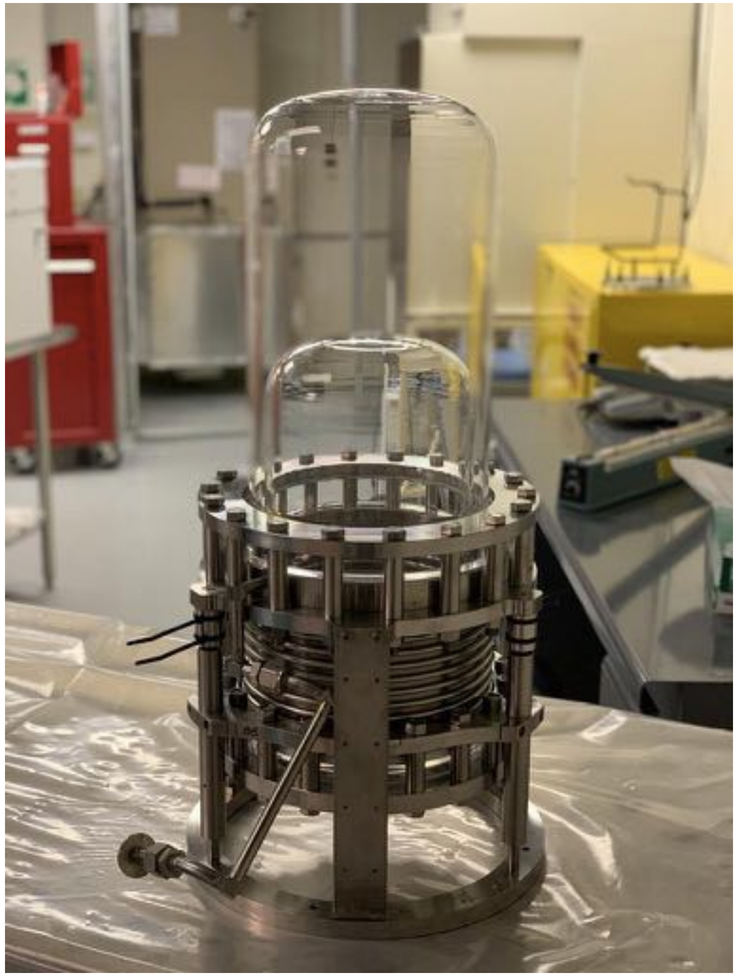
Scintillating Bubble Chambers for GeV-scale Dark Matter Searches

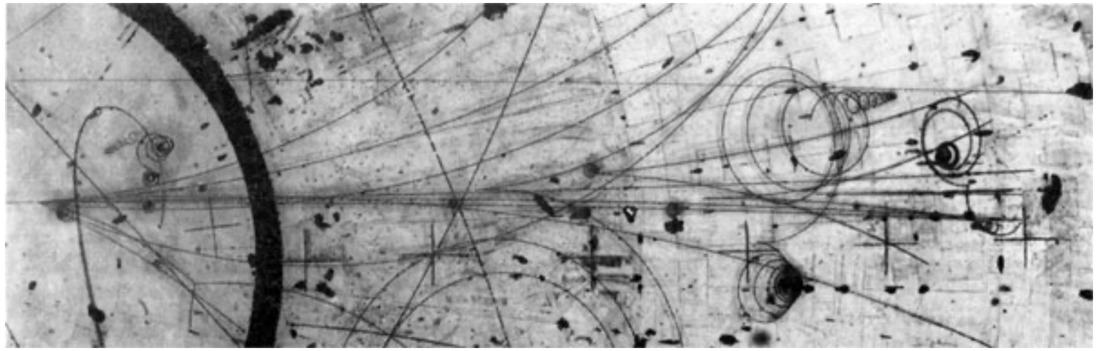
Russell Neilson, Drexel University
for the SBC Collaboration

Dark Side of the Universe
Dec 2022, Sydney



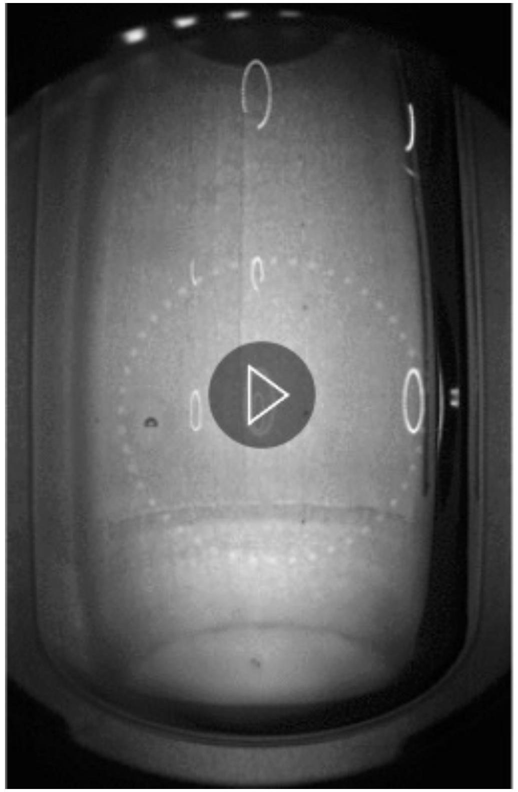
Bubbles chambers: then and now

- 1970s: Neutrino Beam Physics



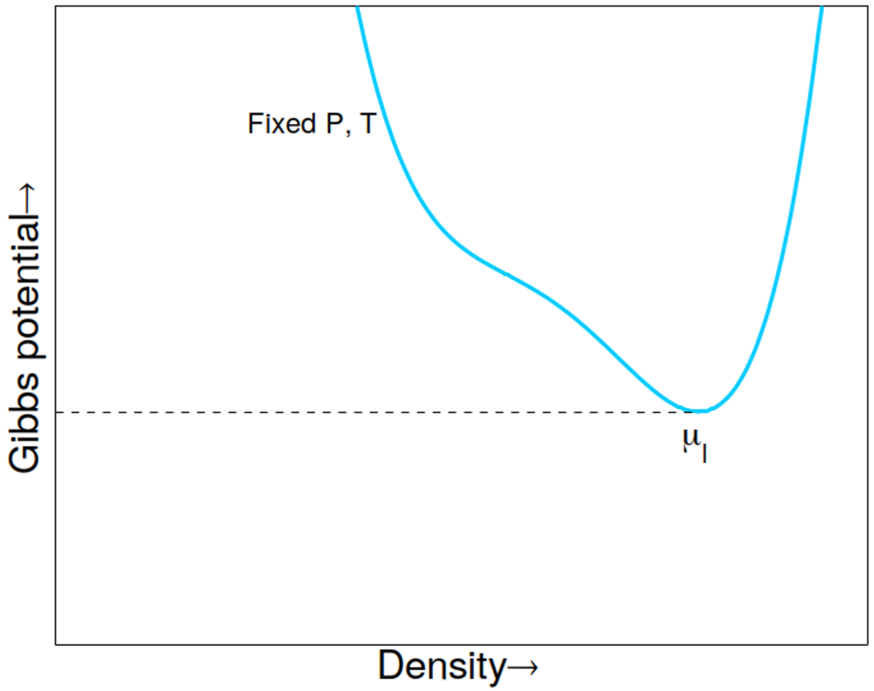
  - Sensitive to minimum ionizing particles

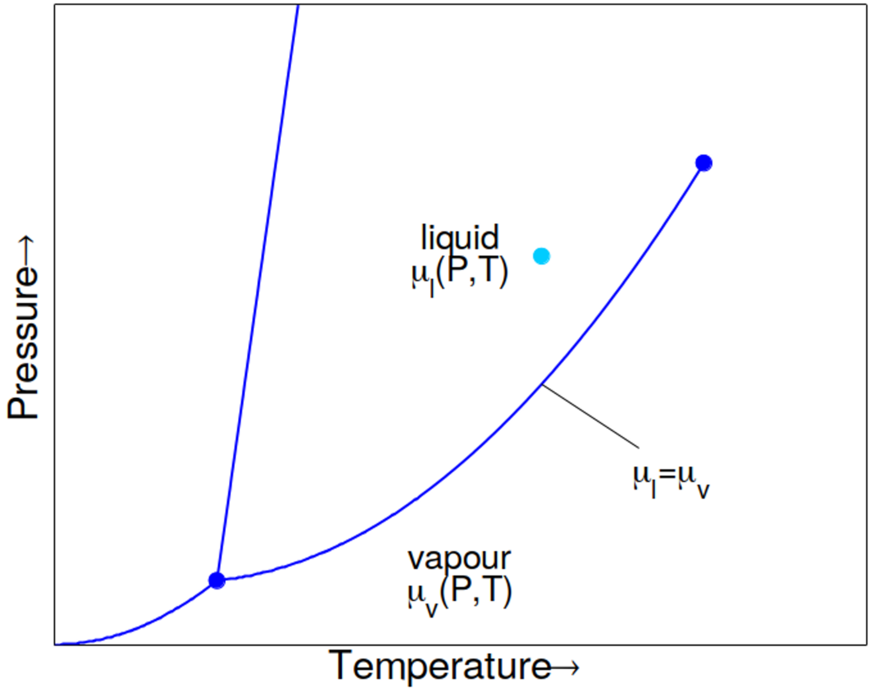
- 2000-today: Nuclear Recoil Detectors
  - Insensitive to minimizing ionizing particles – no electron recoil background.



PICO-60

How bubble chambers work





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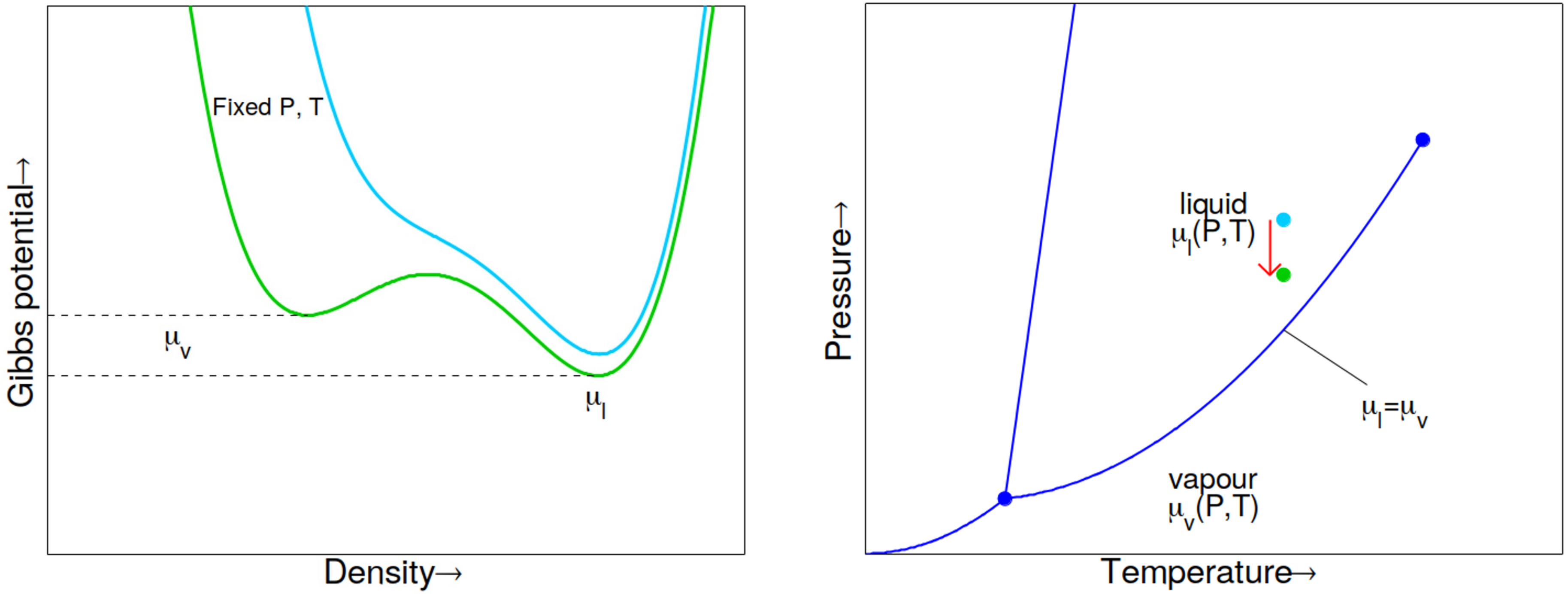
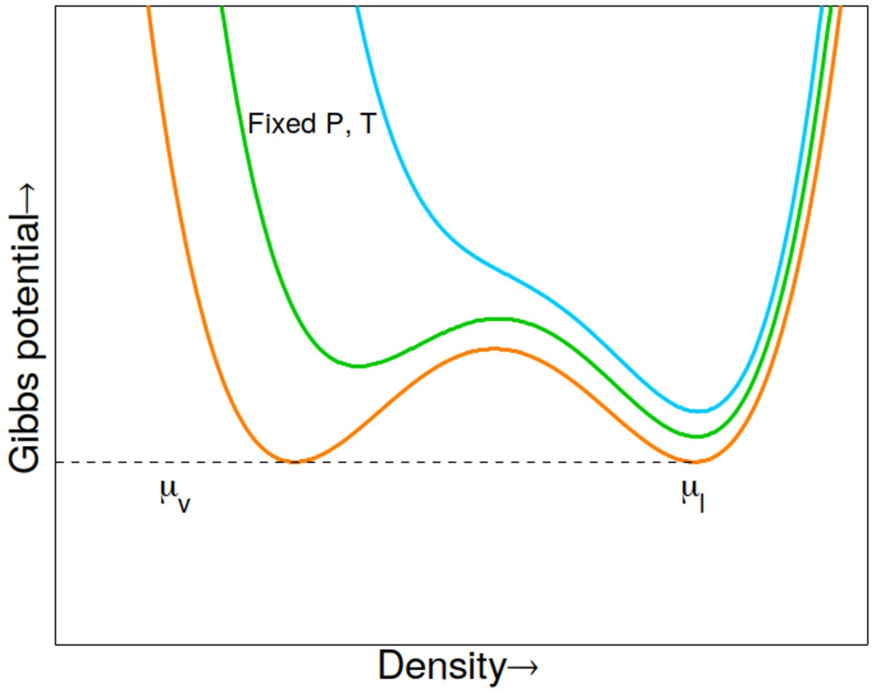
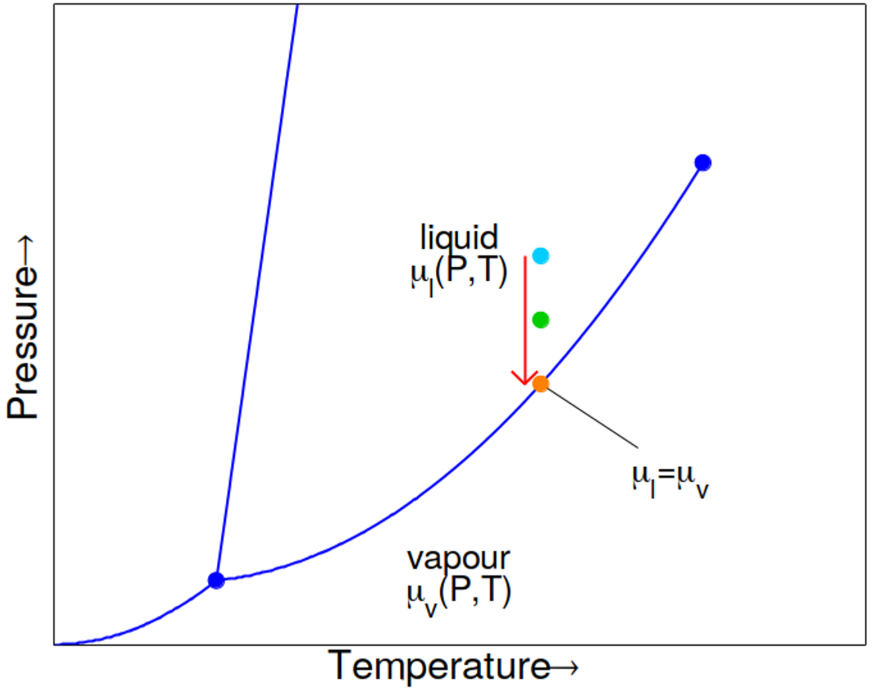


