



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

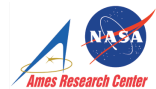
Dark Sector and Gravitational Waves Searches with SRF cavities at SQMS

Bianca Giaccone
SQMS, Fermilab



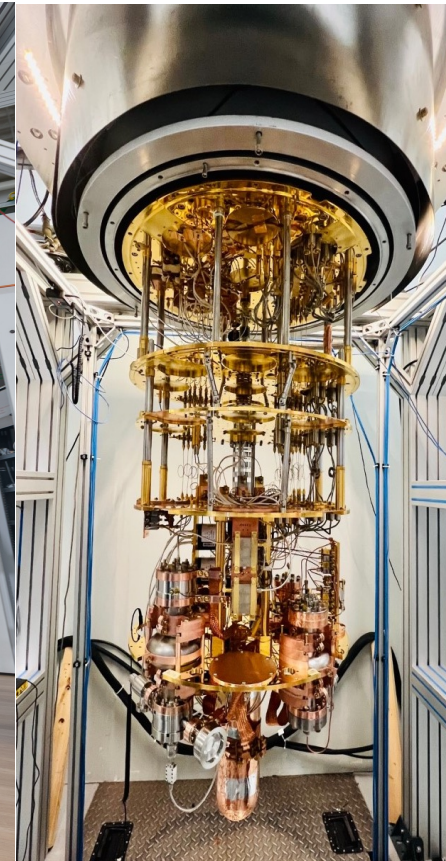
30 Partner Institutions
>500 Collaborators

A DOE National Quantum Information Science Research Center

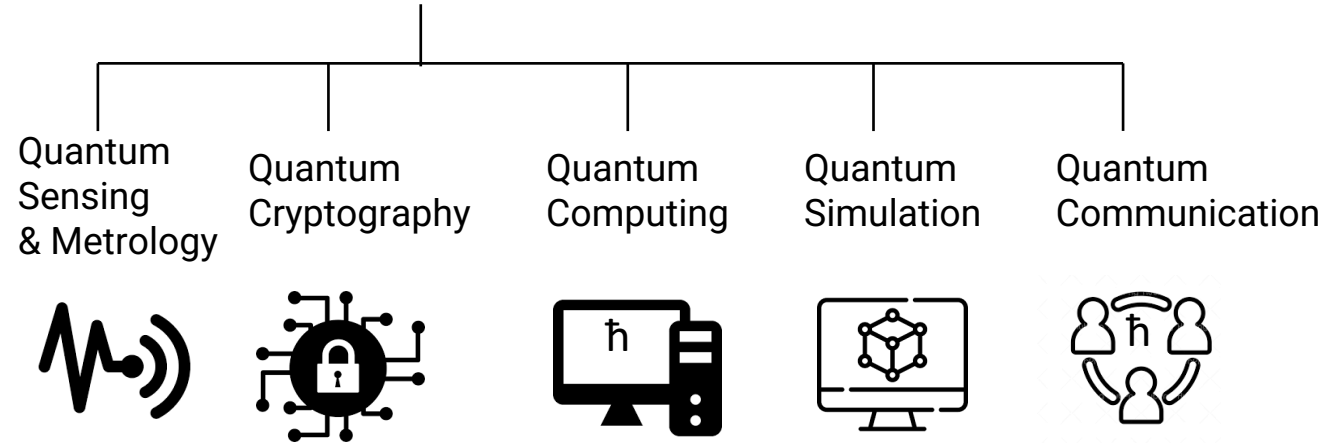


A rich **ecosystem**, multi-institutional and multidisciplinary collaboration **leveraging investments** at DOE national labs, academia, industry and several other federal and international entities

The 'Quantum Garage' @ the SQMS Center, Fermilab



Quantum Information Science



Quantum Information Science

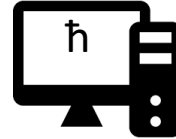
Quantum
Sensing
& Metrology



Quantum
Cryptography



Quantum
Computing



Quantum
Simulation



Quantum
Communication



*Superconducting
materials and RF
cavities*

Cryogenics

*Electronics and
Microwave Controls*

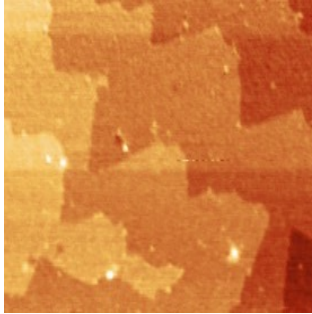
Precision Timing

...

Leveraging unique technologies
for advancing **quantum information science**

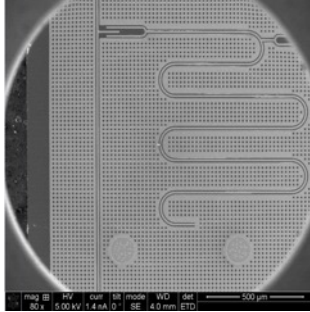
SQMS Science and Technology Innovation Chain

Materials



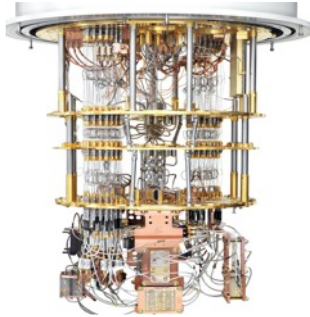
Developing a full understanding of sources of decoherence via a systematic, fundamental science approach

High-coherence devices



Demonstrating devices with systematically and consistently higher coherence at different SQMS partners

Systems integration



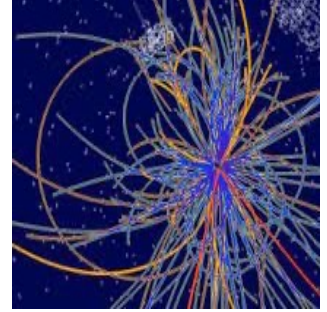
Preserving device high performance through the process of integrating into more complex systems

New platforms for quantum computing & sensing



Deploying quantum platforms of innovative architectures and improved performance

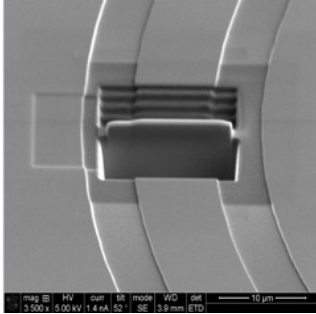
Quantum advantage



Demonstrating quantum computing and sensing advantage for particle physics and other scientific applications

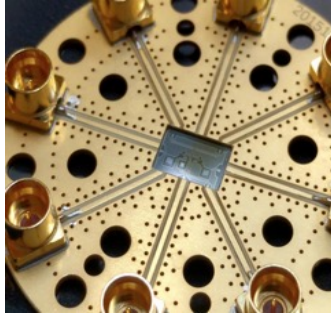
SQMS Science and Technology Progress Highlights

Materials



Extensive coordinated study of qubit fragments has led to understanding of dominant sources of decoherence

High-coherence devices



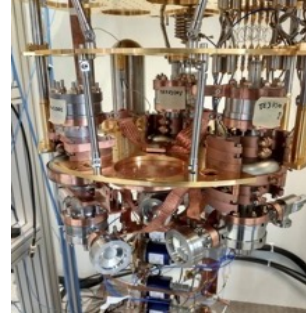
Transmon qubits: demonstrated systematic improvements in coherence times up to a factor of 3 at Fermilab and Rigetti

Systems integration



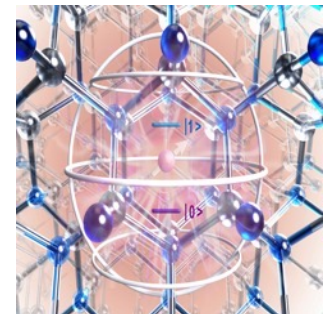
Integrated Rigetti and NIST qubits in Fermilab SRF cavities with successful Fock states generation

New platforms for quantum computing & sensing



Launched co-design activities to develop new 2D and 3D QPUs architectural concepts, designed colossus

Quantum advantage



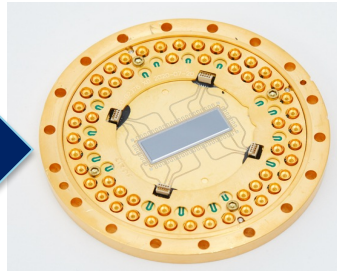
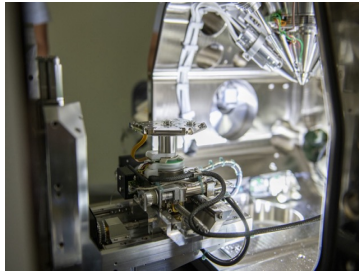
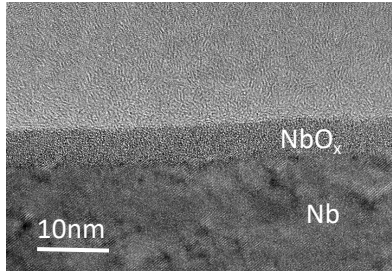
Demonstrated advantage in quantum sensing for fundamental physics in the area of dark sector searches

**Excellent progress across the full stack of innovation chain
thanks to the strength of center coordinated work**

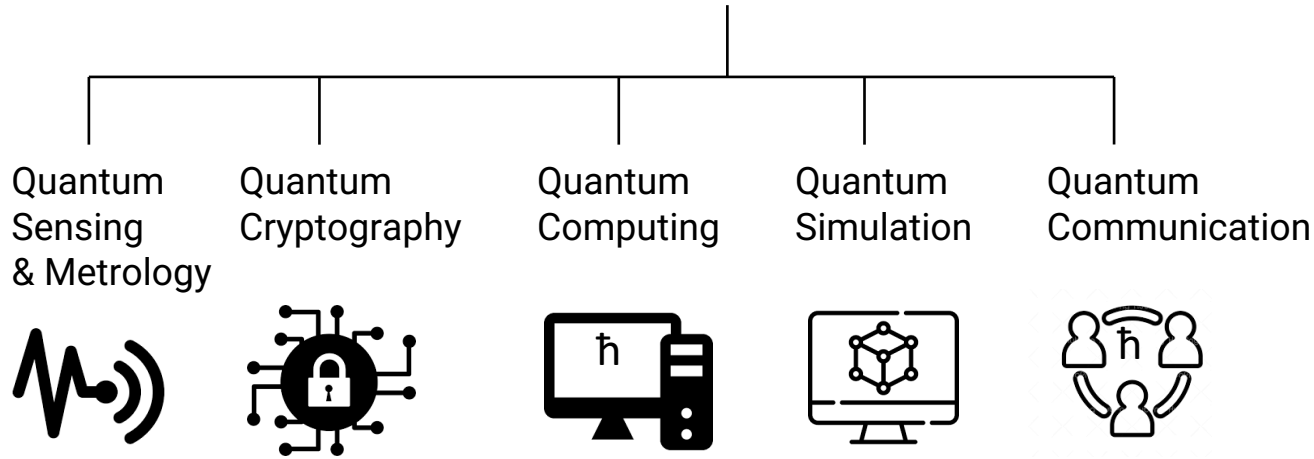
Technology Thrust: Strategy

Basic Understanding -> Coherence Improvement -> 2D and 3D High Coherence QPUs

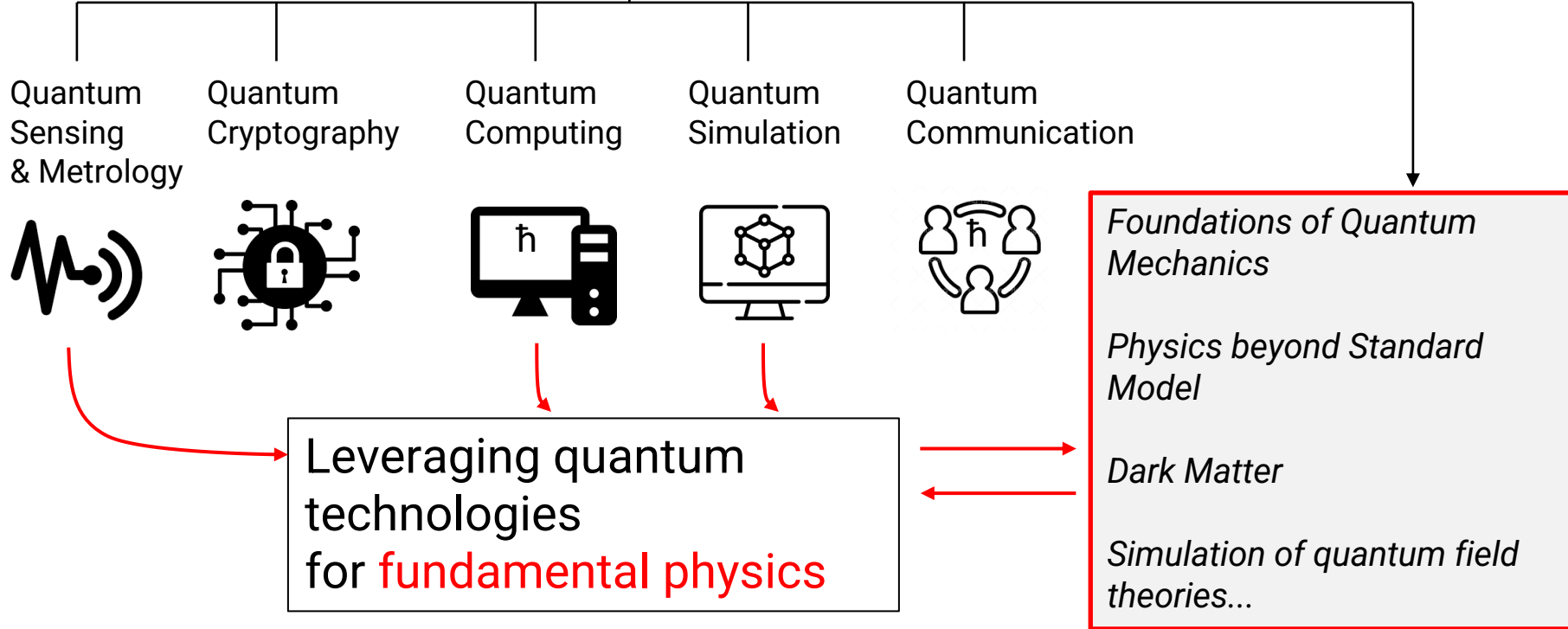
- Build upon **core strengths** of partners
 - Fermilab world's best superconducting RF cavities (3D) – **seconds** of coherence (quality factors $Q > 10^{10}$)
 - Associated deep structural and superconductivity knowledge of niobium (key part of 2D qubits)
 - Microwave, cryogenic, mechanical engineering and large scale integration experience
 - Deep 2D superconducting qubit and quantum processor expertise
 - Deep basic materials and superconductivity expertise



Quantum Information Science



Quantum Information Science



SQMS Science Thrust

- The questions that keep us up:

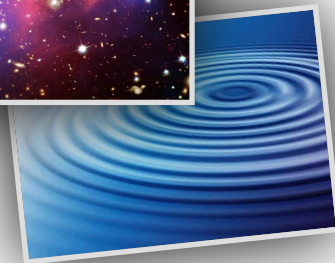
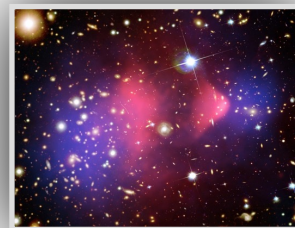
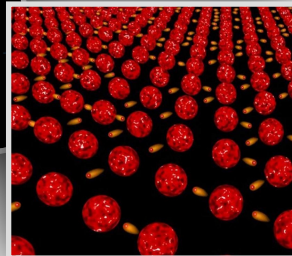
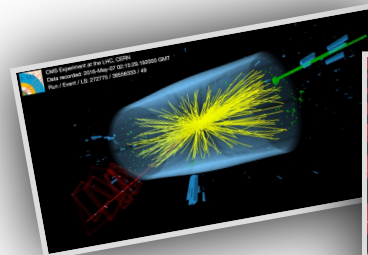
- What was the viscosity of the universe as young?
- How does the Higgs boson (discovered at LHC) happen in “real time”?
- What are the quantum effects in materials?
- What the non-trivial properties of highly entangled systems?
- What is the dark matter?
- Are there new particles that have yet to be discovered?
- Can we detect quantum effects in macroscopic systems?
- How well can we control quantum systems?

