Recent Results and Future Plans for Dark Matter Searches with PICO

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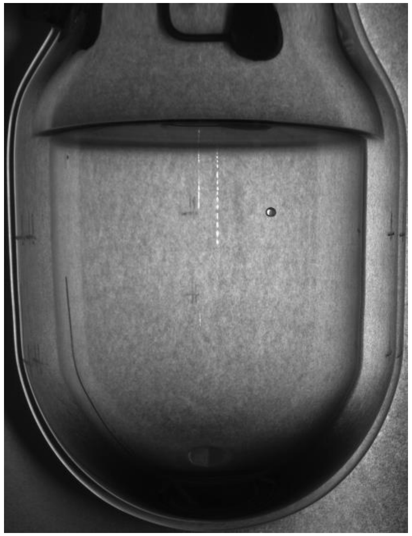
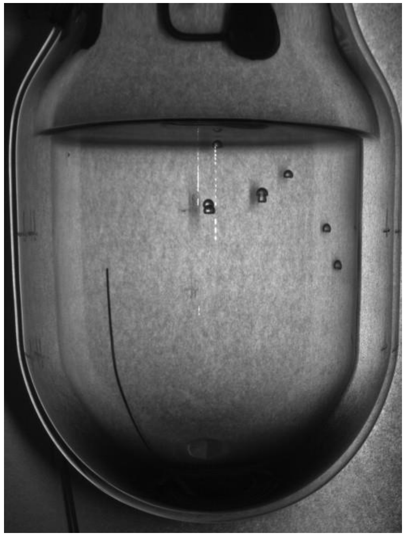




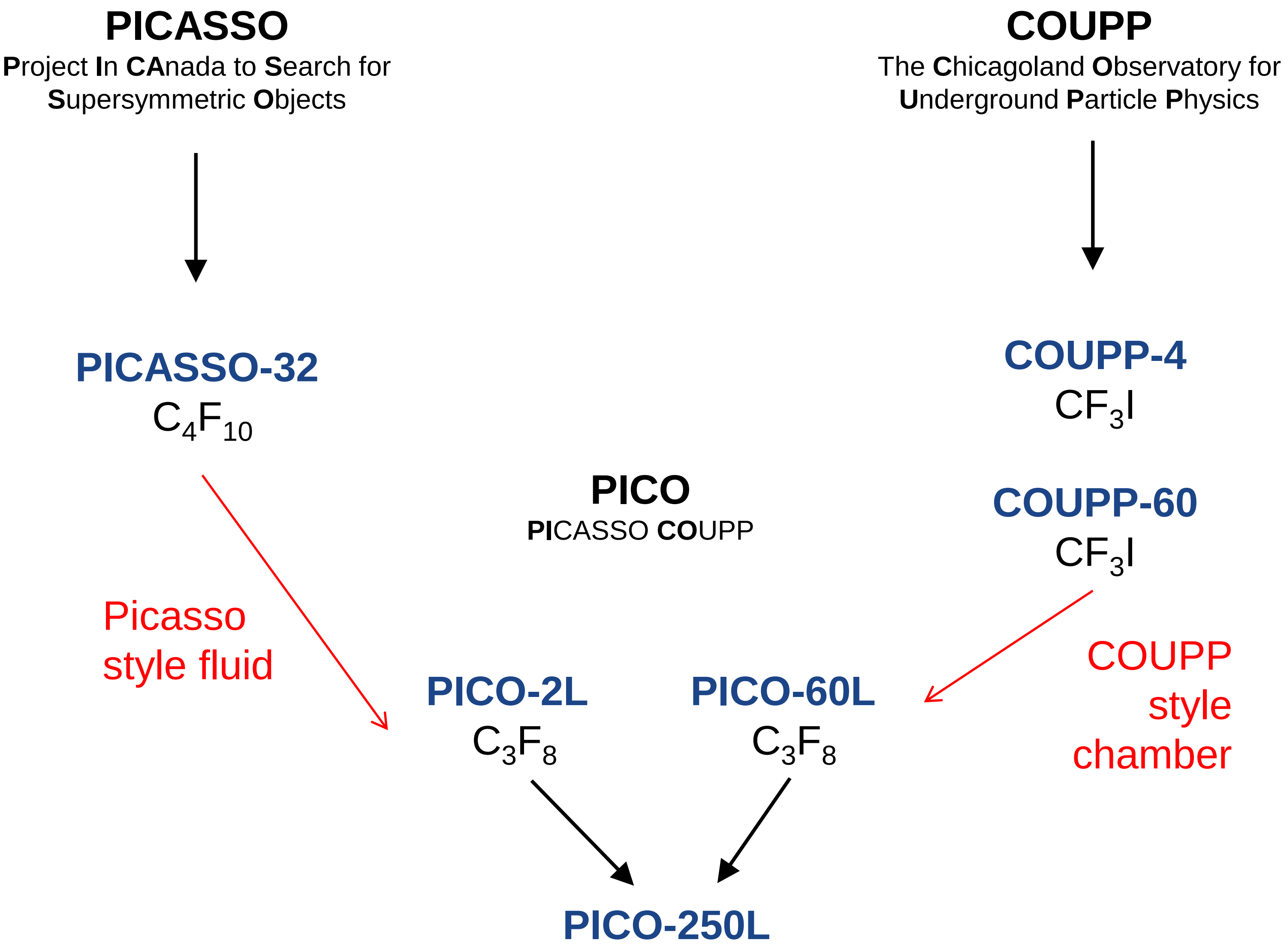
PICO = Merger of **PI**CASSO & **CO**UPP collaborations

The Objectives of the PICO Collaboration:

- To develop the bubble chamber technology with the ultimate goal of building a **tonne scale detector**.
- To fully explore the **Spin-Dependent** sector and have particular sensitivity to **low mass WIMPS**
- To reach this capability with a series of detectors of increasing mass and sophistication.

PICO 2L → PICO 60 L → PICO 250 L

The marriage of PICASSO and COUPP



PICASSO
Project **I**n **CA**nada to **S**earch for
Supersymmetric **O**bjects

COUPP
The **C**hicagoland **O**bservatory for
Underground **P**article **P**hysics

PICASSO-32
C_4F_{10}

COUPP-4
CF_3I

PICO
PICASSO **CO**UPP

COUPP-60
CF_3I

Picasso
style fluid

COUPP
style
chamber

PICO-2L
C_3F_8

PICO-60L
C_3F_8

PICO-250L

PICO

SNOLAB
MINING FOR KNOWLEDGE
CREUSER POUR TROUVER... L'EXCELLENCE

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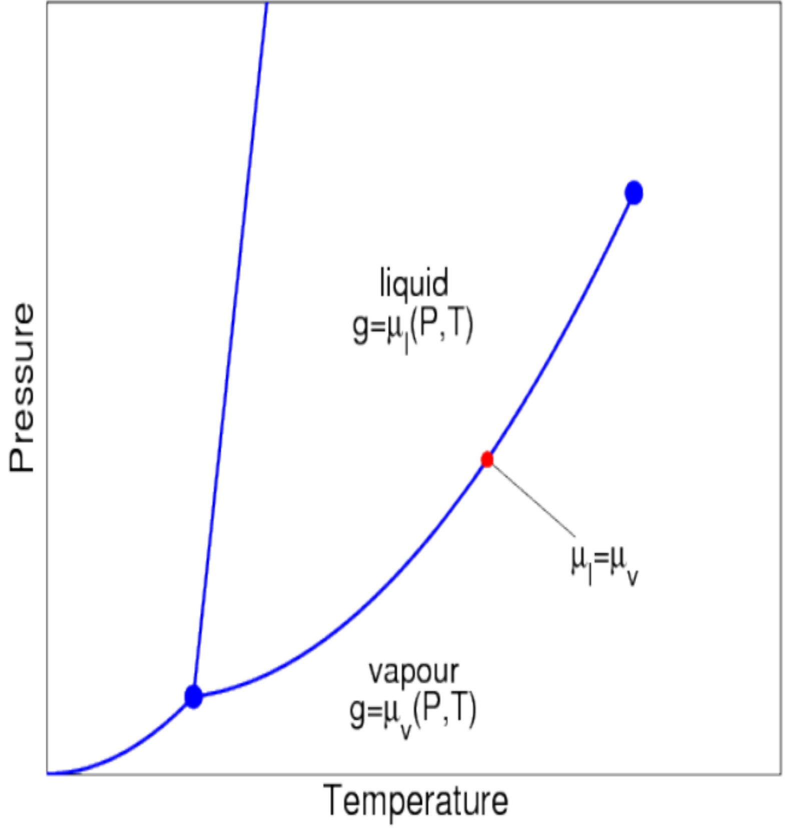
Outline of Presentation

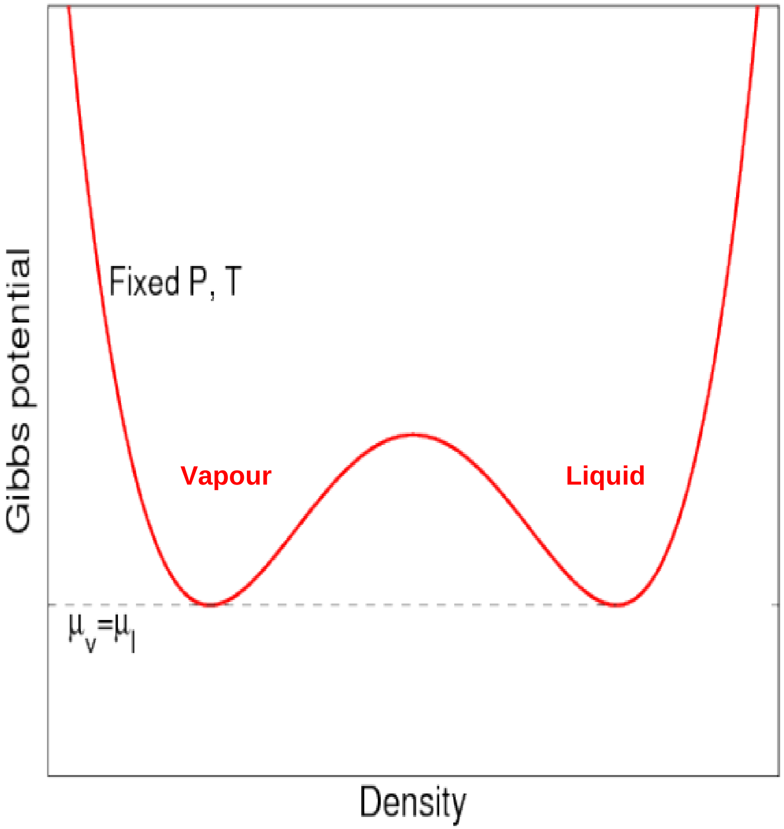
- Overview of the Bubble Chamber Technology
- Status of PICO 2L
  - Detector Operation
  - Analysis of Data
  - Recent Results
- Status of PICO 60L
- Future Plans

Bubble Chamber Operation

Phase diagram



Gibbs free energy

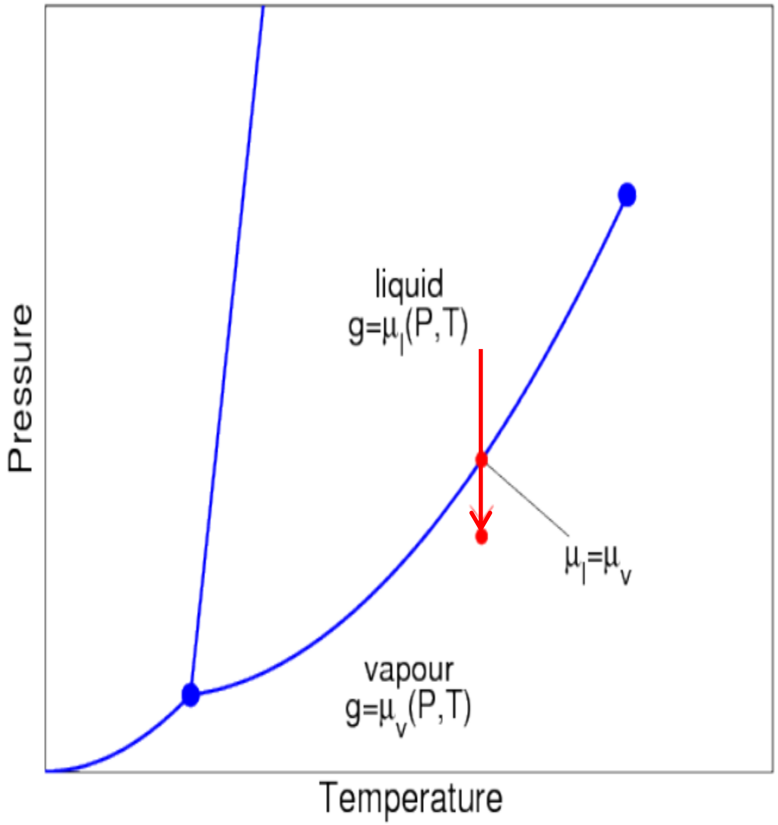


When on the saturation curve, liquid and gas are in equilibrium. (Same pressure, temperature and chemical potential).

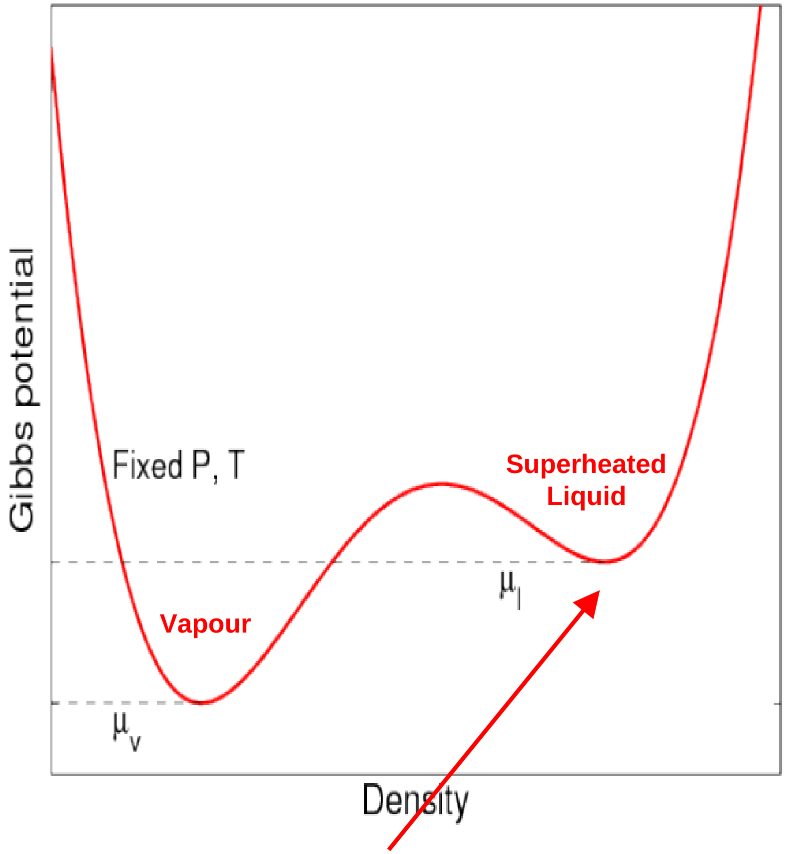
At equilibrium, the potential has two minima (one dominantly gas like and one liquid dominated) according to whether enthalpy or entropy are minimizing the potential.

