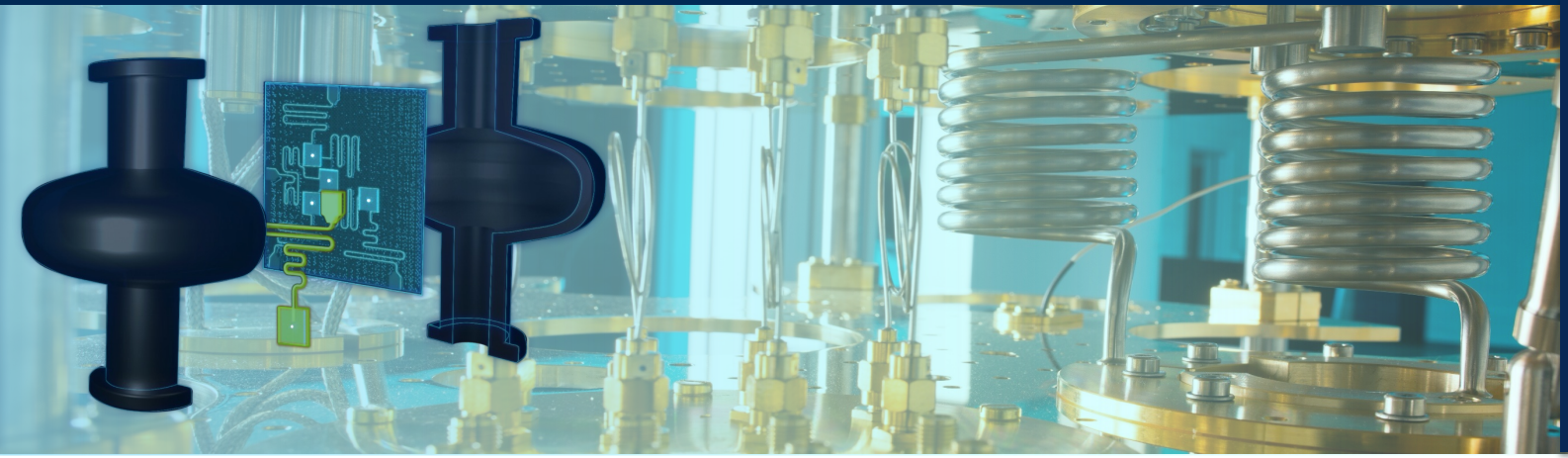
FERMILAB-SLIDES-24-0106-SQMS



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

Application of superconducting cavities as ultra-sensitive RF photon detectors

FRXD3, Friday May 24th, 2024

Bianca Giaccone

Superconducting Quantum Materials and Systems Center (SQMS), Fermilab

SQMS

30 Partner Institutions

>500 Collaborators

A DOE National Quantum Information Science Research Center

Fermilab
Northwestern University
rigetti
AMES NATIONAL LABORATORY
Creating Materials & Energy Solutions
NASA Ames Research Center
NIST
COLORADO SCHOOL OF MINES
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FORMFACTOR™
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INFN
Jefferson Lab
JOHNS HOPKINS UNIVERSITY
LOCKHEED MARTIN
LSU
NPL National Physical Laboratory
NYU
ROYAL HOLLOWAY UNIVERSITY OF LONDON
RUTGERS THE STATE UNIVERSITY OF NEW JERSEY
Stanford
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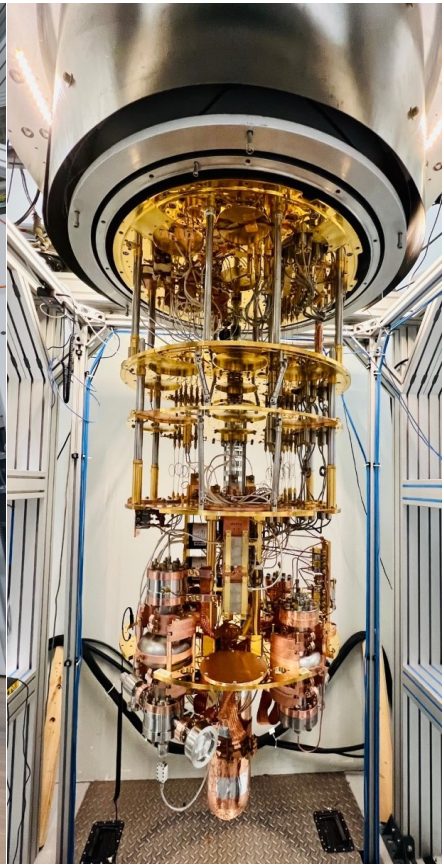
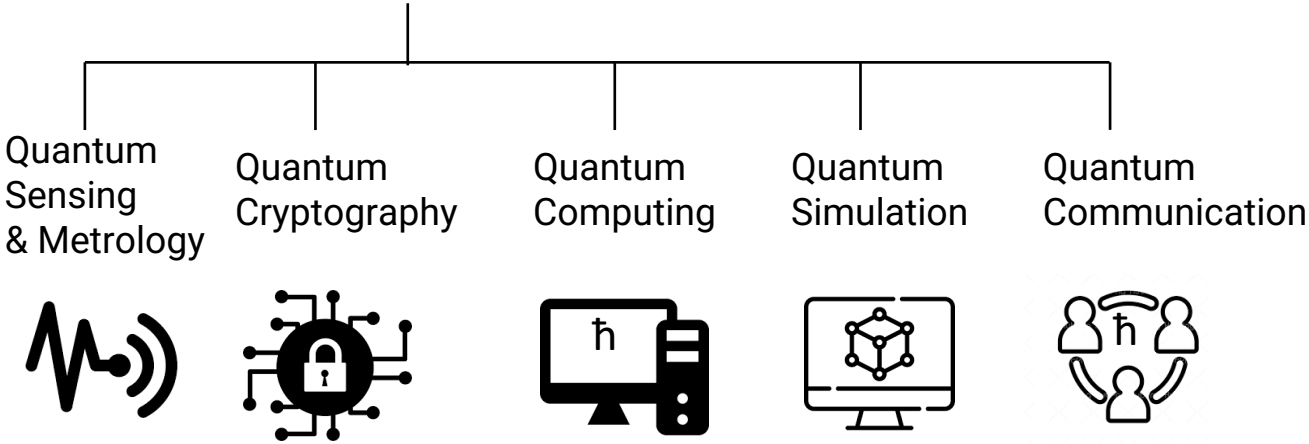
THE UNIVERSITY OF ARIZONA
University of Colorado Boulder
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
UNIVERSITY OF MINNESOTA Driven to Discover®
IN SUPREMÆ DIGNITATIS 1343
UNIVERSITÀ DI PISA
UNIVERSITY OF WATERLOO | IQC Institute for Quantum Computing

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

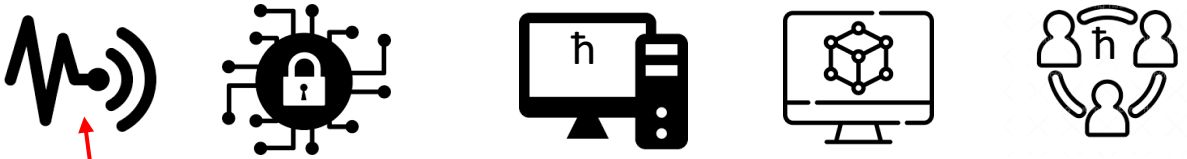
Quantum Sensing & Metrology

Quantum Cryptography

Quantum Computing

Quantum Simulation

Quantum Communication



Superconducting materials and RF cavities

Cryogenics

Electronics and Microwave Controls

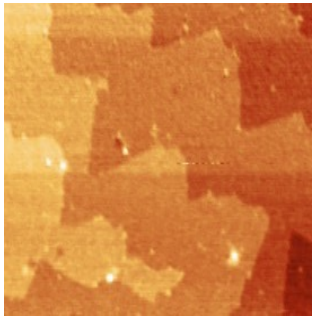
Precision Timing

…

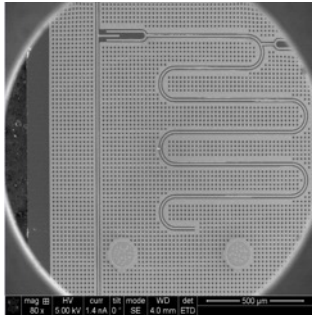
Leveraging unique technologies for advancing quantum information science

SQMS Science and Technology Innovation Chain

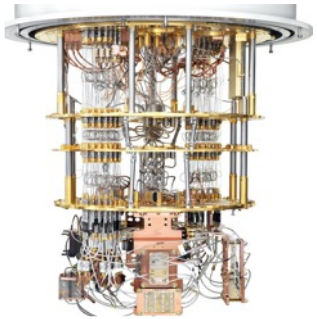
Materials → High-coherence devices → Systems integration → New platforms for quantum computing & sensing → Quantum advantage



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

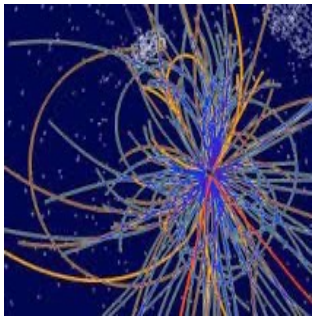


Demonstrating devices with systematically and consistently higher coherence at different SQMS partners



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

Deploying quantum platforms of innovative architectures and improved performance



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

Quantum Information Science

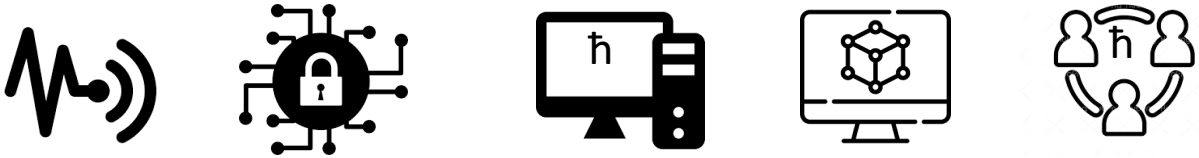
Quantum Sensing & Metrology

Quantum Cryptography

Quantum Computing

Quantum Simulation

Quantum Communication



Leveraging quantum technologies for fundamental physics

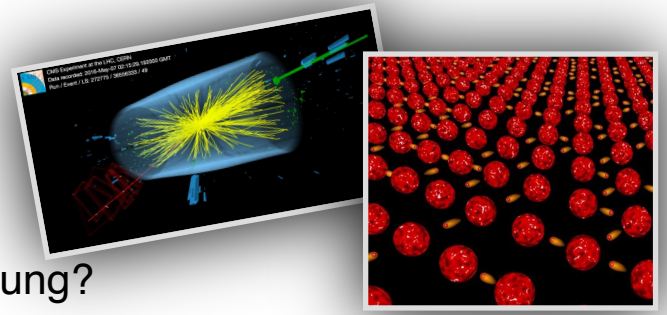
Foundations of Quantum Mechanics

Physics beyond Standard Model

Dark Matter

Simulation of quantum field theories...

SQMS Science Thrust



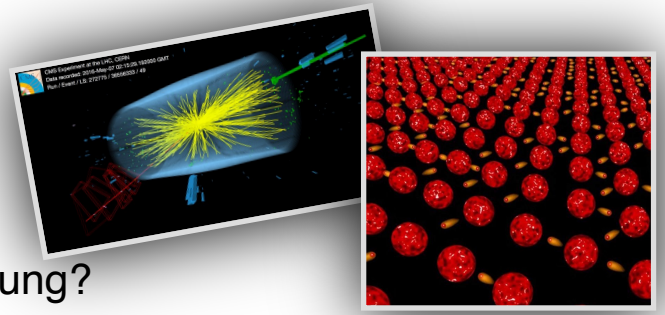
- **The questions that keep us up:**
  - What was the viscosity of the Universe when it was young?
  - How does the transition quarks → hadrons (e.g. at LHC) happen in “real time”?
  - What are the phases of complex quantum materials?
  - What the non-equilibrium dynamics of highly entangled systems?

