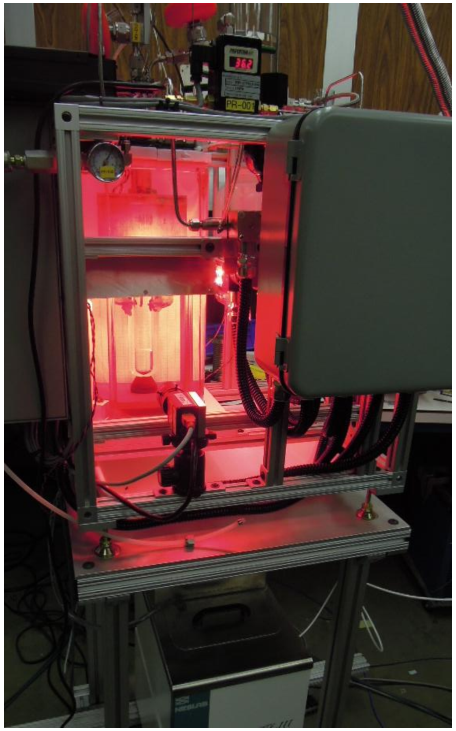
PICO: Dark Matter Direct Detection with Bubble Chambers



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SNOLAB – Mining for Knowledge – Creuser pour trouver... l'excellence
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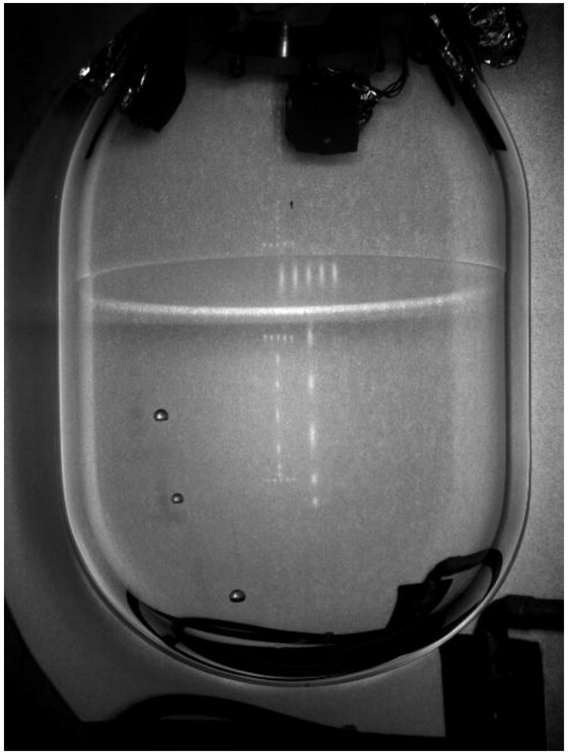
Outline

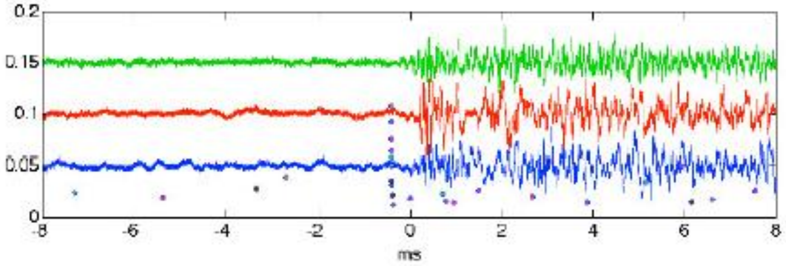
- Introduction to PICO bubble chambers.

- Past/present/future PICO bubble chambers
  – COUPP-4 (past)
  – COUPP-60 (present)
  – PICO-2L (present)
  – PICO-250L (future)

PICO bubble chambers

- COUPP-4: superheated fluid 4 kg of CF_3I
- Observe bubbles with two cameras and piezo-acoustic sensors.





Particle detection with bubble chambers

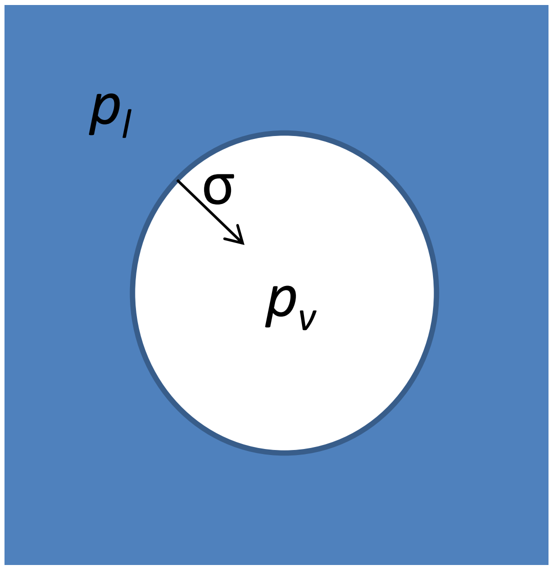
- A bubble chamber is filled a superheated fluid in meta-stable state.
- Energy deposition greater than E_{th} in radius less than r_c from particle interaction will result in expanding bubble *(Seitz "Hot-Spike" Model).*
- A smaller or more diffuse energy deposit will create a bubble that immediately collapses.
- Classical Thermodynamics says-

$$p_v - p_l = \frac{2\sigma}{r_c}$$

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

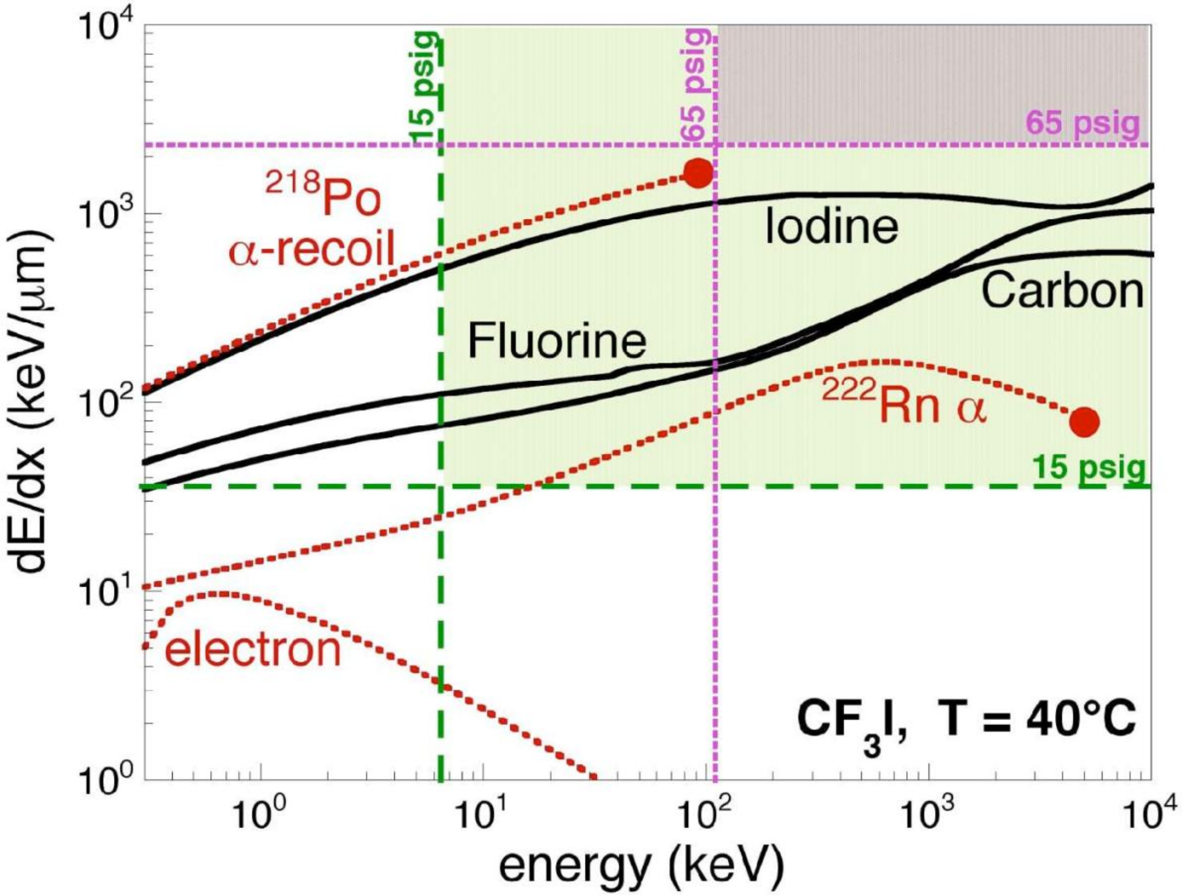
Surface energy

Latent heat



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.

