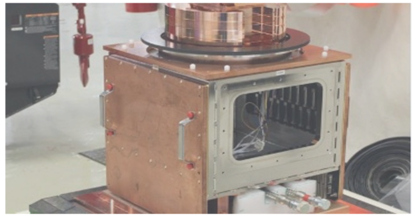
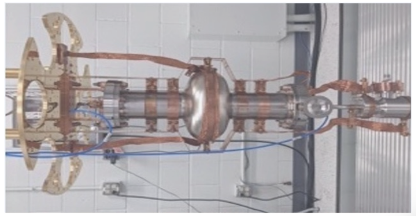
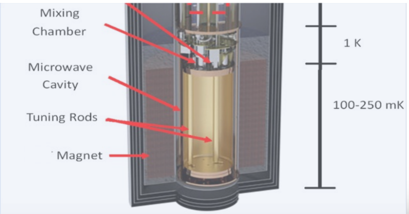
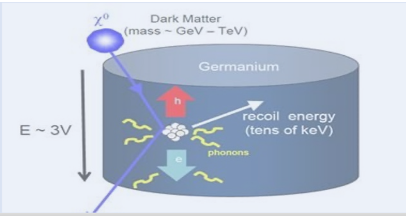
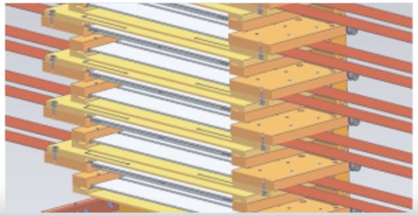
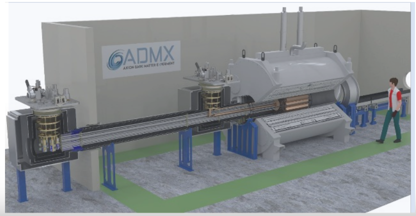






Dark Matter at Fermilab

Stefan Knirck (knirck@fnal.gov)

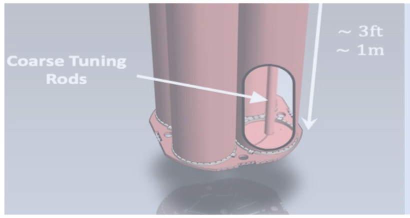
Fermi National Accelerator Laboratory

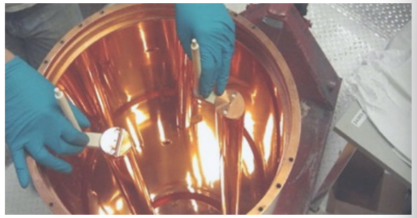
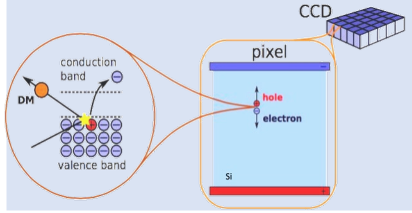
Fermilab

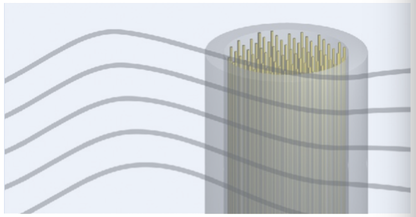
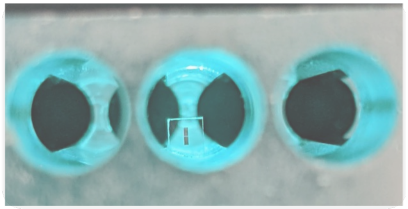
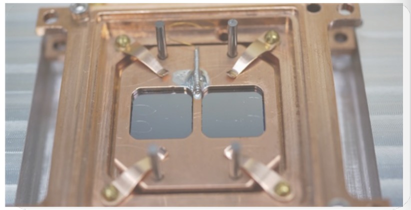
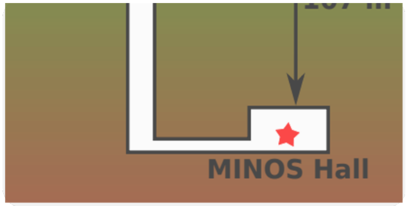
member of ADMX and BREAD

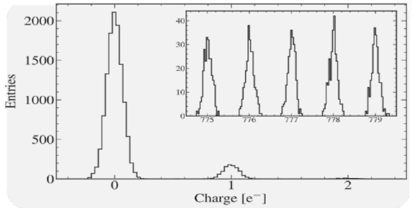
ADMX AXION DARK MATTER EXPERIMENT BREAD COLLABORATION

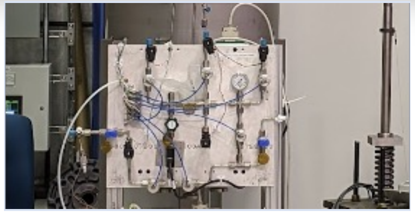
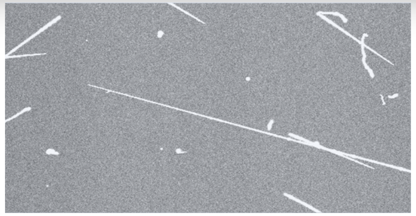
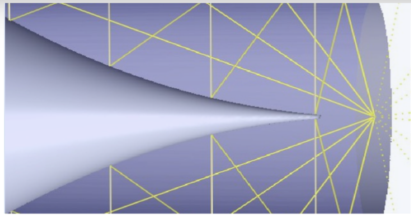




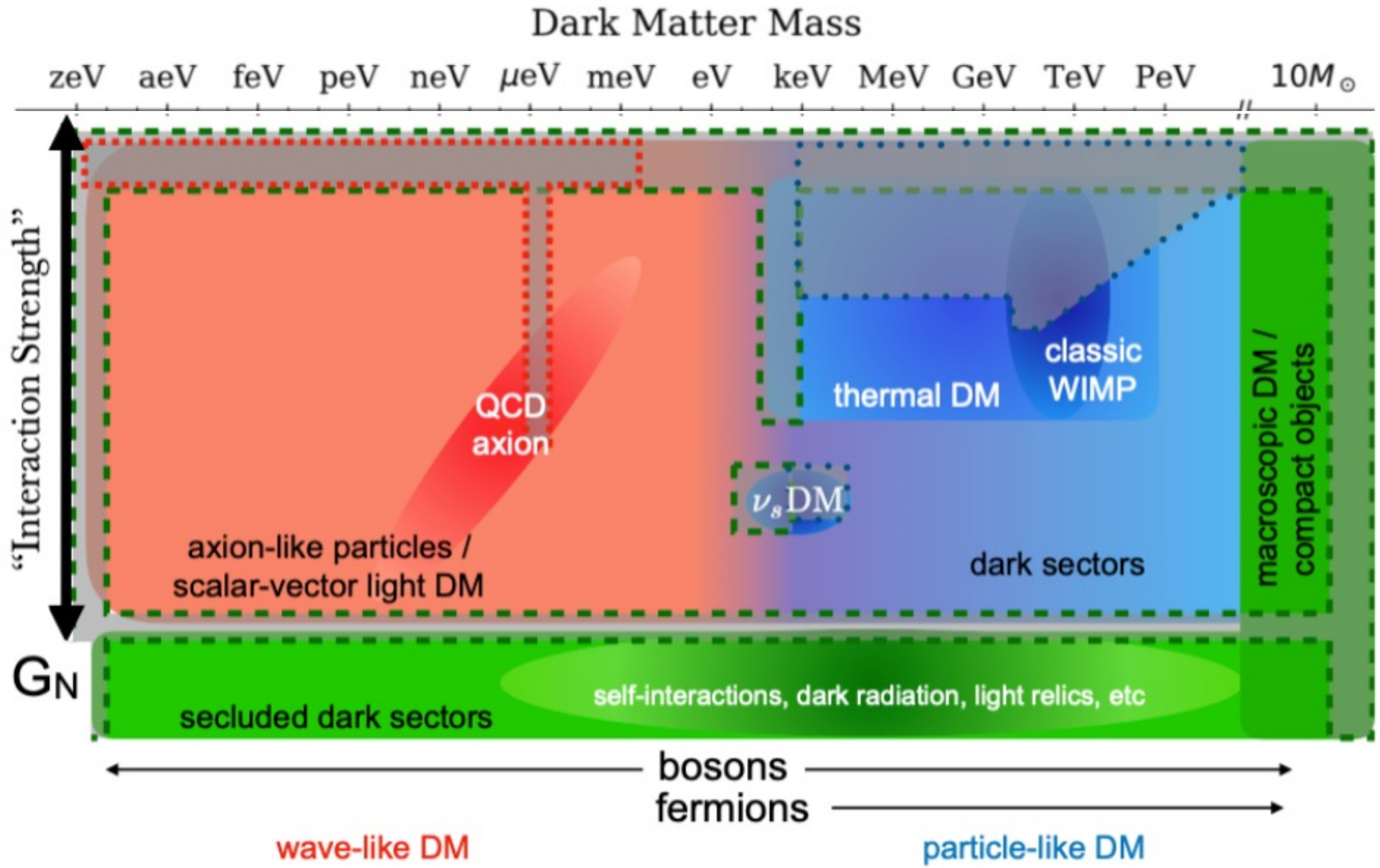


for image sources see corresponding slides

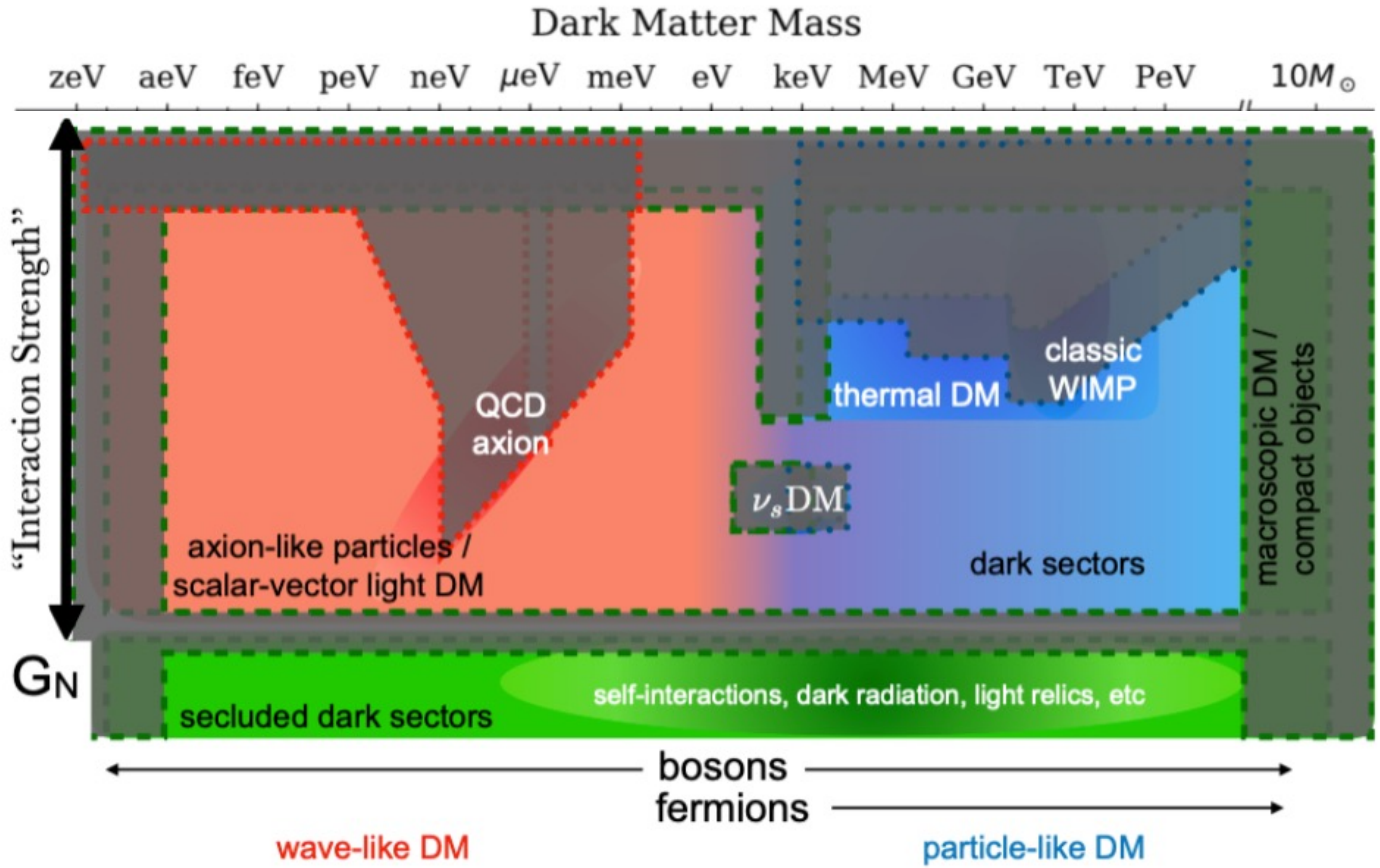
Dark Matter at Snowmass21

[Snowmass21 Cosmic Frontier Report, arXiv:2211.09978]

