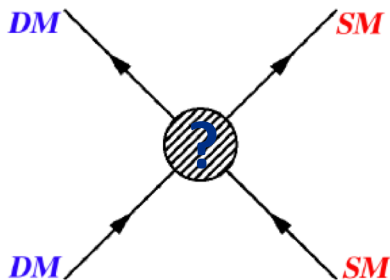# Dark Matter at Fermilab

Daniel Baxter

55th Annual Fermilab Users Meeting
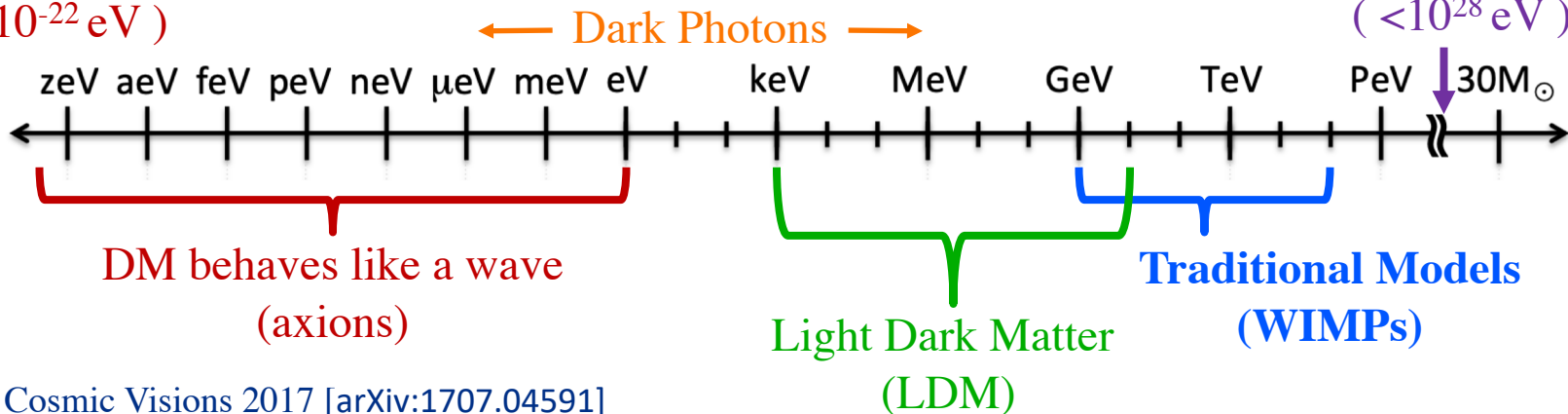
14 June 2022

Dark Matter

- Abundant evidence for cold, particle DM which *might* interact non-gravitationally with the SM

- **<u>Direct detection</u>**: the use of particle physics techniques to measure the energy transfer between galactic DM and SM particles

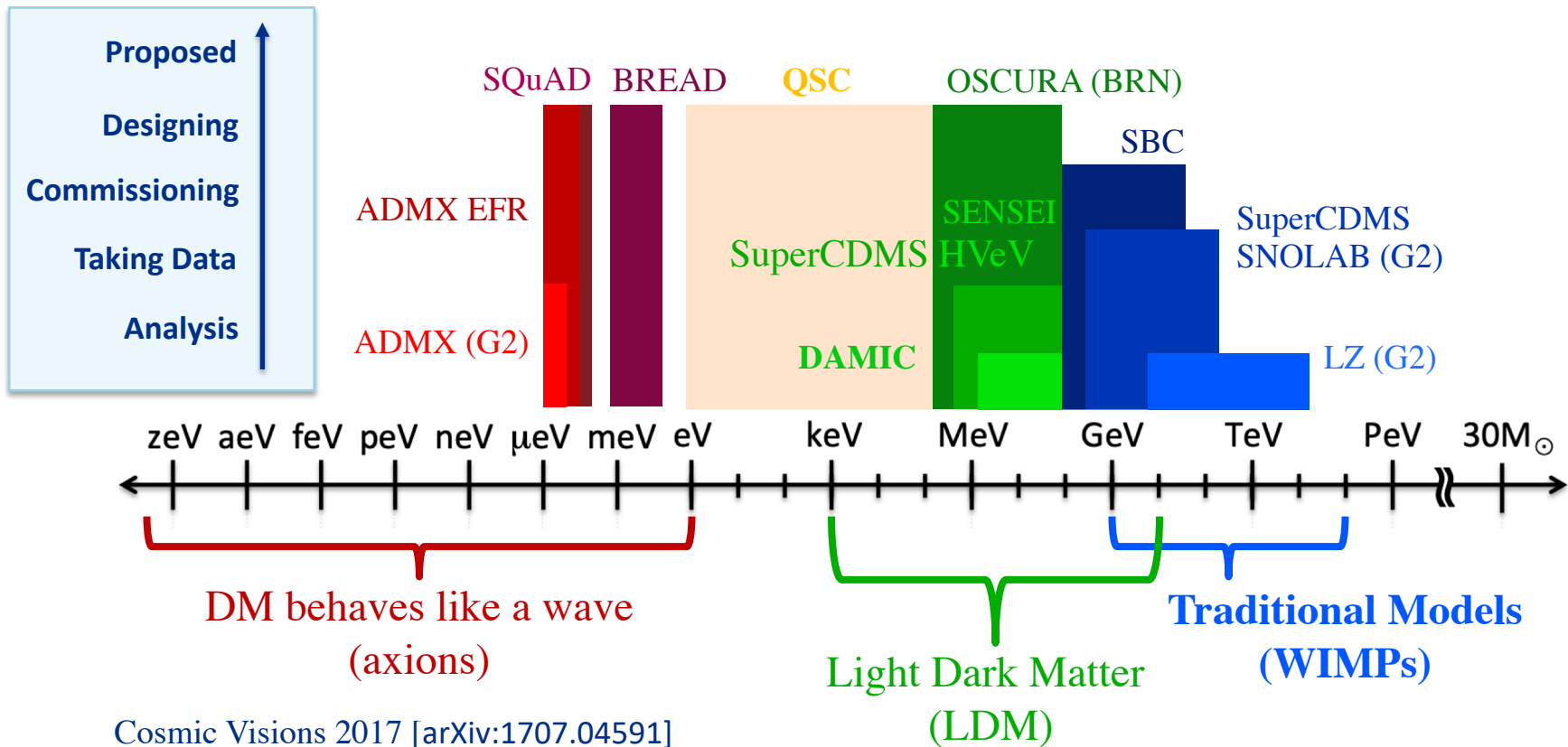**Wavelength Fits in Dwarf Galaxy**
($>10^{-22}$ eV)

Elementary Particle
($<10^{28}$ eV)

← Dark Photons →

zeV aeV feV peV neV μeV meV eV   keV   MeV   GeV   TeV   PeV 30M$_\odot$

DM behaves like a wave (axions)

Light Dark Matter (LDM)

Traditional Models (WIMPs)

Cosmic Visions 2017 [arXiv:1707.04591]

🔷 **Fermilab**

Dark Matter

Cosmic Visions 2017 [arXiv:1707.04591]

🎚 Fermilab

Particle DM Searches – Liquid Nobles

LUX-ZEPLIN (LZ):

All systems operational

- Many FNAL deliverables bearing fruit (PPD-MED Cryo & Controls; Noble R&D/XELDA; Wilson/Lederman/SCGSR)
- Effort at FNAL ramping down, < 0.1 FTE by end of CY22

