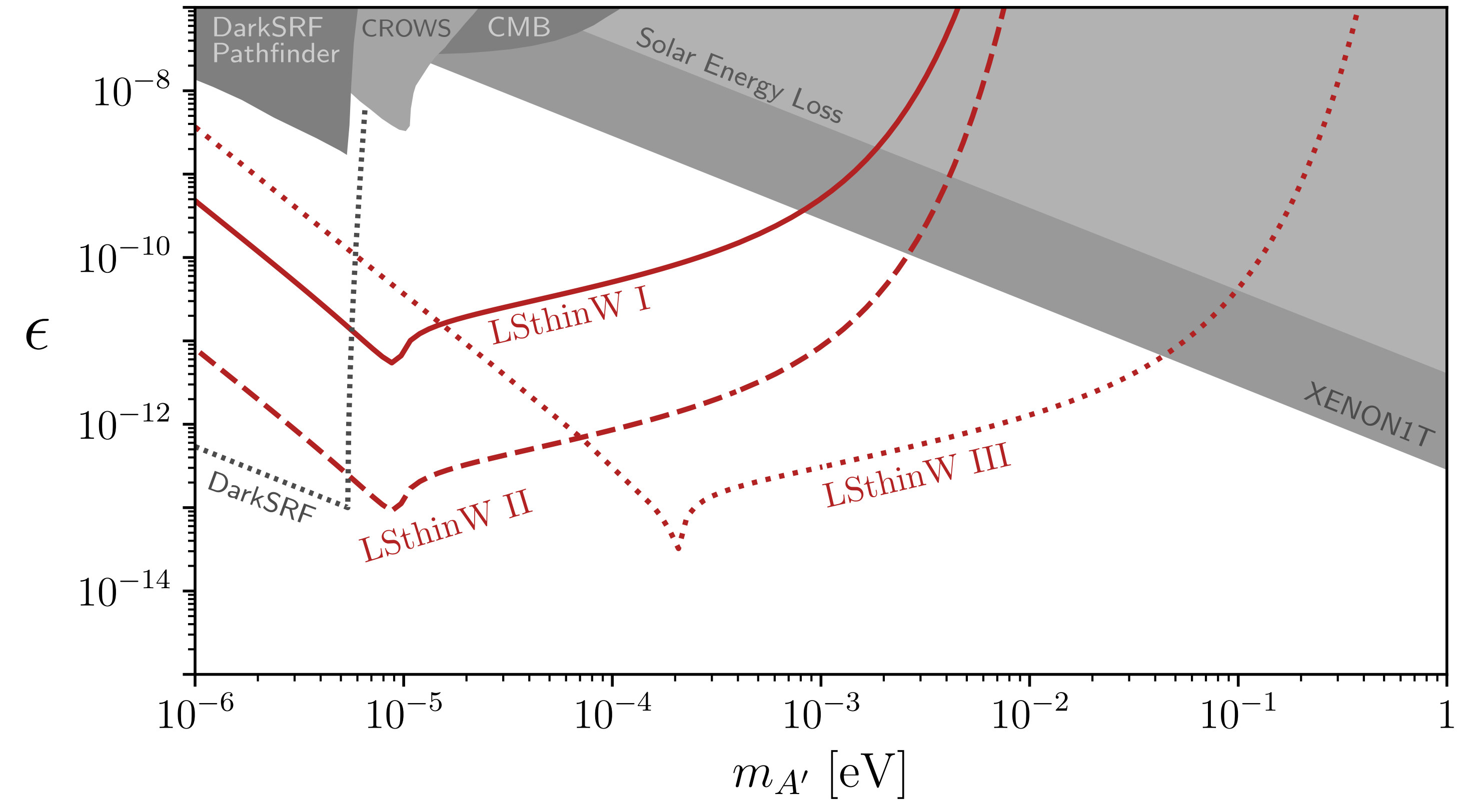
SQMS and Dark Sector Searches

Roni Harnik,
Quantum Theory Department
SQMS

Fermilab SQMS

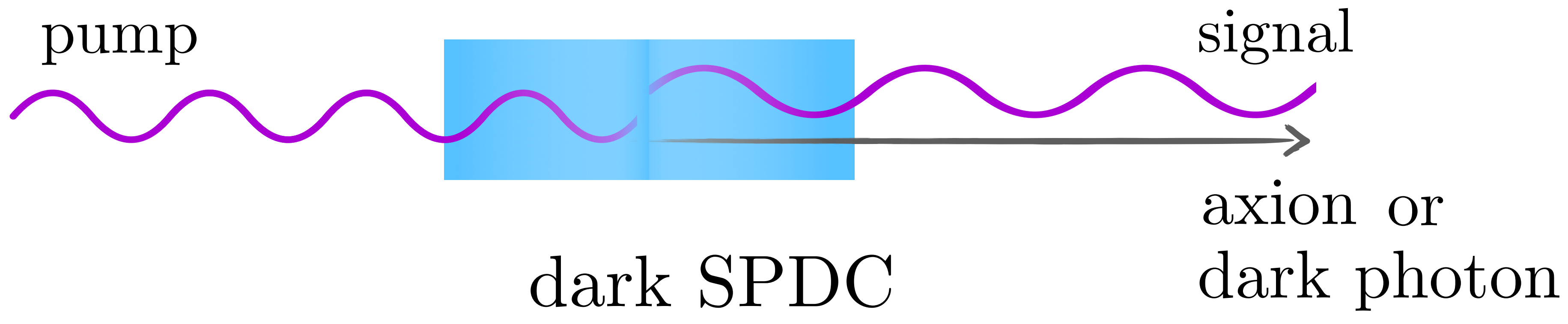
Quantum Theory

- Quantum Theory works ion two areas:
  - Quantum Simulation (a new and exciting field!)
  - Quantum Sensing (more related to this crowd):
    - Asher Berlin, RH
    - Sohitri Gosh, Alex Millar, Tanner Trickle, Christina Gao (JRA), Ryan Janish

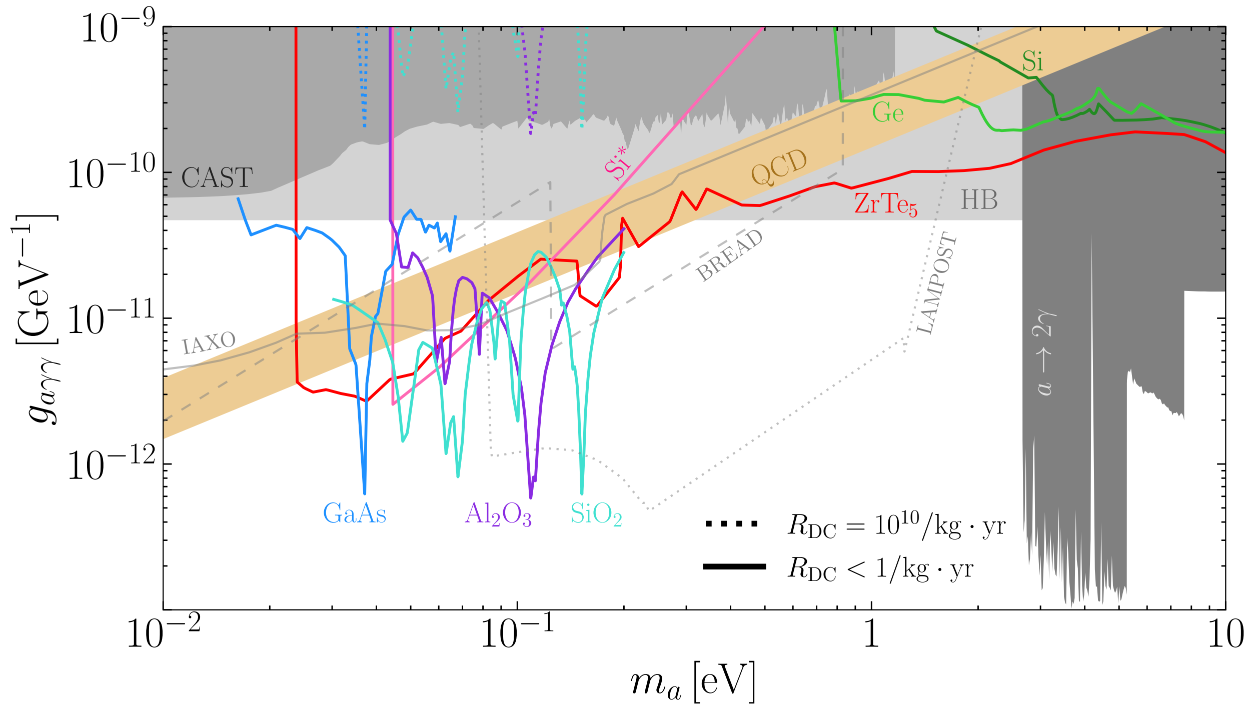


"Light shining thru thin wall", Berlin, Janish, RH

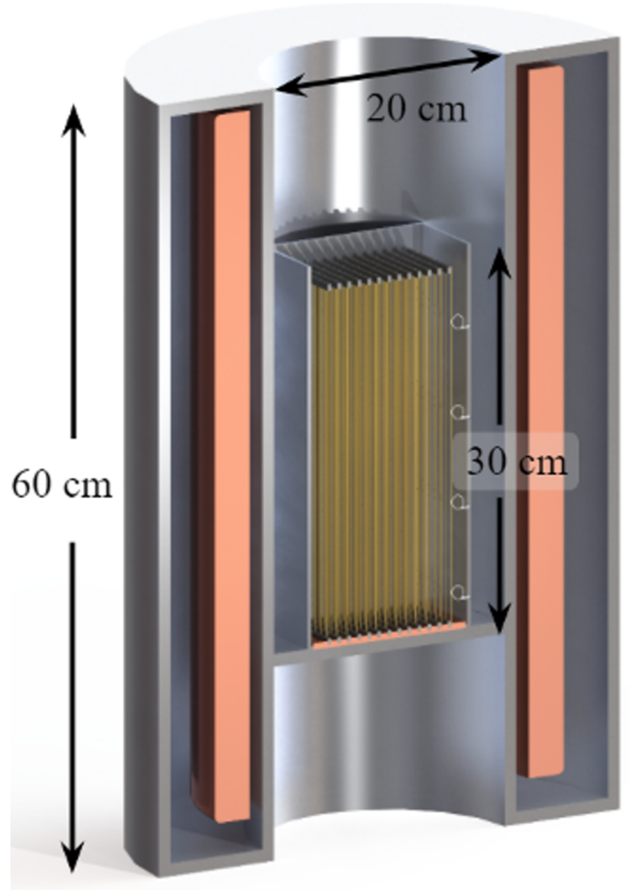
Excited to collaborate!



Dark SPDC, Collaboration with Juan.



"Axion absorption in Magnetized material": Berlin and Trickle



Alpha, Millar et al

SQMS - Superconducting Quantum Materials and Systems:

- SQMS is one of 5 NQI centers. Headed by Fermilab.
- QSC is another of these 5 (headed by ORNL). See Daniel's talk.

"DOE NQISR Centers leverage unique capabilities, expertise and facilities to achieve bold scientific and technological goals in quantum."

SQMS

A DOE National QIS Research Center

SQMS MISSION [excerpt]

Achieve transformational advances in the major cross-cutting challenge of ***understanding & eliminating decoherence mechanisms*** in superconducting devices, enabling construction and deployment of superior quantum systems for computing & ***sensing***.

30
Partner Institutions

450+
Collaborators

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

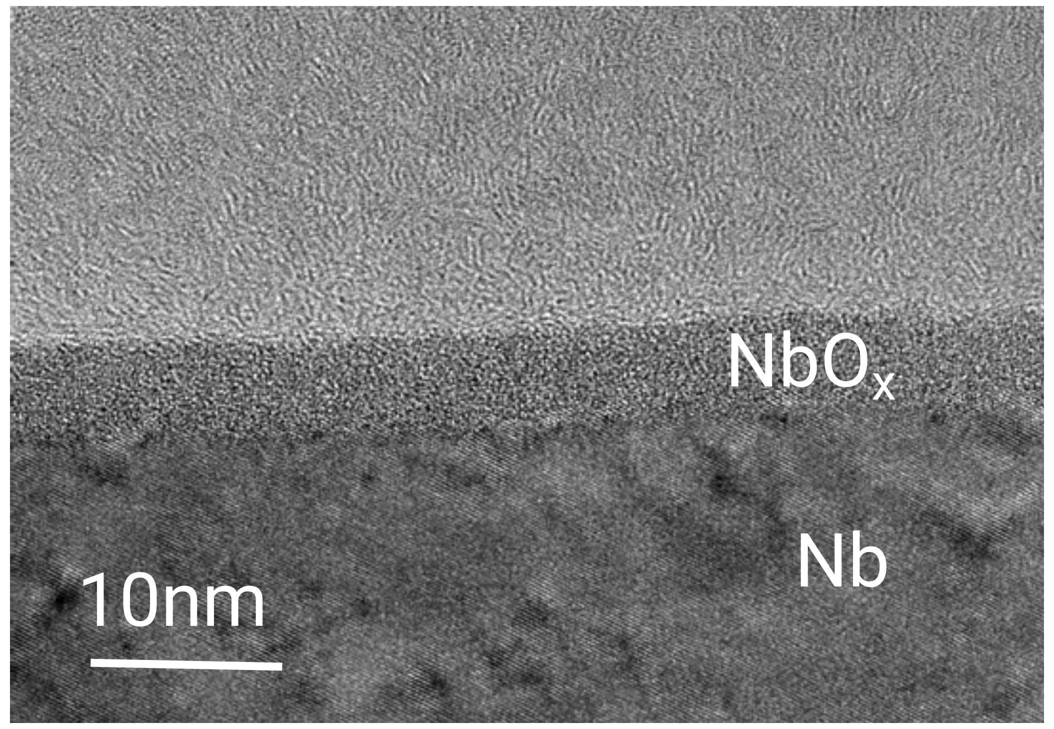
+ LLNL about to join (including ADMX folks)

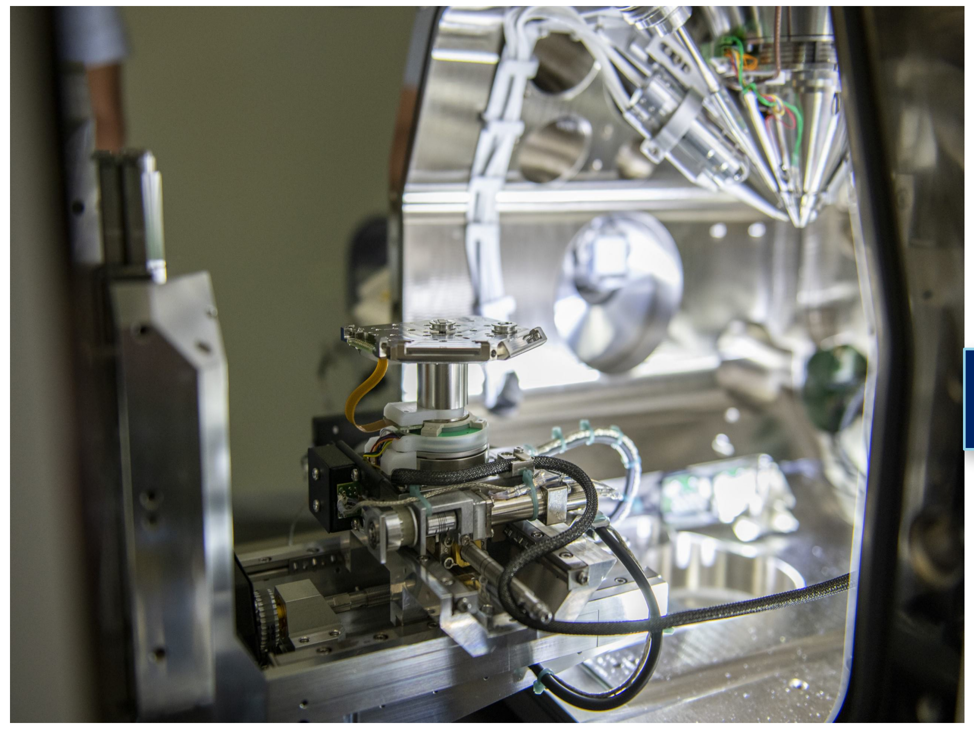
SQMS Technology Thrust - Strategy

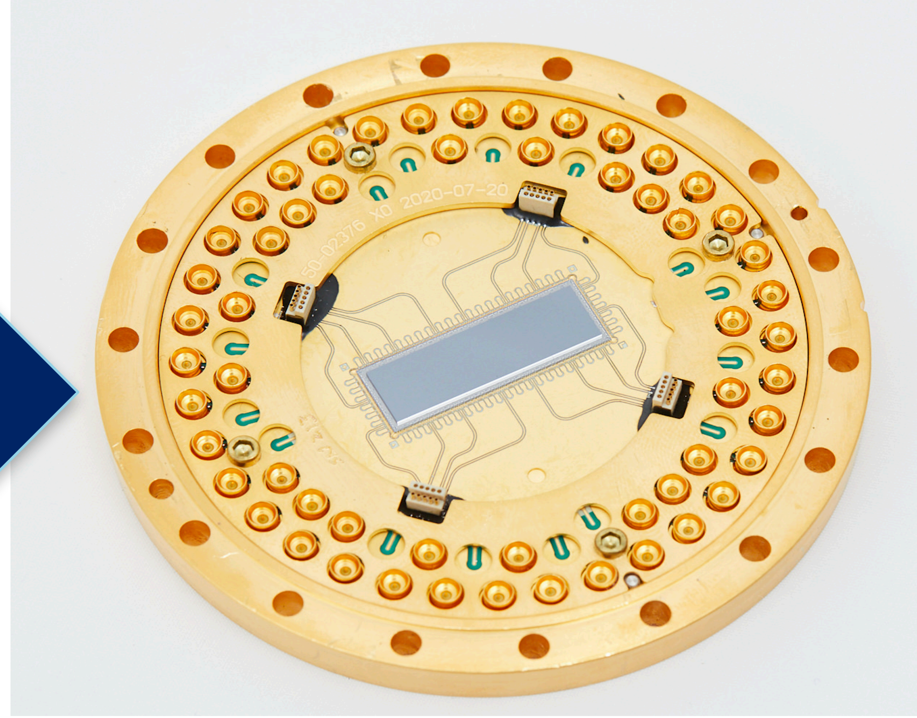
Basic Understanding → Coherence Improvement → 2D and 3D High Coherence QPUs

Build upon core strengths that were developed for accelerators:

- Fermilab world's best superconducting RF cavities (3D)
  – **seconds** of coherence (quality factors $Q > 10^{10}$)
  - Associated deep structural and superconductivity knowledge of Nb (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

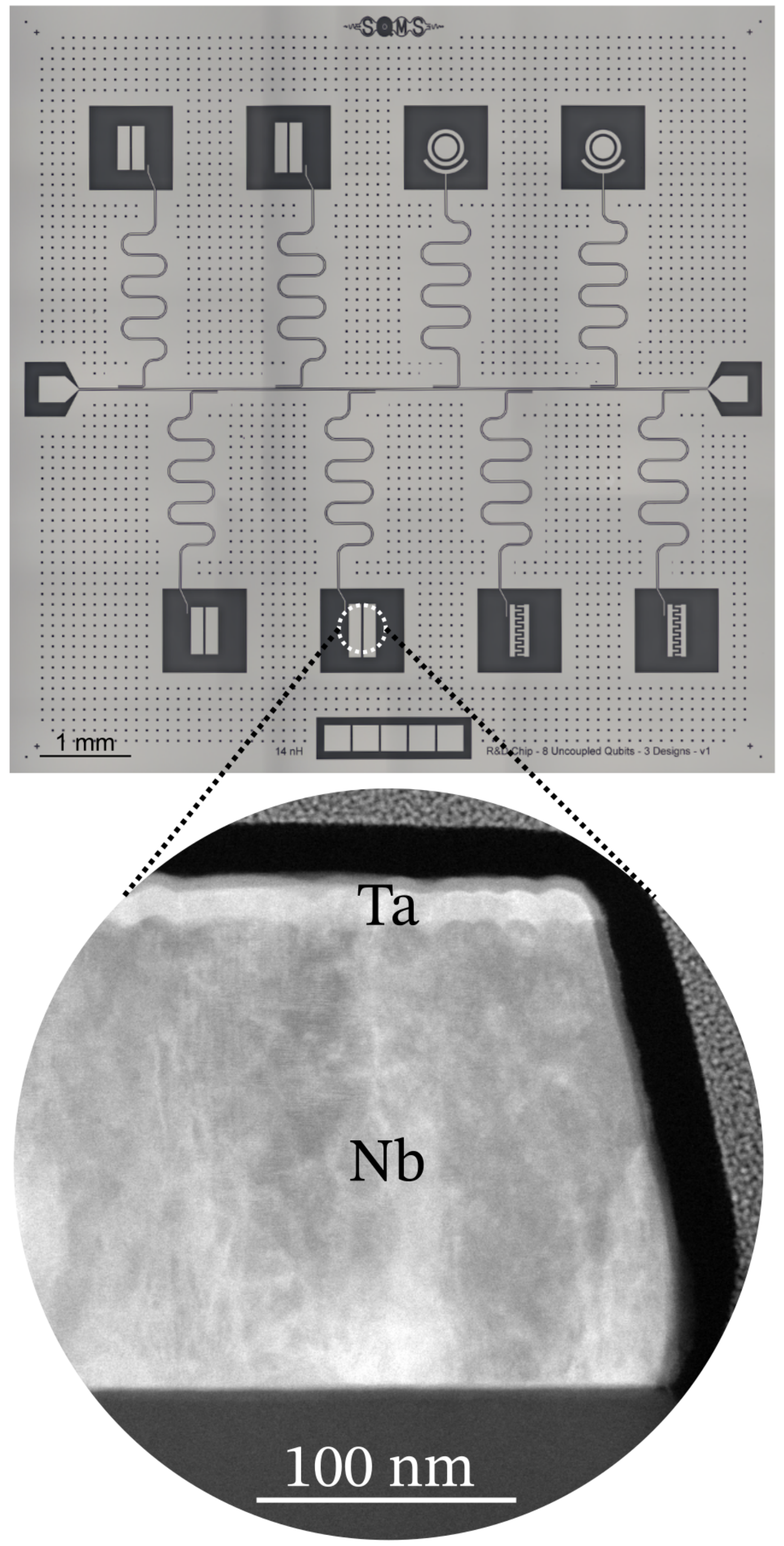






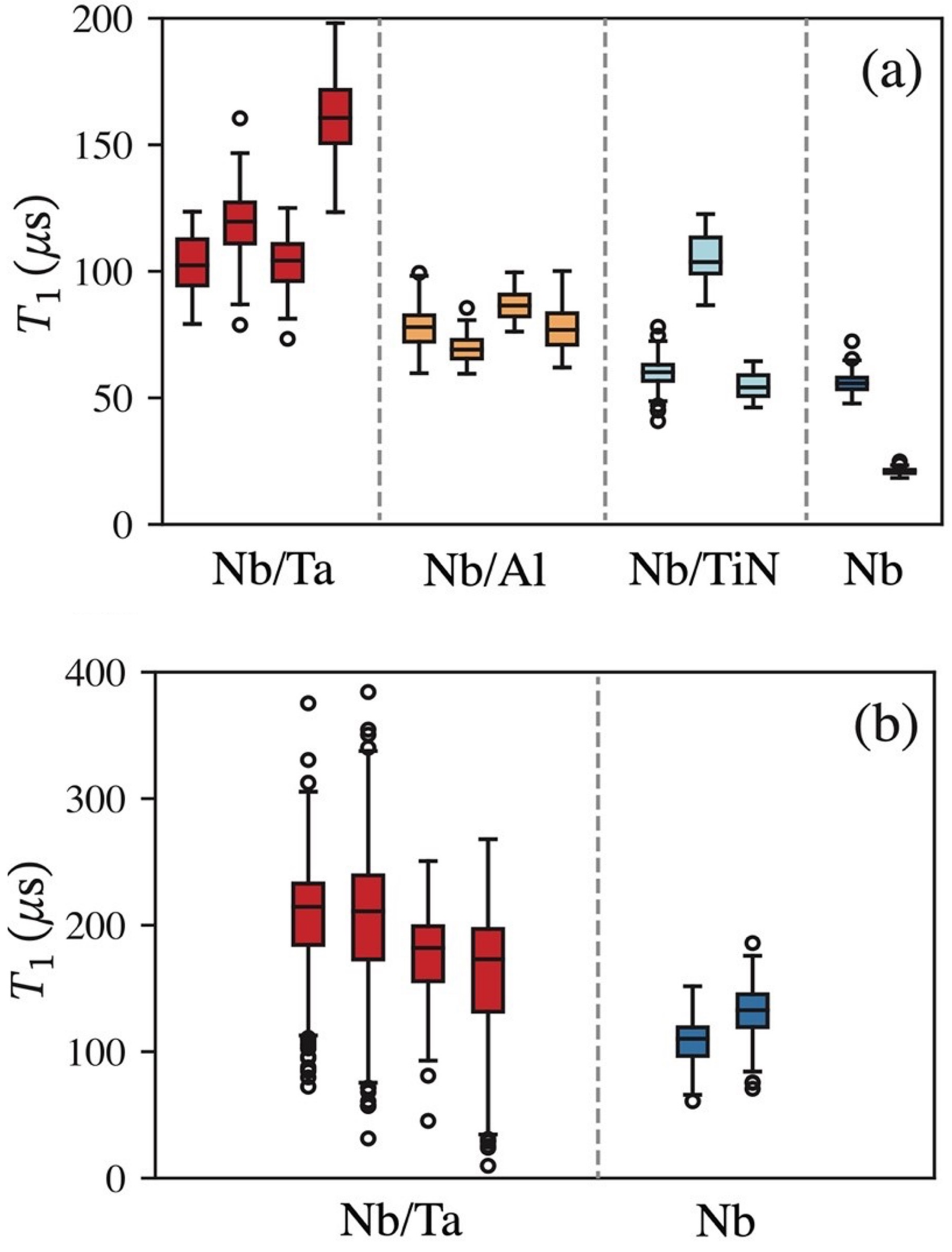
SQMS National Nanofabrication Taskforce

Pushing the Forefront of Qubit Coherence



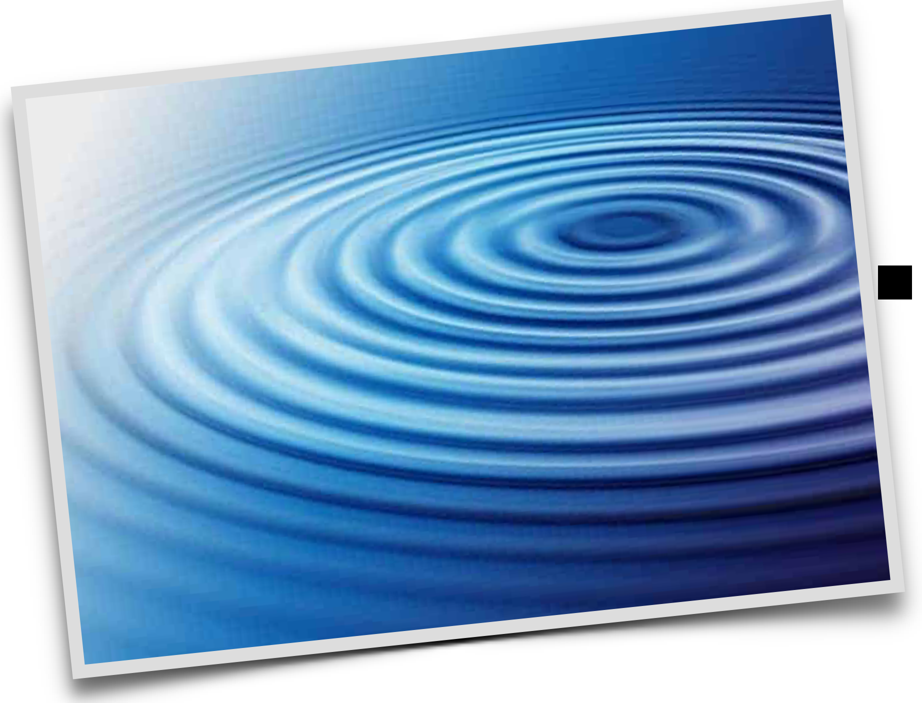
Top published transmon qubit coherence times

