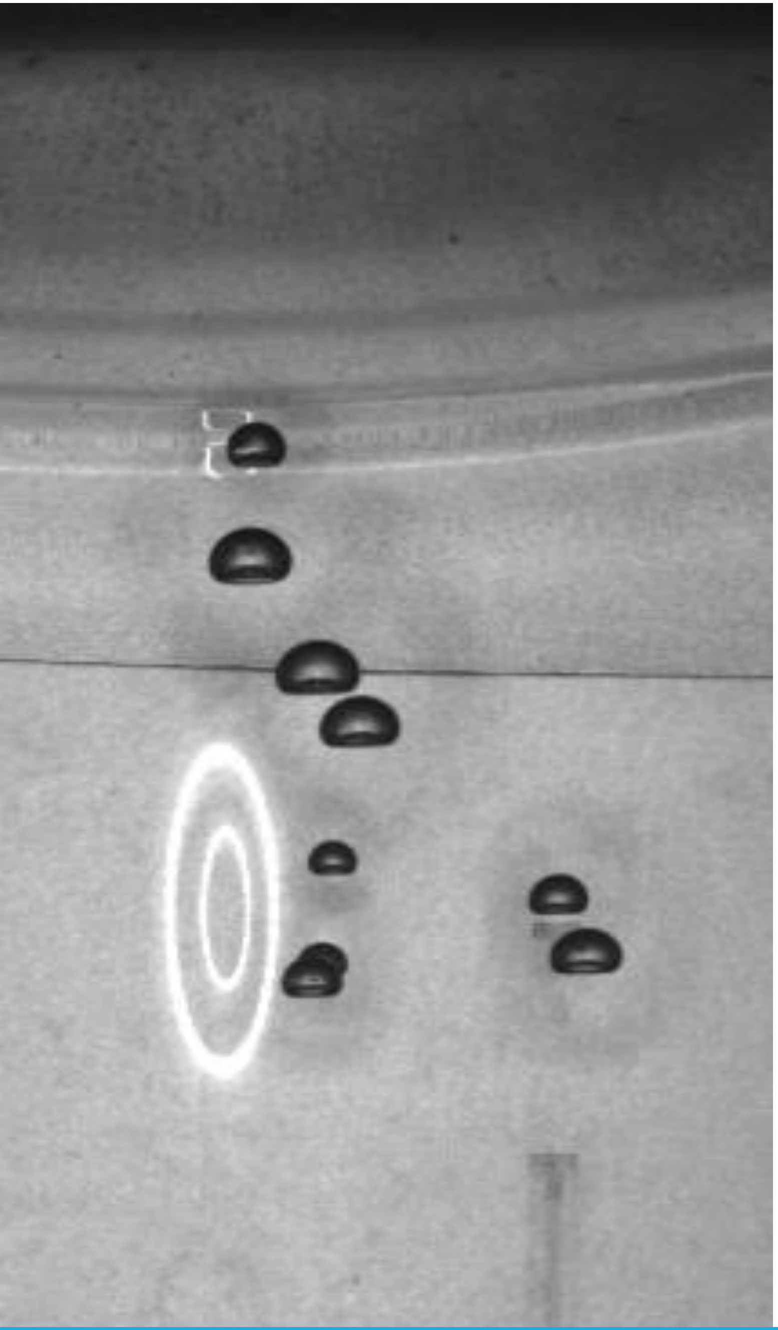


PICO-500 Overview and Calibration

MICHAELA ROBERT, QUEEN'S UNIVERSITY

CAP CONGRESS - JUNE 2023

Queen's UNIVERSITY

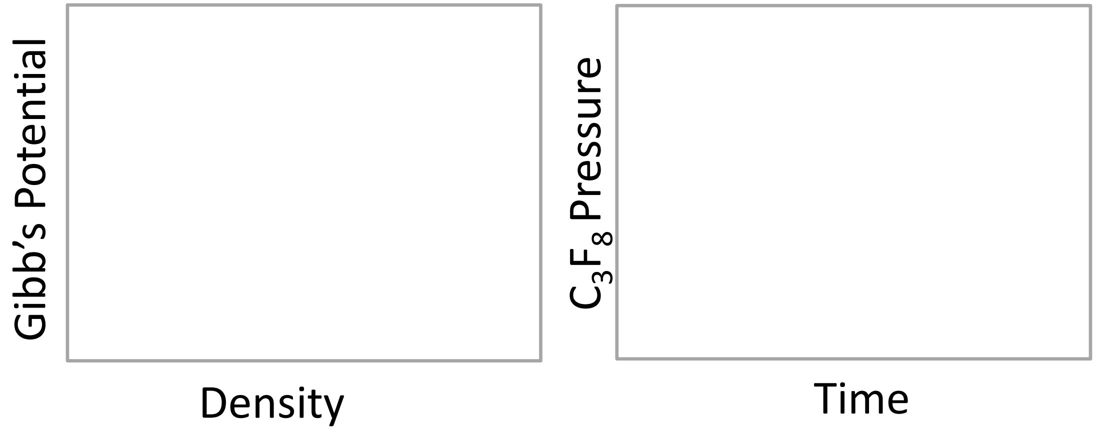
PICO

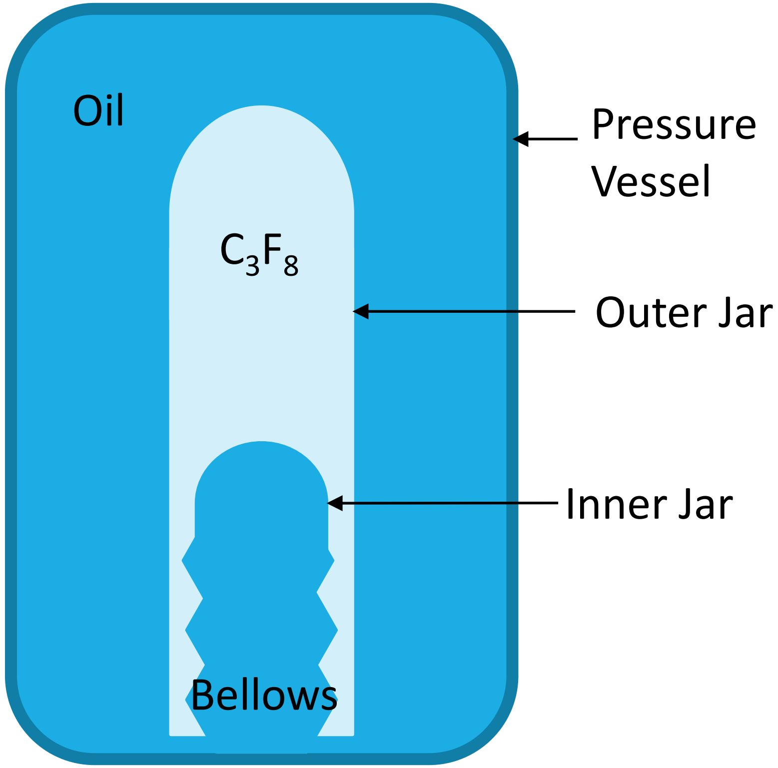
Arthur B. McDonald
Canadian Astroparticle Physics Research Institute

