Dark Matter Experiments

Alan E. Robinson

FNAL Users Meeting

15 June 2016

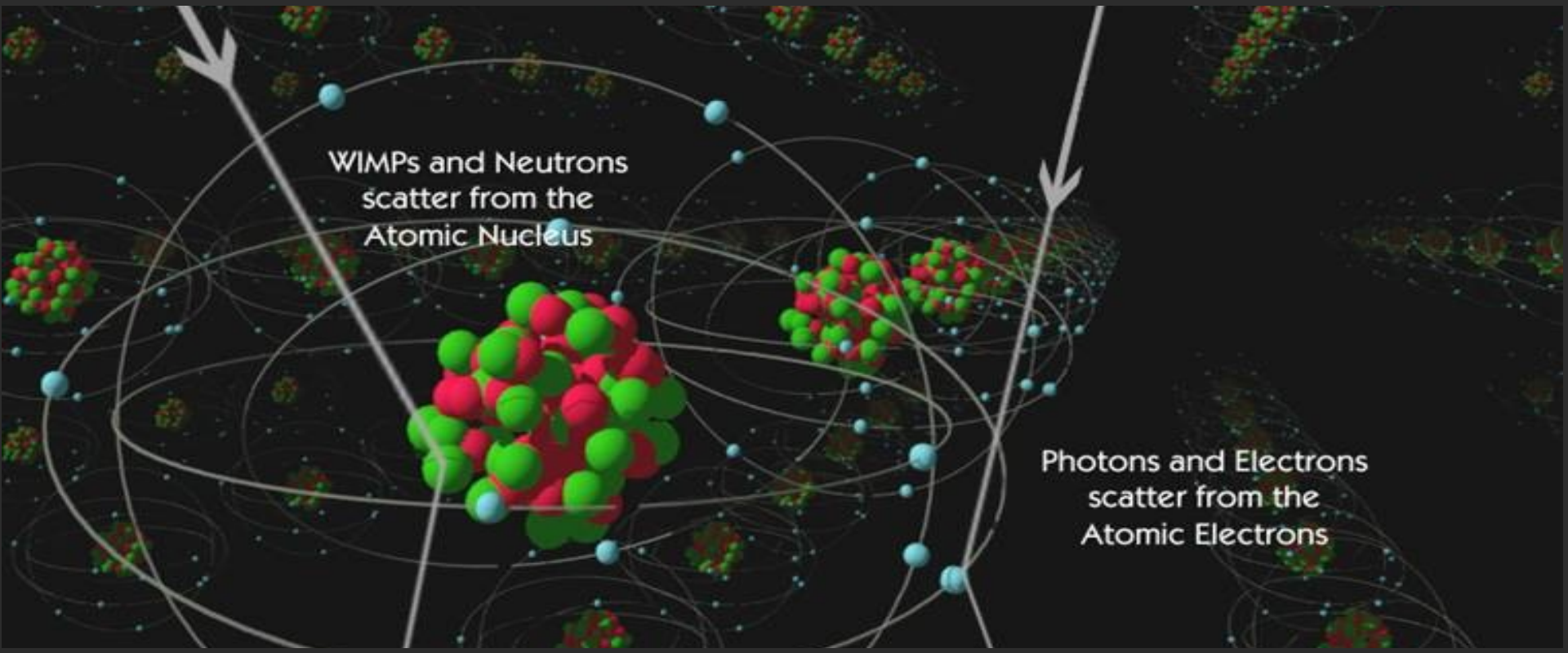
How to Catch a WIMP

- A continuous flux of particles is passing through the earth.
  - Most probable velocity ~220 km/s, v_{esc} ~ 544 km/s
  - Interactions may create inelastic scattering on nuclei

- Example:
  - 1 amu WIMP at ~300 km/s colliding with hydrogen
    - $E_{WIMP} = E'_{recoil,max} = ½ mv^2 = ½ (937 \text{ MeV}/c^2)(0.001 \text{ c})^2 \approx 0.5 \text{ keV}$
  - E_{recoil} is increased for heavier and faster WIMPs.

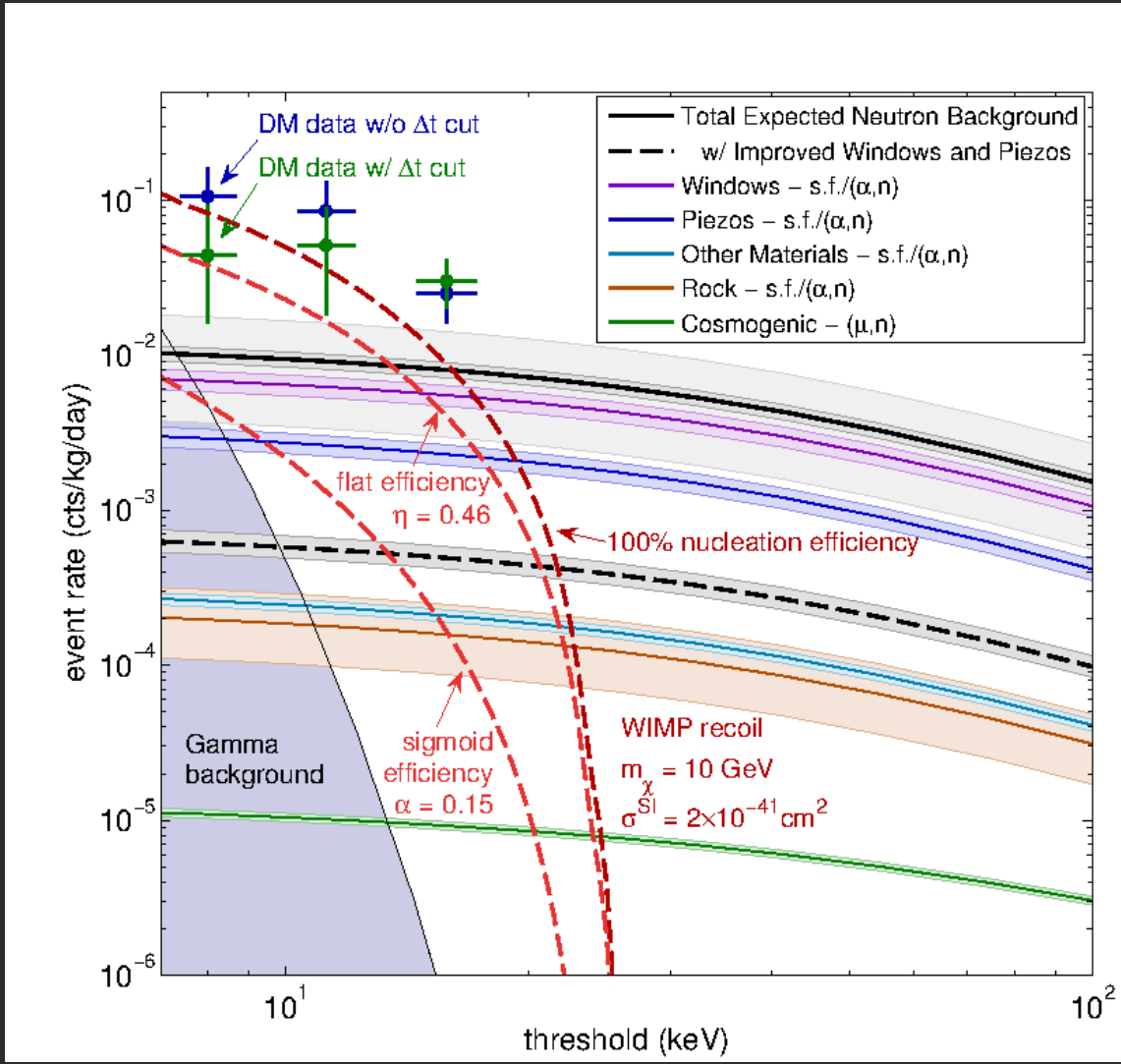
How to Catch a WIMP (Weakly Interacting Massive Particle)

- Very low interaction probability
  (~1 event/year above threshold)
- Rejection of common radiation



How to Catch a WIMP

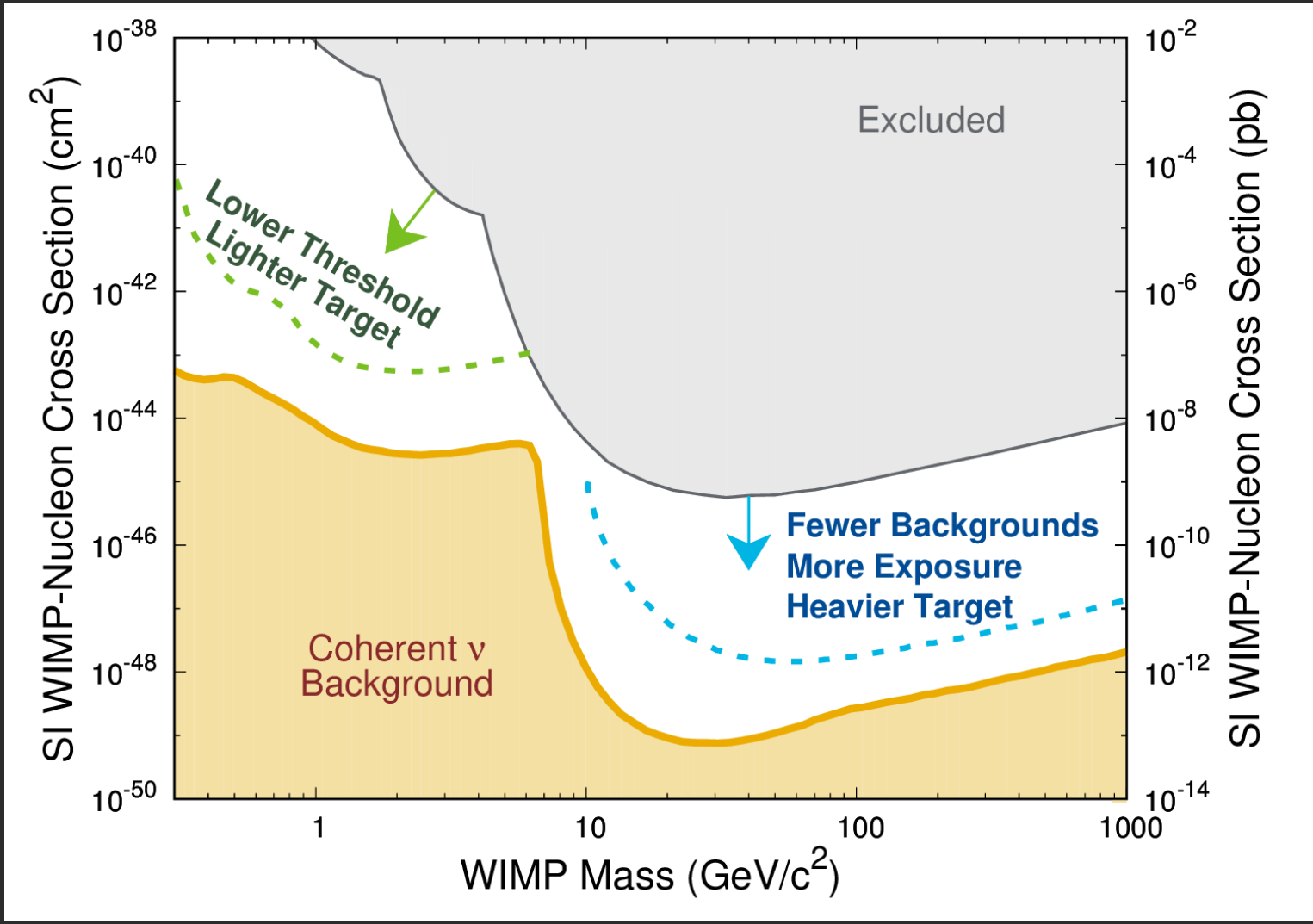
Expected and measured nuclear recoil rates in COUPP-4kg (2010-11)



D.A. Fustin
Ph.D Thesis
UChicago (2012)

