Low-background quantum sensing at Fermilab's underground facility

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Cross Frontier Sessions: Quantum Science & Technology (QST) Instrumentation (IF) & Underground Facilities (UF)

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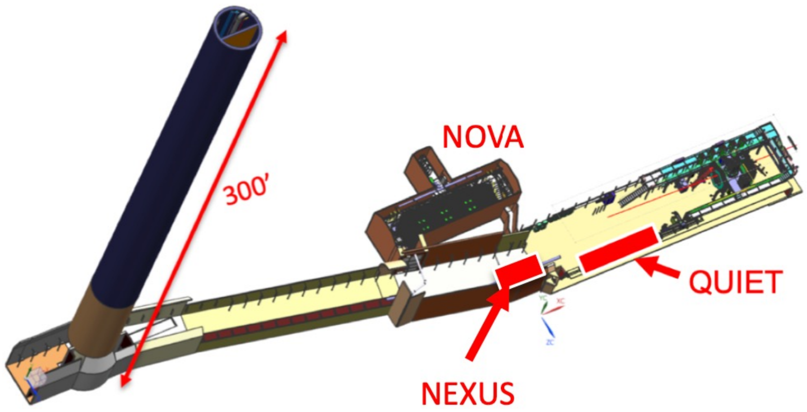
Low-threshold quantum sensing R&D benefits from a purpose-built, low-background facility.

Talk outline:

1. Fermilab facility overview
2. Ongoing and planned R&D
3. “Community needs” assessment

This talk focuses on FNAL capabilities and community needs. Follow links for more info on individual R&D efforts.

MINOS underground experimental area currently hosts several active R&D efforts, and more are planned.



- 107-meter rock overburden (300 mwe)
- Groups hosted underground include:
  - NEXUS
  - SENSEI
  - MAGIS-100 (see Snowmass poster)
  - NQI Quantum Science Center (ORNL)

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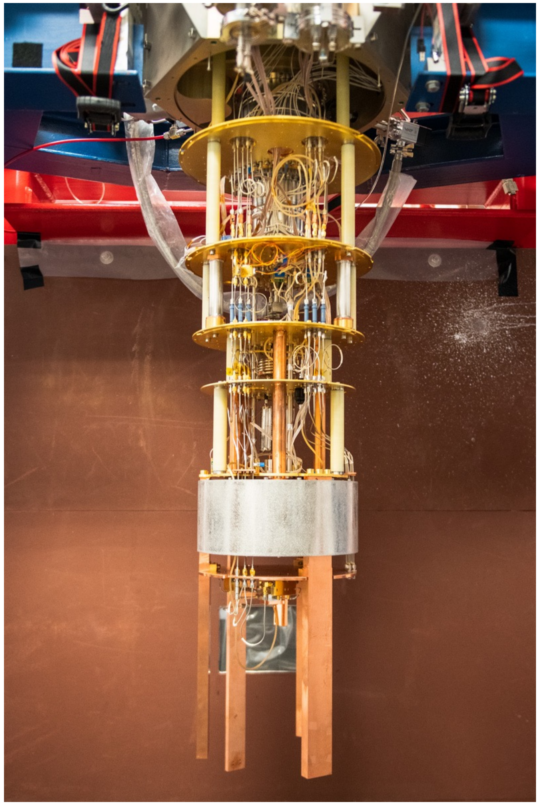
NEXUS: low-background He dilution fridge

- Developed by FNAL detector R&D, SuperCDMS, and Northwestern University
- 10 mK base temp. (CryoConcept HEXADRY)
- Internal lead shield protects RF and DC payload stages; External mu-metal shield
- 3.4 muons/cm2/day; O(100) DRU background rate w/ shield in place
- Planned DD generator gives 2.45 MeV n's for recoil studies
- See below for experimental program summary

QUIET and LOUD: QSC facilities under development

- Quantum Science Center (ORNL-led NQI Center) building two companion facilities at Fermilab:
  - LOUD: high-throughput dilution refrigerator above-ground at Fermilab, for device characterization.
  - QUIET: same model fridge, but shielded and in an underground cleanroom, near NEXUS. Target here is 100 DRU for low-background studies of quantum sensors and other devices.