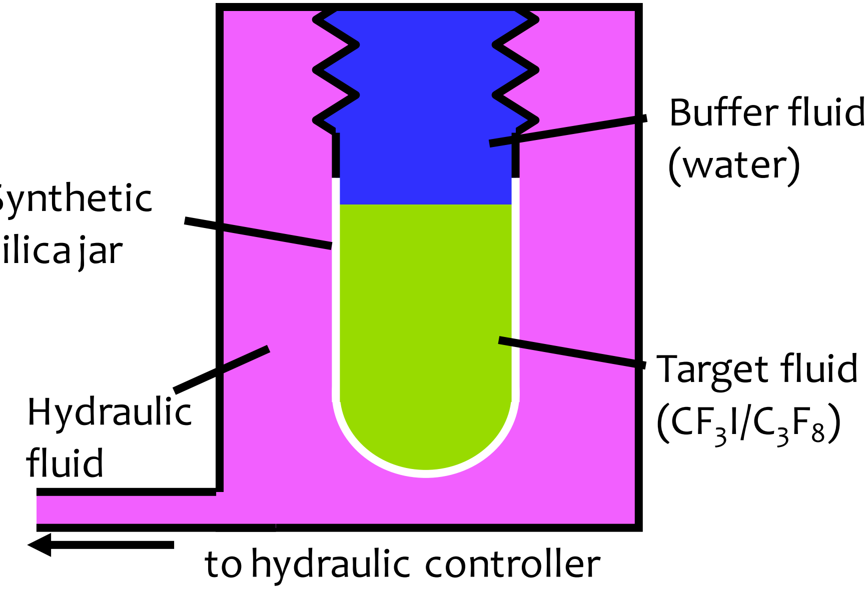


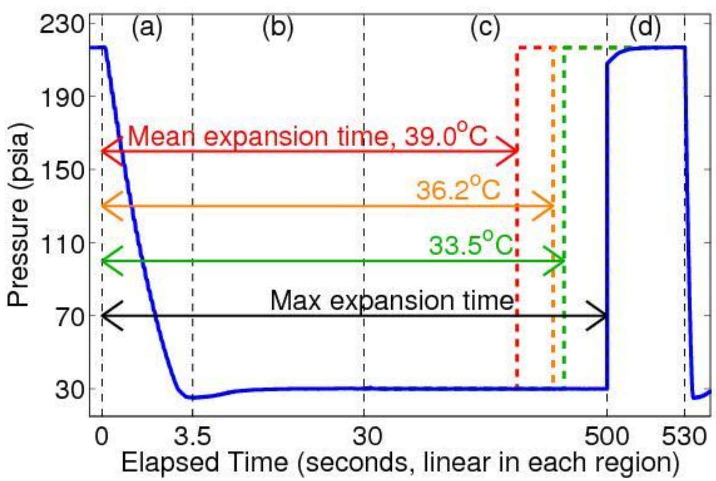
Bubble chamber operation

- Expand the chamber to the superheated state (10sec).

- Cameras see the bubble
  - Trigger
  - Stereoscopic position information

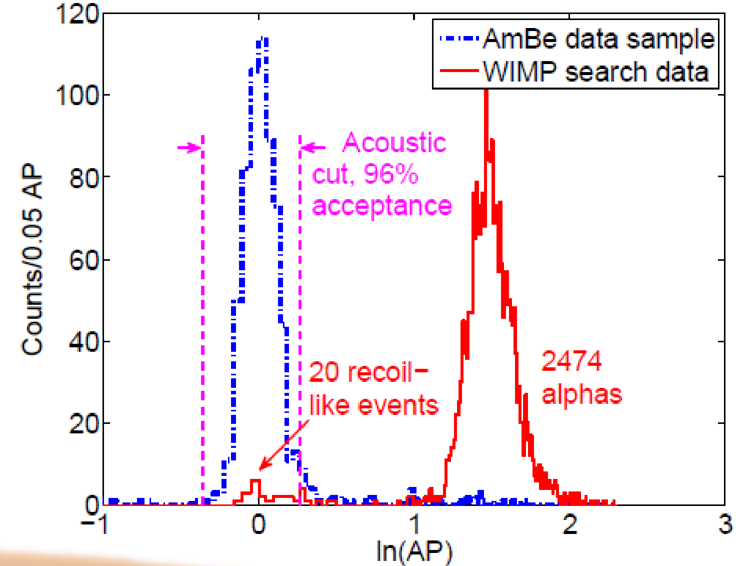
- Recompress the chamber (100msec) and wait 30sec after every bubble.

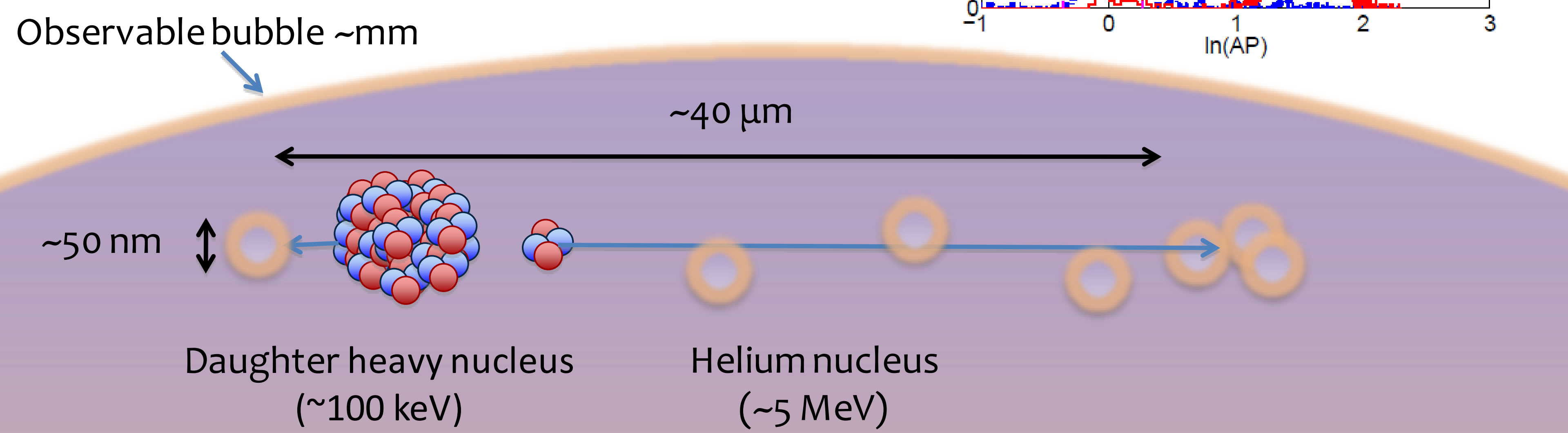




Acoustic discrimination

- Discovery of acoustic discrimination against alphas (Aubin et al., New J. Phys.10:103017, 2008)
  - Alphas deposit their energy over tens of microns.
  - Nuclear recoils deposit theirs over tens of nanometers.
- In COUPP bubble chambers alphas are several times louder.





Bubble chamber fluids

- Could make a dark matter bubble chamber with any liquid.
- Fluorocarbons are ideal:
  - Superheated fluid at room temperature and pressure.
  - Not flammable.
  - Low toxicity.
  - Fluorine is ideal spin-dependent target.
  - Fluorine can be replaced with high-mass halogen (Cl, Br, I) for improved A^2 enhancement.
- COUPP/PICO bubble chambers have until now used CF_3I as active fluid. Now also C_3F_8.

Spin-independent — Spin-dependent

$$\sigma_0 = \frac{4\mu^2}{\pi}\left[f_p N_p + f_n N_n\right]^2 + \frac{32 G_F^2 \mu^2}{\pi}\frac{J+1}{J}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2$$

Nucleus	Z	Odd Nucleon	J	$\langle S_p\rangle$	$\langle S_n\rangle$	C_A^p/C_p	C_A^n/C_n
^{19}F	9	p	1/2	0.477	-0.004	9.10×10^{-1}	6.40×10^{-5}
^{23}Na	11	p	3/2	0.248	0.020	1.37×10^{-1}	8.89×10^{-4}
^{27}Al	13	p	5/2	-0.343	0.030	2.20×10^{-1}	1.68×10^{-3}
^{29}Si	14	n	1/2	-0.002	0.130	1.60×10^{-5}	6.76×10^{-2}
^{35}Cl	17	p	3/2	-0.083	0.004	1.53×10^{-2}	3.56×10^{-5}
^{39}K	19	p	3/2	-0.180	0.050	7.20×10^{-2}	5.56×10^{-3}
^{73}Ge	32	n	9/2	0.030	0.378	1.47×10^{-3}	2.33×10^{-1}
^{93}Nb	41	p	9/2	0.460	0.080	3.45×10^{-1}	1.04×10^{-2}
^{125}Te	52	n	1/2	0.001	0.287	4.00×10^{-6}	3.29×10^{-1}
^{127}I	53	p	5/2	0.309	0.075	1.78×10^{-1}	1.05×10^{-2}
^{129}Xe	54	n	1/2	0.028	0.359	3.14×10^{-3}	5.16×10^{-1}
^{131}Xe	54	n	3/2	-0.009	-0.227	1.80×10^{-4}	1.15×10^{-1}

COUPP-4 results

PRD 86:052001 (2012)

