PICO

= PICASSO + COUPP

Bubble Chambers for Direct Detection

INT-14-57W

Nuclear Aspects of Dark Matter

PICO

SNOLAB
MINING FOR KNOWLEDGE
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Outline

- Bubble Chambers
  - Motivation: Target choice
  - Physics of bubble chambers
  - PICO results from SNOLAB physics runs
  - The future of bubble chambers

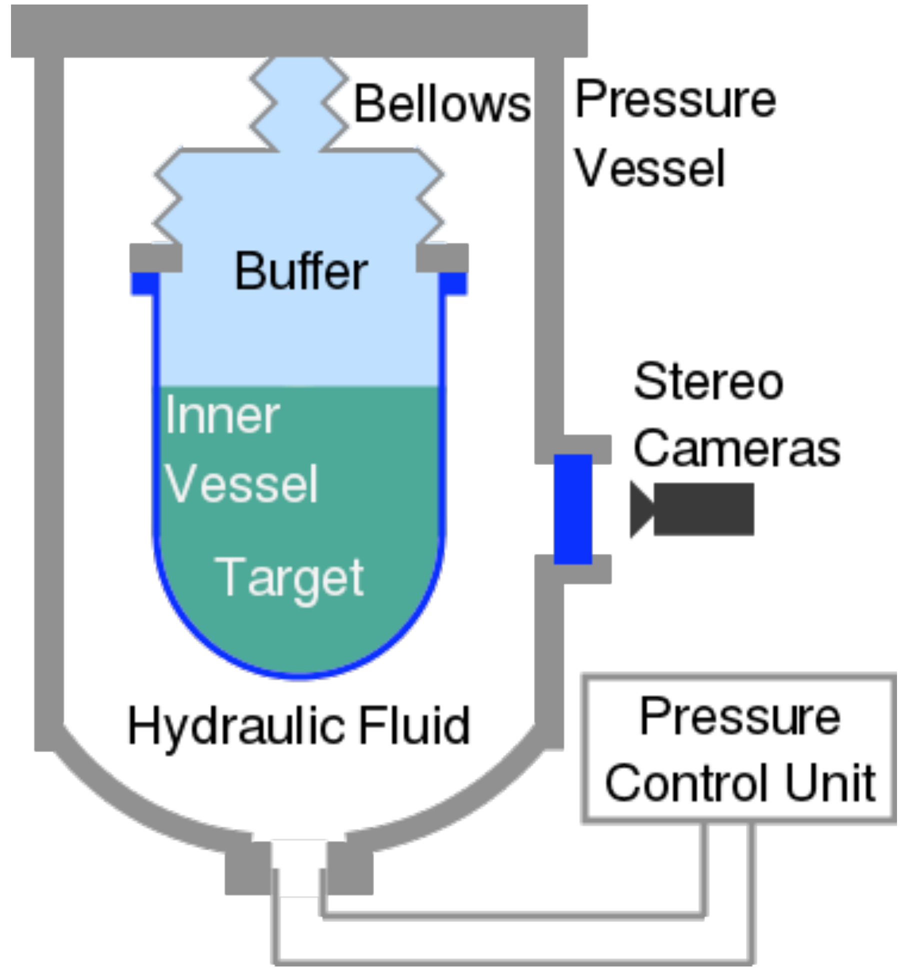
Bubble Chamber Targets

- ONLY discriminating detector with odd-proton targets
  - C_3F_8, sensitive to 3-keV Fluorine recoils
  - CF_3I, sensitive to 15-keV Iodine recoils

- ANY fluid with a vapor pressure works
  - Go-to technique to characterize WIMP-nucleus interaction, *once* we see a signal

Bubble Chamber Basics

- Superheated Target
  - CF_3I, C_3F_8, …
- Particle interactions nucleate bubbles
- Cameras and acoustic sensors capture bubbles
- Chamber recompresses after each event



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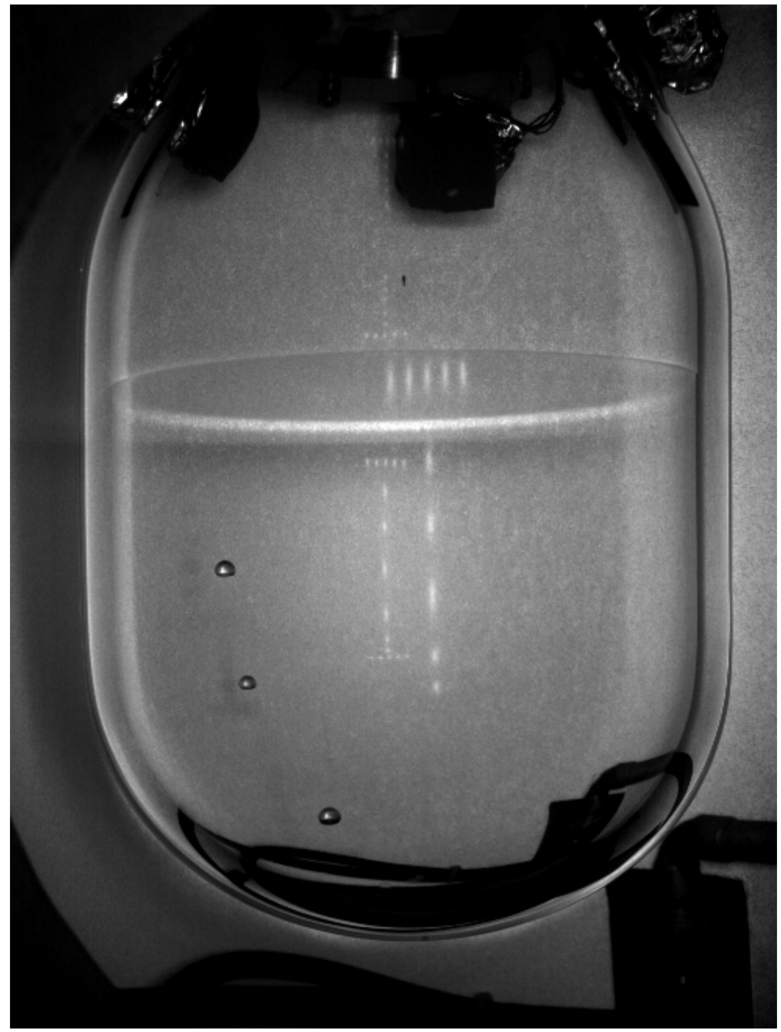
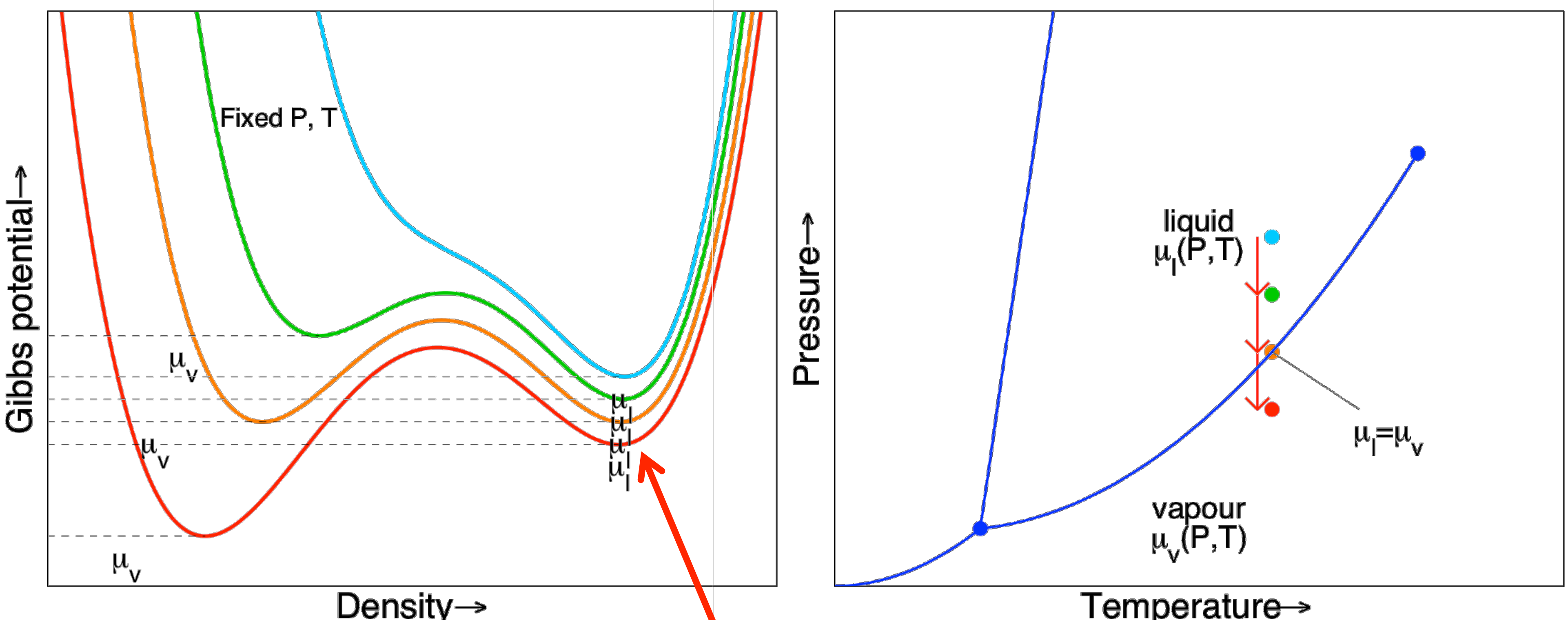


Bubble Chamber Thermodynamics

- Reaching the superheated state



Superheated Liquid

Bubble Chamber Thermodynamics

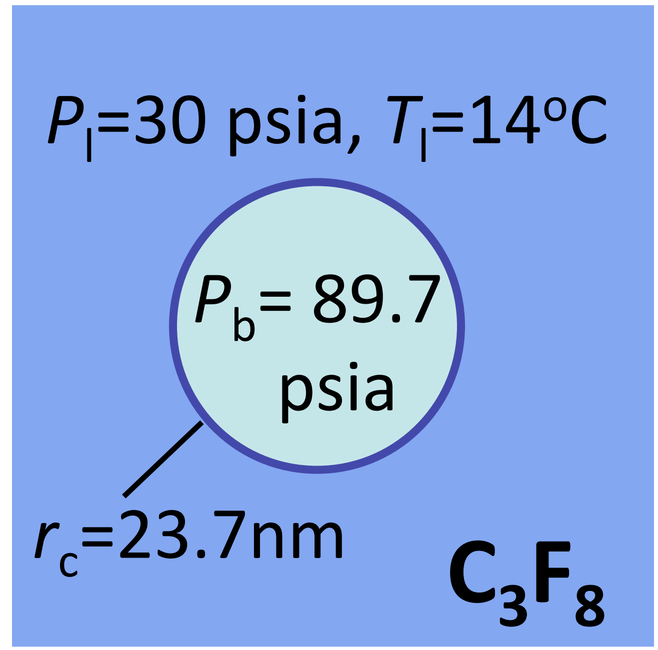
- What does it take to produce critical bubble?

