# Cosmic Quantum

Aaron Chou

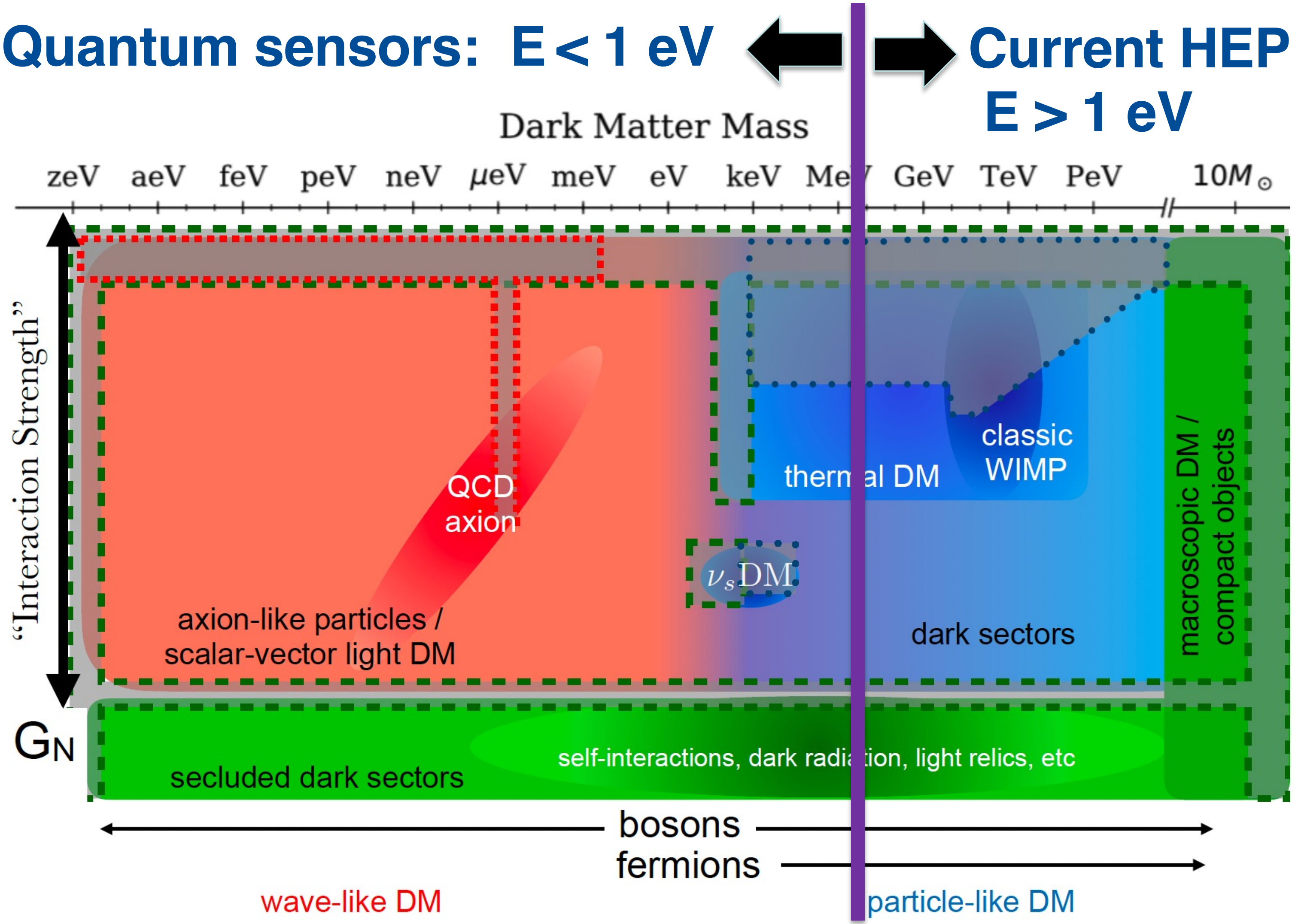
Fermilab Cosmic Day

10/30/2023

# Quantum sensors: $E < 1$ eV

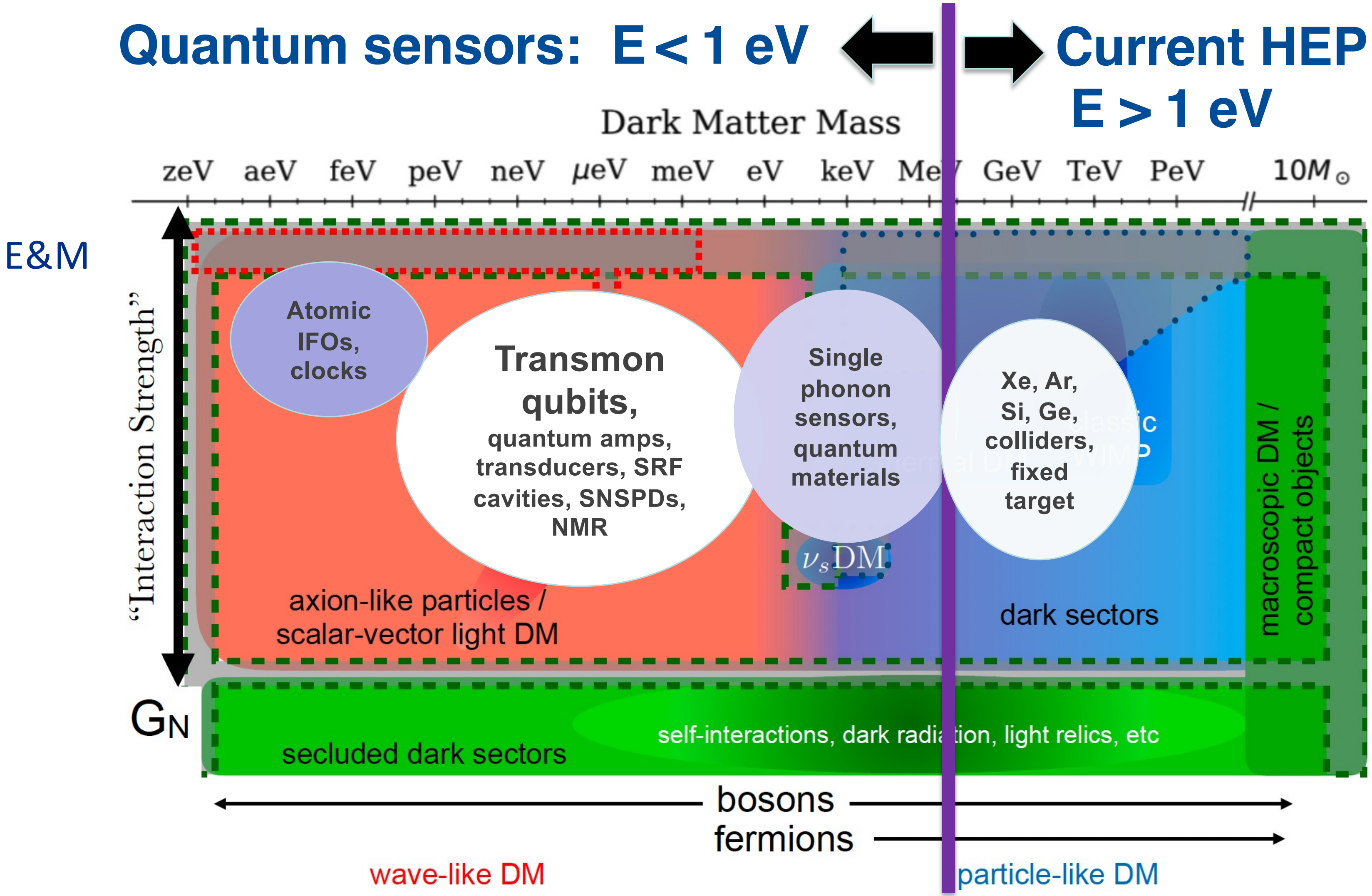
# Current HEP tech: $E > 1$ eV

E&M



Cartoon from Snowmass

# Quantum sensors: E < 1 eV ⟵ ⟶ Current HEP tech: E > 1 eV



Cartoon from Snowmass

# QuantISED Consortium: Quantum Sensing for Dark Matter:

## Engage neighboring fields to adapt quantum technology to HEP science