FERMILAB-SLIDES-23-126-SQMS

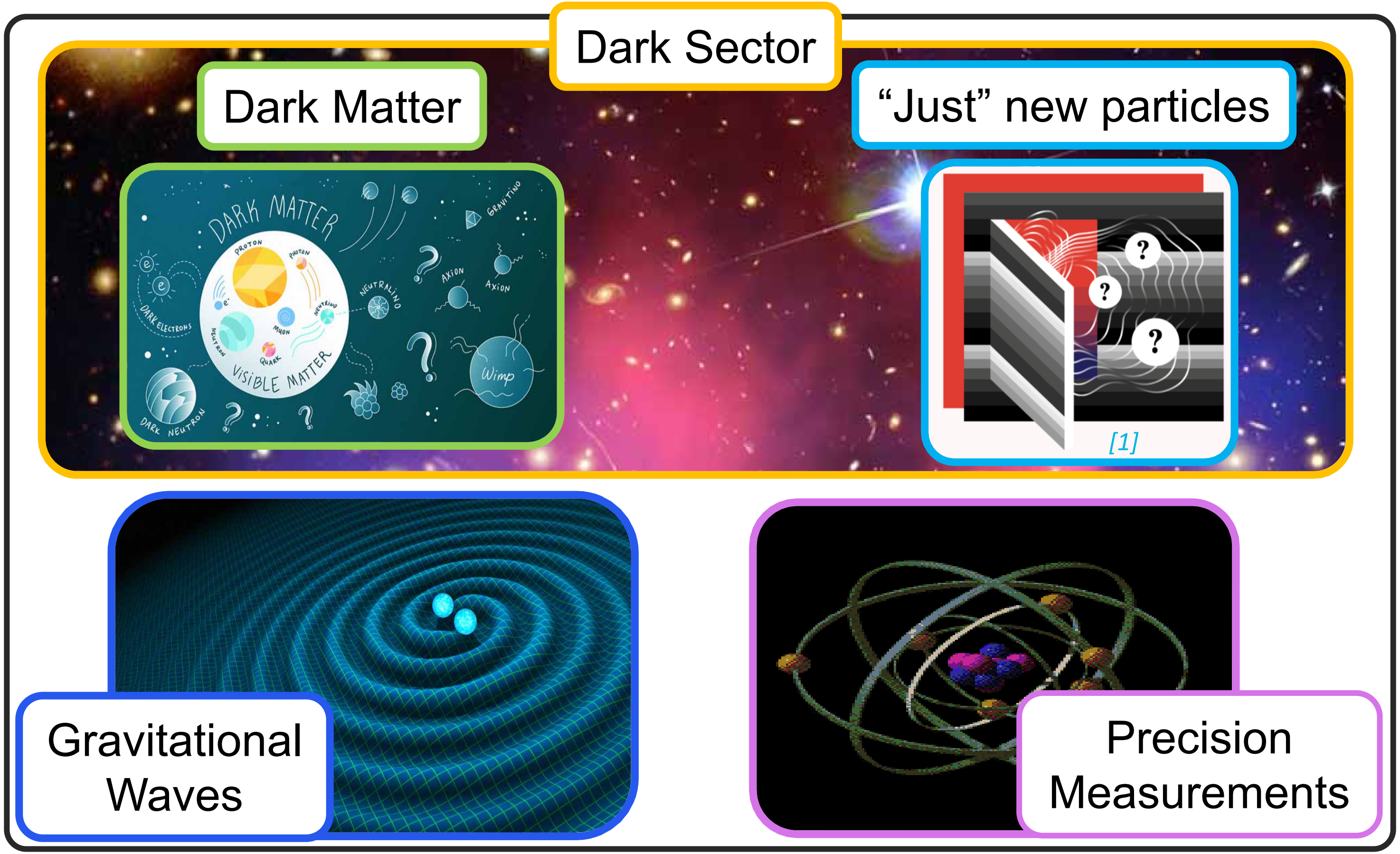
This material is based upon work supported by the U.S. Department of Energy, Office of Science, National Quantum Information Science Research Centers, Superconducting Quantum Materials and Systems Center (SQMS) under contract number DE-AC02-07CH11359

Dark Matter and Gravitational Waves Experiments with SRF Cavities

Bianca Giaccone (Superconducting Quantum Materials & Systems Center, Fermilab)

THIXA06, SRF2023, 06/29/23

Quantum Sensing: new windows into fundamental physics



Fermilab Dark SRF Experiment

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

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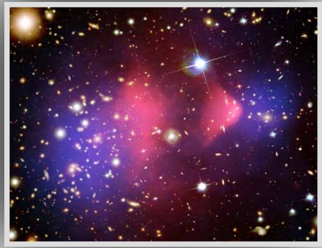
Quantum Sensing for Fundamental Physics

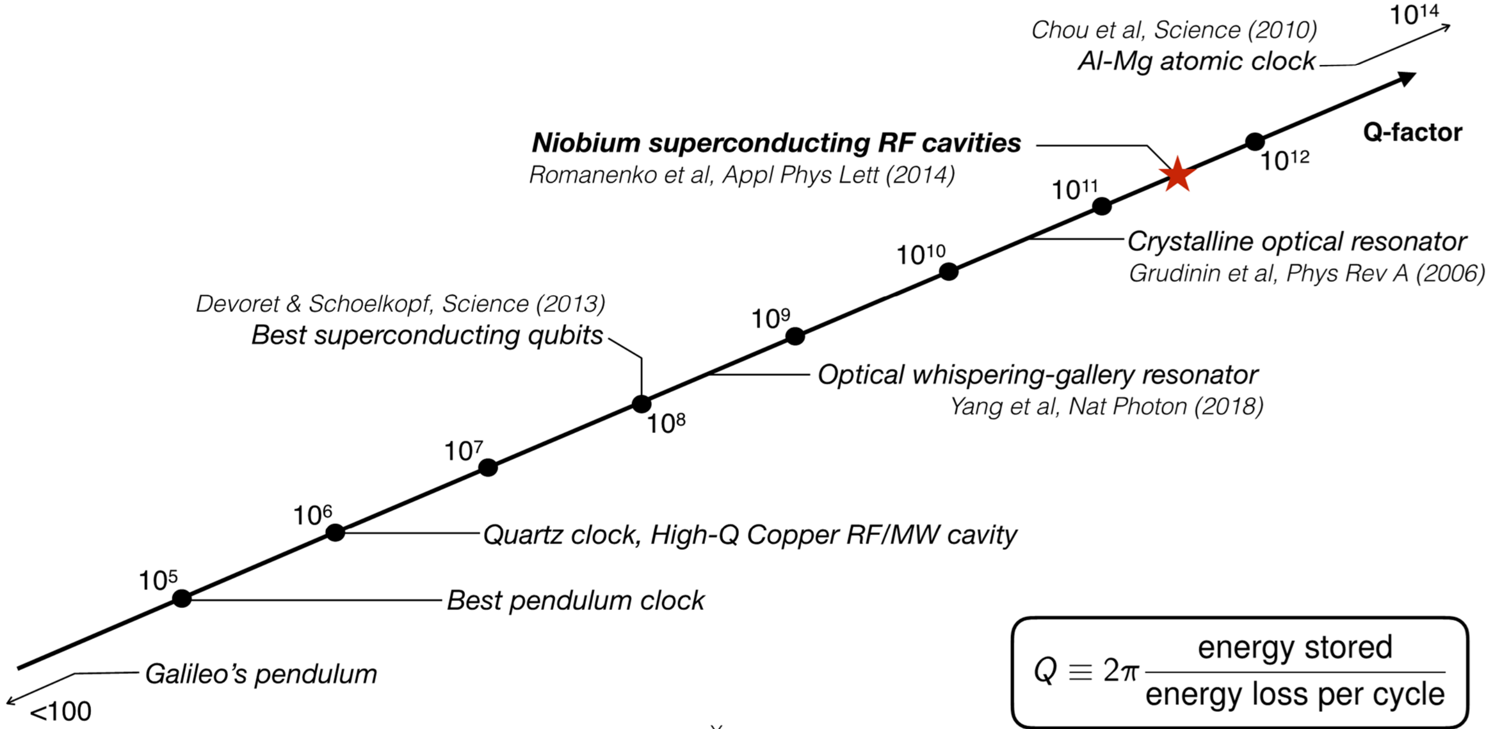
- Quantum sensing: the use of quantum properties of light or matter to enhance sensitivity of measurements.
- Sensing effort is driven by applying our SRF cavities and quantum devices towards physics goals:



  - **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.

Why SRF cavities for quantum sensing?

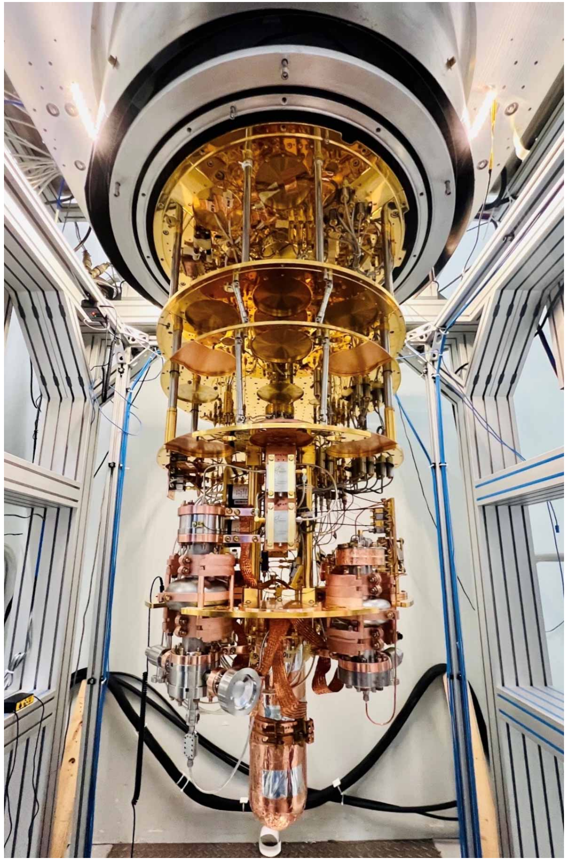
SRF cavities are the most efficient engineered oscillators