Bubble Chamber Operation

Phase diagram



Gibbs free energy

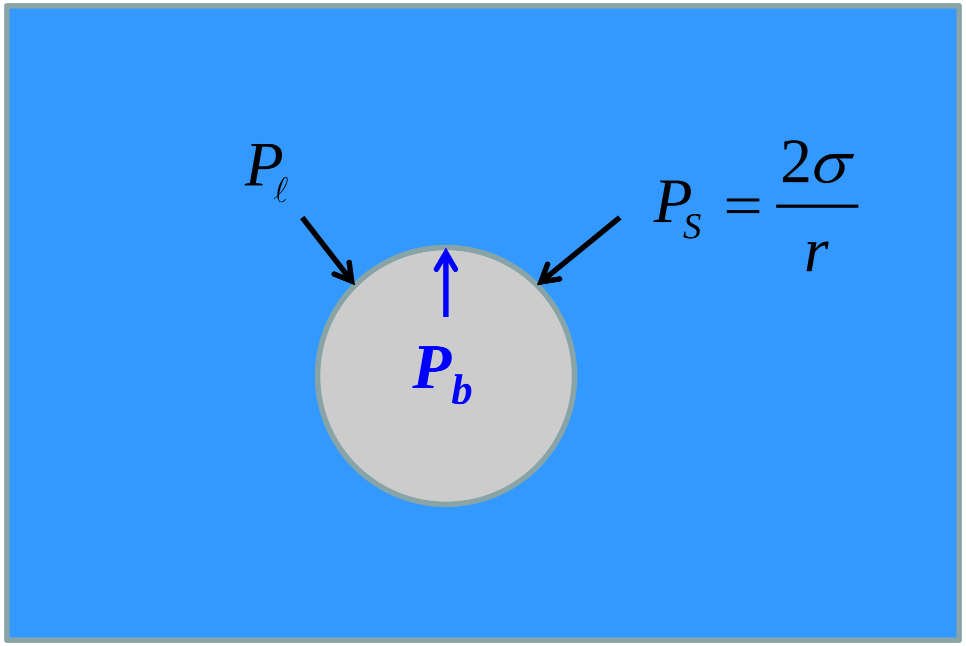


We now lower the pressure of the chamber carefully….starting from the pure liquid phase.

This distorts the potential, leading to a **meta-stable** superheated liquid state. Unless sufficient energy is added, it will stay in meta-stable state.

Bubble Nucleation Dynamics. What Controls Bubble Growth?

1. A small proto-bubble is produced.
2. The bubble begins to expand as the vapour is produced. Outward pressure P_b
3. This is opposed by the external pressure of the liquid P_ℓ, and …
4. It is opposed by the surface tension at the interface.



At equilibrium: $P_\ell + P_S = P_b$

Critical radius for (unstable) equilibrium: $P_\ell + \frac{2\sigma}{r_c} = P_b$

At larger radii, diff pressure is small, bubble grows easily …. Rapid boiling

At smaller radii, diff pressure is large, bubble can’t grow …. Collapse

Particle detection with bubble chambers

- Energy deposition greater than E_{th} in radius less than r_c from particle interaction will result in expanding bubble *(Seitz "Hot-Spike" Model)*.

$$E_{th} = 4\pi r_c^2 \left(\sigma - T \frac{\partial \sigma}{\partial T} \right) + \frac{4}{3} \pi r_c^3 \rho_v h \quad \Bigg\}$$

Depends on T, P and choice of fluid

Surface energy

Latent heat

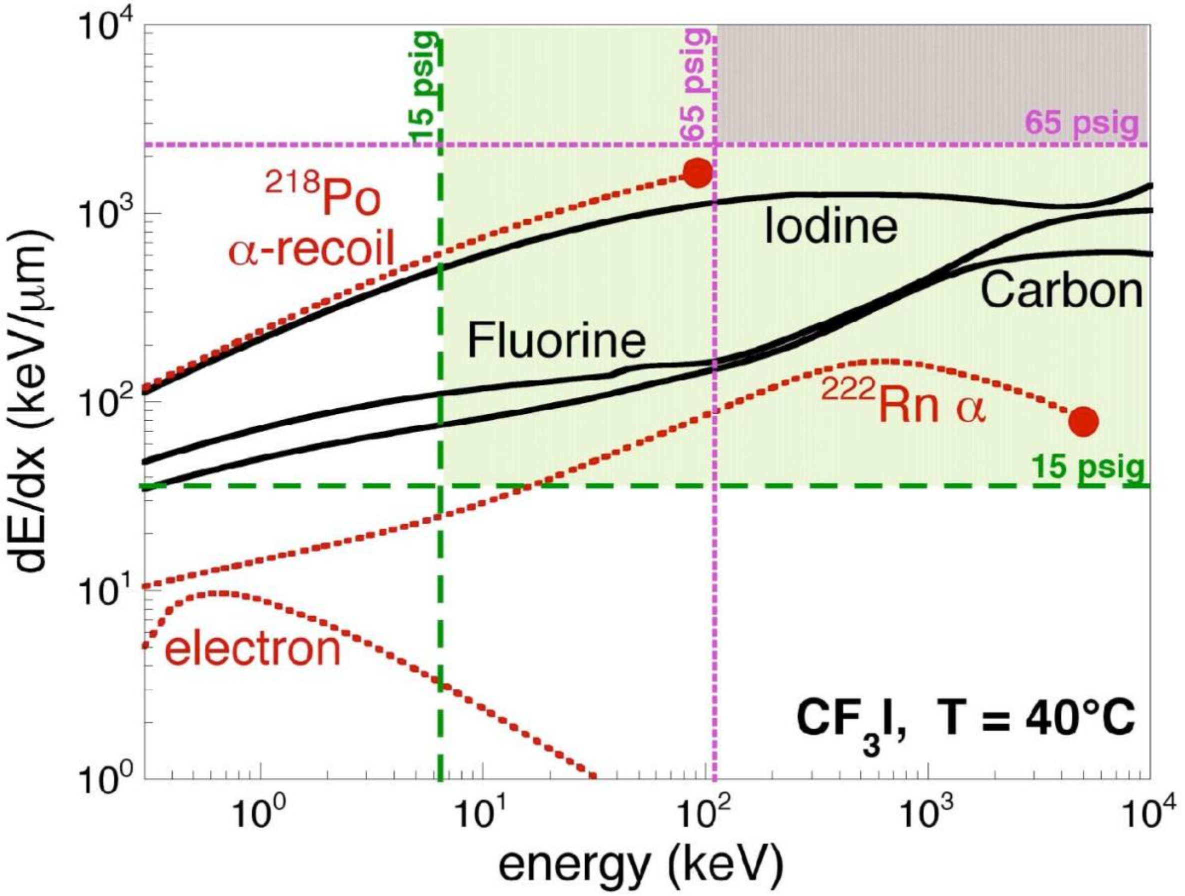
- A smaller or more diffuse energy deposit will create a bubble that immediately collapses.

Take away message:

To be sensitive, particle must deposit enough energy within a critical radius.

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).
- Alphas are (were) a concern because bubble chambers are threshold detectors.

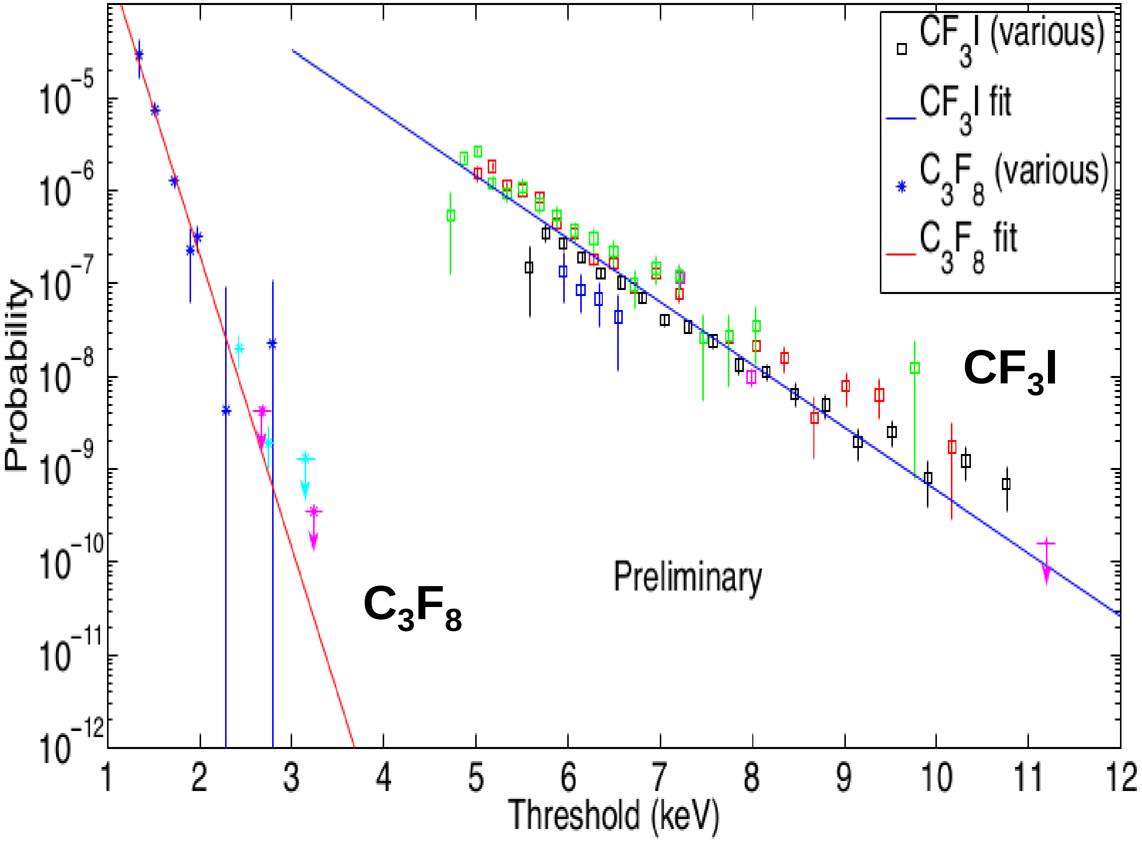


Take away message:

- Energy deposition depends on particle type. So can tune detector to be sensitive to certain types only. → Particle discrimination

Threshold detector:

We can choose superheat parameters (T, P) so that the bubble chamber is blind to electronic recoils (10^{-10} rejection or better)



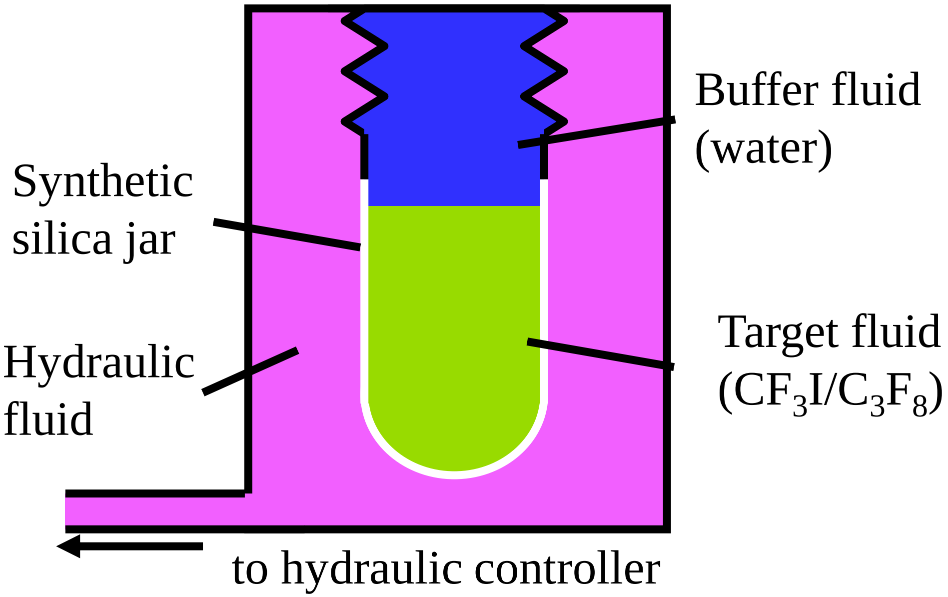
Threshold attainable with 10^{-10} gamma rejection is:

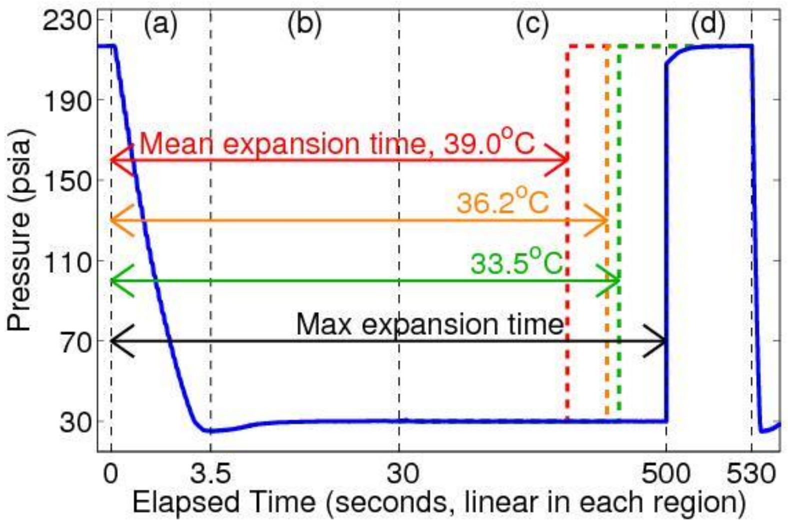
~3 keV with C_3F_8

~ 11 keV with CF_3I

- Excellent electron/gamma rejection has been demonstrated.
- C_3F_8 can reach lower thresholds than CF_3I for same rejection.
- A lower threshold extends the sensitivity to lower mass WIMPs.

Principle of Operation: Bubble Chamber

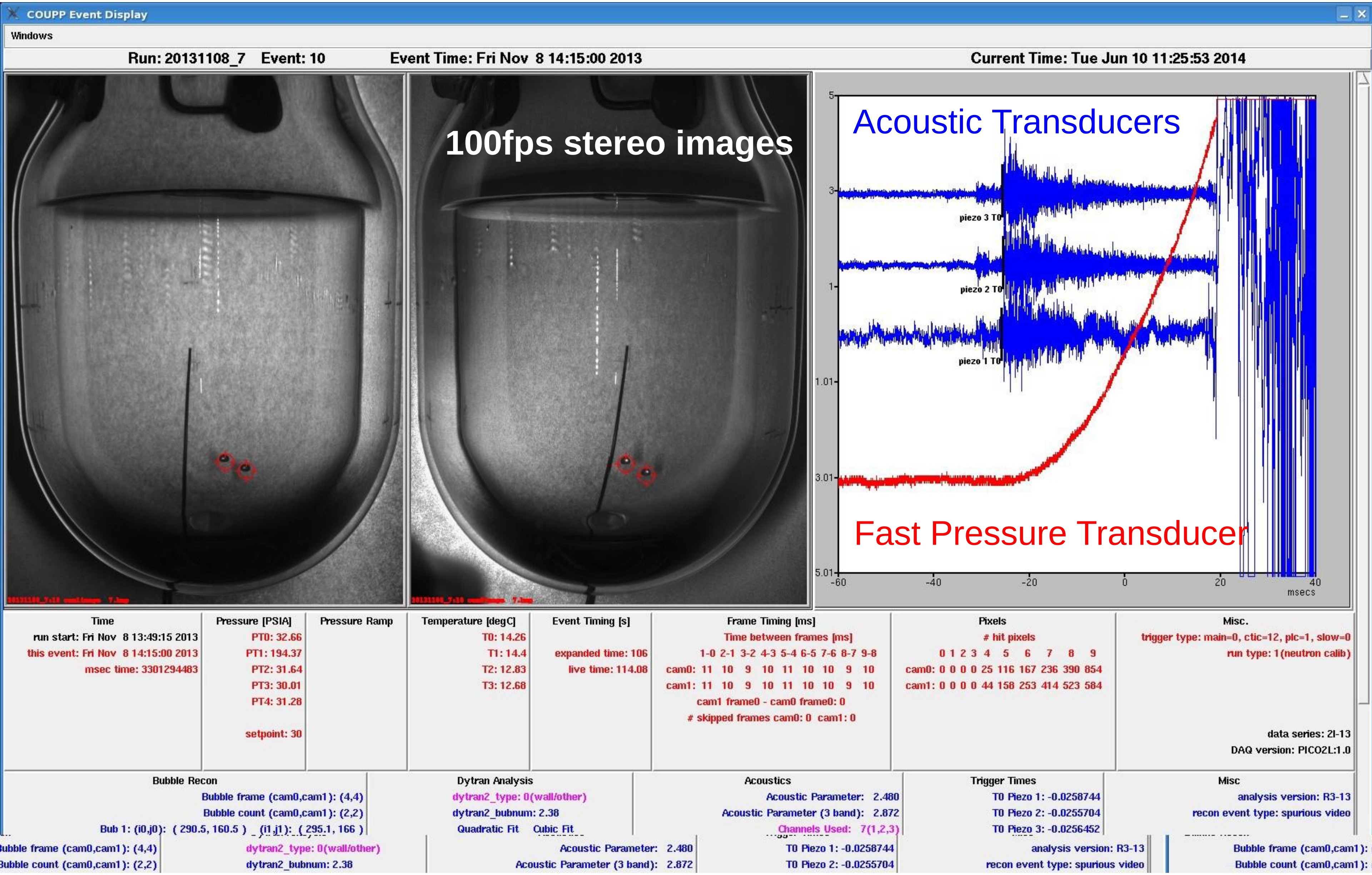




1. Lower the pressure to a superheated state.

2. See the bubble:
   - Cameras trigger. record position, multiplicity
   - Microphones record acoustic trace
   - Fast pressure transducer recording.