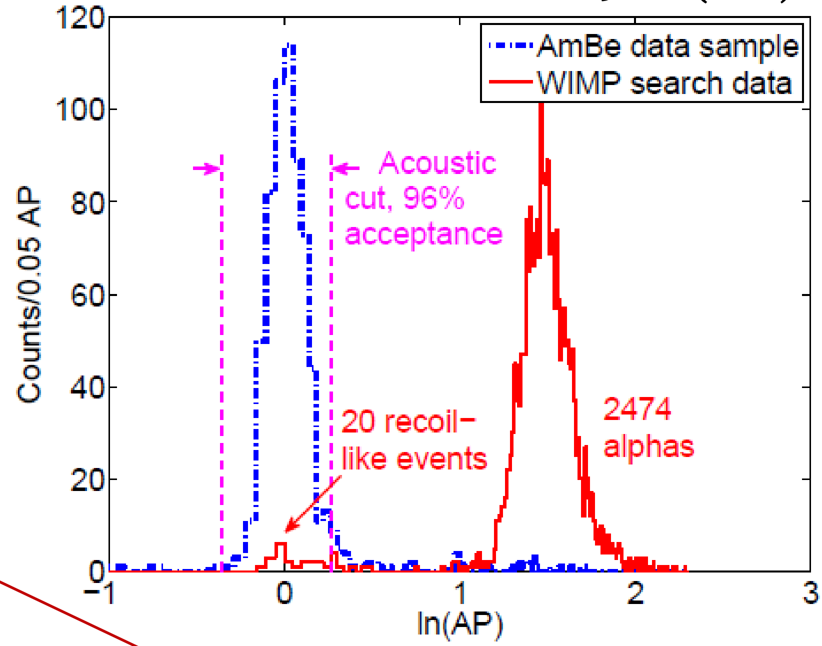
- 20 WIMP candidates
  - 6 at 8keV
  - 6 at 11keV
  - 8 at 16keV

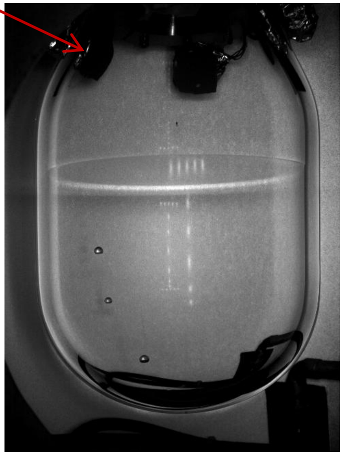
- 3 multiple bubble events → **neutrons**

- 5 expected neutron events from U, Th (α,n) in piezo-acoustic sensors and viewport windows.

- Recoil-like events at low threshold show time clustering, inconsistent with both WIMPs and neutrons.

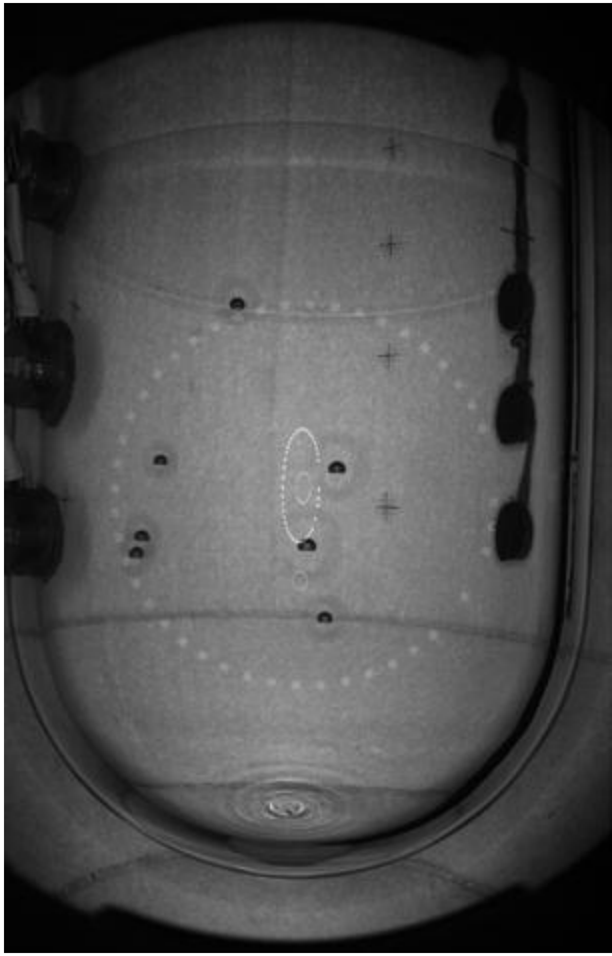
- A second run in 2012 after replacing known neutron sources had similar results (Eric Vazquez Jauregui, Moriond, 2013).





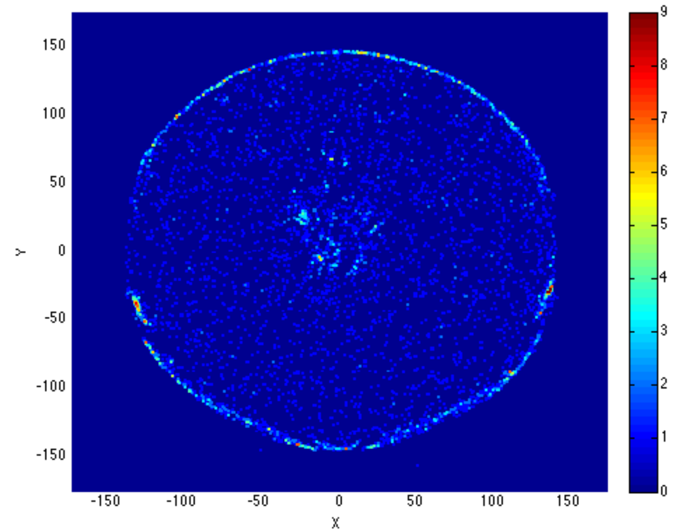
COUPP-60

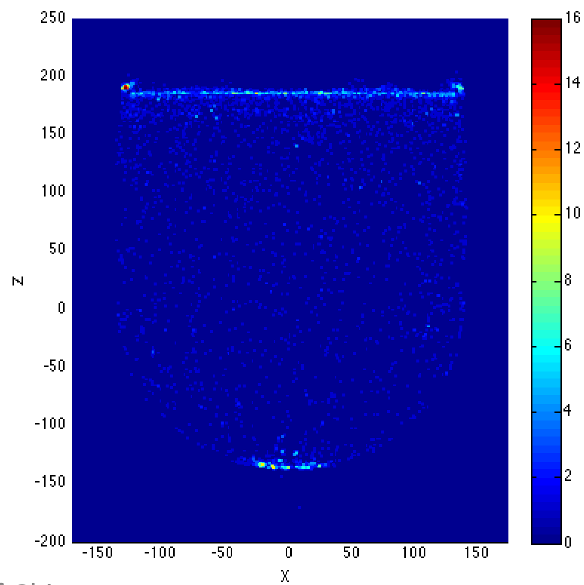
- 37kg CF_3I target (75kg possible in future).
- Taking data since June 2013 at SNOLAB (with ~ 2 month break to fix a hydraulic leak).
- More than 1500 kg-days exposure so far between 10keV and 20keV threshold.



COUPP-60 data

- Zero multiple bubbles
  - No neutron background.
- But , a population of events that sound similar to nuclear recoils but are clearly not WIMPs.
  - Non-istropic distribution.
  - Time dependence.
  - Appear louder on average than nuclear recoils.
  - This population is being studied in detail.

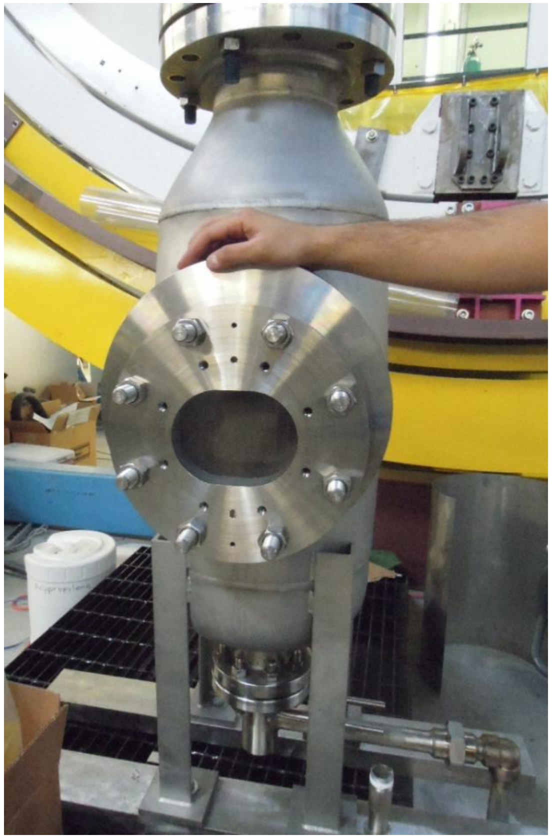




PICO-2L

- Two liter active mass (same as COUPP-4):
  - Re-uses COUPP-4 location, neutron shield, other infrastructure.
- New active fluid
  - C_3F_8 instead of CF_3I.
  - Better fluorine sensitivity:
    - Twice the F density.
    - Lower threshold.
    - Improved efficiency.
    - More stable chemistry.
- New hardware:
  - Lower background.
  - Simpler controls.
  - Prototyping for ton-scale experiment.