How bubble chambers work





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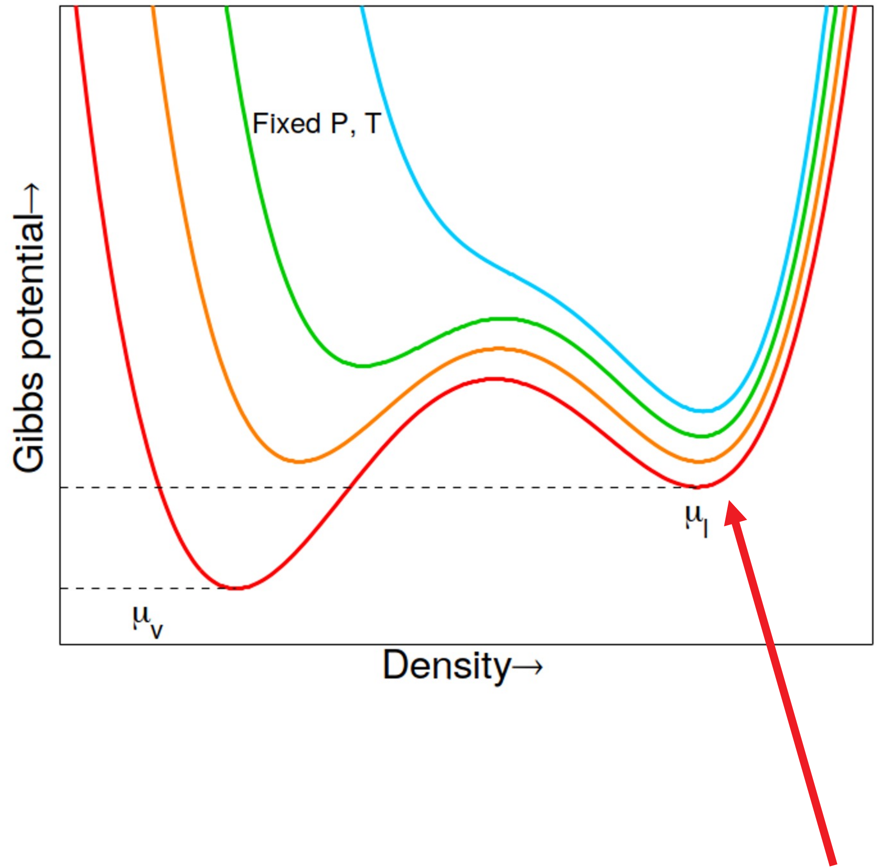
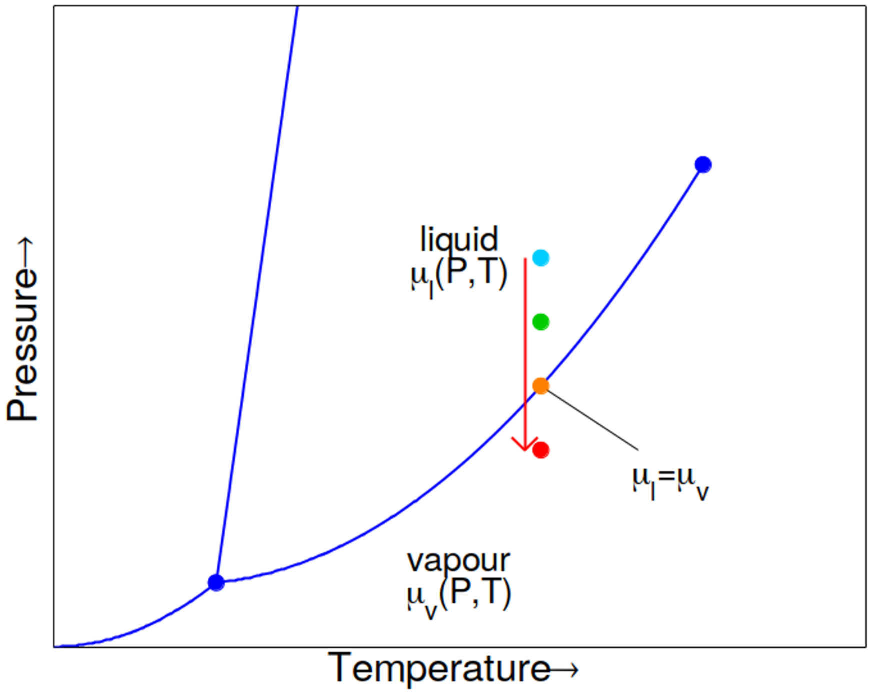
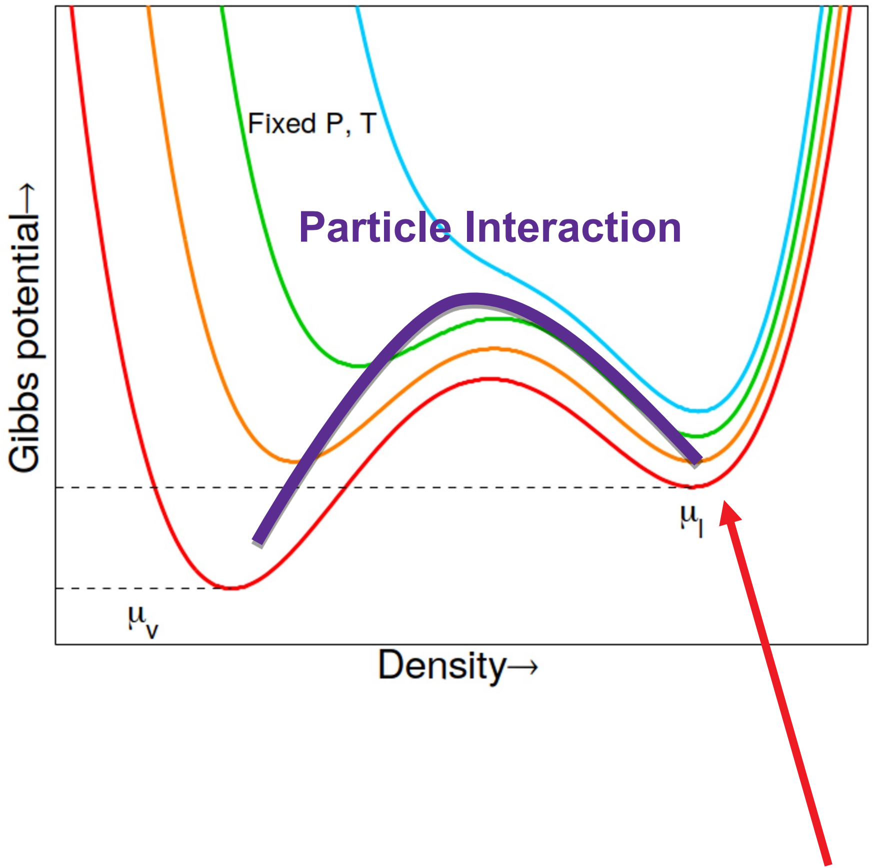
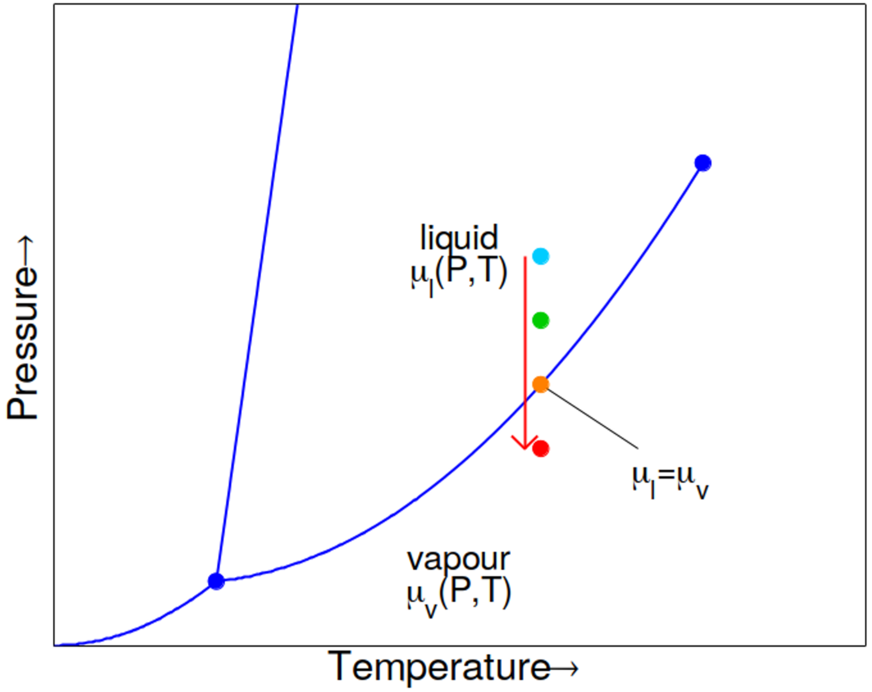




Superheated Liquid

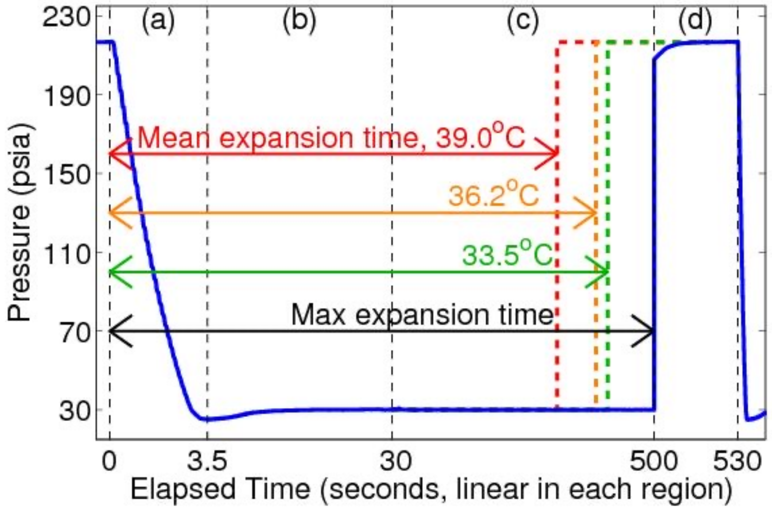
How bubble chambers work



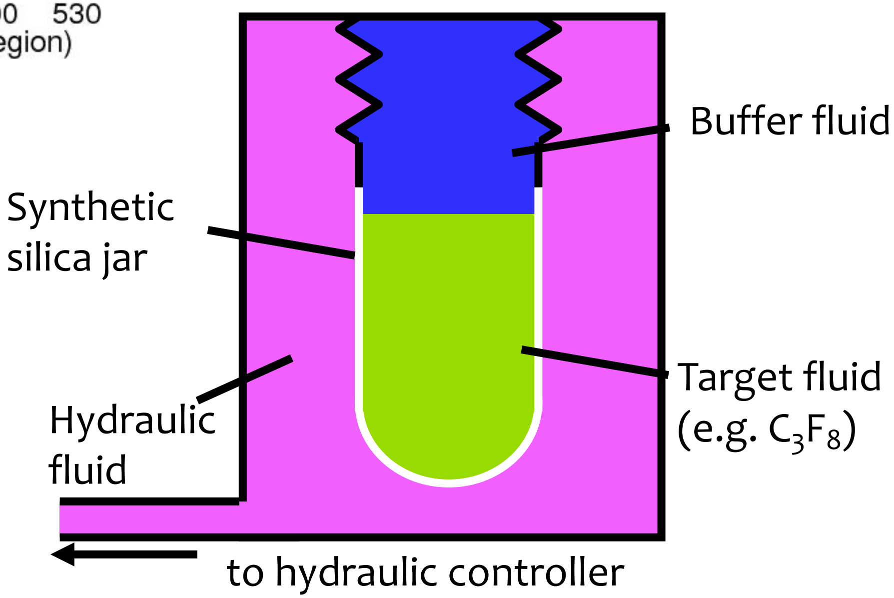


Superheated Liquid

Operation and neutron scatter event



Phys. Rev. D 86, 052001 (2012)



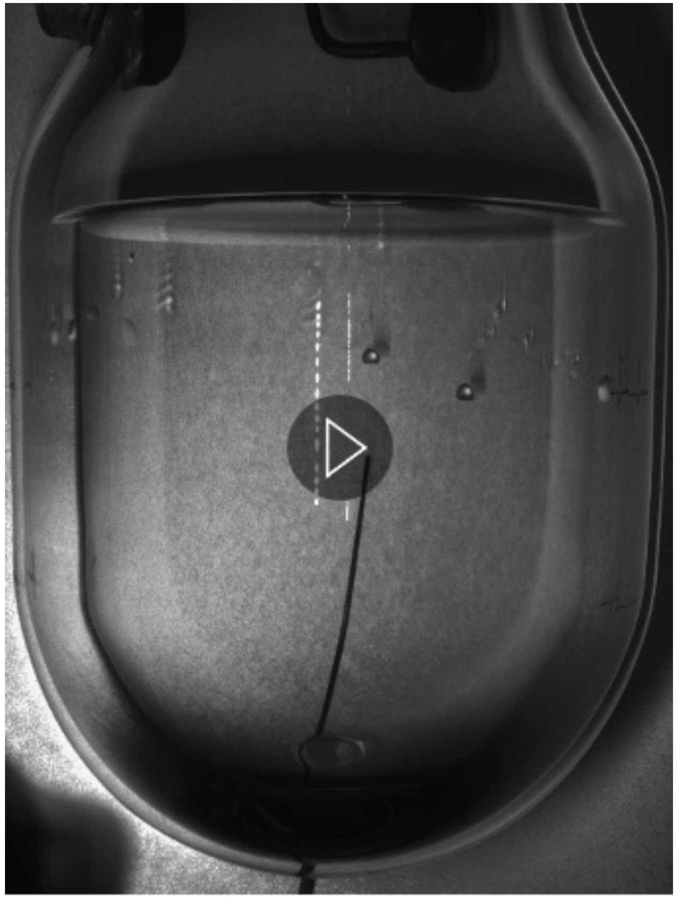
Buffer fluid

Synthetic
silica jar

Target fluid
(e.g. C_3F_8)

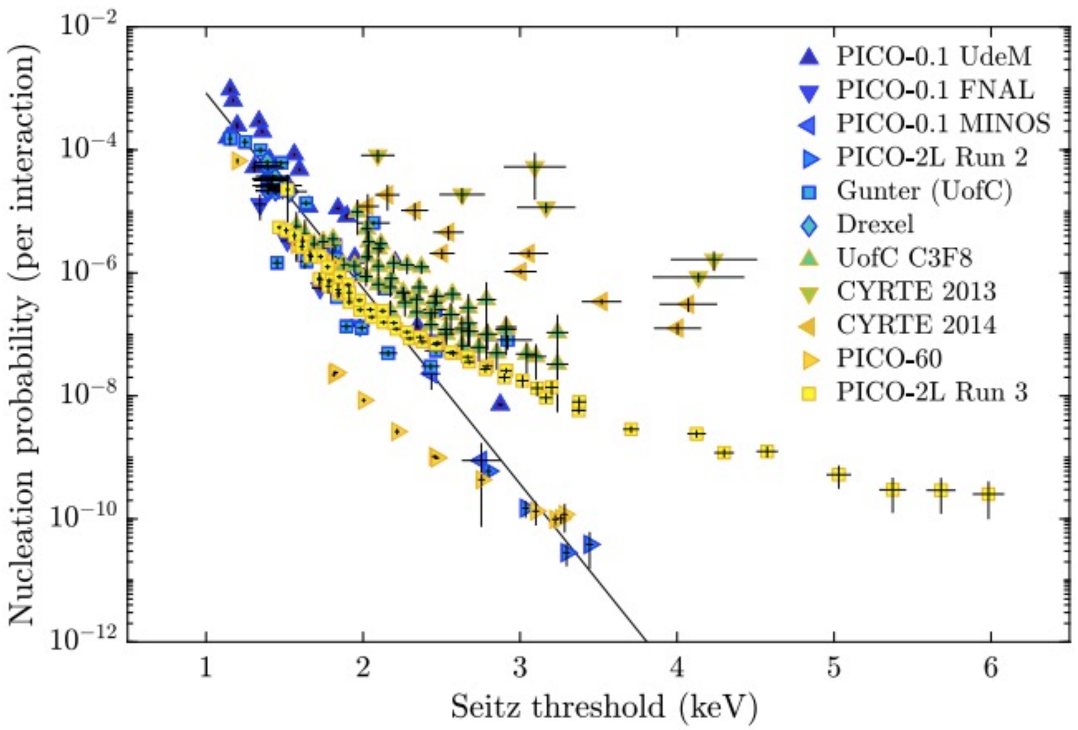
Hydraulic
fluid

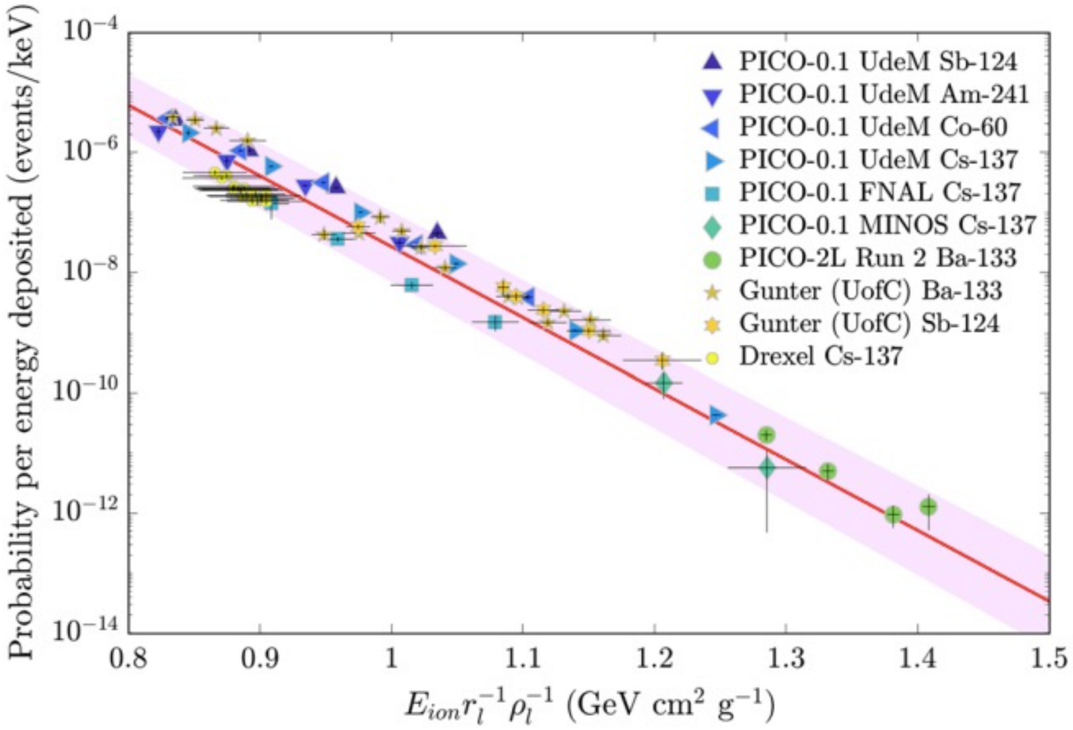
to hydraulic controller



PICO-2L

Electron recoil rejection (C_3F_8)