**Quantum Simulation
and Computation**

Quantum Sensing

These are long term endeavors.

Our goal is to enable breakthroughs in these questions.

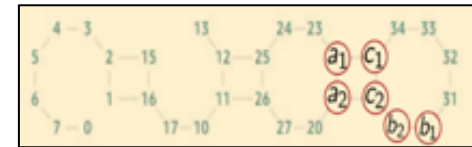
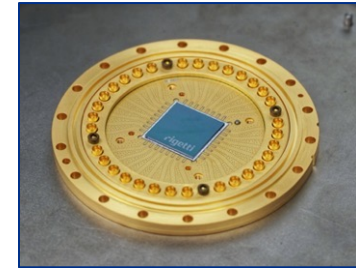
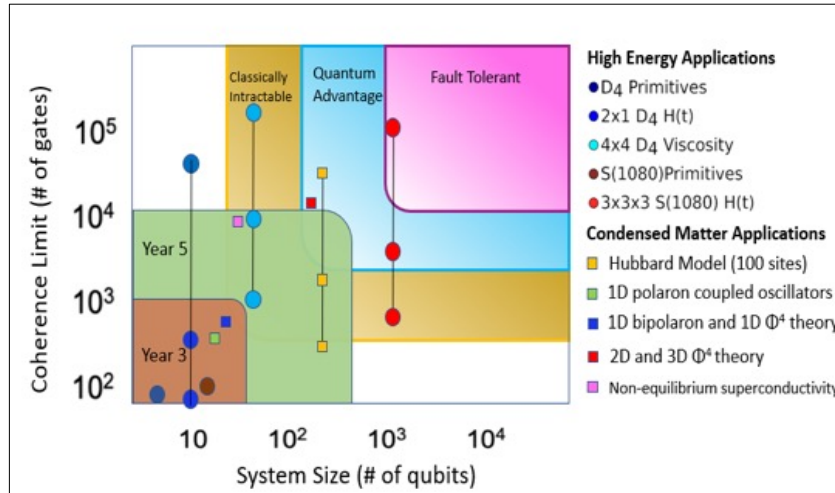


Science Thrust - Focus Area Algorithms, Simulations, Benchmarking

Goal: Investigate and develop quantum algorithms and simulations enabled by the groundbreaking SQMS 3D and 2D prototypes through co-design principles

Deliverables/metrics: Simulations of the dynamics of theories approximating QCD, simulate LHC physics, plasma early universe conditions, quantum materials far from equilibrium, intermediate electron/phonon SC

SQMS
computational
and simulation
science goals
mapped to
prototypes



Qubits considered for a D4 gauge field theory test simulation on the Rigetti hardware.

Science Thrust - Focus Area Quantum Sensing

- Quantum sensing: the use of quantum properties of light or matter to enhance sensitivity of measurements.
- Sensing effort is driven by applying our SRF cavities and quantum devices towards physics goals:



- **Probing Dark sectors:**

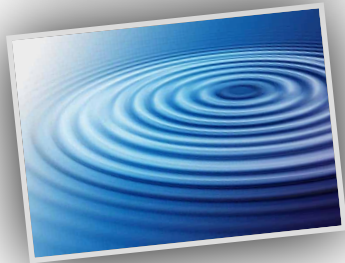
- New light particles: Dark photons and axions.
- Either as the dark matter, or as “just” new particle.
- A multi-search goal. Our most engaging science goal.

- **Precision tests:**

- Tests of the standard model (electron g-2, Euler-Heisenberg)
- Tests of quantum mechanics

- **Gravitational waves:**

- Expanding the frequency for GW detection beyond LIGO/VIRGO.



The People



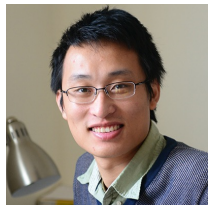
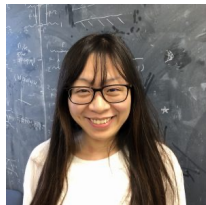
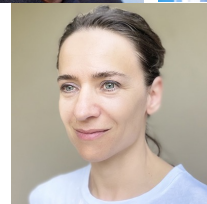
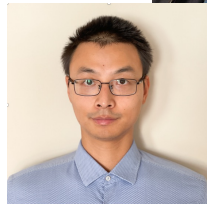
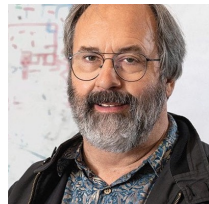
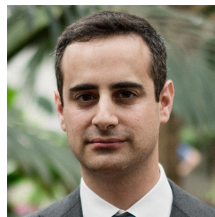
Northwestern
University



LSU



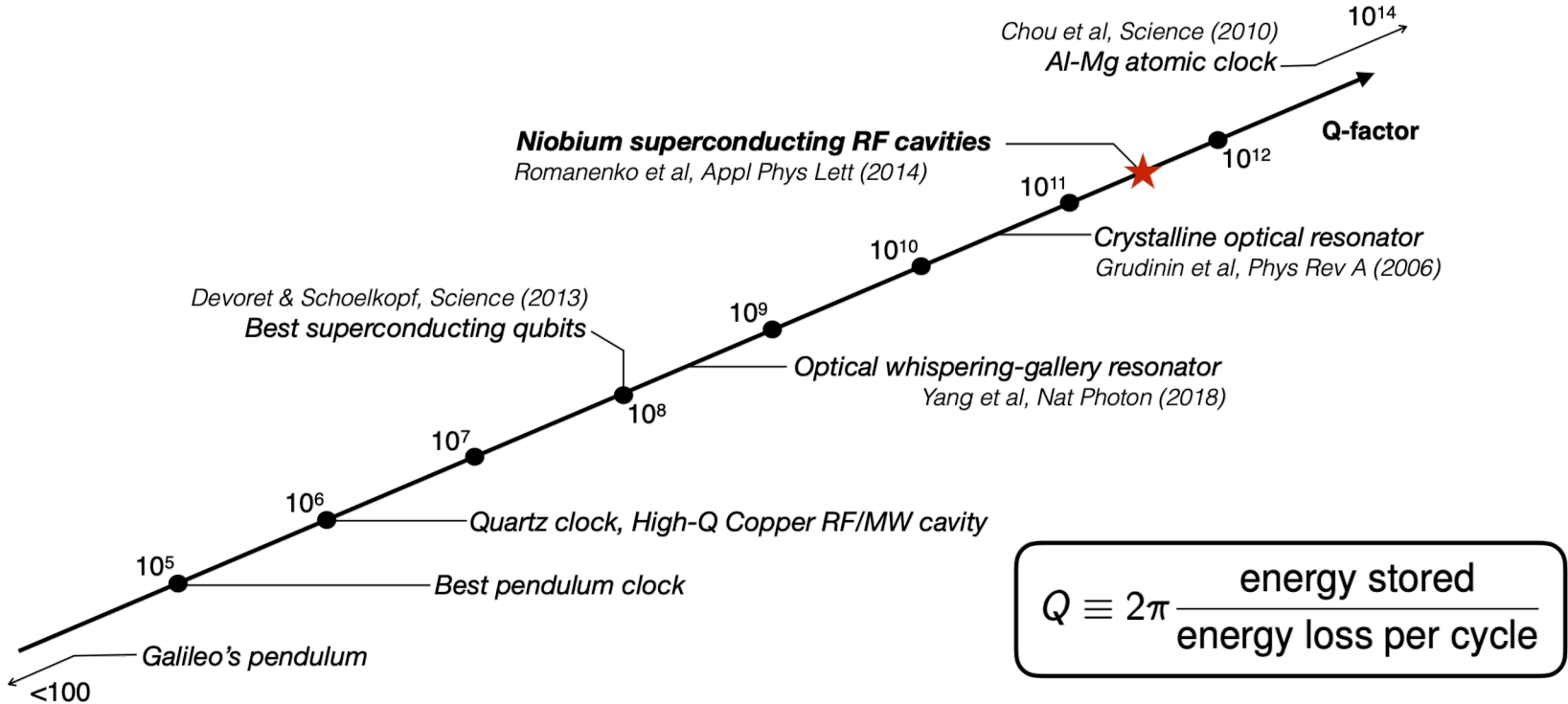
Stanford



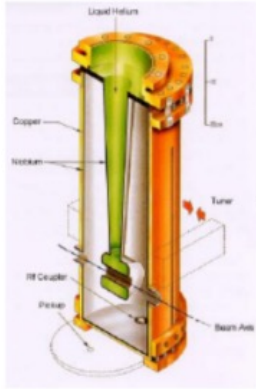
Theorists and experimentalists working closely. Experts in HEP, materials, SRF, sensing, QIS, RF engineering.

Why SRF cavities for quantum sensing?

SRF cavities are the most efficient engineered oscillators

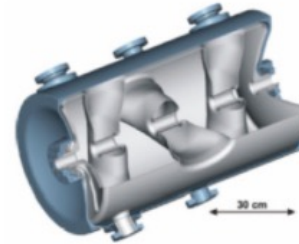


Examples of SRF geometries



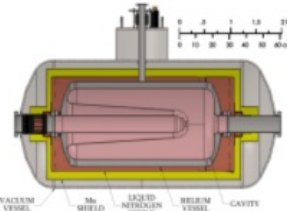
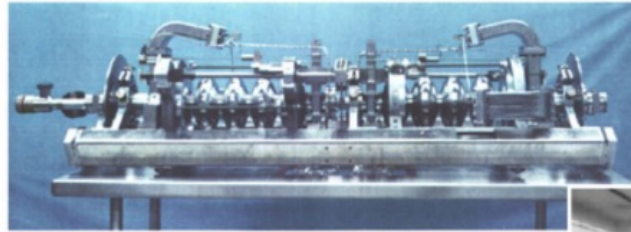
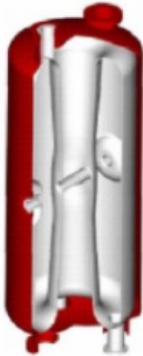
Low β :

a zoo of structures (QWR, split-ring, RFQ, HWR, spoke, H-type,...)



High β :

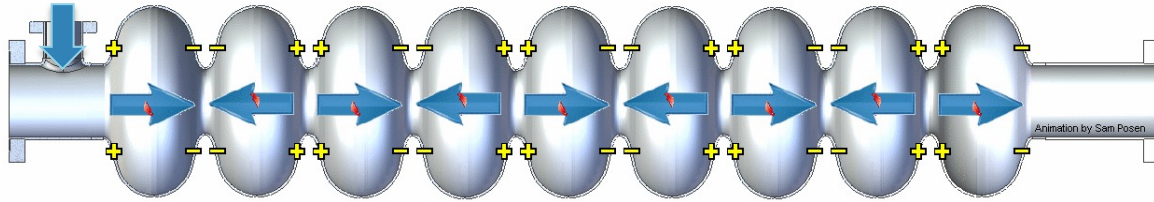
mostly various elliptical shape structures, but ...