Fermilab

Direct Detection Limits



Fermilab

Dark Matter Direct Detection Program

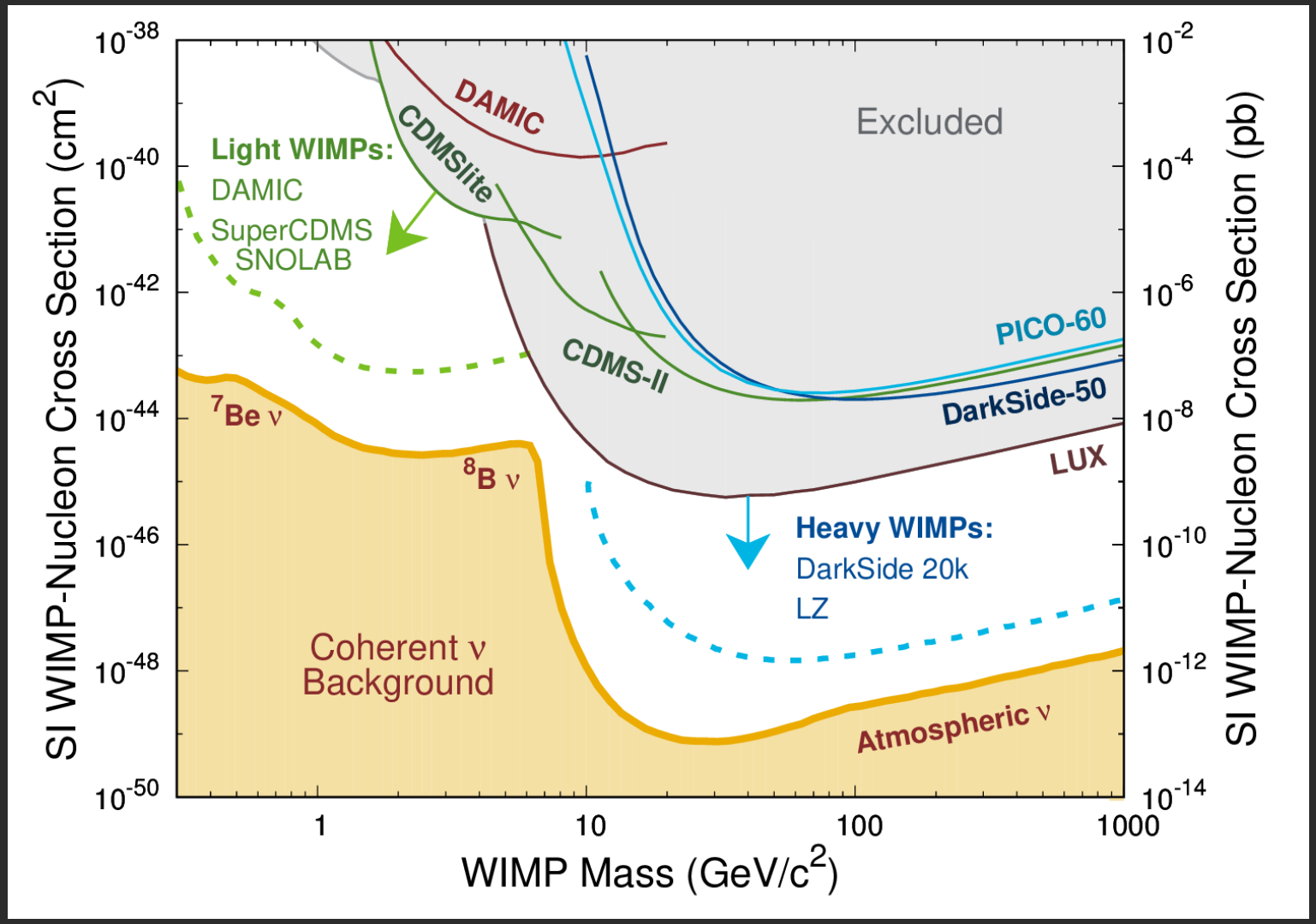
Strong Fermilab involvement in world-leading direct detection experiments.

HEPAP P5 Report Recommendations

- Proceed immediately with a broad second-generation (G2) dark matter direct detection program ...
- Support one or more third-generation (G3) direct detection experiments, guided by the results of the preceding searches. ...

Fermilab

Direct Detection Limits

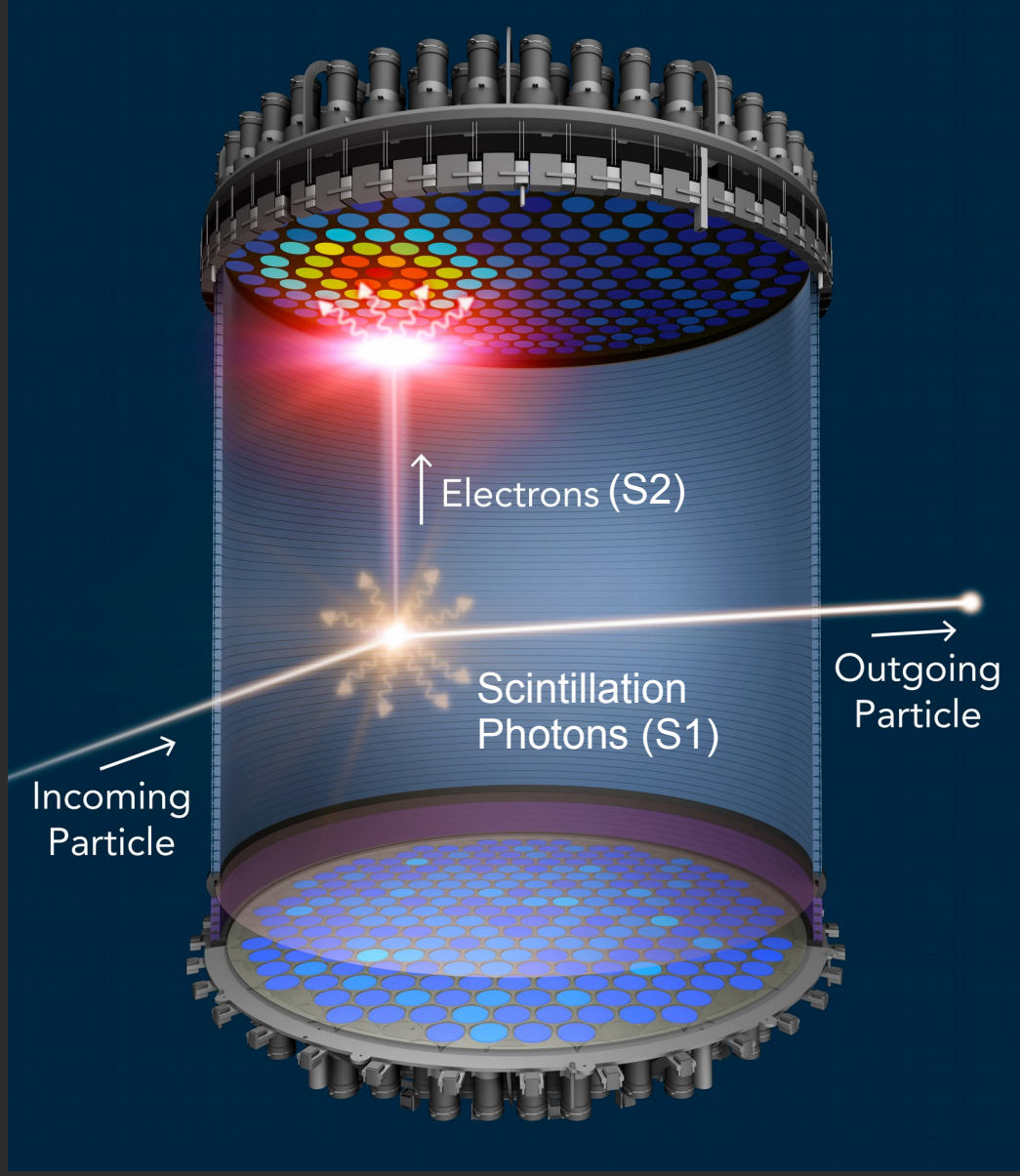


Fermilab

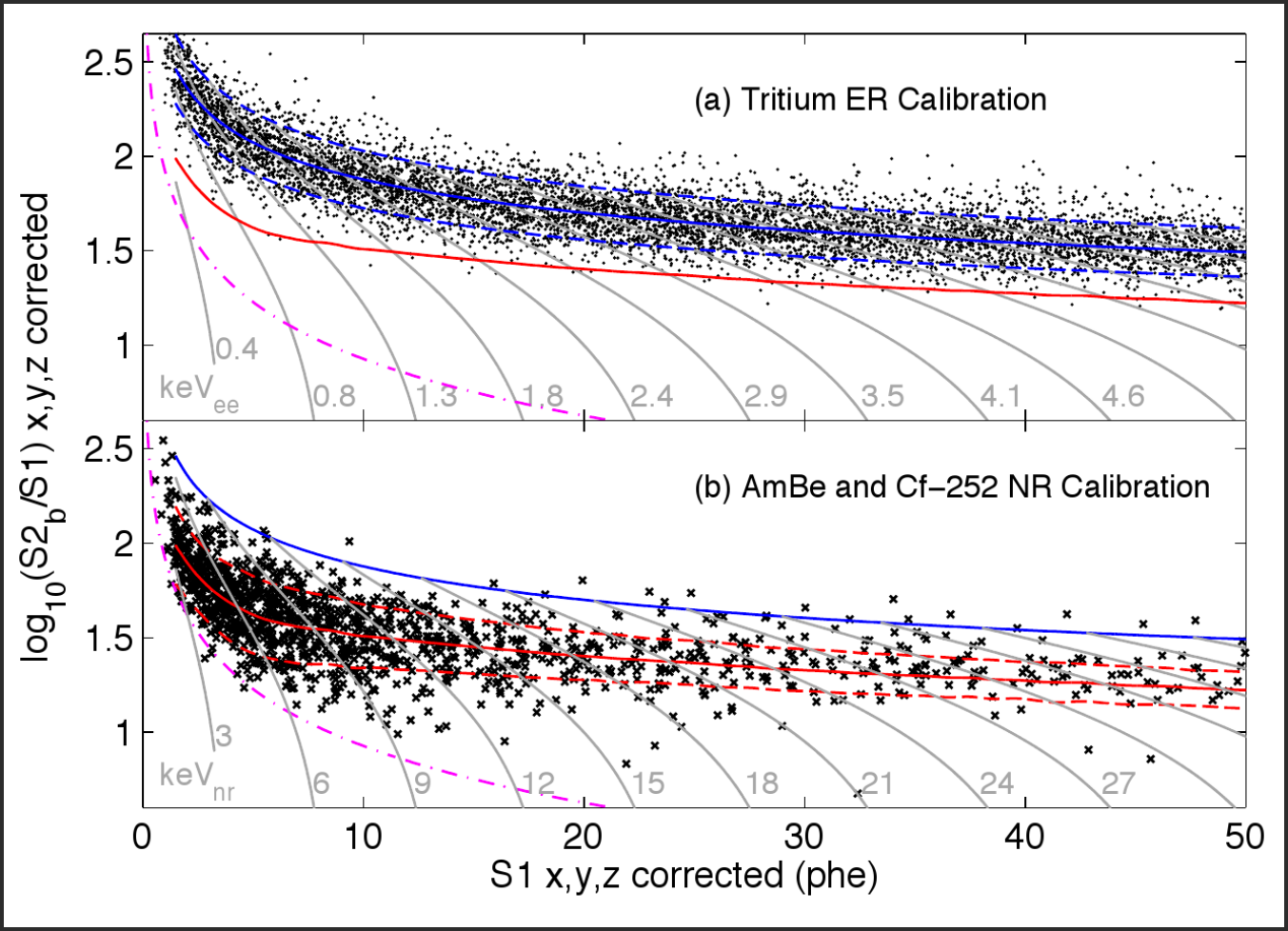
LUX-Zeplin (LZ)

Liquid Xenon 2-phase TPC

- G2 project at SURF
- Leading technology for heavy WIMPs
  - ER/NR discrimination using scintillation / ionization
  - High purity
  - Self-shielding
- FNAL responsible for portions purification system, cryo and HV design.



