The Scintillating Bubble Chamber Liquid Argon 10 kg (SBC-LAr10) Prototype at Fermilab, and Future Neutrino Physics Prospects

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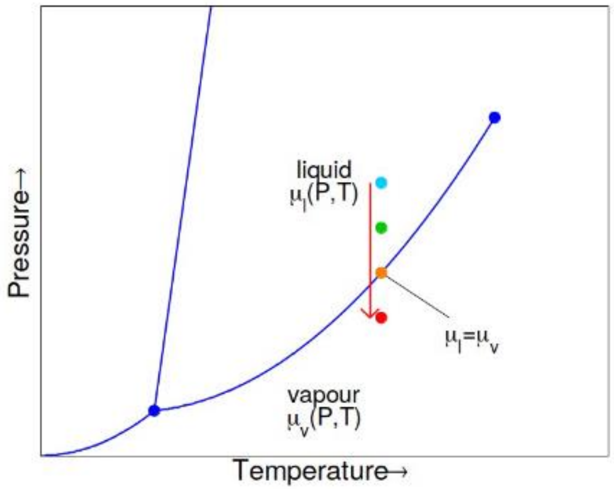
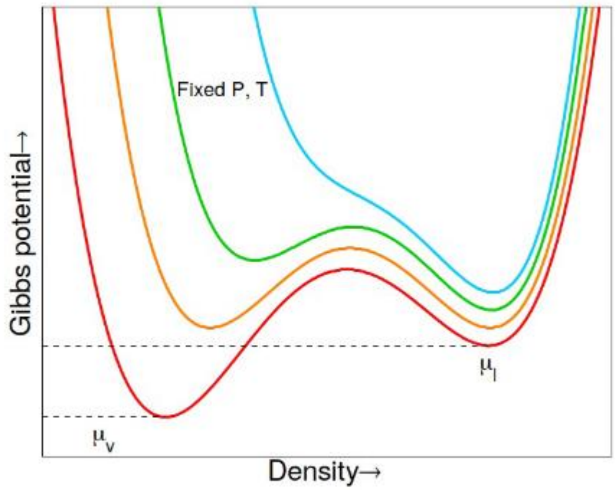
Introduction

- Liquid noble (scintillating) bubble chambers offer the potential to detect low energy (O(100 eV)) nuclear recoils
  - Enable searches for dark matter to $M_\chi \sim 1$ GeV
  - Neutrino CEvNS measurements to $E_\nu \sim 1$ MeV (reactor!)
- SBC-L**Ar**10 is piloting this technology at Fermilab
- I'll discuss SBC LAr10, and the future neutrino physics prospects

Particle Detection with Superheated Liquids

- Superheated liquids get “stuck” in the liquid phase without an impurity or other energy input to transition to a gas

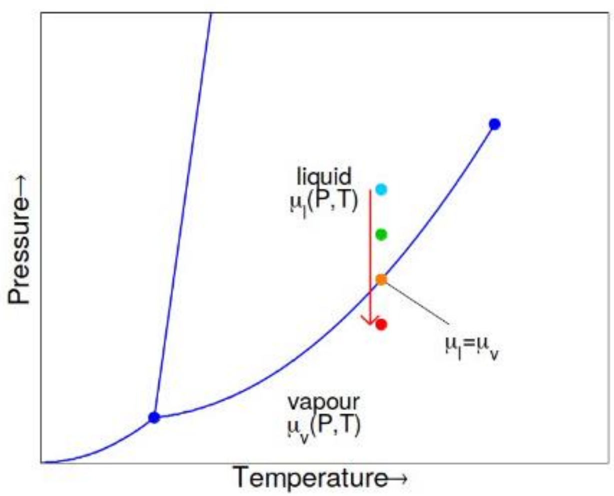


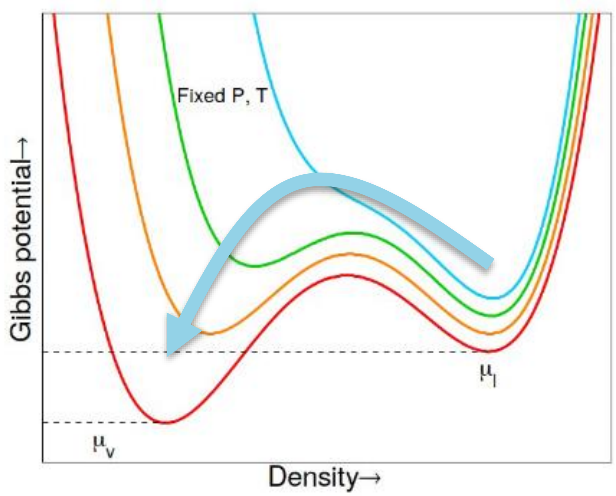


Fermilab

Particle Detection with Superheated Liquids

- Superheated liquids get “stuck” in the liquid phase without an impurity or other energy input to transition to a gas
- A nuclear recoil can provide that energy spike*





*See Ben Boerman SBC talk for more details on detector physics!