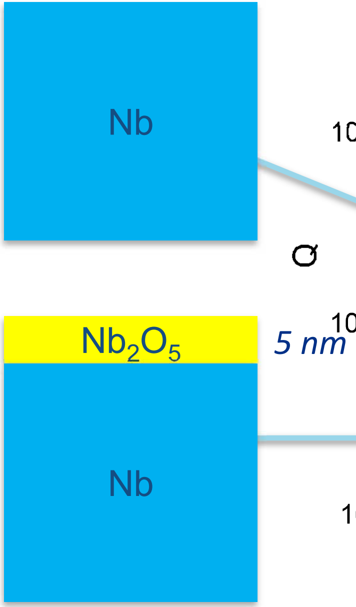
$$Q \equiv 2\pi \frac{\text{energy stored}}{\text{energy loss per cycle}}$$

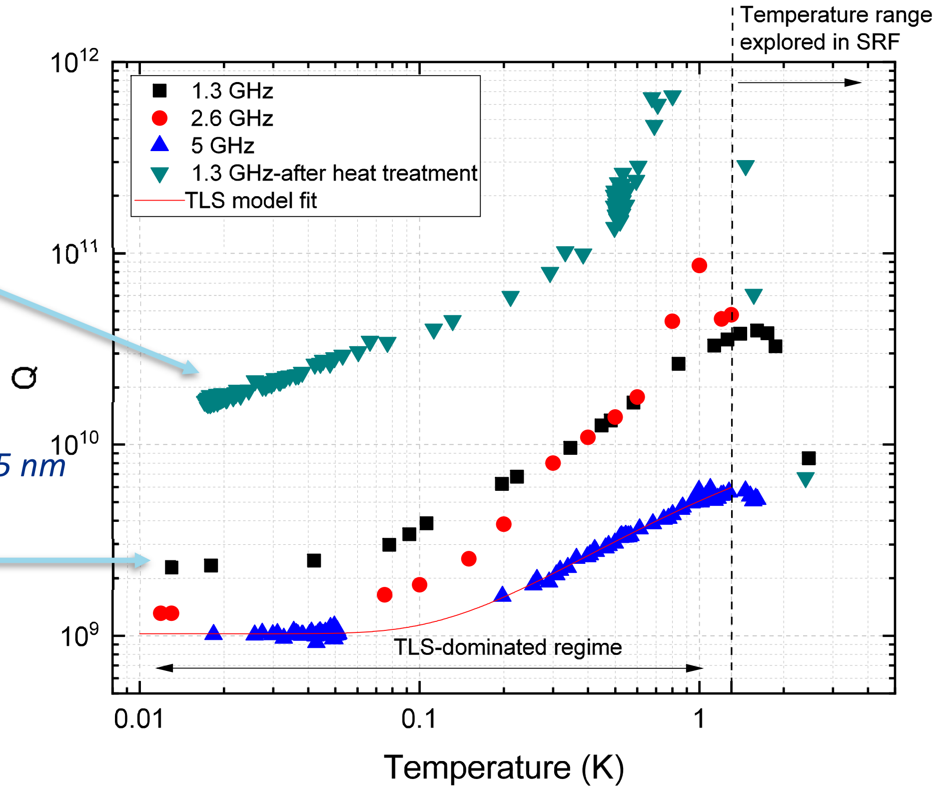
X

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



Dilution Refrigerator (DR)





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

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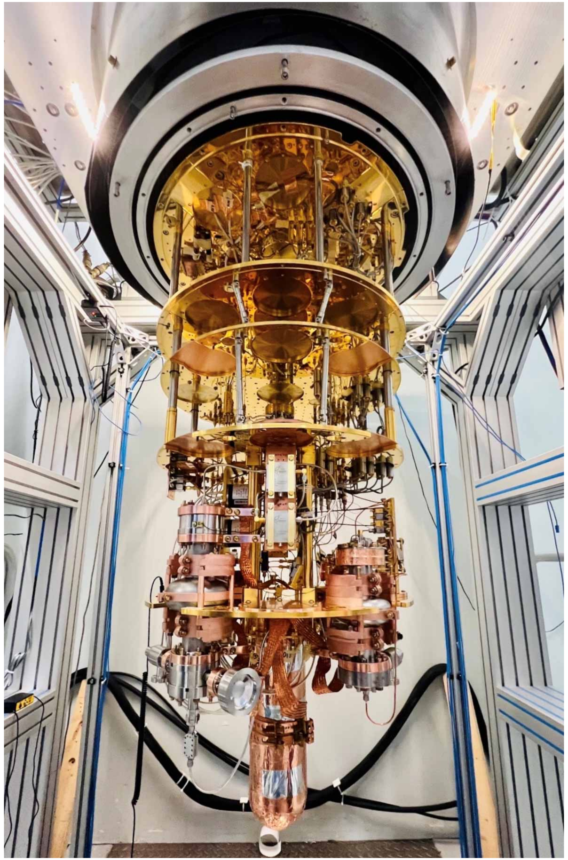
SRF cavities in new regimes: low field research



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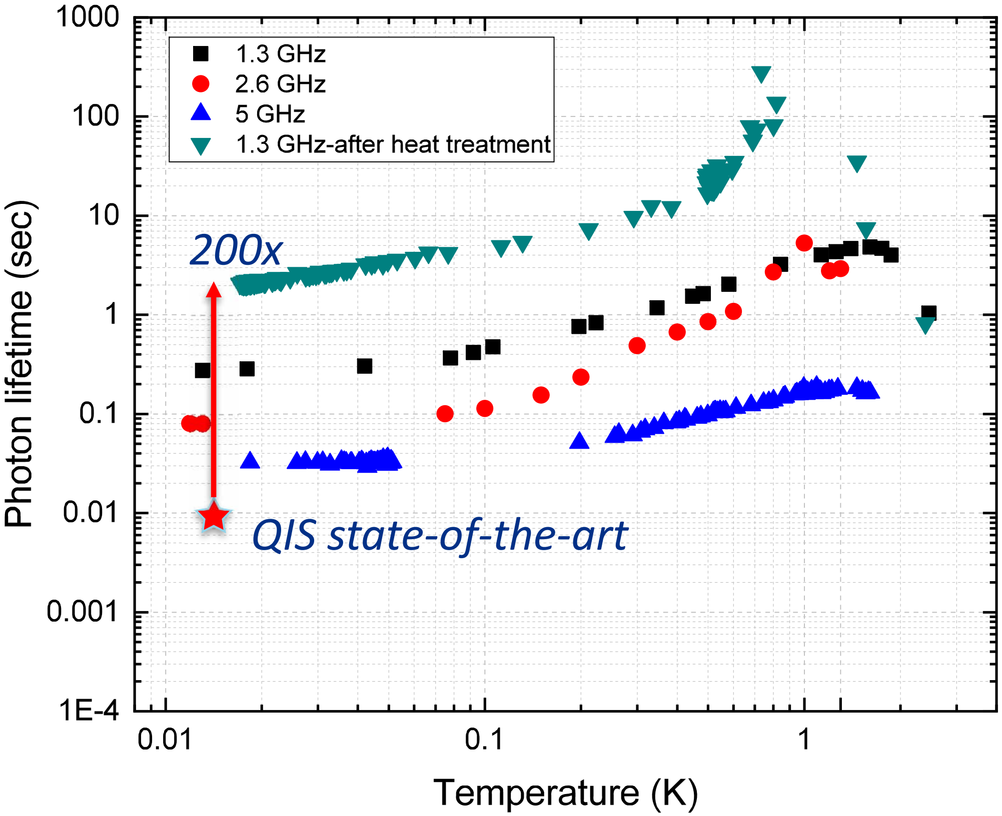
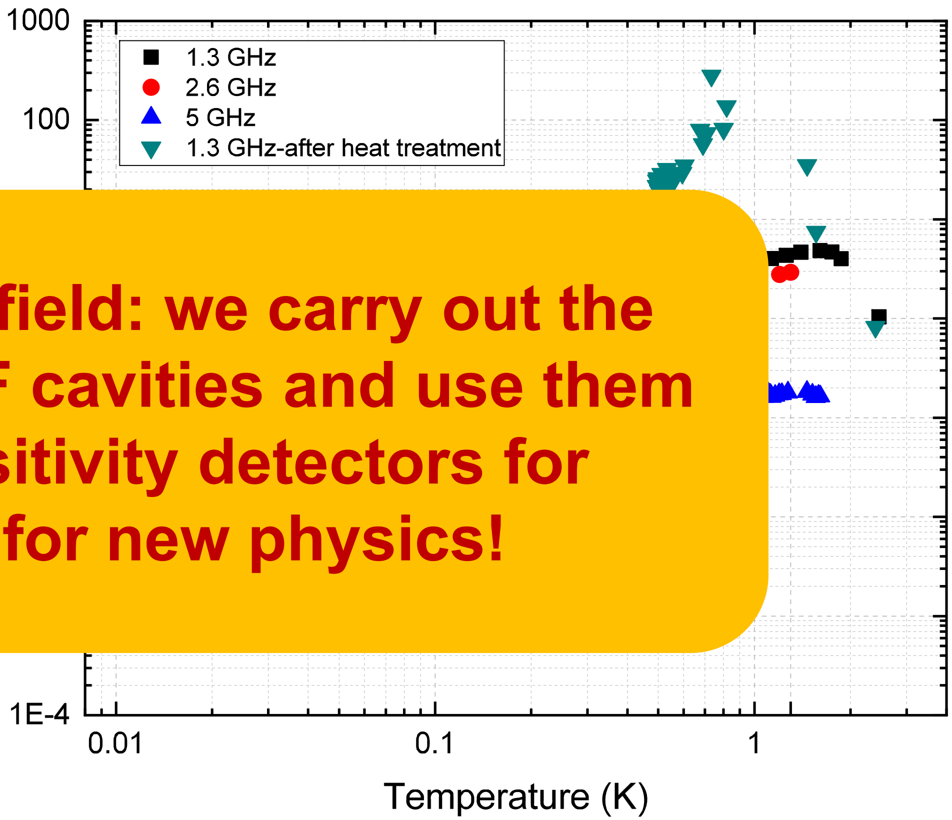


Romanenko et al., Phys. Rev. Applied 13, 034032 (2020)

SRF cavities in new regimes: low field research

Dilution Refrigerator (DR)



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

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!

