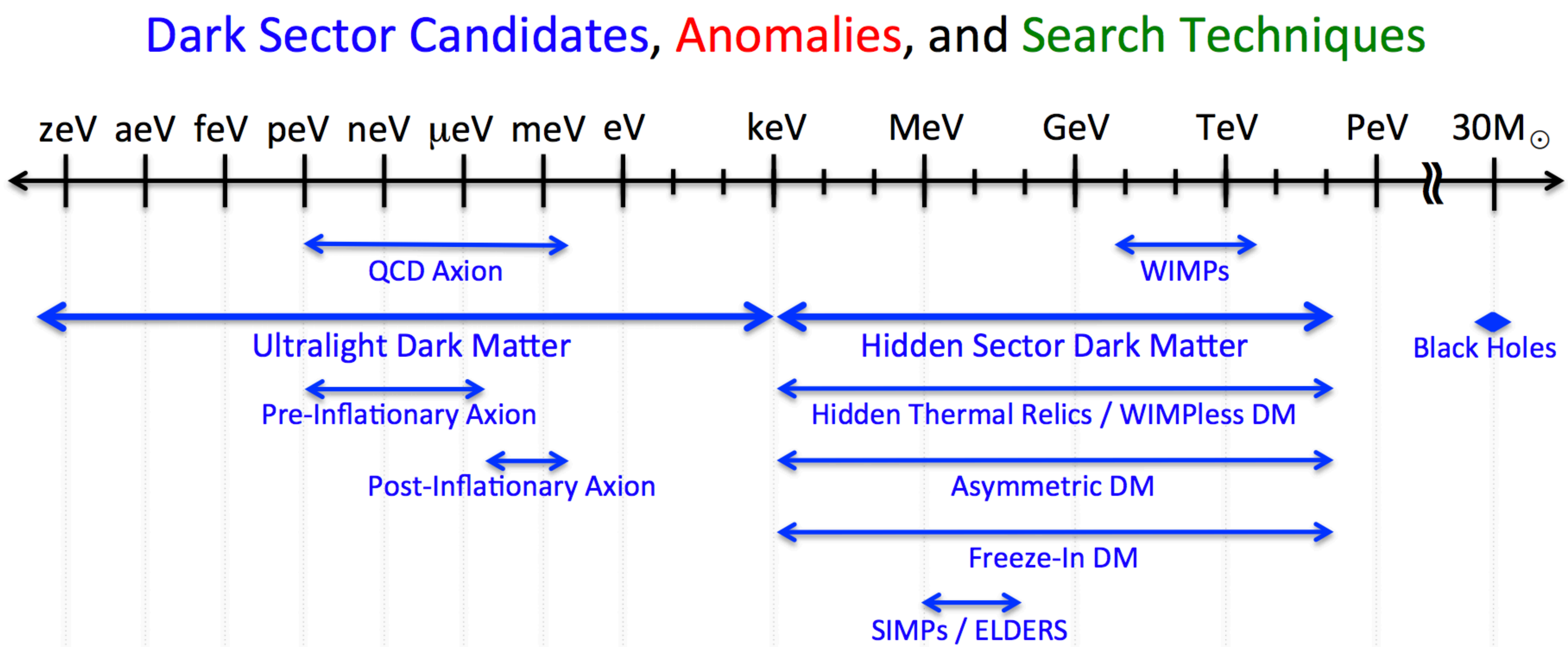
Dark Matter Efforts at Fermilab

Noah Kurinsky

53rd Annual Users' Meeting @ Fermilab (Virtually)

August 11, 2020

Direct Searches for Dark Matter @ FNAL



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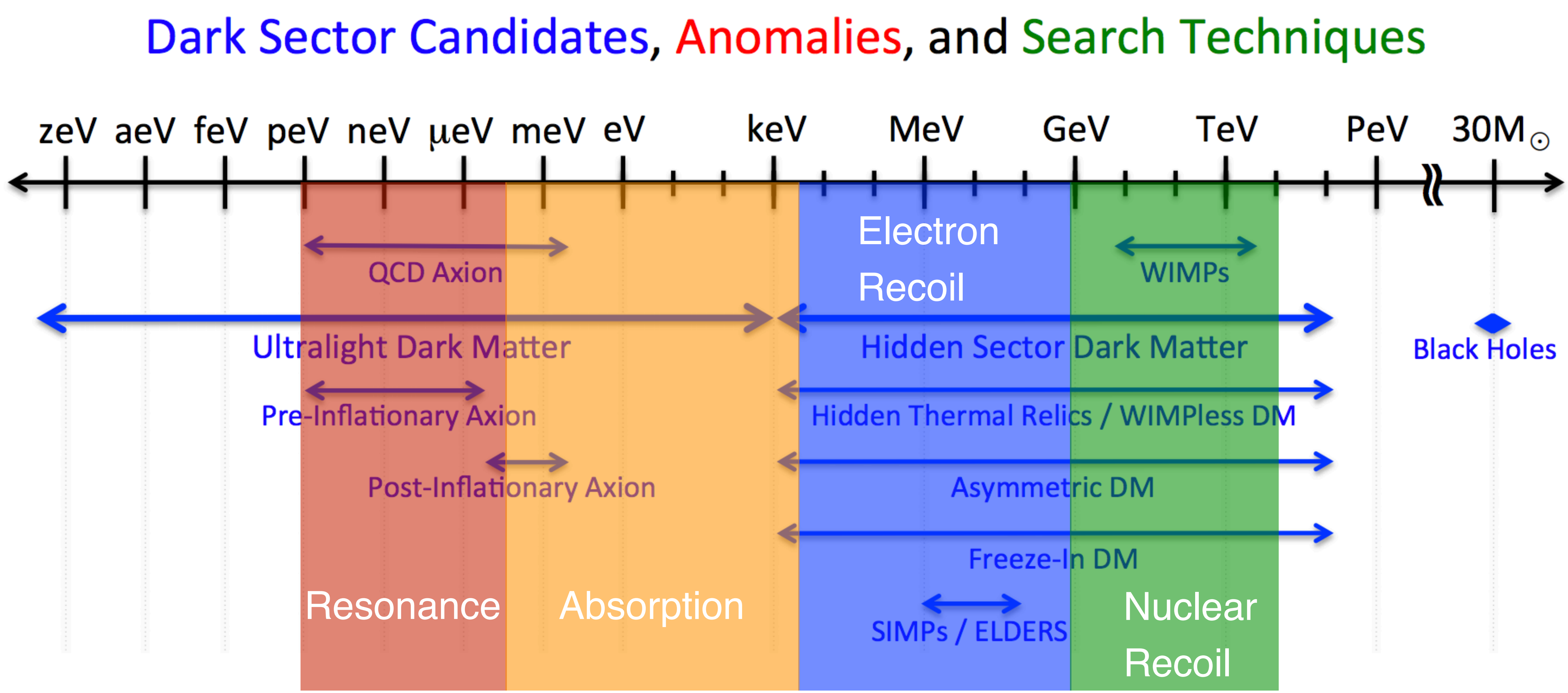
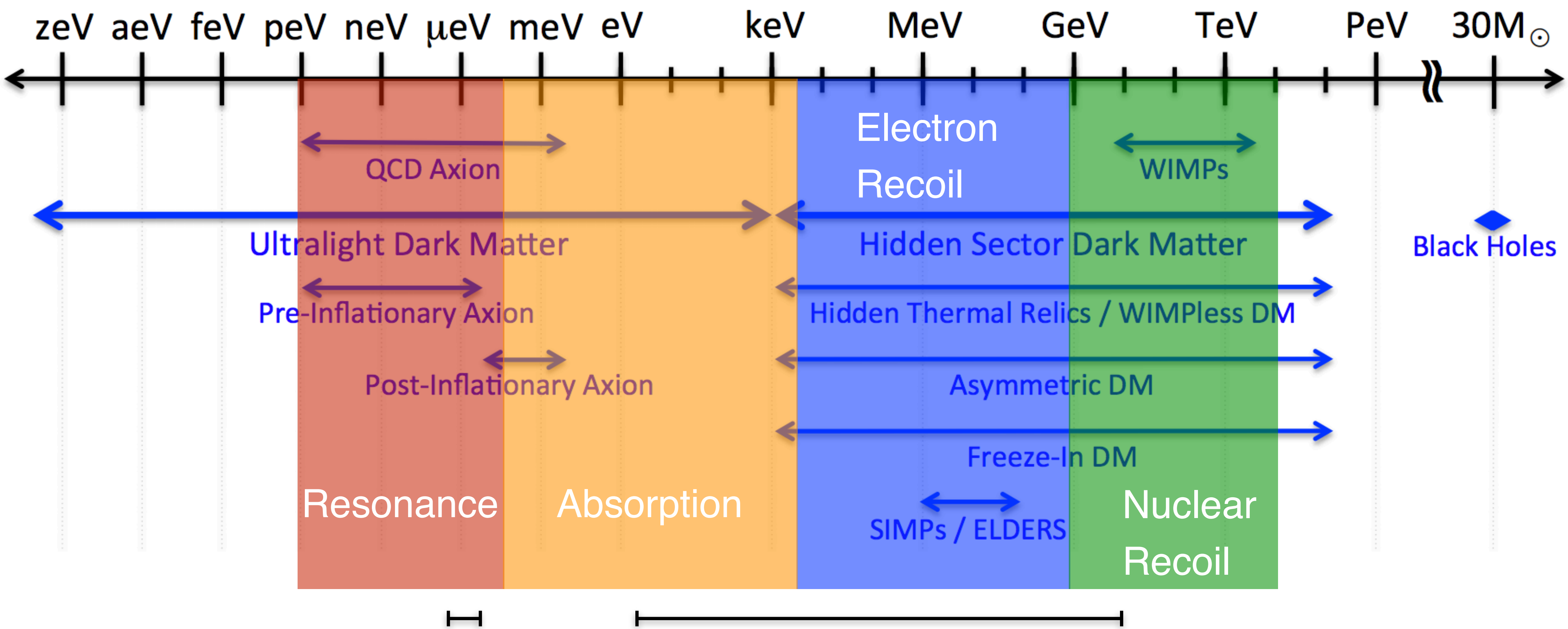


Direct Searches for Dark Matter @ FNAL

Dark Sector Candidates, Anomalies, and Search Techniques



Current Experiments ADMX SuperCDMS, DAMIC, SENSEI

Direct Searches for Dark Matter @ FNAL

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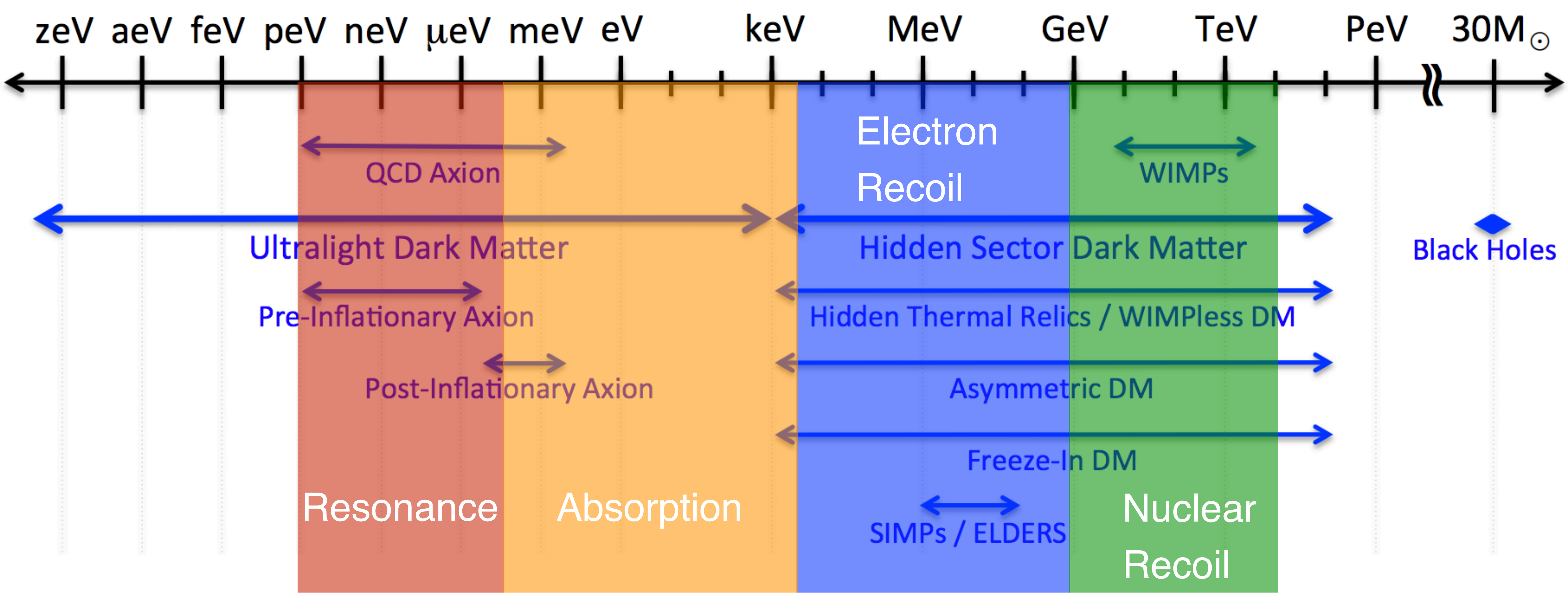
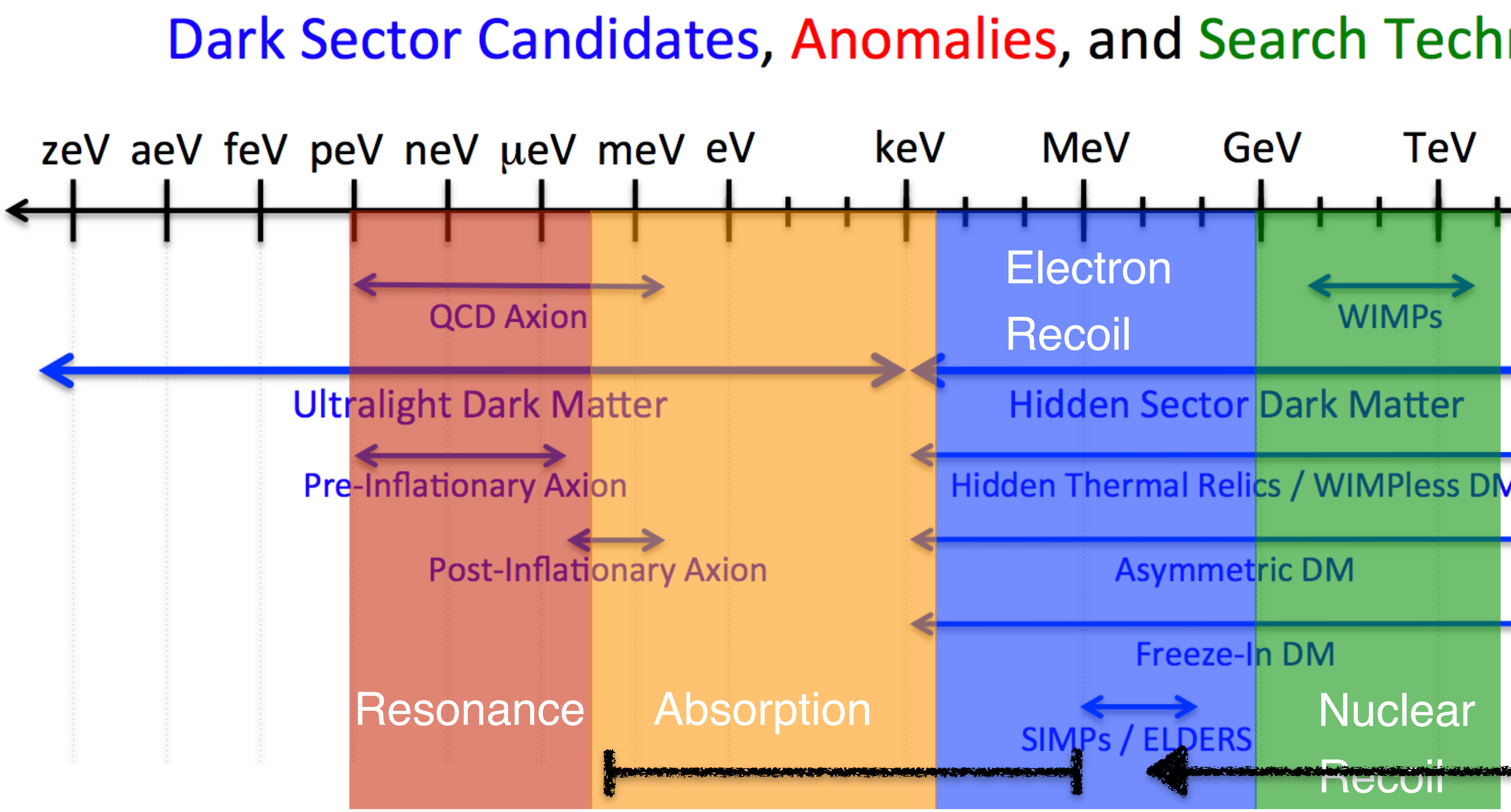