$$E_T = 4\pi r_c^2\left(\sigma - T\left(\frac{\partial\sigma}{\partial T}\right)_\mu\right)$$ 1.53 keV

$$+\frac{4\pi}{3}r_c^3\rho_b\left(h_b - h_l\right)$$ 1.81 keV

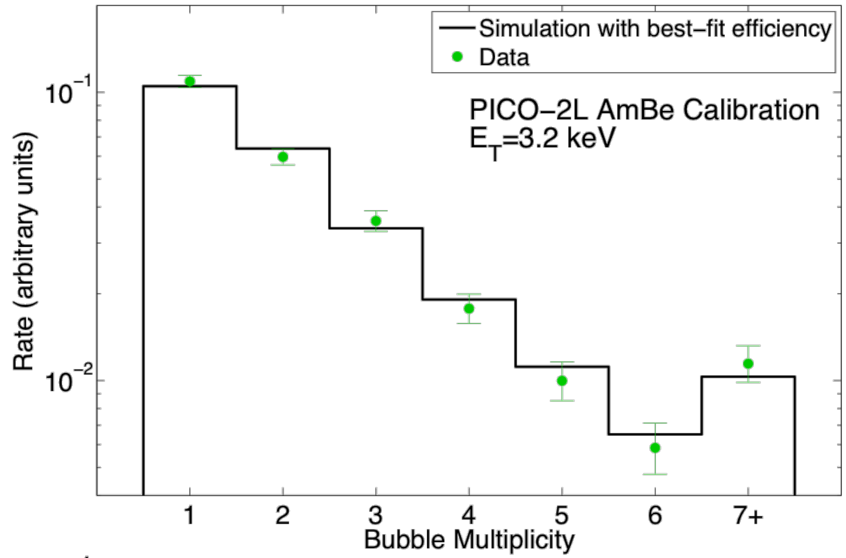
$$-\frac{4\pi}{3}r_c^3\left(P_b - P_l\right)$$ -0.15 keV

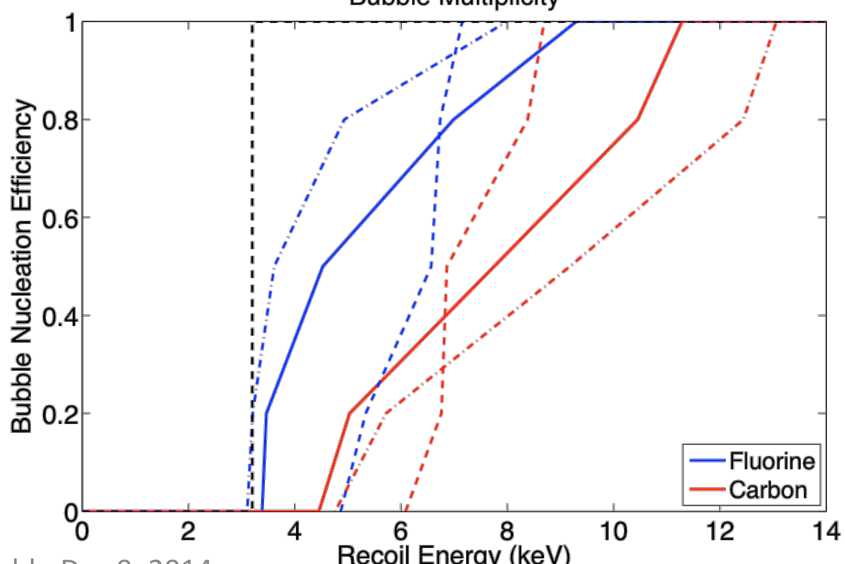
= 3.19 keV total



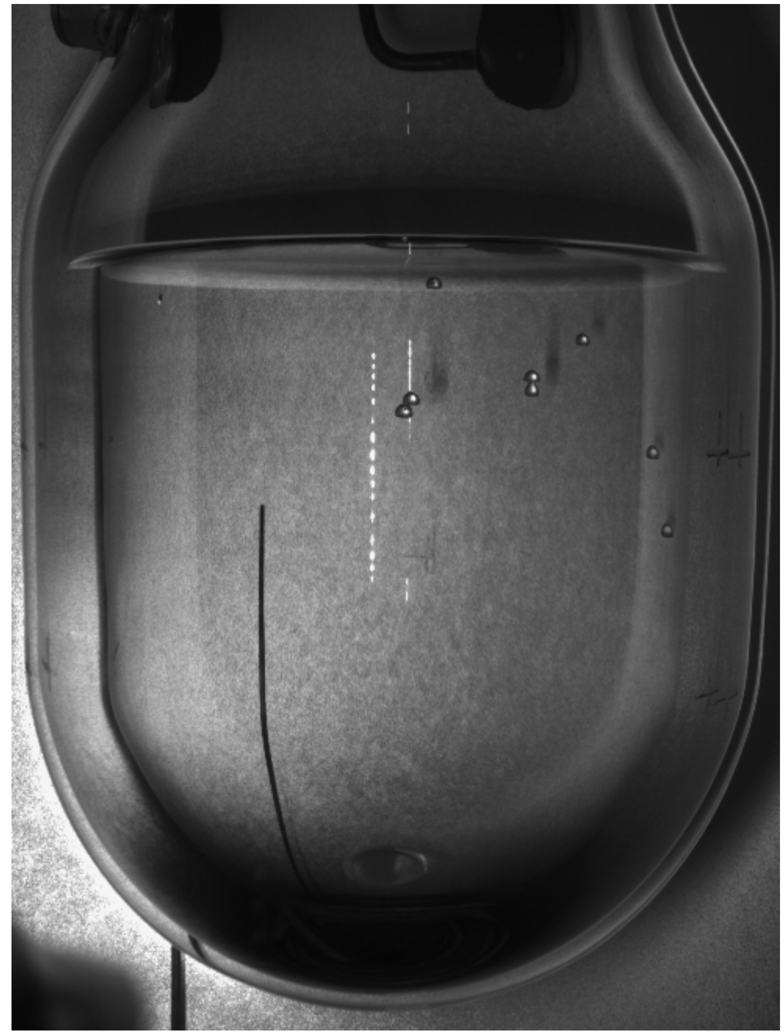
Surface energy, Bulk energy, Reversible Work

Nuclear Recoil Calibration





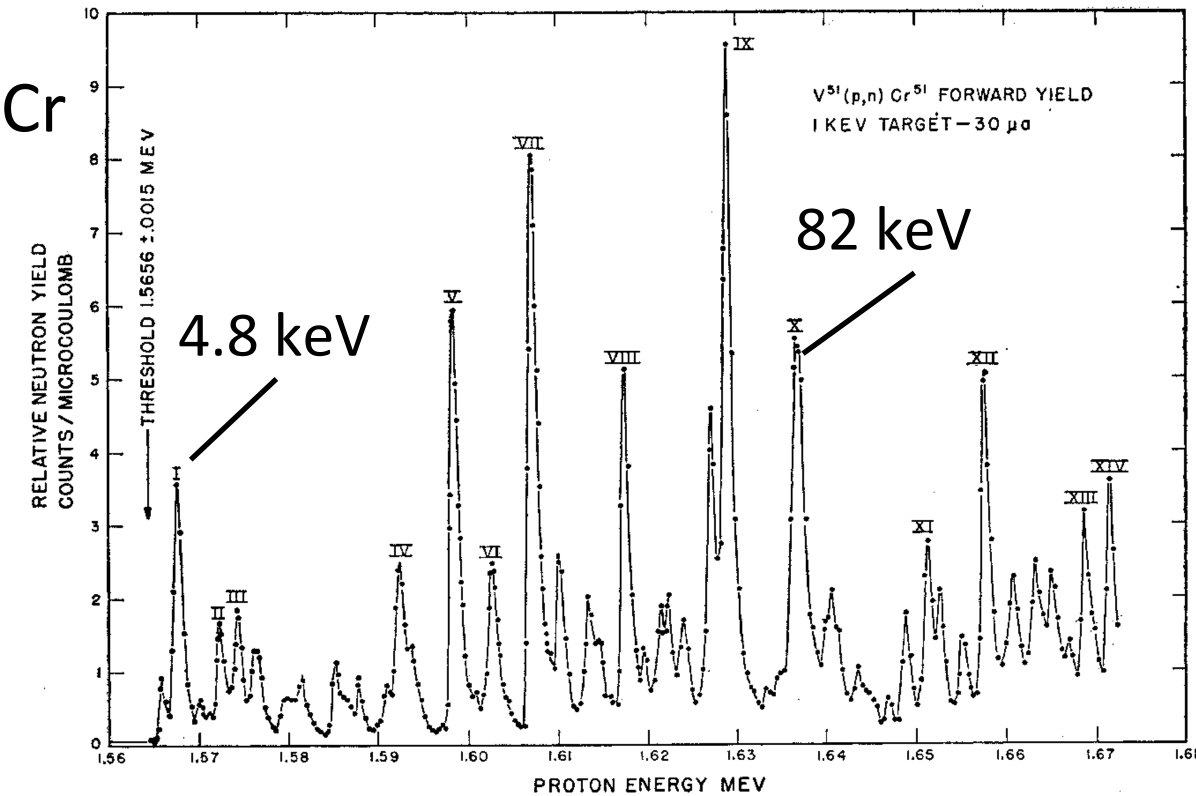
In-situ AmBe neutron source



Beam Recoil Calibrations

- Mono-energetic low-energy neutrons
  - $^{9}Be(\gamma,n)$
    - 156 keV (^{88}Y), 96 keV (^{207}Bi), 24 keV (^{124}Sb)
  - $^{51}V(p,n)\ ^{51}Cr$

