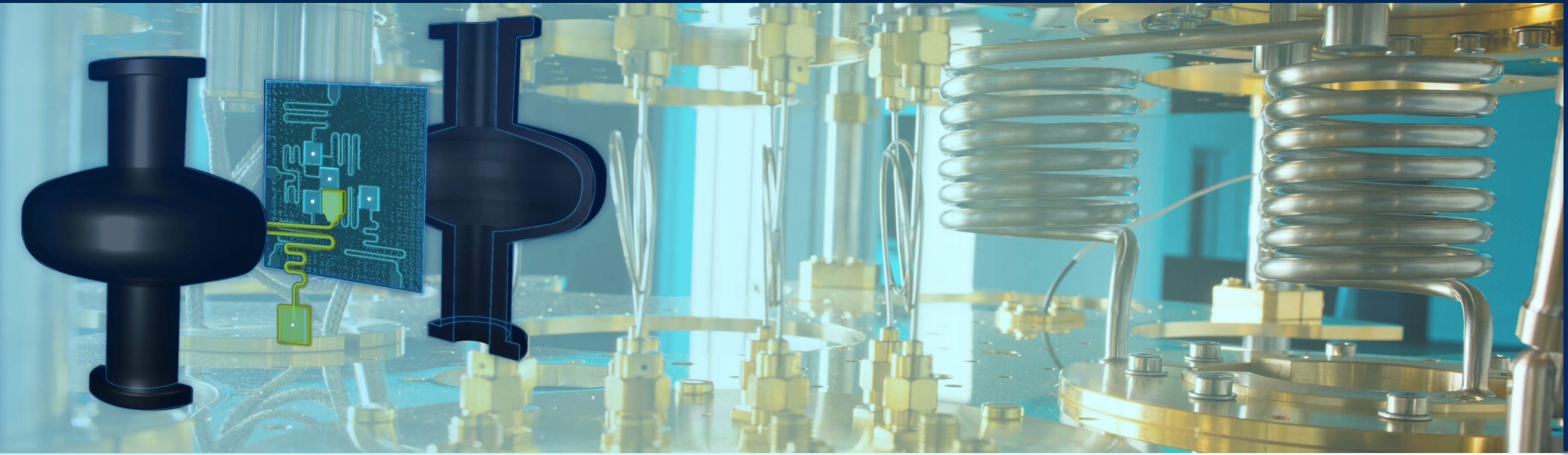
FERMILAB-SLIDES-24-0056-SQMS

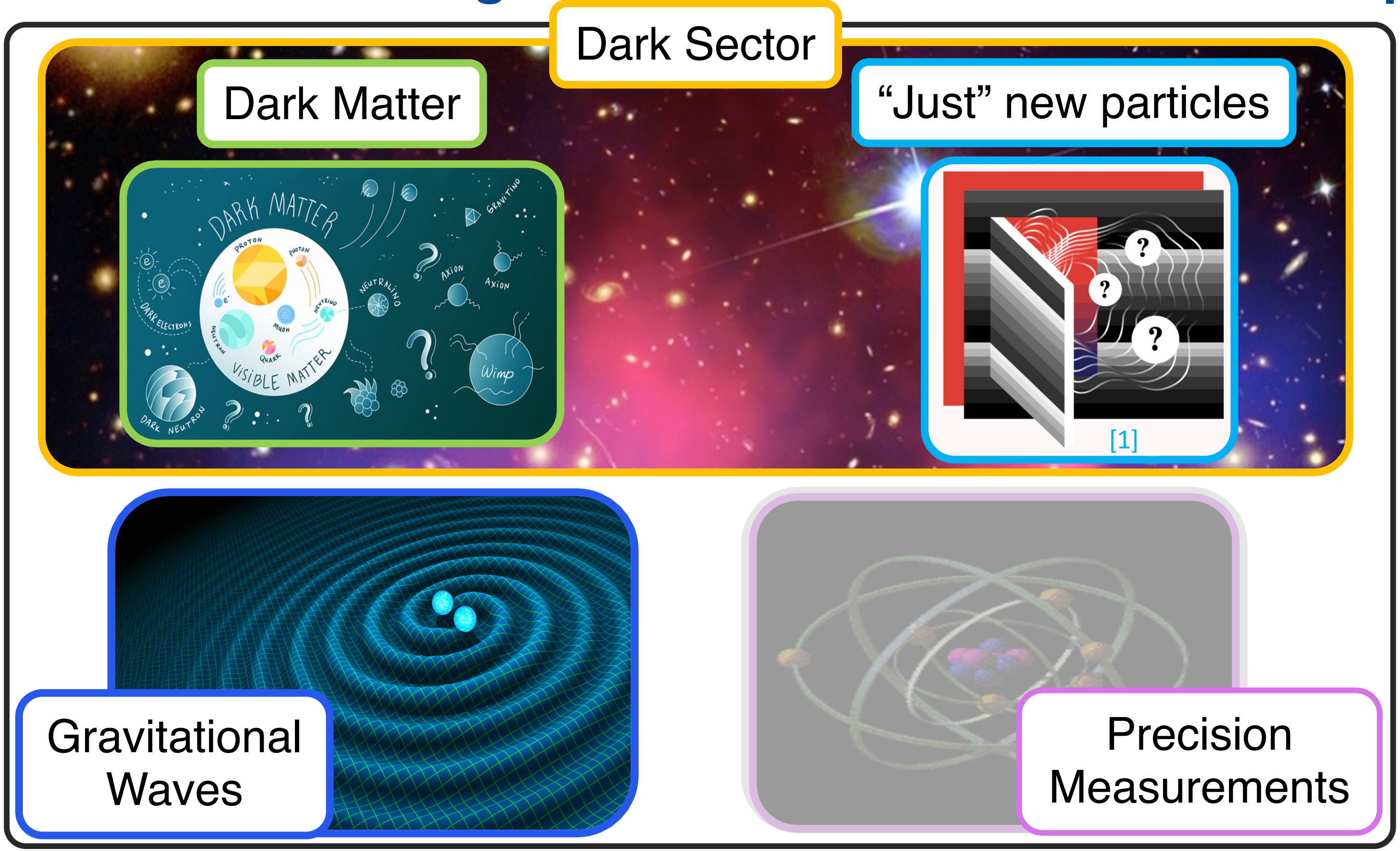


This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Cavity based searches for new particles and gravitational waves

Bianca Giaccone
SQMS, Fermilab

Quantum Sensing: new windows into fundamental physics



Fermilab Dark SRF Experiment

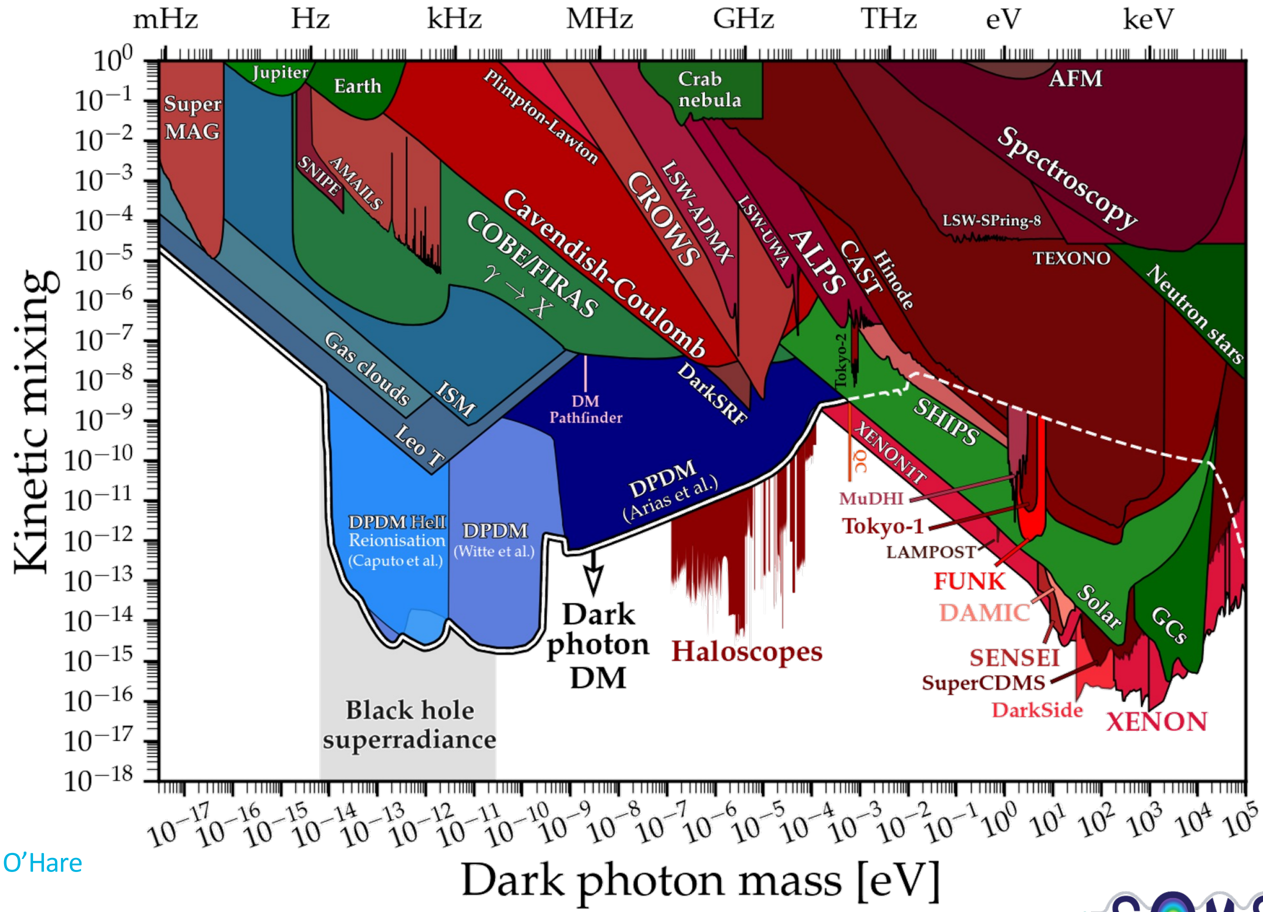
[1] Artwork by Sandbox Studio Chicago with A. Kova symmetrymagazine.org

Quantum Sensing: new windows into fundamental physics

Fermilab Dark SRF Experiment

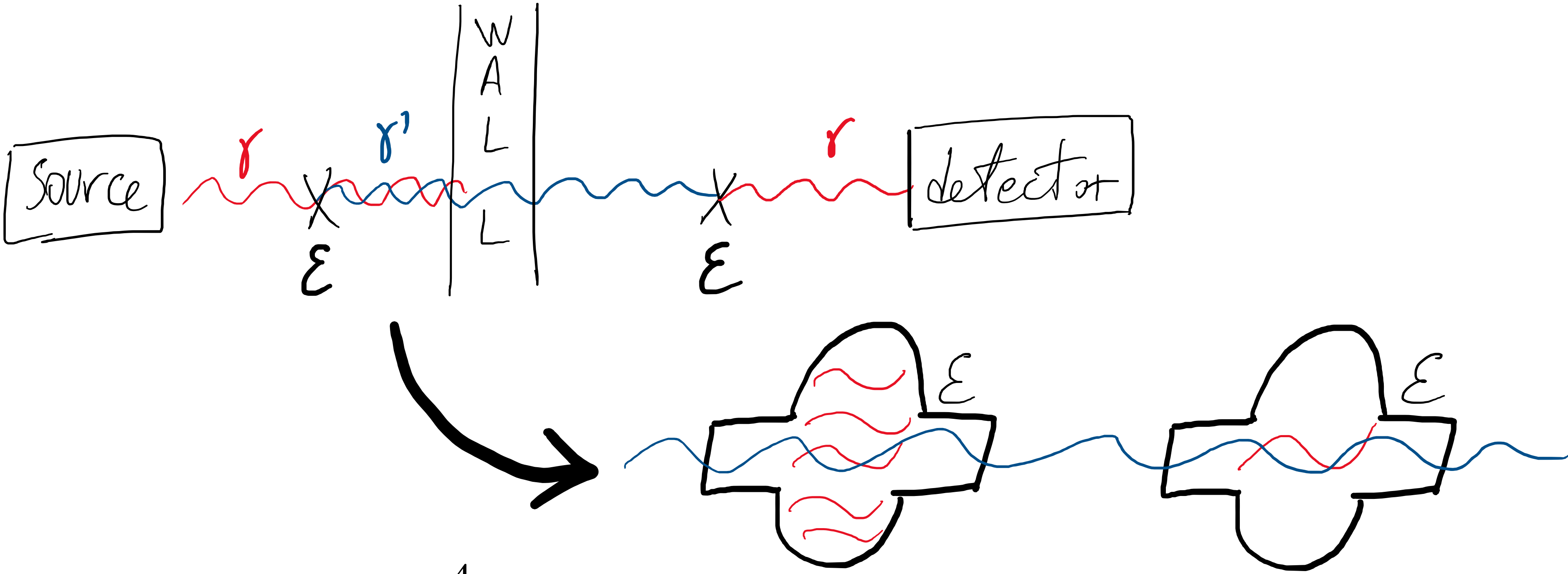
[1] Artwork by Sandbox Studio Chicago with A. Kova symmetrymagazine.org