Current Experiments ADMX SuperCDMS, DAMIC, SENSEI

Future Experiments (DM New Horizons) ADMX Upgrade OSCURA

Direct Searches for Dark Matter @ FNAL



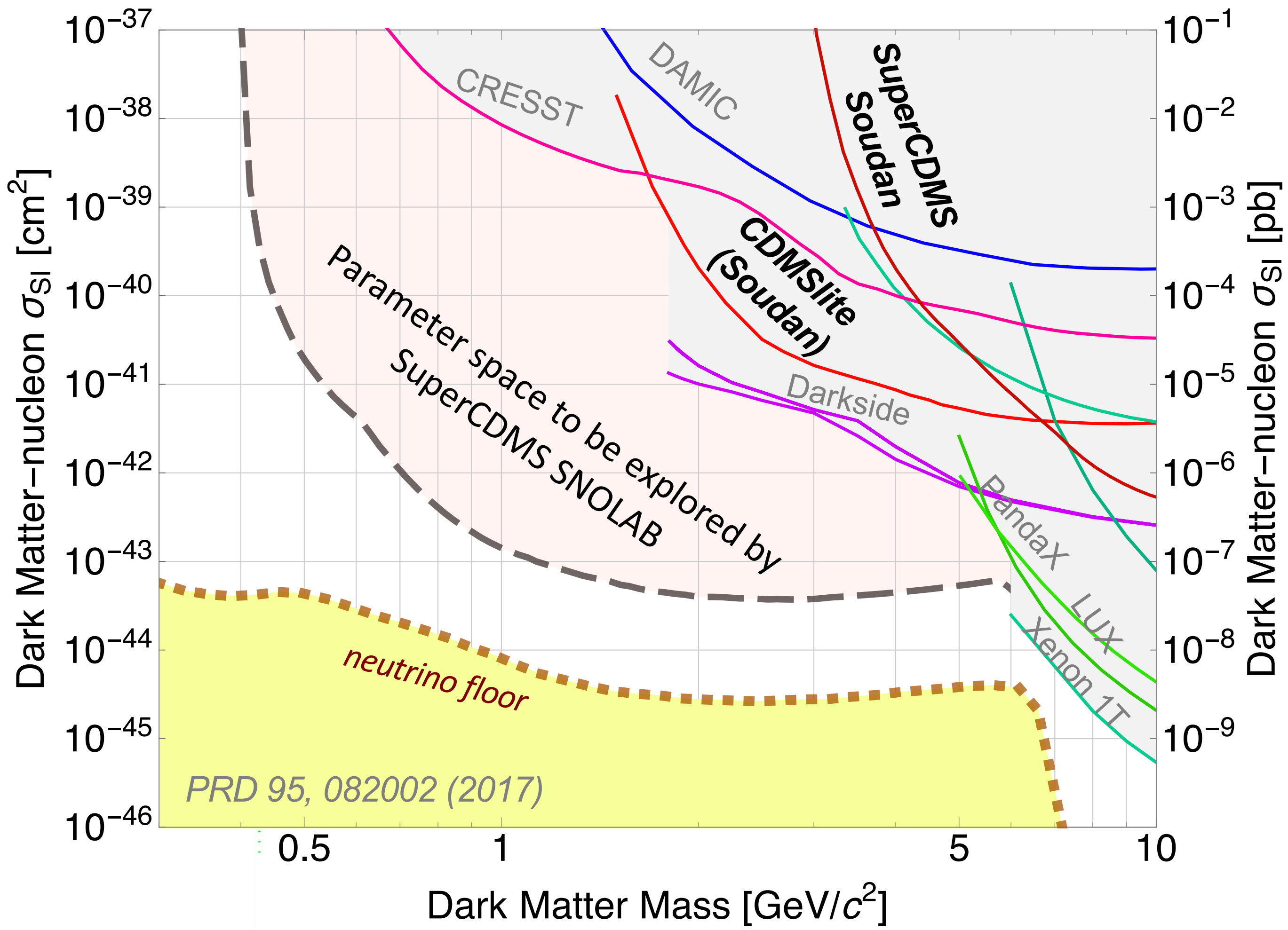
Quantum Sensing R&D

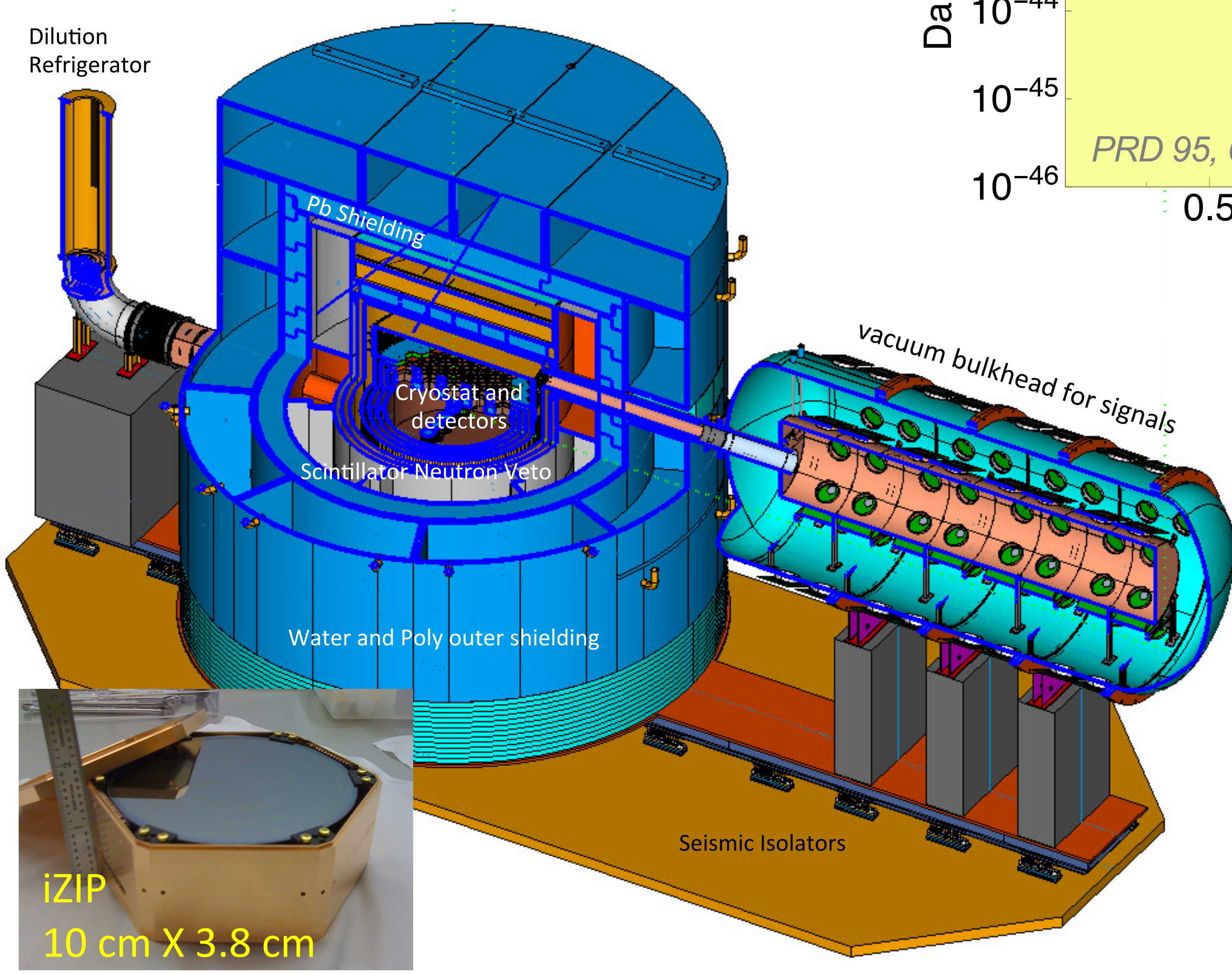
Current Experiments — ADMX — SuperCDMS, DAMIC, SENSEI

Future Experiments (DM New Horizons) — ADMX Upgrade — OSCURA

SuperCDMS SNOLAB

Will provide superb sensitivity to low mass WIMPs with Ge and Si operated in both HV and iZIP modes





Timeline:

- Construction and testing at Fermilab in 2019
- Install and Commission at SNOLAB in 2020
- First physics run in 2021!

1

Science Leading to SuperCDMS SNOLAB

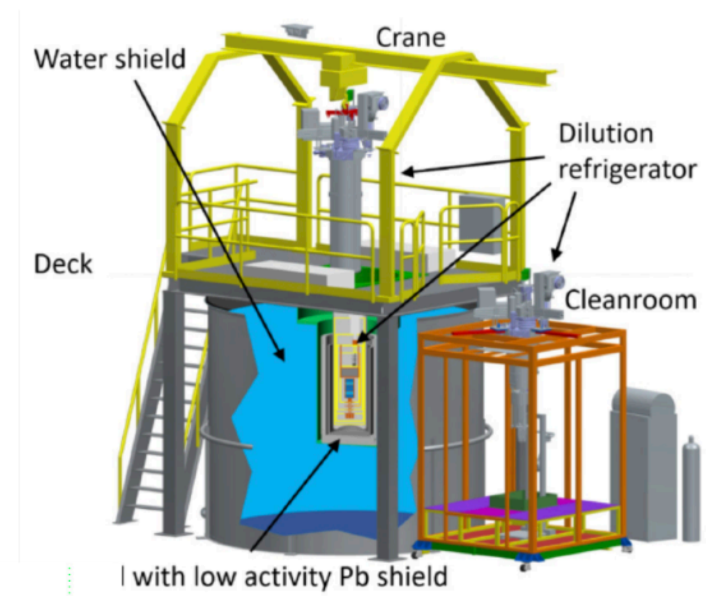
Electron Recoil (Charge Readout)

Nuclear Recoil (Heat Readout)

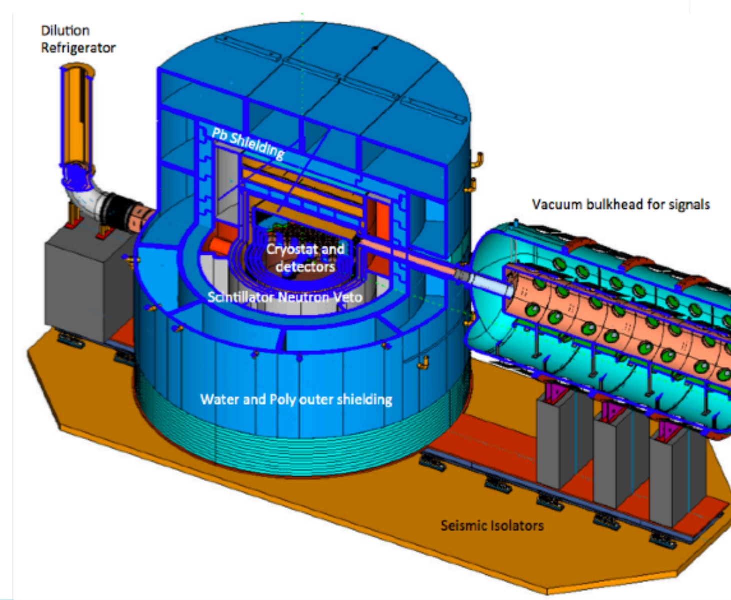
Lower Backgrounds, Larger Exposure

Surface R&D (Lower Threshold, Improve Reconstruction)
(Stanford, Northwestern, Berkeley, Texas A&M)

NEXUS @ FNAL



CUTE @ SNOLAB



SuperCDMS SNOBOX @ SNOLAB

Science Leading to SuperCDMS SNOLAB

First Results Published

Electron Recoil (Charge Readout)

Nuclear Recoil (Heat Readout)

