RDC8 coherent wave detectors summary

Gianpaolo Carosi (LLNL), Silvia Zorzetti (FNAL)

With a contribution from Chelsea Bartram (SLAC)

From the CPAD RDC8 Second Meeting

Thanks to Rakshya Khatiwada & Aritoki Suzuki

Group Interests

Sample size: 42

Pair breaking : 34

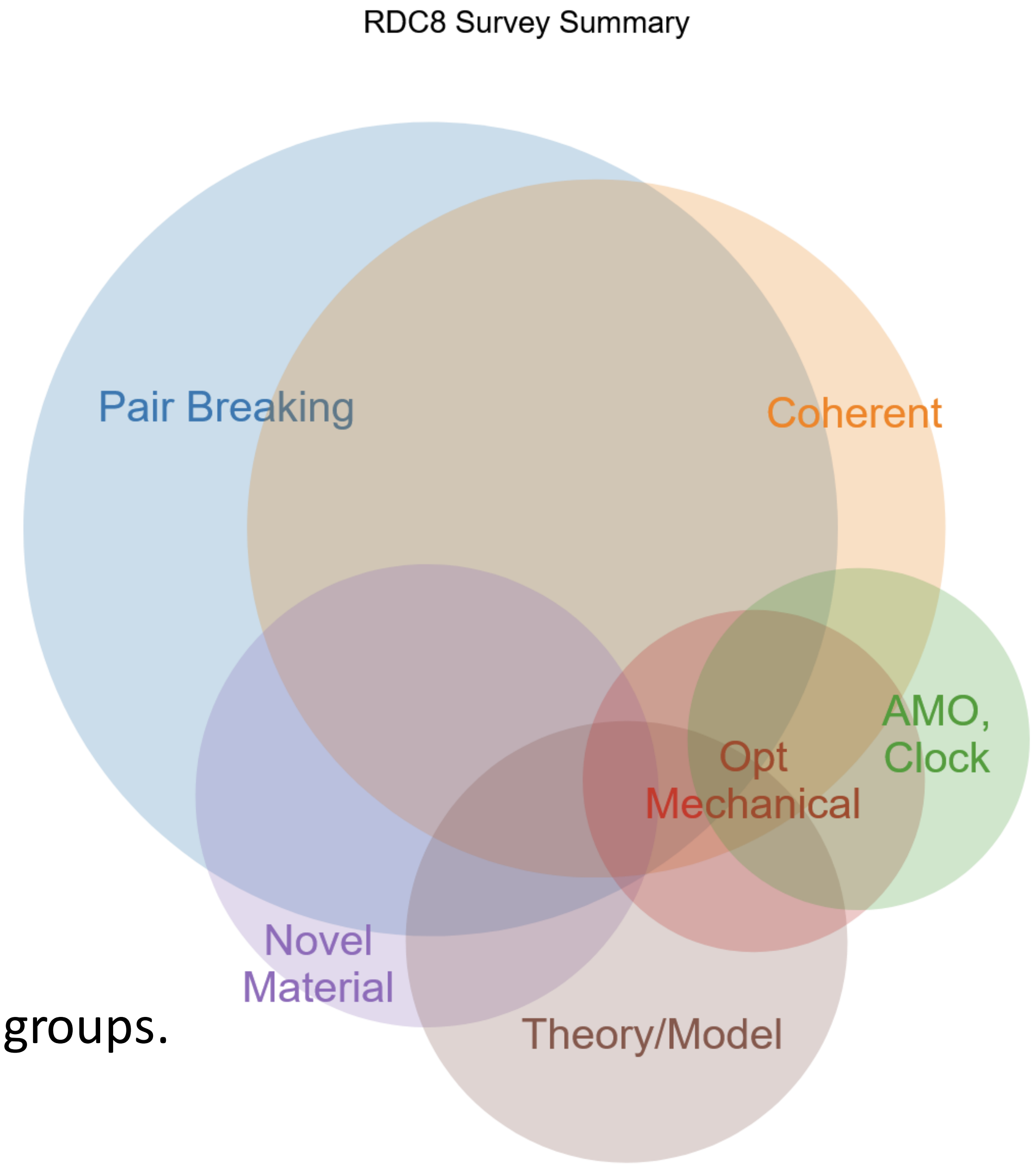
Coherent : 25

AMO, Clock : 6
Opt Mech : 6

Novel Material : 11
Theory : 10

Other : 1

A lot of interest in pair breaking and coherent groups.
Good overlaps between groups as well



Synergies with others RDCs

Sample size: 31/42 (multiple answers possible)

1.Noble Element Detector : 3
2.Photodetectors : 21
3.Solid State Tracking : 2
4.Readout and ASICs : 13
5.Trigger and DAQ : 3
6.Gaseous Detectors : 0
7.Low Background Detectors : 21
8.This RDC
9.Calorimetry : 3
10.Detector Mechanics : 3
Fast Timing : 6

We have synergy with almost every other RDCs.
Three RDCs stood out

Coherent sub-group

Number of Interests: 25

Sub-group lead(s)
- Gianpaolo Carosi (LLNL), Silvia Zorzetti (FNAL)

Summary of topics
- Precision measurements, axions (haloscopes, light shining through wall), dark matter, detection of keV mass, frequency converters, weak signals detection, wave-like DM

Science Targets
- DM, axion detection

Existing Collaborations
- ADMX, ORGAN, MAGIS-100, SQMS, BREAD
- Nat. Labs: SLAC, ANL, Fermilab, LBNL

Facility needs
- Dilution refrigerators, underground cryogenic facilities, cleanrooms, device fabrication, nanofabs, test and production facilities for superconducting devices.

Ideas for work packages
- Phonon physics, qubit-based detection, low noise amplifiers (low-frequency SQUID, JPAs), digital electronics, optomechanical systems, low dark counts single-photon detectors, microelectronics and ASICs, quantum entanglement and sensors networks

This presentation

Coherent wave sensors: JPA, TWPA, KIPA, Squeezed state receivers, microwave to optical transducers, SRF cavities, superconducting/LC circuits, rf quantum upconverters, mechanical tuning of cavities, etc.

This is a review of whitepapers presented at Snowmass

- Instrumentation frontier -> Quantum sensors

We will cover:

1) Quantum Sensors

2) ADMX

Please don't hesitate to contact us if there's anything we may have missed or if you have any suggestions for additions!!