Scintillating Bubble Chambers (SBC):

Low-mass dark matter at large scale

- Objective: GeV-scale dark matter beyond Generation-2 searches
- Objective: High-rate reactor neutrino CEvNS
- 10-kg LAr bubble chamber now commissioning in SiDet
- CY 2023-2024: Calibrate the physics reach of this technique in the MINOS hall
- Canadian collaborators (funded by CFI) preparing for dark matter search at SNOLAB
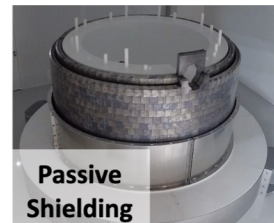
slide from Eric Dahl
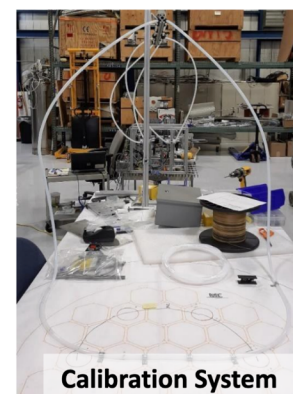
🔷 **Fermilab**

Particle DM Searches – SuperCDMS

- 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

Dilution Fridge

Fridge Gas Handling

Passive Shielding

Fridge Tails

Installation is underway at SNOLAB with commissioning expected in 2023!

Clean room

Crane

Seismic platform

Chilled water system

Cryo PLC System

Calibration System

slide from Lauren Hsu

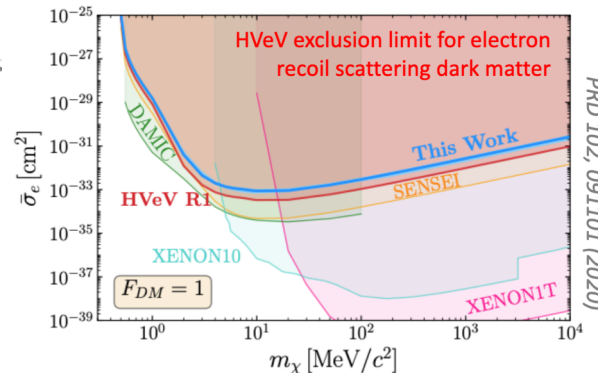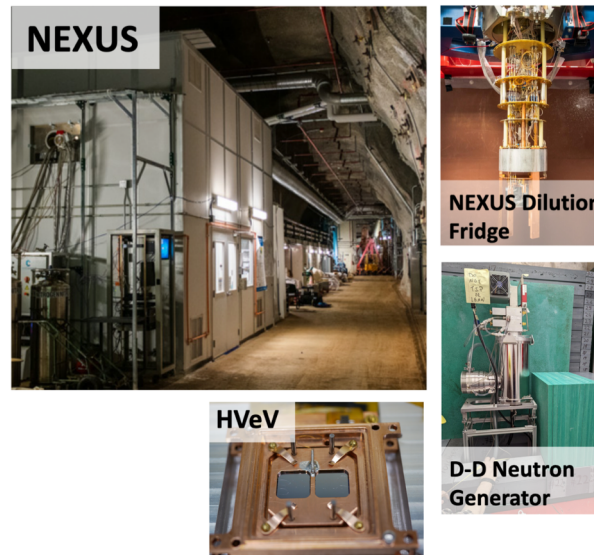🔶 **Fermilab**

Particle DM Searches – NEXUS

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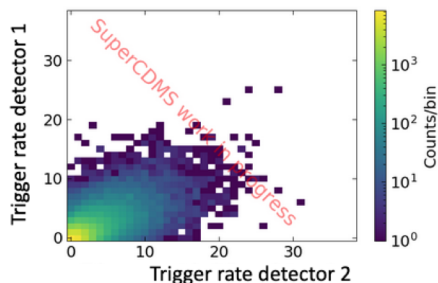
Data taken at NEXUS sheds light on a class of low energy events; will yield substantial improvement in sensitivity - Stay tuned for results!
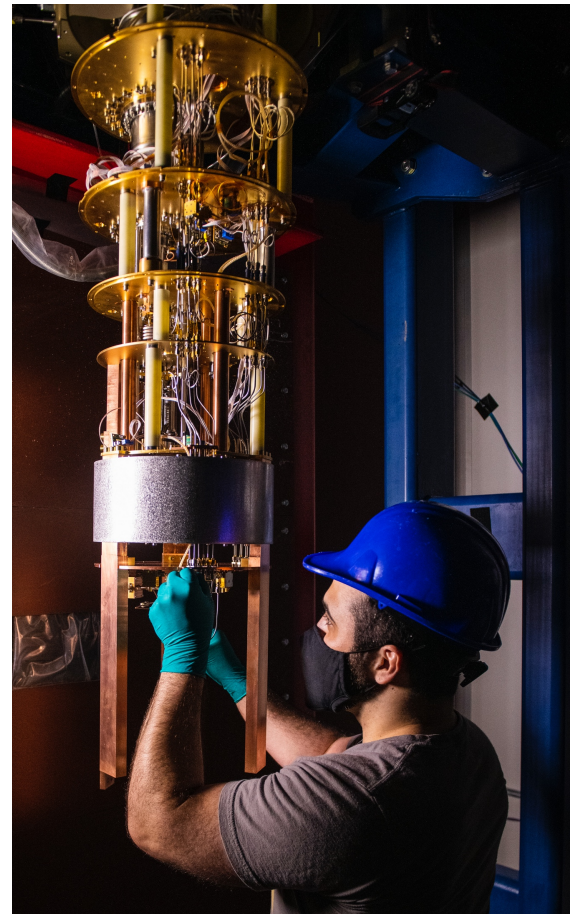

NEXUS

NEXUS Dilution Fridge

HVeV

D-D Neutron Generator

HVeV exclusion limit for electron recoil scattering dark matter

PRD 102, 091101 (2020)

slide from Lauren Hsu

🔷 **Fermilab**

# Particle DM Searches – NEXUS RF Retrofit

- **Quantum Science Center (QSC) seeks to leverage quantum detectors (e.g. qubits) for particle DM detection**
  QSC is one of five quantum centers funded through the National Quantum Initiative (see also SQMS)

- **NEXUS retrofit for RF in collaboration between Daniel Bowring's ECA and QSC**

- **ECA acts as a pilot program for future QSC qubit studies**
- **Check out Sami Lewis's talk at New Perspectives (6/22):**
  "Superconducting qubit studies at NEXUS"

- **Simultaneously studying other sub-eV threshold detectors (e.g. KIDs) to provide complimentary energy resolution**
- **Check out Dylan Temples' talk at New Perspectives (6/22)**
  "NEXUS: A low-background, cryogenic facility for detector development and calibrations"

