

# Updates from the SQMS general meeting at Fermilab (sensing)

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**SQMS-Italia Meeting**

December 15-16, 2022 - Padova, PD

# Overview

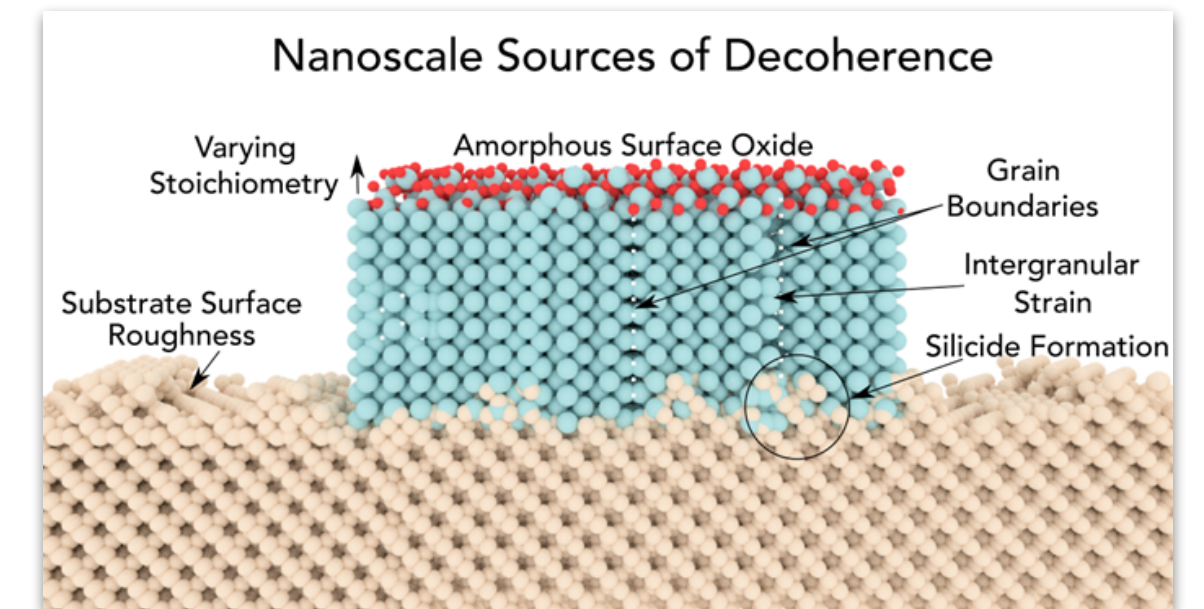
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**1):** Understanding and mitigating decoherence in superconducting quantum devices & sensors;

See A. Cruciani's talk

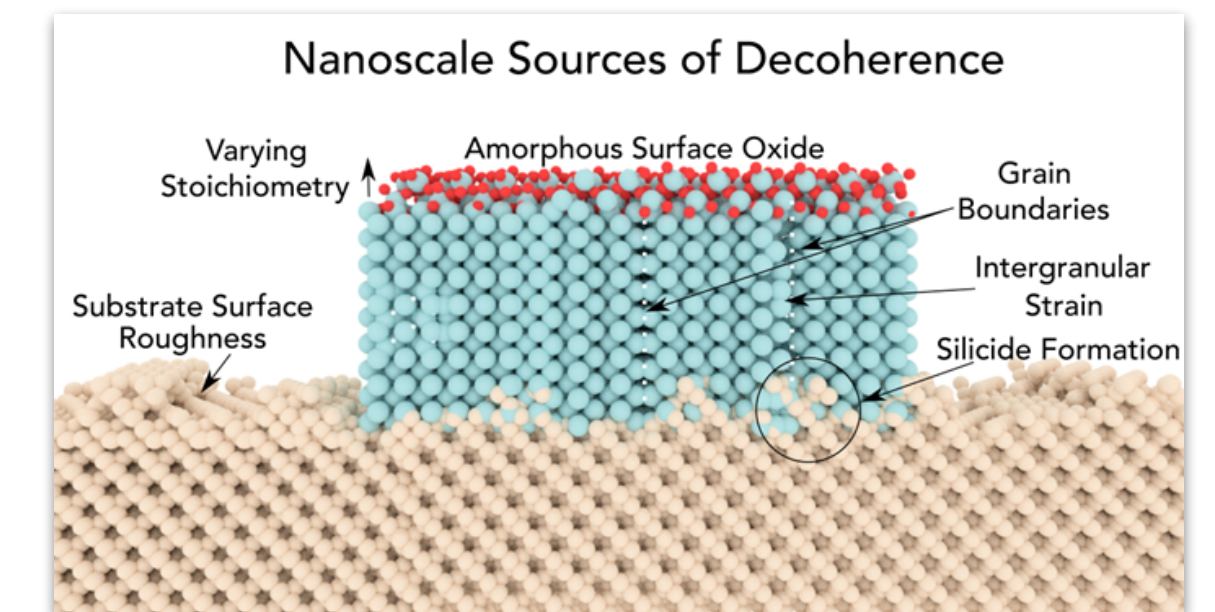


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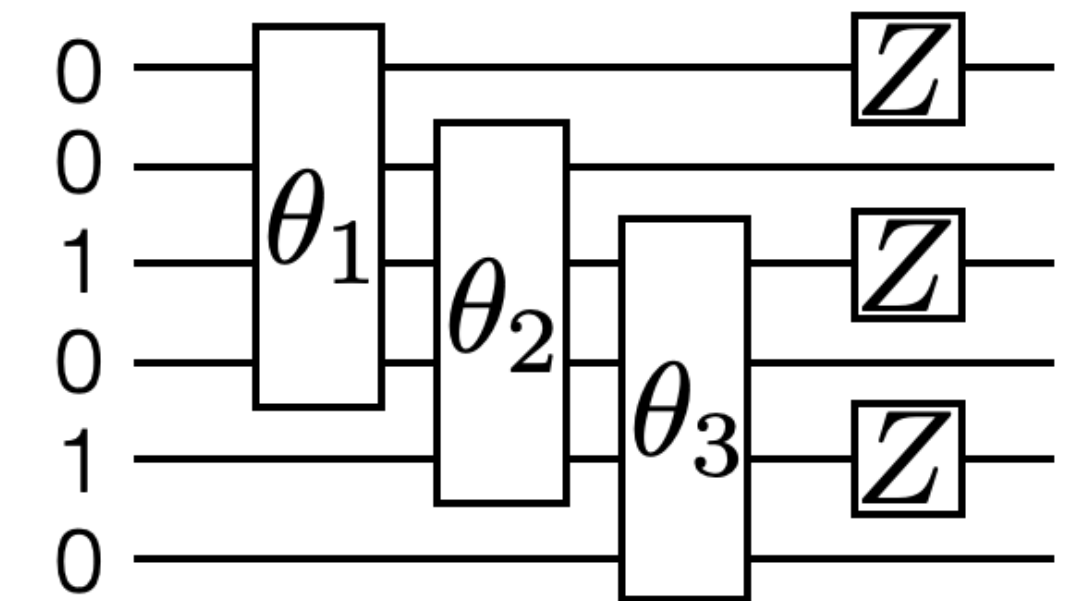
1): Understanding and mitigating decoherence in superconducting quantum devices & sensors;

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2): Deploying 2D/3D QPUs with first applications: 2D processors & algorithms;

Not discussed here

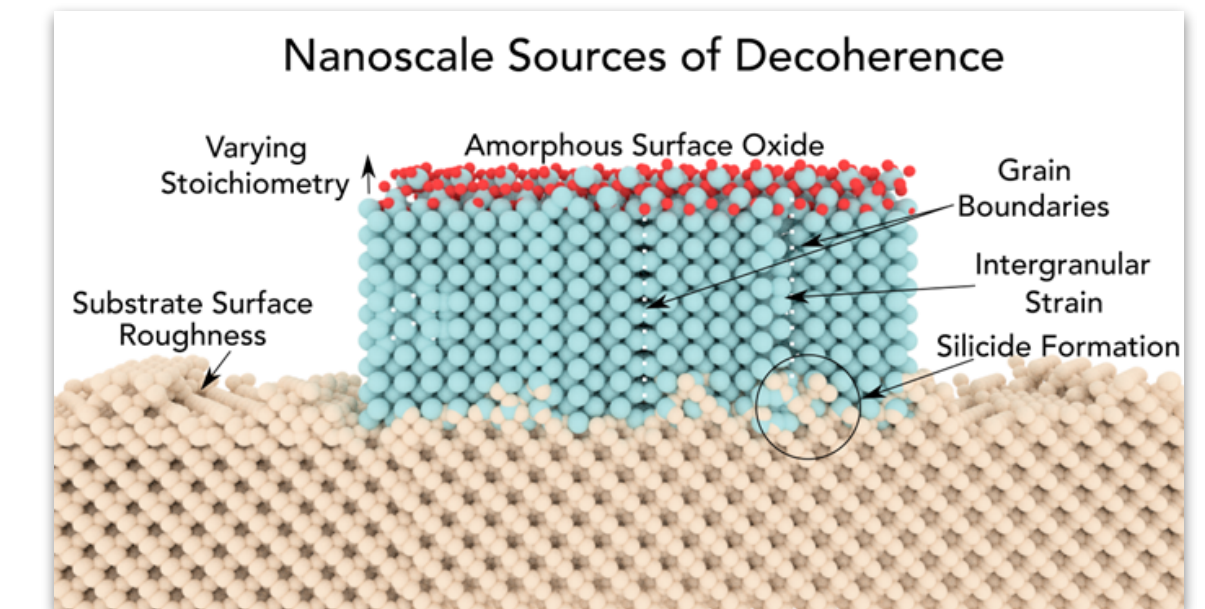


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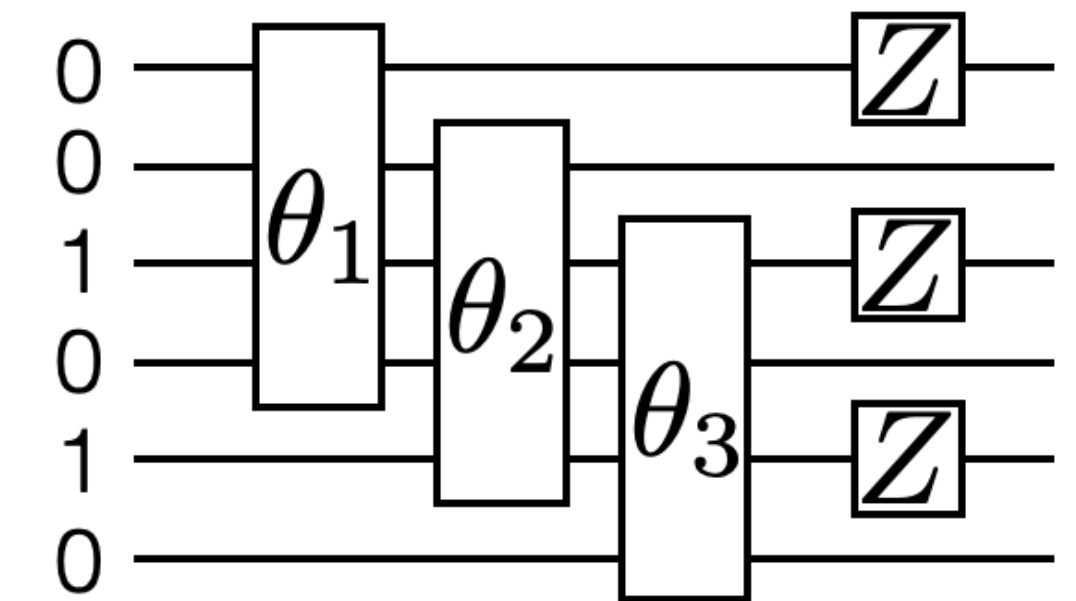
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**2):** Deploying 2D/3D QPUs with first applications: 2D processors & algorithms;

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**3):** Quantum sensing and high-coherence devices for fundamental physics.