LOUD fridge received; commissioning begins soon.

Development of a pulsed, scanning laser for low energy calibration of cryogenic devices

Many science applications: understand phonon transfer in materials, quasiparticle poisoning, position-sensitivity of QIS devices to energy deposits, …

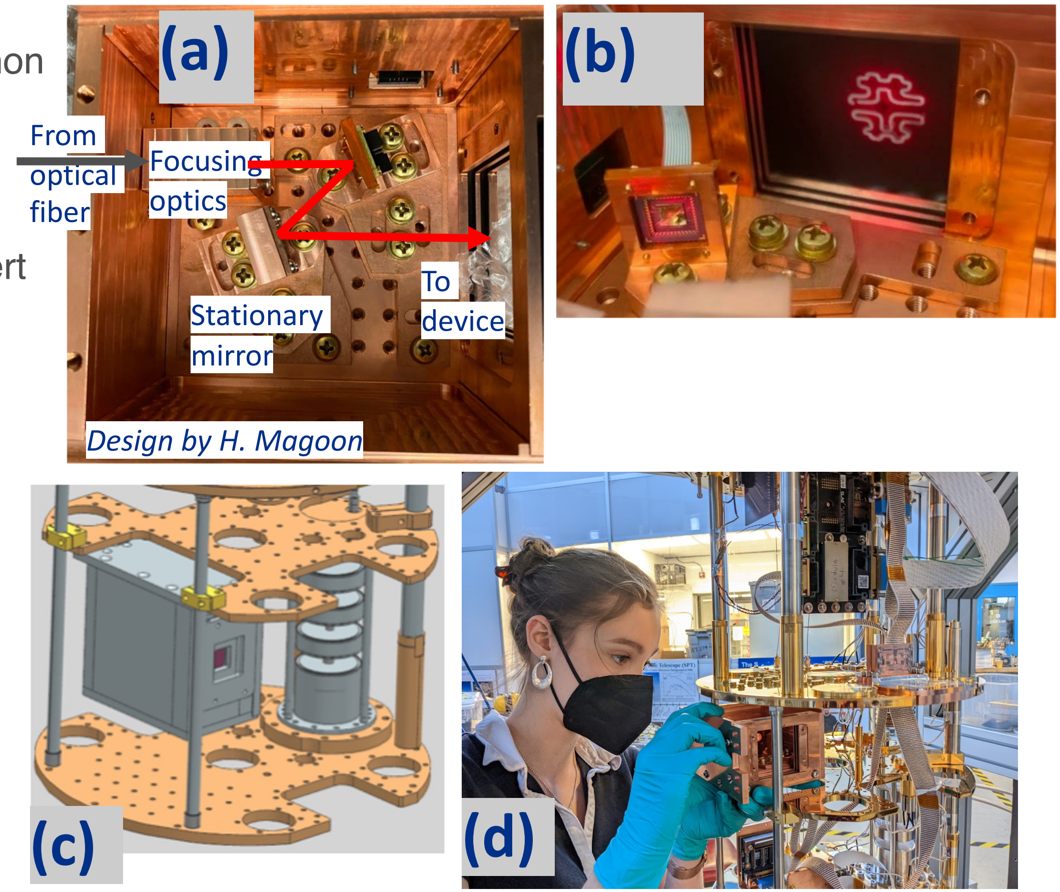
Device-agnostic design: qubits, MKIDs, (insert your favorite cryogenic device here)

Anticipated specs:

- ~1.5” x 1.5” scanning area
- <100µm spot size
- ~10µm position resolution
- O(100)Hz scanning speed
- O(µs) pulse width
- >10mK operating temperature

Nearing first 100mK demonstration (right)

Details: [Snowmass Poster by K. Stifter]



(a) prototype laser scanning device
(b) Scannable area of ~1.5” x 1.5”
(c) Full CAD model of the laser scanning device
(d) Prototype device being fit in dilution refrigerator