🔀 **Fermilab**

Particle DM Searches – Quantum Science Center

- **NEXUS shielding has achieved the ~100 counts/kg/day/keV desired background**
- **First QSC dilution fridge arriving in ~weeks to be installed in SciDet Lab G**
- **Underground QSC dil. fridge arriving end of 2022**
- **MINOS underground clean room procurement on task to have new facility by end of 2022**
- **Expect to be operational early 2023**
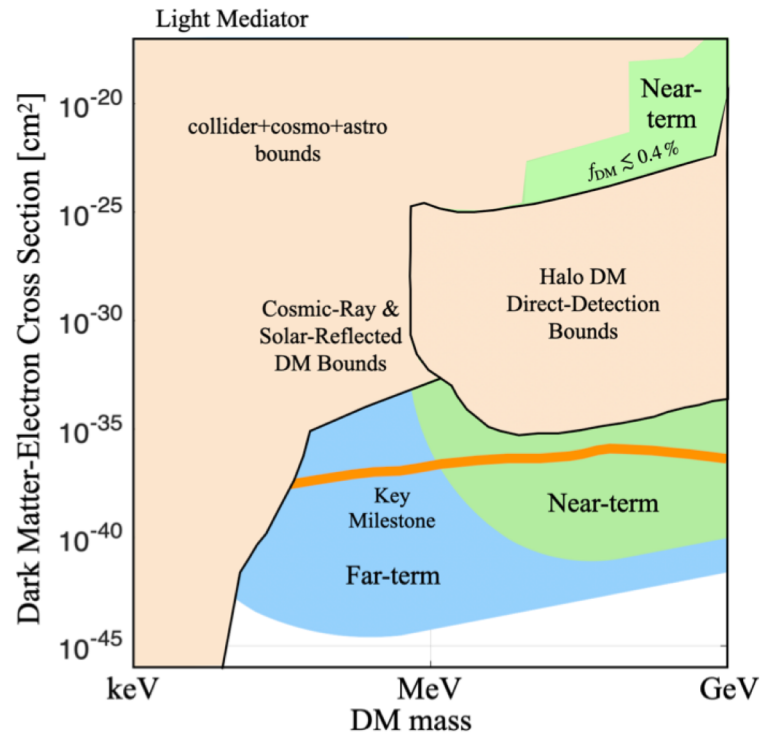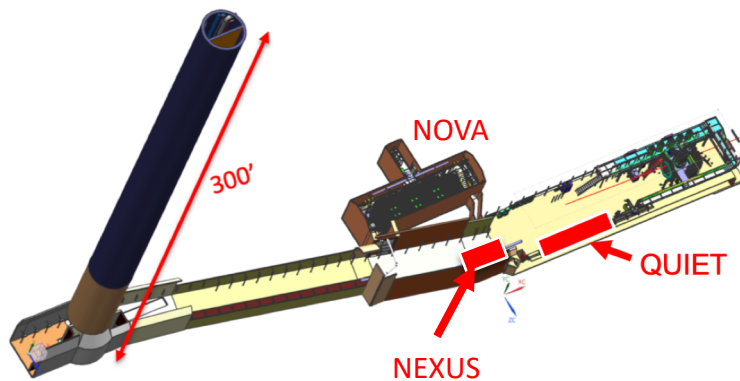
Particle DM Searches – DAMIC

- **DAMIC at SNOLAB sets the strongest limits on sub-GeV WIMPs with silicon**
- **Observes a 3.7σ excess which is currently being investigated in a follow-up run**

🎇 **Fermilab**
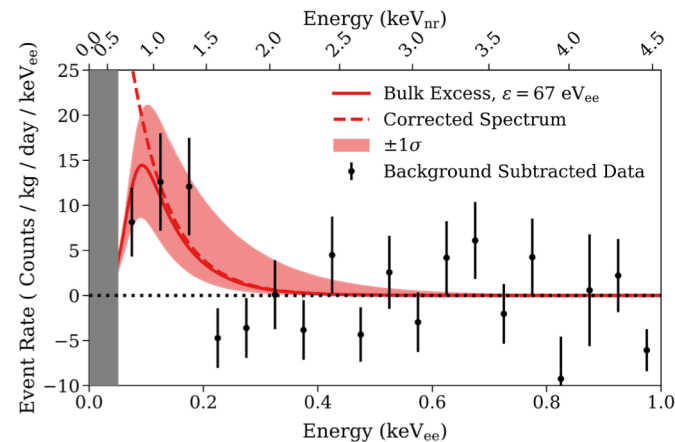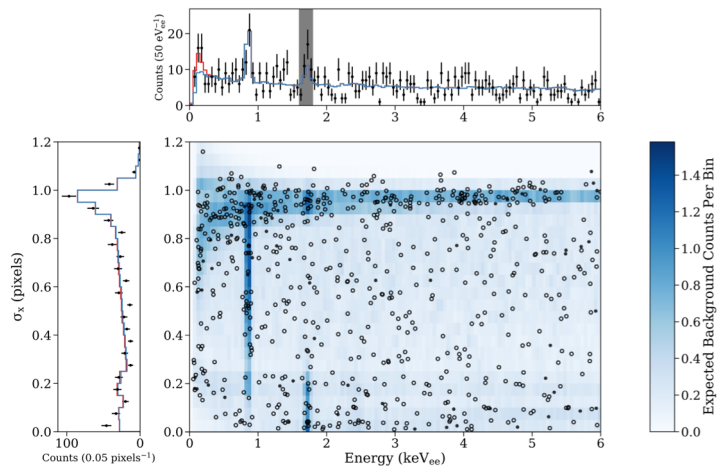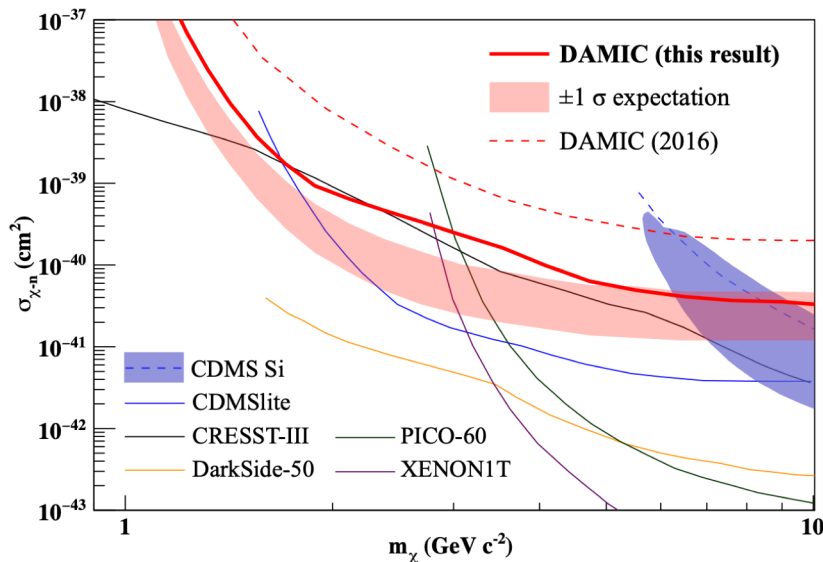
Particle DM Searches – SENSEI

