# Swapan Chattopadhyay & Axions & Dark Matter

February, 2015: Young Aaron Chou meets famous accelerator physicist Swapan Chattopadhyay in Fermilab Director's science advisory committee. **Realizes he is in the presence of greatness!**

Swapan joins Fermilab axion group, contributing RF cavity expertise. Other luminaries like Alvin Tollestrup follow.

May, 2015: Fermilab joins ADMX experiment

Fermilab axion group in new axion lab (old bubble chamber pit SiDet Lab B)

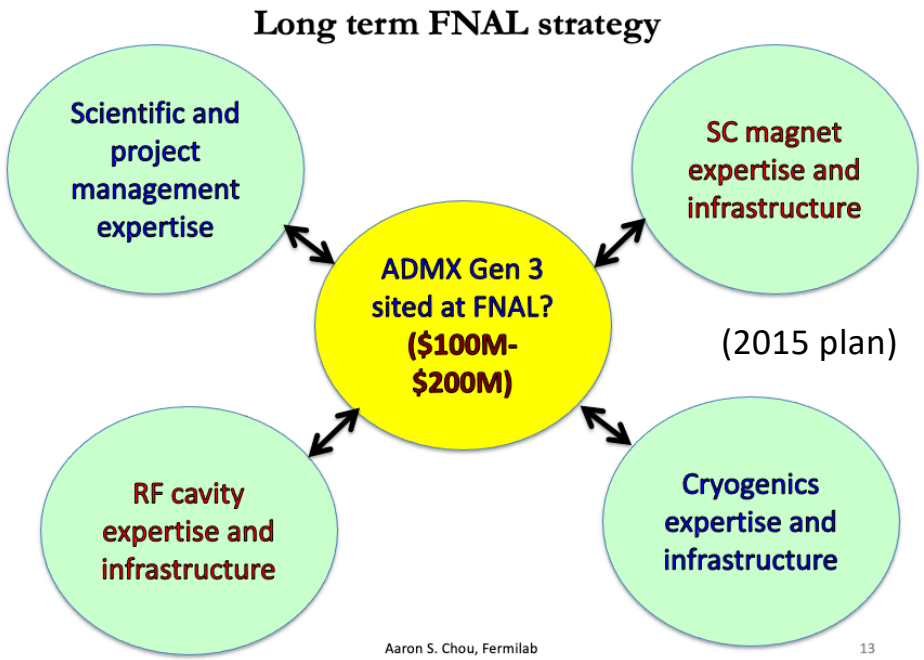
2015 axion R&D proposal to Fermilab KA25 Detector R&D panel rejected.

**Reason: Panel has no evidence that Fermilab Directorate plans to pursue axion science.**

## Axion Dark Matter Cavity FY16 R&D Proposal

**November 6, 2015**

PPD Astro: **Aaron Chou, Andrew Sonnenschein, William Wester**
PPD Theory: **Estia Eichten, Chris Hill**
AD: **Daniel Bowring, Swapan Chattopadhyay, Katsuya Yonehara, Al Moretti**
TD: **Sergey Kazakov**
U.Chicago: **Akash Dixit**



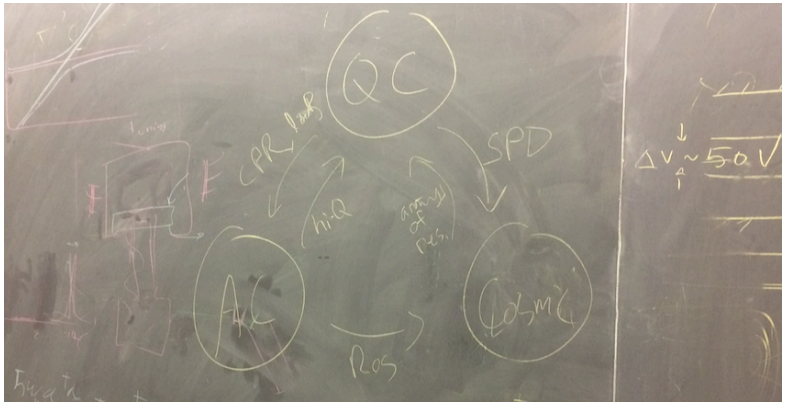

(2015 plan)

→ **September 2016: Fermilab becomes DOE Lead Lab for ADMX-G2 experiment**
→ **Current 2021 ADMX Collaboration plan: Move next generation experiment to Fermilab.**

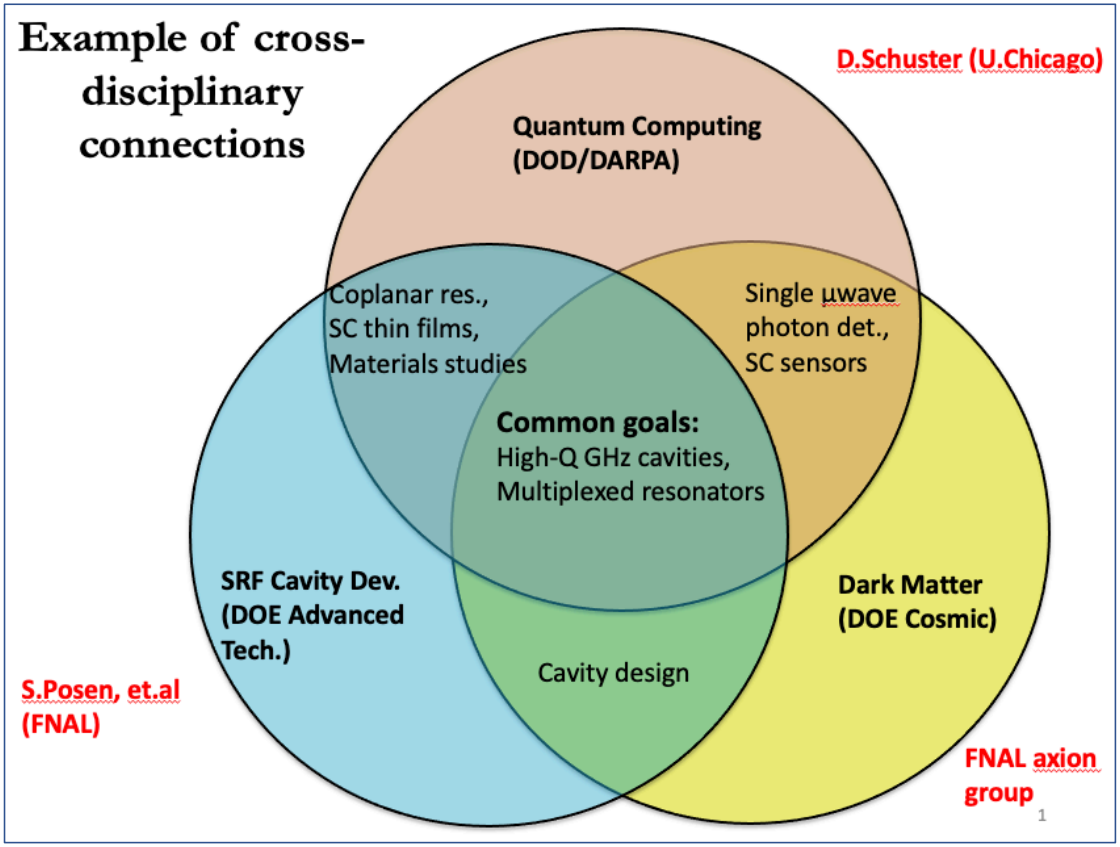
What happened???

