Dark Matter Detection With Superheated Liquids: COUPP and PICO

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Fermilab

2014 Mitchell Workshop
Texas A&M
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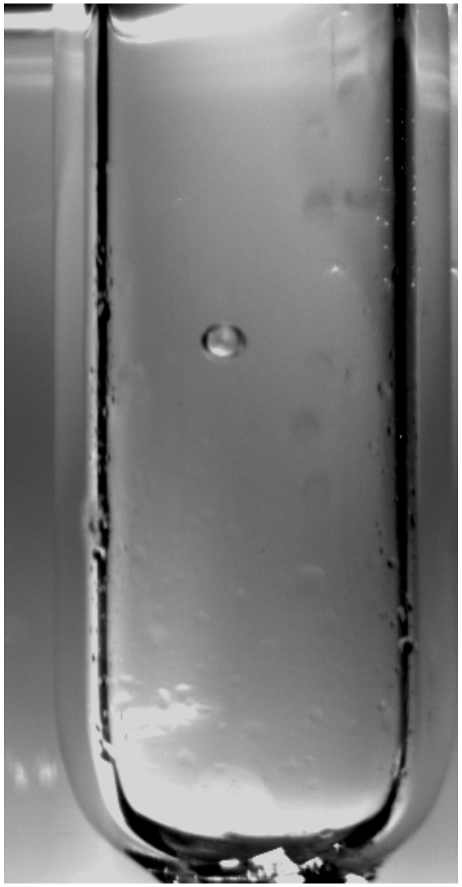


WIMP Dark Matter Detector Wish List

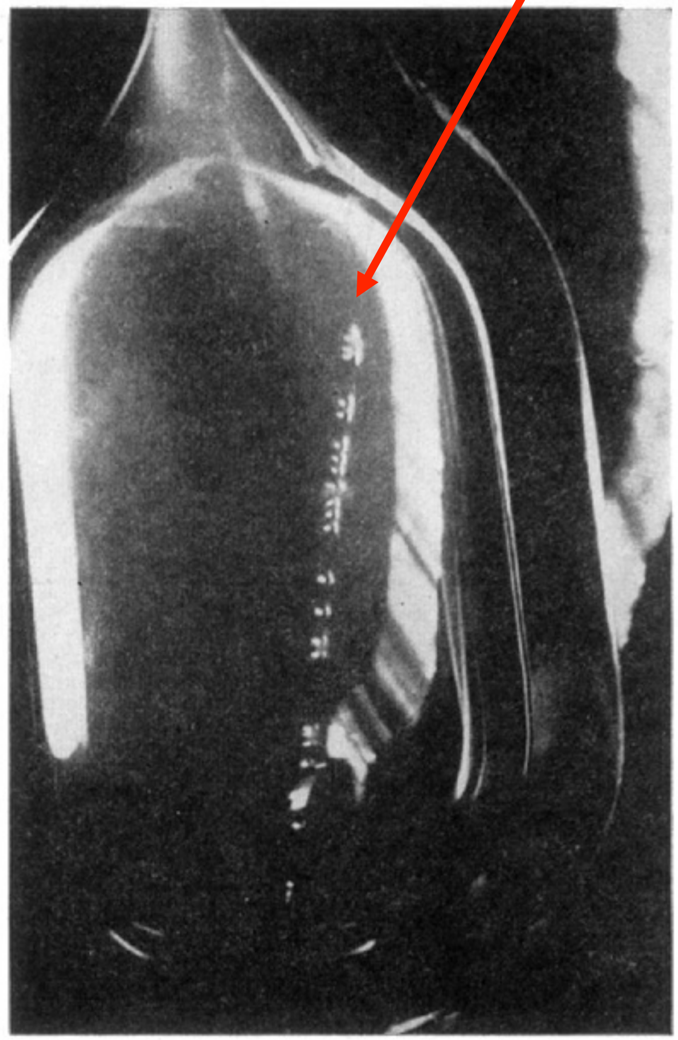
- Large target mass (>1 ton for next generation)
- Low energy threshold. (~ 10 keV for standard WIMPs, ~ 2 keV for current light WIMP models)
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin.
- Zero backgrounds from environmental radioactivity.
- Measure nuclear recoil energies.
- Measure nuclear recoil direction.

BUBBLE CHAMBERS t

- Large target mass (>1 ton for next generation) ✔
- Low energy threshold. (~ 10 keV for standard WIMPs, ~ 2 keV for current light WIMP models) ✔
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin. ✔
- Zero backgrounds from environmental radioactivity.TBD.
- Measure nuclear recoil energies. By varying threshold
- Measure nuclear recoil direction. No

First Bubble Chamber (Glaser, 1952)

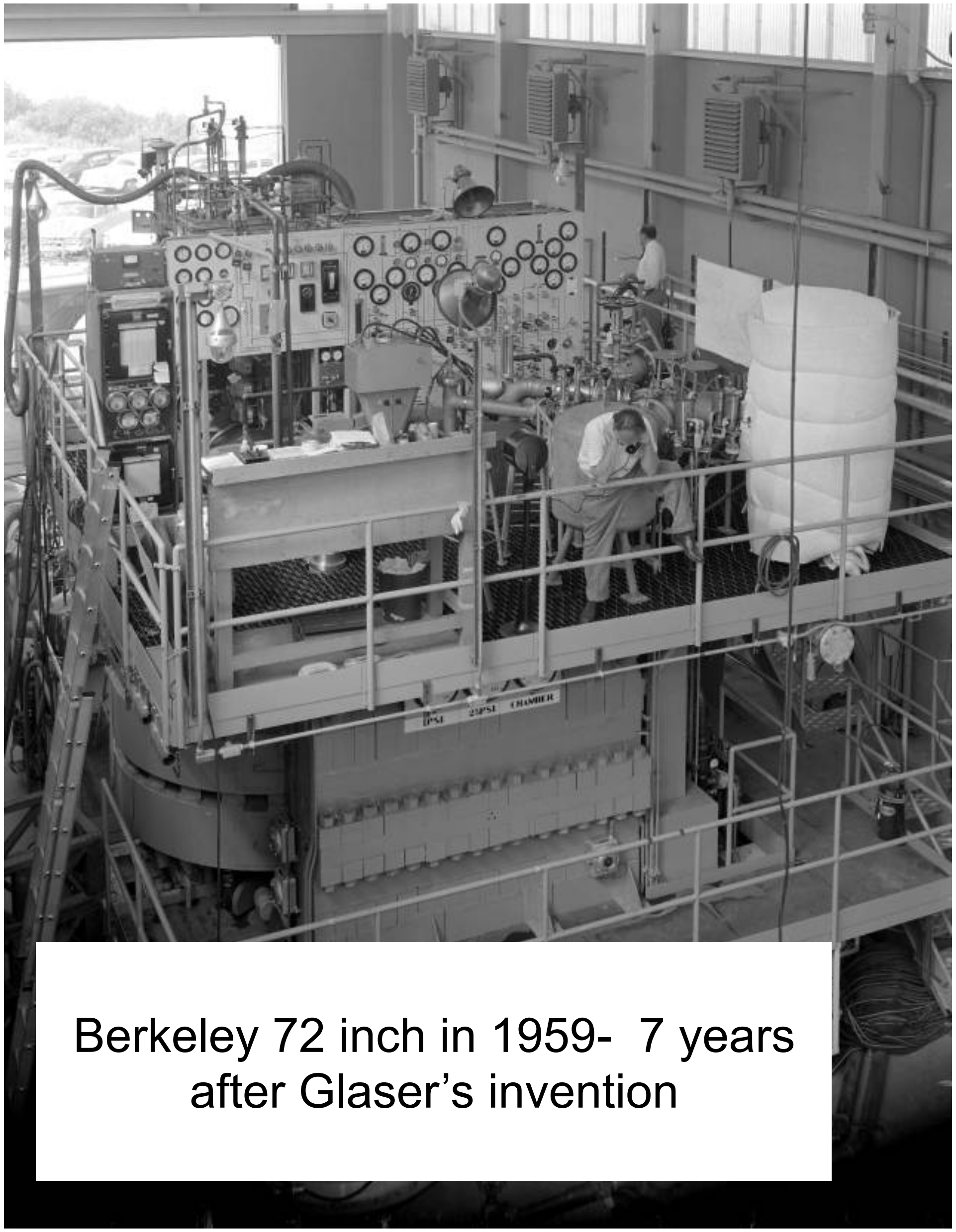
Cosmic ray



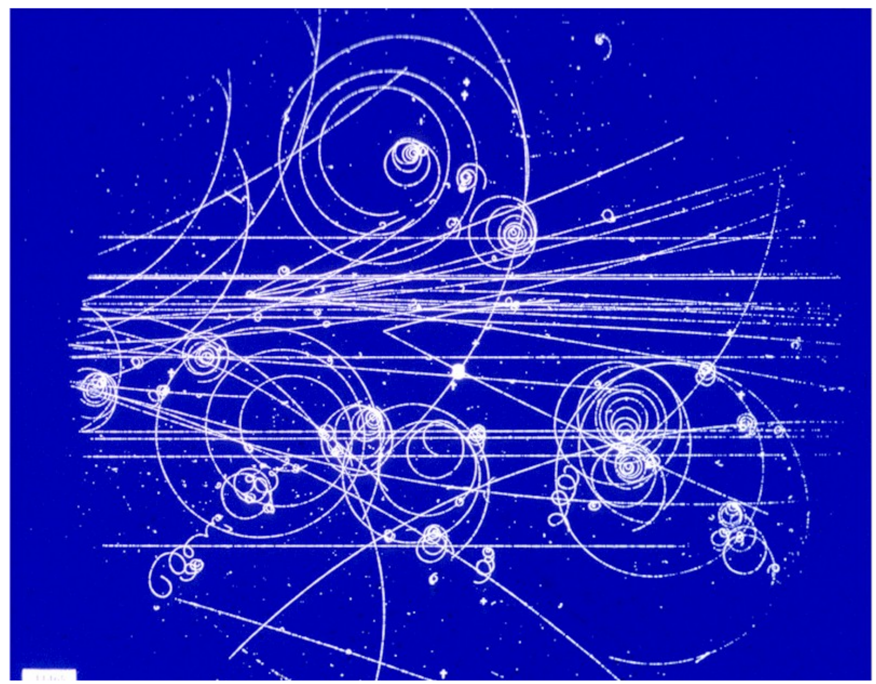
1-cm diameter glass tube, filled with ether

The Bubble Chamber Age: 1952-1987

- Rapid growth in size and sophistication driven by national accelerator labs.
- Precision tracking capability over large volumes at low cost.
- Unfortunately bubble growth process too slow to keep up with interaction rates in modern experiments.



Berkeley 72 inch in 1959- 7 years after Glaser’s invention



New Role: Lawn Ornaments (1987- present)


CERN


SLAC

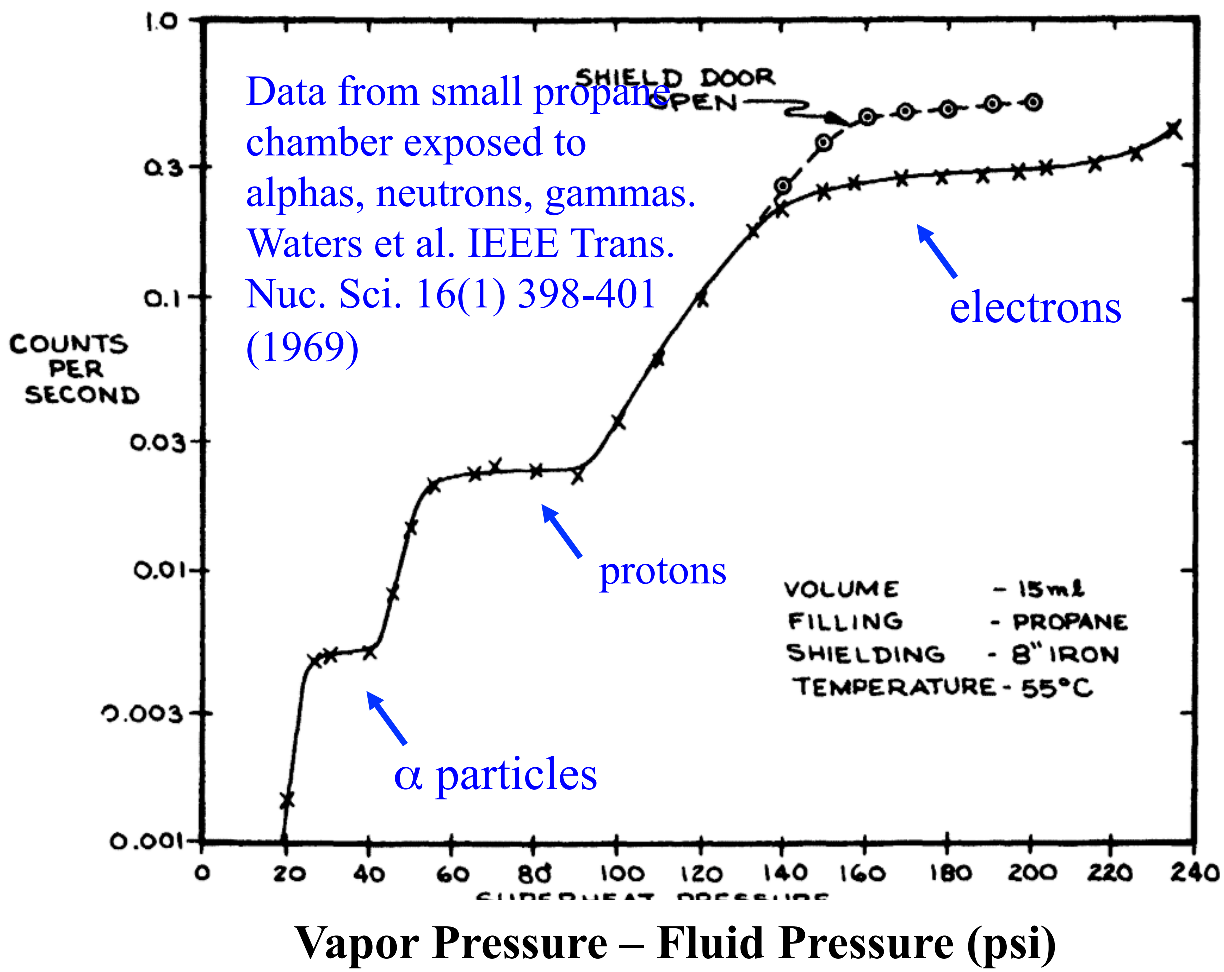

Argonne


Fermilab

Bubble Chambers: What Can They Still Do for us?