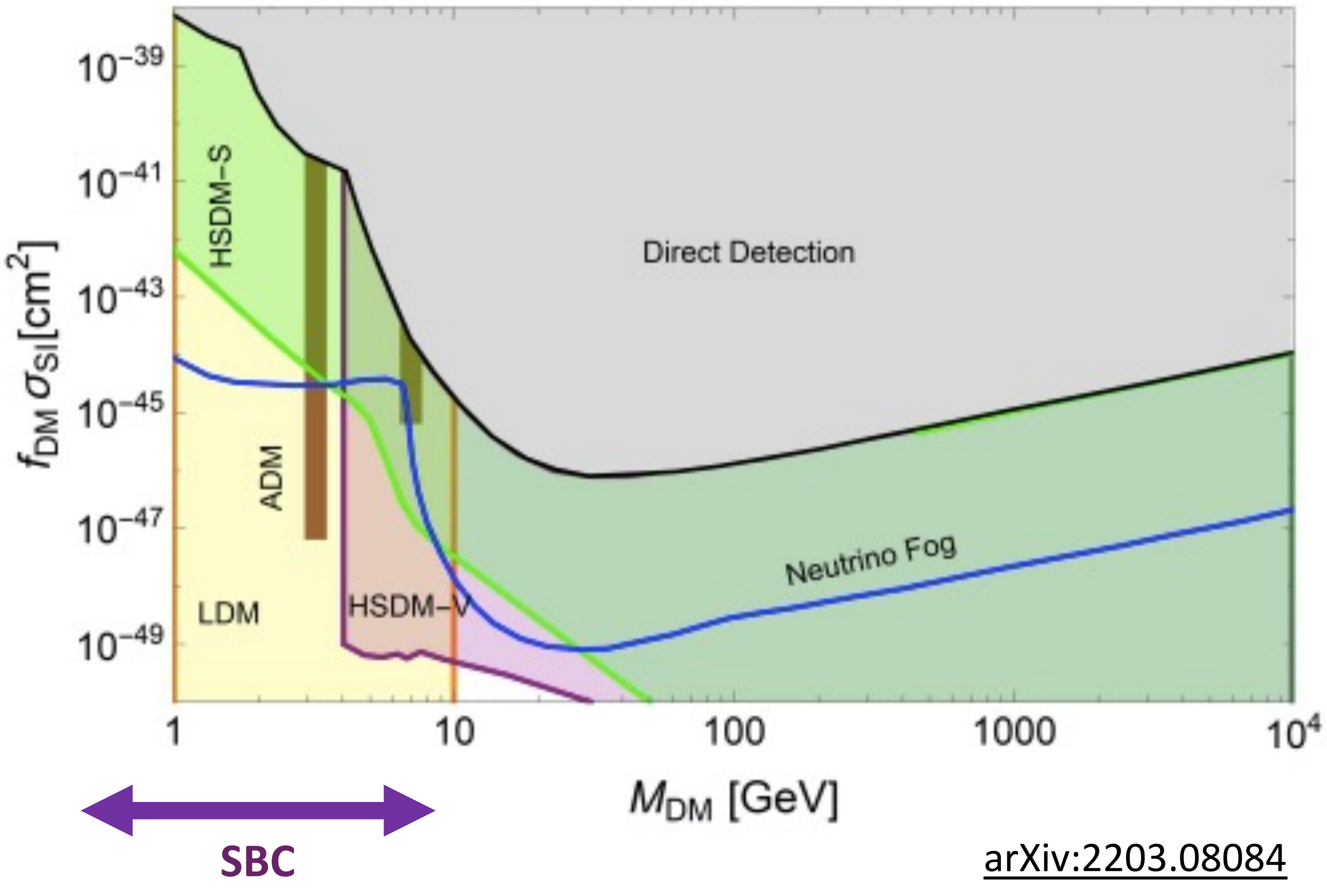




Phys. Rev. D 100, 082006 (2019)

- Superb ER rejection for >3keV threshold.
- ER background becomes dominant below 1 keV - need to improve for GeV-scale WIMP search.

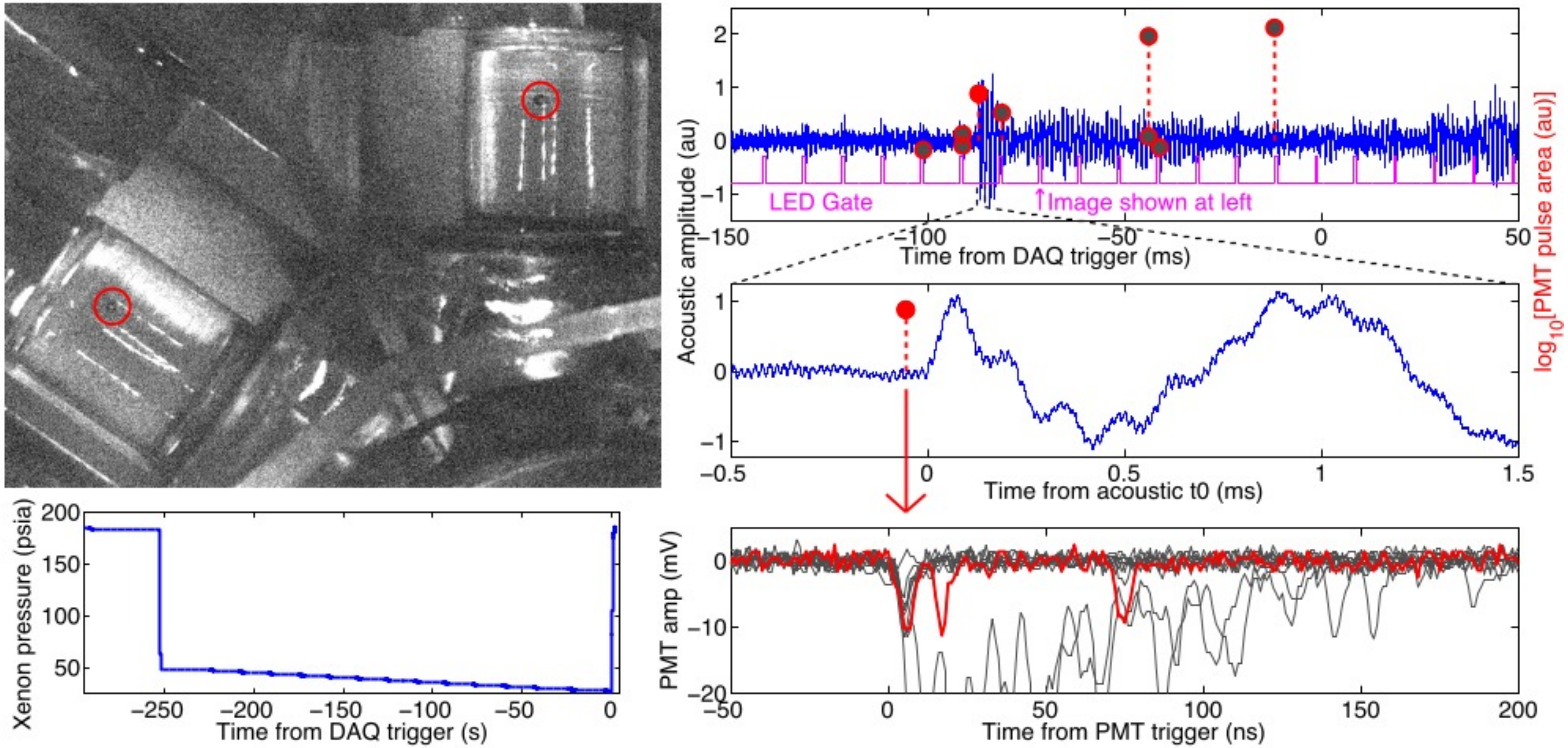
Probing the threshold frontier



arXiv:2203.08084

LXe bubble chamber

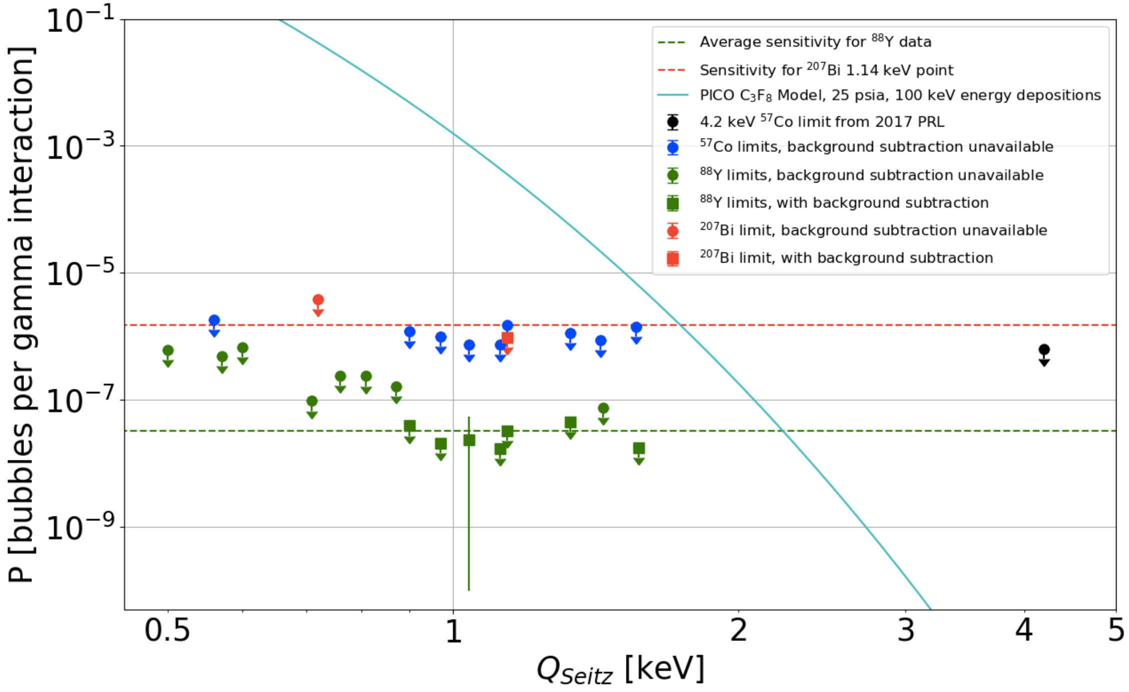
30g demonstration detector at Northwestern



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.**



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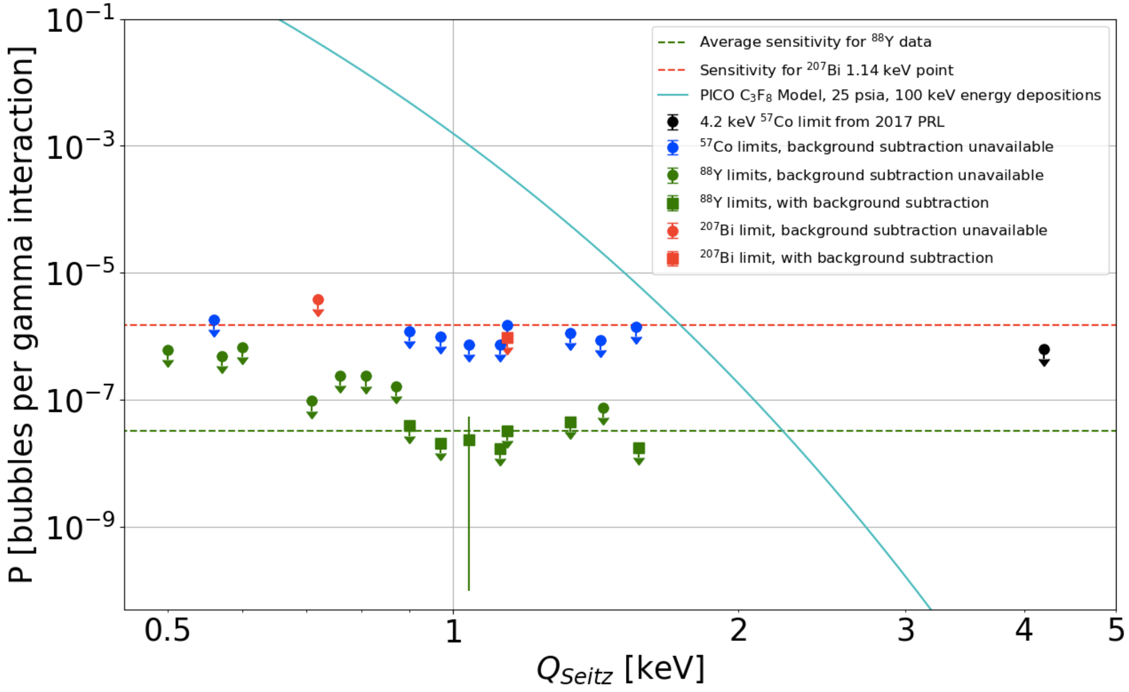

We should have known:
"When the chamber was filled **with liquid xenon** and run under closely similar conditions immediately after the ethylene experiments, **no tracks were obtained**."
- from *Liquid Xenon Bubble Chamber*
J. L. Brown, D. A. Glaser, and M. L. Perl
Phys. Rev. **102**, 586 – Published 15 April 1956