PICO Bubble Chambers

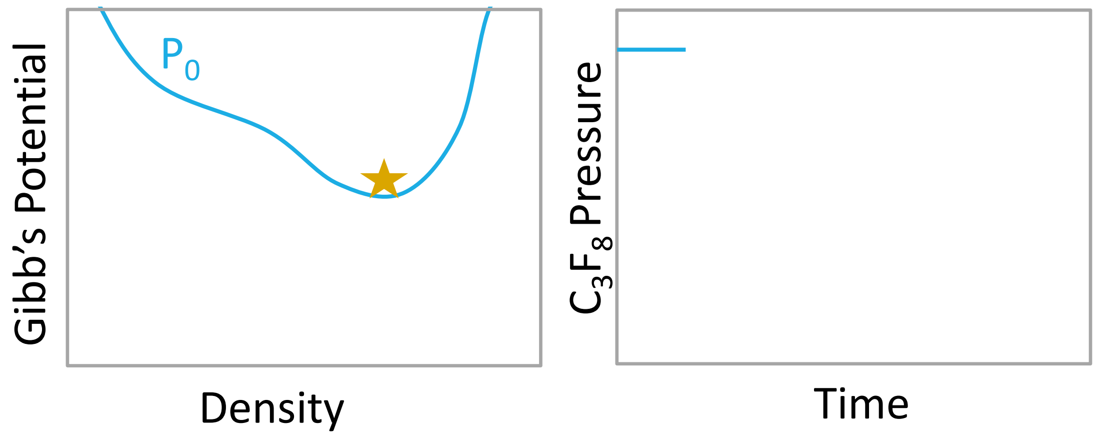
- Series of dark matter detectors operated at SNOLAB
- Aim to directly detect Weakly Interacting Massive Particles (WIMPs) via recoiling of target nuclei
- Cameras watch, piezoelectric transducers listen and pressure transducers feel for bubbles in superheated fluid