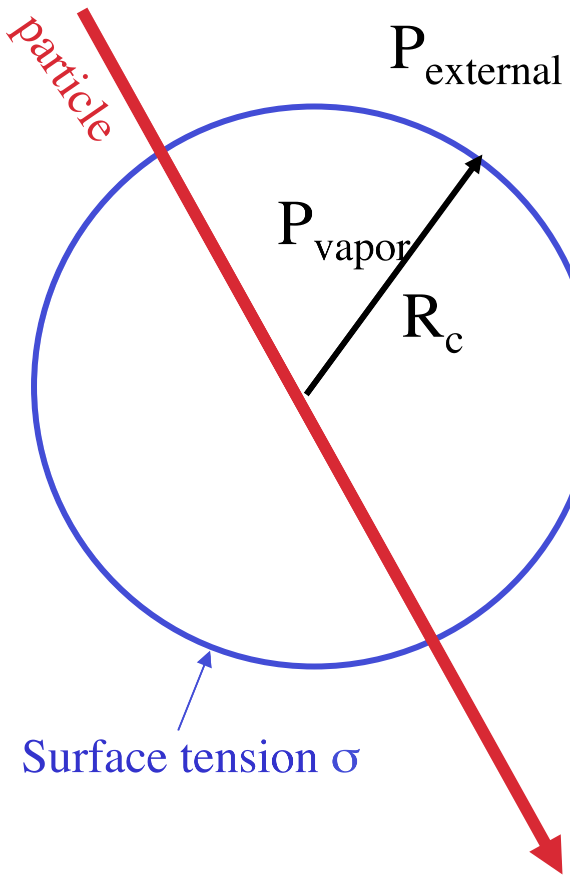
- As tracking devices for high energy particles, bubble chambers are finished.
  - Surpassed first by gaseous devices (faster), then silicon (higher precision).
  - Neutrino experiments requiring large target mass were final frontier for bubble chambers, but liquid argon TPCs are now favored.

- However there is a lesser known history of bubble chamber experiments where tracking was not the goal. Instead, these exploit selective sensitivity to different particle types based on manipulation of thermodynamic conditions for bubble formation.



Bubble Nucleation by Radiation

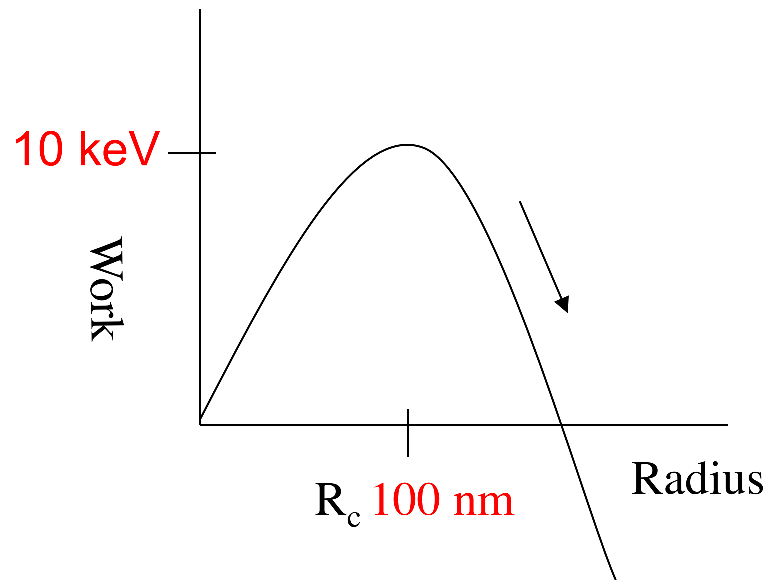
(Seitz, "Thermal Spike Model", 1957)



- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius R_c surface tension balances pressure.

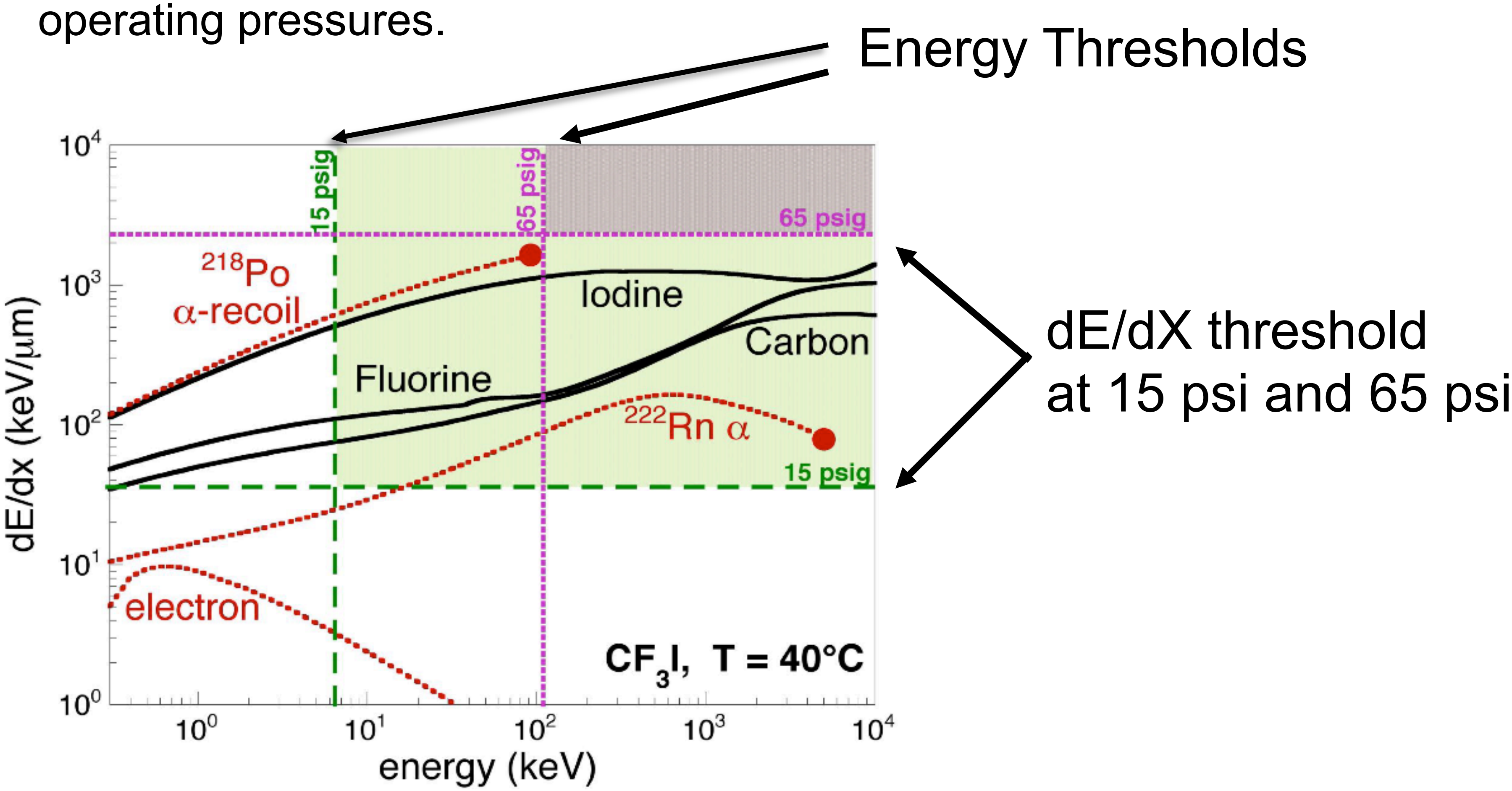
$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

- Bubbles bigger than the critical radius R_c will grow, while smaller bubbles will shrink to zero.
- Boiling occurs when energy loss of throughgoing particle is enough to produce a bubble with radius > R_c



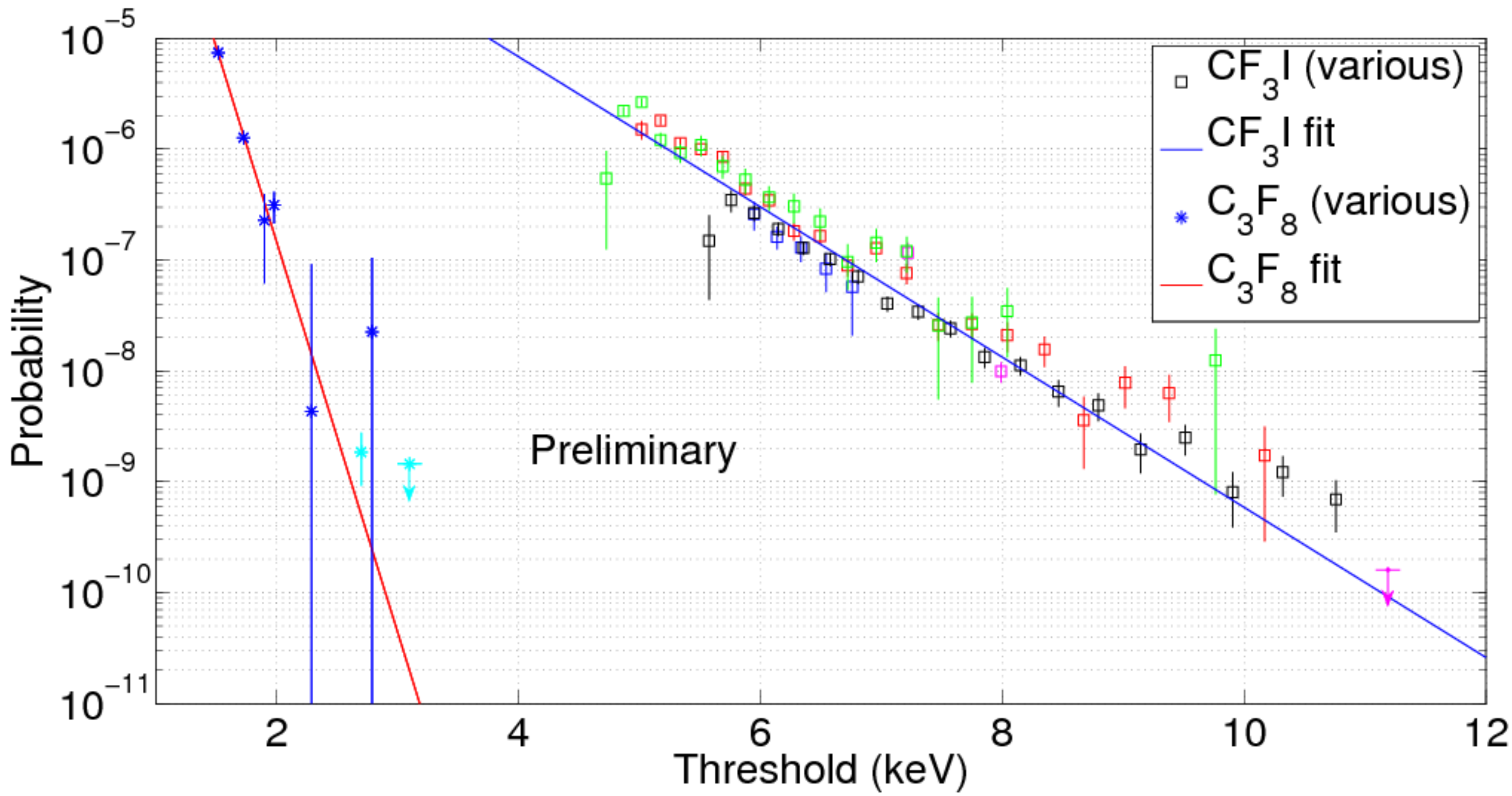
Tuning the dE/dX Threshold for Bubble Nucleation

- The bubble chamber operator chooses a pressure and temperature, fixing the minimum size of bubbles that are allowed to grow against surface tension.
- This simultaneously determines minimum deposited energy and energy loss density (dE/dX) that will nucleate bubbles.
- Example below: superheated CF_3I at fixed temperature, two operating pressures.



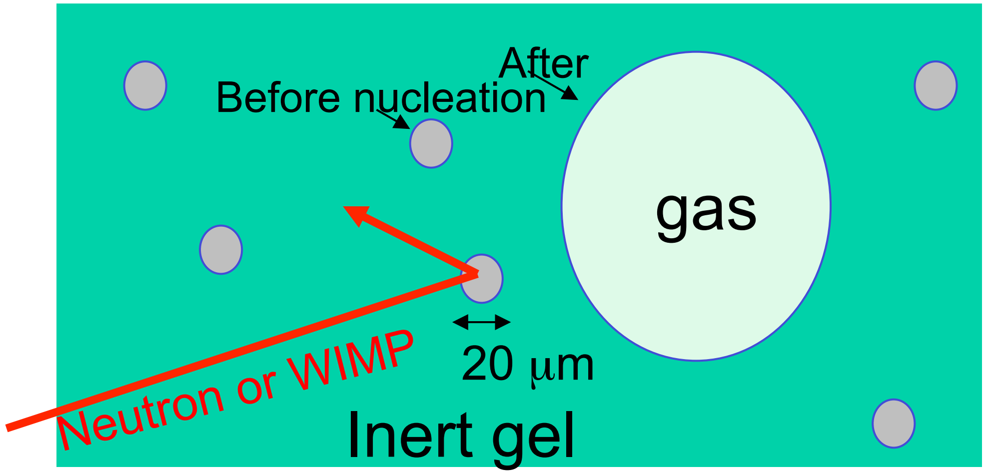
Electron recoil rejection

Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I

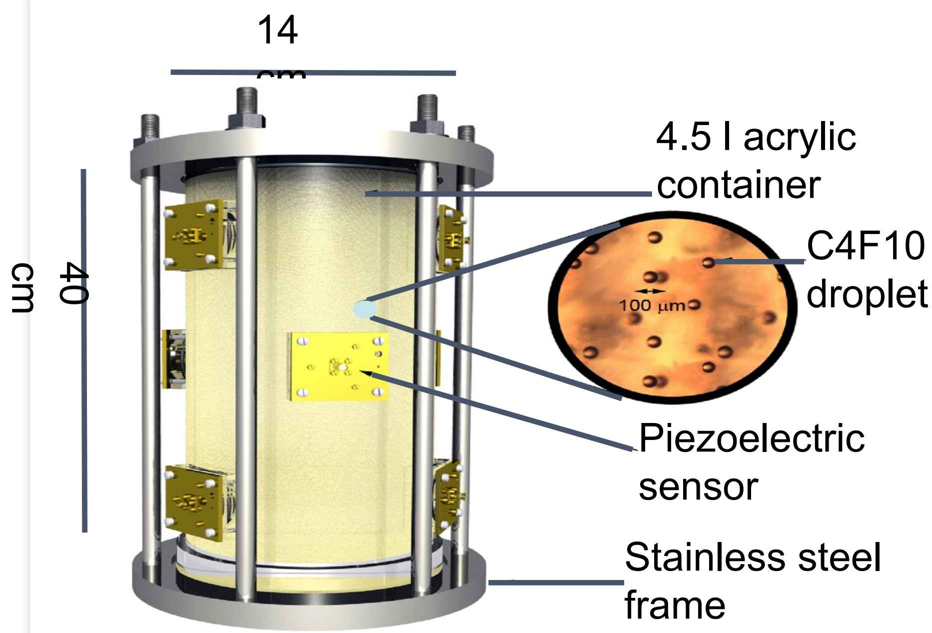


Superheated Droplet Detectors

- Droplets of superheated freon suspended in inert gel.
- Individual droplets can vaporize without affecting neighbors.
- Respond to nuclear recoils from neutrons (or WIMPs) with no gamma sensitivity.
- Dark matter searches: PICASSO and SIMPLE.