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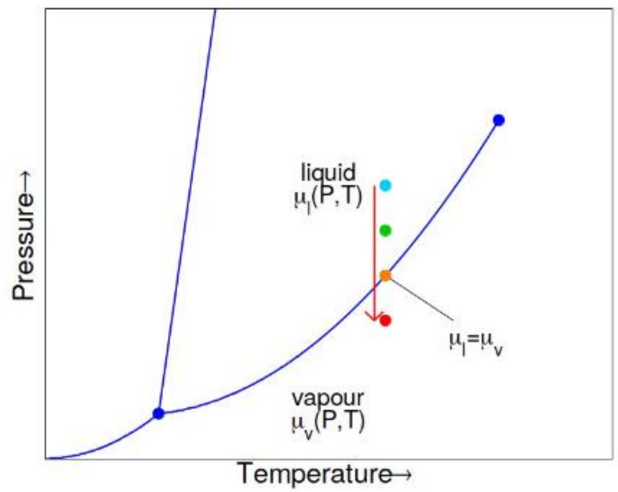
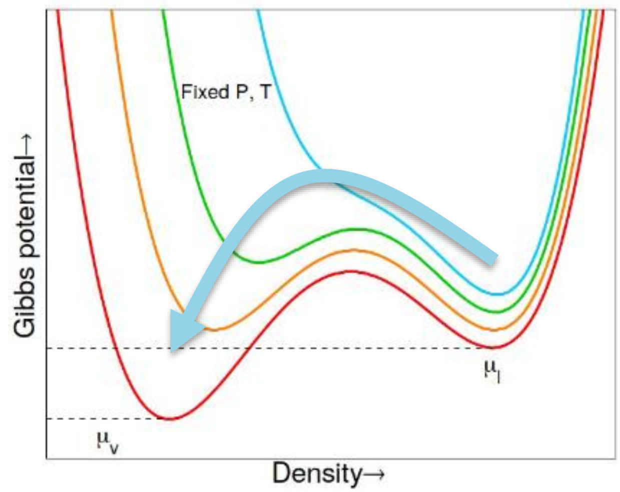


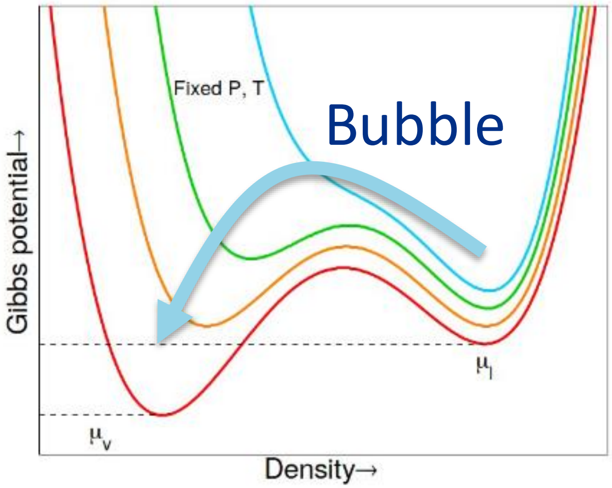


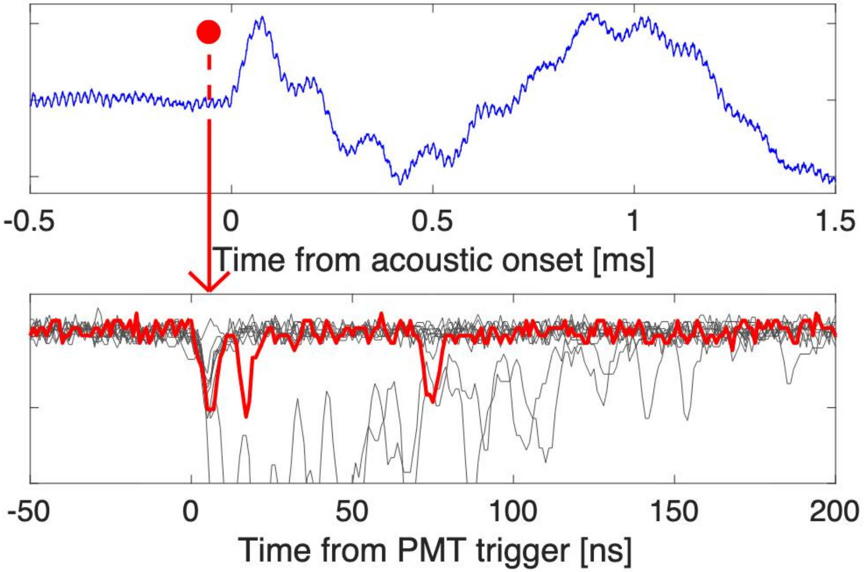
- In noble liquids, electrons do not inject significant heat to nucleate a bubble

*See Ben Boerman SBC talk for more details on detector physics!

Particle Detection with Superheated Liquids

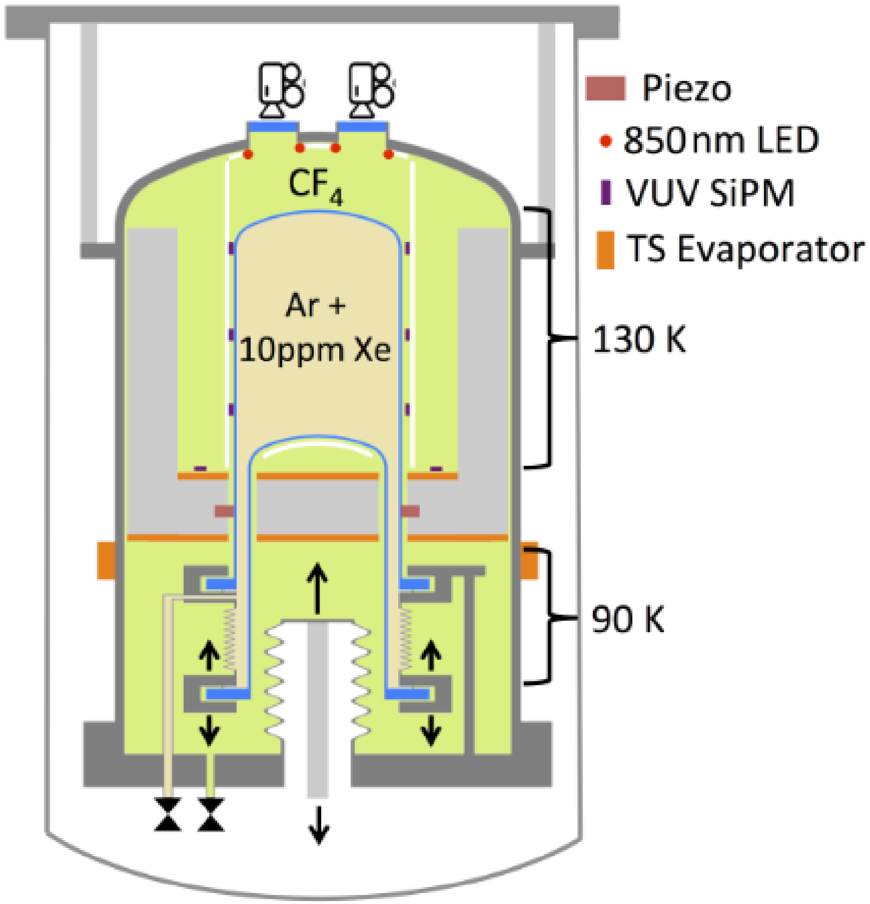
- Bubbles are detected with multiple overlapping sensors:
  - Optical camera picture of ~mm-sized bubble
  - Piezoelectric detection of acoustic shockwave
  - Scintillation light detection