PICO Detectors

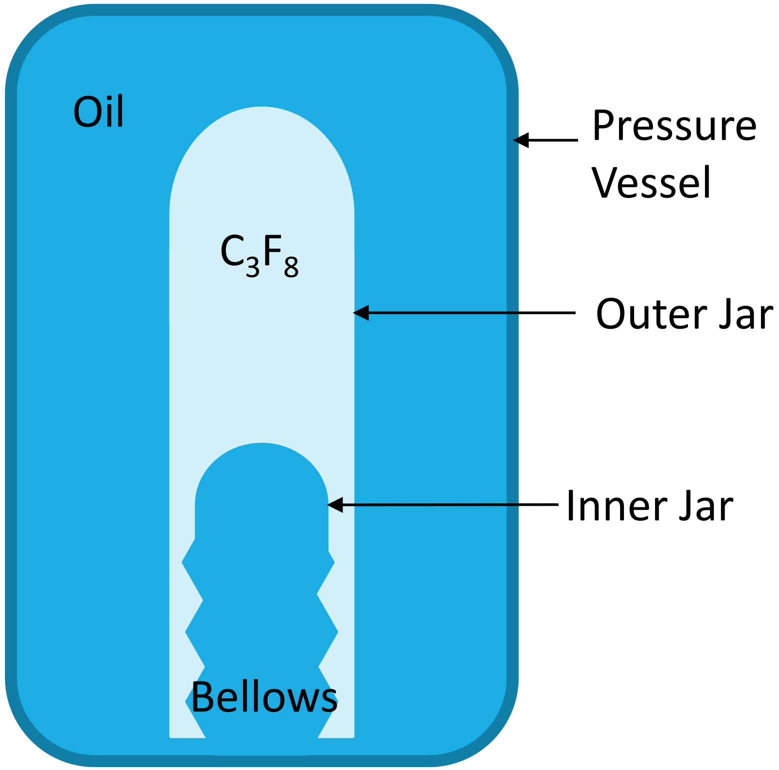




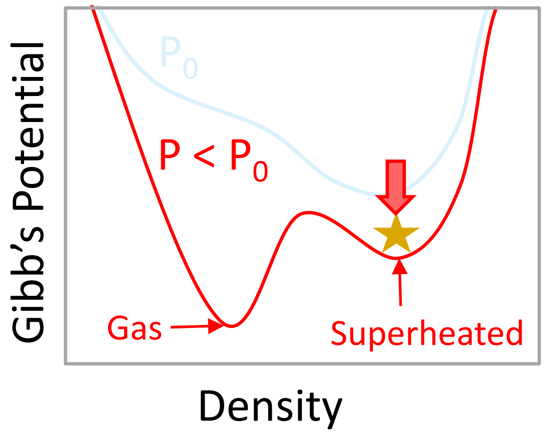
PICO Detectors

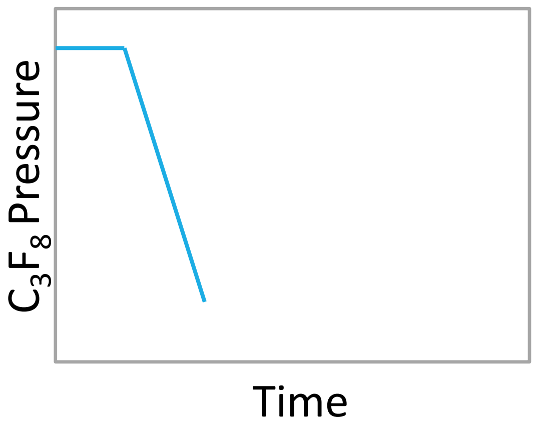


1. C_3F_8 is pressurized to stable liquid state



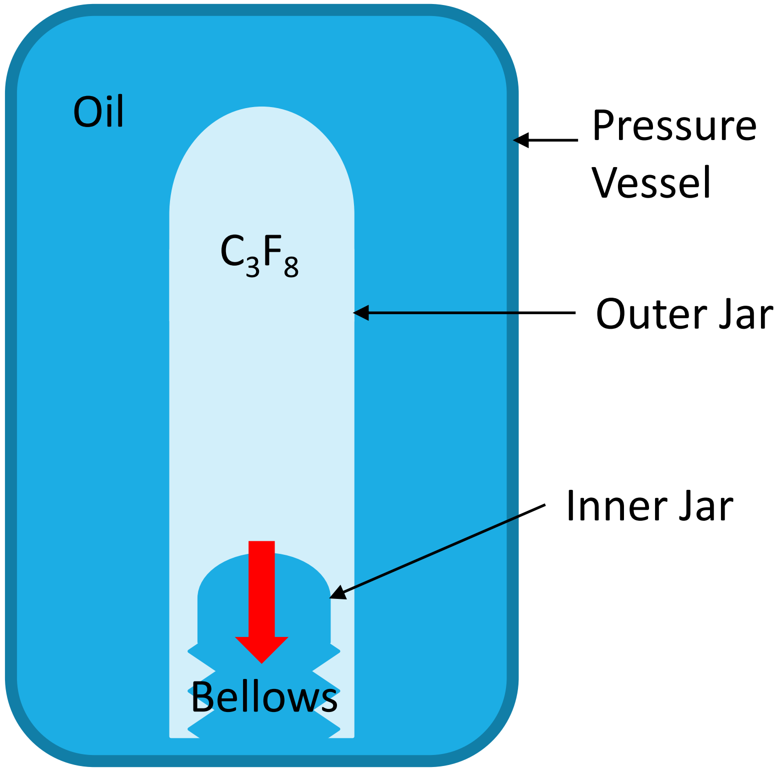
PICO Detectors



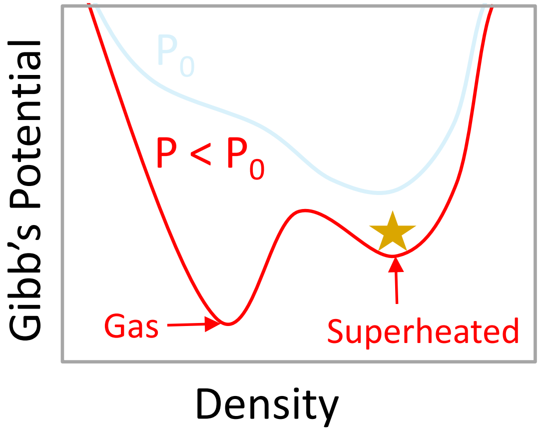


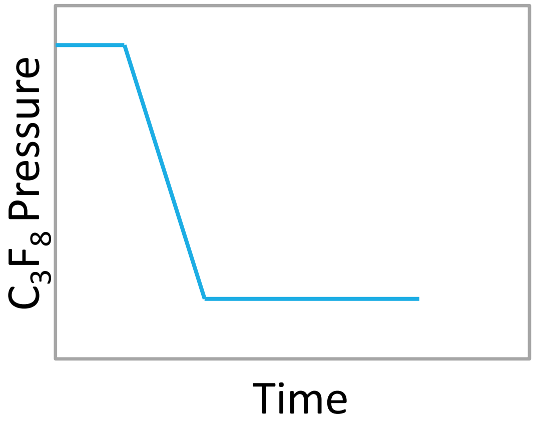
1. C_3F_8 is pressurized to stable liquid state

2. C_3F_8 volume is slowly expanded



PICO Detectors

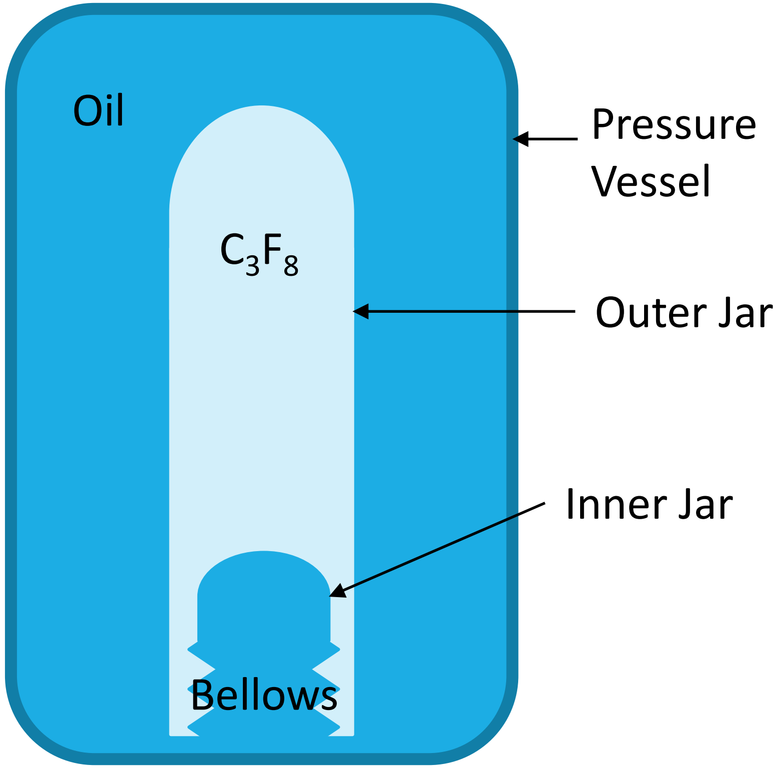




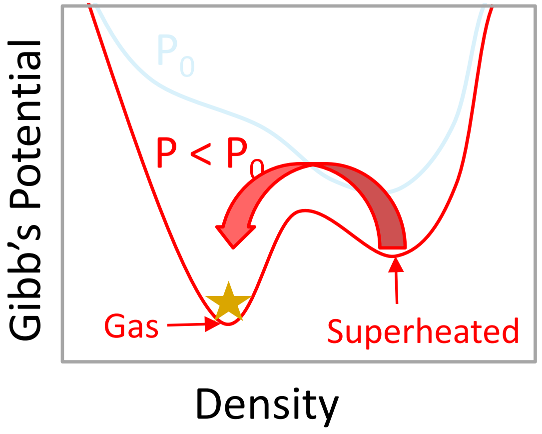
1. C_3F_8 is pressurized to stable liquid state