From: "RF superconductivity for particle accelerators", S. Belomestnykh, USPAS 2017 – Lecture 1

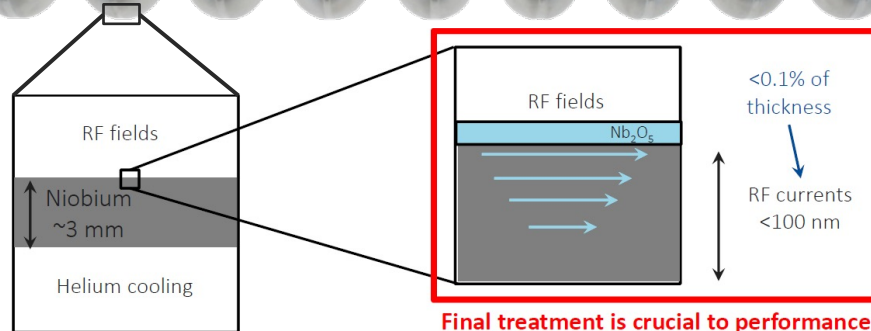
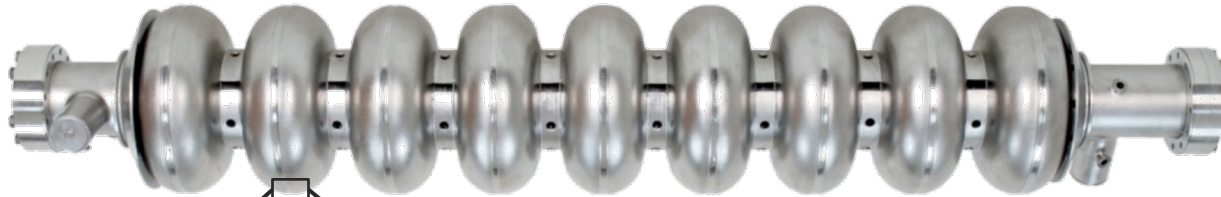
Superconducting Radio Frequency Cavities

Input RF power @ 1.3 GHz



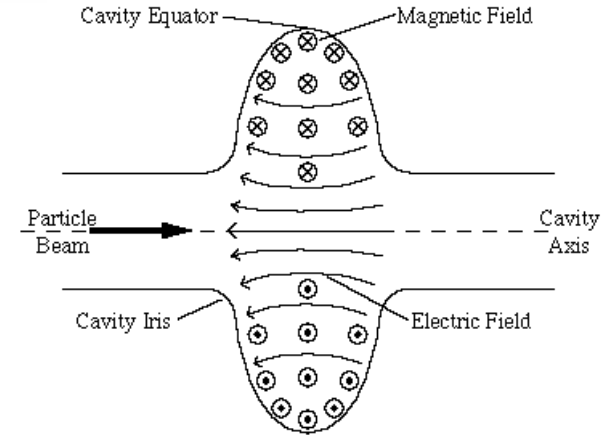
Animation by Sam Posen
Images from linearcollider.org, Wikipedia

Typically operated at $T = 2\text{K}$



Final treatment is crucial to performance

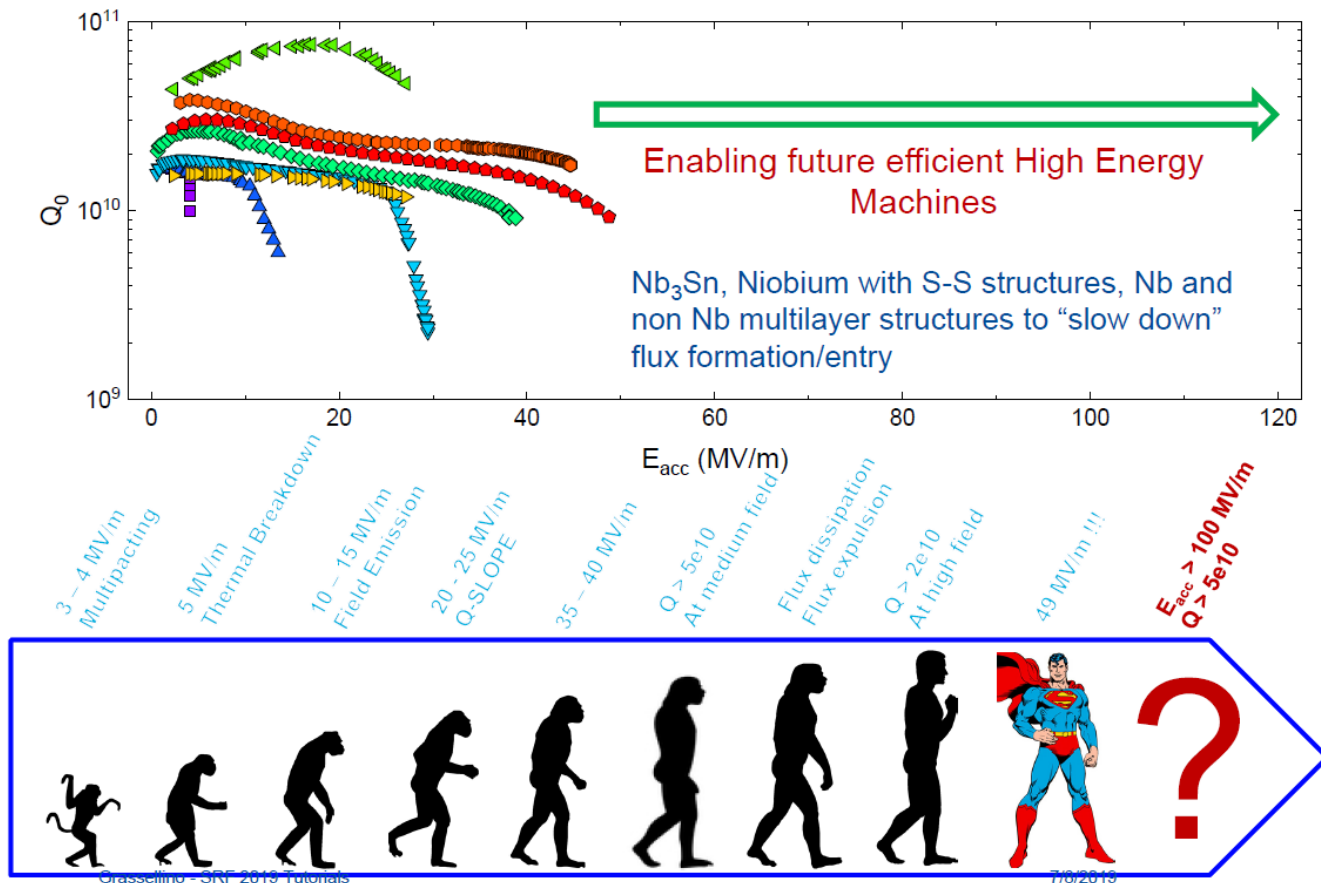
$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$



From: "Pushing Bulk Niobium Limits" A. Grassellino, SRF2019 - Tutorials

B. Aune et al., Phys. Rev. ST Accel. Beams 3, 092001

SRF performance evolution



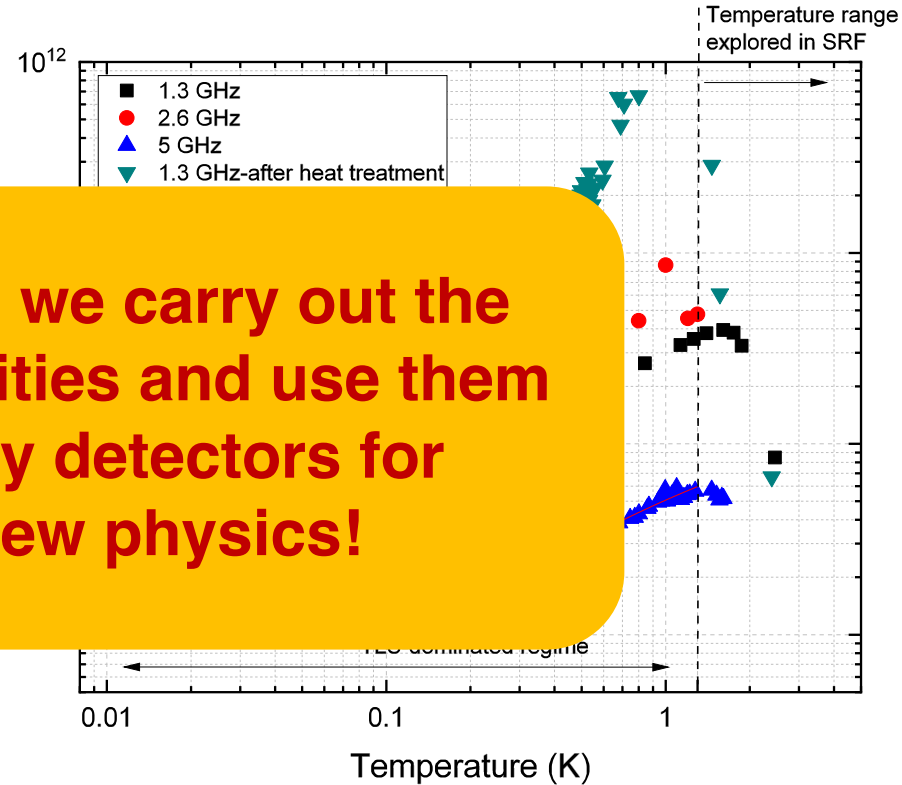
From: “Pushing Bulk Niobium Limits” A. Grassellino, SRF2019 - Tutorials

SRF cavities in new regimes: low field and low T research



Dilution Refrigerator (DR)

New research field: we carry out the R&D on the SRF cavities and use them as high sensitivity detectors for searches for new physics!



Romanenko et al., Phys. Rev. Applied 13, 034032 (2020)

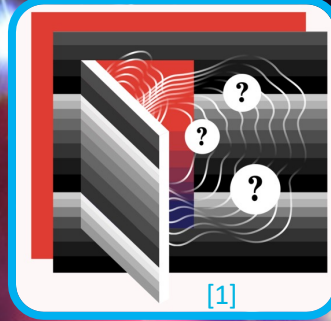
Quantum Sensing: new windows into fundamental physics

Dark Sector

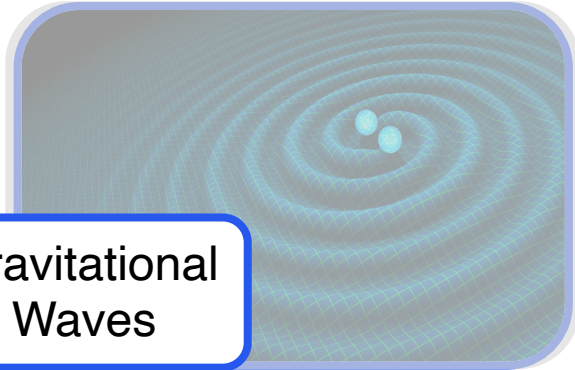
Dark Matter



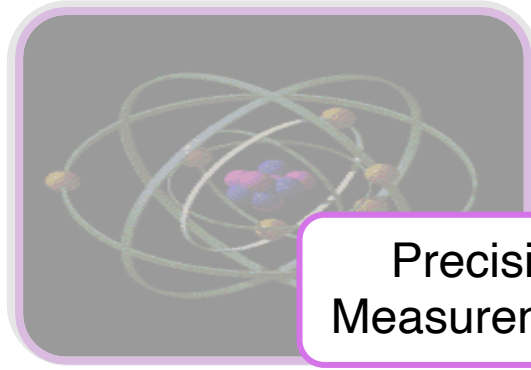
“Just” new particles



Gravitational Waves



Precision Measurements



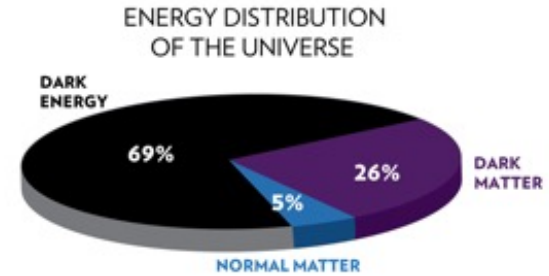
Fermilab Dark SRF Experiment



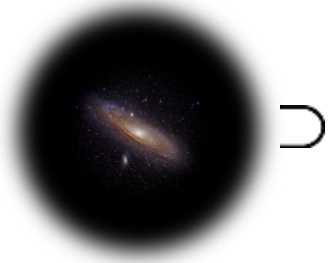
[1] Artwork by Sandbox Studio Chicago with A. Kova
symmetrymagazine.org

Dark Sector

- New light particles are theoretically well motivated.
e.g.
 - Axion like particles (including the QCD axion)
 - Dark photons
- For such light particles two hypotheses can be tested:



Dark matter (and new particle):



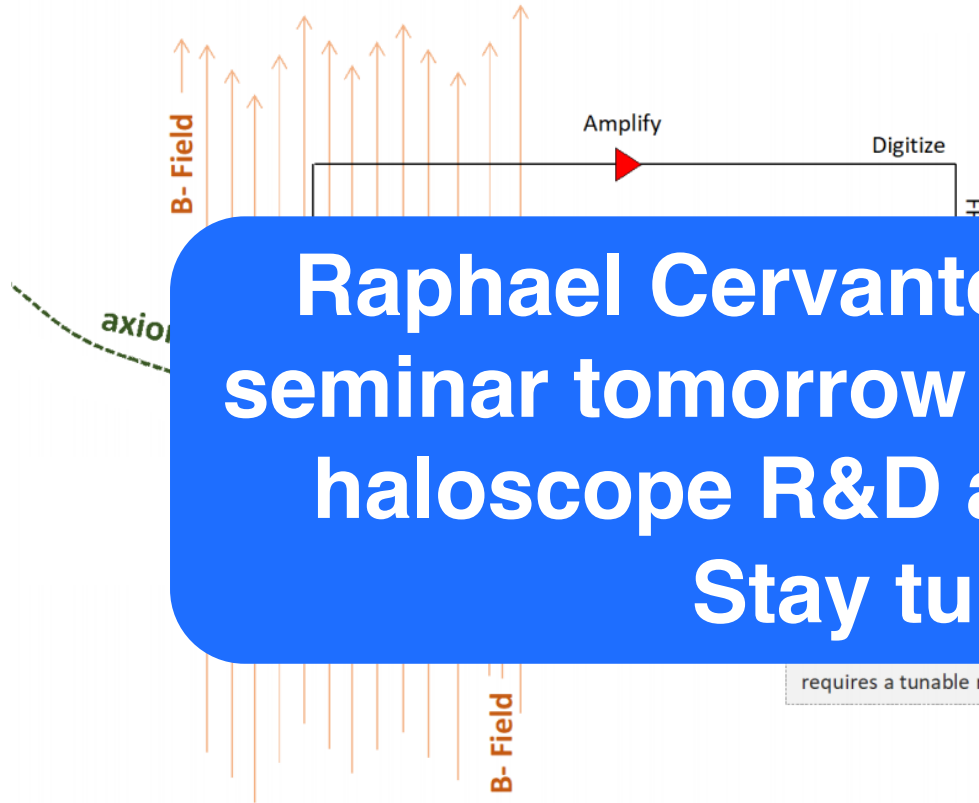
⊃ dark photons?
axions?

New particle:

\mathcal{L} ⊃

dark photons?
axions?
long range force?

Haloscope Search for Dark Matter



Microwave cavities can be used like an AM radio to detect dark photons and axions.

Raphael Cervantes will present seminar tomorrow focusing on the haloscope R&D and searches. Stay tuned!