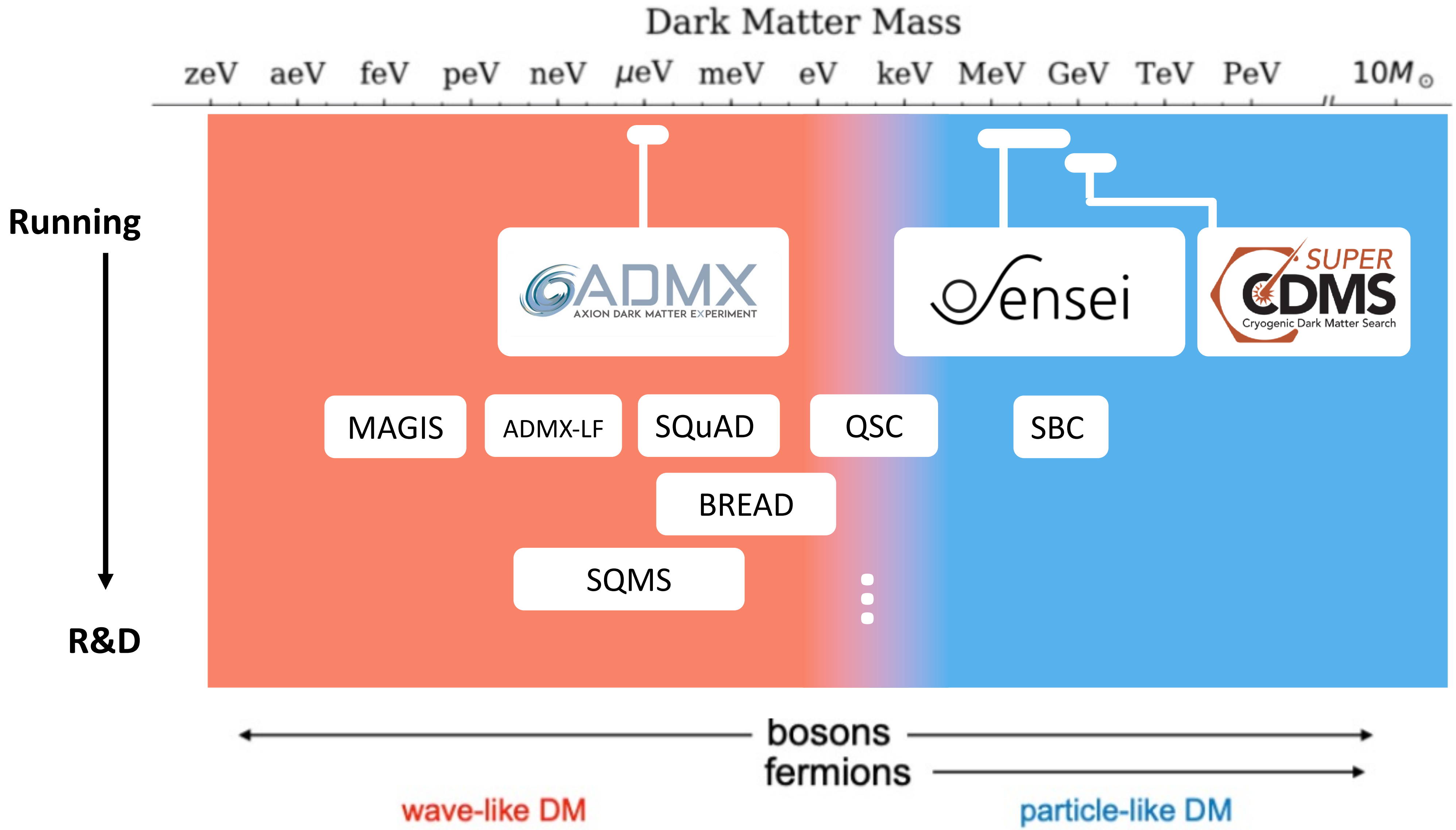


Dark Matter at Snowmass21

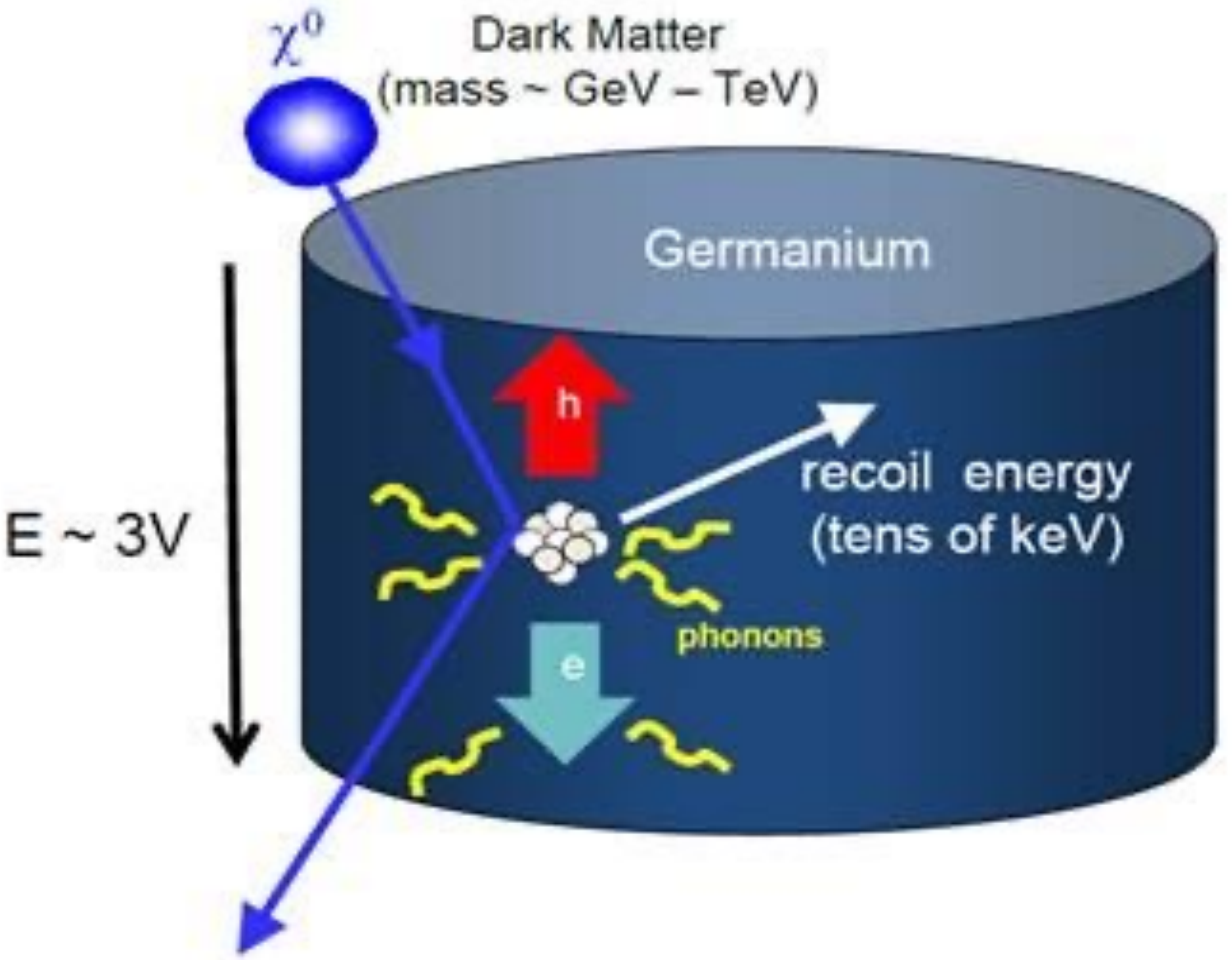
[Snowmass21 Cosmic Frontier Report, arXiv:2211.09978]



Dark Matter Experiments at Fermilab



Nuclear Recoil

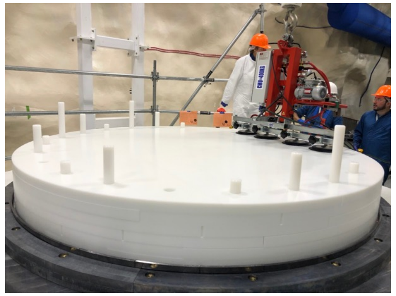


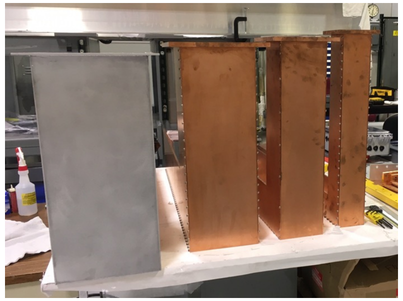
[https://supercdms.slac.stanford.edu/sites/default/files/styles/fix-width-400/public/image002.jpg?itok=Ms2q-Nm1]

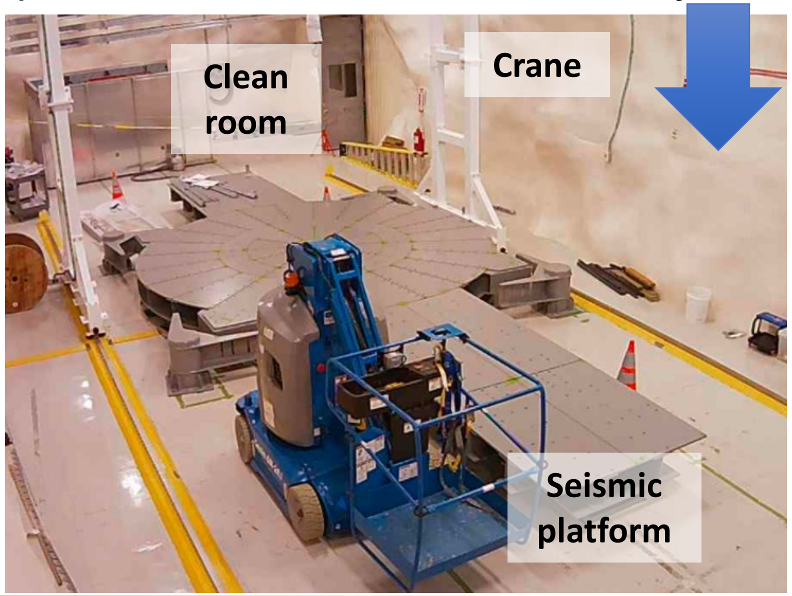
SuperCDMS at SNOLAB

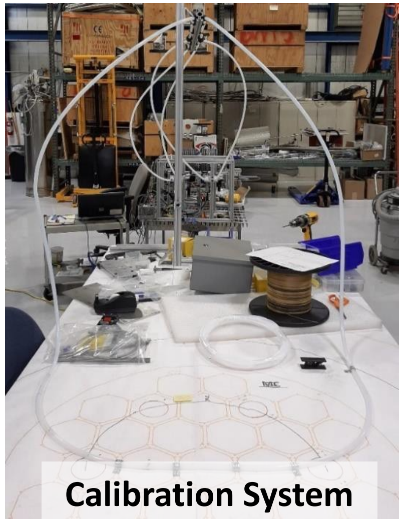
Super Cryogenic Dark Matter Search

- Will provide ***multiple orders of magnitude*** improved sensitivity to dark matter with masses between 0.5-10 GeV/c^2, using cryogenic detectors
- Fermilab continuing ***20 years of leadership*** in SuperCDMS by delivering major subsystems:
  - Cryogenic design and operation
  - Warm electronics design & fabrication
  - Calibration system design and ops
  - Infrastructure design and integration
- Cryo system ready to ship from FNAL! Installation underway at SNOLAB, commissioning in 2024.





