Dark Matter and Neutrino Physics with Scintillating Bubble Chambers

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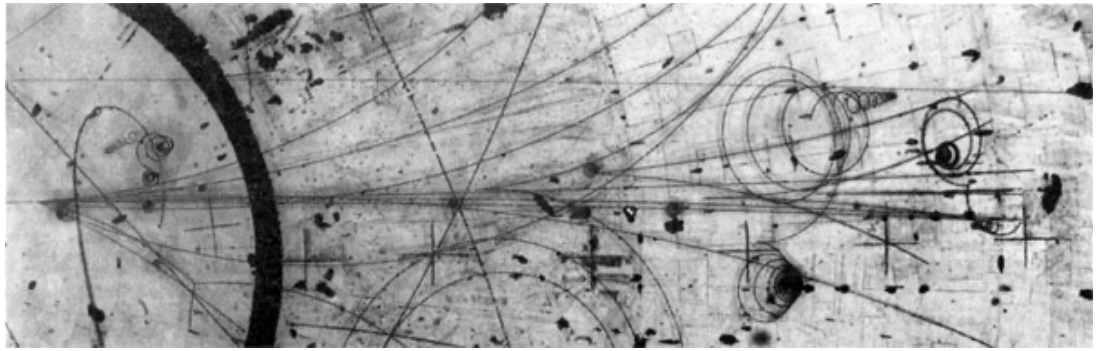
IPMU/ICRR/ILANCE Seminar

14 September 2022

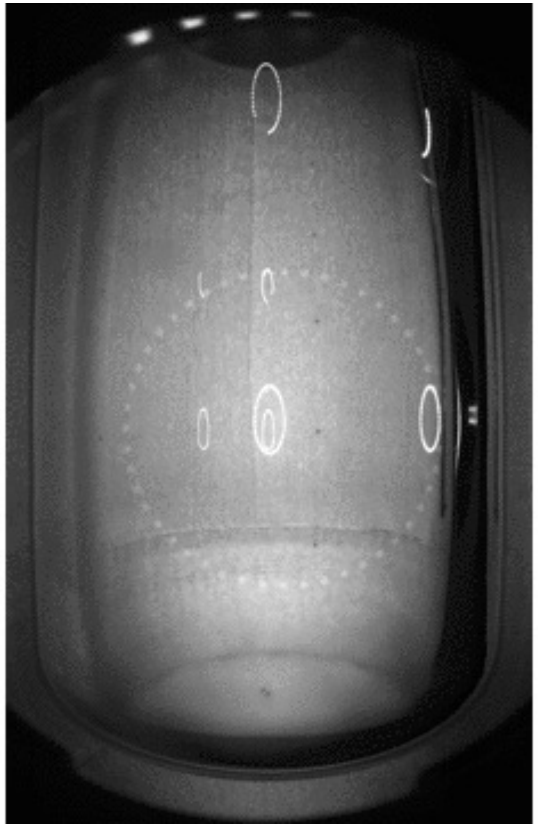
Two phases of bubble chamber physics

- 1970s: Neutrino Beam Physics



  - Sensitive to minimum ionizing particles
  - Particle tracks visible
  - Threshold <<1 keV
  - Multi-ton chambers, multiple fluids

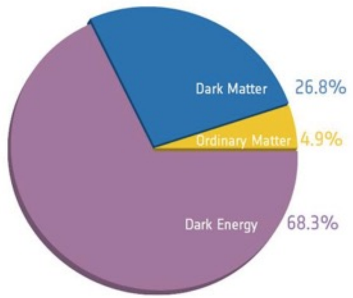
- 2000-today: Nuclear Recoil Detectors
  - Dark matter searches with fluorocarbon bubble chambers
  - Threshold ~3keV
  - Sensitive only to nuclear recoils (electron recoil blind)

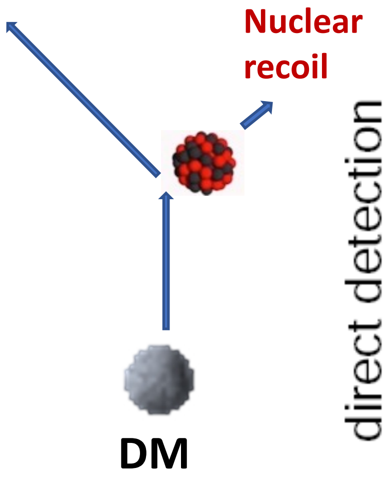


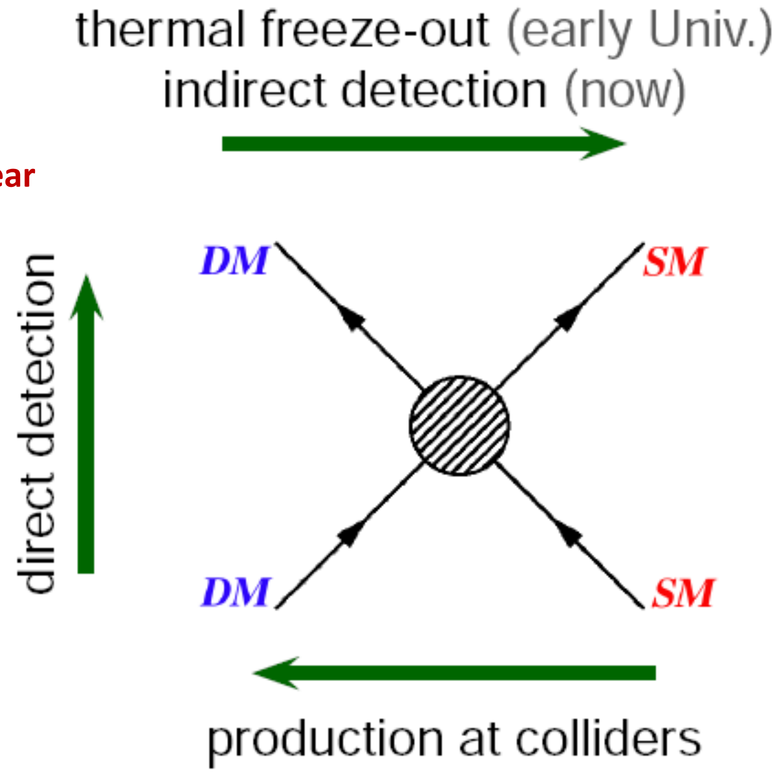
Overview

- Recent highlights from low-background **PICO** fluorocarbon bubble chambers.
- How do bubble chambers work?
- The Scintillating Bubble Chamber (**SBC**) program to develop sub-keV nuclear recoil threshold liquid-noble bubble chambers.
- Physics opportunities with SBC.

Dark matter direct detection







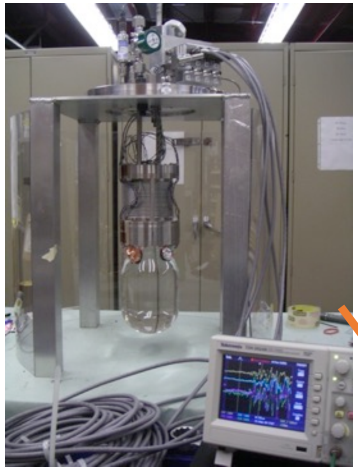
Requires:

- Sensitivity to O(10 keV) nuclear recoils from dark matter particles.
- Discrimination between electron recoils and nuclear recoils.
- Shielding from other sources of nuclear recoils, especially neutrons

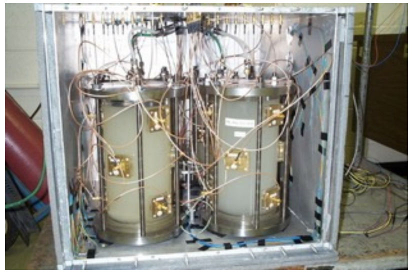
PICO overview

-2012

COUPP



PICASSO



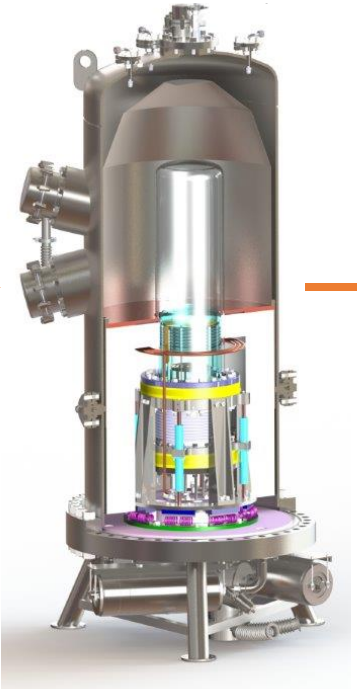
2013-18

PICO-2L

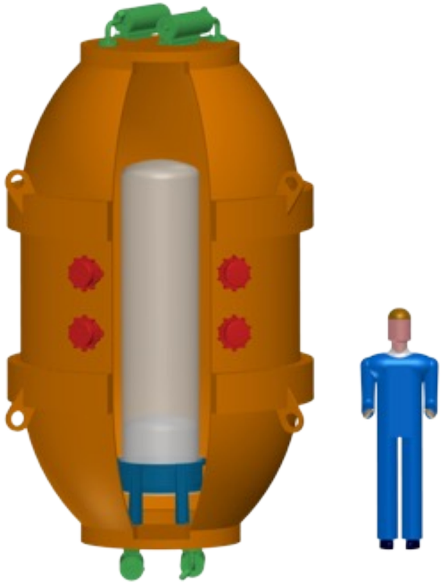
PICO-60

Now/future

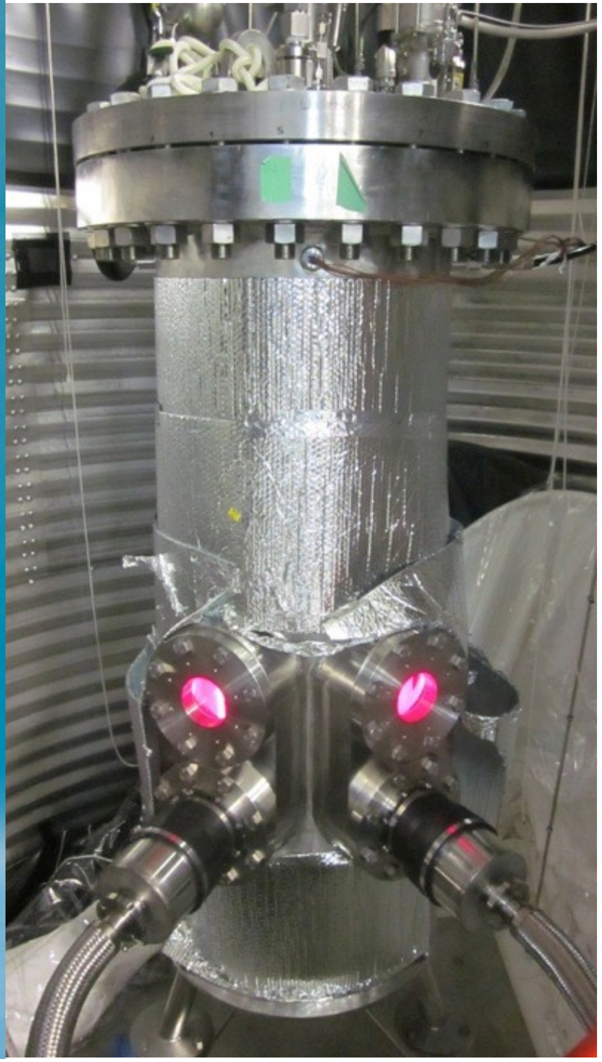
PICO-40L



PICO-500



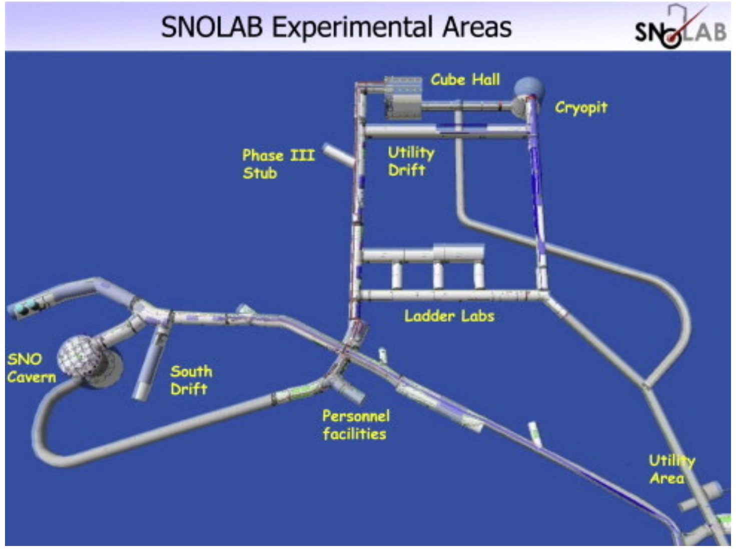
PICO-60

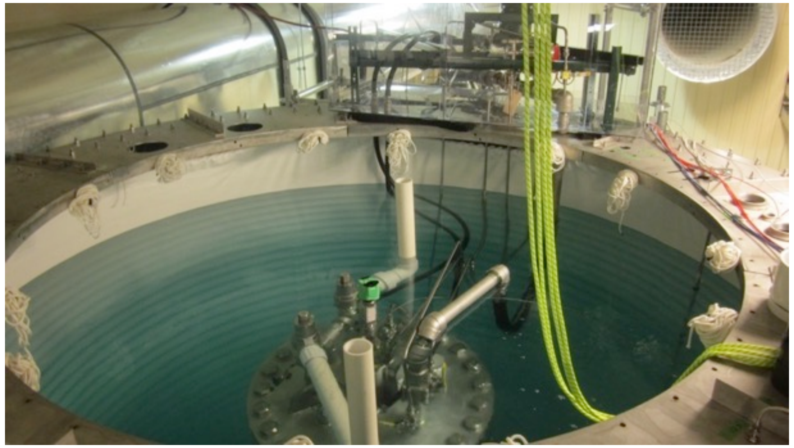


Operated with both CF_3I and C_3F_8 target fluids.

Active volume ~30L.

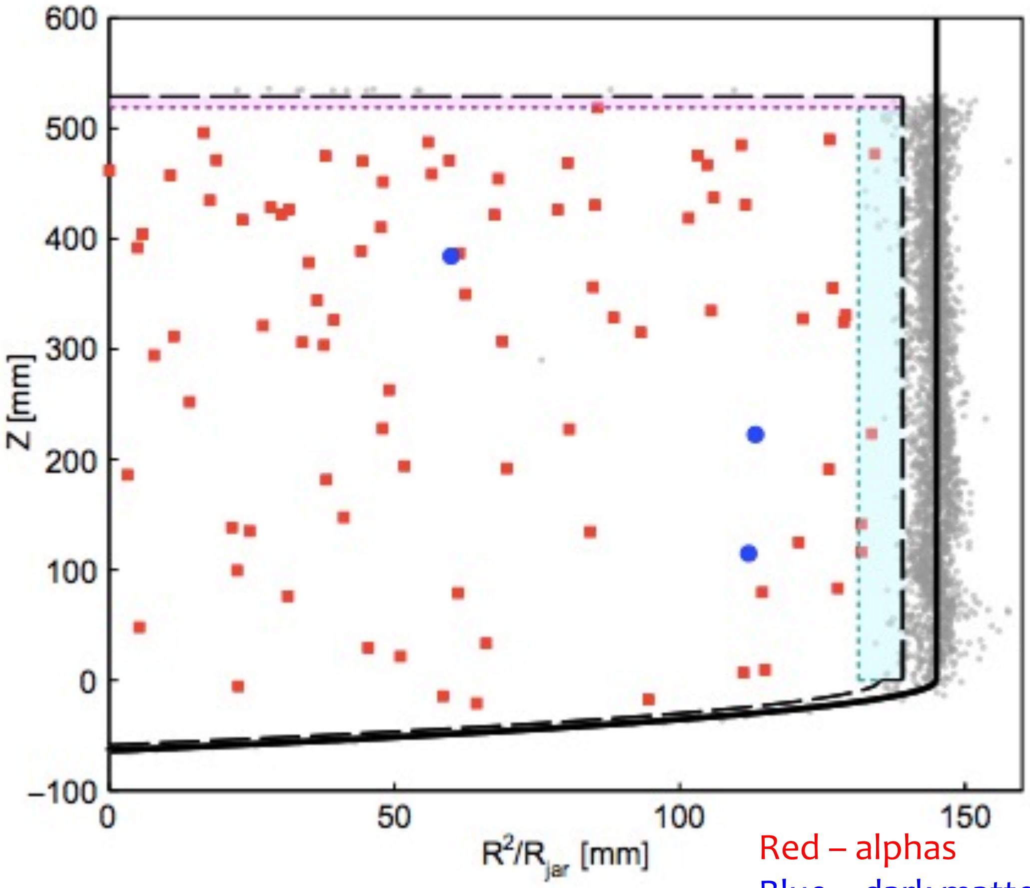
PICO-60 at SNOLAB





Several dark matter search runs at SNOLAB 2013-2018.

Results: 2.45keV C_3F_8 run

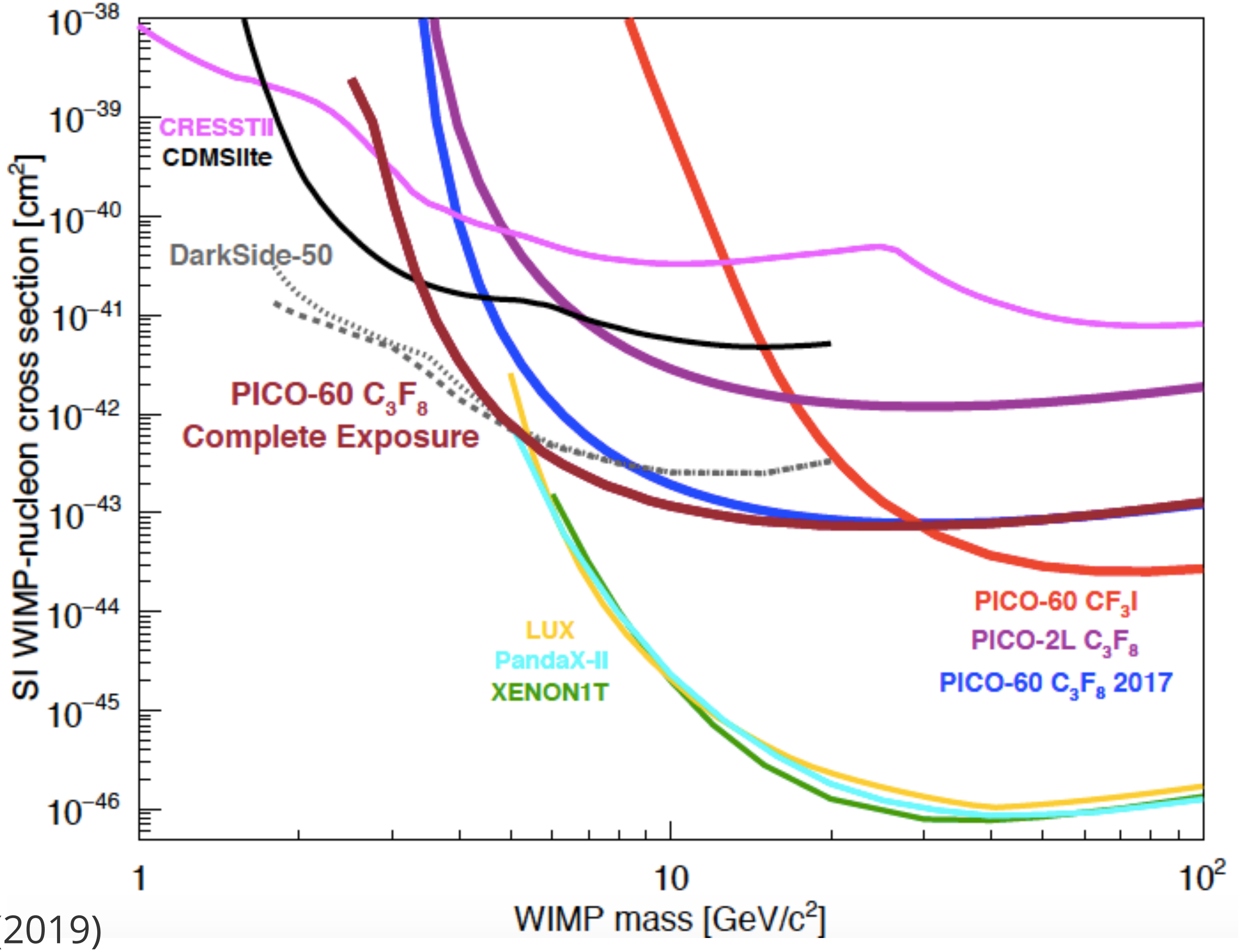


30 days live time, 1400 kg-days exposure.