3. Raise pressure to stop bubble growth (100ms), reset chamber (30sec)



100fps stereo images

Acoustic Transducers

Fast Pressure Transducer

Run: 20131108_7 Event: 10 Event Time: Fri Nov 8 14:15:00 2013 Current Time: Tue Jun 10 11:25:53 2014

Time
run start: Fri Nov 8 13:49:15 2013
this event: Fri Nov 8 14:15:00 2013
msec time: 3301294483

Pressure [PSIA]
PT0: 32.66
PT1: 194.37
PT2: 31.64
PT3: 30.01
PT4: 31.28

setpoint: 30

Pressure Ramp

Temperature [degC]
T0: 14.26
T1: 14.4
T2: 12.83
T3: 12.68

Event Timing [s]
expanded time: 106
live time: 114.08

Frame Timing [ms]
Time between frames [ms]

```
      1-0 2-1 3-2 4-3 5-4 6-5 7-6 8-7 9-8
cam0:  11  10   9  10  11  10  10   9  10
cam1:  11  10   9  10  11  10  10   9  10
```

cam1 frame0 - cam0 frame0: 0
skipped frames cam0: 0 cam1: 0

Pixels
hit pixels

```
      0 1 2 3  4   5   6   7   8   9
cam0: 0 0 0 0 25 116 167 236 390 854
cam1: 0 0 0 0 44 158 253 414 523 584
```

Misc.
trigger type: main=0, ctic=12, plc=1, slow=0
run type: 1(neutron calib)

data series: 2l-13
DAQ version: PICO2L:1.0

Bubble Recon
Bubble frame (cam0,cam1): (4,4)
Bubble count (cam0,cam1): (2,2)
Bub 1: (i0,j0): (290.5, 160.5) (i1,j1): (295.1, 166)

Dytran Analysis
dytran2_type: 0(wall/other)
dytran2_bubnum: 2.38
Quadratic Fit Cubic Fit

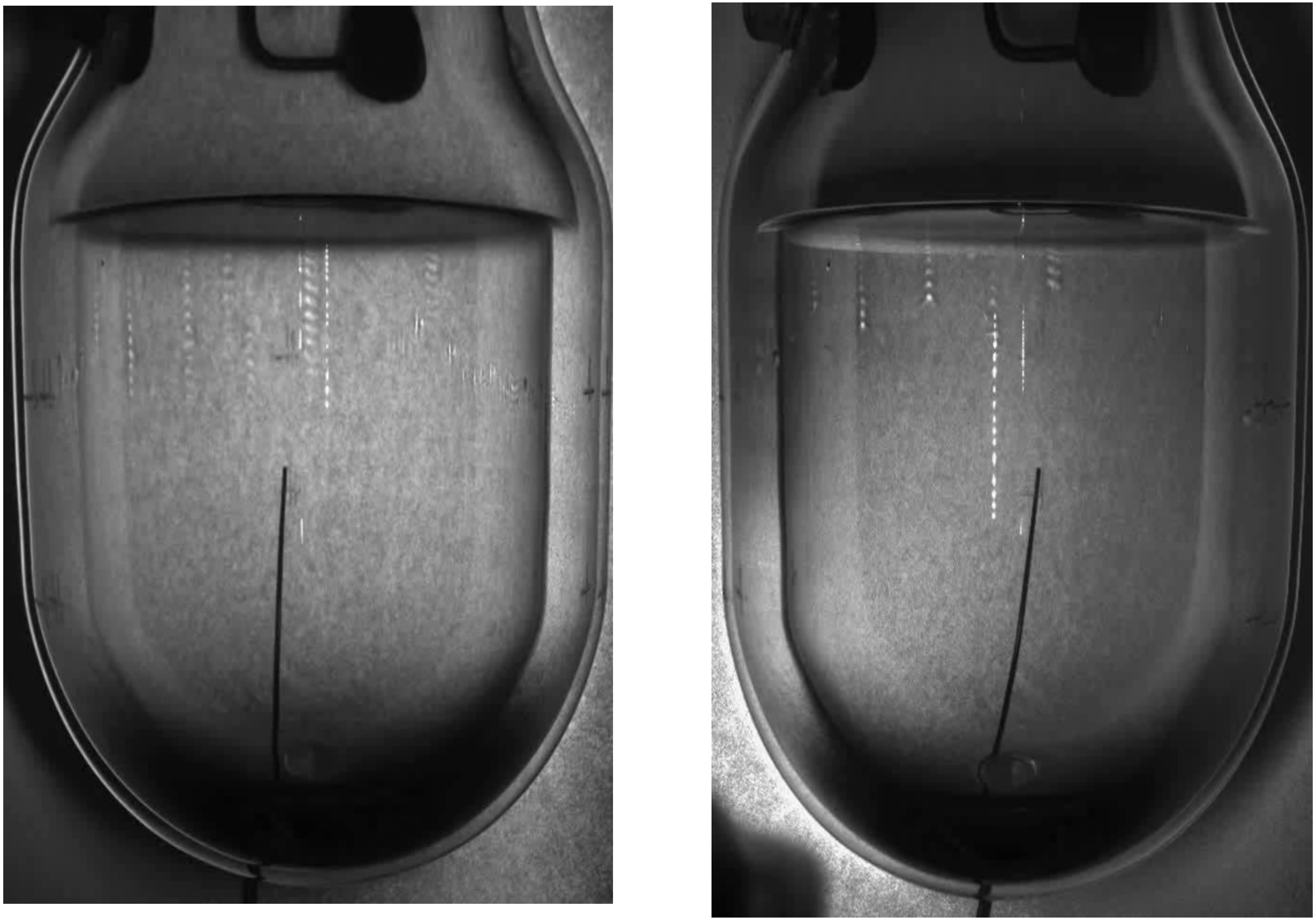
Acoustics
Acoustic Parameter: 2.480
Acoustic Parameter (3 band): 2.872
Channels Used: 7(1,2,3)

Trigger Times
T0 Piezo 1: -0.0258744
T0 Piezo 2: -0.0255704
T0 Piezo 3: -0.0256452

Misc
analysis version: R3-13
recon event type: spurious video

ubble frame (cam0,cam1): (4,4)
ubble count (cam0,cam1): (2,2)
dytran2_type: 0(wall/other)
dytran2_bubnum: 2.38
Acoustic Parameter: 2.480
Acoustic Parameter (3 band): 2.872
T0 Piezo 1: -0.0258744
T0 Piezo 2: -0.0255704
analysis version: R3-13
recon event type: spurious video
Bubble frame (cam0,cam1):
Bubble count (cam0,cam1):

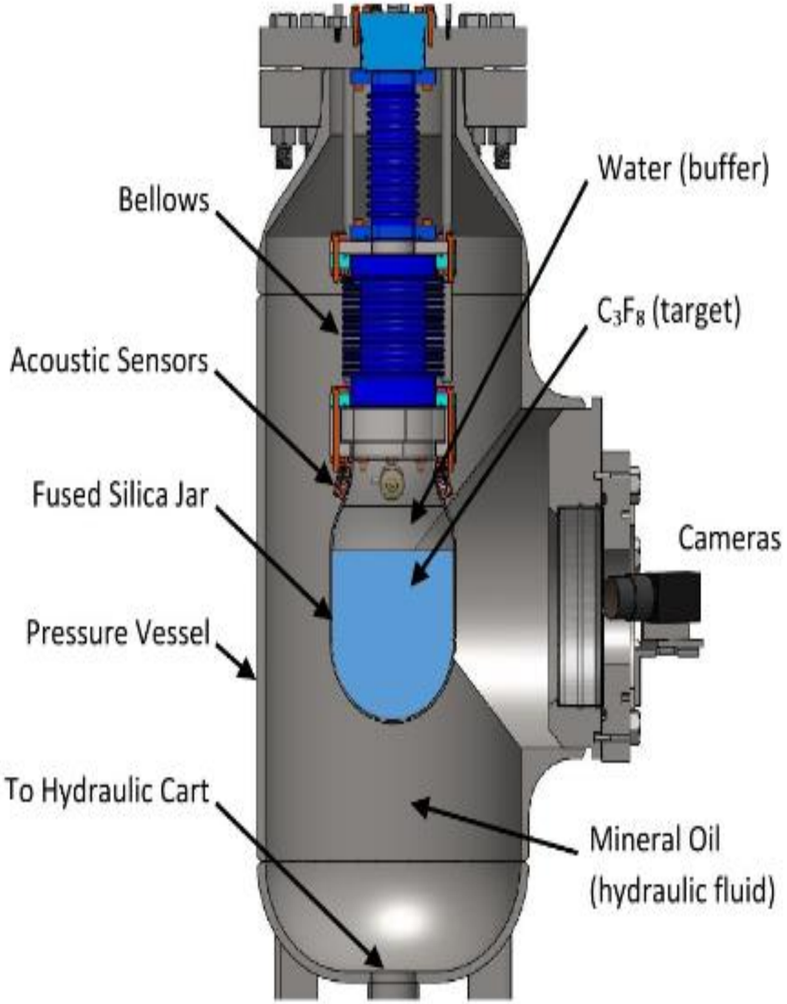
Screen Display during operations



PICO-2L

First joint PICO detector: a 2-litre detector filled with C_3F_8

C_3F_8 has better fluorine sensitivity, lower threshold, more stable chemistry



PICO-2L bellows & inner vessel assembly

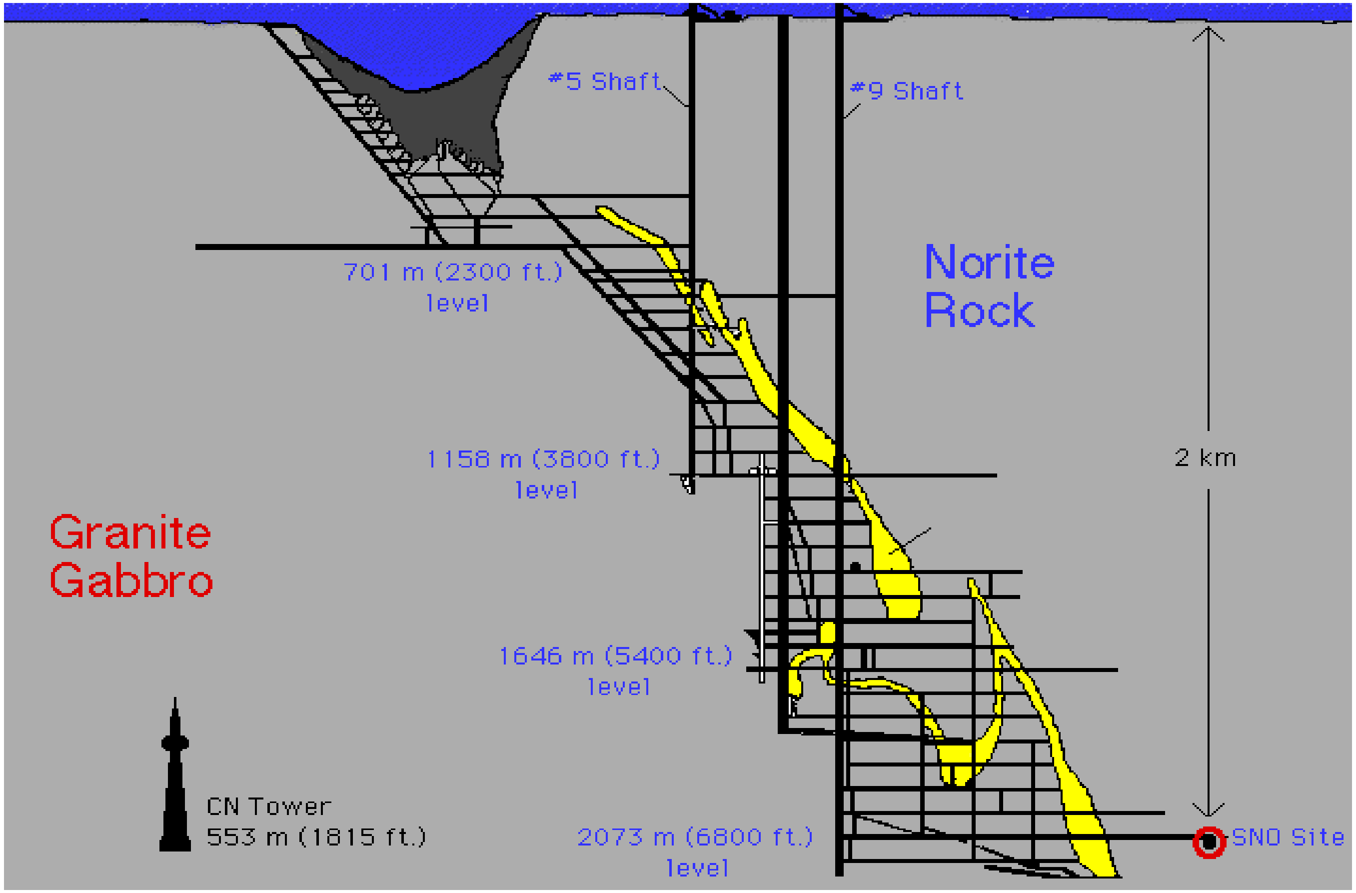
PICO-2L pressure vessel

Backgrounds:

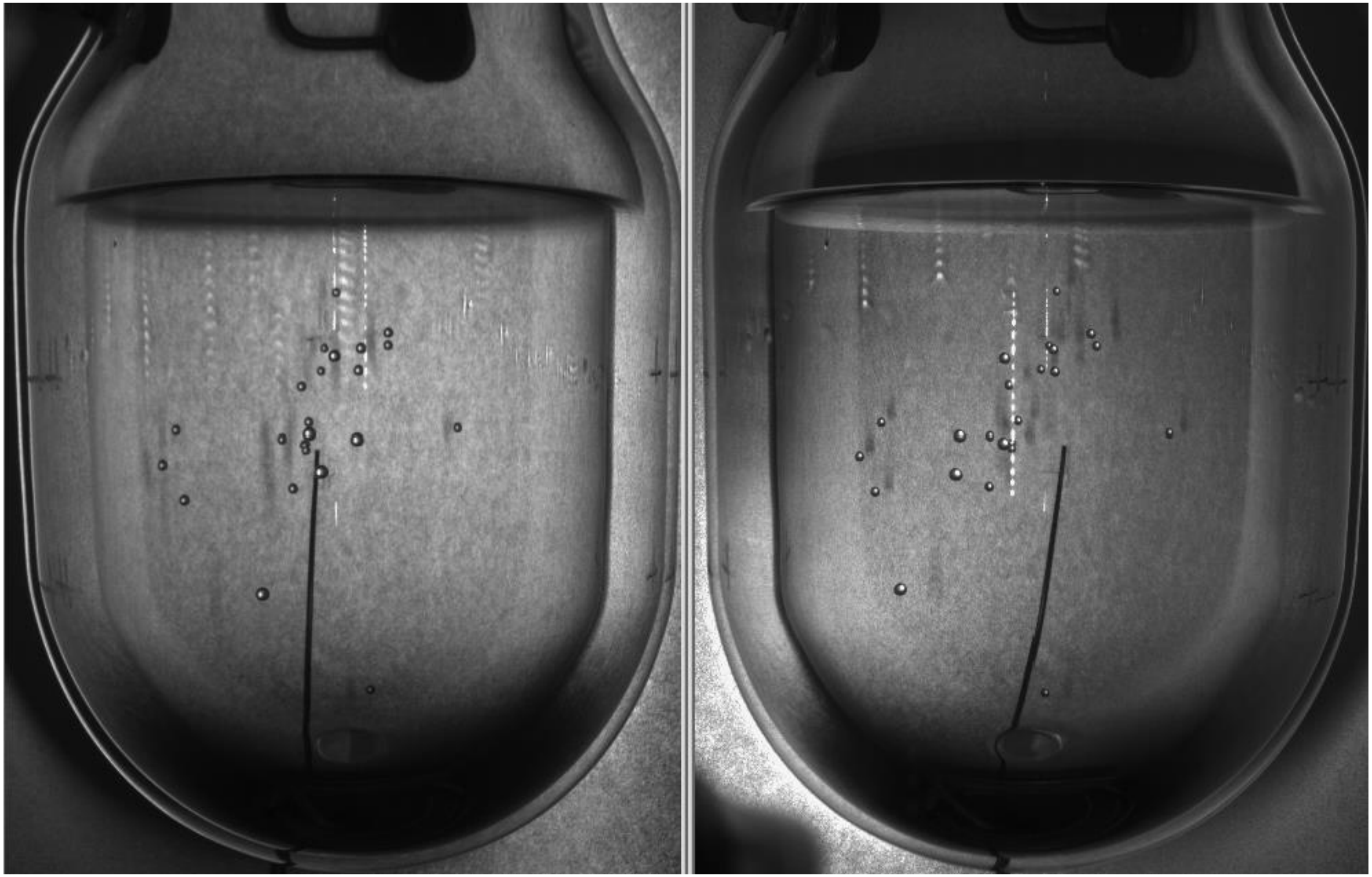
Require very low background environment to see rare events ….

- Go deep underground to escape cosmic rays.
- Provide local shielding
- Use materials with ultra-low levels of radioactivity
- **Develop particle discrimination techniques….**

SNOLAB, CANADA



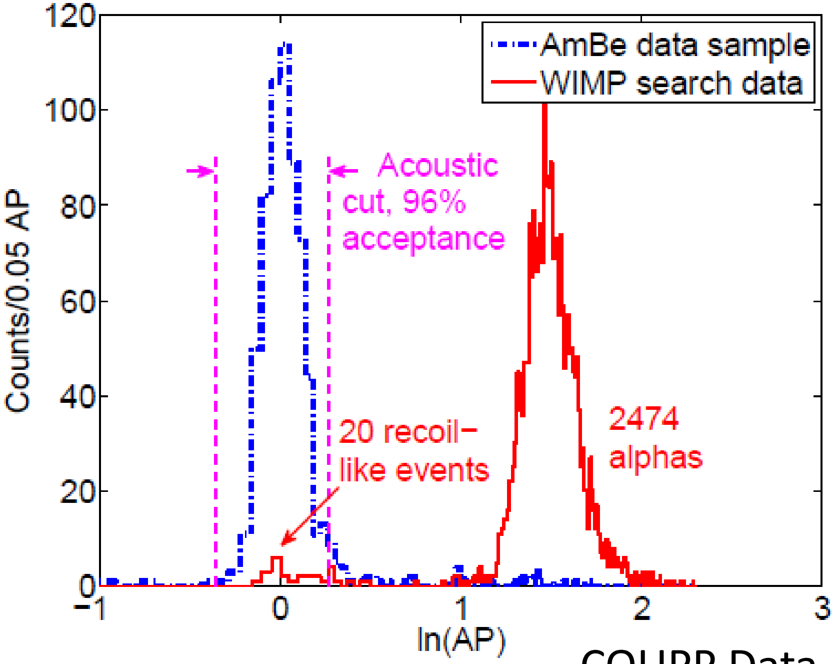
23 bubble AmBe neutron event



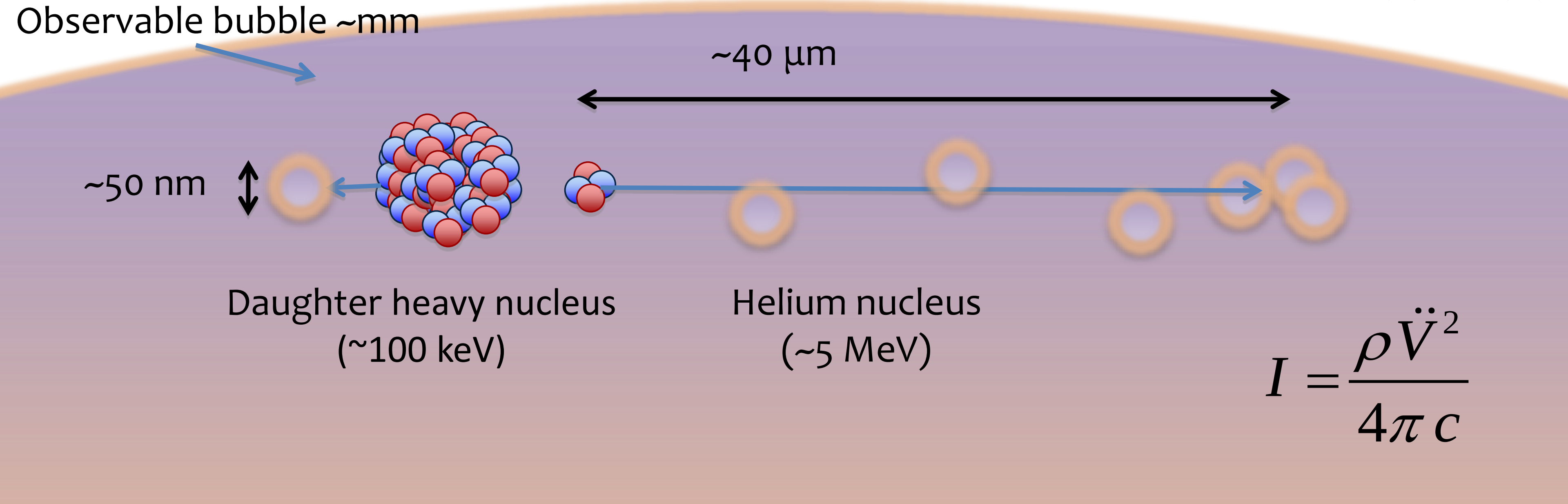
High multiplicity is a result of high bubble nucleation efficiency; 60% of neutron calibration events in C_3F_8 are multiples.

Alpha Acoustic Discrimination

- Discovery of acoustic discrimination between recoils and alphas in PICASSO (Aubin et al., New J. Phys.10:103017, 2008)
  - **Nuclear recoils** deposit their energy over tens of nanometers.
  - **Alphas** deposit their energy over tens of microns.
- In bubble chambers alphas are several times louder due to the expansion rate difference.



COUPP Data



Daughter heavy nucleus
(~100 keV)

Helium nucleus
(~5 MeV)

$$I = \frac{\rho \ddot{V}^2}{4\pi c}$$

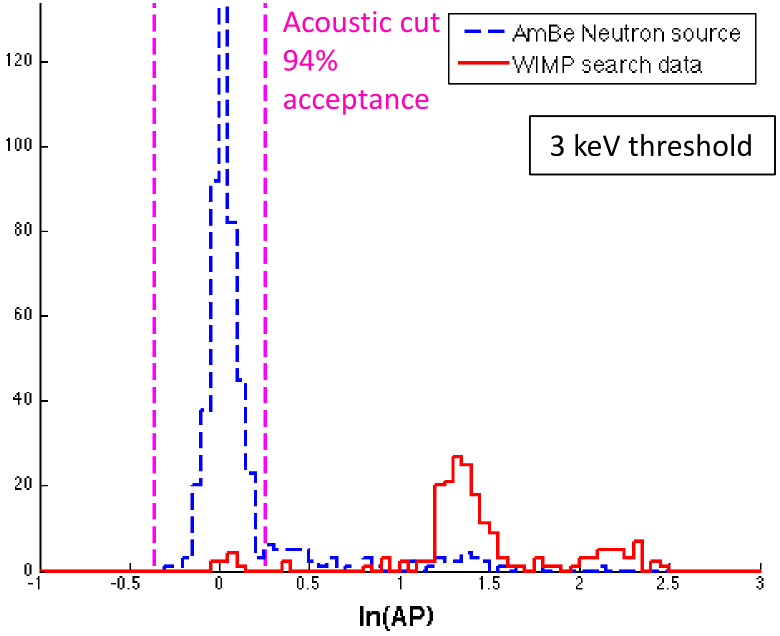
PICO-2L Analysis: Acoustic discrimination

- No multiple bubble events in the low background data
- Two distinct alpha peaks, clearly separated from nuclear recoils
- Timing of events in high AP peaks consistent with radon chain alphas, and indicate that the higher energy ^{214}Po alphas are significantly louder (a new effect not seen in CF_3I)

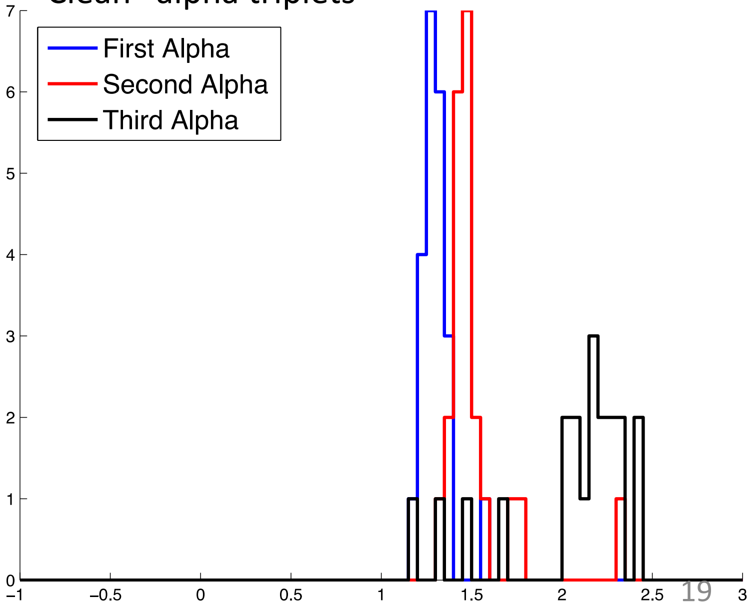
^{222}Rn α(5.6 MeV) → ^{218}Po α(6.1 MeV) → ^{214}Po α(7.9 MeV)

3 minutes

55 minutes

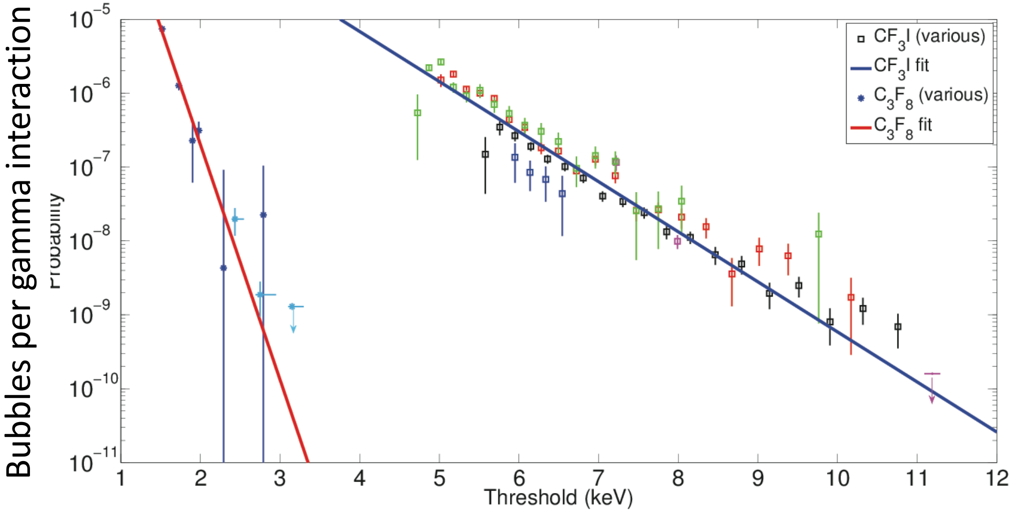


“Clean” alpha triplets

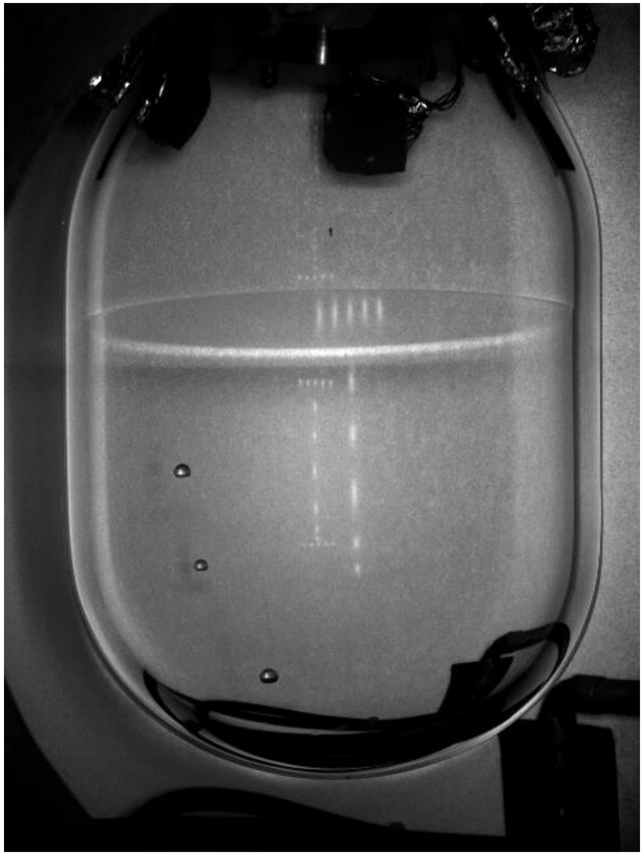


Background Rejection Summary

Gamma/Beta:
- Select materials carefully
- Operate detector above gamma threshold