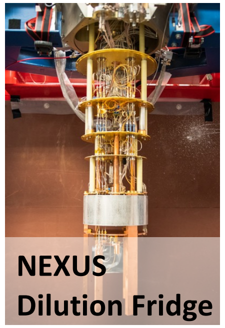


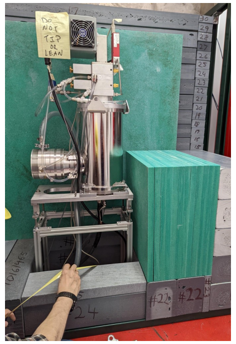


Slide from Lauren Hsu

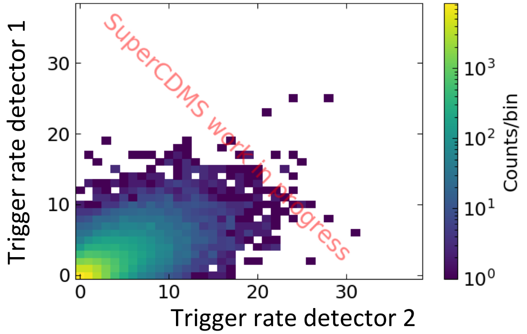
NEXUS: Underground Dark Matter & Cryogenic Detector Test Facility

- Developed jointly by Northwestern and Fermilab as a calibration and low background test facility for SuperCDMS
- Functionality has since been broadened to include QIS devices, KIDs and future neutrino detectors
- Neutron generator commissioning underway; allows precise determination of nuclear recoil energy scale, setting sensitivity for SuperCDMS SNOLAB

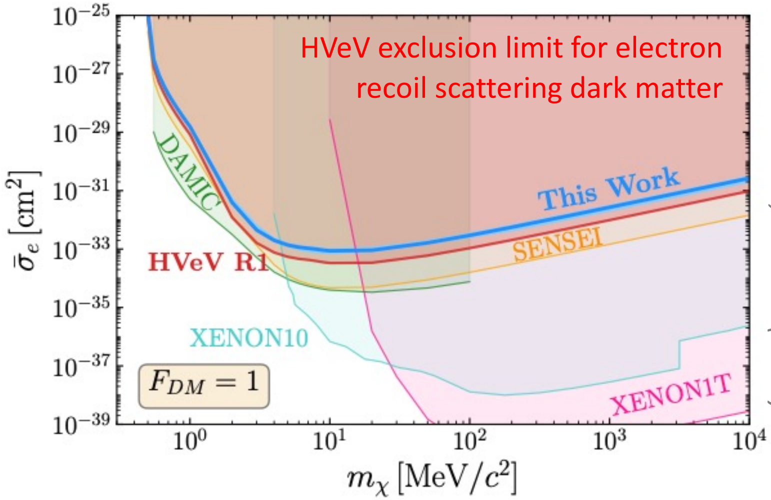




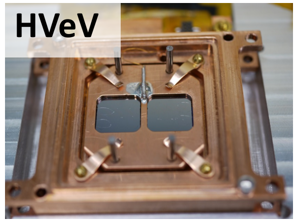
SuperCDMS HVeV detector has world-leading sensitivity to sub-GeV dark matter; provides resolution of single e/h pairs



Data taken at NEXUS sheds light on a class of low energy events; will yield substantial improvement in sensitivity - Stay tuned for results!

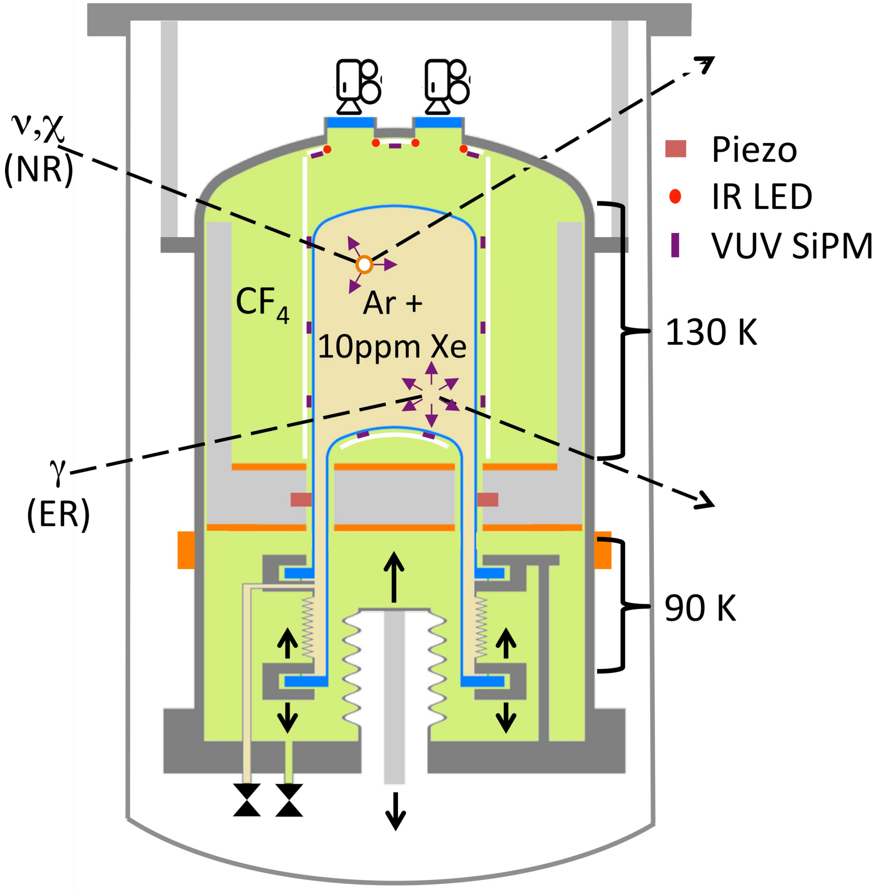


PRD 102, 091101 (2020)



Slide from Lauren Hsu

SBC: Scintillating Bubble Chamber



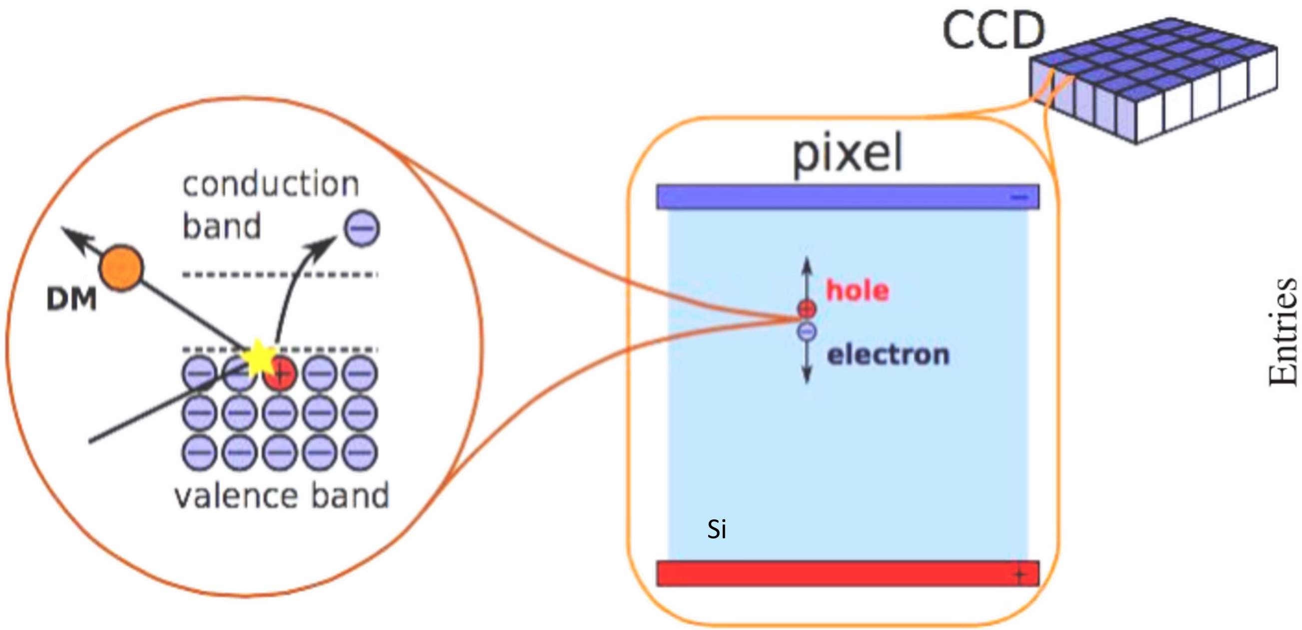
[Snowmass White paper, arXiv:2207.12400]

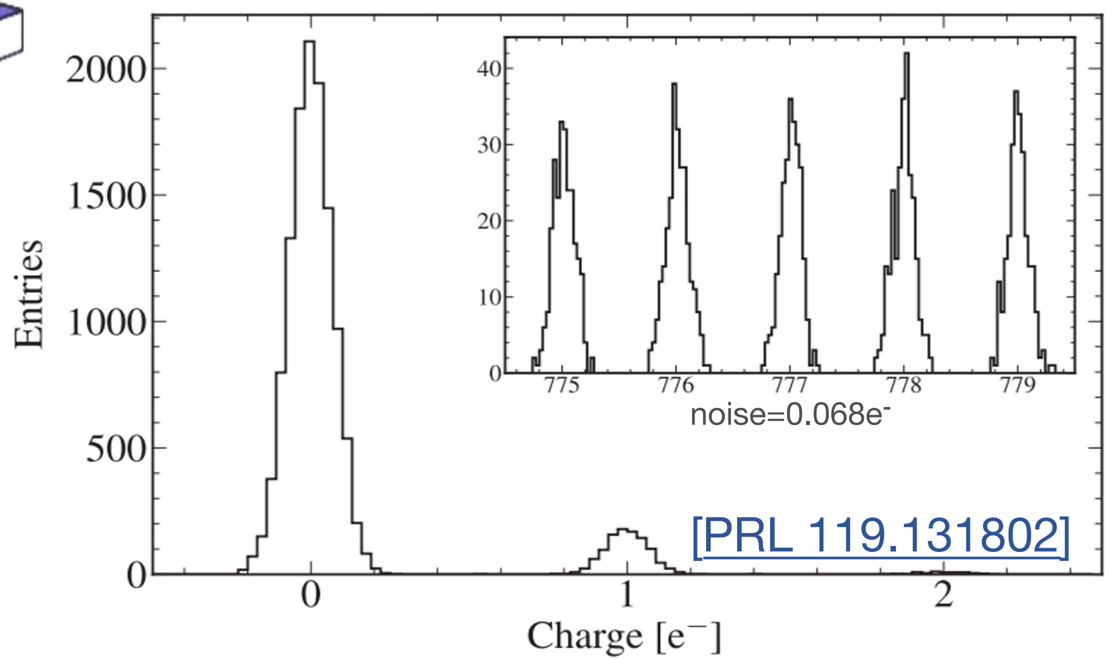
[Eric Dahl, UCLA DM 2023]