The SBC Collaboration

SBC-LAr10 Fermilab



SBC-LAr10 Fermilab
10 kg calibration chamber in MINOS underground tunnel

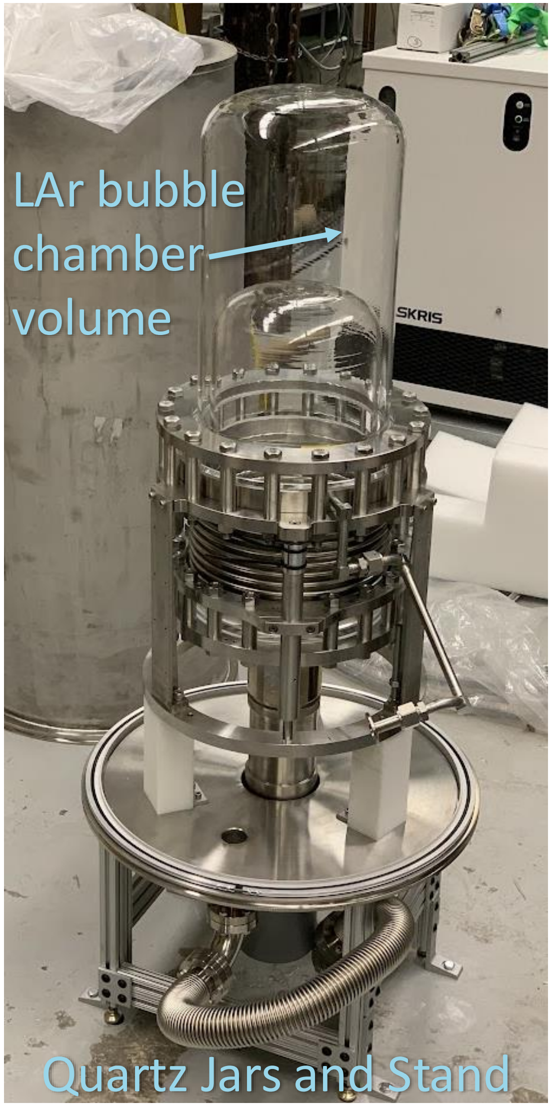
SBC-LAr10 SNOLAB*
Identical, radiopure chamber dark matter search