# November 2015, the beginnings of the DOE QuantISED program (then DOE Connections)

Blackboard sketch at 1st meeting between Aaron Chou and Dave Schuster who realize that QIS and HEP can mutually benefit each other in many more ways than originally envisioned.

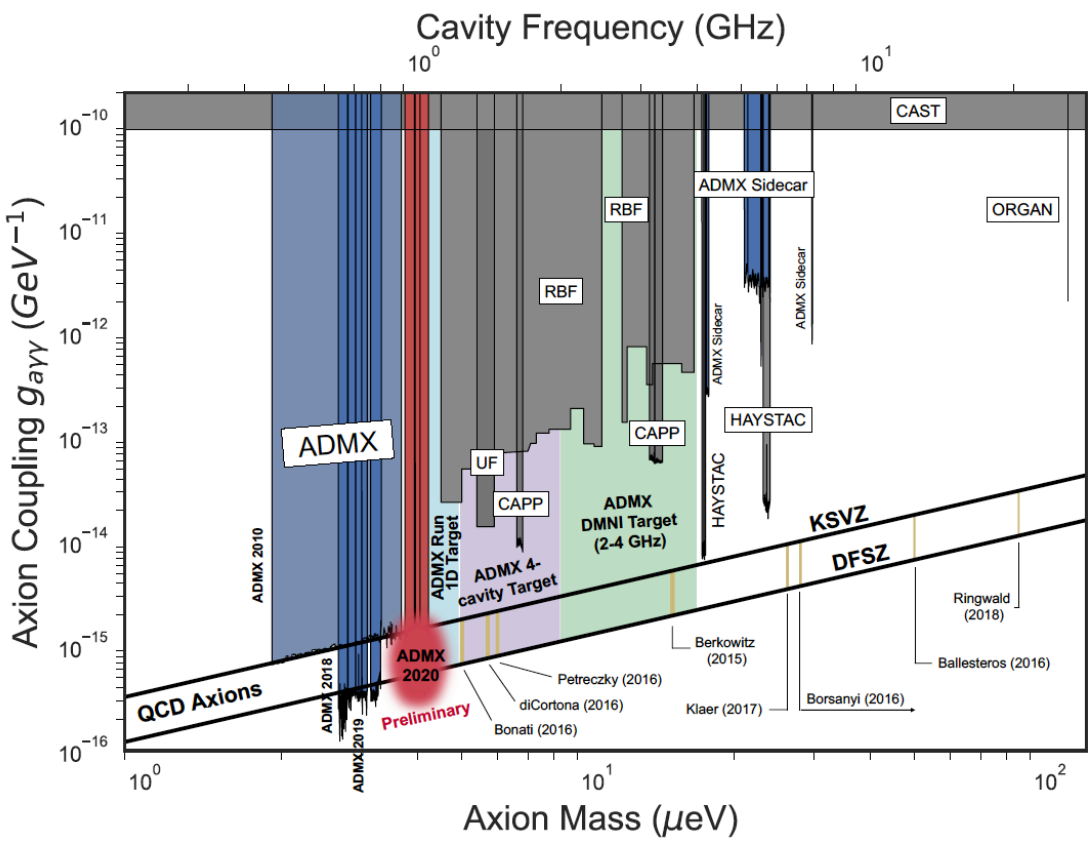



Swapan presents slide to Jim Siegrist and Lali Chatterjee, pre-meeting for roundtable and white paper which starts the QuantISED program.




**→ Dark matter has suddenly become a primary HEP target for quantum sensors and hence part of the quantum strategic plan!**

ADMX is now the *only* cavity haloscope experiment ever to reach sensitivity to QCD axions.

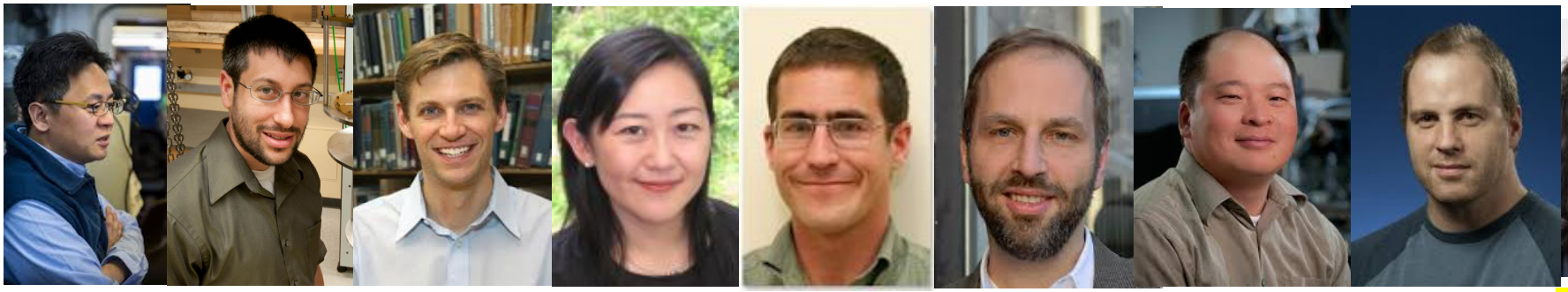



As I've argued, this great success is highly correlated with Swapan arriving at Fermilab in 2014!