Group	Best T_1 (μs)	Freq. (GHz)	Substrate	Primary Material	Publication Year
Yu	503	3.8-4.7	Sapphire	Ta, dry etch	2022
SQMS	**451**	**4.5-5**	**Silicon**	**Ta/Nb, dry etch**	**2023**
Houck	360	3.1-5.5	Sapphire	Ta, wet etch	2021
IBM	340	~4	Silicon	Nb, dry etch	2022
IBM	234	3.808	Silicon	Al, dry etch	2021
SQMS	**198**	**4.5-5**	**Sapphire**	**Ta/Nb, dry etch**	**2023**



arXiv:2304.13257v2

SQMS Physics and Sensing

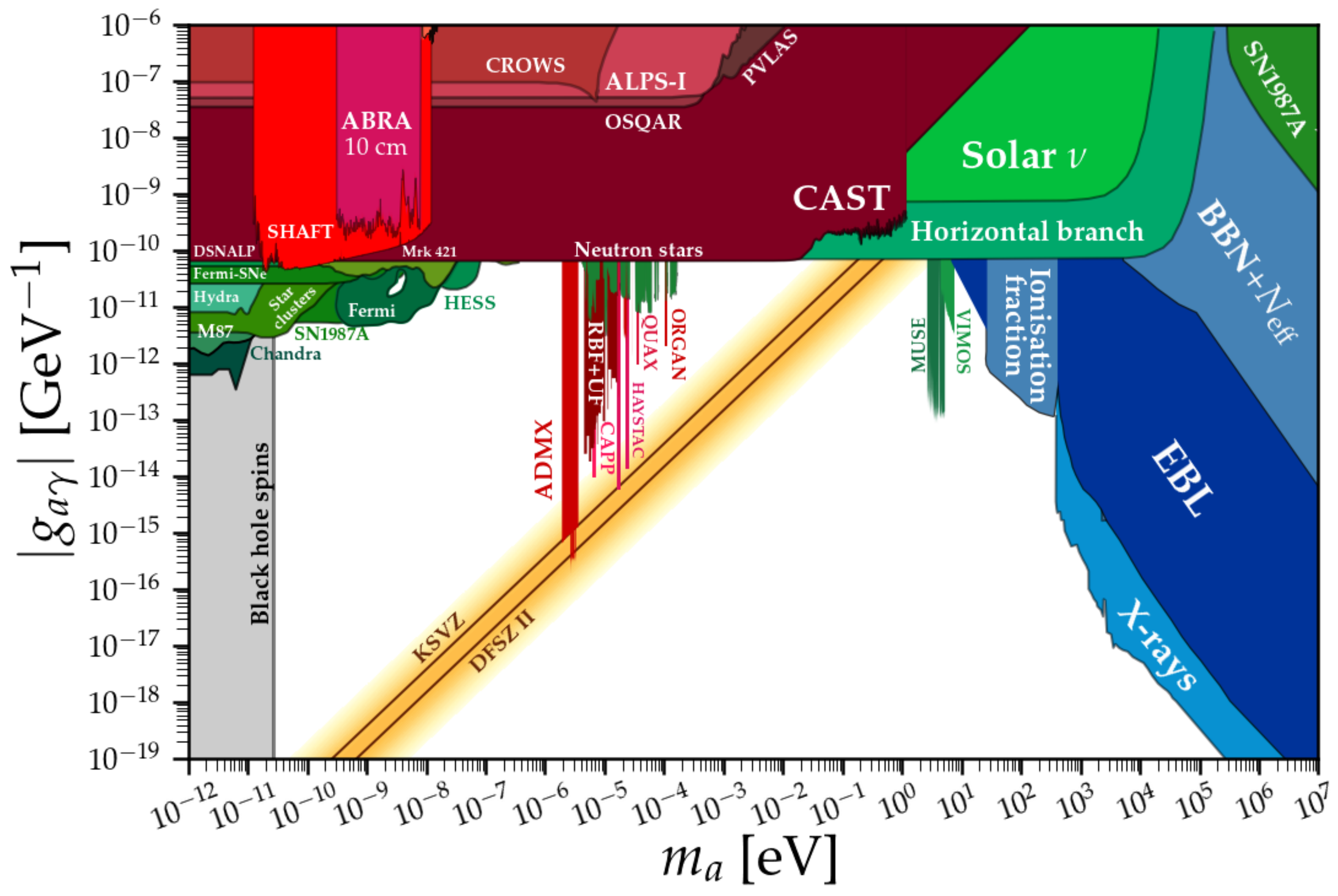


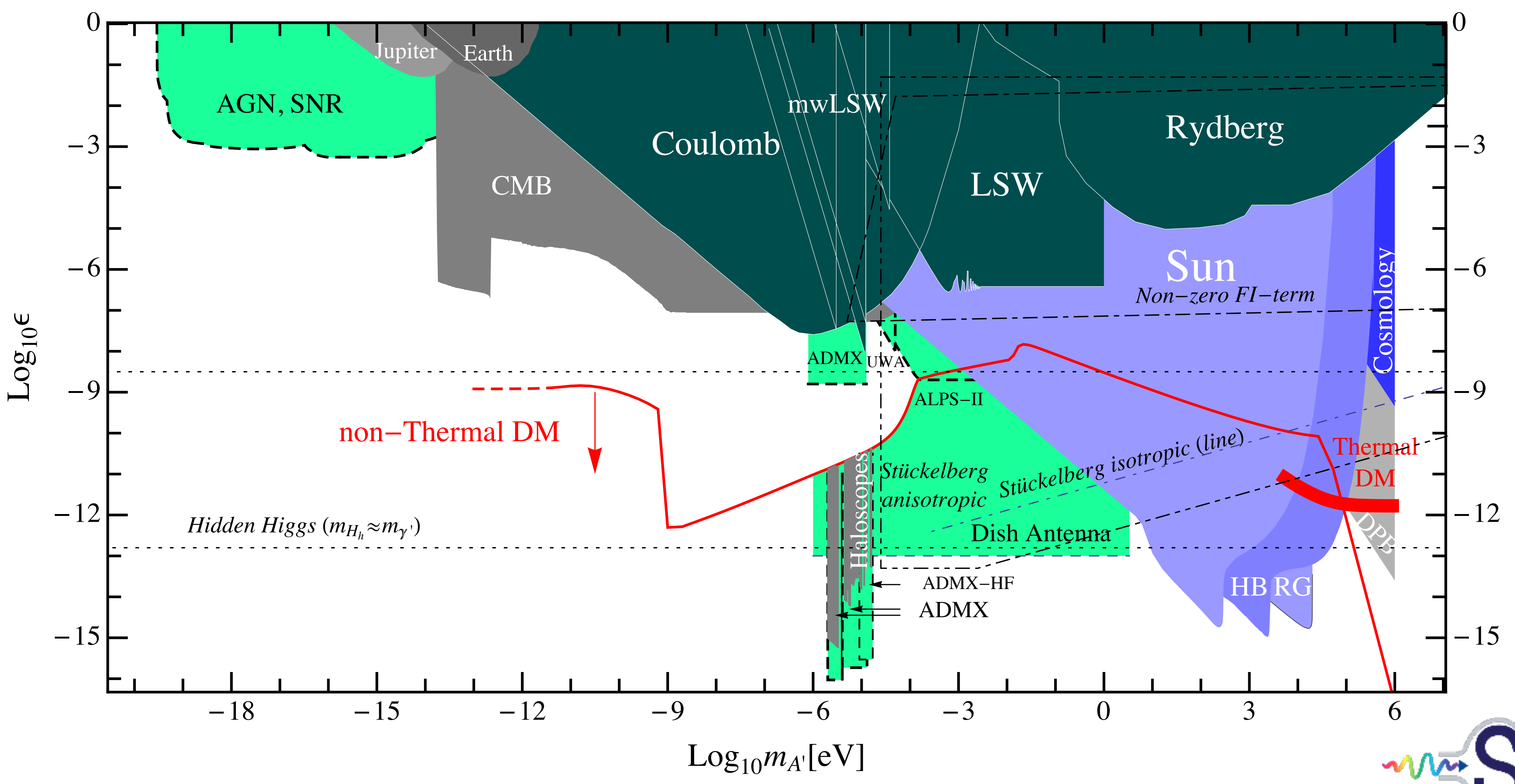
- The SQMS sensing effort is both leveraging and providing ambitious goals for technology
  - **Probing Dark sectors:**
    - New light particles: Dark photons and axions.
    - Either as the dark matter, or as "just" new particle.
    - A multi-search goal. Our most engaging science goal.
  - **Precision 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.

Wave-like DM Detection

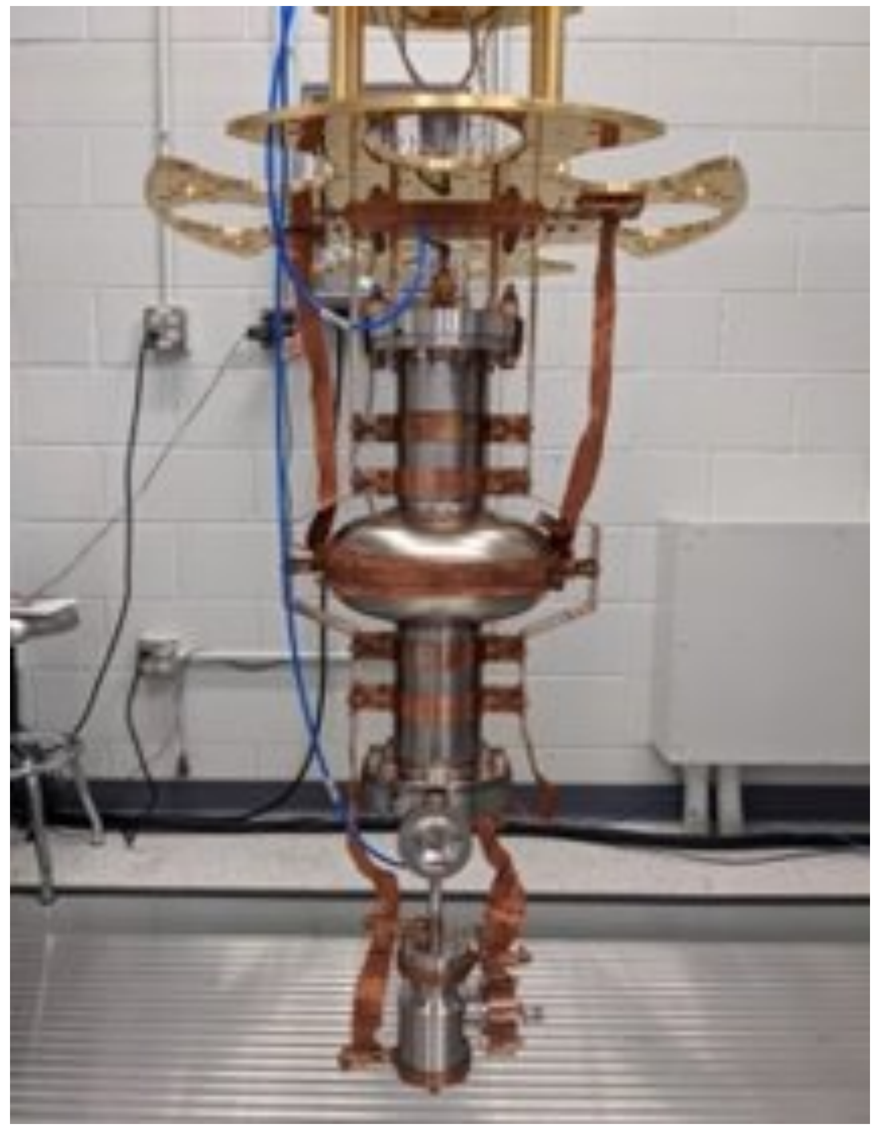
- Several open challenges in Axion and Dark photon DM searches.
- Accelerating the Search in the 1 to tens of GHz:
  - Increase quality factor
  - Going beyond SQL (e.g. photon counting, see Aaron's talk)

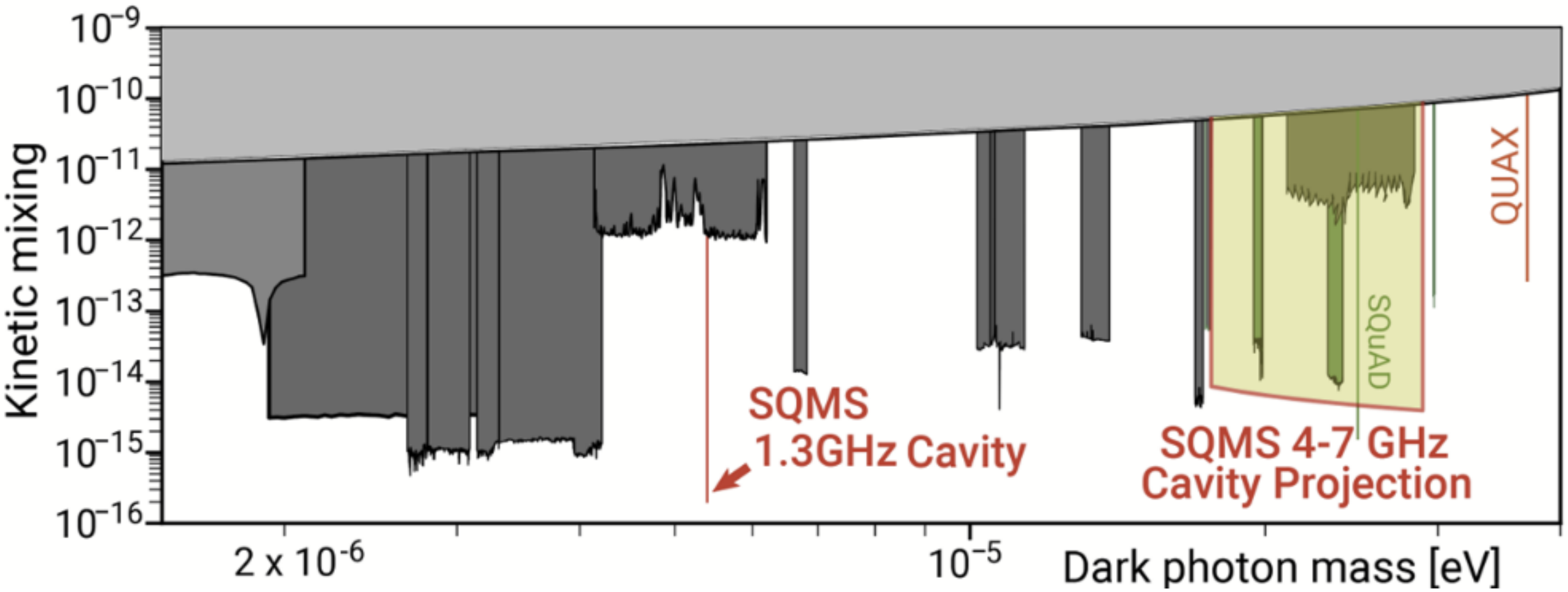
- Expanding the axion/dark photon search window to high and low masses (also non DM searches).





Deepest sensitivity: Ultrahigh Q for Dark photon DM





Cervantes et al., arxiv:2208.03183, in review in Phys. Rev. Lett.

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

Deepest exclusion to wavelike DPDM by an order of magnitude.

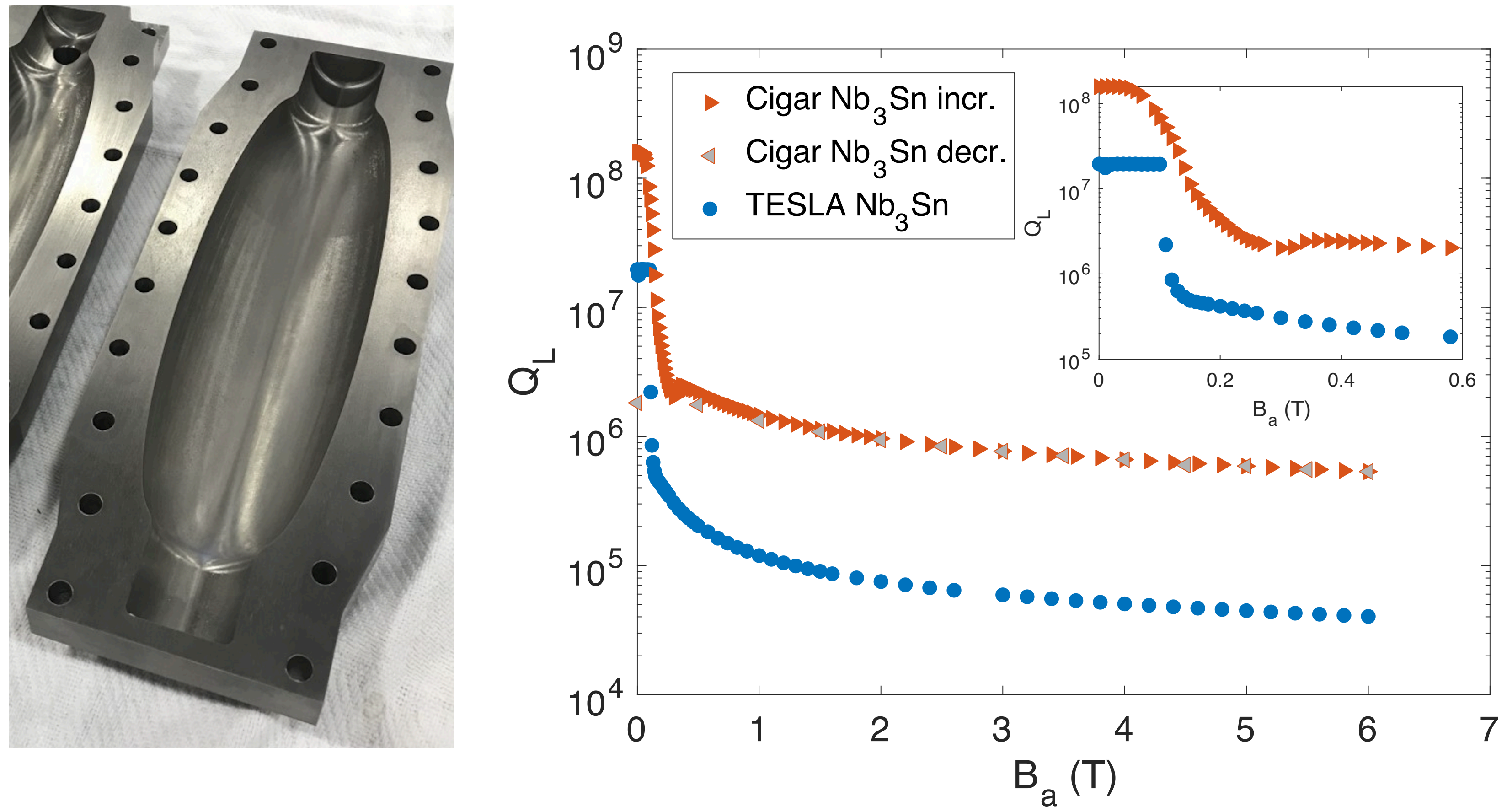
Next steps:

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

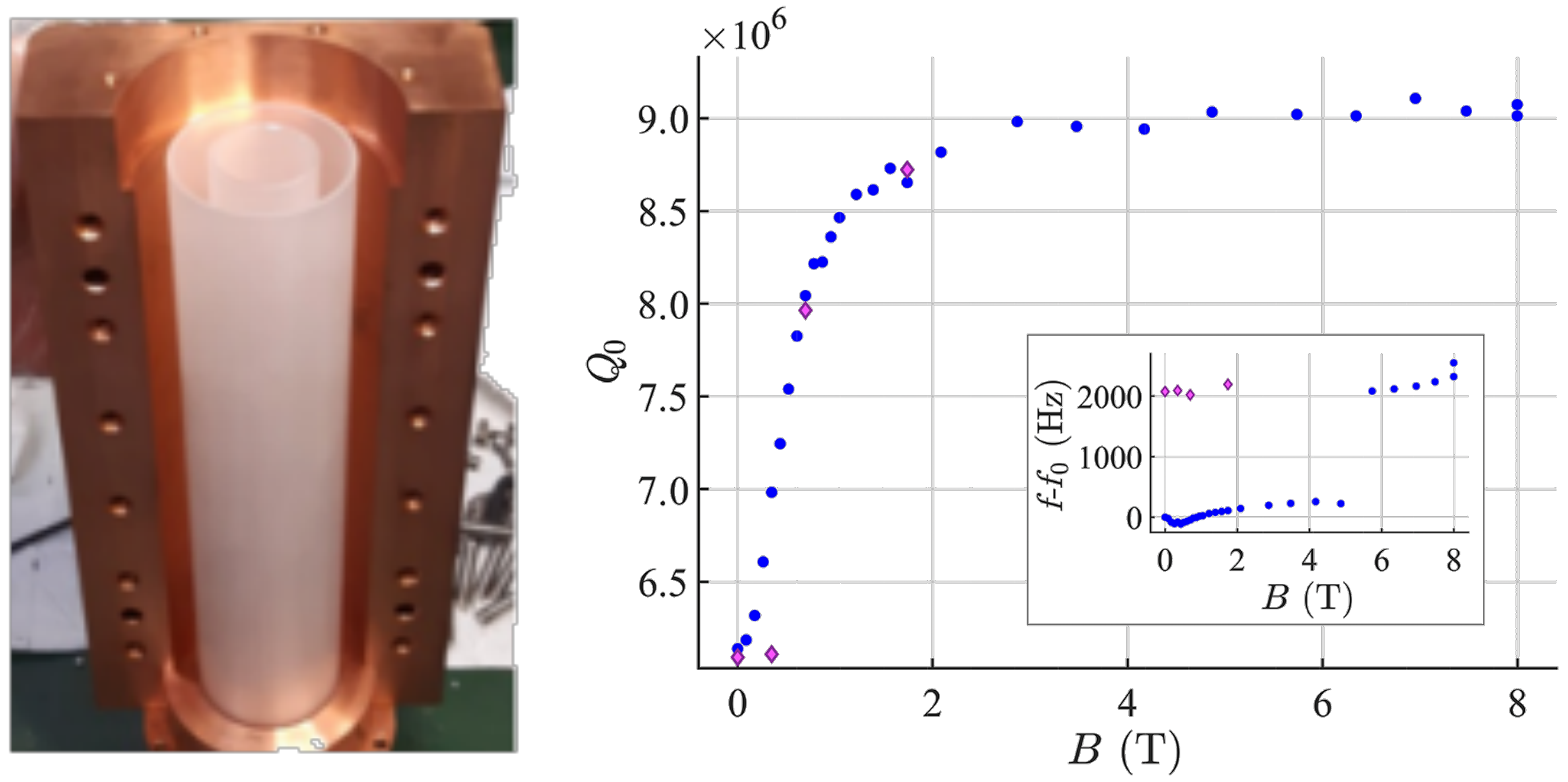
Contacts: Raphael Cervantes

Dark Sector: High Q in Multi-Tesla Fields

- **Axion haloscope**: search for dark matter with high Q cavity in multi-tesla magnetic fields
- **Two SQMS designs** substantially outperform state of the art copper cavities (and these ideas can be combined!)
- Now **partnering with ADMX team** for first demonstration of a hybrid superconducting-normal-conducting cavity in a real axion search.



Superconducting Nb_3Sn cavity (FNAL): Posen et al., arxiv:22014.10733, in review in Phys Rev Applied



Hybrid copper-dielectric cavity (INFN): Di Vora et al., PhysRevApplied.17.054013

Contact: Sam Posen

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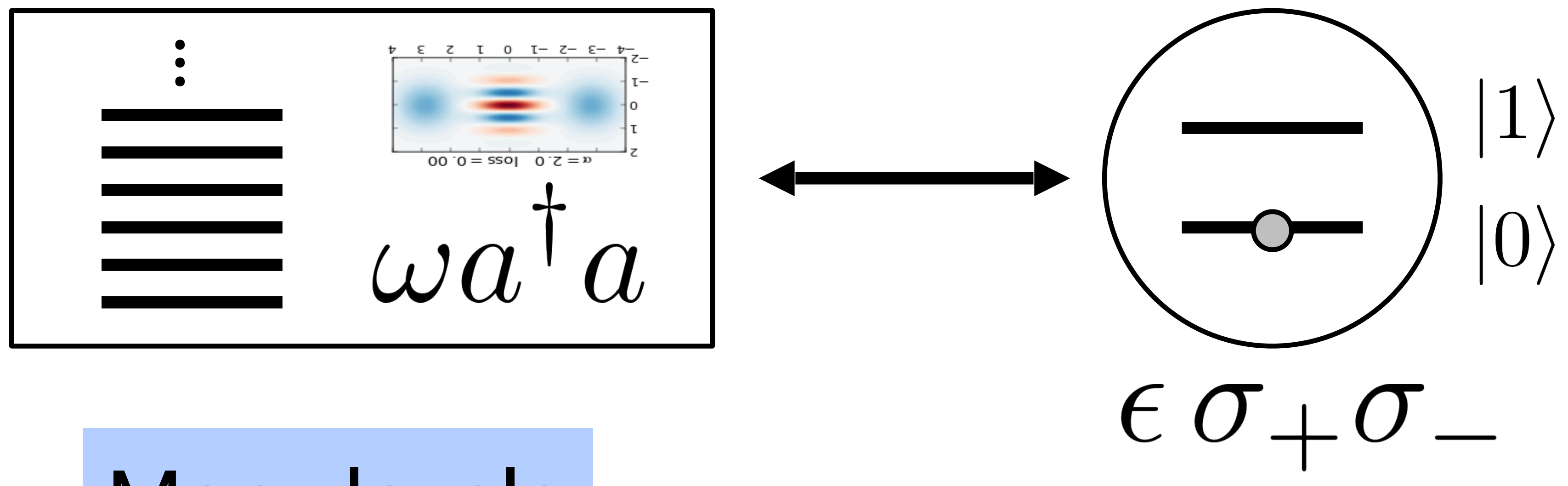
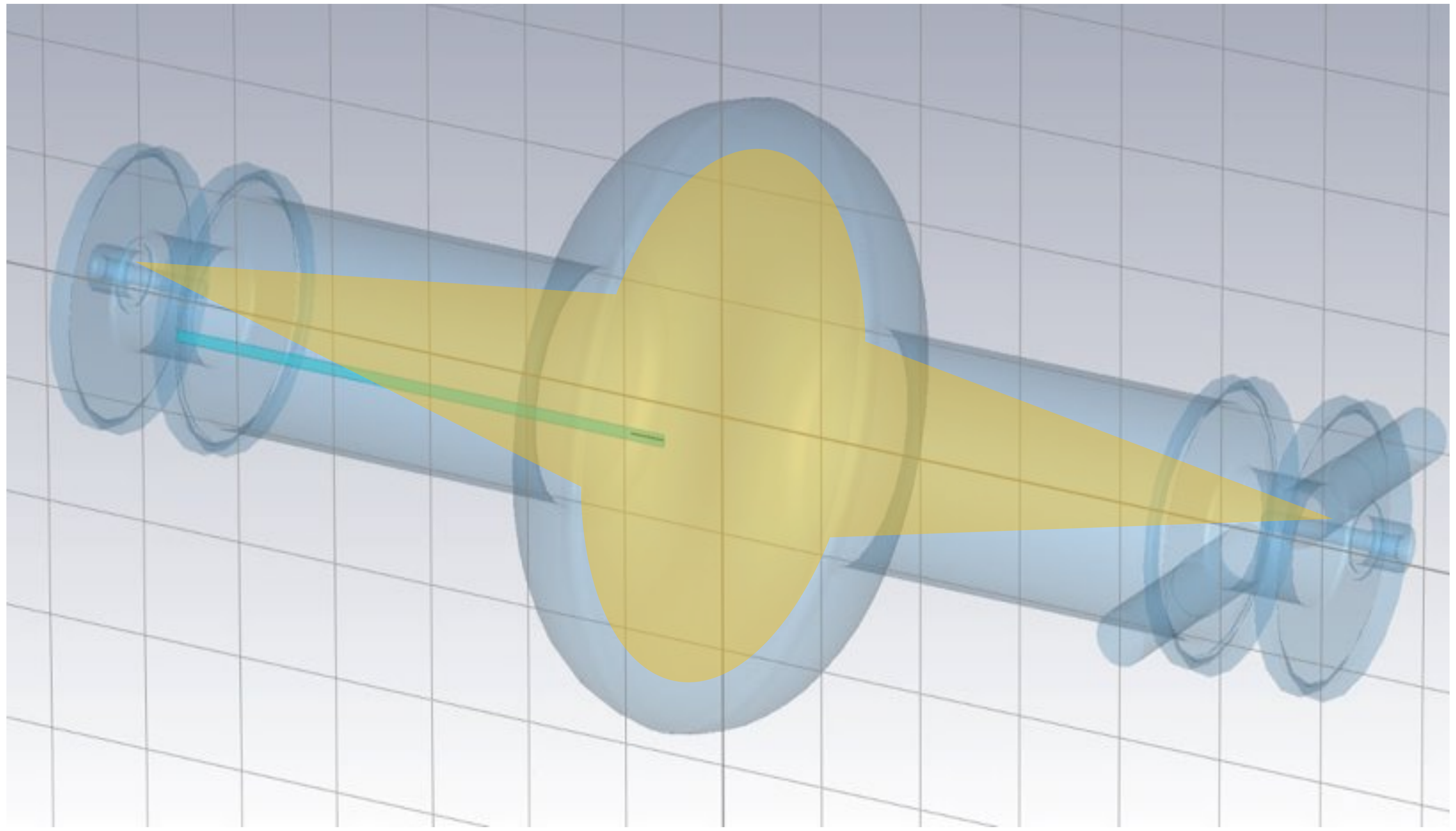
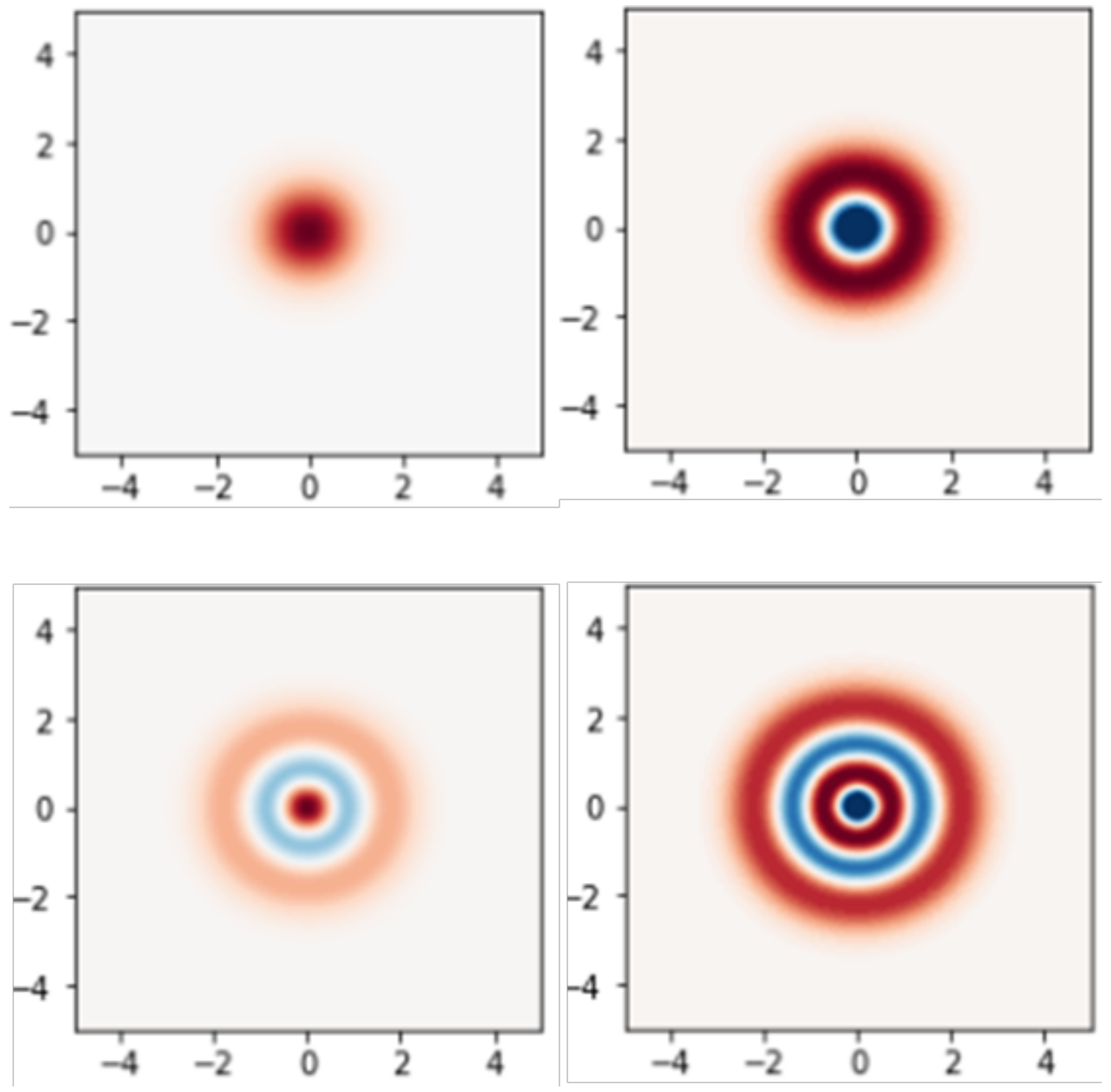
New approach to QC: Qudit