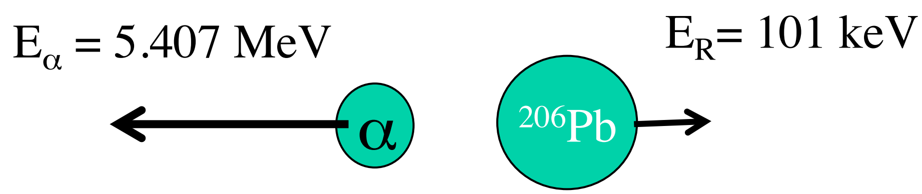
Industrial neutron detector (Bubble Technologies Inc.)



PICASSO

Alpha Particle Backgrounds

- Alpha decay produces monoenergetic, low energy nuclear recoils. Example $^{210}Po \rightarrow ^{206}Pb$:

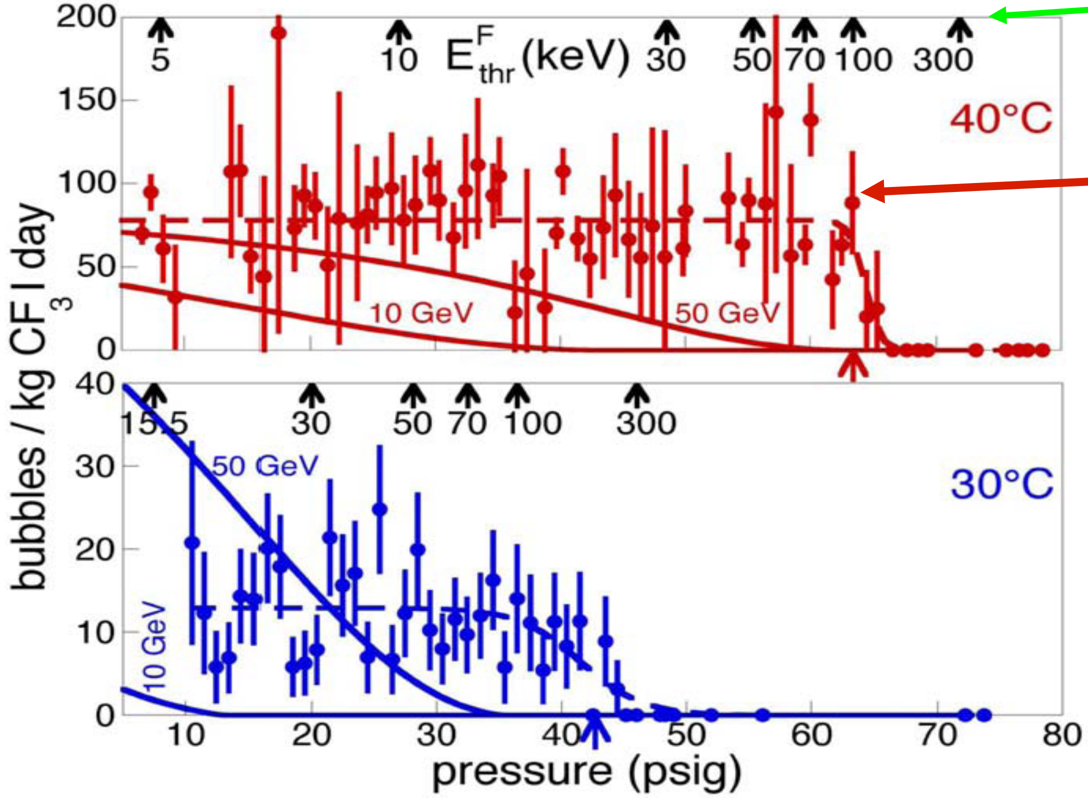


- The recoiling nucleus will nucleate a bubble in any chamber that is sensitive to the lower energy (~10 keV) recoils expected from WIMP scattering.

- The ^{238}U and ^{232}Th decay series include many alpha emitters, including radon (^{222}Rn) and its daughters, which are ubiquitous in the environment.

Data from 2006 Run- 2 kg COUPP Bubble Chamber

- High alpha background rate from radon dissolved in target fluid.
- Used pressure scanning to separate WIMPs/ Alphas on basis of energy spectrum.



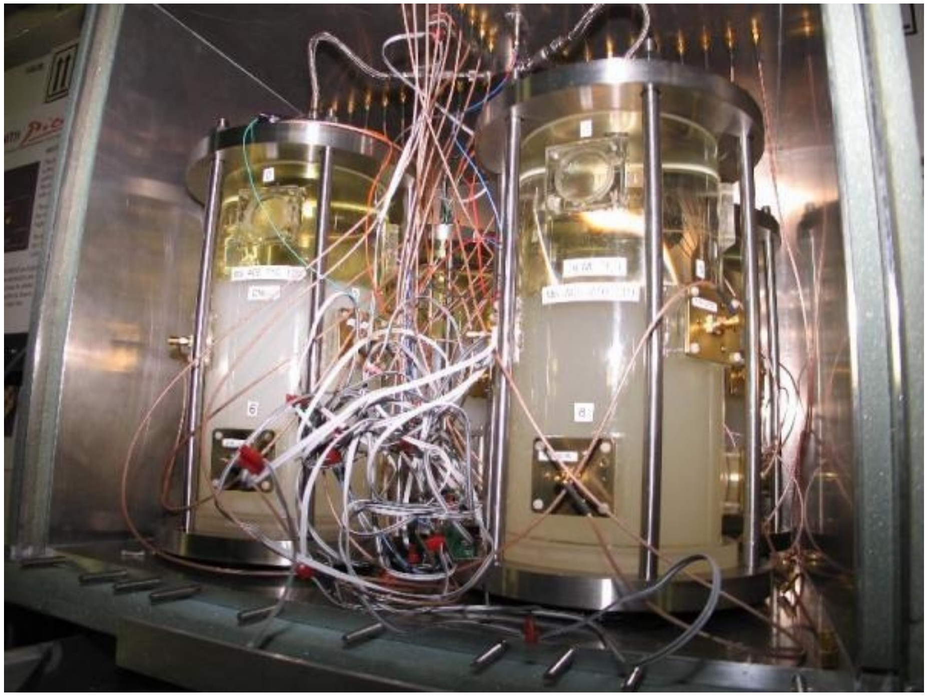
Energy Threshold In KeV

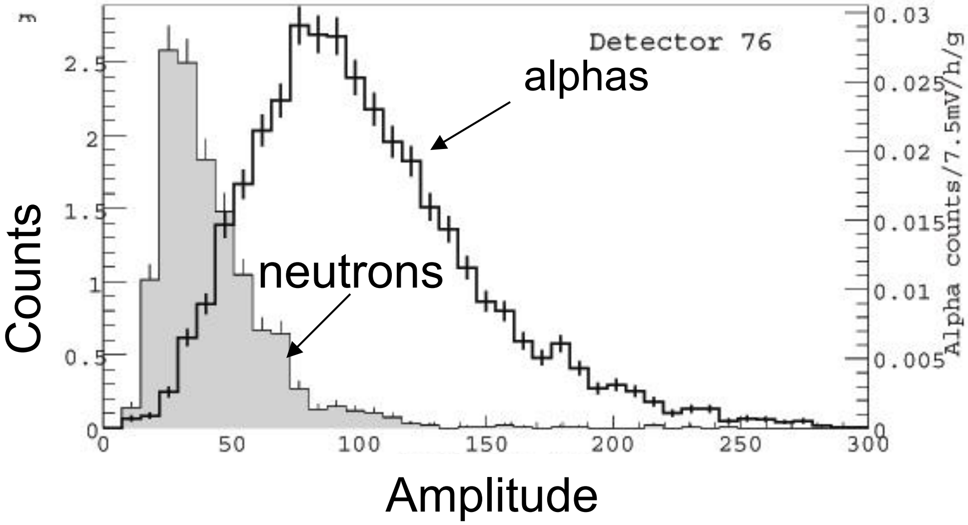
Radon background

Solid lines: Expected WIMP response for $\sigma^{SD(p)}$=3 pb

PIASSO Discovery of Alpha Discrimination Using Sound Waves (2008)

- First seen in superheated emulsion detectors operated by the Picasso collaboration: small droplets (~10 micron) of superheated liquids suspended in a viscous gel.
- Larger amplitude acoustic signals reported for bubbles nucleated by alpha particles compared to nuclear recoils.
- Distributions overlap at the ~10% level.

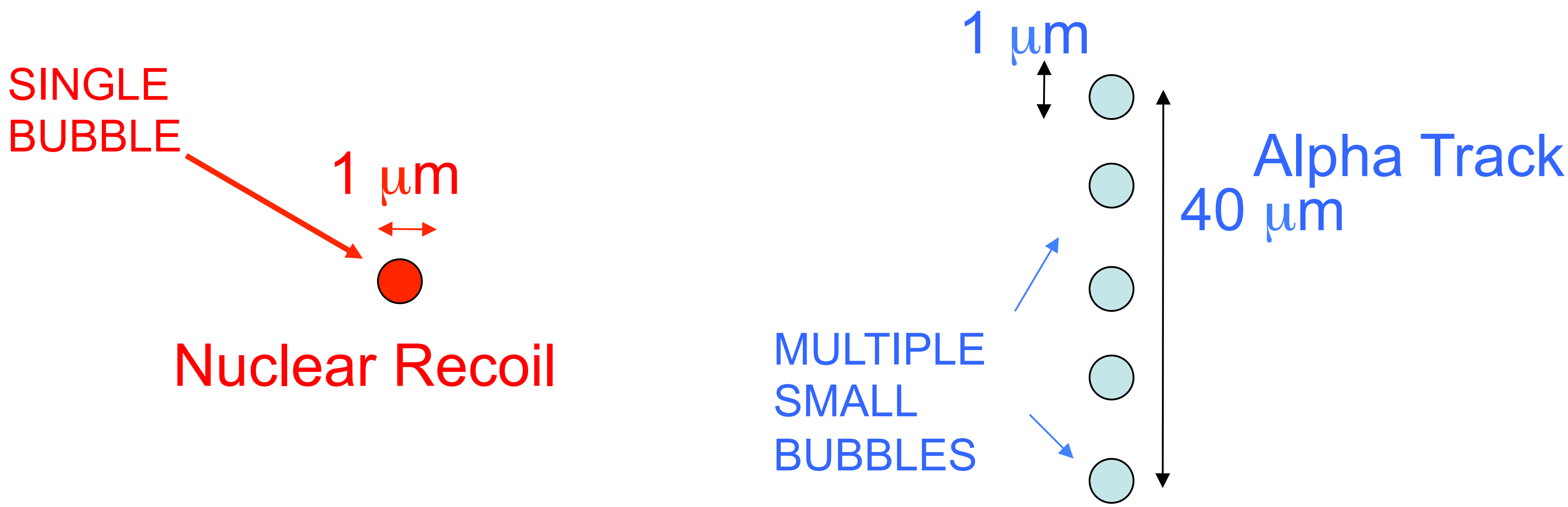




New Journal of Physics arXiv:0807.1536

Discrimination Between Alpha Decay Bubbles and Nuclear Recoils?

Imagine that we could photograph the bubble track with micron resolution a few microseconds after nucleation occurs, while bubbles are still just ~ 1 micron in diameter.



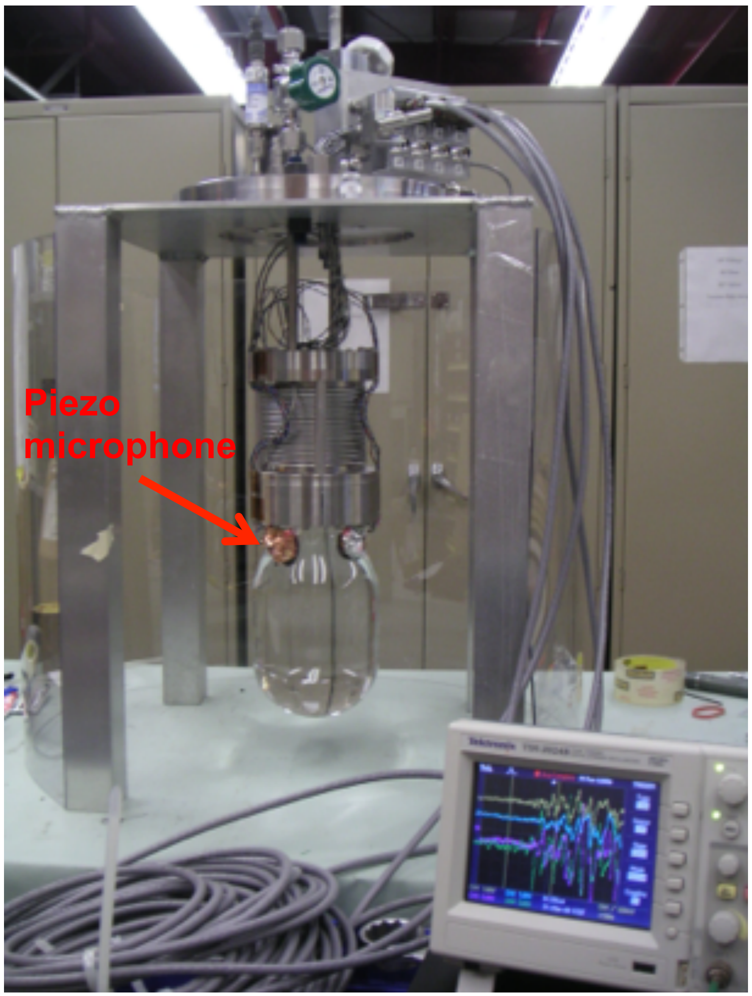
Video imaging of events on these time and distance scales impossible over the large required field of view: e.g. ~ 1 m^3 of volume with ~1 micron resolution at a video rate of ~1 MHz.