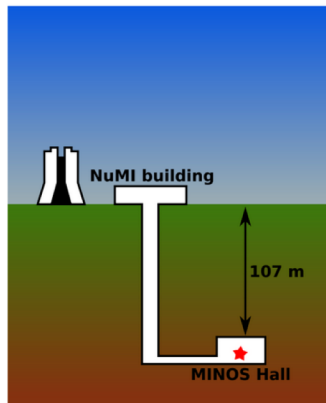| 2017	2018	2019	2020	Ongoing
Demonstrate sub-electron resolution	DM search with proto-SENSEI (0.1 g) at surface	DM search with proto-SENSEI at MINOS (230 m.w.e.)	DM search with science-grade (~2 g) at MINOS	DM search with 100 g of science-grade CCDs at SNOLAB (6000 m.w.e)
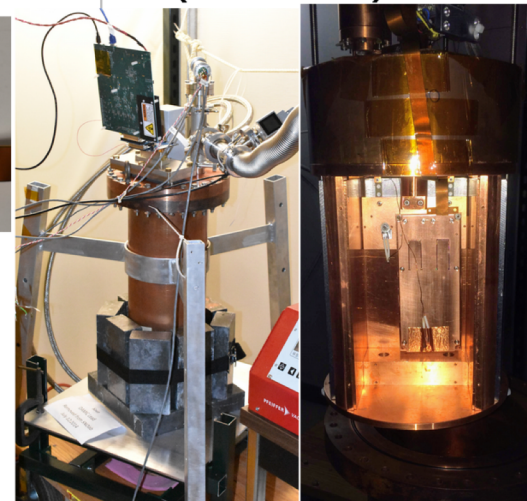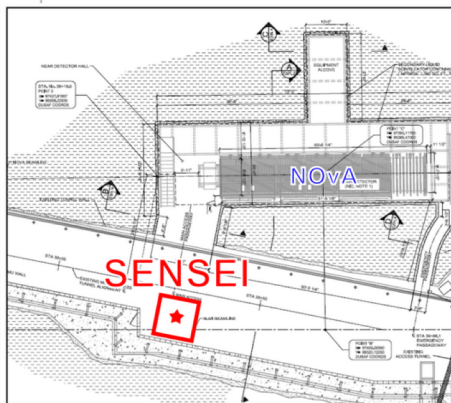
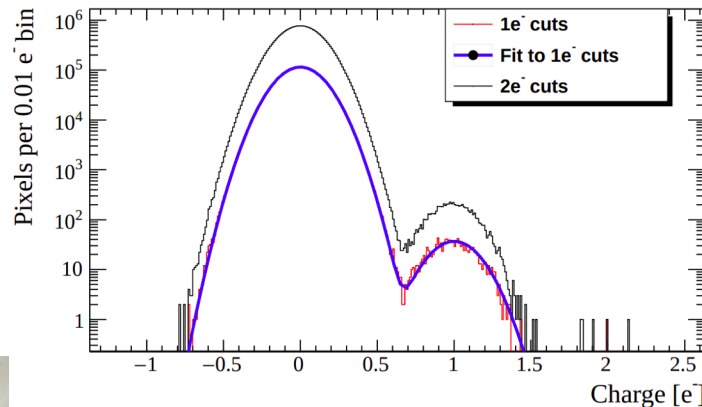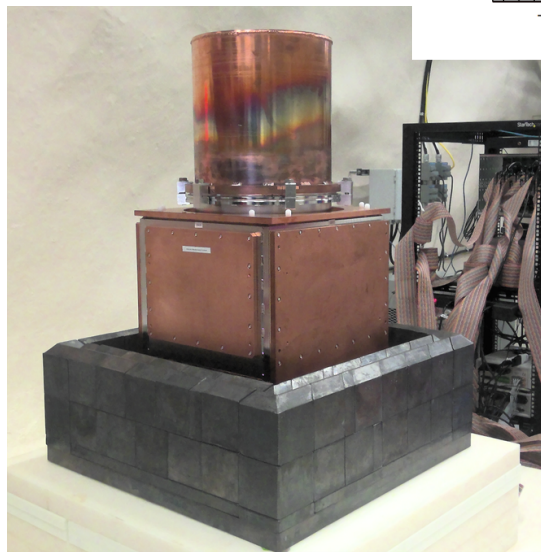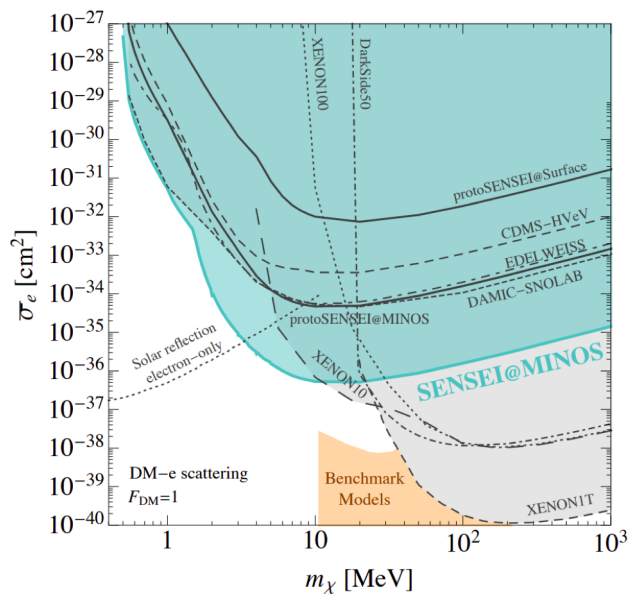The SENSEI Collaboration, PRL 125 (2020): 171802.

details from Juan Estrada

🎗 Fermilab

Particle DM Searches – SENSEI

- **SENSEI at MINOS holds world's strongest limits on sub-10 MeV DM!**
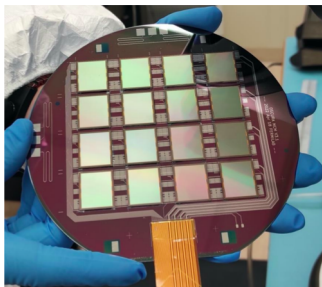- **Single electron resolution using Skipper CCDs (right)**
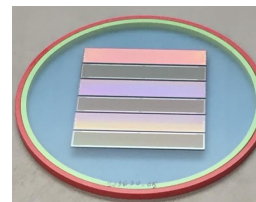
- **SENSEI at SNOLAB is being commissioned now!**

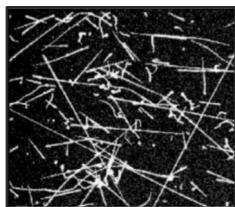*details from Juan Estrada*

🔬 **Fermilab**

Particle DM Searches – OSCURA
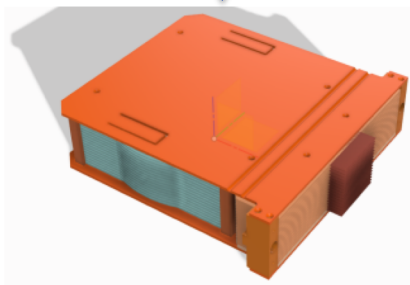

arXiv:2202.10518

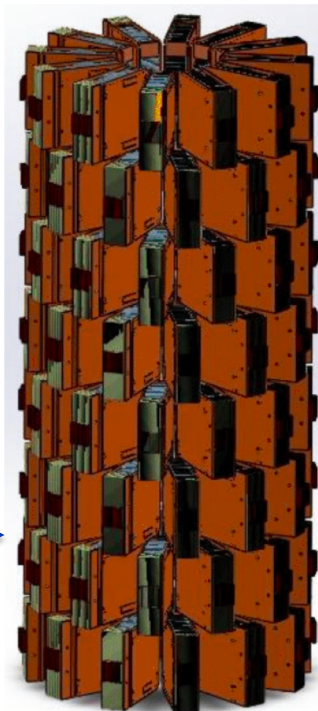*CCD manufacturer is retiring production line of CCDs that have been used for 17+ years.*

