NEXUS: A low-background, cryogenic facility for detector development and calibration

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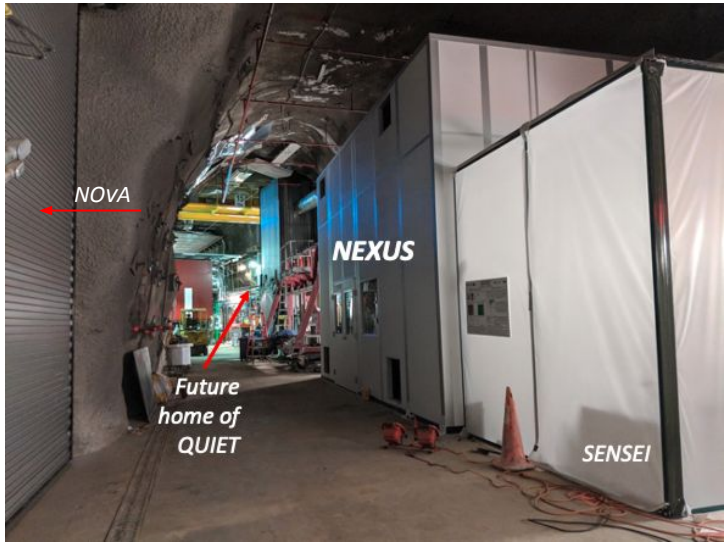
22 June 2022
FERMILAB-SLIDES-22-059-PPD-QIS

NEXUS: Northwestern Experimental Underground Site

A low-background testbed for cryogenic dark matter detectors and solid-state qubits



Located in the MINOS experimental hall at Fermilab, 100 meters underground

Developed as a collaboration between the Fermilab detector R&D program, SuperCDMS, and Northwestern University

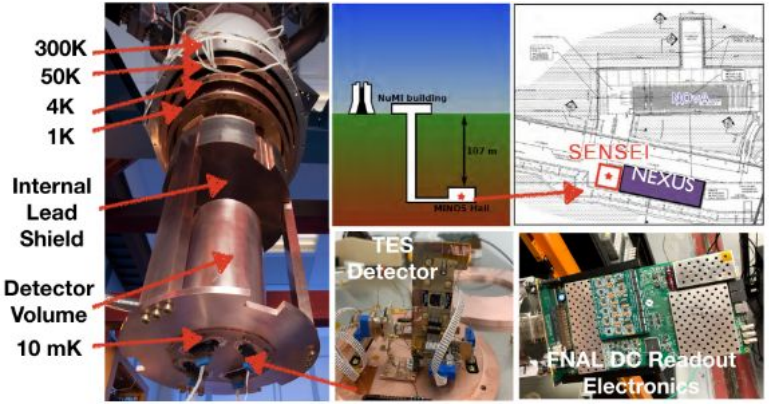
NEXUS: Northwestern Experimental Underground Site

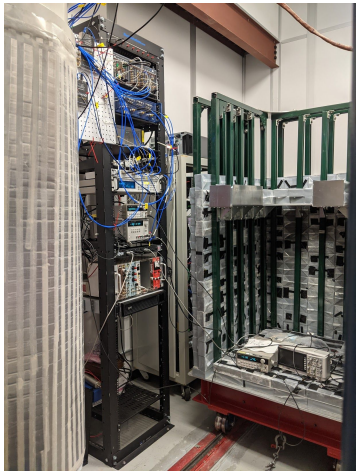
Ingredients for a dark matter search

- Low energy thresholds
  - Cryogenic detectors lead the way
- Low radioactive background
  - Lots of shielding

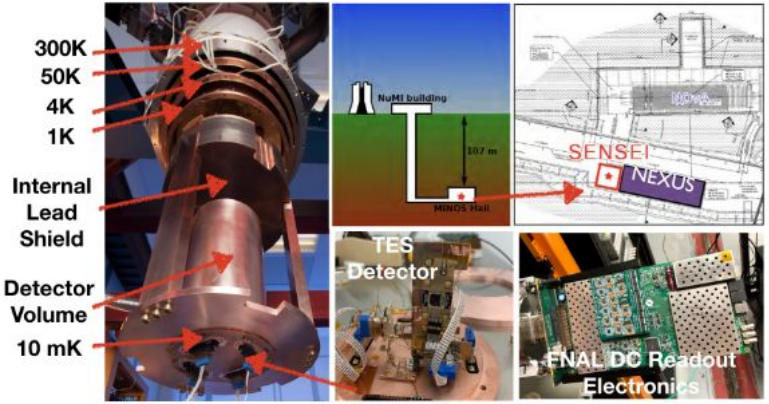
Science targets

- Calibration, evaluation, and science runs of low-threshold solid state detectors
  - Electron recoils: optical photons
  - Nuclear recoils: low-E neutrons
- Operation of superconducting qubits in low-radiation environment



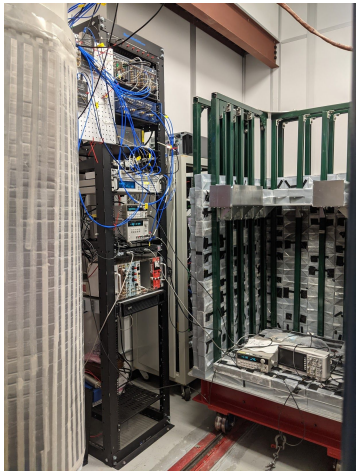


NEXUS: Northwestern Experimental Underground Site



Key facility features:

- 10 mK dilution refrigerator
- Class 10,000 clean room
- 107 m rock overburden (300 mwe)
- $\mathcal{O}$(100) dru background rate
- RF & DC electronics systems
- Optical calibration system



CryoConcept HEXADRY UQT-B200 dilution refrigerator

CryoConcept HEXADRY UQT-B200 dilution refrigerator

- 10 mK base temperature
- Stable operation up to 350 mK
- Active control: 20 μK stability

