FERMILAB-SLIDES-23-398-SQMS-TD

SQMS: MAGO 1.0 and other activities

Bianca Giaccone, On behalf of SQMS Fermilab Physics and Sensing

Dec 4, 2023

SQMS

30 Partner Institutions

>500 Collaborators

A DOE National Quantum Information Science Research Center

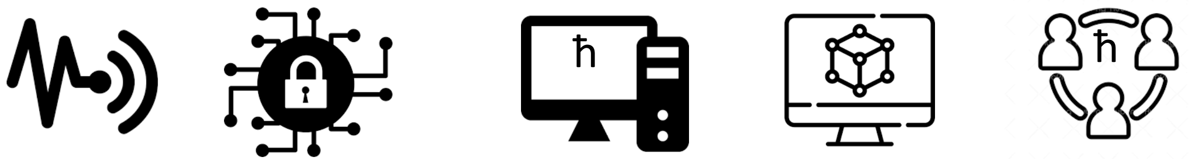
Fermilab
Northwestern University
rigetti
AMES NATIONAL LABORATORY Creating Materials & Energy Solutions
NASA Ames Research Center
NIST
COLORADO SCHOOL OF MINES EARTH • ENERGY • ENVIRONMENT
FORMFACTOR™
Goldman Sachs
ILLINOIS INSTITUTE OF TECHNOLOGY
INFN
Jefferson Lab
JOHNS HOPKINS UNIVERSITY
LOCKHEED MARTIN
LSU
NPL National Physical Laboratory
NYU
ROYAL HOLLOWAY UNIVERSITY OF LONDON
RUTGERS THE STATE UNIVERSITY OF NEW JERSEY
Stanford
Temple University
Unitary Fund
THE UNIVERSITY OF ARIZONA
University of Colorado Boulder
UNIVERSITY OF ILLINOIS URBANA-CHAMPAIGN
UNIVERSITY OF MINNESOTA Driven to Discover®
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

SQMS Annual meeting 2023

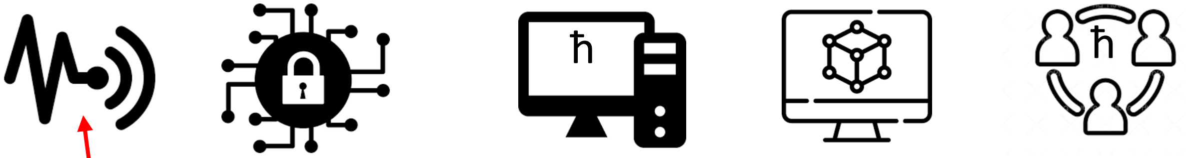
Quantum Information Science

- Quantum Sensing & Metrology
- Quantum Cryptography
- Quantum Computing
- Quantum Simulation
- Quantum Communication



Quantum Information Science

Quantum Sensing & Metrology | Quantum Cryptography | Quantum Computing | Quantum Simulation | Quantum Communication



Superconducting materials and RF cavities

Cryogenics

Electronics and Microwave Controls

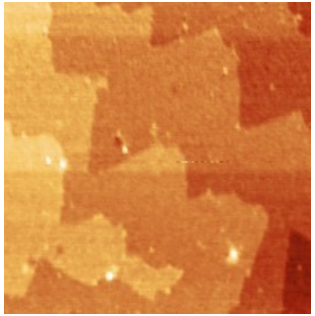
Precision Timing

…

Leveraging unique technologies for advancing quantum information science

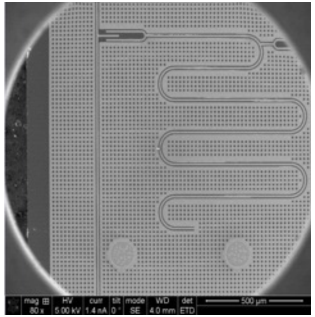
SQMS Science and Technology Innovation Chain

Materials



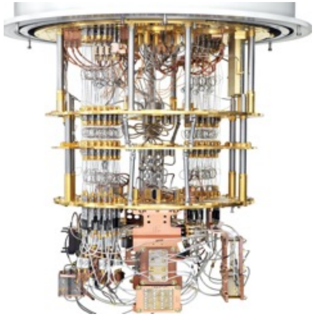
Developing a full understanding of sources of decoherence via a systematic, fundamental science approach

High-coherence devices



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

Systems integration

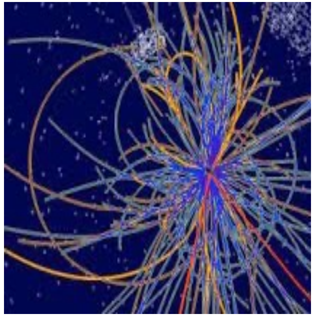


Preserving device high performance through the process of integrating into more complex systems

New platforms for quantum computing & sensing

Deploying quantum platforms of innovative architectures and improved performance

Quantum advantage



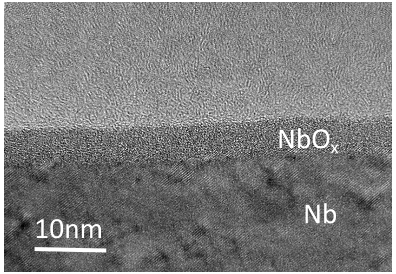
Demonstrating quantum computing and sensing advantage for particle physics and other scientific applications

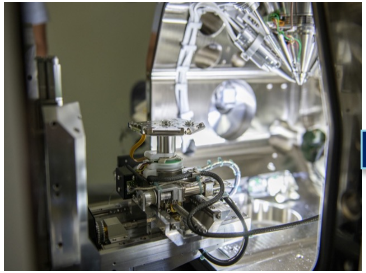
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