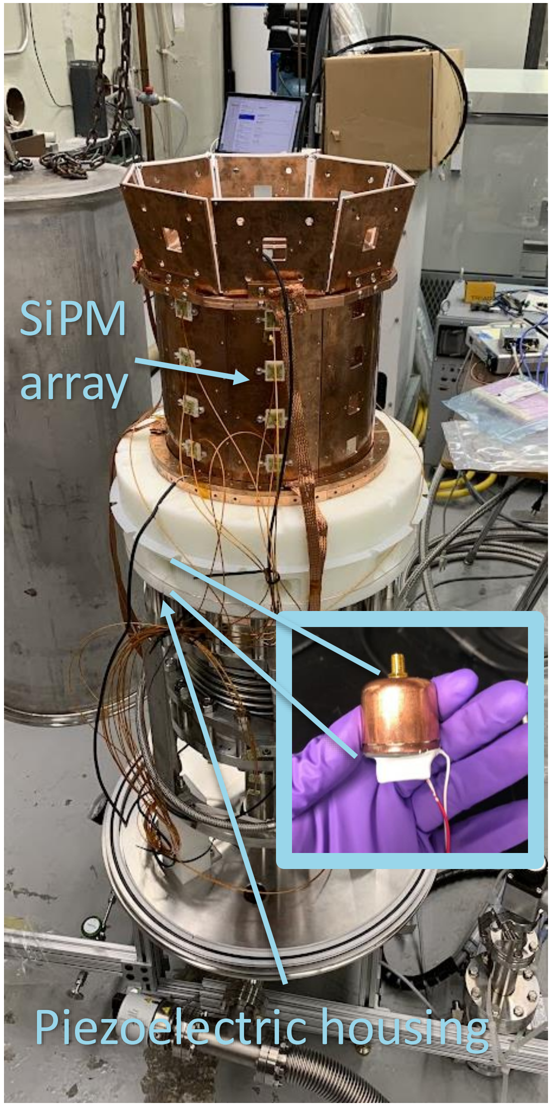
Low energy CEvNS physics

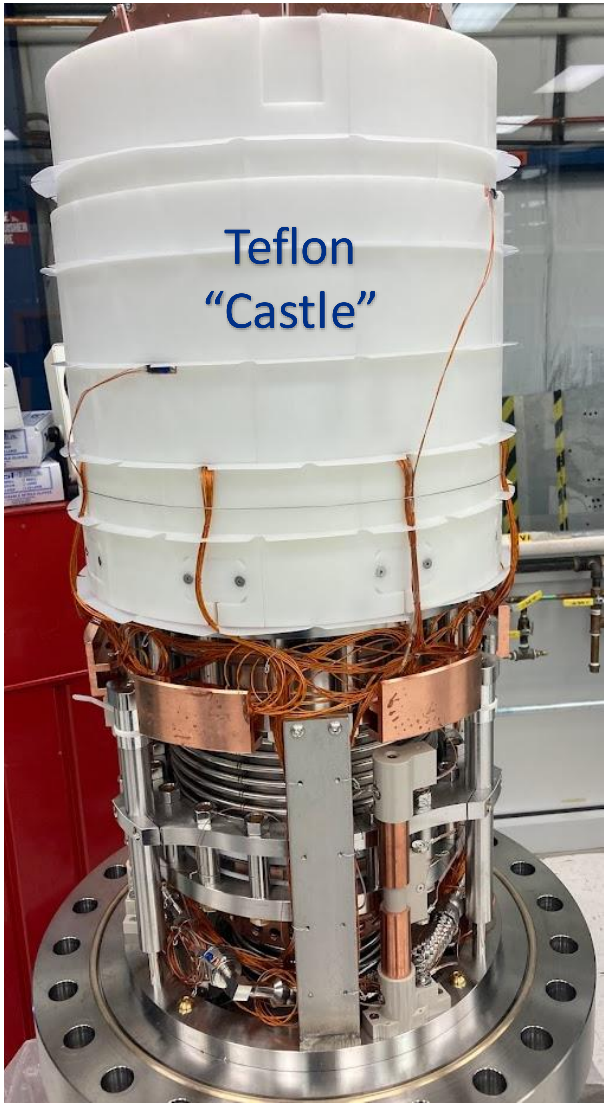
Ton-year chamber
DM search to solar fog

*See Ben Boerman talk on SBC-LAr10 SNOLAB

The SBC LAr10 Matryoshka Doll







The SBC LAr10 Matryoshka Doll

Wrapped in super-insulation and inside vacuum vessel

SBC Installation at MINOS

- Currently installed at MINOS underground facility, gearing up for 1st physics run this summer

Goals of SBC LAr10 @ Fermilab

Calibration questions to answer:

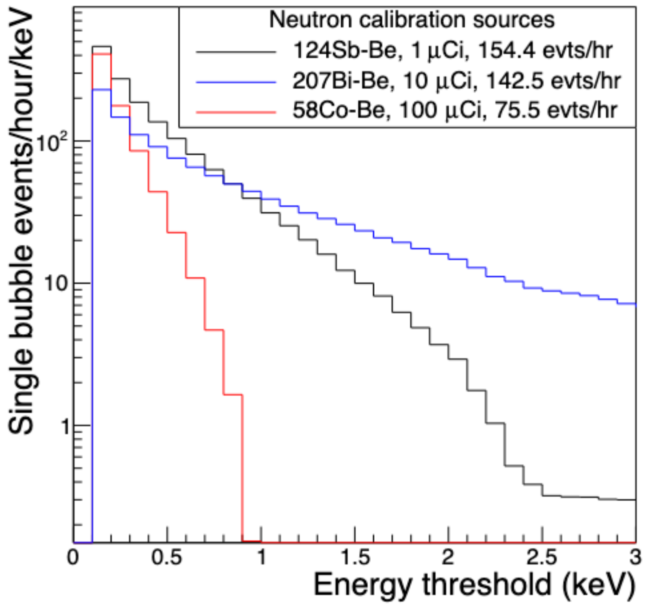
Can we operate the chamber as expected? Do all of the detector arrays work together?

What is the lowest thermodynamic threshold we can operate while remaining insensitive to ERs?

What is the NR bubble nucleation energy at that threshold?

Calibration Steps for SBC-LAr10

- Electron recoils from gamma sources
  - Can also study scintillation light yield in LAr and LCF_4 from ERs
- Nuclear recoils from:
  - Photo-neutron (mono-energetic) sources



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- Electron recoils from gamma sources
  - Can also study scintillation light yield in LAr and LCF_4 from ERs
- Nuclear recoils from:
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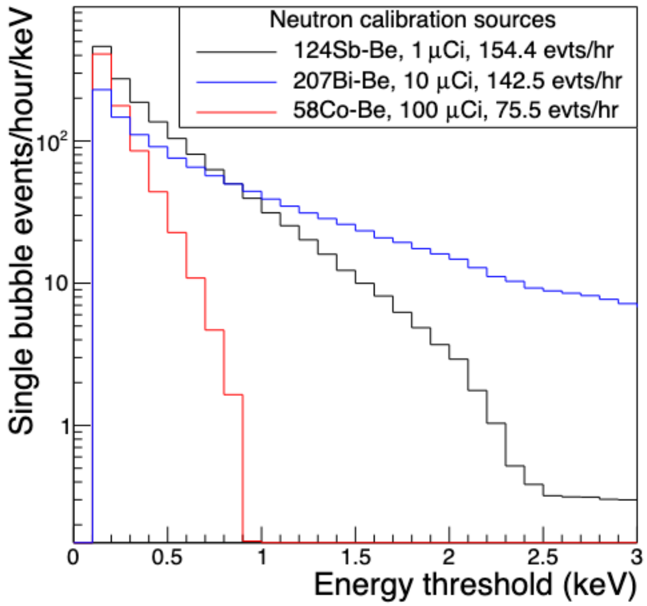
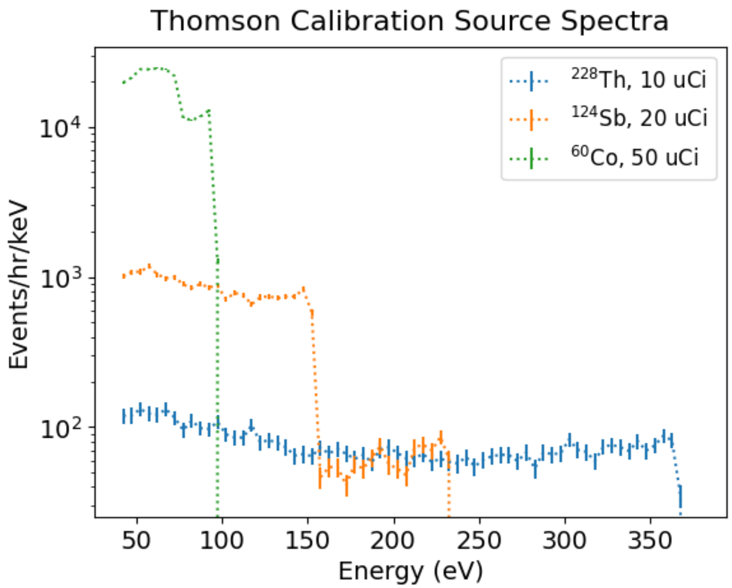
  - Thompson scattering from gamma sources