Main References

- **A Berlin, et al, Searches for new particles, dark matter, and gravitational waves with SRF cavities, arXiv:2203.12714**
- **CB Adams, et al Axion dark matter, arXiv:2203.14923**
- A Armatol, et al., Toward cupid-1t. arXiv:2203.08386
- A Derevianko, et al., Quantum Networks for High Energy Physics, arXiv:2203.16979
- R Pooser, Opportunities for optical quantum noise reduction. Snowmass2021 - Letter of Interest
- T Heinz, et al., Transduction for new regimes in quantum sensing. Snowmass2021 - Letter of Interest
- A Agrawal, et al., Superconducting Qubit Advantage for Dark Matter (SQuAD), Snowmass2021 - Letter of Interest

Superconducting Sensors

- Superconducting radiofrequency (SRF) Cavities
- Qubit-based single photon counting
- Other SRF and cryogenic technology relevant for the instrumentation frontier
  - Networks and transductions
  - Cryogenic Platform for Scaled-up Sensing Experiments
  - Superconducting-nanowire single-photon detectors (SNSPD) *Covered in pair-breaking
  - SQUID
  - MKID

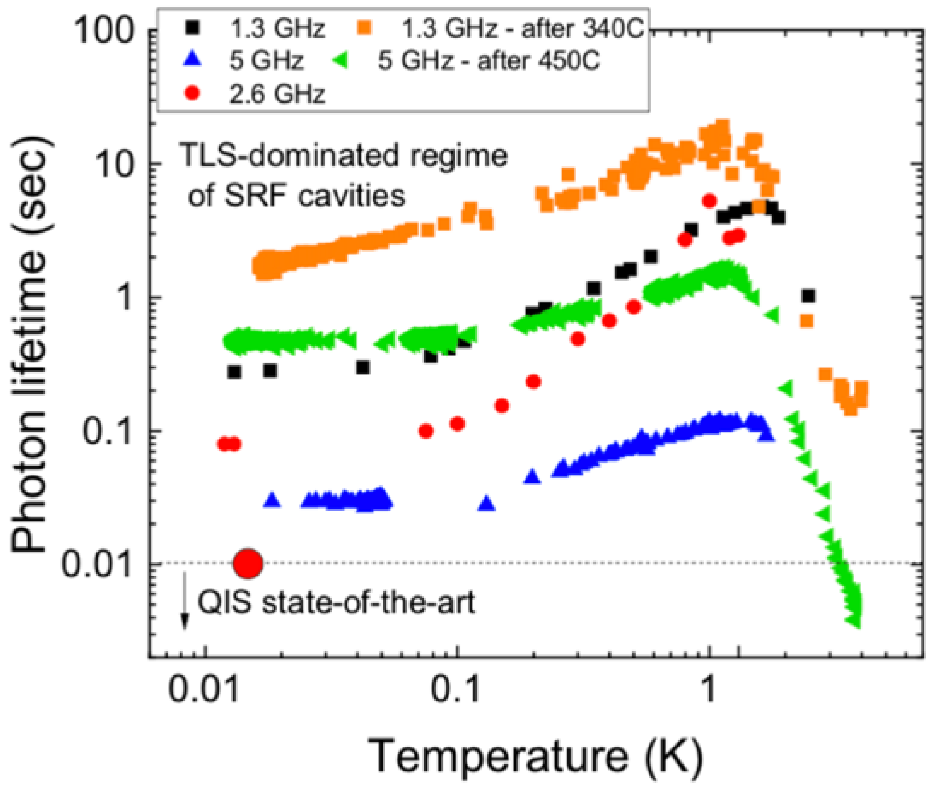
Superconducting Radio Frequency (SRF) Cavities

- Very **high-Q resonators** and critical components in particle accelerators
- **Strong, active interest in quantum information science (QIS)**, with demonstrated record-high photon lifetime $Q>10^{11}$ also in the quantum regime.
- **Opportunities to search for new particles with SRF cavities at SQMS**
- **Dark photons and axion** (or axion-like particles), either as new particles or dark matter, as well as on **gravitational waves**.
    - SRF cavities can be used for GW: the search for gravity waves across the full spectrum of frequencies, particularly since their discovery by LIGO is very well motivated

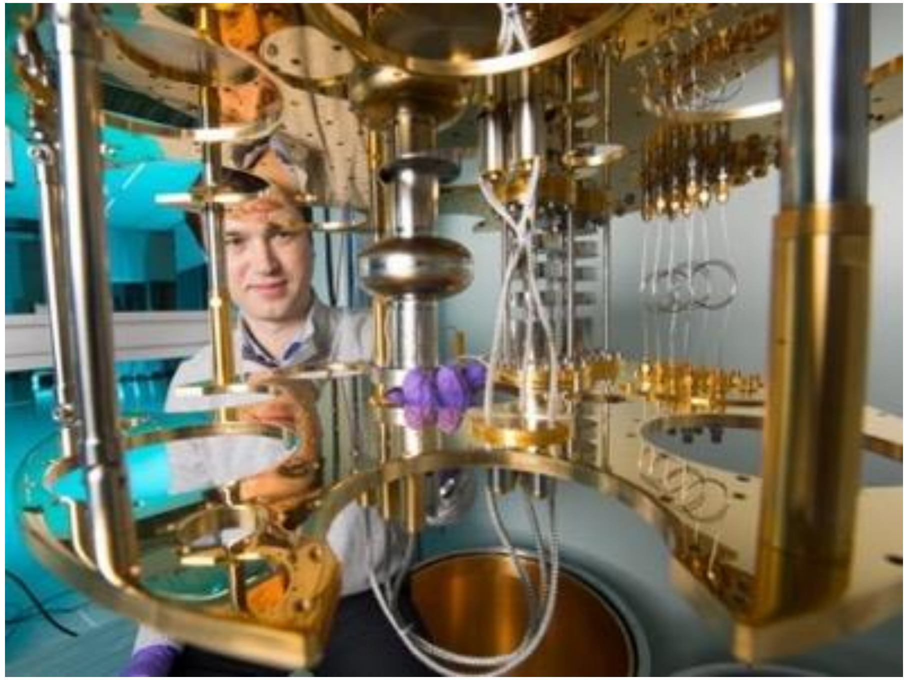
The experimental setup for the Dark SRF experiment consisting of two 1.3 GHz cavities

Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714

Highlight: world record coherence 3D cavities in quantum regime



A. Romanenko et al, Phys. Rev. Applied **13**, 034032, 2020



- Technology originally developed for accelerators
- 2 seconds of coherence demonstrated

Proposals for axion searches using SRF cavities

- **Two cavities with Static Field:** High-Q SRF cavities and large magnetic fields for a LSW axion search is to sequester the required magnetic fields away from the production and detection cavities. With this approach neither SRF cavity is subject to large magnetic fields and neither suffers a degradation of Q-factor.
- **Two Cavities with a pump mode**: An alternative approach is to replace the static B-field with an oscillatory B-field, which can then be directly run inside the receiver cavity.
- **Single-Cavity Axion Search and Euler-Heisenberg**: Search for both the axion-induced and EH nonlinearities using high-Q SRF cavities. This two-cavity scheme is less sensitive to noise sources which generate nonlinearities in the pump region.