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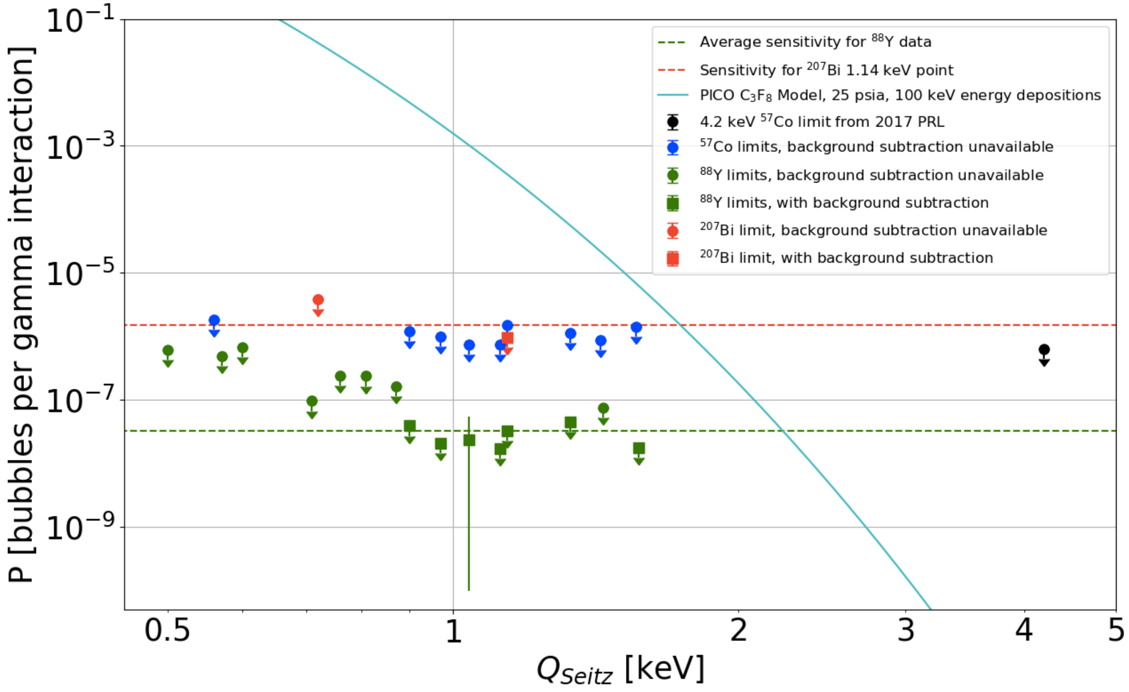
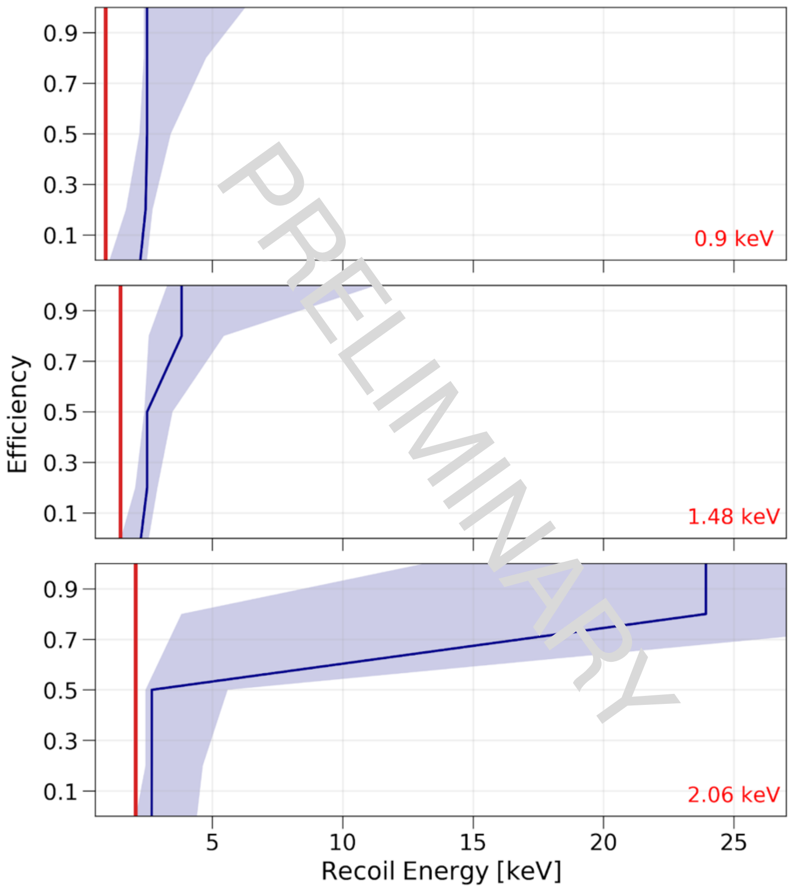
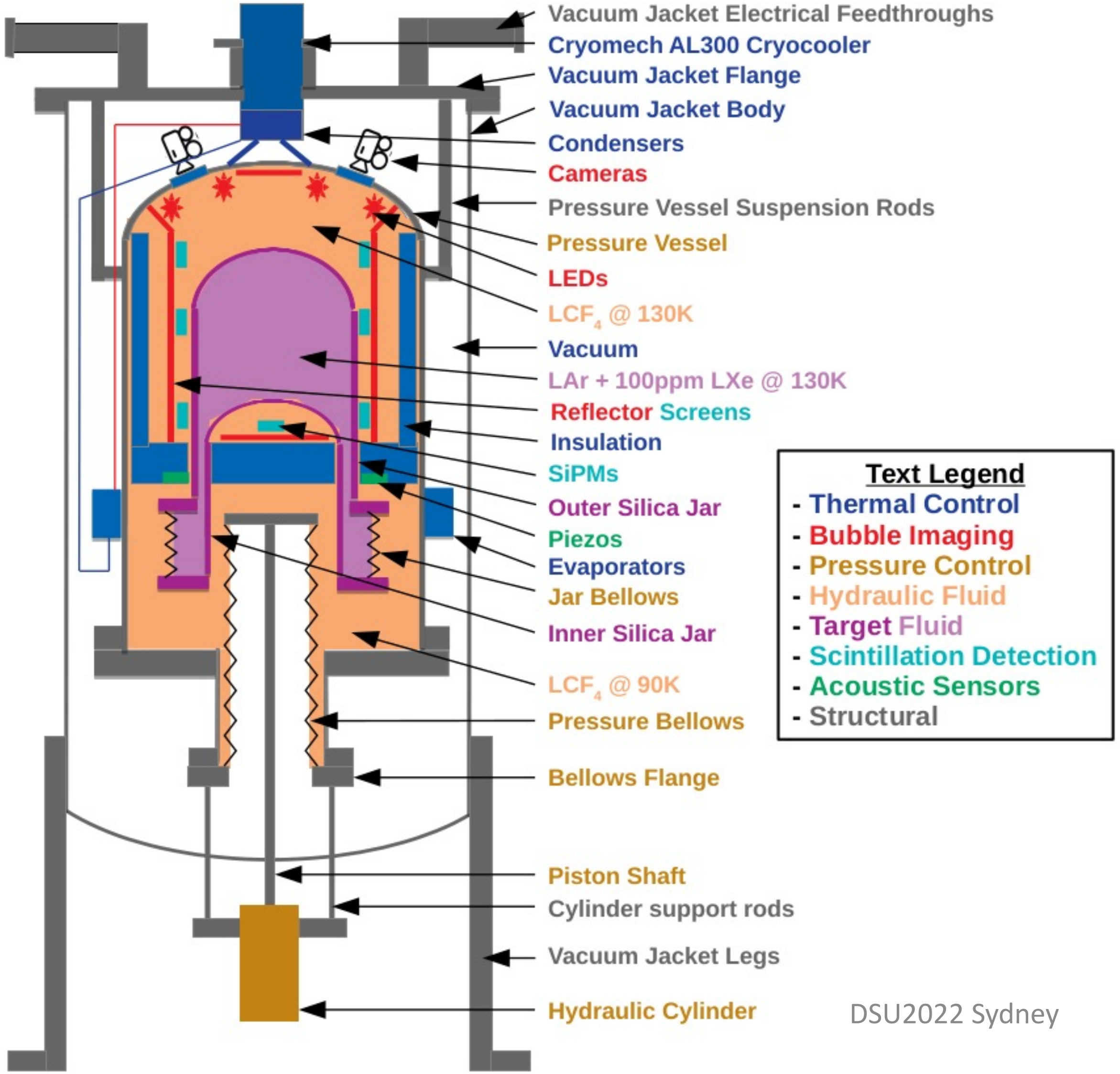


But **nuclear recoils** still make bubbles!



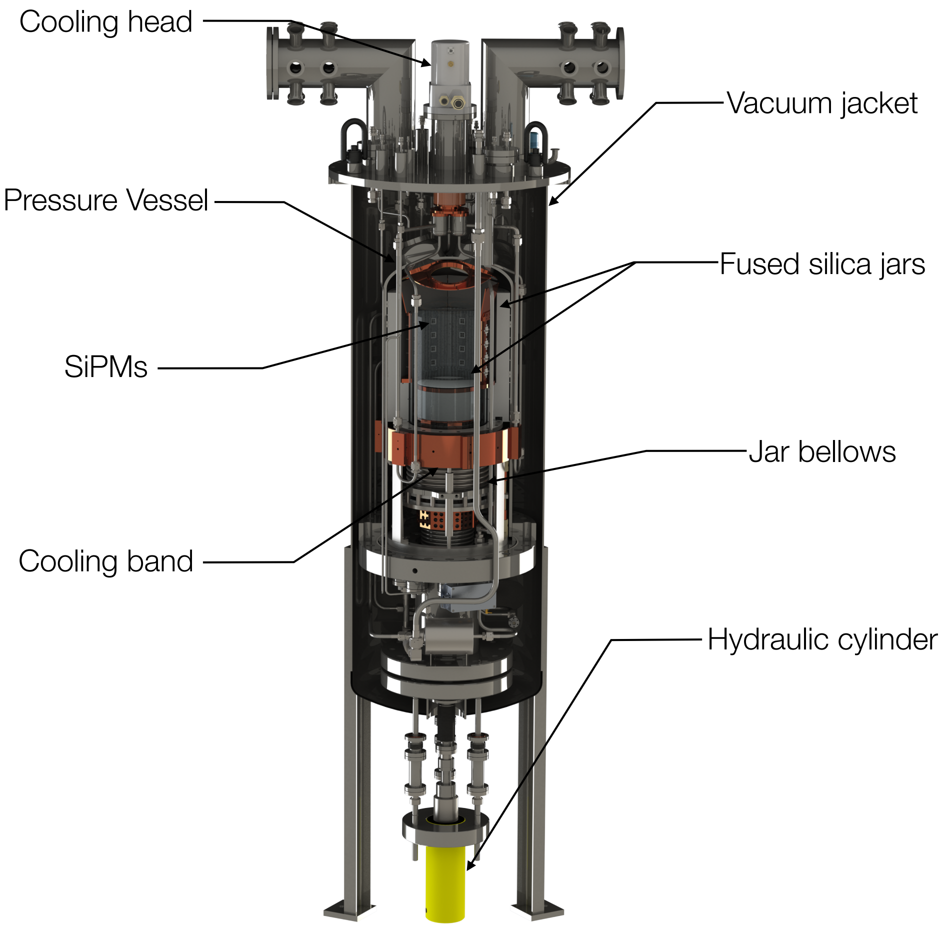
SBC
(Scintillating Bubble Chamber)



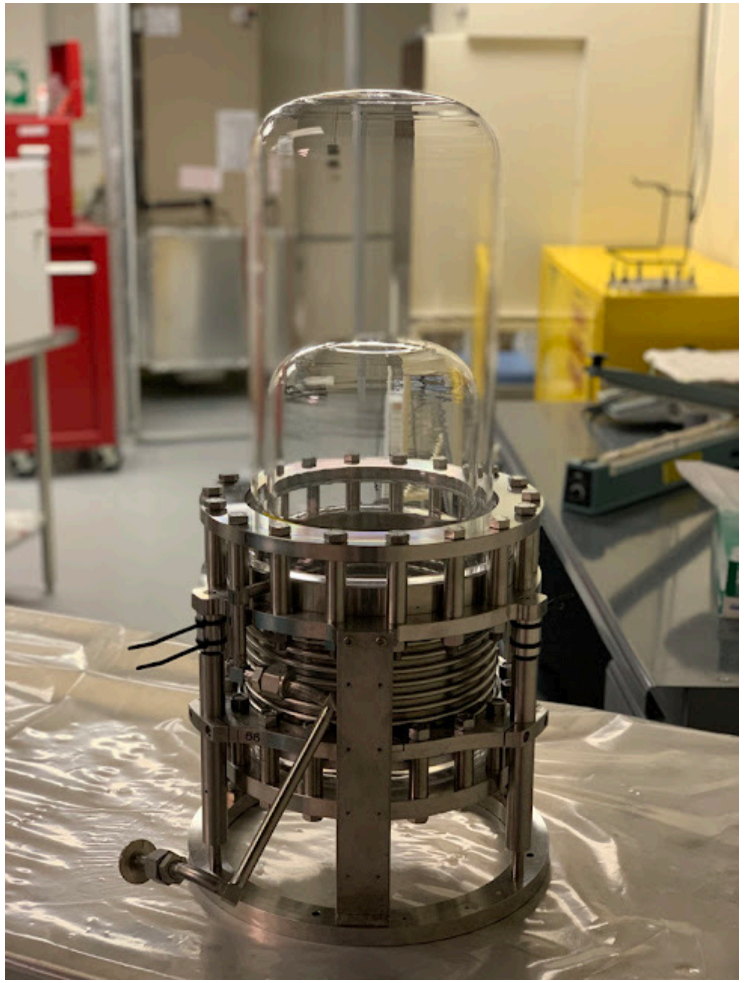
- **10 kg liquid argon** bubble chamber for GeV-scale dark matter and reactor CEνNS.
- Under construction now, with goal of **100 eV nuclear recoil threshold** while remaining electron recoil blind.
- Bubbles detected with cameras and acoustics.
- $O(100)$ ppm xenon for wavelength shifting and SiPMs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