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The People

Fermilab

Northwestern University

University of Minnesota
Driven to Discover®

The University of Arizona

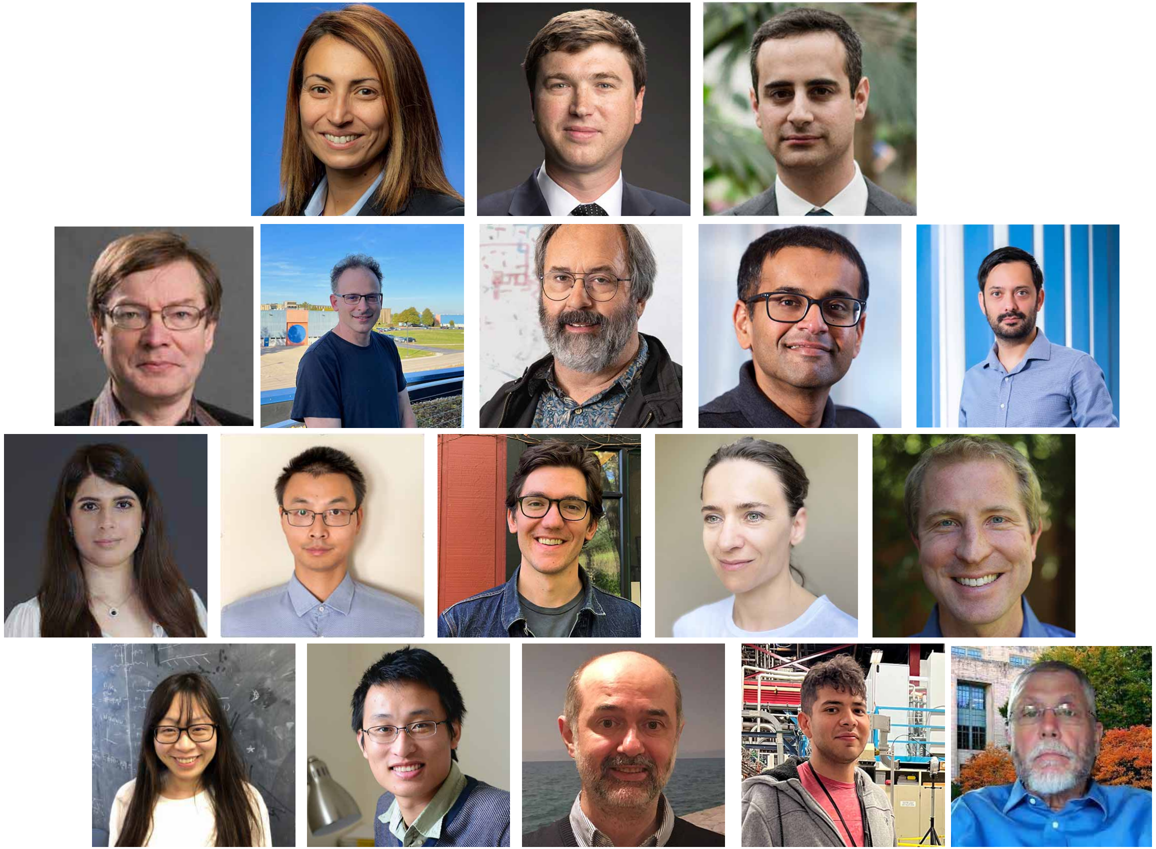
LSU

Johns Hopkins University

University of Illinois Urbana-Champaign

INFN

Stanford



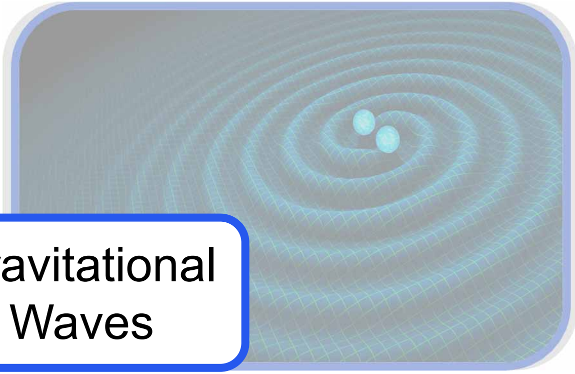
Theorists and experimentalists working closely. Experts in HEP, materials, SRF, sensing, QIS, RF engineering.

Quantum Sensing: new windows into fundamental physics

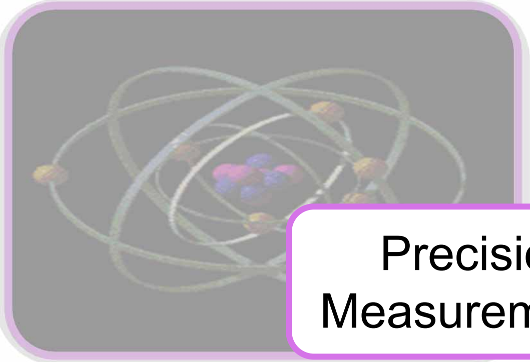
Dark Sector

Dark Matter

“Just” new particles



Gravitational Waves



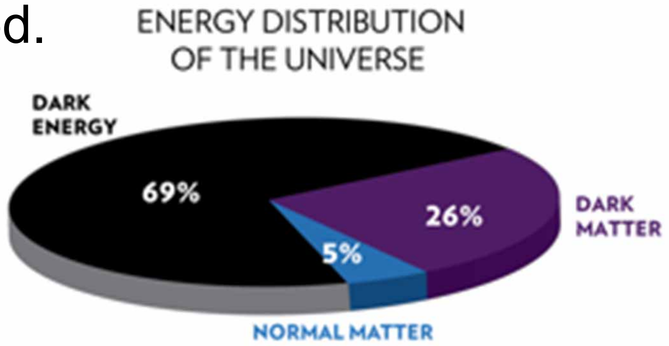
Precision Measurements

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:

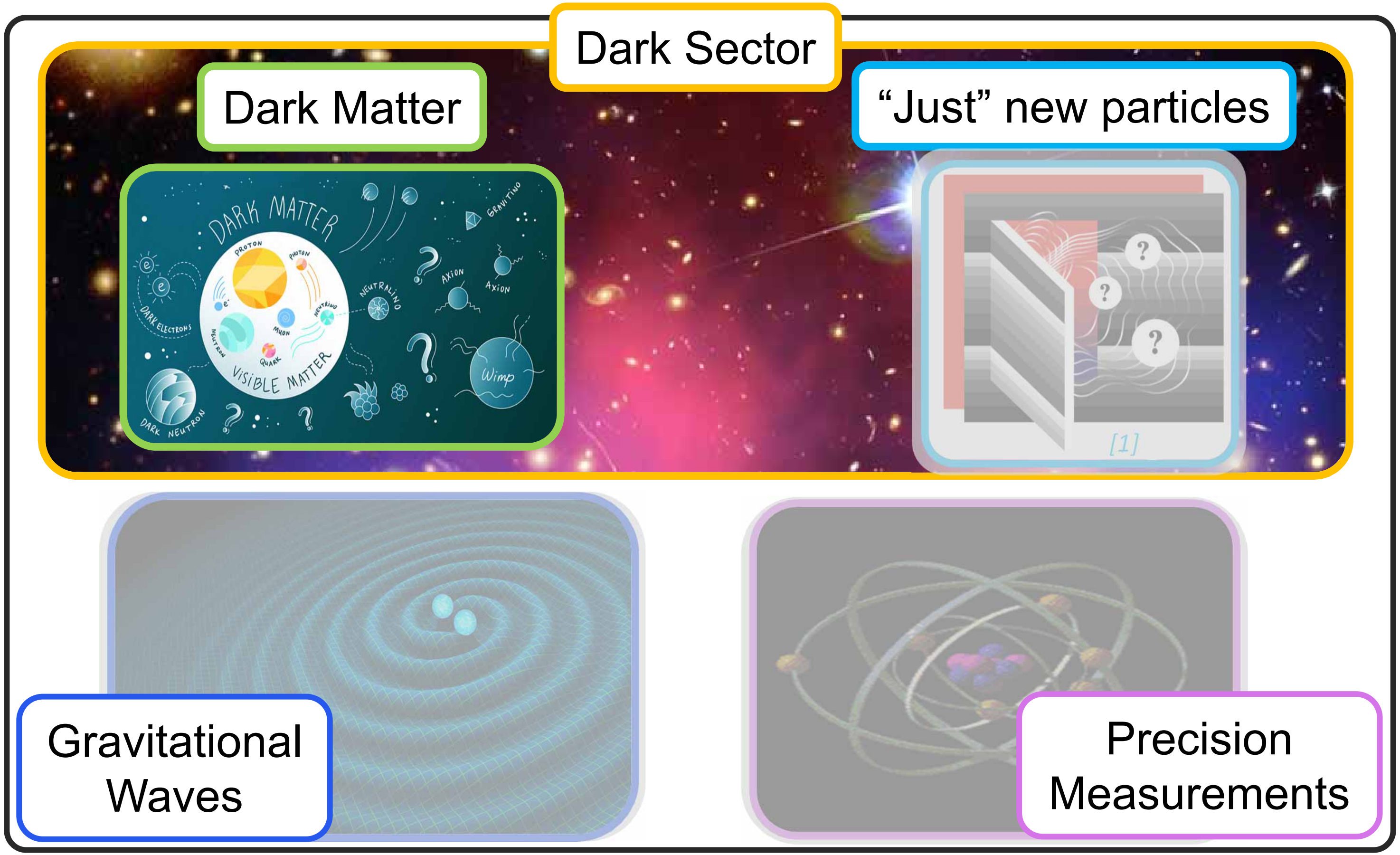
Dark matter (and new particle):

 $\supset$ dark photons? axions?