Access and control higher quantum levels



Many levels

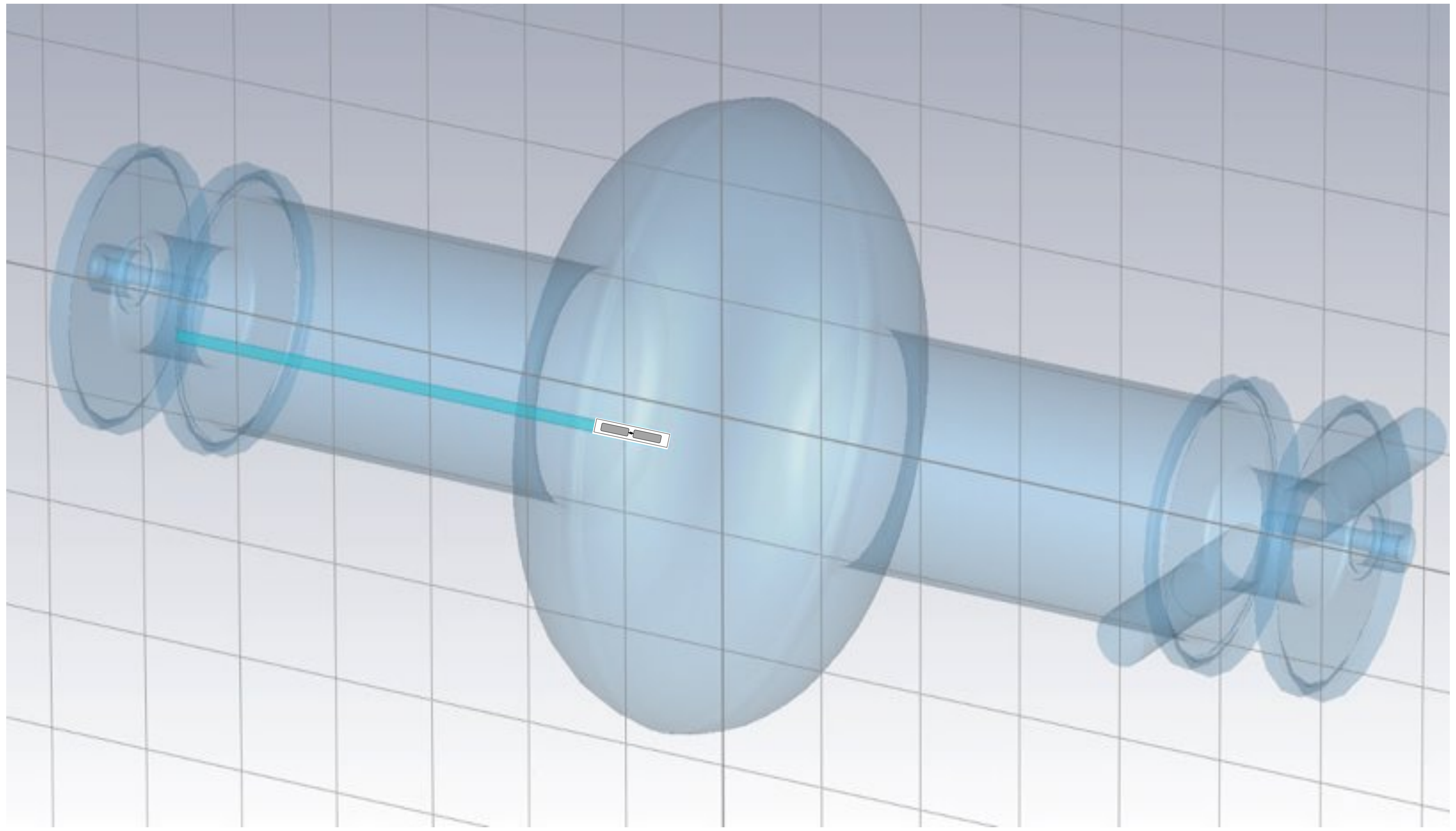


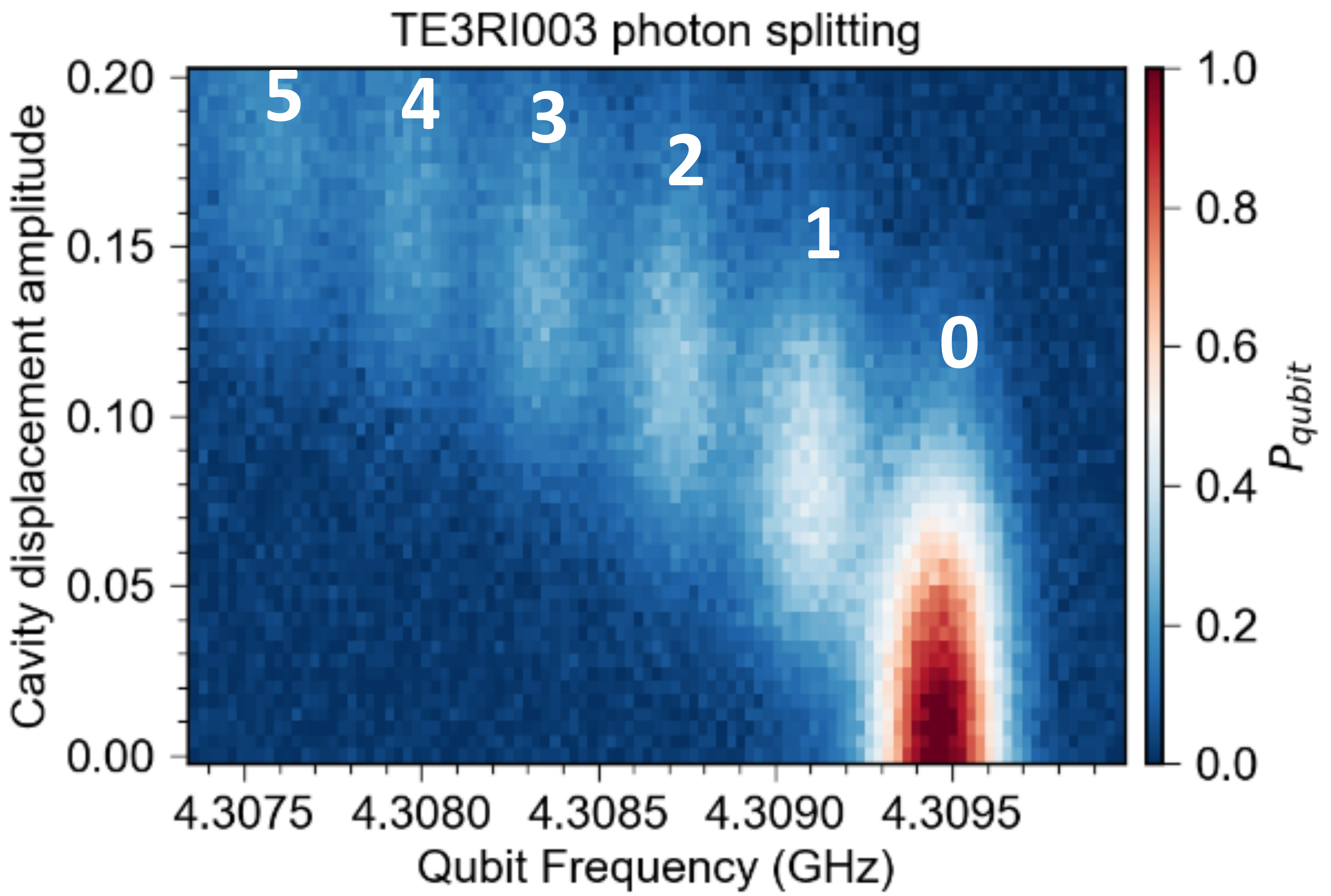


4-levels: Ququart | 2 qubits

8-levels: Quoct | 3 qubits

First Milestone: Photon Counting



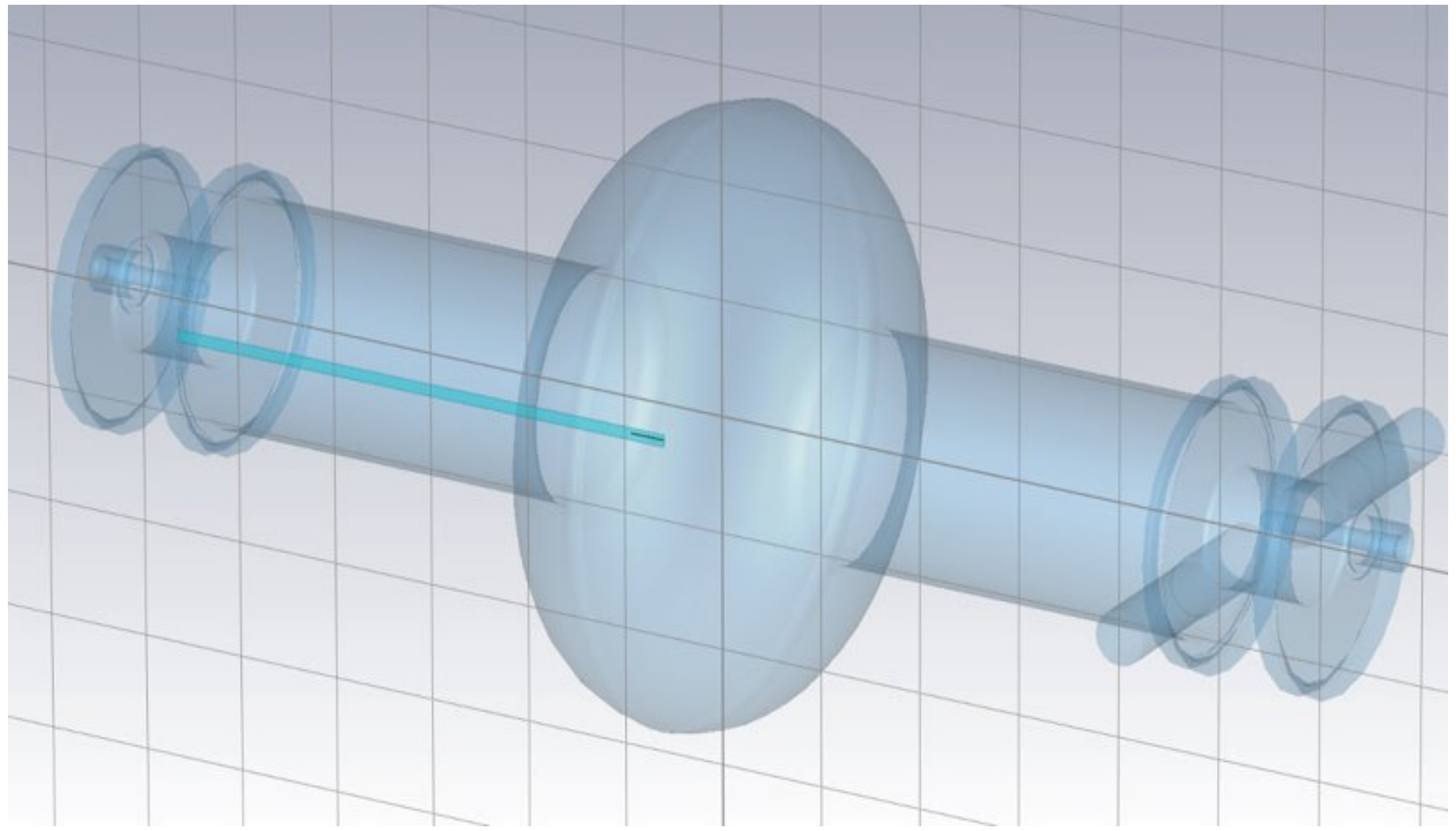


Incorporate Transmon into a TESLA cavity

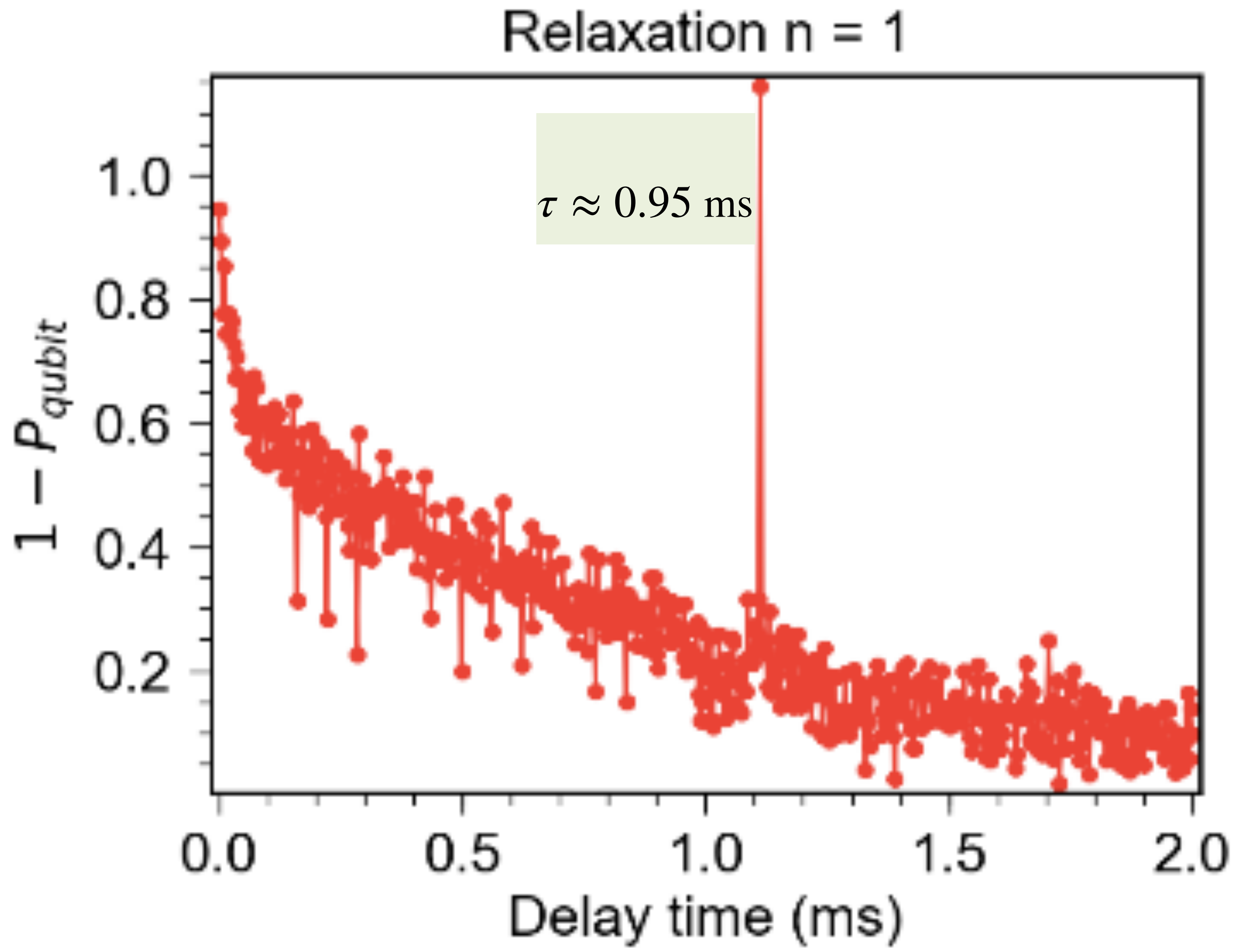
Achieved photon counting

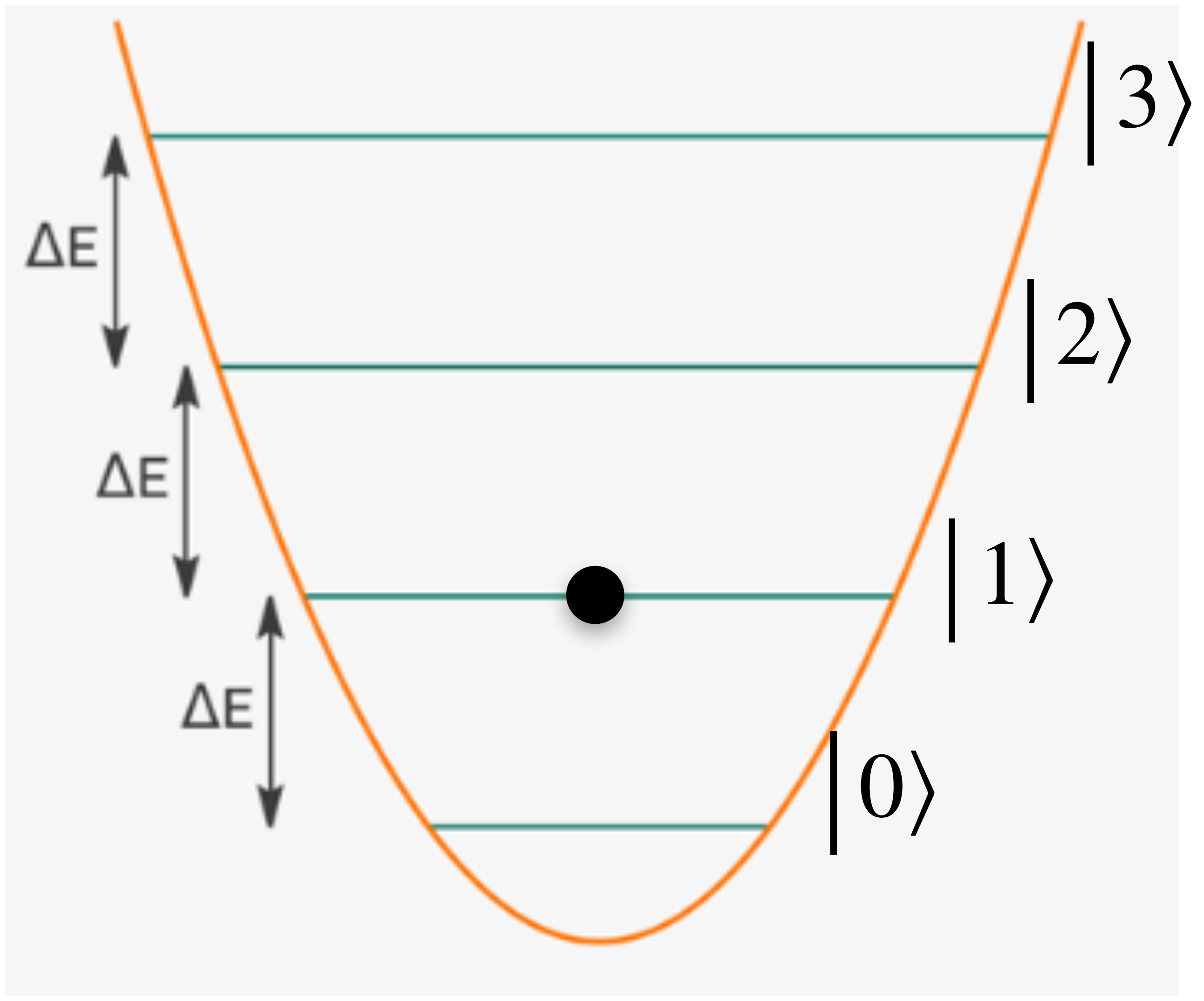
Contacts: Alex Romanenko, Tanay Roy.

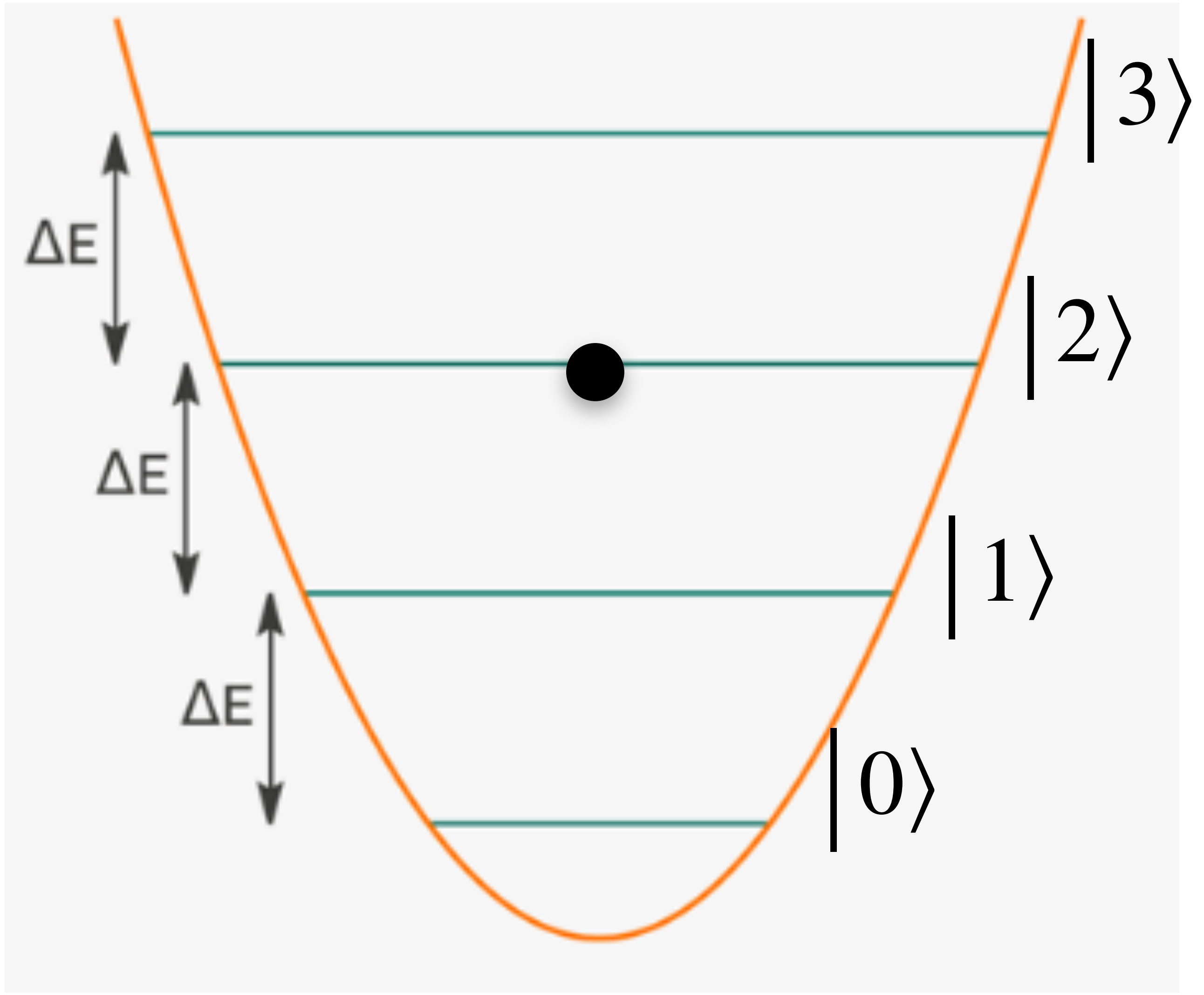
Second Milestone: Fock states



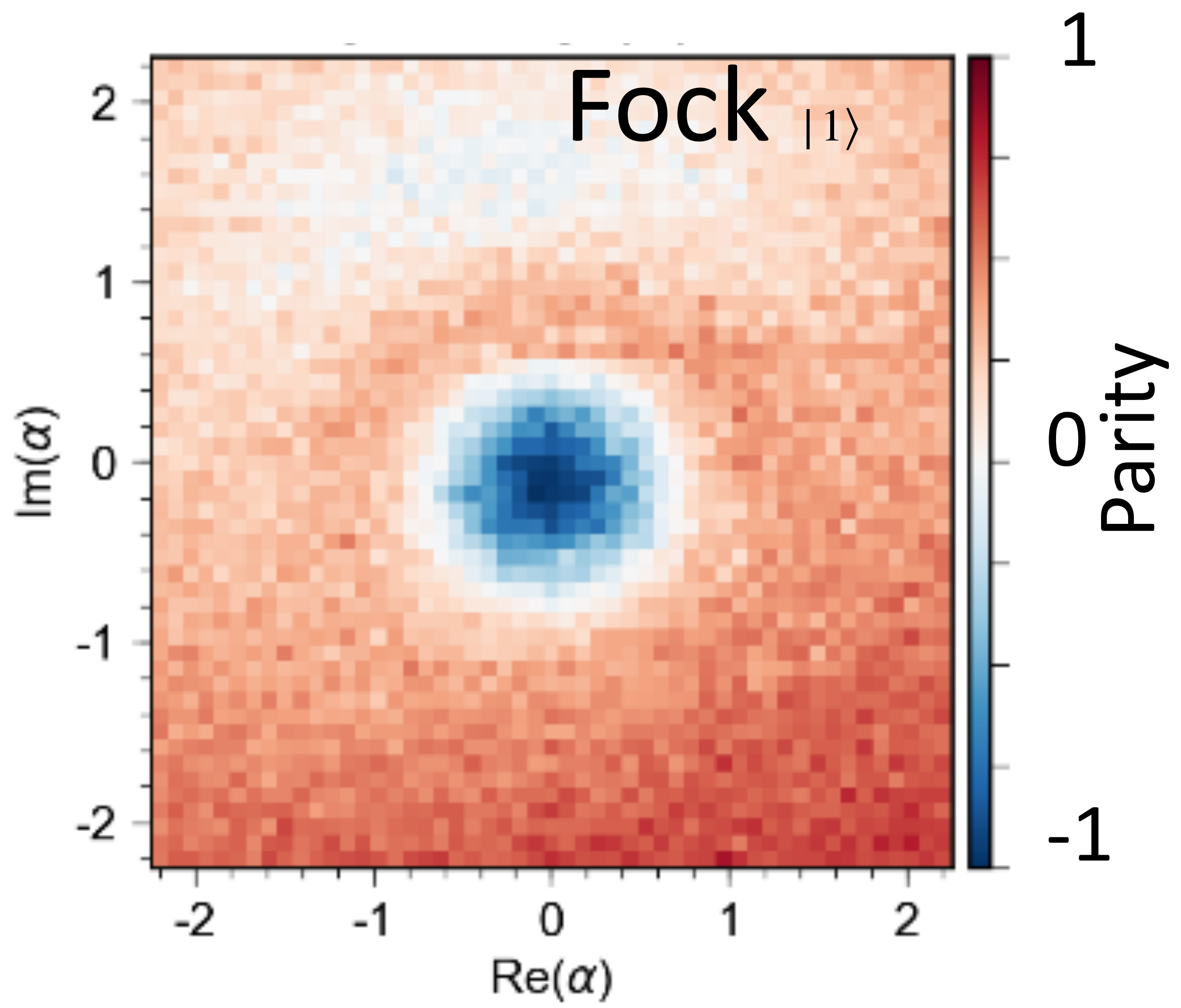
Prepare quantum states

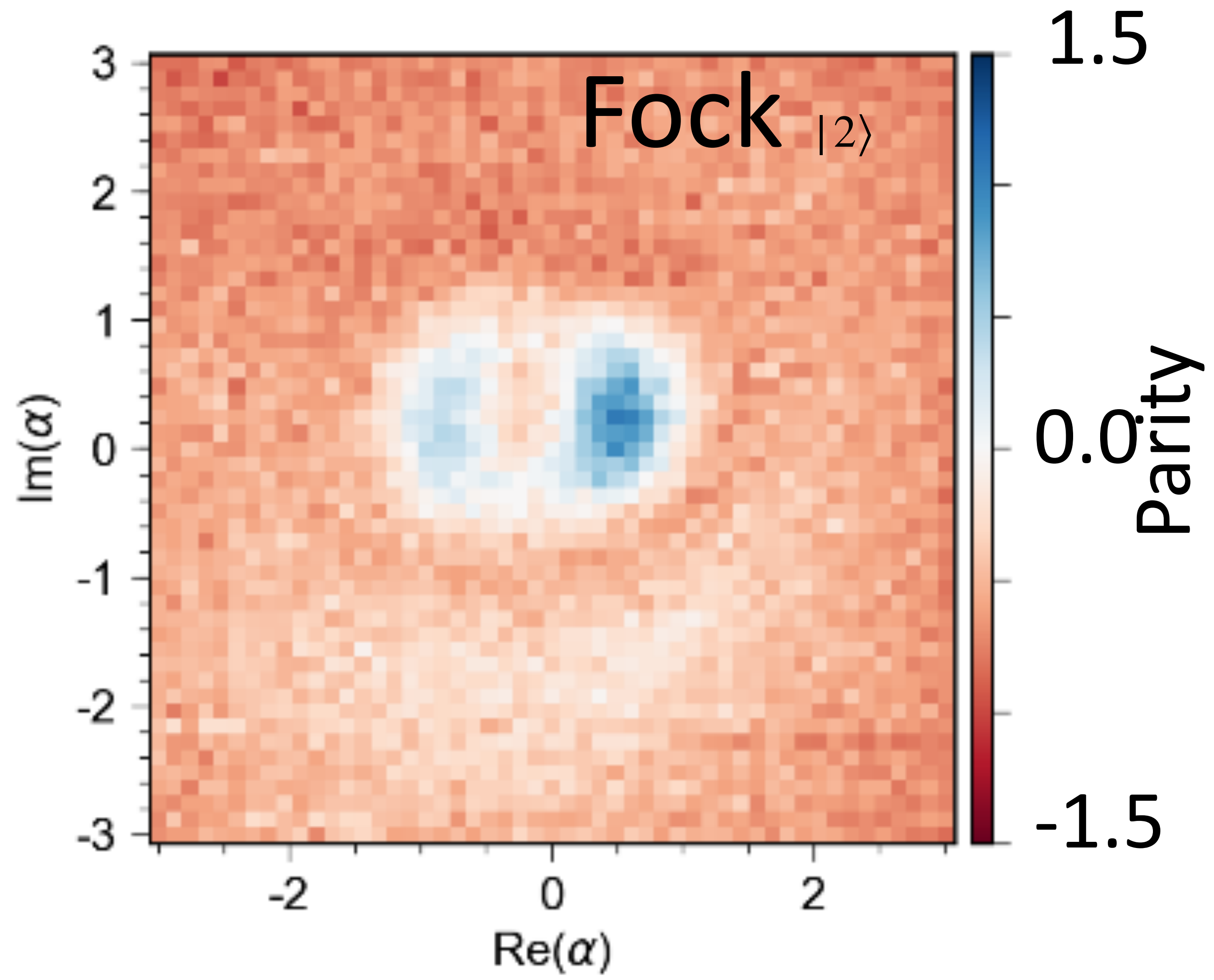






Wigner tomography



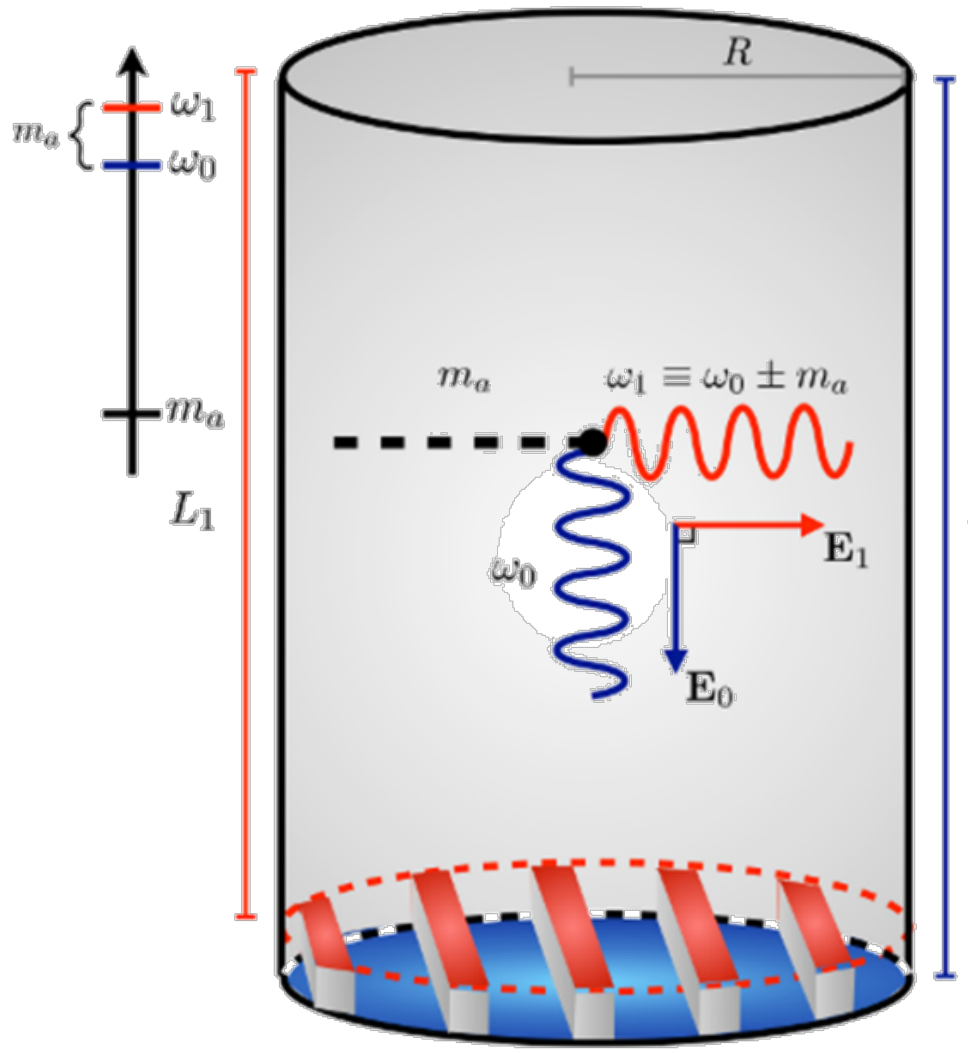


Contacts: Alex Romanenko, Tanay Roy.