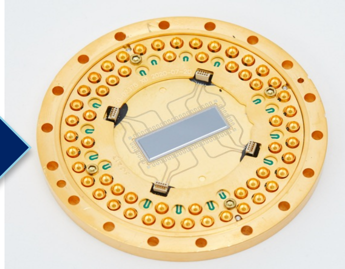
Technology Thrust: Strategy

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

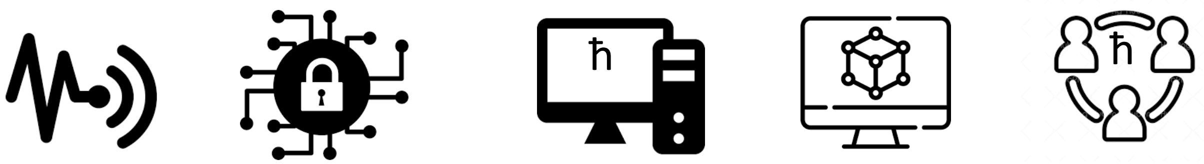




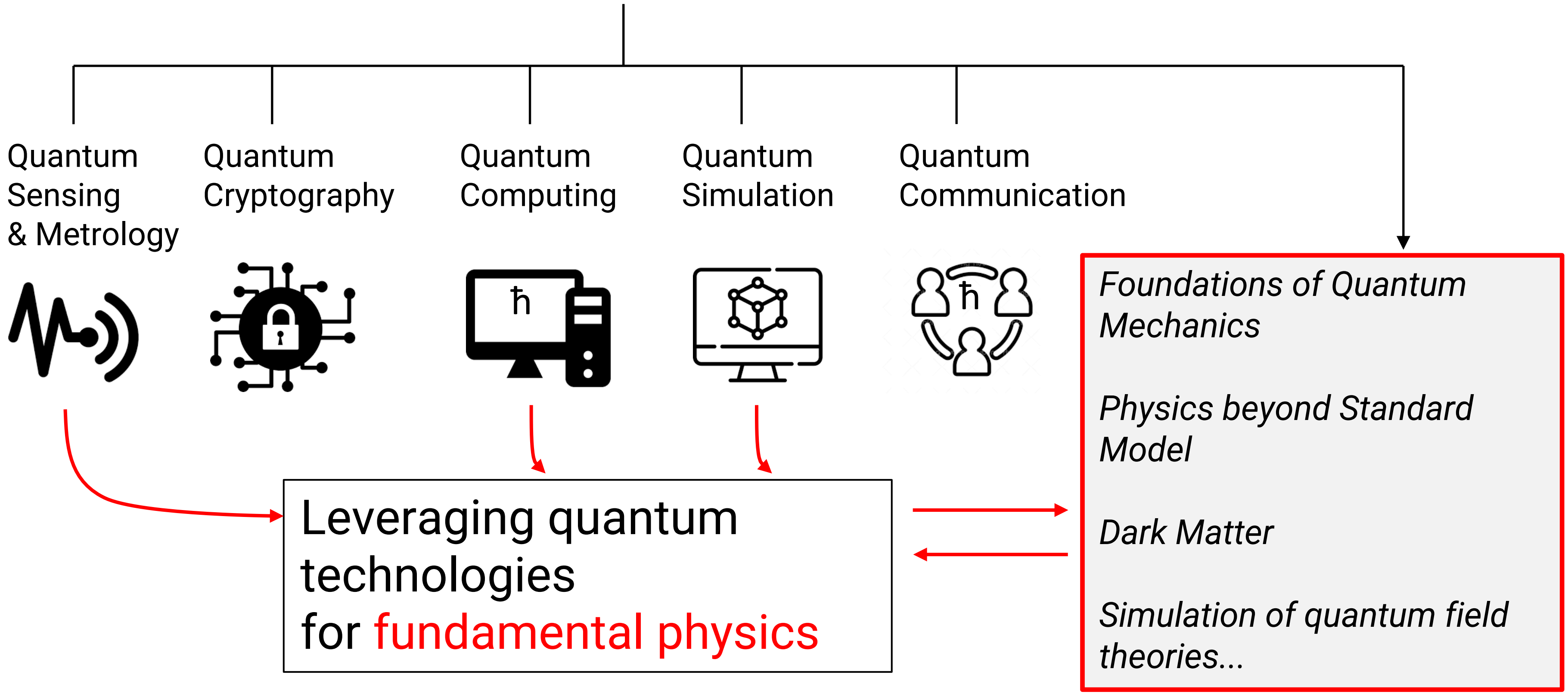


Quantum Information Science

- Quantum Sensing & Metrology
- Quantum Cryptography
- Quantum Computing
- Quantum Simulation
- Quantum Communication



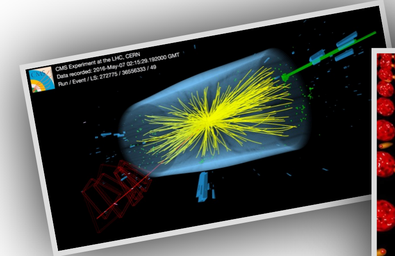
Quantum Information Science

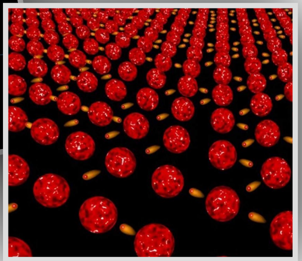


SQMS Science Thrust

- **The questions that keep us up:**
  - What was the … as young?
  - How does the … at LHC) happen in “real time”?
  - What are the … als?
  - What the non … entangled systems?

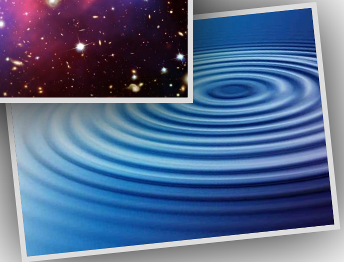
Quantum Simulation and Computation





  - What is the dark matter?
  - Are there new particles … vered?
  - Can we dete…
  - How well ca…

Quantum Sensing



These are long term endeavors.

Our goal is to enable breakthroughs in these questions.