  - What is the dark matter?
  - Are there new particles that we have not yet discovered?
  - Can we detect high frequency gravity waves?
  - How well can we study the electron?

These are long term endeavors.

Our goal is to enable breakthroughs in these questions.

SQMS Science Thrust



- **The questions that keep us up:**

Quantum Simulation and Computation

  - What was the viscosity of the [illegible] as young?
  - How does the [illegible] at LHC) happen in “real time”?
  - What are the [illegible] als?
  - What the non[illegible] entangled systems?

Quantum Sensing

  - What is the dark matter?
  - Are there new particles that we have not yet discovered?
  - Can we dete[illegible]
  - How well ca[illegible]

These are long term endeavors.

Our goal is to enable breakthroughs in these questions.

The People

Fermilab

Northwestern University

University of Minnesota
Driven to Discover®

The University of Arizona

LSU

Johns Hopkins University

University of Illinois Urbana-Champaign

INFN

Stanford

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

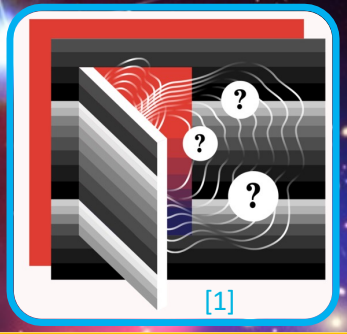
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Quantum Sensing: new windows into fundamental physics

Dark Sector

Dark Matter

"Just" new particles



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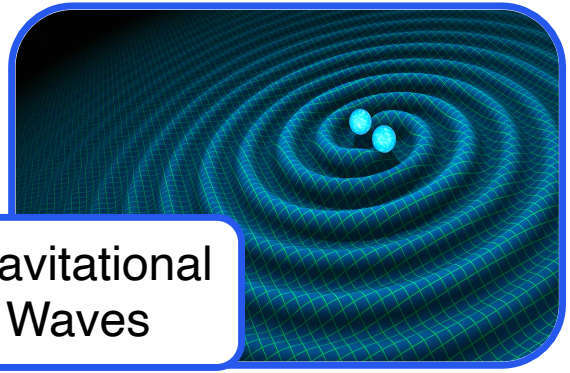
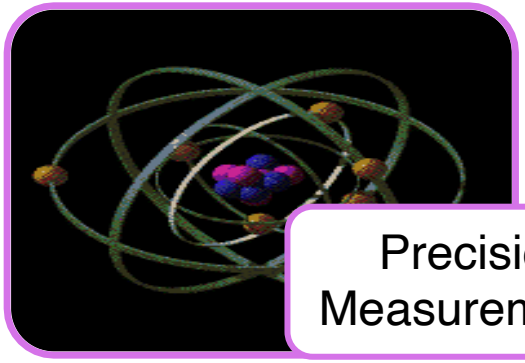


Gravitational Waves



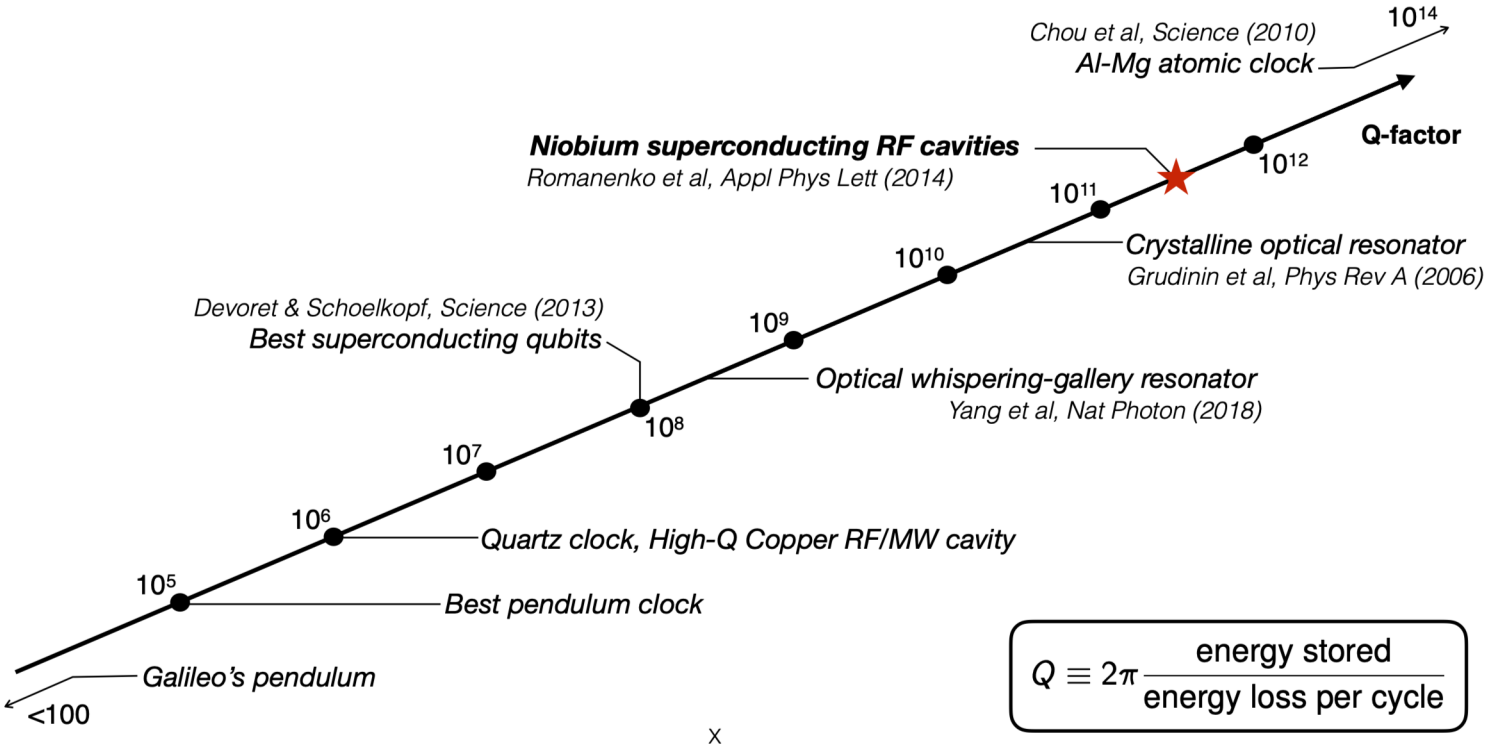
Precision Measurements

Fermilab Dark SRF Experiment

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

Why SRF cavities for quantum sensing?

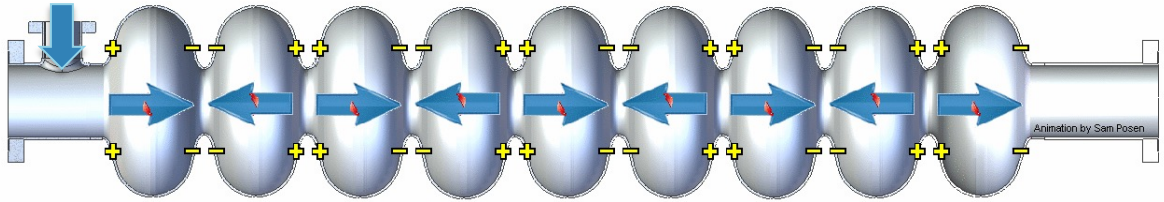
SRF cavities are the most efficient engineered oscillators



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

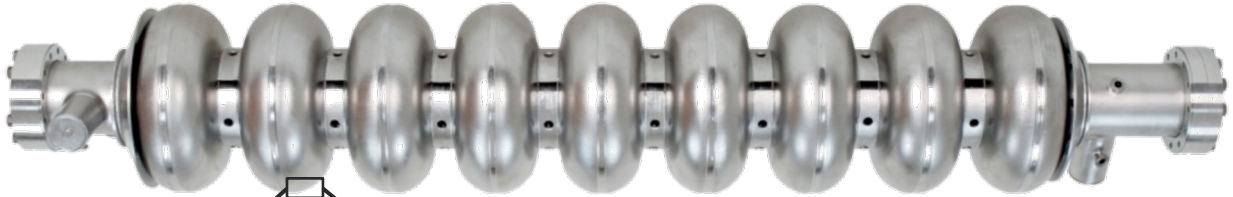
Superconducting Radio Frequency Cavities