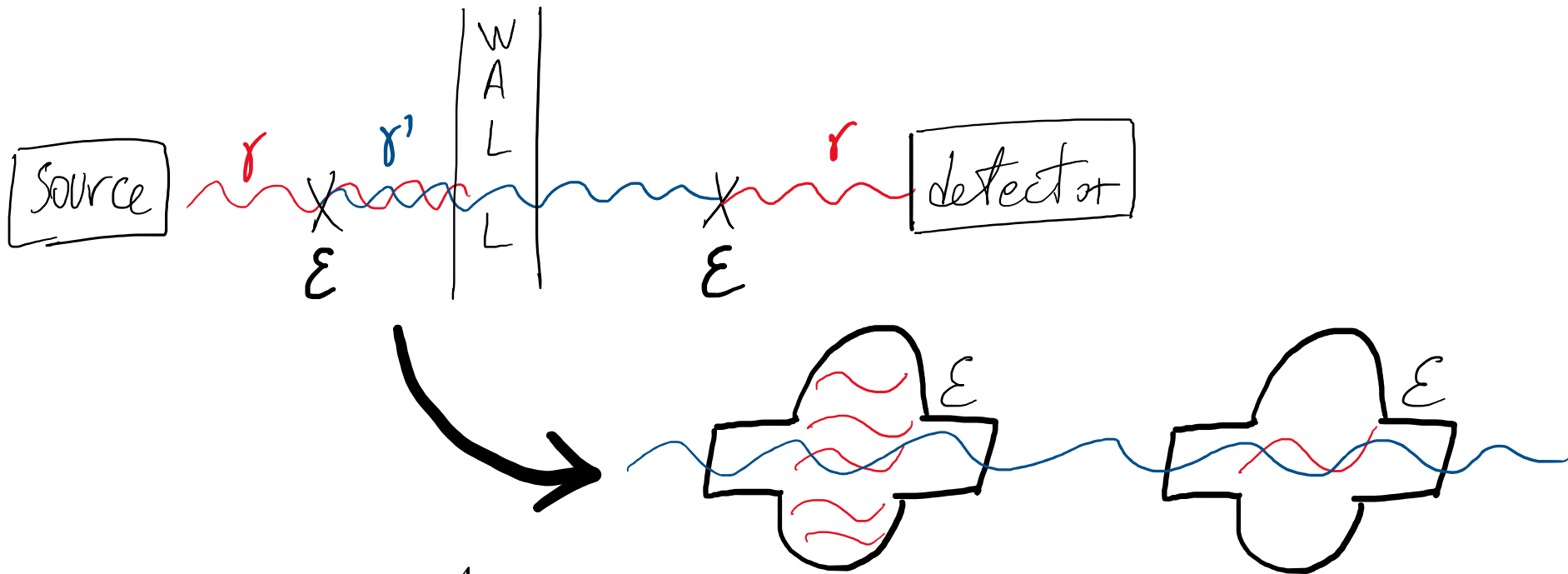


Amazon

Looking for $< 10^{-24}$ W signal over wide range of frequencies.

Credit: C. Boutan

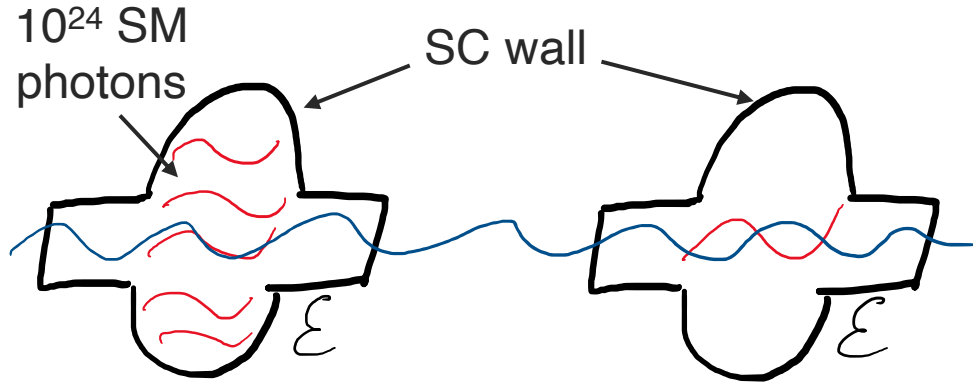
Dark SRF: Light-Shining-through-Wall search



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

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

Receiver cavity,
in the low field regime

**Necessary to match cavities
frequency!**

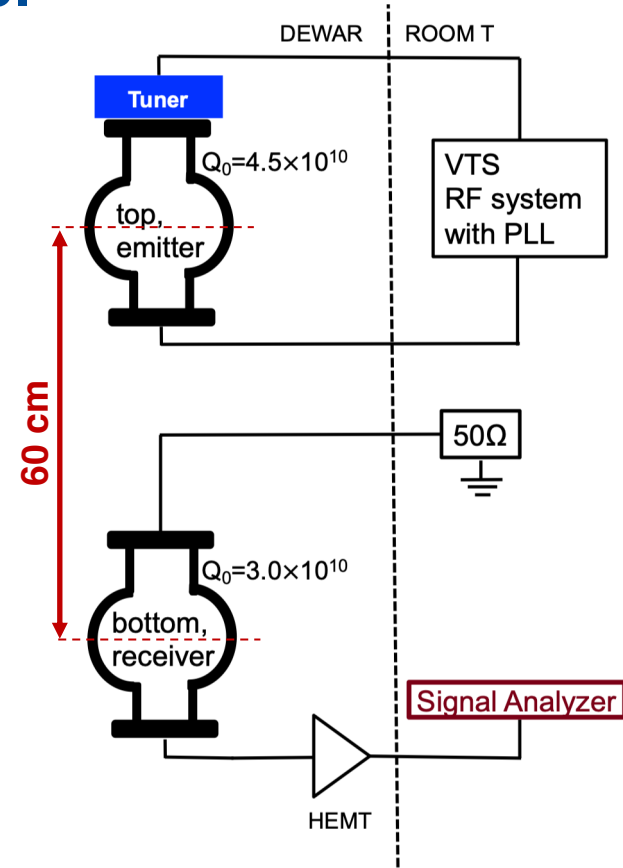


LHe vertical test stand facility at Fermilab



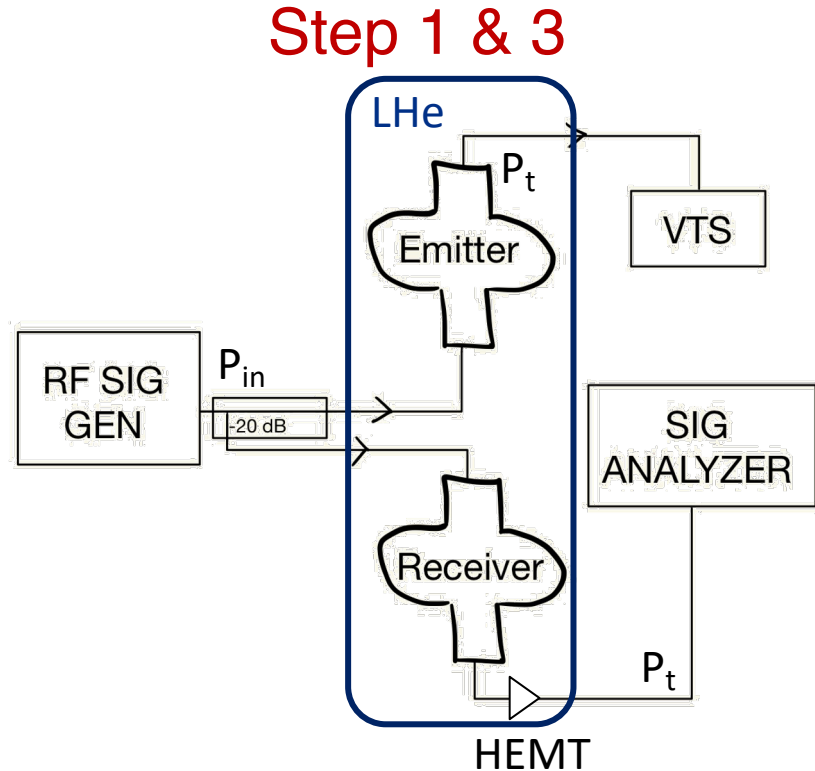
Dark SRF: phase 1 → measurement protocol

- 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



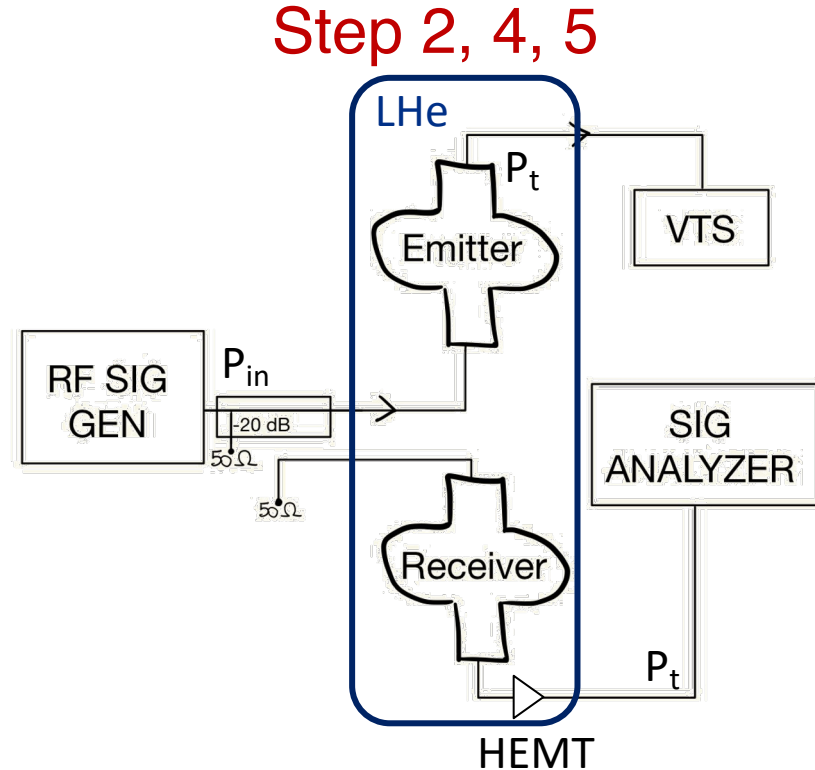
Dark SRF: phase 1 → measurement protocol

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



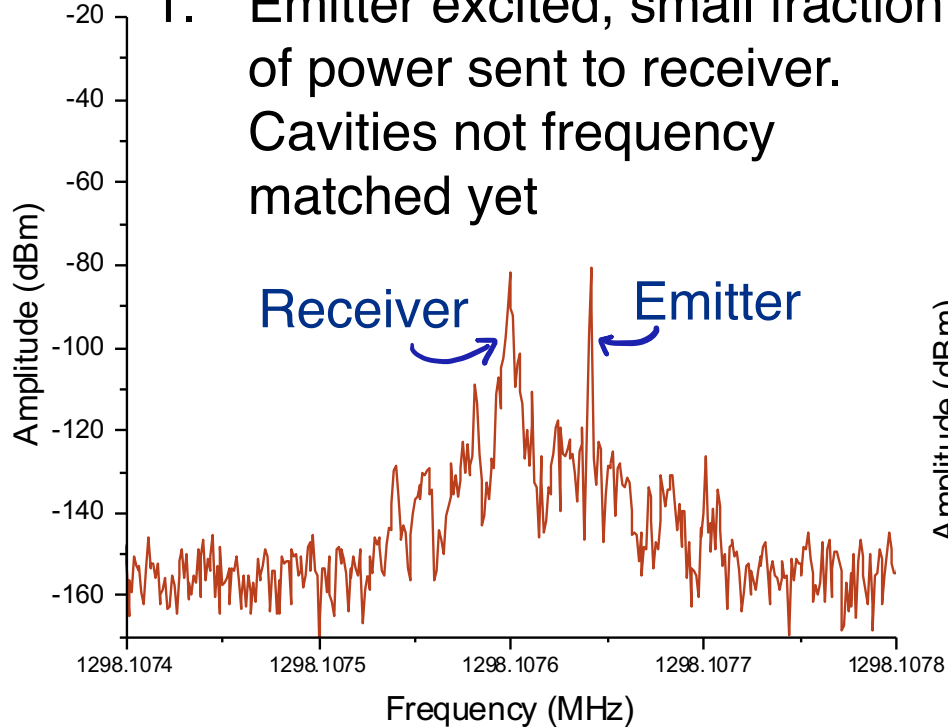
Dark SRF: phase 1 → measurement protocol

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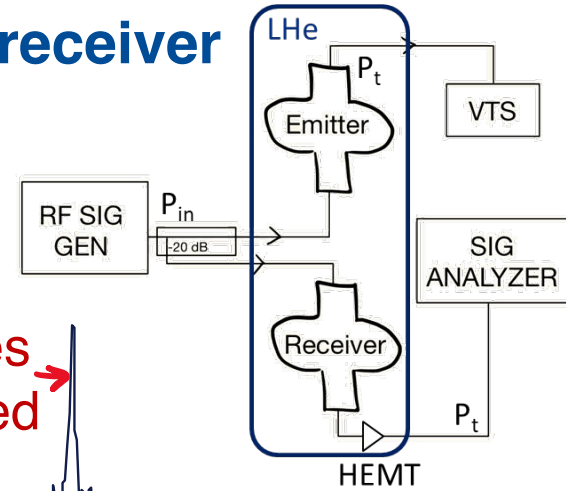
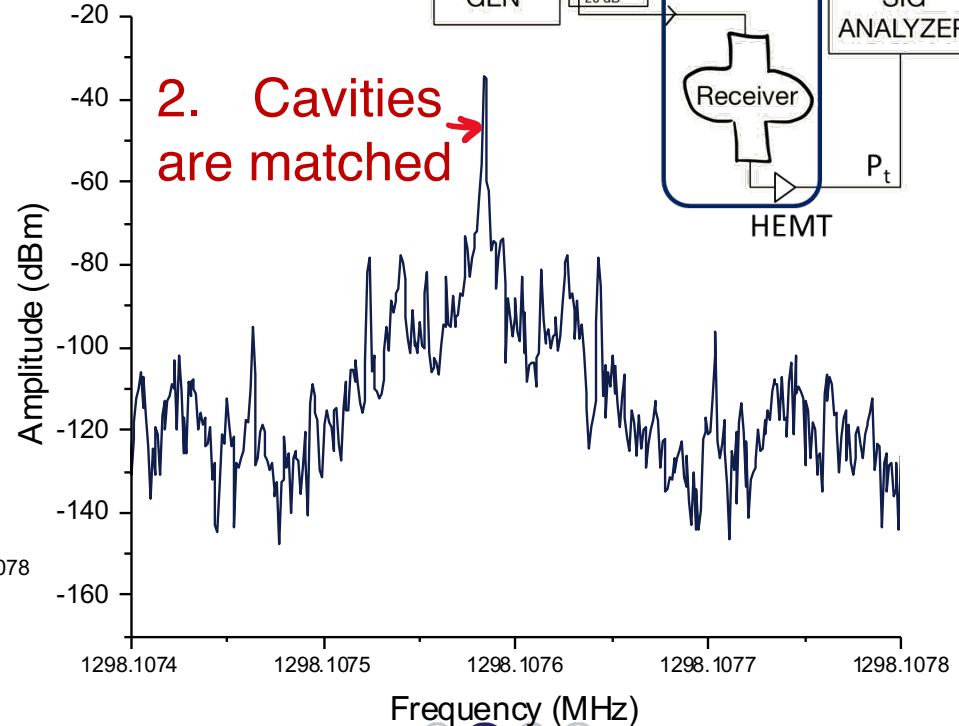