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The People

Fermilab

Northwestern University

University of Minnesota
Driven to Discover®

The University of Arizona

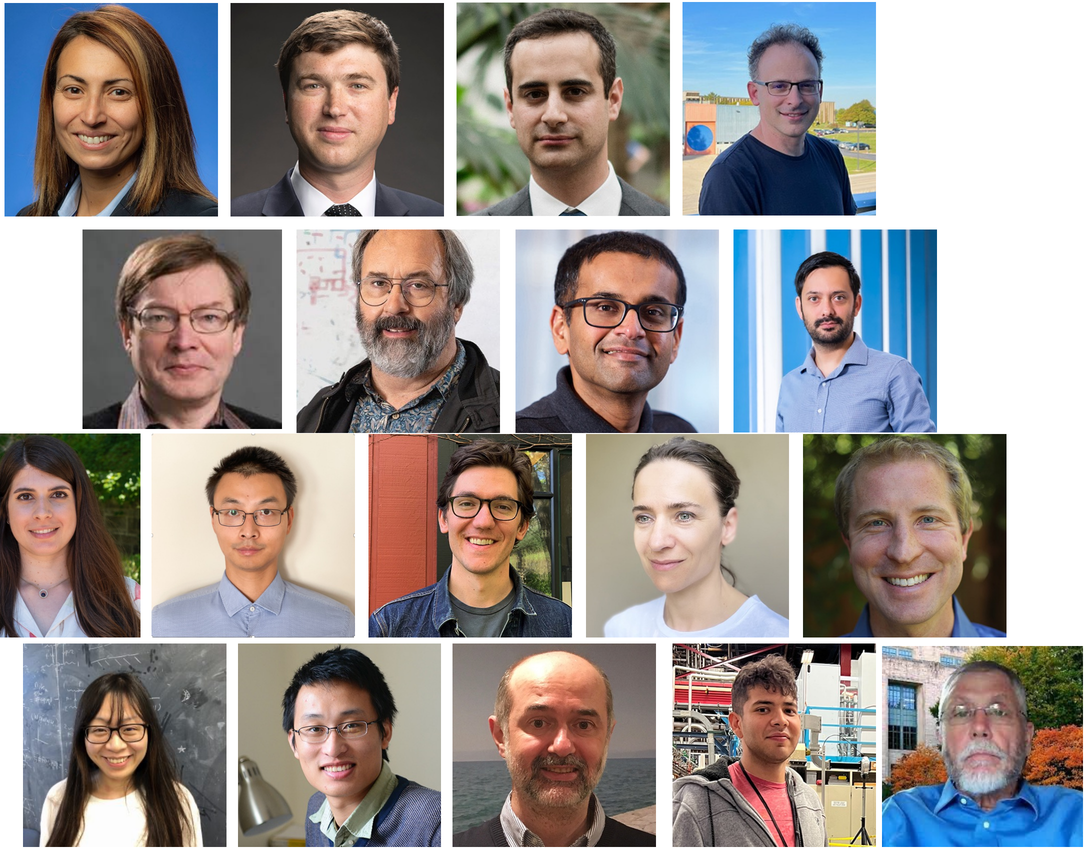
LSU

Johns Hopkins University

University of Illinois Urbana-Champaign

INFN

Stanford



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

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MAGO (1.0)

R. 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

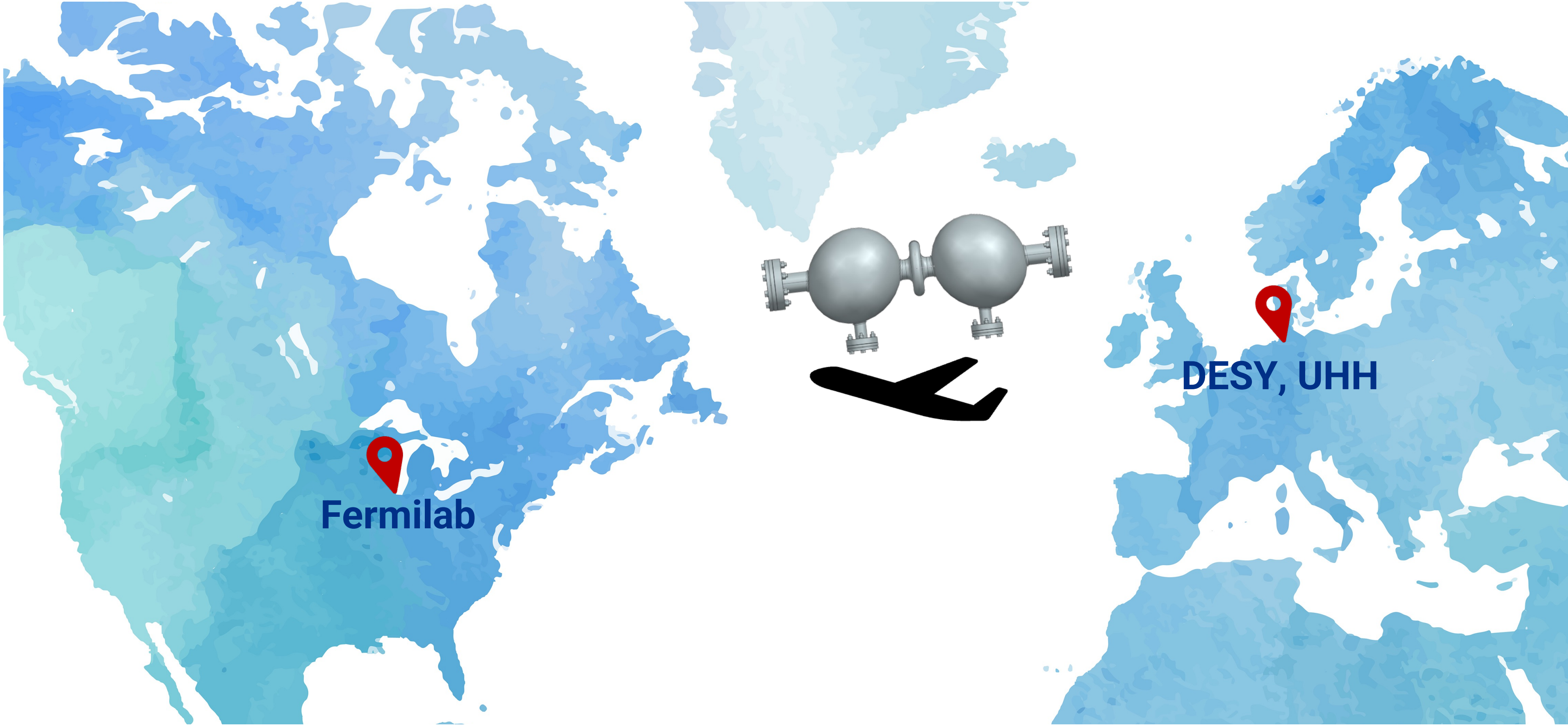
Followed by (2001-2003)

- 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!