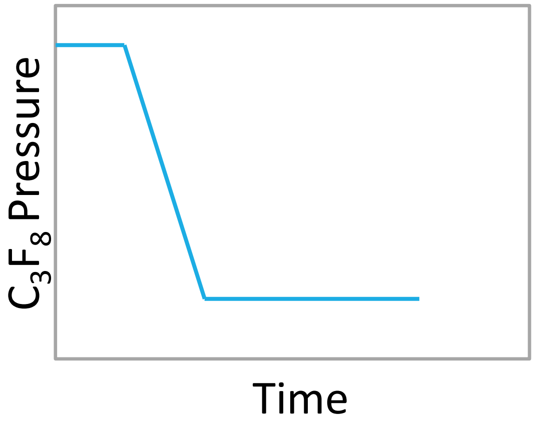
2. C_3F_8 volume is slowly expanded

3. Detector waits for a bubble in superheated state



PICO Detectors



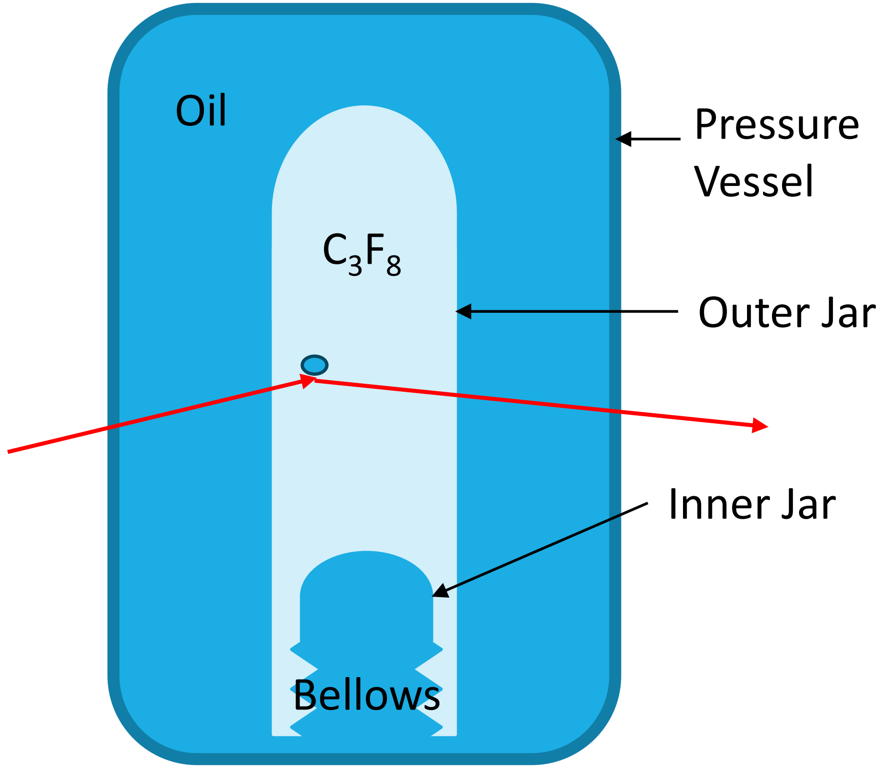


1. C_3F_8 is pressurized to stable liquid state

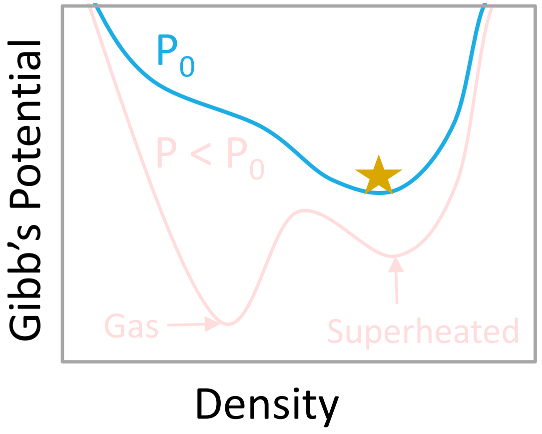
2. C_3F_8 volume is slowly expanded

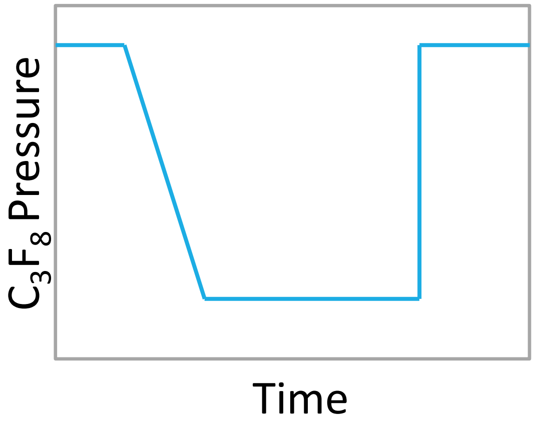
3. Detector waits for a bubble in superheated state

4. Incoming particle causes a nuclear recoil resulting in a bubble - images, pressure and acoustic data are recorded



PICO Detectors





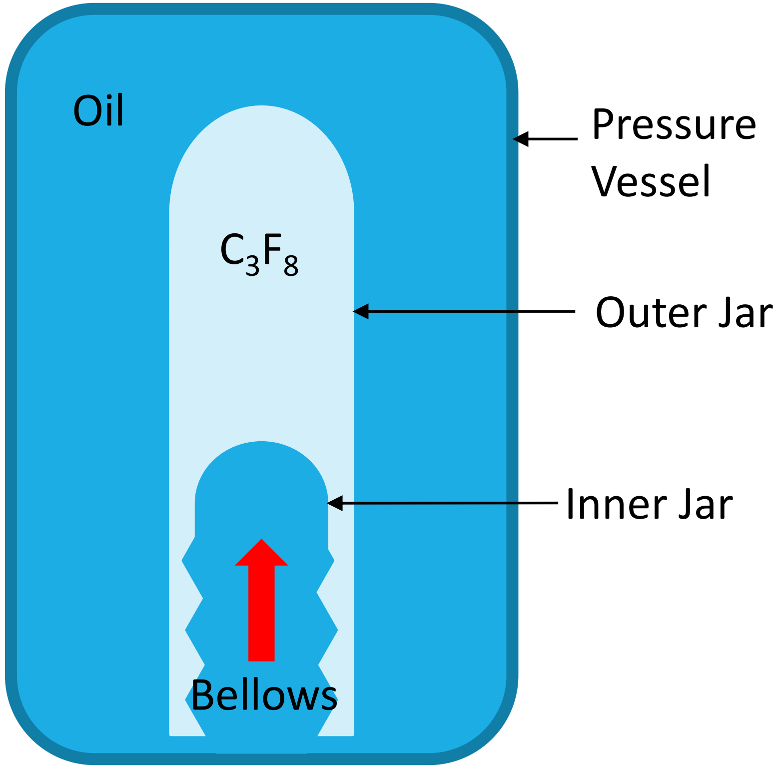
1. C_3F_8 is pressurized to stable liquid state

2. C_3F_8 volume is slowly expanded

3. Detector waits for a bubble in superheated state

4. Incoming particle causes a nuclear recoil resulting in a bubble - images, pressure and acoustic data are recorded

5. Detector compresses to collapse the bubble and reset for next event



Detector Thresholds

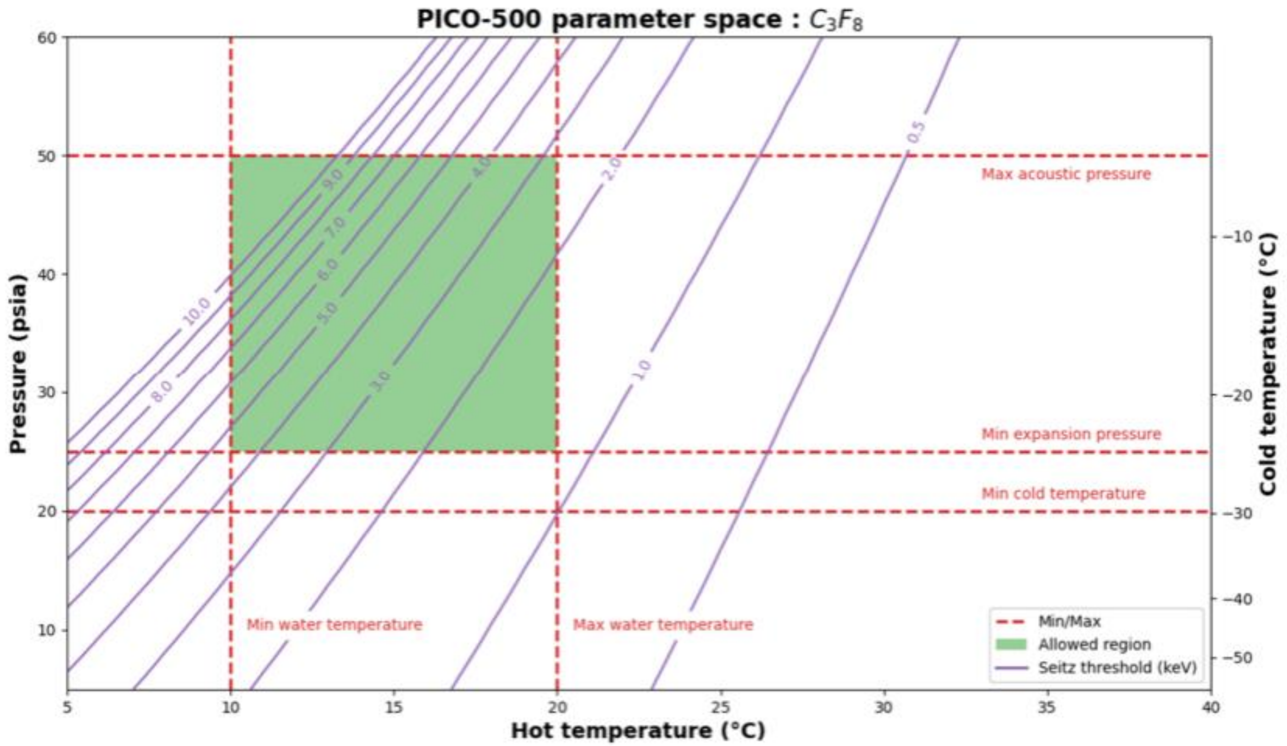
- A small addition of energy, such as a nuclear recoil caused by a WIMP, can trigger a phase transition

- Seitz model: a bubble only sustains itself if the energy deposited within a local region surpasses an energy threshold