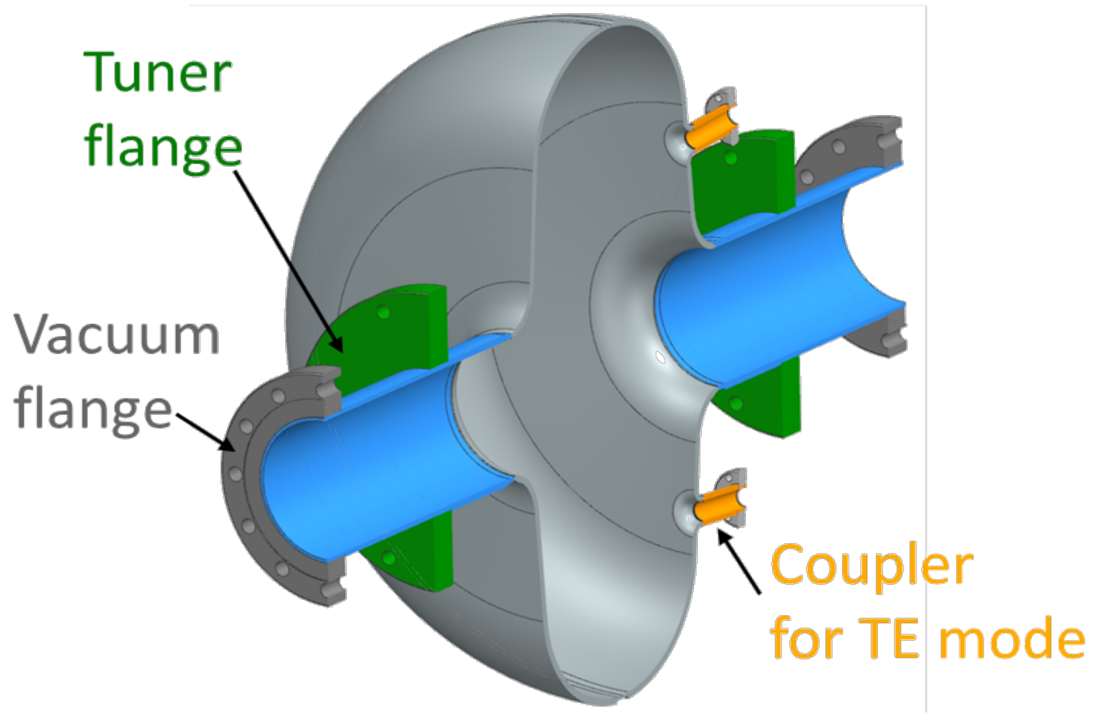
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Multimode searches

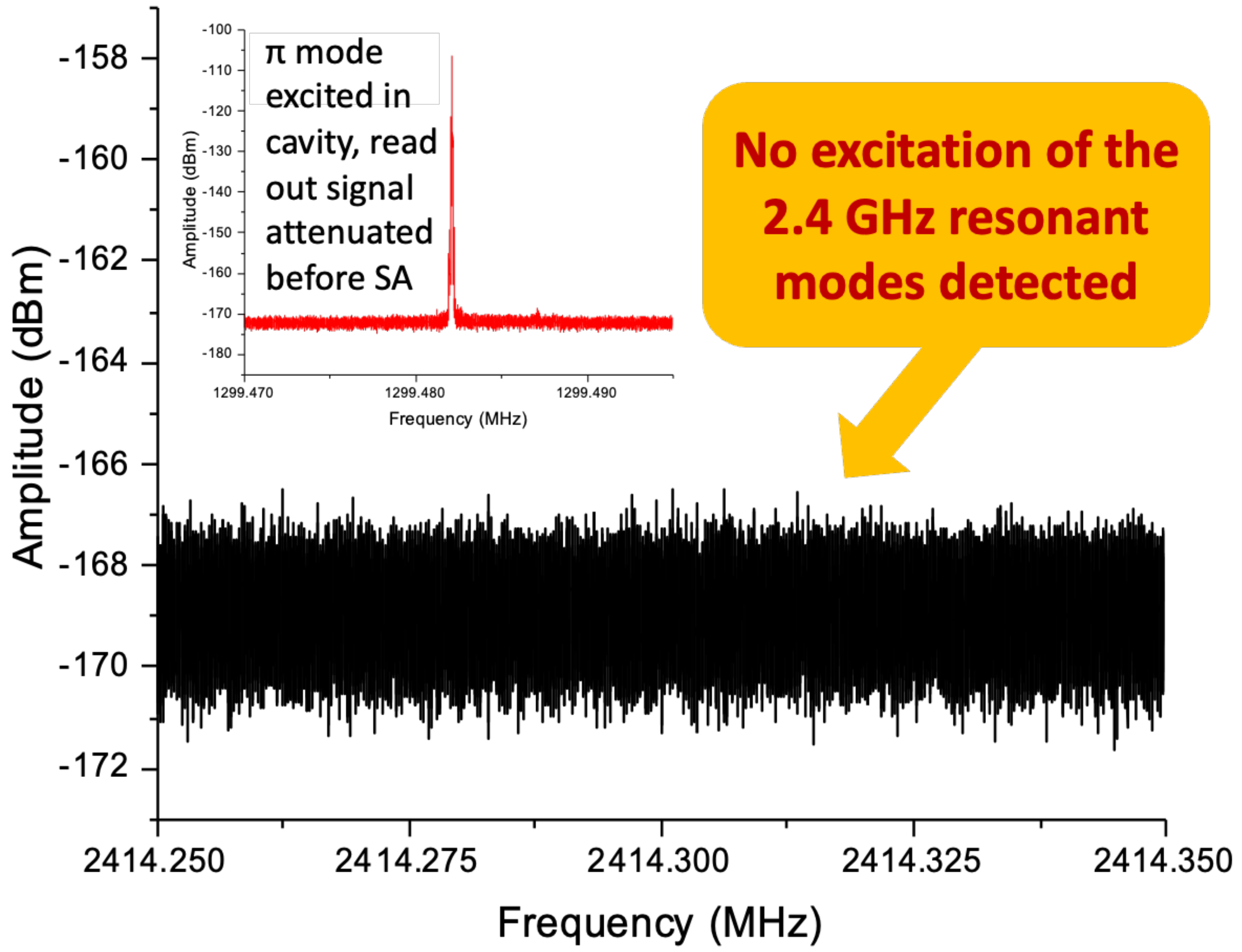
Bogorad, et al., PRL, DOI:10.1103/PhysRevLett.123.021801
Berlin, et al., JHEP, DOI:10.1007/JHEP07 (2020) 088
Gao & Harnik, JHEP, DOI:10.1007/JHEP07 (2021) 053
Berlin, et al., arXiv:2203.12714, Snowmass WP (2022)
Sauls, PTEP, DOI:10.1093/ptep/ptac034 (2022)
Giaccone, et al., arXiv:2207.11346 (2022)



Axion DM search concept



Experimental design for MHz Axion search



- Axion DM search based on the heterodyne detection scheme: cavity design is finalized, contract for cavity fabrication placed (cavity arrival: Fall 2023)
- In preparation for search:
  - Working on RF experimental set up and read out system
  - Addressing experimental challenges such as passive dampening of vibrations in LHe facility
  - Multimode feasibility study

Contacts: Asher Berlin, Bianca Giacone

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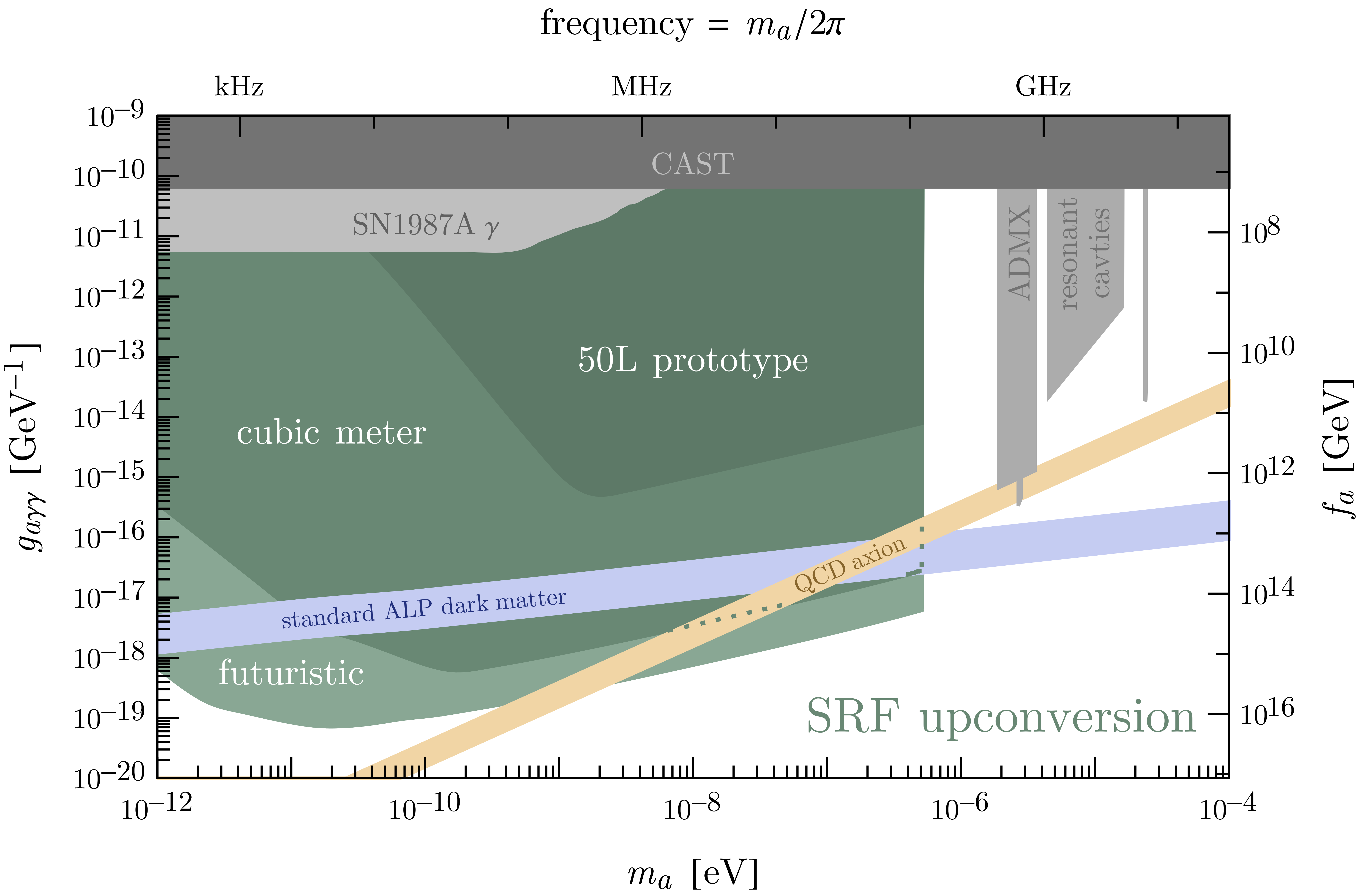
Multimode searches

Berlin, et al., JHEP, DOI:10.1007/JHEP07 (2020) 088
Berlin, et al., arXiv:2203.12714, Snowmass WP (2022)
Giaccone, et al., arXiv:2207.11346 (2022)

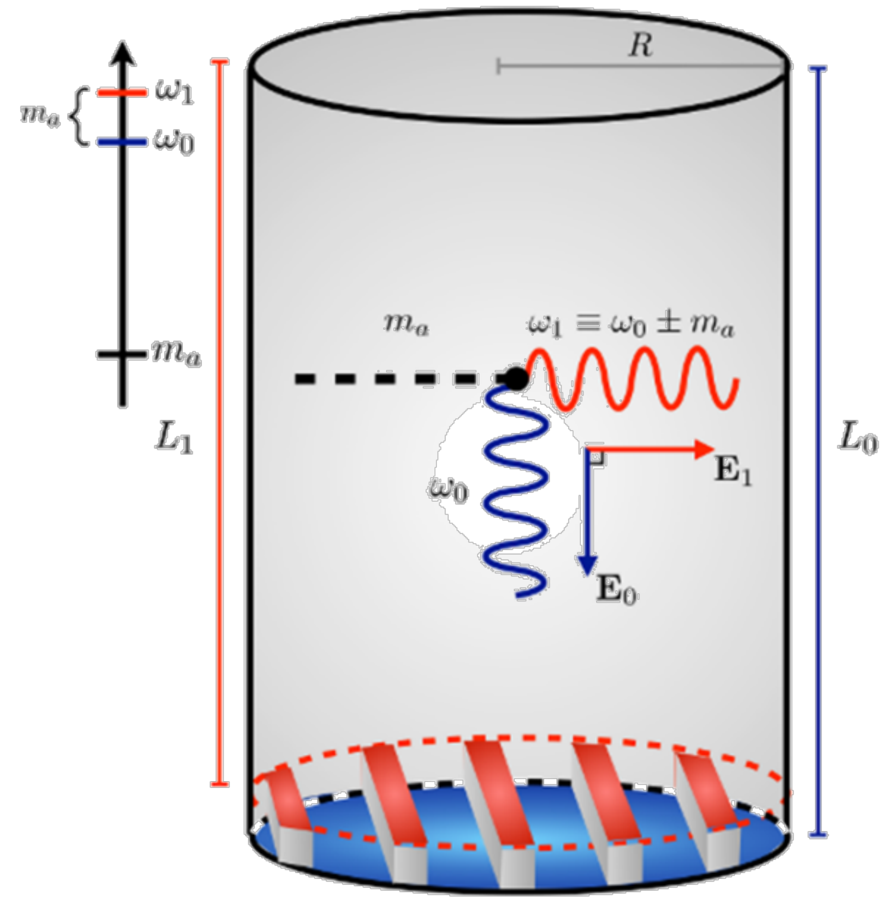


Snowmass name:

SRF-m³

Asher's proposal:

SuperRAD



Contacts: Asher Berlin, Bianca Giacone

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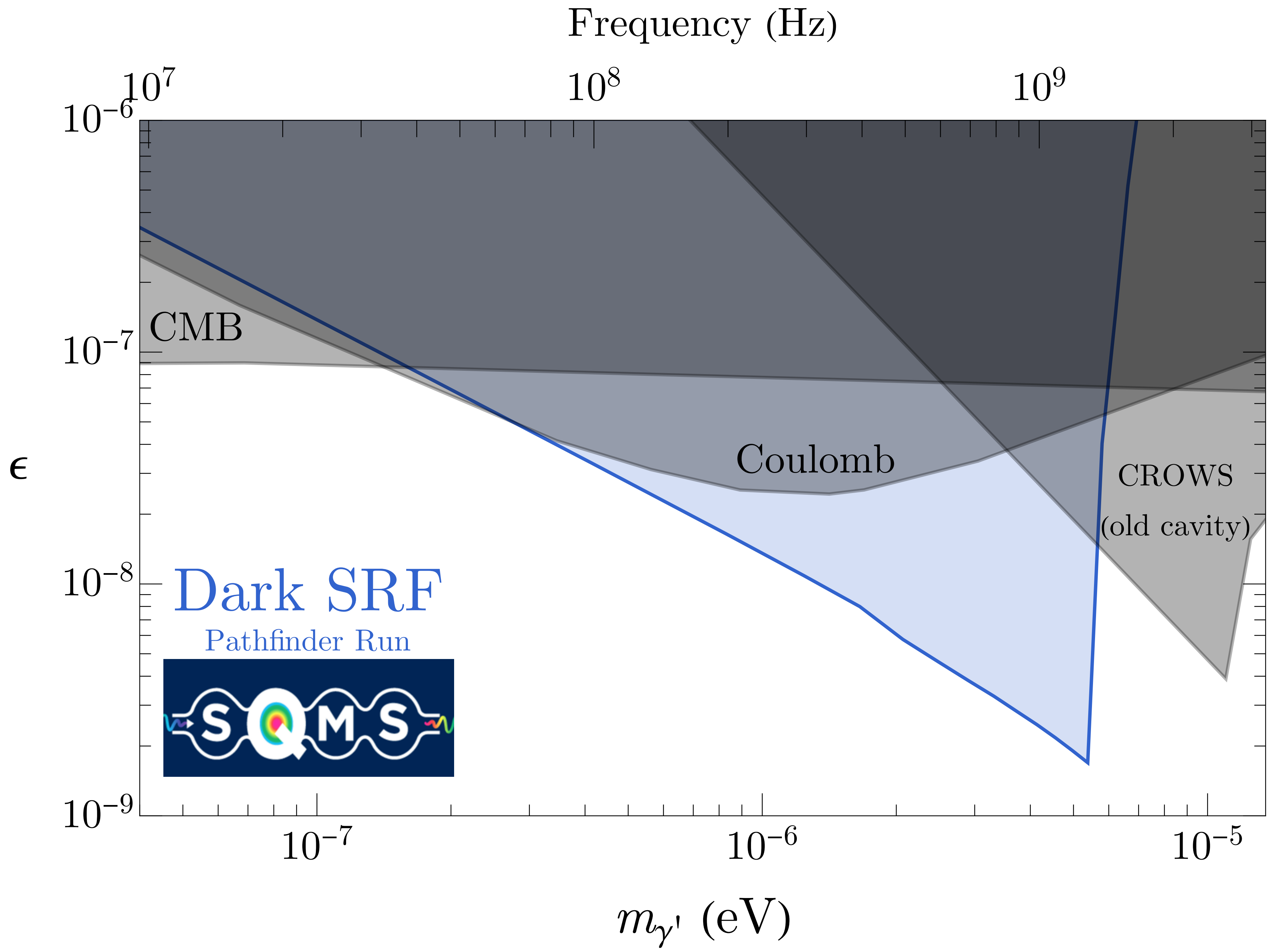
Dark SRF: cavity-based search for the Dark Photon

A light-shining-through-wall experiment.

Phase 1: Pathfinder run in LHe. Demonstrated enormous potential for SRF based searches.



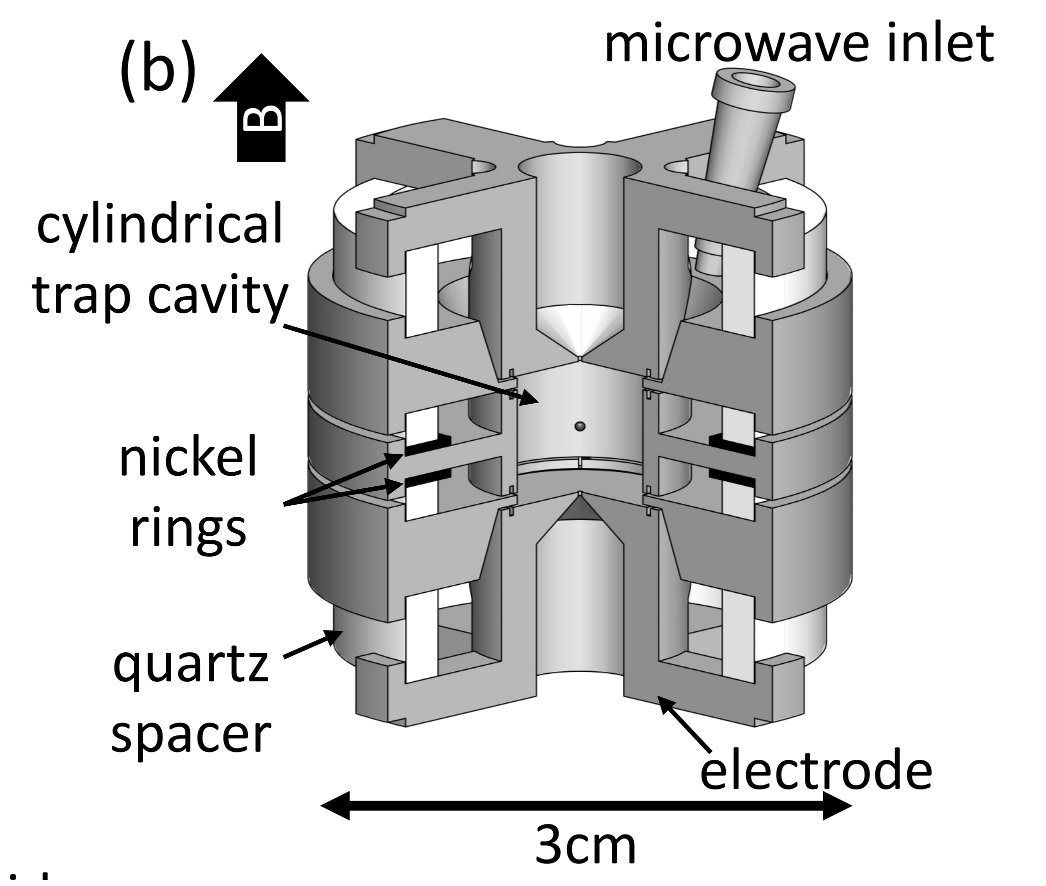
Phase 2: in DR, receiver at ~mk, in quantum regime. Improved frequency stability. Phase sensitive readout.

Will increase the search reach.

Contacts: Alex Melnichuk, RH

Romanenko et al., arXiv:2301.11512 (2023), in review in PRL.

Single Particle Qubit



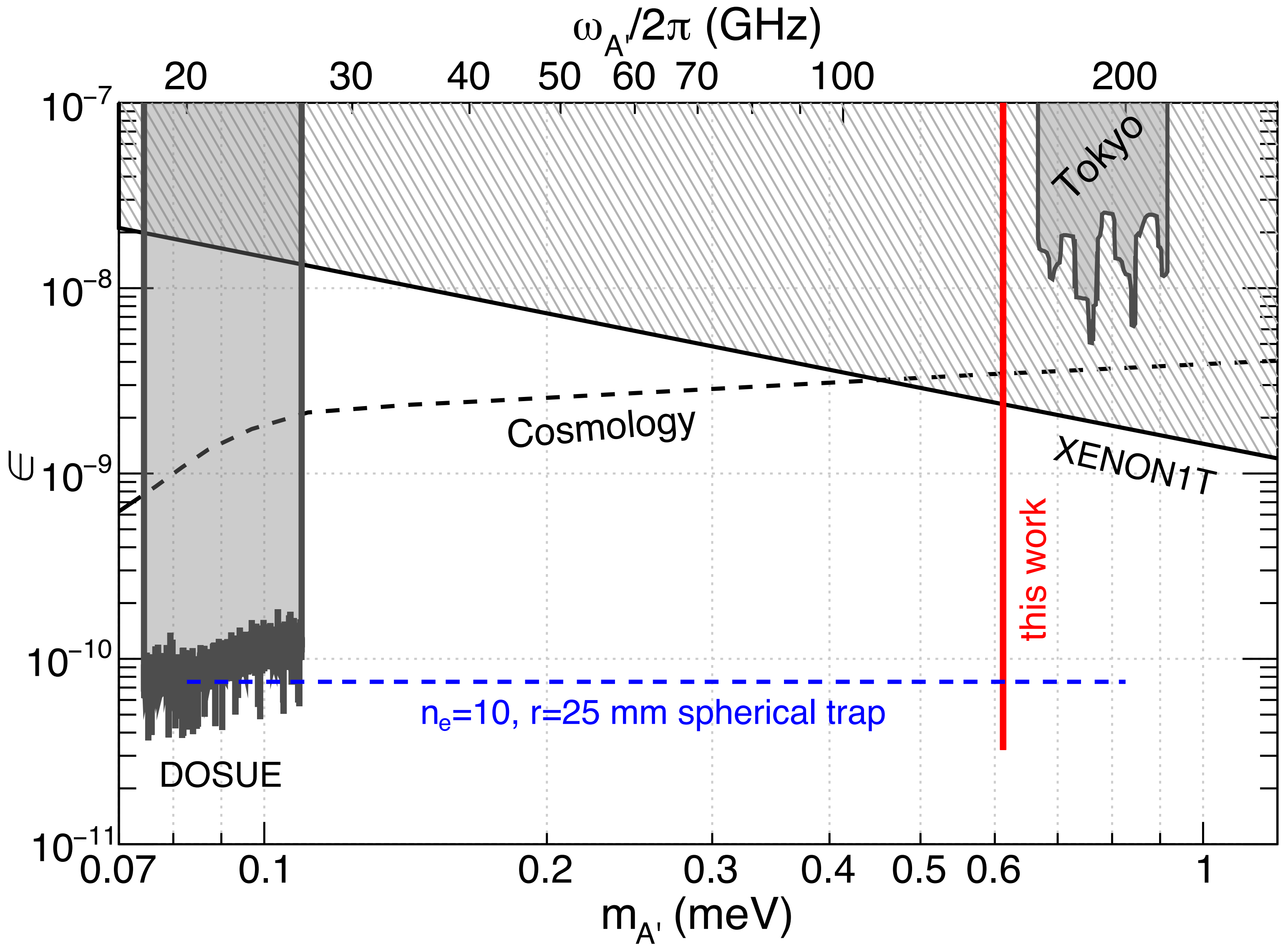
- The most precise theory-experiment comparison in physics:

Electron magnetic moment (g-2)$_e$:
The quantum state of a single electron in a trap is monitored via a **QND measurement**.

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13 \text{ ppt}]$$

Phys. Rev. Lett. 130, 071801 (2023)
Editors choice!

- SQMS joined the effort, contributed to understanding loss sources.



- **SQMS bonus:** We also found that a single-electron qubit is a sensitive DM search in a challenging frequency range!
- Theory + proof-of-concept!

Contacts: RH

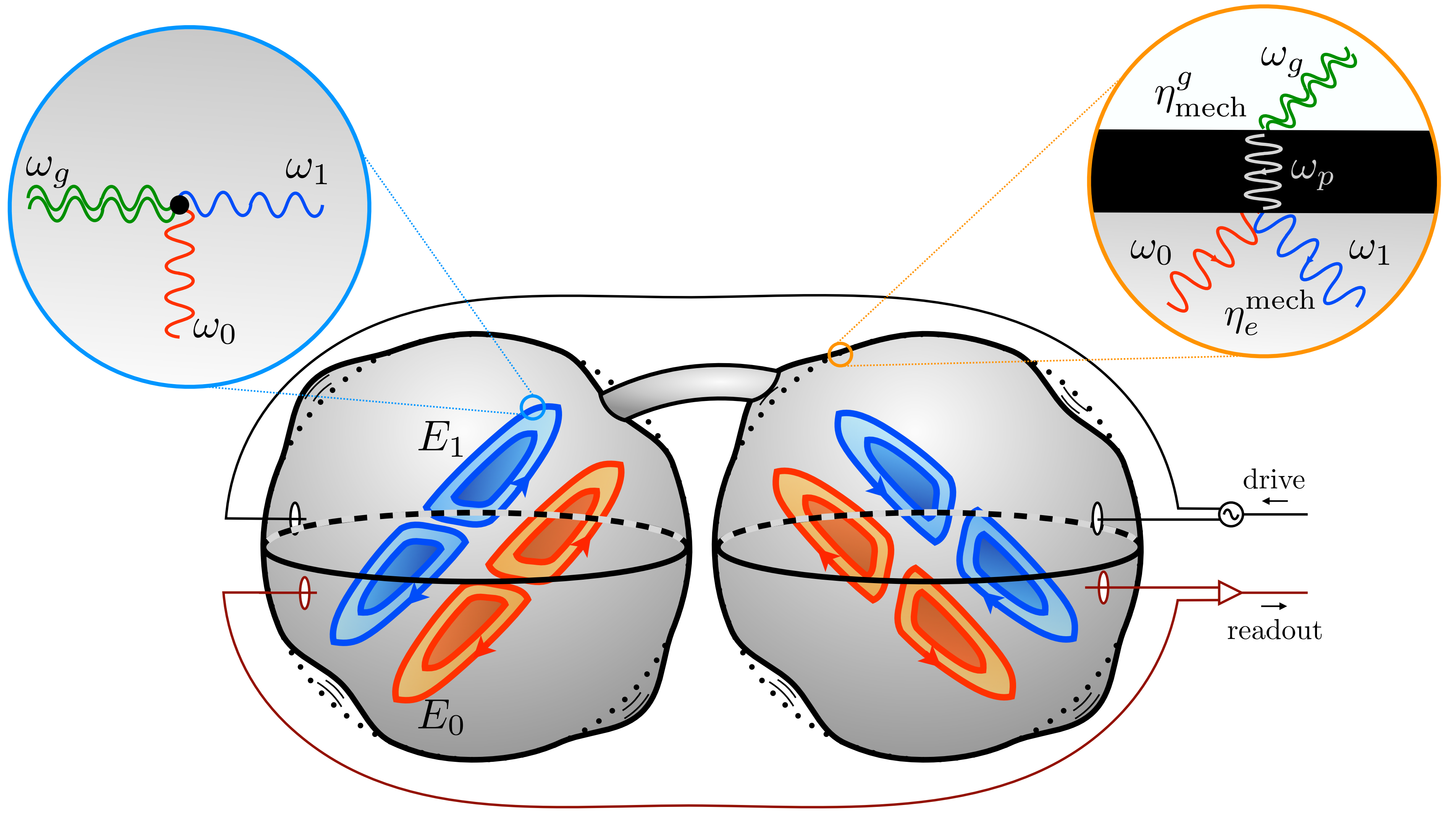
Phys.Rev.Lett. **129 (2022) 26, 261801**
(a new NU-Stanford-Fermilab collaboration)

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

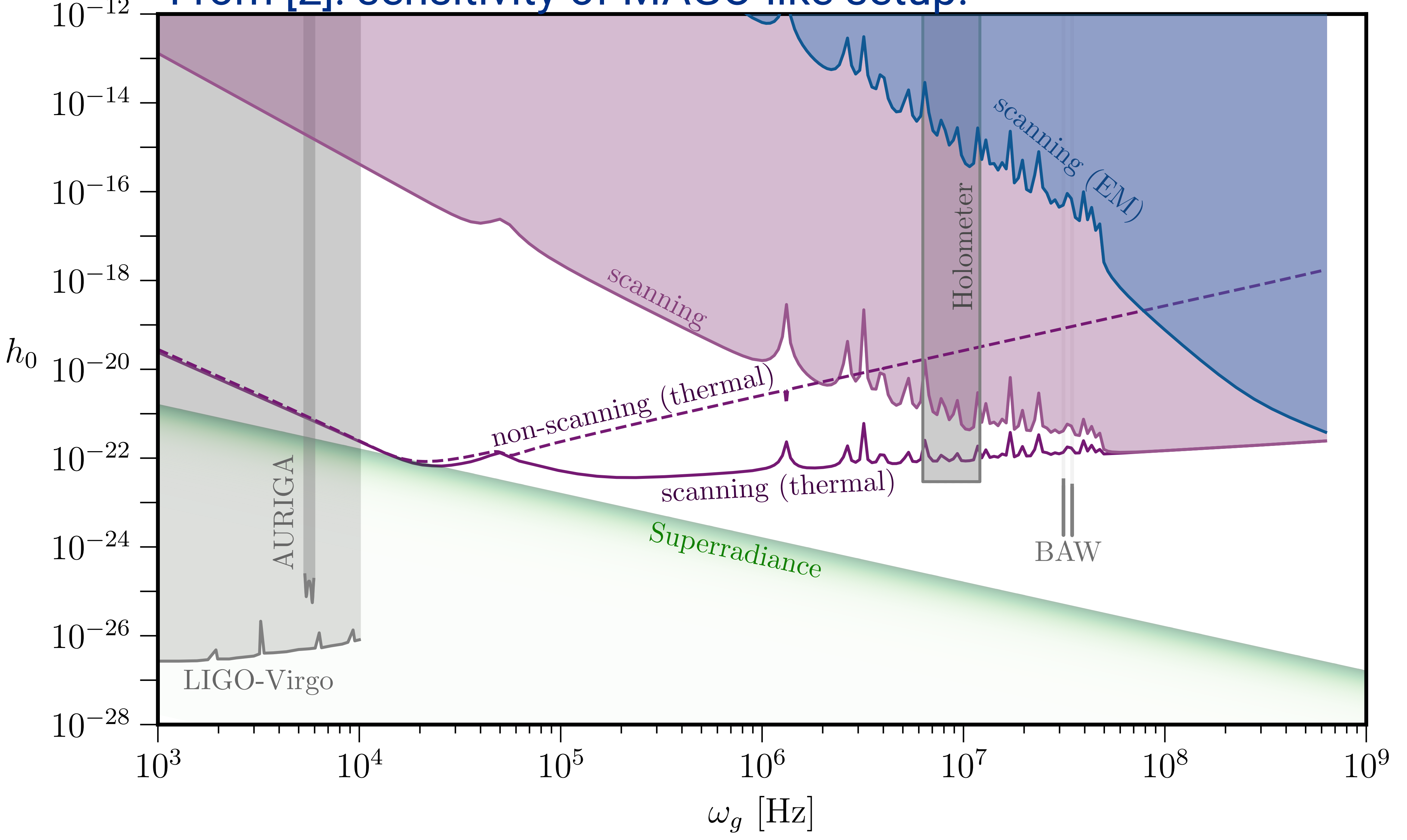
Contacts: Asher Berlon, Bianca Giacone, RH

MAGO2.0: Gravitational waves

- SQMS theorists have laid the formalism for GR-EM cavity interaction.
- Two types of signals: EM and mechanical.
- Current axion experiments have sensitivity to GHz Gravity waves [1].
- A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz [2].
- A new collaboration with INFN and DESY to revive MAGO is being formed.