Three dark matter candidates **consistent with expected neutron background**.

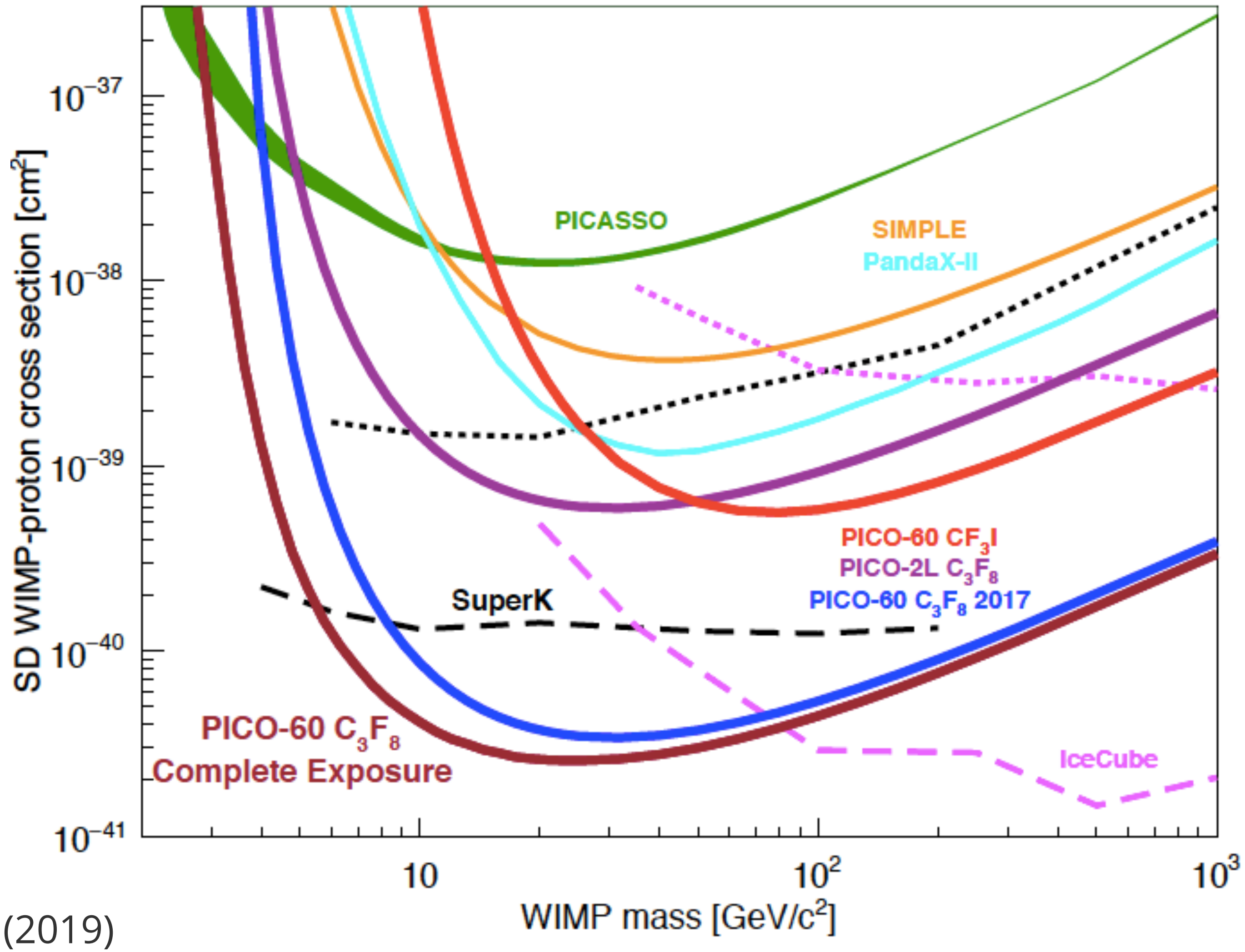
Red – alphas
Blue – dark matter candidates
Grey – Wall/surface

Dark matter exclusion



Phys. Rev. D 100, 022001 (2019)

Spin-dependent exclusion



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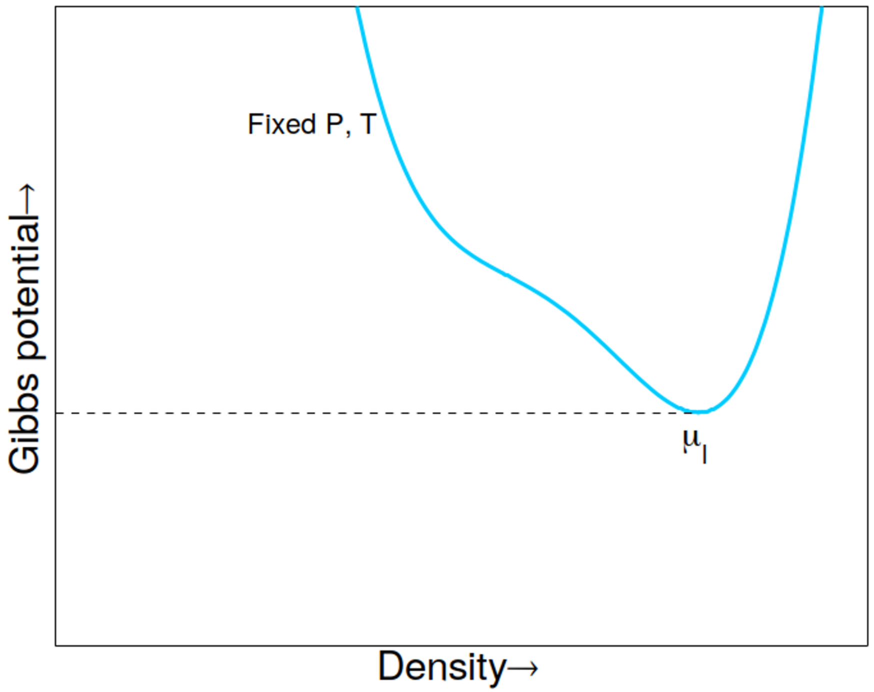
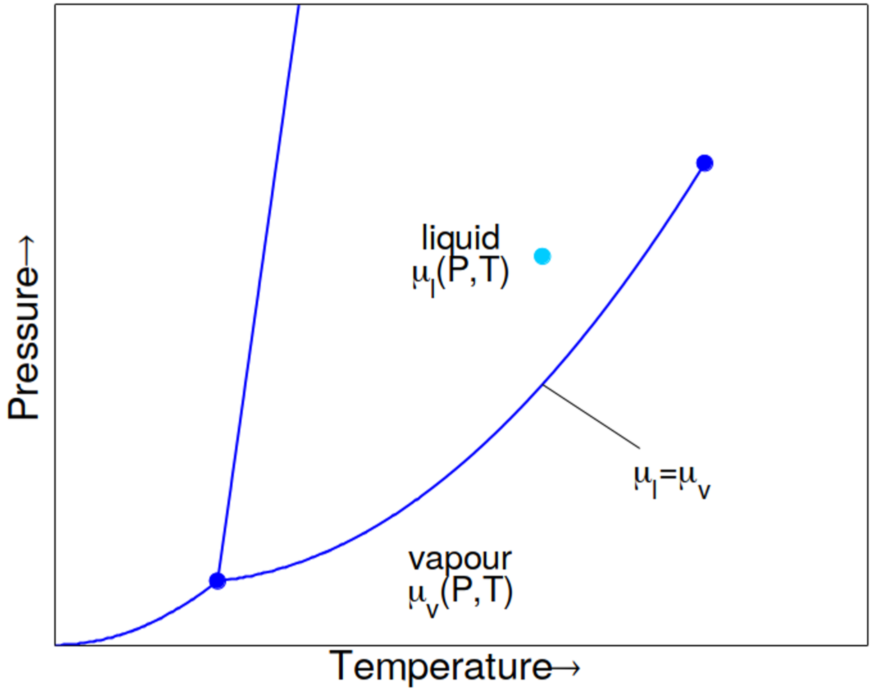
How bubble chambers work





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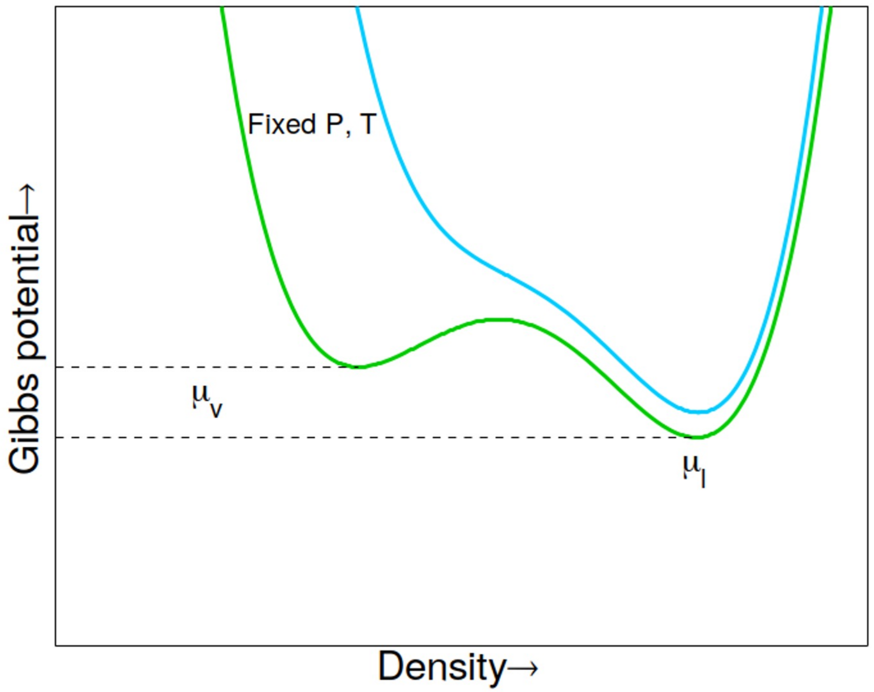

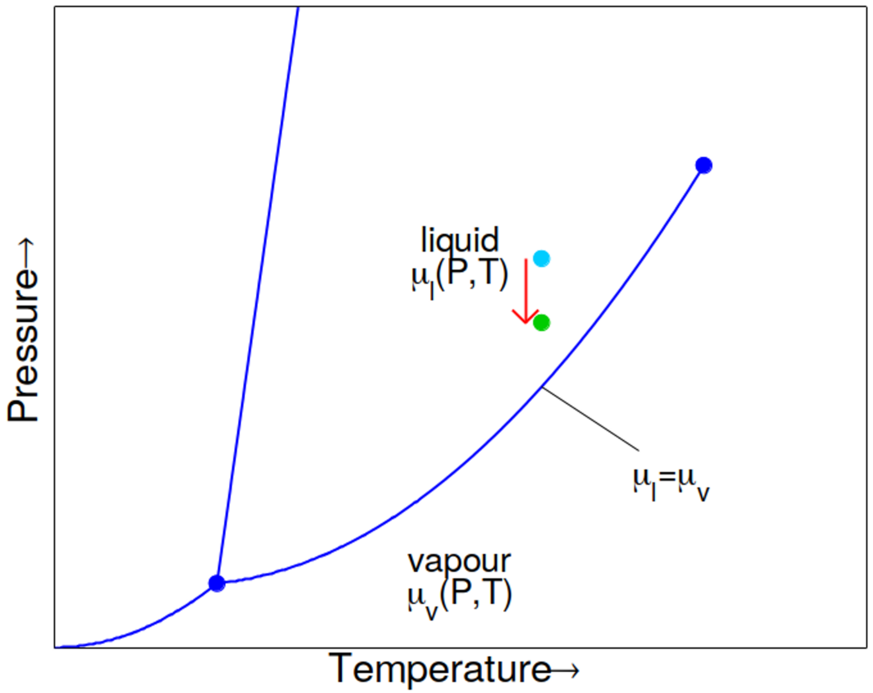

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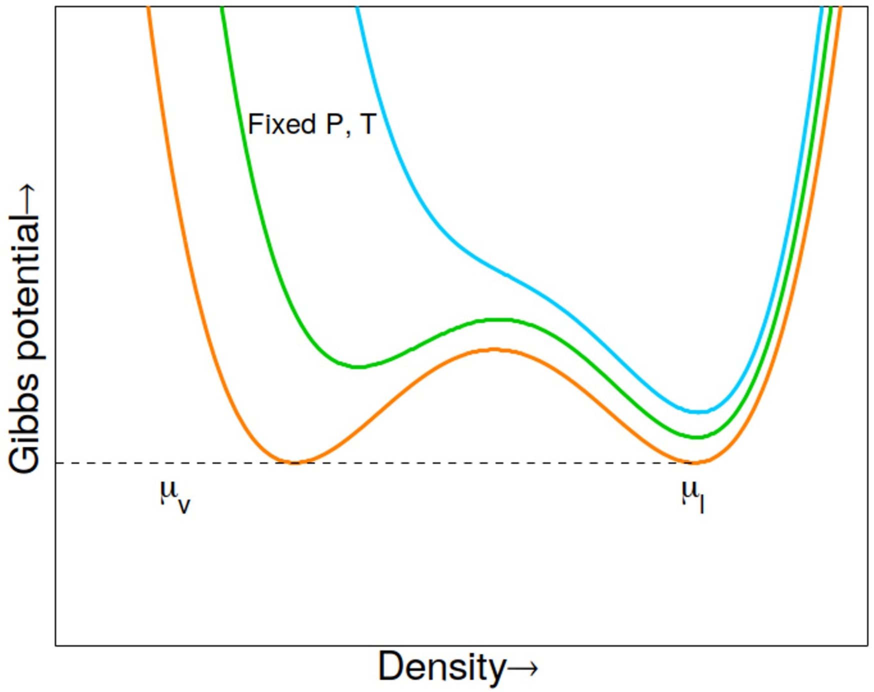