ER/NR discrimination in LXe



- >10^2 NR/ER separation
- Difference in ER and NR energy scales
- Threshold ~1 keVnr

PRL **112** 091303 (2014)

DarkSide

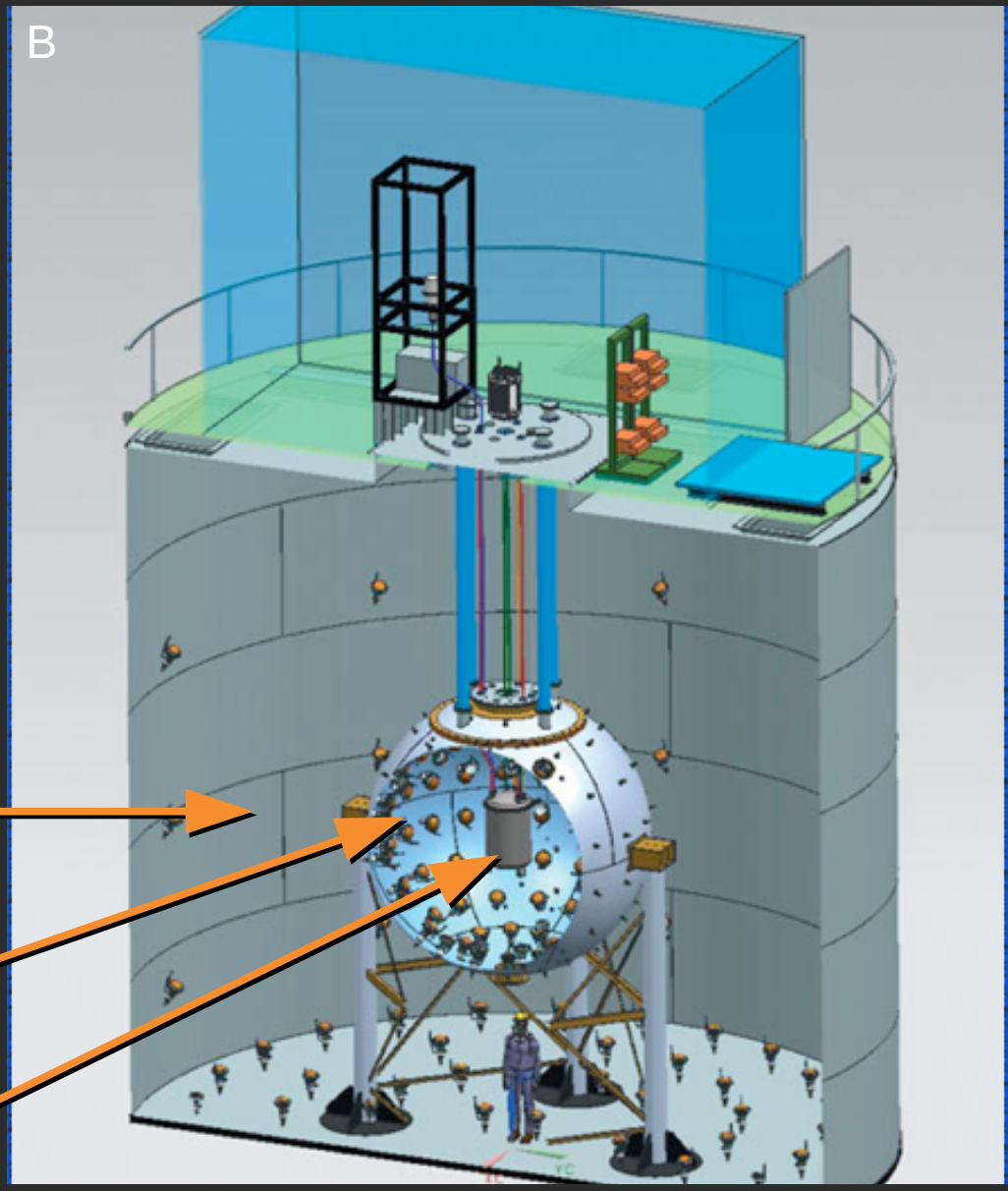
Liquid Argon 2-phase TPC

- $>10^8$ ER/NR discrimination
- ^{39}Ar β contamination
  - Fermilab provides low-radioactivity argon