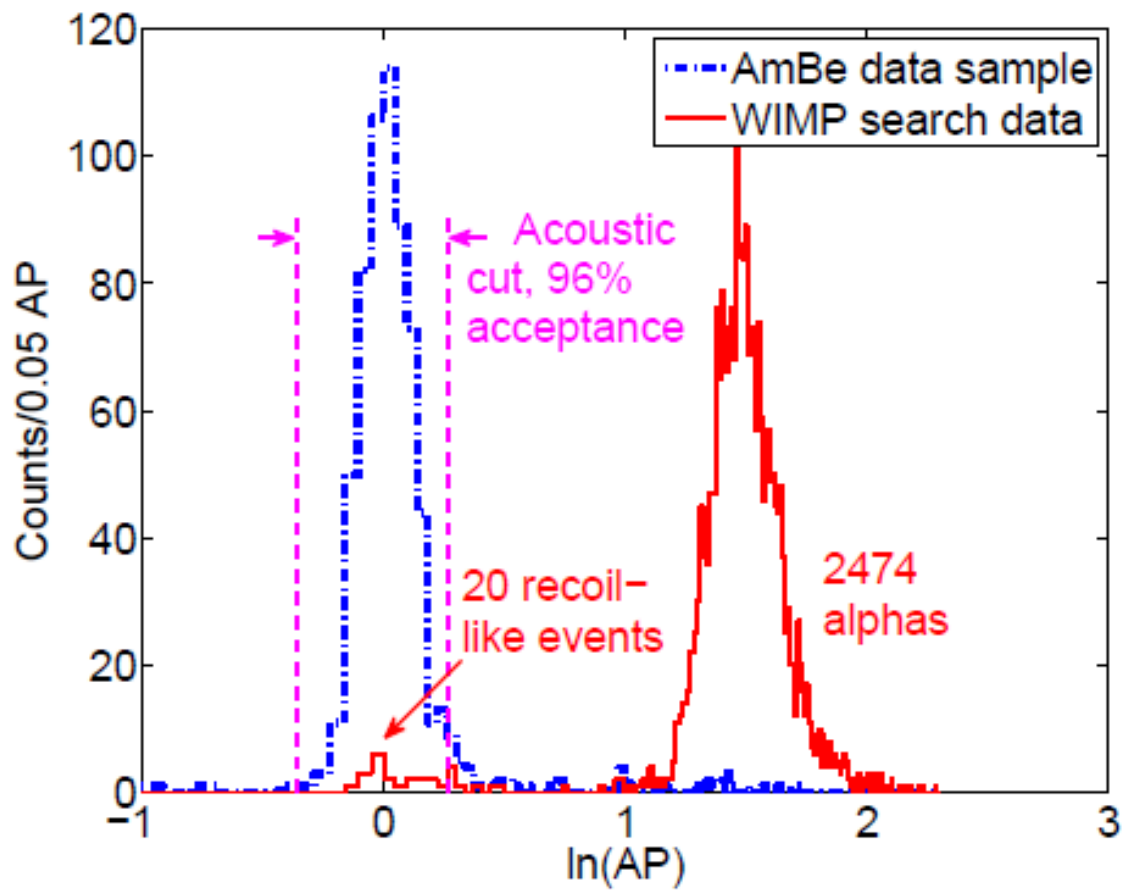
<u>but</u>

Acoustic signal from alpha track is several times louder than recoil signal at high frequencies due to presence of multiple radiating bubbles.

Acoustic Alpha Background Rejection in COUPP4

- Acoustic alpha rejection in bubble chambers much better than in Superheated Droplet Detectors.
- >99.3% of alpha events rejected with 96% acceptance for signal.
- Residual background events belong to a different class?

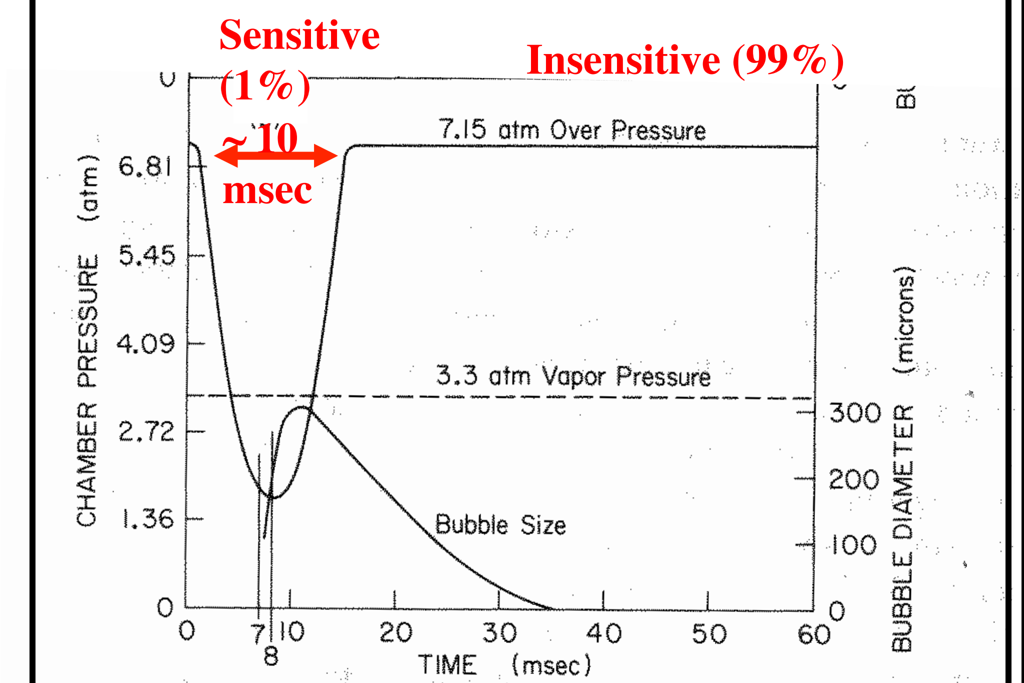




Continuously Sensitive Bubble Chambers: Changes Needed to Conventional Bubble Chamber Designs

- Conventional chambers were designed for pulsed operation and were only sensitive during beam spills.
- Bubble nucleation on internal surfaces of detector required this.
- Problem solved by COUPP through designs that eliminate nucleating surfaces.

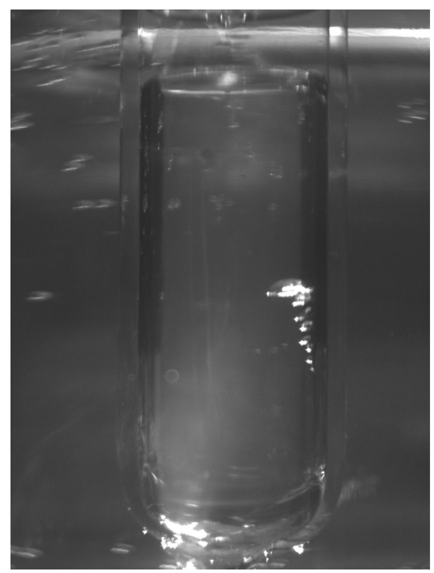
Conventional Bubble Chamber



SLAC 1- meter hydrogen chamber

COUPP 2 cm Glass Chamber

Dirty Surface



Clean surface

Continuously Sensitive Bubble Chambers: Changes Needed to Conventional Bubble Chamber Designs

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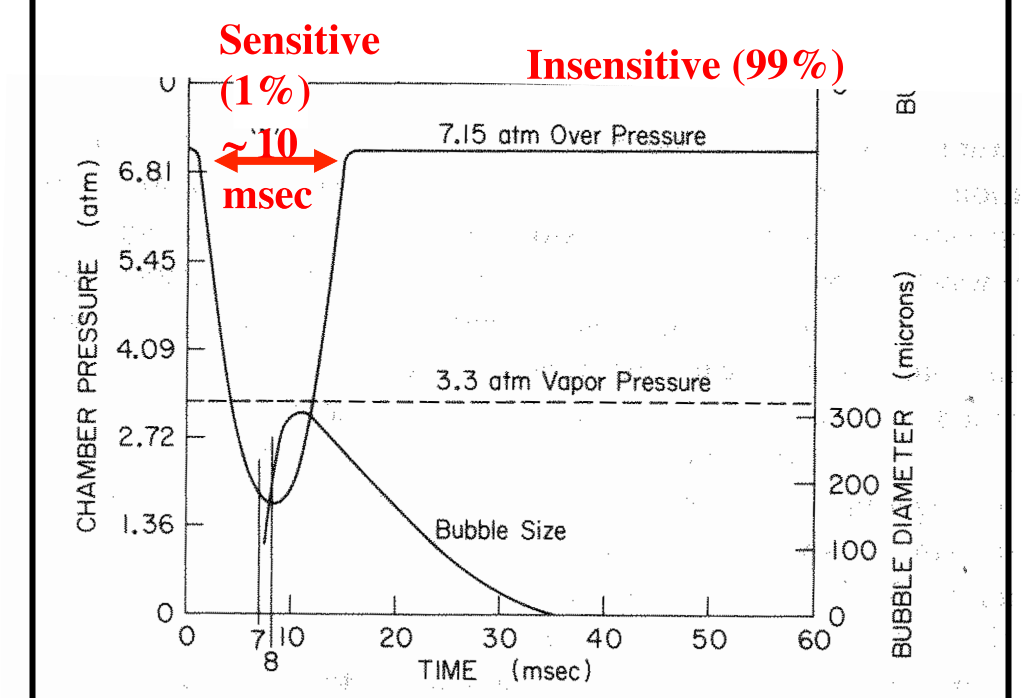
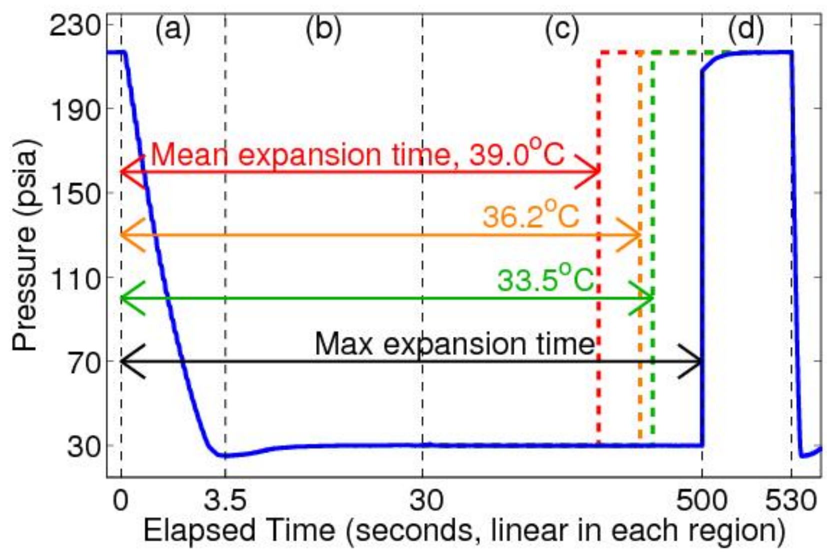
Conventional Bubble Chamber