- 1-10 GeV DM with nuclear recoils
- 10kg LAr (SBC-LAr10) deploying at MINOS
  - → determine max. ER-blind superheat in LAr
  - → NR calibration
- DM Search @SNOLAB

Electron Recoil - SENSEI

Sub-Electron-Noise Skipper-CCD Experimental Instrument





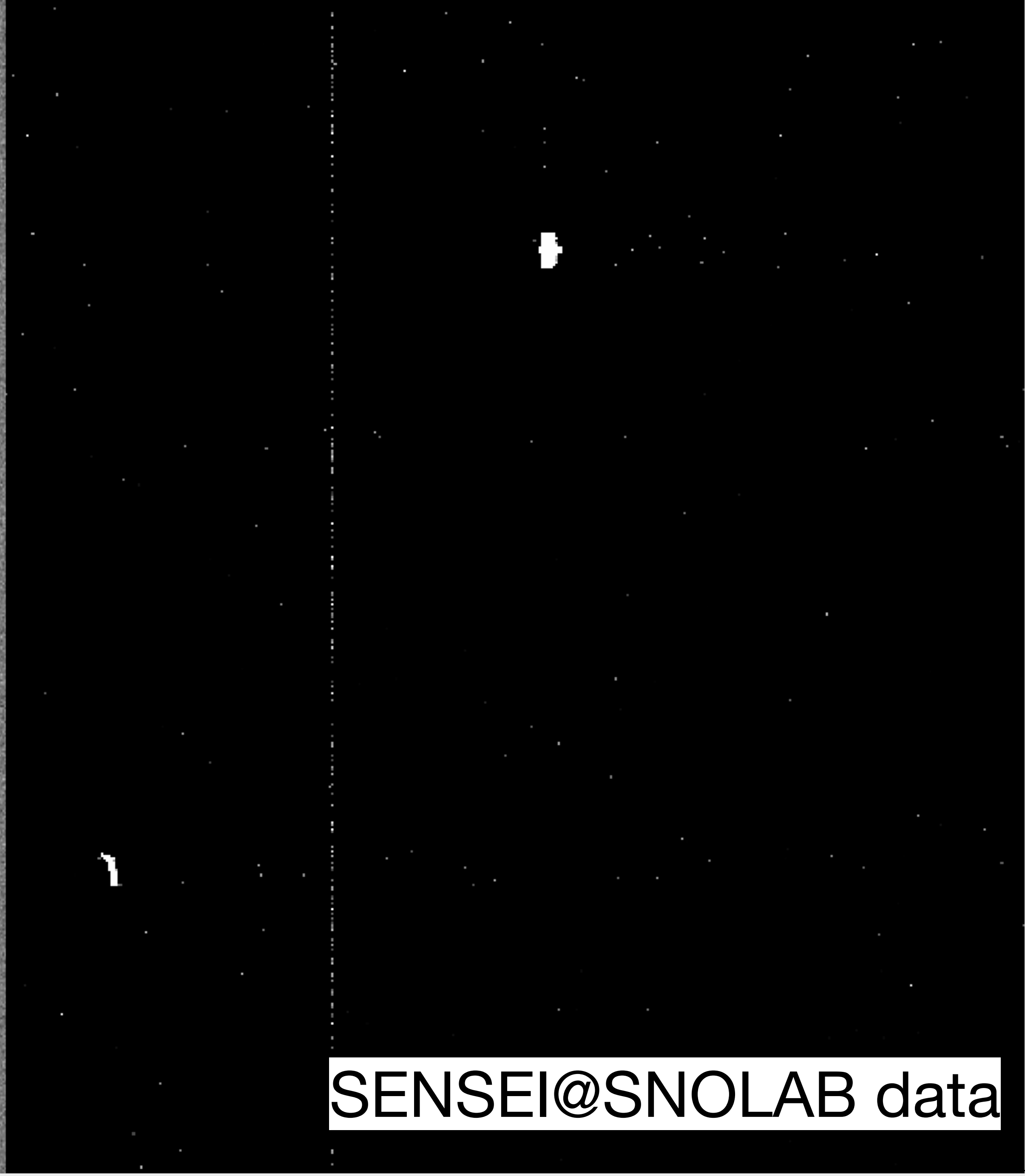
Skipper-CCD (designed by LBNL):

Energy threshold of Si bandgap (~1.1 eV)

Low dark current (~10^{-4} e^-/pix/day)

Sub-electron (~$0.1e^-$) readout noise

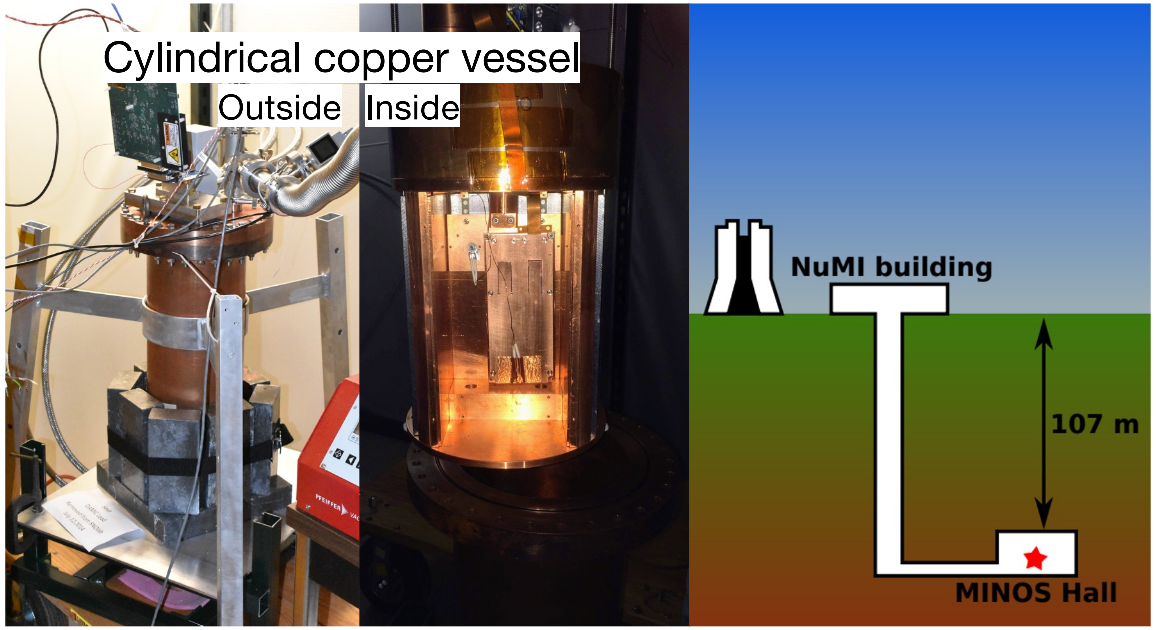
Material from Juan Estrada, Nate Saffold



Images from Brenda Cervantes and Nate Saffold

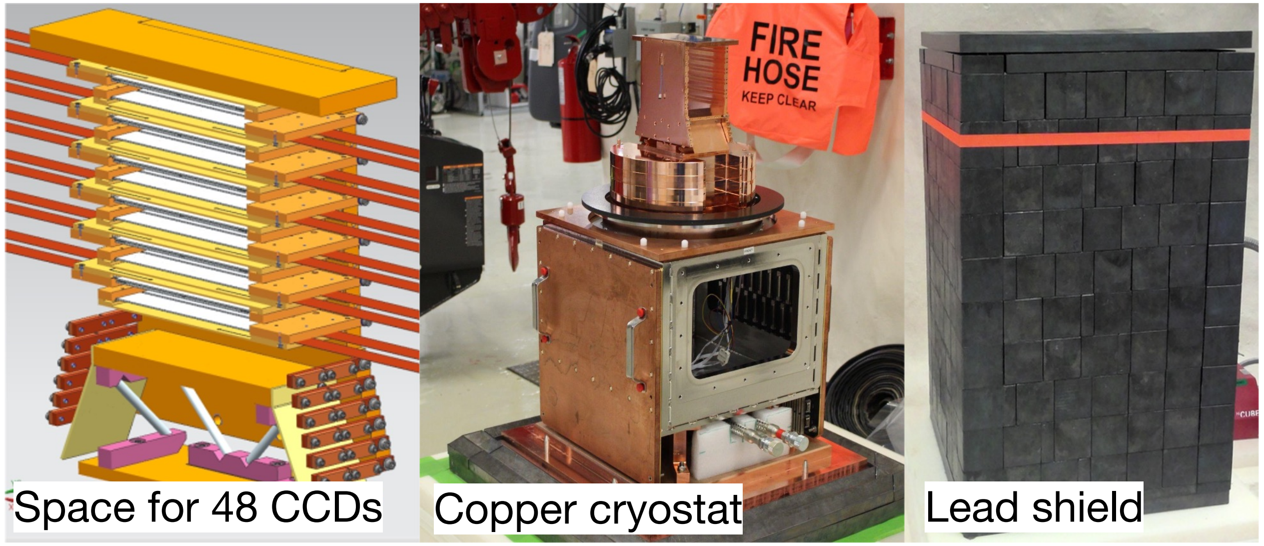
SENSEI: two science-capable setups

SENSEI@MINOS



One CCD module installed in copper cryostat: ~1.925 g, operated at 135 K
Shielding: inner and outer layers of lead shielding, underground site at FNAL in MINOS cavern (~107 m)

SENSEI@SNOLAB

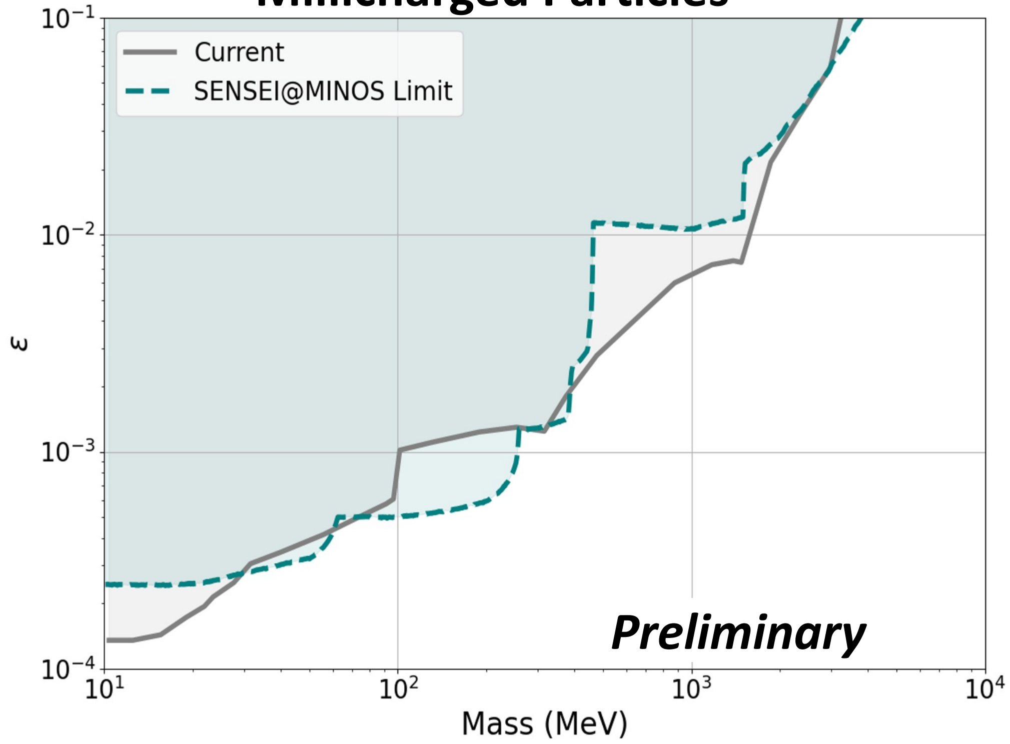


CCDs installed in copper cryostat: Space for 48 CCDs, each with 6144 × 1024 pixels, 15 μm pitch, 675 μm thickness (~100 g)
Shielding: 3” of lead, 20” of polyethylene and water, 2 km of granite overburden