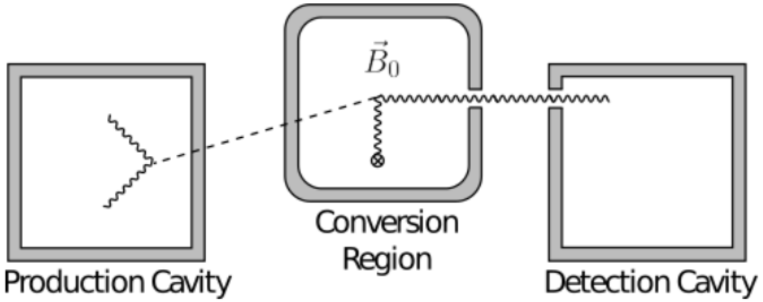
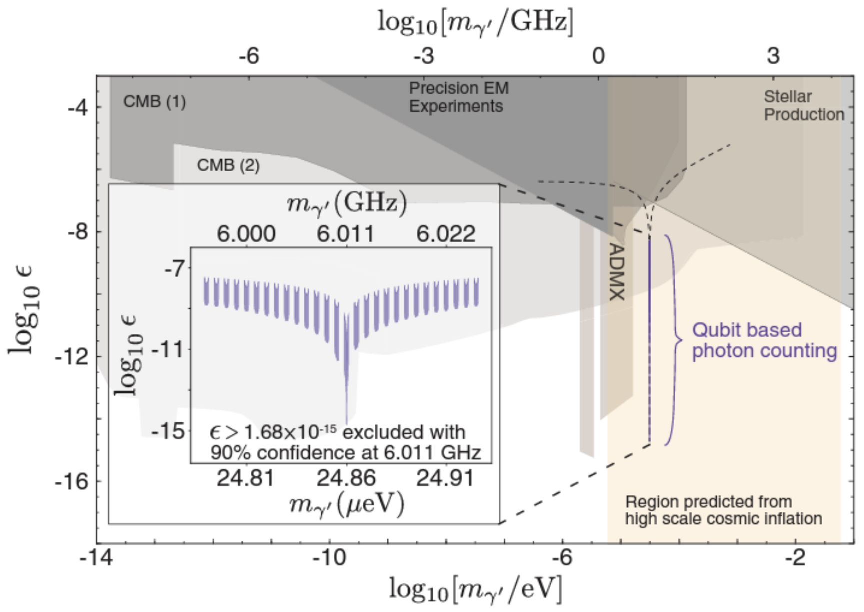


FIG. 3: Schematic depiction of an SRF light-shining-though-wall cavity search for axions [44]. The conversion region is in practice a superconducting toroidal magnet and the coupling to the detector (i.e., receiver) cavity is achieved via a pickup loop in the center of the toroid.

Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714

Qubit-based single photon counting

- Several ongoing or proposed experiments utilizes **SRF resonators coupled to superconducting qubits to detect bosonic dark matter candidates below the SQL.**
  - Photon counting non-demolition measurement for DM searches.
  - For certain DM search schemes, it would also be beneficial to have qubits that can operate successfully **even in high magnetic fields**.
- Two experiments for sub-SQL detection: **HAYSTAC, SQuAD** by implementing qubit-based photon counting
- SQMS also plans to combine SRF cavity technology and **qubit-based photon counting to increase the DM search rate by several order of magnitudes.**
- The Superconducting Qubit Advantage for Dark Matter (**SQuAD**): perform resonant searches for dark matter axions in a broad range from 10-30 GHz using high quality factor dielectric cavities and qubit-based photon counting



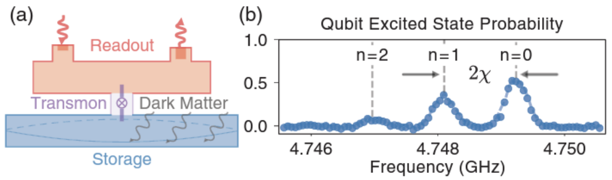


FIG. 1. Superconducting transmon qubit dispersively coupled to high Q storage cavity. (a) Schematic of photon counting device consisting of storage and readout cavities bridged by a transmon qubit [29]. The interaction between the dark matter and electromagnetic field results in a photon being deposited in the storage cavity. (b) Qubit spectroscopy reveals that the storage cavity population is imprinted as a shift of the qubit transition frequency. The photon-number-dependent shift is 2χ per photon.

- Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714
- Axion Dark Matter, arXiv:2203.14923
- Superconducting Qubit Advantage for Dark Matter (SQuAD), Snowmass2021 – LOI
- Dixit, Akash V., et al. "Searching for dark matter with a superconducting qubit." Physical review letters 126.14 (2021): 141302 ** pictures

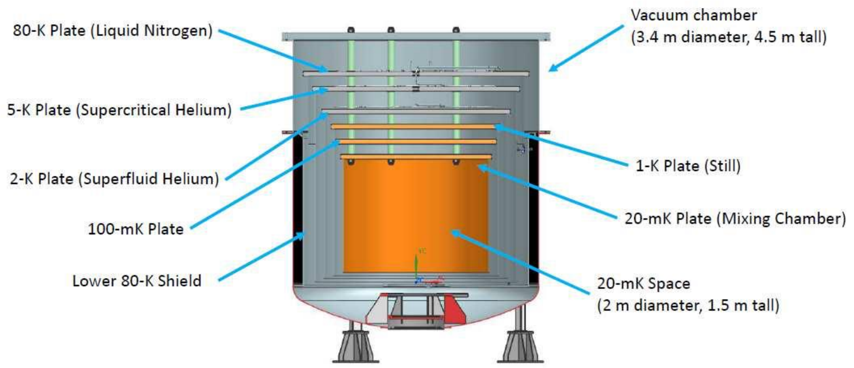
Other SRF and cryogenic technology relevant for the Instrum. Frontier

Networks and Transduction

- **Networks of quantum sensors for enhanced sensitivity to further improve axion DM searchers**
- **Microwave-optical transduction based on 3D SRF cavities to enhance the conversion efficiency** at the quantum threshold, and below the SQL and enable haloscope searches in the THz regime
- **mm-wave regime** in LOI. Low-loss mm-wave photonics could allow preservation of quantum information at room temperature for a simpler network at laboratory scales, frequency range for axions **above ~10 GHz** (~40 μeV)

Cryogenic Platform for Scaled-up Sensing Experiments

- There is growing demand of large dilution cryogenic platforms capable of reaching milli-kelvin temperatures for quantum computing and quantum sensing. **SQMS center at Fermilab is developing a platform in an experimental volume of 2 meters diameter by 1.5 meters in height.**



SQMS cryogenic platform for quantum computing and sensing.