SLAC 1- meter hydrogen chamber

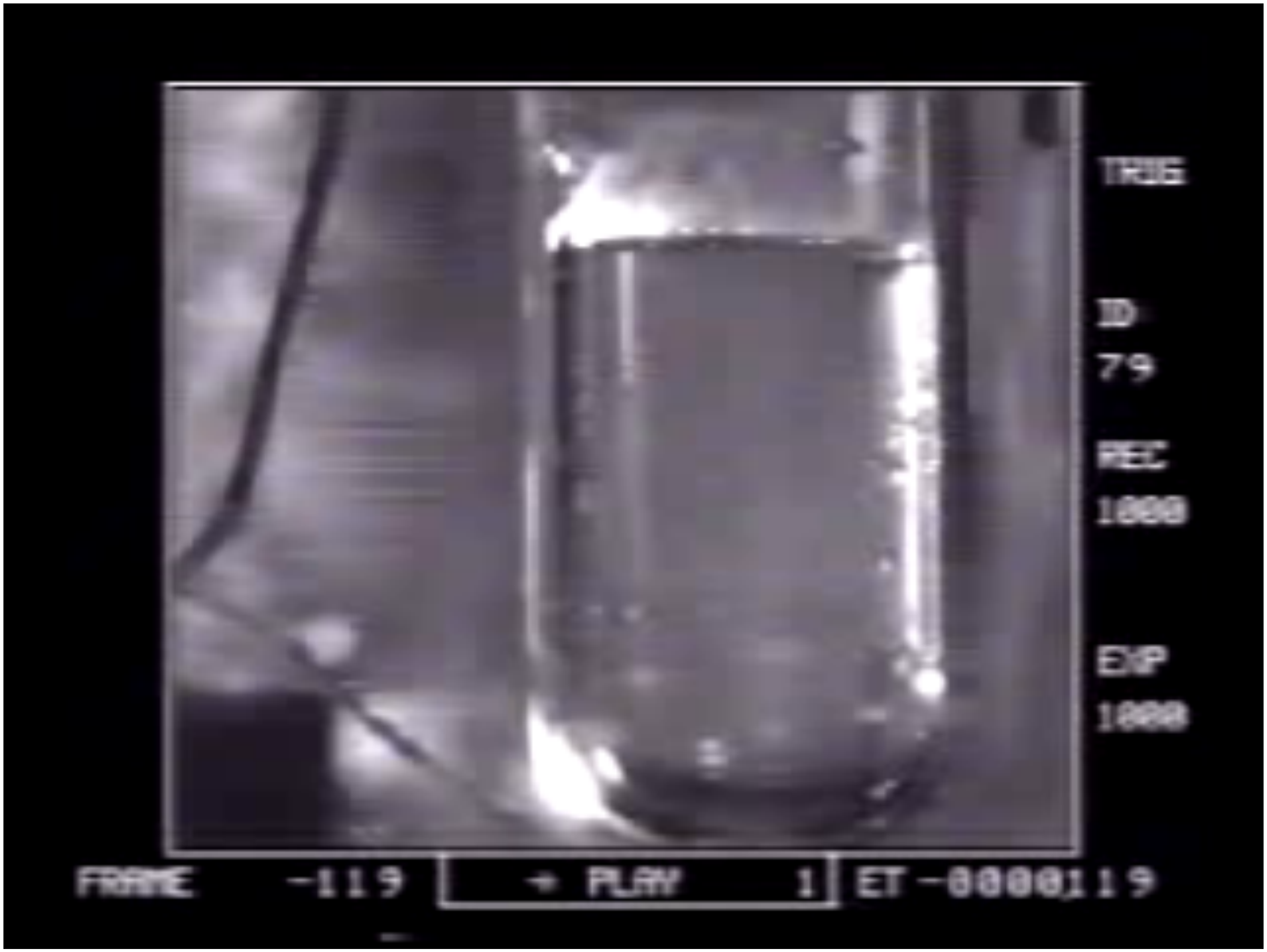
"Continuously Sensitive" Chamber



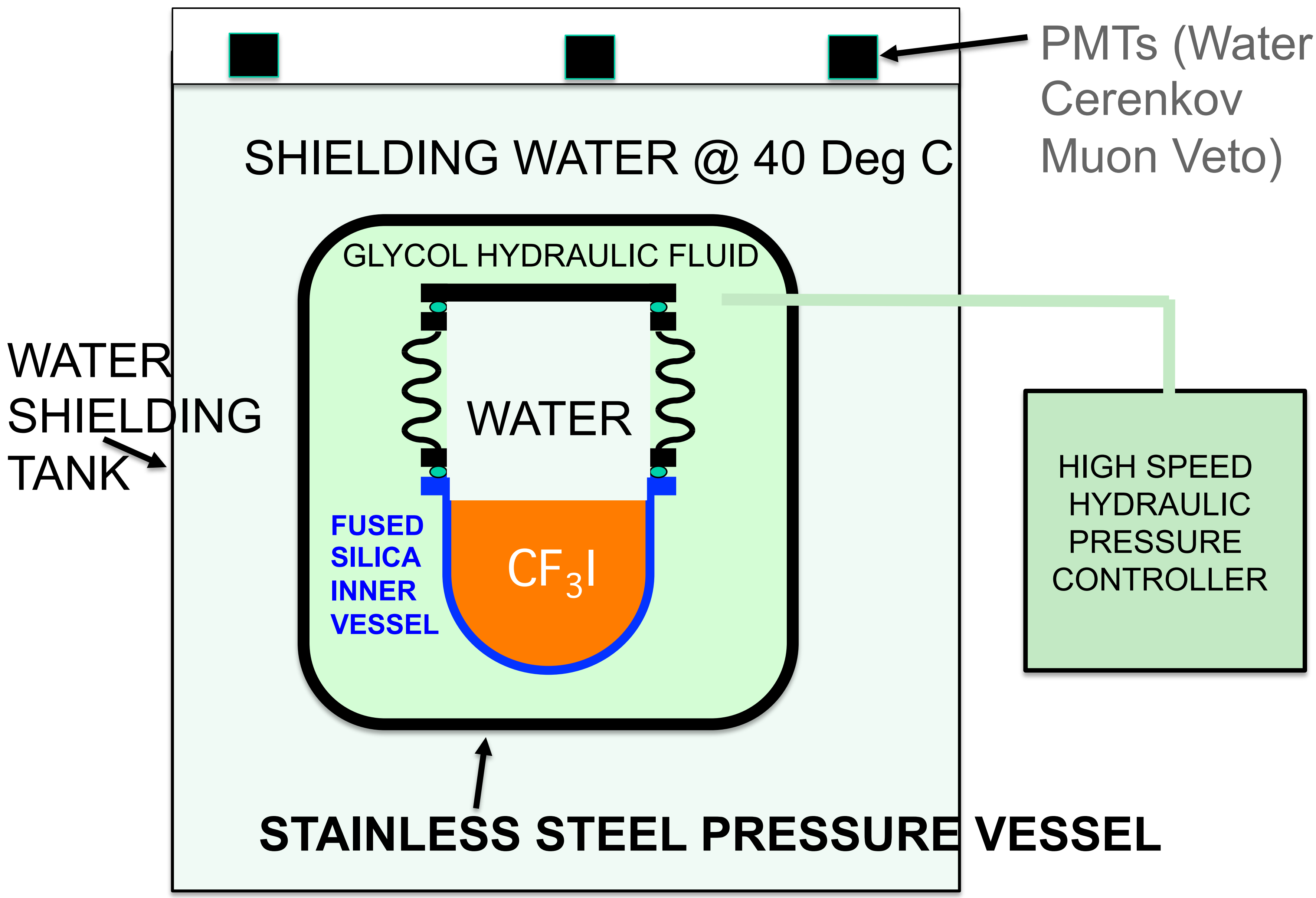
High Speed Bubble Chamber Movie

1000 frames/ second

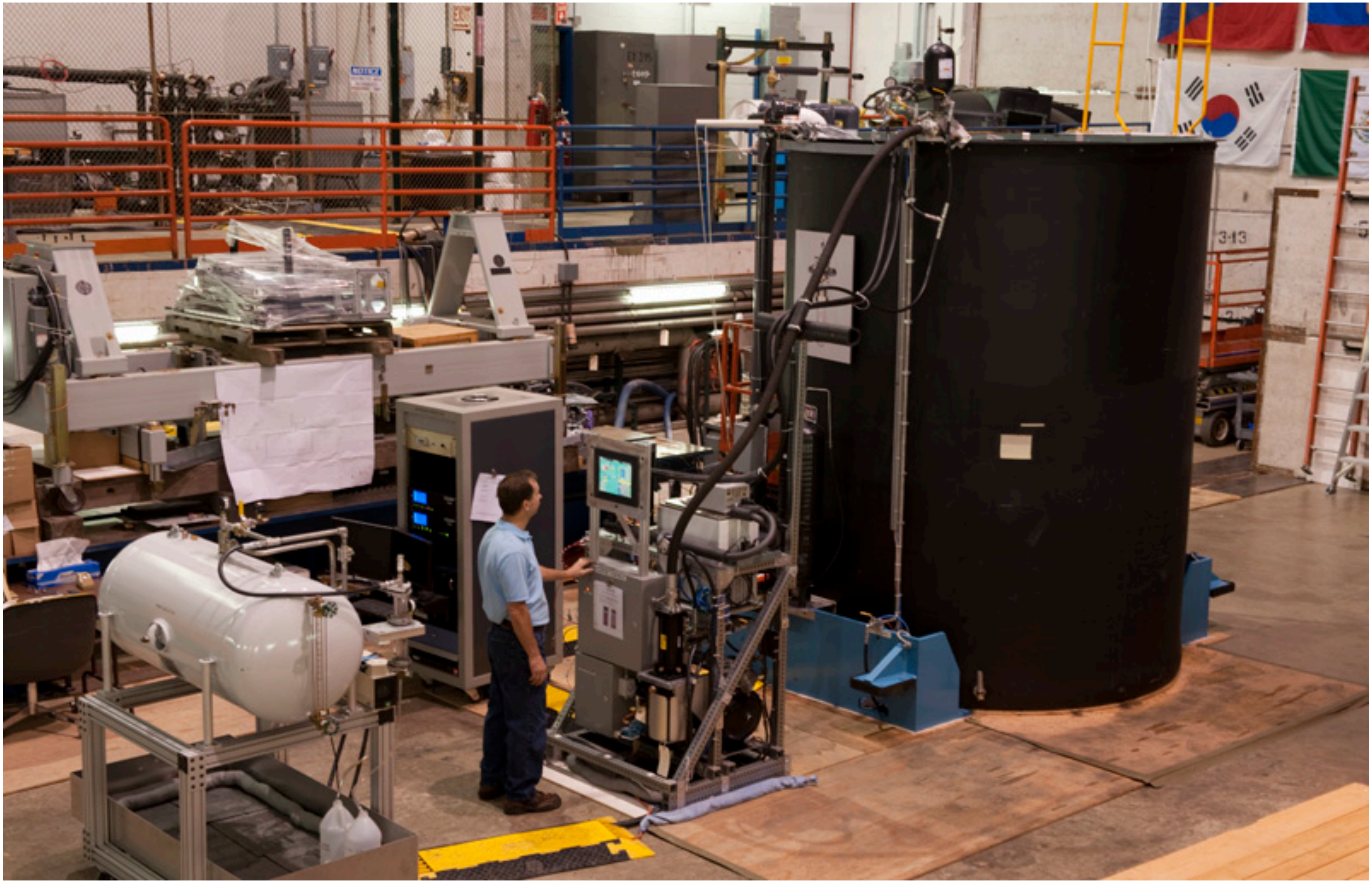
^{241}Am-Be neutron source



Large Bubble Chamber WIMP Detector Cartoon



60-Kg (30 Liter) Chamber Testing at Fermilab

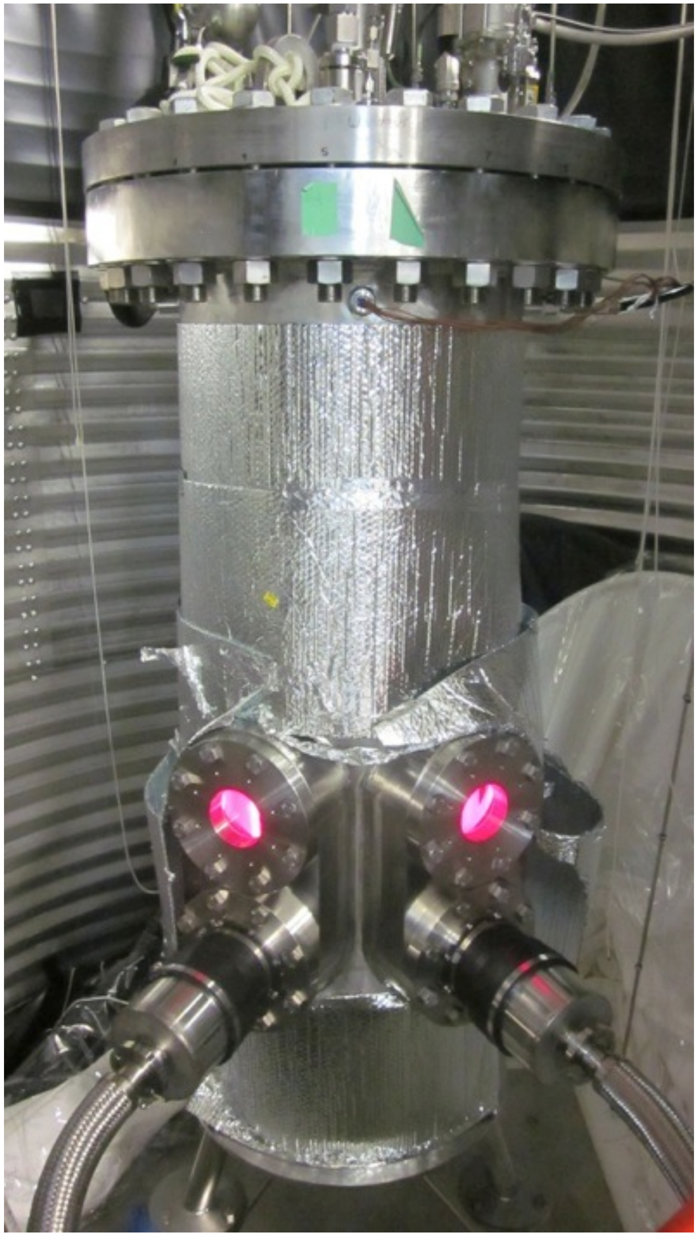


COUPP-60 Pieces

STEEL PRESSURE VESSEL

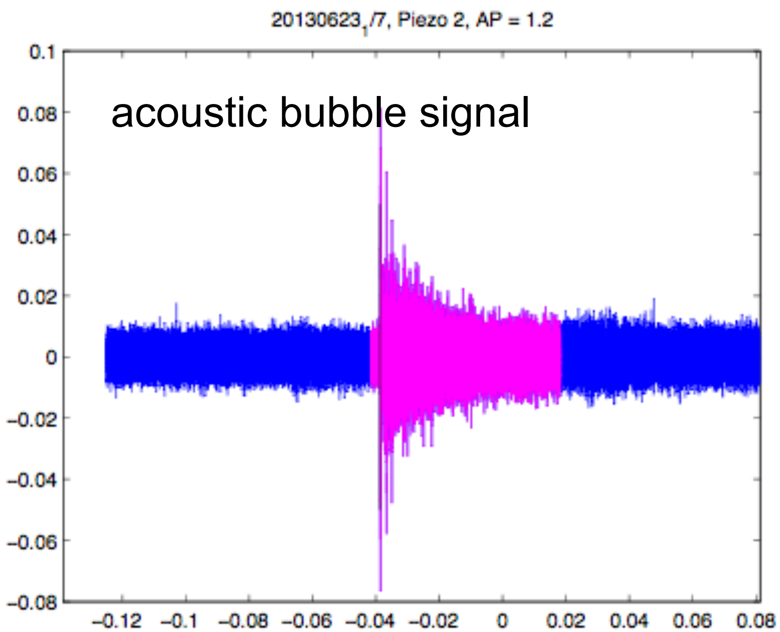
INNER VESSEL ASSEMBLY

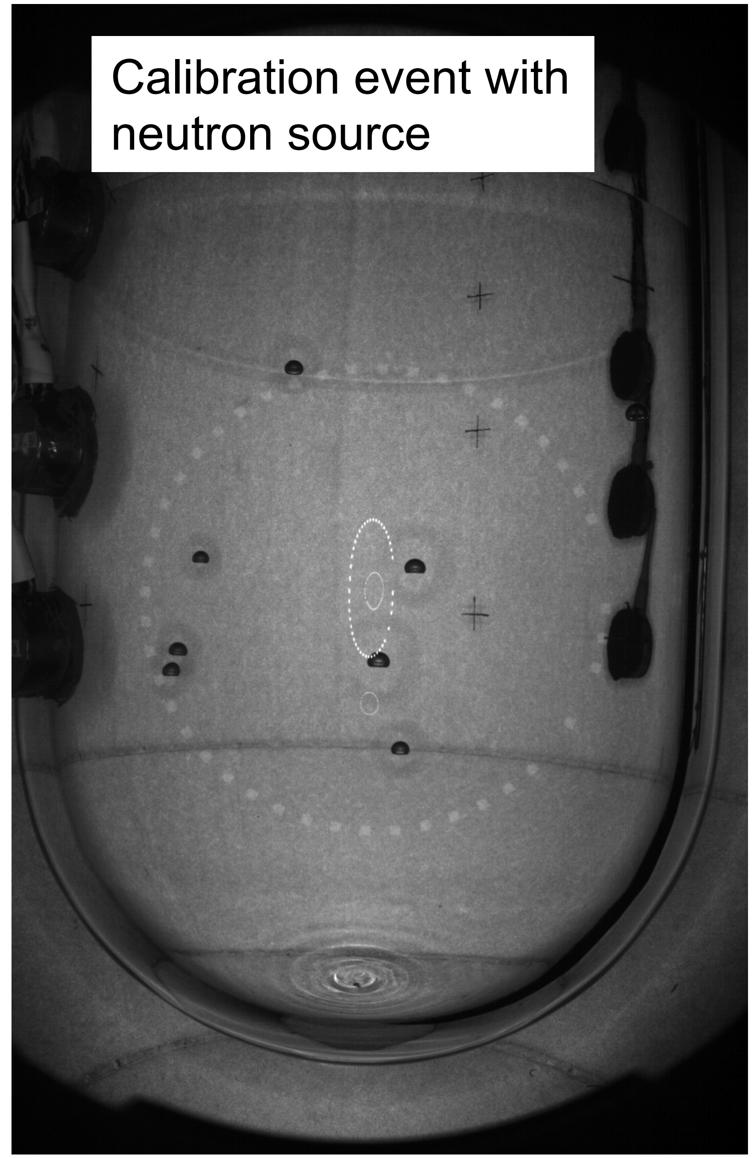
COUPP-60 SNOLAB Installation



COUPP60 Run Status

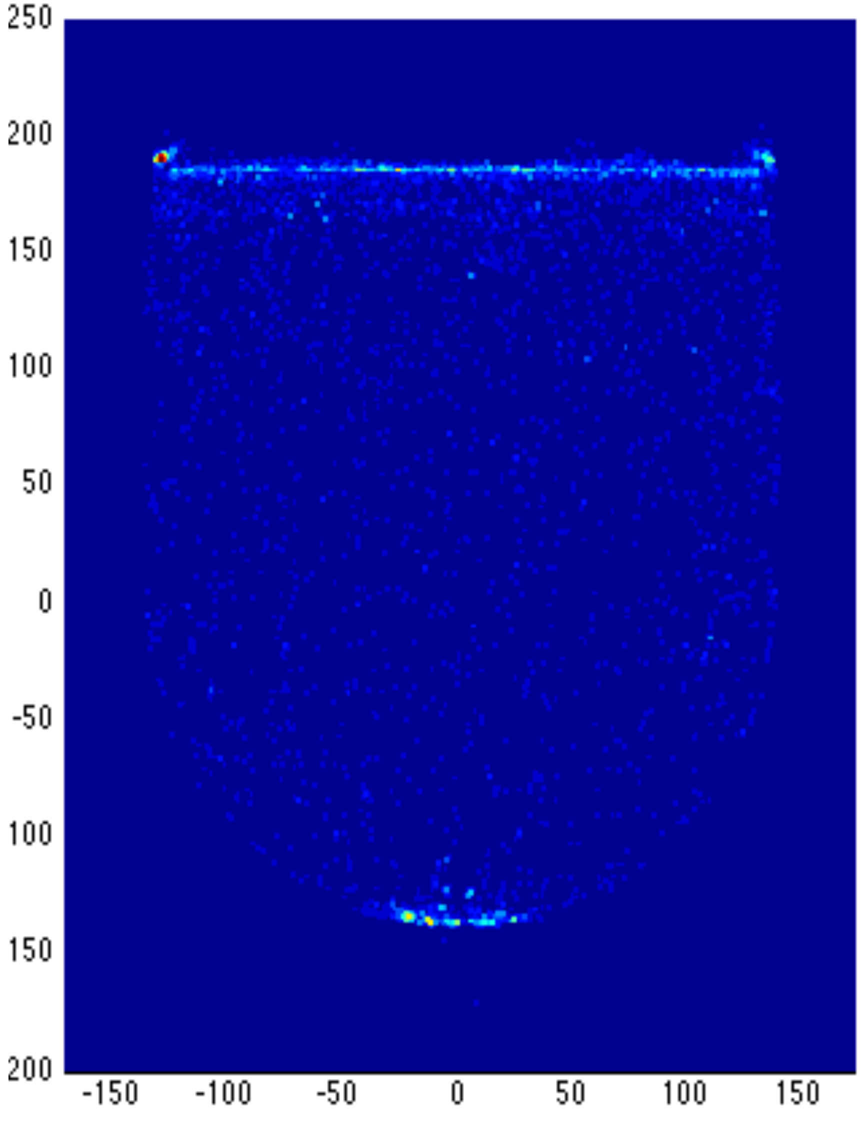
- COUPP-60 installation at SNOLAB was completed June, 2013.
- Running continuously with 37 Kg CF3I in 2013-2014. >90% live time efficiency. Minus 10 week pause to fix hydraulic leak.
- ~5000 kg-day exposure by April '14.
-