Protons from Montreal Tandem Van de Graaf Facility

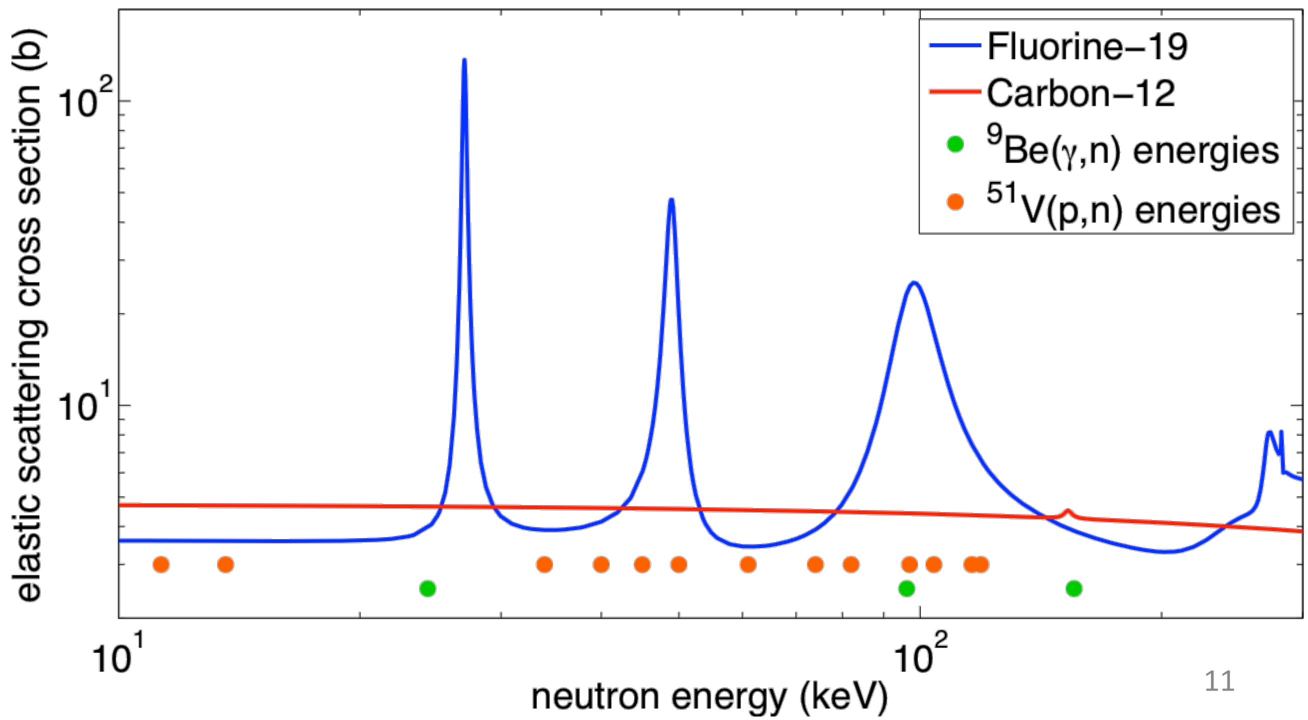


Beam Recoil Calibrations

- Calibrated neutron fluxes
  - ^{3}He counters
  - p and γ flux measurements, plus "known" reaction cross-sections
  - ^{51}Cr measurements (320-kev γ, 28-day half life)
- Data on- and off- Fluorine resonances

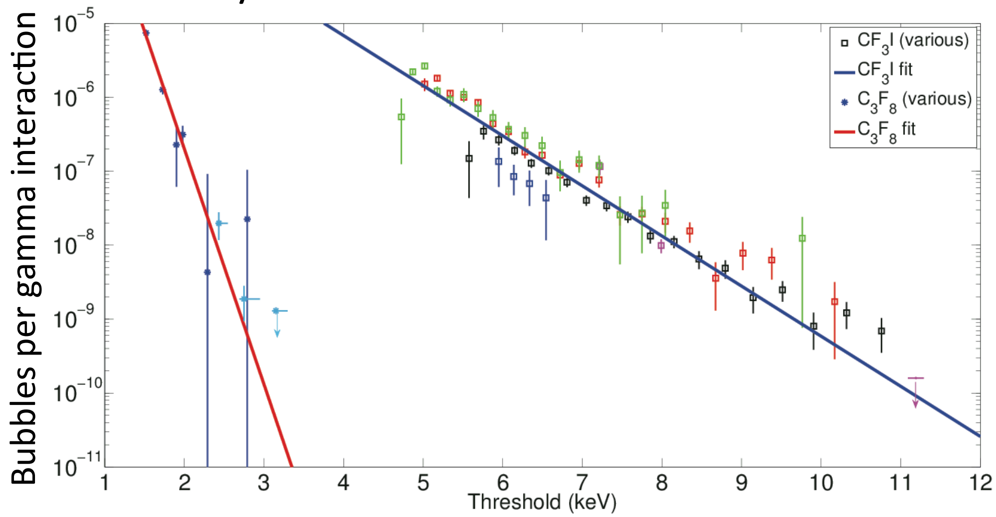
Geant4, MCNP get these resonances *wrong* (simulated as isotropic)

Fixed in:
A. Robinson
PRC 89, 032801 (2014)

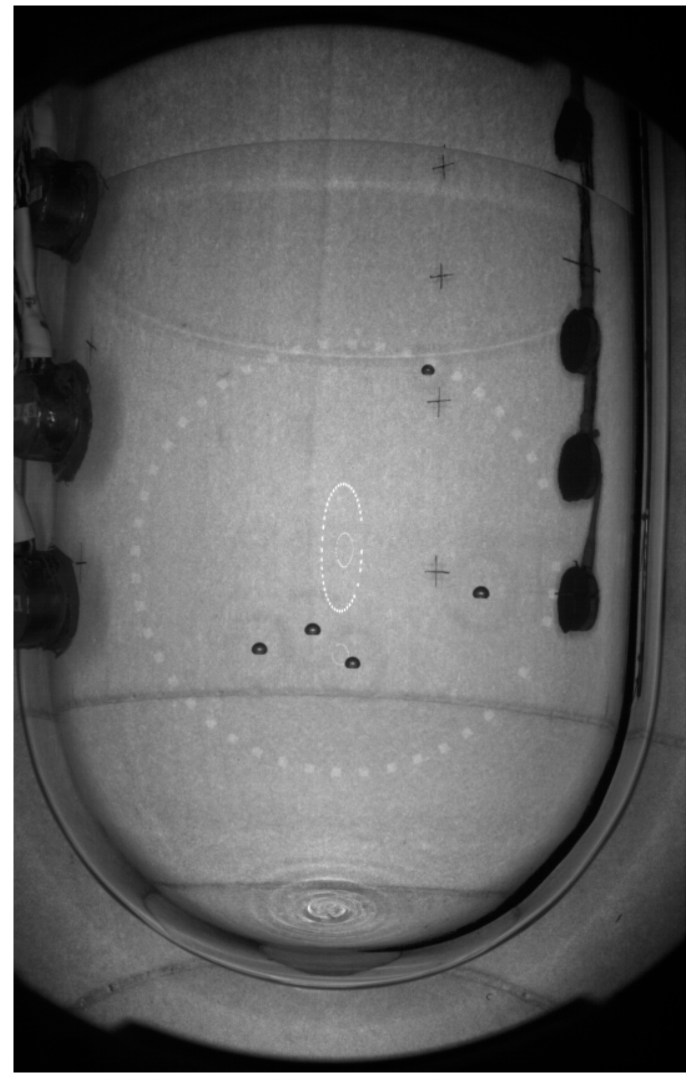


Background Rejection

Gamma/Beta

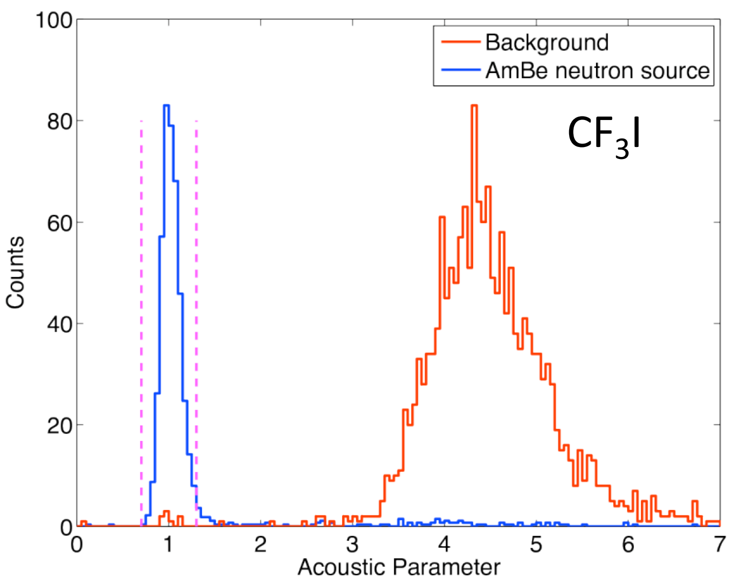


Neutron



Alpha Decay

Alpha-decay
>99.3% Rejection
(background
limited)