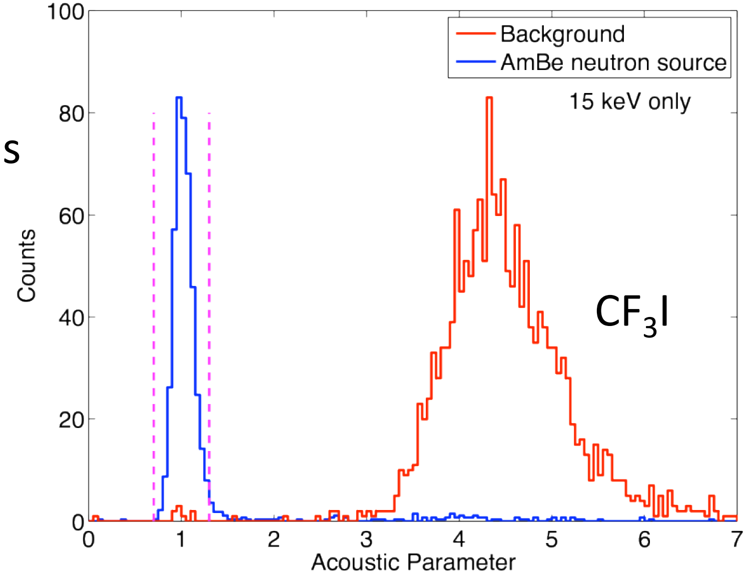


Neutrons:
- Go deep underground
- Add local shielding (water tanks)
- Select materials carefully
- Use multiplicity



Alpha-decay:
- Purify all materials
- Optimize piezo analysis

>99.3% Rejection

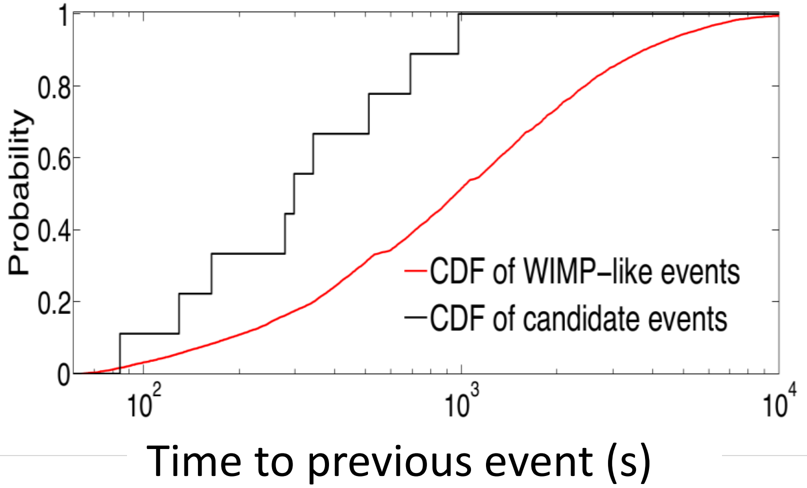


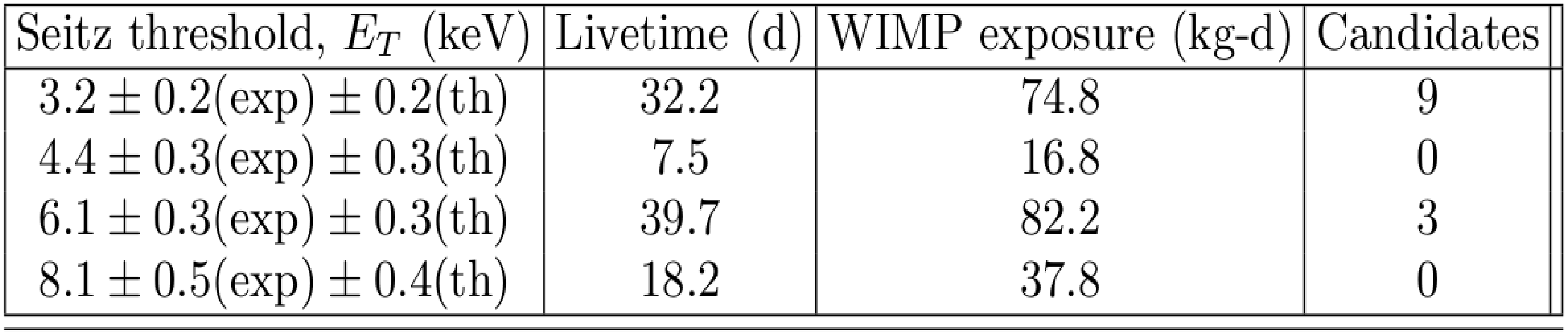
PICO-2L Results

arXiv:1503:00008

- Total exposure 212 kg-days
- 4 energy thresholds ranging from 3.2 to 8.1 keV
- **12 nuclear recoil candidate events (expected ~ 1 background event from neutrons and other sources)**
- Timing not consistent with uniform distribution. Use modified Yellin optimal inteval method
- **No evidence for a dark matter signal**

K-S test p-value = 0.04

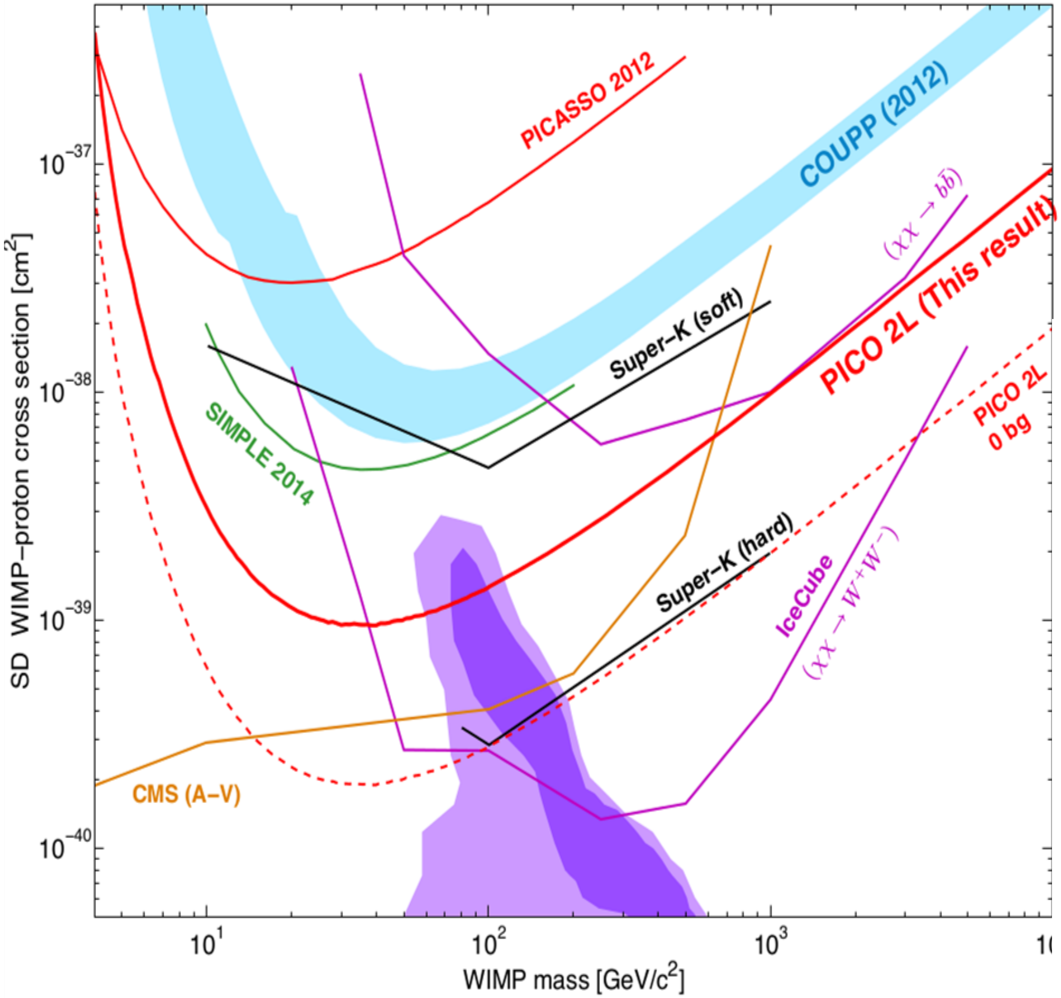




Seitz threshold, E_T (keV)	Livetime (d)	WIMP exposure (kg-d)	Candidates
$3.2 \pm 0.2(\text{exp}) \pm 0.2(\text{th})$	32.2	74.8	9
$4.4 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	7.5	16.8	0
$6.1 \pm 0.3(\text{exp}) \pm 0.3(\text{th})$	39.7	82.2	3
$8.1 \pm 0.5(\text{exp}) \pm 0.4(\text{th})$	18.2	37.8	0

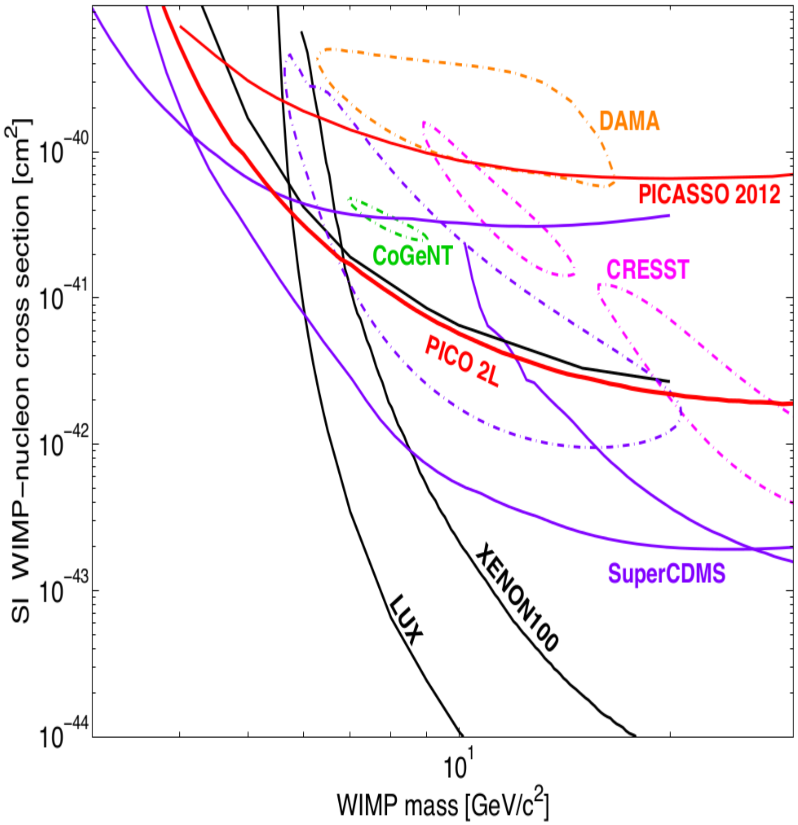
PICO-2L results

arXiv:1503:00008

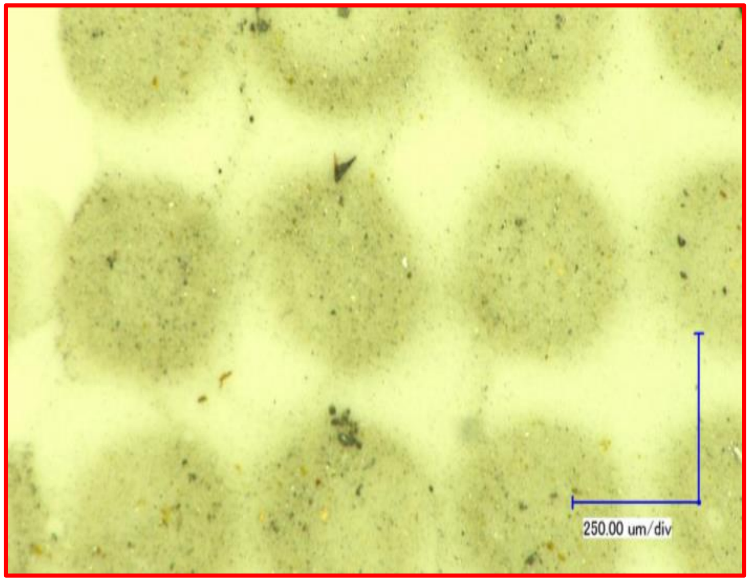


Spin dependent WIMP-proton 90% C.L.
World's best for direct detection!

Spin independent WIMP-nucleon 90% C.L.
PICO-2L challenges signal claims in the
low mass region!

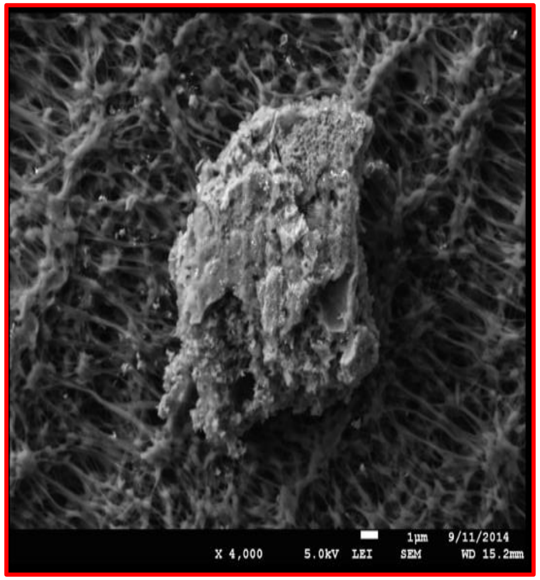


PICO-2L background forensics:



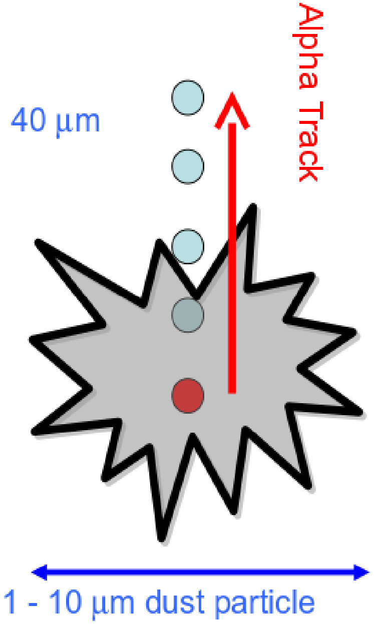
Filter sample from PICO-2L

- Leading hypothesis - particulate contamination
- ICPMS has found enough thorium to explain PICO-2L rate



XRF has identified many components chemically

- Stainless steel
- Quartz
- Gold (from seal)
- Silver (VCR parts?)