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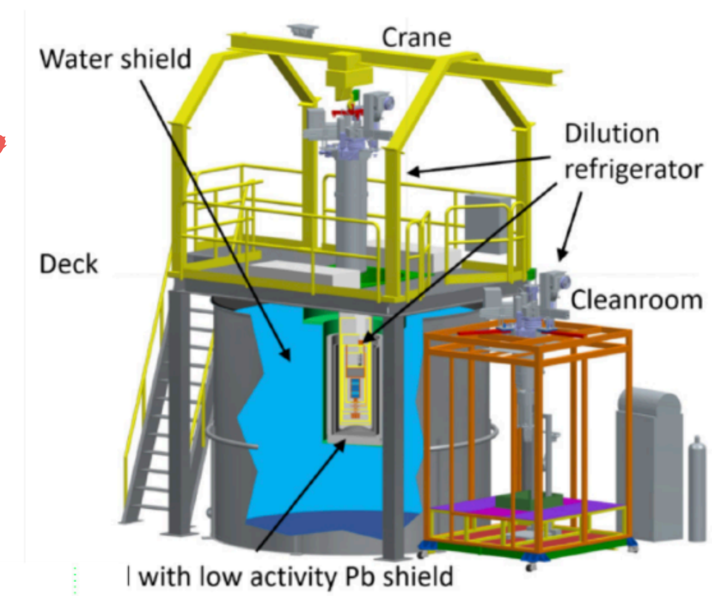
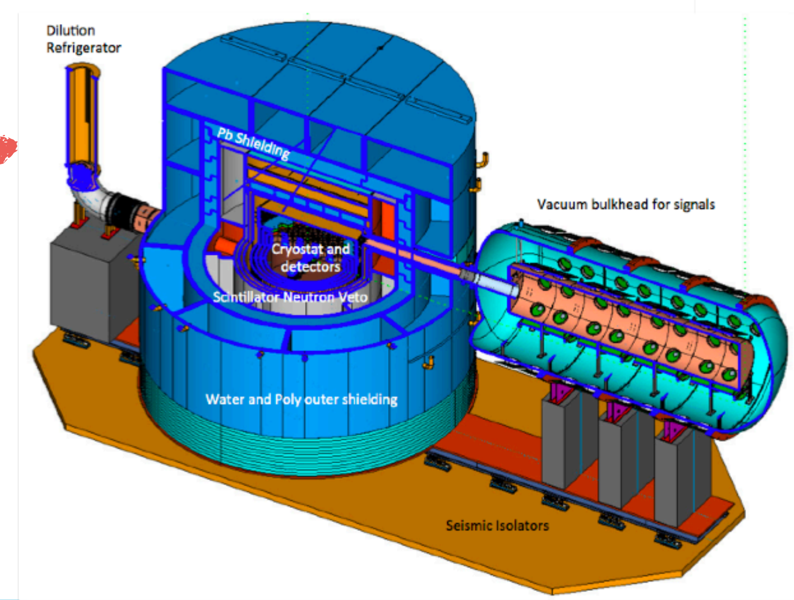
NEXUS @ FNAL

Currently Running



CUTE @ SNOLAB

Installation In Progress



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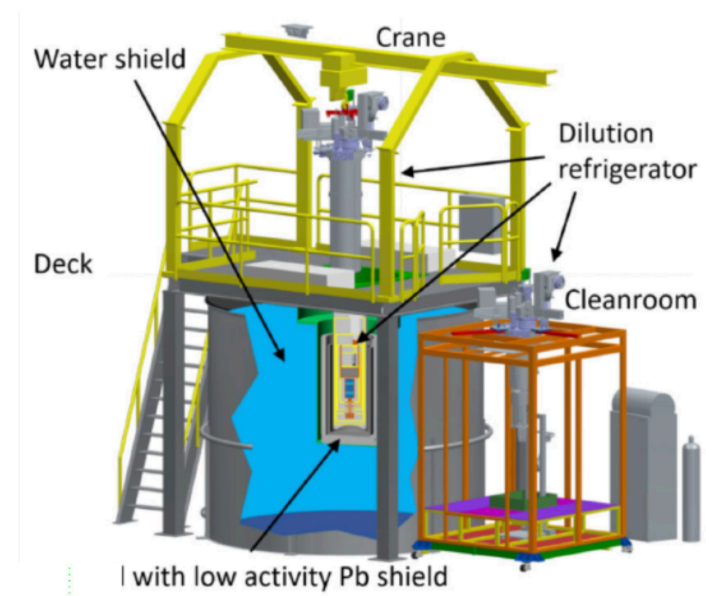

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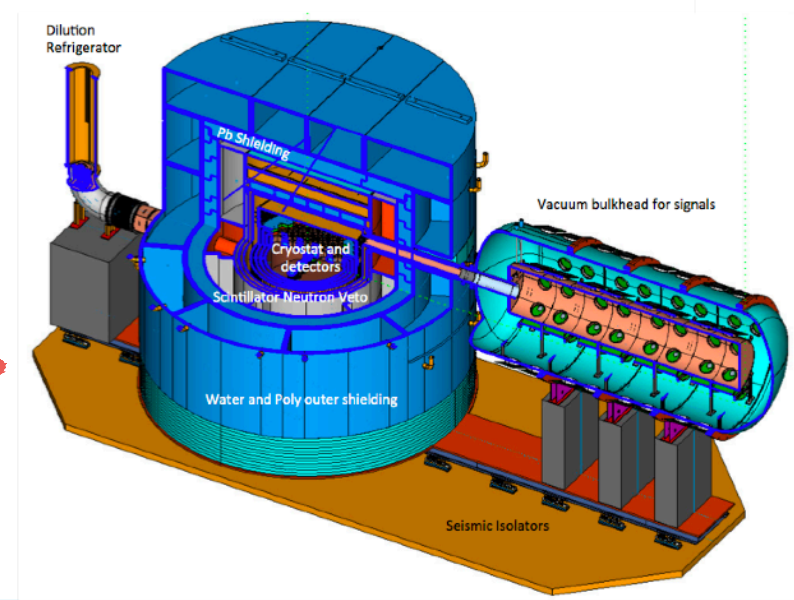

SuperCDMS SNOBOX @ SNOLAB

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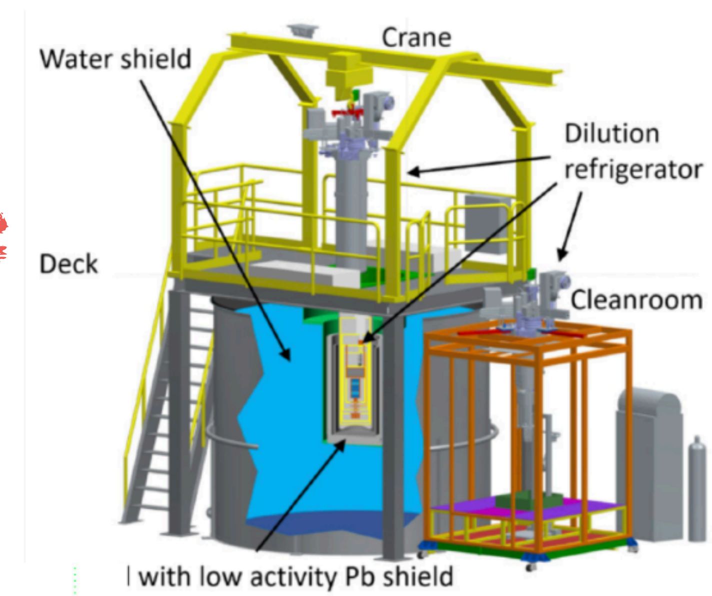

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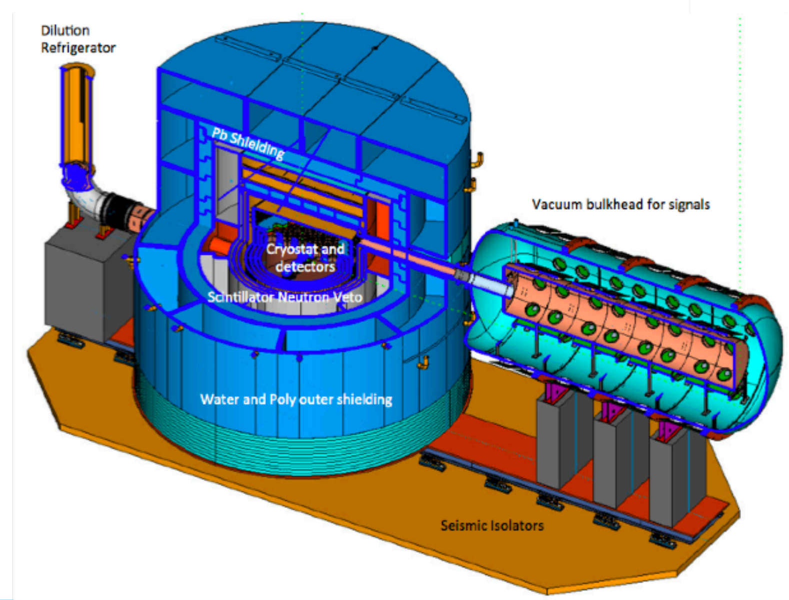
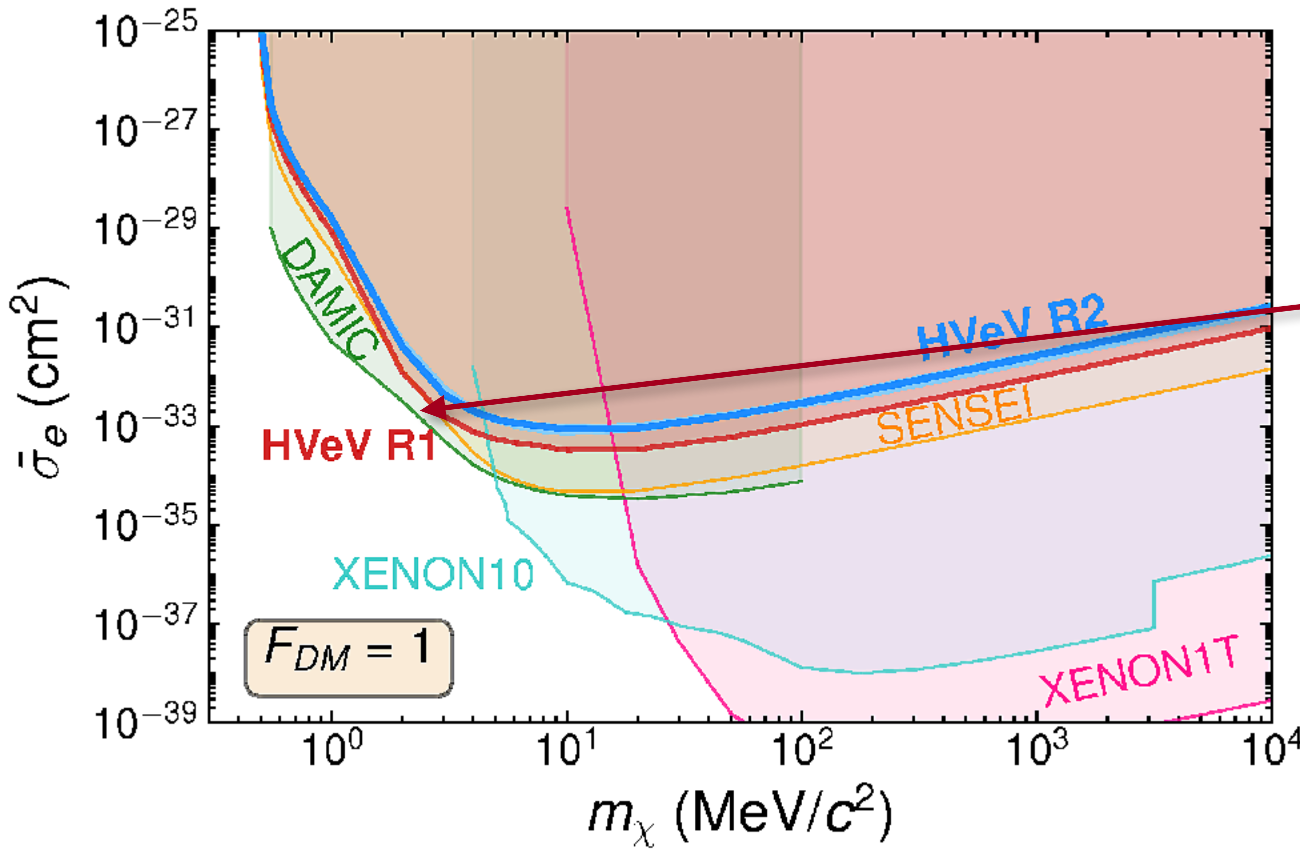