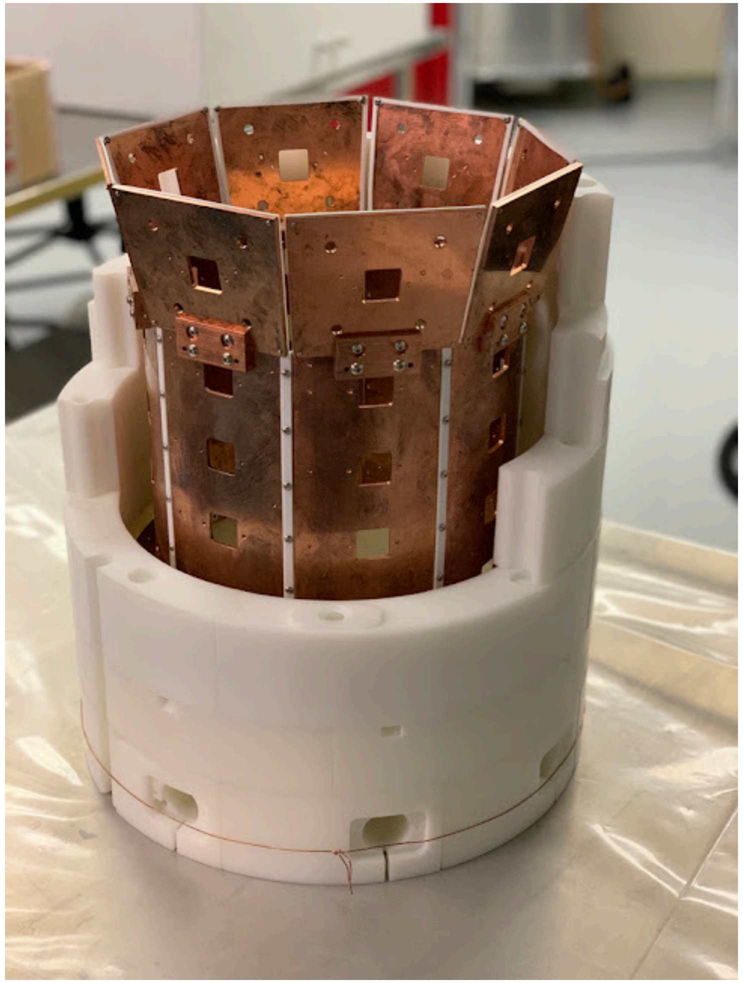
SBC program

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



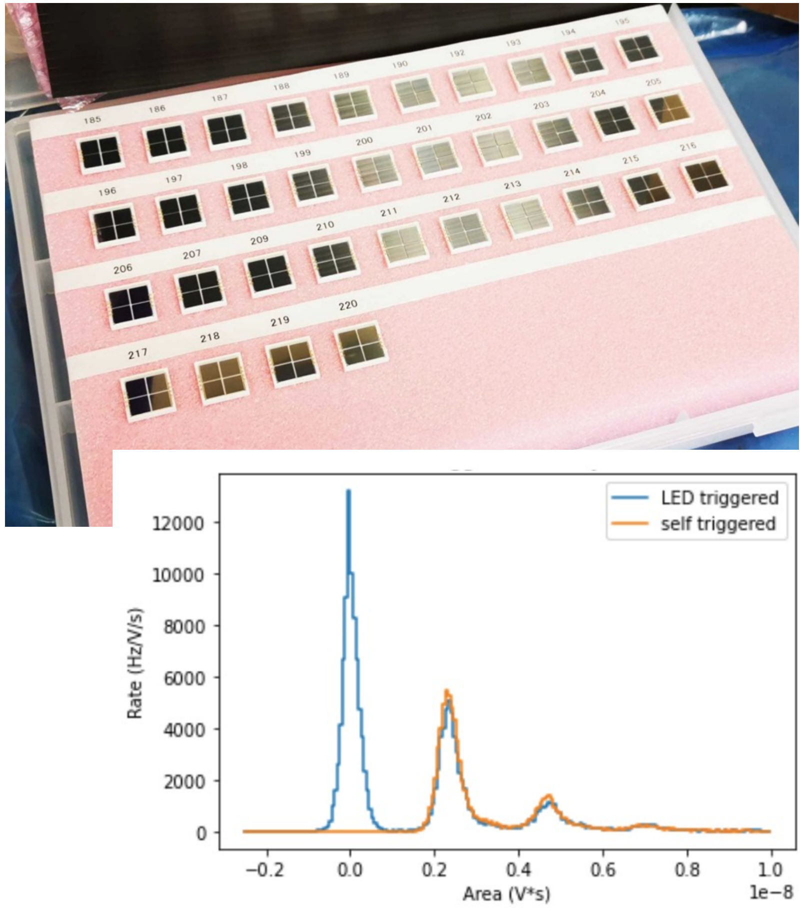
Inner vessel



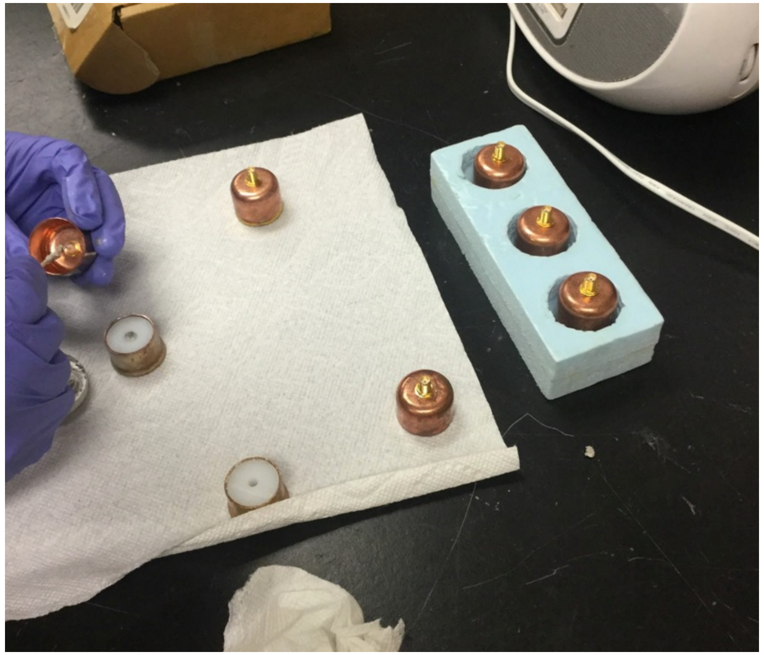


Outer vessels

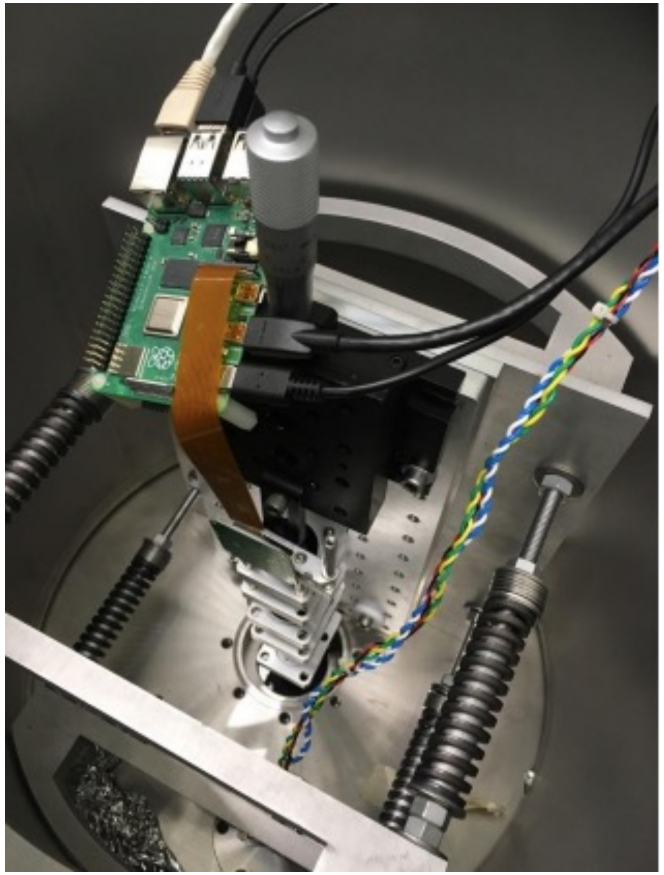
Readout



SiPM performance in LCF$_4$
arxiv:2207.12400



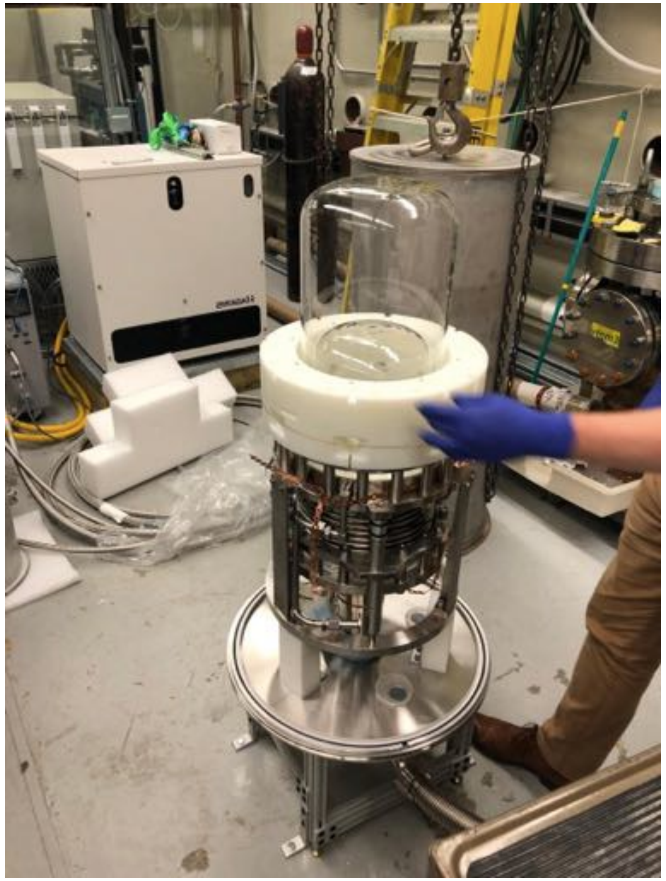
Acoustic sensors



Relay lens system

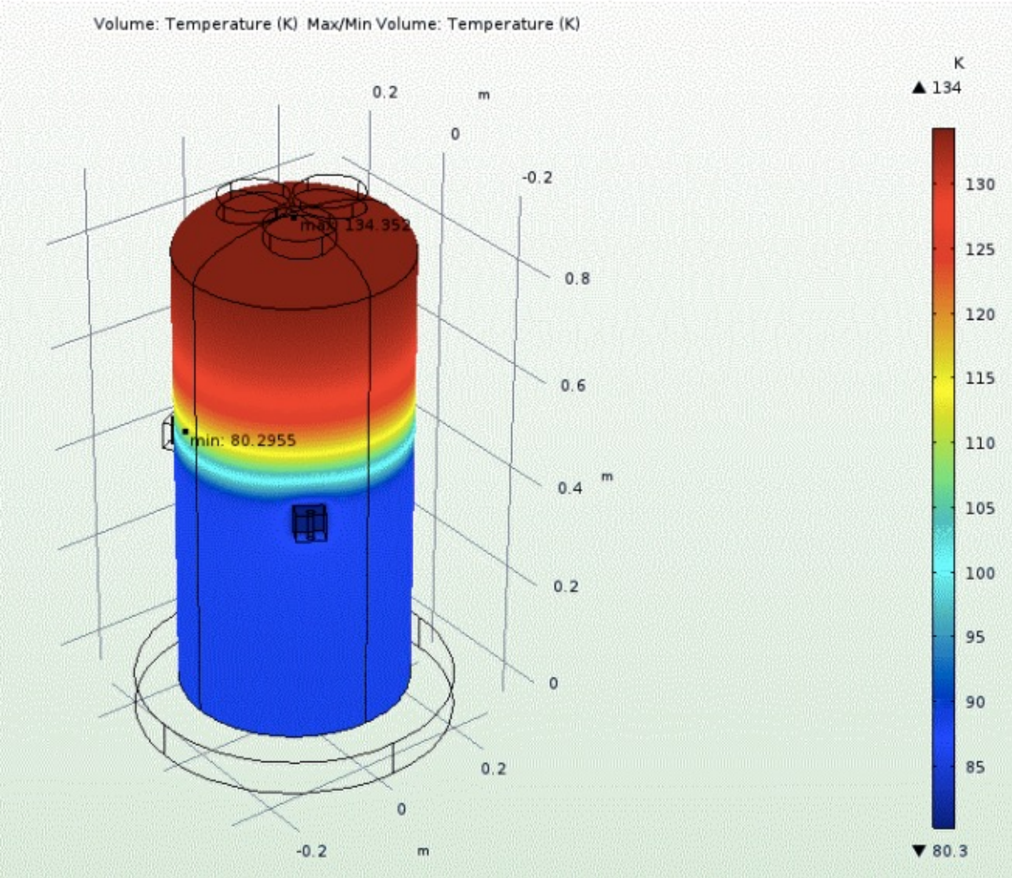
Current status

- Pressure vessel empty (no inner vessel).
- Ready for cooldown tests with liquid argon.
- Inner vessel will be transported from Canada to Fermilab this month.



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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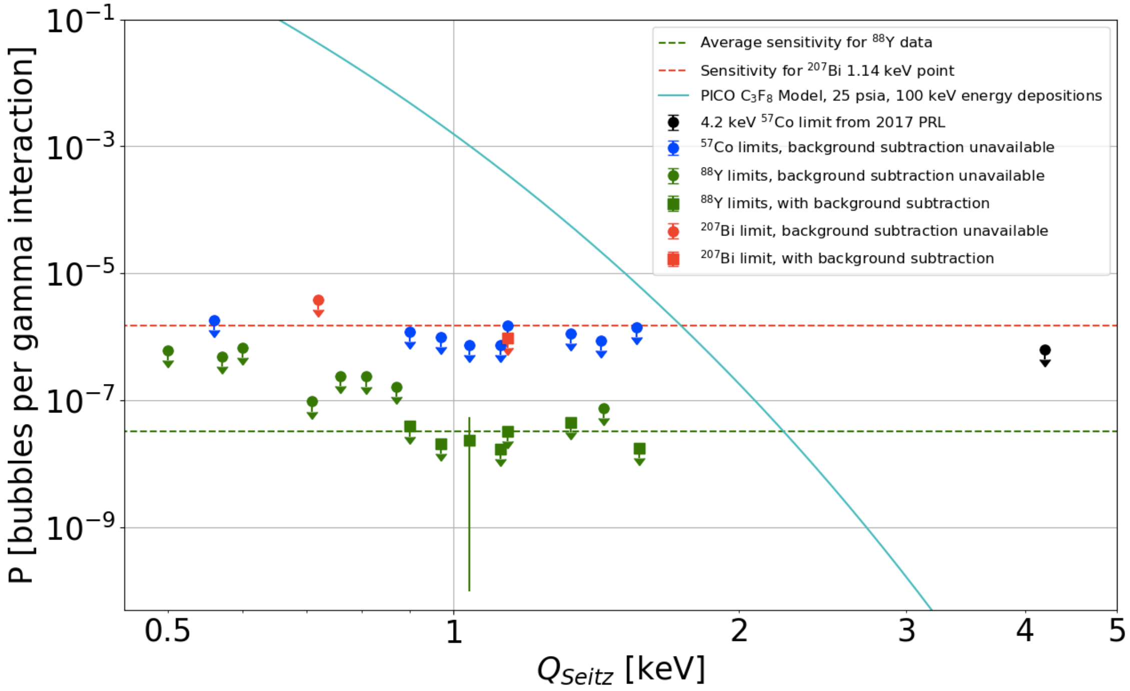

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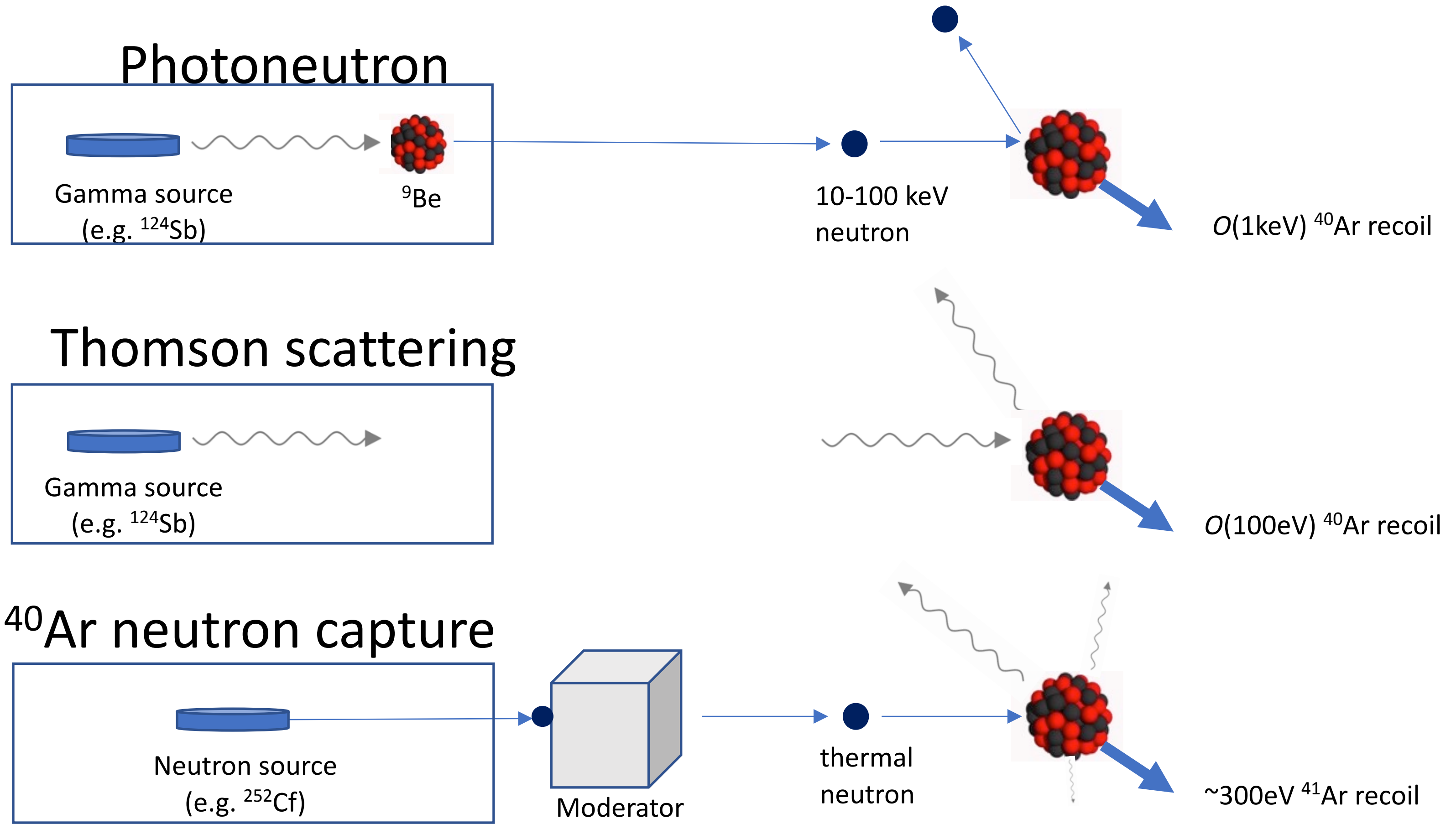


Photoneutron

Gamma source
(e.g. ^{124}Sb)

^{9}Be

10-100 keV
neutron

O(1keV) ^{40}Ar recoil

Thomson scattering

Gamma source
(e.g. ^{124}Sb)