targets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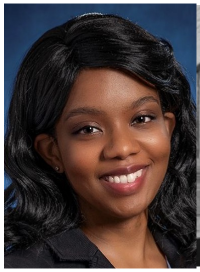
**Bold = PD alumni, now faculty**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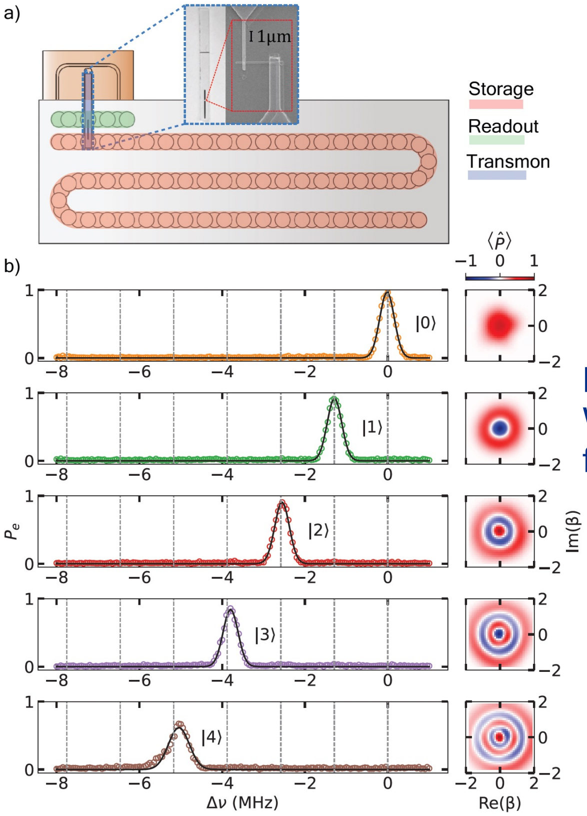
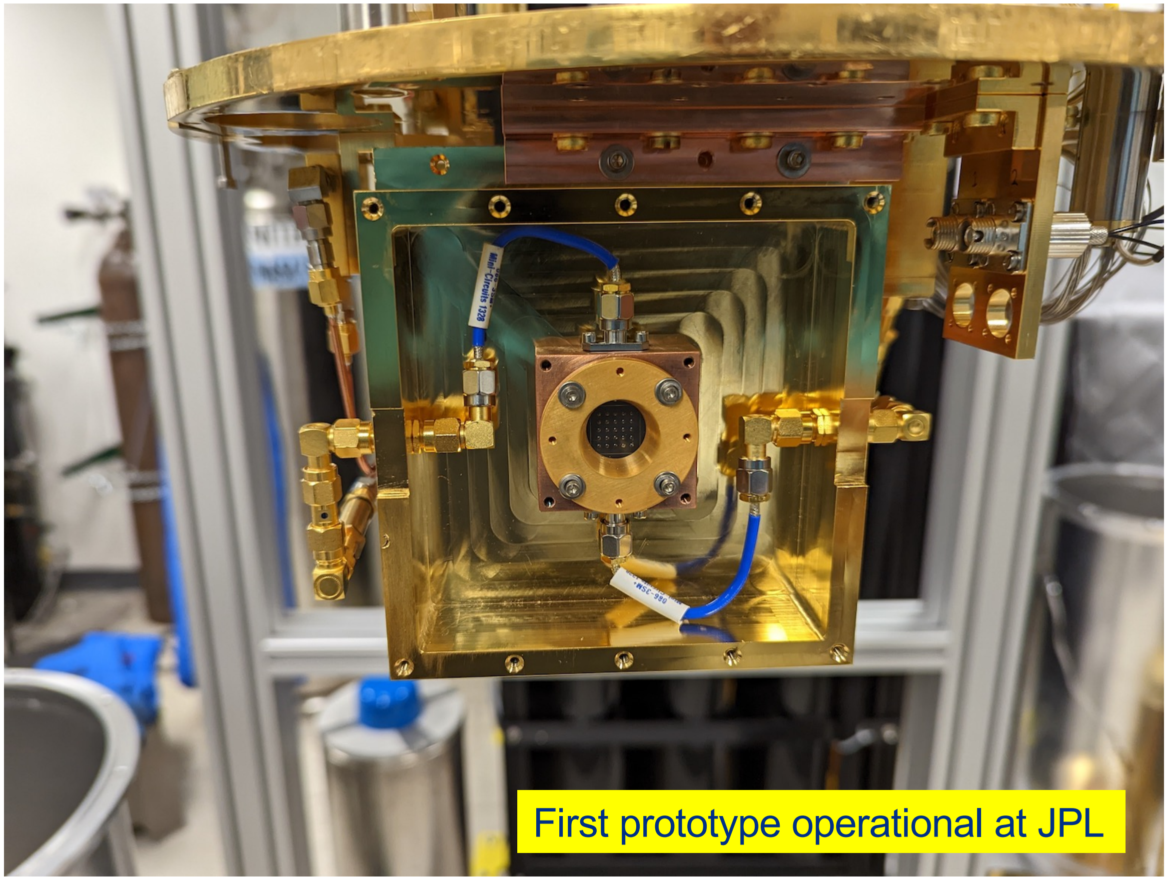
Qubit Stark shifts for Fock states



Measured Wigner functions

**SQuAD experiment:** Prepare cavity mode in Fock state to stimulate the emission of signal photons from classical dark matter waves.