Water Cherenkov muon veto and shield

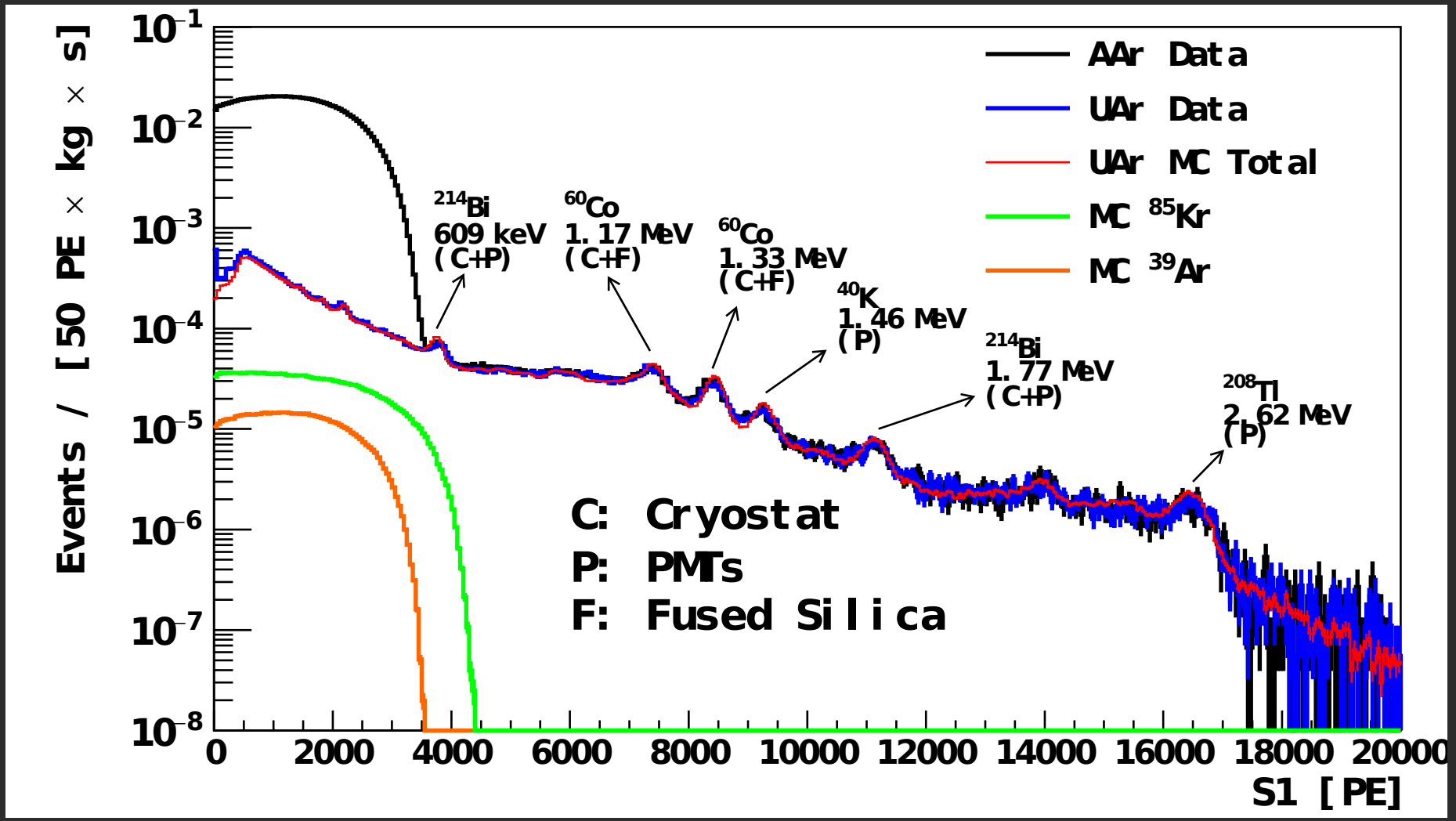
Liquid scintillator neutron veto

Detector



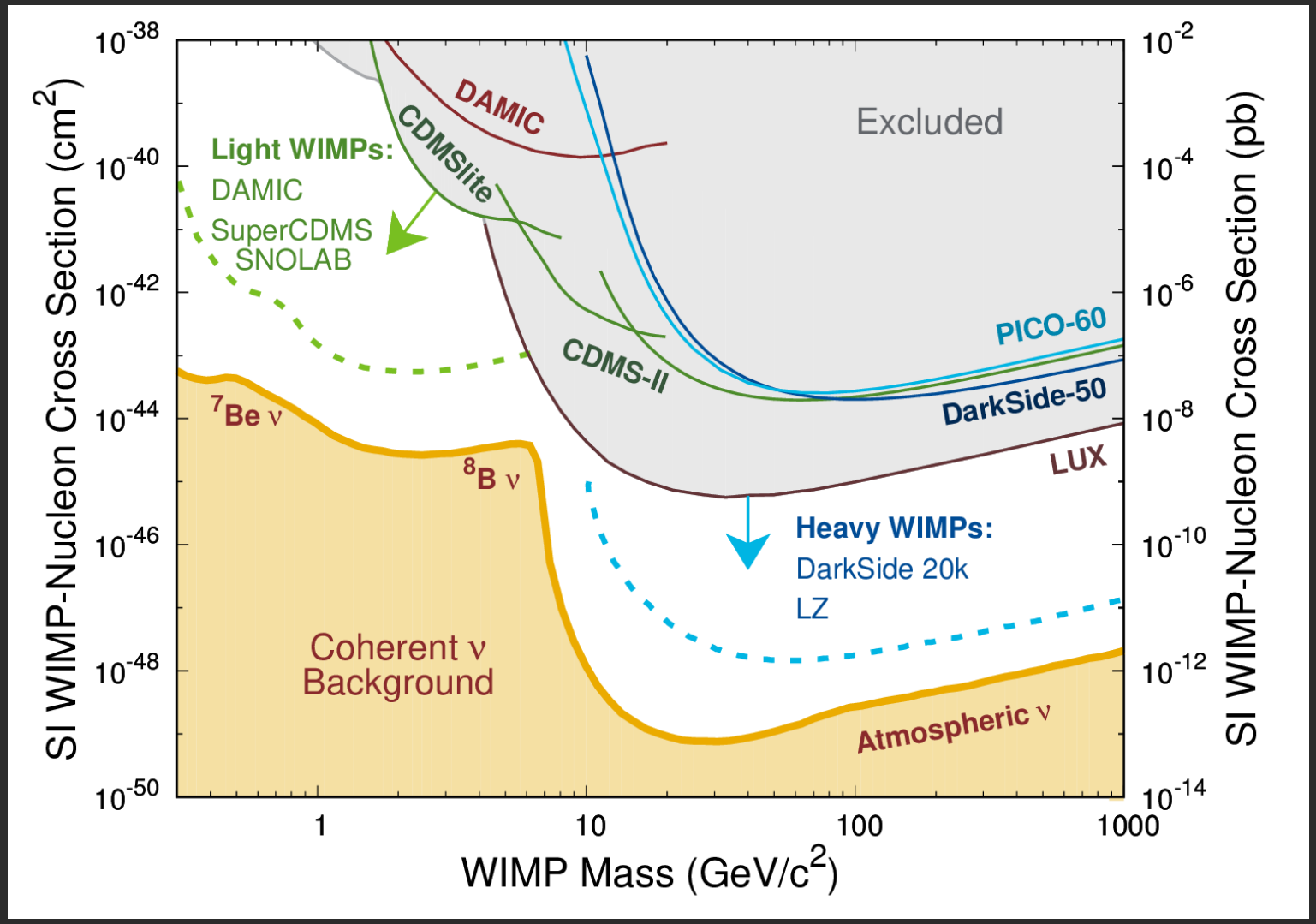
Fermilab

ER background reduction with underground Ar



NOTICE
METHANE
RESTROOM

Light WIMPs



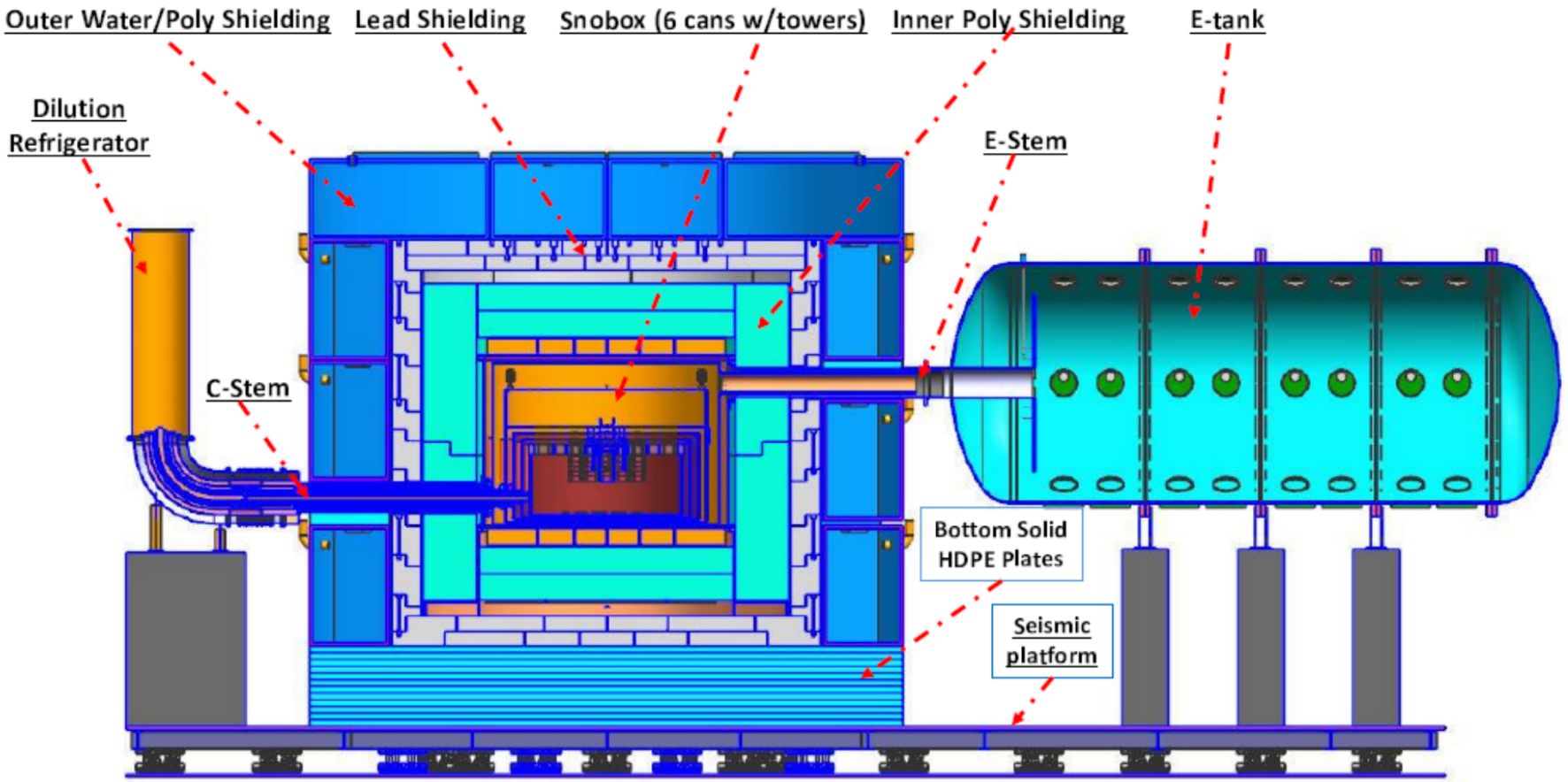
Fermilab

SuperCDMS

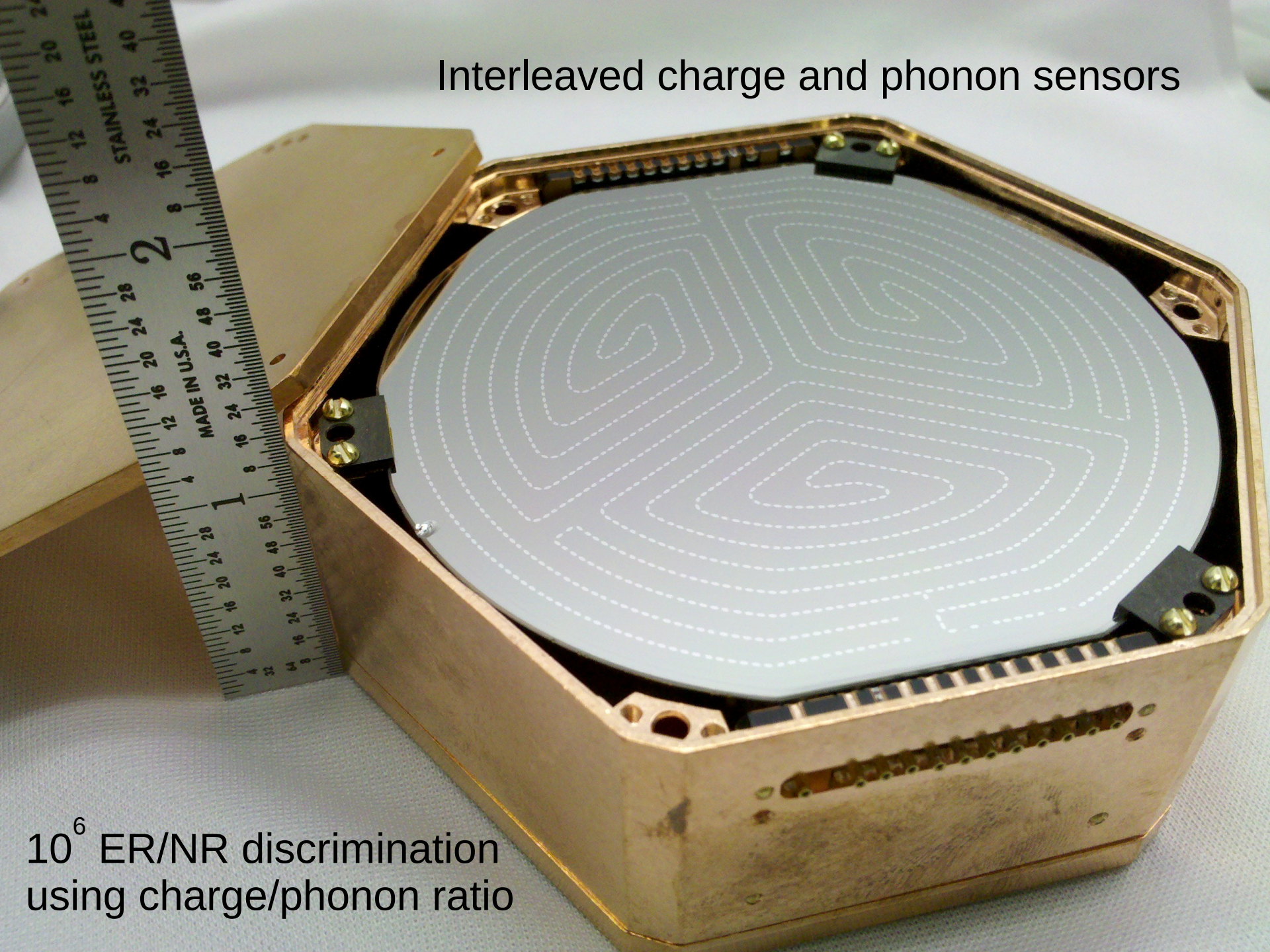
Cryogenic semiconductor

- G2 experiment for light WIMPs
- Si and Ge crystals at 50 mK (present) or 15 mK (future)

SuperCDMS SNOLAB Layout

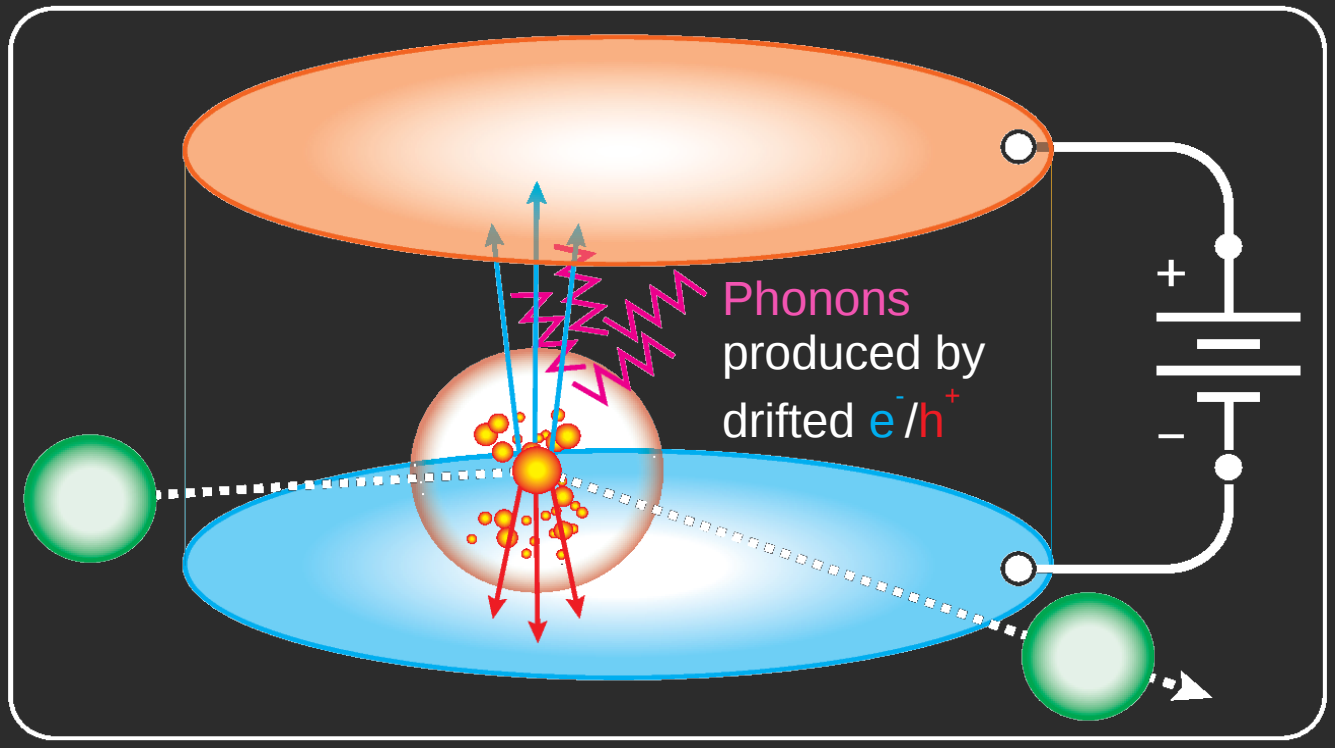


Fermilab responsabilities include cryogenic infrastructure, systems integration, and calibration.


Interleaved charge and phonon sensors
10^6 ER/NR discrimination
using charge/phonon ratio

SuperCDMS

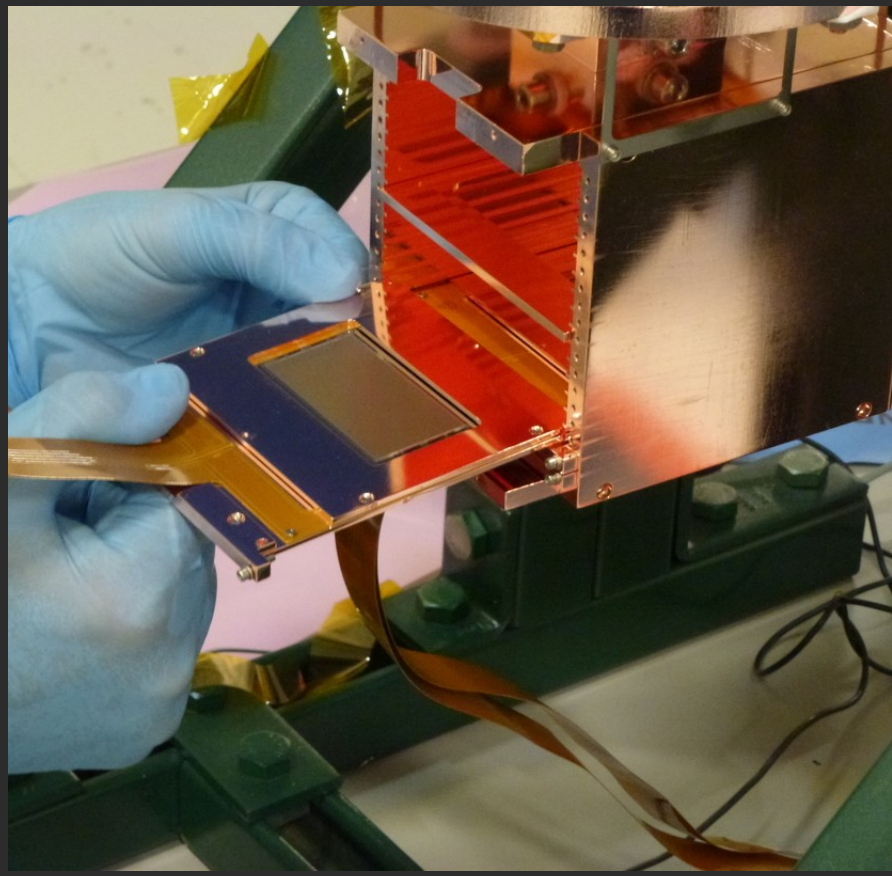
- CDMSlite operating mode
  - Recent breakthrough in low-threshold detection using phonons to amplify ionization signals
  - 100 eV scale thresholds