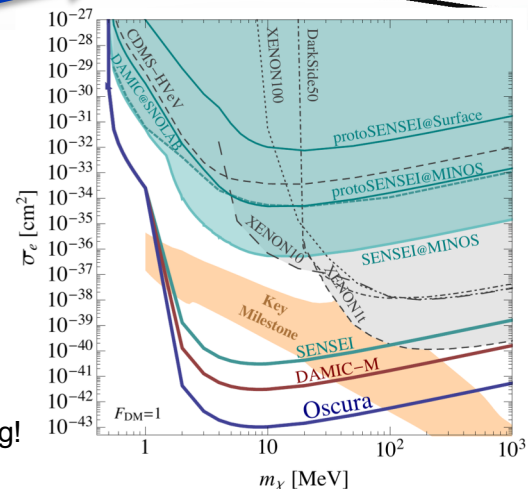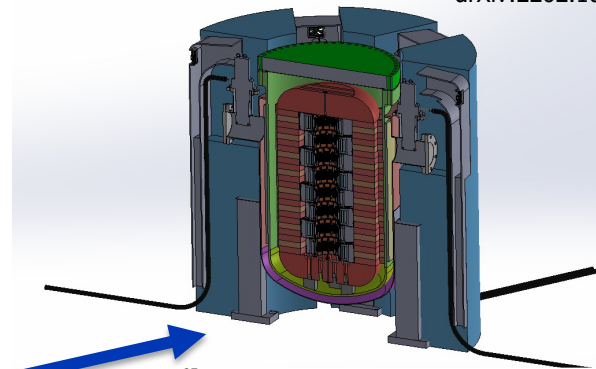**New Microchip solution**

Multi Chip Module (MCM):
16 CCDs mounted on one silicon wafer

Super Module (SM):
16 MCMs housed in electroformed copper

Oscura Experiment:
25,600 CCDs → 1,600 MCMs → 100 SMs → 10 kg!

details from Juan Estrada

🔶 Fermilab

Particle DM Searches – Readout Electronics

Low threshold architecture (LTA)

Science: Dark matter (DAMIC, SENSEI, DAMIC1Kg, Oscura10Kg), CEνNS (CONNIE, Violeta10Kg), DM from space (CubeSAT)

- LTA helps SENSEI scientists win New Horizons 2020. (Tiffenberg (FNAL), et. al.)
  - SENSEI PRL paper chosen "editor's pick" (2nd time for SENSEI)
  - SENSEI at SNOLAB: 200 channels in 2021. Being built at SiDet.
- CONNIE (Coherent Neutrino Nucleus Interaction Experiment) at Angra2 (Brazil) 2015-2020
  - G.F.Moroni URA Tollerstrup award.
- CubeSat LTA: 3 board space hard LTA for cube sat dark matter experiment. In collaboration with PPD, UIUC, NASA.
- Quantum imaging experiments (Dario Rodriguez, UBA, Argentina, Juan Estrada, Javier Tiffenberg, Fermilab)
- Future 1Kg and 10 Kg experiments (DAMIC, Oscura and Violeta will use LTA or a newer version of LTA.

## Quantum Instrumentation Control Kit (QICK)

Science: qubits and quantum devices (e.g., transmon, fluxonium, 3D cavity + qubit, snails, etc.)
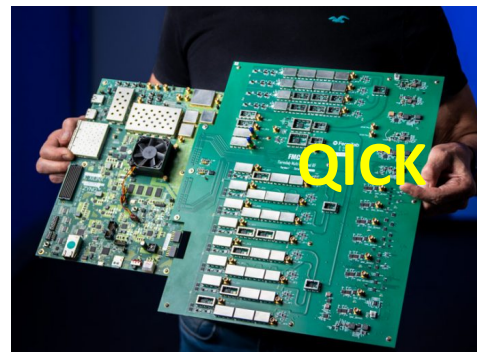
- A fully integrated readout and control system for QIS, quantum networks and superconducting detectors.
  - No extra room temperature hardware needed.
  - QICK paper made the cover of AIP RSI
  - 11 talks at APS March Meeting (not including the 2 from FNAL)
- A factor of ~20 less cost compared to off the shelf equipment
- 100 qubit system by end of 2022. (NOTE: Multiplexing can increase this number).
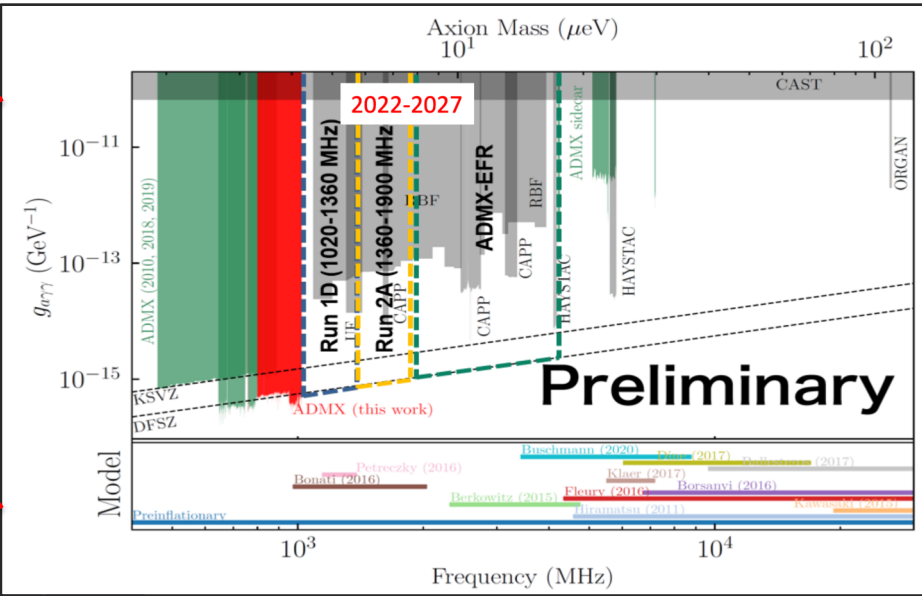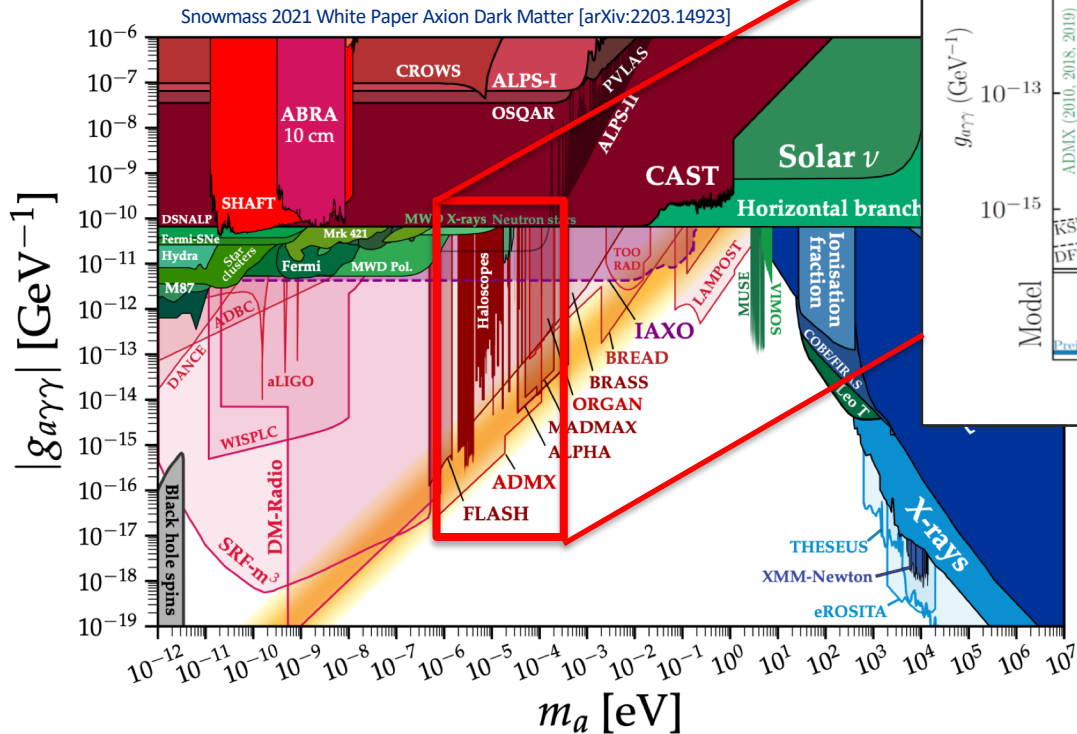- Development at FNAL will continue through QSC