No dark photons have been found yet…



Credit: C. O'Hare

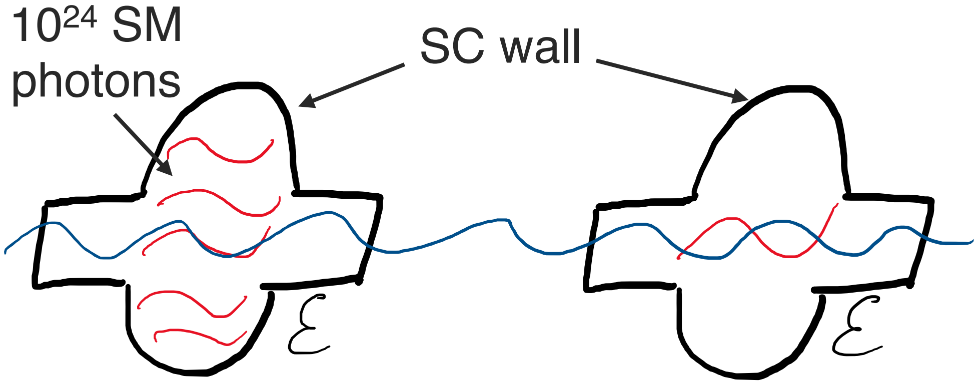
Dark SRF: Light-Shining-through-Wall search



$$P_{rec} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \, \omega \, Q_{rec} \, U_{em}$$

Graham et al., Phys Rev D90, 075017 (2014)
Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Advantage of using high Q cavities



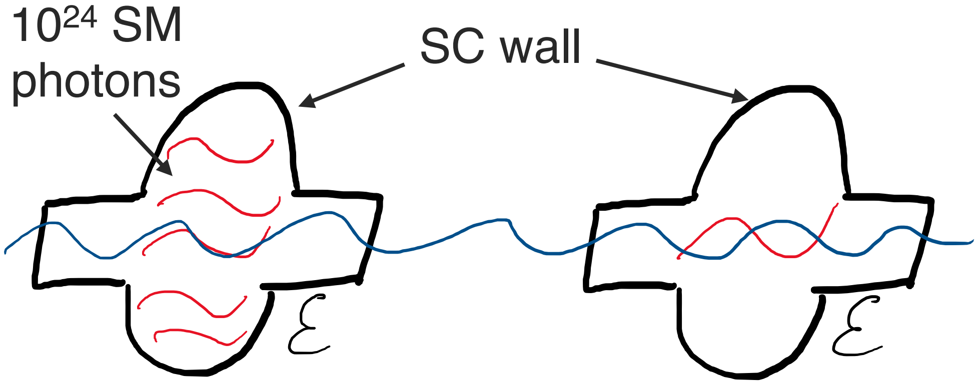
Emitter cavity, in the accelerator regime, high field

High Q_0: increases number of photons

Receiver cavity, in the low field regime

High Q_0: enhances probability of detecting power excess due to dark photons

Advantage of using high Q cavities



Emitter cavity,
in the accelerator regime, high field

Receiver cavity,
in the low field regime

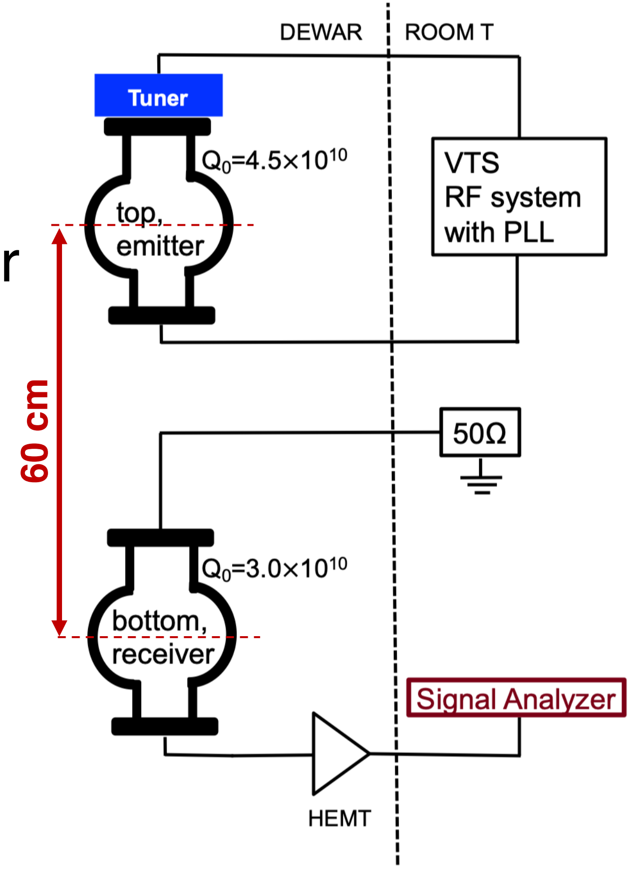
bility
ss

Necessary to match cavities frequency!

LHe vertical test stand facility at Fermilab

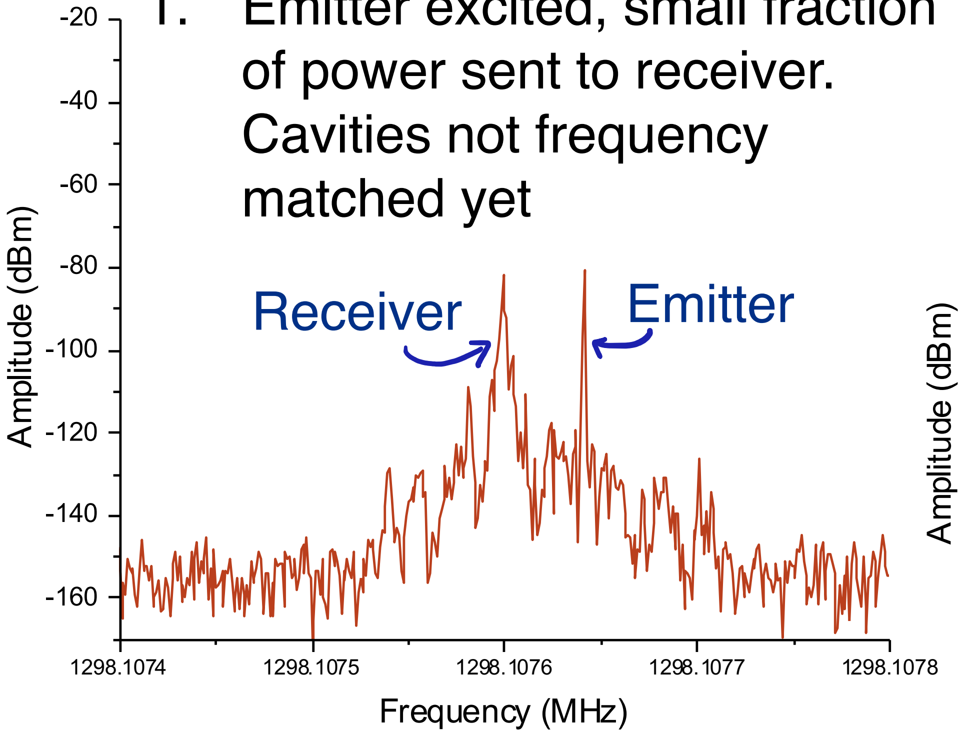
Dark SRF: phase 1 → preparations

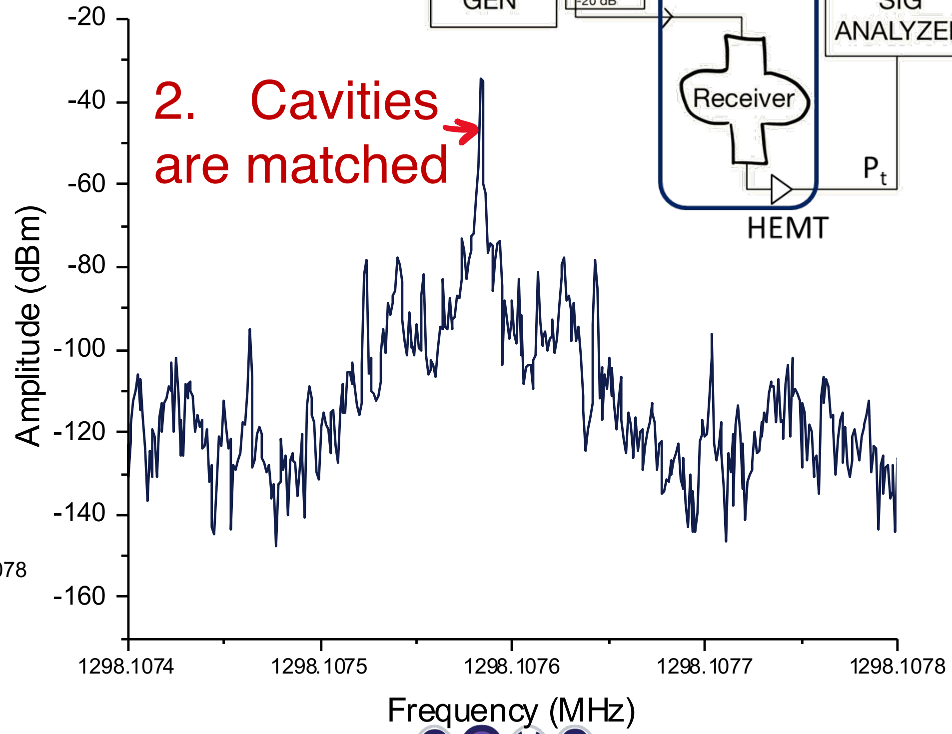
- 1.3GHz single cell cavities sitting in LHe at 1.3-2 K
- Cavities were characterized using accelerator style measurements and calibration
- Want to match the cavities frequency to sub-Hz level using tuner on emitter
- Many tests of frequency monitoring were conducted for both cavities to assess their stability
- HEMT on receiver P_t line → cryo amplifier to raise signal above Room Temp background

