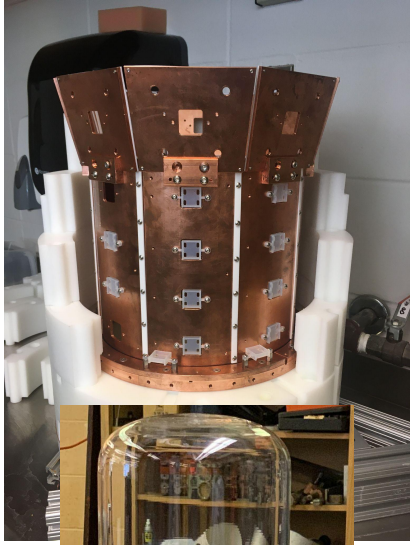
The Scintillating Bubble Chamber Experiment



Ben Broerman
IDM 2022

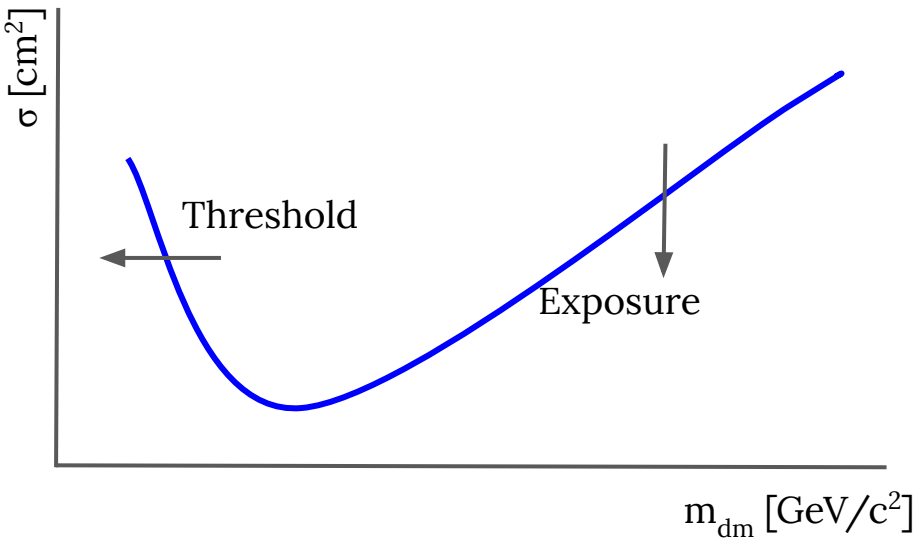
Queen's University

Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

GeV-scale dark matter

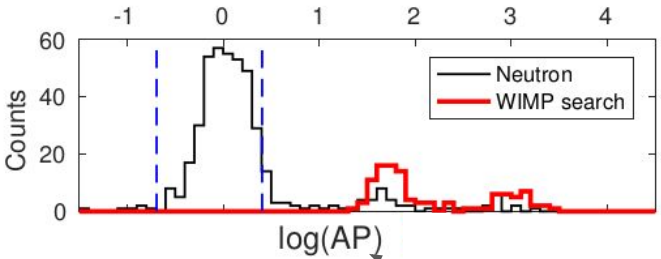
- $m_{DM} \sim m_p$ is motivated if baryon asymmetry is related to DM abundance (e.g. ADM models)

- Difficult kinematics of low mass DM-nucleon scattering require low thresholds
  - Future success here still needs particle identification and scalability

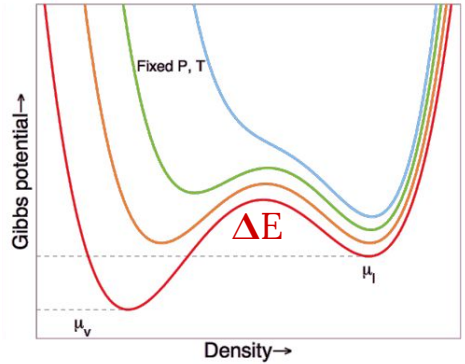


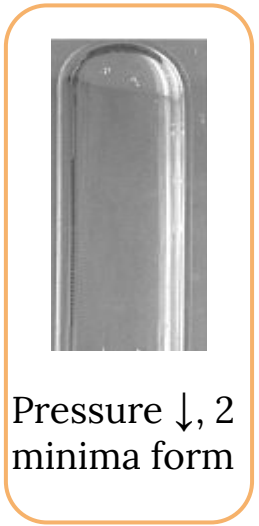
Bubble chambers

- Bubble chambers maintain target fluid in a superheated state
- High efficiency low n.r. threshold, β/γ insensitivity, n.r./α discrimination:

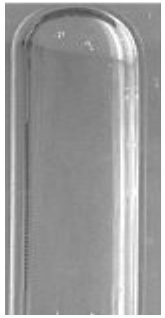


{x,y,z} + acoustics

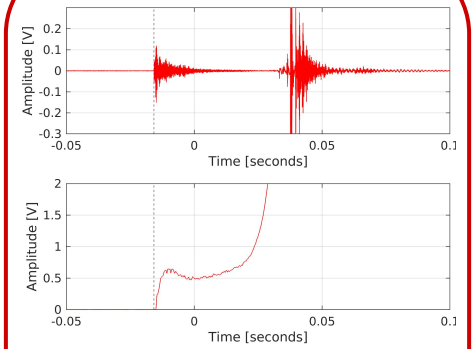


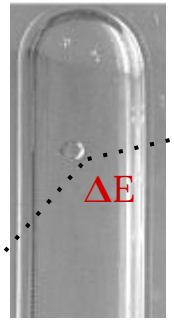


Pressure ↓, 2 minima form



Further P ↓, Metastable superheated





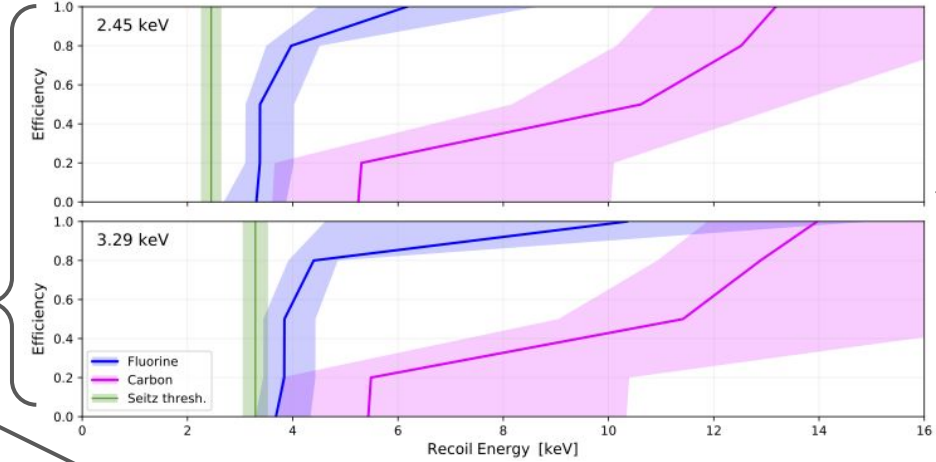
If ΔE deposited, local phase change

See E. Vázquez-Jáuregui's PICO talk

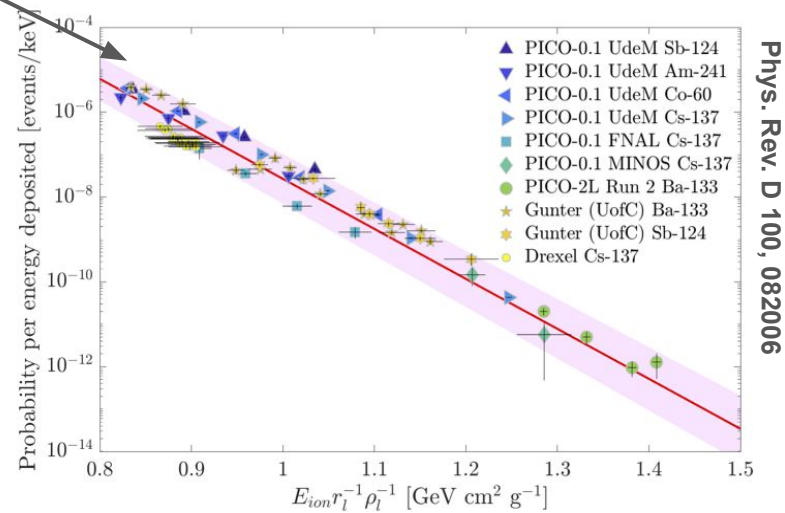
Bubble chambers

- Issues with freon B.C.'s
  - Threshold detectors: no energy information
  - β/γ rejection fails at low thresholds

- Noble liquid B.C.'s
  - Scintillation provides energy information
  - Lack molecular vibrational modes to provide local heating (possible increase in β/γ suppression at low thresholds)
    - **No bubbles in pure Xe B.C., but nucleation in Xe + ethylene (quenched scintillation)**