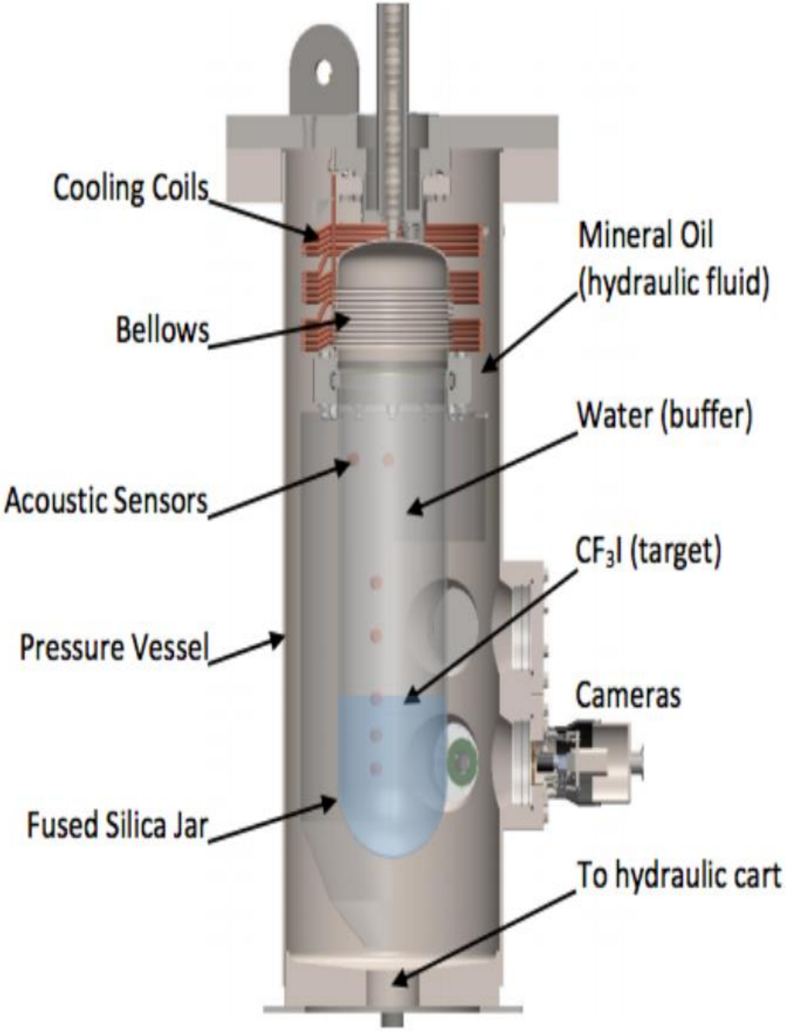
Anomalous background from degraded alpha tracks?

Current PICO-2L status

- PICO new run started early 2015
    - Natural quartz flange replaced with fused silica
    - 6 new piezo transducers
    - Cleaner fill
    - Better temperature control
    - New cameras
    - Camera cooling system
- Currently in stable operations and collecting data at 3 keV threshold

PICO-60

- 30L bubble chamber with ~ **60 kg C_3F_8** target
- Formerly known as COUPP-60 with CF_3I
- Moved at SNOLAB in summer 2014

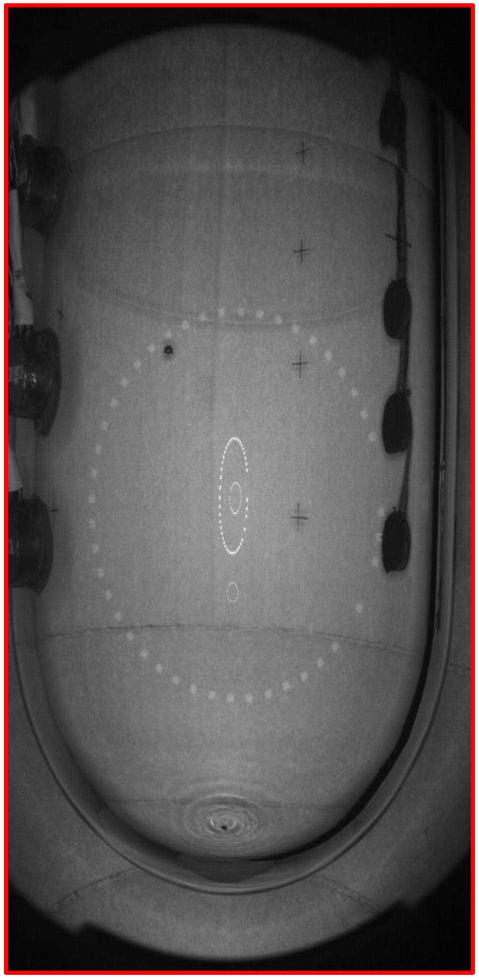


PICO-60

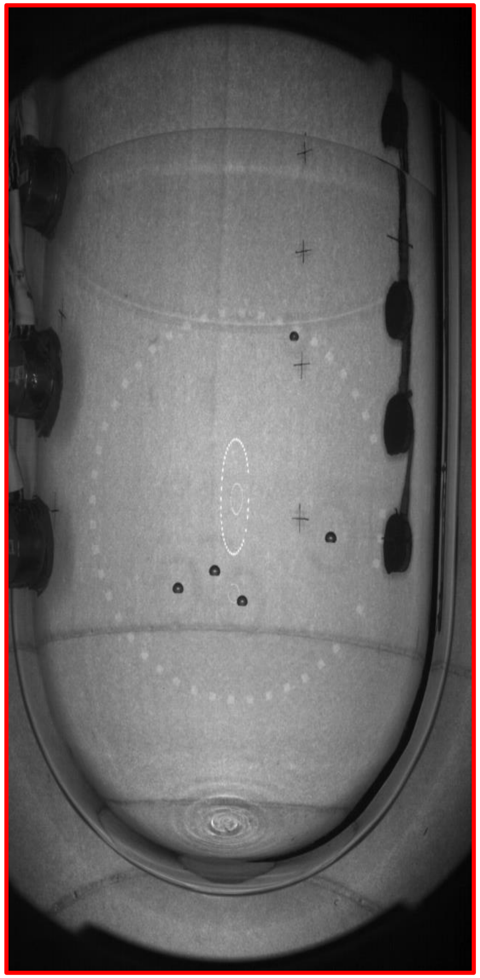
PICO-60 installation in water tank at Snolab

PICO-60
Pressure vessel
inside the water
tank at Snolab

PICO-60 inner vessel preparation



1-bubble event

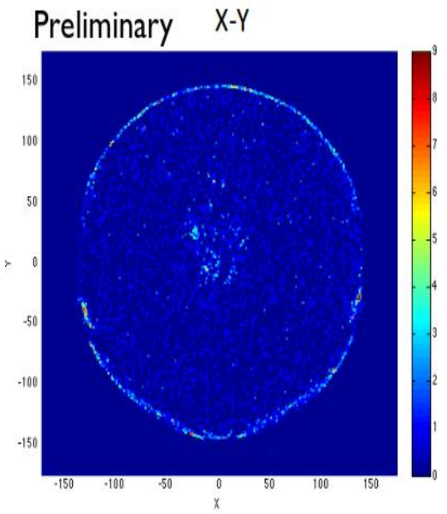


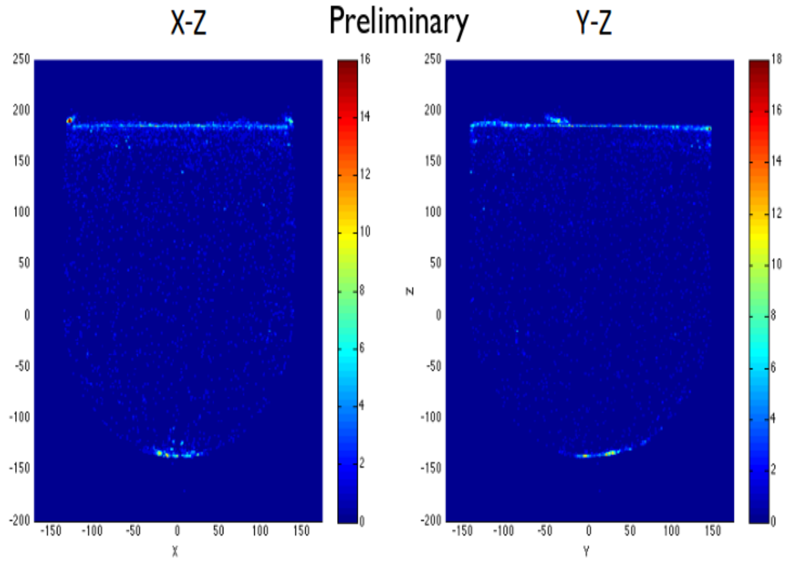
5-bubble event

- Filled with 36.8 kg of CF_3I at the end of April 2014
- Physics data started mid-June
- Collected >2700 kg-days of dark matter search data between 9 and 25 keV thresholds
- Good live fraction (>80%)
- Good detector performance
- Collected >1500 neutron events from calibration runs

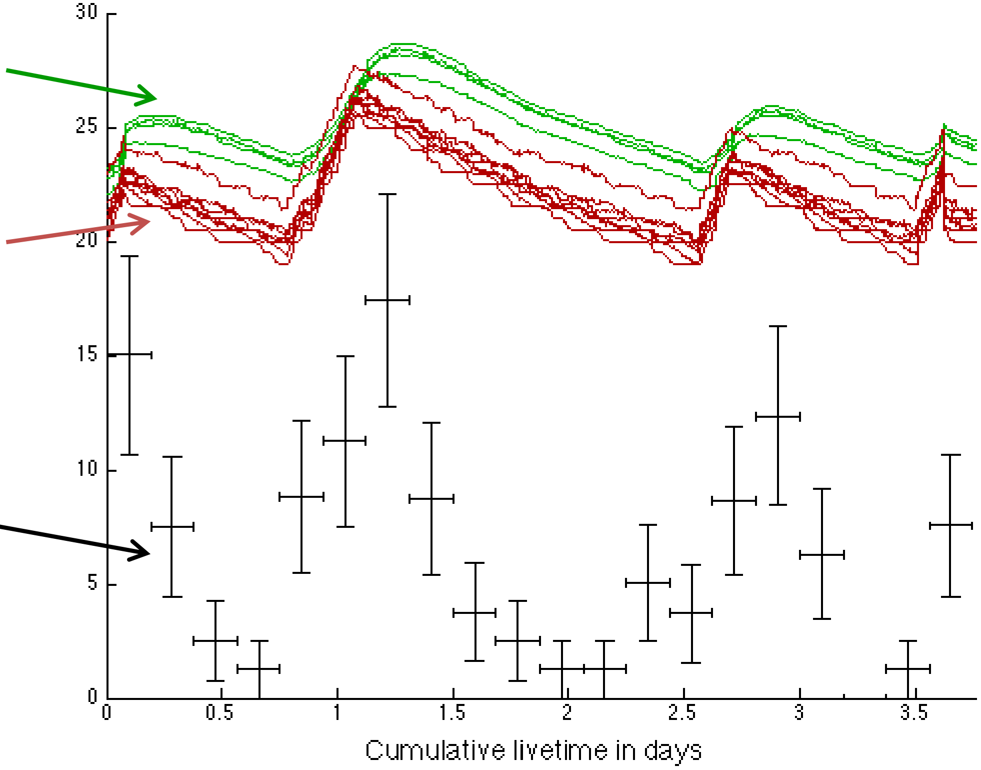
PICO-60 results

- Analysis near completion
- Clear set of events on surface and hemisphere: not a background thanks to fine position reconstruction
- Zero multiple bubbles during dark matter search runs: limit on neutron rate is a factor 6 below observed rate in COUPP-4
- Excellent acoustic discrimination
- Bad news: **population of events that sound like nuclear recoils but are clearly not WIMPS**
- Large number of anomalous events: we can study them in detail





Some classes of events clearly correlated with the temperature of the water and glycol …. Correlation with pump, heaters, electrical noise, vibrations, convection…?



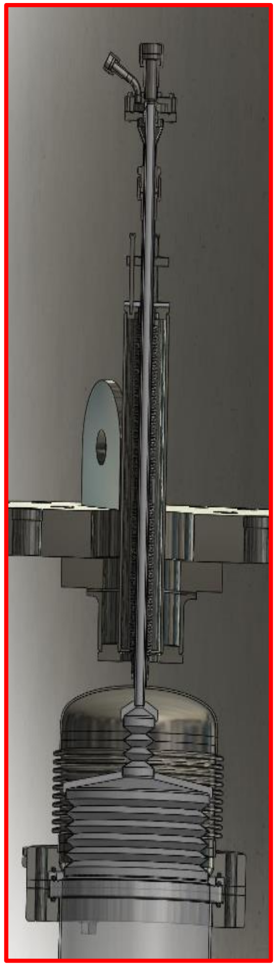
Temperature in Glycol
(not to scale)

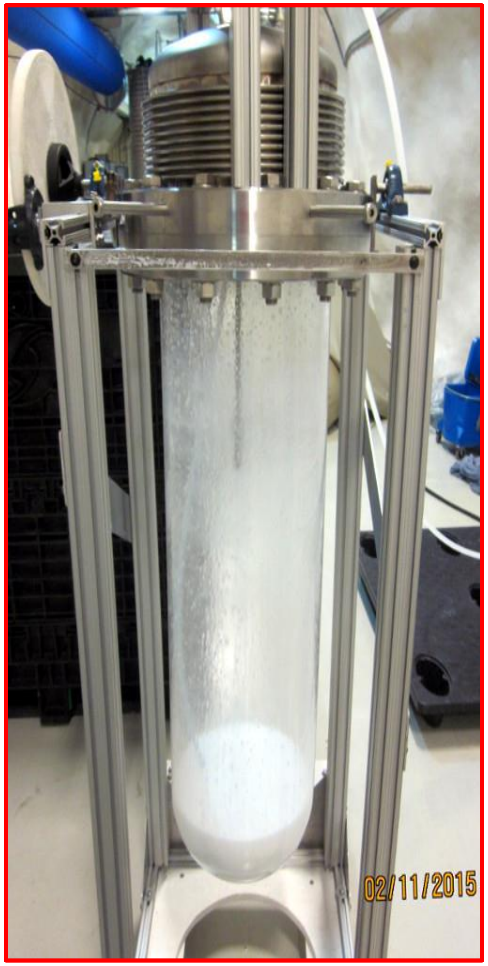
Temperature in Water
(not to scale)

Mystery-Event rate
(not to scale)

PICO-60 upgrade

- Particulate controls being worked on:
  - New fluid handling system: Removal of particulates from buffer and target liquids. 1L per minute flows through 100 nm filter
  - Inner volume high purity plastic bellows liner
  - Inner vessel cleaning with new spray wash system
- Swap the target from CF_3I to C_3F_8 (Lower threshold, better sensitivity in SD sector)
- Swap buffer liquid to LAB (Linear Alkyl Benzene)**?**