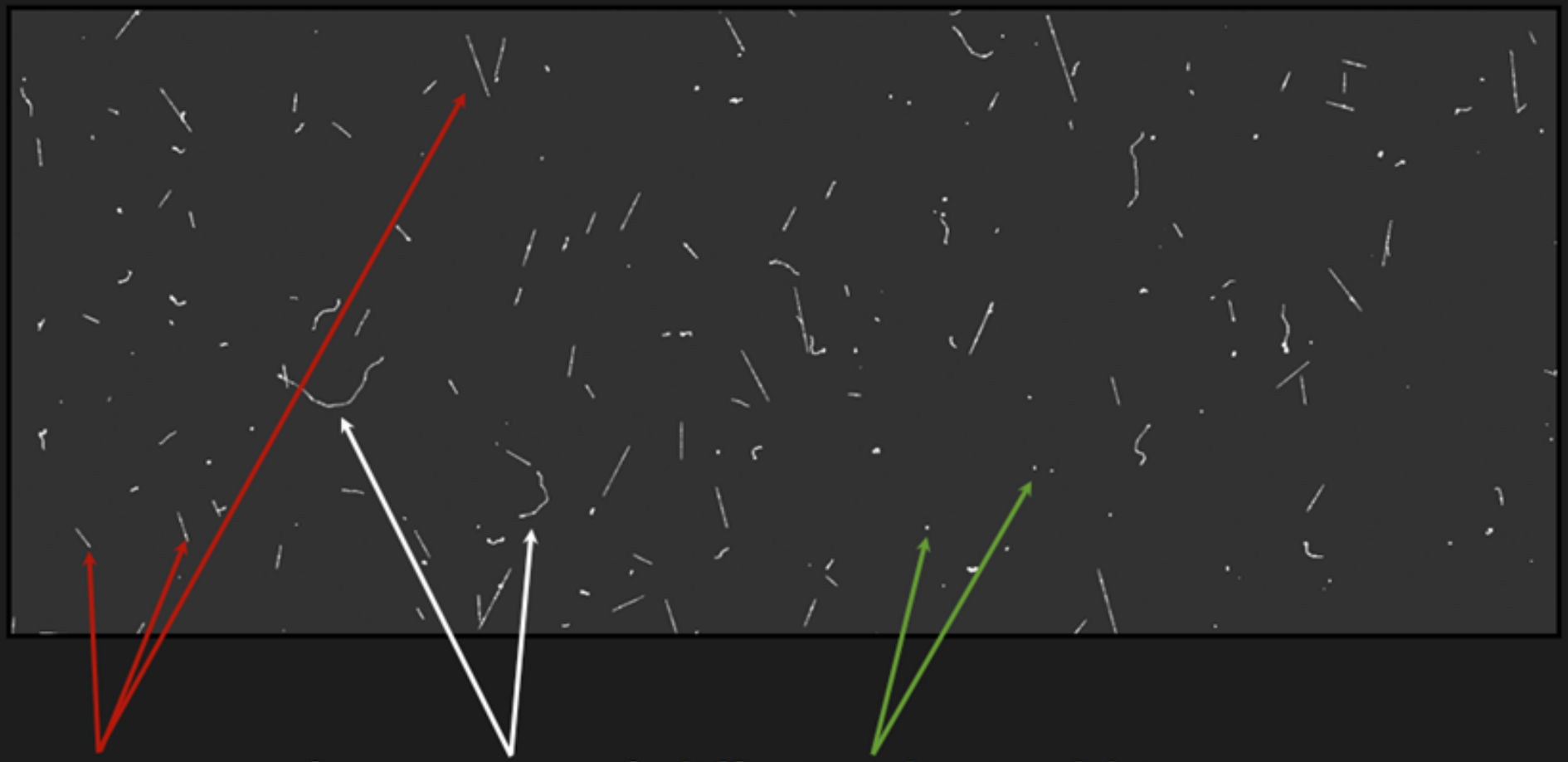
DAMIC

Silicon CCD detector

- Si CCDs developed at Fermilab for DECam
- Low ~35eVee thresholds
- Uses complementary background rejection methods to other experiments



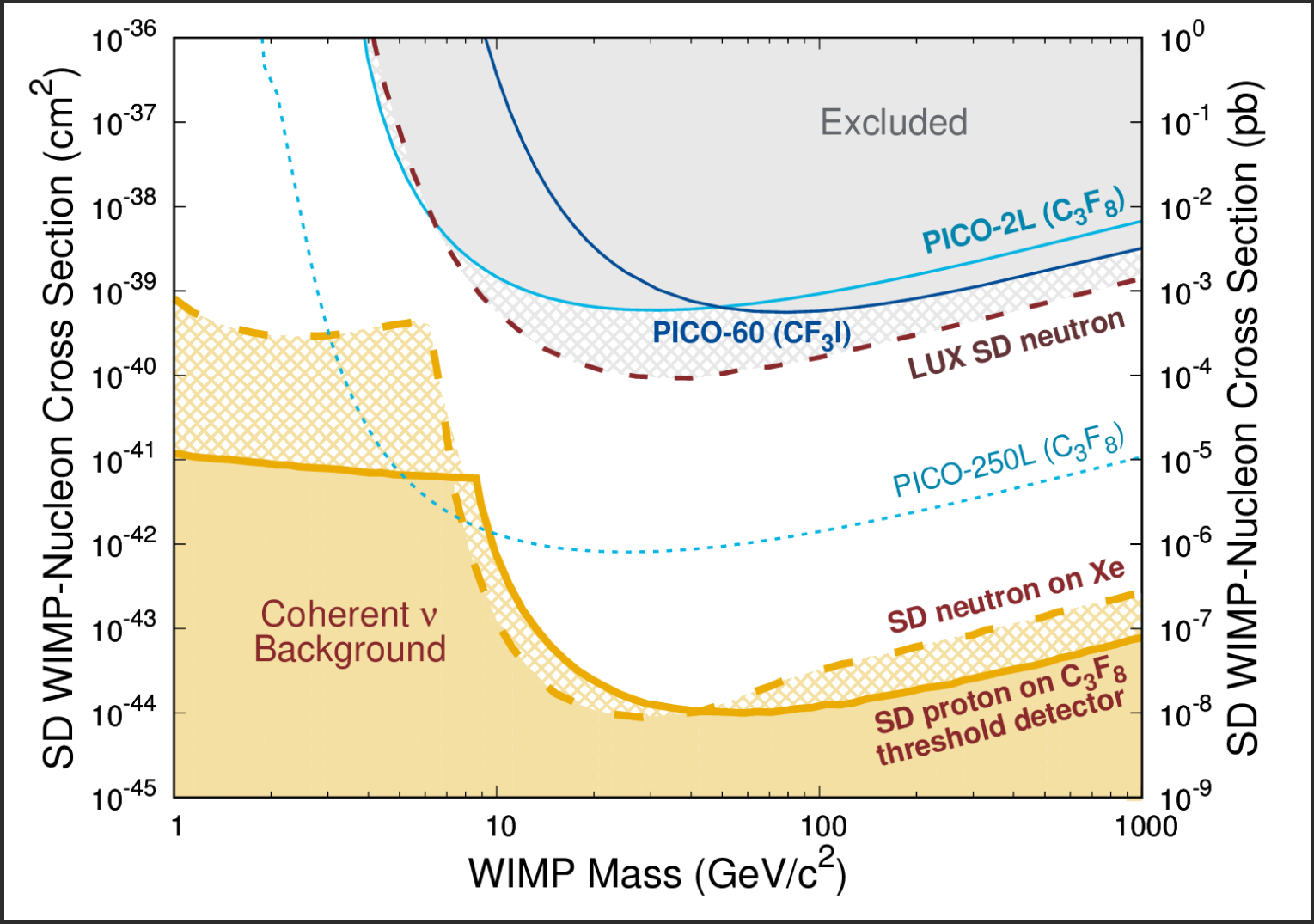
Detection of Particles with CCD



muons, electrons and diffusion limited hits.

nuclear recoils will produce diffusion limited hits

Spin-dependent WIMP interactions

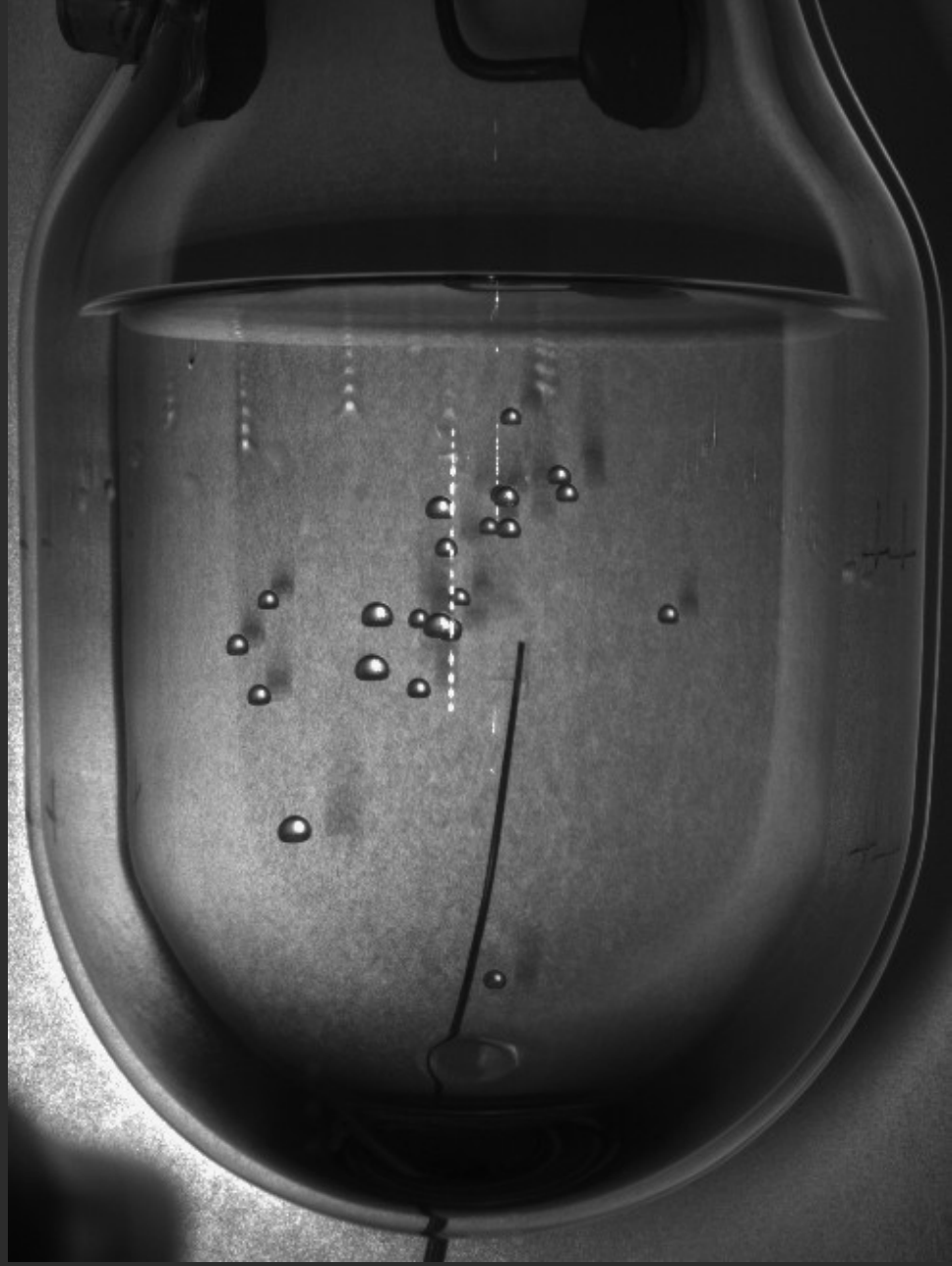


Fermilab

PICO

Bubble chambers

- Fluorine target
  - Spin-dependent sensitivity
- Insensitive to β/γ backgrounds
  - Dual energy and stopping power thresholds
- Technology developed at UChicago, Fermilab, and IUSB