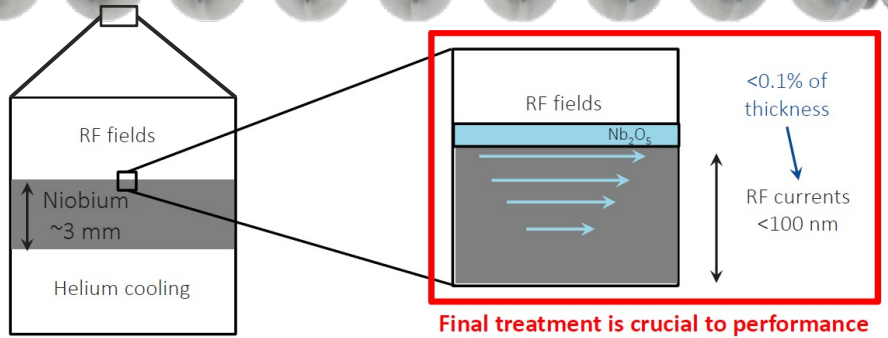
Input RF power @ 1.3 GHz



Animation by Sam Posen
Images from linearcollider.org, Wikipedia

Typically operated at T = 2K

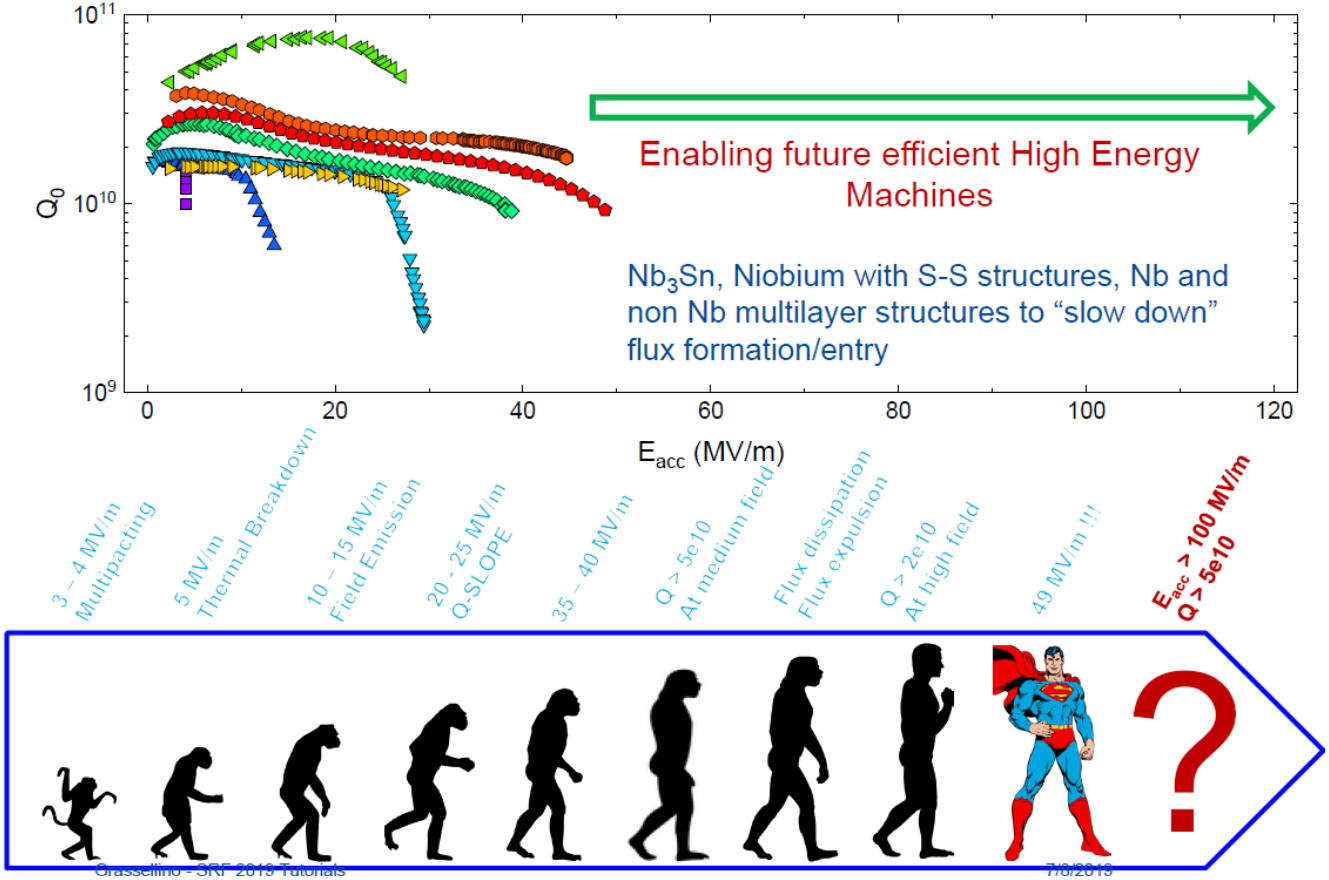




Final treatment is crucial to performance

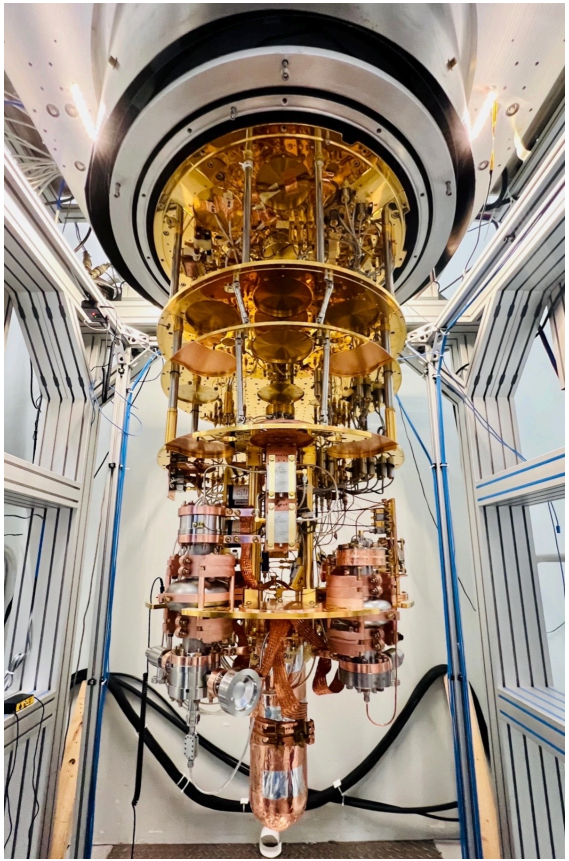
From: "Pushing Bulk Niobium Limits" A. Grassellino, SRF2019 - Tutorials

SRF performance evolution

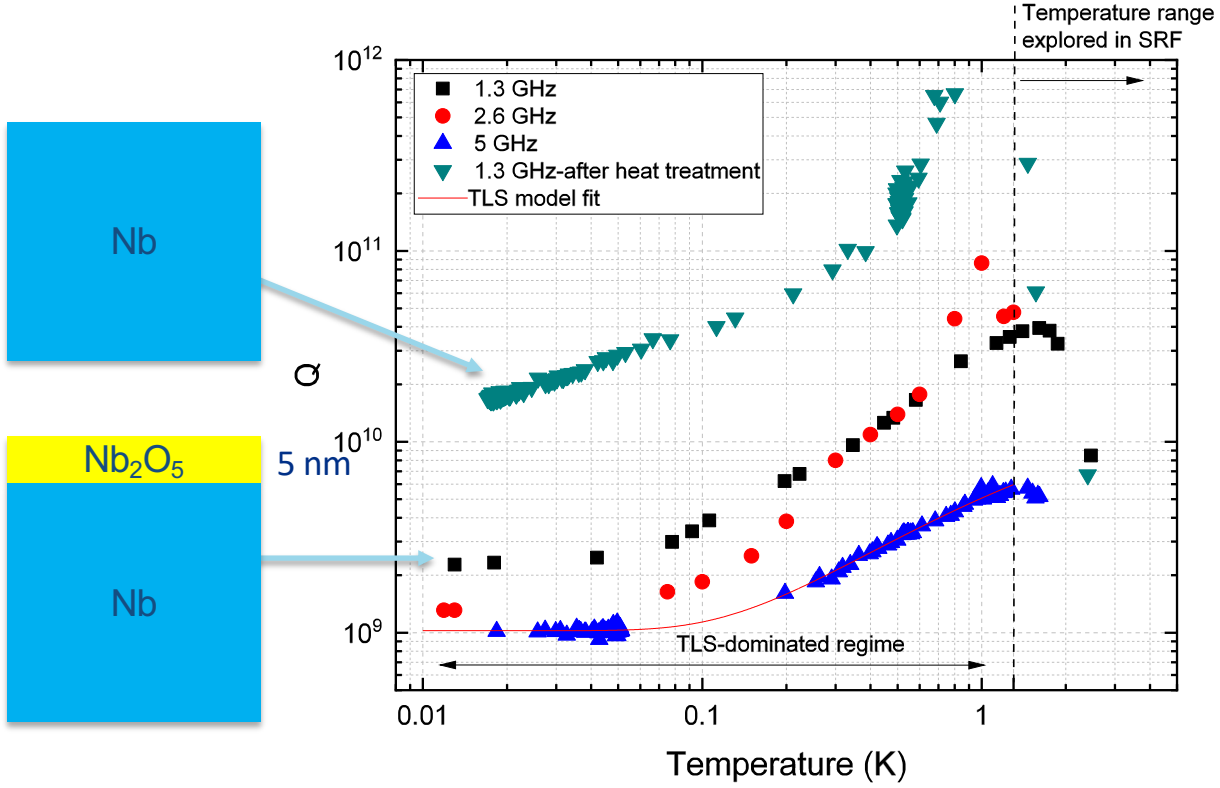


From: "Pushing Bulk Niobium Limits" A. Grassellino, SRF2019 - Tutorials

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



Dilution Refrigerator (DR)

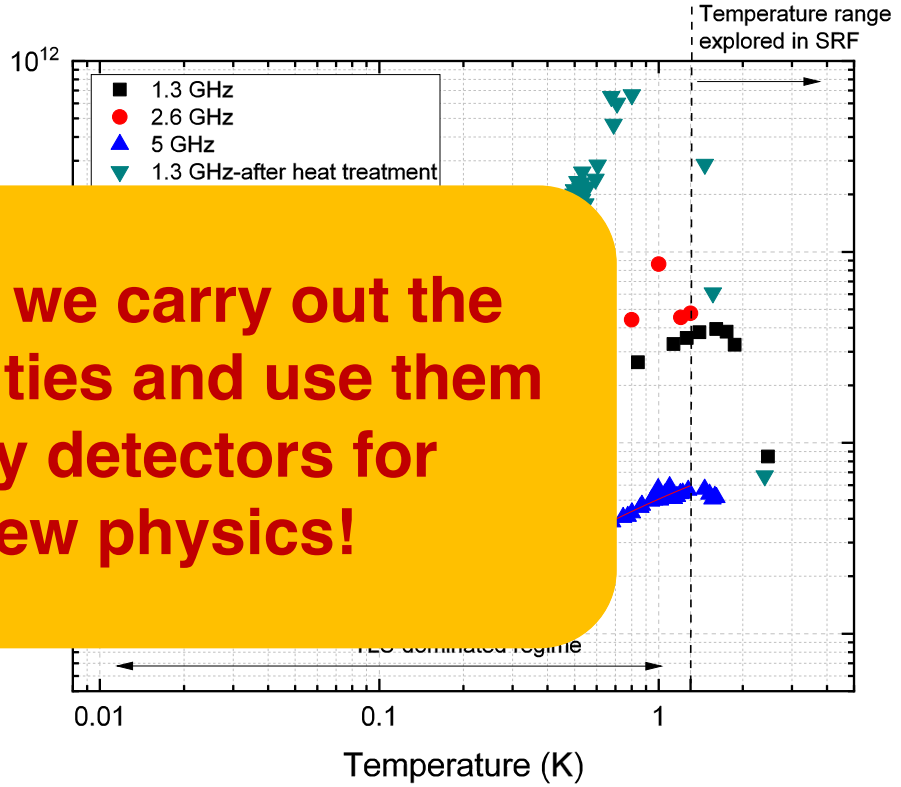


Romanenko et al., Phys. Rev. Applied 13, 034032 (2020)

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!



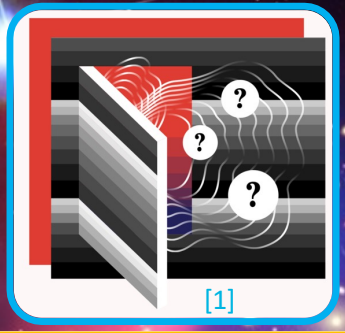
Romanenko et al., Phys. Rev. Applied 13, 034032 (2020)

Quantum Sensing: new windows into fundamental physics

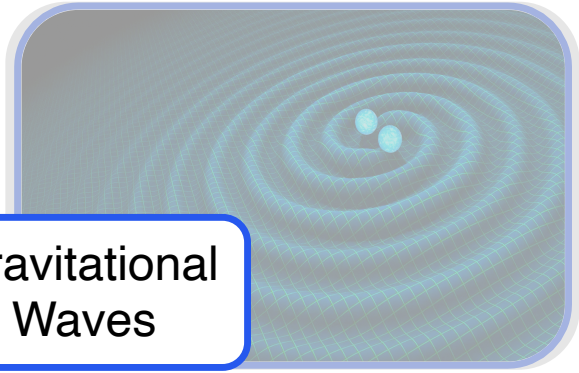
Dark Sector

Dark Matter

"Just" new particles



[1]



Gravitational Waves

Precision Measurements

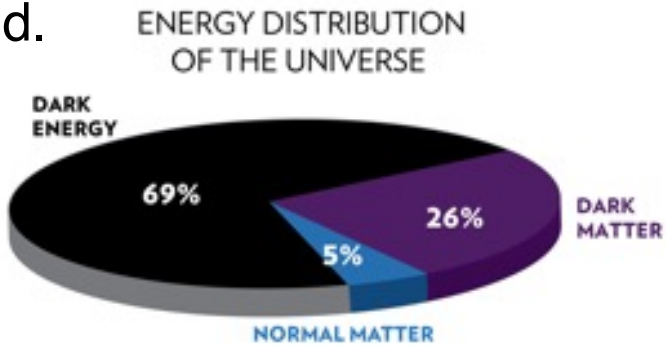
Fermilab Dark SRF Experiment

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

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

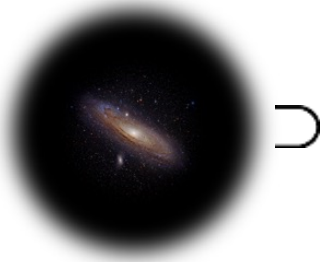
Dark Sector

- 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):



$\supset$ dark photons?
axions?