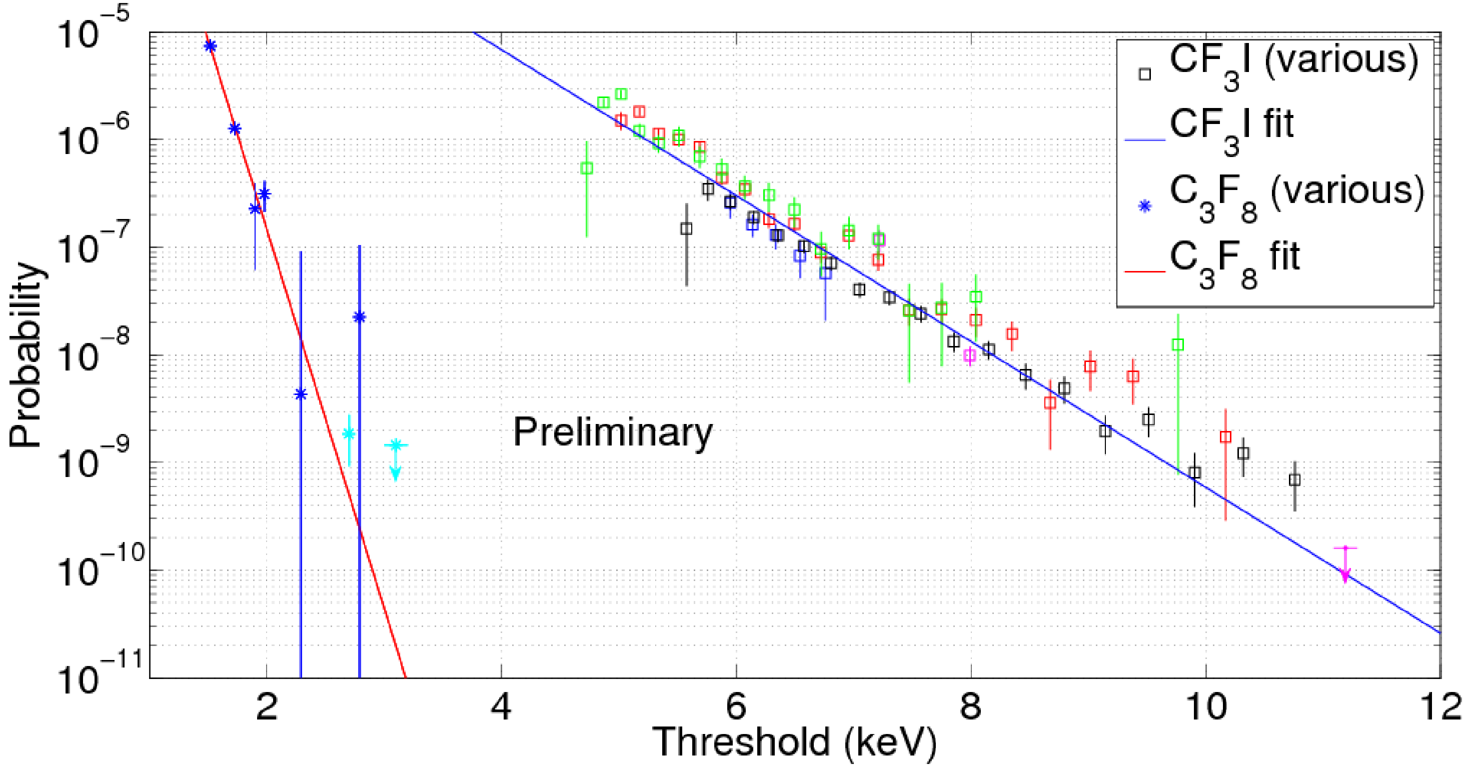
New two-bellows design inner vessel assembly. Silica jar is an exact replica of COUPP-4 jar.



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

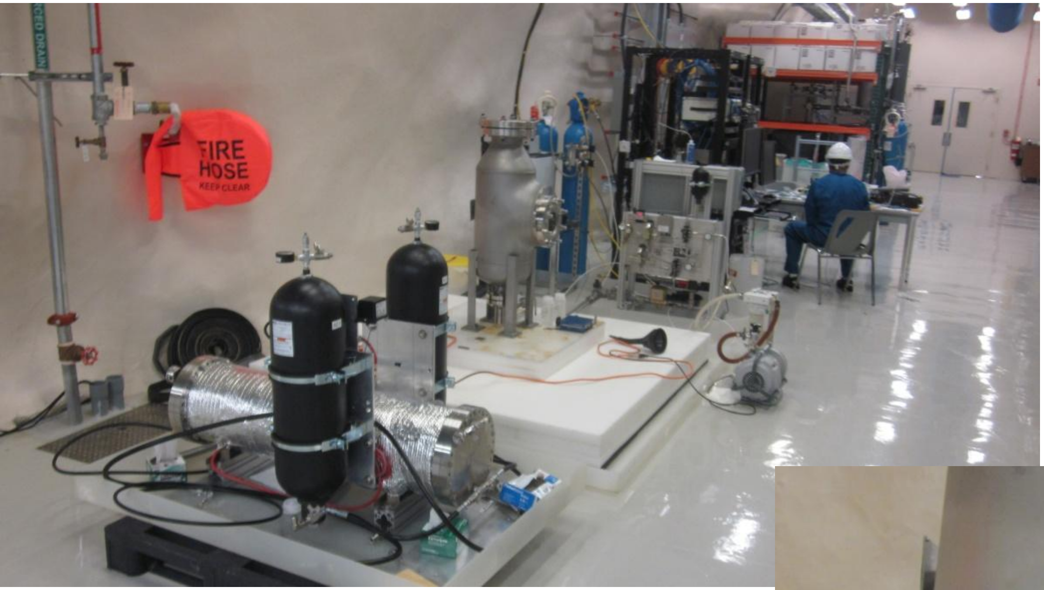
Electron recoil rejection

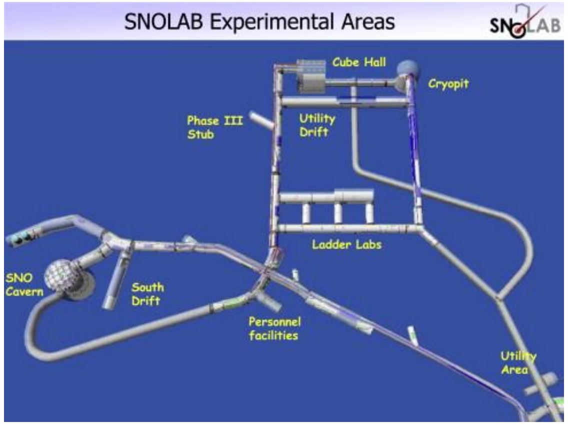
Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I



Preliminary results suggest the same 10^{-10} gamma rejection is possible with C_3F_8, and at a lower nuclear recoil threshold. A lower threshold extends the sensitivity to lower mass WIMPs.