details from Gustavo Cancelo

🔷 **Fermilab**

Wavelike DM Searches – Axions
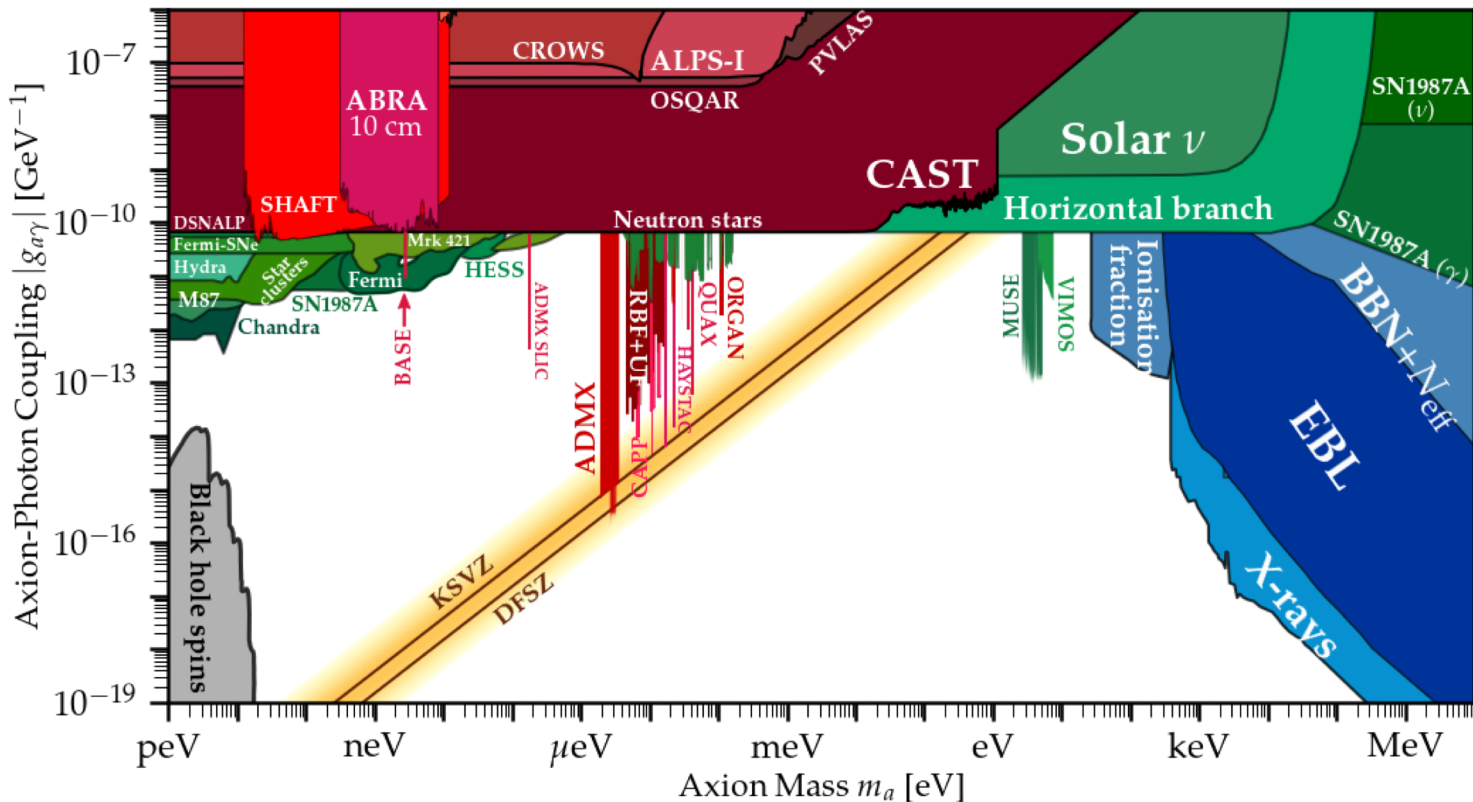
details from Stefan Knirck, Andrew Sonnenschein

🔶 **Fermilab**

Wavelike DM Searches – ADMX

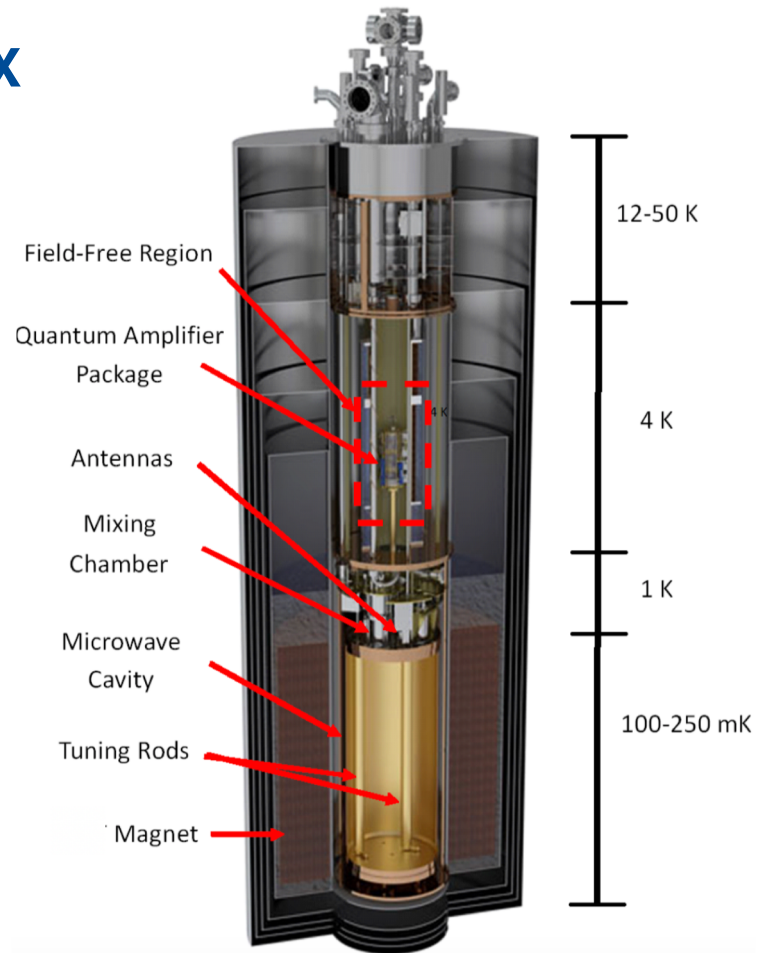Snowmass 2021 White Paper Axion Dark Matter [arXiv:2203.14923]