New particle:

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

Quantum Sensing: new windows into fundamental physics



Fermilab Dark SRF Experiment

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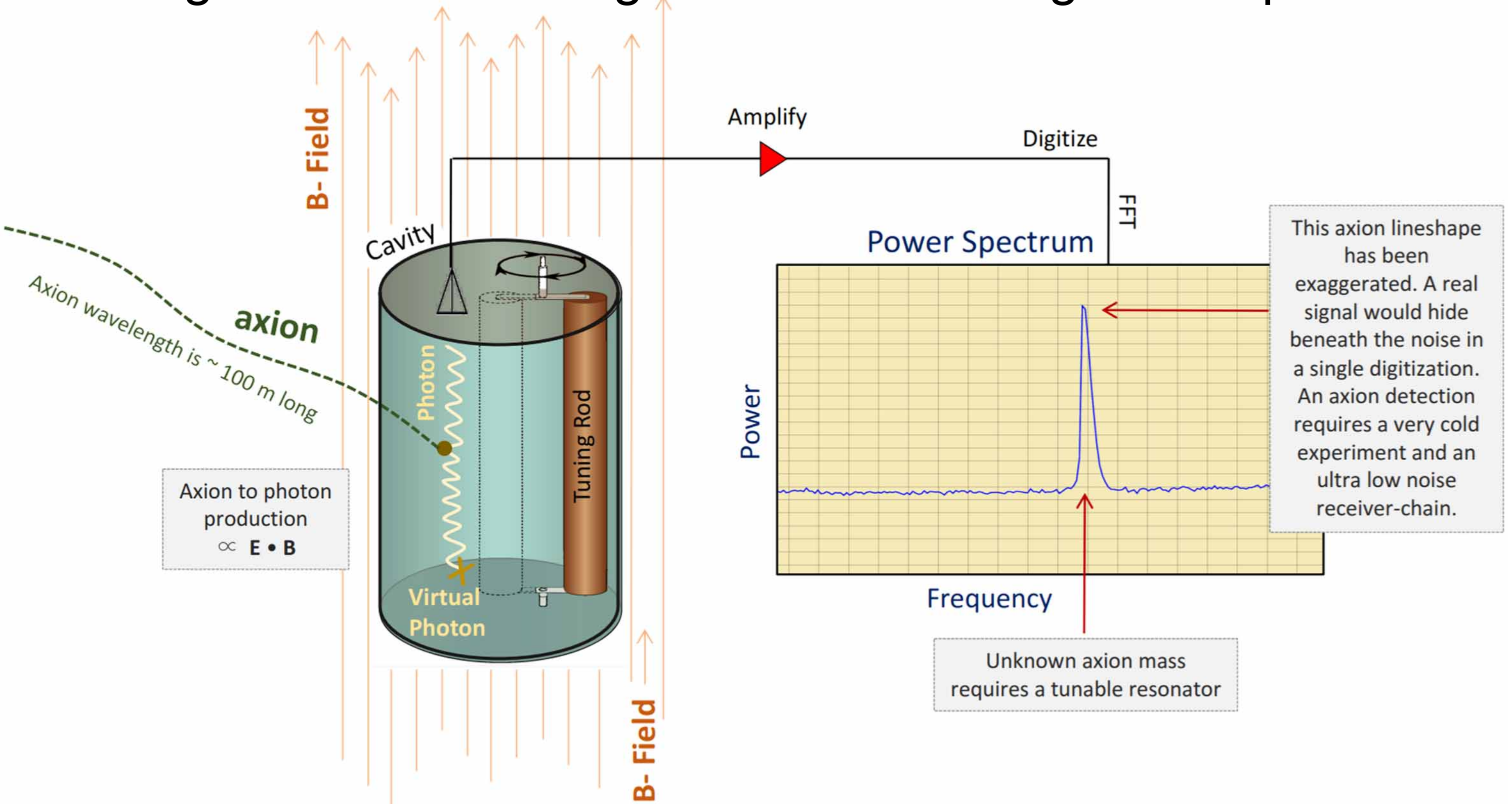
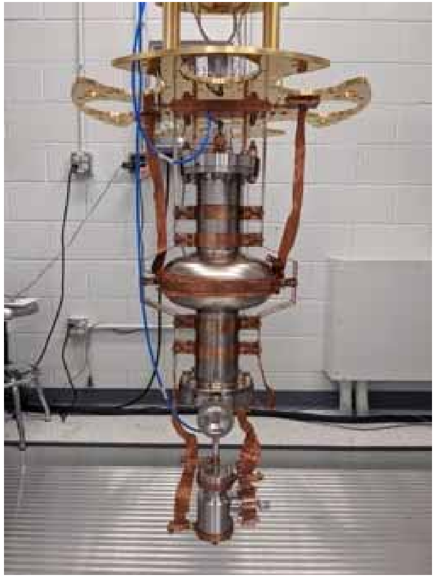
Haloscope Searches for Dark Matter

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



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

SRF Cavities for Dark Matter Searches



SQMS $\rightarrow Q \approx 10^{10}$

Compared to state-of-the-art

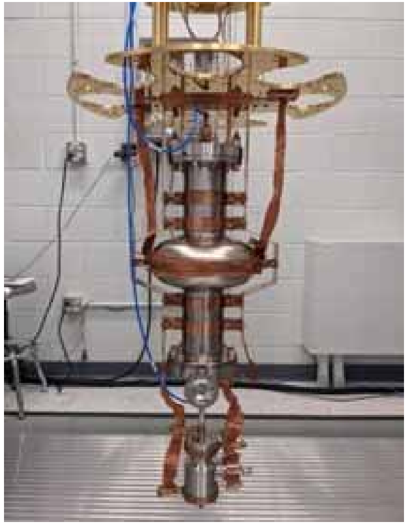
Credit: N. Du

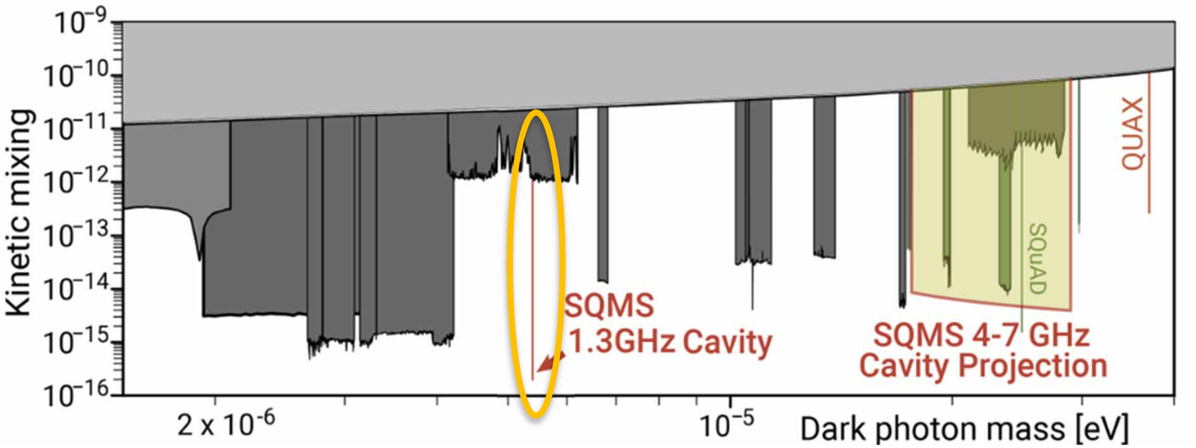
ADMX $\longrightarrow Q \approx 8 \times 10^{4}$

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)

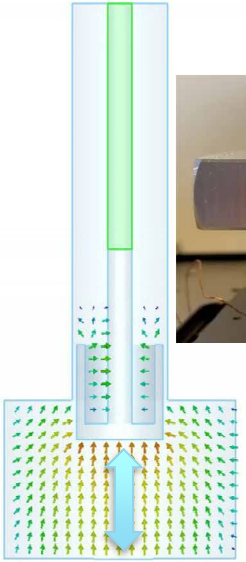
DPDM search with 1.3 GHz cavity with $Q_L \approx 10^{10}$.

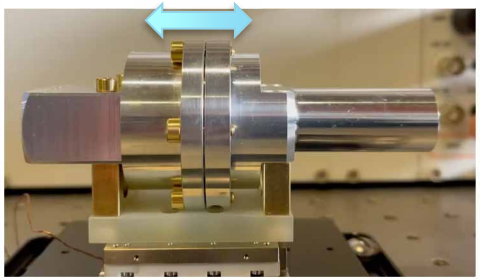
Deepest exclusion to wavelike DPDM by an order of magnitude.

Next steps:

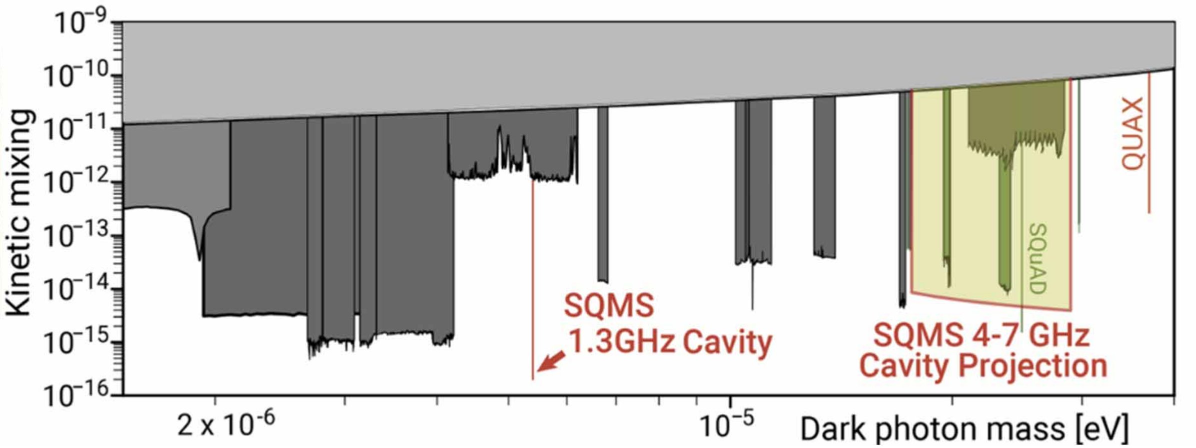
- Tunable DPDM search from 4-7 GHz ("low hanging fruit")
- Implement photon counting to subvert SQL noise limit.