PICO-2L installation at SNOLAB

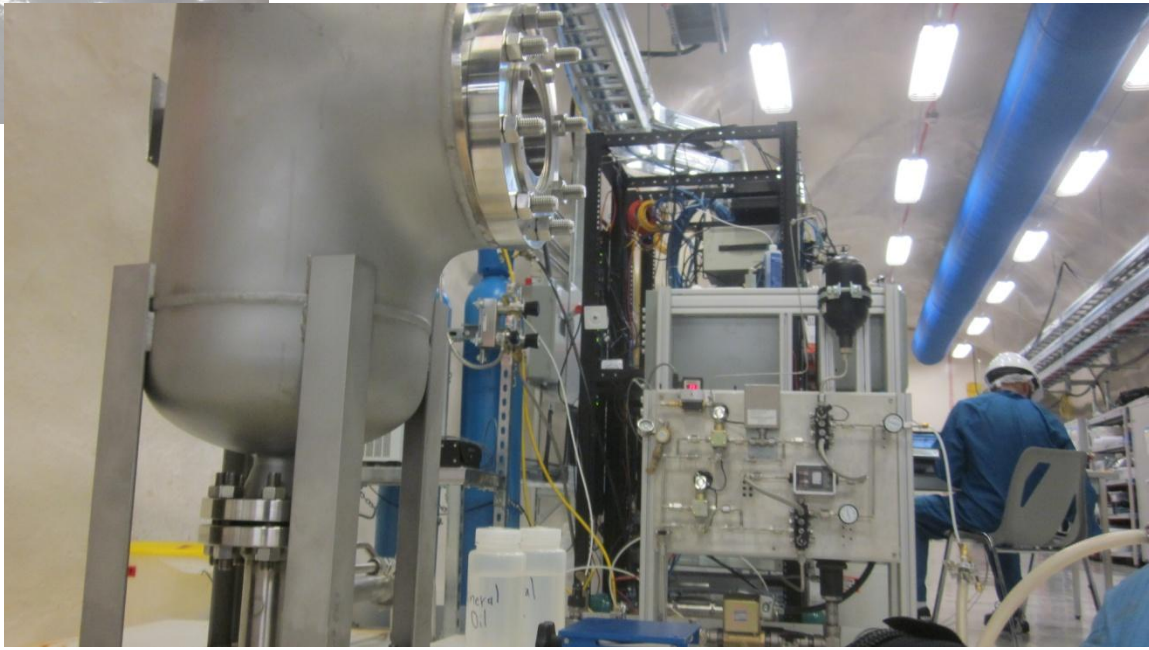




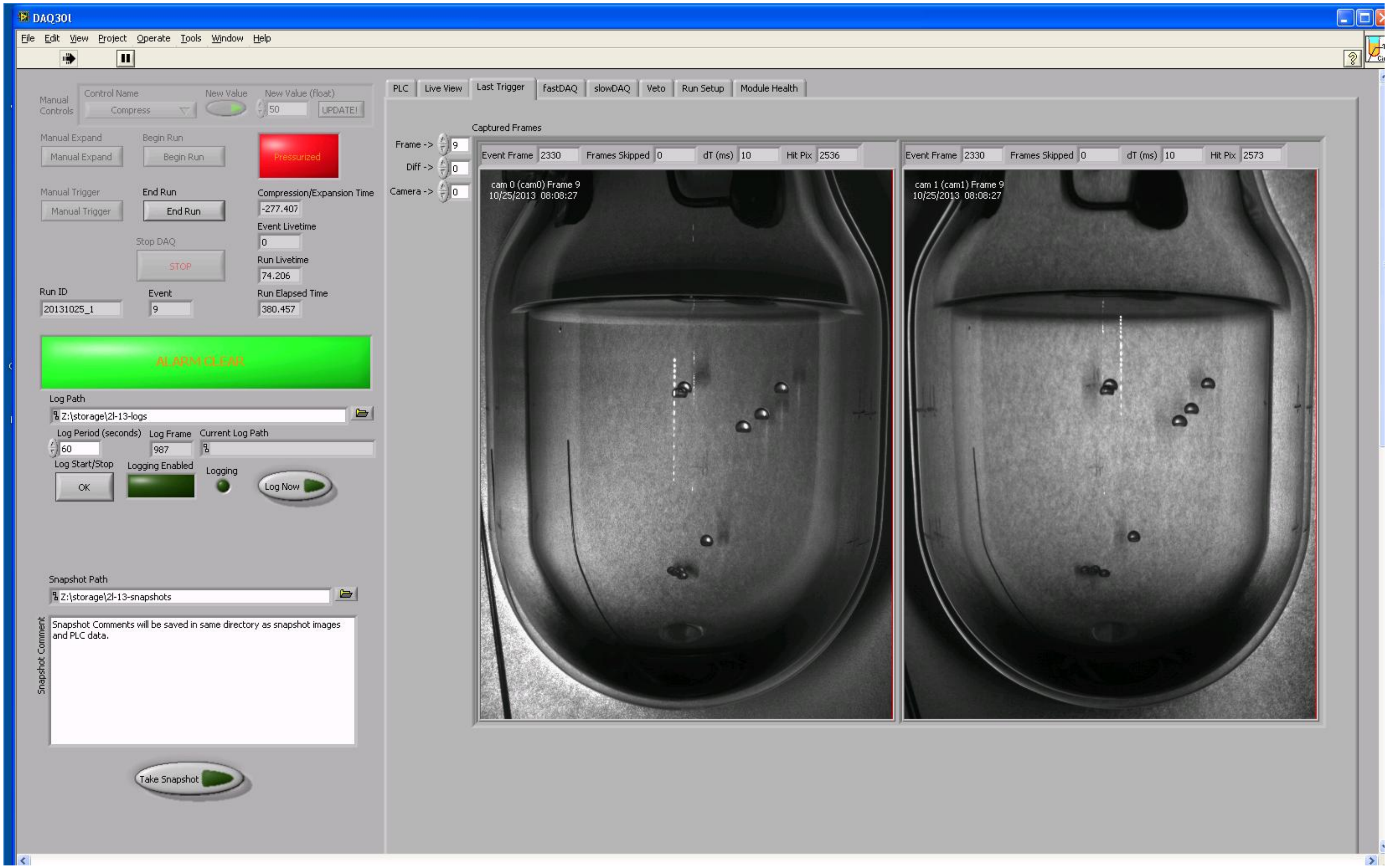
PICO-2L installed at SNOLAB in old COUPP-4 location.

Dark-matter data taking began Oct 28th, 2013.

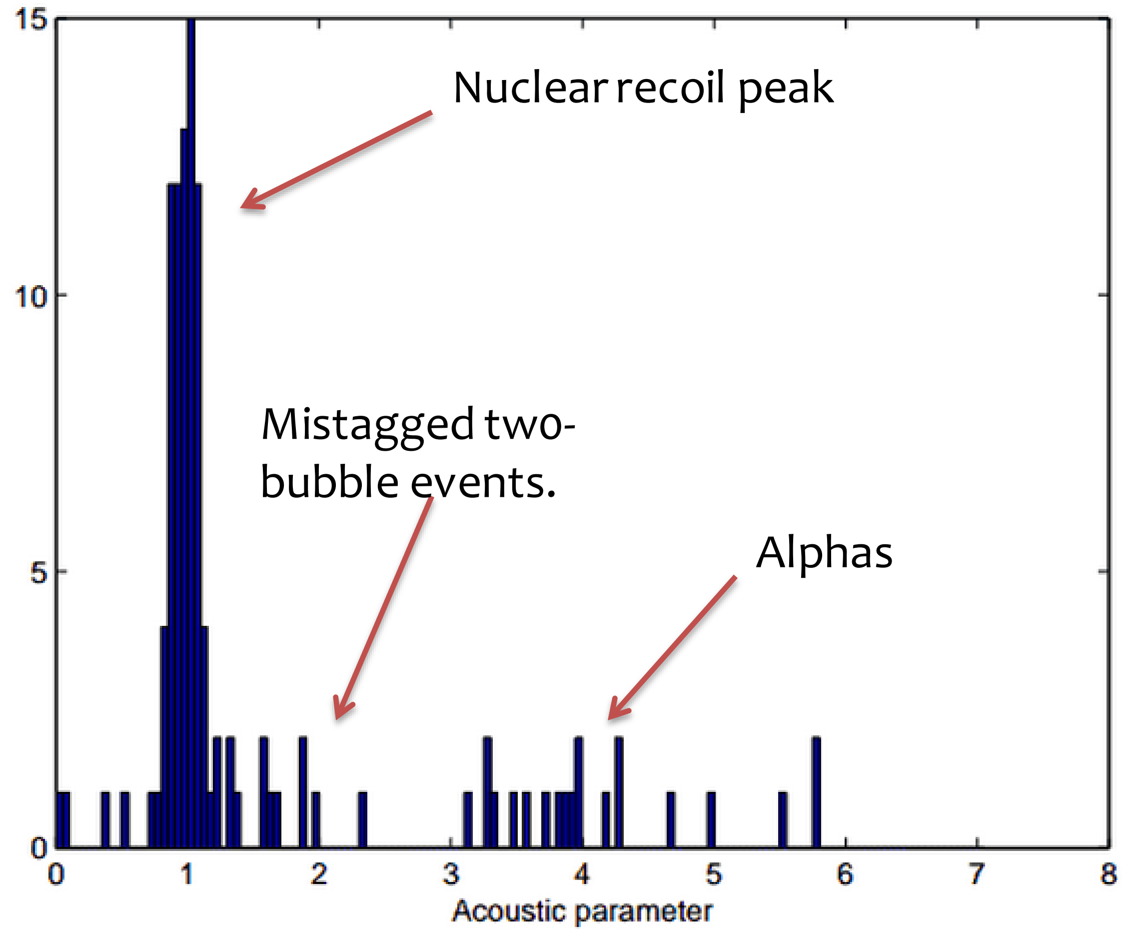
Currently running with 3keVnr threshold.