- Searches for New Particles, Dark Matter, and Gravitational Waves with SRF cavities, arXiv:2203.12714 ** pictures
- Transduction for New Regimes in Quantum Sensing, Snowmass2021 LOI
- Opportunities for optical quantum noise reduction. Snowmass2021 LOI
- Quantum Networks for High Energy Physics, arXiv:2203.16979

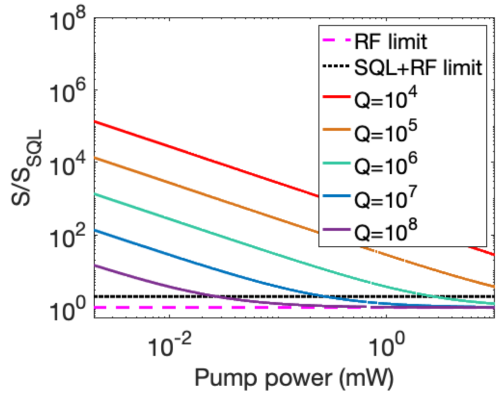
Haloscope using transduction for photon counting

Networks and Transduction

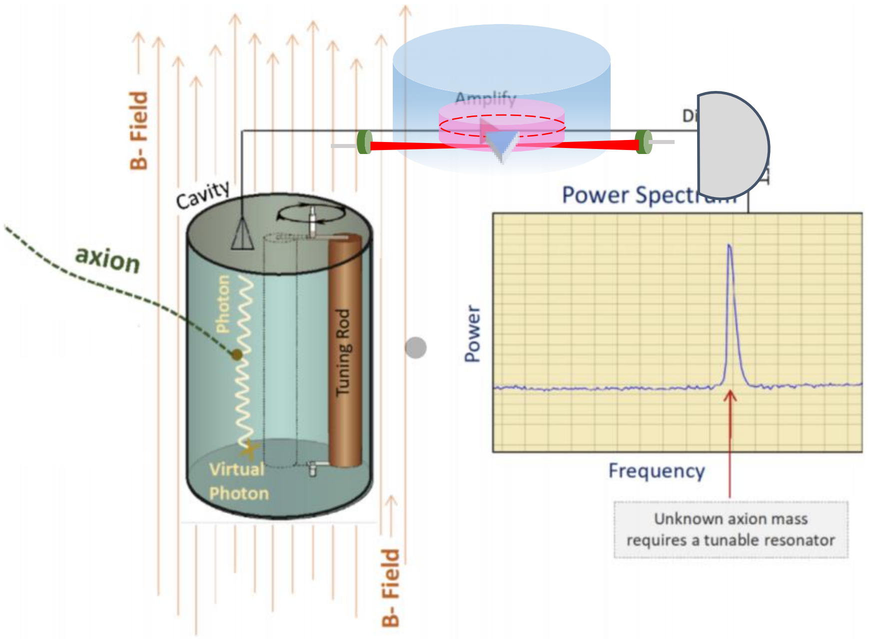
- **Networks of quantum sensors for enhanced sensitivity to further improve axion DM searchers**
- **Microwave-optical transduction based on 3D SRF cavities to enhance the conversion efficiency** at the quantum threshold, and below the SQL and enable haloscope searches in the THz regime
  - Use microwave-optical transducers for ultra-low noise parametric amplification
  - Low dark photon count -> system temperature ~ cavity temperature -> SNR and scan-rate improvement

Aligned with the Priority Research Directions (PRD) published in the DOE Basic Needs for HEP Detector

- Addressing technology needs for light shining through walls experiments and Quantum Chromo Dynamics (QCD) axion searches, including lower noise amplifiers, photon counters and techniques to evade the Standard Quantum Limit (SQL).

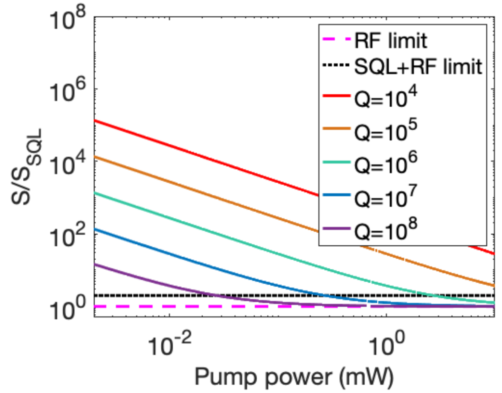


Spectral density (S) with reference to the SQL, with back-action noise cancellation. Both plots evaluate the parameters with increasing RF quality factors (Q)



M-O transducer as a parametric amplifier to enable optical single photon counting of microwave photons