Ankur Agrawal et al., 2305.03700



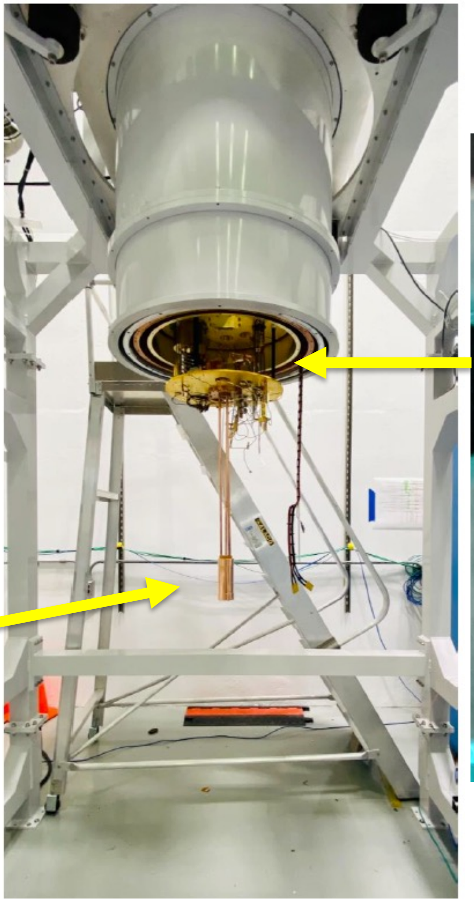
First prototype operational at JPL

**LADERA experiment:** Use Cooper pair-breaking qubit-based detectors to search for THz dark radiation generated by dynamical friction on the rolling dark energy field (FNAL, JPL)

**SQuAD (**Superconducting Qubits for Axion Darkmatter)

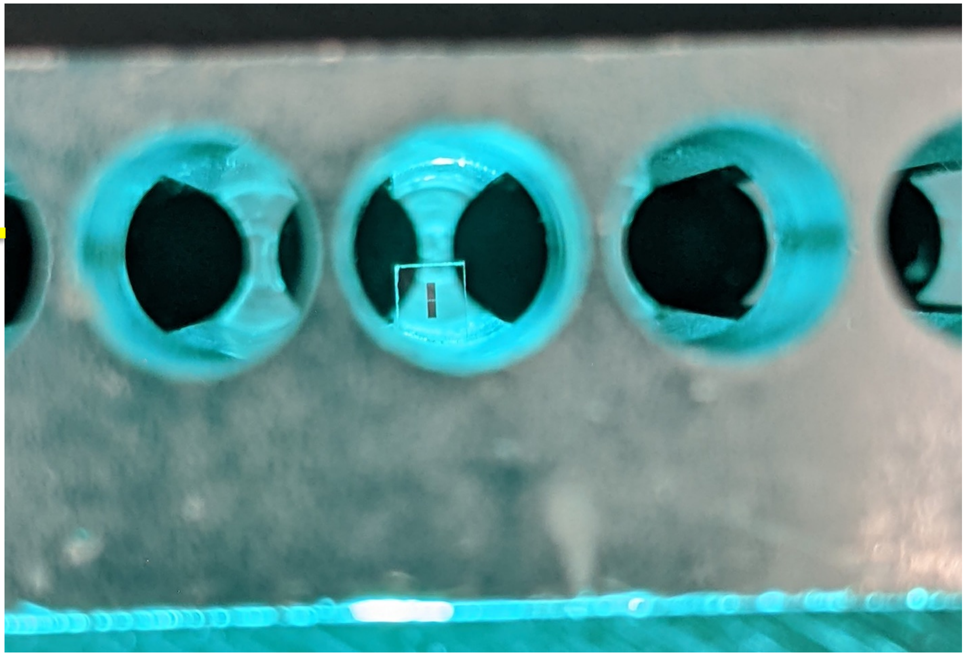
Nested sapphire cavity compatible with high B field needed for axion search: $Q>10^6$, ¼-wave layers reflect photon waves back to center

(based on design from INFN)



Installed in 10 mK dilution refrigerator and 14T solenoid magnet at SiDet Lab B.

Quantum readout electronics in remote, magnetically-shielded region



Transmon qubit performs quantum non-demolition single photon counting with noise 40x lower than zero-point noise.

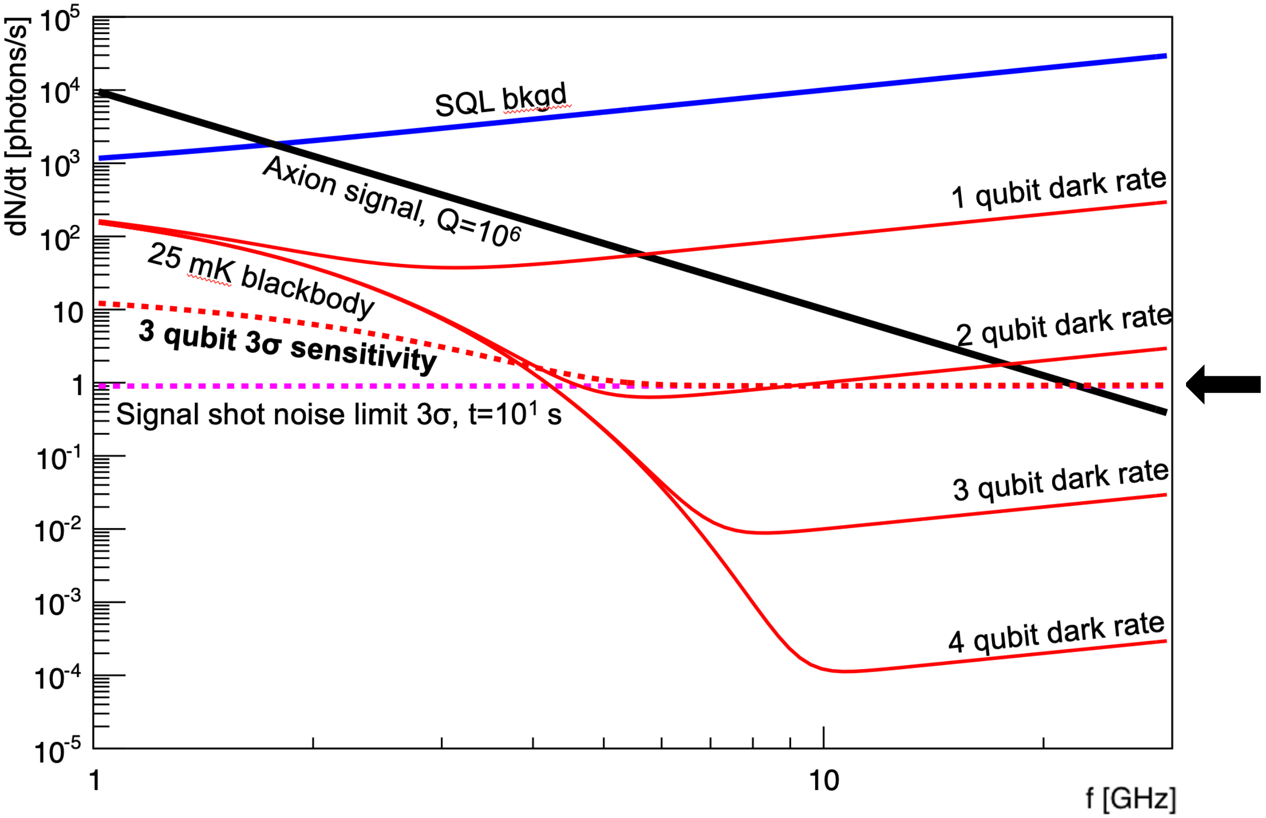
To do: cavity tuning, signal photon transport. Targeting science in FY24.

# Axion signal rate sensitivity is determined by the integration time budget:

if Q=$10^6$ then have maximum t=10 s at each tuning to get 1 octave in mass, i.e. using $10^6$ tunings in 1 year

Assume that quantum sensors will continue to improve until experiments are no longer background-limited.

(Demonstrated qubit DCR=1 Hz is already *nearly* good enough for background-free operation in 10 s integration budget.)