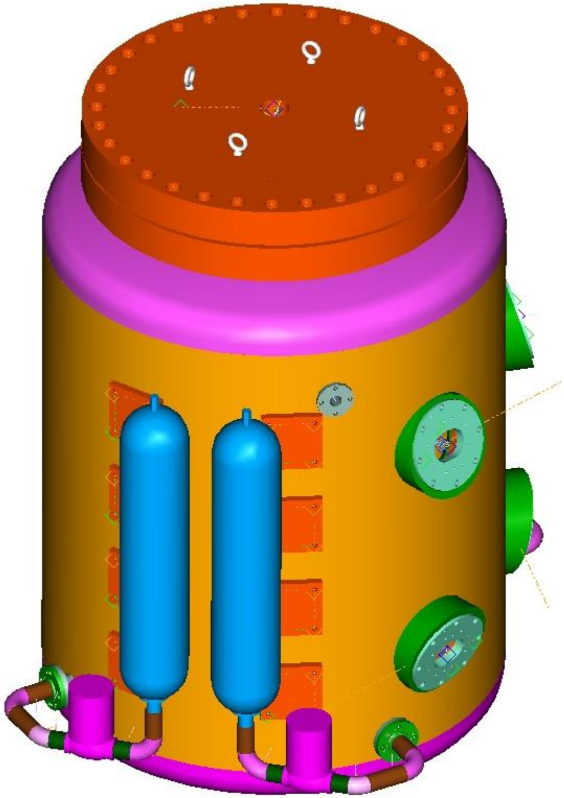


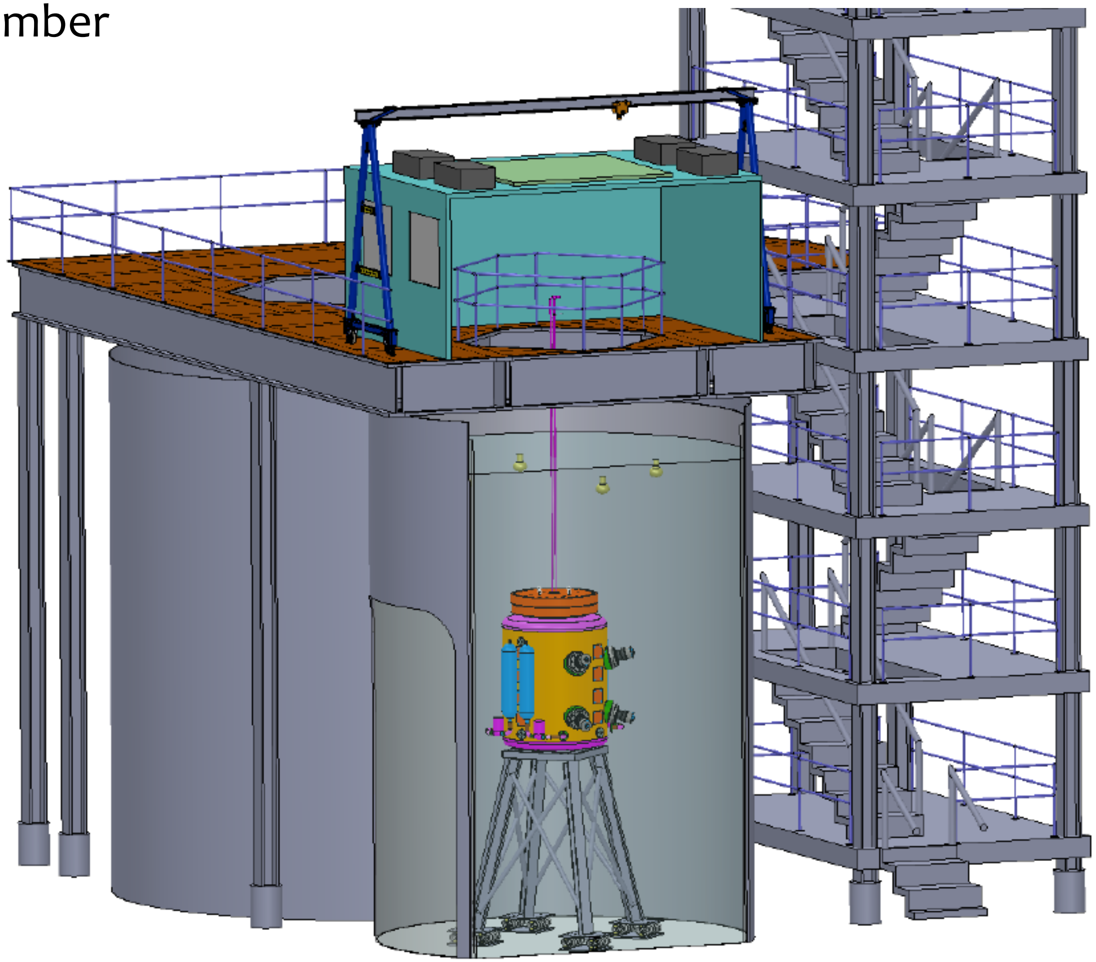
Engineering runs to begin this summer.

Publication on first results in preparation

PICO-250L

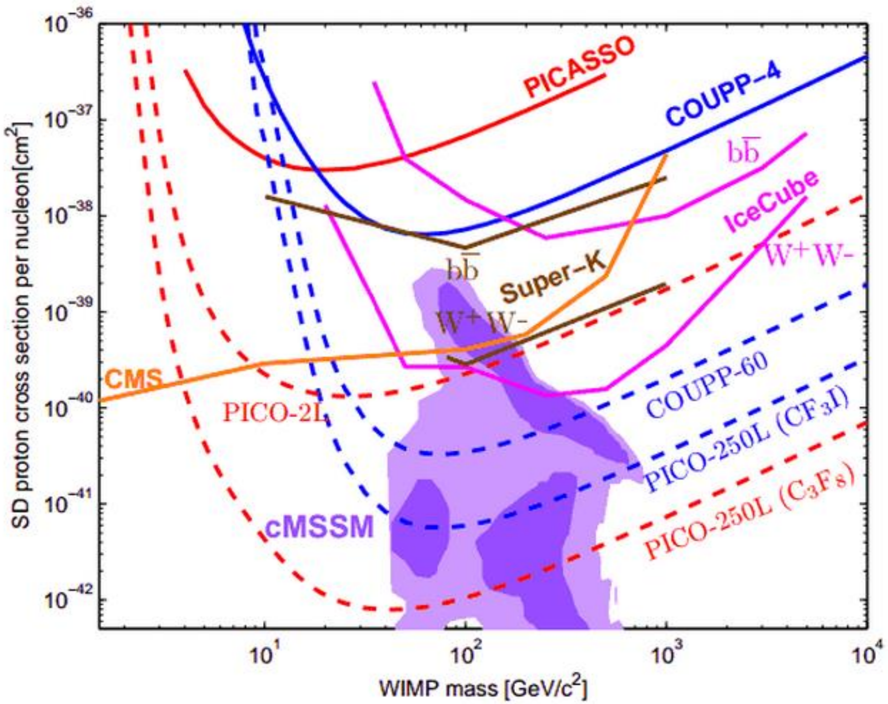
PICO-250L: ton-scale bubble chamber designed for CF_3I or C_3F_8 target



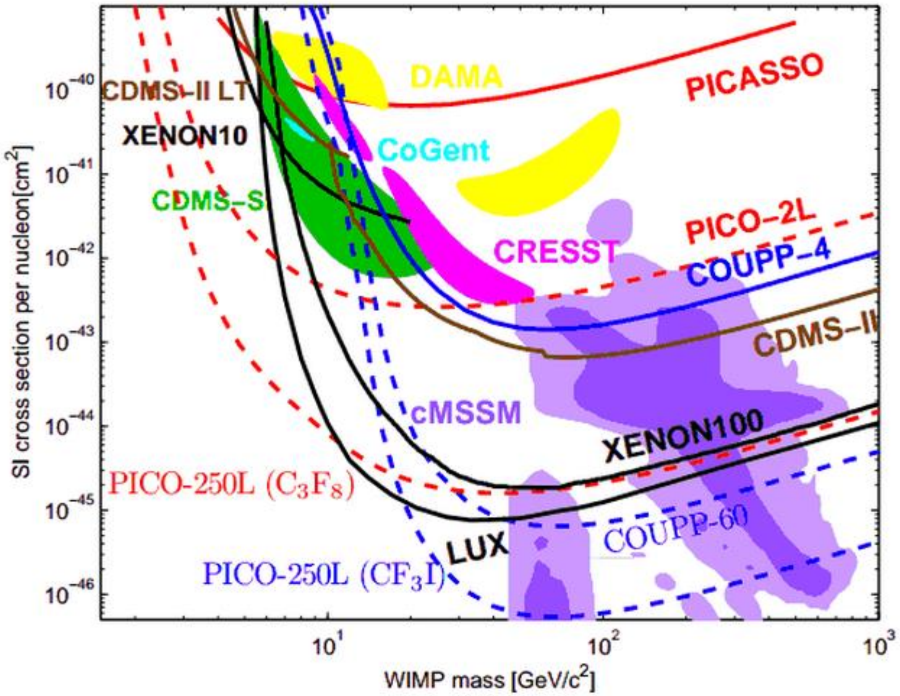


Sensitivity projections

Spin-Dependent



Spin-Independent



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

PICO-2L projection based on 100 live-days of background free data.

Conclusions:

- Bubble Chambers for Dark Matter are coming of age.
- Background free potential.
- Should “own” the Spin-Dependent Sector with C_3F_8
- Inexpensive, engineering understood, …

PICO-2L has demonstrated:

- Successful operation with C_3F_8 at 3keV nuclear recoil threshold
- No neutron background observed and good acoustic rejection of alphas
- **PICO-2L has a new world-best SD WIMP-proton limit**

Ongoing work

- Program to understand background (assays of particulate contamination, spiked test chambers)
- clean runs at SNOLAB with PICO 2L and soon PICO 60

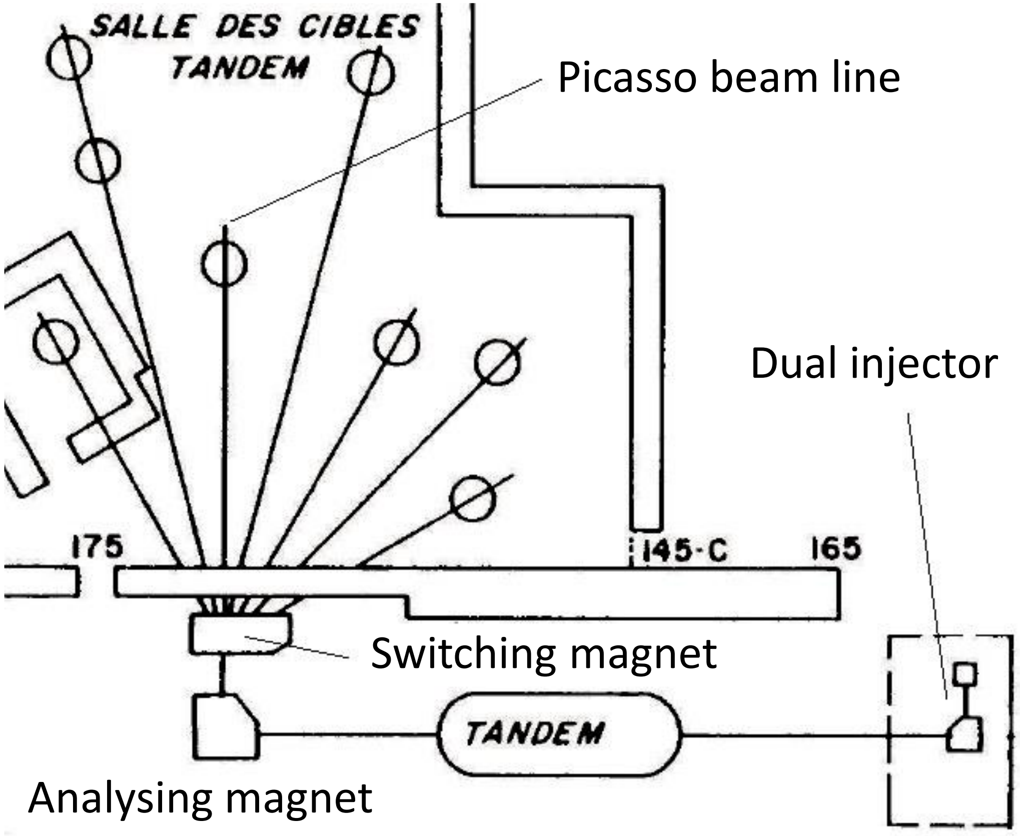
Understanding the Threshold

As a threshold detector, knowing the threshold is critical…But it is not easy:

- The threshold is not abrupt, but can be quite soft depending on the nucleus
- There are several nuclei (C, F, I) each with their own threshold.
- We use a variety of techniques for calibration:

^{241}Am-Be Source.	$^{9}\mathrm{Be}(\alpha,n)\mathrm{C}$	Broad spectrum source
^{88}Y- Be Source	$^{9}\mathrm{Be}(\gamma,n)^{8}\mathrm{Be}$	Monoenergetic n, 152keV
Pion beam scattering	$\pi^{-} + \mathrm{I} \rightarrow \pi^{-\prime} + \mathrm{I}'$	Scattering angle → I recoil energy
Montreal Tandem	$^{51}\mathrm{V}(p,n)^{51}\mathrm{Cr}$	Quasi-monoenergetic. Selectable

Montréal Tandem Van de Graaff



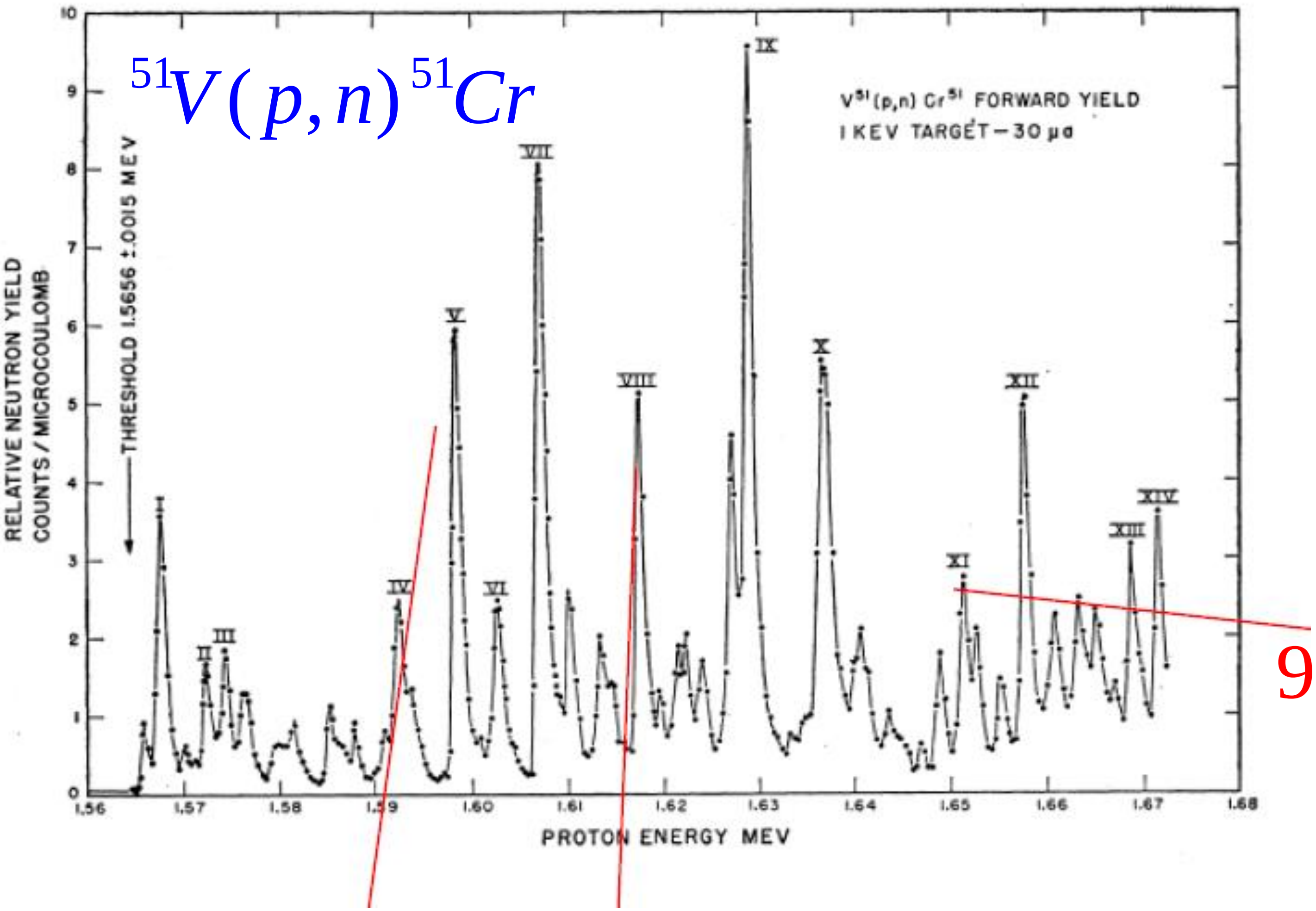
Picasso beam line

Dual injector

Switching magnet

Analysing magnet

By choosing the beam energy and scattering angle, one can generate a beam of quasi-mono-energetic neutrons.