  Typically ~ 25 nm

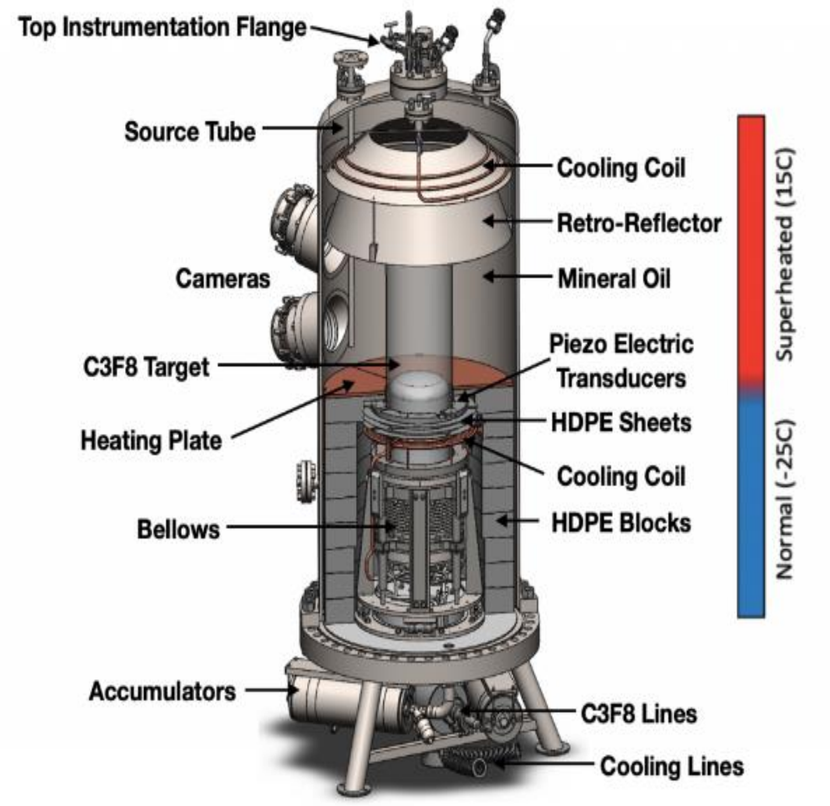
- PICO detectors can be set to ranges of expanded temperatures and pressures to reach various energy thresholds

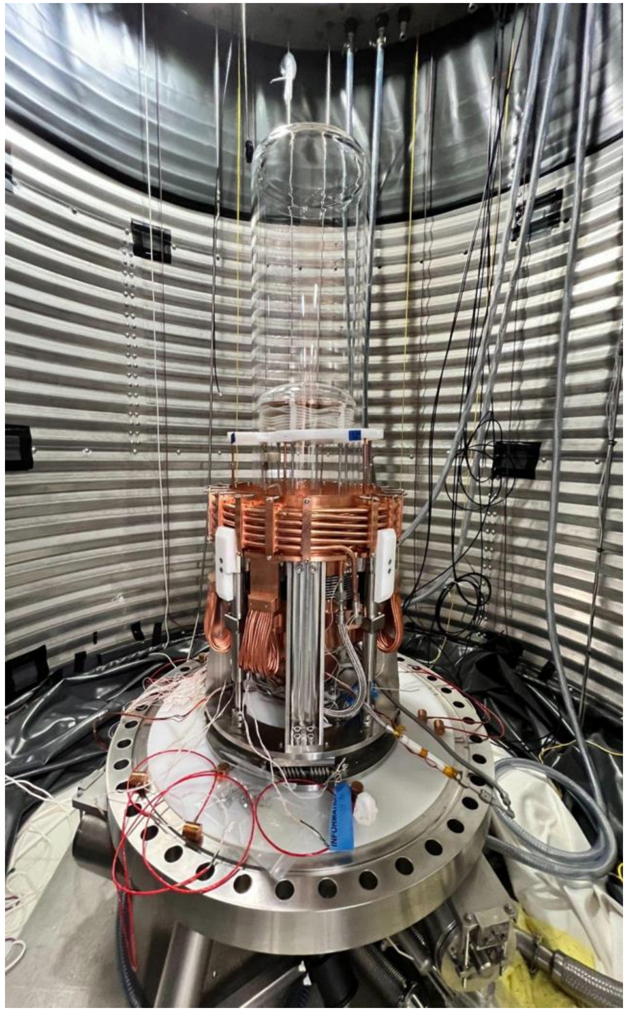
  Typically ~ 3 keV



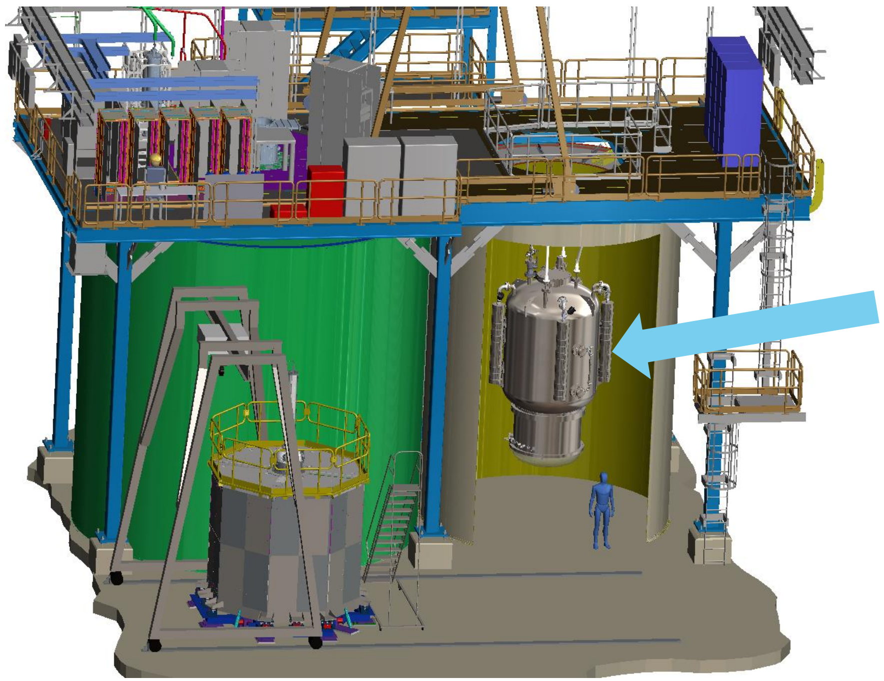
PICO-40L

- Constructed at SNOLAB between 2019-2023
- Currently in commissioning phase
- Projected 10 times improvement on spin-dependent WIMP sensitivity over PICO-60