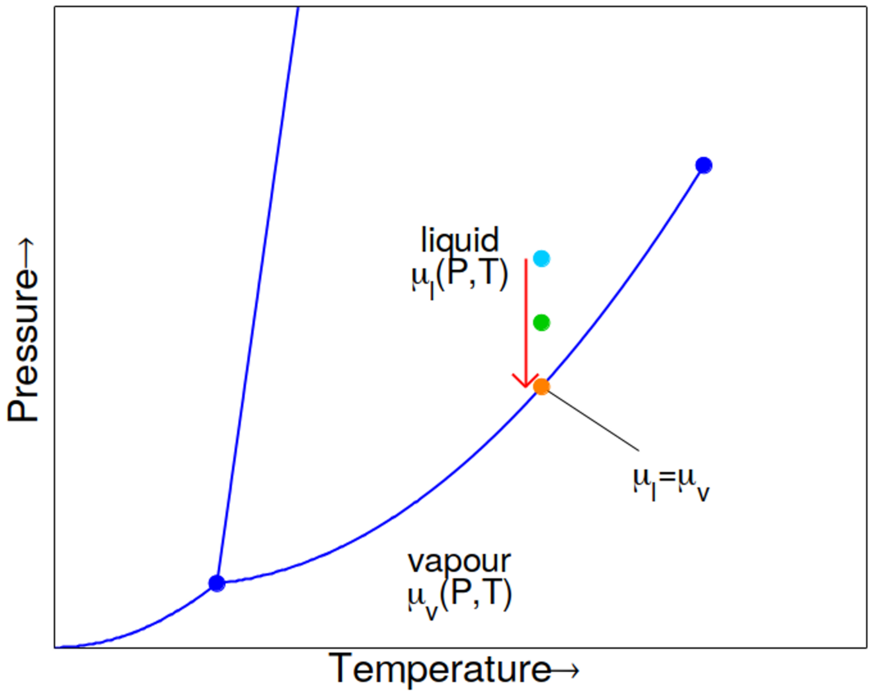

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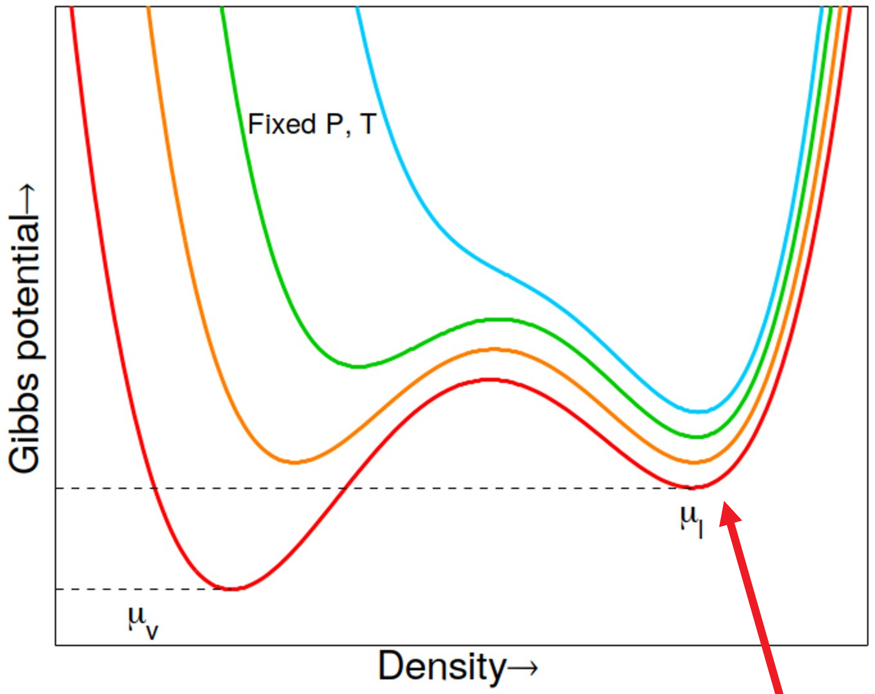
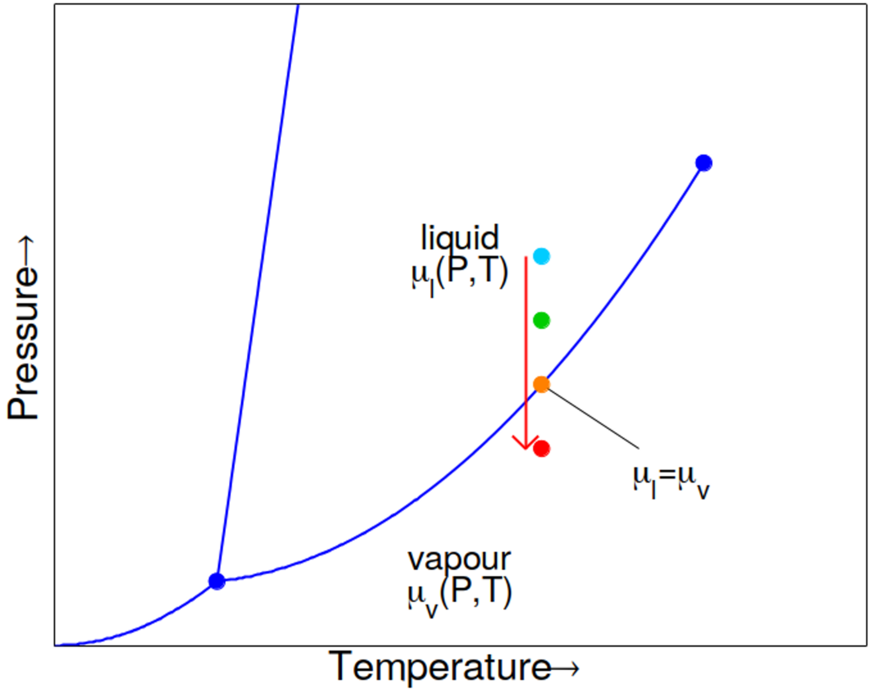
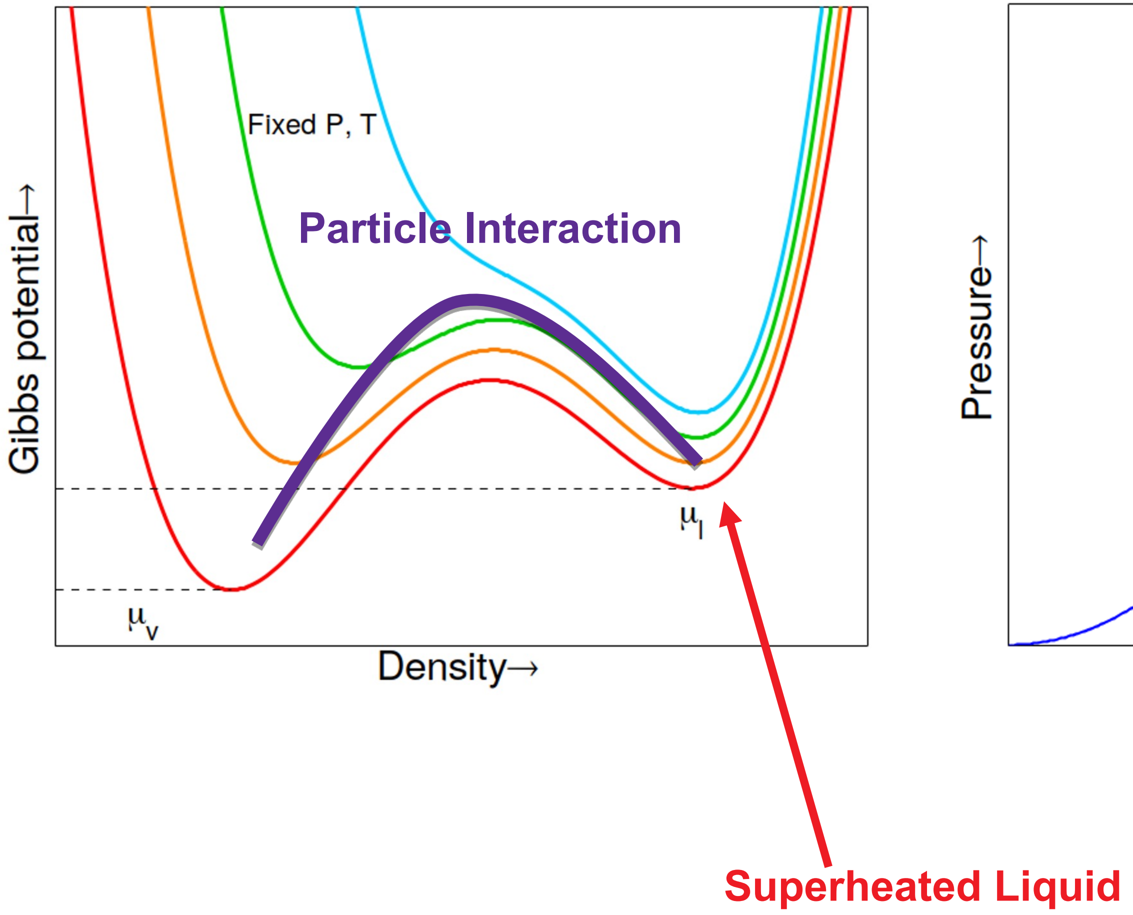
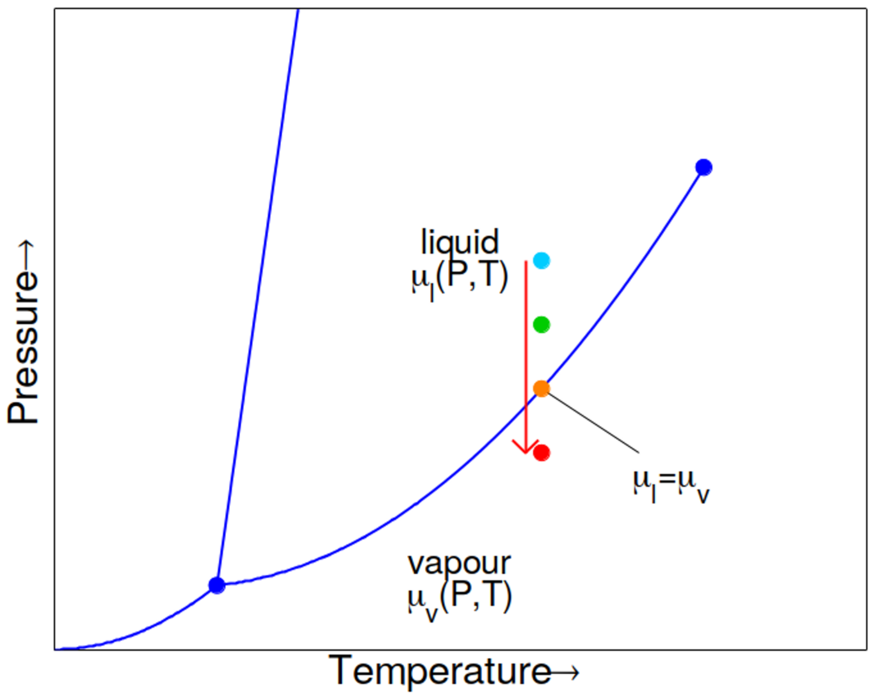




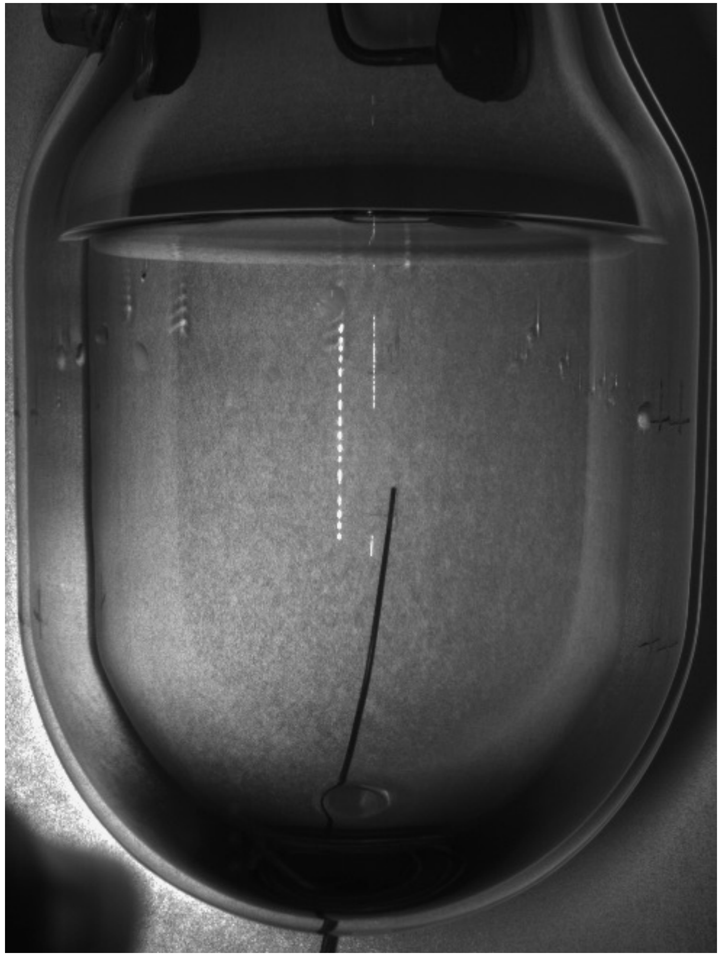
Superheated Liquid

How bubble chambers work



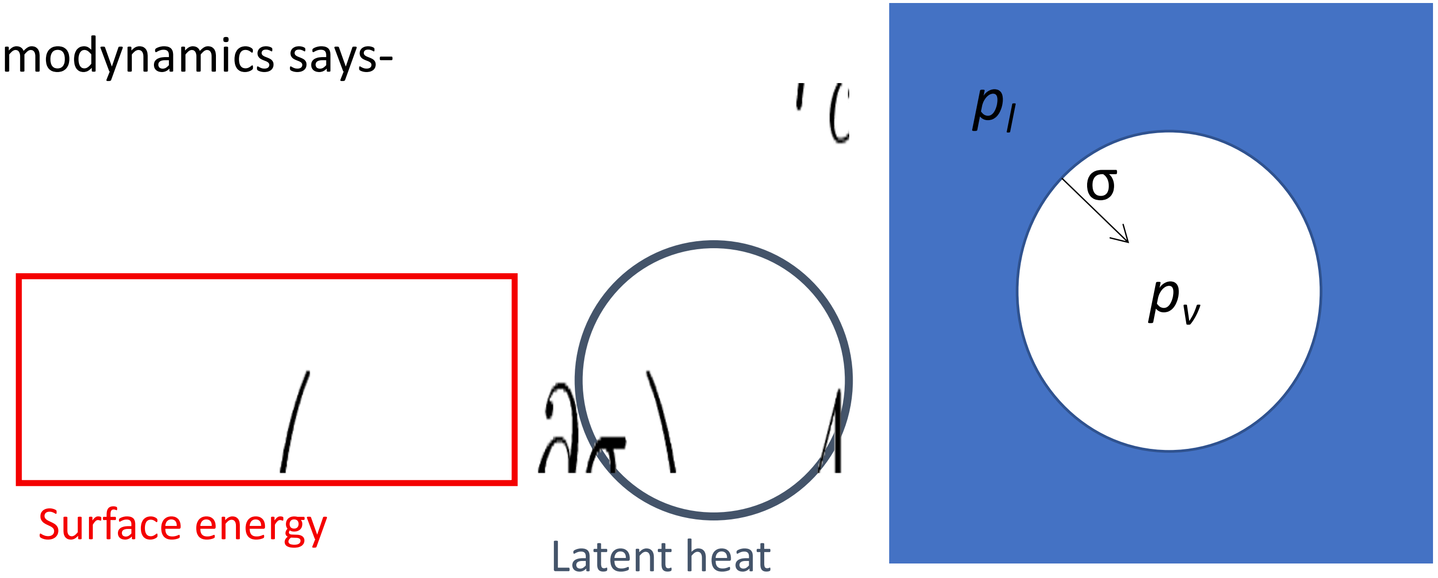


PICO-2L event (calibration)



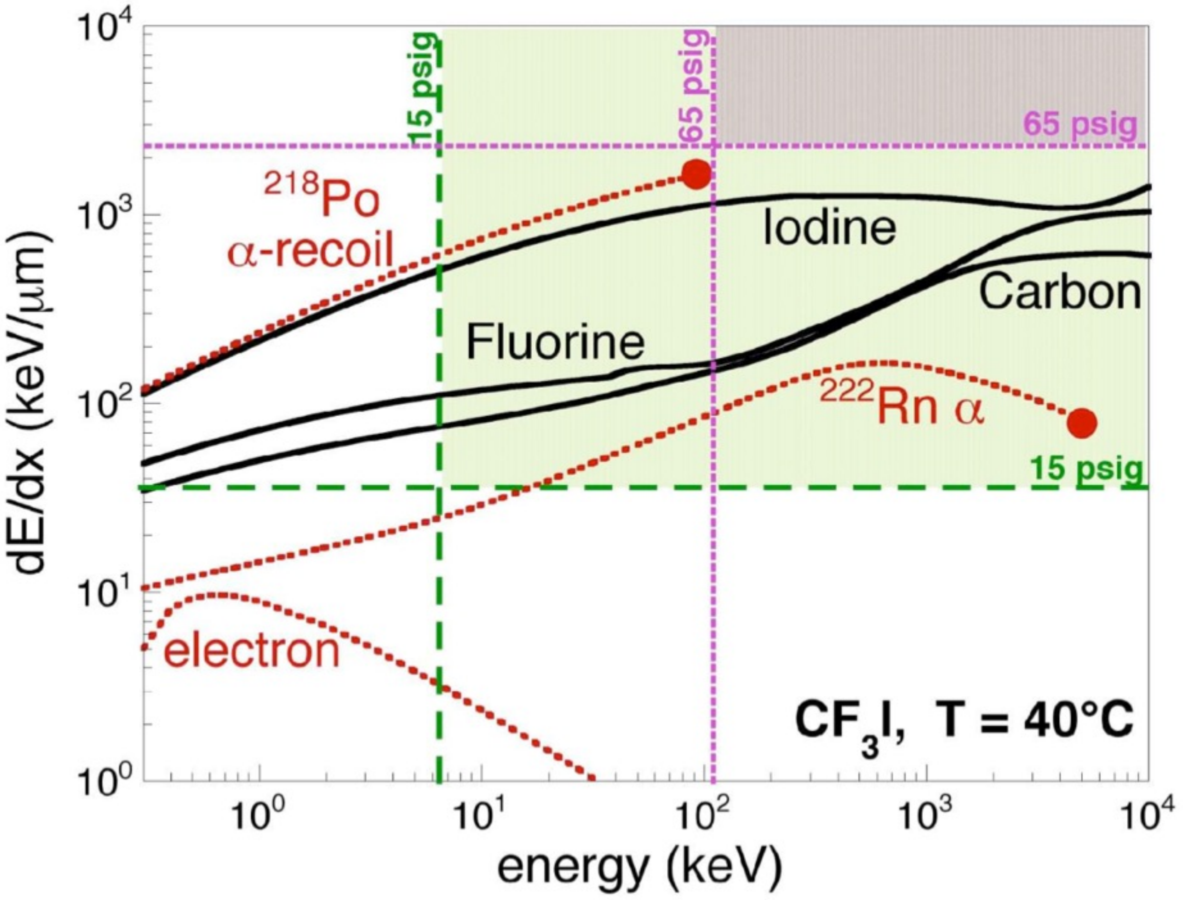
Seitz Model

- A bubble chamber is filled a superheated fluid in meta-stable state.
- Energy deposition greater than E_{th} in radius less than r_c from particle interaction will result in expanding bubble *(Seitz "Hot-Spike" Model).*
- A smaller or more diffuse energy deposit will create a bubble that immediately collapses.
- Classical Thermodynamics says-

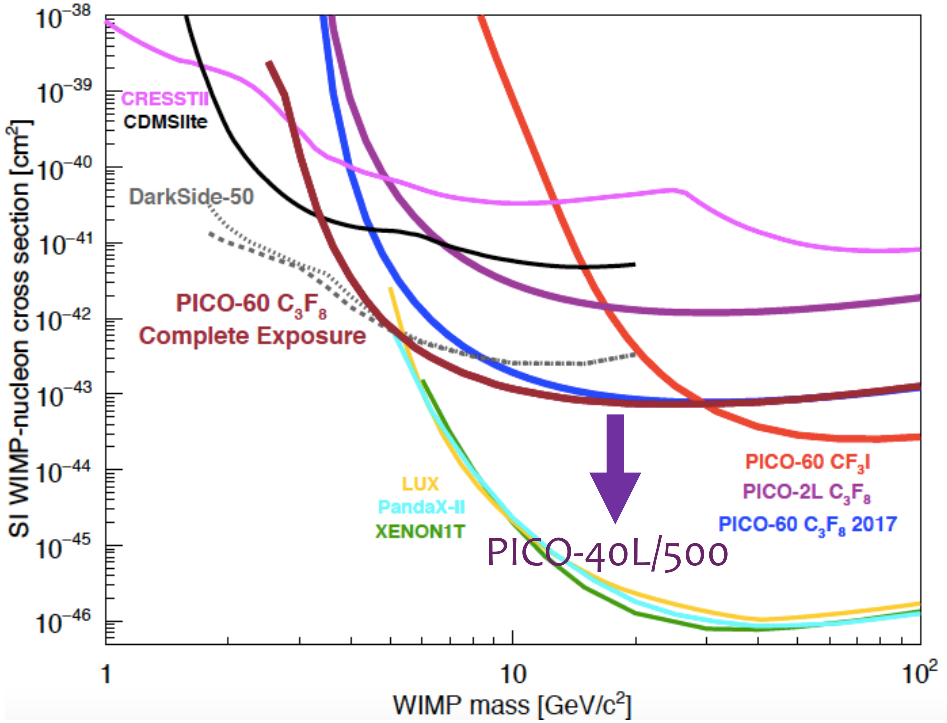


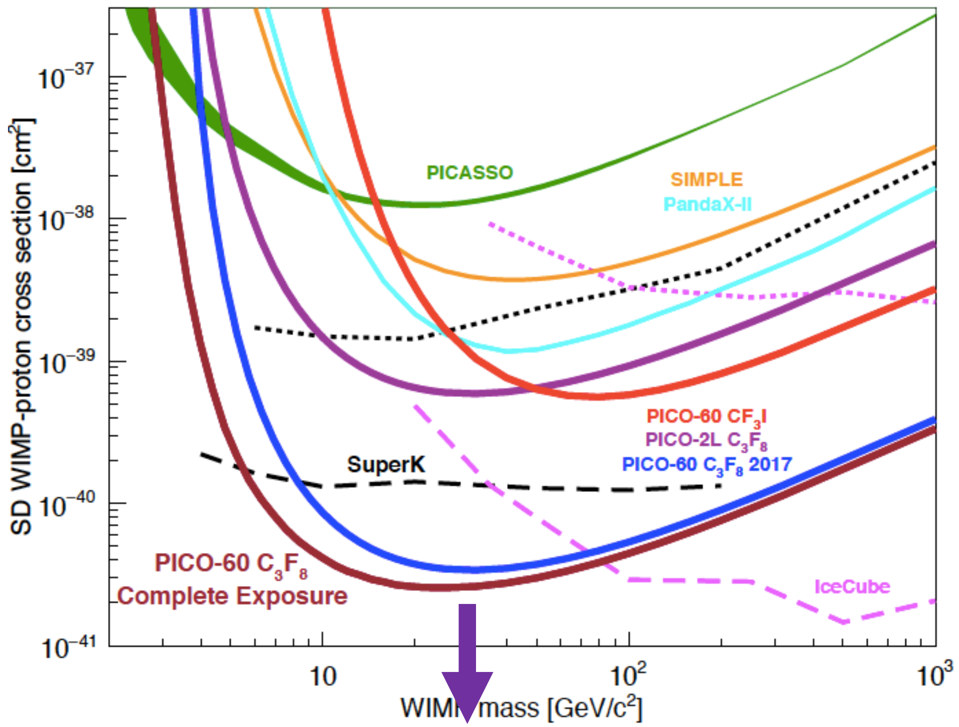
Bubble chambers as nuclear recoil detectors

- Thermodynamic parameters are chosen for sensitivity to nuclear recoils but not electron recoils.
- Better than **10^{-10}** rejection of electron recoils (betas, gammas).