This talk



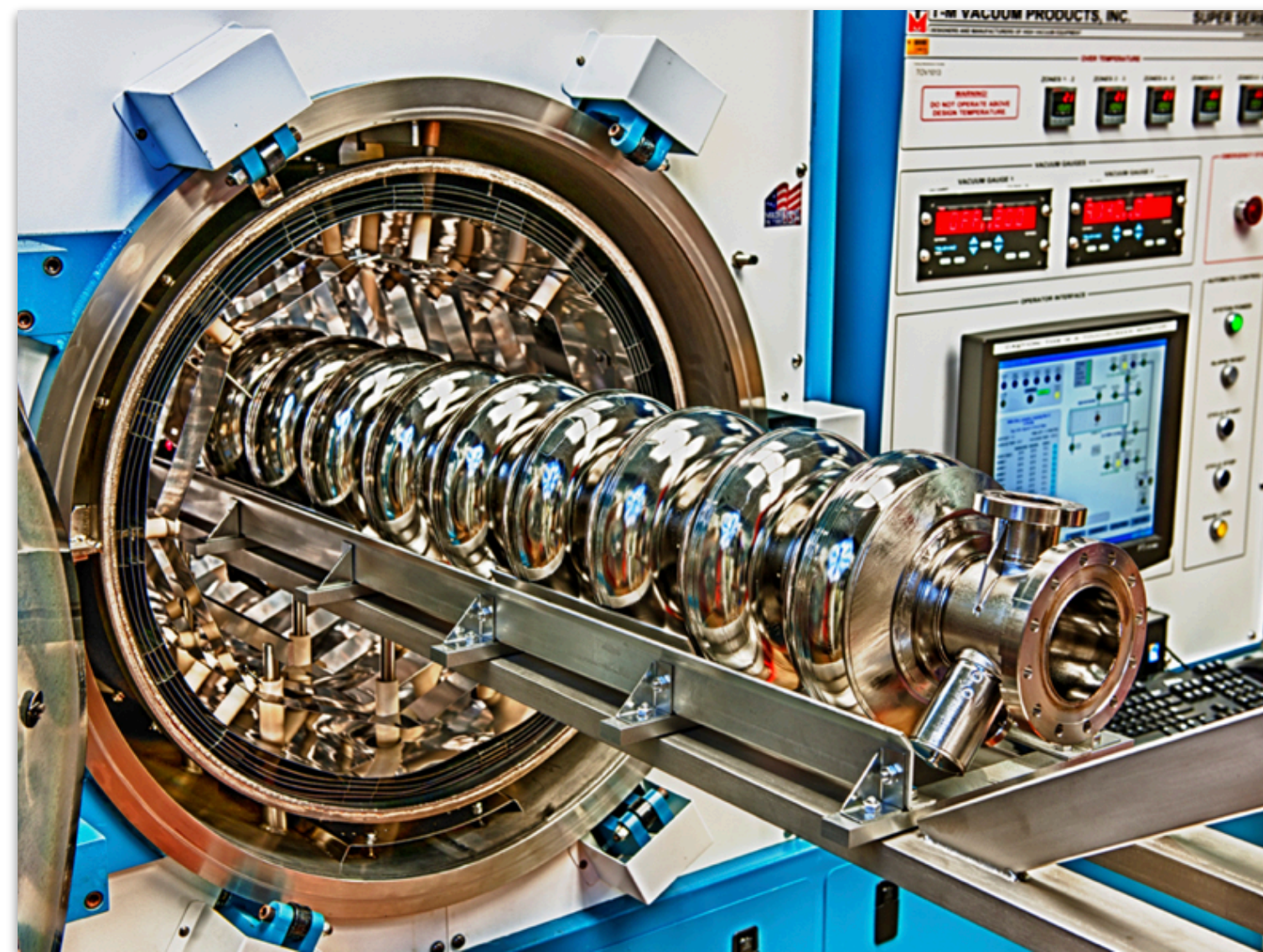
# Motivation

- Searching for **new physics** using quantum sensors
  - Focus primarily on **dark matter** (axions, dark photons), gravitational waves;
- Improvements to **ultra-high precision physics** with high quality factor (Q) cavities;
- **Fundamental quantum physics demonstrations** using SQMS tools.



# Physics and quantum sensing in SQMS

- Slightly different than materials and devices – many milestones assigned to a **single member institution** instead of multiple institutions;
- Leveraging SQMS facilities and equipment in **Superconducting Radio Frequency (SRF) cavities & qubits** (mostly superconducting but also trap) to search for new physics;
- In some cases can even use existing setups from other SQMS experiments to search for new physics in first demonstrations, then build on / expand from there.



# Dark matter vs. new particle searches

**New light particles** are theoretically well motivated.

e.g.

- **Axions** (including the QCD axion) and **axion like particles** (ALPs);
- **Dark photons**.

For such light particles **two hypotheses** can be tested:

**New particle:**

$\mathcal{L} \supset$  Axions?  
ALPs?  
Dark photons?

New degrees of freedom in the Lagrangian which interacts with Standard Model (SM) particles.

**Dark matter (and new particle):**



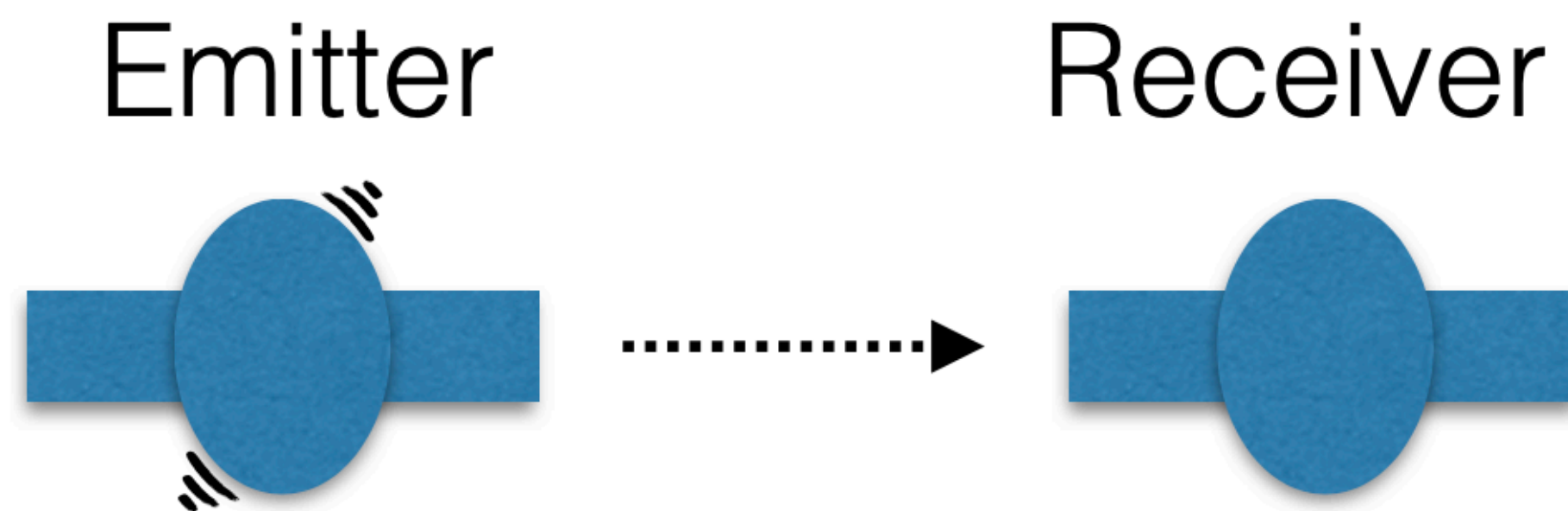
$\supset$

Axions?  
ALPs?  
Dark photons?

New degrees of freedom exists, and in addition these degrees of freedom make up the dark matter (DM).

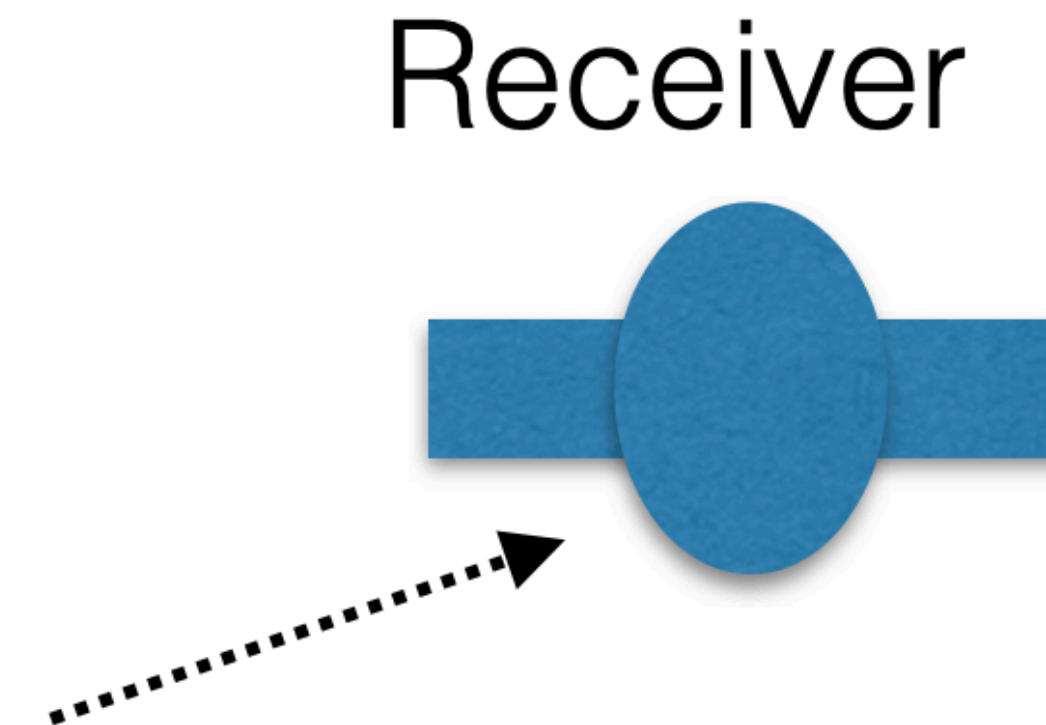
# Basic search schemes

## Light Shining through Wall (LSW):



New particles are produced in the emitter cavity and can travel to the receiver cavity, where they are converted into SM particles and can be detected.

## A dark matter search:



The DM filled Universe is the emitter.