From [2]: sensitivity of MAGO-like setup.



MAGO (INFN)

[1] *Phys.Rev.D* 105 (2022) 11, 116011
[2] Berlin et al, in preparation.

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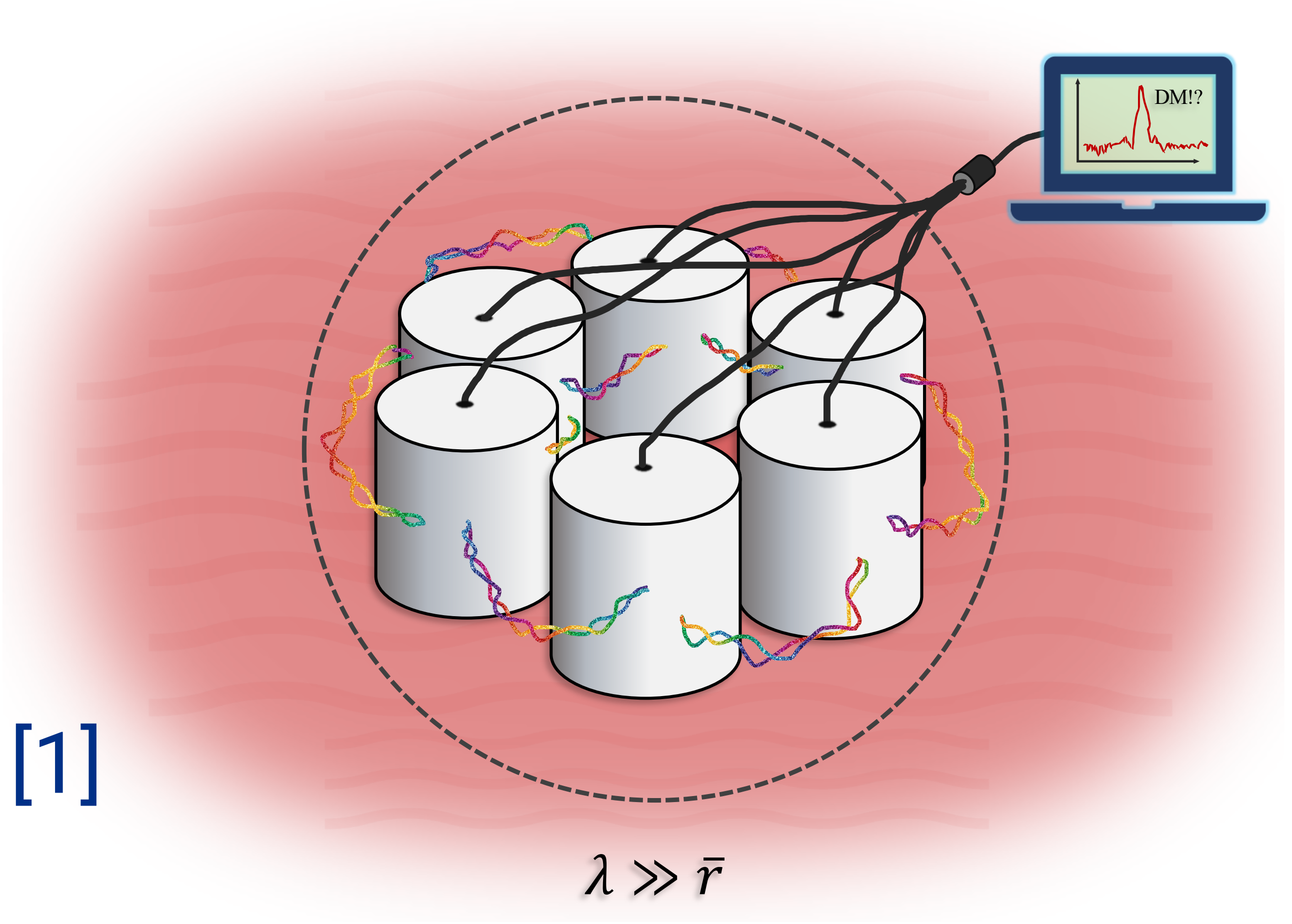
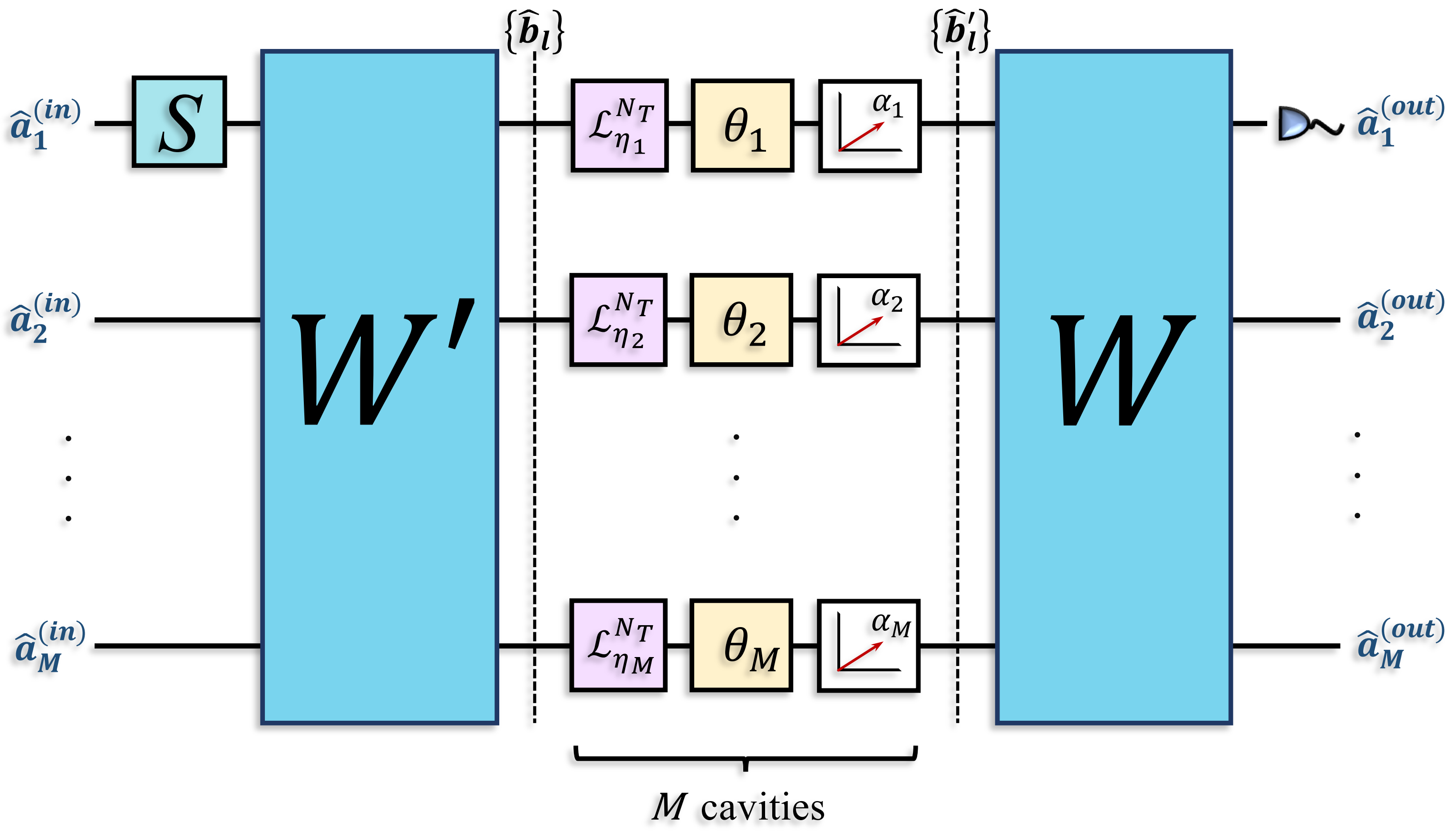
Contacts: RH

Dark Matter - Quantum Sensor Network

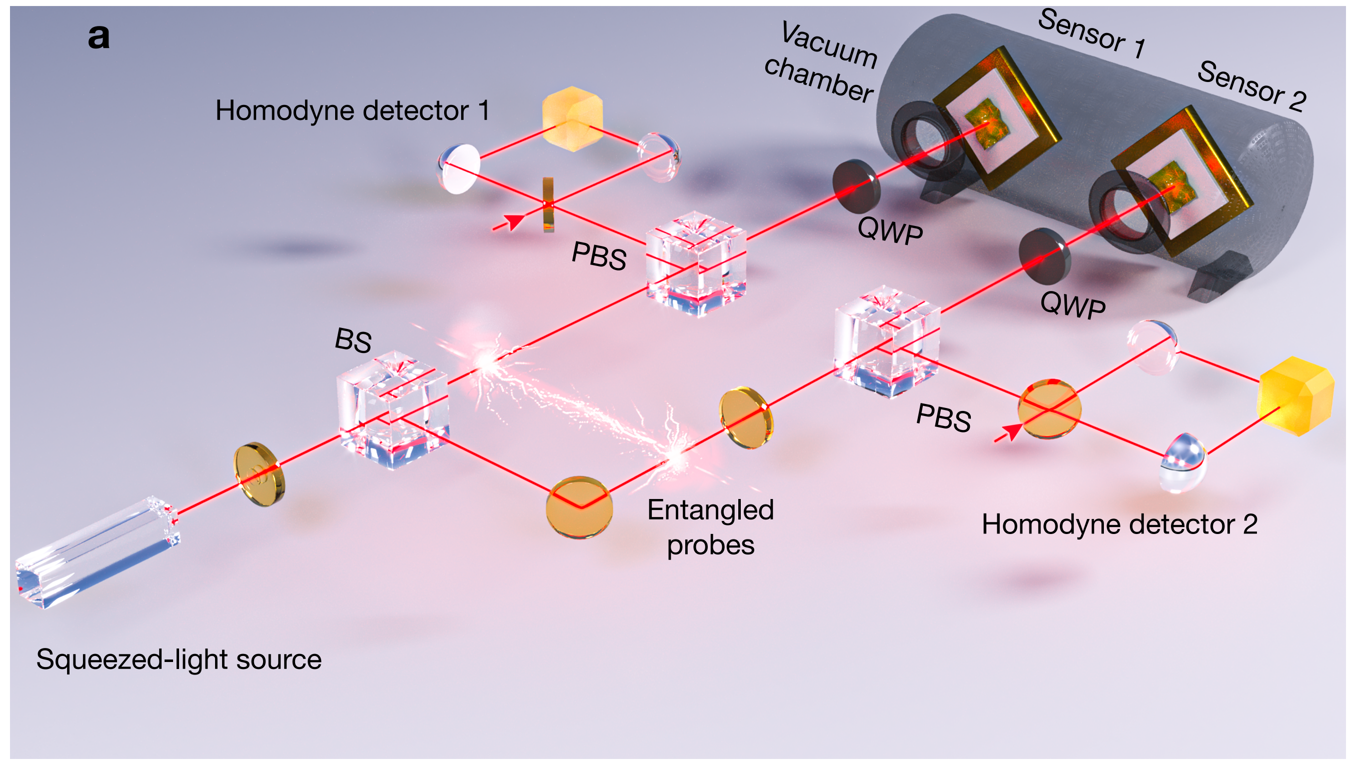
- A network of cavities can be used to enhance the sensitivity to dark matter.
- How should we distribute quantum resources in the network?
- **A distributed quantum sensing protocol for DM searches allows for enhanced scan rate for DM.**



[1]



[2,3]



A new collaboration of HEP and QIS experts from across SQMS:

[1] ***PRX Quantum* 3 (2022) 3, 030333**

[2] 2210.07291 [quant-ph]

[3] 2210.16180 [quant-ph] **(in review by Nature Photonics)**

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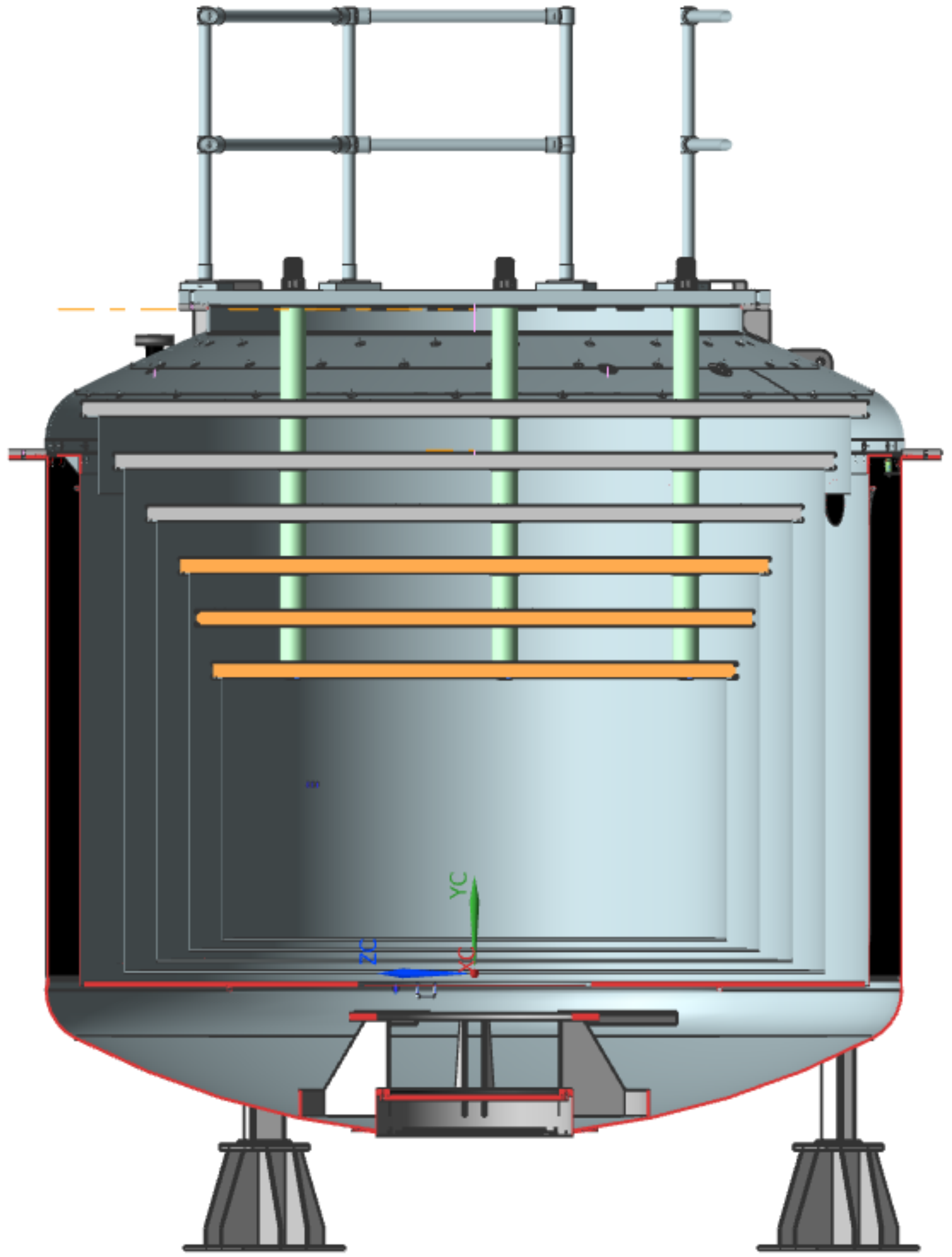
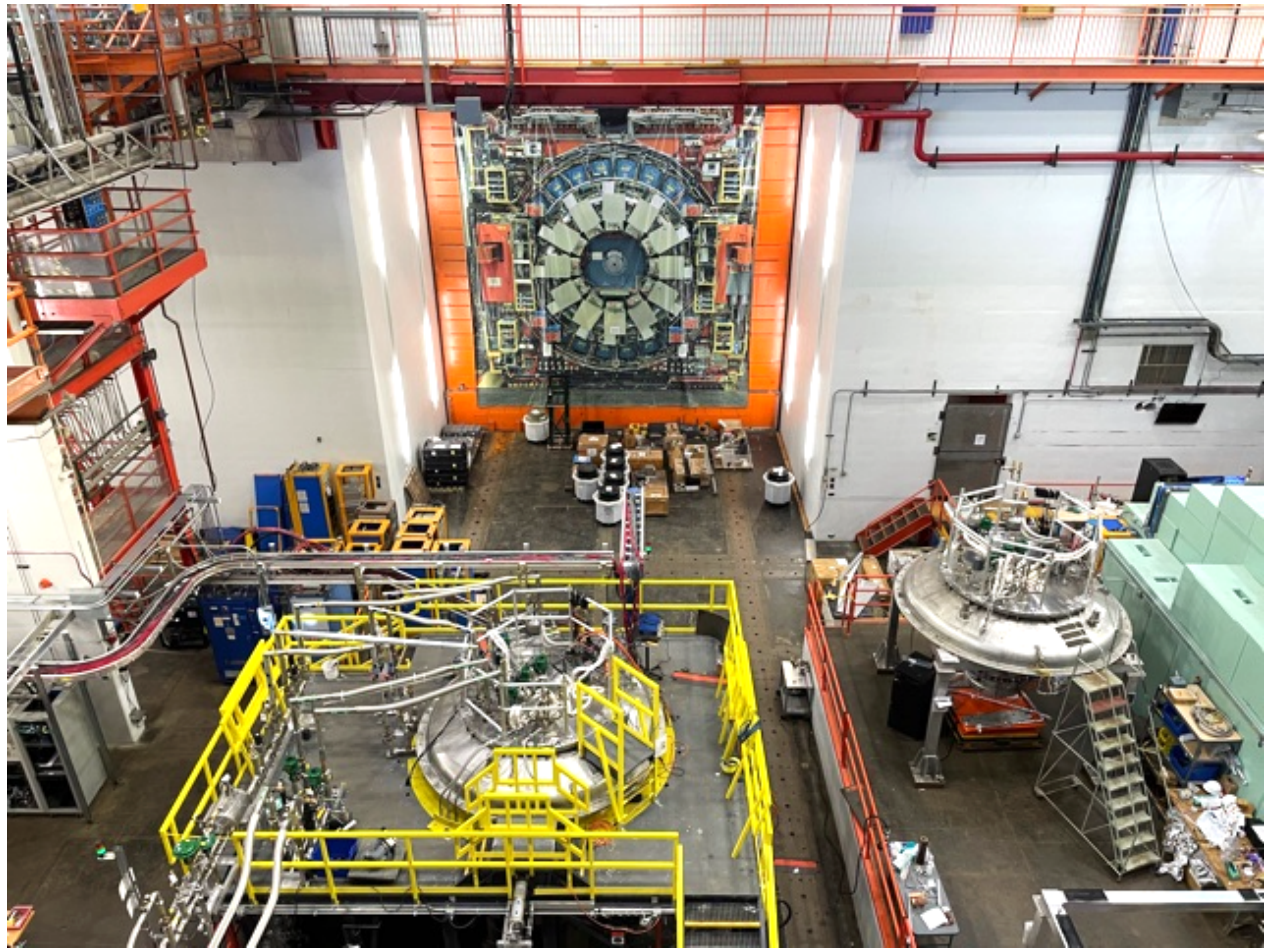
Quantum Garage

Five new DRs. Ribbon cutting next week.

DR 8, with a 9T magnet, has arrived and will be installed soon.

Large Cryogenics Facility: Colossus





A Home for SuperRAD?

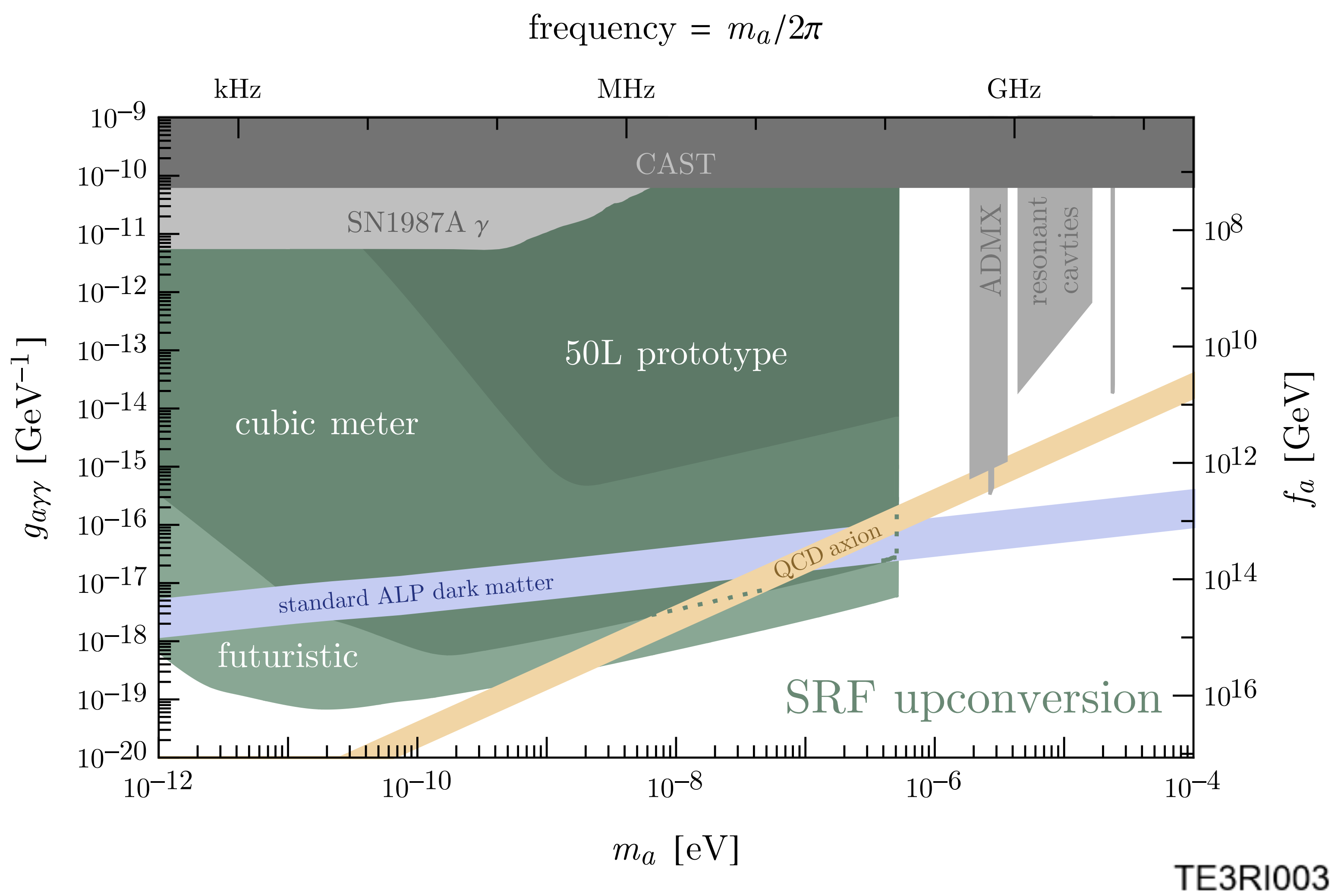
GW experiment?

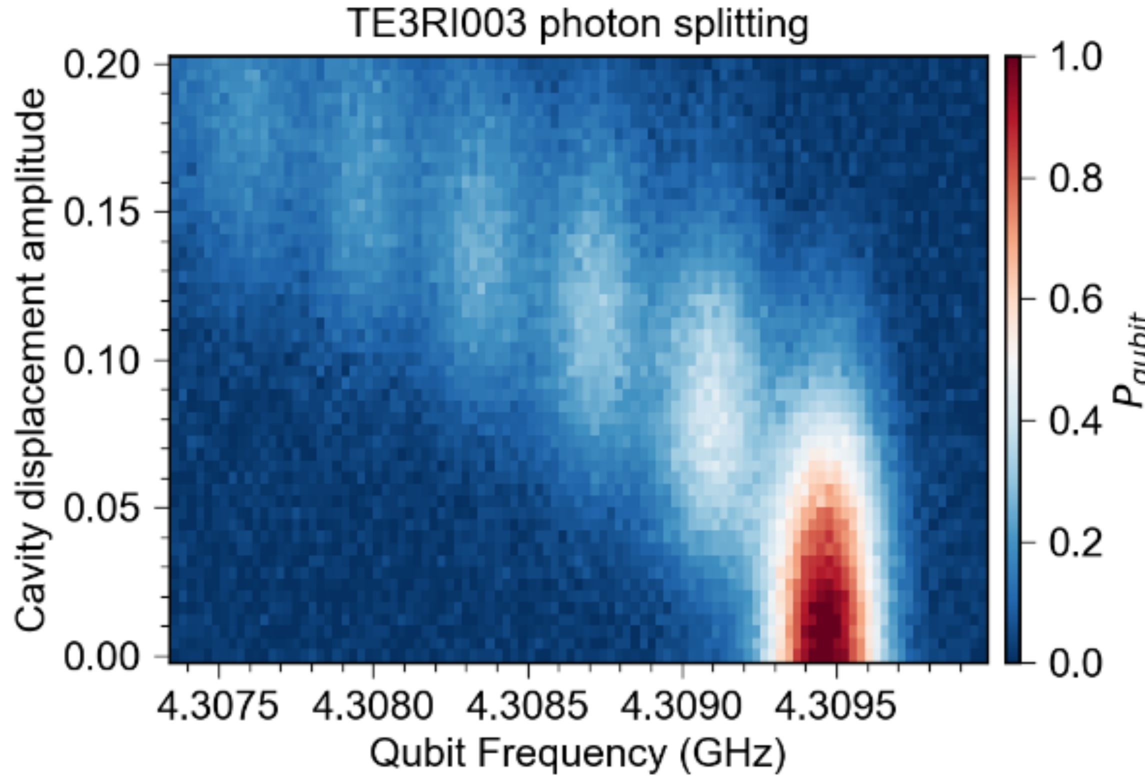
(A quantum data center?)

Capitalizing on millions of dollars in previous investments in cryogenic infrastructure, we have developed the design of a record size dilution fridge, capable of hosting our SQMS 2D and 3D platforms, and quantum sensors

SQMS Physics and Sensing

- Lots going on!
  - Proof-of-concept Axion and Dark Photons searches DM in several frequency ranges.
  - Dark SRF pathfinder is setting new limits.
  - GW searches being developed
  - Tests of QM





- For more details, ask these folks:


Sam Posen


Alex Melnichuk


Raphael Cervantes


Asher Berlin


Bianca Giaccone


Alex Romanenko


Anna Grasselino

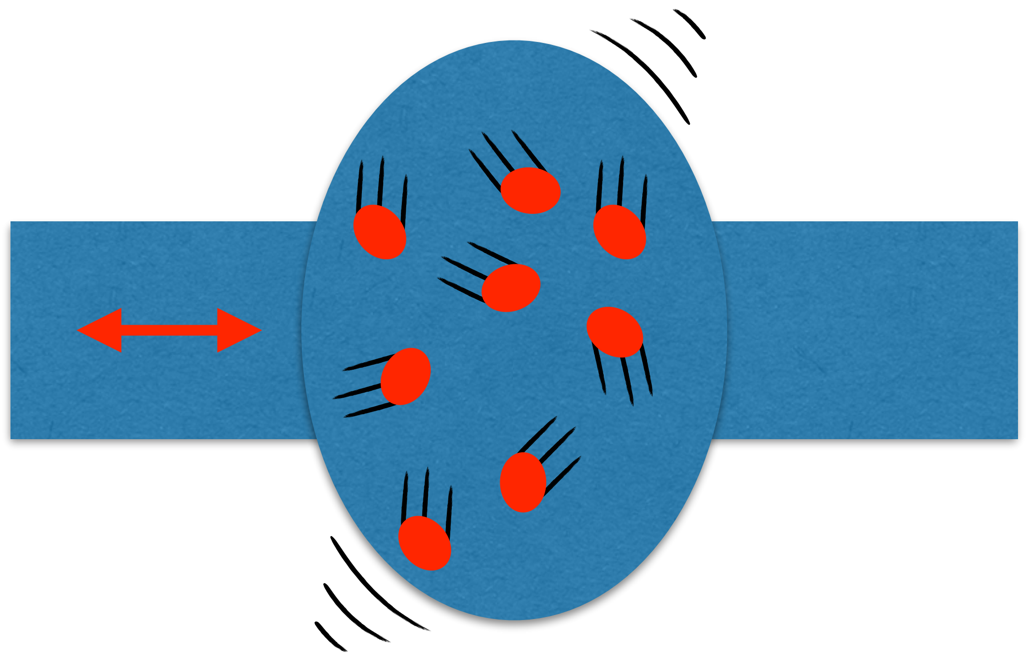

or me.

We are Happy to Collaborate!!