Swapan's advisee Nathan Woollett
→ ADMX postdoc → Rigetti Computing

# DOE QuantISED R&D Consortium: Quantum Sensing for Dark Matter

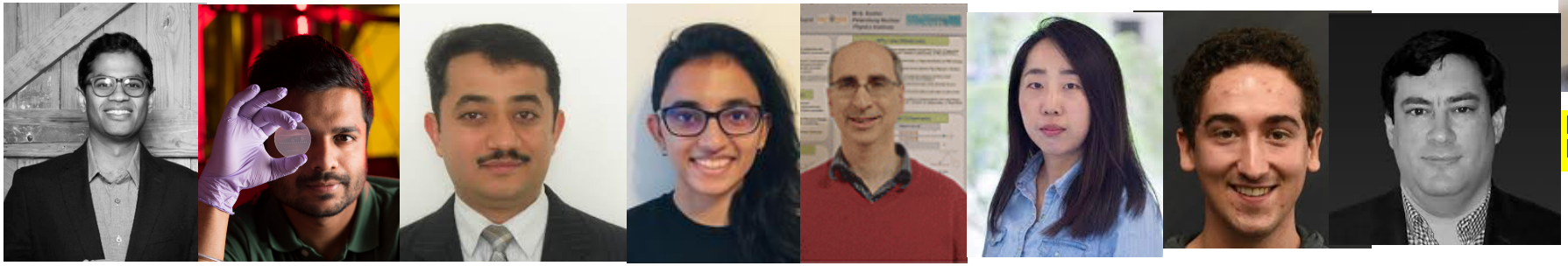
Lead PI – Aaron Chou



New faculty IIT: R. Khatiwada

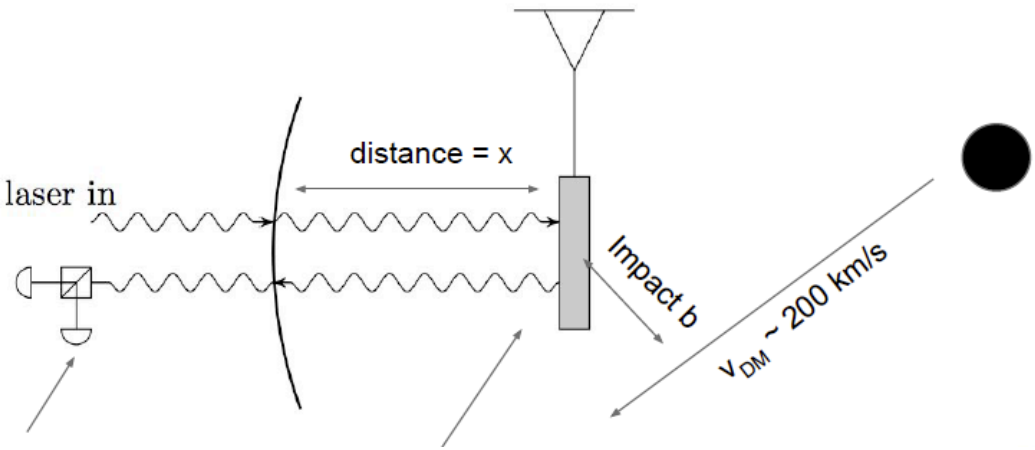
- Aaron Chou (**FNAL**), David Schuster(**Chicago**): QND readout, non-class. states
- Konrad Lehnert (**Colorado**): Squeezed microwave readout, photon transport
- Reina Maruyama (**Yale**): Rydberg atom-based single photon detection
- Robert McDermott (**Wisconsin**): Cooper pair-breaking sensors
- Pierre Echternach (**JPL**): Quantum Capacitance single THz photon detector
- Karl Berggren (**MIT**), Sae Woo Nam (**NIST**): Superconducting nanowire SPD
- Juan Estrada (FNAL): SENSEI parametric downconversion for hidden photon search
- Rakshya Khatiwada (**IIT/FNAL**): single photon detector calibration

New faculty JHU: D. Speller

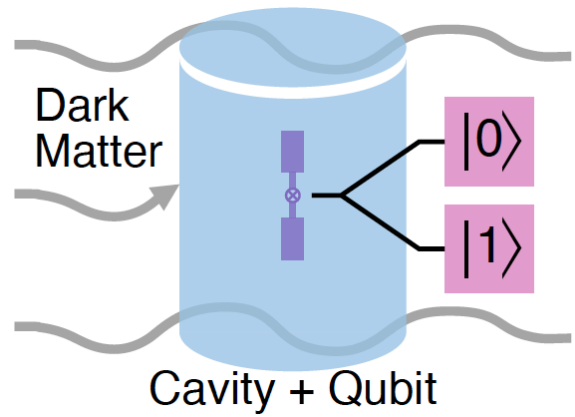


A. Dixit | A. Agrawal | M. Hassan | S. Ghosh | S. Cahn | **F. Zhao (New FNAL PD)** | M. Lynn | M. Hollister

# Dark matter can exert forces on “test oscillators”
# → Read out with Quantum Sensors



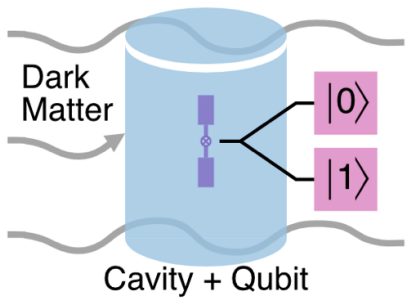

Individual heavy dark matter particles can exert a gravitational force on mechanical oscillators.