Future: go bigger

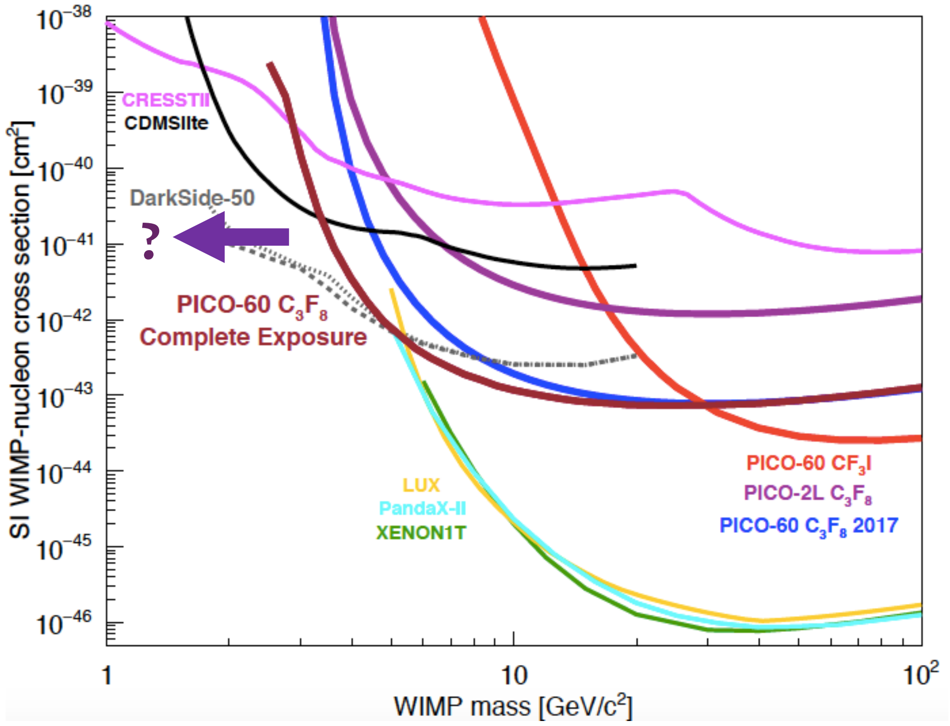


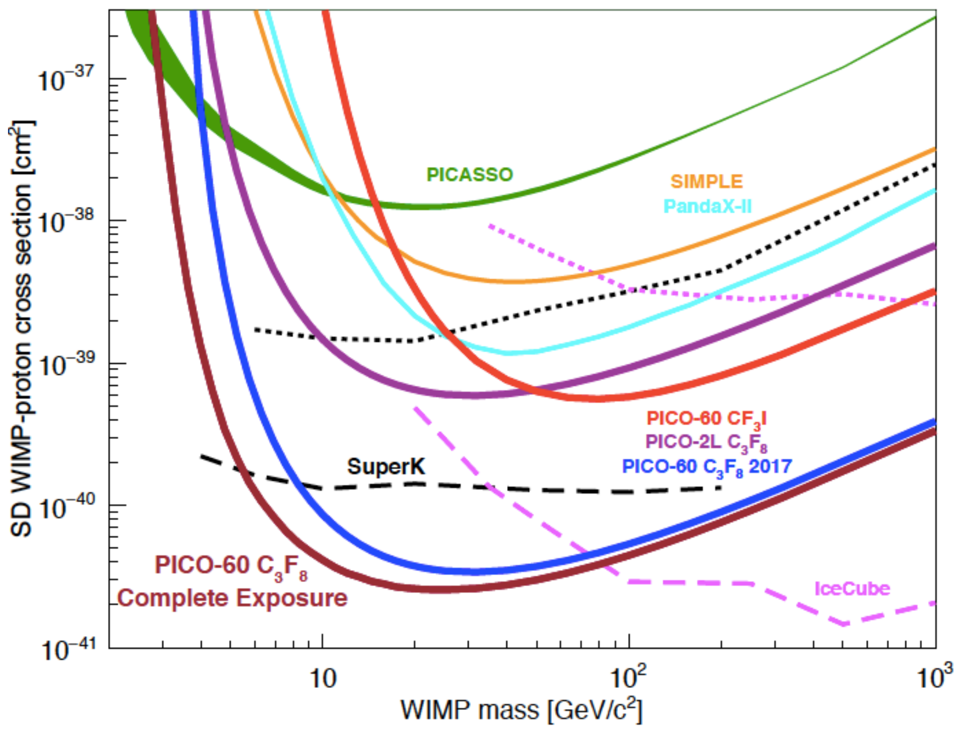


PICO-40L/500

Going larger than PICO-500 requires a new vessel material. R&D on nylon bag (similar to Kamland-Zen)

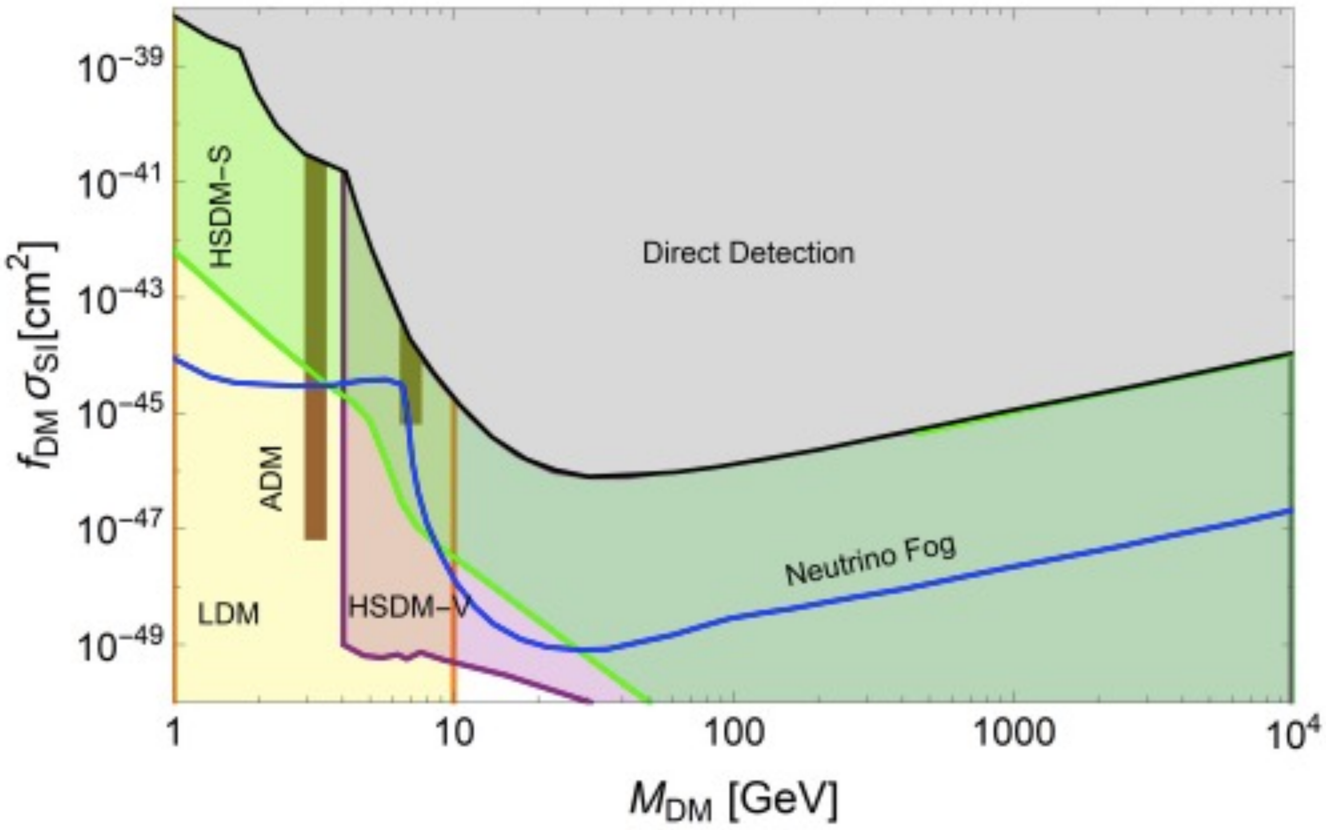
Future: lower mass?





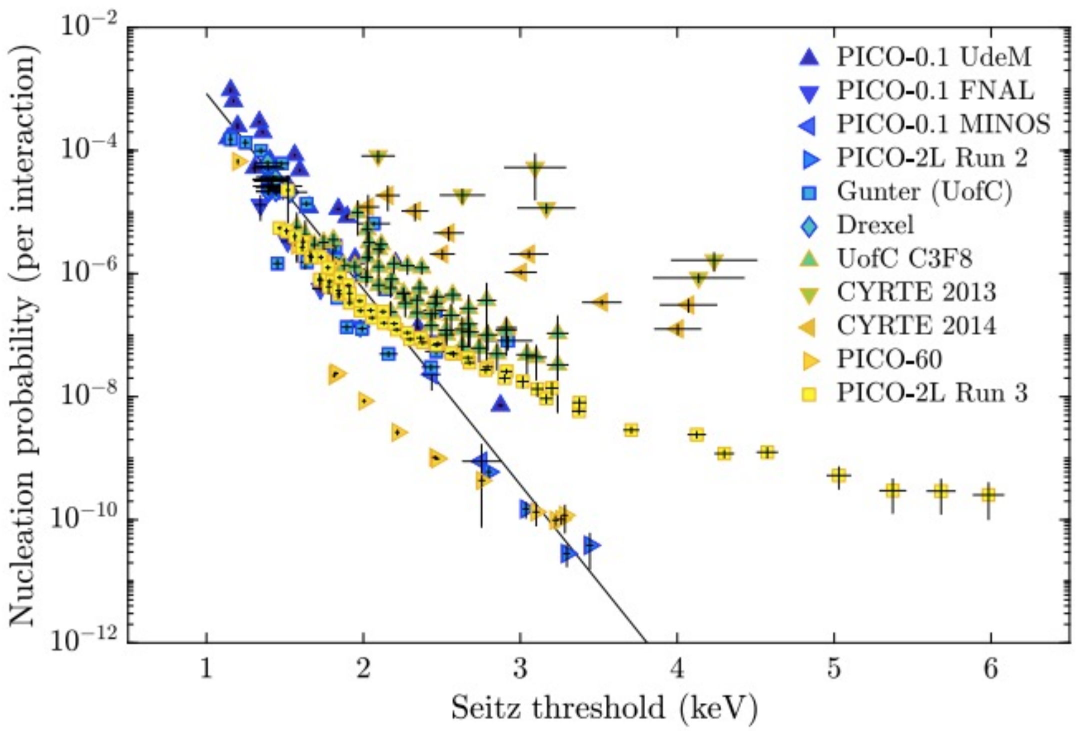
Can we lower the threshold to search for **GeV-scale dark matter**?

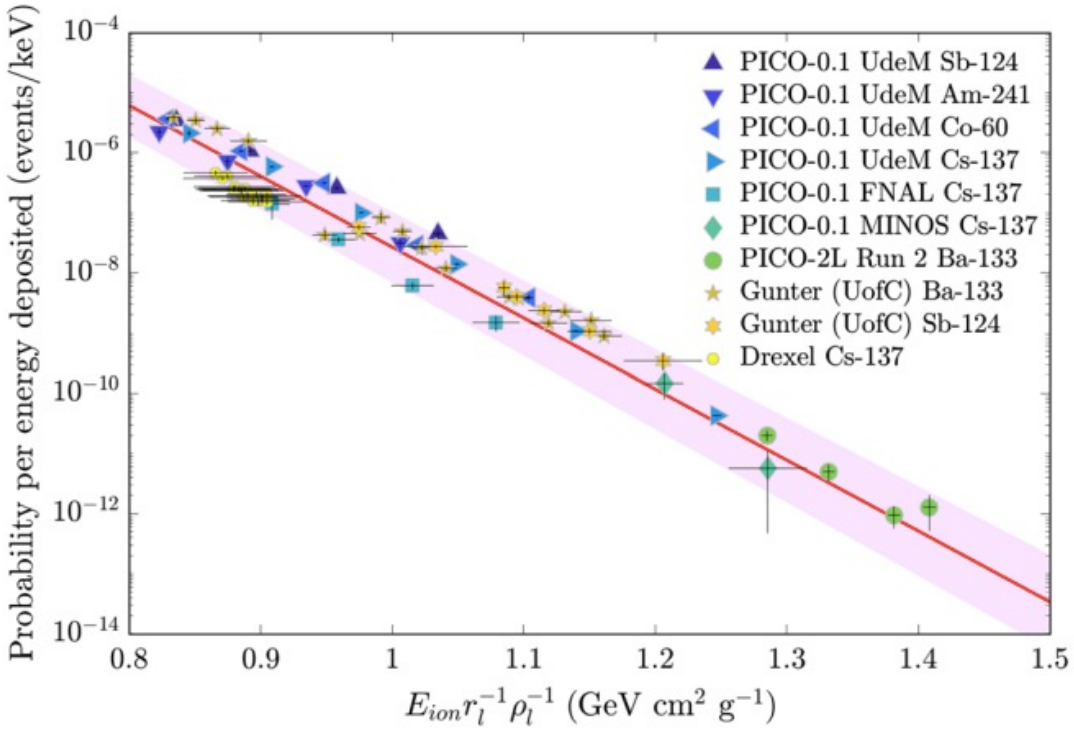
GeV-scale dark matter models



arXiv:2203.08084 **[hep-ex]**

Gamma sensitivity at low threshold

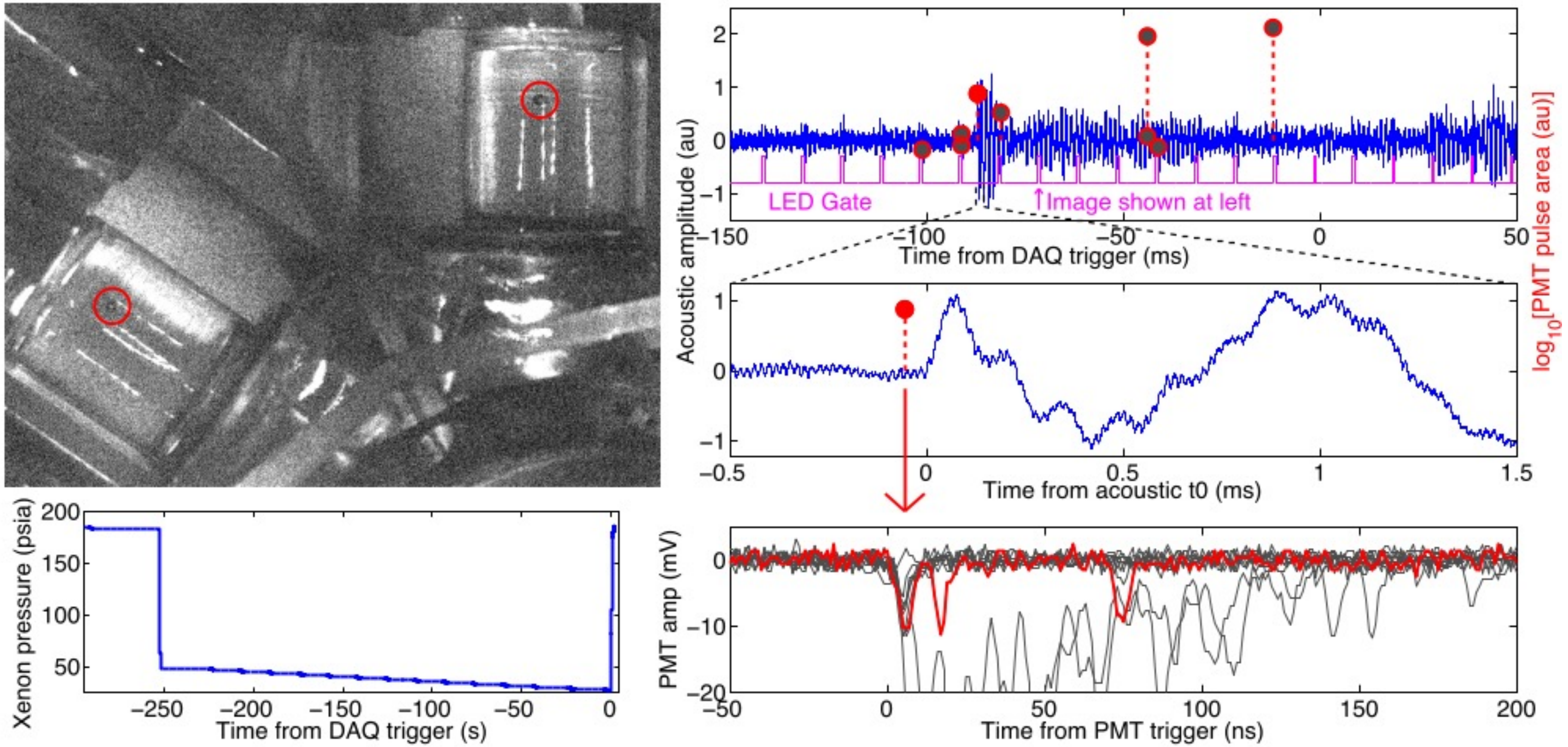




Gamma/electron sensitivity at low thresholds is the main obstacle to **sub-keV nuclear recoil detection needed to search for GeV-scale WIMPs**.

LXe bubble chamber

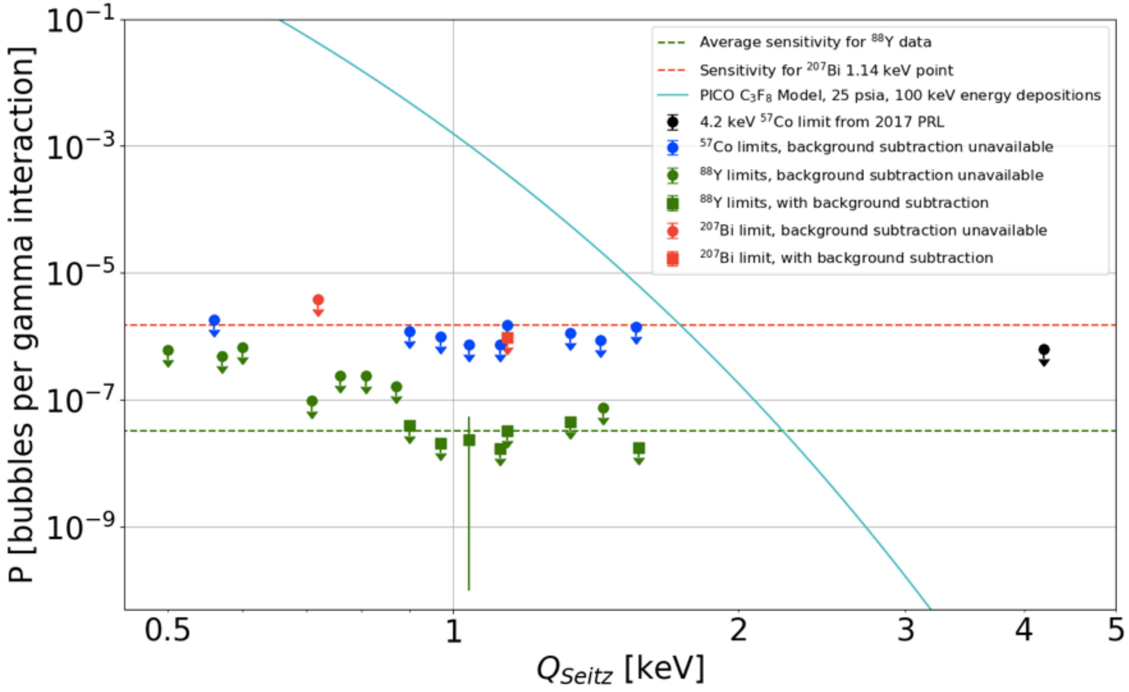
30g demonstration detector at Northwestern



D. Baxter et al., Phys. Rev. Lett. 118, 231301 (2017)

Gamma insensitivity in LXe

Gamma rejection in **LXe much better than C_3F_8 below 1 keV.**



"When the chamber was filled with liquid xenon and run under closely similar conditions immediately after the ethylene experiments, no tracks were obtained."