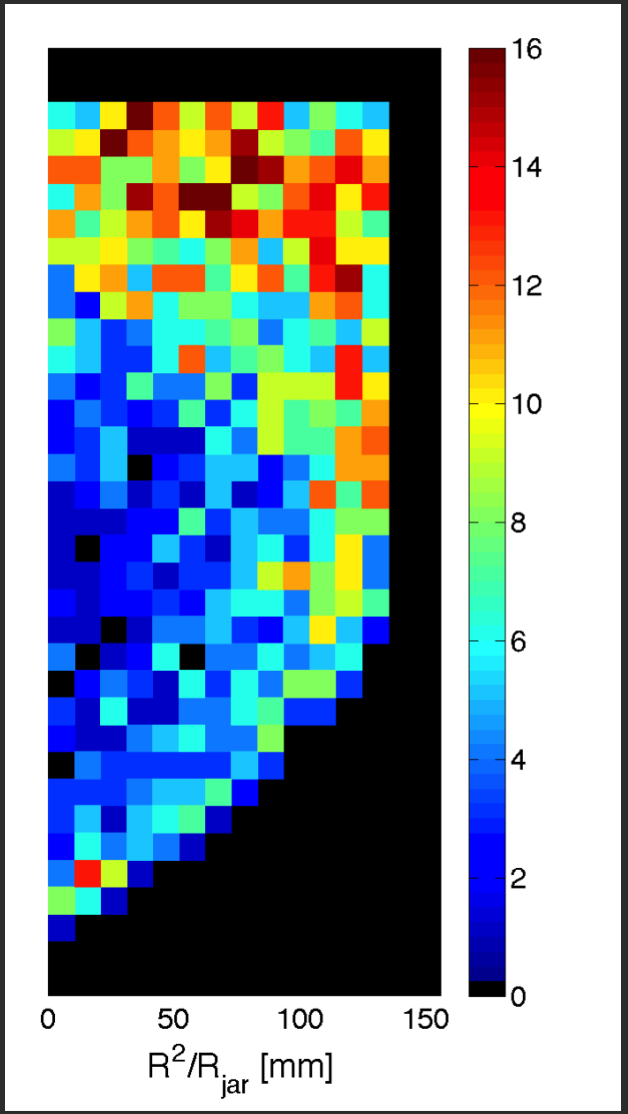


PICO

Campaign to eliminate particulate backgrounds

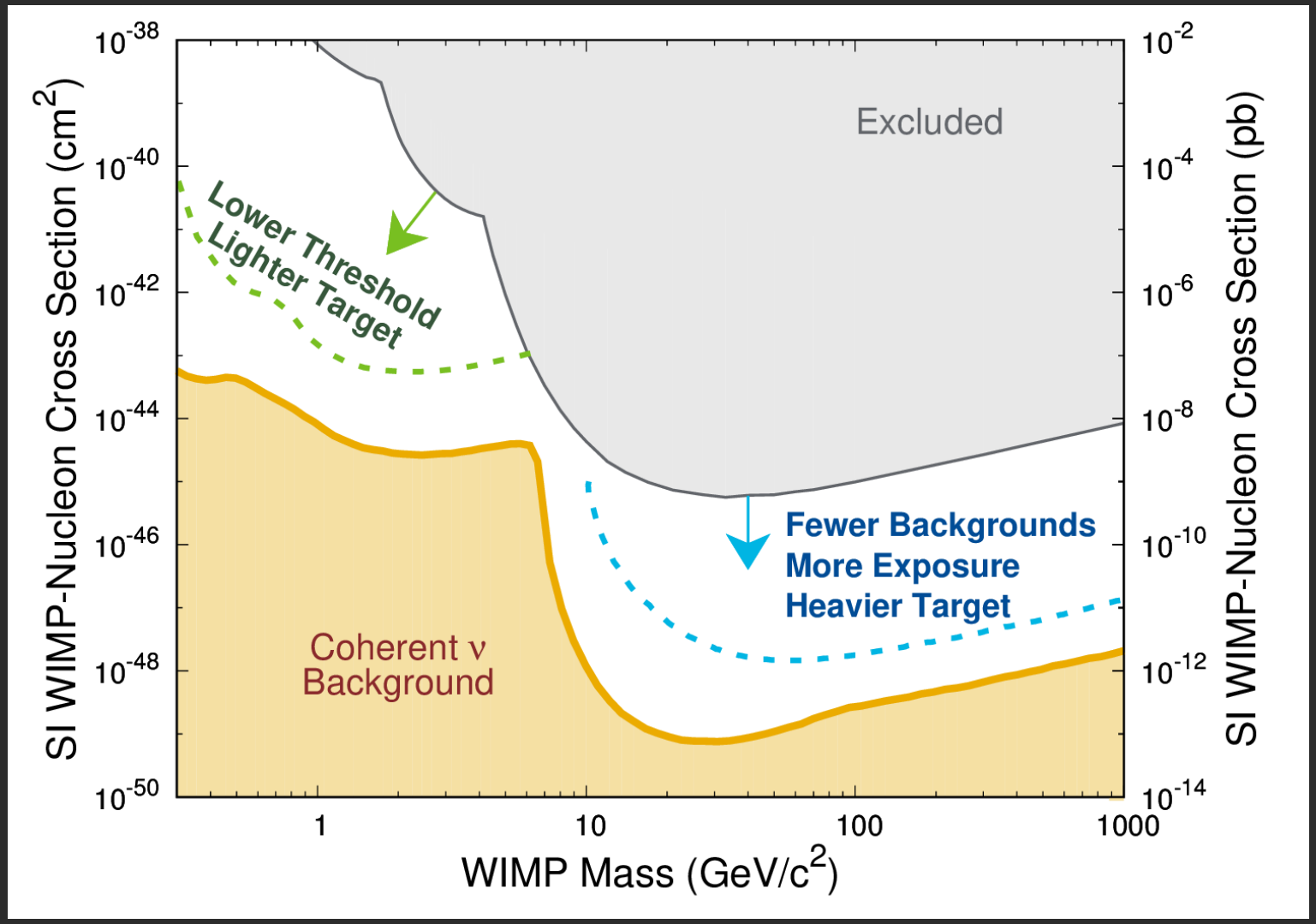
- Recent background free PICO-2L run
- Using lessons learnt for PICO-60 Run 2 (in commissioning)

PICO-60 Run 1 events



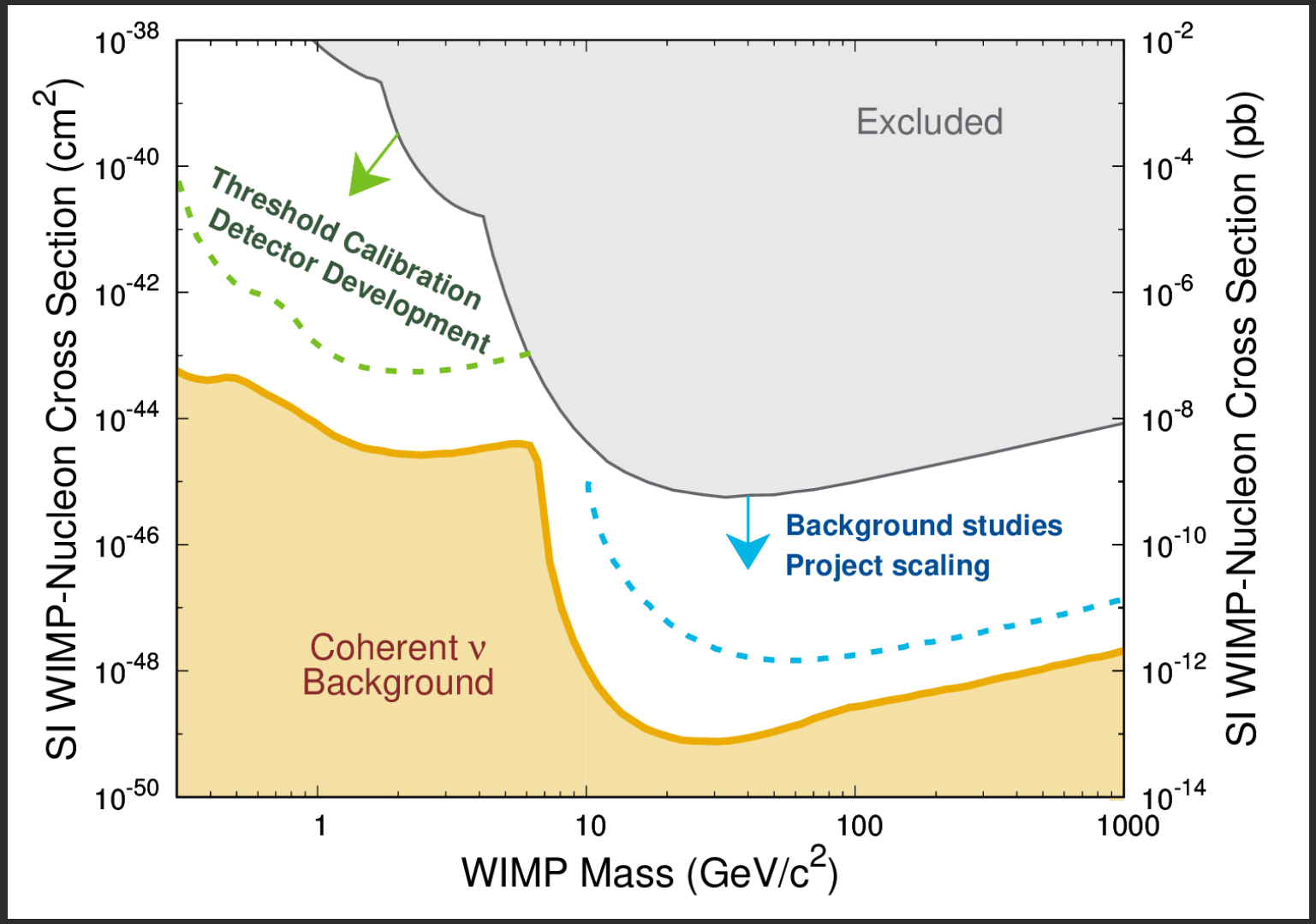
Fermilab

Calibration and Detector Development



Fermilab

Calibration and Detector Development

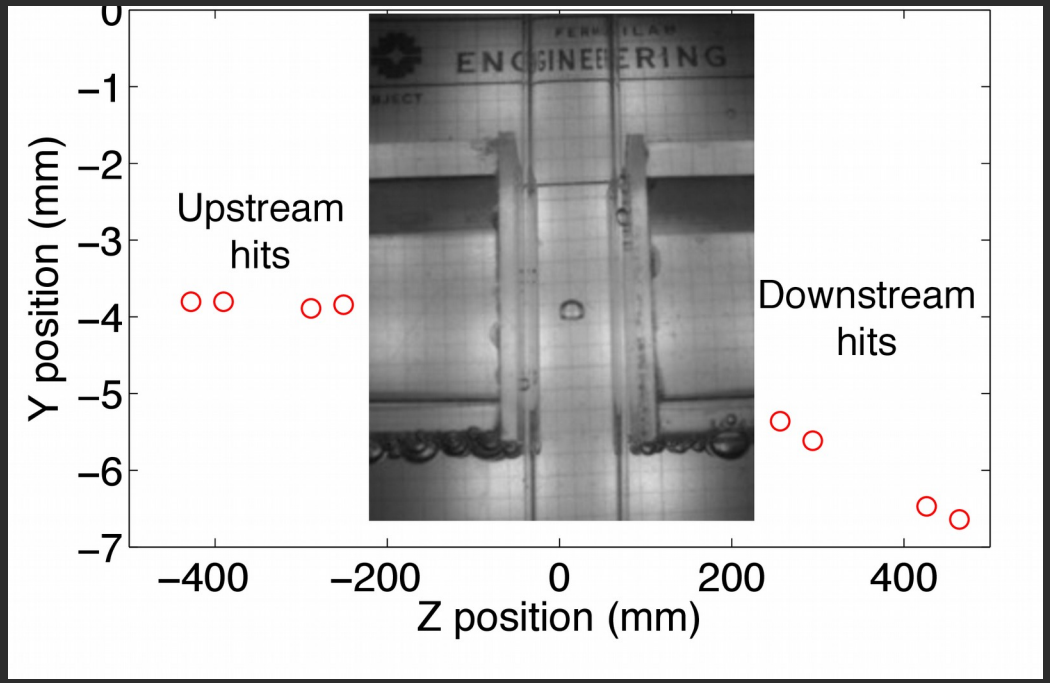


Detector Calibrations

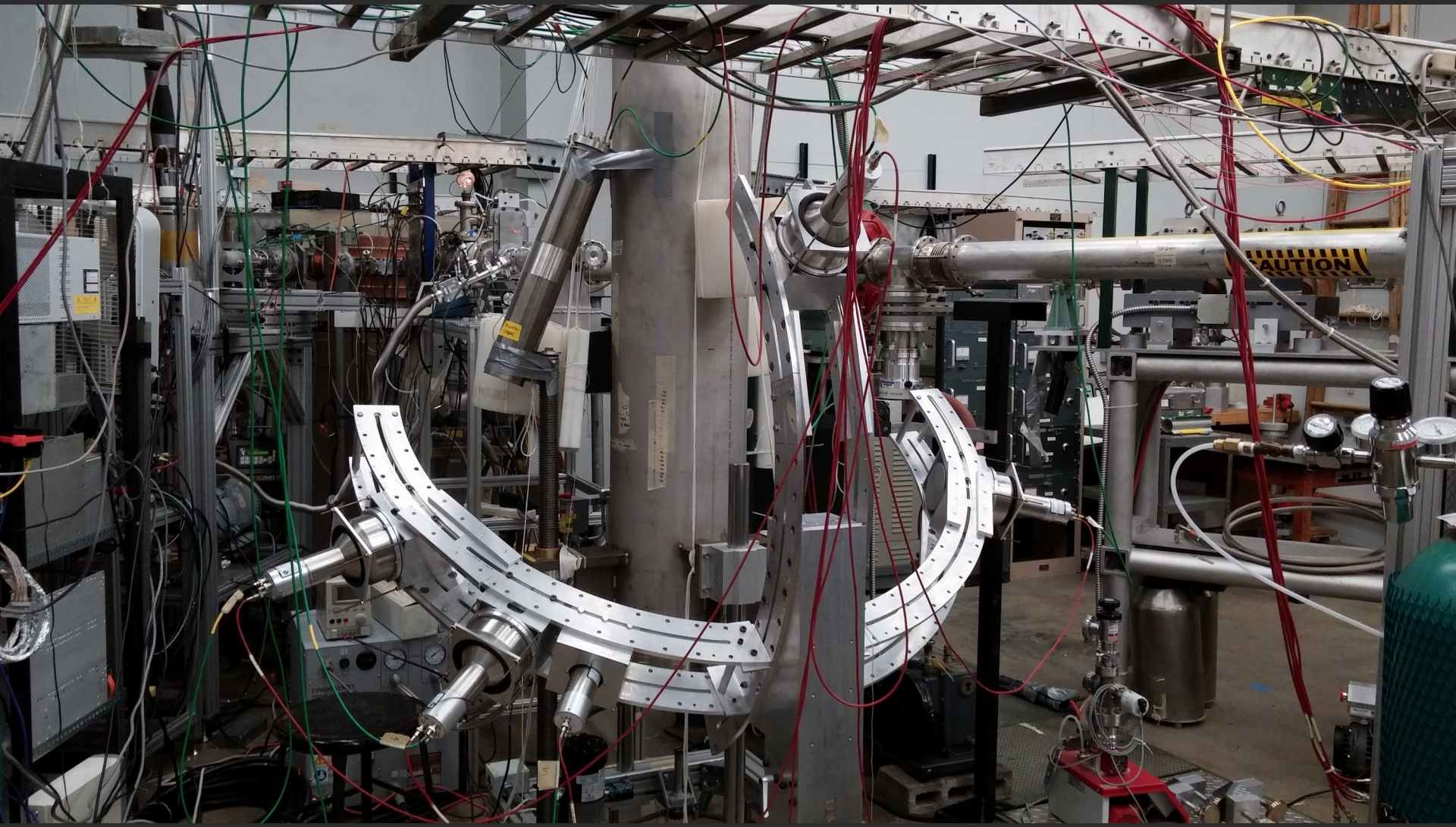
Probing the low-energy frontier

- Use neutron recoils or other techniques to calibrate the energy scale and linearity.
  - LXe : XCD
  - Lar : SCENE
  - CDMS: photoneutron & future neutron scattering experiment
  - DAMIC: Sb/Be, Antonella
  - PICO: CIRTE π^+ scattering, Y/Be, neutron scattering