The cavity is travelling to Fermilab



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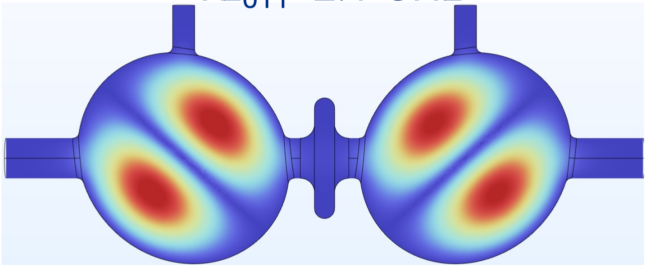
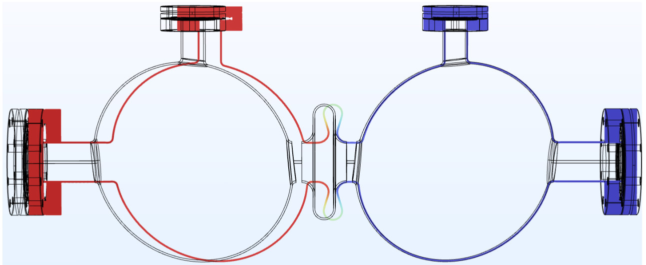
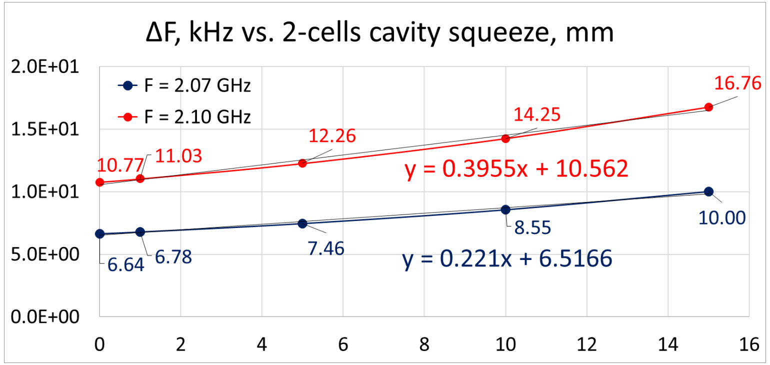
MAGO 1.0 at Fermilab

- RF and mechanical simulations with ideal vs real geometry and thickness
  - Frame optimization to relieve stress from thin coupling cell
- RF fixtures for RT elastic tuning to bring cavity to acceptable starting point
  - Currently no cold tuning plans
- Due to thin walls
  - Bulk BCP or light only? Vertical vs horizontal?

TE_{011}- 2.1 GHz



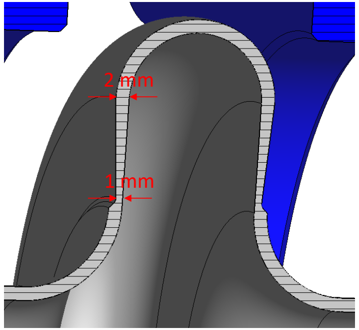


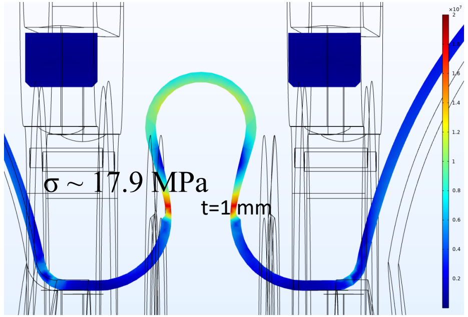


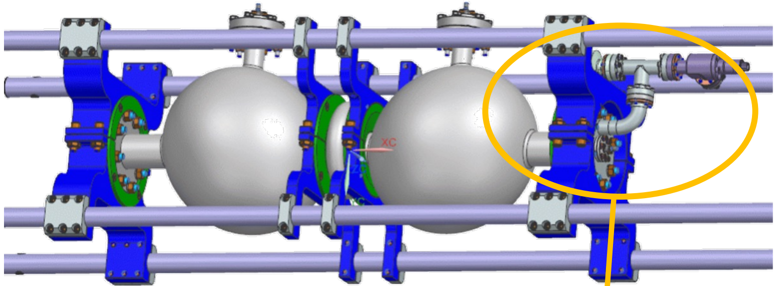
V. Chouhan, C. Contreras, I. Gonin,
T. Khabiboulline, Y. Orlov, O. Pronitchev, Y. Yakovlev

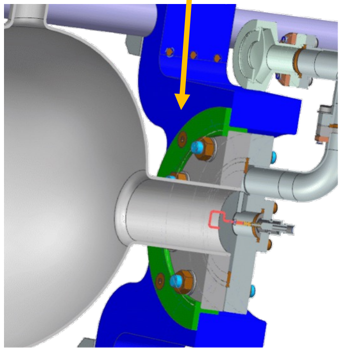
MAGO 1.0 at Fermilab

- HPR → head and nozzle design
- Heat treatment:
  - Stainless steel flanges
  - Unknown brazing material (likely copper based)
- Theoretical work:
  - **Simulate coupled oscillators** subject to **mechanical vibrations** (induced by GW vs ambient noise) derive **expected growth rate of the signal mode** due to parametric energy transfer and non-idealities contribution
  - Inform design for next generation cavity









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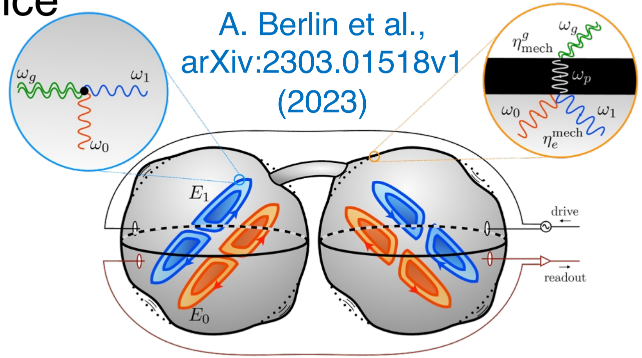
O. Pronitchev,
Y. Yakovlev

Looking forward: MAGO 2.0

- Planning for a broadband non-resonant search
- 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
  - Amplifier noise
  - …