- from *Liquid Xenon Bubble Chamber*

J. L. Brown, D. A. Glaser, and M. L. Perl

Phys. Rev. **102**, 586 – Published 15 April 1956

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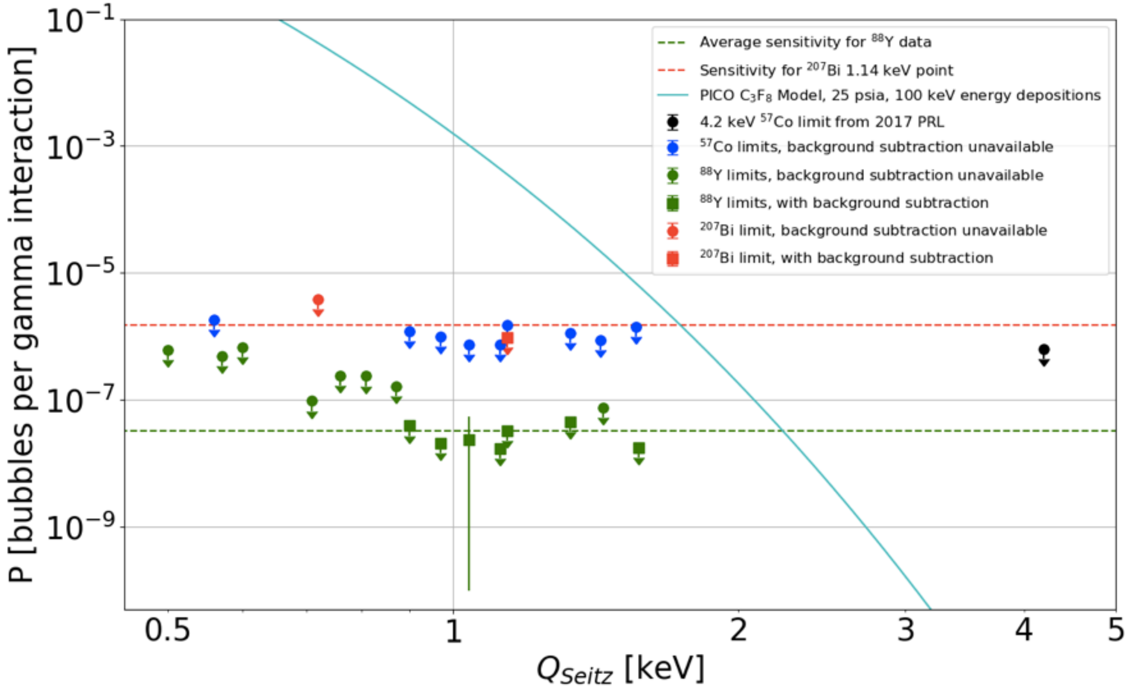

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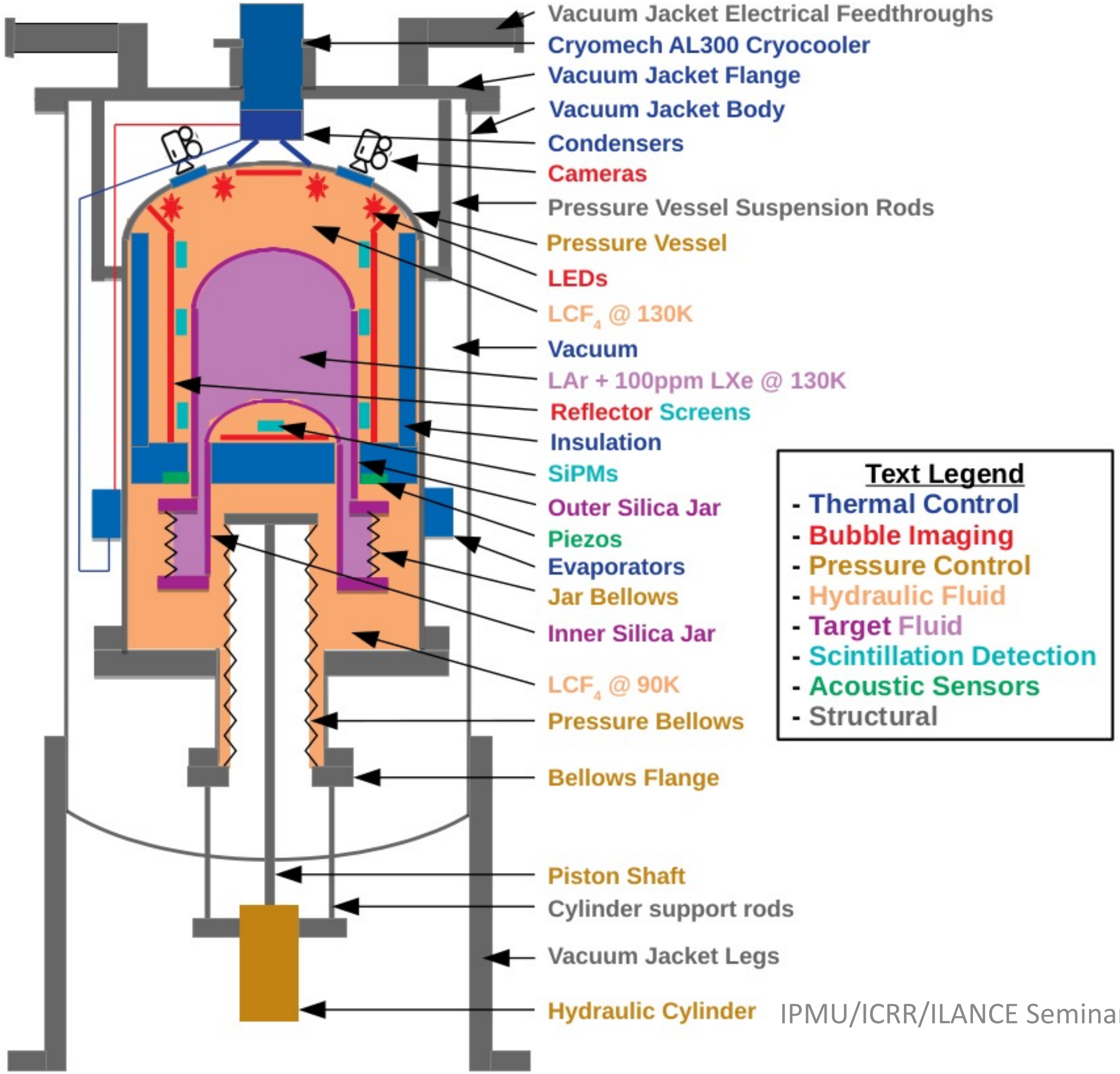
Electron recoil leakage

LXe bubble chamber:	$<10^{-7}$ at <1 keV_{NR}
LXe TPC:	10^{-3} at 3 keV_{NR}
Freon bubble chamber:	10^{-10} at 4 keV_{NR}

SBC
(Scintillating Bubble Chamber)



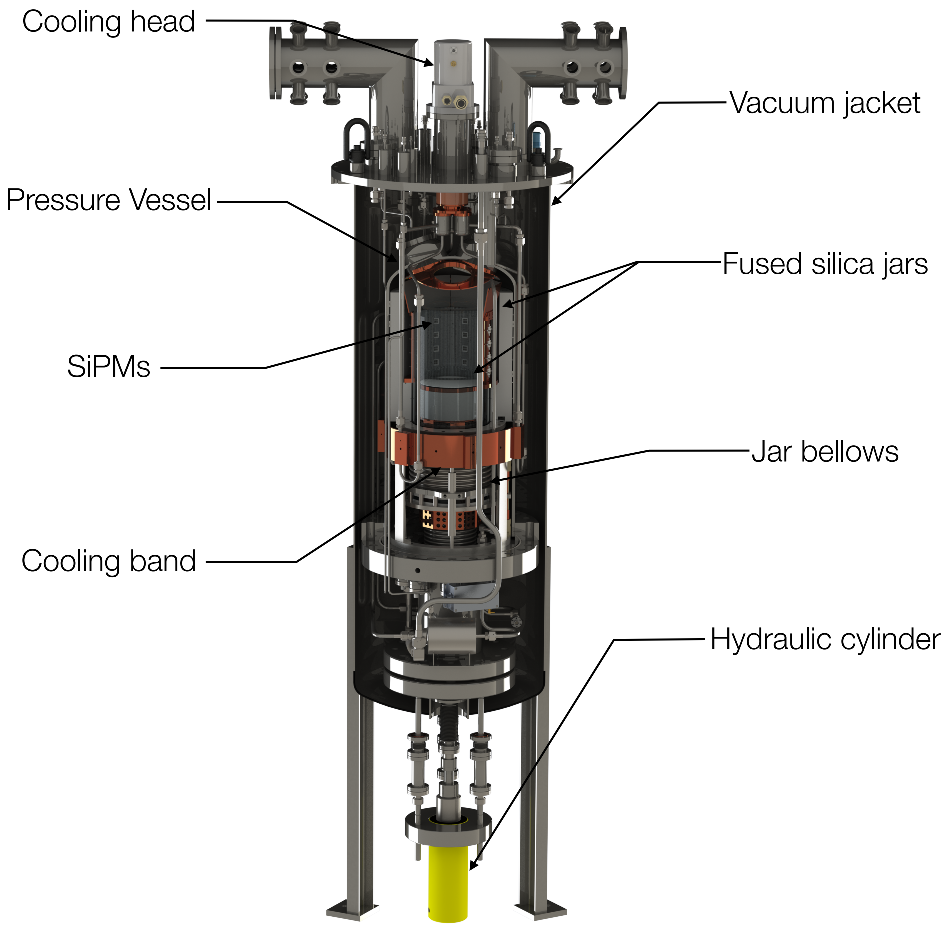
- **10 kg liquid argon** bubble chamber for GeV-scale dark matter and reactor CEνNS.
- Under construction now, with goal of **100 eV nuclear recoil threshold** while remaining electron recoil blind.
- Bubbles detected with cameras and acoustics.
- *O*(100) ppm xenon for wavelength shifting and SiPMs for scintillation detection – scintillation threshold few keV.

SBC Program

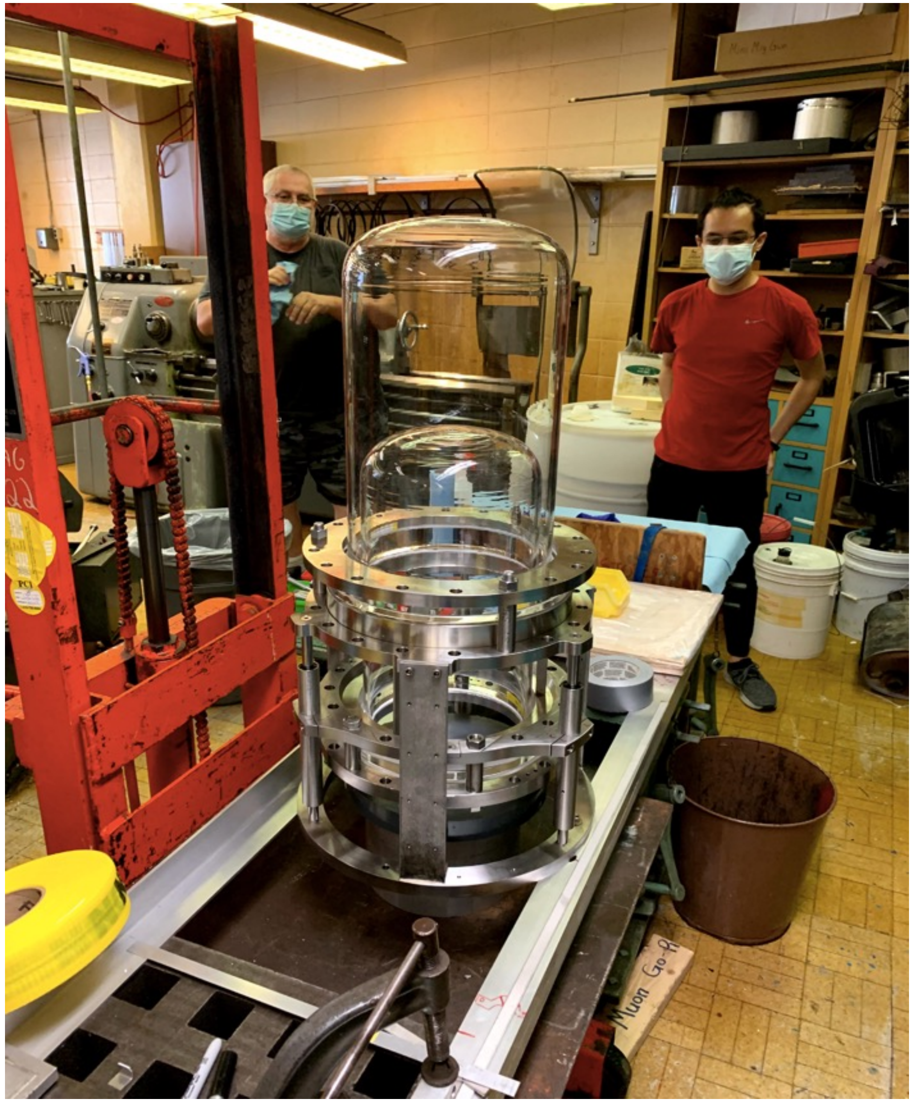
- SBC-Fermilab now **under construction** for calibrations in shallow site. Target nuclear threshold is 100 eV.
  - Science operation 2023-25

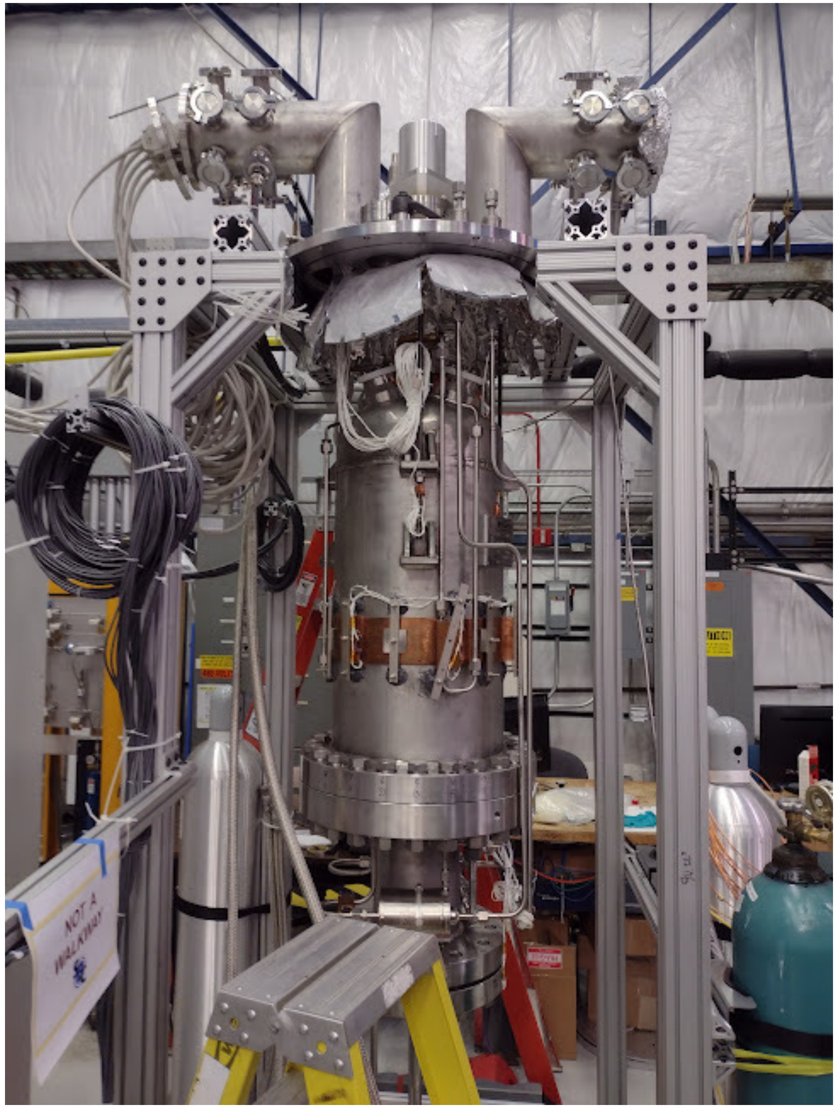
- Dark matter search with duplicate detector, SBC-SNOLAB.
  - Physics ~2024

- Redeploy SBC-Fermilab at a nuclear reactor to look for neutrinos with the CEνNS process.