# Milestones (from Appendix 13)

Focus Area	Major Activity	Deliverables and Benchmarks	Center Year				
			1	2	3	4	5
Quantum Physics and Sensing	(10) DarkSRF Milestones	DarkSRF implementation in dilution fridge					
		DarkSRF first results in quantum regime (10x current exclusion boundary)					
		DarkSRF results with $Q > 1e11$ (100x current exclusion boundary)					
		DarkSRF results with high Q plus phase readout (1000x current exclusion boundary)					
		DarkSRF with $Q \sim 1e12$ and phase readout (10000x current exclusion boundary)					
	(11) Multimode Axion Search Milestones	Axion search with multimode high Q cavity in quantum environment scheme design phase (two cavity setup) and co-design feedback to focus area 1					
		Axion Search scheme first implementation in two cavity setup					
		Prototype cavity with frequency matching for single-cavity axion search and co-design feedback to focus area 1					
		Axion Search scheme first implementation in one cavity setup					
		Lab Axion search downselect (1 versus 2 cavity)					

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## 1) Experiments searching for dark photons

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## 2) Experiments searching for axions and axion-like particles

# Milestones (from Appendix 13)

Focus Area	Major Activity	Deliverables and Benchmarks	Center Year				
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Quantum Physics and Sensing	(12) High Magnetic Field Axion Dark Matter Search	Commissioning of mK testbed with capability to generate Tesla-scale fields					
		First measurements of high Q cavities in Tesla-scale magnetic fields					
		Demonstrate $Q > 1e6$ in SRF cavities in Tesla-scale magnetic fields in quantum regime for axion searches					
		Feedback to focus area 1 for materials needs for high coherence in high magnetic fields and focus area 2 for qubits					
		Axion Dark matter searches coupling best coherence cavities and qubits in low and high magnetic fields					
		Design of Axion dark matter search with AC magnetic field					
		Dark matter axion downselect in various frequency bands to assess sensitivity to QCD axion in the multi-GHz band					

## 3) Experiments searching for axions and axion-like particles as dark matter candidates

# Milestones (from Appendix 13)

Focus Area	Major Activity	Deliverables and Benchmarks	Center Year				
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Quantum Physics and Sensing	(13) Single Particle Penning Trap	Design cavity geometry for single particle Penning trap					
		Prototype single particle trap cavity and squids, and co-design feedback to technology thrust					
		Test optimized single particle cavity with coupled squid					
		Study the sensitivity of next generation electron magnetic moment measurements					
	(14) Other Physics Search Schemes with QIS Methods	Deliver theoretical study of sensitivity to dark radiation					
		Deliver assessment of methods to search for gravitational waves with state of the art SQMS cavities					

## 4) Experiments searching for other physics

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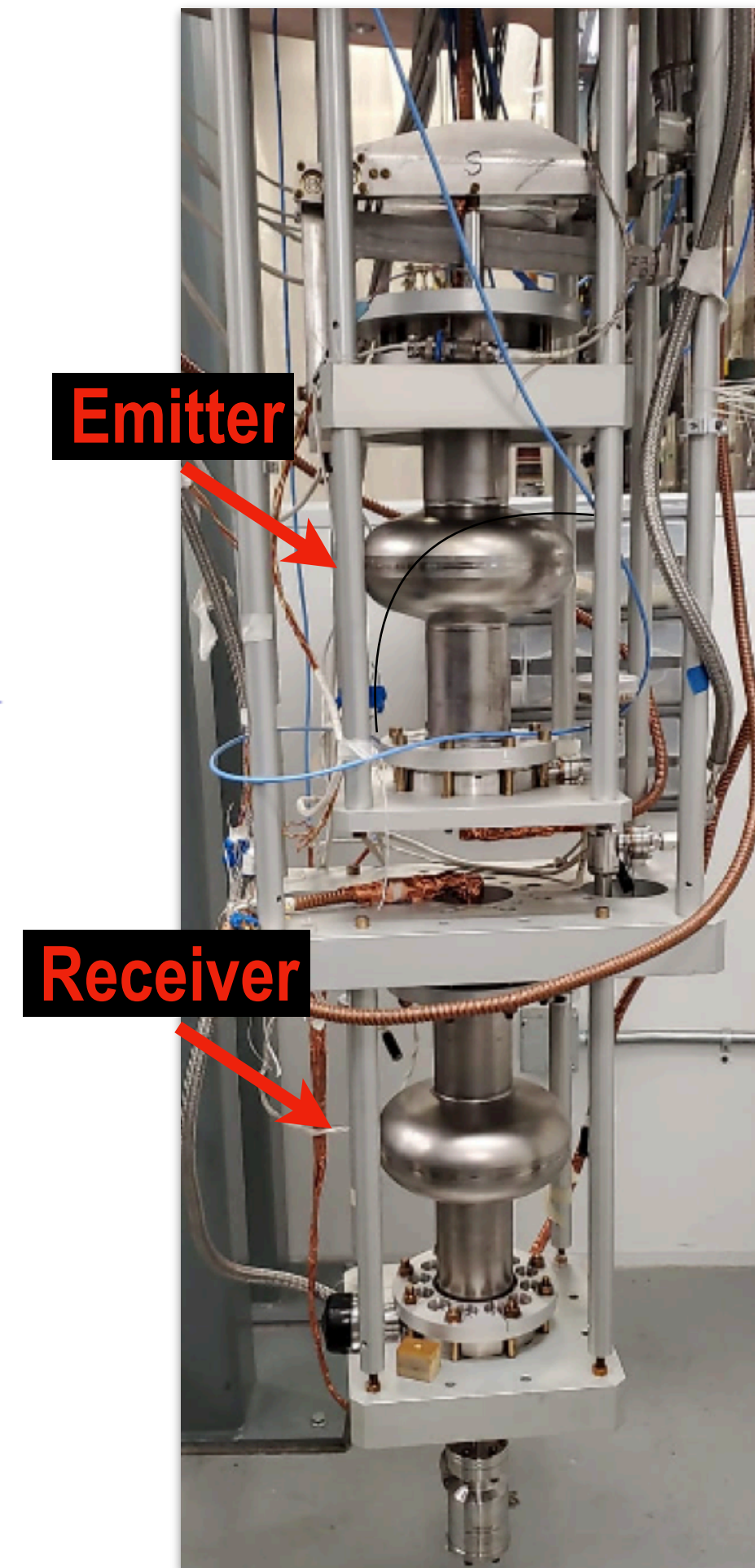
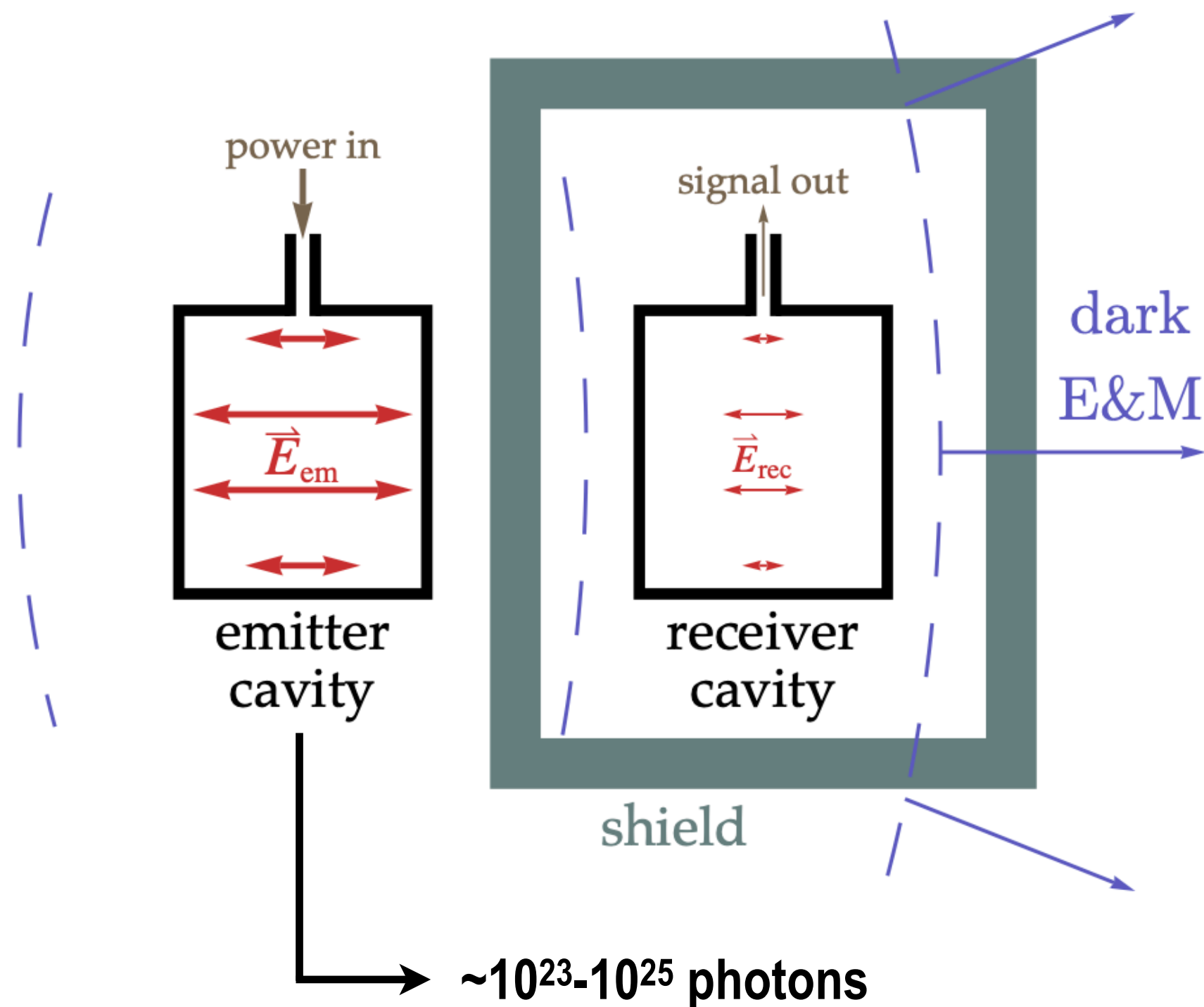
DOE mid-term review  
due in February 2023

## 4) Experiments searching for other physics

# **New particles searches in SQMS**

# DarkSRF

Dark photon search using superconducting radiofrequency (SRF) cavities → LSW experiment.