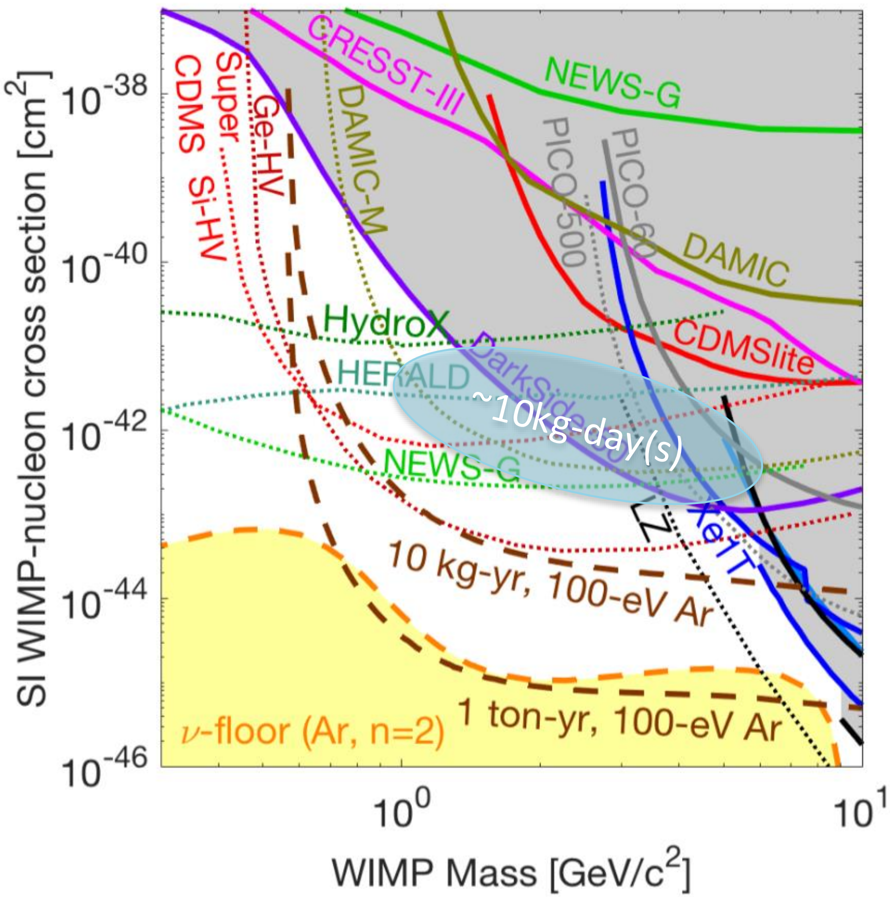


Calibration Steps for SBC-LAr10

- Electron recoils from gamma sources
  - Can also study scintillation light yield in LAr and LCF_4 from ERs
- Nuclear recoils from:
  - Photo-neutron (mono-energetic) sources
  - Thompson scattering from gamma sources
  - Thermal neutron capture

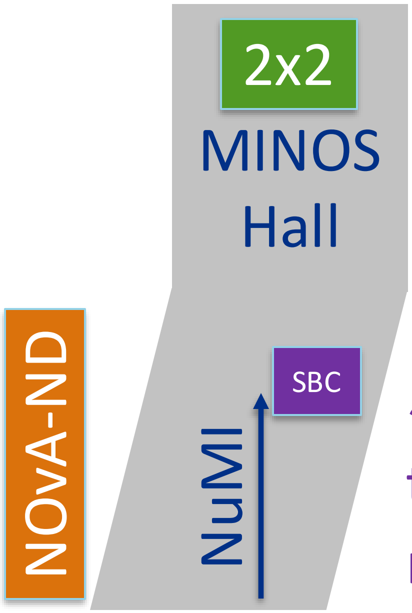
Other Physics at Fermilab

- Low-exposure dark matter search
  - Limits could be competitive even at ~10 kg – day, background free

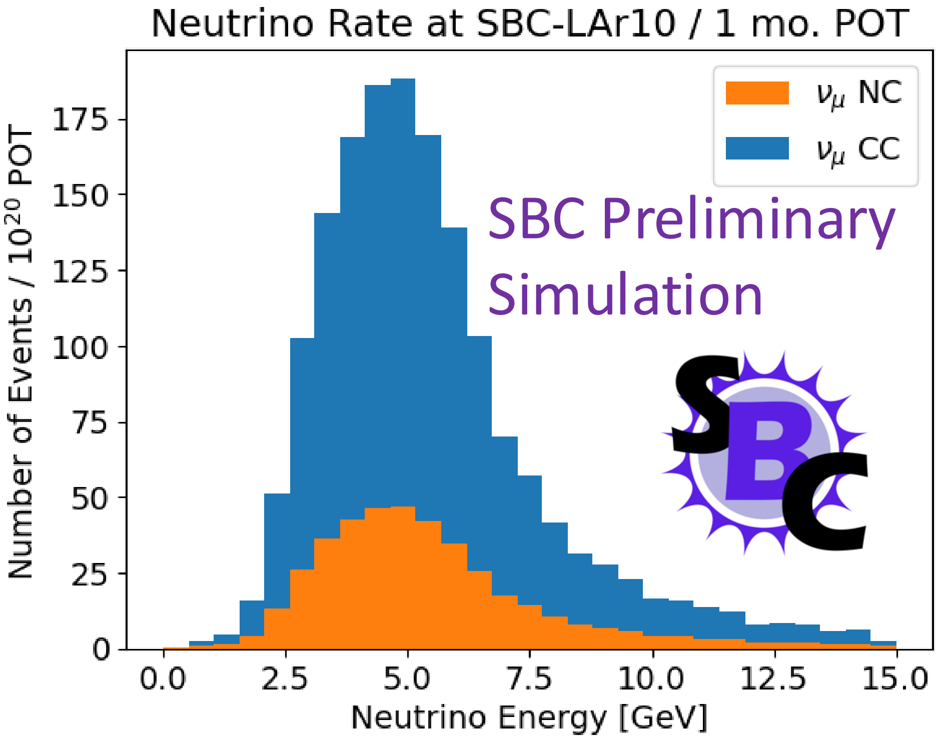


Other Physics at Fermilab

- Low-exposure dark matter search
  - Limits could be competitive even at ~10 kg – day, background free
- Physics in Neutrinos at Main Injector Beam
  - Depends on NuMI operating schedule in FY 2025+26