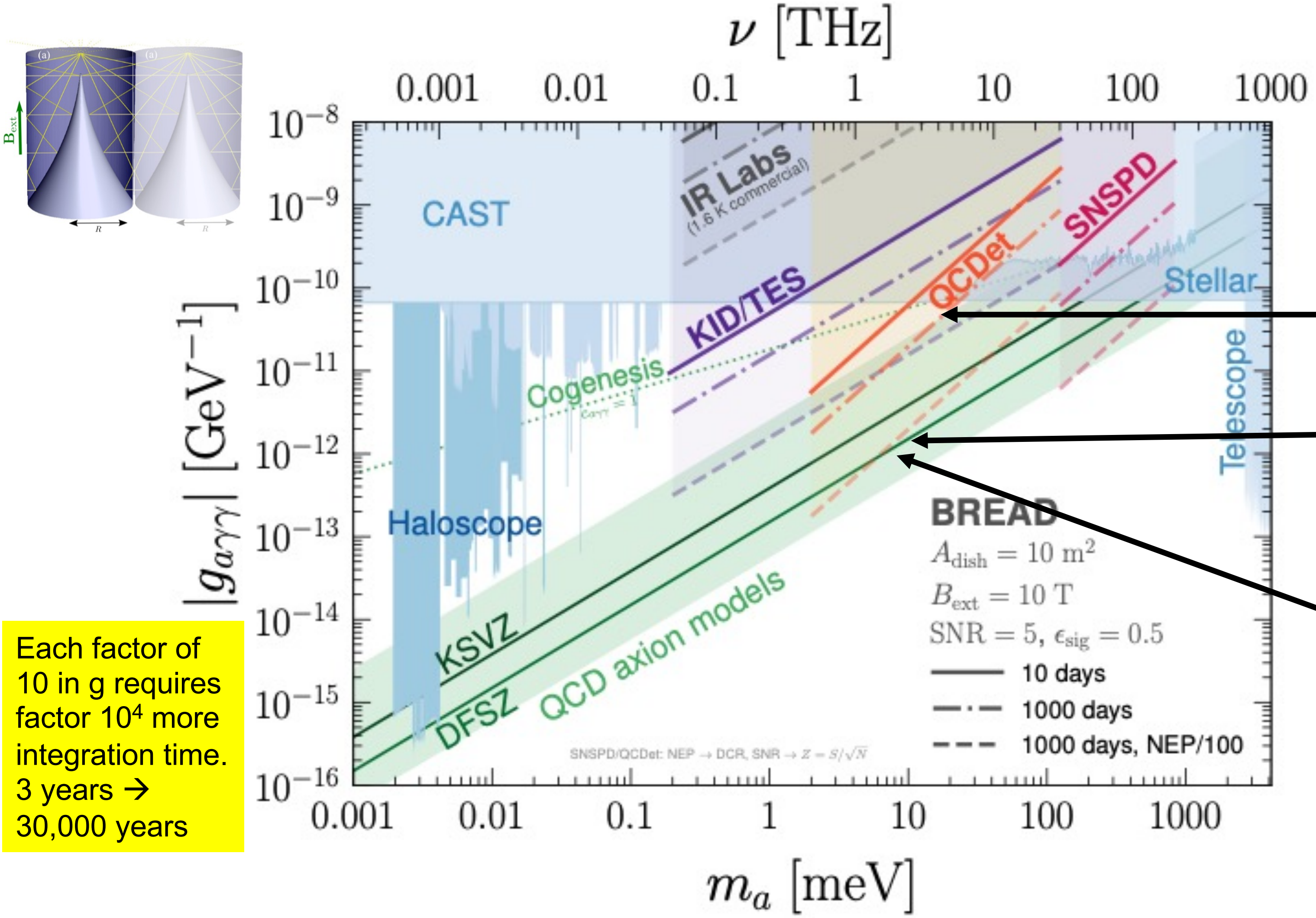


**For t = 10 s, the minimum observable signal rate is $R_s$=1 Hz**

(Signal shot noise limit, need to count 9 ± 3 photons for 3$\sigma$)

**Cavity experiments are signal limited: Need larger $B^2V$ or stimulated emission to go above 20 GHz.**

## BREAD uses long integration times to beat low signal rates, but is then background-limited



DCR=1 Hz
$10^8$ counts in t=$10^8$ s

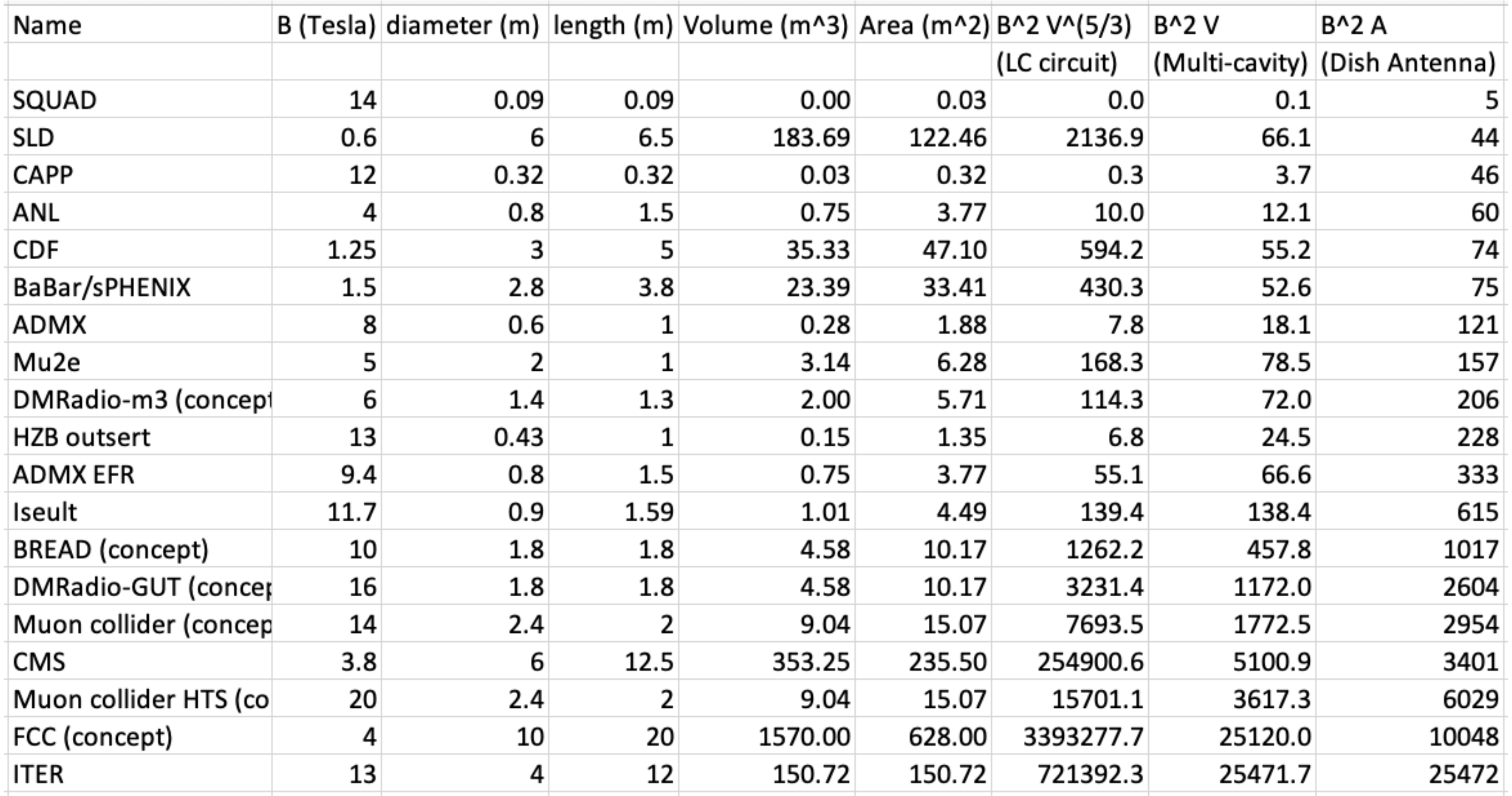
DCR=$10^{-4}$ Hz **(!)**
$10^4$ counts in t=$10^8$ s