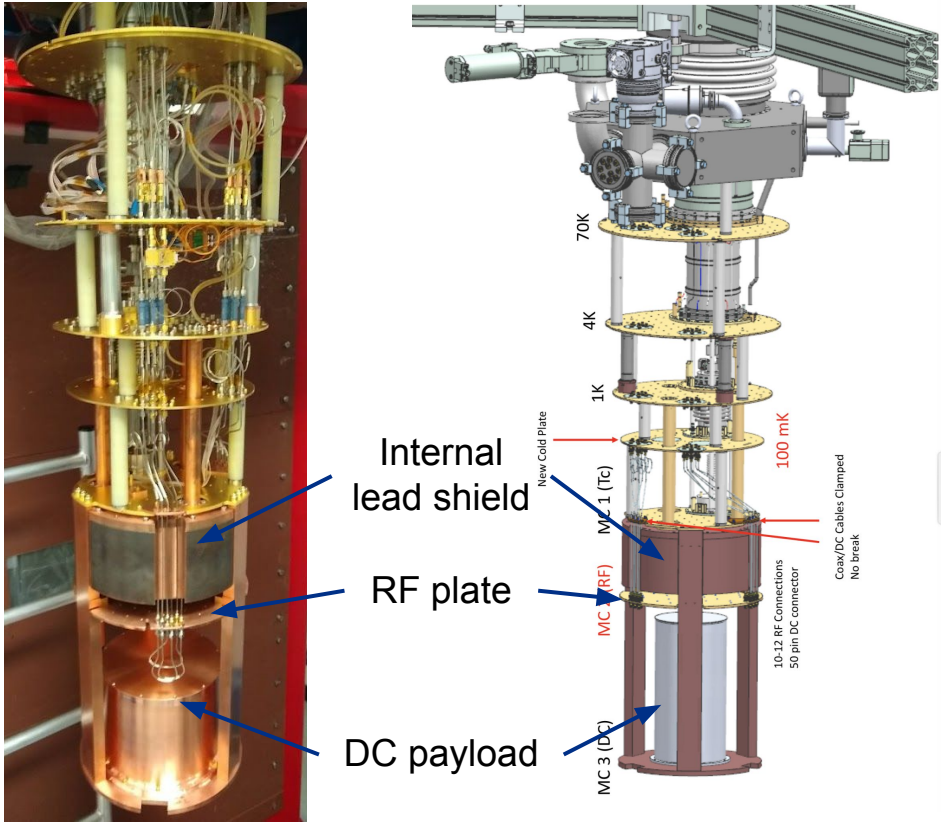
Auxiliary thermometry

Internal lead shield above payload stages

External mu-metal magnetic shield

Payload volume:

- 30 cm diameter x 50 cm vertical
- Dedicated RF plate
- Accommodates g- to kg-scale detectors



Fermilab

RF & DC Electronics Systems

10 RF channels to main stage (10 mK)

- RF retrofit from QSC & D. Bowring's ECA

100+ DC channels to main stage

Fully remote-controllable DC & RF systems

- Low & high-voltage power supplies
- Digitizers, trigger electronics
- Vector network analyzers
- Power meter, spectrum analyzer
- Variable attenuators
- Software-defined radio system
- Frequency reference / Direct Digital Synthesis
- RF circulators and isolators
- Cryogenic and warm amplifiers
  - Josephson traveling wave amplifier [*C. Macklin, Science 350.6258 (2015)*]
- Arbitrary waveform generators
- Resistance bridge (thermometry)

BYOE: plenty of space available

Fermilab

Optical Calibration System

Absolute energy calibration using optical photons

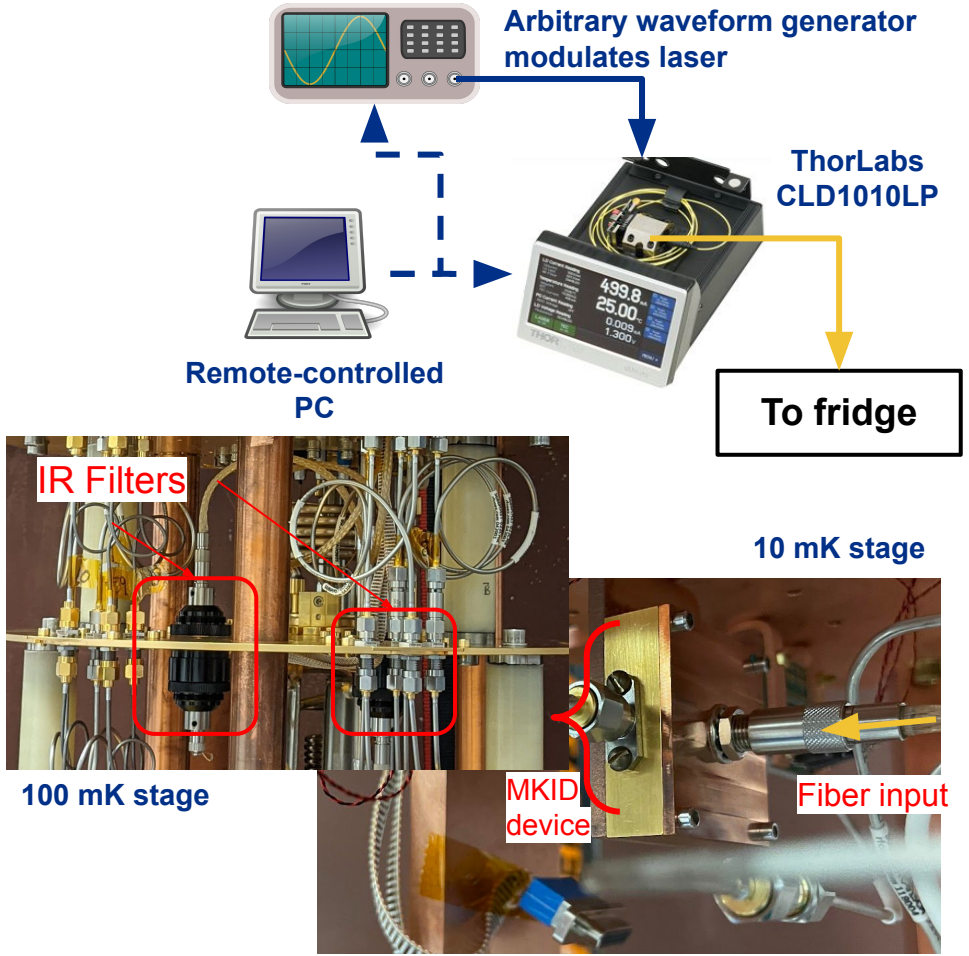
Two optical fiber lines to main stage

- IR filtering at 100 mK
- New programmable laser driver
  - 1550 nm, 850 nm, 635 nm, 520 nm, 405 nm diodes