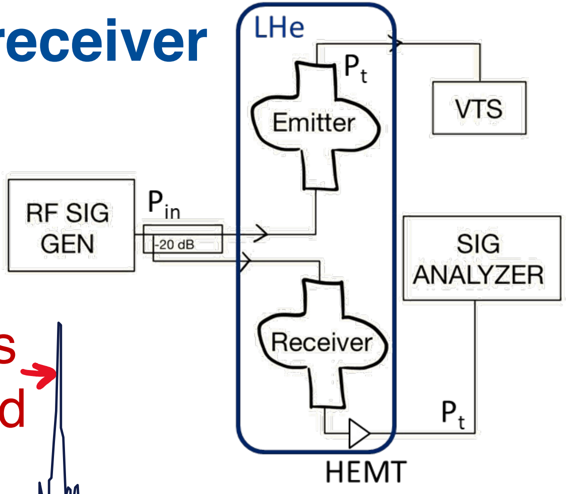


Step 1: excite emitter and match frequency to receiver

1. Emitter excited, small fraction of power sent to receiver. Cavities not frequency matched yet

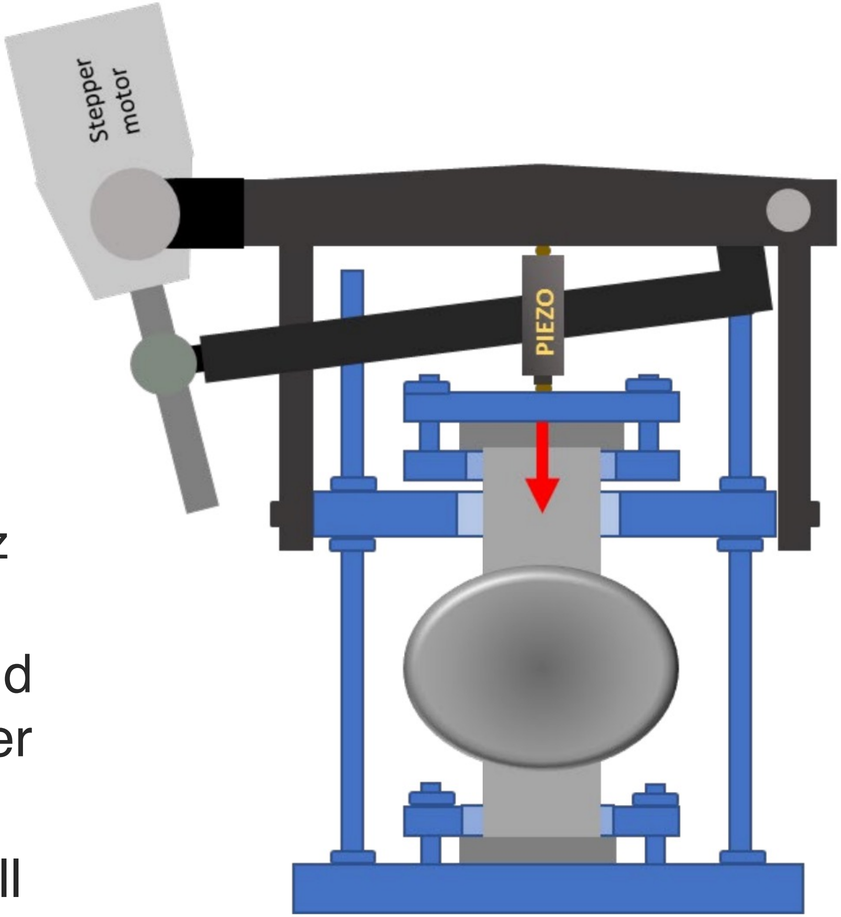






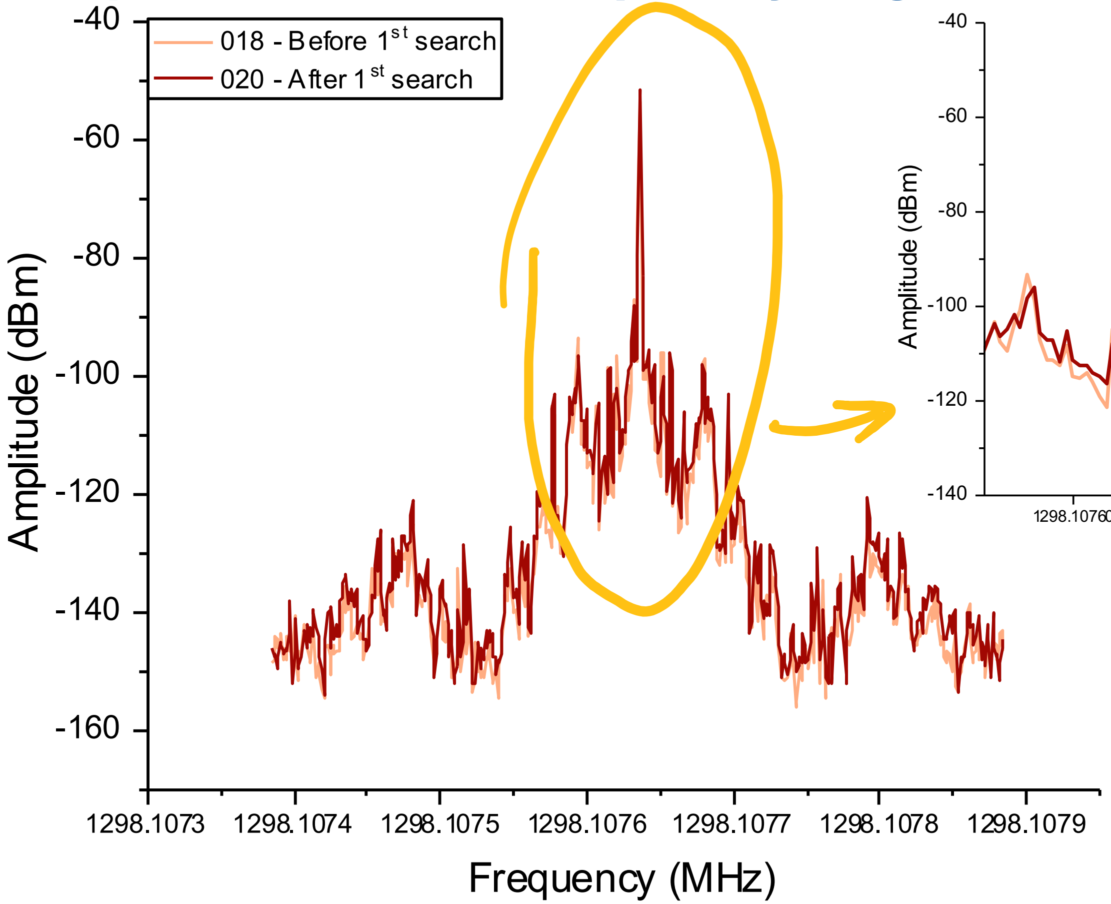
Cavity tuning

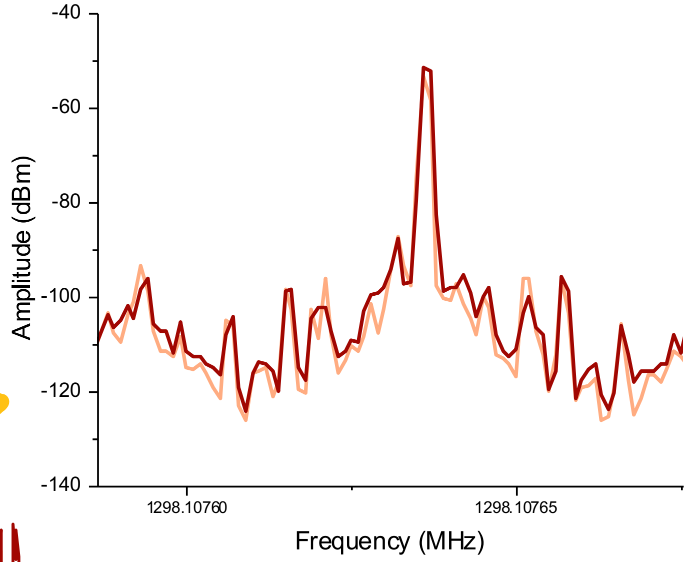
- Tuner mounted on emitter cavity and preloaded
- Tuner composed of stepper motor and piezo
  - Stepper motor: coarse tuning with 5MHz range, ~12Hz resolution
  - Piezo: fine tuning, 8KHz range with 0.1Hz resolution
- Pushes or pulls on the cavity flanges and deforms cavity → larger equator → lower frequency
- (df/dl=2.3MHz/mm for 1.3GHz single cell cavity)



Pischalnikov et al., doi:10.18429/JACoW-SRF2019-TUP085

Step 1 & 3: check frequency alignment before and after search

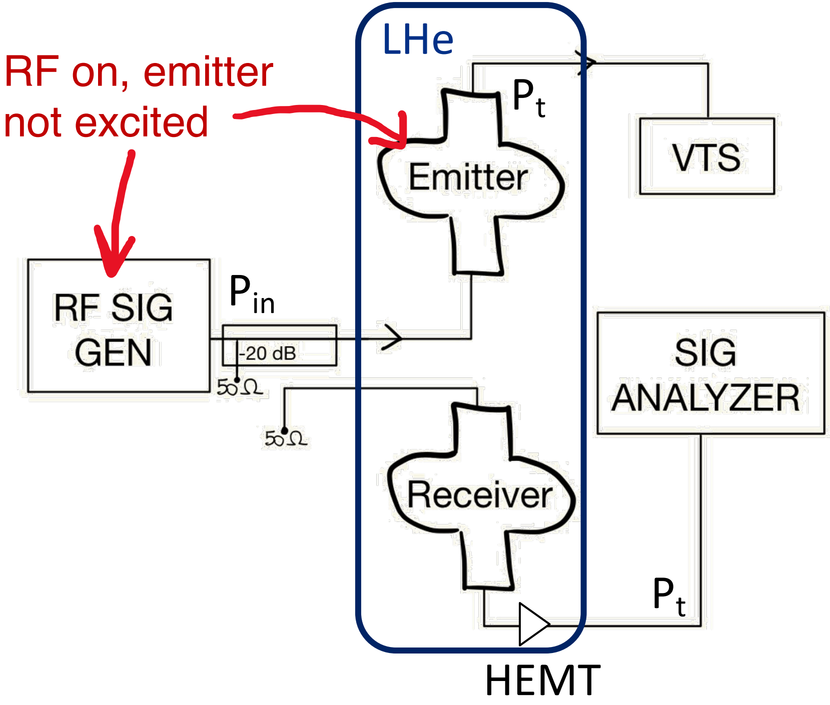




Example of good frequency alignment maintained through search (~35min).

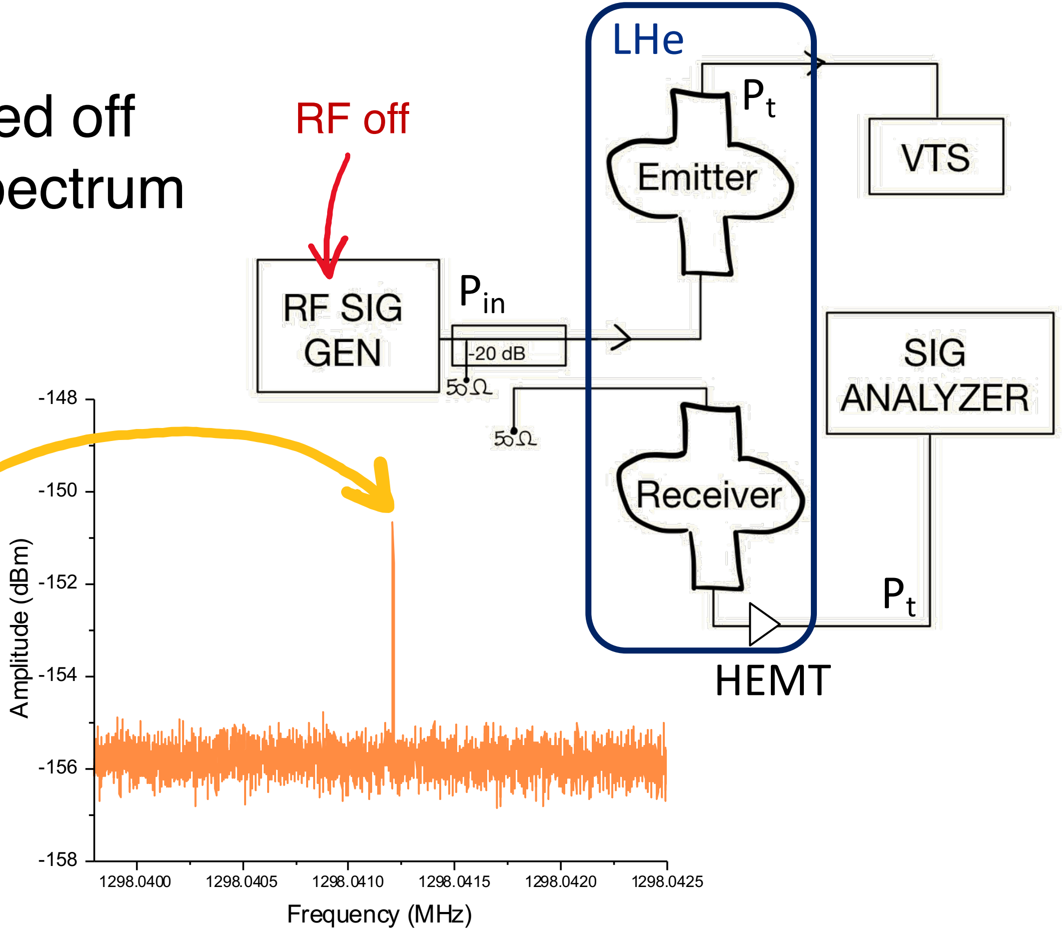
Step 4: cross-talk check

- If peak of excess power found in the receiver cavity: what is its origin?
- Send RF power without exciting emitter (phase locked loop open)
- Does peak in receiver follows frequency of RF signal generator?
  - If yes → peak due to cross-talk
  - If no → more investigation needed