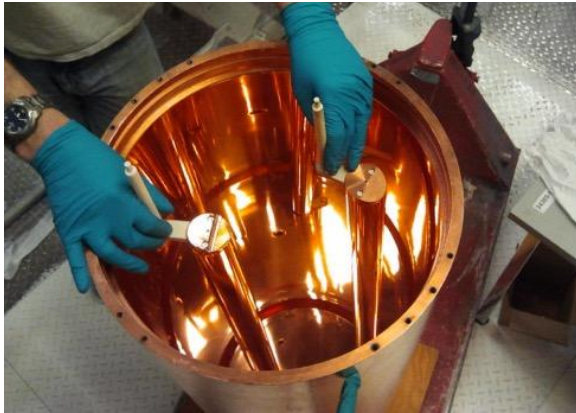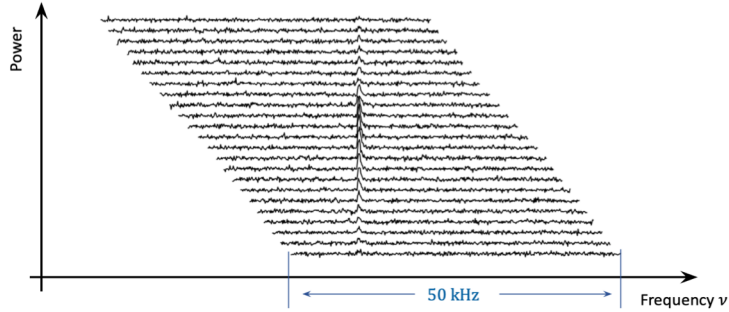- **ADMX has reached sensitivity to the QCD axion as a DM candidate**
- **Now scanning up in frequency (~ mass)**

details from Stefan Knirck, Andrew Sonnenschein

🐝 **Fermilab**

Wavelike DM Searches – ADMX

Field-Free Region

Quantum Amplifier Package

Antennas

Mixing Chamber

Microwave Cavity

Tuning Rods

Magnet

12-50 K

4 K

1 K

100-250 mK

details from Stefan Knirck, Andrew Sonnenschein

Fermilab

Wavelike DM Searches – ADMX EFR

Magnetic shield

Electronics dil. fridge

Resonator dil. fridge

MRI Magnet

Resonator array

Low noise amplifiers

100mK
9.4T

25mK
0.01 Gauss

Site: Fermilab
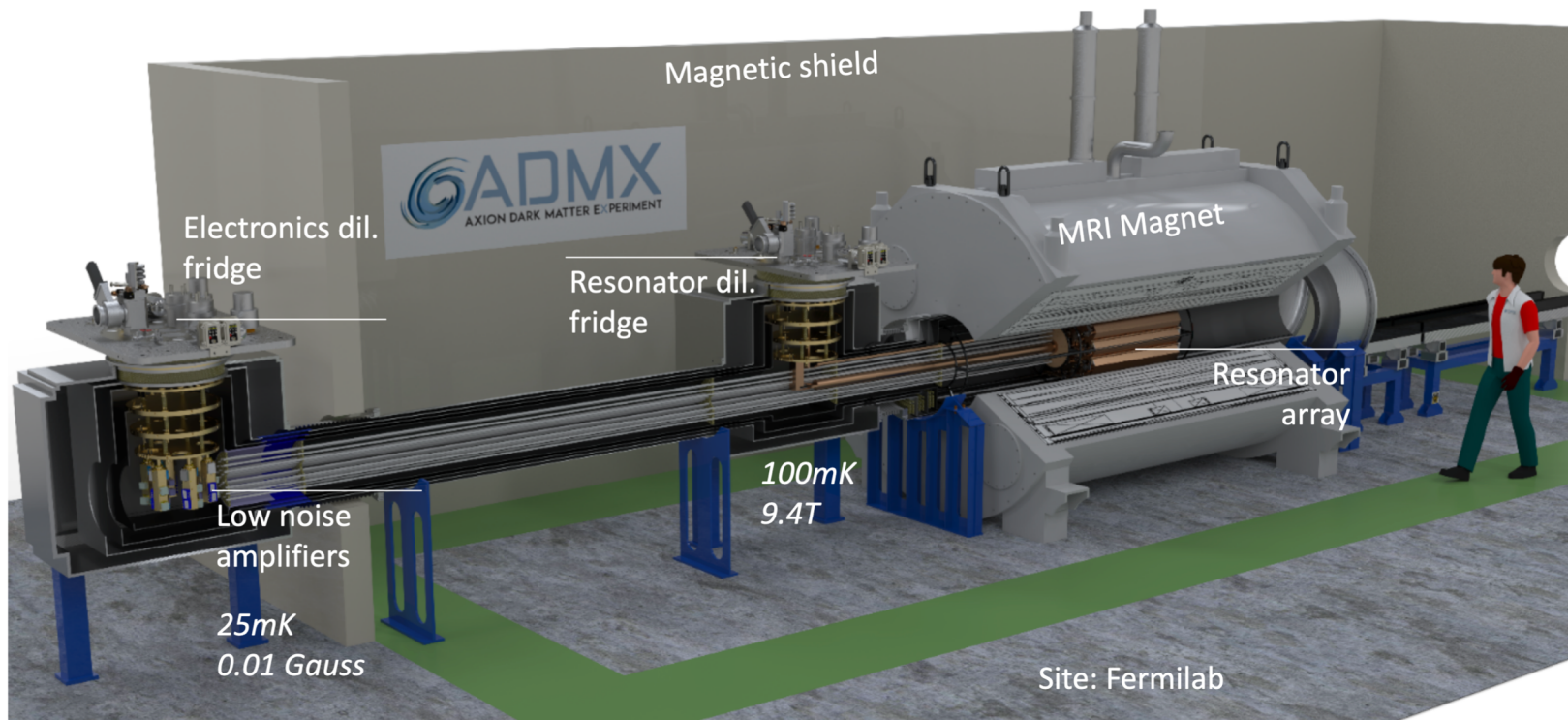
~ 5 × scan speed of current ADMX

slide from Stefan Knirck, Andrew Sonnenschein

🟦 Fermilab

Wavelike DM Searches – SQuAD

253 nm
260 nm
Josephson Junction
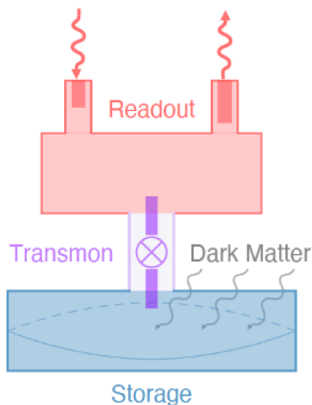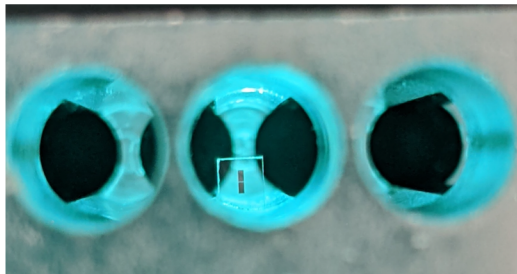A.
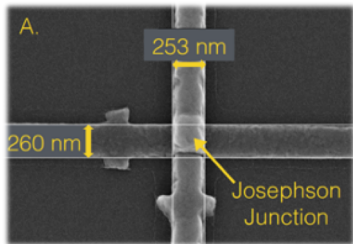
Qubit = **artificial atomic clock** based on the Josephson junction
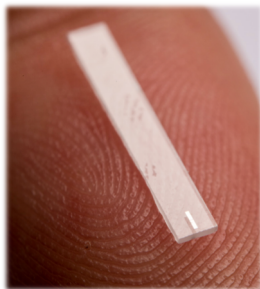
Attach mm-size antennae to couple to rf photons

Readout
Transmon ⊗ Dark Matter
Storage

Qubit in microwave cavity. Single photon signals from dark matter cause qubit frequency errors which can be detected with high fidelity quantum readout.