Haloscope using transduction for photon counting



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Networks and Transduction

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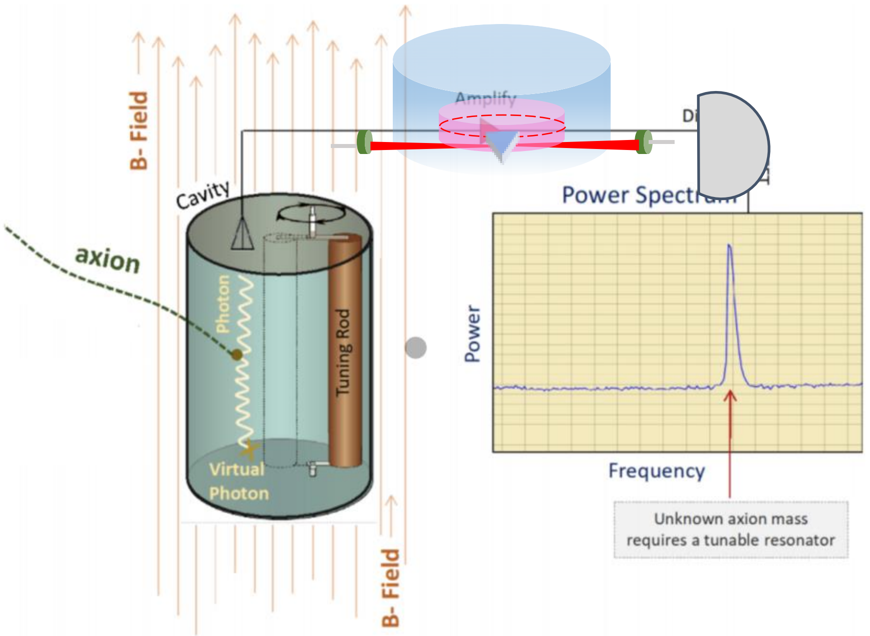
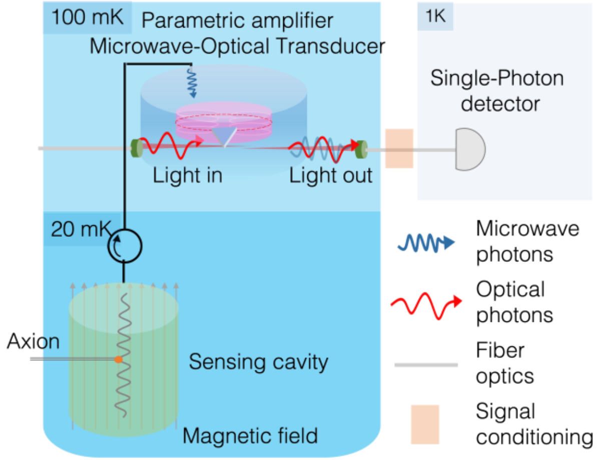


M-O transducer as a parametric amplifier to enable optical single photon counting of microwave photons

Evaluate the scan-rate for ideal homodyne over the scan-rate achieved with transduction (Use Fisher parameters: $\frac{\mathcal{J}_{Hd}}{\mathcal{J}_{Trans}}$)

- Parameters: microwave loss, optical coupling and pump power
- With SRF cavities, it is possible to achieve over double the scan rate



ArXiv in preparation – SQMS/Fermilab and A. Brady (U. Arizona) , Zhuang, (USC)

Other SRF and cryogenic technology

- Read out multiple detectors on a single wire with cryogenic multiplexing technologies with minimal readout noise penalty is to scale experiments to larger detector counts.
- Microwave SQUID multiplexer (µmux): multiplexing factors up to two orders of magnitude larger than conventional cryogenic multiplexing schemes.
- Allow for cryogenic particle detection, such as low-mass threshold dark matter searches, beta decay end point measurements to determine the lightest neutrino mass,
- The CUPID collaboration presents a series of projects underway that will provide advancements in background reduction, cryogenic readout, and physics searches
- CUPID-1T: Microwave Kinetic Inductance Detectors (MKIDs) Metallic Magnetic Calorimeters (MMCs), and high- and low-impedance Transition Edge Sensors (TESes).

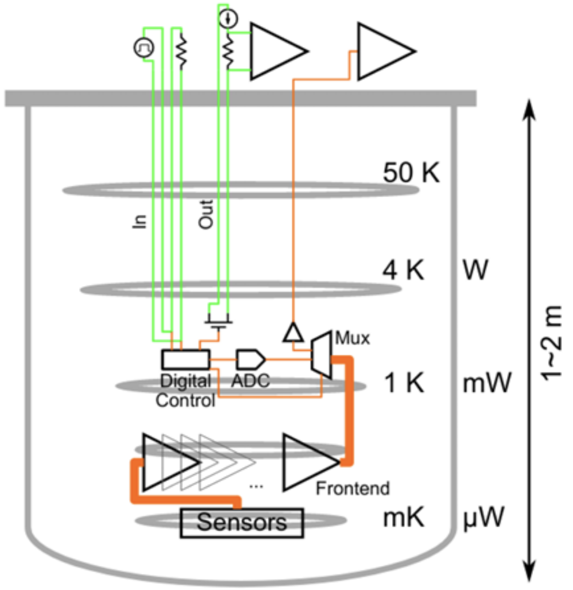
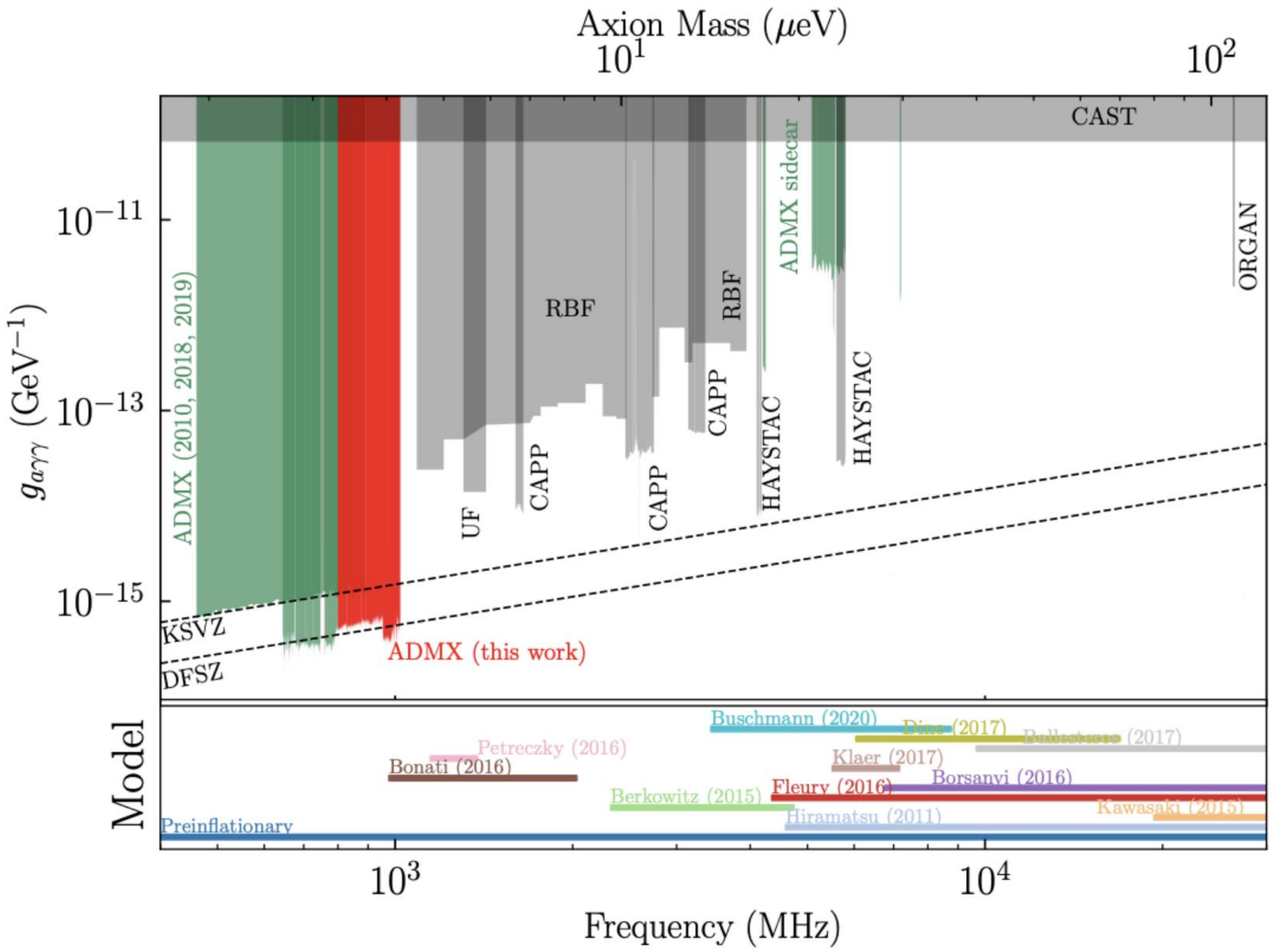