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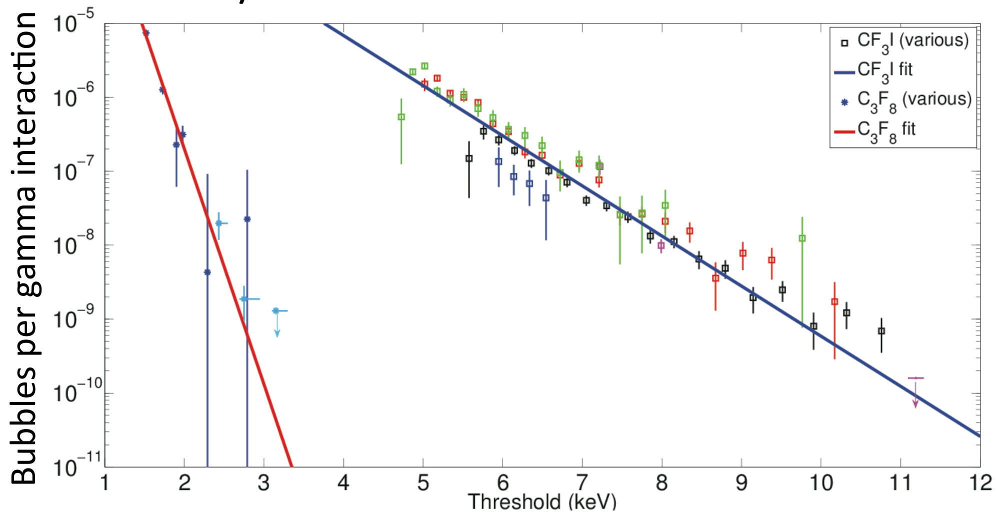
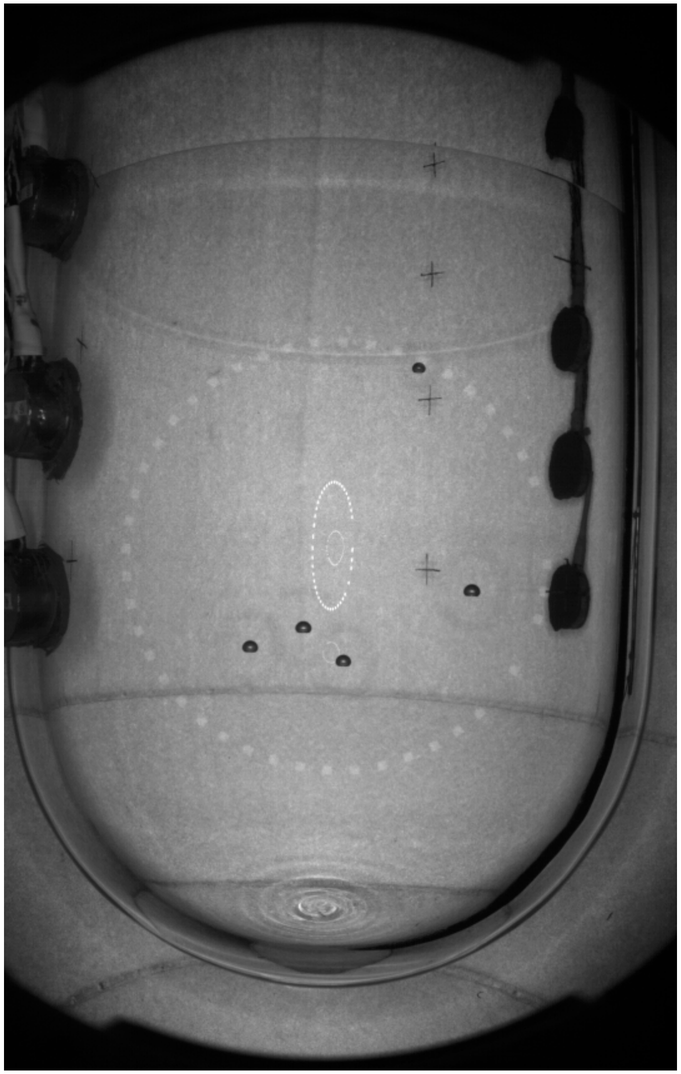
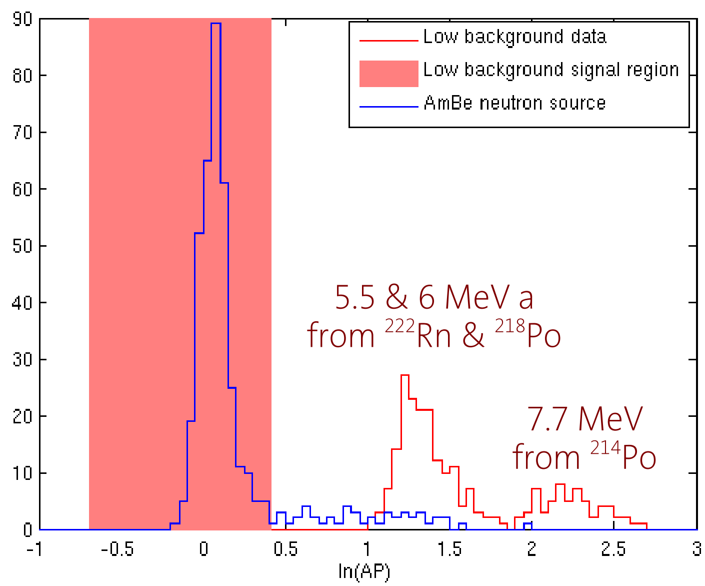


Neutron



Alpha Decay

Alpha-decay
>98.2% Rejection
(statistics
limited)



Sudbury, Ontario

6800 Feet Down

SNOLAB

COUPP-60

- SNOLAB Run 1 completed (June 2013 – May 2014)
- 35-kg CF_3I, upgradable to 80-kg
- >80% livetime (>90% by end of run)
- >4,500 kg-days exposure at 7—20 keV thresholds
- One multi-bubble event (consistent with expected neutron rate)
- Acoustic discrimination in large chamber confirmed

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- 35-kg CF_3I, upgradable to 80-kg
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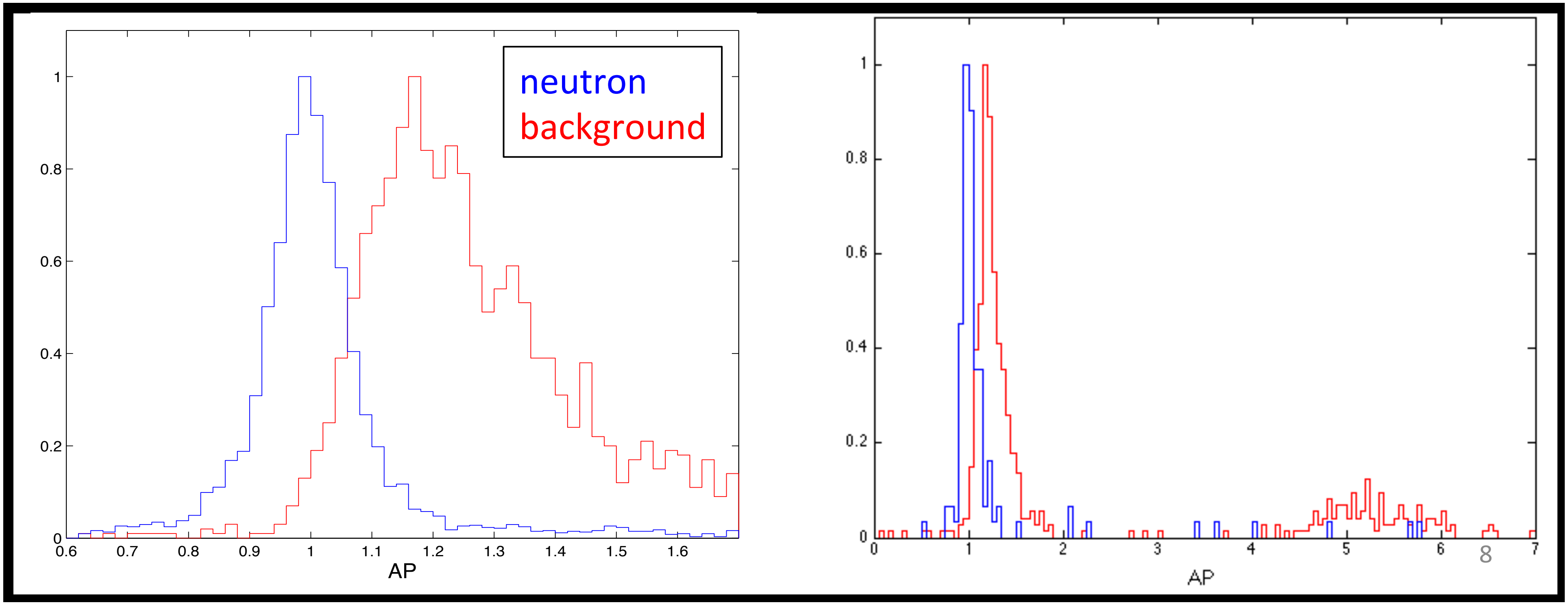
- >4,500 kg-days exposure at 7—20 keV thresholds

3,584 WIMP-like events

NOT WIMPS

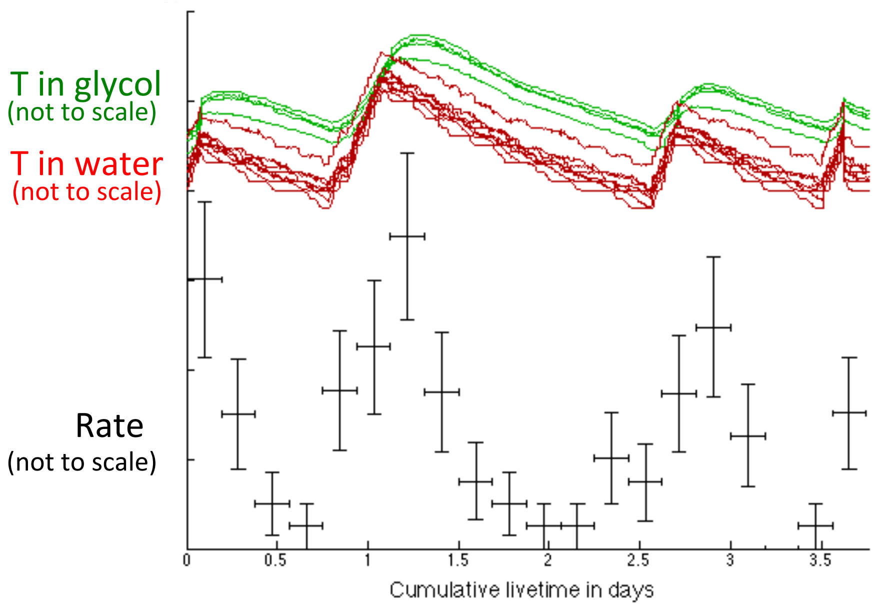
COUPP-60 Background Characteristics

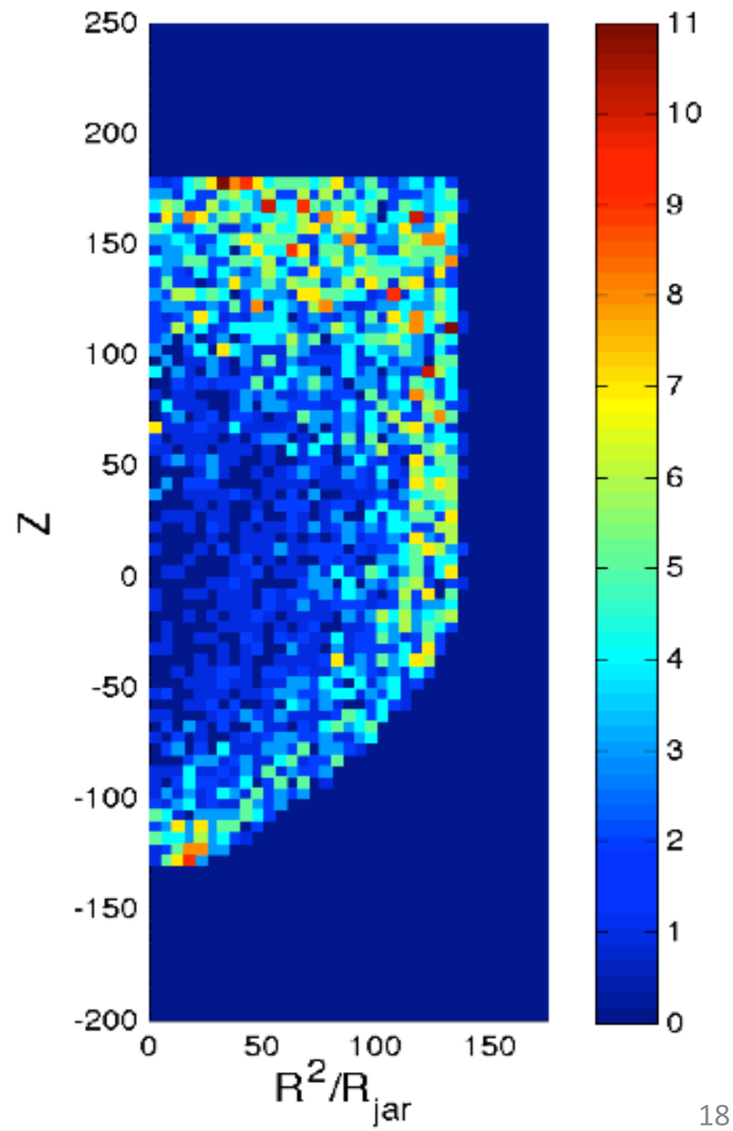
- Acoustic Distribution



COUPP-60 Background Characteristics

- Acoustic Distribution
- Spatial Distribution
- Time Correlations





PICO-2L

- Run 1 complete:
  Sept 2013 – May 2014
- 3-kg C_3F_8,
  3—8 keV thresholds
- 211.6 kg-day exposure
- No multi-bubble events