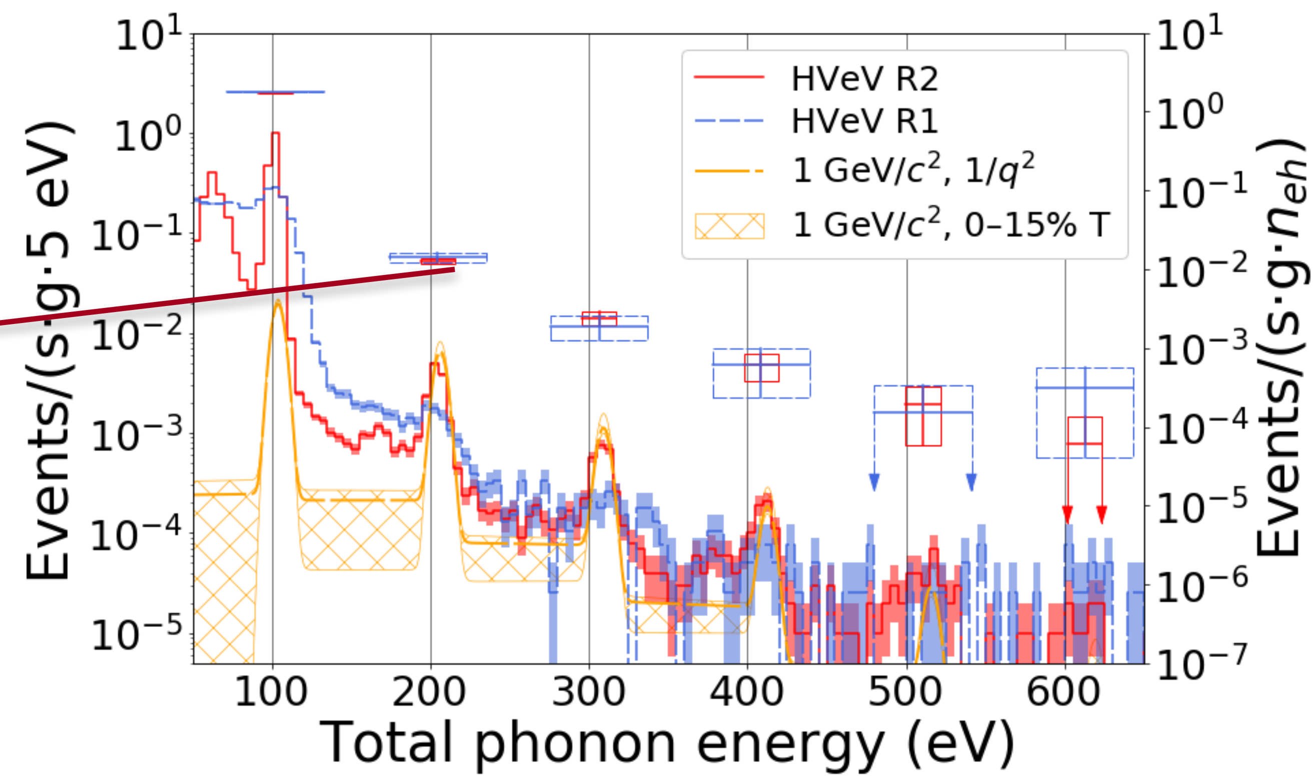
SuperCDMS SNOBOX
@ SNOLAB

Fermilab

HVeV Run 2

SuperCDMS Collaboration 2020 (arXiv:2005.14067)
Supplemental Plots

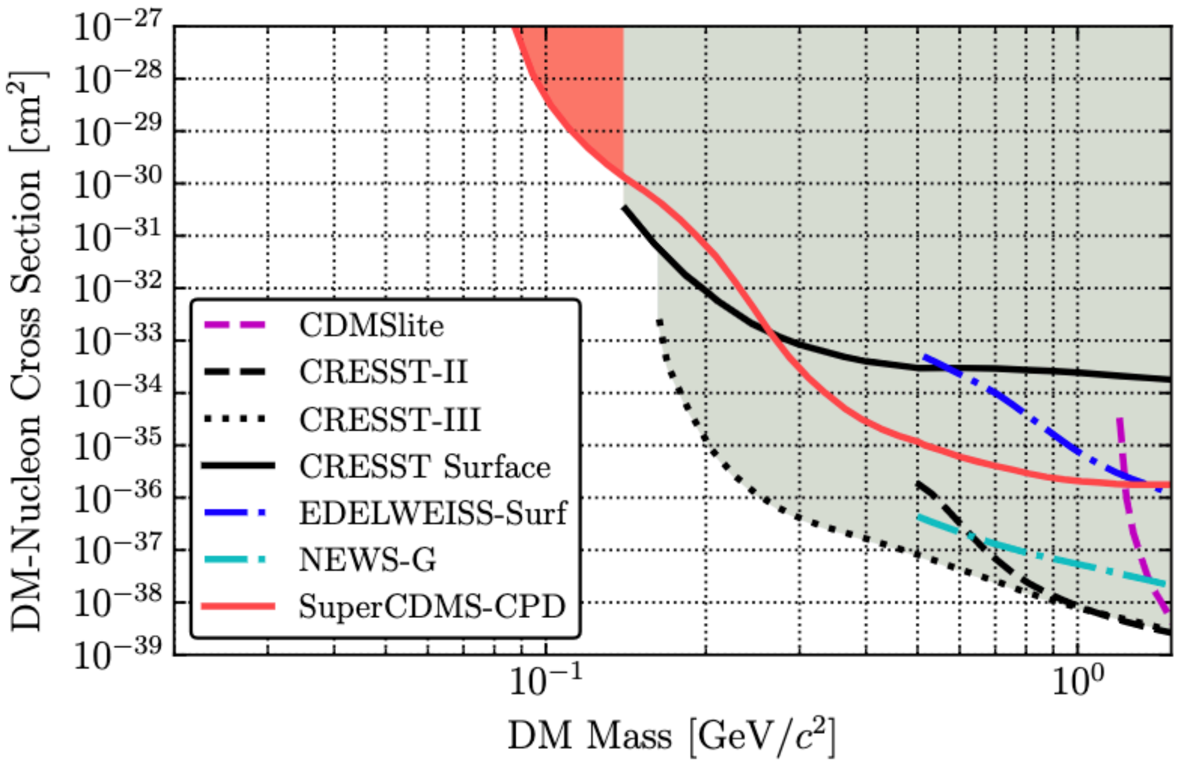


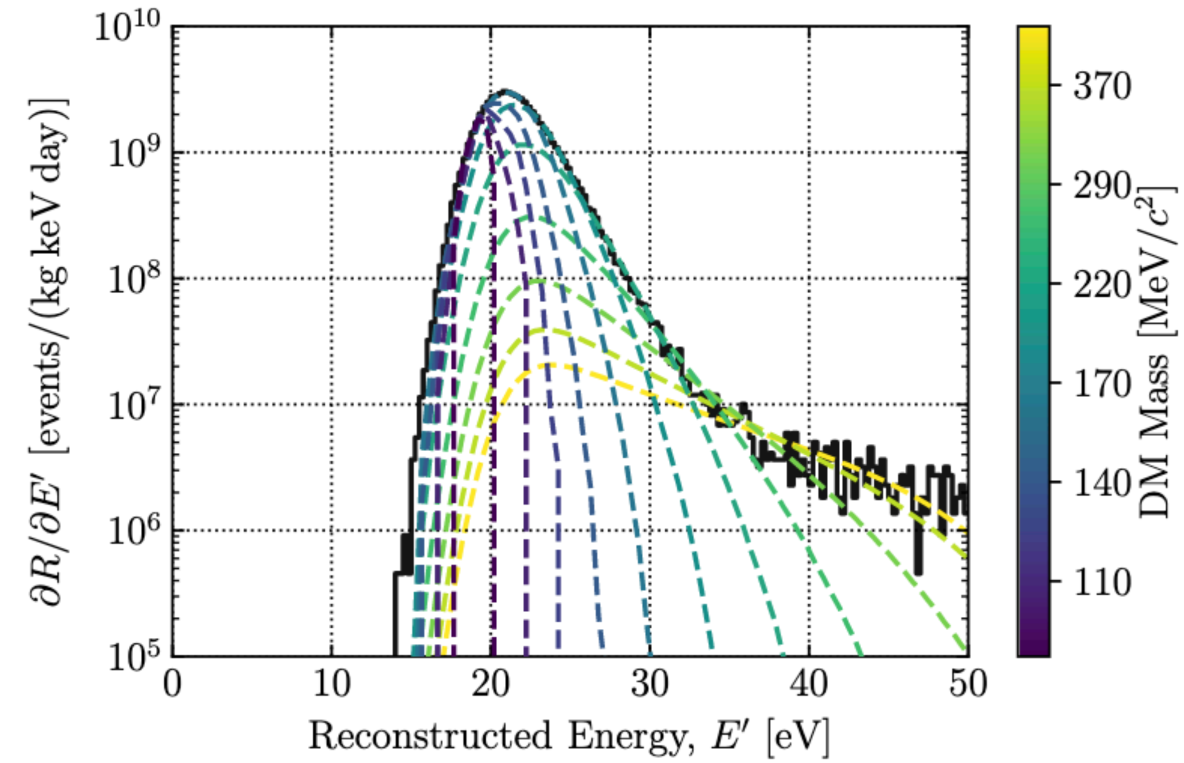


- HVeV second run taken with 3 eV resolution detector over the course of 3 weeks:
  - 60V and 100V spectra show identical backgrounds; signal seen not voltage dependent
  - Different prototype, run in a different lab, in a different state
  - 0V data acquired with ~12 eV threshold, results still being analyzed
  - Rates in *every charge bin* consistent with Run 1…that is completely unexpected

CPD Dark Matter Search Results

arXiv:2007.14289



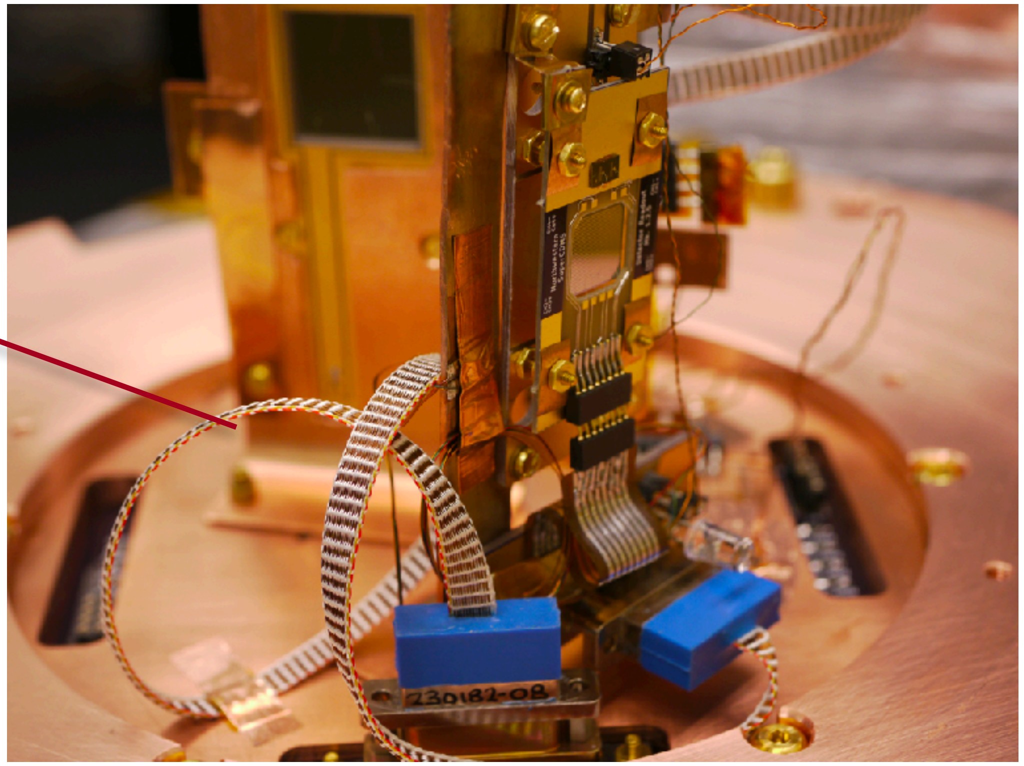


- Detector threshold (online FPGA-based trigger) of 20 eV
- World-leading limits below ~150 MeV
  - First NR result with <100 MeV sensitivity
- Surface run largely limited by high-radioactivity environment
  - More studies now underway at SNOLAB in the CUTE facility!

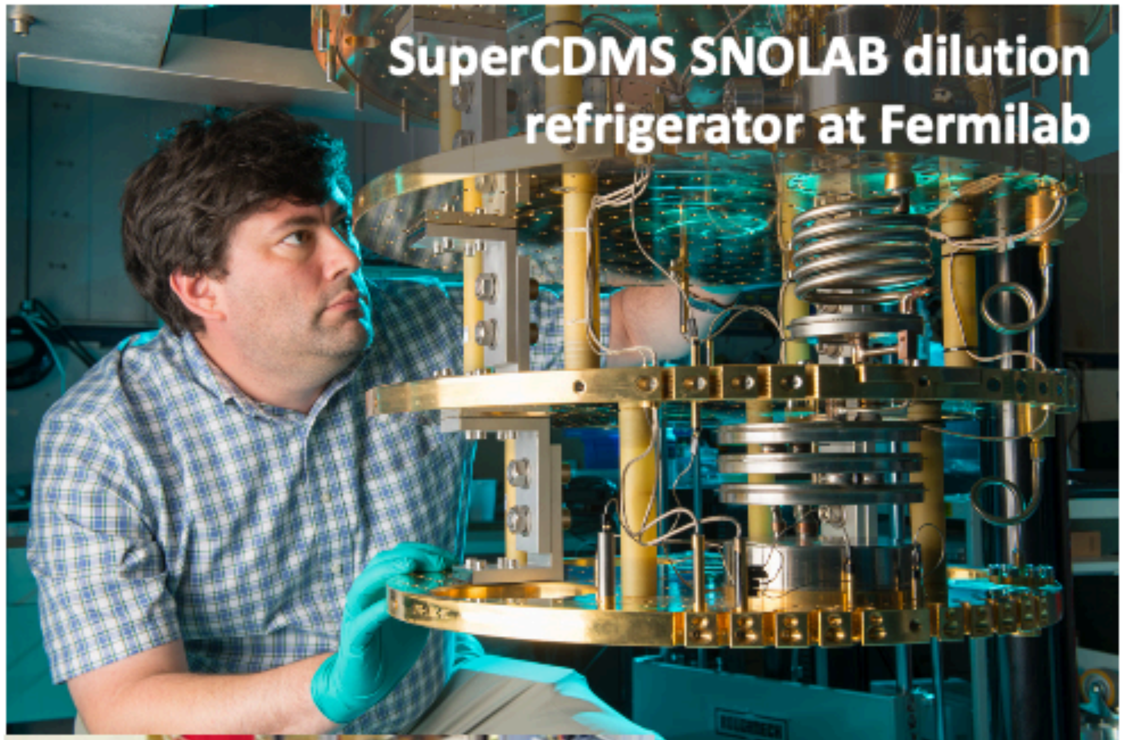
Fermilab

NEXUS: Underground Experimental Site for R&D

- Northwestern EXperimental Underground Site at Fermilab (**NEXUS@FNAL**)
  - Underground cryogenic detector testing facility in class 10,000 clean room
  - 106 m (300 mwe) depth + lead shielding (in progress)
  - expected <100 events/keV/kg/day background
- Run 2 detector already seeing identical performance from surface run



SuperCDMS at FNAL



SuperCDMS SNOLAB dilution refrigerator at Fermilab

SuperCDMS SNOLAB calibration system

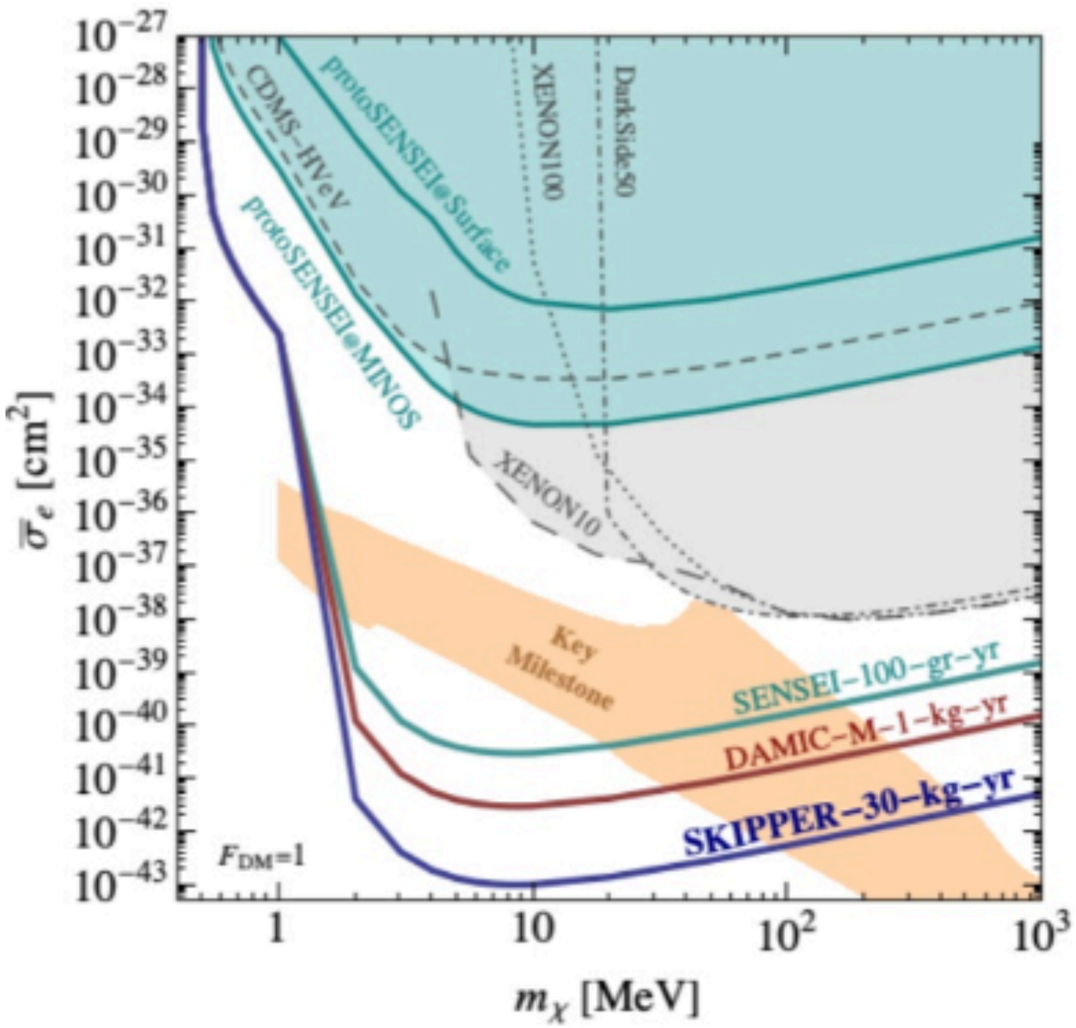
NEXUS experiment under construction at MINOS