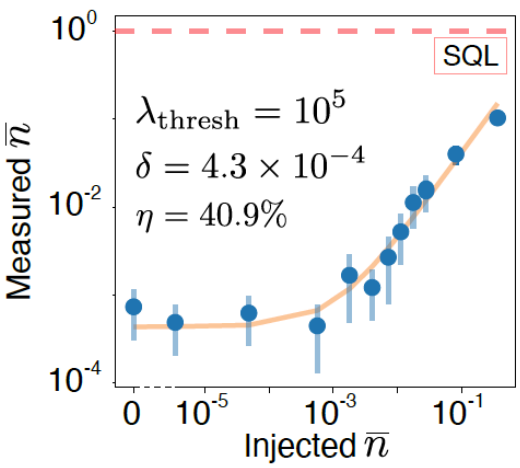


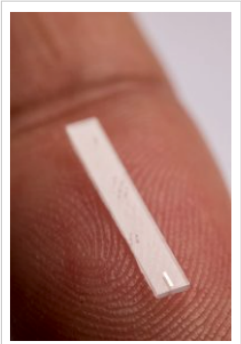

Waves of bosonic dark matter can also directly drive free-space or cavity photon modes

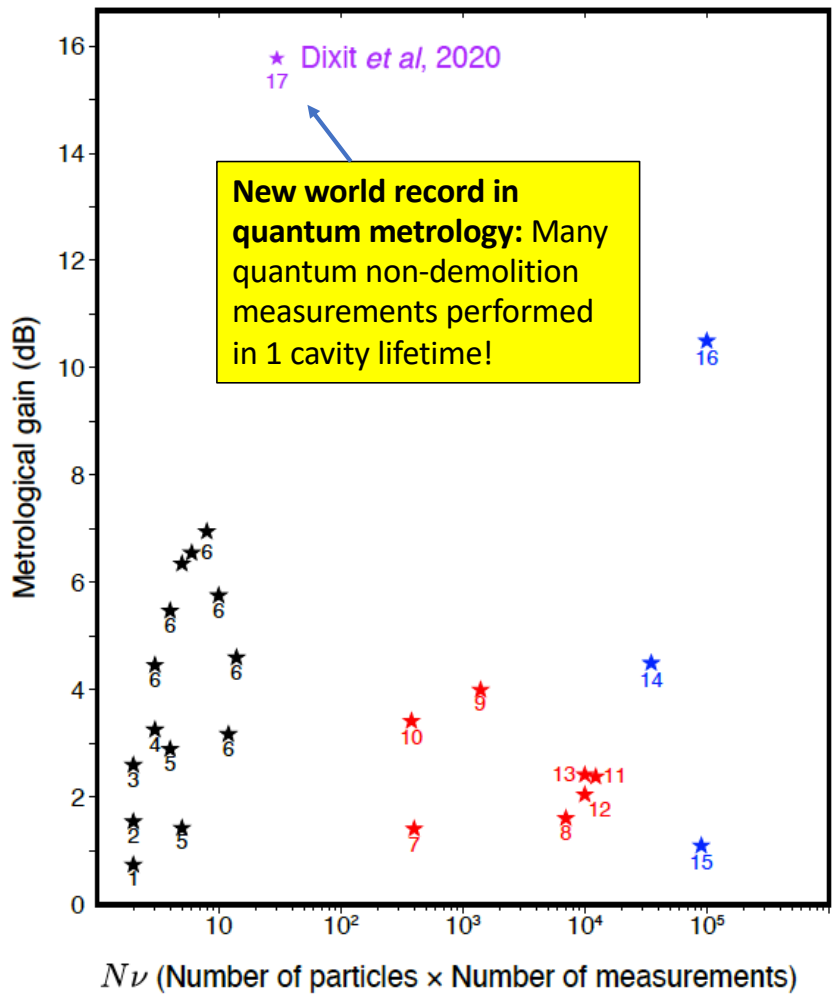
# QuantISED: qubit-based 10 GHz dark matter sensors

A.V. Dixit et.al, Phys. Rev. Lett. 125,141302 (2021)
Equivalent of squeezing zero-point noise by factor of 36, increasing scan speed by factor of 1300.






Trapped Ions
1. Sackett, 2000
2. Meyer, 2001
3. Leibfried, 2003
4. Leibfried, 2004
5. Leibfried, 2005
6. Monz, 2011

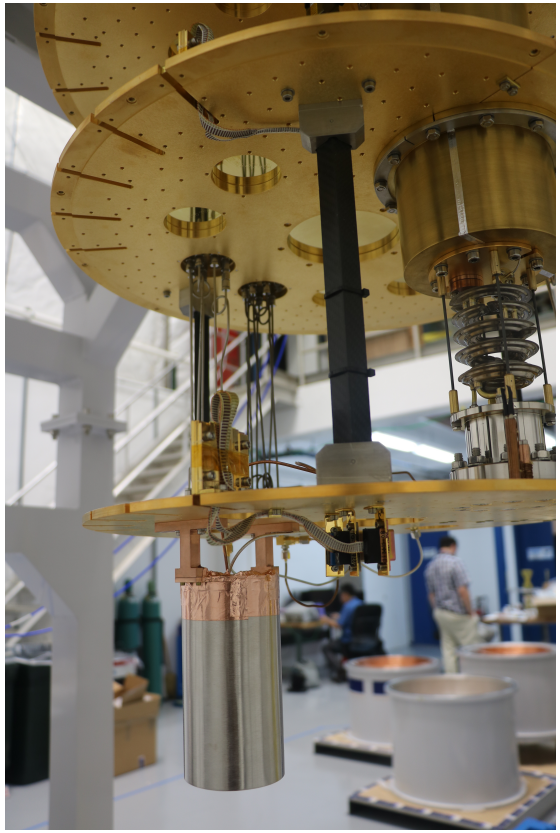
Bose-Einstein Condensates
7. Gross, 2010
8. Lücke, 2011
9. Ockeloen, 2013
10. Strobel, 2014
11. Muessel, 2014
12. Kruse, 2016
13. Zou, 2018