PICO-2L

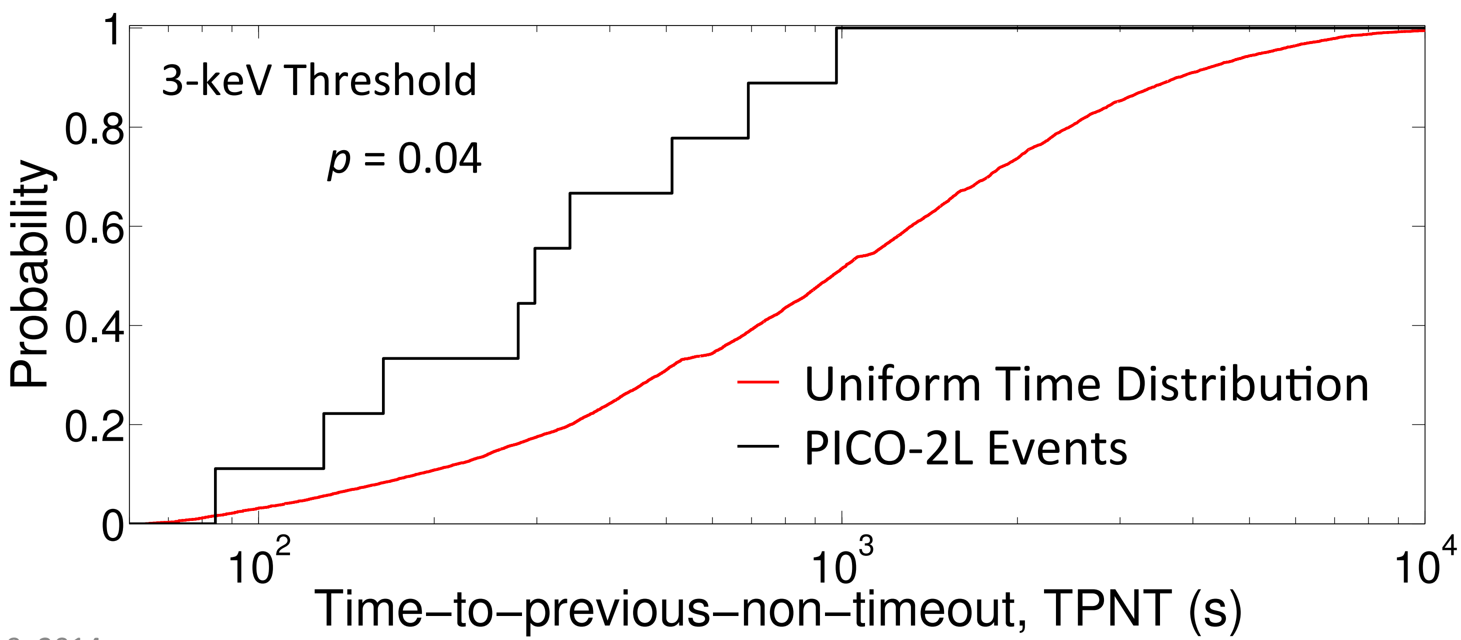
- Run 1 complete:
  Sept 2013 – May 2014

12 WIMP-like events

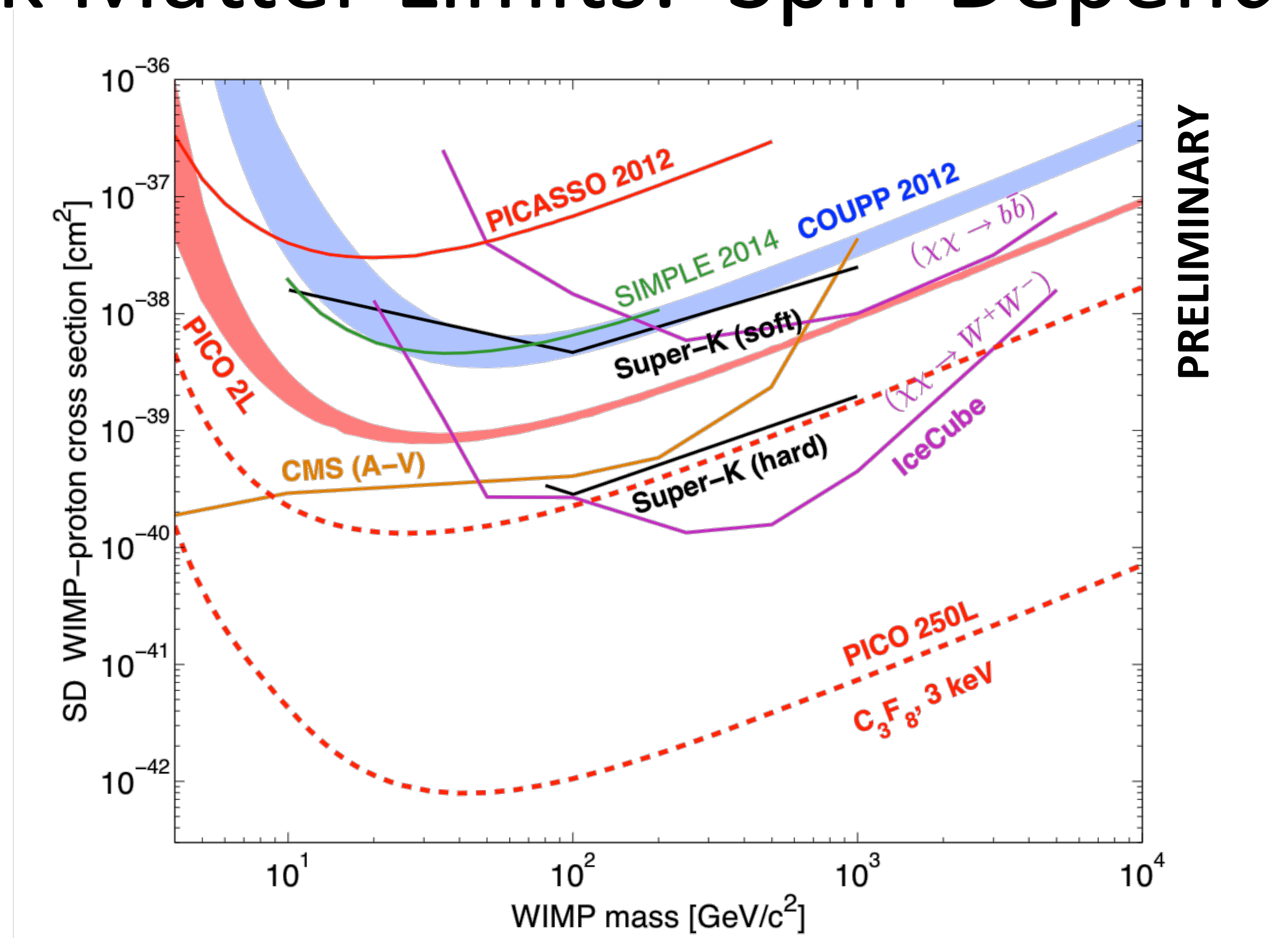
ALSO NOT WIMPS

PICO-2L WIMP candidates

- Acoustic distribution consistent with calibration data
- Time-since-previous-bubble is anomalous
  - Identified as key discriminant in 2012 COUPP-4kg result