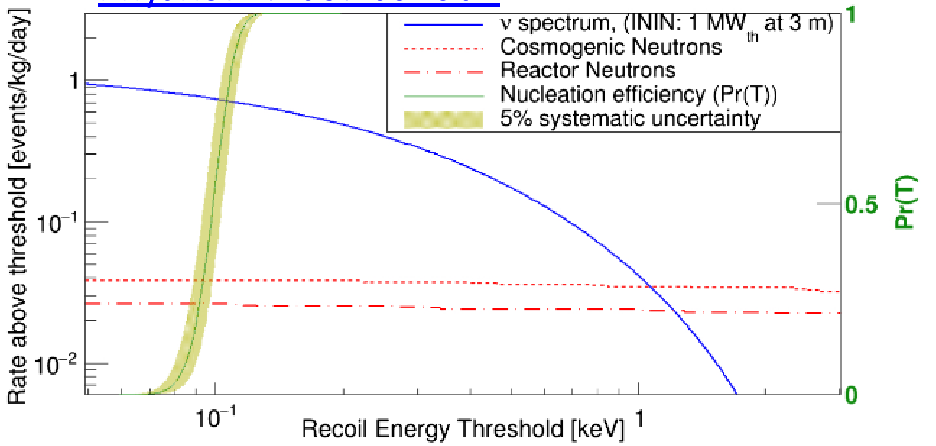
~1km from target, couple mrad off-axis



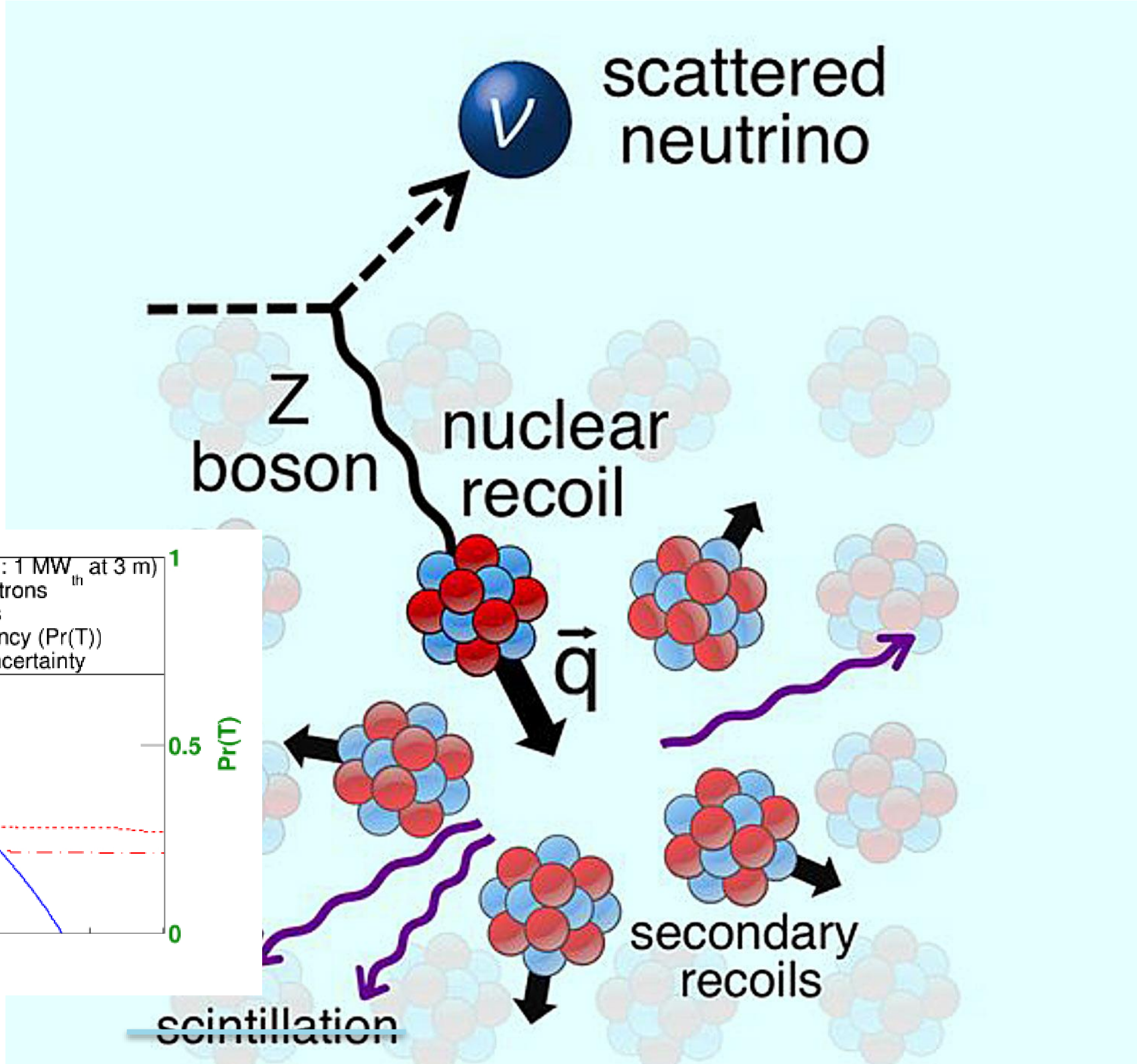
The Future: Neutrino CEvNS at a Reactor Source