O(100eV) ^{40}Ar recoil

^{40}Ar neutron capture

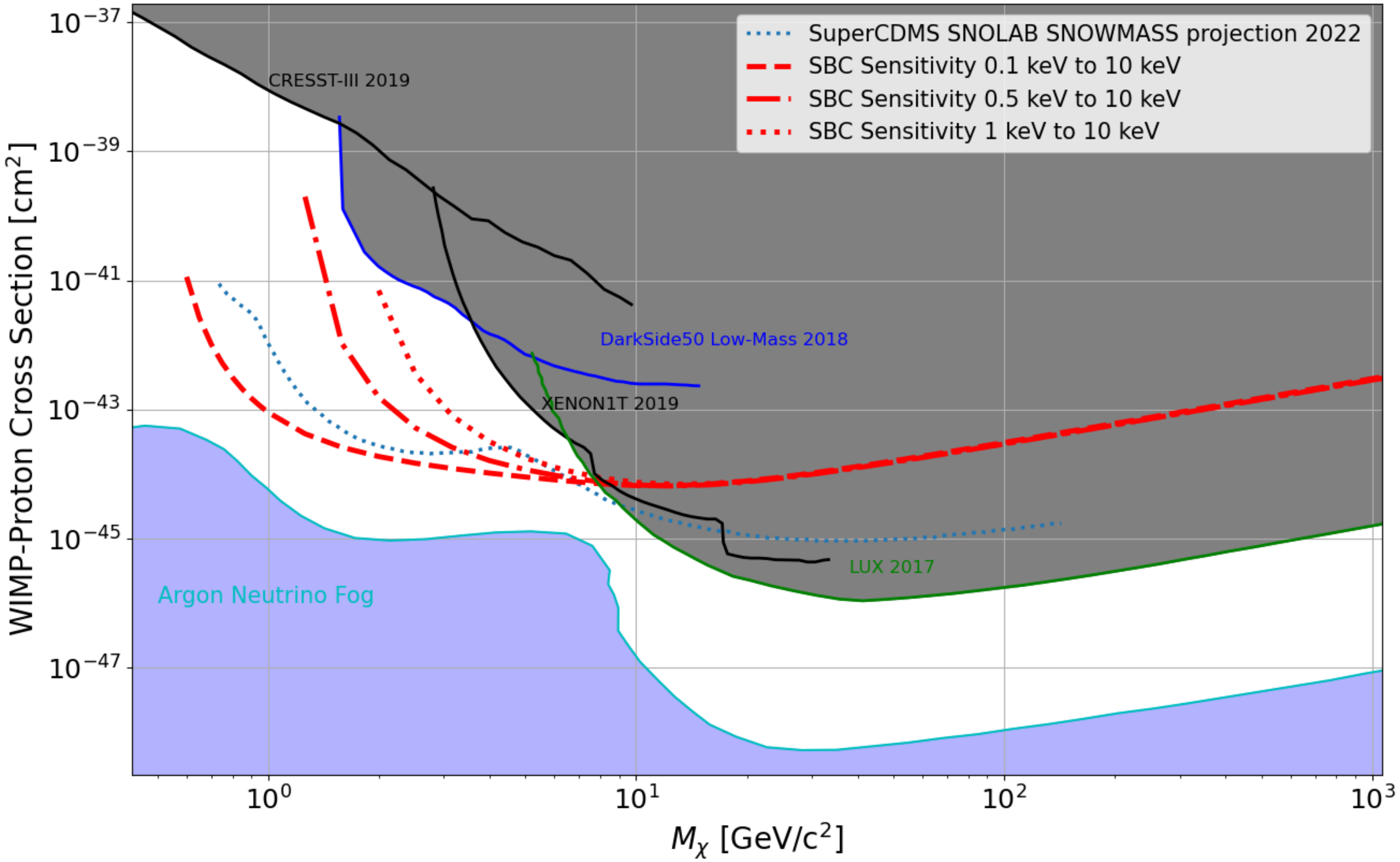
Neutron source
(e.g. ^{252}Cf)

Moderator

thermal
neutron

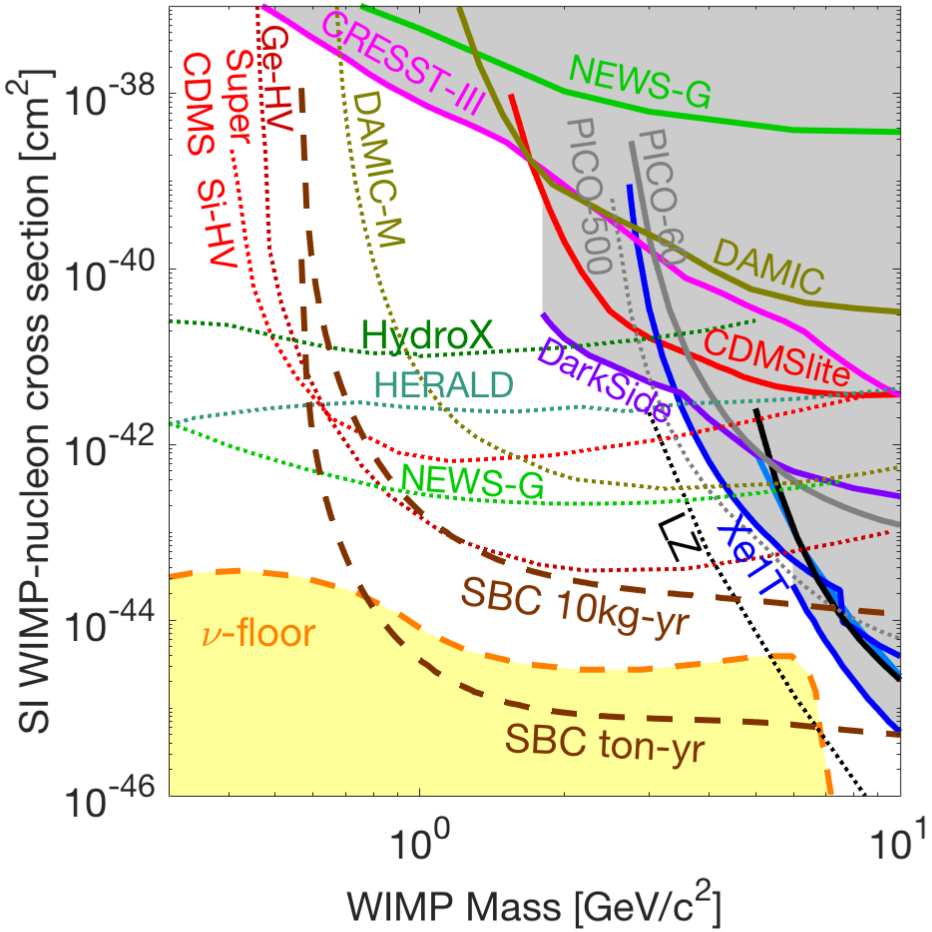
~300eV ^{41}Ar recoil

SBC-SNOLAB sensitivity: 10kg-scale



Ton-scale sensitivity

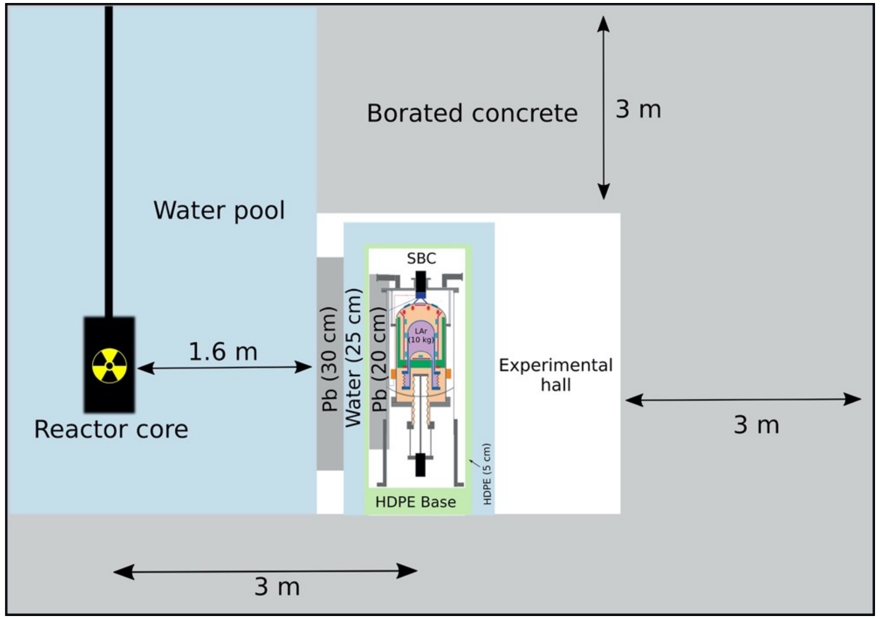
- Monolithic liquid detector.
  - Potential for large exposure and low background.
- A **1 t device** would probe the **solar neutrino fog**.
  - Also sensitive to CEνNS physics from solar νs, SN, pre-SN.

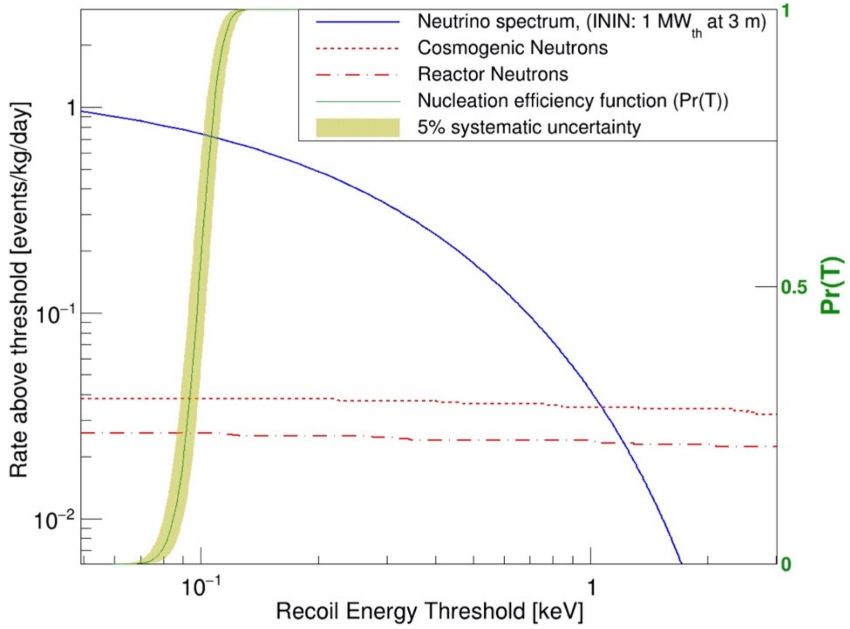


Backgrounds

- Detector is **intrinsically blind to ER**, so primary concern is NR backgrounds.
- (α,n) in detector materials (e.g. SiPMs, cameras, connectors, cables, SS pressure vessel)
  - Materials screening and design.
- Muon-induced neutrons
  - Water and HDPE shielding.
- Nuclear Thomson scattering from U/Th gammas < 0.4 keV_{NR}.
  - High density gamma shielding (e.g. Cu, Pb).
- Solar neutrino CEνNS: irreducible
- Scintillation vetos
  - Argon scintillation channel used to veto high energy recoils (threshold ~5 keV_{NR}).
  - While testing SiPMs, we discovered LCF_4 hydraulic liquid also scintillates. Will have extra SiPMs facing LCF_4 for active veto.

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 measurements: Z’ gauge boson, weak mixing angle, neutrino magnetic moment etc.

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

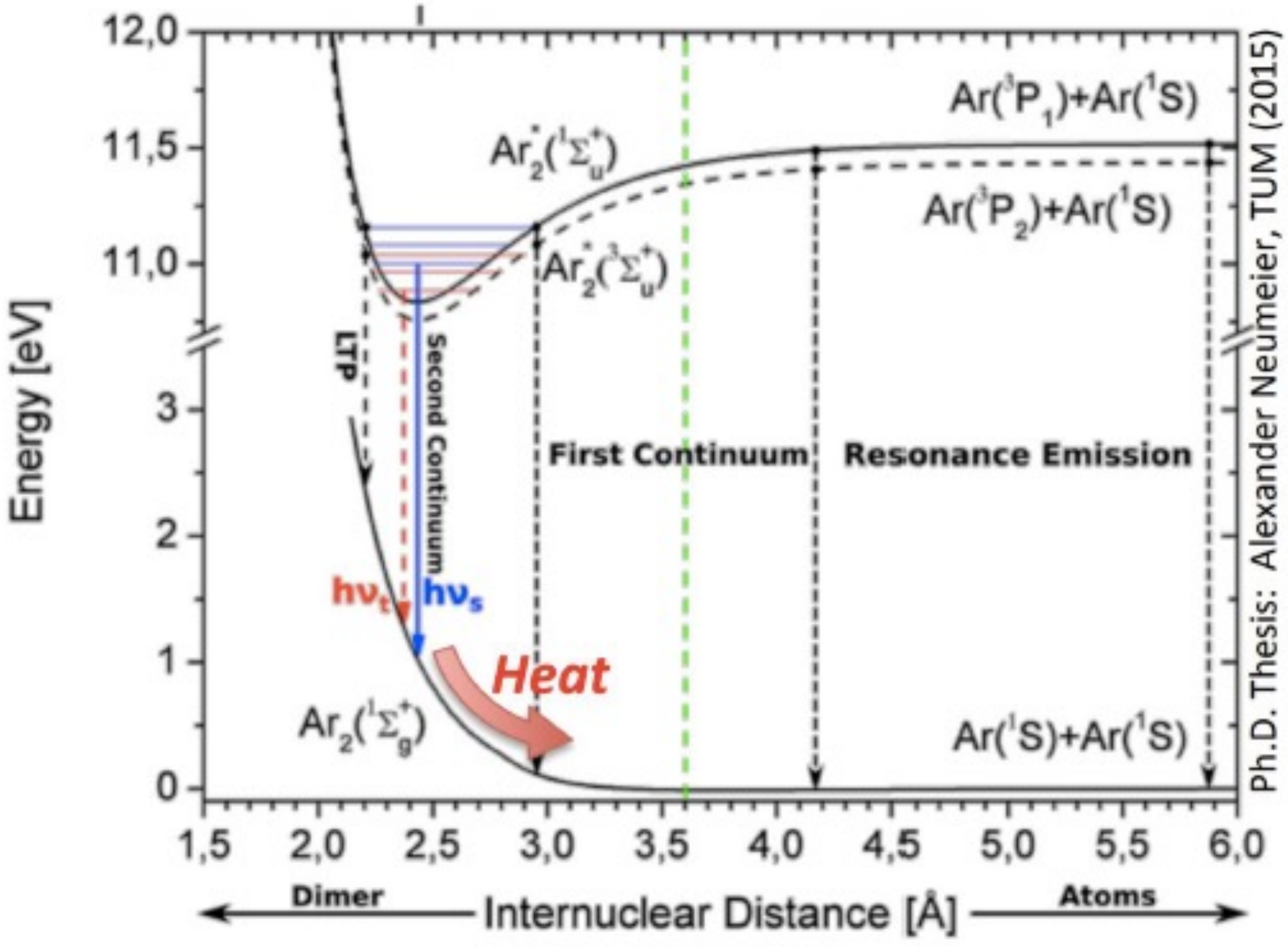
Summary

- 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.
- Check out our Snowmass white paper arxiv:2207.12400

Backup slides

How low in threshold can we go?

- Xe bubble chamber was technically limited to >~0.5keV threshold.
- Liquid Ar bubble chambers have seen tracks with threshold O(10eV).
- We also expect spontaneous nucleation from thermal fluctuations at a similar threshold, but not above 40eV.
- → Design goal of SBC is 40eV Seitz threshold. Dark matter/CEνNS projections based on 100eV$_{nr}$ threshold.



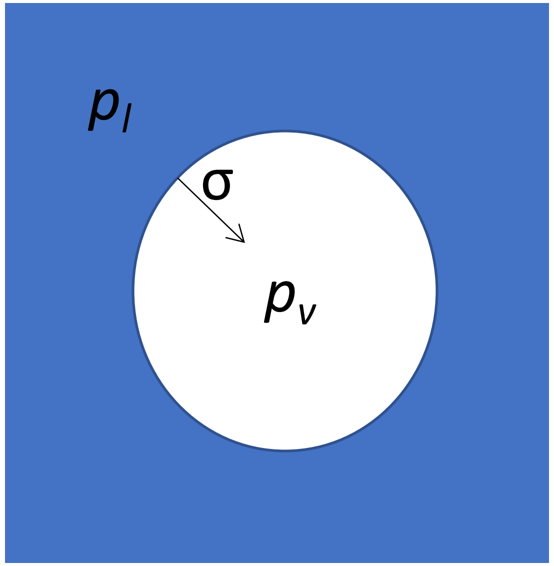
Ph.D. Thesis: Alexander Neumeier, TUM (2015)