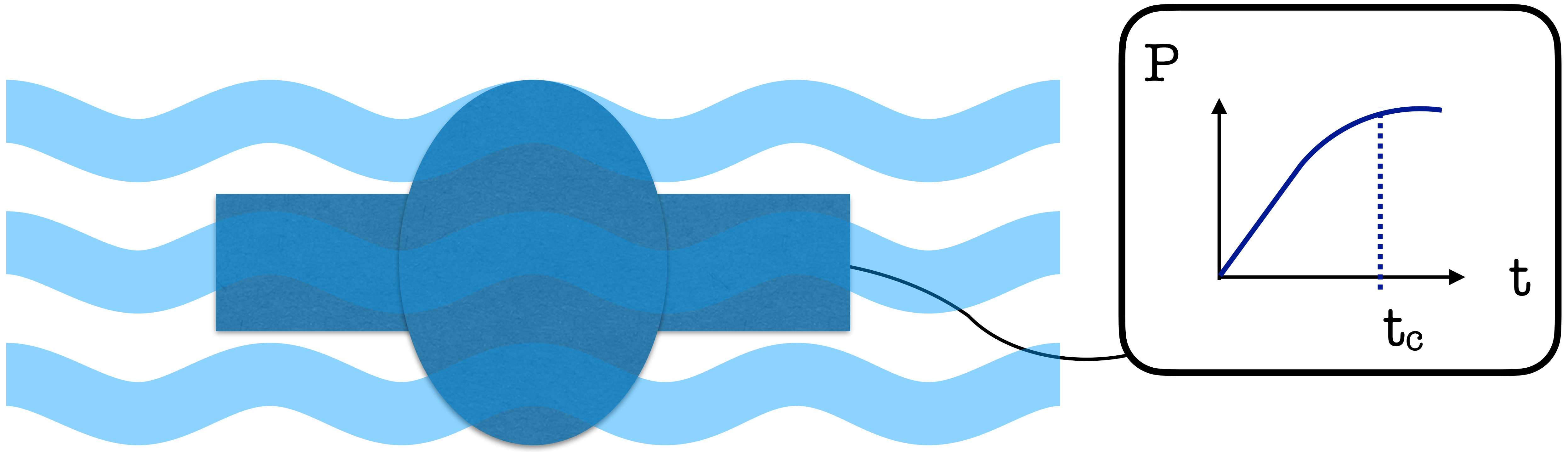
SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Light Shining Through Wall (w/ RF cavities)

- Consider two cavities with with **exactly** same frequency



High Q → we can store more photons. Coherent field.



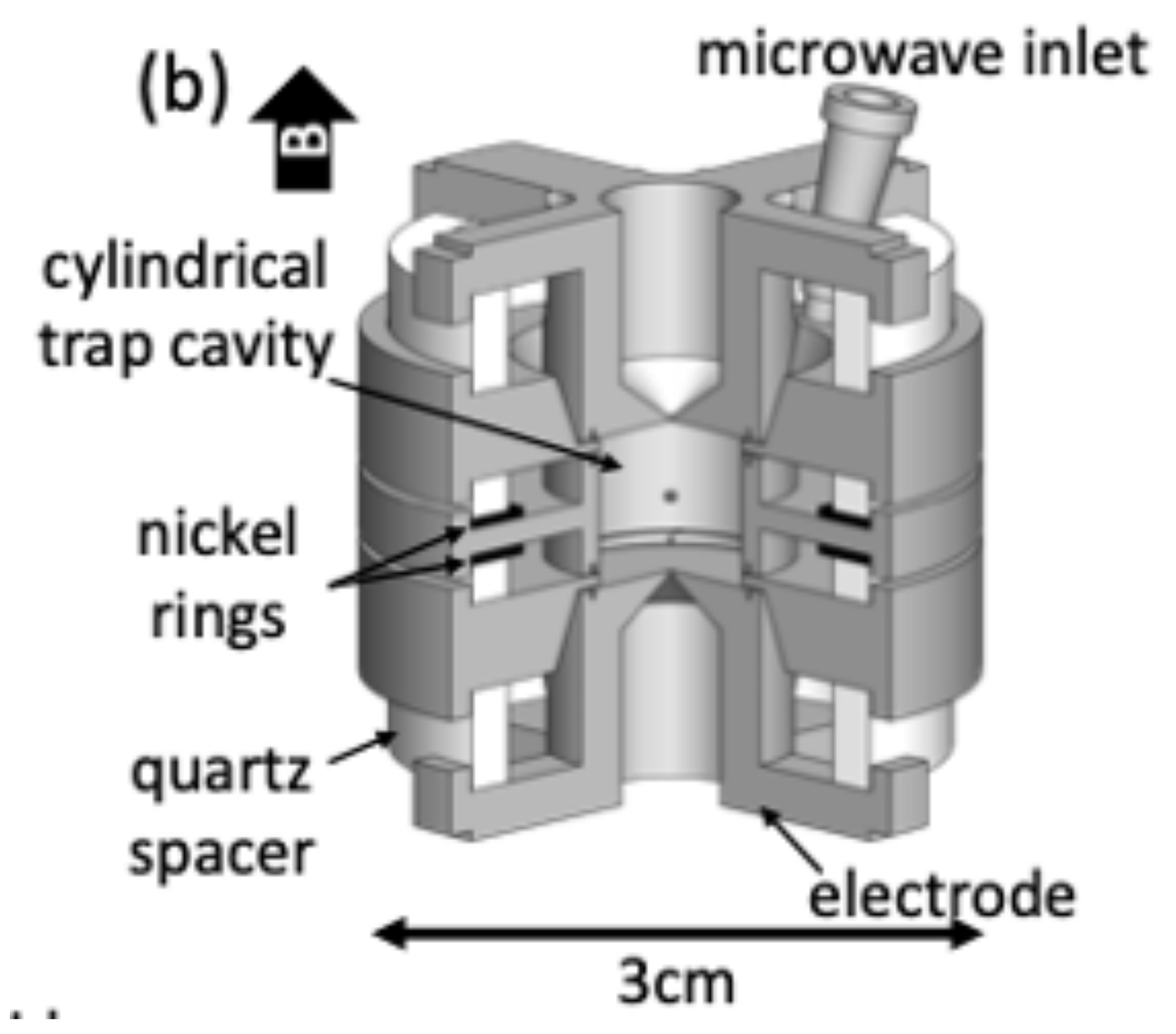
High Q → cavity can ring up for a longer time

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

* Coming clean: scaling with mass depends on the polarization.

Single Particle Qubit

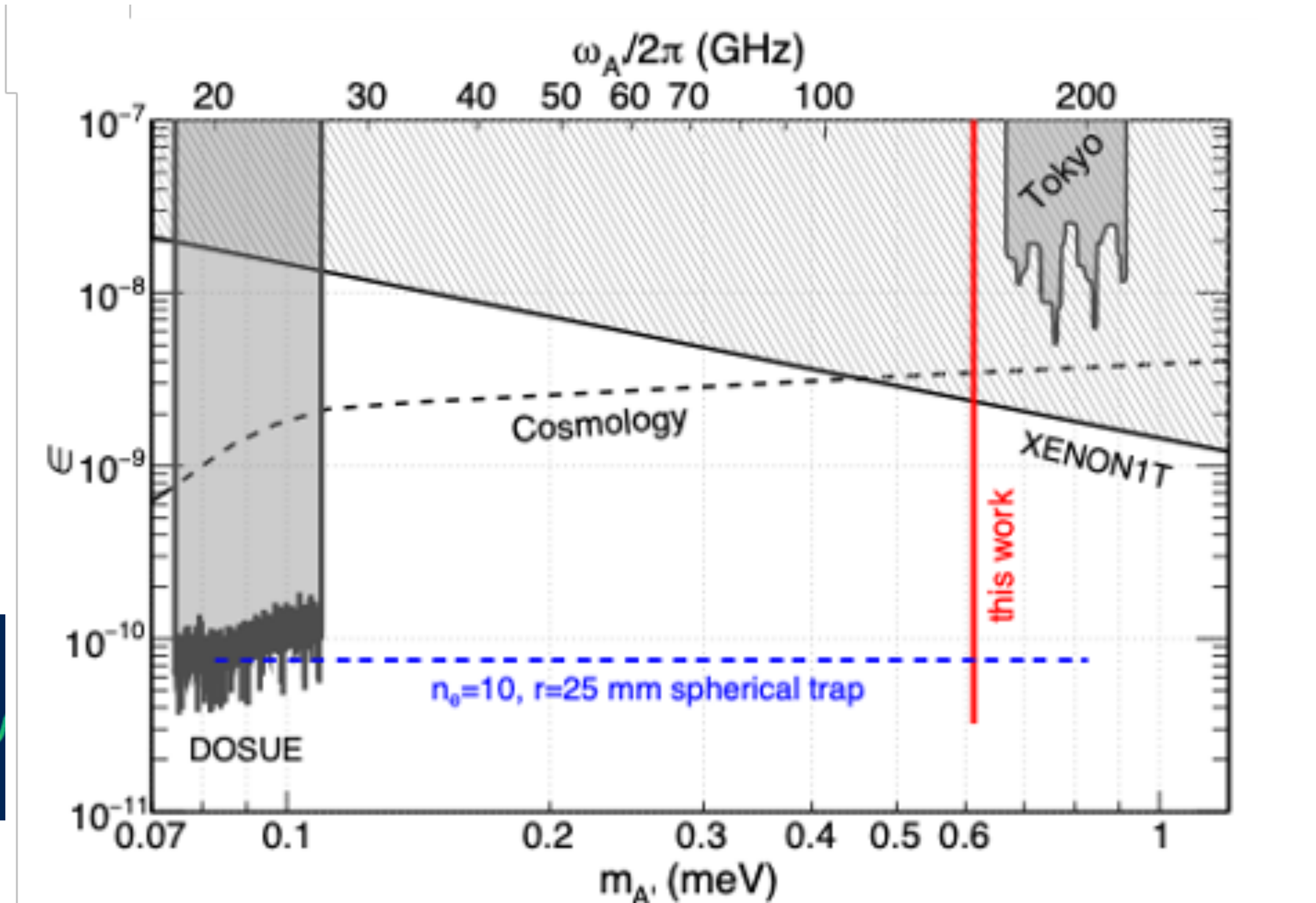
- At Northwestern, the quantum state of a single electron in a Penning trap is monitored with a QND measurement.
- The most precise test of the SM of particle physics!!!



$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13 \text{ ppt}]$$

Phys. Rev. Lett. 130, 071801 (2023)

- This is a quantum-number counting experiment.
- Also sensitive to Dark Photon DM at 150 GHz!



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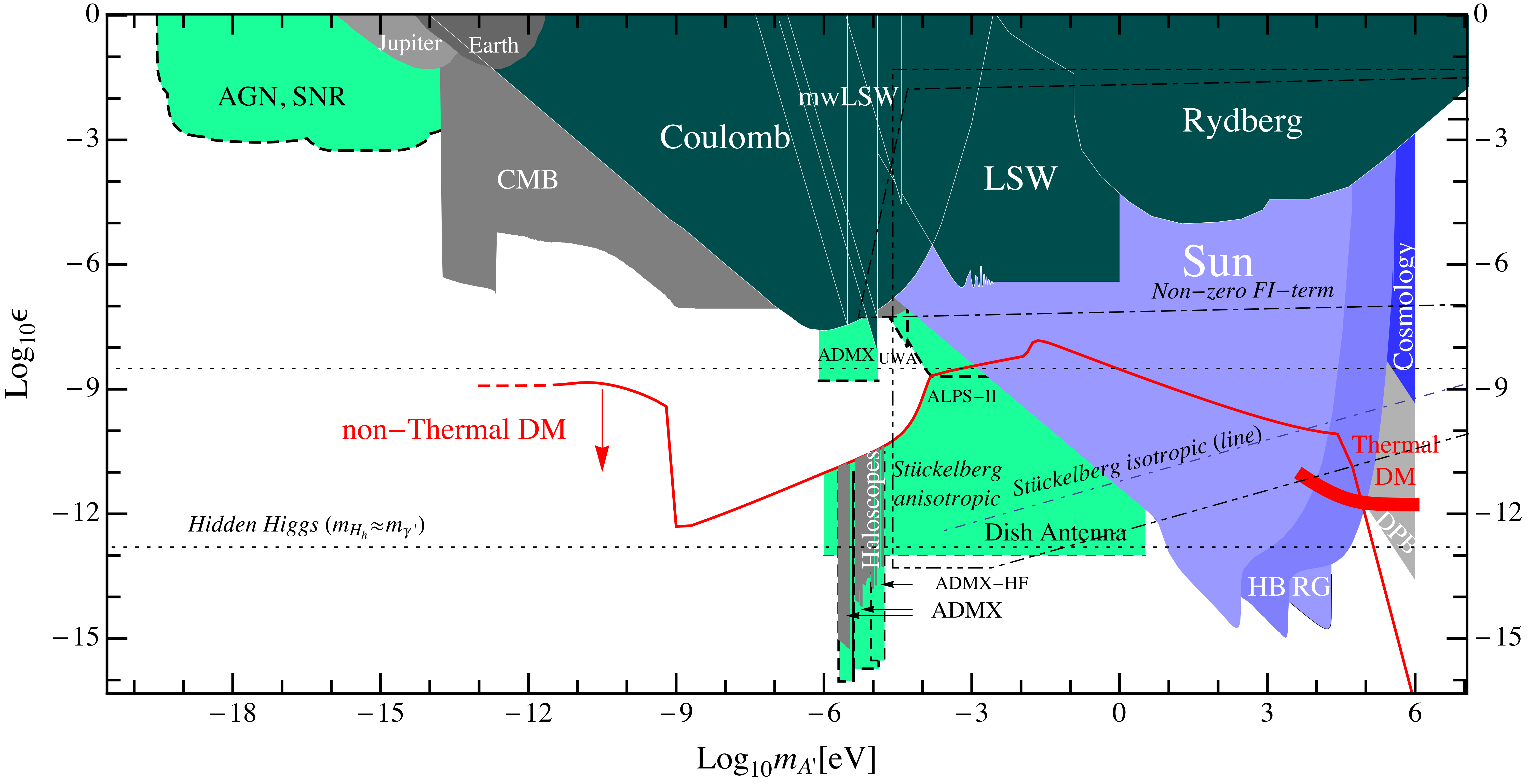
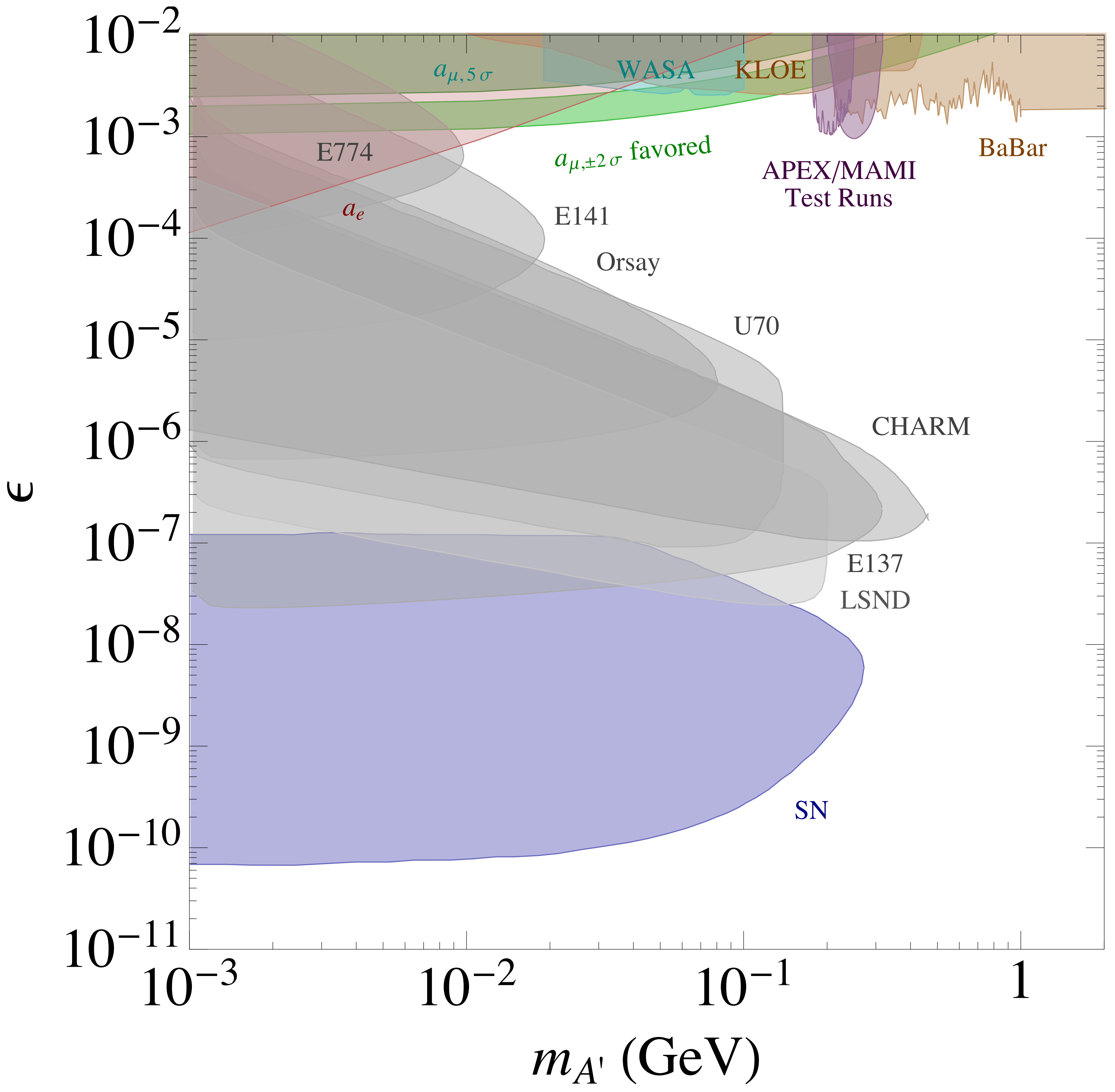
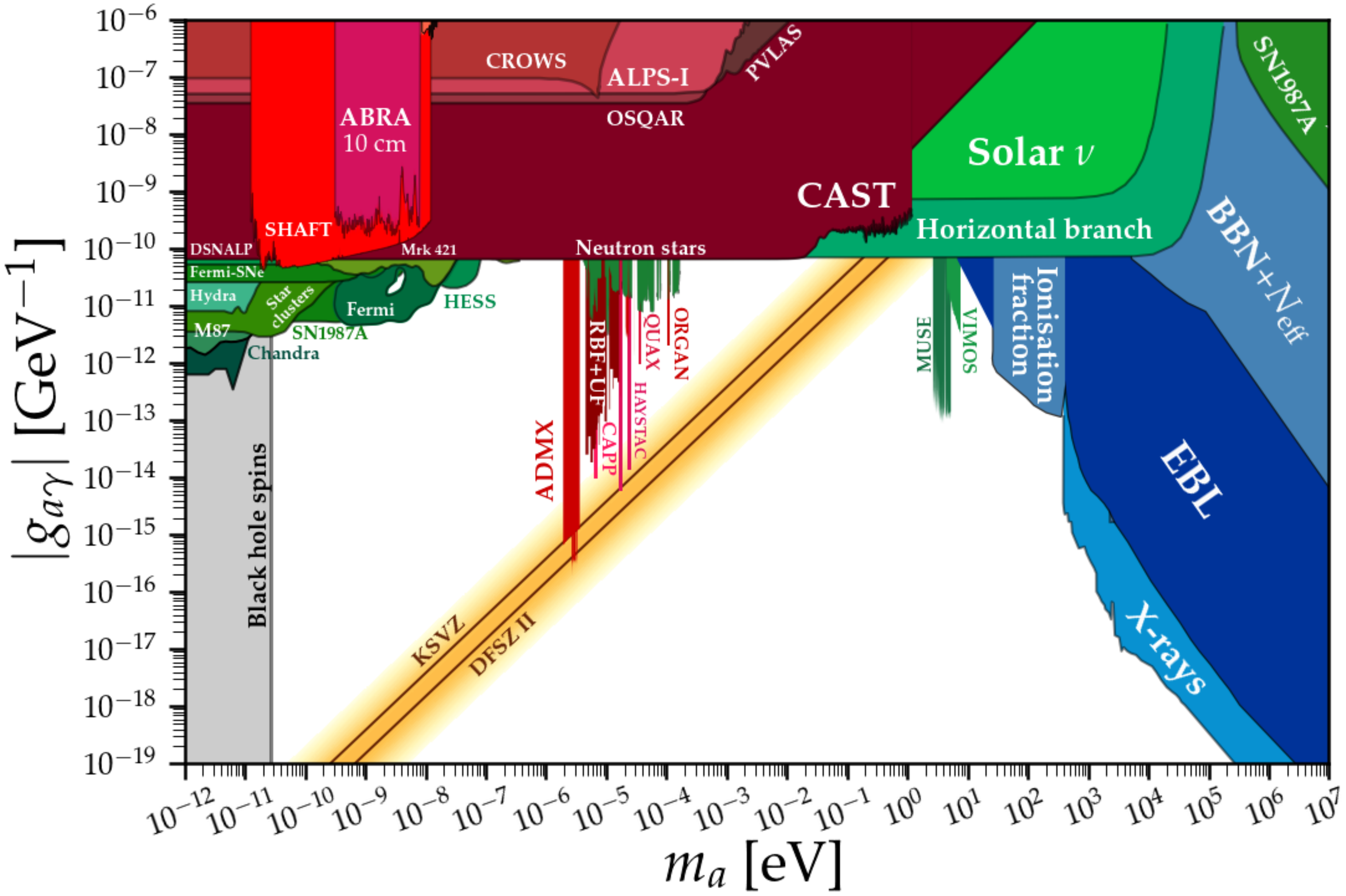
Dark Photon

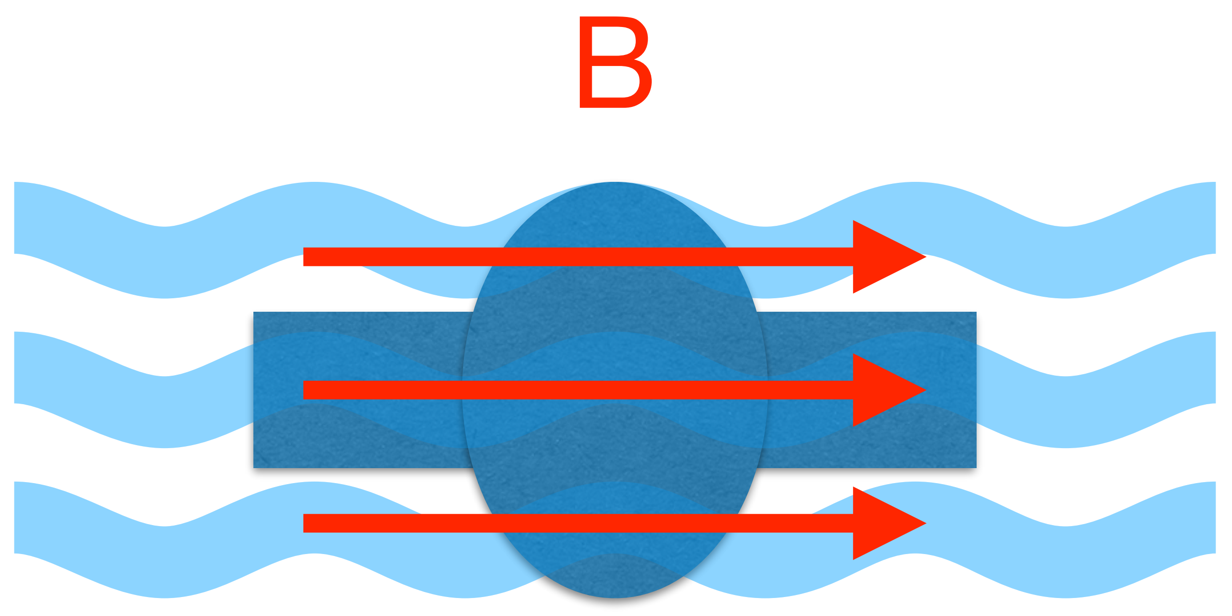
- Many constraints on the dark photon! (a review: Essig et al 1311.0029)





Axions and ALPs





New challenges:

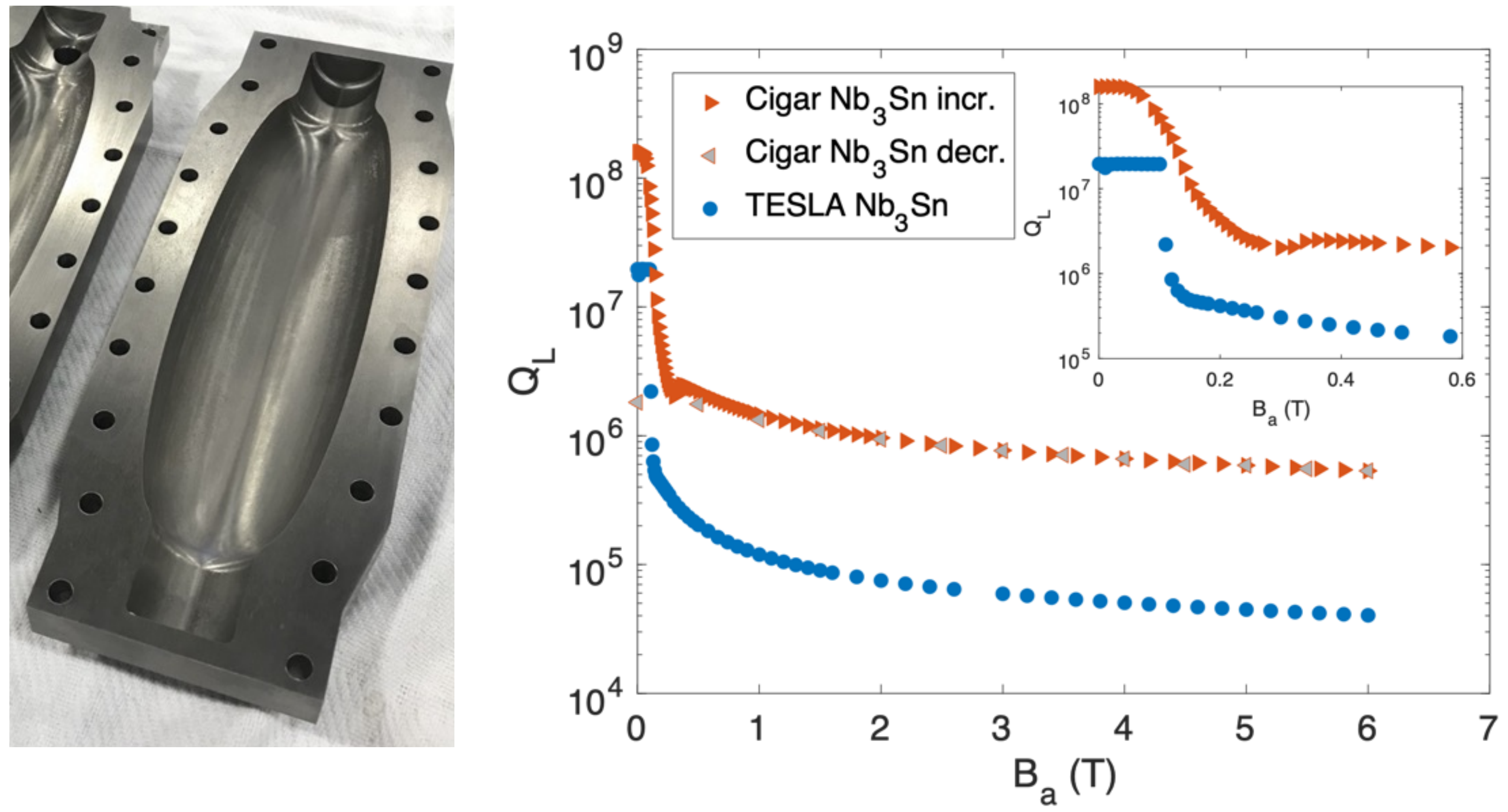
superconducting quantum devices that can operate in (or near) high magnetic fields!

Dark Sector: High Q in Multi-Tesla Fields

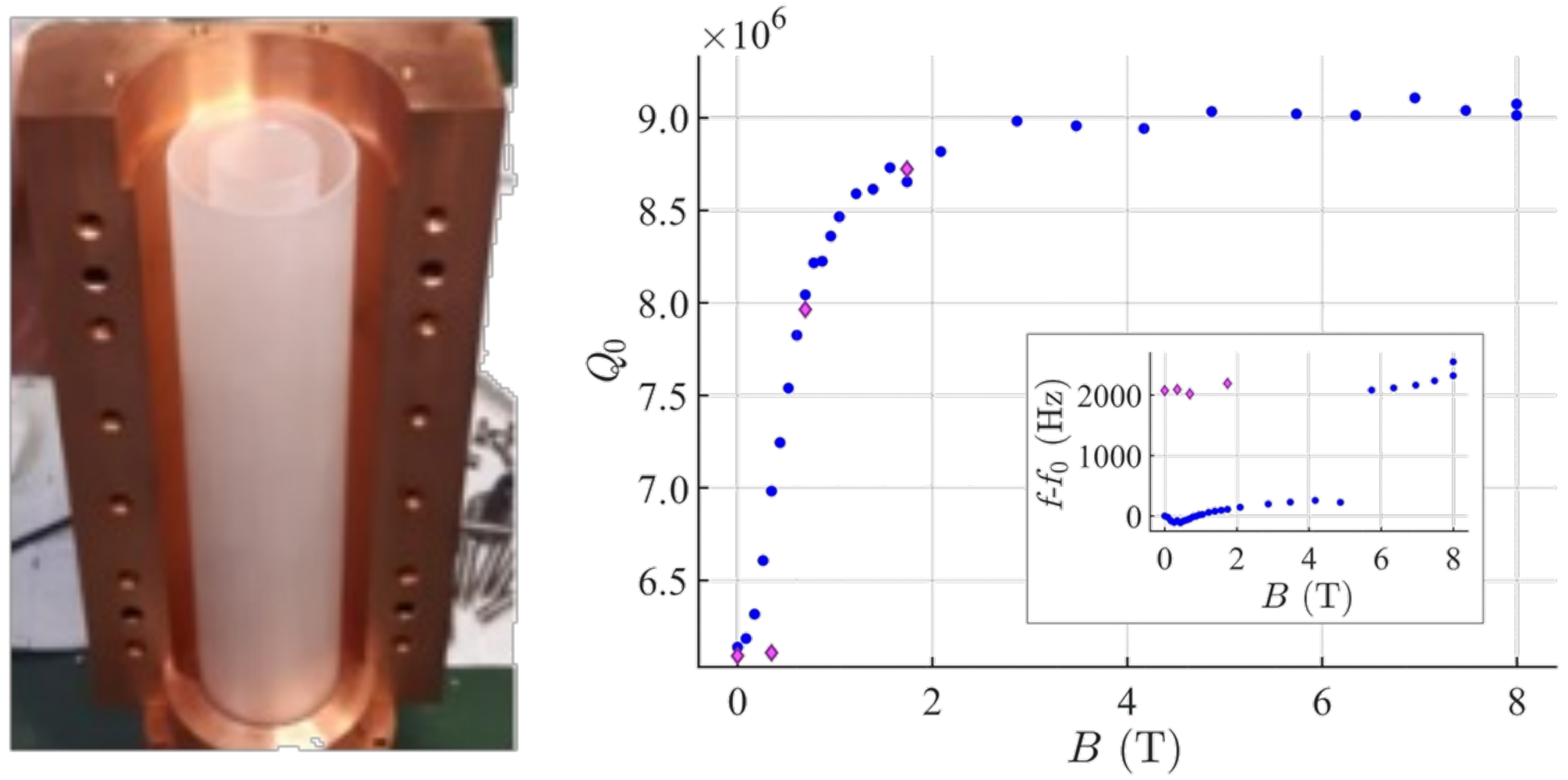
Axion haloscope: search for dark matter with high Q cavity in multi-tesla magnetic fields

Two SQMS designs substantially outperform state of the art copper cavities (and these ideas can be combined!)

Other Challenges: counting photons near a magnetic field. Cavity and qubit frequency tuning. etc.