Cold Thermal Atoms
14. Leoroux, 2010a
15. Louchet-Chauvet, 2010
16. Hosten, 2016

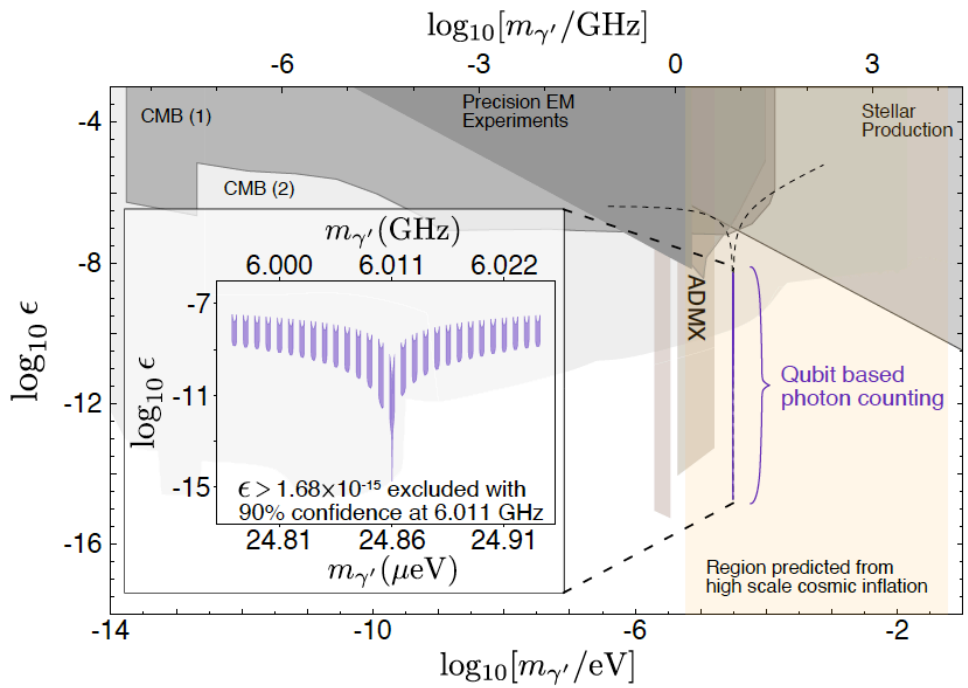
Superconducting Qubit
17. Dixit, 2020

Adapted from Pezze, Smerzi, Oberthaler, Schmied, Treutlein, Rev.Mod.Phys.90 035005 (2018)

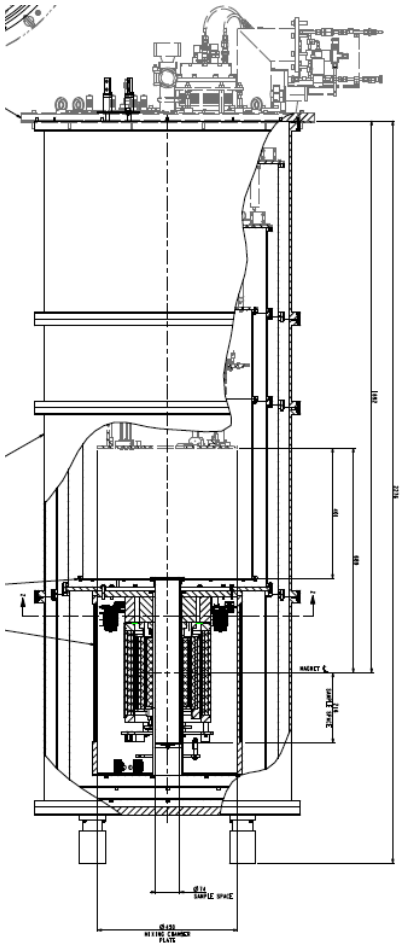
# LDRD-funded 14T-90mm bore solenoid to be installed in SiDet Lab B in May 2021, largest cryogen-free magnet ever built



Designing SQUAD dark photon detector and prototyping quantum state transport for axion search.