PICO-2L ten-bubble AmBe event

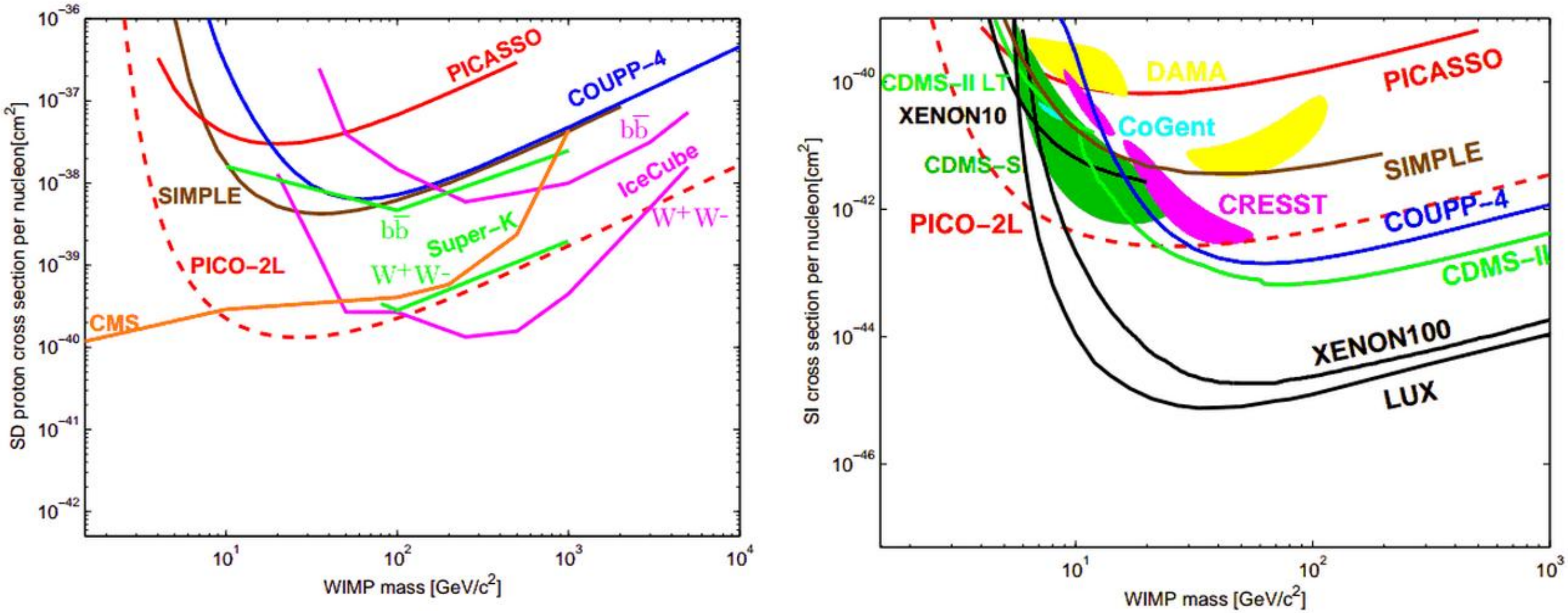


PICO-2L commissioning data



- Commissioning data with an AmBe neutron source.
- Variable threshold (~4keVnr).
- See a decaying population of alphas (radon), acoustically separate from nuclear recoils.
- Rough event reconstruction.

PICO-2L sensitivity projections

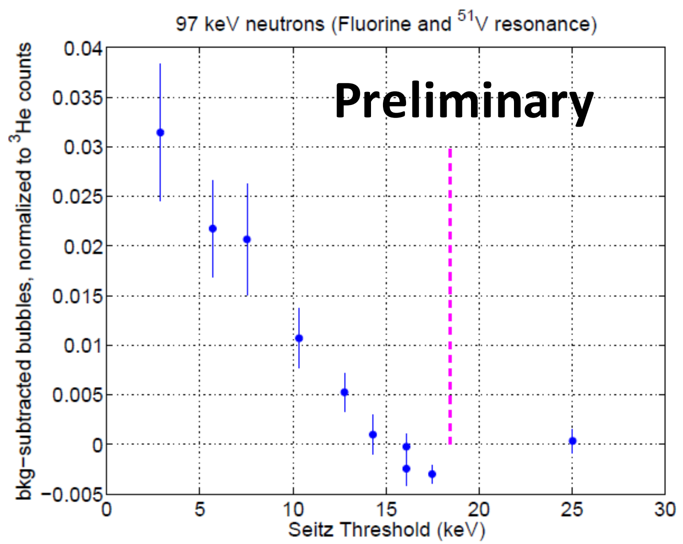


Projection based on 100 live-days, 3keV threshold, zero background.

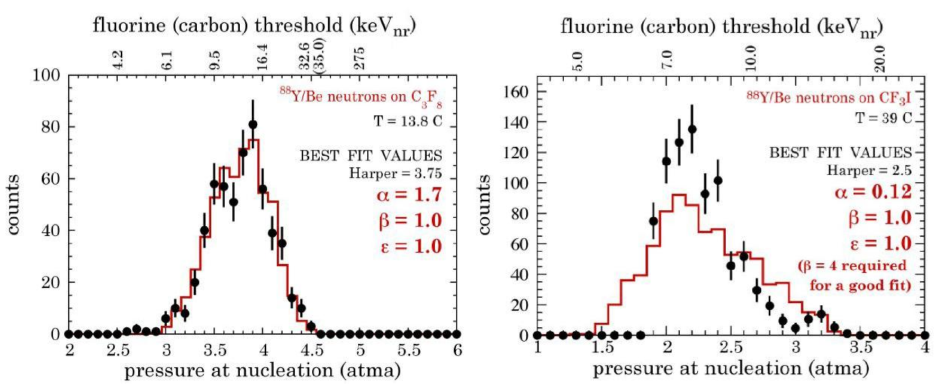
Neutron calibration program for C_3F_8

We are calibrating the nuclear recoil response of C_3F_8 with an in-situ AmBe neutron source as well as multiple low-energy neutron sources on test chambers.

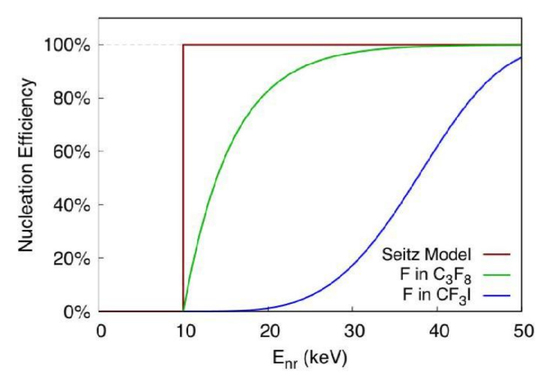
Monoenergetic neutron beam.



Low energy Y/Be neutron source.