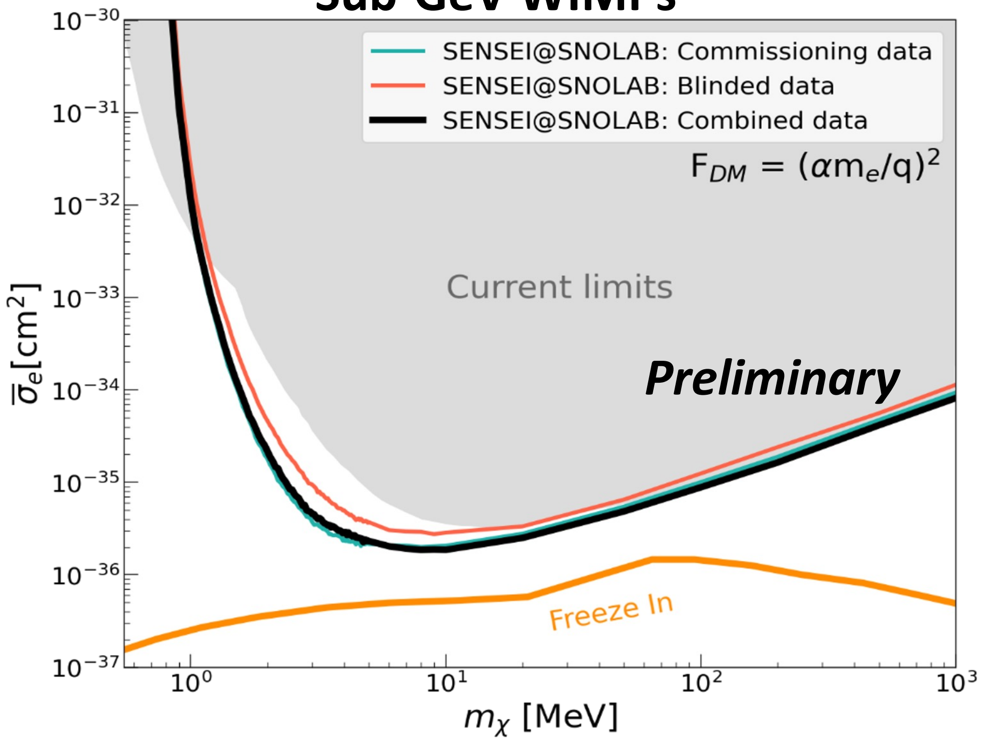
Slide from Nate Saffold

SENSEI: two science-capable setups

SENSEI@MINOS
Millicharged Particles



SENSEI@SNOLAB
Sub-GeV WIMPs



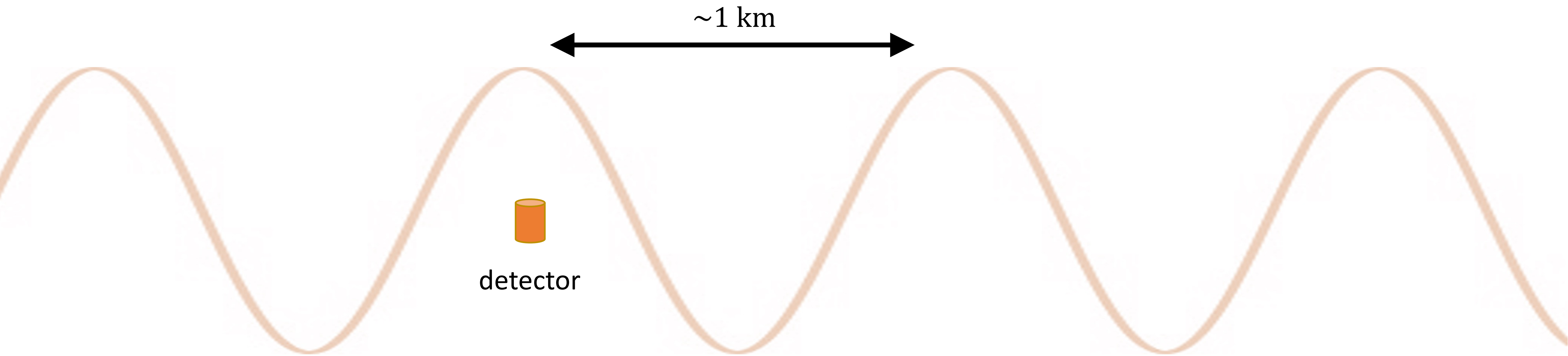
Next Step: OSCURA 10kg skipper-CCD, orders of magnitude improvement

Material from Juan Estrada, Nate Saffold **→ see upcoming talk by Brenda Cervantes**

Similar w/ FNAL involvement: DAMIC [PRL130, 171003] [arXiv:2306.01717]

Wave-Like Dark Matter

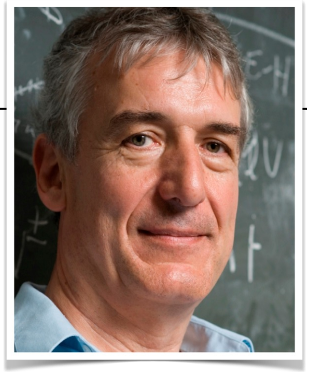
$$\rho_a \sim 0.45 \frac{\text{GeV}}{\text{cm}^3} \qquad \lambda_{\text{DB}} \sim \frac{2\pi}{m_a v} \sim 1\ \text{km} \left(\frac{1\mu\text{eV}}{m_a}\right) \quad \rightarrow \quad \frac{\#\text{particles}}{\lambda_{\text{DB}}^3} \sim 10^{30} \left(\frac{1\mu\text{eV}}{m_a}\right)^4$$

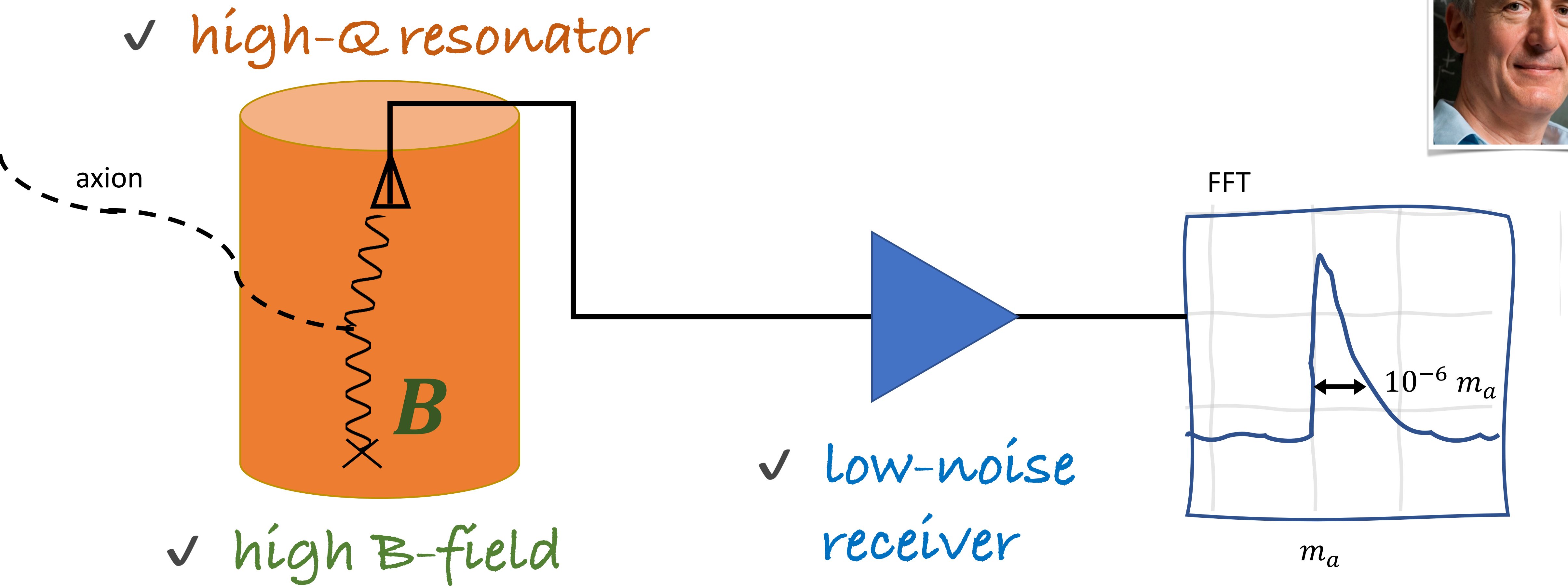


coherent detection

Wave-Like Dark Matter Detection

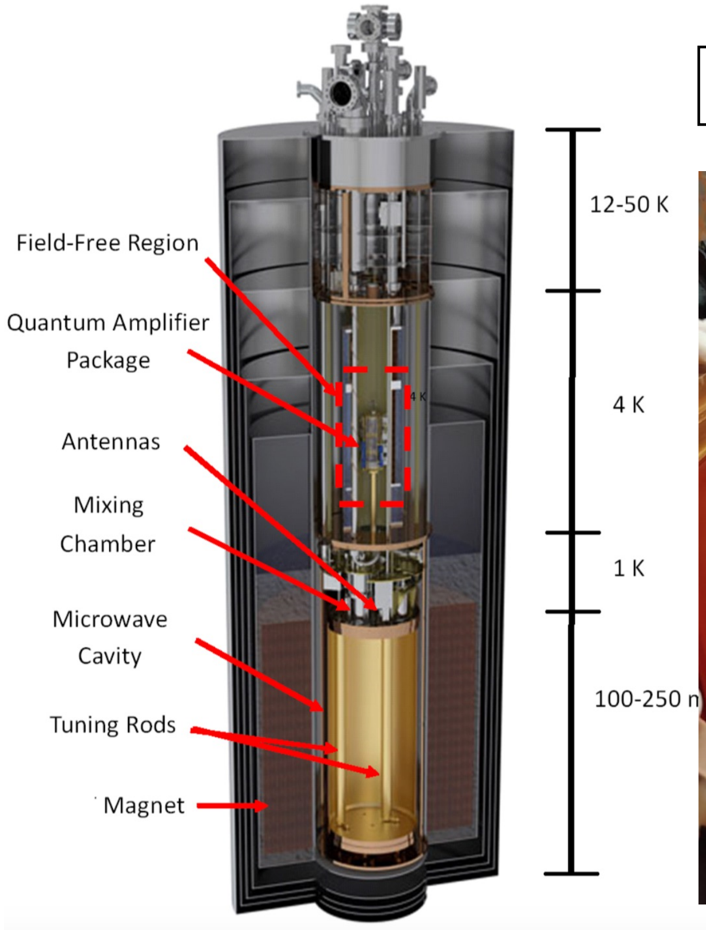
[P. Sikivie, PRL 51, 1415 (1983)]





$$P_{\text{sig}} = 2 \cdot 10^{-23}\ \text{W} \cdot \left(\frac{B}{7.6\ \text{T}}\right)^2 \left(\frac{V}{136\ L}\right) \left(\frac{C}{0.4}\right) \left(\frac{Q}{30{,}000}\right) \left(\frac{g_\gamma}{0.36}\right)^2 \left(\frac{m_a}{3\ \mu\text{eV}}\right) \left(\frac{\rho_{\text{DM}}}{0.45\ \text{GeV cm}^{-3}}\right)$$