New particle:

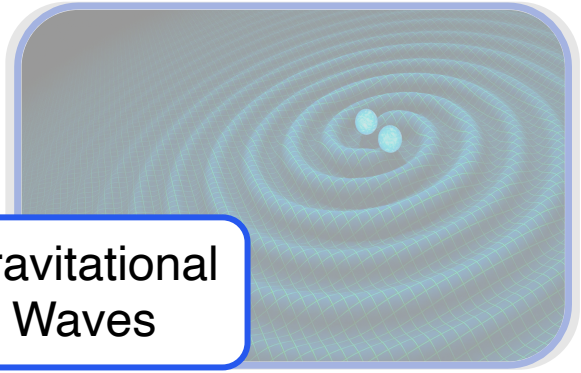
$\mathcal{L} \supset$ dark photons?
axions?
long range force?

Quantum Sensing: new windows into fundamental physics

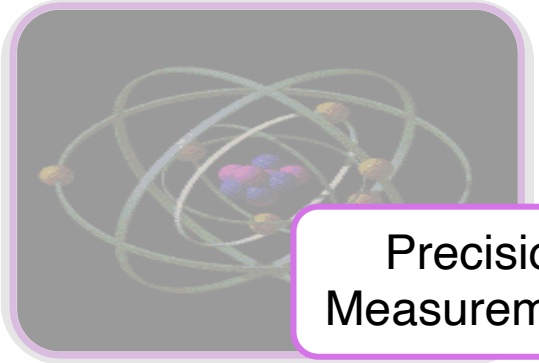
Dark Sector

Dark Matter

"Just" new particles



Gravitational Waves



Precision Measurements

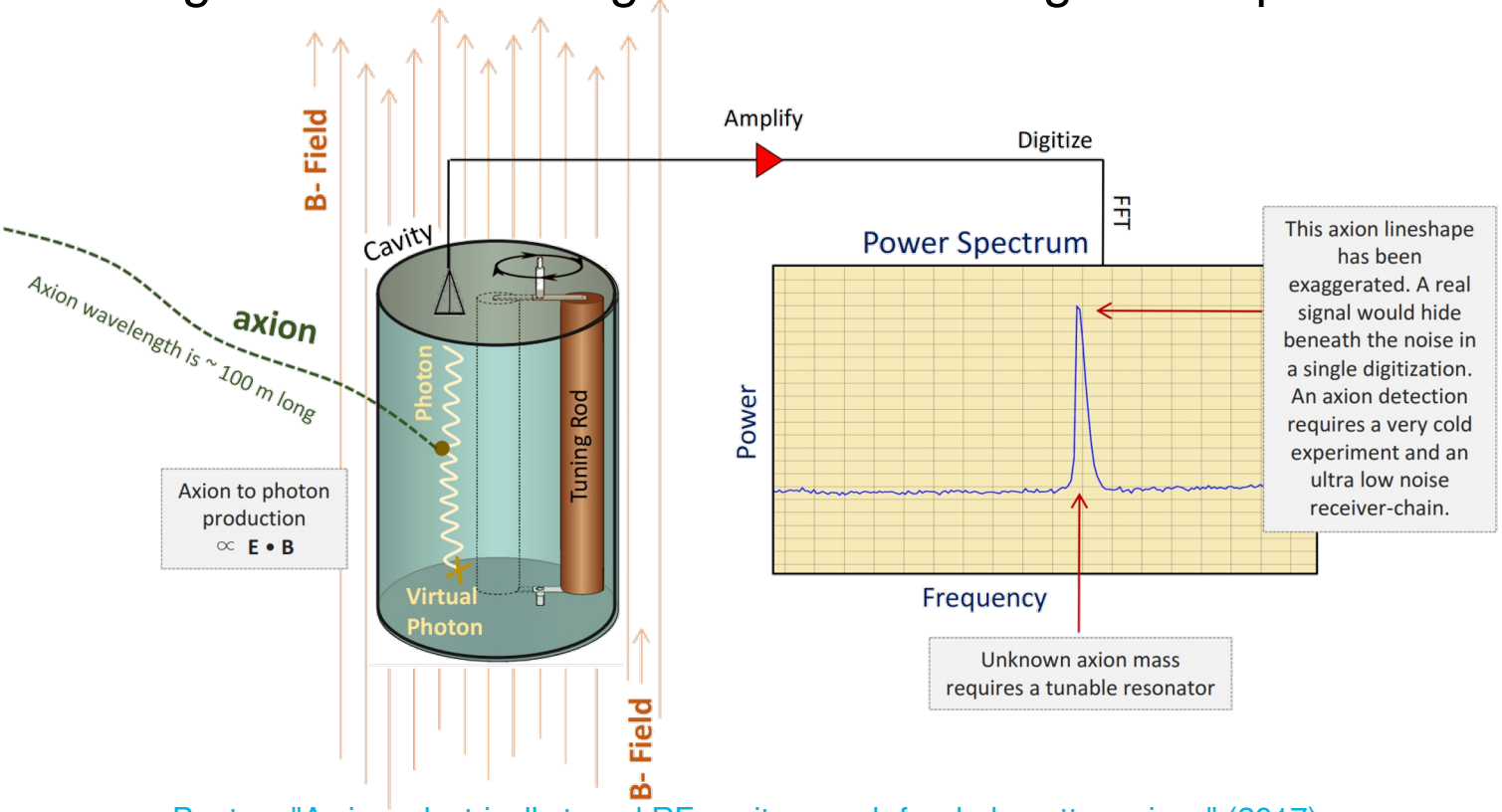
Fermilab Dark SRF Experiment

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

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

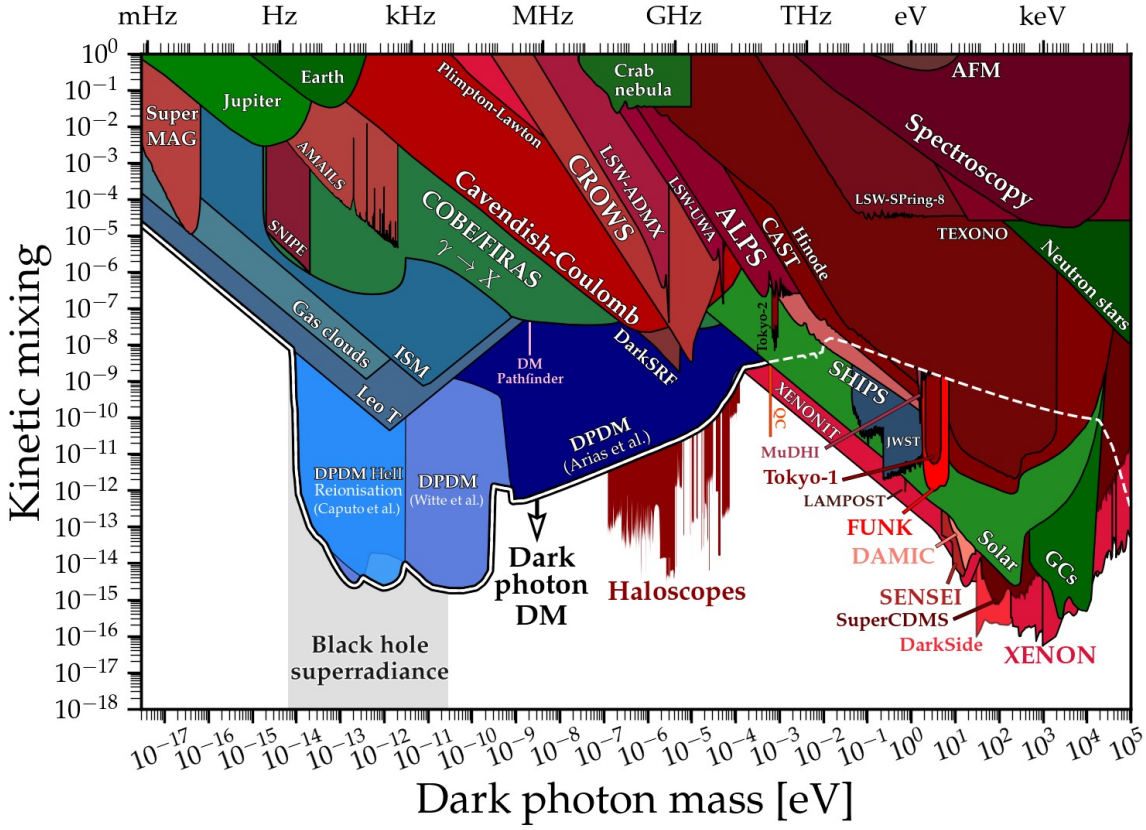
Haloscope Searches for Dark Matter

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



Boutan, "A piezoelectrically tuned RF-cavity search for dark matter axions" (2017)

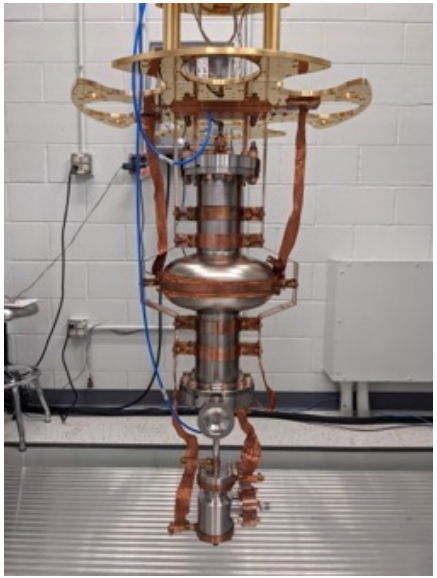
No dark photons (or axions) were found (yet).



Credit: O'Hare, https://cajohare.github.io/AxionLimits/docs/dp.html

- No discovery, but still progress because of the excluded parameter space.
- But a lot more parameter space left to explore…
- "Mowing the lawn."