- SuperCDMS SNOLAB will search for 0.5-10 GeV mass dark matter
  - Construction project will conclude with installation in 2020 and begin operations
  - Expect first science late in 2021 or early in 2022
- NEXUS HVeV detectors will search for 1 MeV to 1 GeV mass dark matter
  - Engineering runs underway now and first science run early in 2020

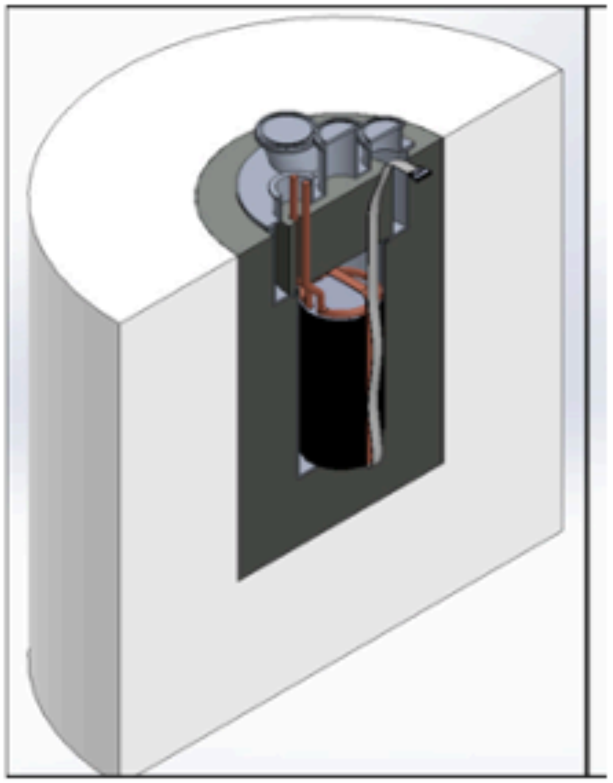
DM w/ Skipper CCDs

Oscura 4 year R&D effort "DOE Dark matter New Initiatives" . FNAL, LBNL, PNNL, U.Chicago, U.Washington, Stony Brook University.

Fermilab is leading the effort to develop the a skipper-CCD dark matter detector with active mass of 10 kg of Silicon.



Taking the skipper-CCDs to their full potential as dark matter detectors.

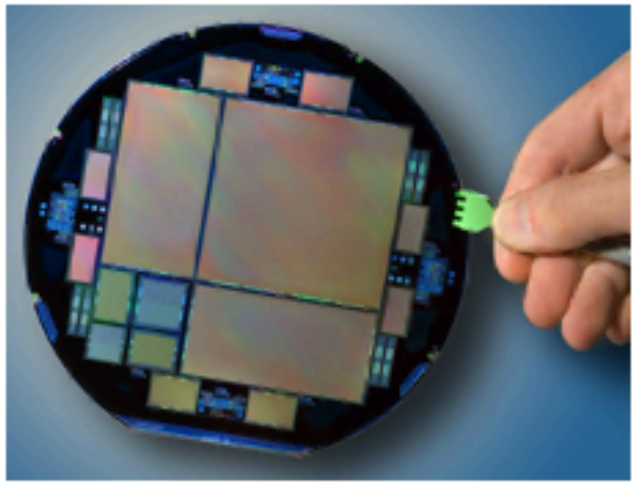


Fabrication of **<u>skipper-CCDs is needs to be adapted to the changes in the semiconductor industry. We have identified new industrial</u>** partners for this, and will be testing them over the next year.

24 Gigapixel digital camera for dark matter!

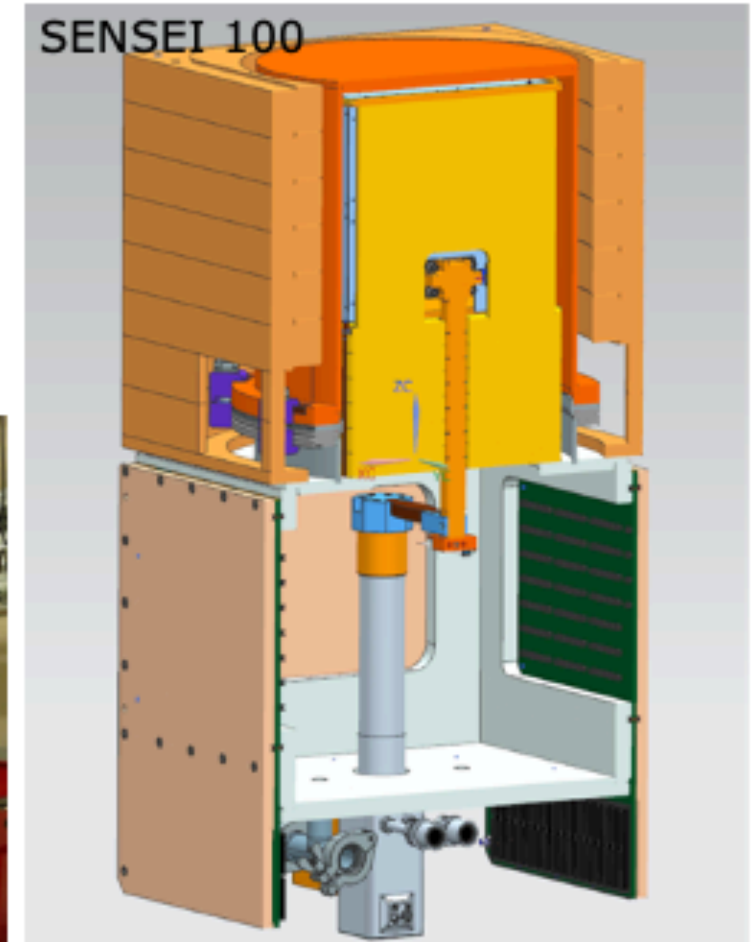
Cooling, readout, packaging and testing of the required **<u>4000 skipper-CCD sensors require engineering solutions that are not available yet for scientific CCDs.</u>**

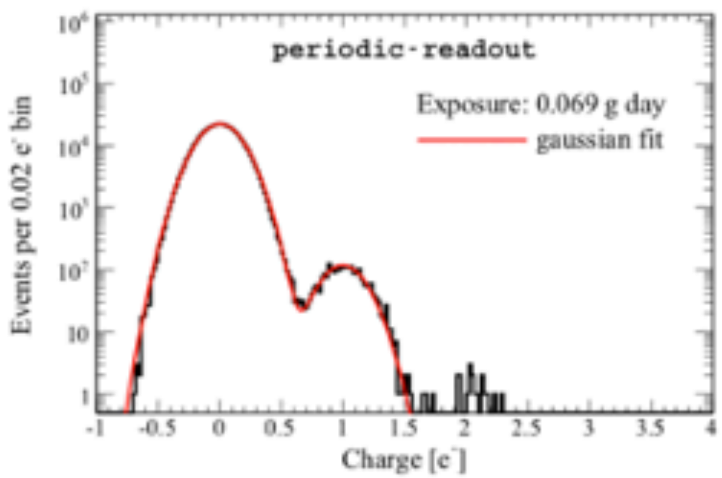
Radiation background required is ~10 lower than state of the art experiments.



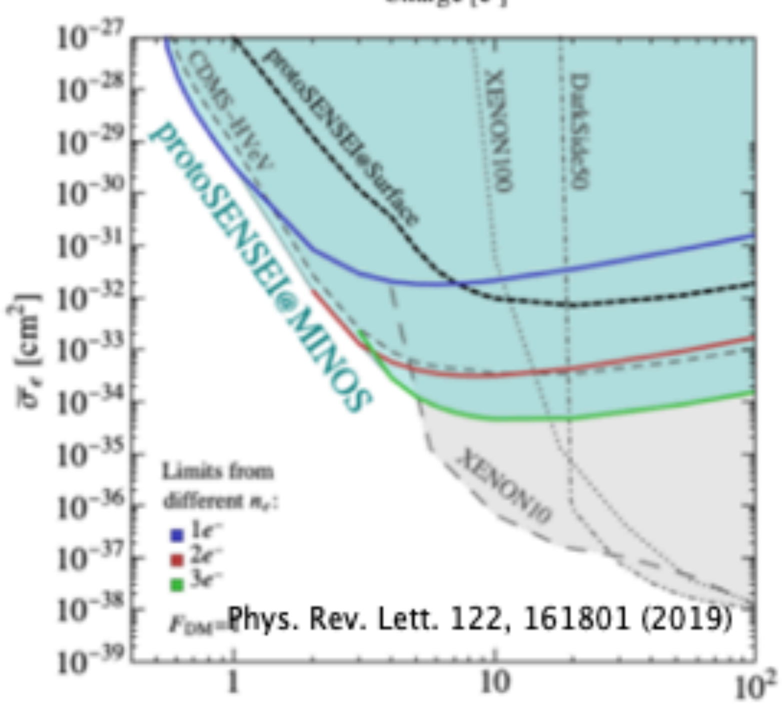
SENSEI

SENSEI prototype is running in MINOS and producing science results. Leading limits on e-recoil dark matter.





Assembly going on NOW at SiDet

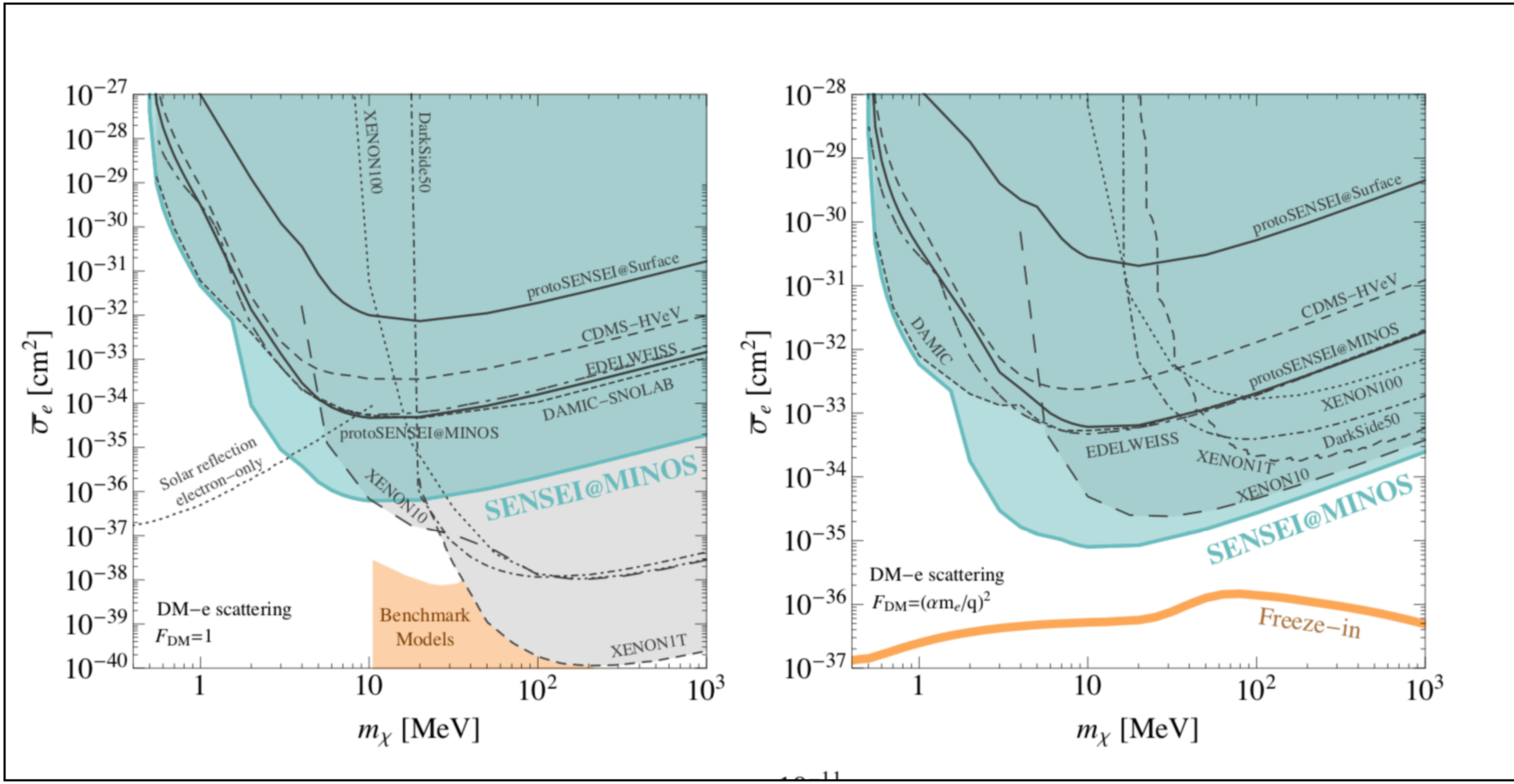


During December we installed the first skipper-CCD at SNOLAB. Results coming soon! (2.5 g active mass)