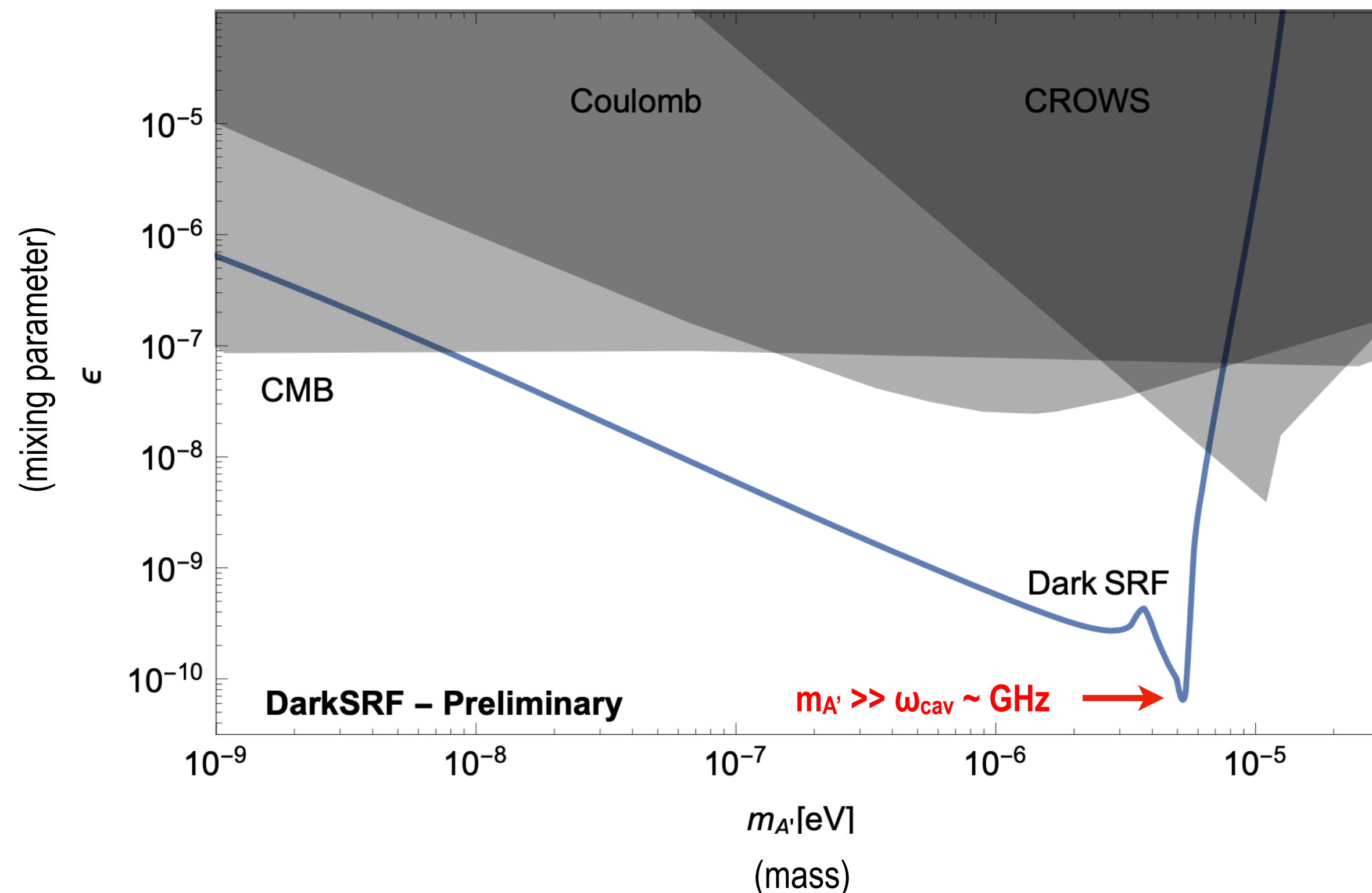
**SM photons do not penetrate the superconducting wall, but dark photons can!**

- 1.3 GHz high quality factor ( $Q \sim 10^{10}$ ) SRF cavities in LHe (1.4 K);
- Resonant cavities increase the number of photons on the emitting side and enhance the probability of conversion of dark photons to visible ones on the receiver side.

# DarkSRF - Results and perspectives

Demonstrated unprecedented sensitivity to **dark photon** using two 1.3 GHz SRF cavities in LHe:

- Exclusion boundary pushed up to 3 orders of magnitude below the state of the art.



*A. Grassellino et al., "First results of DarkSRF: a dark photon search using SRF cavities", QIS for Fundamental Physics Workshop, Aspen Center for Physics (2020)*

*SQMS DarkSRF Collaboration, "A new exclusion for dark photons from an SRF cavity-based search", in progress.*

## Next proposed steps:

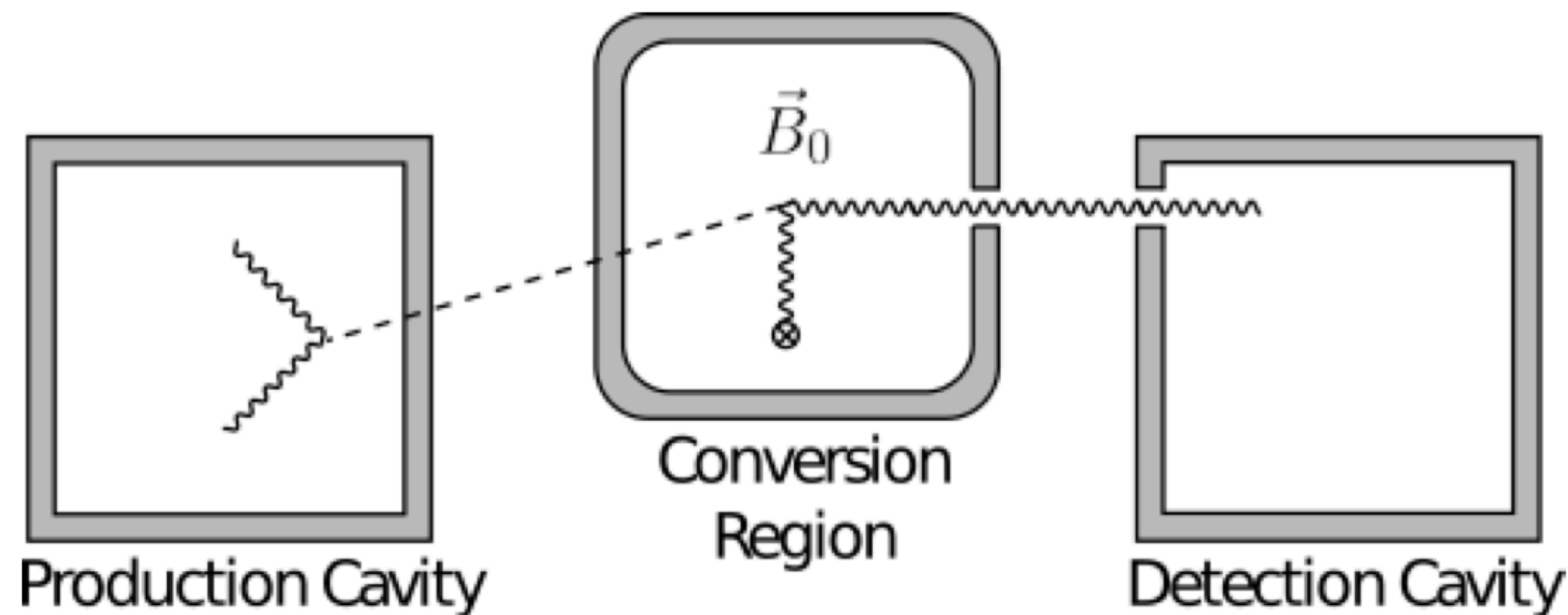
- 2.6 GHz SRF cavities in dilution refrigerator (DR) at mK temperature (quantum regime);
- Improved cavity design (higher Q);
- Phase readout.

**Expected exclusion boundary:  $10^{-13}$  in the higher sensitivity mass region.**

DarkSRF is also sensitive to **ultra-light millicharged particles** and **millicharged DM**.

# LSW-type axion searches - Two cavities with static B-field

## Probe axion-photon couplings



Produced axions will pass through the cavity walls and propagate to the conversion region, where some axions will convert back to photons.

## PROPOSED EXPERIMENT:

- Two high-Q SRF cavities;
- Conversion region containing a confined magnetic field in the form of a superconducting, broken-toroid magnet.

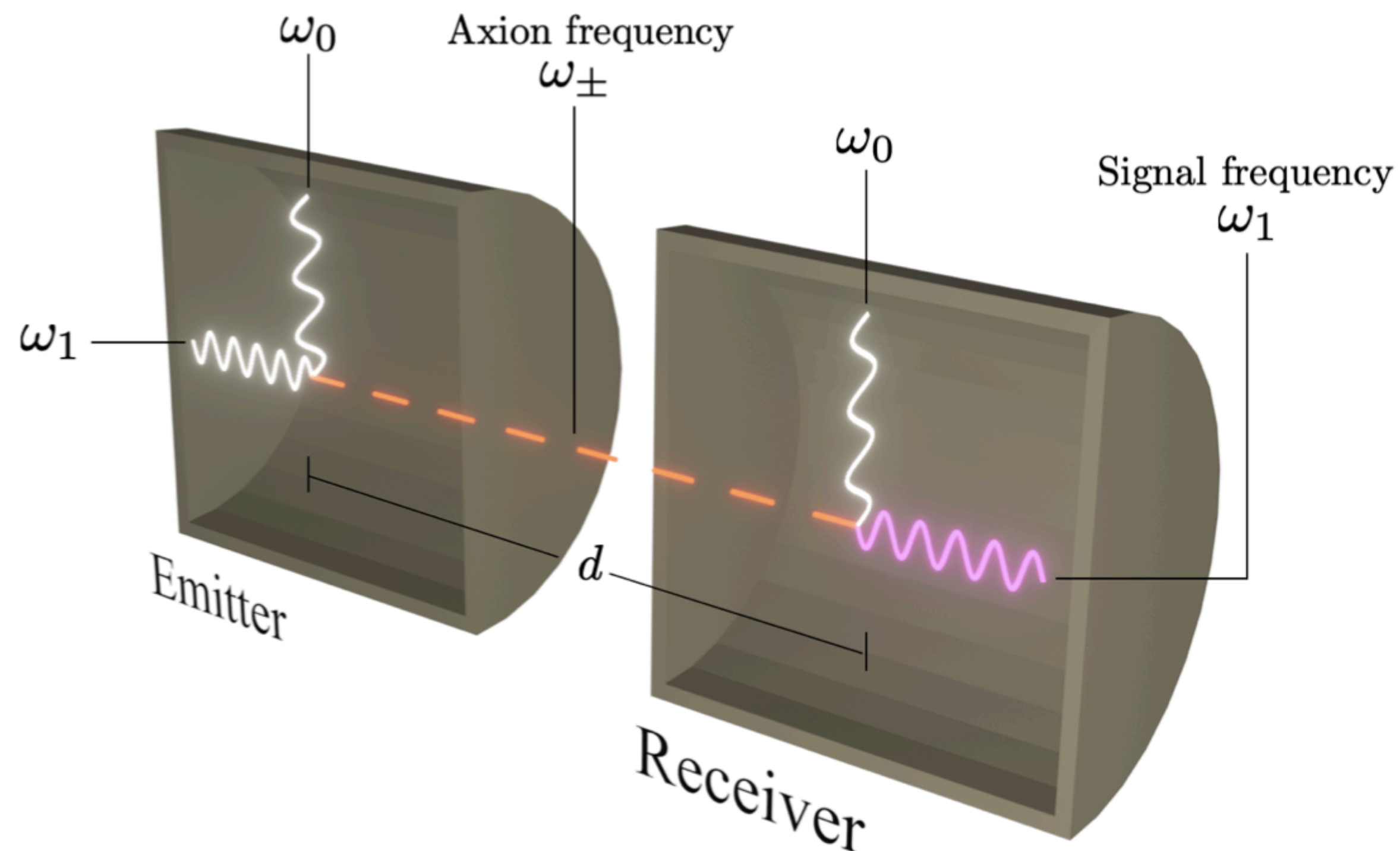
**With this approach neither SRF cavity is subject to large magnetic fields and neither suffers a degradation of Q-factor.**

*R. Janish et al., Phys. Rev. D 100, 015036 (2019)*

# LSW-type axion searches - Two cavities with a pump mode

**Alternative approach:** replace the static B-field with an oscillatory B-field inside the receiver cavity (pump mode of the cavity).