- SBCs would be a sensitive, scalable detector for reactor neutrino CEvNS

[PhysRevD.103.L091301](https://doi.org/10.1103/PhysRevD.103.L091301)



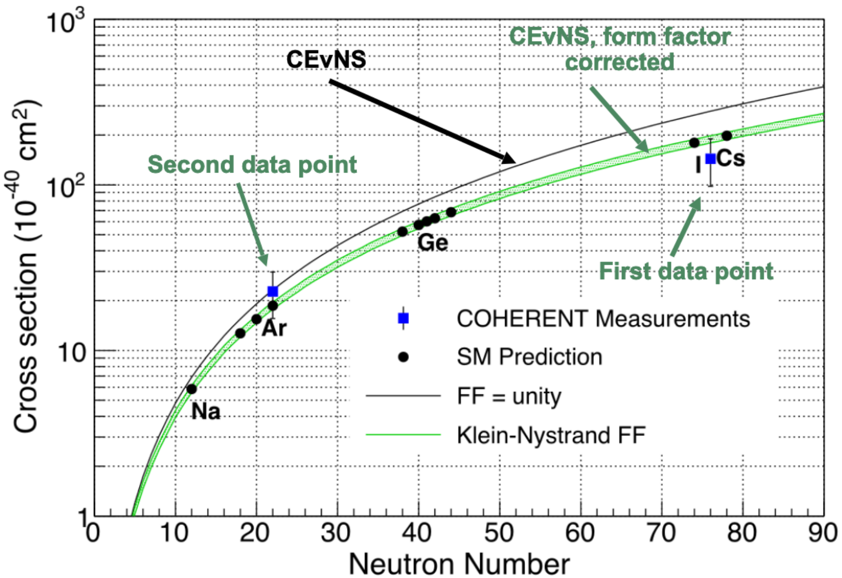
CEvNS rate on Ar, 3 m from a 1 MW reactor



No scintillation at low energy!

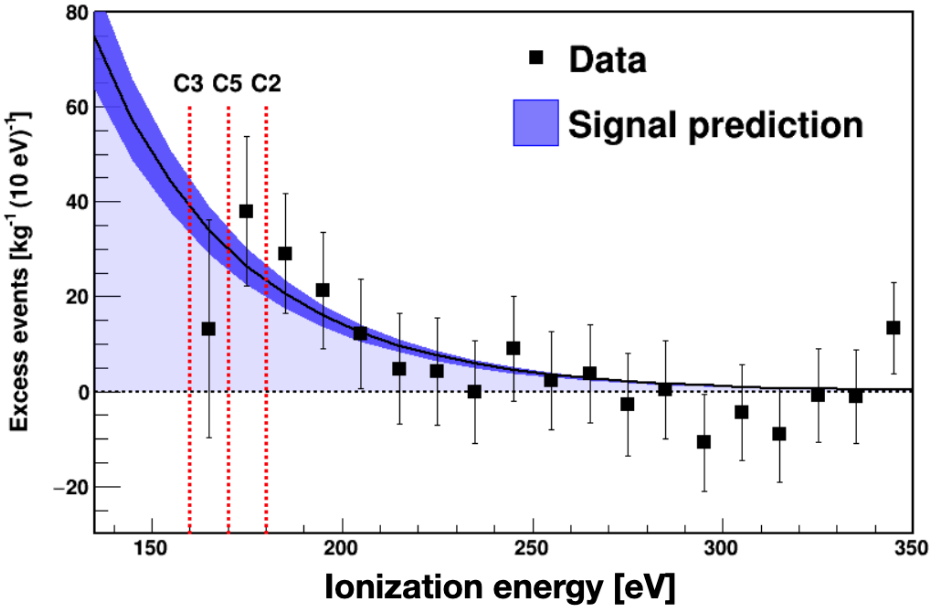
Experimental Landscape of CEvNS Measurements

Variety of CEvNS measurements by COHERENT experiment at SNS at Oak Ridge, TN



π Decay at Rest Source

3.7σ observation by CONUS+ at the nuclear power plant in Leibstadt, Switzerland on germanium