Signal rate
$R_s \sim 10^{-6}$ Hz
100 counts in t=$10^8$ s

$R_s$ limit ~ sqrt($R_b$ / t)

Each factor of 10 in g requires factor $10^4$ more integration time. 3 years → 30,000 years

# What we really need for all experiments are bigger magnets



| Name | B (Tesla) | diameter (m) | length (m) | Volume (m^3) | Area (m^2) | B^2 V^(5/3) (LC circuit) | B^2 V (Multi-cavity) | B^2 A (Dish Antenna) |
|---|---|---|---|---|---|---|---|---|
| SQUAD | 14 | 0.09 | 0.09 | 0.00 | 0.03 | 0.0 | 0.1 | 5 |
| SLD | 0.6 | 6 | 6.5 | 183.69 | 122.46 | 2136.9 | 66.1 | 44 |
| CAPP | 12 | 0.32 | 0.32 | 0.03 | 0.32 | 0.3 | 3.7 | 46 |
| ANL | 4 | 0.8 | 1.5 | 0.75 | 3.77 | 10.0 | 12.1 | 60 |
| CDF | 1.25 | 3 | 5 | 35.33 | 47.10 | 594.2 | 55.2 | 74 |
| BaBar/sPHENIX | 1.5 | 2.8 | 3.8 | 23.39 | 33.41 | 430.3 | 52.6 | 75 |
| ADMX | 8 | 0.6 | 1 | 0.28 | 1.88 | 7.8 | 18.1 | 121 |
| Mu2e | 5 | 2 | 1 | 3.14 | 6.28 | 168.3 | 78.5 | 157 |
| DMRadio-m3 (concept | 6 | 1.4 | 1.3 | 2.00 | 5.71 | 114.3 | 72.0 | 206 |
| HZB outsert | 13 | 0.43 | 1 | 0.15 | 1.35 | 6.8 | 24.5 | 228 |
| ADMX EFR | 9.4 | 0.8 | 1.5 | 0.75 | 3.77 | 55.1 | 66.6 | 333 |
| Iseult | 11.7 | 0.9 | 1.59 | 1.01 | 4.49 | 139.4 | 138.4 | 615 |
| BREAD (concept) | 10 | 1.8 | 1.8 | 4.58 | 10.17 | 1262.2 | 457.8 | 1017 |
| DMRadio-GUT (conce | 16 | 1.8 | 1.8 | 4.58 | 10.17 | 3231.4 | 1172.0 | 2604 |
| Muon collider (concep | 14 | 2.4 | 2 | 9.04 | 15.07 | 7693.5 | 1772.5 | 2954 |
| CMS | 3.8 | 6 | 12.5 | 353.25 | 235.50 | 254900.6 | 5100.9 | 3401 |
| Muon collider HTS (co | 20 | 2.4 | 2 | 9.04 | 15.07 | 15701.1 | 3617.3 | 6029 |
| FCC (concept) | 4 | 10 | 20 | 1570.00 | 628.00 | 3393277.7 | 25120.0 | 10048 |
| ITER | 13 | 4 | 12 | 150.72 | 150.72 | 721392.3 | 25471.7 | 25472 |

Barely reach DFSZ with a lot of hand-waving

Decisively reach DFSZ (g=0.3)

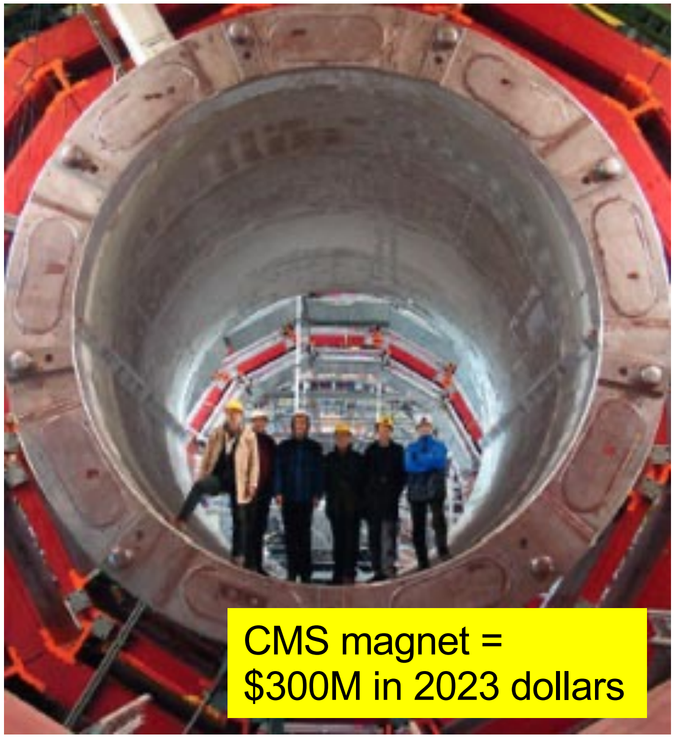
Push to g=0.1 !

**Dish antenna: $g \sim 5 (R_b/t)^{1/4} B^{-1} L^{-1}$**

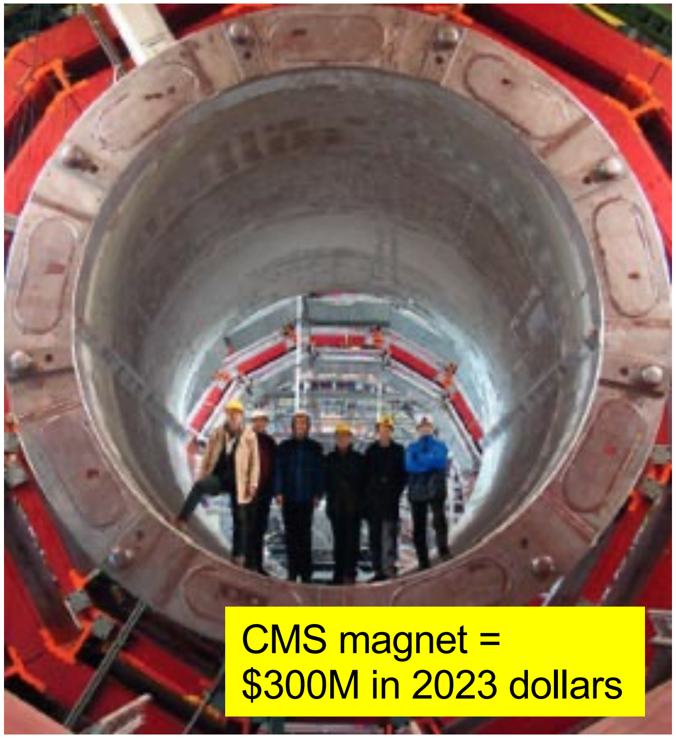
**Even better scaling with magnet size L for multi-cavity or LC experiments.**