Figure 11: Schematic design of cryogenic electronics integrated into CUPID. To minimize their distance to sensors, front-end preamplifiers should be located below the still. Supporting electronics may be placed at slightly higher stages, where more cooling power is available, and from where they can drive the signal up the rest of the cable length to outside the cryostat. (Figure 10.1 in [165])

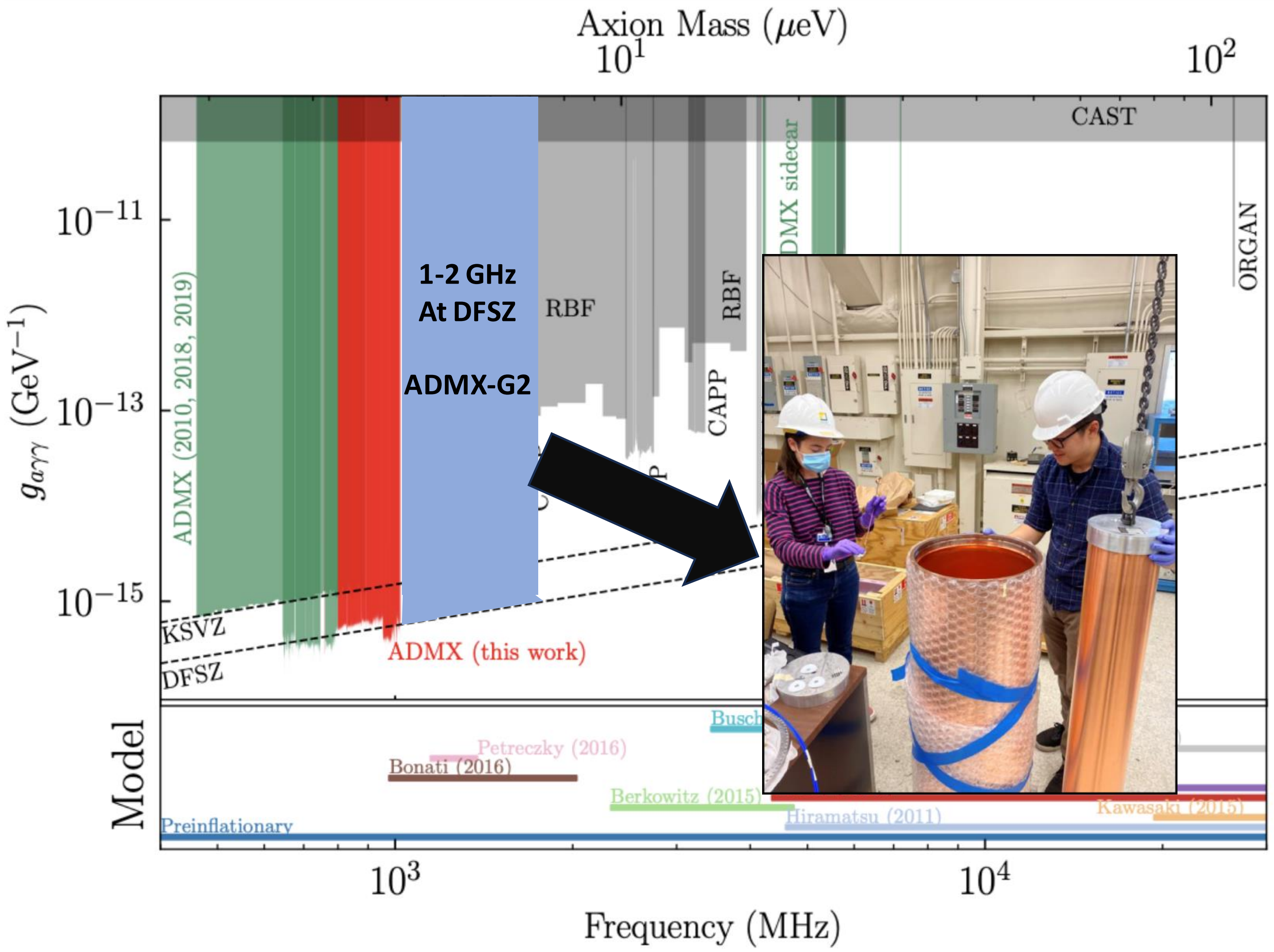
- Axion Dark Matter, arXiv:2203.14923
- A Armatol, et al., Toward cupid-1T. arXiv:2203.08386

ADMX



Axion Mass (μeV)
10^1
10^2
CAST
10^−11
10^−13
10^−15
g_aγγ (GeV^−1)
ADMX (2010, 2018, 2019)
RBF
UF
CAPP
RBF
CAPP
CAPP
HAYSTAC
ADMX sidecar
HAYSTAC
ORGAN
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
Dine (2017)
Petreczky (2016)
Klaer (2017)
Bonati (2016)
Borsanyi (2016)
Fleury (2016)
Berkowitz (2015)
Kawasaki (2015)
Hiramatsu (2011)
Preinflationary
10^3
10^4
Frequency (MHz)