SRF Cavities for Dark Matter Searches



Compared to state-of-the-art

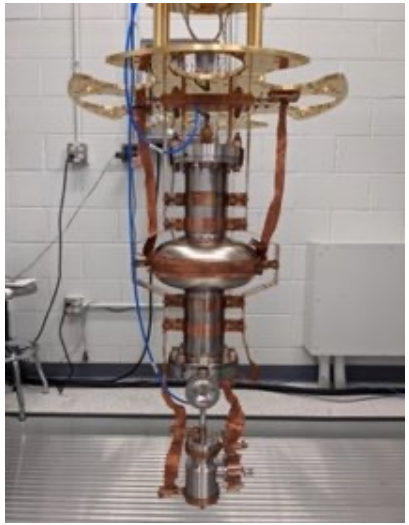
Credit: N. Du

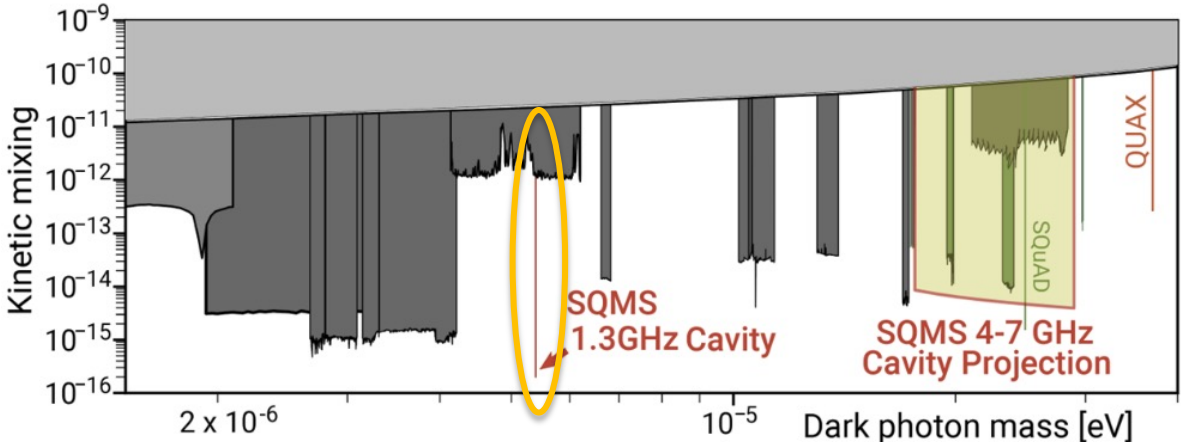
SQMS → $Q \approx 10^{10}$

ADMX → $Q \approx 8 \times 10^{4}$

High Q allows for larger signal and lower noise floor.
Possibly factor 10^5 increase in instantaneous scan rate.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





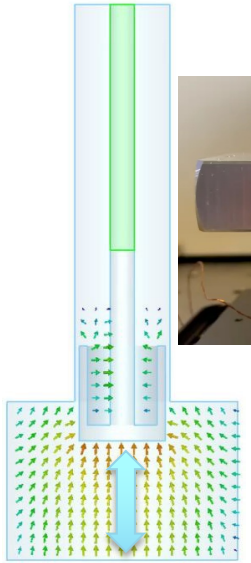
Cervantes et al., arXiv:2208.03183v3 (2022)

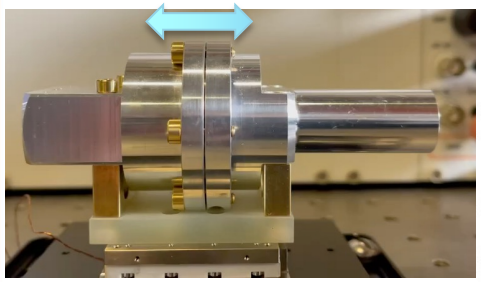
DPDM search with 1.3 GHz cavity with $Q_L \approx 10^{10}$.
Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

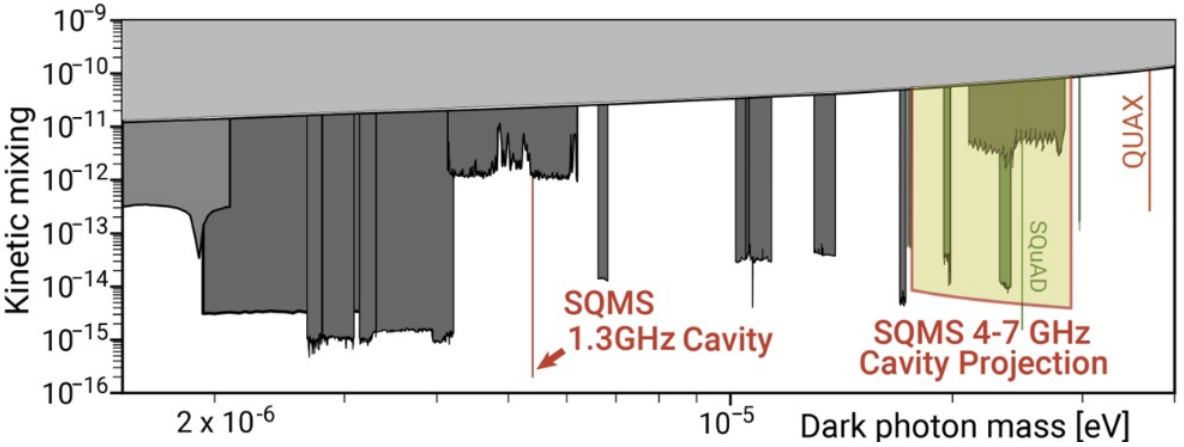
- Tunable DPDM search from 4-7 GHz (“low hanging fruit”)
- Implement photon counting to subvert SQL noise limit.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





"plunger" cavity
4-7 GHz



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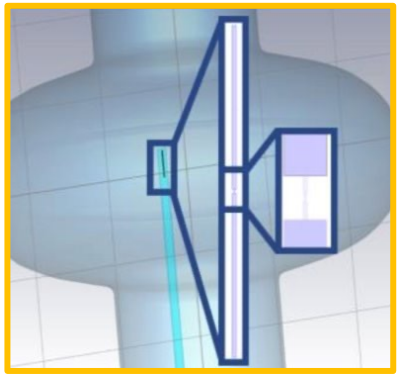
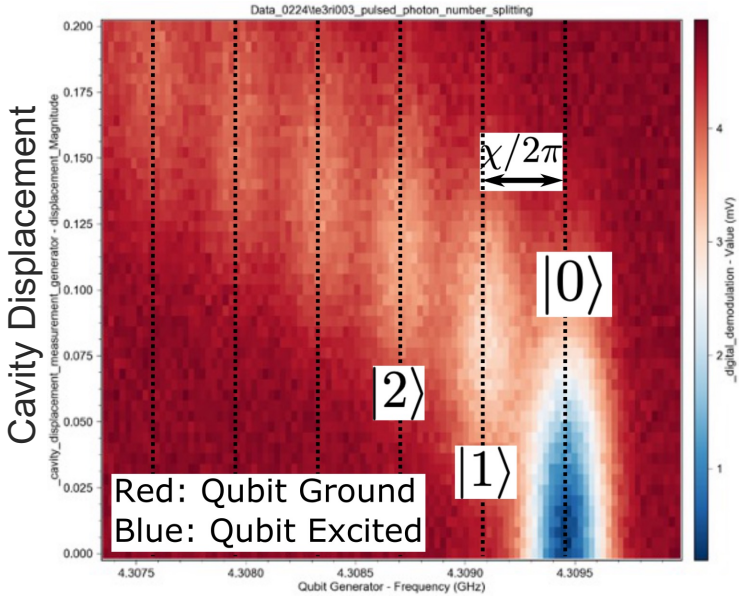
Subverting SQL noise with qubit-based photon counting



Superconducting qubit in SRF cavity.



Qubit Frequency Credit: T. Kim

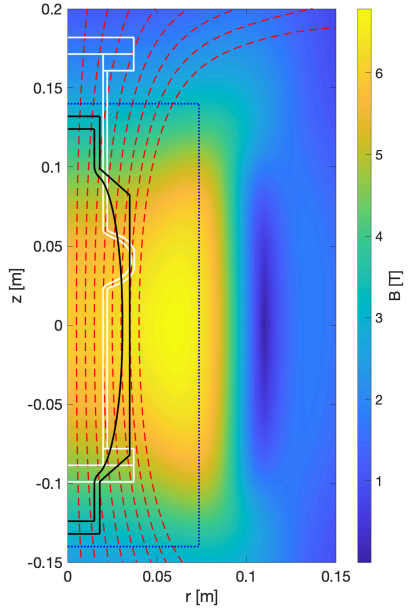
Quantum protocols counts photons non-destructively.

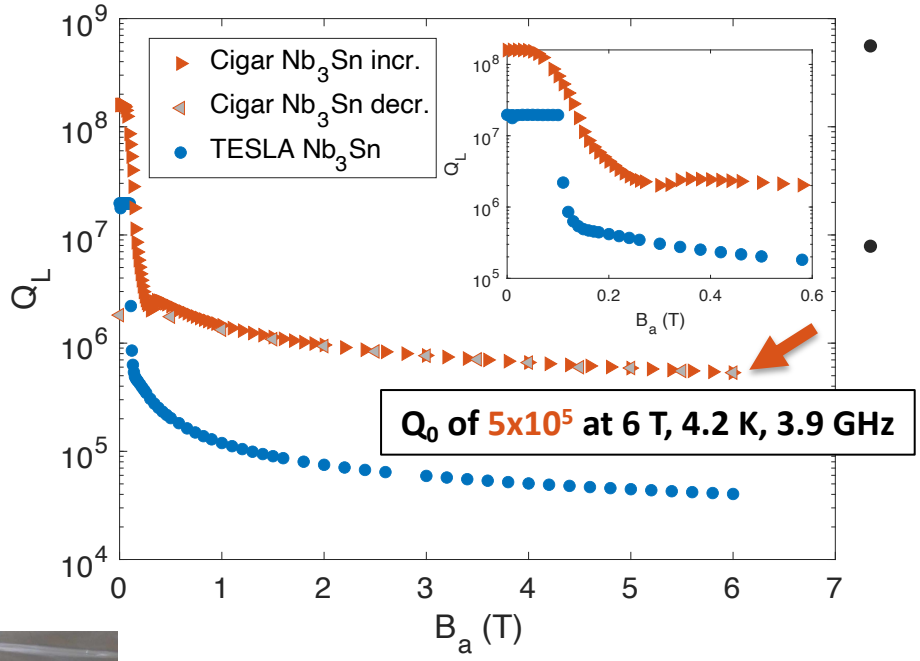
SQL noise: hf/k
240 mK @ 5 GHz

dominates
compared to 30 mK
thermal photons.

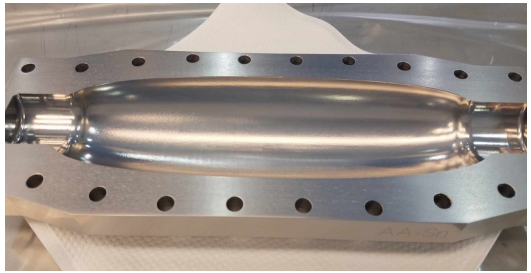
For computing, we regularly perform photon counting with dispersive measurements.

Progress towards high Q cavities for Axion Searches





- First measurements of high Q cavity in tesla scale magnetic fields
- Further optimizations with cavity treatment, magnetic field alignment, and geometry optimization. Implement tuning.

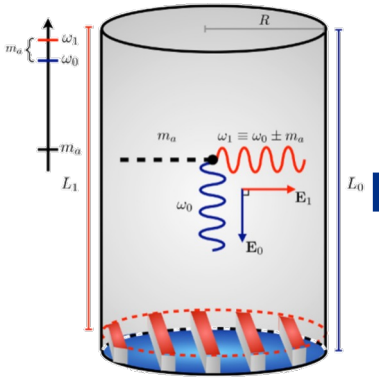


Posen et al., Phys. Rev. Applied 20, 034004 (2023)

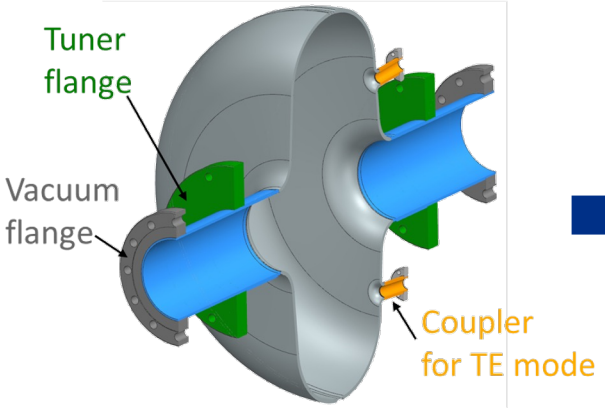
- Explore other SC materials like commercial HTS tapes

See work by: D. Ahn et al., Phys. Rev. Applied **17**, L061005 (2022)
And later reported Q_0 of 1.3×10^7 with HTS tapes, fixed frequency (PATRAS2023)

Heterodyne Axion DM search: toward first demonstration



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



Giaccone et al., arXiv:2207.11346 (2022)

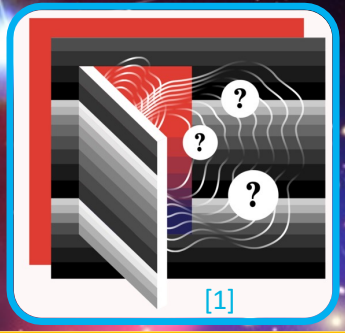
- One SRF cavity, no applied $\vec{B}$
- Pump mode: TM_{020}, Signal mode: TE_{011}
  - By design: $\Delta f \approx 1MHz \rightarrow$ we can search for small axion masses
- Design completed, fabrication was just completed by vendor
  - Stay tuned for first results!