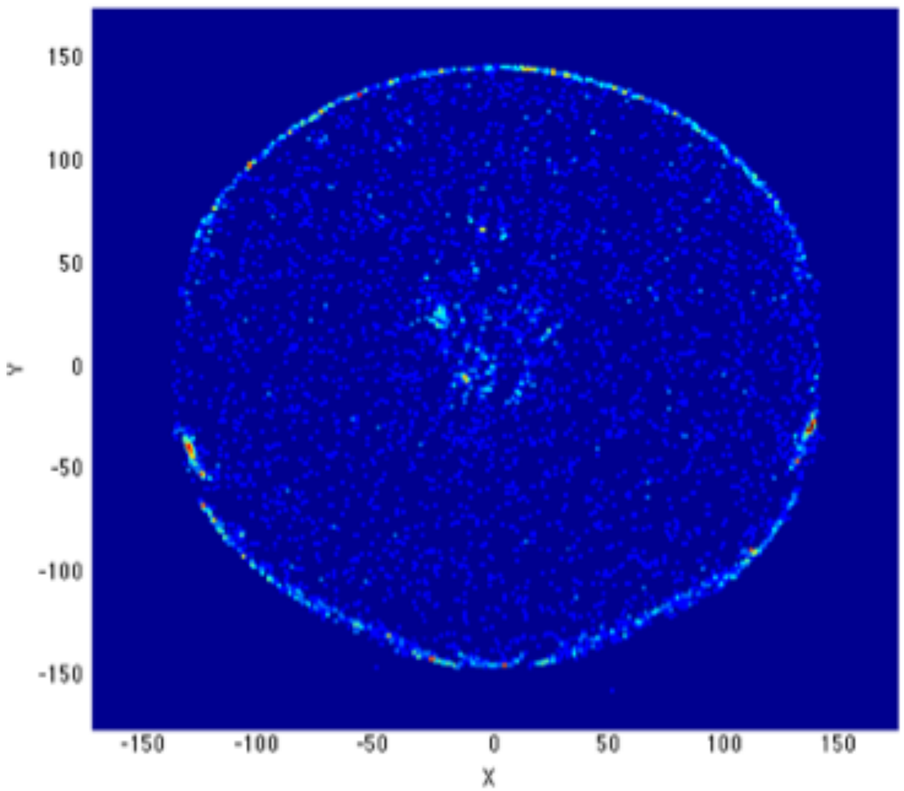


COUPP-60 Spatial Distribution

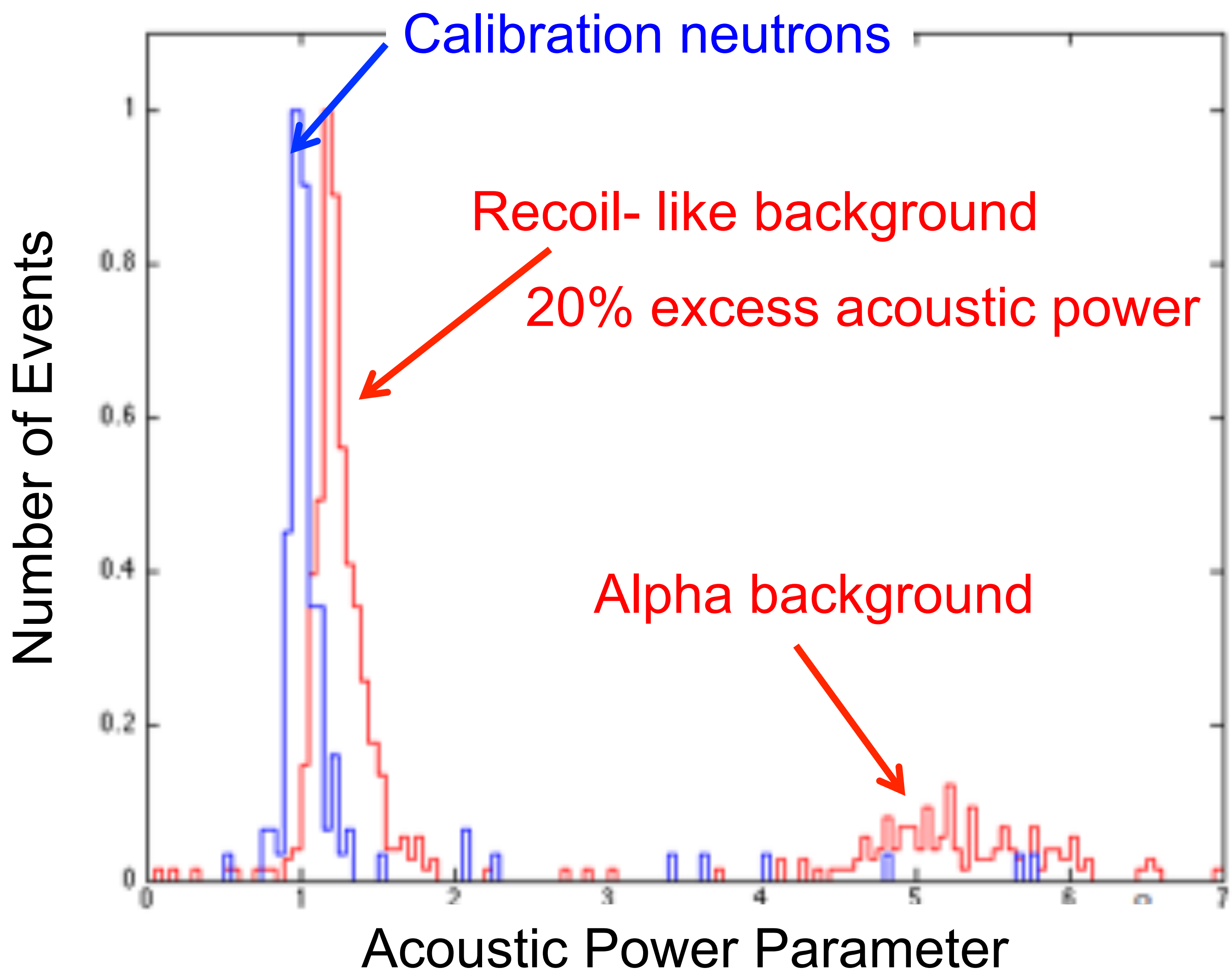
SIDE VIEW



TOP VIEW

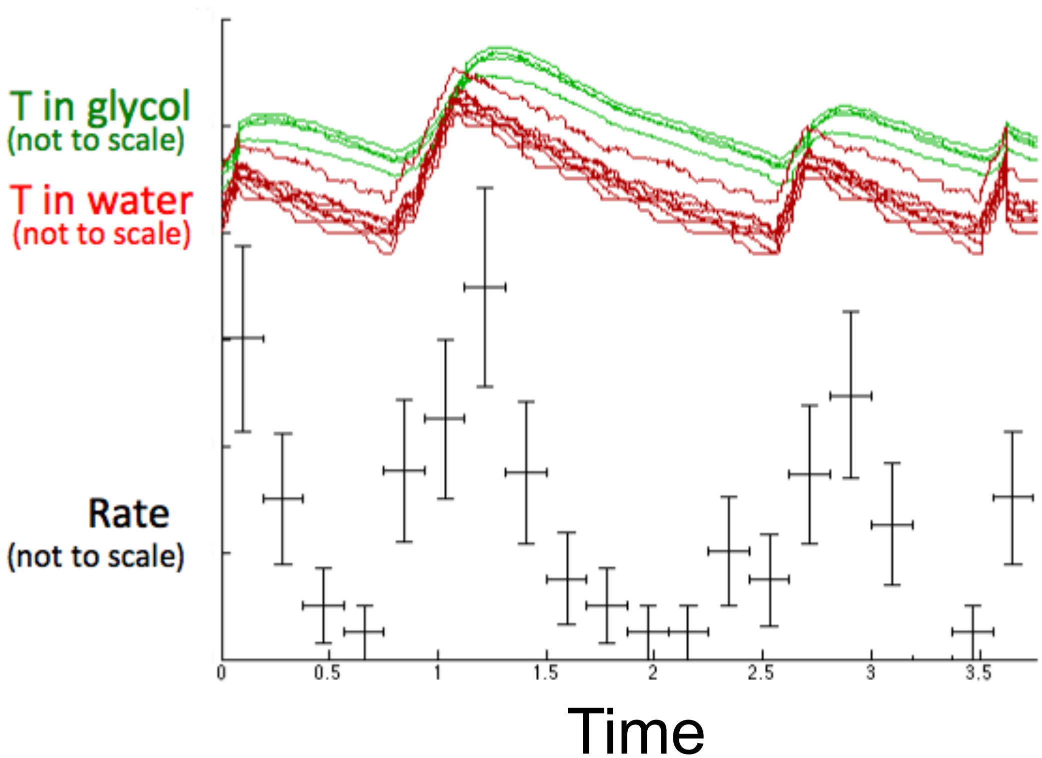


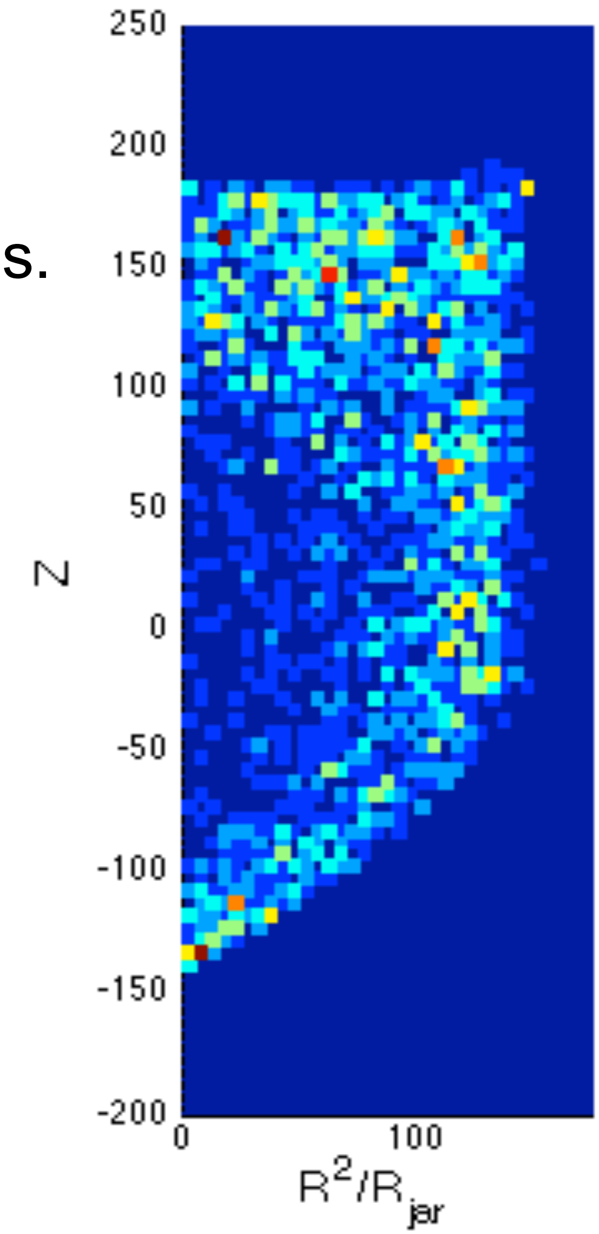
Acoustic Distribution- Preliminary



Space and Time Distribution of Recoil-Like Events

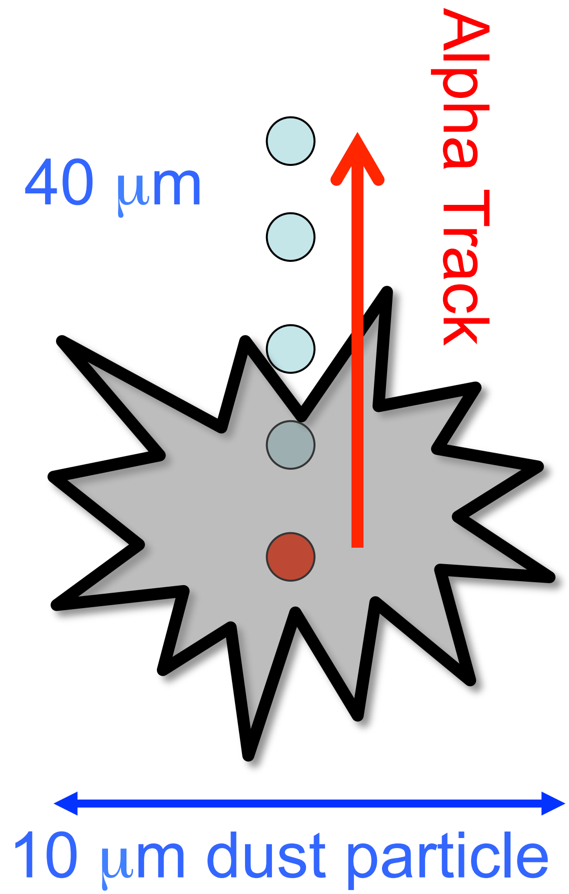
- Acoustically identified recoil-like events have anomalous spatial and time distributions.
- Correlation with temperature changes.
- This cannot be dark matter.





Background Events from Dust?

- We observe a time- and space- varying population of events with acoustic signatures similar to nuclear recoils. In COUPP-60, these events have about 20% excess acoustic power cluster towards surfaces.
- Current best hypothesis: events are caused by alpha emitters imbedded in floating particulates.