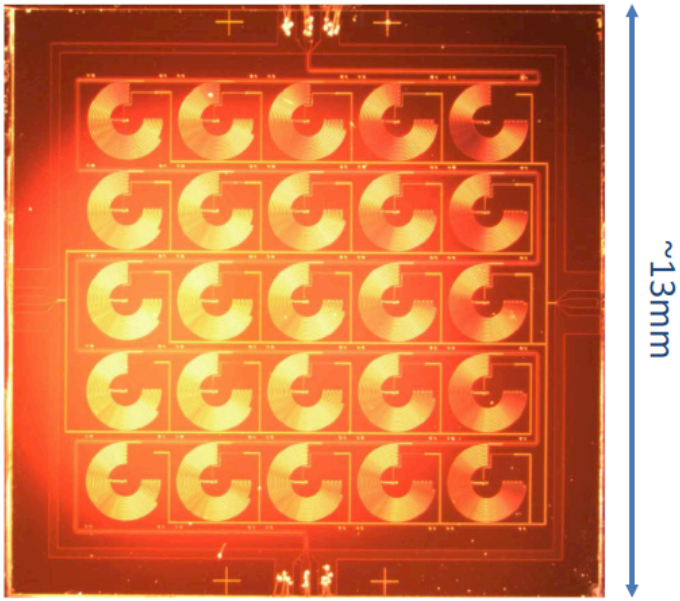



A.V. Dixit et.al, Phys.Rev.Lett. 126 (2021) 14, 141302

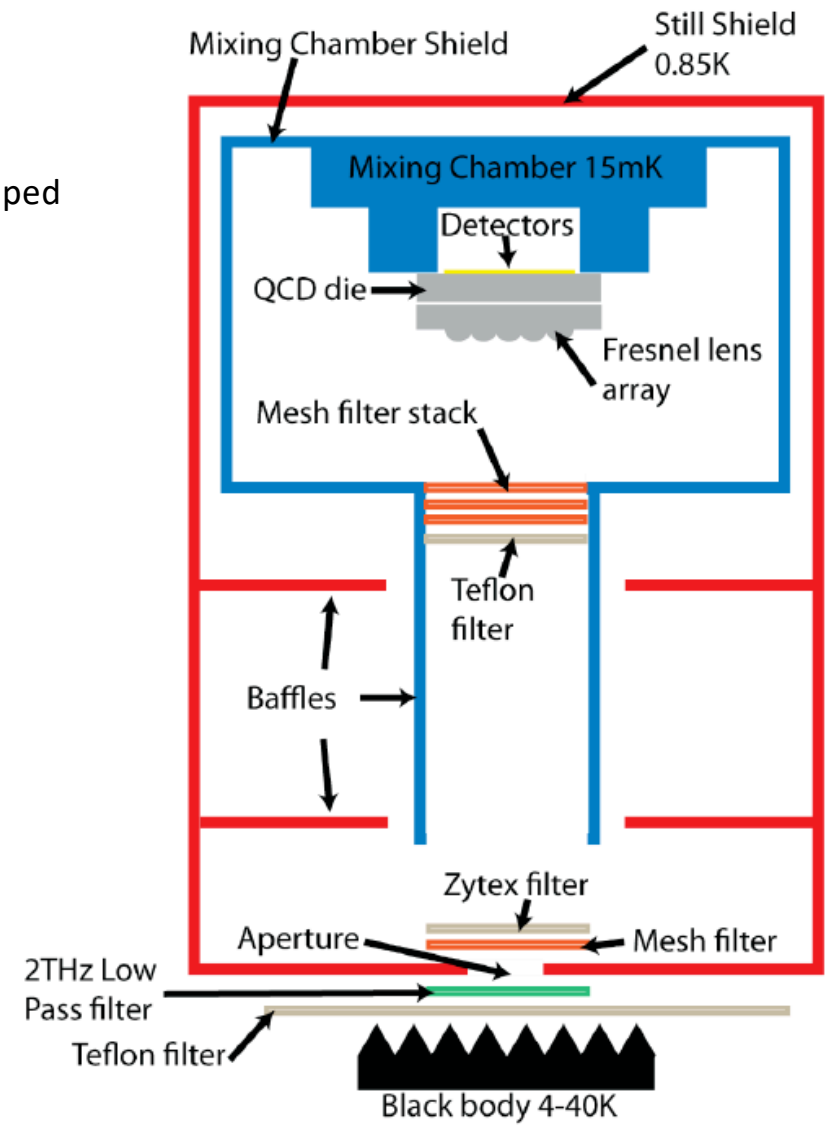


# In progress: 0.1-10 THz single photon detectors

- Deploying array of quantum capacitance detectors developed by JPL (P. Echternach) for space-based THz astronomy.
- Will re-purpose for single photon detection for axions.
- Lowest noise detectors ever made – $10^{-21}$ W/rtHz, but still need to improve by orders of magnitude.




Pierre Echternach talk, LTD 2019



# Fermilab quantum sensing efforts continue in the Quantum Science Center (National Quantum Initiative)

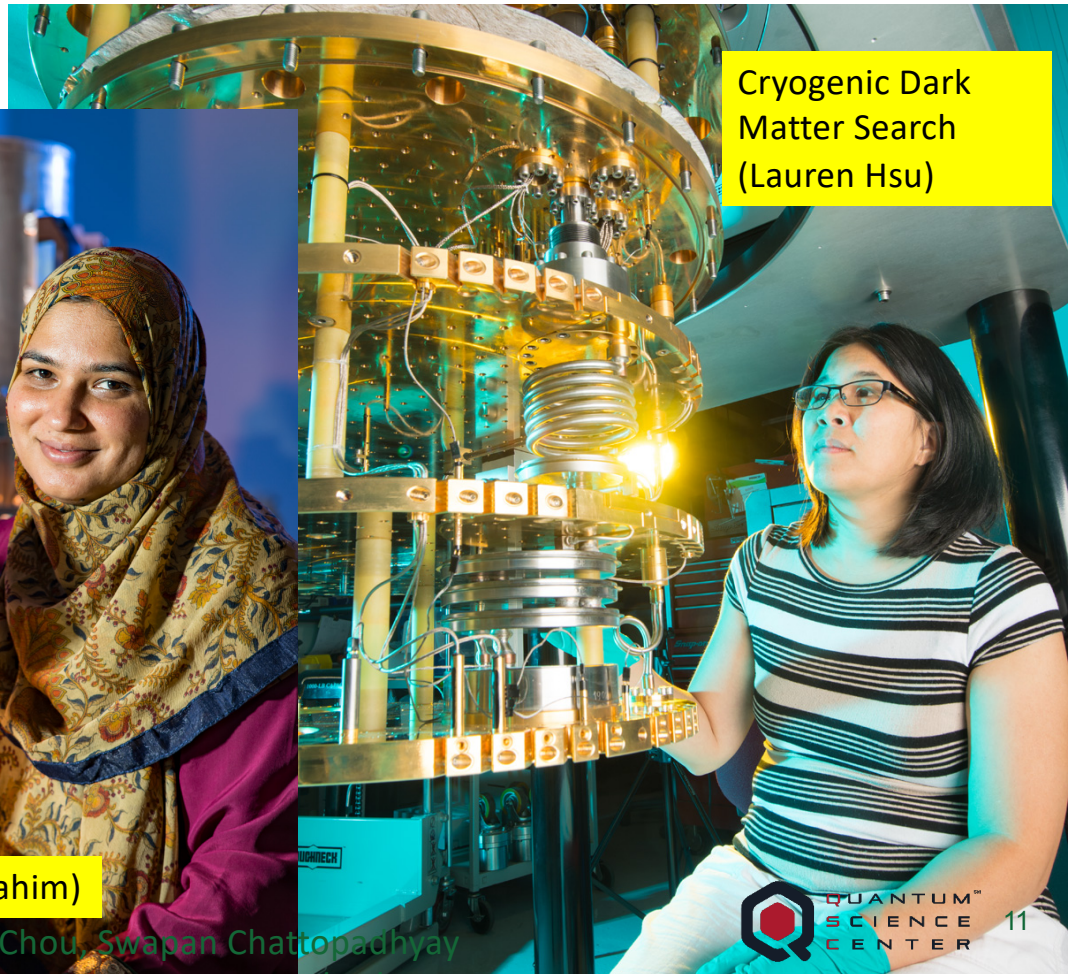
Chou manages Devices/Sensors portfolio (1/3 of QSC R&D efforts)

QSC comprises ~100 researchers across 16 institutions.

Following Swapan's lead in forming connections between **HEP** and **AMO/QIS**, this new collaboration with DOE-Basic Energy Sciences helps HEP employ/deploy state-of-art developments in **condensed matter physics** and **materials science**!

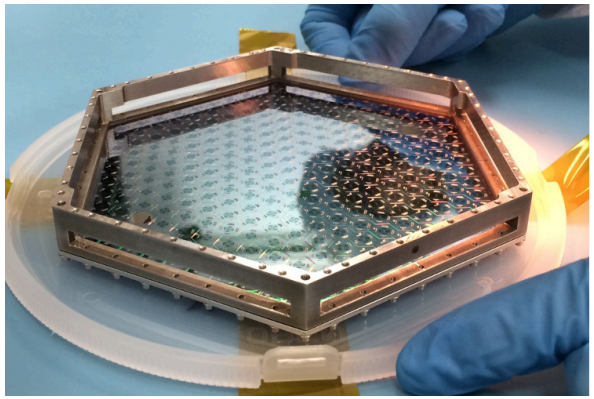
## QSC strategy: again leverage National Lab instrumentation capabilities for QIS R&D