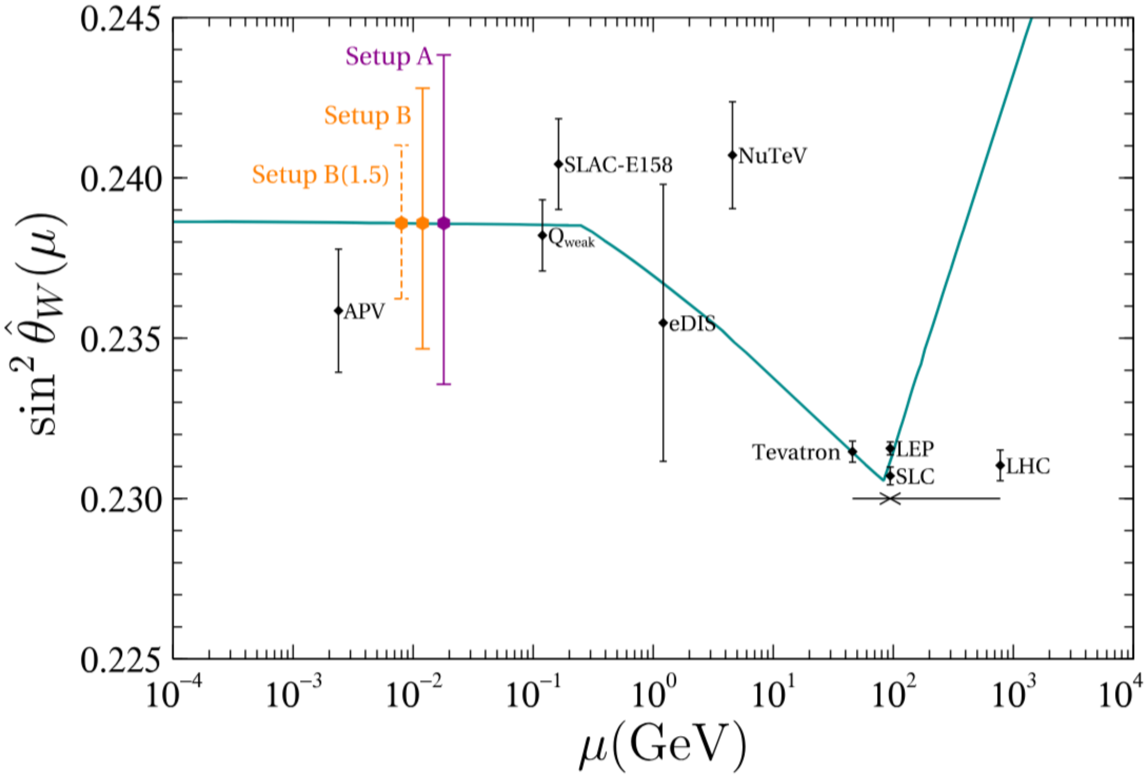


Reactor Source

Physics Reach of Reactor CEvNS

Precision measurements of the weak mixing angle with neutrinos

- Measurements of the CEvNS rate can be inferred as a measurement of $\sin^2 \theta_W$



Projection for SBC

Physics Reach of Reactor CEvNS

- Baseline scenarios from [PhysRevD.103.L091301]

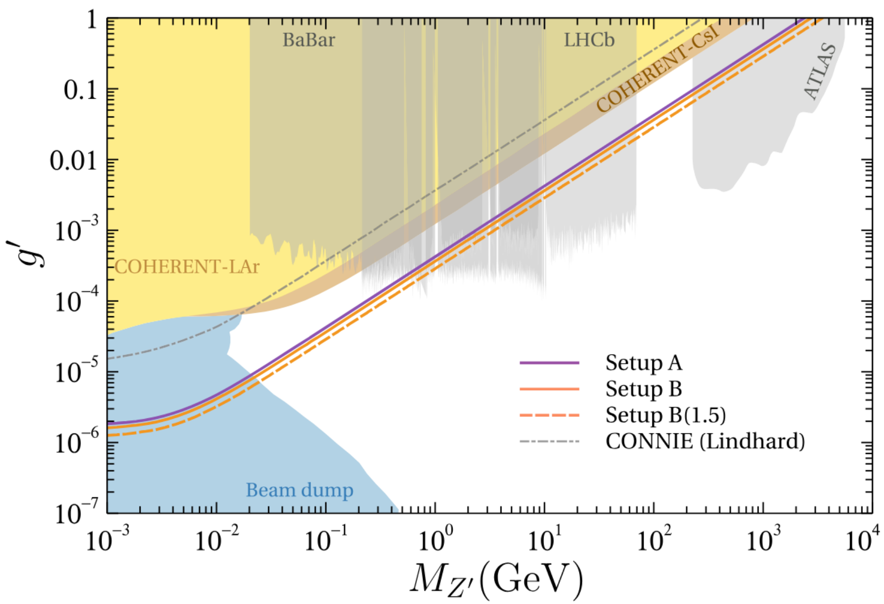
Setup	LAr Mass [kg]	Power [MW]	Distance [m]	ν Flux Unc. [%]	Threshold Unc. [%]
A	10	1	3	2.4	5.0
B	100	2000	30	2.4	5.0
B(1.5)	100	2000	30	1.5*	2.0

*Above the target set by (e.g.) PROSPECT-II, arxiv:2202.12343

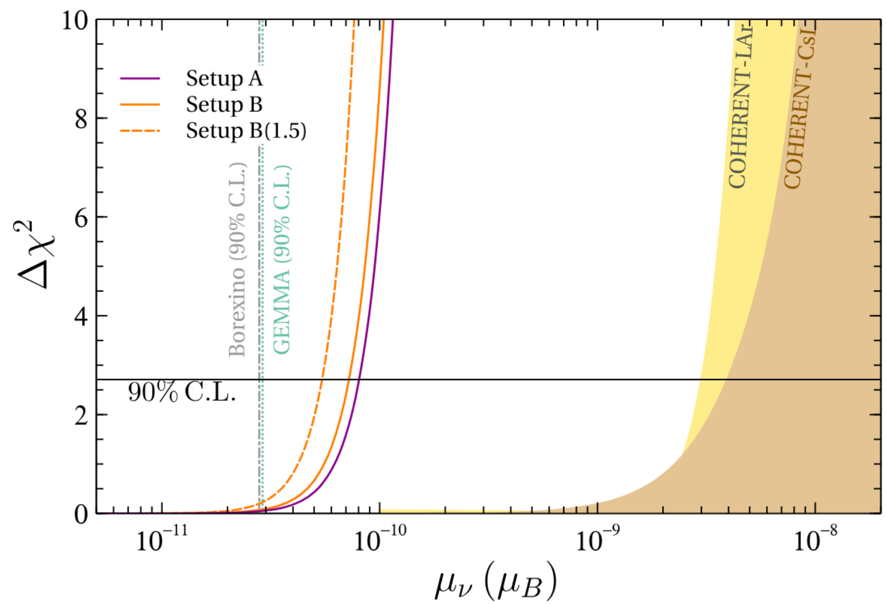
Physics Reach of Reactor CEvNS

- New physics searches in neutrino sector

New Z' Boson



Neutrino Magnetic Moment



Conclusion

- Scintillating bubble chambers offer the potential for scalable (10s kg – ton), low energy nuclear recoil detectors
  - Dark matter to $M_\chi \sim 1$ GeV
  - Neutrino CEvNS to $E_\nu \sim 1$ MeV
- SBC-LAr10, at FNAL, will soon start taking calibration data to demonstrate the technology
- Future physics:
  - Dark matter search at SNOLAB
  - Ton-year dark matter searches and reactor neutrino measurements