Future upgrade: steerable MEMS mirror device for laser pointing

- Lederman Fellow **Kelly Stifter** is lead
- See **Hannah Magoon**'s talk 6/22 10:30

Calibrated energy depositions at precise locations enables study of phonon transport



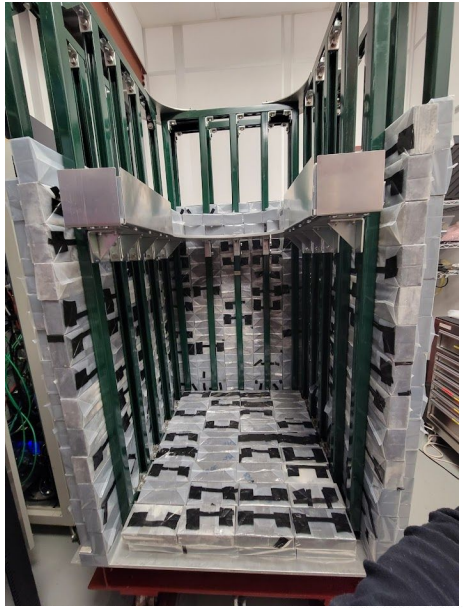
Radiation Shielding

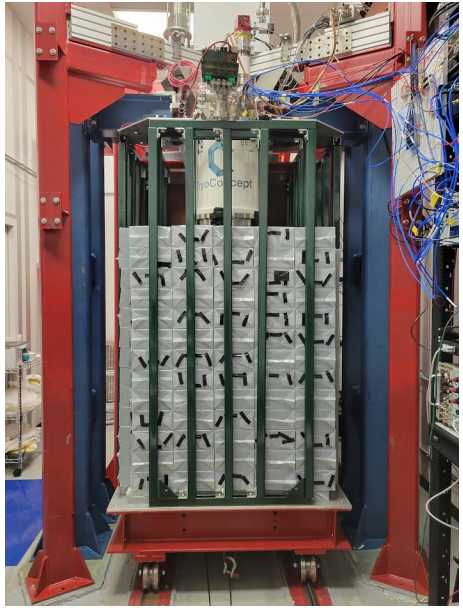
107 m rock overburden (300 mwe)

- 3.4 muons/cm^2/day
- ~425x reduction from sea level

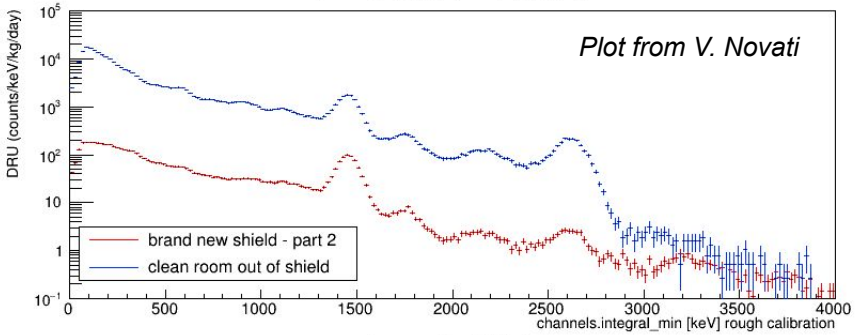
Moveable lead shielding

- 4π coverage (w/ internal fixed shield)
- ~2 orders of magnitude background reduction (w.r.t. clean room)
- 200 DRU max (@ ~100 keV)
- Assays found “hot” bricks, shield rebuilt with clean lead earlier this year



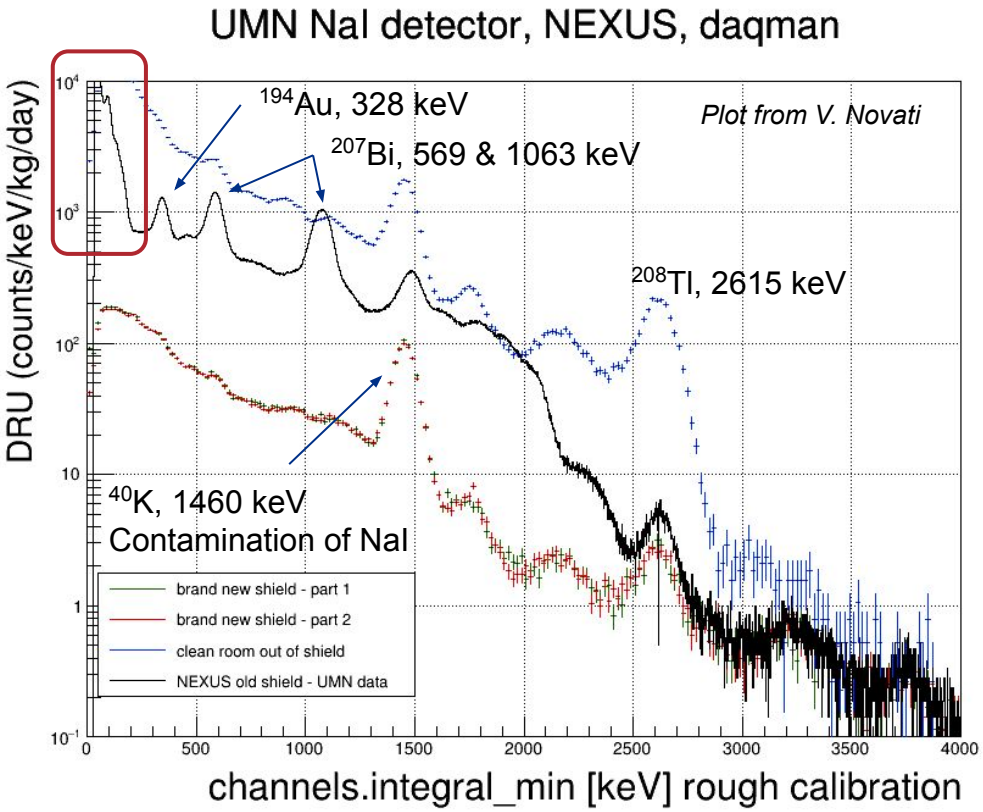


UMN NaI detector, NEXUS, daqman



New Lead Shield! Now lower in background!