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



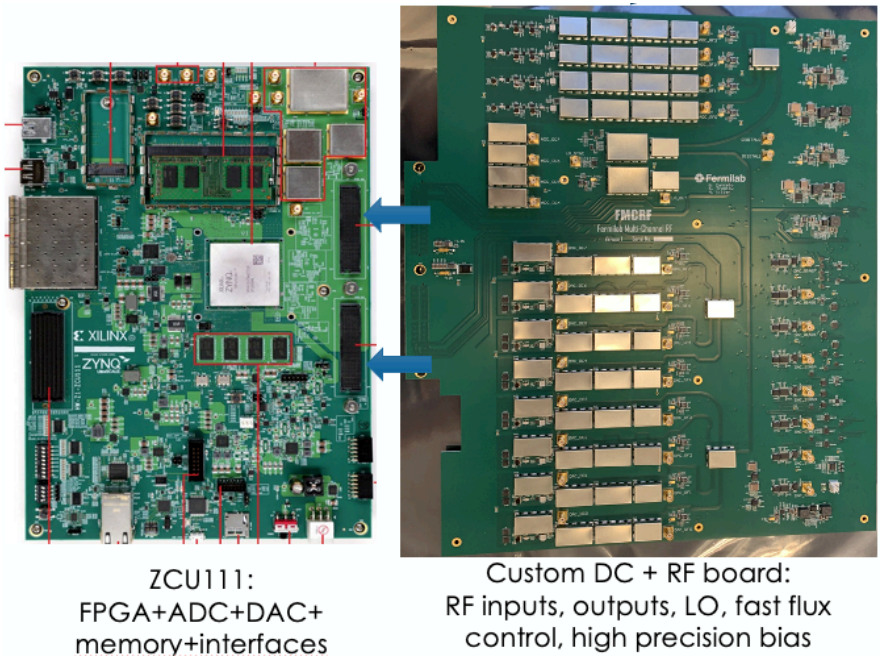

Aaron Chou, Swapan Chattopadhyay

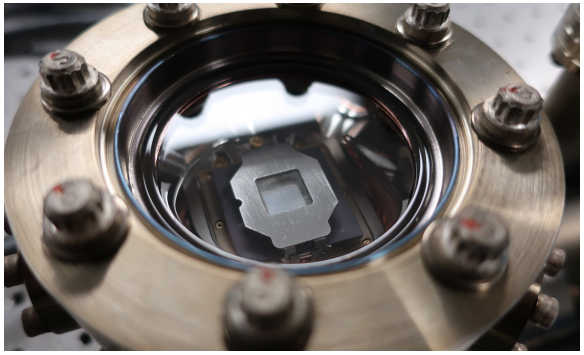
# HEP custom instrumentation for high channel count sensor arrays



Frequency-domain multiplexing for readout of cryogenic sensor arrays, e.g. for Cosmic Microwave Background telescopes (Adam Anderson)

Flexible FPGA system for control, readout of qubits and sensors (Gustavo Cancelo)

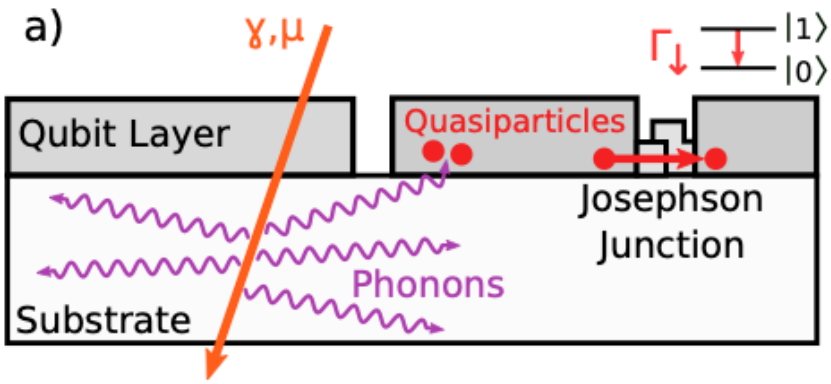


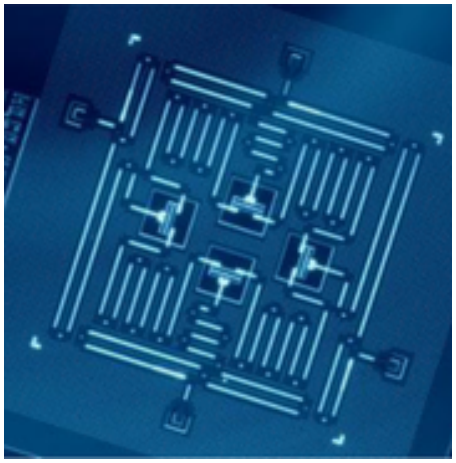
Cryogenic electronics for low noise control of ion trap quantum simulator (Farah Fahim)

# Recent News: Google Sycamore is secretly a SuperCDMS detector with phonon readout via qubits rather than TES.

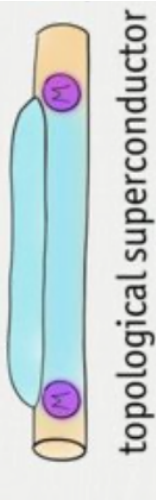
**Ionizing radiation causes "catastrophic," "total chip-wide failure" and presents an "existential challenge" to superconducting quantum computing.**
*M.McEwen et.al, arXiv:2104.05219*




4 transmons, Aluminum **bandgap = $10^{-4}$ eV**



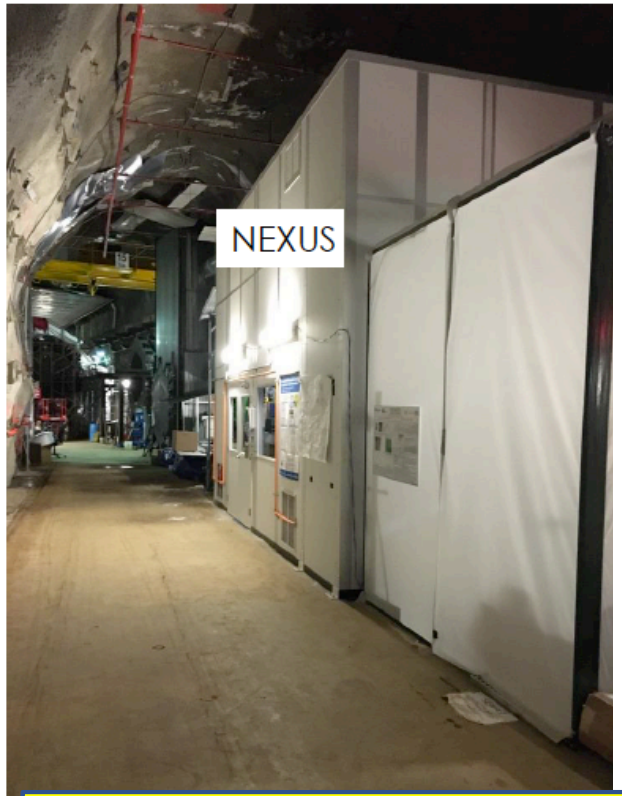
Large amplitude phonon wave induced by ionizing radiation, **100 keV energy deposit**




Majorana zero modes distributed on two ends,

**Bandgap = 0 eV (!)**

Strategic expansion of Fermilab underground cryogenic test facilities.