Step 1: excite emitter and match frequency to receiver

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

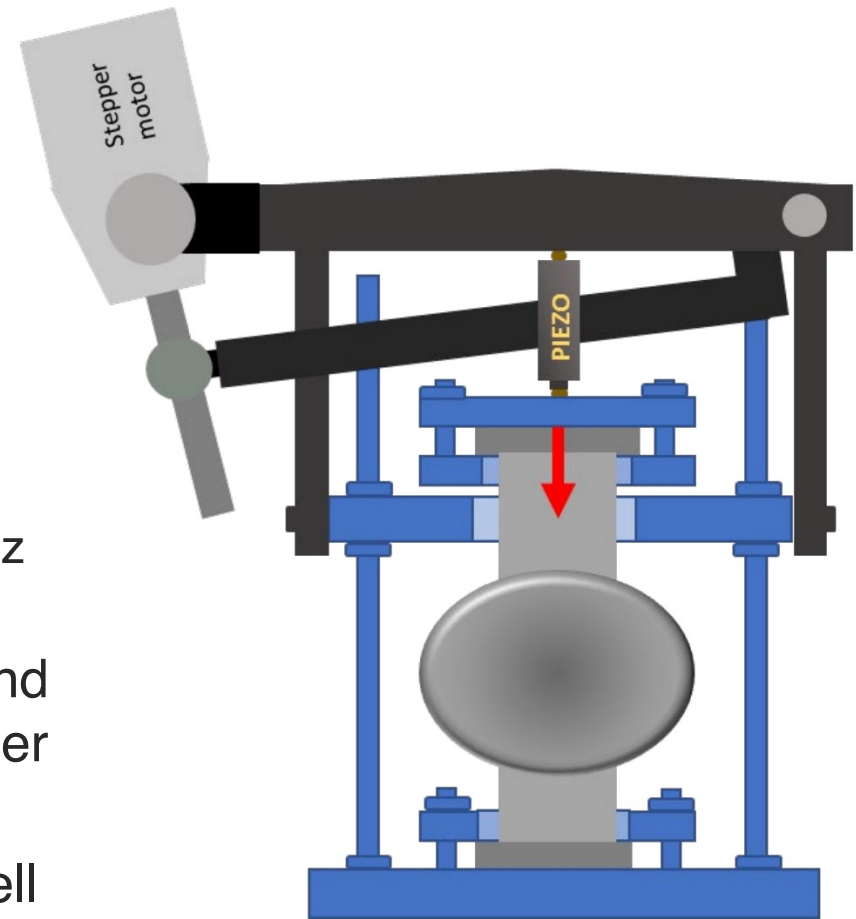


2. Cavities are matched



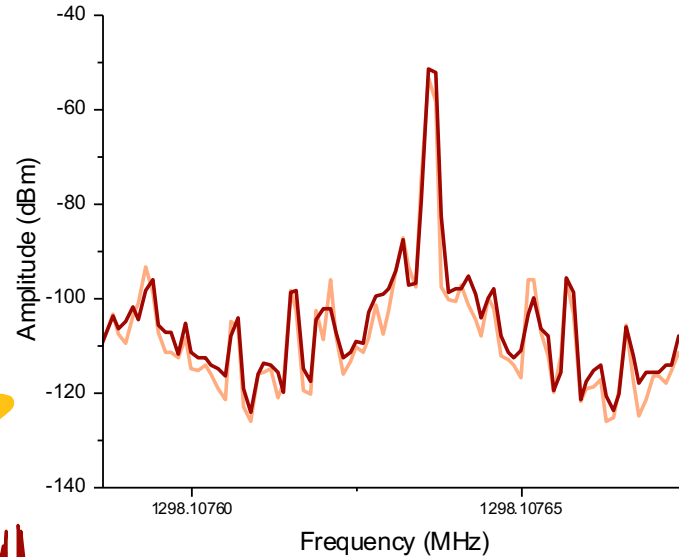
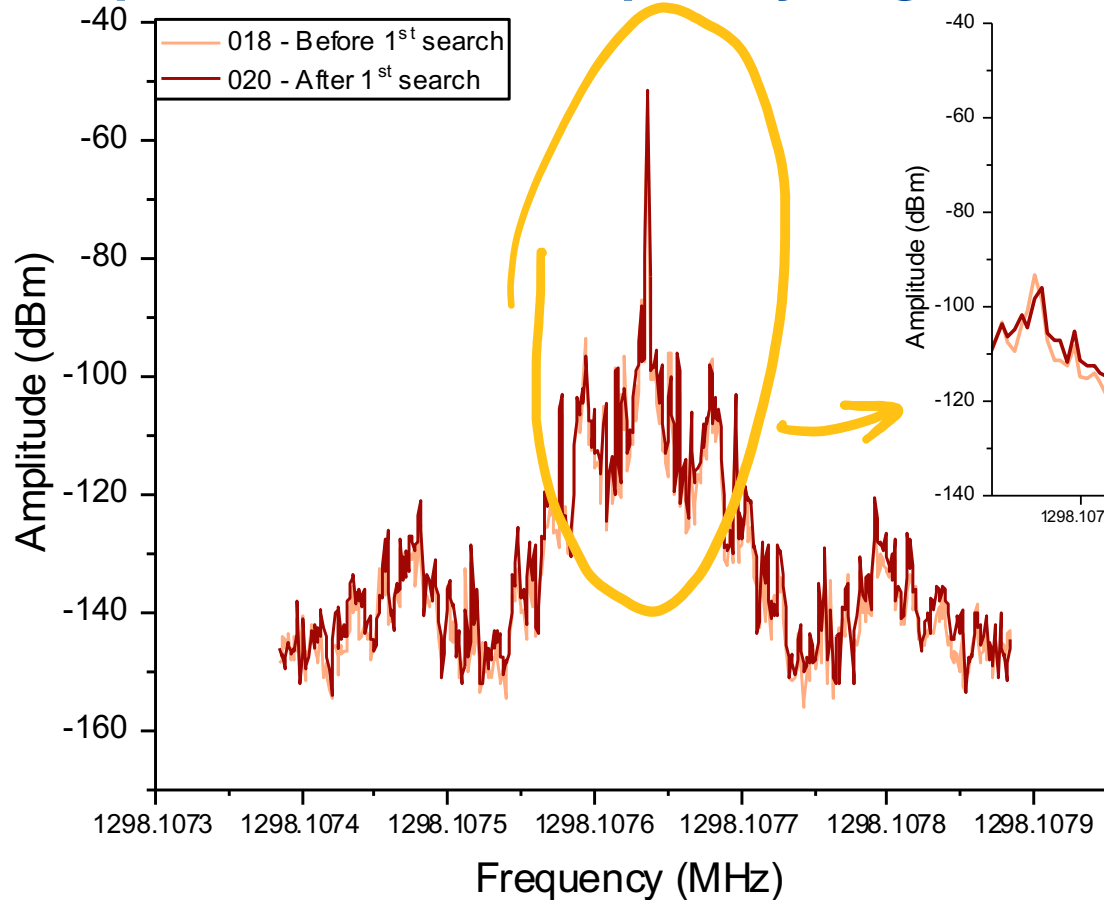
Cavity tuning

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



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

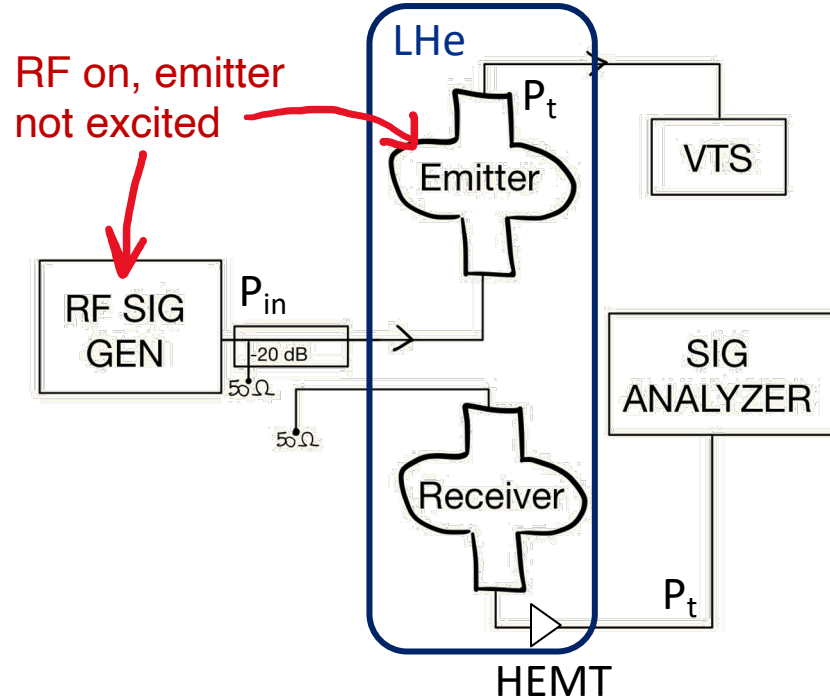
Step 1 & 3: check frequency alignment before and after search