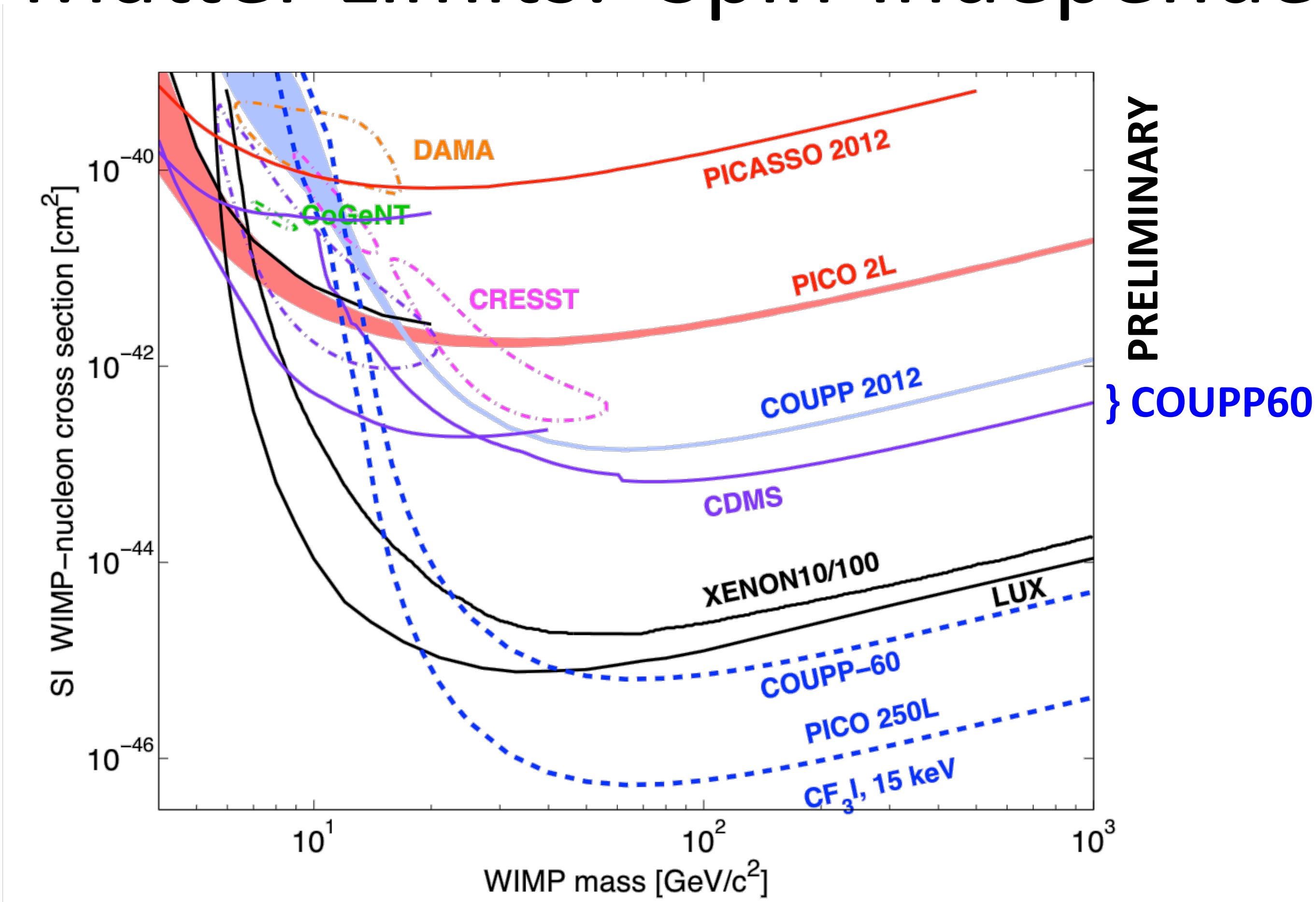


Dark Matter Limits: Spin-Dependent



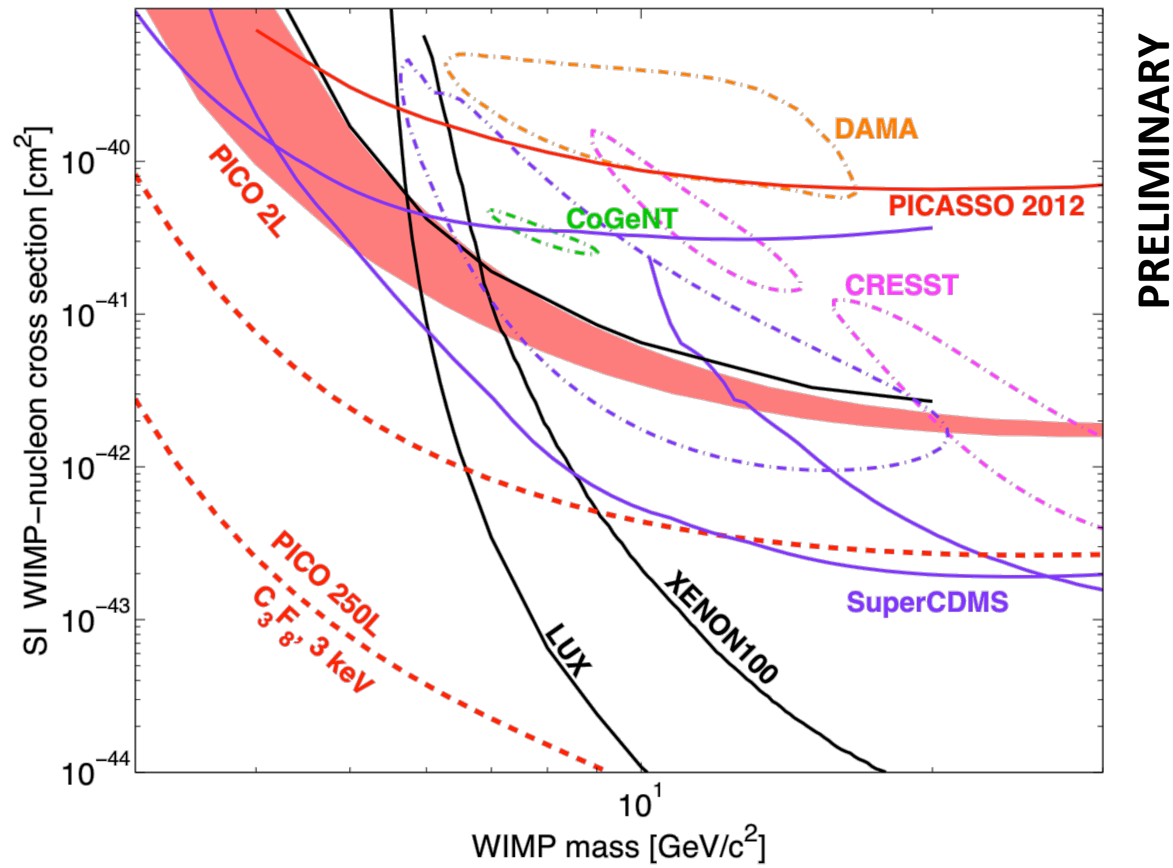
- World-leading direct-detection limit on spin-dependent WIMP-proton coupling

Dark Matter Limits: Spin-Independent



- Competitive at *low masses* in spin-dependent searches

Dark Matter Limits: Spin-Independent



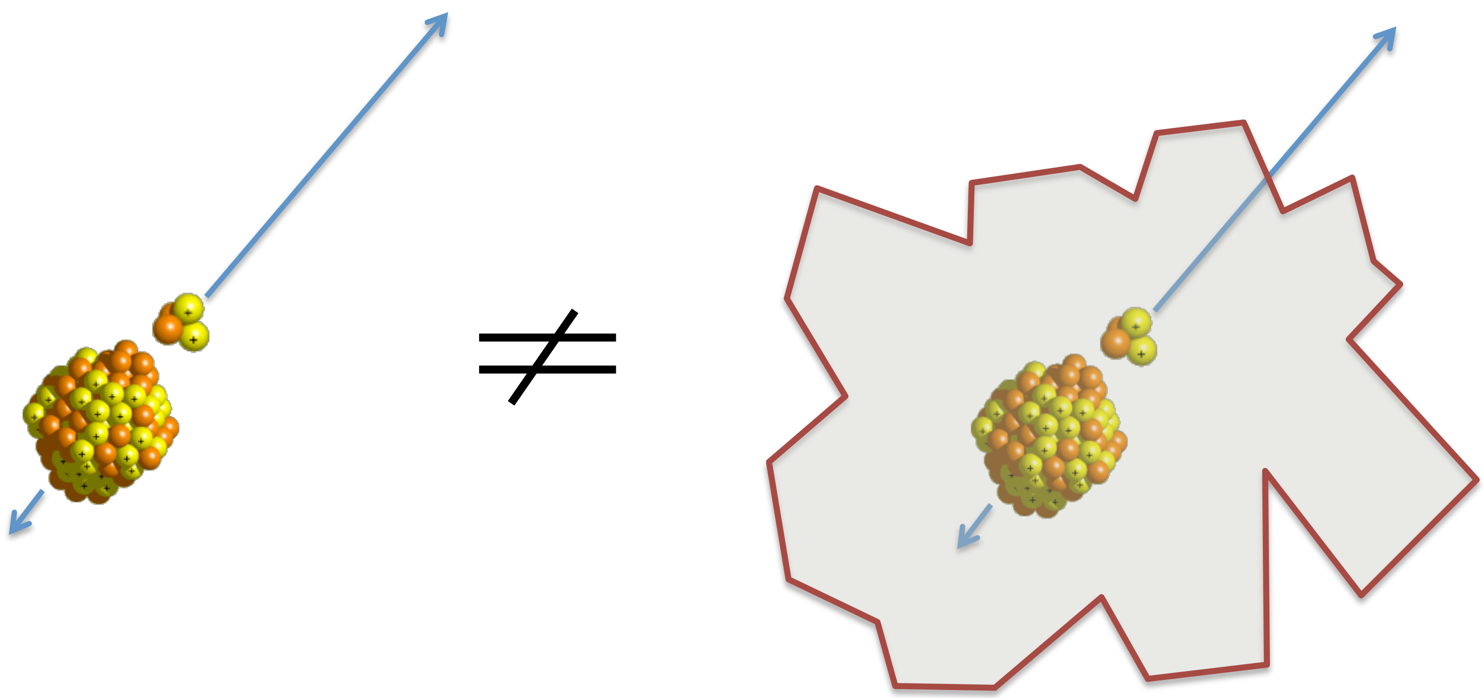
- Competitive at *low masses* in spin-dependent searches

Background Events…

- We see events which are *not* caused by:
  - WIMPs
    - Anomalous timing correlations, acoustic signature, and spatial distribution
  - Neutrons
    - No multi-bubble events
  - Electron recoils
    - In-situ Gamma calibration studies
  - Bulk Alpha-decays
    - In-situ ^{222}Rn studies
  - Chemical reactions
    - Background seen in both CF_3I and C_3F_8