Step 5: thermal background

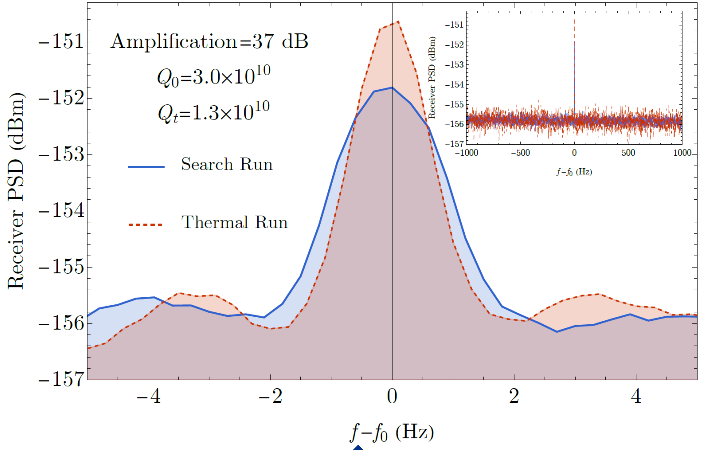
- RF signal generator is turned off
- Measure receiver power spectrum
- Any peak measured?
  - During 2019 run: yes, due to RT photons leaking from receiver input line (data used for limit setting)
  - Later: no, thermal peak eliminates with 30dB attenuation on input line



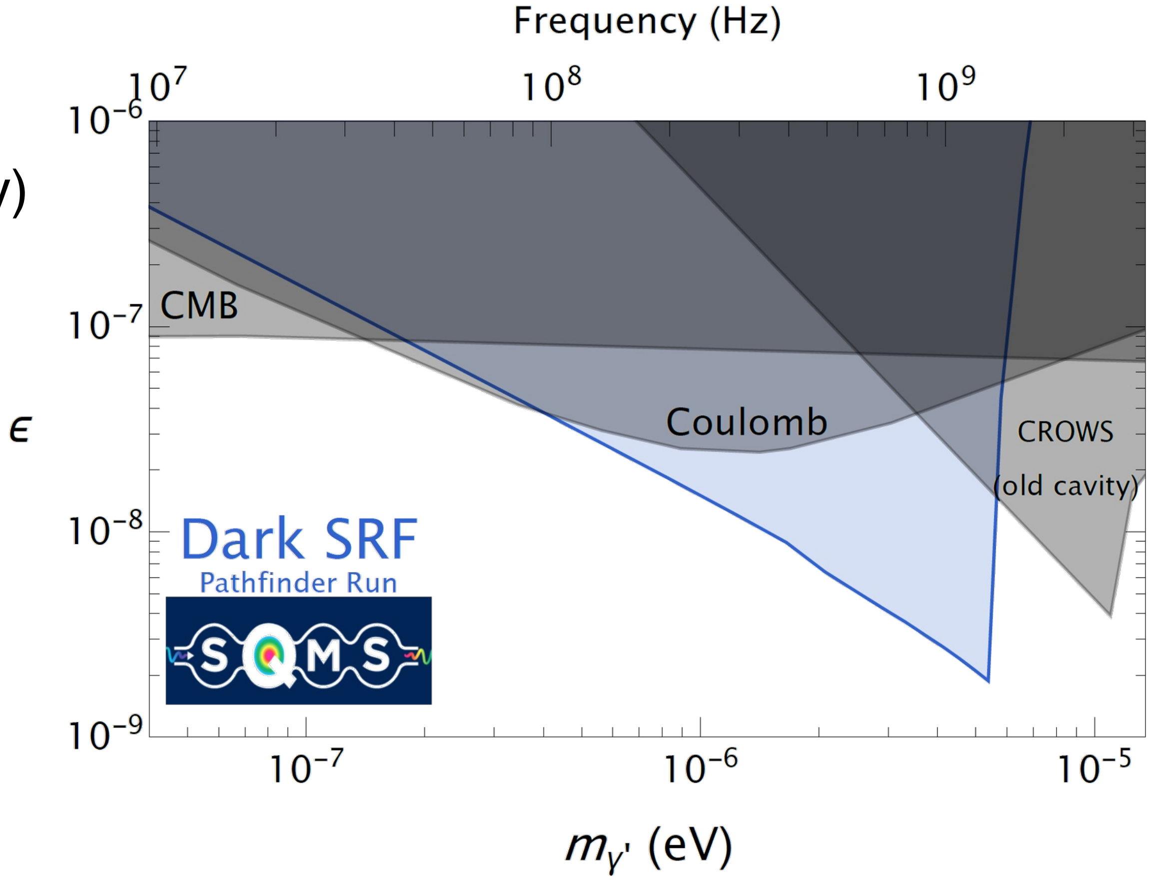
Dark SRF: phase 1 → results

Thermal run vs Search run

Search run conducted at
6.2 MV/m (= 0.6 J stored energy)



Leak of thermal photon
from receiver input line



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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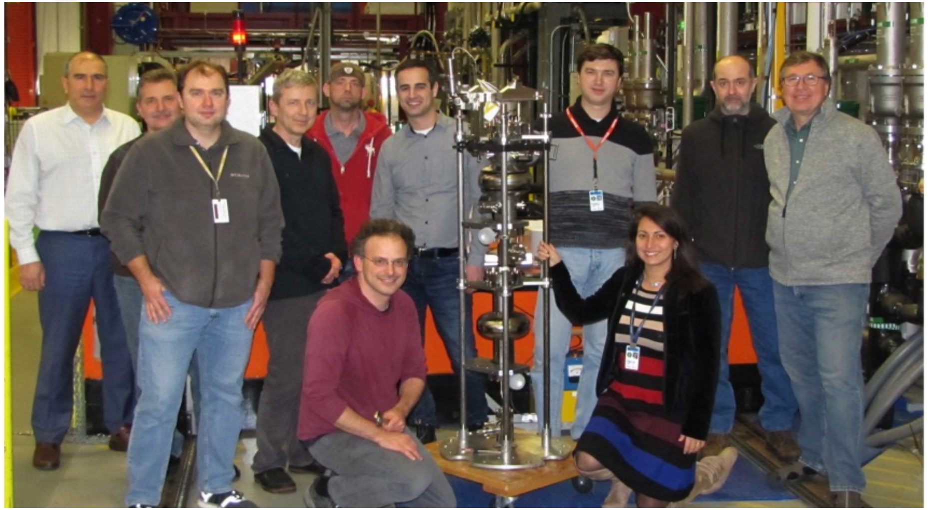
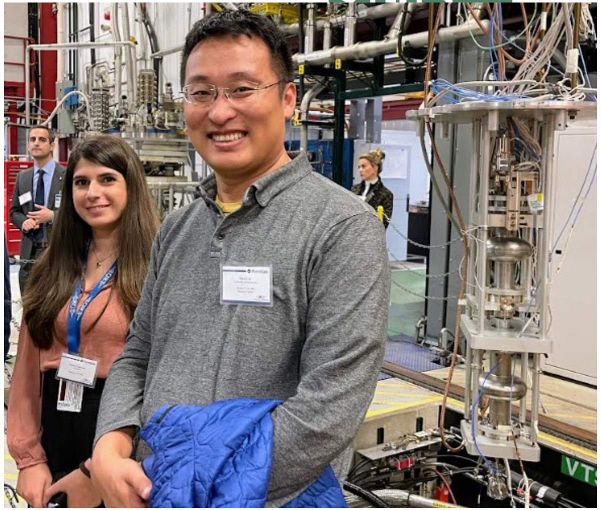
Search for Dark Photons with Superconducting Radio Frequency Cavities

A. Romanenko, R. Harnik, A. Grassellino, R. Pilipenko, Y. Pischalnikov, Z. Liu, O. S. Melnychuk, B. Giaccone, O. Pronitchev, T. Khabiboulline, D. Frolov, S. Posen, S. Belomestnykh, A. Berlin, and A. Hook

Phys. Rev. Lett. **130**, 261801 – Published 26 June 2023

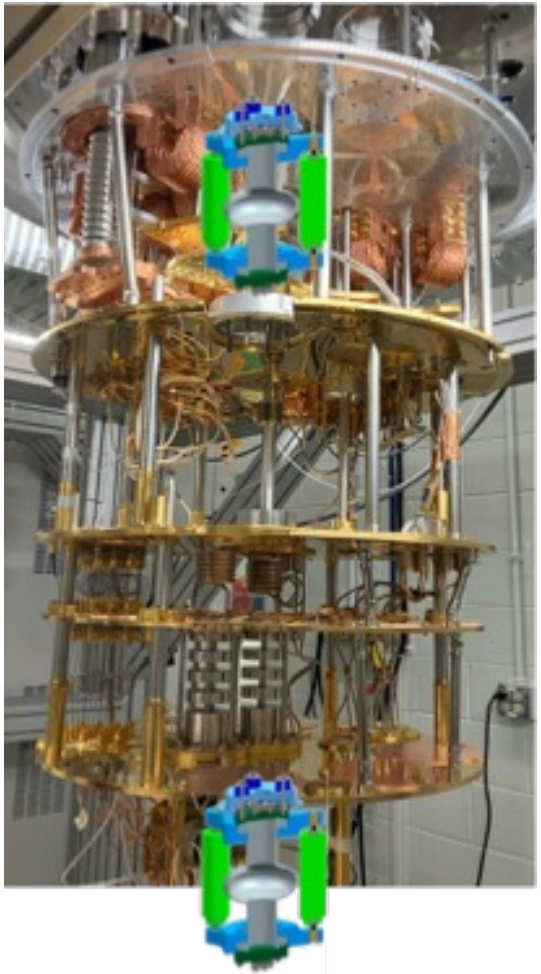
More



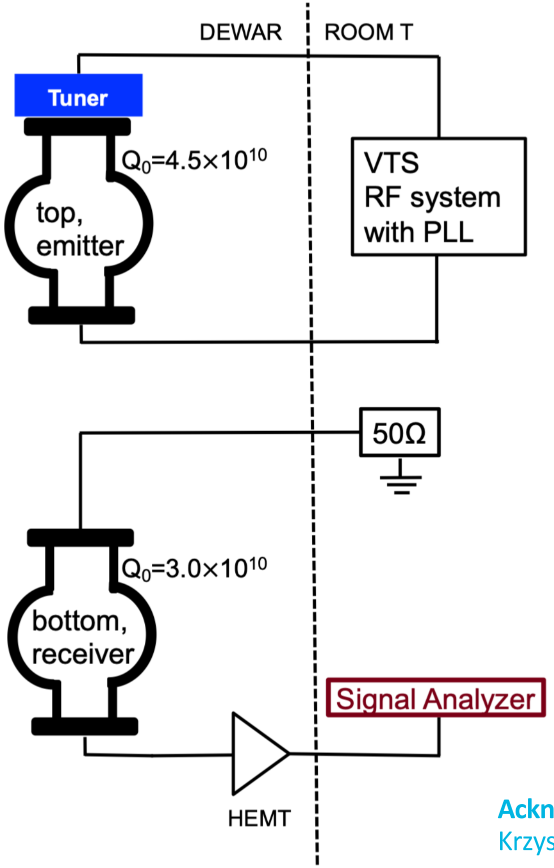


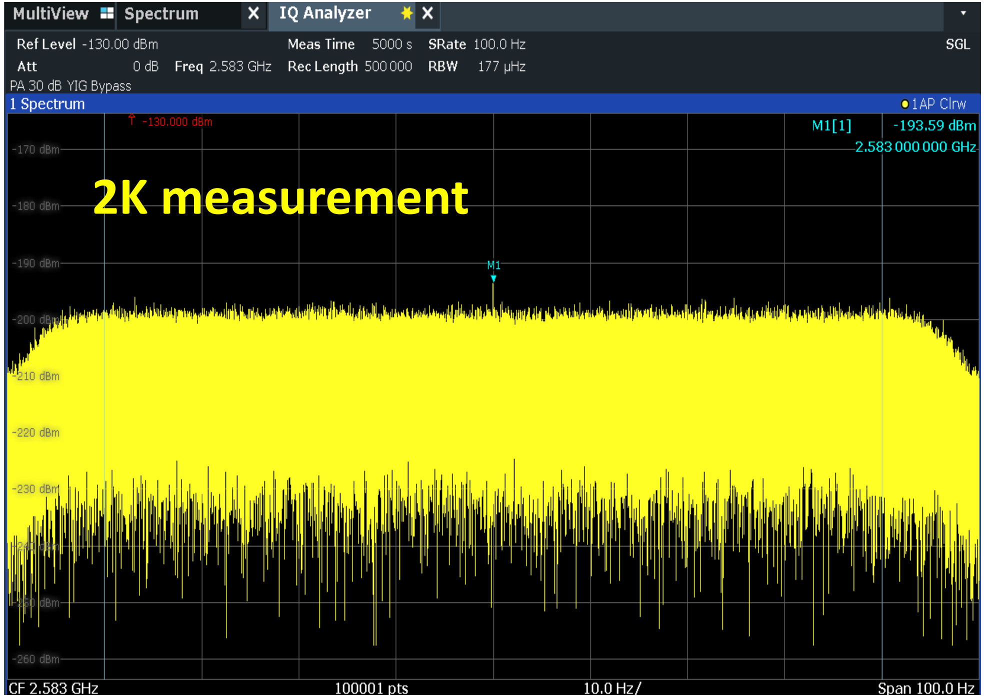
Dark SRF: phase 2 → 2.6GHz cavities in DR