## Build $500M-scale magnet facilities, utilized by many experiments?

CMS magnet?  Need similar for muon collider tracker, need 10x scale-up for FCC detector



CMS magnet =
$300M in 2023 dollars



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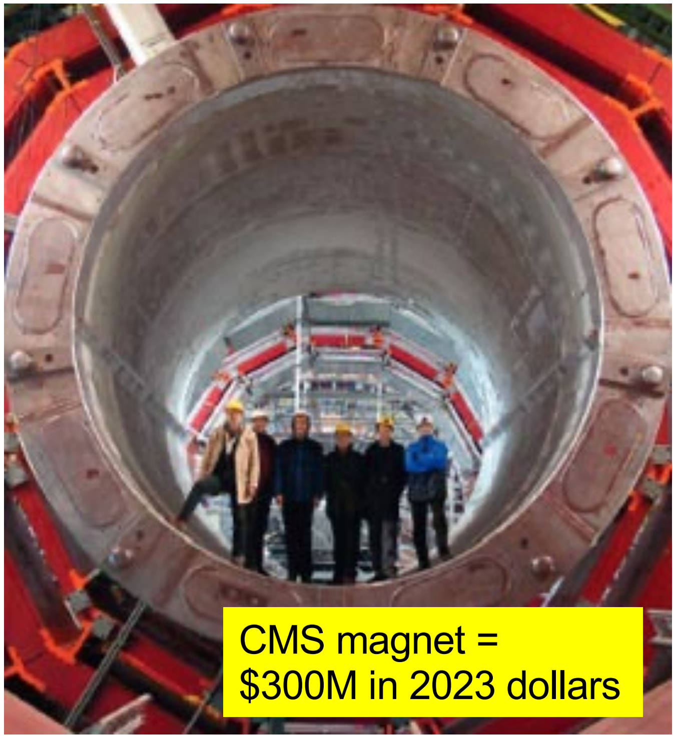
$300M in 2023 dollars



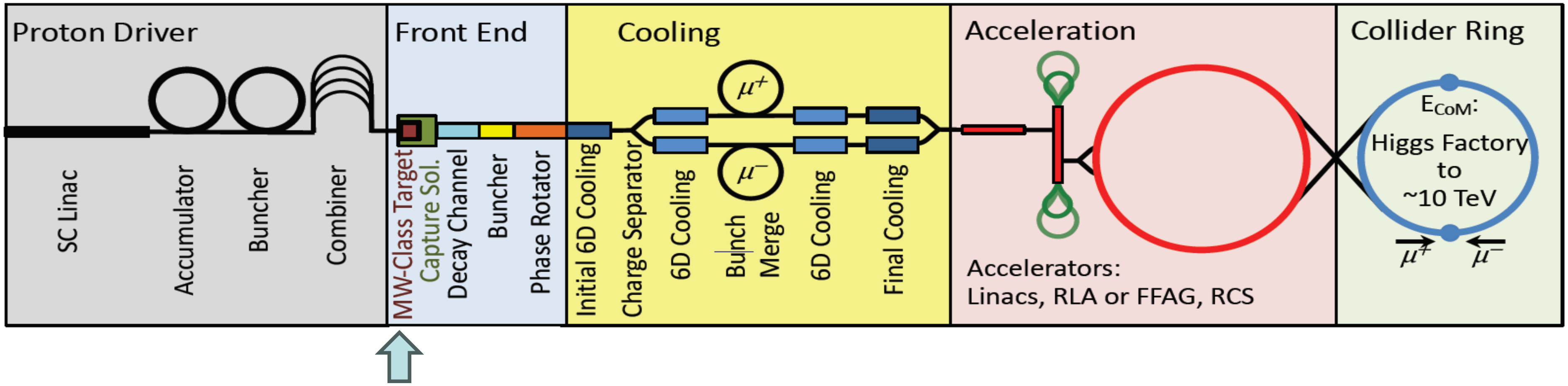
CMS magnet =
$300M in 2023 dollars

**Magnets of this scale take 10 years to build, so if we want them, we better start planning now!**
Who are our partners?

# Muon Collider Facility Overview

J.S. Berg
Fermilab ACE Science Workshop
June, 2023

- Proton driver creating high-power proton beam
- Front end: create pions at target, capture muons, convert to bunch train
- Cooling: reduce emittance, combine into one bunch
- Acceleration: increase energy
- Collider ring



**Axion experiments go here**

# Multi-prong strategy provides many stakeholders, broad science program,

**Energy Frontier:**
**Muon Collider,**
**Tracker magnets**

**Cosmic Frontier:**
**Axion Dark Matter**

**Accelerator Frontier:**
**Magnet R&D,**
**Muon Collider,**
**Accelerator Complex Evolution**

**Rare/Precision Frontier:**
**Charged Lepton Flavor Violation**

**Non-HEP:**
**Plasma fusion,**
**High field MRI,**
**Crystal growth,**
**Quantum magnetic materials**

# Quantum Science Center

QSC overarching goal:
***Overcoming key roadblocks in quantum state resilience, controllability, and ultimately scalability of quantum technologies***