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

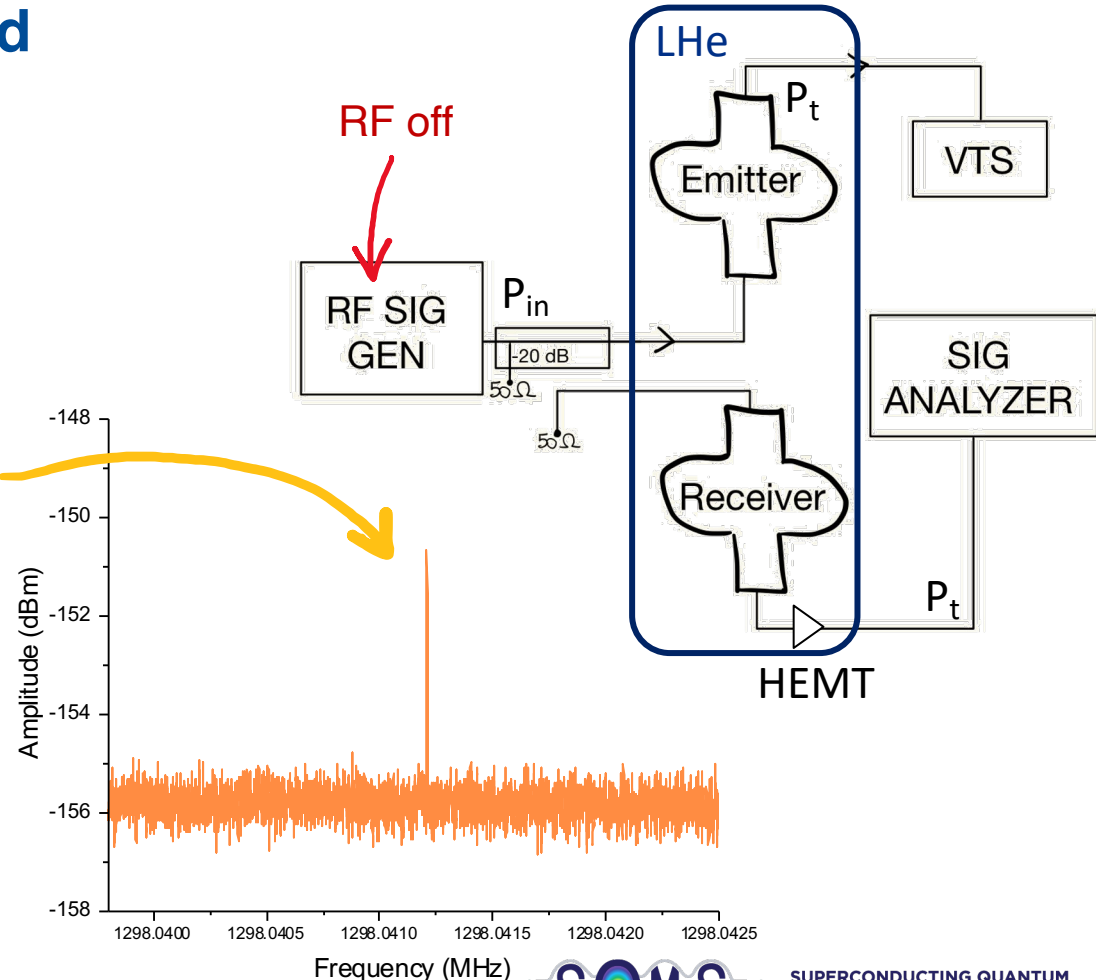
Step 4: cross-talk check

- 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



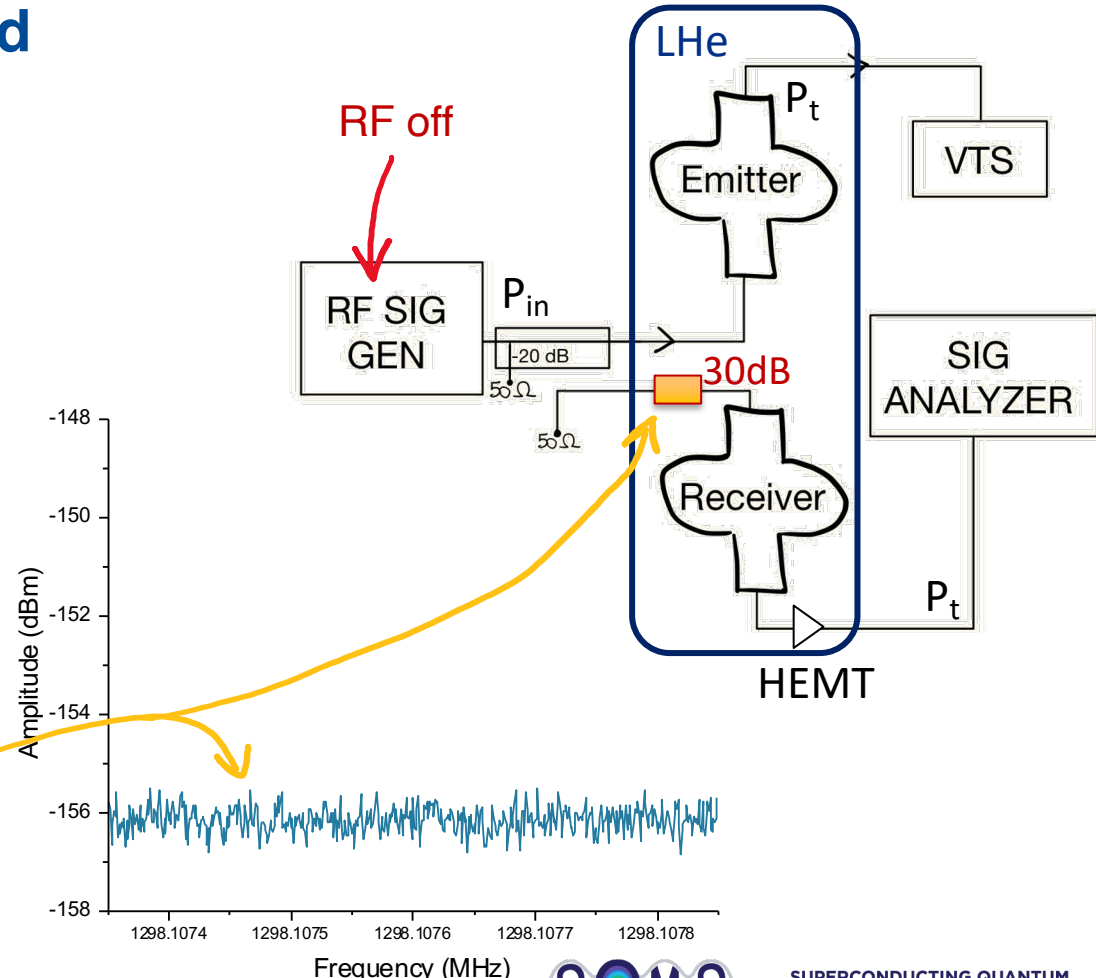
Step 5: thermal background

- 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



Step 5: thermal background

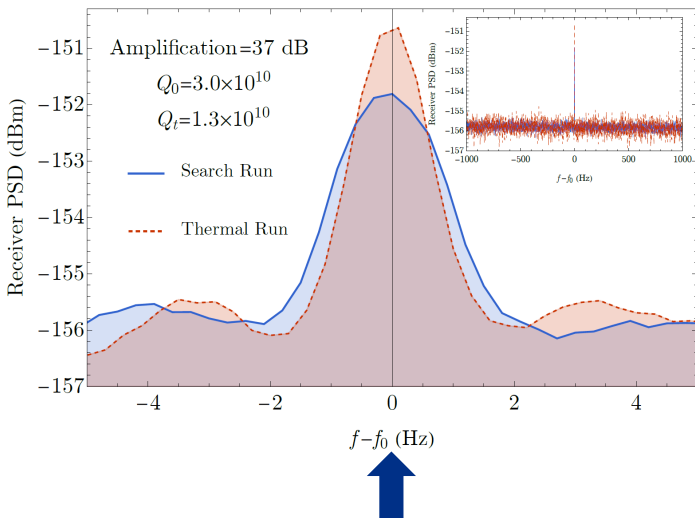
- RF signal generator is turned off
- Measure receiver power spectrum
- Any peak measured?
 - During 2019 run: yes, due to RT photons leaking from receiver input line
 - Later: no, we added 30dB attenuation on input line



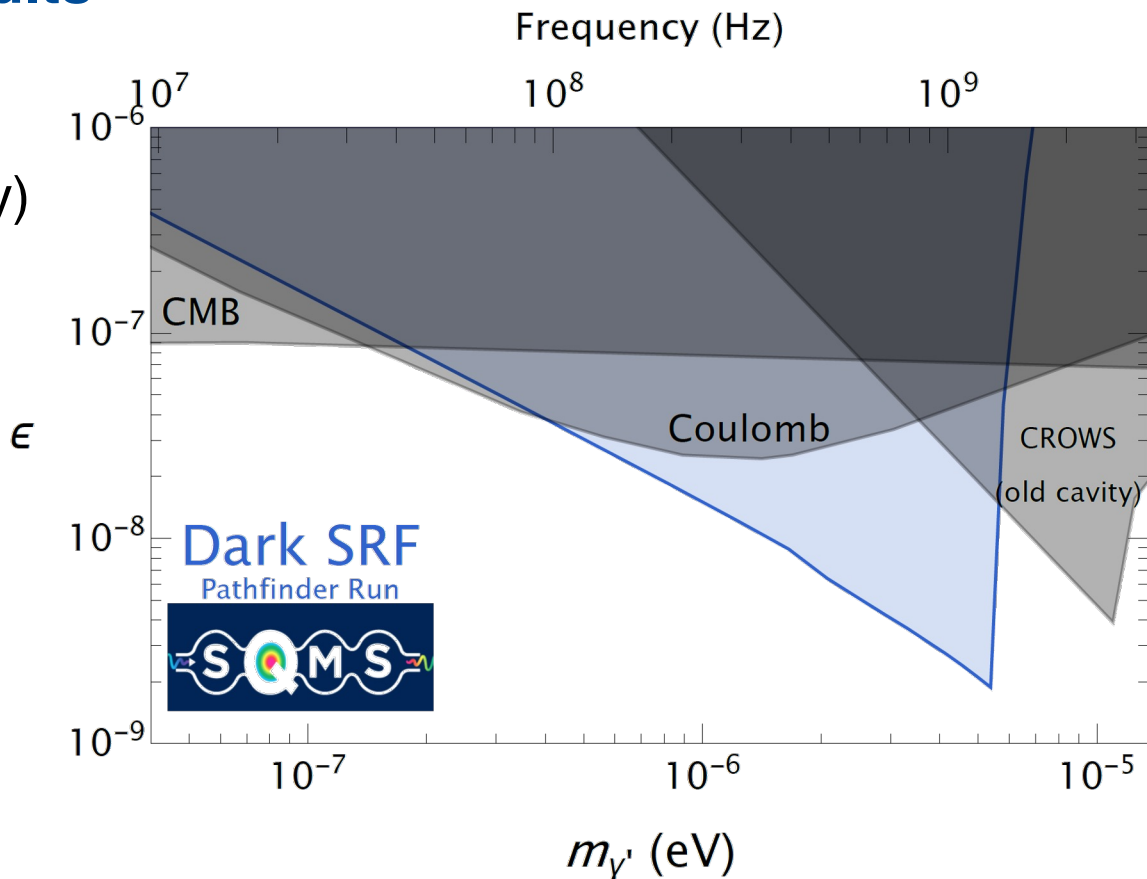
Dark SRF: phase 1 → results

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)

Recent Results

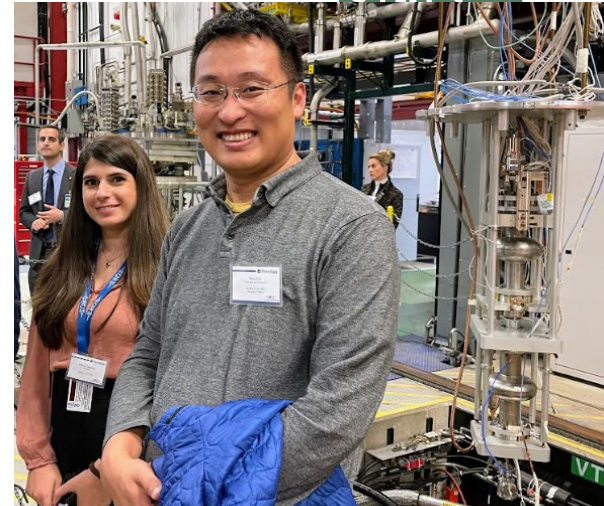
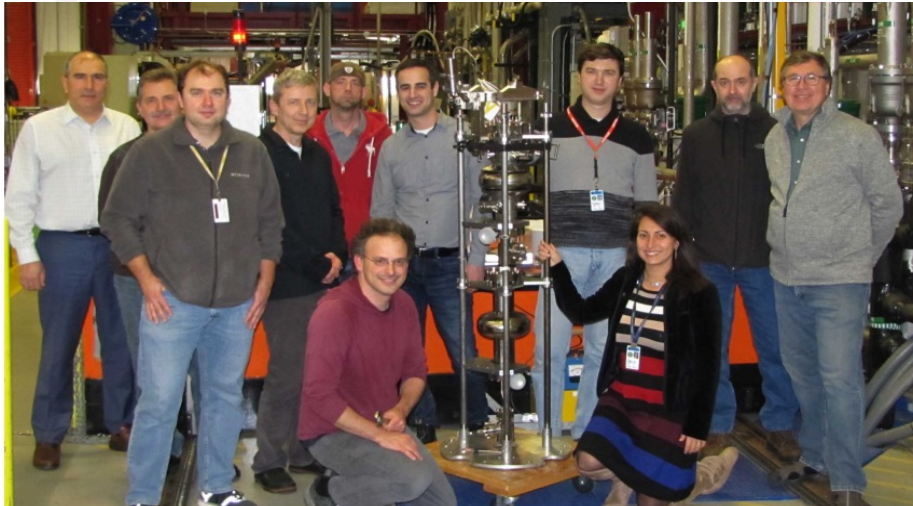
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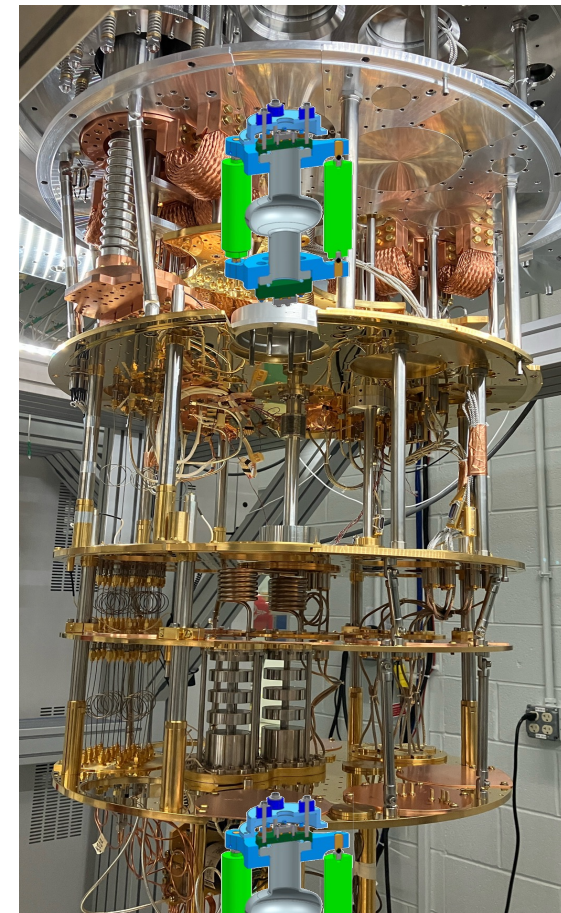
Search for Dark Photons with Superconducting Radio Frequency Cavities

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



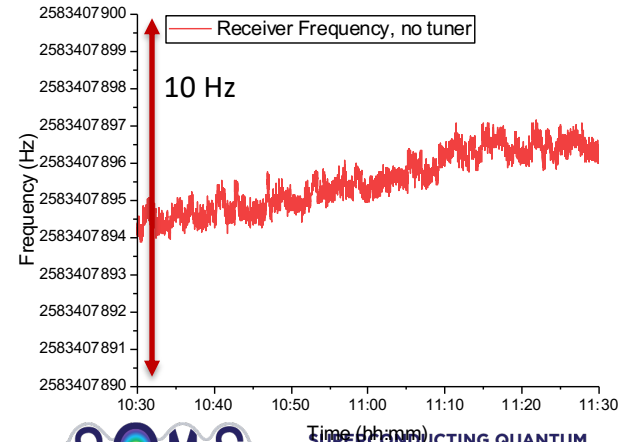
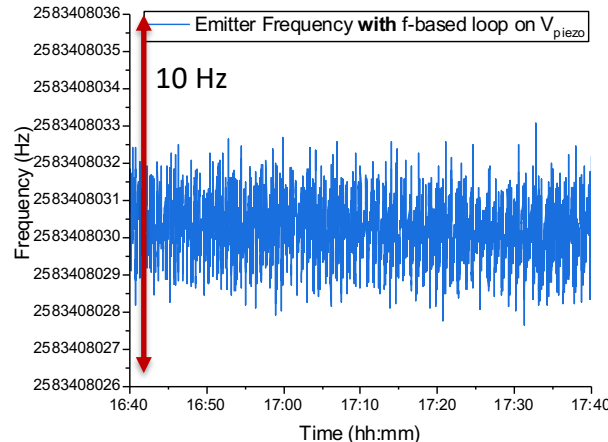
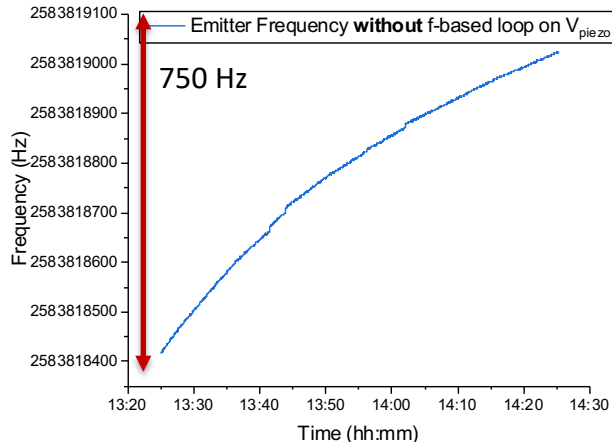
Dark SRF: phase 2 → 2.6GHz cavities in DR

- Deploy Dark SRF in dilution refrigerator (DR) to reduce thermal background
- Emitter cavity on additional 4K plate, receiver on mK plate with JPA on P_t
- Modifications of experimental setup for DR:
 - ✓ Change cavity frequency to 2.6GHz due to size limitation
 - ✓ Modify tuner system (piezo only!)
 - ✓ Verify frequency matching and stability with new tuner
 - ☐ Reduce crosstalk
 - ☐ Move entire setup to dilution refrigerator



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



Dark SRF: phase 2 → frequency control (2)

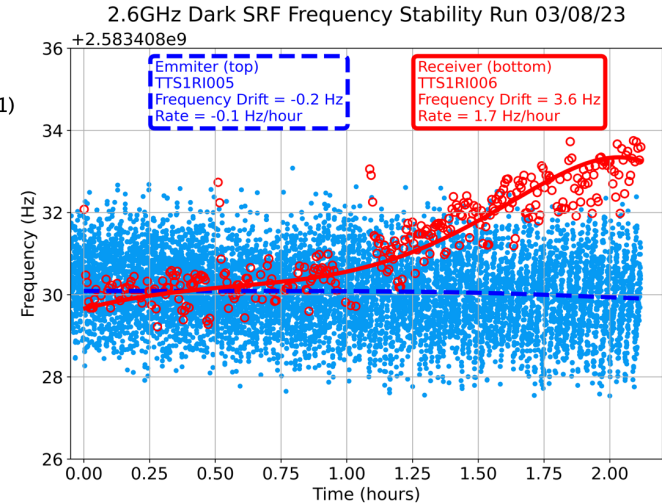
PI Loop Resonance Control for Dark Photon Experiment at 2 K Using a 2.6 GHz SRF Cavity

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](https://arxiv.org/abs/2307.10433) [physics.acc-ph]

	Emitter cavity – 1.3GHz setup	Emitter cavity – 2.6GHz setup
Slow drift in $\sim O(\text{hour})$, absolute value (Hz)	5.7	0.1
Slow drift in $\sim O(\text{hour})$, 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), J.C. 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.