Quantum Sensing: new windows into fundamental physics

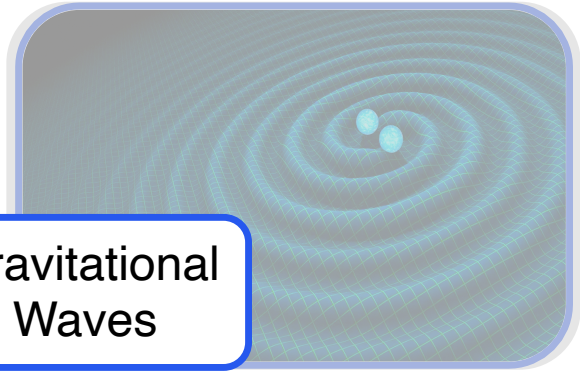
Dark Sector

Dark Matter

"Just" new particles



[1]



Gravitational Waves

Precision Measurements

Fermilab Dark SRF Experiment

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

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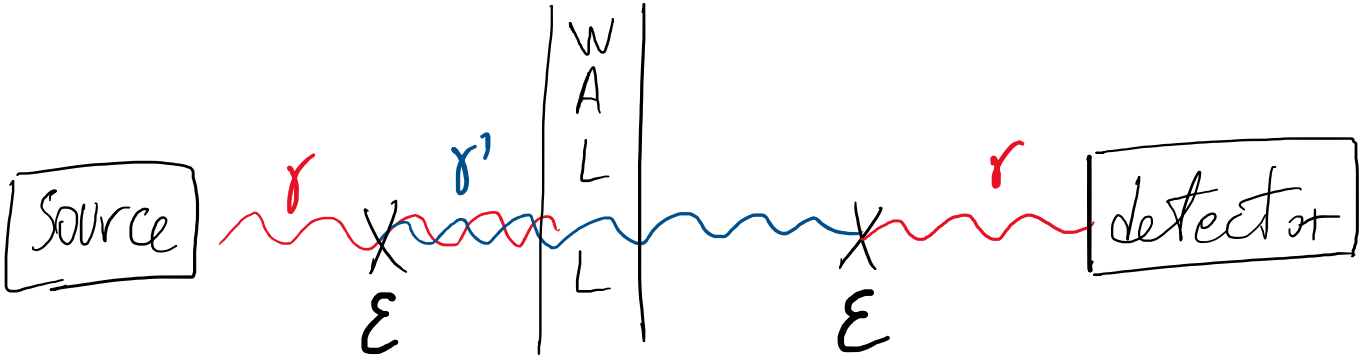
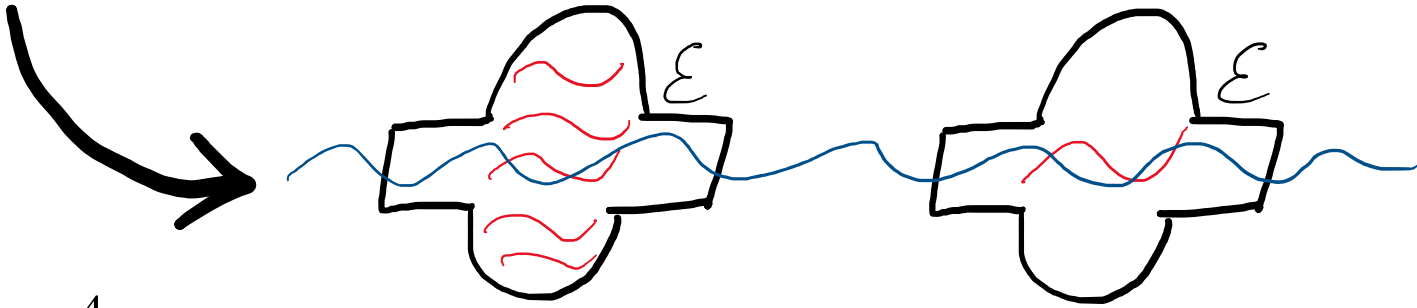
Dark SRF: Light-Shining-through-Wall search

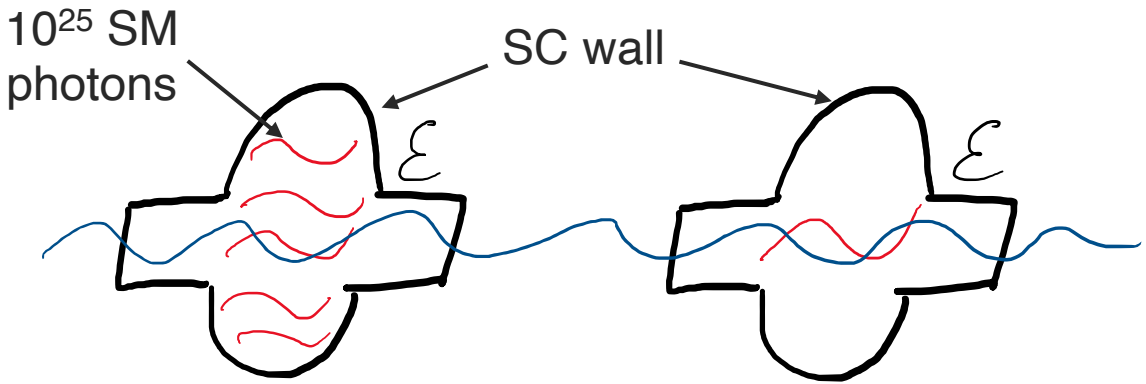




$$P_{rec} = \epsilon^4 \left(\frac{m_{\gamma'}}{\omega}\right)^4 |G|^2 \, \omega \, Q_{rec} \, U_{em}$$

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

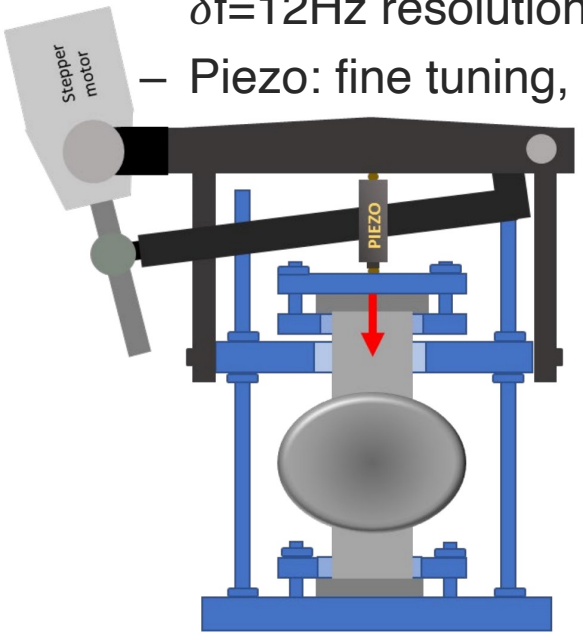
Receiver cavity, in the low field regime

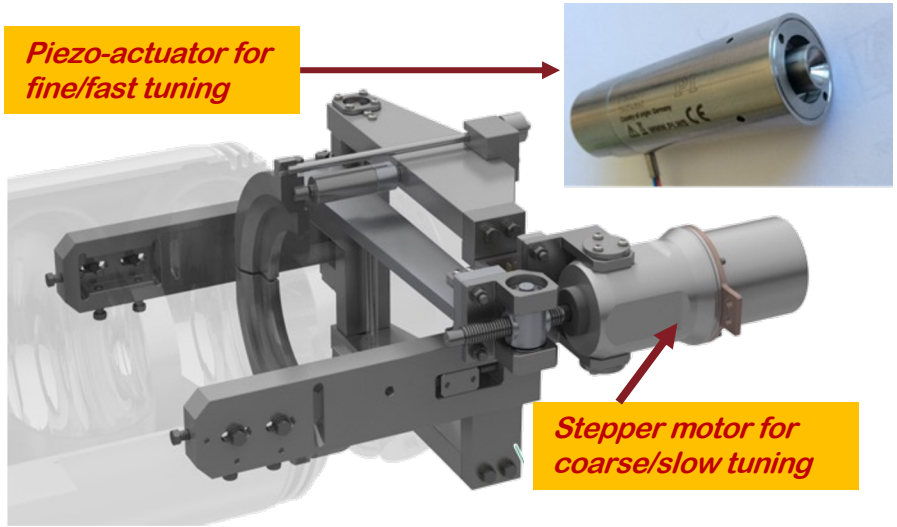
Necessary to match cavities frequency!

bility
ss

Cavity tuning

- LCLS II double lever tuner to tune “transmitter” cavity
- Tuner mounted on emitter cavity and preloaded
  - Stepper motor: coarse tuning with Δx=2mm or Δf=5MHz, and δx=5nm or δf=12Hz resolution
  - Piezo: fine tuning, Δx=3um or Δf=8KHz, and δx=0.05nm or δf=0.1Hz resolution