- Screening campaign of the lead bricks with a NaI detector
- Identified a lead batch with higher radioactivity content, likely due to activation
- Purchased replacement lead bricks -- reduced activity inside shield by factor of 10--50
  - 100x reduction @ ~100 keV



Similar activation profile seen at Brookhaven: https://www.osti.gov/pages/biblio/1425109

DD Neutron Generator & Backing Array

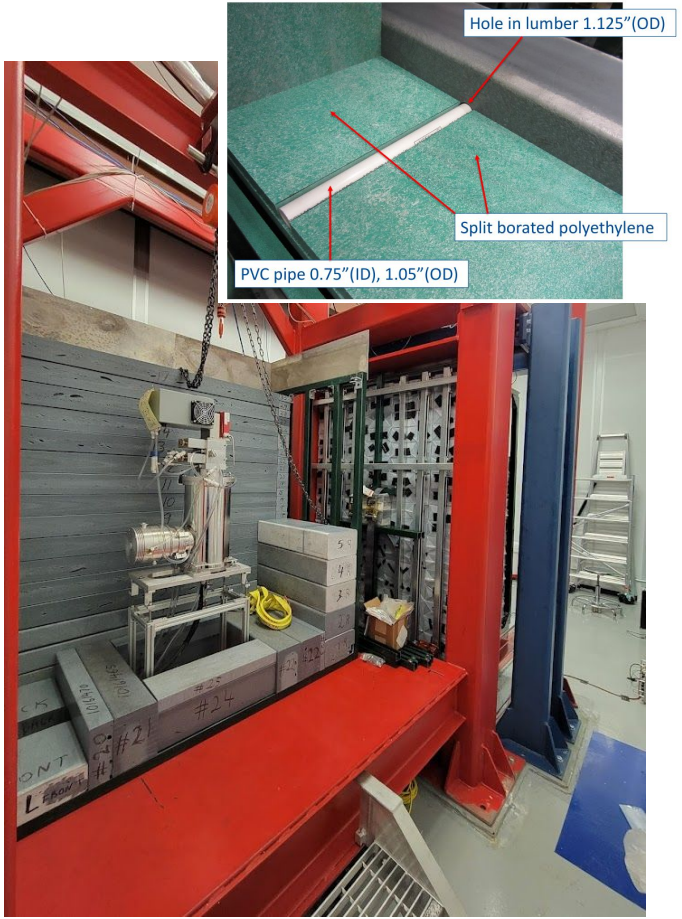
Adelphi DD108 Neutron Generator

- 2.45 MeV neutrons
  - Can be moderated down
- Rate: up to 10^8 n/sec
- Borated polyethylene enclosure
  - Beam tube: 0.75” diameter

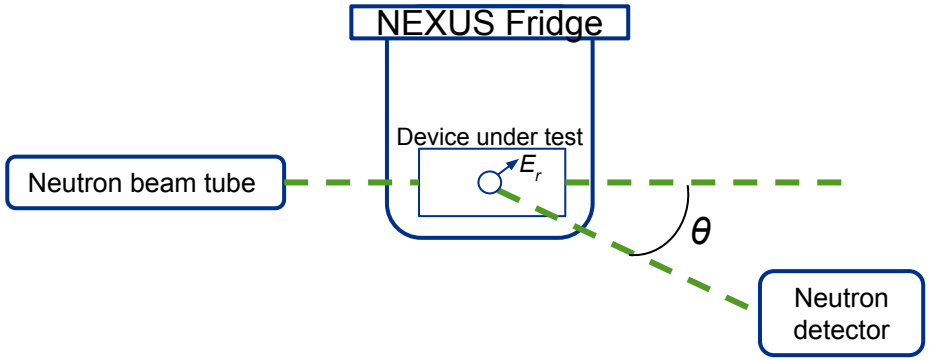
Potential calibrations:

- Elastic nuclear recoils
- Inelastic nuclear recoils (Migdal Effect)
- Neutron capture induced recoils

Simulation work underway



Coming Soon: Backing Array



Backing array of n detectors at fixed angles

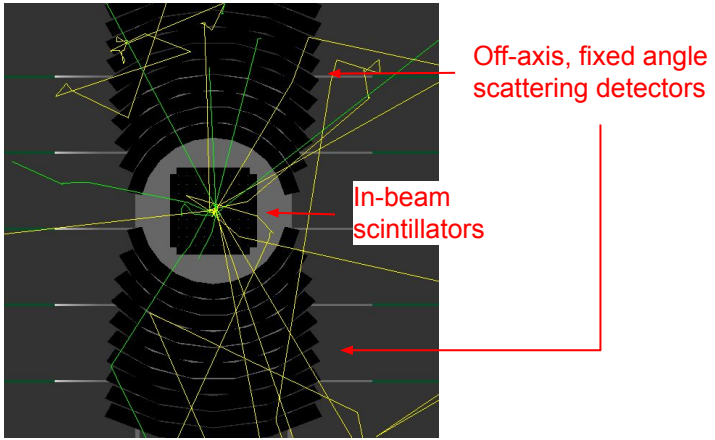
- True energy deposited in scatter

$$E_r = 2E_n \frac{M_N m_n}{(M_N + m_n)^2}(1 - \cos\theta)$$

Silicon photomultipliers coupled to Li-doped scintillators (high n-capture cross-section)