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-

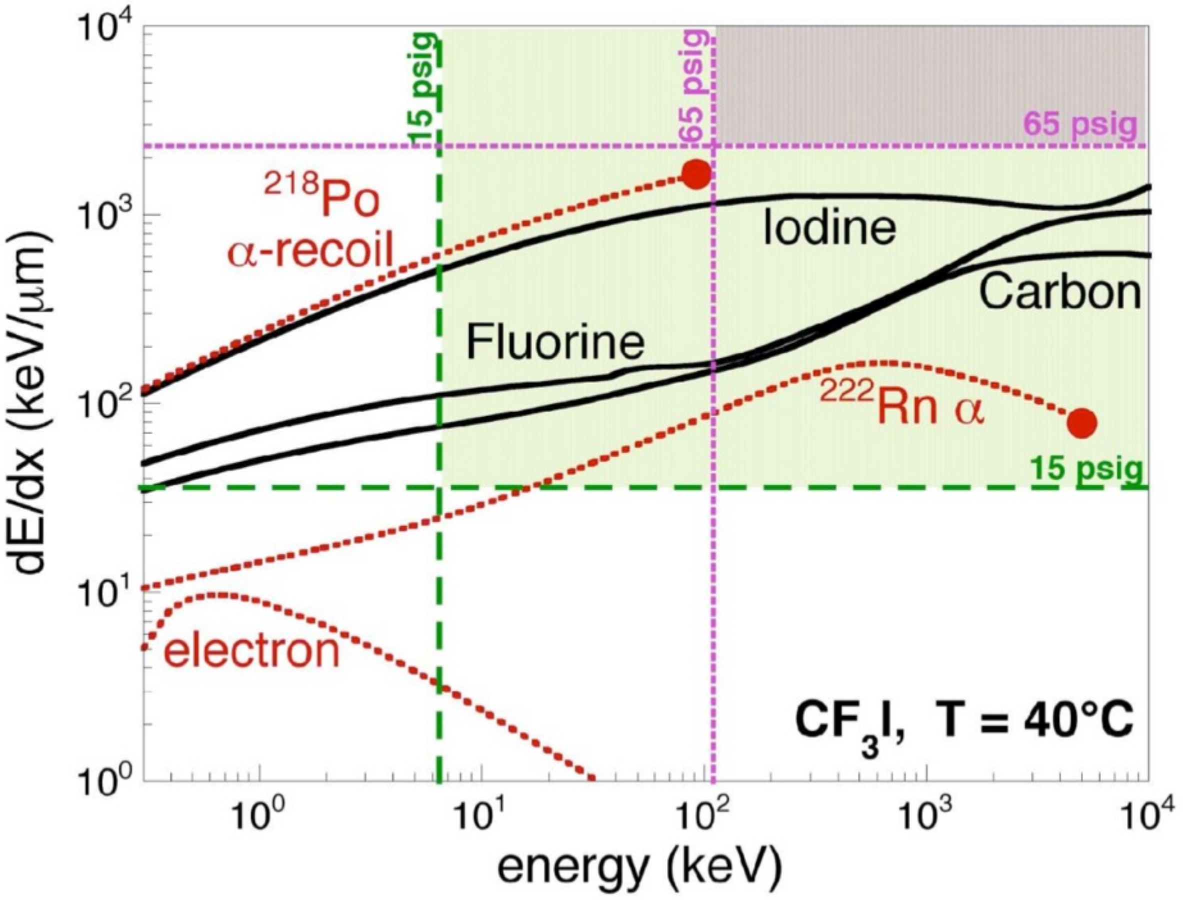
$$p_v - p_l = \frac{2\sigma}{r_c}$$

$$E_{th} = \underbrace{\boxed{4\pi r_c^2\left(\sigma - T\frac{\partial\sigma}{\partial T}\right)}}_{\text{Surface energy}} + \underbrace{\frac{4}{3}\pi r_c^3\rho_v h}_{\text{Latent heat}}$$

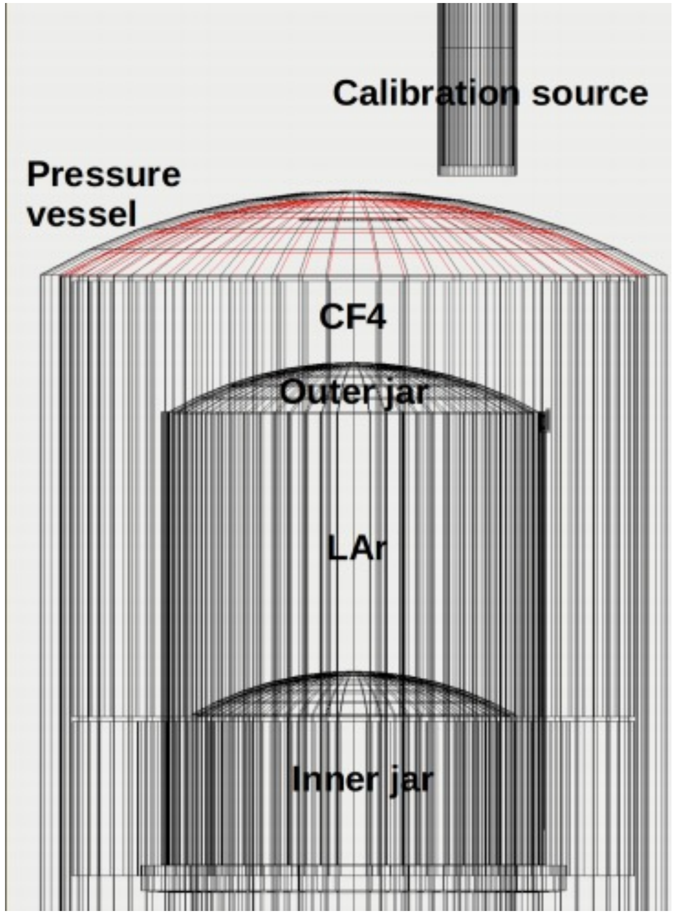


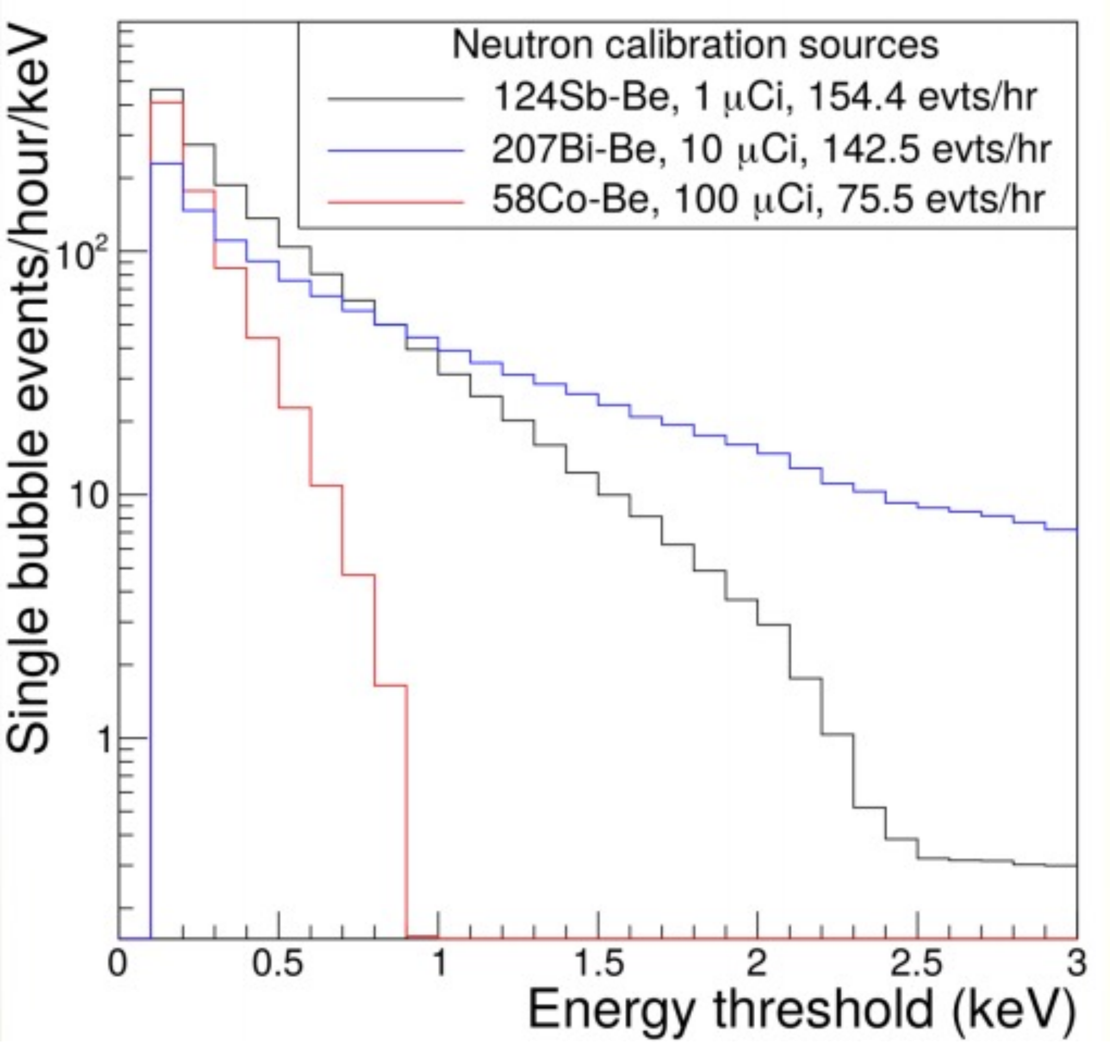
Bubble chambers as nuclear recoil detectors

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



Photoneutron Calibrations





^{9}Be(γ,n), Q=1664keV gives ~monoenergetic neutrons.

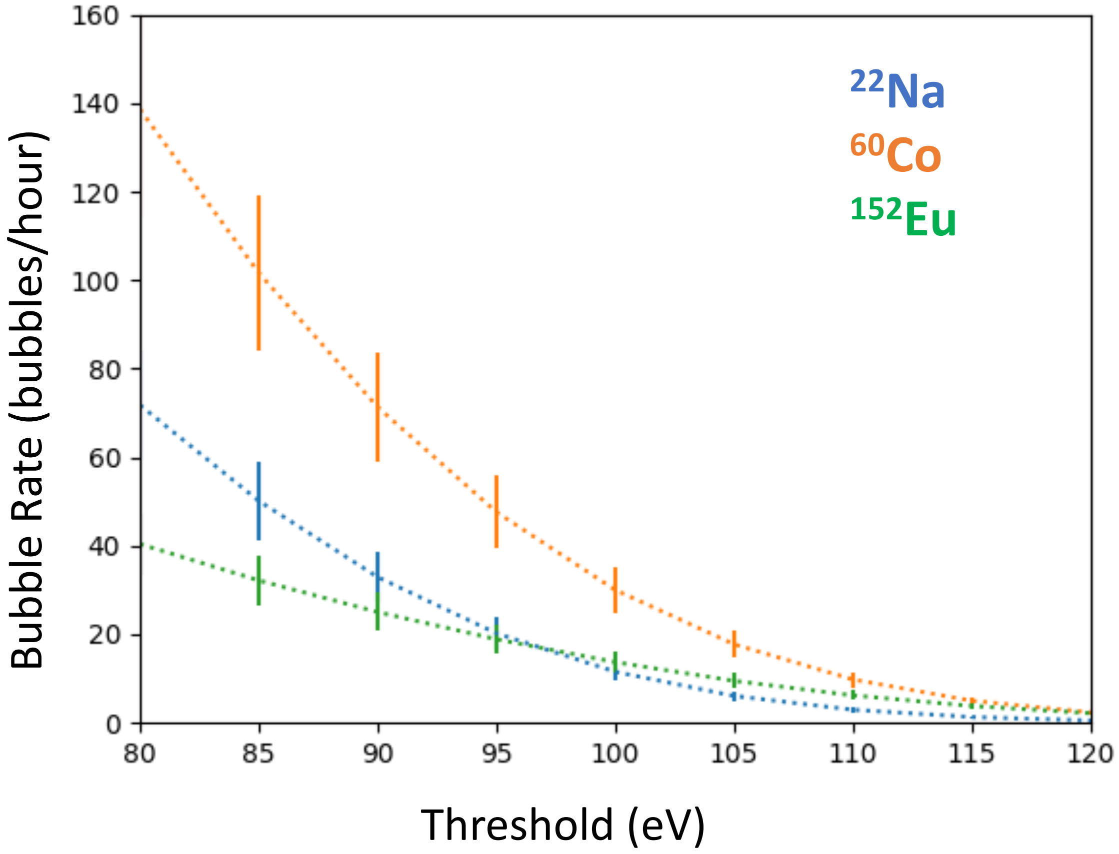
^{207}Bi: 90keV

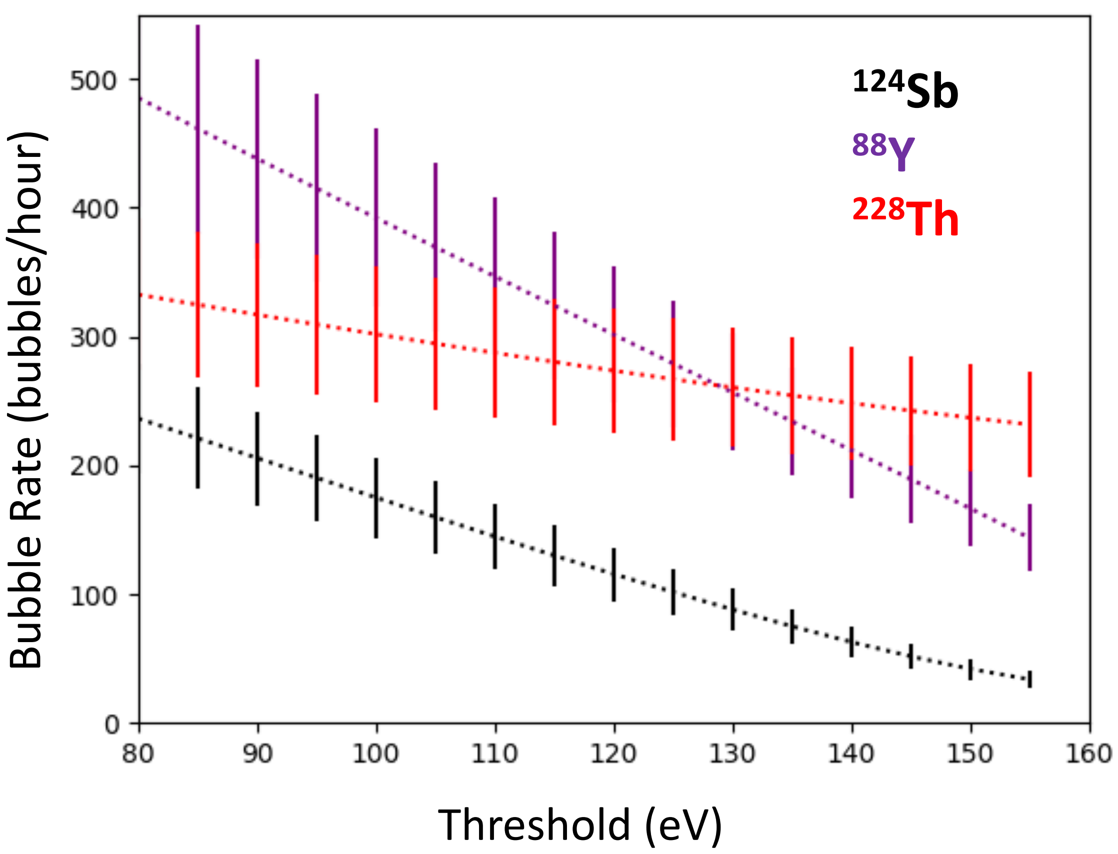
^{124}Sb: 23keV

^{58}Co: 9keV

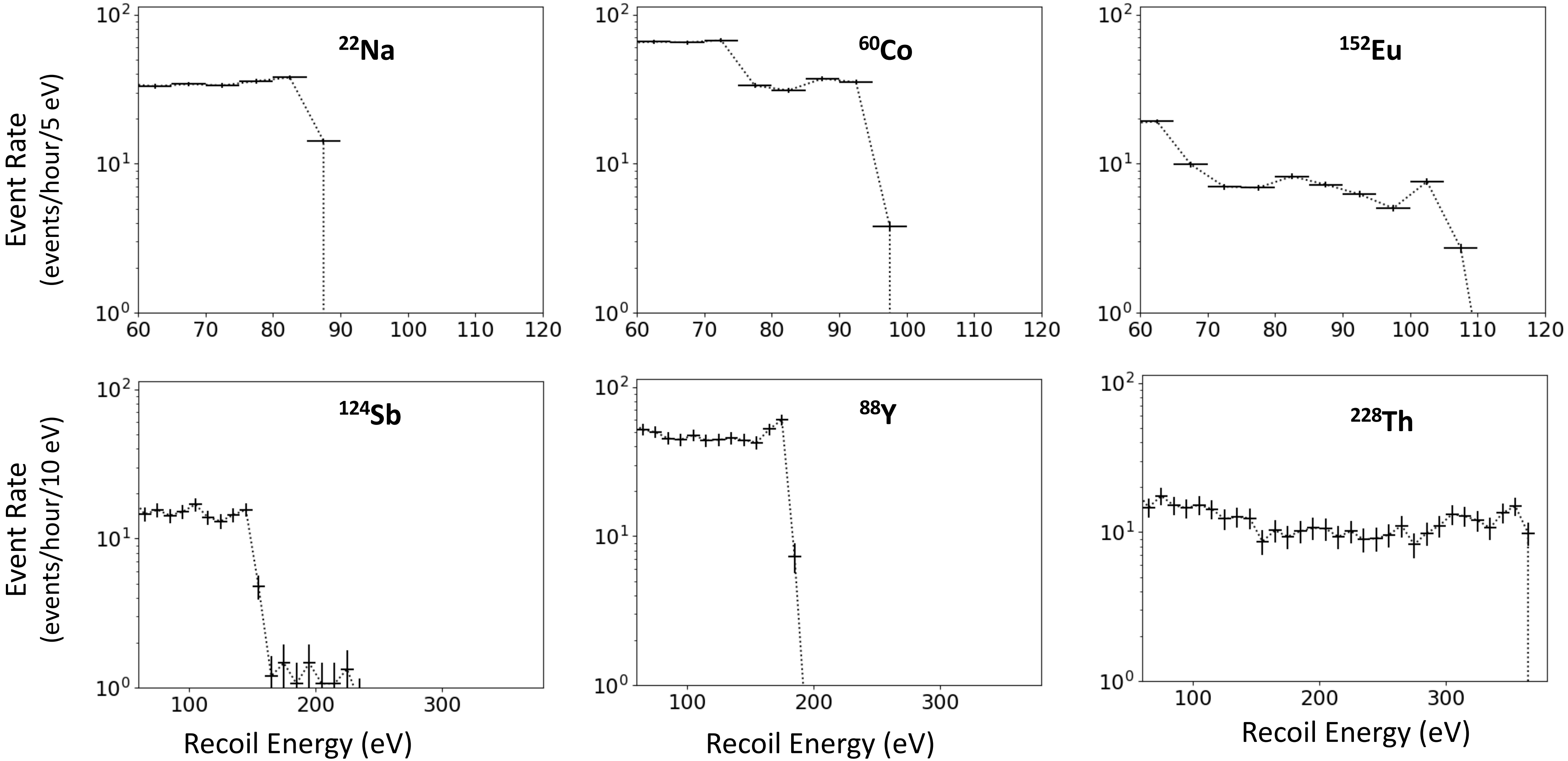
Scattering on Ar gives keV-scale recoils.