**Avoid the introduction of the conversion region, simplifying the design.**

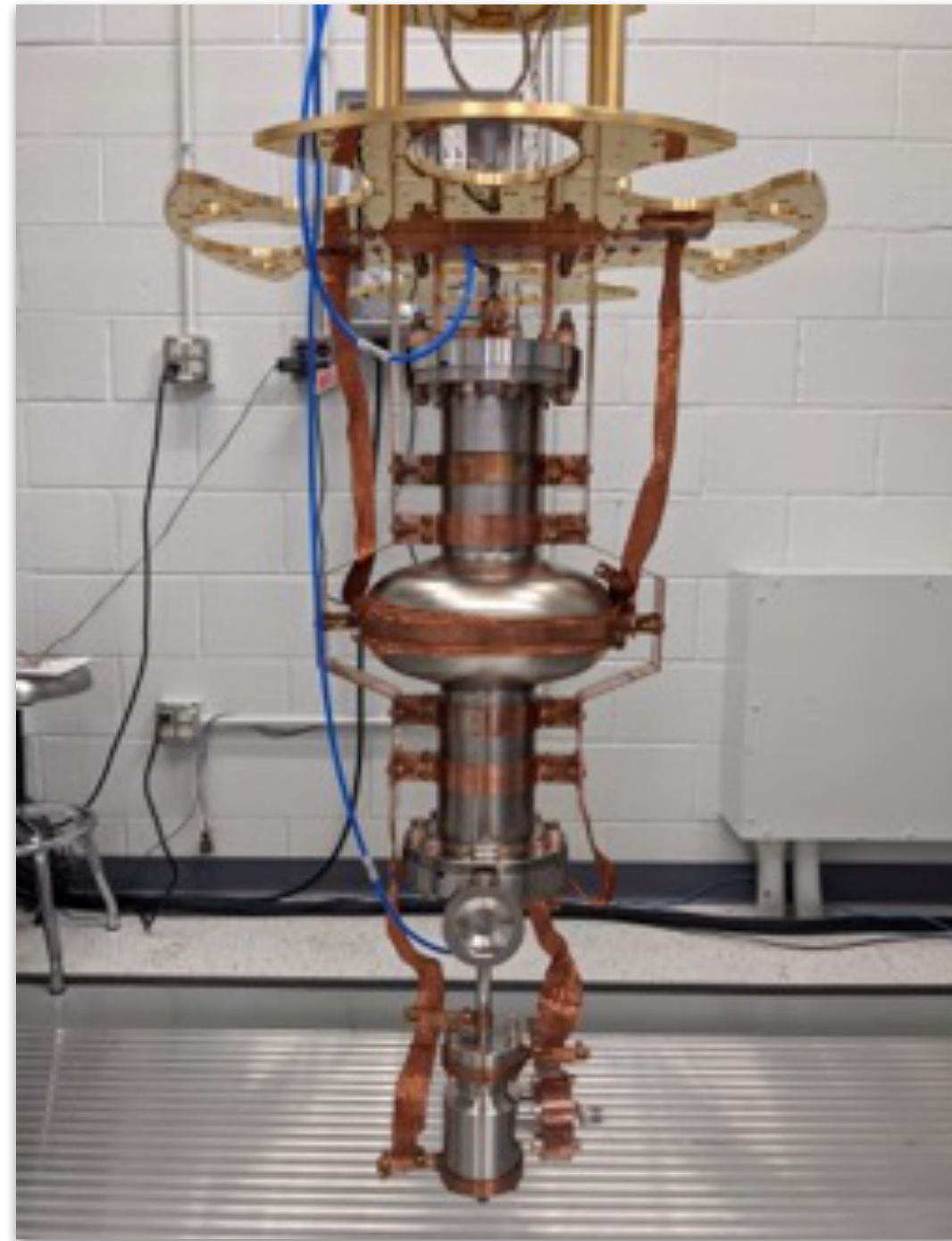


- Axion is produced from the emitter with a frequency equal to the sum or difference of the two active modes of the cavity,  $\omega_{\pm} = \omega_1 \pm \omega_0$ ;
- The axion may in turn produce a photon in the receiver with frequencies equal to  $\omega_{\pm} \pm \omega_0$ , in which the combination that yields  $\omega_1$  can be resonantly produced.

*A. Berlin et al., arXiv:2203.12714 (2022)*

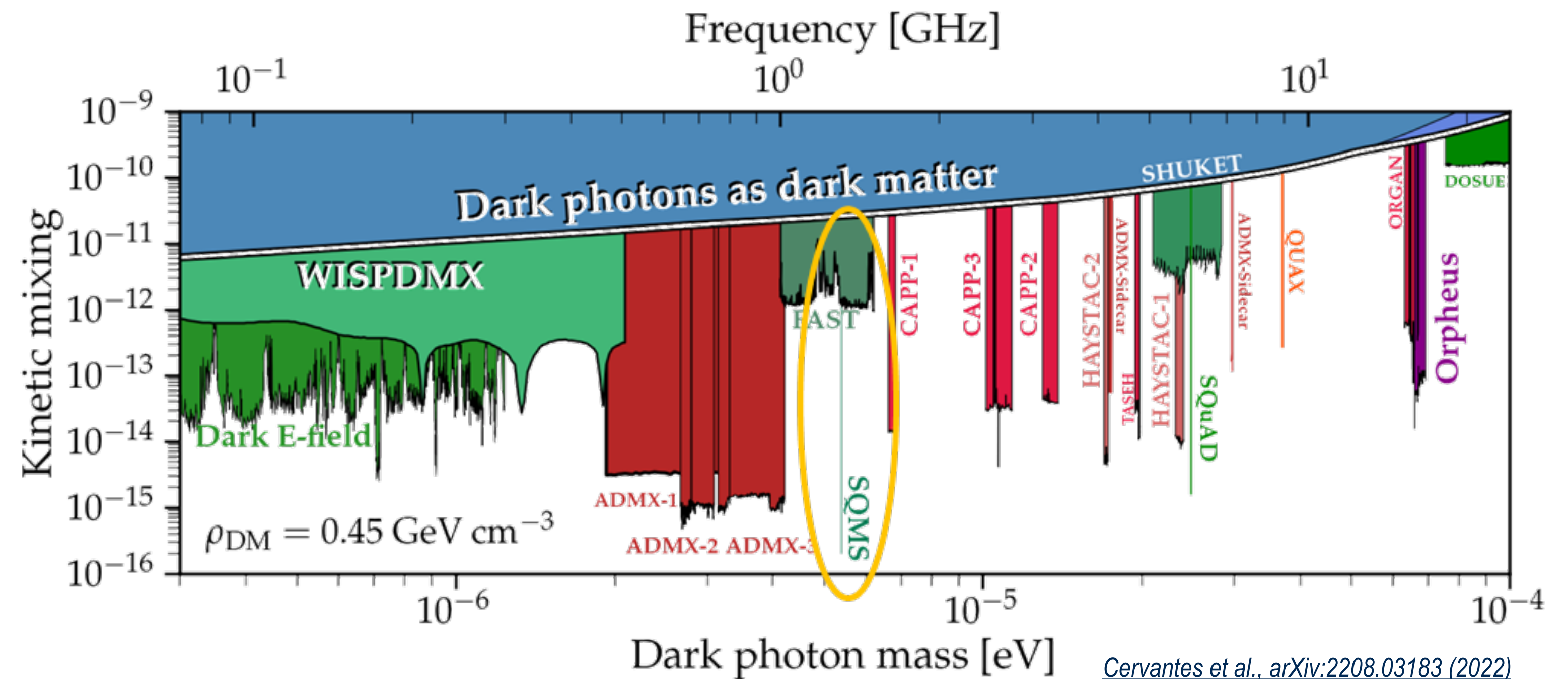
# Dark matter searches in SQMS

# Dark photon dark matter searches



Dark photon dark matter (DPDM) search with 1.3 GHz cavity with  $Q \sim 10^{10}$  in DR.

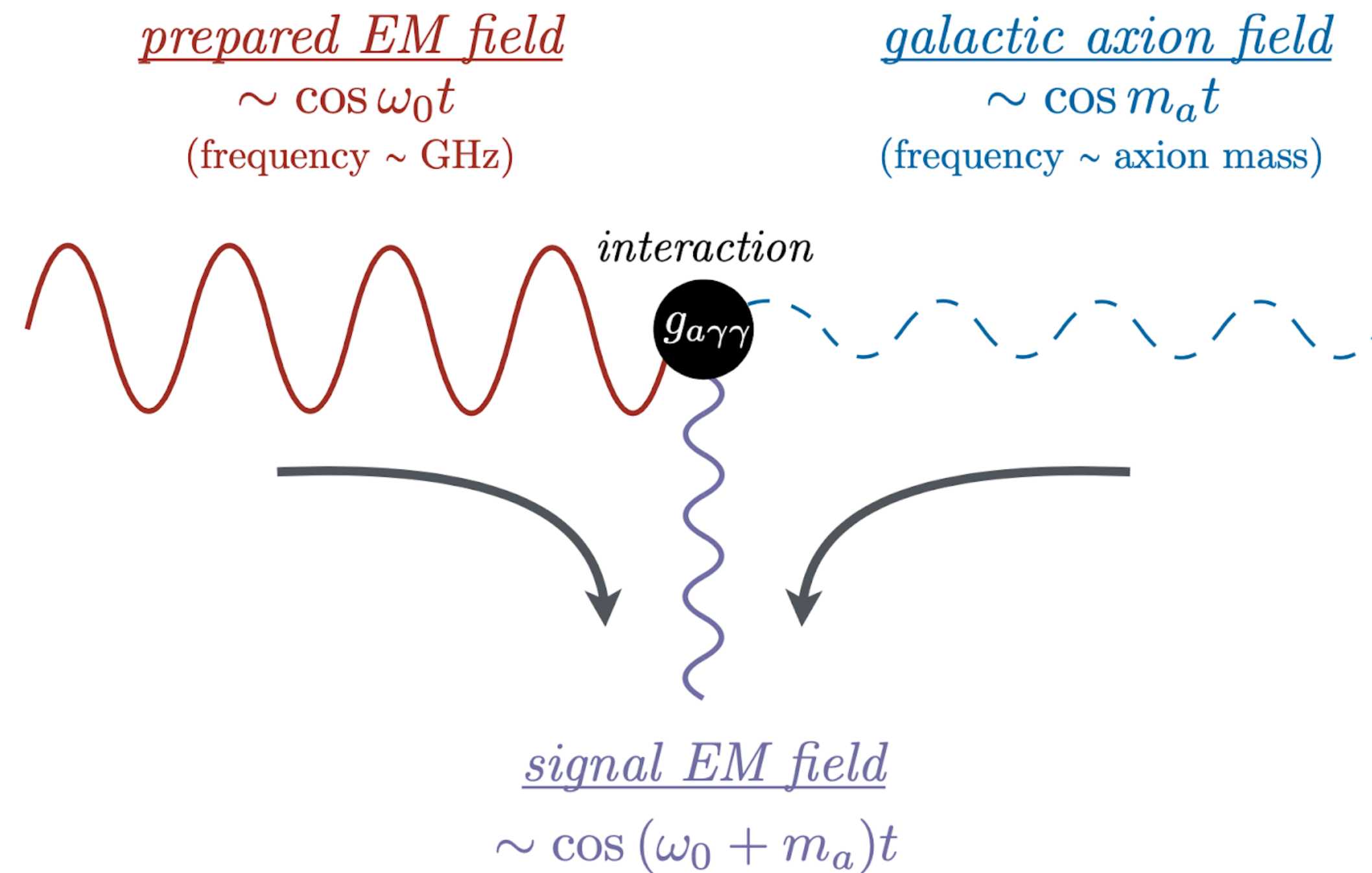
**Deepest exclusion limit to wavelike DPDM by an order of magnitude.**



## Next proposed steps:

- Tunable SRF cavities (5-8 GHz) for DPDM searches;
- Combine SRF cavity technology and qubit-based photon counting to reduce the noise floor below the Standard Quantum Limit (SQL) → increased sensitivity.