Leading Background Suspect…

Alpha-decays from particulate suspended in target fluid



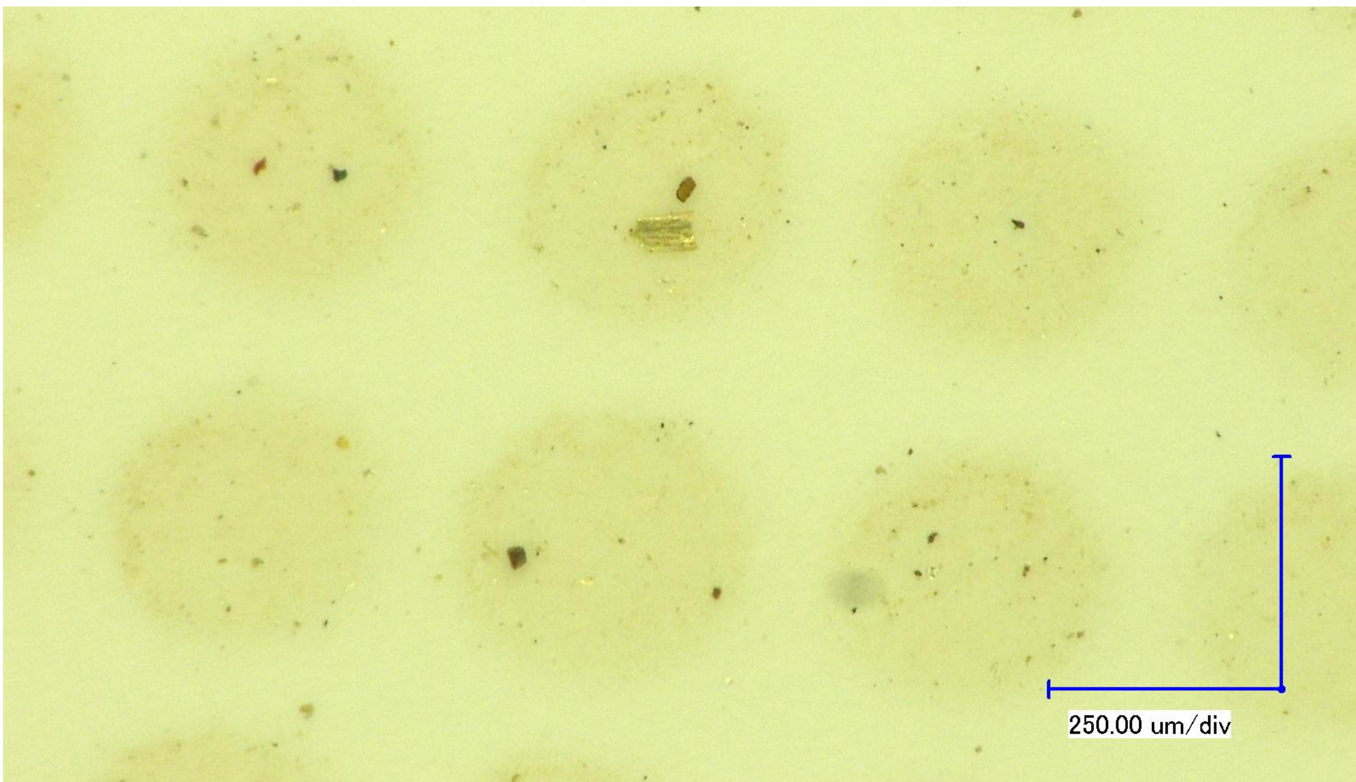
Leading Background Suspect…

Alpha-decays from particulate suspended in target fluid

- Alpha-decays in bulk see bubble nucleation by both the "cannonball" (alpha particle) and the recoiling "cannon" (*e.g.* 112-keV ^{214}Pb nucleus)
- Alpha-decays from >100nm particulate give only the cannonball
- PICASSO has seen in droplet detectors that acoustic discrimination is effective against the former, but not the latter

Particulate in the Chambers

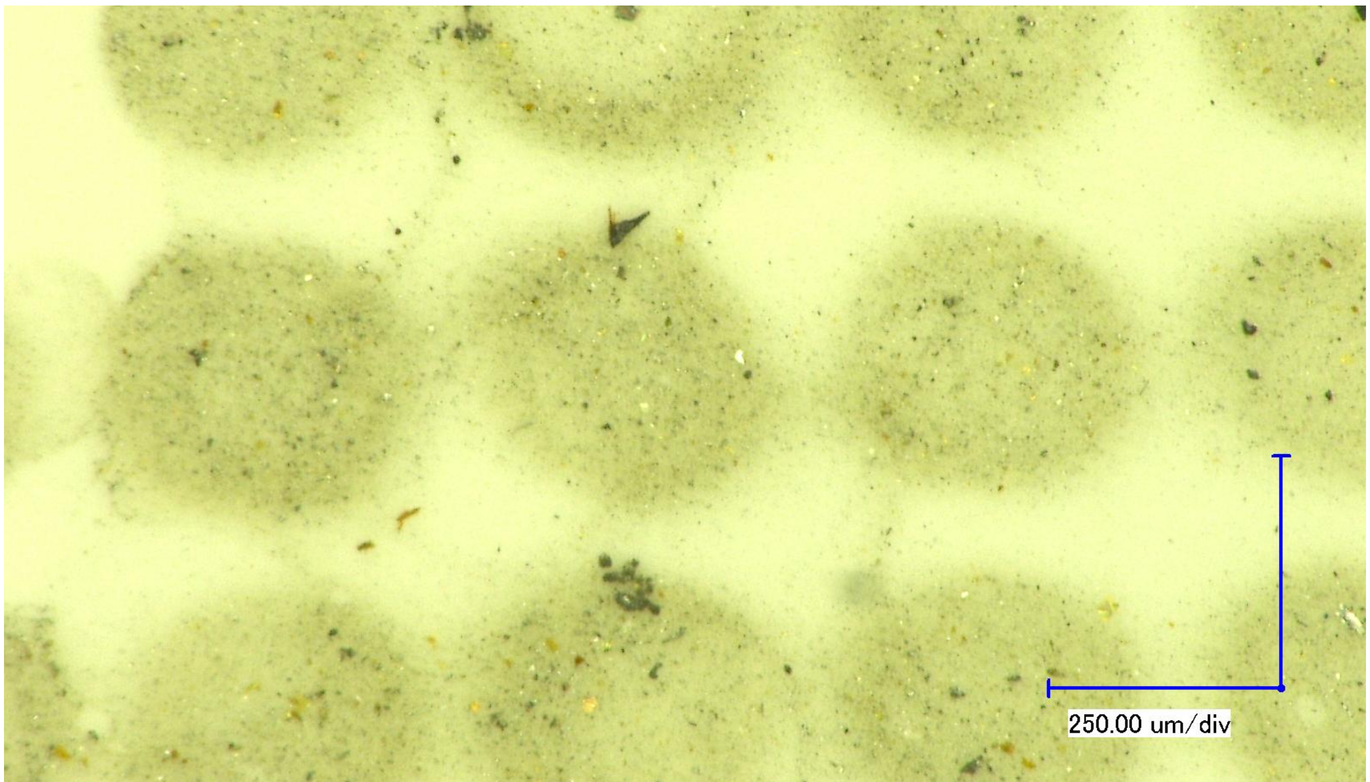
- Are there particulate in chambers?
  - Samples taken in July – answer is YES.



Filter sample from COUPP-60 buffer fluid

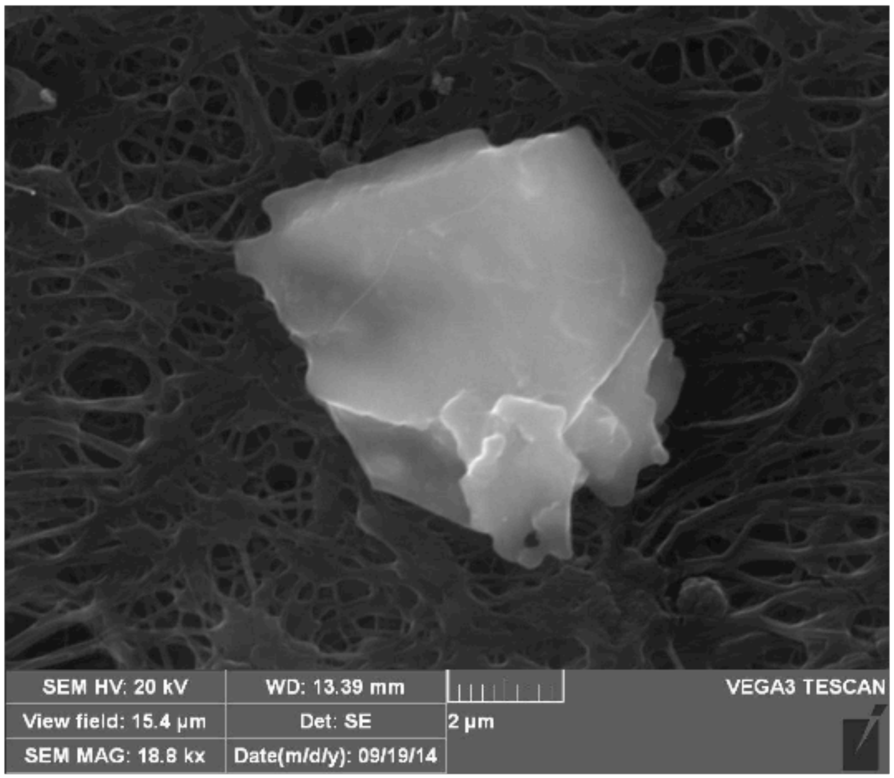
Particulate in the Chambers

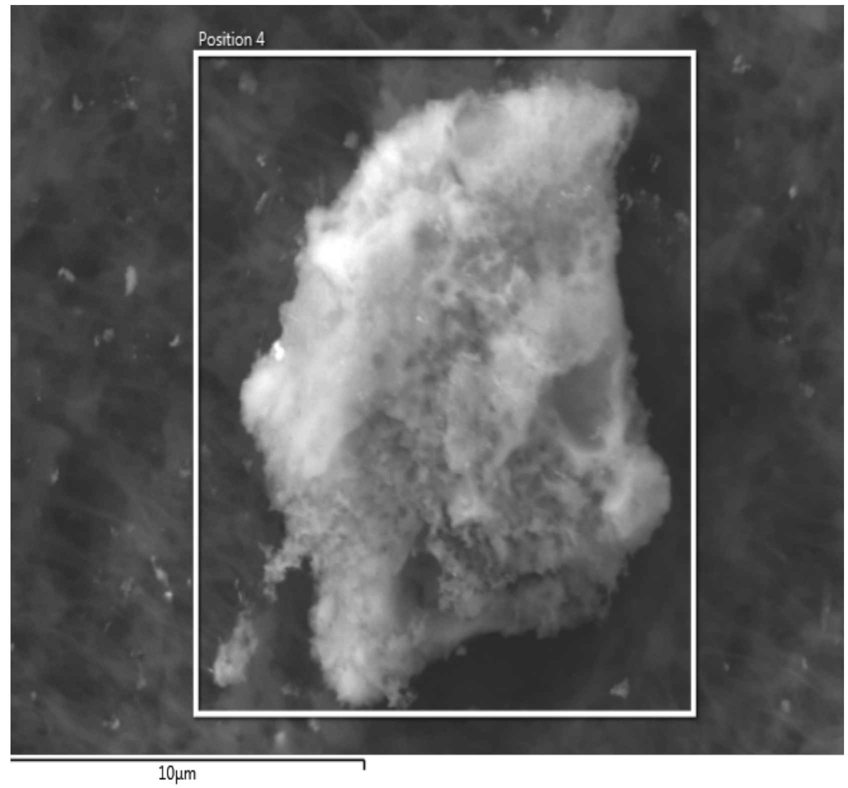
- What are these particulate? Where do they come from? Are they radioactive?