- Planning “dust calibration” and new purification steps to test this idea.



PICO Collaboration

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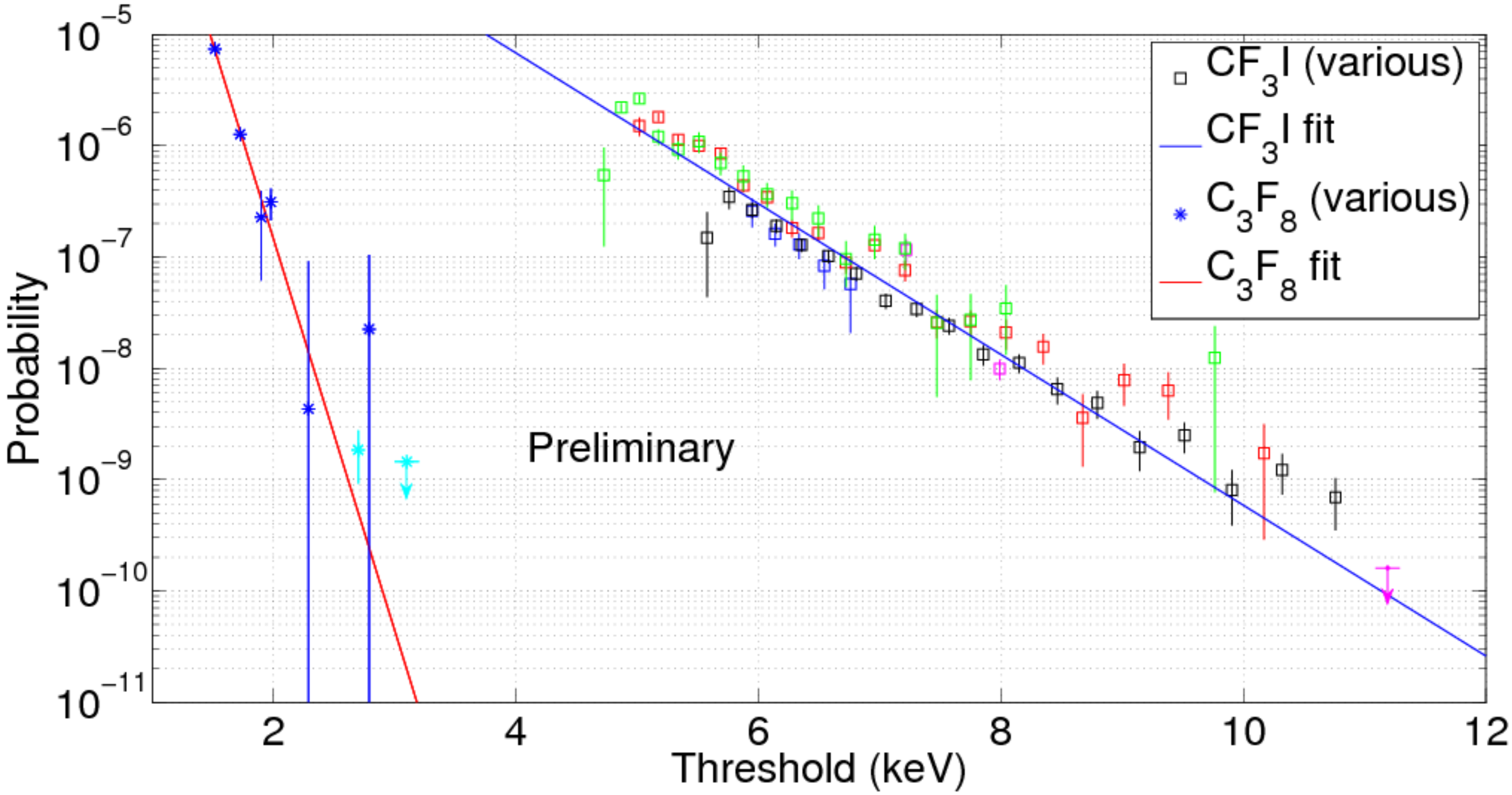
SNOLAB Mining for Knowledge Creuser pour trouver... l'excellence
I. Lawson, E. Vázquez Jáuregui

Electron recoil rejection

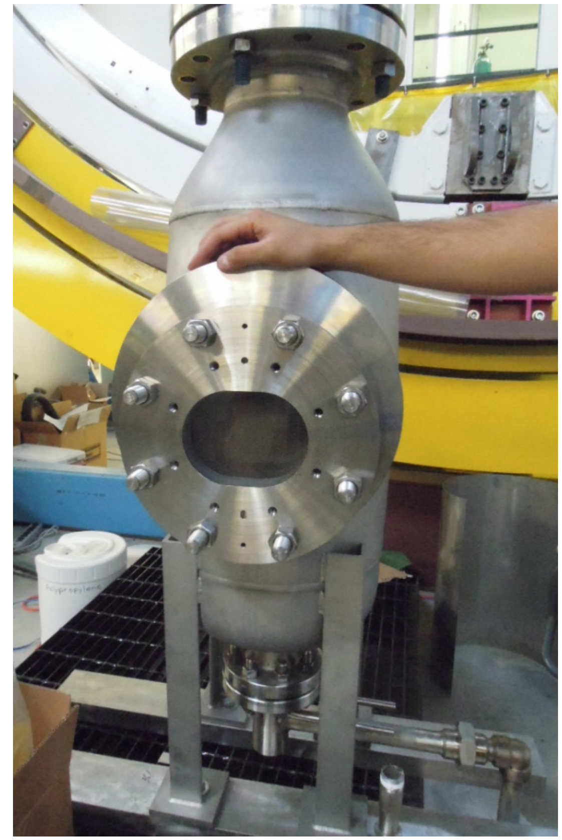
Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I



PICO-2L: A 2- Liter C3F8 Chamber

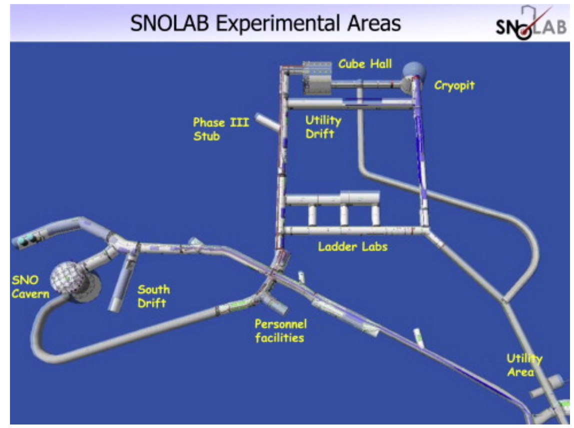
- First product of the COUPP/PICASSO merger.
- Small C3F8 chamber is optimized for a light WIMP search with 3 keV nuclear recoil threshold on Fluorine.
- Prototype technologies for PICO 250L

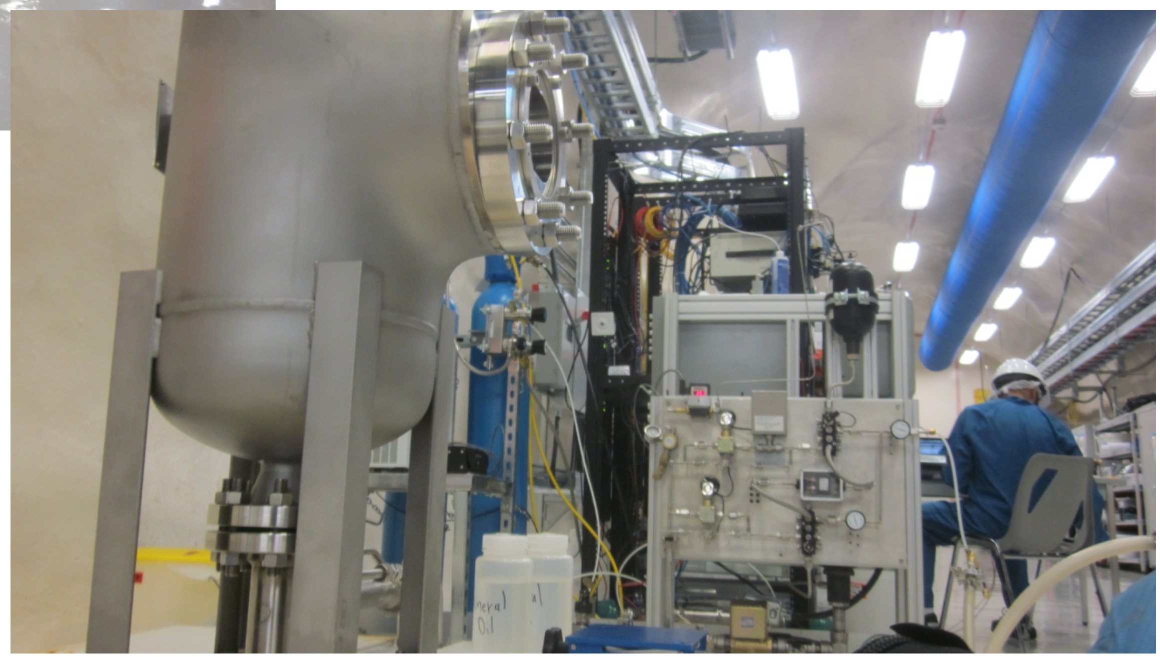
New two-bellows design inner vessel assembly. Silica jar is an exact replica of COUPP-4 jar.