ADMX



Axion Mass (μeV)
10^1
10^2
CAST
ADMX sidecar
ORGAN
RBF
RBF
CAPP
1-2 GHz
At DFSZ
ADMX-G2
ADMX (2010, 2018, 2019)
ADMX (this work)
KSVZ
DFSZ
10^-11
10^-13
10^-15
g_aγγ (GeV^-1)
Model
Petreczky (2016)
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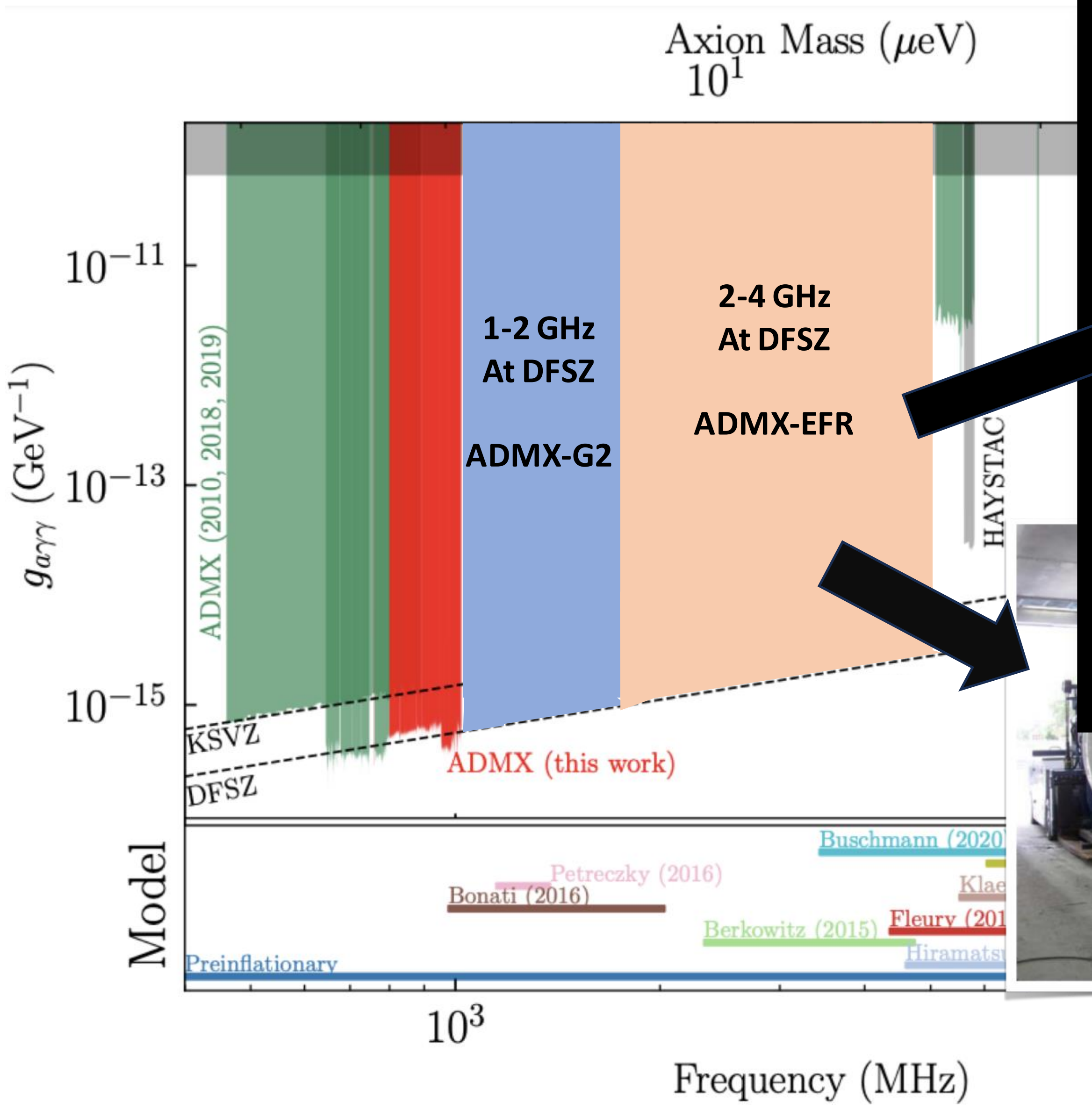
Preinflationary
10^3
10^4
Frequency (MHz)

ADMX



Axion Mass (μeV)
10^1
10^−11
10^−13
10^−15
$g_{a\gamma\gamma}$ (GeV^{-1})
ADMX (2010, 2018, 2019)
1-2 GHz
At DFSZ
ADMX-G2
2-4 GHz
At DFSZ
ADMX-EFR
HAYSTAC
KSVZ
DFSZ
ADMX (this work)
Model
Buschmann (2020)
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Preinflationary
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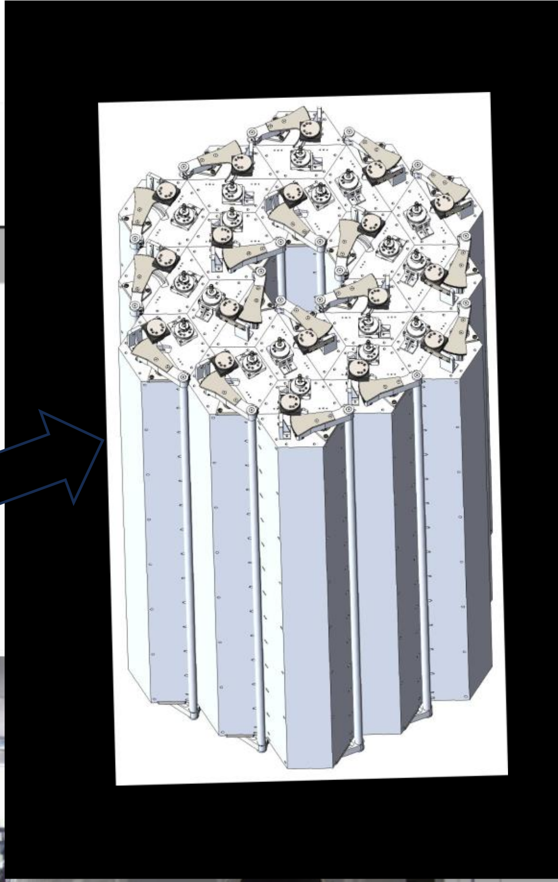
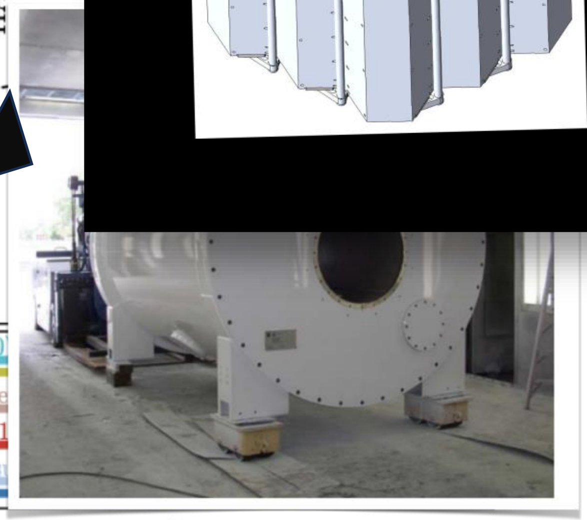
10^4
Frequency (MHz)