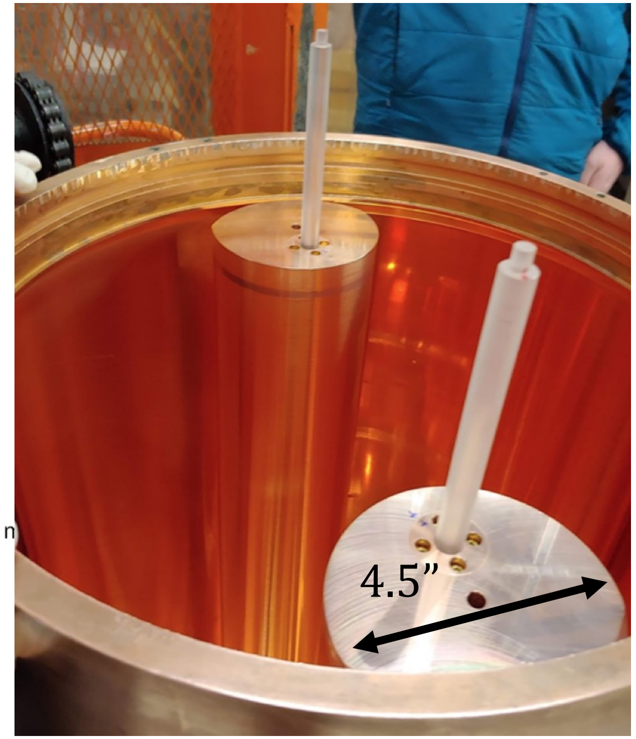
ADMX: Axion Dark Matter eXperiment

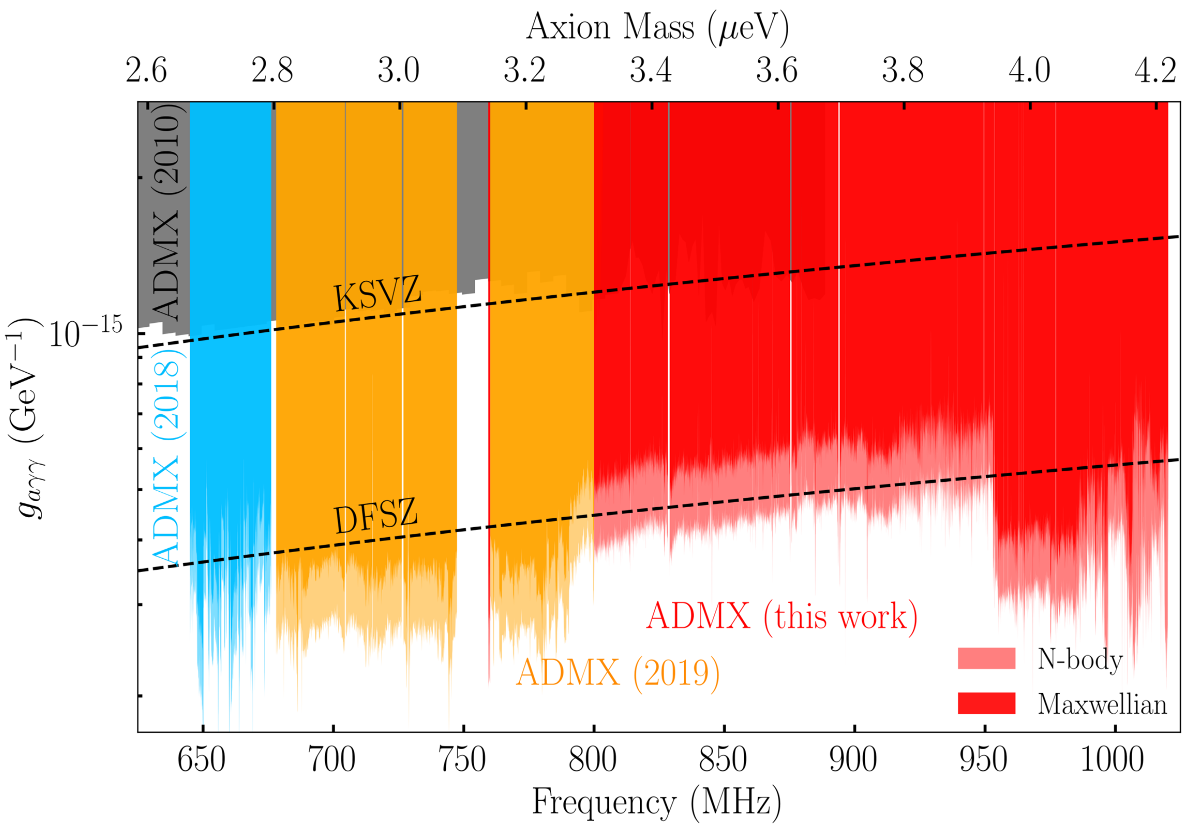


7.6T Magnet

$V \sim 136\ \ell$

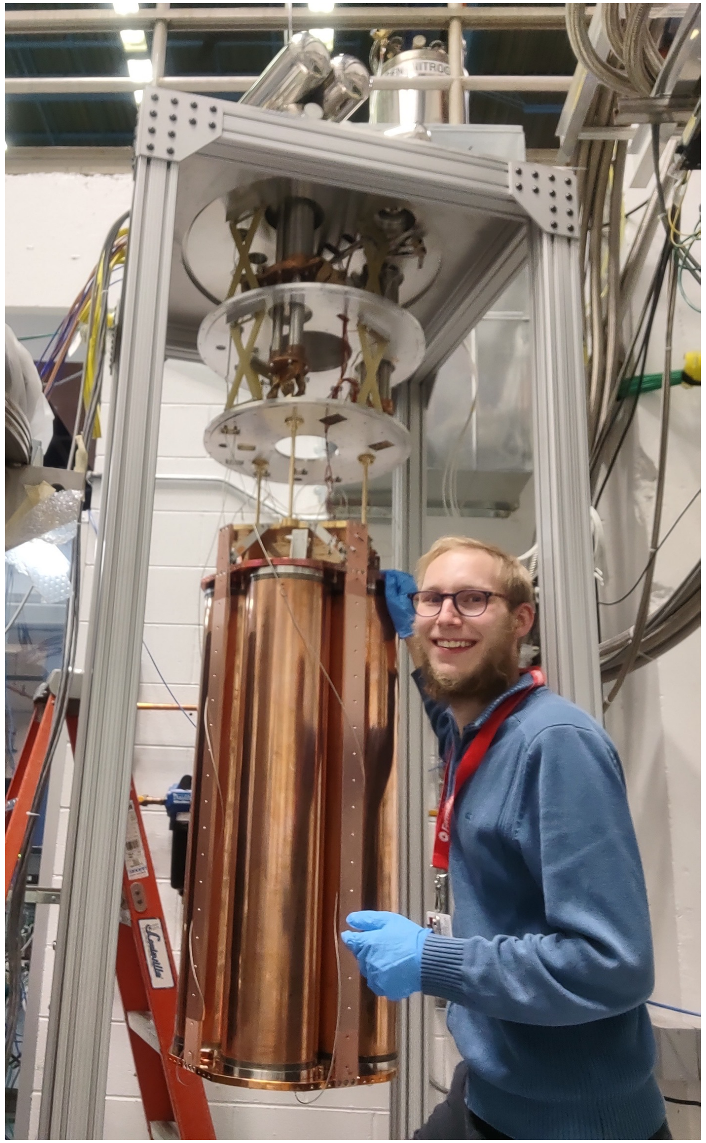
$Q_L \sim 80{,}000$ (cryogenic)

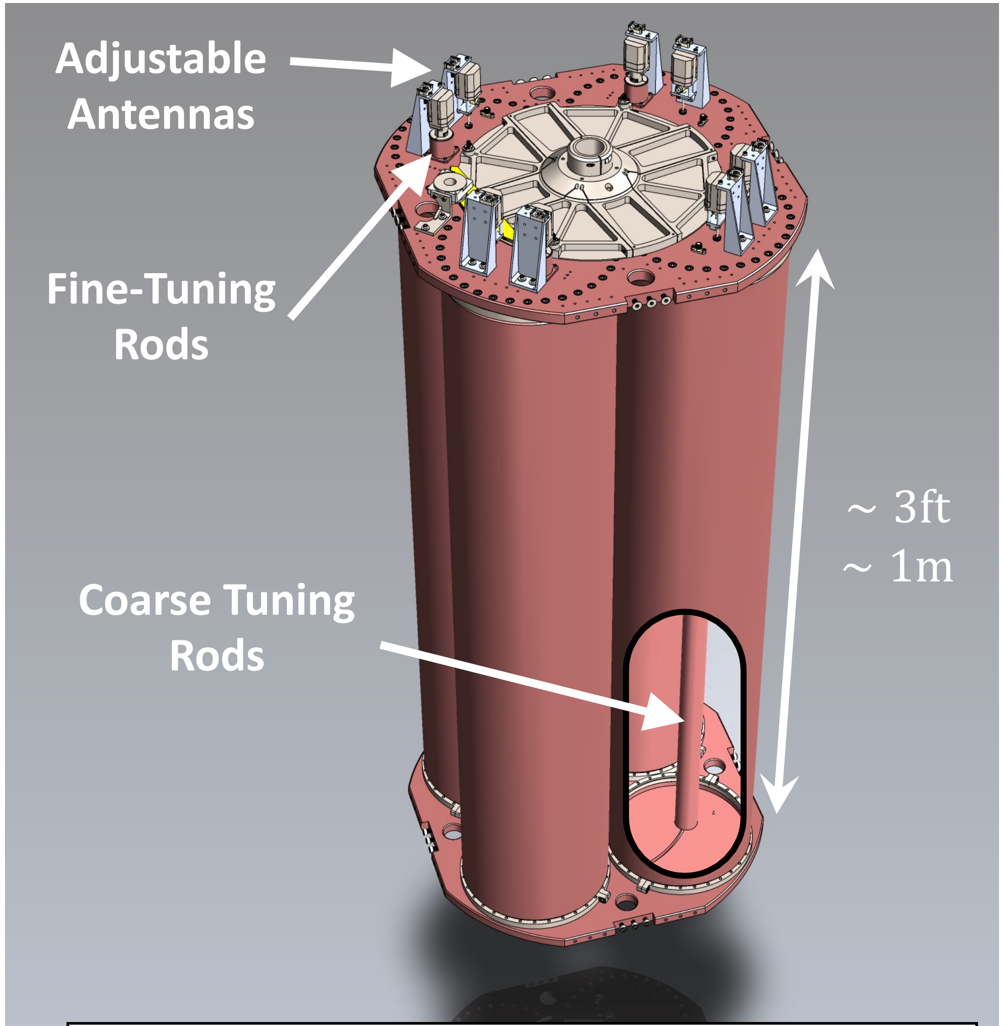




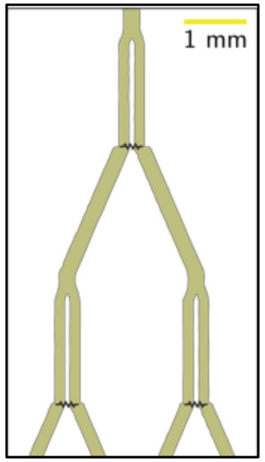
[PRL 124 (2020) 10, 101303]
[PRD 103 (2021) 3, 032002]
[PRL 127, 261803 (2021)]