Filter sample from PICO-2L ultrasonic wash

Particulate in the Chambers





Quartz – $O(1)$ ppb ^{238}U if from walls
$O(100)$ ppb ^{238}U if from jar flange

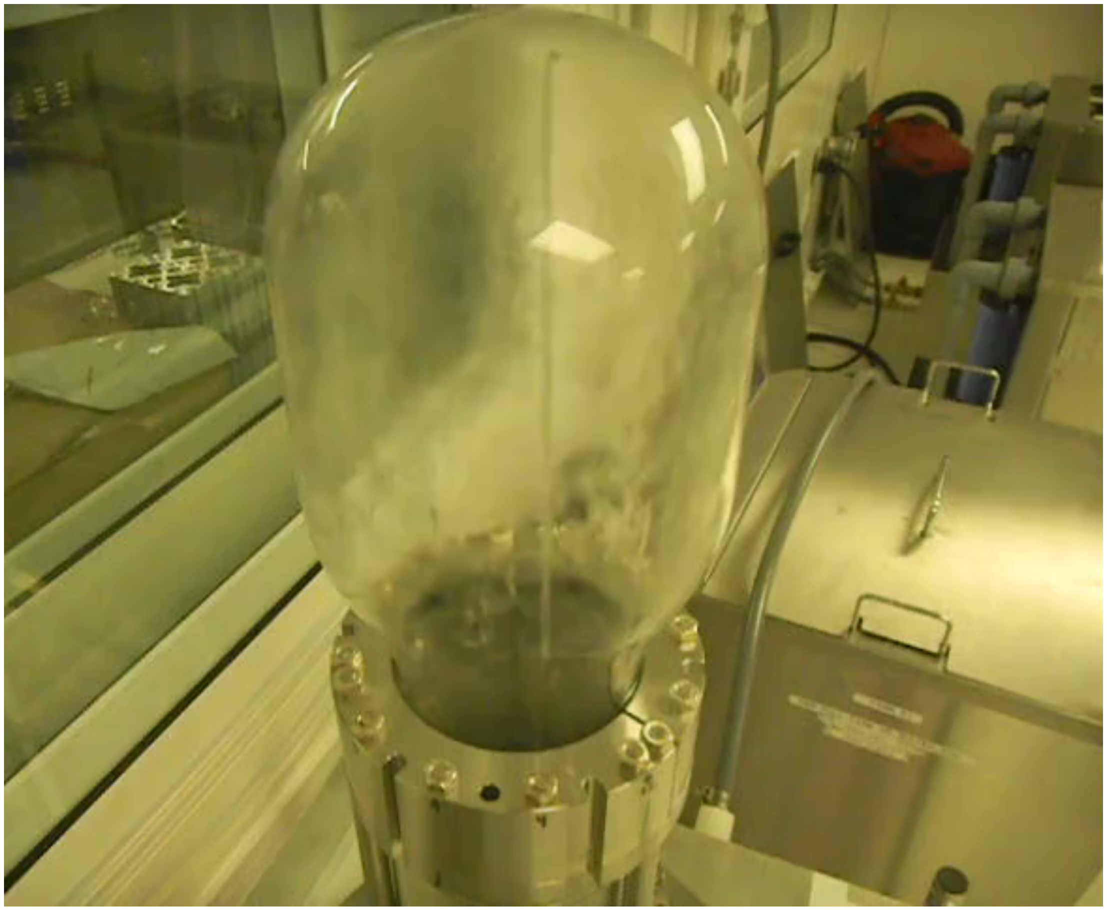
Oxidized Stainless Steel –
$O(1)$ ppb ^{238}U from most inner surfaces (maybe not welds…)

Natural Quartz the culprit?

- It would take ~100mg of flange material to generate COUPP-60 background
- ~100μg recovered on filters, without aggressive cleaning (no ultrasonic)
- Stresses at jar seal may generate particulate

- Easy fix: Use synthetic fused silica (jar wall material) for flange!

PICO-2L Run 2



- New jar with synthetic fused silica flange
- Inner vessel assembled, going to SNOLAB next month
- Will test if quartz flange is *dominant* source of background events

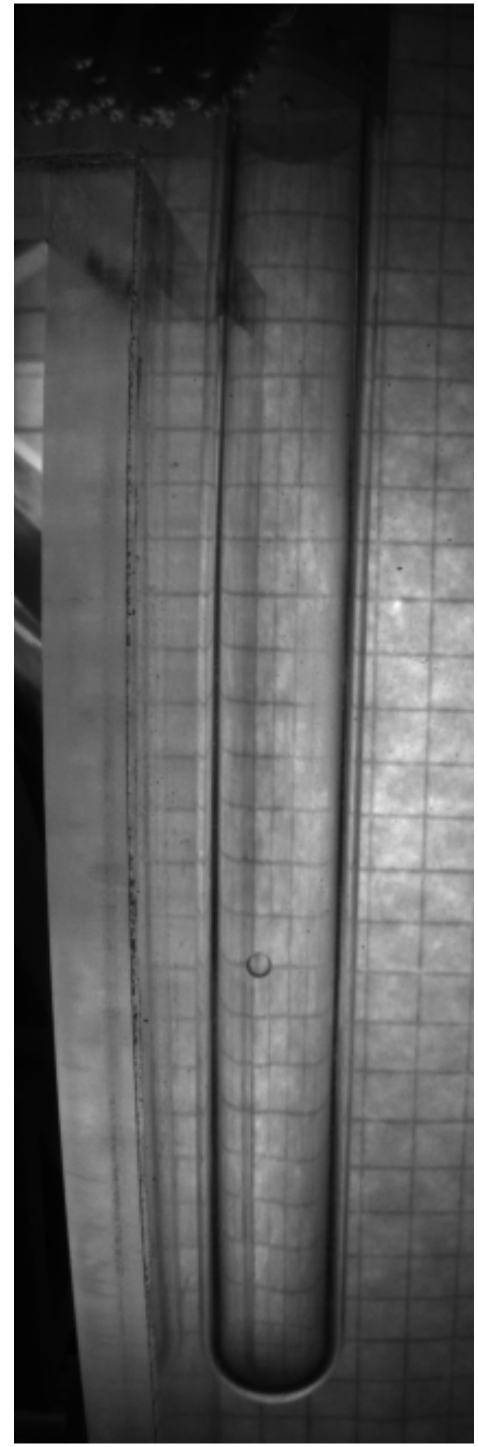
COUPP-60 Run 2

- Installing target- and buffer-fluid recirculation system in COUPP-60 in early 2015
  - Addresses all (radioactive and non-radioactive) particulate background sources

- Starting procurement of new COUPP-60 vessel with synthetic fused silica flange – installation late 2015

Background Studies

- Can we reproduce these backgrounds?
  - Tests underway in 10-ml chamber at Northwestern University
    - Fast (2-day) turnaround to study variety of particulate samples
  - 2nd 10-ml chamber being assembled at Queen's
  - Testing alpha-emitting vs radioclean particulate, pending further guidance from PNNL assays

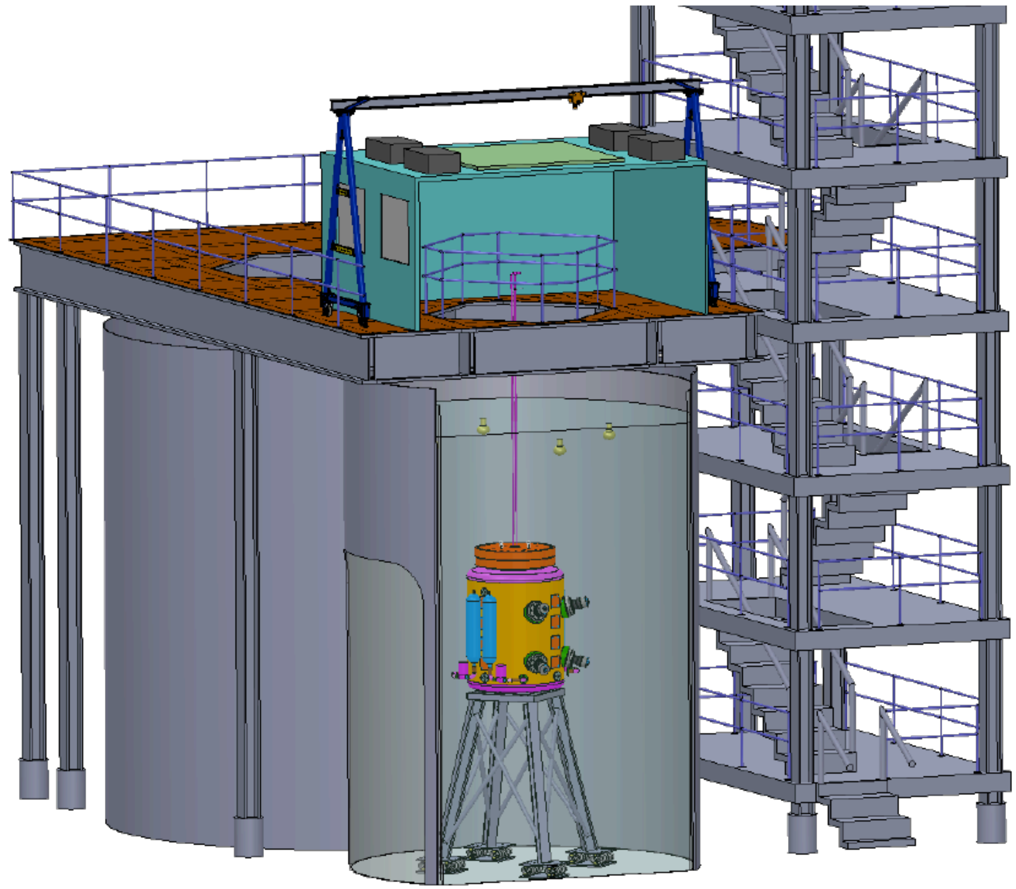


A few "bright" ideas

- Optical (laser) fluid interrogation
  - Measure bulk particulate density?
  - Targeted interrogation after events?
- Scintillating Target Fluid
  - Works like normal PICO chamber, but with PMTs
    - Easiest with liquid xenon
  - Instant leverage against
    - Alpha-decays (in or out of particulate)
    - Non-radioactivity-induced backgrounds (chemistry, non-radioactive particulate, …
  - More information *always* key to fighting pathological backgrounds

The future

- PICO-250L engineering underway
- Only direct-detection proposal with spin-dependent proton sensitivity
- Multiple targets key to understanding future signal



Summary

- PICO-2L has produced world-best SD WIMP-proton limit from direct detection
- Currently background limited
- *Testable* hypothesis for background source
- Future still bright (or even scintillating!)