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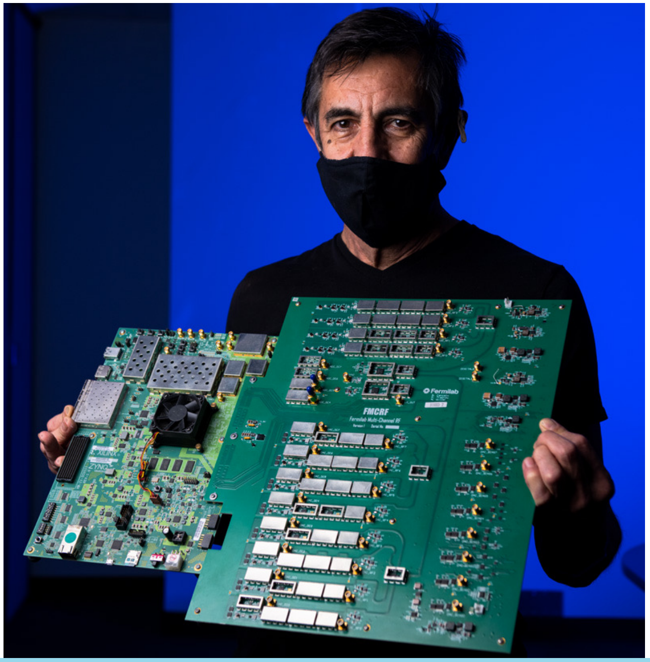
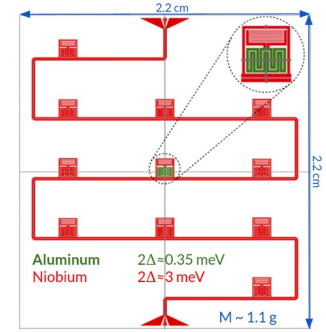
RFSoC for quantum device readout and control

- Xilinx RFSoC-based Quantum Instrument Control Kit (QICK)
- https://arxiv.org/pdf/2110.00557.pdf
- Eight ADC/DAC channels for direct pulse synthesis at GHz frequencies
- Open source software, firmware. Demo code is on GitHub.

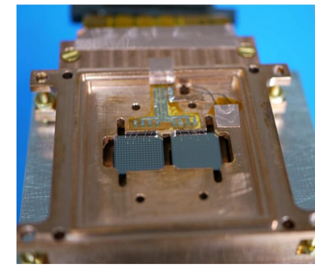


Device R&D programs include:

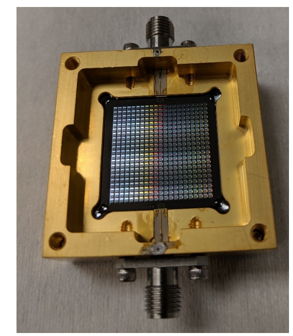
- **Kinetic Inductance Detectors**
  - Lower thresholds [100 eV → ~5(0.5) eV]
  - Increase resolution [σ_E = 40 eV rms → ~1-7(0.1) eV]
  - Absolute energy calibration capability. https://link.springer.com/article/10.1007/s10909-022-02753-5



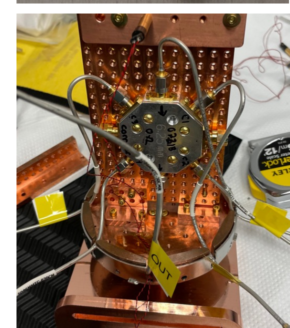
- **Transition Edge Sensors**
  - SuperCDMS HVeV detector R&D: TES coupled to gram-scale Si absorber
  - Single e-h pair sensitivity with 3 eV energy resolution



- **Quantum Capacitance Detector**
  - Photon shot-noise-limited THz detectors based on Cooper Pair Box
  - NEP < 10-20 W/Sqrt Hz at 1.5 THz
  - https://doi.org/10.1117/1.JATIS.7.1.011003 (P. Echternach, JPL/Caltech)



- **Superconducting qubits**
  - Studying the effect of ionizing radiation (cosmics, gammas) on qubit decoherence (C. Wilen et al., Nature 594, pp 369–373 (2021).)
  - Ionizing backgrounds relevant for axion DM searches, but also QC error correction.
  - Four-qubit array from U. Wisconsin-Madison currently taking data.