SQuAD: Superconducting Qubit Advantage for Dark Matter

A. V. Dixit, et al., Phys.Rev.Lett. 126 (2021) 14, 141302
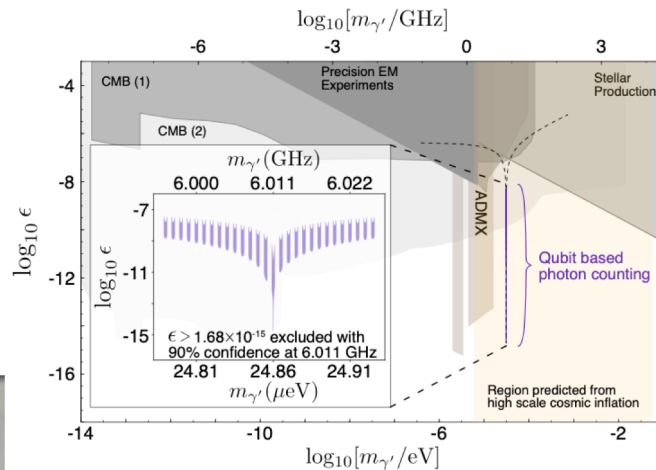
- World record quantum sensor noise suppression -15.7 dB below the standard quantum limit
- World-leading dark photon sensitivity
- Axions next!

slide from Aaron Chou

🐝 **Fermilab**

Snowmass 2021 Cosmic Frontier Leadership

Cosmic Frontier (CF): co-coordinated by FNAL scientist Aaron Chou

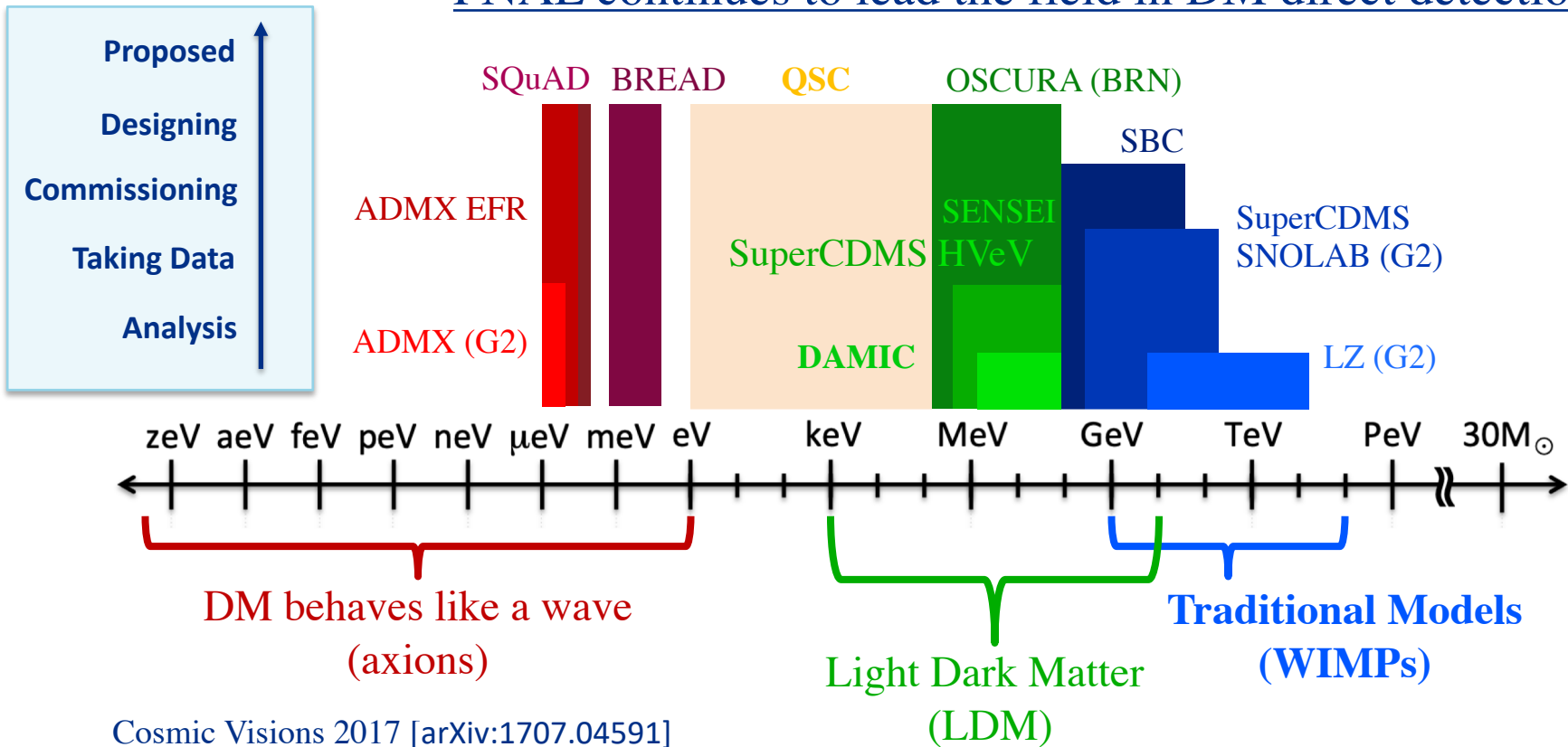**CF1: co-coordinated by former Wilson Fellow Hugh Lippincott**

CF1 (particle-like DM) major contributions to 6 of 8 solicited white papers:

- WP1: WIMP DM – contributions from FNAL scientists
- WP2: sub-GeV DM – contributions for FNAL junior scientists
- WP3: calibration/backgrounds – co-coordinated by FNAL junior scientists
- WP4: modeling/simulation – contributions from FNAL junior scientists
- WP6: DM excesses – contributions from FNAL junior scientists
- WP8: heavy DM – contributions from FNAL scientists

Not even getting into contributions in IF, TF, and unsolicited WPs

🔷 **Fermilab**

Conclusions

Proposed

Designing

Commissioning

Taking Data

Analysis

SQuAD   BREAD   QSC   OSCURA (BRN)

SBC

ADMX EFR

SENSEI
HVeV

SuperCDMS
SNOLAB (G2)

SuperCDMS

ADMX (G2)   DAMIC   LZ (G2)

zeV aeV feV peV neV μeV meV eV   keV   MeV   GeV   TeV   PeV   30M$_\odot$

DM behaves like a wave
(axions)

Light Dark Matter
(LDM)

Traditional Models
(WIMPs)

Cosmic Visions 2017 [arXiv:1707.04591]

🔷 Fermilab

Thank you

Fermilab