Small scattering angles → small energy depositions

Geant Simulation



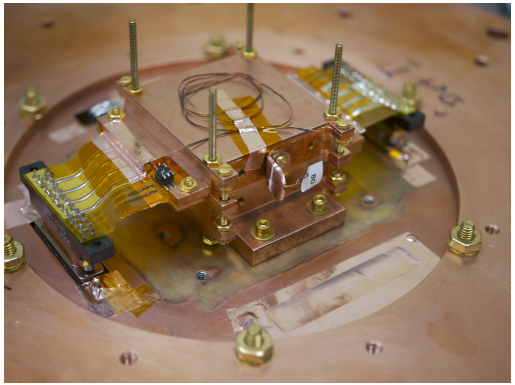
Plane perpendicular to beam axis

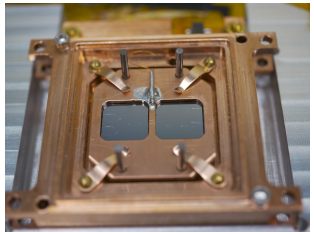
Image from P. Lukens

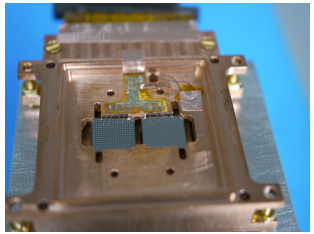
Fermilab

NEXUS Current Payloads: Dark Matter Detector R&D

SuperCDMS HVeV

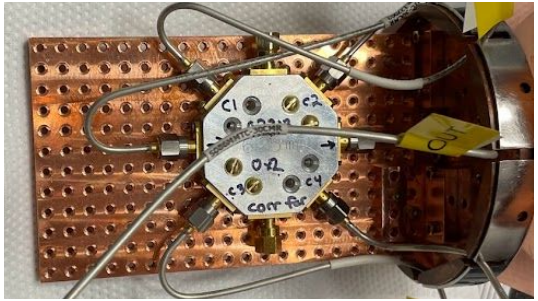


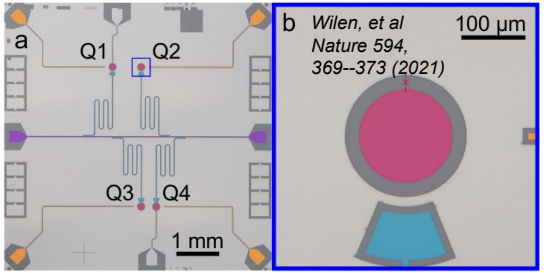




Valentina Novati
Benjamin Schmidt
* talk this session (next)

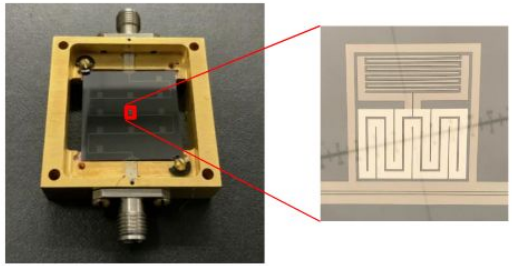
Superconducting Qubit Array

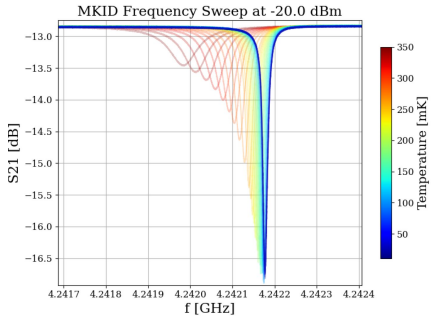




Sami Lewis
* talk this session (9 am)

Kinetic Inductance Detector Array





Dylan Temples

Future Opportunities

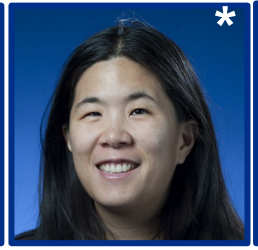
2 new cryogenic facilities: LOUD (SiDet Lab G) and QUIET (MINOS hall), as part of NQI Quantum Science Center, coming online 2022 and 2023

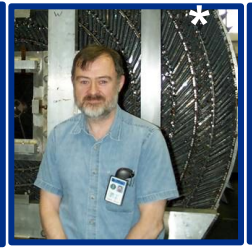
Establishing a CosmiQuantum virtual organization at FNAL to capitalize on computing infrastructure at the lab for NEXUS and new facilities

Do you have a cryogenic detector you'd like to calibrate in a low-background environment? Talk to us!

Thank You!

Not pictured:
Grace Bratrud (Northwestern)
Noah Kurinsky (SLAC)
Hannah Magoon (Tufts/FNAL)
+ others!





D. Baxter *FNAL*
D. Bowring *FNAL*
L. Hsu *FNAL*
S. Lewis *FNAL*
P. Lukens *FNAL*
D. Temples *FNAL*
E. Figueroa Feliciano *Northwestern*
V. Novati *Northwestern*
B. Schmidt *Northwestern*

Abstract

The Northwestern Experimental Underground Site (NEXUS), located in the MINOS cavern at Fermilab, is a user facility for development and calibration of cryogenic detectors. The heart of NEXUS is a dilution refrigerator with a 10 mK base temperature, protected from radiogenic backgrounds by a moveable lead shield and 100 meters of rock overburden. The fridge is outfitted with cabling to support multiple detector payloads, with both RF and DC input and readout. Currently, NEXUS houses three experiments: a superconducting qubit array, SuperCDMS HVeV detectors, and a microwave resonator array. The facility is in the process of being upgraded with a DD neutron generator, an ideal source for calibrating low-energy nuclear recoils and processes like the Migdal effect. In this talk, I will provide an overview of the utilities available at NEXUS and discuss future opportunities.