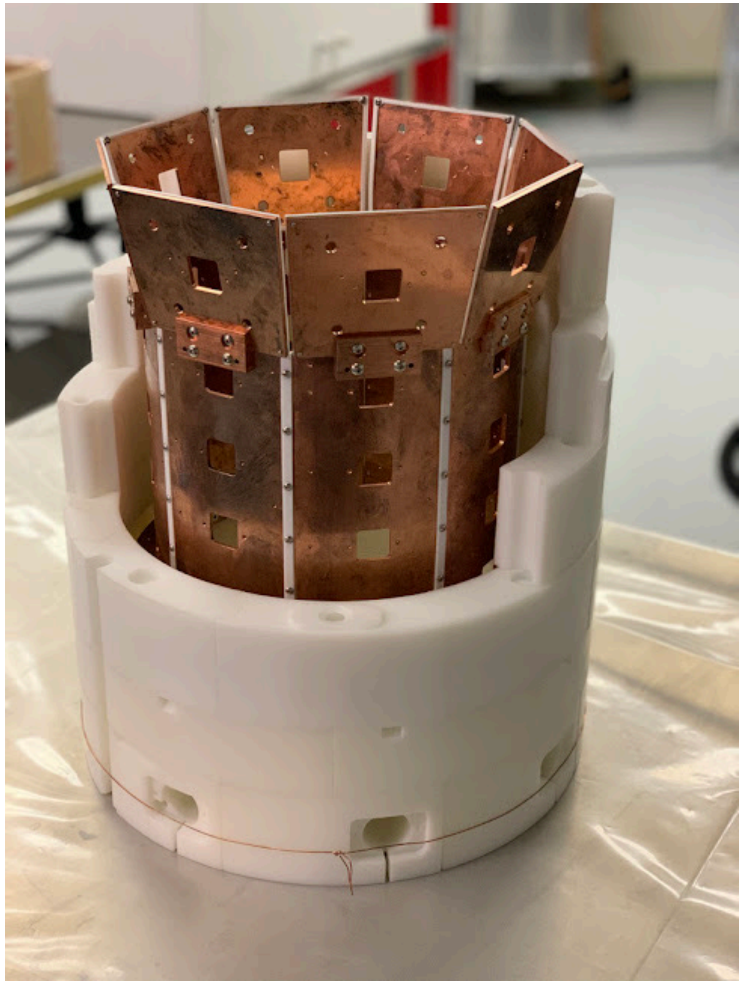


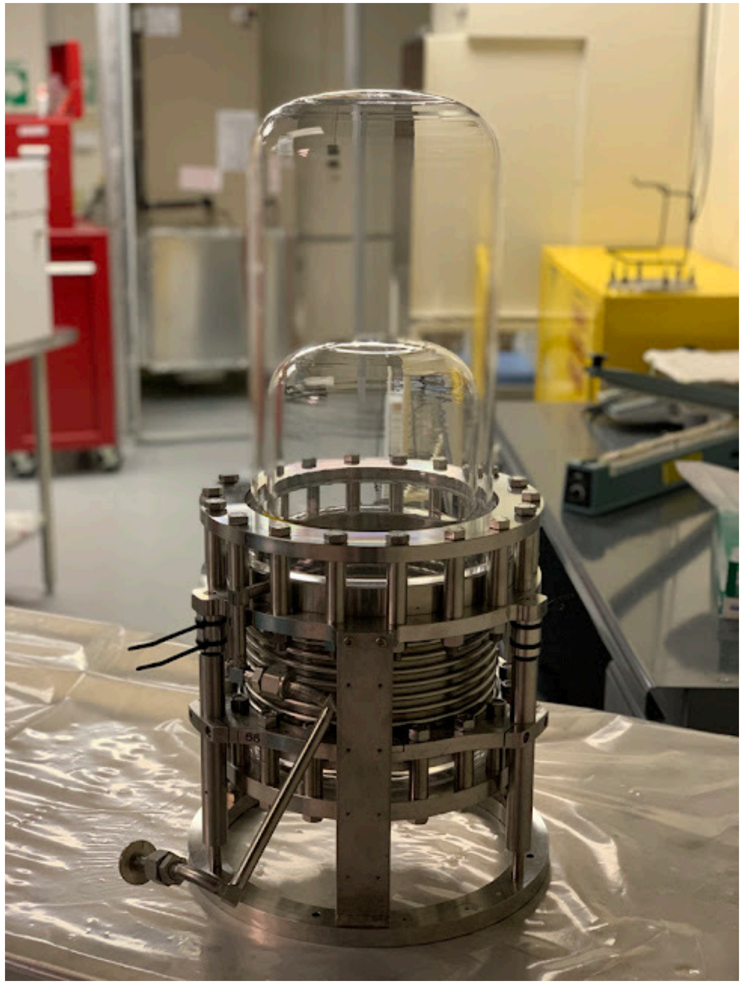
SBC-Fermilab construction



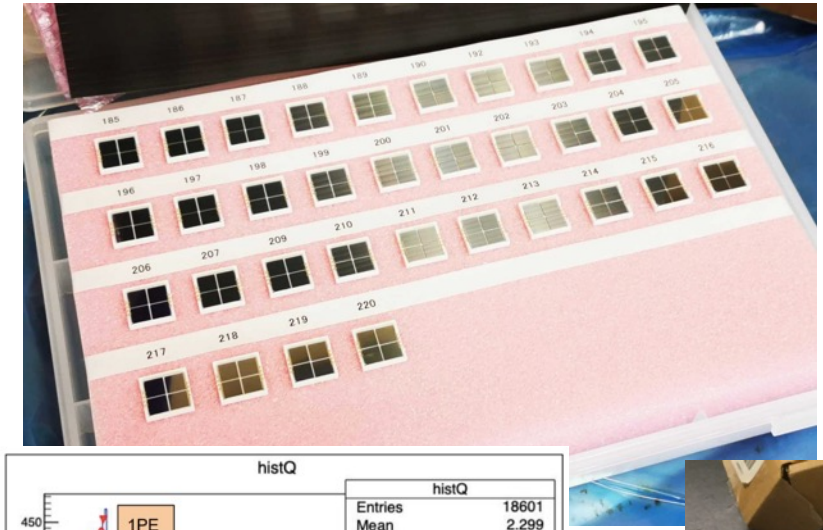


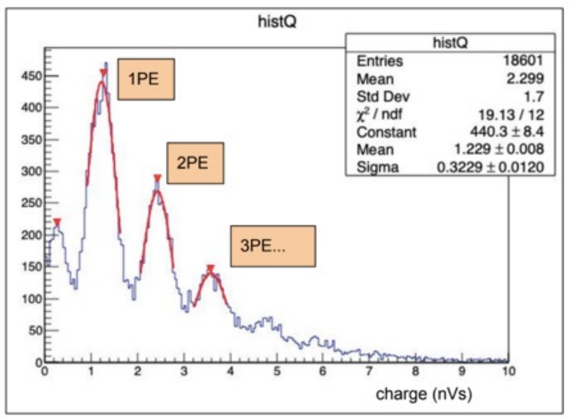
Inner vessel



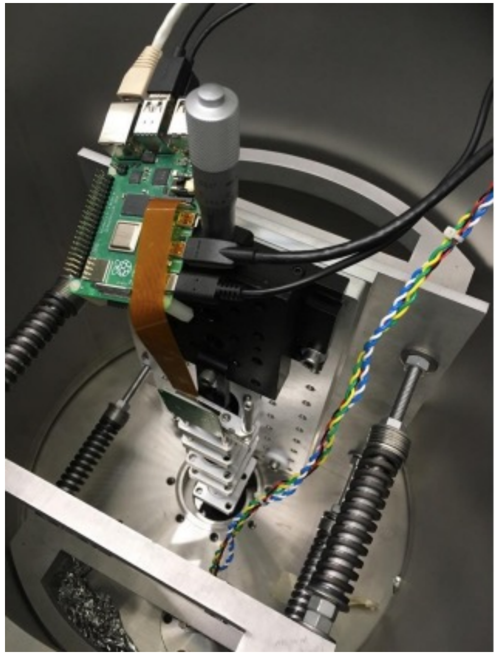


Subsystems

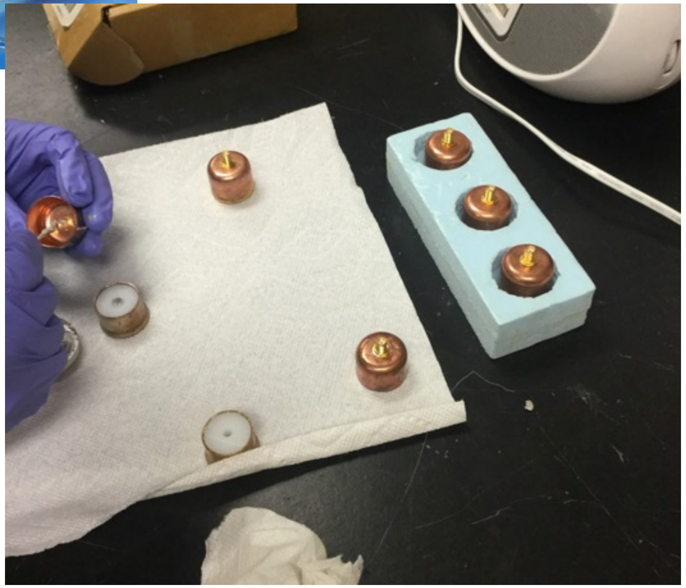




SiPM Performance in LCF_4, credit Austin dSC



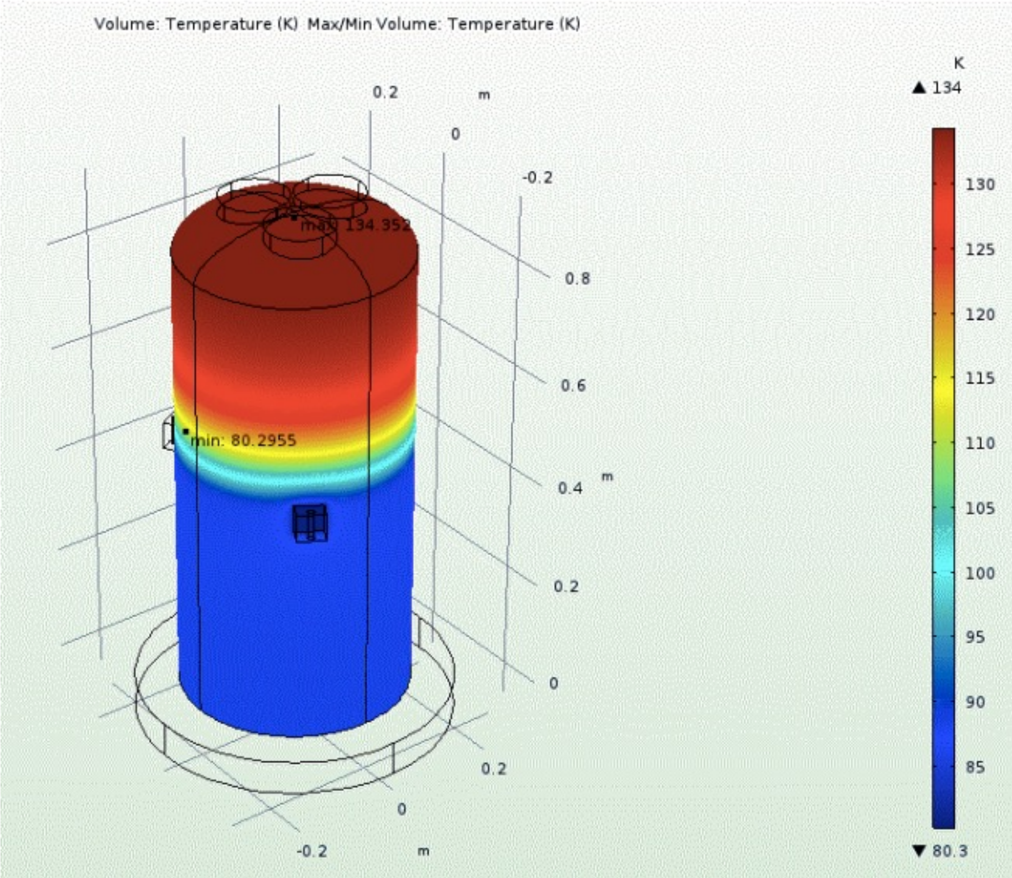
Relay lens R&D



Acoustic sensors

SBC-Fermilab Goals

- Stable operation
  - Thermal model verification
  - Manageable wall nucleation rate.
- Gamma calibration
  - Investigate electron-recoil rejection at O(100 eV) scale
- Nuclear recoil calibration



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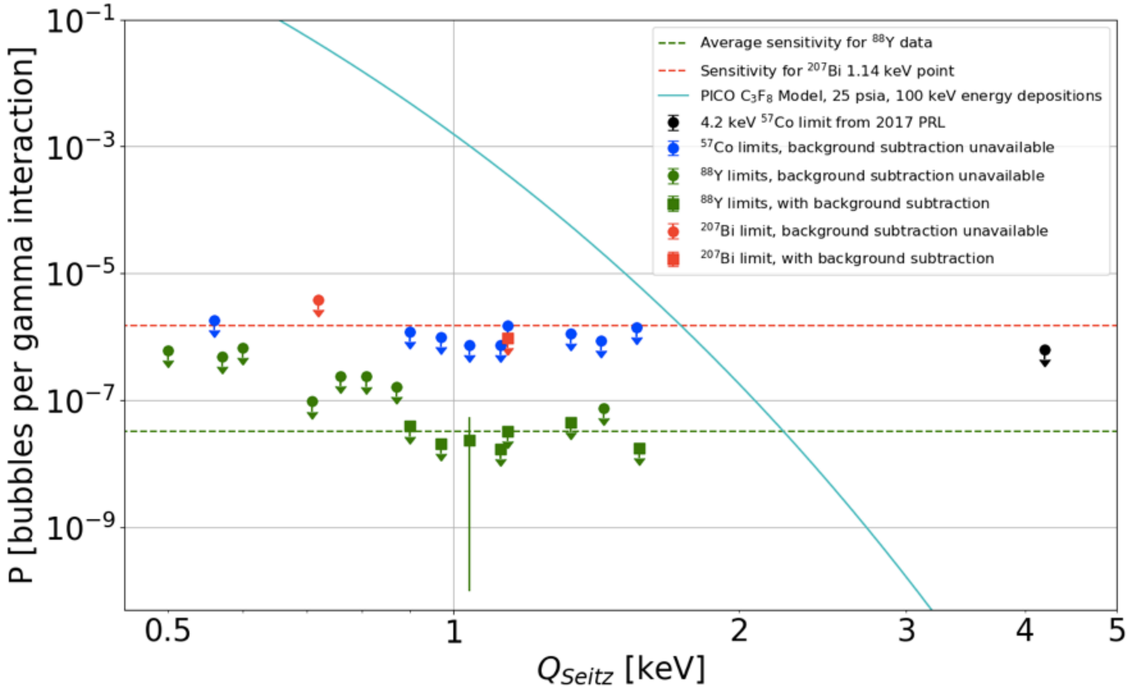

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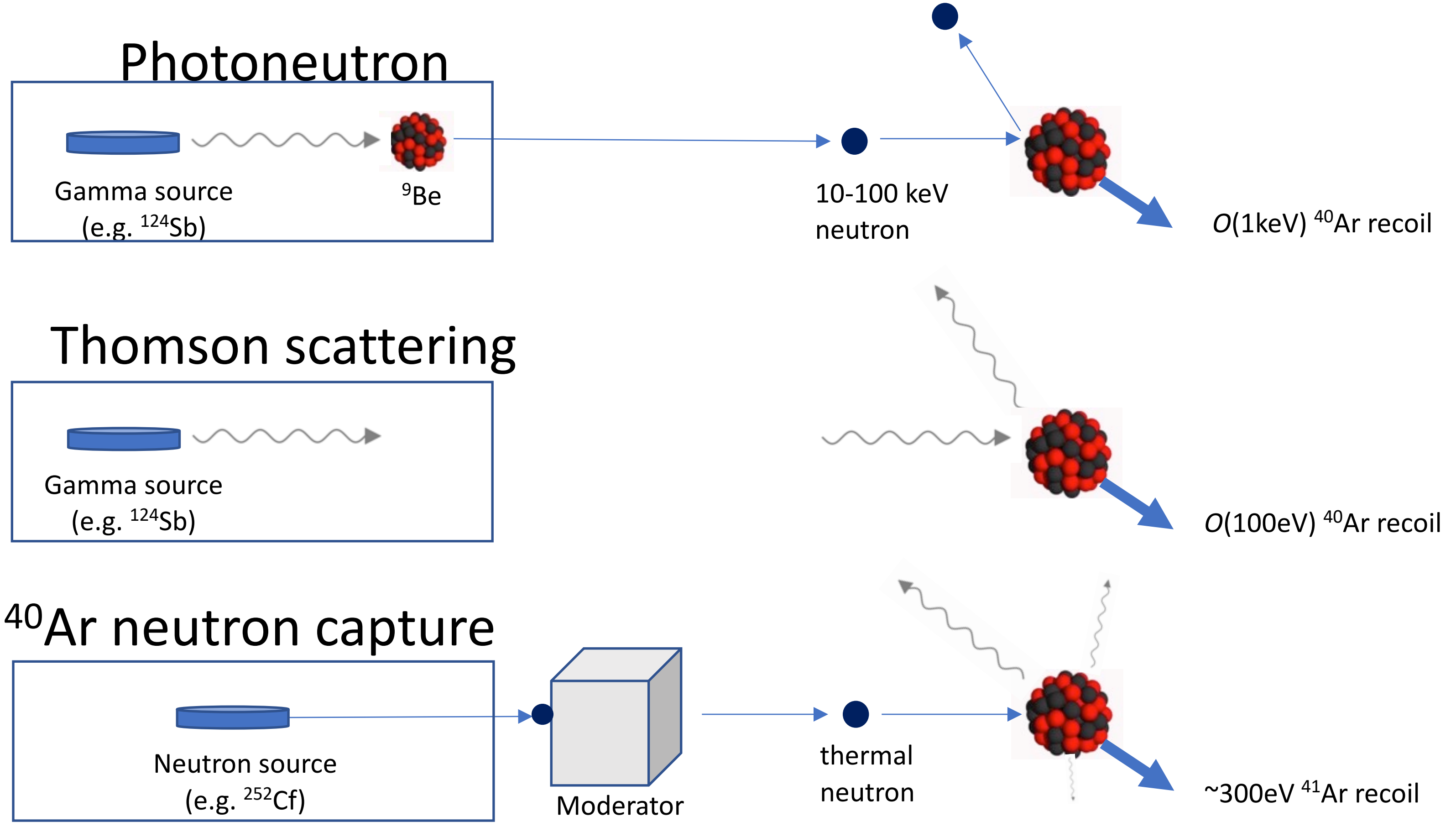
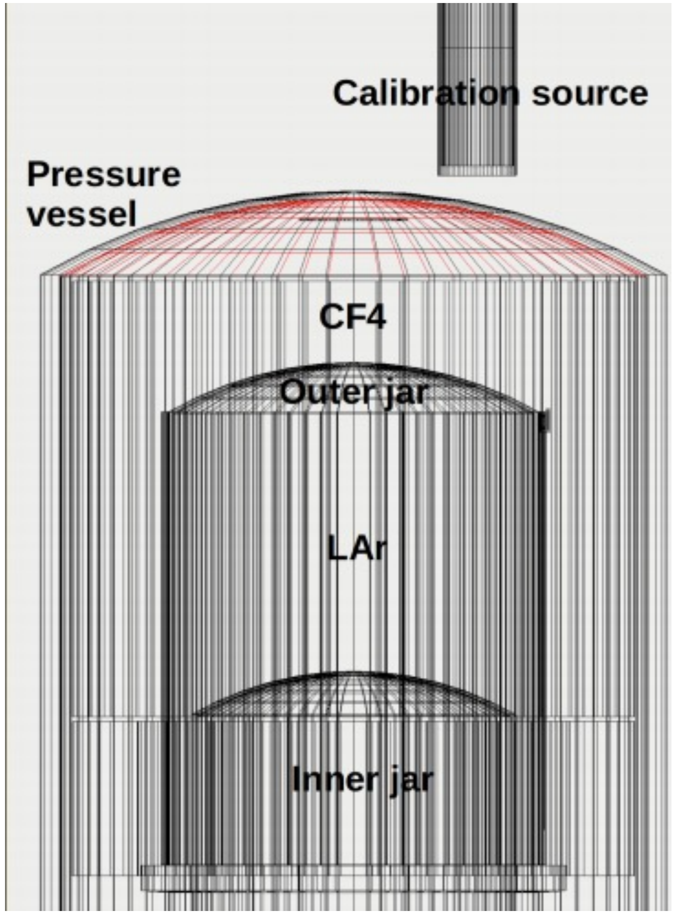
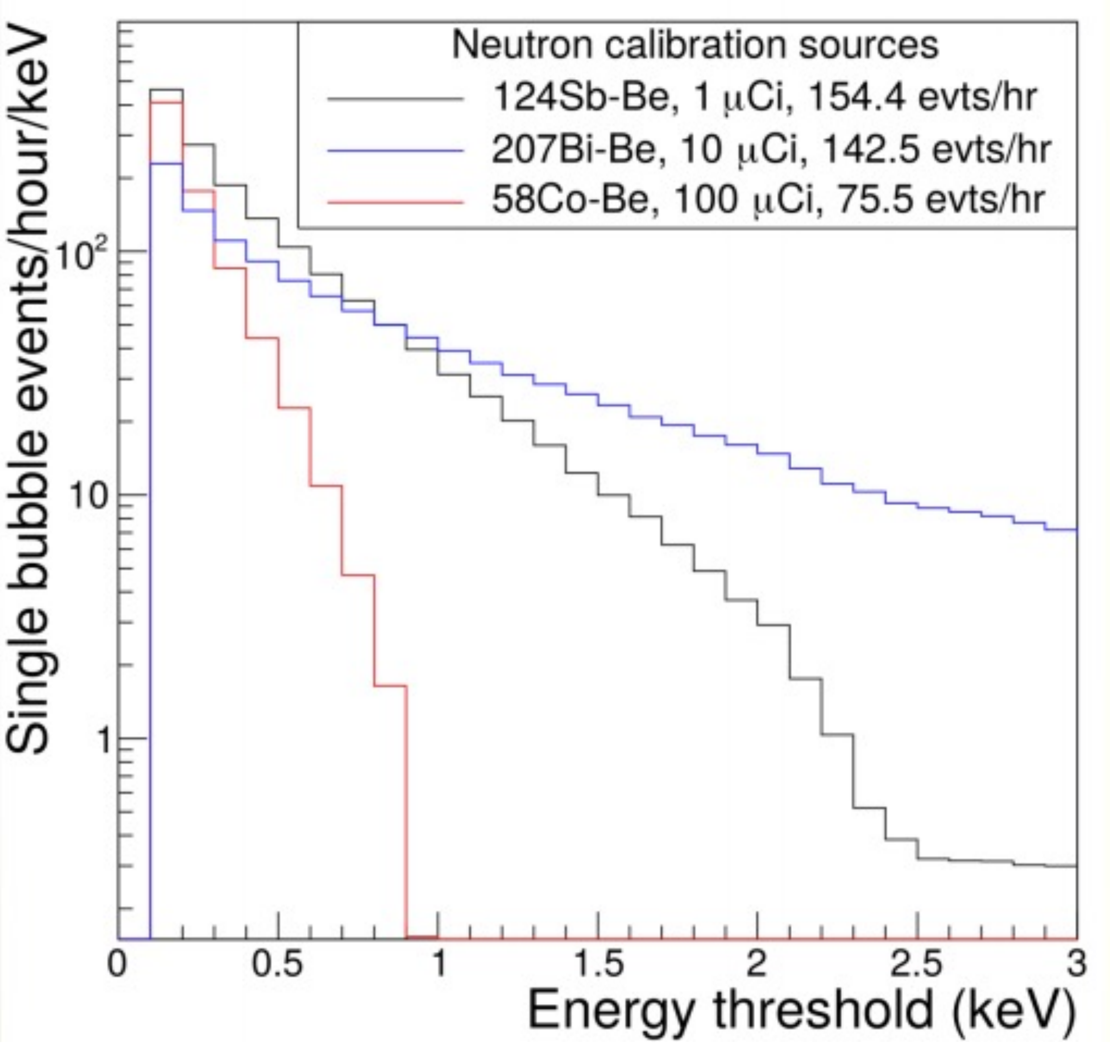