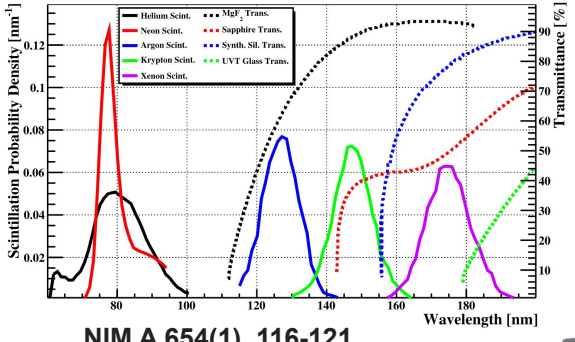
arXiv: 2205.05771, submitted to PRD



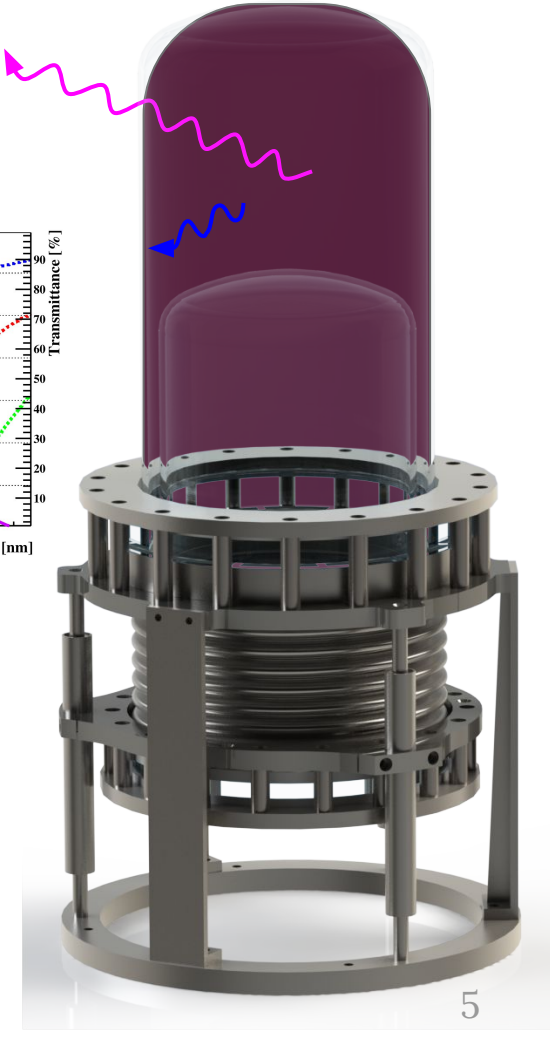
Phys. Rev. D 100, 082006

Liquid noble bubble chambers

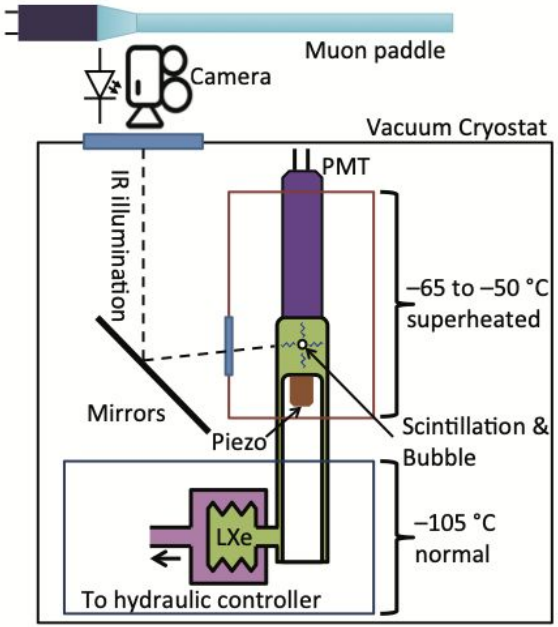
- Argon 3x lighter than Xe
  - Ar for low mass SI, Xe-doping to get the light out
- Cryogenic temperatures
  - Everything that moves, must move cold
- Signal timing difference
  - Scintillation $\mathcal{O}$(ns)
  - Bubble formation/acoustic emission $\mathcal{O}$(μs)
  - Recompression $\mathcal{O}$(ms)



NIM A 654(1), 116-121.