** slide from L Hsu*

History

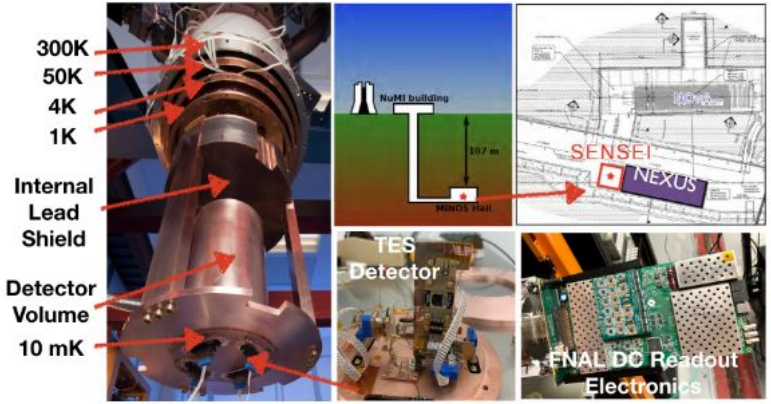
- Built as a joint collaboration between the Fermilab SuperCDMS group and Professor Enectali Figueroa-Feliciano's group at Northwestern University. NEXUS is not a formal collaboration.
- Funded through a combination of Professor Figueroa's startup funds, Fermilab detector R&D and KA23 funds (SuperCDMS operations).
- NEXUS was brought online in 2018 and has been largely operating payloads for SuperCDMS study of low energy background and electron-recoil dark matter search (using HVeV detectors)
- In early 2021, NEXUS was retrofitted with RF readout and a qubit array and mKID device were also installed. The former is a joint endeavor between Daniel Bowring's ECA and QSC. The latter is funded through and LDRD originally awarded to Noah Kurinsky
- In August of 2021, NEXUS chiller failed and has been down for 4 months. Chiller repaired in November. Two short cooldown experienced a circulation blockage. Debugging is ongoing this week (Dec. 9), anticipating next cooldown early in 2022

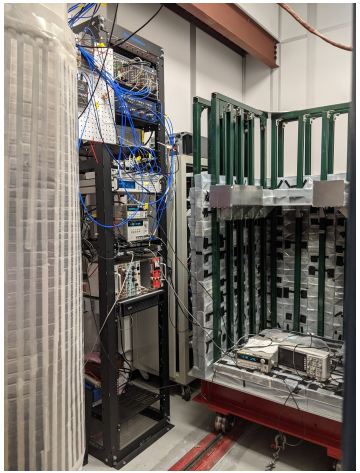
NEXUS: Northwestern Experimental Underground Site

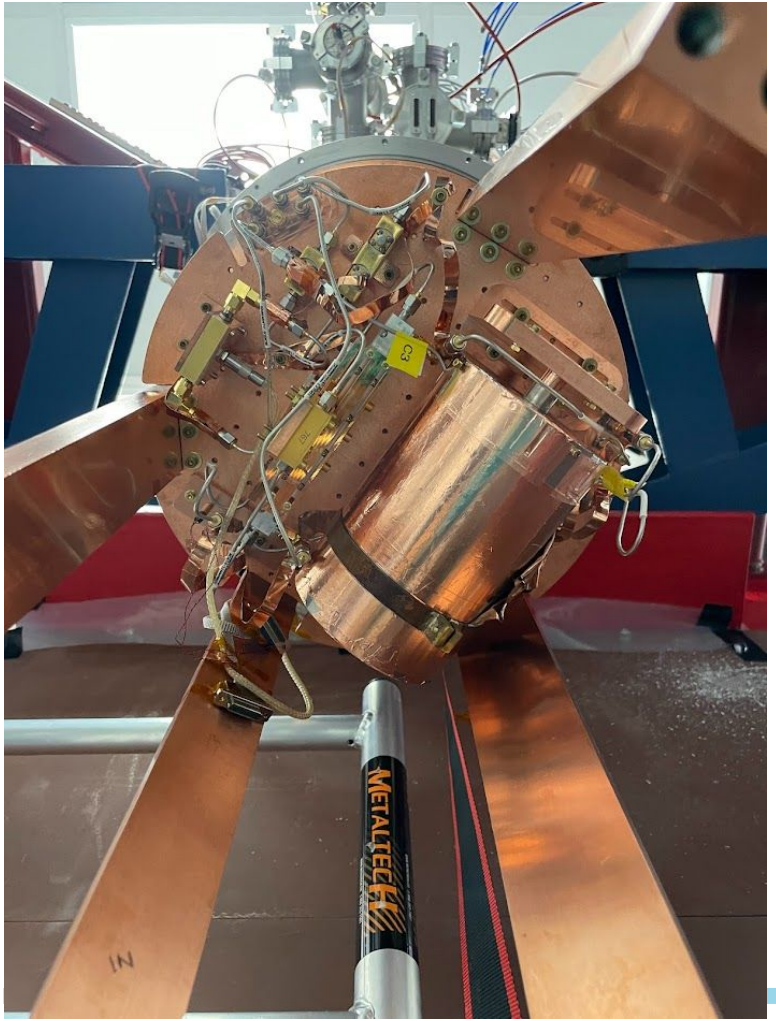
Key features:

- 107 m rock overburden (300 mwe)
- Class 10,000 clean room
- 100 dru background rate
- ~2 week turnaround between runs

- 10 mK dilution refrigerator
- RF & DC electronics systems
- Optical calibration system
- Magnetic shielding
- Moveable external lead shield
- DD neutron generator