**Quantum computing = spin-off tech of HEP dark matter searches**

# Beyond atom interferometry – the WindChime

D.Carney, et.al, Phys.Rev. D102 (2020) 7, 072003

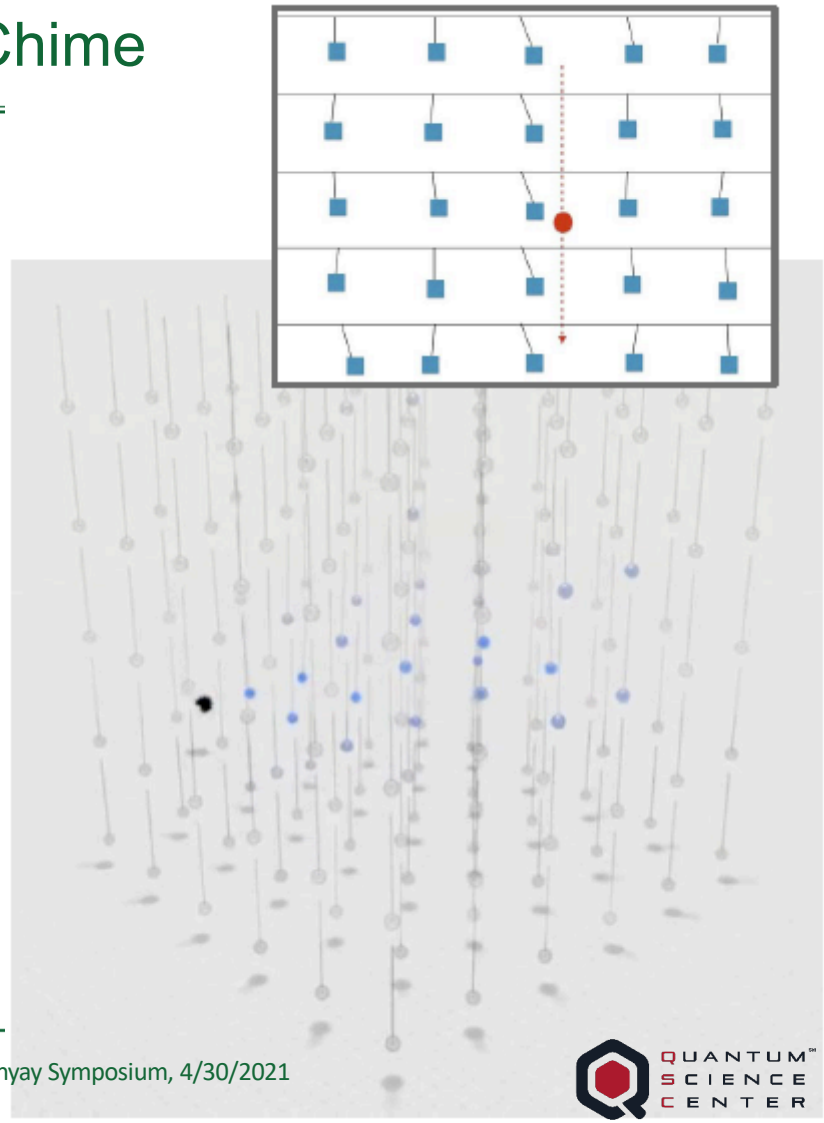
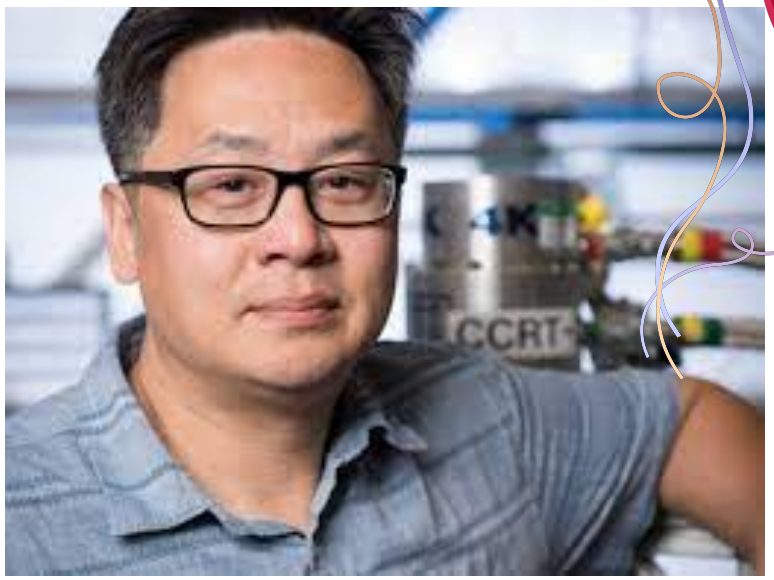
**Proposal for gravitational direct detection of dark matter**

Daniel Carney,[1,2,*] Sohitri Ghosh,[1] Gordan Krnjaic,[2] and Jacob M. Taylor[1,†]
[1]*Joint Quantum Institute/Joint Center for Quantum Information and Computer Science, University of Maryland, College Park, Maryland 20742/National Institute of Standards and Technology, Gaithersburg, Maryland 20899, USA*
[2]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*

Cubic meter array of **$10^9$ accelerometers** with millimeter spacing to detect force from passing dark matter. Read out using distributed squeezed light.

**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
- Diffraction of light? Quantum annealing?
- **Dark matter detector = quantum computer?**
  **→ Provides in-situ processing of tracks**



# Thank you Swapan!