Deepest sensitivity: Ultrahigh Q for Dark photon DM





"plunger" cavity
4-7 GHz



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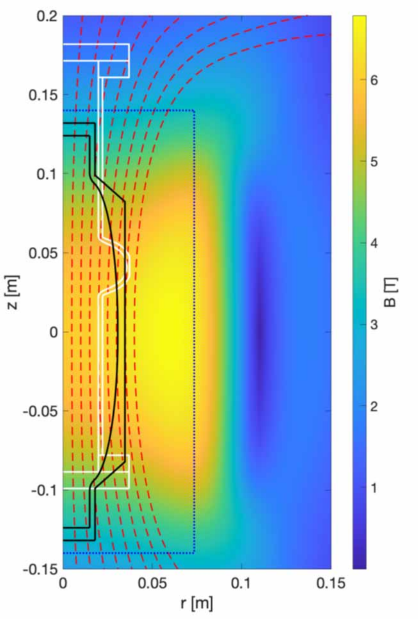
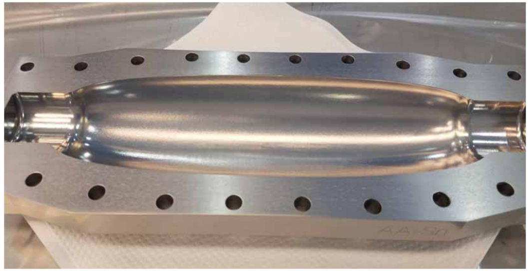
Progress towards high Q cavities for Axion Searches





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

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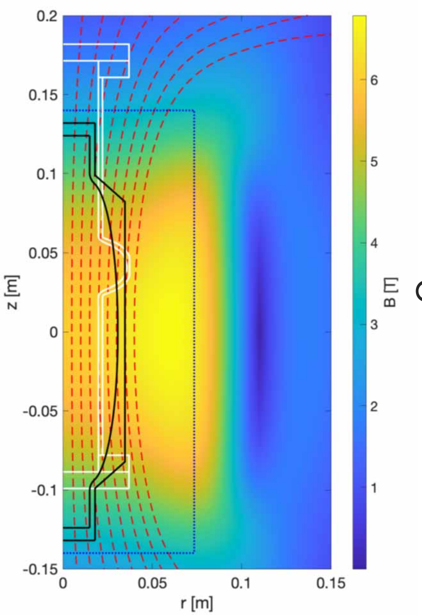
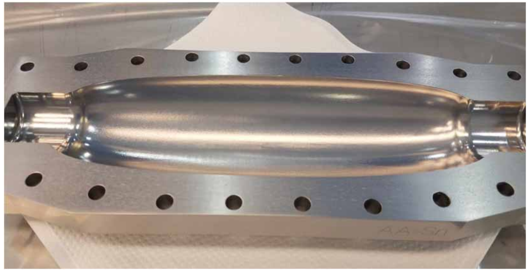
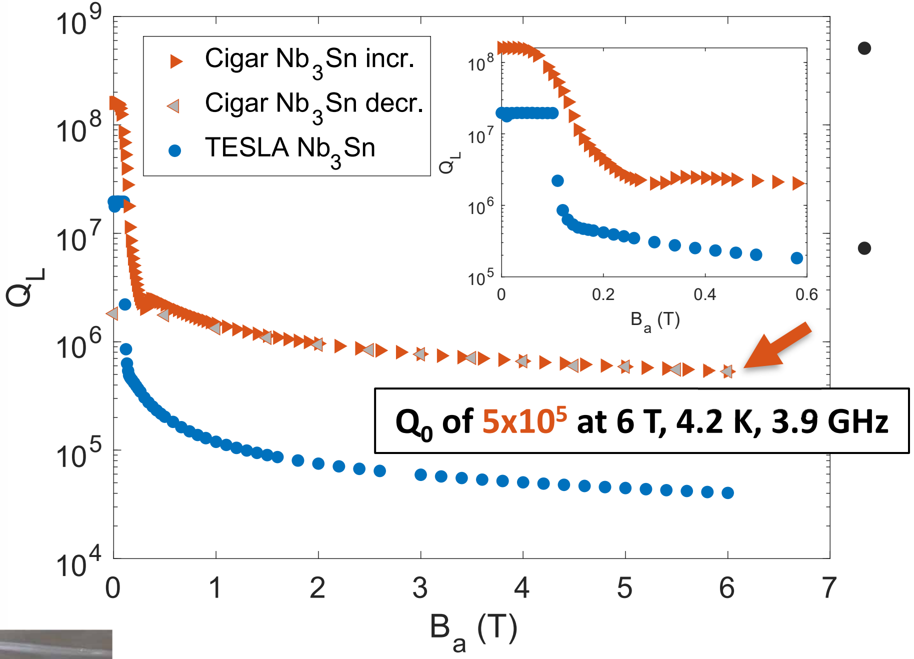
Progress towards high Q cavities for Axion Searches







Posen et al., arXiv:2201.10733v2 (2022)

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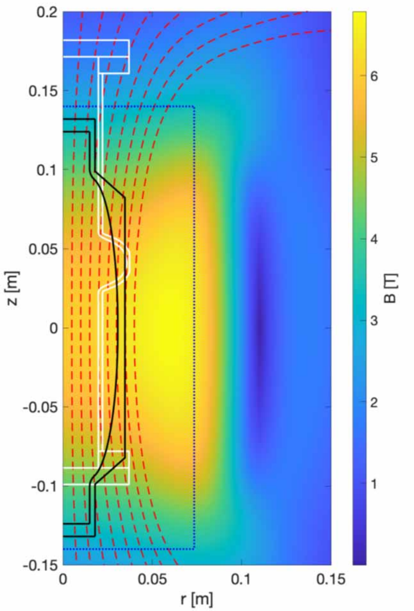

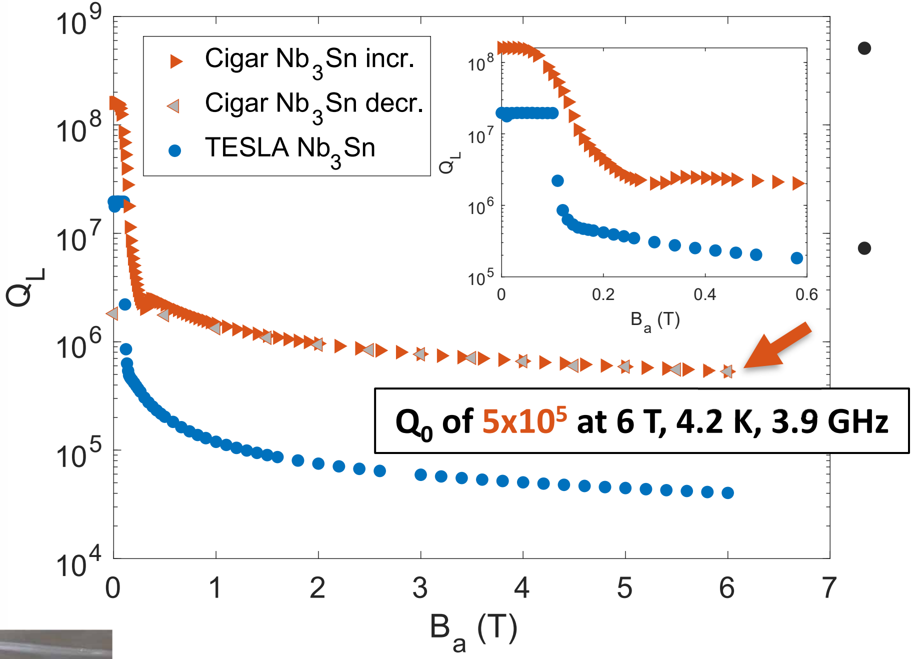

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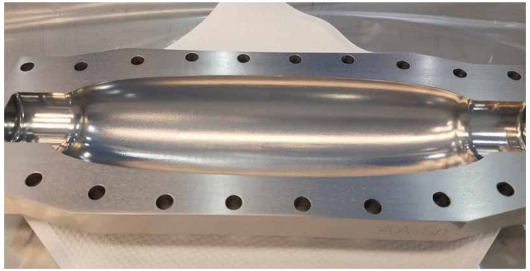
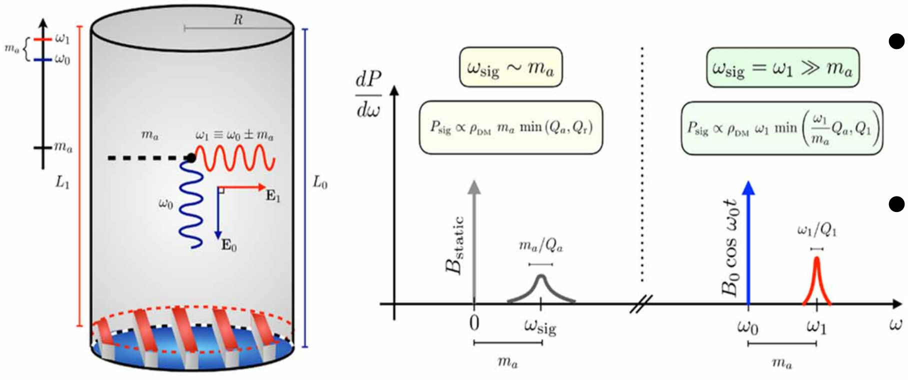


- Explore other SC materials like commercial HTS tapes *See work by: D. Ahn et al., arXiv:2002.08769v4 (2020), and reported Q_0 of 1e7 with HTS tapes, fixed frequency @ PATRAS2022, not published yet*

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!