- Deploy Dark SRF in dilution refrigerator (DR) to reduce thermal background and use quantum technology (JPA) for readout
- Modifications of experimental setup for DR:
  - ✓ 2.6GHz cavities at different temperatures
  - ✓ New tuner system (piezo only!)
  - ✓ Verify frequency matching & stability
  - ❑ Reduce crosstalk (in progress)
  - ❑ Move entire setup to dilution refrigerator
- Possible modifications to the measurement protocol and analysis:
  - Optimal search duration: several minutes vs ~1h
  - Improved microphonics modeling



Dark SRF: phase 2 → cross talk mitigation

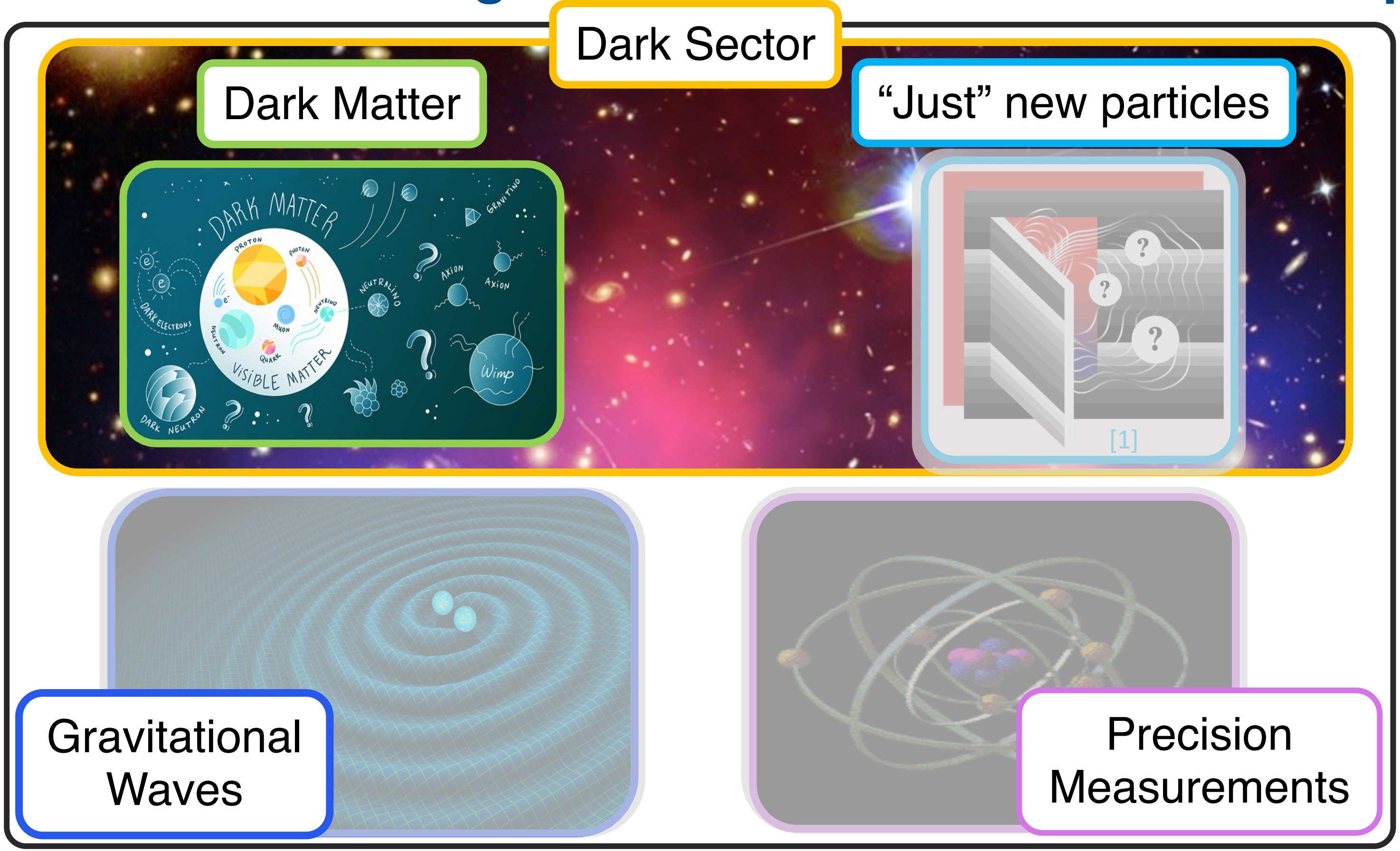




Crosstalk measurements conducted on simplified system. Expected to exaggerate crosstalk effect.

Acknowledgements: Alex Melnychuk, Daniil Frolov, Alex Irigoyen, Krzysztof Kompiel, Roman Pilipenko, Slava Yakovlev & RF team

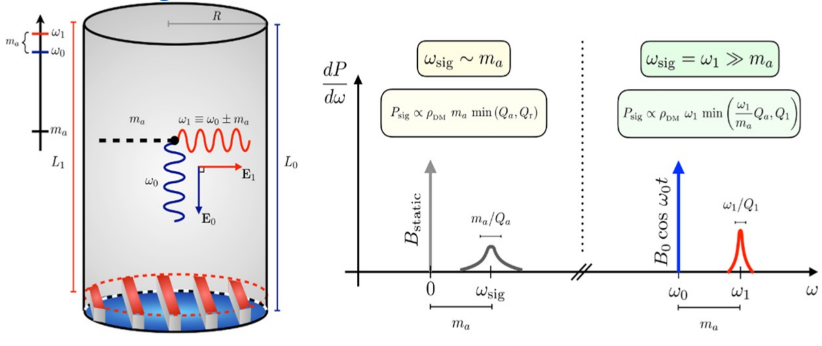
Quantum Sensing: new windows into fundamental physics



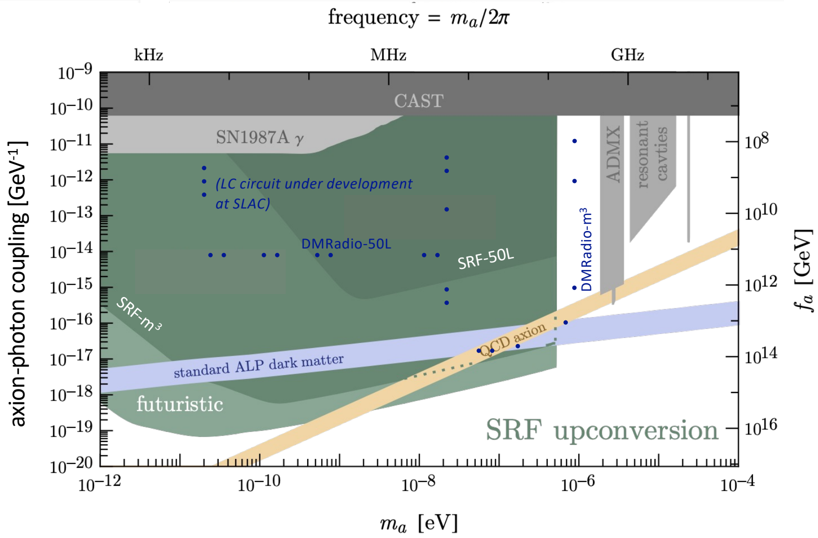
Fermilab Dark SRF Experiment

[1] Artwork by Sandbox Studio Chicago with A. Kova
symmetrymagazine.org

Heterodyne Axion DM search



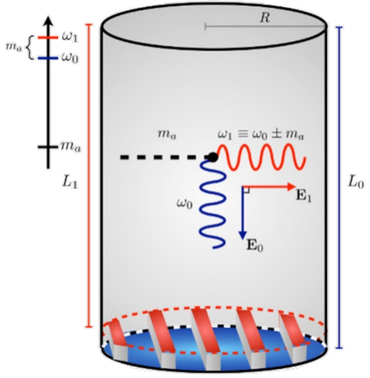
(a) Cartoon of cavity setup. (b) Signal parametrics.



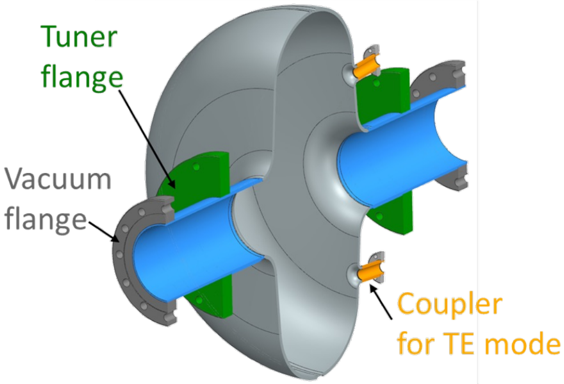
- One SRF cavity, no applied $\vec{B}$
- Modes TE_{011} and TM_{020} used to search for axion DM $\rightarrow m_{axion} \approx \Delta f$
- Enables to search for small masses without using prohibitively large cavities!
- Sensitivity enhanced by large *Q* and oscillating the *B*-field

arXiv:1912.11048, arXiv:1912.11056, arXiv:2007.15656

Heterodyne Axion DM search: from theory to experiment



A. Berlin, et al., Journal of High Energy Physics 2020.7 (2020)



Giaccone et al., arXiv:2207.11346 (2022)

Nb half cell after 1st calibration. Fabrication is in process at vendor

- Pump mode: TM_{020}, Signal mode: TE_{011} → by design: Δf≈1MHz
- Experiment should run in LHe (1.4-2 K)
- Design is completed, currently procuring 2 prototype cavities → expected to arrive in the next couple of months
  - Stay tuned for first results!

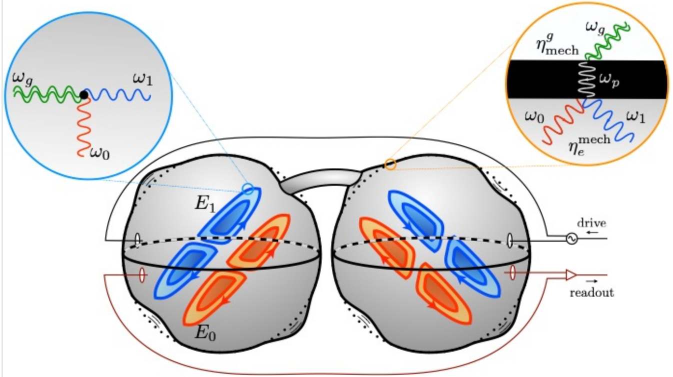
Quantum Sensing: new windows into fundamental physics

Fermilab Dark SRF Experiment

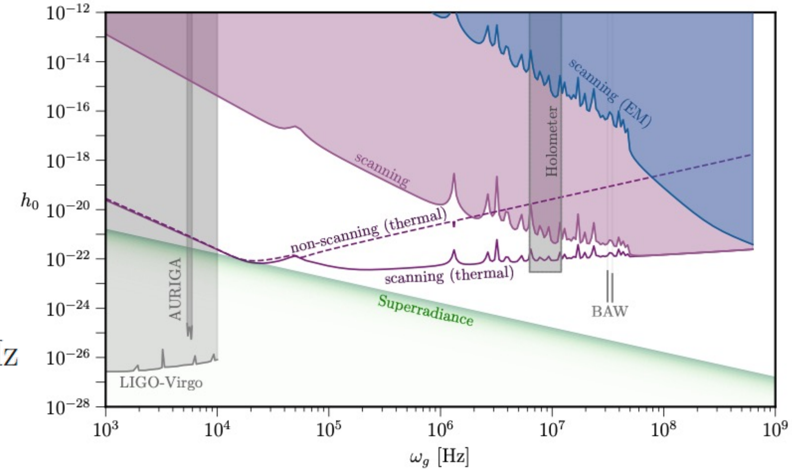
[1] Artwork by Sandbox Studio Chicago with A. Kova
symmetrymagazine.org

SRF cavities for gravitational waves searches

- SQMS theorists have laid the formalism for GW-EM cavity interaction.
- Two types of signals:
  - Direct detection: GW → EM
  - Indirect detection: GW → mechanical → EM
- Current axion experiments have sensitivity to GHz gravitational waves.
- A dedicated cavity experiment, e.g. MAGO, has significant reach at KHz.