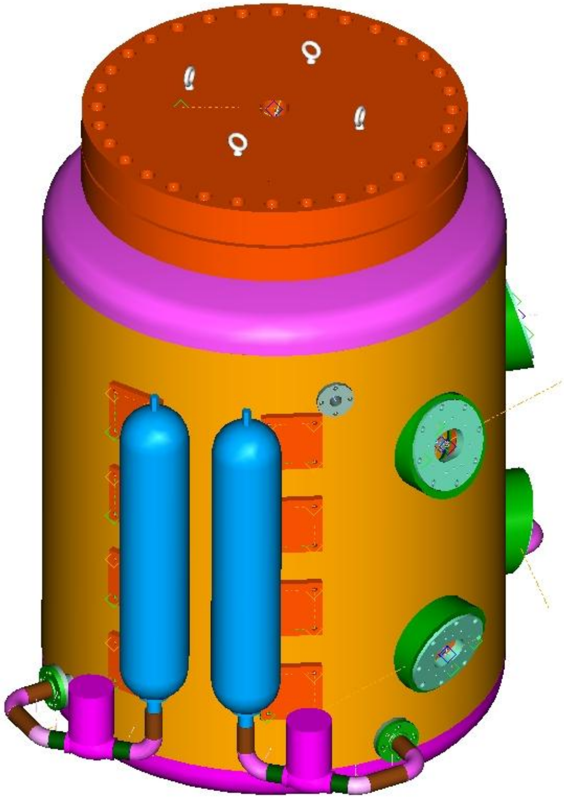


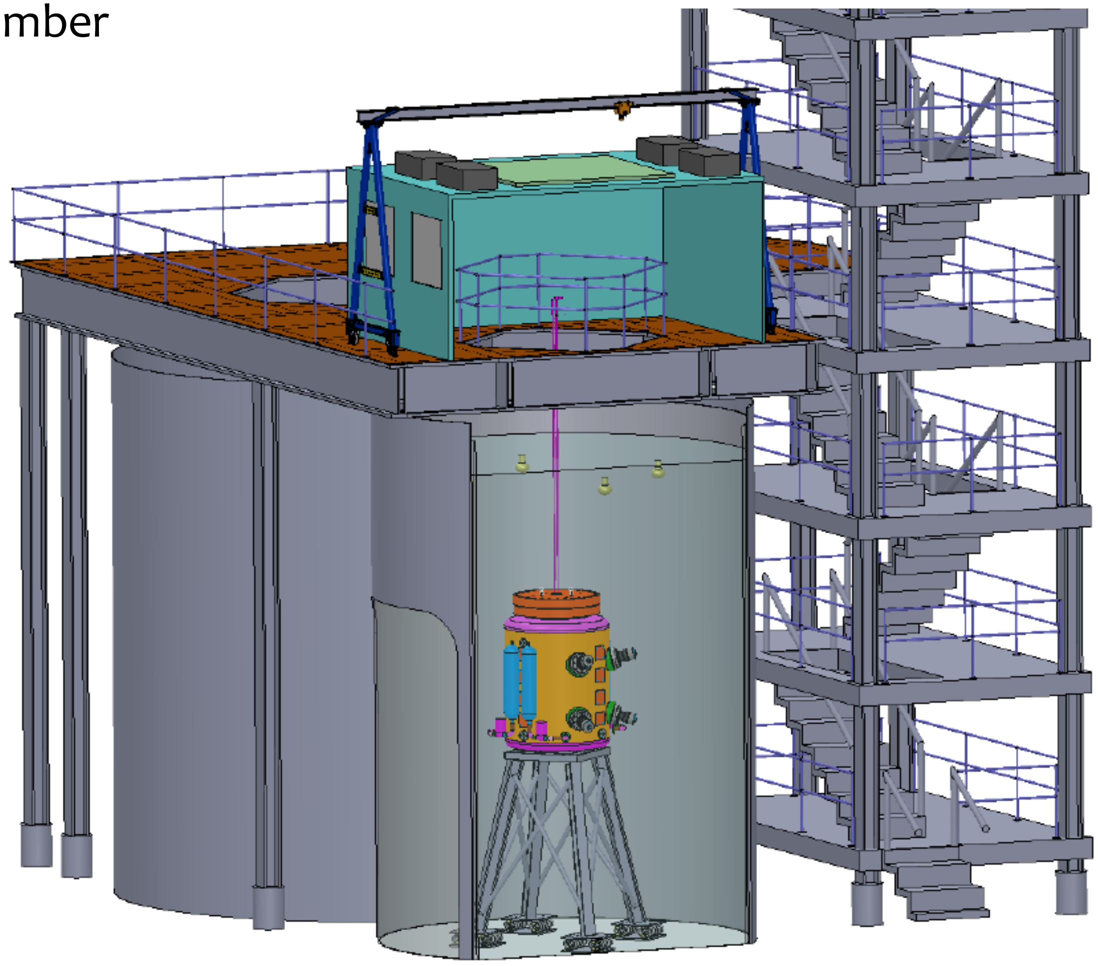
Preliminary



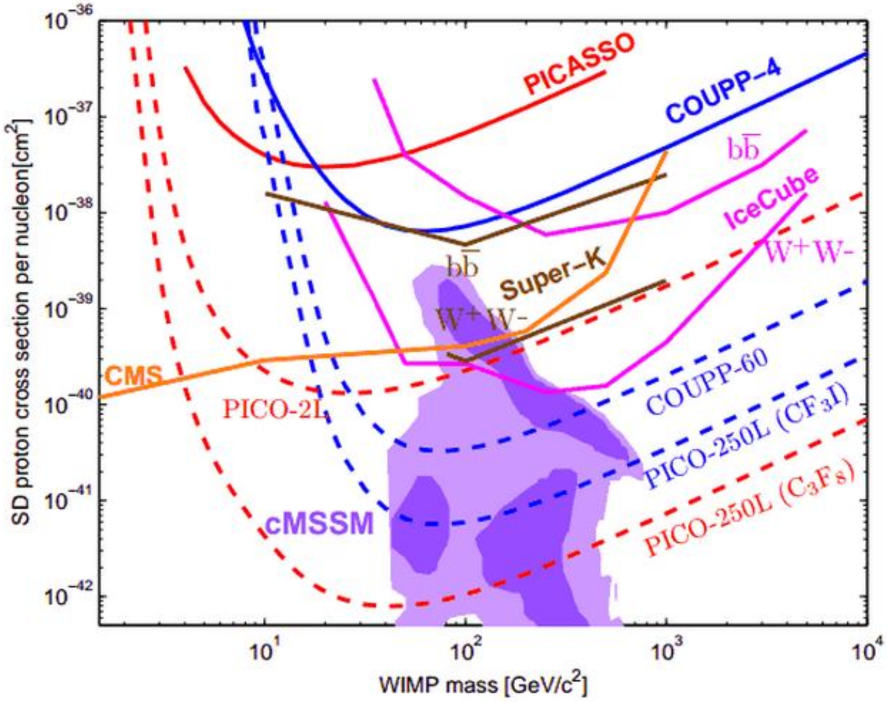
PICO-250L

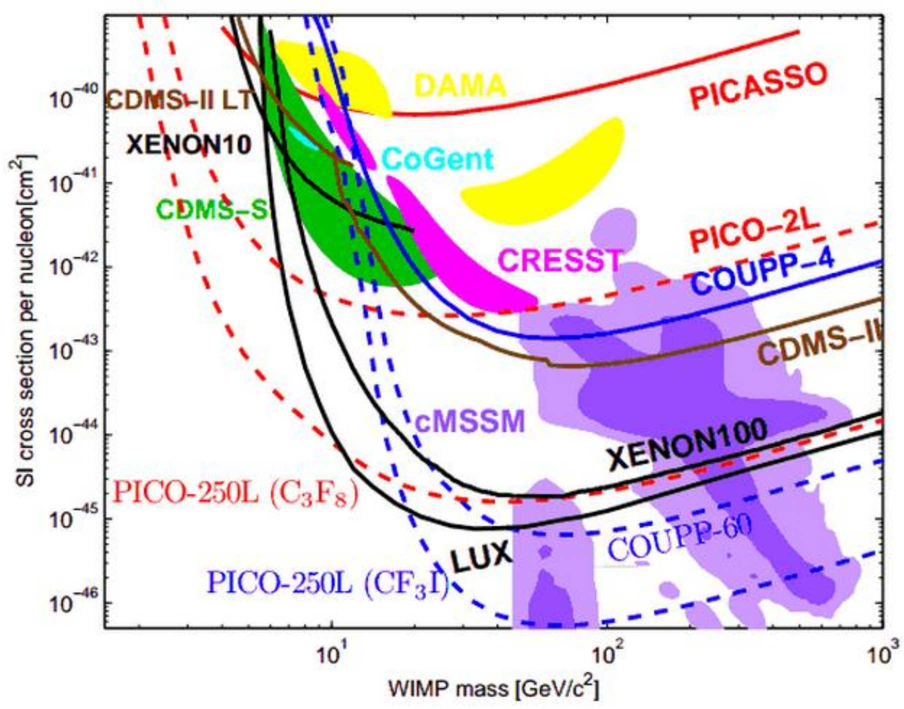
PICO-250L: ton-scale bubble chamber designed for CF_3I or C_3F_8 target





Sensitivity projections





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

Summary

- COUPP and PICASSO have merged to form the PICO collaboration to search for dark matter with superheated liquid detectors.
- COUPP-60 is running with 37kg CF_3I target. No neutron background, but a background population of events under study that are clearly not WIMPs.
- PICO-2L is now running at a 3keV threshold with 2.9kg C_3F_8 target. Projected world leading sensitivity for low mass WIMPs and spin-dependent couplings.
- PICO-250L is being designed with several potential fluids including C_3F_8 and CF_3I for operation beginning in 2016.

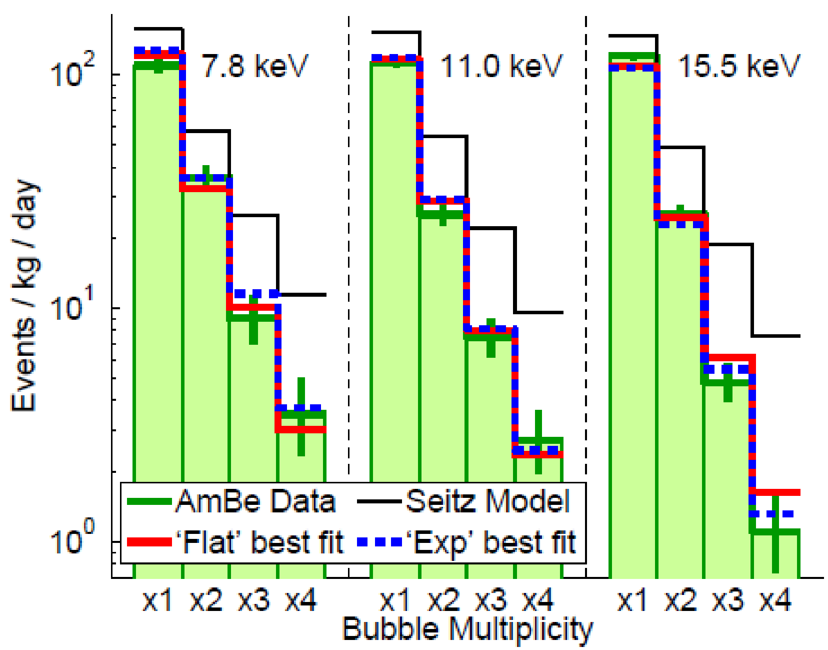
Backup slides

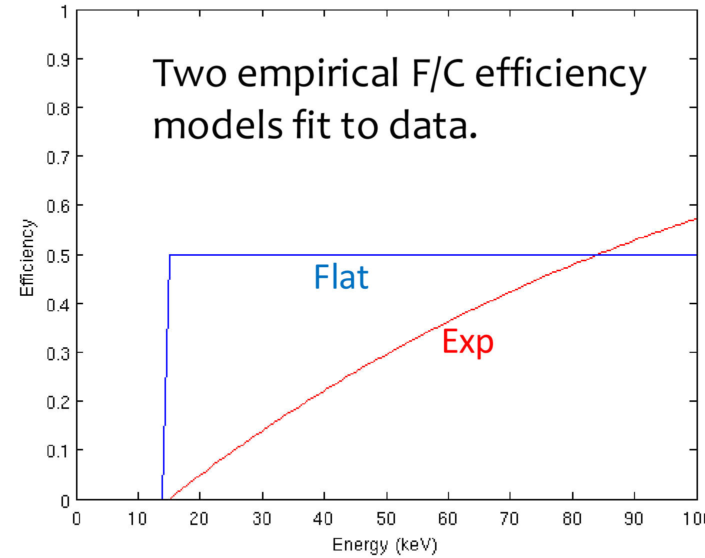
COUPP-4 neutron calibrations

•Threshold is determined using Seitz 'Hot Spike' Model, Phys. Fluids 1, 2 (1958).