SENSEI: Counting single electrons with a CCD

PHYSICAL REVIEW LETTERS **121,** 061803 (2018)

SENSEI: First Direct-Detection Constraints on Sub-GeV Dark Matter from a Surface Run

Michael Crisler,[1,*] Rouven Essig,[2,†] Juan Estrada,[1,‡] Guillermo Fernandez,[1,§] Javier Tiffenberg,[1,∥] Miguel Sofo Haro,[1,3,¶] Tomer Volansky,[4,5,**] and Tien-Tien Yu[6,7,††]

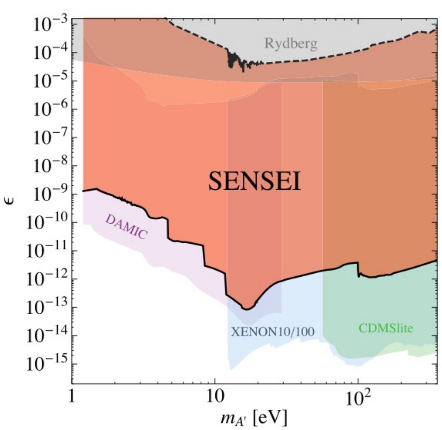
(SENSEI Collaboration)

PHYSICAL REVIEW APPLIED **17,** 014022 (2022)

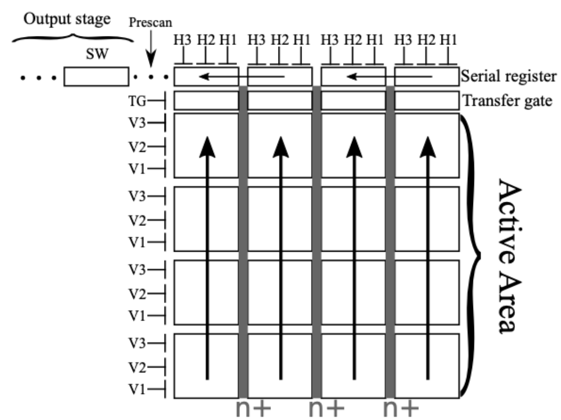
SENSEI: Characterization of Single-Electron Events Using a Skipper Charge-Coupled Device

Liron Barak,[1] Itay M. Bloch,[1] Ana Botti,[2,3] Mariano Cababie,[2,3,*] Gustavo Cancelo,[3] Luke Chaplinsky,[4,5] Fernando Chierchie,[3] Michael Crisler,[3] Alex Drlica-Wagner,[3,6,7] Rouven Essig,[4] Juan Estrada,[3] Erez Etzion,[1] Guillermo Fernandez Moroni,[3] Daniel Gift,[4,5] Stephen E. Holland,[8] Sravan Munagavalasa,[4,5] Aviv Orly,[1] Dario Rodrigues,[2,3] Aman Singal,[5] Miguel Sofo Haro,[3,9] Leandro Stefanazzi,[3] Javier Tiffenberg,[3] Sho Uemura,[1] Tomer Volansky,[1] and Tien-Tien Yu[10]

(SENSEI Collaboration)



Dark photon DM (A’) absorbed by electron with coupling ϵ



Breakthrough in understanding and quantifying e- “dark rates”

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A note on community needs:

- A **standard set of radiation calibrations** would make it much easier for us all to directly compare backgrounds between facilities.
- We will be iterating between design, simulation, and testing a lot in the coming years. **Healthy, multi-disciplinary collaborations** will significantly shorten this cycle and make us all more productive.
- Who makes the qubits we spend months studying? Industrial partners may want the opportunity to provide devices for characterization in our facilities.

Acknowledgements

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  - Northwestern University
  - SLAC