1. "Pump mode" E_0, B_0 driven at $\omega_0 \sim$ GHz
2. GW of frequency $\omega_g \ll$ GHz drives power at $\omega_0 + \omega_g$
3. "Signal mode" E_1, B_1 resonantly excited if $\omega_1 \simeq \omega_0 + \omega_g \sim$ GHz



Sensitivity of MAGO-like setup

Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)
Berlin et al., Phys. Rev. D 105, 116011 (2022)
Berlin et al., arXiv:2303.01518v1 (2023)

MAGO

Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)
Ballantini et al., arXiv:gr-qc/0502054 (2005)

Use high Q SRF cavities to search for GWs

- INFN and CERN (~1998) → Microwave Apparatus for Gravitational Waves Observation
  - Successful proof-of-principle and prototype experiments

Followed by (2001-2003)

  - 2-cell cavity with variable coupling and optimized geometry
    - Never treated nor tested – on shelf for >15y at INFN Genova

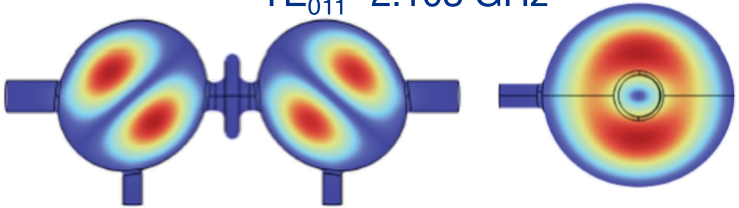
Now: **Collaboration between Fermilab, INFN, DESY, UHH to revive MAGO!**

MAGO 1.0: DESY and UHH activities

UHH CLUSTER OF EXCELLENCE QUANTUM UNIVERSE
Universität Hamburg
DER FORSCHUNG | DER LEHRE | DER BILDUNG

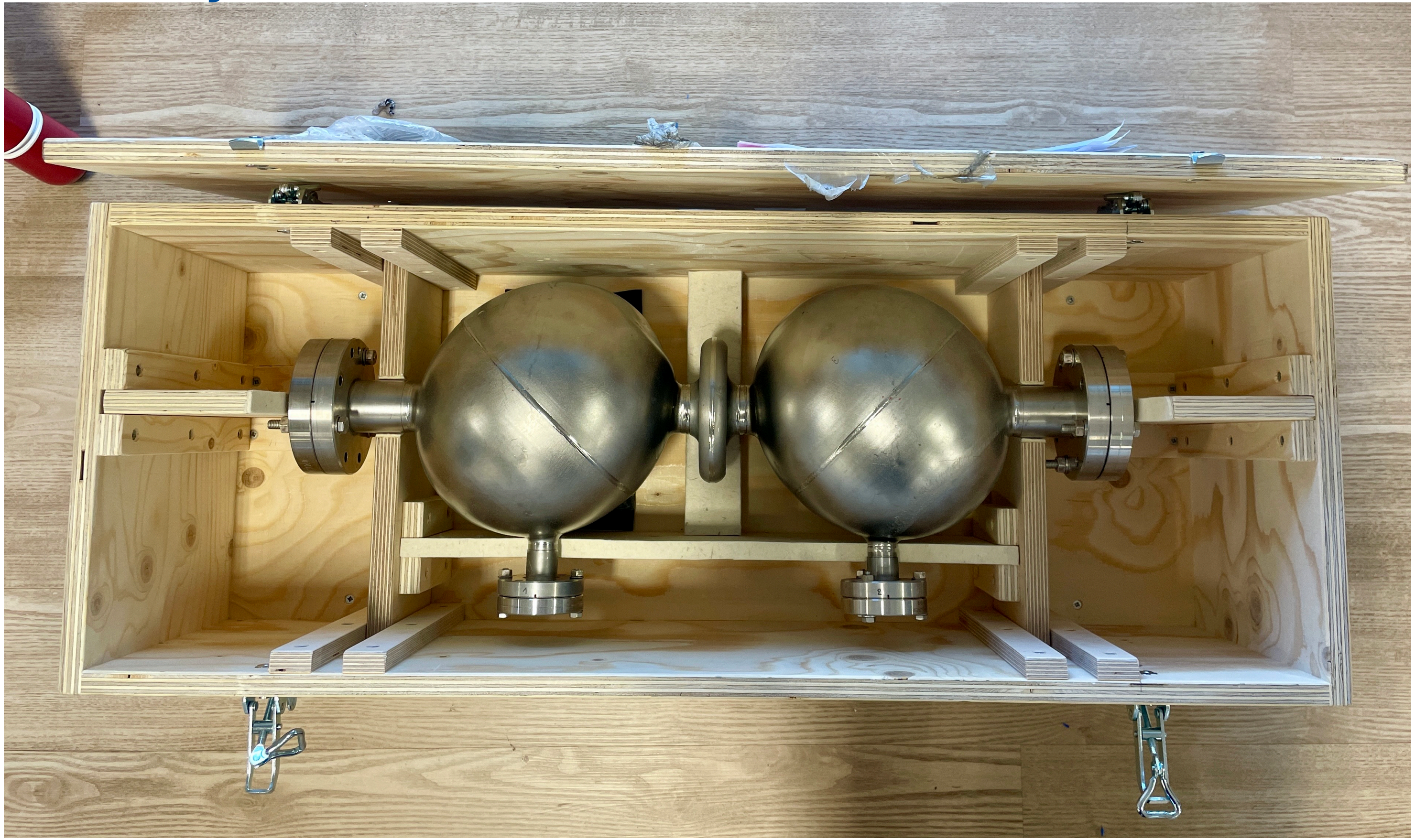
- Conducted inspection, leak check and first measurements after ~15 years!
- Room Temperature RF, mechanical and thickness measurements
- Theoretical work:
  - Multi-parameter optimization for cavity geometry
  - Develop full description of GW-cavity-EM interaction, leave long wavelength regime
- Signal readout: DESY LLRF team responsible for cavity control developed a new technique *carrier suppression interferometer* (CSI)
  - Matches MAGO requirements & conditions

TE_{011}- 2.103 GHz



Adapted from Marc Wenskat presentation at "Quantum Technology for Fundamental Physics" workshop

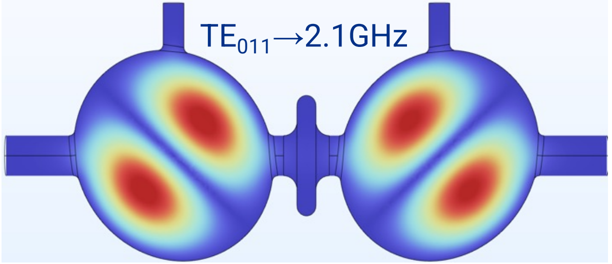
Cavity recently arrived at Fermilab

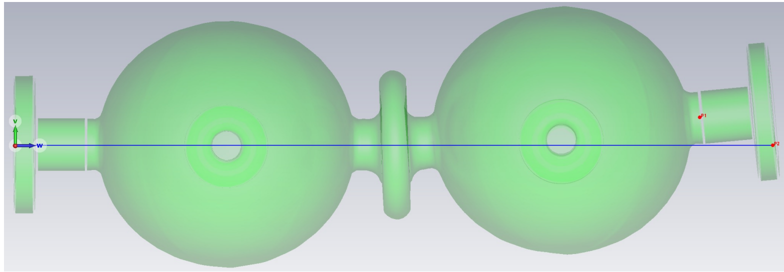


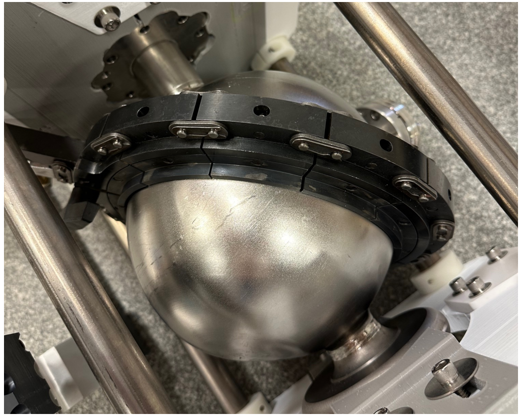
MAGO 1.0: Fermilab activities

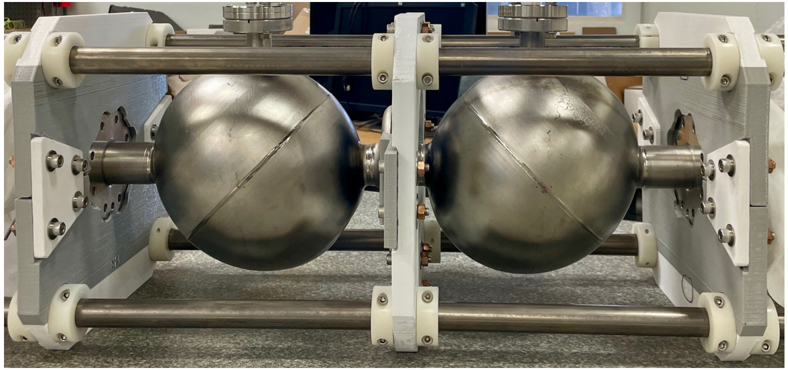
Acknowledgements: V. Chouhan, C. Contreras, I. Gonin, T. Khabiboulline, Y. Orlov, O. Pronitchev, Y. Yakovlev

- Extensive work necessary before RF cold test:
  - RF and mechanical simulations on ideal and real geometry
  - 3D printed frame to sustain cavity during initial room temperature operations
  - Optical inspection
  - Surface treatment
  - Plastic straightening
  - Room temperature tuning of cells
  - …









Current plans for MAGO 1.0

- Characterize cavity through RF cold test(s)
  - Q vs U never measured yet
  - Assess noise sources present in LHe facility relevant for this search
  - Verify necessity for cold tuning on spherical cells
- Test readout systems: CSI vs original magic tees proposal
- Run physics search with chosen readout scheme

- **Overall goal**: revive experiment and gain precious experience and lessons learned to apply to next generation of cavity-based gravitational waves detectors
  - Leverage cavity imperfections to understand effects of cavity design and experimental setup on strain sensitivity

MAGO at Quantum level?

Operating in dilution refrigerator would have pros and cons:

- Vibrational noise will be different, DR3-7 have integrated vibration dampening systems → needs to be measured and assessed
- MAGO scheme: one pump mode excited to high stored energy (U) to enable parametric excitation of photons to signal mode through mechanical mode
- Is this scheme compatible with (our) dilution refrigerators?
  - Cooling power at 20mK: ~30uW, at 100mK: ~1mW
  - At 20mK: U_{max}~ few dozens of μJ (Q_0~10^{10})
  - At 100mK: U_{max}~ hundreds of μJ (Q_0~10^{10})

MAGO at Quantum level? (2)

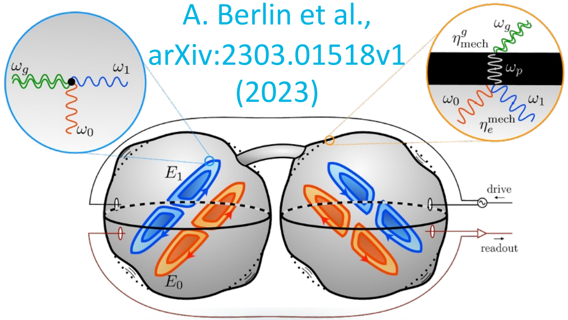
- Advantage of DR: Possible to use quantum amplifiers on signal mode and reach toward SQL (100mK at 2.1GHz)

Beyond JPA?