# Axion dark matter searches with haloscopes



Axion to photon conversion inside **RF cavities**  
in a **strong magnetic field**.

- The feeble EM field oscillating at the axion mass can be detected with a resonator tuned to the same frequency ( $\sim$ GHz  $\rightarrow$   $m_a \sim \mu$ eV).
- Since the resonant frequency is typically controlled by the inverse geometric size of the detector, probing much lighter axion masses requires prohibitively large cavities.

# Axion dark matter searches with haloscopes - QUAX

**QUAX (Q**Uest for **A**Xions) search for axion dark matter with RF copper cavity with dielectric shells.

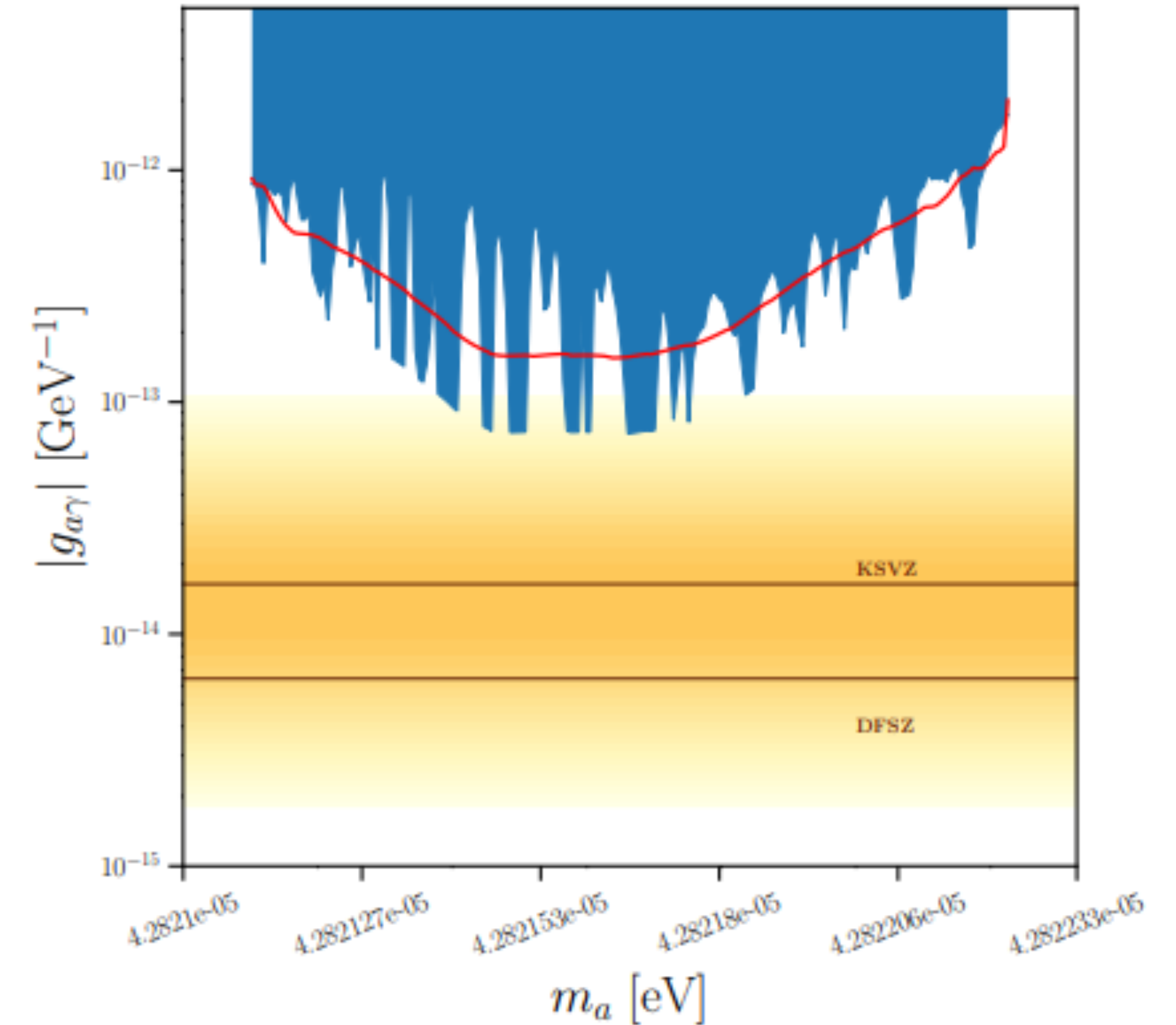


- $Q_0 \sim 9 \times 10^6$ ;
- $B_{\text{ext}} \sim 8 \text{ T}$ .

**Two weeks run @4 K probed axion masses not accessible to other running experiments.**

**Next proposed steps:**

- Cavity in DR;
- Work on integration of high-Q SC cavity.