Conclusions

From the executive summary

- This growth extends far beyond high energy physics (HEP) impacting many areas of science from communications to cryptography to computing.
- Much of the early work in quantum sensors came from outside of 'traditional' HEP but is now poised to make significant contributions to the most fundamental questions in physics.
- Technology advances in quantum information science (QIS) provide exceptional theoretical and experimental resources to advance quantum sensing, with promising ideas and arising research projects that could provide mutual benefits in several areas such as materials, detectors, and devices.

Common areas of development

- Back action evading schemes
- Supporting technology: high-Q SRF cavities, mitigate TLS losses, enhance operation under multi-Tesla magnetic field, strength the link with QIST and leverage quantum computing technology
- Small grants and interaction with industries, e.g. SBIR programs
- Develop infrastructures, underground, magnetic, and large cryogenic facilities
- A strong need for much increased **technology development**, in preparation for the next big step in facilities and experiments while we exploit the ones we are currently developing/building

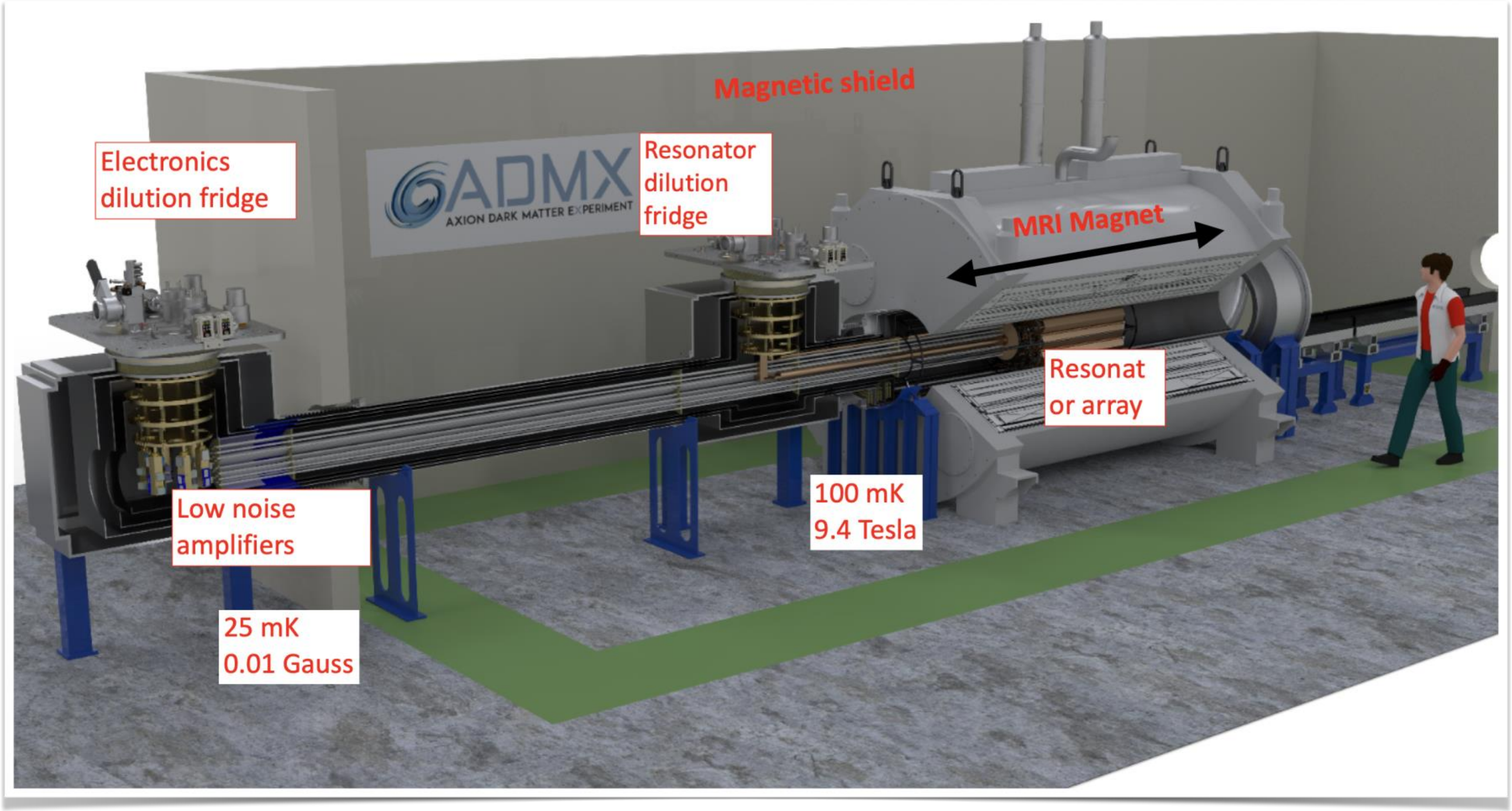
For discussion

- Existing expertise and areas to develop
- Challenges and opportunities
- Groups that are currently addressing these problems
- Synergies between academia, national labs and industries

Technical areas of development

- Cryogenics
- Single photon counting techniques
    - Sub-SQL measurements
    - Implementation of single photon counting in axion Haloscopes
- Noise reduction
- Sensor networks
    - Multi-cavities searches
    - Advantages of networks of sensors
- Materials
    - Superconducting fields in magnetic fields
    - Mitigate TLS in superconducting cavities
- Synergies with other sub-groups

Backup



(ADMX EFR Design)

Other SRF and cryogenic technology relevant for IF1 (2)

Superconducting-nanowire single-photon detectors (SNSPD) or sensing low count-rate signals due to their high internal efficiency and low dark-count rates.

- Recent proposals for axion search either require SNSPDs that can operate in the presence of **large magnetic fields** or require some means of carrying the light generated by the haloscope from the high-field region to a low-field region where the detectors can operate.
- The suitability of SNSPDs to applications requiring low dark-count rates is illustrated by recent progress in the **LAMPOST** prototype search for dark photon dark-matter using these devices

- Axion Dark Matter, arXiv:2203.14923