Simplified pressure vessel – ¼ the mass of steel as COUPP-4.

PICO-2L installation at SNOLAB





PICO-2L was installed and commissioned in Fall 2013.

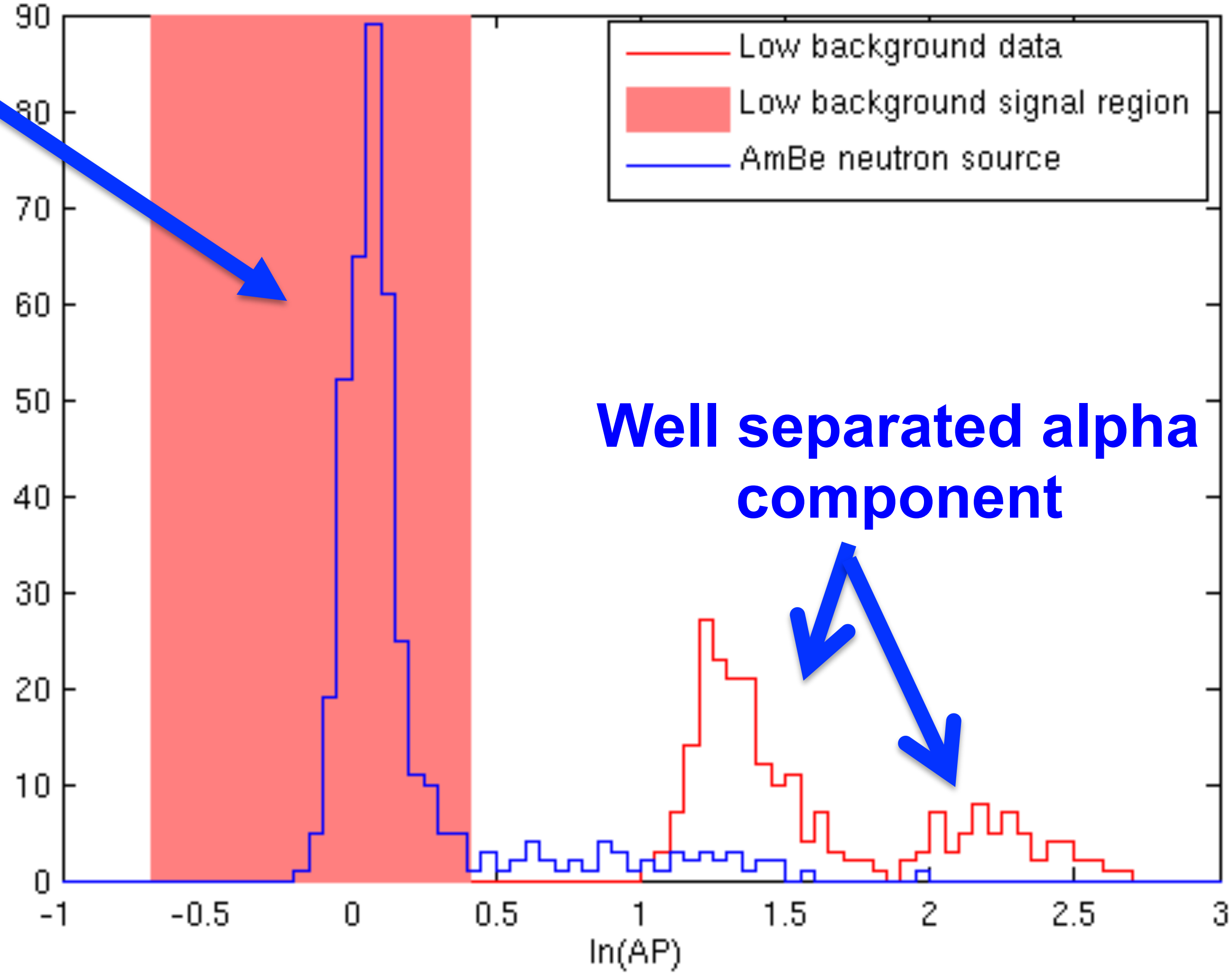
Stable operation with neutron shielding began October 28th 2013.

~150 kg-days of exposure so far, mostly at 3keV nuclear recoil threshold.

Preliminary (Blinded) Look at Low Threshold PICO2L Data

Showing only only neutron calibration data in signal region

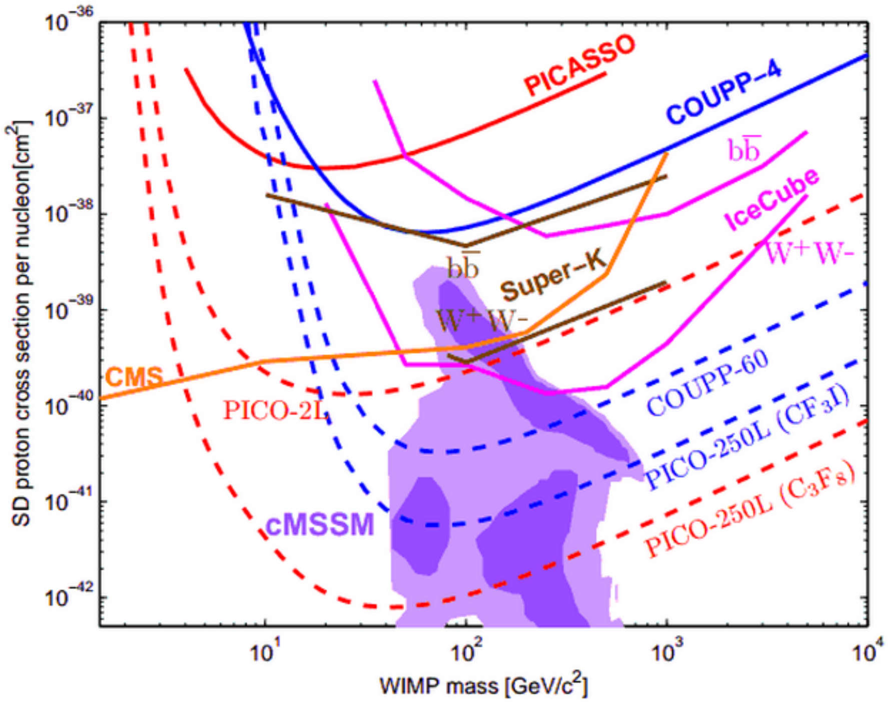
Expect new results in 2014!



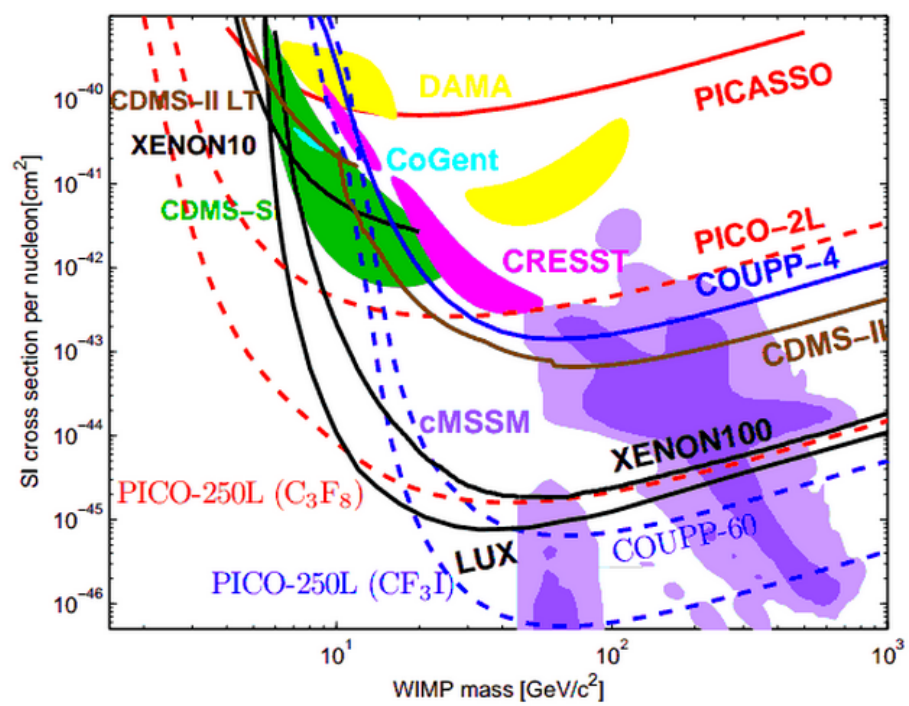
Well separated alpha component

Sensitivity Projections

Spin-Dependent



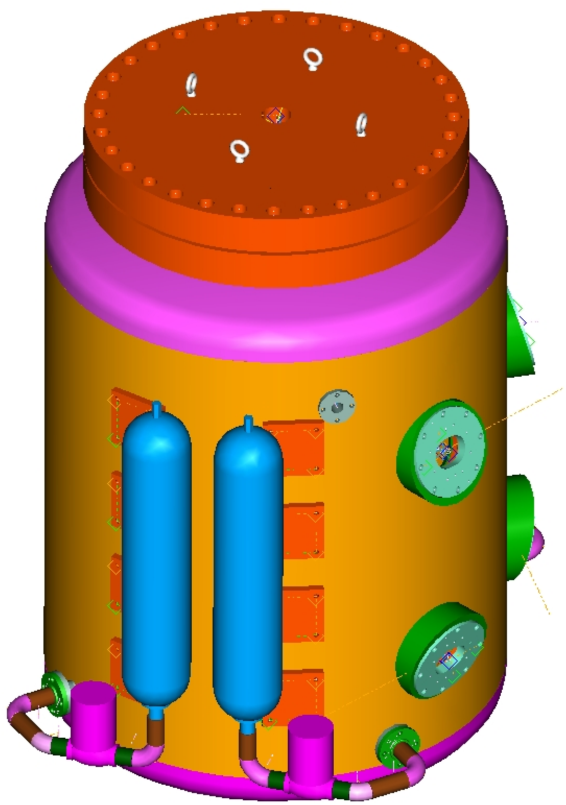
Spin-Independent

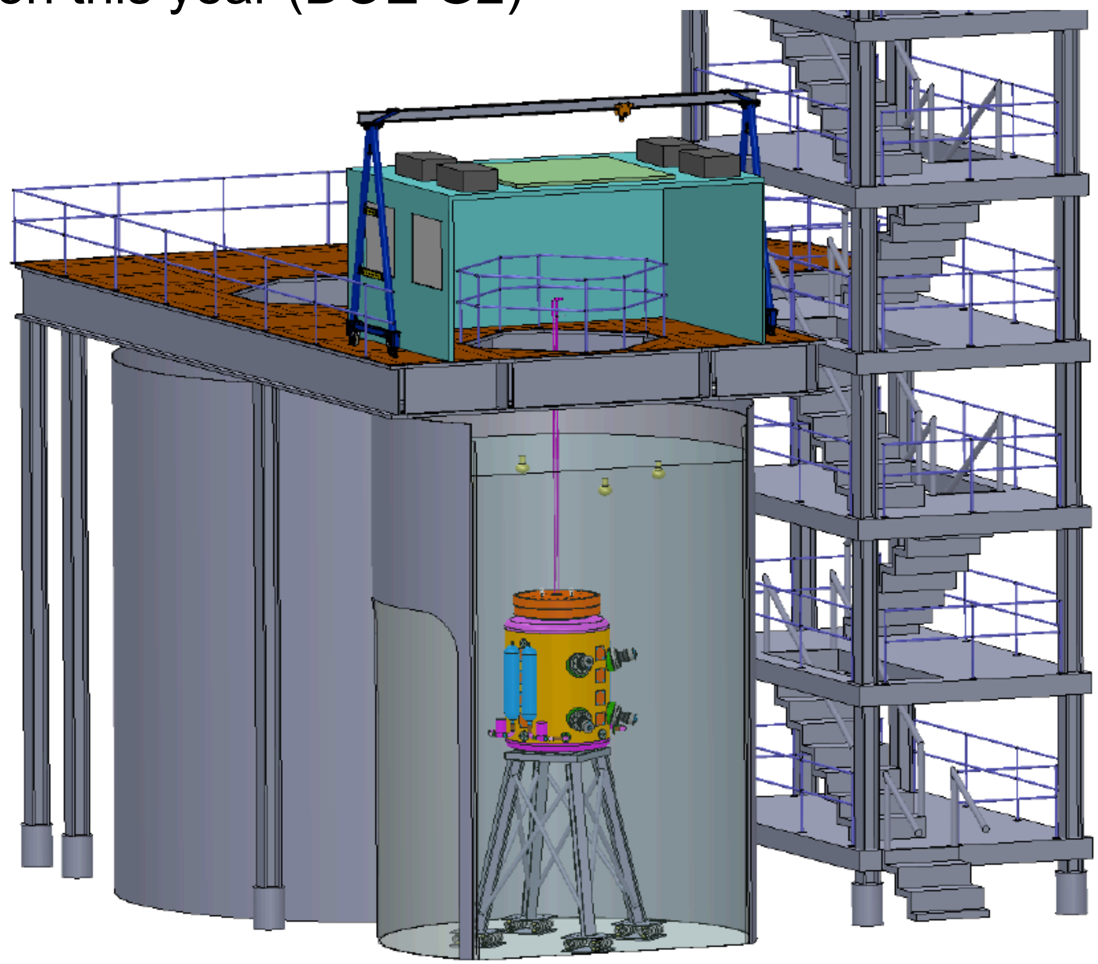


cMSSM model space from Roszkowski et. al., JHEP 0707:075 (2007).

PICO-250L

- PICO-250L: ton-scale bubble chamber designed for CF_3I or C_3F_8 target.
- Currently in design stage.
- Awaiting funding decision this year (DOE G2)





Summary

- Bubble chambers– is the best physics yet to come?

- Currently taking data:
  - 60-kg COUPP-60 CF_3I experiment.
  - 2-kg PICO-2L low threshold C_3F_8 experiment.

- A source of background is present that we are trying to understand and eliminate. Progress on this is critical for future sensitivity gains. May be due to micron-scale particulate contamination of liquids.

- Plans are advancing for a ton-scale detector, which could be installed in 2016 .