CIRTE π^+ scattering



SCENE neutron scattering in LAr



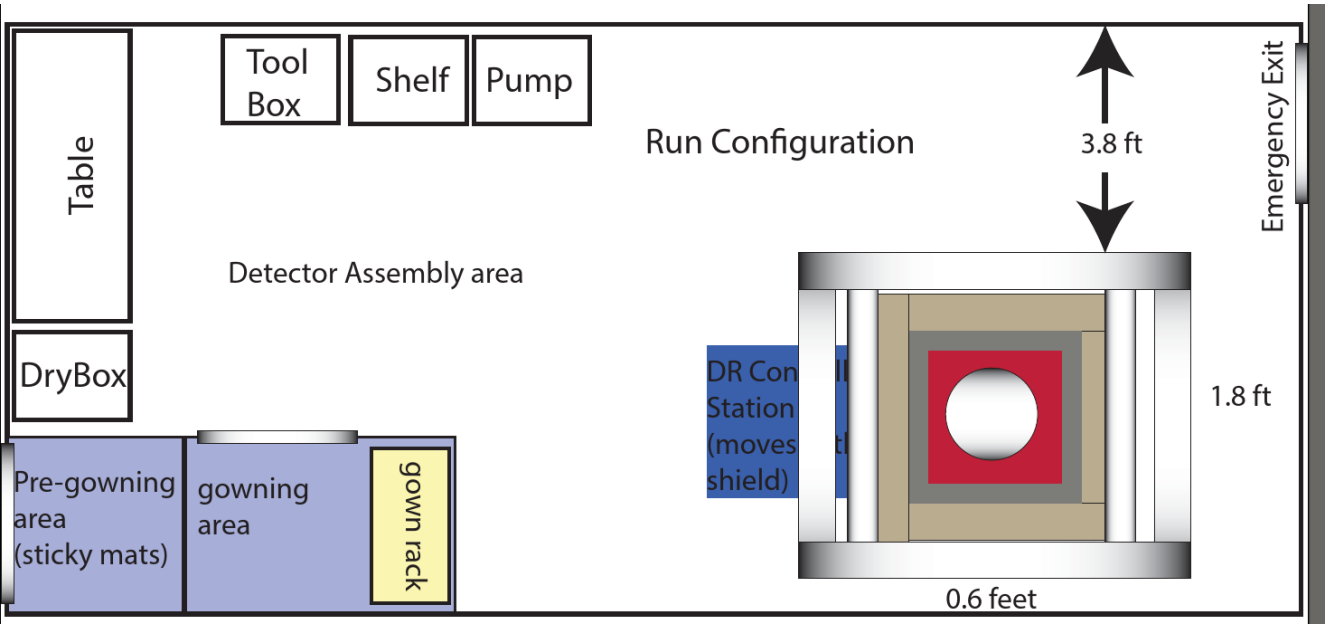
Detector Development

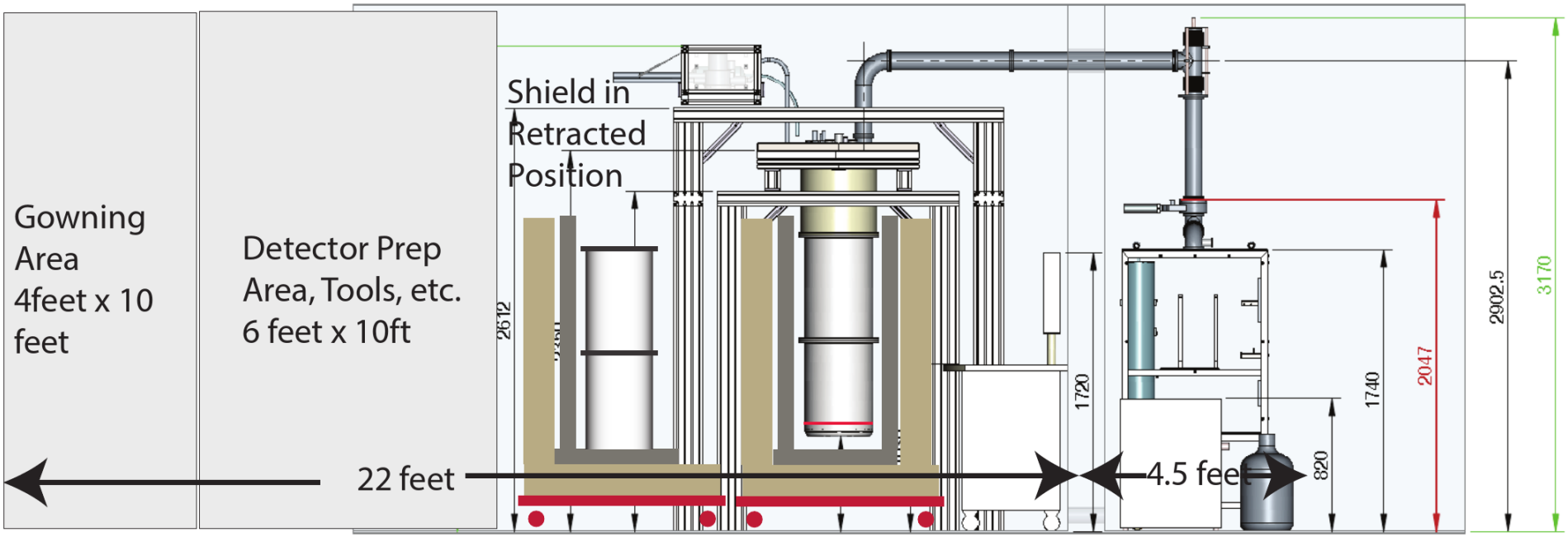
Leveraging Fermilab resources

- Cryogenics
  - Doped LXe
  - Xe bubble chamber
- NuMI underground site to test prototype detectors
  - New facilities to test low-threshold CCDs
  - Planned NEXUS facility to test cryogenic detectors

NEXUS@FNAL concept

In partnership with Northwestern University

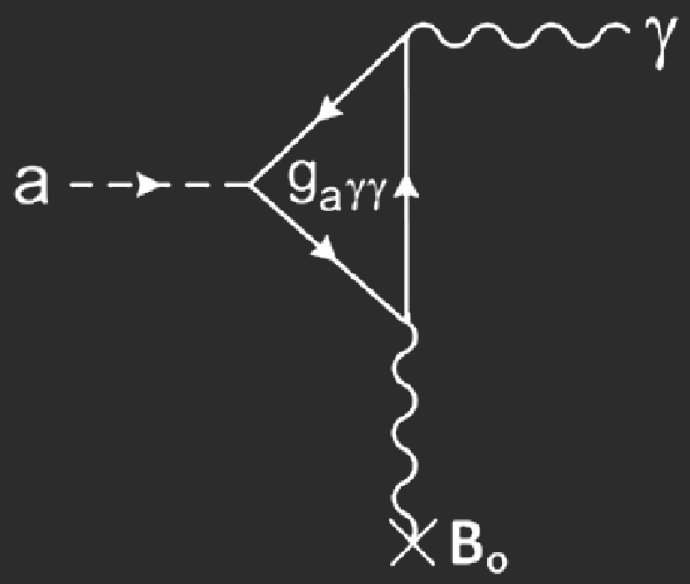


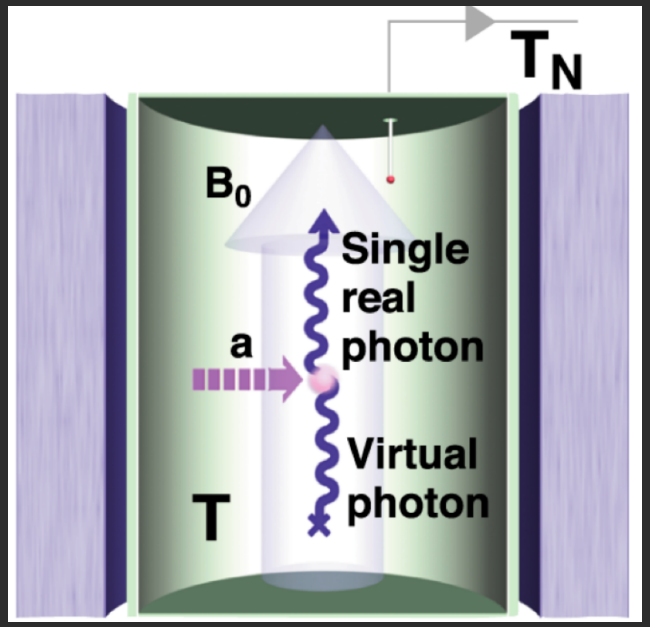


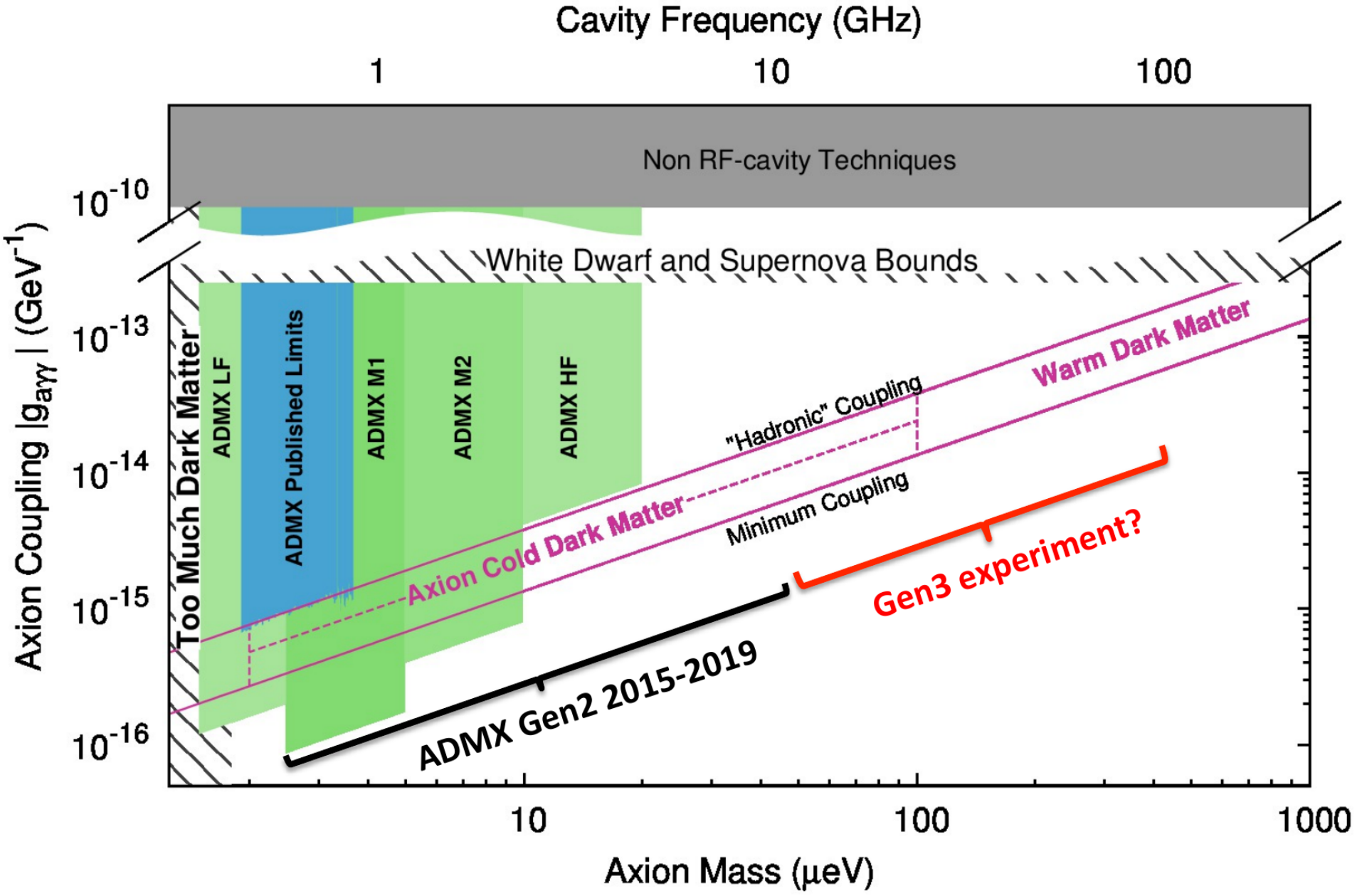
Axions

Axions are the thinking person's dark matter candidate – Michael Turner

- Solution for Cold Dark Matter and the Strong CP problem
- Detected via photon conversion in a strong magnetic field