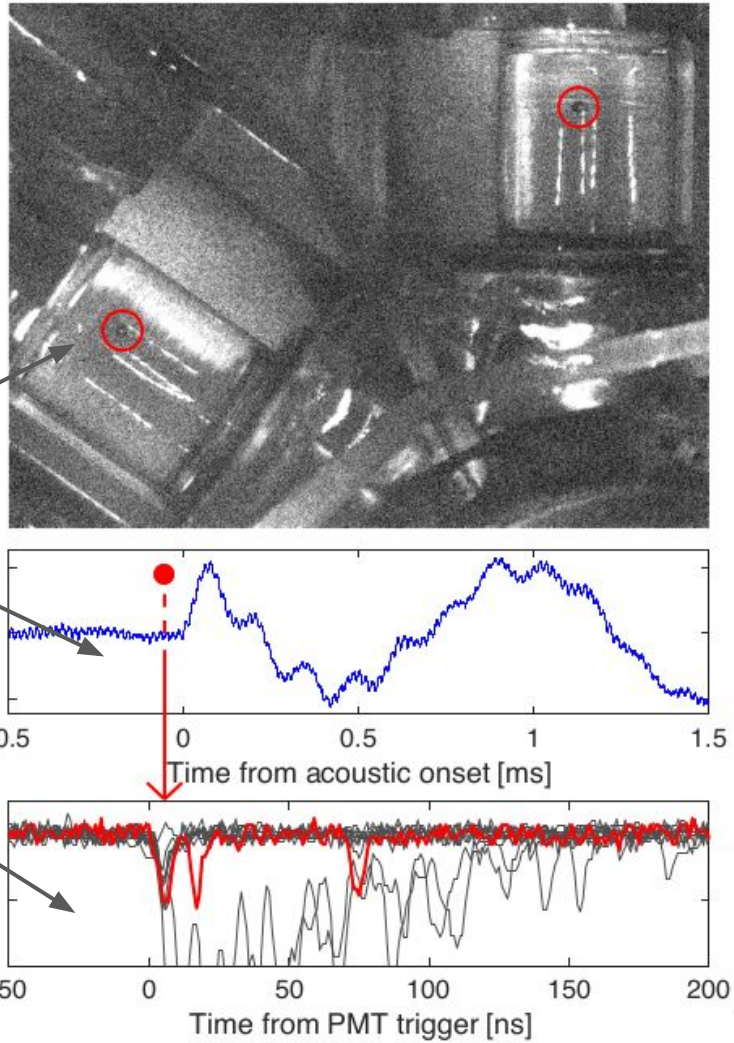


Prototype LXe bubble chamber



Simultaneous measurement of

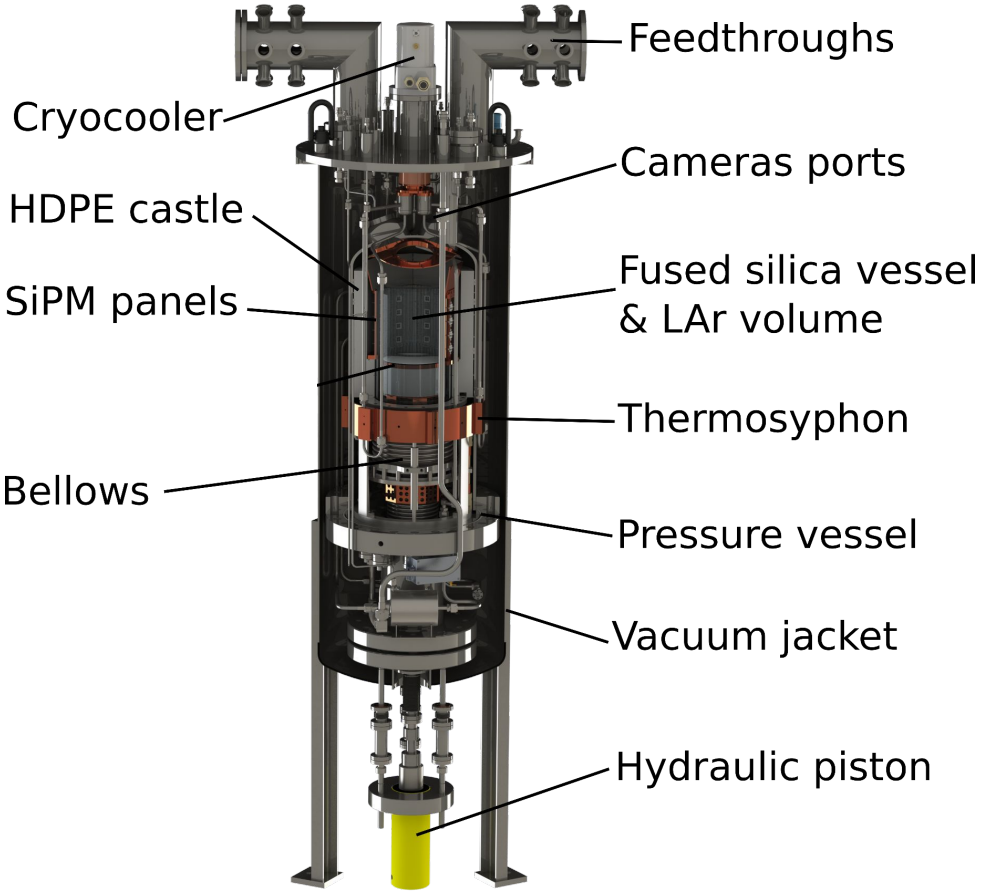
- Bubble position (camera)
- Acoustic emission (piezo transducer)
- Scintillation (UV-grade PMT)



PRL 118.23 (2017) 231301

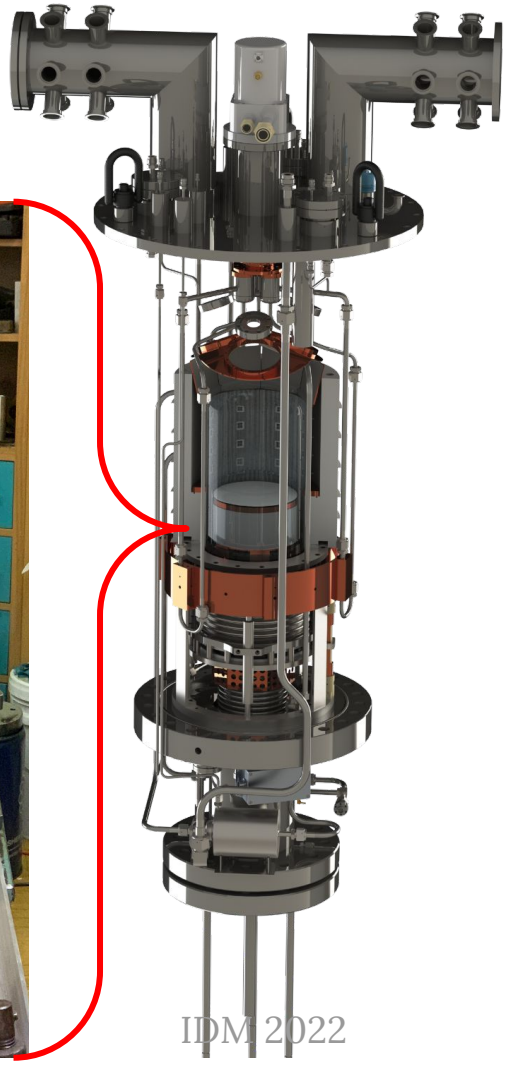
SBC detectors

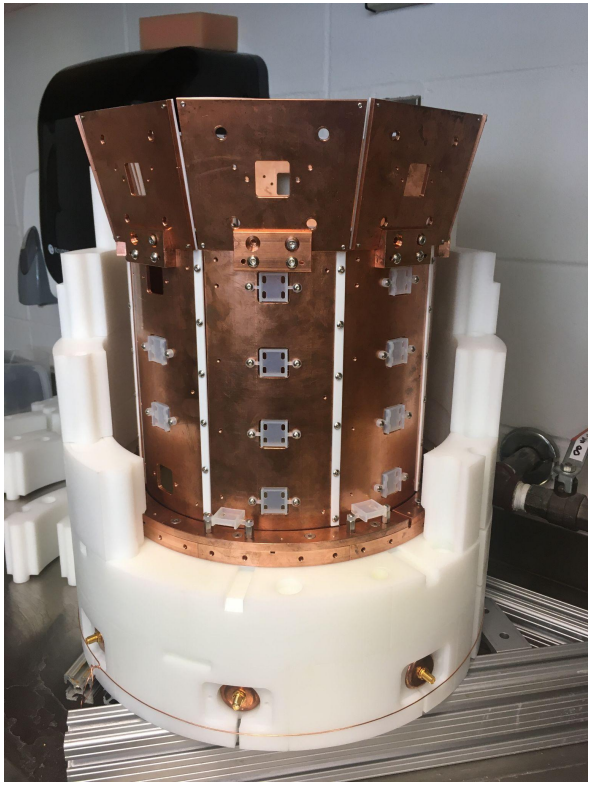
- Two functionally-similar detectors operated at:
  - SBC-LAr10 @ Fermilab (engineering, calibration, CEνNS)
  - SBC-SNOLAB @ SNOLAB (low bkg. dark matter)
- 10 kg LAr + Xe as a wavelength shifter targeting 100 eV n.r. threshold
- Cold region ~90 K, warm region ~130 K
- Expanded ~30 psi, compressed ~200 psi