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

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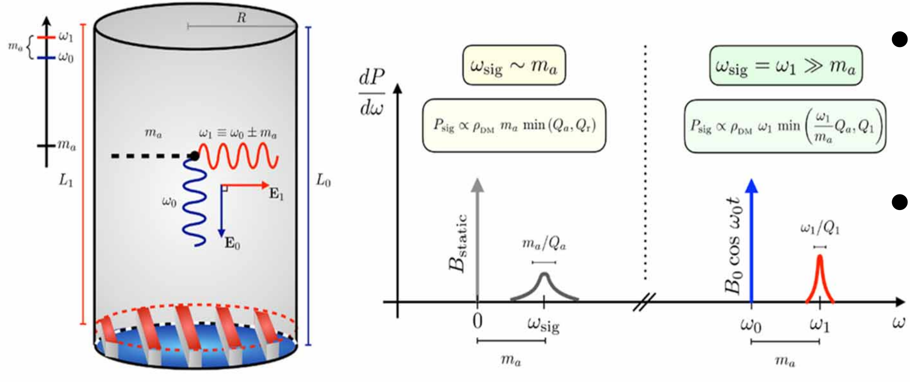
Heterodyne Axion DM search



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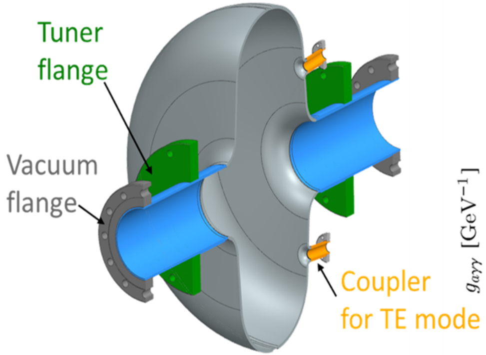

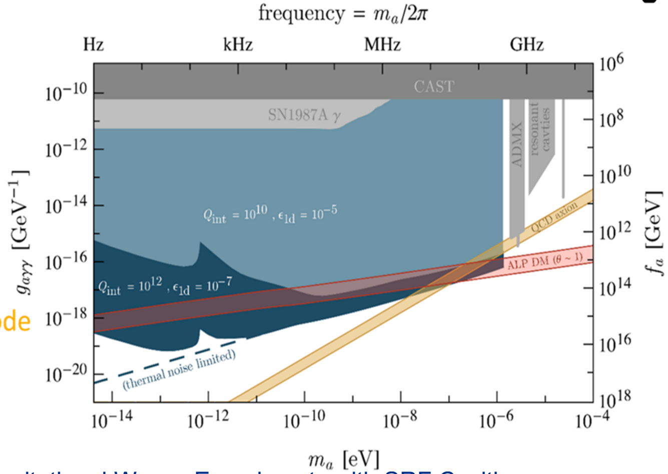

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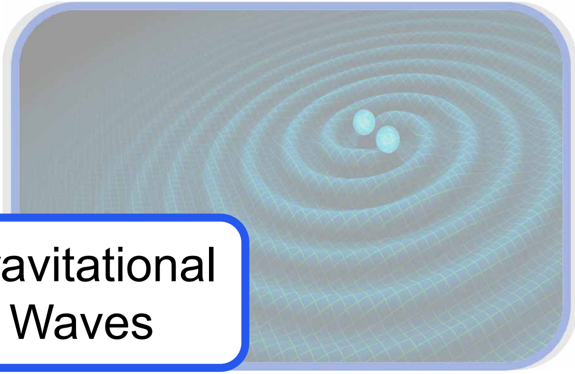
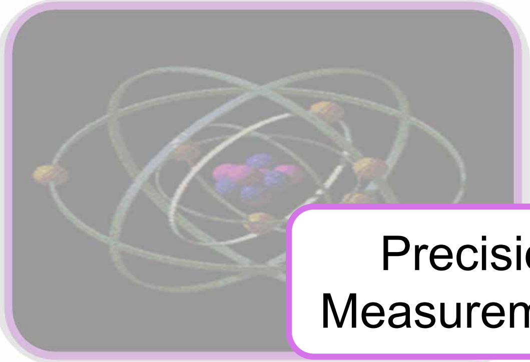
Quantum Sensing: new windows into fundamental physics

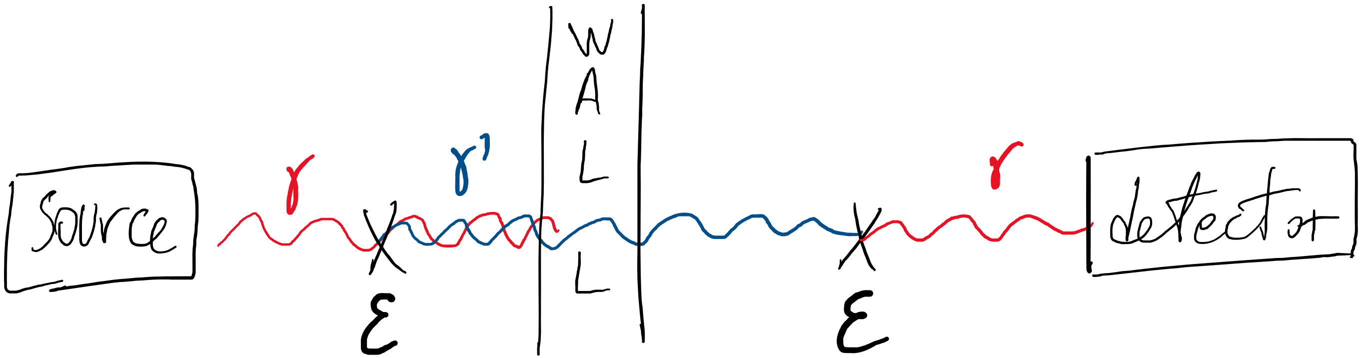




Fermilab Dark SRF Experiment

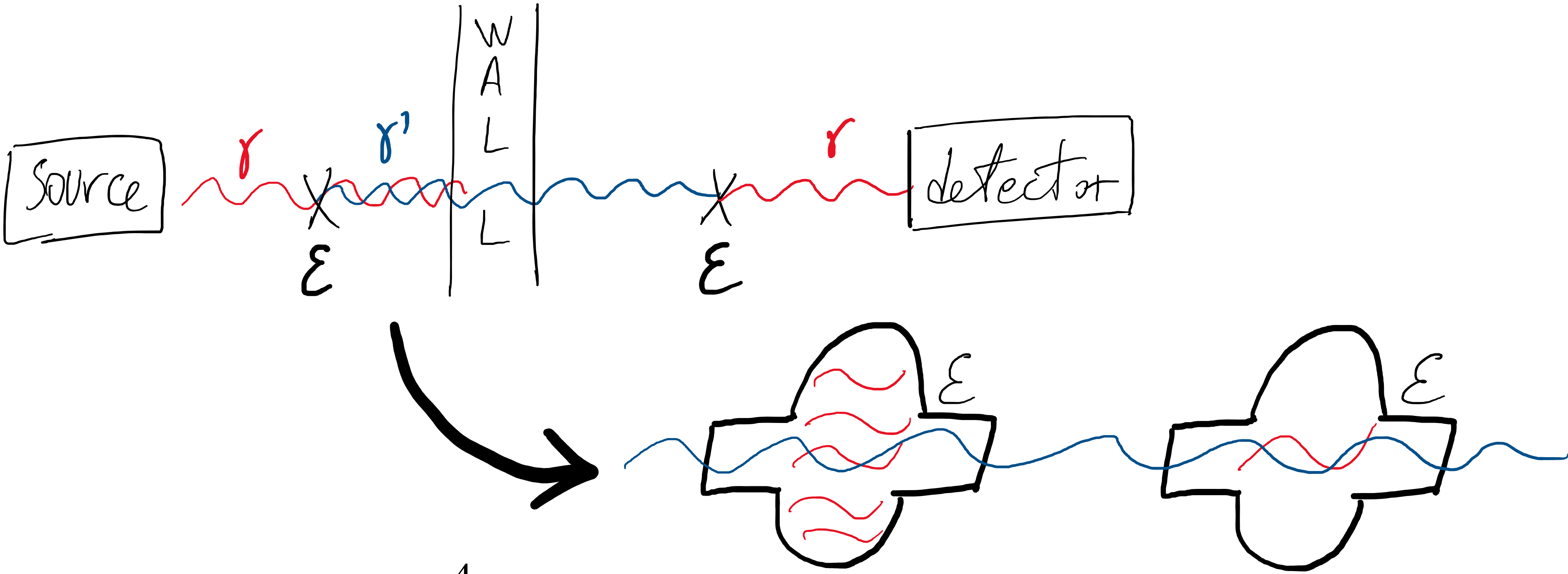
[1] Artwork by Sandbox Studio Chicago with A. Kova symmetrymagazine.org

Dark SRF: Light-Shining-through-Wall search



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

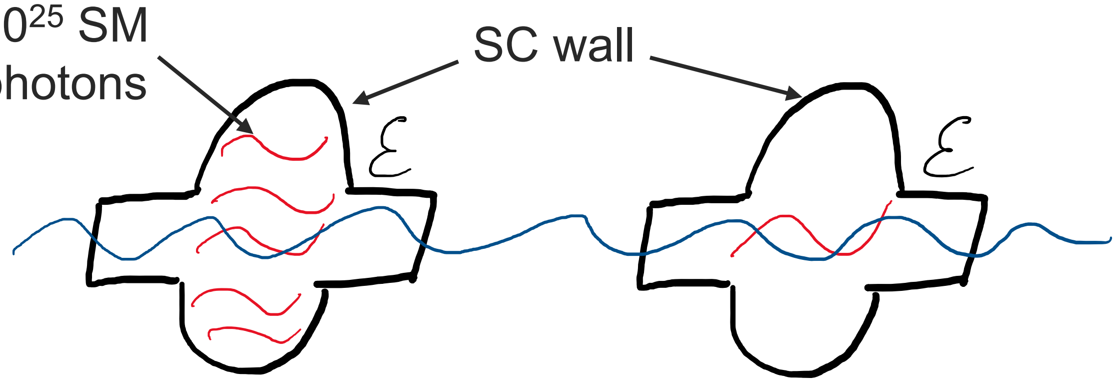
Dark SRF: Light-Shining-through-Wall search