Comments: 21st International Conference on Radio-Frequency Superconductivity (SRF 2023)

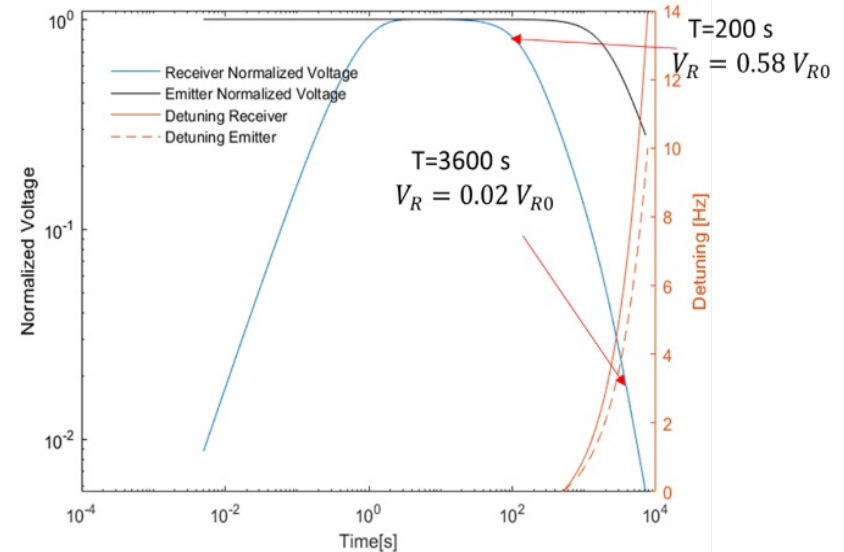
Subjects: Accelerator Physics (physics.acc-ph)

Report number: FERMILAB-CONF-23-265-TD

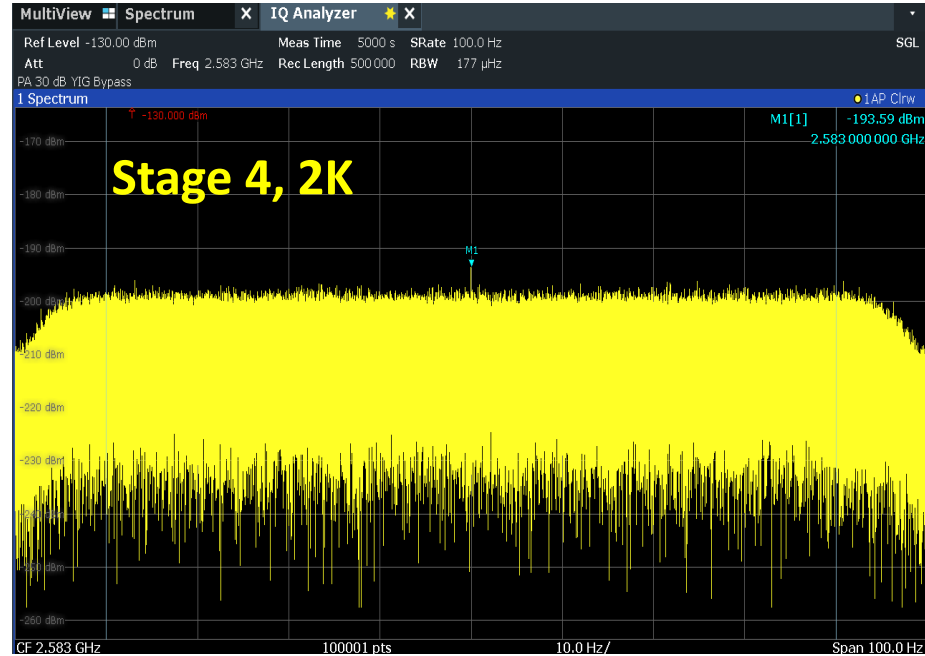
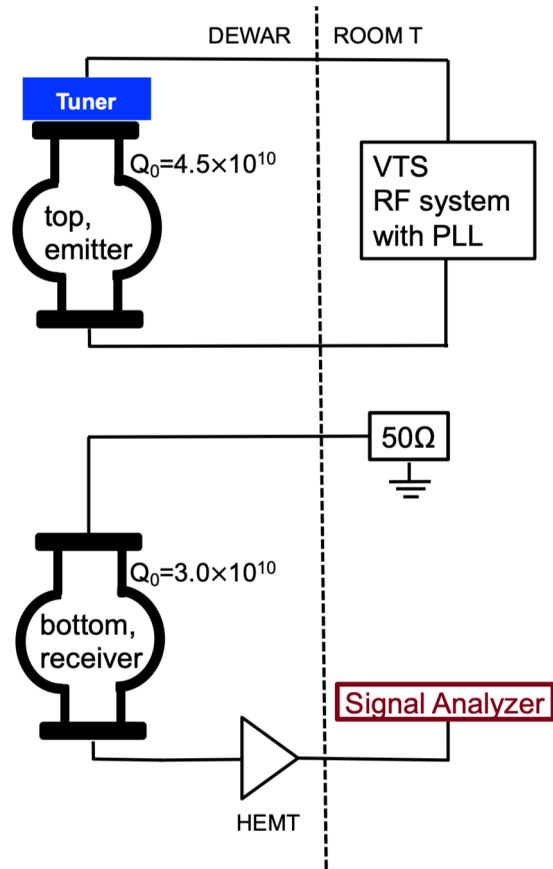
Cite as: [arXiv:2307.10424](https://arxiv.org/abs/2307.10424) [physics.acc-ph]

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



Dark SRF: phase 2 → cross talk



Crosstalk measurements conducted on simplified system

wledgements: Alex Melnychuk, Daniil Frolov, Alex Irigoyen, tof Kompier, Roman Pilipenko, Slava Yakovlev & RF team

Quantum Sensing: new windows into fundamental physics

Dark Sector

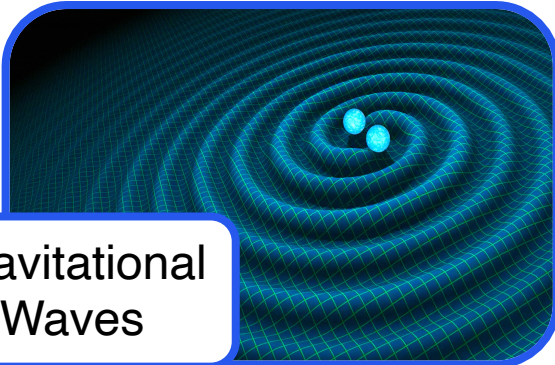
Dark Matter



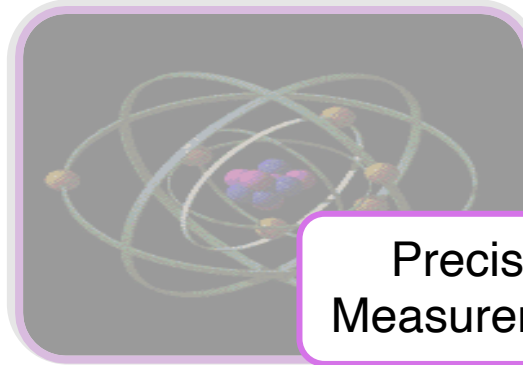
“Just” new particles



Gravitational Waves



Precision Measurements



Fermilab Dark SRF Experiment



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

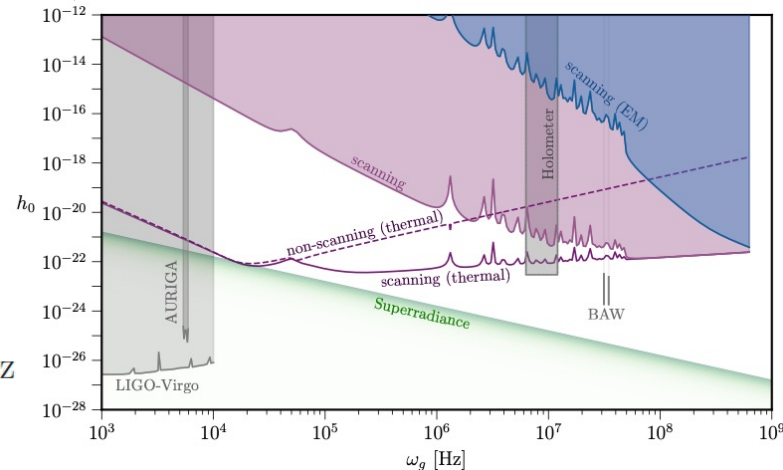
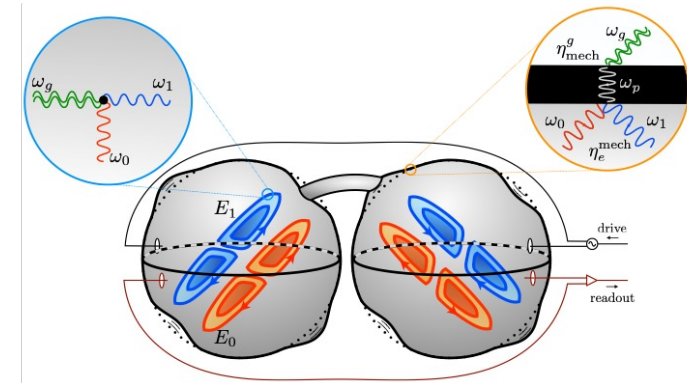
SRF cavities for gravitational waves searches

- SQMS theorists have laid the formalism for GW-EM cavity interaction.
 - Two types of signals:
 - Direct detection: $\text{GW} \rightarrow \text{EM}$
 - Indirect detection: $\text{GW} \rightarrow \text{mechanical} \rightarrow \text{EM}$
 - Current axion experiments have sensitivity to GHz Gravity waves.
 - A dedicated cavity experiment, e.g. MAGO, has significant reach at KHz.
1. “Pump mode” E_0, B_0 driven at $\omega_0 \sim \text{GHz}$
 2. GW of frequency $\omega_g \ll \text{GHz}$ drives power at $\omega_0 + \omega_g$
 3. “Signal mode” E_1, B_1 resonantly excited if $\omega_1 \simeq \omega_0 + \omega_g \sim \text{GHz}$

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)



Sensitivity of MAGO-like setup

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 (1)

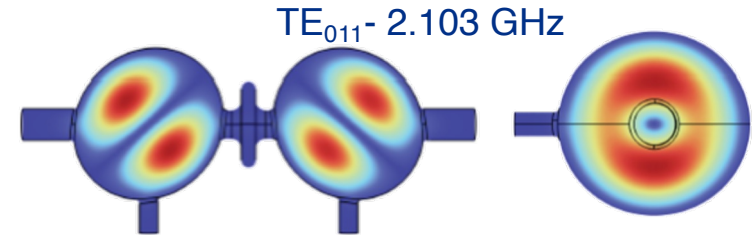


CLUSTER OF EXCELLENCE
QUANTUM UNIVERSE

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
 - Some dents and bents \rightarrow effect on RF modes and GW search?
- Theoretical work:
 - Multi-parameter optimization for cavity geometry
 - Develop full description of GW-cavity-EM interaction, leave long wavelength regime



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

MAGO 1.0: DESY and UHH activities (2)

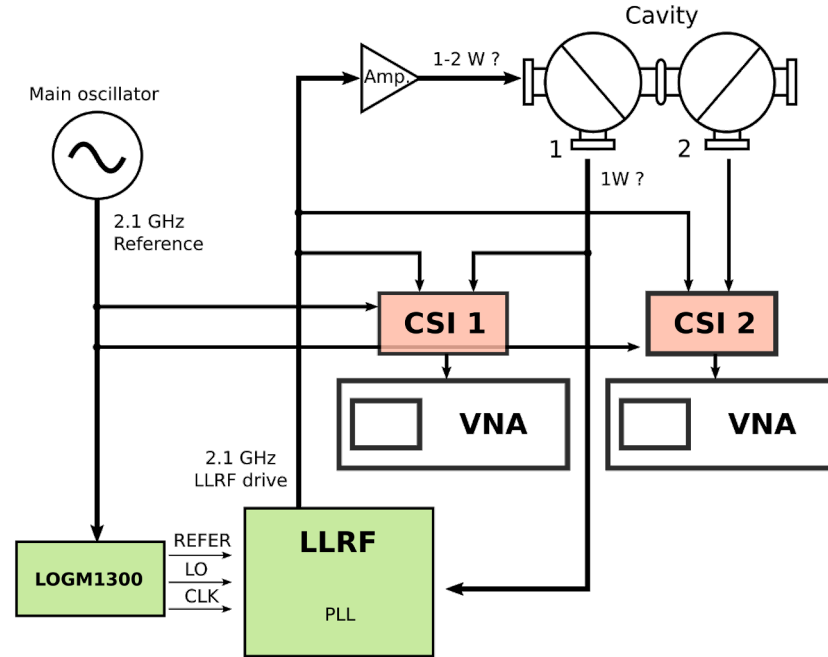


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- Cavity control and signal detection
 - Different approach from PACO
- DESY LLRF team responsible for cavity control developed a new technique *carrier suppression interferometer* (CSI)
- Matches MAGO requirements & conditions:
 - High RF field amplitude for better sensitivity to GW
 - Excited signal by GW is mixed to driving signal, with $\Delta\omega$ in the 10-100 kHz range
- R&D needed to set up CSI at MAGO frequency