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

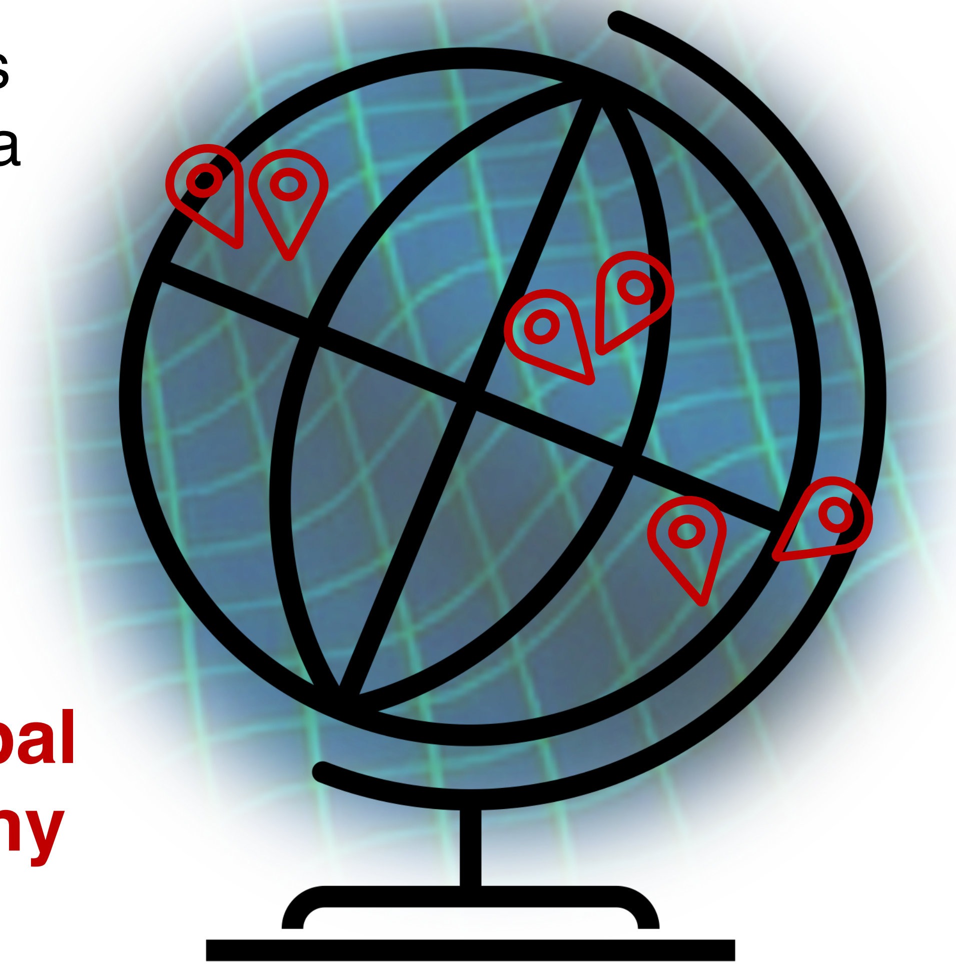


- Currently focusing on design phase for an optimized cavity geometry and tuning system and planning to leverage lessons learned from MAGO 1.0
- US/Japan collaboration → small effort between SQMS Fermilab and University of Tokyo & KEK for SRF based GW searches
- Worth looking into custom cryostat and suspension design

In the case of GW searches is particularly important to have a **series of coordinated and synchronized experiments taking place at different locations**

↓

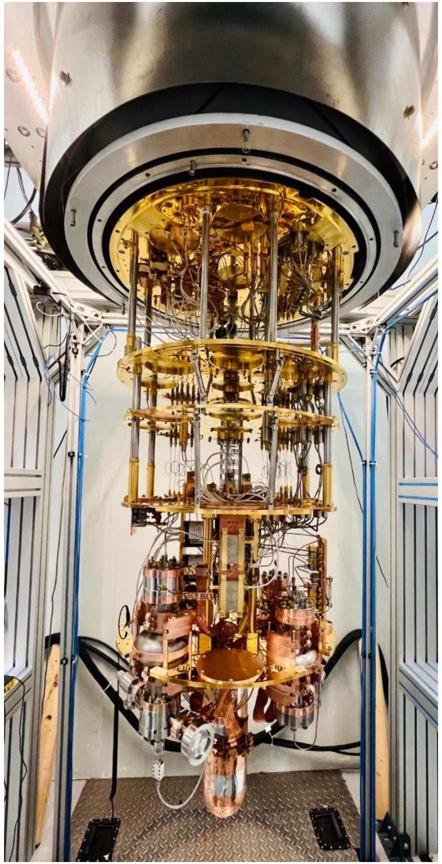
MAGO 2.0 could be a global experiment involving many laboratories!



Facilities

LHe vertical test stand facility at Fermilab

SQMS QCL1 and QCL3 (mK fridges)



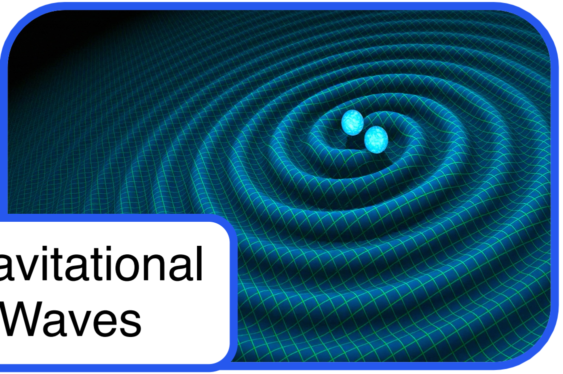
SQMS Physics and Sensing: other experiments