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

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

Advantage of using high Q cavities



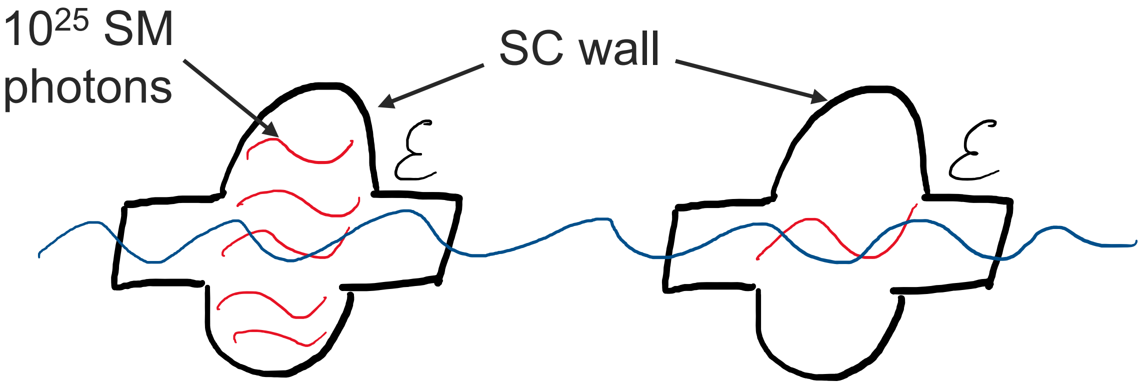
Emitter cavity,
in the accelerator regime, high field

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

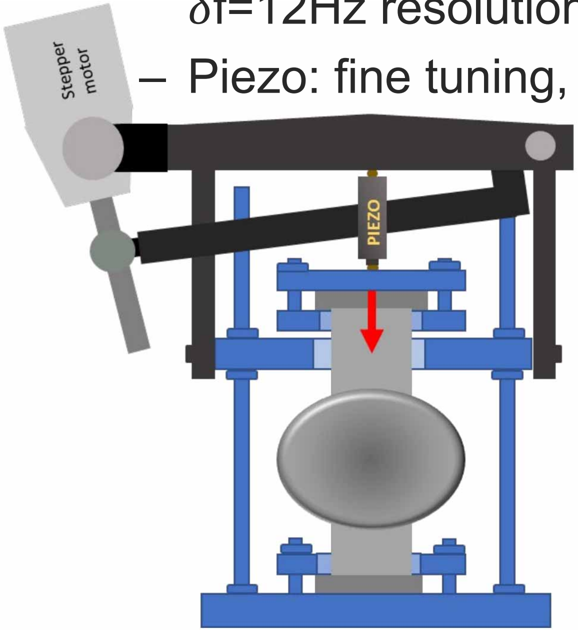
Receiver cavity,
in the low field regime

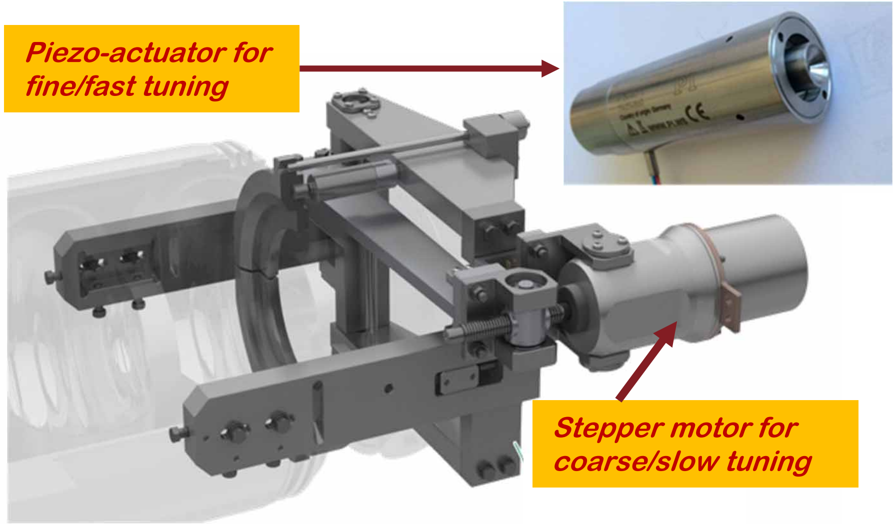
Necessary to match cavities frequency!