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

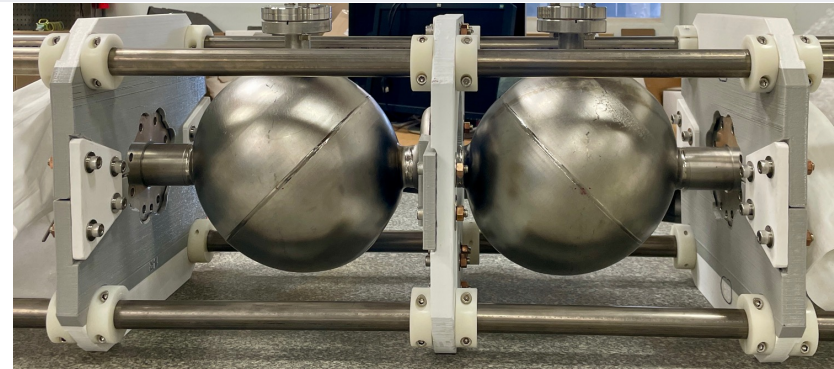
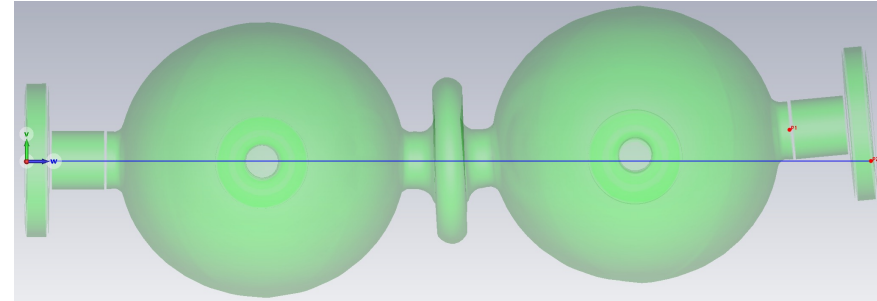
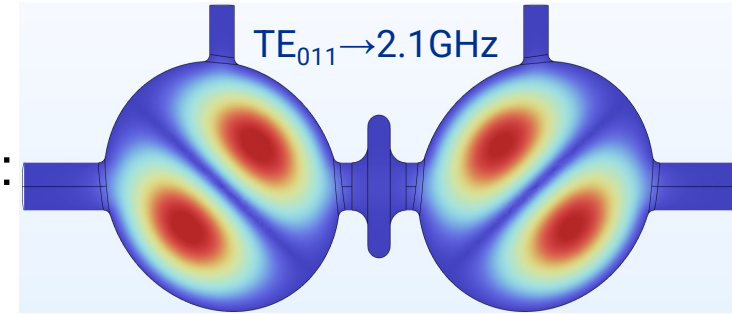
The cavity arrived at Fermilab



MAGO 1.0: Fermilab activities (1)

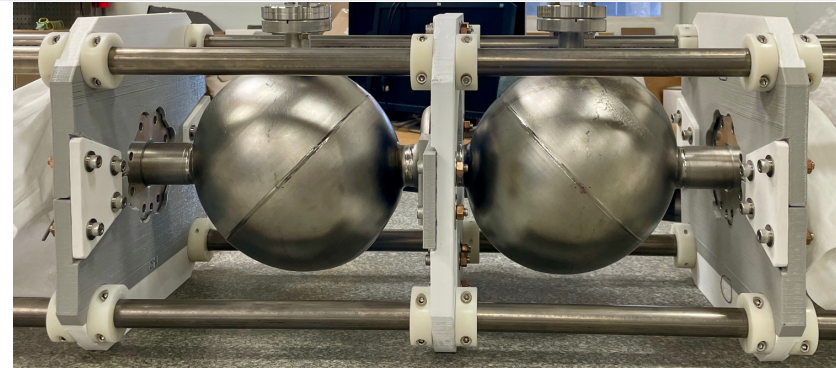
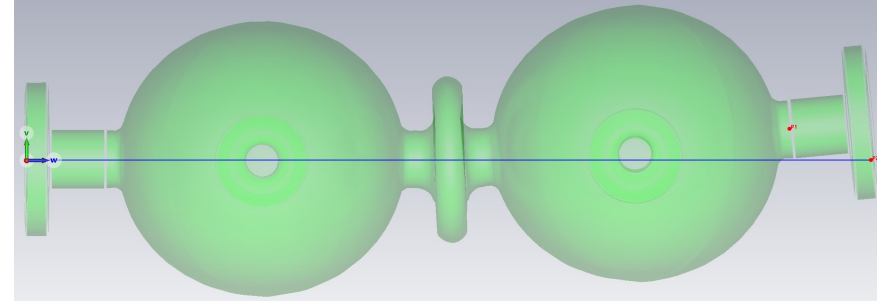
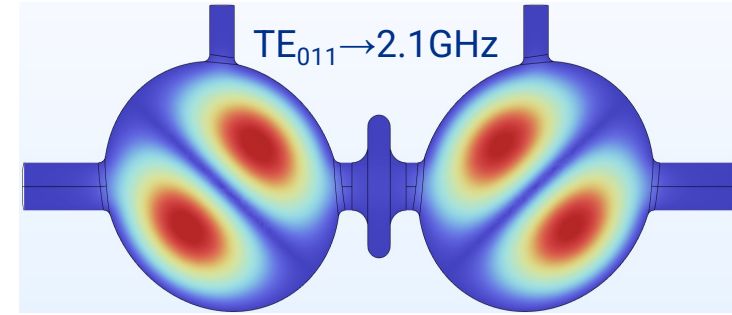
- Extensive work necessary before RF cold test:
 - RF and mechanical simulations on ideal and real geometry
 - 3D printed frame to sustain cavity during room temperature operations until plastic straightening
 - Optical inspection
 - Surface treatment
 - Plastic straightening
 - Room Temperature Tuning
 - High pressure rinsing tool adaptation
 - ...

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



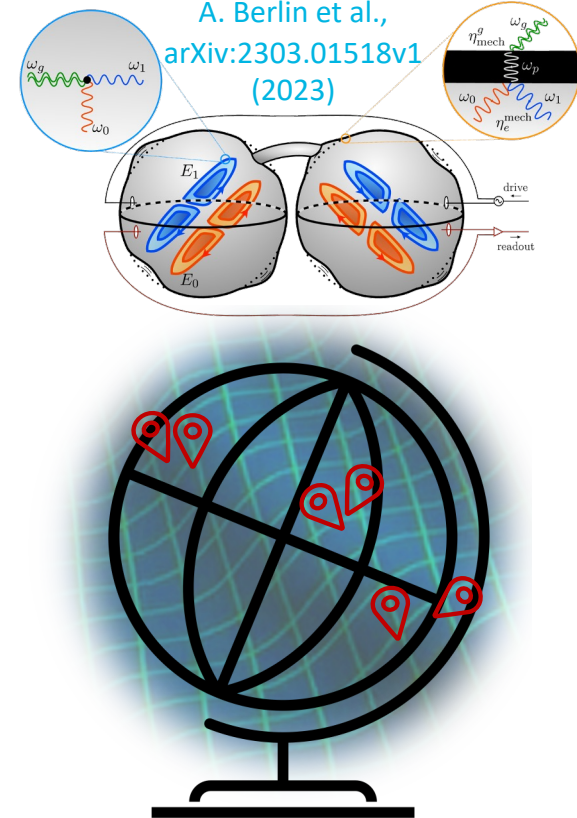
MAGO 1.0: Fermilab activities (2)

- Also working on tuning simulations, antenna design, VTS RF system adaptation to 2.1GHz frequency range
- **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
 - Characterize relevant noise sources for this frequency range and application



SRF cavities for GW: looking forward

- Working to gain better understanding of sensitivity to GW strain on:
 - GW frequency detuning from cavity mechanical resonance
 - Imperfections in cavity shapes and asymmetry between coupled cells
 - Microphonics and high frequency vibrational noise
 - ...
- **US/Japan collaboration** → small effort between SQMS Fermilab and University of Tokyo & KEK for SRF based GW searches
- Fermilab: currently focusing on design phase for an optimized cavity geometry and tuning system and planning to leverage lessons learned from MAGO 1.0
- Long term vision: cavity-based observatory network for high frequency GW



Quantum Sensing: new windows into fundamental physics

Dark Sector

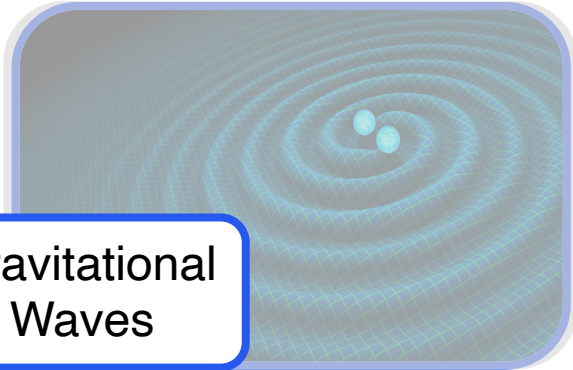
Dark Matter



“Just” new particles



Gravitational Waves



Precision Measurements

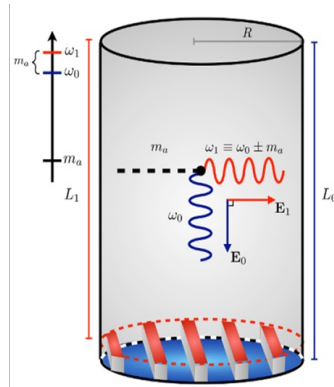


Fermilab Dark SRF Experiment

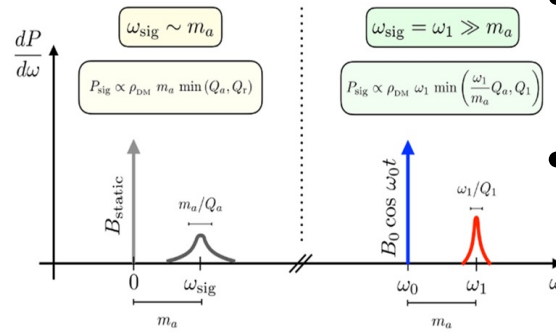


[1] Artwork by Sandbox Studio Chicago with A. Kova
symmetrymagazine.org

Heterodyne Axion DM search

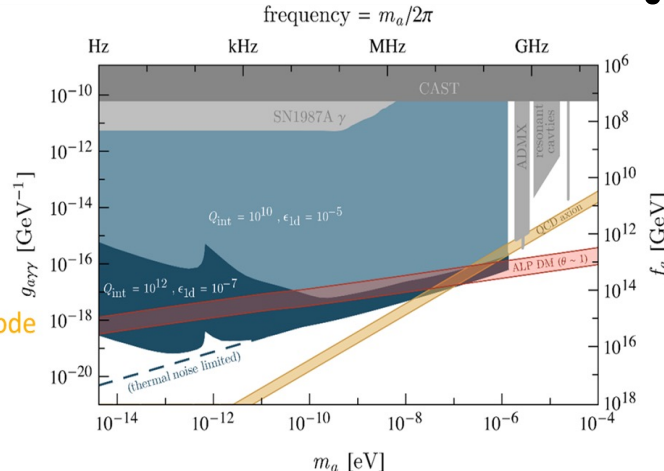
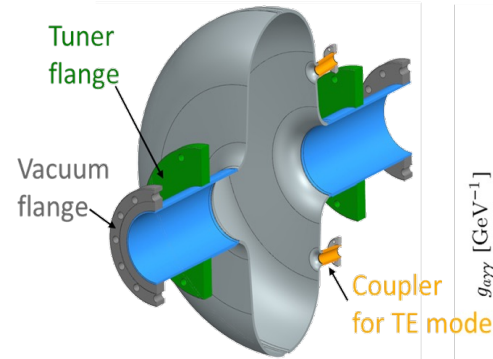


(a) Cartoon of cavity setup.



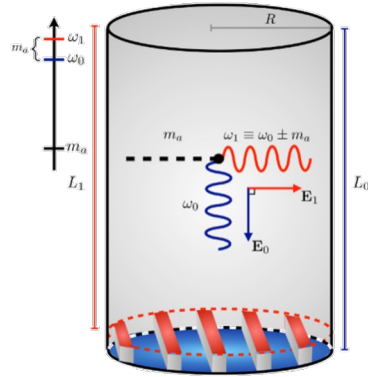
(b) Signal parameters.

- 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!

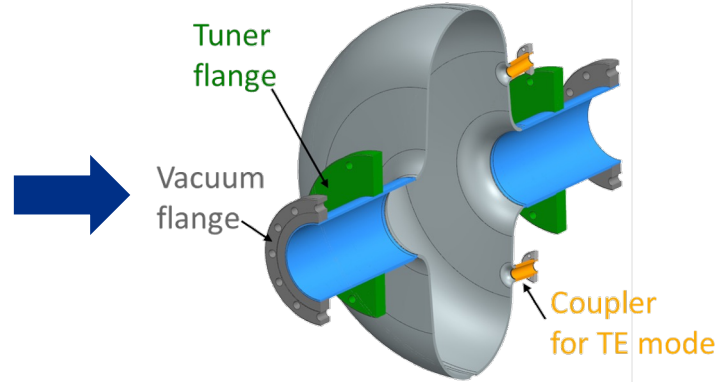


Berlin et al., Journal of High Energy Physics 2020.7 (2020)
Giaccone et al., arXiv:2207.11346 (2022)

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

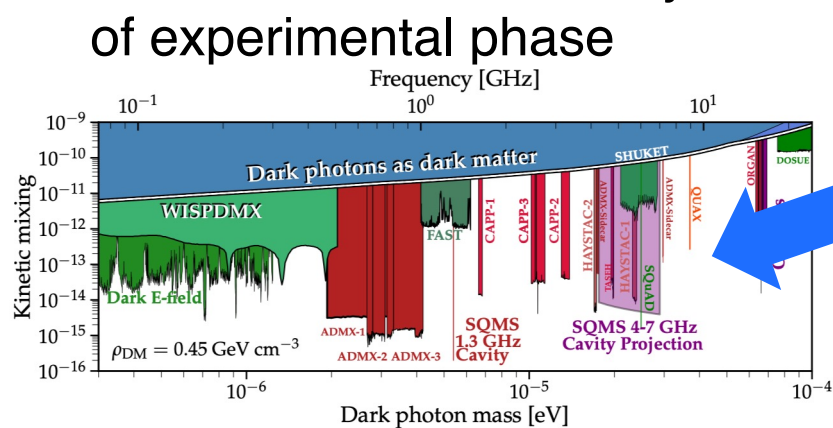
- Design is completed, currently procuring 2 prototype cavities → expected to arrive beginning 2024
- Pump mode: TM_{020} , Signal mode: TE_{011}
 - By design: $\Delta f \approx 1\text{MHz}$

Physics and sensing conclusions

- **Dark SPT** experiment
→ **extended**
– Dark
- **MAGO**
cavity and
- **Axion L**
beginning

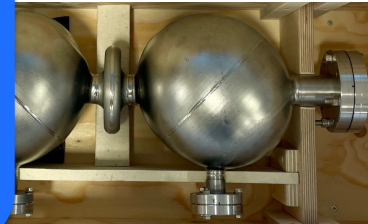
SQMS team has achieved new exclusion limits and is working on many new experiments!

of experimental phase



Cervantes, et al., arXiv:2208.03183v3 (2022)

You will hear more about the DM searches tomorrow!



Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)

Berlin et al., arXiv:2303.01518v1 (2023)

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

Thank you for your attention!

SQMS summary vision: Building new quantum facilities, capabilities and workforce that will enable new scientific discovery