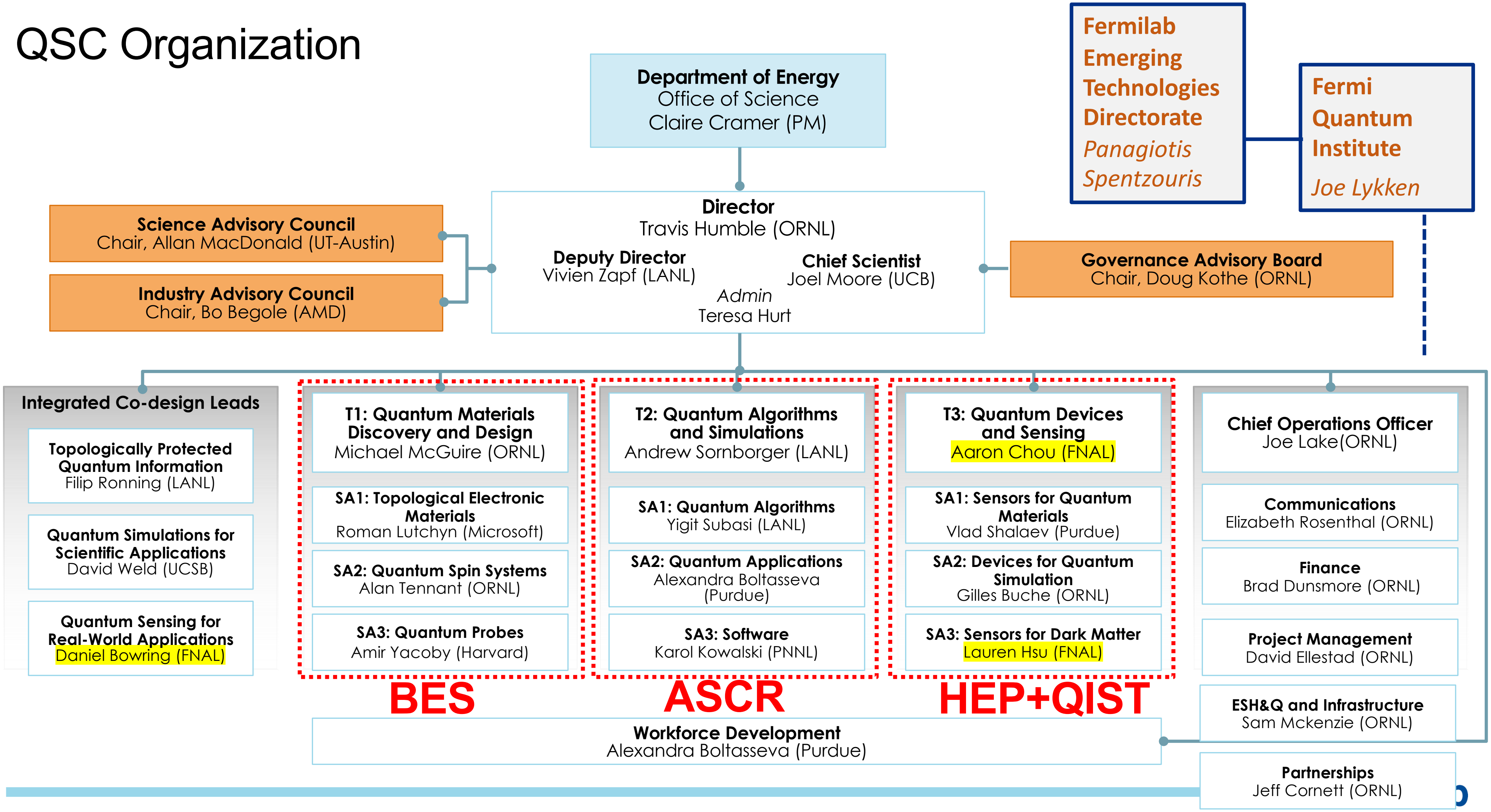
- Address the fragility of quantum states through the design of new topological materials for QIS
- Develop algorithms and software for computation and sensing with current/future QIS hardware
- Design new **quantum devices and sensors to detect dark matter** and topological quasiparticles

QSC comprises ~100 researchers across 16 institutions.

Fermilab headcount:
9 scientists (~2.5 FTE), 3 PD,
5 engineers

Berkeley UNIVERSITY OF CALIFORNIA
Caltech
ColdQuanta The Quantum Atomics Company
Fermilab
HARVARD UNIVERSITY
IBM
Los Alamos NATIONAL LABORATORY EST.1943
Microsoft
OAK RIDGE National Laboratory
Pacific Northwest NATIONAL LABORATORY
PRINCETON UNIVERSITY
PURDUE UNIVERSITY
UCSB UNIVERSITY OF CALIFORNIA SANTA BARBARA
UNIVERSITY OF MARYLAND
THE UNIVERSITY OF TENNESSEE KNOXVILLE
UNIVERSITY of WASHINGTON

# QSC Organization



**Department of Energy**
Office of Science
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**Fermilab Emerging Technologies Directorate**
*Panagiotis Spentzouris*

**Fermi Quantum Institute**
*Joe Lykken*

**Science Advisory Council**
Chair, Allan MacDonald (UT-Austin)

**Industry Advisory Council**
Chair, Bo Begole (AMD)

**Director**
Travis Humble (ORNL)

**Deputy Director**
Vivien Zapf (LANL)

**Chief Scientist**
Joel Moore (UCB)

*Admin*
Teresa Hurt

**Governance Advisory Board**
Chair, Doug Kothe (ORNL)

**Integrated Co-design Leads**

**Topologically Protected Quantum Information**
Filip Ronning (LANL)

**Quantum Simulations for Scientific Applications**
David Weld (UCSB)

**Quantum Sensing for Real-World Applications**
Daniel Bowring (FNAL)

**T1: Quantum Materials Discovery and Design**
Michael McGuire (ORNL)

**SA1: Topological Electronic Materials**
Roman Lutchyn (Microsoft)

**SA2: Quantum Spin Systems**
Alan Tennant (ORNL)

**SA3: Quantum Probes**
Amir Yacoby (Harvard)

**BES**

**T2: Quantum Algorithms and Simulations**
Andrew Sornborger (LANL)

**SA1: Quantum Algorithms**
Yigit Subasi (LANL)

**SA2: Quantum Applications**
Alexandra Boltasseva (Purdue)

**SA3: Software**
Karol Kowalski (PNNL)

**ASCR**

**T3: Quantum Devices and Sensing**
Aaron Chou (FNAL)

**SA1: Sensors for Quantum Materials**
Vlad Shalaev (Purdue)

**SA2: Devices for Quantum Simulation**
Gilles Buche (ORNL)

**SA3: Sensors for Dark Matter**
Lauren Hsu (FNAL)

**HEP+QIST**

**Chief Operations Officer**
Joe Lake(ORNL)

**Communications**
Elizabeth Rosenthal (ORNL)

**Finance**
Brad Dunsmore (ORNL)

**Project Management**
David Ellestad (ORNL)

**ESH&Q and Infrastructure**
Sam Mckenzie (ORNL)

**Partnerships**
Jeff Cornett (ORNL)

**Workforce Development**
Alexandra Boltasseva (Purdue)

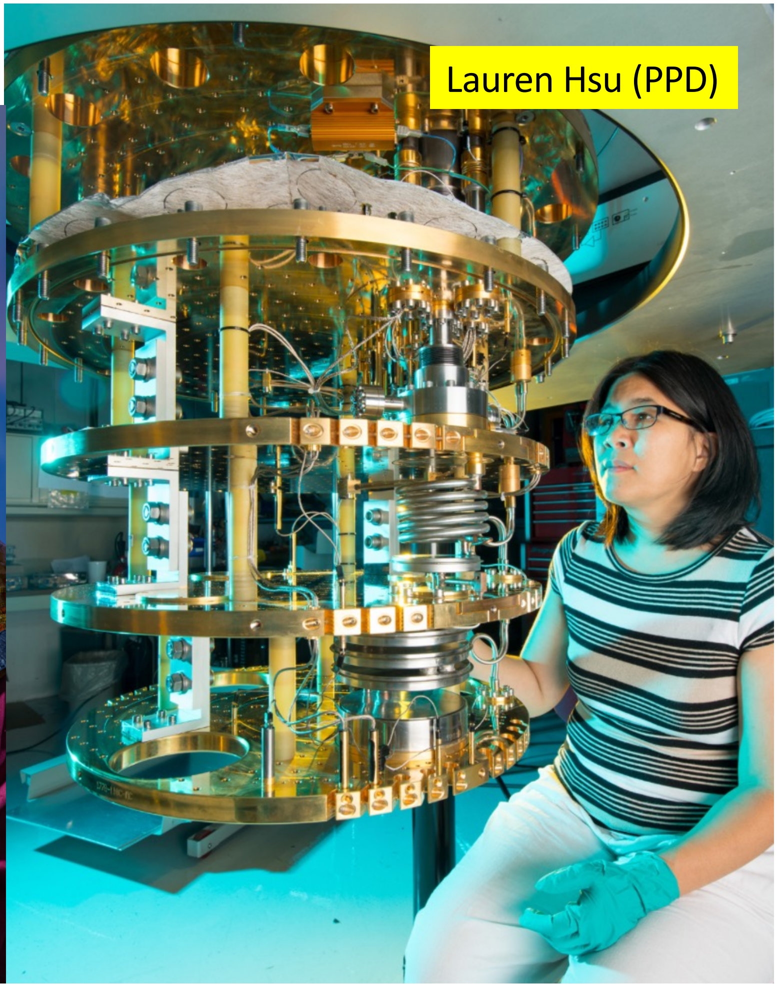
# Strategy: Leverage Fermilab/HEP instrumentation capabilities for QIST R&D

Facilitates development of new quantum materials, devices, and sensors;
Provides testbeds for quantum algorithms for sensing and simulation.