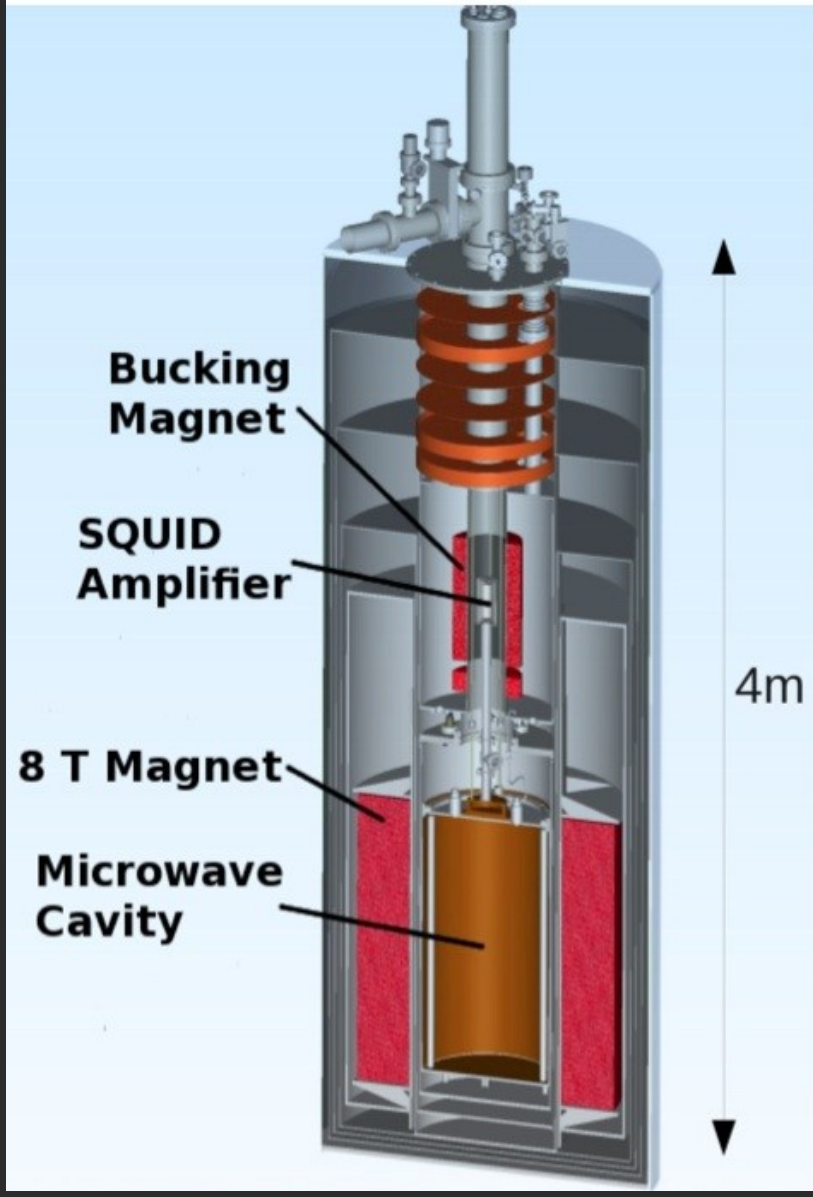



Cavity Frequency (GHz)
1
10
100
Non RF-cavity Techniques
White Dwarf and Supernova Bounds
Too Much Dark Matter
ADMX LF
ADMX Published Limits
ADMX M1
ADMX M2
ADMX HF
"Hadronic" Coupling
Warm Dark Matter
Axion Cold Dark Matter
Minimum Coupling
Gen3 experiment?
ADMX Gen2 2015-2019
Axion Coupling $|g_{a\gamma\gamma}|$ (GeV^{-1})
10^{-10}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10
100
1000
Axion Mass (μeV)

ADMX

High-Q cryogenic microwave cavity in strong magnetic field

- G2 dark matter program
- Fermilab to design next generation 2-8 GHz resonators
- Sensitivity increases with
  - stored magnetic energy
  - cavity quality factor
  - lower temperature
- R&D to reach higher frequencies
  - Lab directed R&D to investigate tunable dielectrics



AI MX

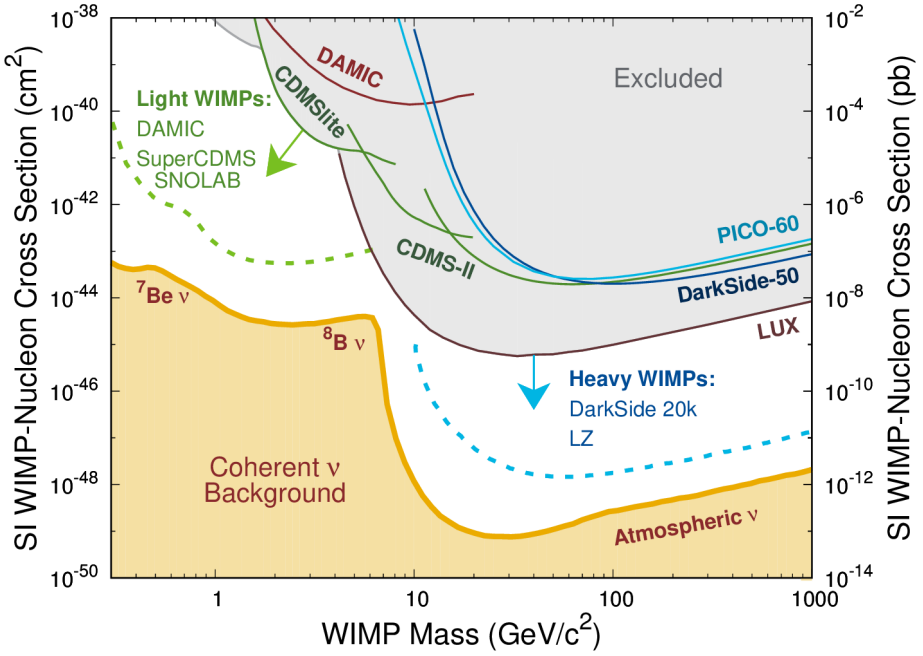
Direct Dark Matter Detection

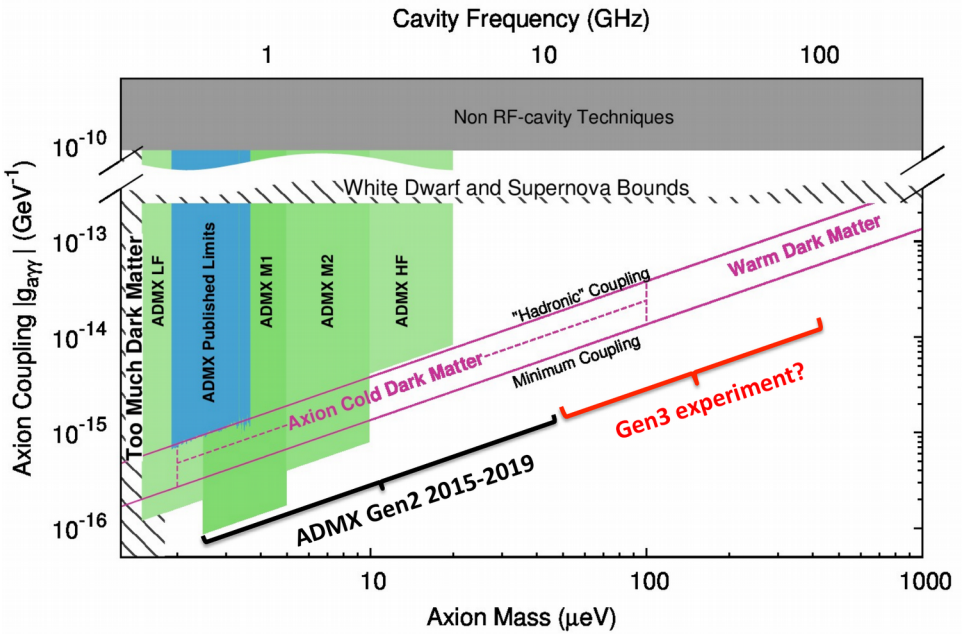
Low rates and weak signals. Successful detection requires

- A spectrum of techiques and target materials
- Understanding of detector performance
- Lowering backgrounds

Fermilab has unique expertise and facilities

- Cryogenics
- Cavities and magnets
- Low threshold calibrations
- Underground facilities
- Detector development expertise


SI WIMP-Nucleon Cross Section (cm^2)
SI WIMP-Nucleon Cross Section (pb)
WIMP Mass (GeV/c^2)
Excluded
DAMIC
CDMSlite
CDMS-II
PICO-60
DarkSide-50
LUX
Light WIMPs:
DAMIC
SuperCDMS
SNOLAB
Heavy WIMPs:
DarkSide 20k
LZ
^{7}Be ν
^{8}B ν
Coherent ν Background
Atmospheric ν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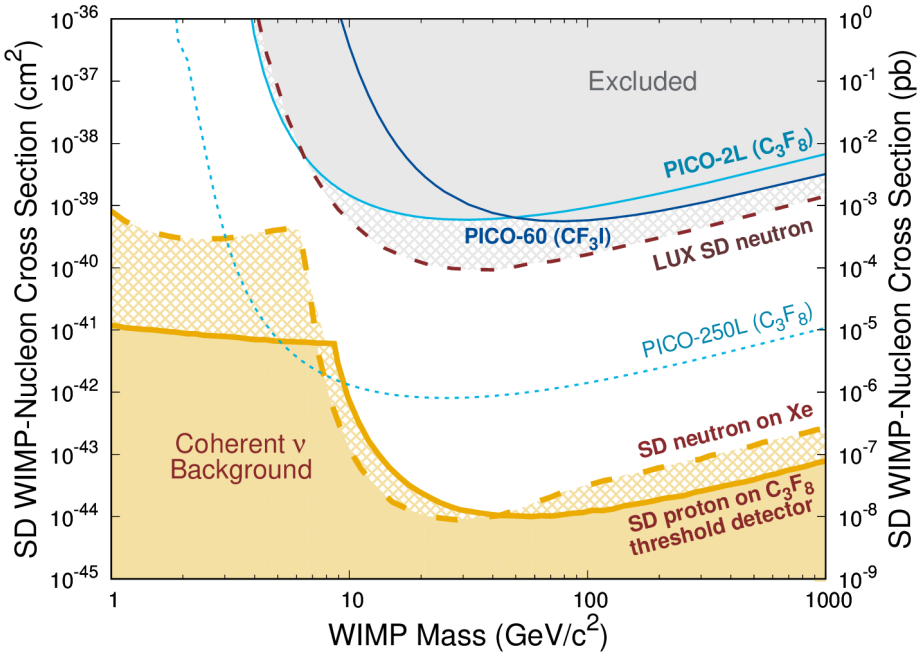
ADMX Gen2 2015-2019


SD WIMP-Nucleon Cross Section (cm^2)
SD WIMP-Nucleon Cross Section (pb)
WIMP Mass (GeV/c^2)
Excluded
PICO-2L (C_3F_8)
PICO-60 (CF_3I)
LUX SD neutron
PICO-250L (C_3F_8)
SD neutron on Xe
SD proton on C_3F_8 threshold detector
Coherent ν Background

North Cage
DANGER