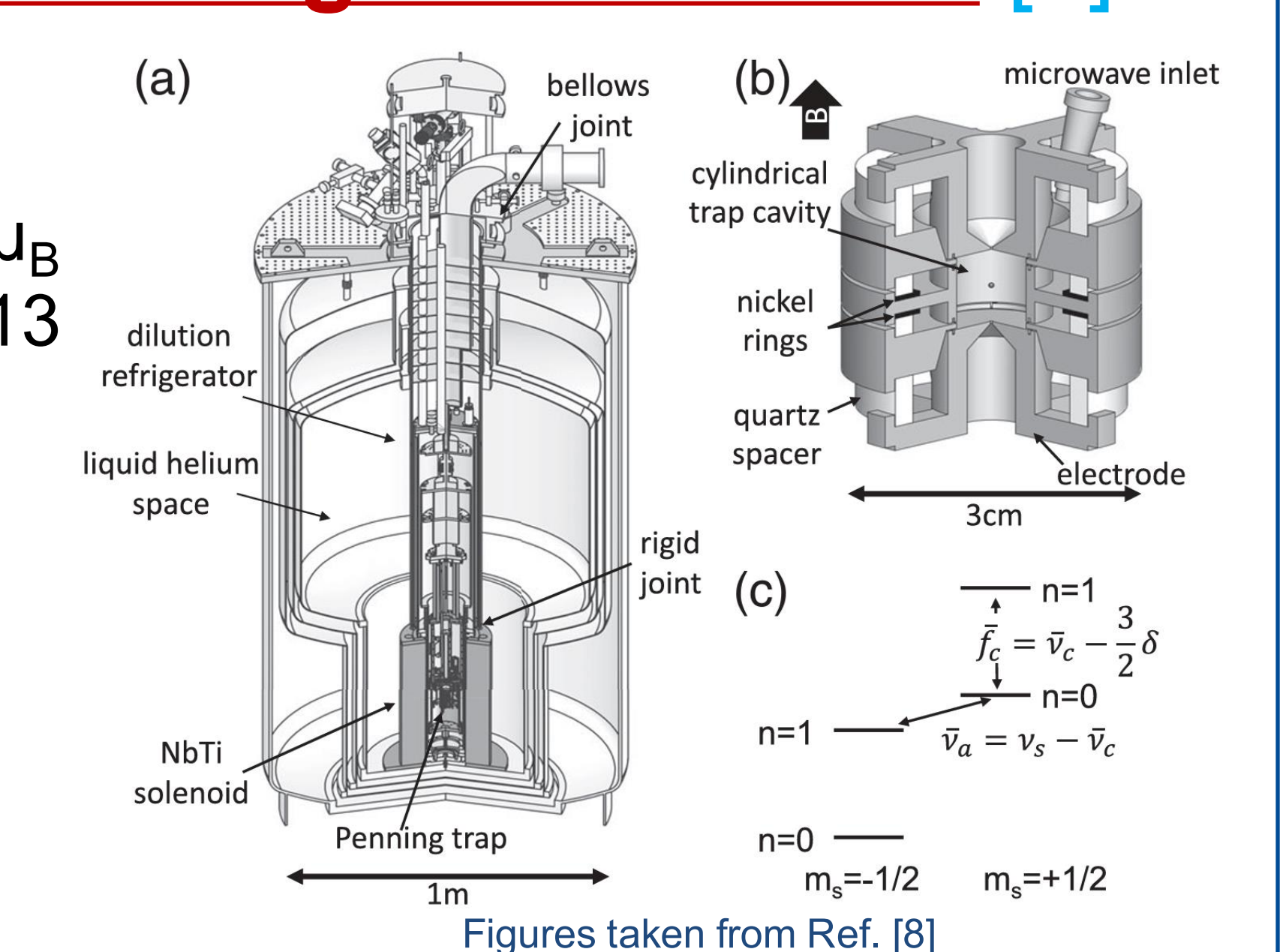


Figure taken from Ref. [7]

Measurement of the Electron Magnetic Moment [8]

An **electron magnetic moment measurement blind to previous measurements and predictions** → $\mu/\mu_B = g/2 = 1.001\,159652\,18059\,(13)\,[0.13\text{ ppt}]$ → **2.2 times more accurate than previous measurements**. The new measurement and SM theory **predict $\alpha^{-1} = 137.035999166\,(15)\,[0.11\text{ ppb}]$ with an uncertainty 10 times smaller than the current disagreement between measured α values.**



Figures taken from Ref. [8]

[1] Berlin, A., et al., arXiv:2203.12714 (2022). [2] Braggio, C., et al., arXiv:2403.02321 (2024). [3] Giaccone, B., et al., arXiv:2207.11346 (2022). [4] Cervantes, R., et al., Phys. Rev. D 110.4 (2024): 043022. [5] Fan, X., et al., Phys. Rev. Lett. 129.26 (2022): 261801. [6] Romanenko, A., et al., Phys. Rev. Lett. 130.26 (2023): 261801. [7] Berlin, A., et al., Phys. Rev. D 108.8 (2023): 084058. [8] Fan, X., et al., Phys. Rev. Lett. 130.7 (2023): 071801. [9] Berlin, A., et al., J. High Energy. Phys. 2020, 88 (2020). [10] Berlin, A., et al., Phys. Rev. D 105, 116011 (2022). [11] Ballantini, R., et al., arXiv:gr-qc/0502054 (2005).

This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359.



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