In return, new collaborations with
BES/ASCR/QIST will enhance HEP science.

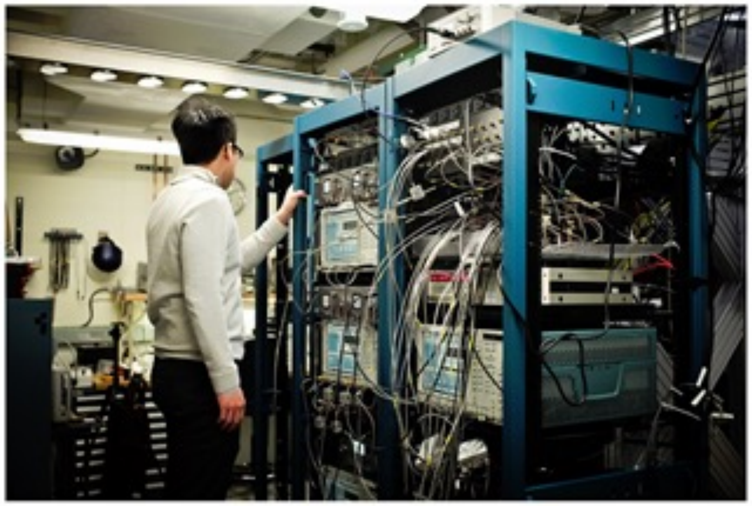

Rakshya Khatiwada (ETD)


Farah Fahim (ETD)

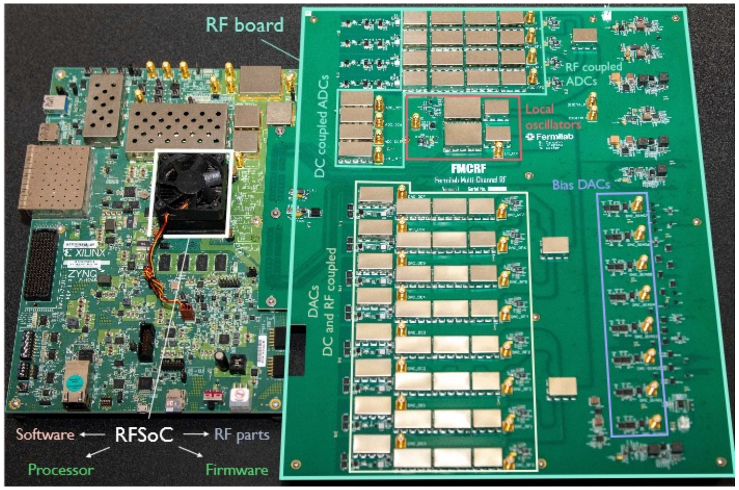

Lauren Hsu (PPD)

# Quantum Intrumentation Control Kit (QICK), Gustavo Cancelo et al.

- **New HEP multiplexed control/readout electronics now being deployed in major quantum computing labs and industries across the country.**
- **Goal: Control 100-1000 qubits per board in quantum computers and quantum sensor arrays. Reduce cost per channel from $100k to < $1. Enable million qubit machine!**



QICK



**Replaces ~$1M, full rack, off-the-shelf**

**with $20K, single pair of boards**

“The development of the Quantum Instrumentation Control Kit is an excellent example of U.S. investment in joint quantum technology research with partnerships between industry, academia and government to accelerate pre-competitive quantum research and development technologies,” said the U.S. Department of Energy’s Harriet Kung.

Review of Scientific Instruments **93**, 044709 (2022); https://doi.org/10.1063/5.0076249

# Windchime concept:

## Larger mass accelerometers needed for detecting gravitational force from Planck mass DM particles

Cubic meter array of $10^9$ **accelerometers** with mm spacing.

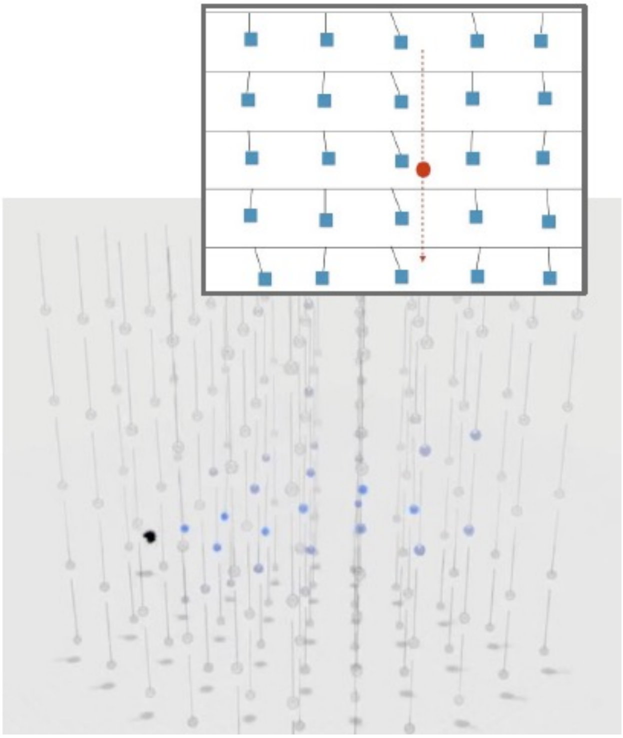
Probably gravitational force is too weak but can still focus on scalar or vector-mediated forces.

**How to affordably read out sensor array and reconstruct track of 1000 excitations in real-time???**

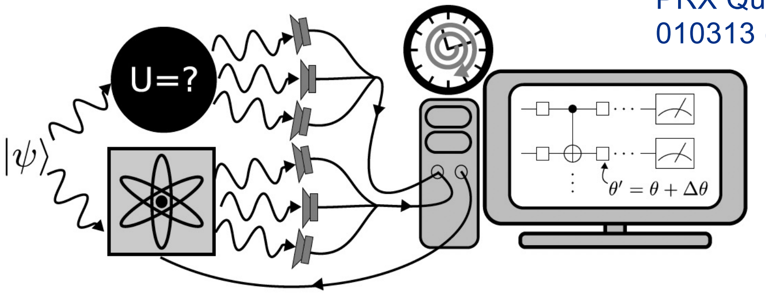
- Probably impossible with classical computers.
  - cf. LHC = 400M channels
  - Heat load = 5 dedicated nuclear power plants
- **If Dark matter detector = Quantum Computer**

  **→ Should provide in-situ processing of tracks**

  Bulk-boundary correspondence?
  Emergent Goldstone bosons?
  Quantum machine learning, annealing?



D. Carney et al.,
Phys.Rev.D 102
(2020) 7, 072003



Z. Holmes et al.,
PRX Quantum 3
010313 (2022)