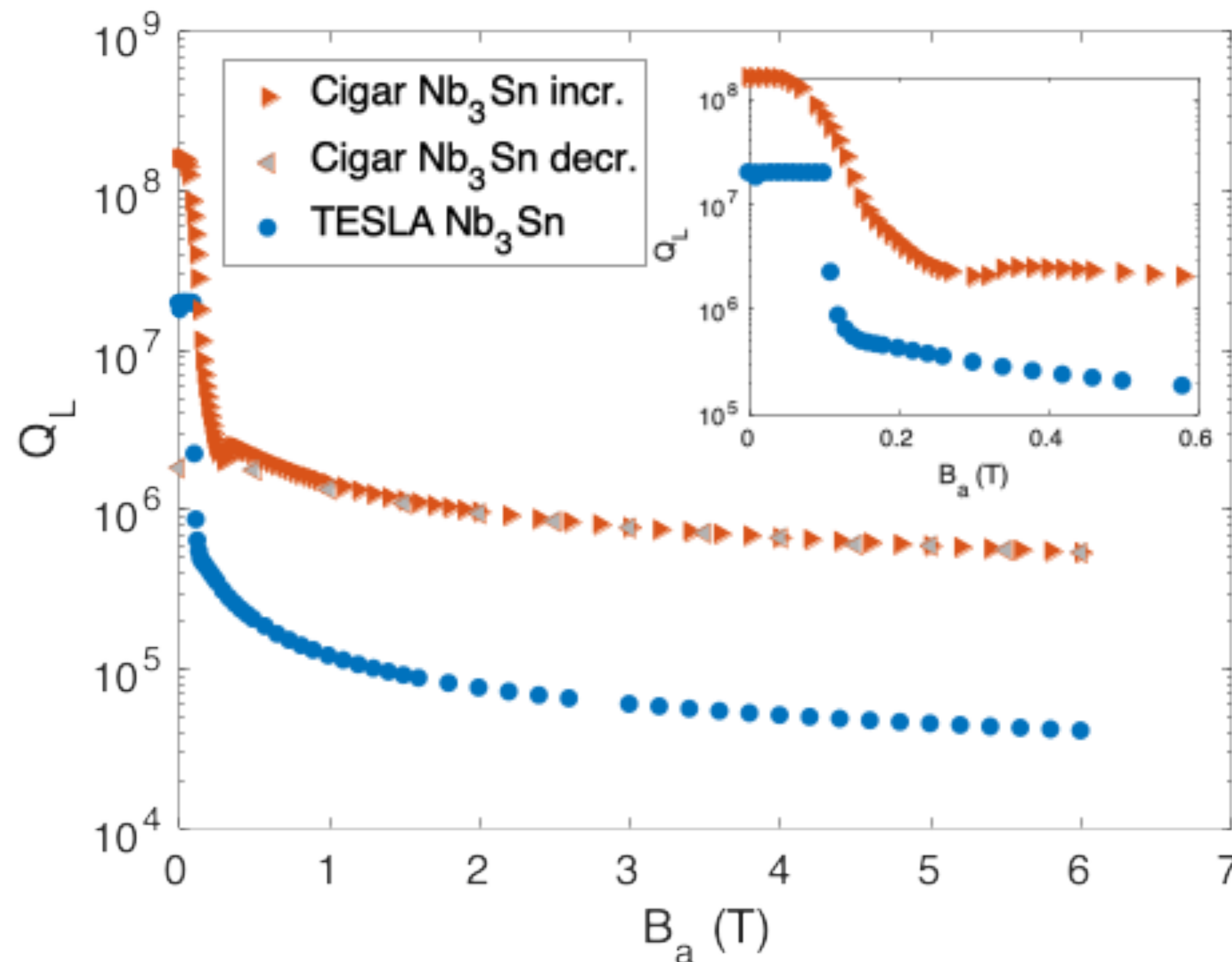


*R. Di Vora et al., Phys. Rev. Appl. 17, 054013 (2022)*

*C. Braggio et al., presented at PATRAS2022*

# Axion searches - High-Q cavities in a static B-field

**Standard haloscope approach:** Typical  $Q \sim 10^4$ - $10^5$ , but sensitivity scales as  $\sqrt{Q}$ .



*S. Posen et al., arXiv:2201.10733 (2022)*

**First measurements of high-Q cavity in tesla scale magnetic field:**

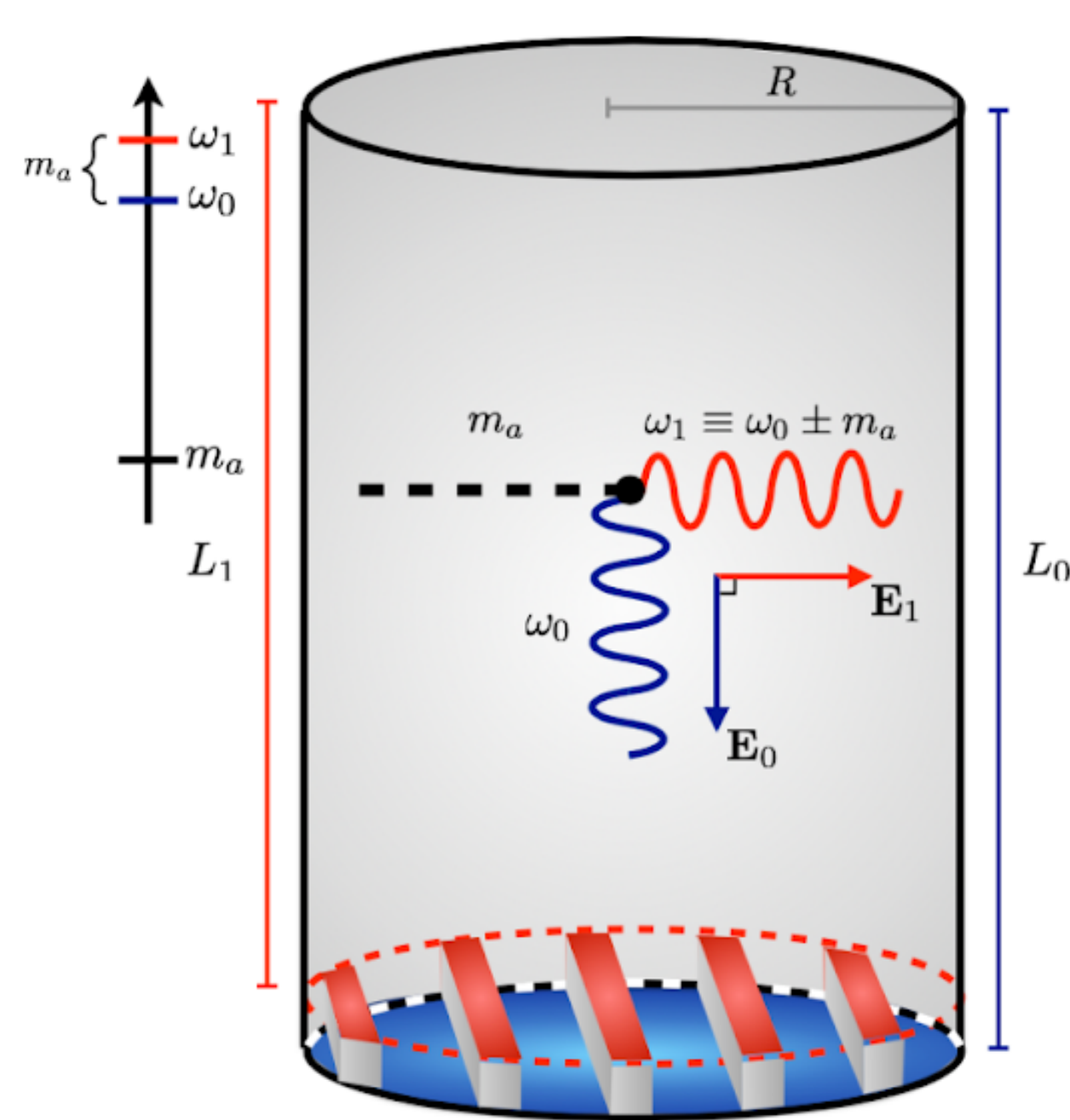
- Nb<sub>3</sub>Sn cavity;
- 6 T magnetic field;
- liquid helium (4.2 K).

**Next proposed steps:**

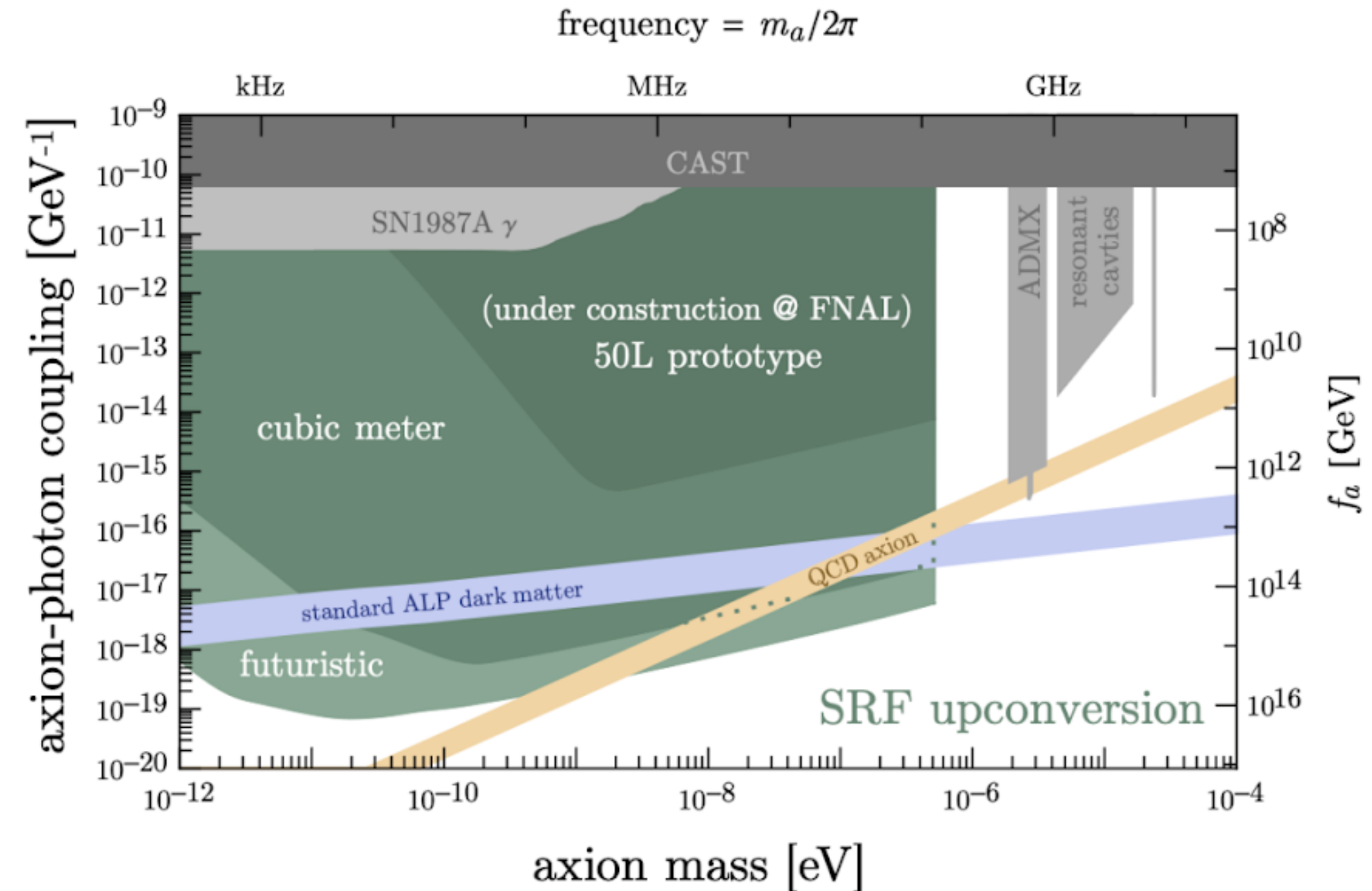
- Further optimizations with cavity treatment, magnetic field alignment, and geometry optimization.
- Implement tuning.
- Explore other superconducting materials like commercial High Temperature Superconductor (HTS) tapes.

# Axion dark matter searches with up-conversion

## Oscillating magnetic field in a resonant SRF cavity



Axion transfers power  
from driven mode to quiet mode.

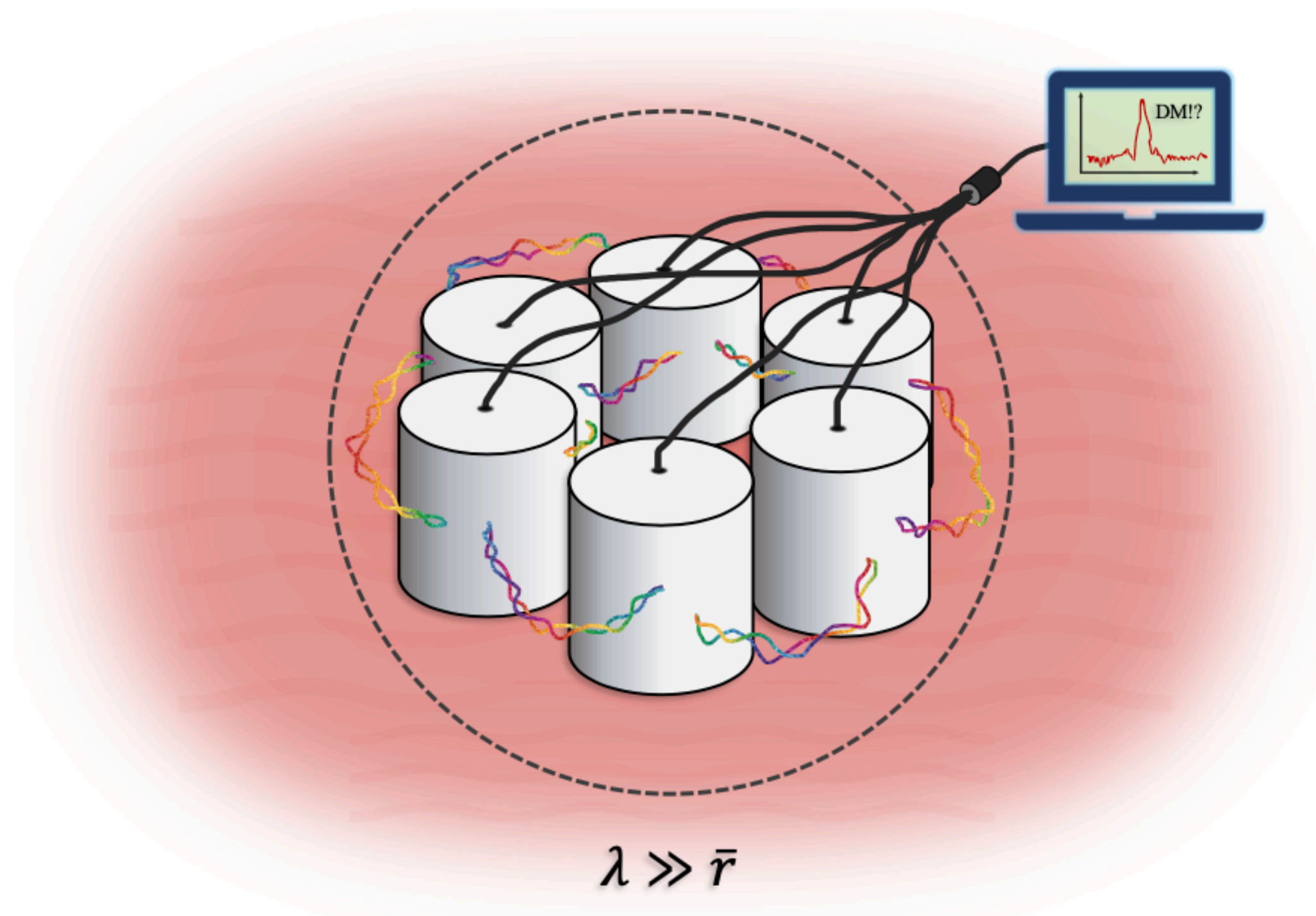


*A. Berlin et al., Phys. Rev. D 104, L111701 (2021)*

A photon at frequency  $\omega_0 \sim \text{GHz}$  is up-converted by axion DM into a nearly degenerate photon of frequency  $\omega_1 = \omega_0 + m_a$ .

**Enhanced signal for light axions:  $\text{GHz}/m_a \gg 1$  and  $Q \sim 10^{11}$**

# A quantum network of haloscopes



A network of microwave cavities will experience a coherent axion signal if the size of the network is less than the axion coherence length.

Arrays of **entangled sensors** can, in principle, **accelerate** the **search** for **DM**.