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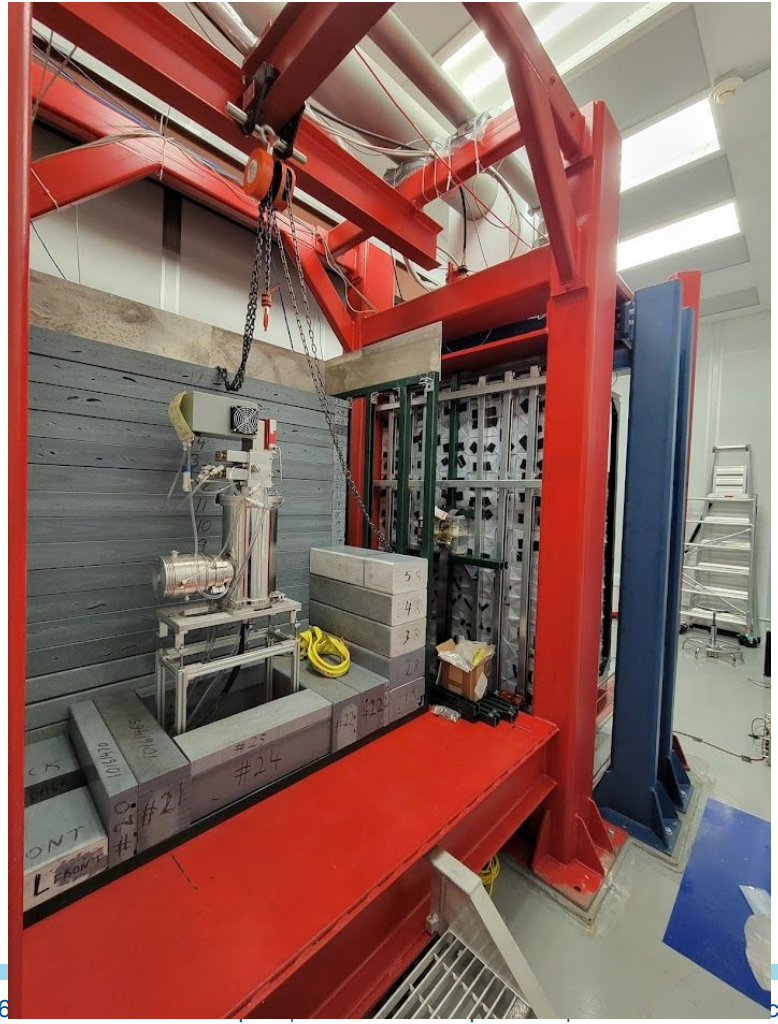
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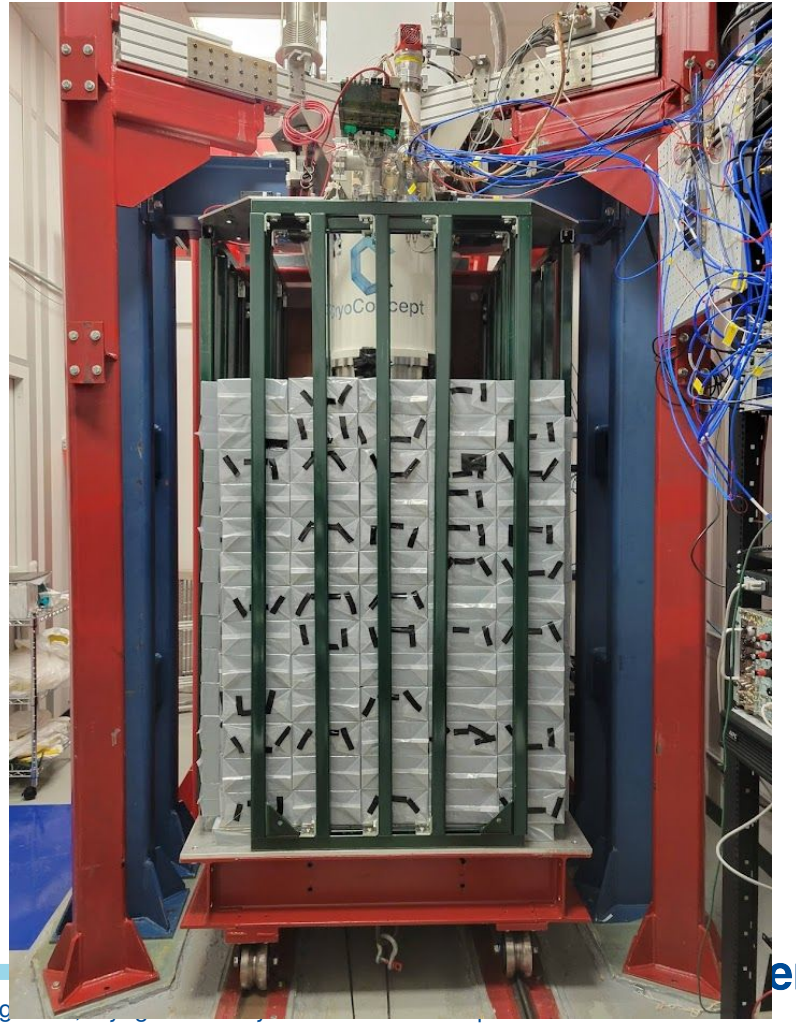
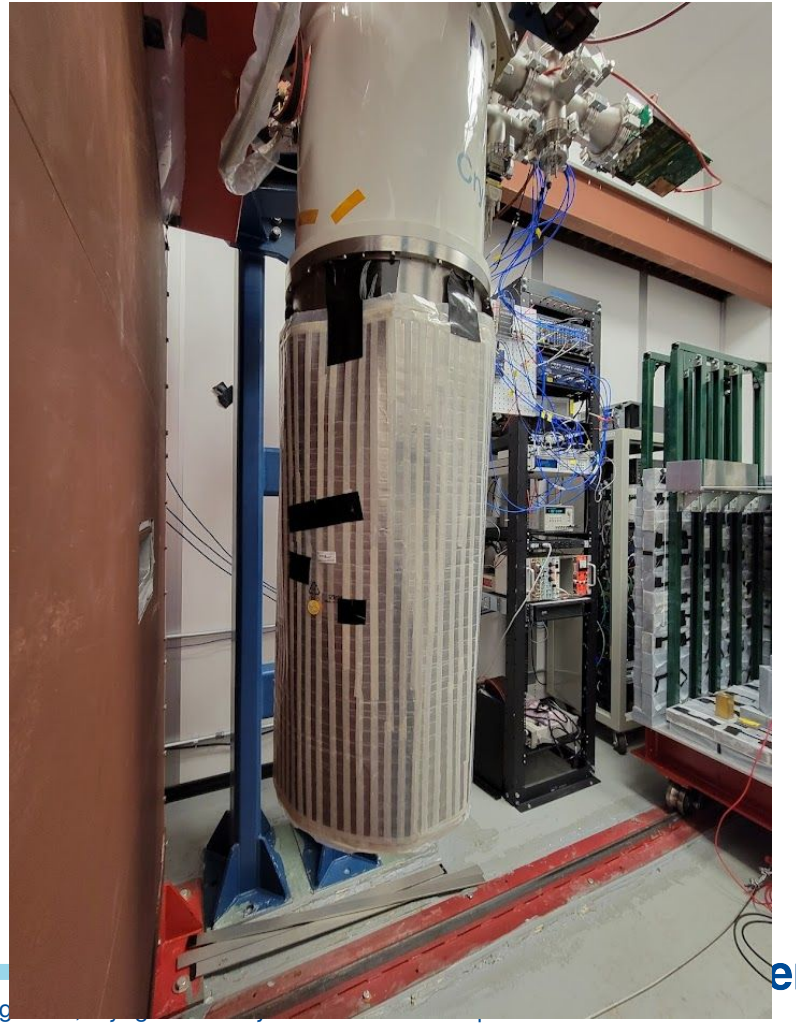
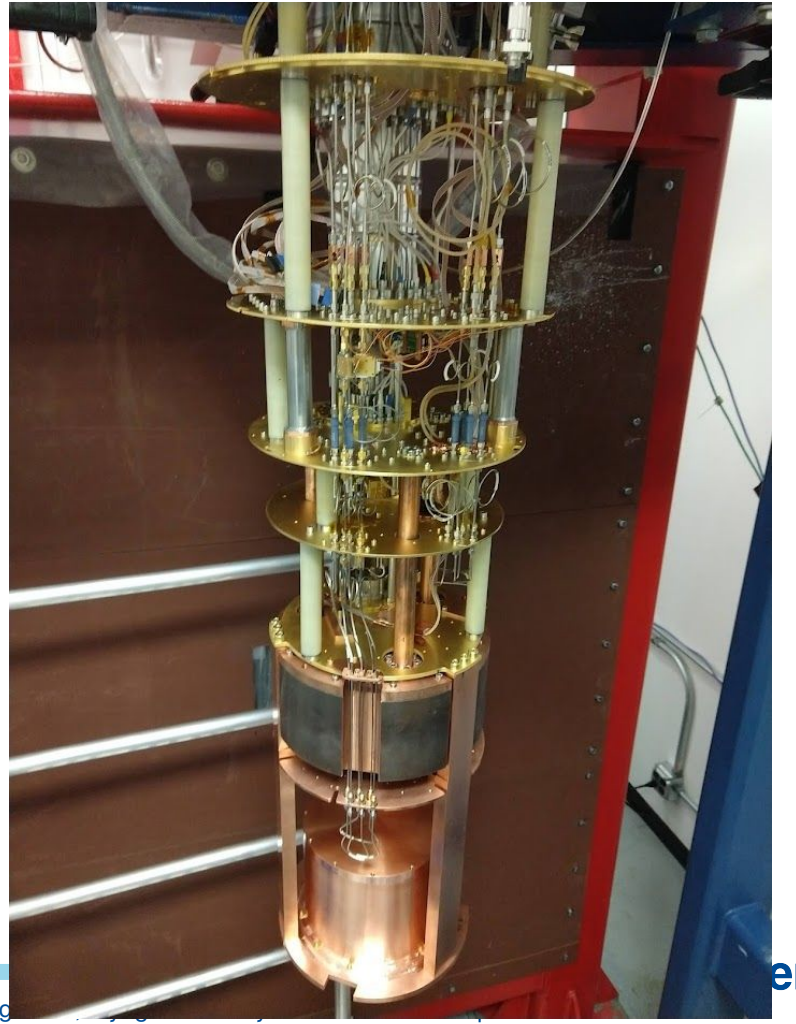
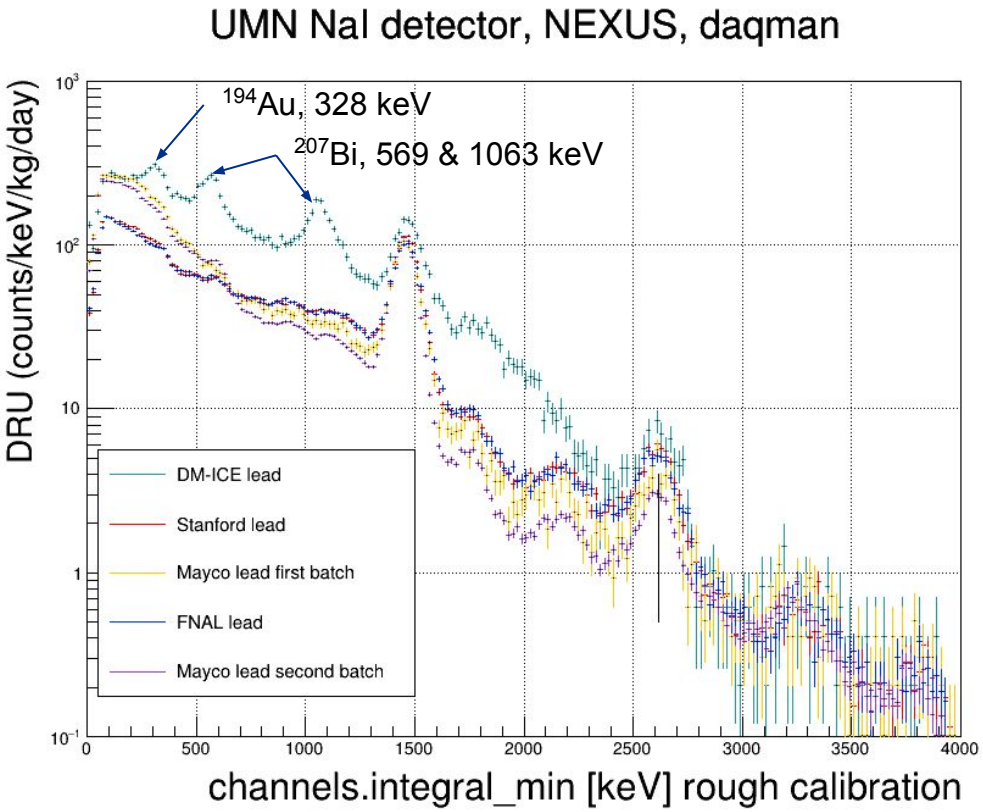






New Lead Shield! Now with less radioactivity

- Screening campaign of the lead bricks with a NaI detector from UMN
- Identified a lead batch with higher event rate likely due to activation in a beam
- New lead was purchased through NU to replace the lead & shipped from SNOLAB

Similar activation profile seen at Brookhaven: https://www.osti.gov/pages/biblio/1425109