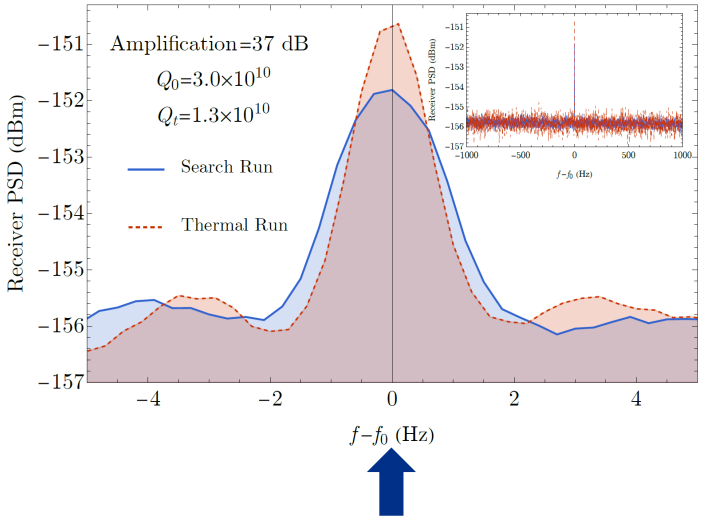


Pischalnikov et al., doi:10.18429/JACoW-SRF2019-TUP085

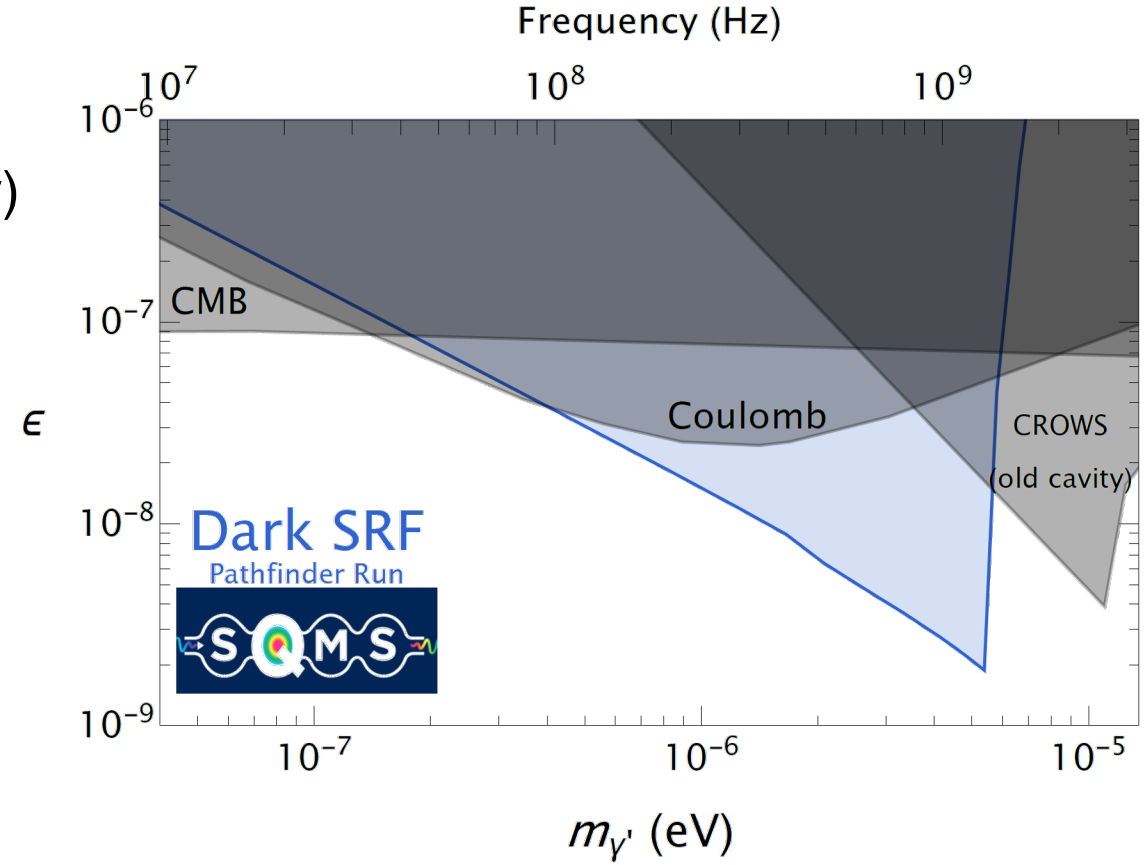
Dark SRF: phase 1 → results

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)

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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

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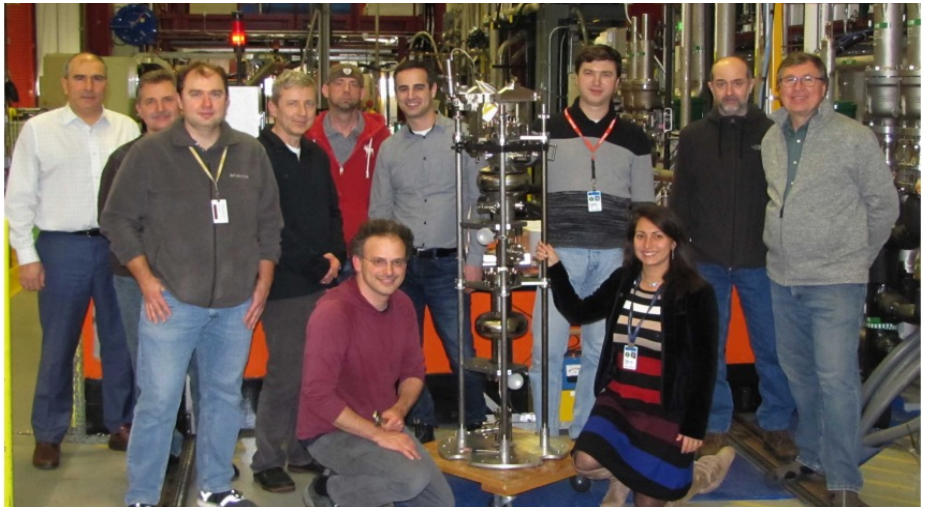

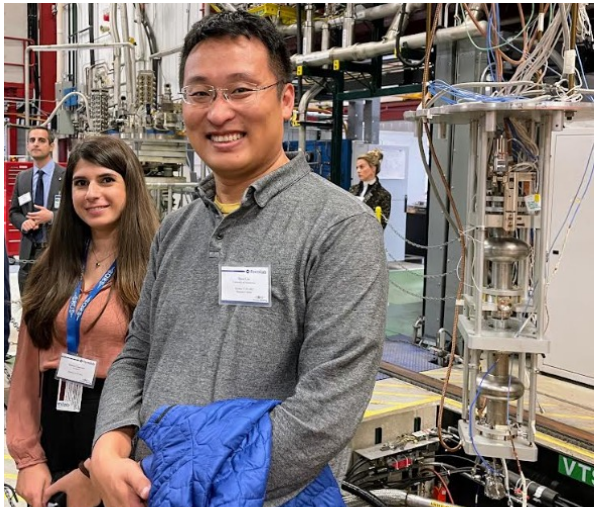

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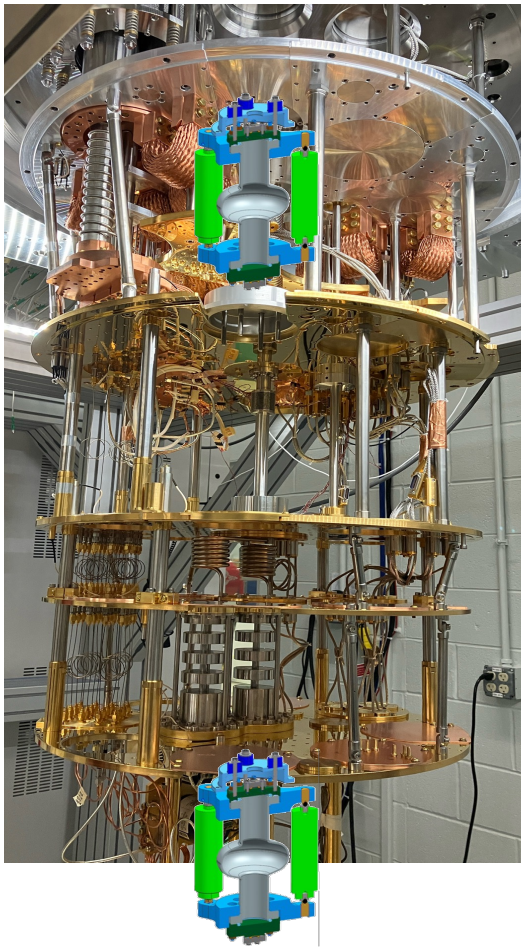
Dark SRF: phase 2 → 2.6GHz cavities in DR

- 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
  - ❑ Move entire setup to dilution refrigerator
- Possible modifications to the measurement protocol and analysis:
  - Dark photon search → optimal search duration: several minutes vs ~1h
  - Improved microphonics modeling



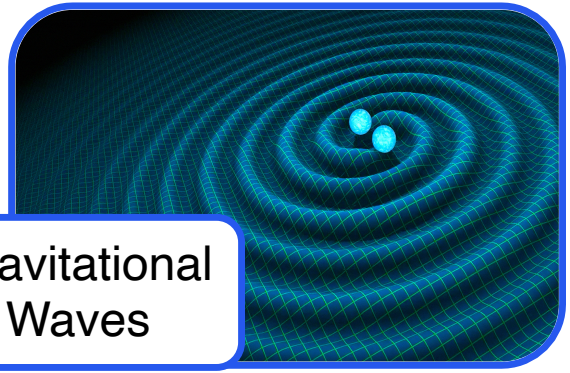
* Contreras-Martinez et al., doi:10.18429/JACoW-SRF2023-WEPWB109 & doi:10.18429/JACoW-SRF2023-WEPWB133

Quantum Sensing: new windows into fundamental physics

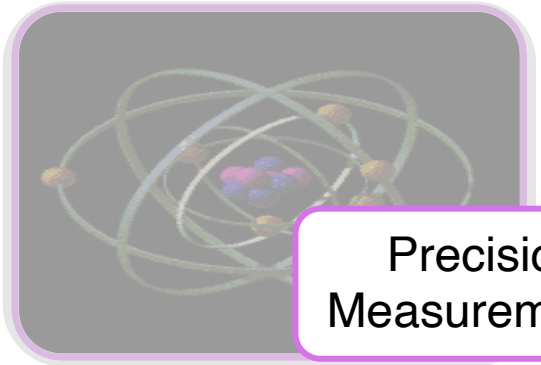
Dark Sector

Dark Matter

"Just" new particles



Gravitational Waves



Precision Measurements

Fermilab Dark SRF Experiment

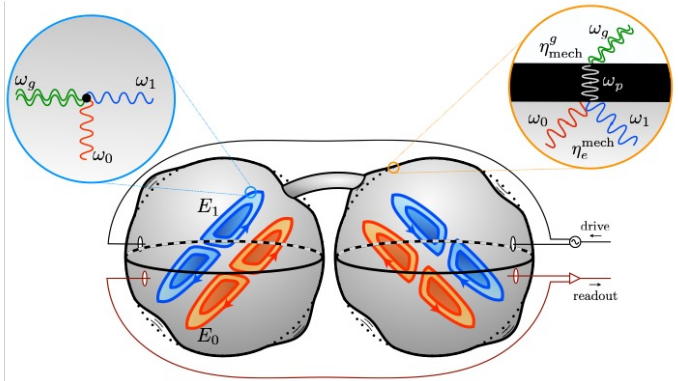
[1] Artwork by Sandbox Studio Chicago with A. Kova symmetrymagazine.org

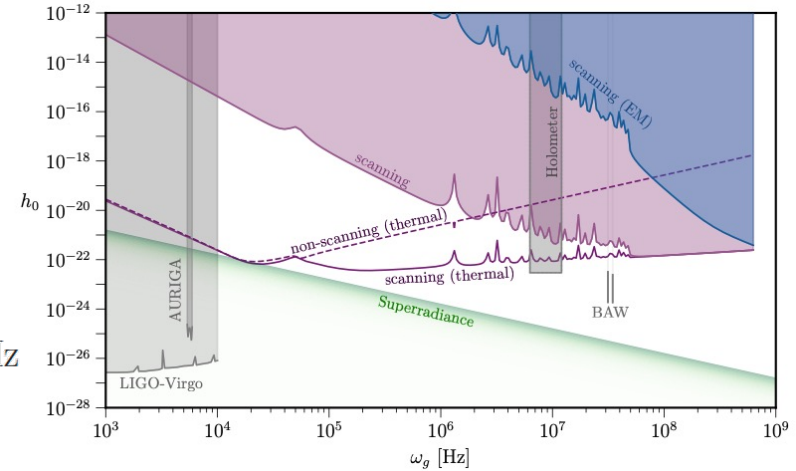
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

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

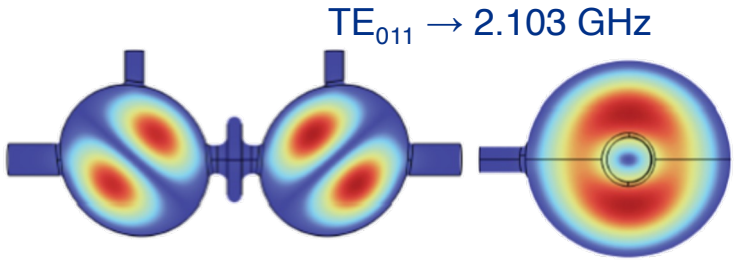
  Followed by (2001-2003)
  - 2-cell cavity with variable coupling and optimized geometry
    - Never treated nor tested – on shelf for >15y at INFN Genova

Now:

Collaboration between Fermilab, INFN, DESY, UHH to revive MAGO!