Inner vessel

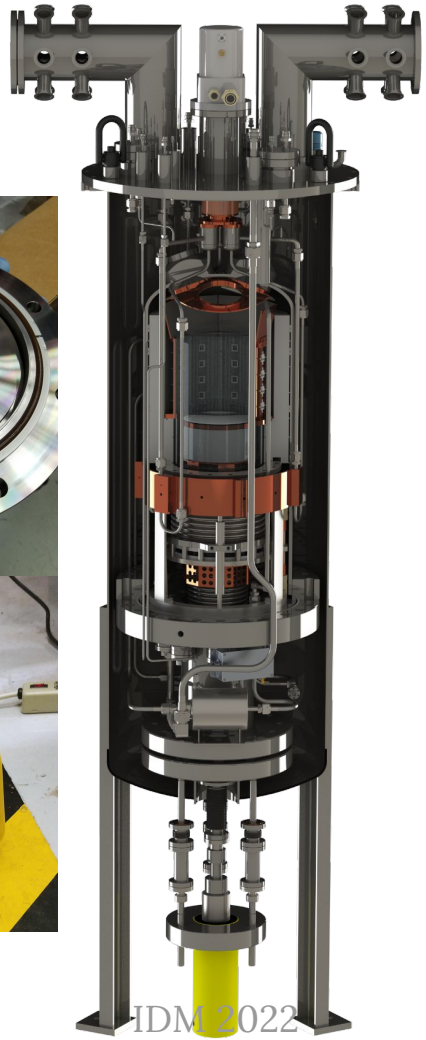
Fused silica vessels and bellows

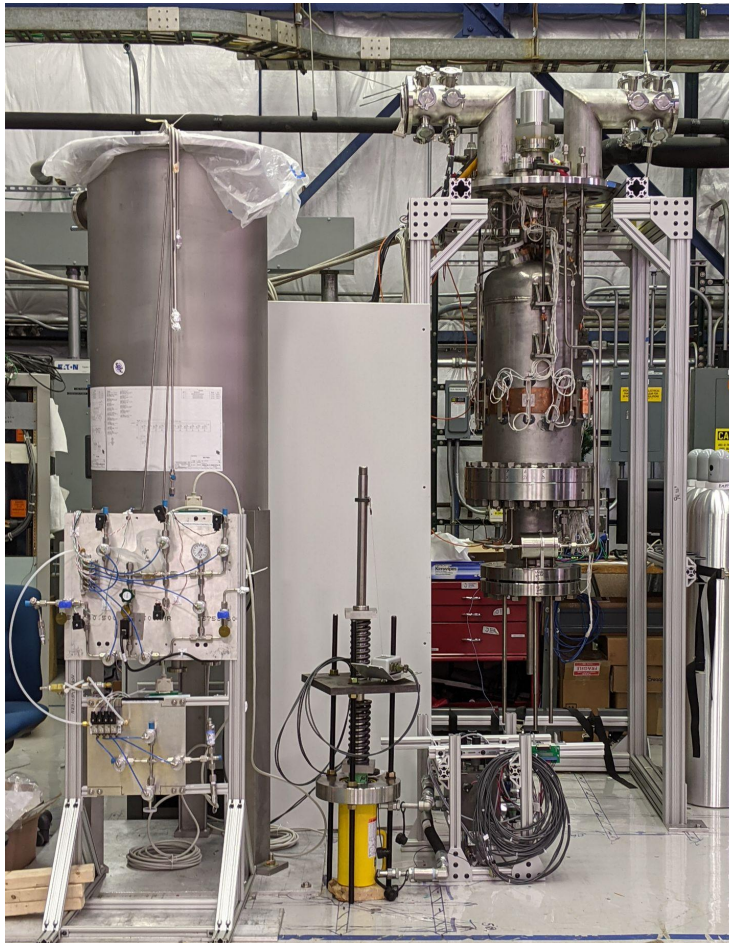




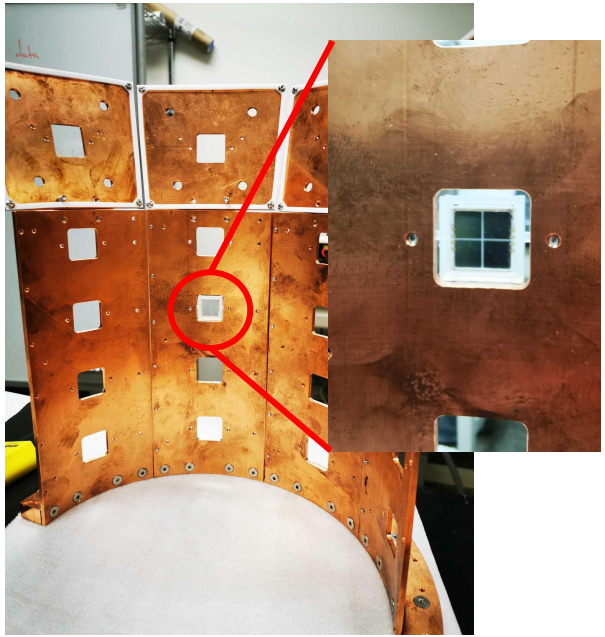
HDPE castle, Cu SiPM holders, and piezo transducers