Photoneutron Calibrations

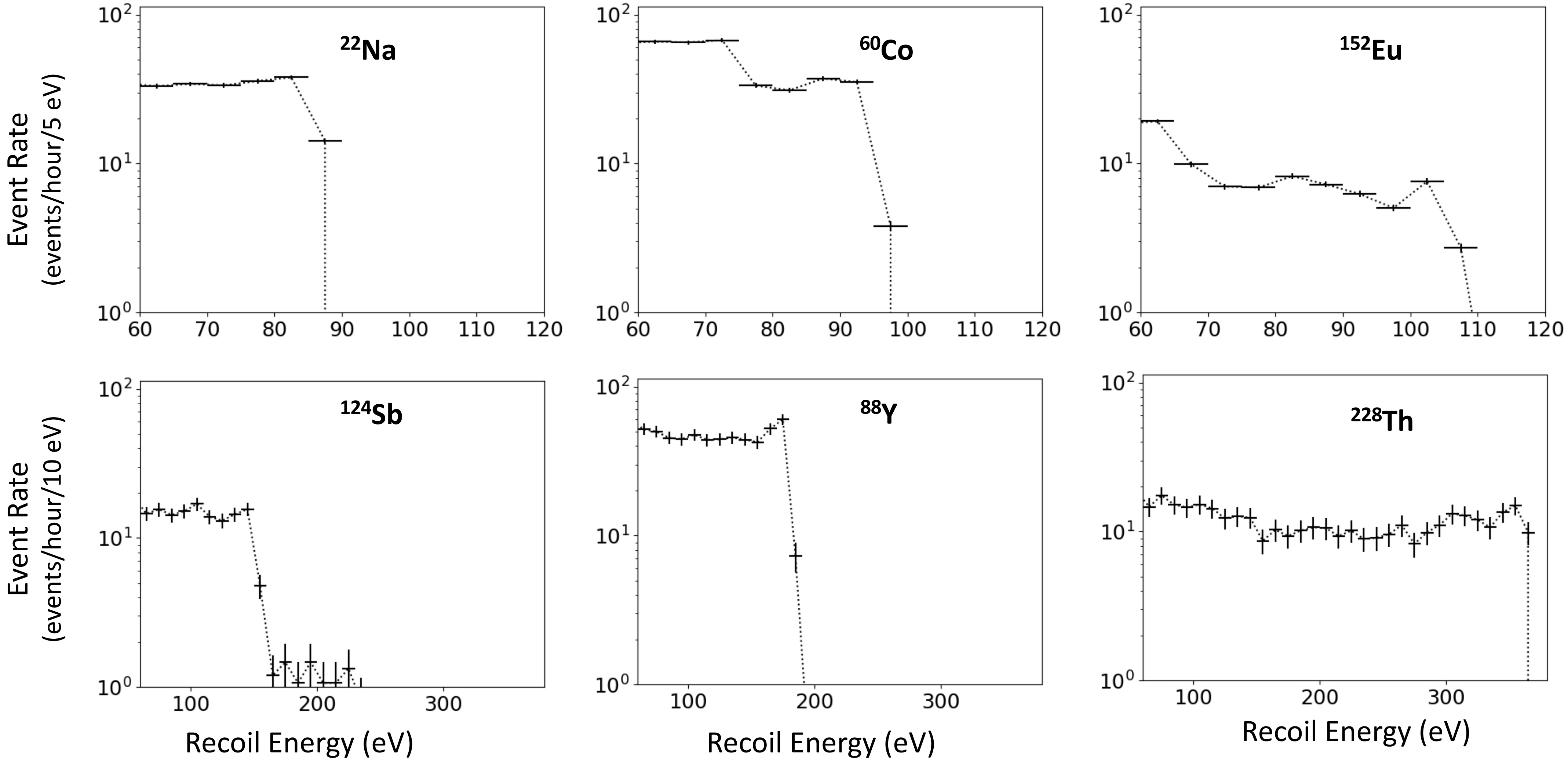




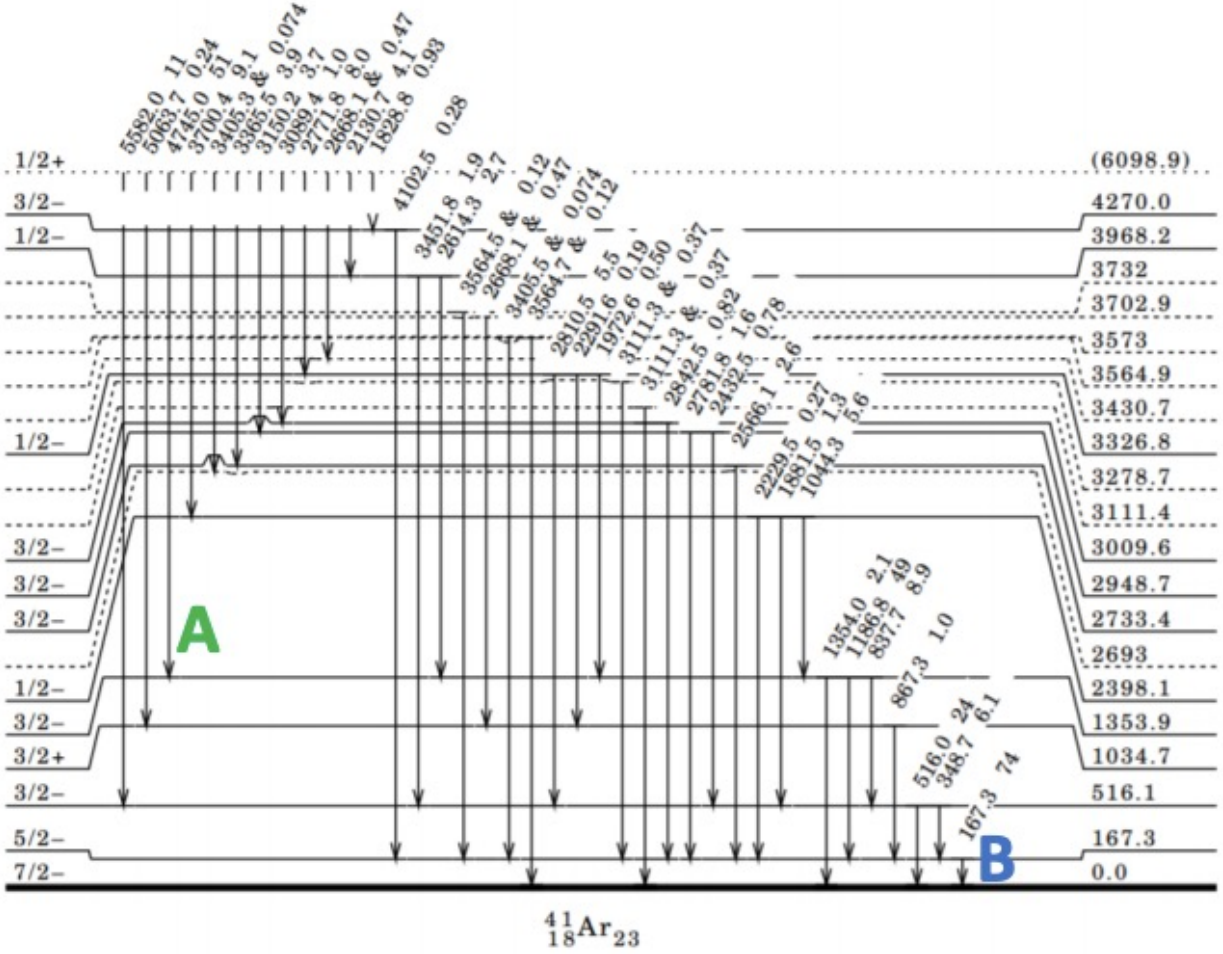
$^{9}Be(\gamma,n)$, Q=1664keV gives ~monoenergetic neutrons.
^{207}Bi: 90keV
^{124}Sb: 23keV
^{58}Co: 9keV

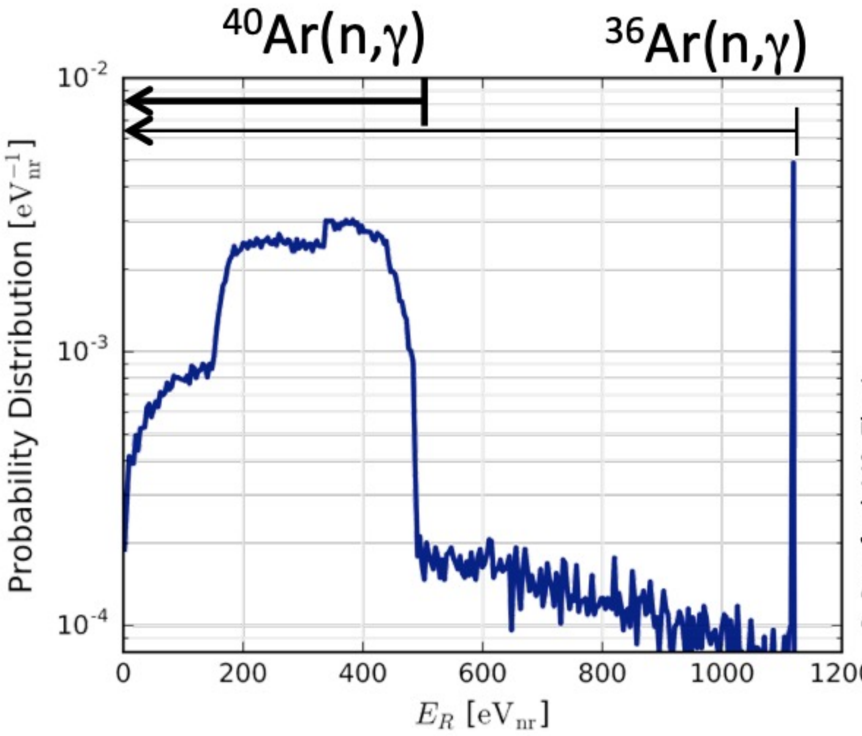
Scattering on Ar gives keV-scale recoils.

Thomson Scattering Calibrations



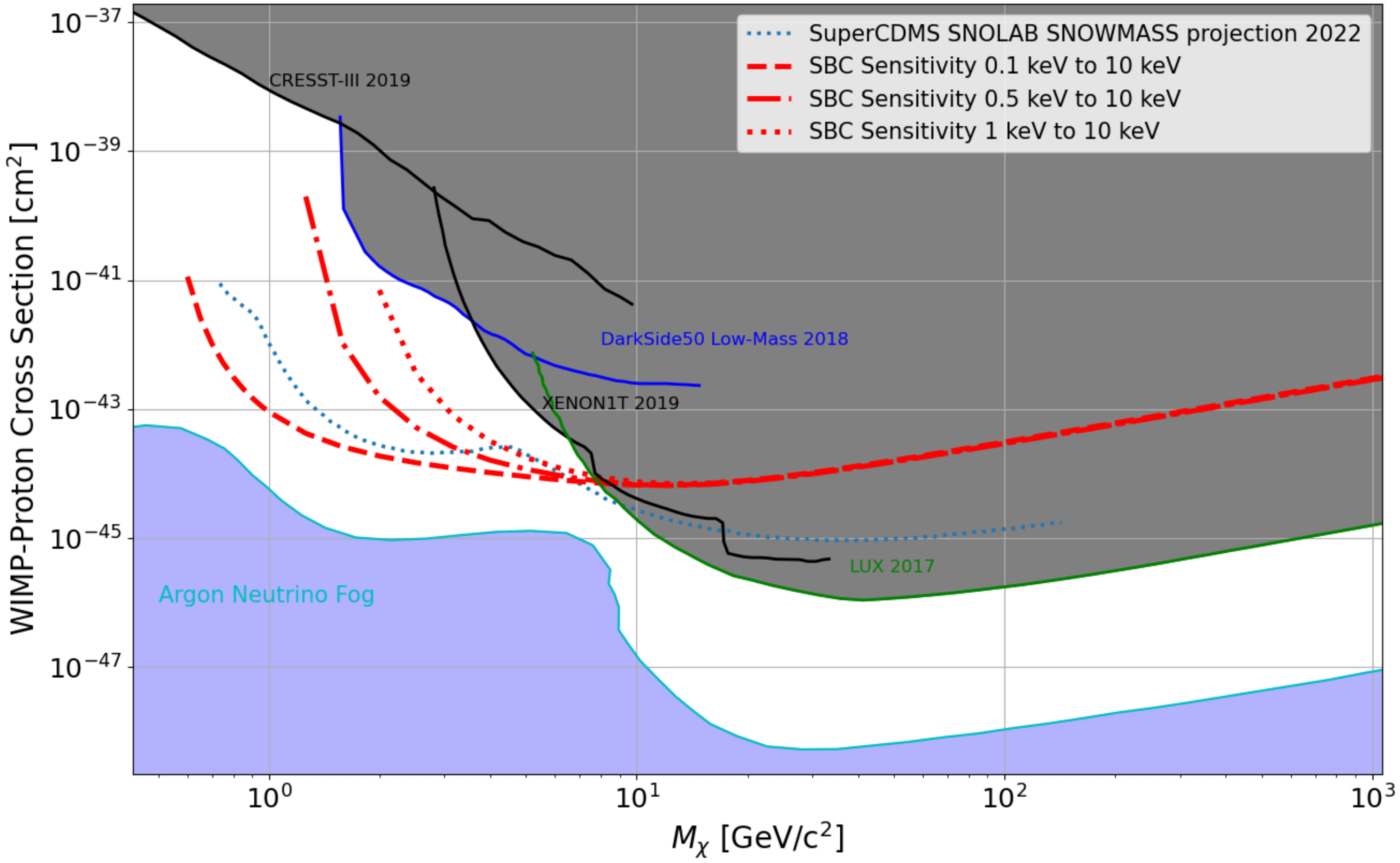
^{40}Ar Neutron Capture





D. Durnford, MSc Thesis
http://hdl.handle.net/1974/24878

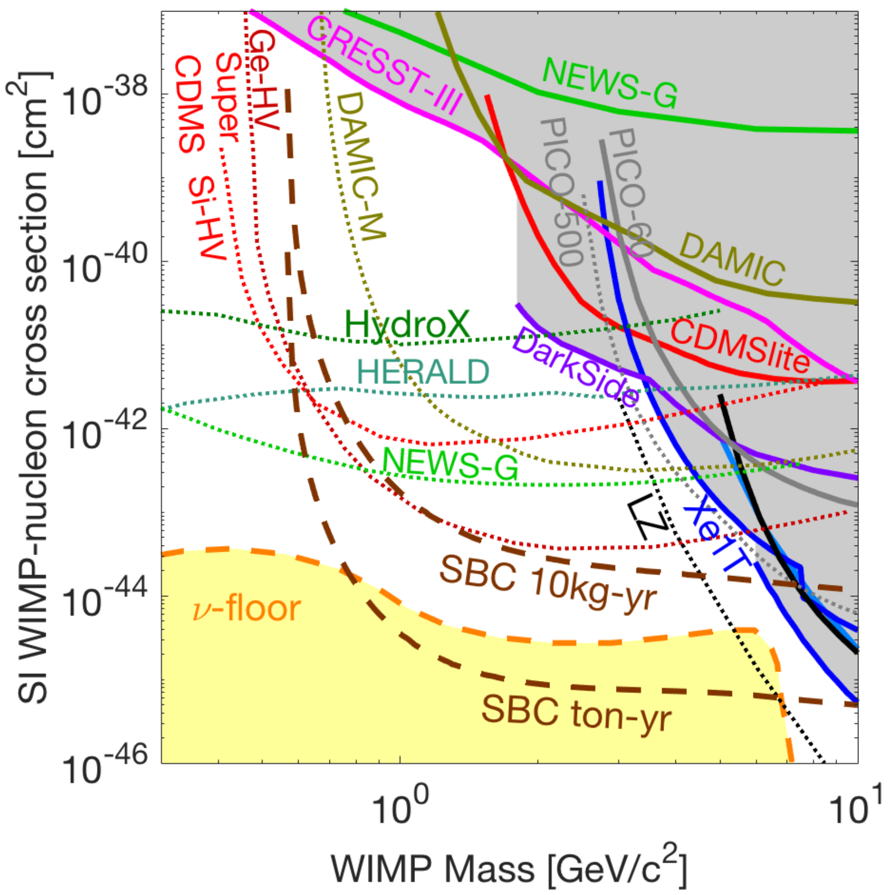
Dark Matter Sensitivity 10kg-scale



Dark matter sensitivity ton-scale

- A **1 t device** would probe down to the **solar neutrino floor/fog**.
  - Also sensitive to CEνNS physics from solar νs, SN, pre-SN.