Quantum Sensing: new windows into fundamental physics

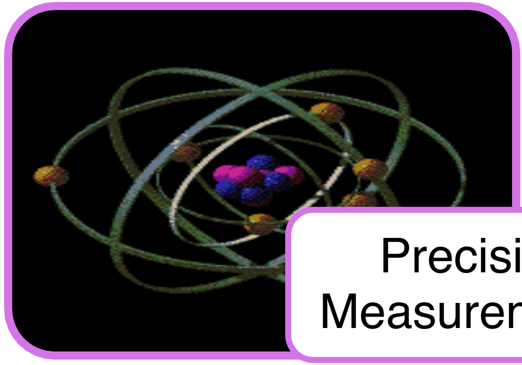
Dark Sector

Dark Matter

"Just" new particles



Gravitational Waves



Precision Measurements

Fermilab Dark SRF Experiment

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

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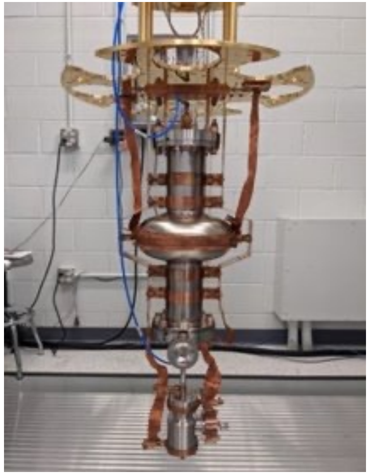
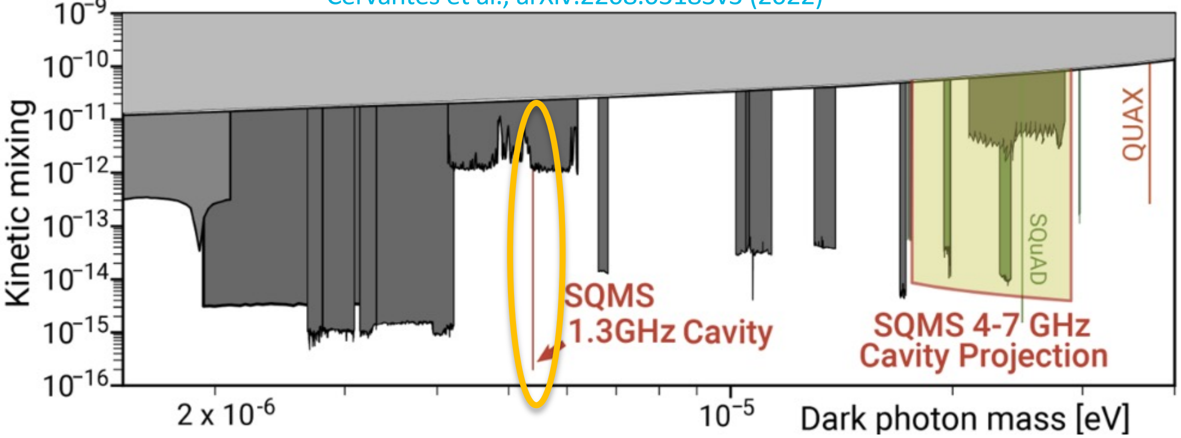
Deepest sensitivity: Ultrahigh Q for Dark photon DM



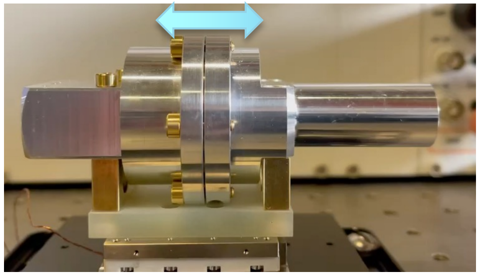
Cervantes et al., arXiv:2208.03183v3 (2022)



DPDM search in DR 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.



"plunger" cavity
4-7 GHz

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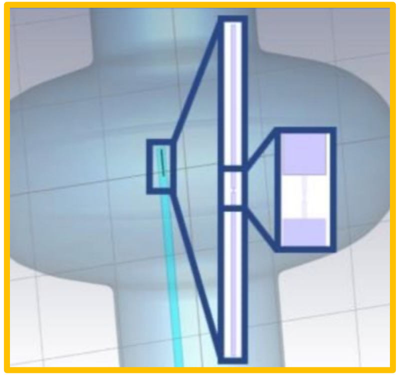
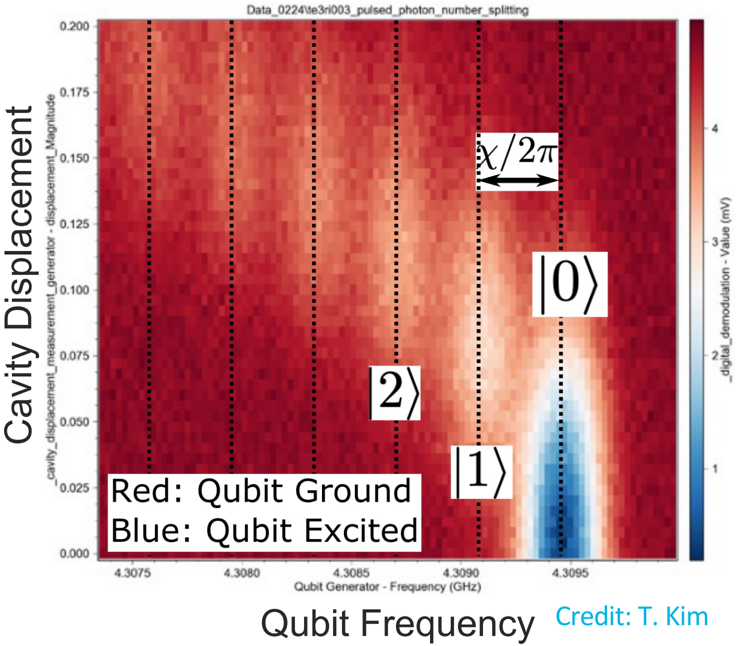
Subverting SQL noise with qubit-based photon counting



Superconducting qubit in SRF cavity.



Credit: T. Kim

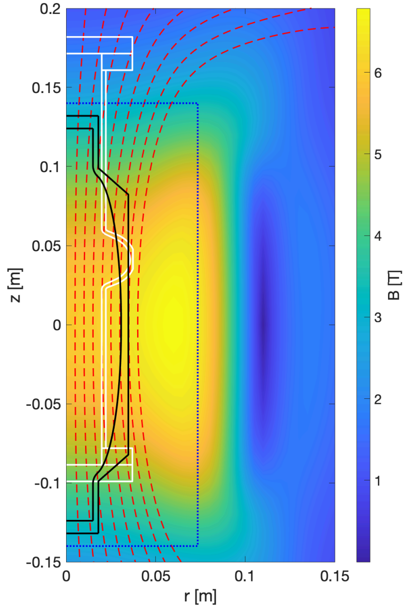
Quantum protocols counts photons non-destructively.

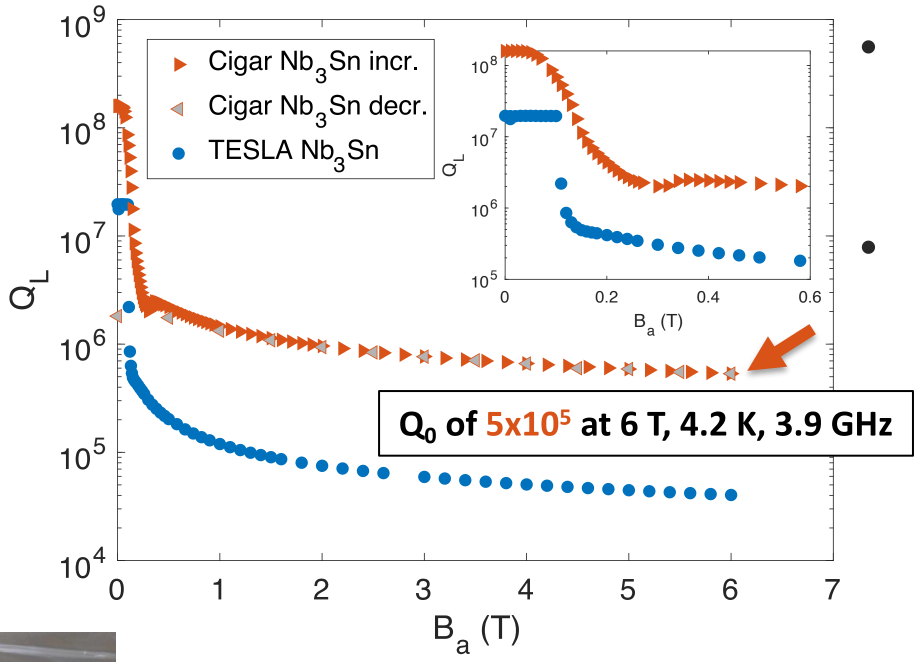
SQL noise: hf/k
240 mK @ 5 GHz

dominates compared to 30 mK thermal photons.