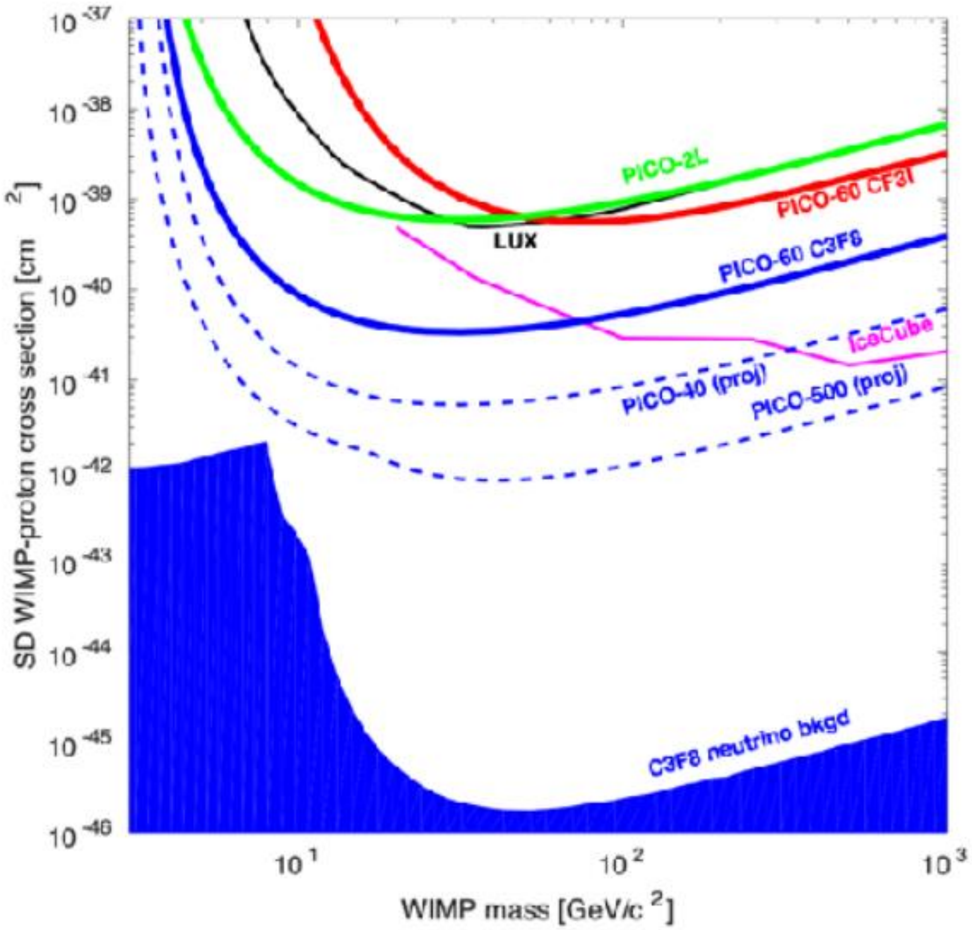
Upscaling to PICO-500



- ~250 litre sensitive volume (limited by available jars), 5 times larger than PICO-40L
- Upgrades to piezos, thermal system, and other systems
- 9000 kg pressure vessel
- To be suspended inside a 25 ft tall, 18.5 ft wide water tank
- To be constructed in Cube Hall at SNOLAB
- Fabrication of components has begun

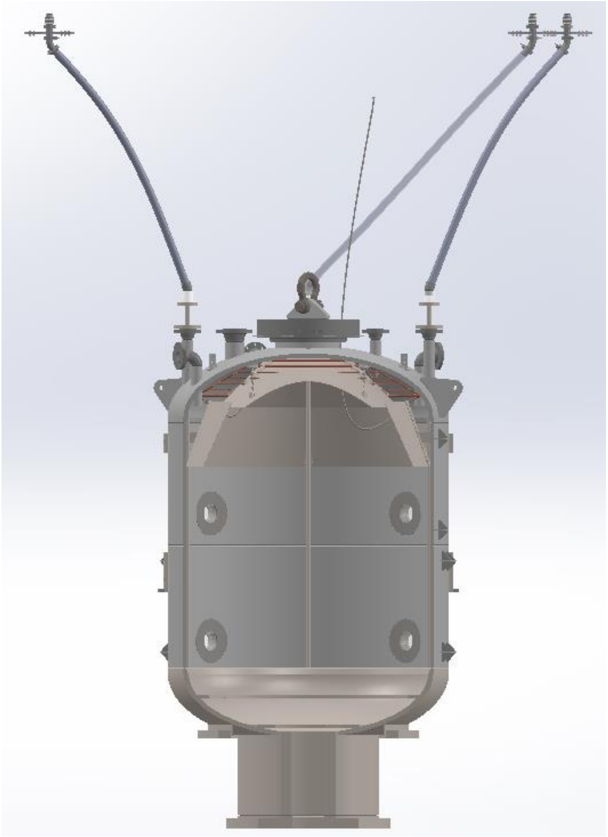
PICO-500 Operation

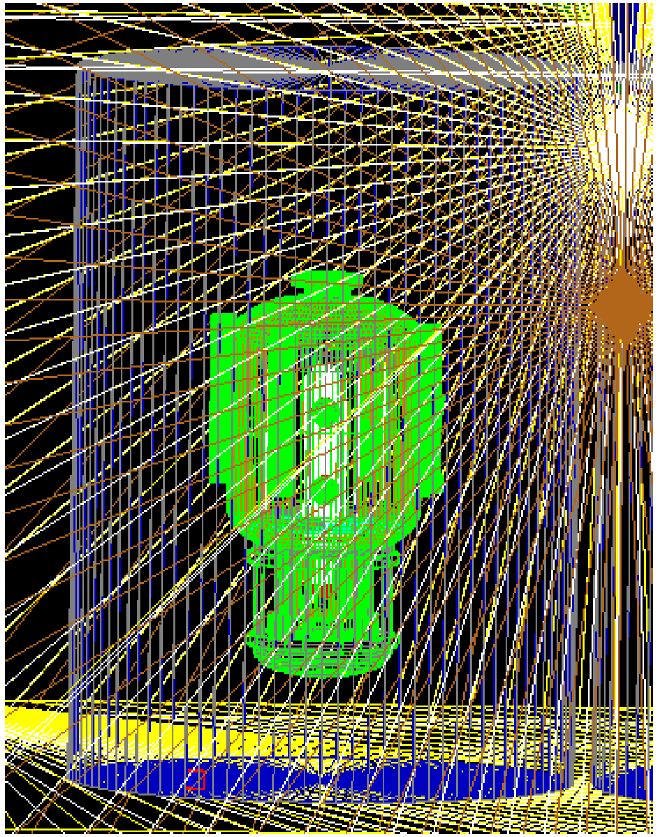
- 1 month of initial calibration to begin in 2024
- 2 years of blind physics data in C_3F_8 at multiple thresholds
  - Low threshold run time limited by neutrino backgrounds
- Projected O(10) times improvement on spin-dependent WIMP sensitivity over PICO-40L
- Potential operation with other liquids:
  - CF_3I
  - CF_3CH_2F (R134a)
- Designed for future sensitive volume upsizing if larger vessels become available



PICO-500 Calibration System

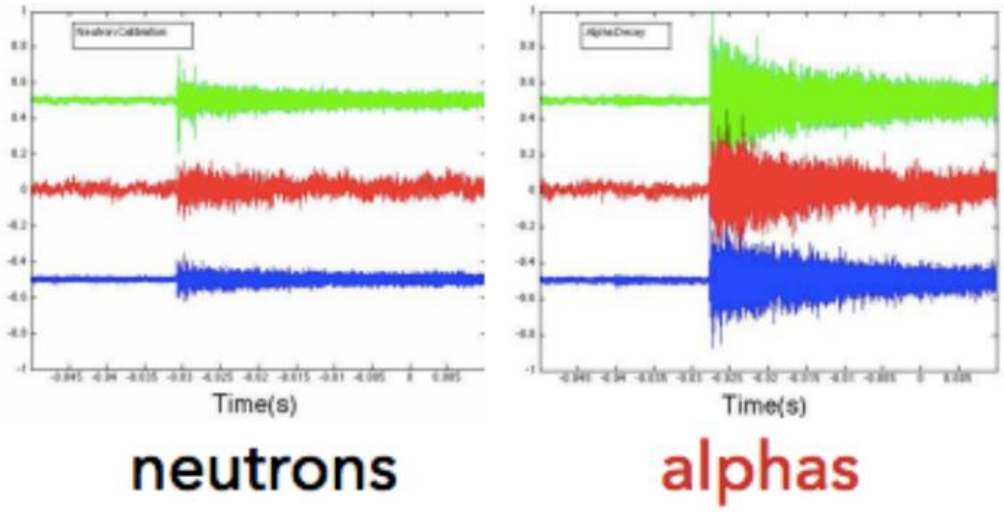
- Deploy calibration sources into the detector through source tubes
- Three source tubes at two different radii from C_3F_8 volume
- Monitor the position of the source for direct comparison of detector responses with simulation results
- Calibrate to establish detector response and stability, to reject backgrounds, etc.