Outer vessel



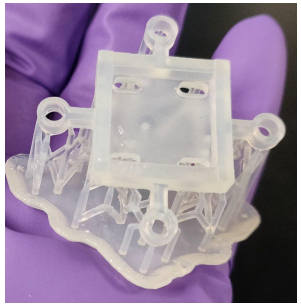


SiPMs, piezos, and cameras

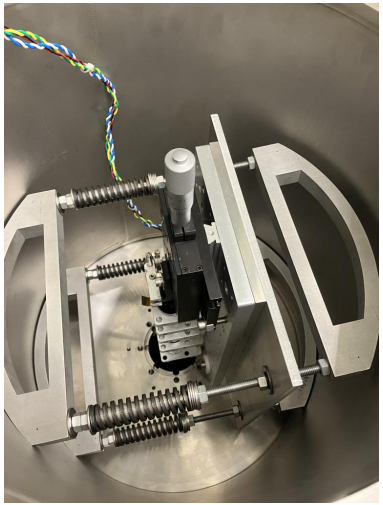


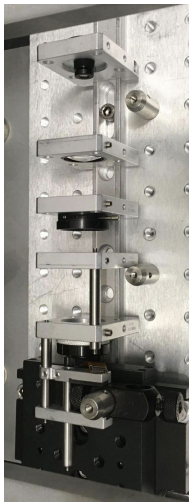
SNOLAB: FBK (25-30% QE)
Fermilab: Hamamatsu (20-25% QE)

Custom PZT piezo transducers



Camera and lens setup





Backgrounds

α-induced

Surface Po, bulk ^{222}Rn decays [purification/cleaning]

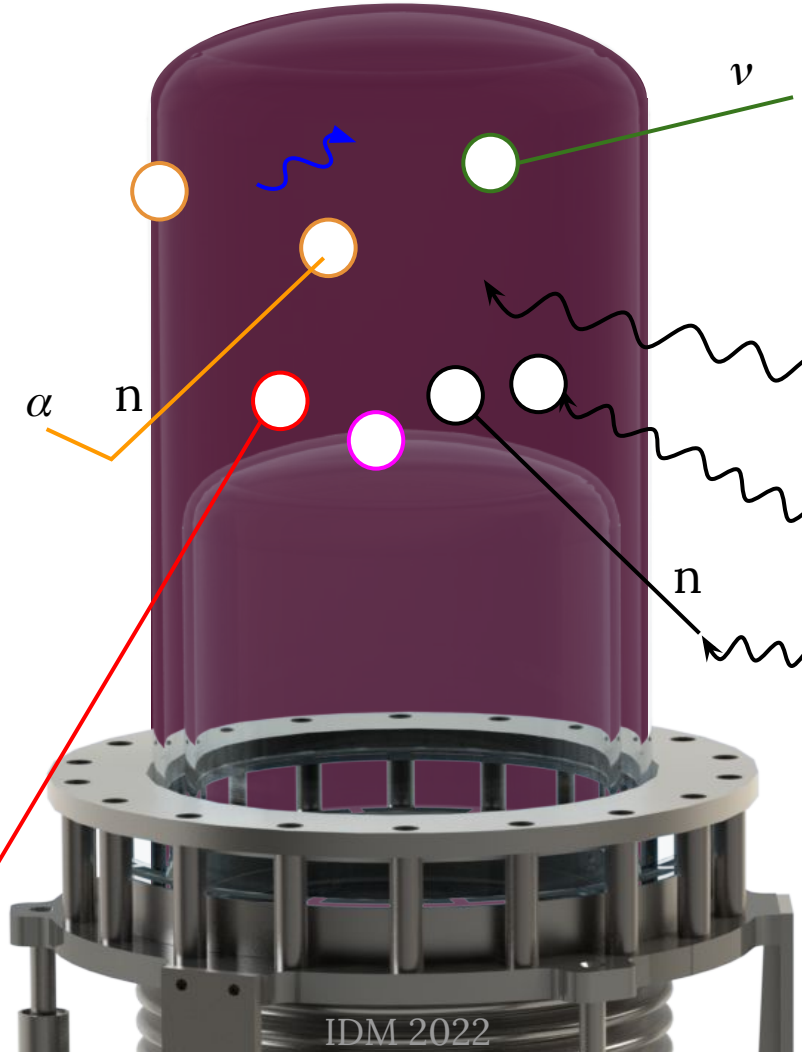
(α,n) in detector materials & LCF_4 [material selection, leaching]

β-induced

^{39}Ar [stray SiPM signals]

n-induced

Fast n [shielding/LCF_4 veto, multiple scatters]



ν-induced

^{8}B CEνNS [irreducible]

γ-induced

Compton [stray SiPM signals, material selection/shielding]

Thomson (^{40}K, ^{208}Tl) [shielding]

(γ,n) reactions in water tank [shielding]