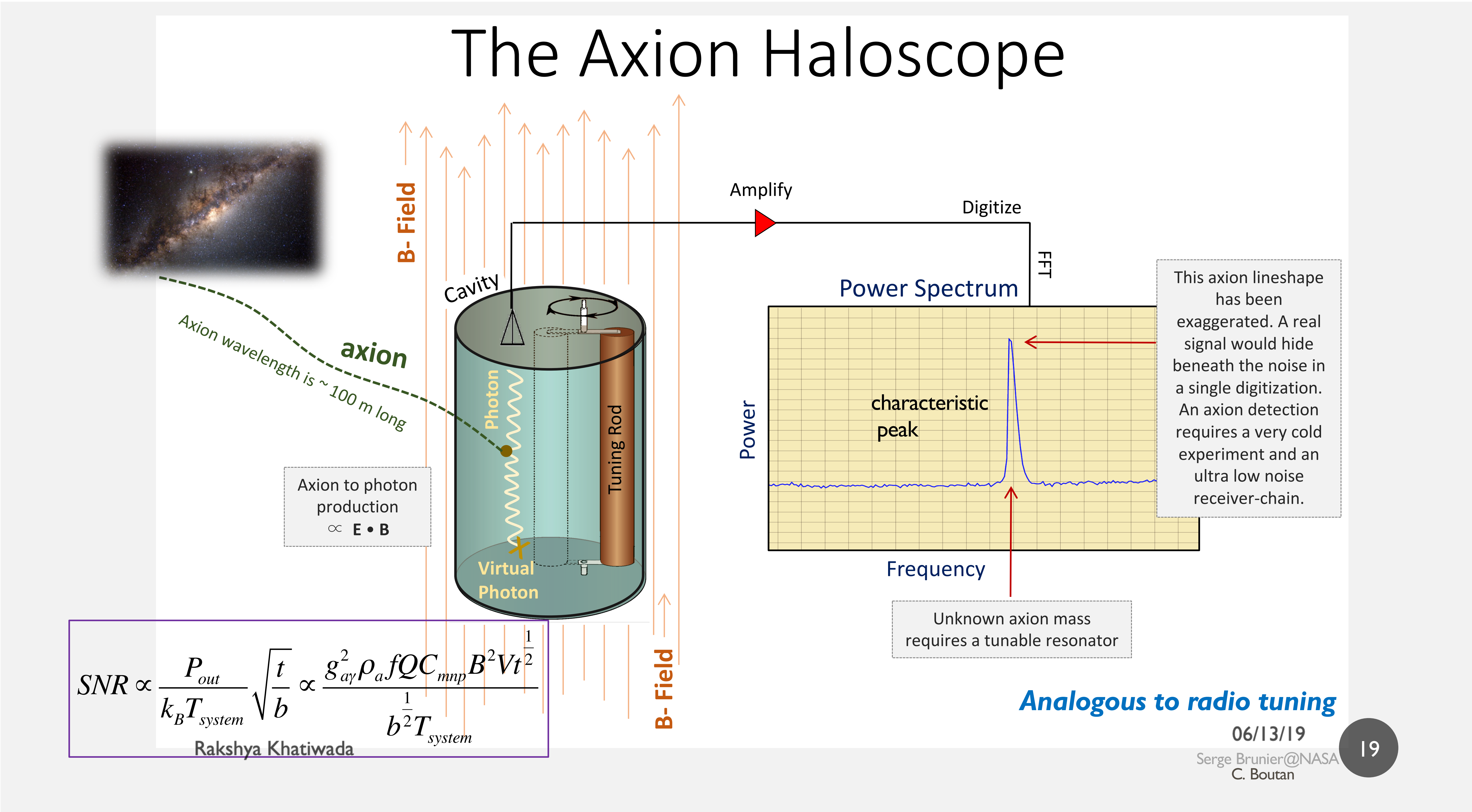
CCD production packaging and testing starting this week at SiDET

Recent Results from SENSEI

prototype 2.5 g experiment at MINOS (FNAL) using skipper-CCDs (SENSEI) is world leading again. Oscura will scale this successful technology. arXiv:2004.11378

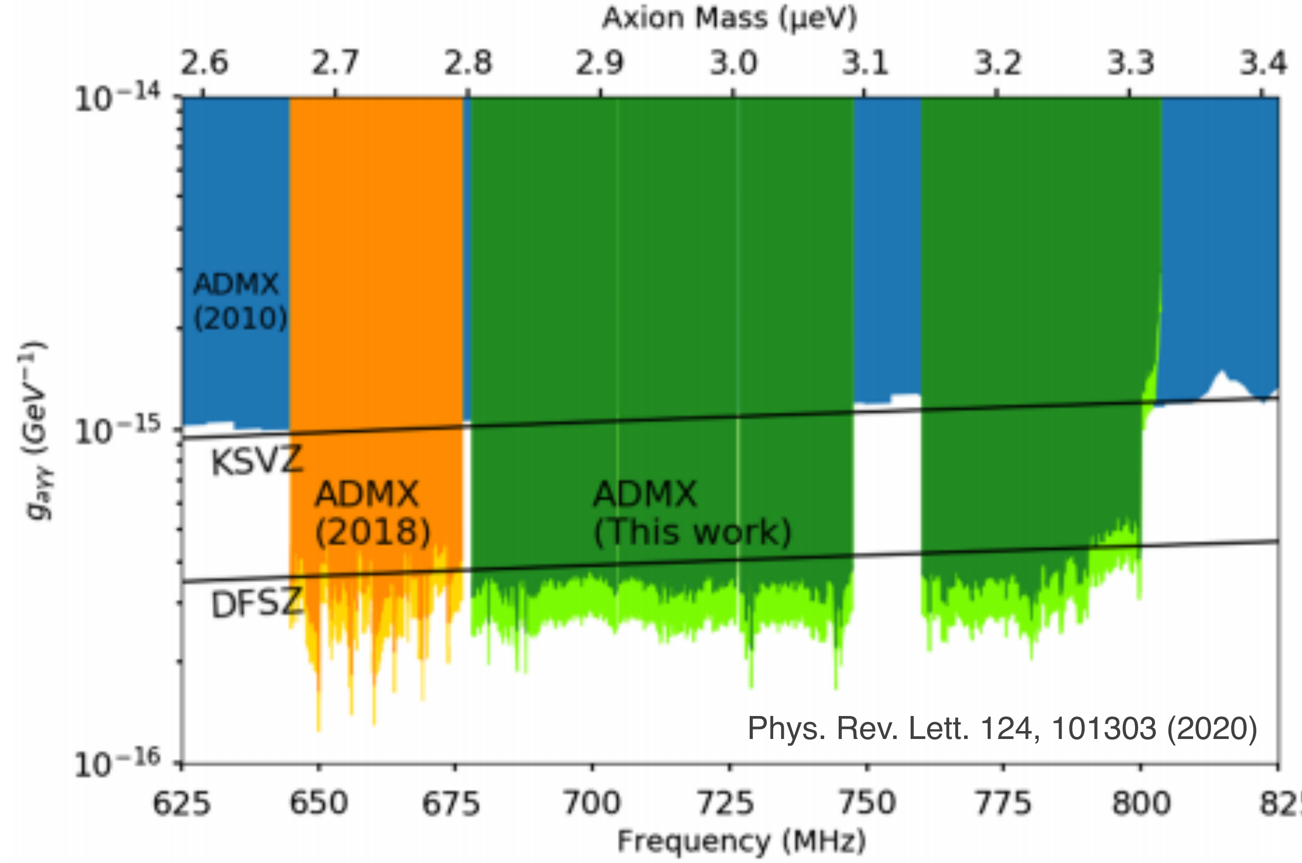


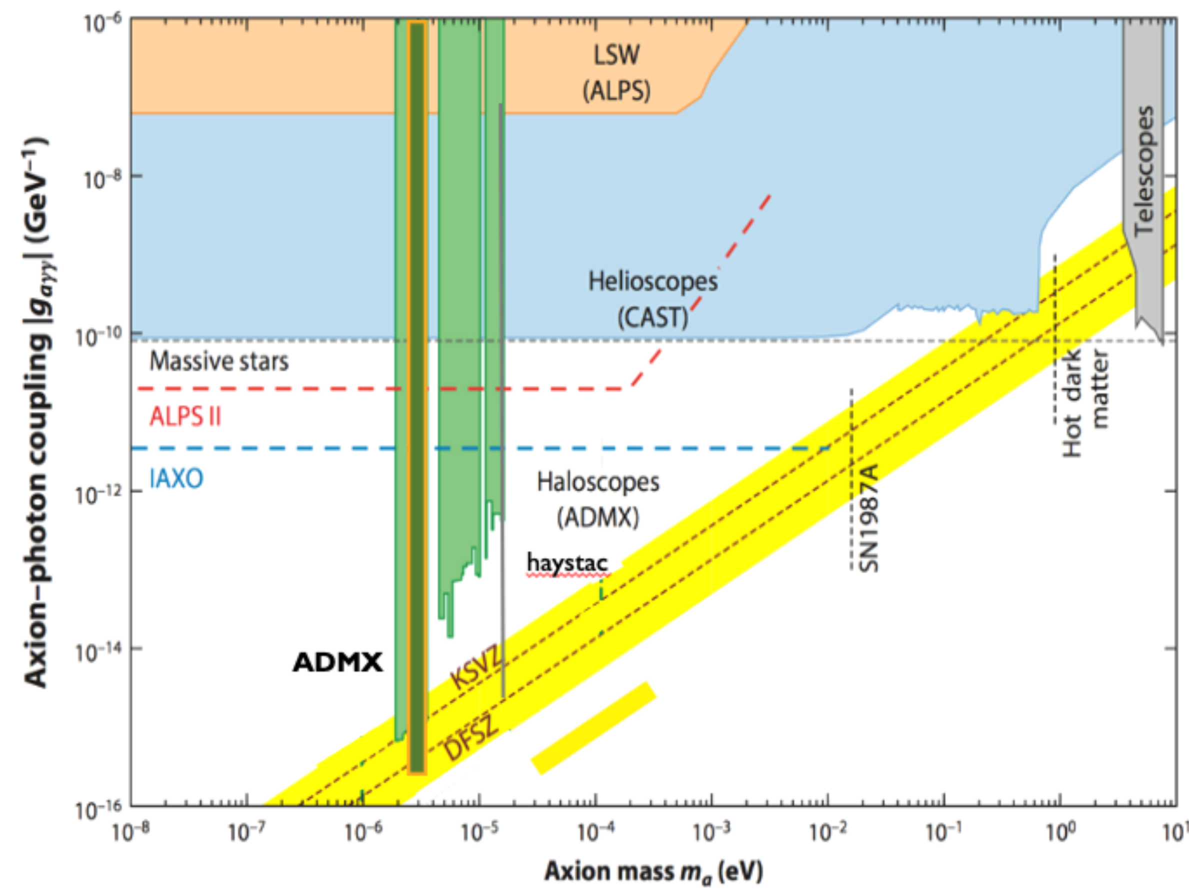
ADMX


The Axion Haloscope
B- Field
Amplify
Digitize
FFT
Cavity
Power Spectrum
This axion lineshape has been exaggerated. A real signal would hide beneath the noise in a single digitization. An axion detection requires a very cold experiment and an ultra low noise receiver-chain.
Axion wavelength is ~ 100 m long
axion
Photon
Tuning Rod
characteristic peak
Power
Axion to photon production $\propto$ E • B
Virtual Photon
Frequency
Unknown axion mass requires a tunable resonator
$SNR \propto \frac{P_{out}}{k_B T_{system}}\sqrt{\frac{t}{b}} \propto \frac{g_{a\gamma}^2 \rho_a f Q C_{mnp} B^2 V t^{\frac{1}{2}}}{b^{\frac{1}{2}} T_{system}}$
Rakshya Khatiwada
B- Field
Analogous to radio tuning
06/13/19
Serge Brunier@NASA
C. Boutan
19

ADMX Results

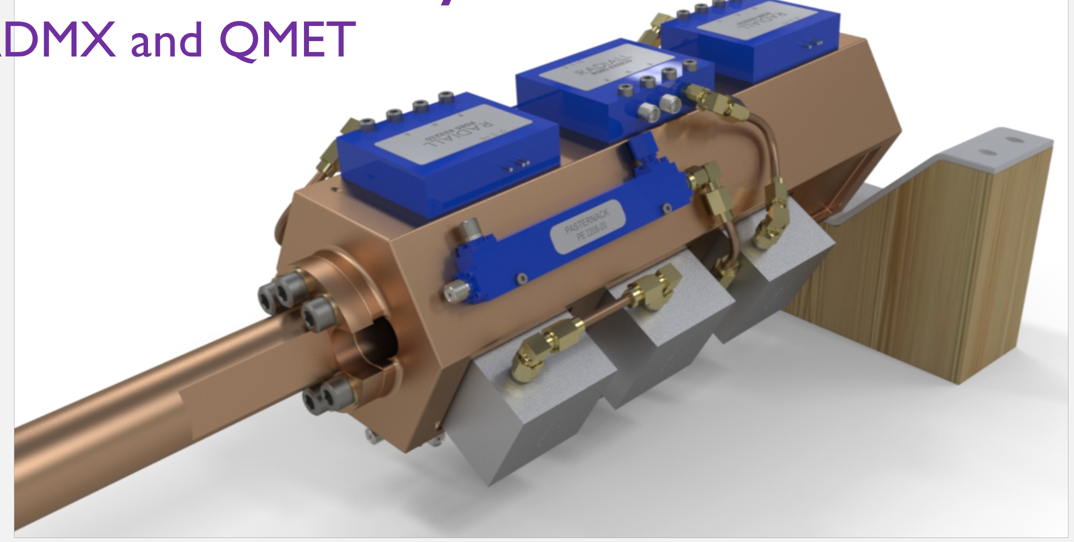
- x4 more frequency covered than 2017
- DFSZ sensitivity -- 680 to 800 MHz
- Axion mass covered to this date: 2.66 to 3.3 μeV
  - Phys. Rev. Lett. 124, 101303 (2020)
- Currently taking > 4 μeV data (985 MHz)

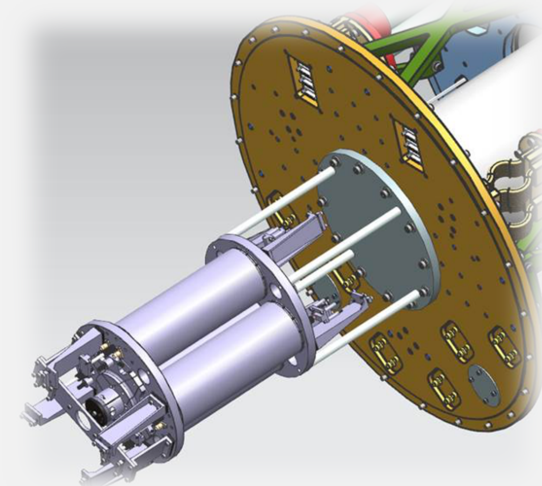


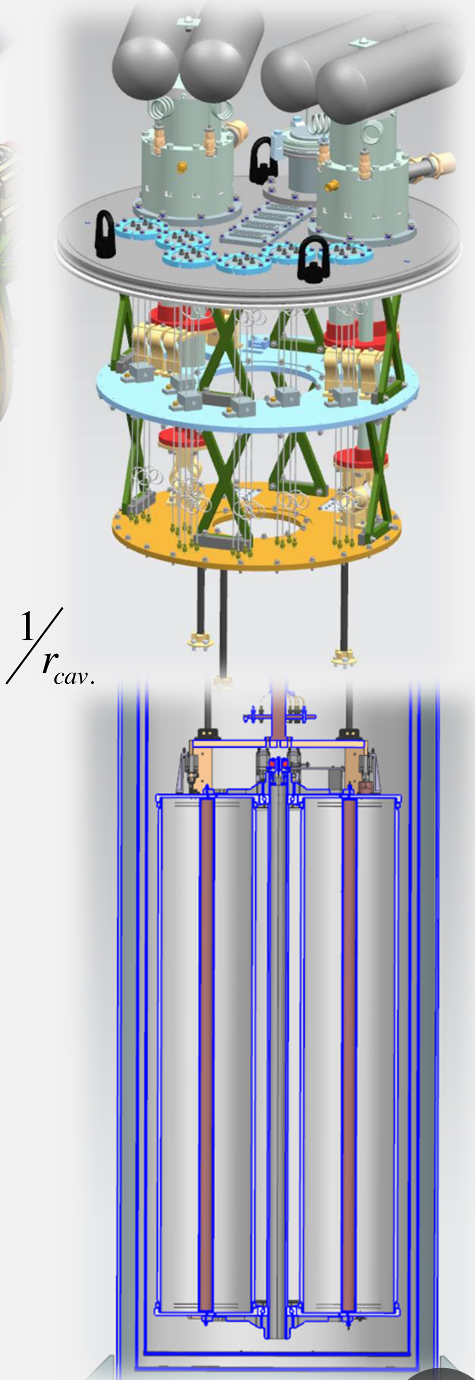


ADMX @ FNAL

Sidet Lab B shared by:
ADMX and QMET







$f_{cav.} \propto {}^{1}\!/_{r_{cav.}}$

- New detector (Run 1c) designed and fabricated at Fermilab, delivered to University of Washington
- **Run1c starting this summer** (800-1200 MHz)(3.3-5 μeV)