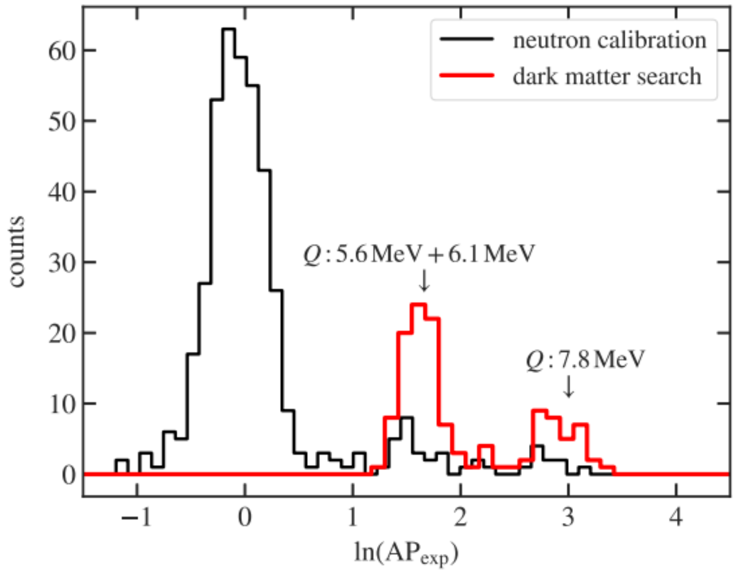




Calibrating for Alpha Rejection

- Alphas make louder bubbles than neutrons/WIMPs as recorded by piezoelectric sensors on outer jar
- Acoustic parameter (AP) describes the bubble's acoustic power
- ^{241}AmBe and/or ^{252}Cf calibration data is used to tune AP coefficients for neutron/WIMP – alpha separation





Tetiana Kozynets, Scott Fallows, and Carsten B. Krauss Phys. Rev. D 100, 052001 (2019)

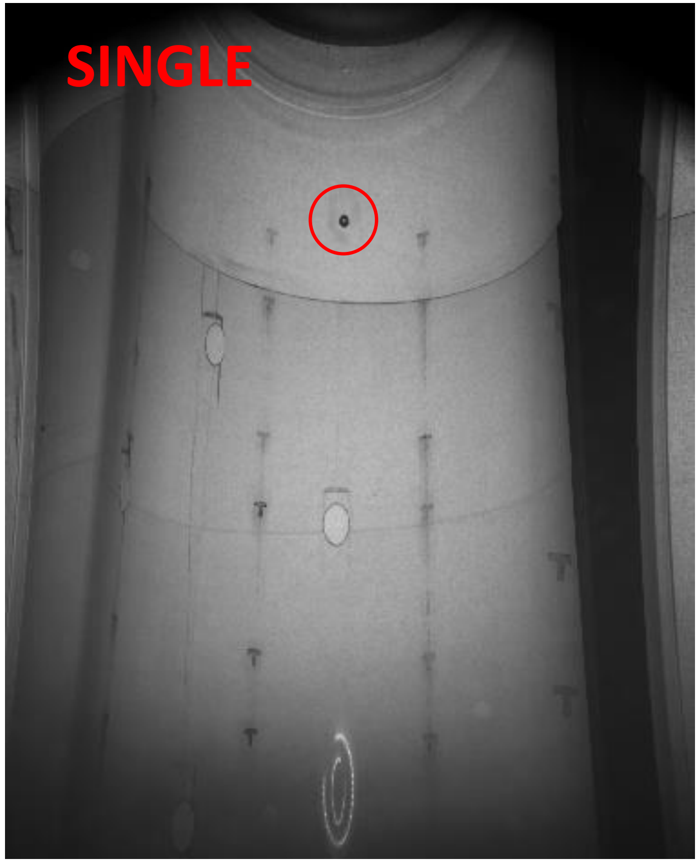
Calibrating for Neutron Rejection

- Neutron MFP ~cm →single/multiple bubbles
- WIMPs interact rarely → single bubble

Statistics are required to pull out WIMP signal!

- PICO-60 multiple to single bubble ratio was 3:1, but must be measured for PICO-500
- O(1-100) neutron/s ^{241}AmBe and/or ^{252}Cf sources are required for optimal neutron calibration run time