Thomson Scattering Calibrations

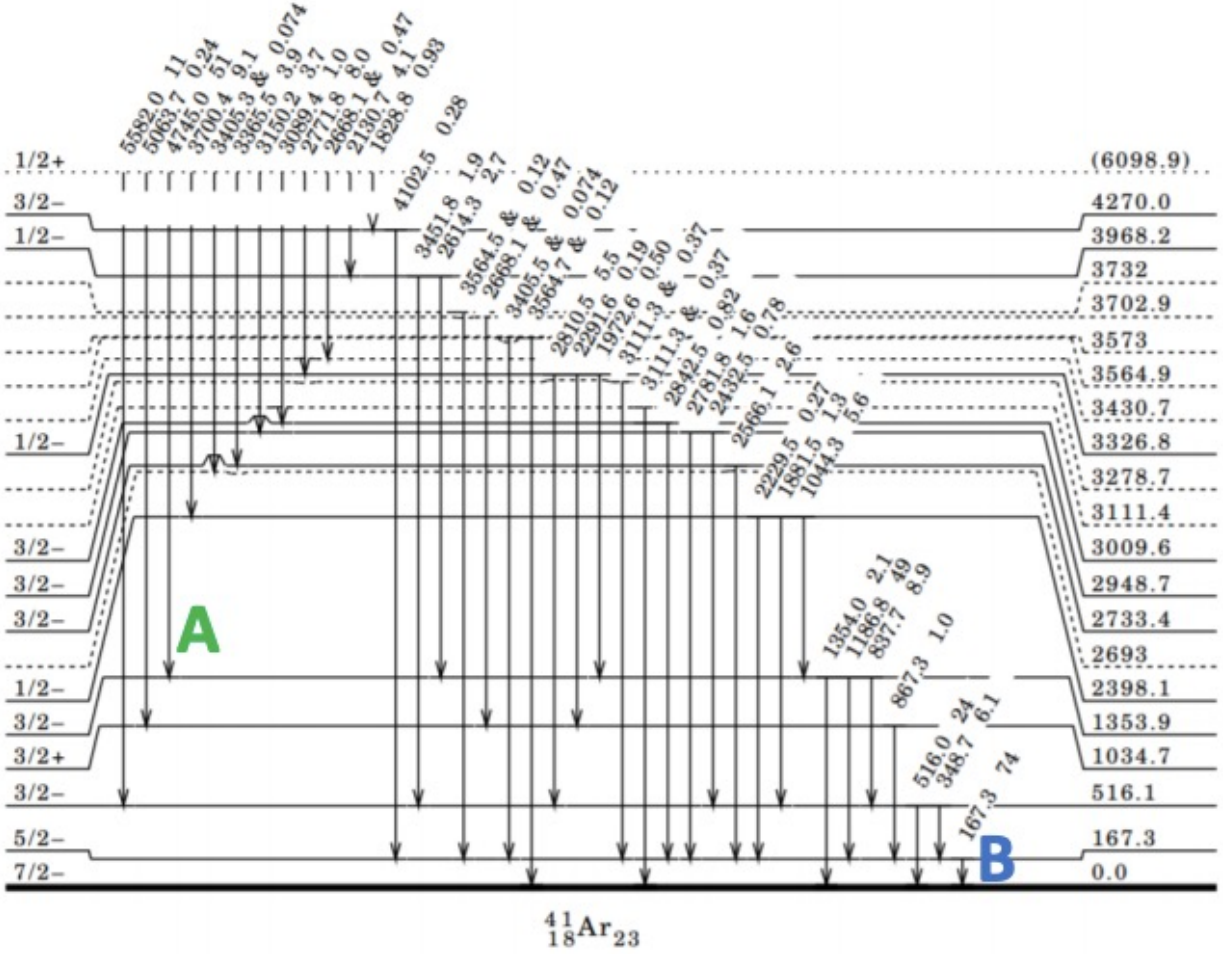


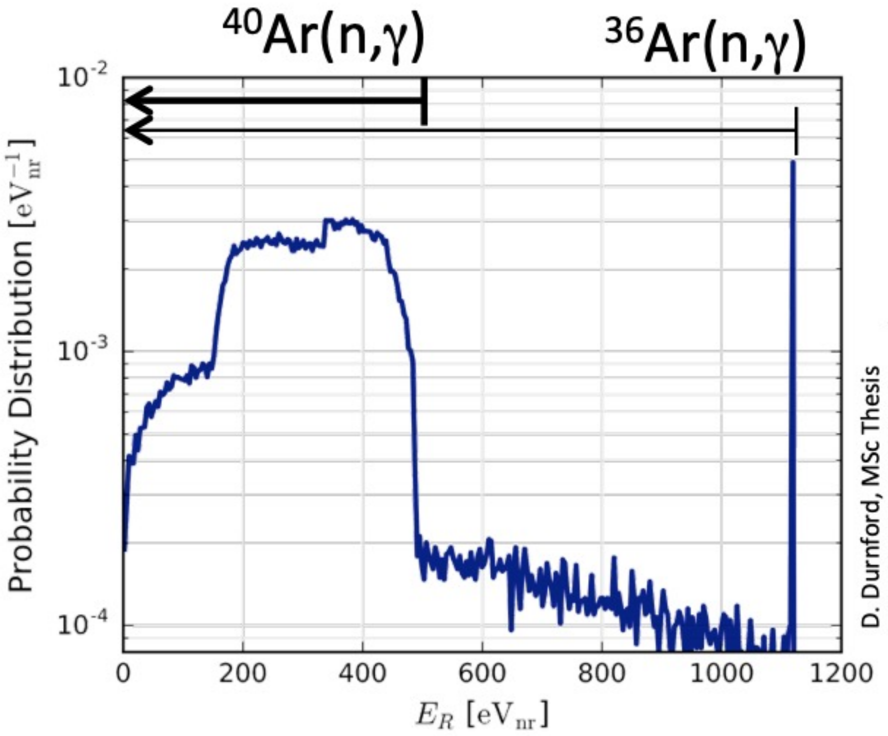


Thomson Scattering Calibrations



^{40}Ar Neutron Capture





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

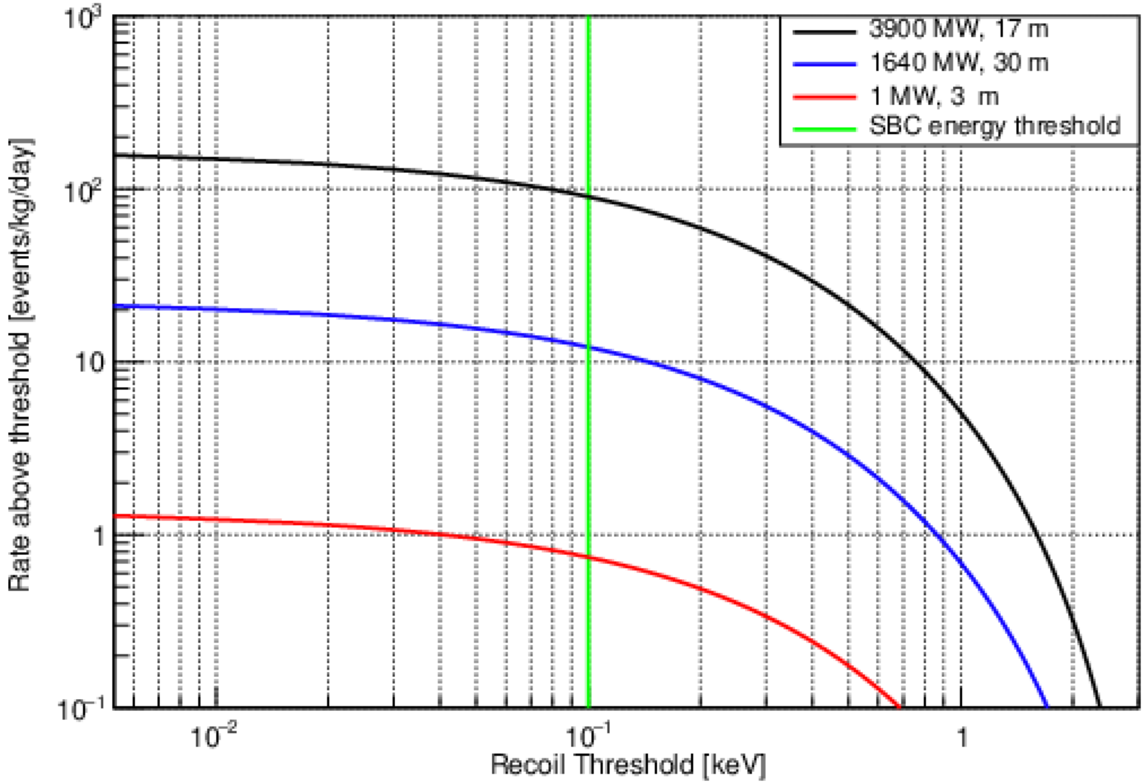
CEνNS - Coherent Elastic Neutrino Nucleus Scattering

- 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.

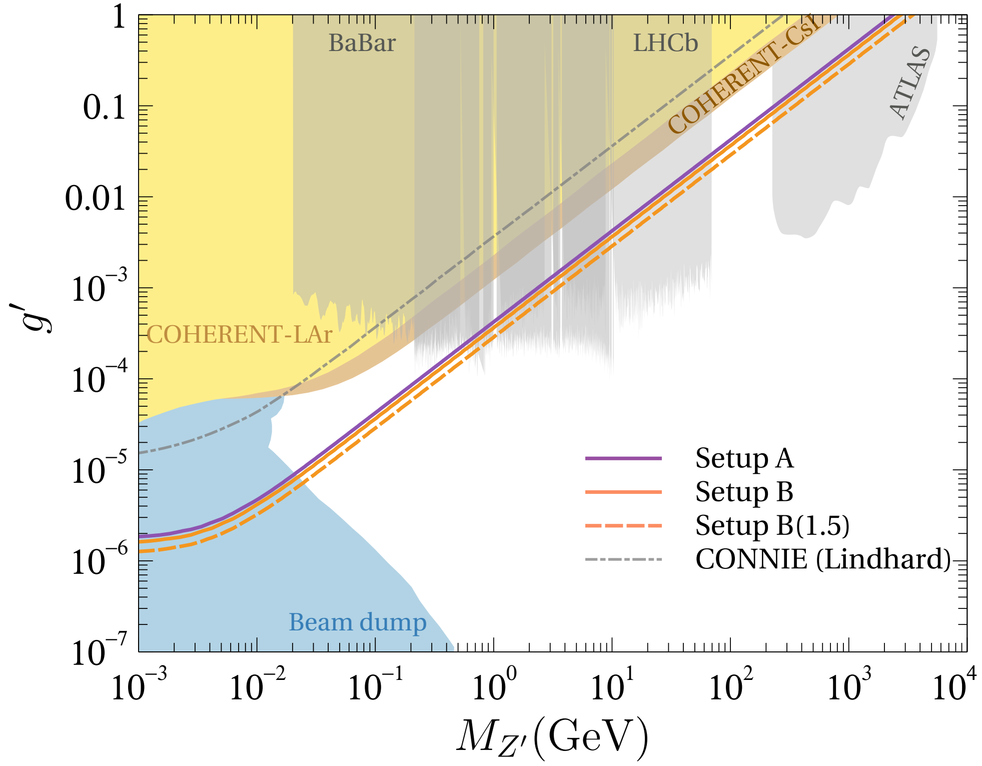
- **100 eV threshold** gives sensitivity to **CEνNS** from **>1.4MeV neutrinos**, covering much of the the reactor antineutrino spectrum.

SBC-CEνNS rates for different reactors



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:

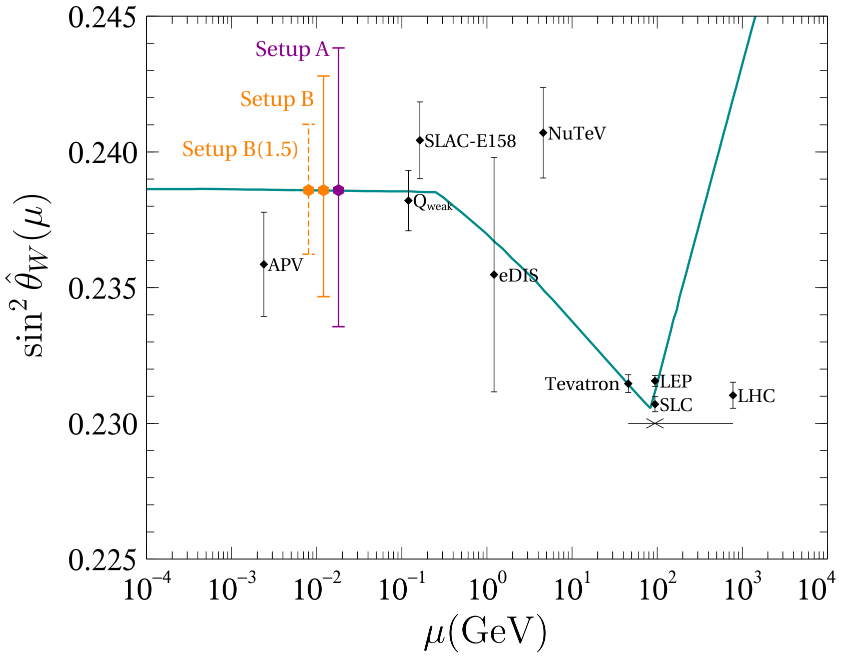
Setup A (ININ): 10kg, $1\mathrm{MW}_{\mathrm{th}}$, 3m, 2.4% flux uncertainty
Setup B: 100kg, $2\mathrm{GW}_{\mathrm{th}}$, 30m, 2.4% flux uncertainty
Setup B(1.5): 100kg, $2\mathrm{GW}_{\mathrm{th}}$, 30m, 1.5% flux uncertainty

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

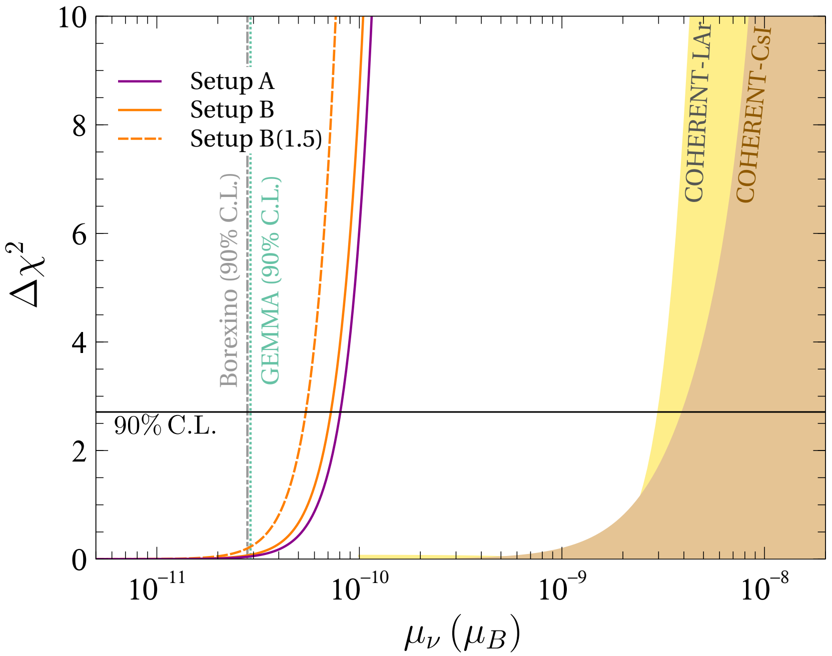
Physics reach: mixing angle, magnetic moment

Weak mixing angle



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

Neutrino magnetic moment



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