Regularly perform photon counting with dispersive measurements.

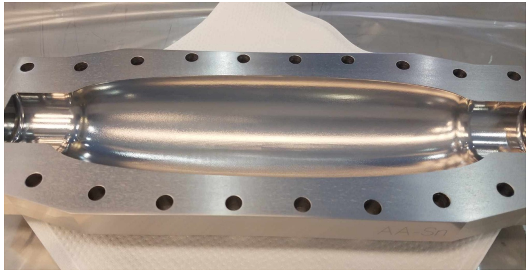
Progress towards high Q cavities for Axion Searches





Q_0 of 5x10^5 at 6 T, 4.2 K, 3.9 GHz

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



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

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Dark SRF: light shining through wall search with SRF cavities

1. Pathfinder run with 1.3GHz cavities in LHe

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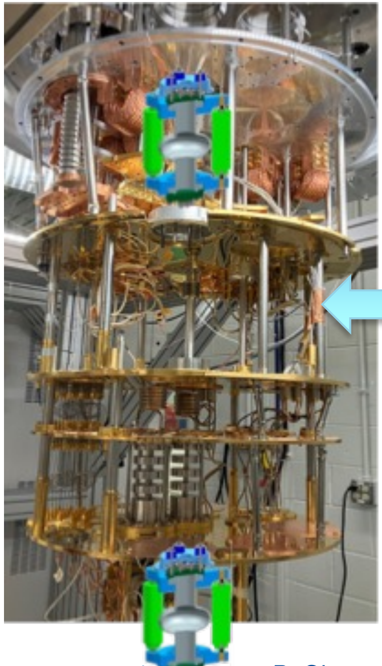
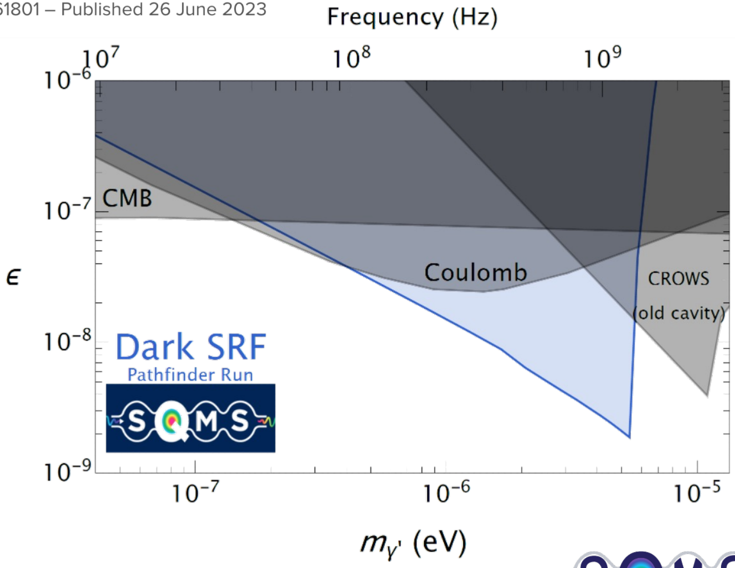
Search for Dark Photons with Superconducting Radio Frequency Cavities

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

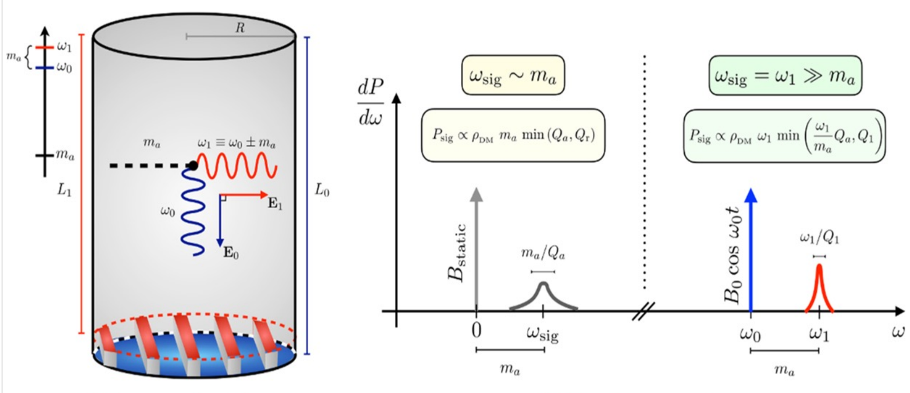
Phys. Rev. Lett. **130**, 261801 – Published 26 June 2023



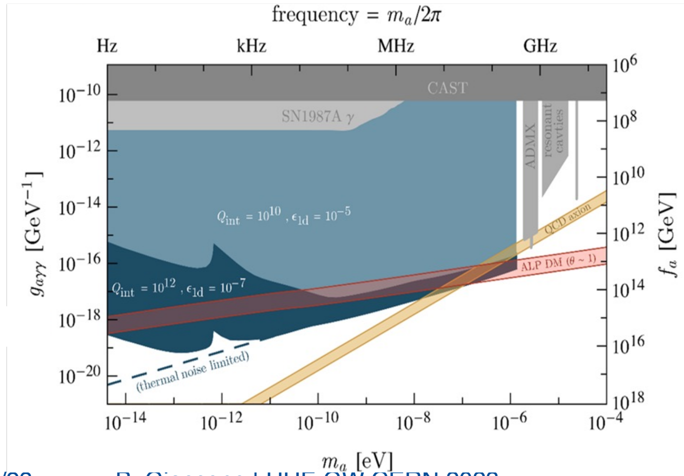
2. Next phase: conduct experiment at ~10s mK in dilution refrigerator to increase sensitivity