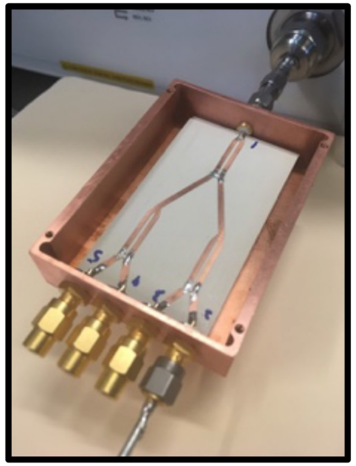
Next ADMX Gen-2: (1.4 - 2.2) GHz





4 cavity array, 85 L





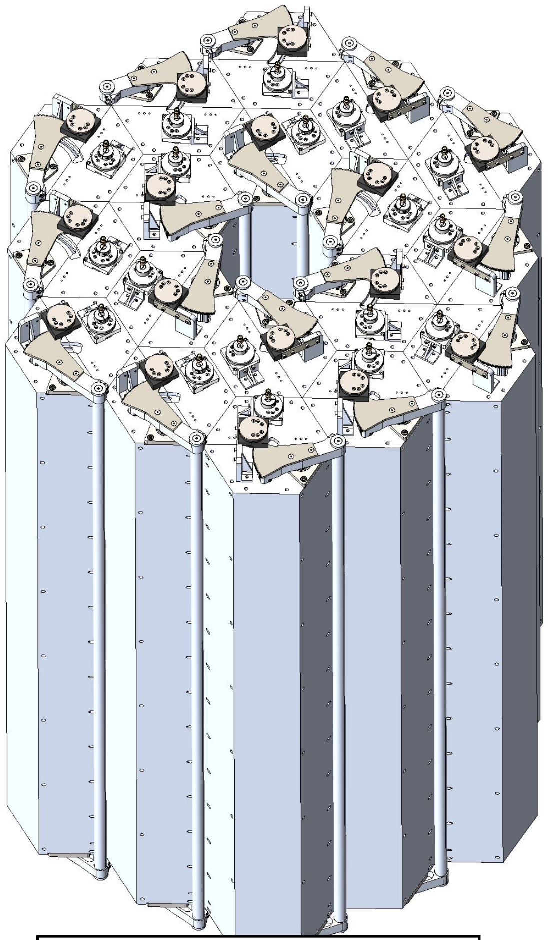
analog power combining

Site: Univ. Washington

Data Taking from ~2024

ADMX-EFR (Extended Frequency Range): 2-4GHz

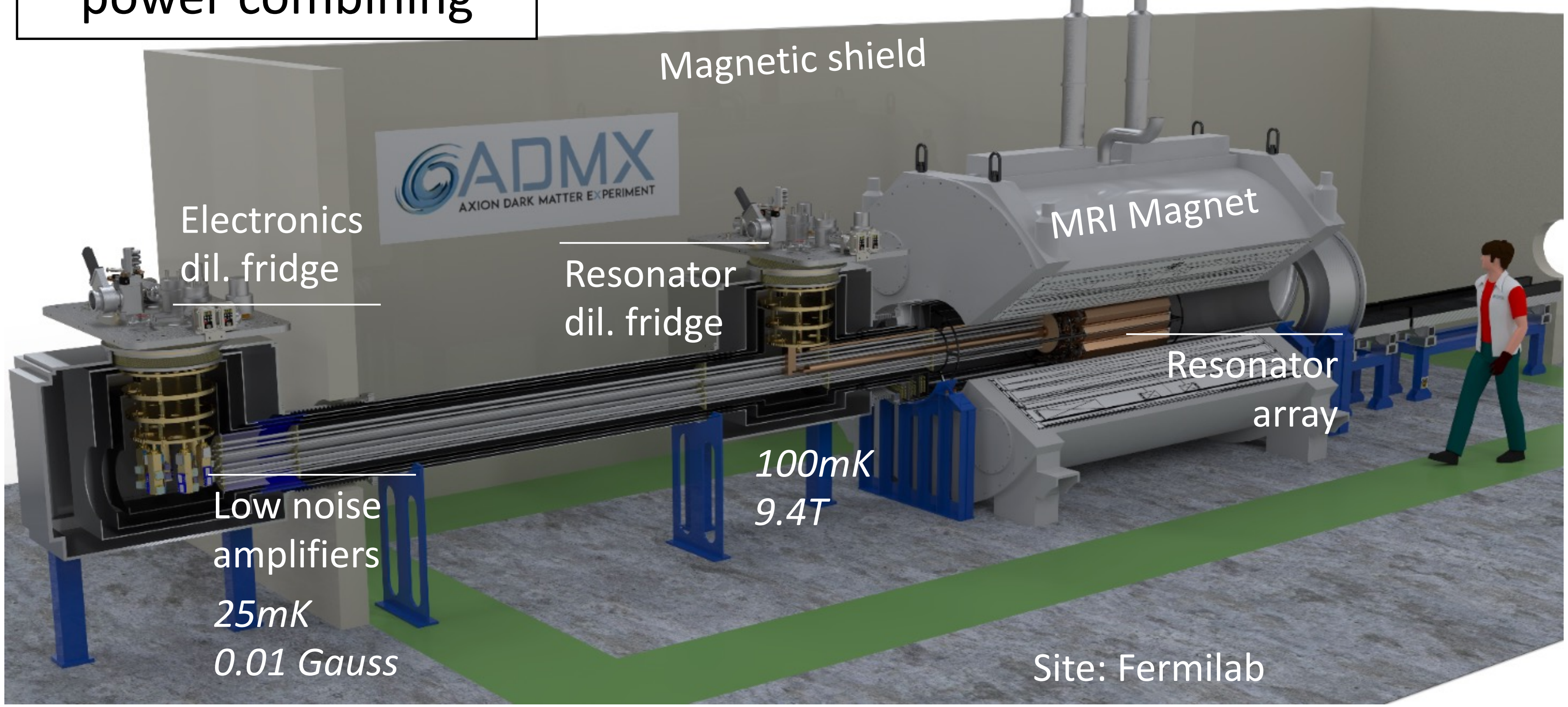
ADMX AXION DARK MATTER EXPERIMENT



18 cavity array

digital power combining

horizontal magnet: 9.4 T, 258 ℓ



Goal: Search 2-4GHz @ DFSZ sensitivity in 3 years scan time

Sub-Quantum-Limited Noise

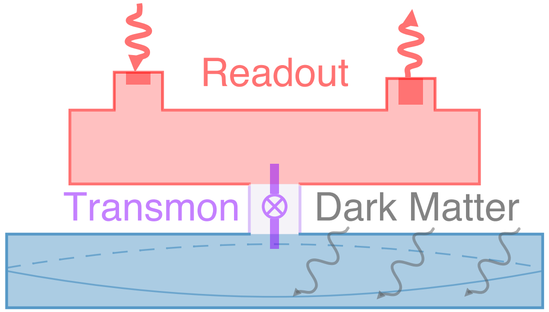
Non-Destructive Qubit Readout: [A. V. Dixit *et al*, PRL 126, 141302]

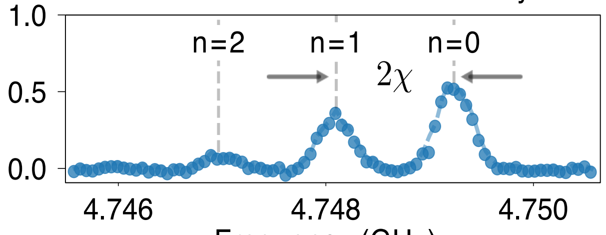
$$\mathcal{H} = \omega_c a^\dagger a + \frac{1}{2}(\omega_q + 2\chi a^\dagger a)\sigma_z$$

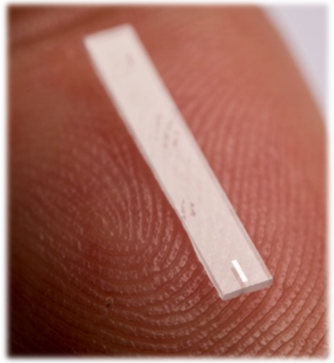
cavity

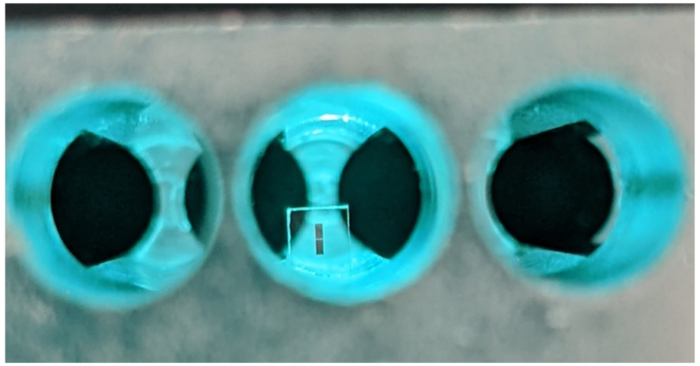
Qubit

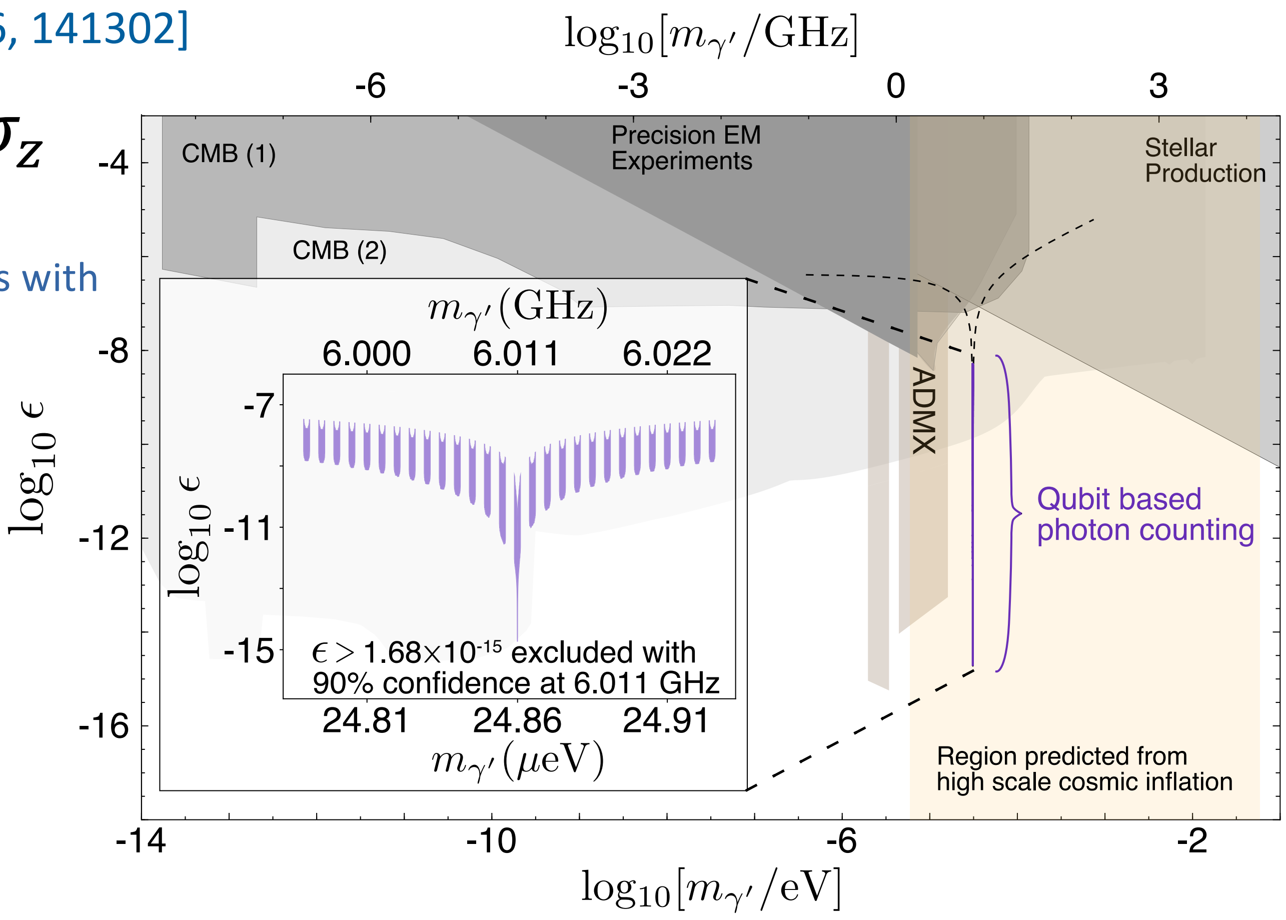
Interaction (commutes with cavity/Qubit!)