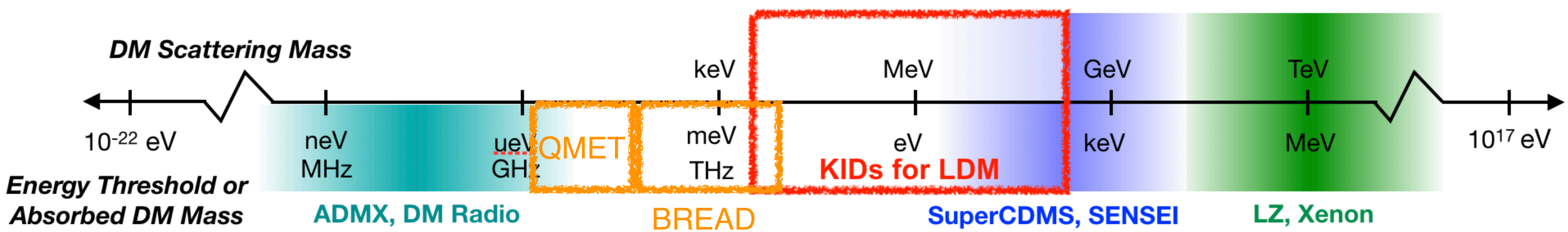
- Higher frequency multi-cavity array 4K test stand ready in the summer 2019
- 4 cavity array (mechanical tuning, motors) to be tested ~ later 2019
- Expected involvement of various collaborating institutions at Fermilab
- Targeted for >2 GHz (>8 μeV) axions

Rakshya Khatiwada 06/13/19 23

Quantum Sensing R&D

- Dark matter searches are currently broken into wave-like and particle-like detection strategies
  - These meet in the THz regime, where technological limitations make wave-like readout challenging, and quanta are small enough that they require sub-Kelvin readout for single particle detection

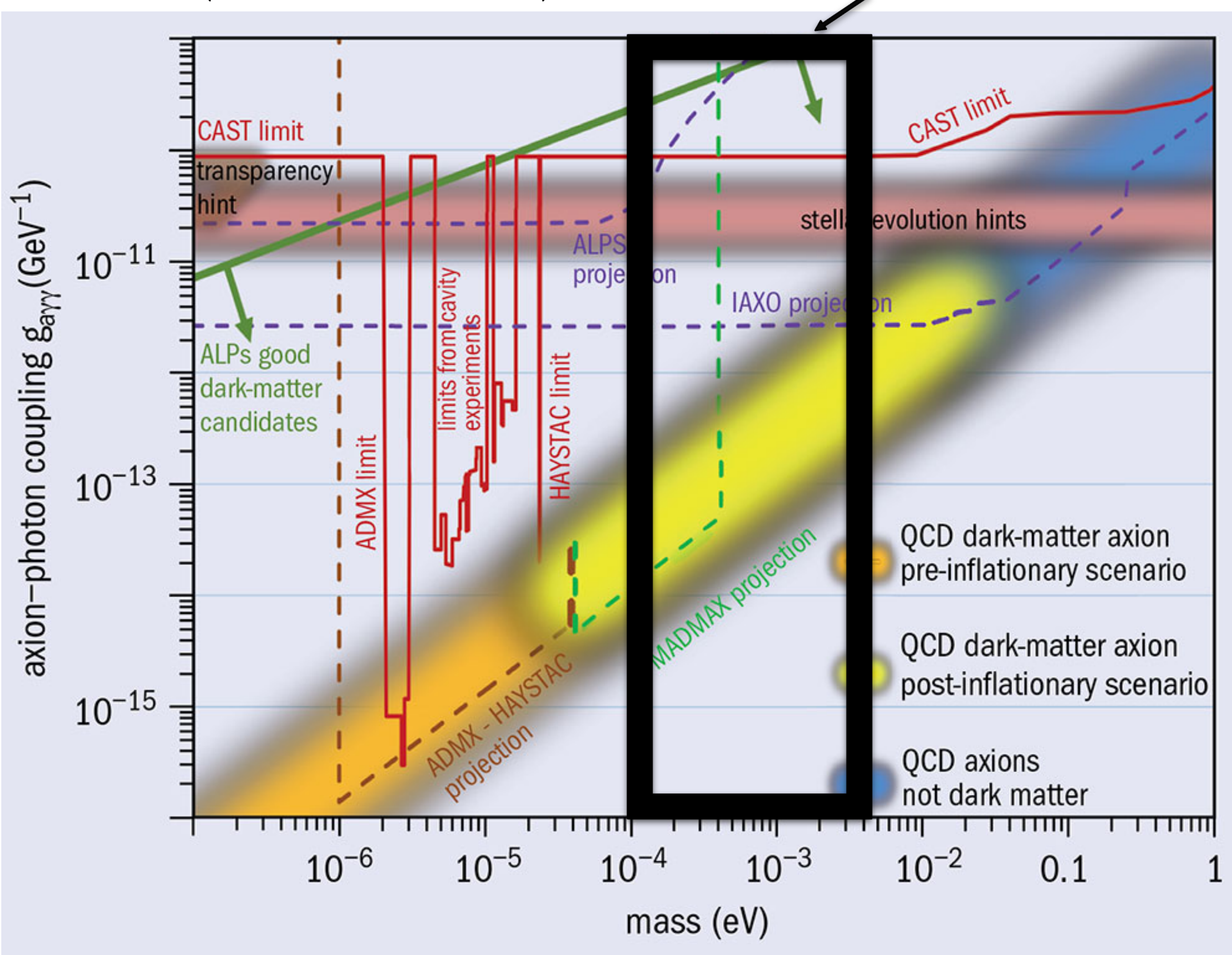
- New efforts based on technologies coming from quantum sensing R&D
  - QMET - single GHz photon detection with resonant qubit cavities
  - BREAD - axion haloscope for meV masses, uses single THz photon detectors
  - mKIDs for DM - meV-threshold phonon calorimeters for low energy DM scattering



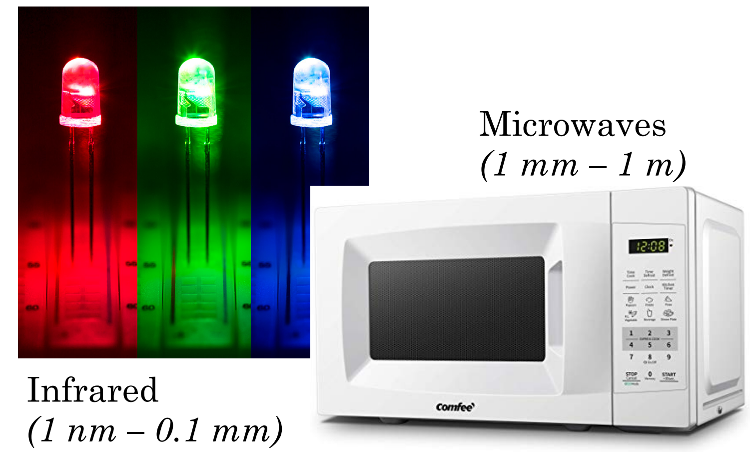
Wide-Band Axion Searches (BREAD)

Physics Motivation (Search)

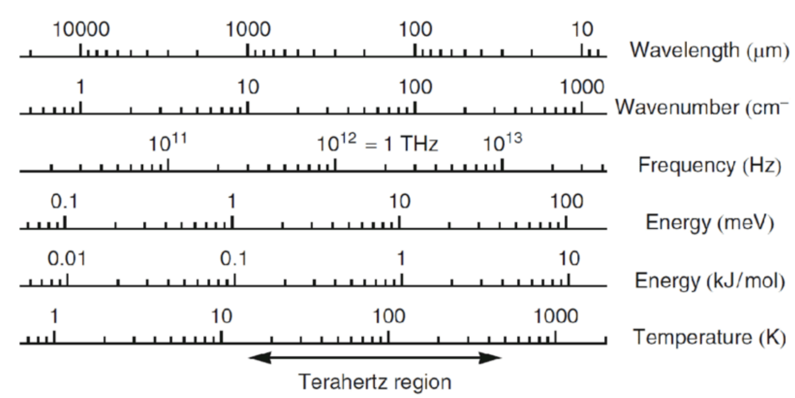
Terahertz Range



Why Terahertz?
There has been a historical gap in development of technology in the THz range *(0.1 mm – 1 mm)*



← Figure 1: Axion-Photon coupling as a function of possible axion mass.
BREAD is looking at a mass range outside of the ADMX limit, while overlapping with QCD theory's ranges. [3]



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Wide-Band Axion Searches (BREAD)

Experiment Plan

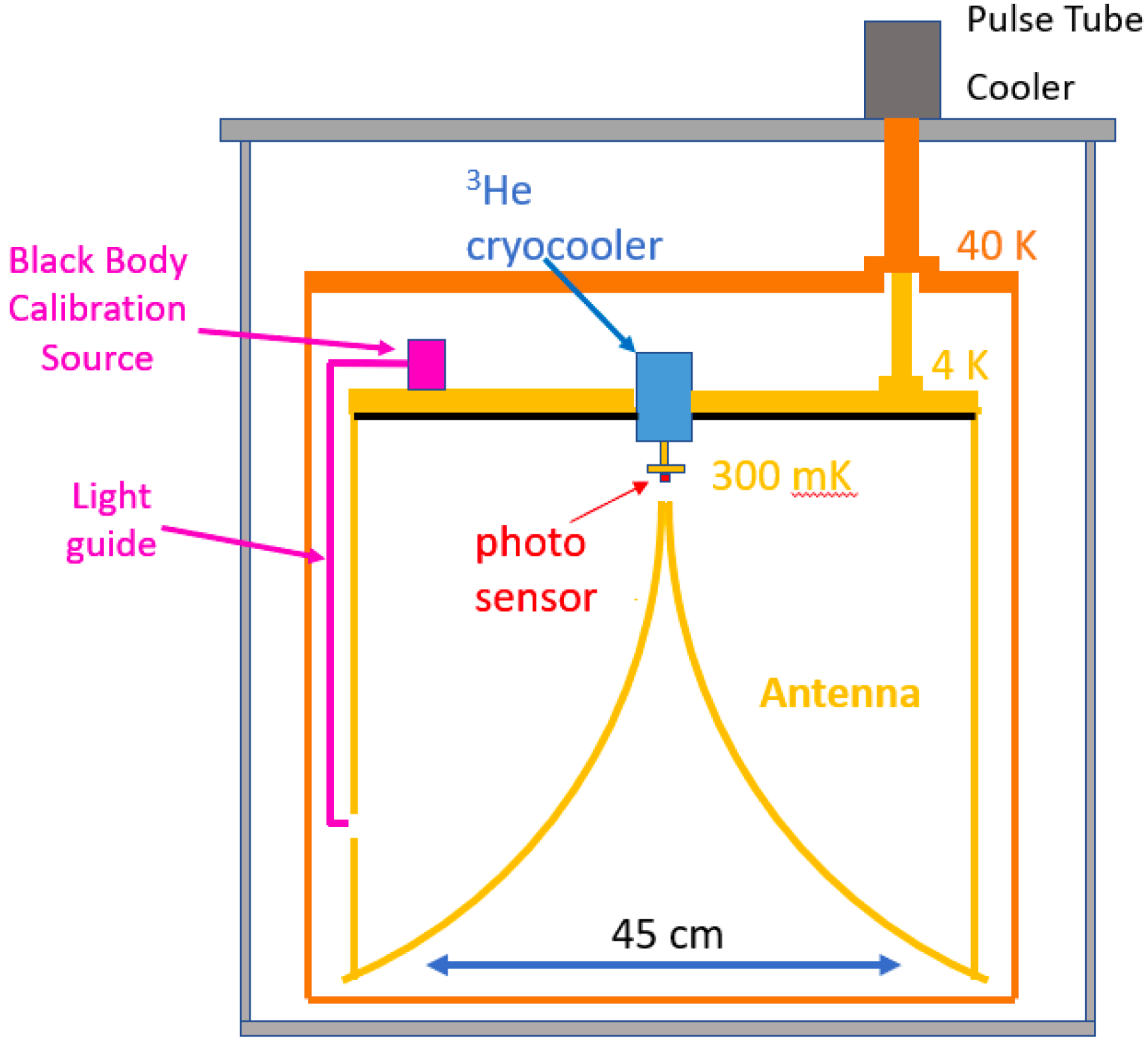


Figure 1: Diagram of experimental setup. [2]

Why Cryogenic?