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 → $m_{axion} \approx \Delta f$
- 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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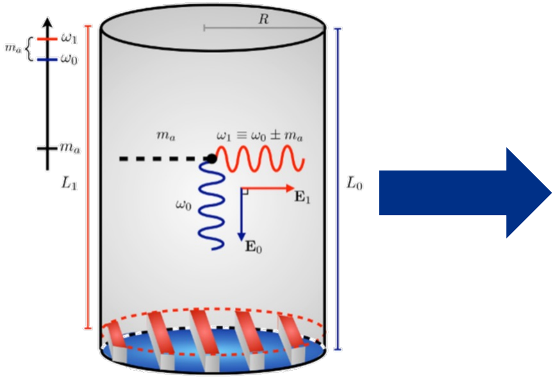
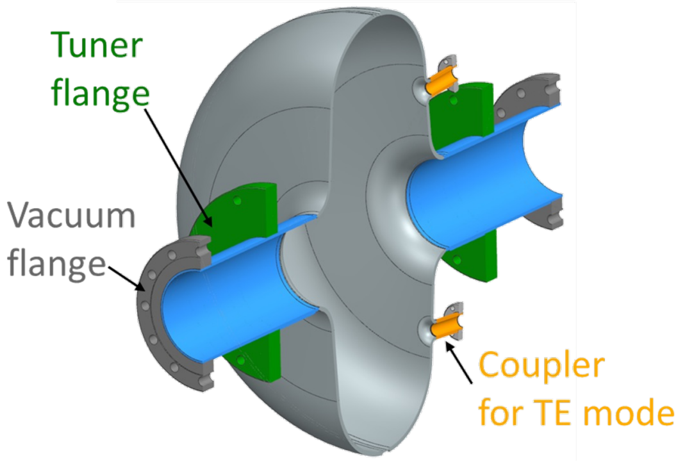
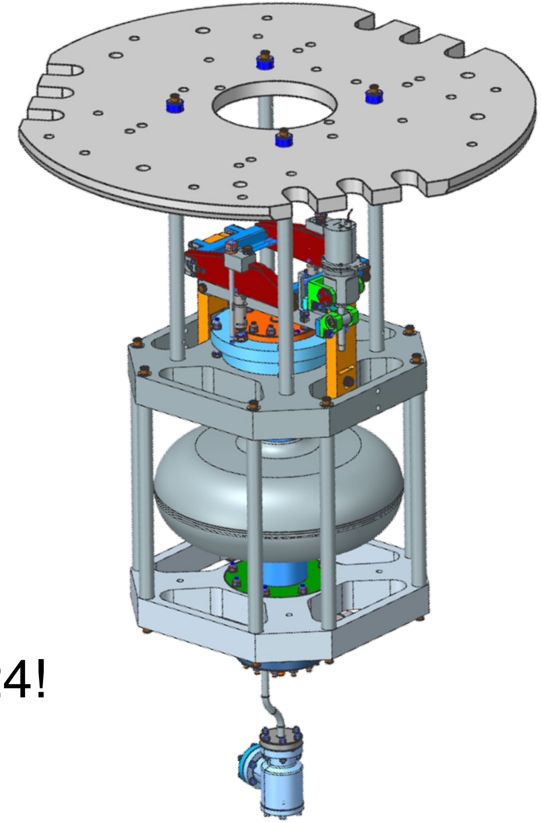
Heterodyne Axion DM search: from theory to experiment







- Design is completed, currently procuring 2 prototype cavities

→ expected to arrive by end of 2023/beginning of 2024!

- Pump mode: TM_{020}, Signal mode: TE_{011}
  - By design: Δf≈1MHz
  - Tuner: same design as Dark SRF tuner

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

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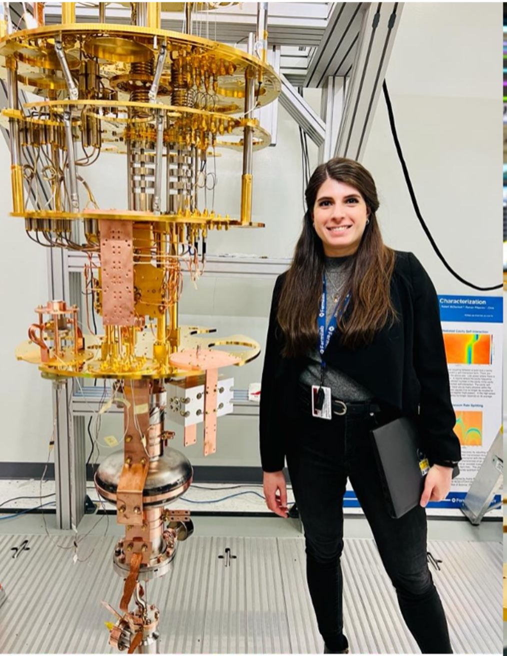
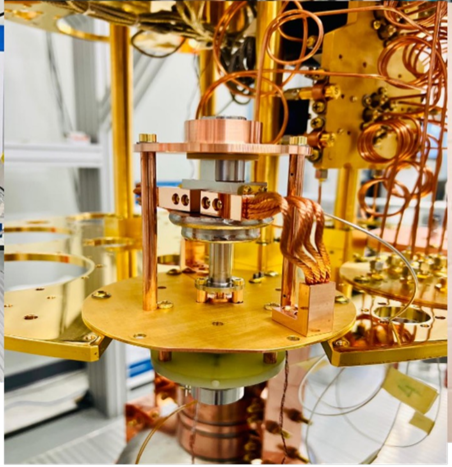
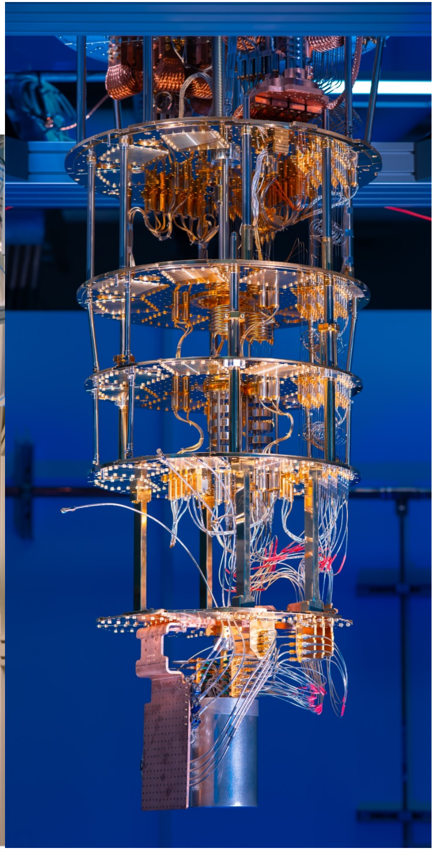
Thank you for your attention!

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









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