15.7 dB advantage over SQL

Superconducting Cavities – SQMS

SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Sikivie Halsocope

Niobium, $Q \sim 10^{10}$ $(B = 0T)$

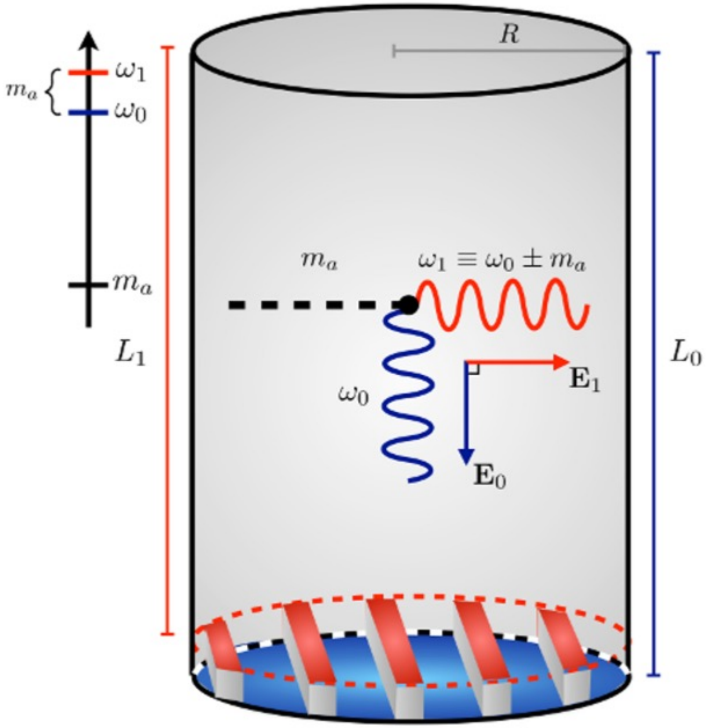
[R. Cervantes *et al,* arXiv:2208.03183]

Nb_3Sn, $Q \sim 10^{6}$ $(B \sim 6T)$

[S. Posen *et al,* arXiv:2201.10733]

→ Collaborating with ADMX

AC Haloscope



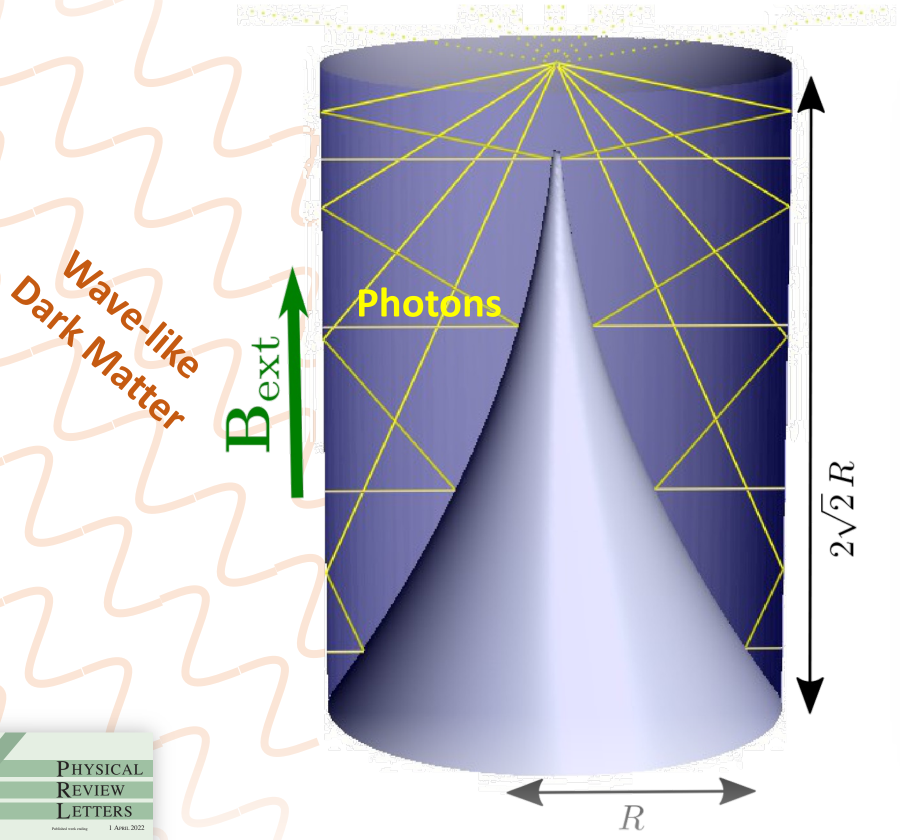
[A. Berlin *et al,* JHEP 88 (2020)]

Light-Shining-Through-Wall

[A. Romanenko *et al,* PRL 130, 261801]

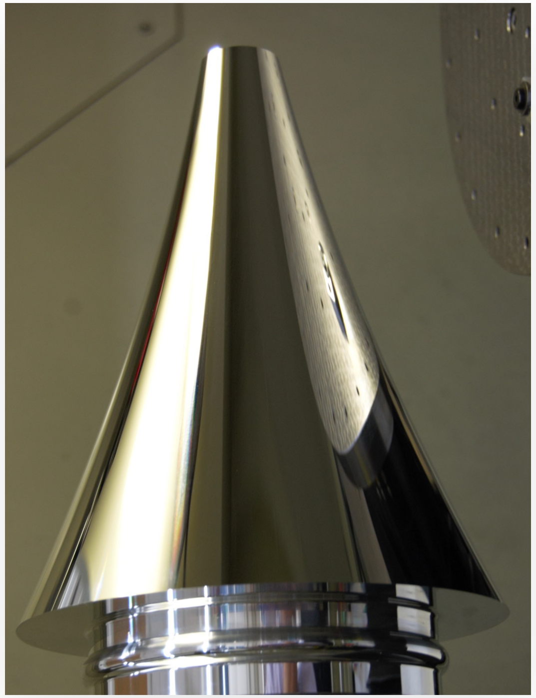
Higher Axion Mass – BREAD

(Broadband Reflector Experiment for Axion Detection)



[PRL 128 (2022) 131801]

InfraBREAD pilot



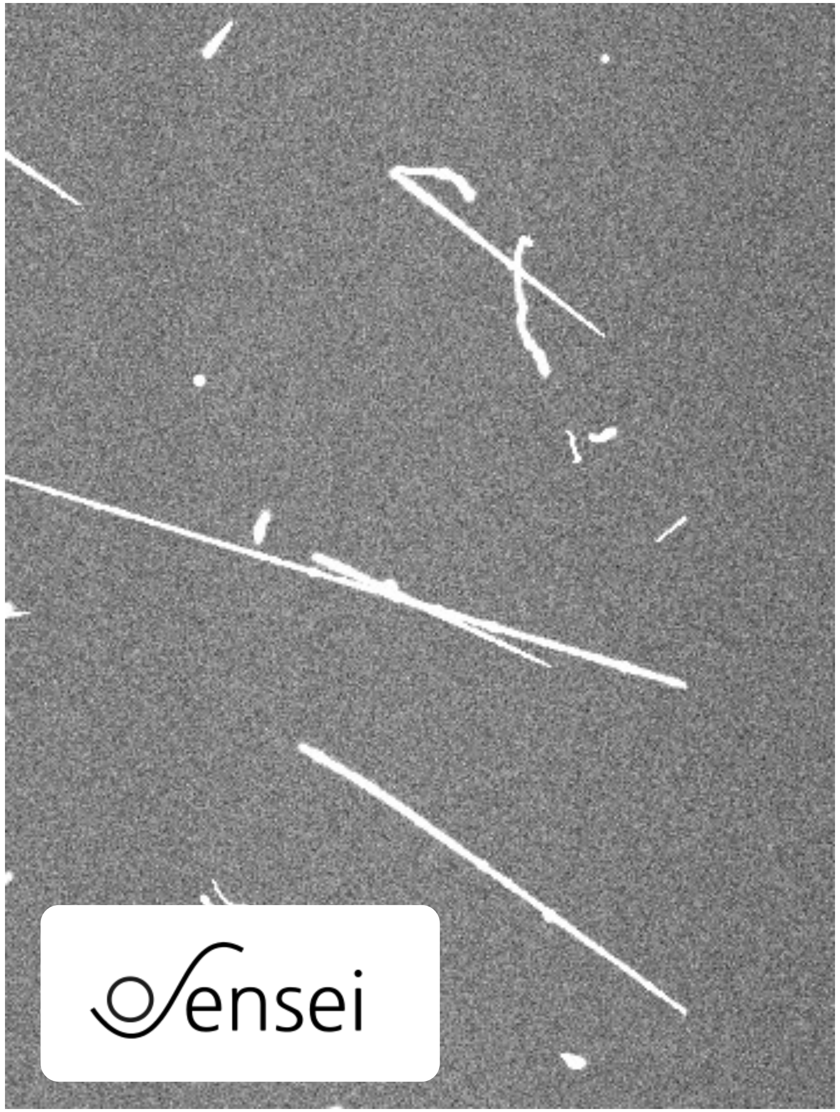
First Optical-Grade Reflector

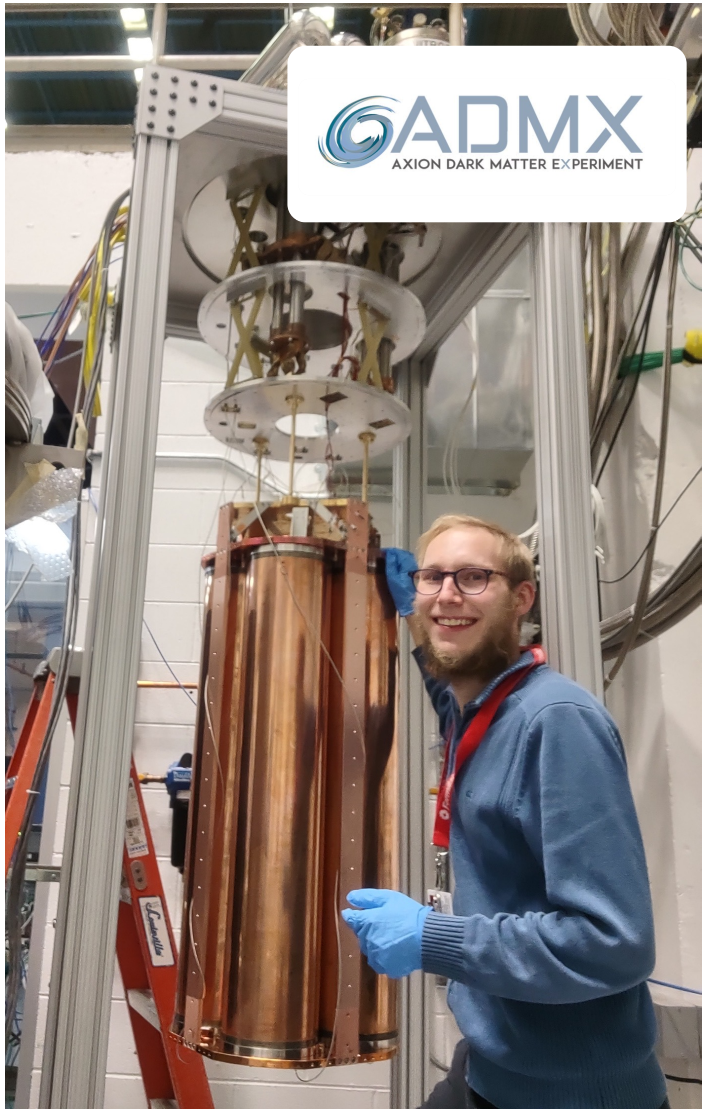
GigaBREAD pilot

*Announcing **First Science Results** at PATRAS next week*

Broadband concept for axions from μeV (GHz) to eV (Infrared)

Thank you very much!





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