- Photon counting for MAGO:
  - Qubit can in principle be coupled to TE mode, optimally at 20mK
  - But can it be coupled to signal mode only, not to pump mode? Δf~10KHz
  - Current TE~2GHz → more advantageous if at higher frequencies
- So…
  - Photon counting could gain orders of magnitude on readout sensitivity and outweigh power reduction in signal mode, but other factors are in play as well (vibrational noise, not optimized frequency, pump mode vs signal mode, …)

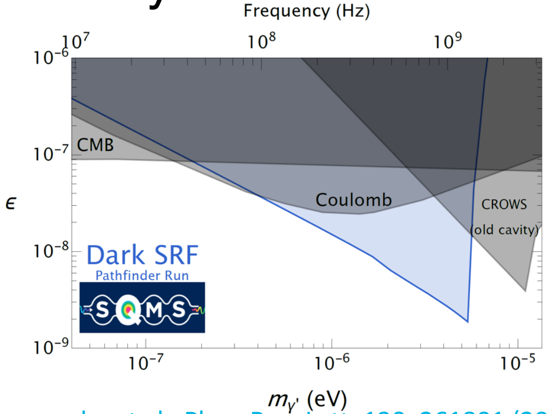
SRF cavities for GW: looking forward

- Through **simulations** and **experimental work** on **MAGO 1.0:** working to gain better understanding of sensitivity to GW strain on multiple factors (GW frequency detuning from mechanical resonance, cavity shape imperfections, microphonics, …)
- **US/Japan collaboration** → small effort between SQMS Fermilab and University of Tokyo & KEK for SRF based GW searches
- **Long term vision**: cavity-based observatory network for high frequency GW

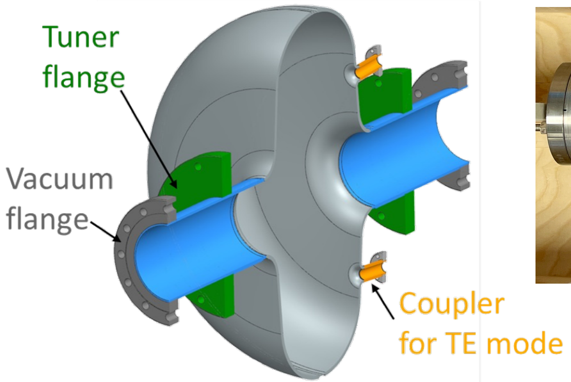


Physics and sensing conclusions

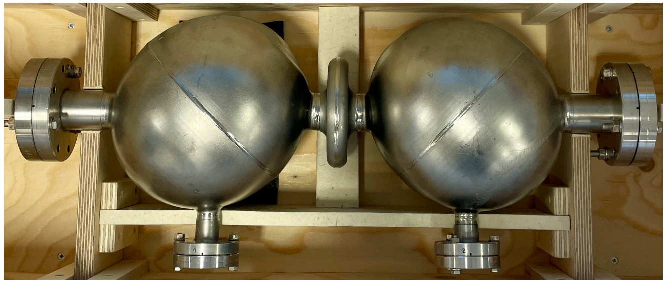
- **Dark SRF**: Realized 1st proof of concept SC cavity-based LSW experiment
  → extended dark photon exclusion limit in broad range of $m_{\gamma'}$ and ε
  - **Dark SRF 2.6GHz in DR:** working to prepare experiment to be deployed in DR
- **Axion DM search**: cavity arrival is imminent, looking forward to beginning of experimental phase
- **MAGO**: collaborating with DESY and INFN on existing variable coupling cavity and with KEK and University of Tokyo on a 2nd generation detector



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)



Berlin, et al., arXiv:1912.11048 (2019)



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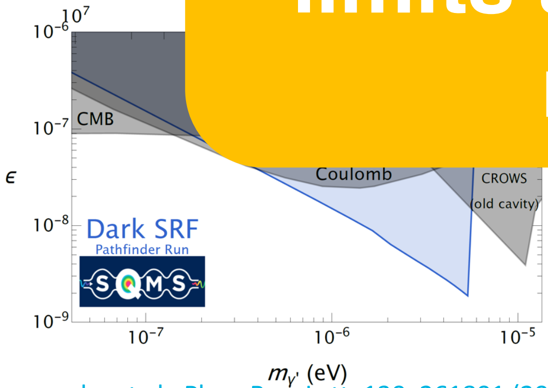
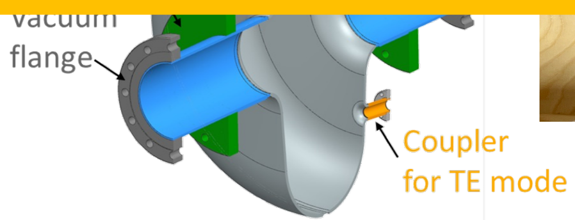
  - **Dark SRF 2.6GHz in DR:** working to prepare experiment to be deployed in DR
- **Axion** ... ginning of exp...
- **MAGO** ... pling cavity ... tector

SQMS physics & sensing team has achieved new exclusion limits and is working on many new experiments!



Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)



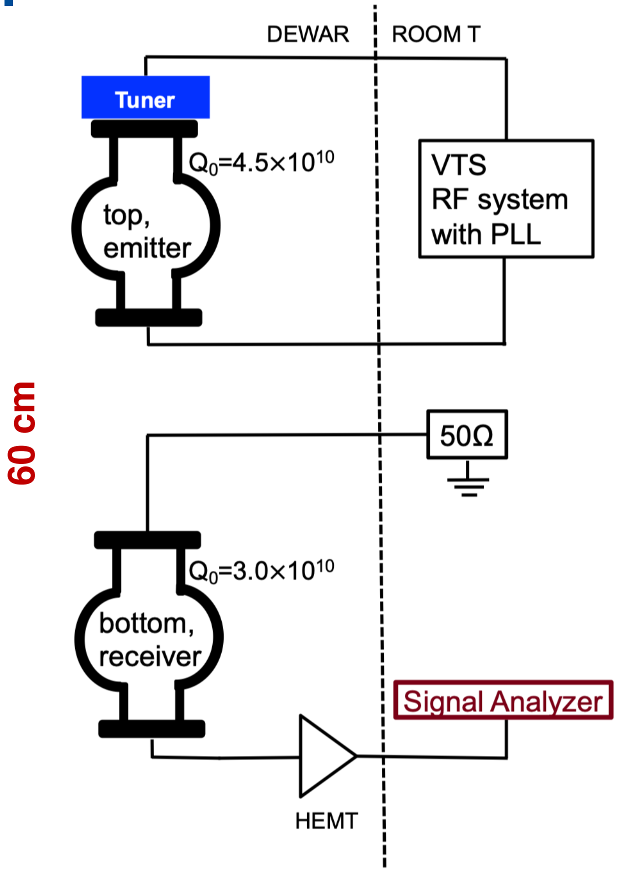
Berlin, et al., arXiv:1912.11048 (2019)

Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)
Berlin et al., arXiv:2303.01518v1 (2023)

Additional slides

Dark SRF: phase 1 → measurement protocol

1. Excite emitter to desired field and match its frequency to receiver
2. Search for Dark photon for ~30min
3. Verify frequency matching
4. Cross-talk check
5. Thermal background check



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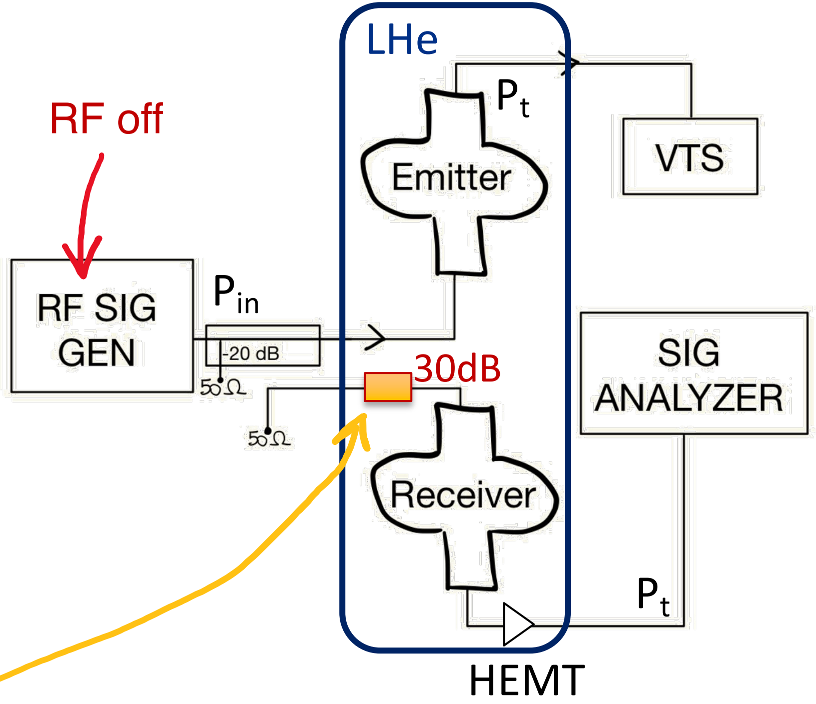
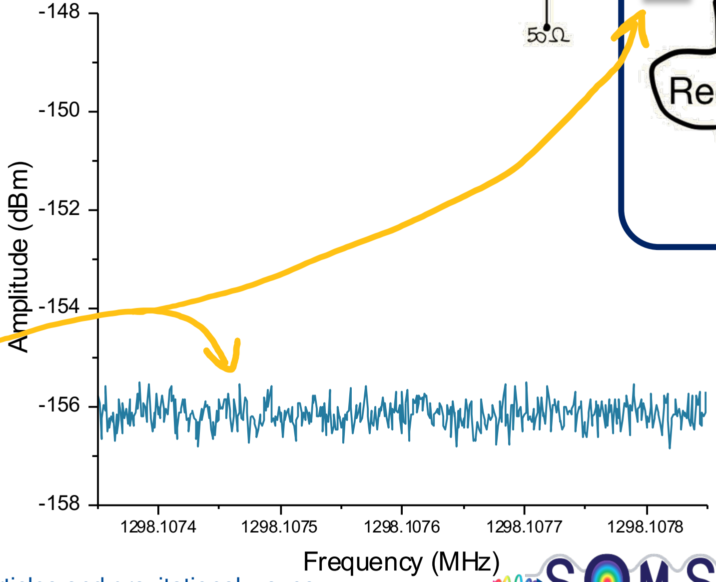
  - Later: no, we added 30dB attenuation on input line





Parameter	Emitter	Receiver
Q_0	4.5×10^{10}	3.0×10^{10}
Q_{in}	1.8×10^{9}	4.5×10^{11}
Q_{t}	2.9×10^{11}	1.3×10^{10}
freq. drift	5.7 Hz	3.0 Hz
microphonics	3.1 Hz	3.1 Hz
P_{loss}	20 dBm	-187 dBm
U	6.7×10^{23}	5.3×10^{3}

TABLE I. Table of key experimental parameters of the Dark SRF low power run used to set dark photon limits. Quality factors (intrinsic Q_0 and externals Q_{in}, Q_{t}) reported in the table are known within 10%. U for the emitter and receiver are the stored number of photons (equivalently, stored energy) in the equilibrium state of the cavities. P_{loss} is the power lost on the cavity walls, defined as $P_{\mathrm{injected}} - P_{\mathrm{transmitted}}$ or $P_{\mathrm{forward}} - P_{\mathrm{reflected}} - P_{\mathrm{transmitted}}$.

Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)

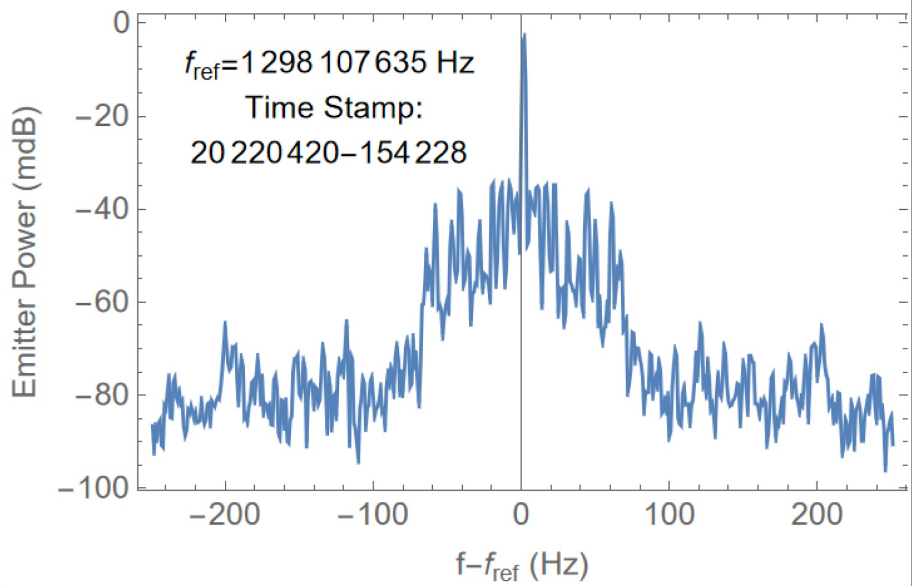
$$P_{\text{rec}} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \, \omega \, Q_{\text{rec}} \, U_{\text{em}}$$

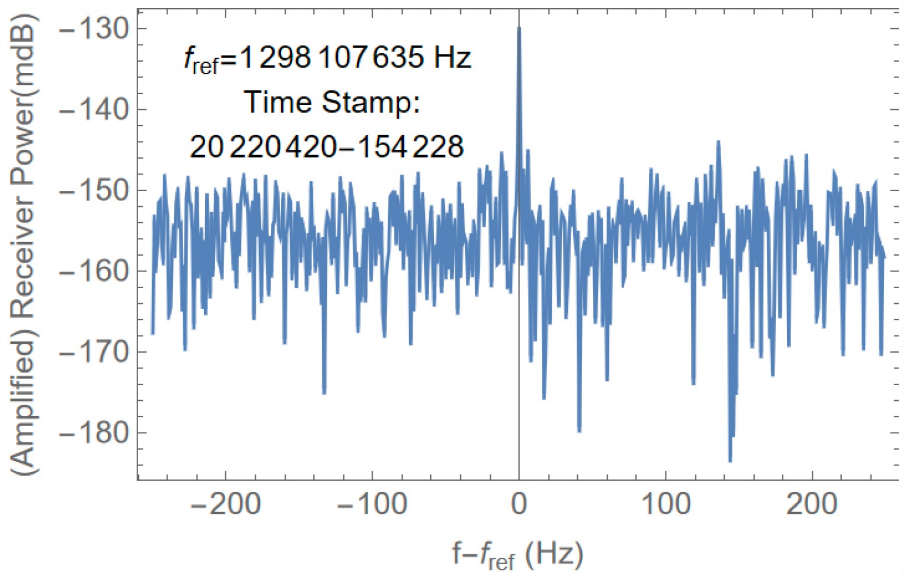
$$\text{SNR} = \frac{P_{\text{rec}}}{P_{\text{th}}} \sqrt{\delta\nu \, t_{\text{int}}} = \frac{P_{\text{rec}}}{k_B T_{\text{eff}}} \sqrt{\frac{t_{\text{int}}}{\delta\nu}}$$

$$\vec{E}_{\text{receiver}}(\vec{r}, t) = -\frac{Q_{\text{rec}}}{\omega} \left[\frac{\int d^3x \vec{E}^*_{\text{cav}}(\vec{x}) \cdot \vec{j}(\vec{x})}{\int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2}\right] \vec{E}_{\text{cav}}(\vec{r}) e^{i\omega t}$$

$$|G|^2 \equiv \frac{1}{\epsilon^4} \left(\frac{\omega}{m_{\gamma'}}\right)^4 \left[\frac{\int d^3x \vec{E}^*_{\text{cav}}(\vec{x}) \cdot \vec{j}(\vec{x})}{\omega \int d^3x |\vec{E}_{\text{cav}}(\vec{x})|^2}\right]^2 \qquad |G|^2 \to \frac{\omega^2}{\omega^2 + 4\delta_\omega^2 Q_{\text{rec}}^2} |G|^2$$

The PSD of the Emitter and Receiver at a given moment

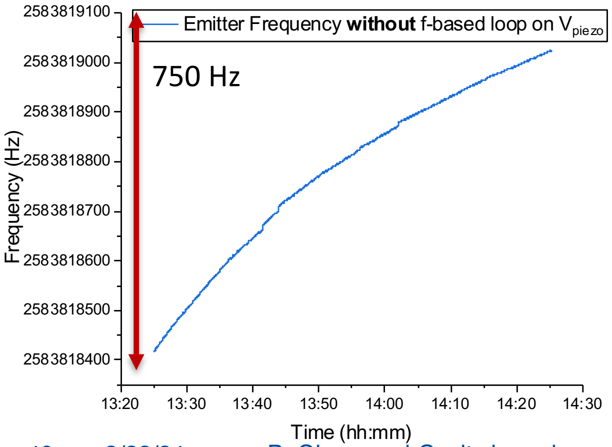


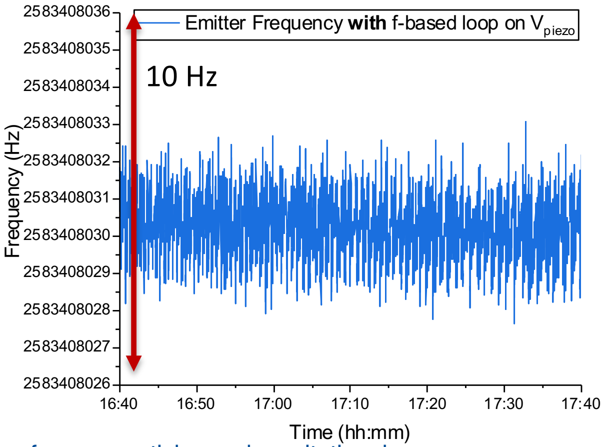


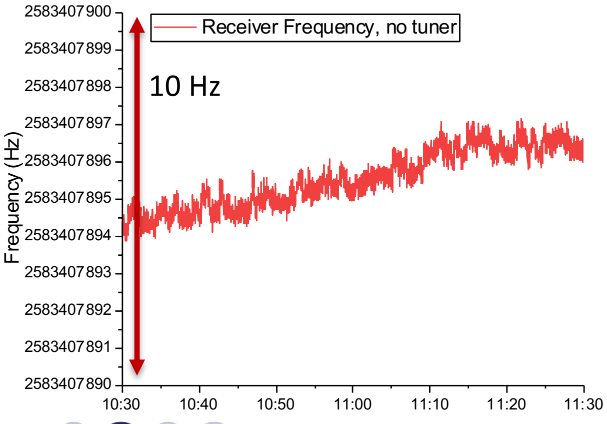
From Z. Liu, presented at "Prospecting for New Physics through Flavor, Dark Matter, and Machine Learning", Aspen Center for Physics, March 2023

Dark SRF: phase 2 → frequency control (1)

- New piezo-based tuner system, troubleshooted through LHe runs
  - Initially measured without feedback loop: huge drifts on both cavities (emitter at 15MV/m: 650Hz in 1 hour!)
  - **Emitter**: implemented f-based loop to control piezo voltage → removed slow drift: frequency AVG stable at 0.1Hz/hr, with 1.5Hz RMS
  - **Receiver**: frequency signal not constantly available (silent cavity!) → removed piezo stacks, made cavity more rigid to minimize frequency shifts: 1.7Hz/hr







SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

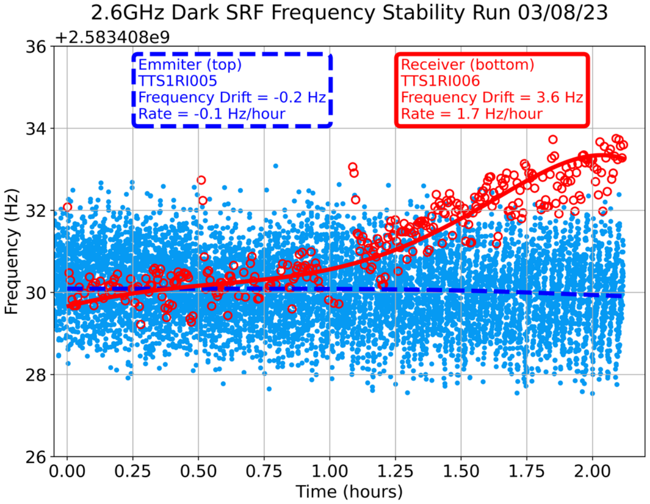
Dark SRF: phase 2 → frequency control (2)

PI Loop Resonance Control for Dark Photon Experiment at 2 K Using a 2.6 GHz SRF Cavity

C. Contreras-Martinez (1), B. Giaccone (1), O. Melnychuk (1), A. Netepenko (1), Y. Pischalnikov (1), S. Posen (1), V. Yakovlev (1)
((1) Fermilab)

Two 2.6 GHz SRF cavities are being used for a dark photon search at the vertical test stand (VTS) in FNAL, for the second phase of the Dark SRF experiment. During testing at 2 K the cavities experience frequency detuning caused by microphonics and slow frequency drifts. The experiment requires that the two cavities have the same frequency within the cavity's bandwidth. These two cavities are equipped with frequency tuners consisting of three piezo actuators. The piezo actuators are used for fine-fast frequency tuning. A proportional-integral (PI) loop utilizing the three piezos on the emitter was used to stabilize the cavity frequency and match the receiver cavity frequency. The results from this implementation will be discussed. The integration time was also calculated via simulation.

Comments: 21st International Conference on Radio-Frequency Superconductivity (SRF 2023)
Subjects: **Accelerator Physics (physics.acc-ph)**
Report number: FERMILAB-CONF-23-264-TD
Cite as: arXiv:2307.10433 [physics.acc-ph]



	Emitter cavity – 1.3GHz setup	Emitter cavity – 2.6GHz setup
Slow drift in ~O(hour), absolute value (Hz)	5.7	0.1
Slow drift in ~O(hour), in units of emitter BW	6.3	0.02

New tuner system and careful frequency monitoring → improved frequency stability!

Dark SRF: phase 2 → frequency control (3)

Testing of the 2.6 GHz SRF Cavity Tuner for the Dark Photon Experiment at 2 K

C. Contreras-Martinez (1), B. Giaccone (1), I. Gonin (1), T. Khabiboulline (1), O. Melnychuk (1), Y. Pischalnikov (1), S. Posen (1), O. Pronitchev (1), JC. Yun (1) ((1) Fermilab)

At FNAL two single cell 2.6 GHz SRF cavities are being used to search for dark photons, the experiment can be conducted at 2 K or in a dilution refrigerator. Precise frequency tuning is required for these two cavities so they can be matched in frequency. A cooling capacity constraint on the dilution refrigerator only allows piezo actuators to be part of the design of the 2.6 GHz cavity tuner. The tuner is equipped with three encapsulated piezos that deliver long and short-range frequency tuning. Modifications were implemented on the first tuner design due to the low forces on the piezos caused by the cavity. Three brass rods with Belleville washers were added to the design to increase the overall force on the piezos. The testing results at 2 K are presented with the original design tuner and with the modification.

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Subjects:	**Accelerator Physics (physics.acc-ph)**
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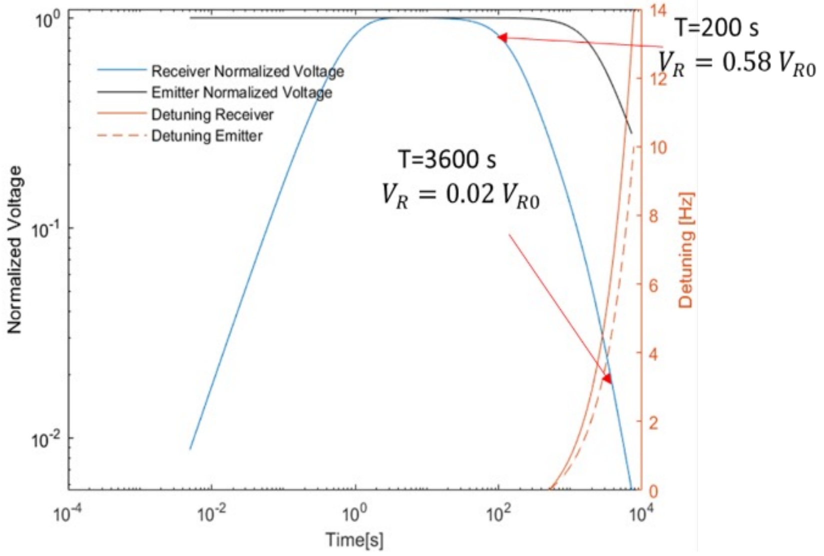
Cite as:	arXiv:2307.10424 [physics.acc-ph]



1. Optimal dark photon search run should be ~several minutes rather than ~hour

2. Confirms choice of conservative assumptions on the drift made for 1.3GHz PRL