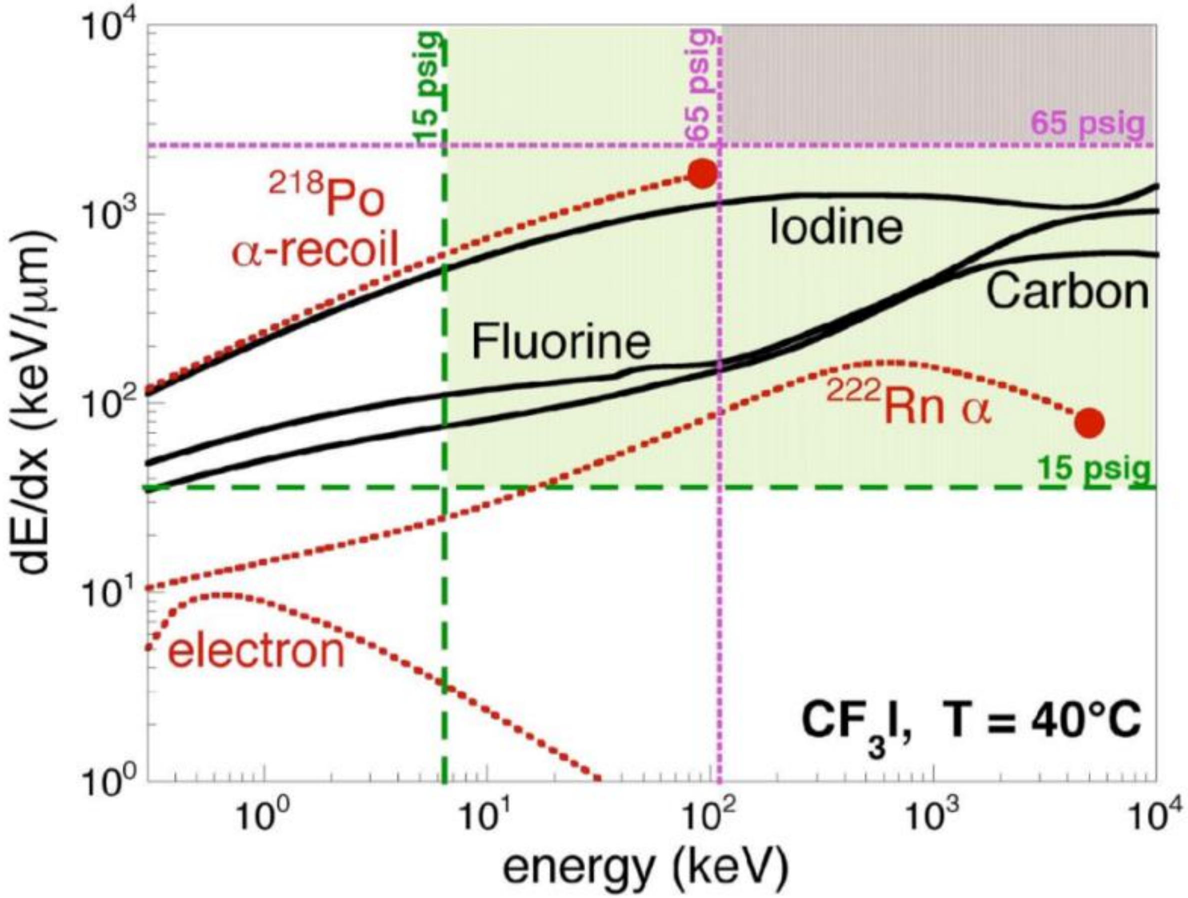
PICO-40L: 20230304_3 83



PICO-40L: 20230304_3 97

Calibrating for Gamma Rejection

- Electron stopping power is low → rarely nucleate bubbles
- Objective to optimize threshold for WIMP sensitivity and gamma insensitivity
- ~18 MBq ^{60}Co source to probe detector response to electron recoils via 1.17 and 1.33 MeV gammas



E. Behnke et al., Spin-Dependent WIMP Limits from a Bubble Chamber. *Science* **319**, 933-936 (2008). DOI: 10.1126/science.1149999

Summary

- PICO-500 is projected to have world leading sensitivity to spin-dependent WIMP-proton interactions, improving on PICO-40L's sensitivity by O(10)

- Commissioning of PICO-500 is to start in 2024

- Calibrations for neutron statistics, alpha rejection, operating thresholds optimization, etc. are to be completed to achieve very low background rates

Thank you!


PICO
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Backup Slides

Seitz Threshold

$$E_T = 4\pi r_c^2 \left(\sigma - T\frac{\partial\sigma}{\partial T}\right) + \frac{4\pi}{3} r_c^3 \rho_b (h_b - h_l) - \frac{4\pi}{3} r_c^3 (P_b - P_l), \qquad P_b - P_l \geq \frac{2\sigma}{r_c}$$

Bubble surface | Latent heat of vaporization | Double counted Work

where,

E_T = Seitz threshold
r_c = critical bubble radius
T = temperature
ρ_b = bubble vapor density
h_i = specific enthalpy of bubble vapor (b) or superheated liquid (l)
P_i = Pressure in bubble (b) or superheated liquid (l)
σ = surface tension

Acoustic Parameter

$$AP = A(T) \sum_{j} G_j \sum_{n} C_n(\vec{x}) \sum_{f_{min}^{n}}^{f_{max}^{n}} f \times psd_f^j$$

Where,

$A(T)$ = scale factor

G_j = gain of j^{th} acoustic transducer

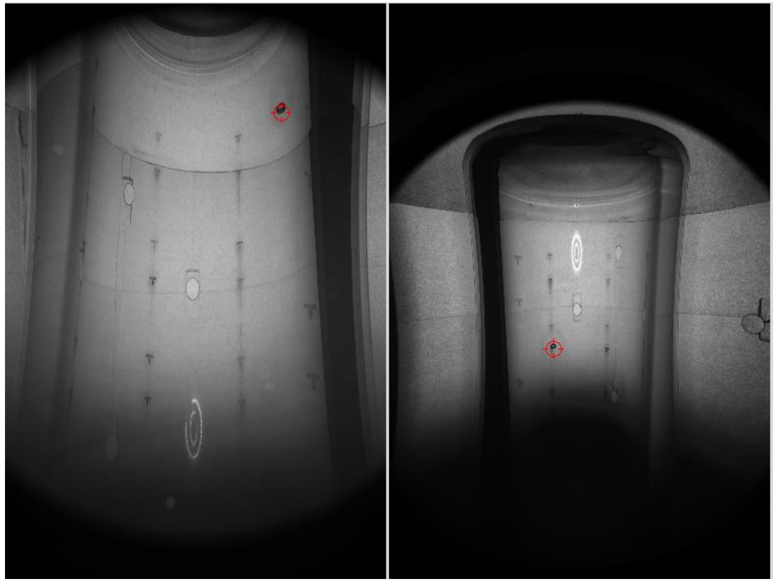
$C_n(\vec{x})$ = position dependence correction factor for n^{th} frequency bin

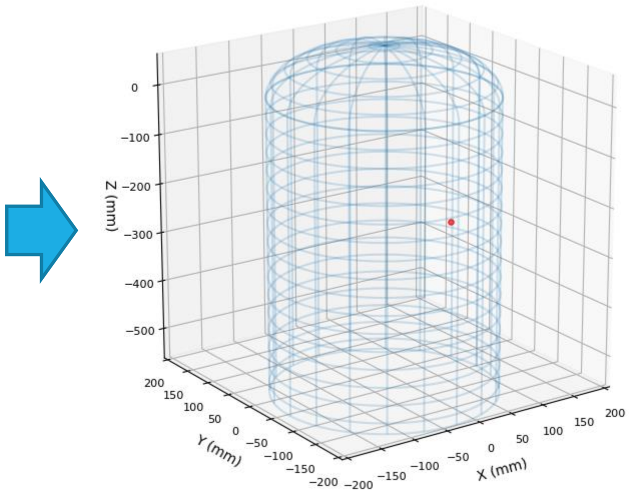
f = center frequency of n^{th} frequency bin

psd_f^j = power spectral density for n^{th} frequency bin and j^{th} acoustic transducer

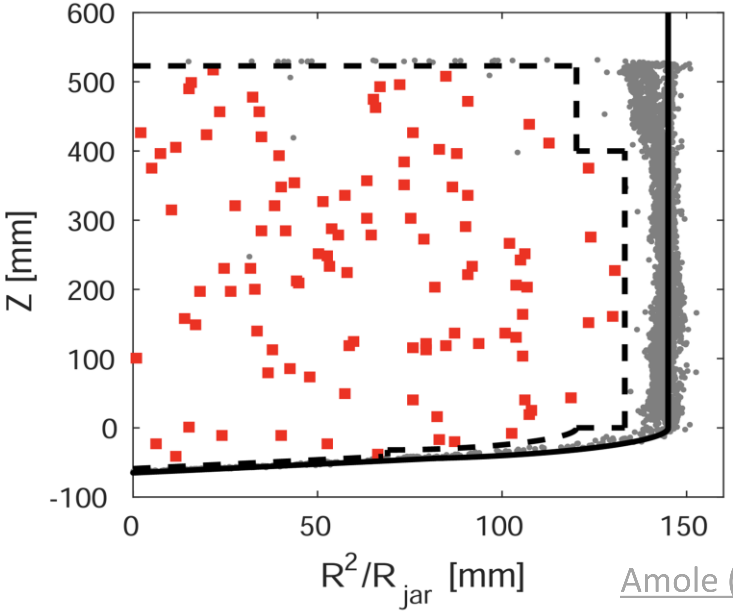
Wall Events

- 4 cameras record images of bubbles, software reconstructs the bubble's location from the images
- Bubbles that nucleate near the walls of the jars are often alphas from the jars or wall events -> Bubbles outside of the fiducial volume are rejected
- ^{241}AmBe and/or ^{252}Cf neutron sources are chosen to induce bubbles at a desired rate


PICO-40L Event



PICO-60 Data



Amole (2017)