Pathological

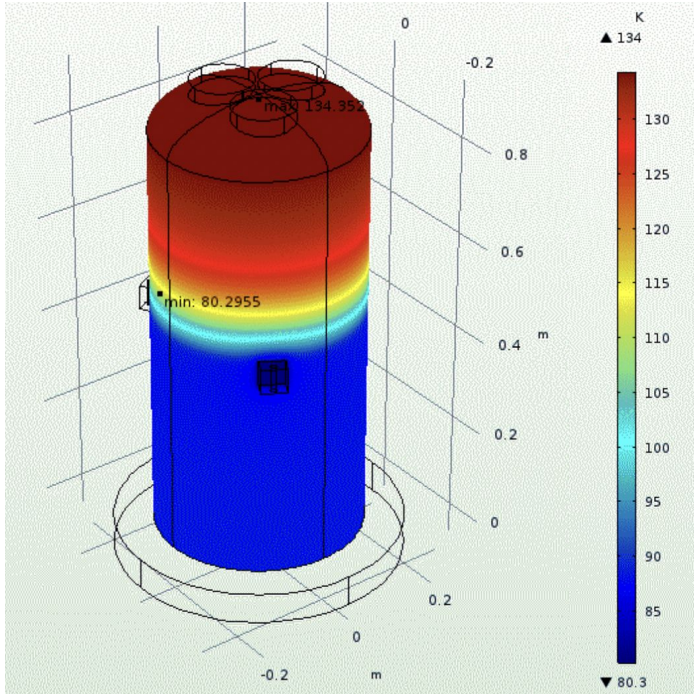
Surface roughness, thermal stability

Initial calibration goals

1) Stable operation
   - Thermal model verification
   - Homogeneous response across sensitive volume
   - Manageable wall nucleation rate

2) Gamma calibration
   - Confirming no e.r. nucleation at keV-scale
   - Probe ultimate thermodynamic limit
   - Investigate e.r. rejection below at/below 100 eV

3) Nuclear recoil calibration
   - Photoneutron (keV)
   - Thomson scattering (sub-keV)
   - Tagged neutron capture (< 100 eV)



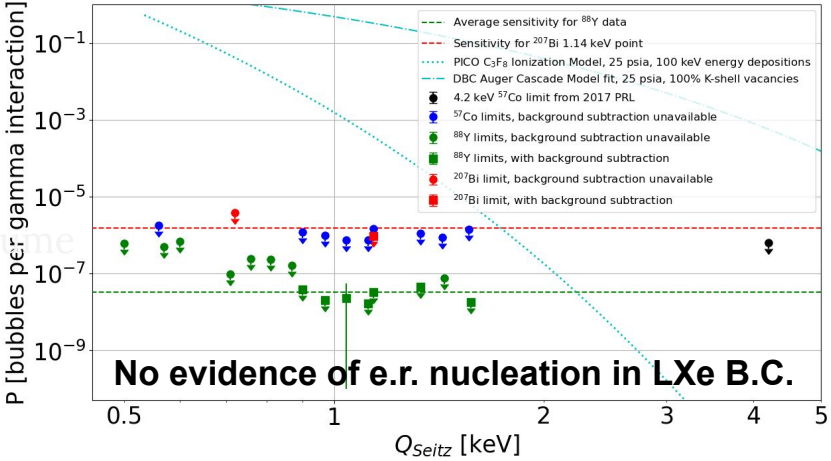
PICO-60 $\mathcal{O}(0.02/\text{liveday}/\text{cm}^2)$

Initial calibration goals

1) Stable operation
   - Thermal model verification
   - Homogeneous response across sensitive volume
   - Manageable wall nucleation rate

2) Gamma calibration
   - Confirming no e.r. nucleation at keV-scale
   - Probe ultimate thermodynamic limit
   - Investigate e.r. rejection below at/below 100 eV

3) Nuclear recoil calibration
   - Photoneutron (keV)
   - Thomson scattering (sub-keV)
   - Tagged neutron capture (< 100 eV)



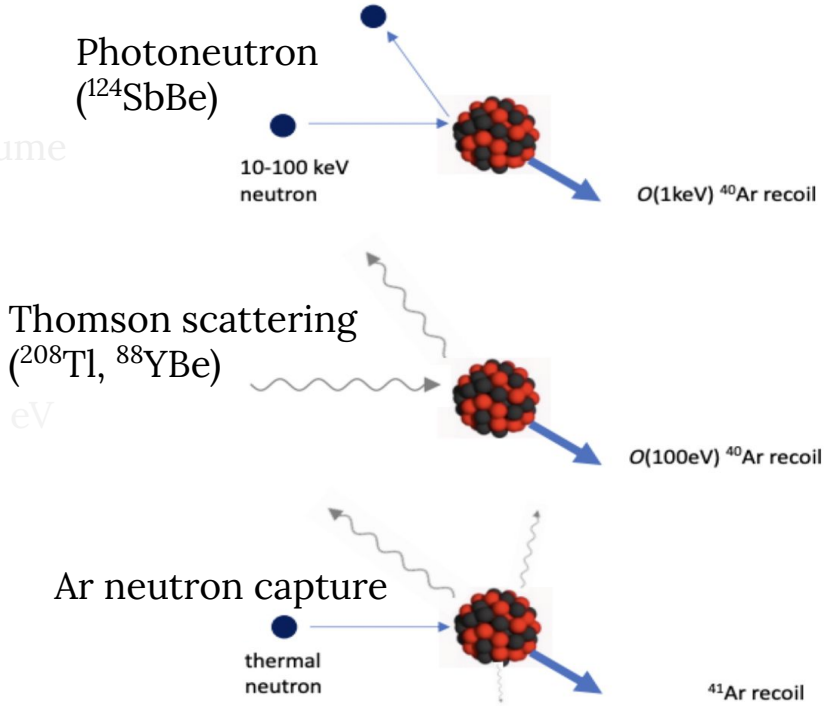
Thermodynamic limit
(spontaneous nucleation)
Ar : ~40 eV
Xe: ~75 eV

Initial calibration goals

1) Stable operation
   - Thermal model verification
   - Homogeneous response across sensitive volume
   - Manageable wall nucleation rate