- Expected very low signal due to axion – photon coupling.
- Large background expected from blackbody radiation: $J \propto T^4$
- Background reduction with decreased temperatures

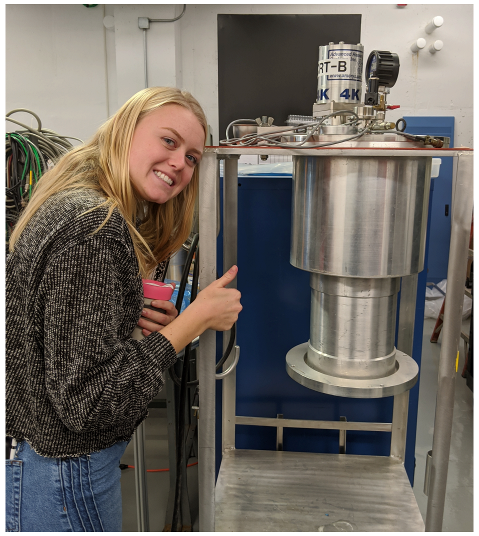
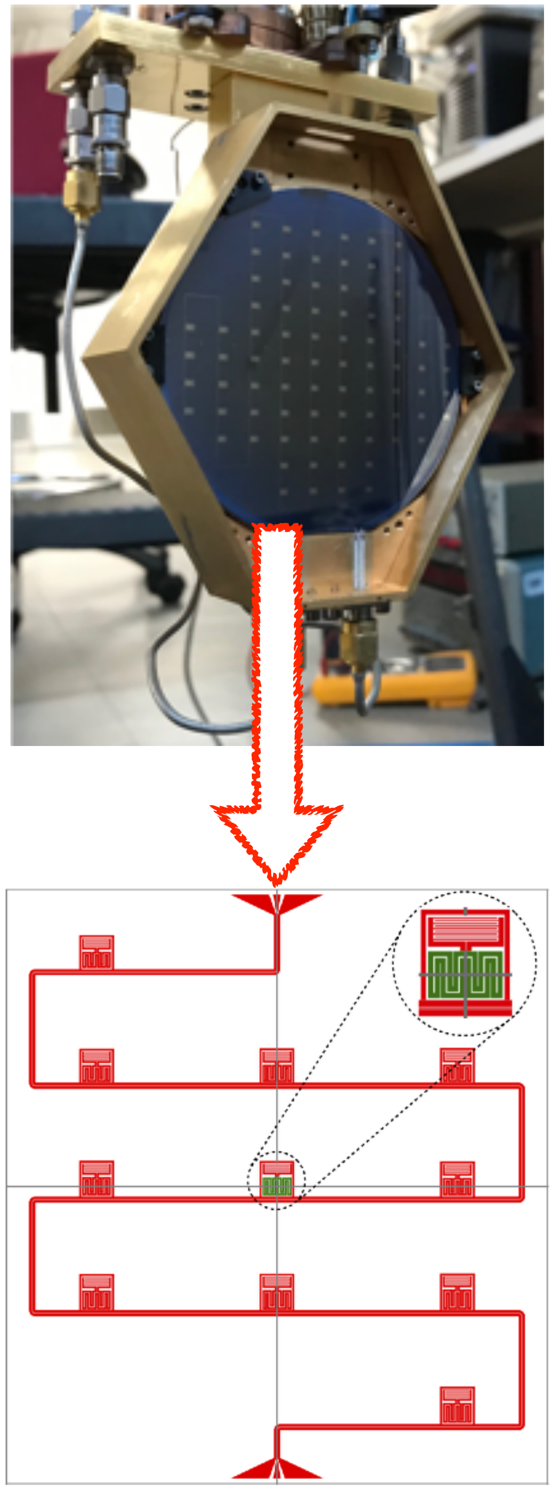


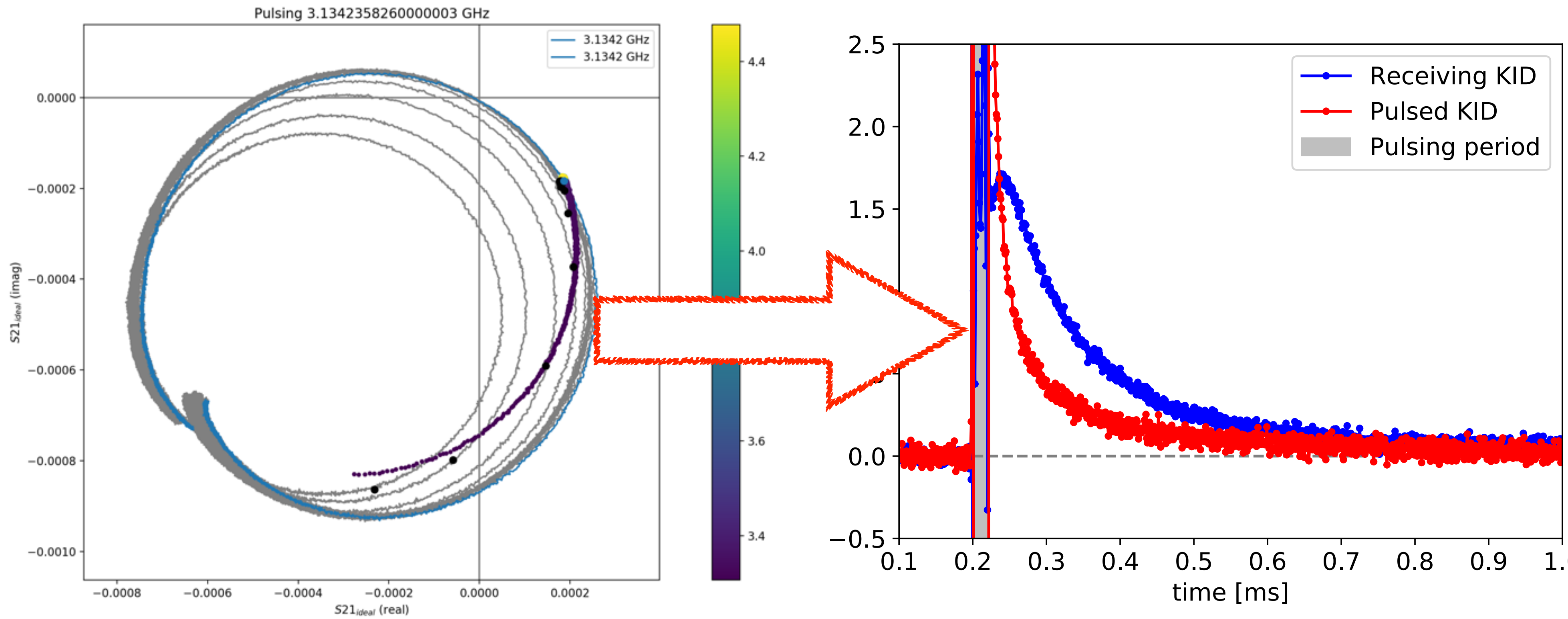
Figure 2: Photograph of cooler, Kristin for scale. (from Fermilab trip 12.19)

Lower temp ~ Lower background

4

KIDs for DM

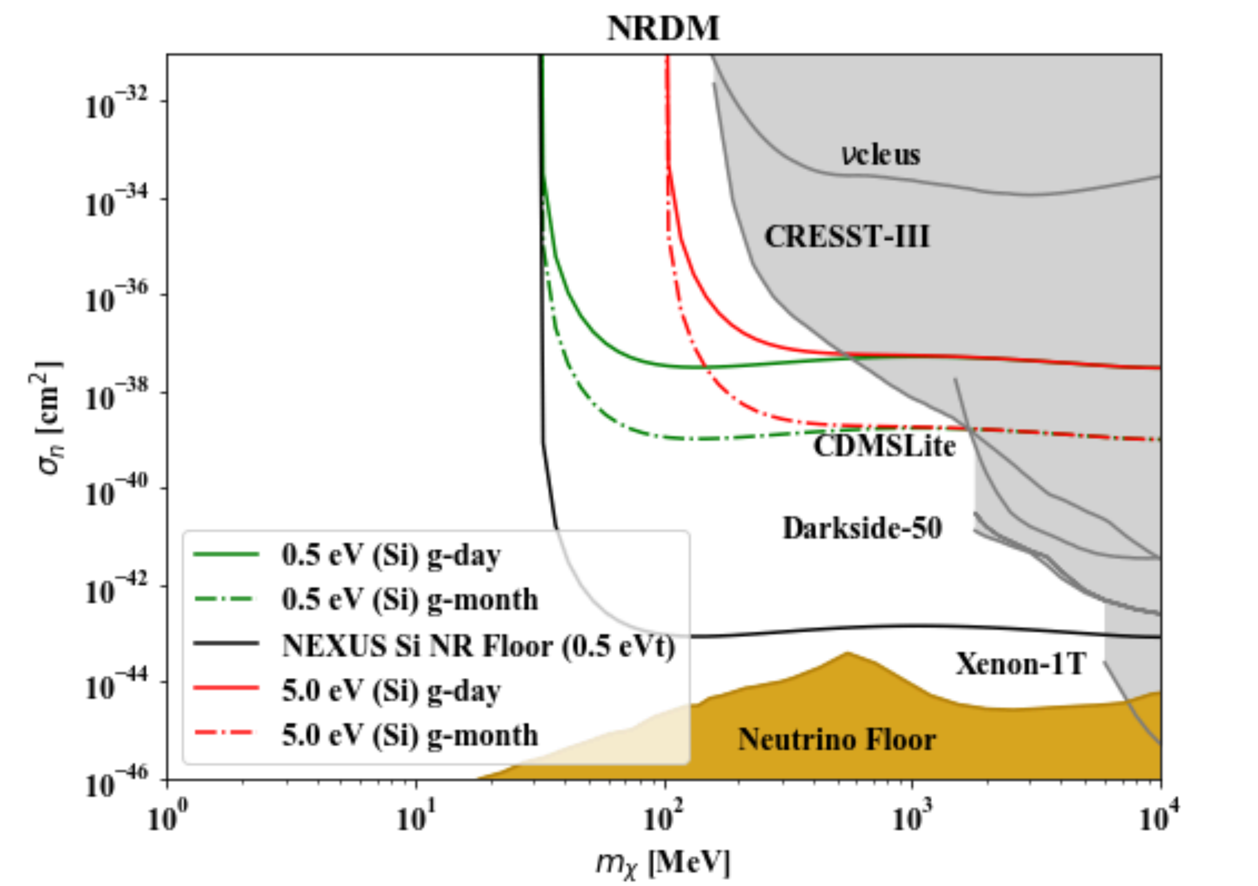


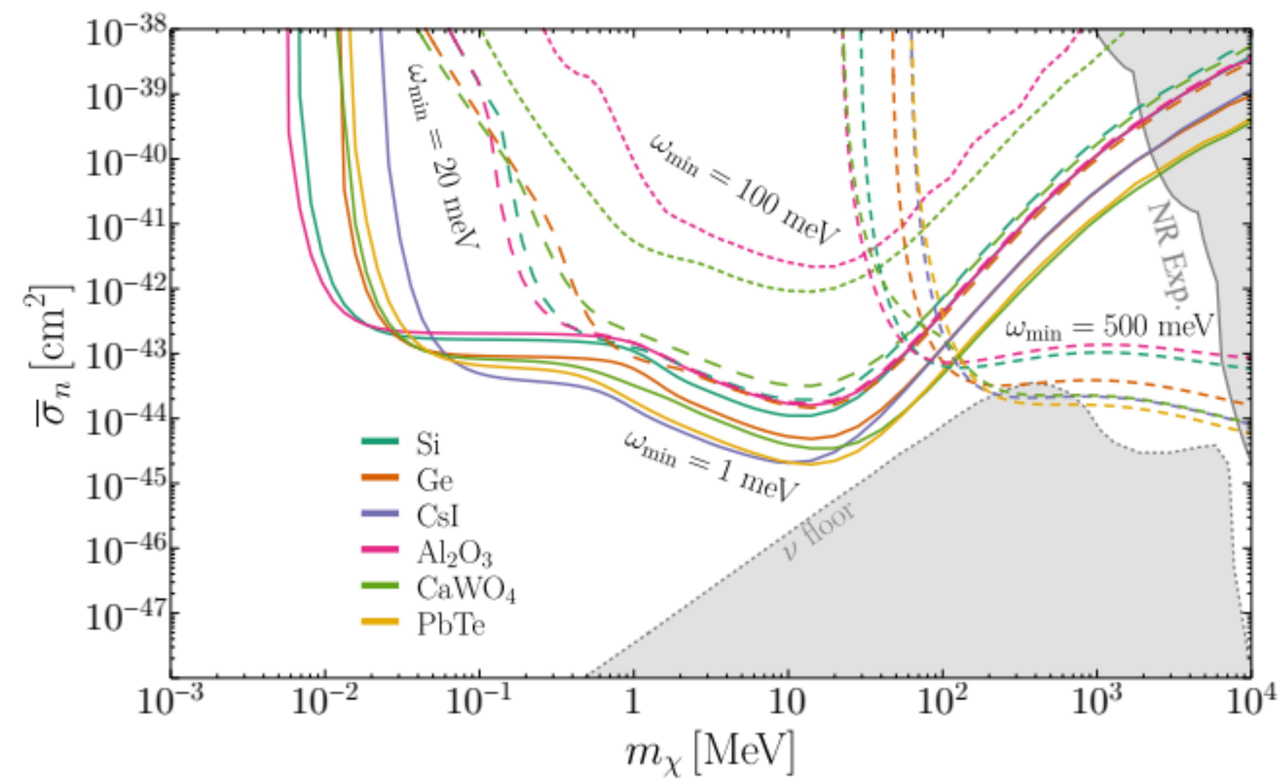


- KIDs are superconducting structures with a resonance frequency that's exquisitely sensitive to energy deposition by the kinetic inductance effect
- Operate in a narrow band; noise is simply limited by the amplifier thermal noise (low-frequency, EMI, etc much less problematic than TESs)
- Devices made by Sunil Golwala's group at Caltech/JPL currently achieving eV-scale resolutions in a fairly high-background environment. Need to develop robust readout system, and move to underground cryostat with lower base temperature, to achieve sub-eV resolution.
  - Targeting 1 eV resolution in Y1, 0.1 eV in Y2-3.
  - Lower resolution (O(10 meV) possible through parallel advances in amplifier technology

KIDs for DM

- Direct searches for dark matter with masses < 1 GeV are likely to be one of the primary recommendations from the next SNOWMASS process
- These searches require new technologies, synergistic with QIS, CMB, and searches for non-standard neutrino interactions
- KIDs are flexible sensors that can accommodate a broad range of targets, able to capitalize on the strengths of different targets.
- We need technologies with smaller gaps than e-h pairs, which largely restricts us to superconducting sensors on solid substrates where phonons or QP's can be produced. Both TESs and KIDs are viable technologies and both should be explored to determine their ultimate practical reach.





Summary

- SENSEI, DAMIC & OSCURA
  - CCD-based experiments
  - SENSEI operating at MINOS, moving to SNOLAB
  - DAMIC moving from SNOLAB to Modane
  - OSCURA will be the 10 kg upgrade to DAMIC with skipper CCD readout

- SuperCDMS
  - Athermal calorimeters with eV-scale resolution, charge readout at high voltage
  - R&D detectors operating in NEXUS, CUTE test facilities
  - SuperCDMS SNOLAB online late 2021/early 2022 with kg-scale payload of Si/Ge detectors
  - Upgrade path includes sub-eV resolution devices fabricated with novel target materials

- ADMX
  - World-leading sensitivity at sub-GHz frequencies, running at ~1 GHz now
  - Funded to extend into >1 GHz frequency range
  - R&D towards ~10 GHz+ sensitivity

- Quantum Sensing for DM
  - R&D phase, promises to close the gap between SuperCDMS/Oscura and ADMX

Who We Are

- SuperCDMS/NEXUS
  - Dan Bauer, Lauren Hsu, Noah Kurinsky, Pat Lukens
- ADMX
  - Daniel Bowring, Aaron Chou, Rakshya Khatiwada, Andrew Sonnenschein
- OSCURA/SENSEI
  - Mike Crisler, Juan Estrada, Guillermo Fernandez, Miguel Sofo Haro, Javier Tiffenberg, Alex Drlica-Wagner
- Plus collaborators from around the world!