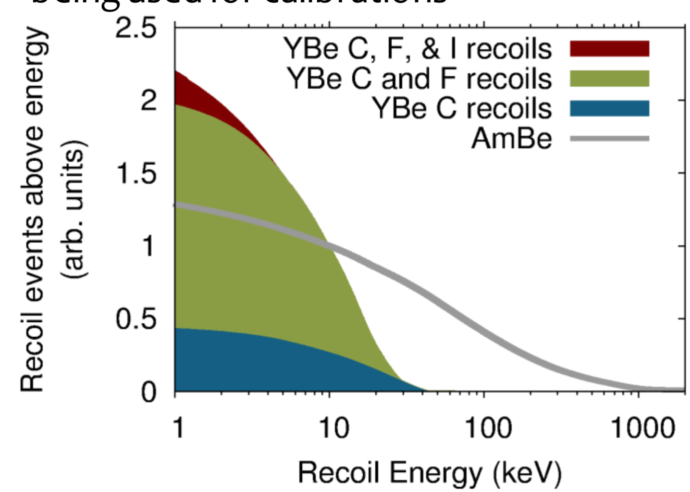
•Checked with neutron sources (AmBe, ^{252}Cf) employed regularly during the run.

•Evidence for a soft threshold in fluorine/carbon.



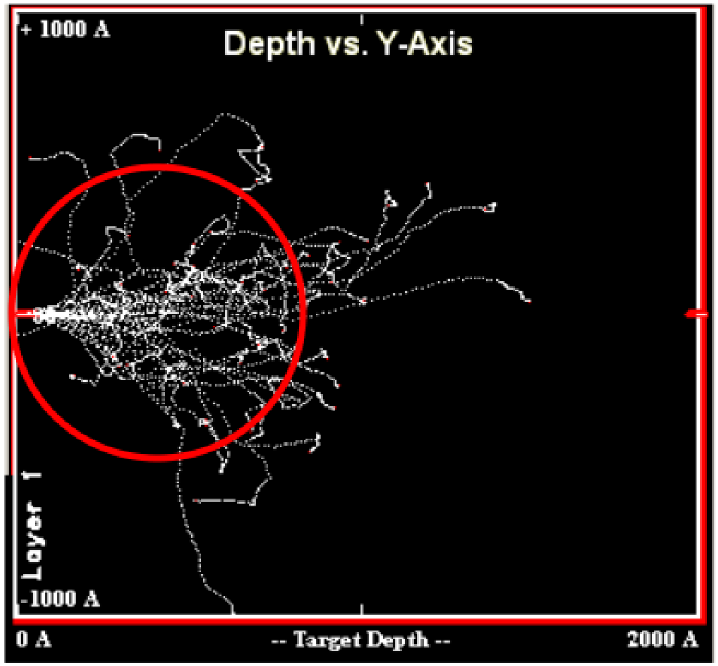


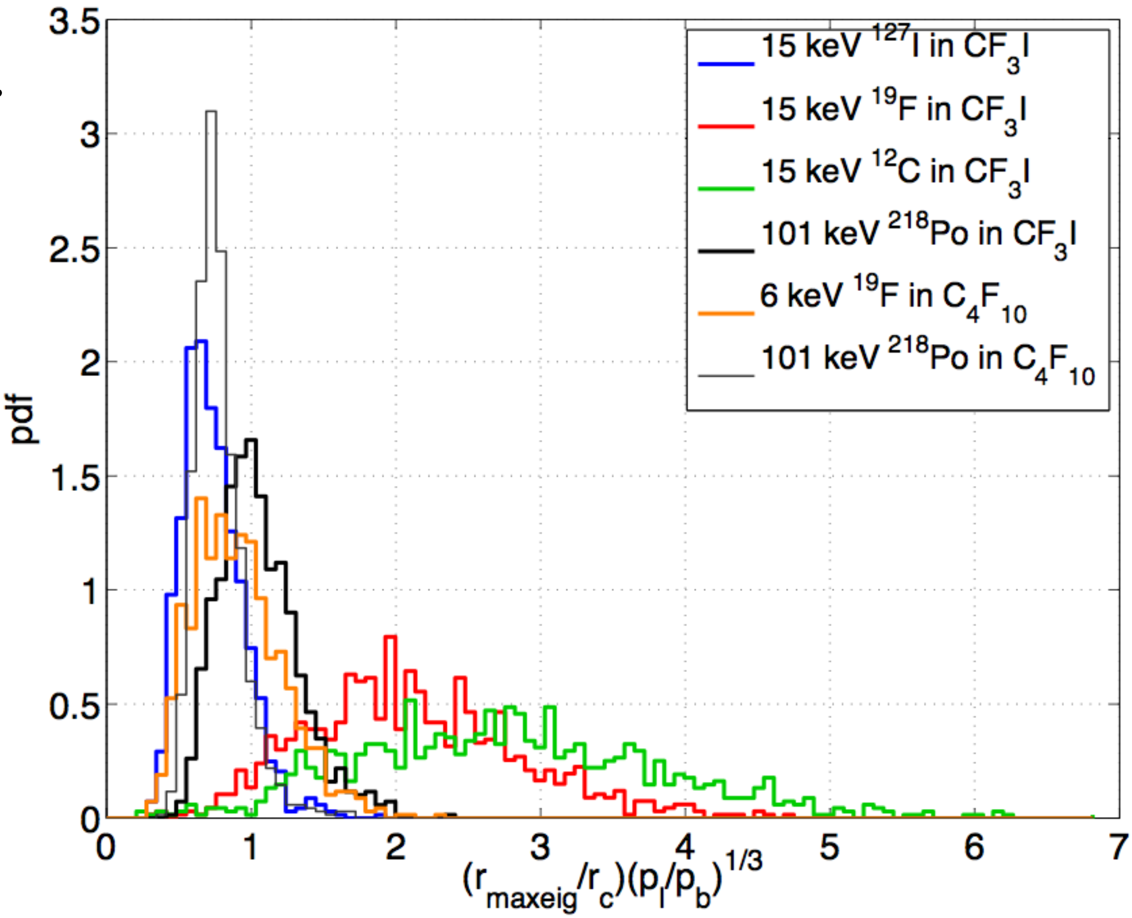
Y/Be low energy neutron source now being used for calibrations



Understanding low efficiency from fluorine recoils

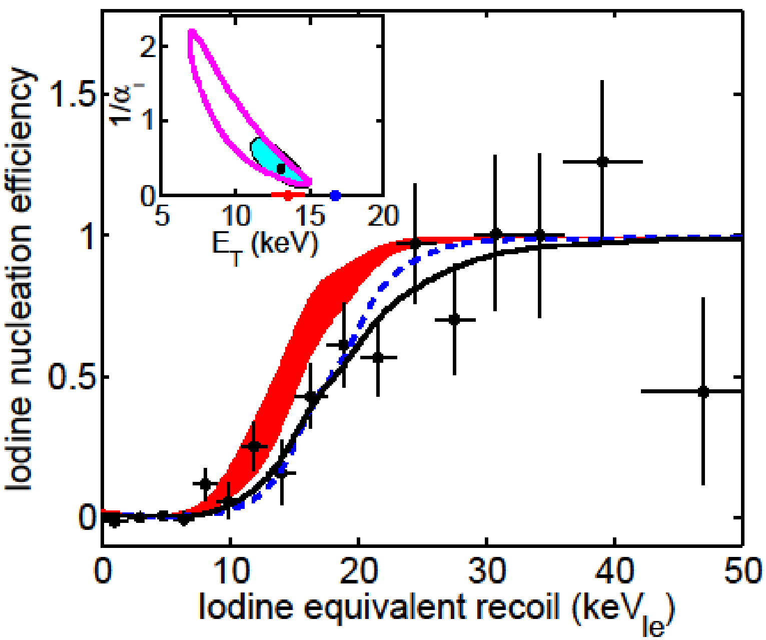
SRIM simulation of 15keV F recoils.





Nuclear recoil efficiency (iodine)

- Pion-scattering calibration of iodine threshold in CF_3I.



arXiv:1304.6001

- 12GeV pion beam with silicon pixel telescope to measure scattering angle.
- Example event: 6mrad scatter, 20keV Iodine recoil.