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



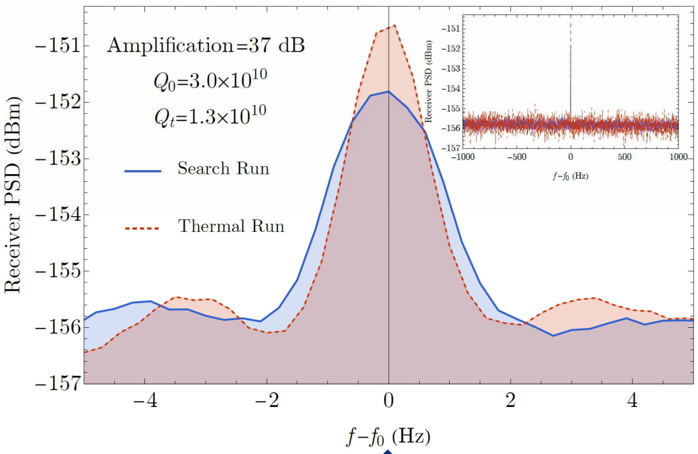


Pischalnikov et al., doi:10.18429/JACoW-SRF2019-TUP085

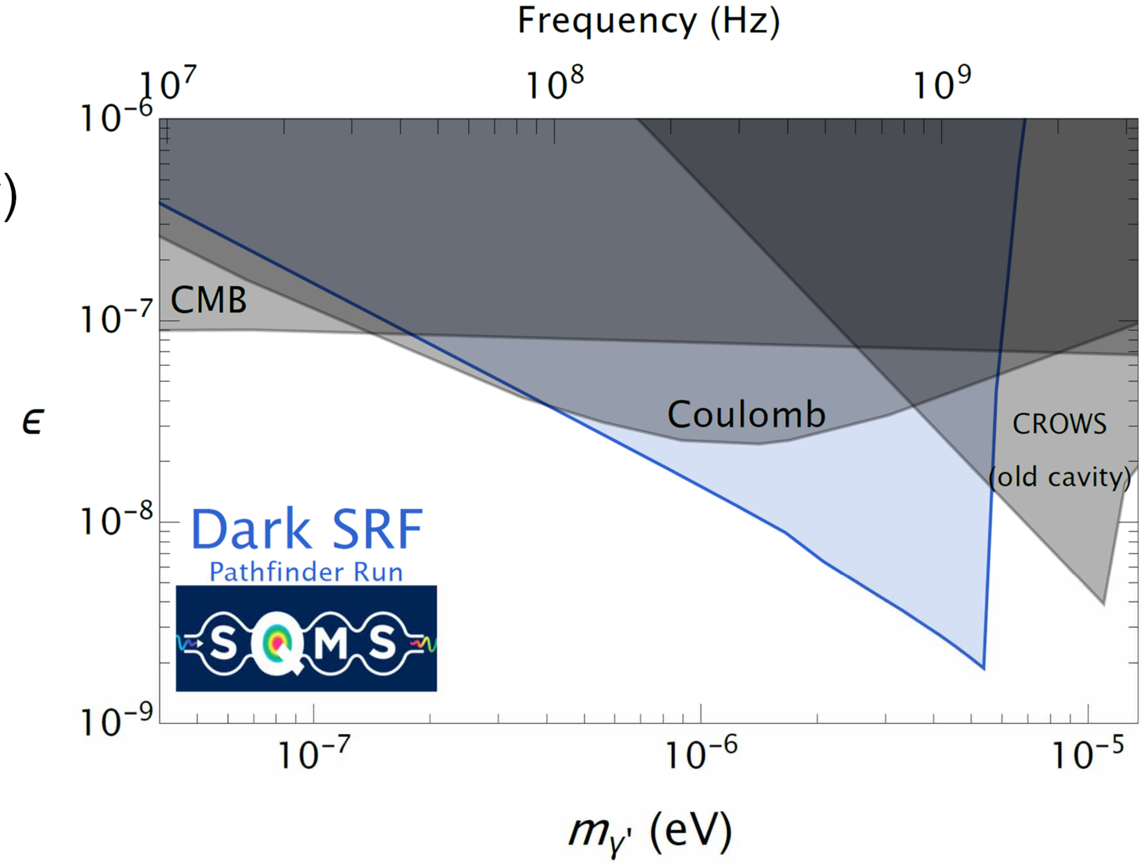
Dark SRF: phase 1 → results

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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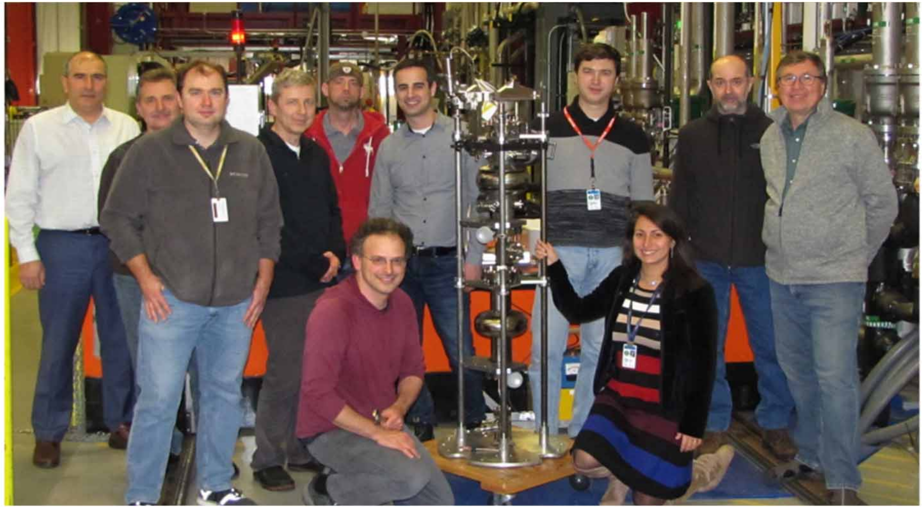
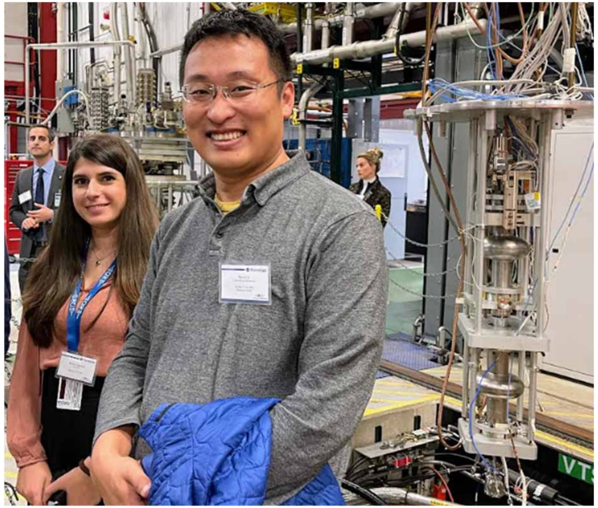
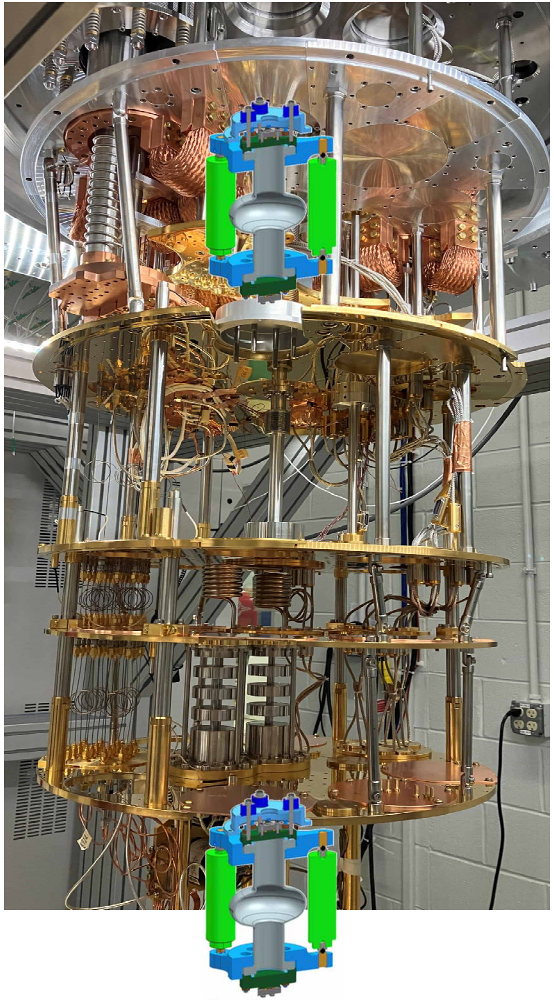




Dark SRF: phase 2 → 2.6GHz cavities in DR

- 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

See ***WEPWB109*** *and* ***WEPWB133*** *by C. Contreras-Martinez*



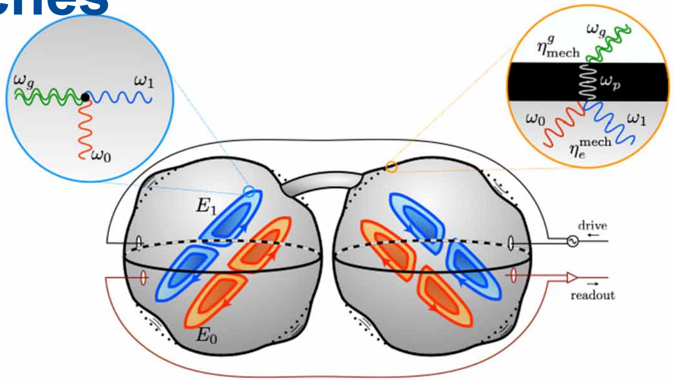
Quantum Sensing: new windows into fundamental physics

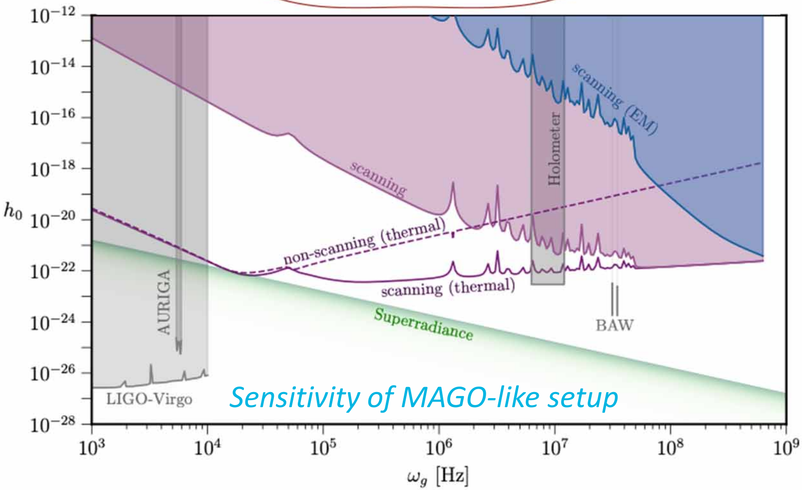
Fermilab Dark SRF Experiment

[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: EM and mechanical.
- Current axion experiments have sensitivity to GHz Gravity waves.
- A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz.
- **New collaboration with INFN and DESY to revive MAGO!**



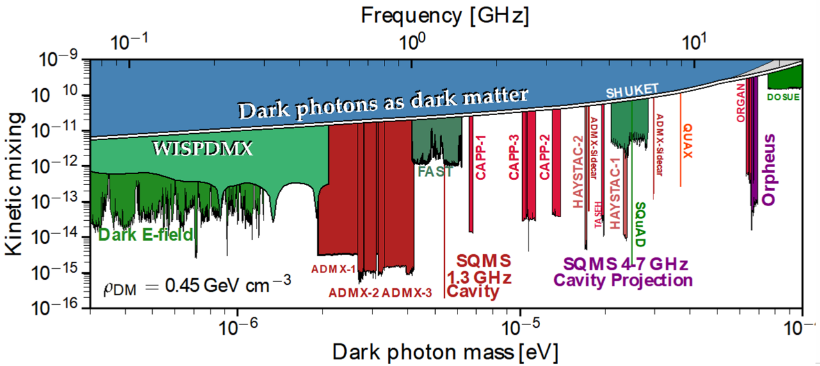


Ballantini et al., Class. Quantum Grav. 20,2003, 3505–3522 (2003)
Ballantini et al., arXiv:gr-qc/0502054 (2005)

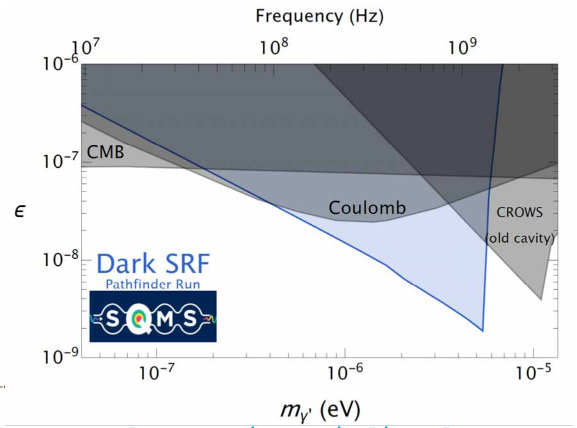
Berlin et al., Phys. Rev. D 105, 116011 (2022)
Berlin et al., arXiv:2303.01518v1 (2023)

Conclusions

- **<u>Haloscope searches</u>**: deepest sensitivity to wavelike DPDM
  - Next: Tuneable plunger cavity in Dil. Fridge, Single photon counting for readout
- **<u>Dark SRF</u>**: 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:** Emitter on 4K plate, receiver on mK plate with JPA on P_t. New tuner system (piezo only).



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



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

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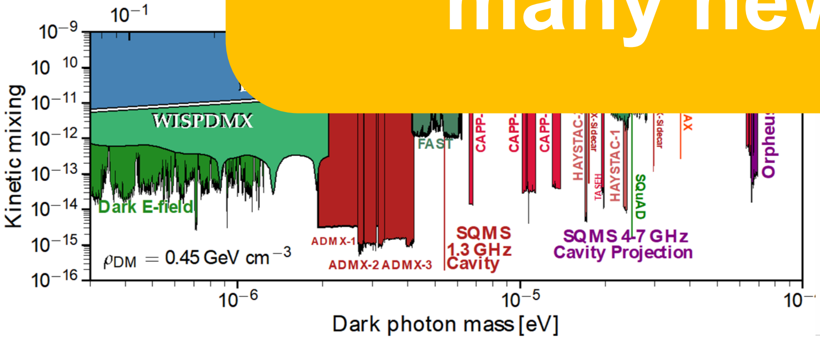
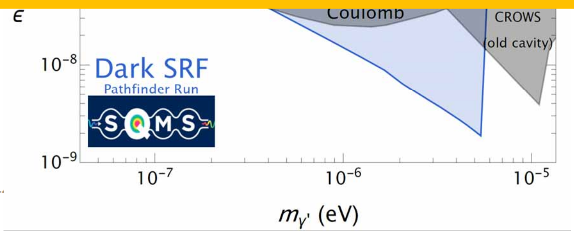
Conclusions

- **Haloscope searches**: deepest sensitivity to wavelike DPDM
  – Next: Tuneable plunger cavity in Dil. Fridge, Single photon counting for readout
- **Dark S**... ...periment
  → **ext**... **and ε**
  – **Dar**... on P_t.
  New...

Already achieved new exclusion limits and we are working on many new experiments!



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



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

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Thank you!