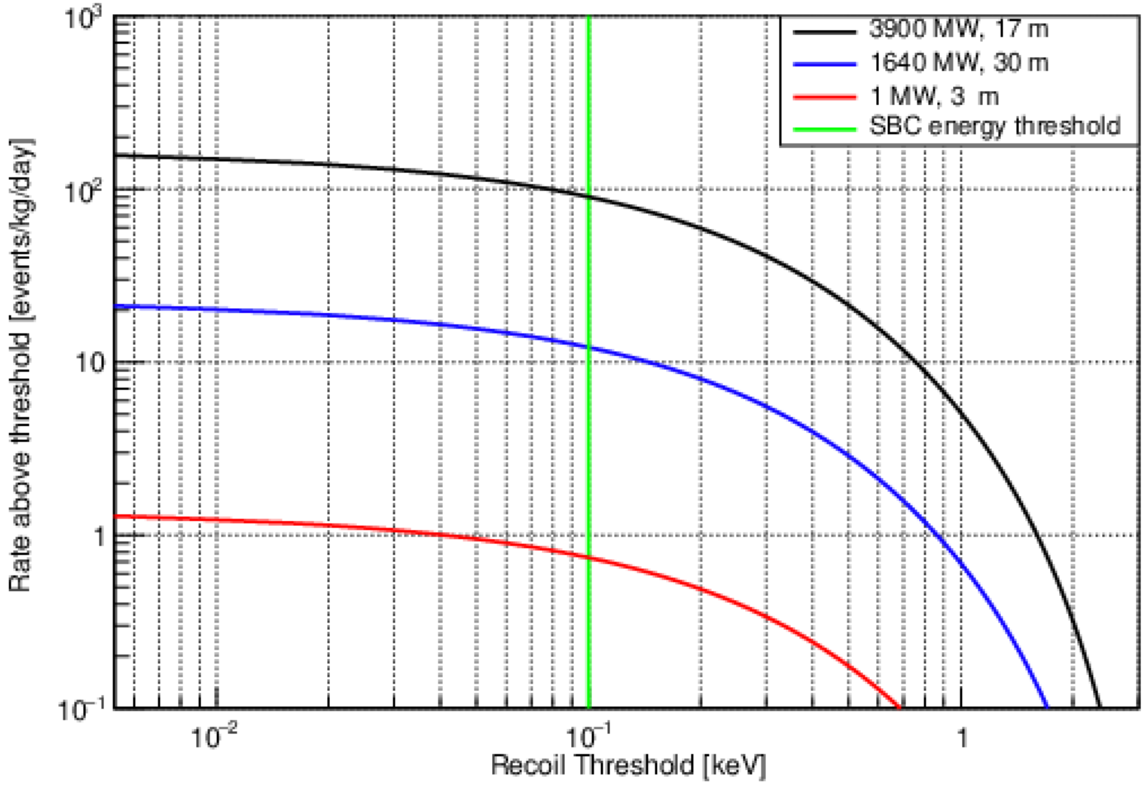
- Main Backgrounds:
  - (α,n) in detector materials.
  - Muon-induced neutrons.
  - Nuclear Thomson scattering from external gammas.
  - Solar neutrinos.
  - Scintillation channel used for background rejection.



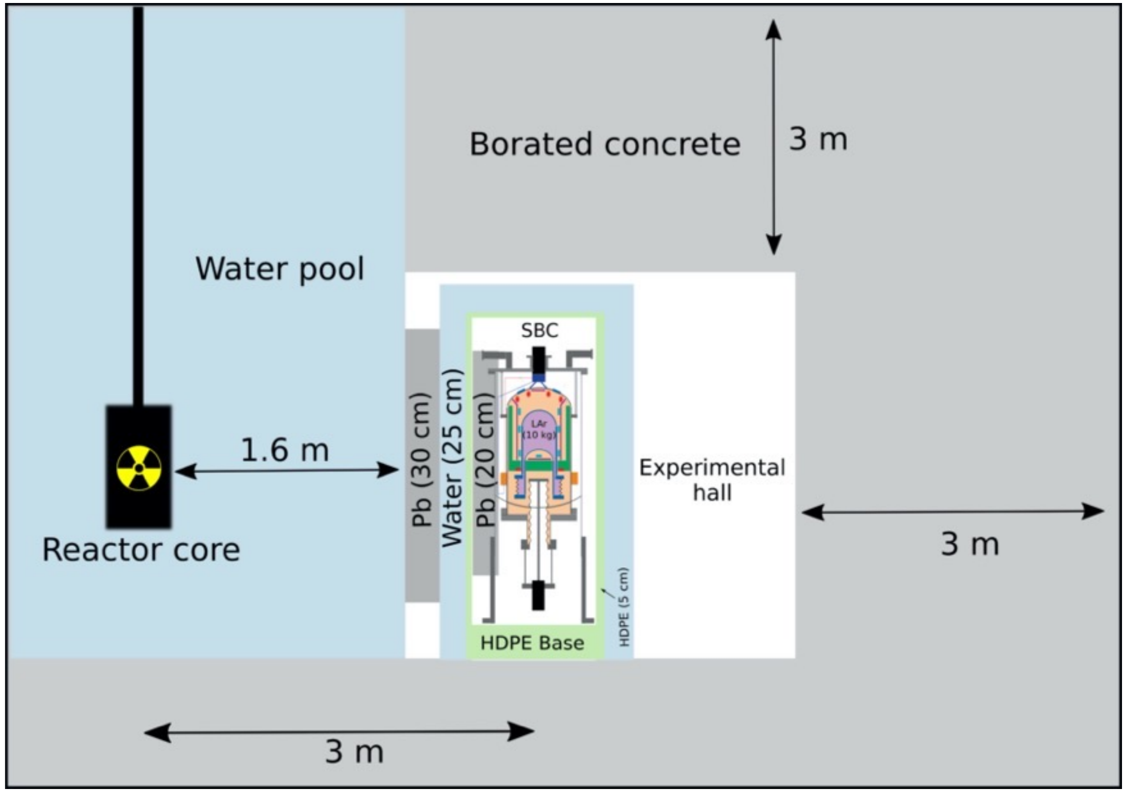
CEνNS - Coherent Elastic Neutrino Nucleus Scattering

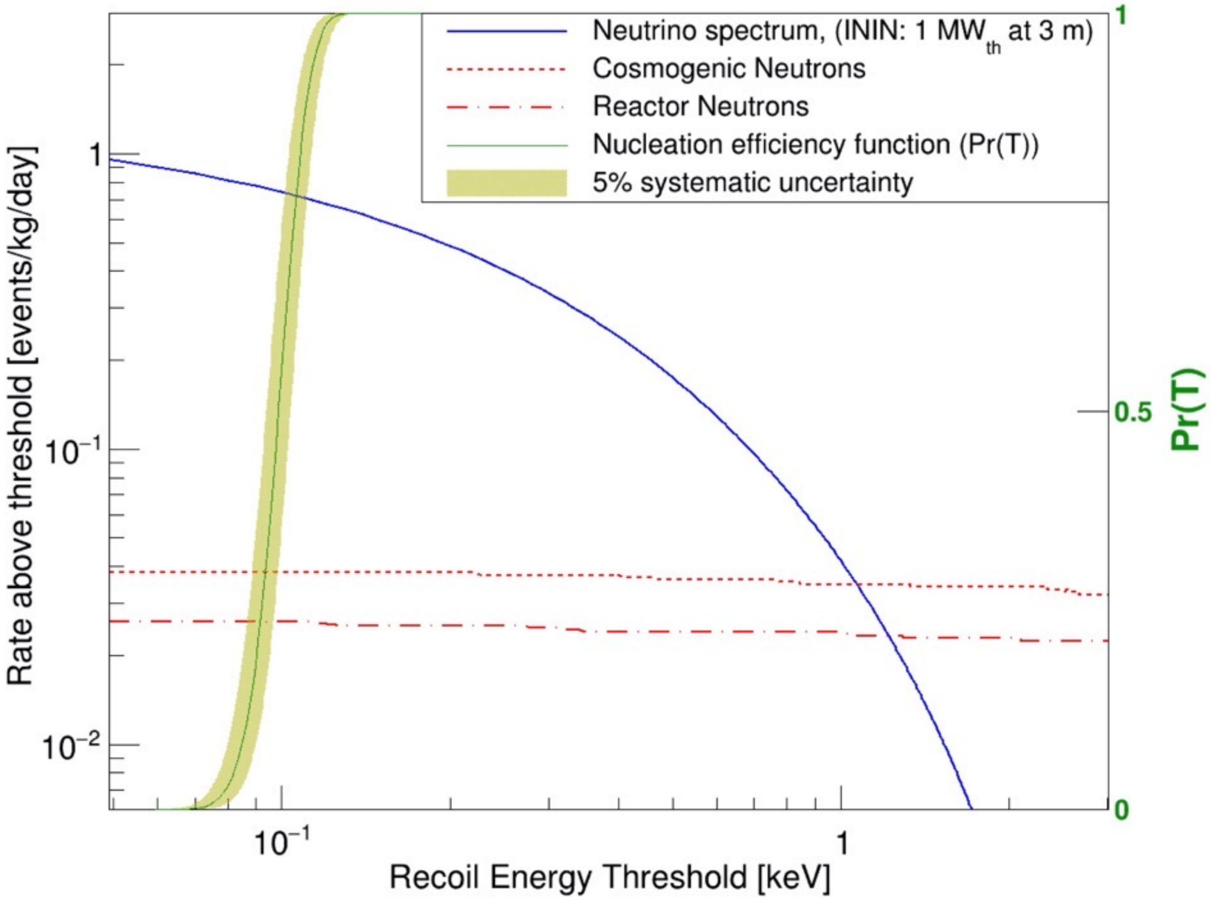
- Sensitivity to O(10 keV) with low background is also what's needed to detect O(10 MeV) neutrinos via CEνNS.
  - Has been observed at the SNS for pion decay-at-rest neutrinos (~50MeV).
- Reactors provide very high flux for precision studies, but 1-10 MeV neutrinos is a challenge.
- **100 eV threshold** gives sensitivity to **CEνNS** from **>1.4MeV neutrinos**, covering much of the the reactor antineutrino spectrum.

SBC-CEνNS rates for different reactors



SBC-CEνNS concept at ININ

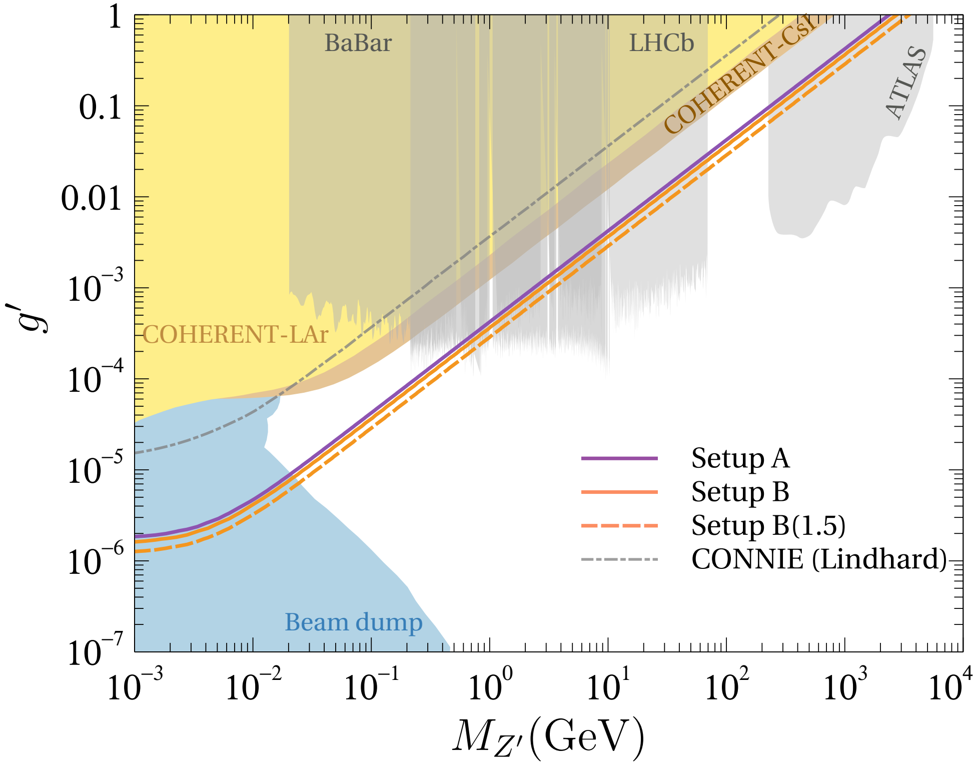




- 1 MW TRIGA Mark-III reactor near Mexico City.
- Borated concrete shields from cosmic rays.
- Water shields from reactor neutrons, lead from reactor gammas (Thomson scattering).
- Detector could be ready for deployment in 2024+

Physics reach: Z’

Z’ (B-L gauge boson)



$$\mathcal{L}_{\text{eff}} = -\frac{g'^2 Q_l Q_q}{q^2 + M_{Z'}^2} \left[\sum_{\alpha} \bar{\nu}_{\alpha} \gamma^{\mu} P_L \nu_{\alpha} \right] \left[\sum_{q} \bar{q} \gamma_{\mu} q \right]$$

Physics reach in 1-year of reactor-on time:

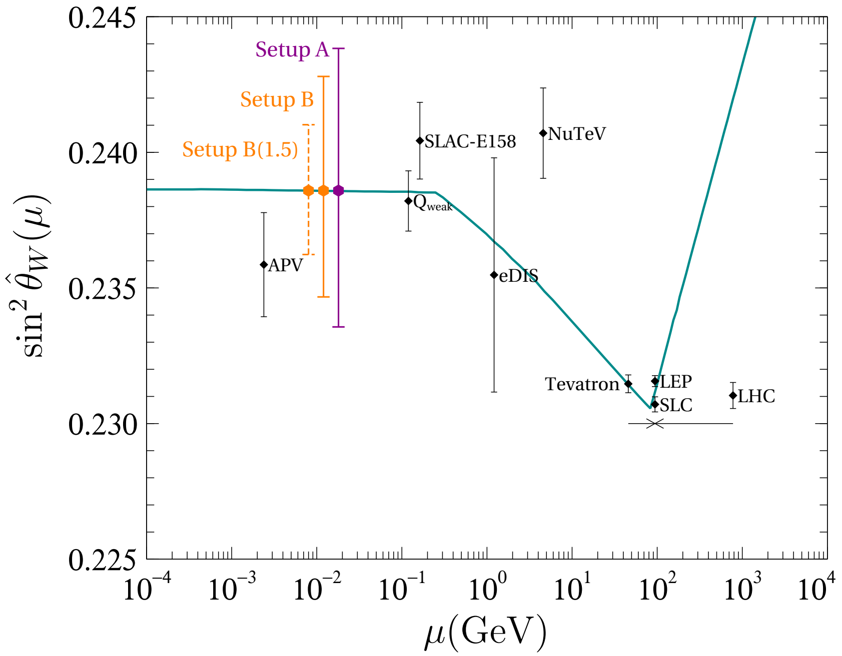
Setup A (ININ): 10kg, 1MW$_{th}$, 3m, 2.4% flux uncertainty
Setup B: 100kg, 2GW$_{th}$, 30m, 2.4% flux uncertainty
Setup B(1.5): 100kg, 2GW$_{th}$, 30m, 1.5% flux uncertainty

For setups B/B(1.5) project *O*(1000) CEνNS events per day.

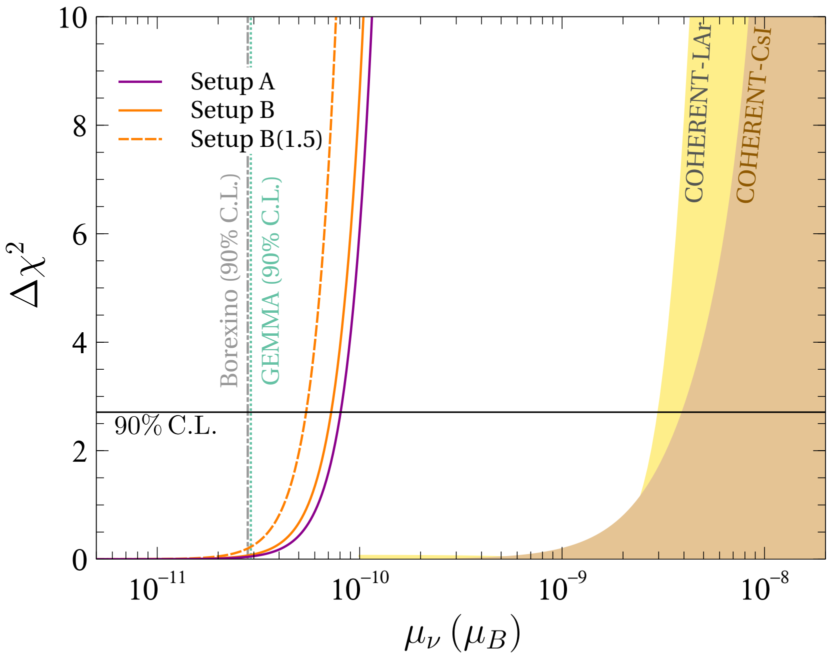
L. J. Flores, et. al , Phys. Rev. D 103 (2021)
https://arxiv.org/abs/2101.08785

Physics reach: mixing angle, magnetic moment

Weak mixing angle



Neutrino magnetic moment



L. J. Flores, et. al , Phys. Rev. D 103 (2021)

- Physics can be done even with a 10-kg detector at a research reactor.
- Higher statistics and improved precision at a power reactor.

Summary

- PICO bubble chambers continue to provide world-leading sensitivity to spin-dependent dark matter couplings.
- The SBC collaboration is developing liquid argon bubble chambers as a scalable, electron recoil blind, GeV-scale WIMP and reactor CEνNS detection technique.
- A calibration detector with 10kg LAr active mass is currently under construction at Fermilab. Goal is 100eVnr threshold.
- SBC-SNOLAB will conduct a GeV-scale WIMP search. A future 1 t device will have sensitivity down to the solar neutrino floor.
- SBC- CEνNS at a research or power reactor could detect reactor CEνNS and has potential for precision studies of new physics.

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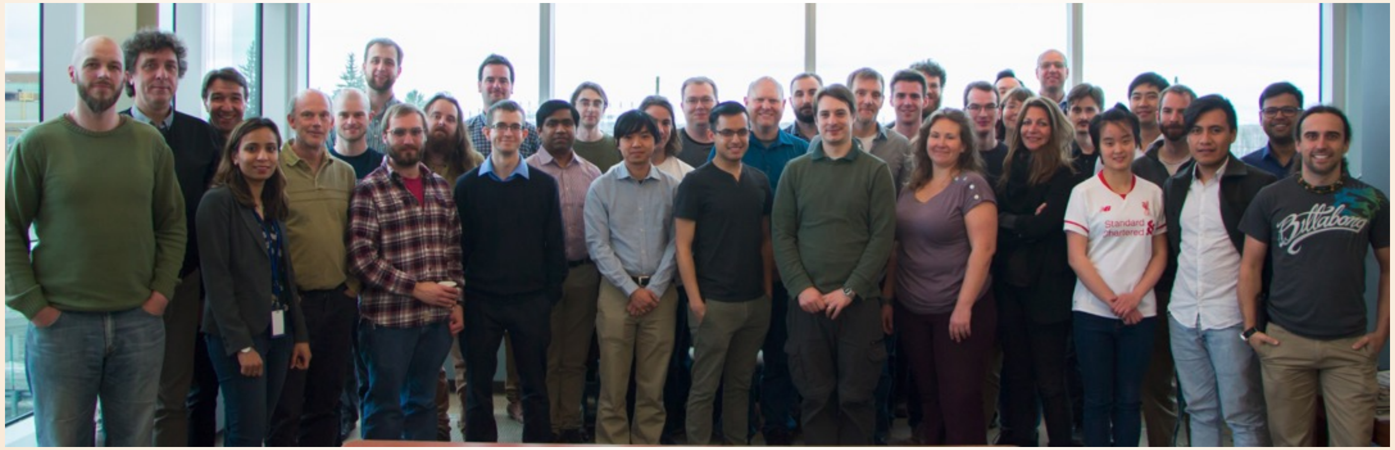

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