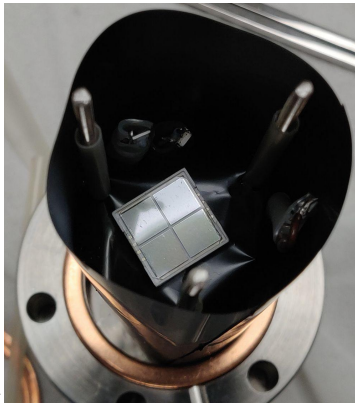
2) Gamma calibration
   - Confirming no e.r. nucleation at keV-scale
   - Probe ultimate thermodynamic limit
   - Investigate e.r. rejection below at/below 100 eV

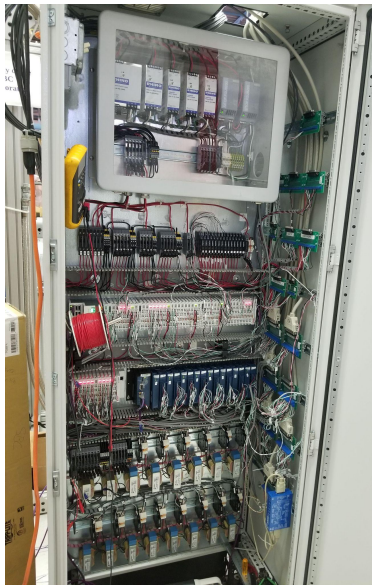
3) Nuclear recoil calibration
   - Photoneutron (keV)
   - Thomson scattering (sub-keV)
   - Tagged neutron capture (< 100 eV)

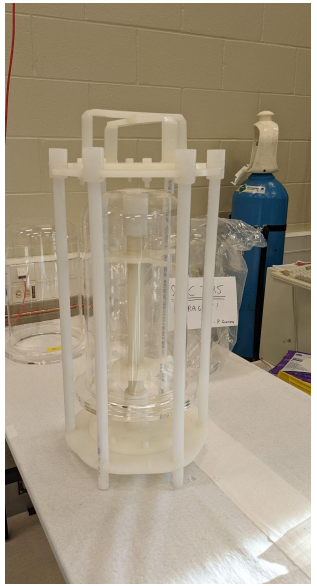


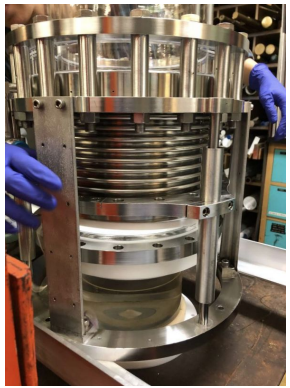
Current status

- Component testing
  - Cryogenic seal testing and inner vessel test assembly
  - SiPM cold tests/ DAQ development
  - Camera & optics development
  - CF_4 scintillation studies
  - Background studies
- Fermilab detector
  - Pressure vessel and vacuum jacket construction
  - Commissioning hydraulic system and slow controls
- SNOLAB detector
  - Space allocated underground
  - Procurement of long-lead items

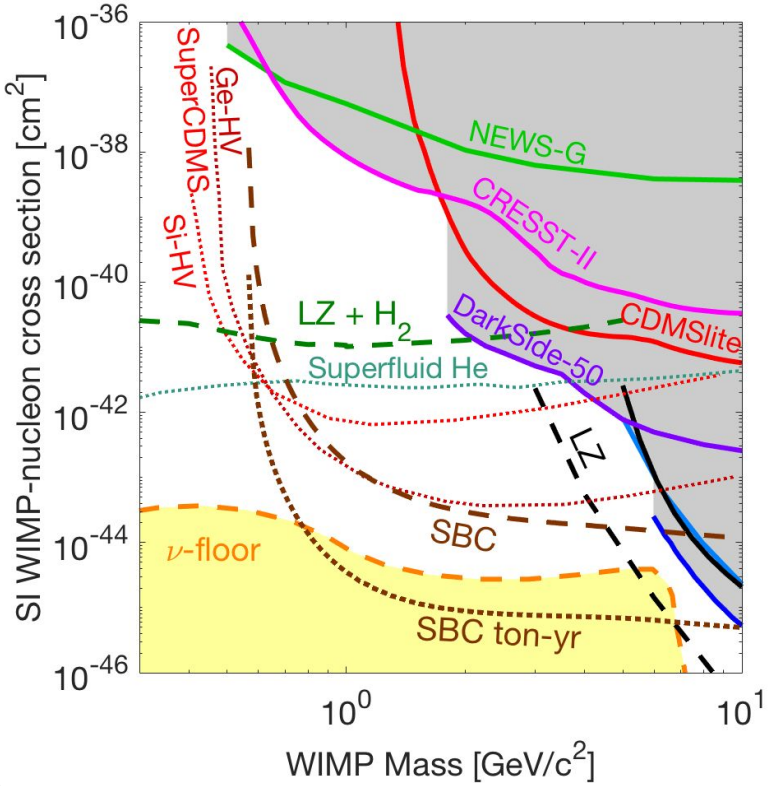








Physics potential



- n.r. region of interest: 0.1 keV - 10 keV
- SNOLAB chamber, 10 kg-year can reach 10^{-43} cm^2 @ 1 GeV/c^2
- If we achieve calibration goals and have long-term stable operation at SNOLAB, ton-year can reach boundary of the Ar ν-fog

For CEνNS potential: PRD **103**, L091301 (2021)

Conclusion

- Noble liquid bubble chamber will probe GeV-scale dark matter
- Commissioning at Fermilab through 2022, SNOLAB construction in 2023
- SBC collaboration consists of institutions from Canada, USA, Mexico (new collaborators always welcome)
- Check out our Snowmass white paper (in preparation)