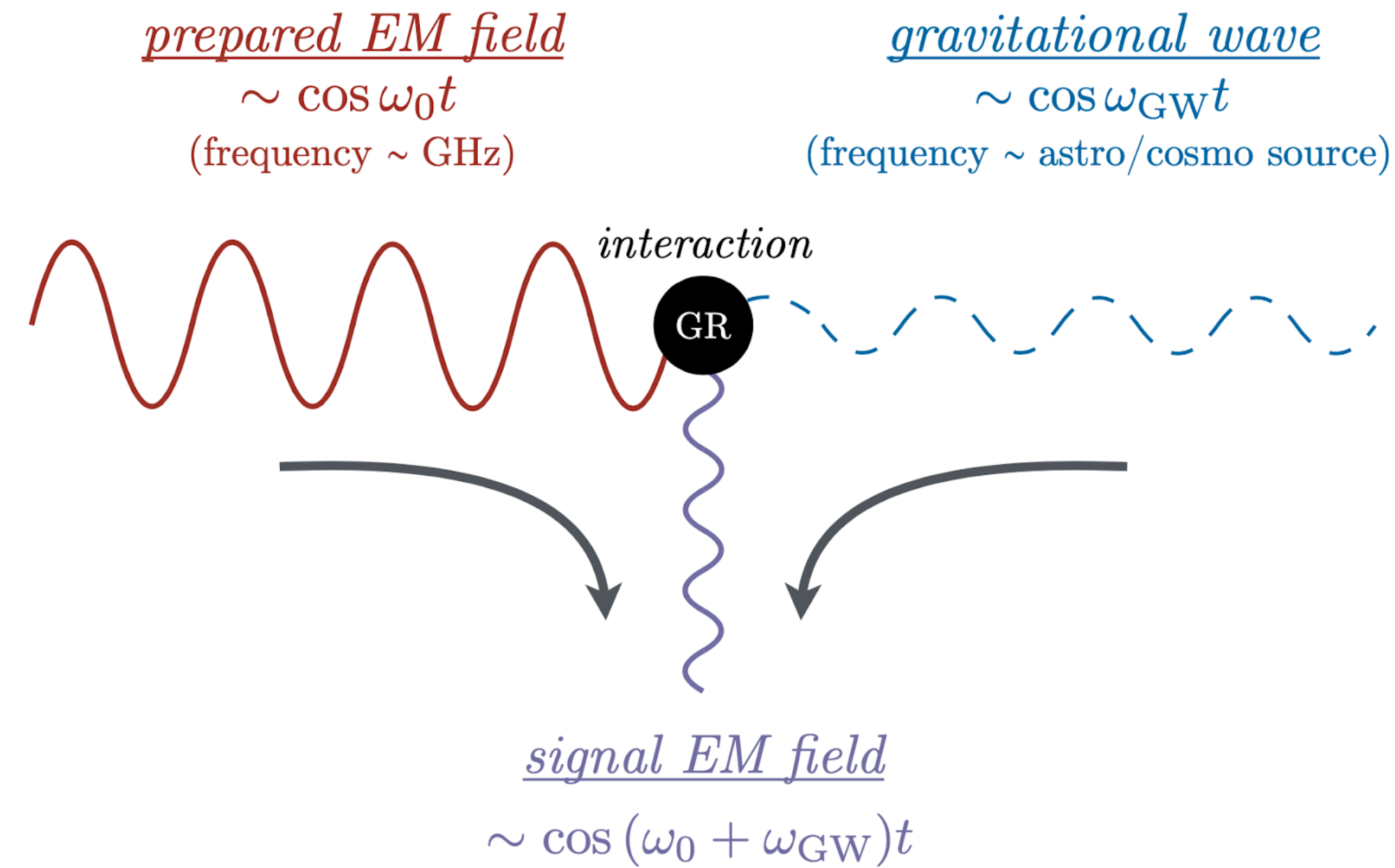
## Proof-of-principle experiment with two mechanical oscillators:

- Squeezed vacuum + linear optics to generate entanglement;
- Simultaneous benefits from
  1. quantum correlations of input radiation (**global reduction of noise**);
  2. classical correlations of DM field (**boosted signal**).

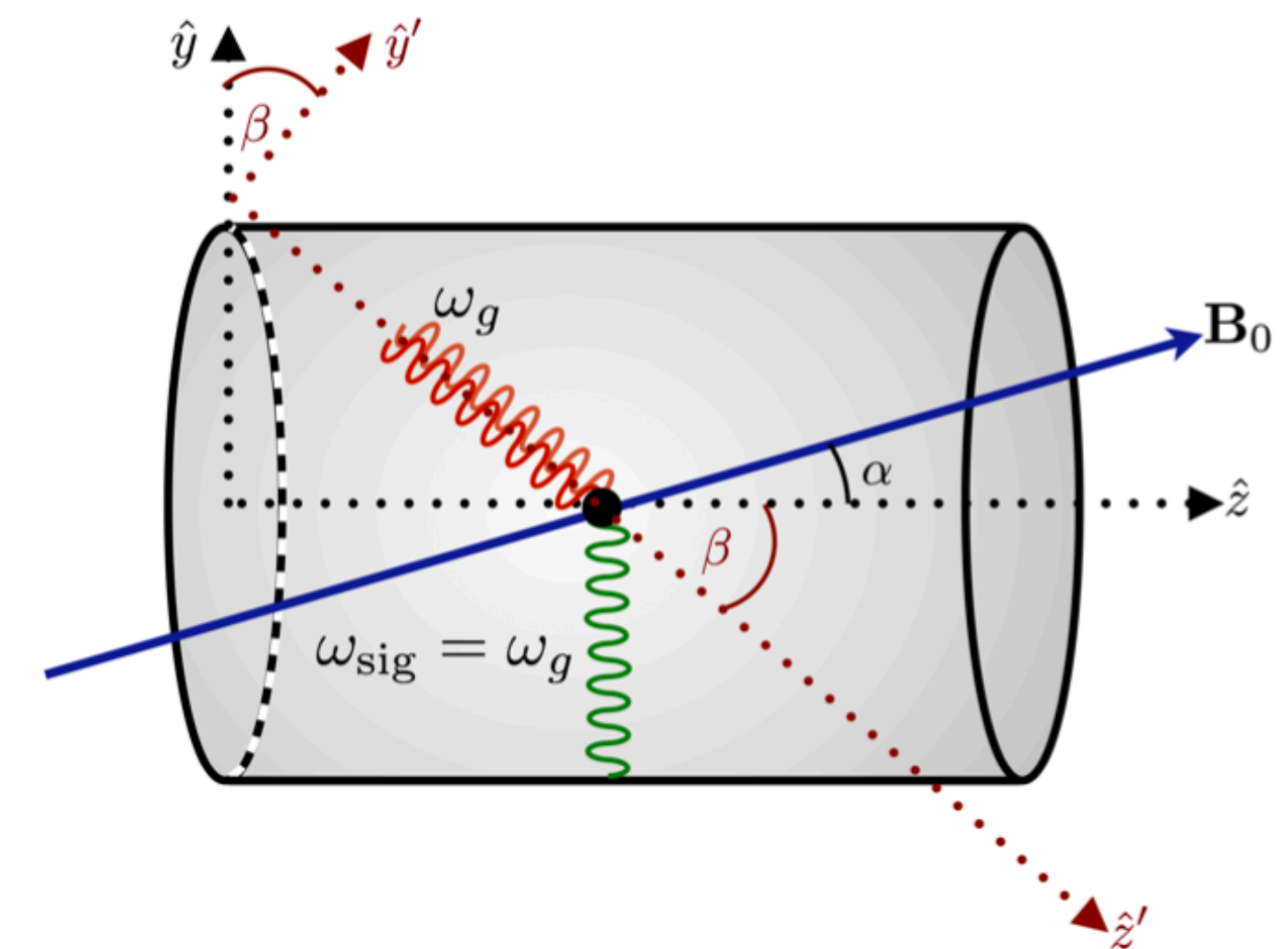
*A. J. Brady et al., PRX QUANTUM 3, 030333 (2022)*

# Other searches in SQMS

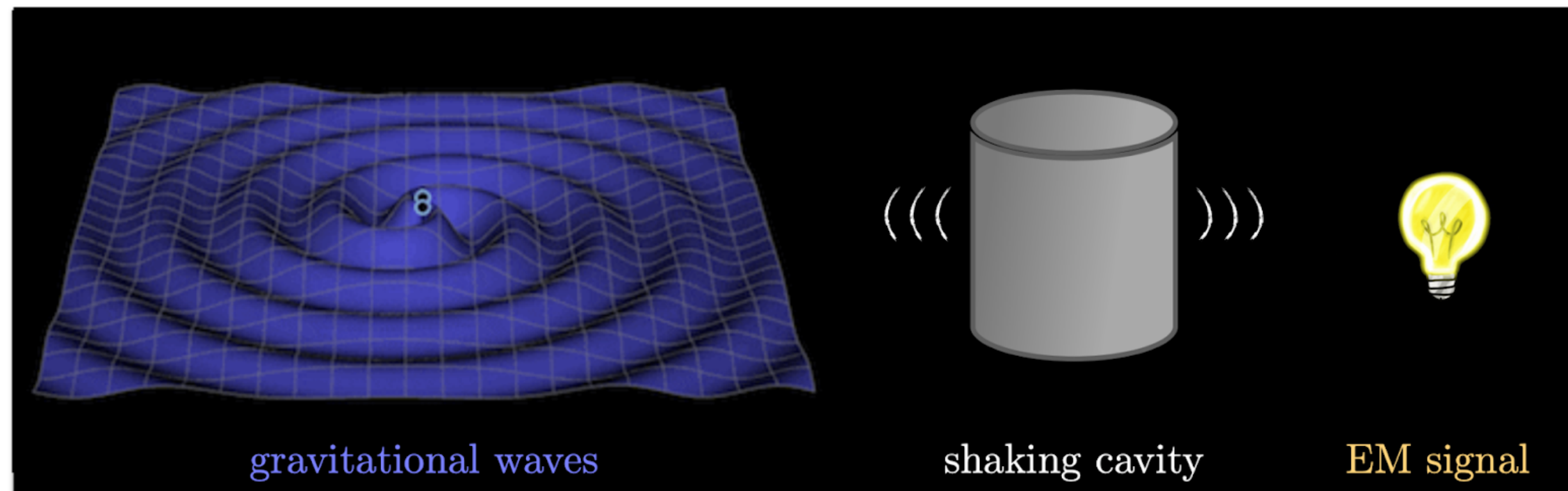
# High frequency gravitational waves searches



Microwave cavities can also be used to detect **high-frequency gravitational waves (GWs)**.



A **gravitational wave** interacts with a **static external B-field**, resonantly exciting a **cavity mode**.



*A. Berlin et al., arXiv:2112.11465 (2021)*

# Conclusions

**What still needs to be done to reach Appendix 13 deliverables for the DOE mid-term review?**

**What are the long term goals of SQMS in the quantum sensing focus area?**

- DarkSRF: finalize DR implementation, increase Q, implement phase readout;
- Commission DR with 10 T magnet;
- For all cavities currently in design phase (Multimode axion cavities, DPDM plunger cavity, HTS cavity):
  - ▶ Procure cavities and design experiment layout;
  - ▶ Run searches;
  - ▶ Publish results;
- Work on cavity plus qubit based DPDM and axion DM searches.



# Thank you for your attention!



All the materials of the SQMS Annual Meeting 2022 can be found at:

<https://indico.fnal.gov/event/56576/timetable/#20221018.detailed>

SQMS Annual Meeting 2022 @Fermilab