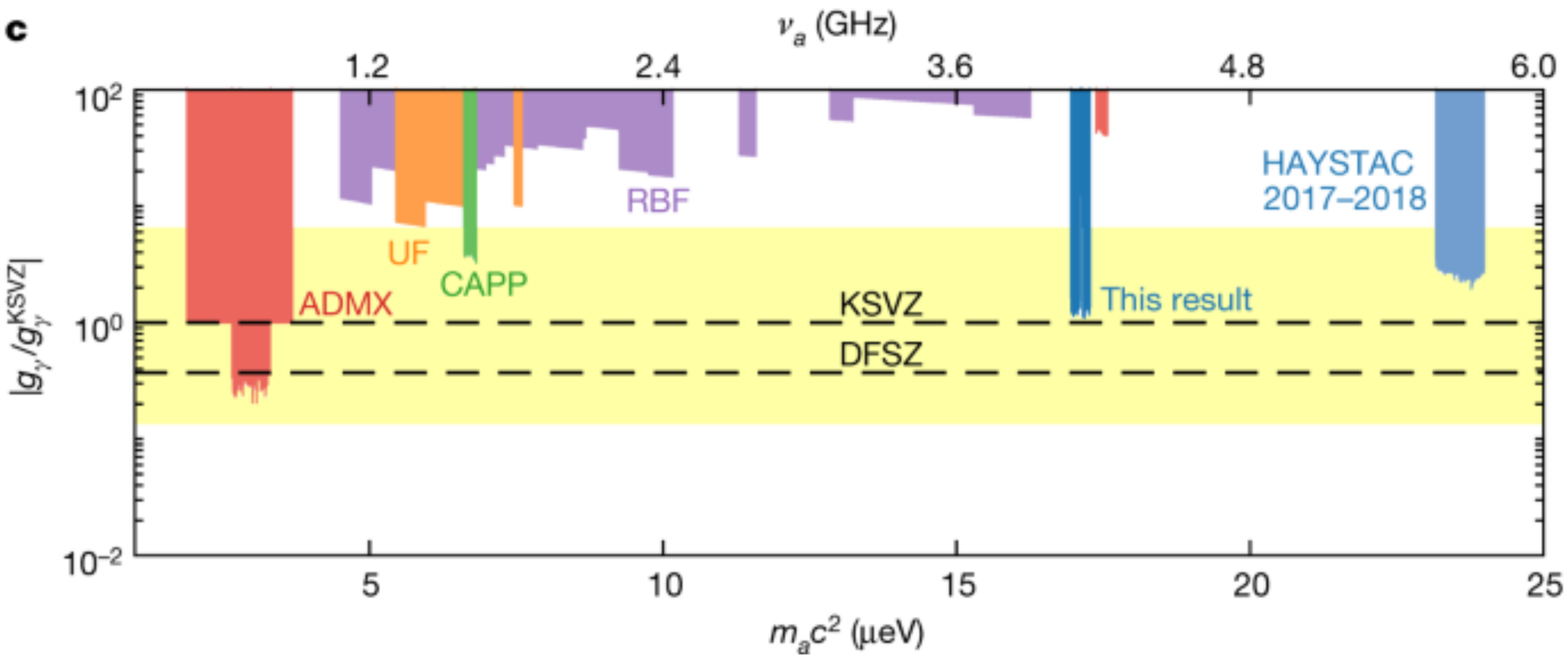
Superconducting Nb_3Sn cavity (FNAL): Posen et al., arxiv:22014.10733, in review in Phys Rev Applied

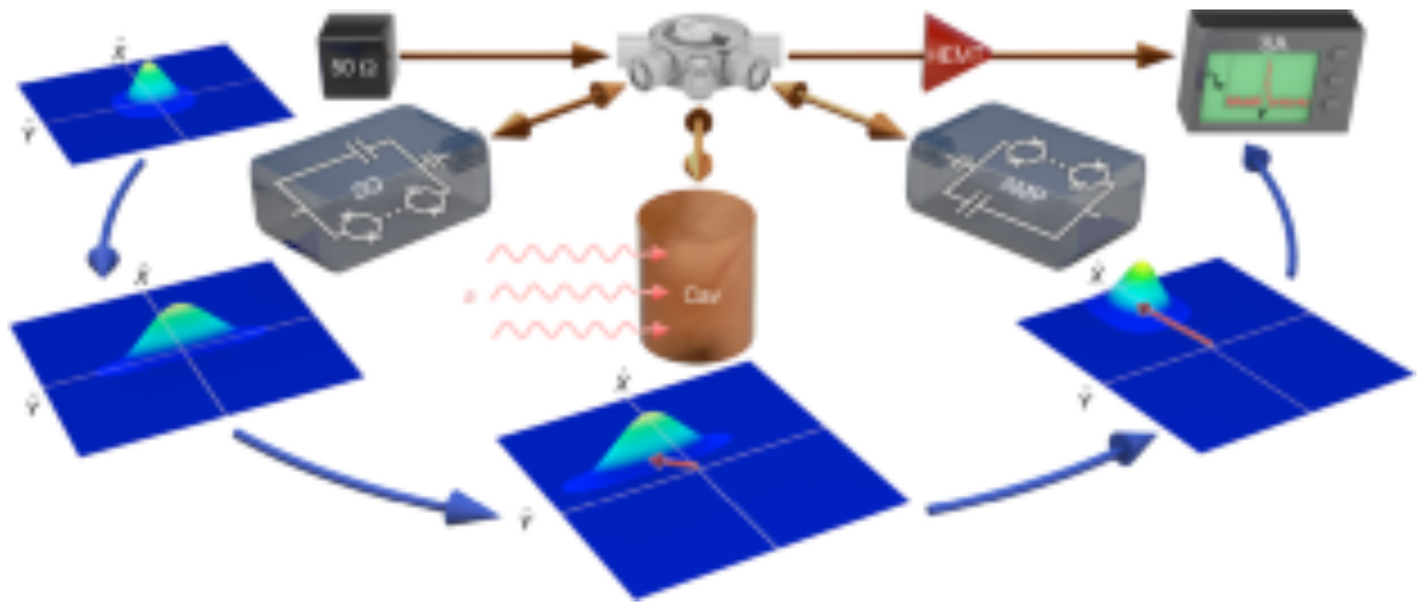


Hybrid copper-dielectric cavity (INFN): Di Vora et al., PhysRevApplied.17.054013

SQMS SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Axions and ALPs

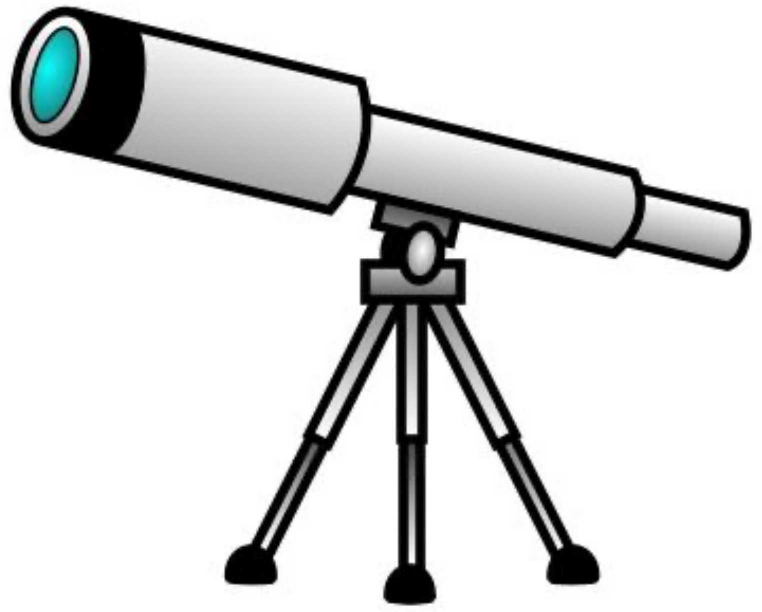


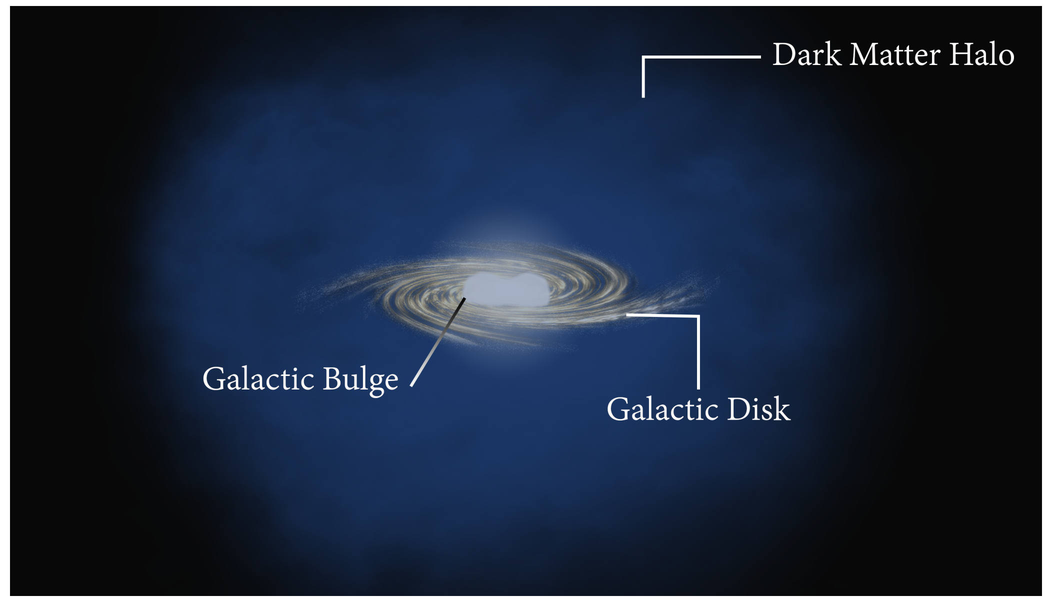


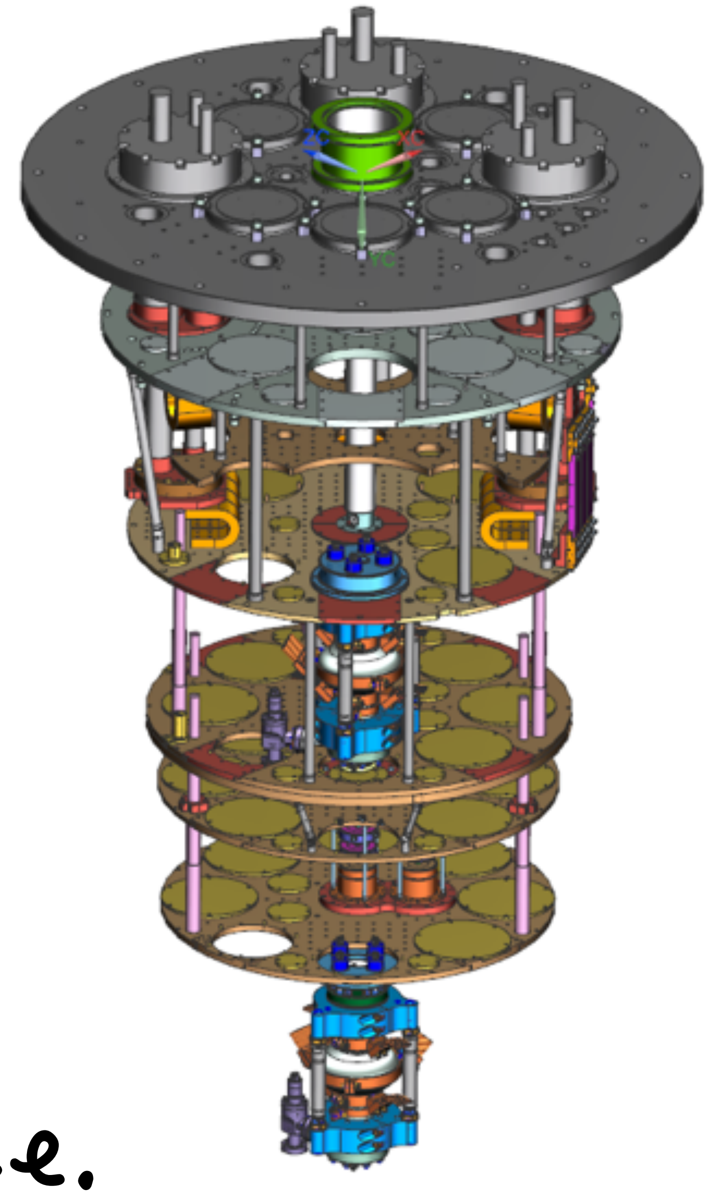
Quantum sensing already playing a role for Axion DM:
e.g. **HAYSTAC** used squeezed states for factor of 2 in scan speed.

Backes, K.M., Palken, D.A., Kenany, S.A. *et al.*
A quantum enhanced search for dark matter axions. *Nature* **590**, 238–242 (2021)

In Conclusion







- We are curious about the Universe?
  - What new particles exist?
  - What is dark matter?
  - What can we learn from gravitational waves?
- These ambitious questions require the most sensitive detectors in existence.
- We can let standard quantum limits get in our way! We need QIS!

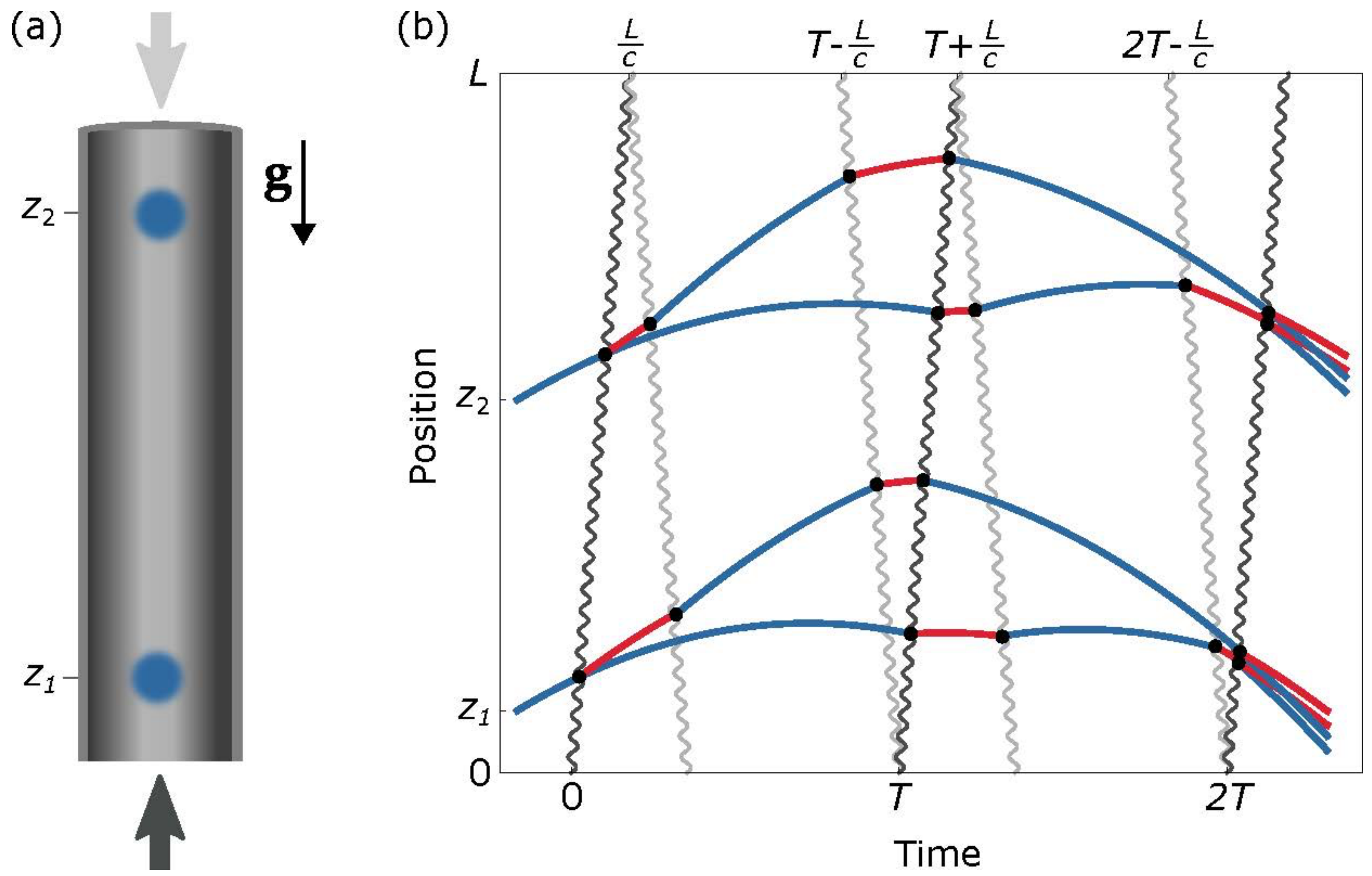
SQMS

Deleted scenes

Atom Interferometers

- Superposition allowed for more cool stuff.
- E.g. atomic clocks: am atom in a superposition of quantum states can keep time!

$$|\psi_1\rangle + e^{i\Delta E t/\hbar}|\psi_2\rangle$$



MAGIS 100, under construction, will look for gravity waves!

(The distance between clocks oscillating…)

Gravitational waves

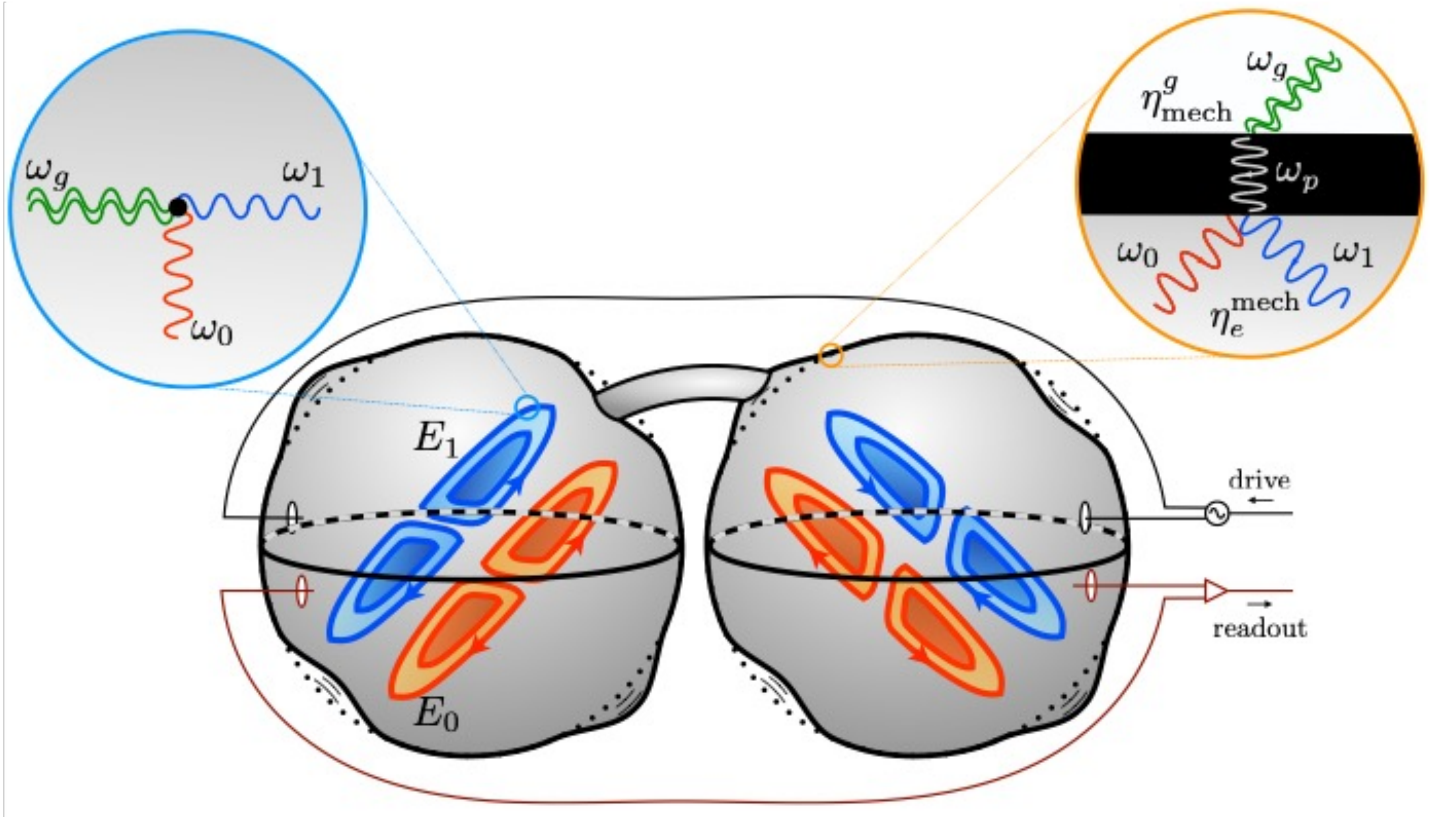
SQMS theorists have laid the formalism for GR-EM cavity interaction.

Two types of signals: EM and mechanical.

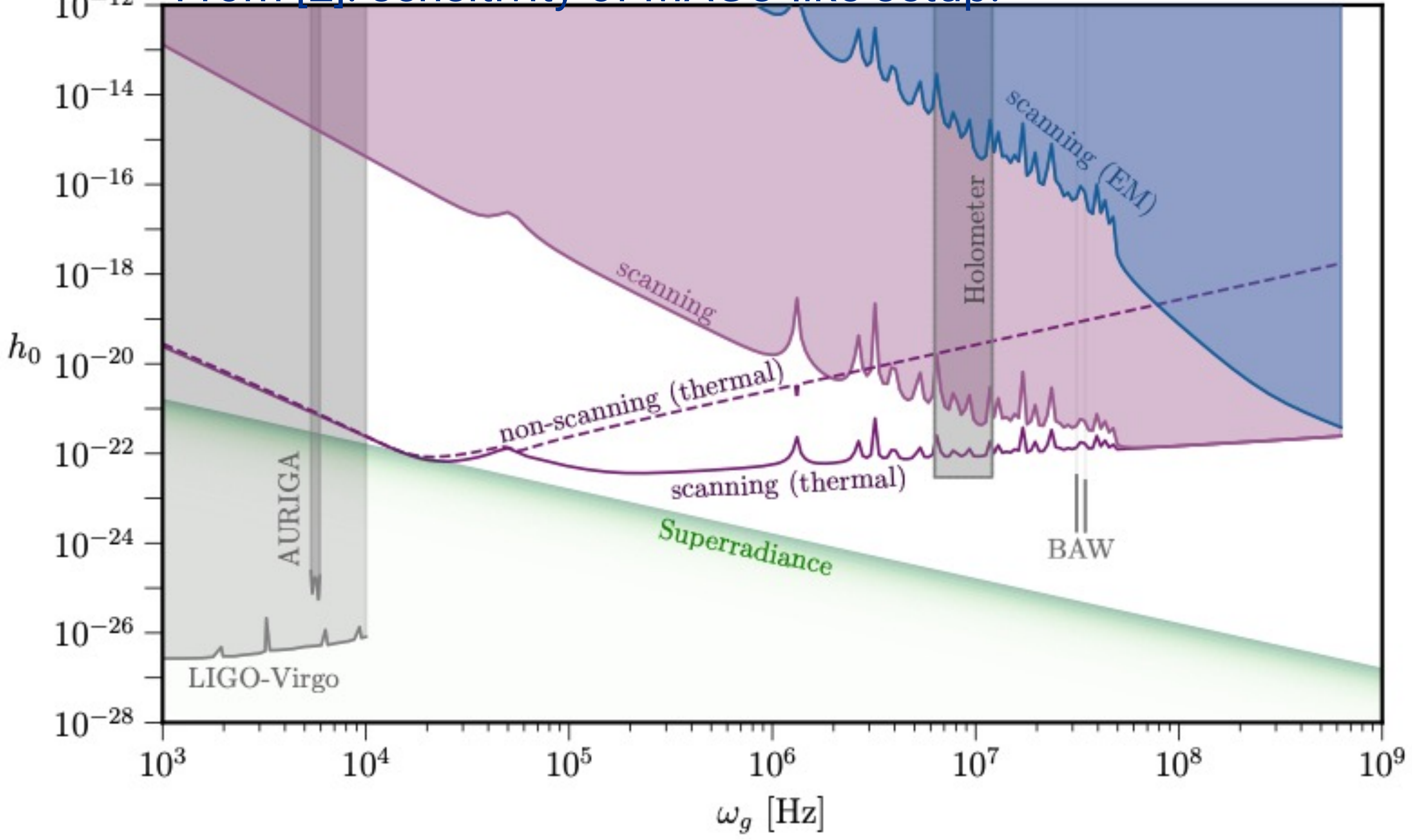
Current axion experiments have sensitivity to GHz Gravity waves [1].

A dedicated cavity experiment, e.g. MAGO, has significant reach at MHz [2].

A new collaboration with INFN and DESY to revive MAGO is being formed.



From [2]: sensitivity of MAGO-like setup.

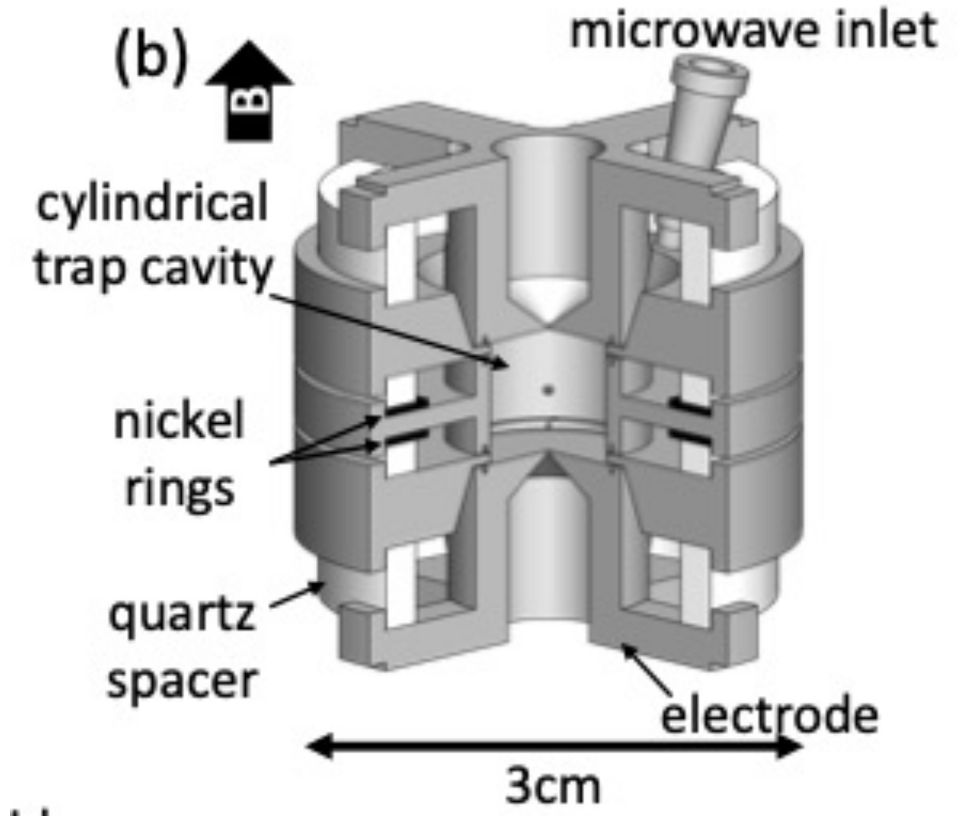


MAGO (INFN)

[1] *Phys.Rev.D* 105 (2022) 11, 116011

[2] Berlin et al, in preparation.

Single Particle Qubit



The most precise theory-experiment comparison in physics:

Electron magnetic moment (g-2)e:
The quantum state of a single electron in a trap is monitored via a **QND measurement**.

$$-\frac{\mu}{\mu_B} = \frac{g}{2} = 1.001\,159\,652\,180\,59\,(13) \quad [0.13\text{ ppt}]$$

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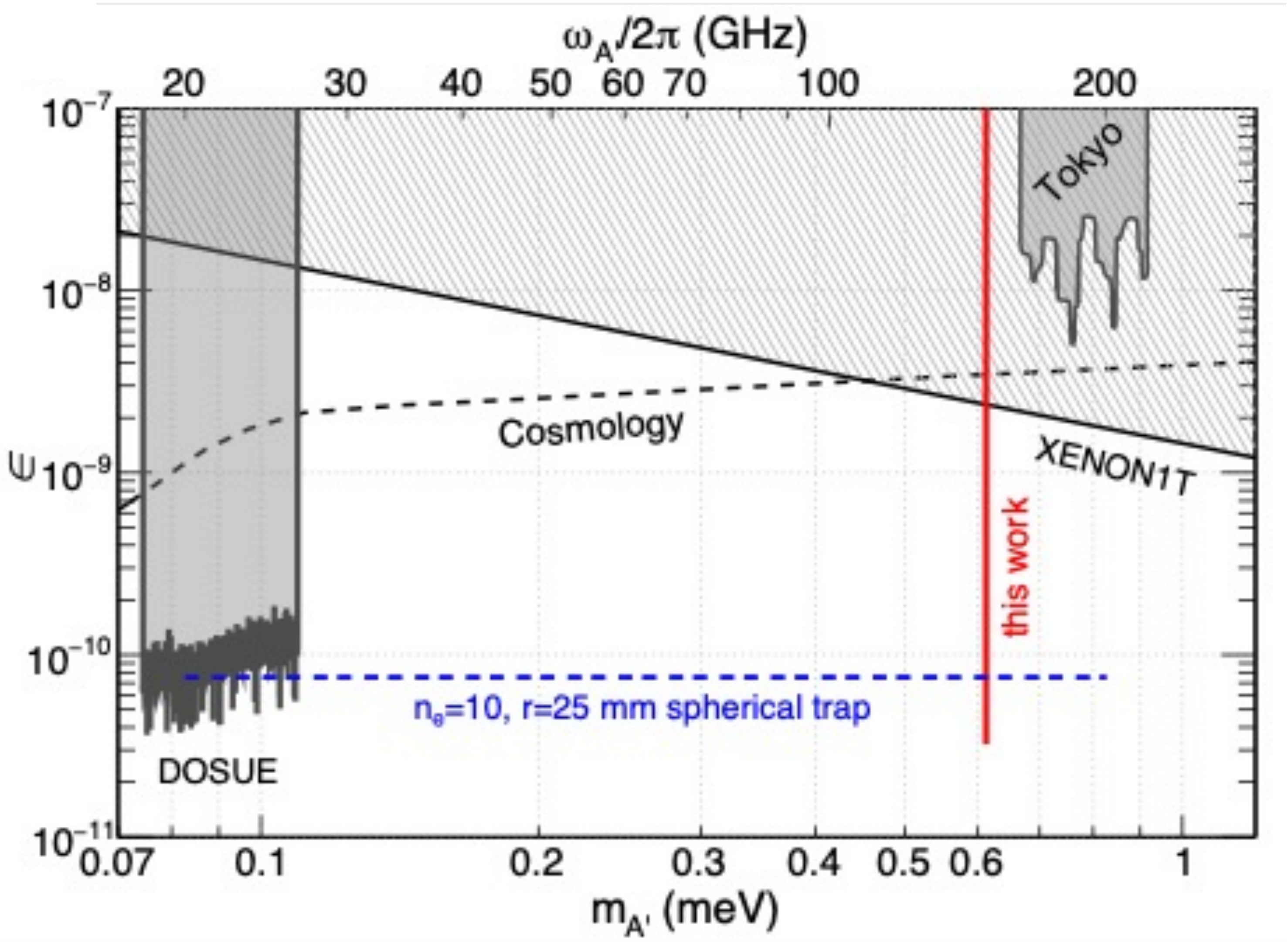
Editors choice!

SQMS joined the effort, contributed to understanding loss sources.