$^{51}V(p,n)^{51}Cr$

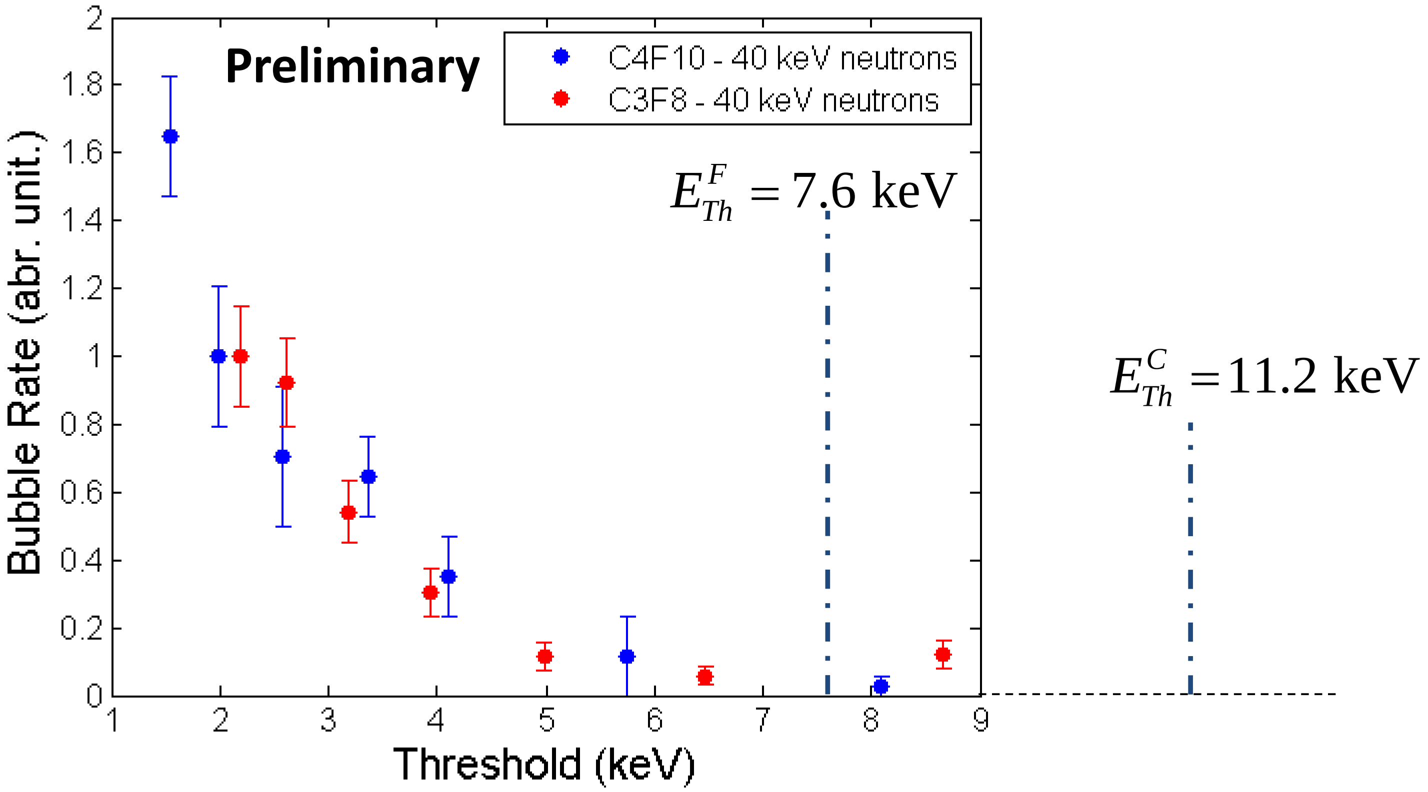
97 keV

40 keV

61 keV

Recent example… preliminary. 40 keV neutrons, scan temperature

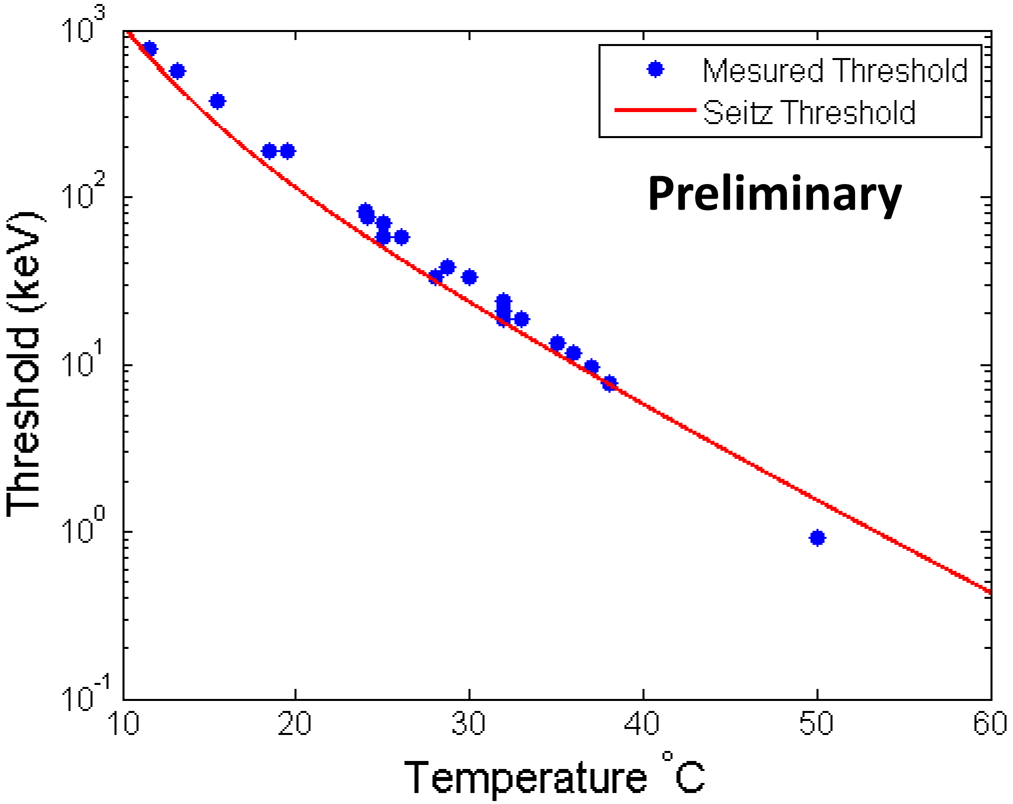
- Obtain shape of threshold.
- Good agreement with Seitz theory.



$$E_{Th}^{F} = 7.6 \text{ keV}$$

$$E_{Th}^{C} = 11.2 \text{ keV}$$

Good agreement between experimental results and theoretical predictions.



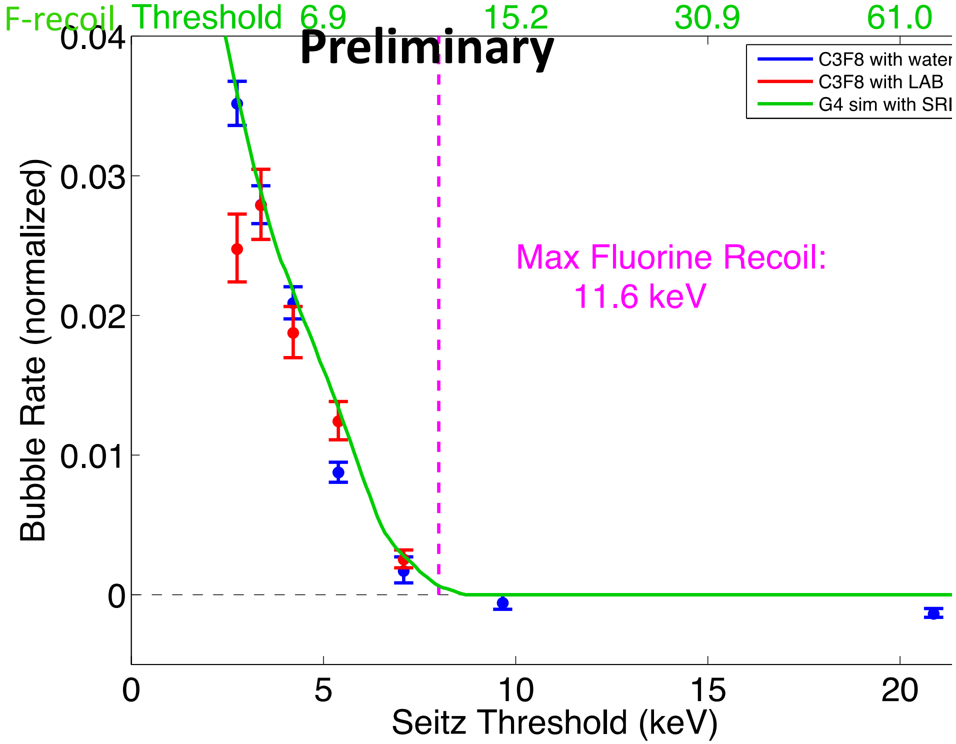
C_3F_8 Sensitivity Calibrations

In addition to in-situ AmBe calibrations we are calibrating the nuclear recoil response of C_3F_8 with low-energy neutron sources on test chambers.

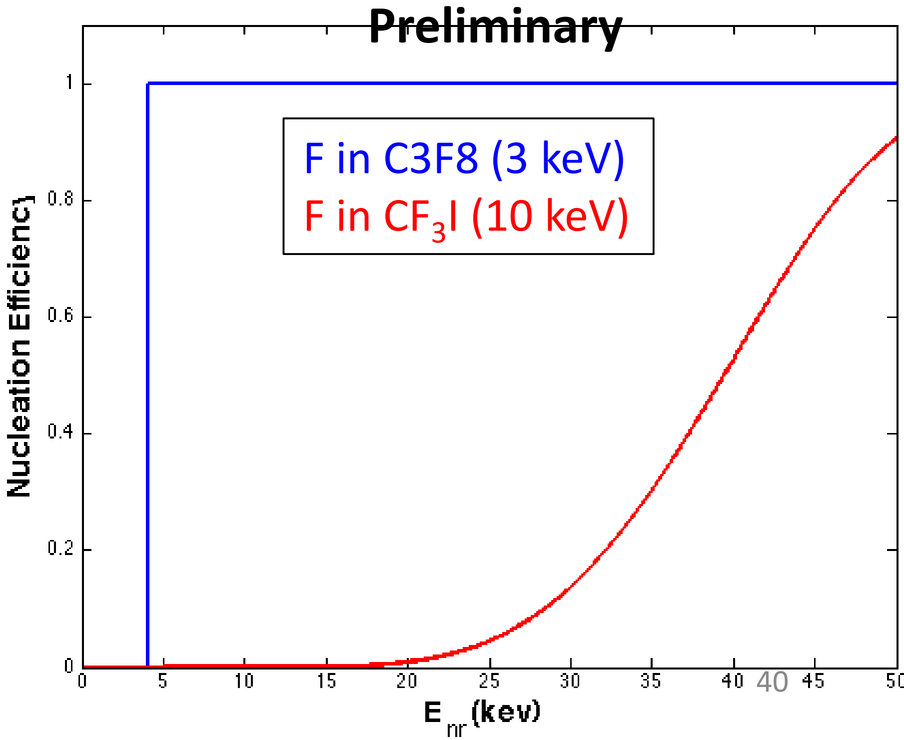
$^{51}V(p,n)$ at Montreal w/ Northwestern

$^{9}Be(\gamma,n)$ at U Chicago

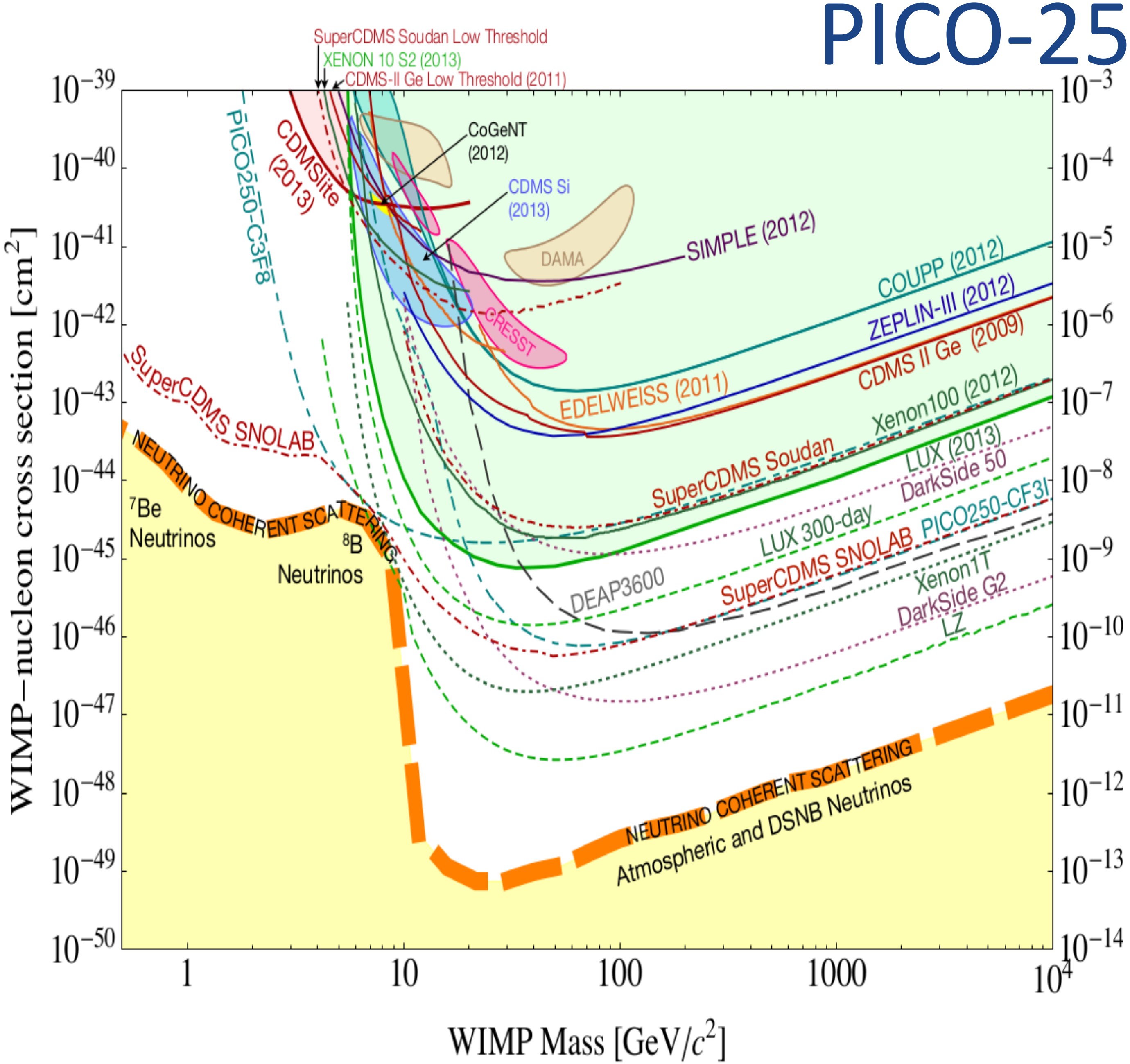
61-keV neutrons at Montreal Tandem van de Graaf



Fluorine Efficiency Model



PICO-250L


SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE (2012)
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
Xenon100 (2012)
LUX (2013)
DarkSide 50
SuperCDMS Soudan
LUX 300-day
PICO250-CF3I
SuperCDMS SNOLAB
Xenon1T
DarkSide G2
LZ
DEAP3600
CRESST
CDMSlite
(2013)
PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be
Neutrinos
^{8}B
Neutrinos
NEUTRINO COHERENT SCATTERING
Atmospheric and DSNB Neutrinos
WIMP–nucleon cross section [cm^2]
10^{-39}
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10^{-47}
10^{-48}
10^{-49}
10^{-50}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
1
10
100
1000
10^4
WIMP Mass [GeV/c^2]