MAGO 1.0: DESY and UHH activities

- 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

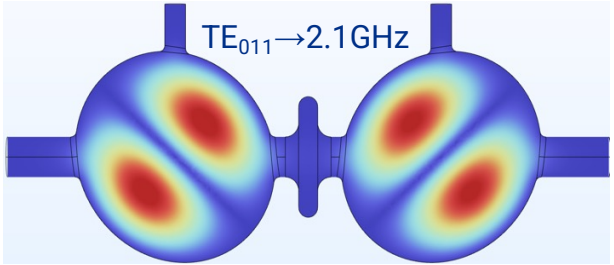


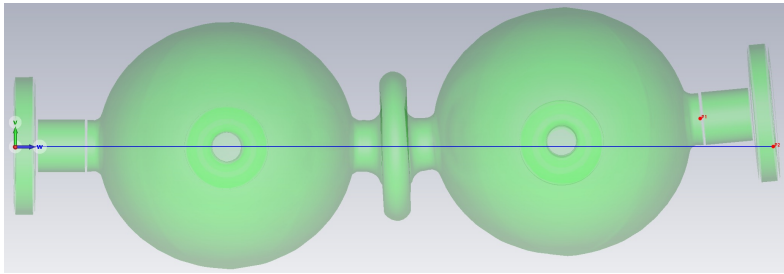
Adapted from Marc Wenskat presentation at “Quantum Technology for Fundamental Physics” workshop

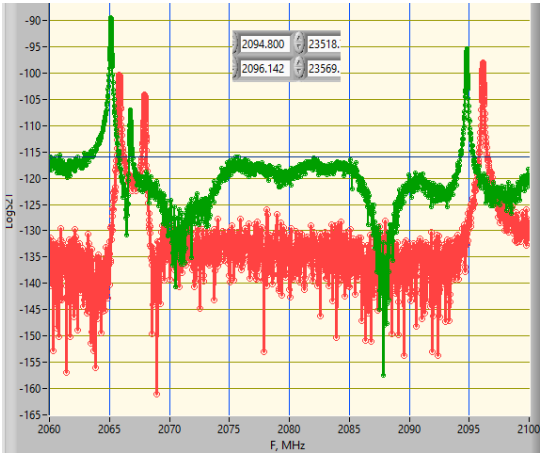
Acknowledgements: V. Chouhan, C. Contreras, I. Gonin, T. Khabiboulline, Y. Orlov, O. Pronitchev, Y. Yakovlev

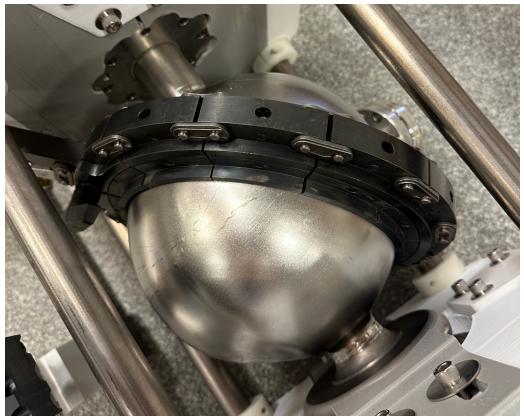
MAGO 1.0: Fermilab activities

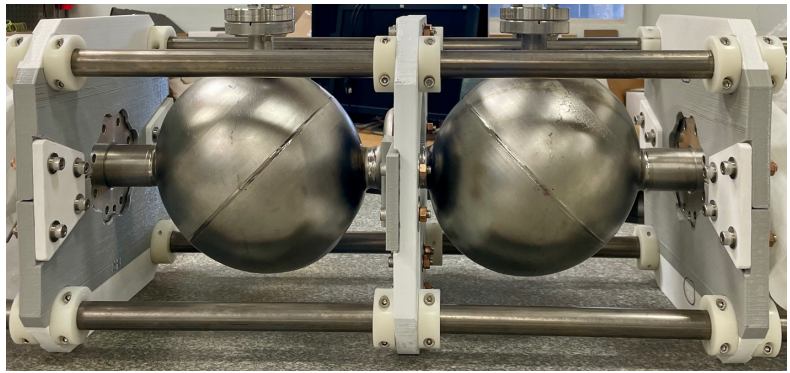
- Extensive work necessary before RF cold test:
  - RF and mechanical simulations on ideal and real geometry
  - 3D printed frame to sustain cavity during initial room temperature operations
  - Optical inspection
  - Surface treatment
  - Plastic straightening
  - Room temperature tuning of cells
 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







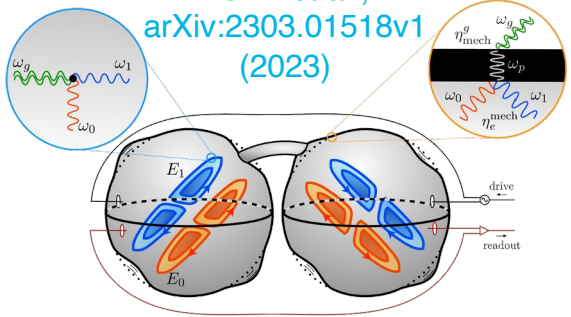




SRF cavities for GW: looking forward

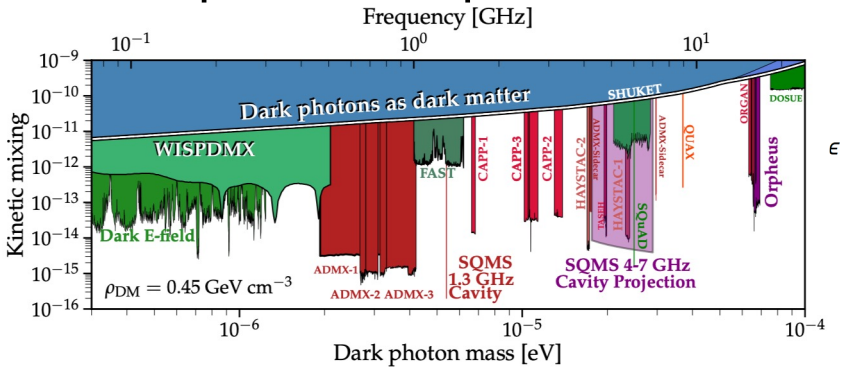
- Through **simulations** and **experimental work** on **MAGO 1.0:** working to gain better understanding of sensitivity to GW strain on multiple factors (GW frequency detuning from mechanical resonance, cavity shape imperfections, microphonics, …)
- **US/Japan collaboration** → small effort between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

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

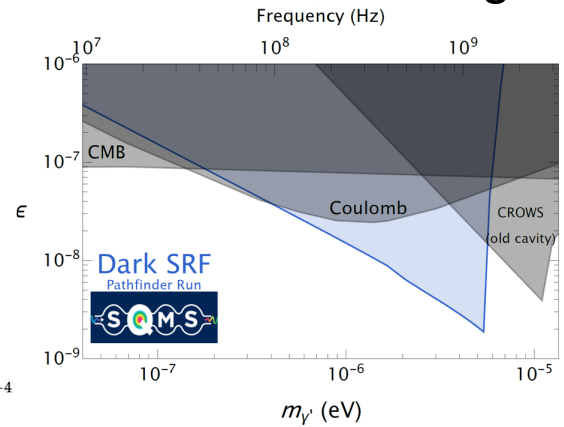


Physics and sensing conclusions

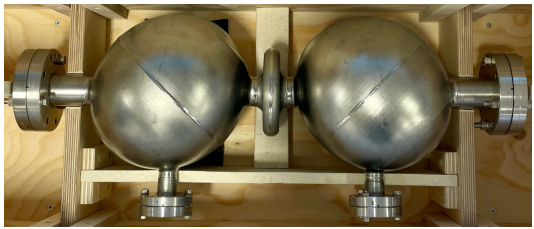
- **Dark SRF**: Realized 1st proof of concept SC cavity-based LSW experiment
  → **extended dark photon exclusion limit in broad range of $m_{\gamma'}$ and ε**
  - **Dark SRF 2.6GHz in DR:** working to prepare experiment to be deployed in DR
- **MAGO**: collaborating with DESY and INFN on existing variable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



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



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



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

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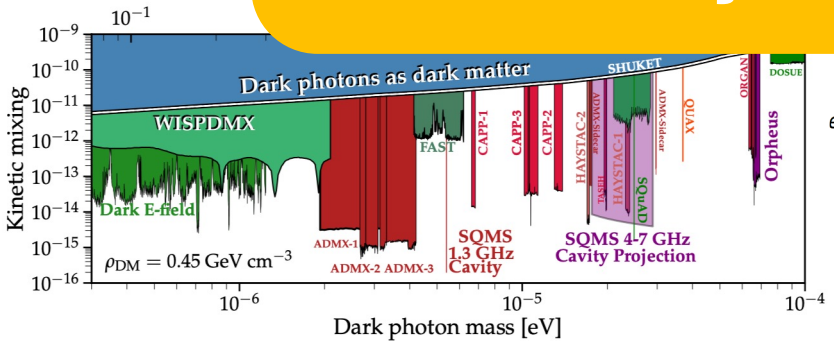
  – **Dark S** ed in DR
- **MAGO** upling
  cavity a tector
- **Axion** ginning
  of expe

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



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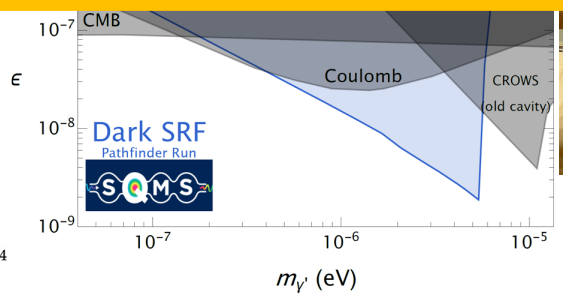
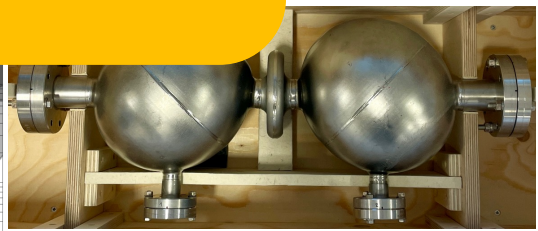


Romanenko et al., Phys. Rev. Lett. 130, 261801 (2023)



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

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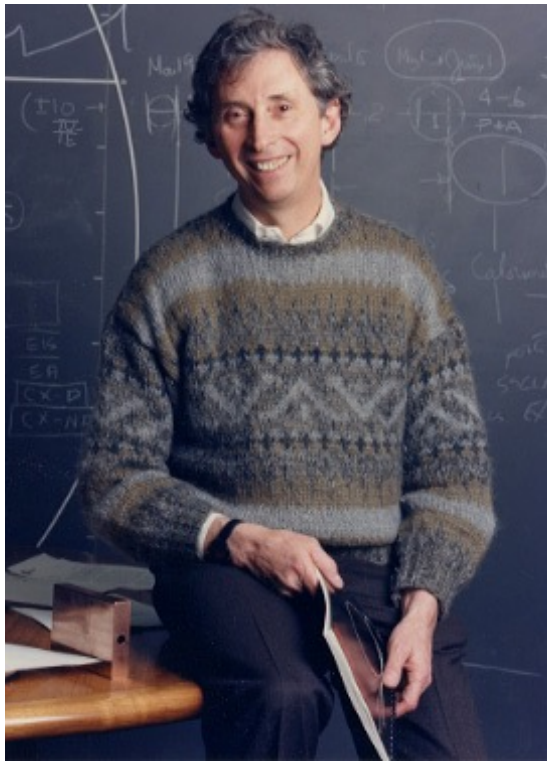
2024 Peoples Fellowship at Fermilab



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(or feel free to contact me at giaccone@fnal.gov if you want to know more)