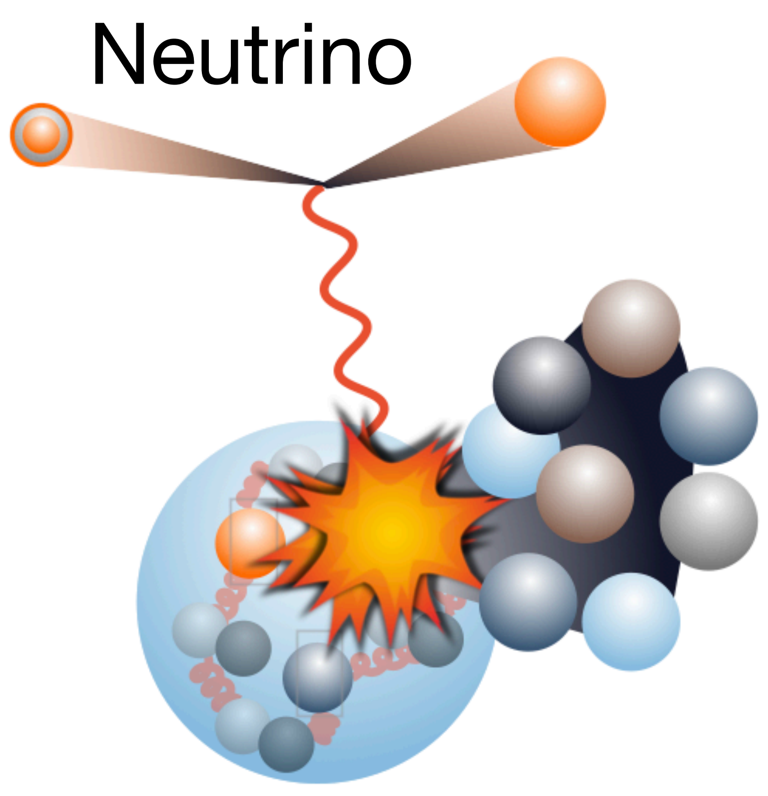
SQMS bonus: We also found that a single-electron qubit is a sensitive DM search in a challenging frequency range!

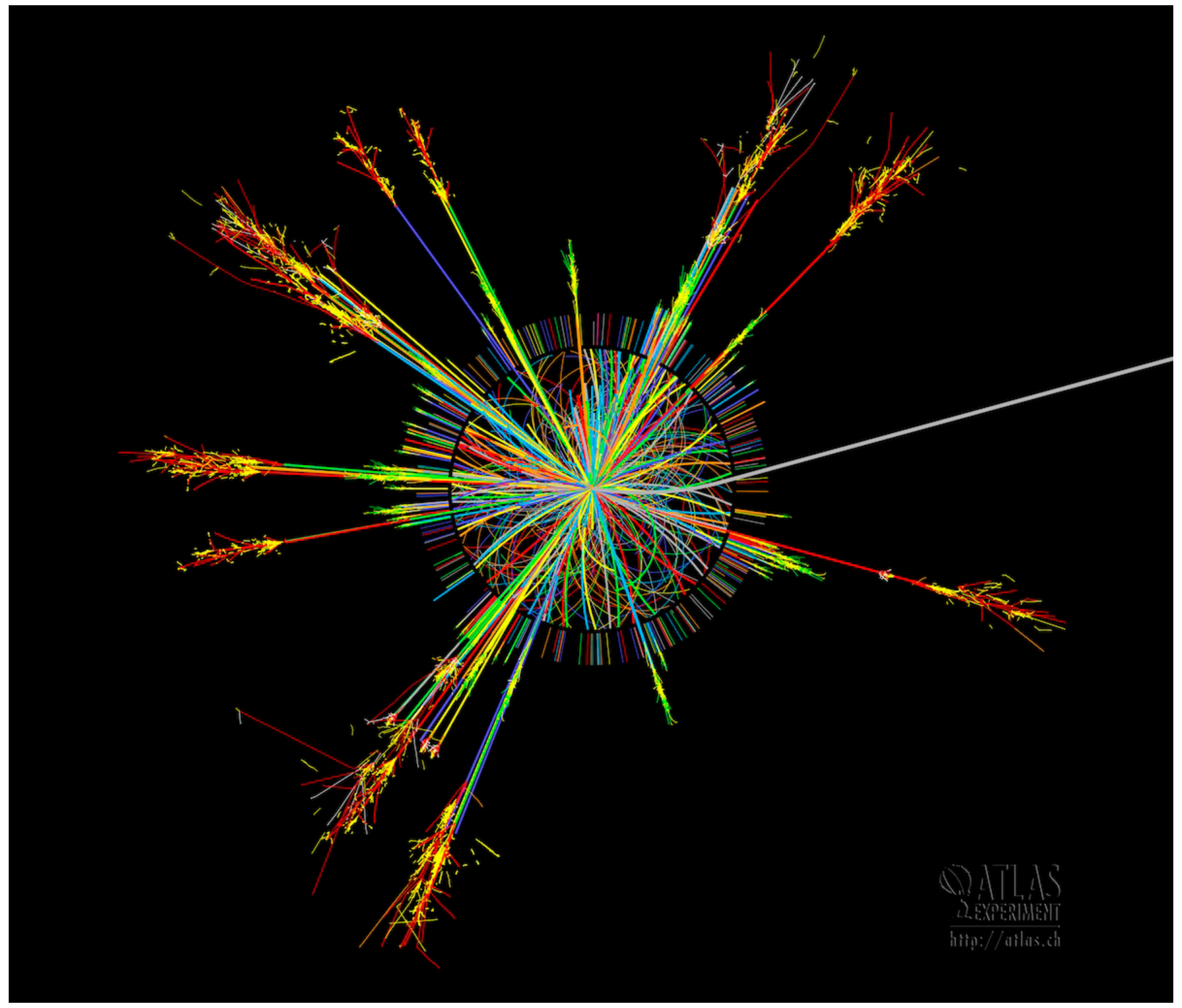
Theory + proof-of-concept!

Phys.Rev.Lett. **129 (2022) 26, 261801**
(a new NU-Stanford-Fermilab collaboration)

Quantum Simulation

- We would like to simulate particle physics processes.
- Perturbation theory does not always work!





- Feynman: "Nature isn't classical, dammit! and if you want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem, because it doesn't look so easy."

Quantum Simulation

- But why should we make it quantum mechanical?
- Here is a reason: Simulating a quantum system evolving in time is numerically hard!

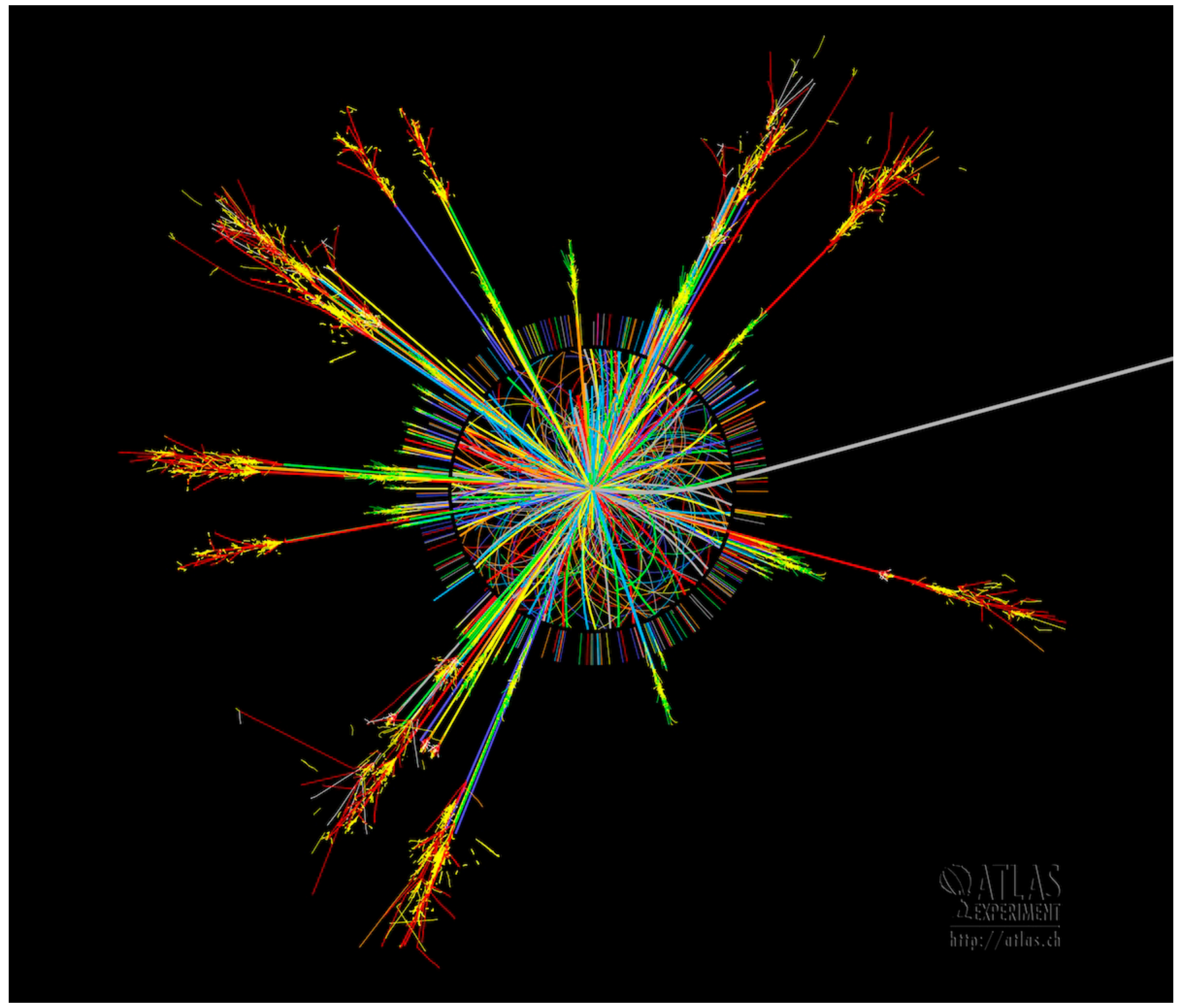
A “sign problem”

$$\psi(t) = e^{iEt/\hbar}\psi(0)$$

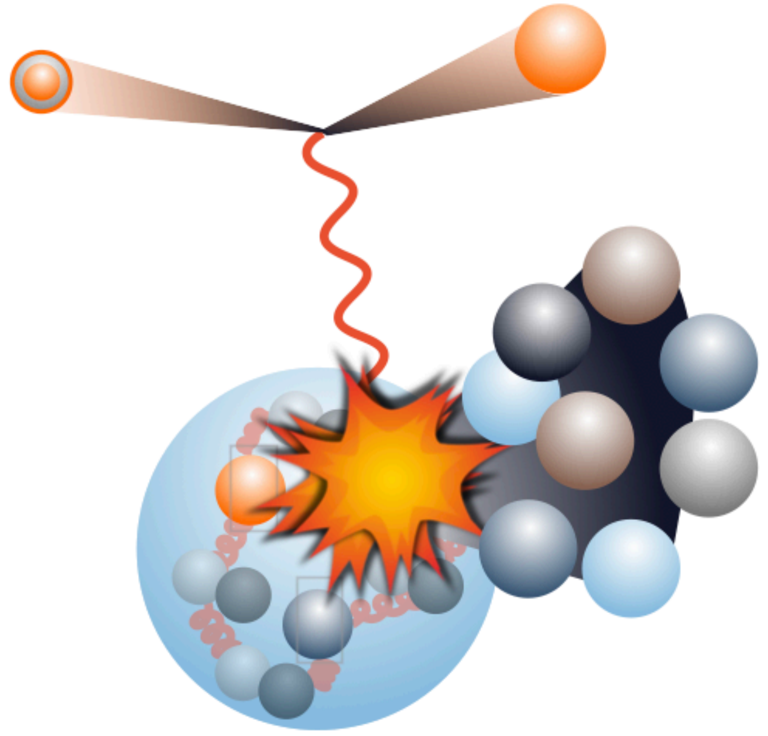
Rapid oscillation!

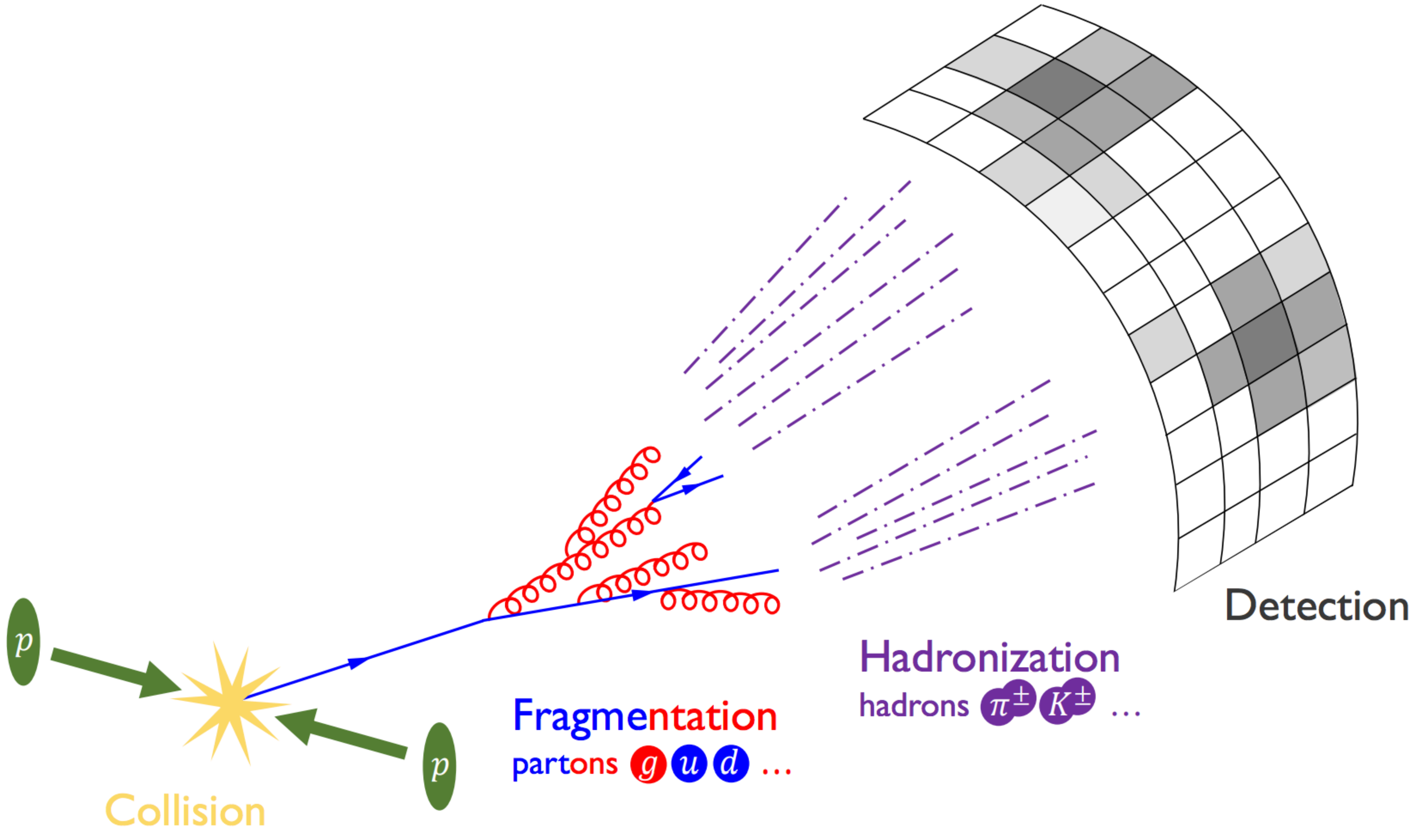
A quantum system will keep track of this inherently

Quantum Simulation



- What would we simulate?
- For example, some day, Hadronization
- Neutrino interacting with a nucleus.
- Processes in the early Universe





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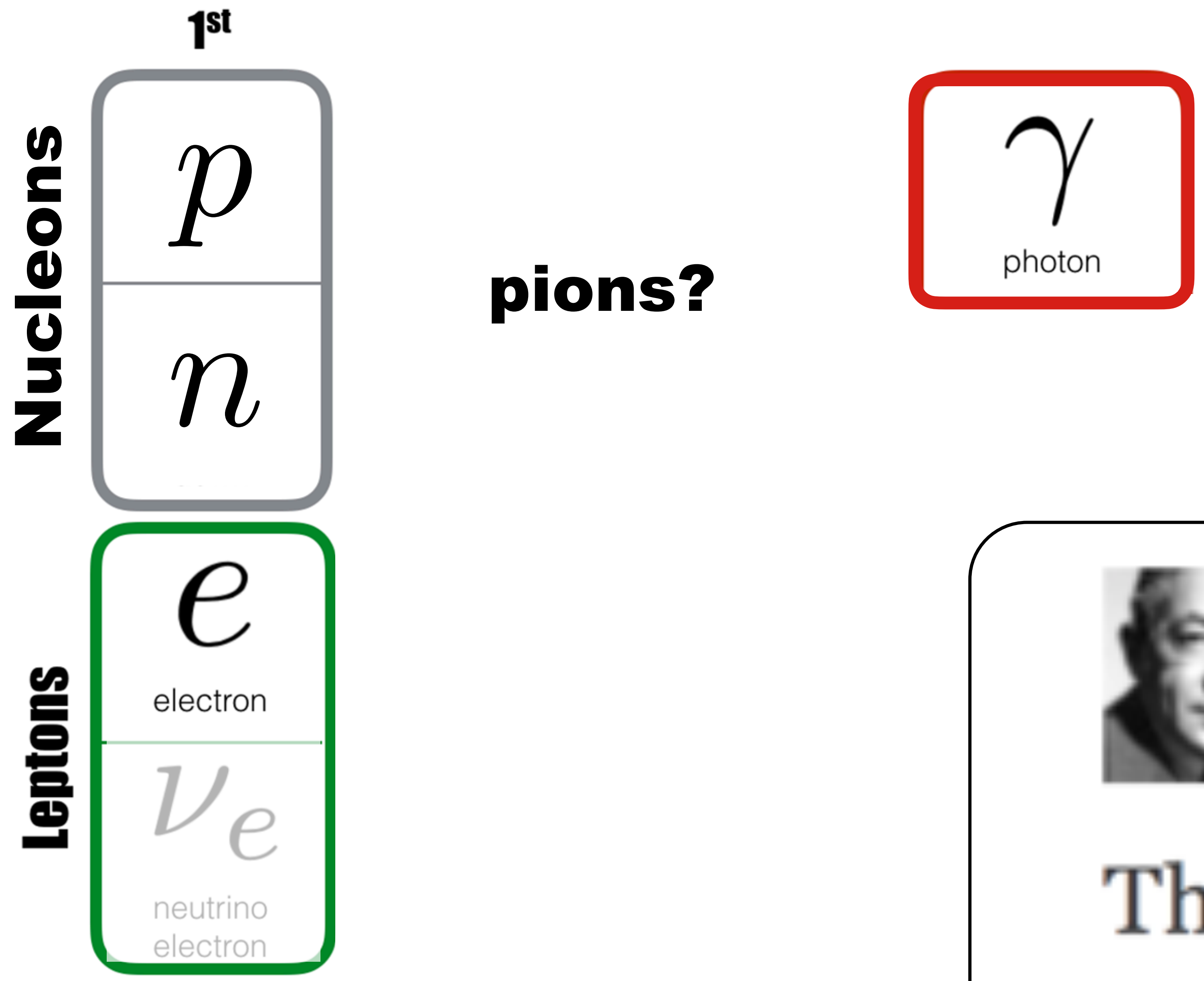
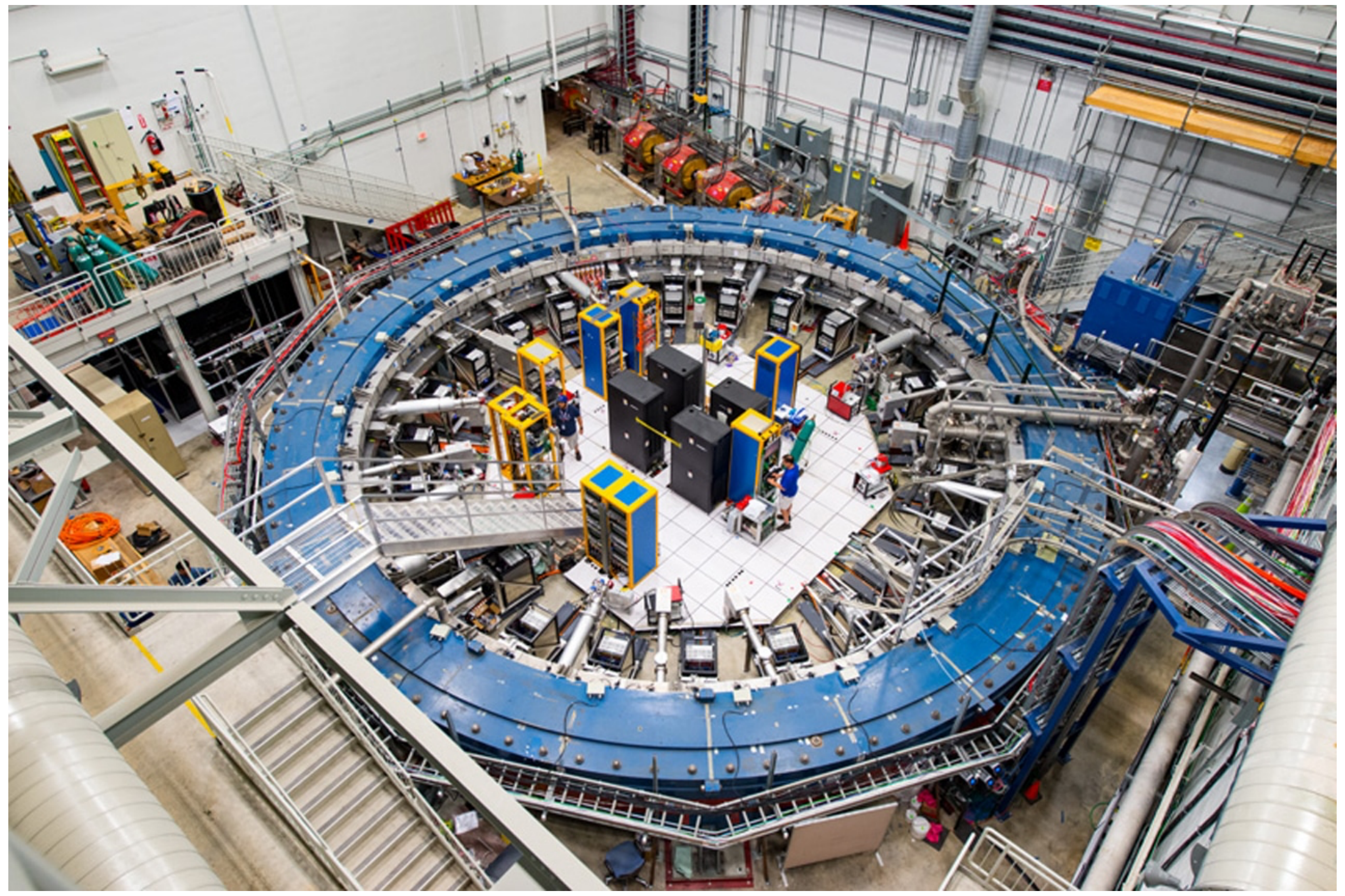
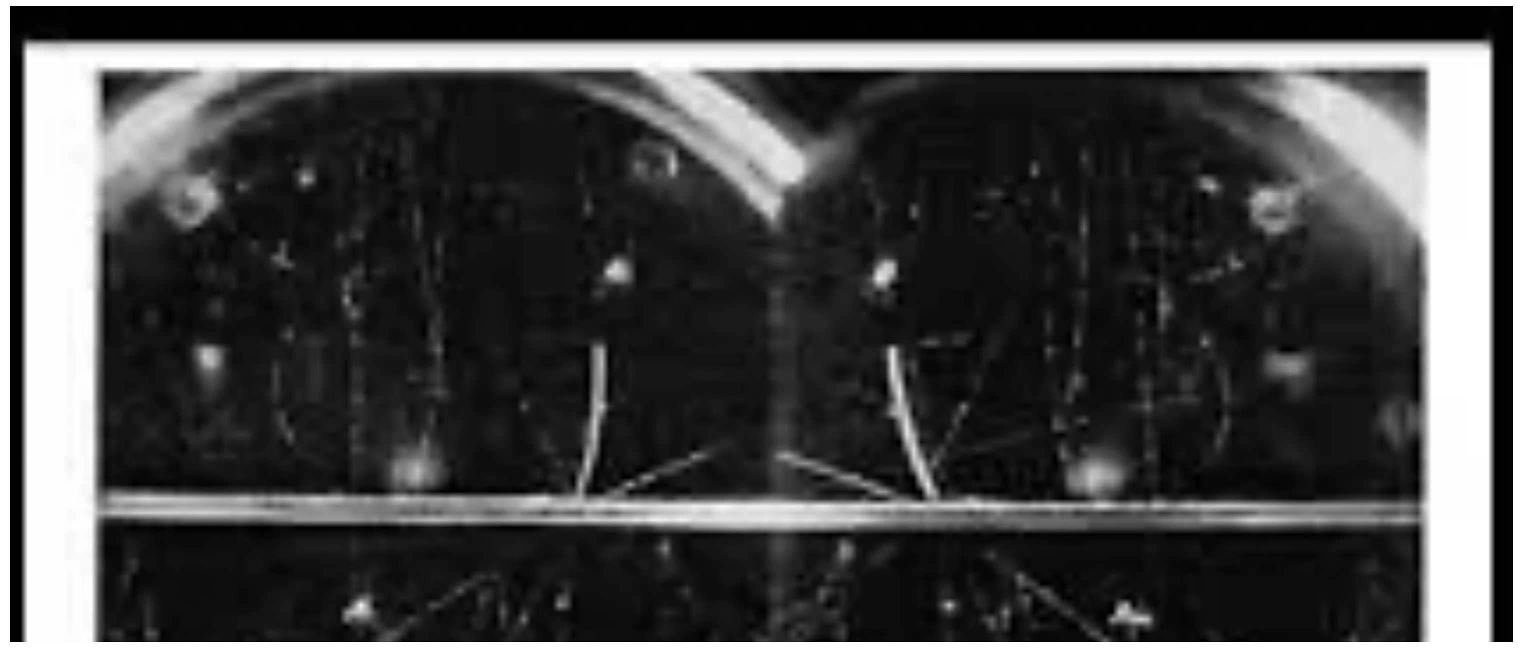
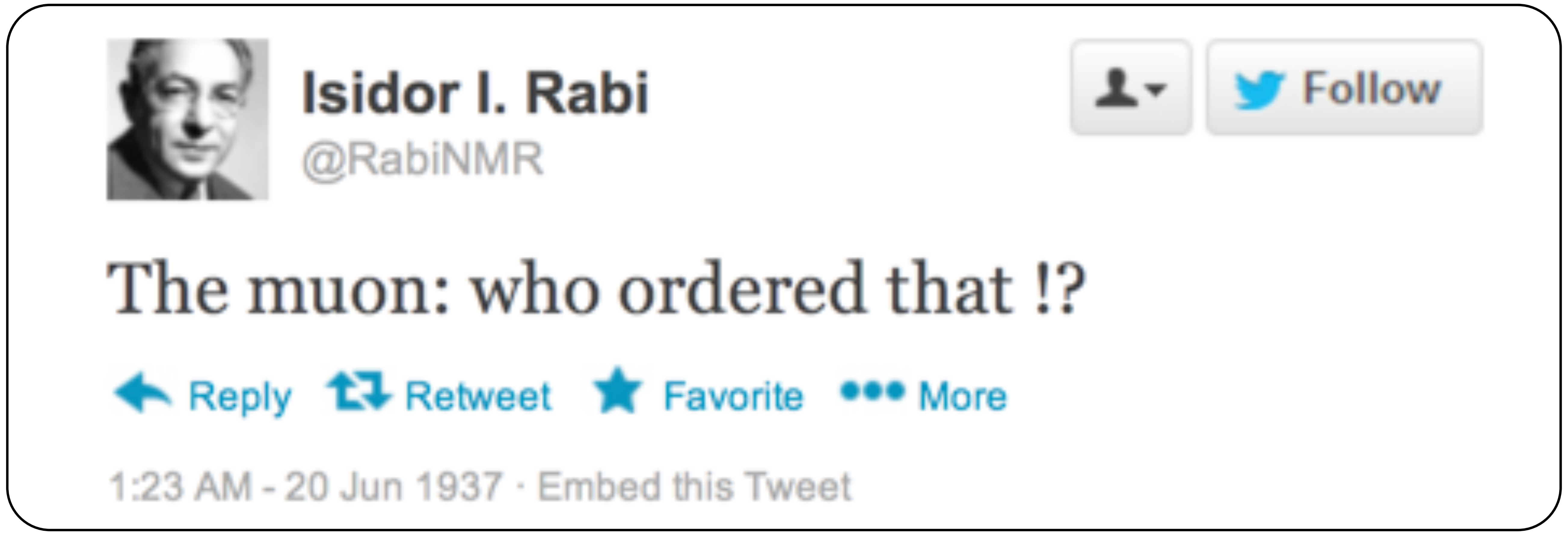
The Muon

- Yes, that muon!
- Recall the mid-30's: The SM of the time is









So you don't always get what you ordered . . .

Rates:

$$\Gamma_{\rm SPDC} \sim \frac{P_p {\chi_{\rm eff}^{(2)}}^2 \omega_s \omega_i L}{\pi n_p n_s n_i A_{\rm eff}}$$

Motivates long crystals too.

$$\Gamma_{\rm dSPDC}^{(A'_L)} \sim \epsilon^2 \frac{m_{A'}^2}{\omega_{A'}^2} \frac{P_p {\chi_{A'_L}^{(2)}}^2 \omega_s \omega_{A'} L}{n_p n_s A_{\rm eff}}$$

$$N_{\rm events}^{(A'_L)} \sim 10^{21} \left(\epsilon^2 \frac{m_{A'}^2}{\omega_{A'}^2}\right) \left(\frac{P_p}{\rm Watt}\right) \left(\frac{L}{\rm m}\right) \left(\frac{t_{\rm int}}{\rm year}\right)$$

$$\Gamma_{\rm dSPDC}^{(\rm axion)} \sim \frac{P_p g_{a\gamma\gamma}^2 \omega_s L}{\omega_{\rm axion} n_p n_s A_{\rm eff}}$$

$$N_{\rm events}^{(\rm axion)} \sim 40 \left(\frac{g_{a\gamma}}{10^{-6}\ {\rm GeV}^{-1}}\right)^2 \left(\frac{P_p}{\rm Watt}\right) \left(\frac{L}{\rm m}\right) \left(\frac{t_{\rm int}}{\rm year}\right)$$

	Dark Photon ($m_{A'} = 0.1$ eV)	Axion-like particle ($m_a = 0.1$ eV)
Current lab limit	$\epsilon < 3 \times 10^{-7}$	$g_{a\gamma} < 10^{-6}$ GeV^{-1}
Example dSPDC setup	$P_p = 1$ W	$P_p = 1$ kW
	$L = 1$ cm	$L = 10$ m
	$\Gamma = 10$/day	$\Gamma = 10$/day
Current Solar limit	$\epsilon < 10^{-10}$	$g_{a\gamma} < 10^{-10}$ GeV^{-1}
Example dSPDC setup	$P_p = 1$ W	$P_p = 100$ kW
	$L = 10$ m	$L = 100$ m
	$\Gamma = 10$/year	$\Gamma = 10$/year